Numerical Simulations of Galaxy Formation & Evolution

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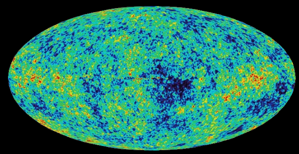
with special thanks to S. Colombi (IAP)

Outline

I : What we mean by numerical simulations of galaxy formation & evolution:
the physics at play and its numerical implementation

II : Some of the most important results & limitations

Content of the expanding Universe (Dunkley et al 2009)



- -Collisionless dark matter : Ω_{DM}=0.216
- -Baryons (gas & stars) : Ω_b=0.044
- -Dark energy : Ω_Λ=0.74

Basic equations ruling the dynamics (plus expansion)

$$\frac{\partial f}{\partial t} + \mathbf{u}.\nabla f - \nabla\Phi.\nabla_u f = 0$$
Vlasov : dark matter, stars

$$\frac{\partial \rho_\mathrm{b}}{\partial t} + \nabla.(\rho_\mathrm{b}\mathbf{u}) = 0$$
Continuity : gas

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}.\nabla).\mathbf{u} = -\nabla\Phi - \frac{\nabla p}{\rho_\mathrm{b}}$$
Euler : gas

$$\frac{\partial \varepsilon}{\partial t} + \mathbf{u}.\nabla\varepsilon = -\frac{p}{\rho_\mathrm{b}}\nabla.\mathbf{u}$$
Energy : gas

$$p = (\gamma - 1)\varepsilon\rho_\mathrm{b}$$
Equation of state : gas

$$\nabla^2\Phi = 4\pi G\left[\int f d^3u + \rho_\mathrm{b}\right]$$
Poisson : everything

But in fact the Universe is NOT quite that simple :

- **Initial conditions**:
  → WMAP observations make it a well def. pb. in CDM context

- **Collisionless fluid**: Cold Dark Matter & star particles
  → Vlassov-Poisson (very well understood)

- **Collisional fluid**: gas heated & cooled radiatively (atomic, molecular)
  → Euler-Poisson + homogeneous cooling & heating + chemistry: with light elements (well understood)

- **Additional physics**: star formation and feedback on the surrounding gas
  → Supernovae, turbulence, black hole growth, jets, MHD, accurate of radiative transfer, chemistry of heavy elements, dust…
  NOT well understood at all.

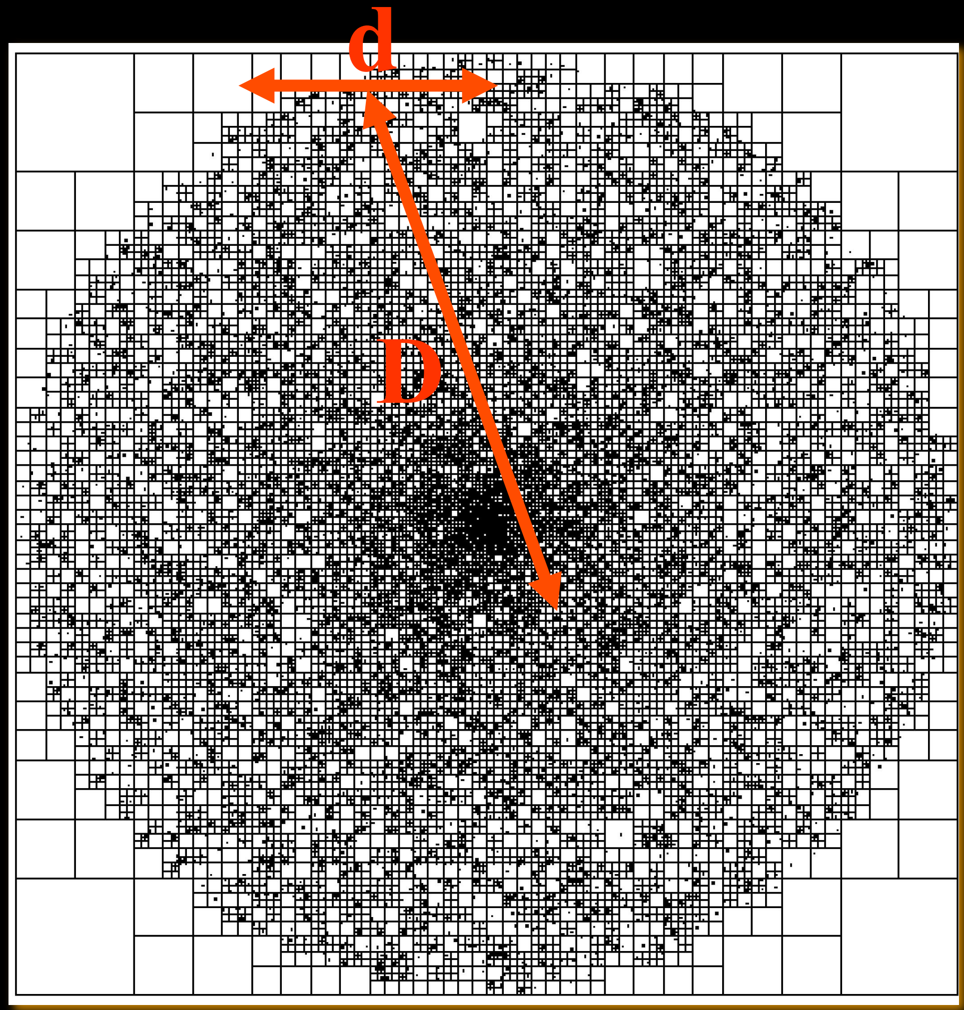
Collisionless part: facts

$$\frac{d\mathbf{x}_{\mathrm{p}}}{dt} = \mathbf{u}_{\mathrm{p}}$$
$$\frac{d\mathbf{u}_{\mathrm{p}}}{dt} = -\nabla\Phi$$

- The fluid is represented by particles : concept of mass resolution
- Need to soften gravitational force on small scales : concept of spatial resolution, or softening length ε
- Given theses 2 concepts, the codes differ only by the way Poisson equation is solved

Collisionless part: methods

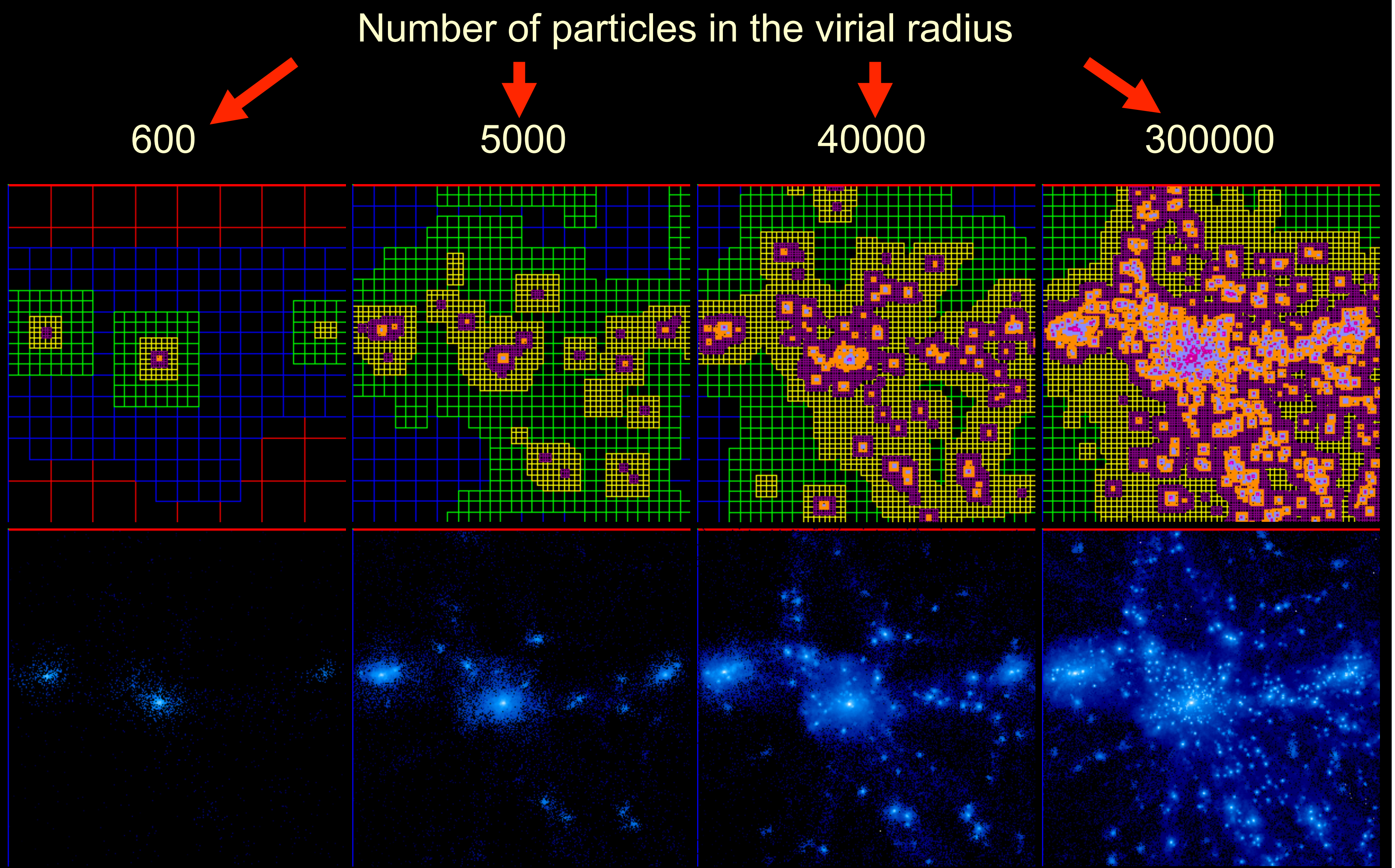
- Brute force (PP) : fixed ε
- Particle mesh (PM) : (large) fixed ε
- Treecode : fixed ε
- Hybrid methods: P3M : PM+local PP : fixed ε
  AMR : PM with adaptive grid (tree) : varying ε
  treePM : PM+local tree : fixed ε
  Metric methods (grid shape follows dynamics) : varying ε



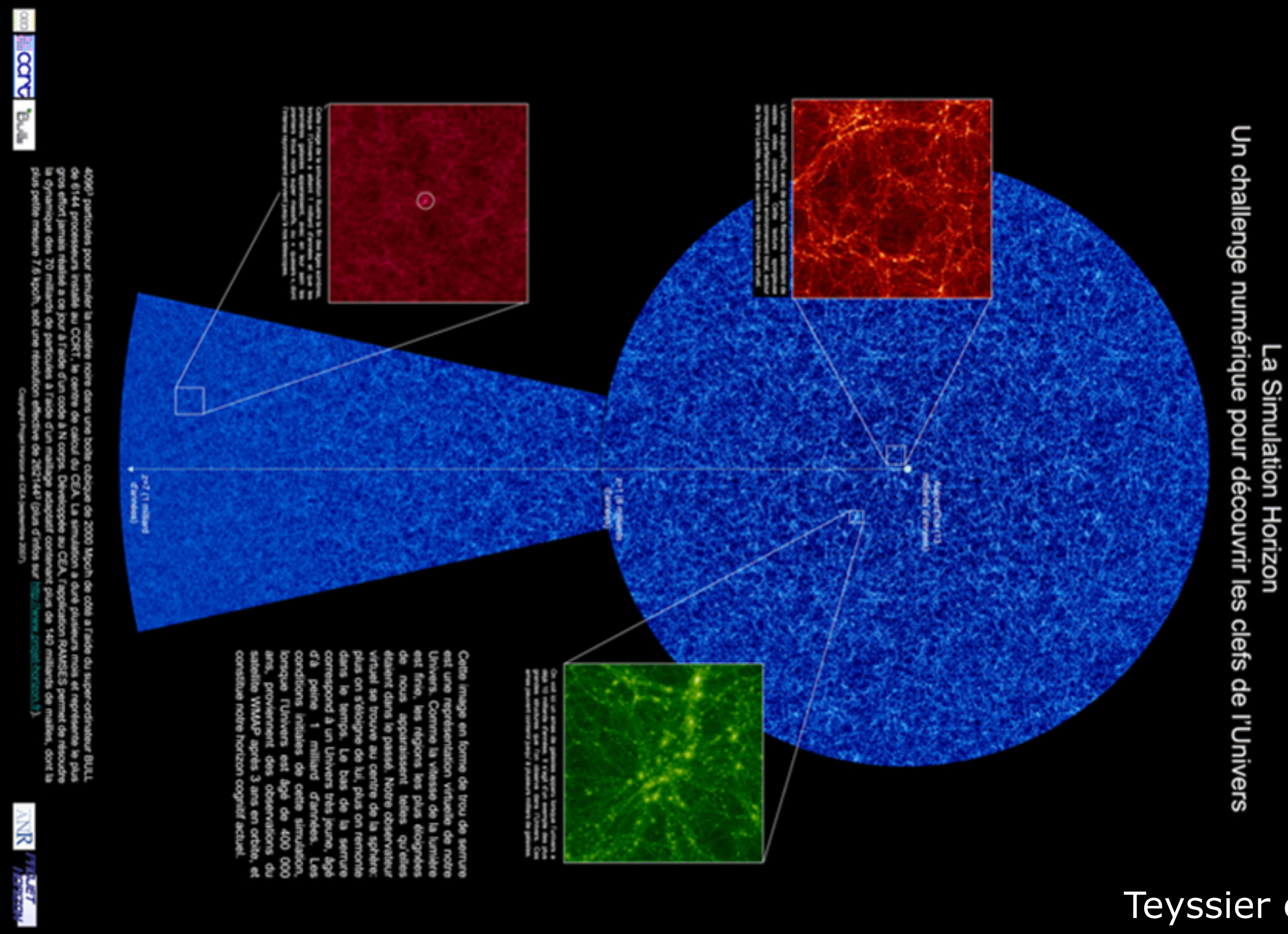
A ``quad tree'' (Salmon & Zurek 1994) to explain the classic treecode implementation of Barnes and Hut (1986)

AMR simulations: effects of mass resolution

Teyssier et al. 2002



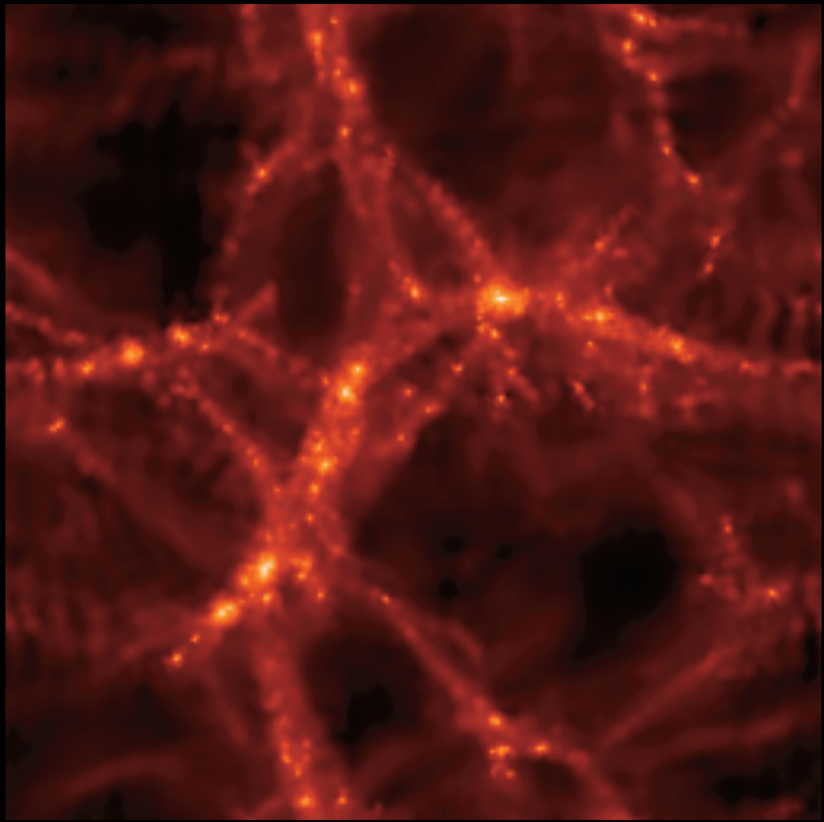
An example of large scale DM simulations:
HORIZON 4Π: 4096^3 particles in 2000h^{-1} Mpc box



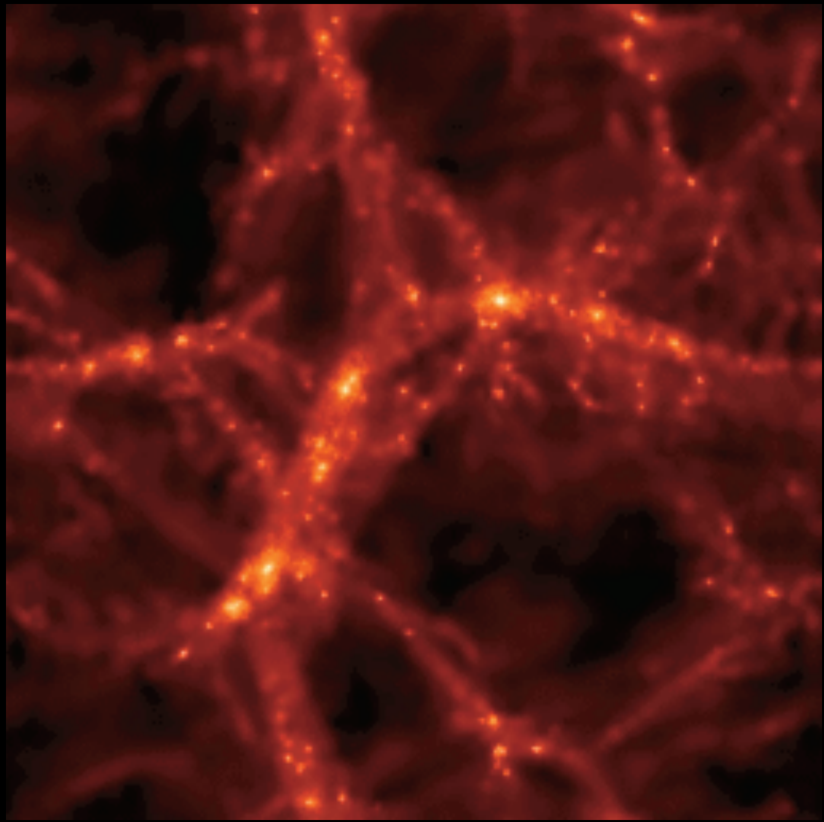
Teyssier et al. 2008

Comparison of Methods

TreeCode : GADGET



AMR : ENZO



Minor differences, especially on large scales
but even on small scales

O'Shea et al 2005

Collisional gas : facts

- The gas is collisional: the macroscopic velocity field is single valued at each each point in space: fluid can represented by particles (concept of mass resolution) or sampled on a (adaptive) grid (concept of spatial resolution)

Collisional gas : methods

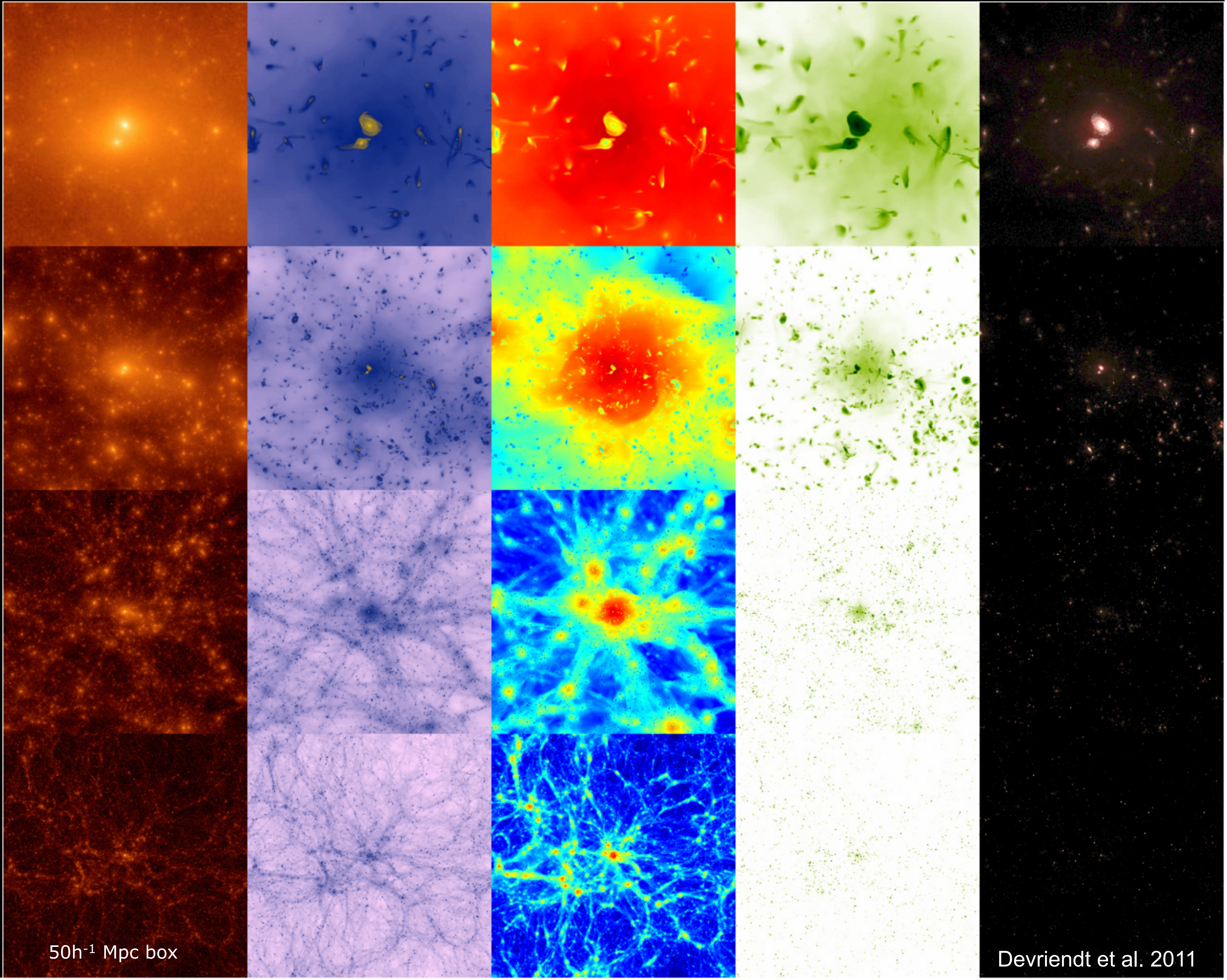
- Particle representation: Smoothed Particle Hydrodynamics (SPH) : each particle is a smooth (Lagrangian) cloud carrying the hydrodynamical informations (density, pressure, temperature, velocity)

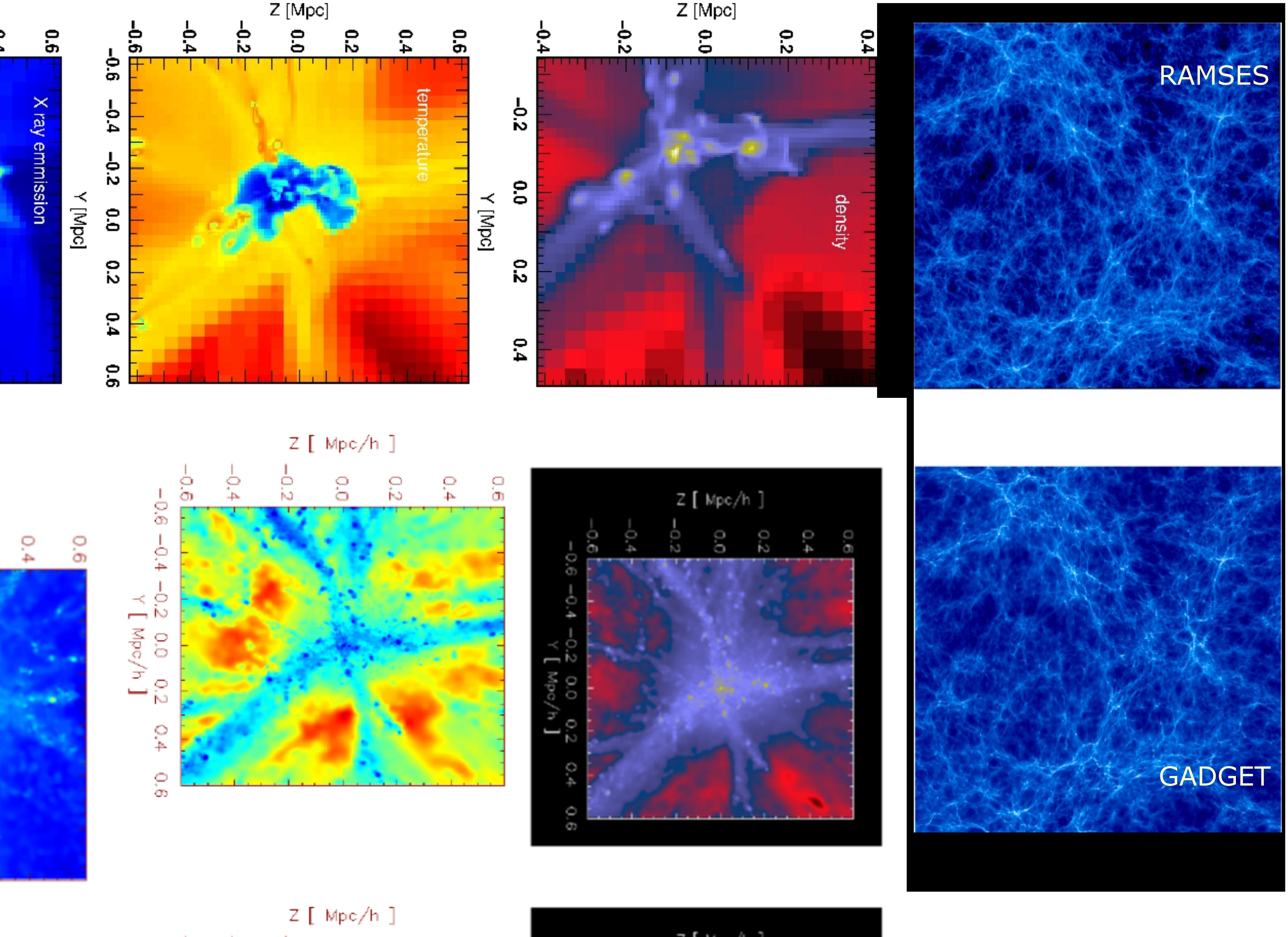
→ TreeSPH (e.g. GADGET)

- Grid sampling : finite difference (basic discretisation of Euler equations) or finite volume methods (conservations laws)
  Modern approach : Riemann solvers

→ AMR hydro codes (e.g. RAMSES)

The Mare Nostrum 1024^3 AMR hydro simulation



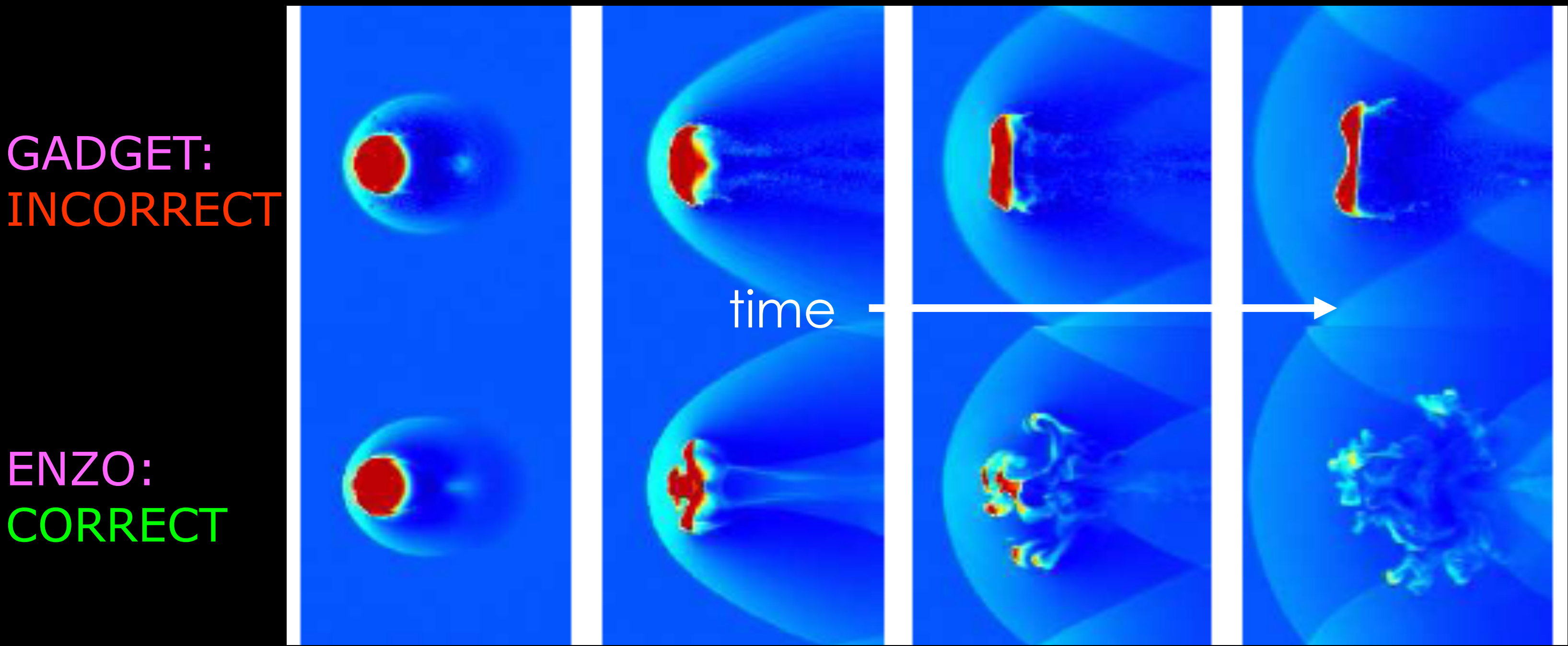


RAMSES
GADGET
density
temperature
X ray emmission
Z [Mpc]
Y [Mpc]
Z [Mpc/h]
Y [Mpc/h]

Note : contrary to DM, hydro discrepancies between SPH and AMR are marked: "vanilla" SPH technique has pb with instabilities

E.g. destruction of a cloud by Kelvin Helmoltz instability

Agertz et al. 2007



Additional physics : facts

- Stars form and supernovae explode in galaxies, supermassive blackholes are born, grow and release energy and momentum in the interstellar and intergalactic medium

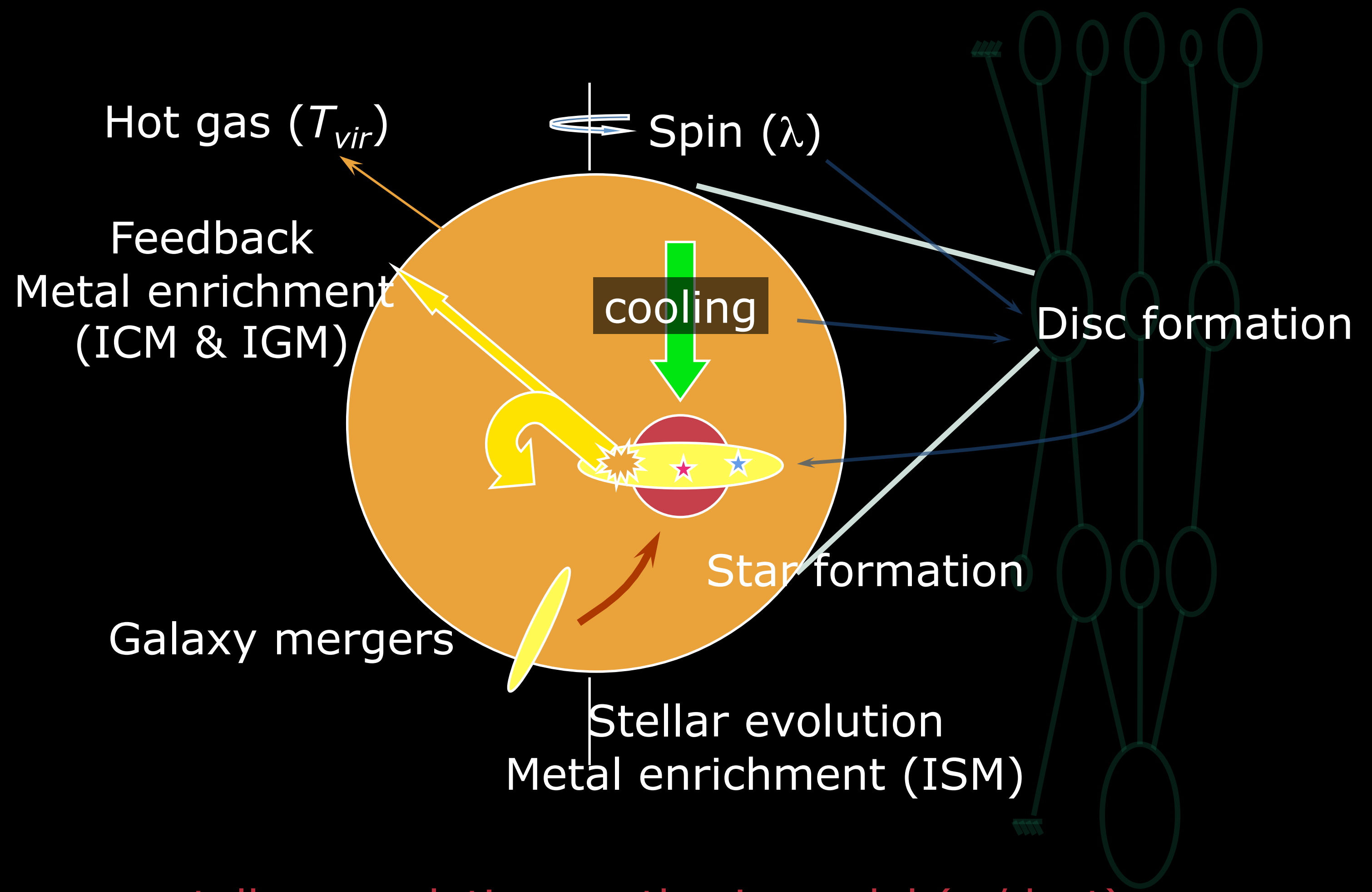
- Simulations are always going to lack resolution at some point to model these phenomena.

Additional physics : methods

- "subgrid" modelisation of the above phenomena in hydro simulations: its actual implementation depends on the hydrodynamic method used

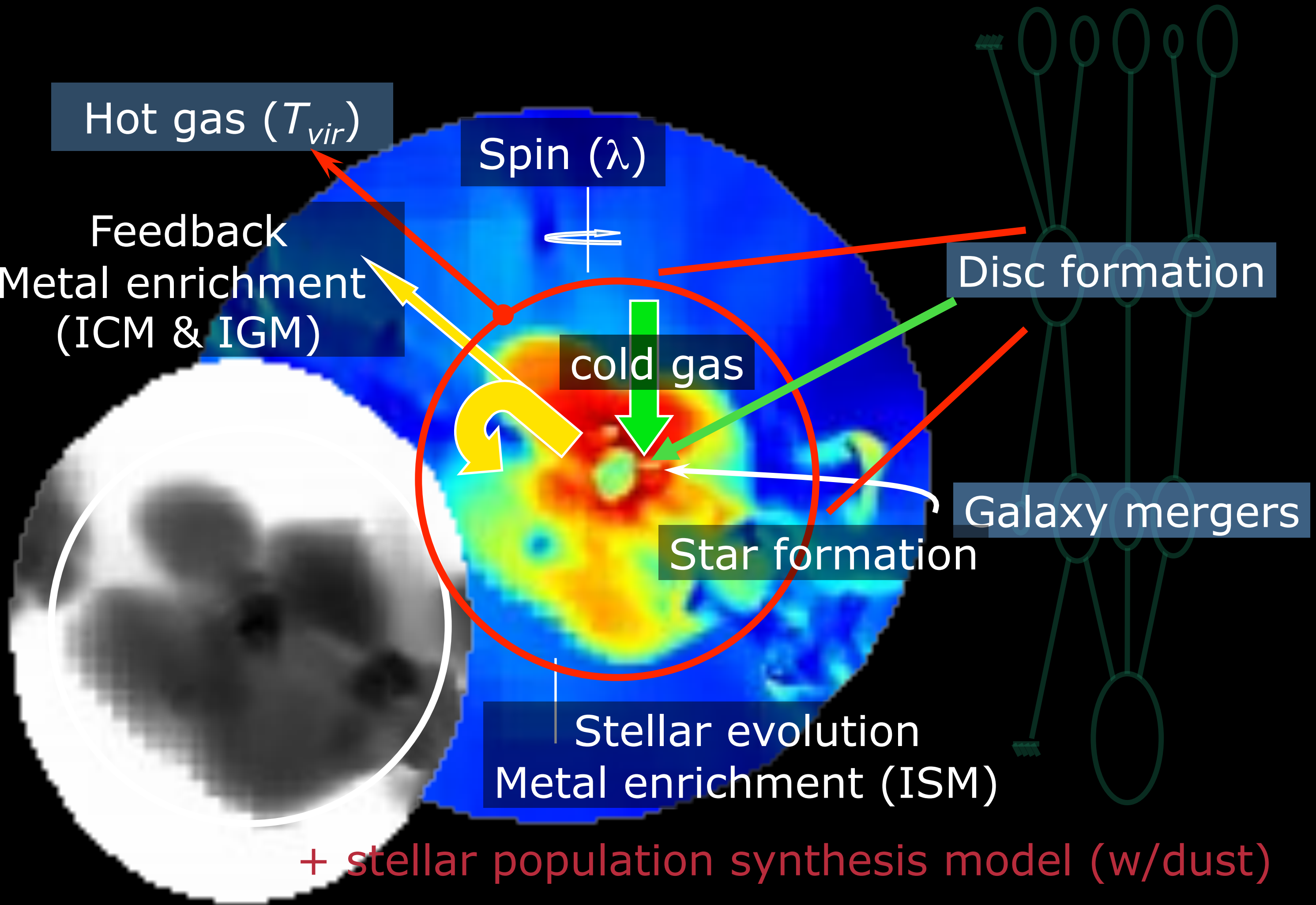
- full semi-analytic modelisation of baryonic physics in pure dark matter simulations: as many models as modelers although a lot of common features

Physics of baryons : a cartoon

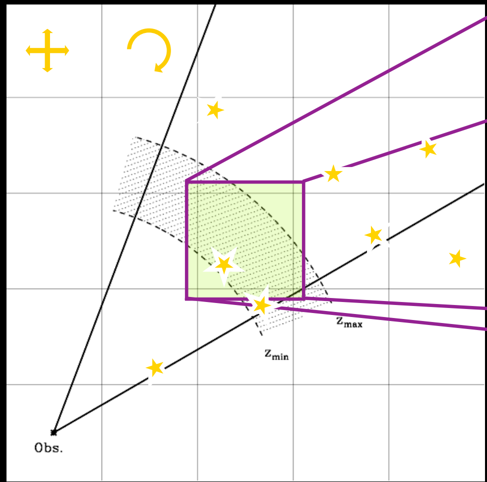


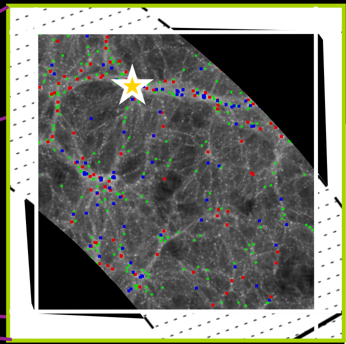
+ stellar population synthesis model (w/dust)

Subgrid physics of baryons

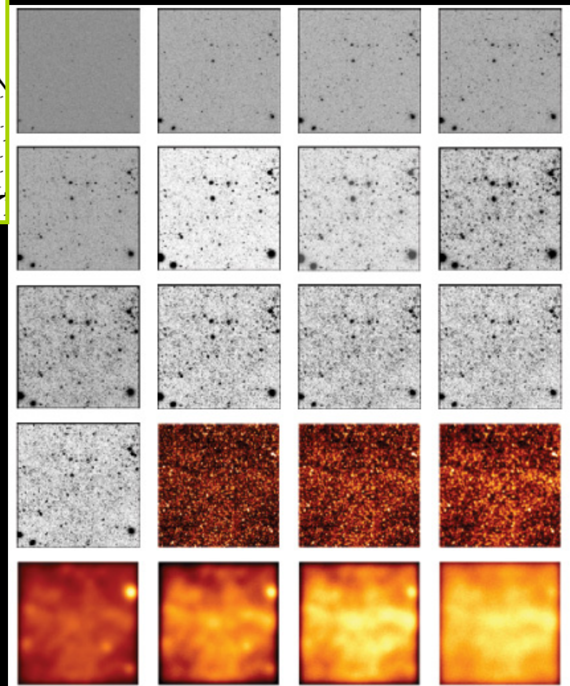


Note : from simulations to mock observations



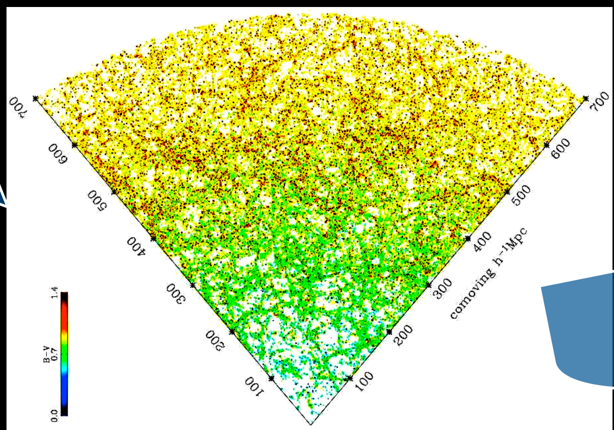


SDSS



Planck

MoMaF : the Mock Map Facility
Blaizot et al. 2005



A word on the CDM paradigm at this stage

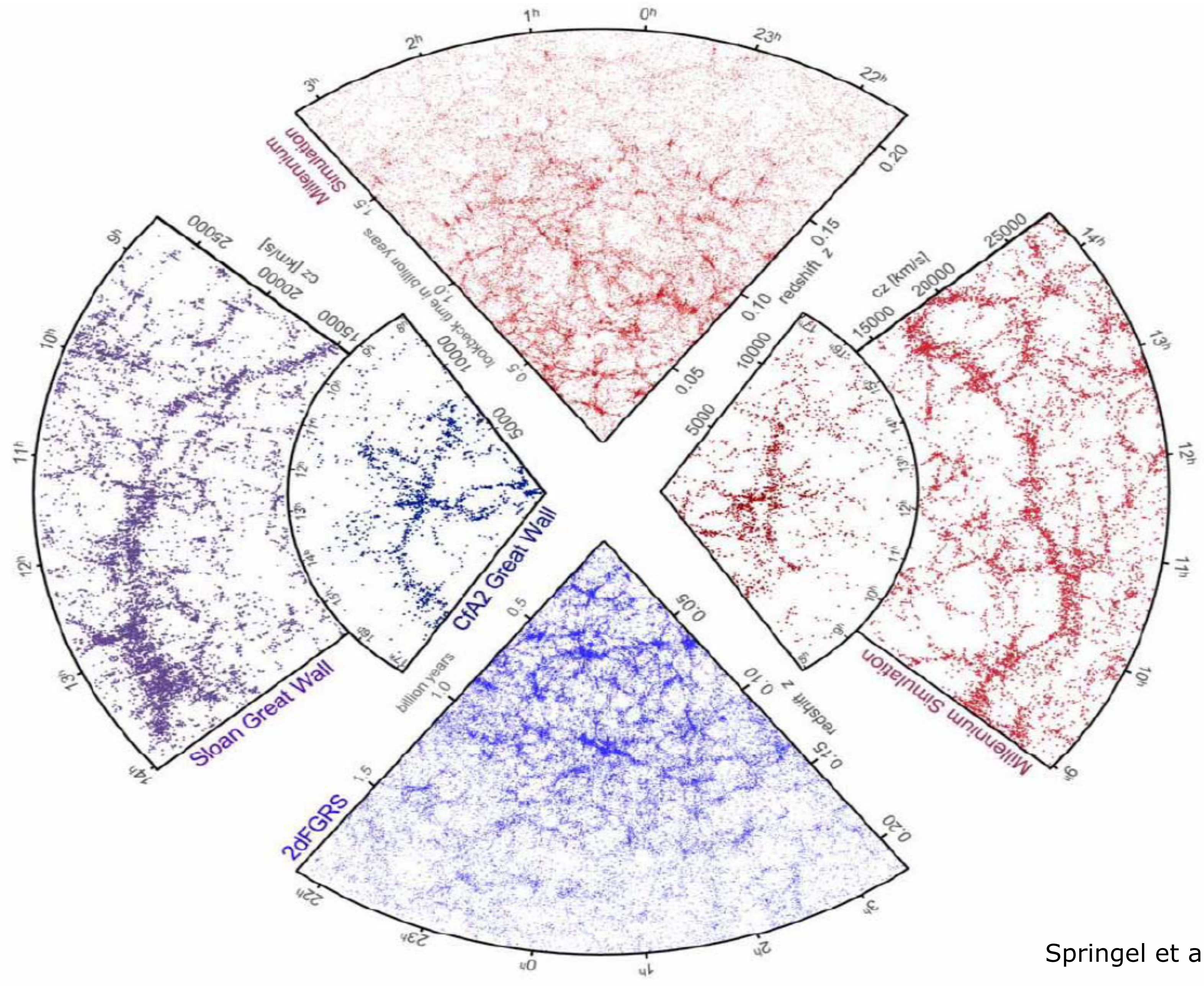
Most of the alternatives of CDM imply ***small modifications*** on small (sub-galactic, dwarf galaxy) scales which are quite insignificant on larger scales (e.g. WDM is still quite cold) and rather easy to simulate properly.

What really needs to be understood is the ***impact of baryons on the dark matter***.

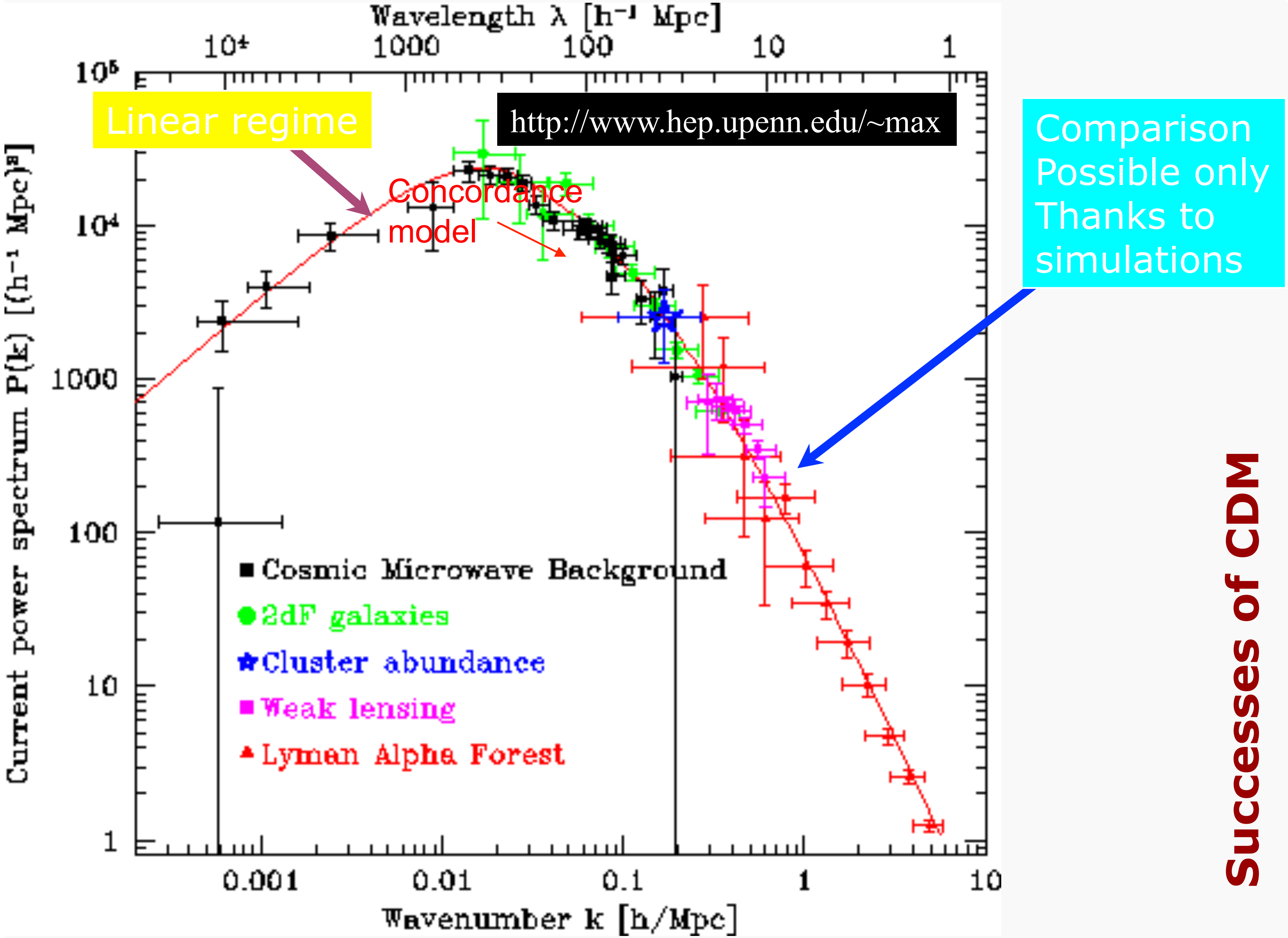
NB: this is all the more true when considering alternative to GR (e.g. MOND) where DM can be superfluous …

Major simulation
success stories
(mainly large scales)
and
limitations
(mainly small scales)

Reproducing large scale structures



Springel et al. 2006

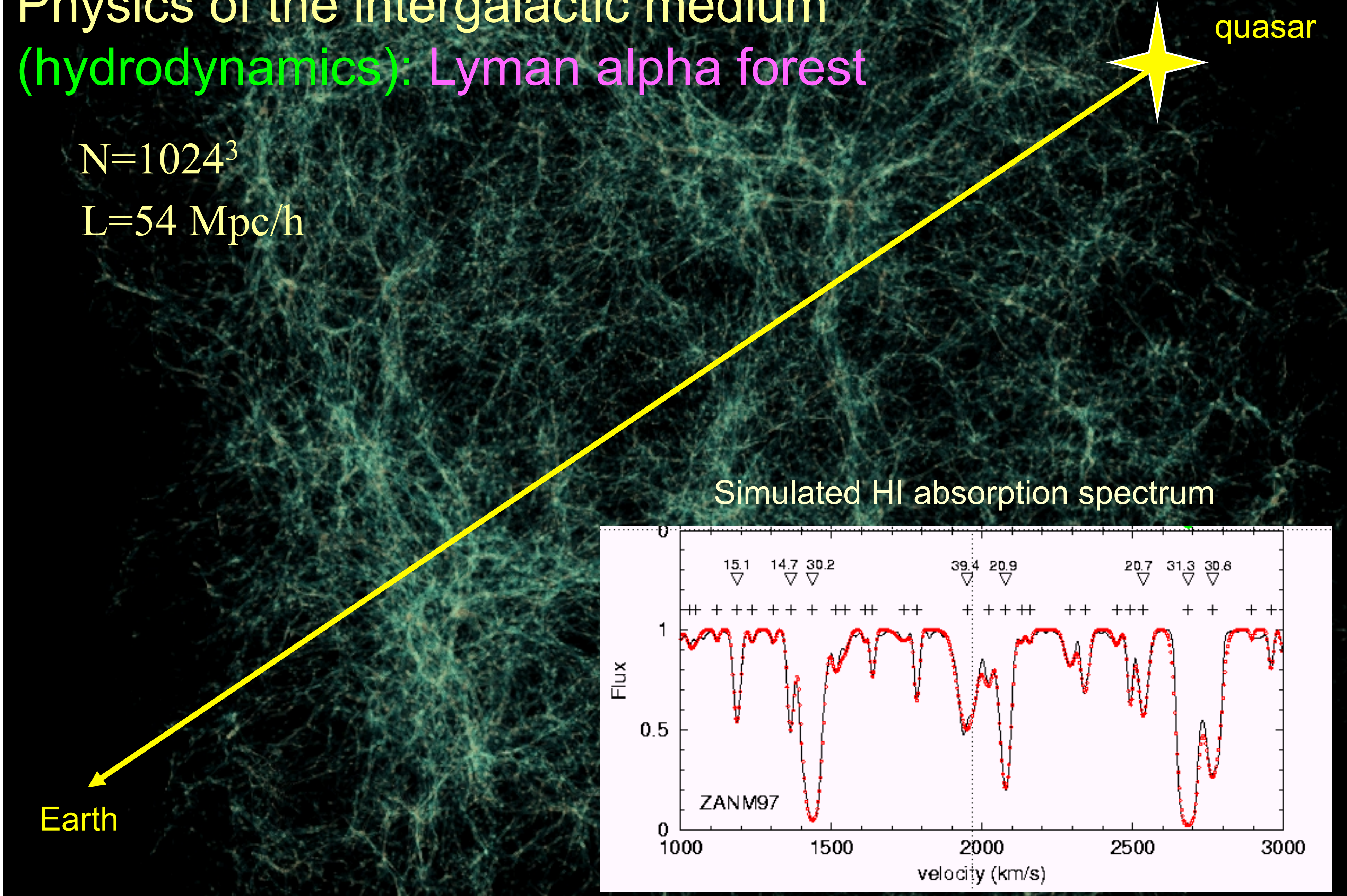


Successes of CDM

Physics of the intergalactic medium (hydrodynamics): Lyman alpha forest

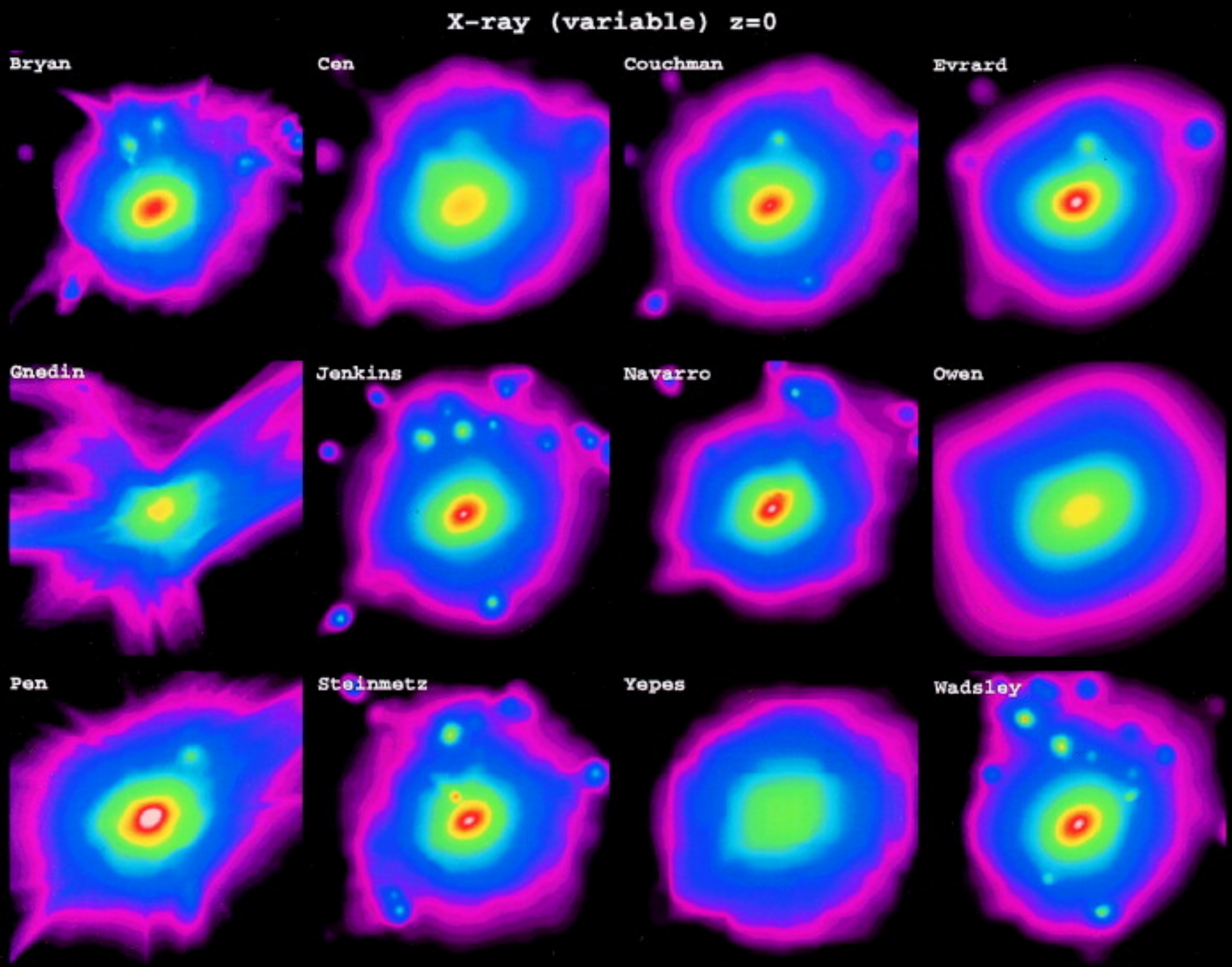
$N=1024^3$

$L=54$ Mpc/h



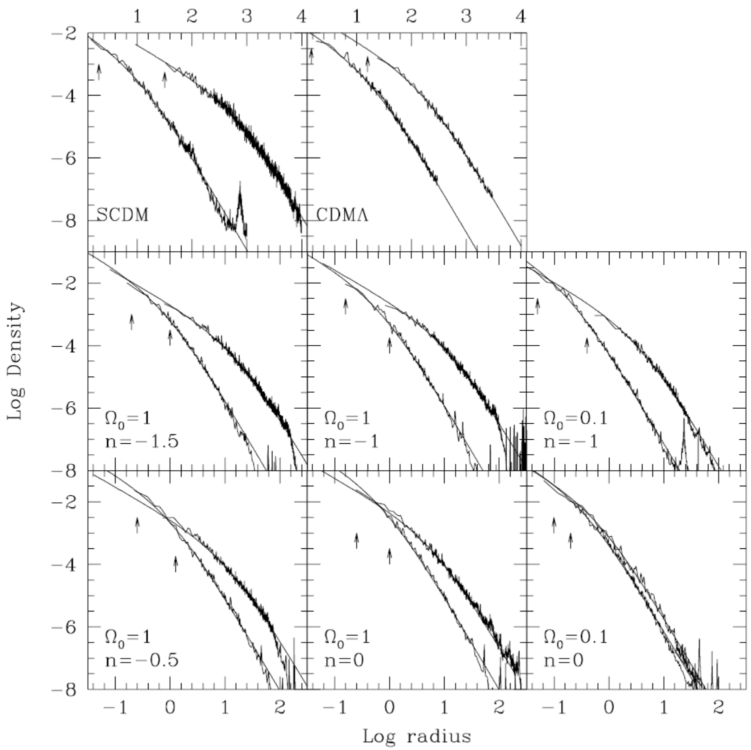
“Adiabatic” hydrodynamics of galaxy clusters :

e.g. Frenk et al. 1999

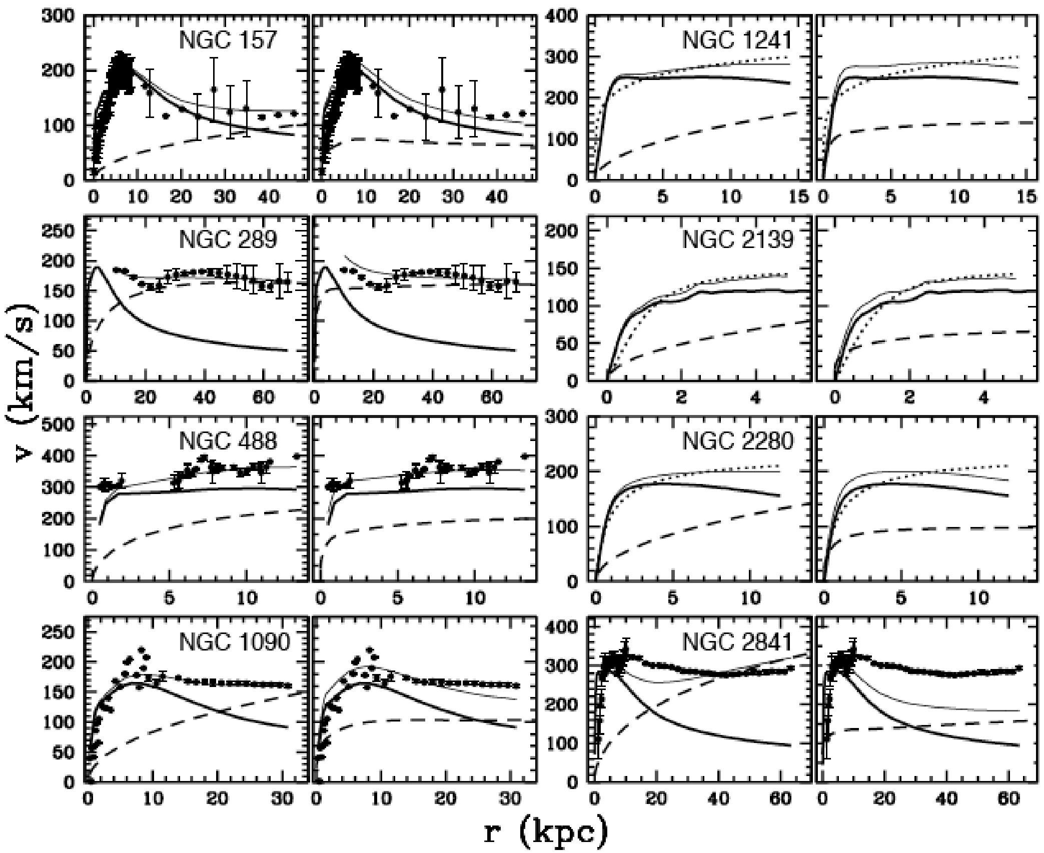


Cusp of host halo: clusters OK but galaxies? Why does scale matter?

NFW / Einasto halo profiles (Navarro et al. 1996)



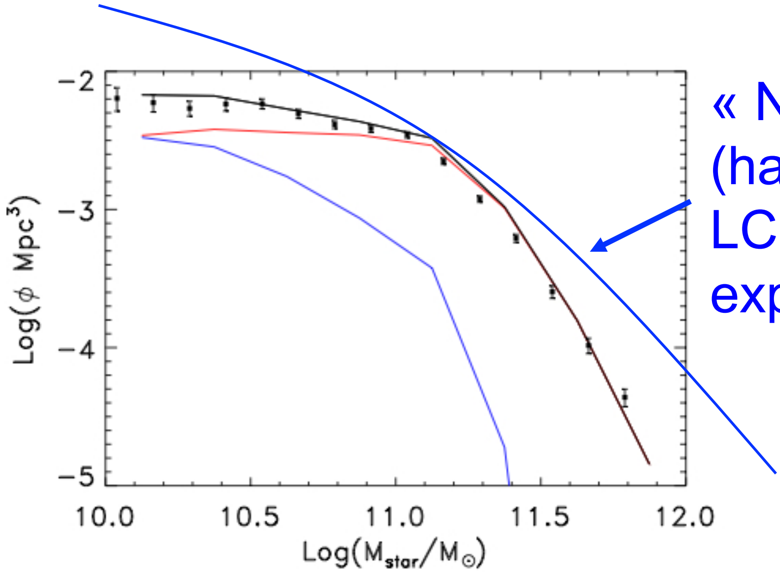
the rotational velocity curves of galaxies: Kassin et al 2006 →



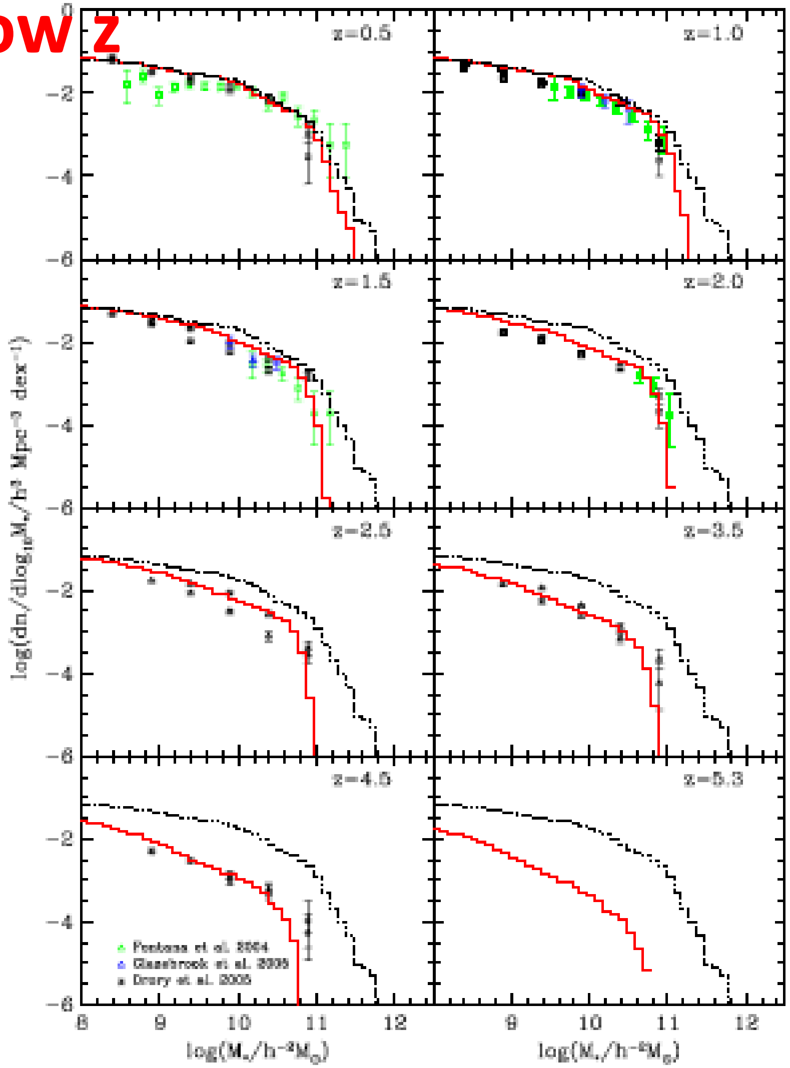
Observations show inner regions of galaxies with lower concentrations than predicted by **pure** N-body simulations and adiabatic contraction due to baryons makes things worse except if strong feedback.

Another galaxy problem: stellar mass functions at high and low z

Bell et al 03 K-band determination



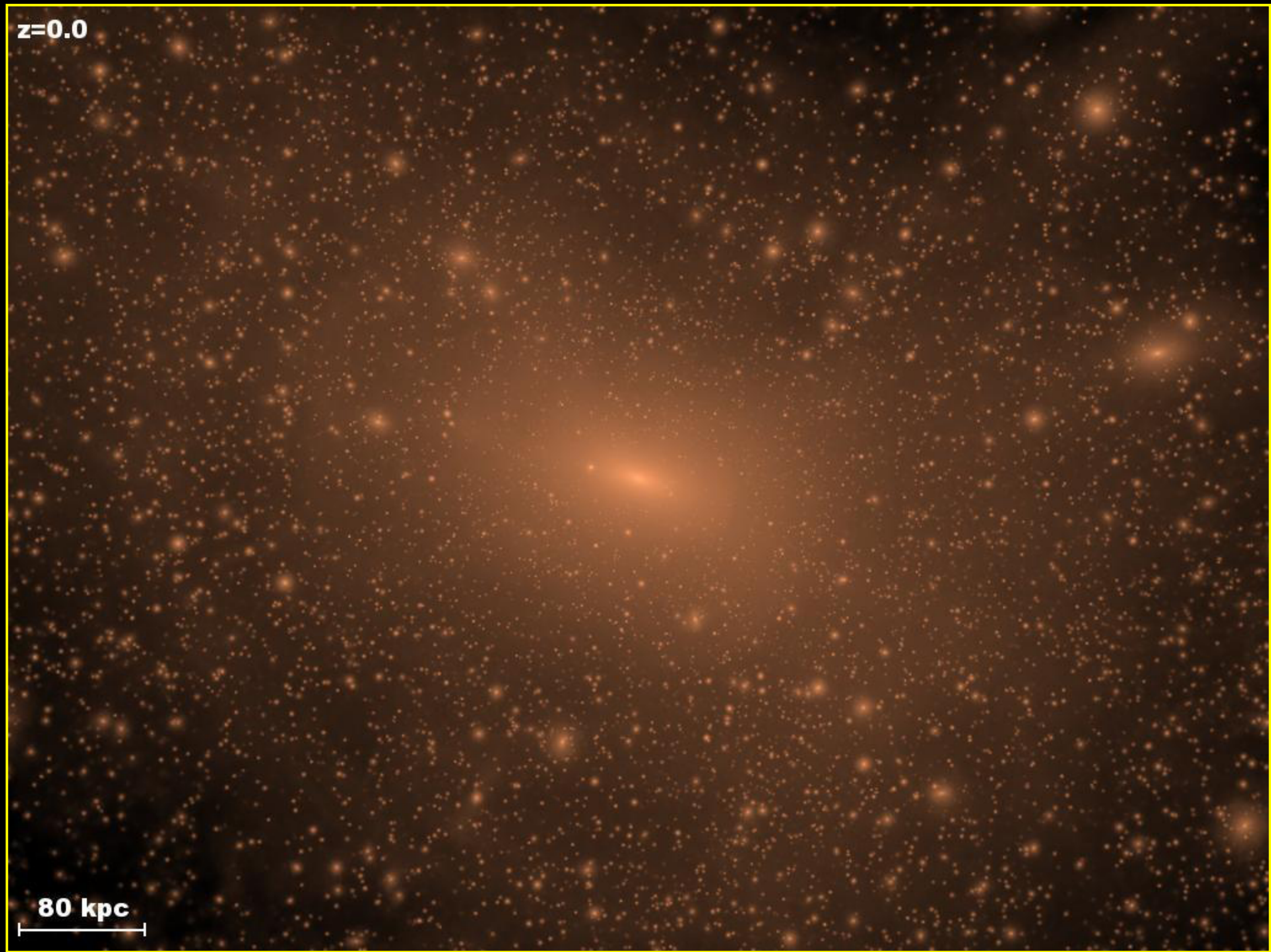
« Naïve »
(halo based)
LCDM
expectation



« Breaking the hierarchy »
Bower et al 2006
Data: Drory et al 2005,
Fontana et al 2004
Glazebrook et al 2004

also De Lucia et al 2006 and
Hopkins et al 2006

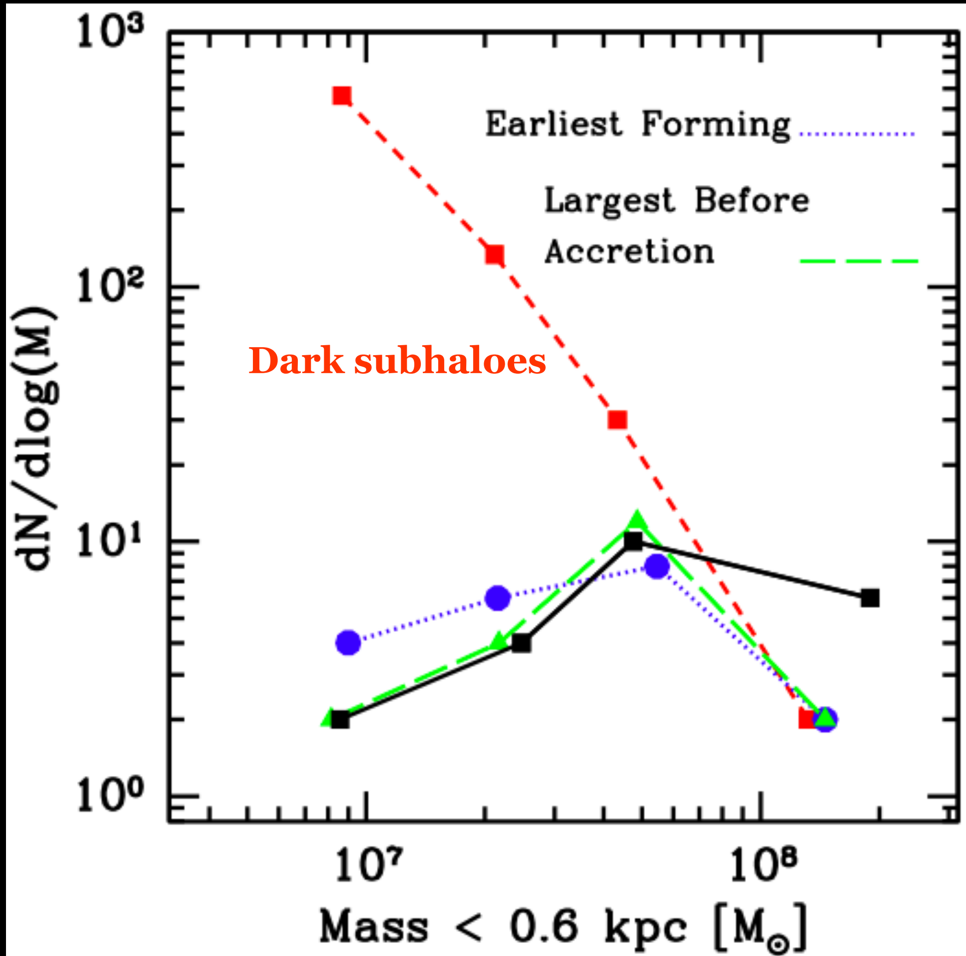
Further down in scale: substructure in CDM haloes: the N-body prediction



Via Lactea simulation (J. Diemand & al, 2006)

The magnitude of the problem

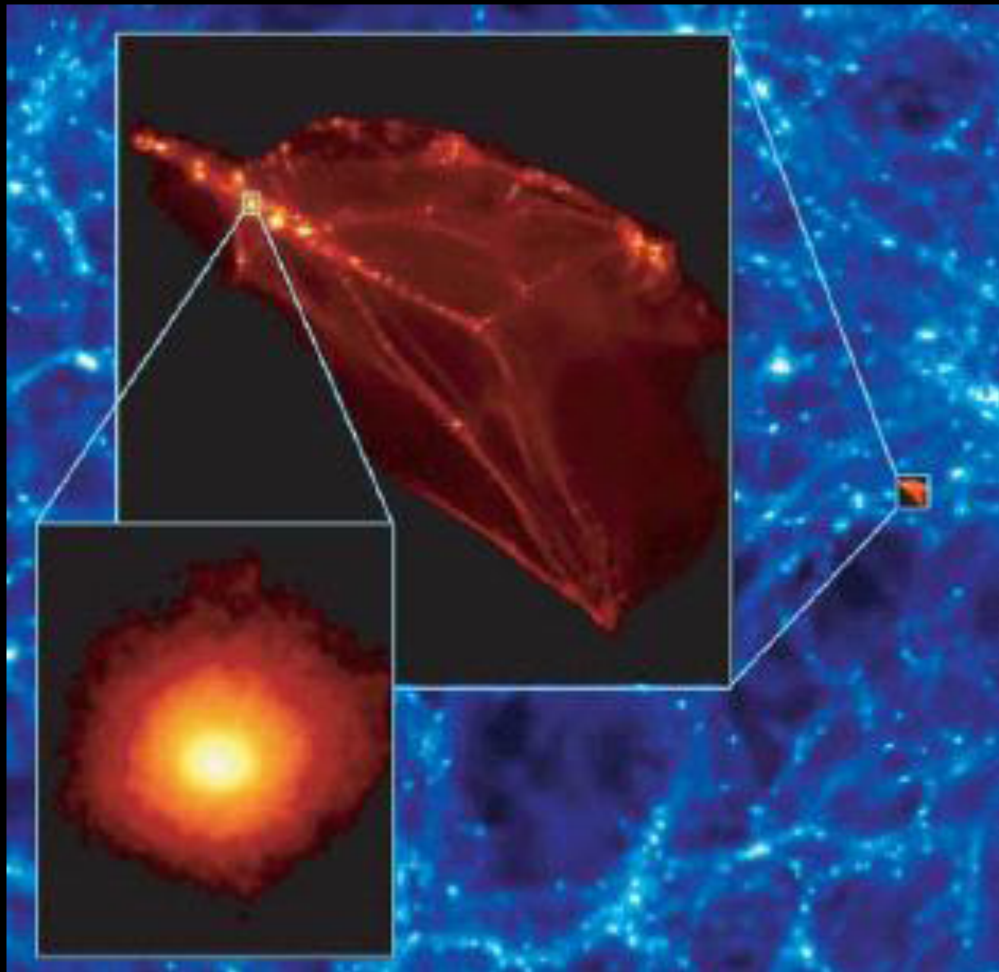
Strigari et al. 2007



The ultimate CDM substructures :

earth mass minihaloes

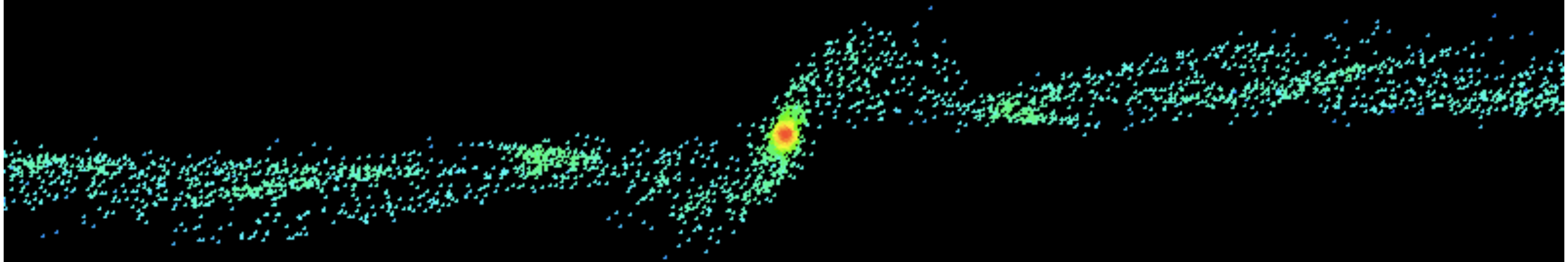
specific assumptions about nature of CDM



Clue about nature of DM?

Lovell et al 2012 CDM vs WDM

However even micro-halos ($< 10^{-3}$ M_{sun}) can be destroyed by disk (baryons) potential !



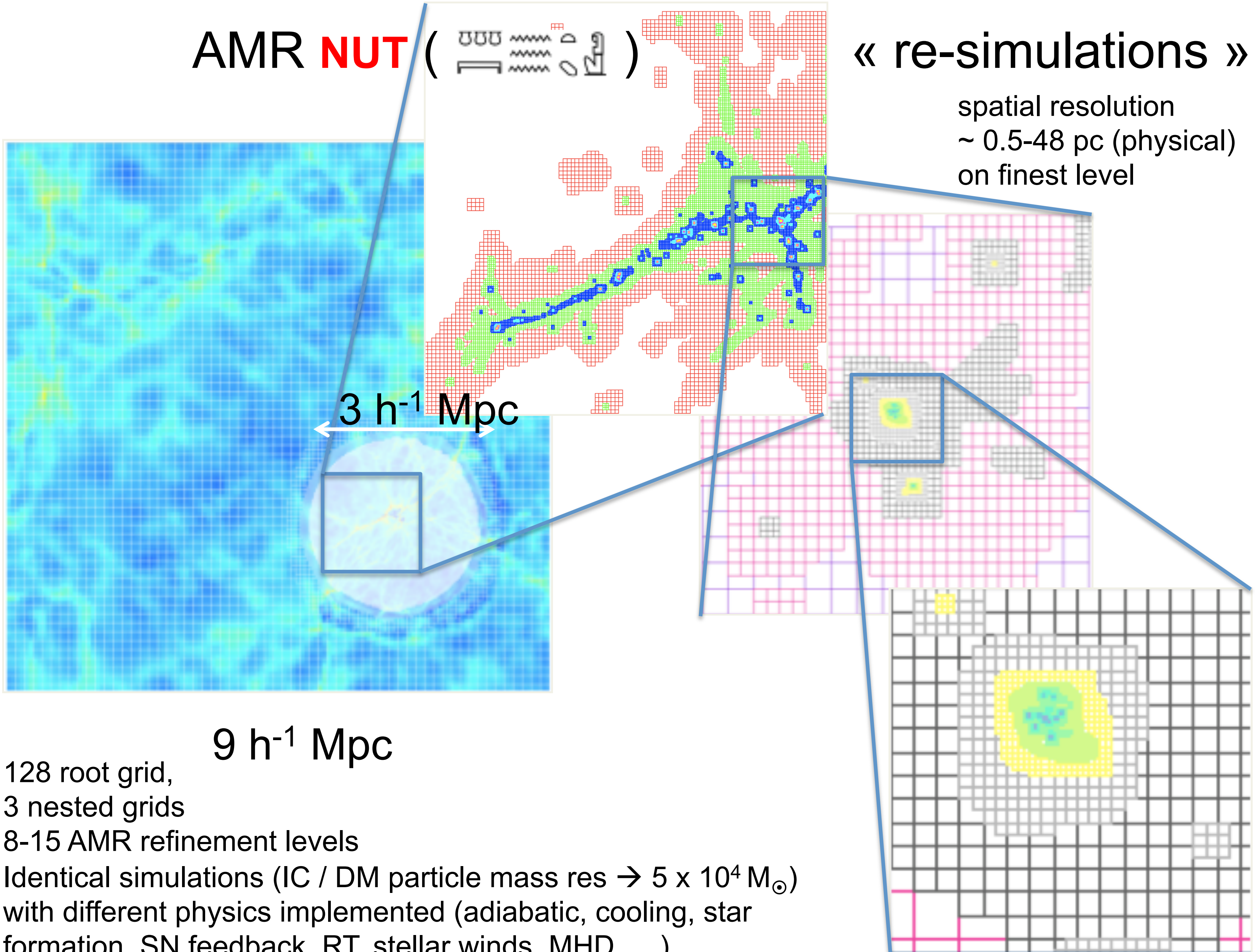
e.g. Schneider et al 2011

Moreover, quid of the cusp of inner halo profile?

Indeed it is still present in WDM N-body simulations!

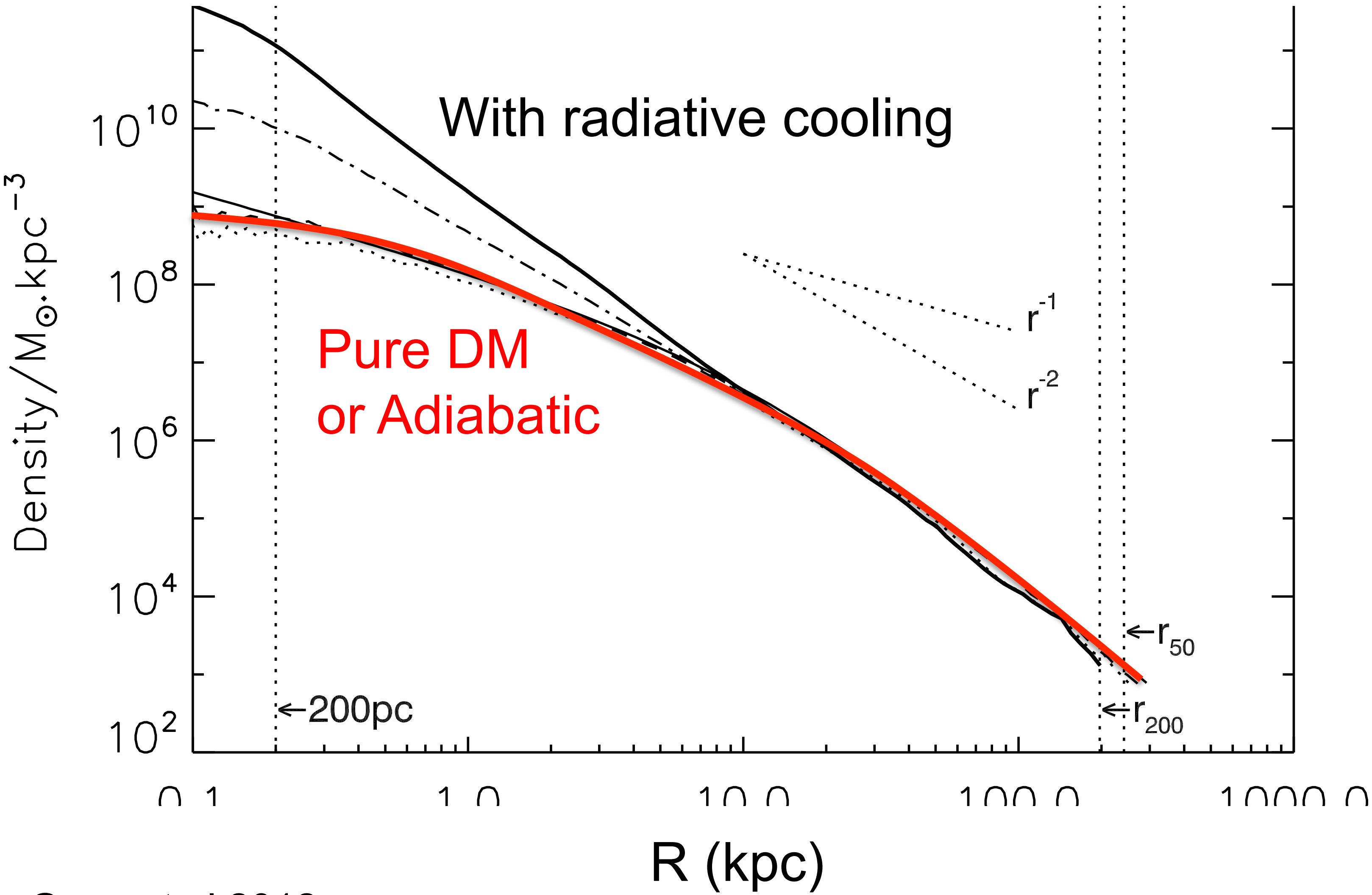
AMR NUT ( ) « re-simulations »

spatial resolution
~ 0.5-48 pc (physical)
on finest level



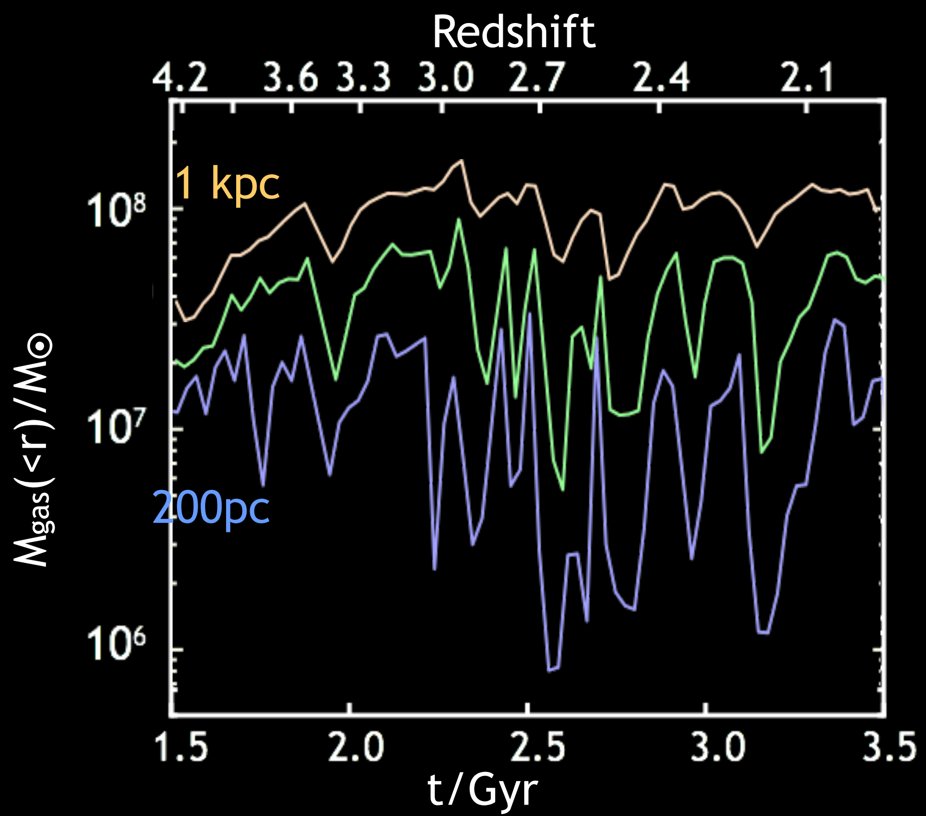
128 root grid,
3 nested grids
8-15 AMR refinement levels
Identical simulations (IC / DM particle mass res → 5 x 10^4 $M_\odot$)
with different physics implemented (adiabatic, cooling, star formation, SN feedback, RT, stellar winds, MHD …)

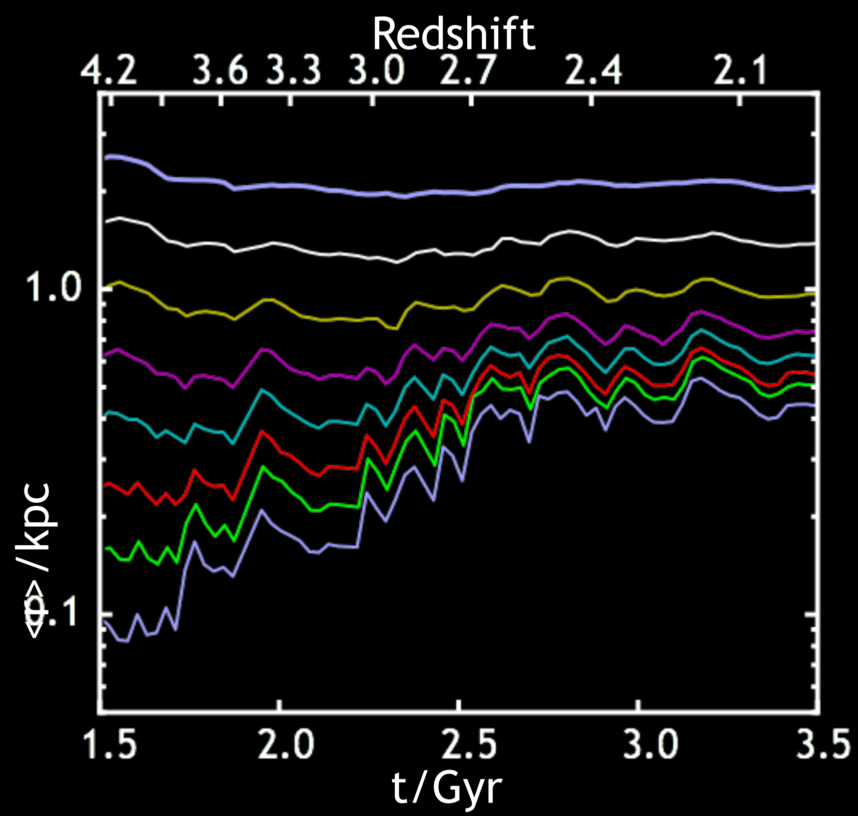
Baryon cooling impact on density profile of a MW like halo



Geen et al 2012

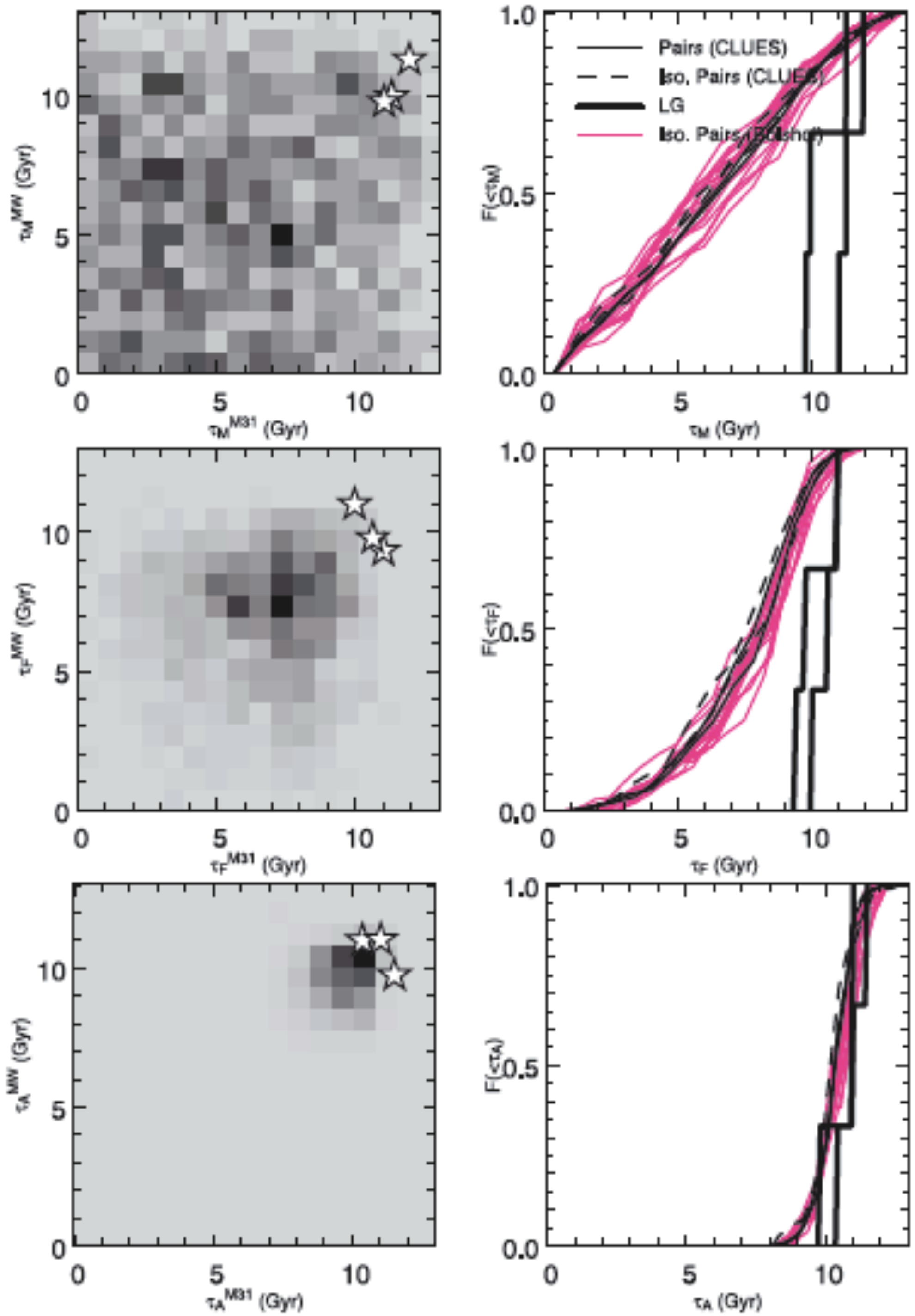
But … SN feedback?





Rapid (<dynamical time) gas expansion/contraction → Outward migration of DM particle orbits

Pontzen & Governato 2012, arXiv:1106.0499, MNRAS in press



Direct & indirect DM detection: how typical is the MW halo?

a.k.a. an initial condition problem

Forero-Romero et al 2011 (CLUES project)

LG (MW + Andromeda): 12-17 % of halos of same mass have same MAH, 1-3% same formation properties!

Main conclusions

- Collisionless DM dynamics quite well understood

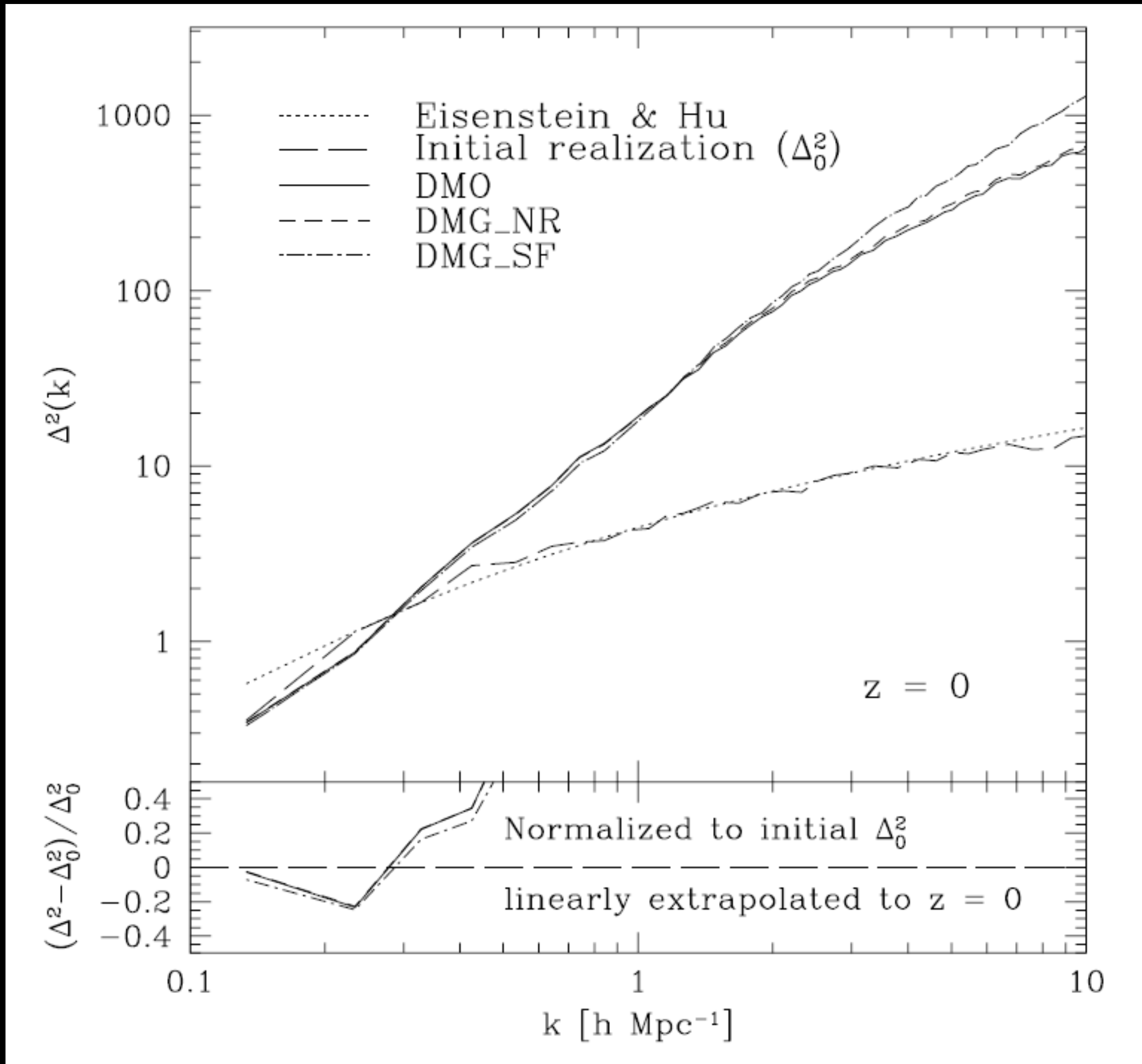
- Baryon dynamics well understood in the simplest cases where the additional (subgrid) physics does not play a major role (first stars, lyman alpha forest, clusters)

- Every result involving semi-analytic (subgrid) modelling is ***questionable***

Unfortunately, to understand the fine details of (cold) dark matter dynamics, ***we need to address the issue of the physics of the baryons.***

The importance of baryons in precision CDM cosmology

Rudd et al. 2008



Formation of the first stars: