Outline

- accelerating Universe from Geometry
- modified Newtonian dynamics
- Anomalies: merging rate, giant galaxies, reionization epoch, voids, etc
- Remedy: scalar interaction in the dark sector

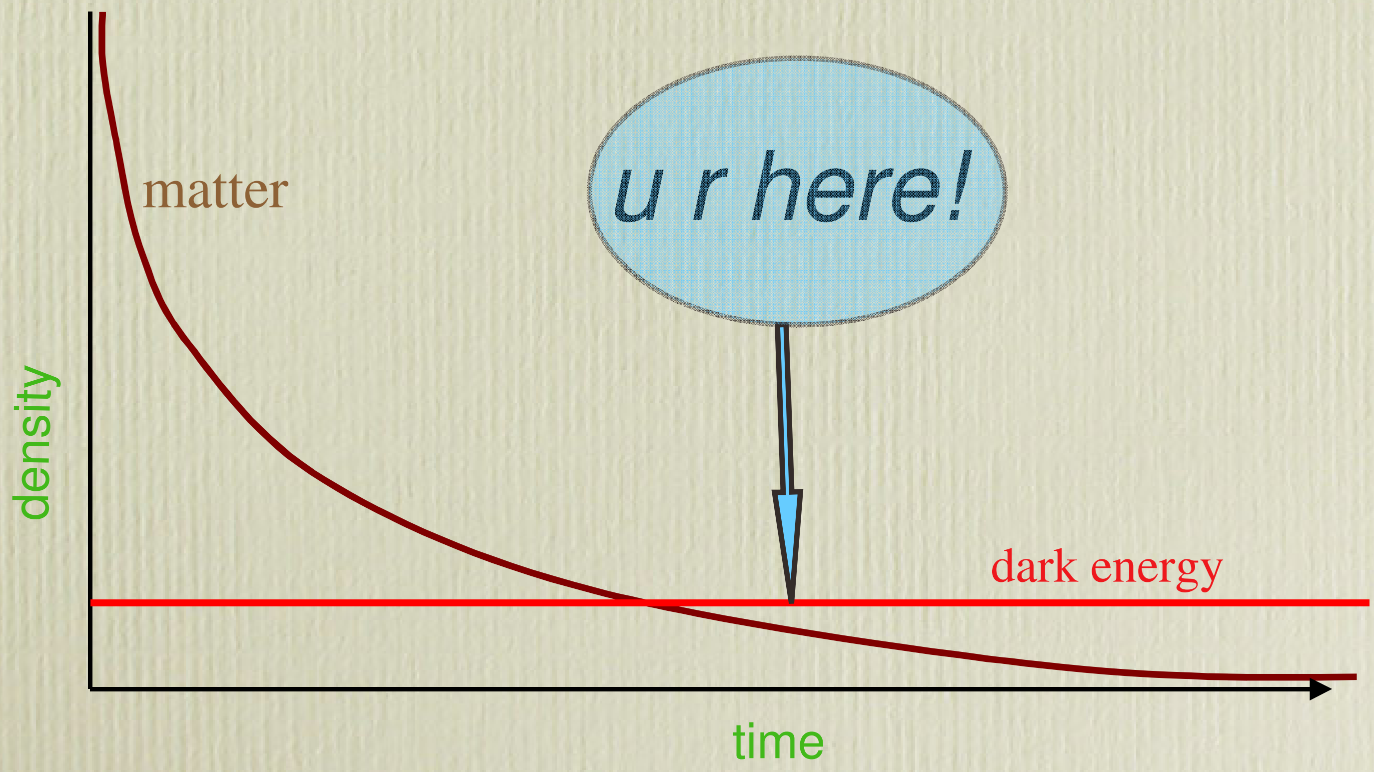
Matter & Energy in the Universe

$$\rho = \rho_{bm} + \rho_{dm} + \rho_v$$

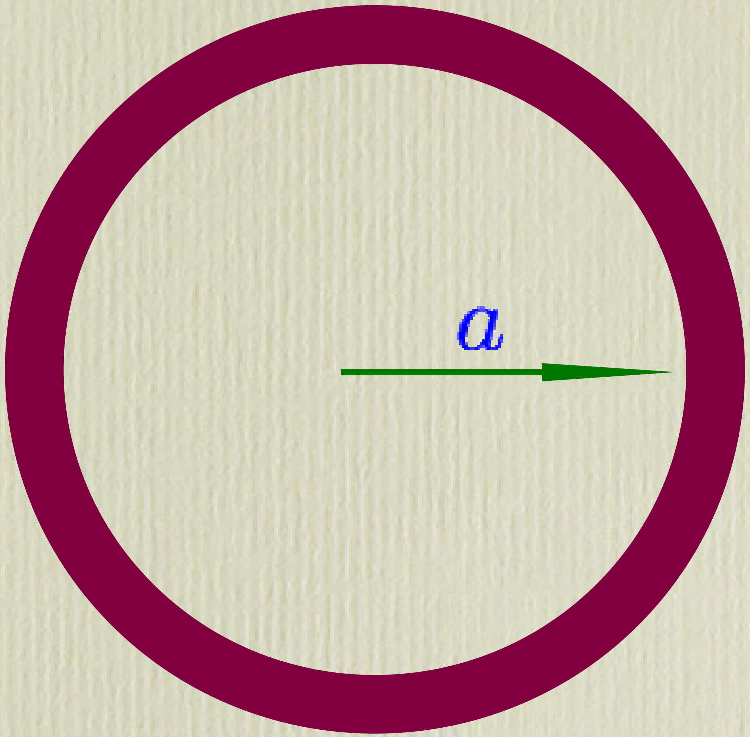
$$\rho_m \propto 1/a^3(t)$$

For *dark-energy* or *vacuum energy* or *cosmological constant*:

$$\rho_v = const \qquad P = -\rho_v$$

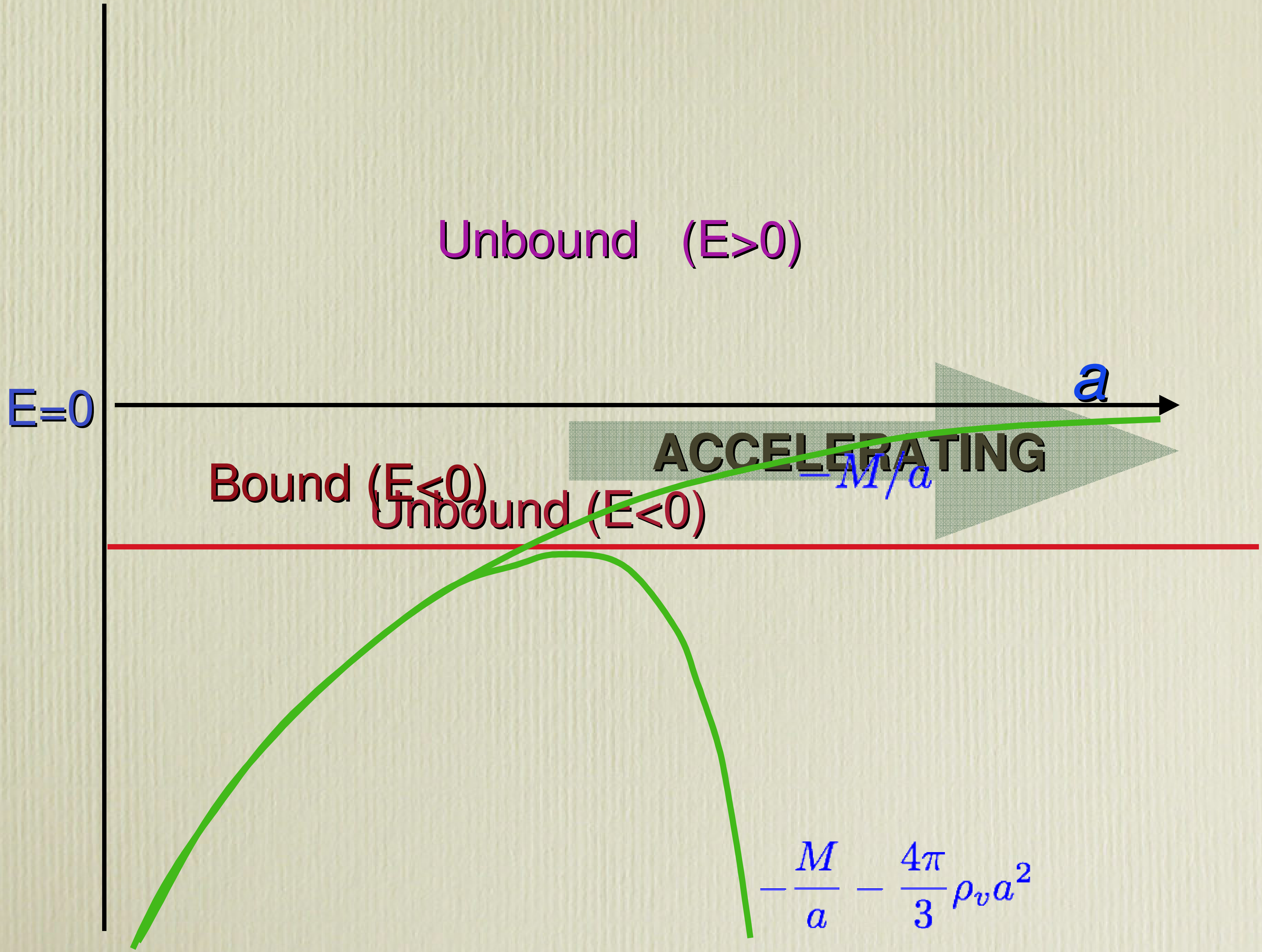


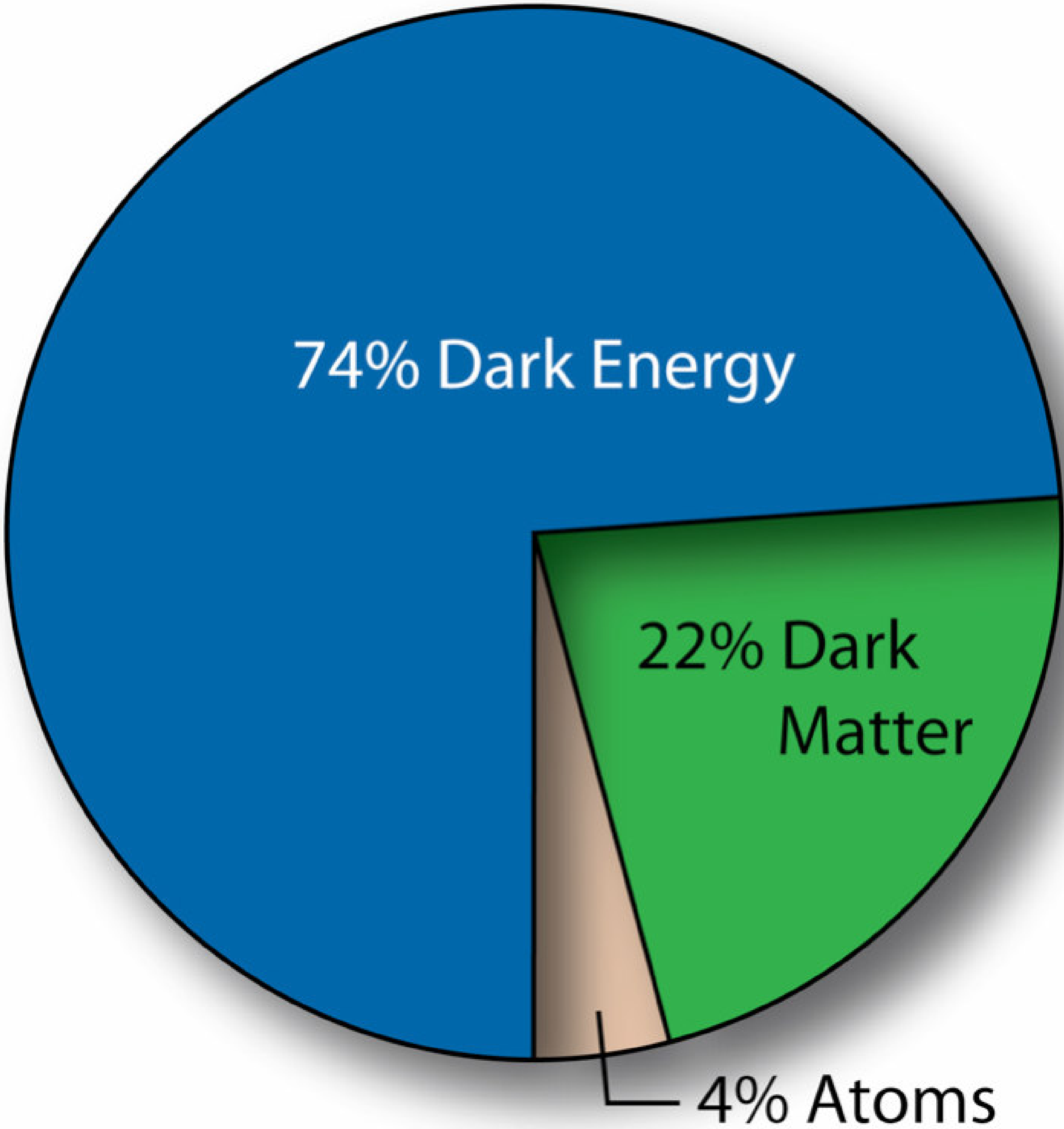
DYNAMICS OF THE EXPANSION



eneral relativity:

$$E = \frac{\dot{a}^2}{2} - \frac{GM}{a} \quad - \frac{4\pi G}{3}\rho_v a^2$$


Unbound (E>0)
E=0
a
ACCELERATING
Bound (E<0)
Unbound (E<0)
$-M/a$
$-\frac{M}{a} - \frac{4\pi}{3}\rho_v a^2$


74% Dark Energy
22% Dark Matter
4% Atoms

Cosmological backgrounds in f(R) gravity

S.M.Carroll, A. De Felice, V.Duvvuri, D. A. Easson, M.Trodden, M.S. Turner, Phys.Rev. D71 (2005) 063513.

A.D. Dolgov, M. Kawasaki,Phys.Lett. B573 (2003) 1.

S. Nojiri and S.Odintsov, preprint hep-th/0601213.

consider the action

$$S = -\frac{1}{l_p^2}\int d^4x\sqrt{-g}\,(R + f(R) - L_m)$$

We will work with a spatially flat FRW metric

$$ds^2 = d\tau^2 - a^2(\tau)(dx^2 + dy^2 + dz^2)$$

$$R = -6\left(\frac{\ddot{a}}{a} + \left(\frac{\dot{a}}{a}\right)^2\right), \quad R_0^0 = -3\left(\frac{\ddot{a}}{a}\right), \quad \dot{a} = \frac{1}{H_0}\frac{da}{d\tau}$$

$$y = (\Omega_m\, a + \Omega_r) - \left[\frac{df(R)}{dR}\left(y - \frac{a}{2}\frac{dy}{da}\right) - \frac{a^4}{6}\, f(R) + a\, y \frac{d}{da}\left(\frac{df(R)}{dR}\right)\right]$$

$$y(a) \equiv (\dot{a}a)^2$$

In the case $f(R) = const$ → $y = \Omega_m\, a + \Omega_r + \Omega_\Lambda\, a^4$

Consider $\quad f(R) = -\alpha R^n$

$$\beta\left[n(n-1)y''y + \frac{(1-n)}{2}(y')^2 + n(4-3n)\frac{y'y}{a}\right] = \frac{(y')^{2-n}}{a^{4-3n}}(y - \Omega_m a - \Omega_r)$$

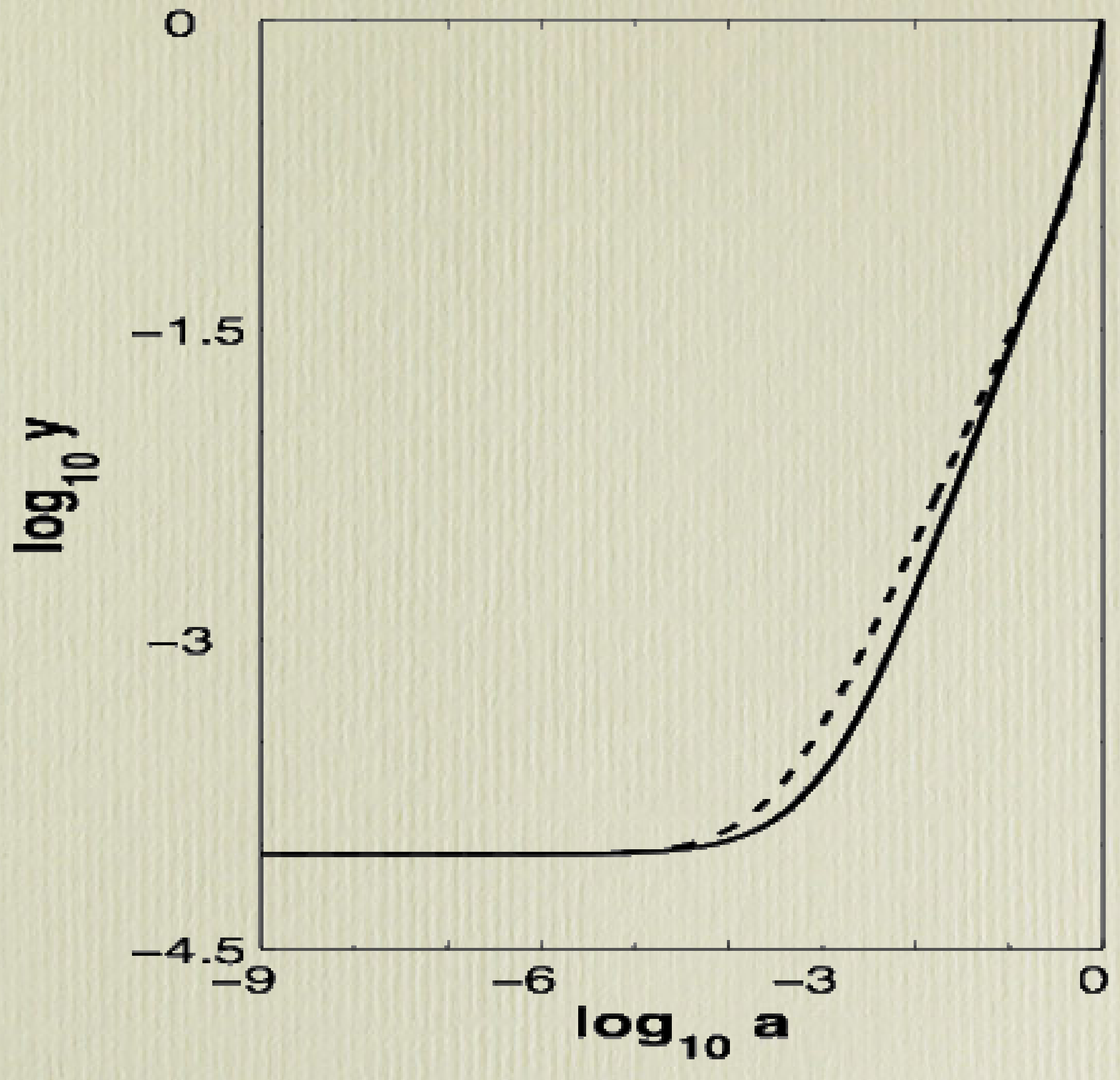
$$\beta = (-3)^{n-1}\alpha.$$

Standard cosmology (with $f(R) = 0$) is obtained for $f(R) \neq 0$ if the l.h.s vanished. For $\Omega_r = 0$ this is obtained for

$$n_1 = (7+\sqrt{73})/12 \simeq 1.295.$$

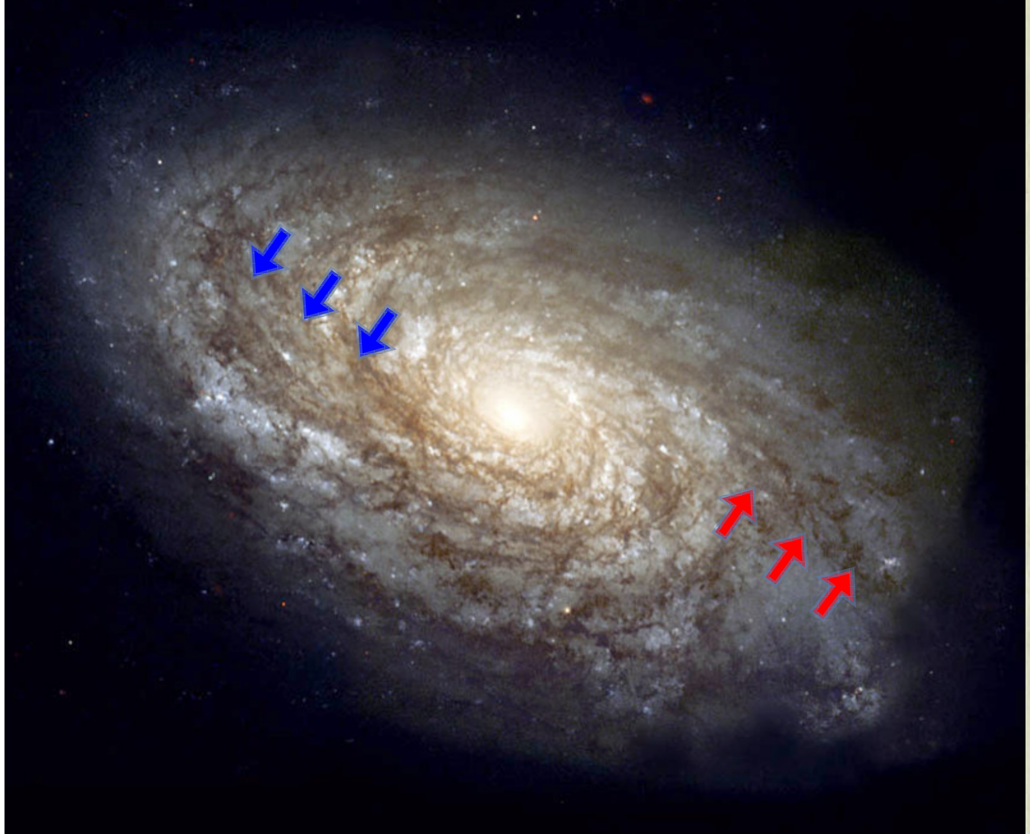
Tokareva & Nusser 06

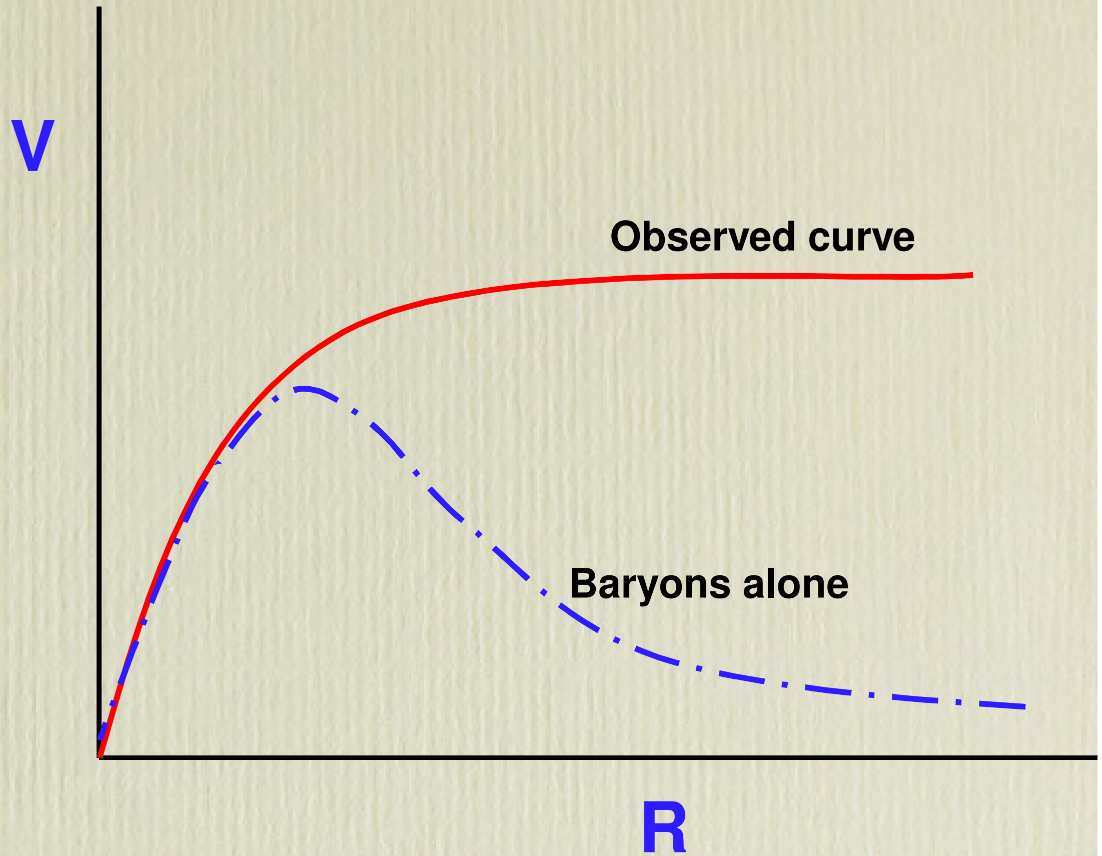
$$y(a) \equiv (\dot{a}a)^2$$



The usual thermal history can be obtained for a wide range of matter content

Modification of Newtonian Gravity: MOND



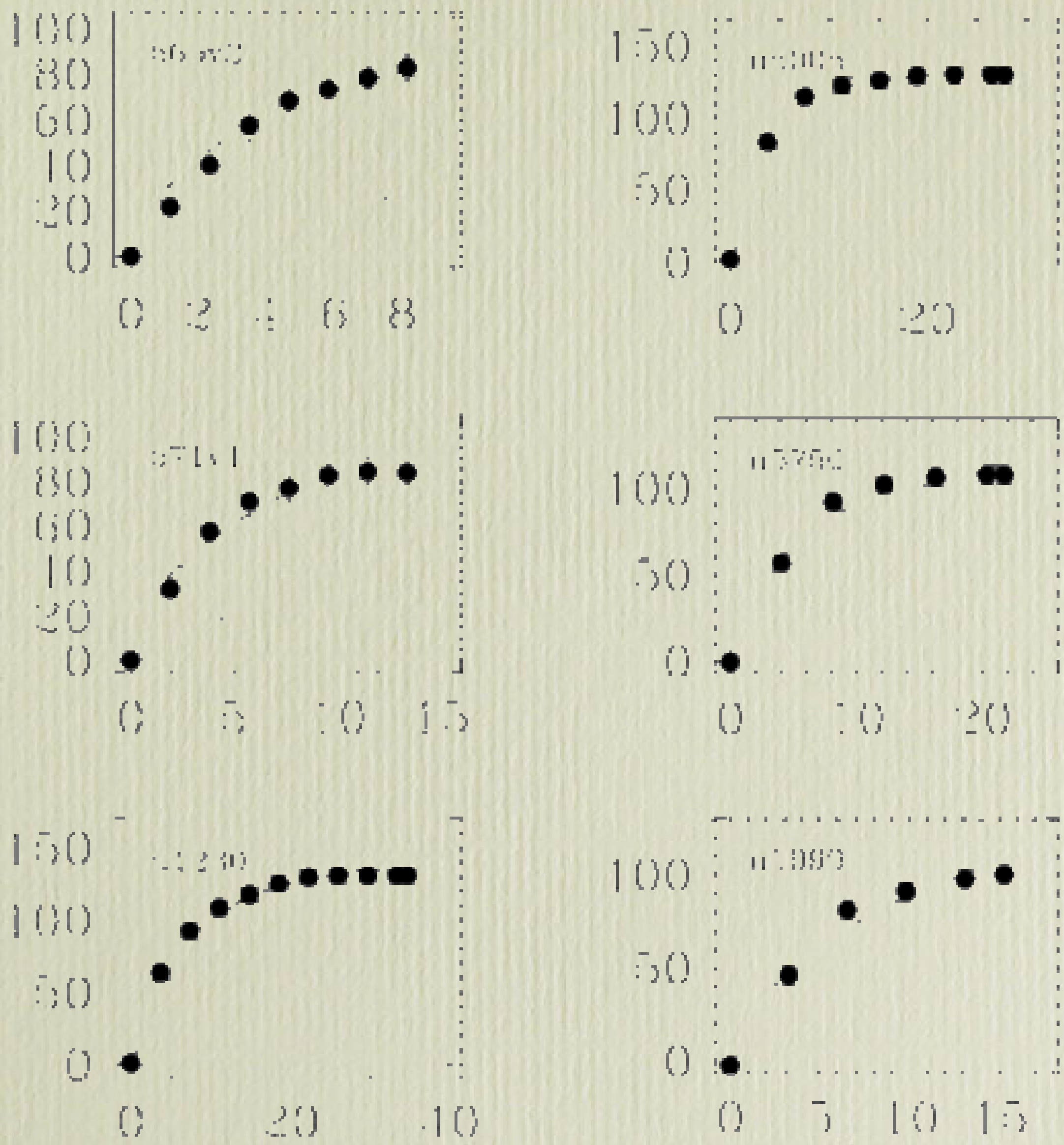


In Newtonian gravity $$\frac{GM}{R^2} = \frac{V^2}{R}$$

$$\xrightarrow{V \sim const} \quad M(R) \propto R$$

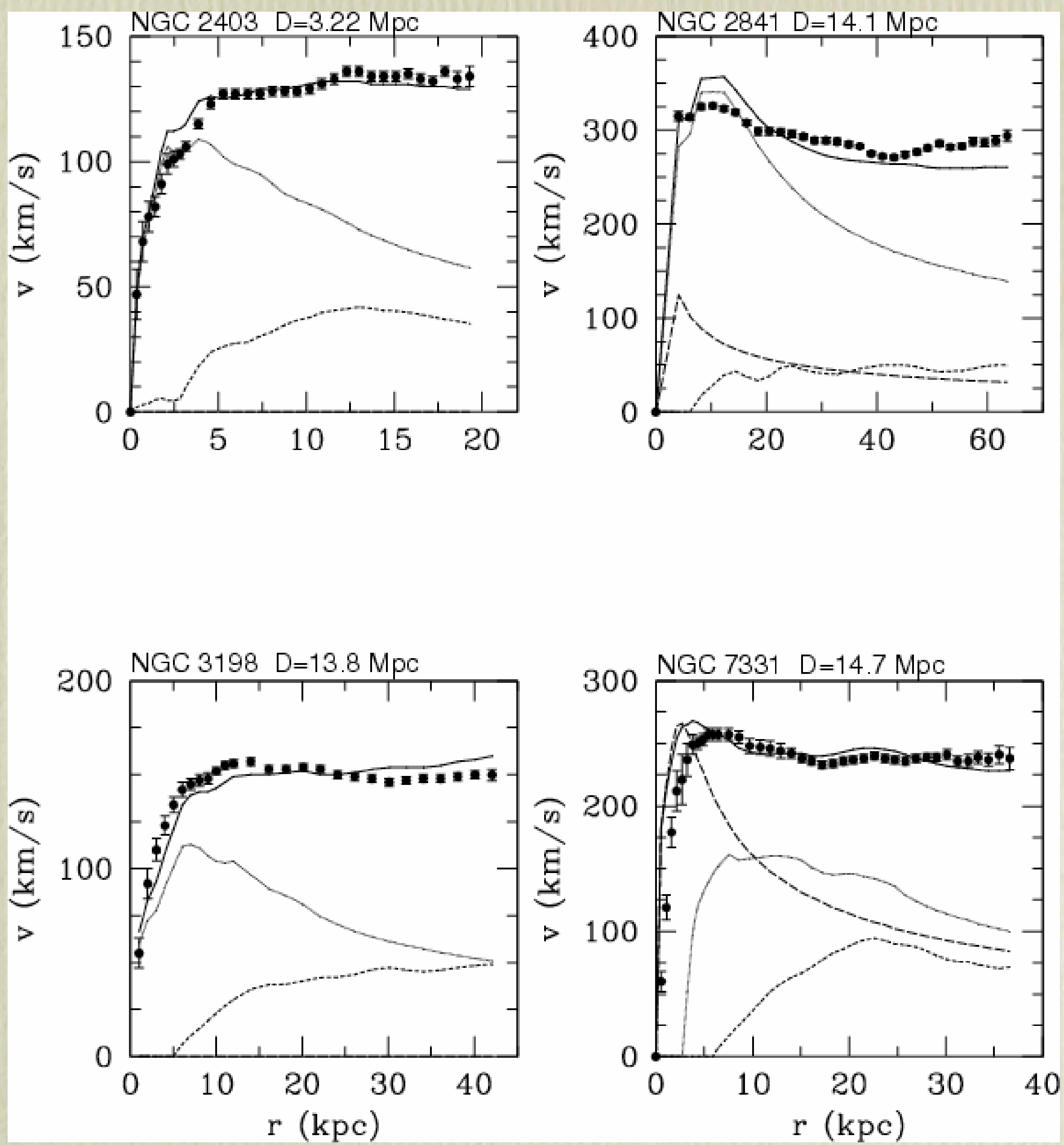
Testing Modified Newtonian Dynamics with Low Surface Brightness Galaxies — Rotation curve fits

W.J.G. de Blok[1] and S.S. McGaugh[2]



M/L<10

Bottema, Pestaña, Rothberg, Sanders 02



MOND rotation curves compared to observed H I rotation curves for the four galaxies with Cepheid-based distances. The dotted, long-dashed, and short-dashed lines are the Newtonian rotation curves of the stellar disc, bulge, and gaseous components respectively.

Modified Newtonian Dynamics

Refs: Milgrom 1983

In MOND, no dark matter is invoked.

Gravity is modified such that

$$\frac{F}{m} = g = \begin{cases} g_N = \frac{GM}{R^2} & \text{if} \quad g_N > g_0 = 1.2 \times 10^{-8} \mathrm{cm/s^2} \\ \sqrt{g_0 g_N} & \text{otherwise} \end{cases}$$

$$\Longrightarrow \qquad \sqrt{g_0 g_N} = \frac{\sqrt{g_0 G M}}{R} = \frac{V^2}{R}$$

$$\xrightarrow{V \sim const} \qquad M(R) \sim const \sim \frac{V^4}{g_0 G}$$

Modified Newtonian Dynamics of Large Scale Structure

the continuity equation

$$\frac{\partial \delta}{\partial t} + \nabla_x \cdot (1+\delta)\mathbf{u} = 0 \,,$$

the Euler equation of motion,

$$\frac{\mathrm{d}\mathbf{u}}{\mathrm{d}t} + 2H\mathbf{u} = \mathbf{g}/a \,,$$

and the Poisson equation,

$$\boxed{\frac{1}{a}\nabla_x \cdot \mathbf{g} = -4\pi G\bar{\rho}\delta = -\frac{3}{2}\Omega H^2\delta} \,.$$

replace the Poisson equation with

$$\boxed{\frac{1}{a}\nabla_x \cdot \left(\frac{|\mathbf{g}|}{g_0}\mathbf{g}\right) = -\frac{3}{2}\Omega H^2\delta} \,.$$

Epoch of MOND domination

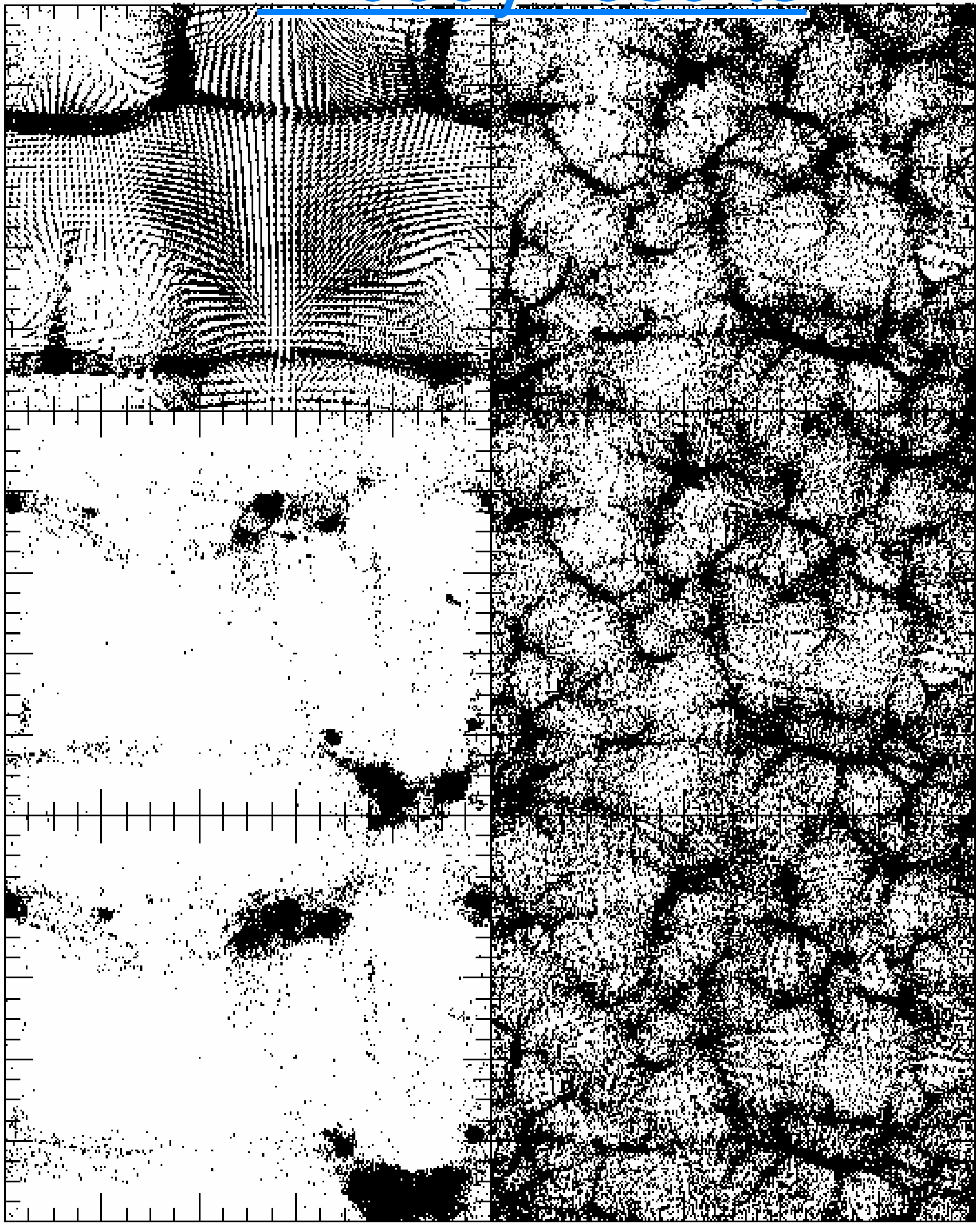
$$g_N \sim G\delta \bar{M}/(ax)^2$$

→ g_N decreases with time if $\delta \sim t^\alpha$ with $\alpha < 2$.

In linear Newtonian theory, $\alpha \leq 1$ and so at early enough times $g_N > g_0$ and the fluctuations would be in the Newtonian regime. At later times g_N drops below g_0 and the fluctuations enter the MOND regime.

the power-index in the MOND regime is $n_{mond} = -1$.

N-body results



A lot more work needs to be done.

We still do not know how to form structure in MOND.

Bekenstein's relativistic TeVes is hard!

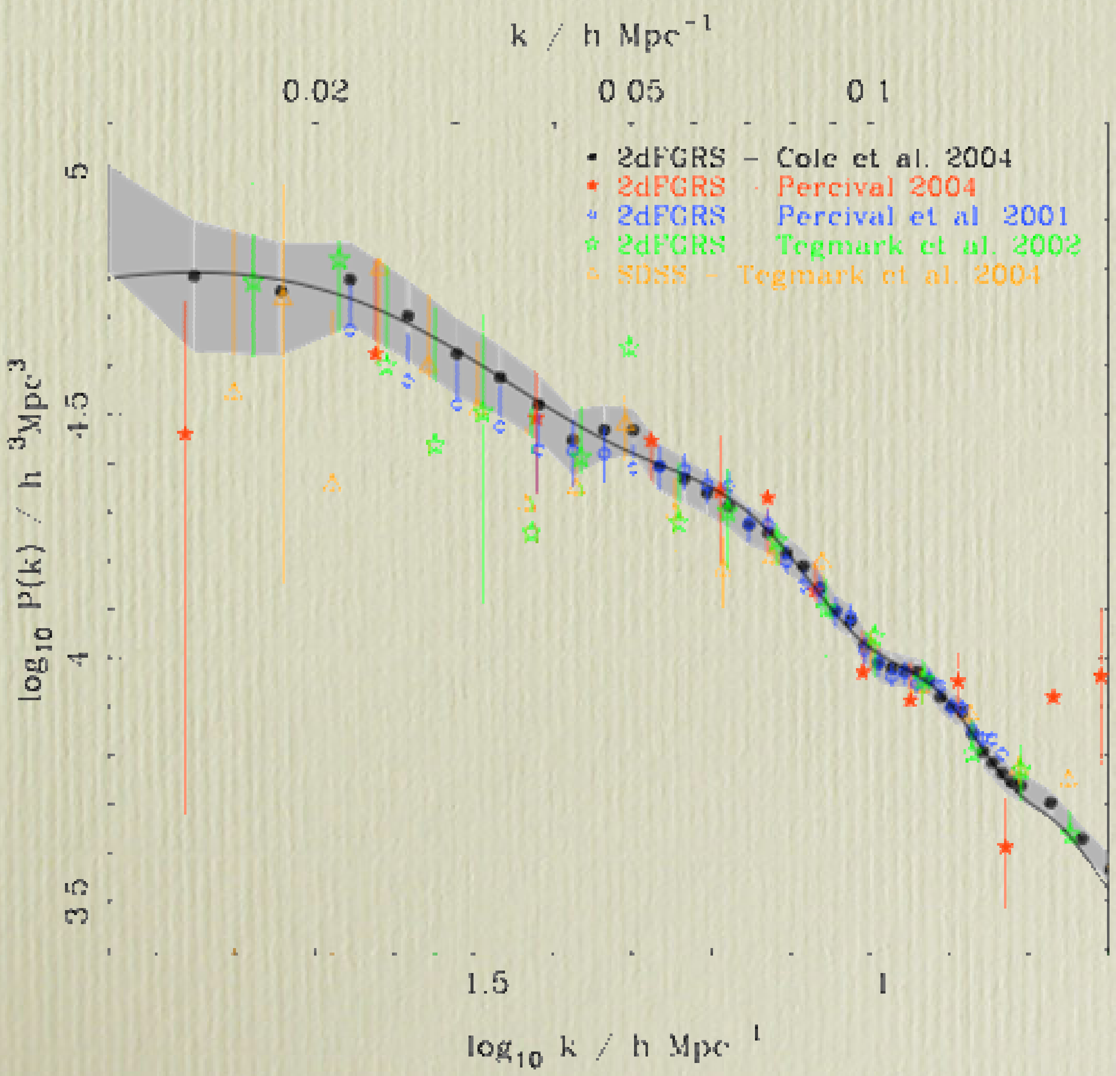
Back to Dark Matter

There is a strong case for the LCDM, but there are some annoying *anomalies*!

Can a simple modification of the physics in the dark sector resolve these anomalies?

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, Ivan Baldry, Joss Bland-Hawthorn, Terry Bridges, Russell Cannon, Matthew Colless, Chris Collins, Warrick Couch, Nicholas J.G. Cross[1,2], Gavin Dalton, V.R. Eke[1], Roberto De Propris, Simon P. Driver, George Efstathiou, Richard S. Ellis, Karl Glazebrook[1], Carole Jackson, Adrian Jenkins, Ofer Lahav, Ian Lewis, Stuart Lumsden, Steve Maddox, Darren Madgwick, Bruce A. Peterson, Will Sutherland[12], Keith Taylor[13] (The 2dF-GRS Team)



$$\Omega_m = 0.231 \pm 0.021$$

$$\Omega_b = 0.042 \pm 0.002$$

$$h = 0.766 \pm 0.032$$

$$n_s = 1.027 \pm 0.050.$$

Anomalies of the ΛCDM model

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

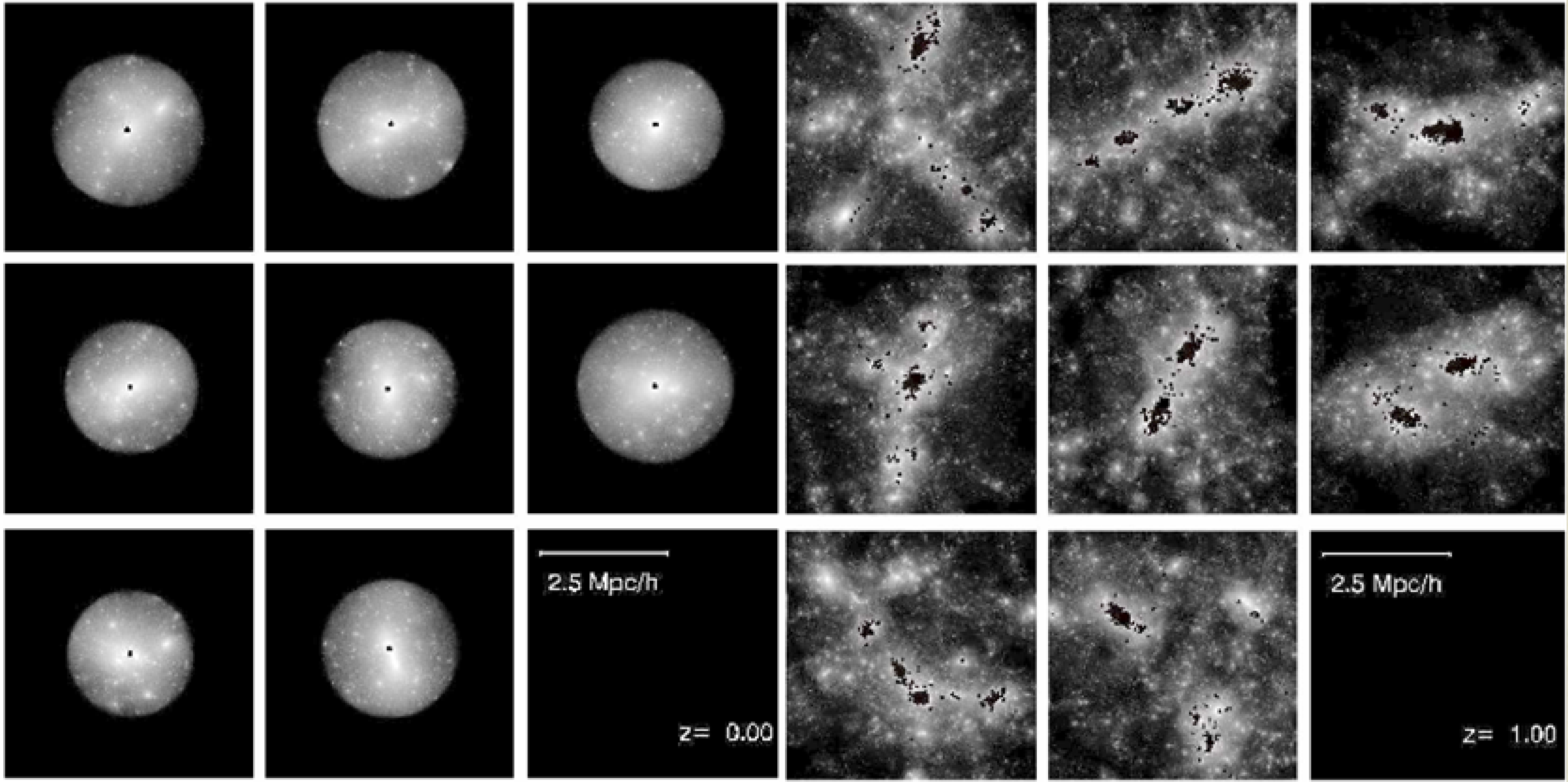


Fig. 2.— Images of the mass distribution at $z = 0, 1$ and 3 in our 8 simulations of the assembly of cluster mass halos. Each plot shows only those particles which lie within r_{200} of halo center at $z = 0$. Particles which lie within $10h^{-1}$ kpc of halo center at this time are shown in black. Each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

STELLAR CHEMICAL SIGNATURES AND HIERARCHICAL GALAXY FORMATION

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Thus, the chemical signatures of most of the dSph stars are distinct from the stars in each of the kinematic components of the Galaxy. This result rules out continuous merging of low-mass galaxies similar to these dSph satellites during the formation of the Galaxy. However, we do not rule out very early merging of low-mass dwarf galaxies, since up to one-half of the most metal-poor stars ([Fe/H] ≤ -1.8) have chemistries that are in fair agreement with Galactic halo stars. We also do not rule out merging with higher mass galaxies, although we note that the LMC and the remnants of the Sgr dwarf galaxy are also chemically distinct from the majority of the Galactic halo stars. Formation of the Galaxy's thick disk by heating of an old thin disk during a merger is also not ruled out; however, the Galaxy's thick disk itself cannot be comprised of the remnants from a low-mass (dSph) dwarf galaxy, nor of a high-mass dwarf galaxy like the LMC or Sgr, because of differences in chemistry.

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 ⟨[Fe/H]⟩ ∼ −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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MATTHIAS STEINMETZ[3]
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VINCENT R. EKE[4]

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

An H I survey of the Centaurus and Sculptor groups

Constraints on the space density of low mass galaxies

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Abstract. We present results of two 21-cm H I surveys performed with the Australia Telescope Compact Array in the nearby Centaurus A and Sculptor galaxy groups. These surveys are sensitive to compact H I clouds and galaxies with H I masses as low as $\sim 3 \times 10^6\ M_\odot$, and are therefore among the most sensitive extragalactic H I surveys to date. The surveys consist of sparsely spaced pointings that sample approximately 2% of the groups' area on the sky. We detected previously known group members, but we found no new H I clouds or galaxies down to the sensitivity limit of the surveys. If the H I mass function had a faint end slope of $\alpha = 1.5$ below $M_{\rm HI} = 10^{7.5}\ M_\odot$ in these groups, we would have expected ~ 3 new objects. Cold dark matter theories of galaxy formation predict the existence of a large number low mass dark matter sub-halos that might appear as tiny satellites in galaxy groups. Our results support and extend similar conclusions derived from previous H I surveys that a H I rich population of these satellites does not exist.

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

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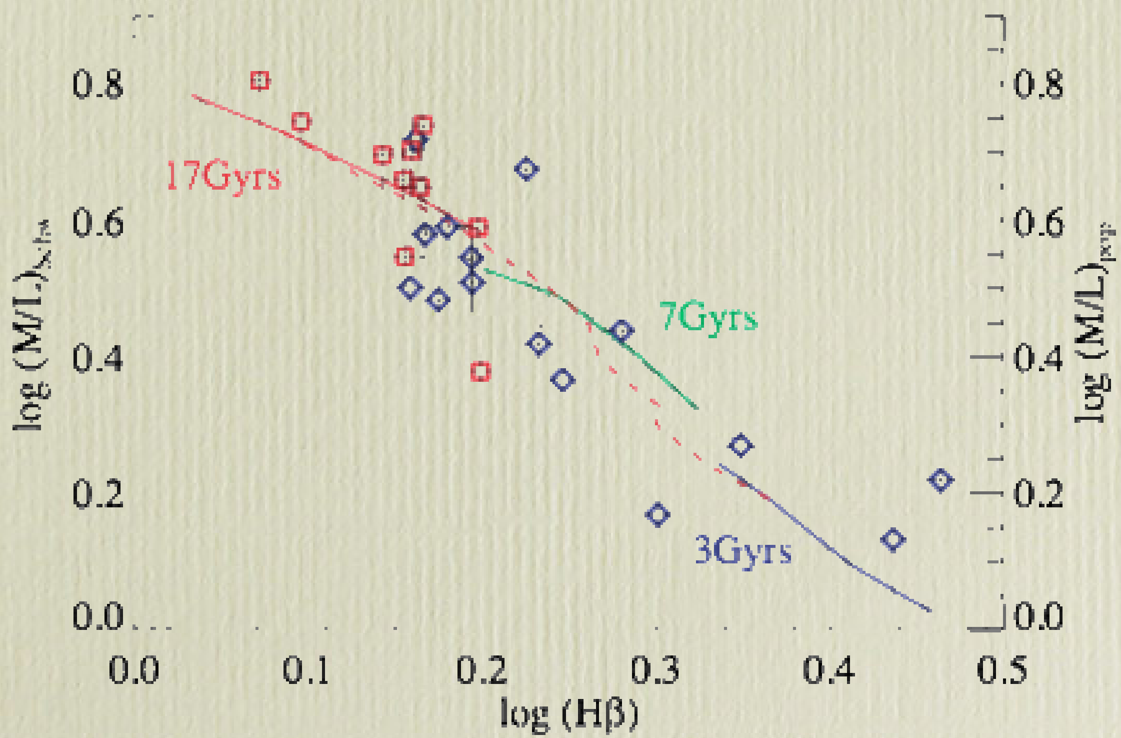

J. B. Oke
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F. Mardirossian et al. (eds.), Clusters and Groups of Galaxies, 99–107.

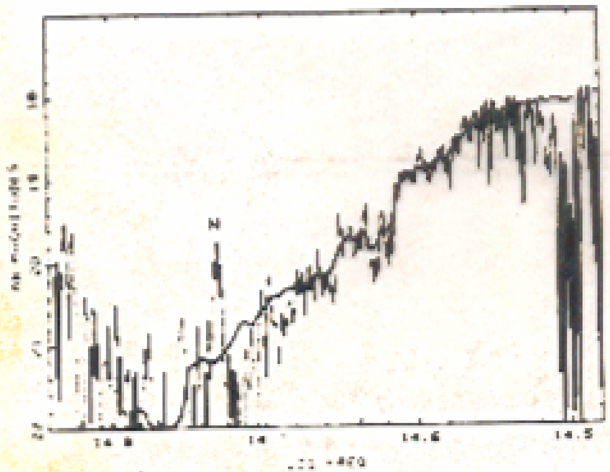


Figure 3. PFUEI observation of 0021.3+0406 at a redshift of z = 0.830.

When all the present data are reduced we will have about 130-140 cluster redshifts in the range z = 0.15 to 0.92; most of them are in the range 0.20 to 0.75. This should be a large enough sample so that the uncertainty in q_o due to the limited sample size should be no more than 0.1 to 0.2.

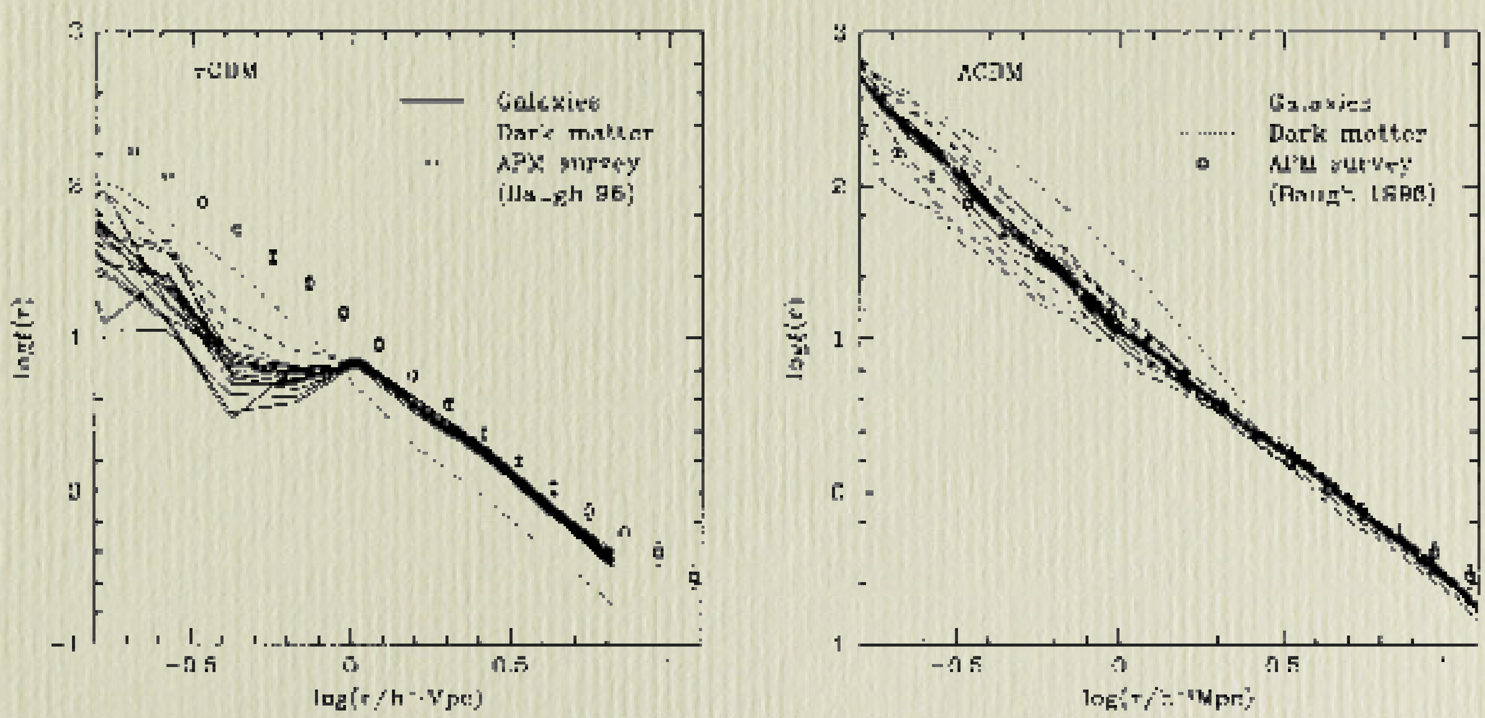
4. EVOLUTIONARY CHANGES

When one looks at the spectra of first-rank cluster galaxies over the whole range of z covered one is impressed by the fact that the vast majority are very similar to each other and to nearby ellipticals. A few percent of the galaxies have such unusual spectra that it is unlikely that they represent simple evolutionary effects. To quantify the

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

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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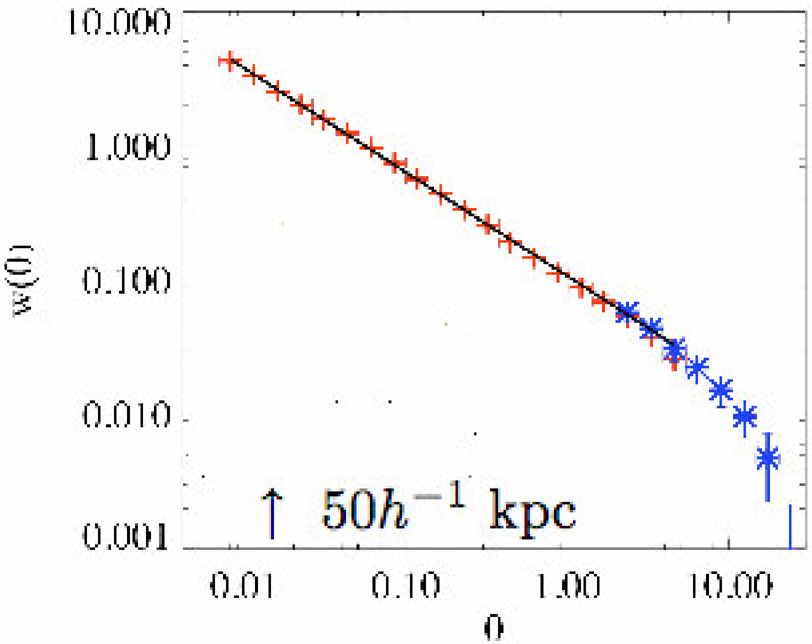
NGC 4676; HST image

Stefan's Quintet; Jayanne English et al.

2MASS



Maller, et al. astro-ph/0304005 analysis of 2MASS

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

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

Lorentz factor
factor

$$S = \int \underbrace{d^3x\, dt \Phi_{,i}\Phi^{,i}} - \sum_{particles} \int \left[\underbrace{M_+(\Phi)\, dt \sqrt{1 - v_+^2}} - \underbrace{M_-(\Phi)\, dt \sqrt{1 - v_-^2}} \right]$$

kinetic term of the field

relativistic Lagrangian of a particle

Text book: Landau & Lifshitz, *mechanics*

$$S = \int \mathrm{d}^3x\,\mathrm{d}t\,\Phi_{,i}\Phi^{,i} - \sum_{particles} \int \left[M_+(\Phi)\,\mathrm{d}t\sqrt{1 - v_+^2} + M_-(\Phi)\,\mathrm{d}t\sqrt{1 - v_-^2} \right]$$

$$= \int \mathrm{d}^3x\,\mathrm{d}t\,\Phi_{,i}\Phi^{,i} - \int \mathrm{d}^3\mathbf{x}\,\mathrm{d}t \Big[\underbrace{\sqrt{1 - v_+^2}\; n_+(\mathbf{x}) M_+(\Phi) + \sqrt{1 - v_-^2}\; n_-(\mathbf{x}) M_-(\Phi)}_{V(\Phi)} \Big]$$

If $\quad \dfrac{\mathrm{d}M_+}{\mathrm{d}\Phi} < 0\,, \qquad \dfrac{\mathrm{d}M_-}{\mathrm{d}\Phi} > 0$

$\Longrightarrow$ to minimize the energy the field will acquire large values where there are (+) particles and smaller values where there are (-) particles $\Longrightarrow$ attractive force between like particles, repulsive force between unlike particles.

The particle equation of motion $\qquad \dfrac{1}{\sqrt{1 - v_\pm^2}} \dfrac{\mathrm{d}}{\mathrm{d}t} \left[\dfrac{M_\pm(\Phi)\mathbf{v}_\pm}{\sqrt{1 - v_\pm^2}} \right] = \nabla M_\pm(\Phi) = \dfrac{\mathrm{d}M_\pm}{\mathrm{d}\Phi} \nabla\Phi$

The Brandenberger-Vafa choice

Two non-relativistic species: $M_{-} = M_{0-} - y_{+}\Phi \; ; M_{-} = M_{0-} + y_{-}\Phi$

Minimization of the action gives the quasi-stationary solution:

$$\nabla^2\Phi = -y_{+}n_{+}(\mathbf{x}) + y_{-}n_{-}(\mathbf{x})$$

$$F_{\pm} = y_{\pm}\nabla\Phi$$

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

The "screening" mechanism

The (-) particles are relativistic and the (+) are not:

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

In this case $$\nabla^2\Phi = -y n_{DM}(r) + y_s \bar{n}_s < \sqrt{1 - v_s^2} >$$

The energy of a relativistic particle is $\epsilon_s = M_s/\sqrt{1-v^2} = y_s\Phi/\sqrt{1-v^2}$

$$\Longrightarrow < \sqrt{1 - v^2} > = y_s\Phi/\epsilon_s$$

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

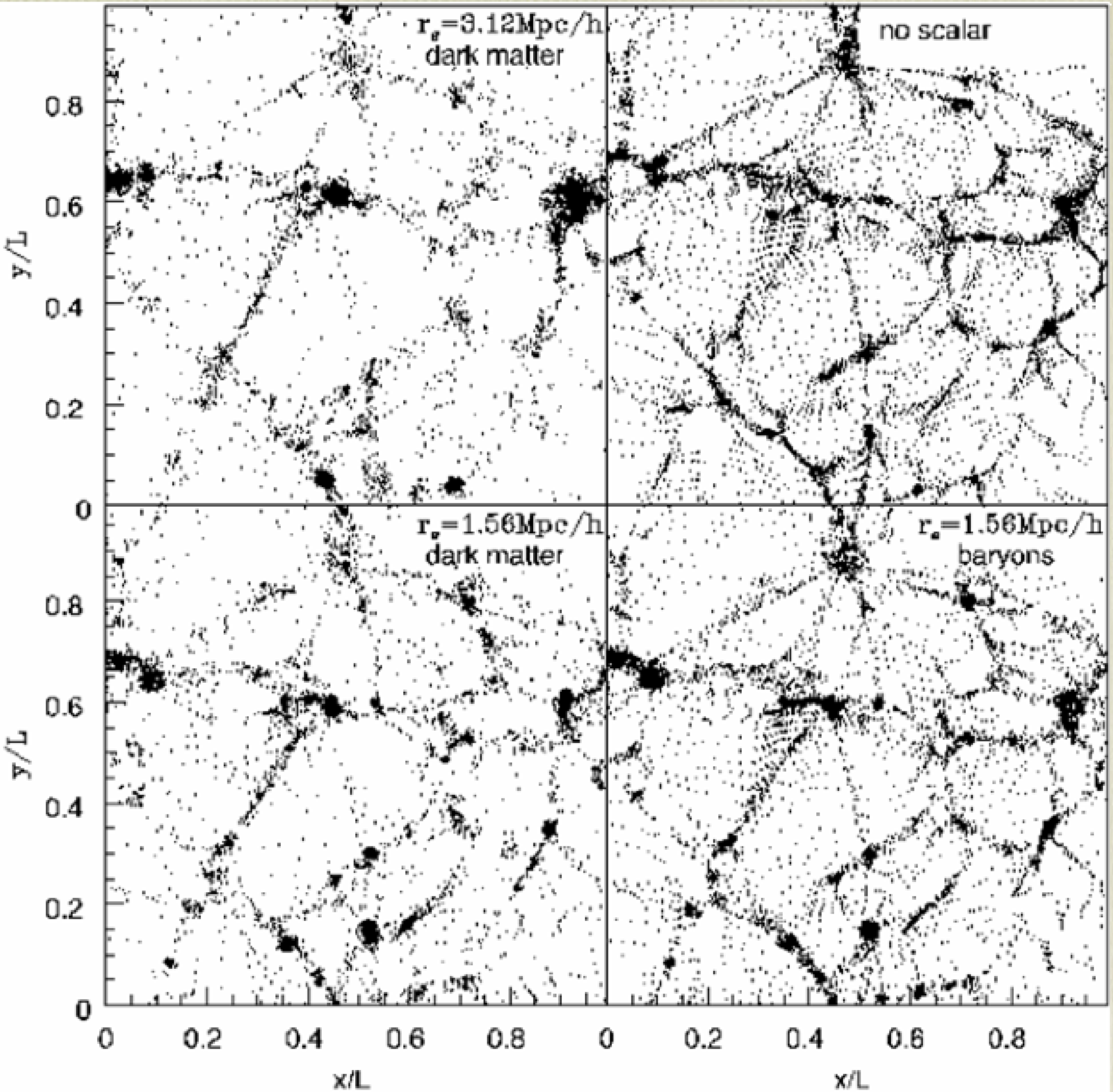
$$r_s = \sqrt{\epsilon_s/y_s^2 \bar{n}_s} \propto a(t)$$

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

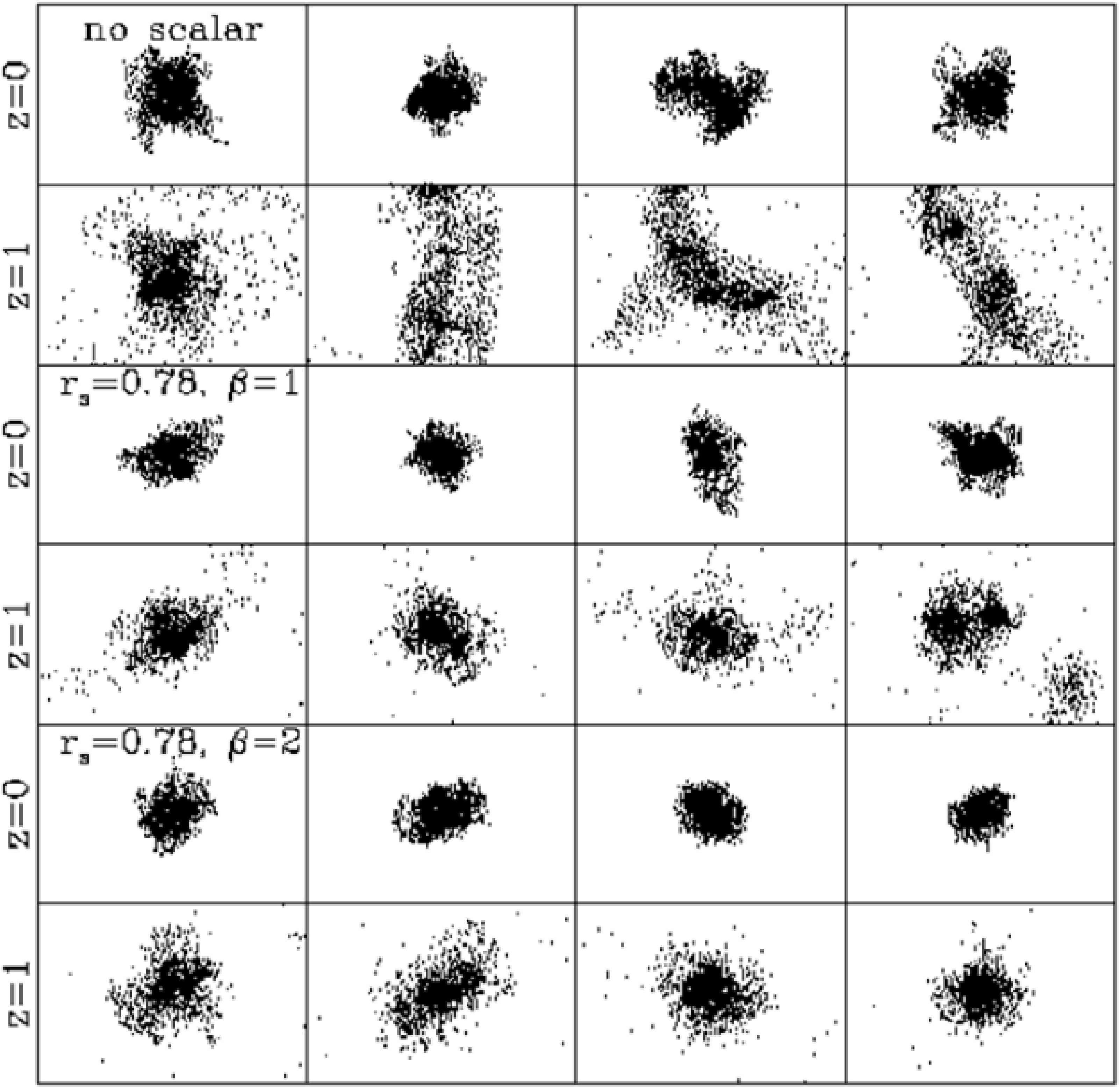
The scalar attraction force between two DM particles is

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

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
x/L


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

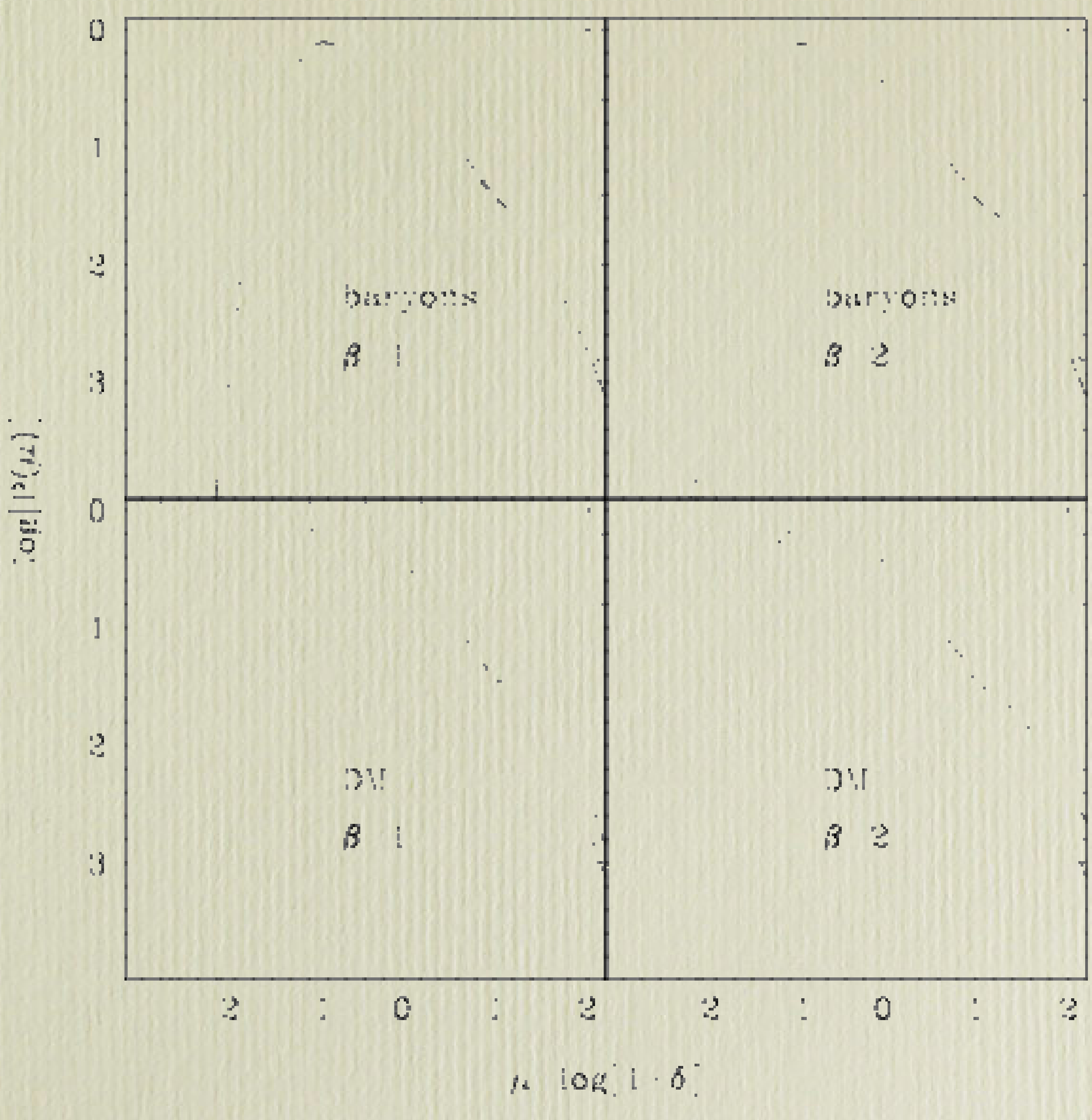
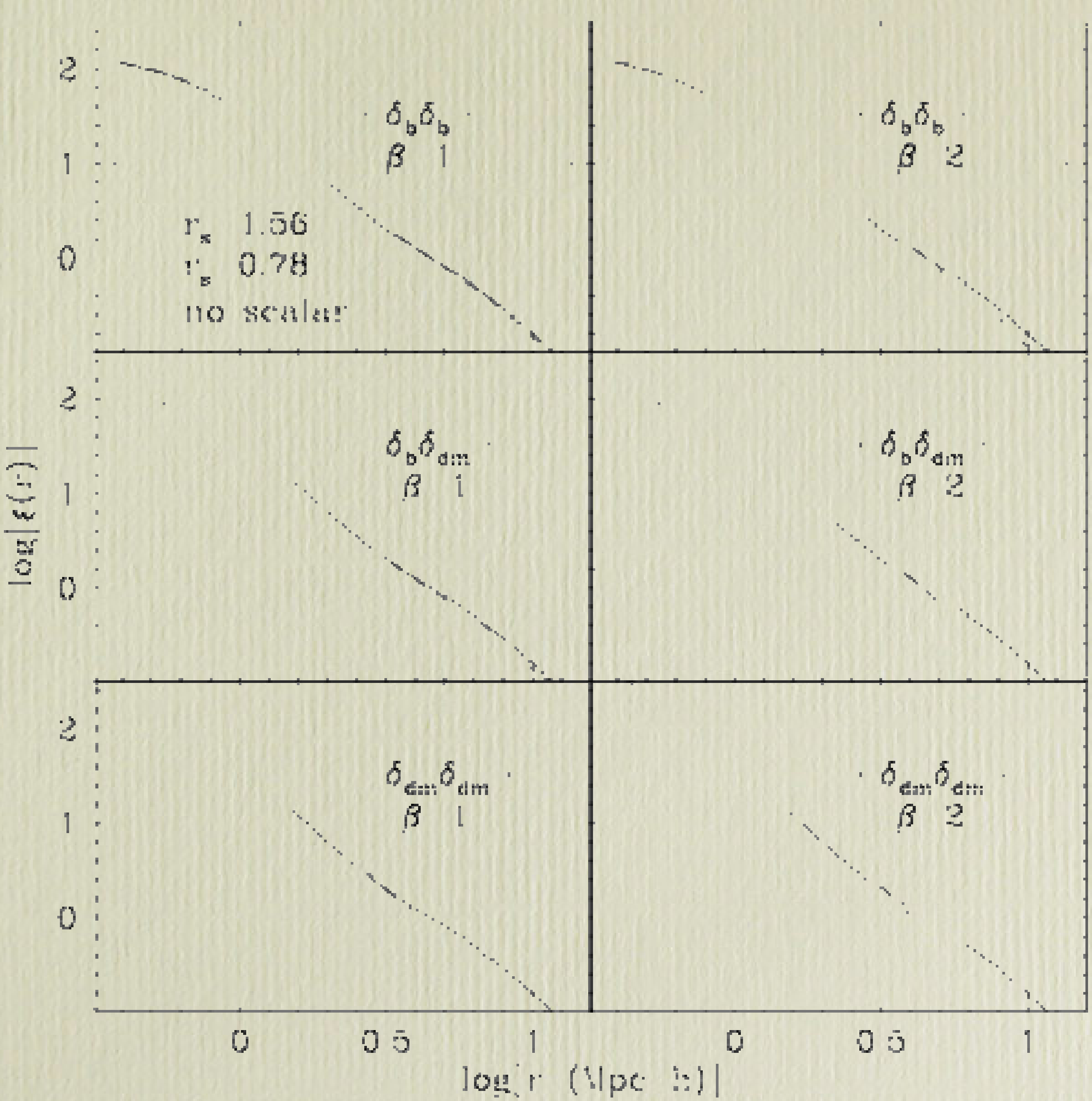
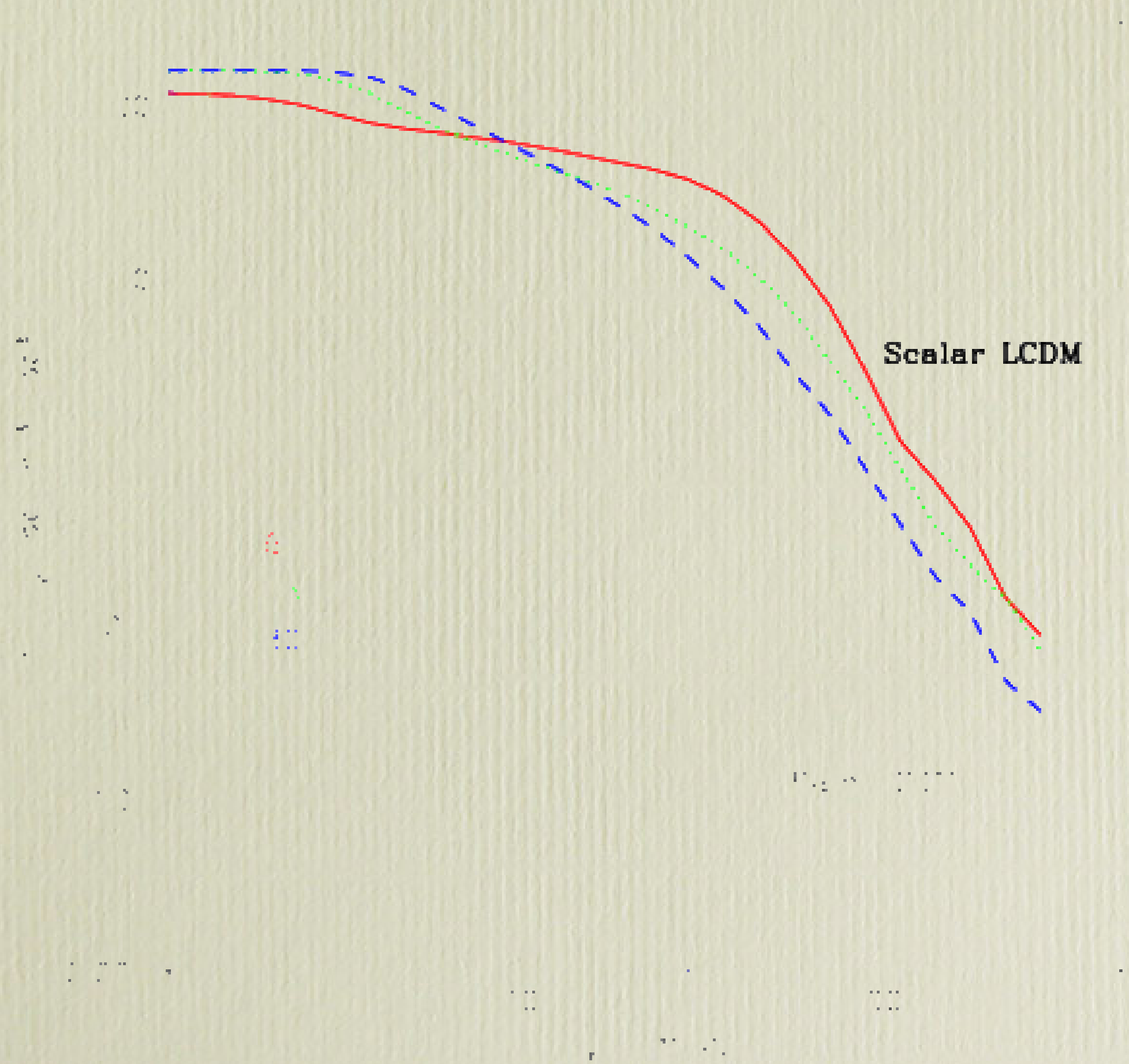


FIG. 3: The distributions of the density contrasts in dark matter and baryons smoothed with a top-hat spherical window of radius $1.5h^{-1}$ Mpc at the present epoch. The standard model is the solid curve, the dotted curve shows the effect of the scalar force with $r_s = 0.78h^{-1}$ Mpc, and the dashed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



r_s 1.56
r_s 0.78
no scalar
δ_b δ_b
β 1
δ_b δ_b
β 2
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)|
0
0.5
1

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



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