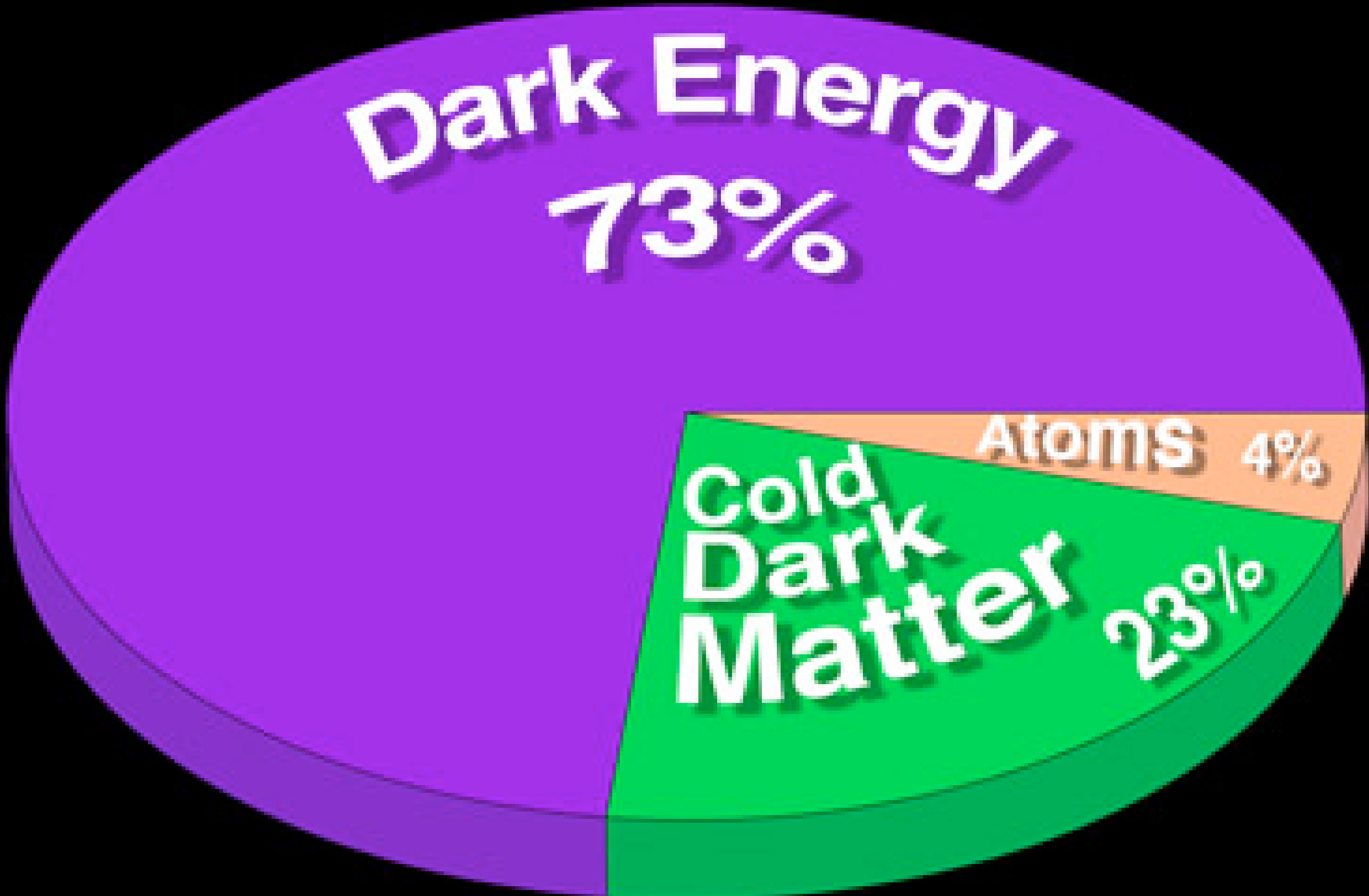
outline

- Basics of standard cosmological model
- Constraints on the model
- Anomalies: merging rate, giant galaxies, reionization epoch, voids, etc
- Remedy: scalar interaction in the dark sector

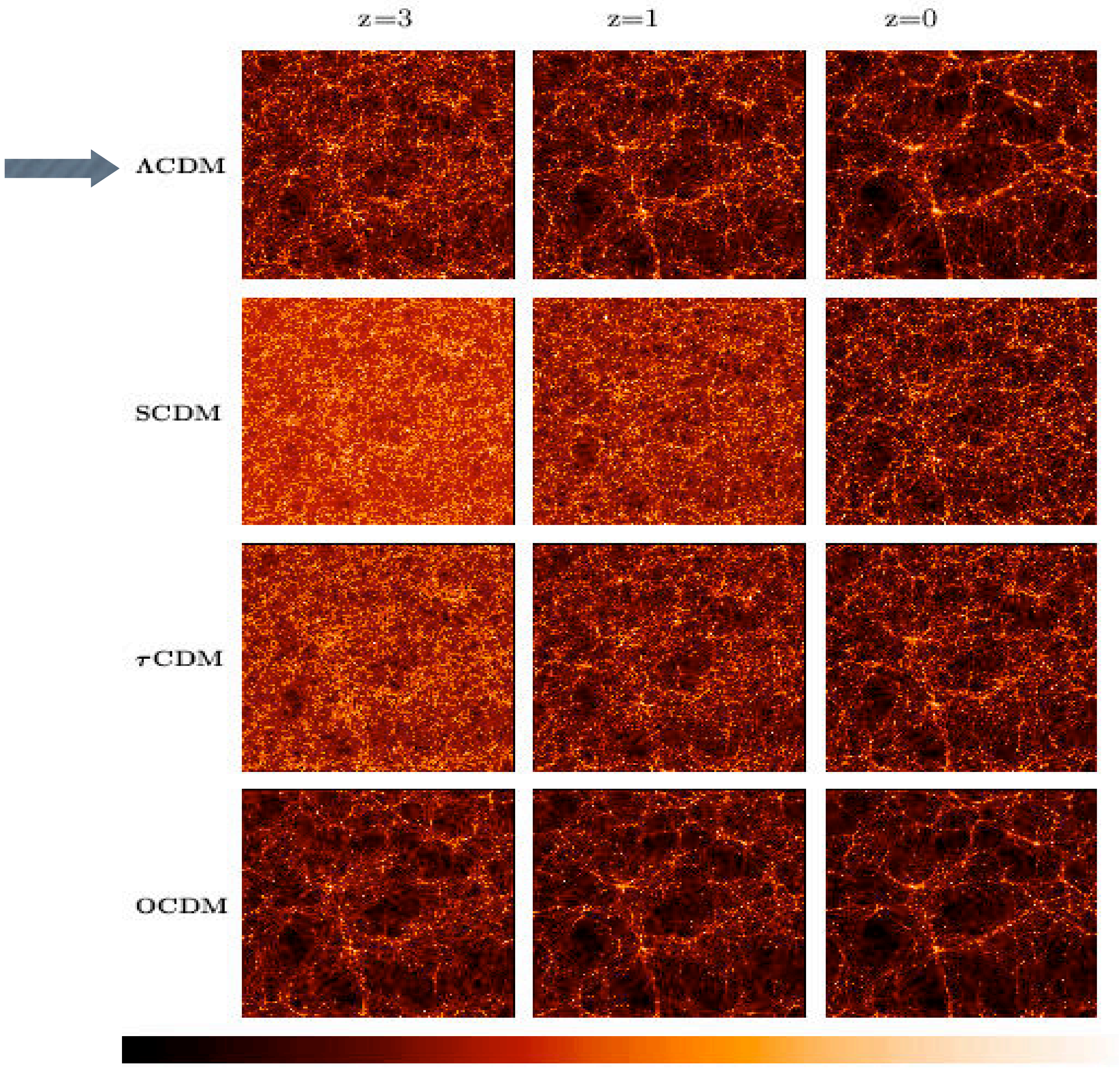
Collaborators:

Steve Gubser (Princeton)

Jim Peebles (Princeton)

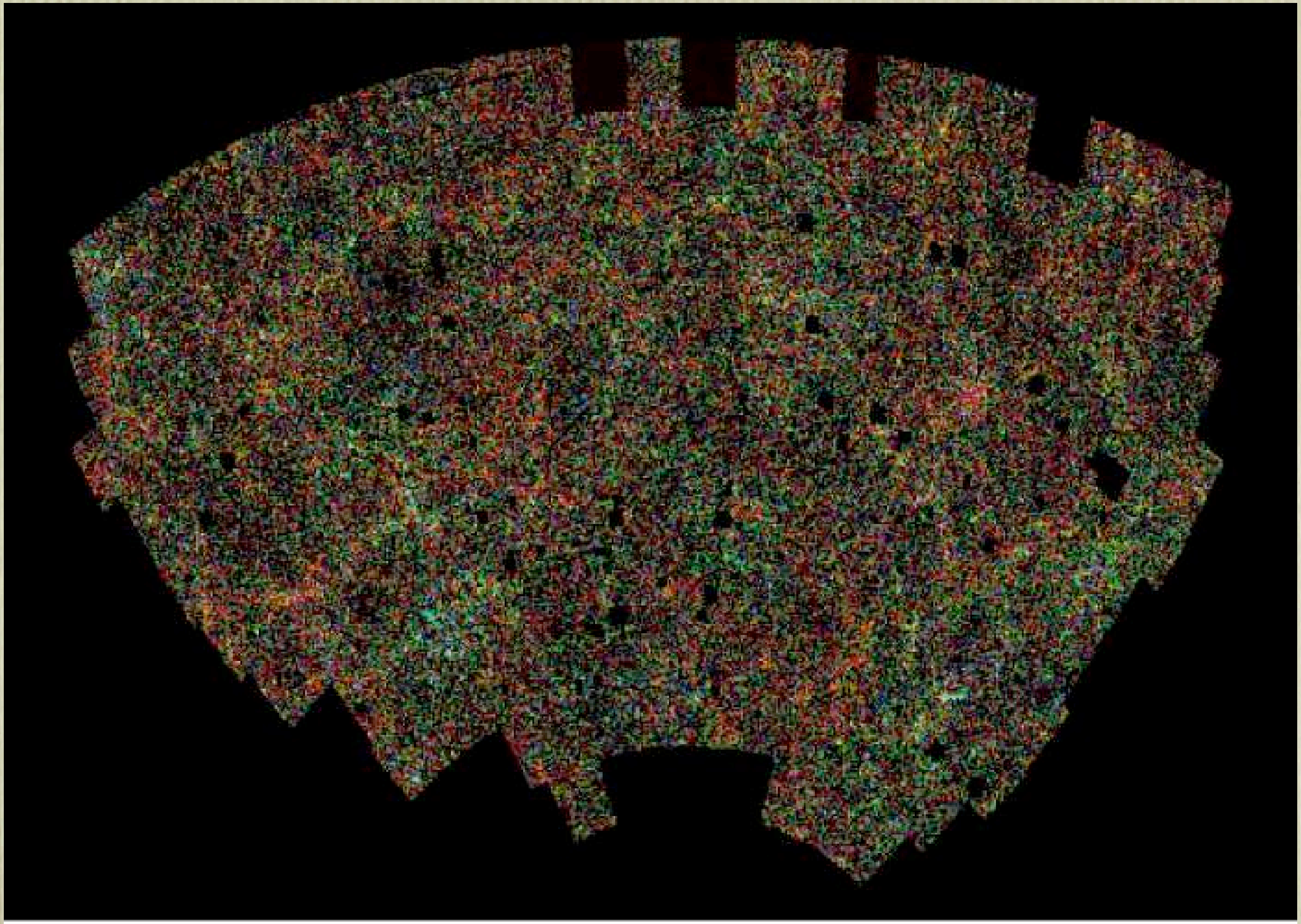

Dark Energy
73%
Atoms 4%
Cold
Dark
Matter
23%

Vacuum energy dominated universe



The VIRGO Collaboration 1996

The galaxy distribution are the traditional probes of the power spectrum

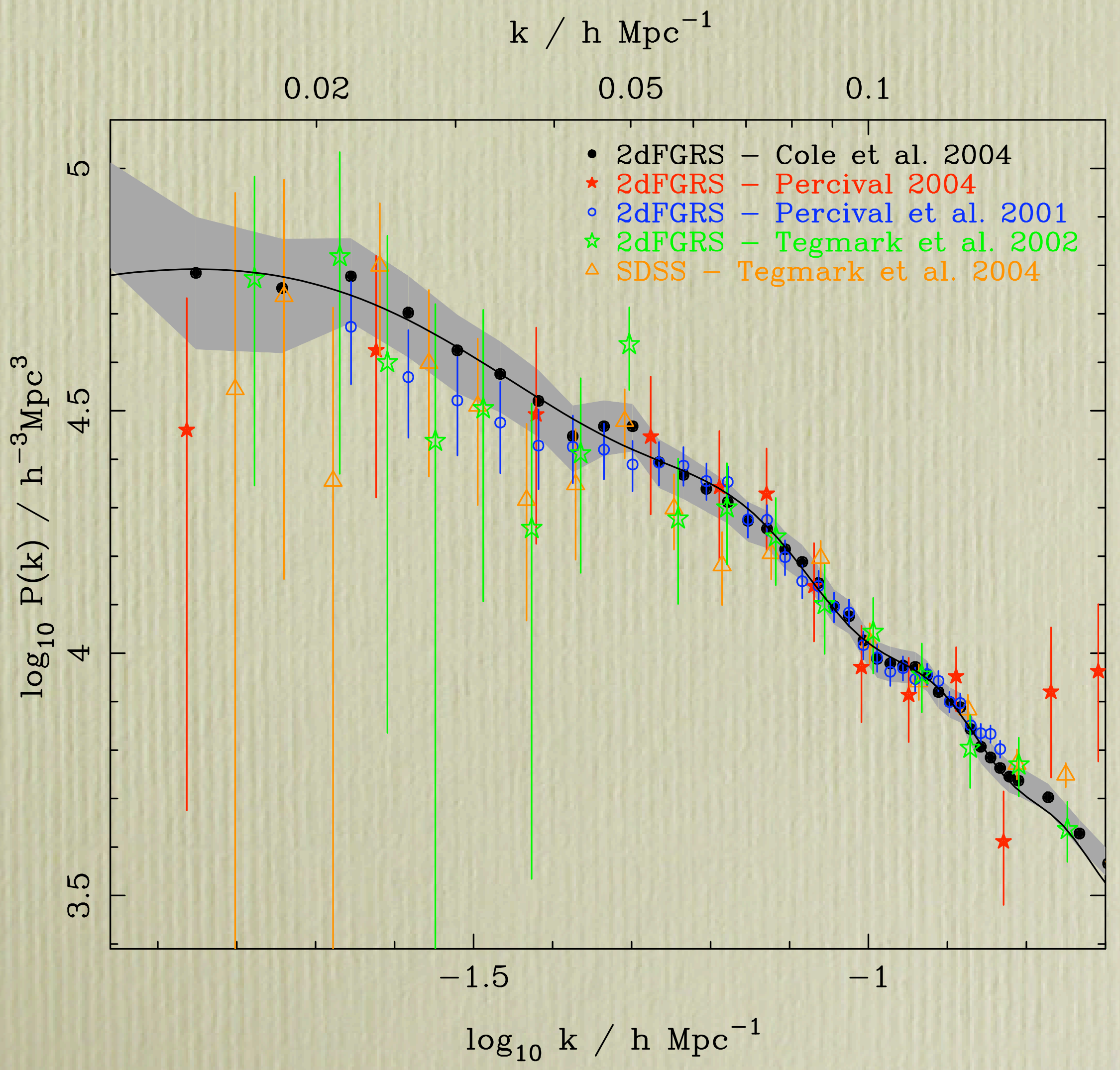


APM Survey picture of a large part of the sky, about 30 degrees across, showing almost a million galaxies out to a distance of about 2 billion light years.

MAP990047

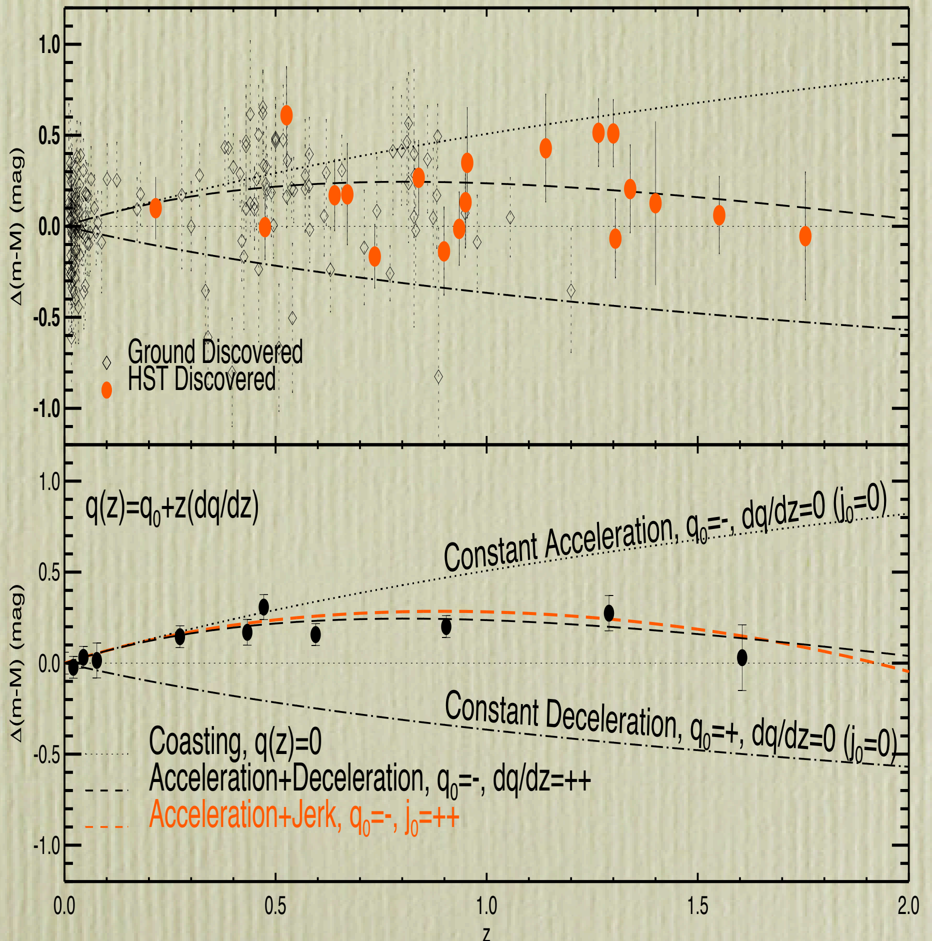
The 2dF Galaxy Redshift Survey: Power-spectrum analysis of the final dataset and cosmological implications

Shaun Cole[1], Will J. Percival[2], John A. Peacock[2], Peder Norberg[3], Carlton M. Baugh[1], Carlos S. Frenk[1], Ivan Baldry[4], Joss Bland-Hawthorn[5], Terry Bridges[6], Russell Cannon[5], Matthew Colless[5], Chris Collins[7], Warrick Couch[8], Nicholas J.G. Cross[4,2], Gavin Dalton[9], V.R. Eke[1], Roberto De Propris[10], Simon P. Driver[11], George Efstathiou[12], Richard S. Ellis[13], Karl Glazebrook[4], Carole Jackson[14], Adrian Jenkins[1], Ofer Lahav[15], Ian Lewis[9], Stuart Lumsden[16], Steve Maddox[17], Darren Madgwick[12], Bruce A. Peterson[11], Will Sutherland[12], Keith Taylor[13] (The 2dF-GRS Team)

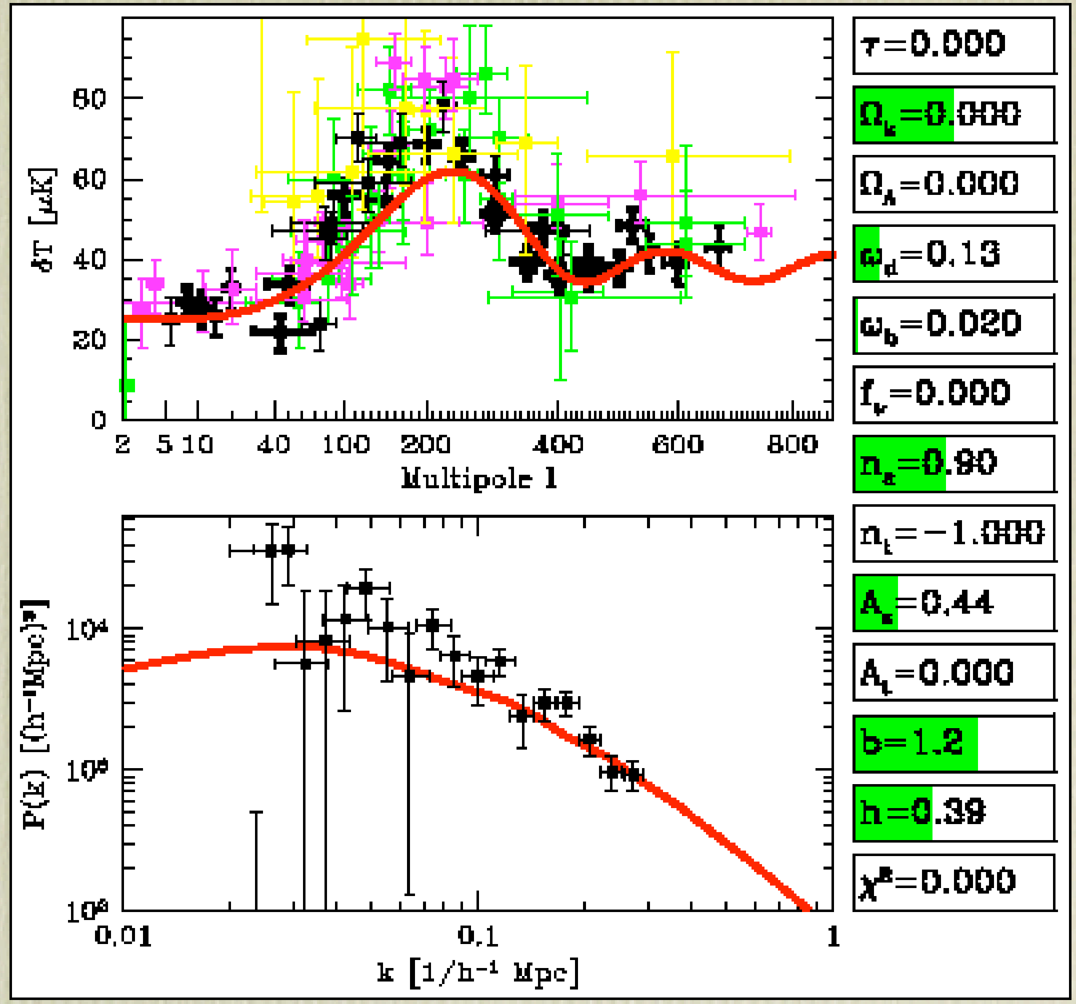


$$\Omega_m = 0.231 \pm 0.021$$
$$\Omega_b = 0.042 \pm 0.002$$
$$h = 0.766 \pm 0.032$$
$$n_s = 1.027 \pm 0.050.$$

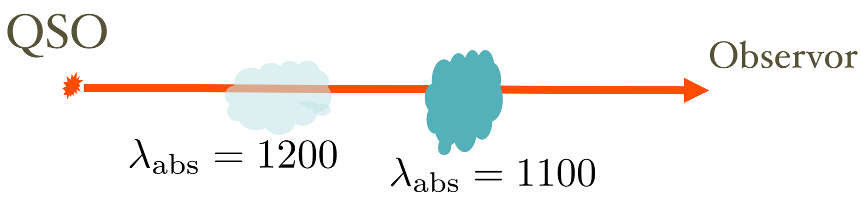
High z SN Search (Riess et. al. 2004)

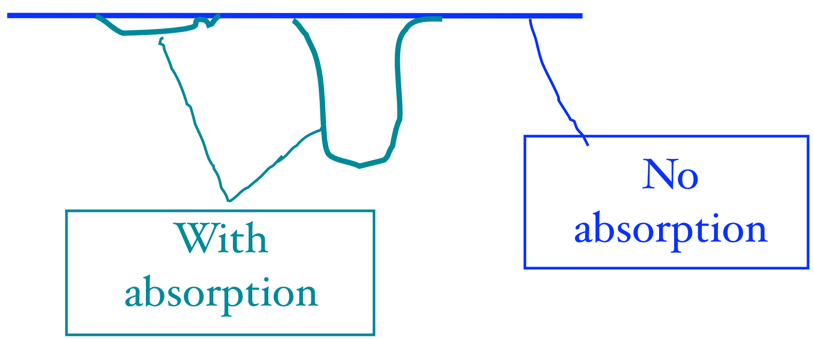


The cosmic microwave background 2dF power spectrum

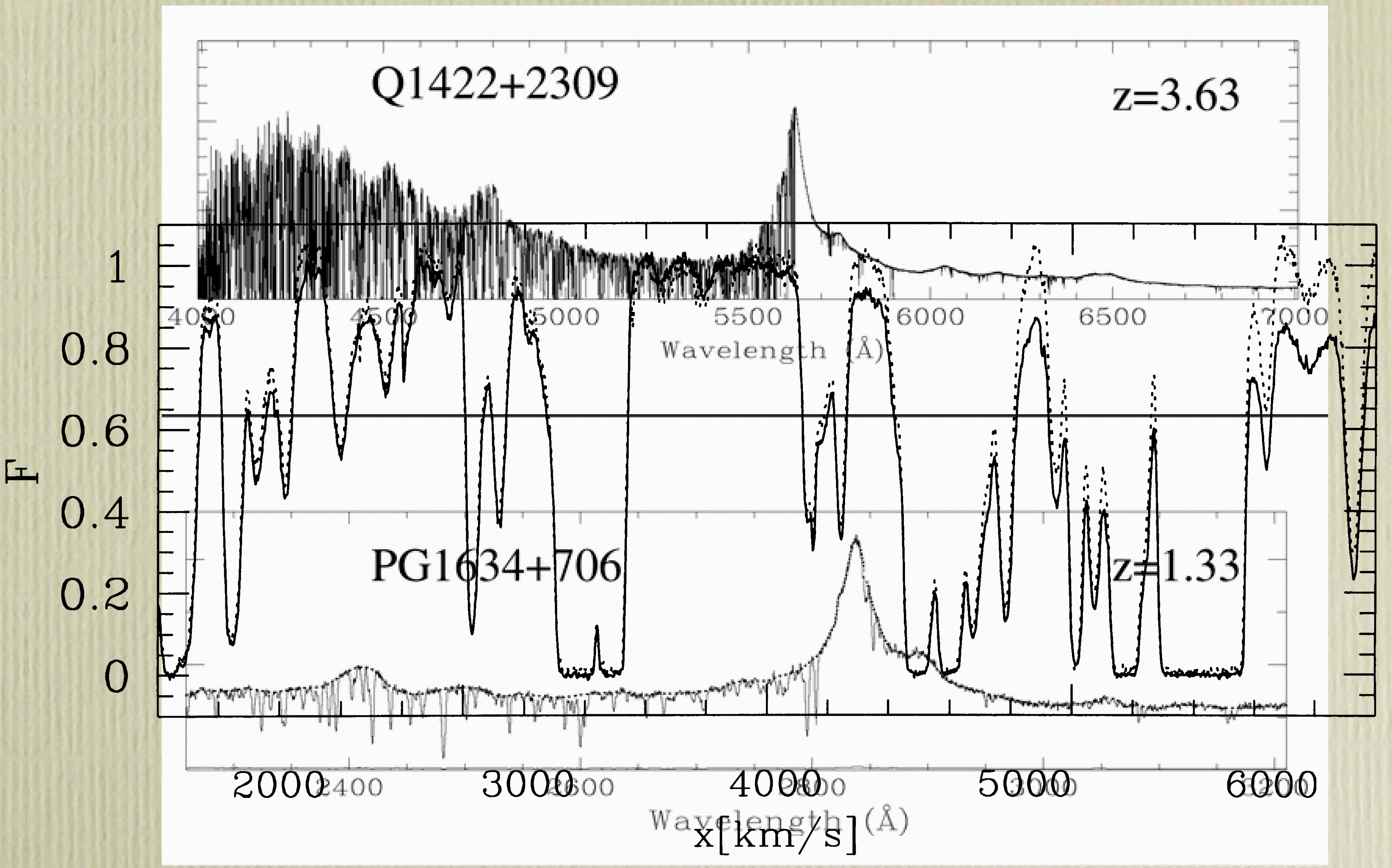


Cosmology with the Ly-alpha forest

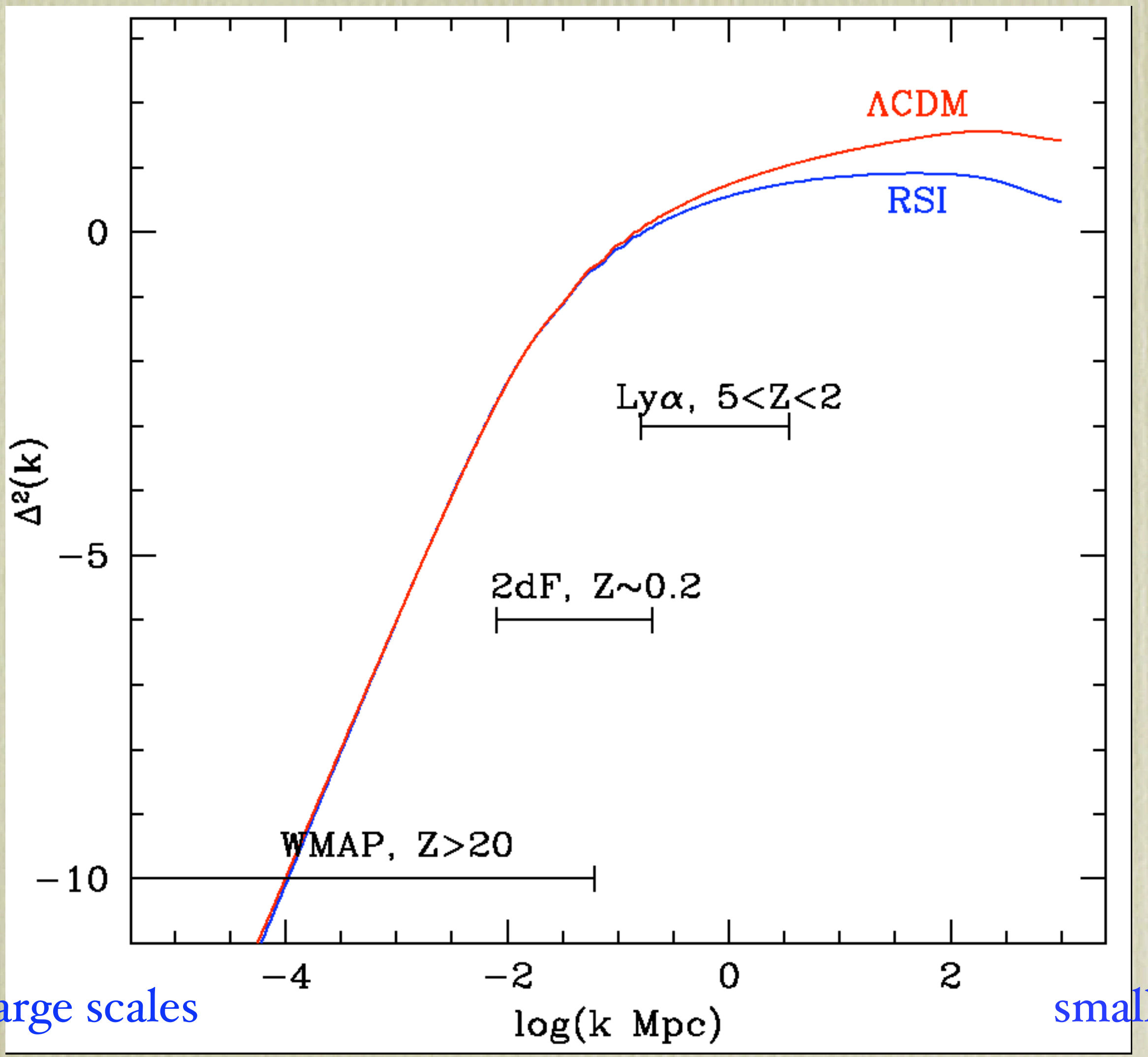




$$F = \exp(-\tau) \; , \quad \tau \propto n_{HI}$$


Q1422+2309
z=3.63
4000
4500
5000
5500
6000
6500
7000
Wavelength (Å)
PG1634+706
z=1.33
2400
2600
2800
3000
3200
Wavelength (Å)
1
0.8
0.6
0.4
0.2
0
F
2000
3000
4000
5000
6000
x[km/s]

Models, scales, redshifts



large scales

small scales

ignorance

Joint modeling of the probability distribution and power spectrum of the Lyα forest : comparison with observations at $z = 3$

Vincent Desjacques[1] and Adi Nusser[1,2]

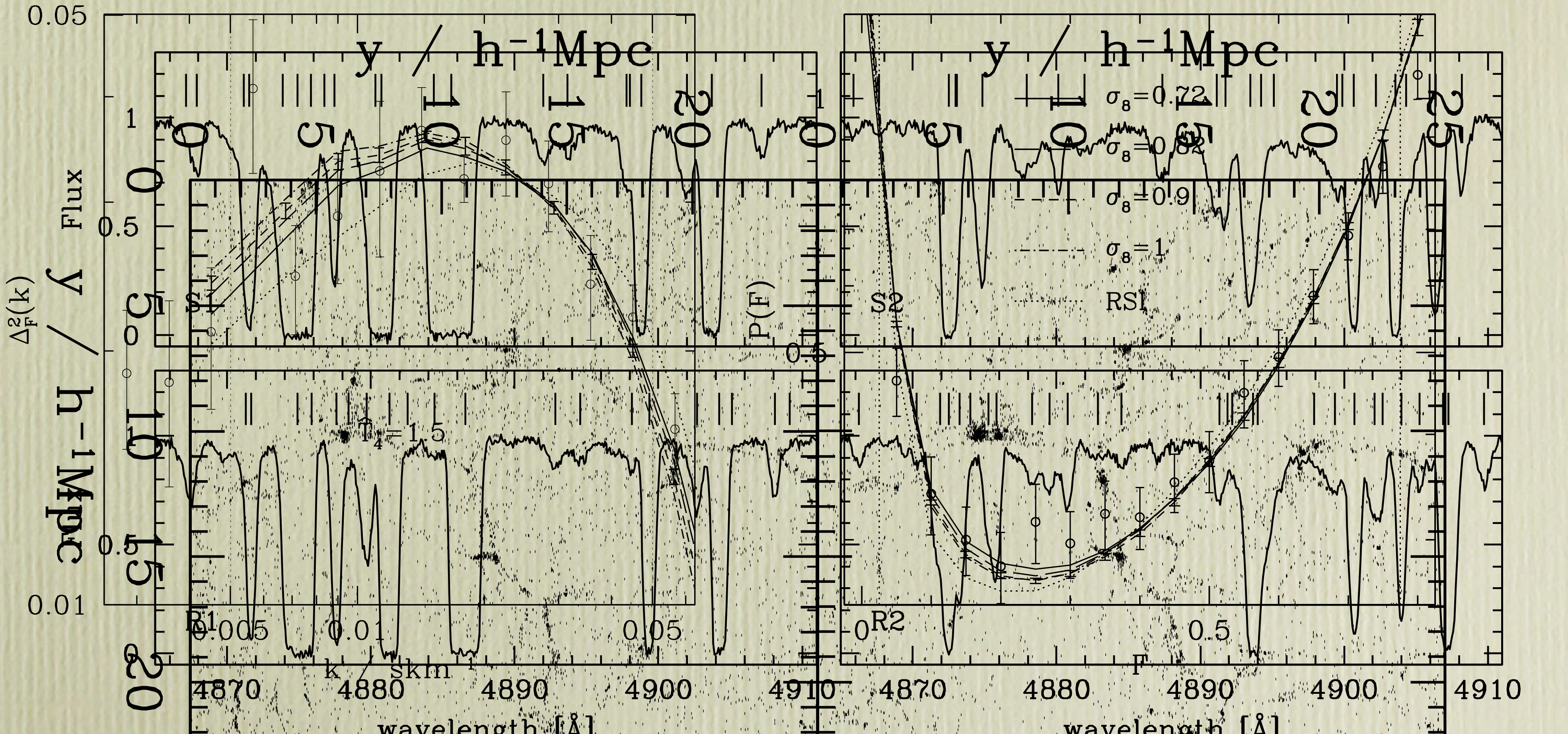
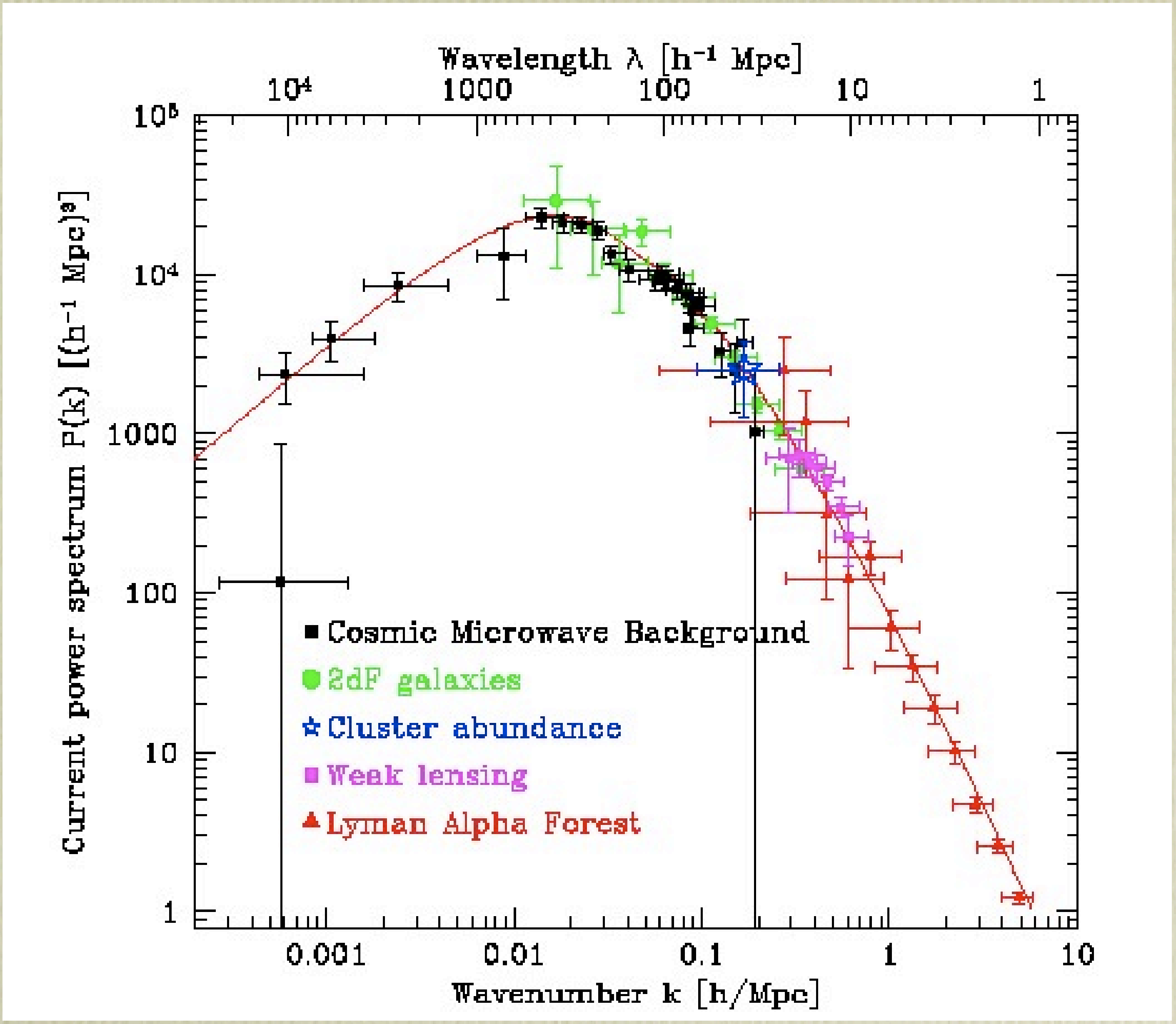


Figure 7. A comparison between the flux PS (left panel) and PDF (right panel) of scale-invariant models with rms density fluctuation $\sigma_8 = 0.72$ (solid), 0.82 (long-dashed), 0.9 (short dashed) and 1 (dashed-dotted curve). The RSI model is shown as dotted curves. All the models have a temperature $T_4 = 1.5$. The errorbars attached to the model with σ_8 show our estimate of the cosmic variance error (cf. text).

Figure 2. Synthetic spectra extracted from each of the simulations at $z = 3$. The vertical bars above the spectra show the position of the lines with fitted column densities $N_{\rm HI}$ exceeding $10^{12.5}$ cm^2. The comoving length of each spectrum is $L = 25\ h^{-1}$Mpc, which corresponds to a redshift interval $\Delta z \sim 0.04$ at $z = 3$.

“Concordance” model fits the power spectrum data



credit: Garcia-Bellido 02

Anomalies of the ΛCDM model

ΛCDM tends to produce too much merging at $z < 1$

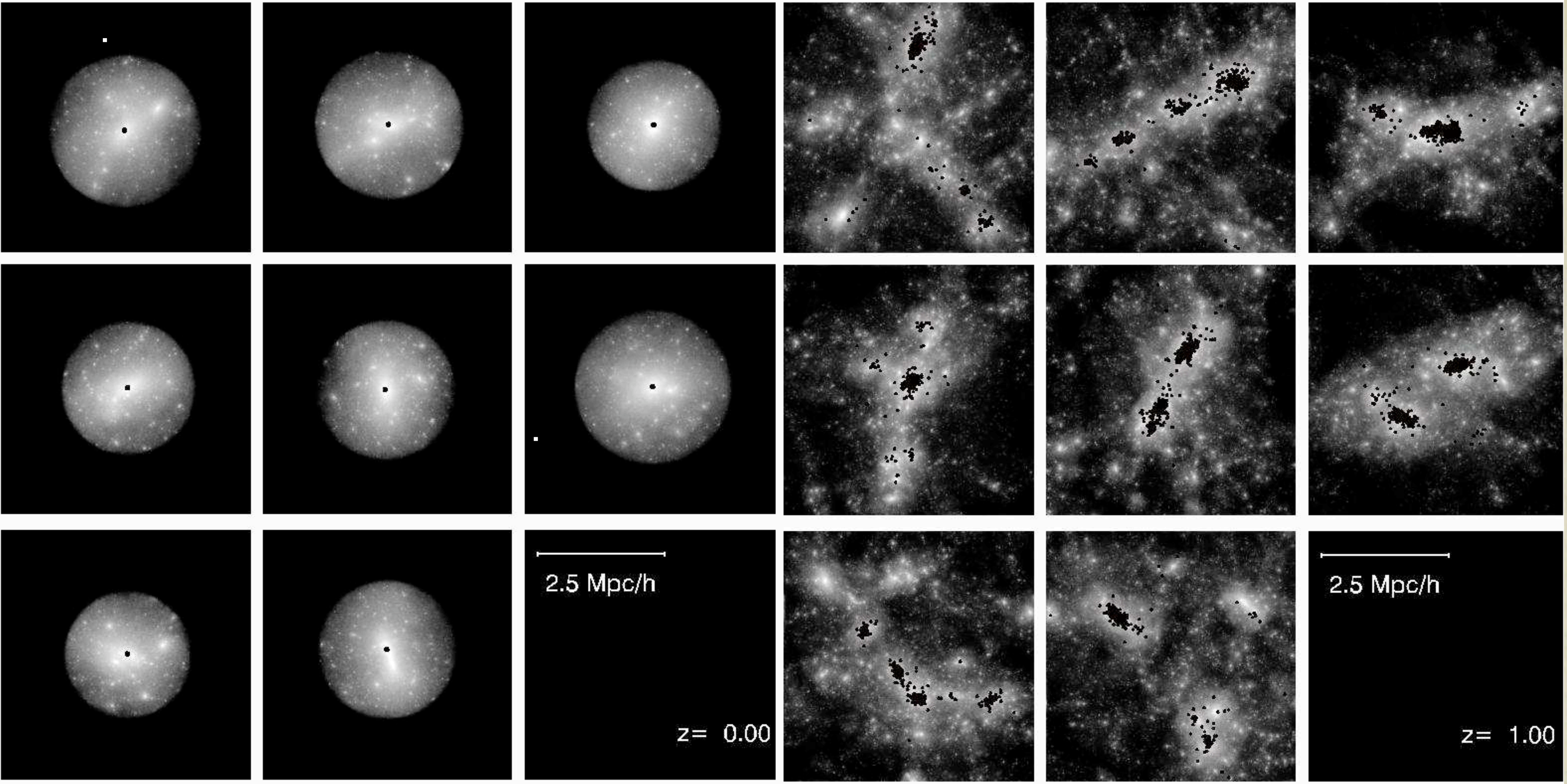


Fig. 2.— Images of the mass distribution at $z = 0, 1$ and 3 in our 8 simulations of the assembly of cluster mass halos. Each plot shows only those particles which lie within r_{200} of halo center at $z = 0$. Particles which lie within $10h^{-1}$ kpc of halo center at this time are shown in black. Each image is $5h^{-1}$Mpc on a side in physical (not comoving) units.

Early Formation and Late Merging of the Giant Galaxies

Liang Gao[1] Abraham Loeb[2] P. J. E. Peebles[3] Simon D. M. White[1] and Adrian Jenkins[4]

Kinematics of stars a few kpc above the midplane of the disk:

DECIPHERING THE LAST MAJOR INVASION OF THE MILKY WAY

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Received 2002 May 10; accepted 2002 June 14; published 2002 June 25

ABSTRACT

We present first results from a spectroscopic survey of ~2000 F/G stars 0.5–5 kpc from the Galactic plane, obtained with the Two Degree Field facility on the Anglo-Australian Telescope. These data show the mean rotation velocity of the thick disk about the Galactic center a few kiloparsecs from the plane is very different than expected, being ~100 km s^{-1} rather than the predicted ~180 km s^{-1}. We propose that our sample is dominated by stars from a disrupted satellite that merged with the disk of the Milky Way some 10–12 Gyr ago. We do not find evidence for the many substantial mergers expected in hierarchical clustering theories. We find yet more evidence that the stellar halo retains kinematic substructure, indicative of minor mergers.

if LCDM

Pieces of the puzzle: Ancient substructure in the Galactic disk

Amina Helmi*[1], J. F. Navarro†[2,3], B. Nordström[4,5], J. Holmberg[6], M. G. Abadi[2]‡ and M. Steinmetz[7]§

extra-Galactic provenance. It is possible to identify three coherent Groups among these stars, that, in all likelihood, correspond to the remains of disrupted satellites. The most metal-rich group ([Fe/H] > -0.45 dex) has 120 stars distributed into two stellar populations of ~ 8 Gyr (33%) and ~ 12 Gyr (67%) of age. The second Group with $\langle[\mathrm{Fe/H}]\rangle \sim -0.6$ dex has 86 stars, and shows evidence of three populations of 8 Gyr (15%), 12 Gyr (36%) and 16 Gyr (49%) of age. Finally, the third Group has 68 stars, with typical metallicity around -0.8 dex, and a single age of ~ 14 Gyr. The identification of substantial amounts of debris in the Galactic disk whose origin can be traced back to more than one satellite galaxy, provides undisputable evidence of the hierarchical formation of the Milky Way.

probably not LCDM

SIMULATIONS OF GALAXY FORMATION IN A Λ COLD DARK MATTER UNIVERSE. II. THE FINE STRUCTURE OF SIMULATED GALACTIC DISKS

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Department of Physics and Astronomy, University of Victoria, Victoria, BC V8P 1A1, Canada

Matthias Steinmetz[3]
Steward Observatory, 933 North Cherry Avenue, Tucson, AZ 85721; and Astrophysikalisches Institut Potsdam, An der Sternwarte 16, D-14482 Potsdam, Germany

and

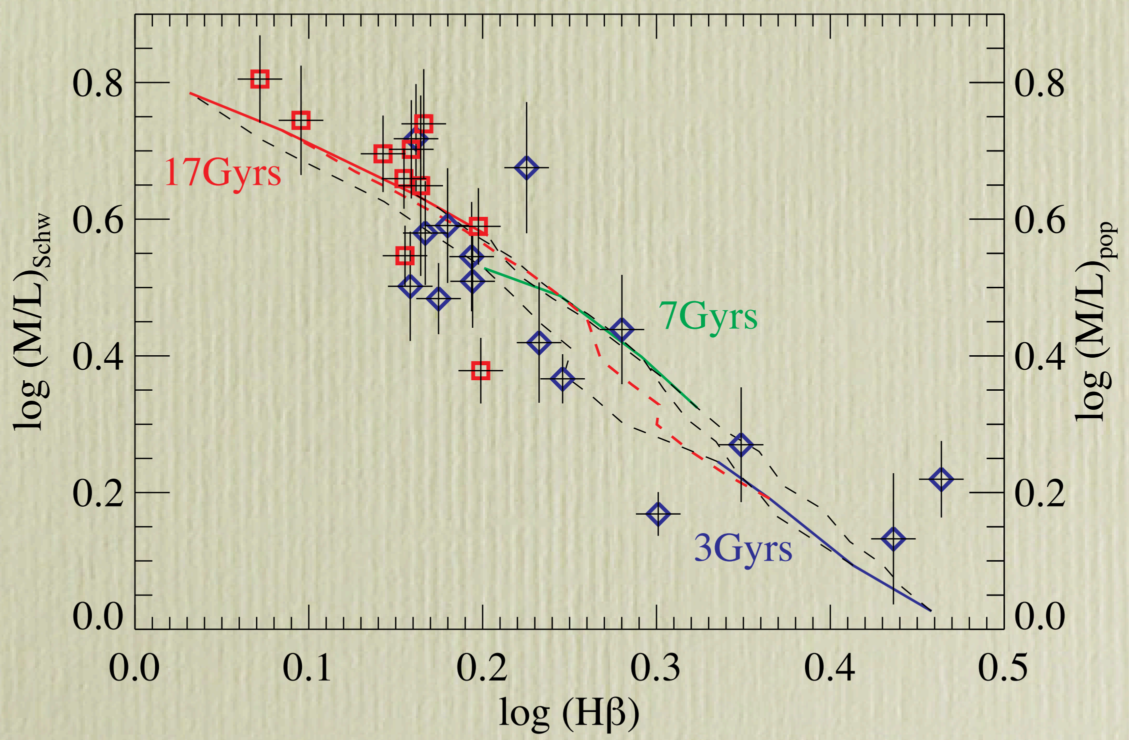
Vincent R. Eke[4]

. The galaxy forms in a dark matter halo chosen so that mergers and accretion events are unimportant dynamically after $z \sim 1$.

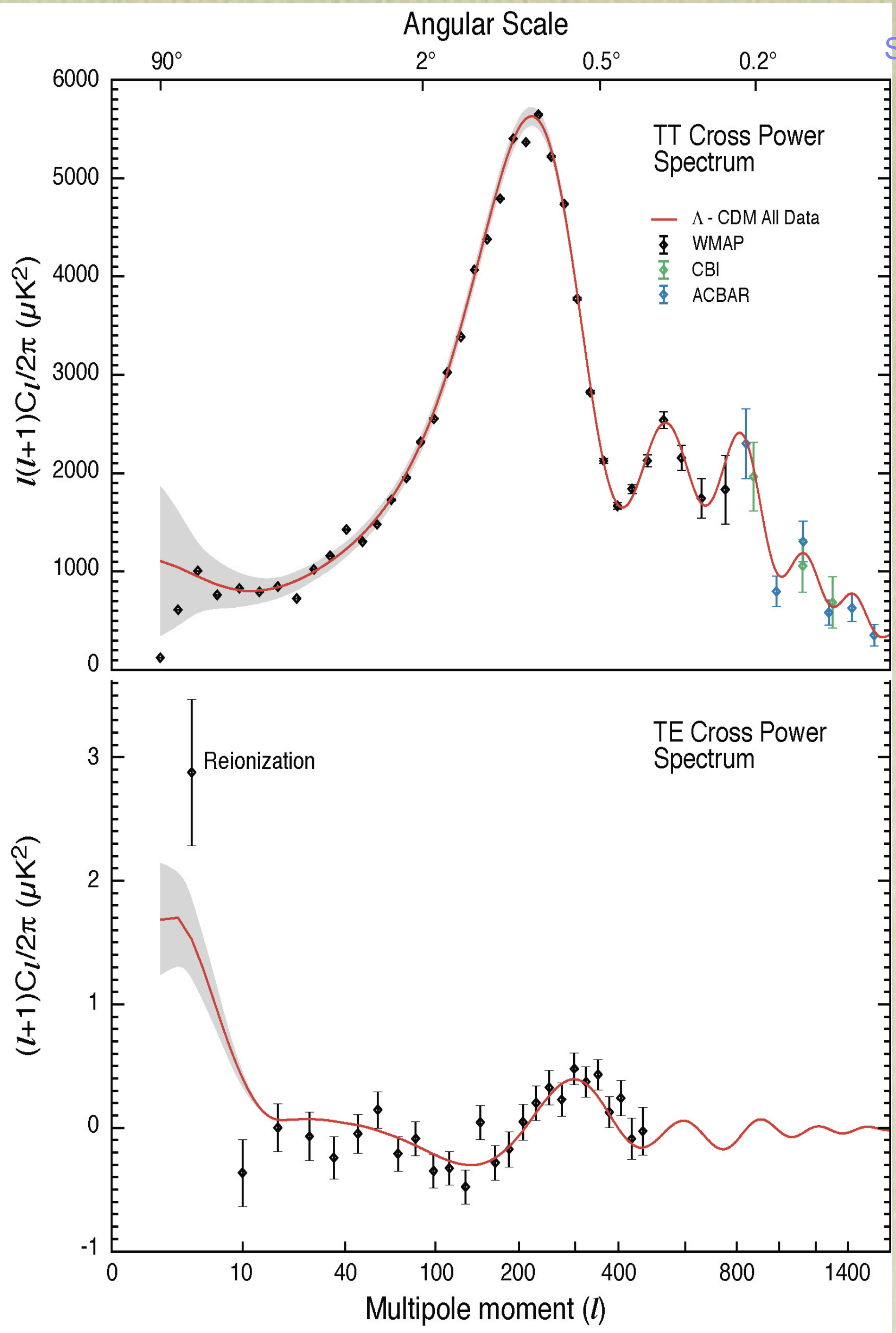
Downsizing: big galaxies are old, small galaxies are young

The SAURON project – IV. The mass-to-light ratio, the virial mass estimator and the fundamental plane of elliptical and lenticular galaxies

Michele Cappellari,[1⋆] R. Bacon,[2] M. Bureau,[3] M. C. Damen,[1] Roger L. Davies,[3] P. Tim de Zeeuw,[1] Eric Emsellem,[2] Jesús Falcón-Barroso,[1] Davor Krajnović,[3] Harald Kuntschner,[4] Richard M. McDermid,[1] Reynier F. Peletier,[5] Remco C. E. van den Bosch,[1] and Glenn van de Ven[1]

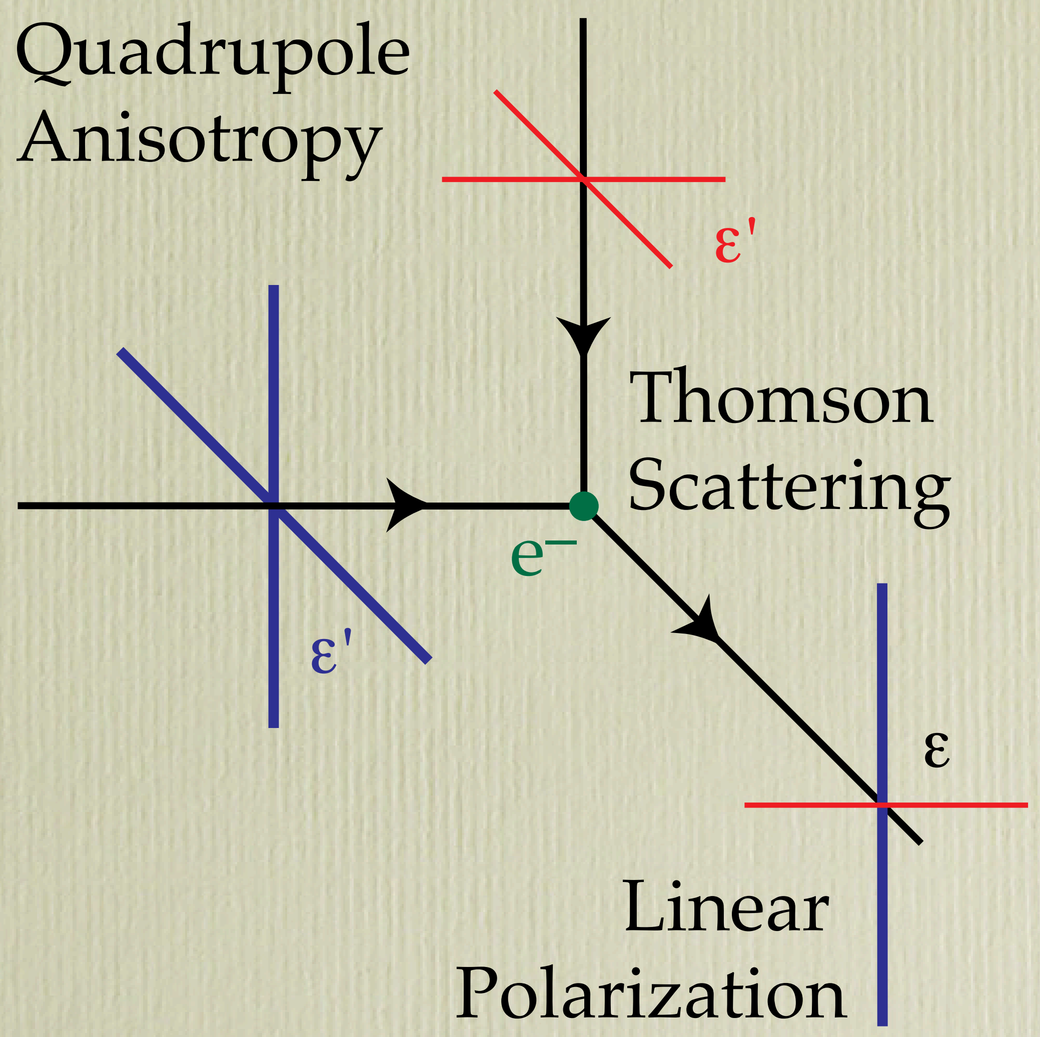


ΛCDM does not comfortably account for early ($z > 6$) hydrogen reionization



Spergel etal 03

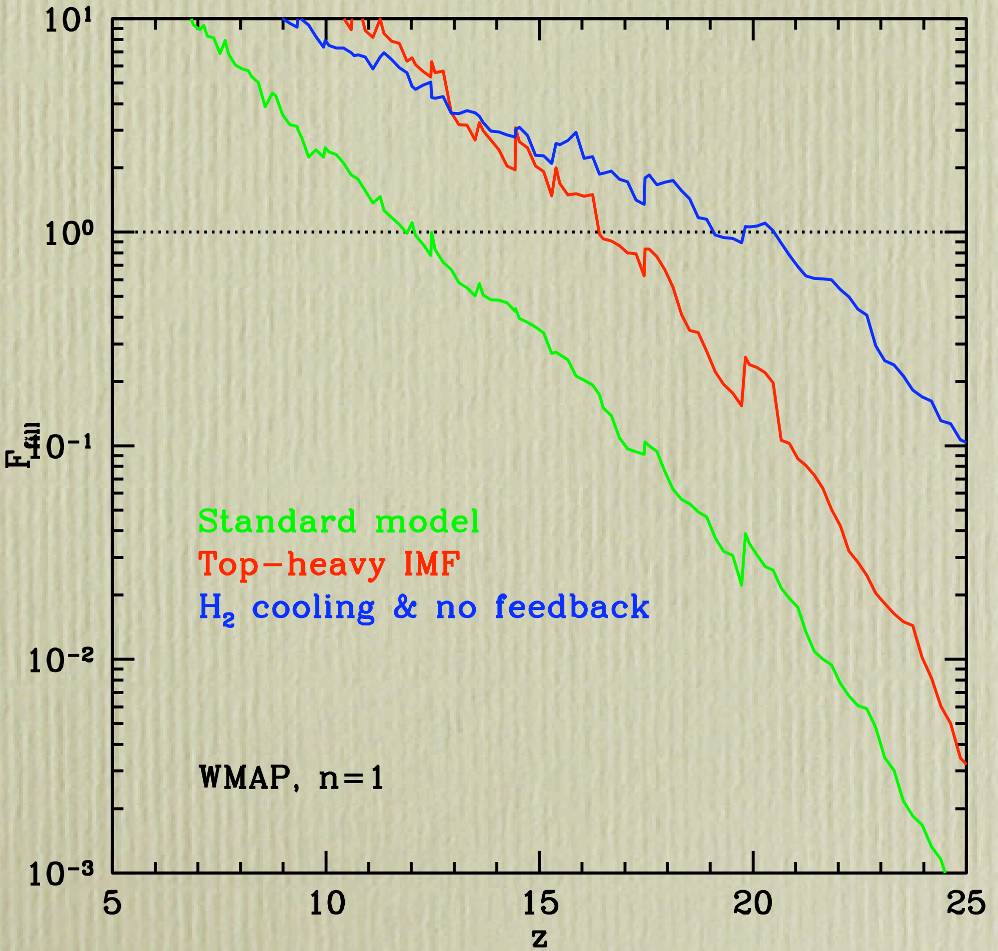
Polarization

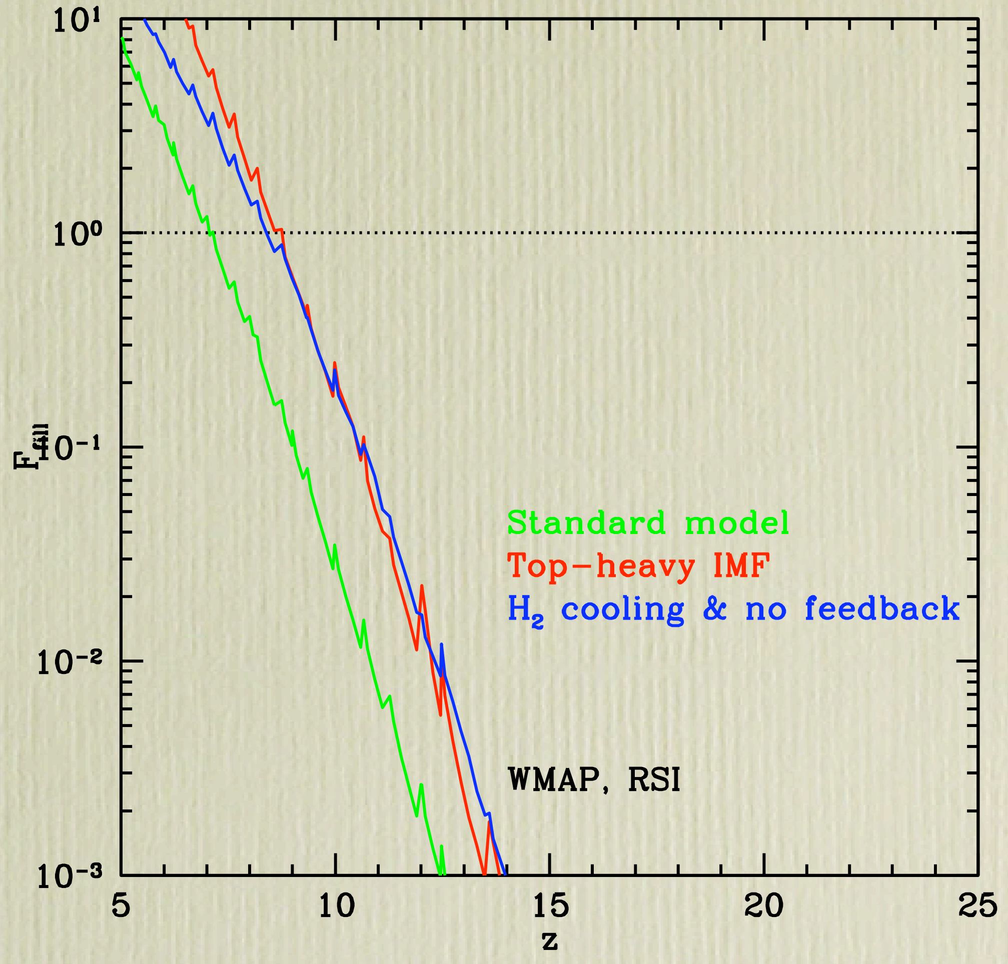


$$\tau_T = 0.166 \pm 0.071$$

If reionization is sudden and complete by Z_i then $12 < z_i < 16$

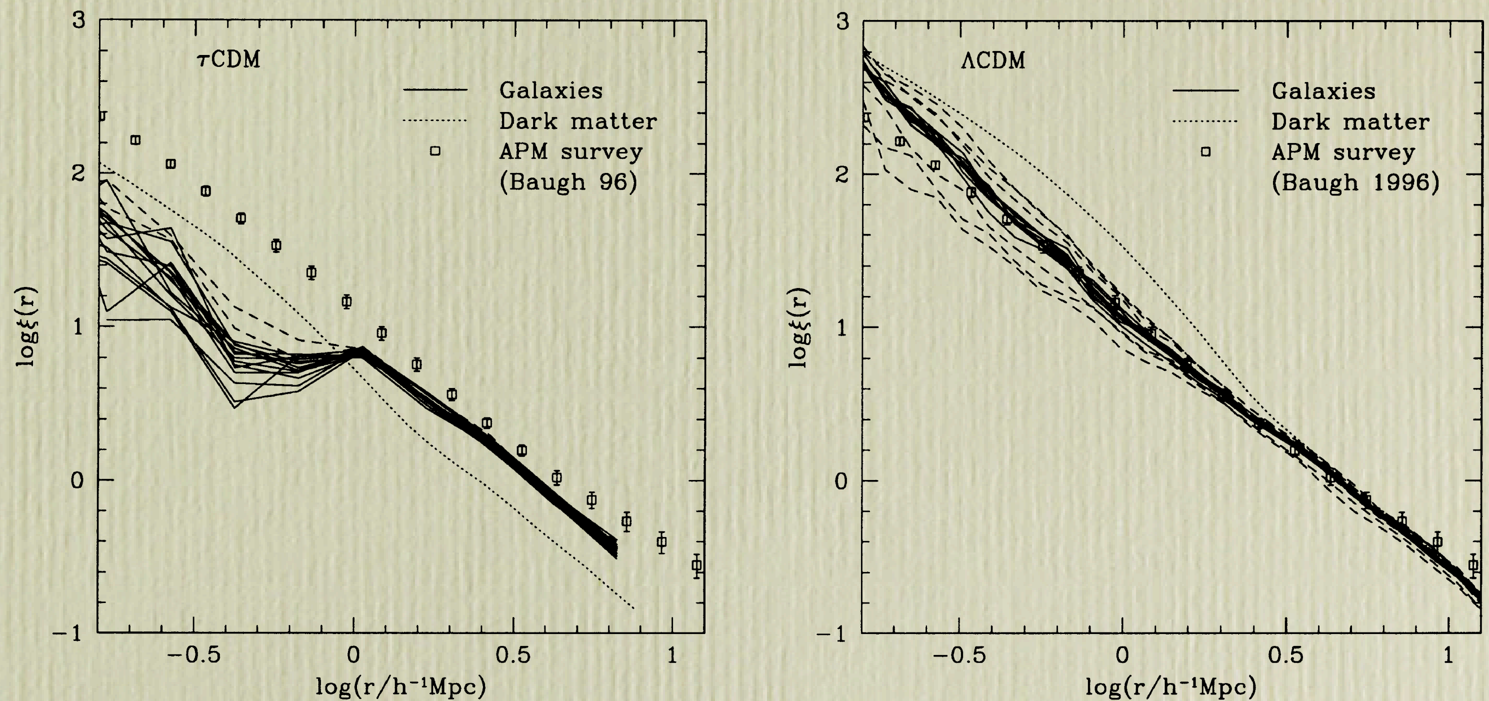
Benson, Nusser & Sugiyama 04





it seems that voids in ΛCDM are not large enough

The observed correlation function of galaxies is a power down to very small scales



A. J. Benson,[1★] S. Cole,[1★] C. S. Frenk,[1★] C. M. Baugh[1★] and C. G. Lacey[1,2★]

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Partial remedy with minimal # of new free parameters

Increasing the small scale clustering rate:

I. will give more objects at high redshift

II. will suppress merging at low redshift

Long Range Interactions in the Dark Sector

Collaborators: Jim Peebles & Steve Gubser

Assume two species of dark matter particles of masses $M_+(\Phi)$ and $M_-(\Phi)$ that depend on a scalar field Φ. Consider the action

$$\int \mathrm{d}^4x \Phi_{,i}\Phi^{,i} - \sum_{particles} \int [m_+(\Phi)\,\mathrm{d}s_+ + m_-(\Phi)\,\mathrm{d}s_-]$$

$$\text{where} \quad \frac{\mathrm{d}M_+}{\mathrm{d}\Phi} < 0\,, \qquad \frac{\mathrm{d}M_-}{\mathrm{d}\Phi} > 0\,.$$

To minimize the energy the field will acquire large values where there are (+) particles and smaller values where there are (-) particles. I.e., like particles will attract, unlike particles will repel.

Brandenberger-Vafa: If $M_+ = M_{0+} - y_+ \Phi$, $M_- = M_{0-} + y_- \Phi$., then minimization of the actions yields

$$\nabla^2 \Phi = -y_+ n_+(r) + y_- n_-$$

$$F_{++} = -\frac{y_+^2}{4\pi r^2}\ , \quad F_{+-} = \frac{y_+^2}{4\pi r^2}\ , \quad F_{--} = -\frac{y_-^2}{4\pi r^2}$$

Compare with electromagentism!

Screening mechanism:

$$M_+ = M_{DM} - y\Phi \ , \qquad M_- = y_-\Phi \approx 0$$

I.e., the (-) particles are relativistic and the (+) are not. In this case

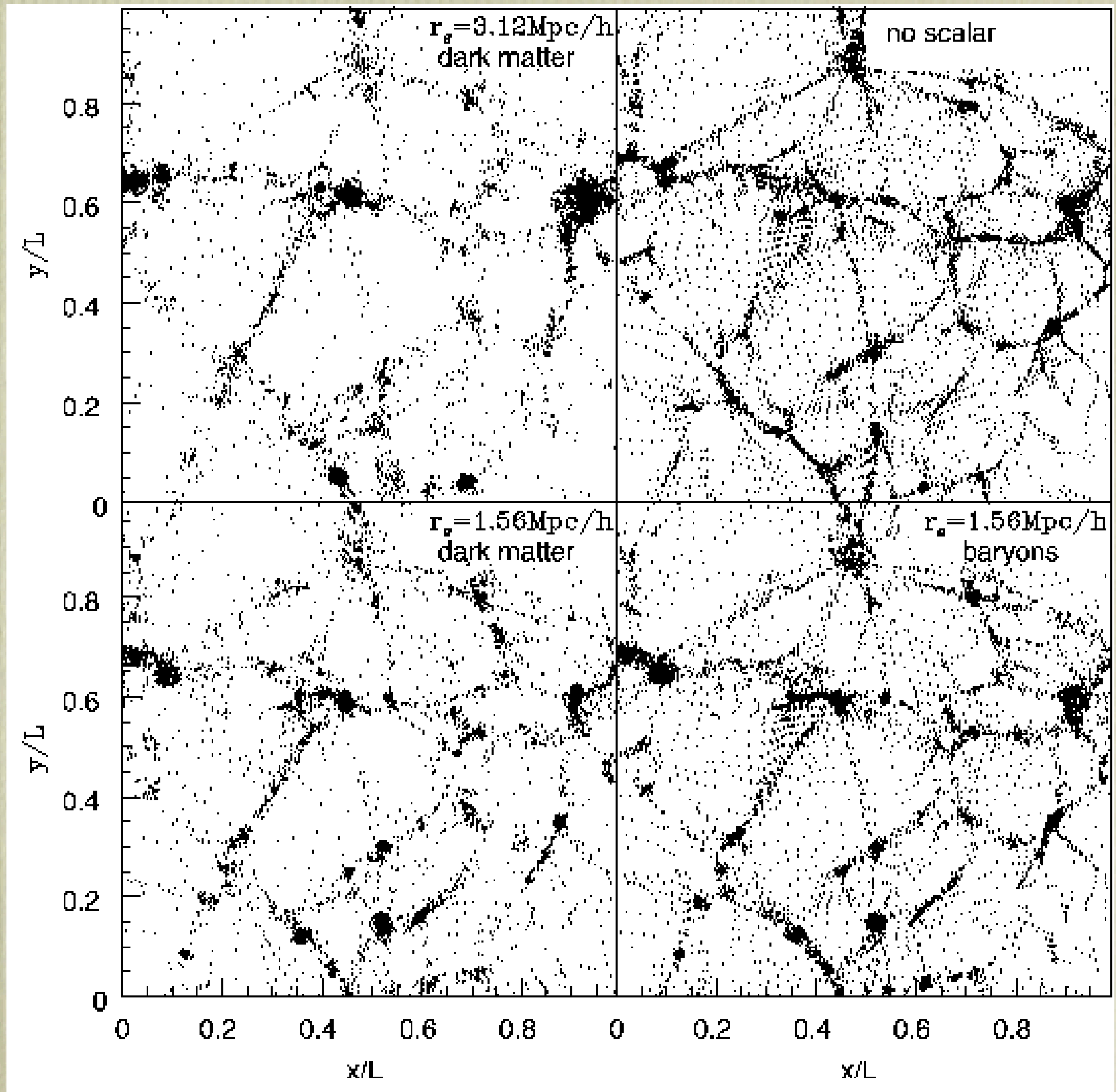
$$\nabla^2\Phi = \frac{\Phi}{r_s^2} - y n_{_{DM}}(r)$$

where $r_s \propto a(t)$ and depends on a combination of y_- and the assumed energy of the relativistic species.

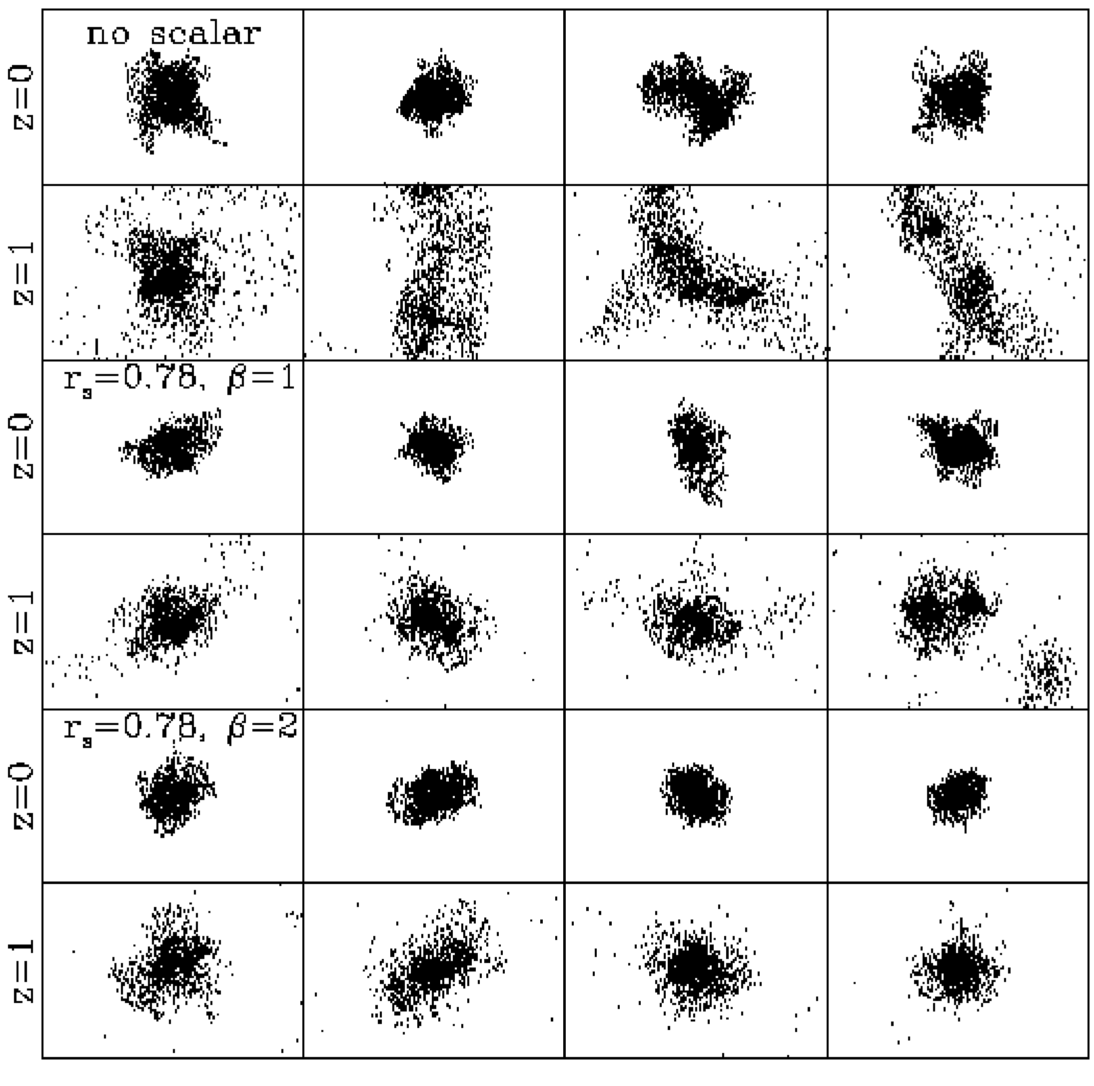
The scalar attraction force between two DM particles is

$$F_s = y^2 \frac{\mathrm{e}^{-r/rs}}{r^2}$$

to be added to $Gm_{_{DM}}^2/r^2$.



r_s=3.12Mpc/h
dark matter
no scalar
r_s=1.56Mpc/h
dark matter
r_s=1.56Mpc/h
baryons
y/L
y/L
x/L
x/L
0
0.2
0.4
0.6
0.8


no scalar
z=0
z=1
r_s=0.78, β=1
z=0
z=1
r_s=0.78, β=2
z=0
z=1

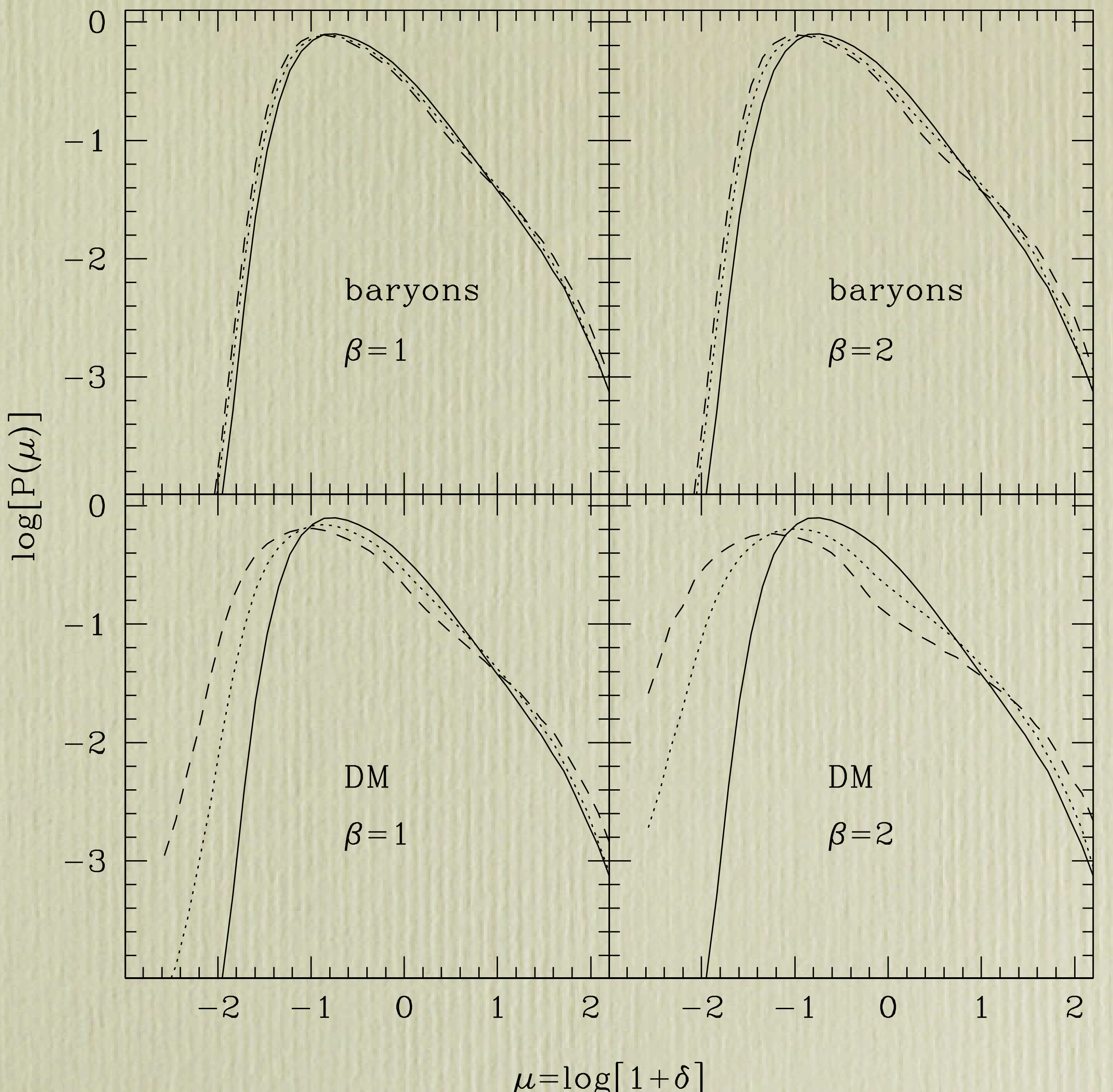
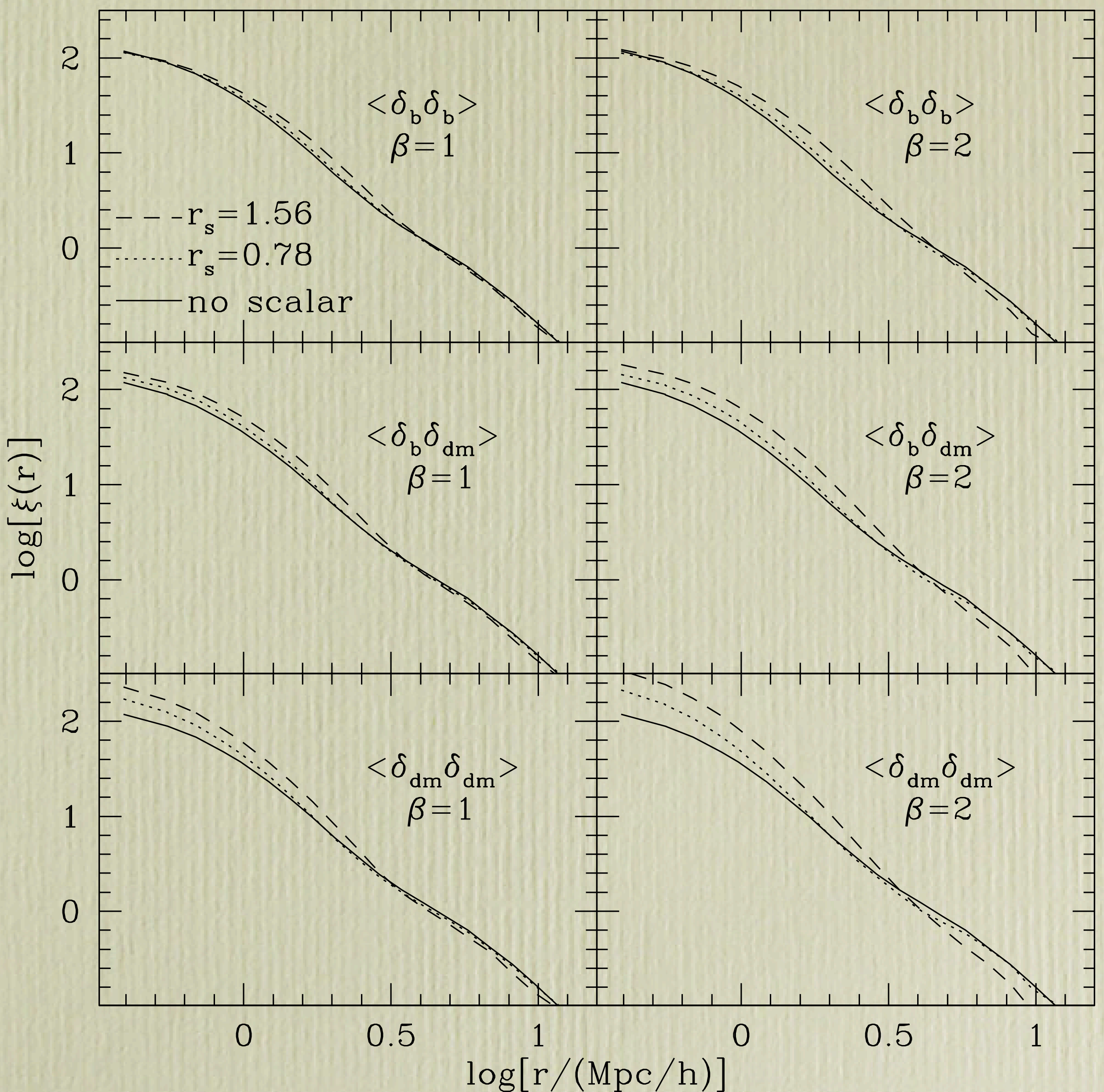
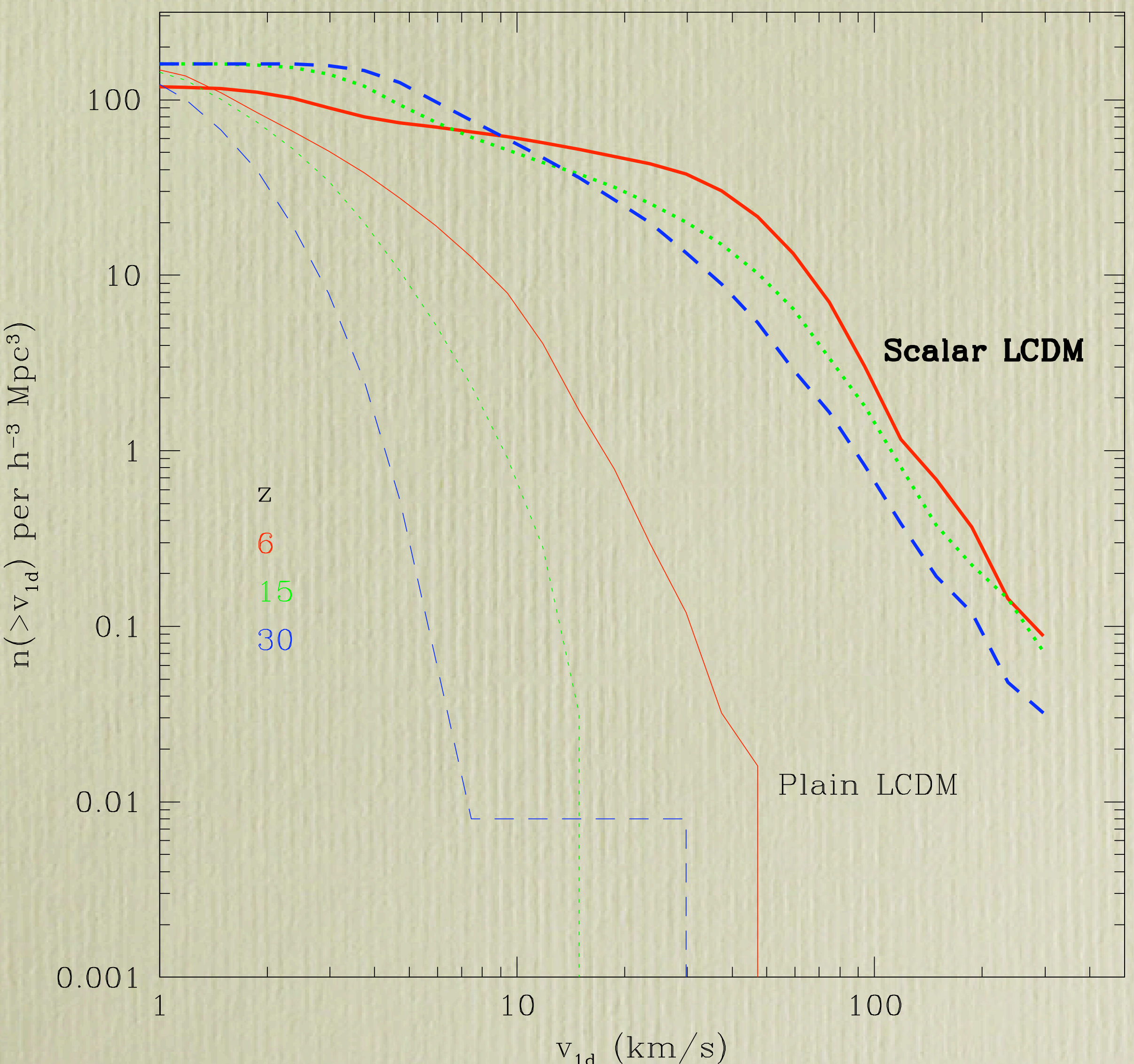


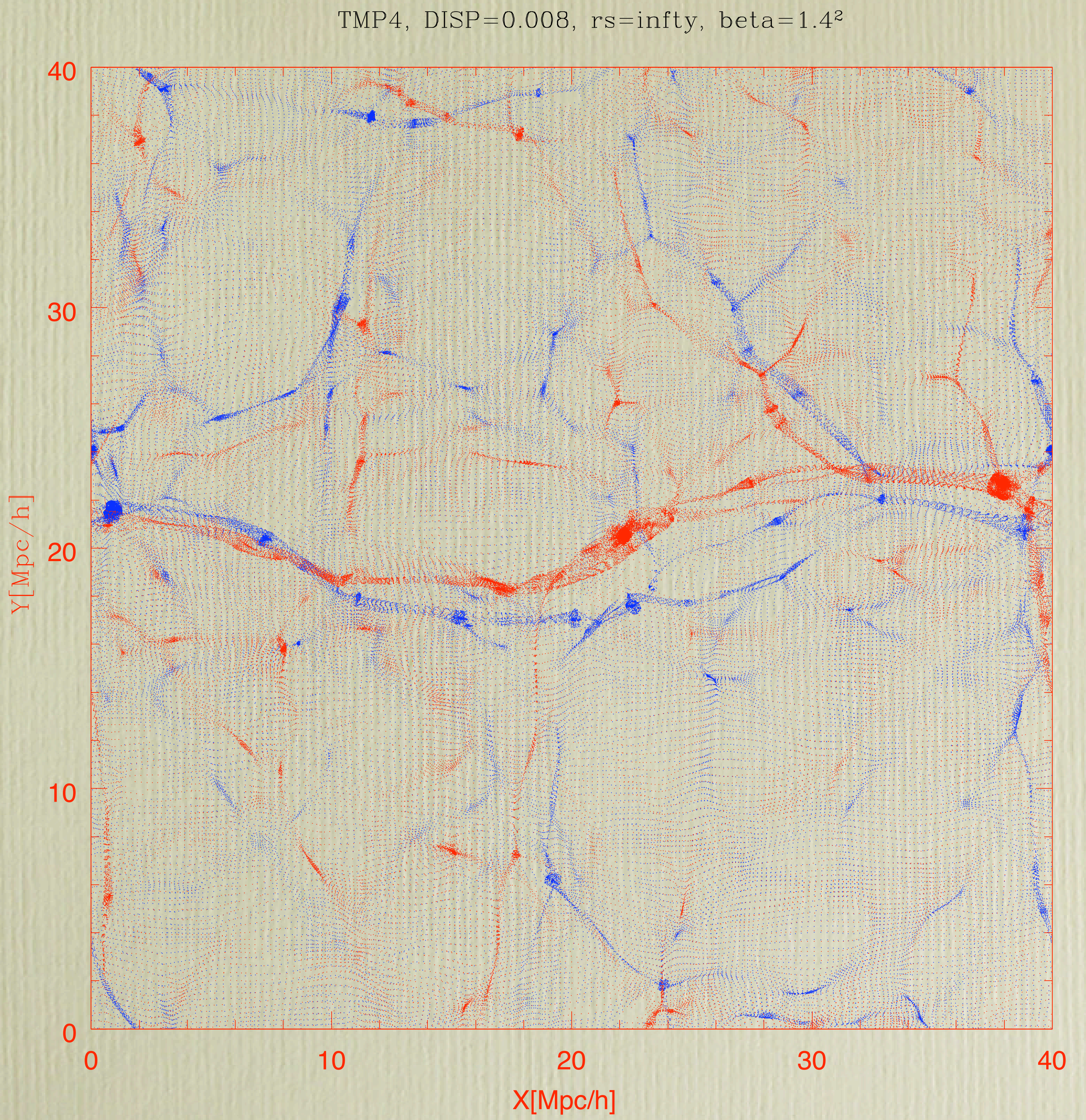
FIG. 3: The distributions of the density contrasts in dark matter and baryons smoothed with a top-hat spherical window of radius $1.5h^{-1}$ Mpc at the present epoch. The standard model is the solid curve, the dotted curve shows the effect of the scalar force with $r_s = 0.78h^{-1}$ Mpc, and the dashed curve shows $r_s = 1.56h^{-1}$ Mpc. The simulation box width is $50h^{-1}$ Mpc.



<δ_b δ_b> β=1
<δ_b δ_b> β=2
r_s=1.56
r_s=0.78
no scalar
<δ_b δ_dm> β=1
<δ_b δ_dm> β=2
<δ_dm δ_dm> β=1
<δ_dm δ_dm> β=2
log[ξ(r)]
log[r/(Mpc/h)]

Mass function at high z (simulation by R. Cen)





TMP4, DISP=0.008, rs=infty, beta=1.4²
Y[Mpc/h]
X[Mpc/h]
0
10
20
30
40

screening with A/ϕ^α

$$V(\phi) = \frac{A}{\phi^\alpha} + n_1|m_0 - y\phi| + n_2(m_0 + y\phi)$$

Lets look for the minimum of $V(\phi)$ for $n_1 = n_2 = \bar{n}$ with $\bar{n}$ being the mean number density of either species. Because of the absolute value, the minimum is clearly not at $\phi = \infty$. Lets find it. Assume that the minimum is at $\phi_0 > m_0/y$. Then we must minimize the function

$$\frac{A}{\phi^\alpha} + \bar{n}(y\phi + m_0) + \bar{n}(m_0 + y\phi)$$

This gives $\phi_0 = \left[\frac{2\bar{n}}{\alpha A}\right]^{\frac{1}{1+\alpha}}$.

First lets assume that $y\phi_0 \gg m_0$ (the condition $\gg$ is for simplicity only). Lets write $\phi = \phi_0 + \delta\phi$. Then for small $\delta\phi$ we have

$$V(\delta\phi) \approx -\alpha\frac{A}{\phi_0^{\alpha+1}}\delta\phi + \alpha(\alpha+1)\frac{A}{2\phi_0^{\alpha+2}}(\delta\phi)^2 + n_1(y\delta\phi + m_1) + n_2(y\delta\phi + m_2)$$

where $m_1 = |m_0 - y\phi_0| \approx y\phi_0$ and $m_2 = m_0 + y\phi_0 \approx m_1$. From this we get the equation

$$\frac{1}{a^2}\nabla_x^2 \delta\phi = \frac{\delta\phi}{R_s^2} + y(\delta n_1 + \delta n_2)$$

where $R_s = \phi_0^{\alpha+2}/A/\alpha/(\alpha+1) \propto a^{\frac{3(\alpha+2)}{2(\alpha+1)}}$ which is constant neither in comoving nor in physical coordinates. Note that the equation of motion for any of the two species is $F = -y\nabla\phi$. Therefore, **this model naturally gives you screening. This differs from the screening we had in our paper in that the the screening length here is $R_s \propto a^\beta$ with $\beta > 1.5$ which is not bad at all.**

Final Remarks

- **We have a good working model:** the "concordance" ΛCDM

  –good match to power spectra

- **No One owes Humanity Anything**: the dark sector physics of this model is extremely simple

- **Anomalies**: galaxy evolution, rotation curves, properties of X-ray clusters... might be a reflection of new physics in the dark sector

- **Scalar interactions** in the dark sector are useful

  –merging is suppressed at low redshifts

  –reionization at high redshift is easier

  –voids are emptier

  –mass functions looks closer to the luminosity function

- **Potentially serious problems for scalar interactions:**

  –I. how much substructure should we expect?

  –II. halo profiles?

- **Future work on scalar interactions:**

  –semi-analytic galaxy formation models

  –better estimates of the expected initial power spectrum

  –higher resolution simulations targeted at specific effects: reionization (R. Cen), halo profiles, hydrodynamics, Ly-α forest...

  – exploring other variants of the model