Numerical modelling of galaxy formation and evolution

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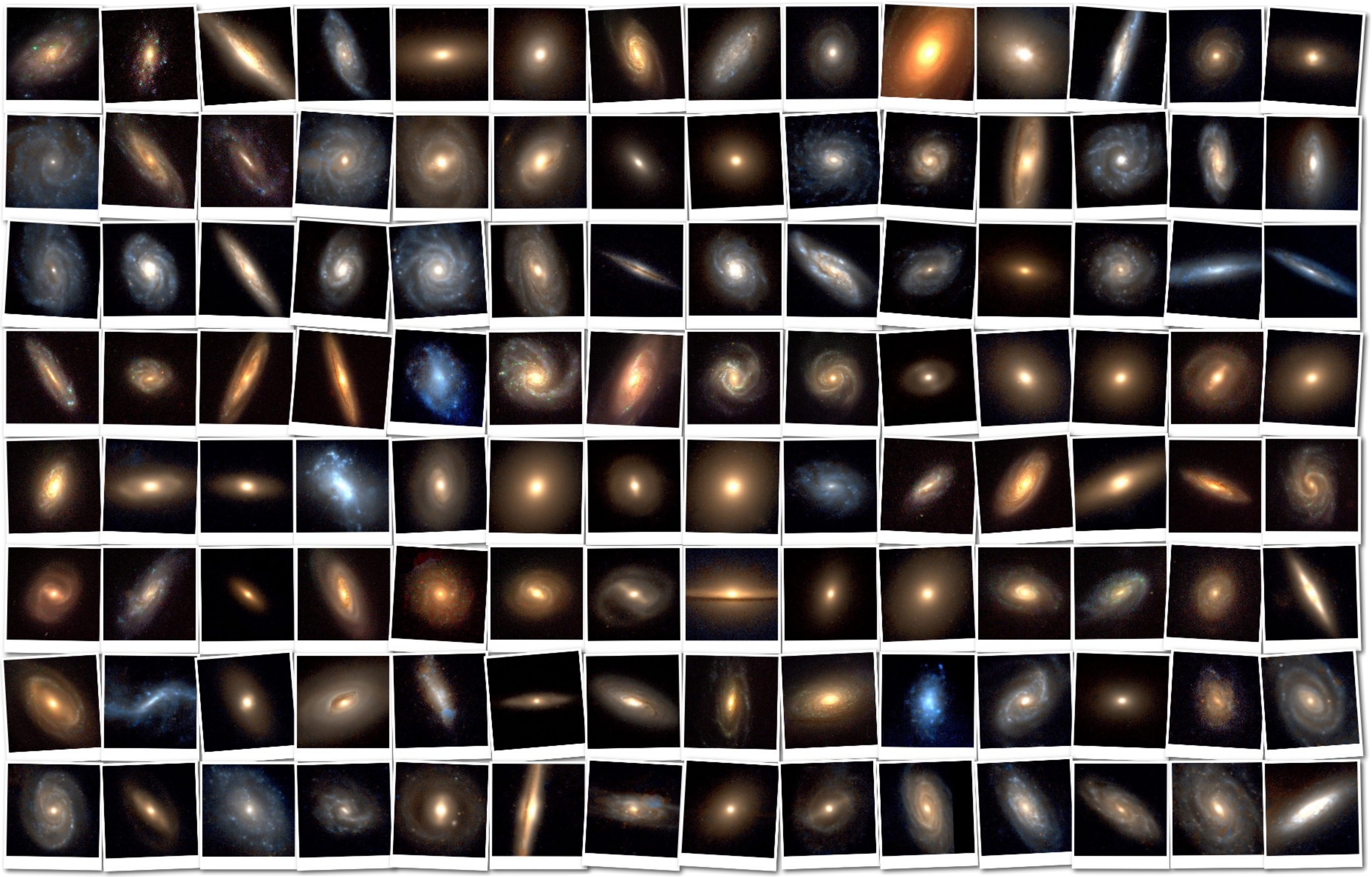
Cosmology School in the Canary Islands 2017

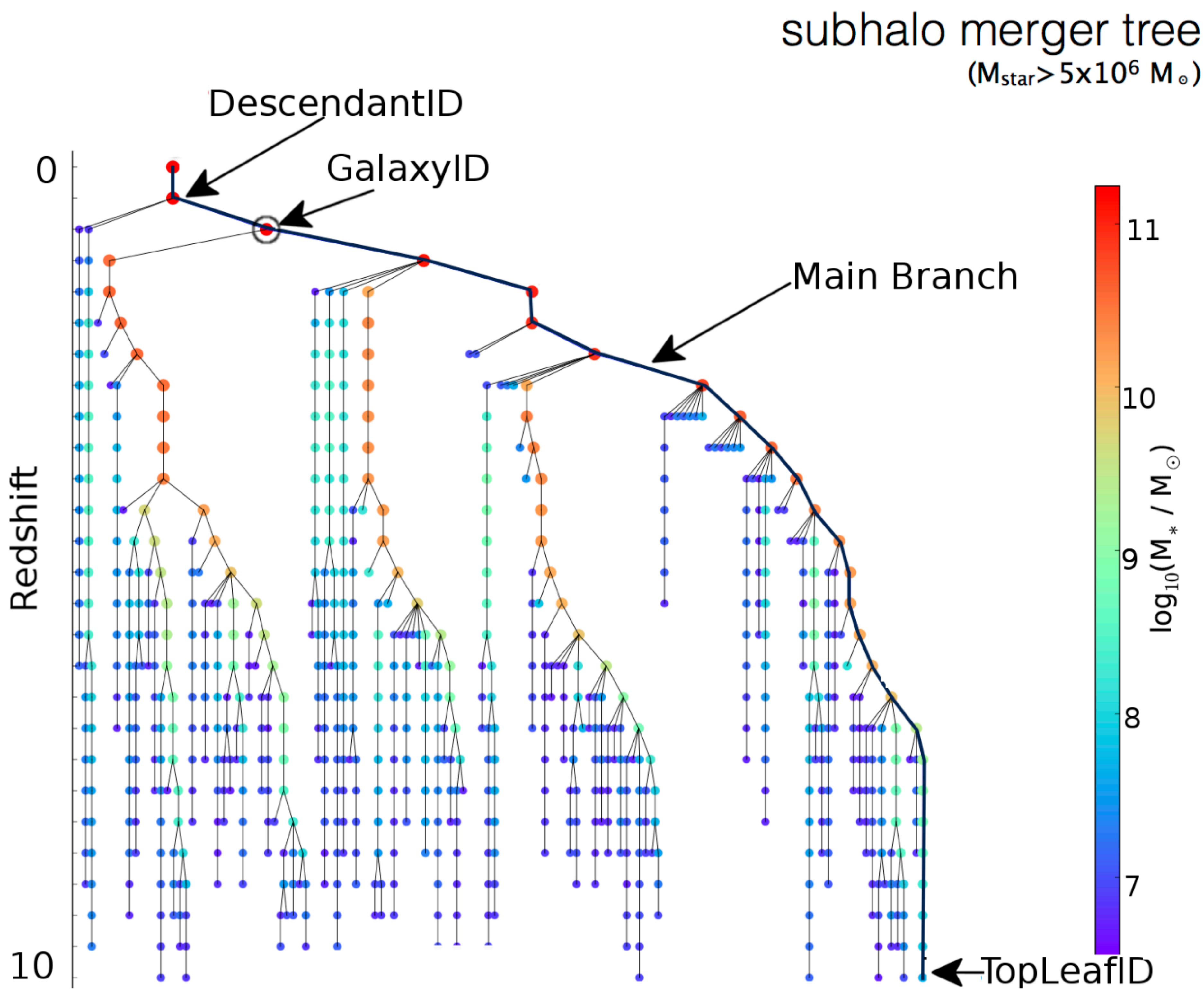
Outline

- **The physics of cosmological hydrodynamical simulation**
- **The results of recent simulations**
- **The effect of baryonic physics on matter distribution**

How do we get to this?



Time evolution



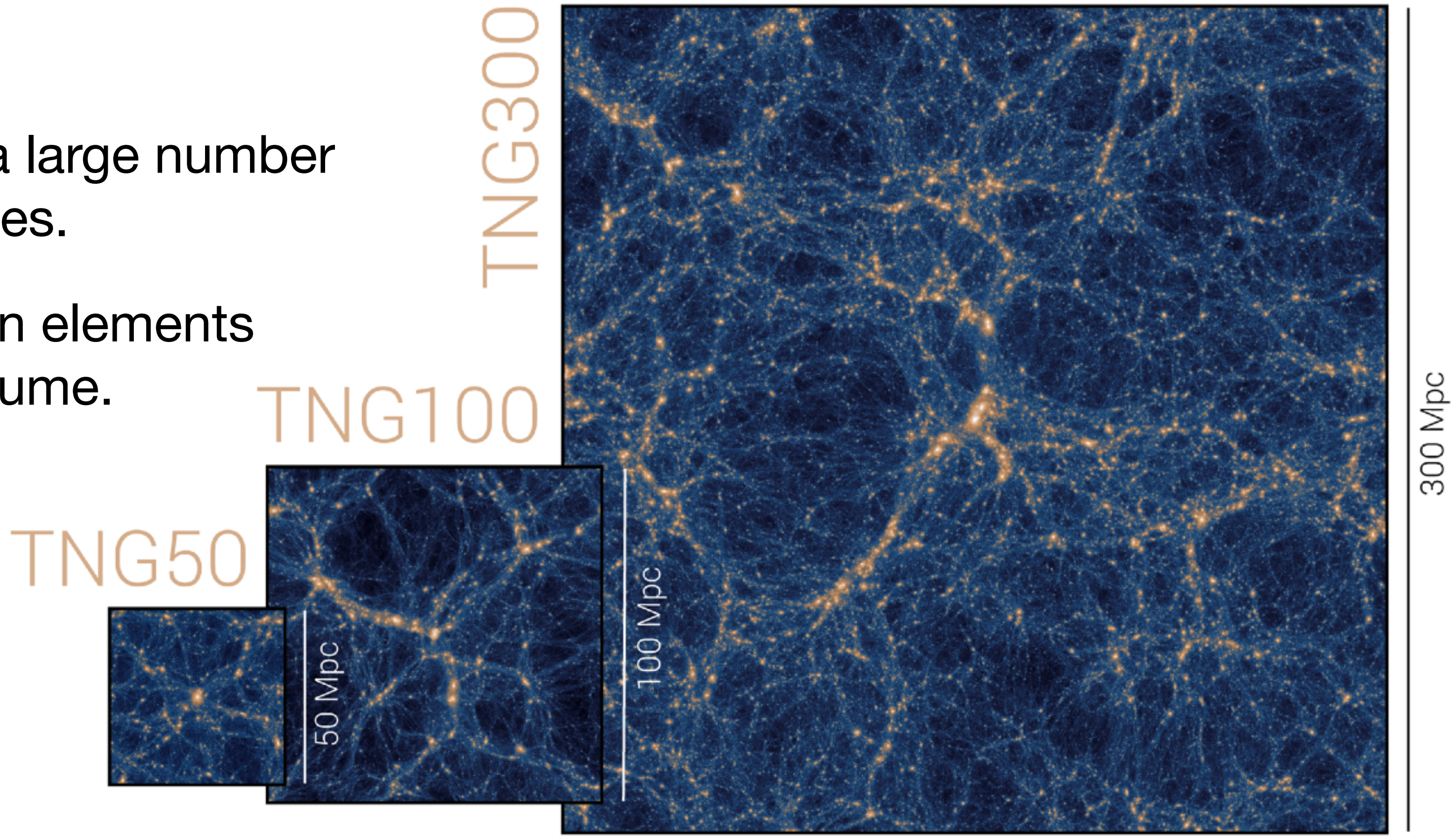
(McAlpine et al., 2008)

Cosmological hydrodynamic simulations

Full cosmological volume

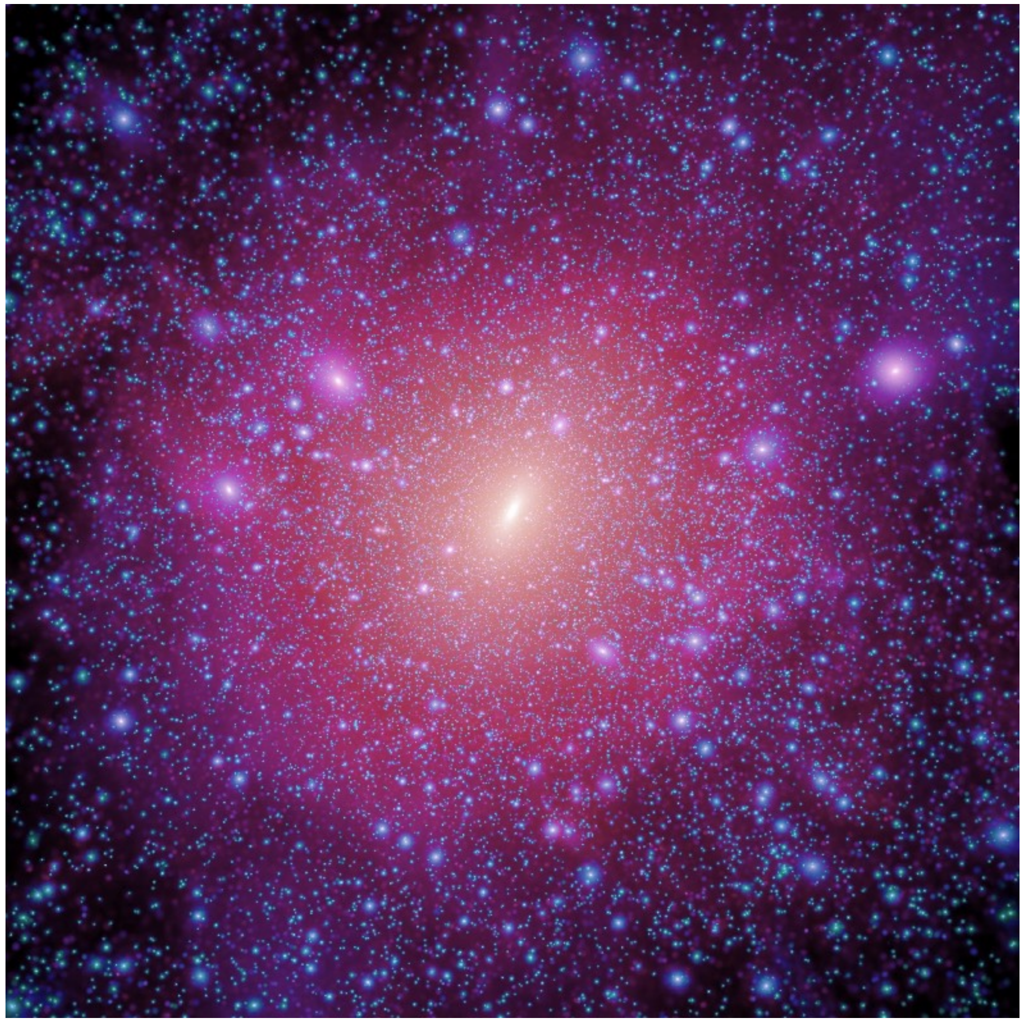
Ideal for statistical studies because they contain a large number of haloes and galaxies over a large range of masses.

Computational cost limits the number of resolution elements (particles and/or cells) sampling the simulated volume.



Illustris-TNG simulations (Pillepich et al., 2017)

Aquarius simulation (Springel et al., 2008)



Zoom-in cosmological simulations

Used to simulate at high resolution one object of interest in a cosmological environment. High resolution is reached in a sub-volume containing the object. In the rest of the cosmological volume, resolution is degraded with distance.

Allows to reach high resolution without loosing information on the large-scale structure and the mass assembly through mergers.

It is limited to one object per simulation. Poor statistics.

(see Chris and Arianna's talks)

Full cosmological volume

These simulations do not resolve the multiphase inter-stellar medium and are limited by computational costs.

$$L \approx 100 \text{ Mpc}$$

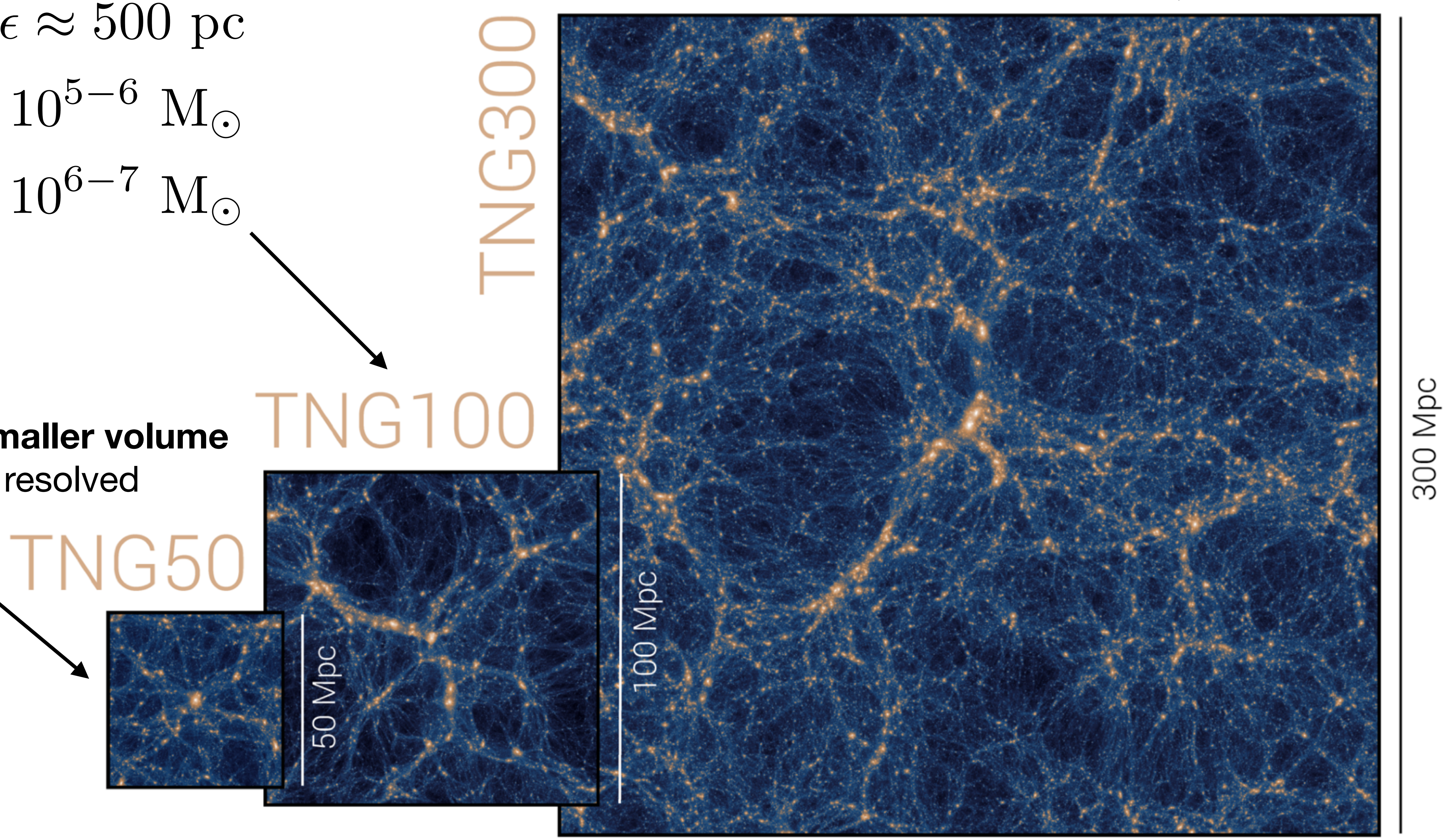
$$\epsilon \approx 500 \text{ pc}$$

$$m_{\rm gas} \approx 10^{5-6} \text{ M}_\odot$$

$$m_{\rm DM} \approx 10^{6-7} \text{ M}_\odot$$

Lower resolution, larger volume
Larger number of clusters

Higher resolution, smaller volume
Dwarf galaxies better resolved

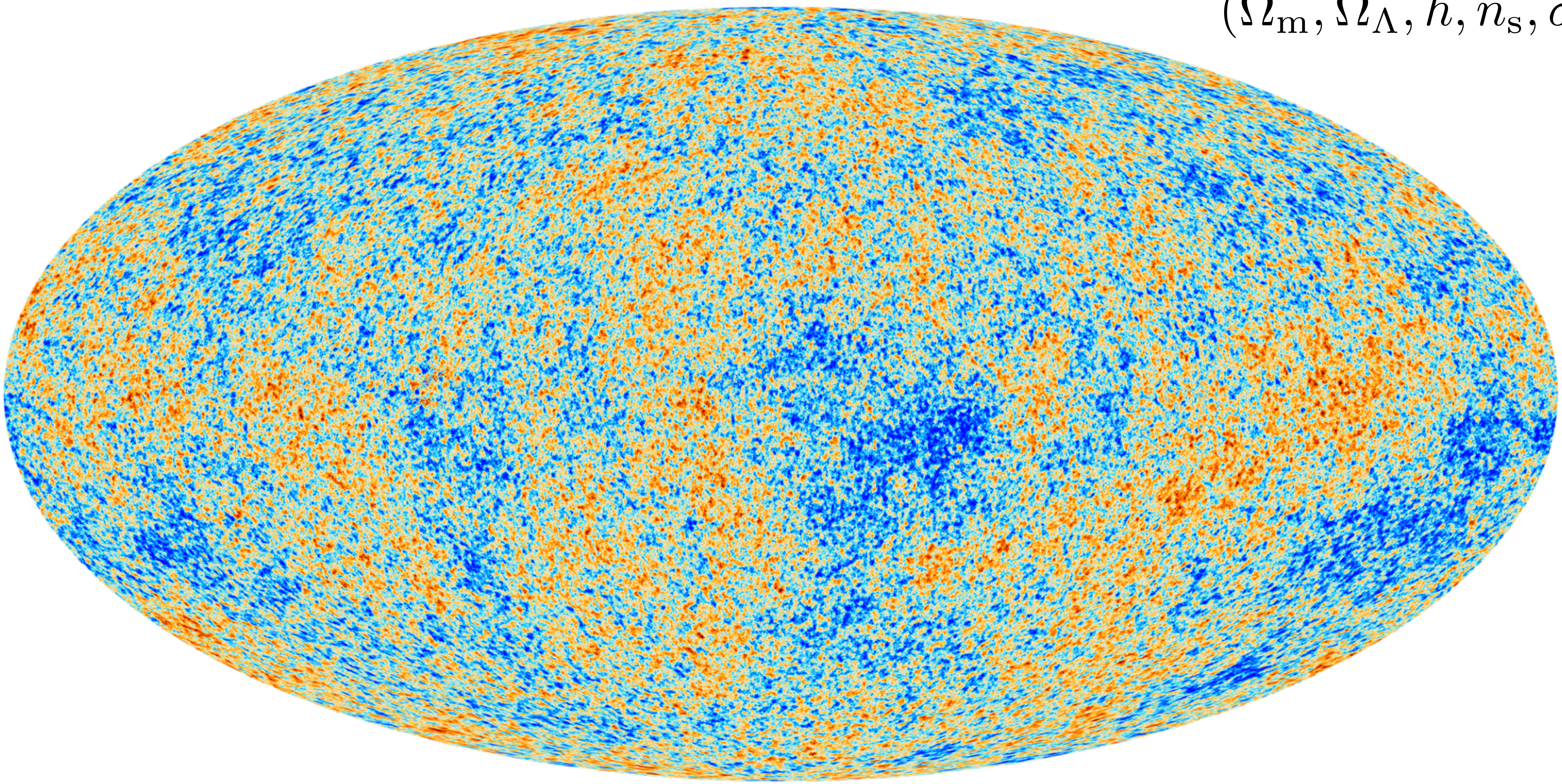


Illustris TNG simulation (Pillepich et al., 2017)

Initial conditions

CMB data provides the cosmological parameters used to generate the initial conditions. They consist in a perturbed density field and the corresponding velocity field from which the structure of the universe will grow.

$$(\Omega_{\rm m}, \Omega_{\Lambda}, h, n_{\rm s}, \sigma_8)$$



Planck CMB map

Gravity

Dark Matter or **Dark Matter-only** or **N-Body** simulations model the growth of the (large-scale) structure driven by gravity.

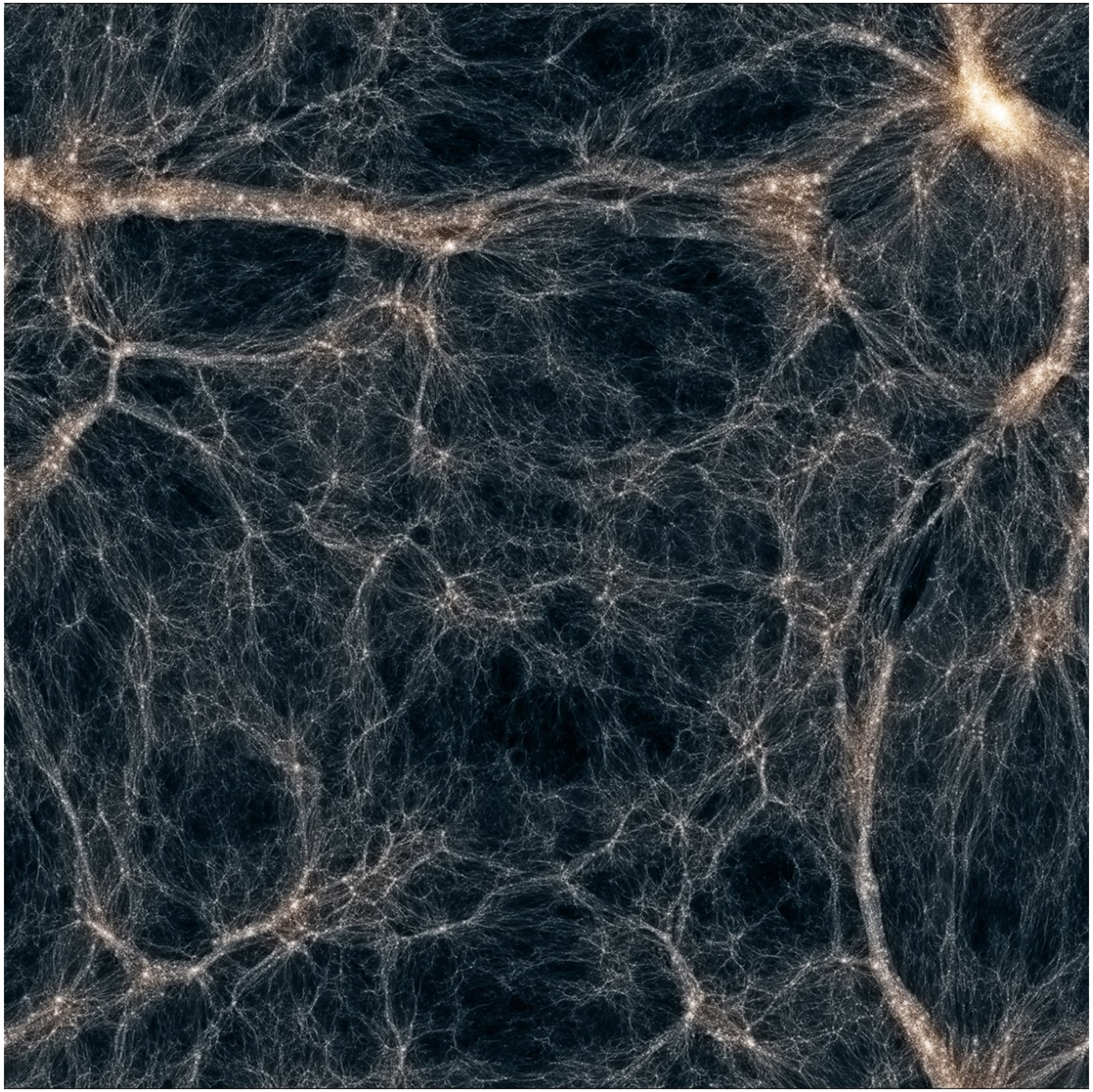
What matter is in dark matter simulations?

$$\Omega_{\rm DM}? \qquad \Omega_{\rm m}?$$

In N-body simulations, **all matter** in the Universe is treated as collisionless, thus it feels only gravitational forces.

However, we know from the CMB that **17% of matter is baryonic**, and **baryons feel pressure forces and cool.** Pressure forces work against gravity in the collapse of structures. Cooling allows baryons to condense to much higher densities than those only gravity would give.

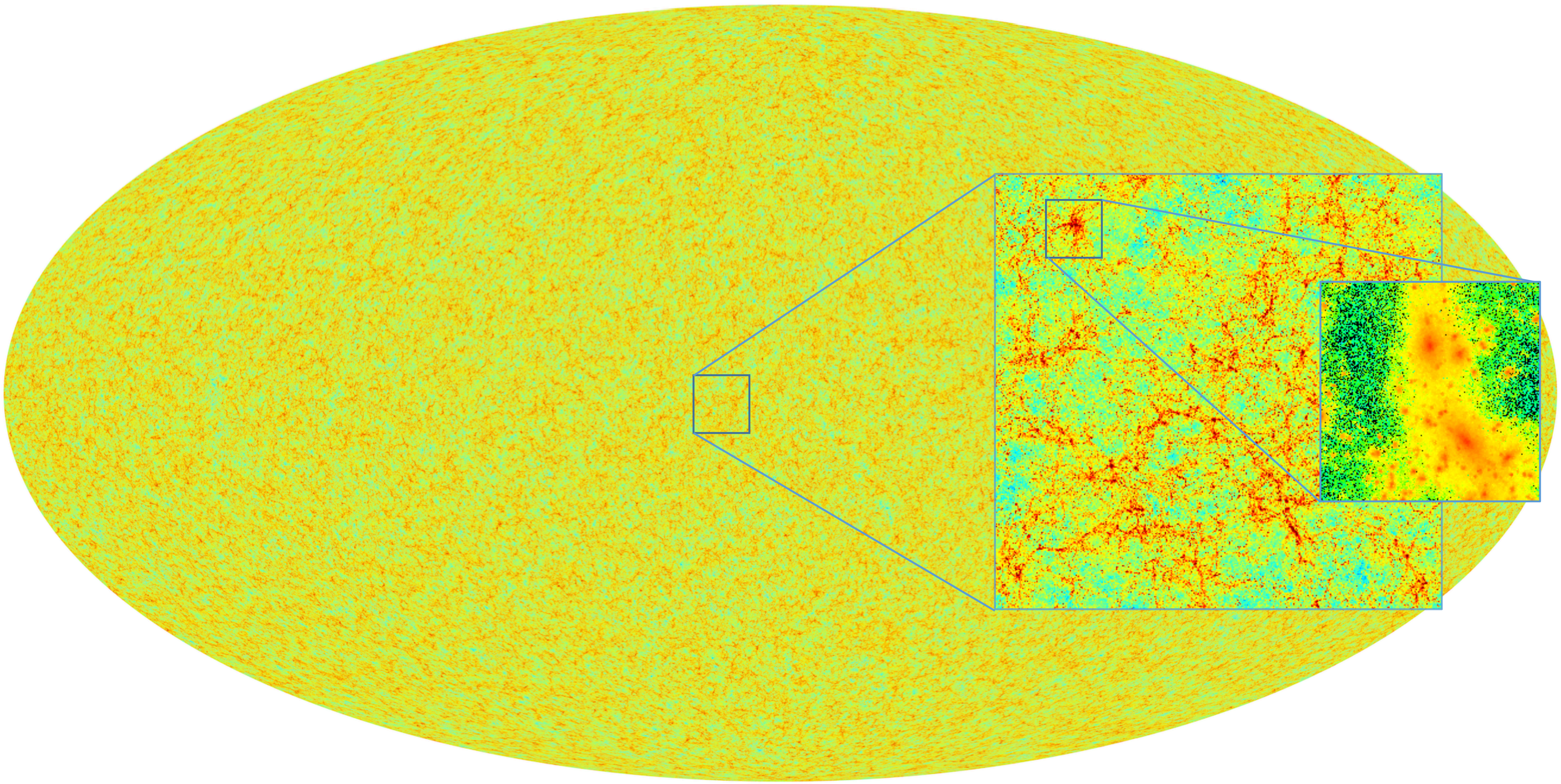
Galaxy formation simulations study how baryons embedded in the cosmic web evolve into the galaxies we observe.



N-body simulation performed with ChaNGA

Methods: particle-mesh (PM), particle-particle particle-mesh (P^3M), oct-tree, fast multipole method (FMM)…

PKDGRAV3



One of the largest dark matter simulation ever performed contains **2x10^{12} particles** (Potter, Stadel & Teyssier 2017). It was run on **>4000 GPU nodes** on Piz Daint supercomputer (Switzerland), **80 hours.**

Hydrodynamics

Solve the system of conservation equations:

Mass $$\frac{\mathrm{d}\rho}{\mathrm{d}t} + \rho\nabla\cdot\vec{v} = 0$$

Momentum $$\frac{\mathrm{d}v}{\mathrm{d}t} = -\frac{\nabla P}{\rho} - \nabla\phi$$

Energy $$\frac{\mathrm{d}u}{\mathrm{d}t} = -\frac{P}{\rho}\nabla\cdot\vec{v}$$

Equation of state of an ideal gas relates pressure to density and internal energy

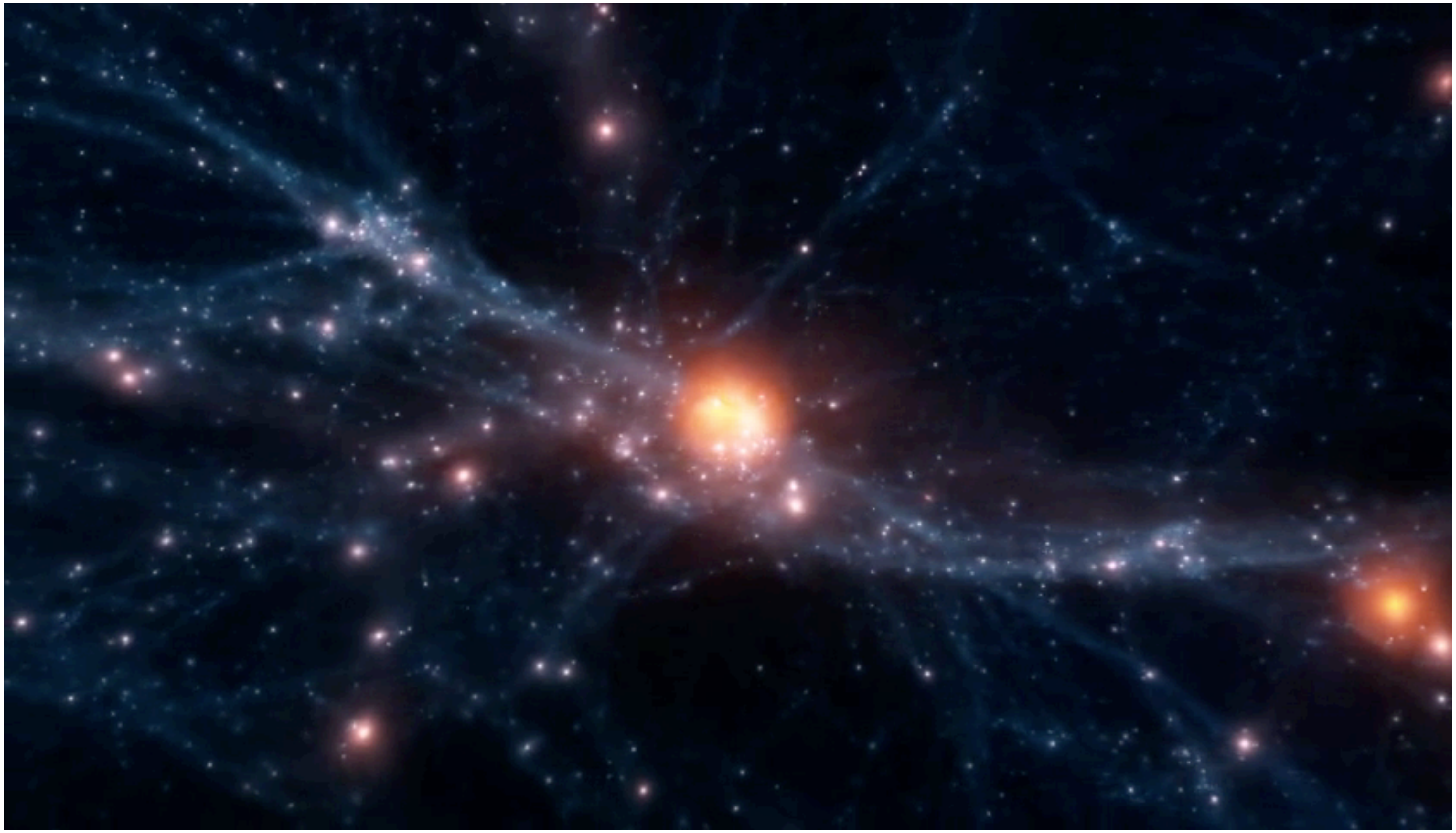
$$P = (\gamma - 1)\rho u$$

Kelvin-Helmholtz instability simulation performed with Shadowfax

Accurate modelling of hydrodynamical instabilities, shocks, turbulence, etc., down to the scales that are resolved in the simulated volume.

Methods: smoothed particle hydrodynamics (SPH), adaptive mesh refinement (AMR), unstructured grid or moving mesh hydrodynamics, mesh-free hydrodynamics…

Non-radiative cosmological simulation



Simulation of the formation of a cluster of galaxies without cooling and without star formation

Cooling and heating

Atomic cooling is a crucial ingredient in galaxy formation. Gas cools, whereas dark matter does not. This means that gas can contract by dissipating both momentum (thermalising shocks) and internal energy (cooling) and reach the high densities required for star formation.

Cooling rate $$\left(\frac{\mathrm{d}u}{\mathrm{d}t}\right)_{\mathrm{cool}} \propto n_{\mathrm{H}}^2$$

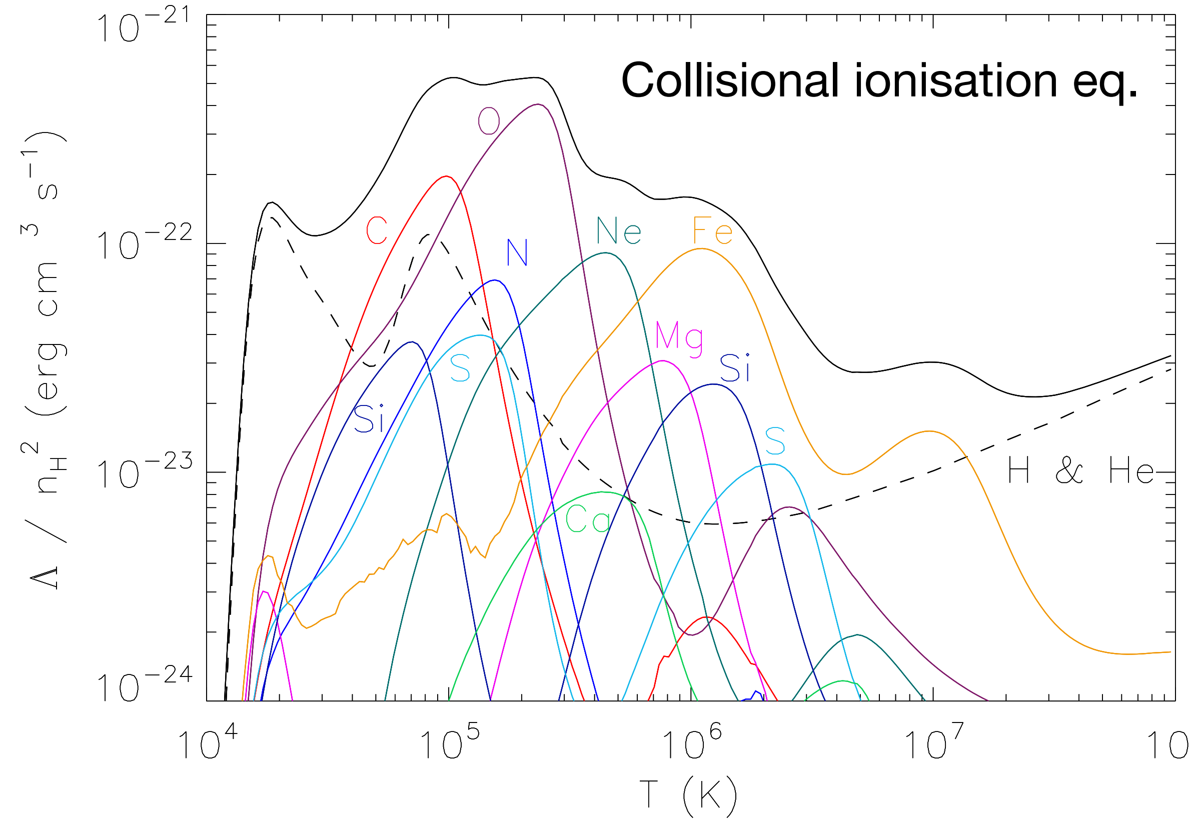
Cooling is very effective above 10^4 K. Below this temperature the gas is mostly neutral and **atomic** cooling efficiency drops by orders of magnitude. **Molecular, dust** and **metal lines** cooling can lower the gas temperature.

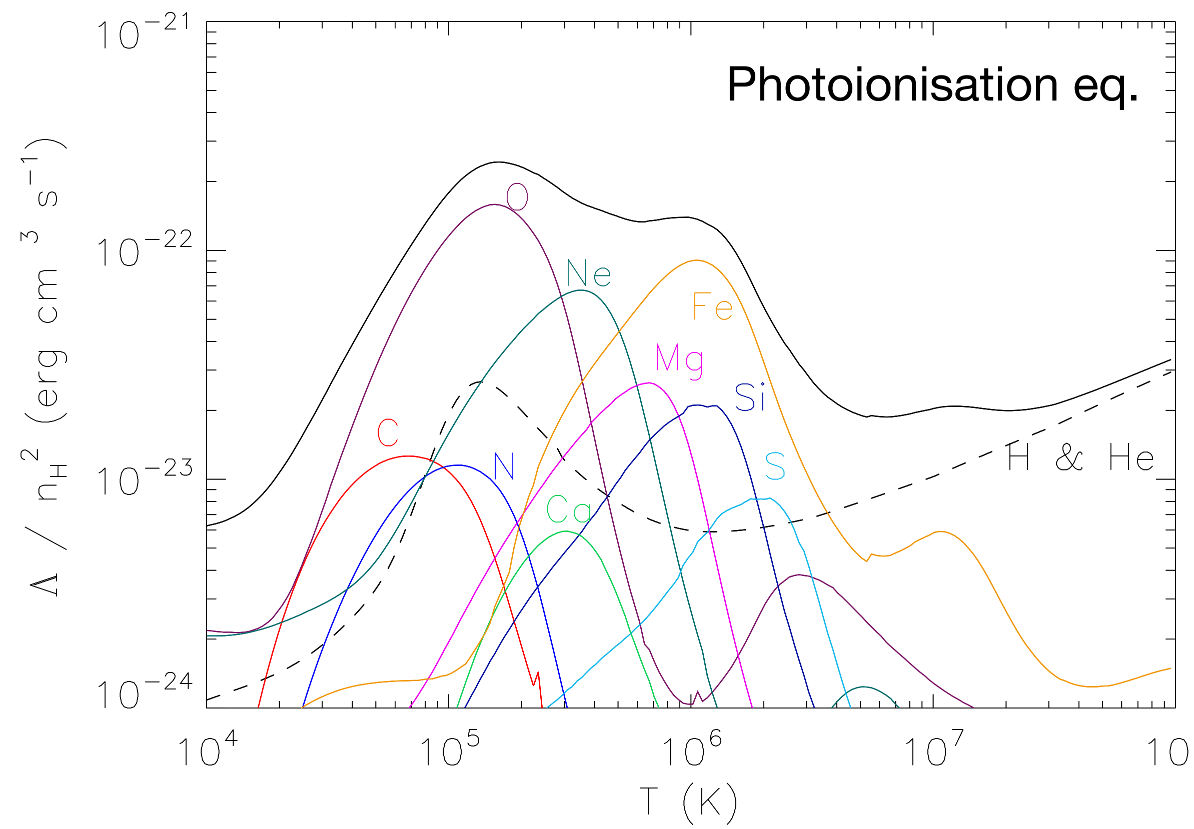
Photo-ionisation from the cosmic UV background modifies the cooling function, and it is now considered in most of the numerical models. It provides heating.

Heating rate $$\left(\frac{\mathrm{d}u}{\mathrm{d}t}\right)_{\mathrm{heat}} \propto n_{\mathrm{H}} n_{\gamma}$$

For high gas densities cooling is stronger than heating.

Wiersma, Schaye & Smith, 2009

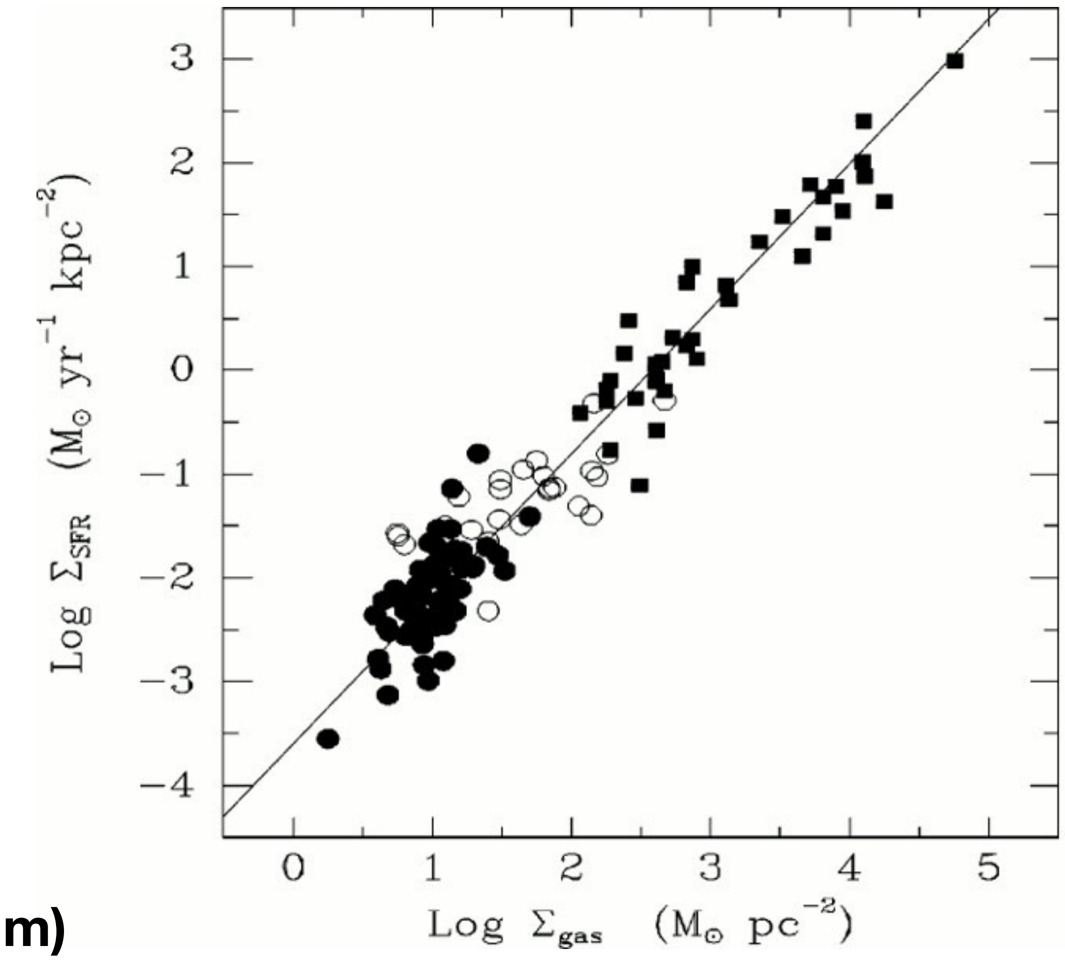




Sub-grid physics

All the following physical processes are happening at scales much smaller than the resolution of cosmological simulations. Analytic laws have to be used.

(Kennicutt 1998)



Star formation

Mainly driven by cooling. The gas looses pressure support, and eventually collapse catastrophically due to its self gravity. Numerical models can capture the initial phase of the collapse, but cannot resolve the subsequent fragmentation into molecular clouds and star formation within them.

Some SFR laws are calibrated to reproduce the observed Kennicutt-Schmidt law, others are derived from it.

An initial mass function (IMF) describes the distribution of stellar masses in the resolution element converted into a star particle (simple stellar population, SSP).

Stellar evolution (chemical evolution of the inter-stellar medium)

Each SSP is evolved according to stellar evolution models. This provides the number of SNe produced **(energetic feedback)** and the amount of heavy elements SNe and AGB stars return to the ISM.

Black holes growth

Accretion rates are computed with “modified” Bondi-Hoyle laws. Few percent of the accreted mass is emitted as radiation, of which few percent is coupled to the gas **(energetic feedback).**

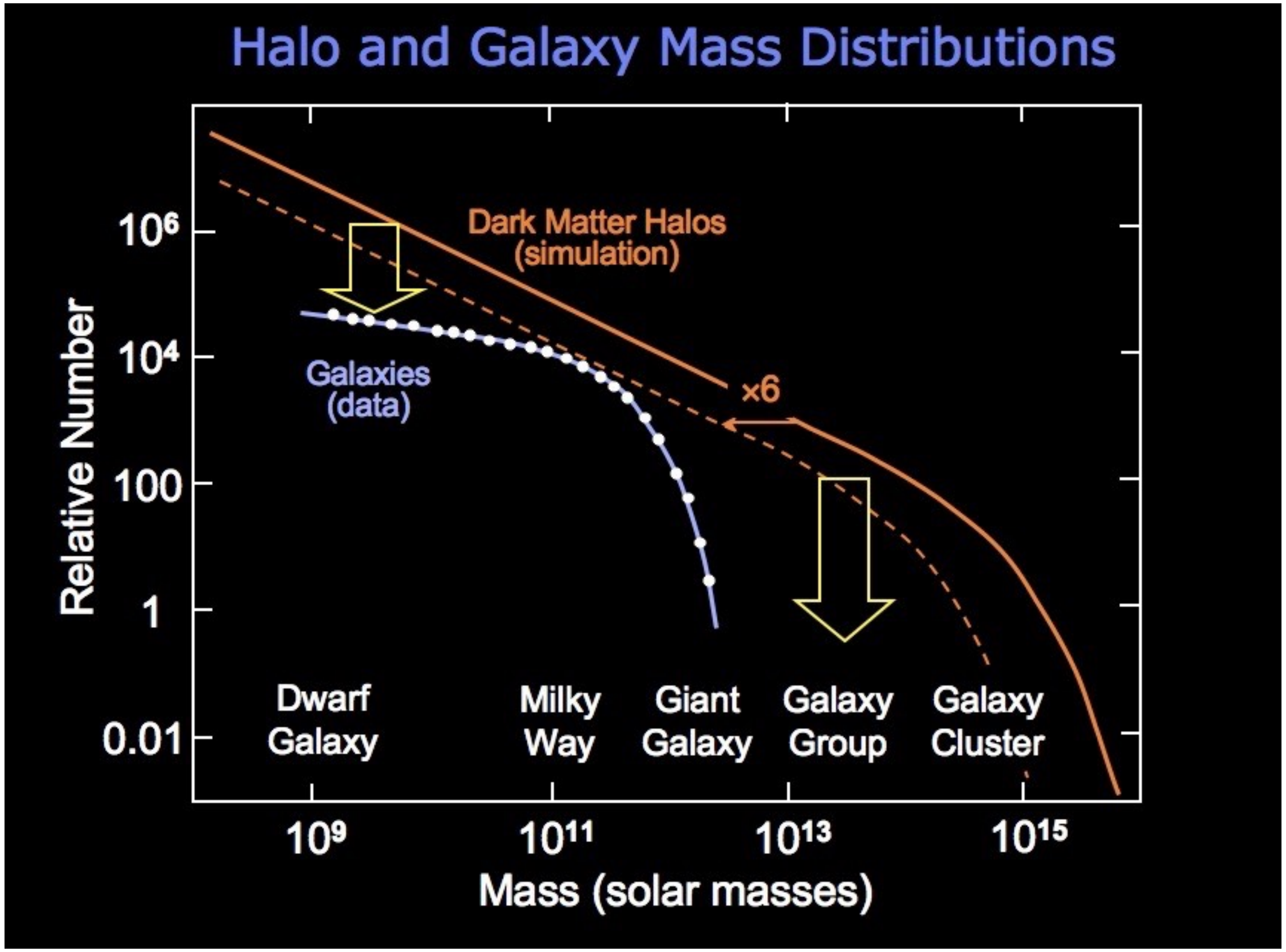
$$\dot{M}_{\rm BH} = \frac{\pi \rho G^2 M_{\rm BH}^2}{c_{\rm s}^3}$$

Feedback

SN explosions and SMBH feedback provides enough energy to regulate star formation and black hole growth. Feedback decreases gas density by producing (galactic) outflows and/or by quenching cooling.

Why do we need it?

If we were assuming that the fraction of baryons in haloes was constant, and that the efficiency of converting baryons into stars was also constant, we would expect the shape of the galaxy stellar mass function (GSMF) to be that of the halo mass function (HMF). Observations show this is not the case, and the GSMF is very different from the HMF.



SN feedback shapes the low-mass end of the GSMF, whereas BH feedback shapes the high-mass end.

Feedback generates galactic outflows and redistribute the gas within galaxies. This produces the enrichment of the IGM. Within the halo it can redistribute low angular momentum gas.

What else?

There are several other processes that are relevant to galaxy formation and the evolution of the ISM/IGM. Some require increasing the resolution of simulations by orders of magnitudes to be modelled.

Cooling: Molecular cooling, non-equilibrium cooling, dust cooling…

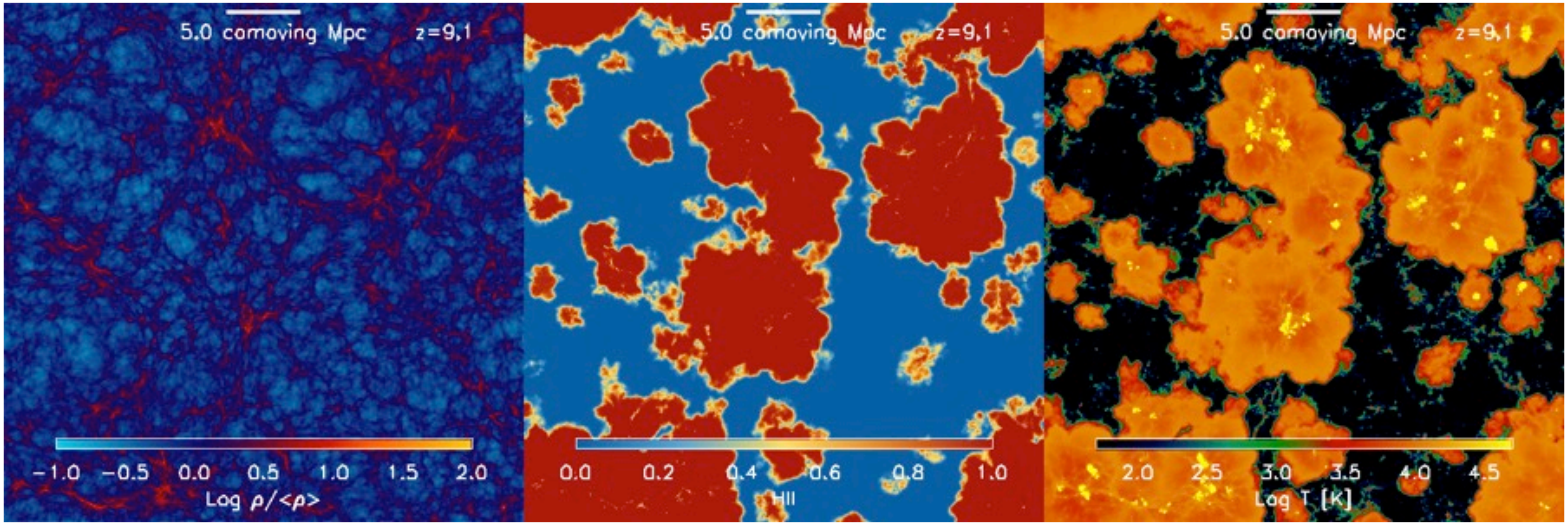
Feedback: Radiation pressure from young stars, X-ray feedback…

Non-thermal pressure therms: Magnetic fields and cosmic rays…

Radiation transport: Modelling of the re-ionisation epoch, galaxy inside-out ionisation…

(…)

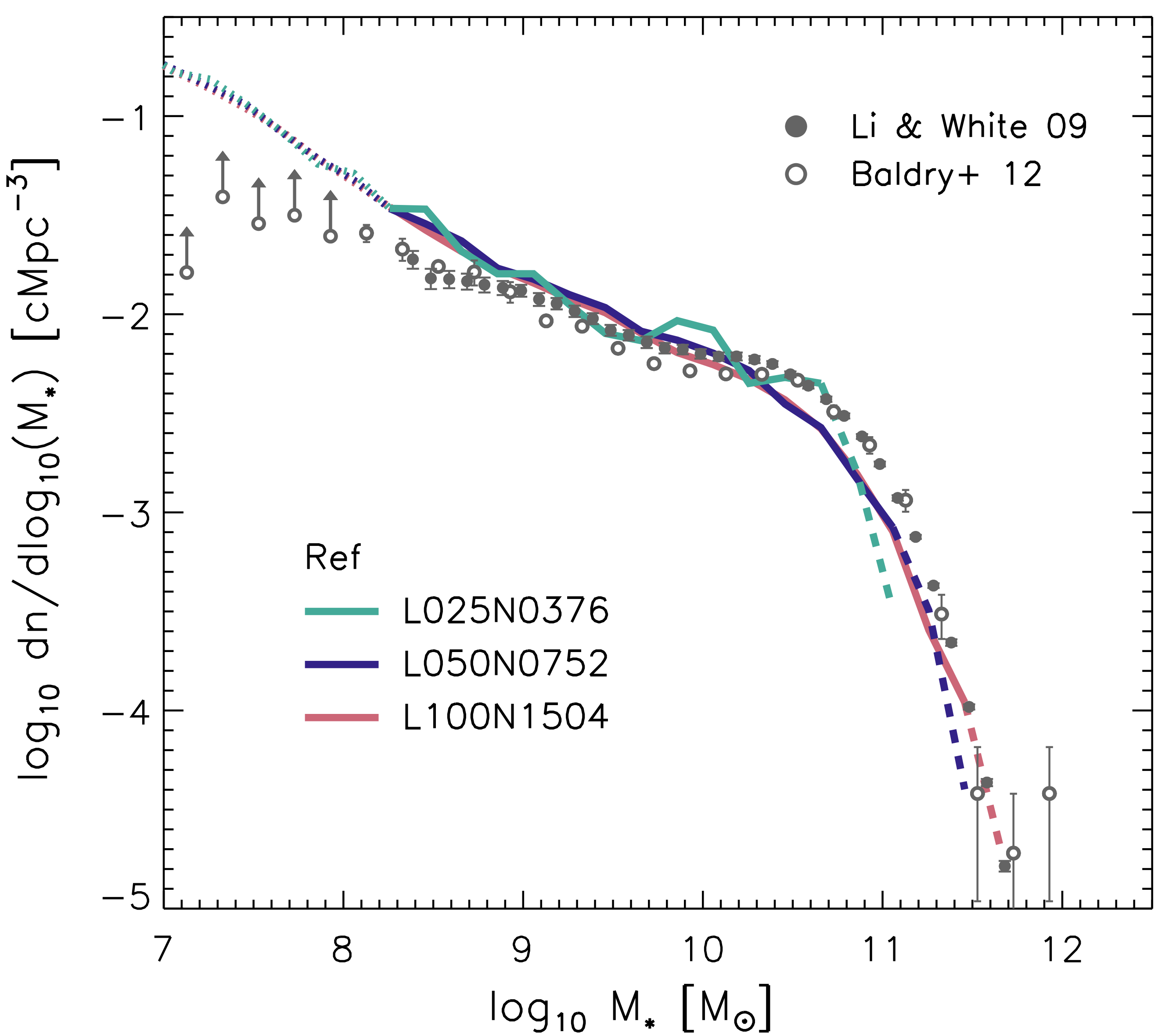
Simulation of the re-ionisation epoch (Pawlik et al. 2015)



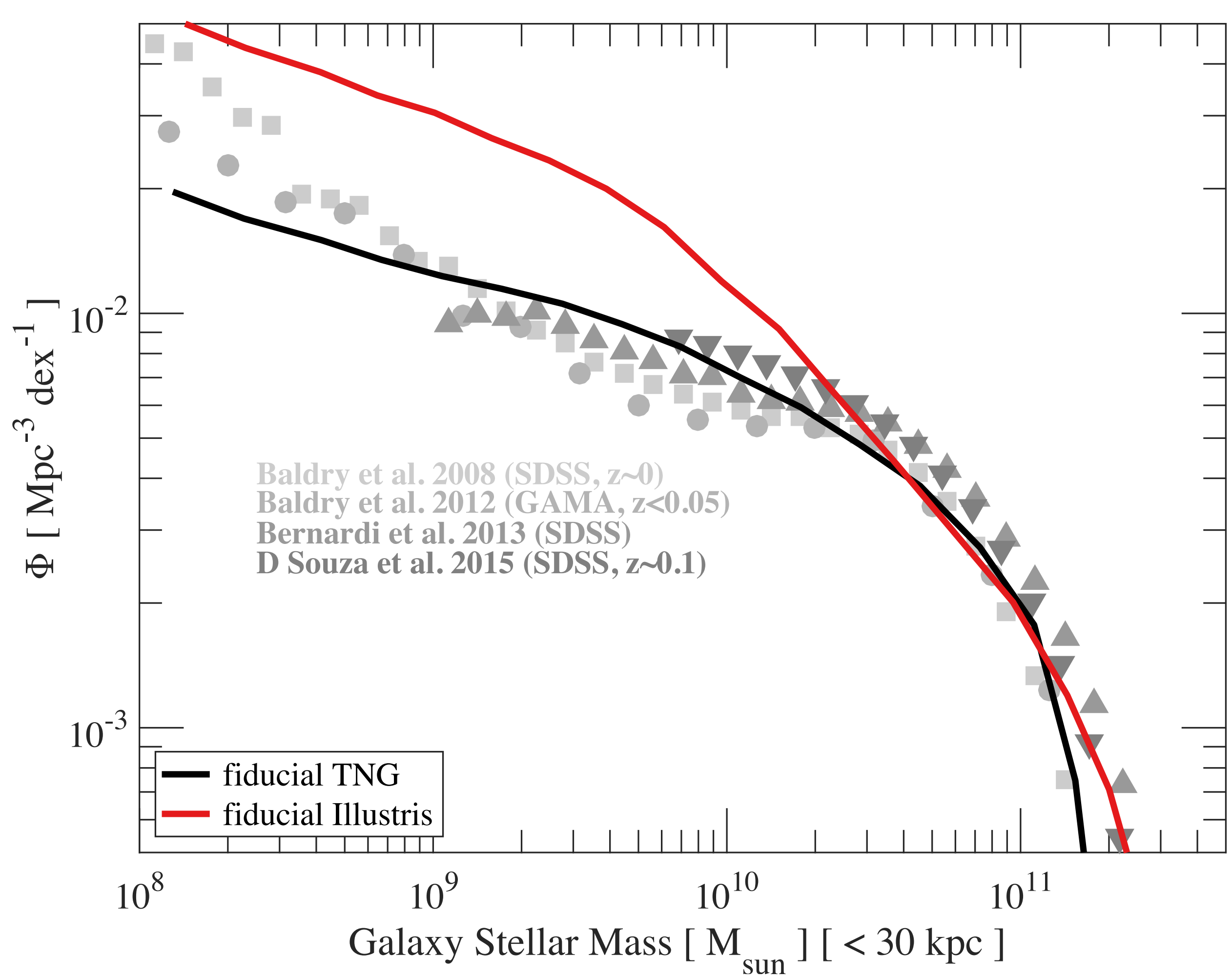
Galaxy stellar mass function

Cosmological simulations can match well the observed galaxy stellar mass function. Matching the GSMF is a good test of the performance of the feedback model over a large range of stellar masses. As shown by Crain et al. (2015) there is a large degeneracy, with different implementation of stellar feedback reproducing the GSMF. Another proxy has to be used to break the degeneracy (e.g. the galaxy size-galaxy mass relation).

(EAGLE, Crain et al. 2015)



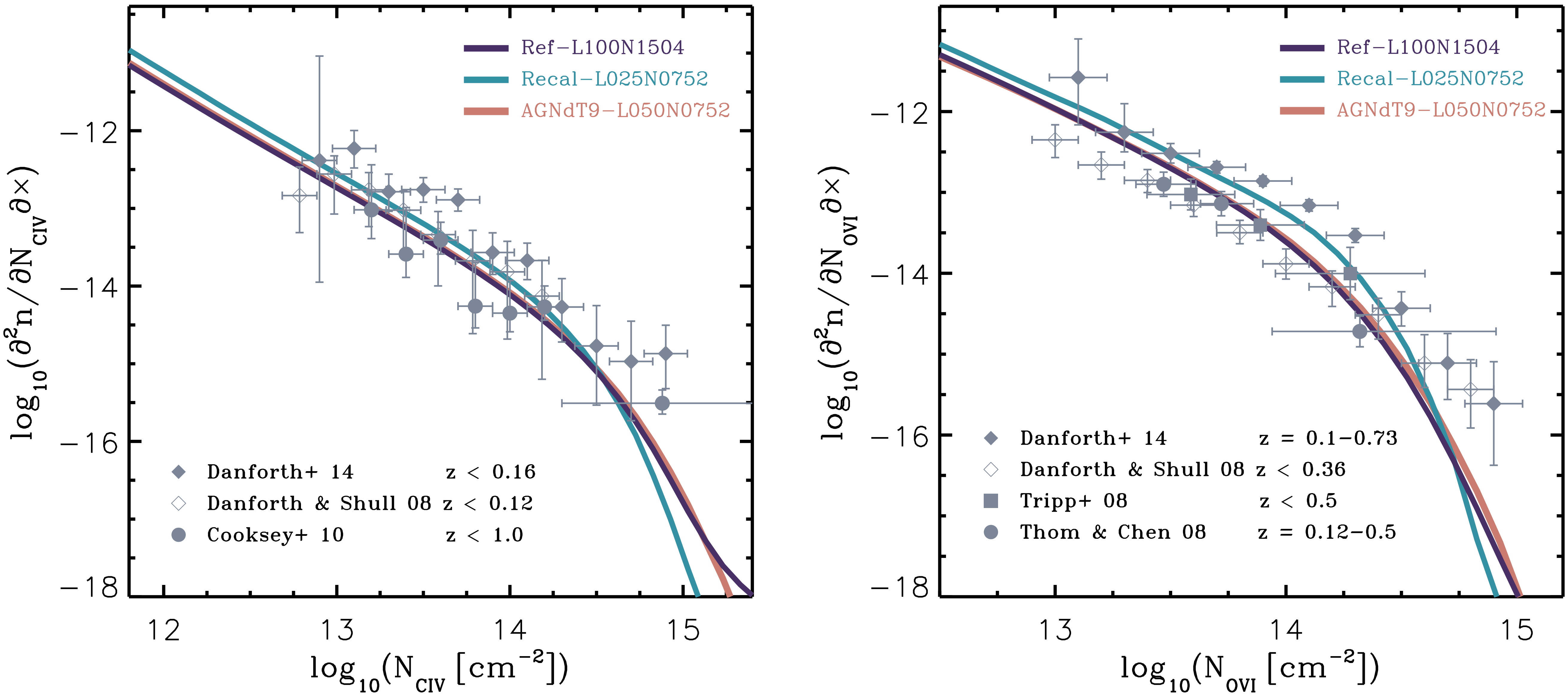
(IllustrisTNG, Pillepich et al. 2017)



Properties of the IGM

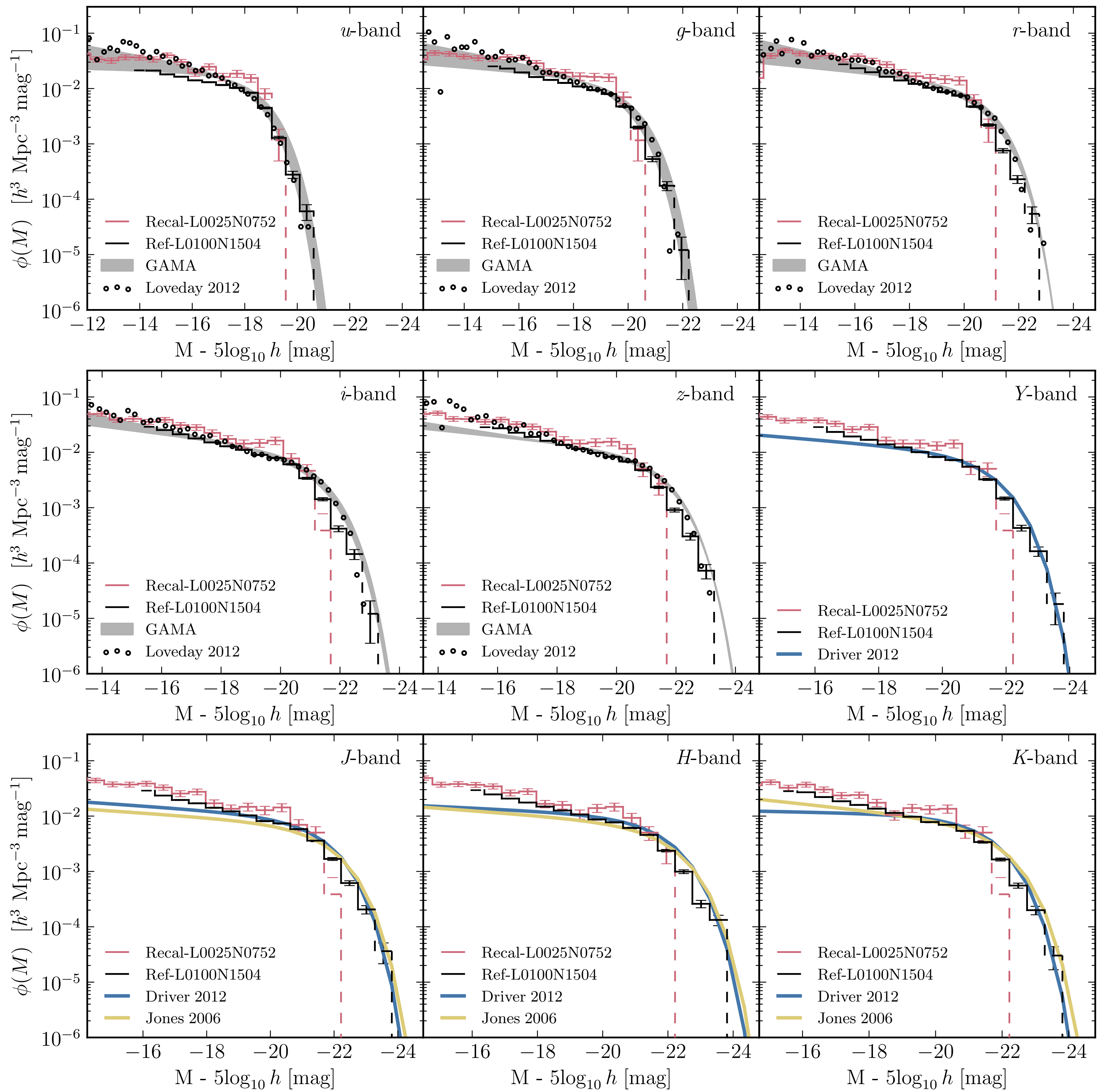
A good test for feedback processes is measuring the enrichment of the IGM. This is done by integrating along random line of sight through the simulated volume the column density of heavy elements and comparing it with that observed.

(EAGLE, Schaye et al. 2015)



Properties of the galaxy population

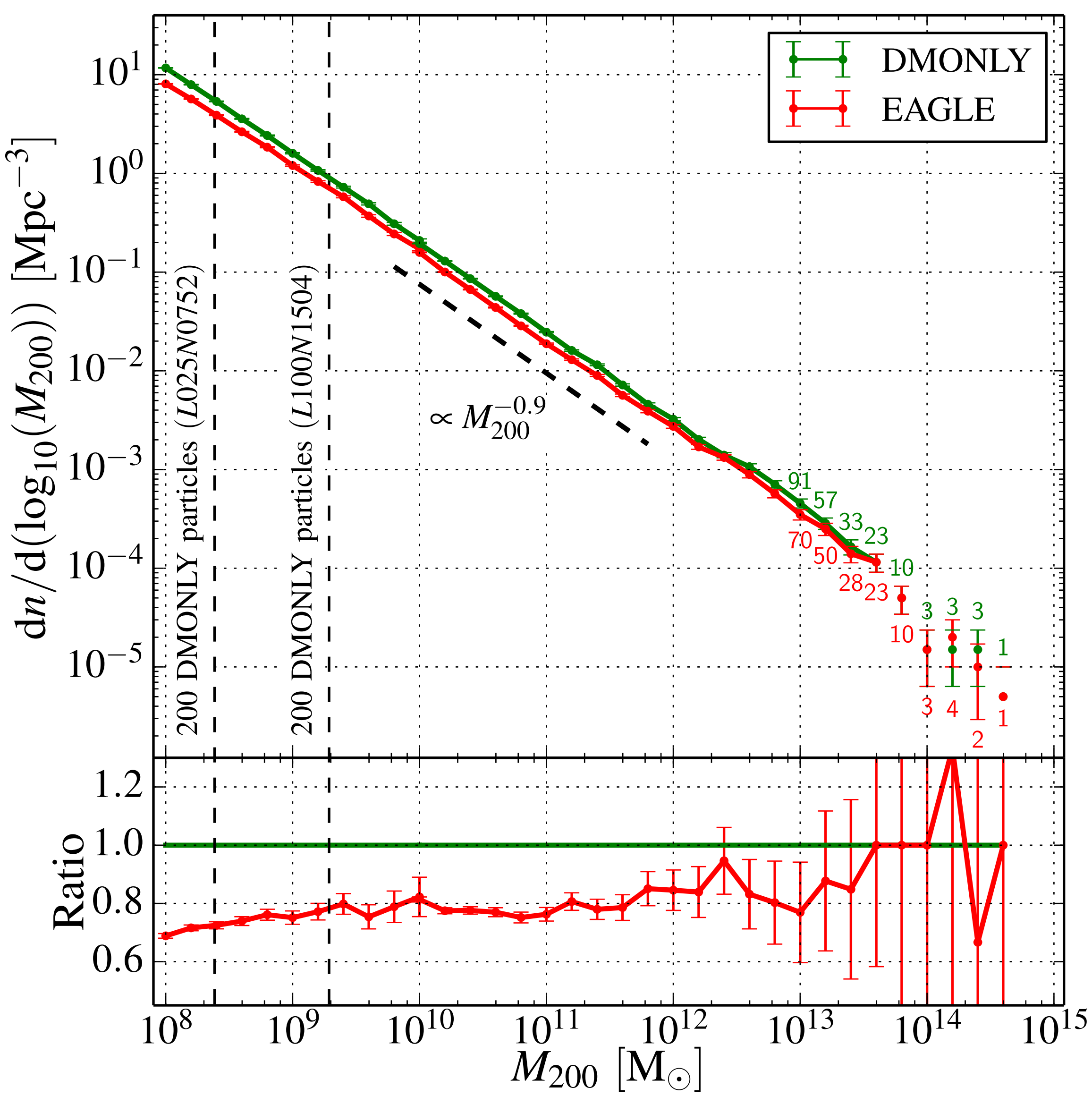
(EAGLE, Trayford et al. 2015)

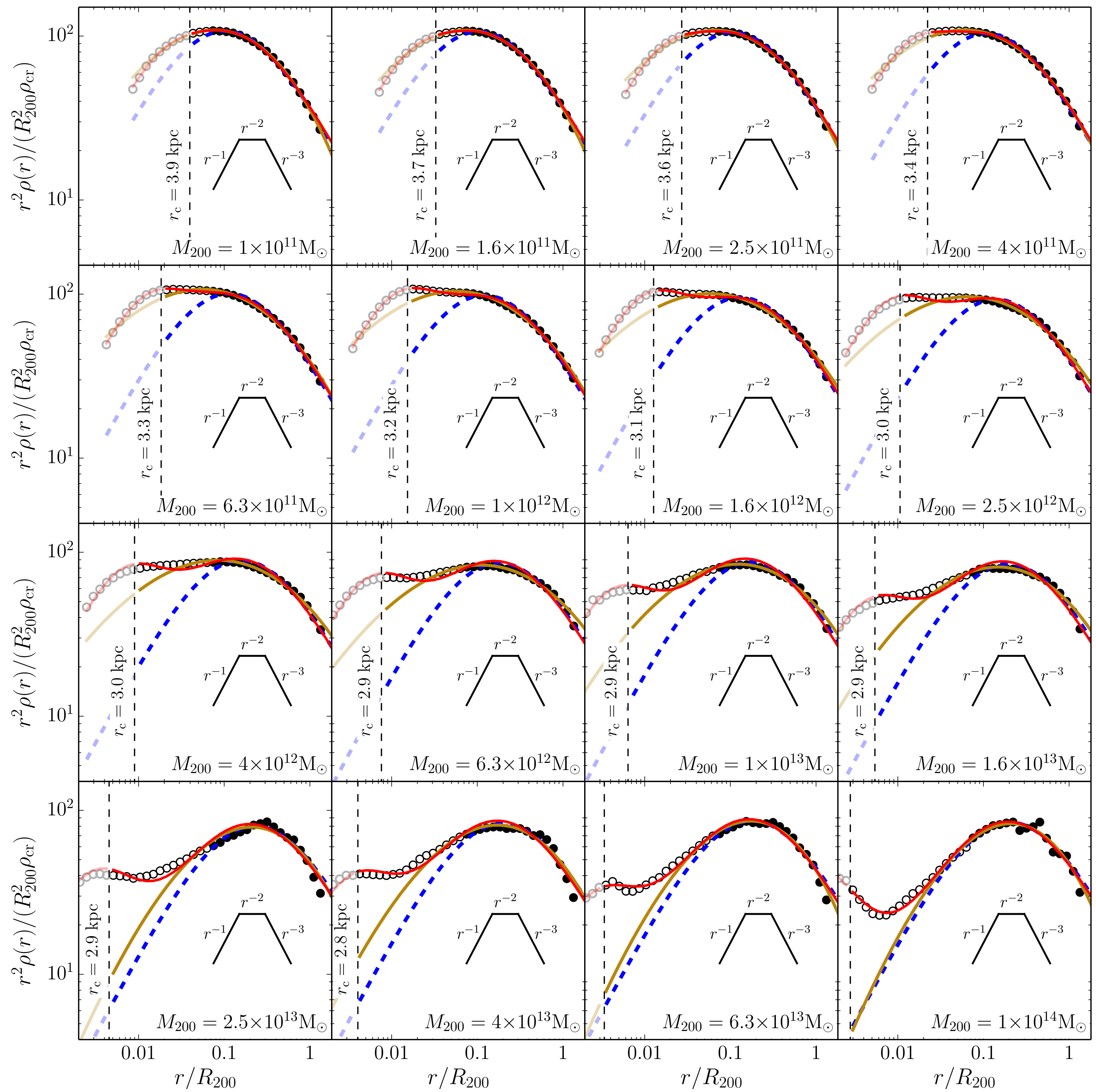


Effects of baryon physics

The halo mass is reduced by the inclusion of baryons and associated energy feedback effects. At the low mass end, feedback from star formation expels gas and this reduces the total mass, radius and growth factor of the halo. This reduction is progressively smaller for larger halos as the source of feedback shifts from star formation to AGN.

(EAGLE, Schaller et al. 2015)



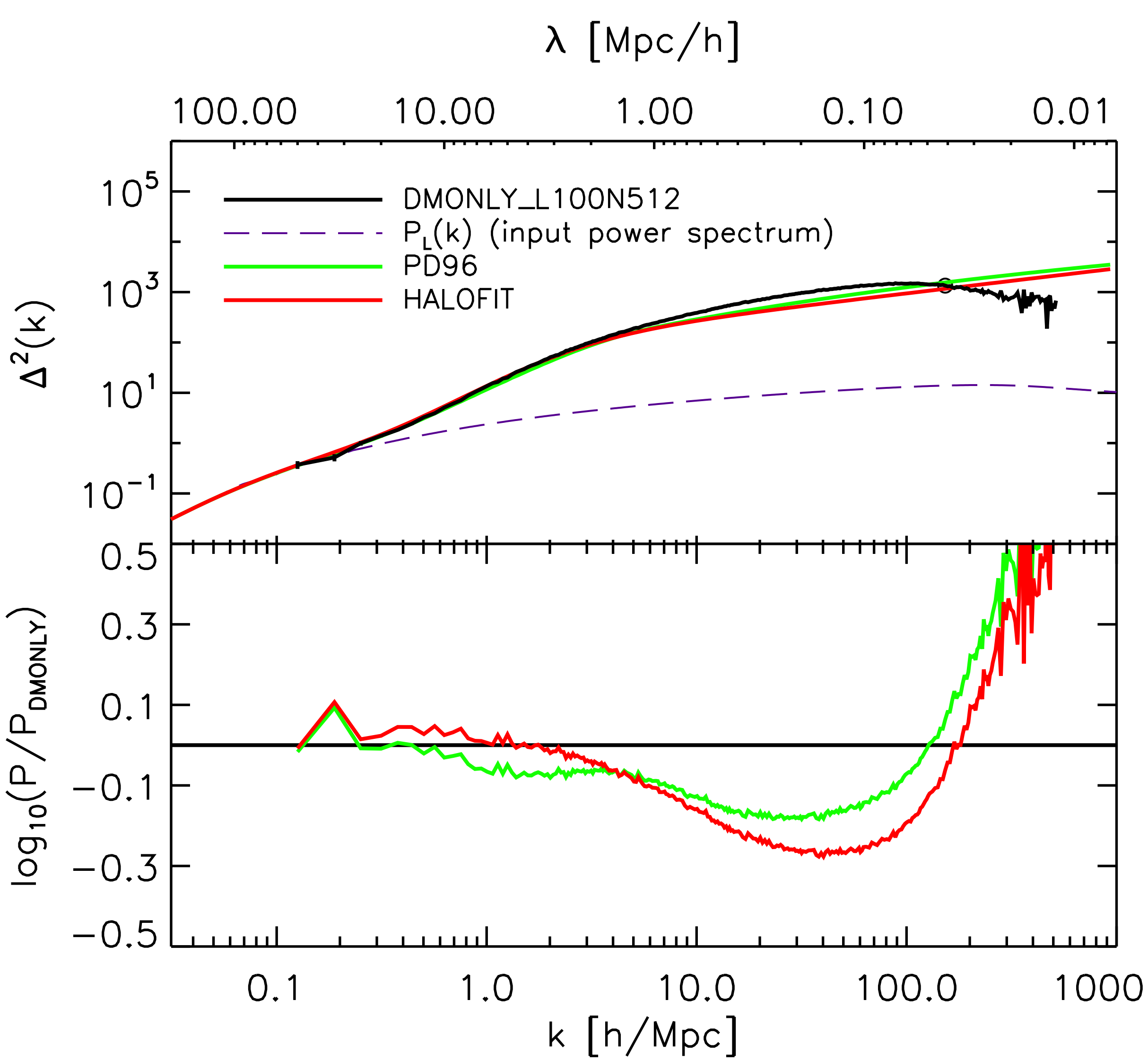


Radial density profiles change in the very centre of halo while in the outer part are well described by NFW.

Effects of baryons physics

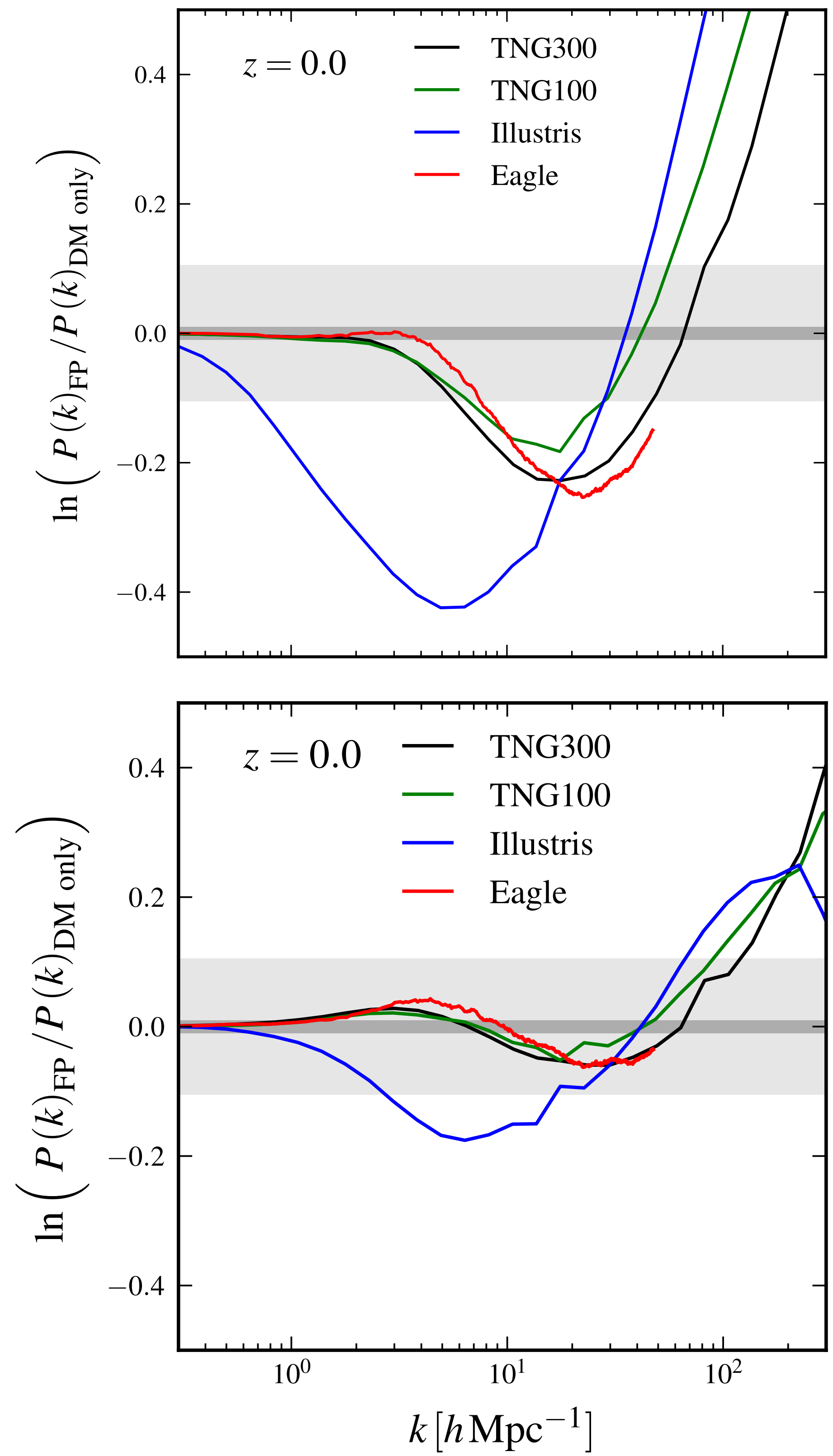
Baryonic effects increase the clustering of dark matter on small scales and damp the total matter power spectrum on scales up to ~10 h/Mpc by 20%.

Different models reproducing the properties of the galaxy population agrees well on the effect of baryonic physics on the distribution of matter. Same exercise can be done for the two-points correlation function.



(OWLS, van Daalen et al. 2011)

(IllustrisTNG, Springel et al. 2017)



Summary

Cosmological simulations have reached a high level of refinement in the last years.

Not only the global properties of the observed, low redshift galaxy population are well reproduced by numerical models, but also their evolution with time.

Internal structure of galaxies

With increasing the resolution and adding relevant physics (e.g. molecular network, molecular cooling, radiation transport) we will be able to resolve the multiphase structure of the ISM and the internal structure of galaxies.

Large-scale hydrodynamical simulations

With increasing the size of the simulated volume and using the current physics we will be able to sample higher overdensities and simulated consistently the galaxy population up to the most massive observed clusters.