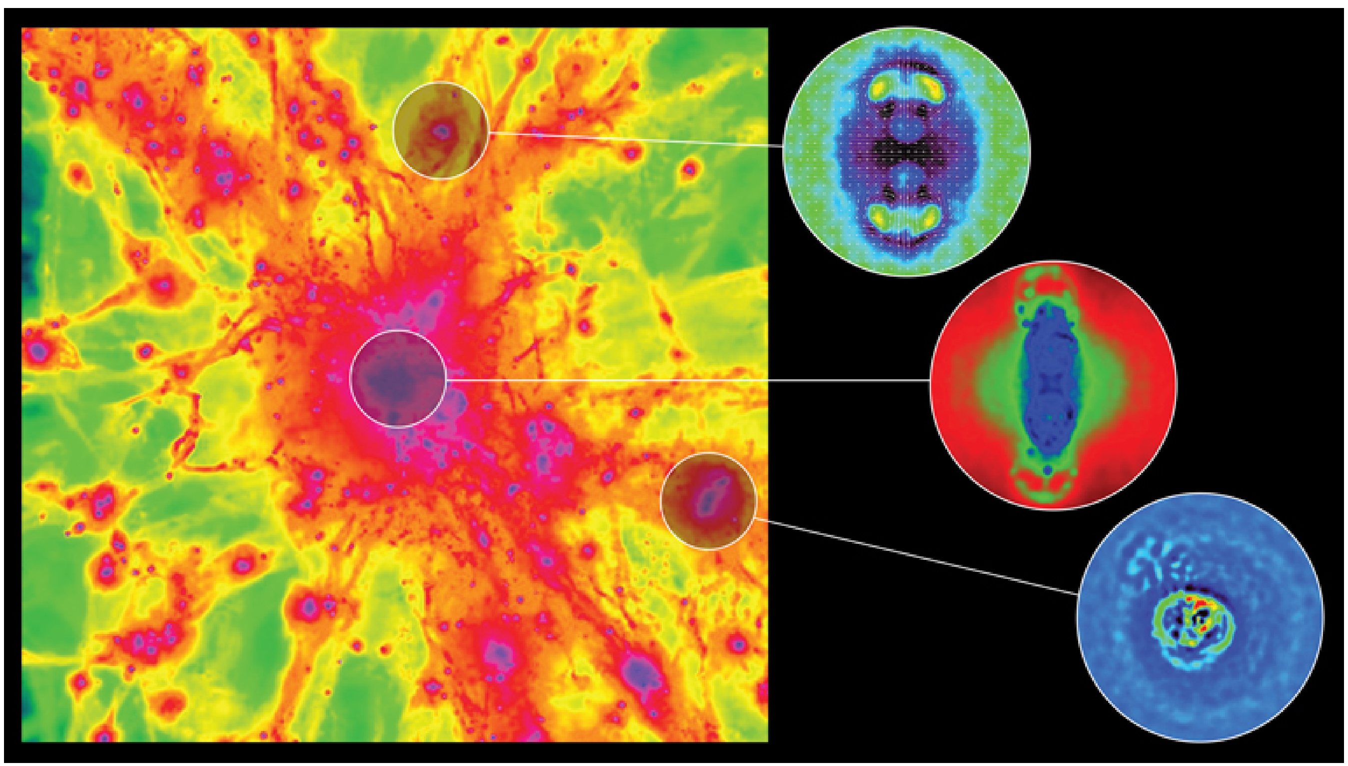
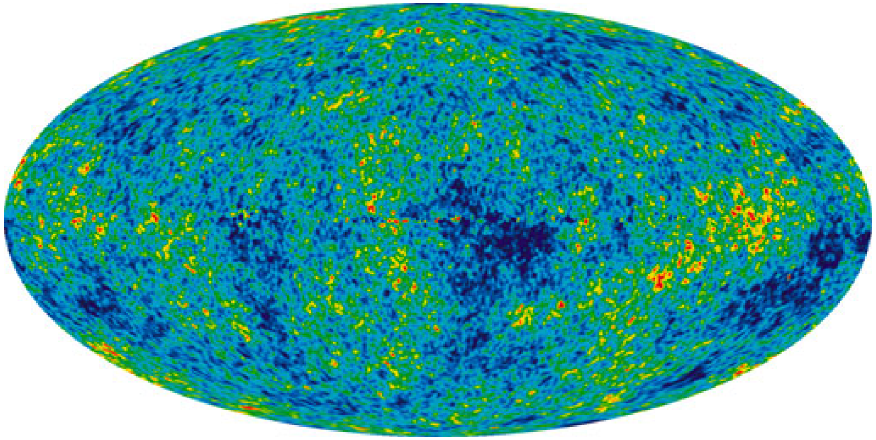
Cosmological simulations of galaxy formation



Debora Sijacki
IoA & KICC
Cambridge

EGEE Bologna
Sept 15 2014

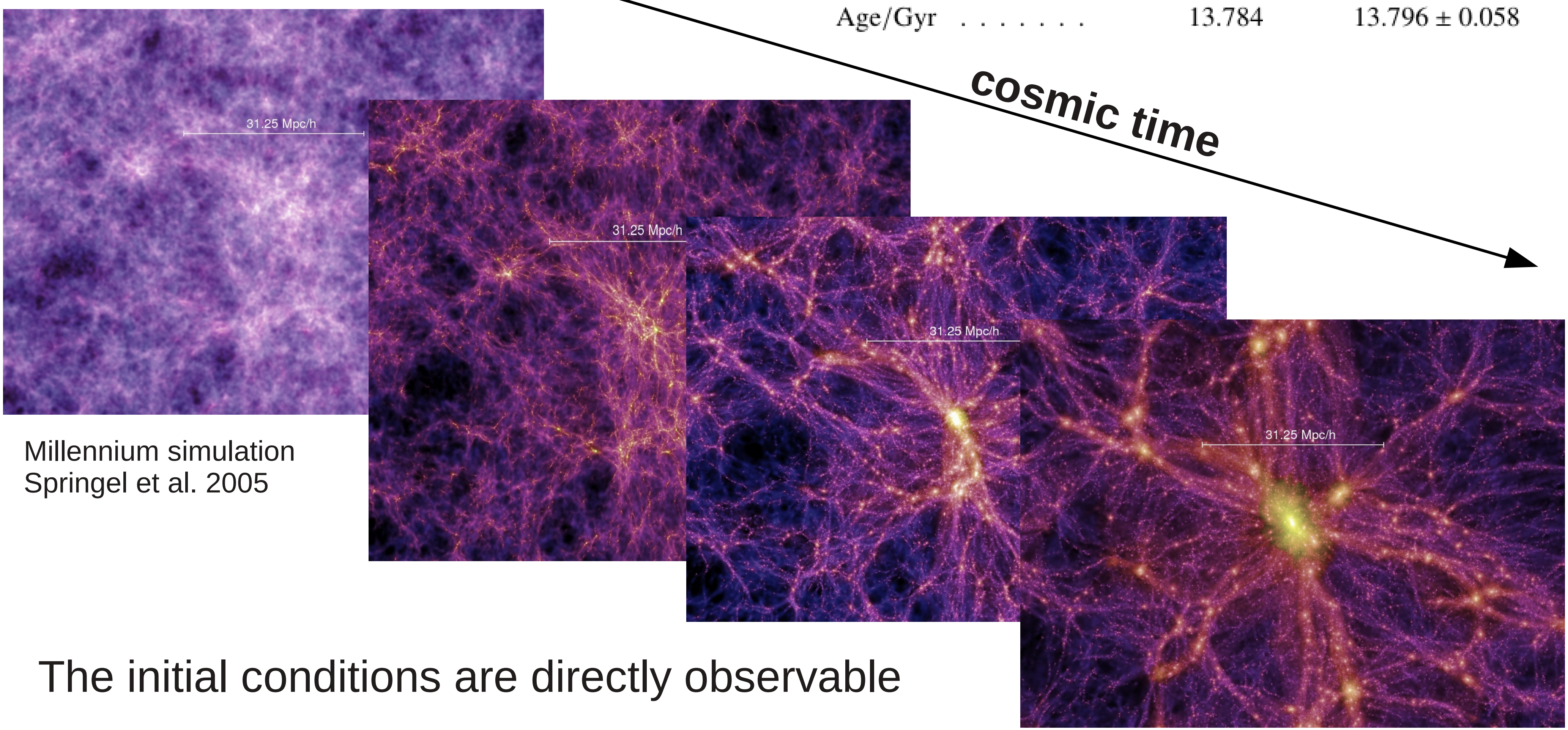
Cosmological simulations of galaxy and structure formation



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

cosmic time



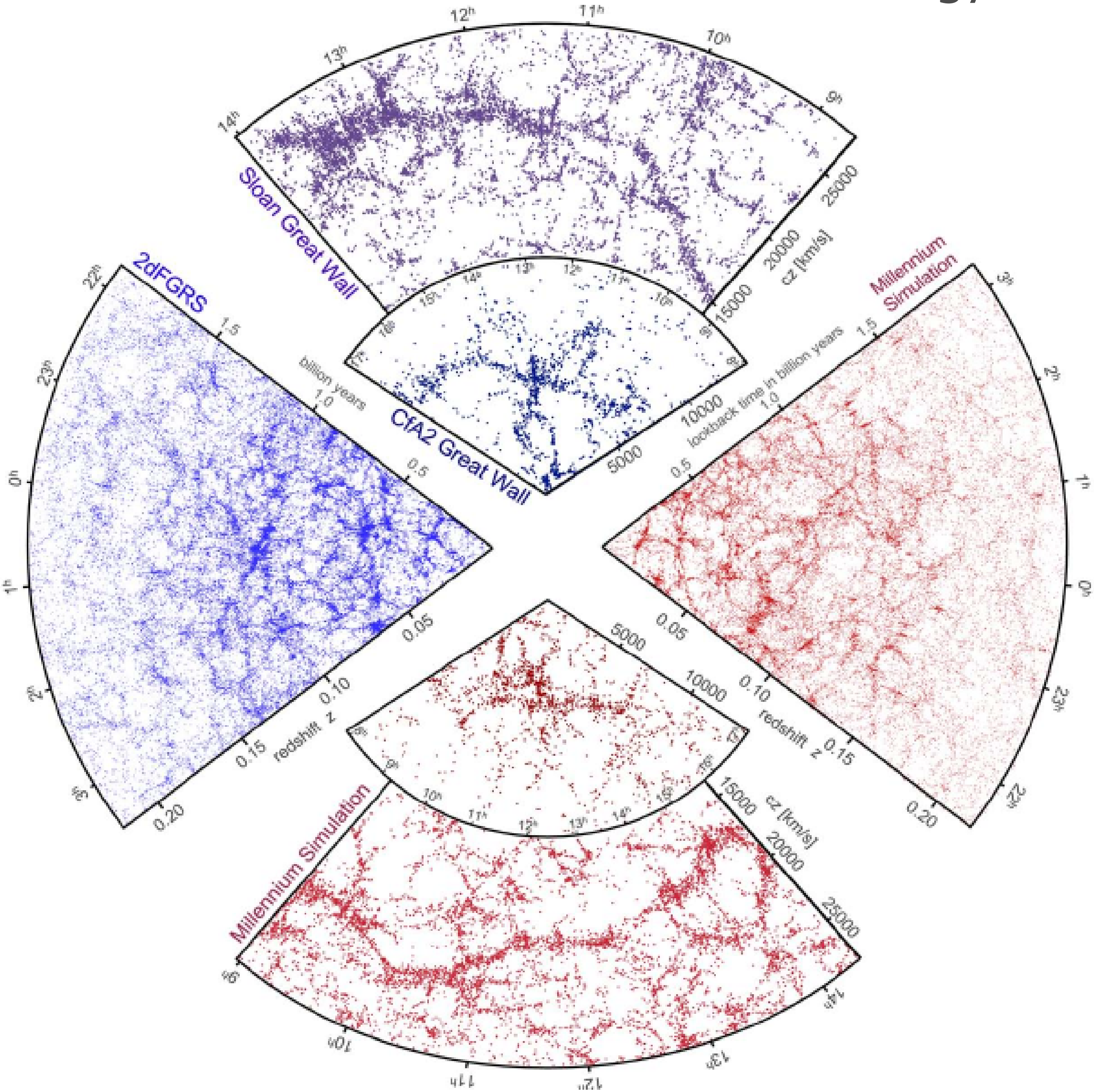
Millennium simulation
Springel et al. 2005

The initial conditions are directly observable

Pure dark matter simulations in ΛCDM cosmology

Simulated and observed large-scale structure in the galaxy distribution

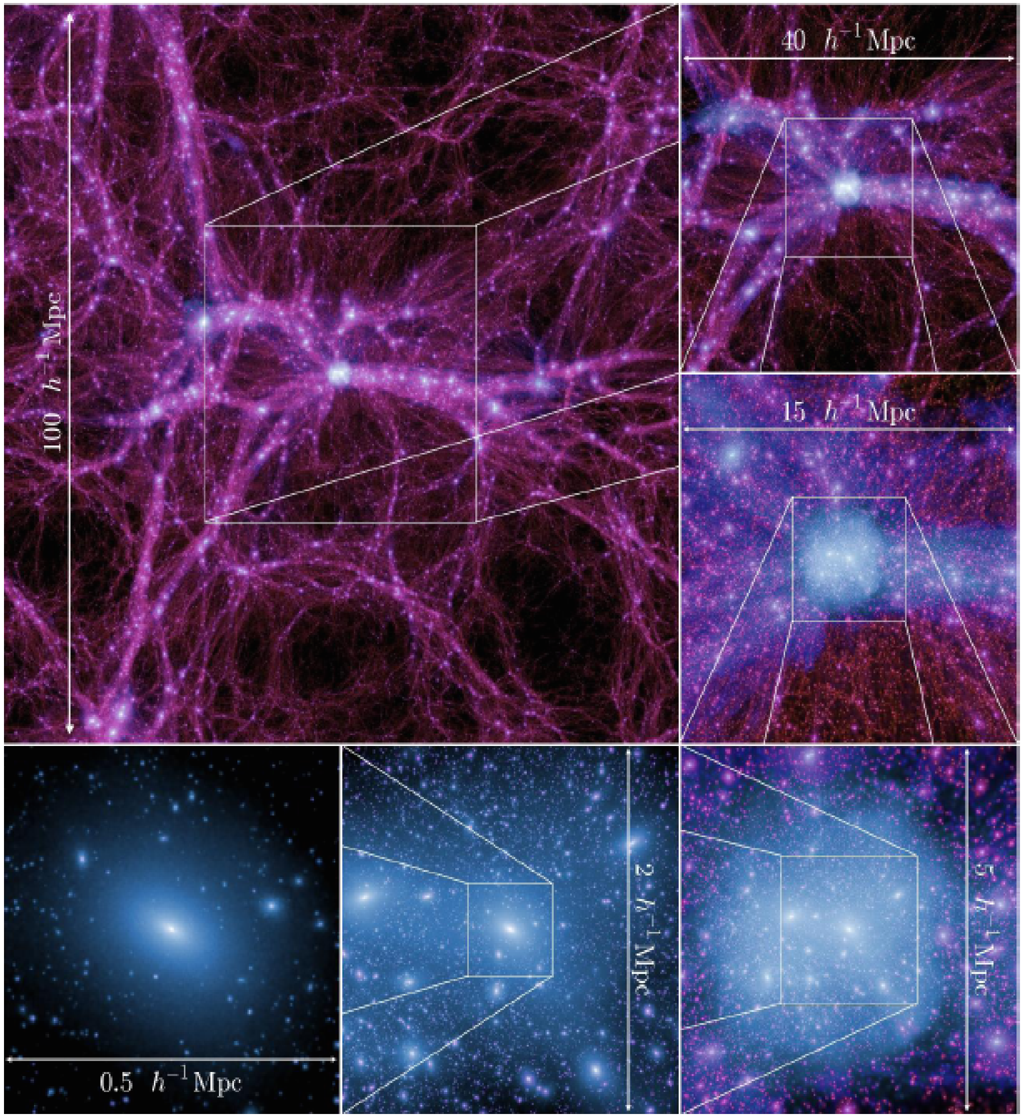
MOCK PIE DIAGRAMS COMPARED TO SDSS, 2DFGRS, AND CFA-2



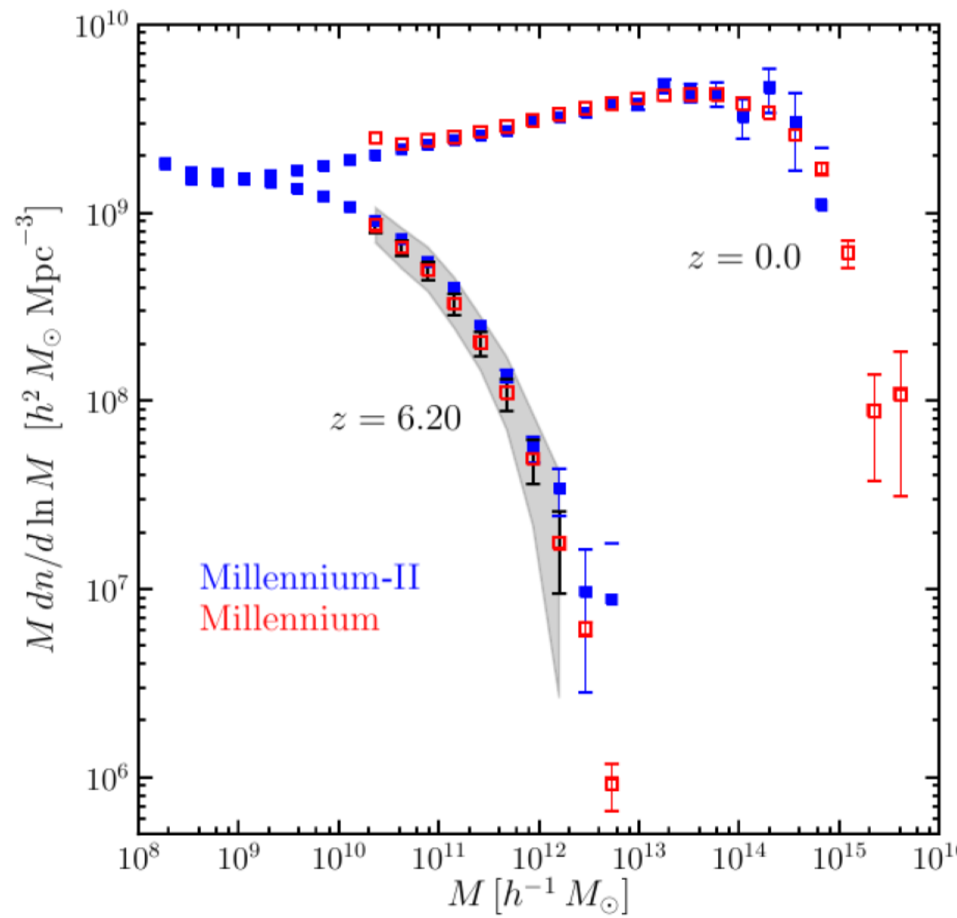
Springel et al. (2006)

Pure dark matter simulations in ΛCDM cosmology

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



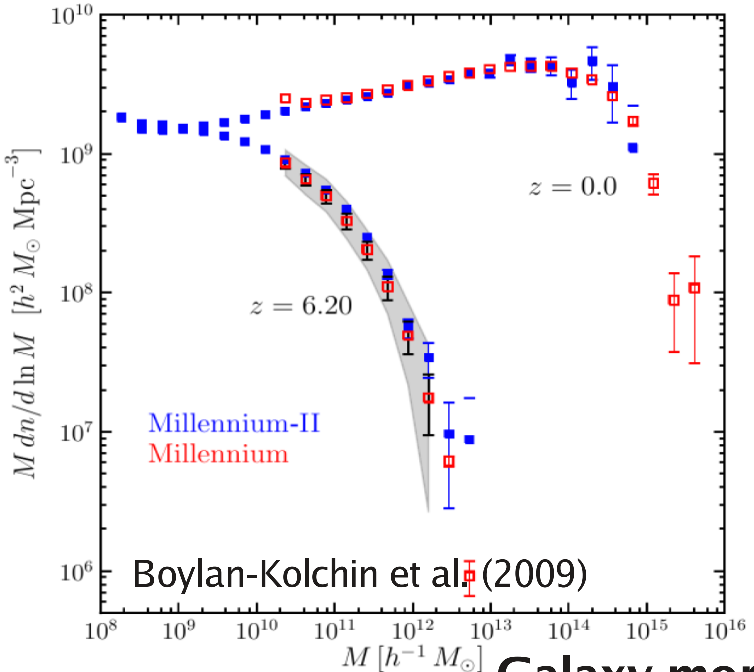
halo mass function



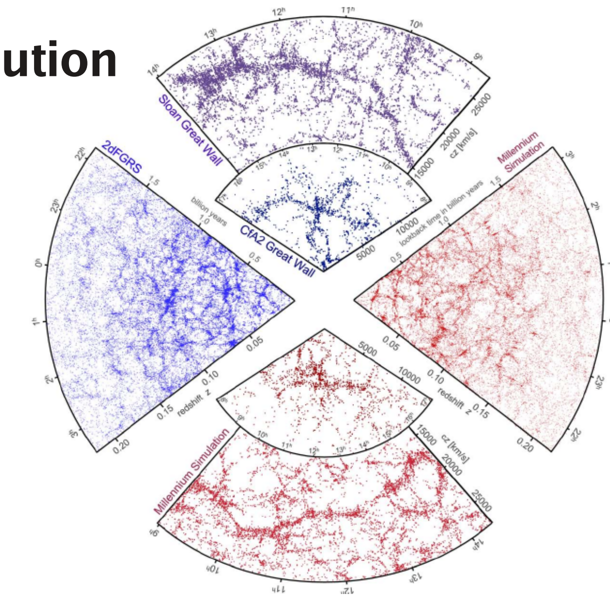
Boylan-Kolchin et al. (2009)

From dark matter to baryons

Hierarchical growth of dark matter halos

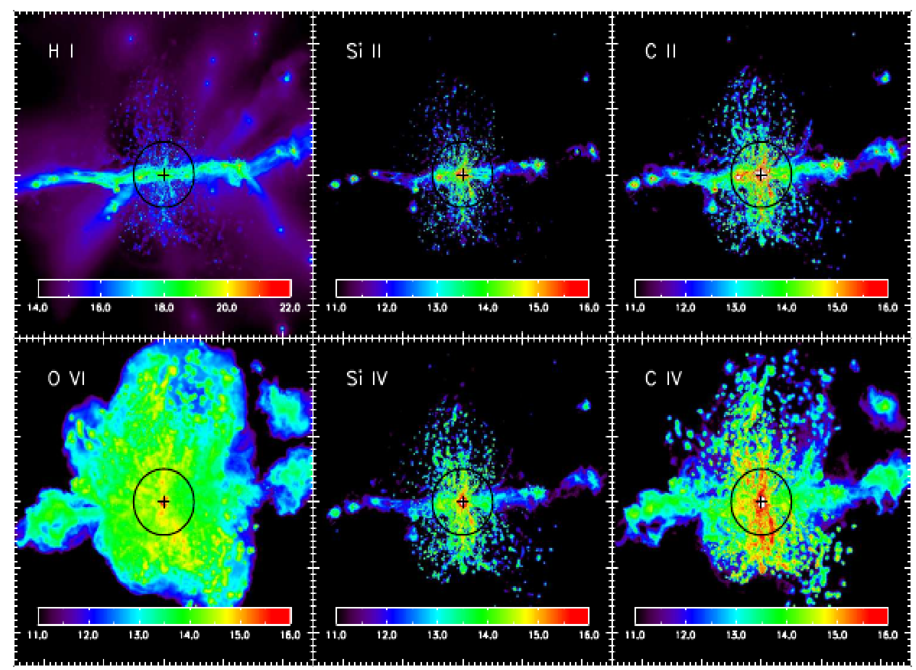


Large scale distribution of galaxies



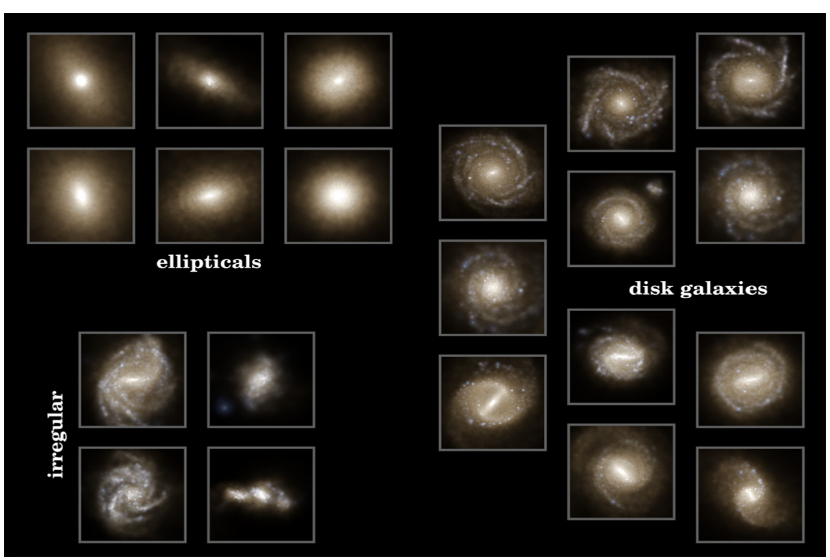
Springel et al. 2005

Large scale environments of galaxies: inflows and outflows



Shen et al. 2013

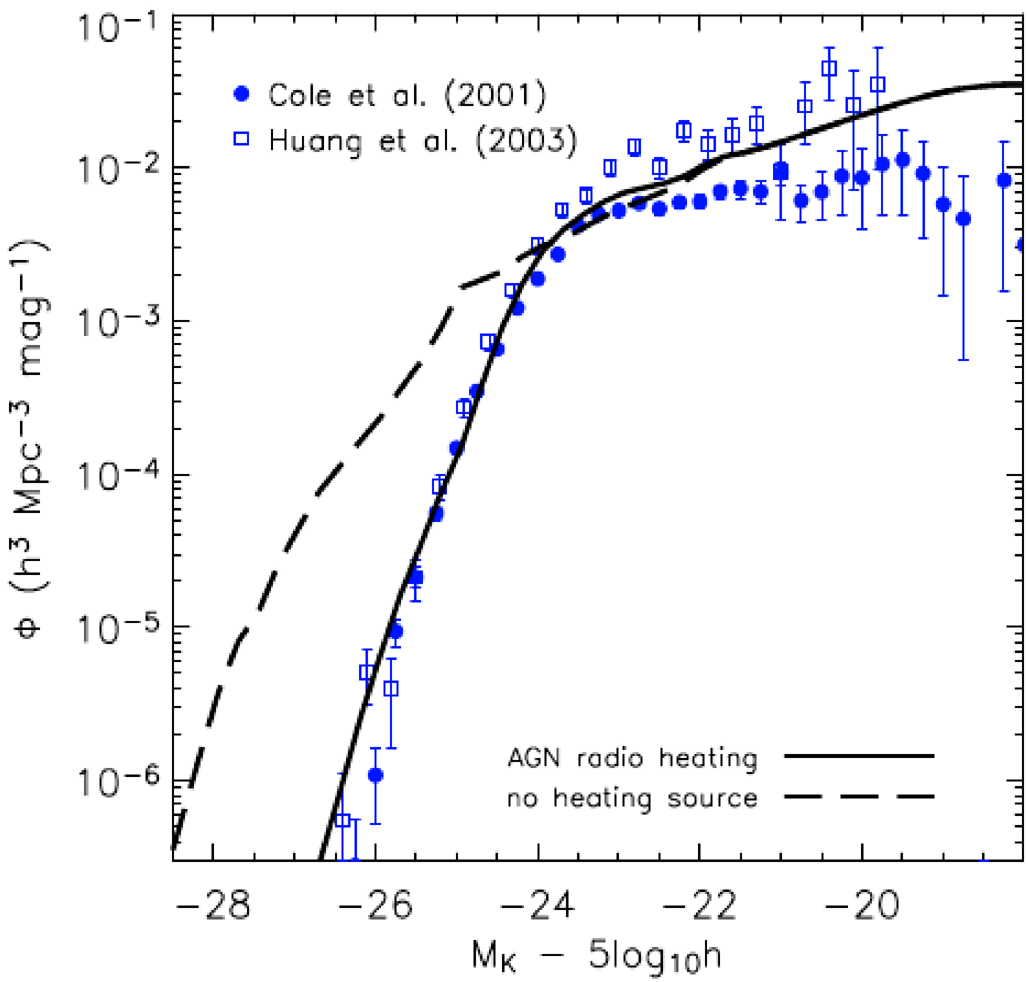
Galaxy morphologies Illustris project



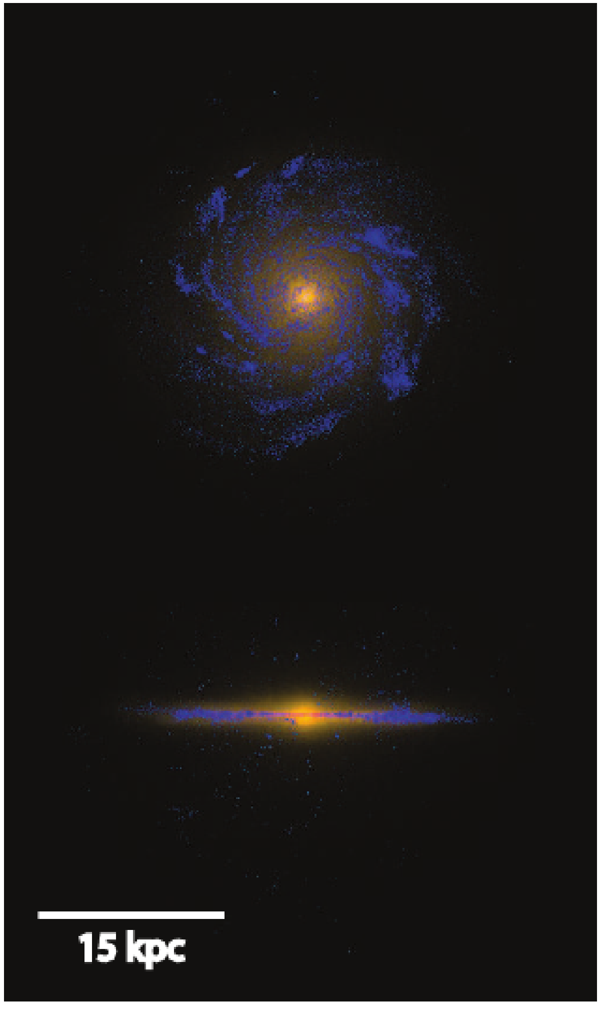
From dark matter to baryons

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:

$$\boldsymbol{U} = \begin{pmatrix} \rho \\ \rho \boldsymbol{v} \\ \rho e \end{pmatrix} = \begin{pmatrix} \rho \\ \rho \boldsymbol{v} \\ \rho u + \frac{1}{2} \rho \boldsymbol{v}^2 \end{pmatrix}$$

Flux vector:

$$\boldsymbol{F}(\boldsymbol{U}) = \begin{pmatrix} \rho \boldsymbol{v} \\ \rho \boldsymbol{v} \boldsymbol{v}^T + P \\ (\rho e + P) \boldsymbol{v} \end{pmatrix}$$

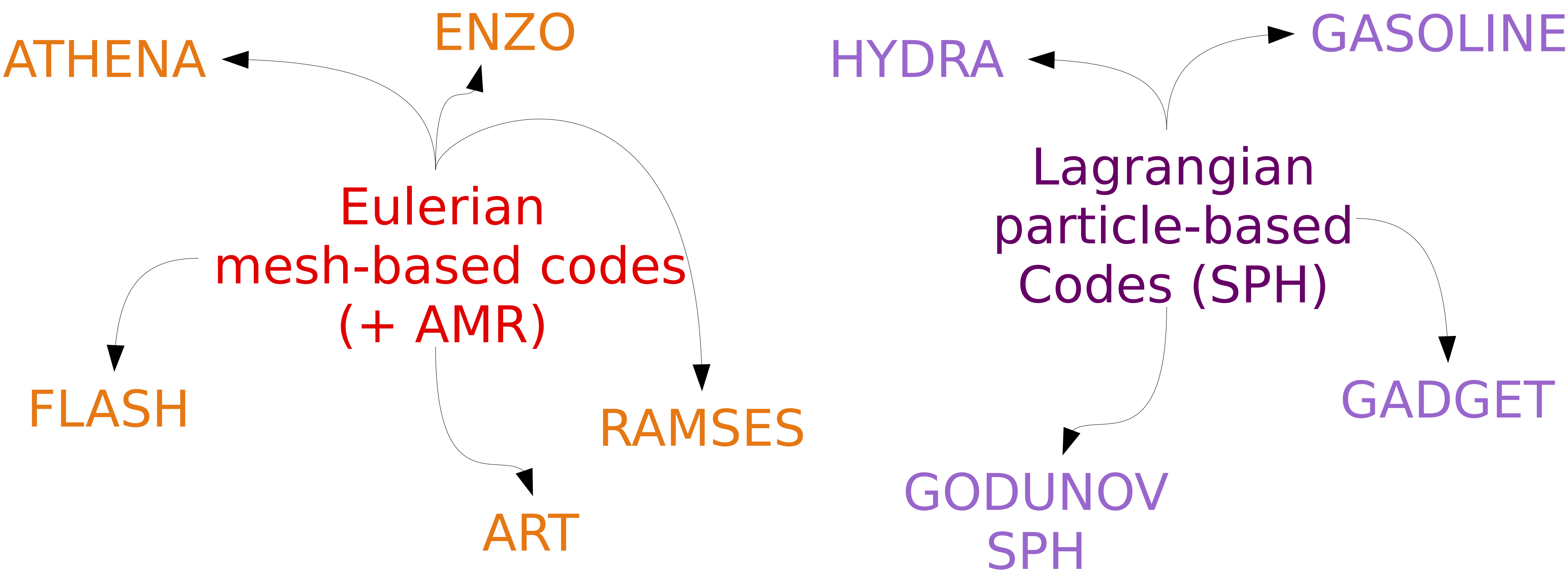
Equation of state:

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

Uncertainties in...

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

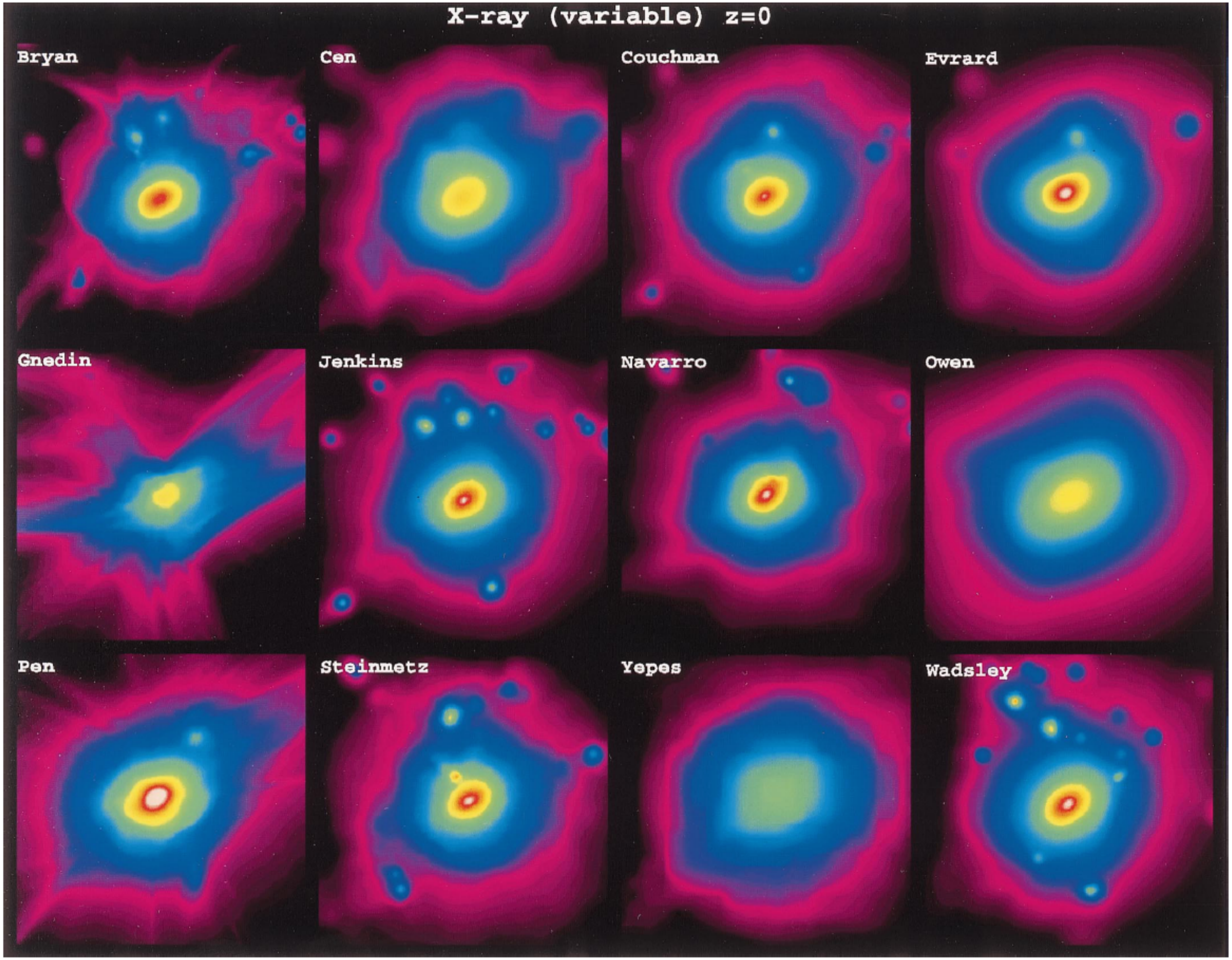
- Much more careful code comparisons are needed!
- Improvements in basic code solvers



The Santa Barbara Cluster Comparison Project

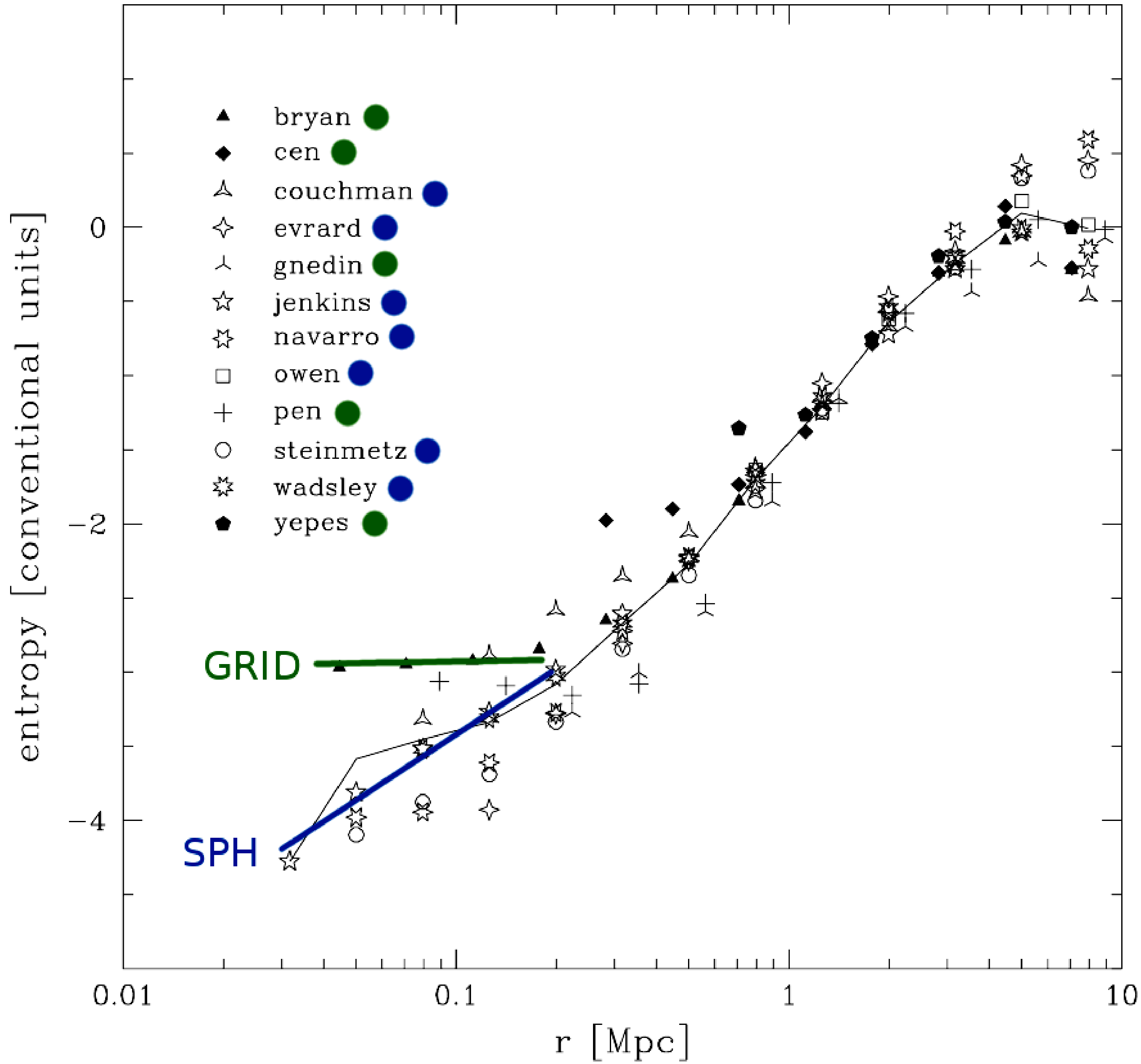
Frenk et al. 1999

Non-radiative cosmological hydrodynamical simulations
comparison of 12 different codes



The Santa Barbara Cluster Comparison Project

Frenk et al. 1999



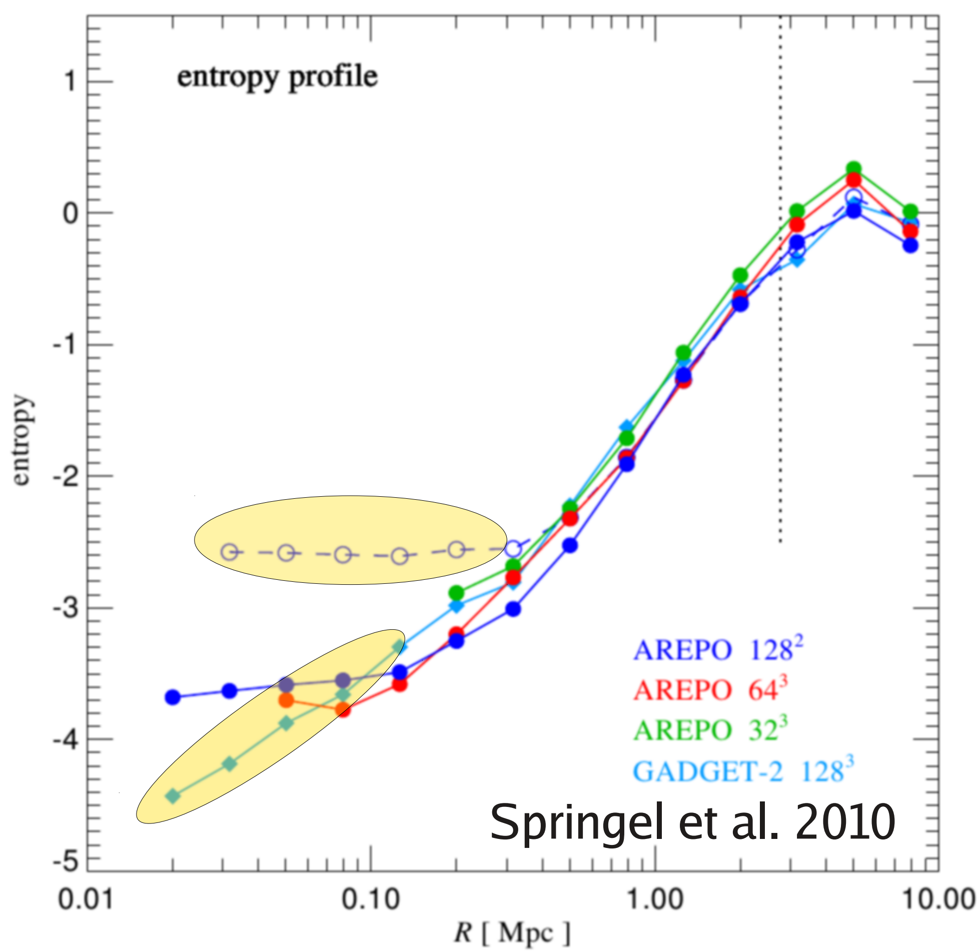
SPH simulations:
power-law entropy profiles

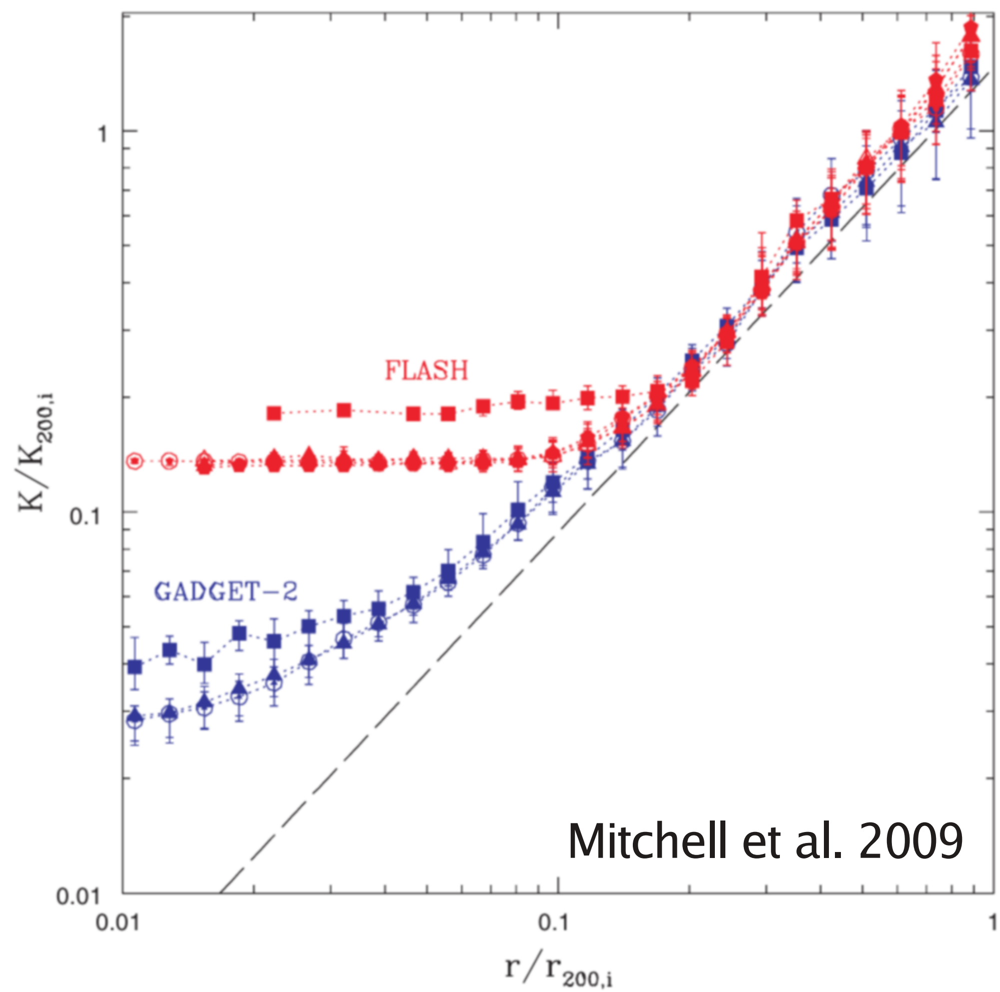
GRID-based simulations:
cored entropy profiles

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?
- ???

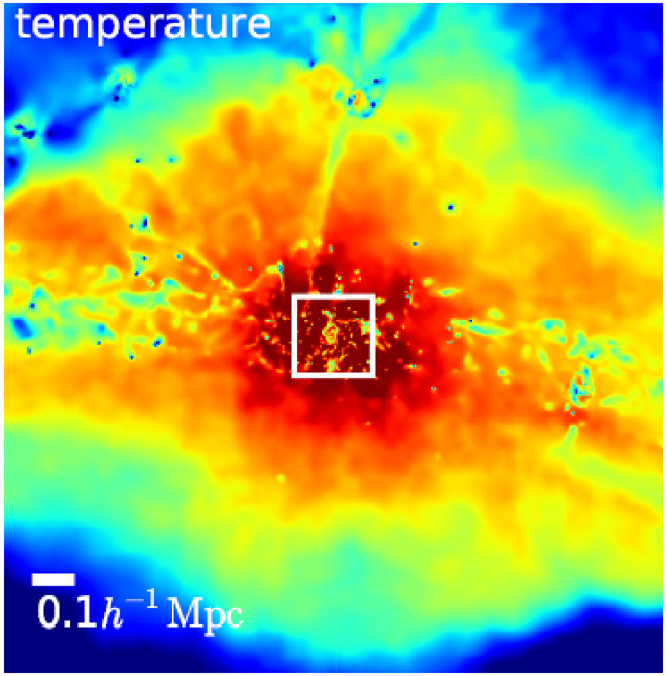




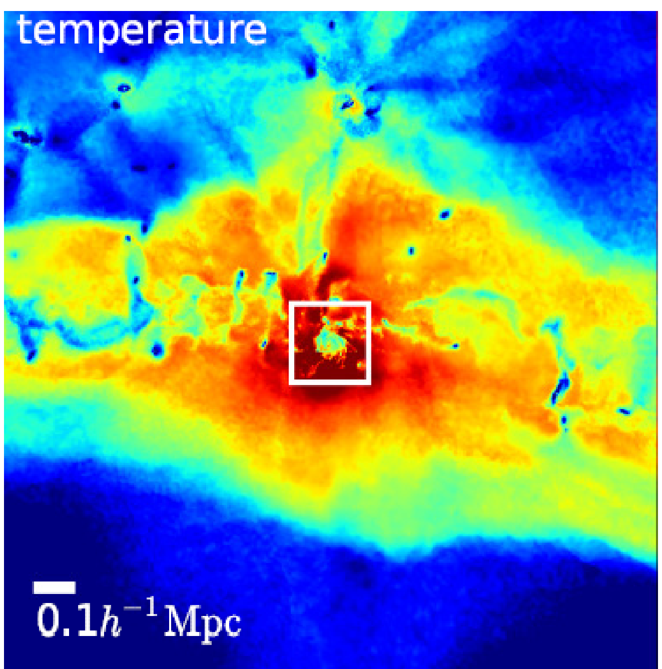
FUNDAMENTAL IMPLICATIONS FOR:
- **UNDERSTANDING ASTROPHYSICS OF GALAXY CLUSTERS**
- **USING GALAXY CLUSTERS AS HIGH-PRECISION COSMOLOGICAL PROBES**

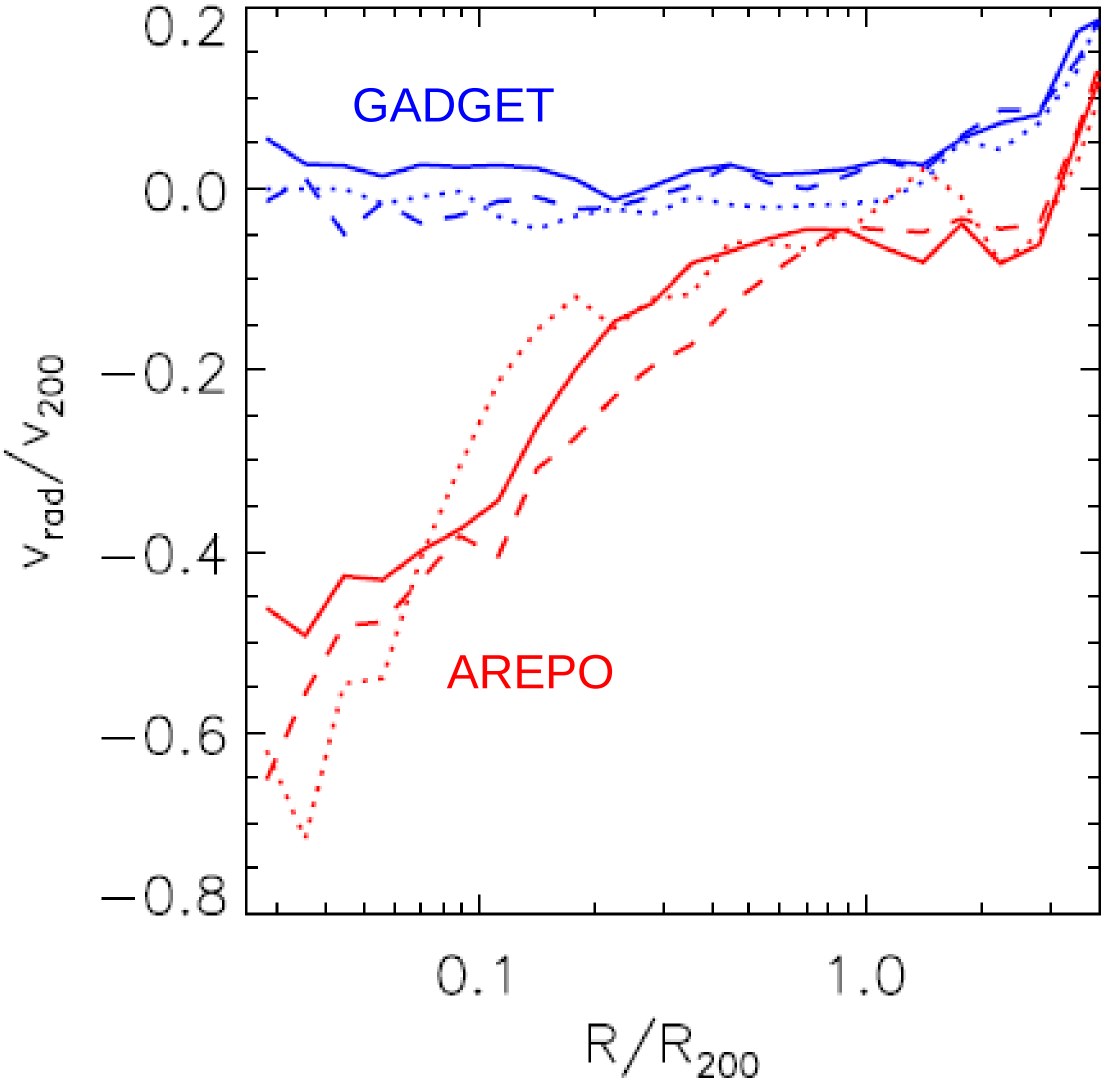
Gas cooling in dark matter halos

GADGET



AREPO

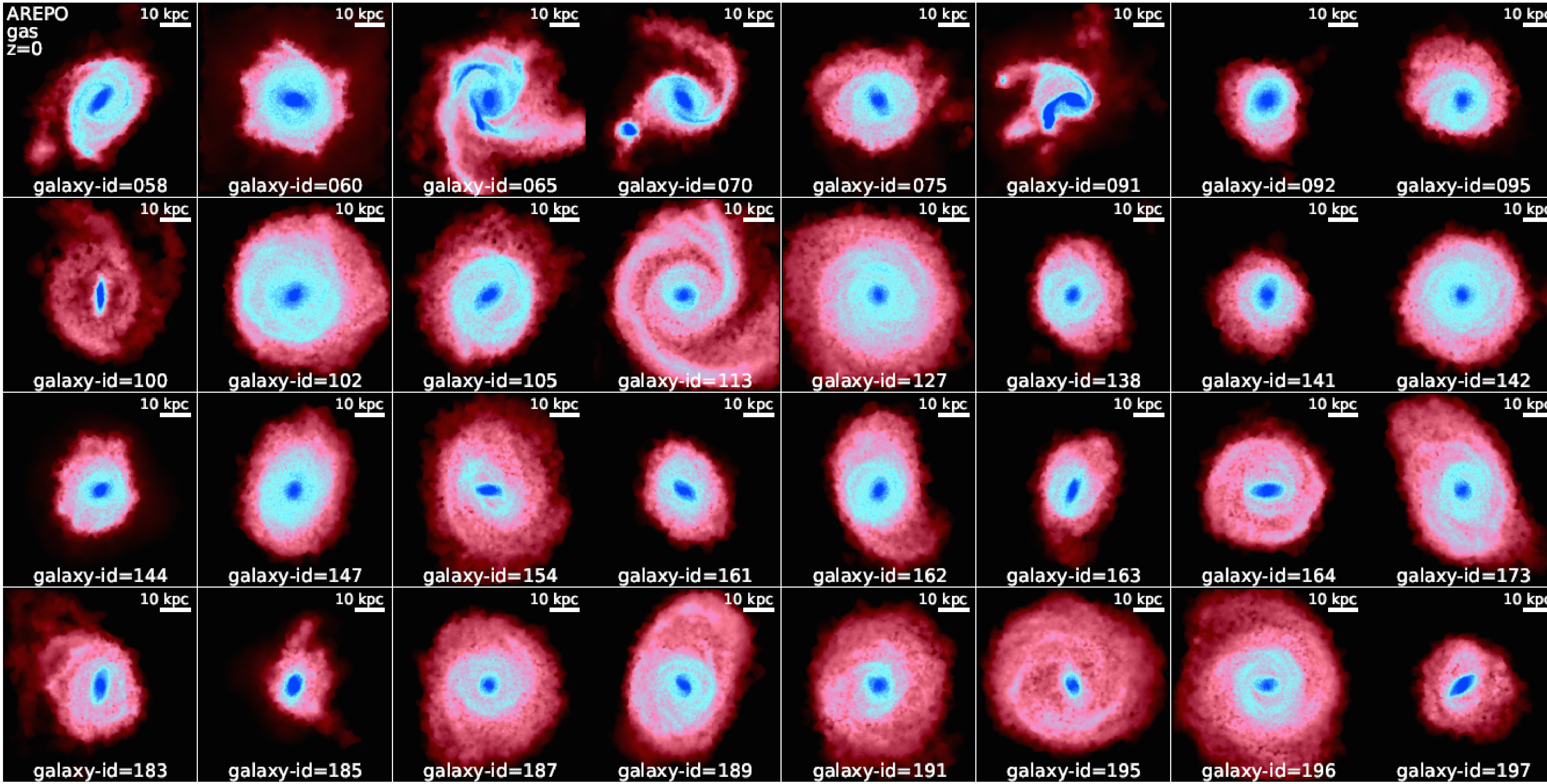




Vogelsberger et al. 2012
Keres et al. 2012
see also Bauer&Springel 2012

Galaxy morphology

AREPO



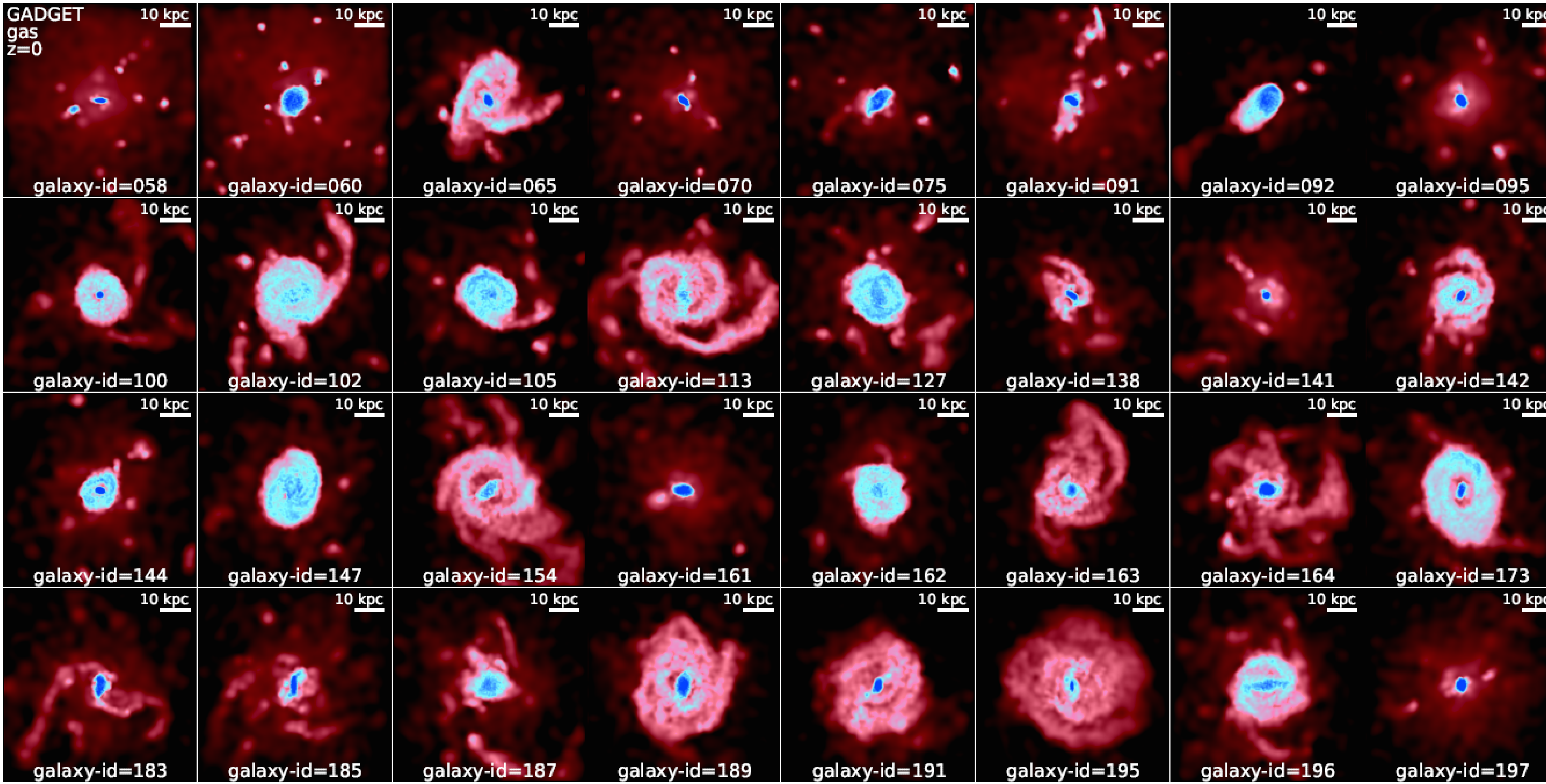
sample of galaxies selected at z=0 (projected gas density, face on):

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

moving mesh approach forms extended disks

Galaxy morphology

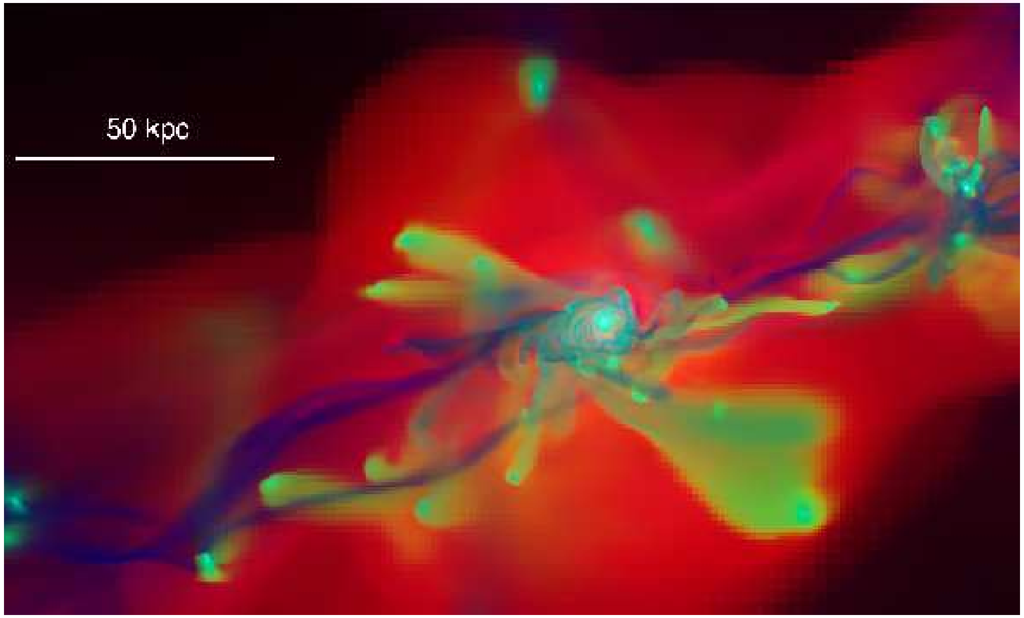
GADGET

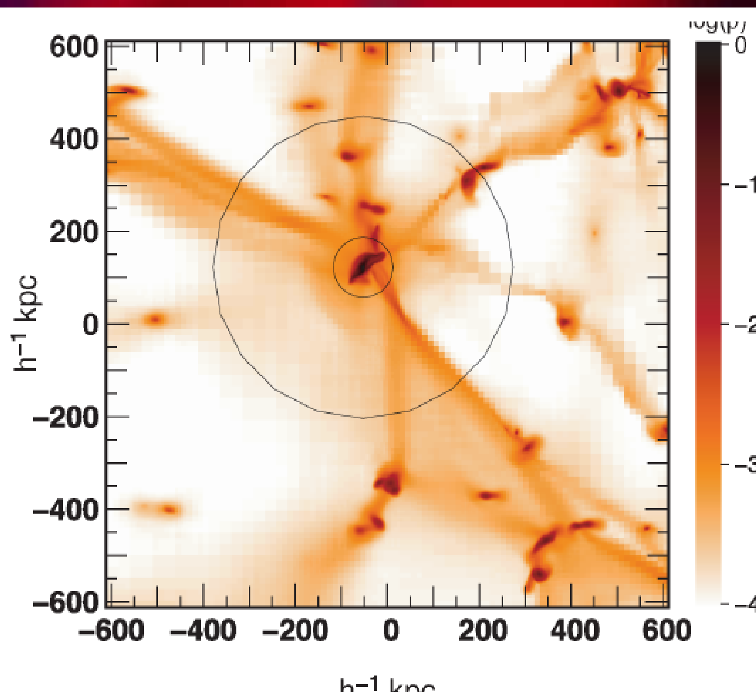


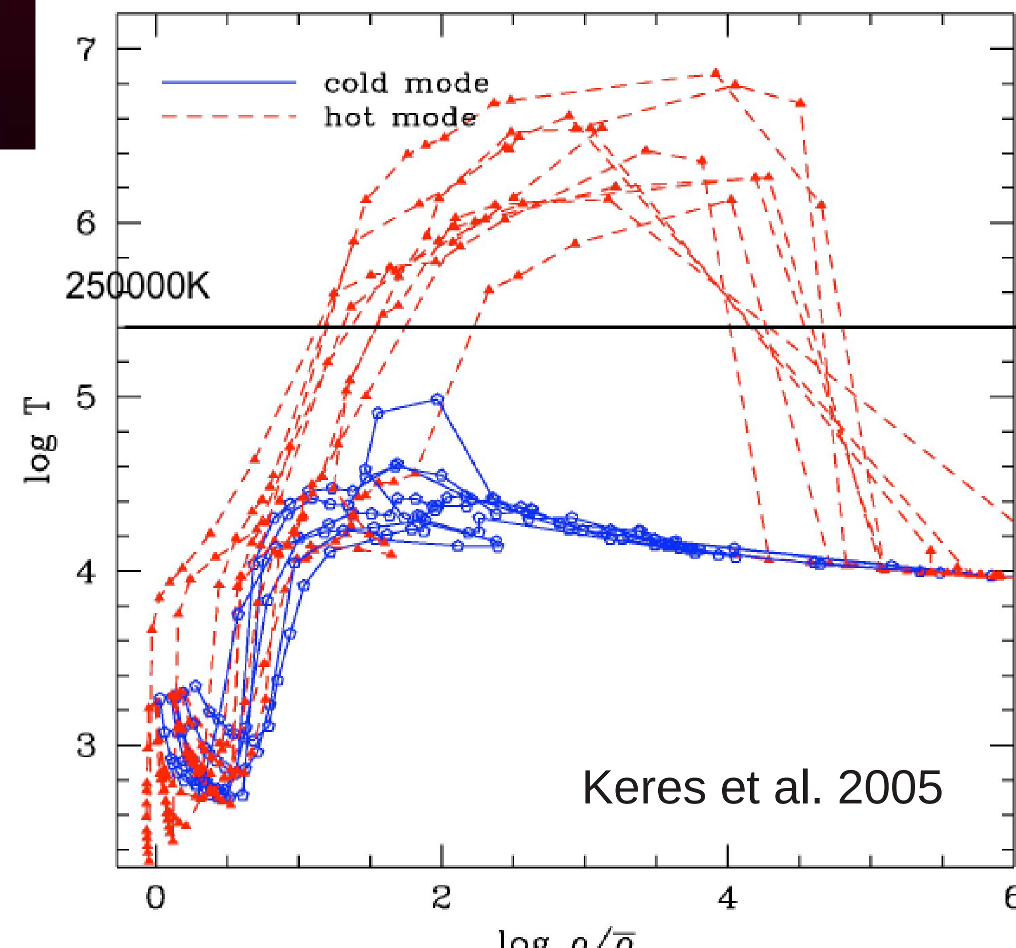
same galaxies but now with SPH: in many cases no extended disk is formed

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

Hot and cold flows onto the galaxies

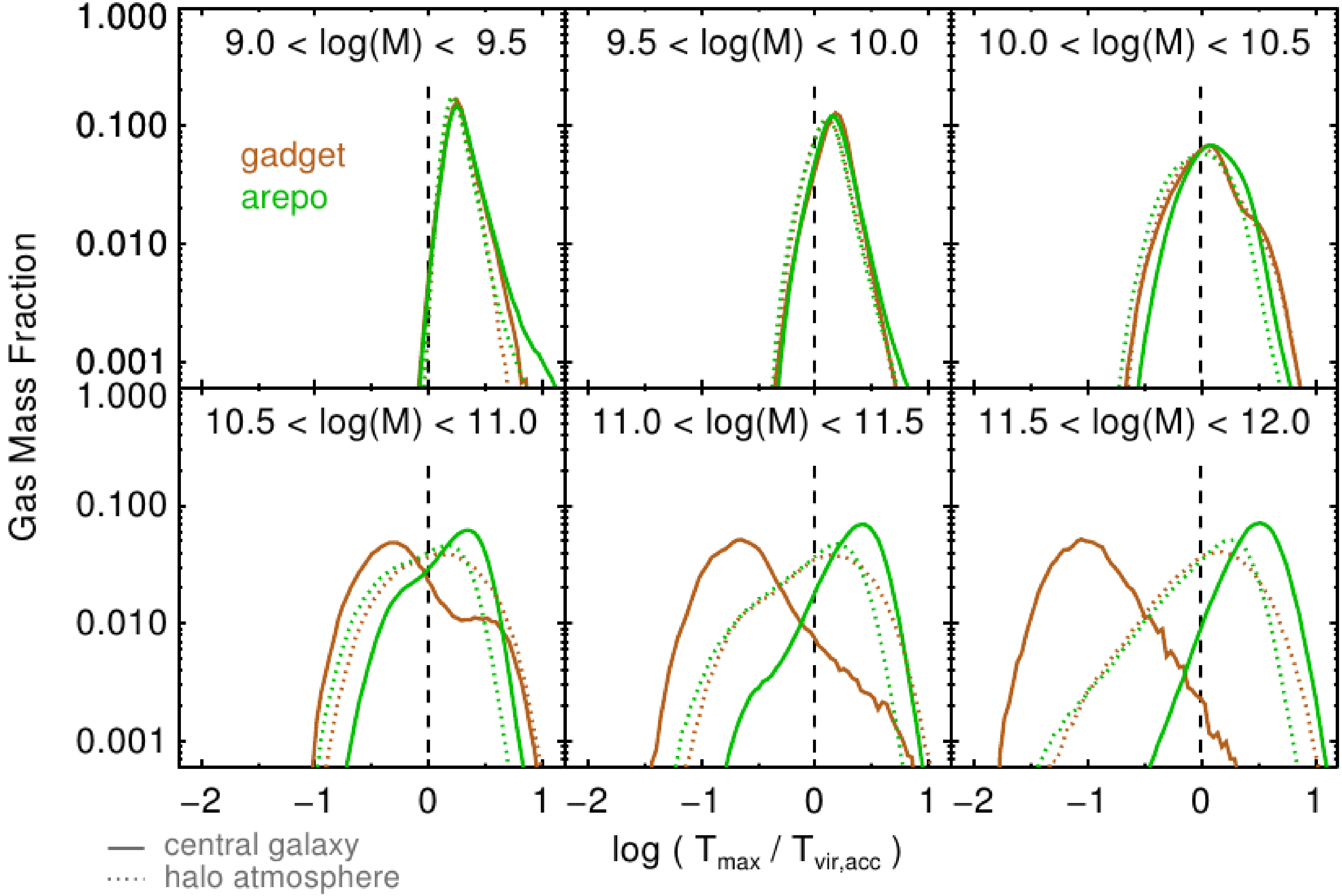






Ocvirk 2008 (MareNostrum, RAMSES)
Agertz 2009 (High-z galaxy, RAMSES)

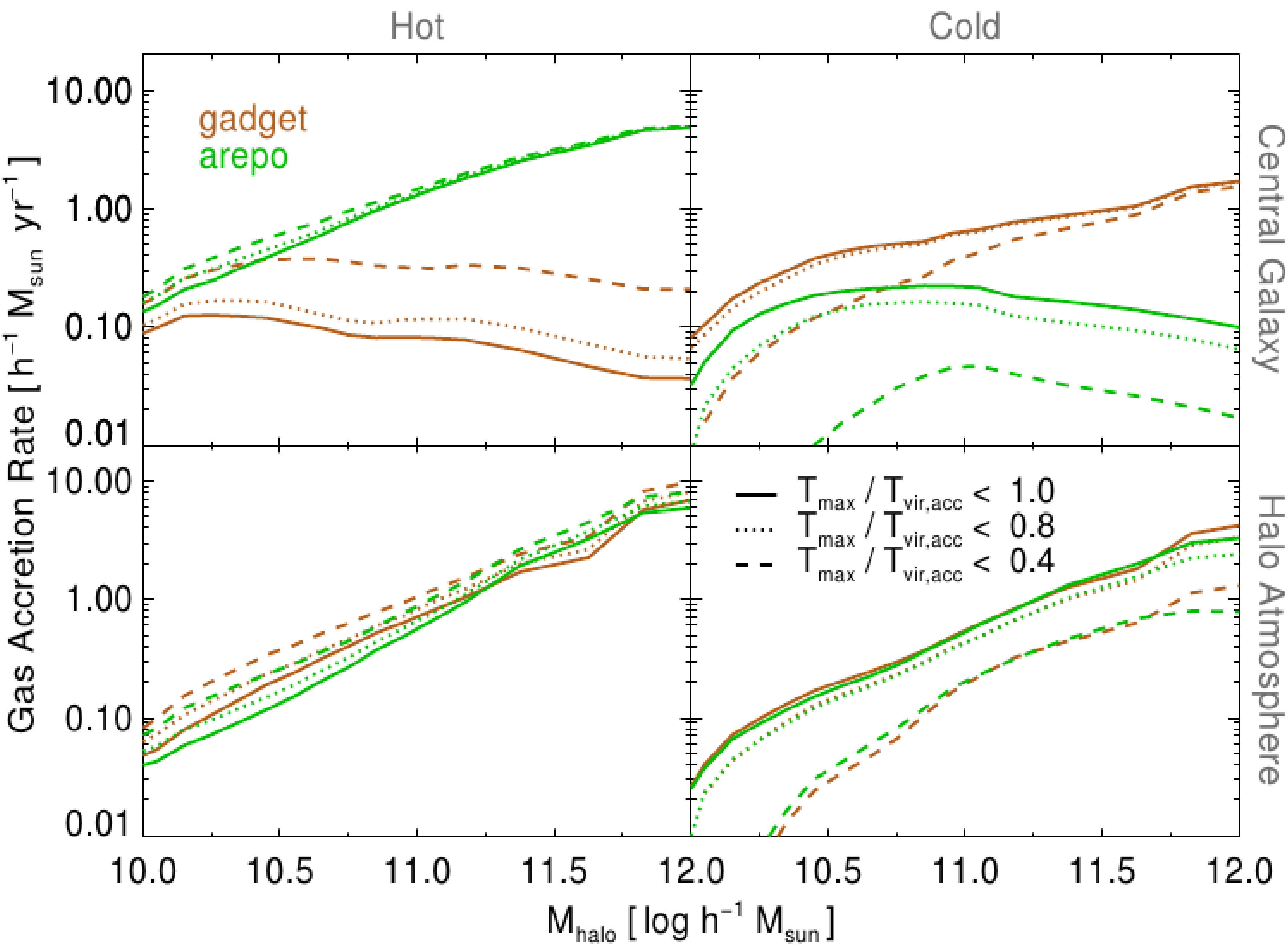
Hot and cold flows onto the galaxies



there could still be numerical uncertainties due to resolution effects, shock broadening,...

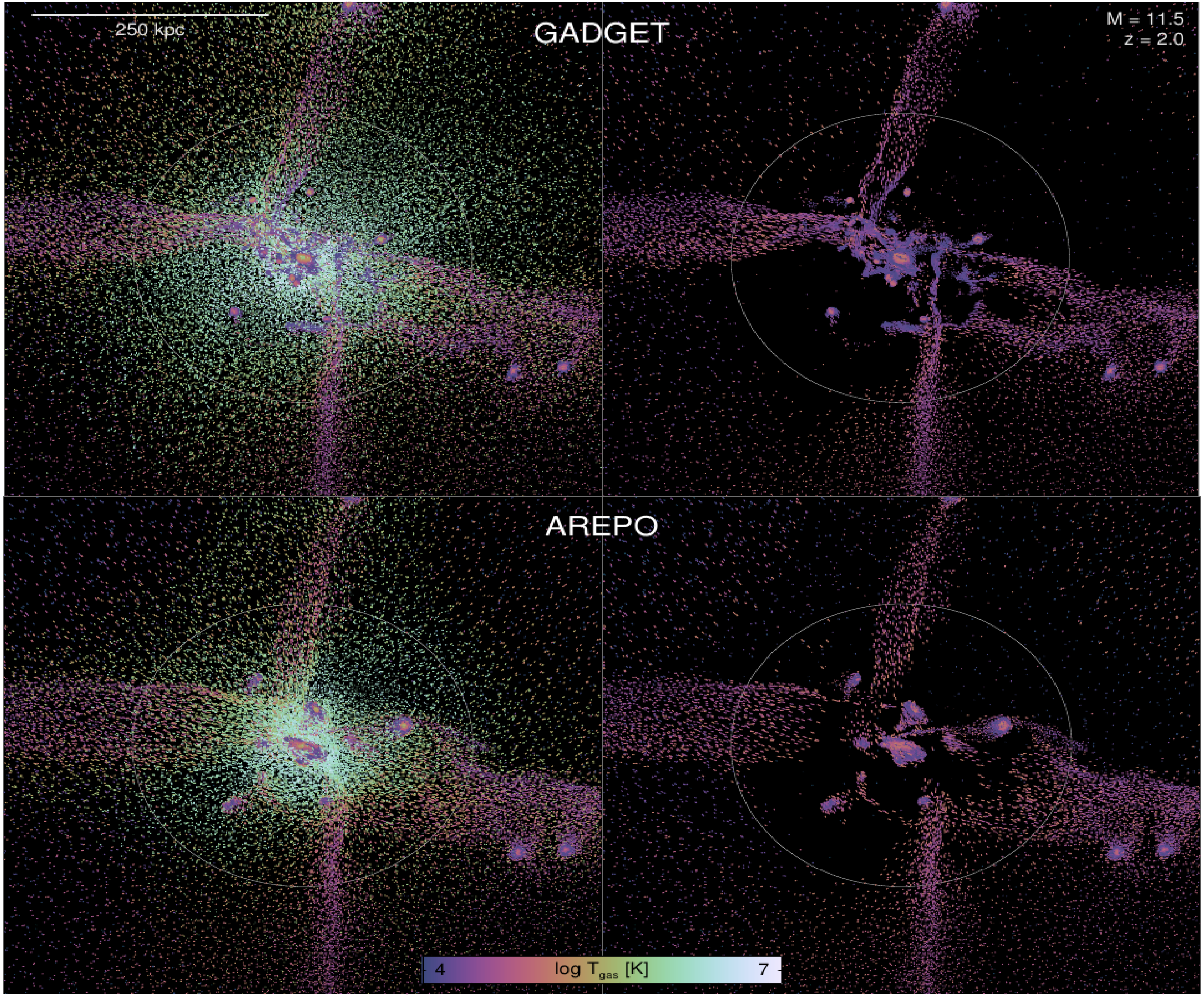
Nelson, Vogelsberger, Genel, Sijacki, Springel, Hernquist, 2013, MNRAS

Hot and cold flows onto the galaxies



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

Hot and cold flows onto the galaxies

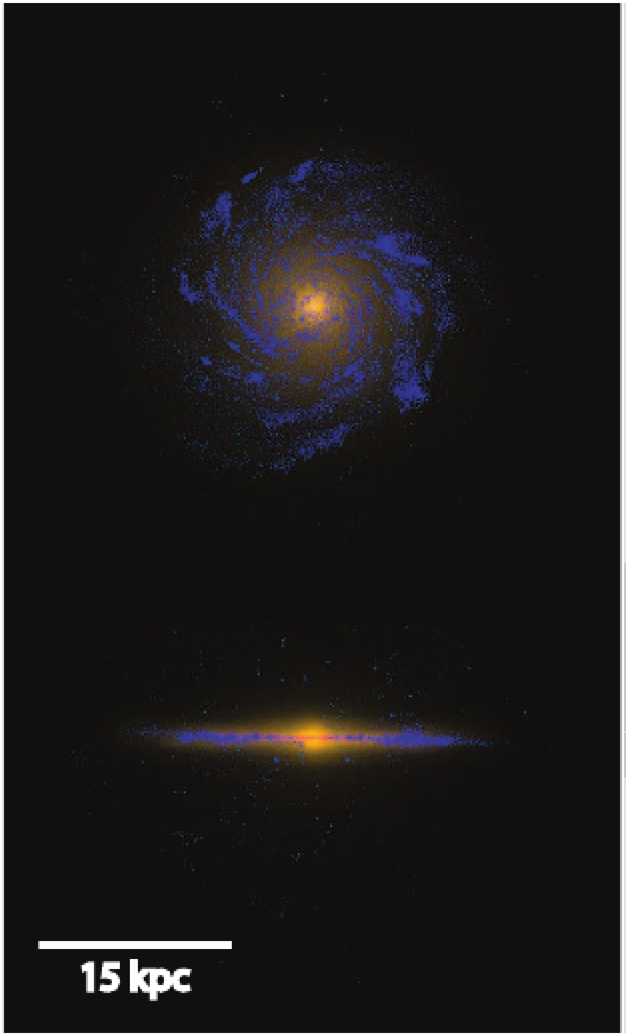


But what about all the relevant physics?

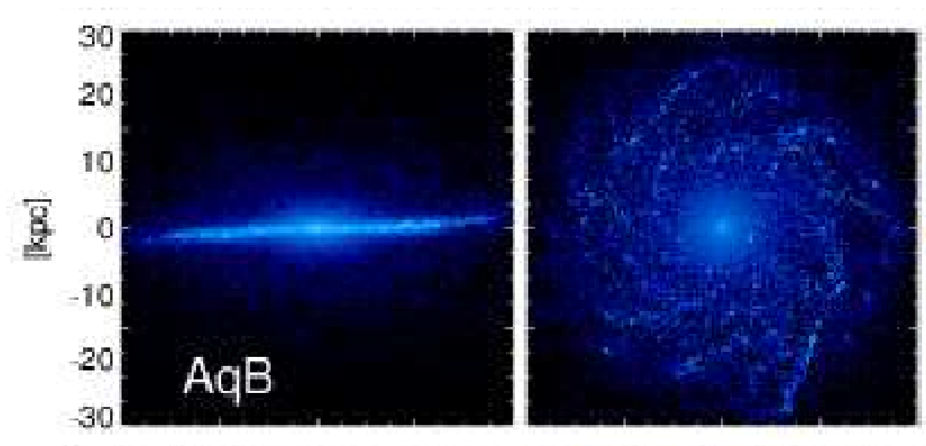
- radiative cooling and heating processes
- star formation
- supernovae feedback and stellar winds
- black holes and AGN heating
- non-ideal plasma effects
- non-thermal pressure support
- magnetic fields,...

Perseus cluster, Fabian et al.

Galaxy formation simulations

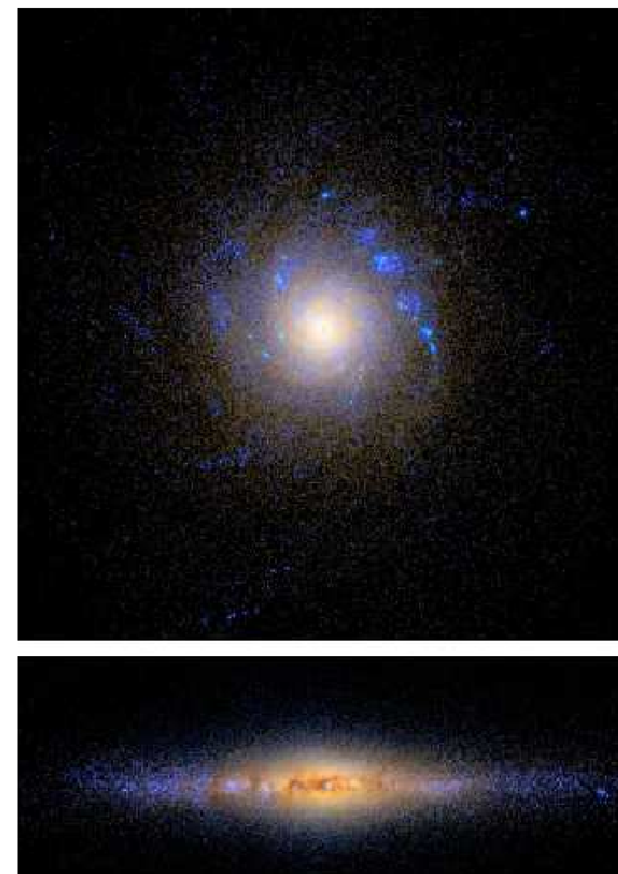


Guedes et al. 2011



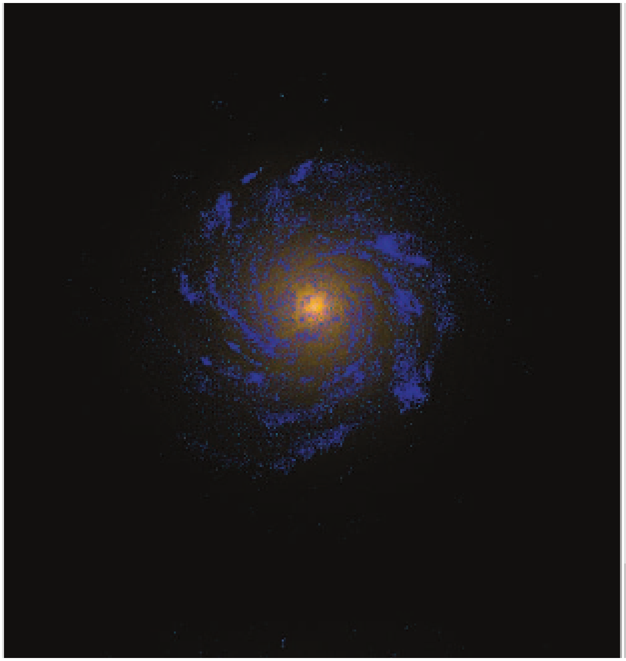
Aumer et al. 2013

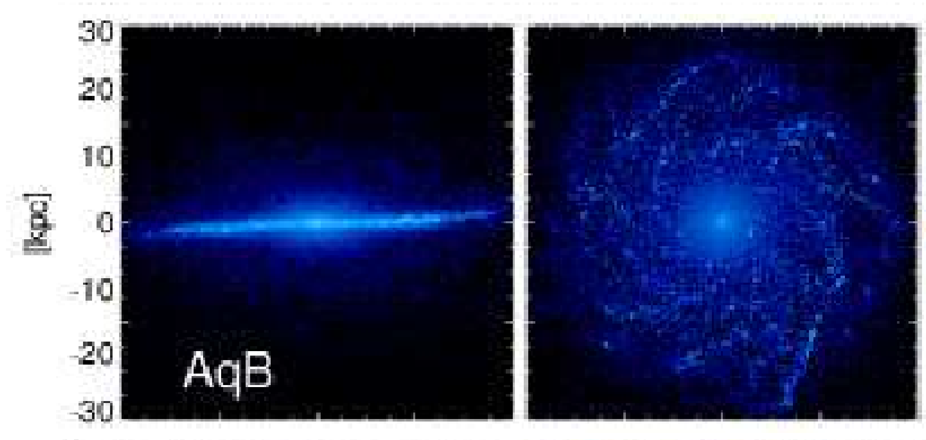
Marinacci et al. 2013



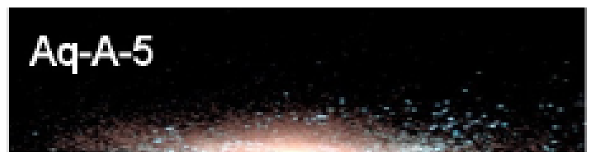
Stinson et al. 2013 MAGICC

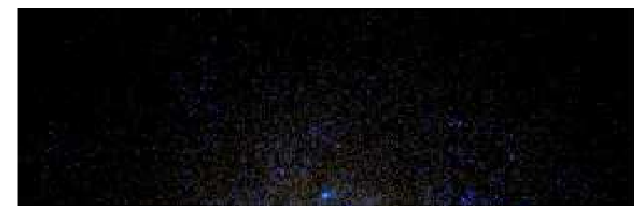
Galaxy formation simulations





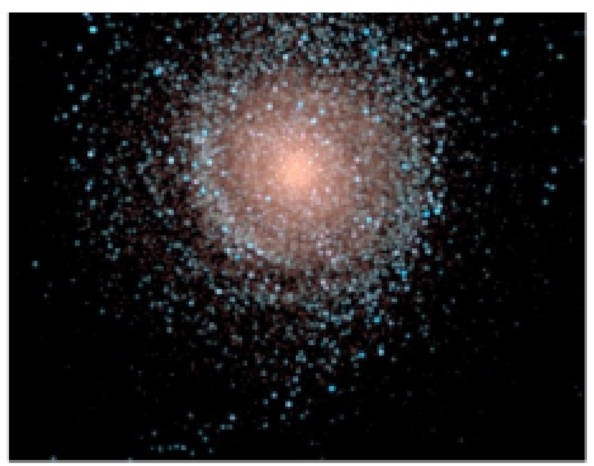
Aumer et al. 2013

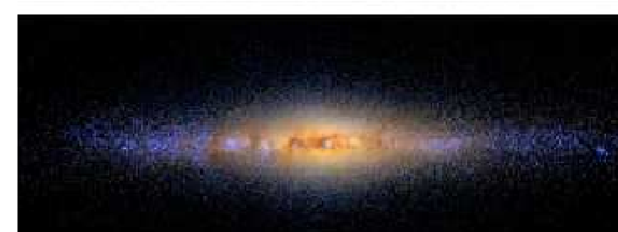




This success in producing realistic disc galaxies is reached without resorting to a high density threshold for star formation, a low star formation efficiency, or early stellar feedback, factors deemed crucial for disc formation by other recent numerical studies.

Guedes et al. 2011





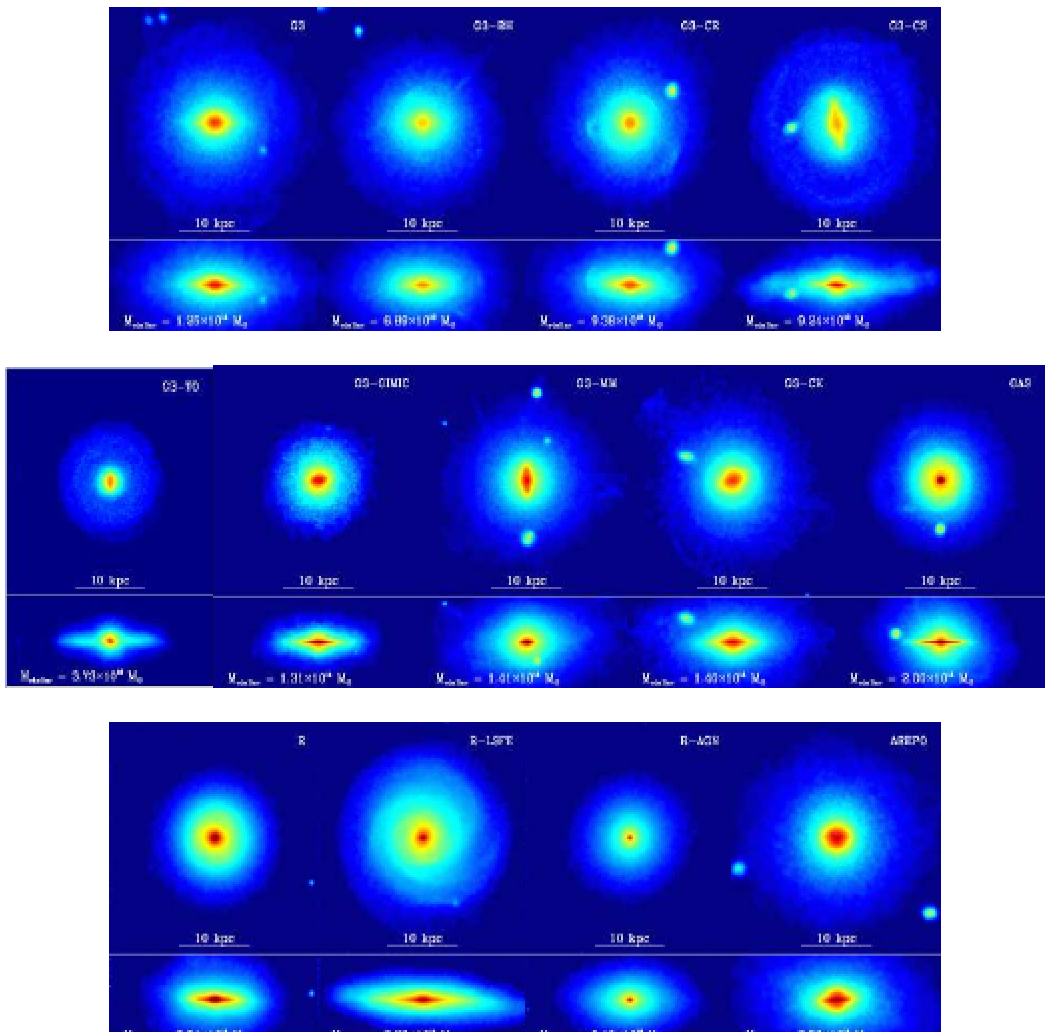
Marinacci et al. 2013

Stinson et al. 2013 MAGICC

Physical modeling uncertainties

The Aquila comparison project Scannapieco et al. 2012

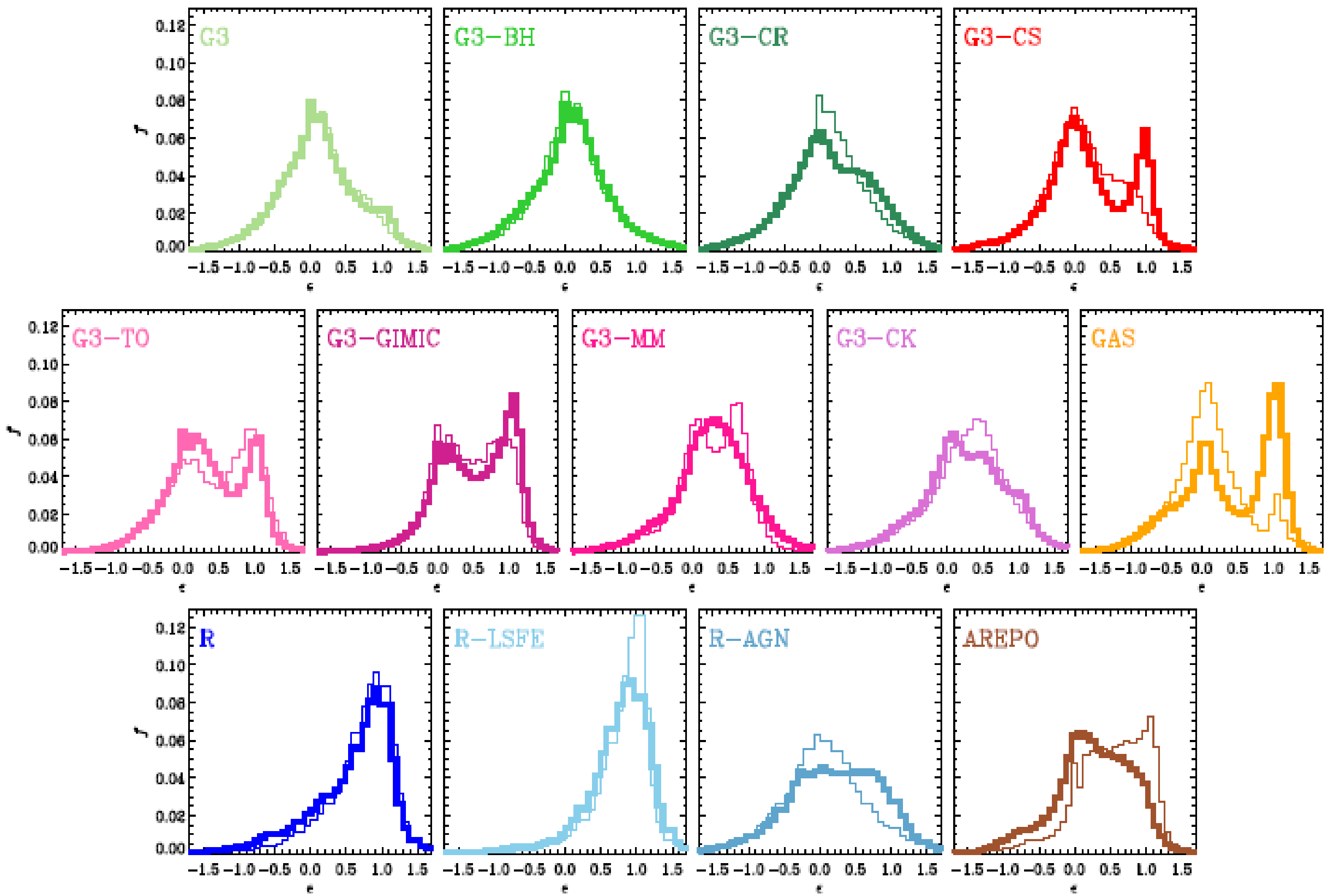
9 different codes, 13 runs with the same ICs but different physics
“Despite the common halo assembly history, we find large code-to-code variations in the stellar mass, size, morphology and gas content of the galaxy at z=0, due mainly to the different implementations of star formation and feedback.



Physical modeling uncertainties

The Aquila comparison project Scannapieco et al. 2012

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



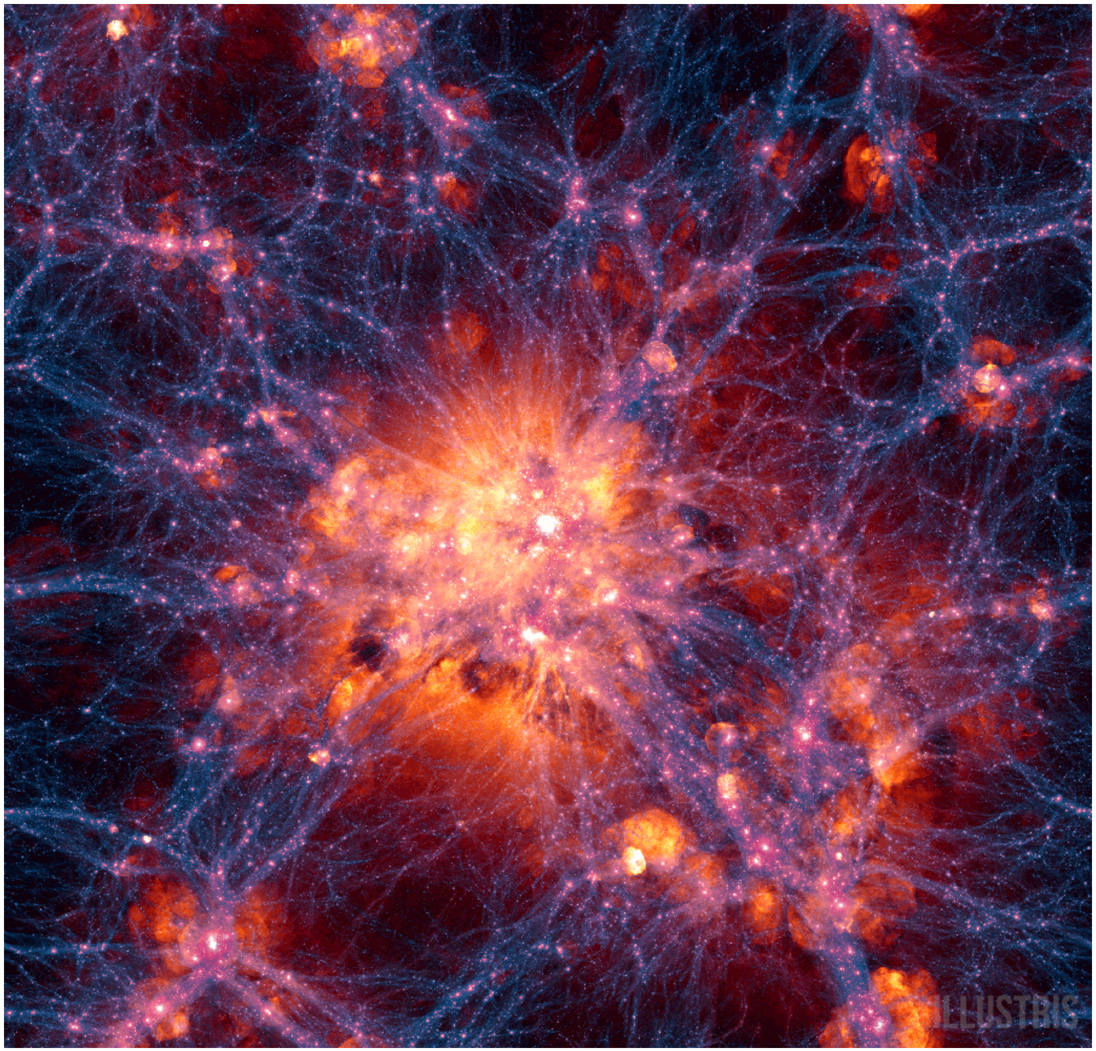
Physical modeling uncertainties

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

DM DENSITY with overlaid GAS VELOCITY



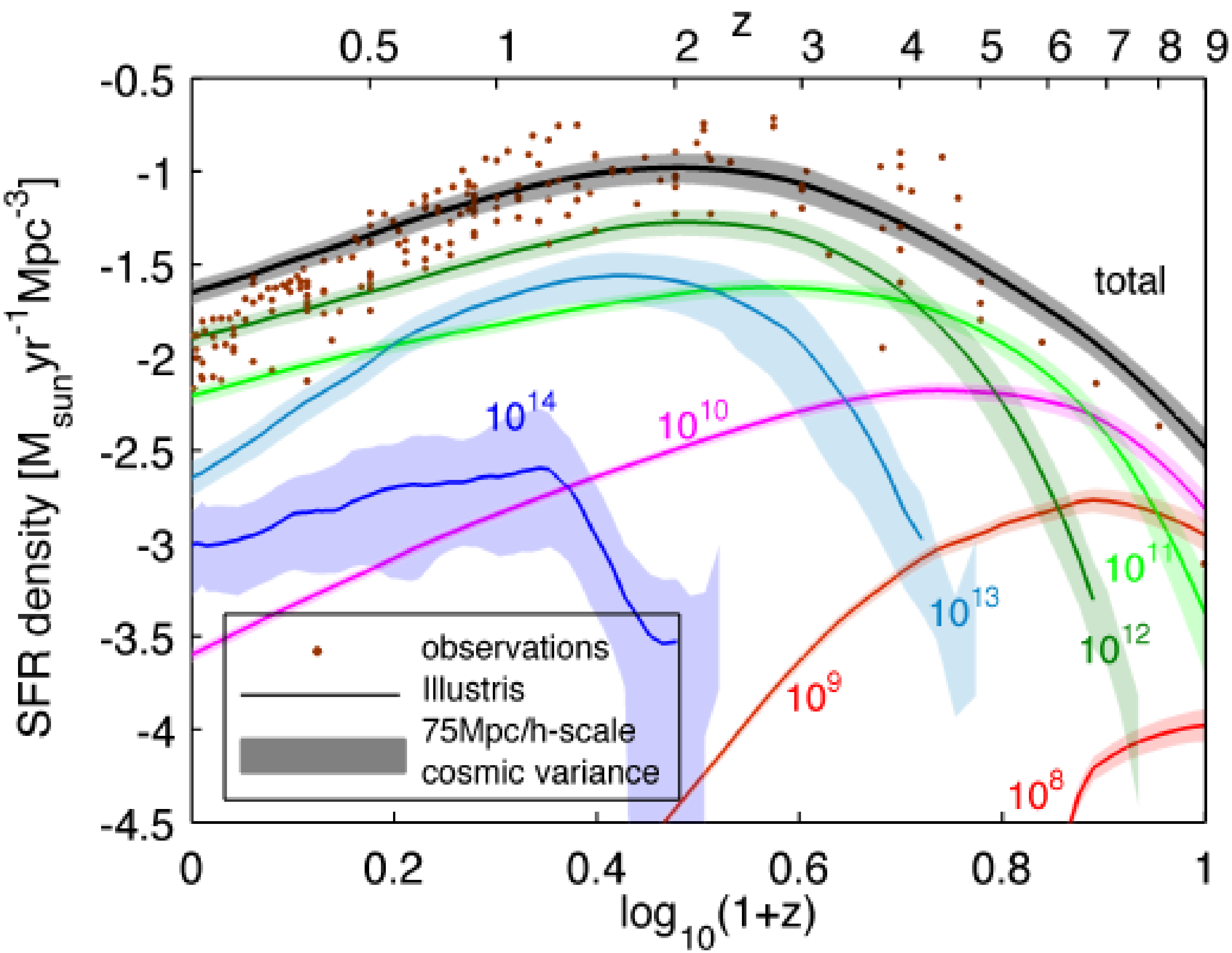
Box size = 106.5Mpc
Min cell size = 48pc
3 x 1820^3
dark matter particles
gas cells
passive tracers -> 18 billion
8192 cores, 19 MCPUh

Physics:

primordial & metal line cooling
+ self-shielding
stellar evolution
stellar feedback
gas recycling
chemical enrichment
black hole growth
black hole feedback:
quasar, radiative and radio bubbles
(see Springel et al. 2005
Sijacki et al. 2007,
Vogelsberger et al. 2013)

The Illustris project

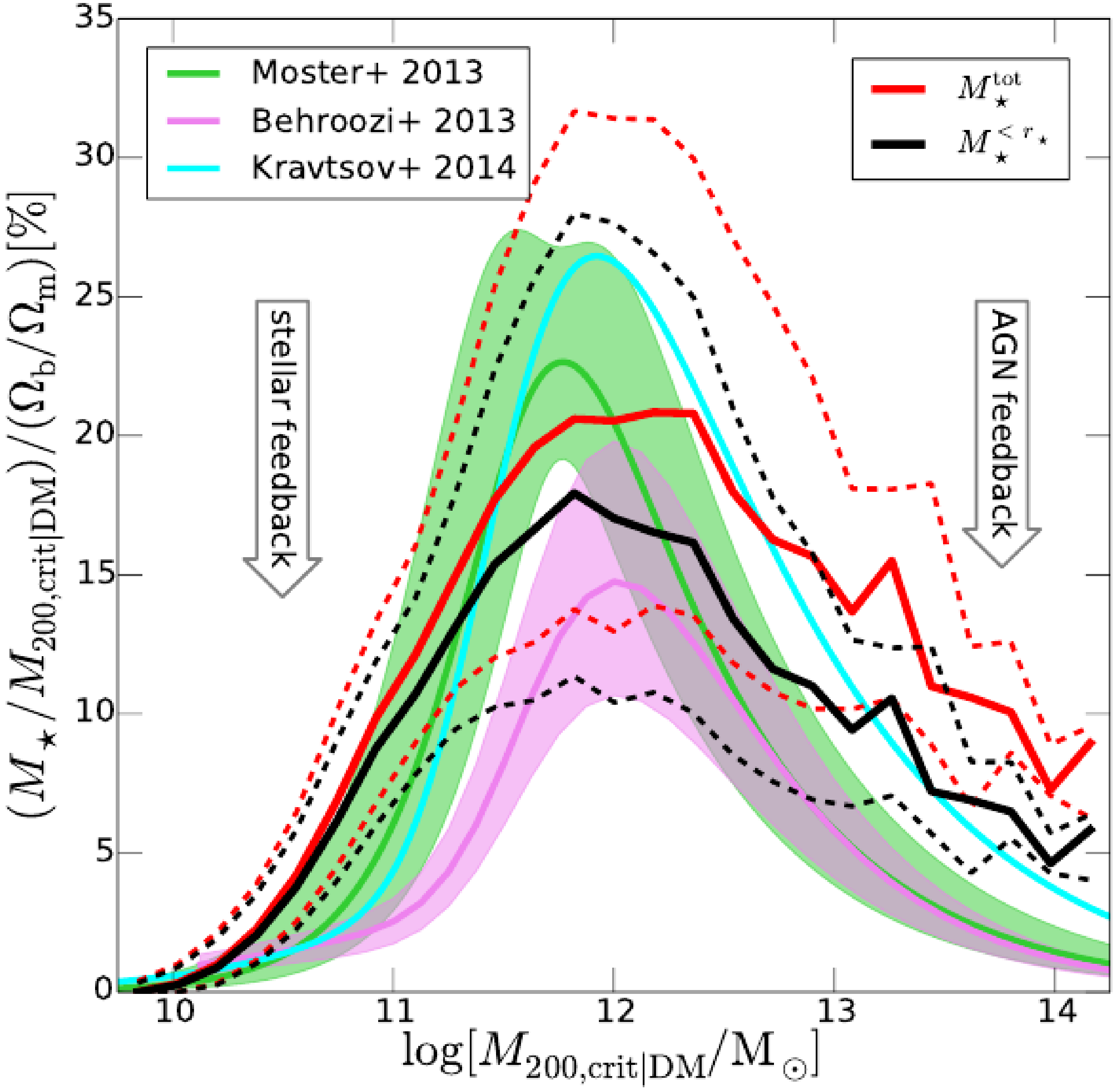
COSMIC STAR FORMATION RATE DENSITY



Genel, Vogelsberger, Springel, Sijacki, et al., MNRAS, 2014

The Illustris project

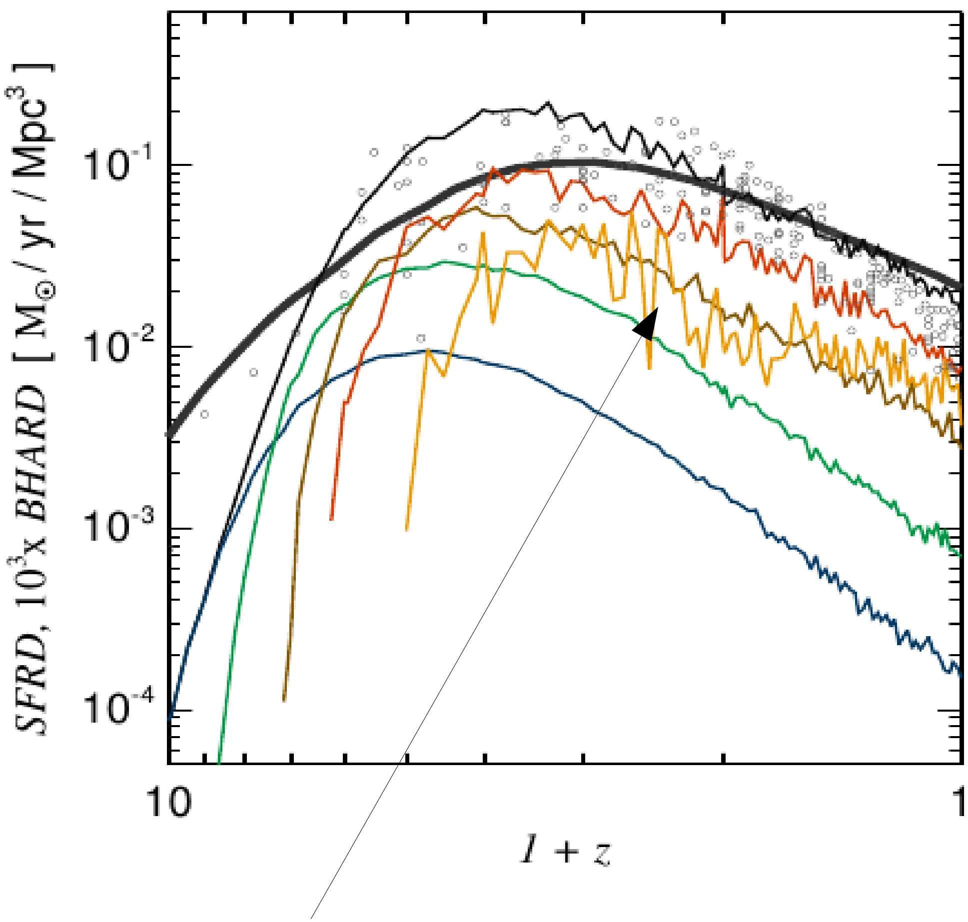
STELLAR VS. HALO MASS



Vogelsberger, Genel, Springel, Torrey, Sijacki, et al., MNRAS, 2014

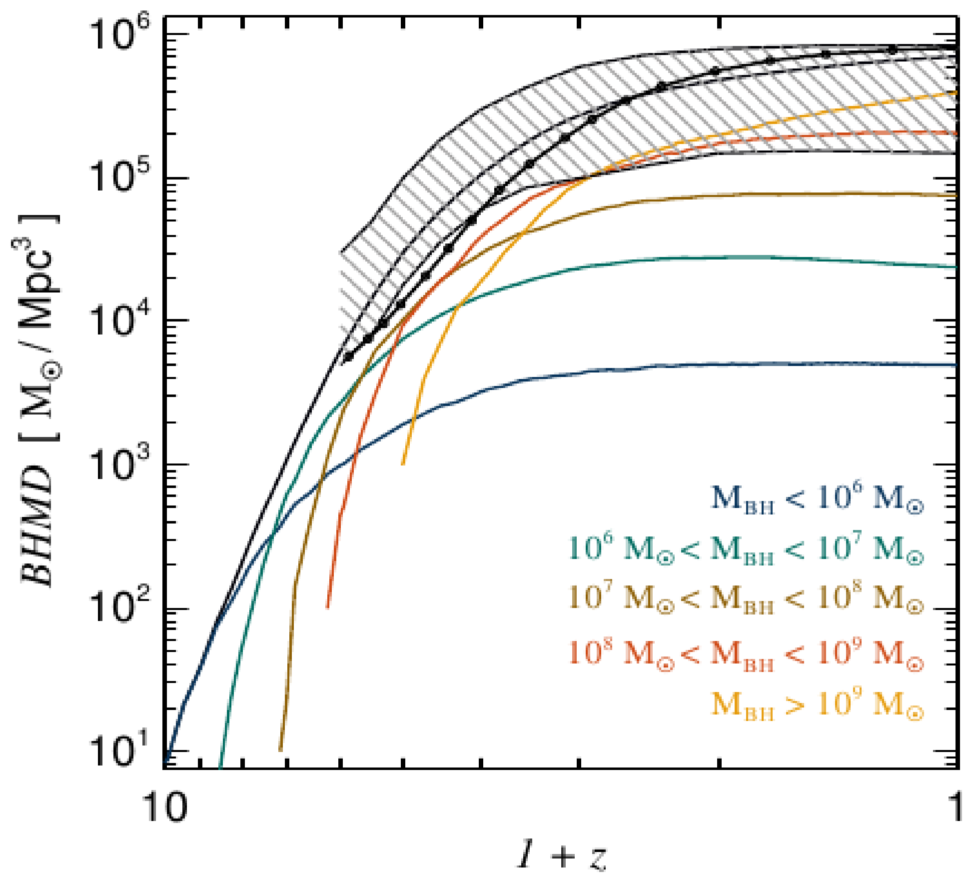
BHs in Illustris

SFR DENSITY &
BH ACCRETION RATE DENSITY



DUTY CYCLE DUE TO THE RADIO MODE

BH MASS DENSITY

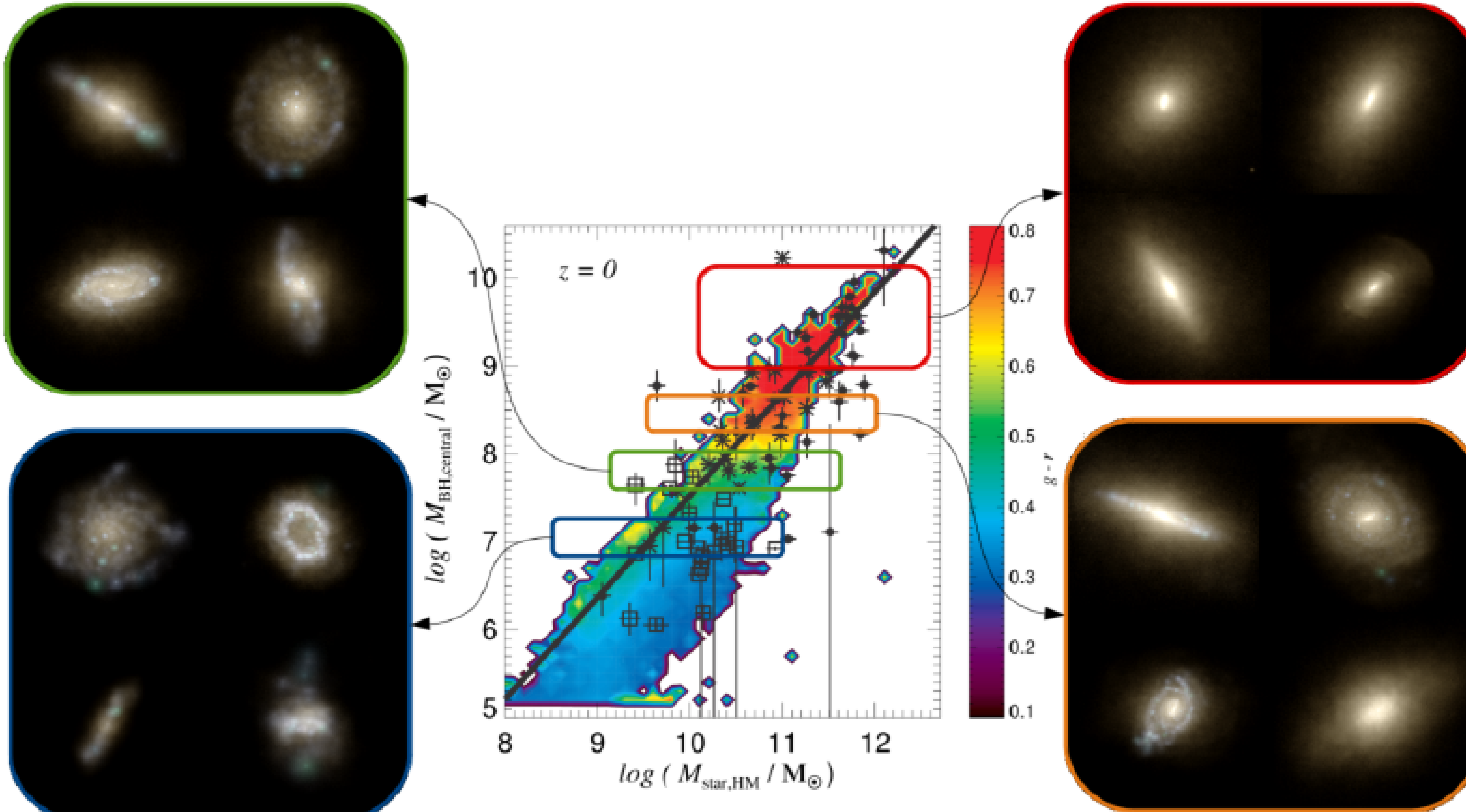


- Ueda et al. 2014
- Volonteri et al. 2013

Sijacki, Vogelsberger, Genel, Springel, Torrey, Snyder, Nelson, Hernquist, 2014
MNRAS submitted, arXiv: 1408.6842

BHs in Illustris

BH MASS – BULGE MASS RELATION



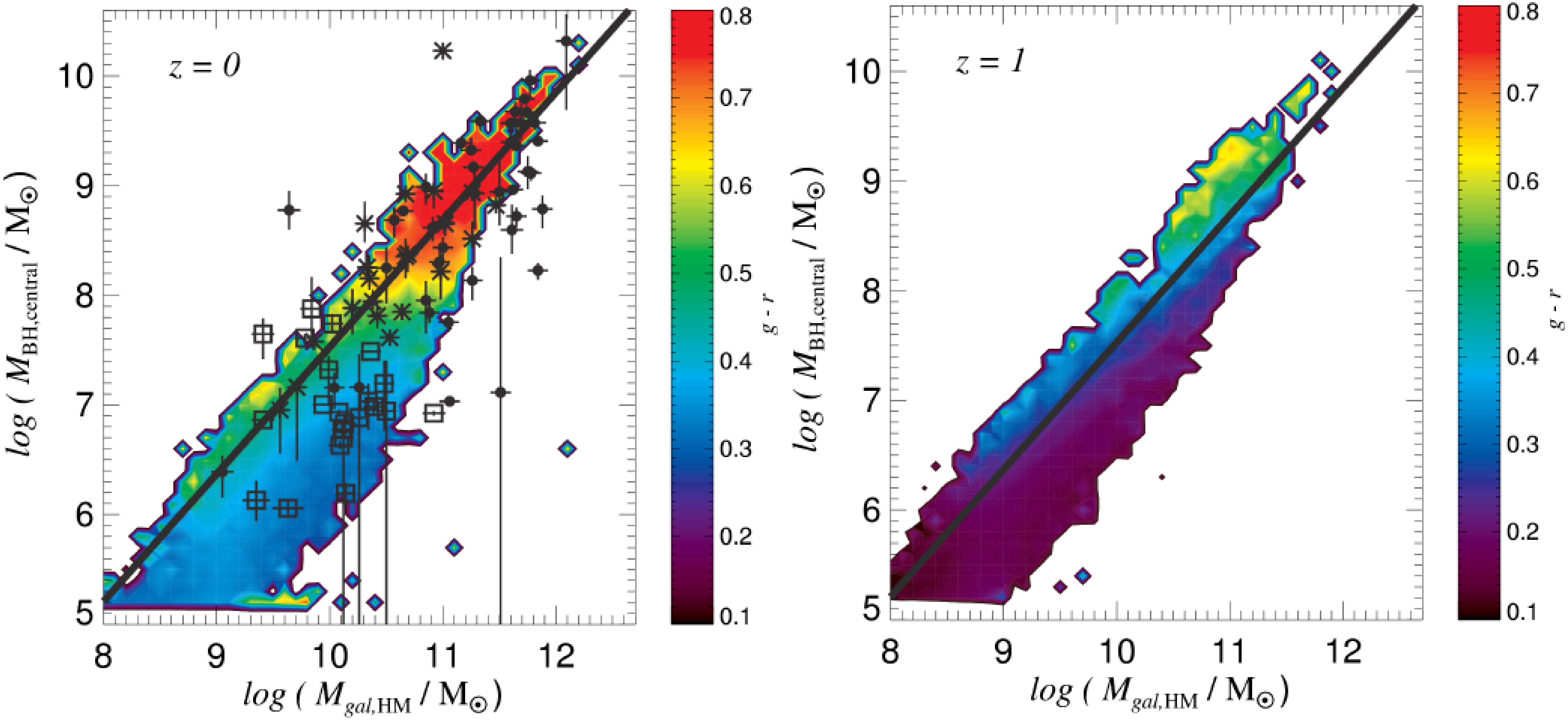
Kormendy & Ho, 2013

circles: ellipticals; stars: spirals with bulges; squares: pseudo bulges

Sijacki et al, 2014

BHs in Illustris

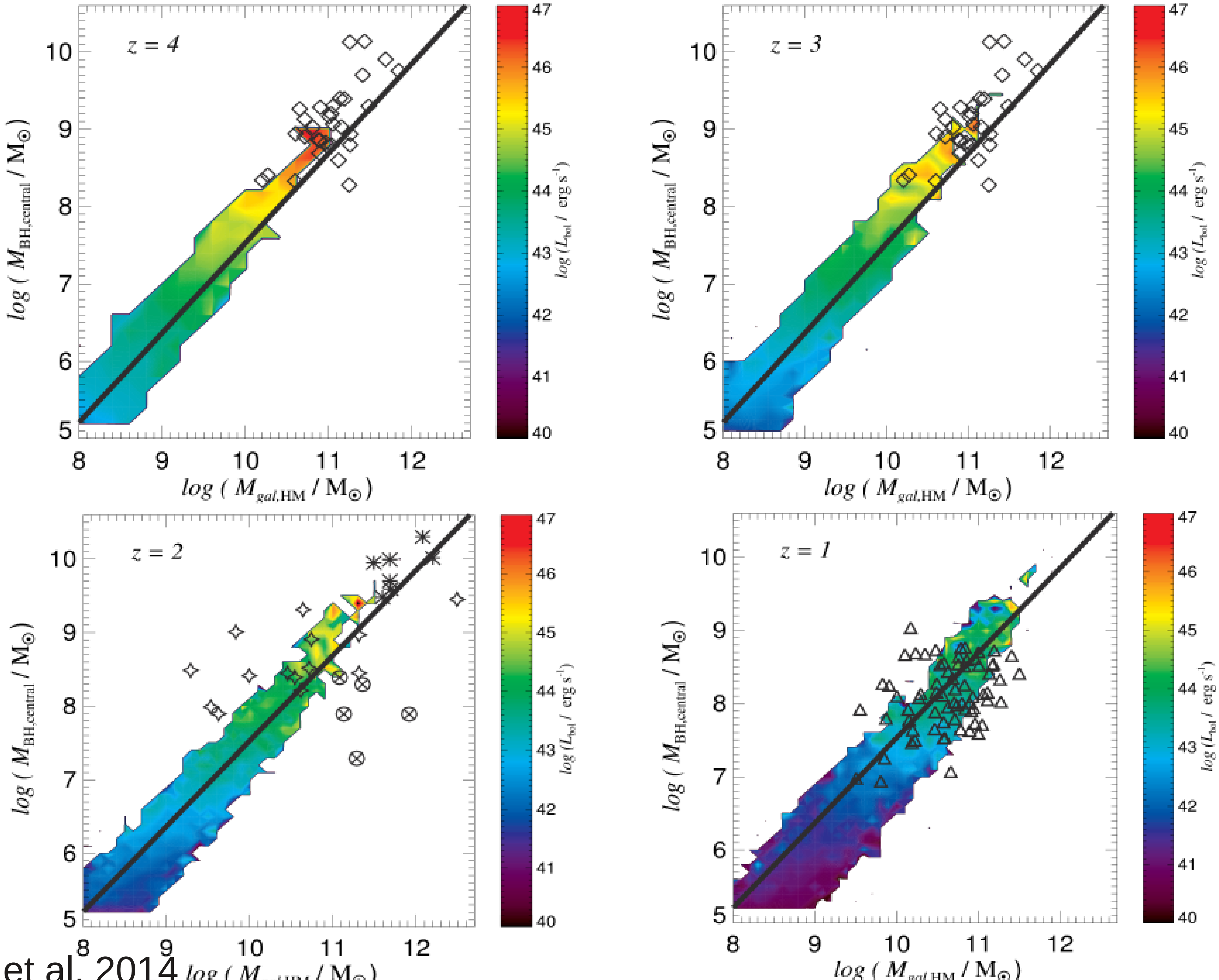
BH MASS – BULGE MASS RELATION
redshift evolution



Kormendy & Ho, 2013
circles: ellipticals; stars: spirals with bulges; squares: pseudo bulges

Sijacki et al, 2014

BHs in Illustris

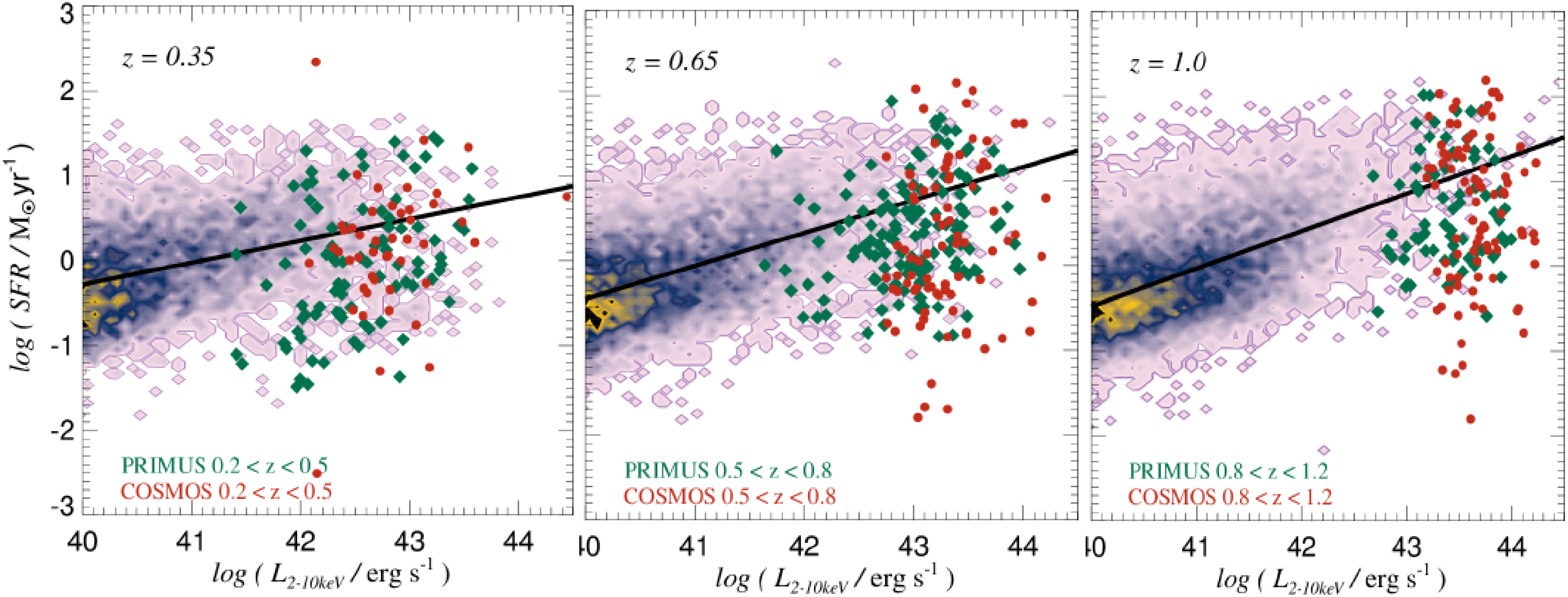


Kormendy & Ho, 2013
AGN/QSOs z = 0.1-4
RGs and SMGs z = 2

Sijacki et al, 2014

BHs in Illustris

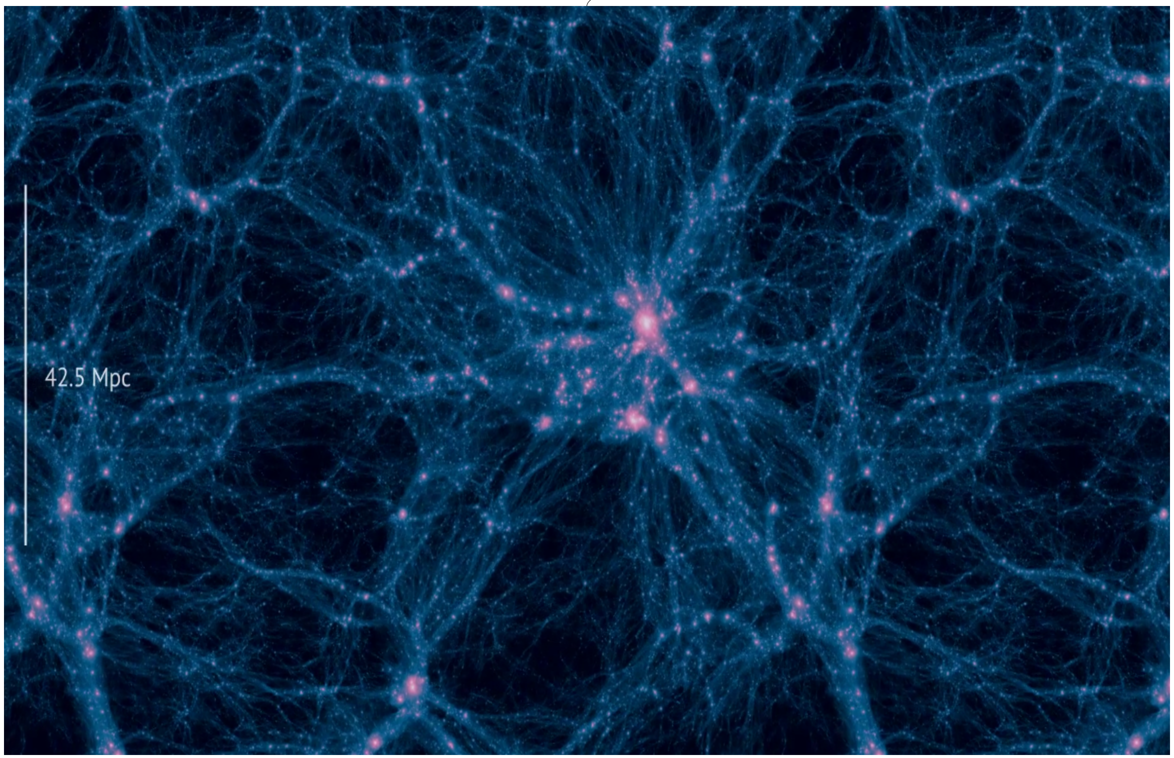
SF VS. AGN TRIGGERING
SFR and Lx



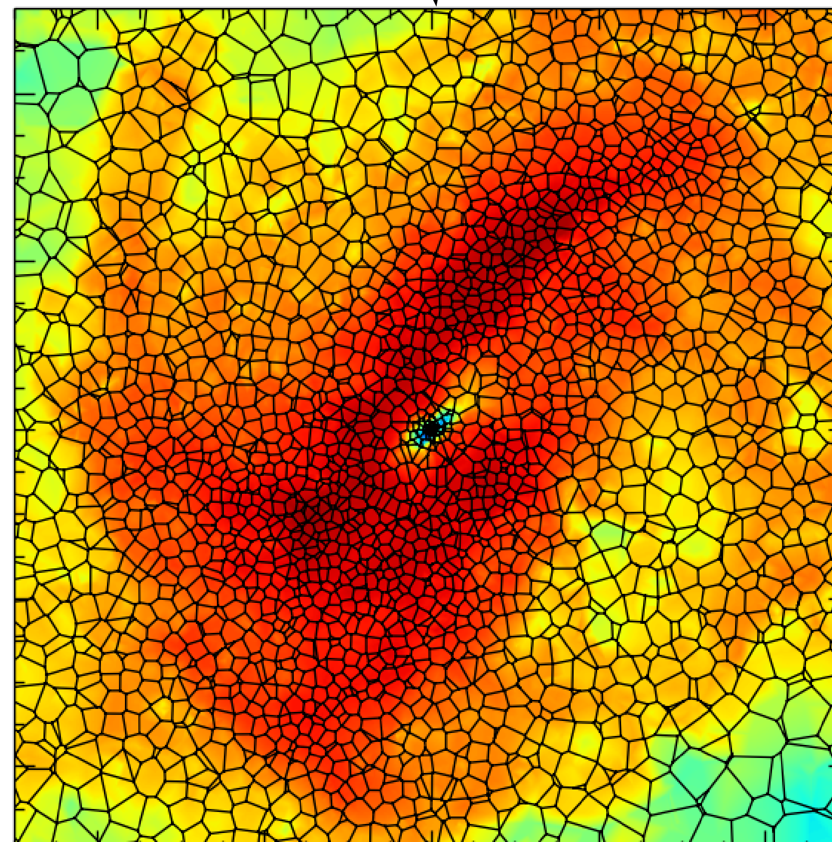
Sijacki et al, 2014

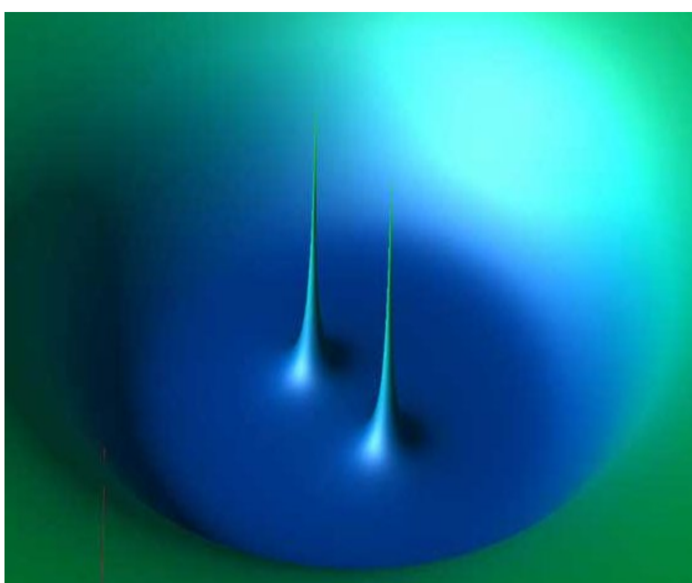
The Future

large scale cosmological simulations 10^9 pc



inner galaxy disk structure 10^2 pc





GR simulations of merging BH binaries 10^{-6} pc