Knots for Quantum Computation from Defect branes

Urs Schreiber on joint work with Hisham Sati

NYU AD Science Division, Program of Mathematics

& Center for Quantum and Topological Systems

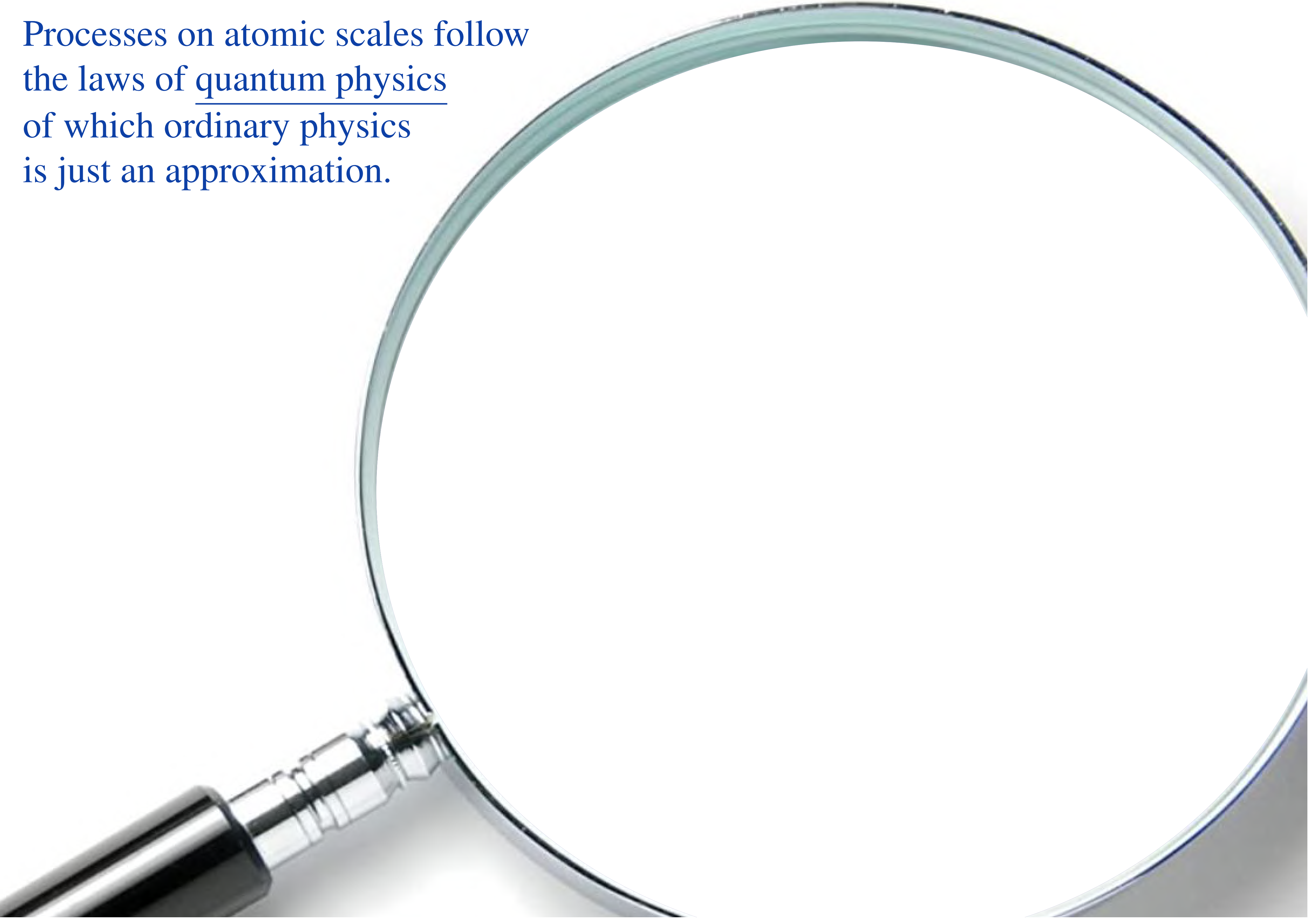
New York University, Abu Dhabi

talk at:

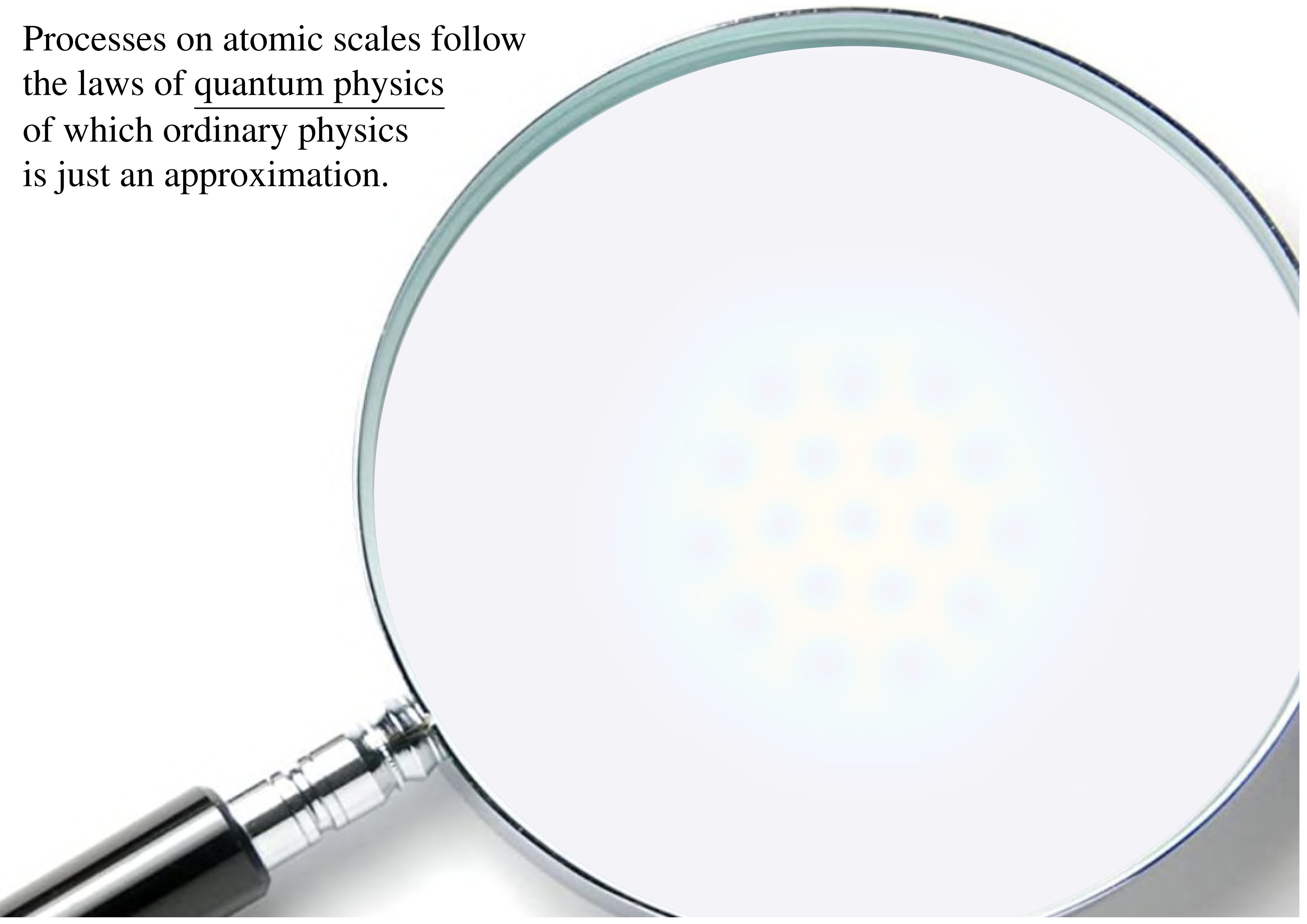
Topological Methods in Mathematical Physics @ Erice, 2 Sep 2022

slides and pointers at: https://ncatlab.org/schreiber/show/Knots+for+Quantum+Computation

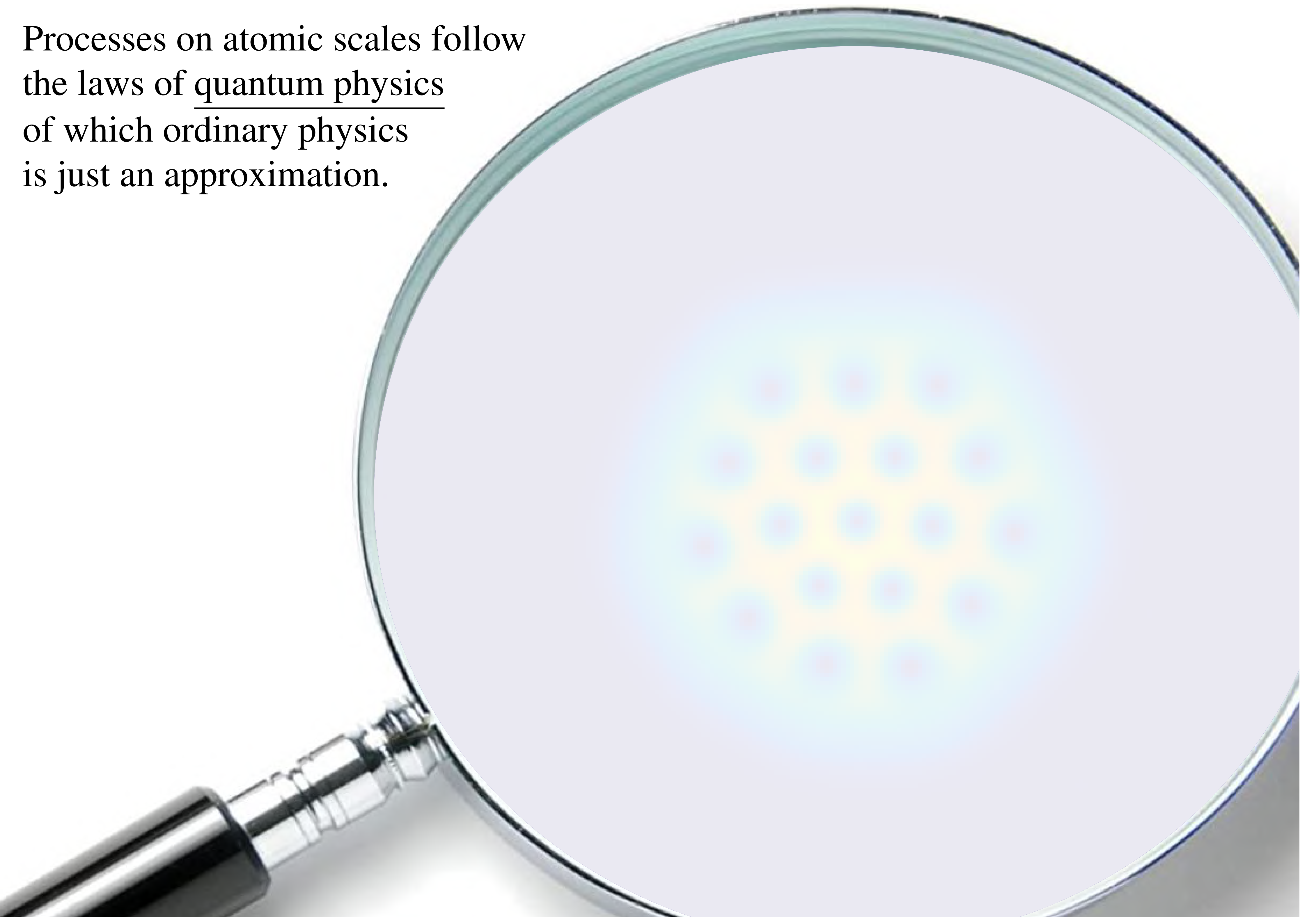
Processes on atomic scales follow
the laws of quantum physics
of which ordinary physics
is just an approximation.



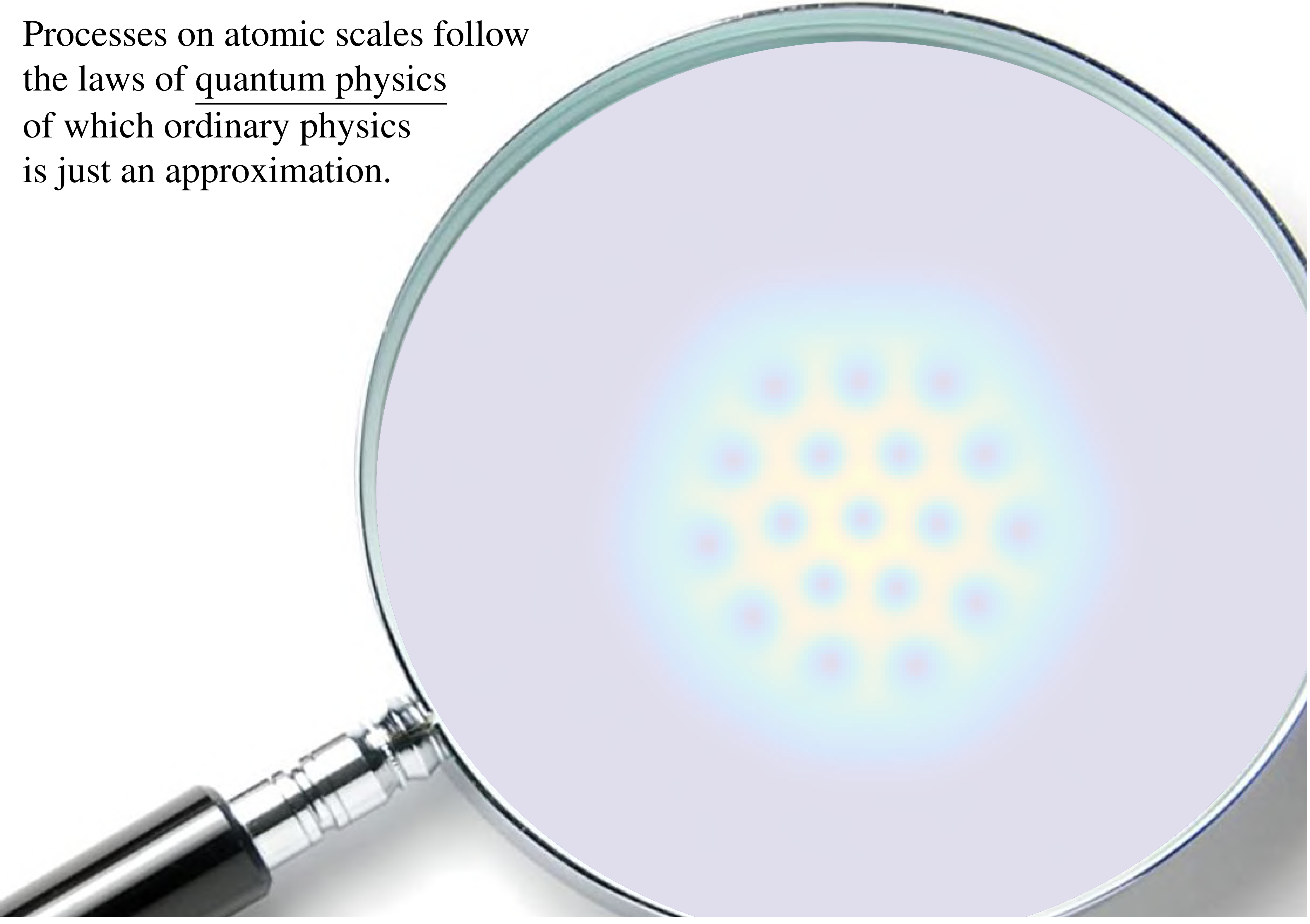
Processes on atomic scales follow
the laws of quantum physics
of which ordinary physics
is just an approximation.



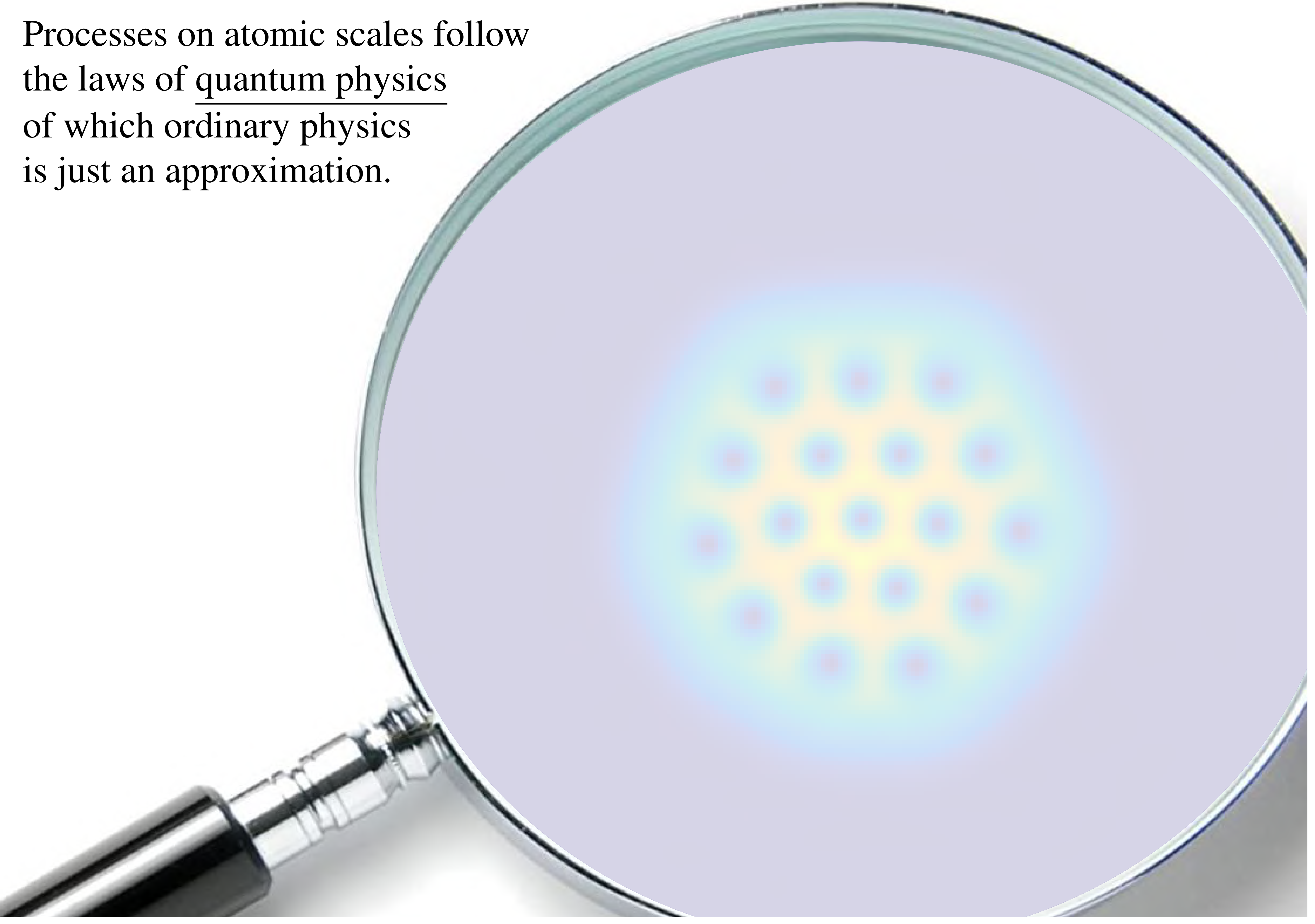
Processes on atomic scales follow
the laws of quantum physics
of which ordinary physics
is just an approximation.



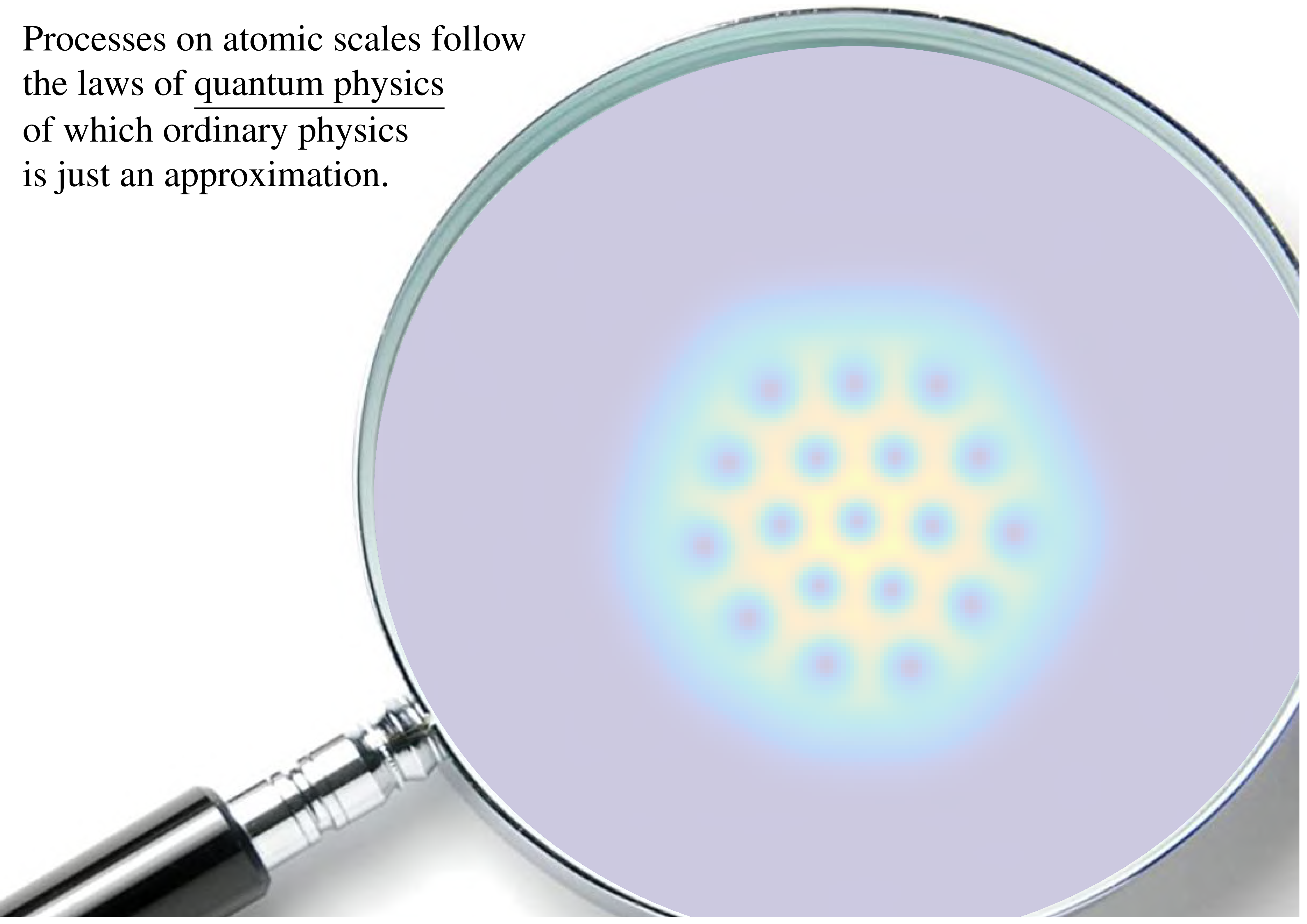
Processes on atomic scales follow
the laws of quantum physics
of which ordinary physics
is just an approximation.



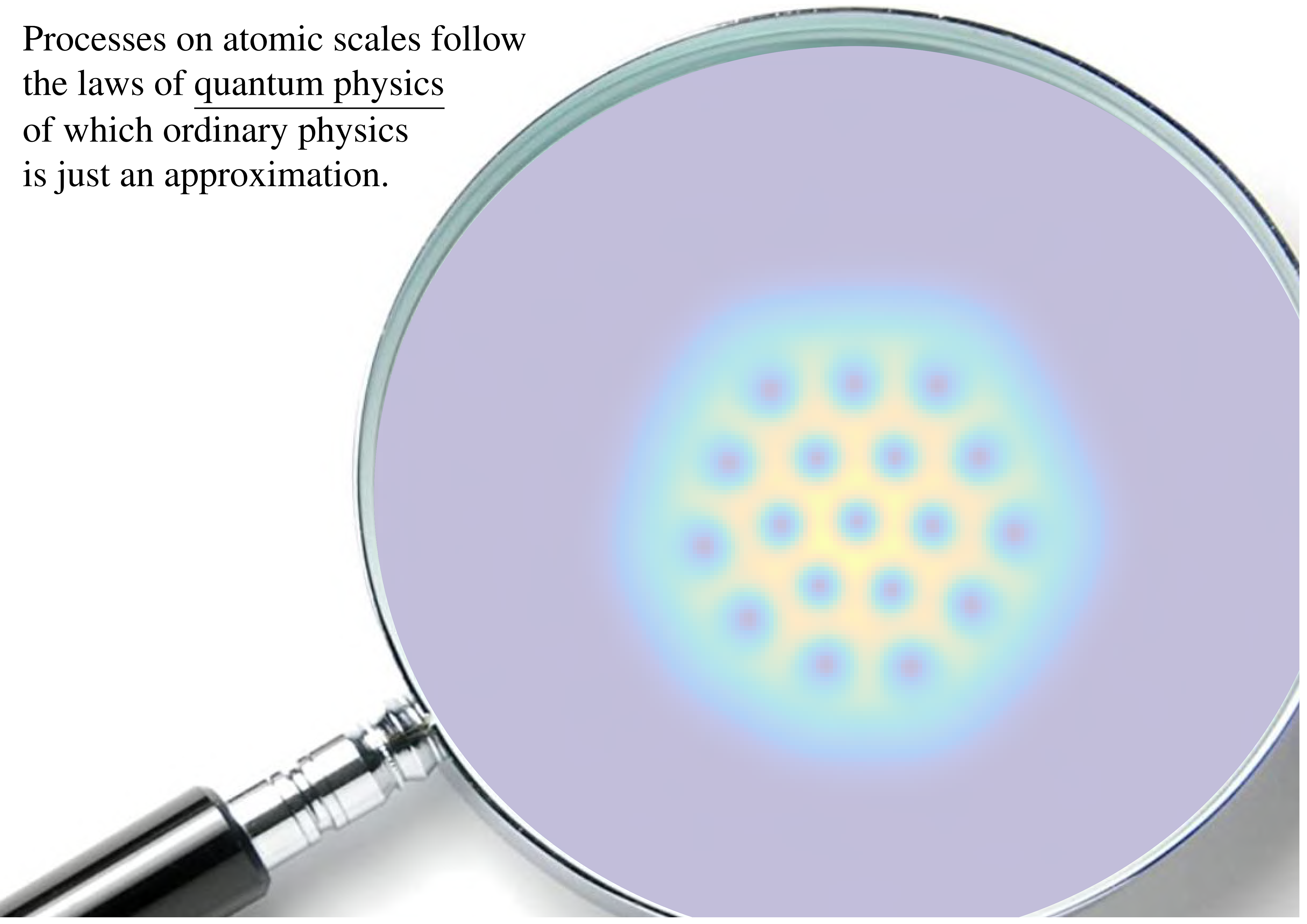
Processes on atomic scales follow
the laws of quantum physics
of which ordinary physics
is just an approximation.



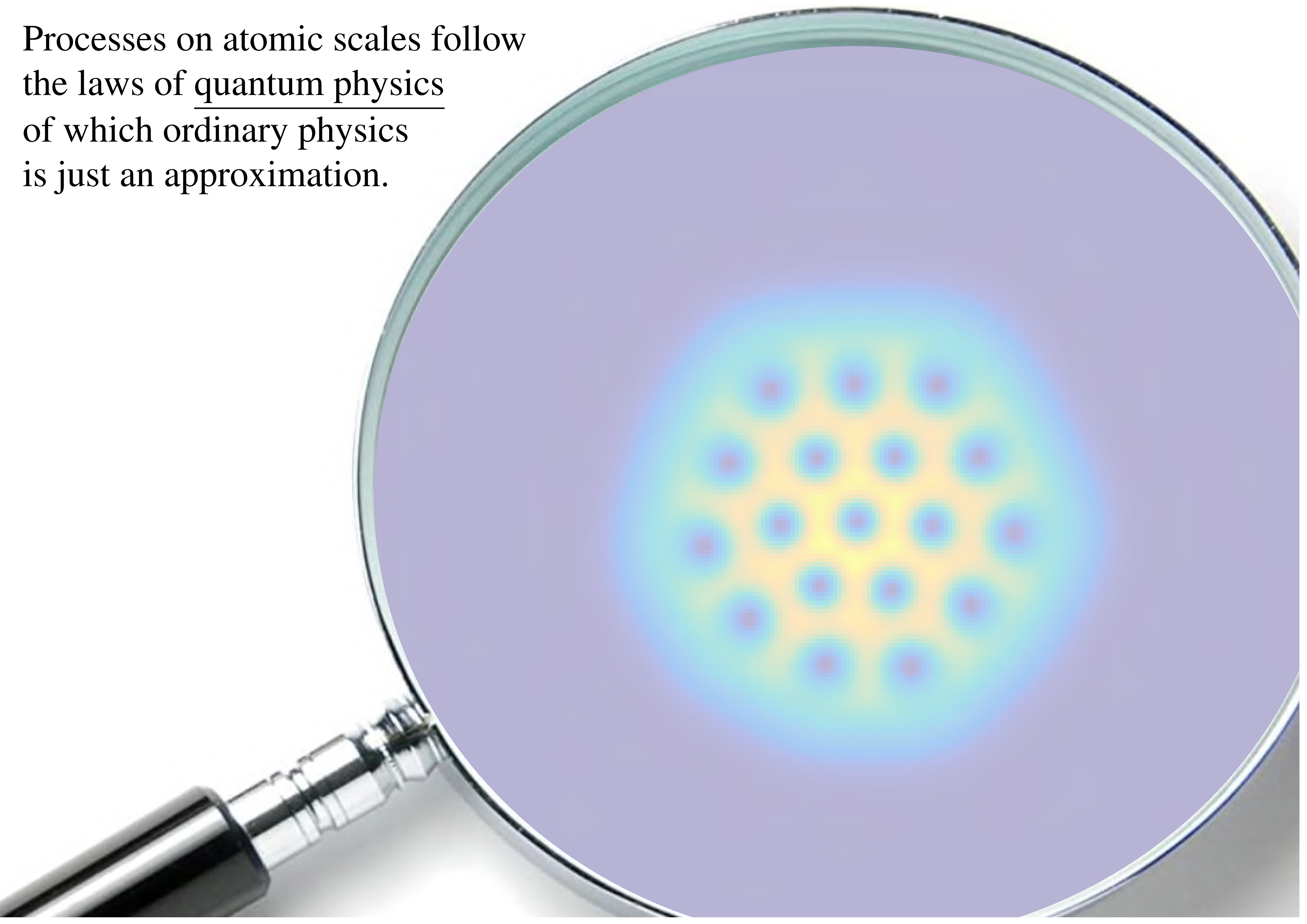
Processes on atomic scales follow
the laws of quantum physics
of which ordinary physics
is just an approximation.



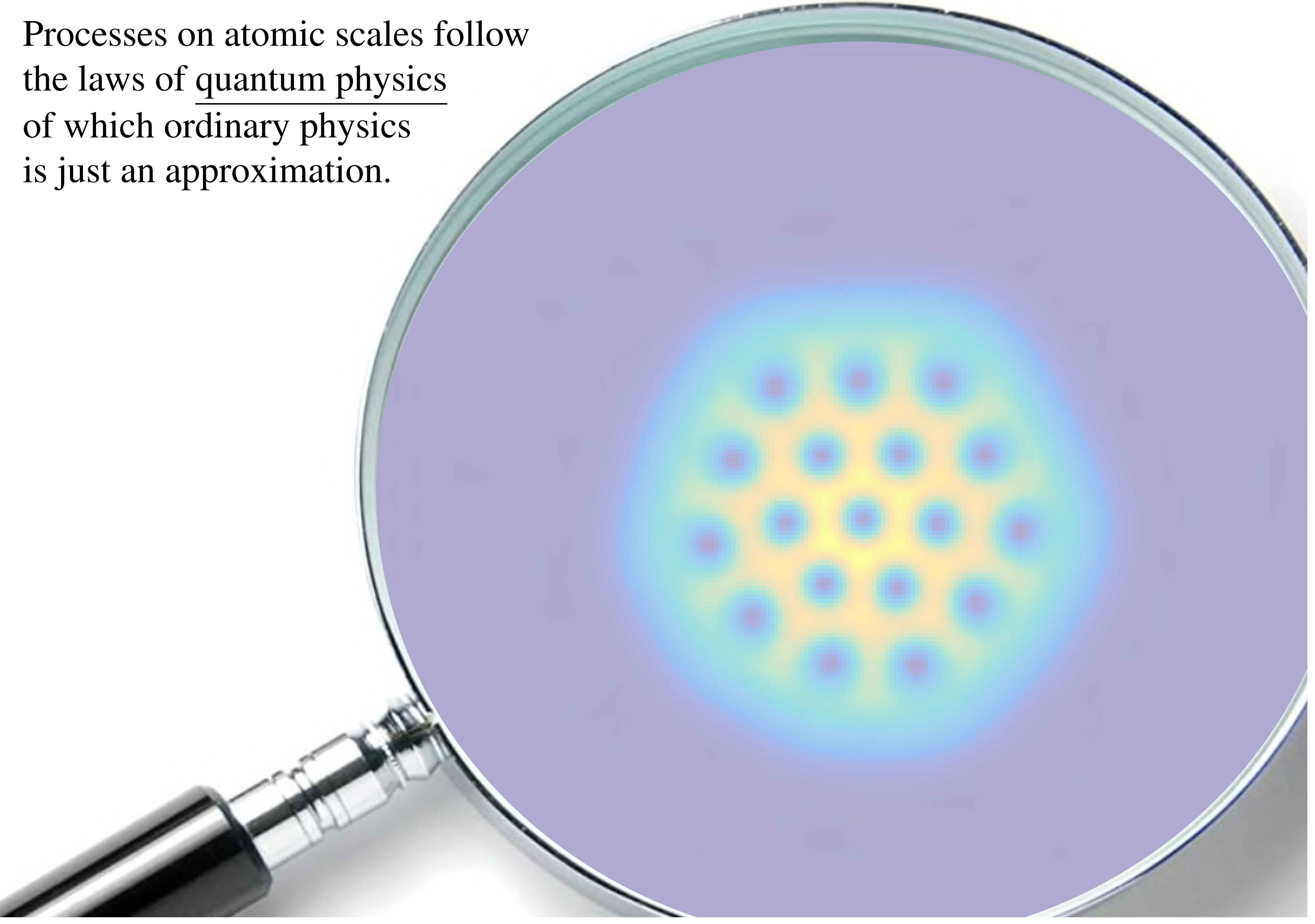
Processes on atomic scales follow the laws of quantum physics of which ordinary physics is just an approximation.



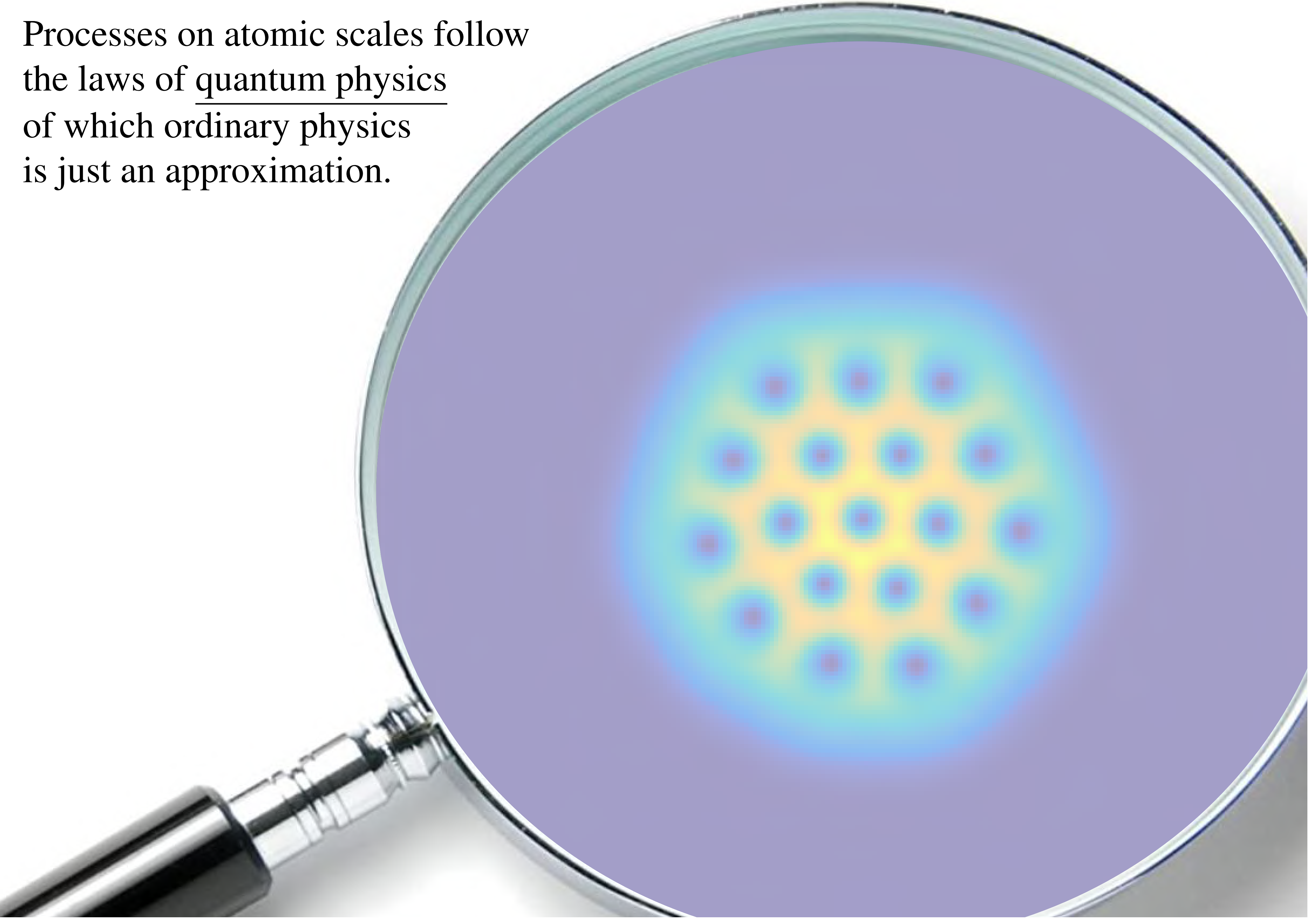
Processes on atomic scales follow the laws of quantum physics of which ordinary physics is just an approximation.



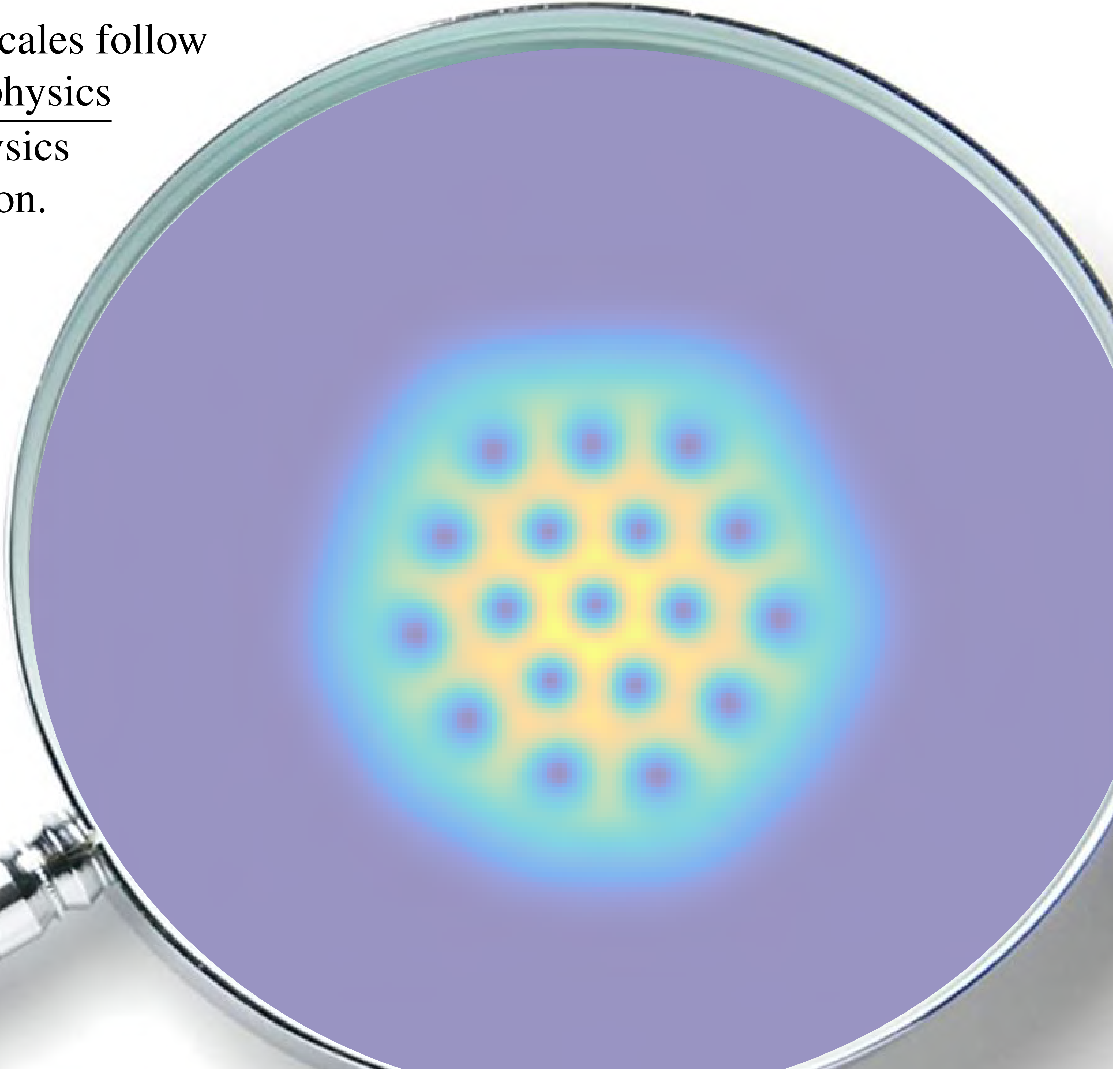
Processes on atomic scales follow the laws of quantum physics of which ordinary physics is just an approximation.



Processes on atomic scales follow the laws of quantum physics of which ordinary physics is just an approximation.



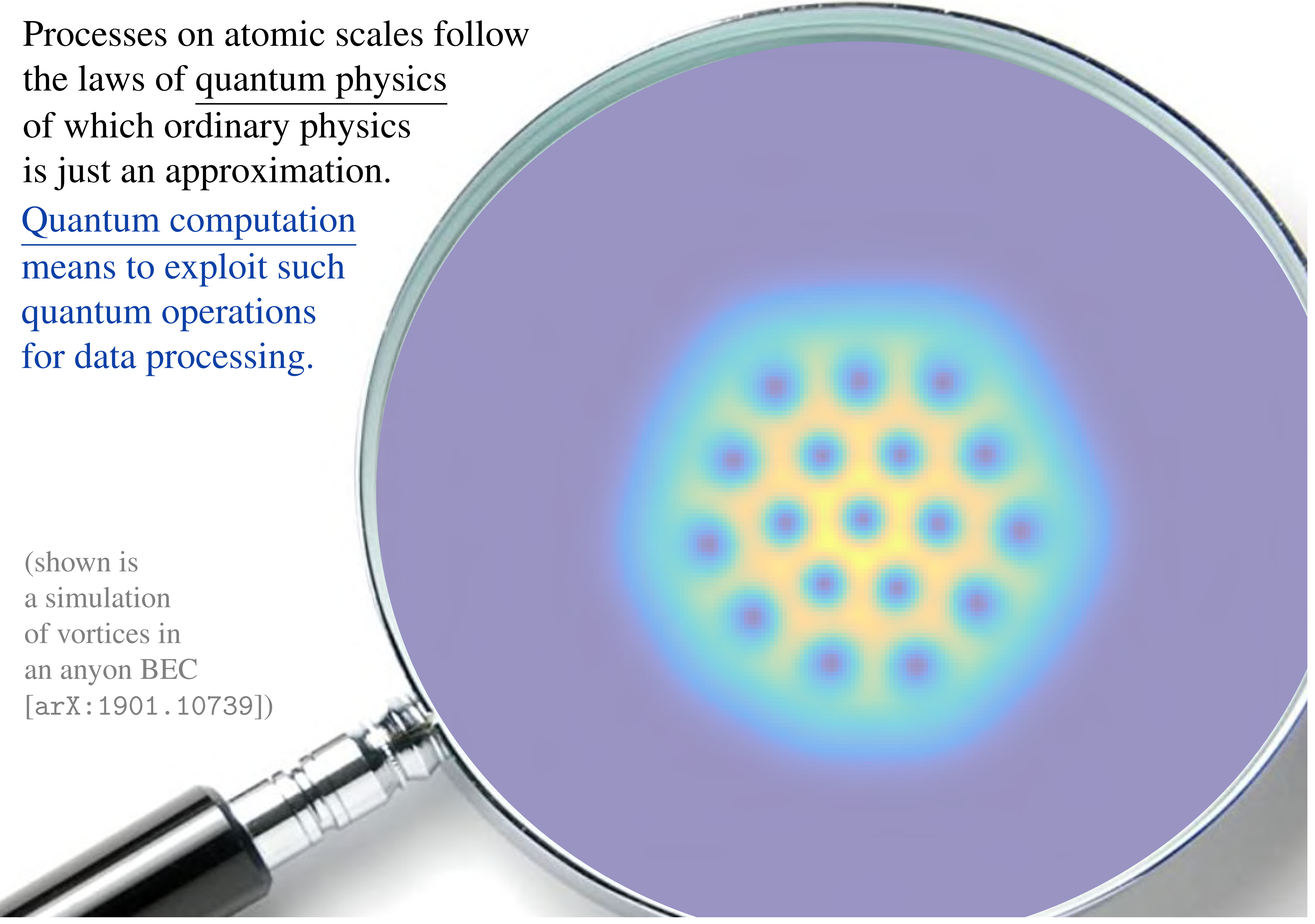
Processes on atomic scales follow the laws of quantum physics of which ordinary physics is just an approximation.



(shown is a simulation of vortices in an anyon BEC [arX:1901.10739])

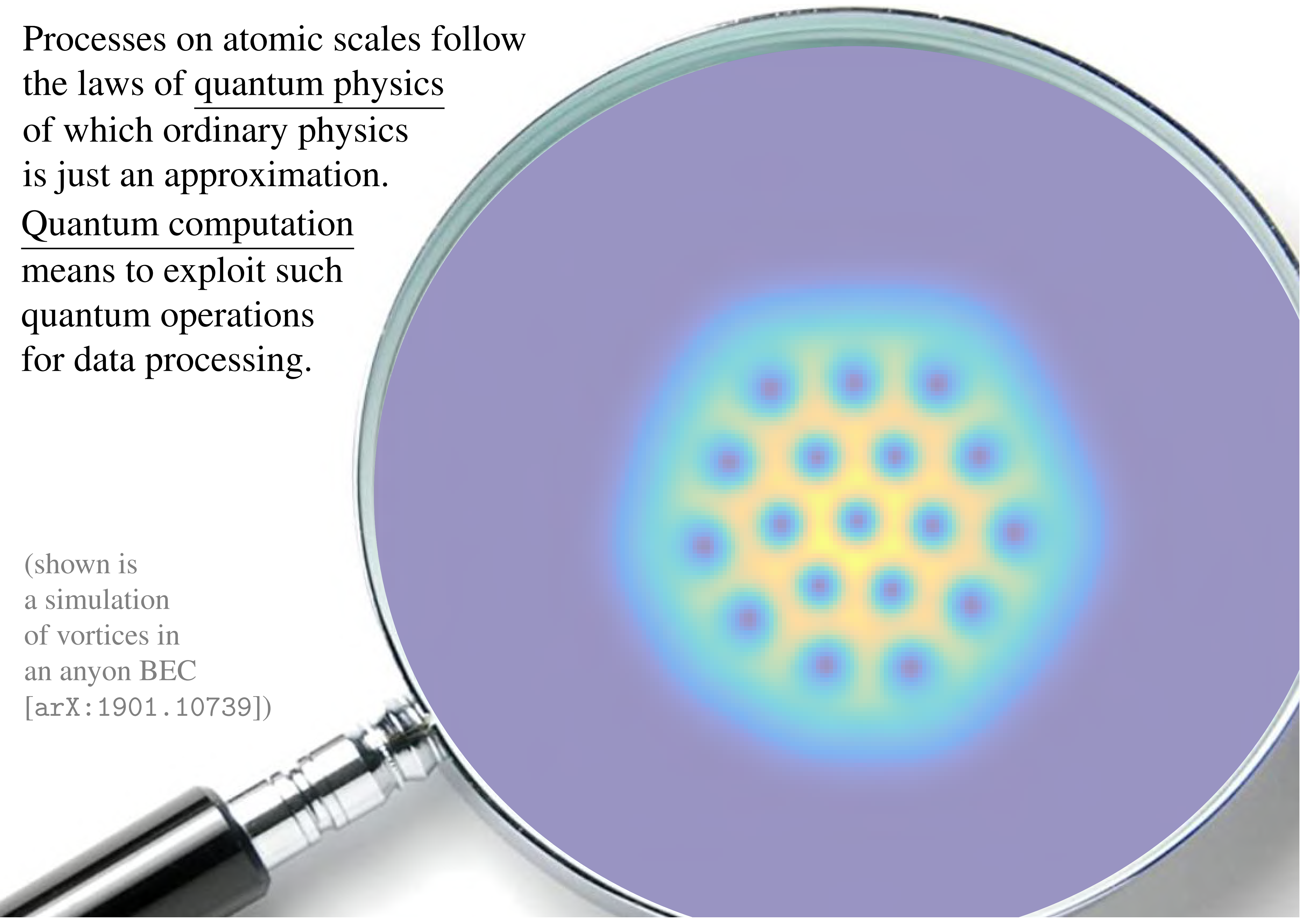
Processes on atomic scales follow the laws of quantum physics of which ordinary physics is just an approximation.

Quantum computation means to exploit such quantum operations for data processing.



(shown is a simulation of vortices in an anyon BEC [arX:1901.10739])

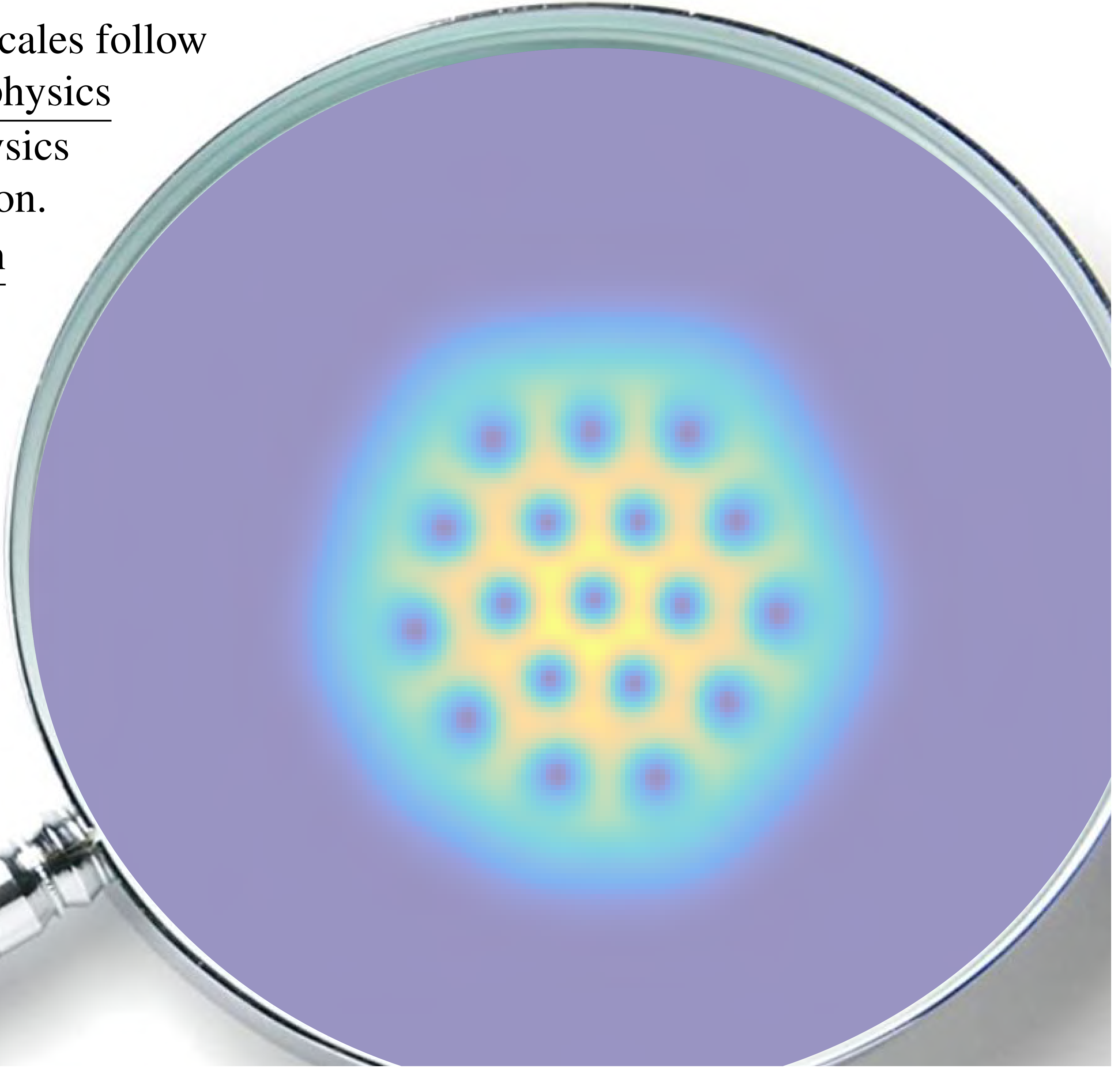
Processes on atomic scales follow the laws of quantum physics of which ordinary physics is just an approximation. Quantum computation means to exploit such quantum operations for data processing.



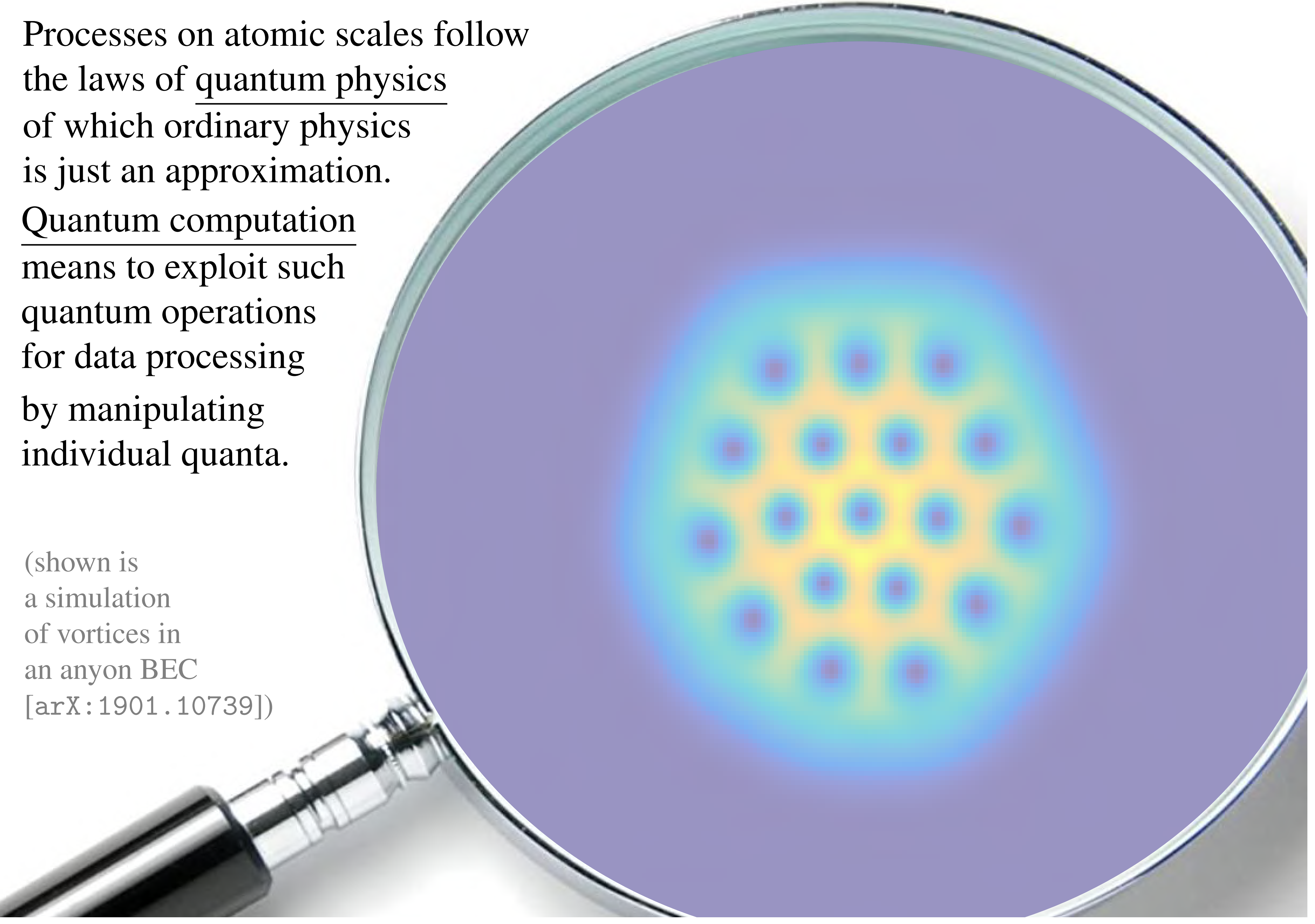
(shown is a simulation of vortices in an anyon BEC [arX:1901.10739])

Processes on atomic scales follow
the laws of quantum physics
of which ordinary physics
is just an approximation.
Quantum computation
means to exploit such
quantum operations
for data processing
by manipulating
individual quanta.

(shown is
a simulation
of vortices in
an anyon BEC
[arX:1901.10739])

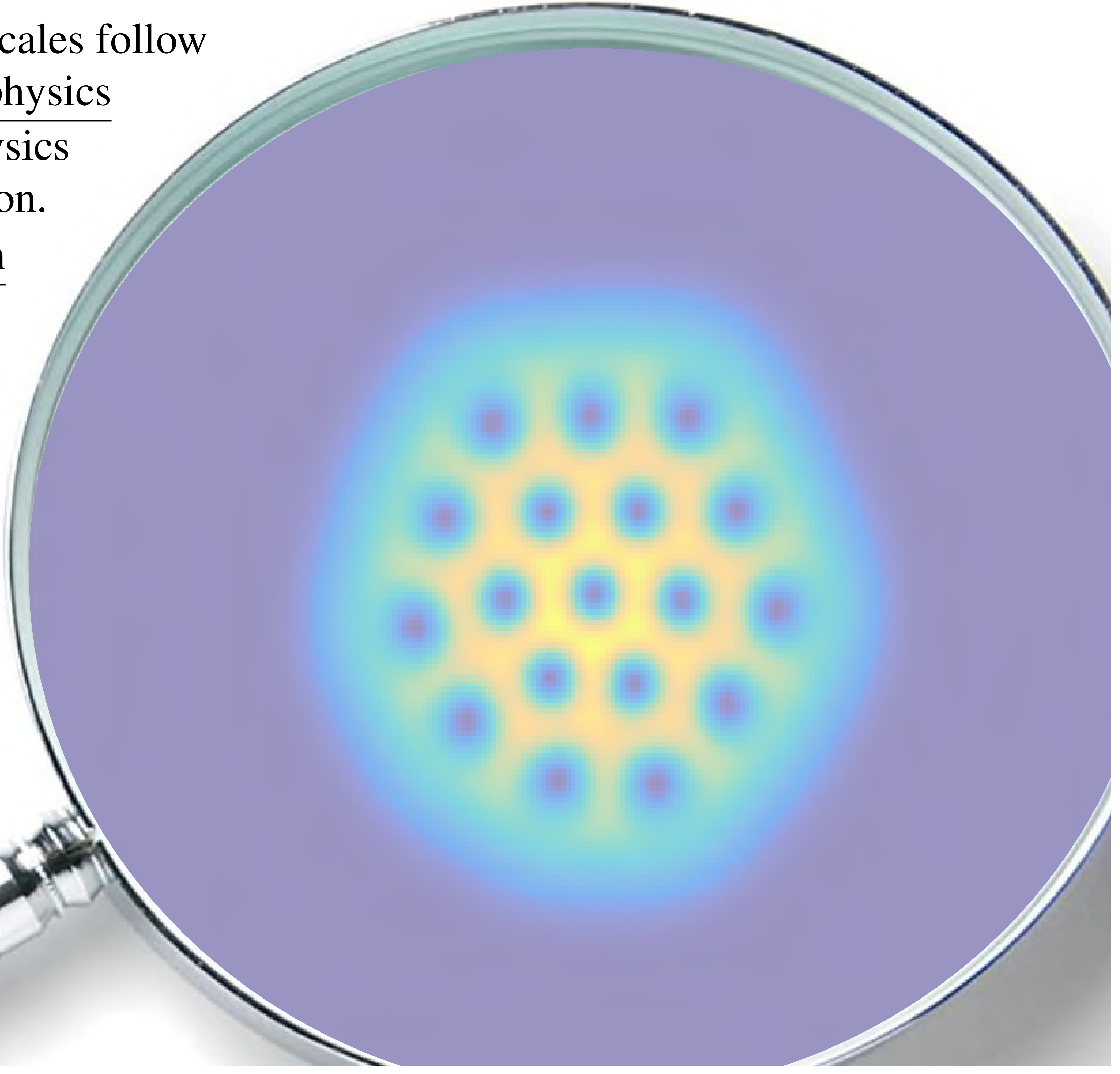


Processes on atomic scales follow the laws of quantum physics of which ordinary physics is just an approximation. Quantum computation means to exploit such quantum operations for data processing by manipulating individual quanta.



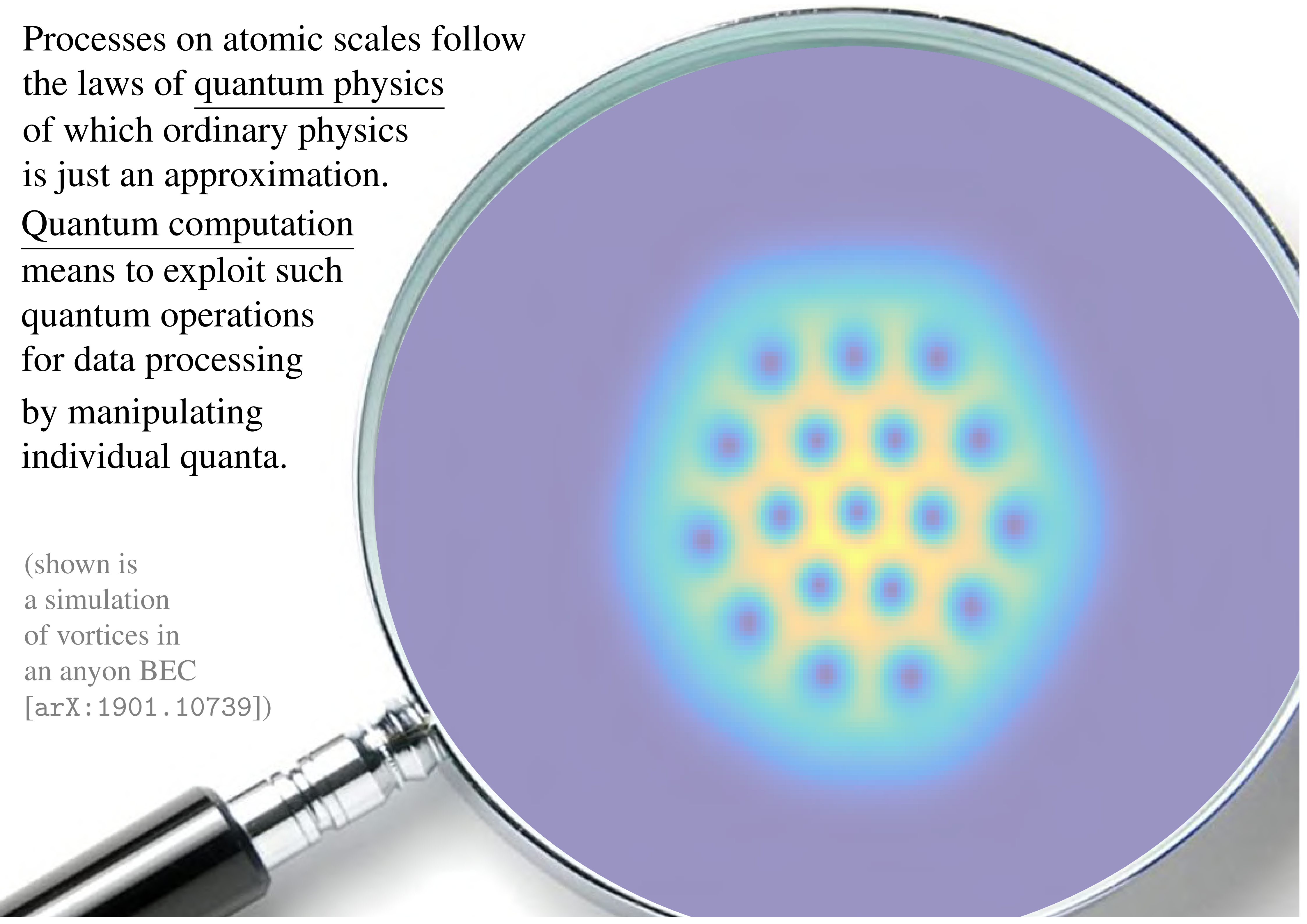
(shown is a simulation of vortices in an anyon BEC [arX:1901.10739])

Processes on atomic scales follow the laws of quantum physics of which ordinary physics is just an approximation. Quantum computation means to exploit such quantum operations for data processing by manipulating individual quanta.



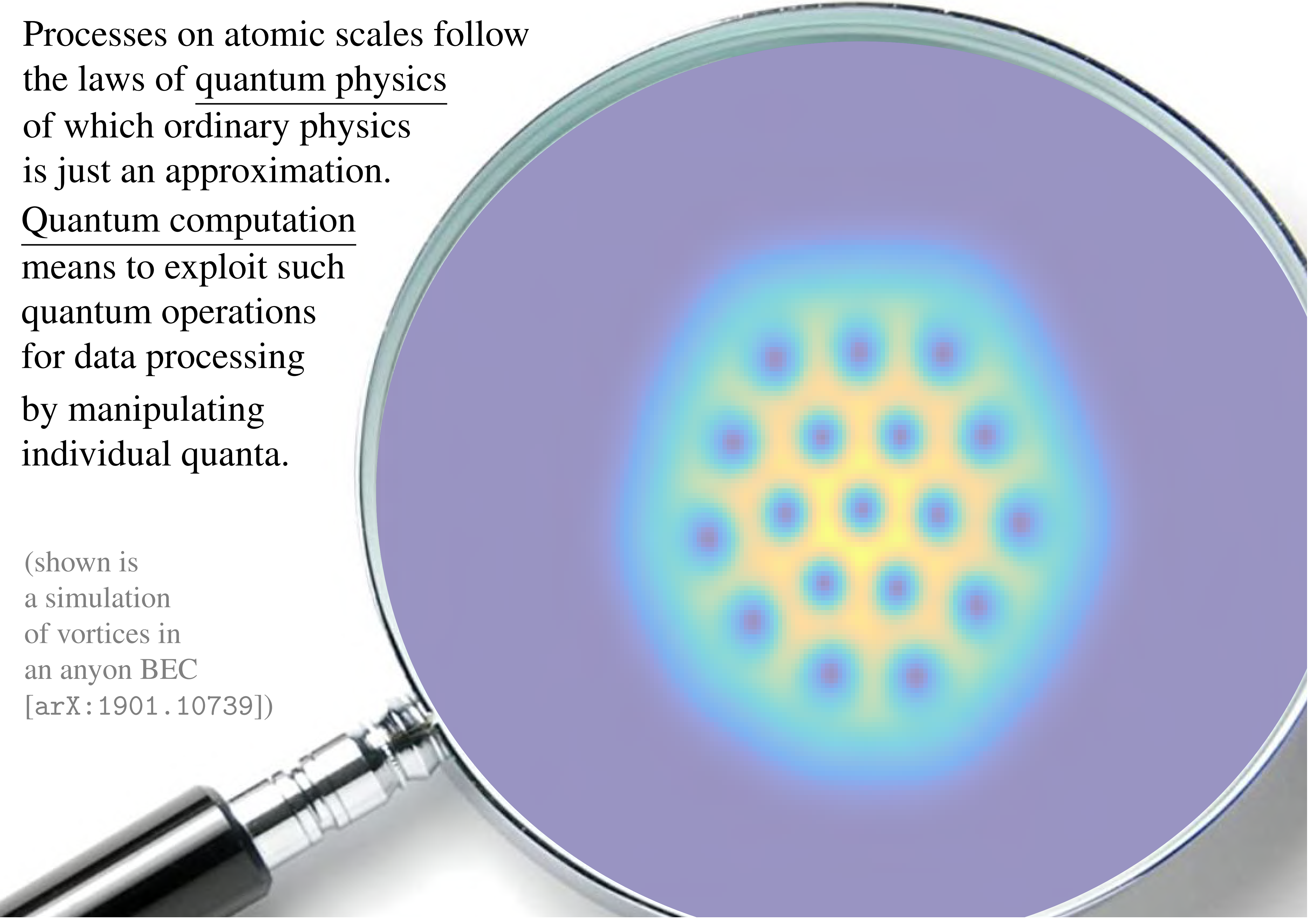
(shown is a simulation of vortices in an anyon BEC [arX:1901.10739])

Processes on atomic scales follow the laws of quantum physics of which ordinary physics is just an approximation. Quantum computation means to exploit such quantum operations for data processing by manipulating individual quanta.



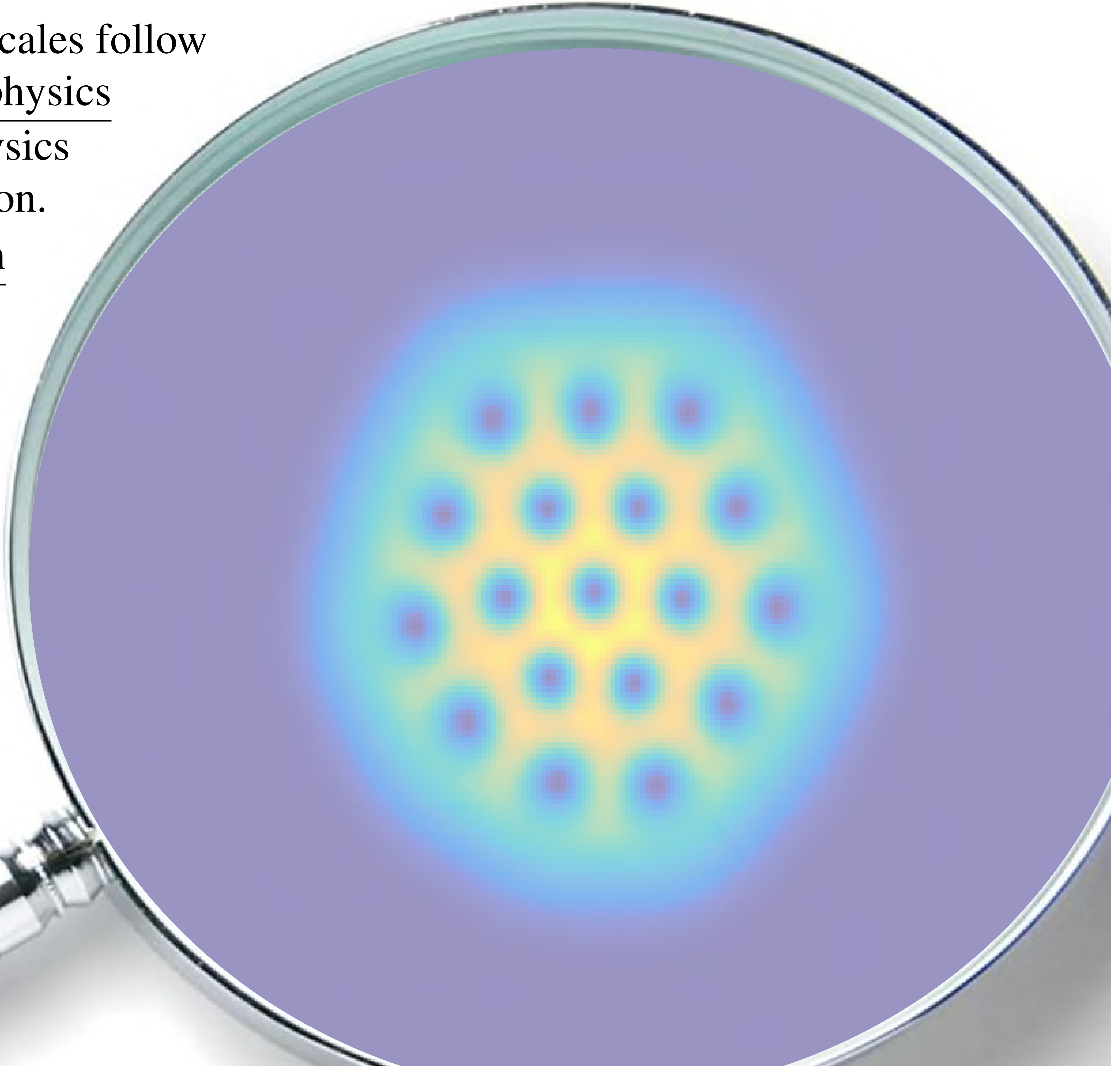
(shown is a simulation of vortices in an anyon BEC [arX:1901.10739])

Processes on atomic scales follow the laws of quantum physics of which ordinary physics is just an approximation. Quantum computation means to exploit such quantum operations for data processing by manipulating individual quanta.



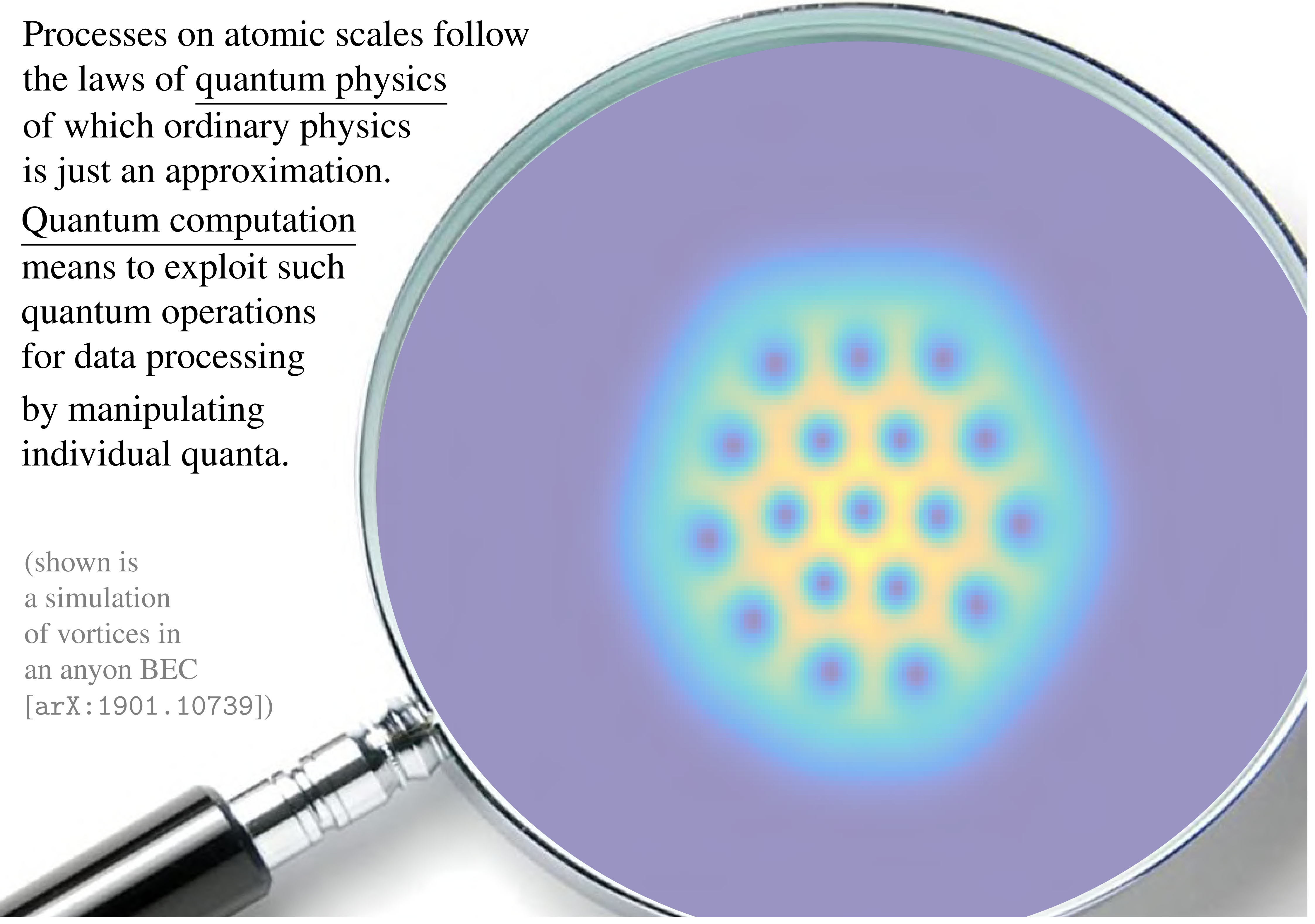
(shown is a simulation of vortices in an anyon BEC [arX:1901.10739])

Processes on atomic scales follow the laws of quantum physics of which ordinary physics is just an approximation. Quantum computation means to exploit such quantum operations for data processing by manipulating individual quanta.



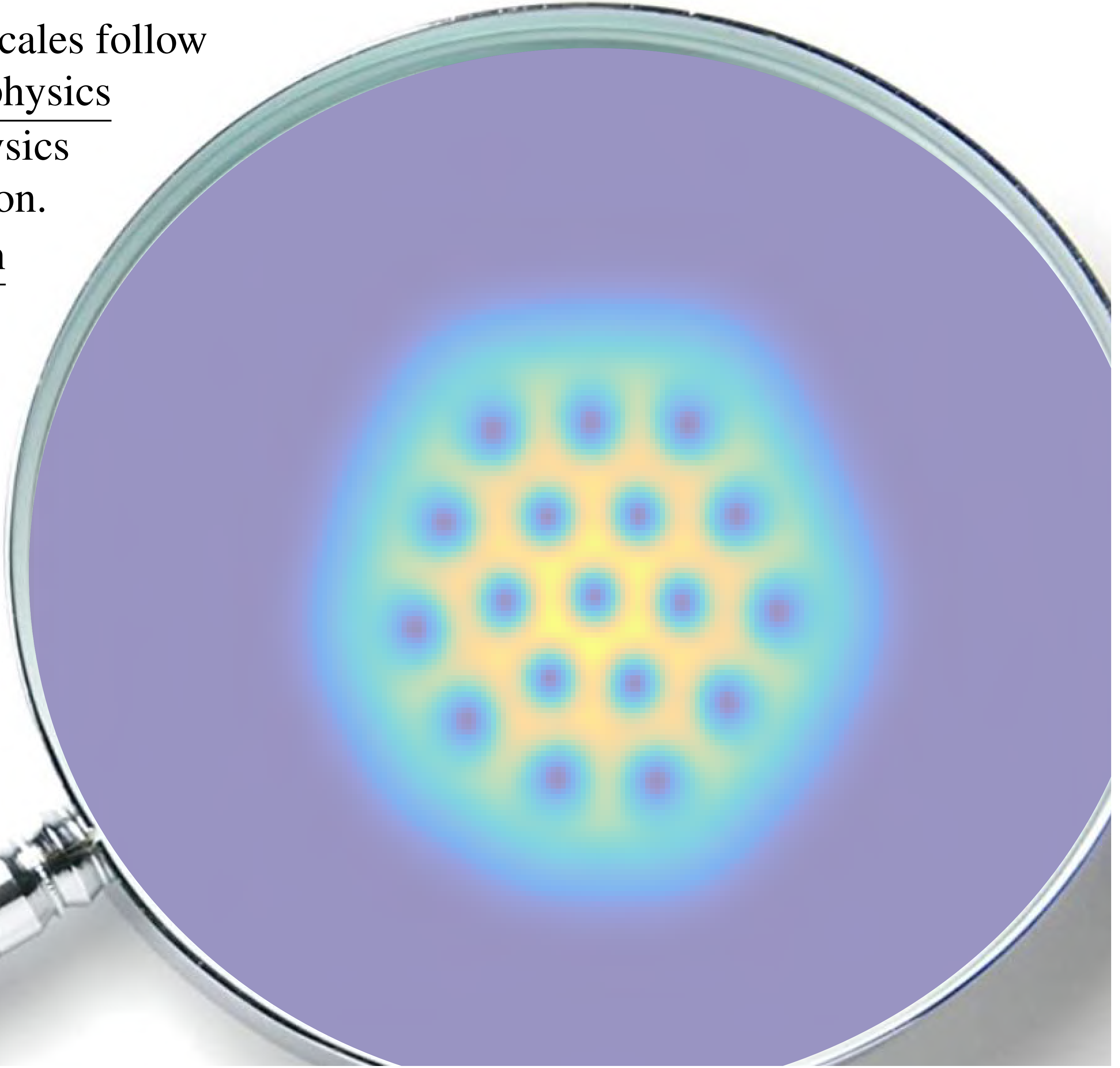
(shown is a simulation of vortices in an anyon BEC [arX:1901.10739])

Processes on atomic scales follow
the laws of quantum physics
of which ordinary physics
is just an approximation.
Quantum computation
means to exploit such
quantum operations
for data processing
by manipulating
individual quanta.



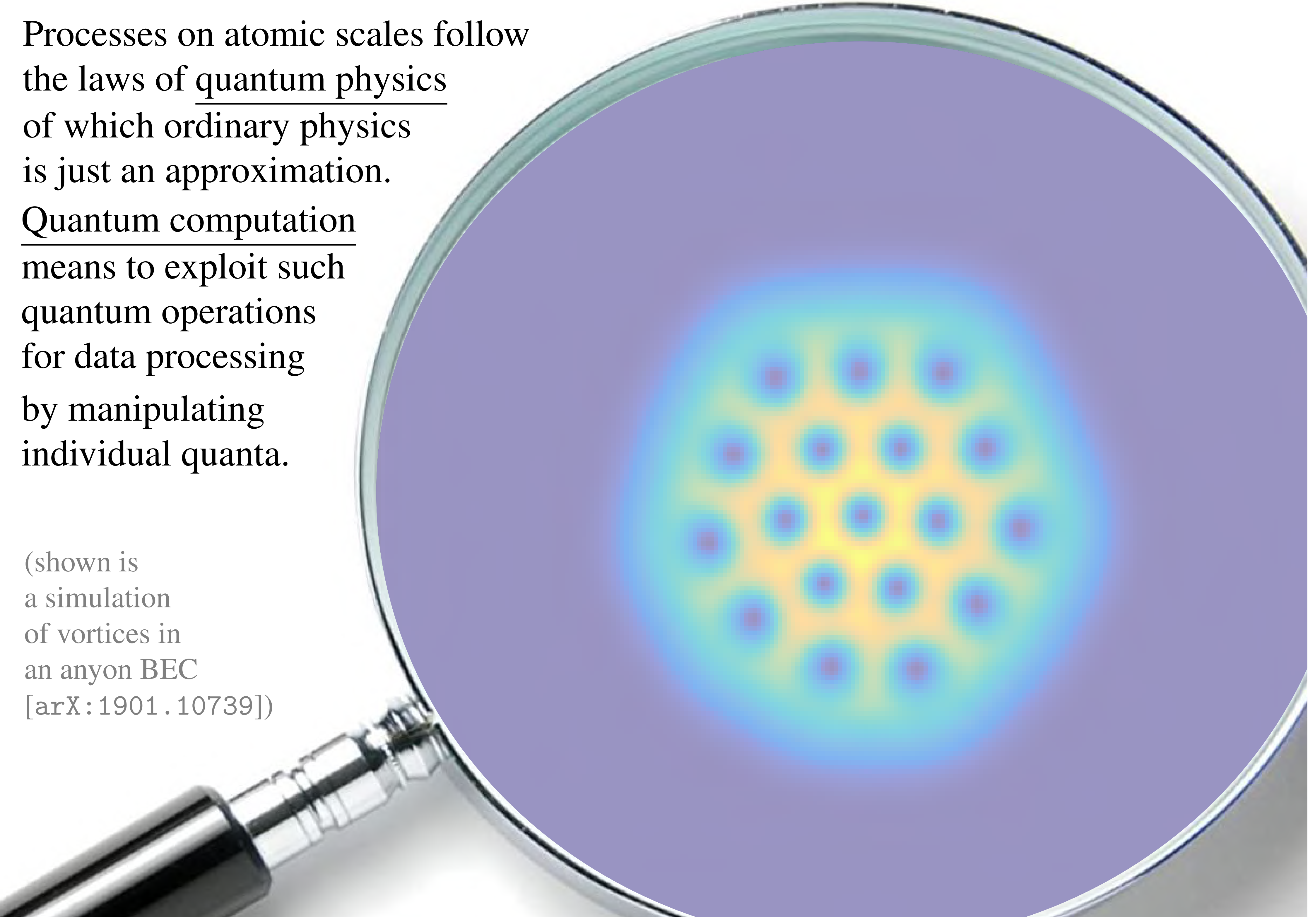
(shown is
a simulation
of vortices in
an anyon BEC
[arX:1901.10739])

Processes on atomic scales follow the laws of quantum physics of which ordinary physics is just an approximation. Quantum computation means to exploit such quantum operations for data processing by manipulating individual quanta.



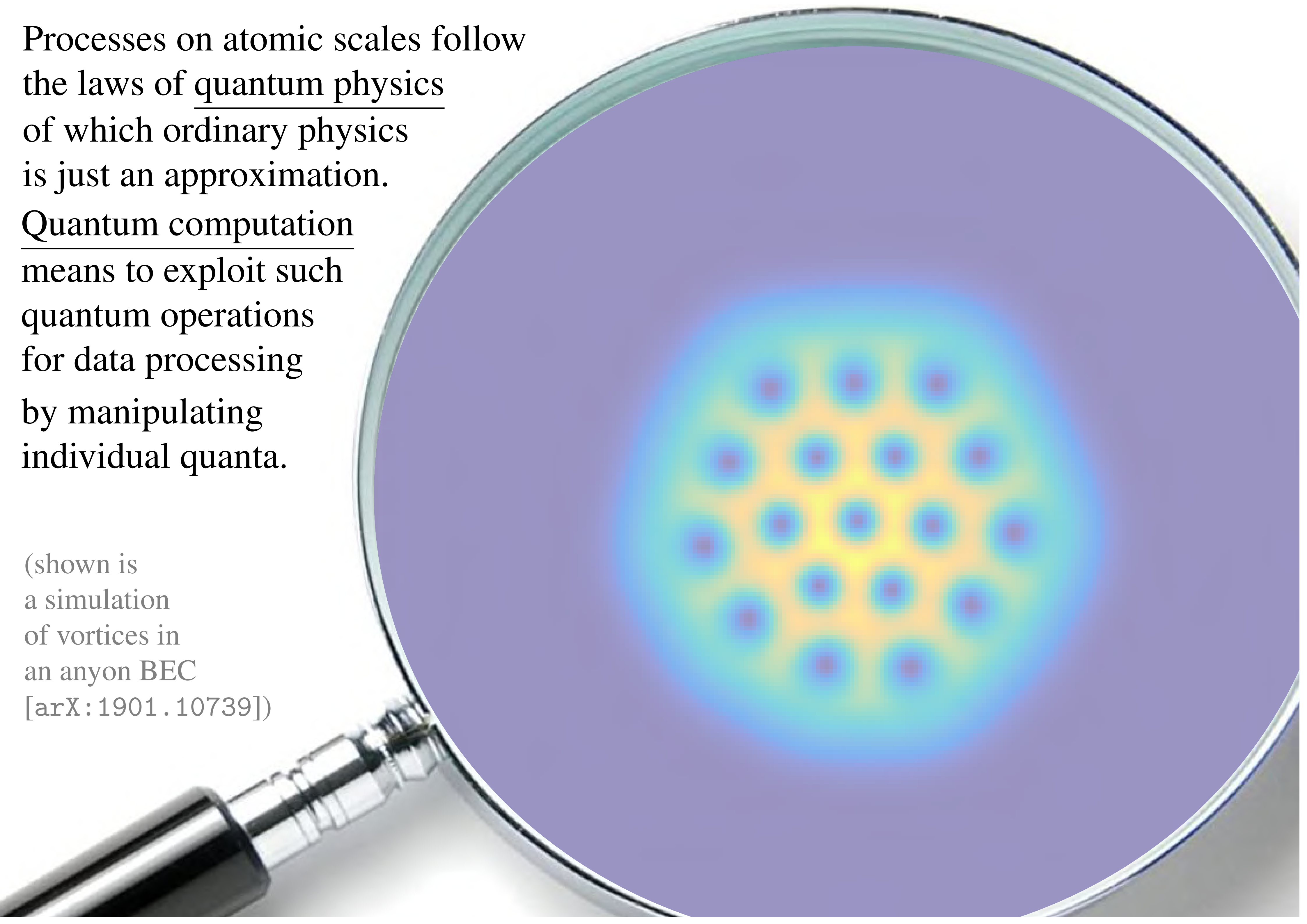
(shown is a simulation of vortices in an anyon BEC [arX:1901.10739])

Processes on atomic scales follow the laws of quantum physics of which ordinary physics is just an approximation. Quantum computation means to exploit such quantum operations for data processing by manipulating individual quanta.



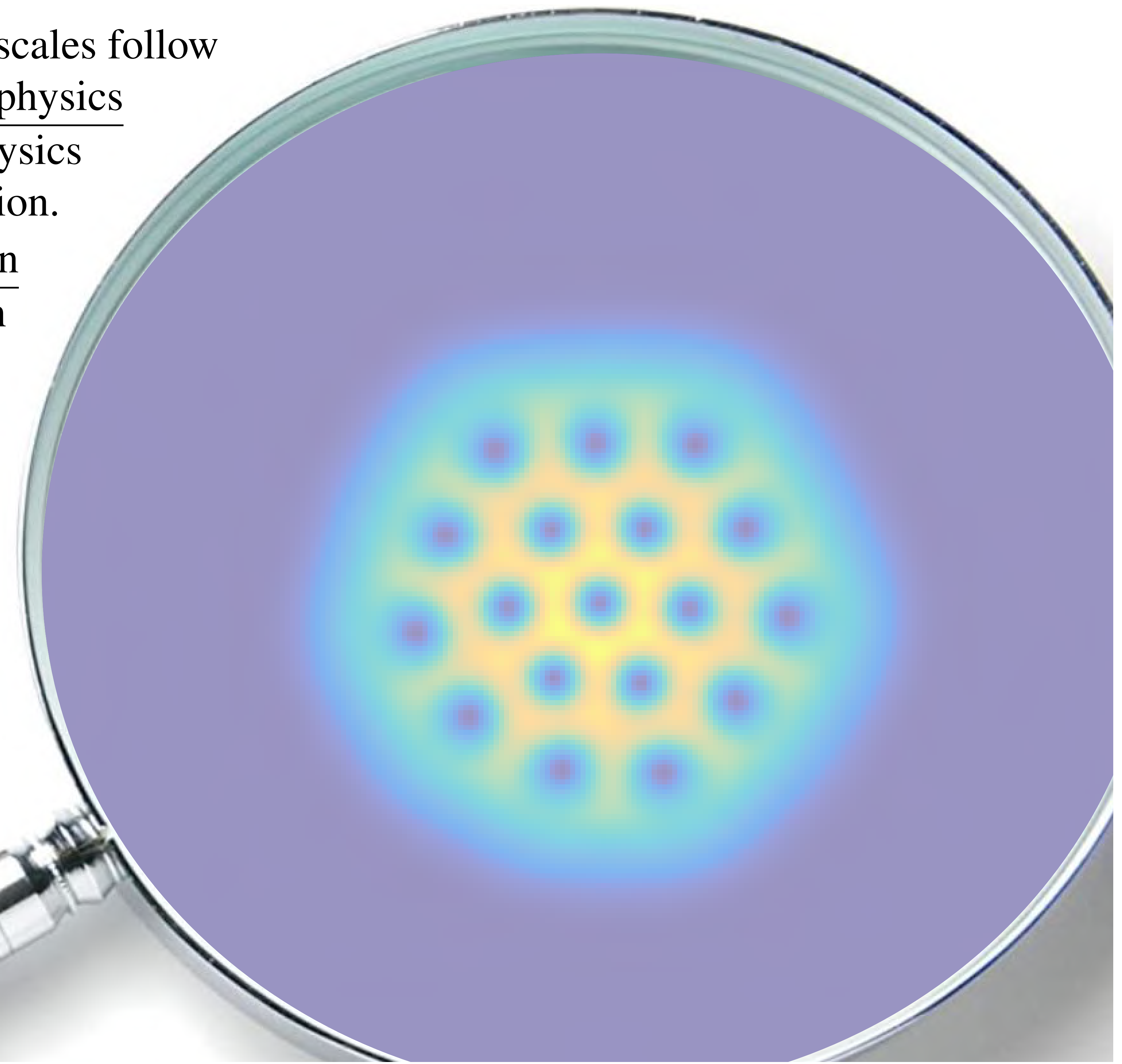
(shown is a simulation of vortices in an anyon BEC [arX:1901.10739])

Processes on atomic scales follow the laws of quantum physics of which ordinary physics is just an approximation. Quantum computation means to exploit such quantum operations for data processing by manipulating individual quanta.



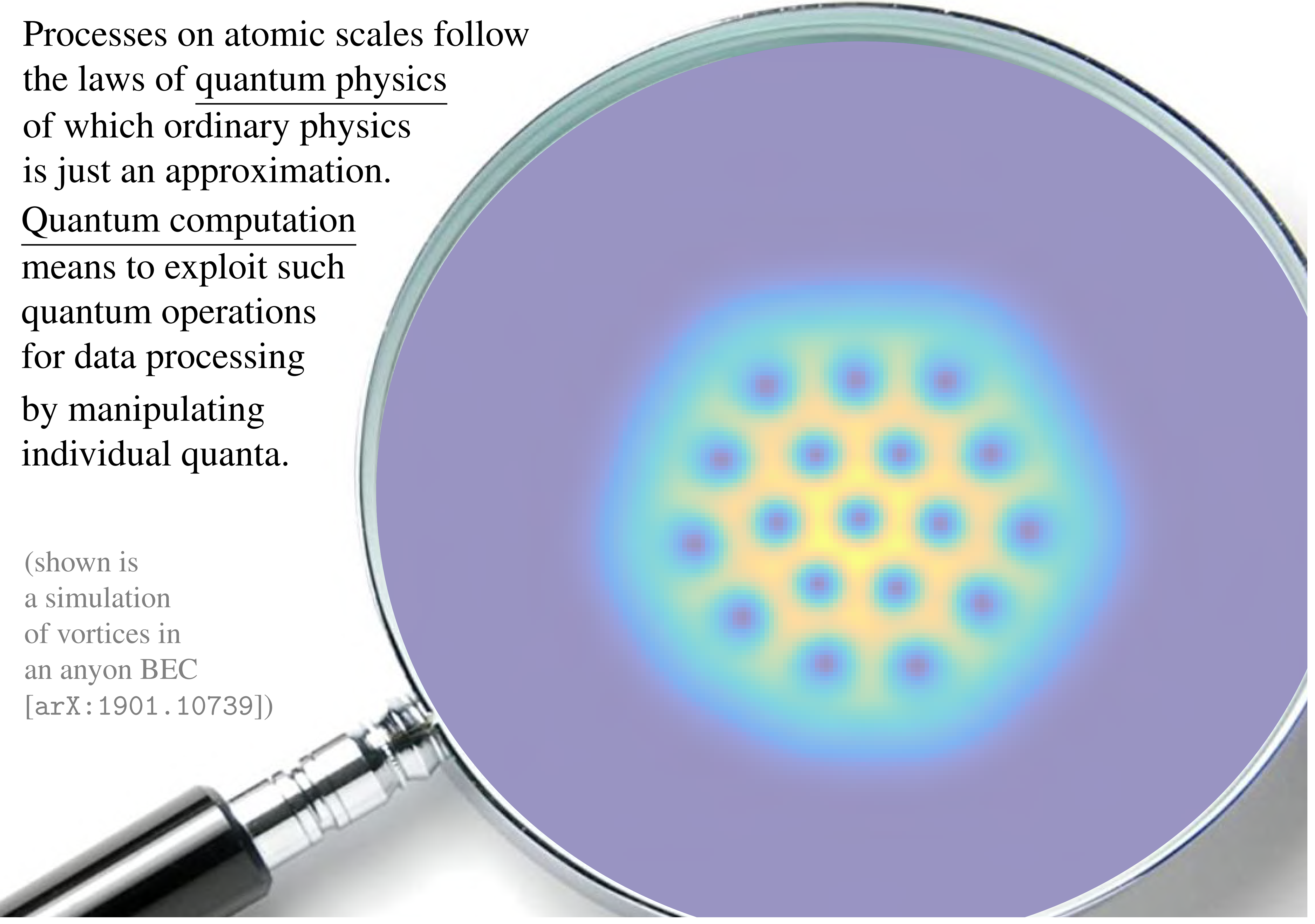
(shown is a simulation of vortices in an anyon BEC [arX:1901.10739])

Processes on atomic scales follow the laws of quantum physics of which ordinary physics is just an approximation. Quantum computation means to exploit such quantum operations for data processing by manipulating individual quanta.



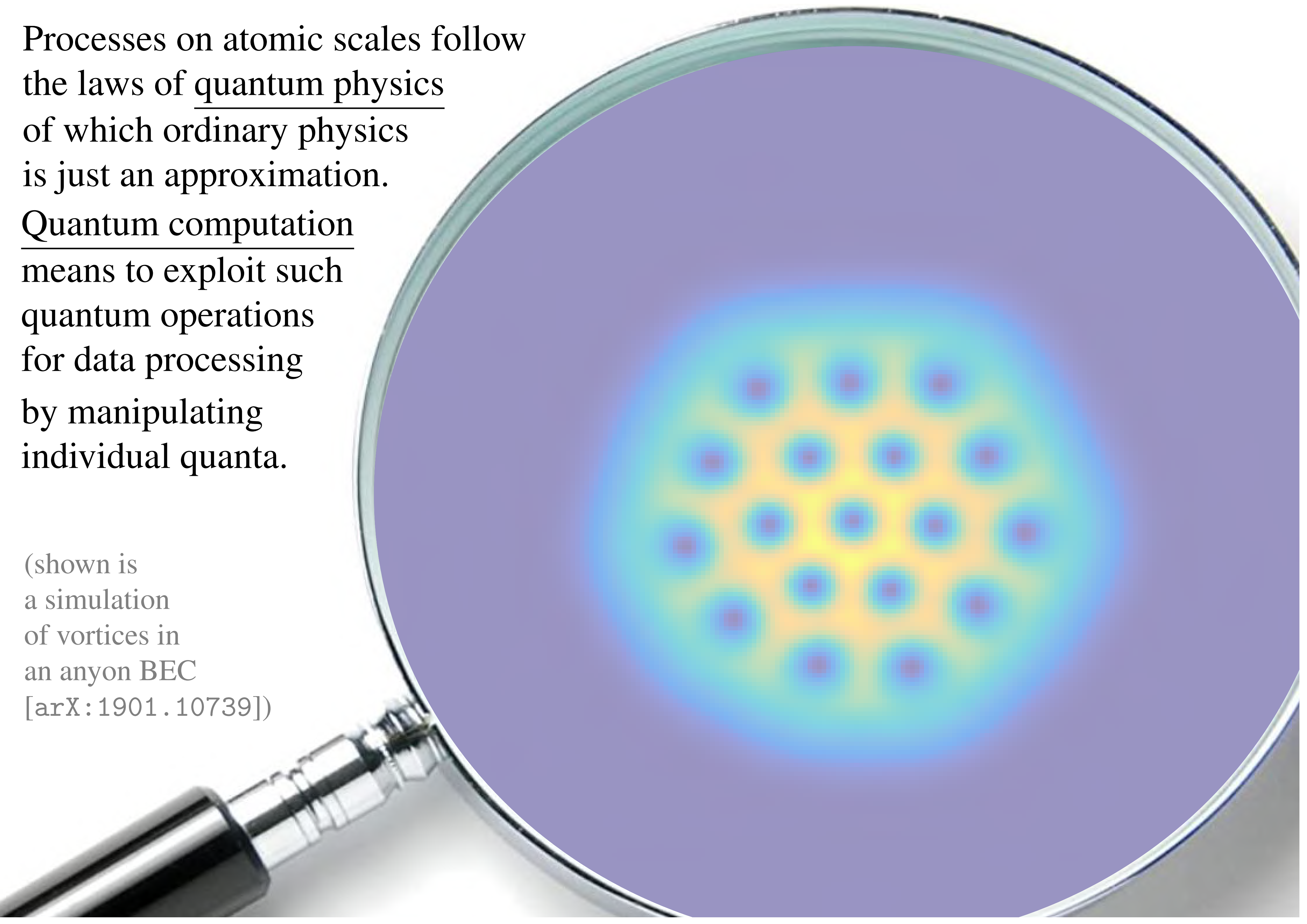
(shown is a simulation of vortices in an anyon BEC [arX:1901.10739])

Processes on atomic scales follow the laws of quantum physics of which ordinary physics is just an approximation. Quantum computation means to exploit such quantum operations for data processing by manipulating individual quanta.



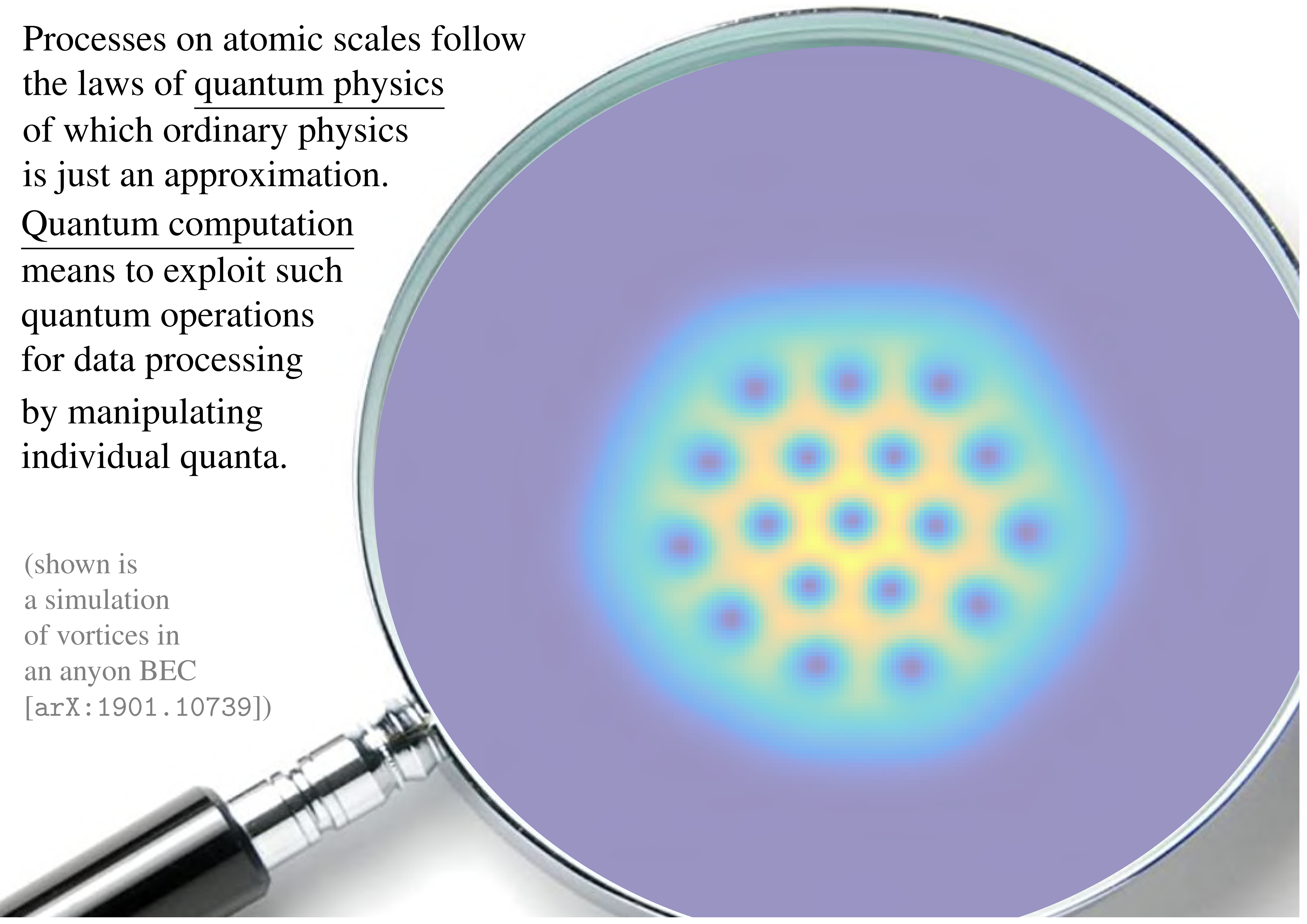
(shown is a simulation of vortices in an anyon BEC [arX:1901.10739])

Processes on atomic scales follow
the laws of quantum physics
of which ordinary physics
is just an approximation.
Quantum computation
means to exploit such
quantum operations
for data processing
by manipulating
individual quanta.



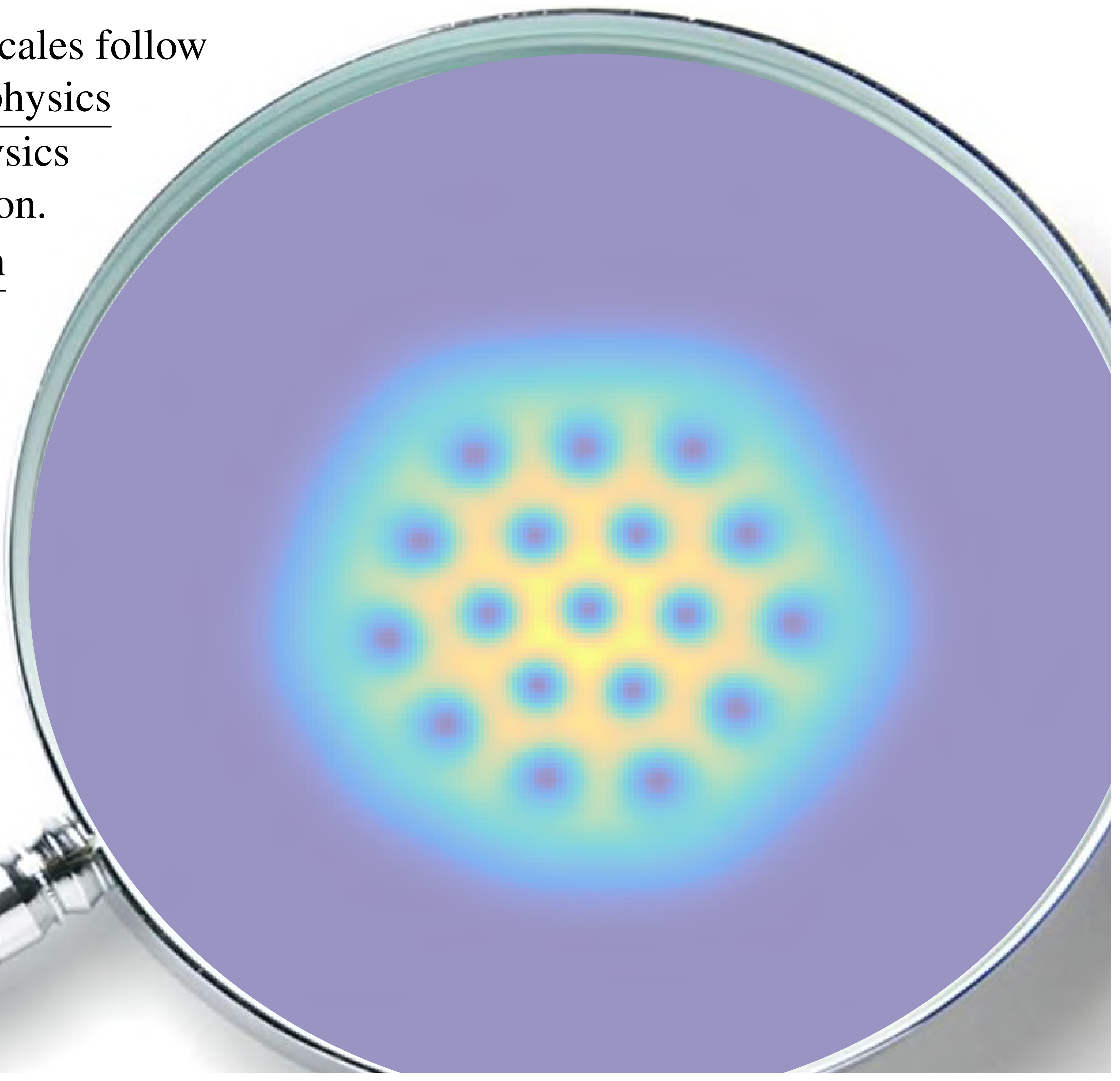
(shown is
a simulation
of vortices in
an anyon BEC
[arX:1901.10739])

Processes on atomic scales follow the laws of quantum physics of which ordinary physics is just an approximation. Quantum computation means to exploit such quantum operations for data processing by manipulating individual quanta.



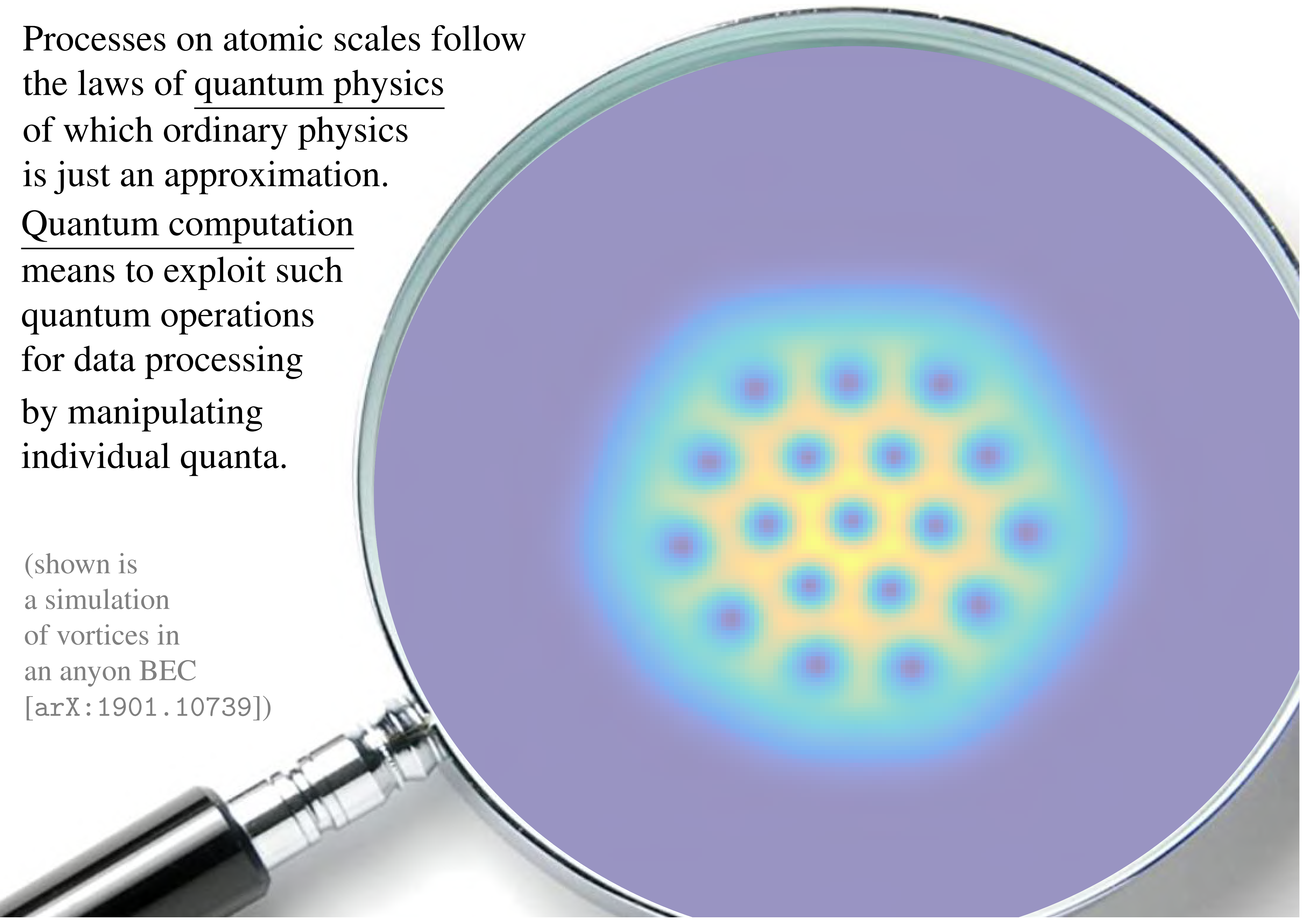
(shown is a simulation of vortices in an anyon BEC [arX:1901.10739])

Processes on atomic scales follow the laws of quantum physics of which ordinary physics is just an approximation. Quantum computation means to exploit such quantum operations for data processing by manipulating individual quanta.



(shown is a simulation of vortices in an anyon BEC [arX:1901.10739])

Processes on atomic scales follow the laws of quantum physics of which ordinary physics is just an approximation. Quantum computation means to exploit such quantum operations for data processing by manipulating individual quanta.

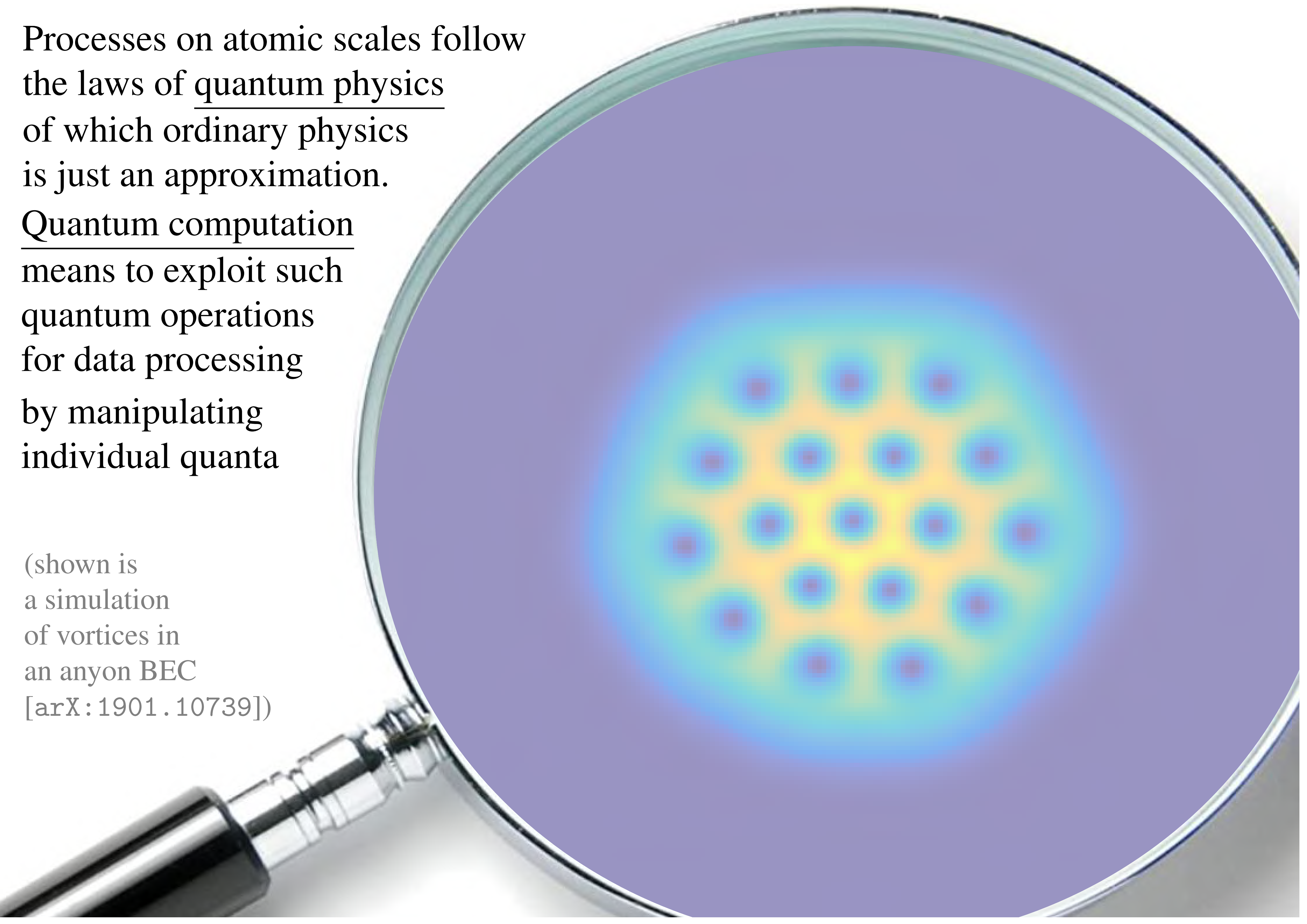


(shown is a simulation of vortices in an anyon BEC [arX:1901.10739])

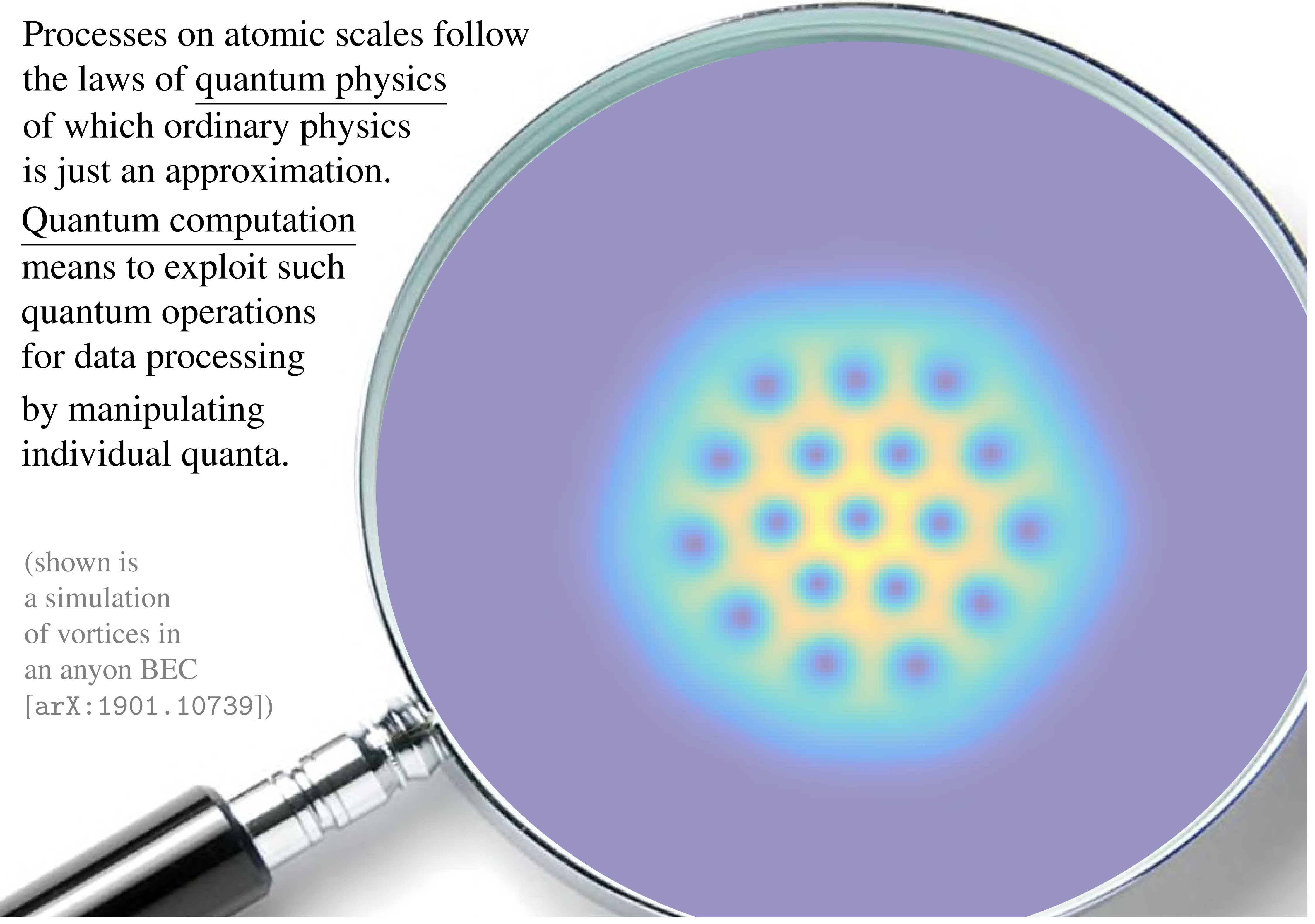
Processes on atomic scales follow the laws of quantum physics of which ordinary physics is just an approximation.

Quantum computation means to exploit such quantum operations for data processing by manipulating individual quanta

(shown is a simulation of vortices in an anyon BEC [arX:1901.10739])

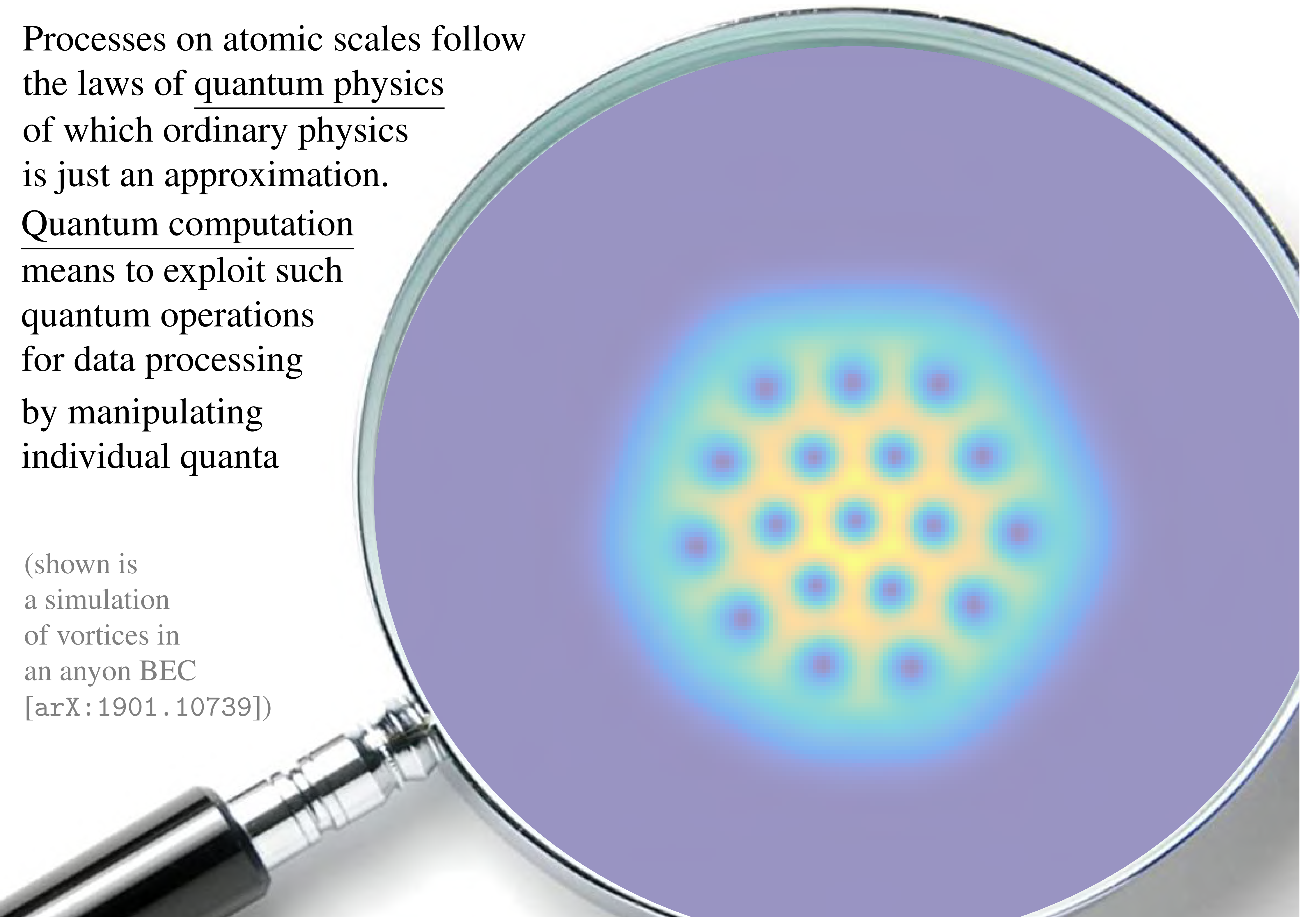


Processes on atomic scales follow the laws of quantum physics of which ordinary physics is just an approximation. Quantum computation means to exploit such quantum operations for data processing by manipulating individual quanta.



(shown is a simulation of vortices in an anyon BEC [arX:1901.10739])

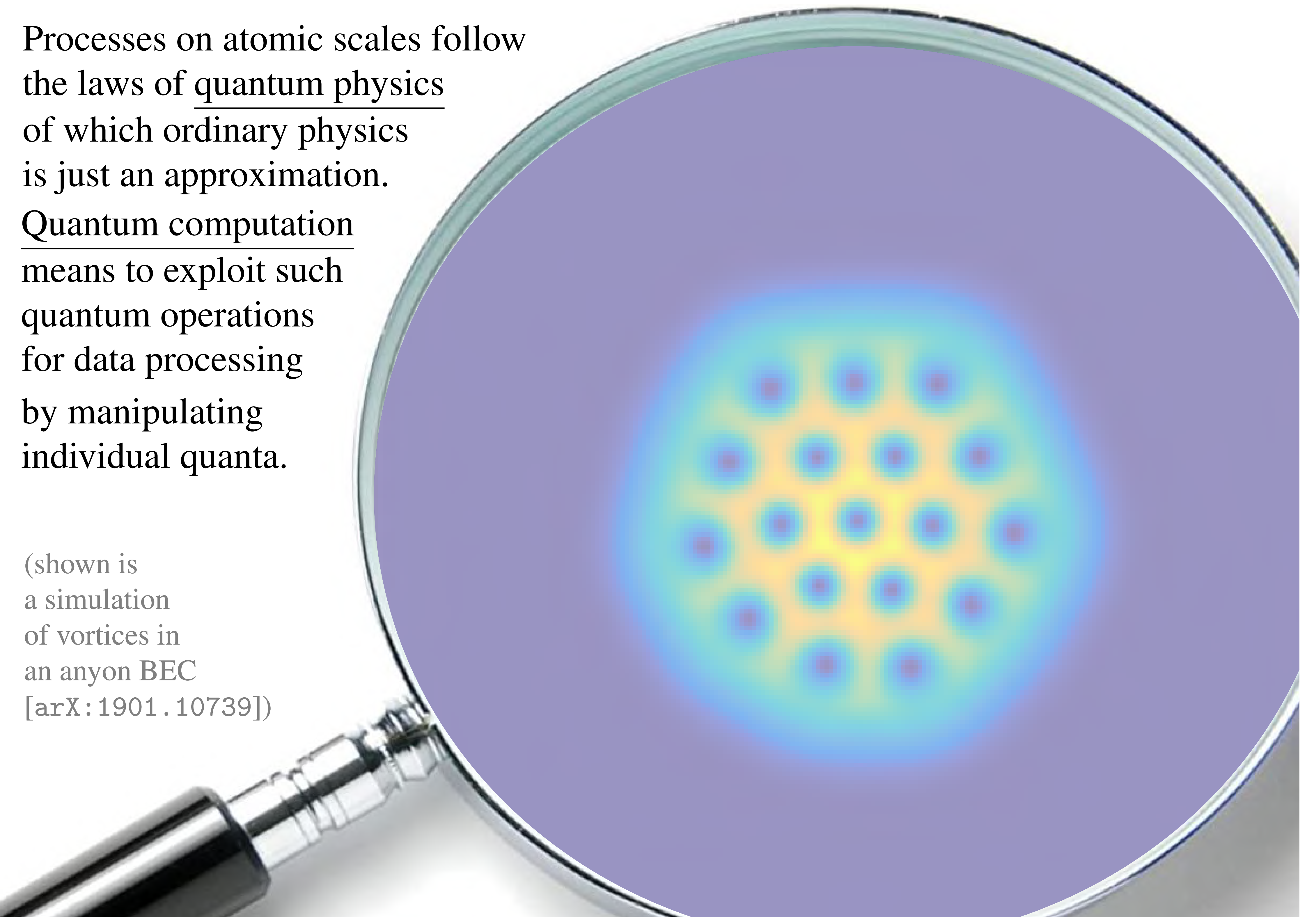
Processes on atomic scales follow
the laws of quantum physics
of which ordinary physics
is just an approximation.
Quantum computation
means to exploit such
quantum operations
for data processing
by manipulating
individual quanta



(shown is
a simulation
of vortices in
an anyon BEC
[arX:1901.10739])

Processes on atomic scales follow the laws of quantum physics of which ordinary physics is just an approximation.

Quantum computation means to exploit such quantum operations for data processing by manipulating individual quanta.



(shown is a simulation of vortices in an anyon BEC [arX:1901.10739])

Quantum Supremacy

Quantum Supremacy:

Quantum Computation is expected to be enormously more powerful than Classical Digital Computation

Quantum Supremacy:

Quantum Computation is expected to be enormously more powerful than Classical Digital Computation for special but crucial applications:

"because nature isn't classical, dammit, if you want to make a simulation of nature, you'd better make it quantum mechanical"

analysis of quantum matter [Feynman (1981)]

especially: quantum chemistry

& molecular biology [Manin (1980), Lloyd (1996)]

Quantum Supremacy:

Quantum Computation is expected to
be enormously more powerful
than Classical Digital Computation
for special but crucial applications:

analysis of	quantum matter	[Feynman (1981)]
especially:	quantum chemistry	
&	molecular biology	[Manin (1980), Lloyd (1996)]
but also, e.g.	database search	[Grover (1996)]
and notably:	cryptography	[Simon (1997), Shor (1997)]

Quantum factoring would break existing encryption
while Quantum Encryption would be unbreakable.

Quantum Supremacy:

Quantum Computation is expected to be enormously more powerful than Classical Digital Computation for special but crucial applications:

analysis of	quantum matter	[Feynman (1981)]
especially:	quantum chemistry	
&	molecular biology	[Manin (1980), Lloyd (1996)]
but also, e.g.	database search	[Grover (1996)]
and notably:	cryptography	[Simon (1997), Shor (1997)]

Quantum Supremacy:

Quantum Computation is expected to be enormously more powerful than Classical Digital Computation

laboratory race started in 2019:

Quantum Supremacy:

Quantum Computation is expected to be enormously more powerful than Classical Digital Computation

laboratory race started in 2019:

Quantum Supremacy:

Quantum Computation is expected to be enormously more powerful than Classical Digital Computation

laboratory race started in 2019:

Quantum Supremacy:

Quantum Computation is expected to be enormously more powerful than Classical Digital Computation

laboratory race started in 2019:

Quantum Supremacy:

Quantum Computation is expected to be enormously more powerful than Classical Digital Computation

But

Quantum Instability:

so far
these demonstrations are contrived
and have all been contested

Quantum Supremacy:

Quantum Computation is expected to be enormously more powerful than Classical Digital Computation (for special but crucial applications).

Quantum Instability:

But Quantum Computation is prone to instability and hence to errors

Quantum Supremacy:

Quantum Computation is expected to be enormously more powerful than Classical Digital Computation (for special but crucial applications).

Quantum Instability:

But Quantum Computation is prone to instability and hence to errors

arXiv > quant-ph > arXiv:1801.00862

Search...

Help | Adv

Quantum Physics

[Submitted on 2 Jan 2018 (v1), last revised 31 Jul 2018 (this version, v3)]

Quantum Computing in the NISQ era and beyond

John Preskill

Noisy Intermediate-Scale Quantum (NISQ) technology will be available in the near future. Quantum computers with 50-100 qubits may be able to perform tasks which surpass the capabilities of today's classical digital computers, but noise in quantum gates will limit the size of quantum circuits that can be executed reliably.

Quantum Supremacy:

Quantum Computation is expected to be enormously more powerful than Classical Digital Computation (for special but crucial applications).

Quantum Instability:

But Quantum Computation is prone to instability and hence to errors when operated by traditional means.

arXiv > quant-ph > arXiv:1801.00862

Search...

Help | Adv

Quantum Physics

[Submitted on 2 Jan 2018 (v1), last revised 31 Jul 2018 (this version, v3)]

Quantum Computing in the NISQ era and beyond

John Preskill

Noisy Intermediate-Scale Quantum (NISQ) technology will be available in the near future. Quantum computers with 50-100 qubits may be able to perform tasks which surpass the capabilities of today's classical digital computers, but noise in quantum gates will limit the size of quantum circuits that can be executed reliably.

Quantum Supremacy:

Quantum Computation is expected to be enormously more powerful than Classical Digital Computation (for special but crucial applications).

Quantum Instability:

But Quantum Computation is prone to instability and hence to errors when operated by traditional means.

Topological Quantum Computation:

is an ambitious but plausible strategy for retaining supremacy while defeating instability.

Quantum Supremacy:

Quantum Computation is expected to be enormously more powerful than Classical Digital Computation (for special but crucial applications).

Quantum Instability:

But Quantum Computation is prone to instability and hence to errors when operated by traditional means.

Topological Quantum Computation:

is an ambitious but plausible strategy for retaining supremacy while defeating instability.

BULLETIN (New Series) OF THE
AMERICAN MATHEMATICAL SOCIETY
Volume 40, Number 1, Pages 31–38
S 0273-0979(02)00964-3
Article electronically published on October 10, 2002

TOPOLOGICAL QUANTUM COMPUTATION

MICHAEL H. FREEDMAN, ALEXEI KITAEV, MICHAEL J. LARSEN, AND ZHENGHAN WANG

ABSTRACT. The theory of quantum computation can be constructed from the abstract study of anyonic systems. In mathematical terms, these are unitary topological modular functors. They underlie the Jones polynomial and arise in Witten-Chern-Simons theory. The braiding and fusion of anyonic excitations in quantum Hall electron liquids and 2D-magnets are modeled by modular functors, opening a new possibility for the realization of quantum computers. The chief advantage of anyonic computation would be physical error correction

Quantum Supremacy:

Quantum Computation is expected to
be enormously more powerful
than Classical Digital Computation
(for special but crucial applications).

Quantum Instability:

But Quantum Computation is prone to
instability and hence to errors
when operated by traditional means.

Topological Quantum Computation:

is an ambitious but plausible strategy for
retaining supremacy while defeating instability.

Both its math & physics need further development.

Quantum Supremacy:

Quantum Computation is expected to
be enormously more powerful
than Classical Digital Computation
(for special but crucial applications).

Quantum Instability:

But Quantum Computation is prone to
instability and hence to errors
when operated by traditional means.

Topological Quantum Computation:

is an ambitious but plausible strategy for
retaining supremacy while defeating instability.

Both its math & physics need further development.

Das Sarma, MIT Tech Rev (2022):

“*The quantum-bit systems we have today are a tremendous scientific achievement,*

Quantum Supremacy:

Quantum Computation is expected to be enormously more powerful than Classical Digital Computation (for special but crucial applications).

Quantum Instability:

But Quantum Computation is prone to instability and hence to errors when operated by traditional means.

Topological Quantum Computation:

is an ambitious but plausible strategy for retaining supremacy while defeating instability.

Both its math & physics need further development.

Das Sarma, MIT Tech Rev (2022):

"*The quantum-bit systems we have today are a tremendous scientific achievement,*

but they take us no closer to having a quantum computer that can solve a problem that anybody cares about.

Quantum Supremacy:

Quantum Computation is expected to be enormously more powerful than Classical Digital Computation (for special but crucial applications).

Quantum Instability:

But Quantum Computation is prone to instability and hence to errors when operated by traditional means.

Topological Quantum Computation:

is an ambitious but plausible strategy for retaining supremacy while defeating instability.

Both its math & physics need further development.

Das Sarma, MIT Tech Rev (2022):

"*The quantum-bit systems we have today are a tremendous scientific achievement, but they take us no closer to having a quantum computer that can solve a problem that anybody cares about.*

What is missing is the breakthrough bypassing quantum error correction by using far-more-stable quantum-bits, in an approach called topological quantum computing."

Quantum Supremacy:

Quantum Computation is expected to be enormously more powerful than Classical Digital Computation (for special but crucial applications).

Quantum Instability:

But Quantum Computation is prone to instability and hence to errors when operated by traditional means.

Topological Quantum Computation:

is an ambitious but plausible strategy for retaining supremacy while defeating instability.

Both its math & physics need further development.

Das Sarma, MIT Tech Rev (2022):

"*The quantum-bit systems we have today are a tremendous scientific achievement,*

but they take us no closer to having a quantum computer that can solve a problem that anybody cares about.

What is missing is the breakthrough bypassing quantum error correction by using far-more-stable quantum-bits, in an approach called topological quantum computing."

We claim that
we have made
some progress
on the problem.

We claim that
we have made
some progress
on the problem.

arXiv > hep-th > arXiv:2203.11838

Search...

Help | Ac

High Energy Physics - Theory

[Submitted on 22 Mar 2022]

Anyonic Defect Branes and Conformal Blocks in Twisted Equivariant Differential (TED) K-theory

Hisham Sati, Urs Schreiber

We demonstrate that twisted equivariant differential K-theory of transverse complex curves accommodates exotic charges of the form expected of codimension=2 defect branes, such as of D7-branes in IIB/F-theory on A-type orbifold singularities, but also of their dual 3-brane defects of class-S theories on M5-branes.

We claim that we have made some progress on the problem.

arXiv > hep-th > arXiv:2203.11838

Search...

Help | Ad

High Energy Physics - Theory

[Submitted on 22 Mar 2022]

Anyonic Defect Branes and Conformal Blocks in Twisted Equivariant Differential (TED) K-theory

Hisham Sati, Urs Schreiber

We demonstrate that twisted equivariant differential K-theory of transverse complex curves accommodates exotic charges of the form expected of codimension=2 defect branes, such as of D7-branes in IIB/F-theory on A-type orbifold singularities, but also of their dual 3-brane defects of class-S theories on M5-branes.

Anyonic Topological Order in Twisted Equivariant Differential (TED) K-Theory

Hisham Sati, Urs Schreiber

While the classification of non-interacting crystalline topological insulator phases by equivariant K-theory has become widely accepted, its generalization to anyonic interacting phases -- hence to phases with topologically ordered ground states supporting topological braid quantum gates -- has remained wide open. On the contrary, the success of K-theory with classifying non-interacting phases seems to have tacitly been perceived as precluding a K-theoretic classification of interacting topological order; and instead a mix of other proposals has been explored. However, only K-theory connects closely to the actual physics of valence electrons; and self-consistency demands that any other proposal must connect to K-theory.
Here we provide a detailed argument for the classification of symmetry protected/enhanced su(2)-anyonic topological order, specifically in interacting 2d semi-metals, by the twisted equivariant differential (TED) K-theory of configuration spaces of points in the complement of nodal points inside the crystal's Brillouin torus orbi-orientifold.

We claim that we have made some progress on the problem.

arXiv > hep-th > arXiv:2203.11838

Search...

Help | Ac

High Energy Physics - Theory

[Submitted on 22 Mar 2022]

Anyonic Defect Branes and Conformal Blocks in Twisted Equivariant Differential (TED) K-theory

Hisham Sati, Urs Schreiber

We demonstrate that twisted equivariant differential K-theory of transverse complex curves accommodates exotic charges of the form expected of codimension=2 defect branes, such as of D7-branes in IIB/F-theory on A-type orbifold singularities, but also of their dual 3-brane defects of class-S theories on M5-branes.

Anyonic Topological Order in Twisted Equivariant Differential (TED) K-Theory

Hisham Sati, Urs Schreiber

While the classification of non-interacting crystalline topological insulator phases by equivariant K-theory has become widely accepted, its generalization to anyonic interacting phases -- hence to phases with topologically ordered ground states supporting topological braid quantum gates -- has remained wide open. On the contrary, the success of K-theory with classifying non-interacting phases seems to have tacitly been perceived as precluding a K-theoretic classification of interacting topological order; and instead a mix of other proposals has been explored. However, only K-theory connects closely to the actual physics of valence electrons; and self-consistency demands that any other proposal must connect to K-theory.
Here we provide a detailed argument for the classification of symmetry protected/enhanced su(2)-anyonic topological order, specifically in interacting 2d semi-metals, by the twisted equivariant differential (TED) K-theory of configuration spaces of points in the complement of nodal points inside the crystal's Brillouin torus orbi-orientifold.

PLanQC 2022

Thu 15 Sep 2022 11:00 - 11:25 at M2 - Hardware-aware quantum programming

☆ Topological Quantum Programming in TED-K

While the realization of scalable quantum computation will arguably require topological stabilization and, with it, topological-hardware-aware quantum programming and topological-quantum circuit verification, the proper combination of these strategies into dedicated *it topological quantum programming* languages has not yet received attention.

Here we describe a fundamental and natural scheme that we are developing, for typed functional (hence verifiable) topological quantum programming which is *topological-hardware aware* – in that it natively reflects the universal fine technical detail of topological q-bits, namely of symmetry-protected (or enhanced) topologically ordered Laughlin-type anyon ground states in topological phases of quantum materials.

We claim that we have made some progress on the problem.

What follows is general motivation & gentle exposition.

arXiv > hep-th > arXiv:2203.11838

Search...

Help | Ad

High Energy Physics - Theory

[Submitted on 22 Mar 2022]

Anyonic Defect Branes and Conformal Blocks in Twisted Equivariant Differential (TED) K-theory

Hisham Sati, Urs Schreiber

We demonstrate that twisted equivariant differential K-theory of transverse complex curves accommodates exotic charges of the form expected of codimension=2 defect branes, such as of D7-branes in IIB/F-theory on A-type orbifold singularities, but also of their dual 3-brane defects of class-S theories on M5-branes.

Anyonic Topological Order in Twisted Equivariant Differential (TED) K-Theory

Hisham Sati, Urs Schreiber

While the classification of non-interacting crystalline topological insulator phases by equivariant K-theory has become widely accepted, its generalization to anyonic interacting phases -- hence to phases with topologically ordered ground states supporting topological braid quantum gates -- has remained wide open. On the contrary, the success of K-theory with classifying non-interacting phases seems to have tacitly been perceived as precluding a K-theoretic classification of interacting topological order; and instead a mix of other proposals has been explored. However, only K-theory connects closely to the actual physics of valence electrons; and self-consistency demands that any other proposal must connect to K-theory.

Here we provide a detailed argument for the classification of symmetry protected/enhanced su(2)-anyonic topological order, specifically in interacting 2d semi-metals, by the twisted equivariant differential (TED) K-theory of configuration spaces of points in the complement of nodal points inside the crystal's Brillouin torus orbi-orientifold.

PLanQC 2022

Thu 15 Sep 2022 11:00 - 11:25 at M2 - Hardware-aware quantum programming

☆ Topological Quantum Programming in TED-K

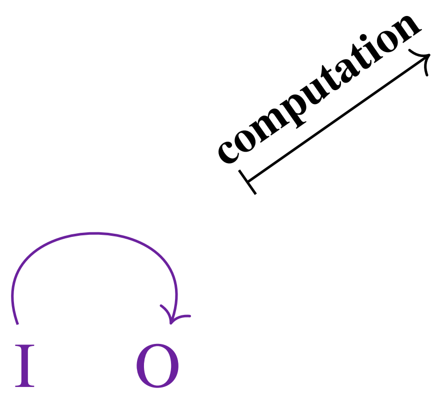
While the realization of scalable quantum computation will arguably require topological stabilization and, with it, topological-hardware-aware quantum programming and topological-quantum circuit verification, the proper combination of these strategies into dedicated *it topological quantum programming* languages has not yet received attention.

Here we describe a fundamental and natural scheme that we are developing, for typed functional (hence verifiable) topological quantum programming which is *topological-hardware aware* – in that it natively reflects the universal fine technical detail of topological q-bits, namely of symmetry-protected (or enhanced) topologically ordered Laughlin-type anyon ground states in topological phases of quantum materials.

To compute is

cf. [van Leeuwen & Wiedermann (2017)]

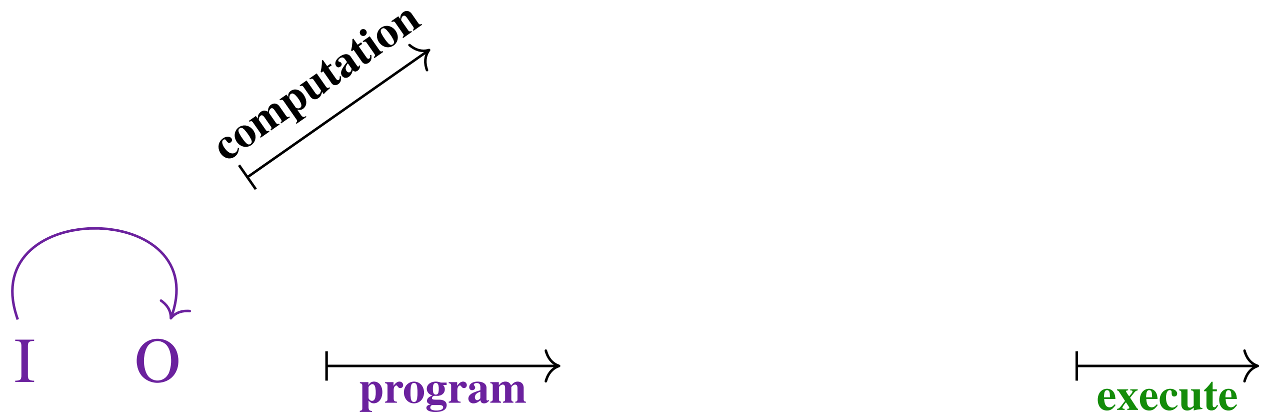
[Sati & Schreiber, PlanQC **2022** 33 (2022)]



To compute is to **execute**

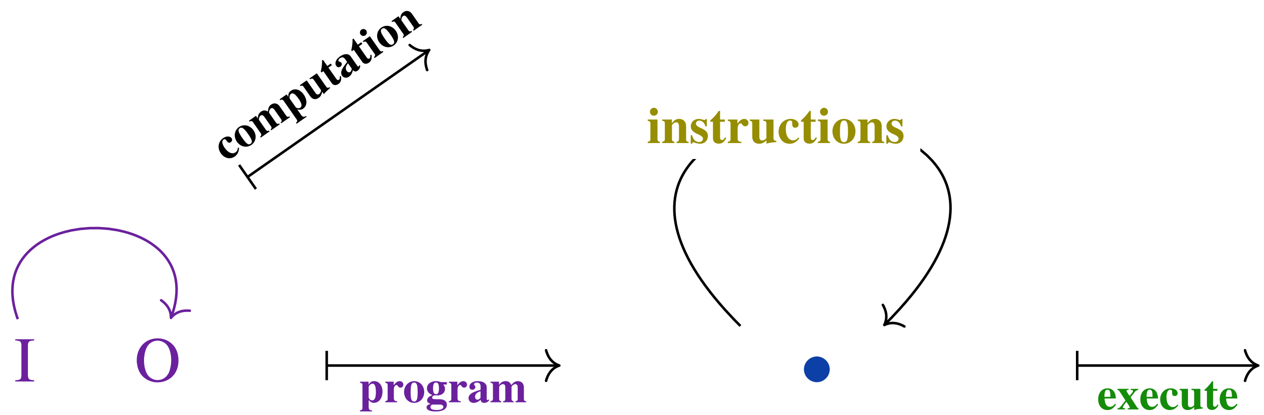
cf. [van Leeuwen & Wiedermann (2017)]

[Sati & Schreiber, PlanQC **2022** 33 (2022)]



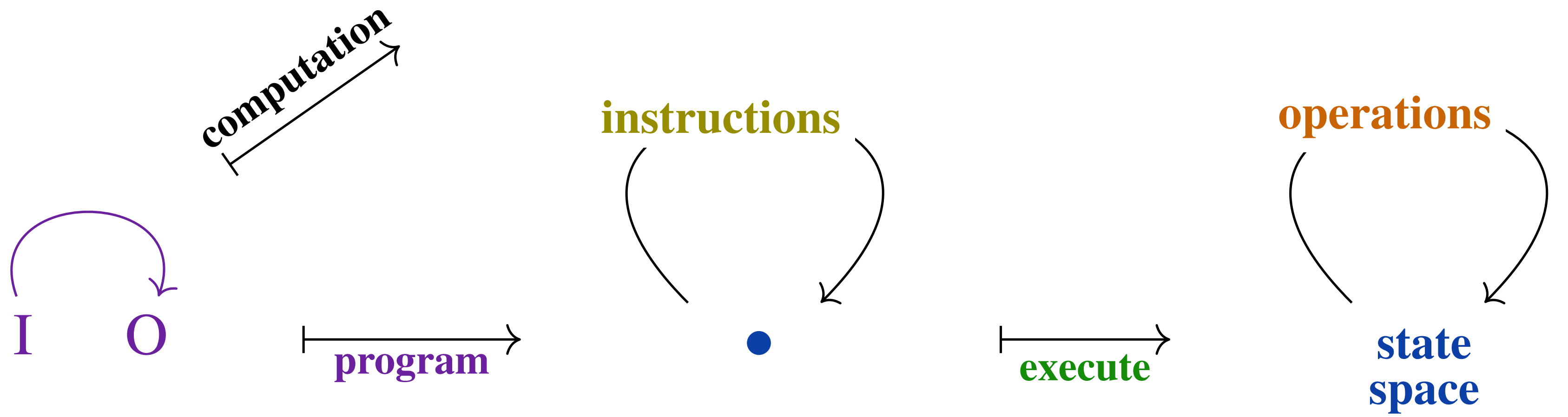
To compute is to **execute**
sequences of **instructions**

cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]



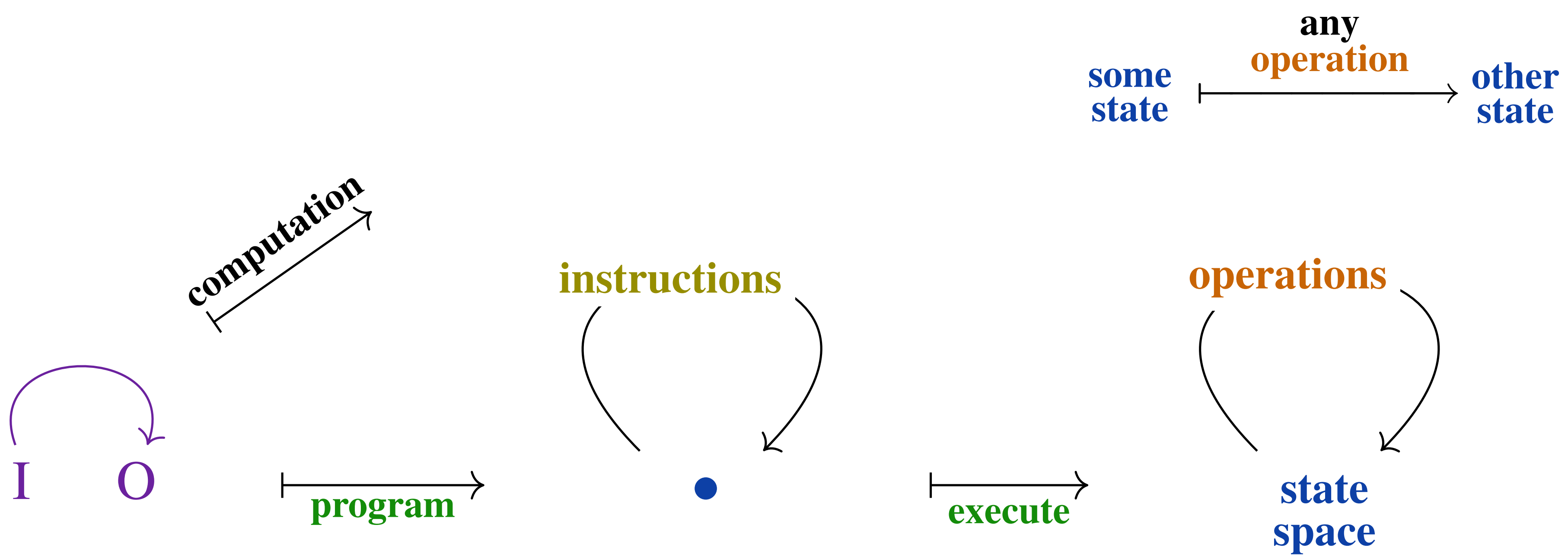
To compute is to **execute**
sequences of **instructions**
as composable **operations**

cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]



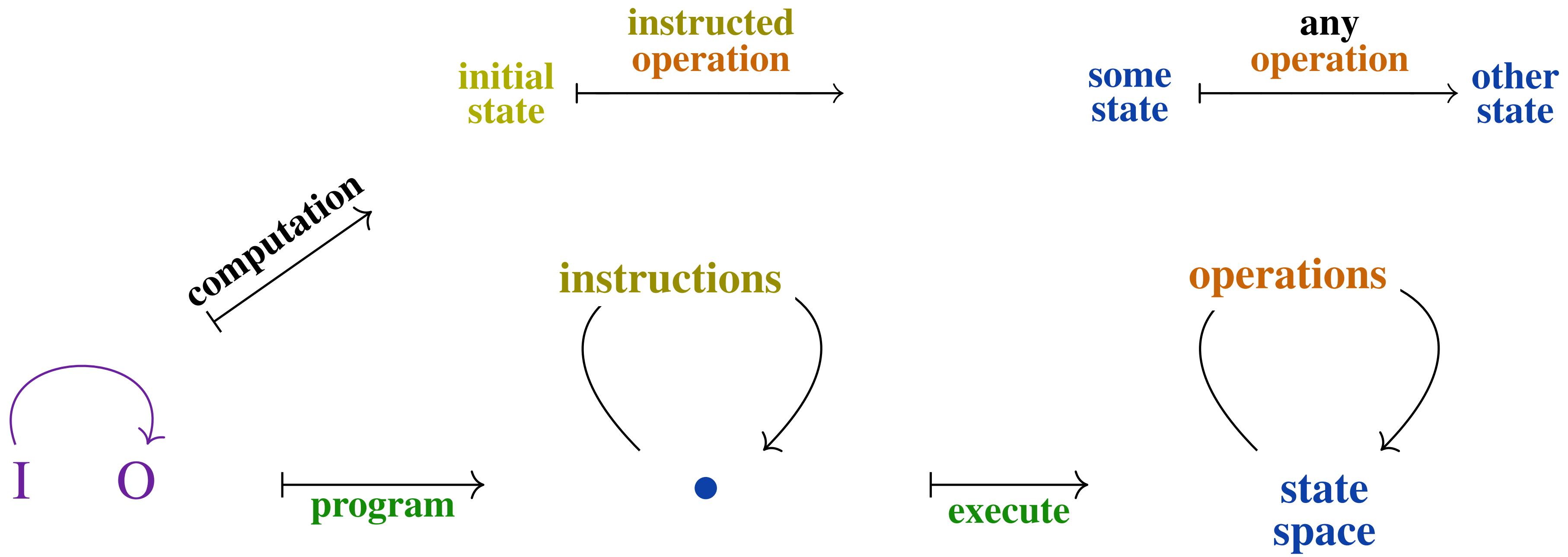
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,

cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]



To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,
turning a given **initial state**

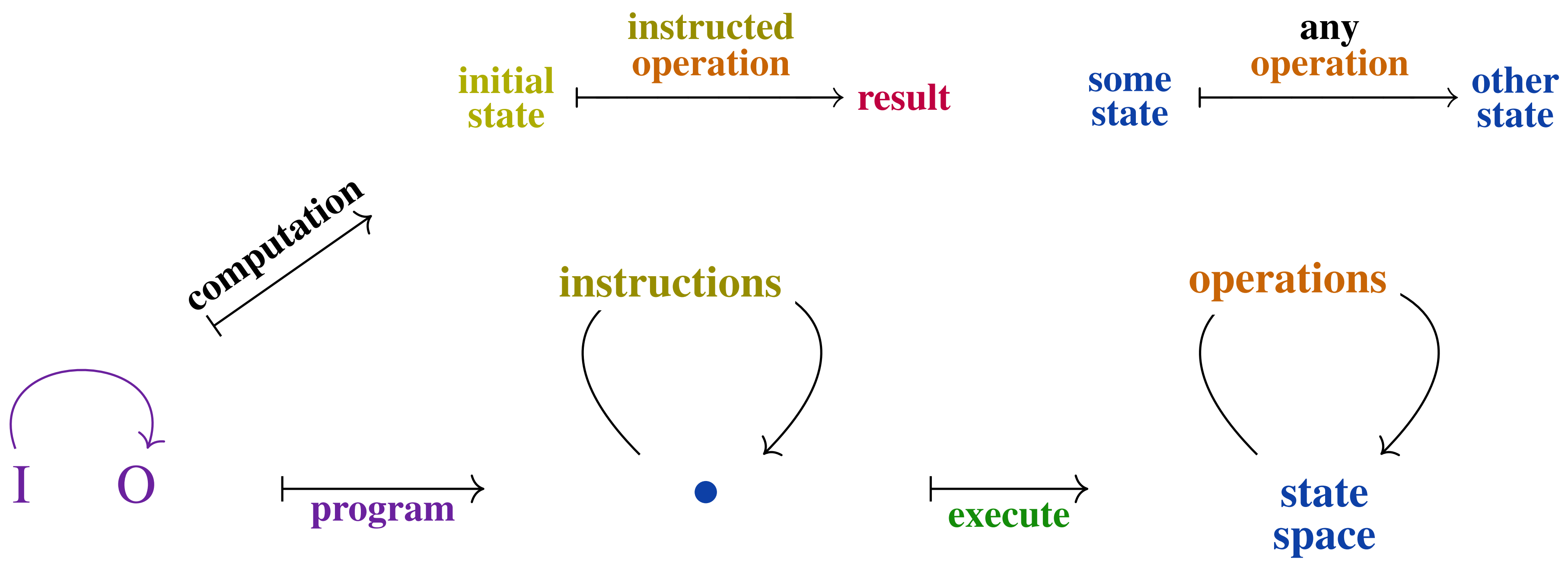
cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]



To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,

turning a given **initial state**
into the computed **result**.

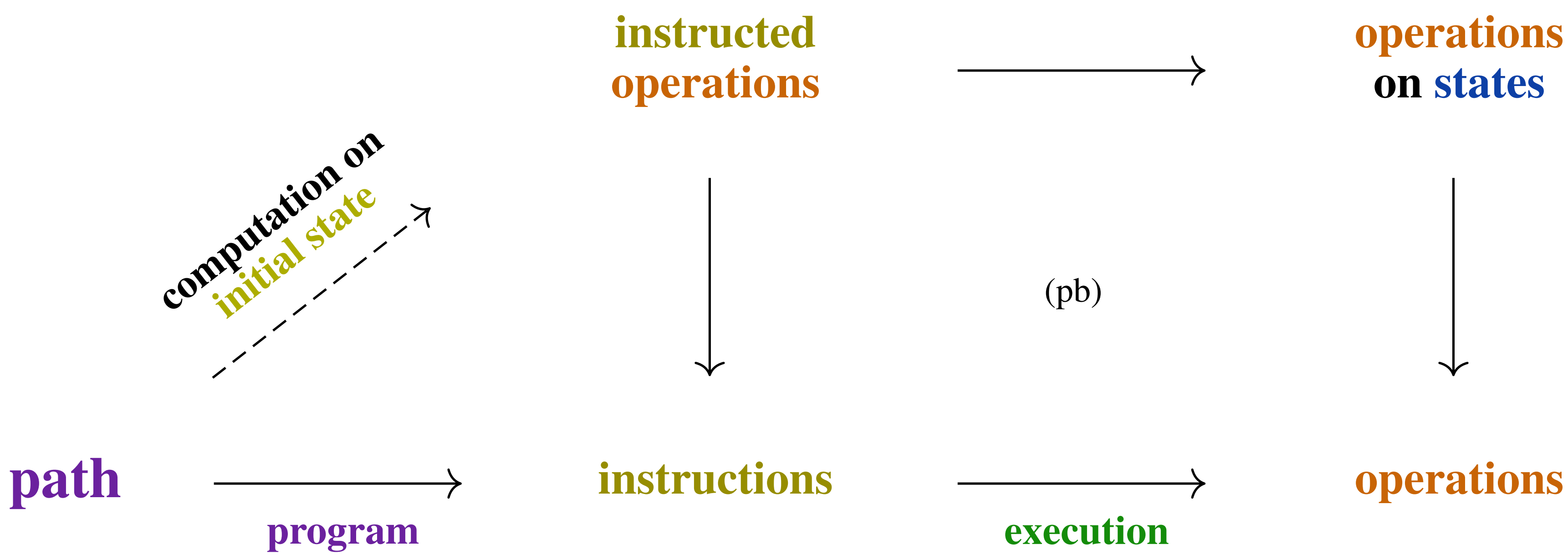
cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]



To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,

turning a given **initial state**
into the computed **result**.

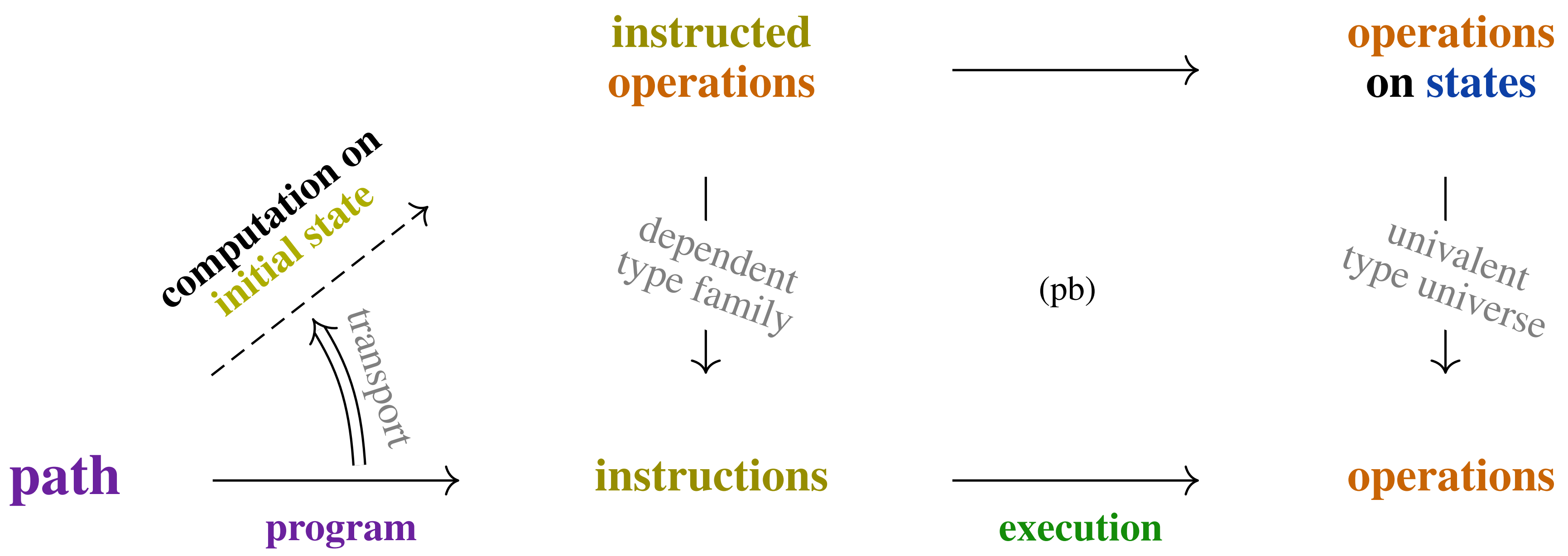
cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]



To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,
turning a given **initial state**
into the computed **result**.

[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Aside: Formalization by transport in Homotopy Type Theory:

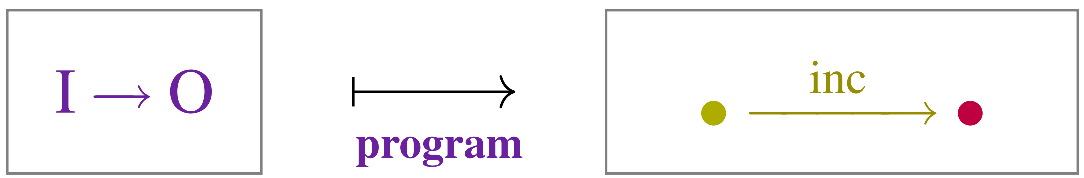


To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,

turning a given **initial state**
into the computed **result**.

cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Example: Classical computation resulting in cyclic permutation of 3 numbers:



To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,

turning a given **initial state**
into the computed **result**.

cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Example: Classical computation resulting in cyclic permutation of 3 numbers:

$$\boxed{\mathrm{I} \to \mathrm{O}} \xmapsto{\;\textbf{program}\;} \boxed{\bullet \xrightarrow{\;\mathrm{inc}\;} \bullet} \xmapsto{\;\textbf{execution}\;} \boxed{\mathbb{F}_3^3 \xrightarrow{(\bullet+1) \bmod 3} \mathbb{F}_3^3}$$

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,

turning a given **initial state**
into the computed **result**.

cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Example: Classical computation resulting in cyclic permutation of 3 numbers:

$$\mathbb{F}_3^3 \xrightarrow{(\bullet + 1) \bmod 3} \mathbb{F}_3^3$$

$$[v_i]_{i=1}^{3} \mapsto \left[v_i + 1 \bmod 3\right]_{i=1}^{3}$$

$$\downarrow$$

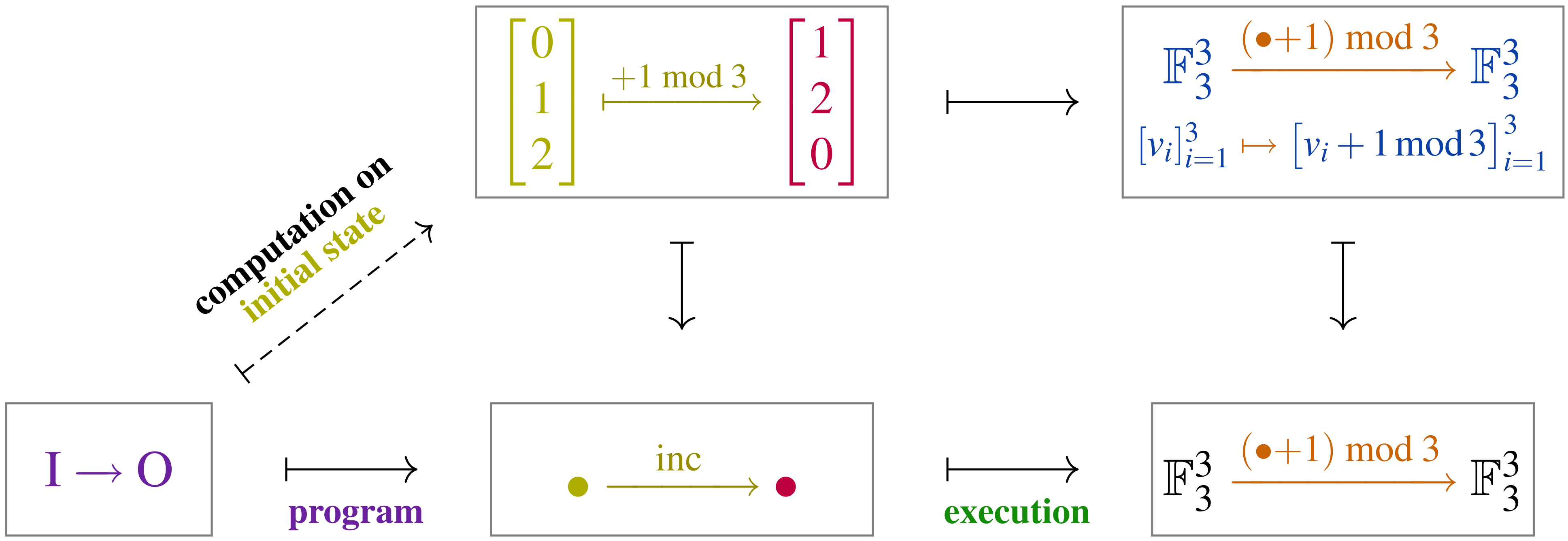
$$\boxed{\mathrm{I} \to \mathrm{O}} \xmapsto{\textbf{program}} \boxed{\bullet \xrightarrow{\text{inc}} \bullet} \xmapsto{\textbf{execution}} \boxed{\mathbb{F}_3^3 \xrightarrow{(\bullet + 1) \bmod 3} \mathbb{F}_3^3}$$

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,

turning a given **initial state**
into the computed **result**.

cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Example: Classical computation resulting in cyclic permutation of 3 numbers:



To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,
turning a given **initial state**
into the computed **result**.

cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Notice: *Fundamentally*,
all computation is
along *continuous* paths.

To compute is to **execute** sequences of **instructions** as composable **operations** on a chosen **state space**,

turning a given **initial state** into the computed **result**.

cf. [van Leeuwen & Wiedermann (2017)]

[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Notice: *Fundamentally*, all computation is along *continuous* paths.

e.g. mechanical gates:

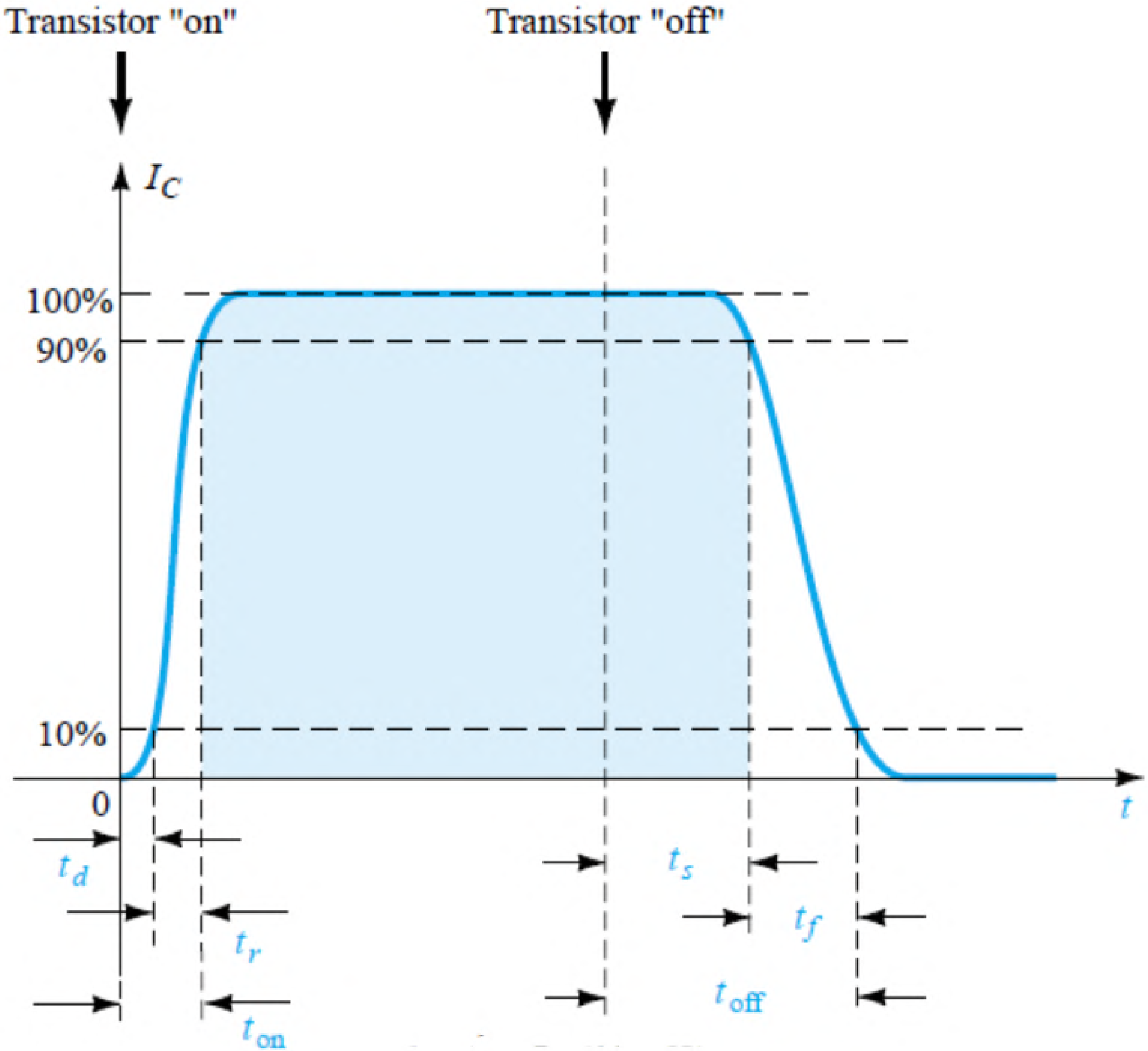
cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]

To compute is to **execute** sequences of **instructions** as composable **operations** on a chosen **state space**,

turning a given **initial state** into the computed **result**.

Notice: *Fundamentally*, all computation is along *continuous* paths.

e.g. electronic gates:



To compute is to **execute** sequences of **instructions** as composable **operations** on a chosen **state space**,

turning a given **initial state** into the computed **result**.

cf. [van Leeuwen & Wiedermann (2017)]

[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Notice: *Fundamentally*, all computation is along *continuous* paths.

schematically:

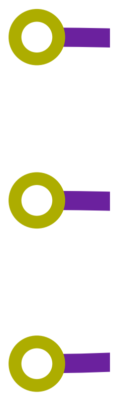
cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]

To compute is to **execute** sequences of **instructions** as composable **operations** on a chosen **state space**,

turning a given **initial state** into the computed **result**.

Notice: *Fundamentally*, all computation is along *continuous* paths.

schematically:



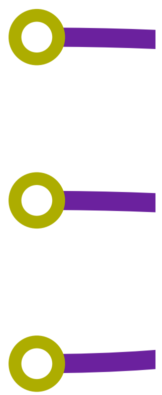
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,

turning a given **initial state**
into the computed **result**.

cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Notice: *Fundamentally*,
all computation is
along *continuous* paths.

schematically:



To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,

turning a given **initial state**
into the computed **result**.

cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Notice: *Fundamentally*,
all computation is
along *continuous* paths.

schematically:

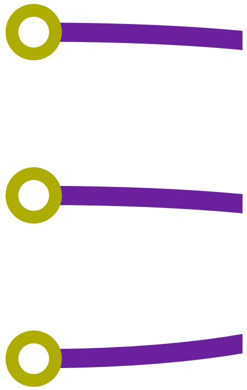
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,

turning a given **initial state**
into the computed **result**.

cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Notice: *Fundamentally*,
all computation is
along *continuous* paths.

schematically:



To compute is to **execute** sequences of **instructions** as composable **operations** on a chosen **state space**,

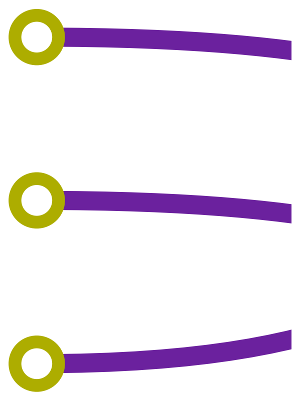
turning a given **initial state** into the computed **result**.

cf. [van Leeuwen & Wiedermann (2017)]

[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Notice: *Fundamentally*, all computation is along *continuous* paths.

schematically:



To compute is to **execute** sequences of **instructions** as composable **operations** on a chosen **state space**,

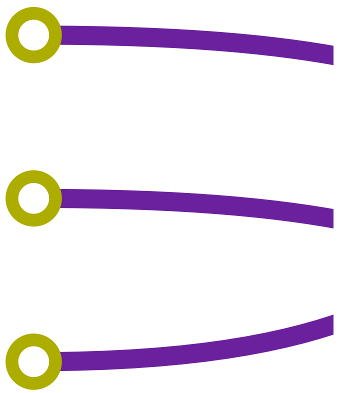
turning a given **initial state** into the computed **result**.

cf. [van Leeuwen & Wiedermann (2017)]

[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Notice: *Fundamentally*, all computation is along *continuous* paths.

schematically:



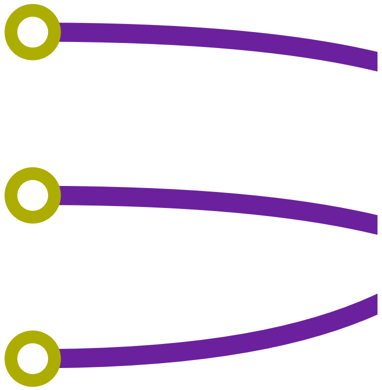
To compute is to **execute** sequences of **instructions** as composable **operations** on a chosen **state space**,

turning a given **initial state** into the computed **result**.

cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Notice: *Fundamentally*, all computation is along *continuous* paths.

schematically:



To compute is to **execute** sequences of **instructions** as composable **operations** on a chosen **state space**,

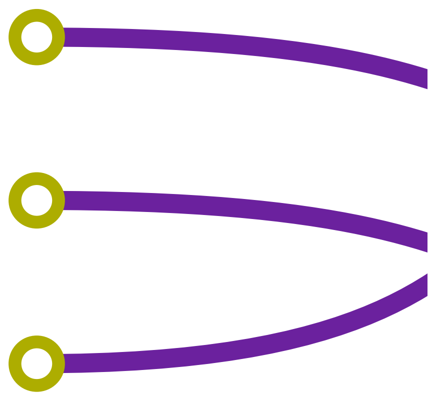
turning a given **initial state** into the computed **result**.

cf. [van Leeuwen & Wiedermann (2017)]

[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Notice: *Fundamentally*, all computation is along *continuous* paths.

schematically:



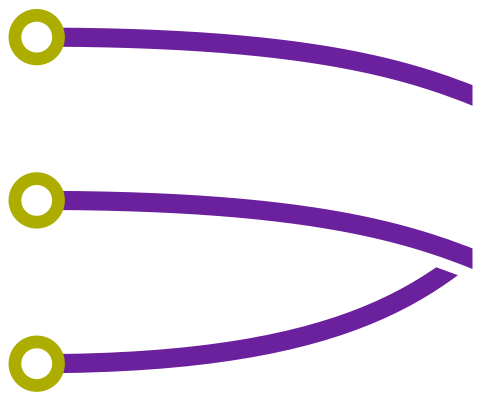
To compute is to **execute** sequences of **instructions** as composable **operations** on a chosen **state space**,

turning a given **initial state** into the computed **result**.

cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Notice: *Fundamentally*, all computation is along *continuous* paths.

schematically:



To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,

turning a given **initial state**
into the computed **result**.

cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Notice: *Fundamentally*,
all computation is
along *continuous* paths.

schematically:

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,

turning a given **initial state**
into the computed **result**.

cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Notice: *Fundamentally*,
all computation is
along *continuous* paths.

schematically:

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,

turning a given **initial state**
into the computed **result**.

cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Notice: *Fundamentally*,
all computation is
along *continuous* paths.

schematically:

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,

turning a given **initial state**
into the computed **result**.

cf. [van Leeuwen & Wiedermann (2017)]

[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Notice: *Fundamentally*,
all computation is
along *continuous* paths.

schematically:

To compute is to **execute** sequences of **instructions** as composable **operations** on a chosen **state space**,

turning a given **initial state** into the computed **result**.

cf. [van Leeuwen & Wiedermann (2017)]

[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Notice: *Fundamentally*, all computation is along *continuous* paths.

schematically:

cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,

turning a given **initial state**
into the computed **result**.

Notice: *Fundamentally*,
all computation is
along *continuous* paths.

schematically:

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,

turning a given **initial state**
into the computed **result**.

cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Notice: *Fundamentally*,
all computation is
along *continuous* paths.

schematically:

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,
turning a given **initial state**
into the computed **result**.

cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Notice: *Fundamentally*,
all computation is
along *continuous* paths.

schematically:

cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,

turning a given **initial state**
into the computed **result**.

Notice: *Fundamentally*,
all computation is
along *continuous* paths.

schematically:

To compute is to **execute** sequences of **instructions** as composable **operations** on a chosen **state space**,

turning a given **initial state** into the computed **result**.

cf. [van Leeuwen & Wiedermann (2017)]

[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Notice: *Fundamentally*, all computation is along *continuous* paths.

schematically:

To compute is to **execute** sequences of **instructions** as composable **operations** on a chosen **state space**,

turning a given **initial state** into the computed **result**.

cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Notice: *Fundamentally*, all computation is along *continuous* paths.

schematically:

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,

turning a given **initial state**
into the computed **result**.

cf. [van Leeuwen & Wiedermann (2017)]
[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Notice: *Fundamentally*,
all computation is
along *continuous* paths.

schematically:

reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,

turning a given **initial state**
into the computed **result**.

reliably

To compute is to **execute** sequences of **instructions** as composable **operations** on a chosen robust **state space**, turning a given **initial state** into the computed **result**.

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,
turning a given **initial state**
into the computed **result**.

reliably

robust

consistently

reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **state space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒

result should be stable
under small deformations
of the computation path

reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust state **space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of Classical Digital Computation:
Coarse-grain state space into a bit lattice.

(effective but brutal truncation of
underlying physical processes)

reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.

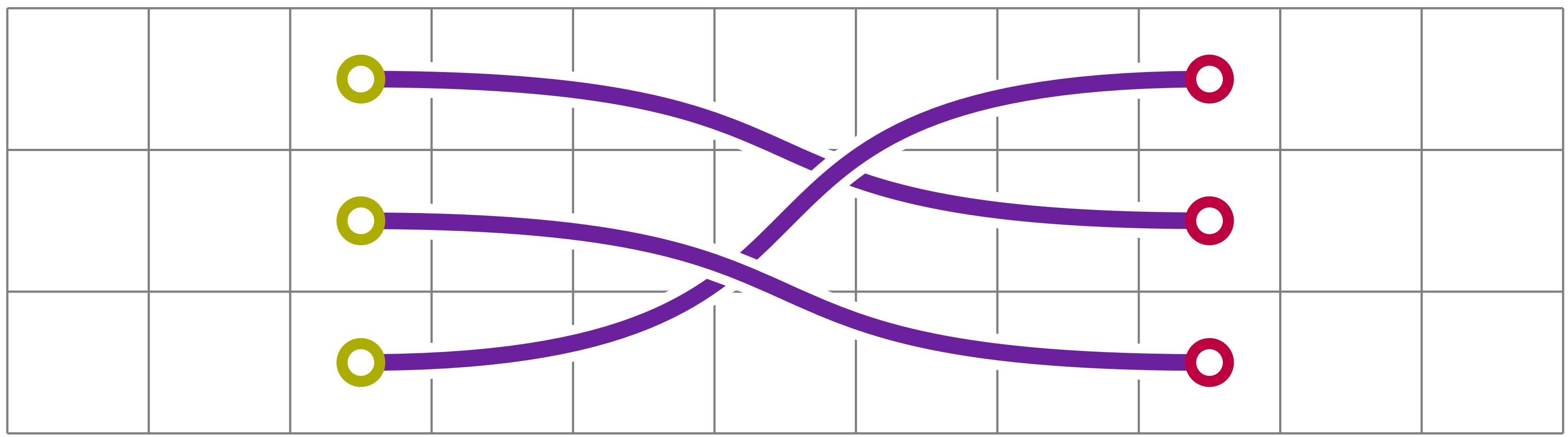
consistently

⇒

result should be stable
under small deformations
of the computation path

Strategy of **Classical Digital Computation:**
Coarse-grain state space into a bit lattice.

(effective but brutal truncation of
underlying physical processes)



reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**

robust

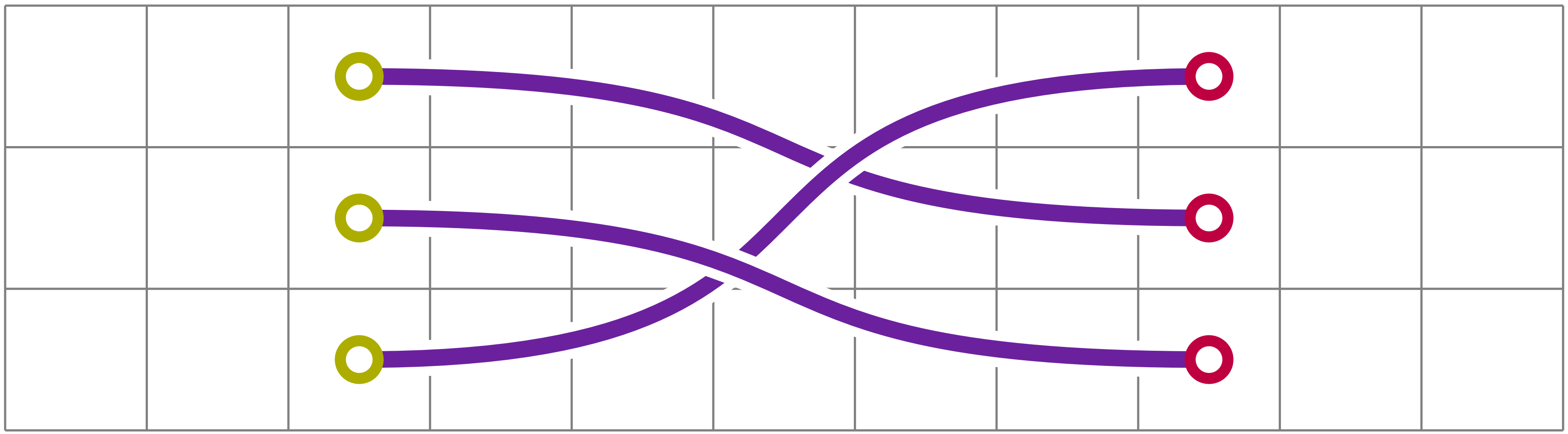
on a chosen **state space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Classical Digital Computation:**
Coarse-grain state space into a bit lattice.

(effective but brutal truncation of
underlying physical processes)



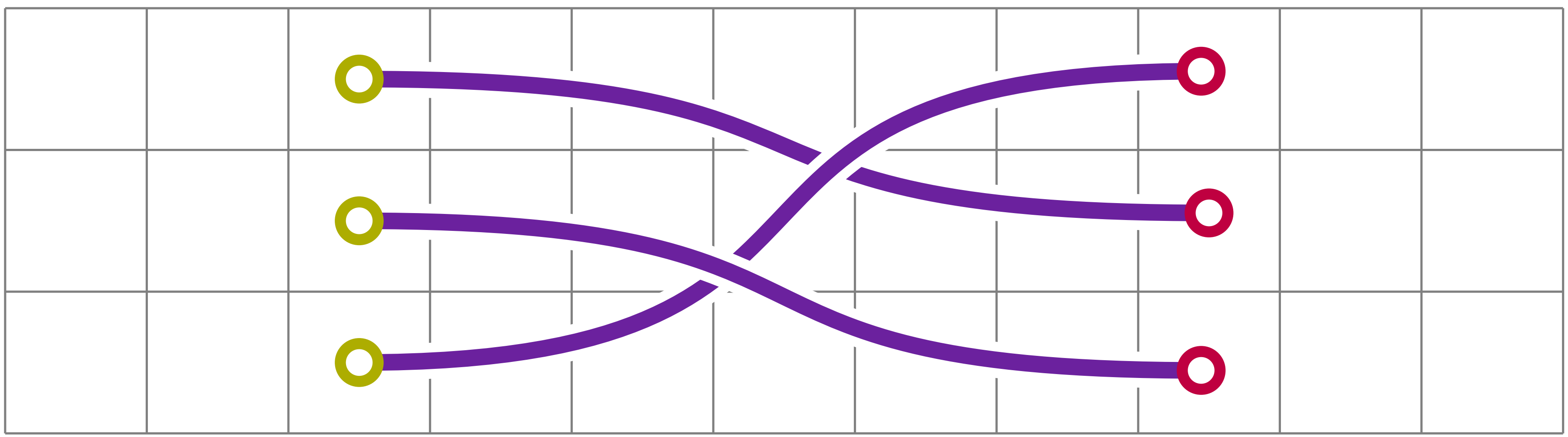
reliably

To compute is to **execute** sequences of **instructions** as composable **operations** on a chosen robust **state space**, turning a given **initial state** into the computed **result**. consistently

⇒ result should be stable under small deformations of the computation path

Strategy of **Classical Digital Computation:** Coarse-grain state space into a bit lattice.

(effective but brutal truncation of underlying physical processes)



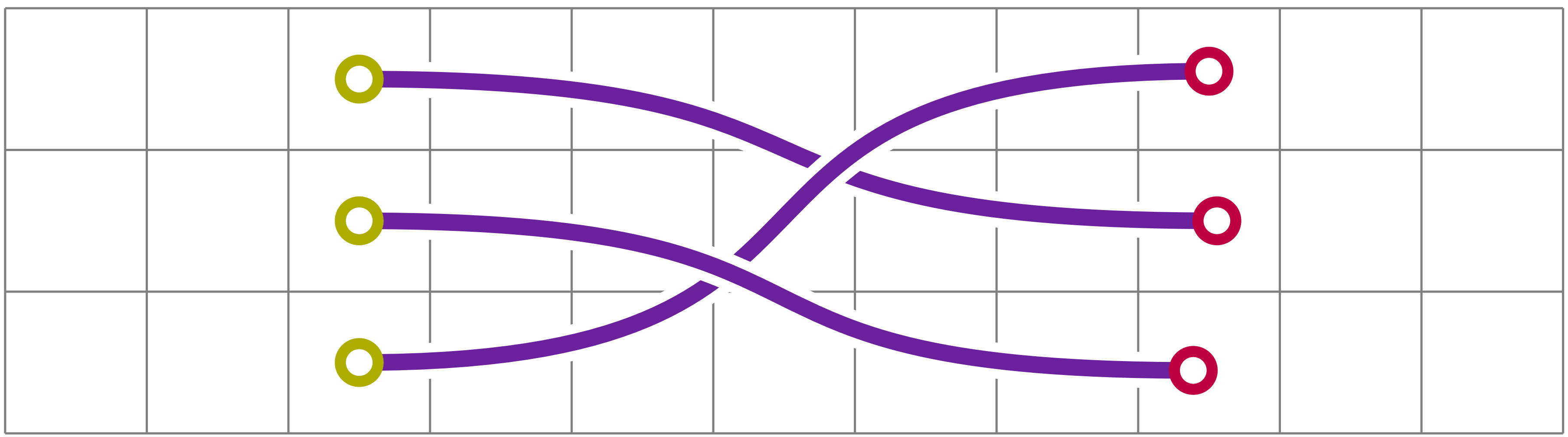
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **state space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of Classical Digital Computation:
Coarse-grain state space into a bit lattice.

(effective but brutal truncation of
underlying physical processes)

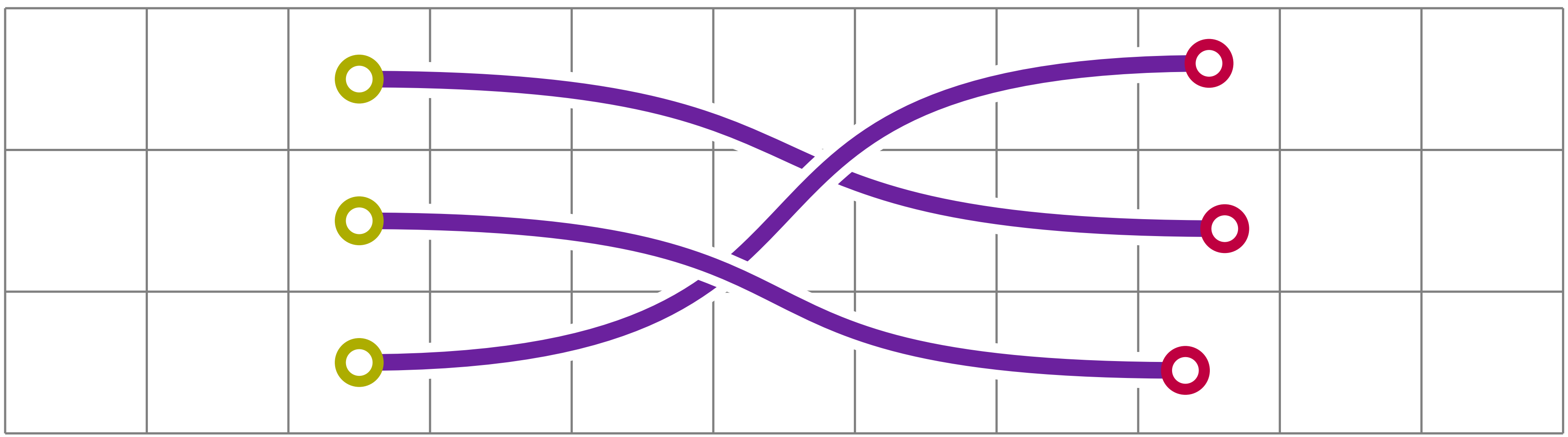


[reliably] **To compute** is to **execute** sequences of **instructions** as composable **operations** on a chosen [robust] **space**, turning a given **initial state** into the computed **result**. [consistently]

⇒ result should be stable under small deformations of the computation path

Strategy of Classical Digital Computation:
Coarse-grain state space into a bit lattice.

(effective but brutal truncation of underlying physical processes)



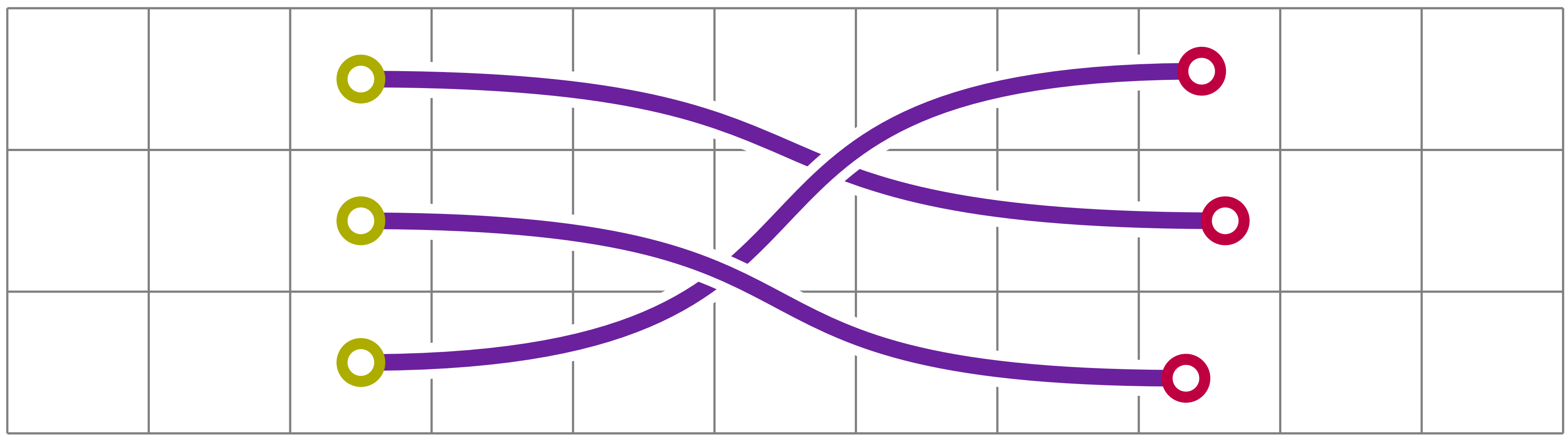
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **state space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Classical Digital Computation:**
Coarse-grain state space into a bit lattice.

(effective but brutal truncation of
underlying physical processes)



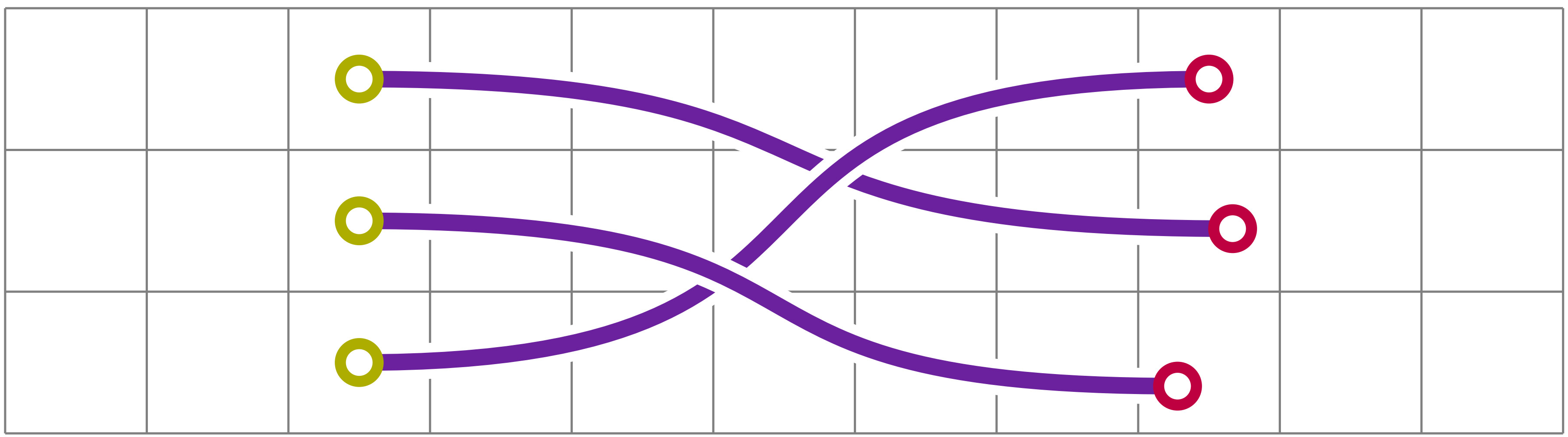
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Classical Digital Computation:**
Coarse-grain state space into a bit lattice.

(effective but brutal truncation of
underlying physical processes)



reliably

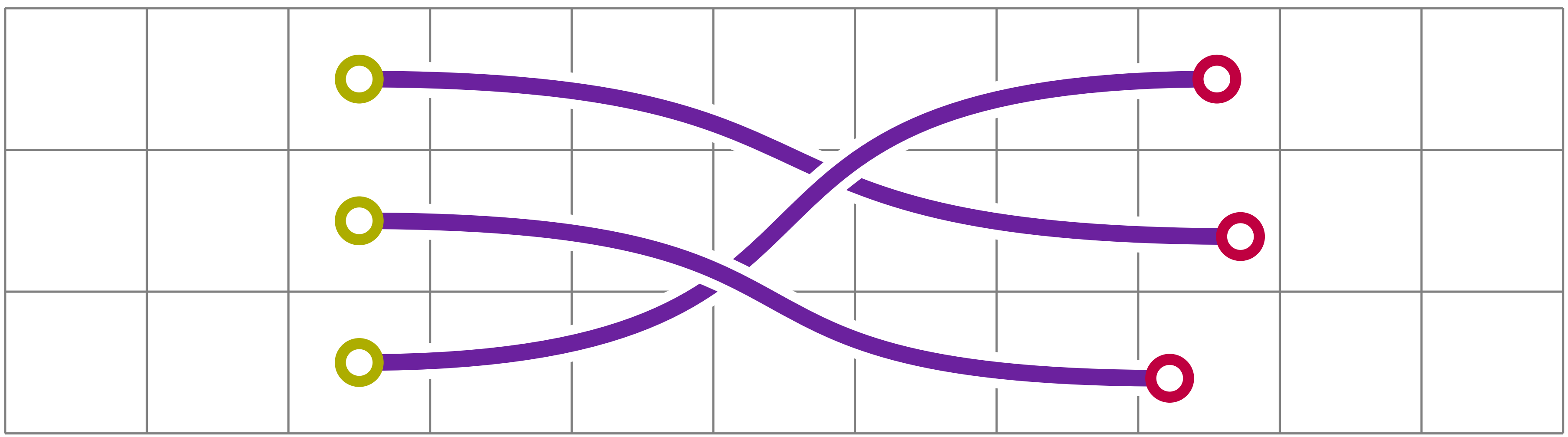
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **state space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of Classical Digital Computation:
Coarse-grain state space into a bit lattice.

(effective but brutal truncation of
underlying physical processes)

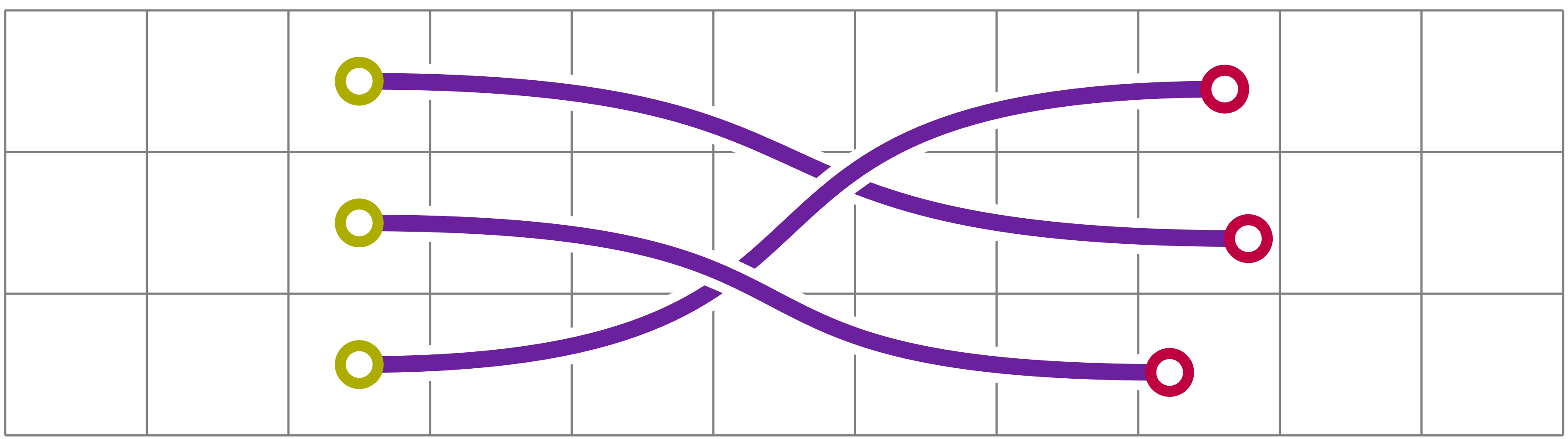


[reliably] **To compute** is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen [robust] state **space**,
turning a given **initial state**
into the computed **result**. [consistently]

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Classical Digital Computation:**
Coarse-grain state space into a bit lattice.

(effective but brutal truncation of
underlying physical processes)



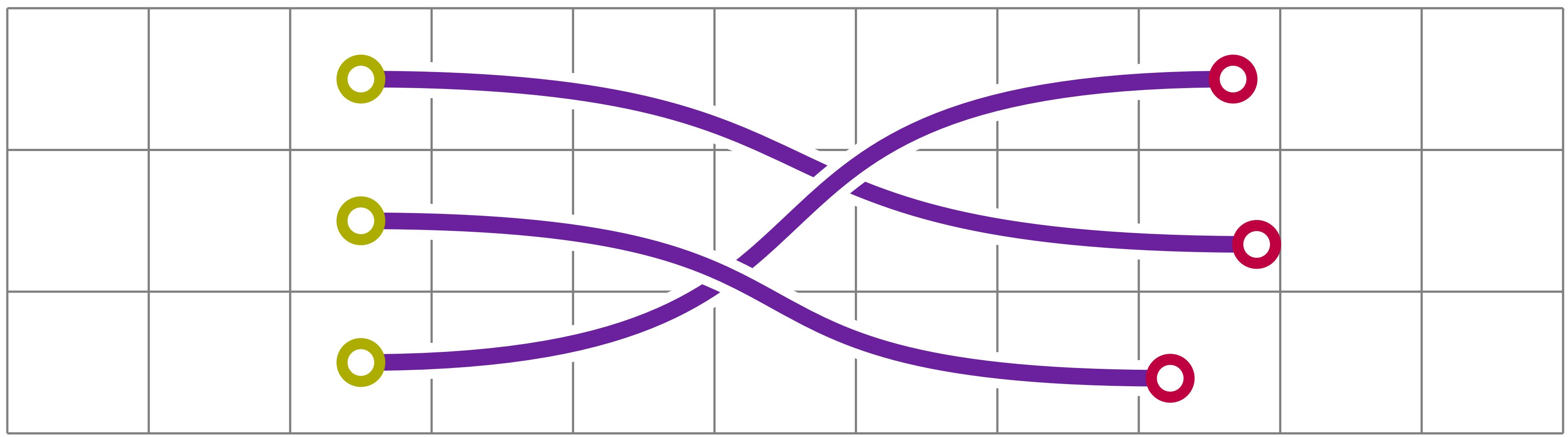
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.
consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Classical Digital Computation:**
Coarse-grain state space into a bit lattice.

(effective but brutal truncation of
underlying physical processes)



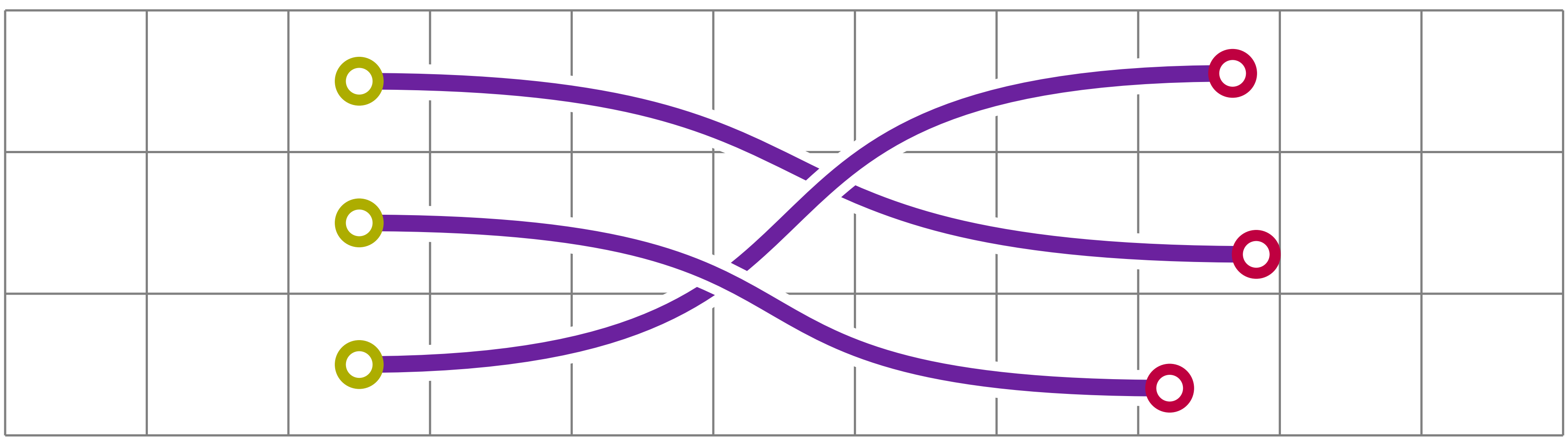
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **state space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of Classical Digital Computation:
Coarse-grain state space into a bit lattice.

(effective but brutal truncation of
underlying physical processes)



reliably

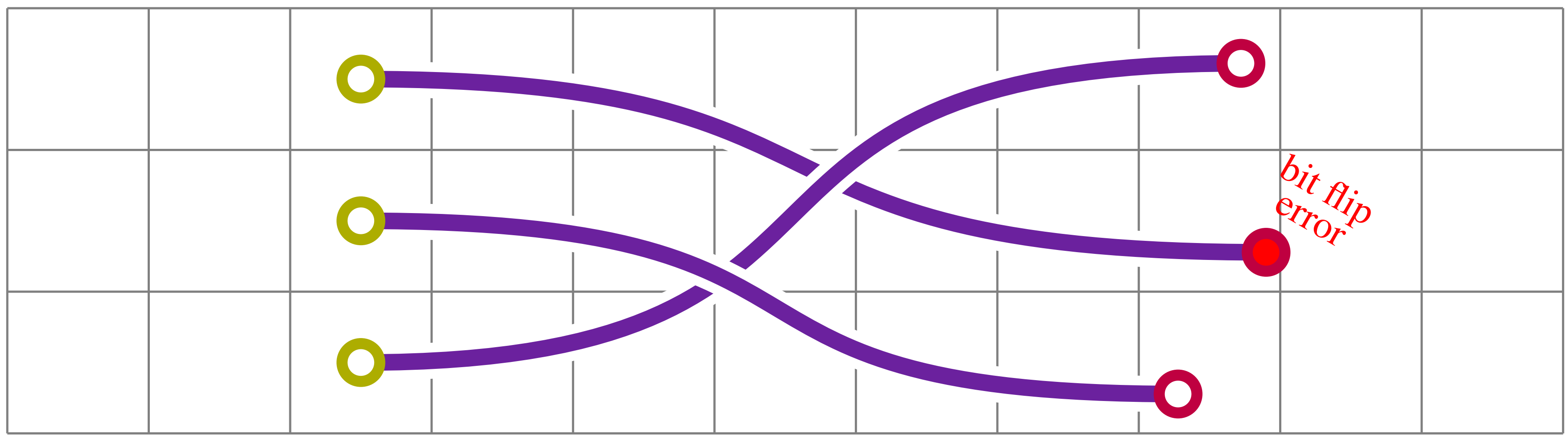
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**. consistently

⇒

result should be stable
under small deformations
of the computation path

Strategy of **Classical Digital Computation:** Coarse-grain state space into a bit lattice.

(effective but brutal truncation of underlying physical processes)



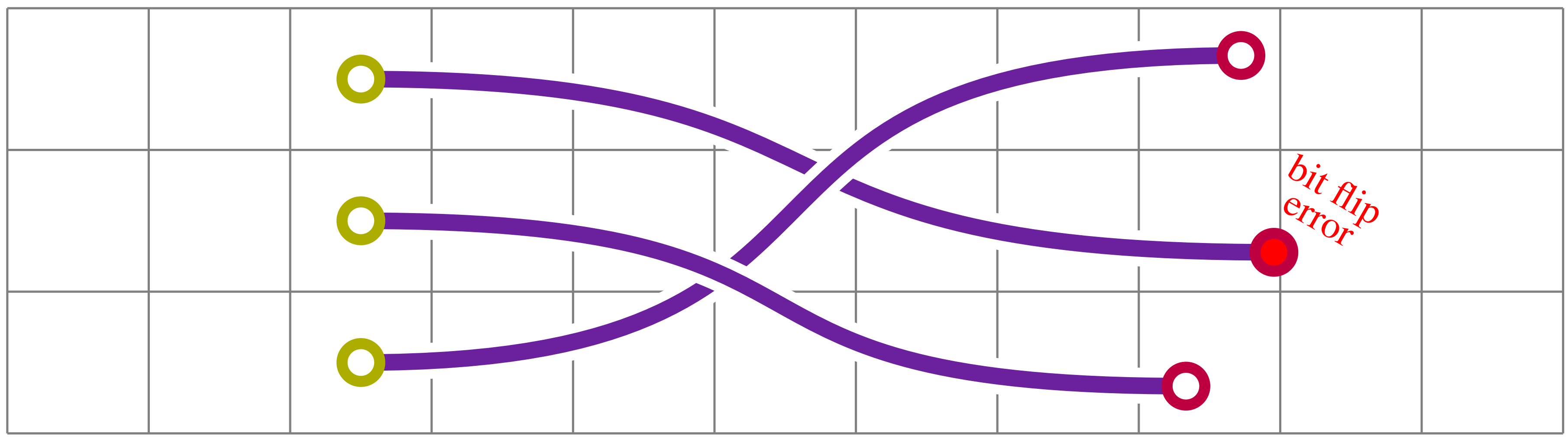
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **state space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Classical Digital Computation:** Coarse-grain state space into a bit lattice.

(effective but brutal truncation of
underlying physical processes)



reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**

robust

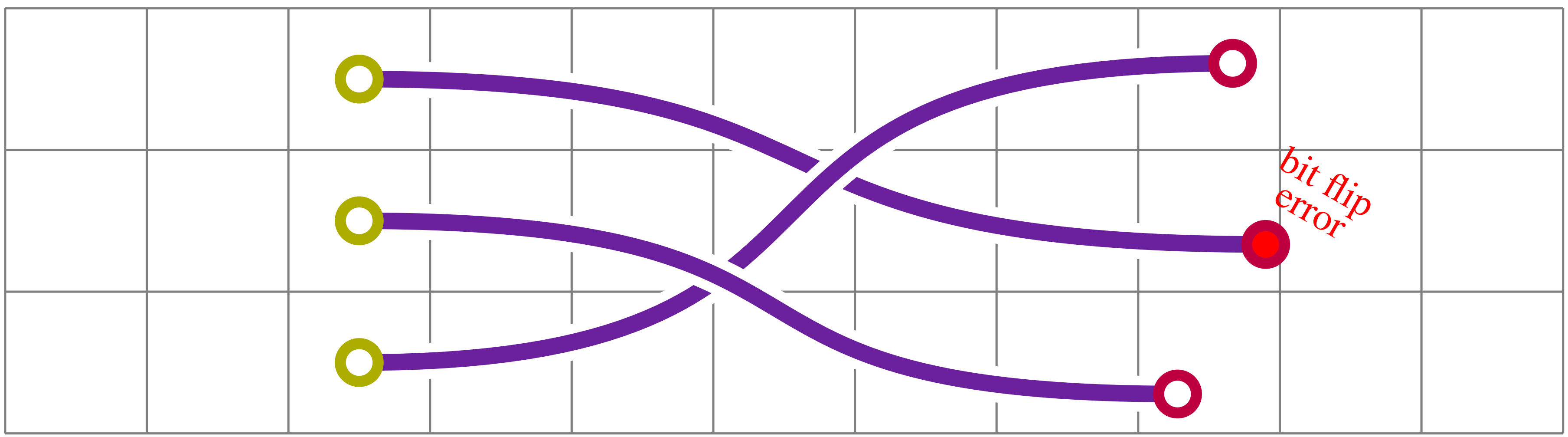
on a chosen **state space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Classical Digital Computation:**
Coarse-grain state space into a bit lattice.

(effective but brutal truncation of
underlying physical processes)



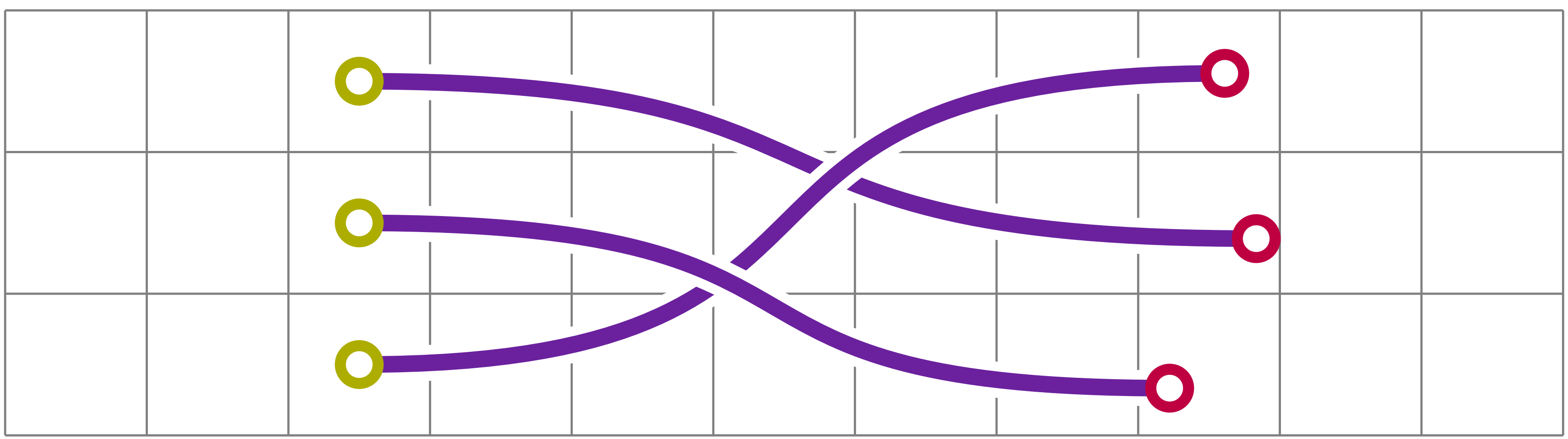
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **state space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Classical Digital Computation:**
Coarse-grain state space into a bit lattice.

(effective but brutal truncation of
underlying physical processes)

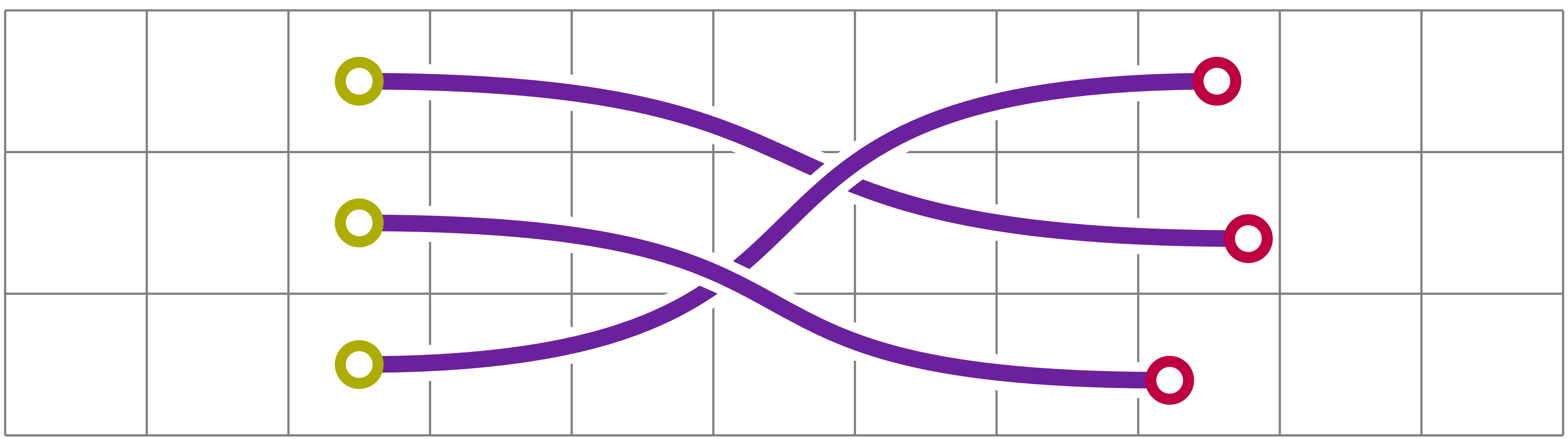


To compute [reliably] is to **execute** sequences of **instructions** as composable **operations** on a chosen [robust] **state space**, turning a given **initial state** into the computed **result** [consistently].

⇒ result should be stable under small deformations of the computation path

Strategy of Classical Digital Computation: Coarse-grain state space into a bit lattice.

(effective but brutal truncation of underlying physical processes)



reliably

To compute is to **execute** sequences of **instructions** as composable **operations** on a chosen **state space**, turning a given **initial state** into the computed **result**.

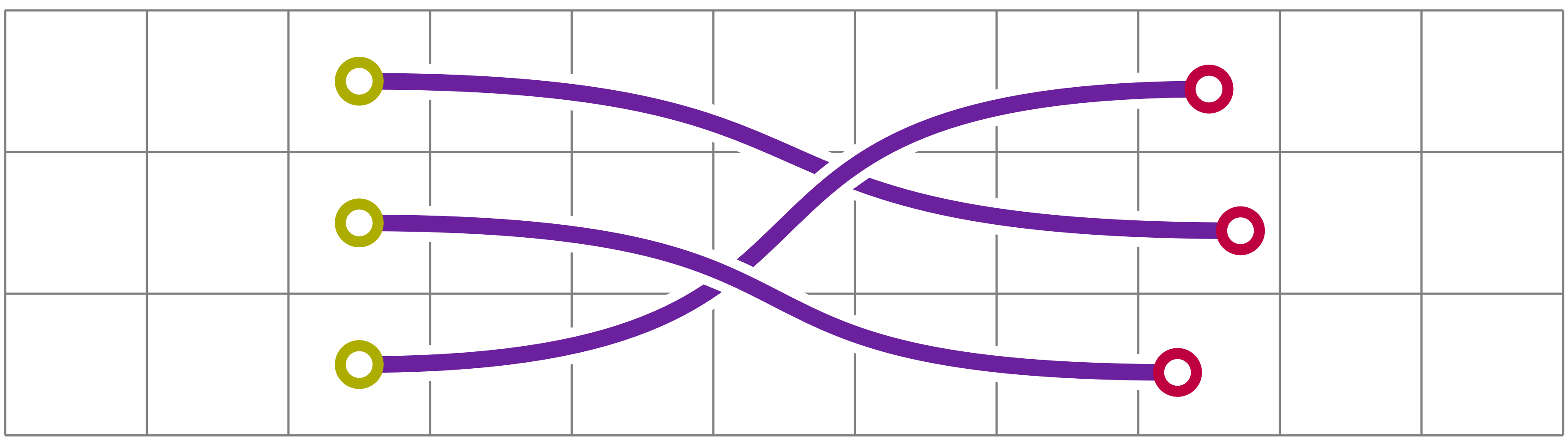
robust

consistently

⇒ result should be stable under small deformations of the computation path

Strategy of Classical Digital Computation:
Coarse-grain state space into a bit lattice.

(effective but brutal truncation of underlying physical processes)



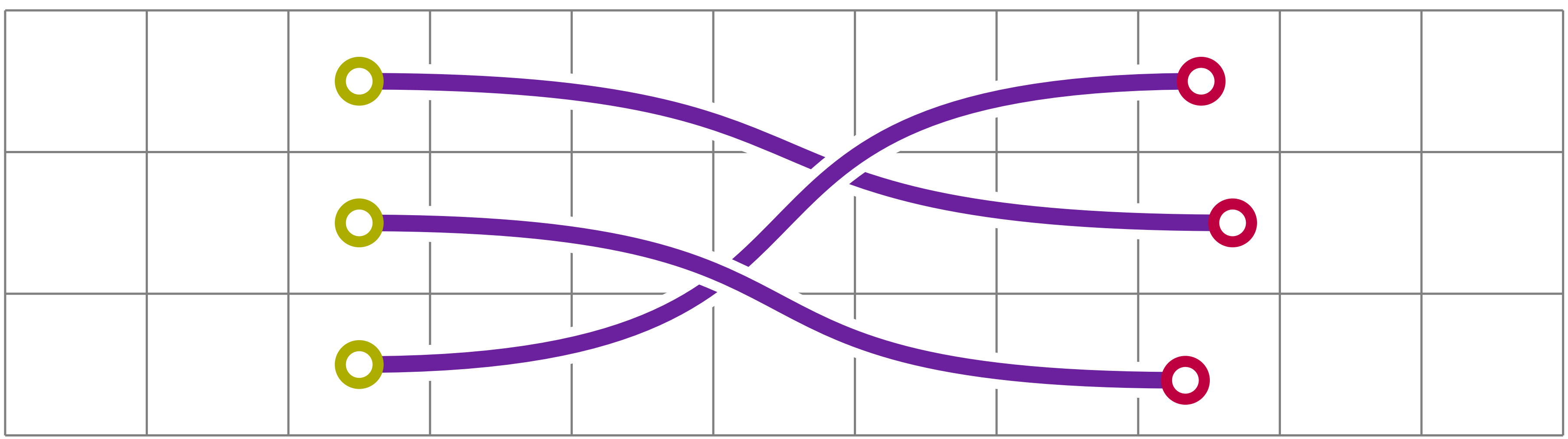
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **state space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Classical Digital Computation:** Coarse-grain state space into a bit lattice.

(effective but brutal truncation of
underlying physical processes)



reliably

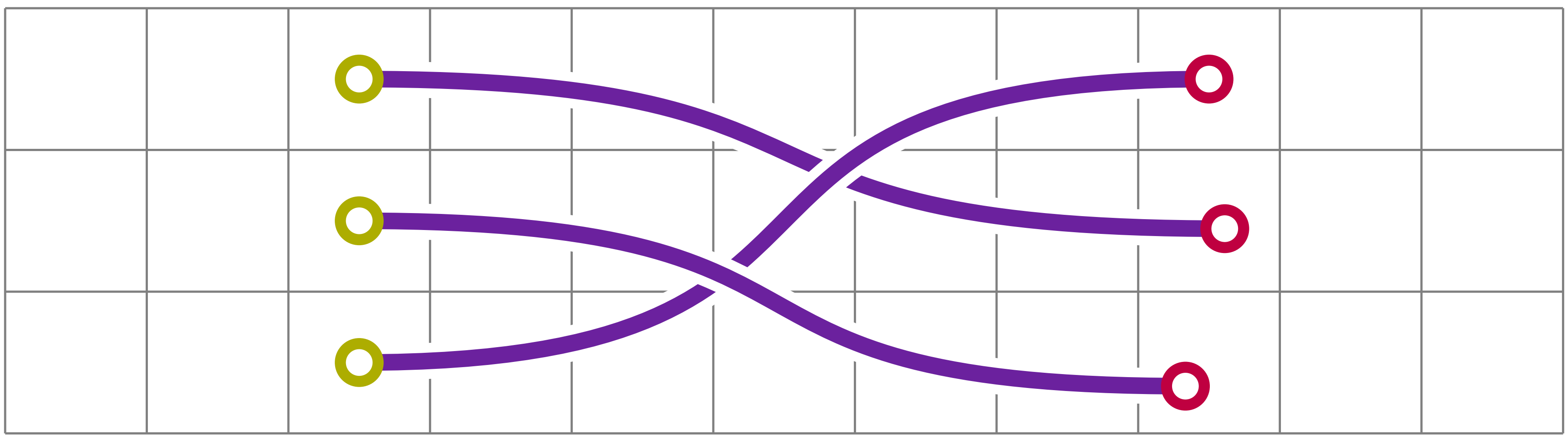
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Classical Digital Computation:** Coarse-grain state space into a bit lattice.

(effective but brutal truncation of
underlying physical processes)



reliably

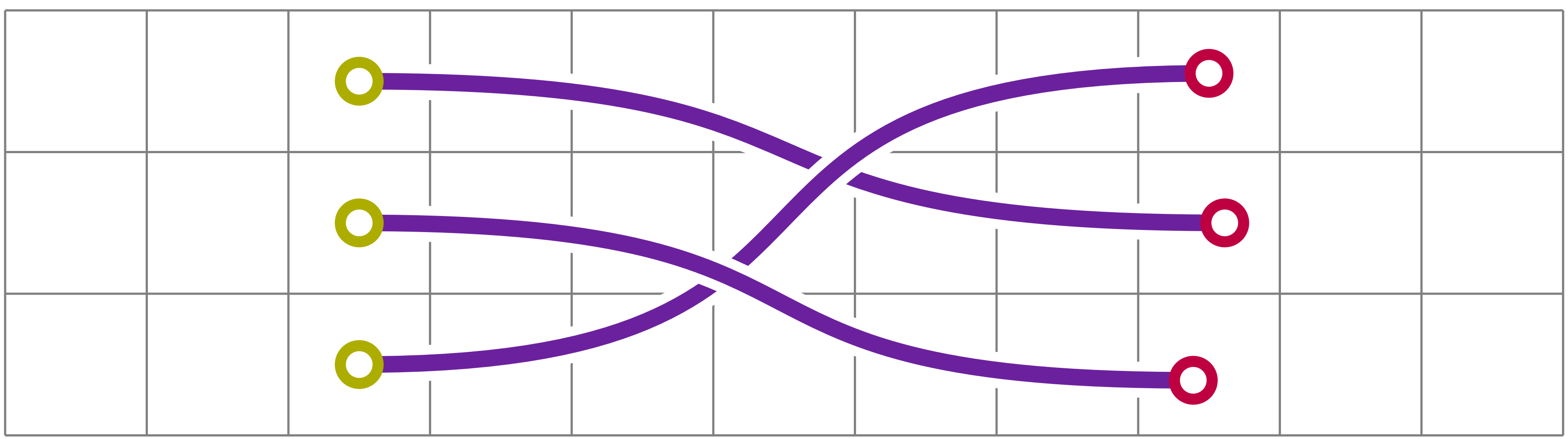
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Classical Digital Computation:** Coarse-grain state space into a bit lattice.

(effective but brutal truncation of
underlying physical processes)



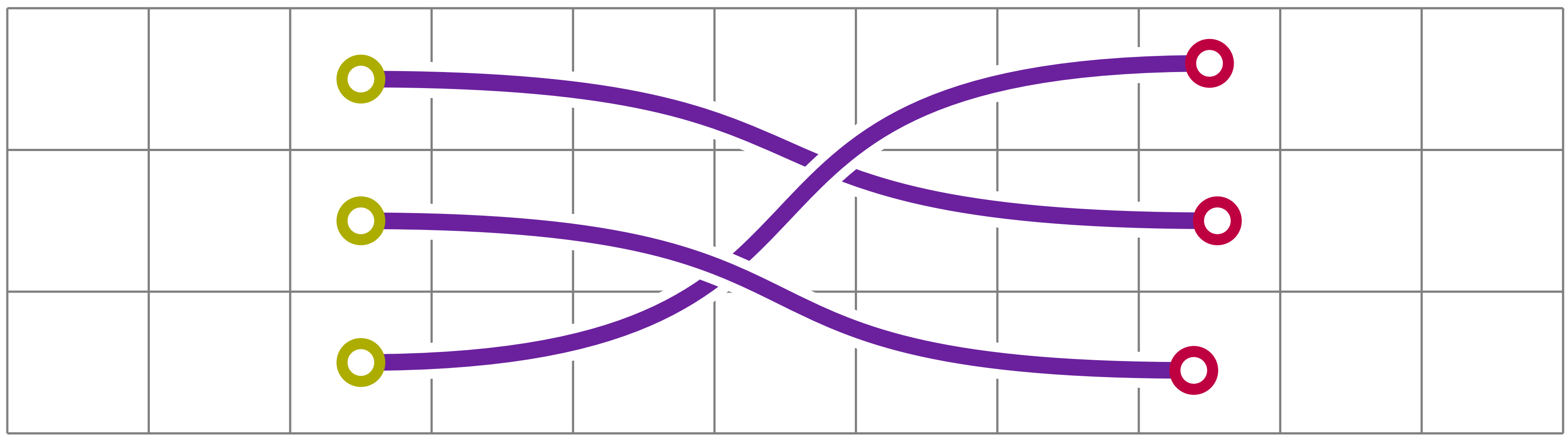
reliably

To compute is to **execute** sequences of **instructions** as composable **operations** on a chosen robust **space**, turning a given **initial state** into the computed **result**. consistently

⇒ result should be stable under small deformations of the computation path

Strategy of **Classical Digital Computation:**
Coarse-grain state space into a bit lattice.

(effective but brutal truncation of underlying physical processes)



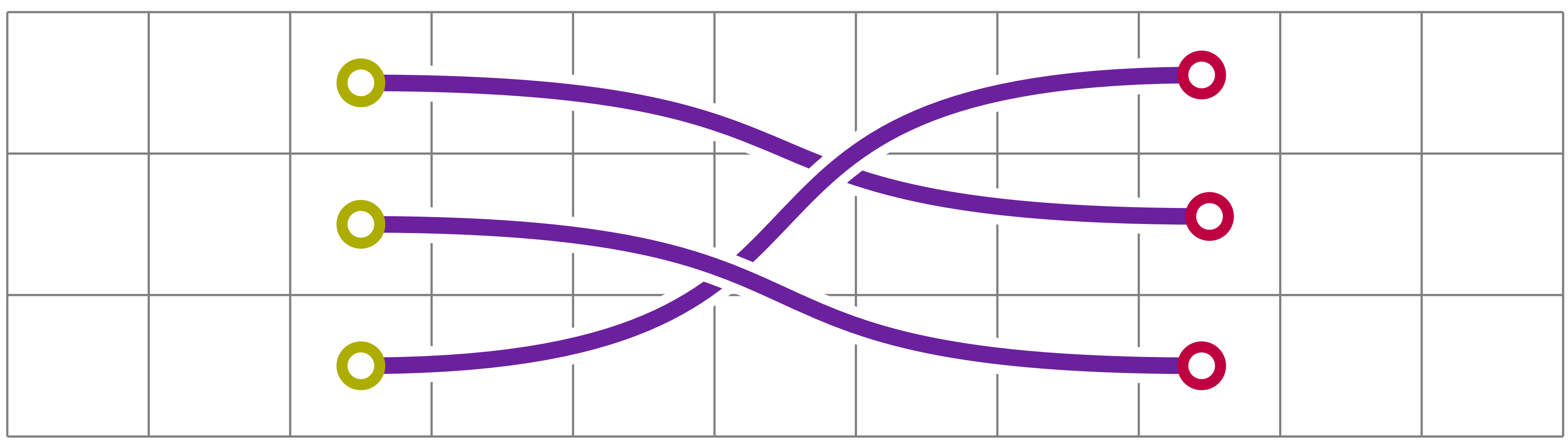
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **state space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Classical Digital Computation:**
Coarse-grain state space into a bit lattice.

(effective but brutal truncation of
underlying physical processes)



reliably

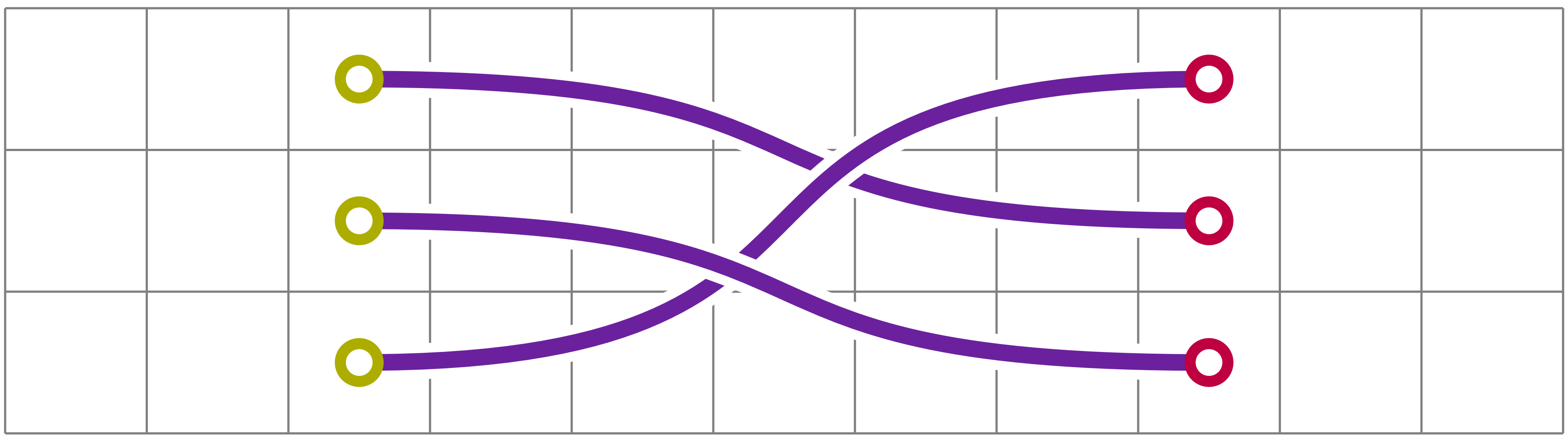
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of Classical Digital Computation:
Coarse-grain state space into a bit lattice.

(effective but brutal truncation of
underlying physical processes)



reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

reliably

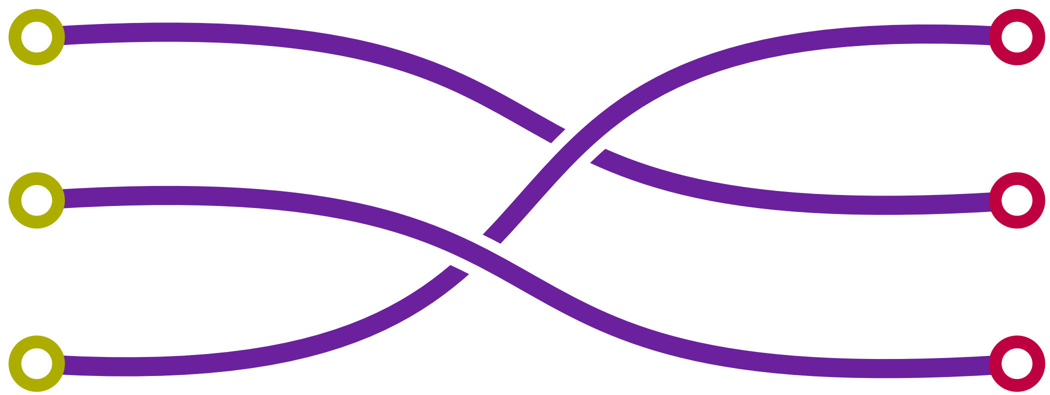
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **state space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

i.e.: *invariant* under reasonable disturbances

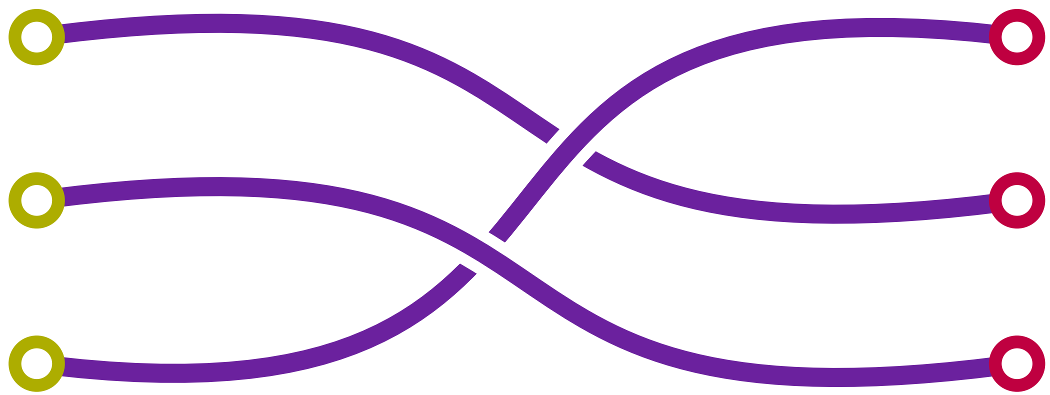


[reliably]
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen [robust] **space**,
turning a given **initial state**
into the computed **result**. [consistently]

⇒ result should be stable
under small deformations
of the computation path

Strategy of Topological Quantum Computation:
Use topologically invariant quantum processes.

i.e.: *invariant* under reasonable disturbances



reliably

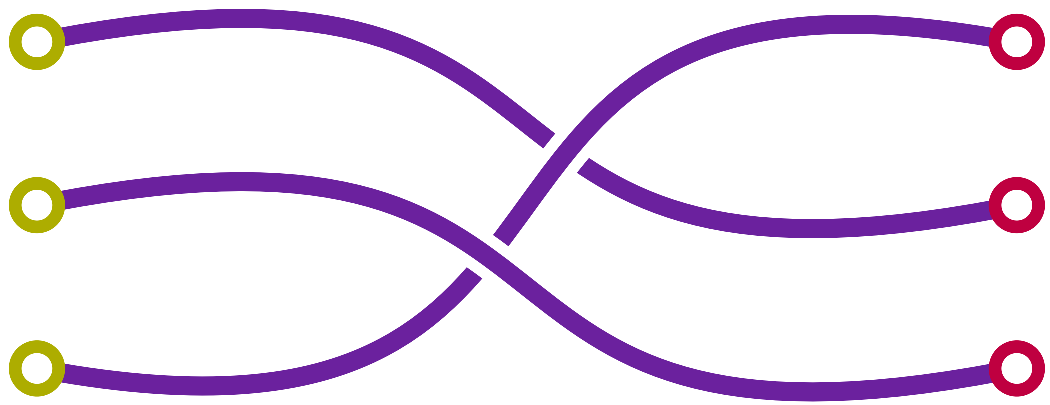
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

i.e.: *invariant* under reasonable disturbances



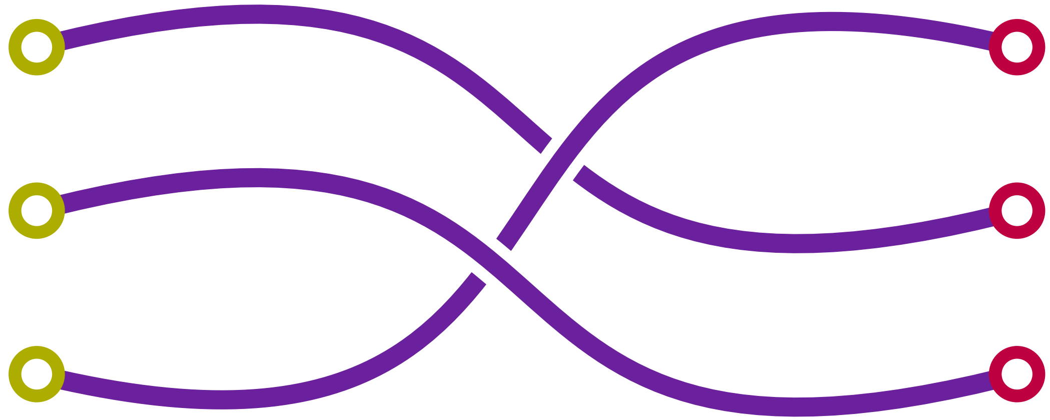
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust state **space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

i.e.: *invariant* under reasonable disturbances



reliably

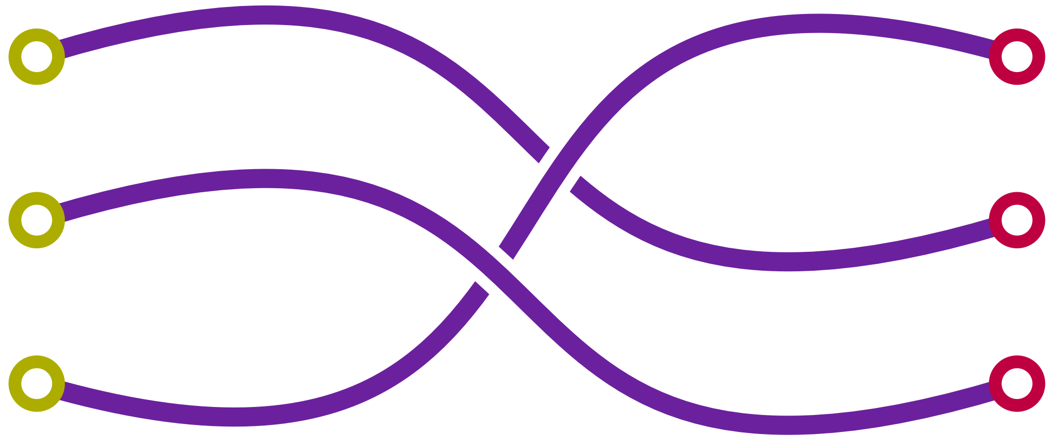
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **state space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:** Use topologically invariant quantum processes.

i.e.: *invariant* under reasonable disturbances



reliably

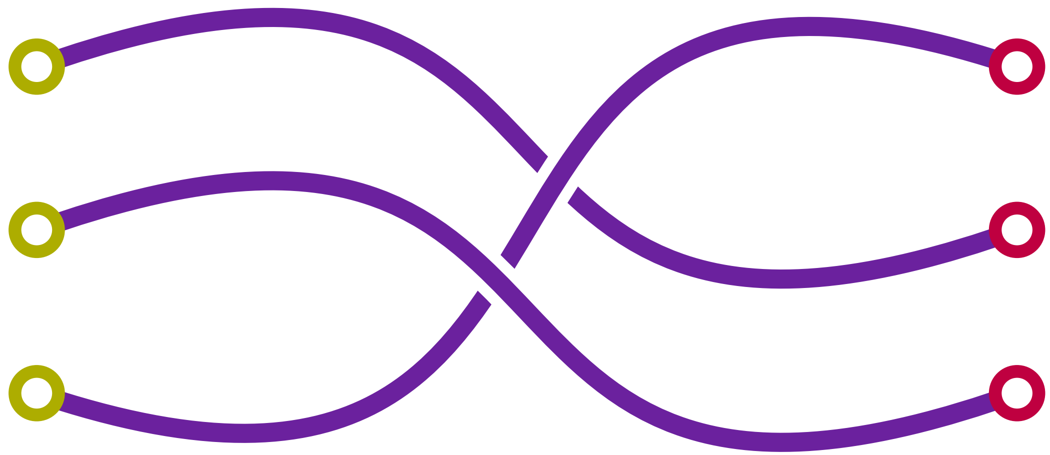
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

i.e.: *invariant* under reasonable disturbances



reliably

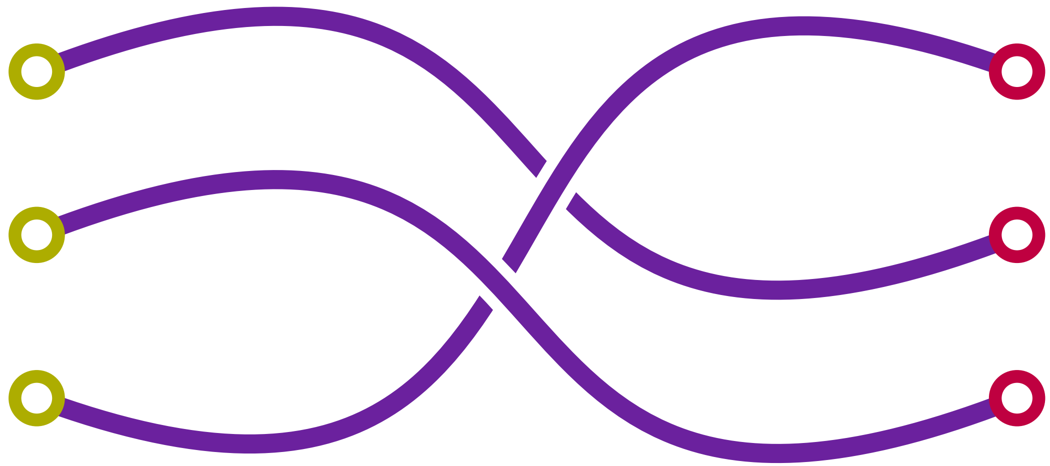
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of Topological Quantum Computation:
Use topologically invariant quantum processes.

i.e.: *invariant* under reasonable disturbances



reliably

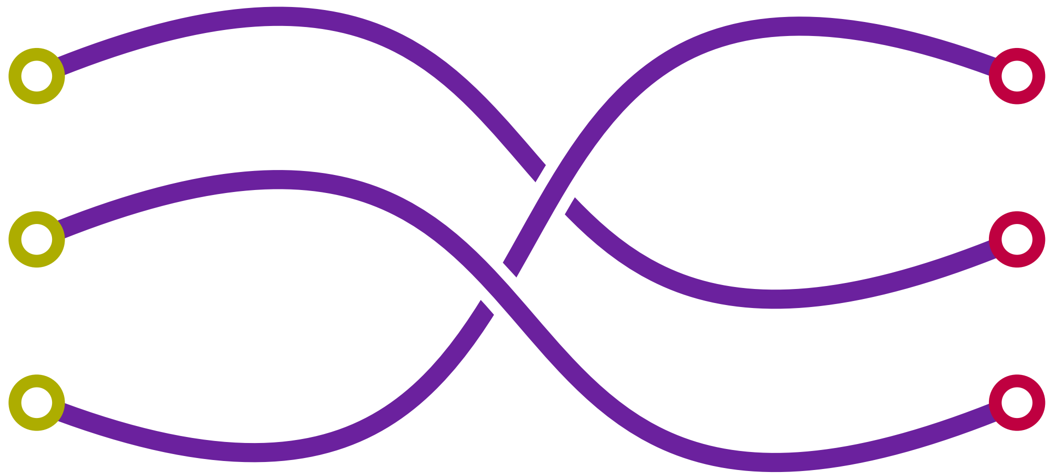
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

i.e.: *invariant* under reasonable disturbances



reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,
turning a given **initial state**
into the computed **result**.

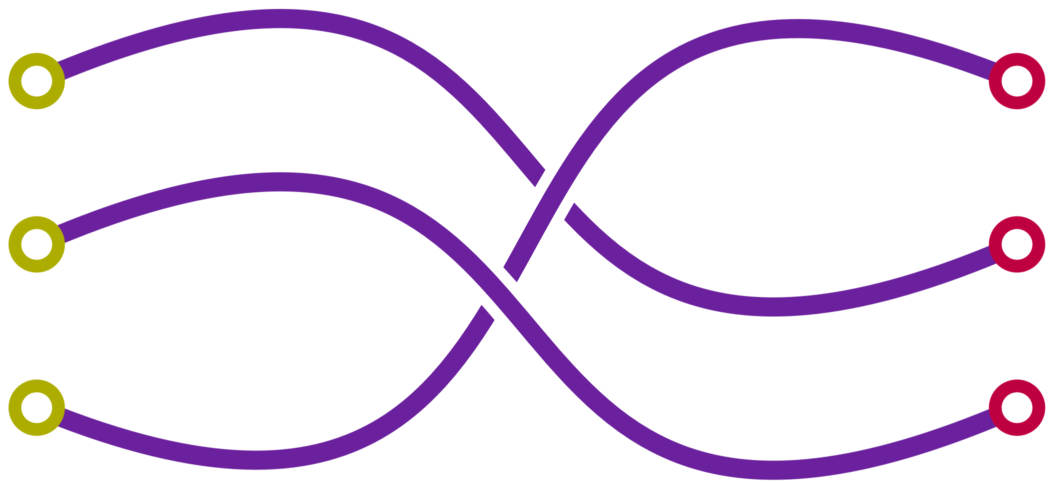
robust

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

i.e.: *invariant* under reasonable disturbances



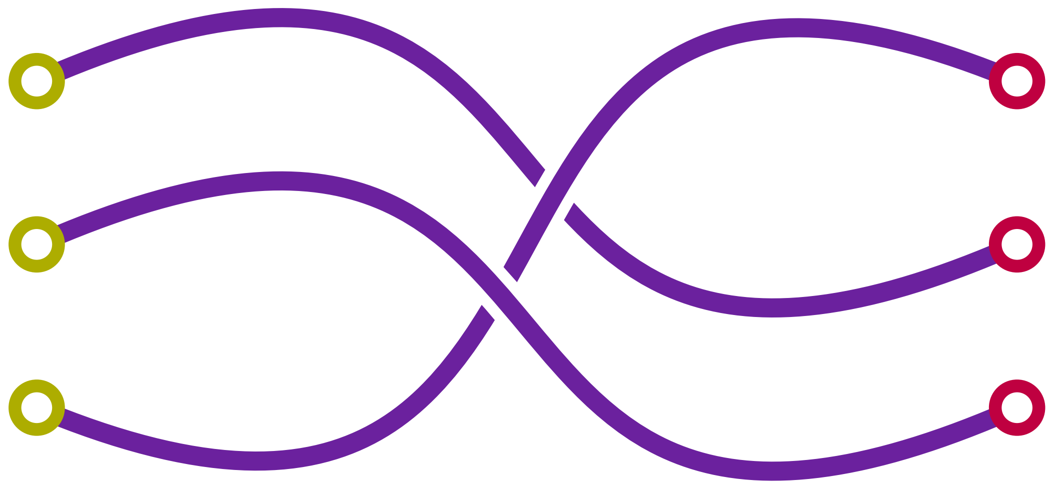
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
robust
on a chosen state **space**,
turning a given **initial state**
into the computed **result**.
consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

i.e.: *invariant* under reasonable disturbances



reliably

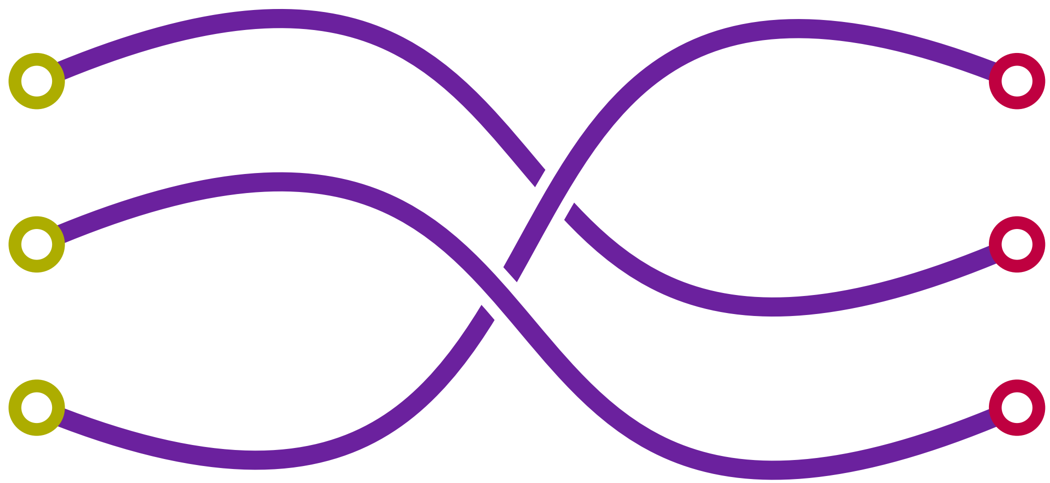
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **state space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of Topological Quantum Computation:
Use topologically invariant quantum processes.

i.e.: *invariant* under reasonable disturbances



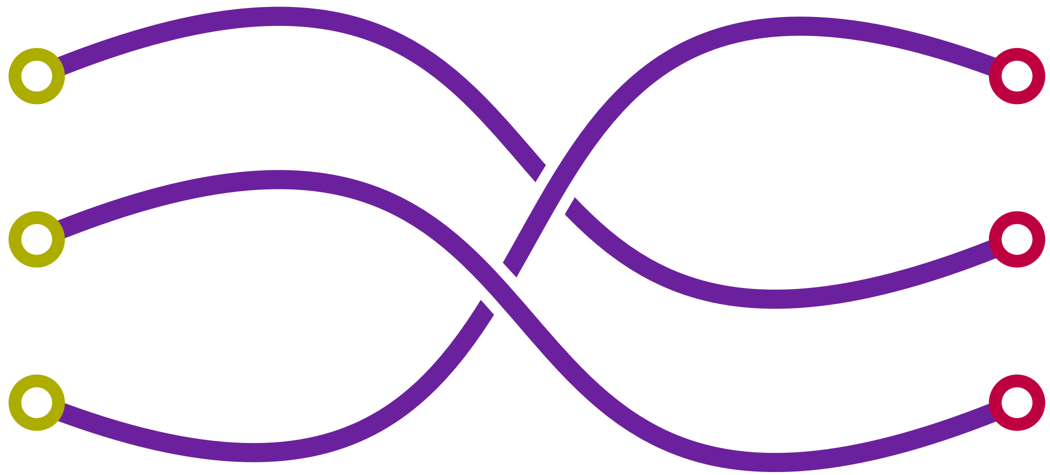
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.
consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

i.e.: *invariant* under reasonable disturbances



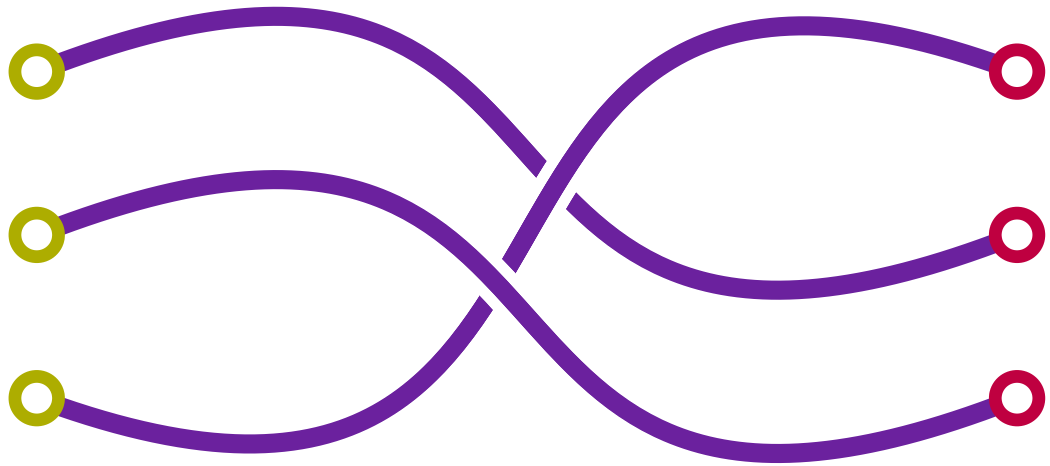
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
robust
on a chosen **space**,
turning a given **initial state**
into the computed **result**.
consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

i.e.: *invariant* under reasonable disturbances



reliably

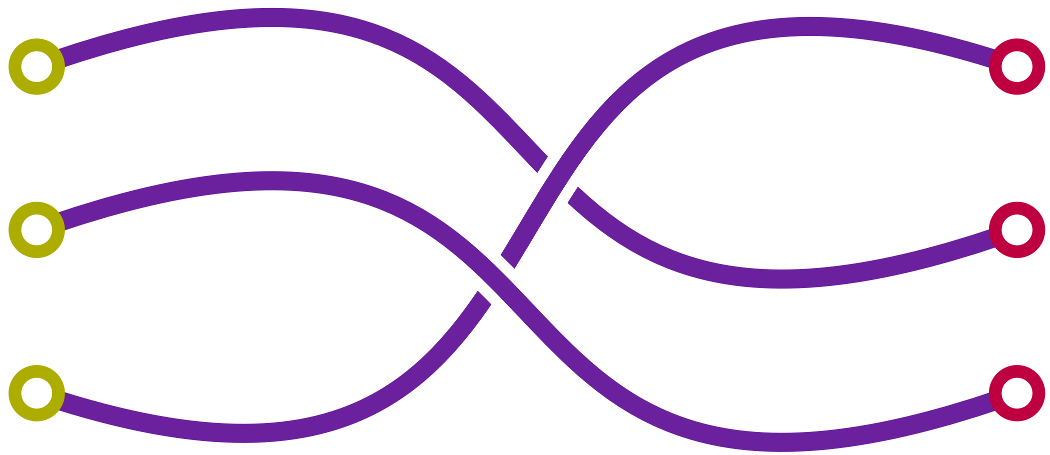
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

i.e.: *invariant* under reasonable disturbances



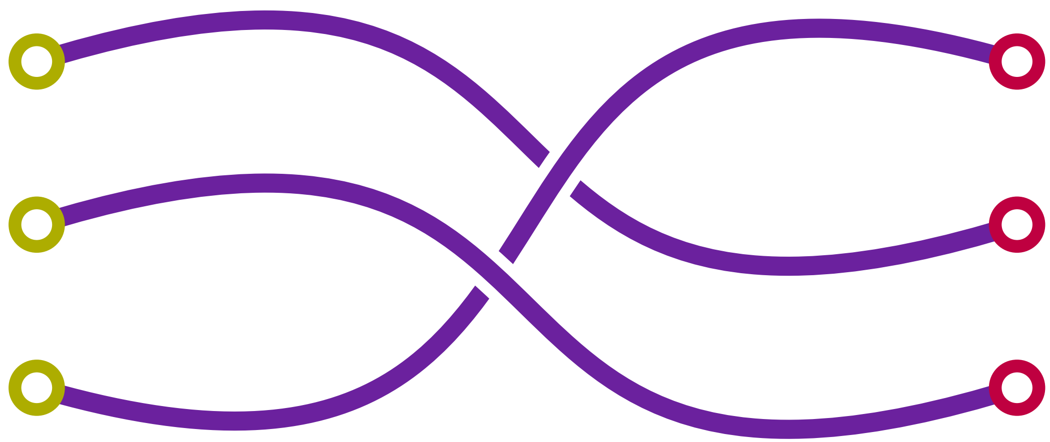
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **state space**,
turning a given **initial state**
into the computed **result**.
consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

i.e.: *invariant* under reasonable disturbances



reliably

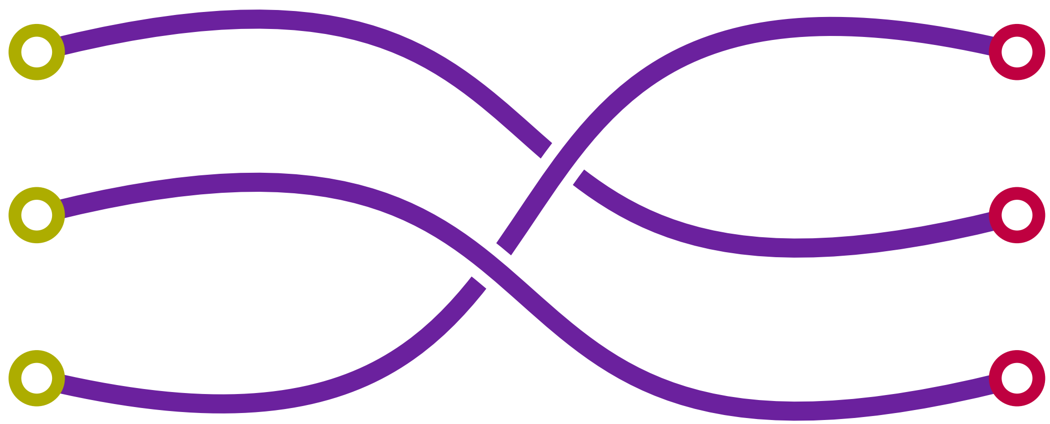
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **state space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

i.e.: *invariant* under reasonable disturbances



reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**

robust

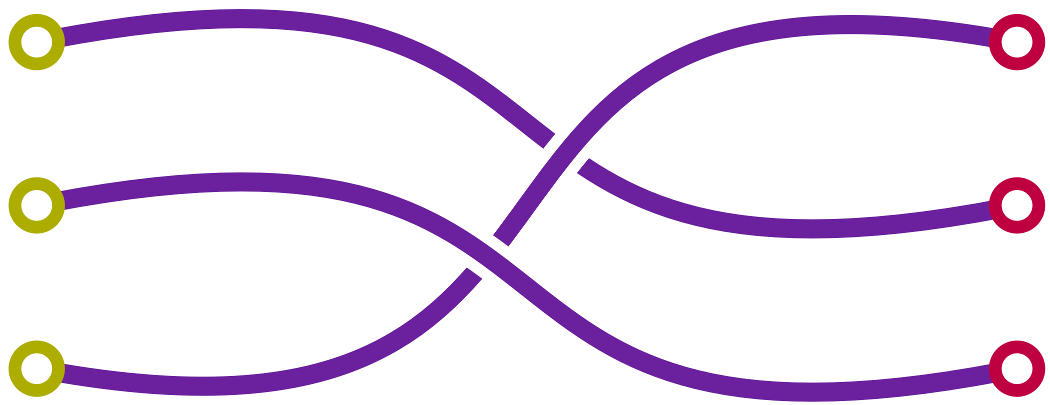
on a chosen **state space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

i.e.: *invariant* under reasonable disturbances



reliably

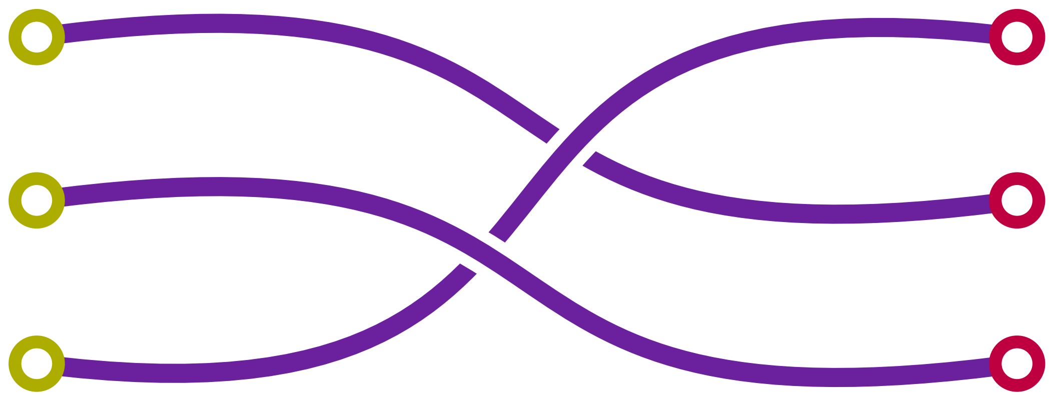
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust state **space**,
turning a given **initial state**
into the computed **result**. consistently

⇒

result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



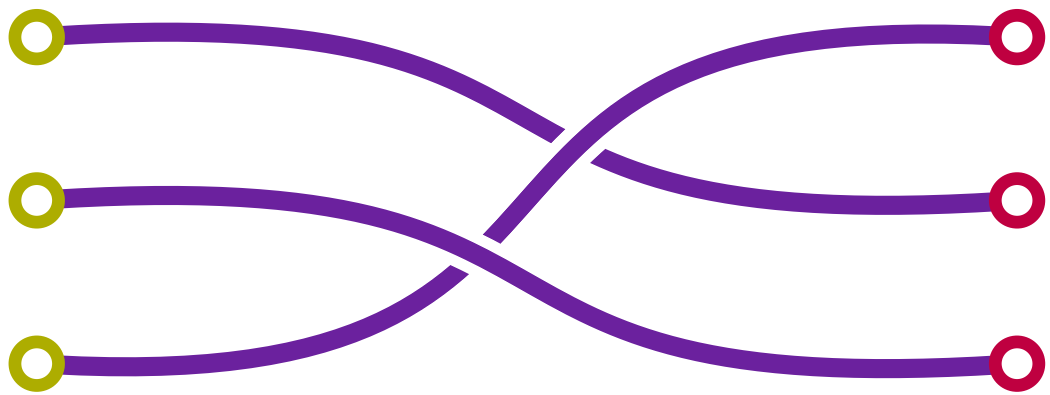
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.
consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.
consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of Topological Quantum Computation:
Use topologically invariant quantum processes.

⇒ knots as quantum gates

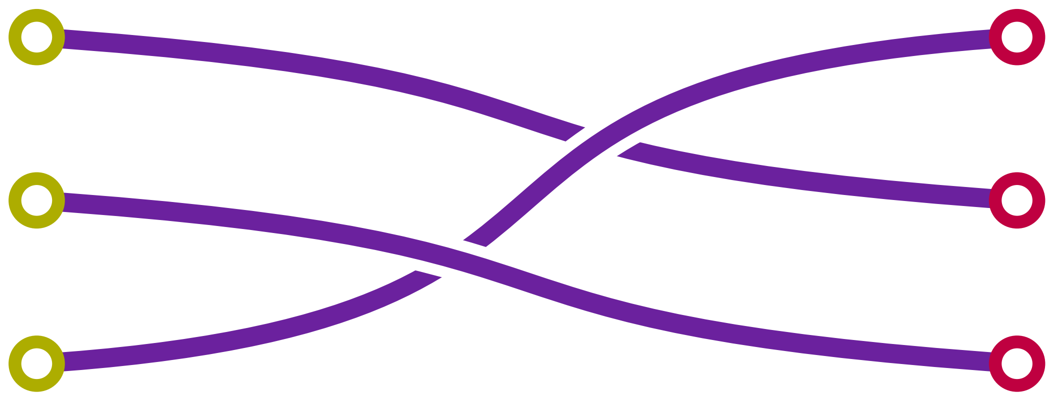
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of Topological Quantum Computation:
Use topologically invariant quantum processes.

⇒ knots as quantum gates



reliably

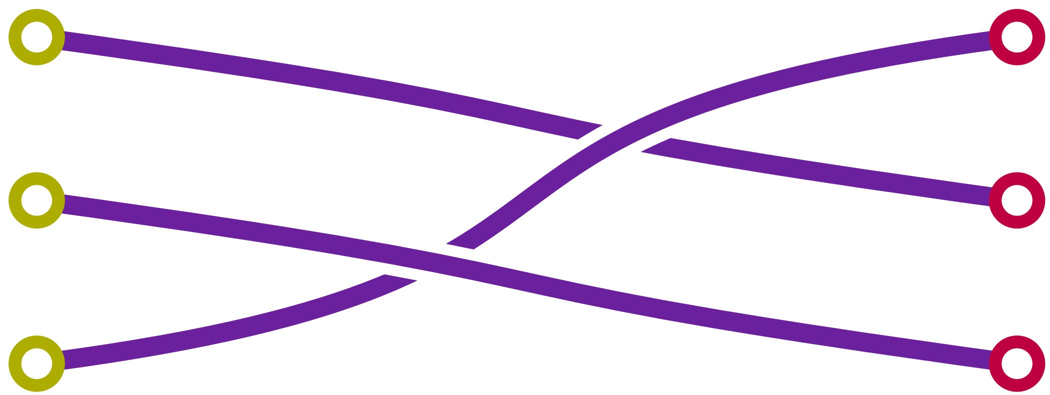
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:** Use topologically invariant quantum processes.

⇒ knots as quantum gates



reliably

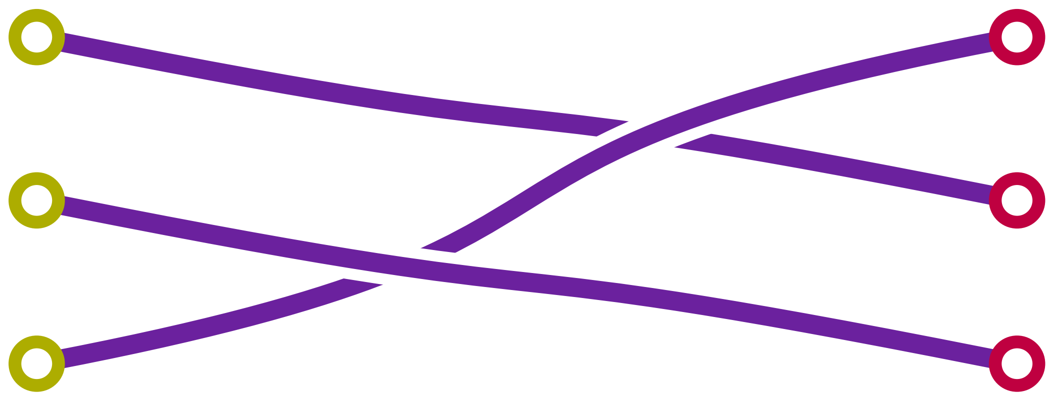
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒

result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates

reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of Topological Quantum Computation:
Use topologically invariant quantum processes.

⇒ knots as quantum gates

reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
robust
on a chosen **space**,
turning a given **initial state**
into the computed **result**.
consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates

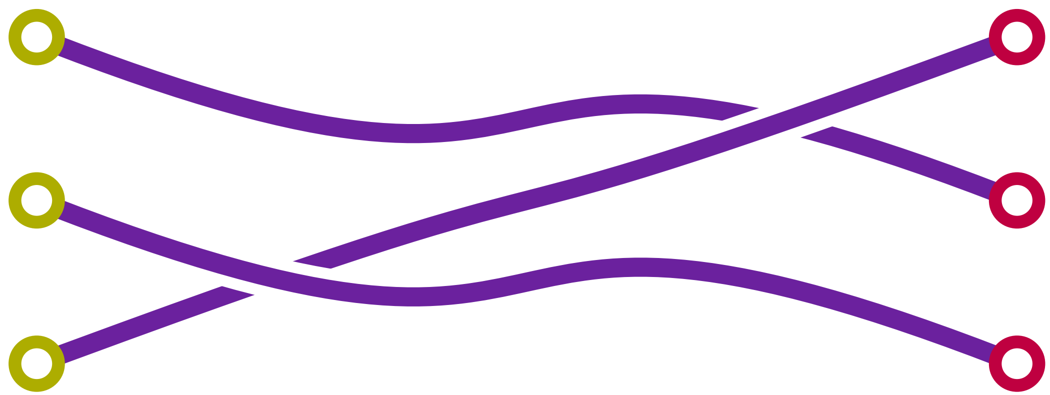
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **state space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



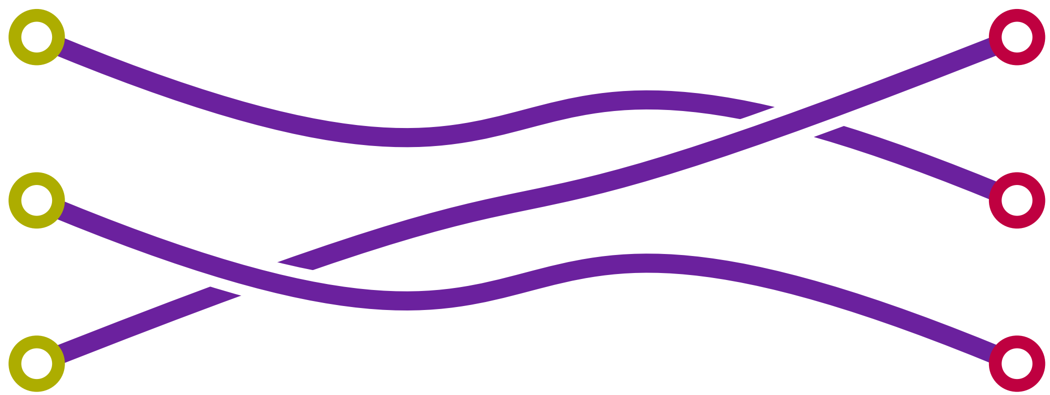
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.
consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



reliably

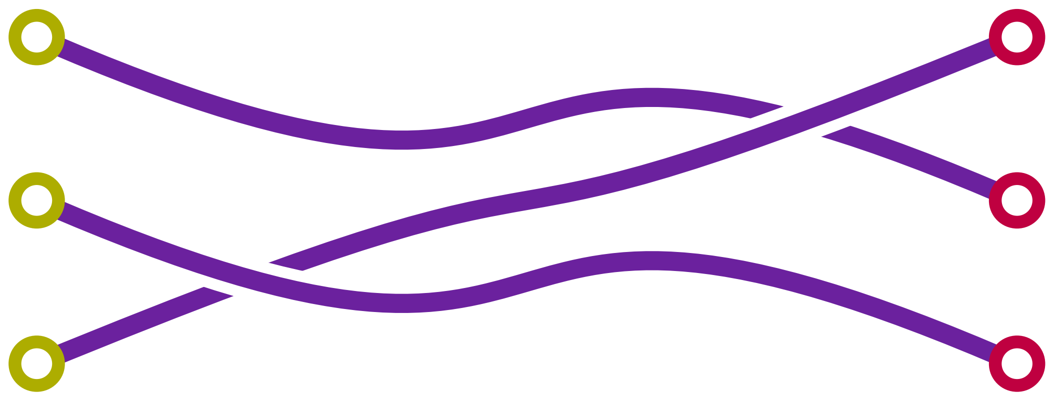
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.
consistently

⇒

result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



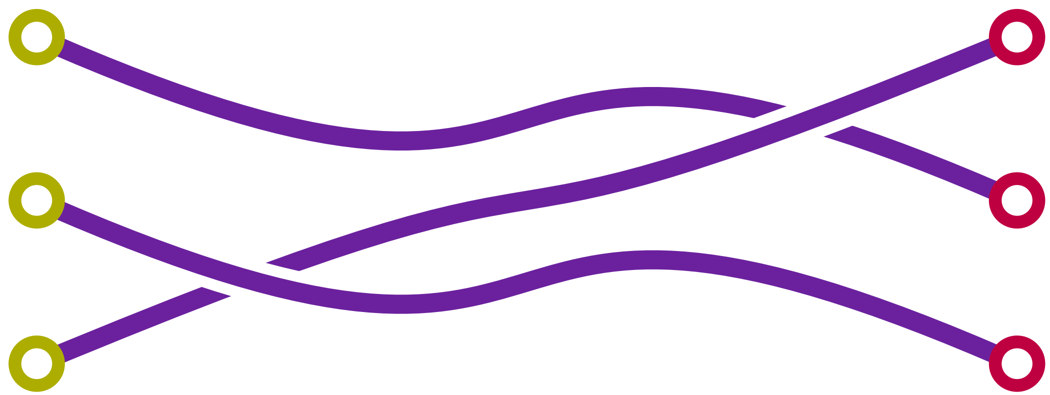
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **state space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



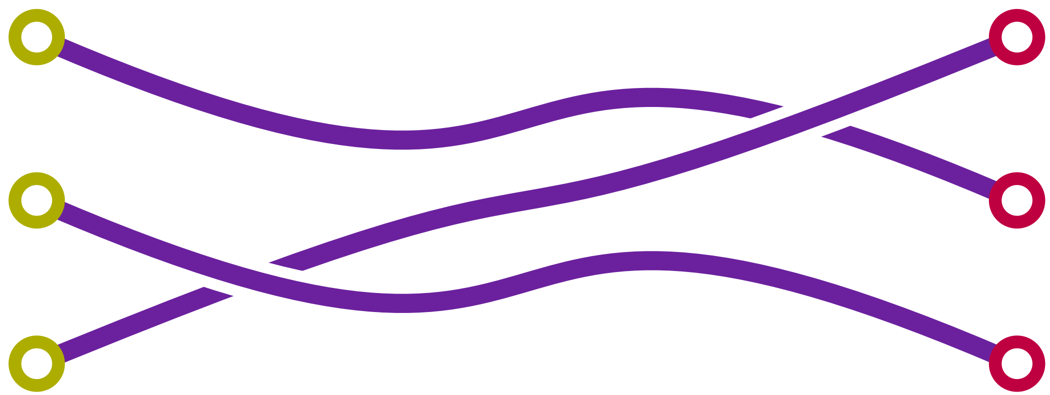
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



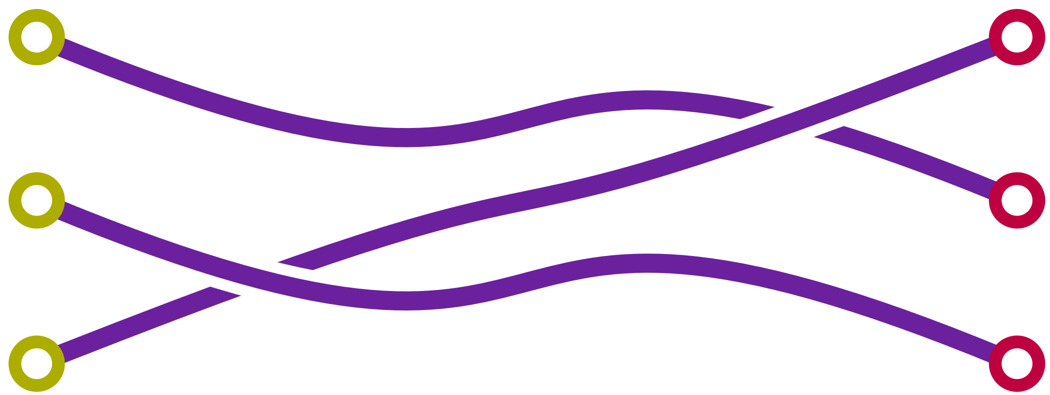
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **state space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



reliably

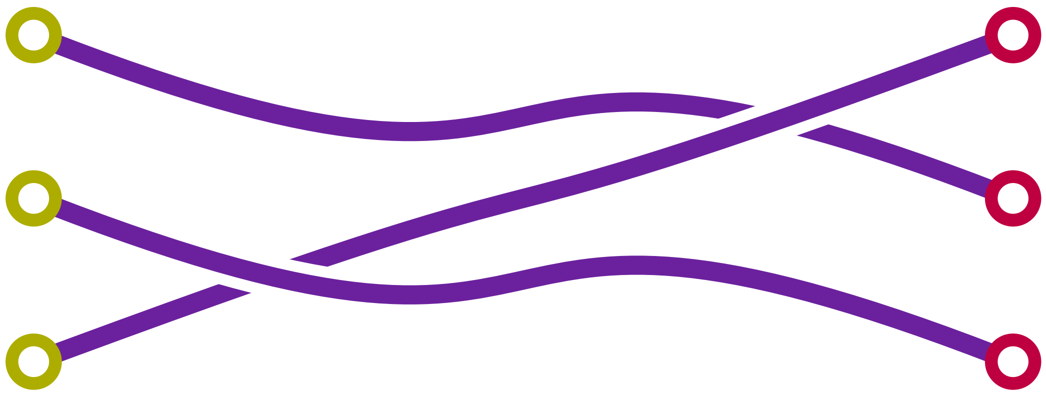
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

> Strategy of **Topological Quantum Computation:**
> Use topologically invariant quantum processes.

⇒ knots as quantum gates



reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates

reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result** consistently.

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates

reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates

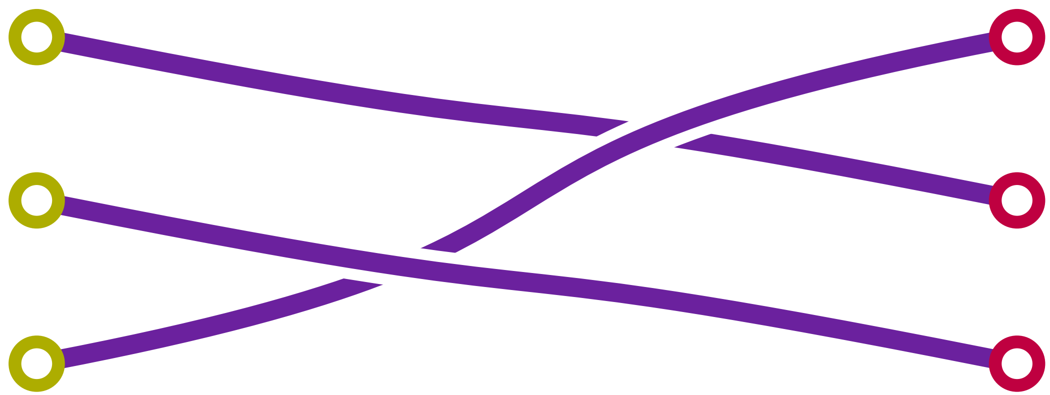
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen *robust* **space**,
turning a given **initial state**
into the computed **result**. *consistently*

⇒ result should be stable
under small deformations
of the computation path

Strategy of Topological Quantum Computation:
Use topologically invariant quantum processes.

⇒ knots as quantum gates



reliably

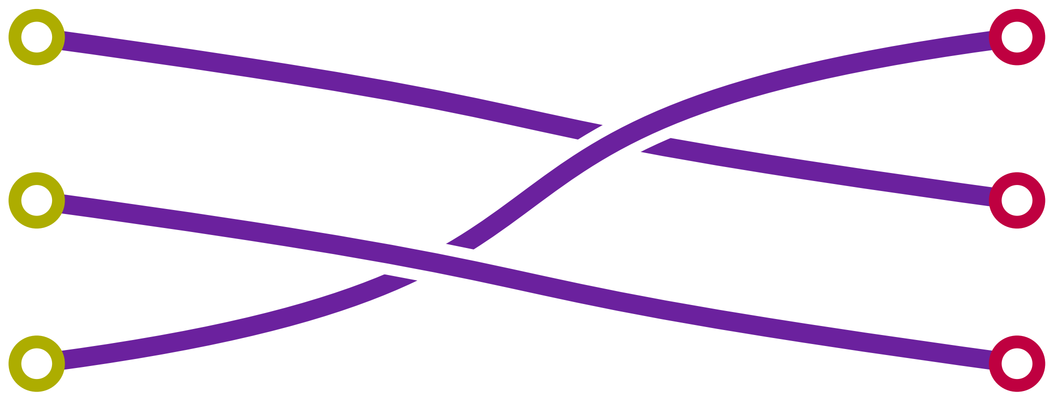
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of Topological Quantum Computation:
Use topologically invariant quantum processes.

⇒ knots as quantum gates



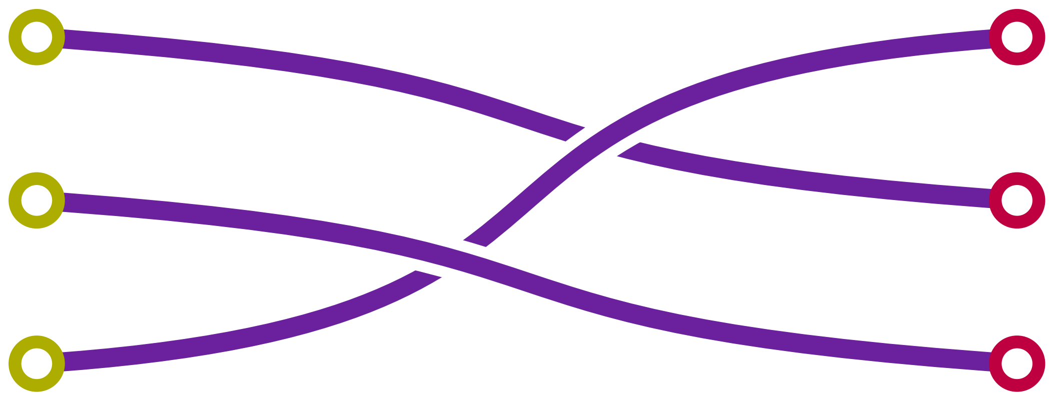
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.
consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates

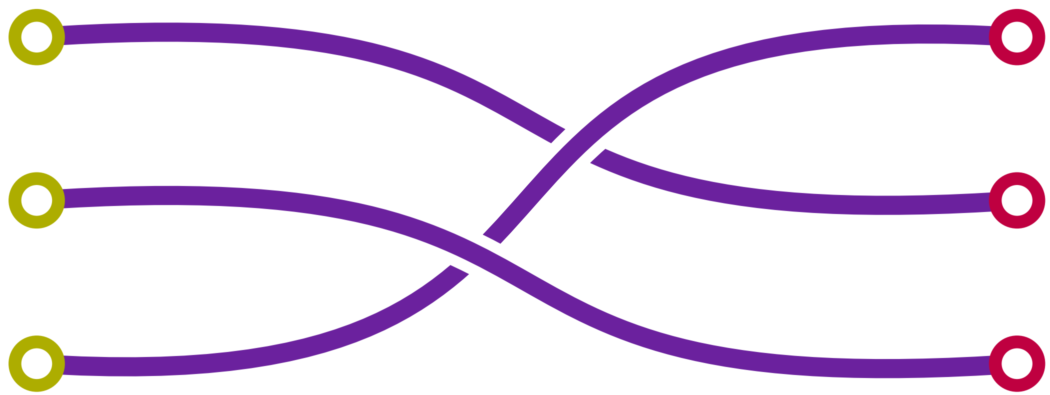
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



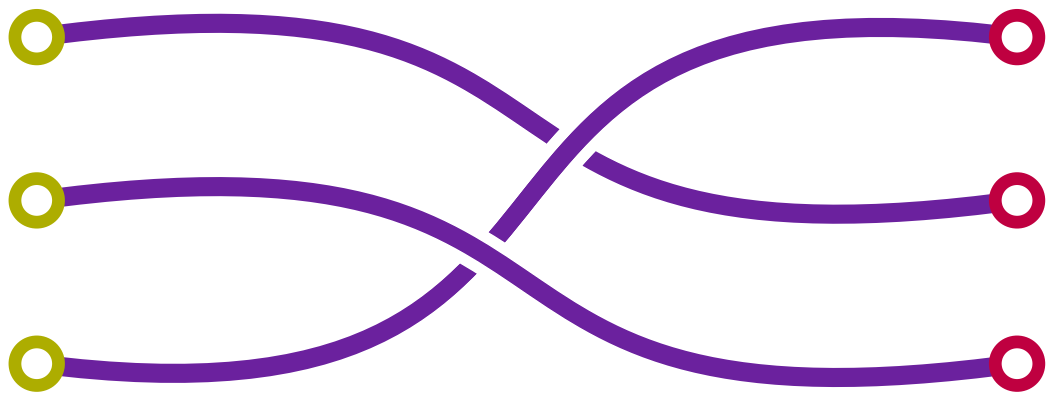
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.
consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of Topological Quantum Computation:
Use topologically invariant quantum processes.

⇒ knots as quantum gates



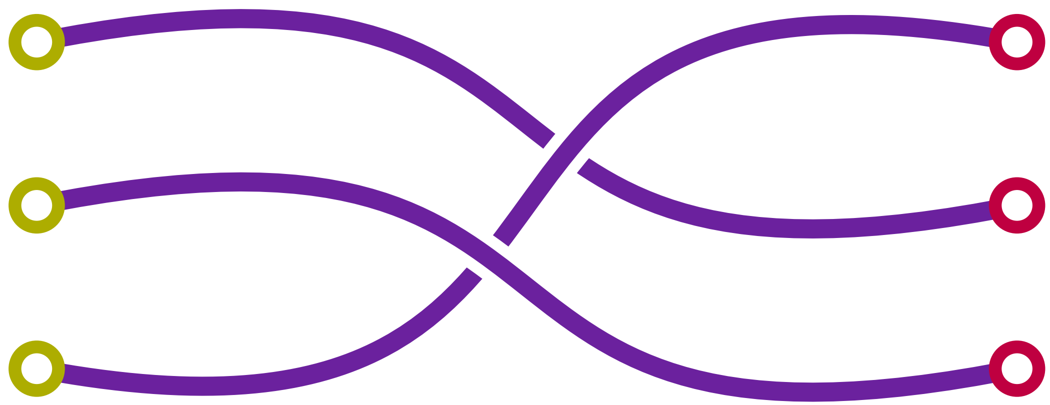
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of Topological Quantum Computation:
Use topologically invariant quantum processes.

⇒ knots as quantum gates



reliably

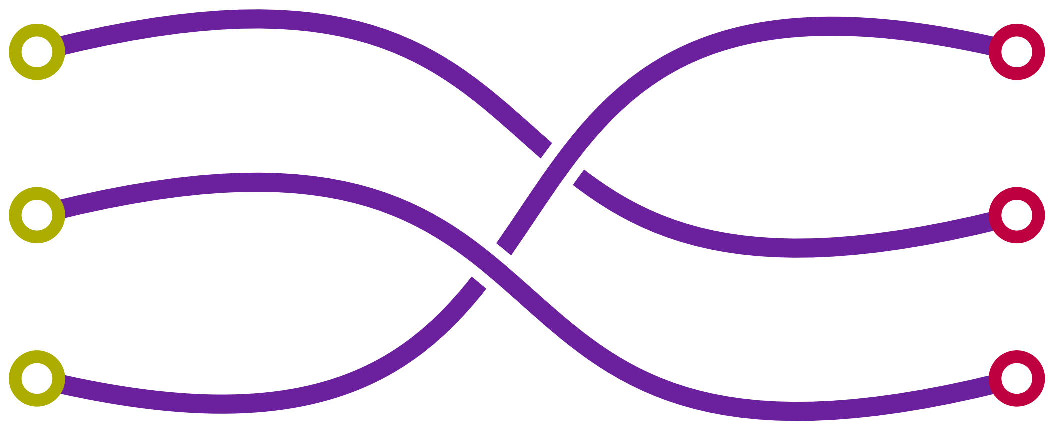
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



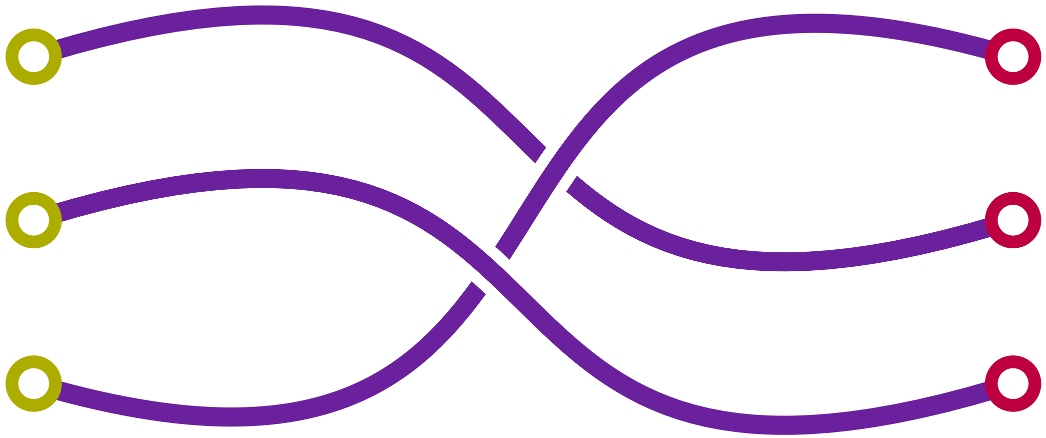
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



reliably

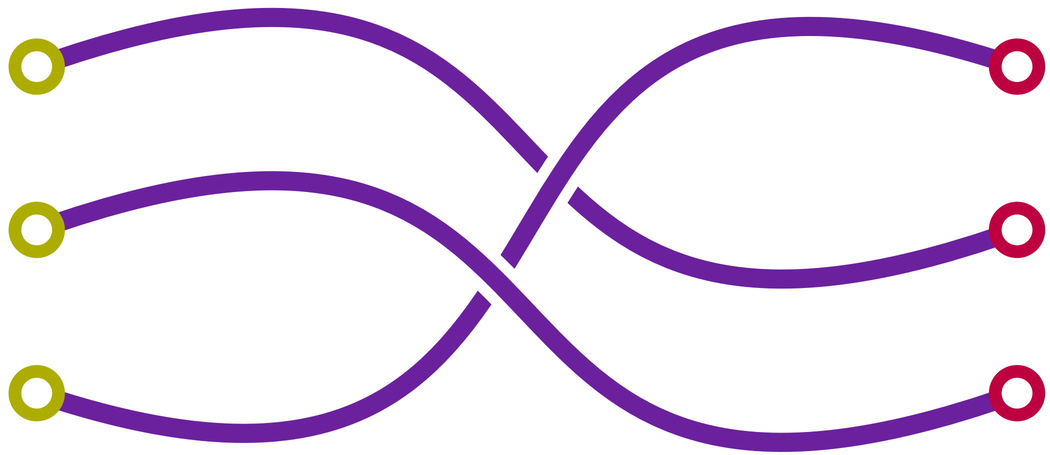
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**

robust

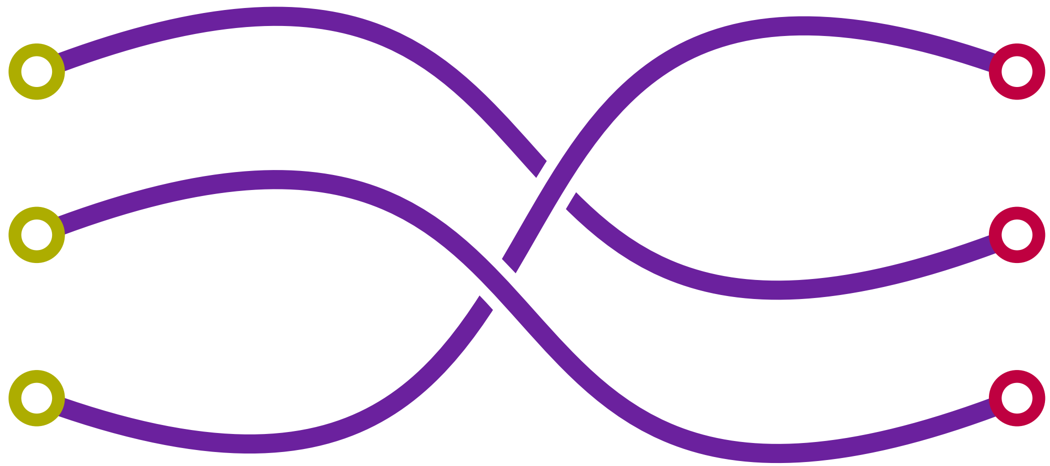
on a chosen **state space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



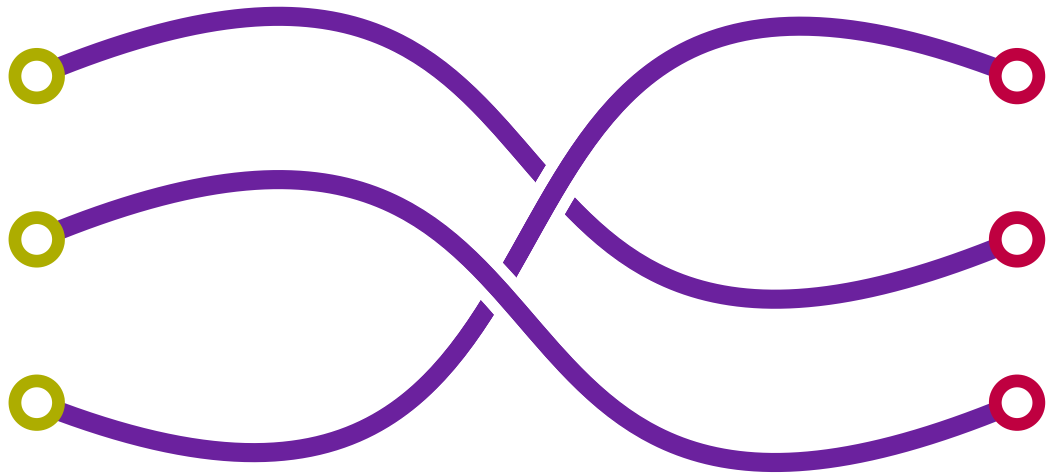
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:** Use topologically invariant quantum processes.

⇒ knots as quantum gates



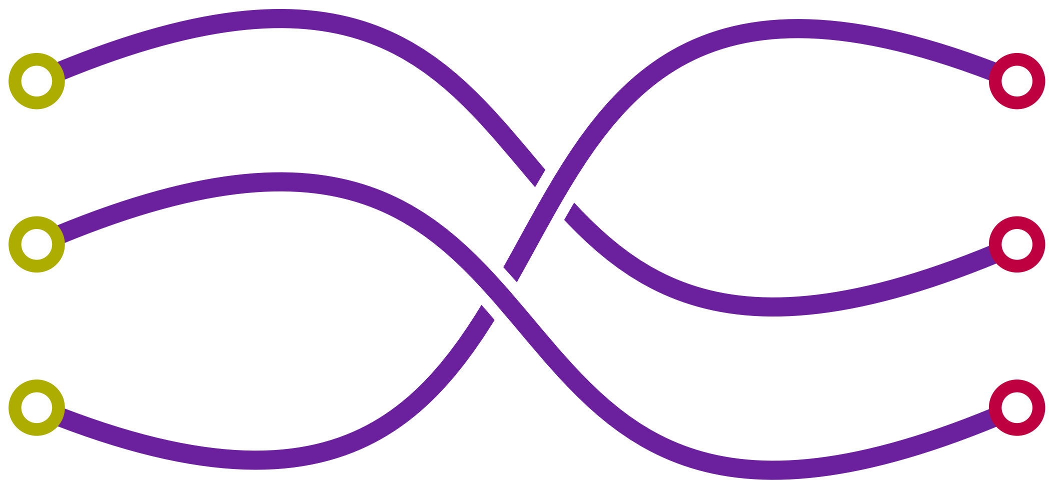
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of Topological Quantum Computation:
Use topologically invariant quantum processes.

⇒ knots as quantum gates



reliably

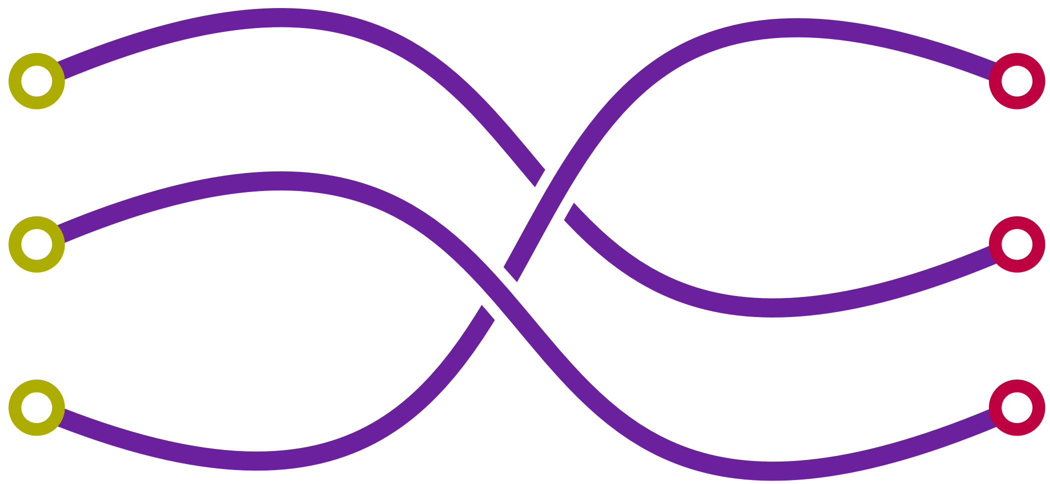
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **state space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of Topological Quantum Computation:
Use topologically invariant quantum processes.

⇒ knots as quantum gates



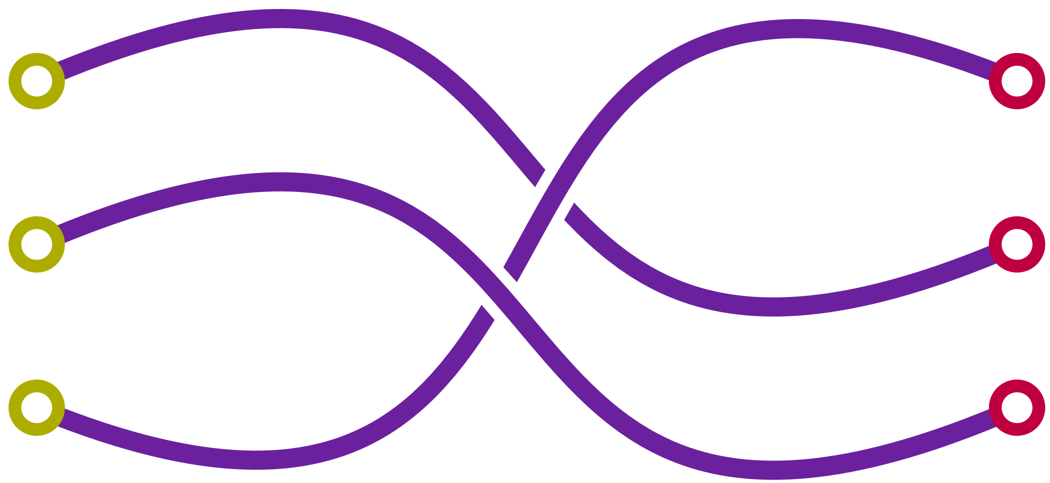
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **state space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:** Use topologically invariant quantum processes.

⇒ knots as quantum gates



reliably

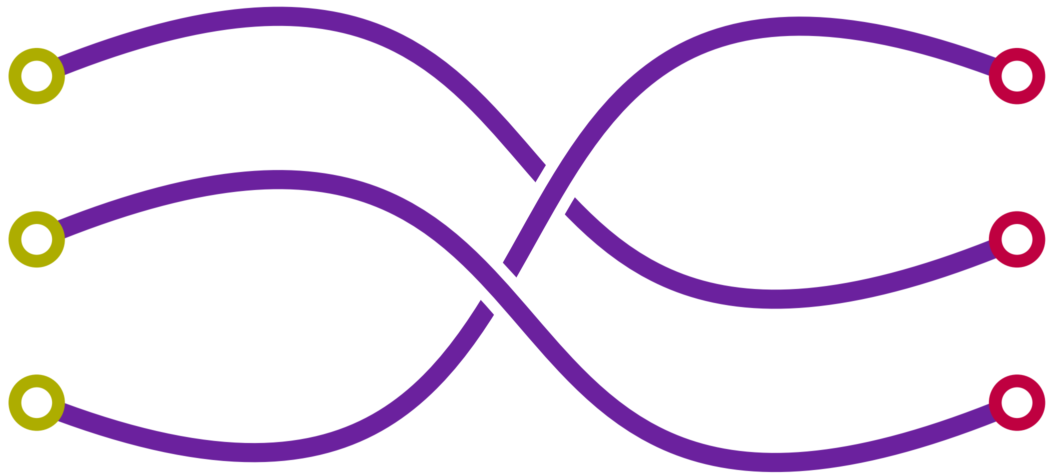
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



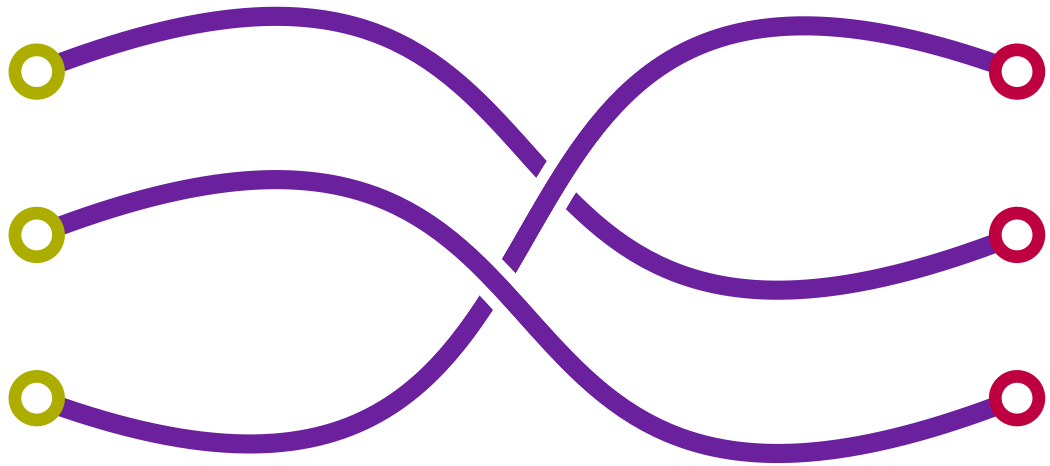
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust state **space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of Topological Quantum Computation:
Use topologically invariant quantum processes.

⇒ knots as quantum gates



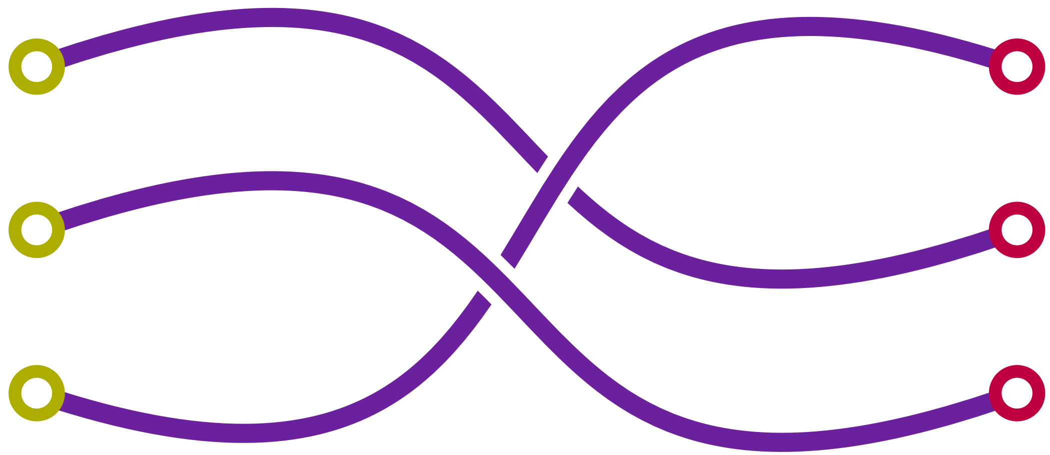
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **state space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



reliably

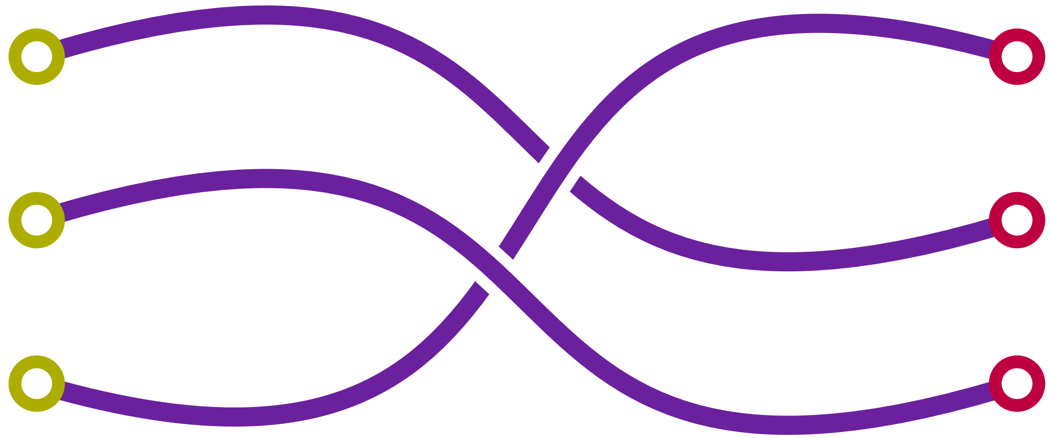
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



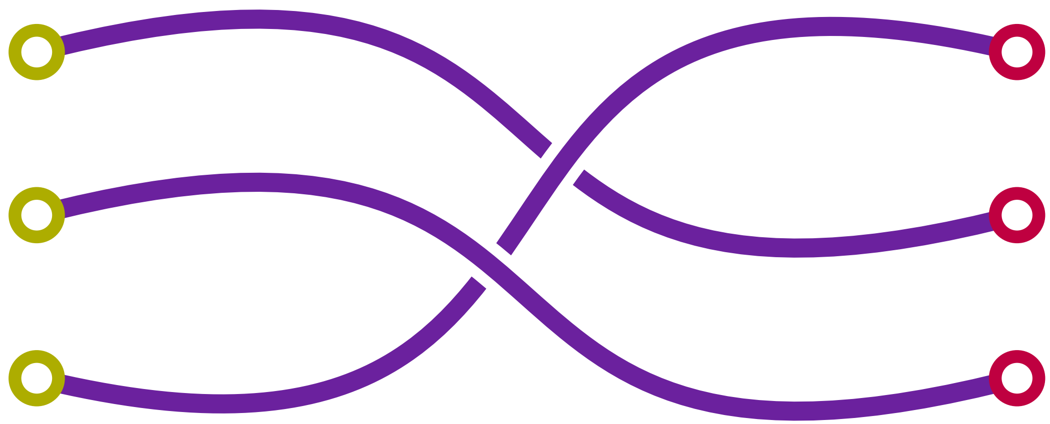
[reliably]

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen [robust] **space**,
turning a given **initial state**
into the computed **result**. [consistently]

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



reliably

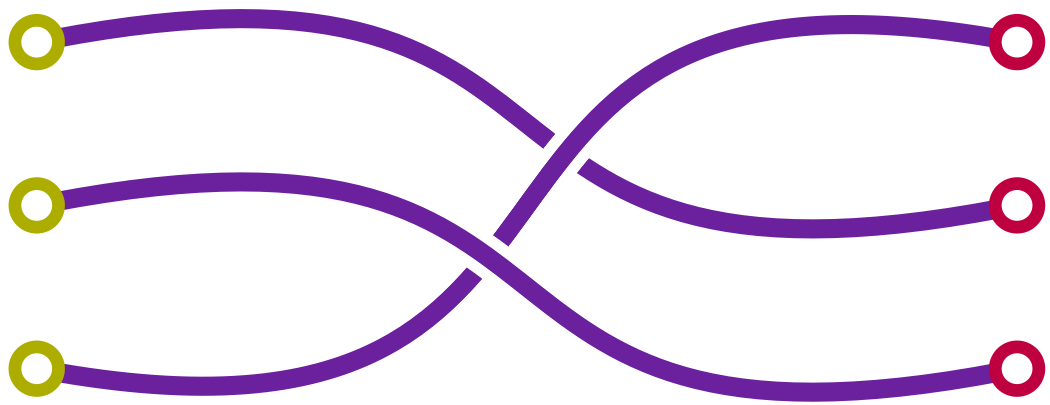
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.
consistently

⇒

result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**

robust

on a chosen **space**,

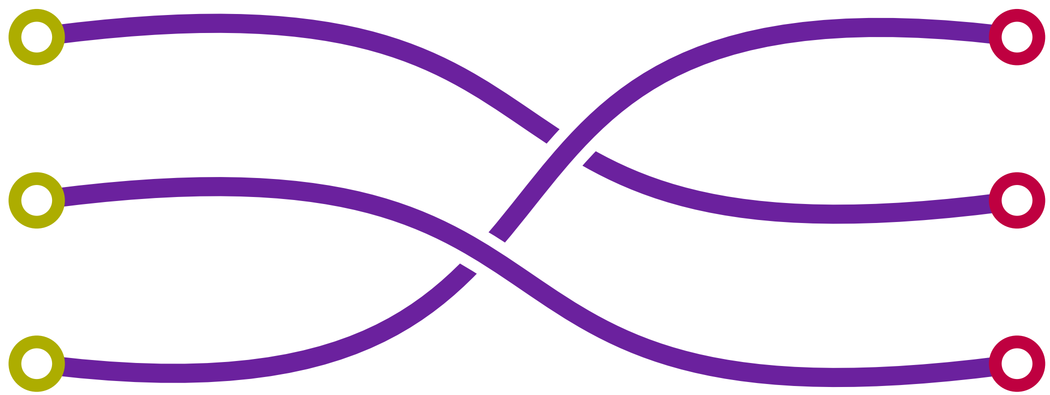
consistently

turning a given **initial state**
into the computed **result**.

⇒ result should be stable
under small deformations
of the computation path

Strategy of Topological Quantum Computation:
Use topologically invariant quantum processes.

⇒ knots as quantum gates



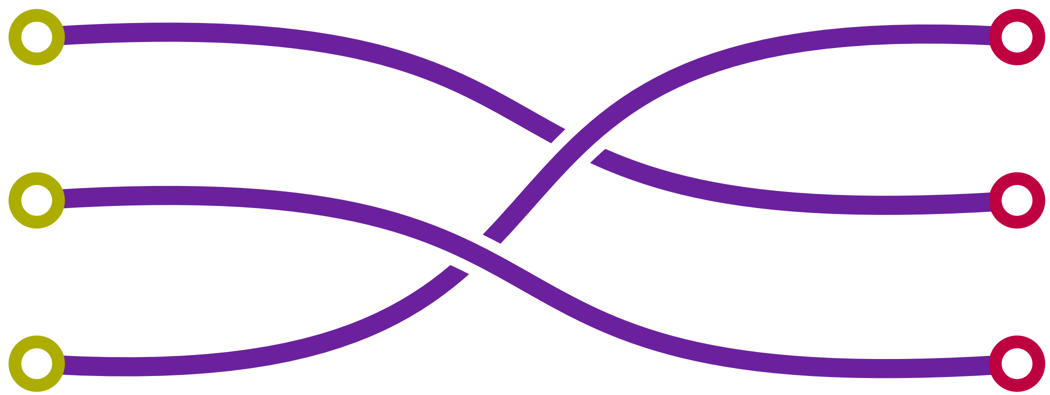
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **state space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.
consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of Topological Quantum Computation:
Use topologically invariant quantum processes.

⇒ knots as quantum gates

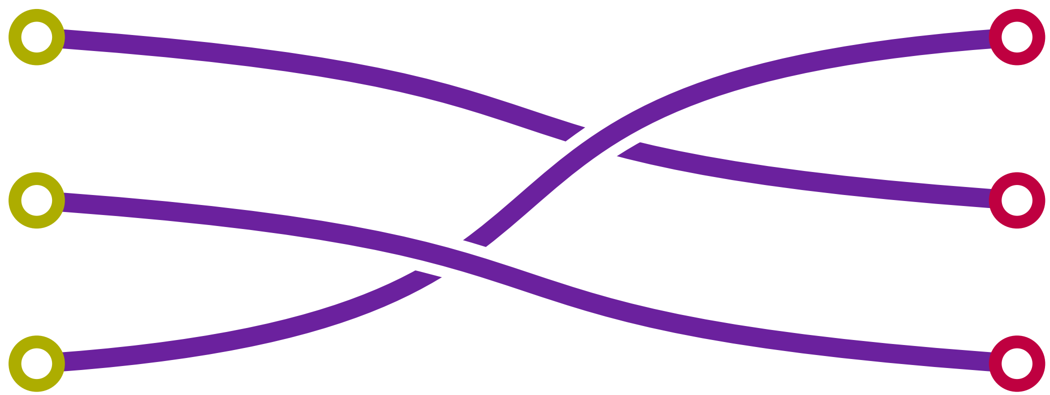
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust state **space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



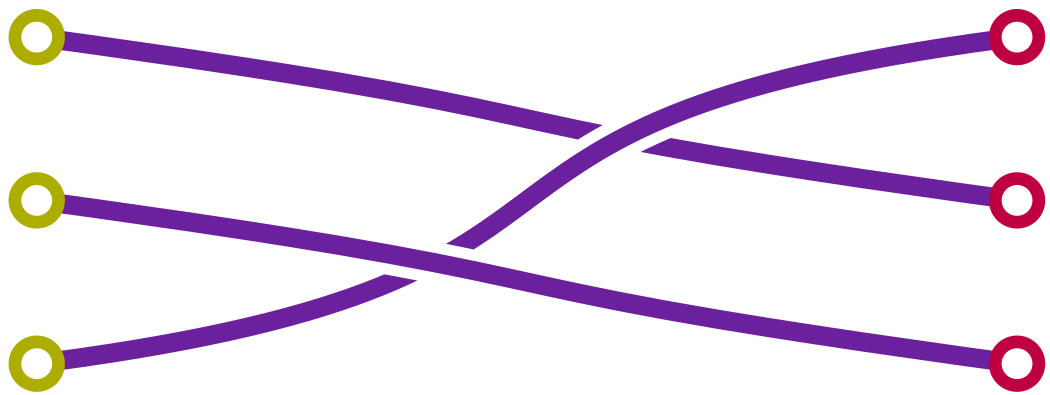
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **state space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



reliably

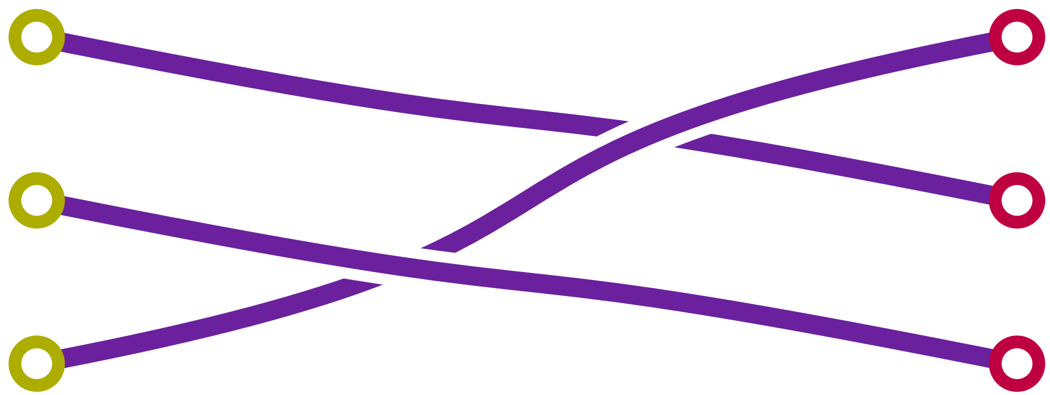
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of Topological Quantum Computation:
Use topologically invariant quantum processes.

⇒ knots as quantum gates

reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**

robust

on a chosen **state space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates

reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.
consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates

reliably

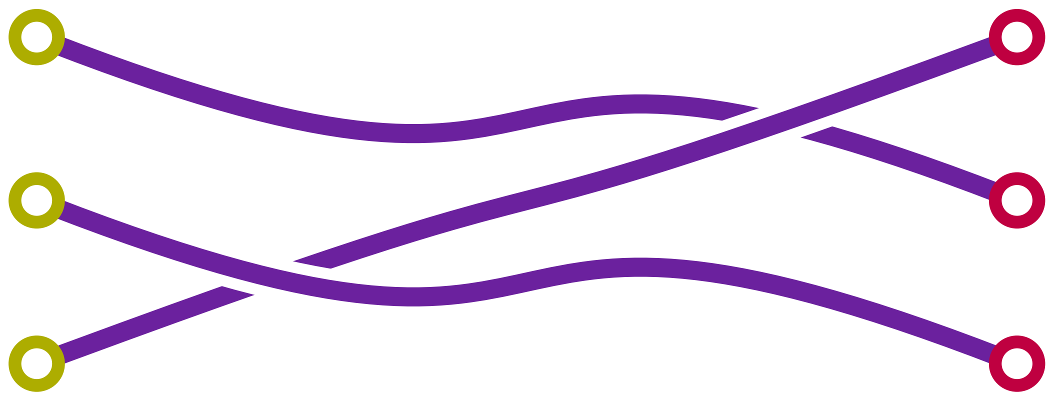
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of Topological Quantum Computation:
Use topologically invariant quantum processes.

⇒ knots as quantum gates



reliably

To compute is to **execute** sequences of **instructions** as composable **operations** on a chosen **state space**, turning a given **initial state** into the computed **result**.

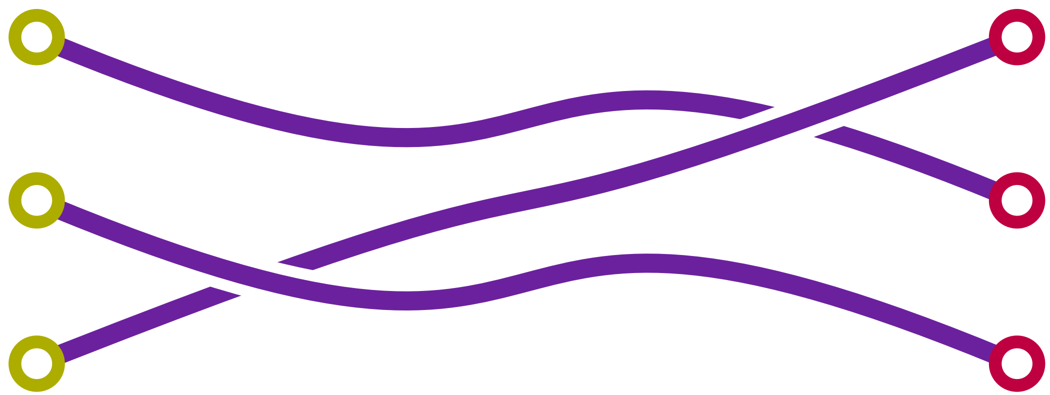
robust

consistently

⇒ result should be stable under small deformations of the computation path

Strategy of **Topological Quantum Computation:** Use topologically invariant quantum processes.

⇒ knots as quantum gates

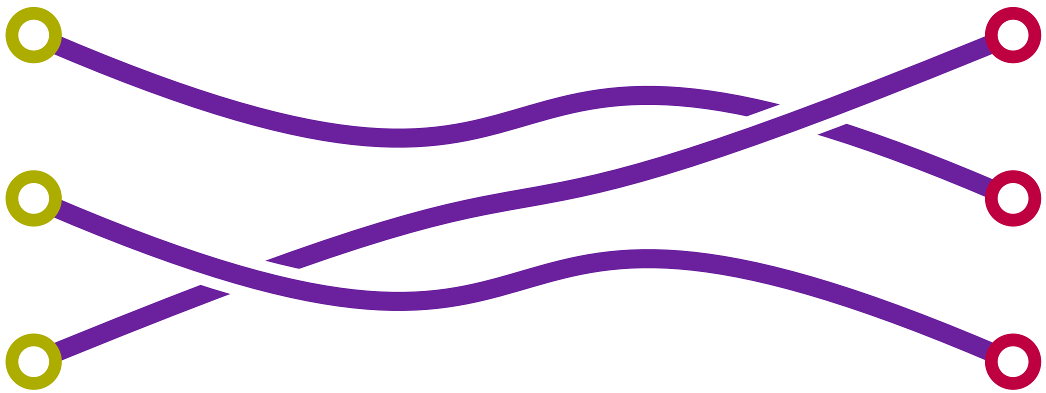


[reliably] **To compute** is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen [robust] state **space**,
turning a given **initial state**
into the computed **result**. [consistently]

⇒ result should be stable
under small deformations
of the computation path

Strategy of Topological Quantum Computation:
Use topologically invariant quantum processes.

⇒ knots as quantum gates



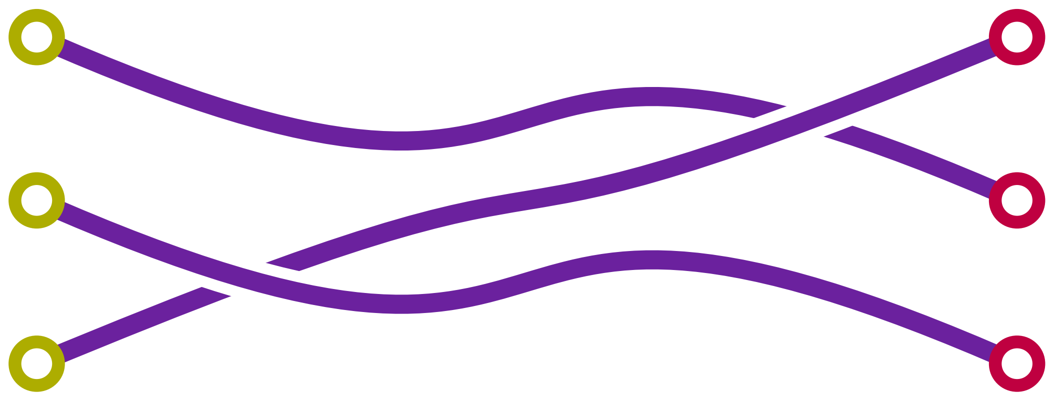
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**.
consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



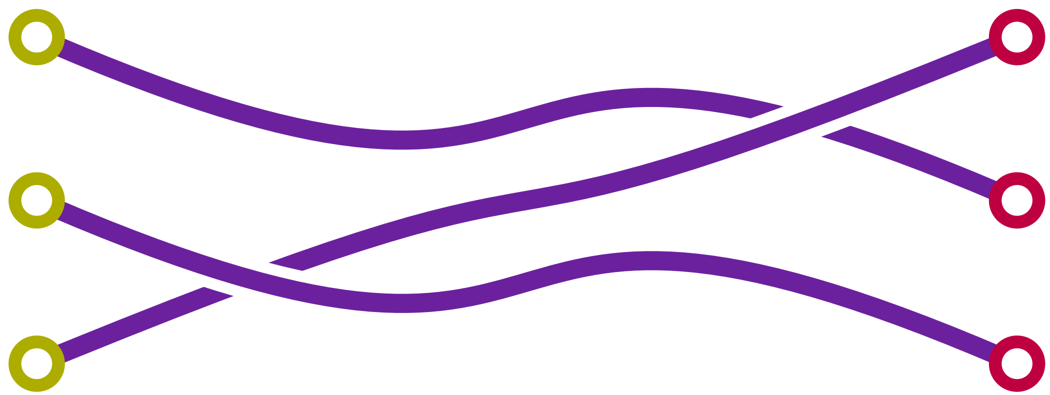
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **state space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



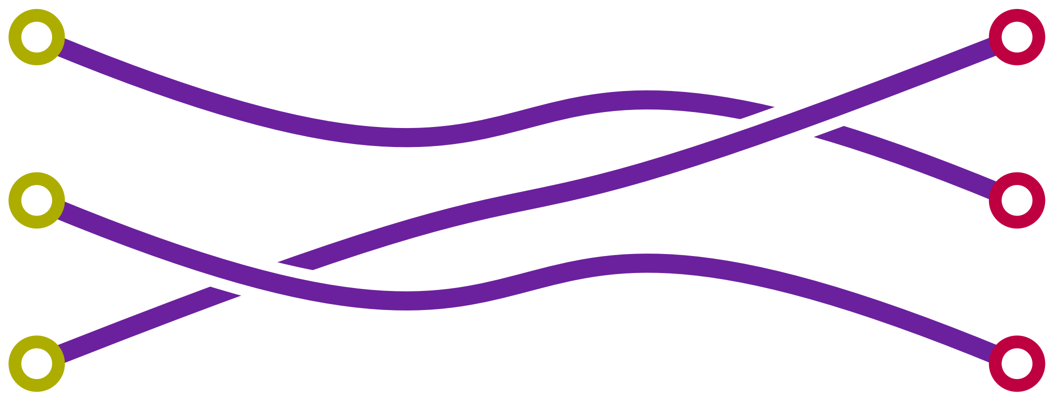
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of Topological Quantum Computation:
Use topologically invariant quantum processes.

⇒ knots as quantum gates



reliably

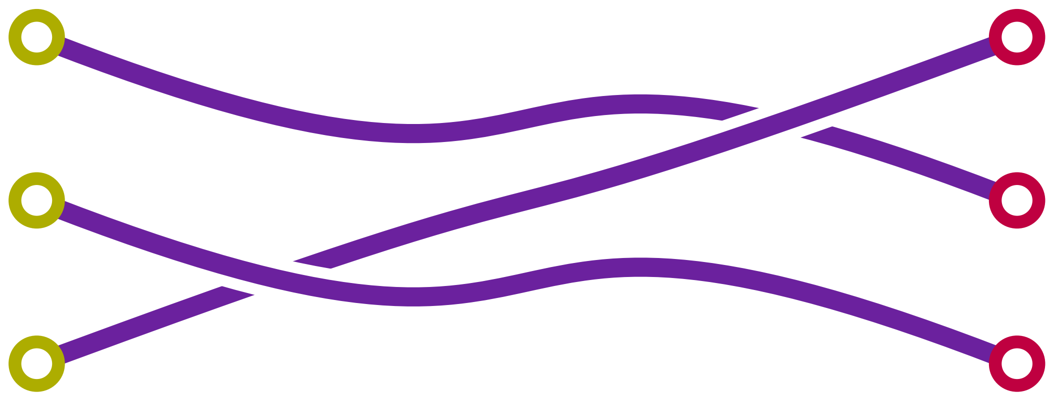
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen *robust* **space**,
turning a given **initial state**
into the computed **result**.

consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of Topological Quantum Computation:
Use topologically invariant quantum processes.

⇒ knots as quantum gates



reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
robust
on a chosen state **space**,
turning a given **initial state**
into the computed **result**.
consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates

reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates

reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **state space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates

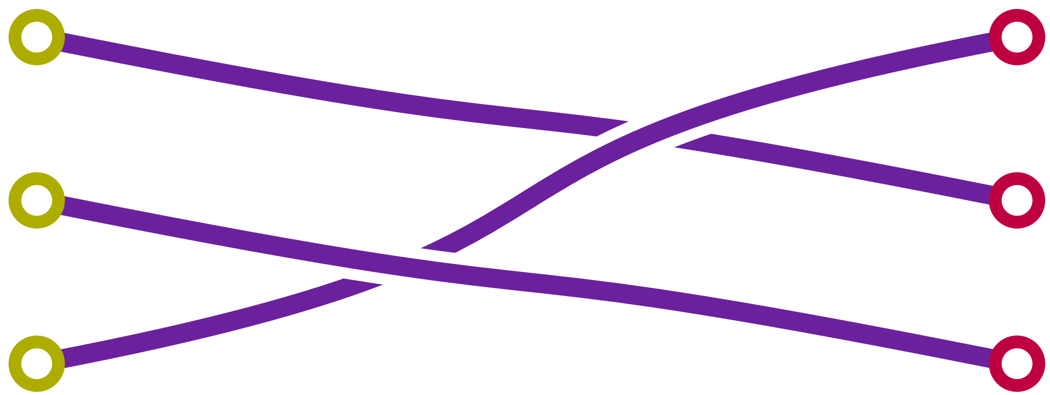
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



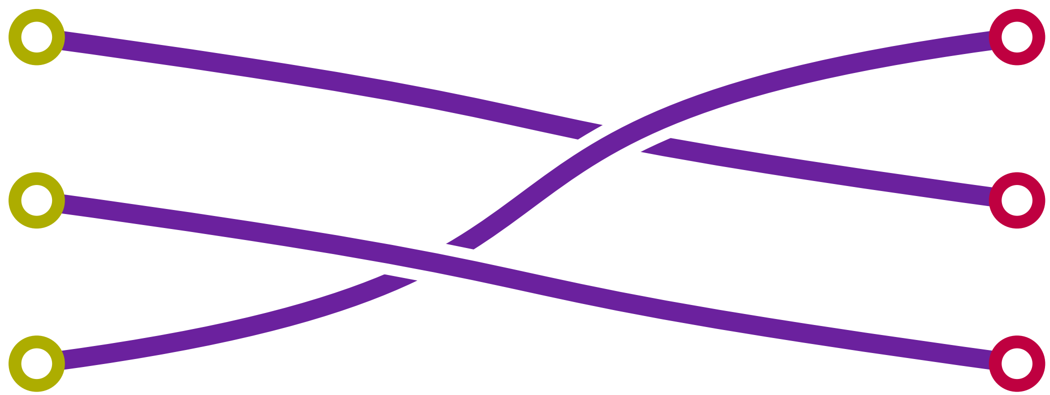
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **state space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



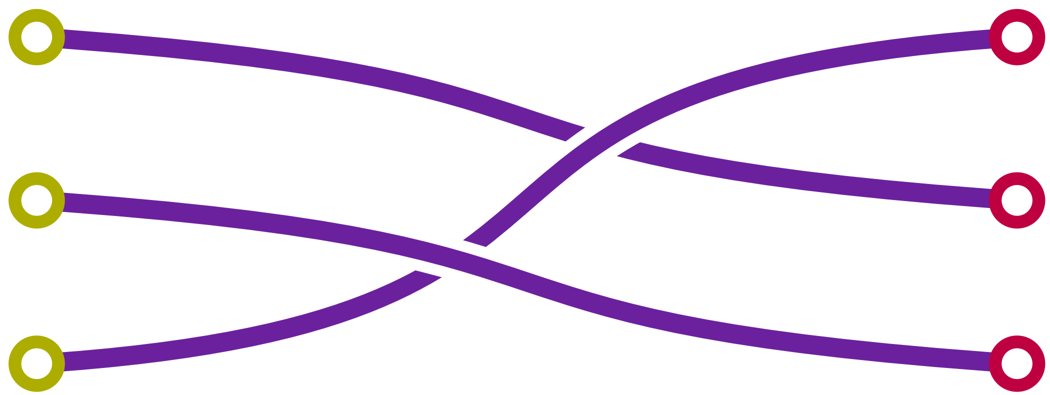
reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates



reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen robust **space**,
turning a given **initial state**
into the computed **result**. consistently

⇒ result should be stable
under small deformations
of the computation path

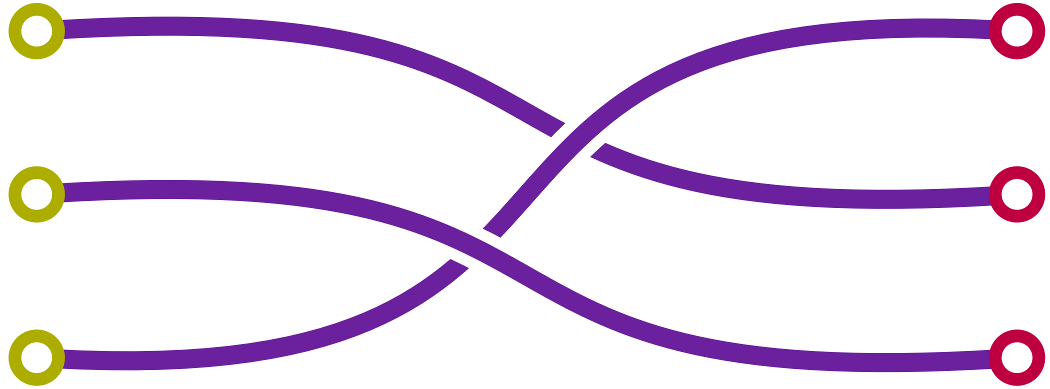
Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates

But (why and where) do such processes even exist?

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

$\Rightarrow$ knots as quantum gates



But (why and where) do such processes even exist?

Strategy of **Topological Quantum Computation:**
Use topologically invariant quantum processes.

⇒ knots as quantum gates

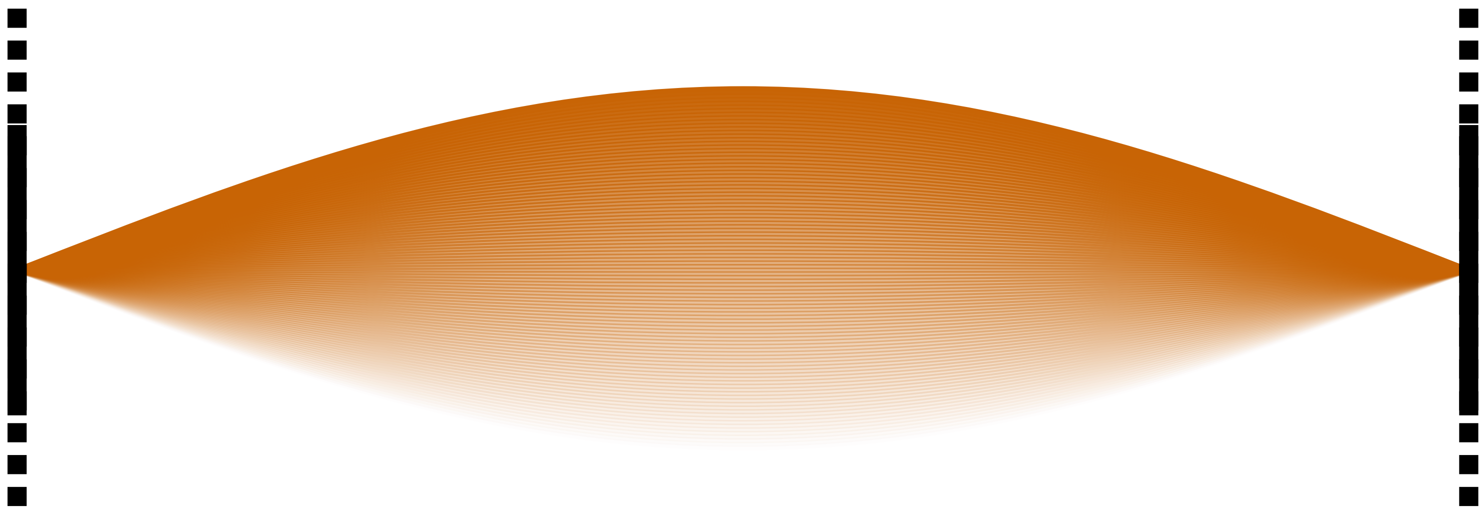
But (why and where) do such processes even exist?

On atomic scales, particles are waves; whose energy is *quantized*.

ground state: $E = 0$

But (why and where) do such processes even exist?

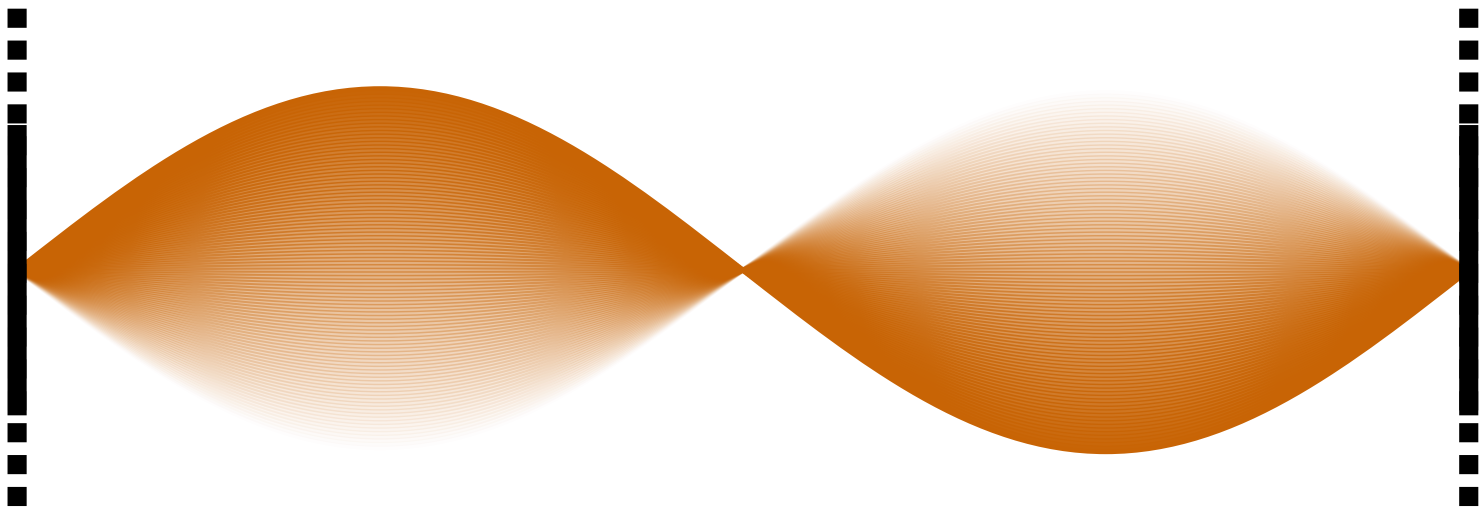
On atomic scales, particles are waves; whose energy is *quantized*.



first excited state: $E = \hbar\omega$

But (why and where) do such processes even exist?

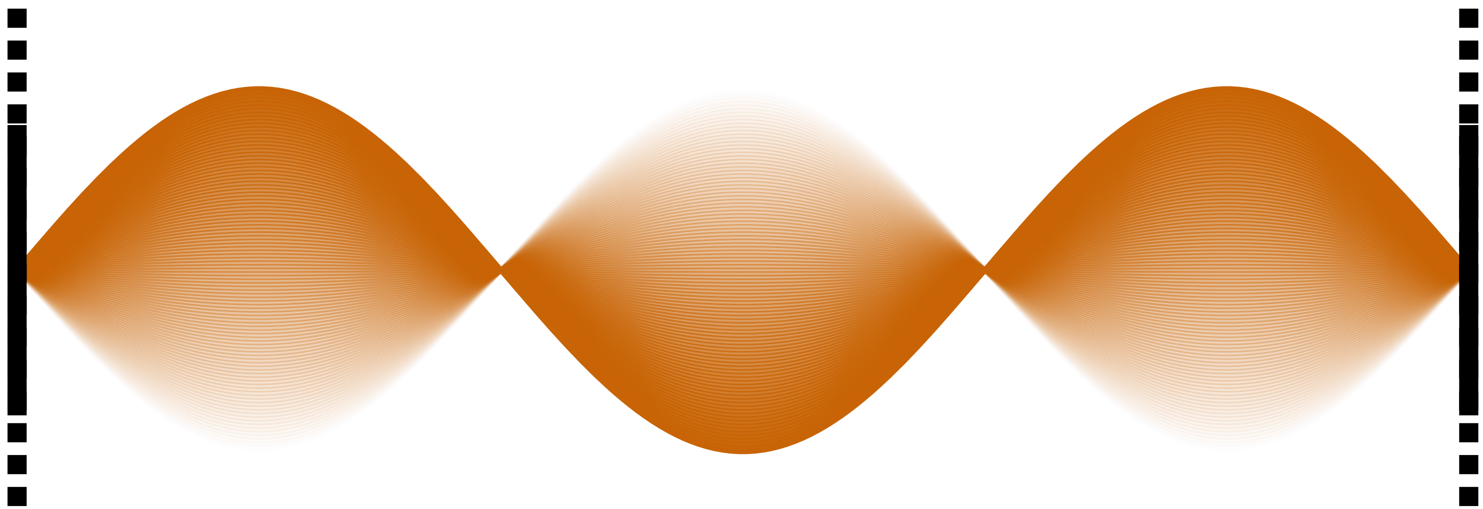
On atomic scales, particles are waves; whose energy is *quantized*.



second excited state: $E = 2\hbar\omega$

But (why and where) do such processes even exist?

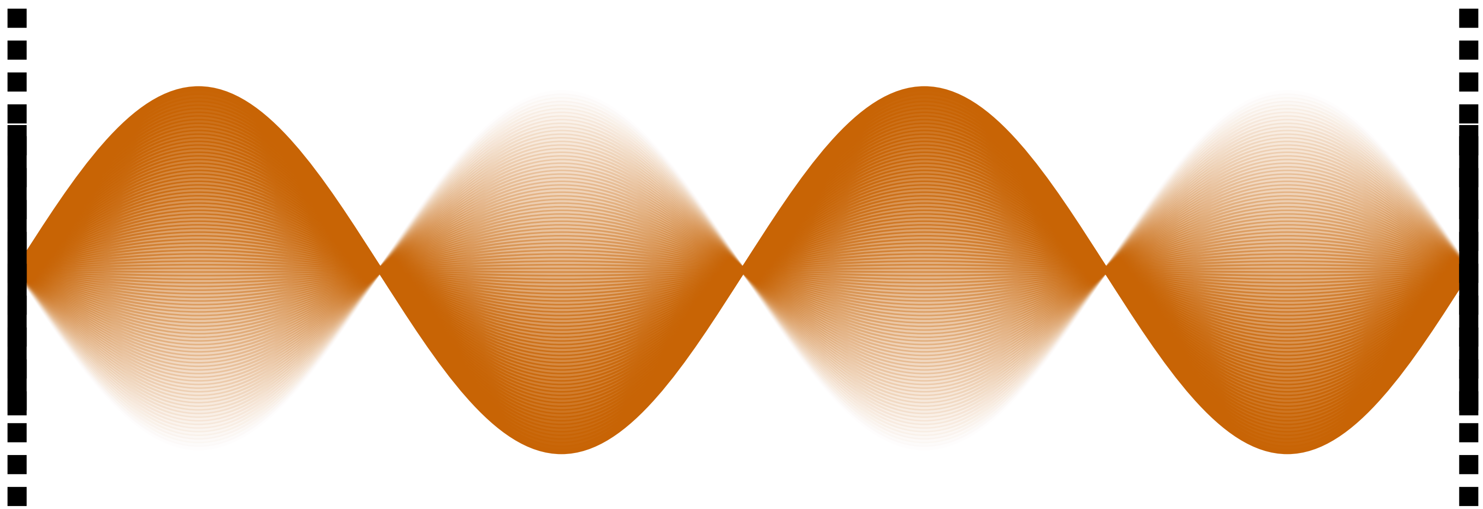
On atomic scales, particles are waves; whose energy is *quantized*.



third excited state: $E = 3\hbar\omega$

But (why and where) do such processes even exist?

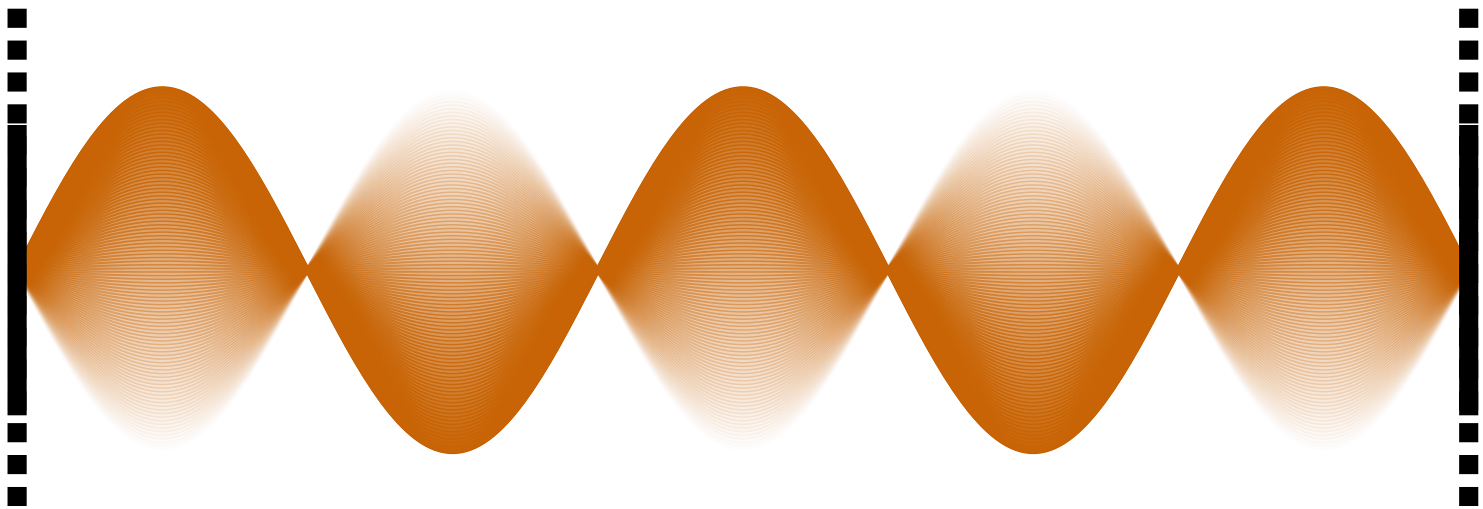
On atomic scales, particles are waves; whose energy is *quantized*.



fourth excited state: $E = 4\hbar\omega$

But (why and where) do such processes even exist?

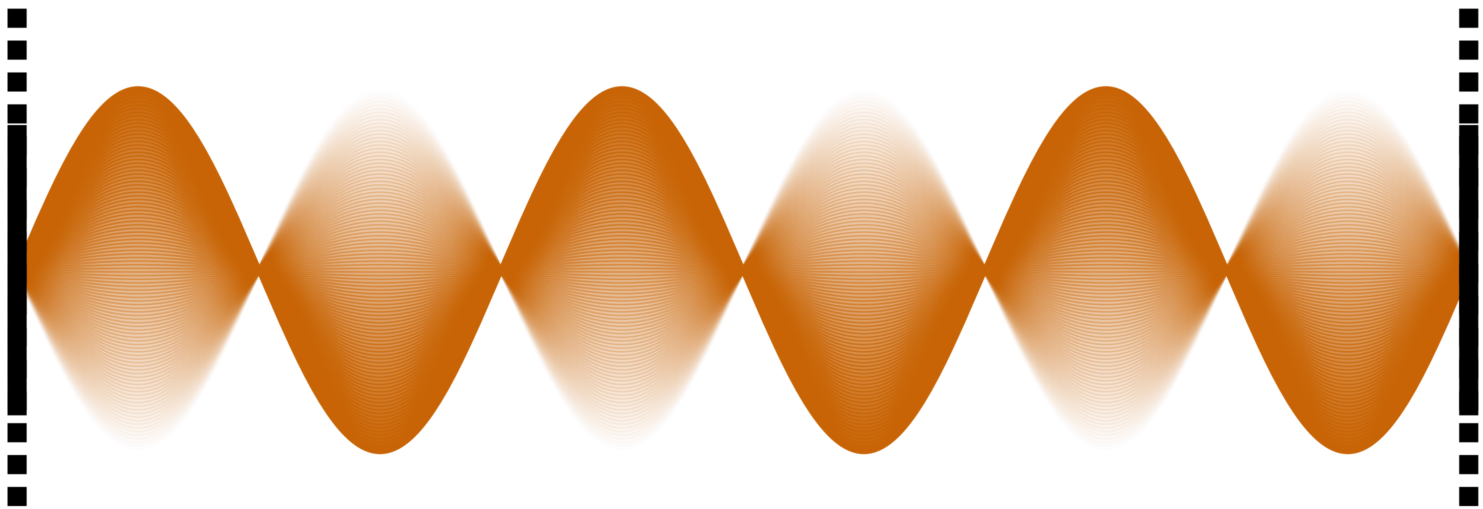
On atomic scales, particles are waves; whose energy is *quantized*.



fifth excited state: $E = 5\hbar\omega$

But (why and where) do such processes even exist?

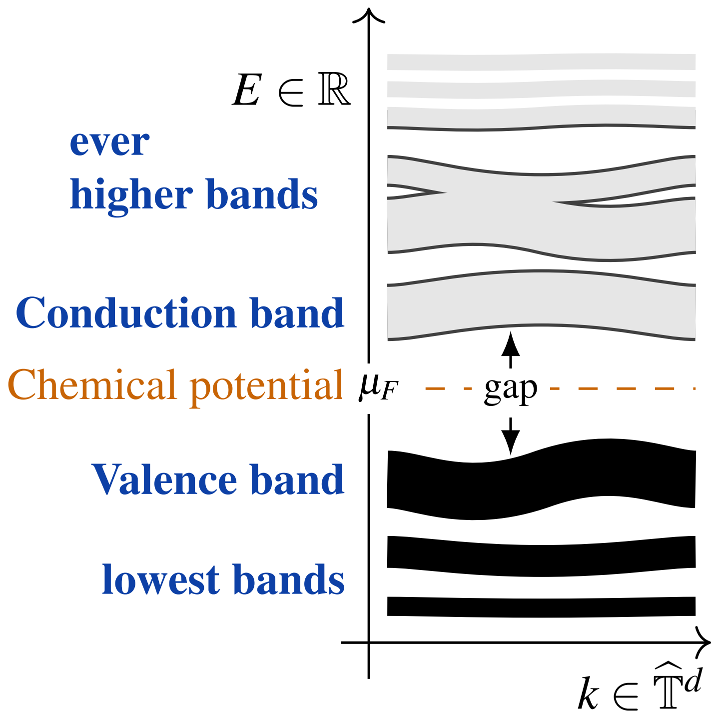
On atomic scales, particles are waves; whose energy is *quantized*.



sixth excited state: $E = 6\hbar\omega$

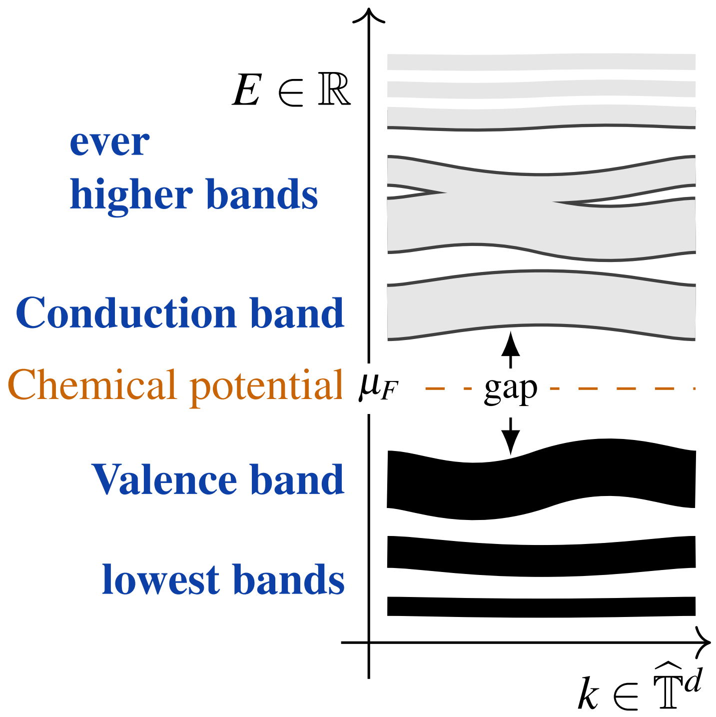
But (why and where) do such processes even exist?

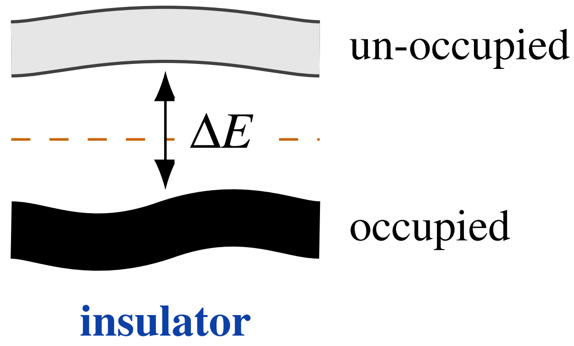
As very many particles come together in a crystal
their excitation energies accumulate in “bands”
but energy gaps *may* remain.



But (why and where) do such processes even exist?

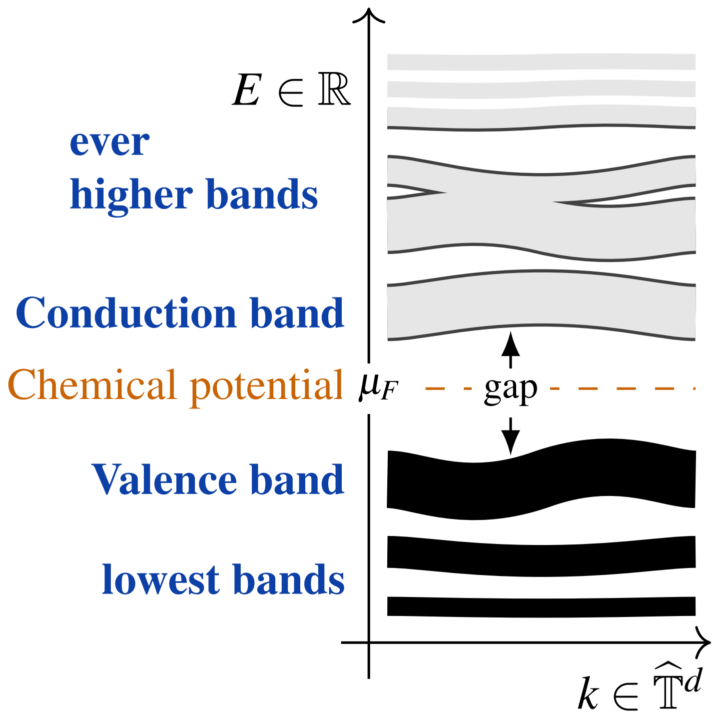
If the ground state remains separated by an energy gap ΔE then it is *completely* undisturbed by disturbances $< \Delta E$.

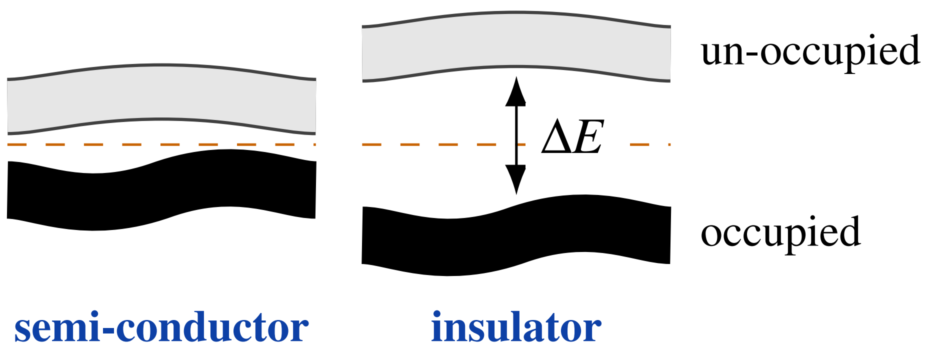




But (why and where) do such processes even exist?

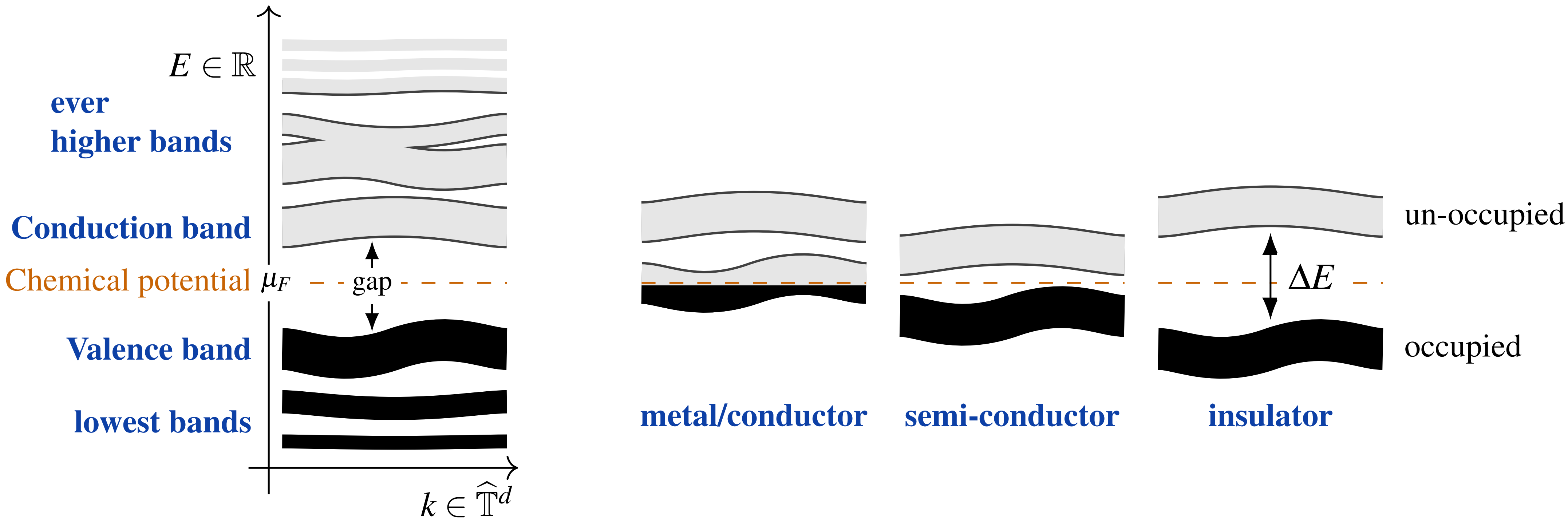
If the ground state remains separated by an energy gap ΔE
then it is *completely* undisturbed by disturbances $< \Delta E$.





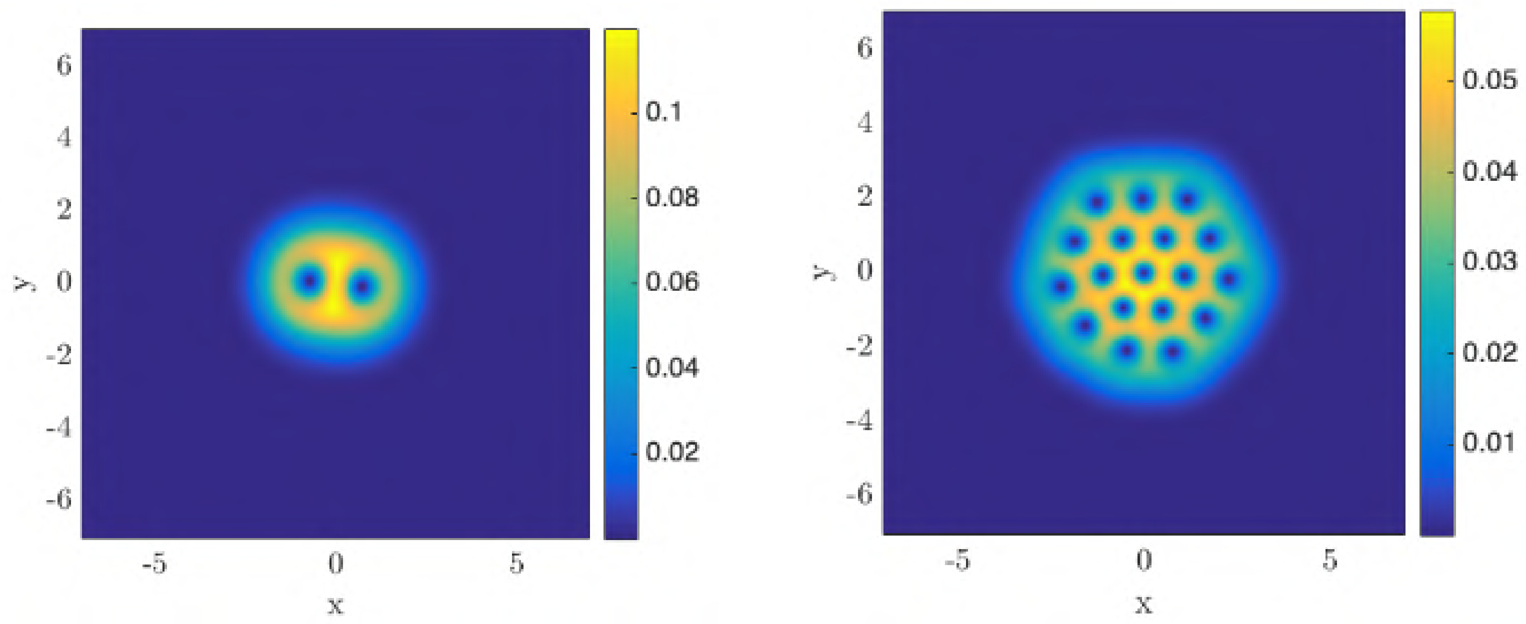
But (why and where) do such processes even exist?

If the ground state remains separated by an energy gap ΔE then it is *completely* undisturbed by disturbances $< \Delta E$.



But (why and where) do such processes even exist?

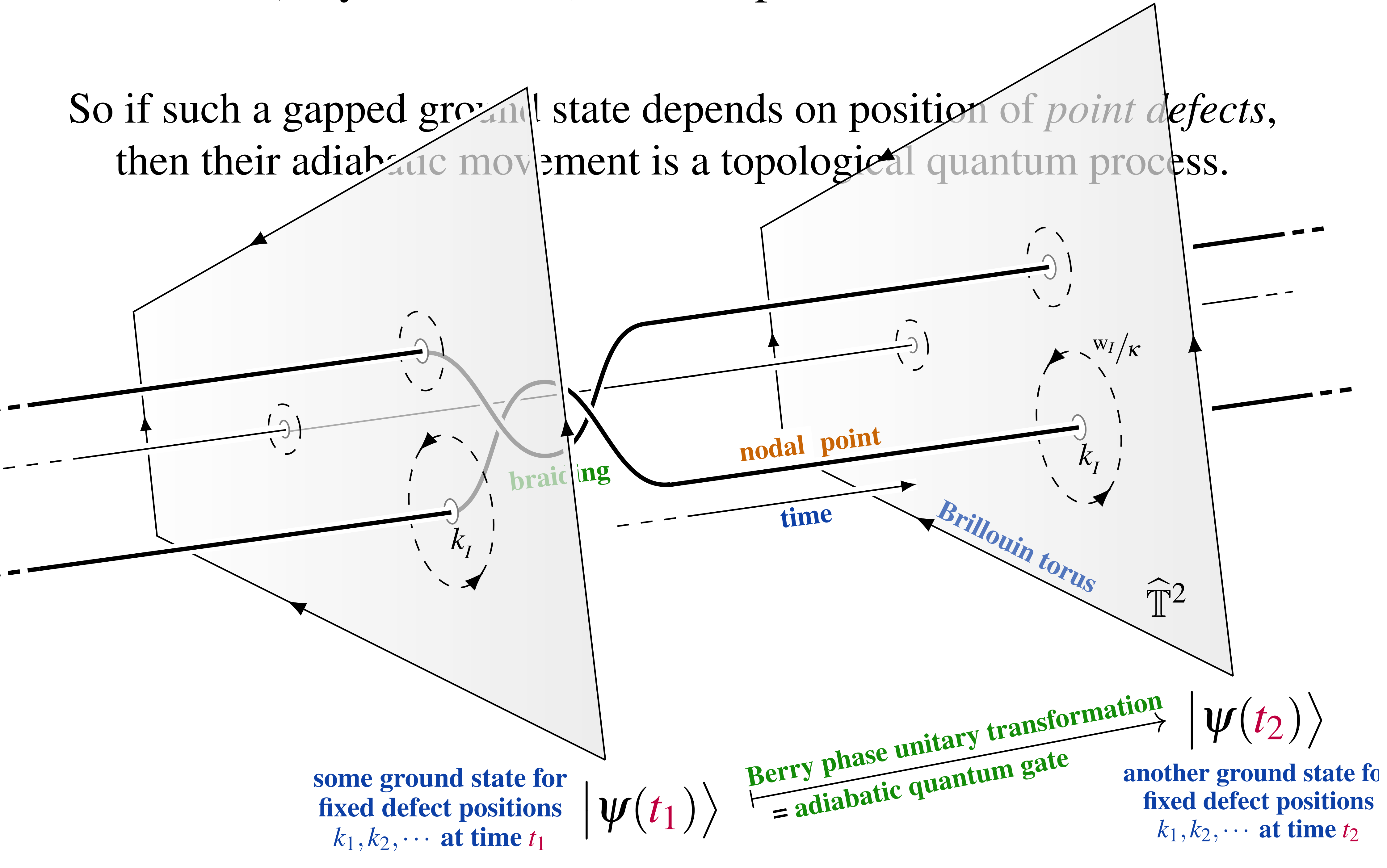
So if such a gapped ground state depends on position of *point defects*, then their adiabatic movement is a topological quantum process.



(numerical simulation from `arXiv:1901.10739`)

But (why and where) do such processes even exist?

So if such a gapped ground state depends on position of *point defects*,
then their adiabatic movement is a topological quantum process.



reliably

To compute is

the case of

Topological Quantum Computation

[Sati & Schreiber, PlanQC **2022** 33 (2022)]

reliably

To compute is to **execute**

the case of

Topological Quantum Computation

[Sati & Schreiber, PlanQC **2022** 33 (2022)]

topological quantum computation

$\mathrm{I} \longrightarrow \mathrm{O}$

braid representation

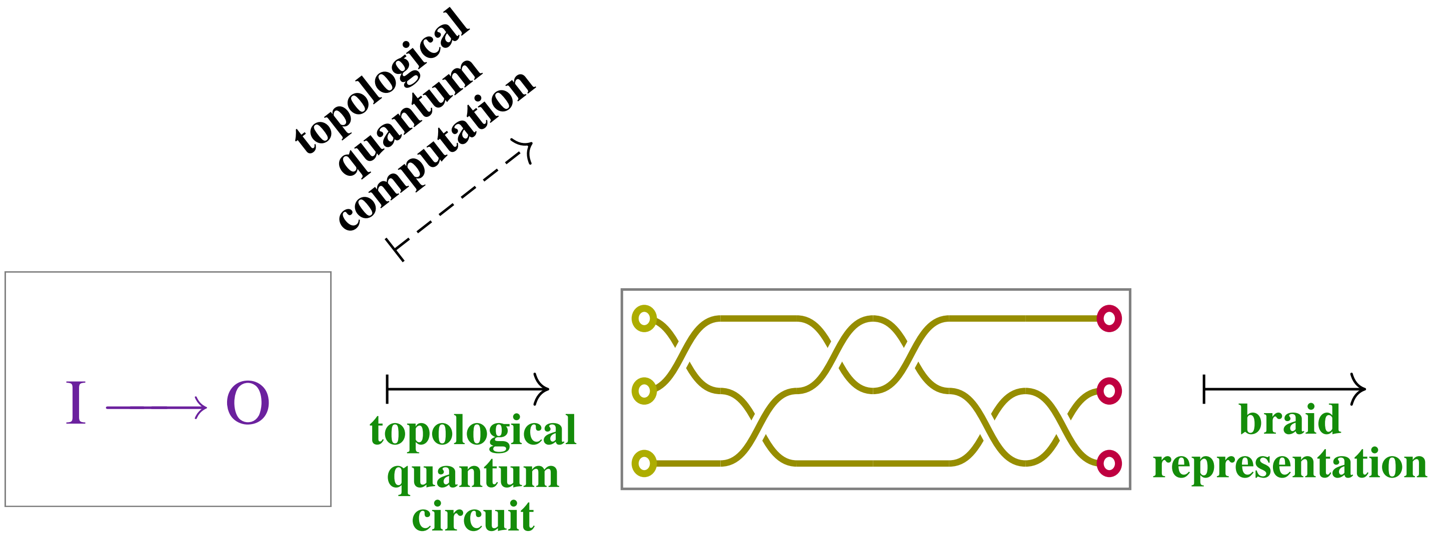
reliably

To compute is to **execute** sequences of **instructions**

the case of

Topological Quantum Computation

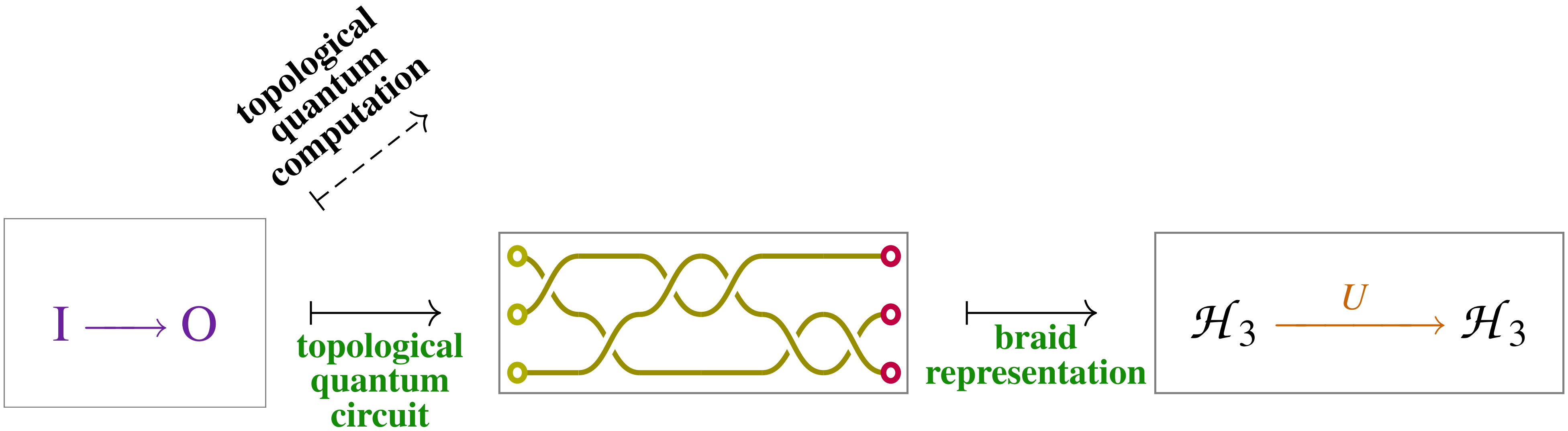
[Sati & Schreiber, PlanQC **2022** 33 (2022)]



reliably

To compute is to **execute** sequences of **instructions** as composable **operations**

the case of
Topological Quantum Computation
[Sati & Schreiber, PlanQC **2022** 33 (2022)]



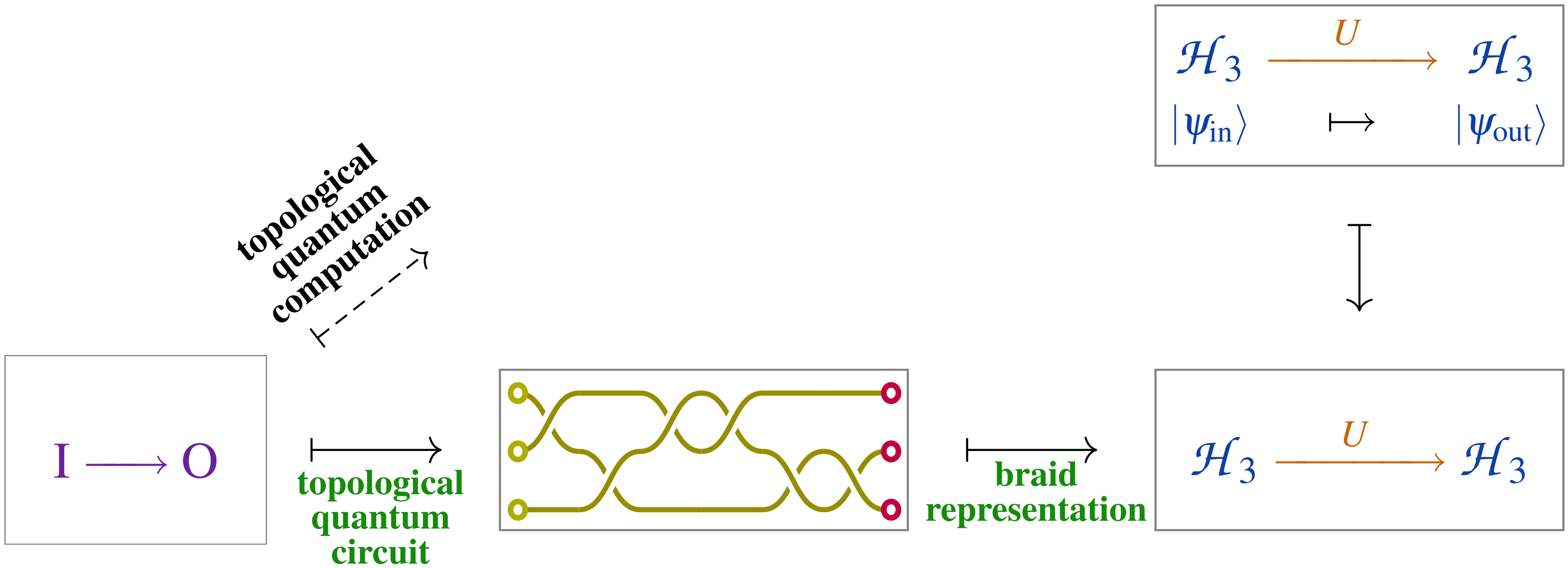
reliably

To compute is to **execute** sequences of **instructions** as composable **operations** on a chosen **state space**,

the case of

Topological Quantum Computation

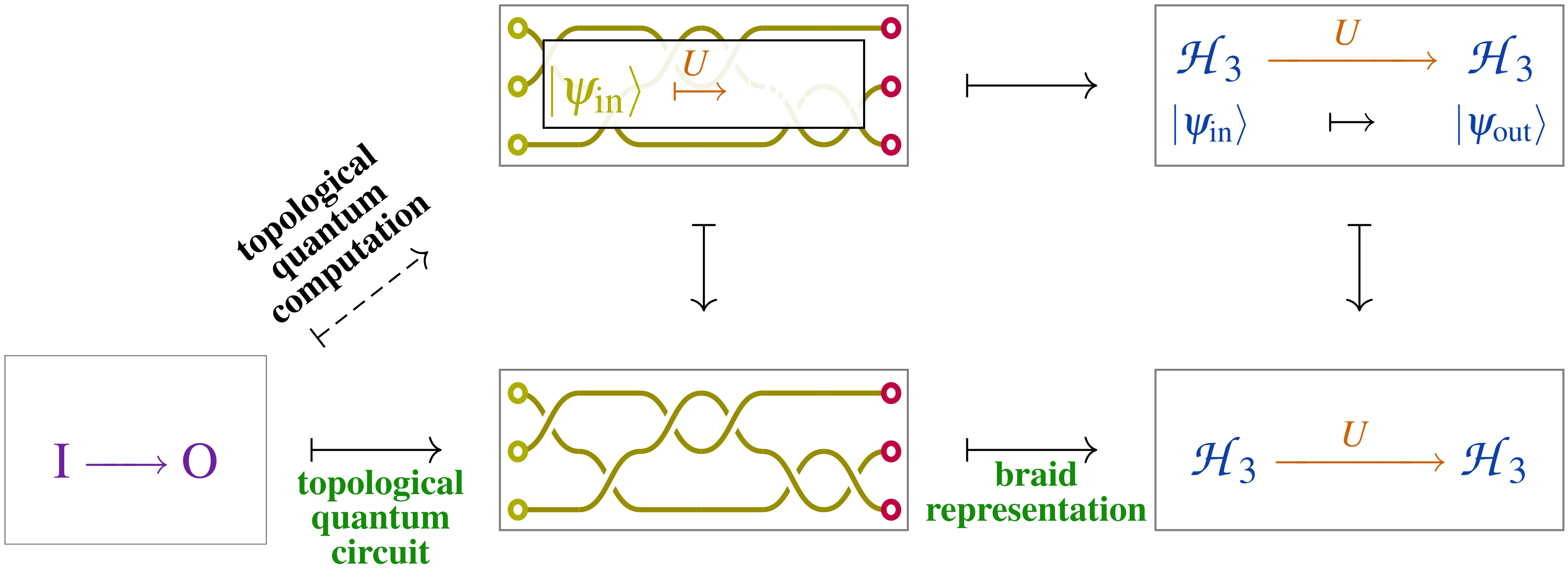
[Sati & Schreiber, PlanQC **2022** 33 (2022)]



reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,
turning a given **initial state**

the case of
Topological Quantum Computation
[Sati & Schreiber, PlanQC **2022** 33 (2022)]

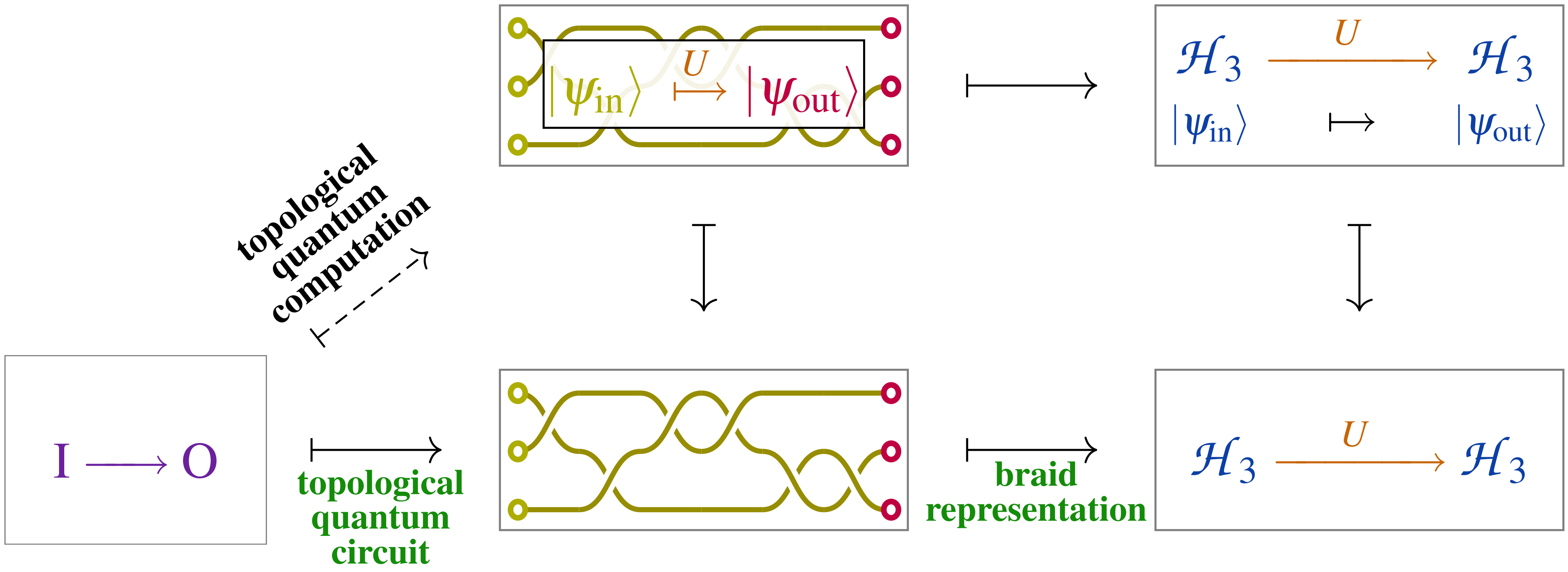


reliably

To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,

turning a given **initial state**
into the computed **result**.

the case of
Topological Quantum Computation
[Sati & Schreiber, PlanQC **2022** 33 (2022)]

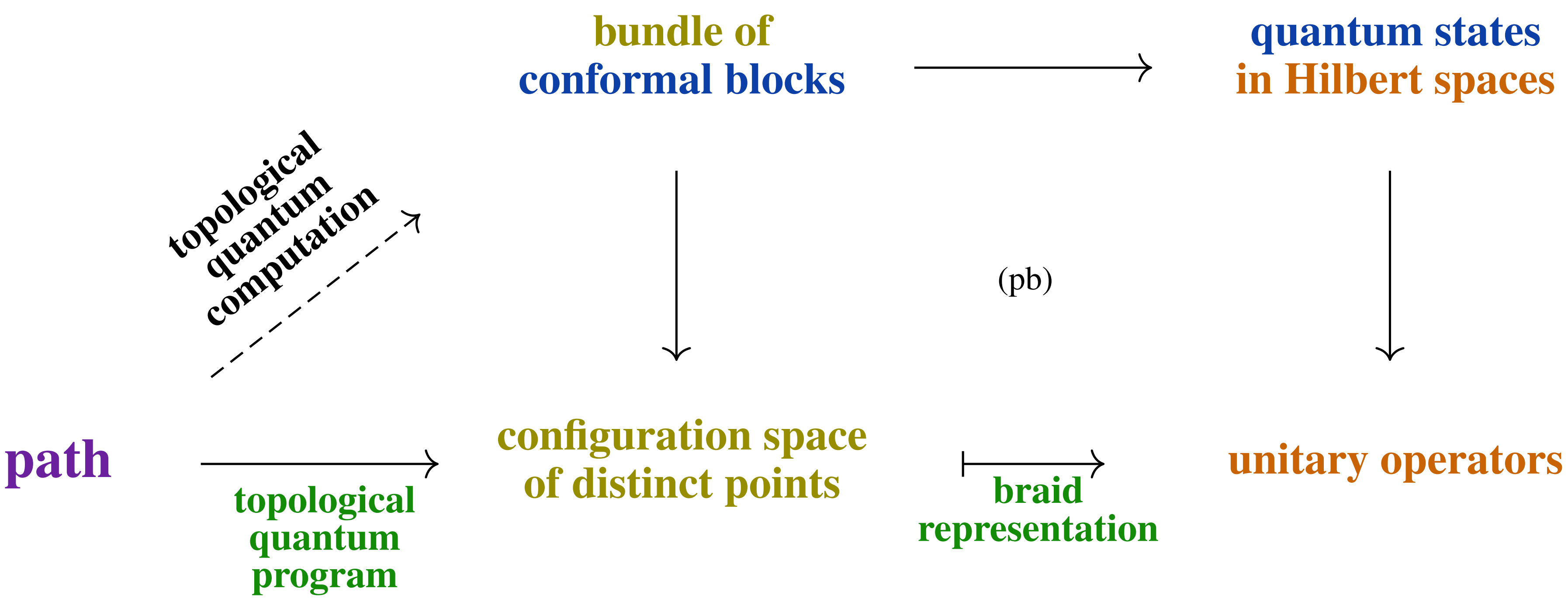


reliably

To compute is to **execute** sequences of **instructions** as composable **operations** on a chosen **state space**,

turning a given **initial state** into the computed **result**.

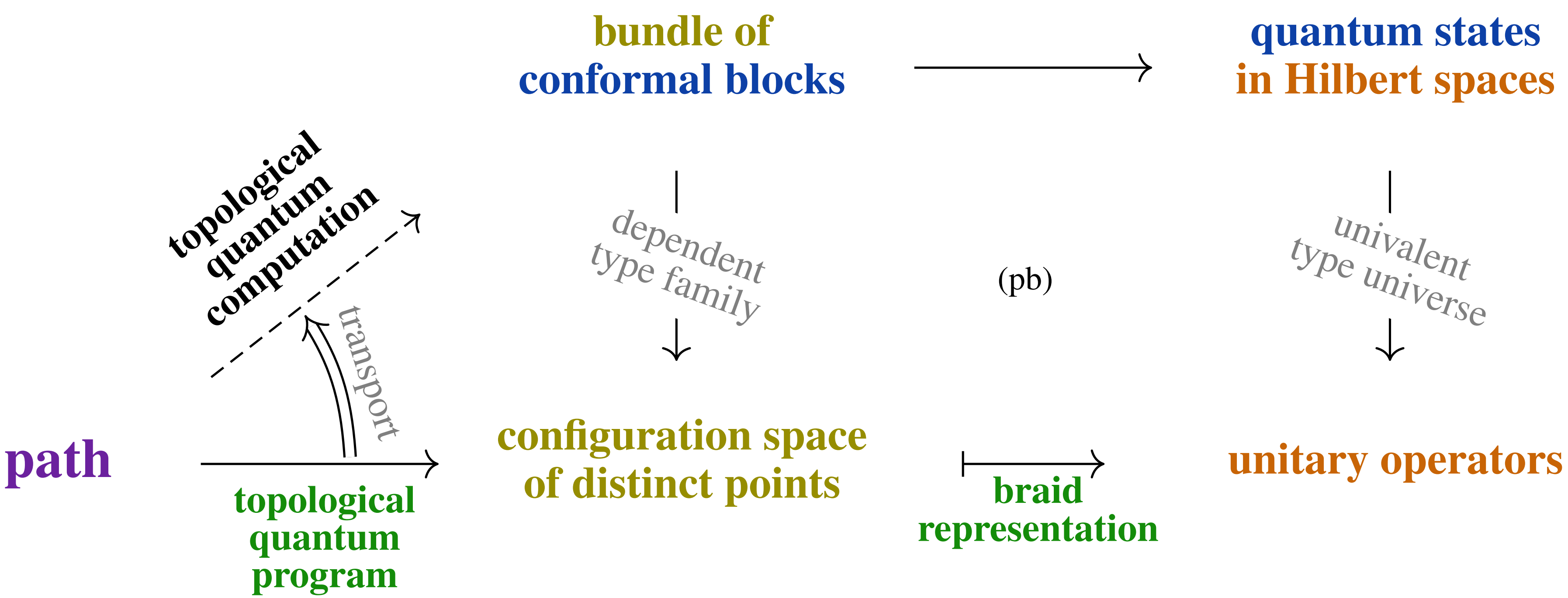
the case of
Topological Quantum Computation
[Sati & Schreiber, PlanQC **2022** 33 (2022)]



(reliably)
To compute is to **execute**
sequences of **instructions**
as composable **operations**
on a chosen **state space**,
turning a given **initial state**
into the computed **result**.

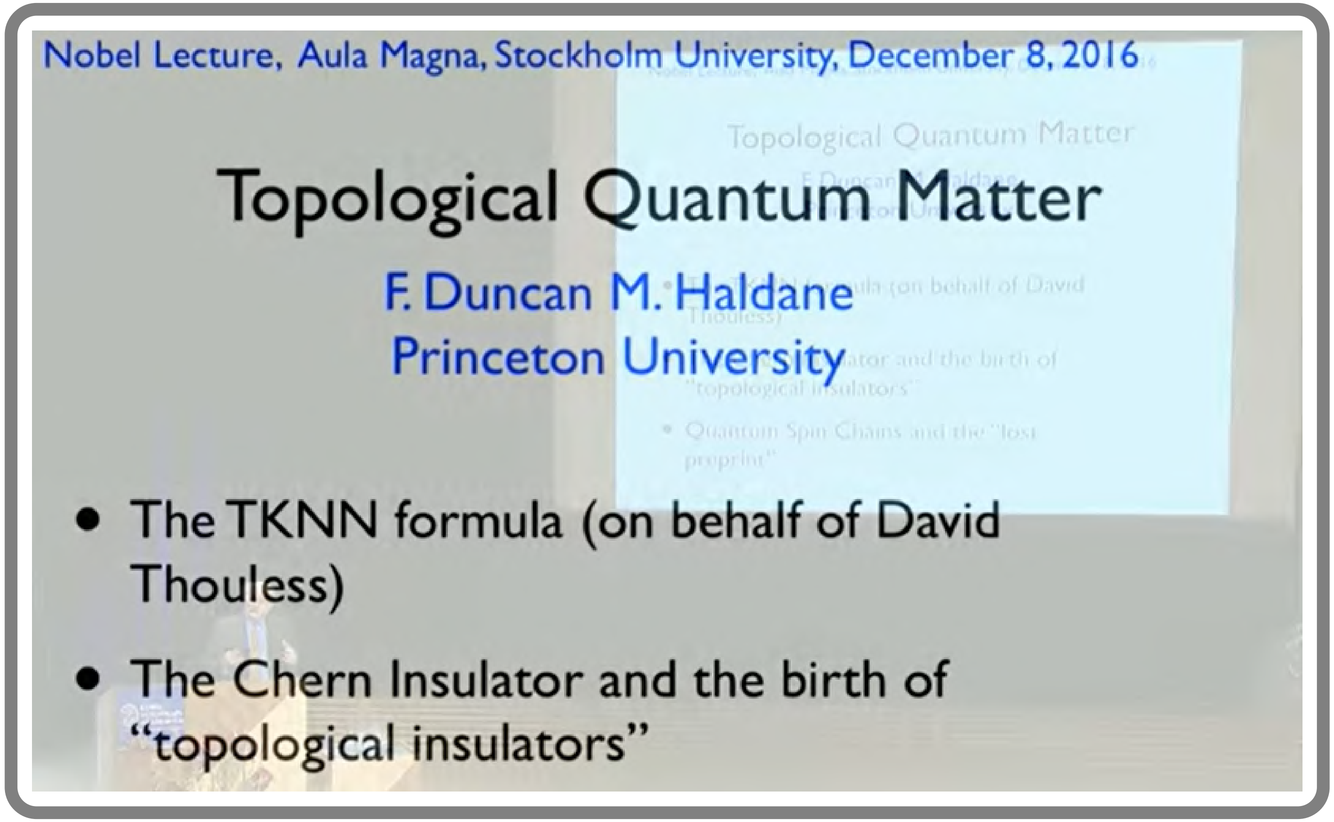
the case of
Topological Quantum Computation
[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Claim: This has natural construction in Homotopy Type Theory:



Quantum materials with these properties are called topological phases of matter

Quantum materials with these properties are called topological phases of matter



Quantum materials with these properties are called topological phases of matter

Quantum materials with these properties are called topological phases of matter exhibiting topological order.

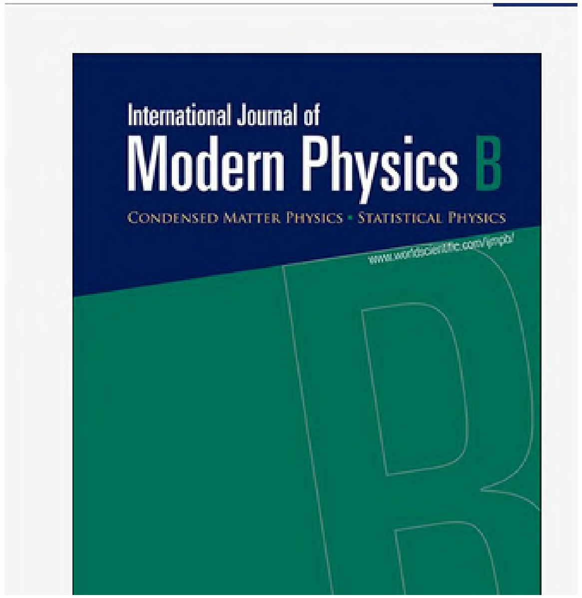
Quantum materials with these properties are called topological phases of matter exhibiting topological order.

International Journal of Modern Physics B
| Vol. 05, No. 10, pp. 1641-1648 (1991)
| IV. CHERN-SIMONS FIELD ...

TOPOLOGICAL ORDERS AND CHERN-SIMONS THEORY IN STRONGLY CORRELATED QUANTUM LIQUID

XIAO-GANG WEN

https://doi.org/10.1142/S0217979291001541 | Cited by: 98



Quantum materials with these properties are called topological phases of matter exhibiting topological order.

Quantum materials with these properties are called topological phases of matter exhibiting topological order.

Their point defects are known as anyons.

Quantum materials with these properties are called topological phases of matter exhibiting topological order.

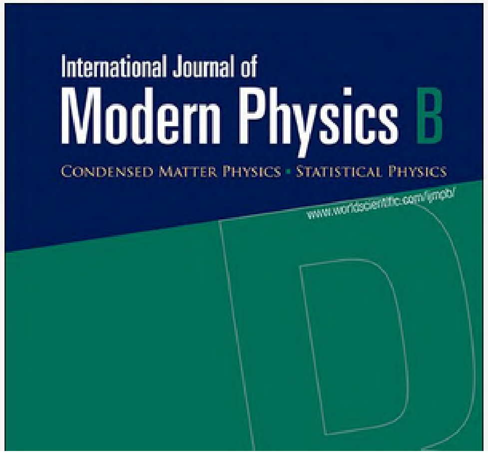
Their point defects are known as anyons.

International Journal of Modern Physics B
| Vol. 03, No. 07, pp. 1001-1067 (1989)
| Research Papers

ON ANYON SUPERCONDUCTIVITY

YI-HONG CHEN, FRANK WILCZEK, EDWARD WITTEN and BERTRAND I. HALPERIN

https://doi.org/10.1142/S0217979289000725 | **Cited by:** 525



Quantum materials with these properties are called topological phases of matter exhibiting topological order.

Their point defects are known as anyons.

Quantum materials with these properties are called topological phases of matter exhibiting topological order.

Their point defects are known as anyons.

Such materials are expected to exists
but have remained somewhat elusive:

experimentally as well as theoretically:

Quantum materials with these properties are called
topological phases of matter exhibiting topological order.

Their point defects are known as anyons.

Such materials are expected to exists
but have remained somewhat elusive:

experimentally as well as theoretically:

search for "Majorana zero modes"
had no reproducible success, and
would lack topological braiding;

Quantum materials with these properties are called
topological phases of matter exhibiting topological order.

Their point defects are known as anyons.

Such materials are expected to exists
but have remained somewhat elusive:

experimentally as well as theoretically:

search for "Majorana zero modes"
had no reproducible success, and
would lack topological braiding;

but braiding in momentum space
has very recently been demonstrated:
promising! – needs more investigation

Quantum materials with these properties are called
topological phases of matter

Their point defects a

Such materials are
but have remained

experimentally as w

search for "Majorana zero modes"
had no reproducible success, and
would lack topological braiding;

but braiding in momentum space
has very recently been demonstrated:
promising! – needs more investigation

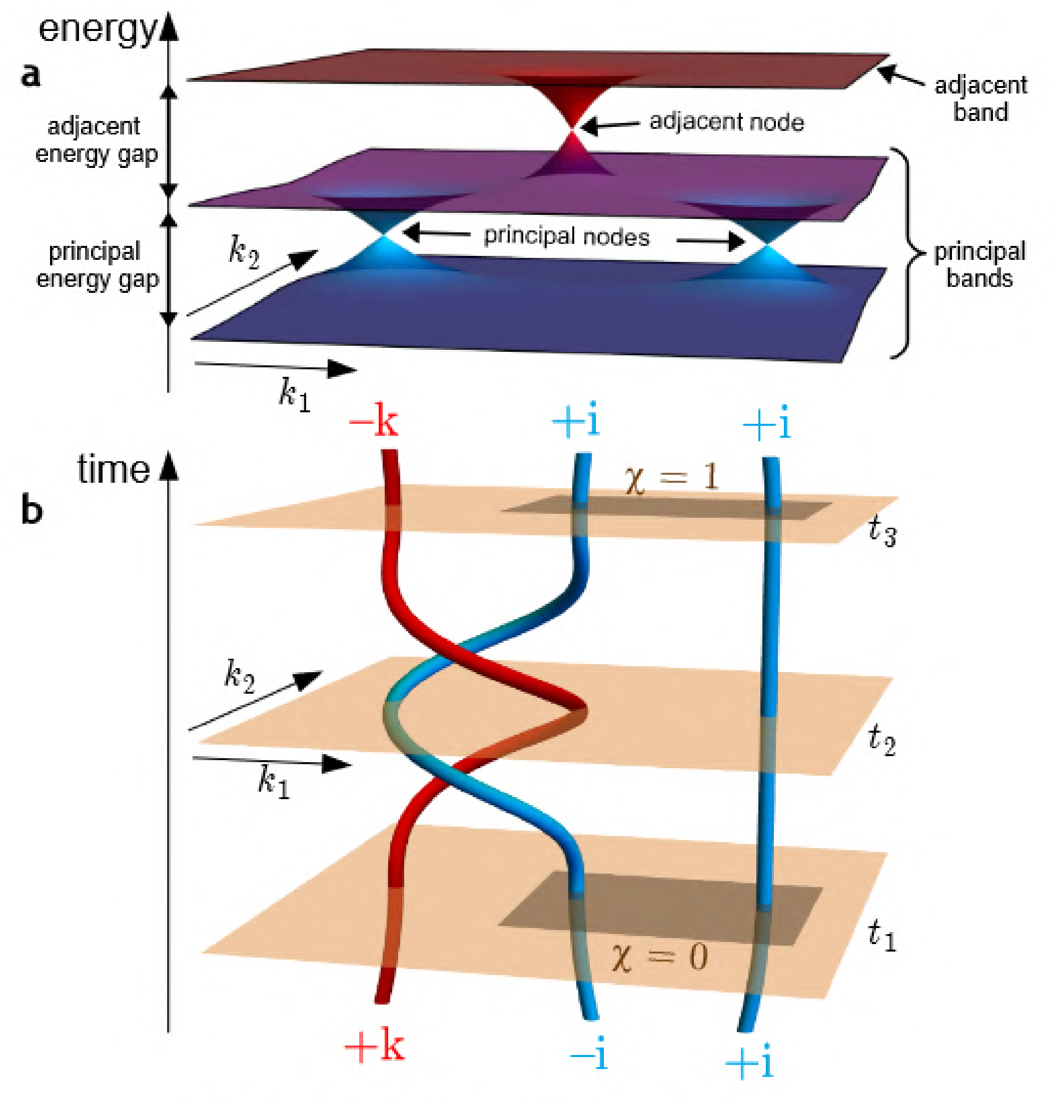


FIG. 1. **Reciprocal braiding of band nodes.**

Bzdušek et al., Nature Phys. **16** (2020)

Quantum materials with these properties are called
topological phases of matter exhibiting topological order.

Their point defects are known as anyons.

Such materials are expected to exists
but have remained somewhat elusive:

experimentally as well as theoretically:

search for "Majorana zero modes"
had no reproducible success, and
would lack topological braiding;

but braiding in momentum space
has very recently been demonstrated:
promising! – needs more investigation

Quantum materials with these properties are called topological phases of matter exhibiting topological order.

Their point defects are known as anyons.

Such materials are expected to exists
but have remained somewhat elusive:

experimentally as well as theoretically:

search for "Majorana zero modes" had no reproducible success, and would lack topological braiding;

but braiding in momentum space has very recently been demonstrated: promising! – needs more investigation

most successful theory for top. phases was thought not to apply to top. order,

Quantum materials with these properties are called topological phases of matter exhibiting topological order.

arXiv > cond-mat > arXiv:0901.2686

Search...

Help | A

Condensed Matter > Mesoscale and Nanoscale Physics

[Submitted on 18 Jan 2009 (v1), last revised 20 Jan 2009 (this version, v2)]

Periodic table for topological insulators superconductors

Alexei Kitaev

Gapped phases of noninteracting fermions, with and without charge conservation and time-reversal symmetry, are classified using Bott periodicity. The symmetry and spatial dimension determines a general universality class, which corresponds to one of the 2 types of complex and 8 types of real Clifford algebras. The phases within a given class are further characterized by a topological invariant, an element of some Abelian group that can be 0, Z, or Z_2. The interface between two infinite phases with different topological numbers must carry some gapless mode. Topological properties of finite systems are described in terms of K-homology. This classification is robust with respect to disorder, provided electron states near the Fermi energy are absent or localized. In some cases (e.g., integer quantum Hall systems) the K-theoretic classification is stable to interactions, but a counterexample is also given.

e known as anyons.

expected to exists

somewhat elusive:

ll as theoretically:

most successful theory for top. phases was thought not to apply to top. order,

Quantum materials with these properties are called
topological phases of matter exhibiting topological order.

Their point defects are known as anyons.

Such materials are expected to exists
but have remained somewhat elusive:

experimentally as well as theoretically:

search for "Majorana zero modes"
had no reproducible success, and
would lack topological braiding;

but braiding in momentum space
has very recently been demonstrated:
promising! – needs more investigation

most successful theory for top. phases
was thought not to apply to top. order,

Quantum materials with these properties are called
topological phases of matter exhibiting topological order.

Their point defects are known as anyons.

Such materials are expected to exists
but have remained somewhat elusive:

experimentally as well as theoretically:

search for "Majorana zero modes"
had no reproducible success, and
would lack topological braiding;

but braiding in momentum space
has very recently been demonstrated:
promising! – needs more investigation

most successful theory for top. phases
was thought not to apply to top. order,
until recently: Sati & Schreiber (2022b)

Quantum materials with these properties are called
topological phases of matter exhibiting topological order.

Their point defects are known as anyons.

Such materials are expected to exists
but have remained somewhat elusive:

experimentally as well as theoretically:

search for "Majorana zero modes"
had no reproducible success, and
would lack topological braiding;

but braiding in momentum space
has very recently been demonstrated:
promising! – needs more investigation

most successful theory for top. phases
was thought not to apply to top. order,
until recently: Sati & Schreiber (2022b)

our new theory in fact *predicts*
anyon braiding in momentum space
of topological semi-metals.

Quantum materials with these properties are called
topological phases of matter exhibiting topological order.

Their point defects are known as anyons.

Such materials are expected to exists
but have remained somewhat elusive:

experimentally as well as theoretically:

search for "Majorana zero modes"
had no reproducible success, and
would lack topological braiding;

but braiding in momentum space
has very recently been demonstrated:
promising! – needs more investigation

most successful theory for top. phases
was thought not to apply to top. order,
until recently: Sati & Schreiber (2022b)

our new theory in fact *predicts*
anyon braiding in momentum space
of topological semi-metals.

Physics underlying Topological Quantum Computation

Theory controlling Topological Quantum Computation

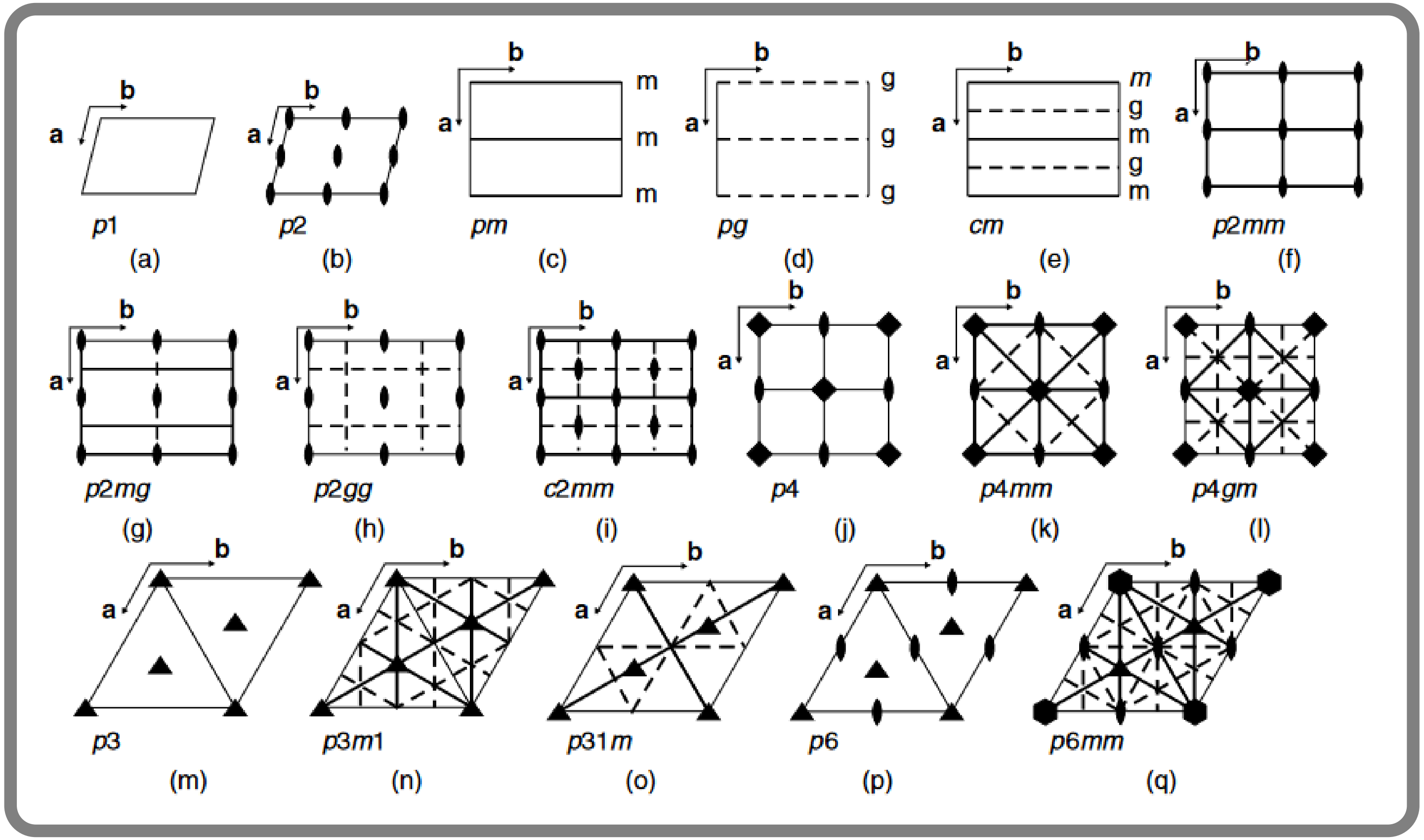
Concretely, we arrive at the following resolution.

Physics Theory underlying controlling Topological Quantum Computation

electron states $\leftrightarrow$ Brillouin torus

[Brillouin (1930)]

Physics Theory underlying controlling Topological Quantum Computation



electron states $\leftrightarrow$ Brillouin torus

[Brillouin (1930)]

Physics Theory
underlying controlling
Topological Quantum Computation

electron states $\leftrightarrow$ Brillouin torus

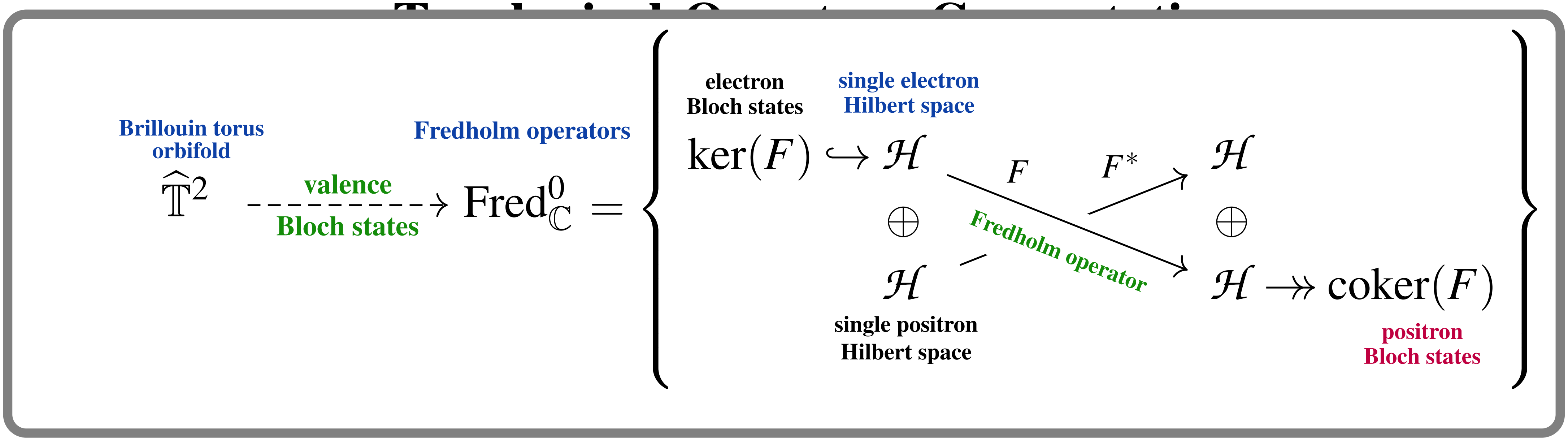
[Brillouin (1930)]

Physics		**Theory**
underlying		**controlling**
Topological	**Quantum**	**Computation**

topological phases		topological
(deformation classes)	$\leftrightarrow$	K-theory of
electron states	$\leftrightarrow$	Brillouin torus

[Kitaev (2009)]

Physics underlying | **Theory controlling**



topological phases (deformation classes) $\leftrightarrow$ topological K-theory of

electron states $\leftrightarrow$ Brillouin torus

[Kitaev (2009)]

Physics		**Theory**
underlying		**controlling**
Topological	**Quantum**	**Computation**

topological phases		topological
(deformation classes)	$\leftrightarrow$	K-theory of
electron states	$\leftrightarrow$	Brillouin torus

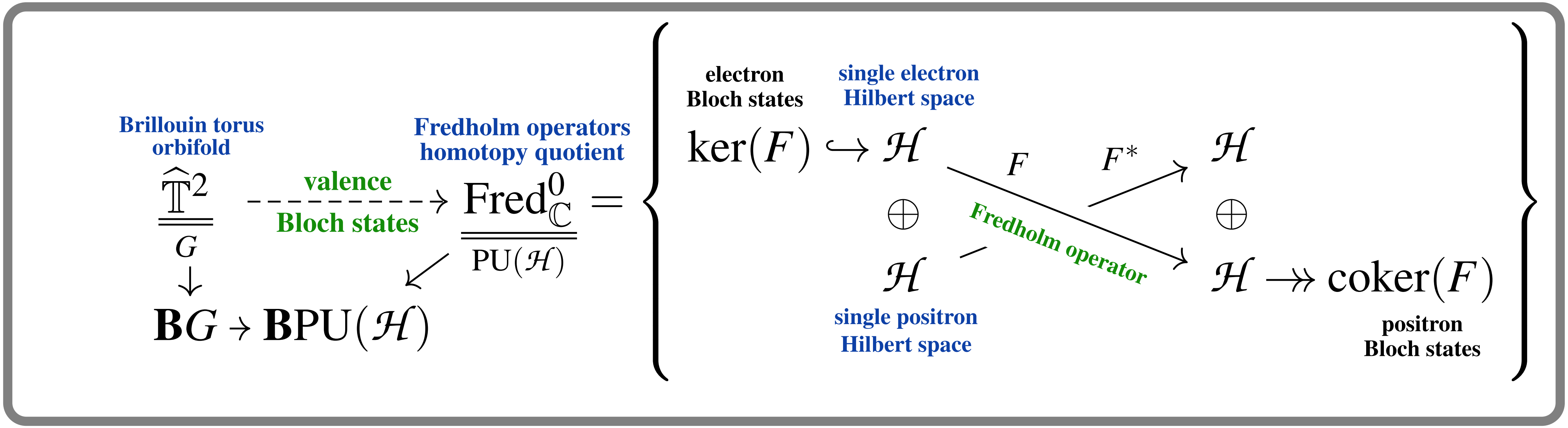
[Kitaev (2009)]

Physics		**Theory**
underlying		**controlling**
Topological	**Quantum**	**Computation**
quantum symmetries	$\leftrightarrow$	equivariant
topological phases	$\leftrightarrow$	topological
deformation classes	$\leftrightarrow$	K-theory of
electron states	$\leftrightarrow$	Brillouin torus

[Freed & Moore (2013)]

Physics Theory
underlying controlling
Topological Quantum Computation

quantum symmetries $\leftrightarrow$ equivariant



[Freed & Moore (2013)]

Physics Theory
underlying controlling
Topological Quantum Computation

quantum symmetries	$\leftrightarrow$	equivariant
topological phases	$\leftrightarrow$	topological
deformation classes	$\leftrightarrow$	K-theory of
electron states	$\leftrightarrow$	Brillouin torus

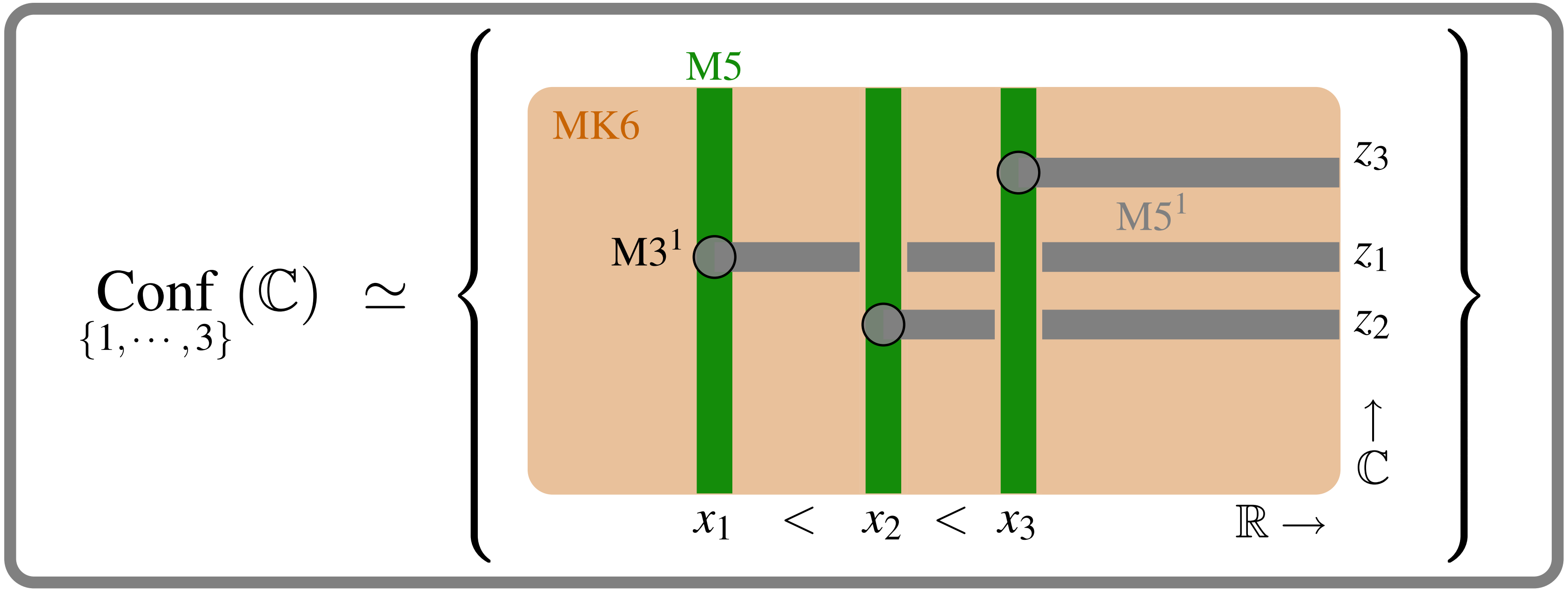
[Freed & Moore (2013)]

Physics Theory
underlying controlling
Topological Quantum Computation

quantum symmetries	↔	equivariant
topological phases	↔	topological
deformation classes	↔	K-theory of
strongly interacting	↔	configurations in
electron states	↔	Brillouin torus

[Sati & Schreiber (2022a) (2022b)]

Physics Theory underlying controlling Topological Quantum Computation



strongly interacting ↔ configurations in

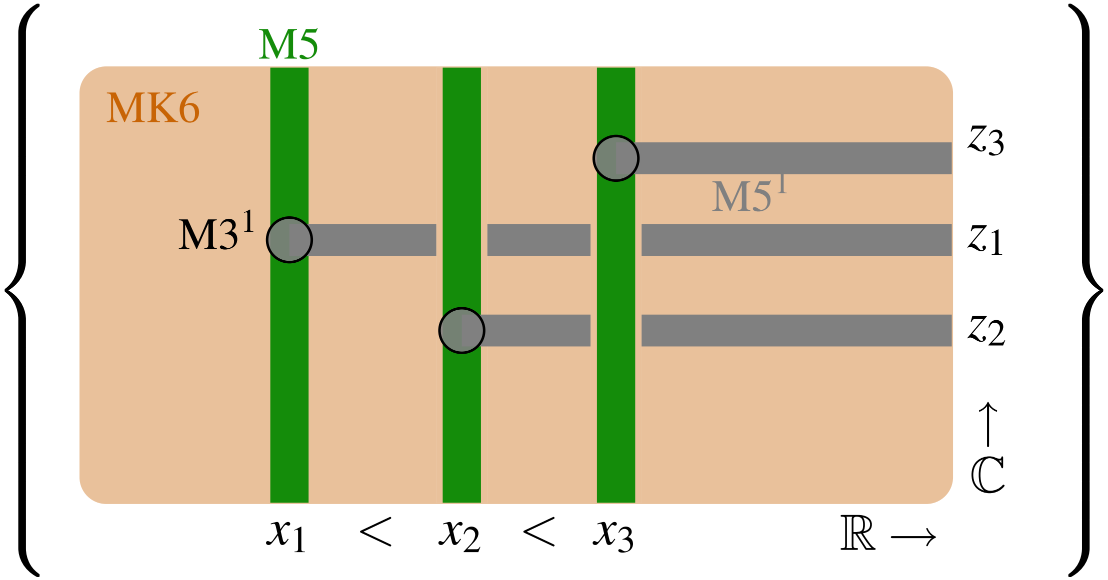
electron states ↔ Brillouin torus

[Sati & Schreiber (2022a) (2022b)]

Physics underlying Topological Quantum Computation

Theory controlling

$$\underset{\{1,\cdots,3\}}{\mathrm{Conf}}(\mathbb{C}) \simeq$$



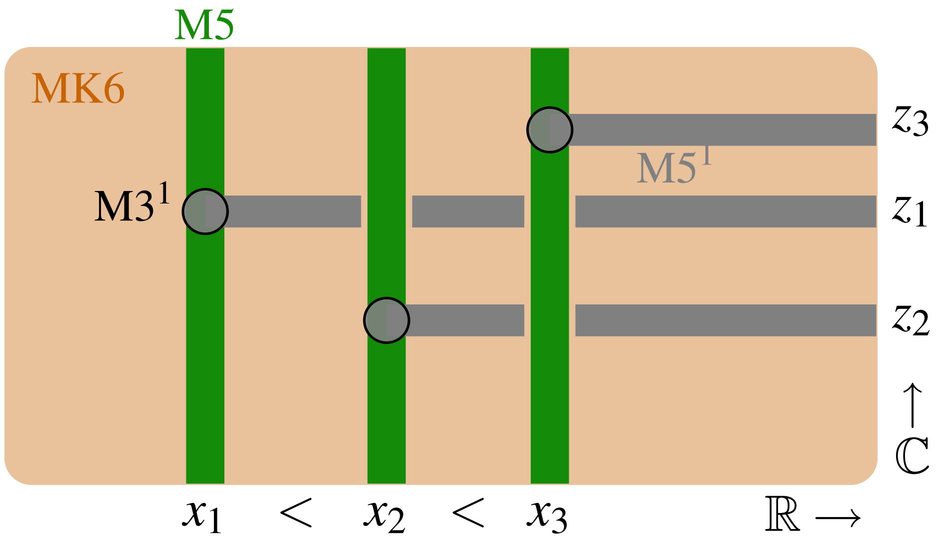
strongly interacting electron states $\leftrightarrow$ configurations in Brillouin torus

[Sati & Schreiber (2022a) (2022b)]

Physics underlying Topological Quantum Computation

Theory controlling

$$\underset{\{1,\cdots,3\}}{\mathrm{Conf}}(\mathbb{C}) \simeq \left\{ \text{[diagram]} \right\}$$



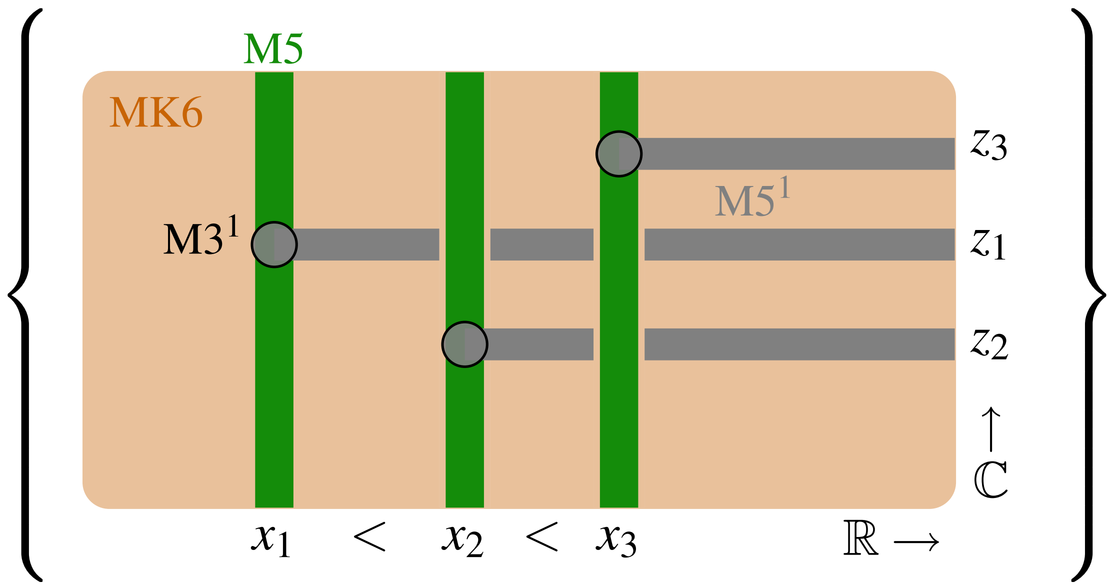
strongly interacting $\leftrightarrow$ configurations in

electron states $\leftrightarrow$ Brillouin torus

[Sati & Schreiber (2022a) (2022b)]

Physics underlying Topological Quantum Theory controlling Computation

$$\underset{\{1,\cdots,3\}}{\mathrm{Conf}}(\mathbb{C}) \simeq$$



strongly interacting ⟷ configurations in

electron states ⟷ Brillouin torus

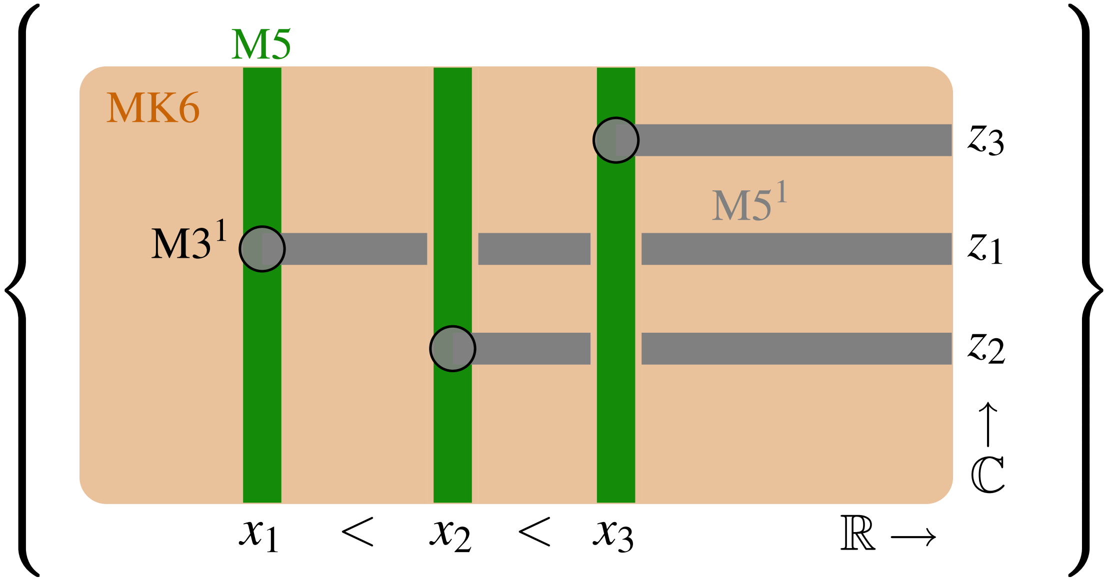
[Sati & Schreiber (2022a) (2022b)]

Physics Theory

underlying controlling

Topological Quantum Computation

$\underset{\{1,\cdots,3\}}{\mathrm{Conf}}(\mathbb{C}) \simeq$

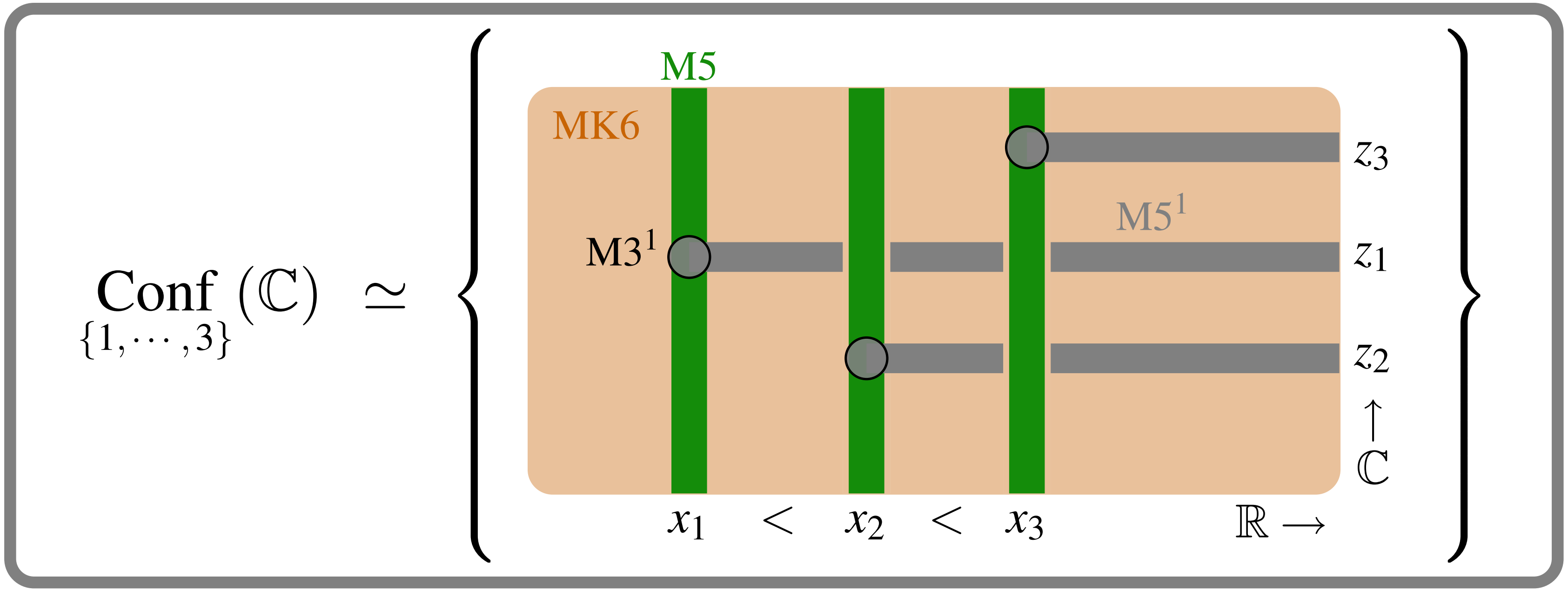


strongly interacting ↔ configurations in

electron states ↔ Brillouin torus

[Sati & Schreiber (2022a) (2022b)]

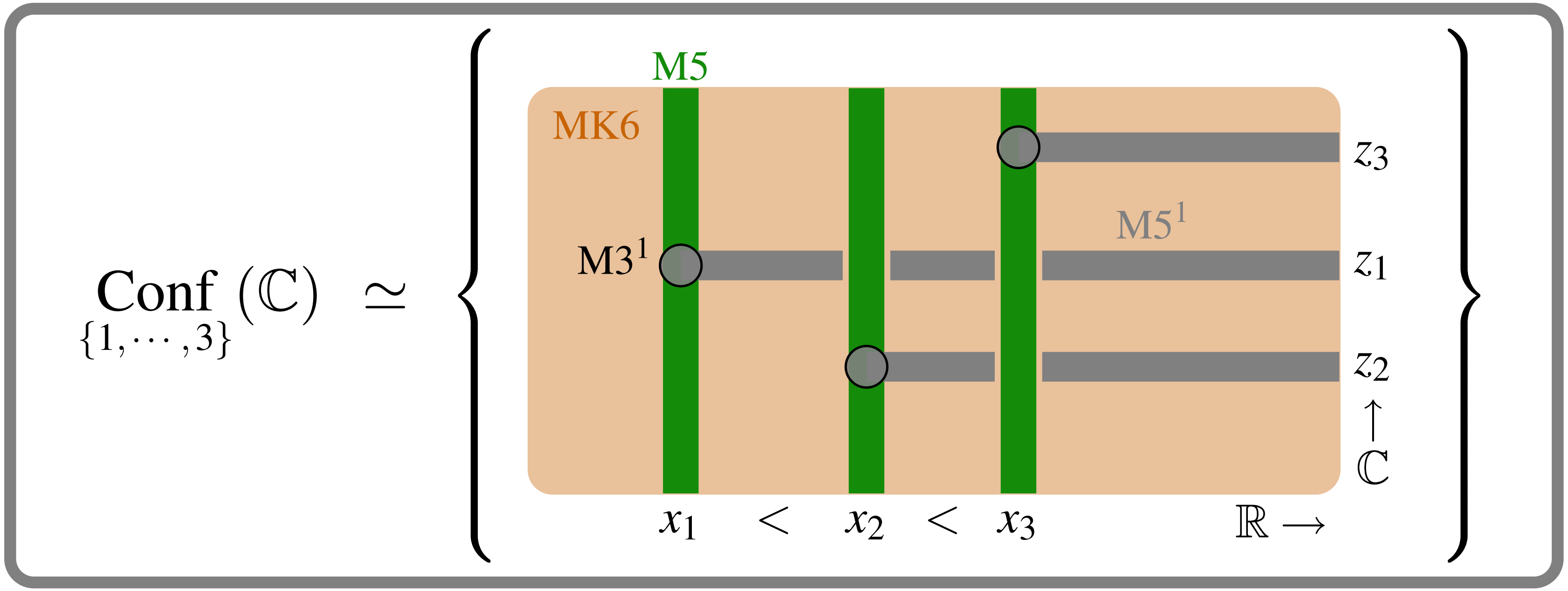
Physics Theory
underlying controlling
Topological Quantum Computation



strongly interacting ↔ configurations in
electron states ↔ Brillouin torus

[Sati & Schreiber (2022a) (2022b)]

Physics Theory
underlying controlling
Topological Quantum Computation



strongly interacting $\leftrightarrow$ configurations in

electron states $\leftrightarrow$ Brillouin torus

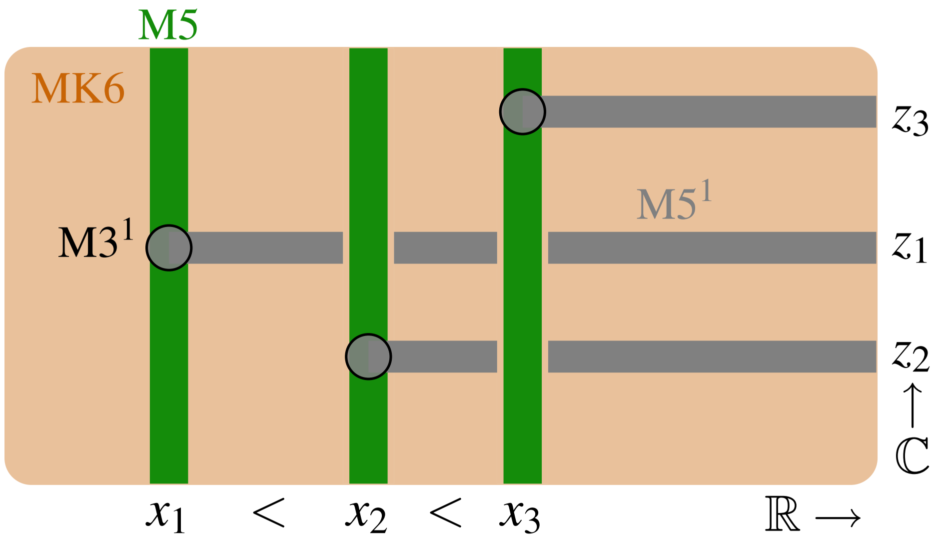
[Sati & Schreiber (2022a) (2022b)]

Physics Theory

underlying controlling

Topological Quantum Computation

$$\underset{\{1,\cdots,3\}}{\mathrm{Conf}}(\mathbb{C}) \simeq \left\{ \; \right\}$$

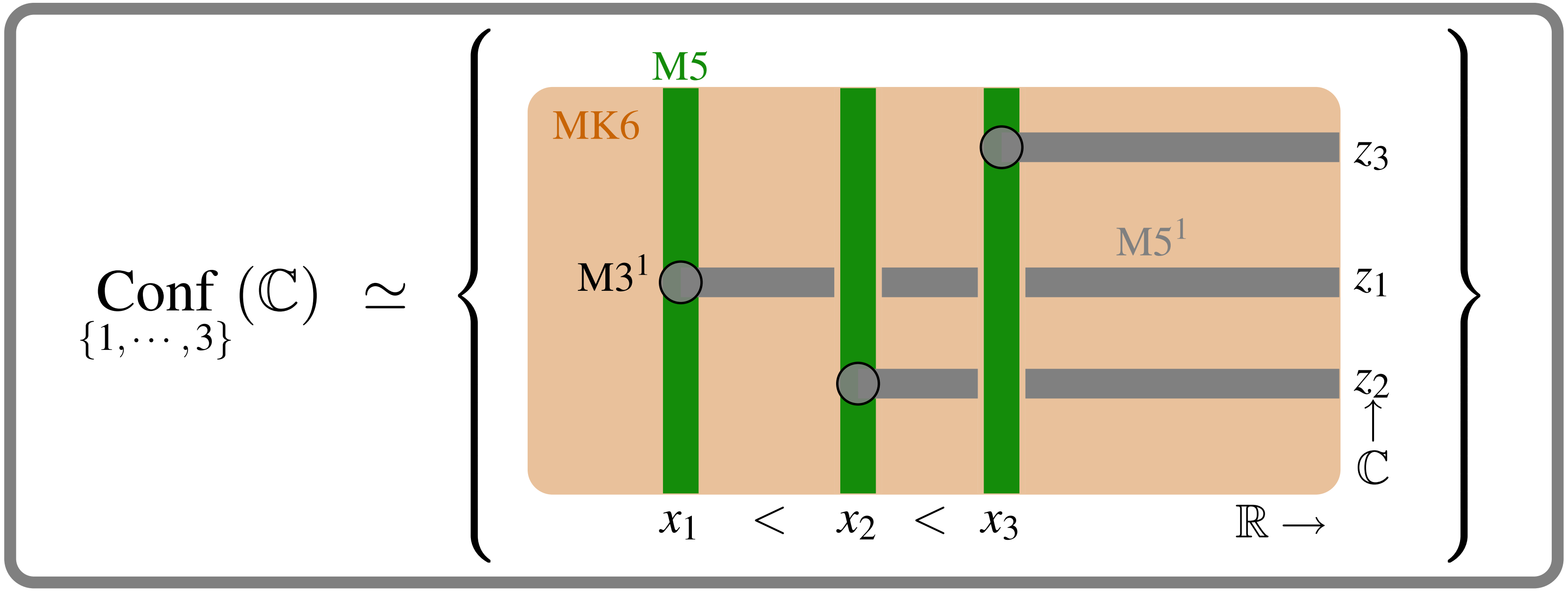


strongly interacting ⟷ configurations in

electron states ⟷ Brillouin torus

[Sati & Schreiber (2022a) (2022b)]

Physics **Theory**
underlying **controlling**
Topological Quantum Computation



strongly interacting ⟷ configurations in

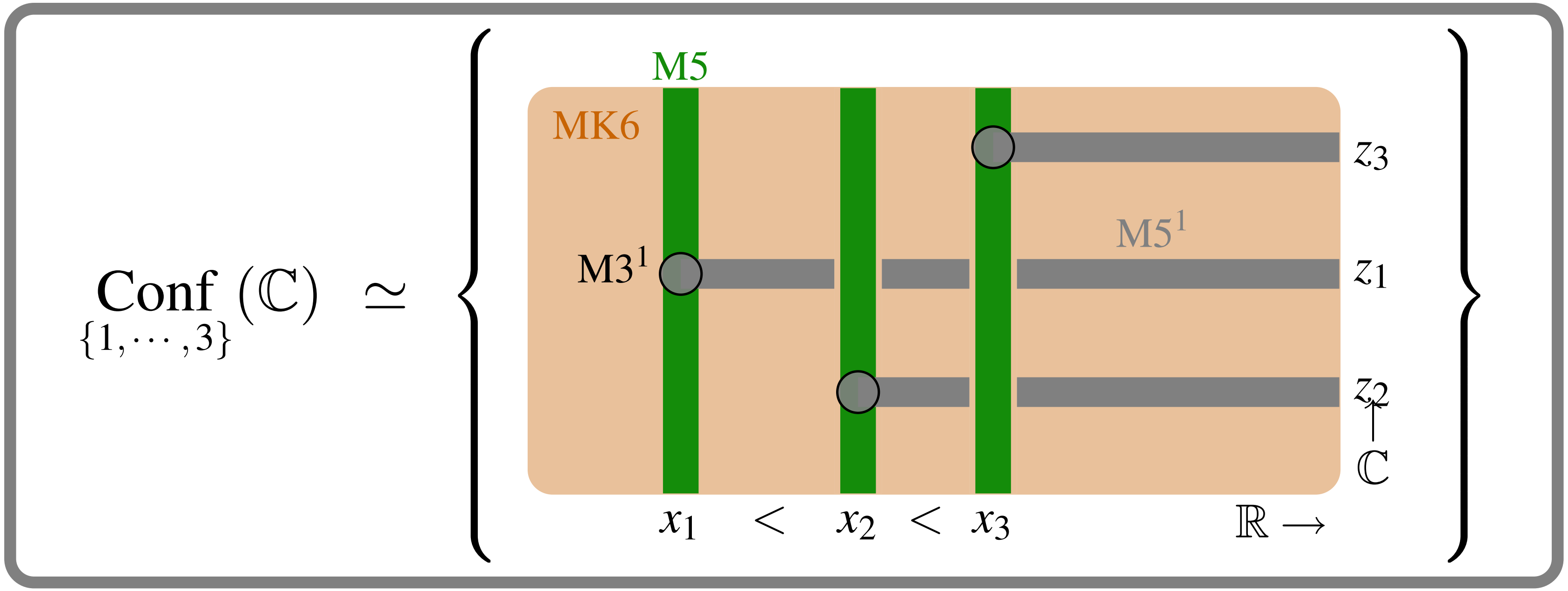
electron states ⟷ Brillouin torus

[Sati & Schreiber (2022a) (2022b)]

Physics Theory

underlying controlling

Topological Quantum Computation



strongly interacting ⟷ configurations in

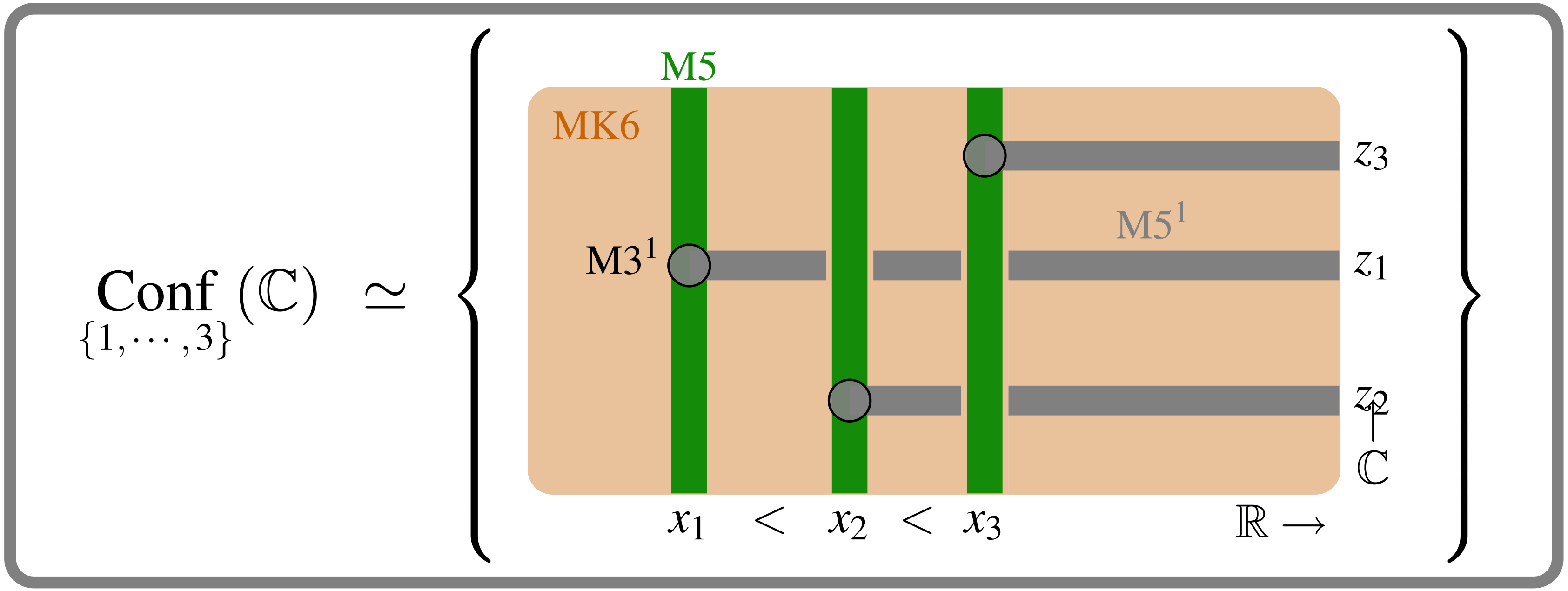
electron states ⟷ Brillouin torus

[Sati & Schreiber (2022a) (2022b)]

Physics Theory

underlying controlling

Topological Quantum Computation

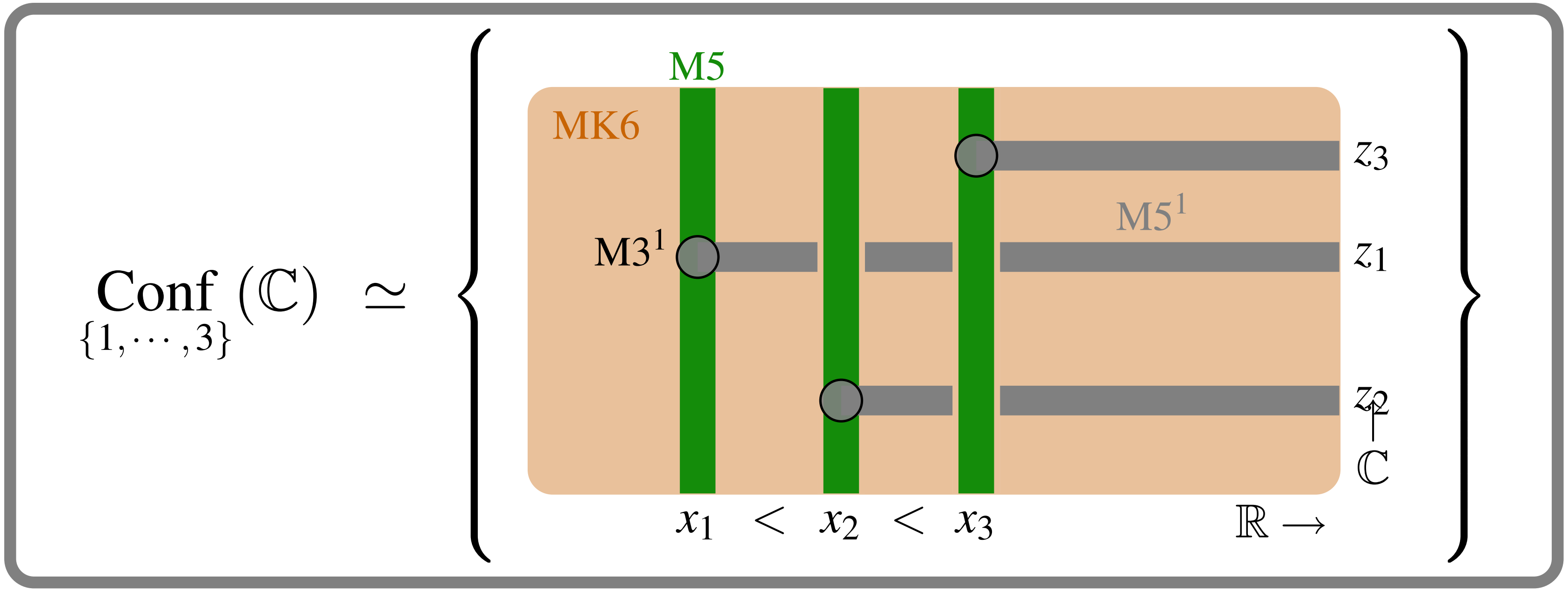


strongly interacting ⟷ configurations in

electron states ⟷ Brillouin torus

[Sati & Schreiber (2022a) (2022b)]

Physics Theory
underlying controlling
Topological Quantum Computation



strongly interacting ⟷ configurations in
electron states ⟷ Brillouin torus

[Sati & Schreiber (2022a) (2022b)]

Physics Theory
underlying controlling
Topological Quantum Computation

quantum symmetries	↔	equivariant
topological phases	↔	topological
deformation classes	↔	K-theory of
strongly interacting	↔	configurations in
electron states	↔	Brillouin torus

[Sati & Schreiber (2022a) (2022b)]

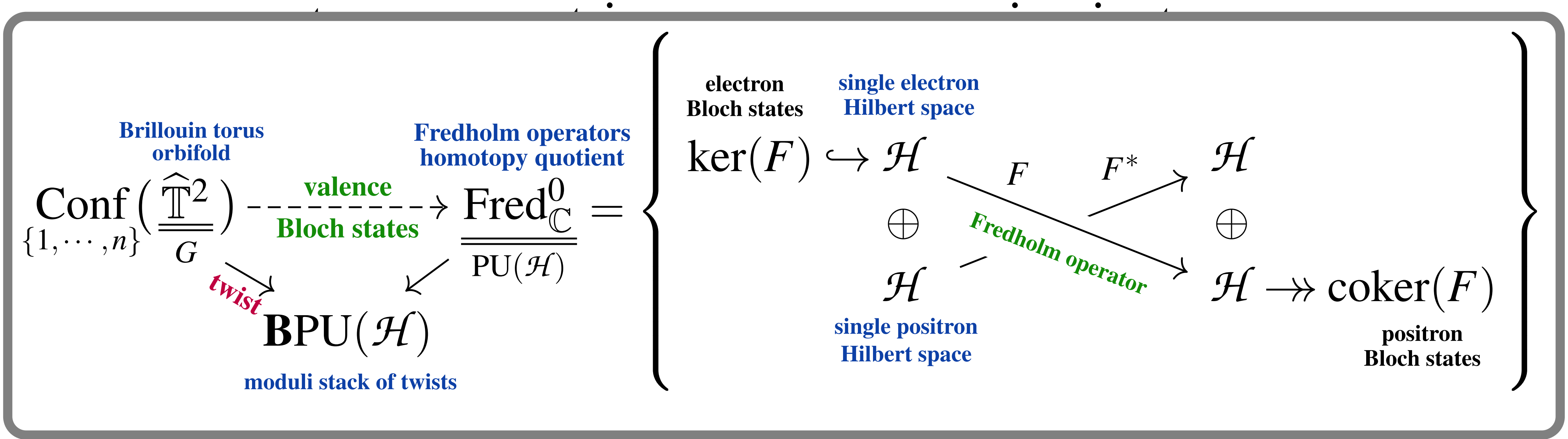
Physics Theory
underlying controlling
Topological Quantum Computation

anyon species	$\leftrightarrow$	twisted
quantum symmetries	$\leftrightarrow$	equivariant
anyon wavefunctions	$\leftrightarrow$	differential
topological phases	$\leftrightarrow$	topological
deformation classes	$\leftrightarrow$	K-theory of
strongly interacting	$\leftrightarrow$	configurations in
electron states	$\leftrightarrow$	Brillouin torus

[Sati & Schreiber (2022b)]

Physics Theory
underlying controlling
Topological Quantum Computation

anyon species ↔ twisted



electron states ↔ Brillouin torus

[Sati & Schreiber (2022b)]

Physics underlying Topological Quantum Computation

anyon species	↔	twisted
quantum symmetries	↔	equivariant
anyon wavefunctions	↔	differential
topological phases	↔	topological
deformation classes	↔	K-theory of
strongly interacting	↔	configurations in
electron states	↔	Brillouin torus

Theory controlling Topological Quantum Computation

[Sati & Schreiber (2022b)]

Physics		**Theory**
underlying		**controlling**
Topological	**Quantum**	**Computation**
anyon braiding	$\leftrightarrow$	GM-connection on
anyon species	$\leftrightarrow$	twisted
quantum symmetries	$\leftrightarrow$	equivariant
anyon wavefunctions	$\leftrightarrow$	differential
topological phases	$\leftrightarrow$	topological
deformation classes	$\leftrightarrow$	K-theory of
strongly interacting	$\leftrightarrow$	configurations in
electron states	$\leftrightarrow$	Brillouin torus

[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Physics underlying Topological Quantum Computation | **Theory controlling**

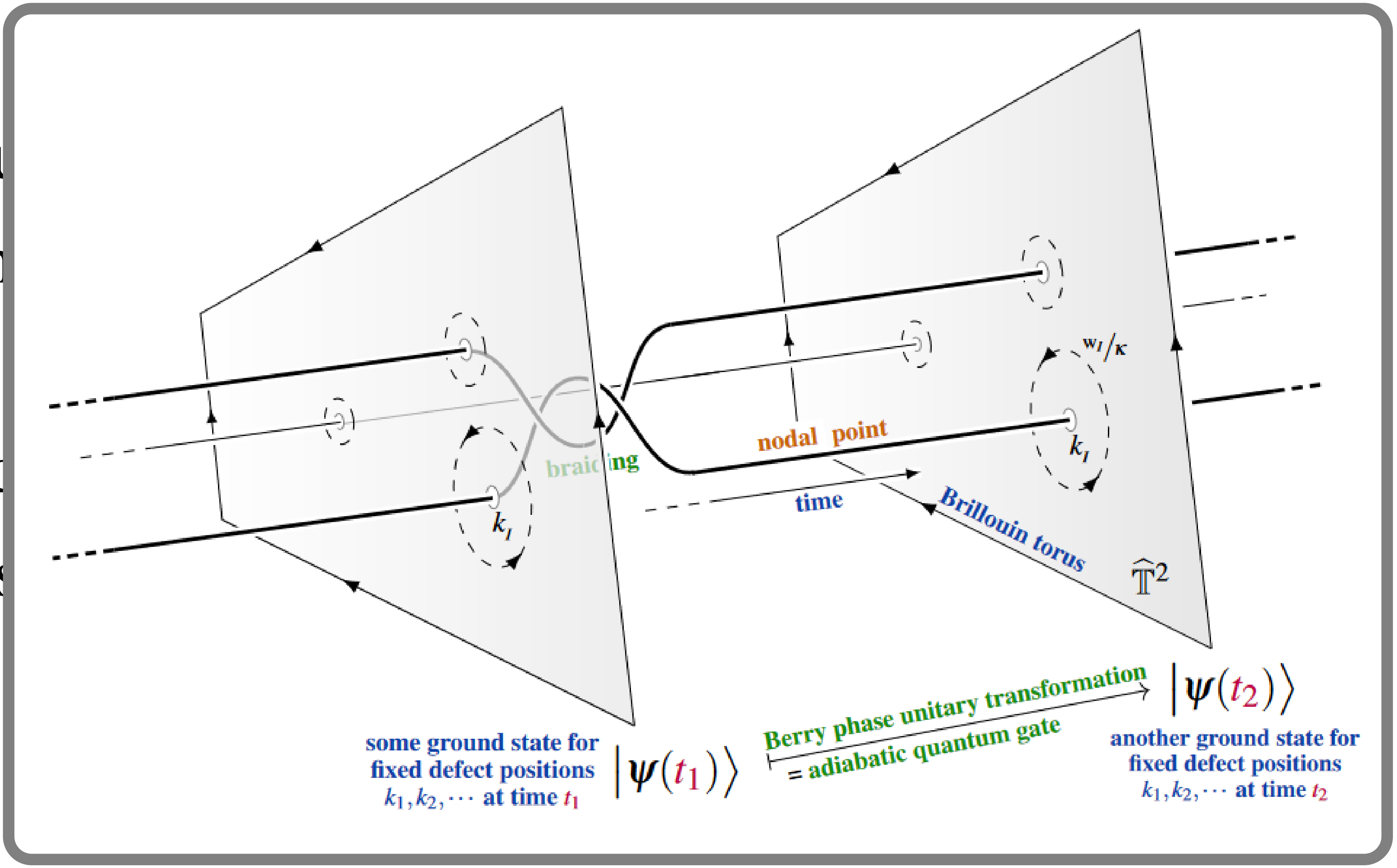
anyon braiding ↔ GM-connection on

qu

an

c

s



Physics underlying	**Topological Quantum**	**Theory controlling Computation**
anyon braiding	↔	GM-connection on
anyon species	↔	twisted
quantum symmetries	↔	equivariant
anyon wavefunctions	↔	differential
topological phases	↔	topological
deformation classes	↔	K-theory of
strongly interacting	↔	configurations in
electron states	↔	Brillouin torus

[Sati & Schreiber, PlanQC **2022** 33 (2022)]

Physics underlying		**Theory controlling**
Topological Quantum		**Computation**
anyon braiding	$\leftrightarrow$	GM-connection on
anyon species	$\leftrightarrow$	twisted
quantum symmetries	$\leftrightarrow$	equivariant
anyon wavefunctions	$\leftrightarrow$	differential
topological phases	$\leftrightarrow$	topological
deformation classes	$\leftrightarrow$	K-theory of
strongly interacting	$\leftrightarrow$	configurations in
electron states	$\leftrightarrow$	Brillouin torus

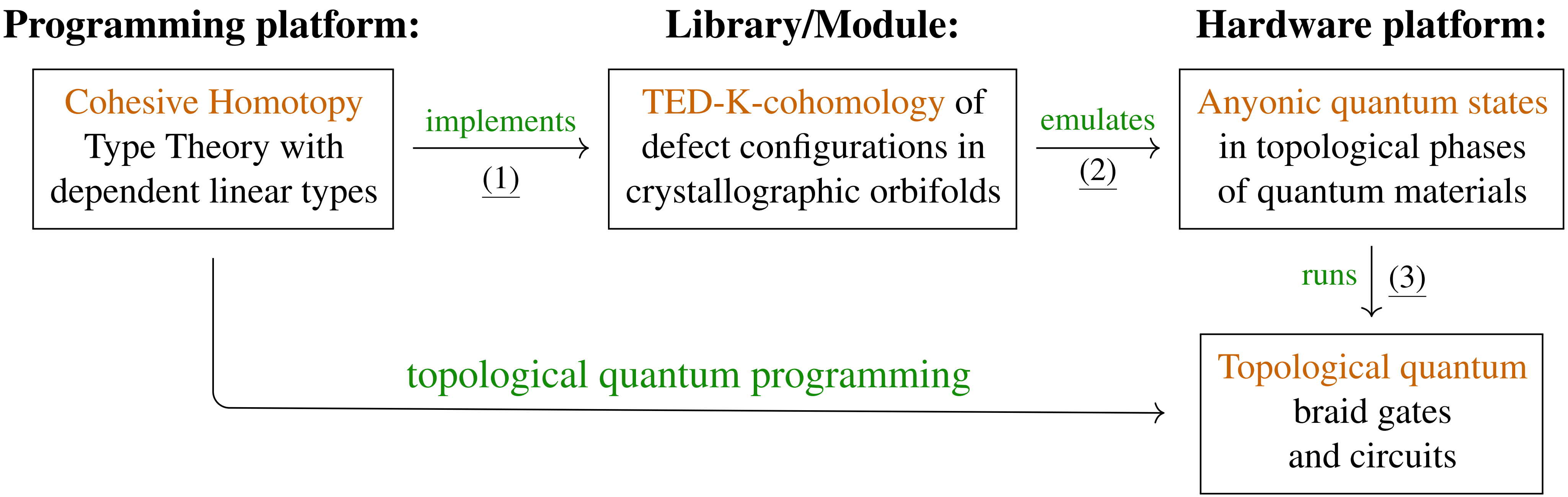
[Kitaev (2003)] [Freedman, Kitaev, Larsen & Wang (2003)]

Physics **Theory**
underlying **controlling**
Topological Quantum Computation

anyon braiding	$\leftrightarrow$	GM-connection on
anyon species	$\leftrightarrow$	twisted
quantum symmetries	$\leftrightarrow$	equivariant
anyon wavefunctions	$\leftrightarrow$	differential
topological phases	$\leftrightarrow$	topological
deformation classes	$\leftrightarrow$	K-theory of
strongly interacting	$\leftrightarrow$	configurations in
electron states	$\leftrightarrow$	Brillouin torus

[Sati & Schreiber (2022a) (2022b) (2022c)]

Claim: This insight yields a striking prospect
for naturally implementing quantum simulators
that actually reflect fine detail of braid grates
for anyonic topological quantum computation.



[Sati & Schreiber, PlanQC **2022** 33 (2022)]

We are developing this program
at our newly launched
research center...

Center for Quantum& Topological Systems

جامعة نيويورك أبوظبي

NYU | ABU DHABI

We are developing this program
at our newly launched
research center...

Center for Quantum and Topological Systems

CQTS just launched

جامعة نيويورك ابوظبي
NYU | ABU DHABI

Research Institute Centers

The NYUAD Research Institute is a world-class center of cutting-edge and innovative research, scholarship, and cultural activity. It supports centers that address questions of global significance and local relevance and allows leading faculty members from across the disciplines to carry out creative scholarship and high-level research on a range of complex issues with depth, scale, and longevity that otherwise would not be possible.

Faculty

November 30, 2021

NYU Abu Dhabi Research Institute Announces Four New Research Centers

The NYU Abu Dhabi Research Institute is pleased to announce the funding decisions from its AY20-21 Request For Proposals (RFP) cycle. The quality of the proposals this year was superb, with every full proposal lauded by the external reviewers. Four new centers have been selected for funding, each of which will bring exceptional scholarship, stellar impact, and strategic alignment with the research priorities of NYUAD and the UAE. The establishment of these centers is a testament not only to the quality of the proposals, but also to the commitment of NYUAD and our partners to growing research at NYUAD.

https://nyuad.nyu.edu/en/research/faculty-labs-and-projects/center-for-quantum-and-topological-sys

Alumni News Events Quick Links عربي All NYU

Academics Admissions Research Campus Life About

Home / Research / Faculty Labs and Projects / Center for Quantum and Topological Systems

Center for Quantum and Topological Systems

Now in launch phase:
new hires arriving this week!

Principal Investigator

Hisham Sati

Professor of Mathematics

Co-Principal Investigators

Muhammad Shafique

Associate Professor of Electrical and Computer Engineering

Saurabh Ray

Associate Professor of Computer Science

Farah Shamout

Assistant Professor and Emerging Scholar of Electrical and Computer Engineering

Tuka Alhanai

Assistant Professor and Emerging Scholar of Electrical and Computer Engineering

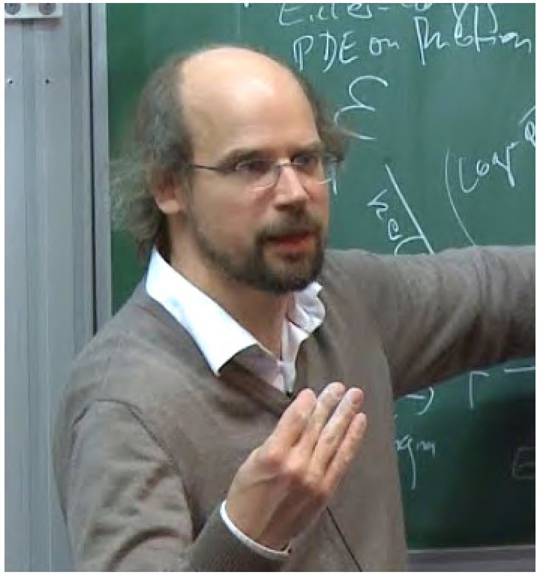
Tim Byrnes

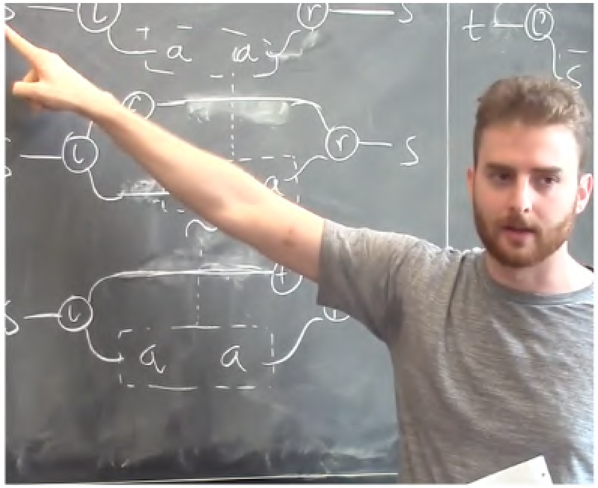
Assistant Professor of Physics (NYUSH)

Pilkyung Moon

Assistant Professor of Physics (NYUSH)

Researchers


Urs Schreiber


Mitchell Riley


David Myers


Tatiana Ezubova


Marwa Mannai


Sachin Valera


Amaria Javed


Adrian Clough

CQTS is part of the Quantum Initiative at NYU Abu Dhabi in the United Arab Emirates

U.AE

Home

Information and services

About the UAE > Science and technology

Quantum computing in the UAE

To enable innovation and a sustainable knowledge-based economy, the UAE is investing in the area of quantum computing and its innovative applications to solve some of the world's toughest challenges considering its immense power compared to current computers.

UAE joins the race to produce a usable quantum computer

As part of its ongoing effort to keep up with the latest technology, the United Arab Emirates has begun work on the region's first quantum computer

This article can also be found in the Premium Editorial Download: CW Middle East: CW Middle East: What does Saudi Arabia's autonomous vehicle agenda mean for the world?

By **Pat Brans**, Pat Brans Associates/Grenoble Ecole de Management

Published: 10 Dec 2021 10:48

Tuesday 29 March 2022

UAE

UAE | CORONAVIRUS | GULF | MENA | WORLD | BUSINESS | OPINION | LIFESTYLE | ARTS & CULTURE | TRAVEL

Expo 2020 | Courts | Government | Education | Heritage | Health | Transport | Science | Environment | Megaprojects | UAE in

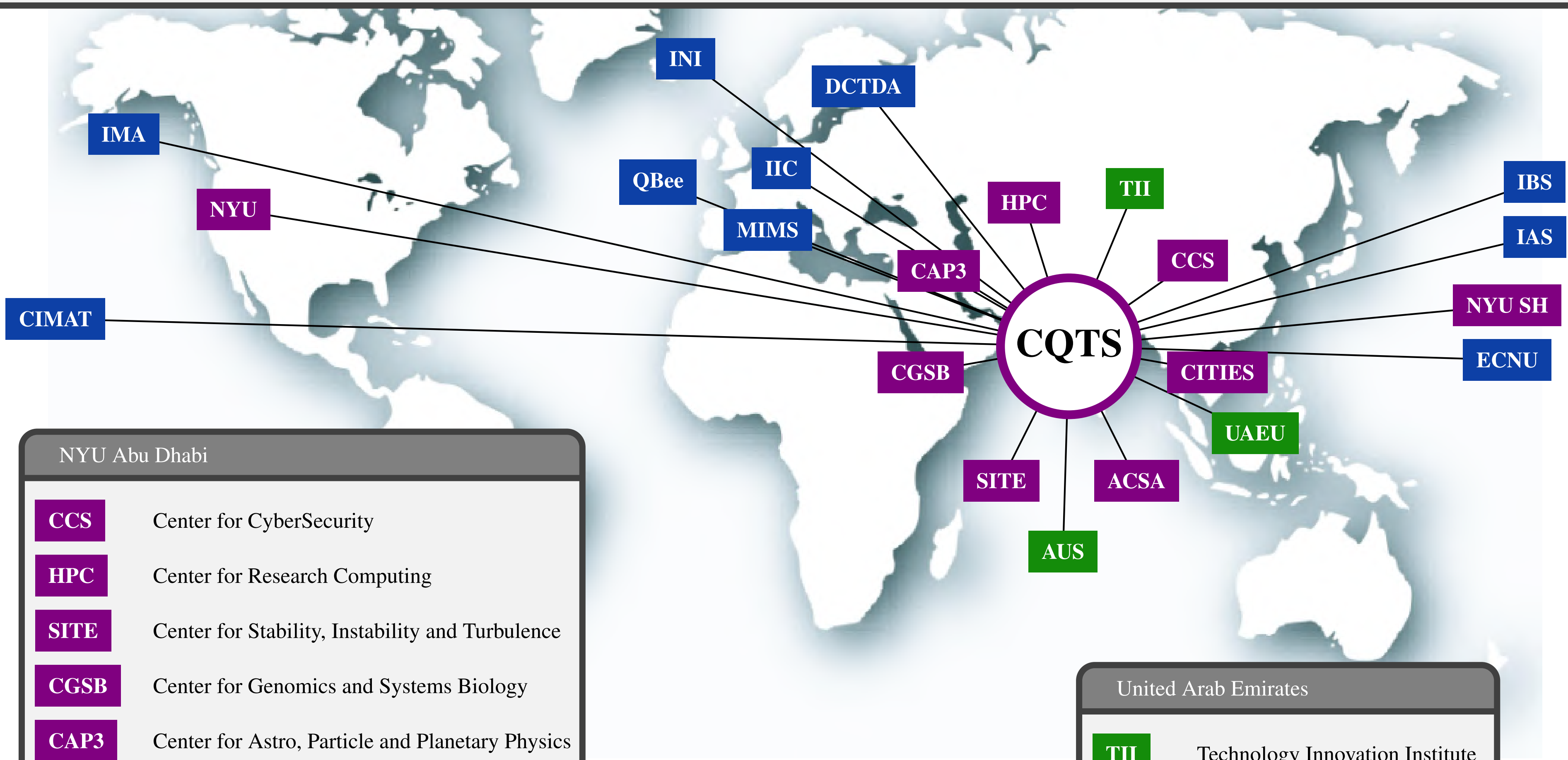
How Abu Dhabi's new quantum computer could help solve the mysteries of science

▶ The emirate is building its own quantum computer, the first in the UAE, in collaboration with Barcelona-based Qilimanjaro Quantum Tech

Collaborations and Partnerships: NYU-global, local, and international

The World

QBee	The Quantum Accelerator Company Porto, Portugal
IIC	Institute for Integrated Circuits University of Linz, Austria
CIMAT	Centro de Investigación en Matemáticas Guanajuato, Mexico
DCTDA	Dioscuri Centre in Topological Data Analysis Polish Academy of Sciences, Warsaw, Poland
INI	Isaac Newton Institute for Math. Sciences Cambridge University, UK
IBS	Institute for Basic Science Dajeon, South Korea
MIMS	Mediterranen Institute for the Mathematical Sciences Tunis, Tunisia
IMA	Institute for Mathematics and its Applications University of Minnesota, USA
CAC	Center for Advanced Computation Korean Institute for Advanced Study, Seoul, S. Korea
SKLPS	State Key Lab. of Prec. Spectroscopy East China Normal University, Shanghai, China



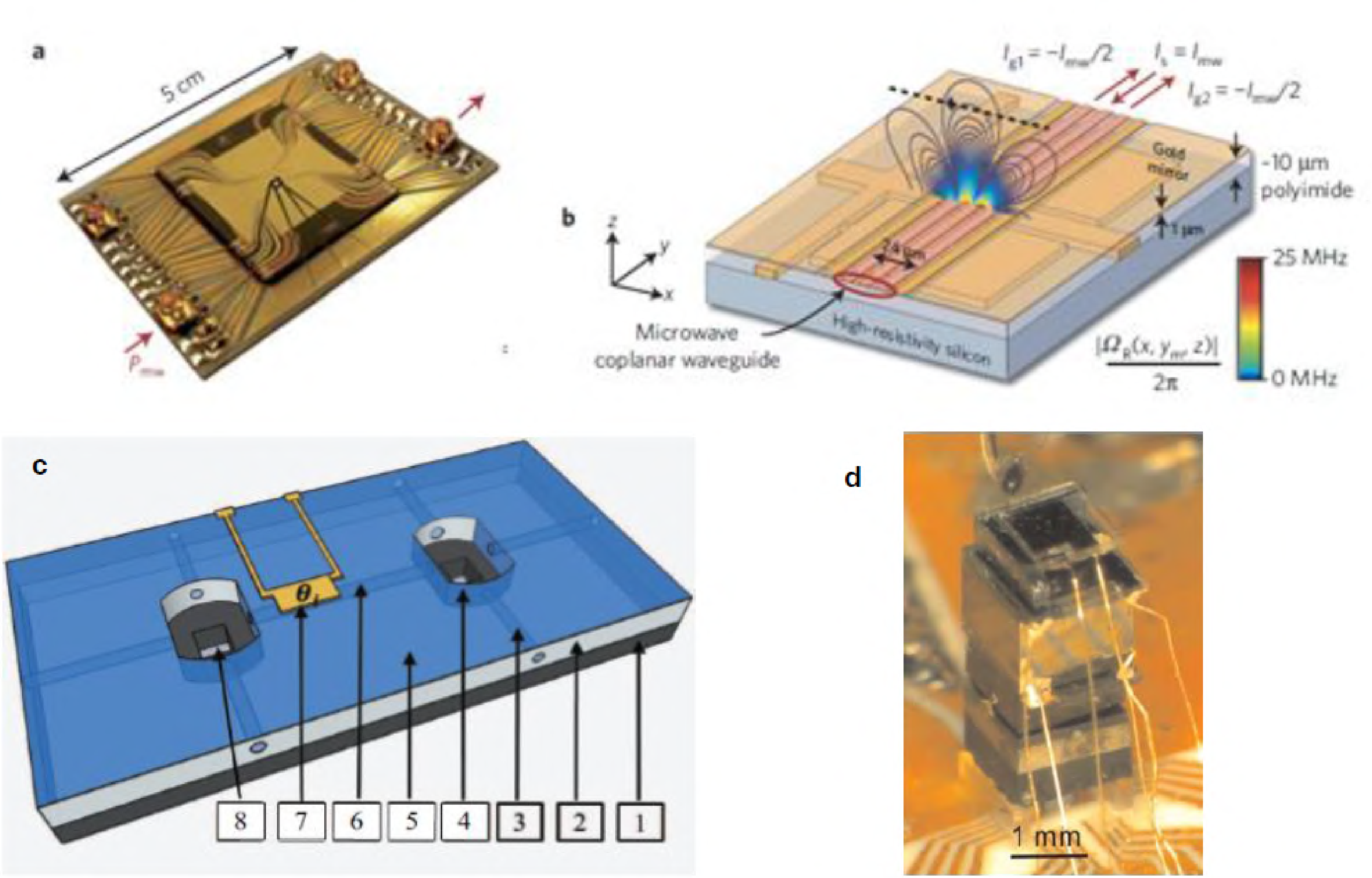
NYU Abu Dhabi

CCS	Center for CyberSecurity
HPC	Center for Research Computing
SITE	Center for Stability, Instability and Turbulence
CGSB	Center for Genomics and Systems Biology
CAP3	Center for Astro, Particle and Planetary Physics
CITIES	Center for Interacting Urban Networks
ACSA	Arab Center for the Study of Art

United Arab Emirates

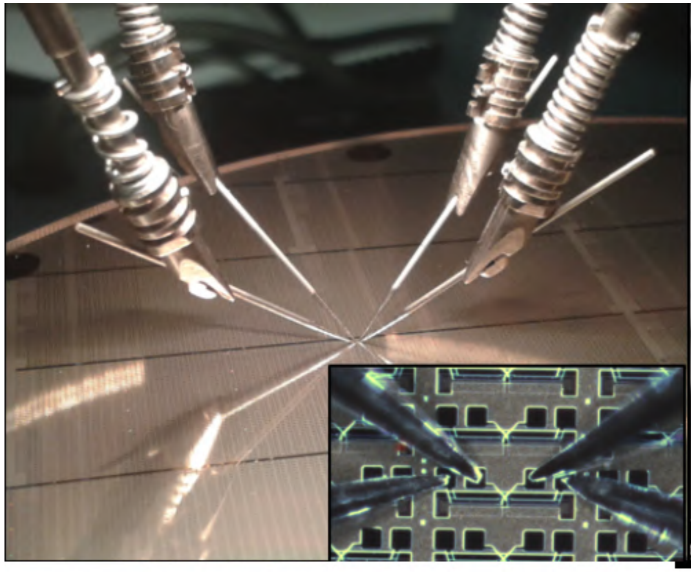
TII	Technology Innovation Institute
AUS	American University Of Sharjah
UAEU	United Arab Emirates University

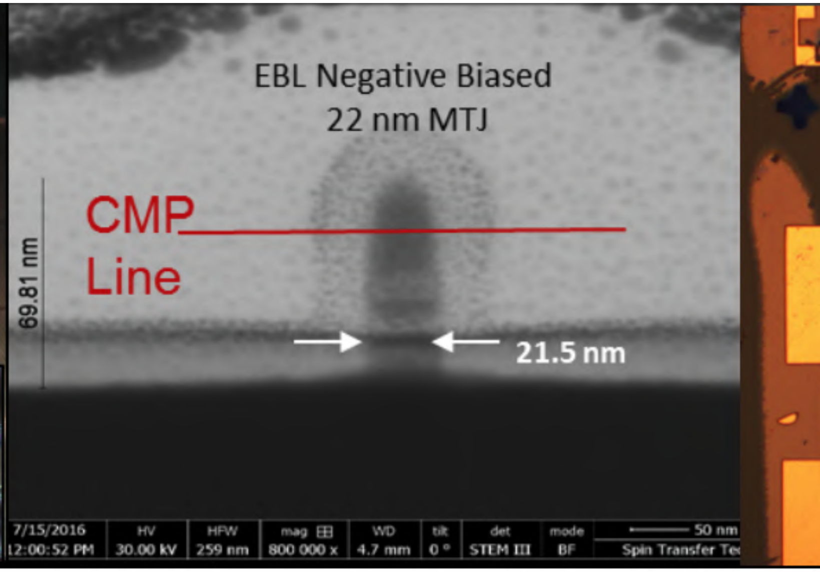
Partnership with **NYU Shanghai**, Quantum Technology Lab

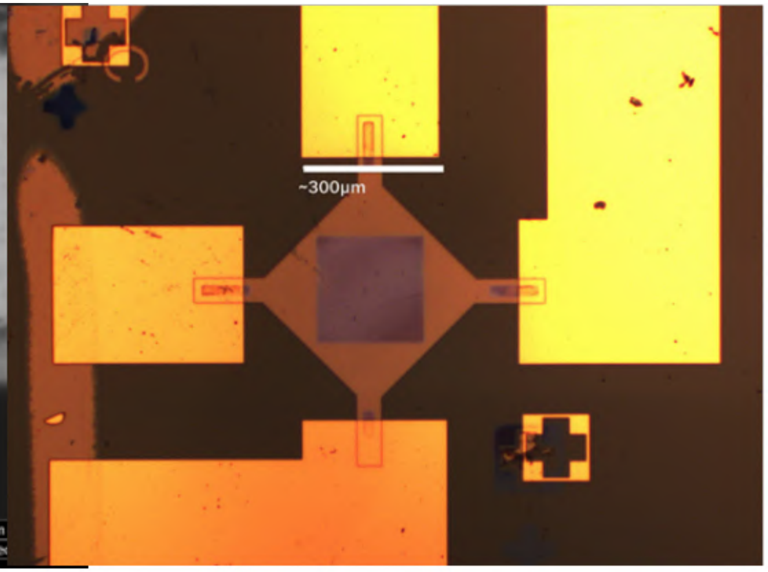


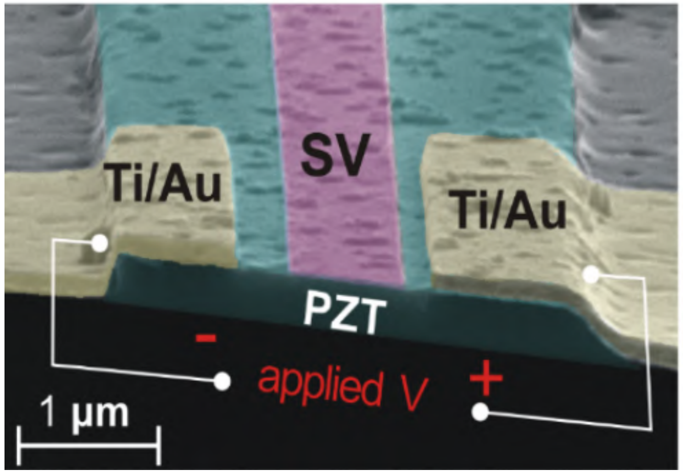
Quantum computing, Quantum information, Bose-Einstein condensates, ...

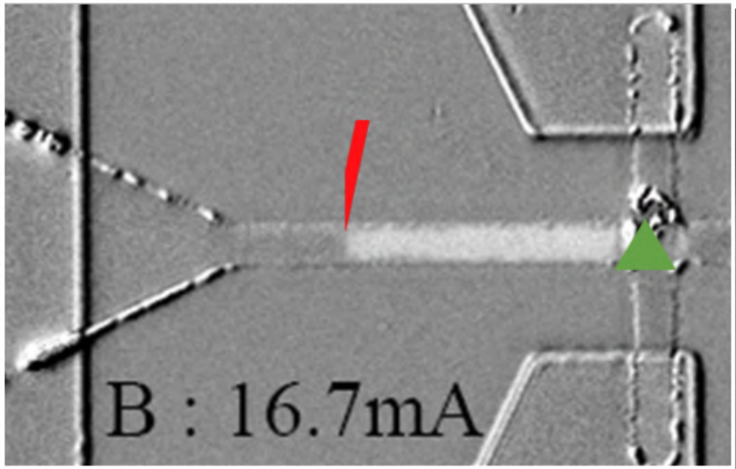
Partnership with **Center for Quantum Phenomena (CQP)**, NYU

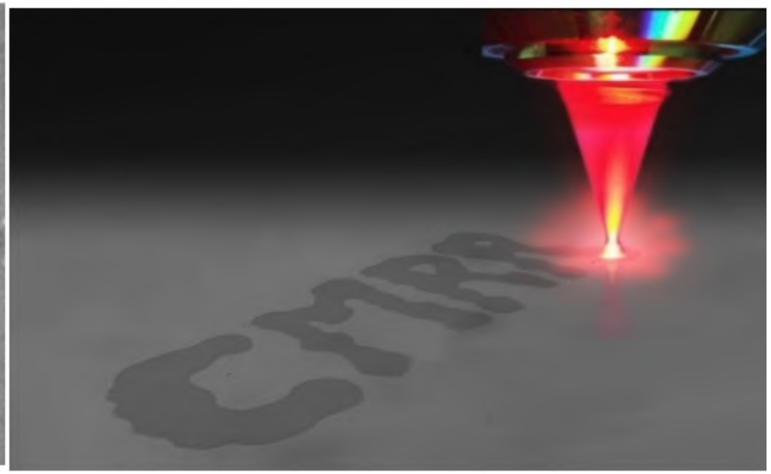












Condensed matter physics, quantum materials,
and quantum information technology, ...

Partnership with the **Technology Innovation Institute (TII)** in Abu Dhabi

Through their **Quantum Research Center (QRC)**,
TII is building the UAE's first NISQ quantum computer.

Quantum Supremacy:

Quantum Computation is expected to be enormously more powerful than Classical Digital Computation (for special but crucial applications).

Quantum Instability:

But Quantum Computation is prone to instability and hence to errors when operated by traditional means.

now for CQTS to bring in Topology

Topological Quantum Computation:

is an ambitious but plausible strategy for retaining supremacy while defeating instability.

Both its math & physics need further development.

Das Sarma, MIT Tech Rev (2022):

"*The quantum-bit systems we have today are a tremendous scientific achievement, but they take us no closer to having a quantum computer that can solve a problem that anybody cares about.*

What is missing is the breakthrough bypassing quantum error correction by using far-more-stable quantum-bits, in an approach called topological quantum computing."

Quantum Supremacy:

Quantum Computation is expected to be enormously more powerful than Classical Digital Computation (for special but crucial applications).

Quantum Instability:

But Quantum Computation is prone to instability and hence to errors when operated by traditional means.

now for CQTS to bring in Topology

Topological Quantum Computation:

is an ambitious but plausible strategy for retaining supremacy while defeating instability.

Both its math & physics need further development.

Das Sarma, MIT Tech Rev (2022):

"The qubit systems we have today are a tremendous scientific achievement, but they take us no closer to having a quantum computer that can solve a problem that anybody cares about.

via *duality* of condensed matter with String Theory

What is missing is the breakthrough bypassing quantum error correction by using far-more-stable quantum-bits, in an approach called topological quantum computing."

It is largely folklore that:

Topological K-theory

fully Twisted & Equivariant & Differential (TED)

classifies

free topological phases
in condensed matter theory

stable D-branes
in string theory

It is largely folklore that:

Topological K-theory

fully Twisted & Equivariant & Differential (TED)

classifies

free topological phases
in condensed matter theory

stable D-branes
in string theory

and *some*
enhancement to

interacting phases

non-perturbative effects

is needed

It is largely folklore that:

Topological K-theory

fully Twisted & Equivariant & Differential (TED)

classifies

free topological phases in condensed matter theory		stable D-branes in string theory
	and *some* enhancement to	
interacting phases		non-perturbative effects
	is needed to account for	
topological order		M-branes

It is largely folklore that:

Topological K-theory

fully Twisted & Equivariant & Differential (TED)

classifies

free topological phases in condensed matter theory		stable D-branes in string theory
	and *some* enhancement to	
interacting phases		non-perturbative effects
	is needed to account for	
topological order		M-branes
	harbouring	
anyon statistics for topological quantum gates		$N \sim 1$ YM theory for hadrodynamics

It is largely folklore that:

had never really been constructed

Topological K-theory

fully Twisted & Equivariant & Differential (TED)

classifies

free topological phases in condensed matter theory		stable D-branes in string theory
	and *some* enhancement to	
interacting phases		non-perturbative effects
	is needed to account for	
topological order		M-branes
	harbouring	
anyon statistics for topological quantum gates		$N \sim 1$ YM theory for hadrodynamics

It is largely folklore that:

Topological K-theory

fully Twisted & Equivariant & Differential (TED)

had never really been constructed

classifies

free topological phases
in condensed matter theory

stable D-branes
in string theory

had remained notoriously elusive

and *some* enhancement to

interacting phases

non-perturbative effects

is needed
to account for

topological order

M-branes

harbouring

anyon statistics
for topological quantum gates

$N \sim 1$ YM theory
for hadrodynamics

It is largely folklore that:

Topological K-theory

fully Twisted & Equivariant & Differential (TED)

had never really been constructed

classifies

free topological phases in condensed matter theory		stable D-branes in string theory
	and *some* enhancement to	
interacting phases		non-perturbative effects
	is needed to account for	
topological order		M-branes
	harbouring	
anyon statistics for topological quantum gates		$N \sim 1$ YM theory for hadrodynamics

had remained notoriously elusive

is actually *practically* **relevant**

We had suggested a solution:

Topological K-theory

fully Twisted & Equivariant & Differential (TED)

had never really been constructed

classifies

free topological phases
in condensed matter theory

stable D-branes
in string theory

had remained notoriously elusive

and *some*
enhancement to

interacting phases

non-perturbative effects

is needed
to account for

topological order

M-branes

harbouring

anyon statistics
for topological quantum gates

$N \sim 1$ YM theory
for hadrodynamics

is actually *practically* **relevant**

We had suggested a solution:

(1) **Systematic construction of TED K-theory via "cohesive ∞-topos theory".**

had never really been constructed

Topological K-theory

fully Twisted & Equivariant & Differential (TED)

classifies

free topological phases in condensed matter theory

stable D-branes in string theory

had remained notoriously elusive

and *some* enhancement to

interacting phases

non-perturbative effects

is needed to account for

topological order

M-branes

harbouring

anyon statistics for topological quantum gates

$N \sim 1$ YM theory for hadrodynamics

is actually *practically* relevant

We had suggested a solution:

(1) Systematic construction of TED K-theory via "cohesive ∞-topos theory".

had never really been constructed

Topological K-theory
fully Twisted & Equivariant & Differential (TED)

classifies

free topological phases in condensed matter theory

stable D-branes in string theory

had remained notoriously elusive

(2) Precise proposal for interacting enhancement via "Hypothesis H"

and *some* enhancement to

interacting phases

non-perturbative effects

is needed to account for

topological order

M-branes

harbouring

anyon statistics for topological quantum gates

$N \sim 1$ YM theory for hadrodynamics

is actually *practically* relevant

We had suggested a solution:

(1) Systematic construction of TED K-theory via "cohesive ∞-topos theory". — *had never really been constructed*

(2) Precise proposal for interacting enhancement via "Hypothesis H" — *had remained notoriously elusive*

(3) Concrete implementation of topological quantum gates via `TED-K` in "cohesive homotopy type theory" — *is actually practically relevant*

Topological K-theory

fully Twisted & Equivariant & Differential (TED)

classifies

free topological phases in condensed matter theory

stable D-branes in string theory

and *some* enhancement to

interacting phases

non-perturbative effects

is needed to account for

topological order

M-branes

anyon statistics for topological quantum gates

$\mathcal{N} \sim 1$ YM theory for hadrodynamics

(1) Systematic construction of TED K-theory via "cohesive ∞-topos theory".

(2) Precise proposal for interacting enhancement via "Hypothesis H"

(3) Concrete implementation of topological quantum gates via `TED-K` in "cohesive homotopy type theory"

(1) Systematic construction of TED K-theory using cohesive ∞-topos theory

(for finite equivariance as befits the “very good” orbifolds appearing in CMT and ST)

[arX:2008.01101][arX:2009.11909][arX:2011.06533][arX:2203.11838][SS22-TEC]

(1) Systematic construction of TED K-theory using cohesive ∞-topos theory

(for finite equivariance as befits the "very good" orbifolds appearing in CMT and ST)

[arX:2008.01101][arX:2009.11909][arX:2011.06533][arX:2203.11838][SS22-TEC]

key technicality:
constructing twisted equivariant Chern character as map of equivariant moduli stacks
(⇒ flat TED K-theory is homotopy fiber of TE Chern character in equivariant stacks)

(1) Systematic construction of TED K-theory using cohesive ∞-topos theory

(for finite equivariance as befits the "very good" orbifolds appearing in CMT and ST)

[arX:2008.01101][arX:2009.11909][arX:2011.06533][arX:2203.11838][SS22-TEC]

key technicality:
constructing twisted equivariant Chern character as map of equivariant moduli stacks
(⇒ flat TED K-theory is homotopy fiber of TE Chern character in equivariant stacks)

this is subtle and previously under-developed, because
equivariant classifying spaces are generally far from simply-connected/nilpotent

(1) Systematic construction of TED K-theory using cohesive ∞-topos theory

(for finite equivariance as befits the "very good" orbifolds appearing in CMT and ST)

[arX:2008.01101][arX:2009.11909][arX:2011.06533][arX:2203.11838][SS22-TEC]

key technicality:
constructing twisted equivariant Chern character as map of equivariant moduli stacks
($\Rightarrow$ flat TED K-theory is homotopy fiber of TE Chern character in equivariant stacks)

this is subtle and previously under-developed, because
equivariant classifying spaces are generally far from simply-connected/nilpotent

But the Galois-theoretic effect hidden in this technicality is responsible for the appearance of conformal blocks and braid group statistics in TED-K (more below)

(1) Systematic construction of TED K-theory using cohesive ∞-topos theory

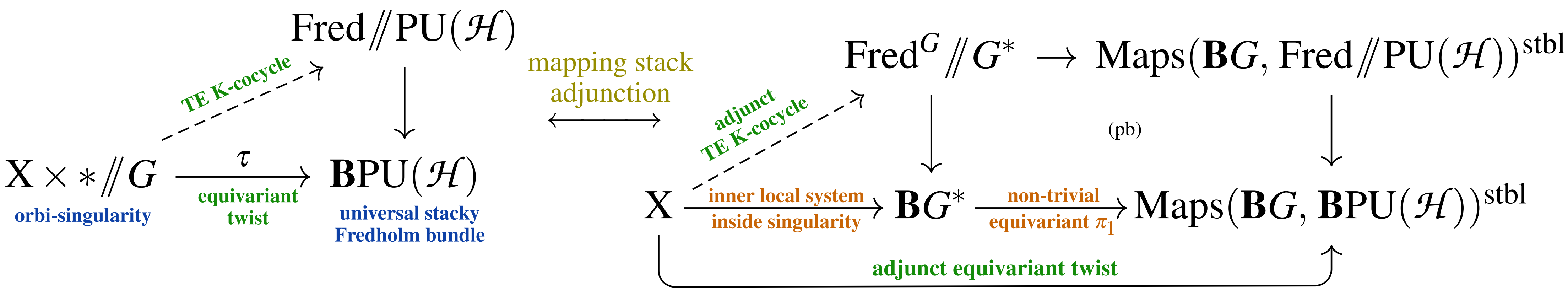
(for finite equivariance as befits the "very good" orbifolds appearing in CMT and ST)

[arX:2008.01101][arX:2009.11909][arX:2011.06533][arX:2203.11838][SS22-TEC]

key technicality:
constructing twisted equivariant Chern character as map of equivariant moduli stacks
($\Rightarrow$ flat TED K-theory is homotopy fiber of TE Chern character in equivariant stacks)

this is subtle and previously under-developed, because
equivariant classifying spaces are generally far from simply-connected/nilpotent

But the Galois-theoretic effect hidden in this technicality is responsible for the appearance of conformal blocks and braid group statistics in TED-K (more below)



(2) Precise proposal for interacting enhancement via “Hypothesis H” [JMP **59** (’18)]

(2) **Precise proposal for interacting enhancement** via "Hypothesis H" [JMP **59** ('18)]

Evaluate TED K-cohomology not on Brillouin torus/spacetime-orbifold itself,
but on its configuration space of points, and generally: on its Cohomotopy moduli

[CMP **377** (2020)] [JMP **62** (2021)] [ATMP **26** 4 (2022)] [RMP **34** 5 (2022)] [arX:2103.01877]

(see below)

(2) Precise proposal for interacting enhancement via "Hypothesis H" [JMP **59** ('18)]

Evaluate TED K-cohomology not on Brillouin torus/spacetime-orbifold itself, but on its configuration space of points, and generally: on its Cohomotopy moduli

[CMP **377** (2020)] [JMP **62** (2021)] [ATMP **26** 4 (2022)] [RMP **34** 5 (2022)] [arX:2103.01877]

(see below)

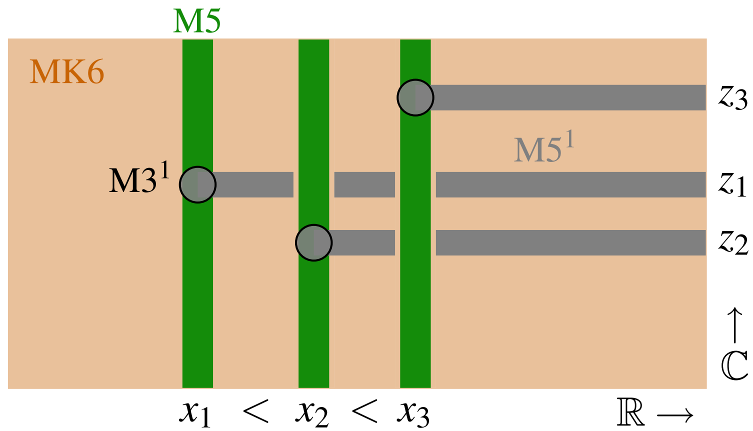
Configuration space of ordered points in the plane

3-Cohomotopy cocycle space for codim=1 branes: $\mathrm{Map}^*(\mathbb{R}_+ \wedge \mathbb{C}_{\mathrm{cpt}}, S^3) \simeq \bigcup_n \mathrm{Conf}_n(\mathbb{C}; \mathbb{R}_{\mathrm{cpt}})$

3-Cohomotopy cocycle space for codim-2 branes: $\mathrm{Map}^*(\mathbb{R}_{\mathrm{cpt}} \wedge \mathbb{C}_+, S^3) \simeq \bigcup_n \mathrm{Conf}_n(\mathbb{R}; \mathbb{C}_{\mathrm{cpt}})$

$$\coprod_n \underset{\{1,\cdots,n\}}{\mathrm{Conf}}(\mathbb{C}) \simeq \bigcup_n \mathrm{Conf}_n(\mathbb{C}; \mathbb{R}_{\mathrm{cpt}}) \underset{\bigcup_n \mathrm{Conf}_n(\ast; (\mathbb{R}\times\mathbb{C})_{\mathrm{cpt}})}{\times} \bigcup_n \mathrm{Conf}_n(\mathbb{R}; \mathbb{C}_{\mathrm{cpt}})$$

Fiber product of respective configuration spaces (of un-ordered points escaping to transverse infinity) reflecting the brane intersections

e.g.: $\underset{\{1,\cdots,3\}}{\mathrm{Conf}}(\mathbb{C}) \simeq \left\{ \right.$  $\left. \right\}$

The moduli space of flat M3-branes according to *Hypothesis H* is the configuration space of ordered points in their transverse plane.

(2) Precise proposal for interacting enhancement via "Hypothesis H" [JMP **59** ('18)]

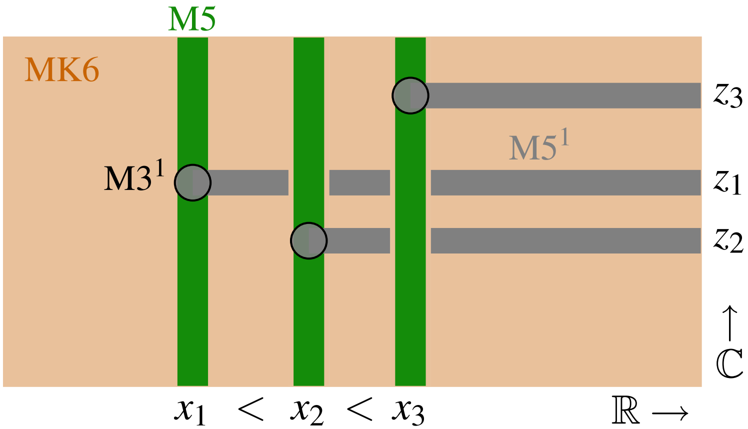
Evaluate TED K-cohomology not on Brillouin torus/spacetime-orbifold itself, but on its configuration space of points, and generally: on its Cohomotopy moduli

[CMP **377** (2020)] [JMP **62** (2021)] [ATMP **26** 4 (2022)] [RMP **34** 5 (2022)] [arX:2103.01877]

(see below)

$$
\underbrace{\coprod_n \underset{\{1,\cdots,n\}}{\mathrm{Conf}}(\mathbb{C})}_{\text{Configuration space of ordered points in the plane}}
\;\simeq\;
\overbrace{\bigcup_n \mathrm{Conf}_n\big(\mathbb{C};\, \mathbb{R}_{\mathrm{cpt}}\big)}^{\substack{\text{3-Cohomotopy cocycle space for codim=1 branes}\\ \mathrm{Map}^*(\mathbb{R}_+ \wedge \mathbb{C}_{\mathrm{cpt}},\, S^3)\,\simeq}}
\underset{\bigcup_n \mathrm{Conf}_n\big(*;\, (\mathbb{R}\times\mathbb{C})_{\mathrm{cpt}}\big)}{\times}
\overbrace{\bigcup_n \mathrm{Conf}_n\big(\mathbb{R};\, \mathbb{C}_{\mathrm{cpt}}\big)}^{\substack{\text{3-Cohomotopy cocycle space for codim-2 branes}\\ \mathrm{Map}^*(\mathbb{R}_{\mathrm{cpt}} \wedge \mathbb{C}_+,\, S^3)\,\simeq}}
$$

Fiber product of respective configuration spaces (of un-ordered points escaping to transverse infinity) reflecting the brane intersections

e.g.: $\underset{\{1,\cdots,3\}}{\mathrm{Conf}}(\mathbb{C}) \simeq \left\{ \right.$  $\left. \right\}$

The moduli space of flat M3-branes according to *Hypothesis H* is the configuration space of ordered points in their transverse plane.

Claim: The TED K-cohomology of n-point configurations in Brillouin torus classifies valence bundle of n-electron interacting states [arX:2206.13563]

(3) Concrete implementation of topological quantum gates via TED-K in cohesive homotopy type theory:

[PlanQC **2022** 33]
[arX:2206.13563]

(3) Concrete implementation of topological quantum gates
via TED-K in cohesive homotopy type theory:

[PlanQC **2022** 33]
[arX:2206.13563]

Claim: The TED K-theoretic Chern characters of configuration spaces of points contain the $\mathfrak{su}(2)$-affine conformal blocks at admissible fractional levels & genus=0

(see below)

(3) Concrete implementation of topological quantum gates

via TED-K in cohesive homotopy type theory:

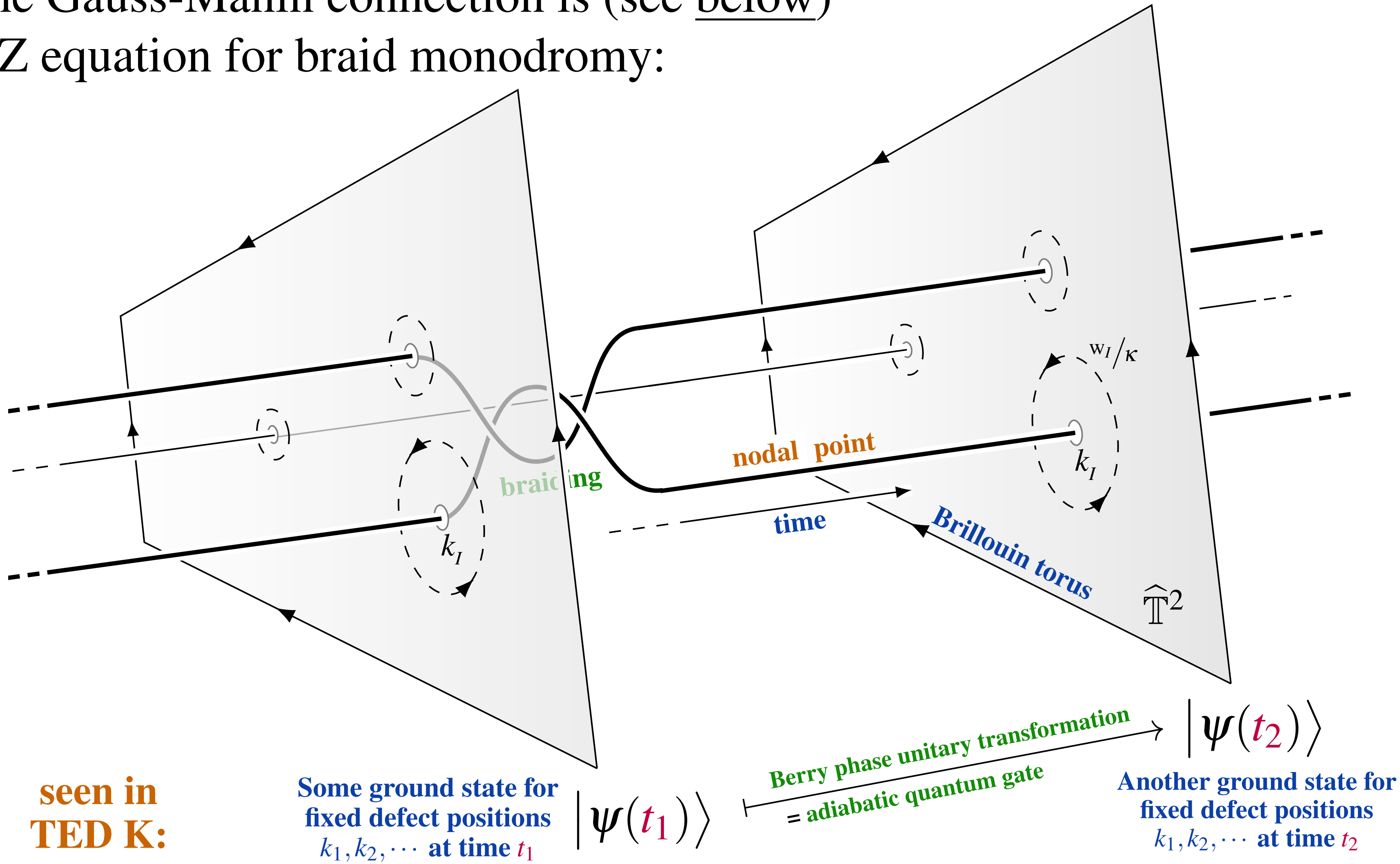
[PlanQC **2022** 33]
[arX:2206.13563]

Claim: The TED K-theoretic Chern characters of configuration spaces of points contain the $\mathfrak{su}(2)$-affine conformal blocks at admissible fractional levels & genus=0 and the Gauss-Manin connection is (see below) the KZ equation for braid monodromy:

(3) Concrete implementation of topological quantum gates
via TED-K in cohesive homotopy type theory:

[PlanQC **2022** 33]
[arX:2206.13563]

Claim: The TED K-theoretic Chern characters of configuration spaces of points contain the $\mathfrak{su}(2)$-affine conformal blocks at admissible fractional levels & genus=0 and the Gauss-Manin connection is (see below)
the KZ equation for braid monodromy:



(3) Concrete implementation of topological quantum gates [PlanQC **2022** 33]
via `TED-K` in cohesive homotopy type theory: [arX:2206.13563]

Remarkably, for such constructions in cohesive ∞-topos theory [EPTCS **158** (2014)]
there is developed a programming language: "cohesive HoTT" [arX:1402.7041]

Knots for Quantum Computation from Defect branes

Urs Schreiber on joint work with Hisham Sati

جامعـة نيويورك أبـوظبي
NYU | ABU DHABI

NYU AD Science Division, Program of Mathematics
& Center for Quantum and Topological Systems
New York University, Abu Dhabi

Center for Quantum & Topological Systems

Thanks!

talk at:

Topological Methods in Mathematical Physics @ Erice, 2 Sep 2022

slides and pointers at: https://ncatlab.org/schreiber/show/Knots+for+Quantum+Computation