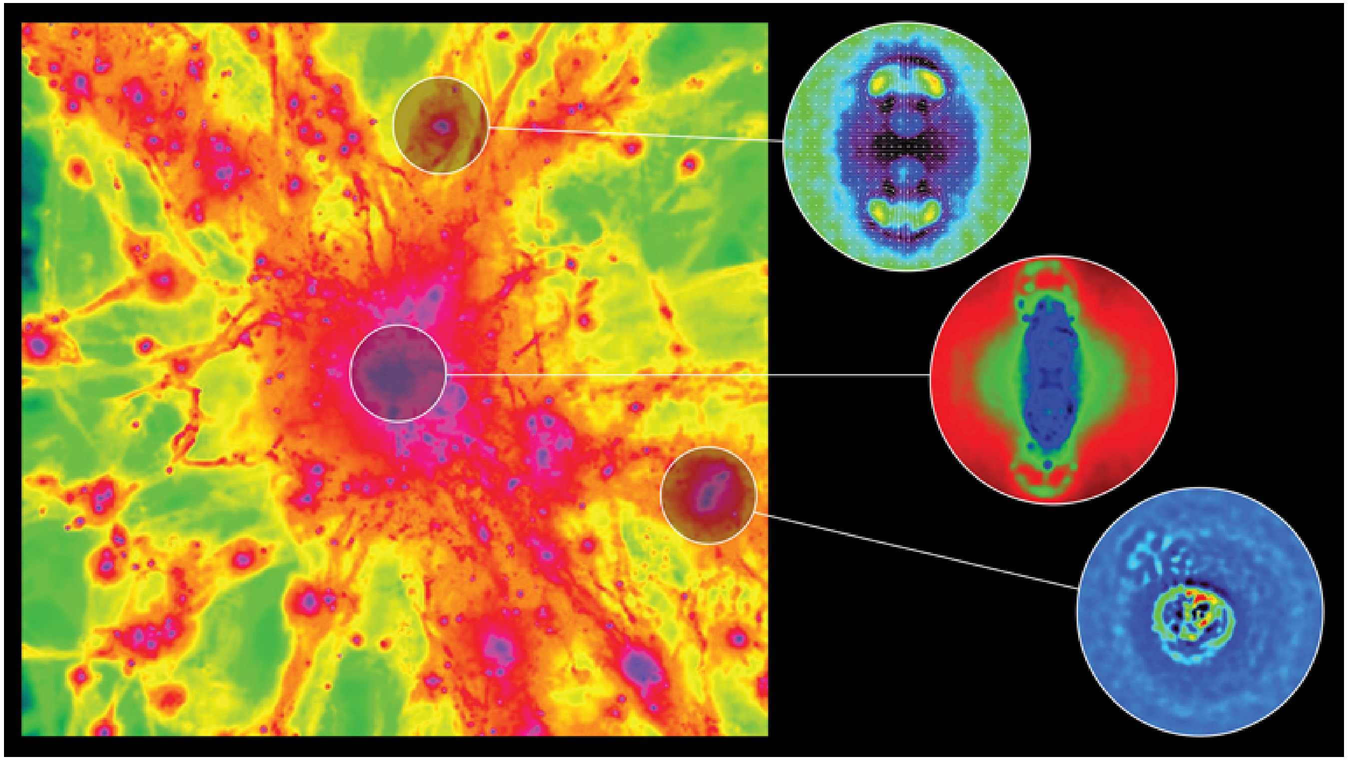
Simulating galaxy formation:

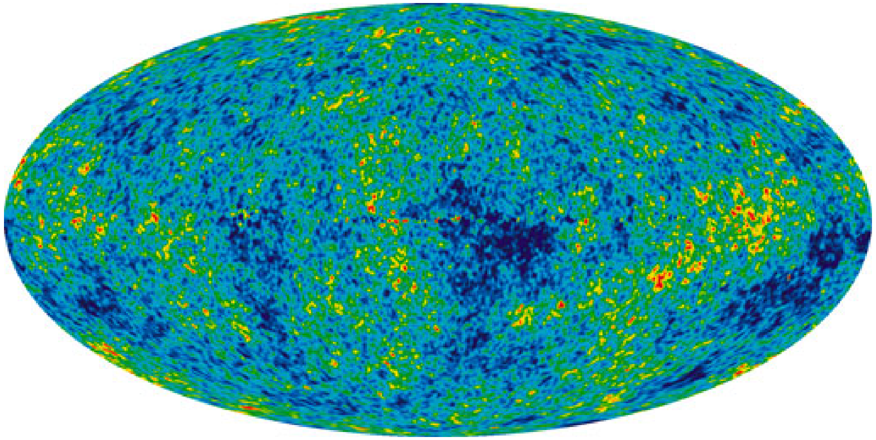
numerical and physical uncertainties



Debora Sijacki
IoA & KICC
Cambridge

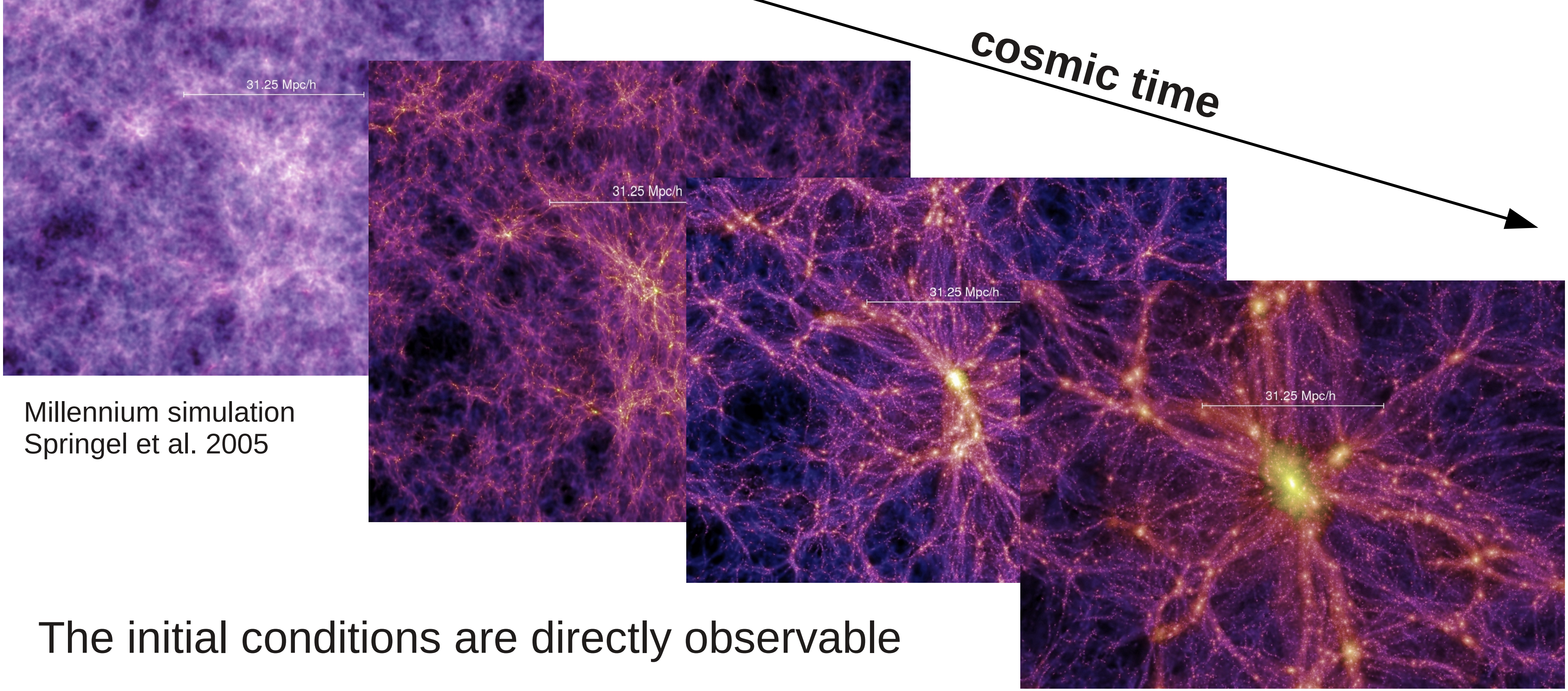
Trieste Seminar
April 9 2014

Cosmological simulations of galaxy and structure formation



Planck data, 2013

Parameter	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031
Ω_Λ	0.6964	0.693 ± 0.019
σ_8	0.8285	0.823 ± 0.018
H_0	68.14	67.9 ± 1.5
Age/Gyr	13.784	13.796 ± 0.058



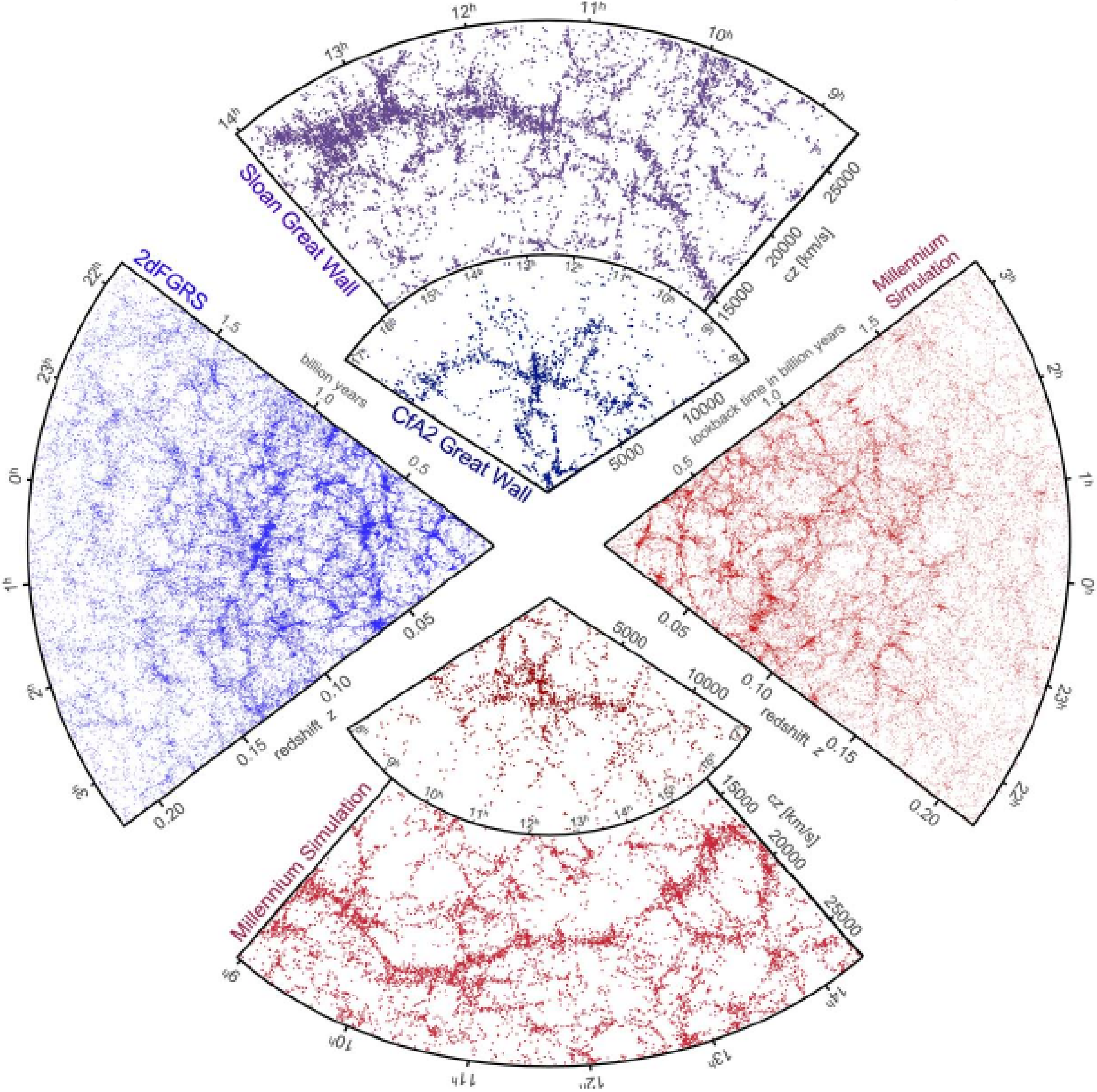
Millennium simulation
Springel et al. 2005

The initial conditions are directly observable

Pure dark matter simulations in ΛCDM cosmology

Simulated and observed large-scale structure in the galaxy distribution

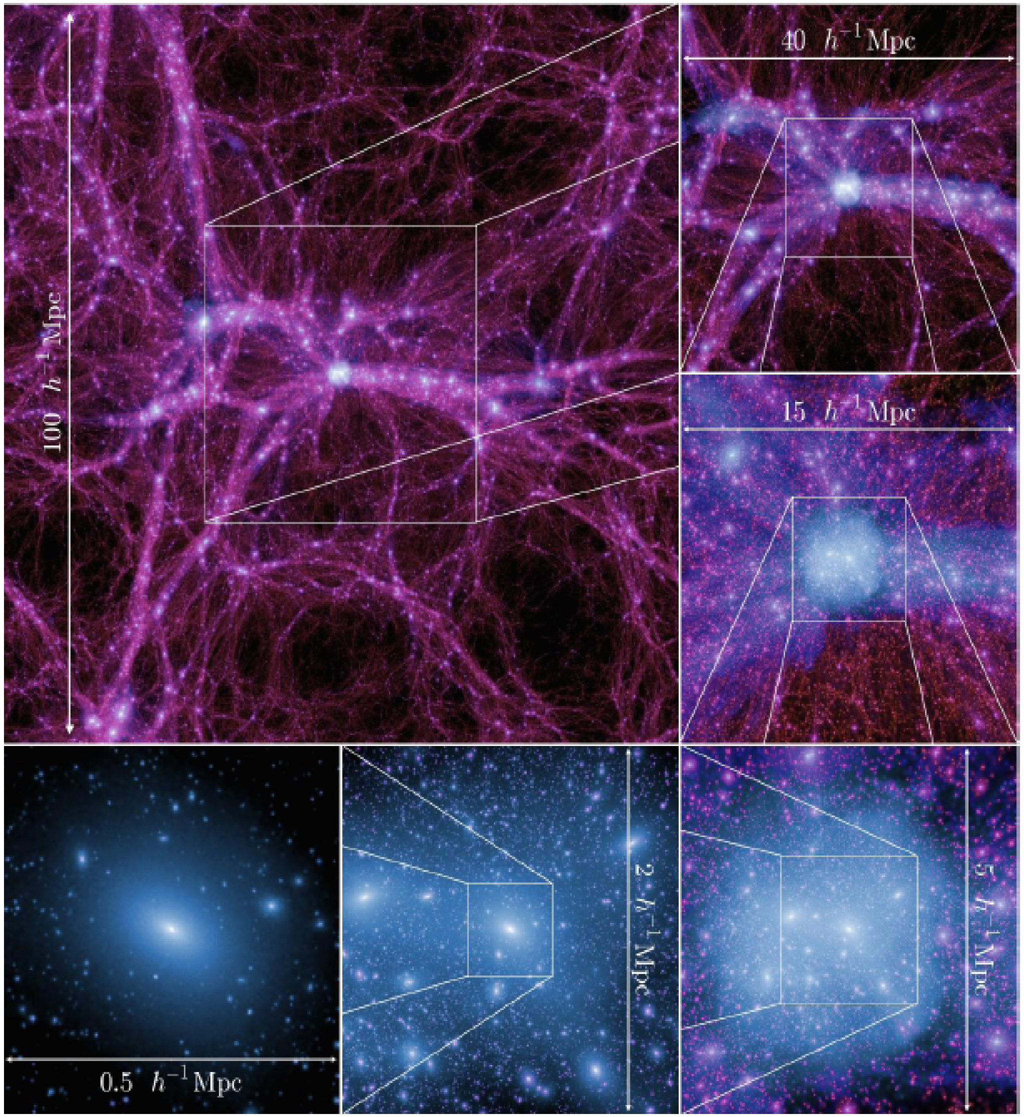
MOCK PIE DIAGRAMS COMPARED TO SDSS, 2DFGRS, AND CFA-2



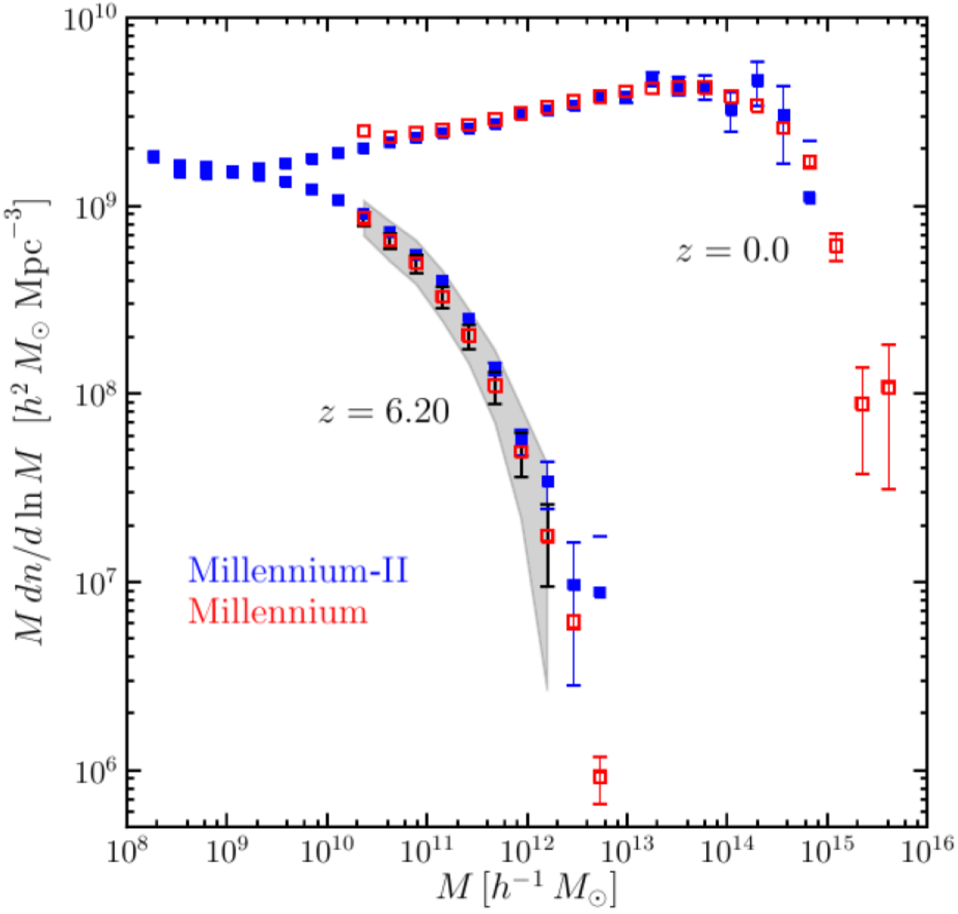
Springel et al. (2006)

Pure dark matter simulations in ΛCDM cosmology

Hierarchical growth of structure: need for a huge dynamical range!



halo mass function

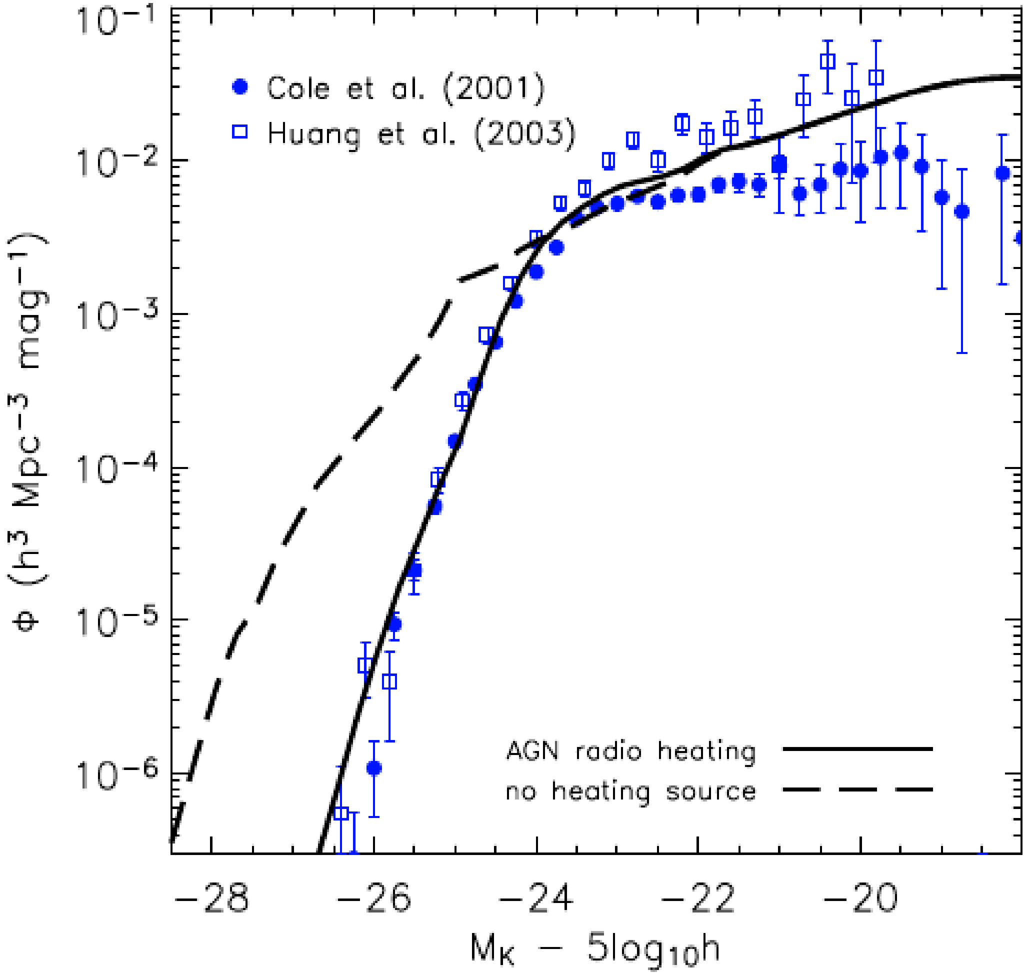


Boylan-Kolchin et al. (2009)

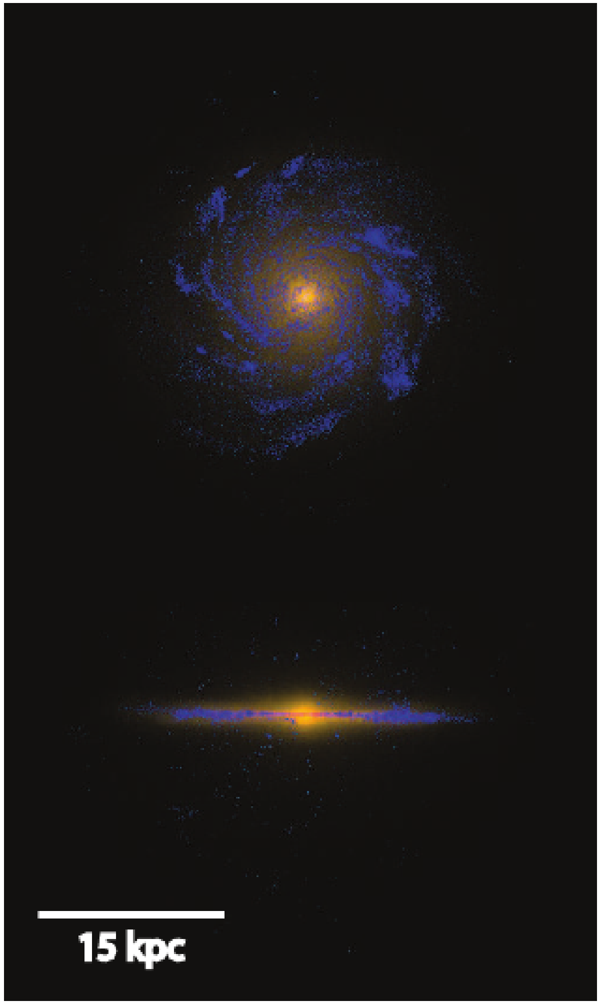
From dark matter to baryons

semi-analytical modeling

hydrodynamics simulations



e.g. Croton et al. (2006), DeLucia & Blazoit (2007), Benson (2010),...



e.g. Guedes et al. 2011

Hydrodynamical simulations

For ideal inviscid gas

Euler equations: conservation laws for mass, momentum and energy

$$\frac{\partial \boldsymbol{U}}{\partial t} + \boldsymbol{\nabla} \cdot \boldsymbol{F} = 0$$

State vector:

$$\boldsymbol{U} = \left(\begin{array}{c} \rho \\ \rho \boldsymbol{v} \\ \rho e \end{array} \right) = \left(\begin{array}{c} \rho \\ \rho \boldsymbol{v} \\ \rho u + \frac{1}{2} \rho \boldsymbol{v}^2 \end{array} \right)$$

Flux vector:

$$\boldsymbol{F}(\boldsymbol{U}) = \left(\begin{array}{c} \rho \boldsymbol{v} \\ \rho \boldsymbol{v} \boldsymbol{v}^T + P \\ (\rho e + P) \boldsymbol{v} \end{array} \right)$$

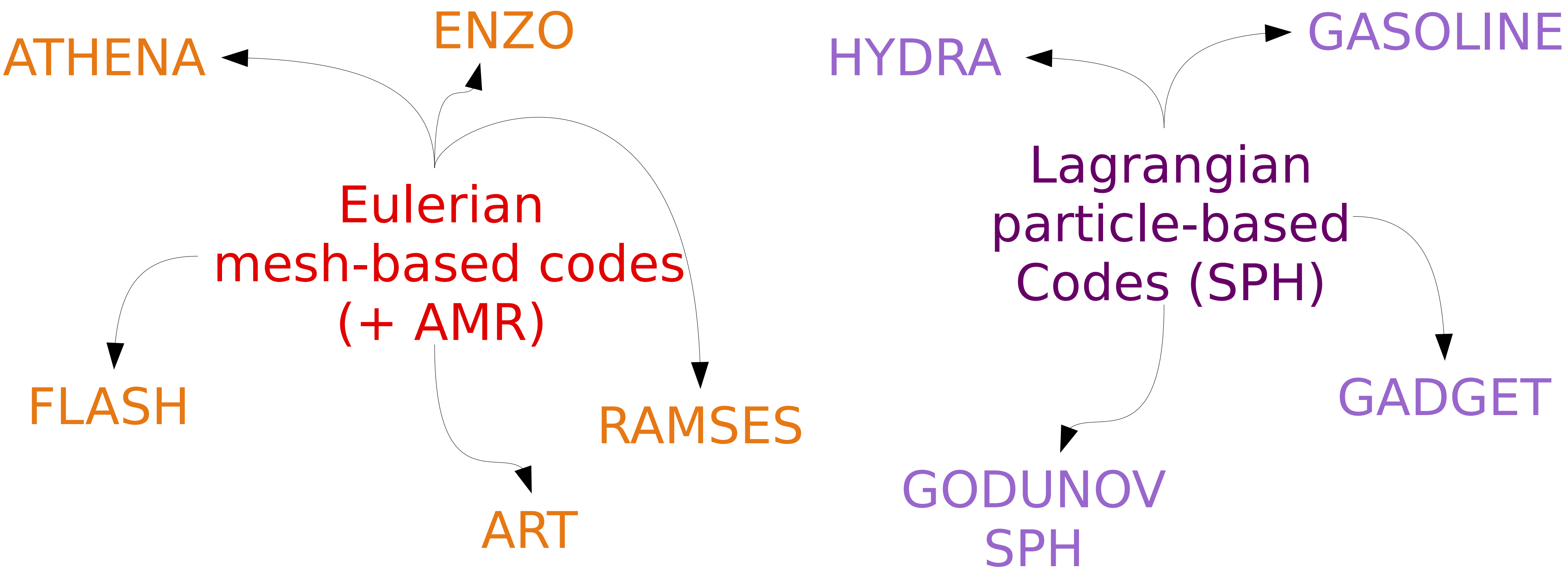
Equation of state:

$$P = (\gamma - 1) \rho u$$

Uncertainties in...

...hydro and gravity solvers of different codes used to simulate galaxy formation

- Much more careful code comparisons are needed!
- Improvements in basic code solvers



Eulerian mesh-based codes (+ AMR)

ATHENA

ENZO

FLASH

ART

RAMSES

Lagrangian particle-based Codes (SPH)

HYDRA

GASOLINE

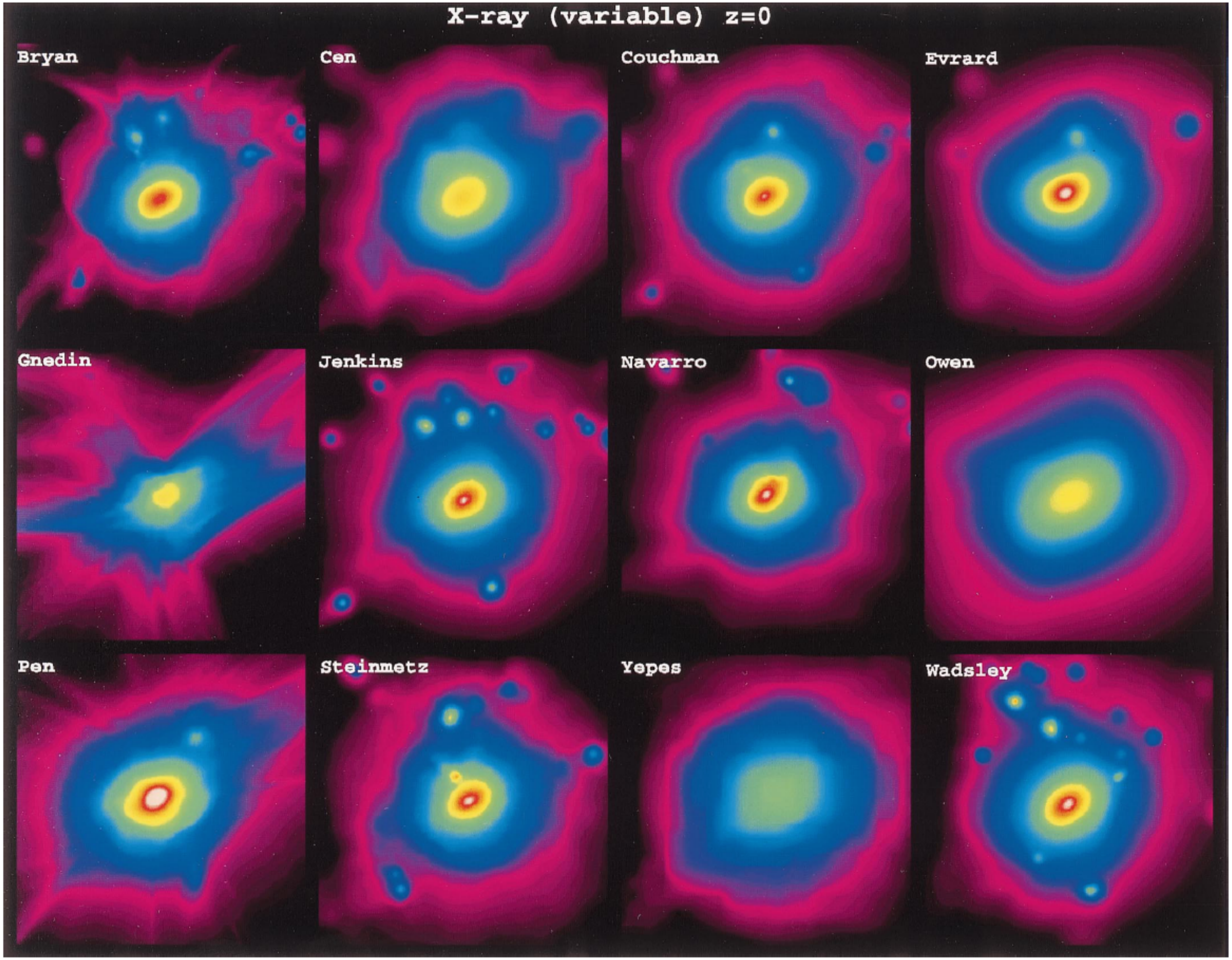
GADGET

GODUNOV SPH

The Santa Barbara Cluster Comparison Project

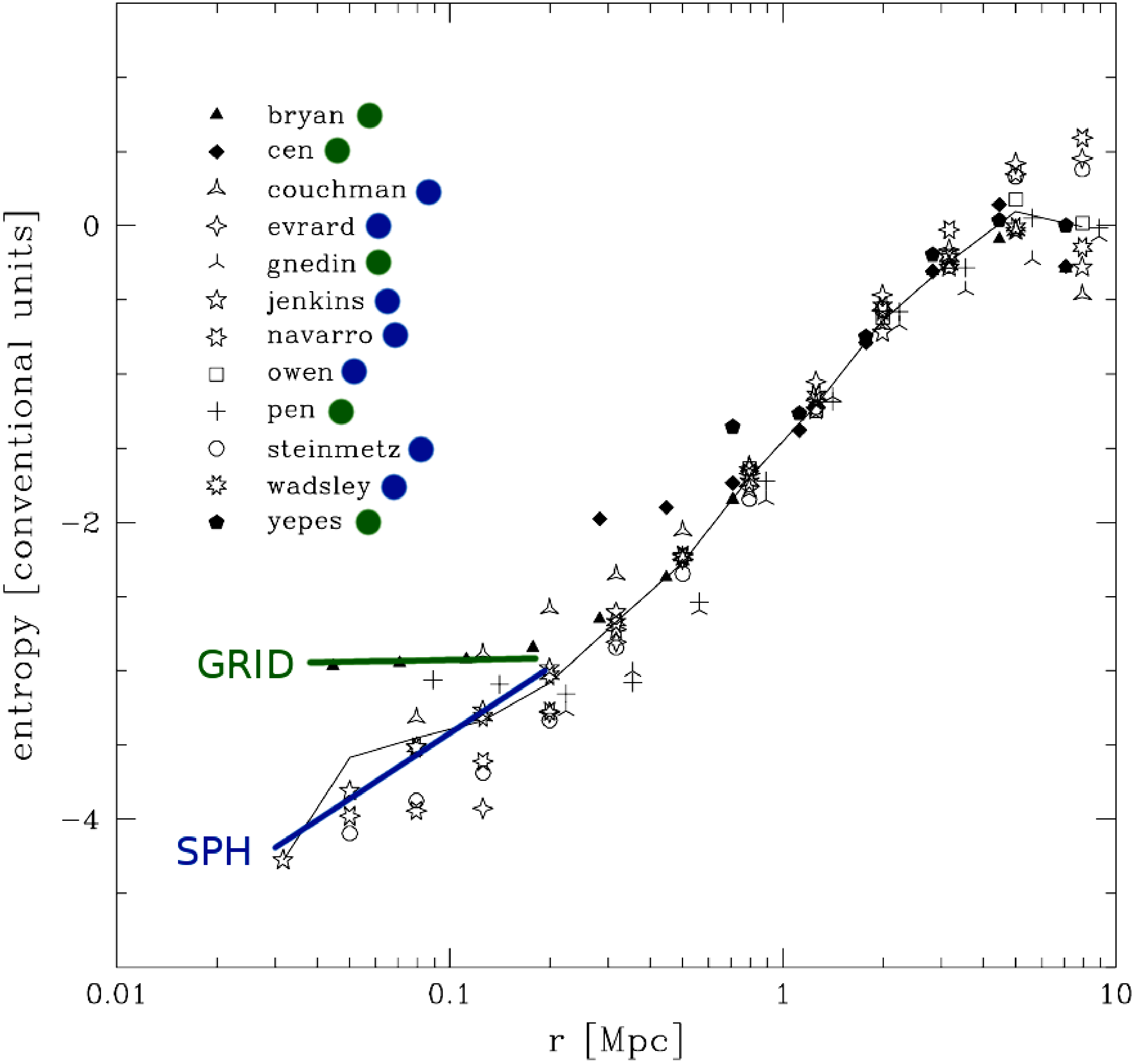
Frenk et al. 1999

Non-radiative cosmological hydrodynamical simulations
comparison of 12 different codes



The Santa Barbara Cluster Comparison Project

Frenk et al. 1999



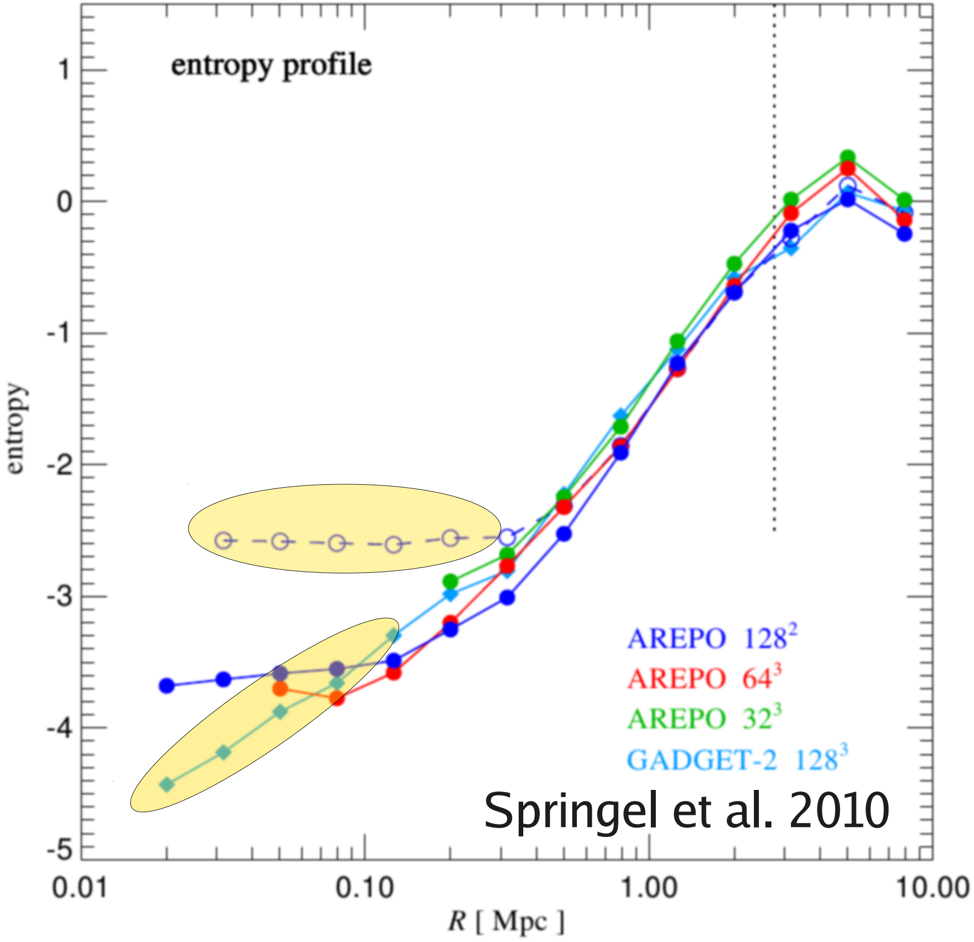
SPH simulations:
power-law entropy profiles

GRID-based simulations:
cored entropy profiles

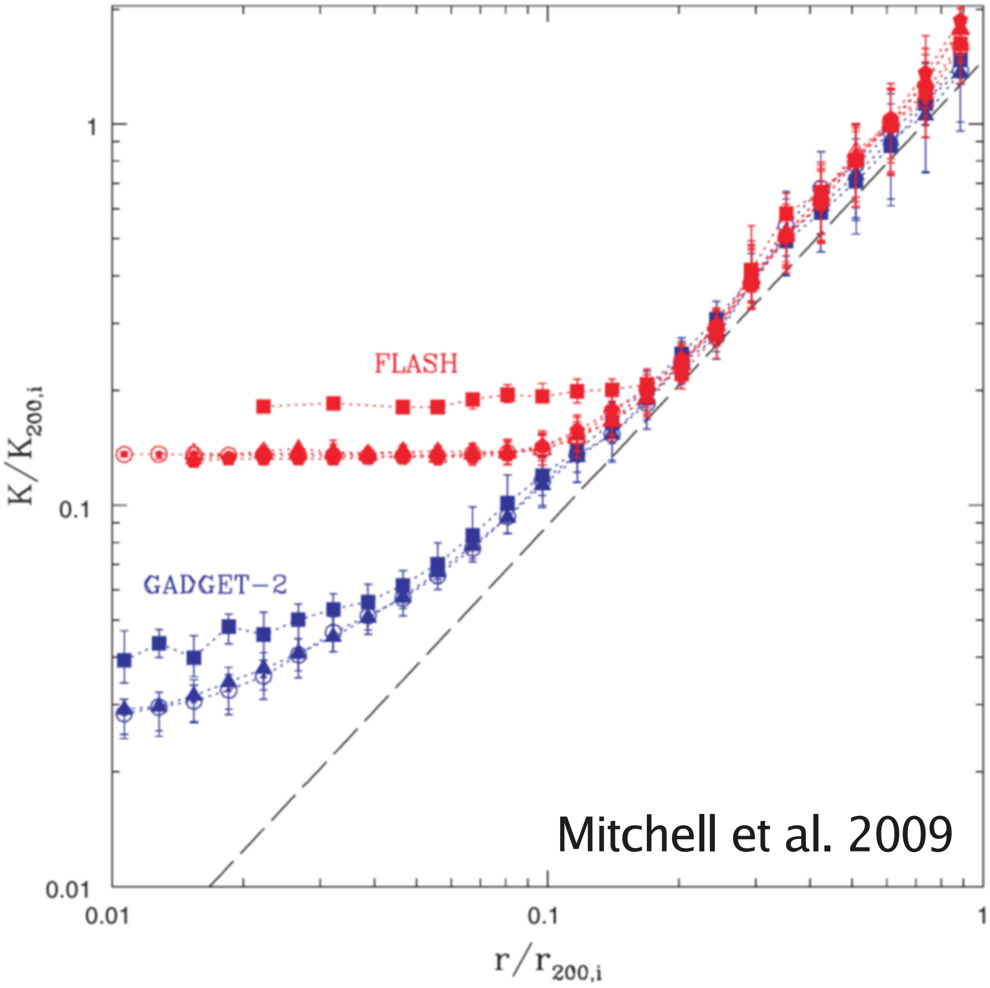
Discrepancy between SPH and grid entropy profiles

What causes this discrepancy?

- lower effective resolution of grid codes?
- different gravity solvers?
- Galilean non-invariance of grid codes?
- artificial viscosity of SPH codes?
- treatment of fluid instabilities?
- gravitational N-body noise?
- ???



Springel et al. 2010



Mitchell et al. 2009

FUNDAMENTAL IMPLICATIONS FOR:
- **UNDERSTANDING ASTROPHYSICS OF GALAXY CLUSTERS**
- **USING GALAXY CLUSTERS AS HIGH-PRECISION COSMOLOGICAL PROBES**

CODE COMPARISON PROJECT

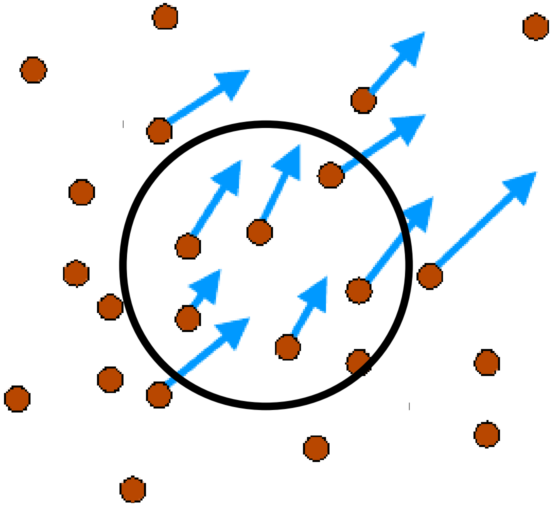
standard SPH

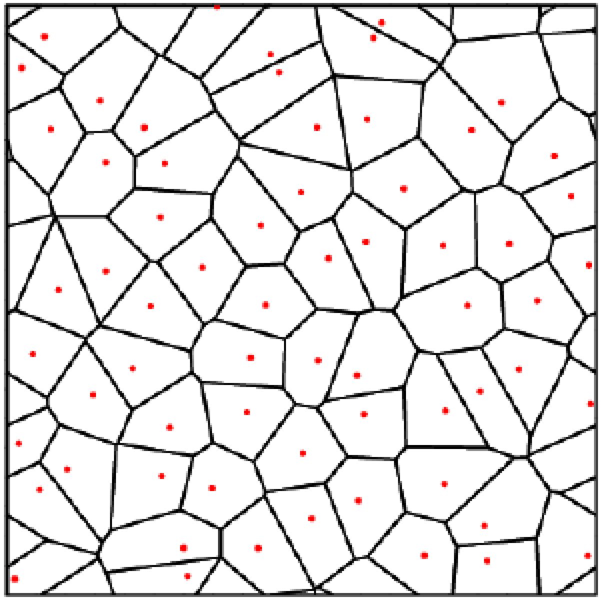
GADGET (Springel et al. 2005)
Lagrangian method (SPH)
particles act as fluid elements

AREPO (Springel et al. 2010)
finite volume method on a
moving mesh (Lagrangian nature)

- fluid represented by a set of particles
- gas density, velocity etc. estimated by kernel averaging over a certain number of particles

- fluid represented by a set of cells
- compute fluxes at cell faces





CODE COMPARISON PROJECT

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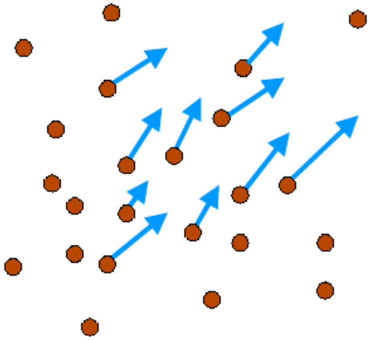
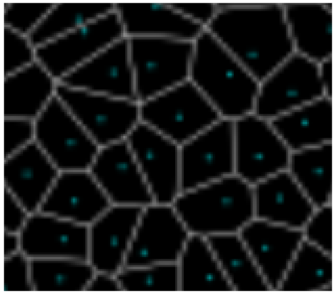


IDENTICAL INITIAL CONDITIONS
IDENTICAL GRAVITY SOLVER
IDENTICAL SUB-GRID PHYSICS



DIFFERENT
HYDRO SOLVER

TESTS WITH INCREASING COMPLEXITY
from idealized experiments with known analytic solutions to realistic, cosmologically motivated simulations

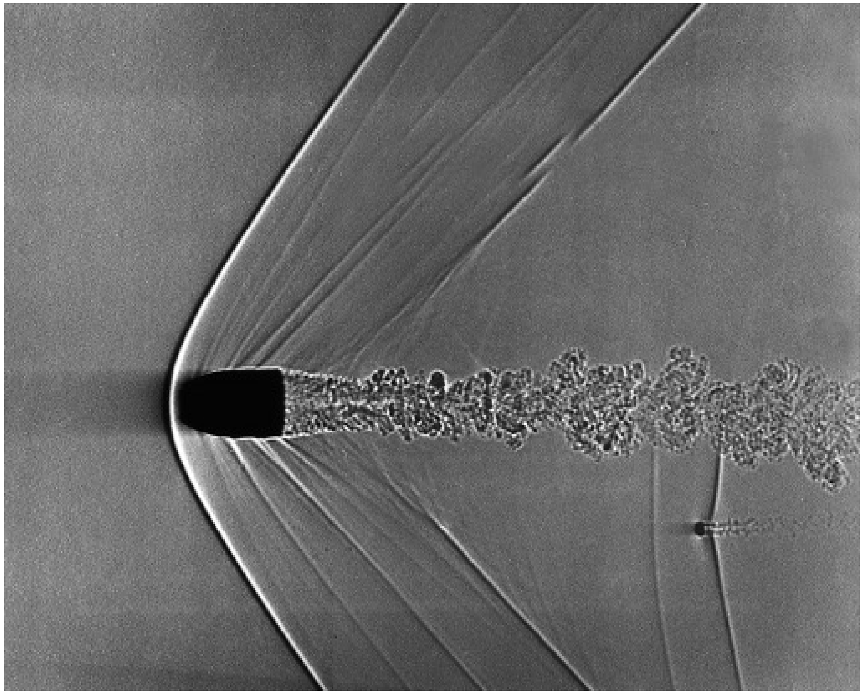
UNDERSTAND DIFFERENCES
IN FULL COSMOLOGICAL SIMULATIONS

Bow shock in 3D

“BLOB” experiment (e.g. Agertz et al. 2007):

- high density blob in pressure equilibrium with surrounding hot medium

- high external medium velocity



tests:

- development of dynamical instabilities, such as RT and KH

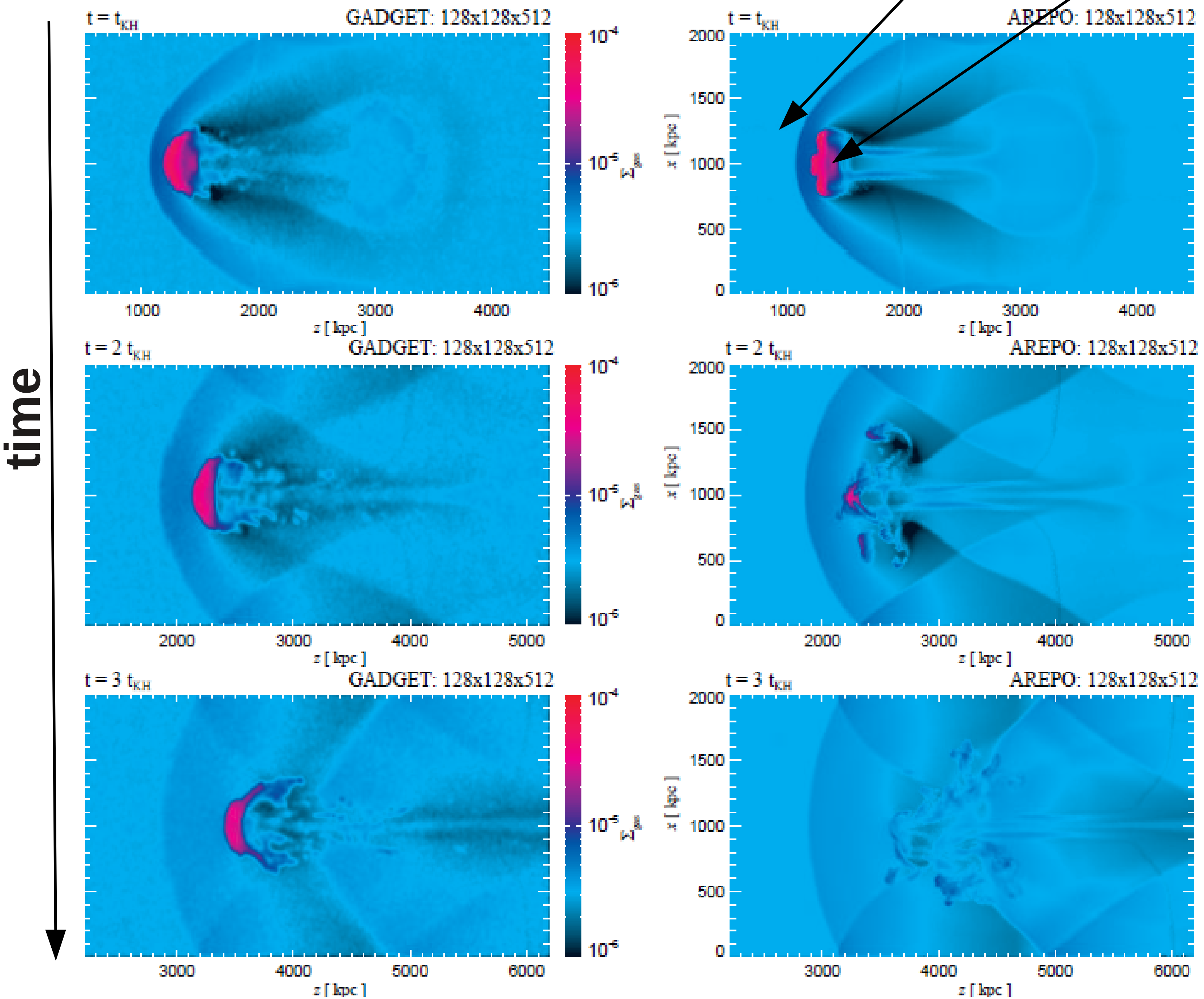
implications for:
- survival of satellites in clusters
- mixing of multi-phase medium
- level of turbulence

Bow shock in 3D

“BLOB” experiment:

HOT WINDTUNNEL

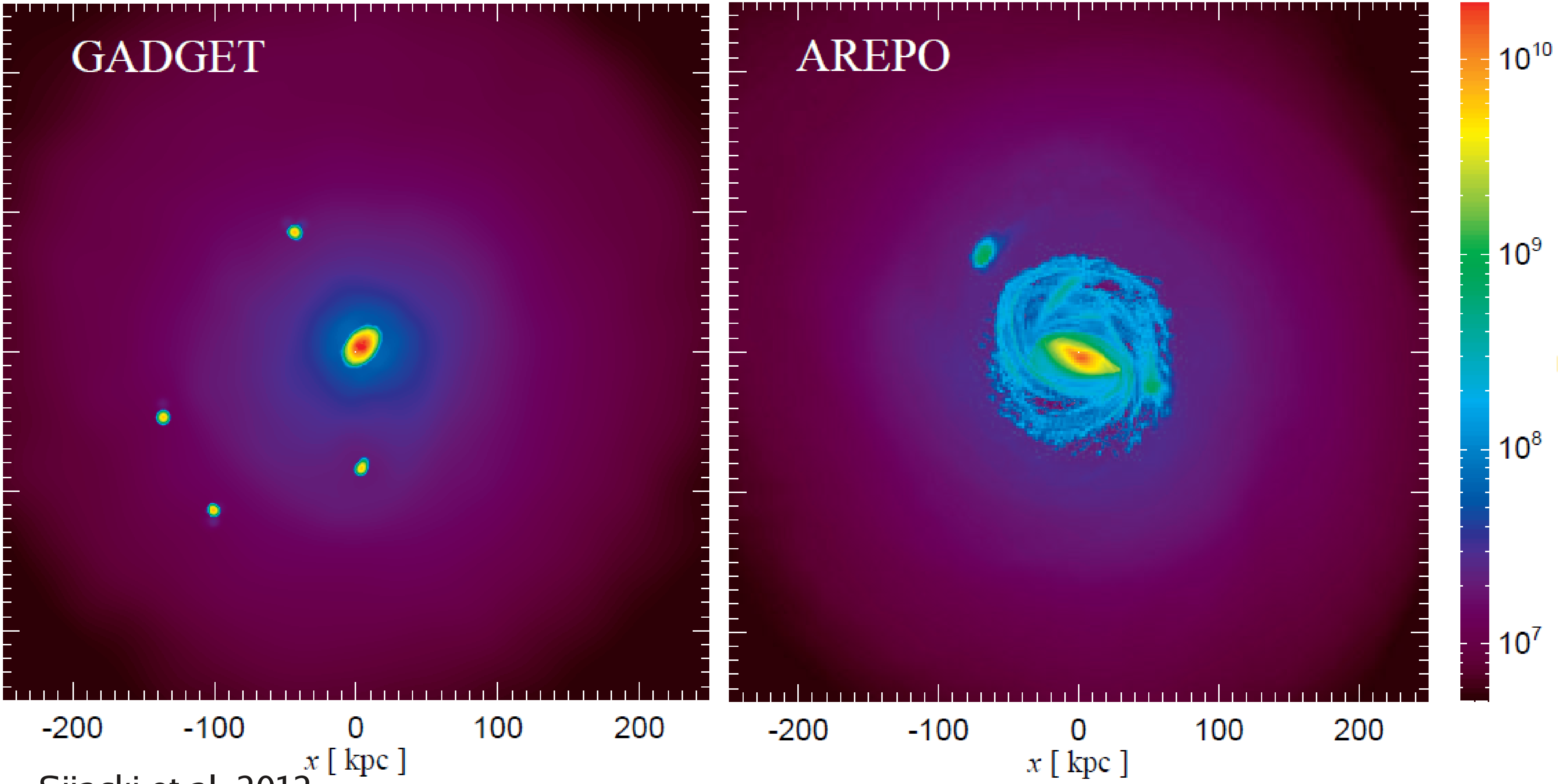
COLD BLOB



Sijacki et al. 2012

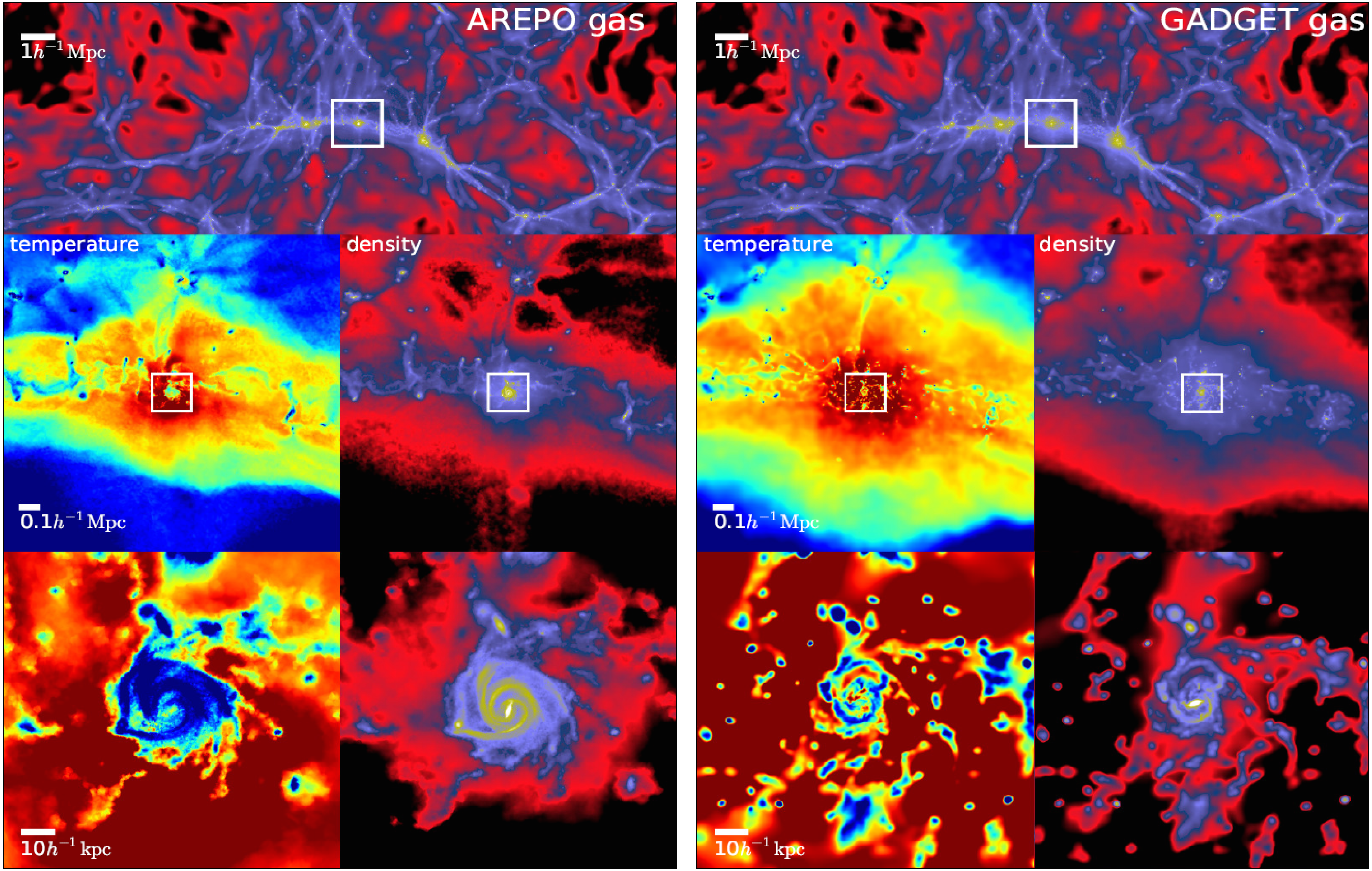
Inside-out disk formation

- static dark matter halo with a Hernquist profile
- gas in hydrostatic equilibrium which cools and has a net spin → disk forms
- 10 realistic gas+stars+DM substructures with v = 200-500km/s



Sijacki et al. 2012

Cosmological simulations with GADGET and AREPO



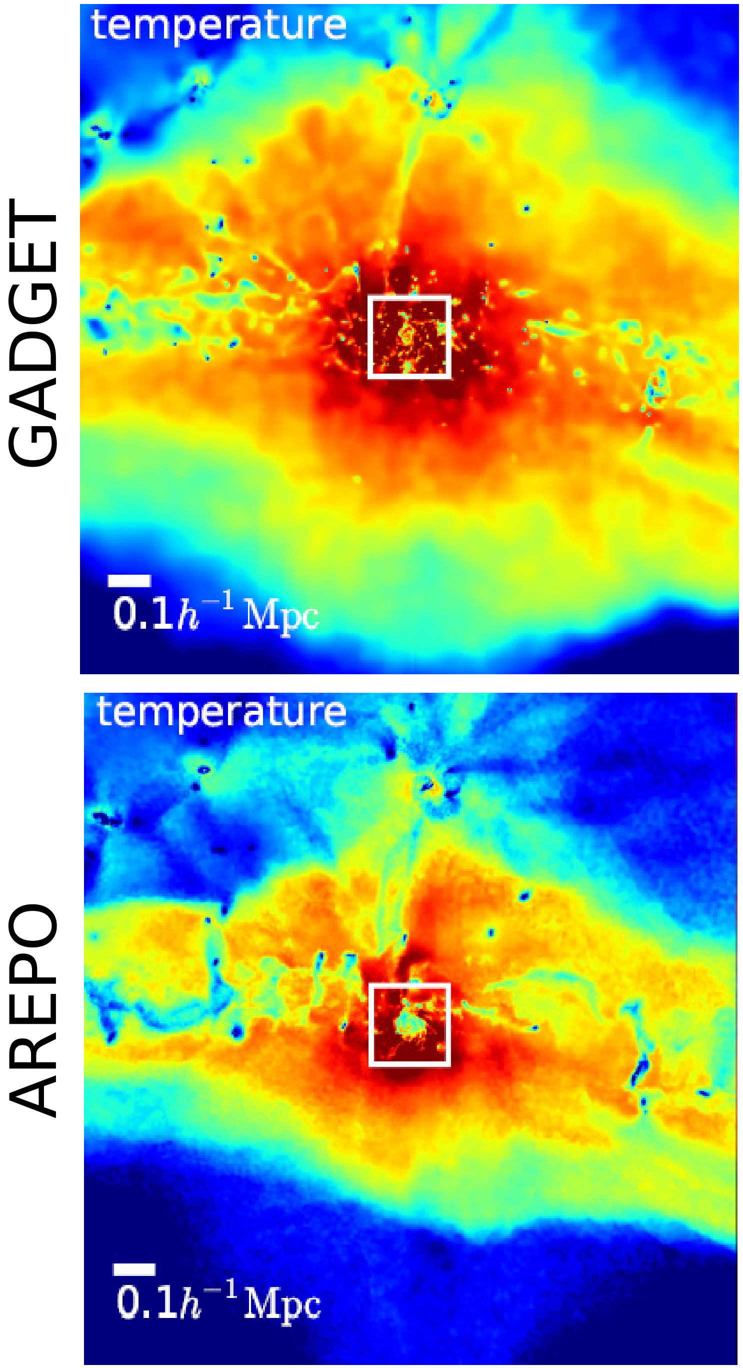
AREPO

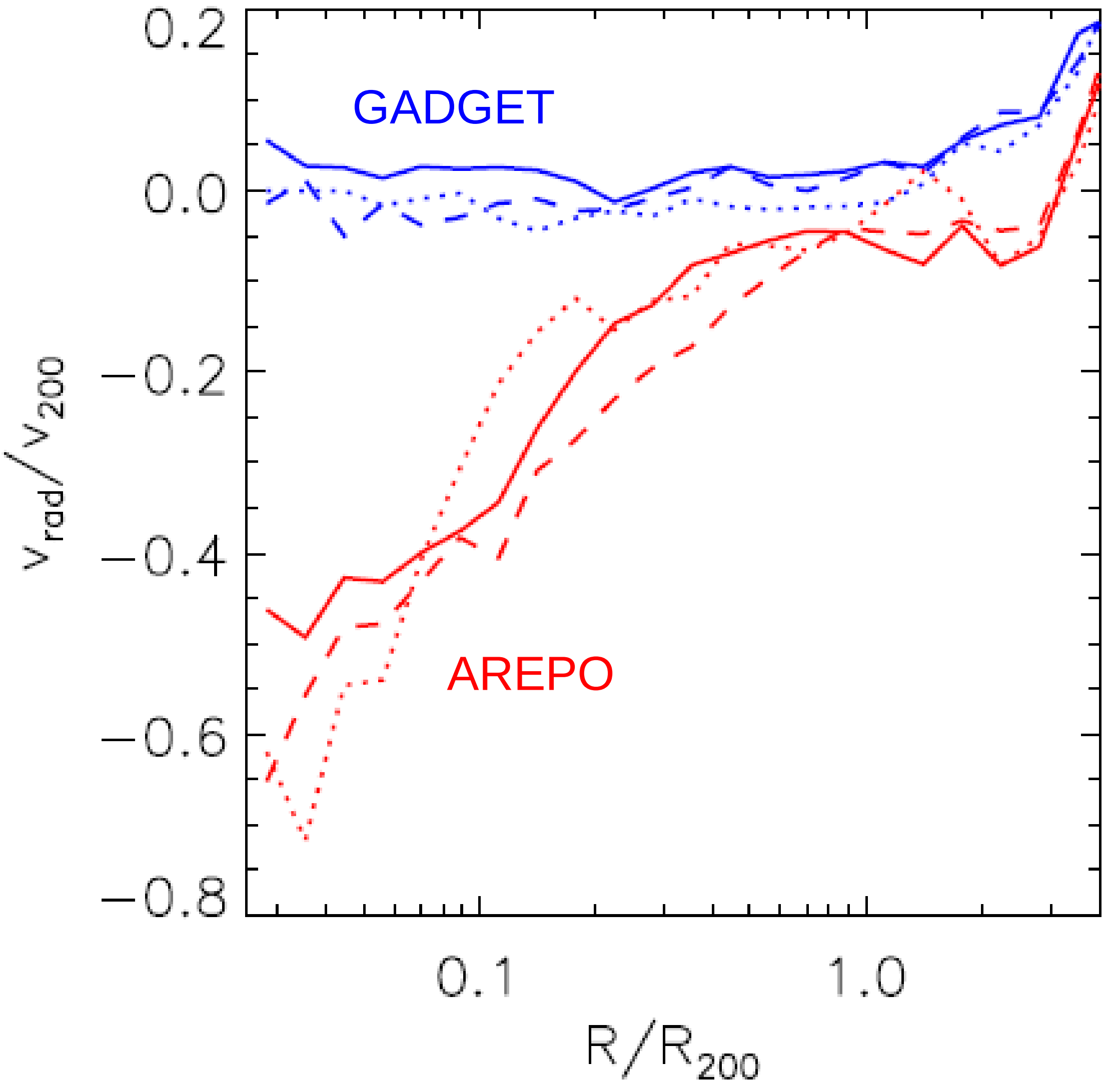
GADGET

Vogelsberger, Sijacki, Keres,
Springel, Hernquist (2012)

the same galaxy

Gas cooling in dark matter halos

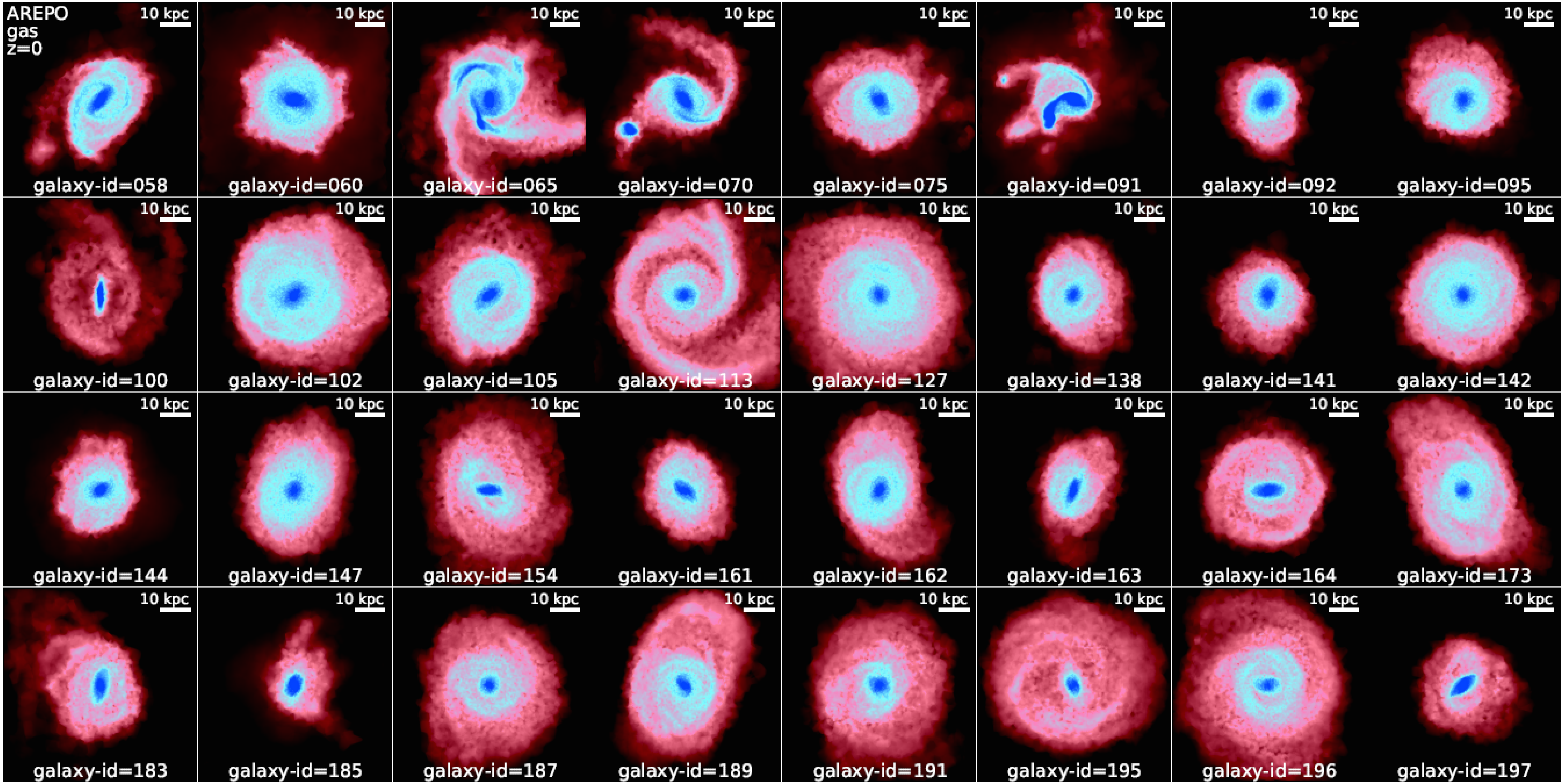




Vogelsberger et al. 2012
Keres et al. 2012
see also Bauer&Springel 2012, Nelson et al. 2013

Galaxy morphology

AREPO

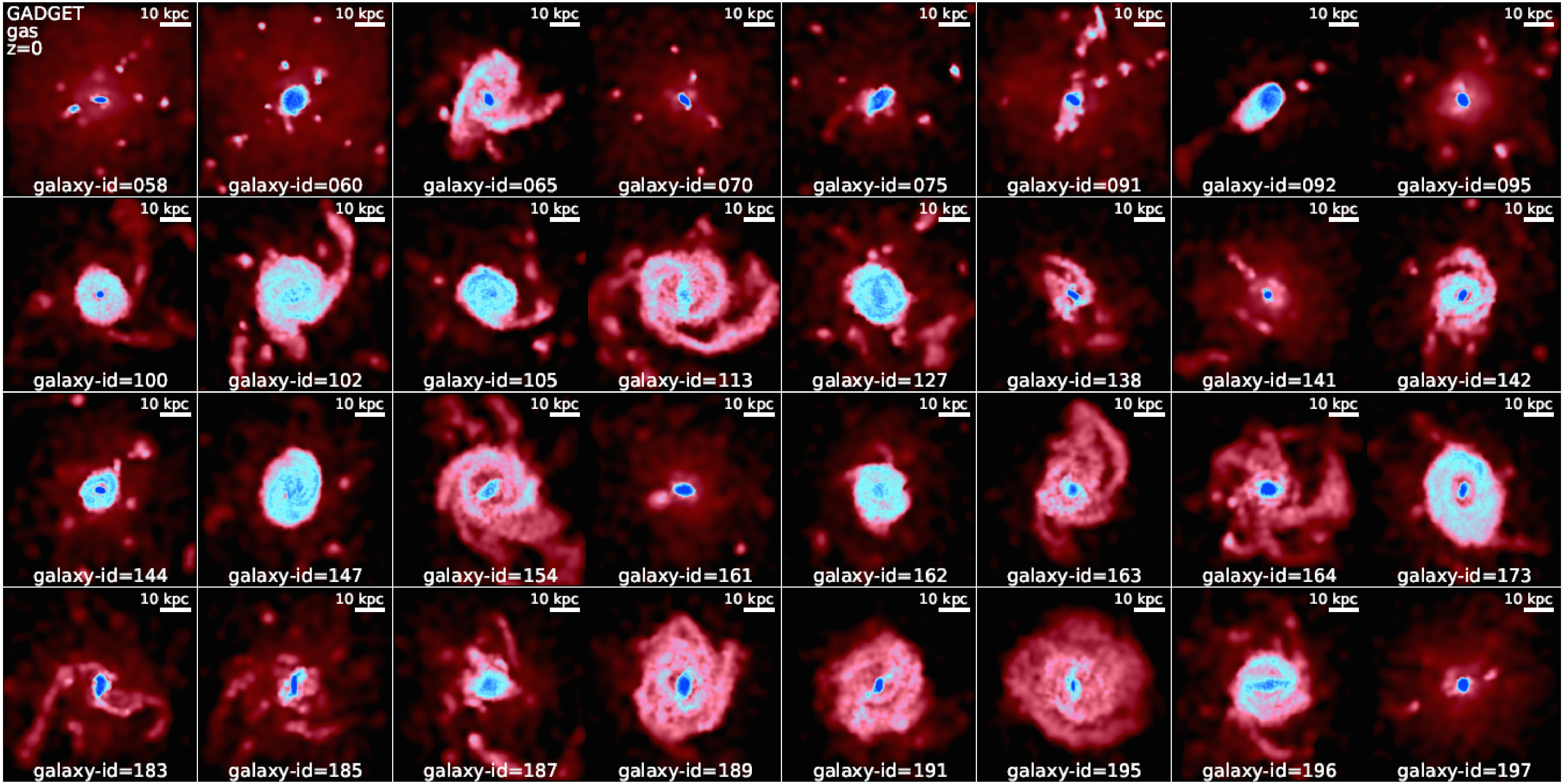


sample of galaxies selected at z=0 (projected gas density, face on):
moving mesh approach forms extended disks

Vogelsberger, Sijacki, Keres,
Springel, Hernquist (2012)

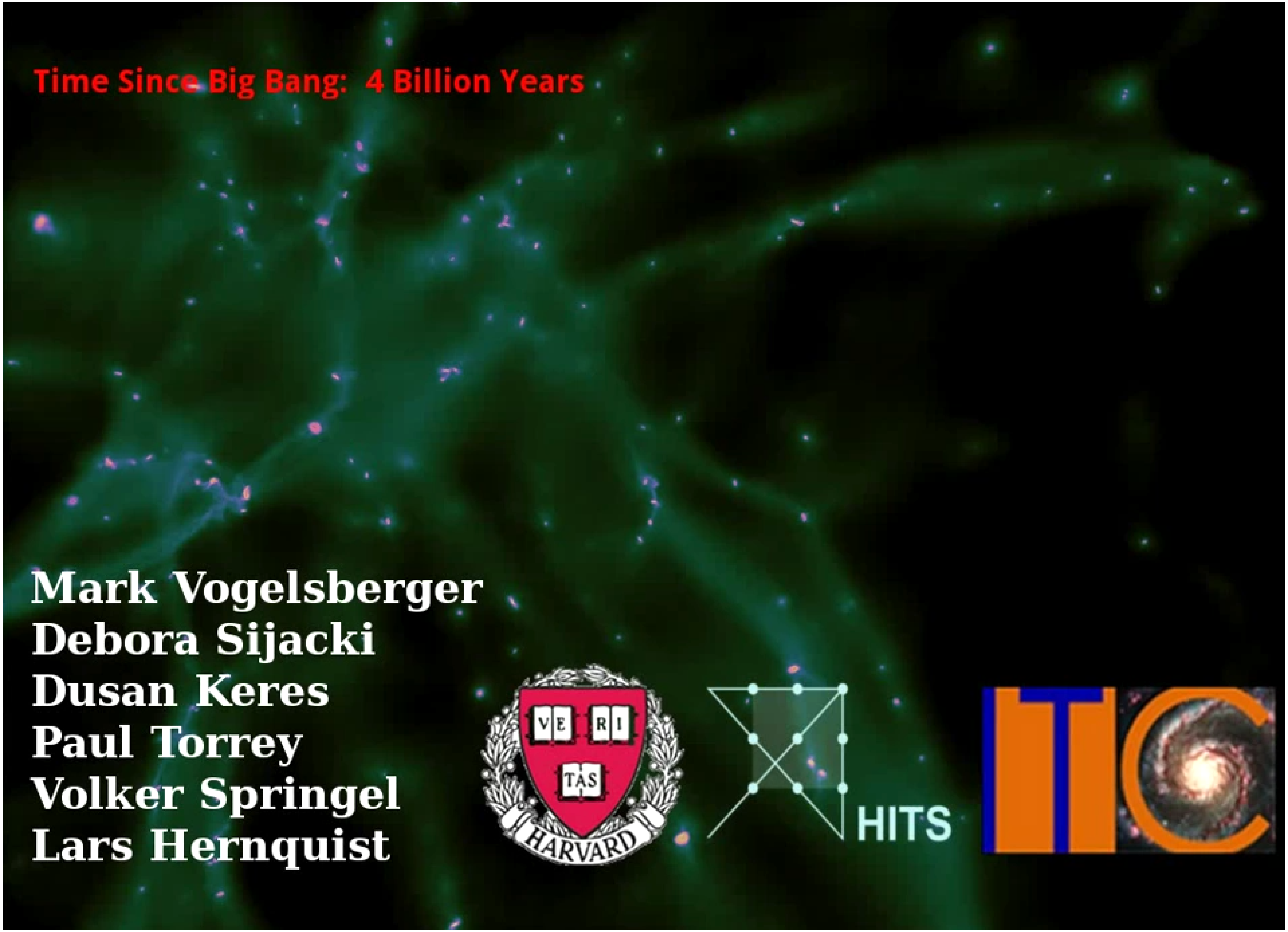
Galaxy morphology

GADGET



same galaxies but now with SPH: in many cases no extended disk is formed

Vogelsberger, Sijacki, Keres,
Springel, Hernquist (2012)



Time Since Big Bang: 4 Billion Years

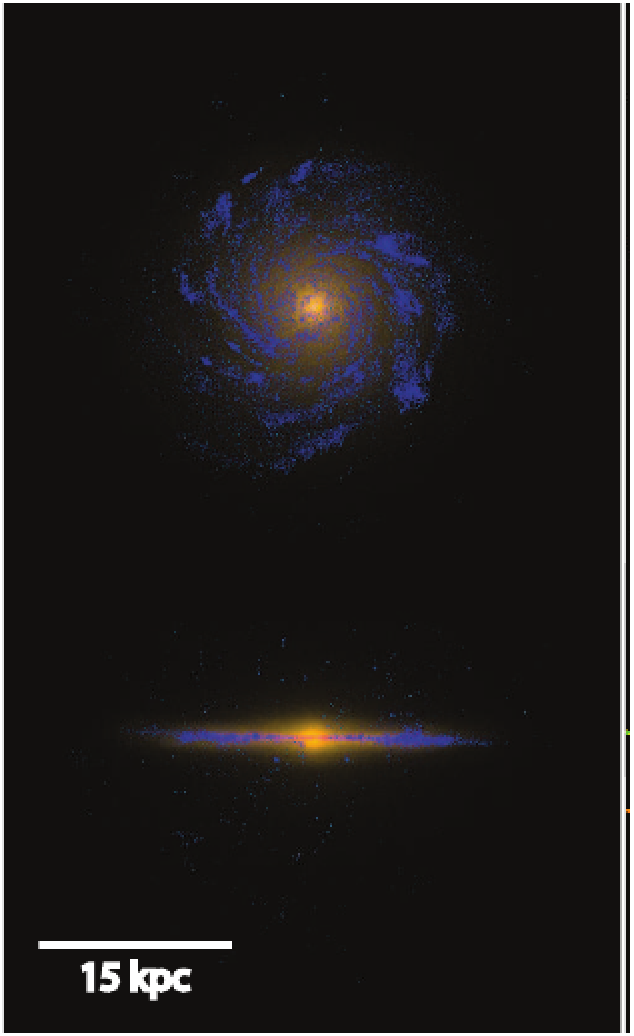
Mark Vogelsberger
Debora Sijacki
Dusan Keres
Paul Torrey
Volker Springel
Lars Hernquist

But what about all the relevant physics?

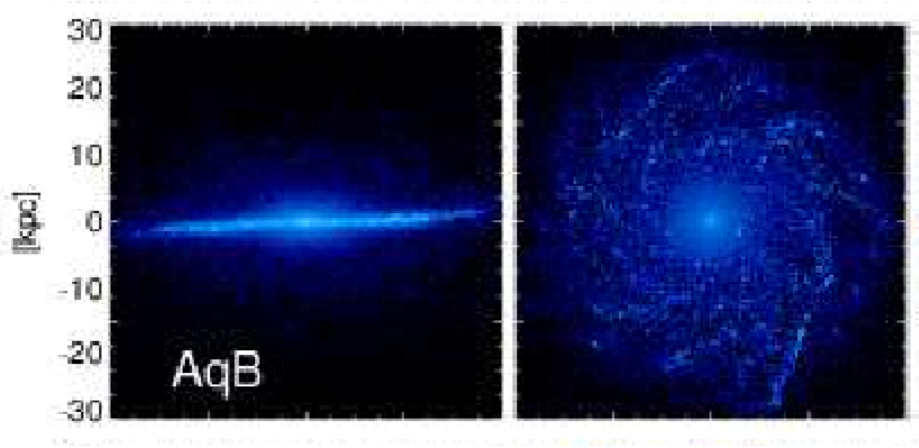
- radiative cooling and heating processes
- star formation
- supernovae feedback and stellar winds
- black holes and AGN heating
- non-ideal plasma effects
- non-thermal pressure support
- magnetic fields,...

Perseus cluster, Fabian et al.

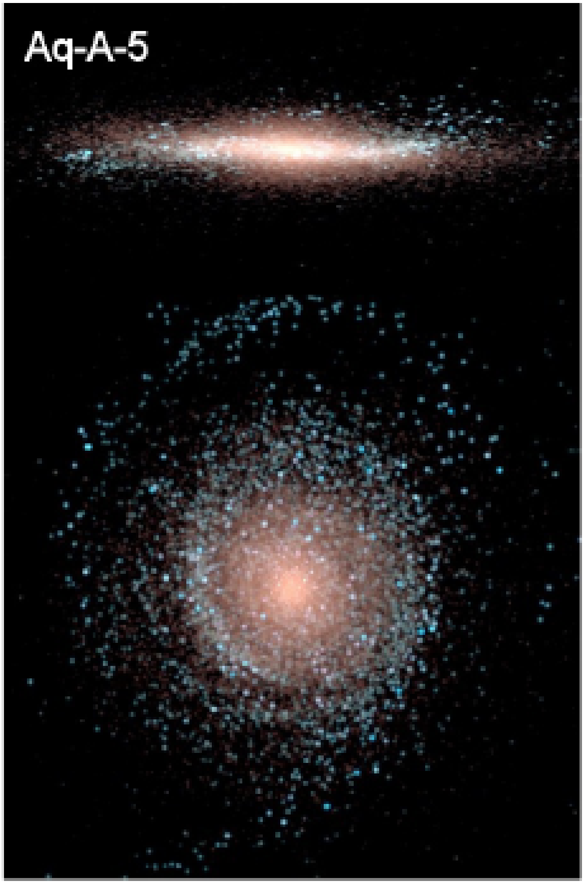
Galaxy formation simulations



Guedes et al. 2011



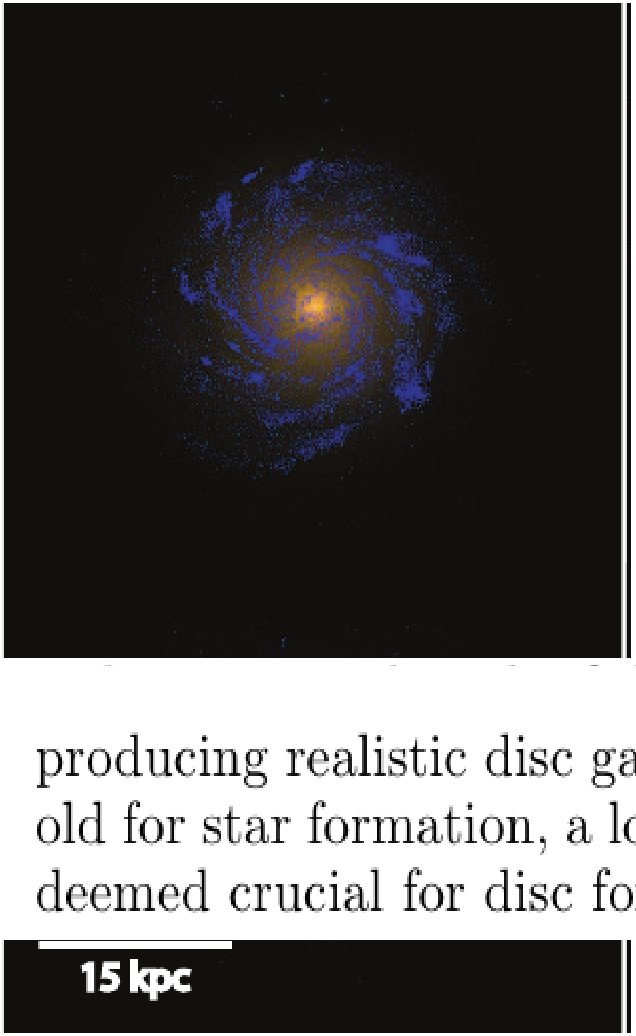
Aumer et al. 2013



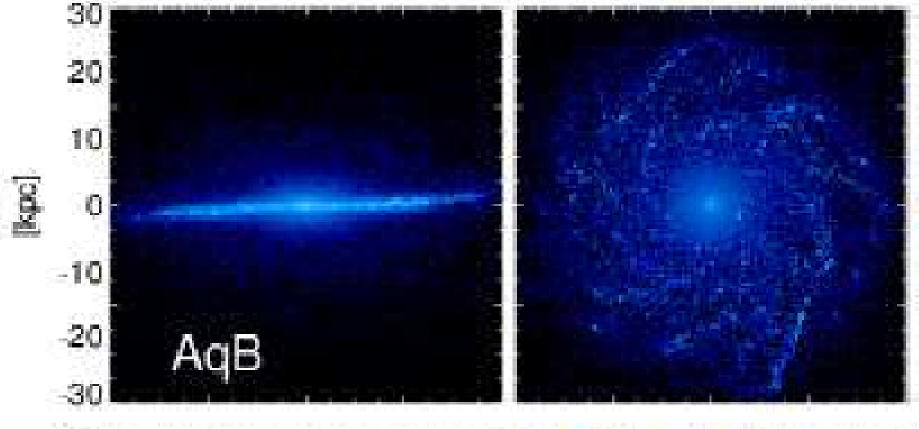
Marinacci et al. 2013

Stinson et al. 2013 MAGICC

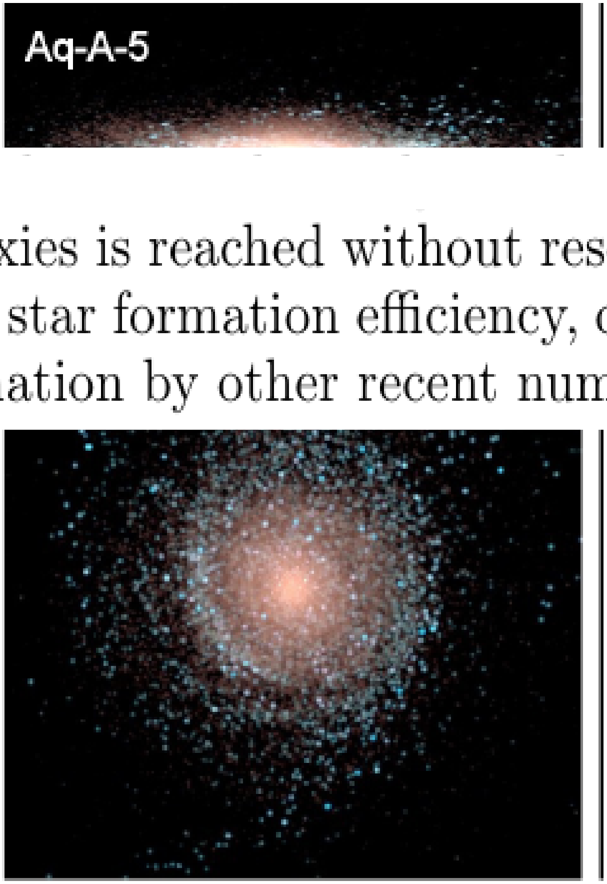
Galaxy formation simulations



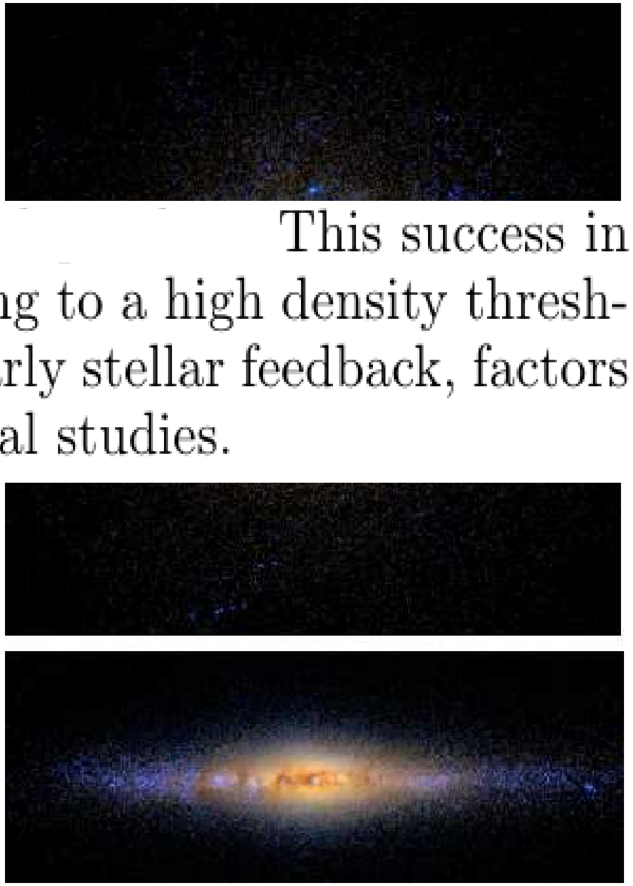
Guedes et al. 2011



Aumer et al. 2013



Marinacci et al. 2013



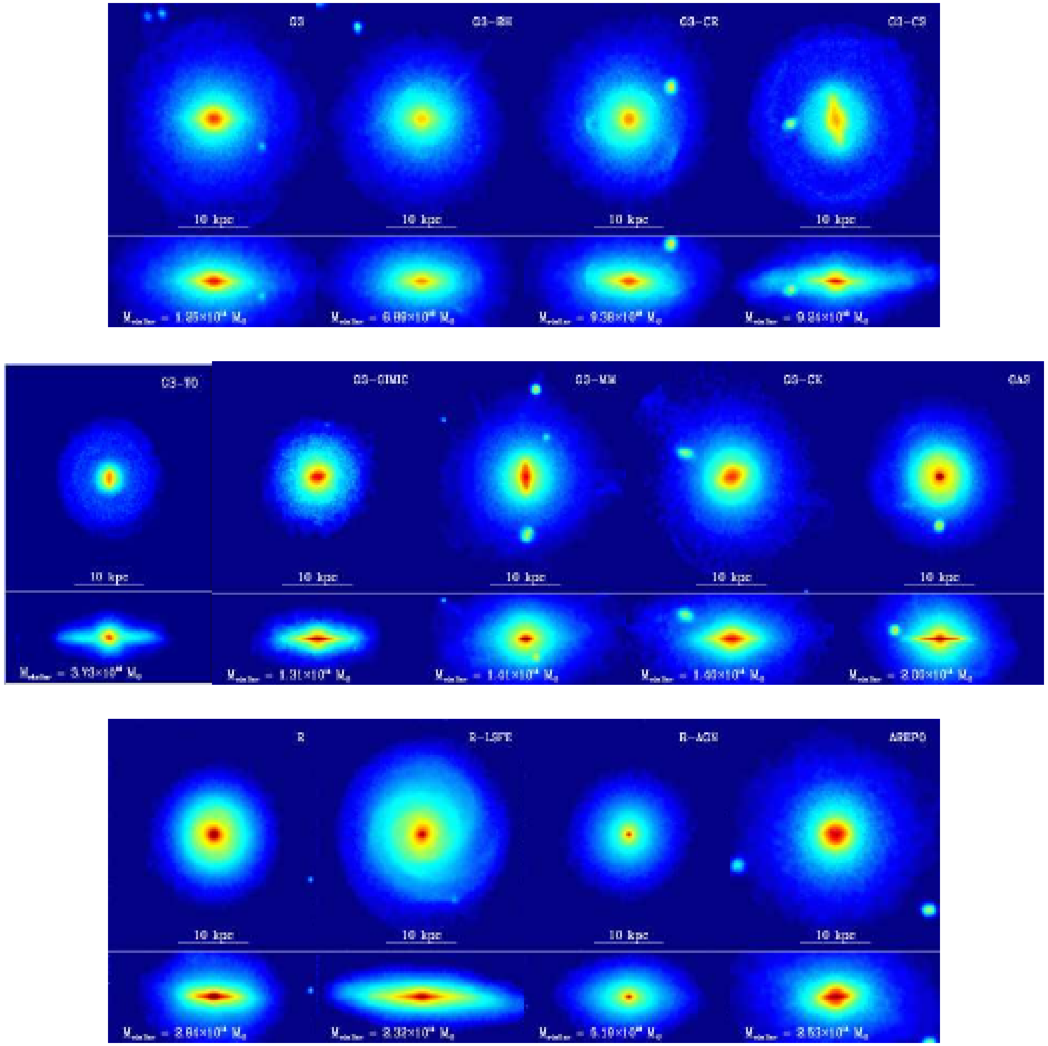
Stinson et al. 2013 MAGICC

This success in producing realistic disc galaxies is reached without resorting to a high density threshold for star formation, a low star formation efficiency, or early stellar feedback, factors deemed crucial for disc formation by other recent numerical studies.

Physical modeling uncertainties

The Aquila comparison project Scannapieco et al. 2012

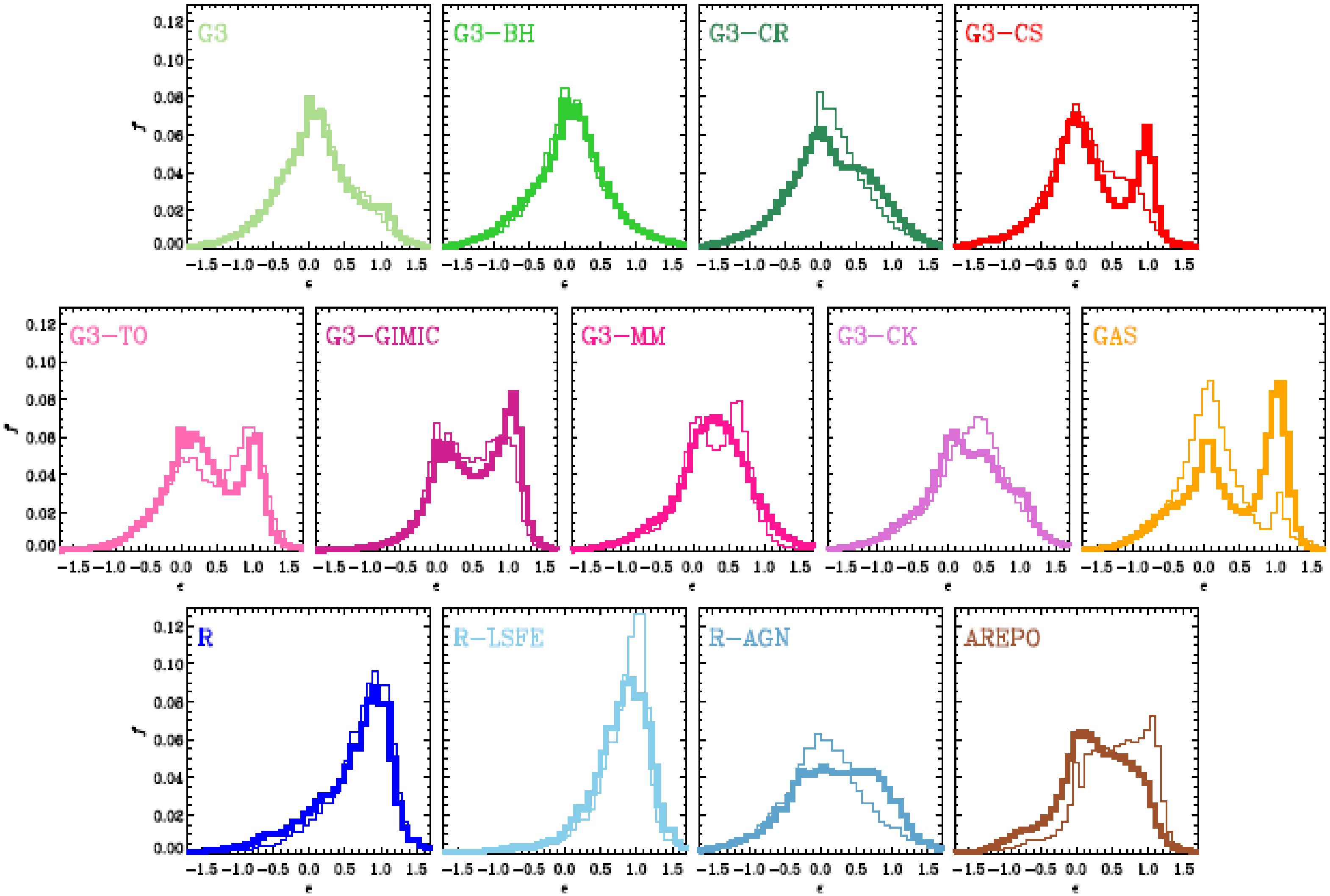
9 different codes, 13 runs with the same ICs but different physics
“Despite the common halo assembly history, we find large code-to-code variations in the stellar mass, size, morphology and gas content of the galaxy at z=0, due mainly to the different implementations of star formation and feedback.



Physical modeling uncertainties

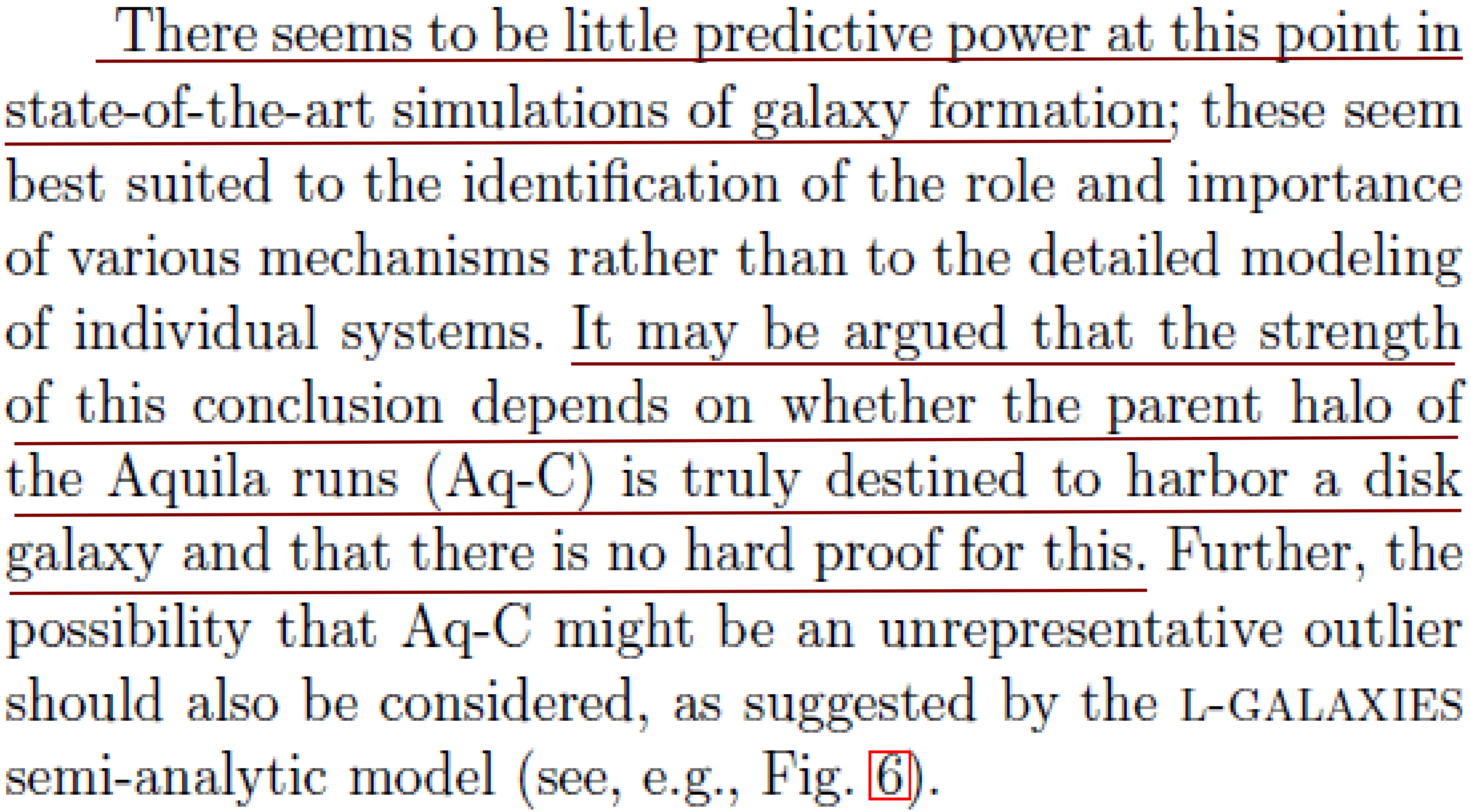
The Aquila comparison project Scannapieco et al. 2012

Distribution of stellar circularities (Jz/Jcirc) for different codes at different resolutions



Physical modeling uncertainties

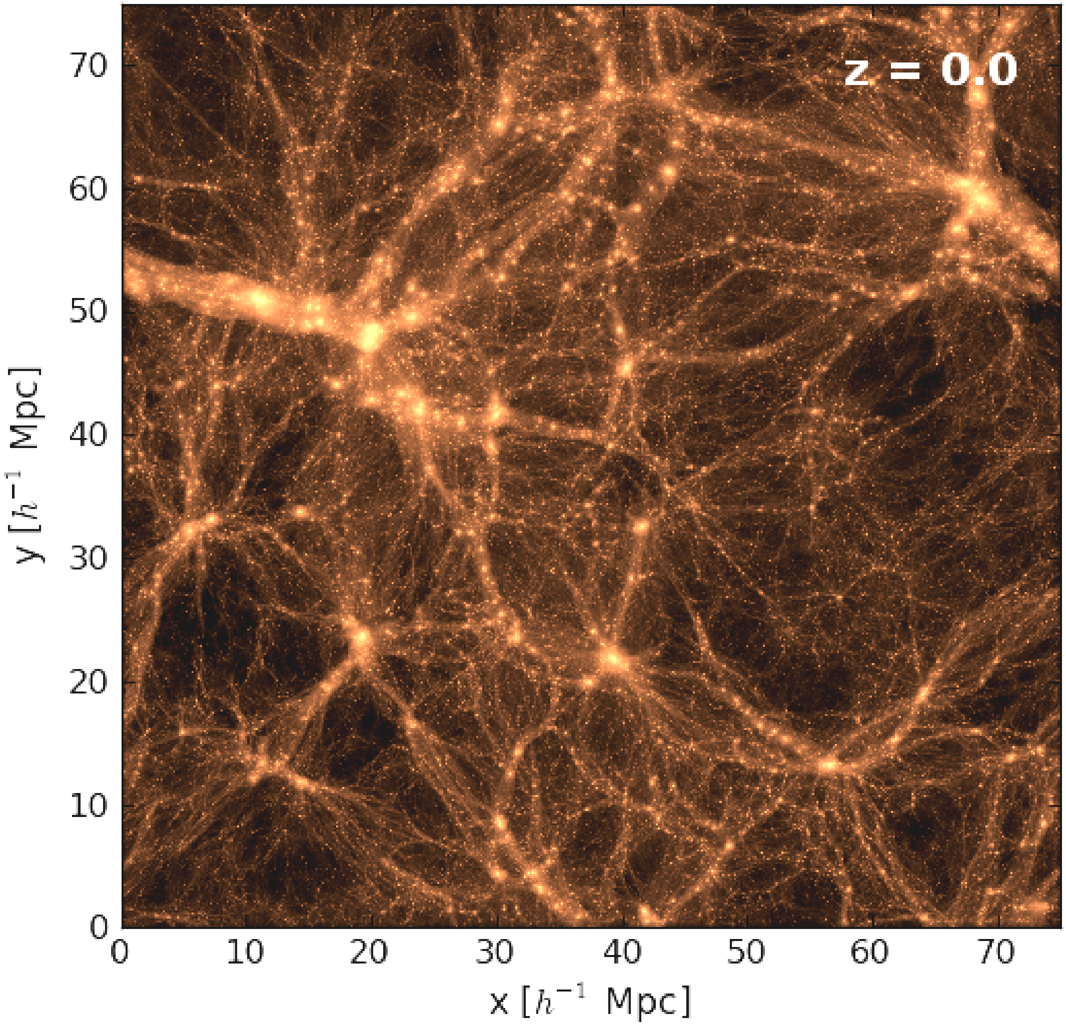
The Aquila comparison project Scannapieco et al. 2012



There seems to be little predictive power at this point in state-of-the-art simulations of galaxy formation; these seem best suited to the identification of the role and importance of various mechanisms rather than to the detailed modeling of individual systems. It may be argued that the strength of this conclusion depends on whether the parent halo of the Aquila runs (Aq-C) is truly destined to harbor a disk galaxy and that there is no hard proof for this. Further, the possibility that Aq-C might be an unrepresentative outlier should also be considered, as suggested by the L-GALAXIES semi-analytic model (see, e.g., Fig. 6).

The Illustris project

Large-scale cosmological simulations with AREPO



26 Million CPU hours on XSEDE
20 Million CPU hours on Curie
1.2x10^{10} particles in 75Mpc^3 box
8000 cores

2 simulations with different physics:

1. DM only ✓
2. cooling & star formation
   +galactic winds
   +black holes ✓

planning to make the data public!

Team: Shy Genel, Lars Hernquist, Debora Sijacki, Volker Springel, Paul Torrey, Mark Vogelsberger

The Illustris project

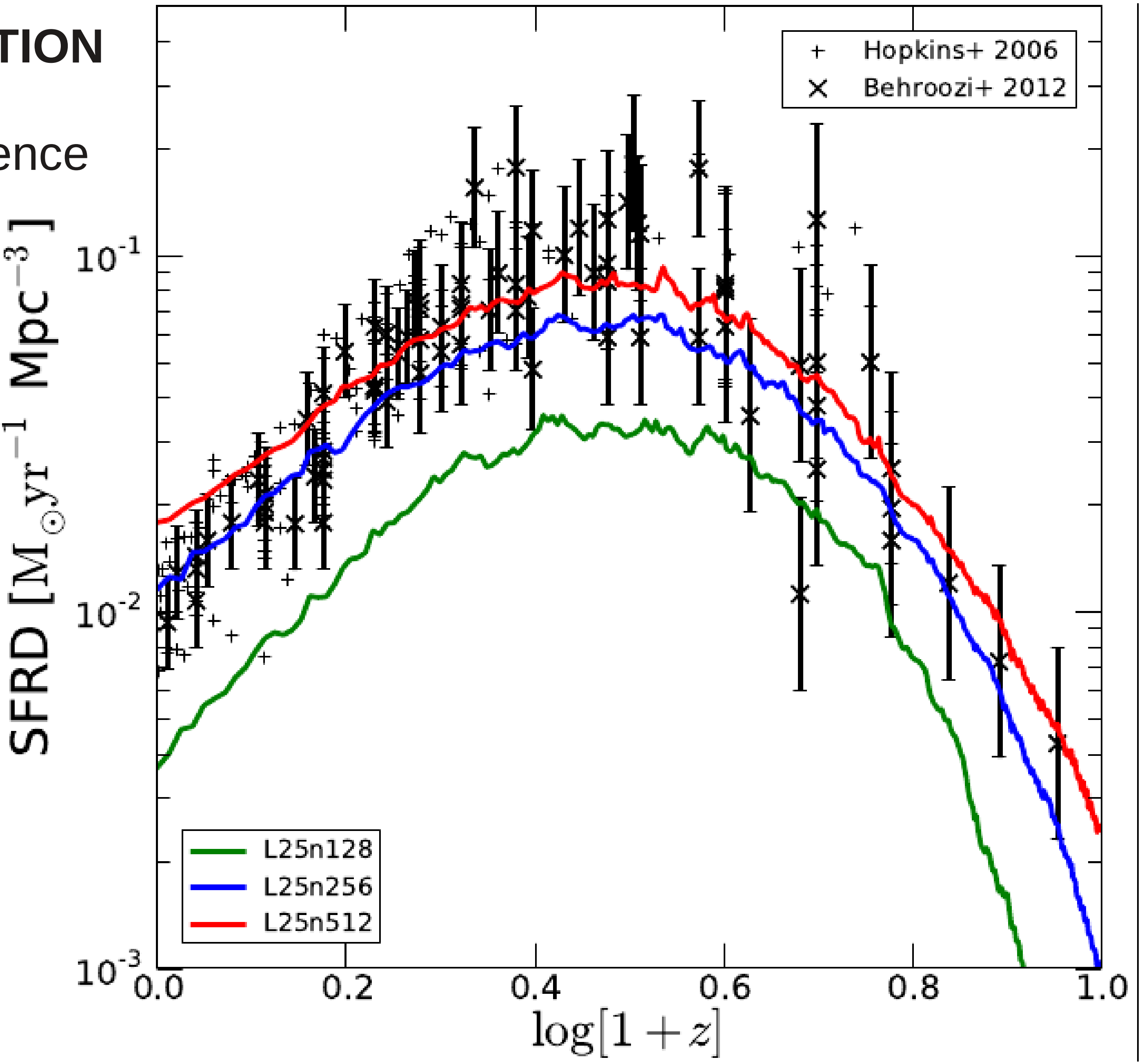
Physical modules:

- chemical enrichment (9 elements)
- metal line cooling + UV photo-ionization
- galactic winds and outflows:
  energy & momentum driven
- stellar mass loss and gas recycling
- spatially dependent QSO UV heating
- AGN feedback:
  quasar and radio mode

The Illustris project

COSMIC STAR FORMATION RATE DENSITY

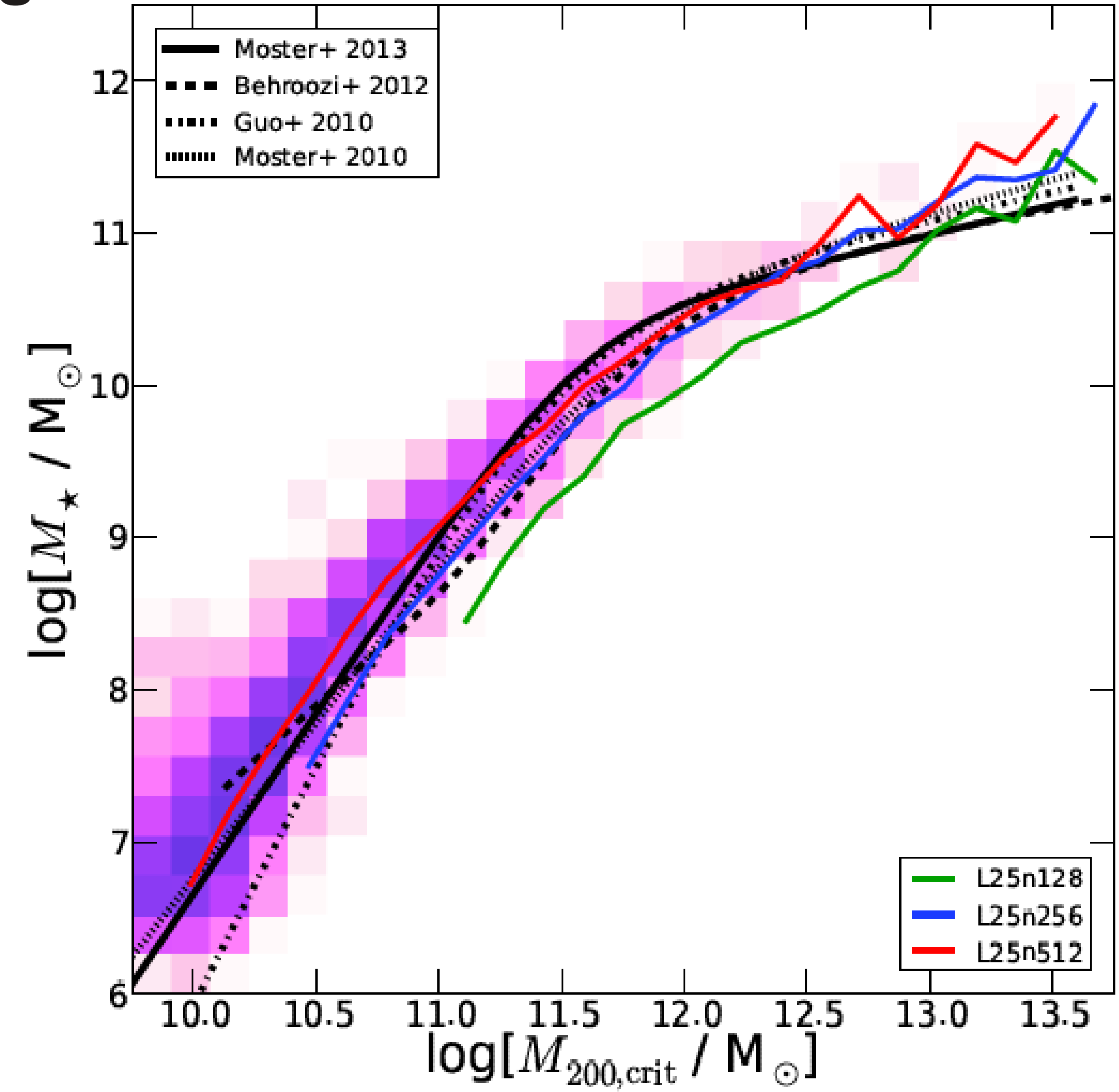
good numerical convergence



Vogelsberger, Genel, Sijacki, Torrey, Springel, Hernquist, MNRAS, 2013

The Illustris project

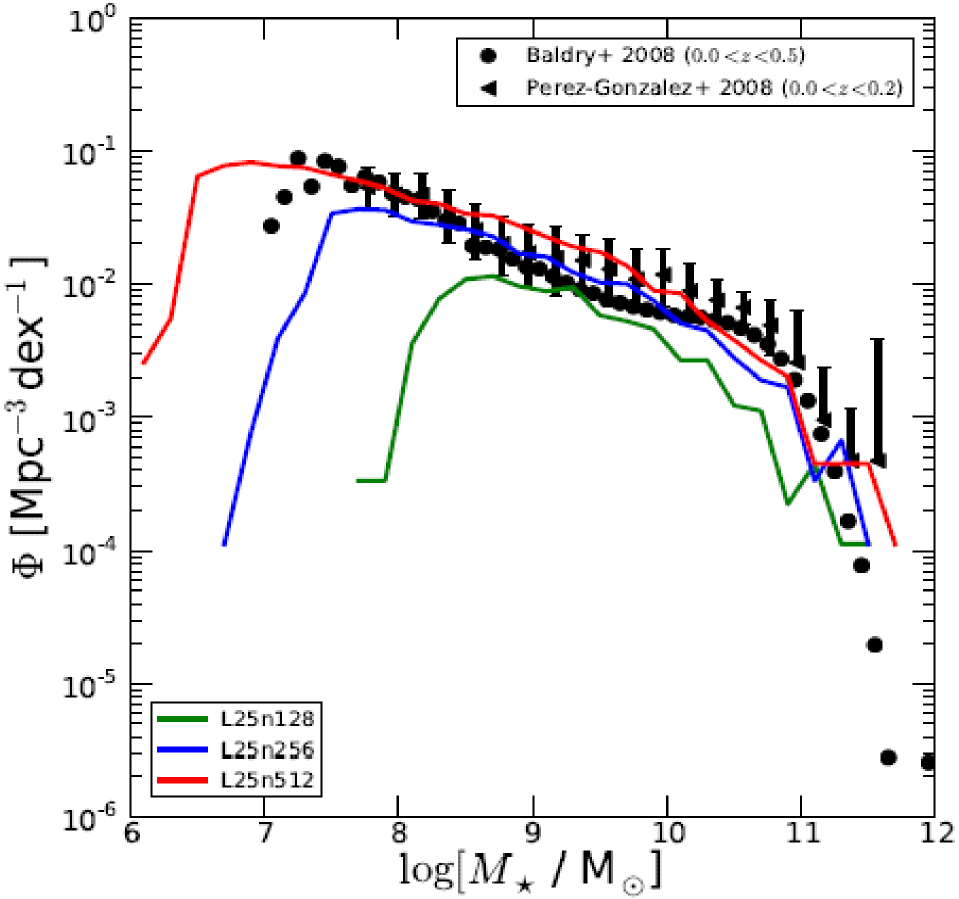
STELLAR VS. HALO MASS

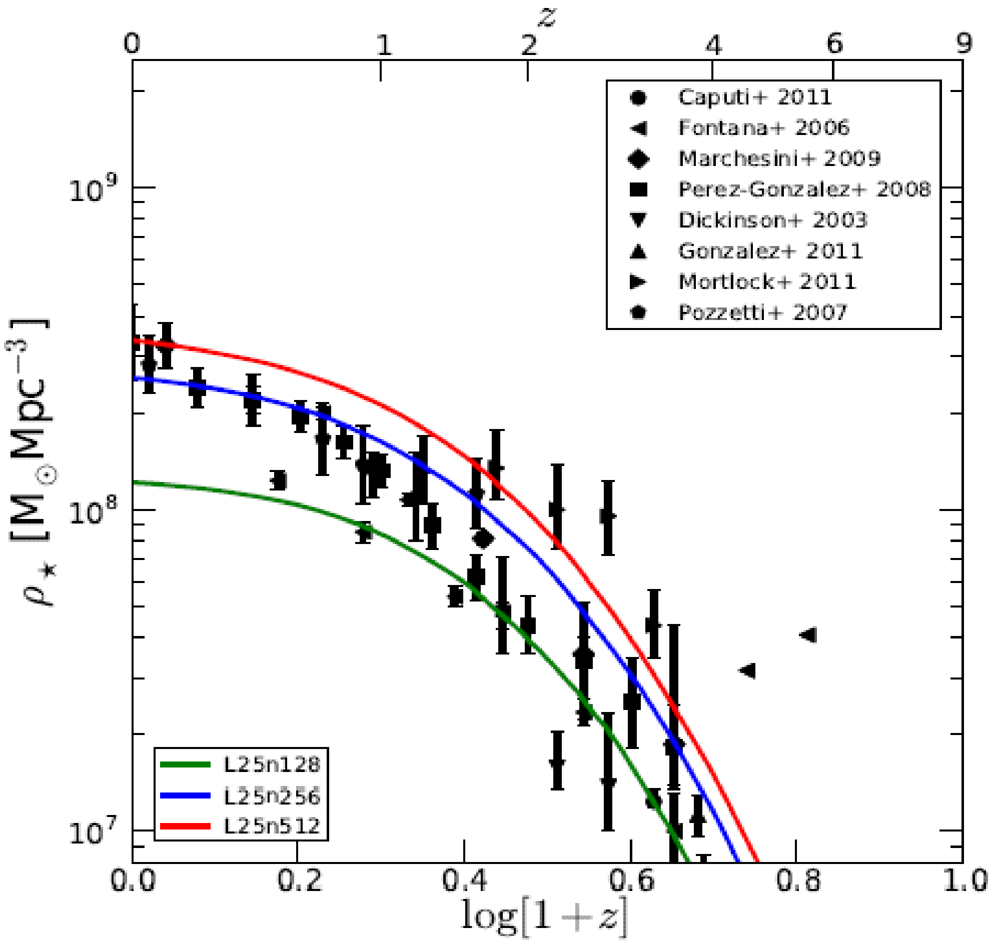


Vogelsberger, Genel, Sijacki, Torrey, Springel, Hernquist, MNRAS, 2013

The Illustris project

STELLAR MASS FUNCTION AND STELLAR MASS DENSITY

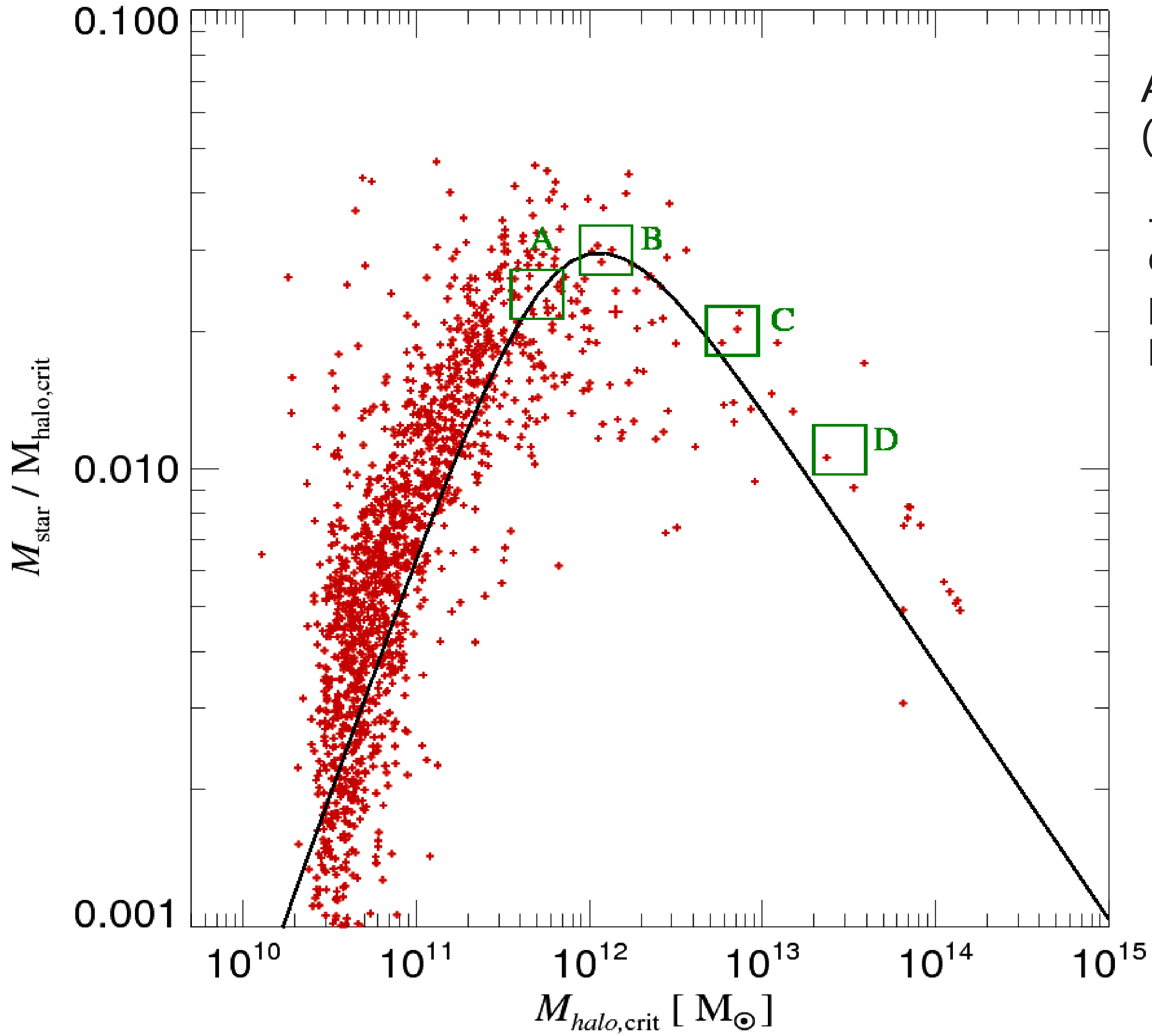




Vogelsberger, Genel, Sijacki, Torrey, Springel, Hernquist, MNRAS, 2013

The Illustris project

25Mpc/h box + high resolution zoom-in clusters



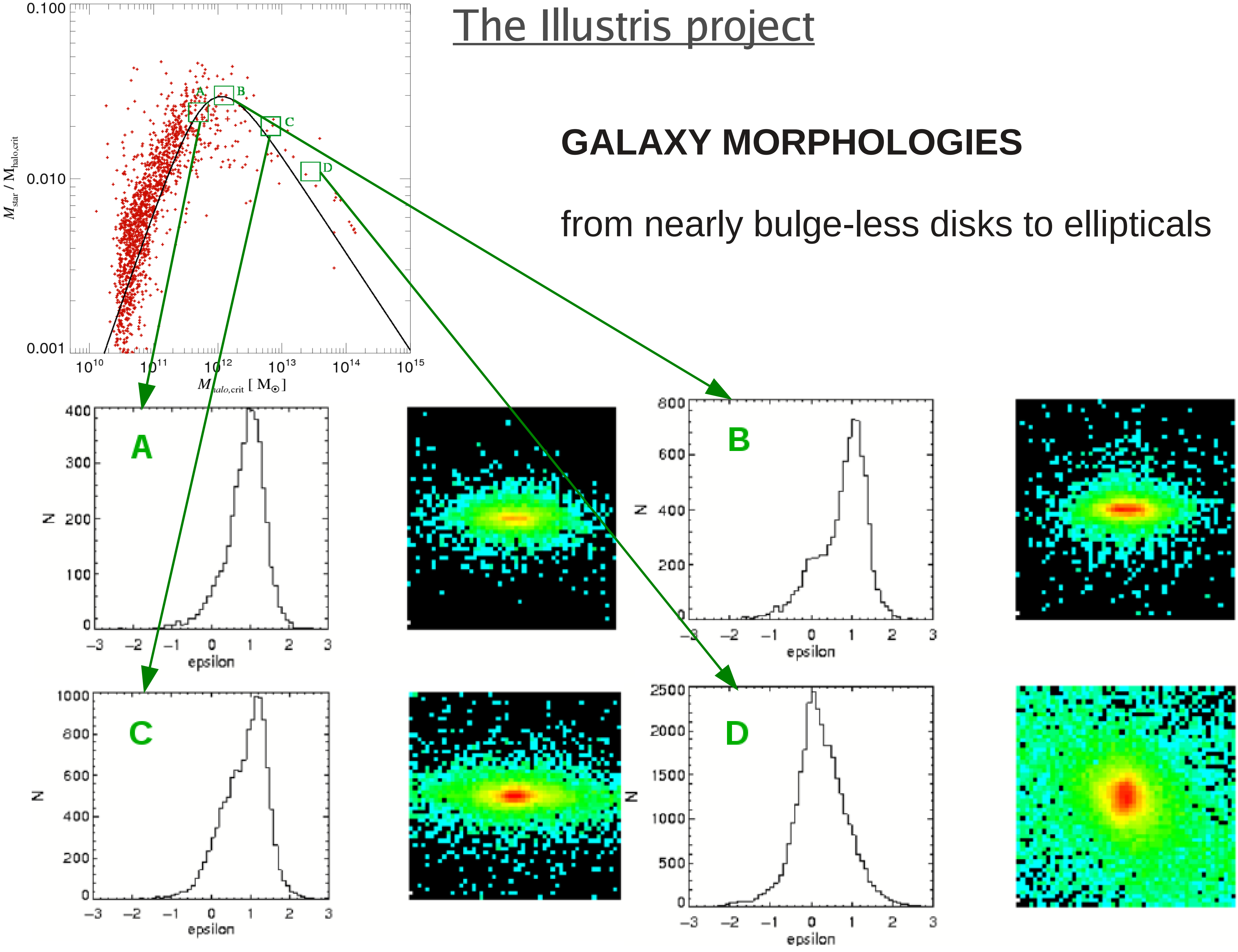
Abundance matching
(e.g. Moster et al. 2010)

- notoriously difficult to obtain realistic $M_{\rm star}$ both at the low and the high mass end

The Illustris project

GALAXY MORPHOLOGIES

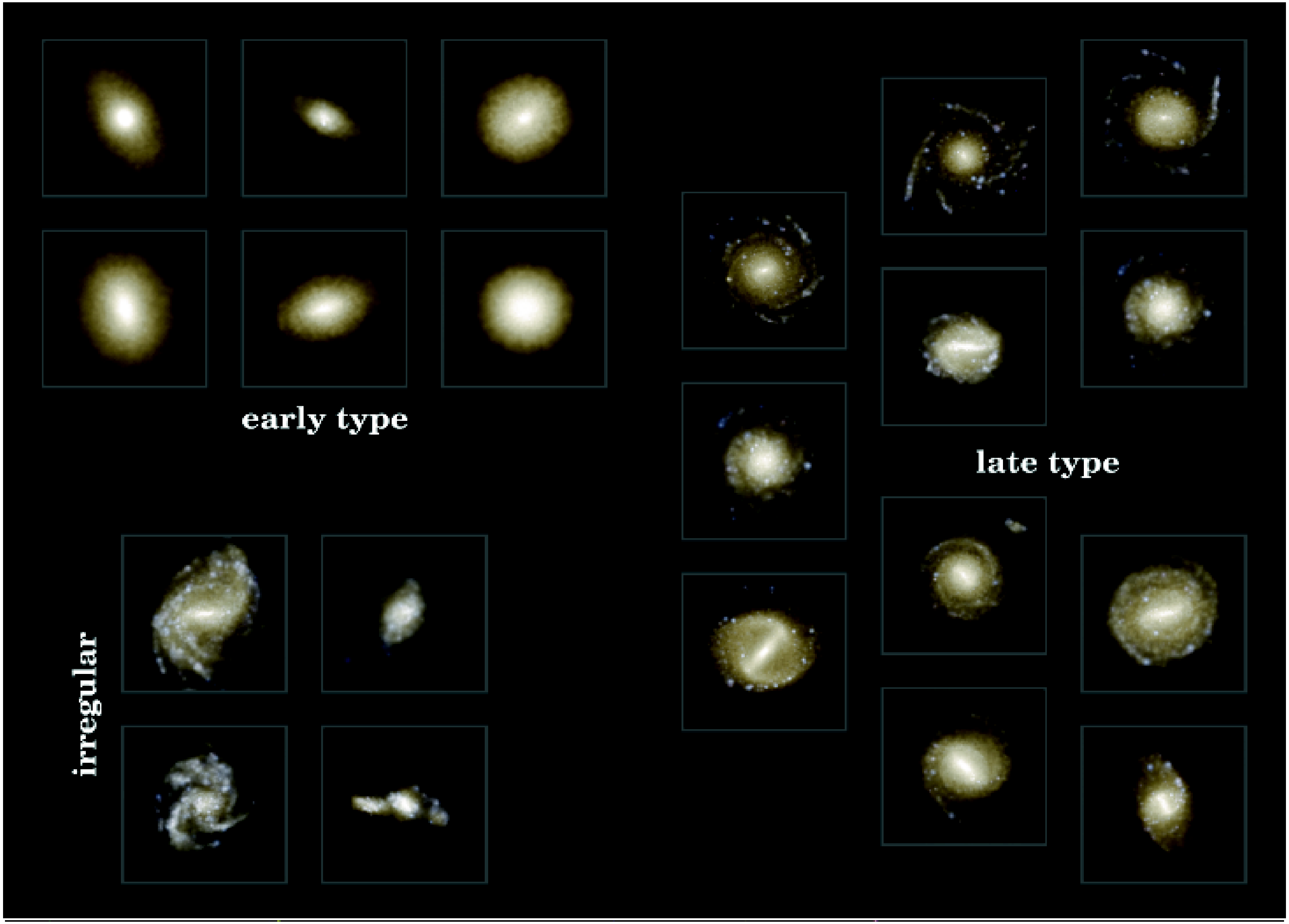
from nearly bulge-less disks to ellipticals



The Illustris project

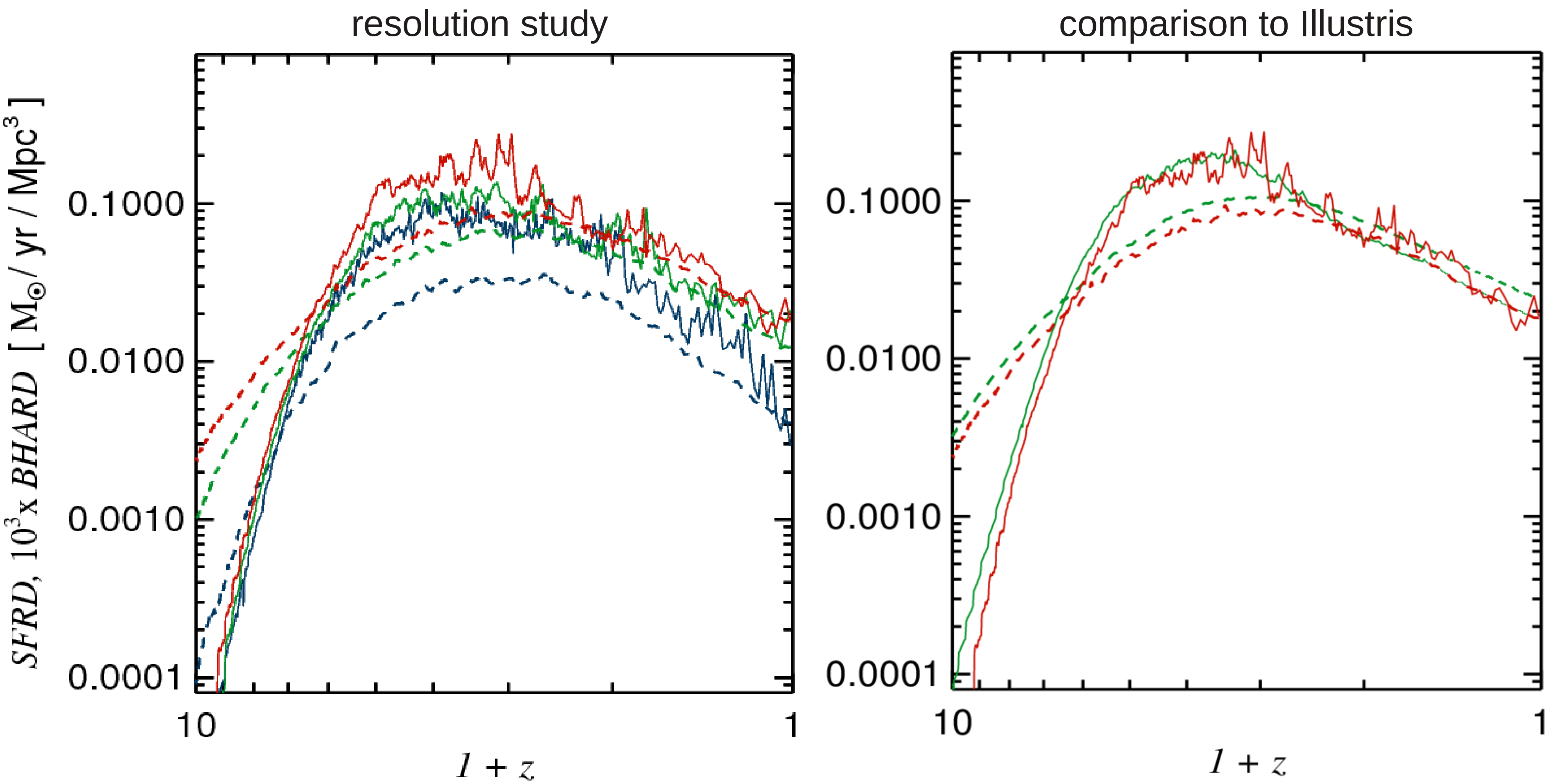
GALAXY MORPHOLOGIES

Greg Snyder (Illustris catalogue, g,r and i bands)



The Illustris project

BLACK HOLE PROPERTIES
cosmic accretion rate density


resolution study

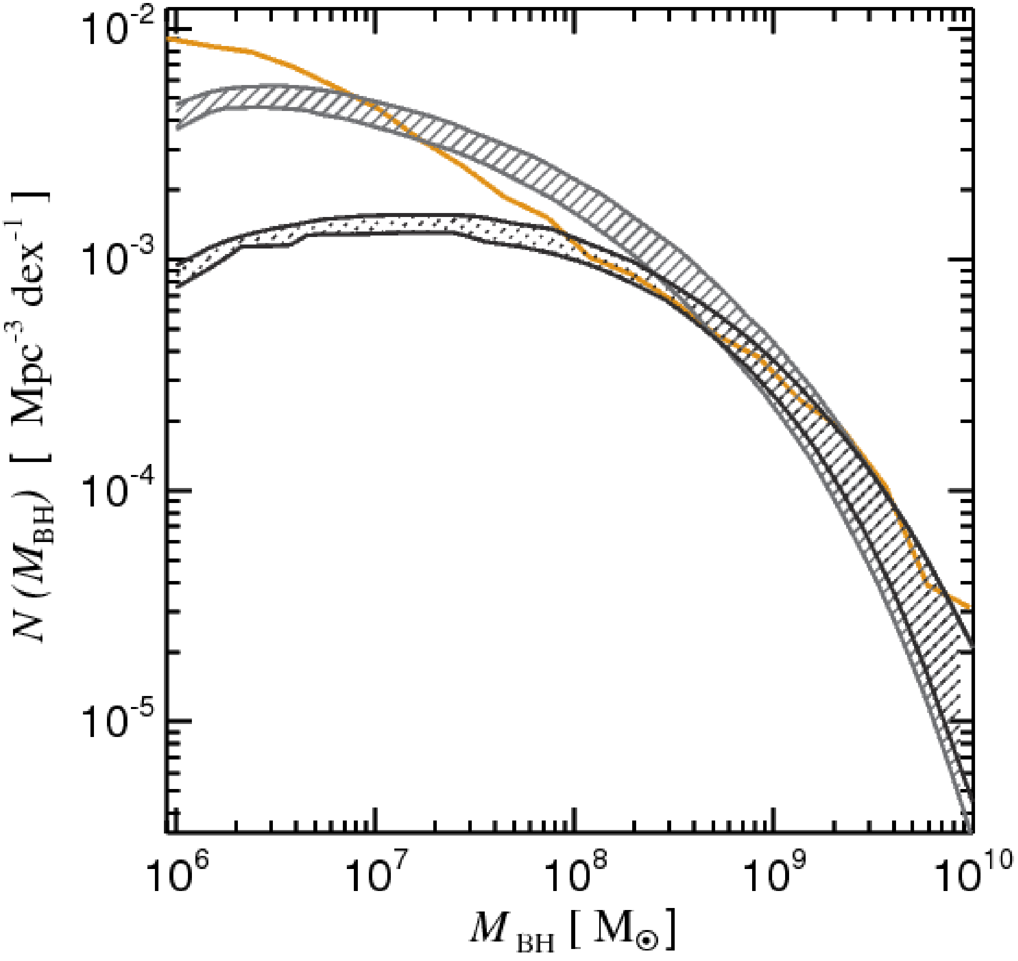
comparison to Illustris

Sijacki et al. 2014, in prep.

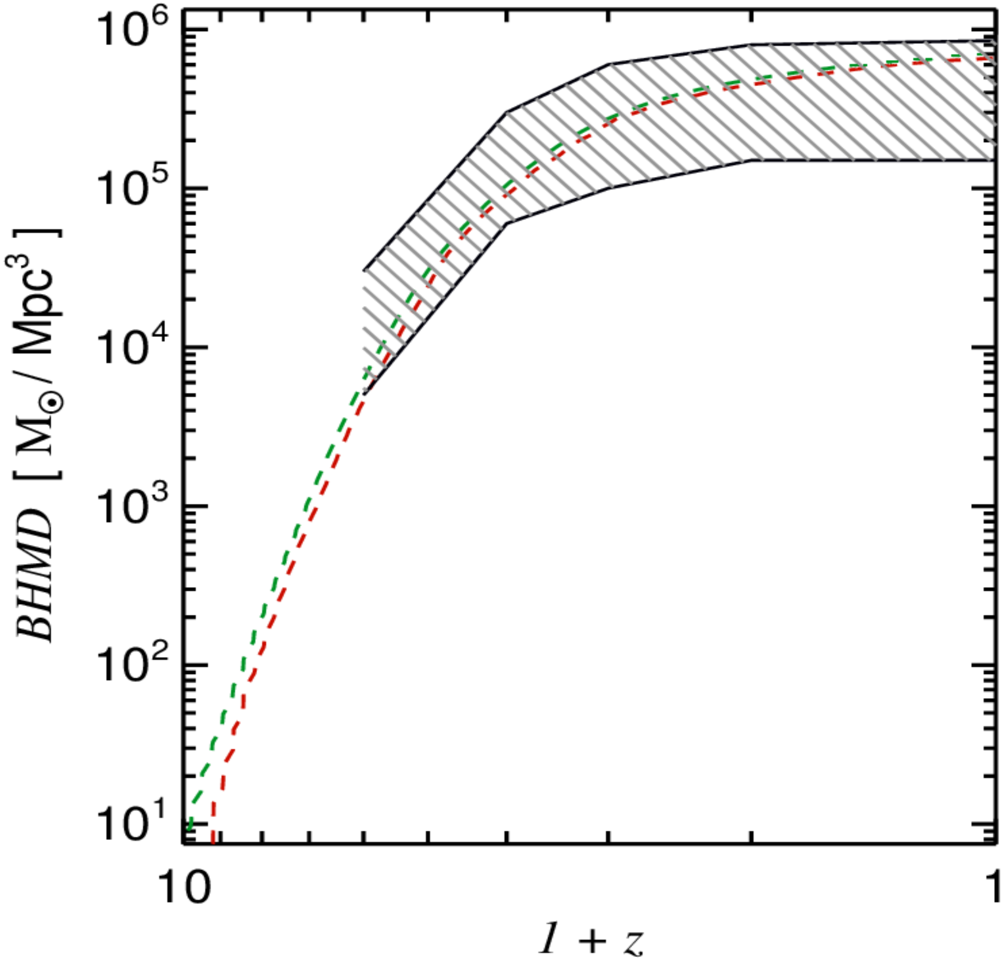
The Illustris project

BLACK HOLE PROPERTIES
differential mass function and mass density

Illustris BHMF (Shankar et al.)



25Mpc box comparison to Illustris



Sijacki et al. 2014, in prep.