Oxford Workshop on DM

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Cosmological Simulations

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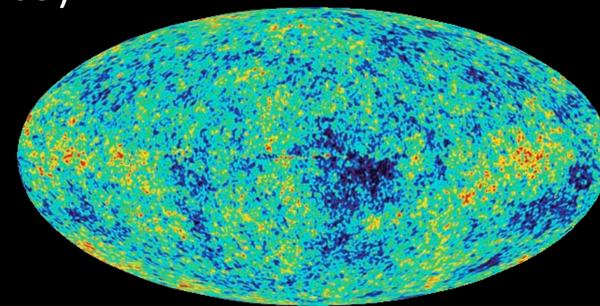
Outline

- Cosmological simulations / resimulations: overview of the problem and solution(s)
- The success story of LCDM on large scales
- Small scale issues: why are predictions for direct/indirect dark matter detection in our neighborhood so hard to obtain/trust?
- Conclusions/Summary

Content of the expanding Universe (Dunkley et al. 2009)



- -Collisionless dark matter : Ω_{DM}=0.20
- -Baryons (gas & stars) : Ω_b=0.04
- -Dark energy : Ω_Λ=0.76

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

$$\frac{\partial \rho_b}{\partial t} + \nabla.(\rho_b \mathbf{u}) = 0$$

Continuity : gas

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}.\nabla).\mathbf{u} = -\nabla\Phi - \frac{\nabla p}{\rho_b}$$

Euler : gas

$$\frac{\partial \varepsilon}{\partial t} + \mathbf{u}.\nabla\varepsilon = -\frac{p}{\rho_b}\nabla.\mathbf{u}$$

Energy : gas

$$p = (\gamma - 1)\varepsilon\rho_b$$

Equation of State : gas

$$\nabla^2\Phi = 4\pi G\left[\int f d^3u + \rho_b\right]$$

Poisson : everything

In fact problem NOT QUITE that simple :

- **Collisionless fluid**: Cold Dark Matter & star particles
  → Vlasov-Poisson : we know quite well how to do that

- **Collisional fluid**: gas heated & cooled radiatively (atomic, molecular)
  → Euler-Poisson + homogeneous radiative cooling & heating + chemistry: we sort of know (with light elements (no stars))

- **BUT 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…: we don't understand how to model this (yet?)!

Collisionless part: facts

$$\frac{d\mathbf{x}_p}{dt} = \mathbf{u}_p$$
$$\frac{d\mathbf{u}_p}{dt} = -\nabla\Phi$$

- The fluid is represented by particles : concept of mass resolution, discretization

- 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

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 cloud carrying the hydrodynamical informations (density, pressure, temperature, velocity, etc)

→ TreeSPH (e.g. GADGET -- Springel et al. 2001)

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

→ AMR hydro codes (e.g. RAMSES -- Teyssier 2002)

Additional physics : facts

- Stars form and supernovae explode in galaxies, supermassive black holes 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.

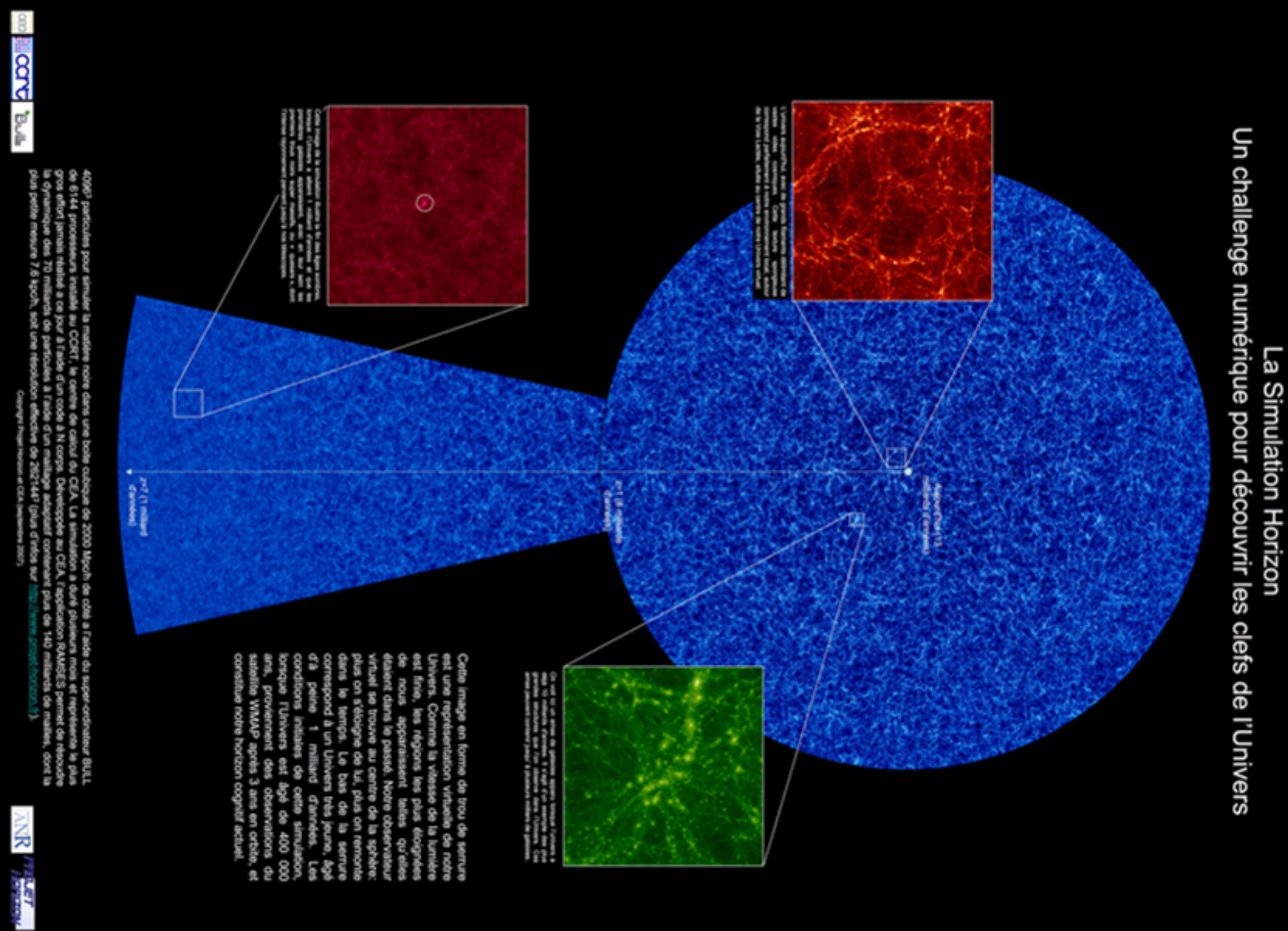
Additional physics : methods

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

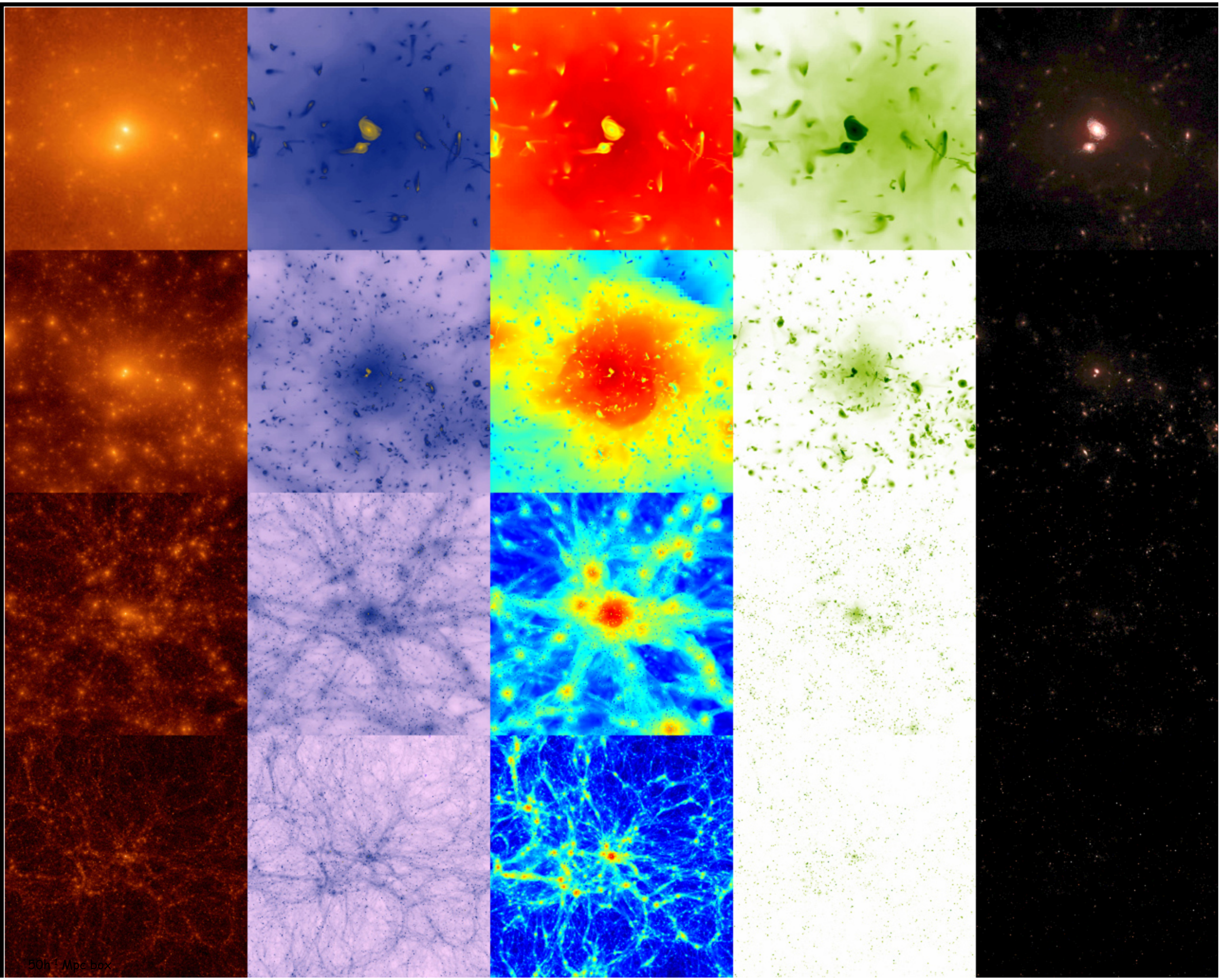
- full semi-analytic modeling of baryonic physics in pure dark matter simulations (e.g. Kauffmann et al 1999, Hatton et al 2003)

Example of a large scale DM simulation:

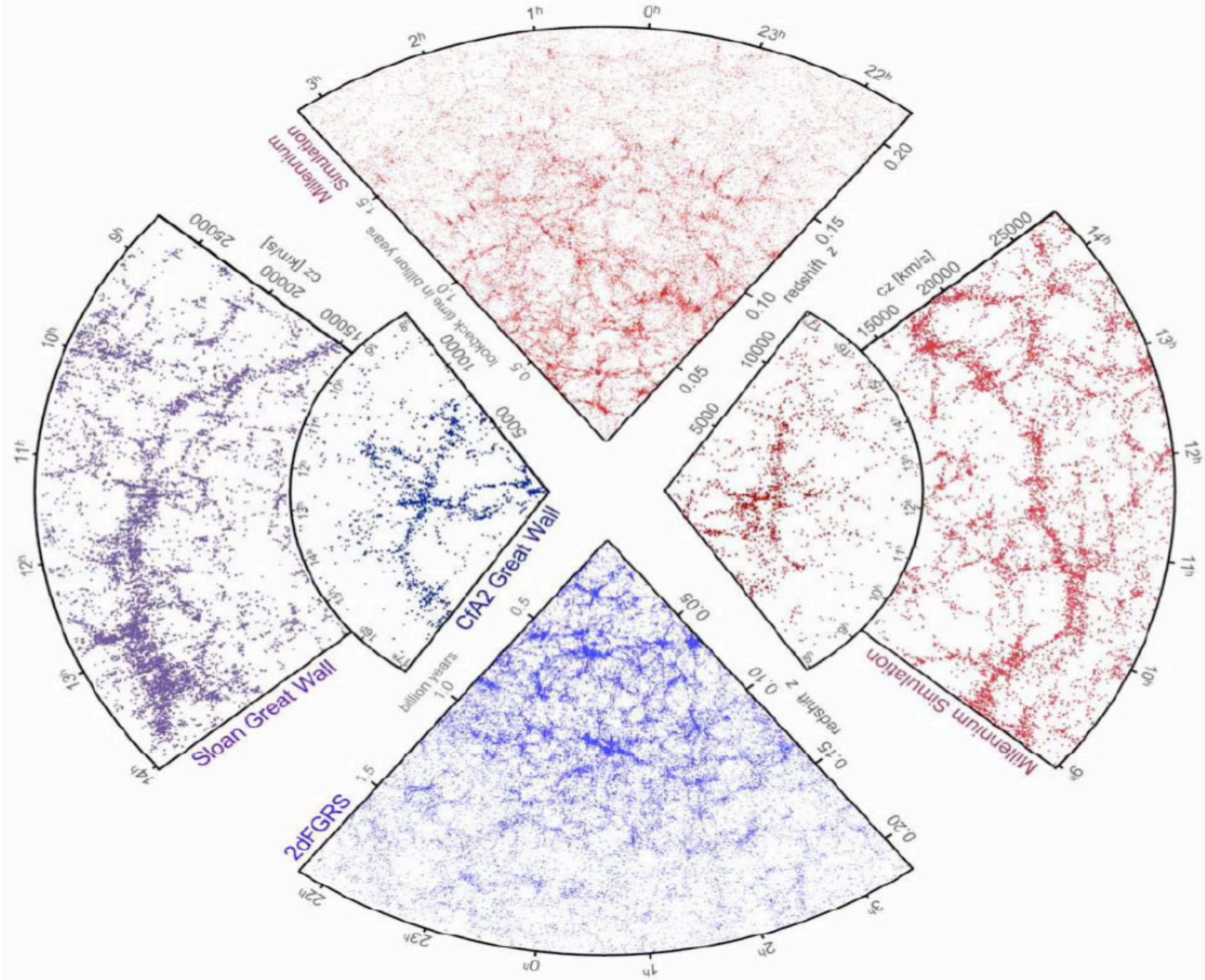
HORIZON 4Π: 4096^3 particles in $2000h^{-1}$ Mpc box

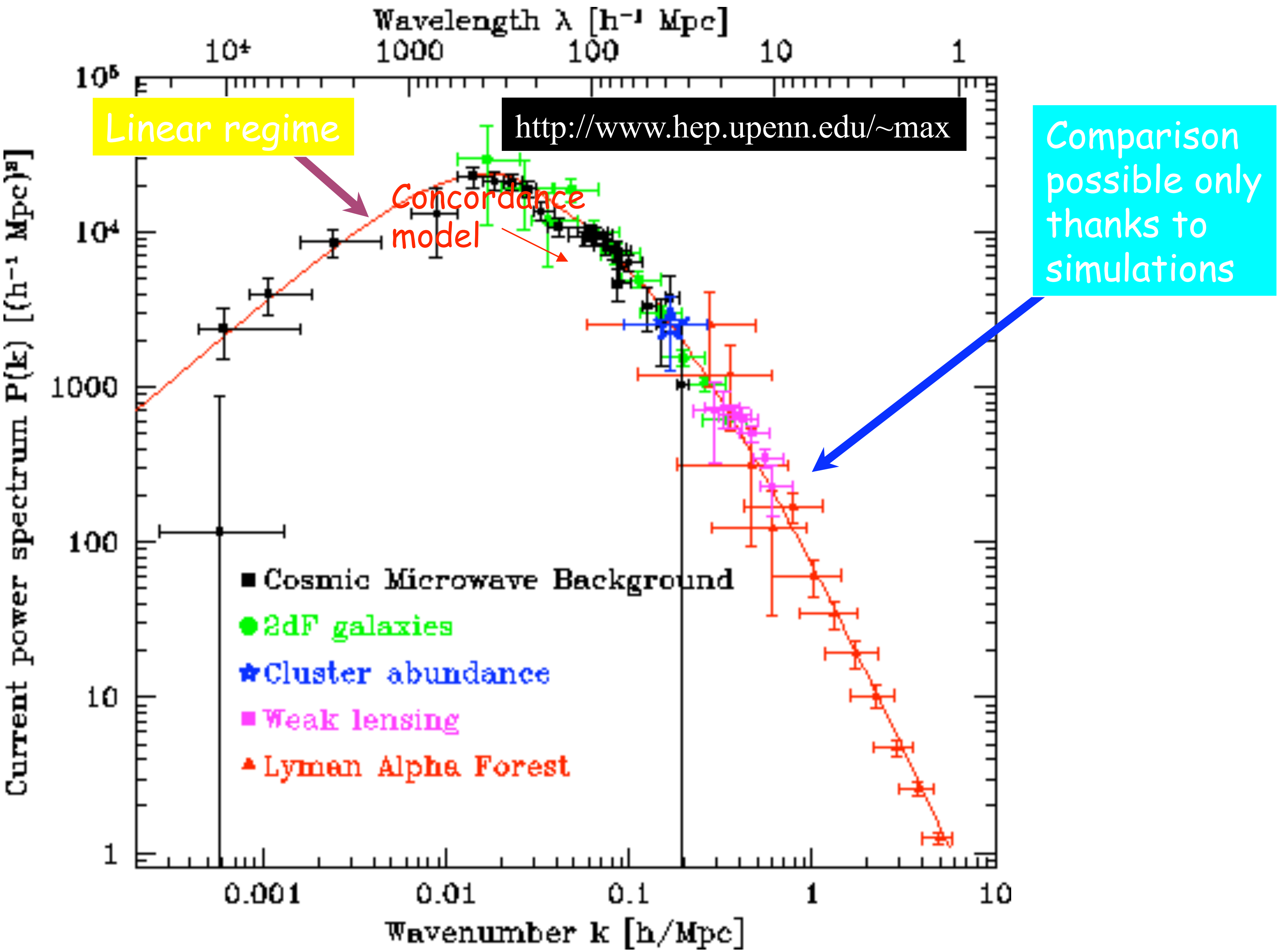


Example : The Mare Nostrum 1024^3 AMR hydro simulation

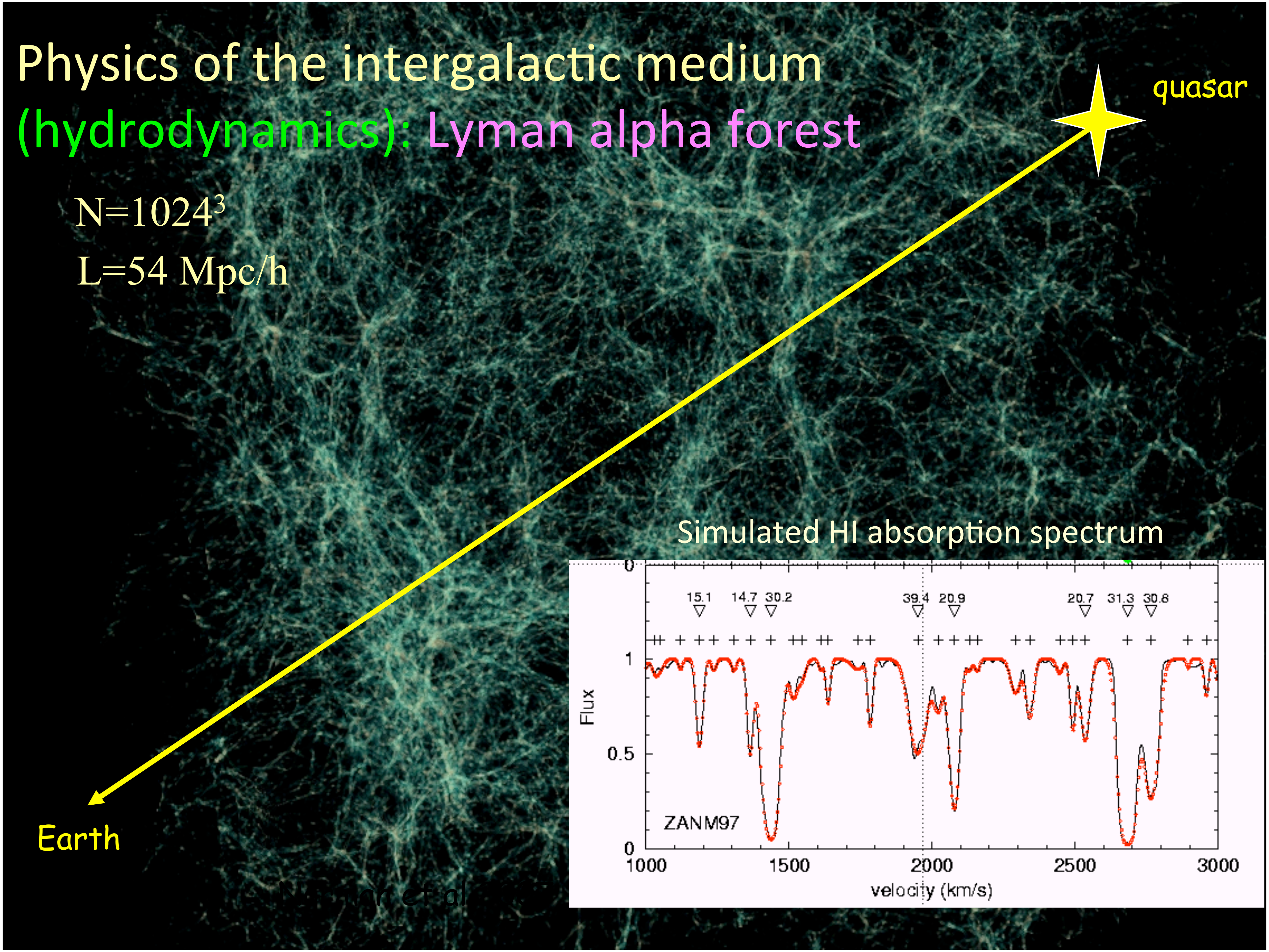


Main success of CDM to reproduce large scale structures a.k.a. galaxy clustering





Wavelength λ [h⁻¹ Mpc]
10⁴
1000
100
10
1
10⁵
10⁴
1000
100
10
1
Current power spectrum P(k) [(h⁻¹ Mpc)³]
0.001
0.01
0.1
1
10
Wavenumber k [h/Mpc]
Linear regime
http://www.hep.upenn.edu/~max
Concordance model
Comparison possible only thanks to simulations
Cosmic Microwave Background
2dF galaxies
Cluster abundance
Weak lensing
Lyman Alpha Forest

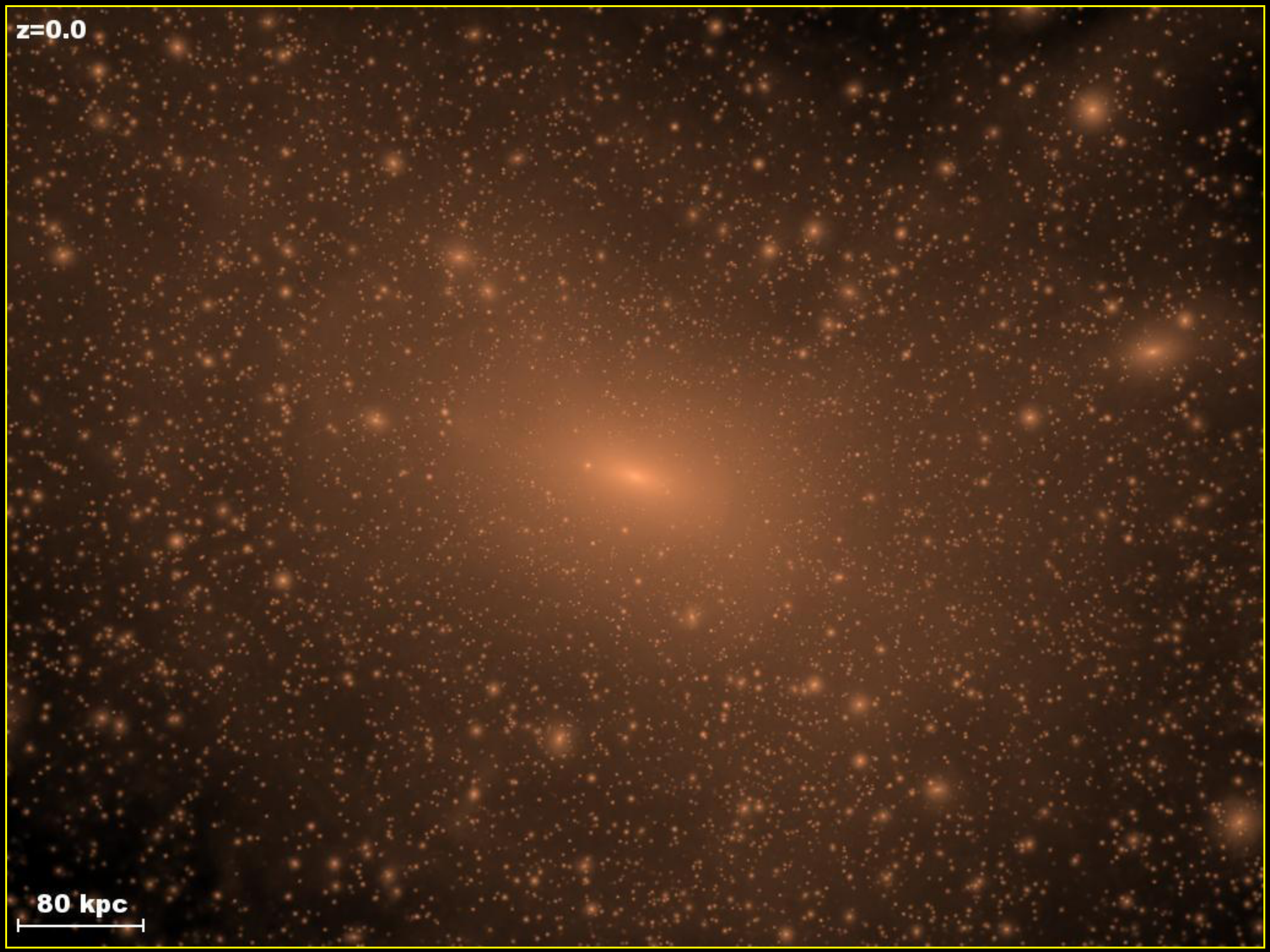

Physics of the intergalactic medium
(hydrodynamics): Lyman alpha forest
N=1024³
L=54 Mpc/h
quasar
Earth
Simulated HI absorption spectrum
15.1
14.7
30.2
39.4
20.9
20.7
31.3
30.8
Flux
0
0.5
1
ZANM97
1000
1500
2000
2500
3000
velocity (km/s)

Small Scales = Big Deal for LCDM?

4 main problems (possibly correlated):

- Number of satellites
- Cuspiness of density profile
- Initial conditions for local predictions
- ***Baryons*** ????

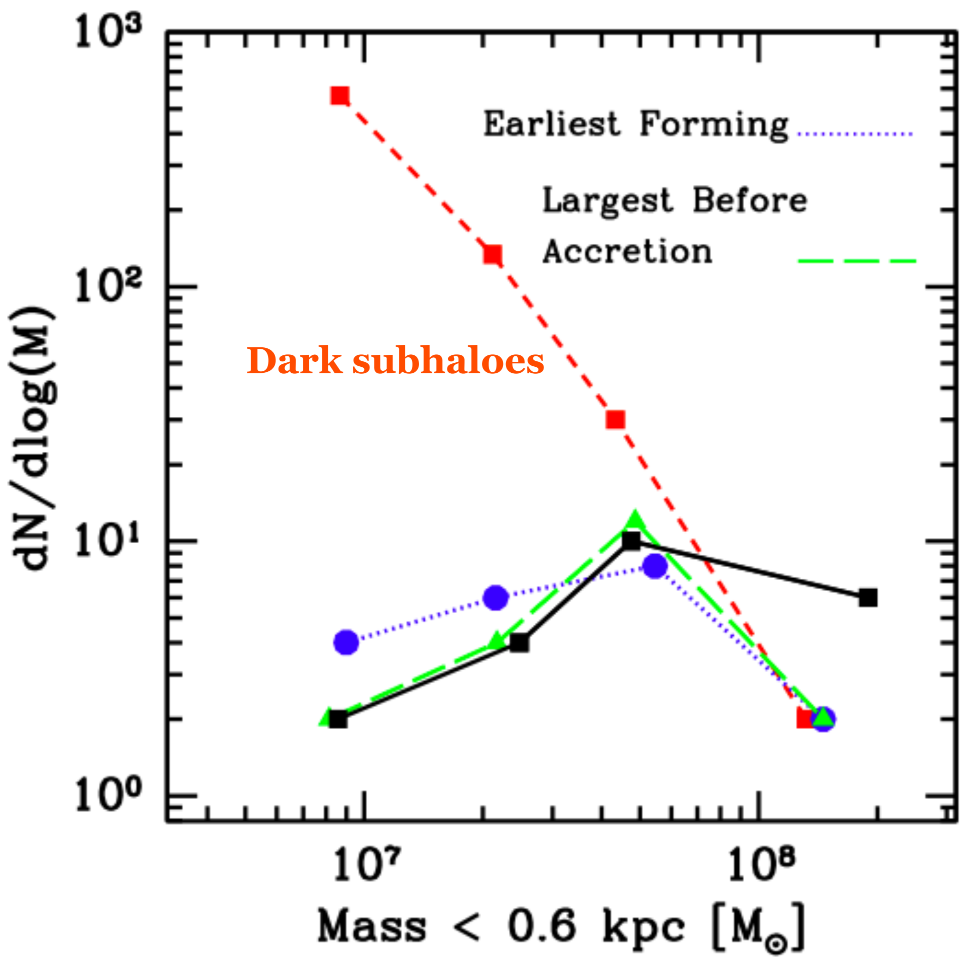
Substructures in CDM haloes:



Via Lactea simulation (J. Diemand & al, 2006) but also Aquarius (Springel et al 2008) and GHALO (Stadel et al 2009)

The CDM substructure problem seen in simulations

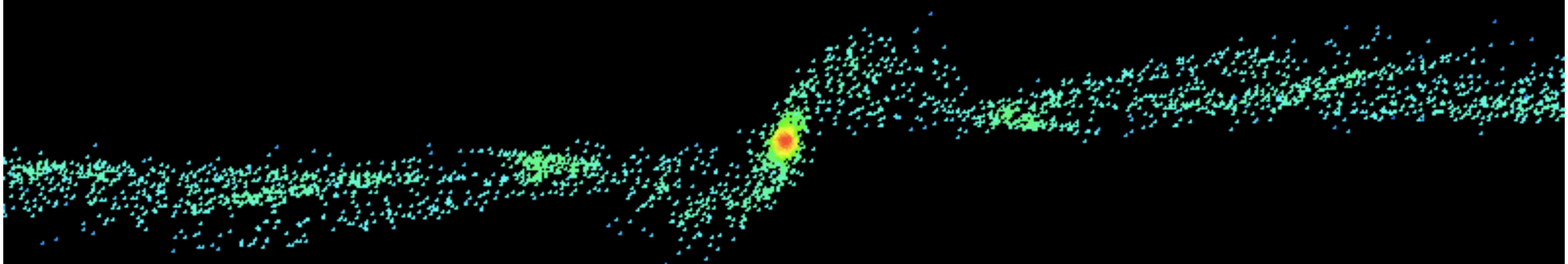
e.g. Strigari et al. 2007



Clue on nature of DM?

Lovell et al 2012 CDM vs WDM

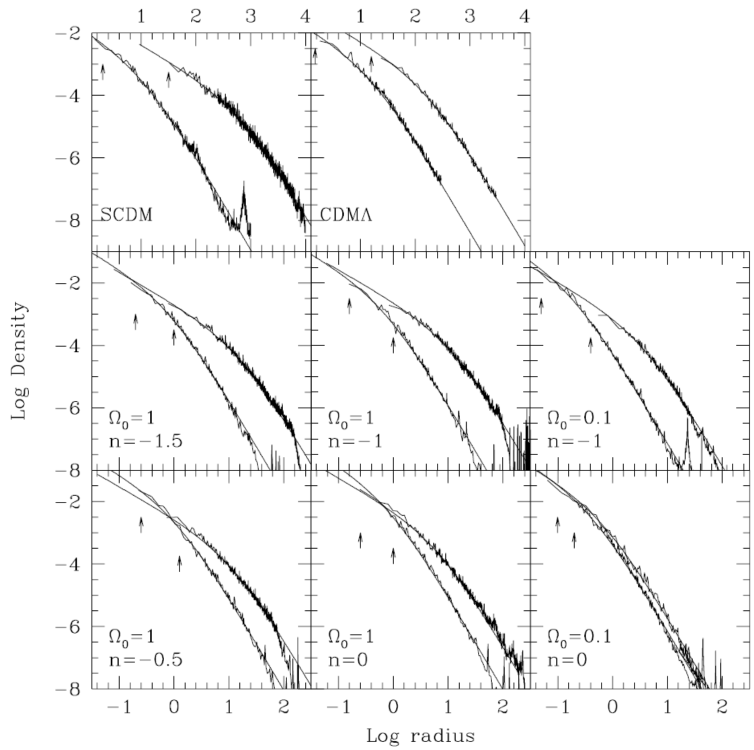
However even micro-halos ($< 10^{-3} M_{sun}$) can be destroyed by disk (baryons) potential !

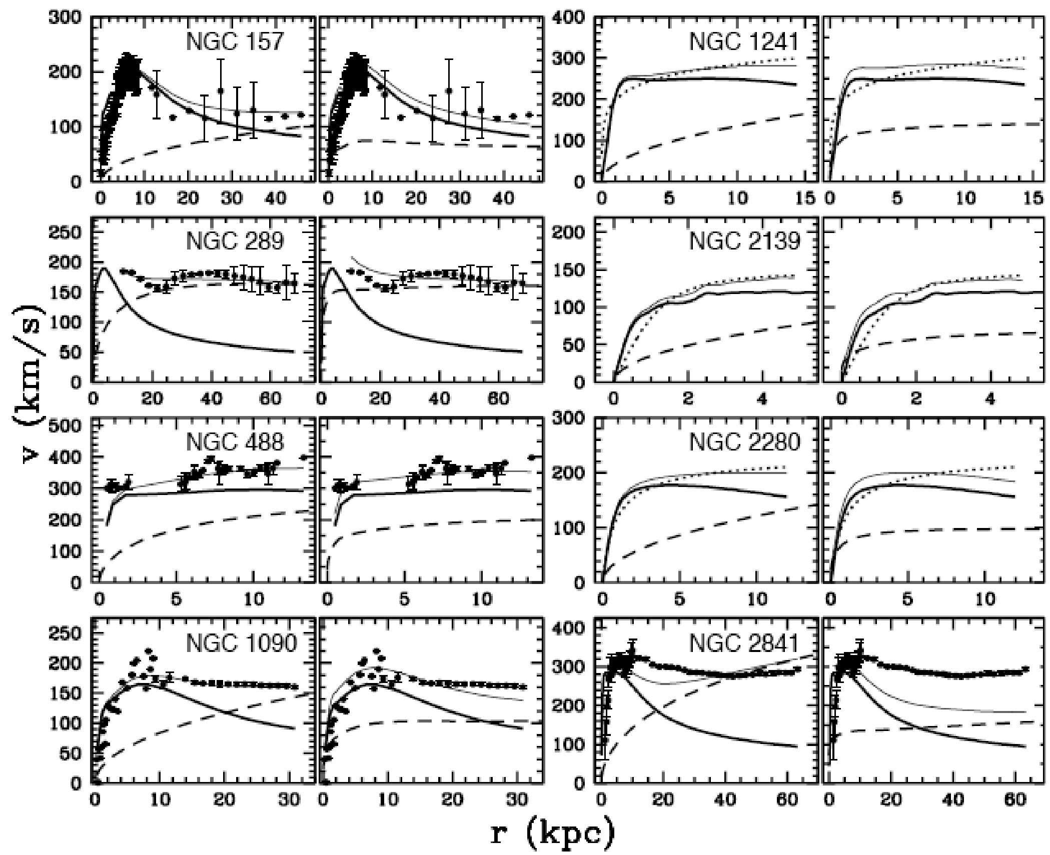


e.g. Schneider et al 2011

And anyways cusp of host (MW) halo still present!

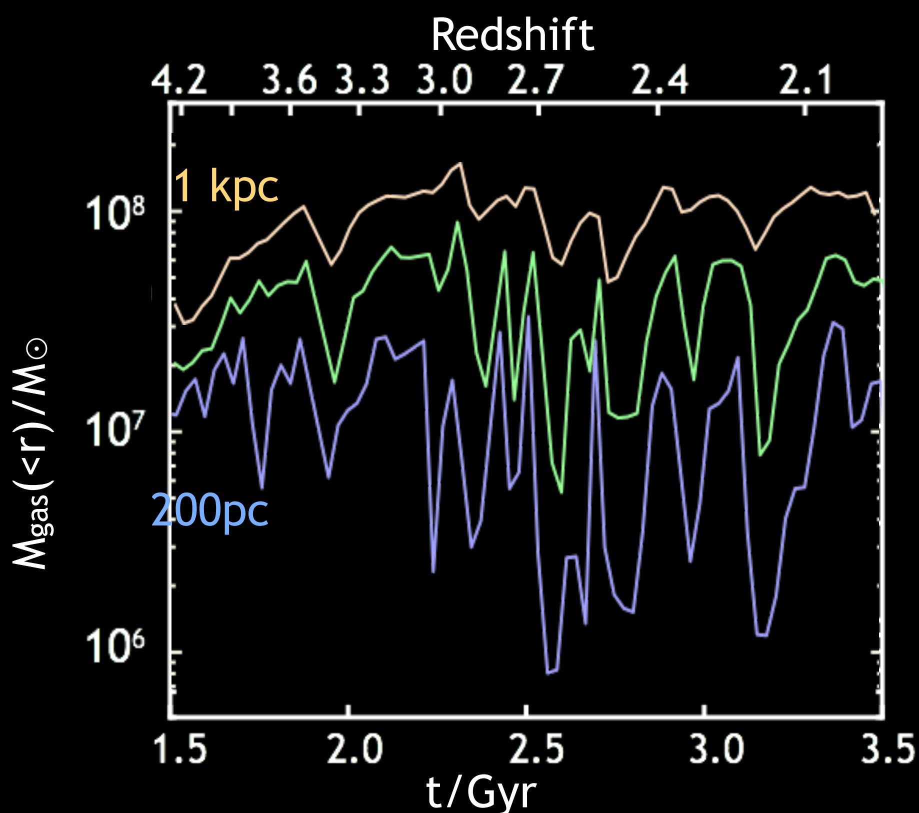
NFW halo profiles
(Navarro et al. 1996)

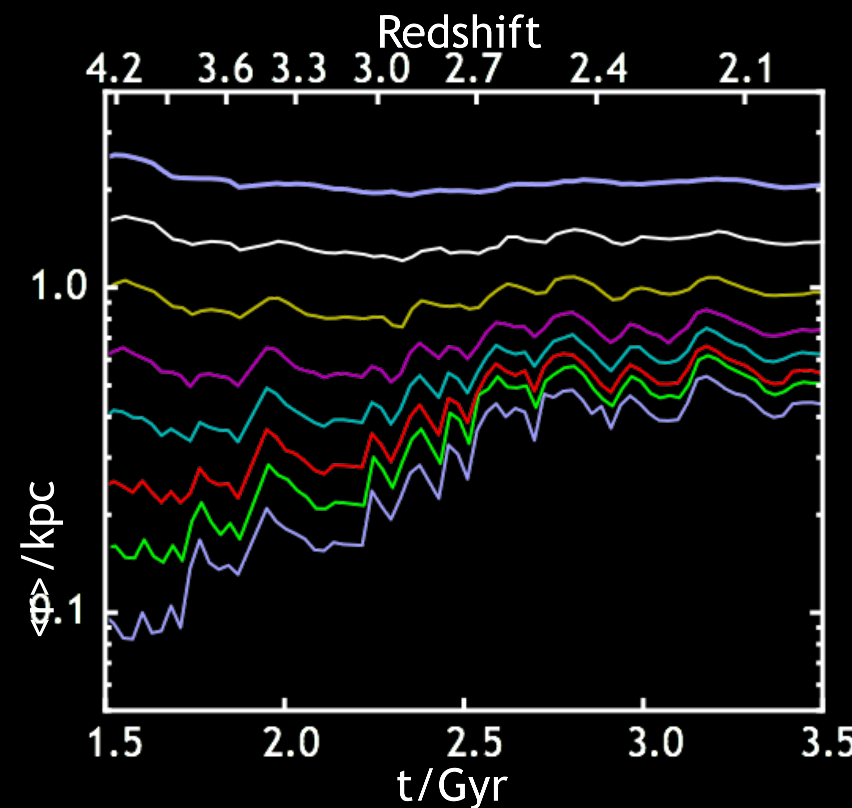




the rotational velocity curves of galaxies: Kassin et al 2006 →

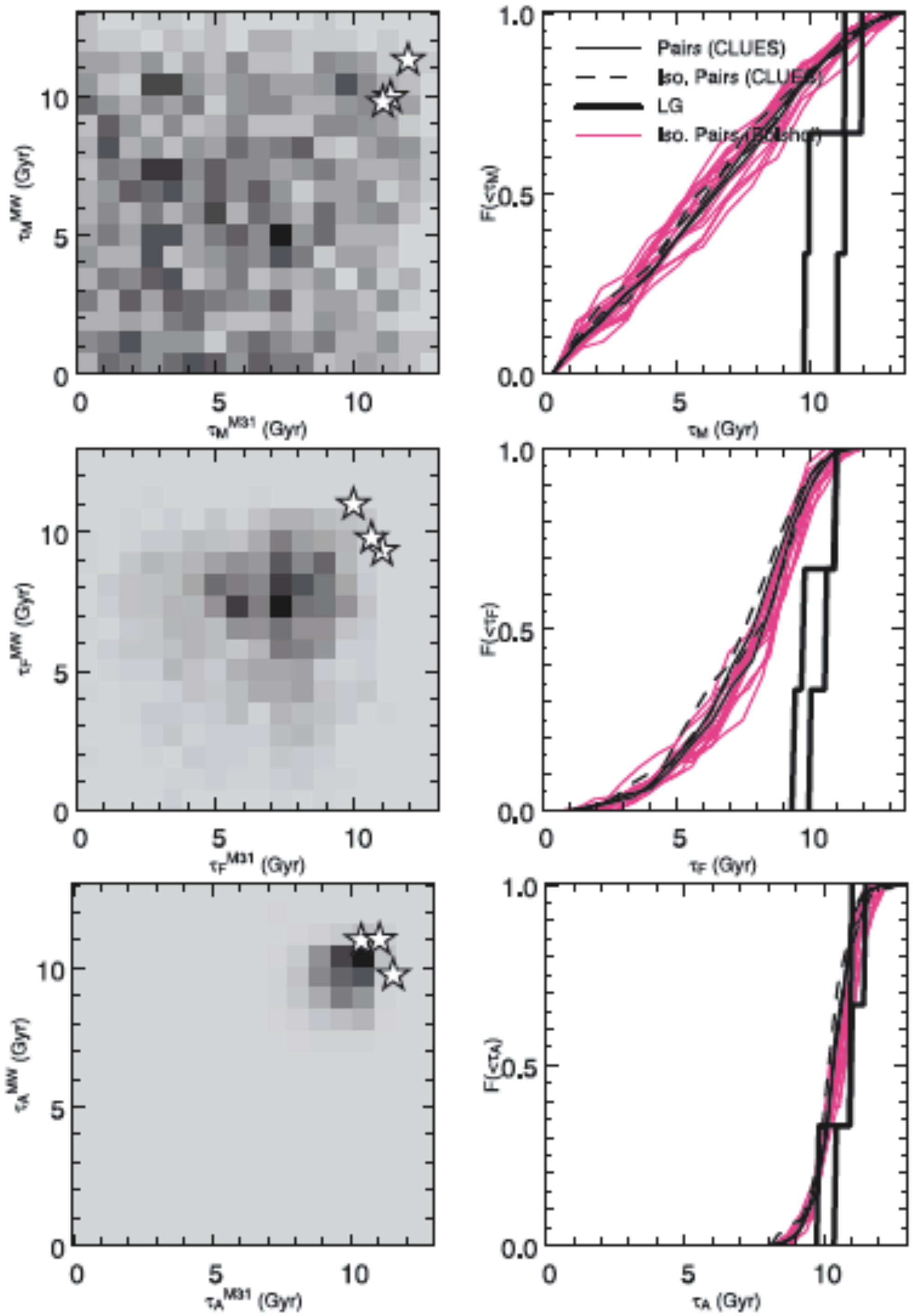
Observations show inner regions of galaxies with lower concentrations than predicted by **pure** N-body simulations and adiabatic contraction due to baryons makes things worse except if strong feedback.





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

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



Initial conditions: how typical is the MW halo?

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!

Conclusions / Summary

- Collisionless DM dynamics quite well understood and we note that LCDM structure formation models seem to work very well on large scales where DM is expected to dominate.

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

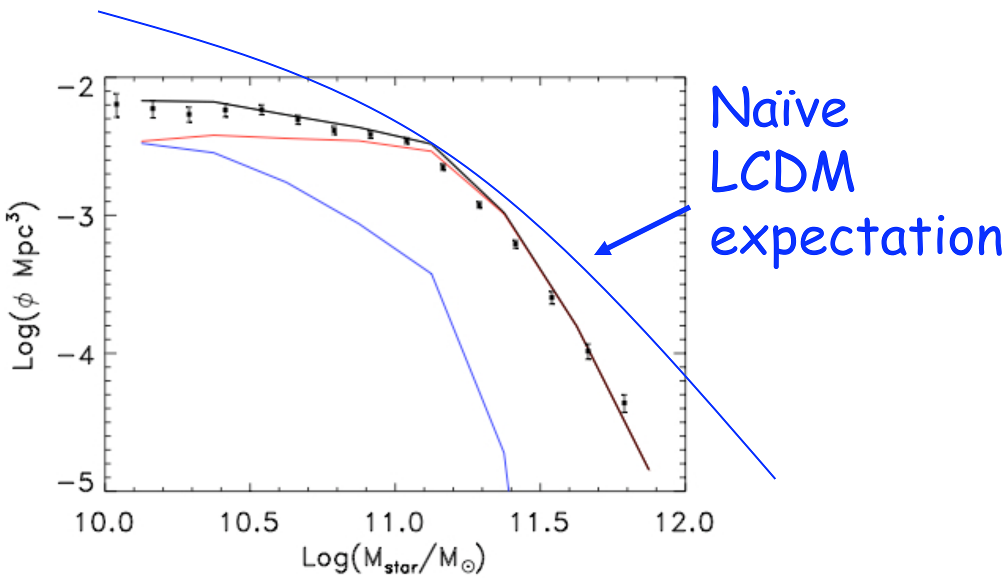
- Every result involving semi-analytic (subgrid) modelling is ***questionable and should be questioned*** but nevertheless these approaches (as crude as they may still be) have the merit to point out that there exist plausible solutions to the CDM structure formation "crisis" on small scales which do not involve exotic new physics.

Unfortunately and inevitably, this means that to understand the fine details of non linear (cold) dark matter dynamics, ***we absolutely need to address the issue of the physics of the baryons.***

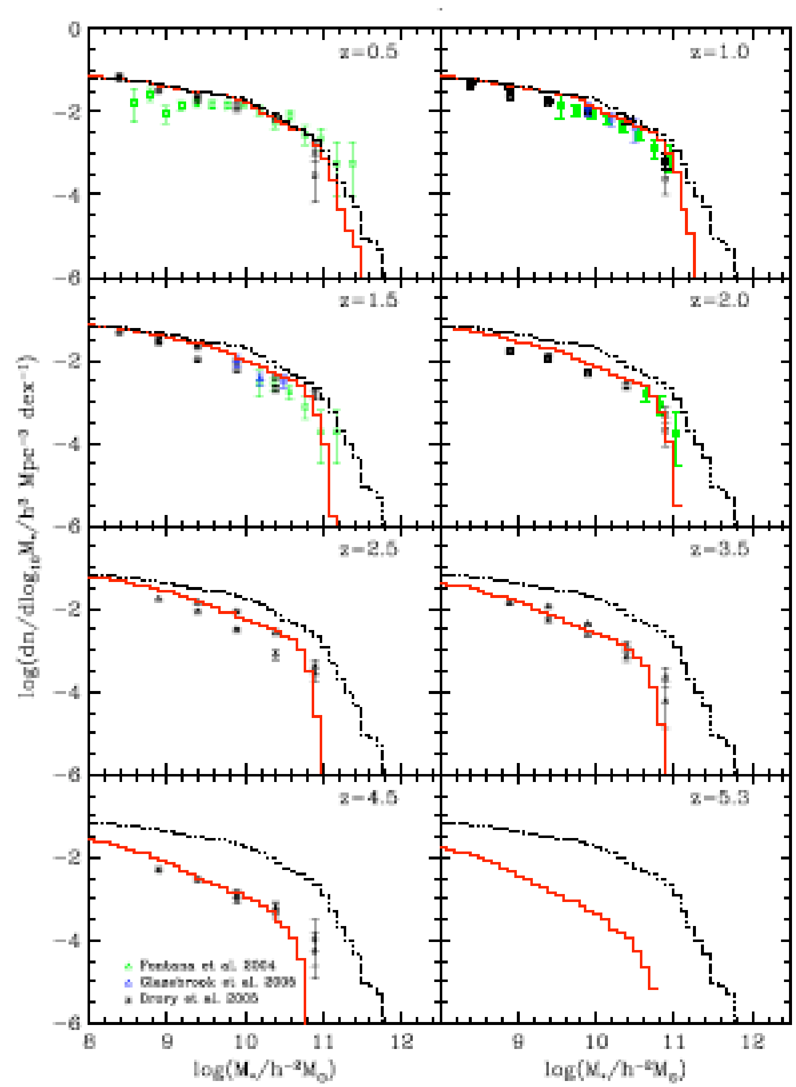
Other problems (and possible baryonic solutions) in LCDM galaxy formation models

Galaxy stellar mass functions at high and low z

Bell et al 03 K-band determination



« 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