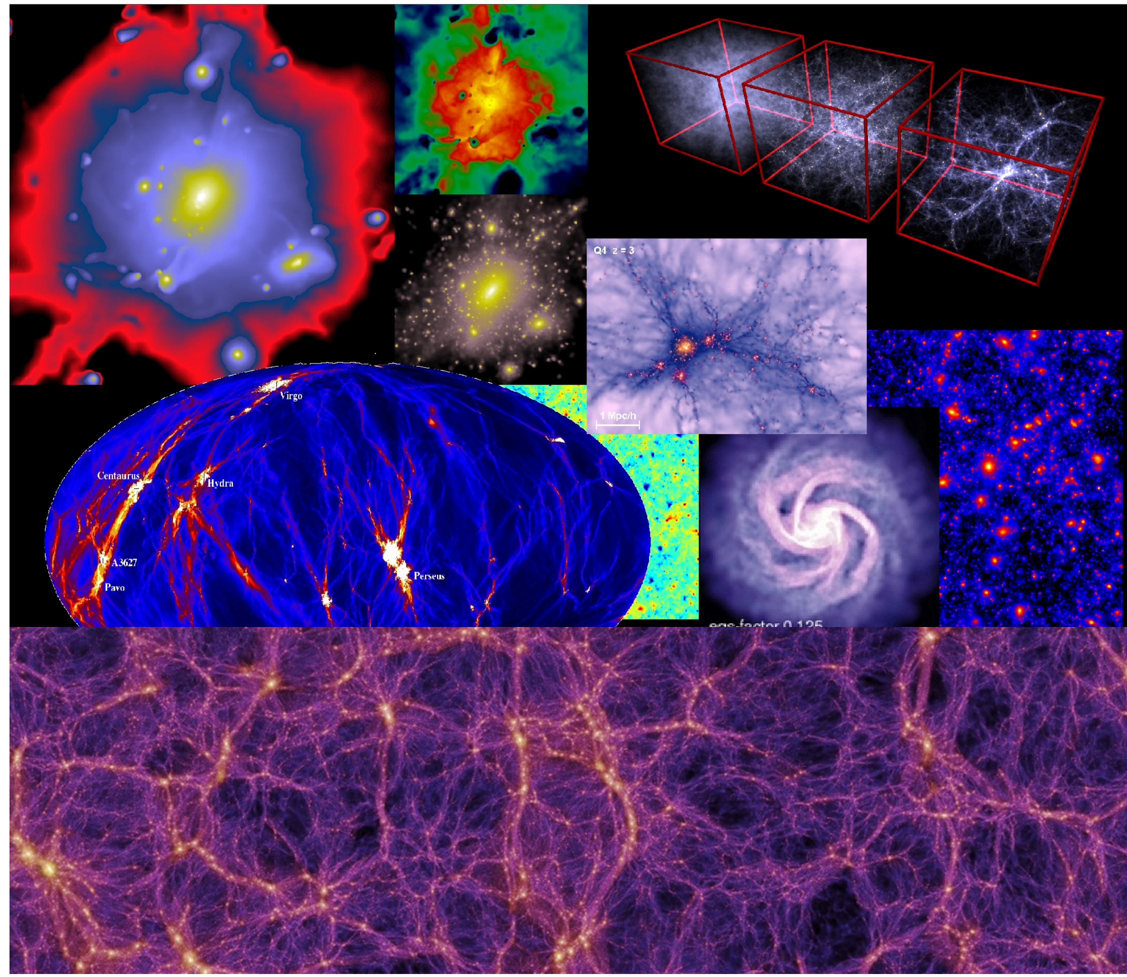
Simulations of Cosmic Structure Formation

Volker Springel

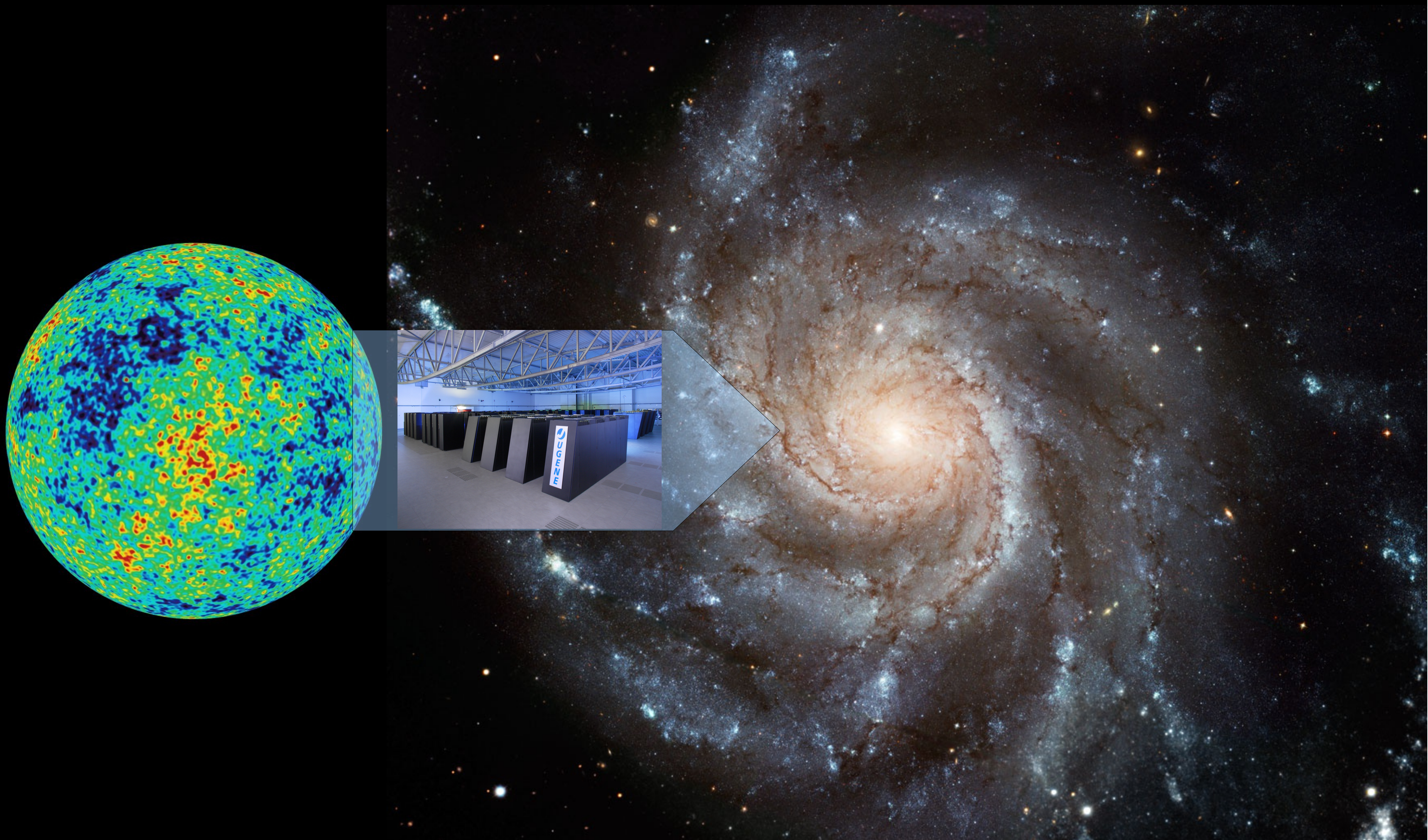


- The role of simulations in cosmology
- High-resolution N-body simulations
- Millennium XXL
- Hydrodynamic simulations and recent results for galaxy formation

Heidelberg Institute for Theoretical Studies
HITS
Universität Heidelberg

USP Cosmology Conference
Sao Paulo, February 2013

Cosmological simulations aim to bridge 13.6 billion years of evolution



Structure formation in the dark matter reduces to an N-body system

BASIC EQUATIONS AND THEIR DISCRETIZATION

Gravitation
General theory of relativity
(Newtonian approximation in an expanding space-time)

Friedmann-Lemaitre model

$$H(a) = H_0 \sqrt{a^{-3}\Omega_0 + a^{-2}(1-\Omega_0-\Omega_\Lambda) + \Omega_\Lambda}$$

Dark matter is collisionless

Collisionless Boltzmann equation with self-gravity

$$\frac{\mathrm{d}f}{\mathrm{d}t} \equiv \frac{\partial f}{\partial t} + \mathbf{v}\frac{\partial f}{\partial \mathbf{x}} - \frac{\partial \Phi}{\partial \mathbf{r}}\frac{\partial f}{\partial \mathbf{v}} = 0$$

$$\nabla^2\Phi(\mathbf{r},t) = 4\pi G \int f(\mathbf{r},\mathbf{v},t)\mathrm{d}\mathbf{v}$$

↓

Monte-Carlo integration as **N-body System**

Hamiltonian dynamics in expanding space-time

$$H = \sum_i \frac{\boldsymbol{p}_i^2}{2\,m_i\,a(t)^2} + \frac{1}{2}\sum_{ij}\frac{m_i m_j\,\varphi(\boldsymbol{x}_i - \boldsymbol{x}_j)}{a(t)}$$

$$\nabla^2\varphi(\boldsymbol{x}) = 4\pi G\left[-\frac{1}{L^3} + \sum_{\boldsymbol{n}}\tilde{\delta}(\boldsymbol{x}-\boldsymbol{n}L)\right]$$

↓

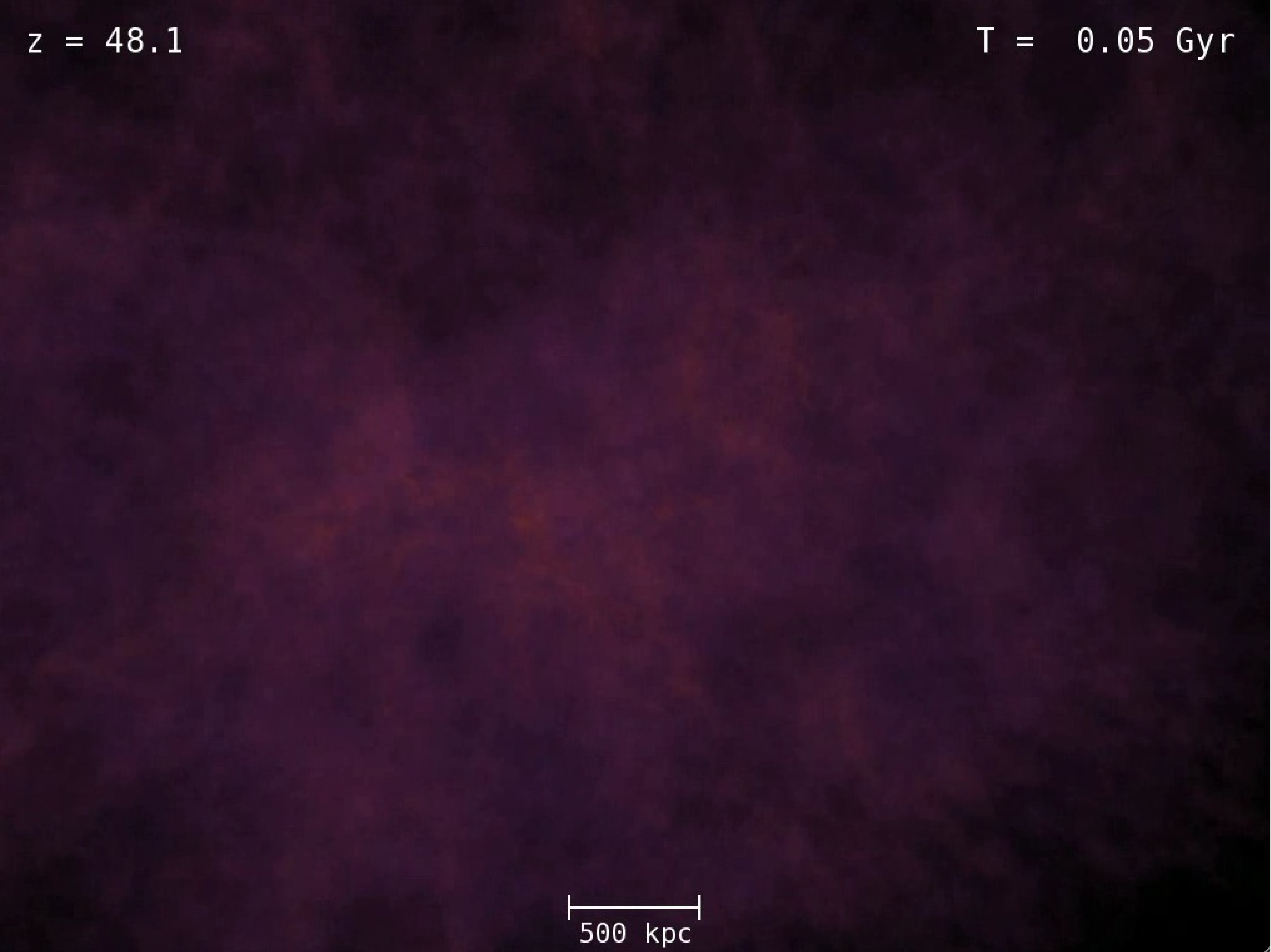
3N **coupled**, non-linear differential equations of second order

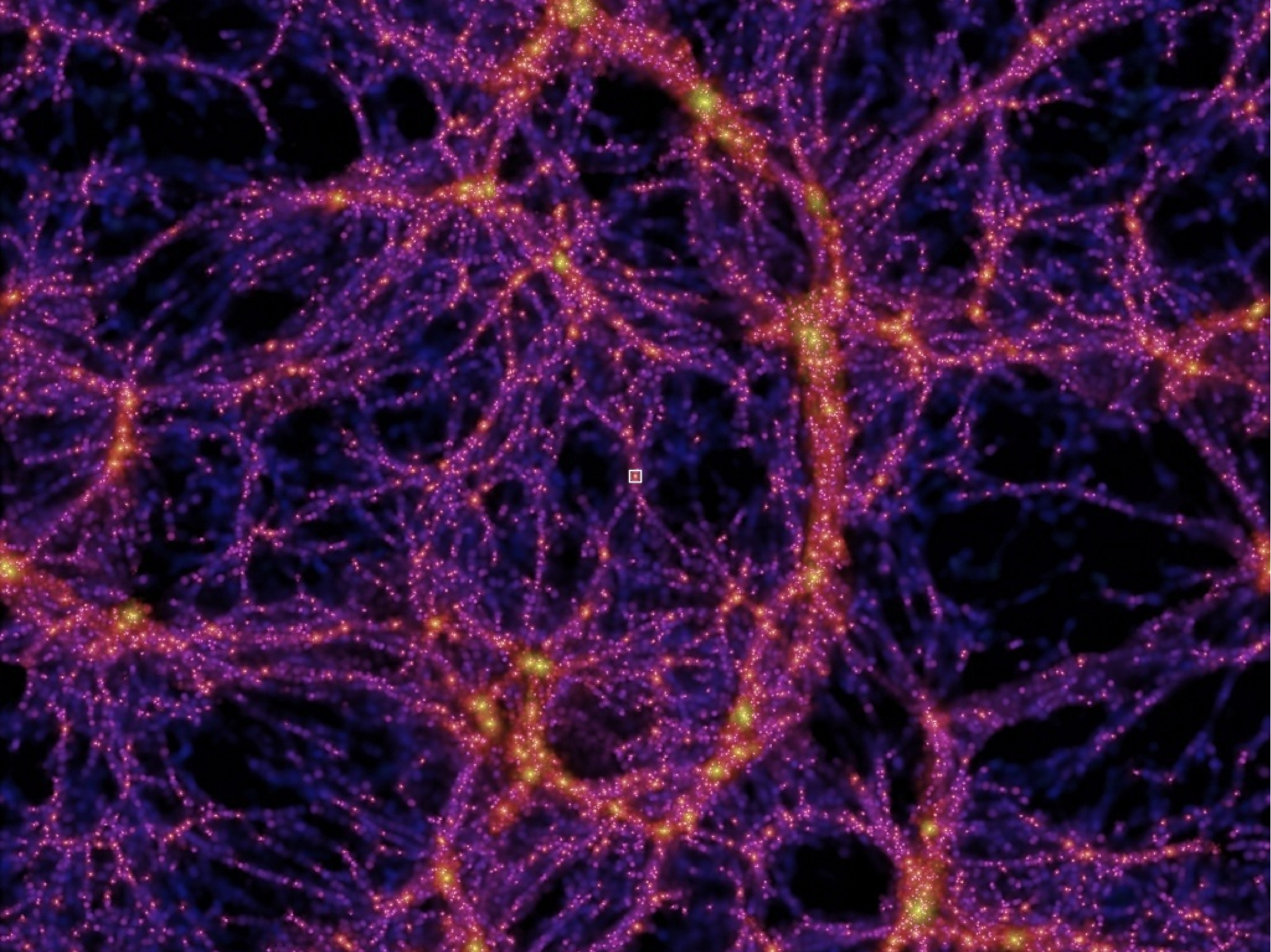
→

Problems:
N ist very large
All equations are coupled with each other

Currently the fastest supercomputers carry out about ~1 Petaflop, which are one million billion floating point operations per second

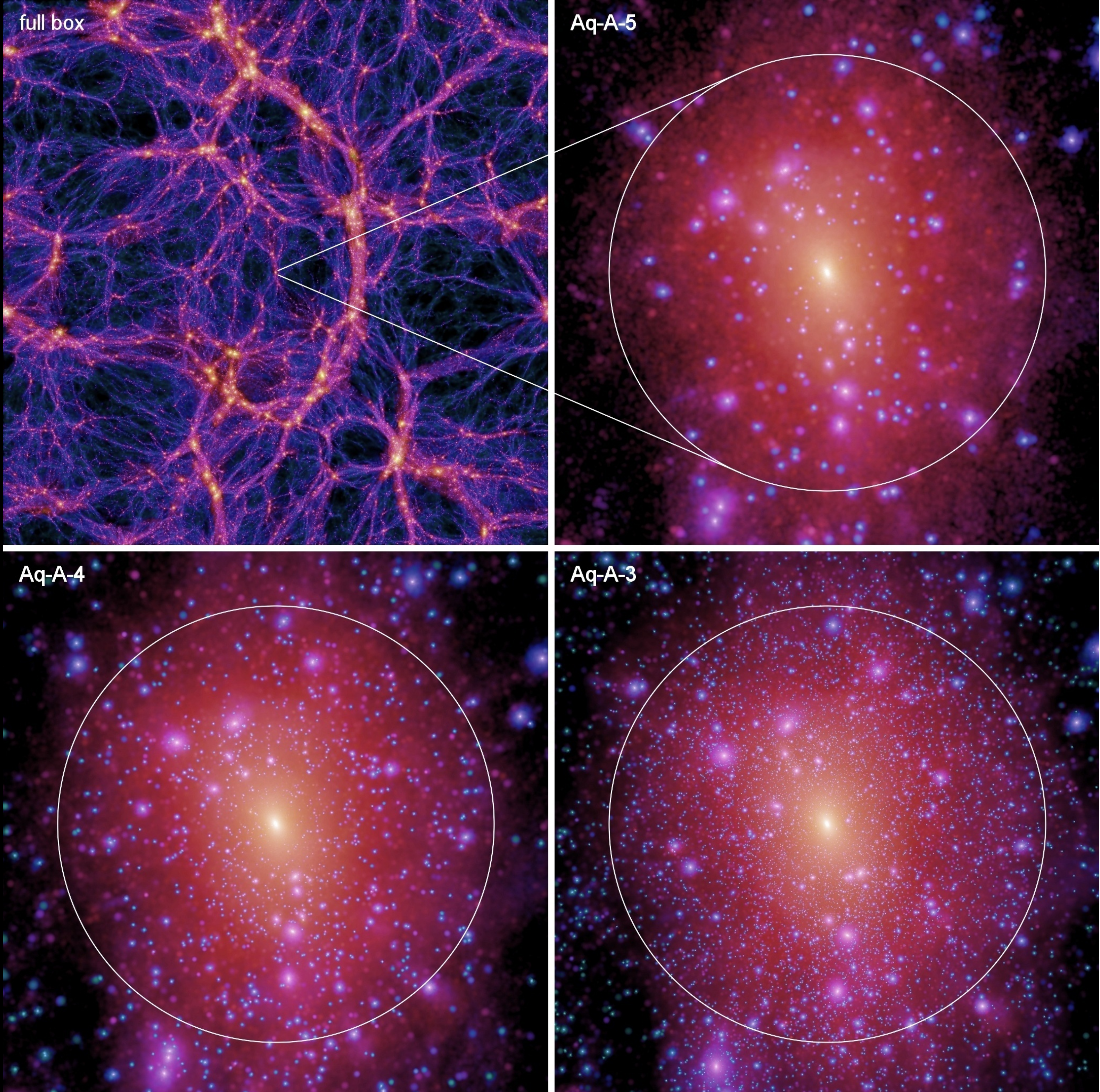
JUGENE IN JUELICH

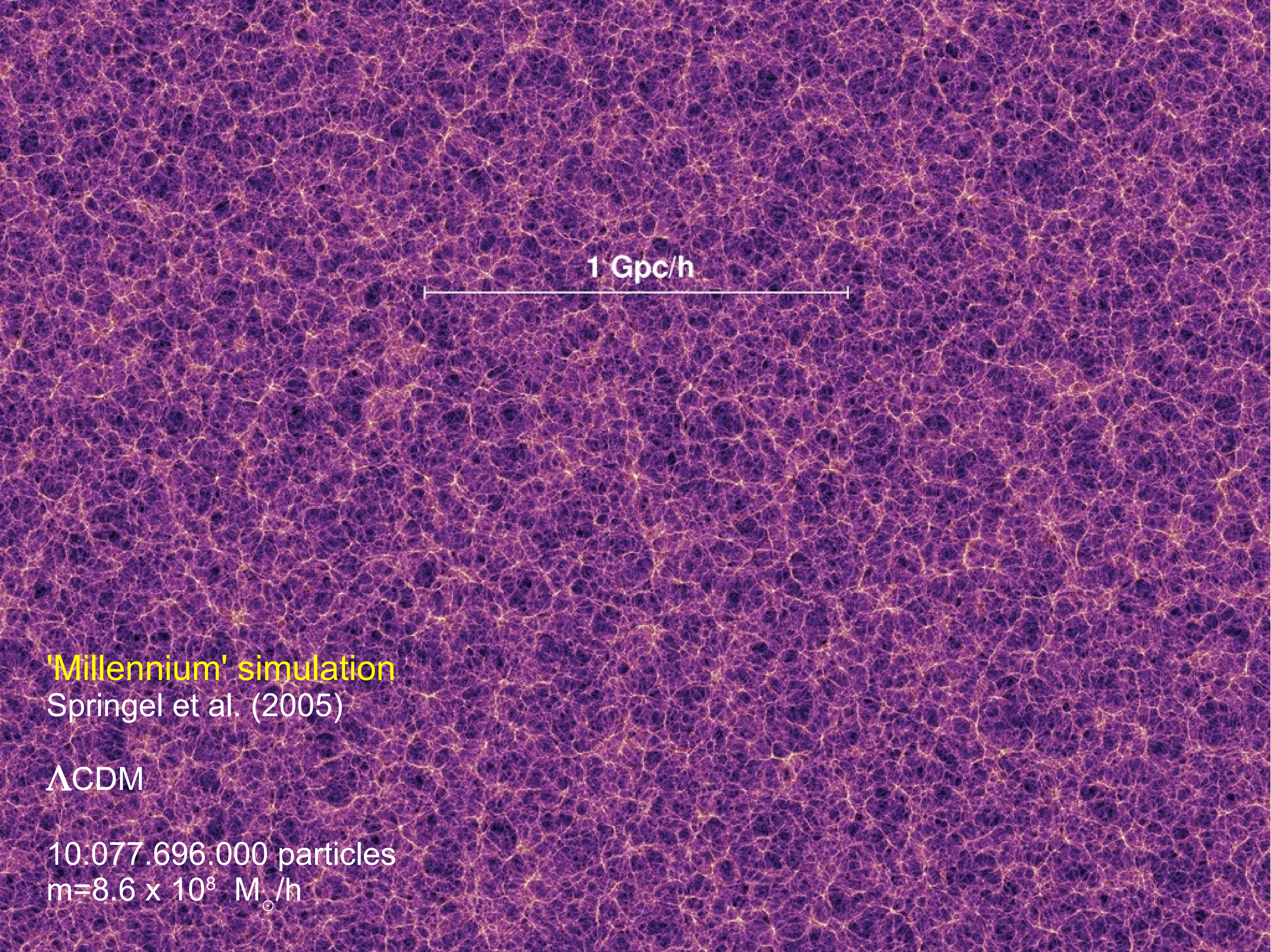

z = 48.1
T = 0.05 Gyr
500 kpc



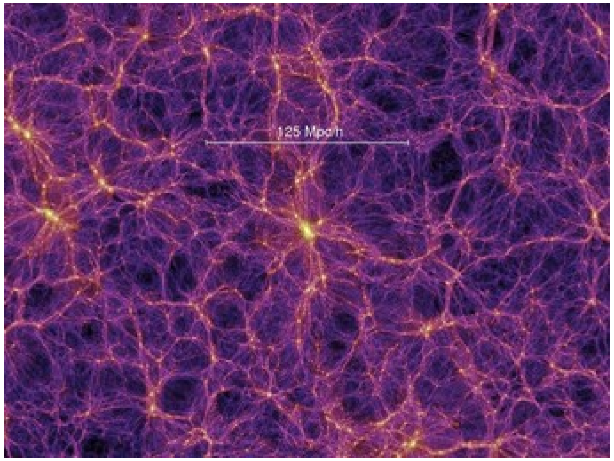
Zooming in on dark matter halos reveals a huge abundance of dark matter substructure

DARK MATTER DISTRIBUTION IN A MILKY WAY SIZED HALO AT DIFFERENT RESOLUTION




1 Gpc/h
'Millennium' simulation
Springel et al. (2005)
ΛCDM
10.077.696.000 particles
m=8.6 x 10^8 M☉/h

Why are **cosmological simulations** of structure formation **useful for studying the dark universe**?



Simulations are the theoretical tool of choice for calculations in the non-linear regime.

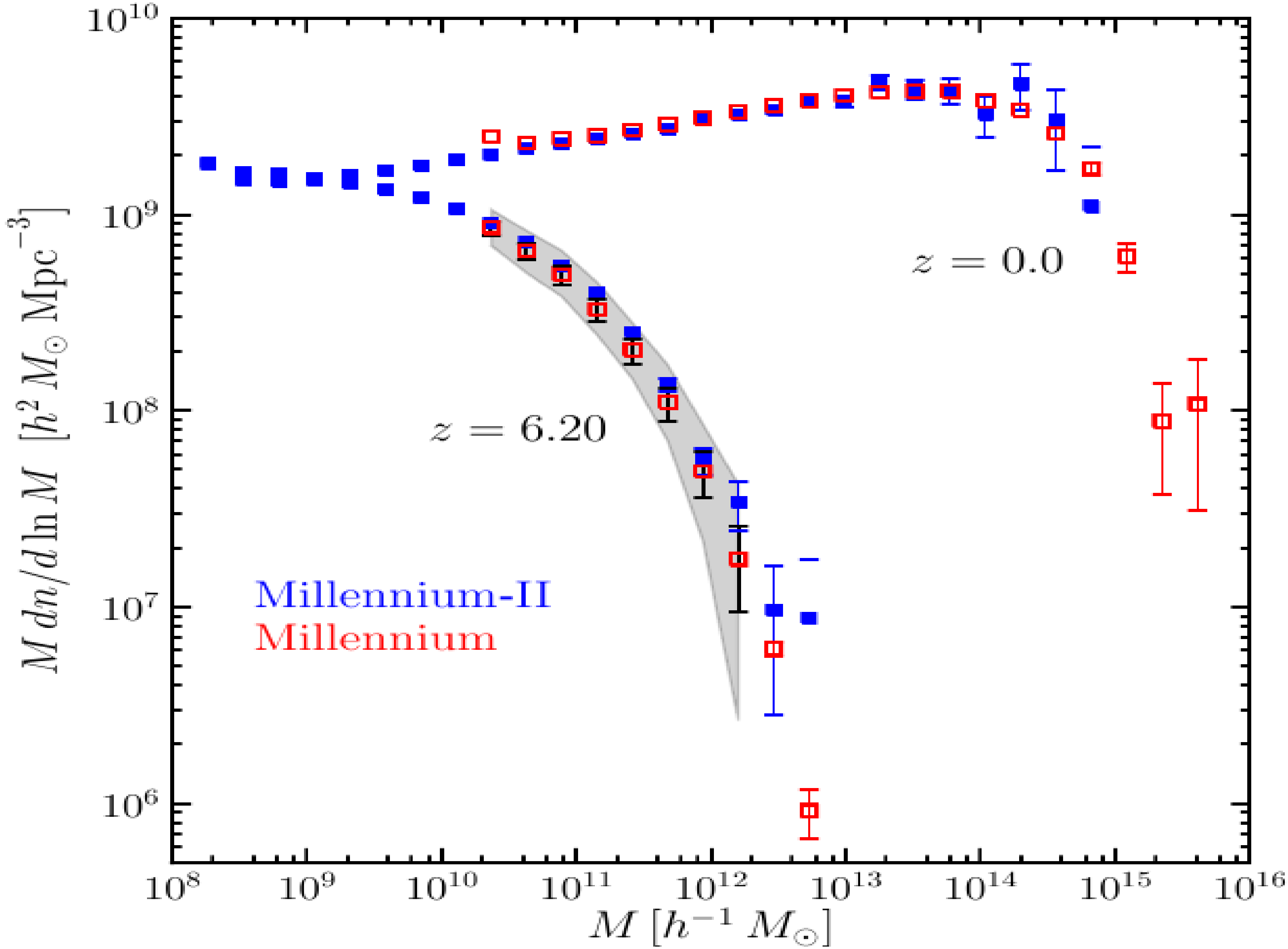
They connect the (simple) cosmological initial conditions with the (complex) present-day universe.

Predictions from N-body simulations:

- Abundance of objects (as a function of mass and time)
- Their spatial distribution
- Internal structure of halos (e.g. density profiles, spin)
- Mean formation epochs
- Merger rates
- Detailed dark matter distribution on large *and* fairly small scales
- Galaxy formation models
- Gravitational lensing
- Baryonic acoustic oscillations in the matter distribution
- Integrated Sachs-Wolfe effect
- Dark matter annihilation rate
- Morphology of large-scale structure (“cosmic web”)
- ....

Simulations provide accurate measurements for halo abundance as a function of time

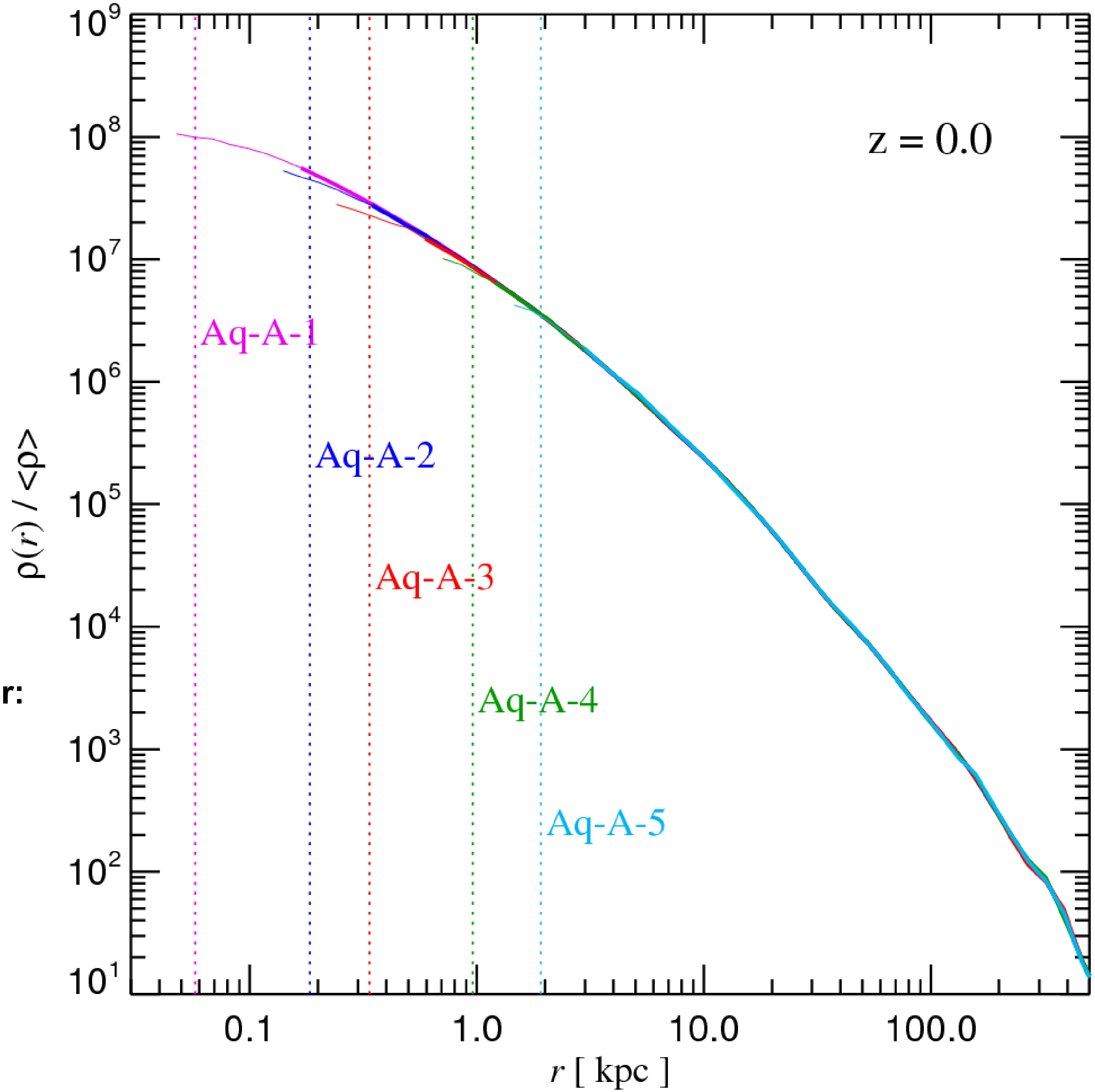
CONVERGENCE RESULTS FOR HALO ABUNDANCE



Boylan-Kolchin, Springel, White, et al. (2009)

Spherically averaged density profiles of dark matter halos have a nearly universal shape

DENSITY PROFILE AS A FUNCTION OF RADIUS

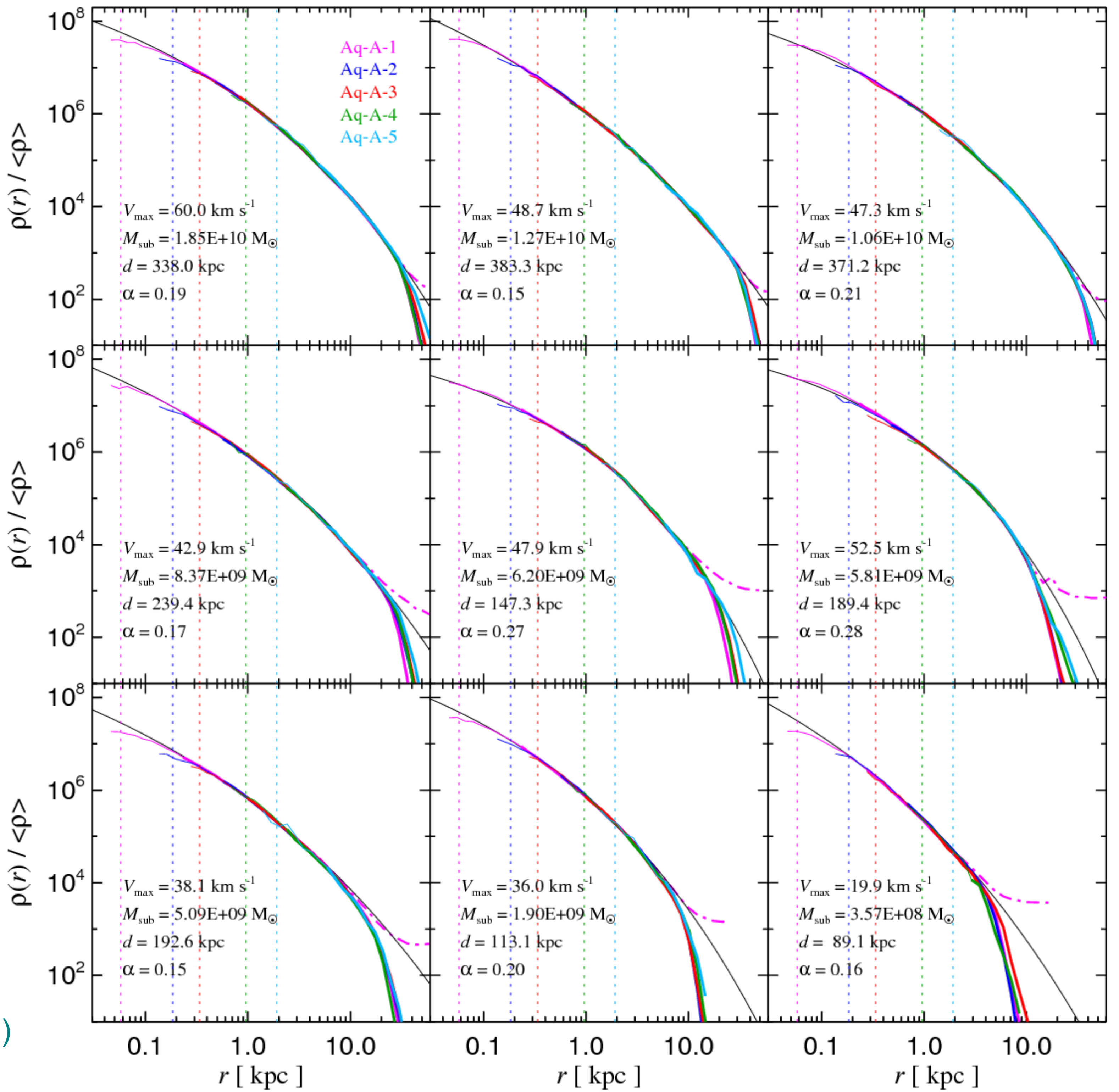


Fundamental importance for:

- Rotation curve of galaxies
- Internal structure of galaxy clusters
- Gravitational lensing
- DM annihilation
- Galaxy mergers

Simulations allow us to study the convergence of **subhalo density profiles**

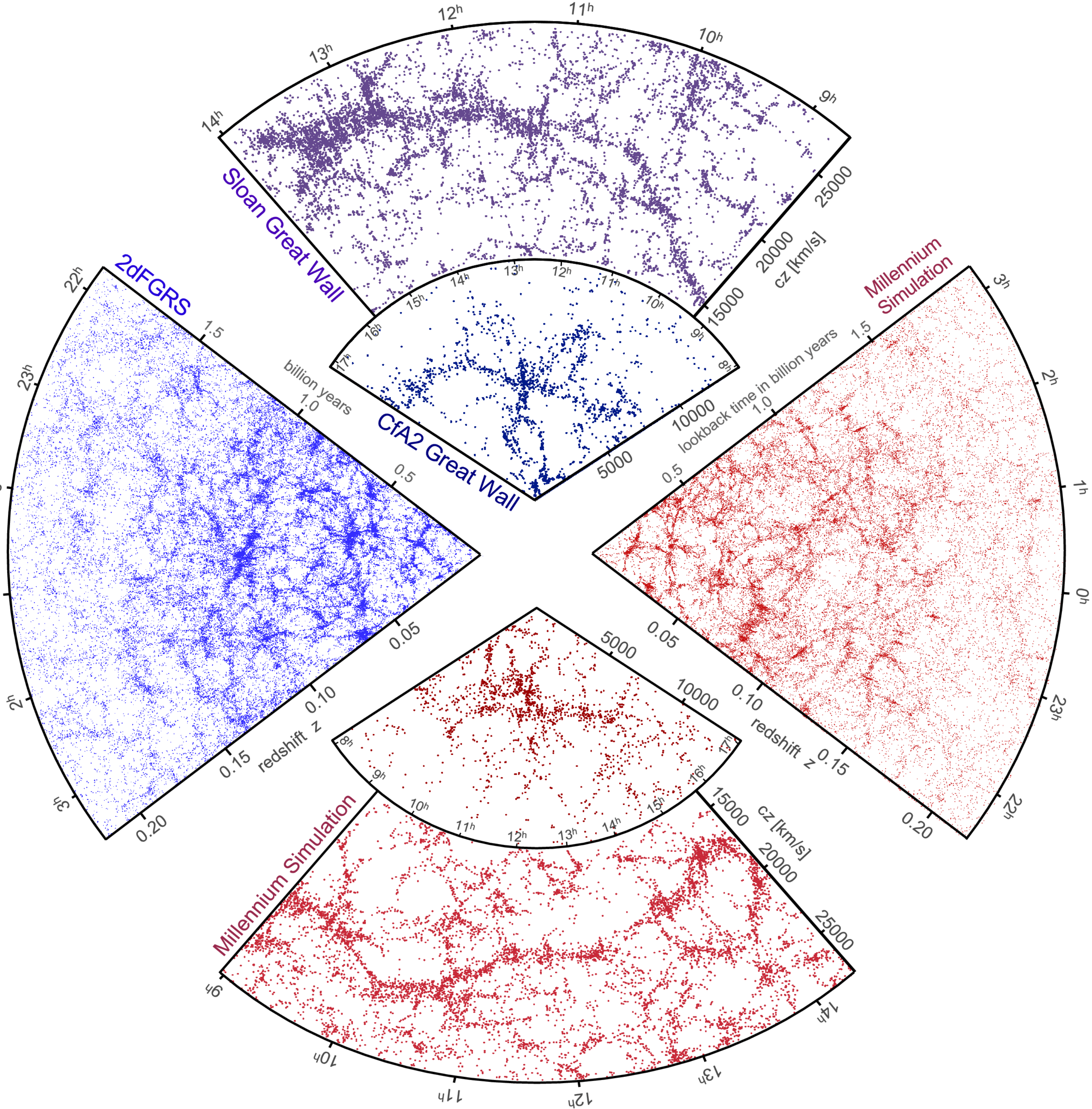
SPHERICALLY AVERAGED DENSITY PROFILES IN THE AQ-A HALO AT DIFFERENT RESOLUTION



Springel et al. (2008)

Simulated and observed large-scale structure in the galaxy distribution

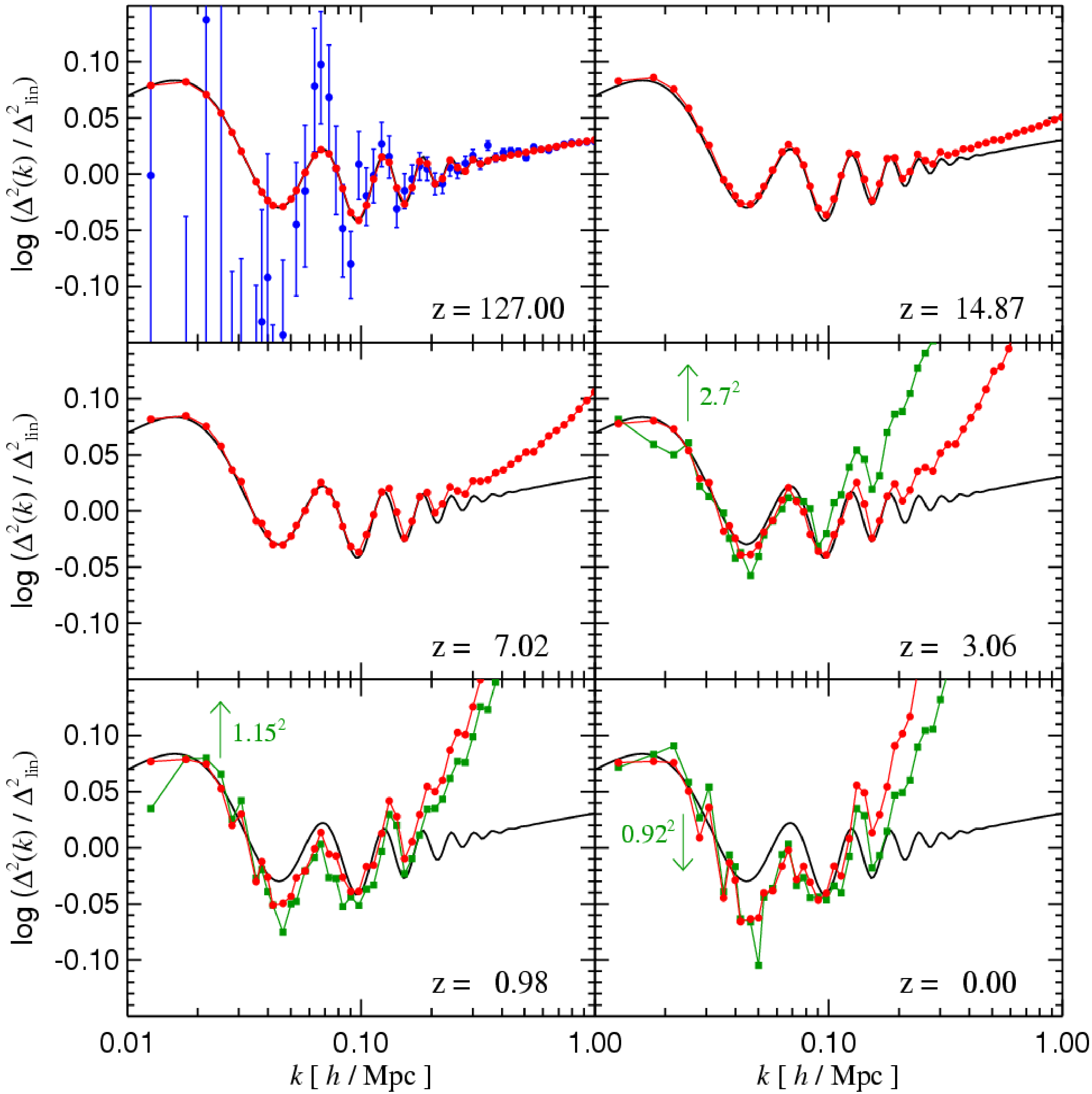
MOCK PIE DIAGRAMS COMPARED TO SDSS, 2DFGRS, AND CFA-2



Springel et al. (2006)

The baryonic wiggles remain visible in the galaxy distribution down to low redshift and may serve as a "standard ruler" to constrain dark energy

DARK MATTER AND GALAXY POWER SPECTRA FROM THE MILLENNIUM SIMULATION IN THE REGION OF THE WIGGLES



Springel et al. (2005)

Millennium-XXL

Largest
high-resolution
N-body simulation

303 billion particles

L = 3 Gpc/h

~700 million halos
at z=0

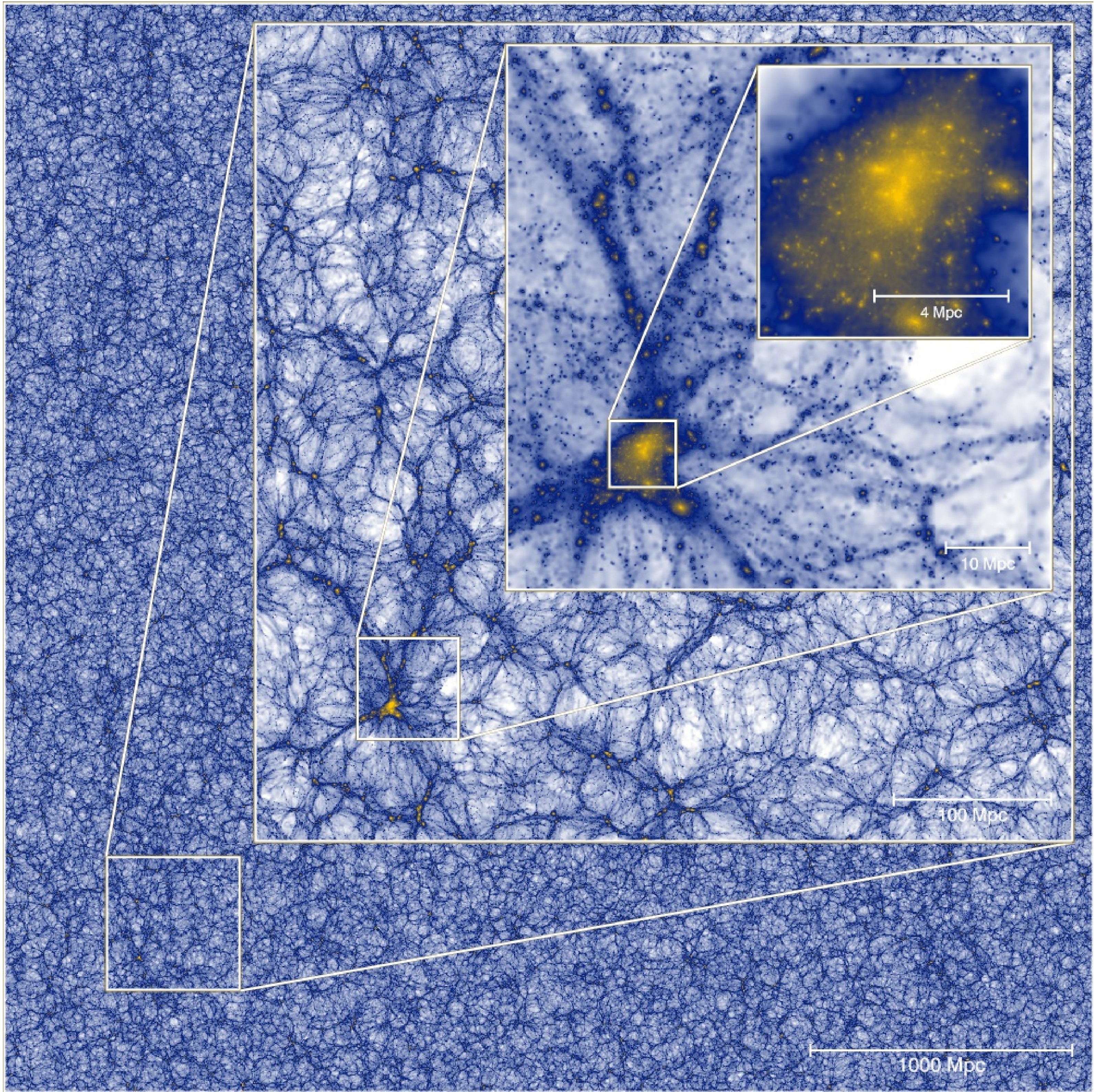
~25 billion (sub)halos
in mergers trees

$m_p = 6.1 \times 10^9\ M_{\odot}/h$

12288 cores,
30 TB RAM on
Supercomputer
JuRoPa in Juelich

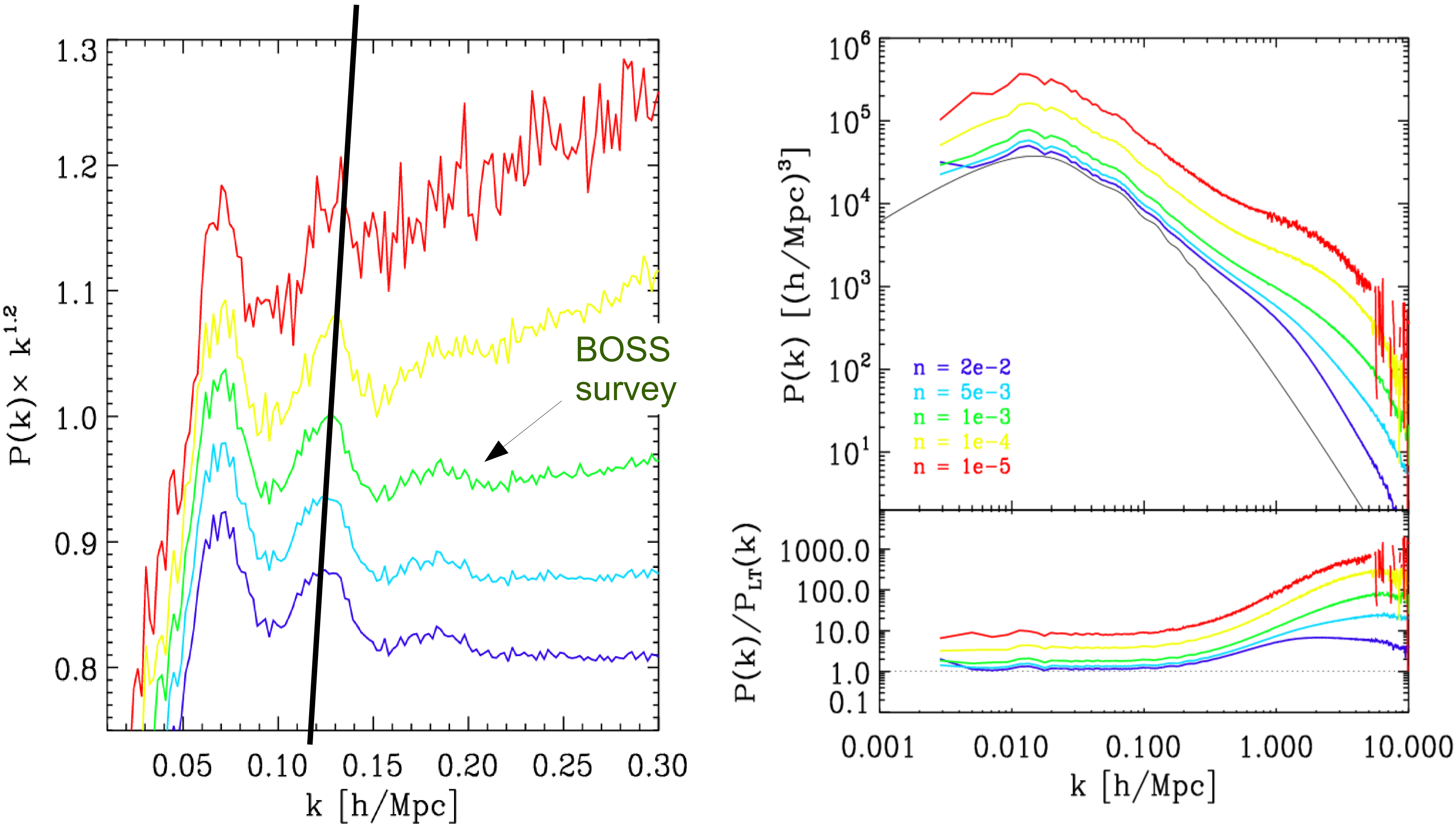
2.7 million CPU-hours

Angulo et al. (2011)

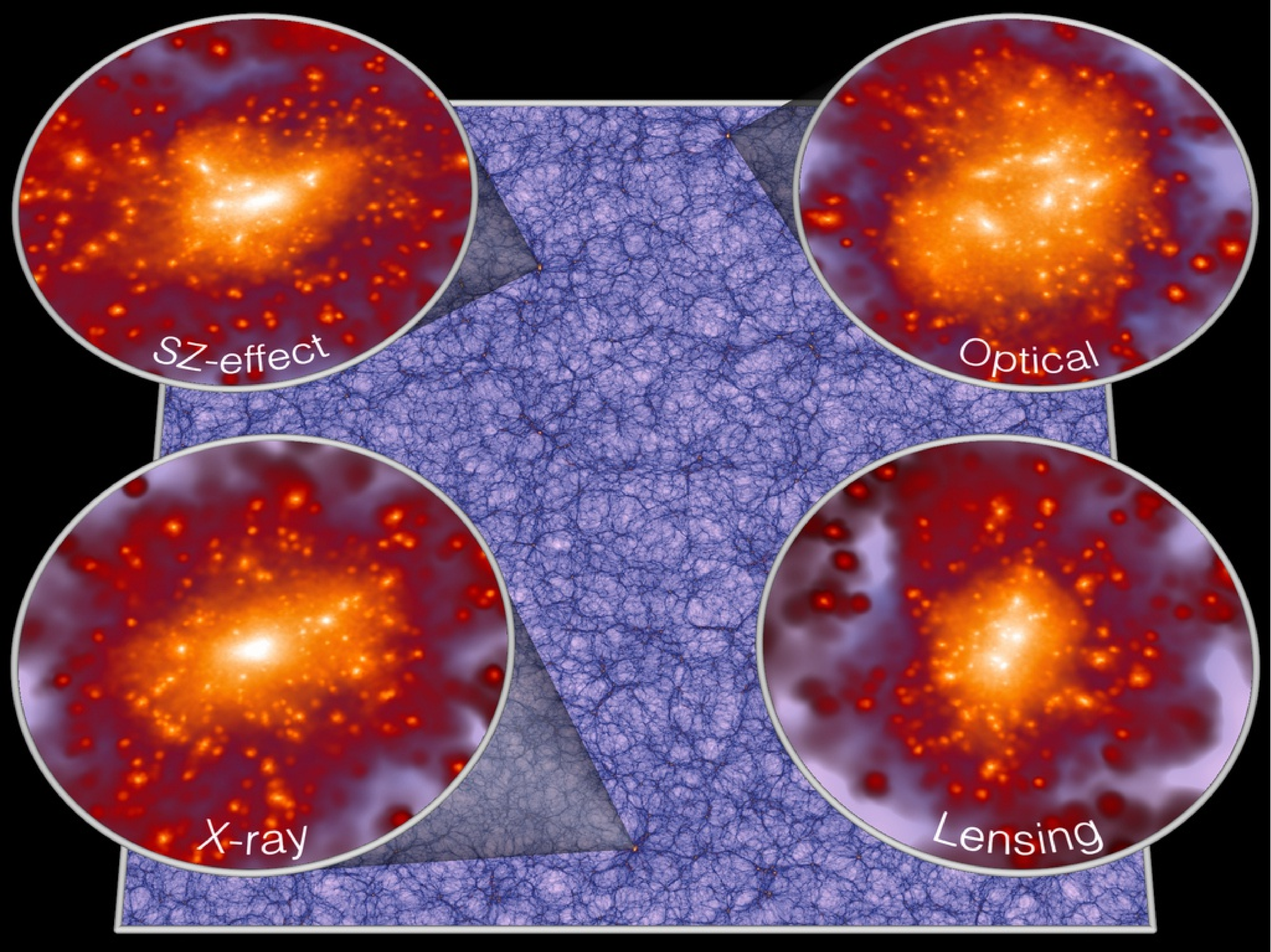


Different galaxy catalogues in the MXXL simulation trace the BAO features with a scale-dependent bias

POWER SPECTRA OF THE GALAXY DISTRIBUTION AT Z=0 FOR DIFFERENT SPACE DENSITIES

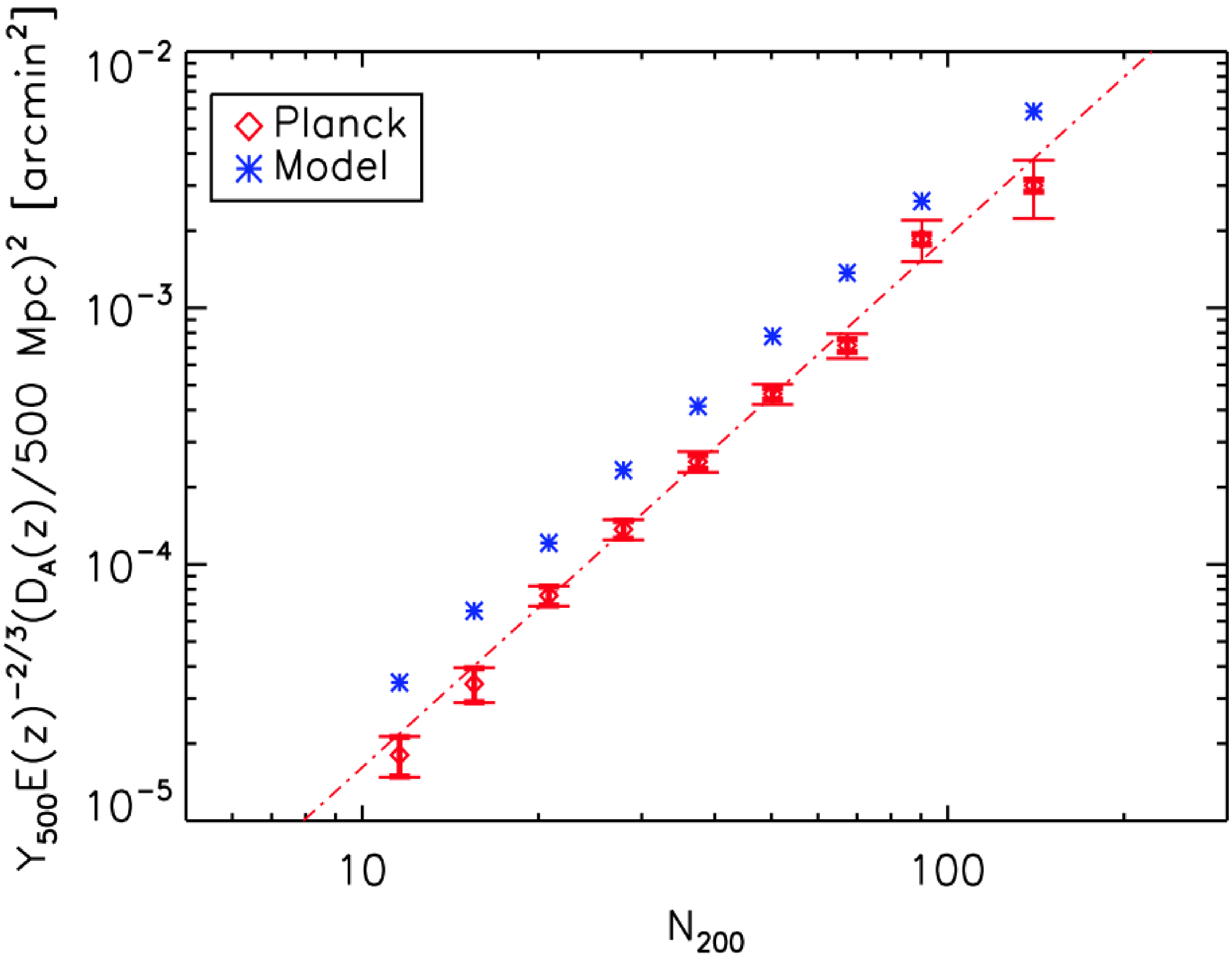


Angulo et al. (2012)


SZ-effect
Optical
X-ray
Lensing

The mean SZ-signal in PLANCK-data for clusters of given optical richness (from the MaxBCG catalogue) is lower by a factor ~2 than expected

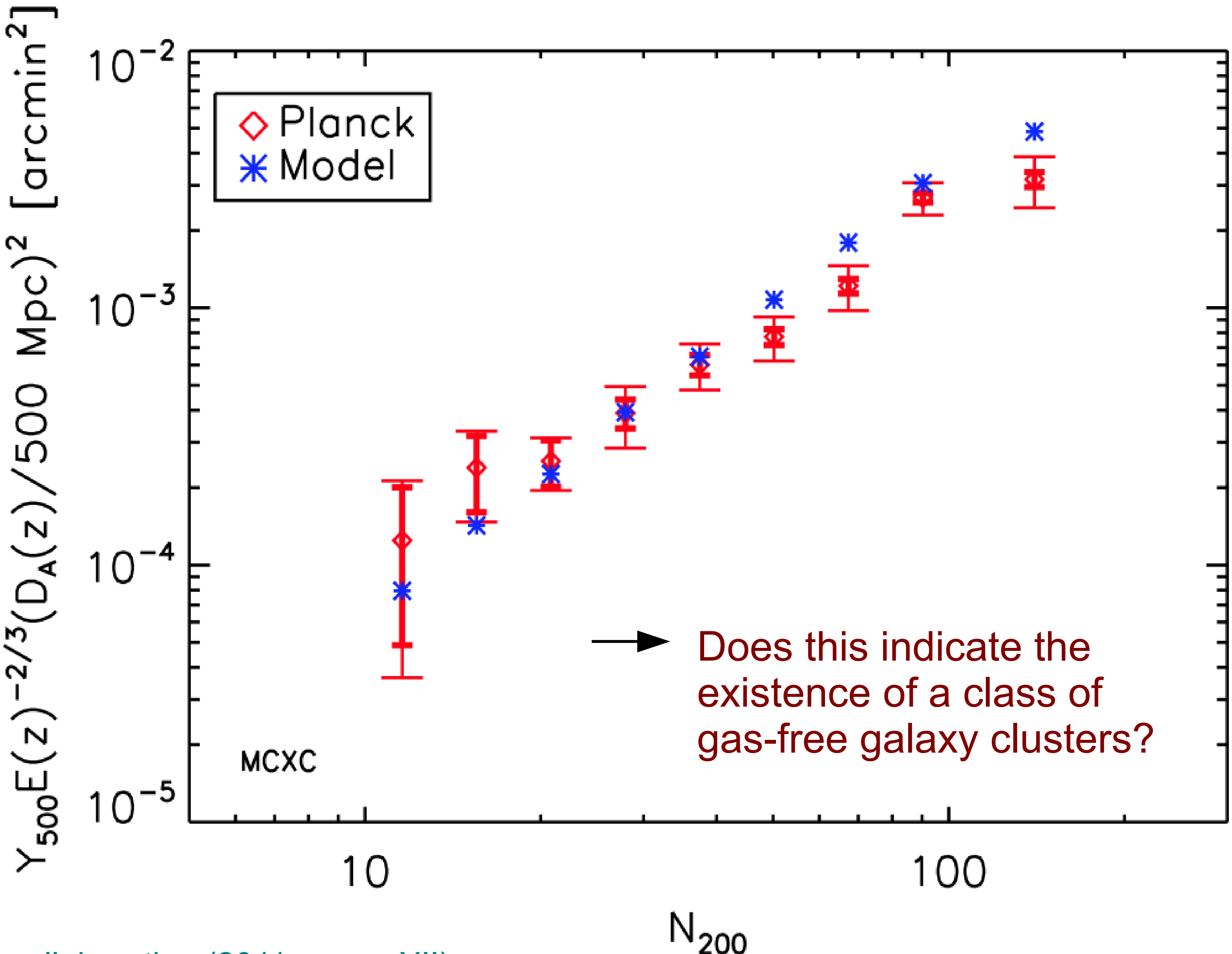
SZ vs. OPTICAL REACHNESS MEASURED BY PLANCK COMPARED TO MODEL EXPECTATIONS



Planck collaboration (2011, paper XII)

For the subsample of clusters with individual X-ray measurements, the PLANCK-data for the SZ matches the model expectations

SZ vs. OPTICAL REACHNESS FOR X-RAY DETECTED CLUSTER SUBSAMPLE

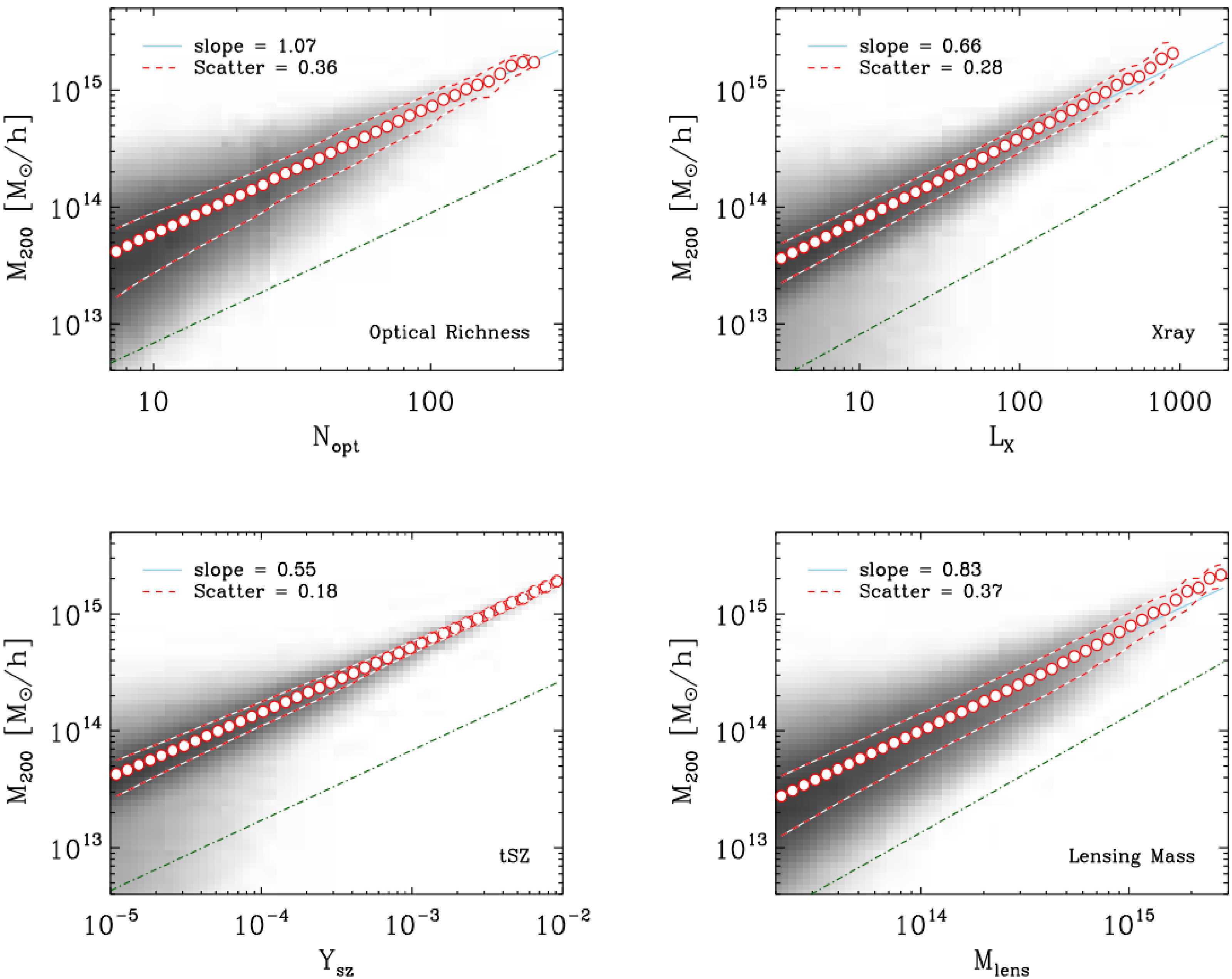


Does this indicate the existence of a class of gas-free galaxy clusters?

Planck collaboration (2011, paper XII)

Mock catalogues from the MXXL allow a study of the expected cluster scaling relations, and their modification due to systematic effects

DIFFERENT CLUSTER SCALING RELATIONS AND THEIR SCATTER

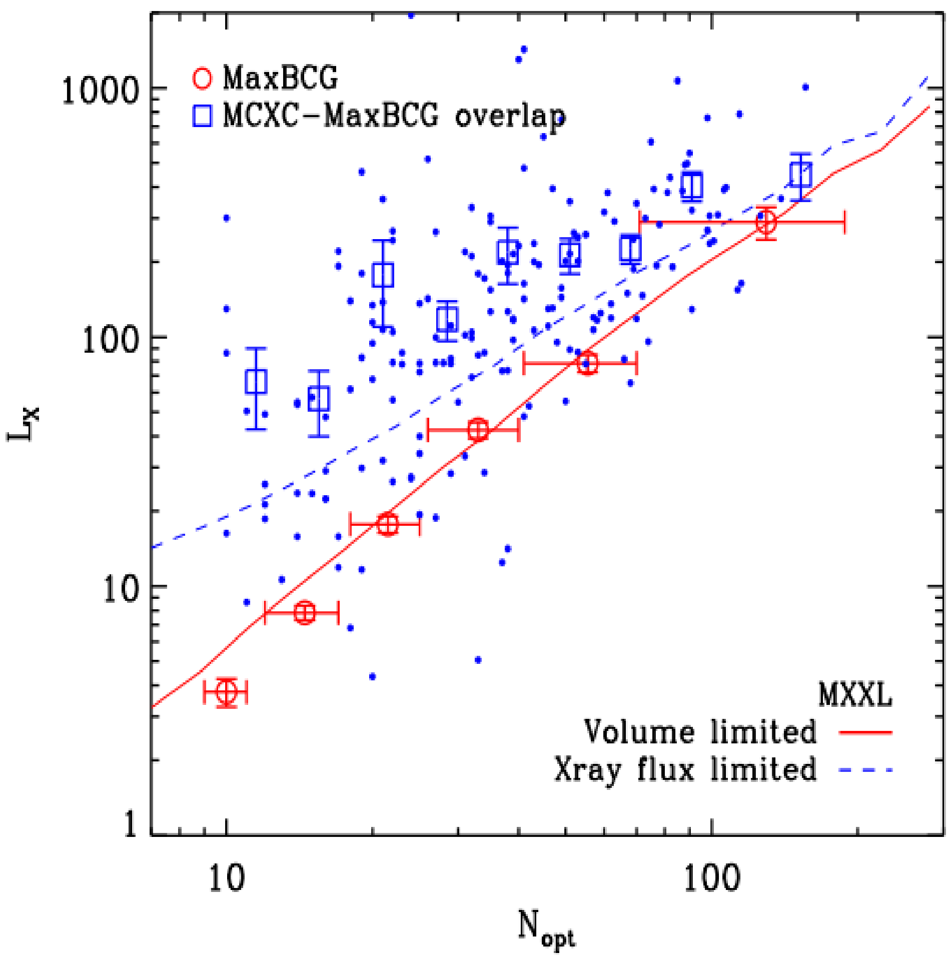


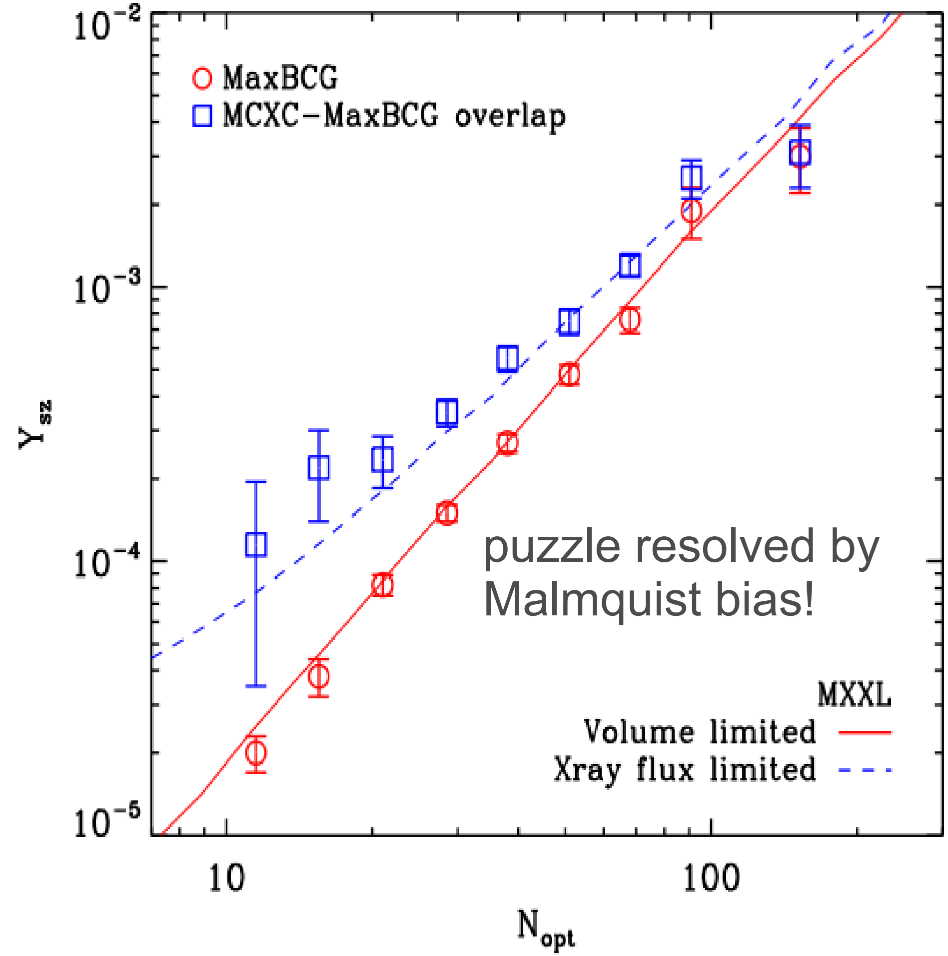
Systematic effects that influence the scaling relations:

- Sample selection
- Spurious cluster identification
- Miscentering
- Contamination due to line-of-sight foreground structures

The biases introduced in the measured relations can quantitatively account for the difference detected in the PLANCK analysis

Lx/SZ vs. OPTICAL REACHNESS FOR DIFFERENT SAMPLES





Angulo, Springel, White, Frenk, Jenkins & Baugh (2012)

Dynamics of structure formation in baryonic matter

BASIC EQUATIONS

Astrophysical plasmas are extremely thin, with (usually) negligible viscosity

Euler equations of inviscid ideal gas dynamics

$$\frac{\partial \rho_c}{\partial t} + \frac{1}{a}\boldsymbol{\nabla}_c(\rho_c \boldsymbol{v}) = 0$$

$$\frac{\partial(\rho_c \boldsymbol{v})}{\partial t} + \frac{1}{a}\boldsymbol{\nabla}_c[(\rho_c \boldsymbol{v}\boldsymbol{v}^T + P_c)\boldsymbol{v}] = -H(a)\,\rho_c \boldsymbol{v} - \frac{\rho_c}{a^2}\boldsymbol{\nabla}_c \Phi_c$$

$$\frac{\partial(\rho_c e)}{\partial t} + \frac{1}{a}\boldsymbol{\nabla}_c[(\rho_c e + P_c)\boldsymbol{v}] = -2H(a)\,\rho_c e - \frac{\rho_c \boldsymbol{v}}{a^2}\boldsymbol{\nabla}_c \Phi_c$$

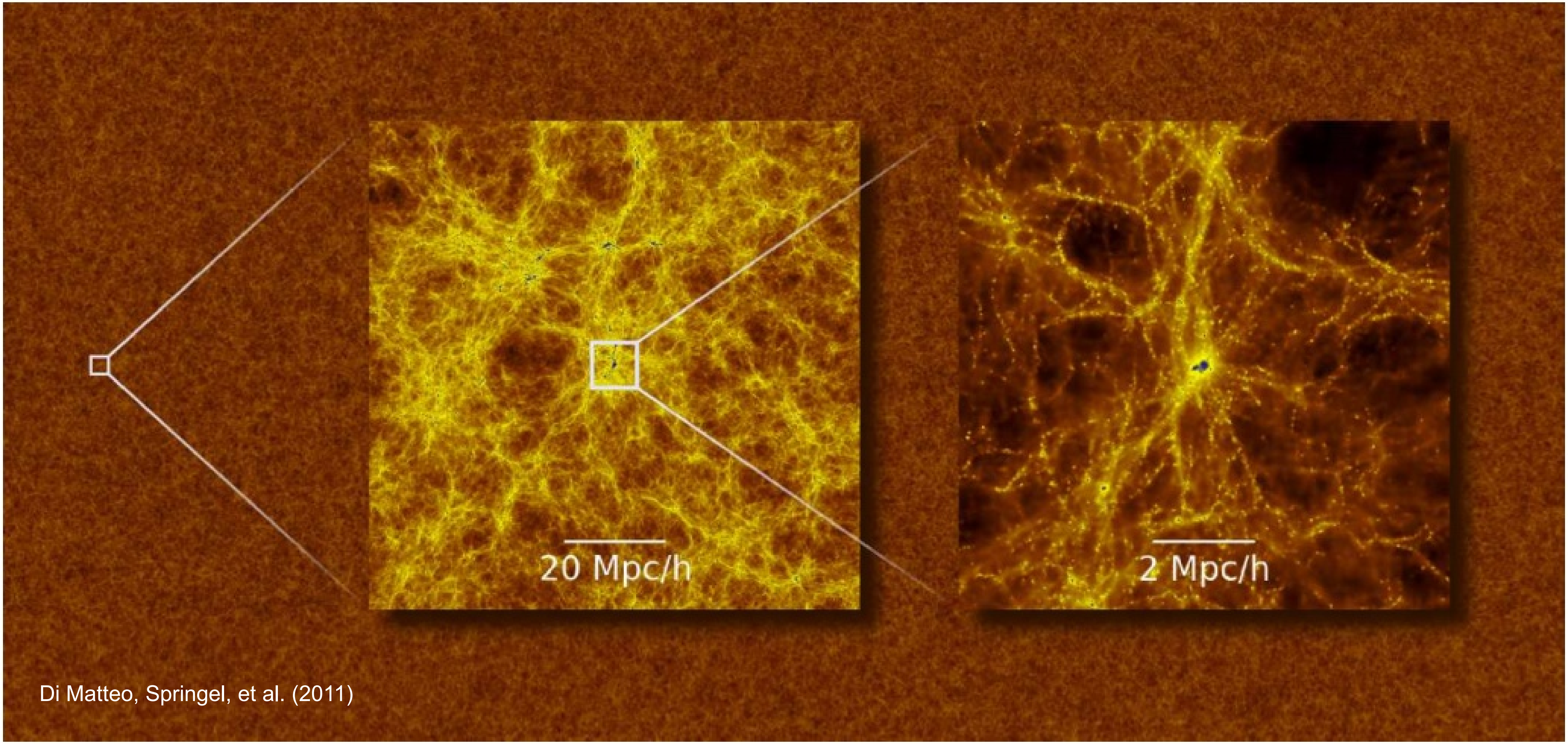
$$\nabla_c^2 \Phi_c = 4\pi G\,[\rho_c(\boldsymbol{x}) - \overline{\rho_c}]$$

Important hydrodynamical processes

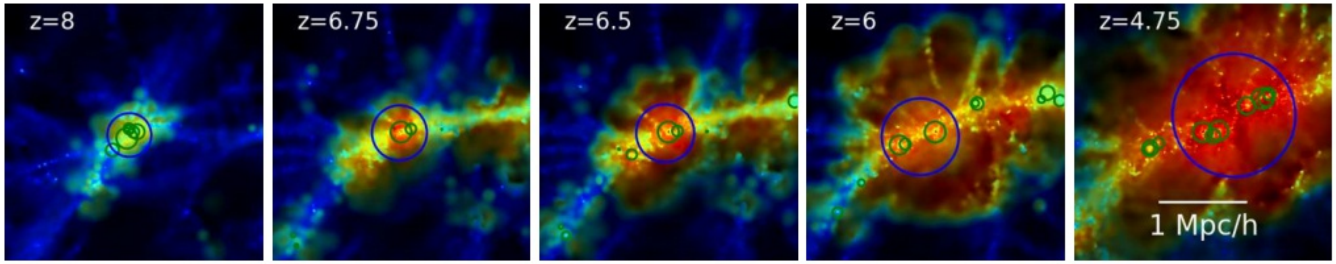
Shock waves
Turbulence
Radiative transfer
Magnetic fields
Star formation
Supernova explosions
Black holes, etc...

The *MassiveBlack* simulation is the largest astrophysical SPH simulation to date

TRACKING THE FORMATION OF THE FIRST QUSARS ON A PETAFLOP MACHINE



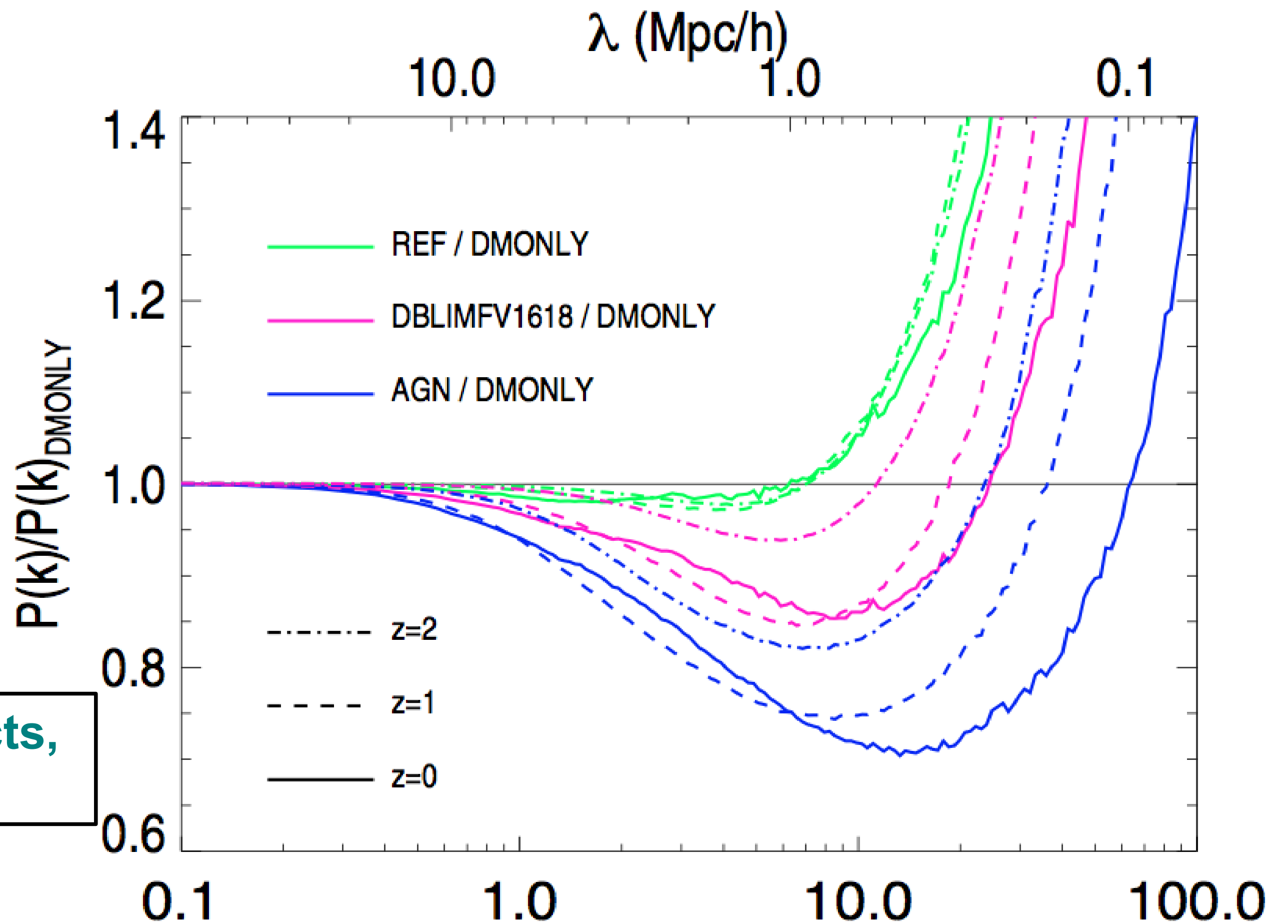
- 2 x 3200^3 ~ 65.5 billion particles
- 533 Mpc/h box
- **10^5 cores on Kraken** (Cray XT-5)
- Multi-threaded P-GADGET3 code



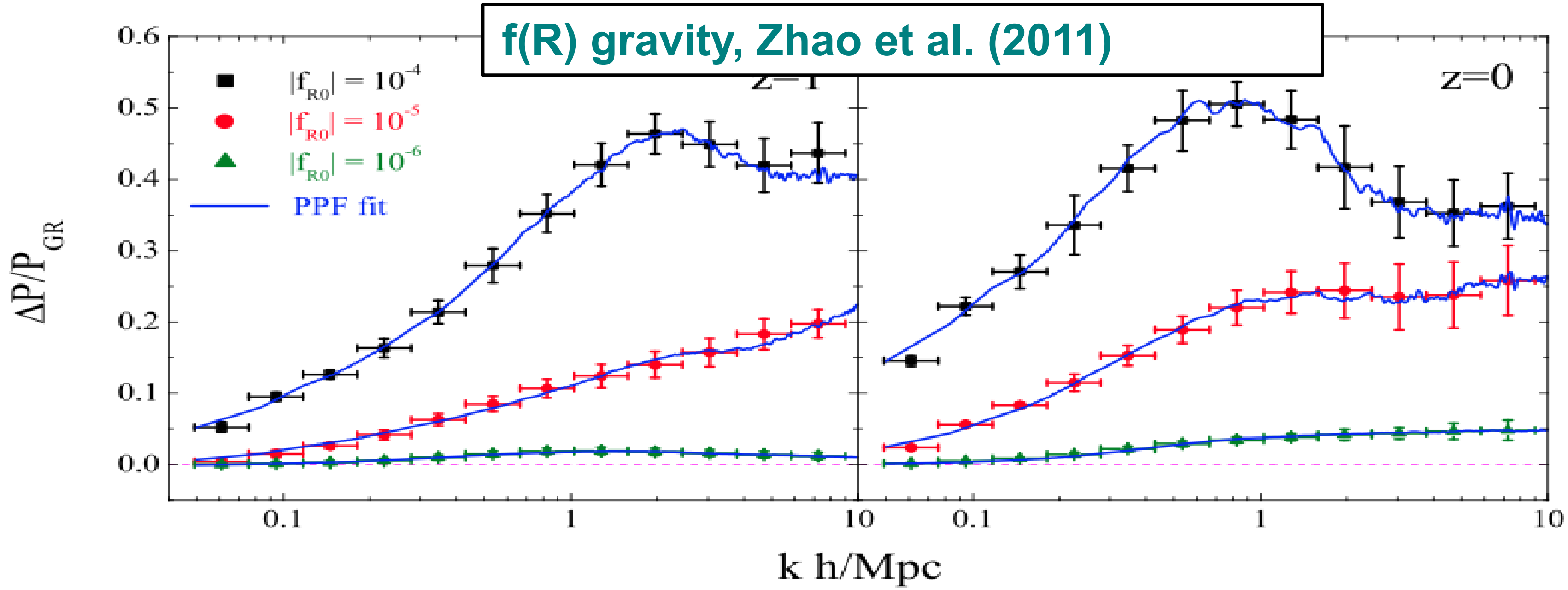
Baryonic physics and modified gravity effects on the matter power spectrum are of similar magnitude

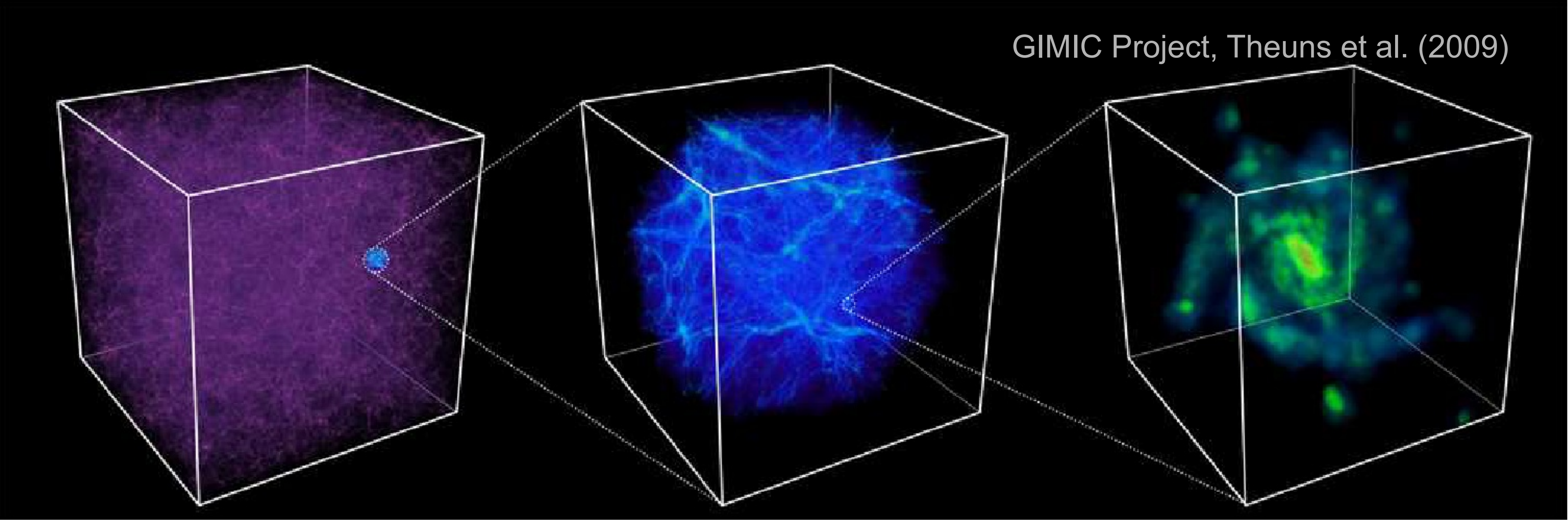
POWER SPECTRA IN DIFFERENT MODELS

baryonic feedback effects, Semboloni et al. (2011)



f(R) gravity, Zhao et al. (2011)



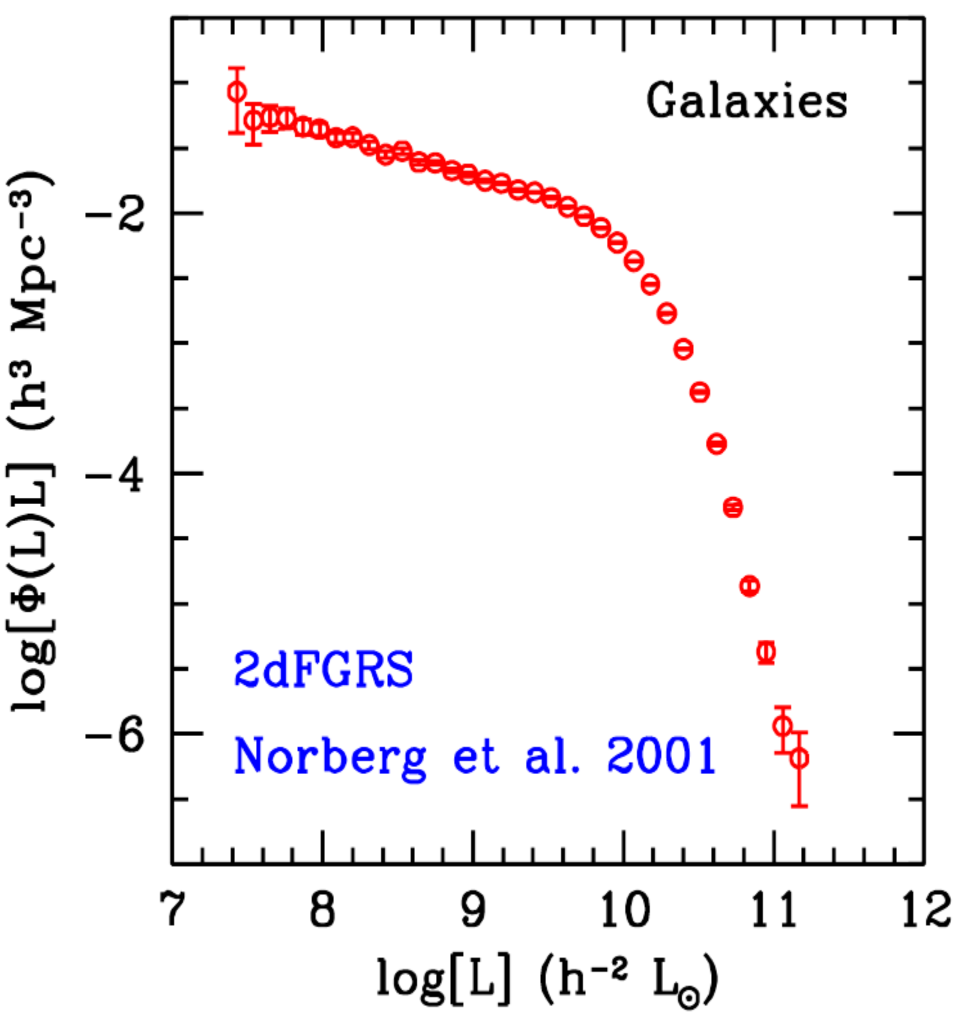


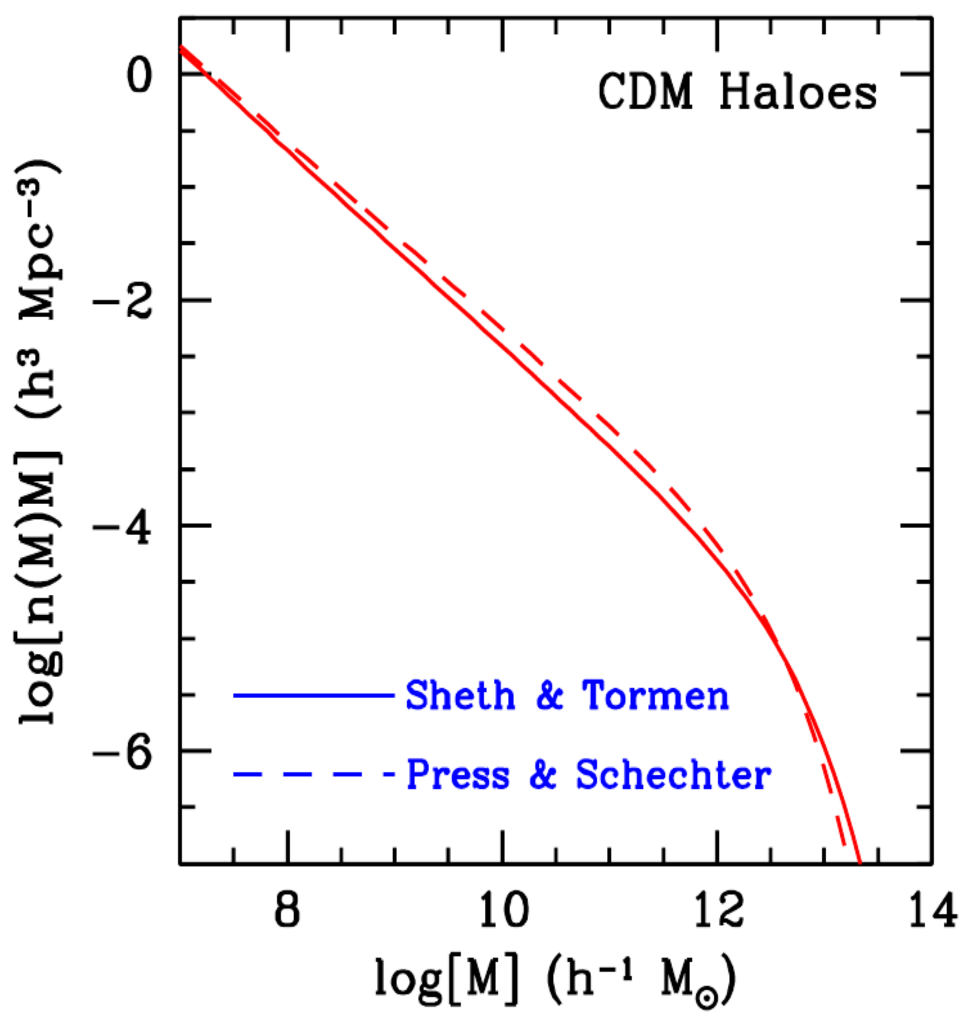
Hydrodynamical simulations aim to predict:

- **Morphology of galaxies**
- **Fate of the diffuse gas, WHIM, metal enrichment**
- **X-ray atmospheres in halos**
- **Turbulence in halos and accretion shocks**
- **Large-scale regulation of star formation in galaxies through feedback processes from stars and black holes**
- **Transport processes (e.g. conduction)**
- **Radiative transfer**
- **Dynamical transformations (e.g. ram-pressure stripping)**
- **Magnetic fields**

A long standing issue in galaxy formation theory: The shapes of the CDM halo mass function and the galaxy luminosity function are very different

THE OBSERVED LF COMPARED TO THE SHAPE OF THE CDM HALO MASS FUNCTION



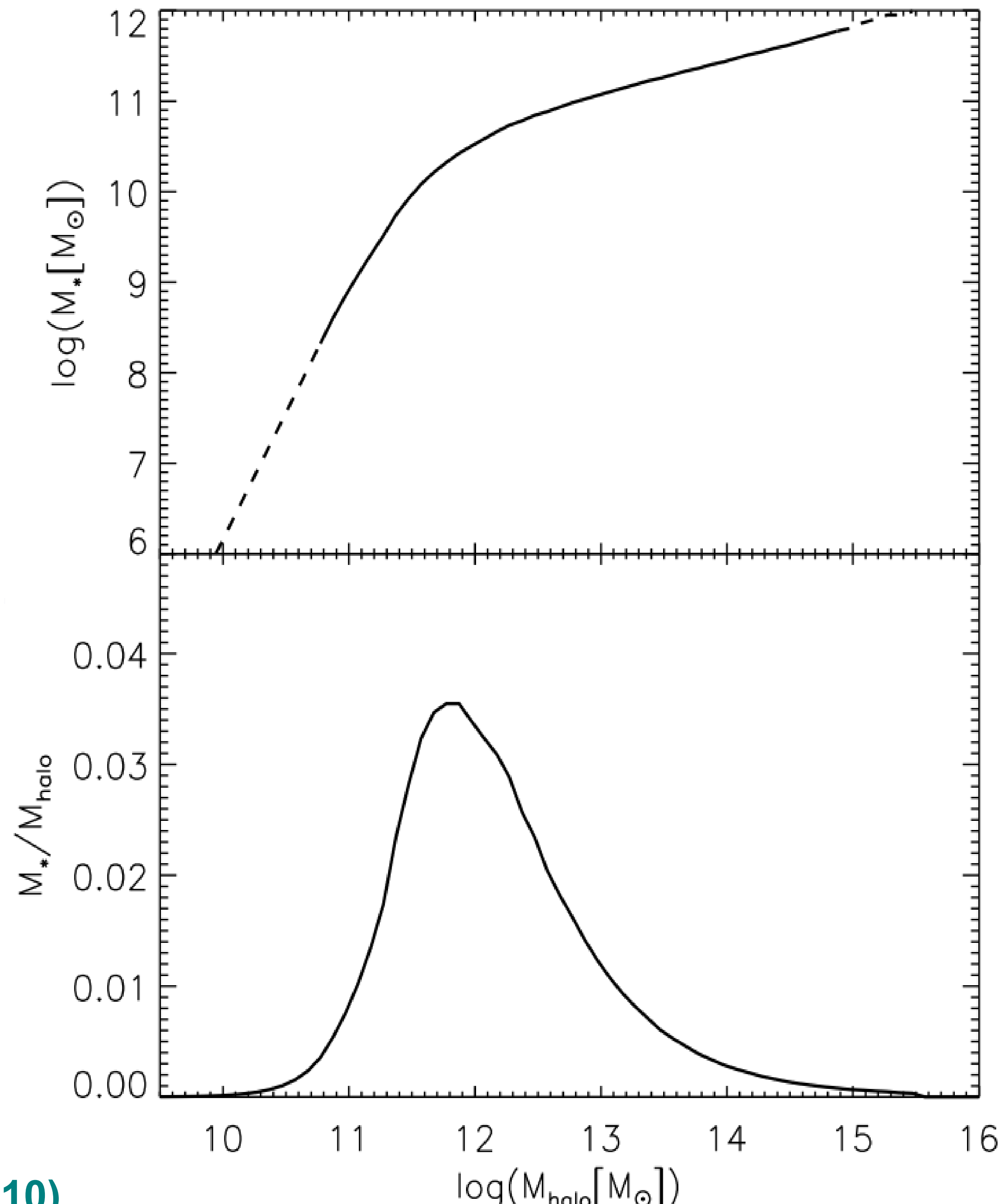


van den Bosch et al. (2004)

Abundance matching gives the expected halo mass – stellar mass relation in ΛCDM

STELLAR MASSES FROM SDSS/DR7 MATCHED TO ΛCDM SIMULATION EXPECTATIONS

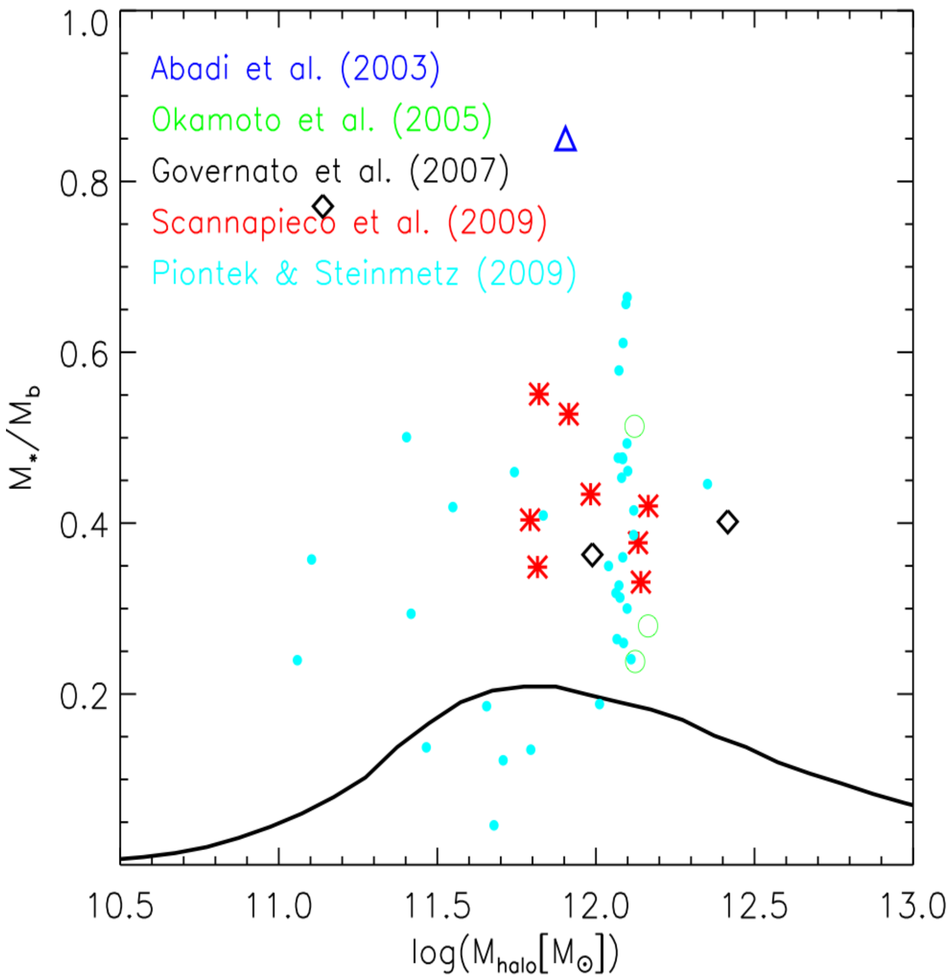
Assumption:
Stellar mass is monotonically increasing with halo mass



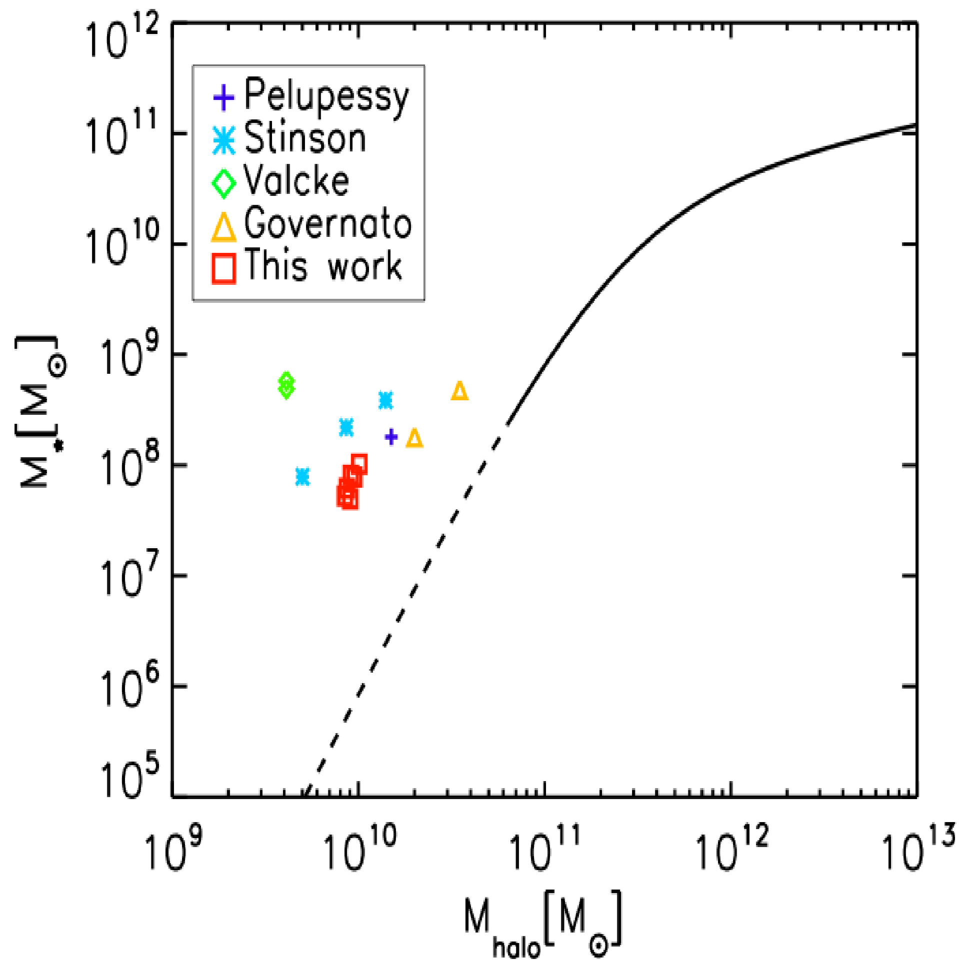
Guo, White & Boylan-Kolchin (2010)

Current cosmological hydrodynamic simulations have trouble to explain such a low galaxy formation efficiency

GALAXY FORMATION EFFICIENCY AS A FUNCTION OF HALO MASS



Guo, White & Boylan-Kolchin (2010)



Sawala & White (2010)

Future progress with cosmological simulations requires....

- **Better resolution (more computing power...)**
- **Higher accuracy of numerical codes**
- **More complete and realistic physics models**

Trouble ahead in the Exaflop regime ?

10^{18} in 2018

How long would the Millennium-XXL take on a Exaflop Supercomputer at peak performance?

15 min

One of the main problems:
Power Consumption

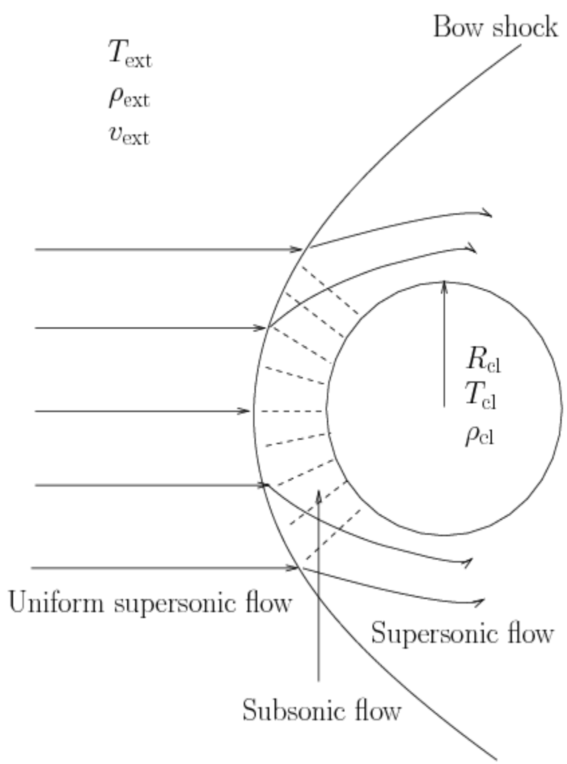
Petaflop Computer: **6 MW**

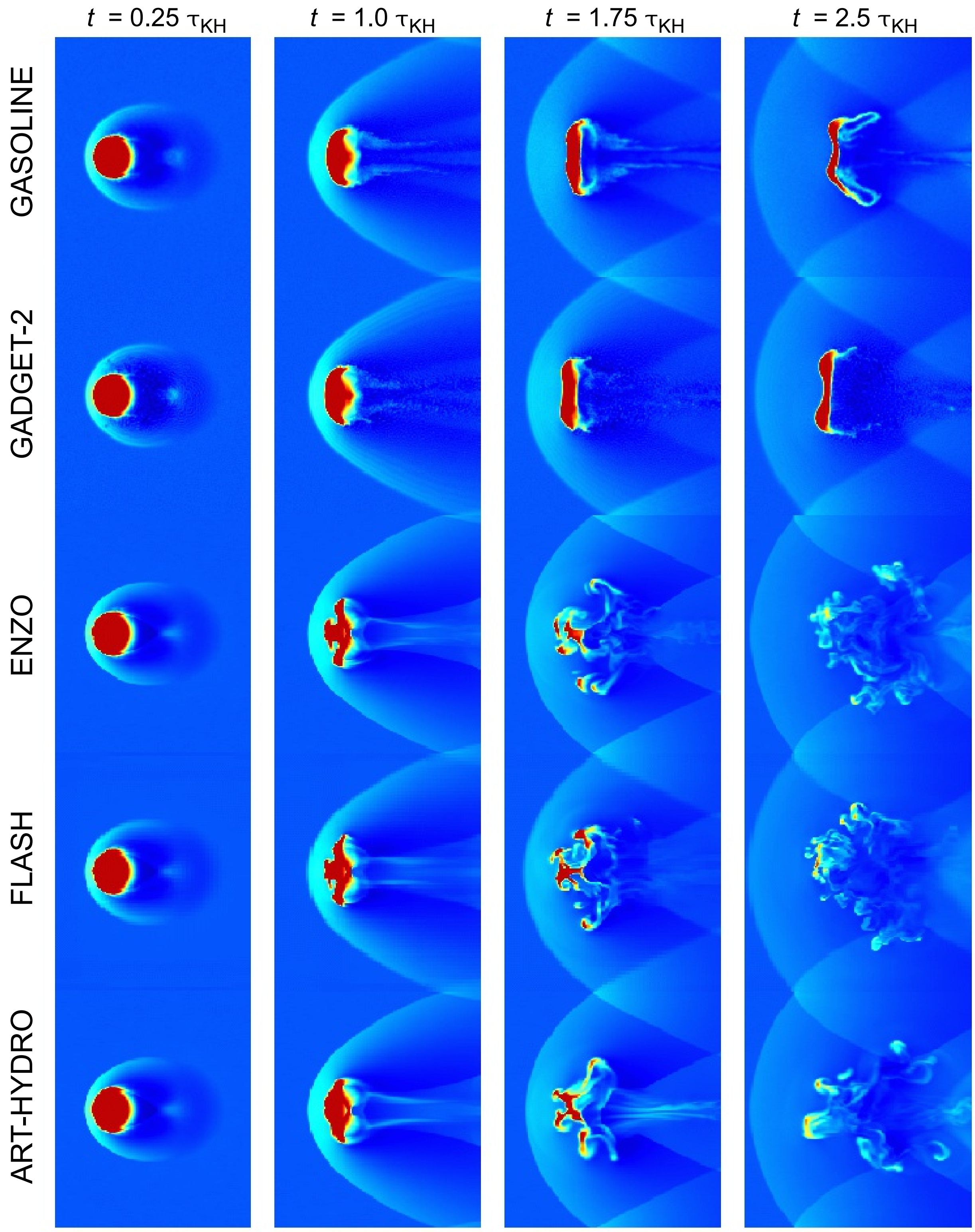
Exaflop Computer: **~ GW ?**

Need to get this down to **20-40 MW**

A cloud moving through ambient gas shows markedly different long-term behavior in SPH and Eulerian mesh codes

DISRUPTION OF A CLOUD BY KELVIN-HELMHOLTZ INSTABILITIES





Agertz et al. (2007)

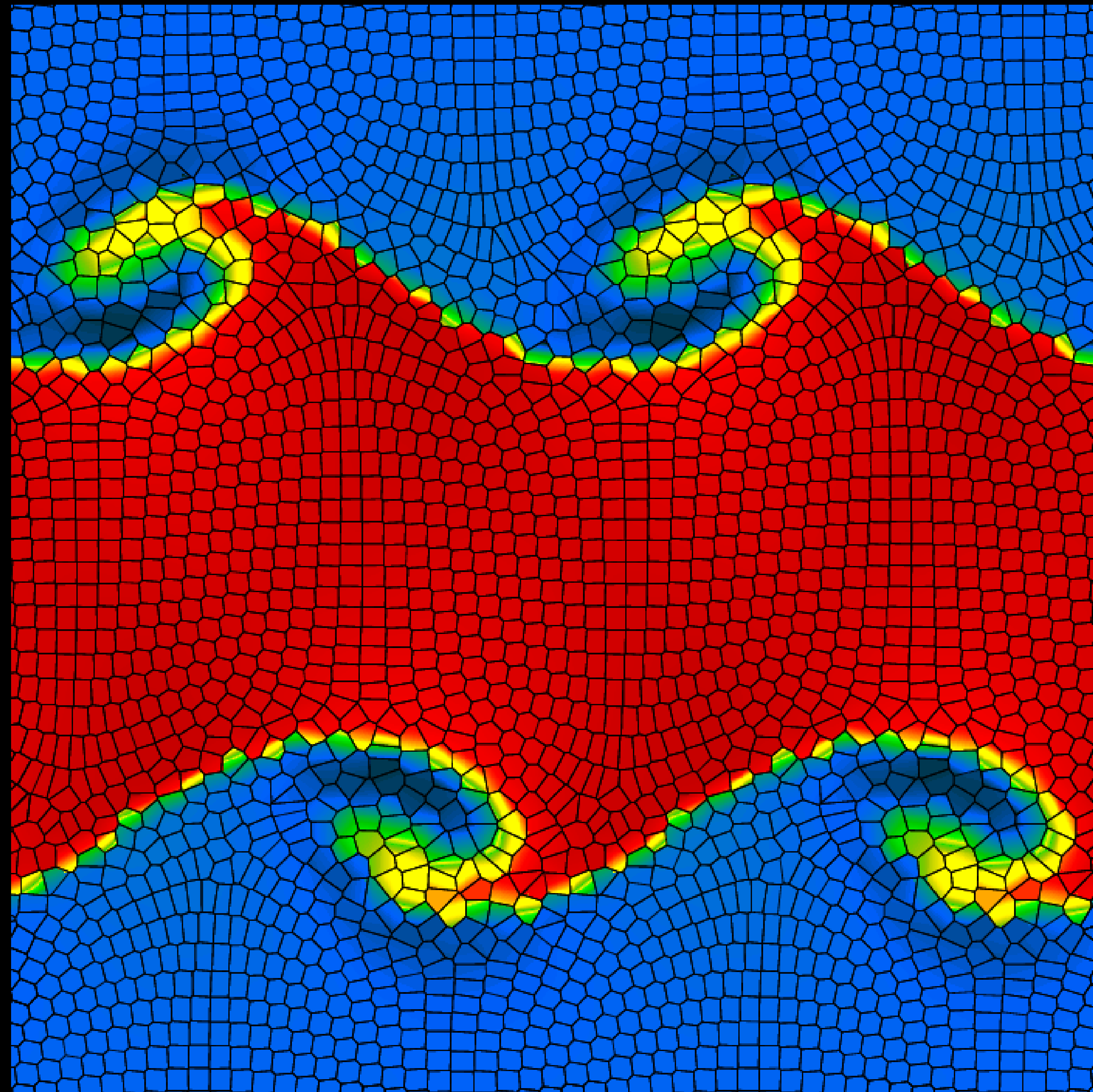
Moving-mesh hydrodynamics with AREPO

Volker Springel

Heidelberg Institute for Theoretical Studies

HITS

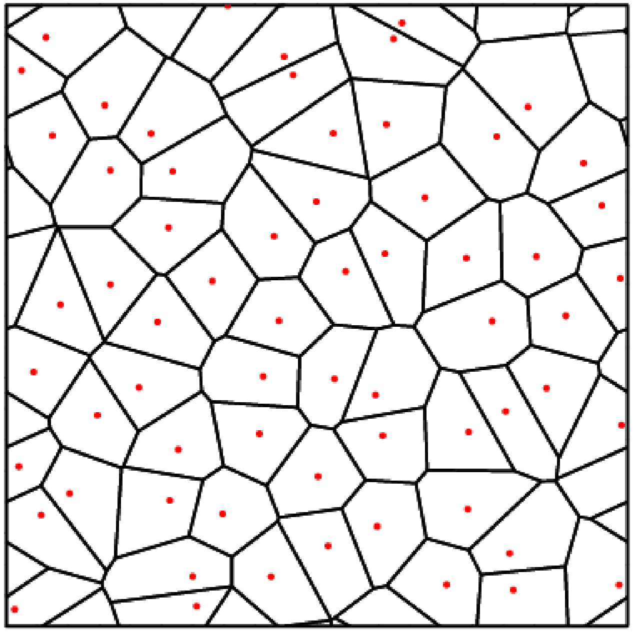
Universität Heidelberg



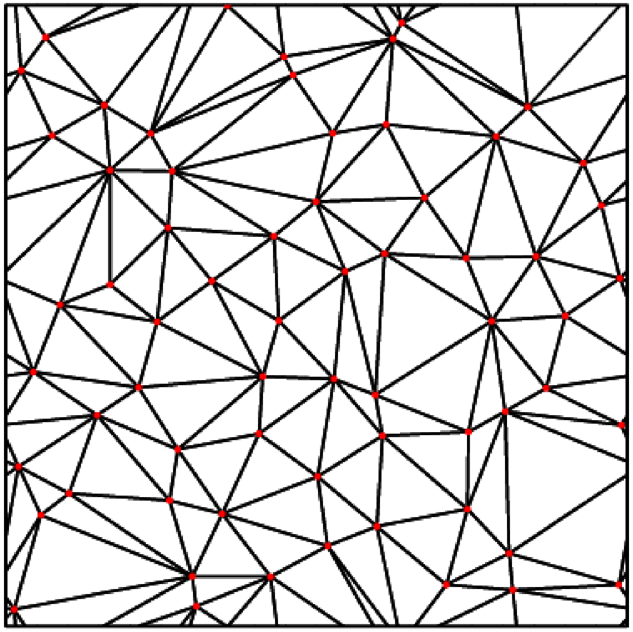
Voronoi and Delaunay tessellations provide unique partitions of space based on a given sample of mesh-generating points

BASIC PROPERTIES OF VORONOI AND DELAUNAY MESHES

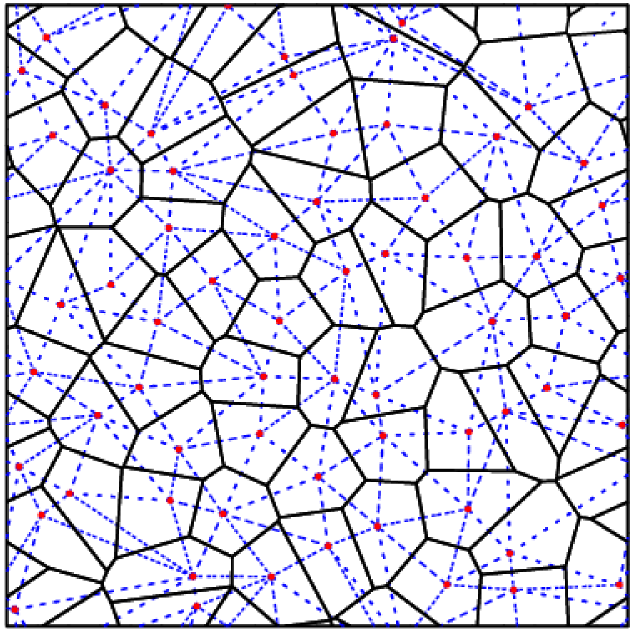
Voronoi mesh



Delaunay triangulation



both shown together



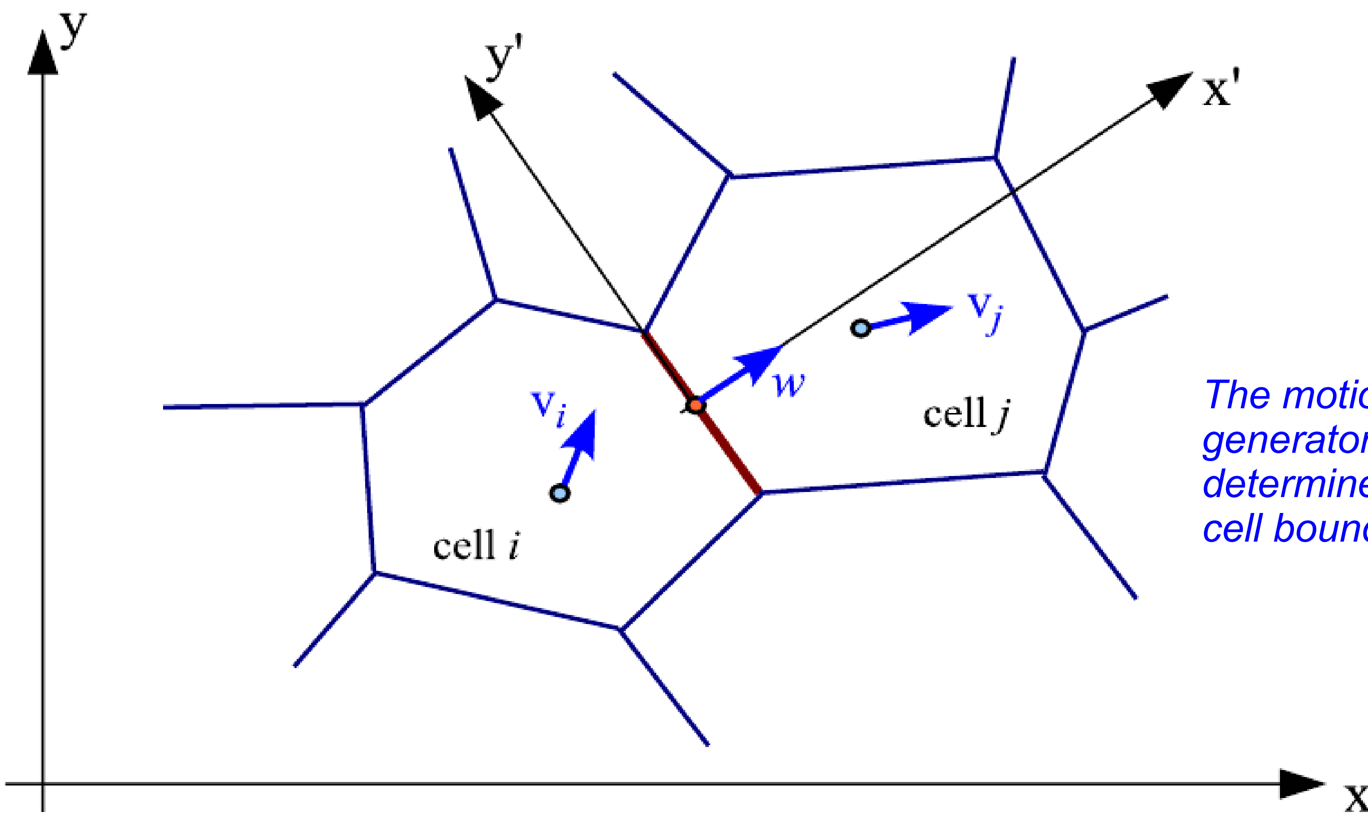
Each Voronoi cell contains the **space closest** to its generating point

The Delaunay triangulation contains only triangles with an **empty circumcircle**. The Delaunay tiangulation maximizes the minimum angle occurring among all triangles.

The centres of the circumcircles of the Delaunay triangles are the vertices of the Voronoi mesh. In fact, the two tessellations are the topological **dual graph** to each other.

The fluxes are calculated with an exact Riemann solver in the frame of the moving cell boundary

SKETCH OF THE FLUX CALCULATION



The motion of the mesh generators uniquely determines the motion of all cell boundaries

State left of cell face

$$\begin{pmatrix} \rho_L \\ \mathbf{v}_L \\ P_L \end{pmatrix}$$

State right of cell face

$$\begin{pmatrix} \rho_R \\ \mathbf{v}_R \\ P_R \end{pmatrix}$$

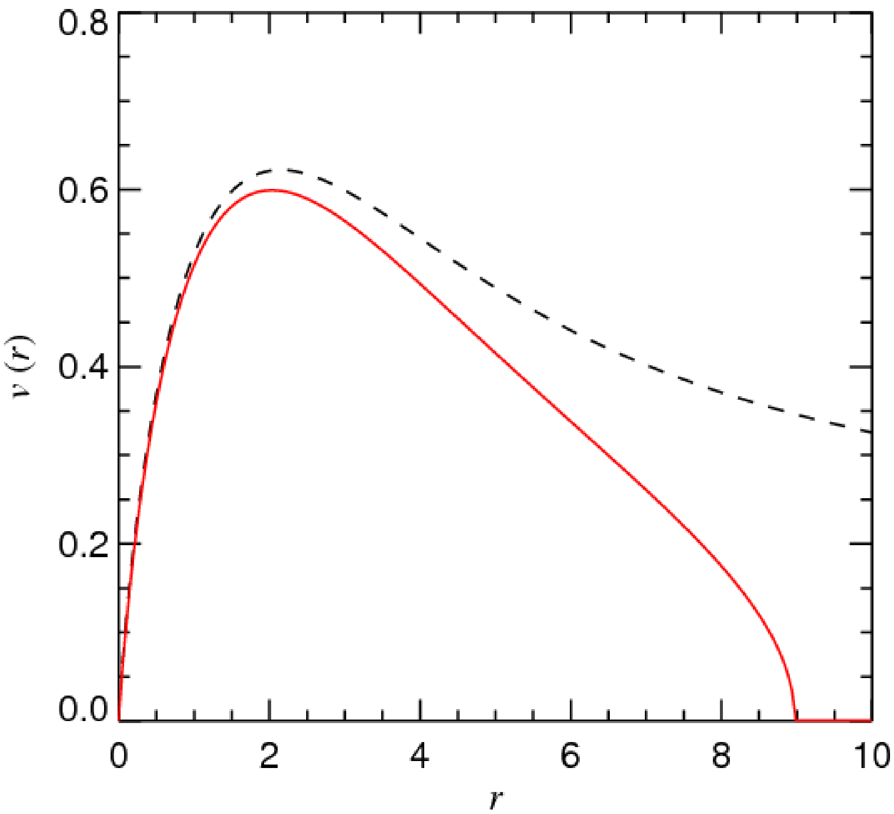
→ **Riemann solver** (in frame of cell face) → $\begin{pmatrix} \rho \\ \mathbf{v} \\ P \end{pmatrix}$ → $\mathbf{F}(\mathbf{U})$

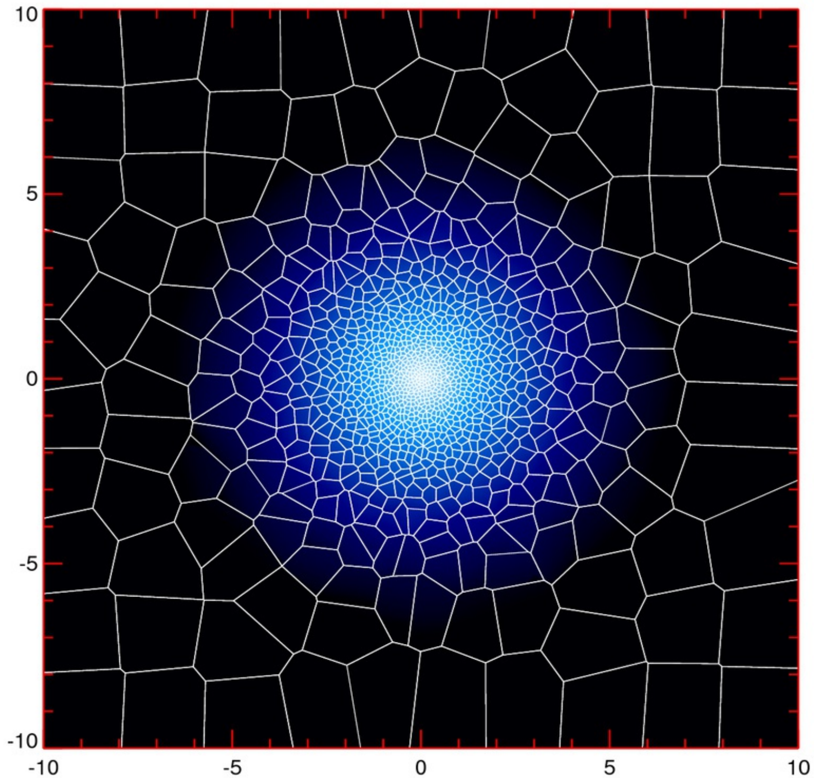
A differentially rotating gaseous disk with strong shear can be simulated well with the moving mesh code

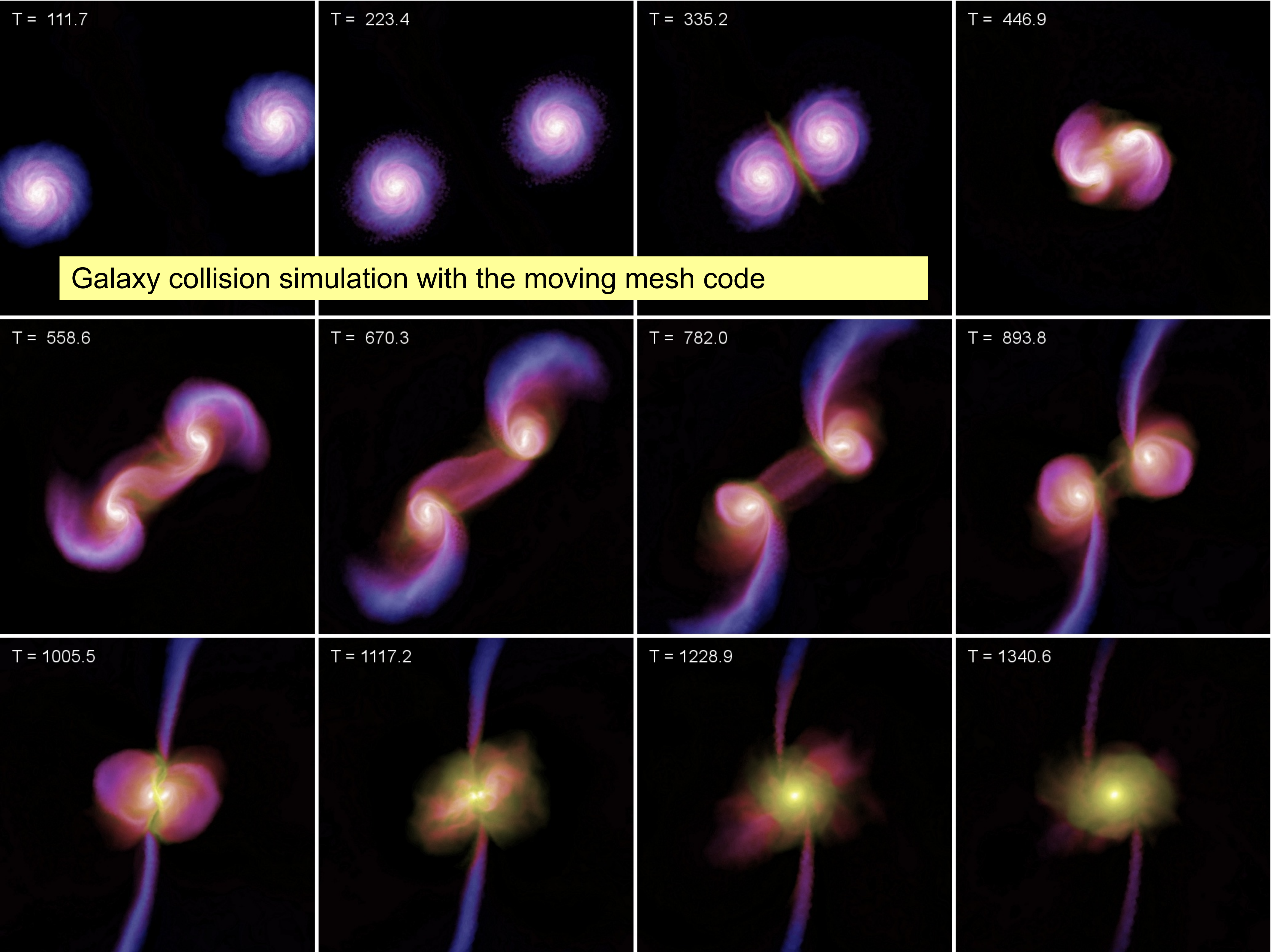
MODEL FOR A CENTRIFUGALLY SUPPORTED, THIN DISK

$$\Sigma(r) = \Sigma_0 \exp(-r/h)$$

$$v_c^2(r) \equiv r\frac{\partial \Phi}{\partial r} = 2\frac{Gm}{h} y^2 \left[I_0(y)K_0(y) - I_1(y)K_1(y)\right]$$

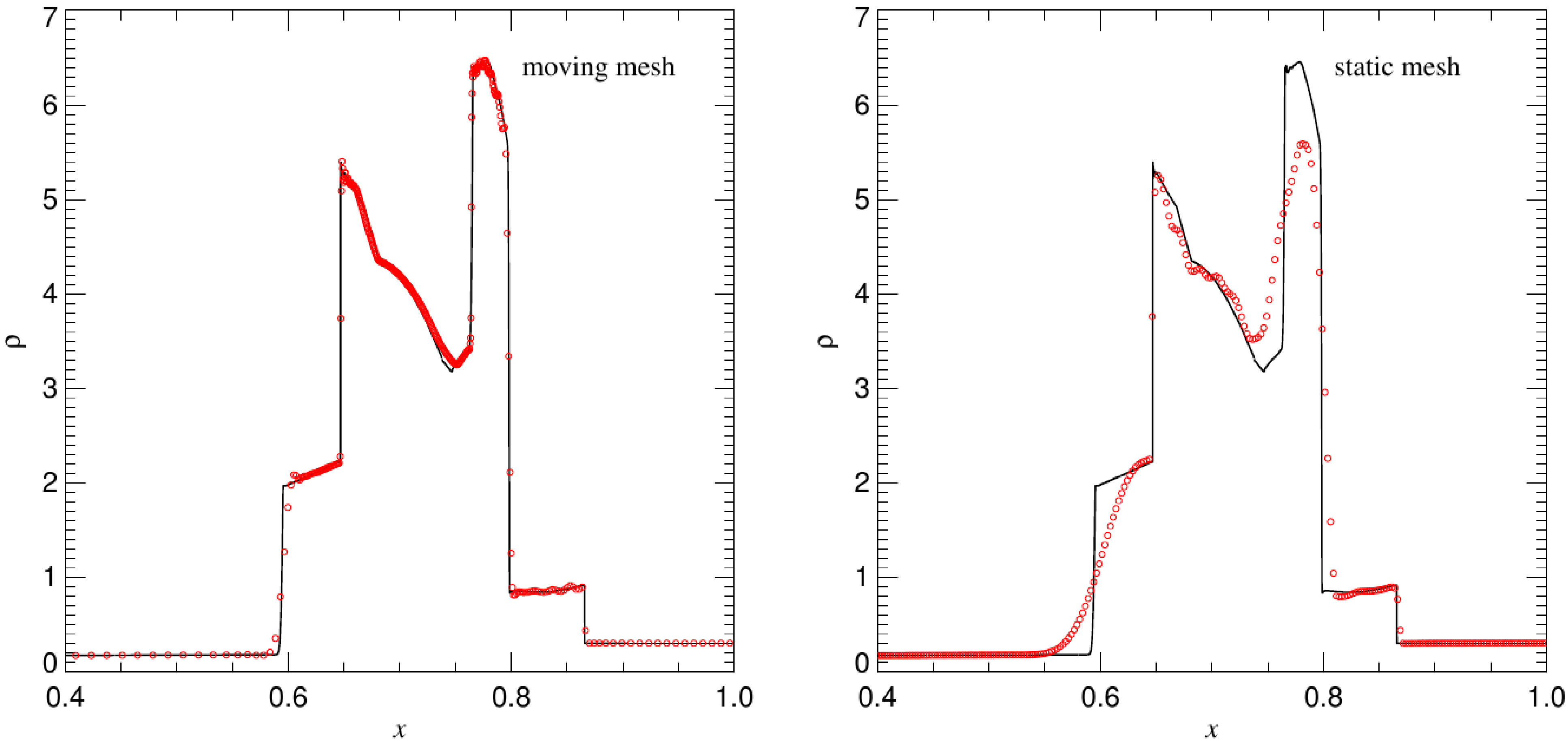





T = 111.7
T = 223.4
T = 335.2
T = 446.9
Galaxy collision simulation with the moving mesh code
T = 558.6
T = 670.3
T = 782.0
T = 893.8
T = 1005.5
T = 1117.2
T = 1228.9
T = 1340.6

The moving-mesh code deals well will problems that involve complicated shock interactions

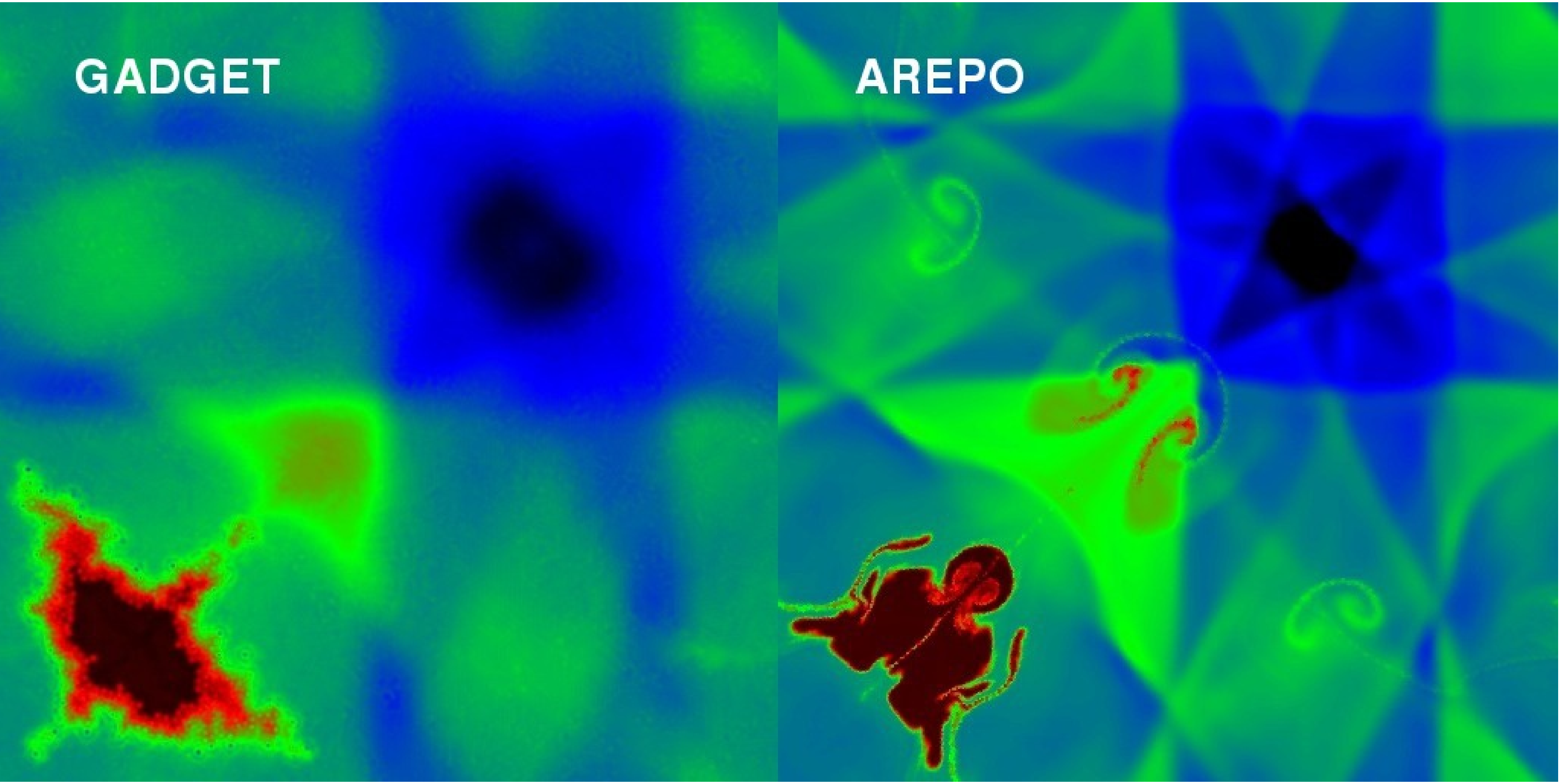
WOODWARD & COLELLA'S INTERACTING DOUBLE BLAST PROBLEM



Interacting shock waves reveal significant differences in vorticity production

TWO-DIMENSIONAL IMPLOSION PROBLEM

Sijacki et al. (2011)



But in the end: **Does it matter for cosmological simulations?**

Moving-mesh cosmology: First applications of AREPO

Mark Vogelsberger
Debora Sijacki
Dusan Keres
Paul Torrey
Lars Hernquist
Volker Springel

4 new papers, astro-ph (2011)

20 Mpc/h box, WMAP7 cosmology

Resolutions: 2 x 128^3, 2 x 256^3, 2 x 512^3

AREPO and GADGET runs

equal physics, equal gravity solver

Andreas Bauer & VS (2011)

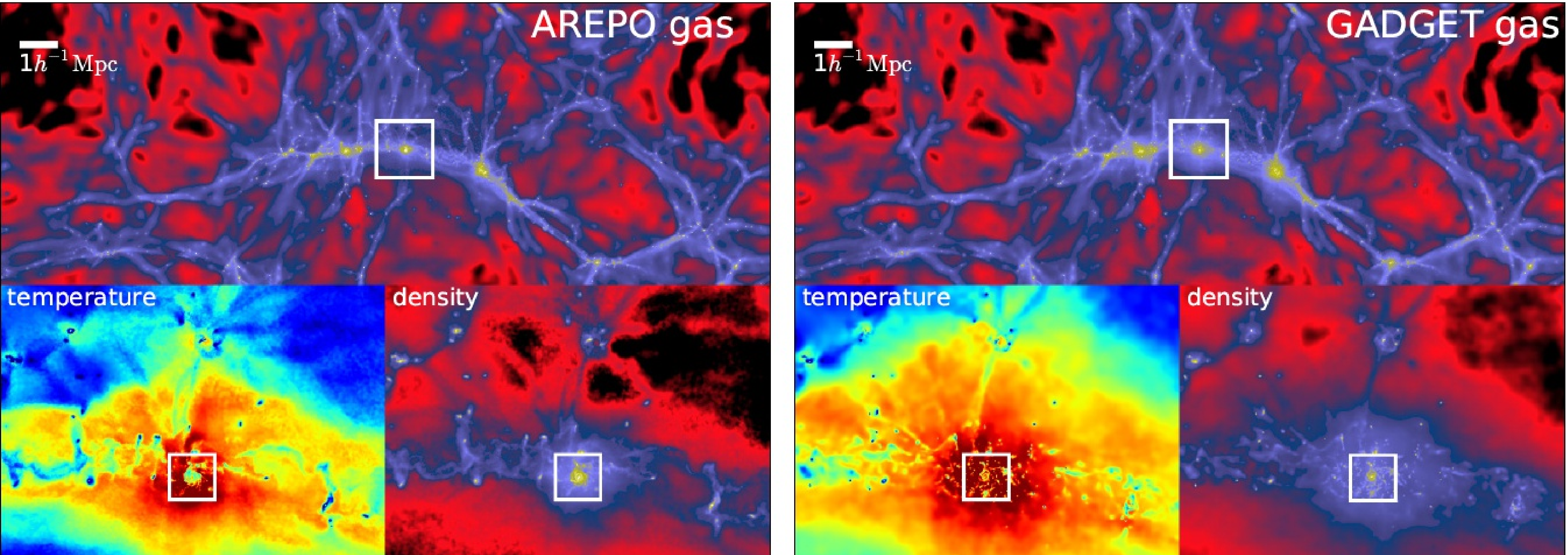
Subsonic turbulence in moving-mesh and SPH

Thomas Greif, VS, et al. (2011)

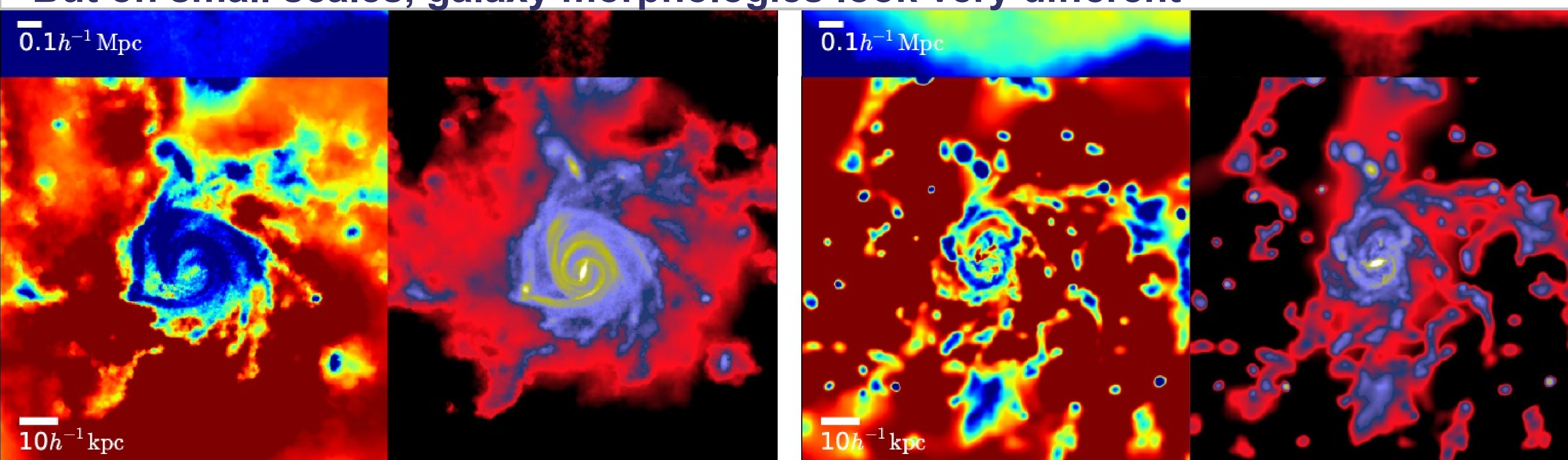
Population III star formation

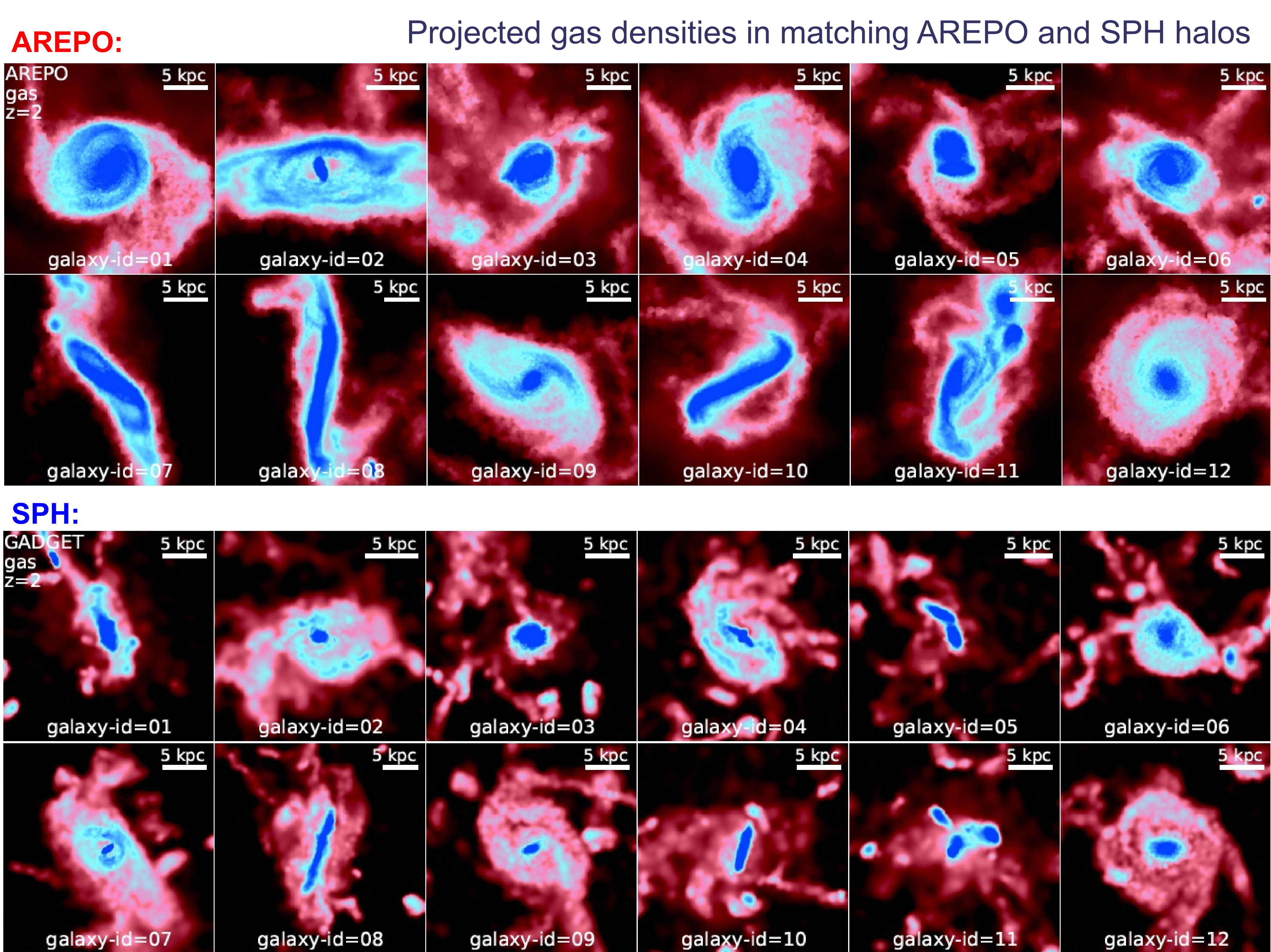
On large scales, the code produces similar results as standard SPH techniques

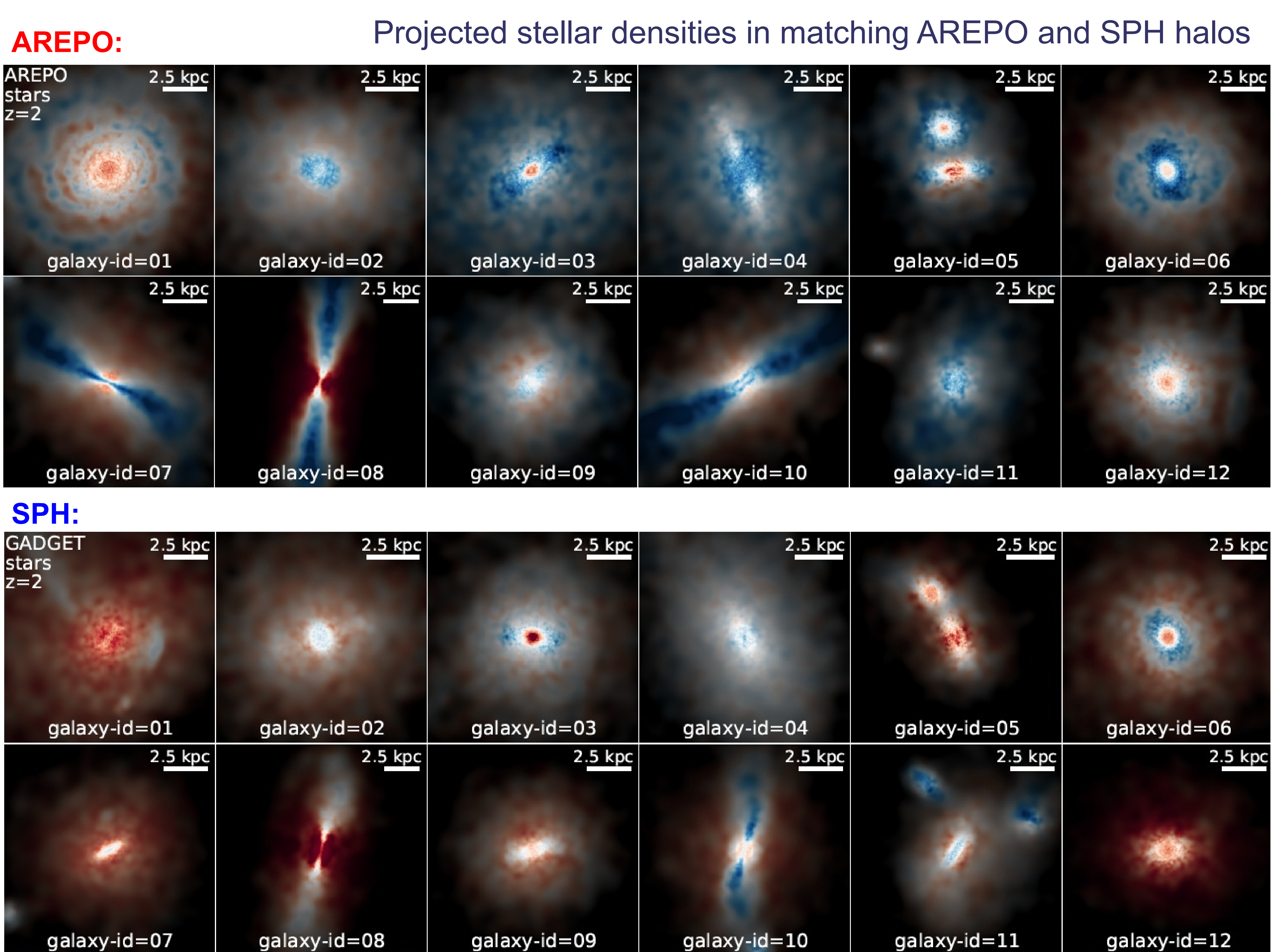
GAS AND TEMPERATURE FIELDS IN A COSMOLOGICAL HYDRODYNAMIC SIMULATION



But on small scales, galaxy morphologies look very different



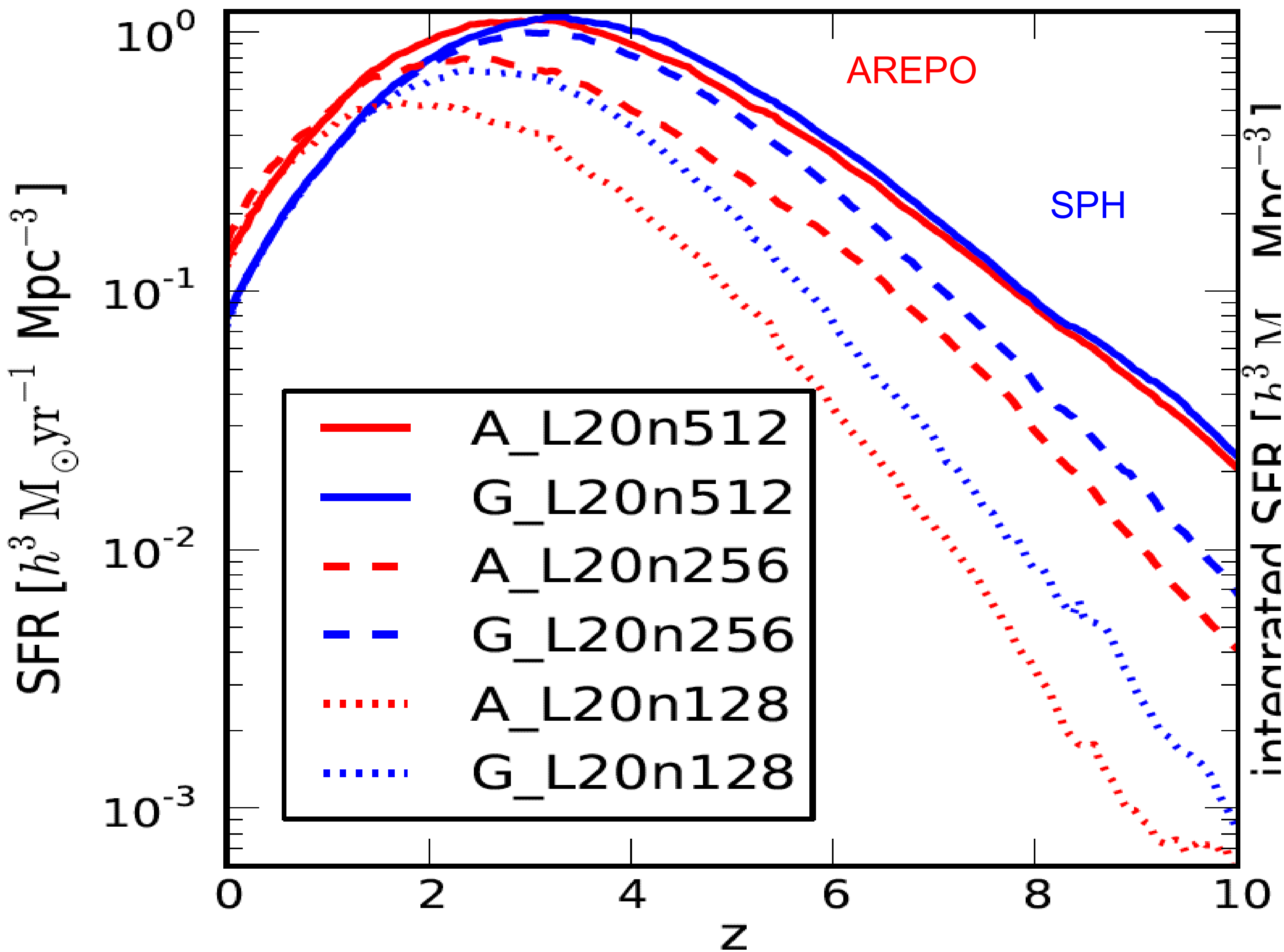

AREPO:
Projected gas densities in matching AREPO and SPH halos
AREPO
gas
z=2
5 kpc
galaxy-id=01
galaxy-id=02
galaxy-id=03
galaxy-id=04
galaxy-id=05
galaxy-id=06
galaxy-id=07
galaxy-id=08
galaxy-id=09
galaxy-id=10
galaxy-id=11
galaxy-id=12
SPH:
GADGET
gas
z=2
5 kpc
galaxy-id=01
galaxy-id=02
galaxy-id=03
galaxy-id=04
galaxy-id=05
galaxy-id=06
galaxy-id=07
galaxy-id=08
galaxy-id=09
galaxy-id=10
galaxy-id=11
galaxy-id=12


AREPO:
Projected stellar densities in matching AREPO and SPH halos
AREPO
stars
z=2
2.5 kpc
galaxy-id=01
galaxy-id=02
galaxy-id=03
galaxy-id=04
galaxy-id=05
galaxy-id=06
galaxy-id=07
galaxy-id=08
galaxy-id=09
galaxy-id=10
galaxy-id=11
galaxy-id=12
SPH:
GADGET
stars
z=2
2.5 kpc
galaxy-id=01
galaxy-id=02
galaxy-id=03
galaxy-id=04
galaxy-id=05
galaxy-id=06
galaxy-id=07
galaxy-id=08
galaxy-id=09
galaxy-id=10
galaxy-id=11
galaxy-id=12

Compared with SPH, the cosmic star formation rate density is higher in AREPO at low redshift

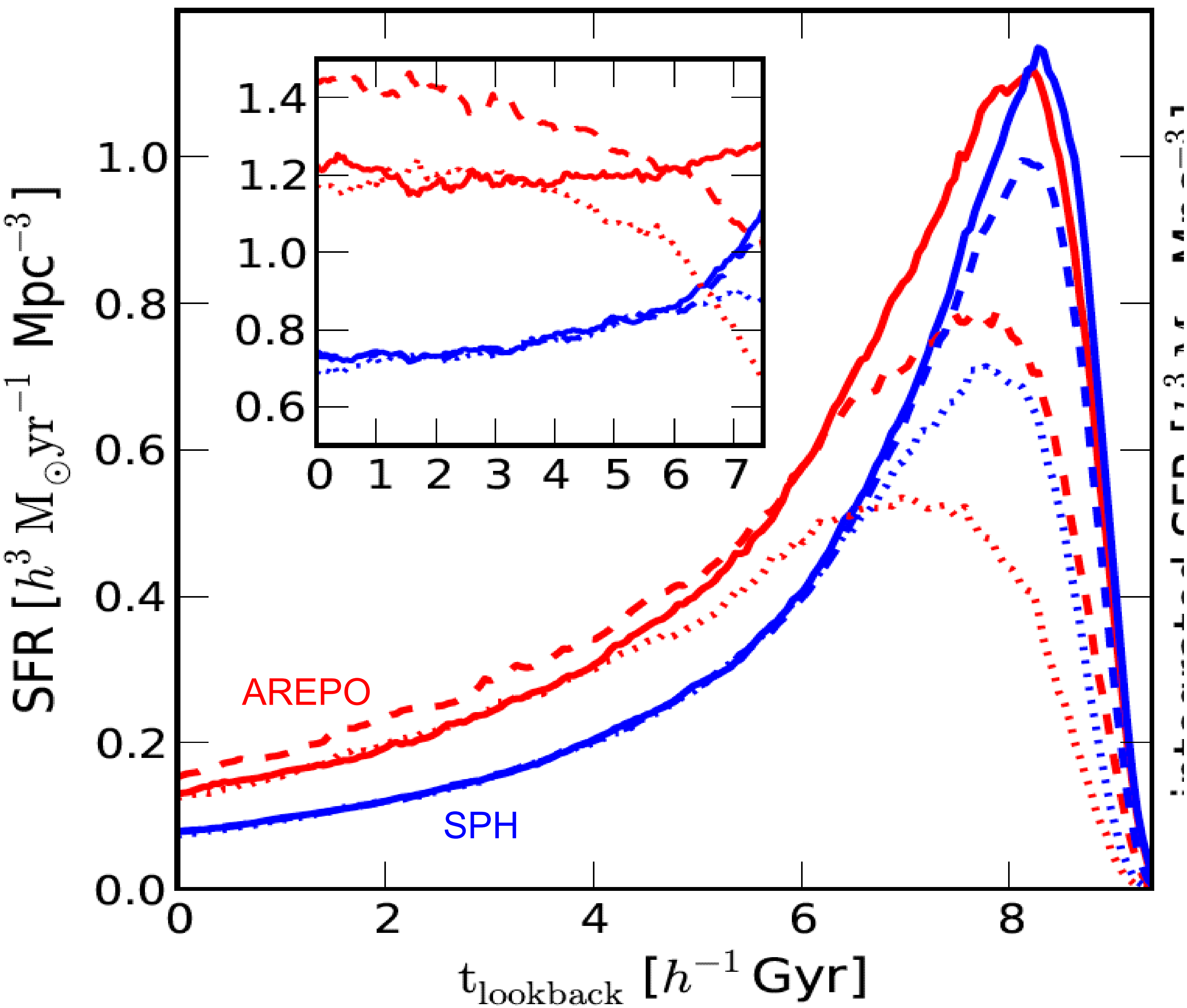
SFR-DENSITY AS A FUNCTION OF REDSHIFT FOR DIFFERENT RESOLUTIONS AND CODES

Vogelsberger et al. (2011)



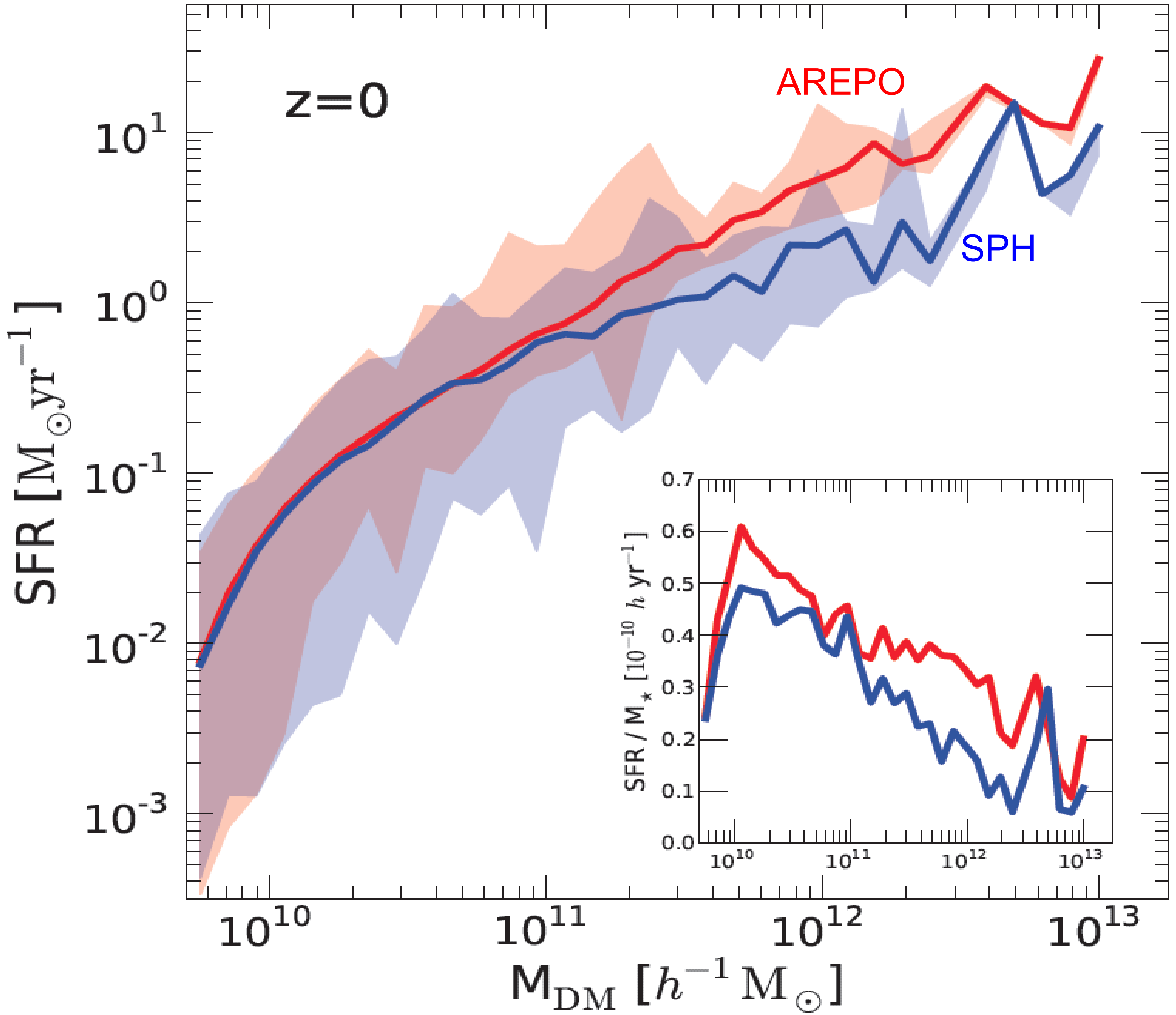
Compared with SPH, the cosmic star formation rate density is higher in AREPO at low redshift

SFR-DENSITY AS A FUNCTION OF TIME FOR DIFFERENT RESOLUTIONS AND CODES



The difference in star formation originates in massive halos

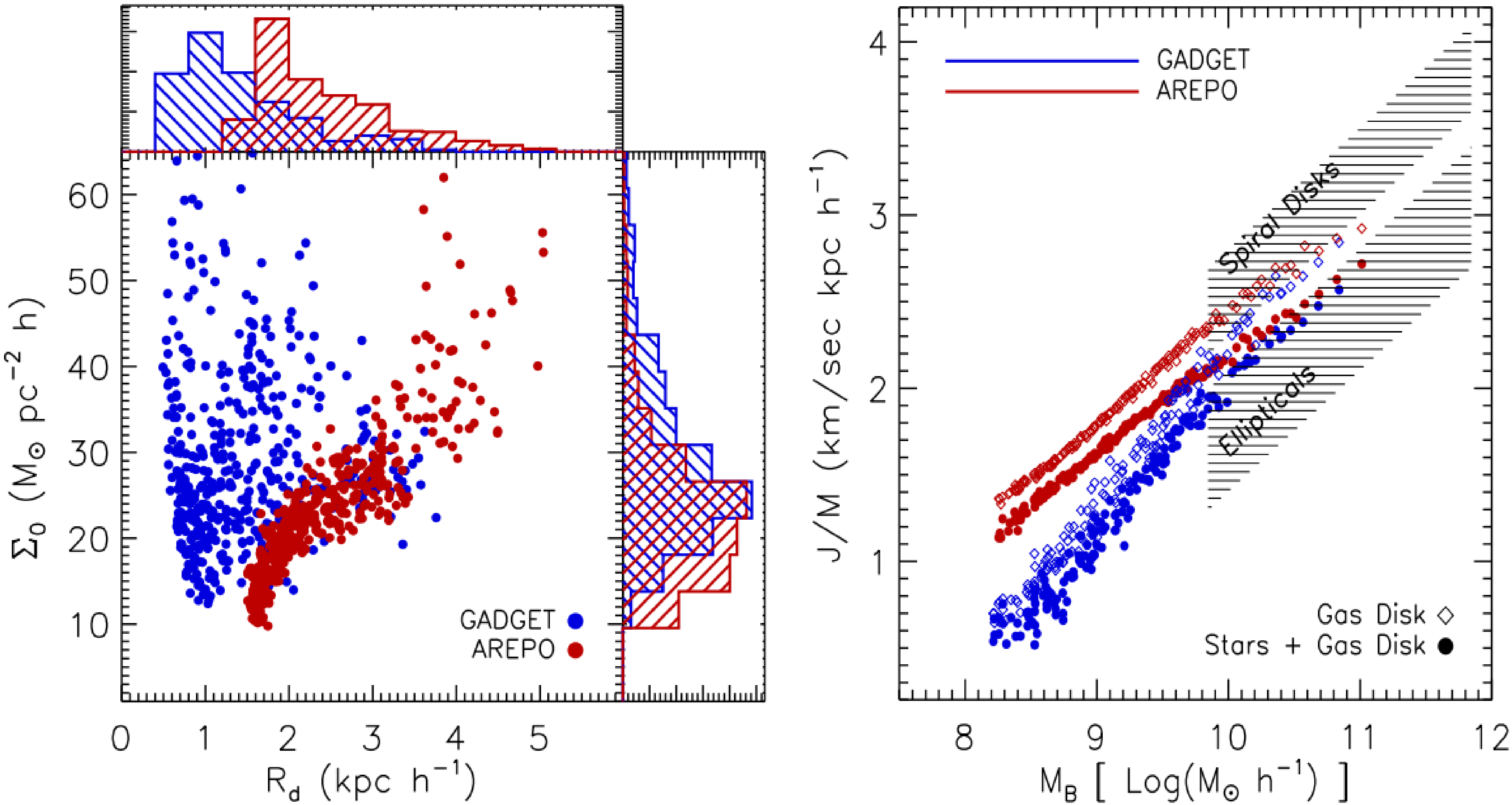
STAR FORMATION RATE AS A FUNCTION OF HALO MASS



Gasous disk scale lengths are much larger in the moving-mesh code

DISK SCALE LENGTHS AND ANGULAR MOMENTUM IN GADGET AND AREPO

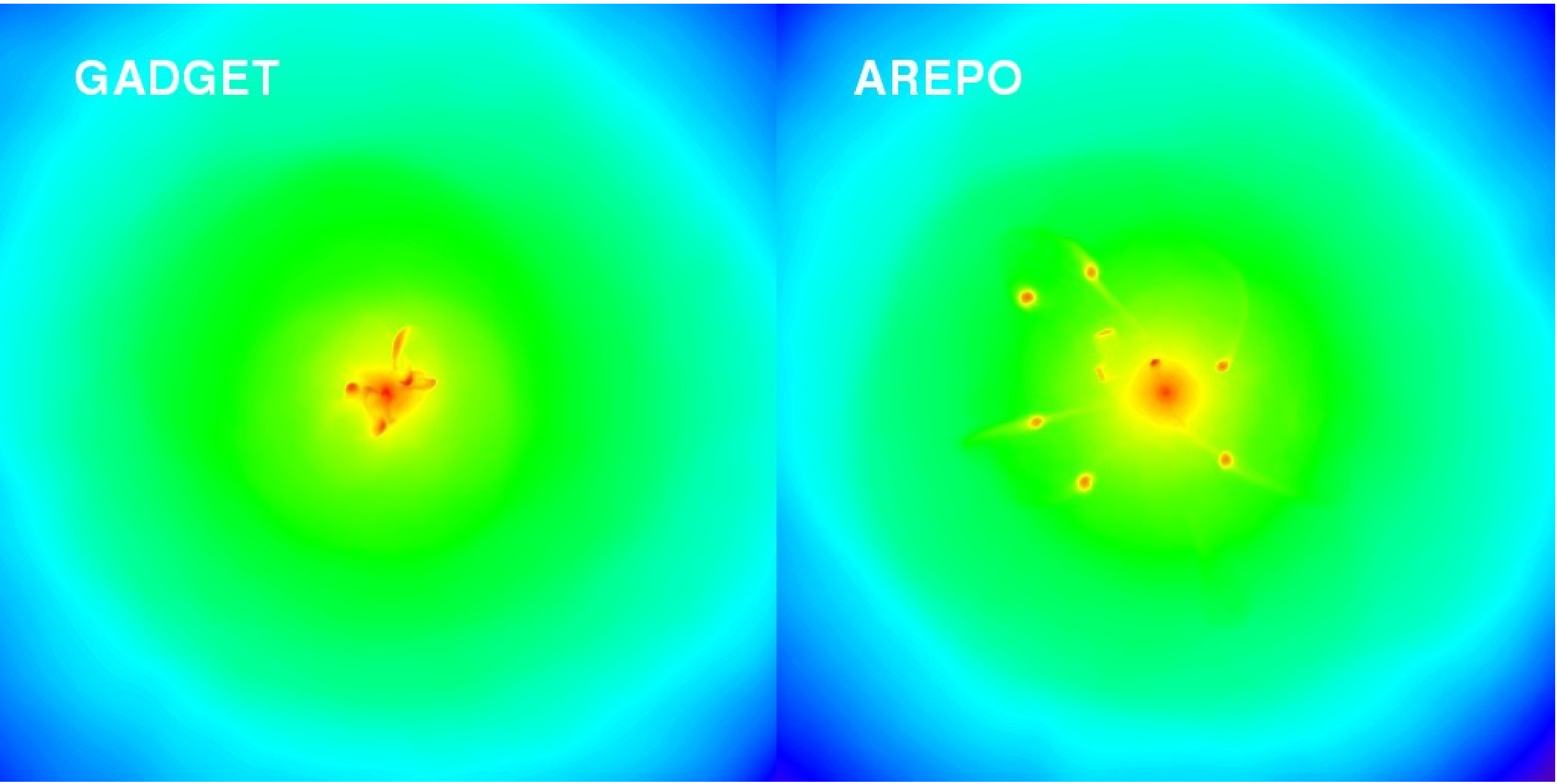
Torrey et al. (2011)



Satellite mass loss and orbitial decay is different in SPH and AREPO

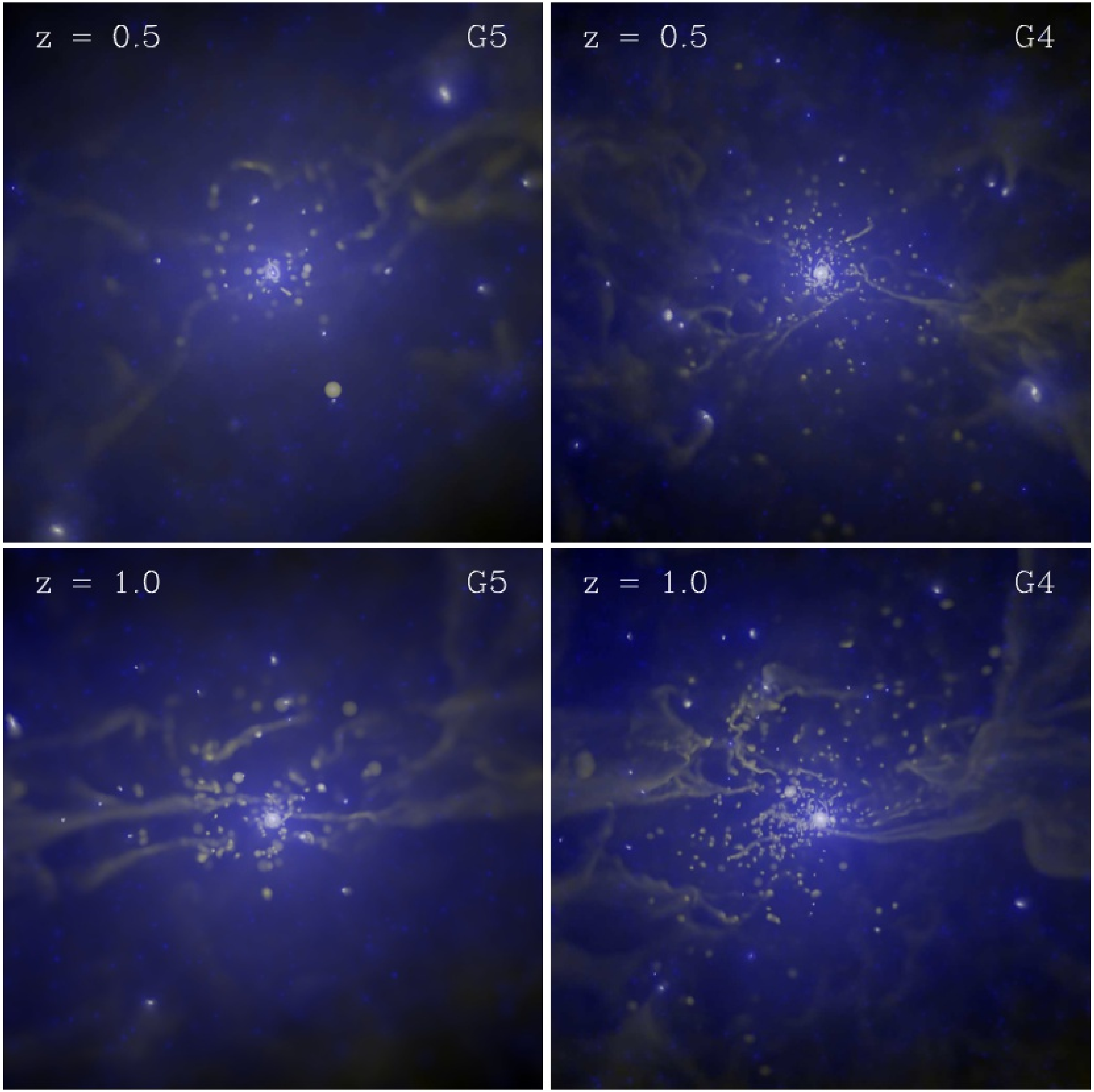
FIDUCIAL GAS BLOBS IN ORBIT IN A CLUSTER

Sijacki et al. (2011)



Clumpy gas distribution around Aquila galaxy in GADGET

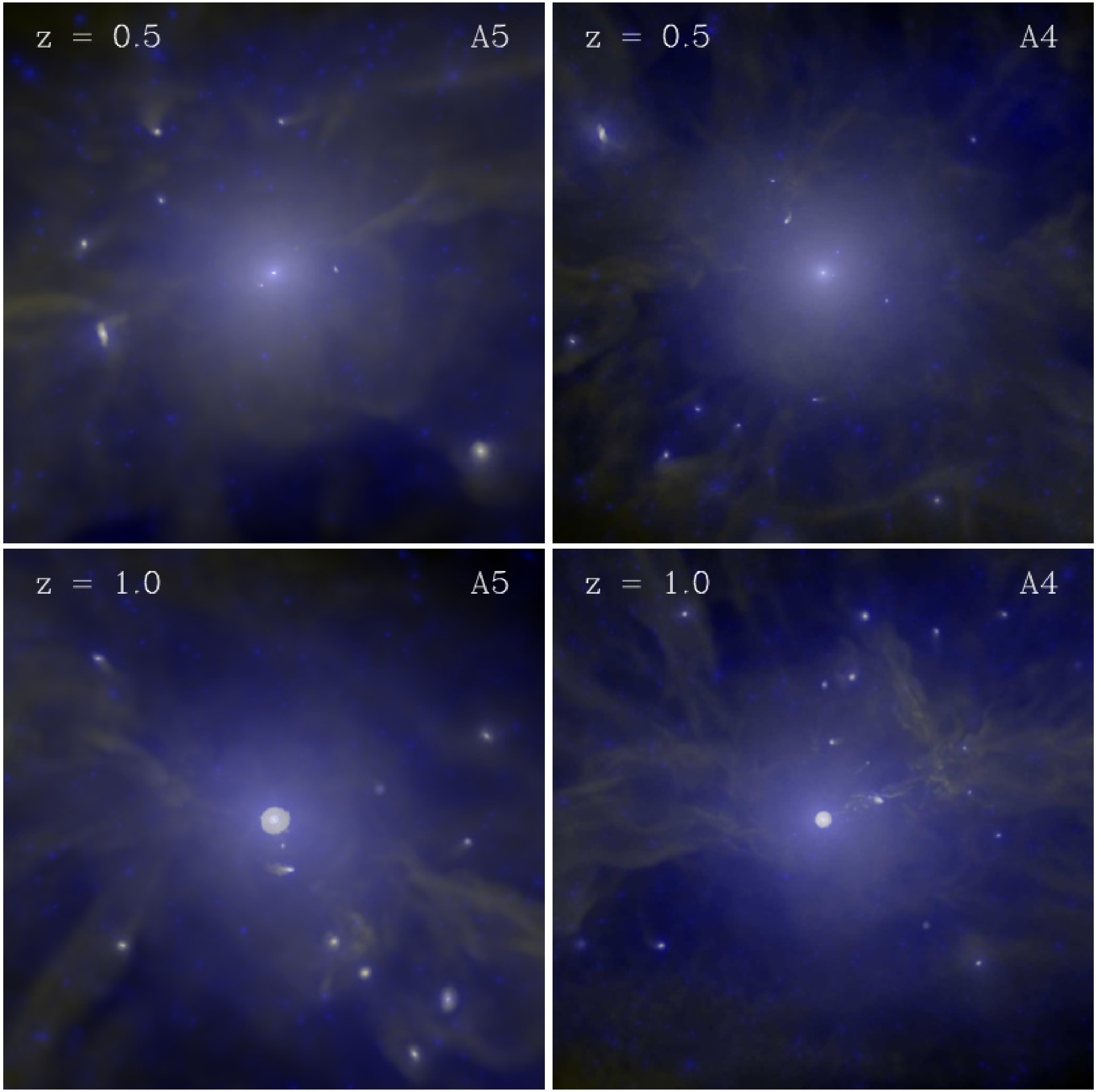
GAS BLOBS IN ORBIT AROUND AQUILA AT DIFFERENT TIMES AND RESOLUTIONS



Also seen, e.g, in ERIS (Guedes et al., 2011)

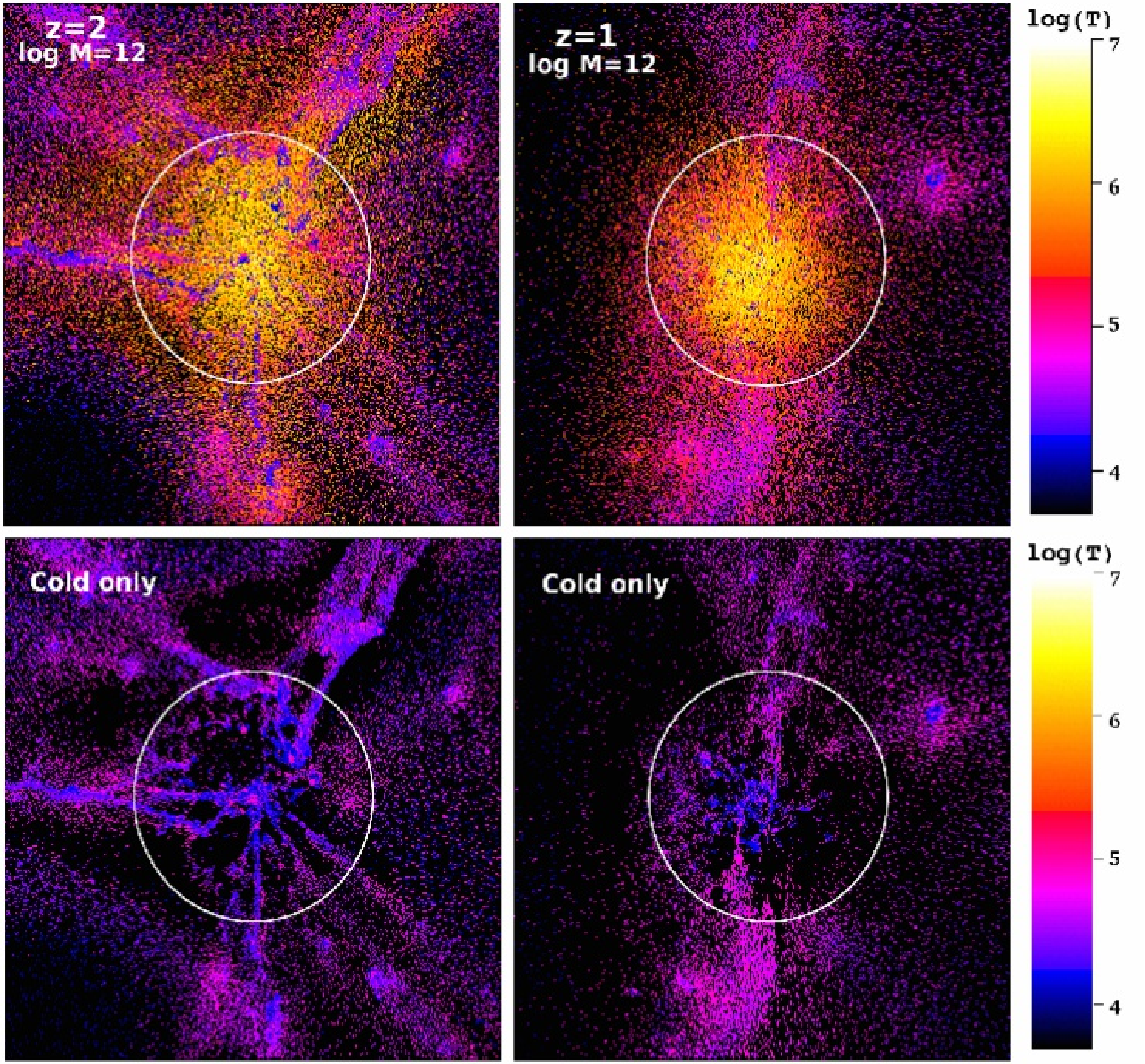
Smooth gas distribution around Aquila galaxy in AREPO

GAS IN THE HALO AT DIFFERENT TIMES AND RESOLUTIONS



How do galaxies get their gas?

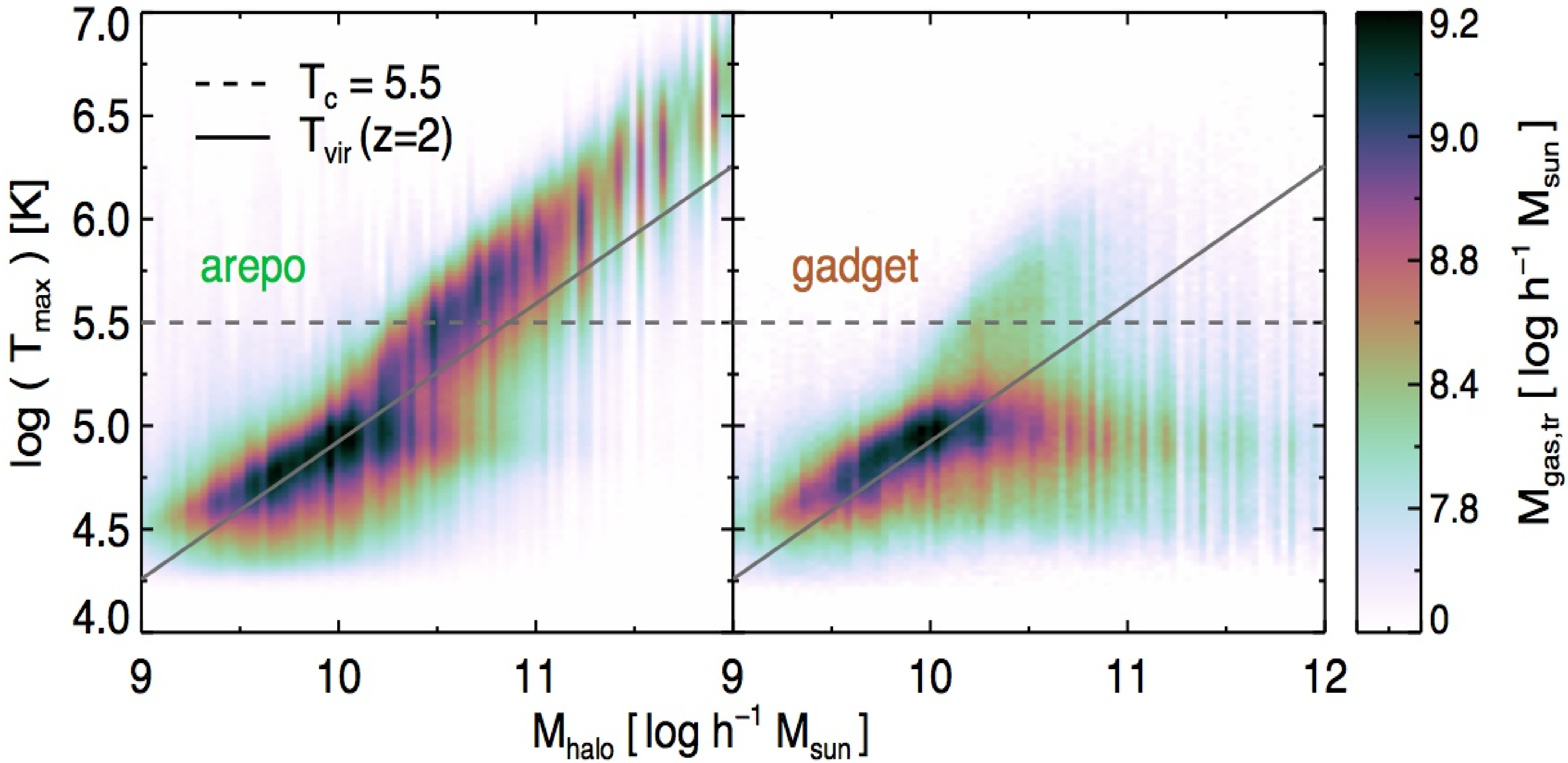
"COLD ACCRETION" HAS BEEN SUGGESTED AS DOMINANT MODE EVEN FOR LARGE HALOS



Keres et al. (2005, 2009)

There are marked differences in cold vs. hot accretion for massive galaxies

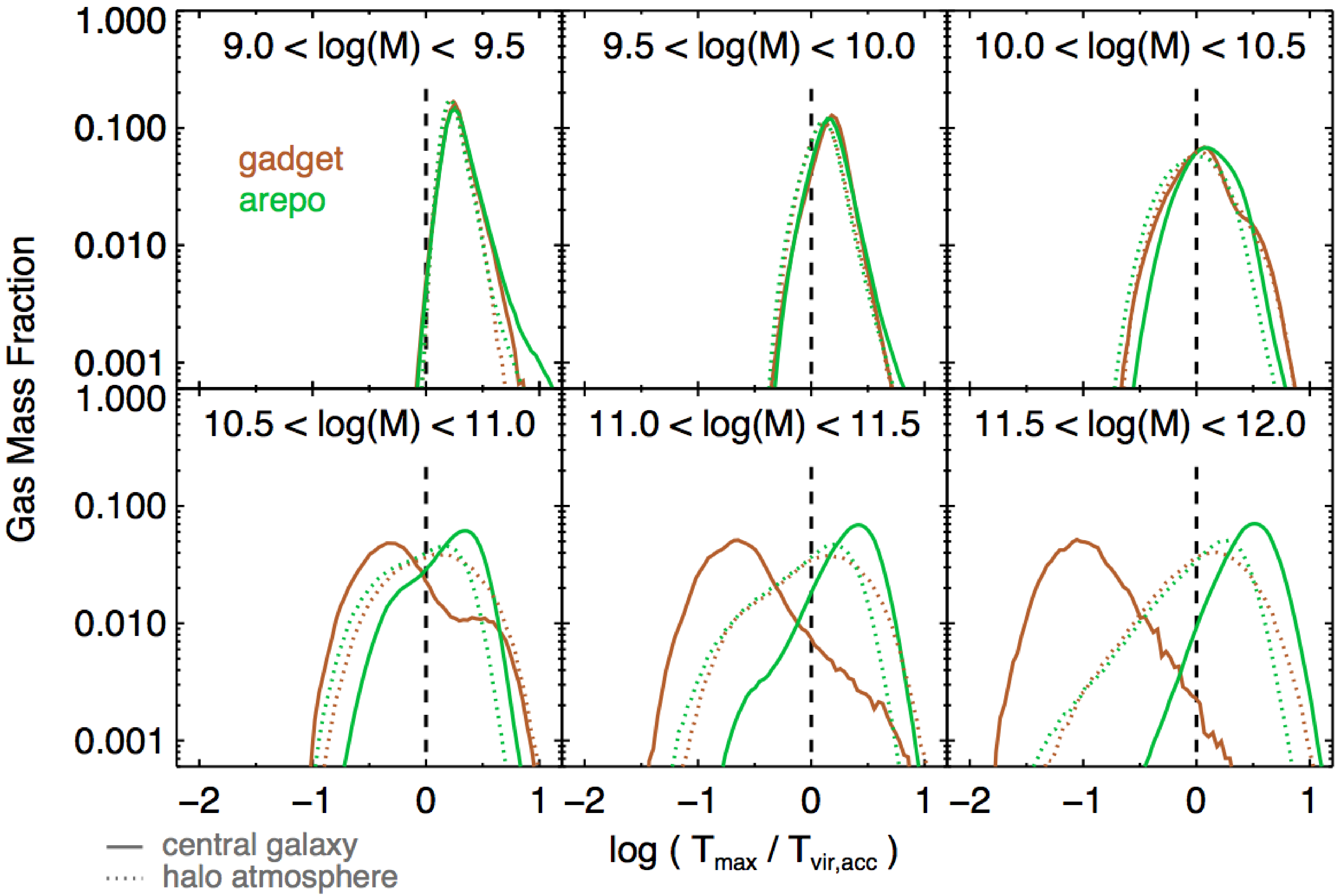
PAST MAXIMUM TEMPERATURE OF GAS ACCRETED ONTO CENTRAL GALAXIES



Nelson et al. (2012)

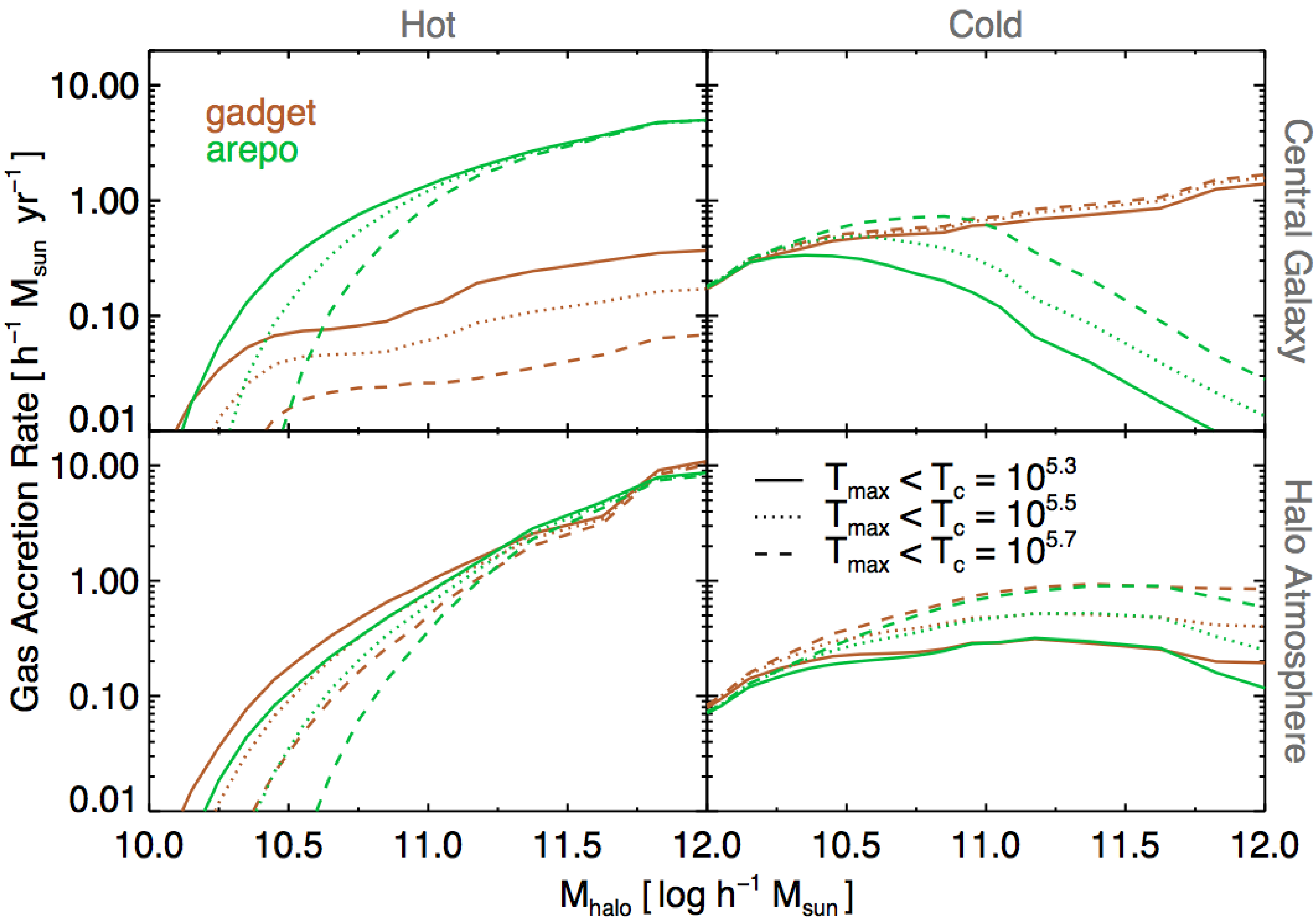
There are marked differences in cold vs. hot accretion for massive galaxies

DISTRIBUTION OF PAST MAXIMUM TEMPERATURE OF ACCRETED GAS AT Z = 2



The relative importance of "hot" and "cold" modes of accretion are different for massive halos

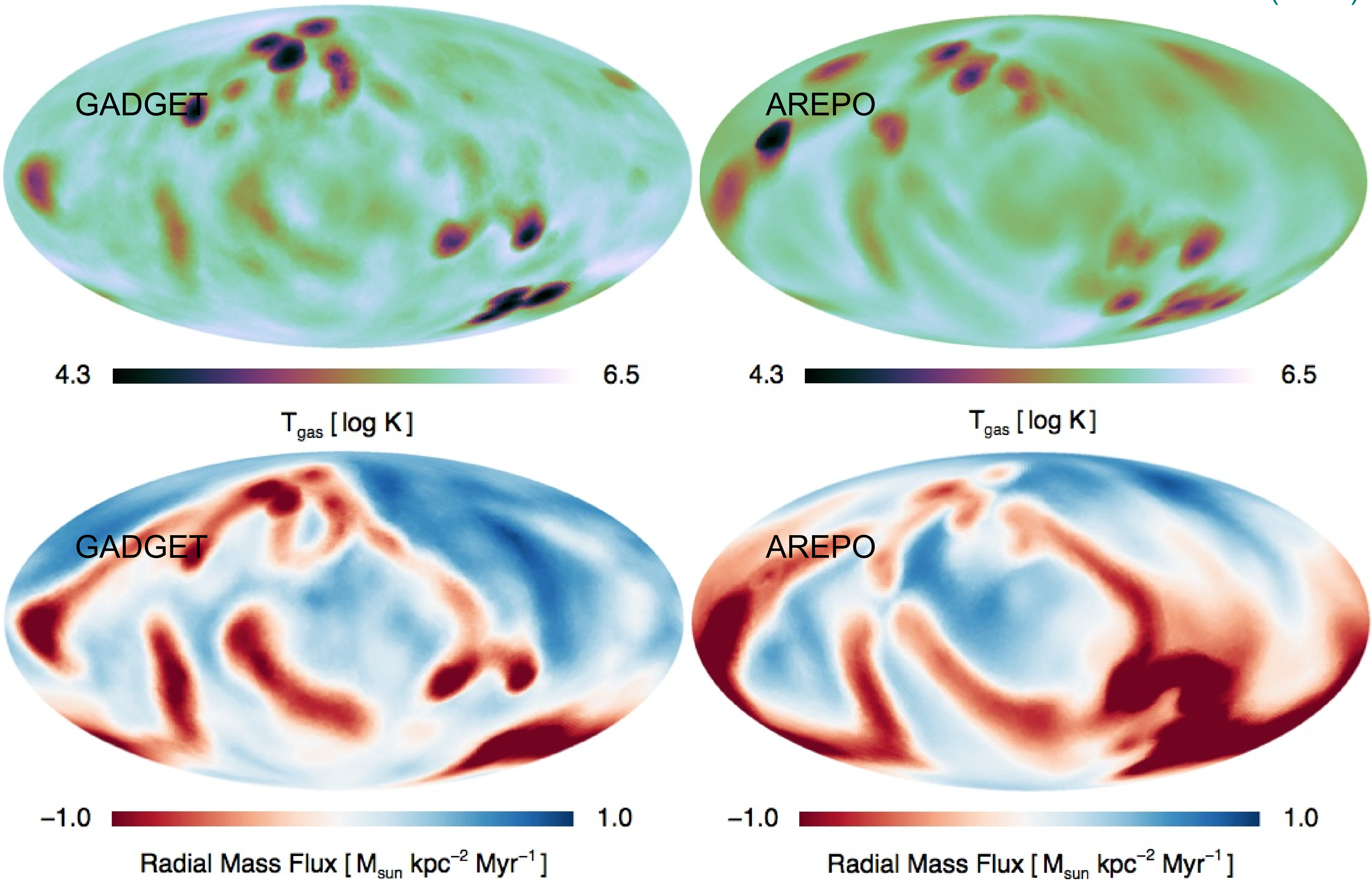
ACCRETION RATES OF HOT AND COLD GAS AS A FUNCTION OF HALO MASS AT Z = 2



At **the virial radius**, only moderate differences in the gas flow are seen

ALL-SKY MAPS OF GAS PROPERTIES AROUND A TYPICAL log(M)=11.5 HALO AT Z=2

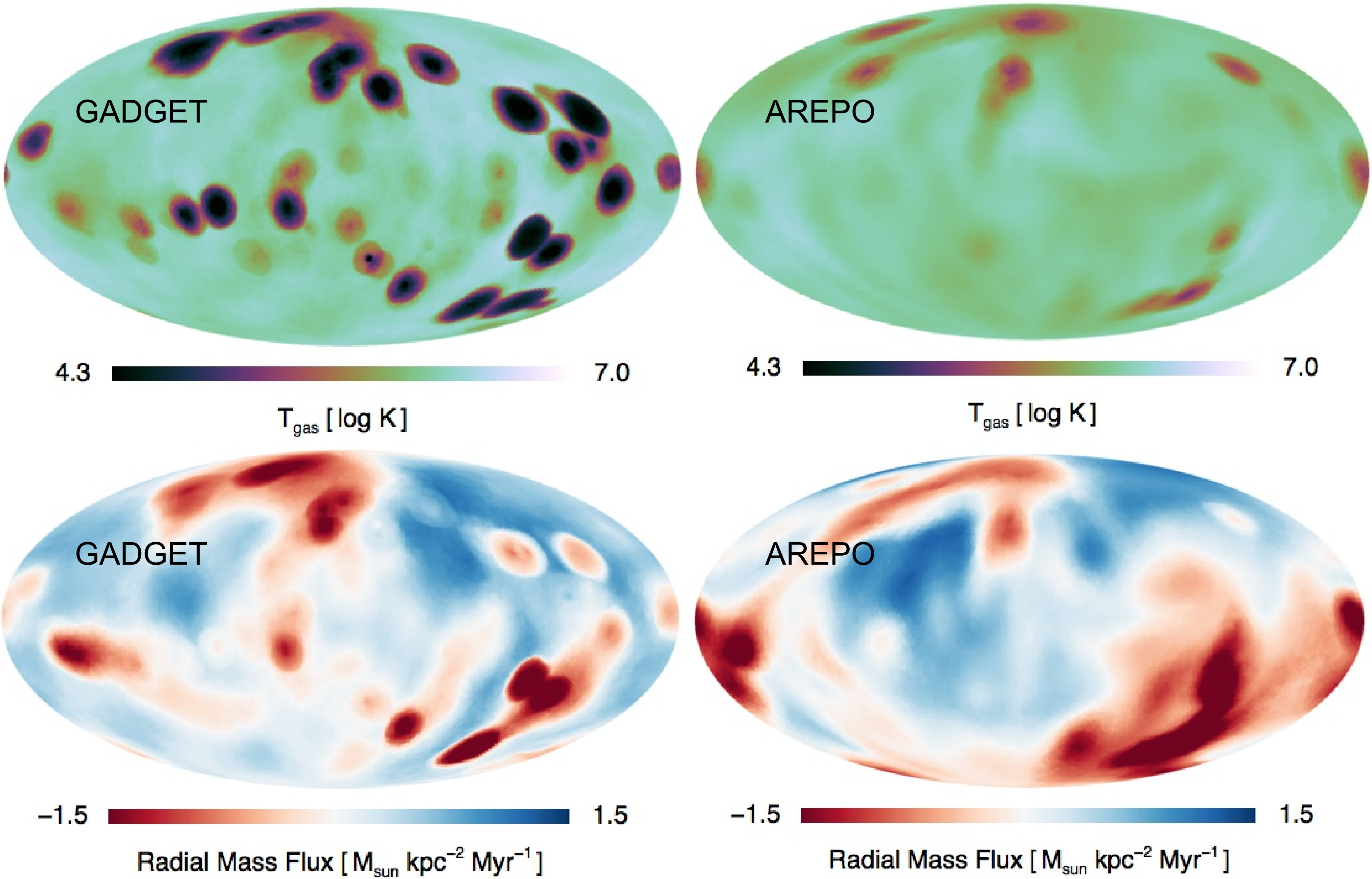
Nelson et al. (2012)



At **half the virial radius**, pronounced differences in the gas flow are apparent

ALL-SKY MAPS OF GAS PROPERTIES AROUND A TYPICAL HALO

Nelson et al. (2012)



Summary points

- Direct numerical simulations have become indispensable for studying the non-linear growth of structures in ΛCDM and modified gravity cosmologies.

- Current numerical techniques allow high-resolution simulations with an unprecedented dynamic range.

  One presently reaches $N>10^{11}$, with a dynamic range of $10^5 - 10^7$ in 3D.

- Understanding galaxy formation physics remains a serious challenge in ΛCDM, both at the faint and the bright end.

- New moving-mesh techniques provide an accurate alternative technique for structure formation simulations. First results suggest that they are of great help to arrive at more reliable predictions for galaxy formation.