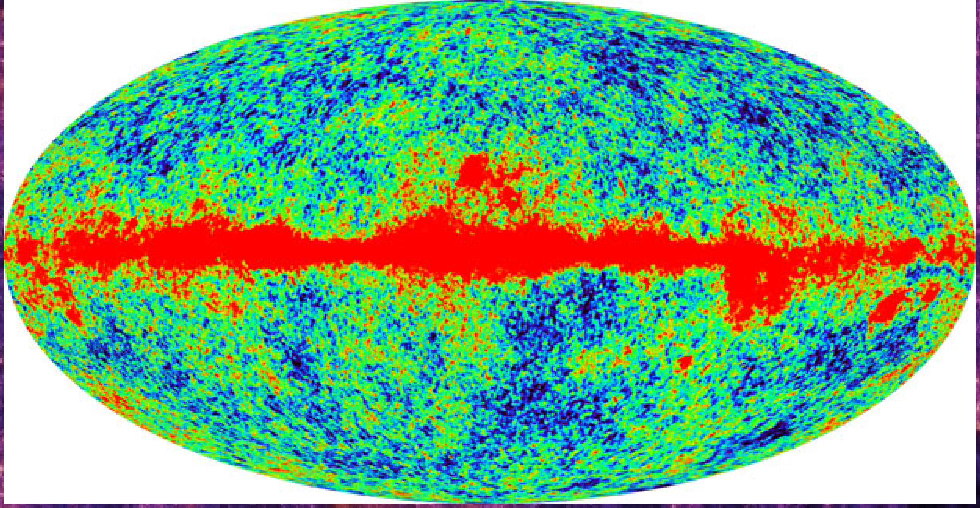

Dark Matter – a debate

Simon White
Max Planck Institut für Astrophysik

Dark Matter..

..is the dominant material constituent by mass of all objects larger than individual galaxies. It has so far been inferred only from its gravitational effects

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If yes, what is it made of?

Dark Matter..

..is the dominant material constituent by mass of all objects larger than individual galaxies. It has so far been inferred <u>only</u> from its gravitational effects

Does it exist, or is our theory of gravity wrong?

If yes, what is it made of?

Could it be a new kind of elementary particle?

Elementary particle Dark Matter?

- Neutron: Need identified by Ambartsumian & Ivenko 1930

  Existence verified by Chadwick 1932

- Neutrino: Need identified by Pauli 1930

  Existence verified by Cowan & Reines 1956

- Dark matter: Need identified by Zwicky 1933

  All known particle candidates excluded 1983

  Existence verified by ???? > 2010?

Astronomical detections by gravity

- Neptune: Predicted by LeVerrier and Adams 1846

  Existence verified by Galle 1846

- Vulcan: Predicted by LeVerrier in 1859

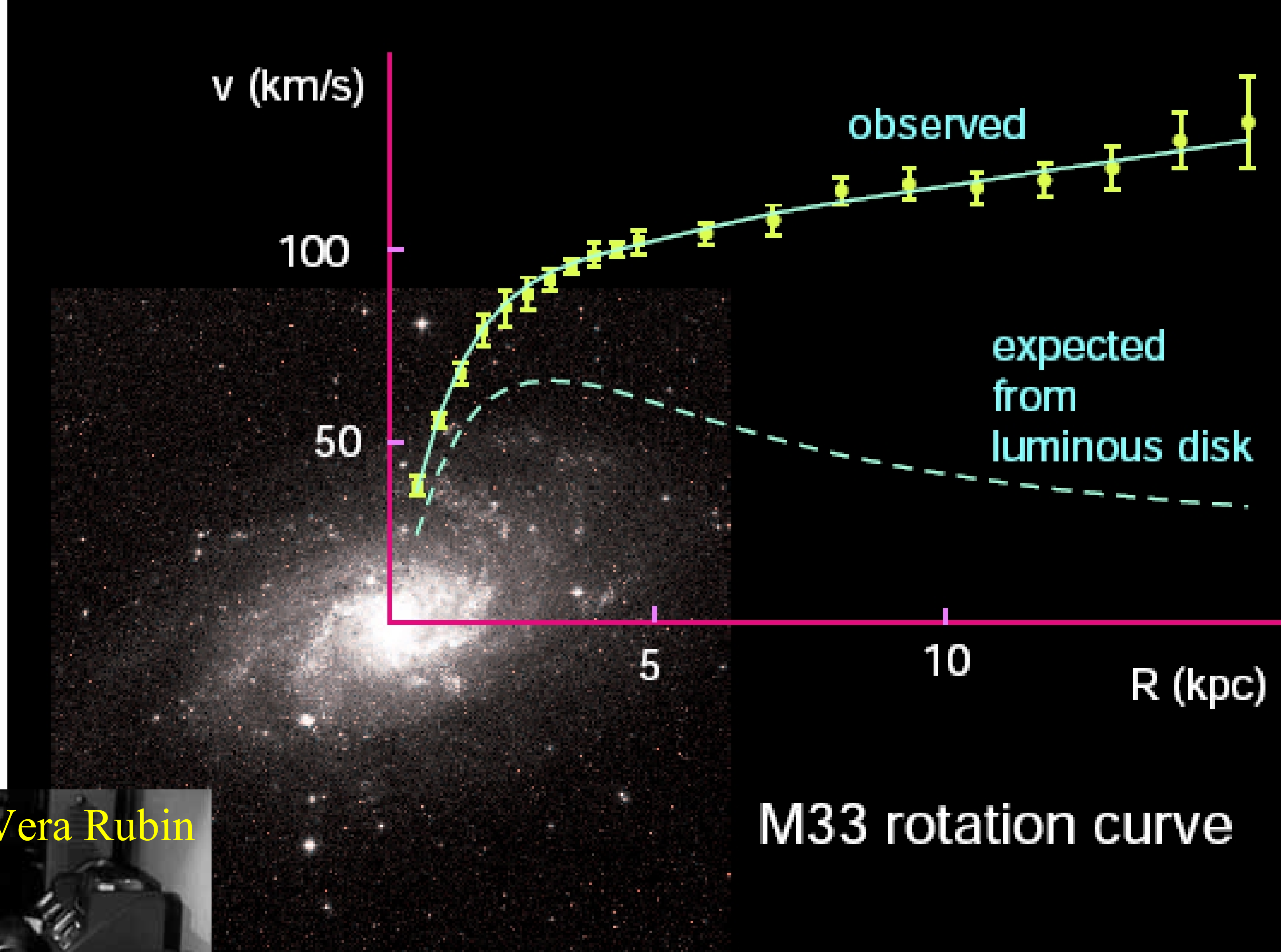
  Perihelion advance explained by Einstein 1915

- Extrasolar planets: ~400 out of the ~500 known found only through gravitational effects on their stars

- Supermassive black holes: detected only through motions of the surrounding stars

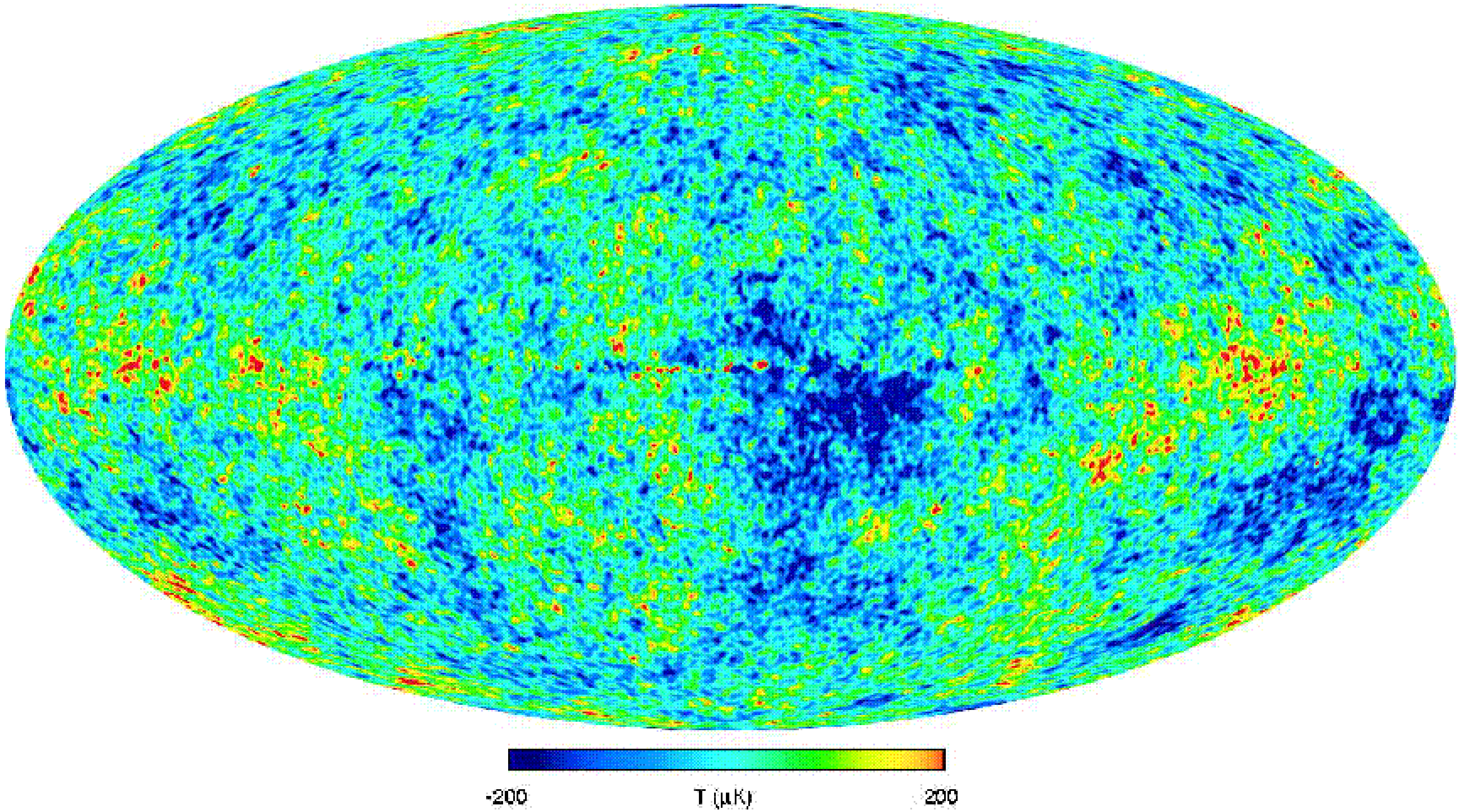
The Coma Galaxy Cluster

The Triangulum Nebula (M33)


v (km/s)
100
50
5
10
R (kpc)
observed
expected
from
luminous disk
M33 rotation curve


Vera Rubin

The *WMAP* of the whole CMB sky



Bennett et al 2003

The *WMAP* 7-year power spectrum

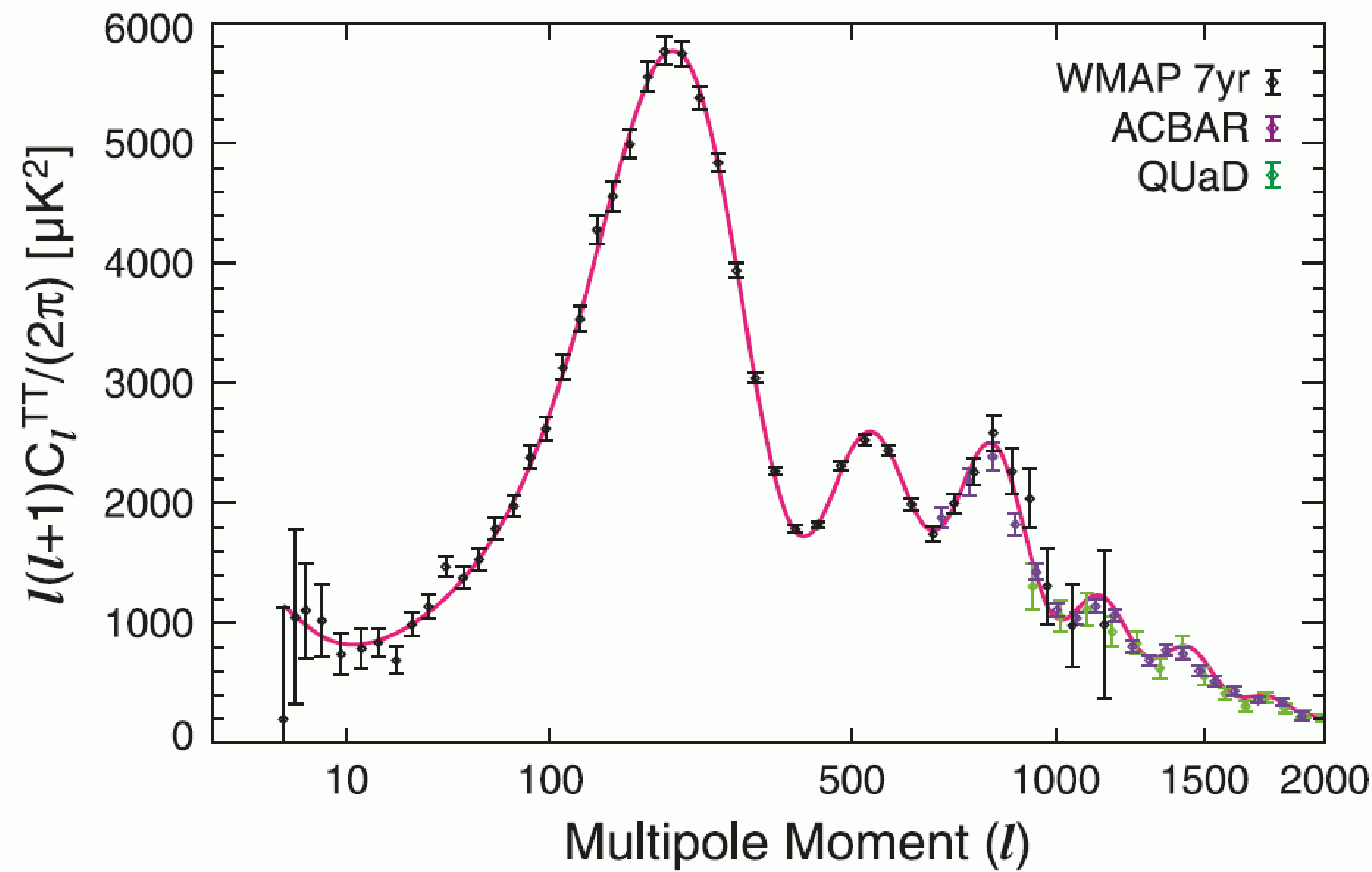


TABLE 1

SUMMARY OF THE COSMOLOGICAL PARAMETERS OF ΛCDM MODEL[a]

Class	Parameter	*WMAP* 7-year Mean[c]	*WMAP*+BAO+H_0 Mean
Primary	$100\Omega_b h^2$	$2.249^{+0.056}_{-0.057}$	2.255 ± 0.054
	$\Omega_c h^2$	0.1120 ± 0.0056	0.1126 ± 0.0036
	Ω_Λ	$0.727^{+0.030}_{-0.029}$	0.725 ± 0.016
	n_s	0.967 ± 0.014	0.968 ± 0.012
	τ	0.088 ± 0.015	0.088 ± 0.014
	$\Delta^2_{\mathcal{R}}(k_0)$[d]	$(2.43 \pm 0.11) \times 10^{-9}$	$(2.430 \pm 0.091) \times 10^{-9}$
Derived	σ_8	$0.811^{+0.030}_{-0.031}$	0.816 ± 0.024
	H_0	70.4 ± 2.5 km/s/Mpc	70.2 ± 1.4 km/s/Mpc
	Ω_b	0.0455 ± 0.0028	0.0458 ± 0.0016
	Ω_c	0.228 ± 0.027	0.229 ± 0.015
	$\Omega_m h^2$	$0.1345^{+0.0056}_{-0.0055}$	0.1352 ± 0.0036
	$z_{\rm reion}$[e]	10.6 ± 1.2	10.6 ± 1.2
	t_0[f]	13.77 ± 0.13 Gyr	13.76 ± 0.11 Gyr

Komatsu et al 2010 (WMAP7)

Komatsu et al 2010 (WMAP7)

Name	Case	WMAP 7-year	WMAP+BAO+H_0
Grav. Wave[b]	No Running Ind.	$r < 0.36$[c]	$r < 0.24$
Running Index	No Grav. Wave	$-0.084 < dn_s/d\ln k < 0.020$[c]	$-0.061 < dn_s/d\ln k < 0.017$
Curvature	$w = -1$	N/A	$-0.0133 < \Omega_k < 0.0084$
Adiabaticity	Axion	$\alpha_0 < 0.13$[c]	$\alpha_0 < 0.077$
	Curvaton	$\alpha_{-1} < 0.011$[c]	$\alpha_{-1} < 0.0047$
Parity Violation	Chern-Simons[d]	$-5.0^\circ < \Delta\alpha < 2.8^\circ$[e]	N/A
Neutrino Mass[f]	$w = -1$	$\sum m_\nu < 1.3$ eV[c]	$\sum m_\nu < 0.58$ eV[g] ←
	$w \neq -1$	$\sum m_\nu < 1.4$ eV[c]	$\sum m_\nu < 1.3$ eV[h]

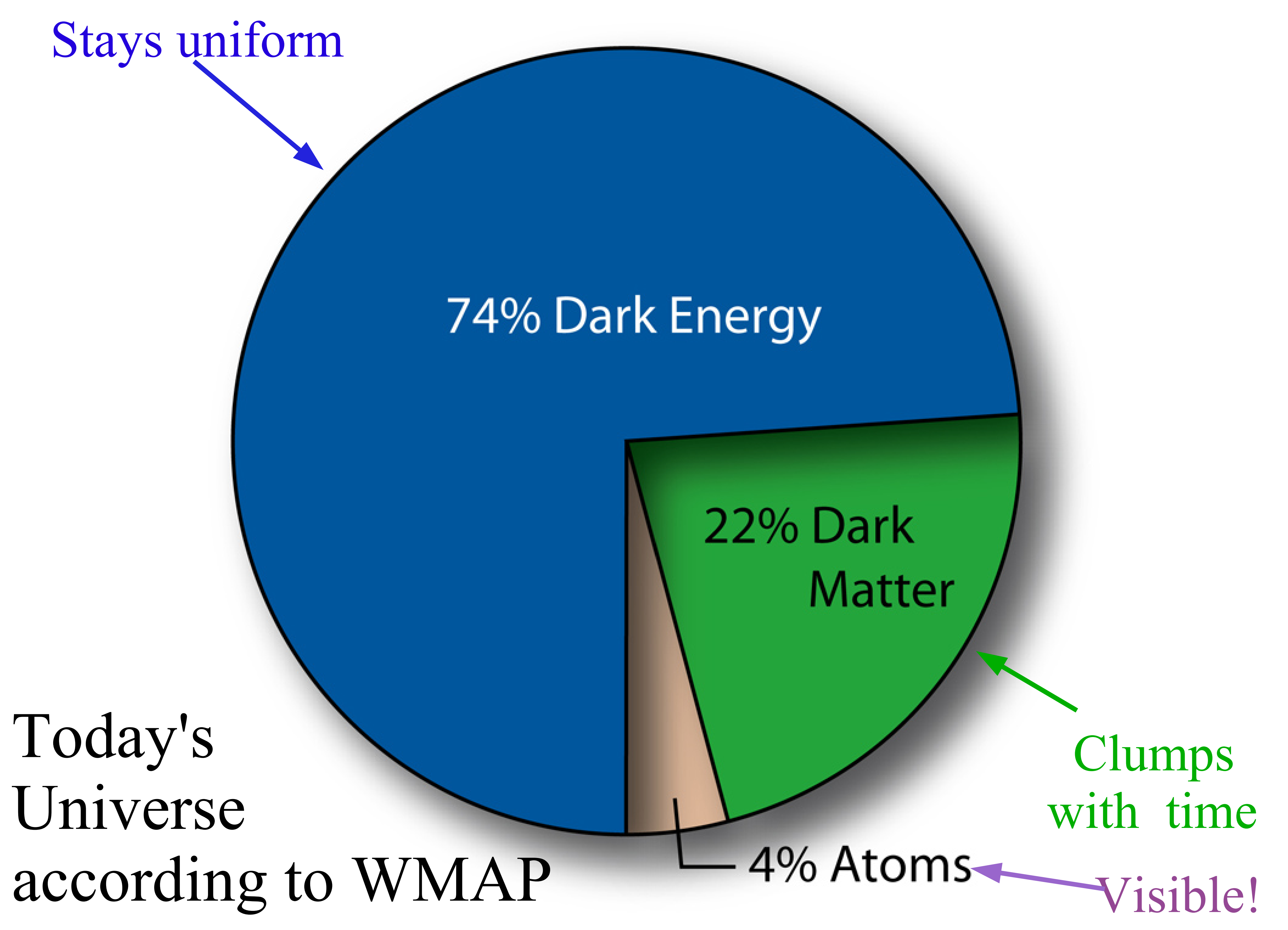
The 95% upper limit on the sum of the neutrino masses does *not* depend on late time structure formation and translates into

$$\Omega_\nu h^2 < 0.0059 = 0.26\,\Omega_{bar} h^2$$

Neutrinos contribute *less* than baryons to the cosmic mass budget

At an age of 400,000 years, the mass-energy content of the Universe was dominated by a nonrelativistic, nonuniform component with only weak/gravitational interactions with the baryon-photon fluid.

This could not consist of neutrinos or any other known elementary particle


Stays uniform
74% Dark Energy
22% Dark Matter
4% Atoms
Clumps with time
Visible!
Today's Universe according to WMAP

Dark matter structure in a ΛCDM Universe

- The growth of dark matter structures in a thin slice

- A flight through the dark matter distribution

Structure in pregalactic gas at high redshift

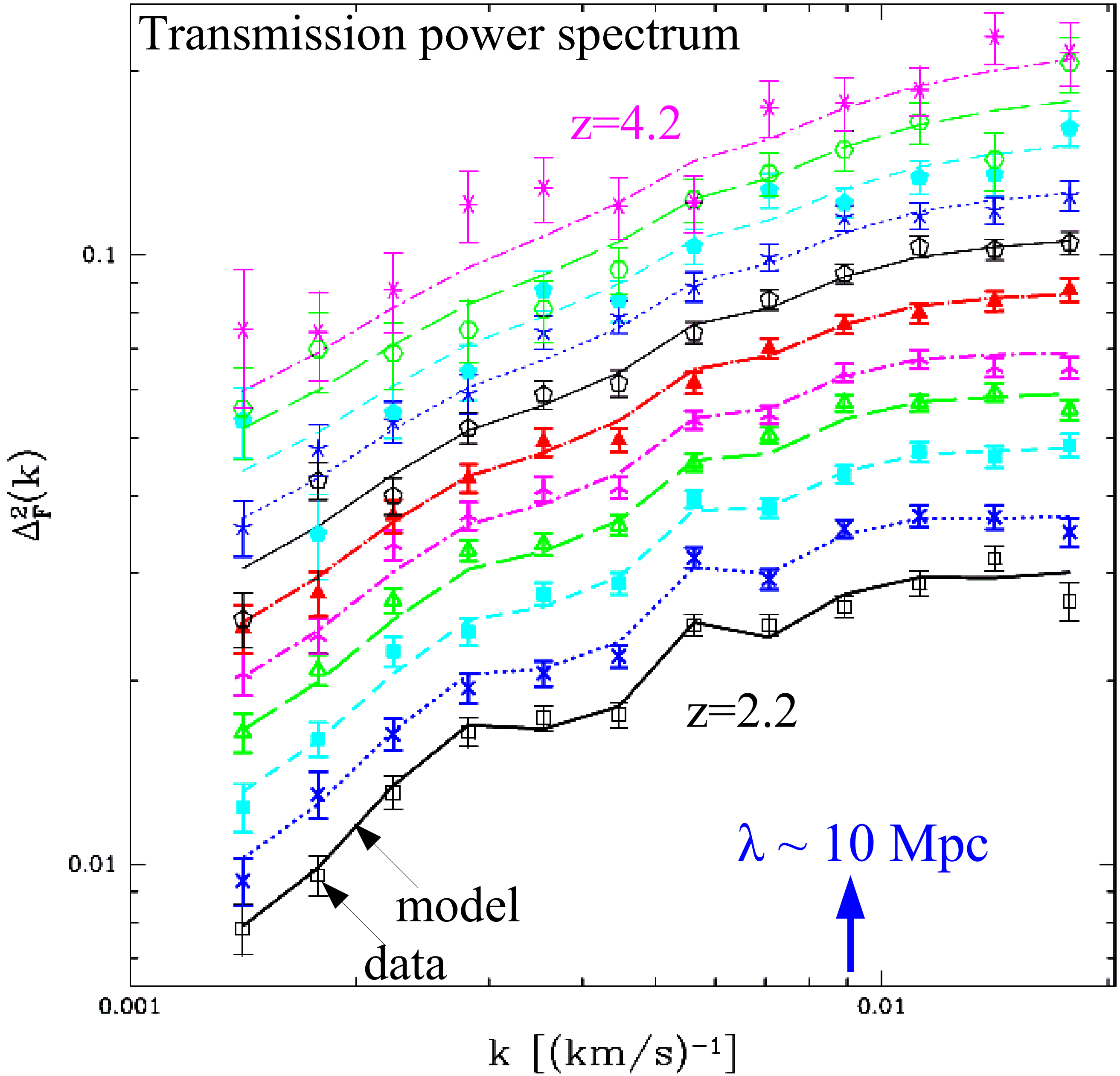
McDonald et al 2005

Diffuse intergalactic gas at high redshift can be observed through its Ly α absorption in QSO spectra

Structure in the absorption is due to fluctuations in the density and gravitationally induced velocity

Data - 3300 SDSS quasars

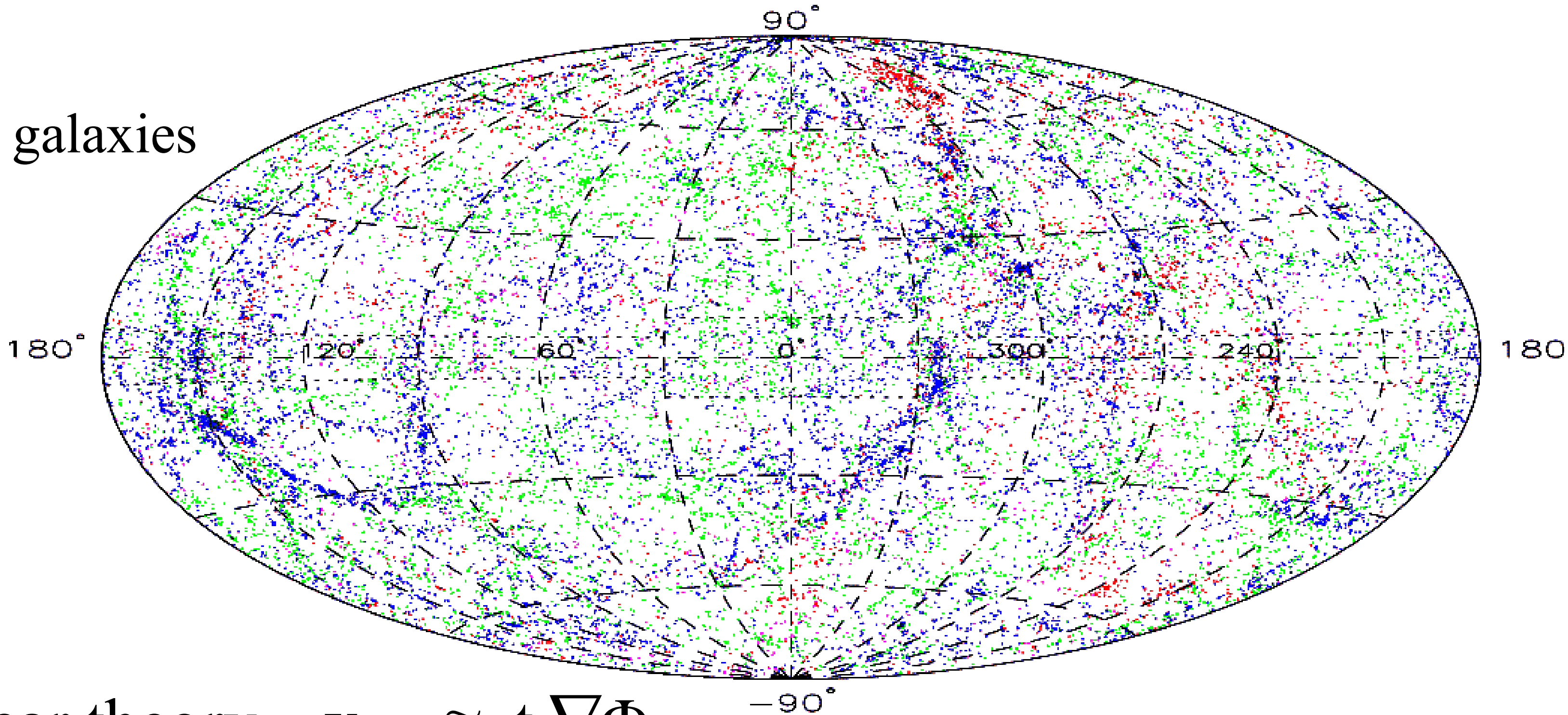
Model - ΛCDM



At redshifts between 4 and 2 the density and velocity perturbations in the diffuse pregalactic baryons are a close match to those expected for Dark-Matter-driven quasilinear growth from the structure seen at $z=1000$

Generation of the Local Group motion: v_{pec}

2MASS galaxies



In linear theory $\mathbf{v}_{pec} \approx t\,\nabla\Phi$

$\mathbf{v}_{pec}$ can be measured from the CMB dipole – 627 ± 22 km/s

$\nabla\Phi$ can be estimated from the galaxy distribution.

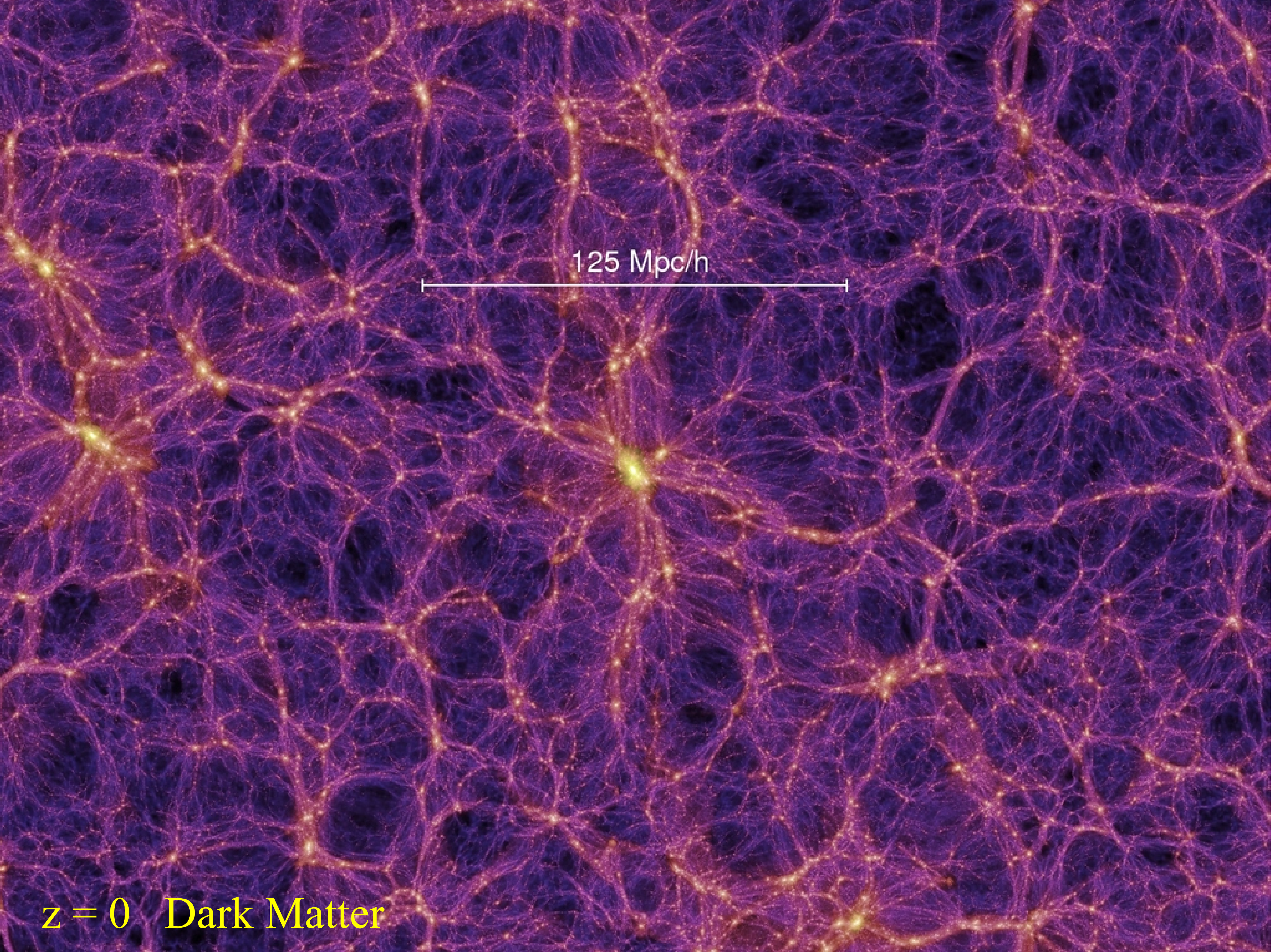
The directions agree to 15 to 20 degrees

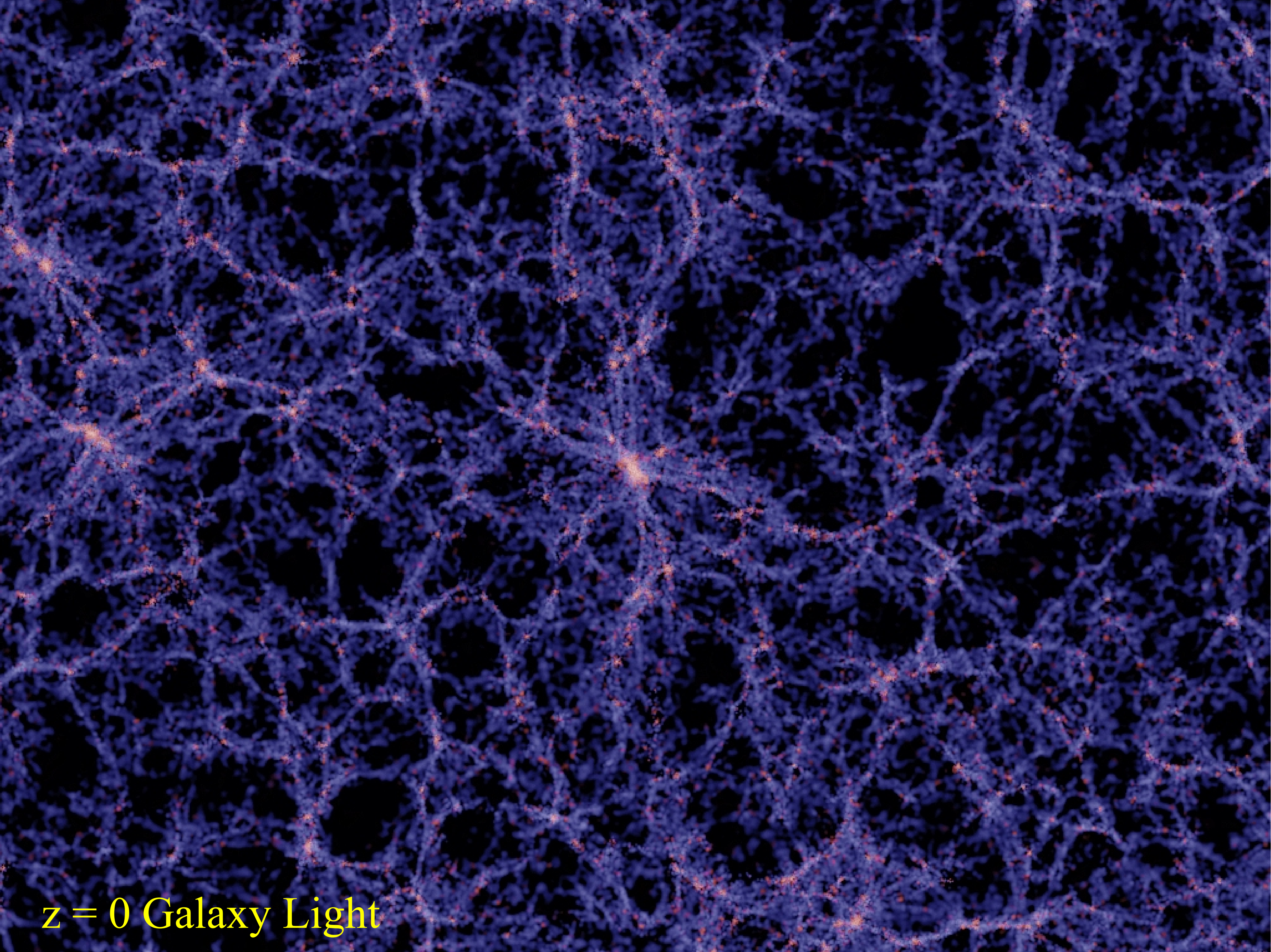
→ $\Omega^{0.6} / b = 0.40 \pm 0.09$ (Erdogdu et al 2006)

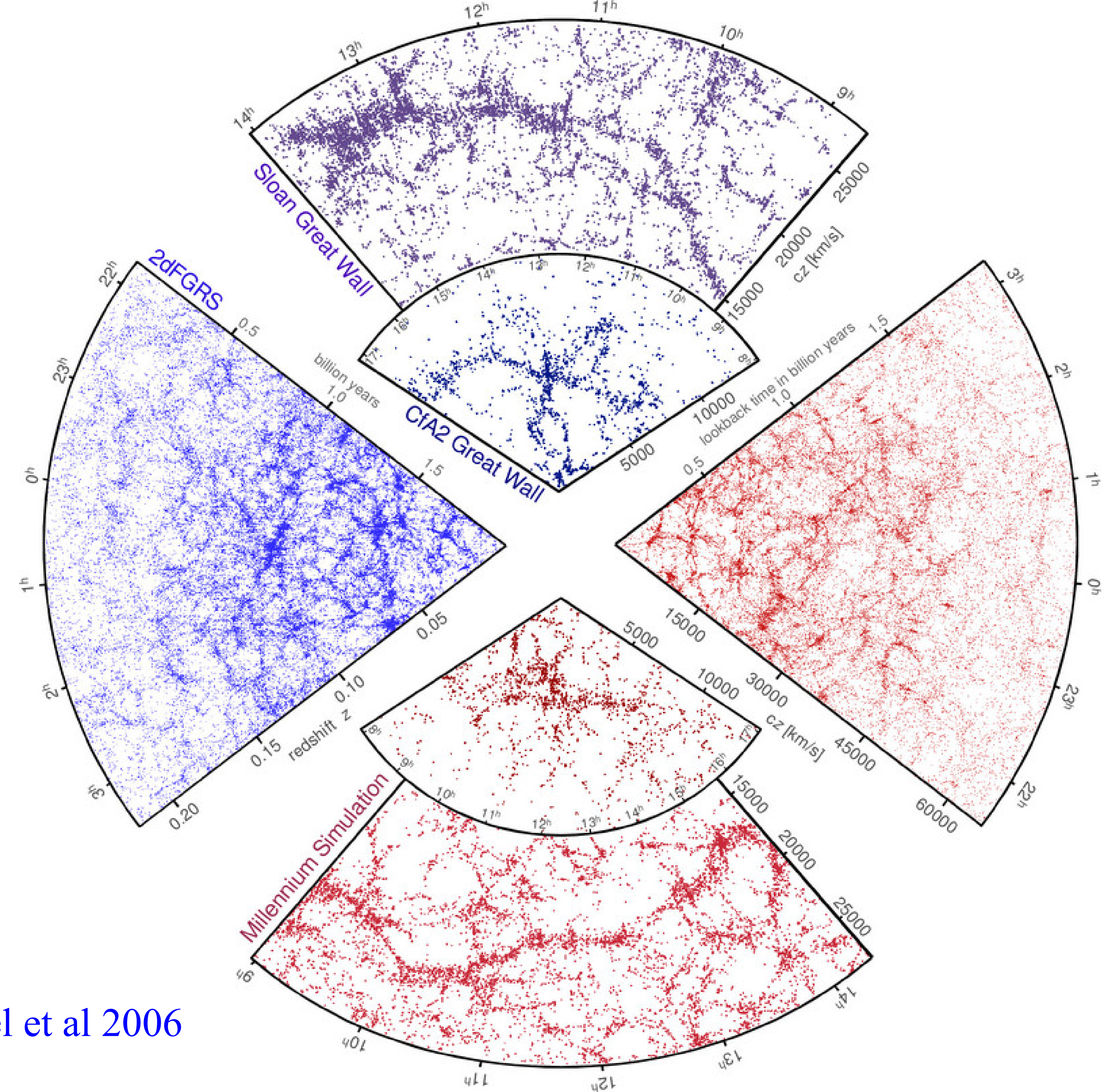
The WMAP/ΛCDM model gives $\Omega^{0.6} / b = 0.36$

The present-day motion of the Milky Way is linked to the large-scale distribution of nearby galaxies as expected for linear growth according to standard gravity in a Universe with the properties inferred from the CMB

The same is true for the overall large-scale velocity field in the local Universe


125 Mpc/h
z = 0 Dark Matter

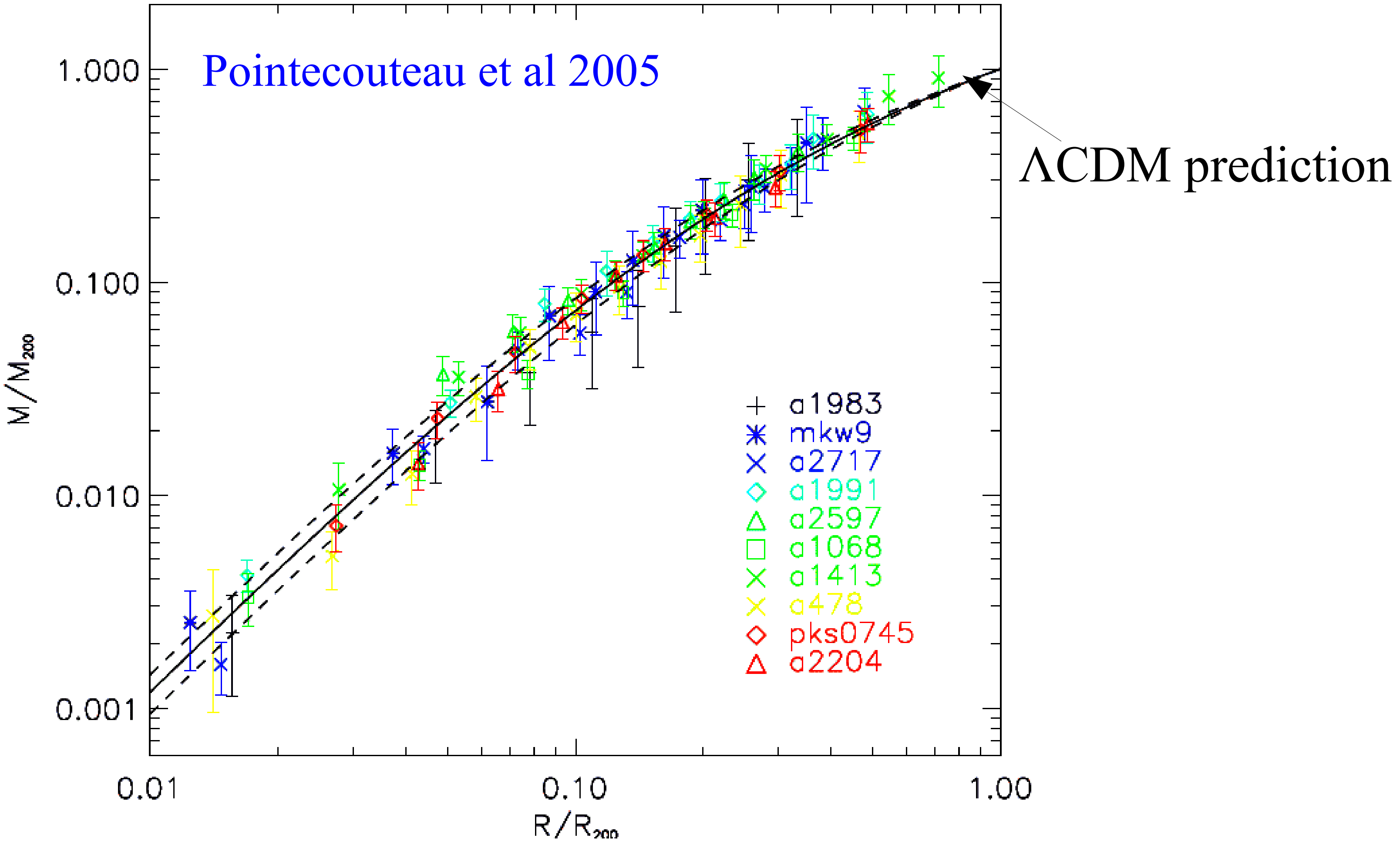

z = 0 Galaxy Light



Springel et al 2006

The statistics of the large-scale distribution of galaxies agree in detail with those predicted for growth according to standard gravity from the IC's seen in the CMB -- assuming that galaxies form through the condensation of gas at the centres of dark matter halos

Mass profiles of clusters from X-ray data



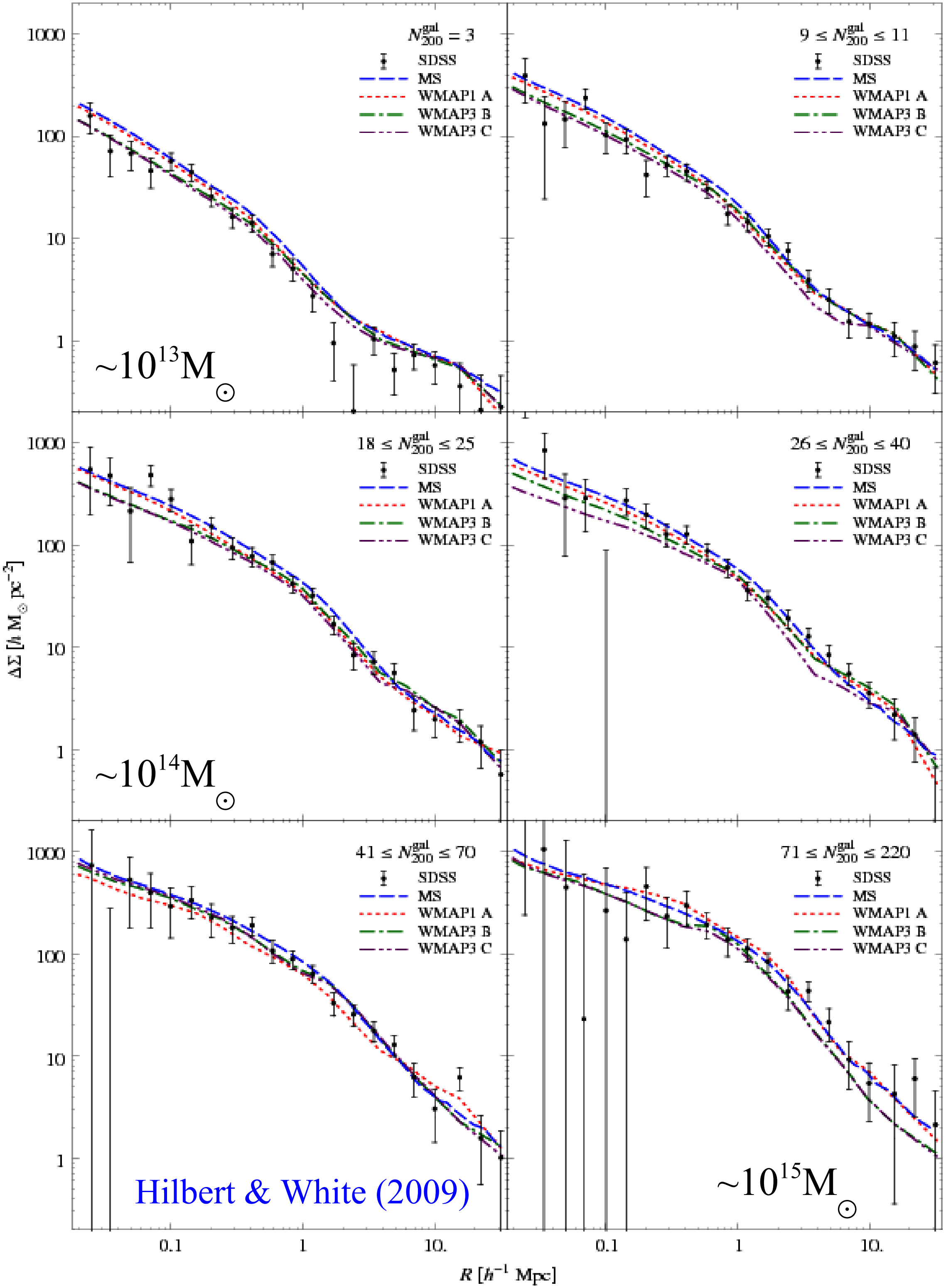
X-ray telescopes measure ρ(r) and T(r) for the hot gas in clusters

Hydrostatic equilibrium → M(r) for standard gravity

Measured mass profile agrees well with ΛCDM prediction

The Galaxy Cluster, Abell 2218

Galaxy formation simulations fit low-z groups and clusters



The simulated cluster population fits the *detailed* shape of the mean mass profile of groups and clusters as a function of richness

This holds for total masses

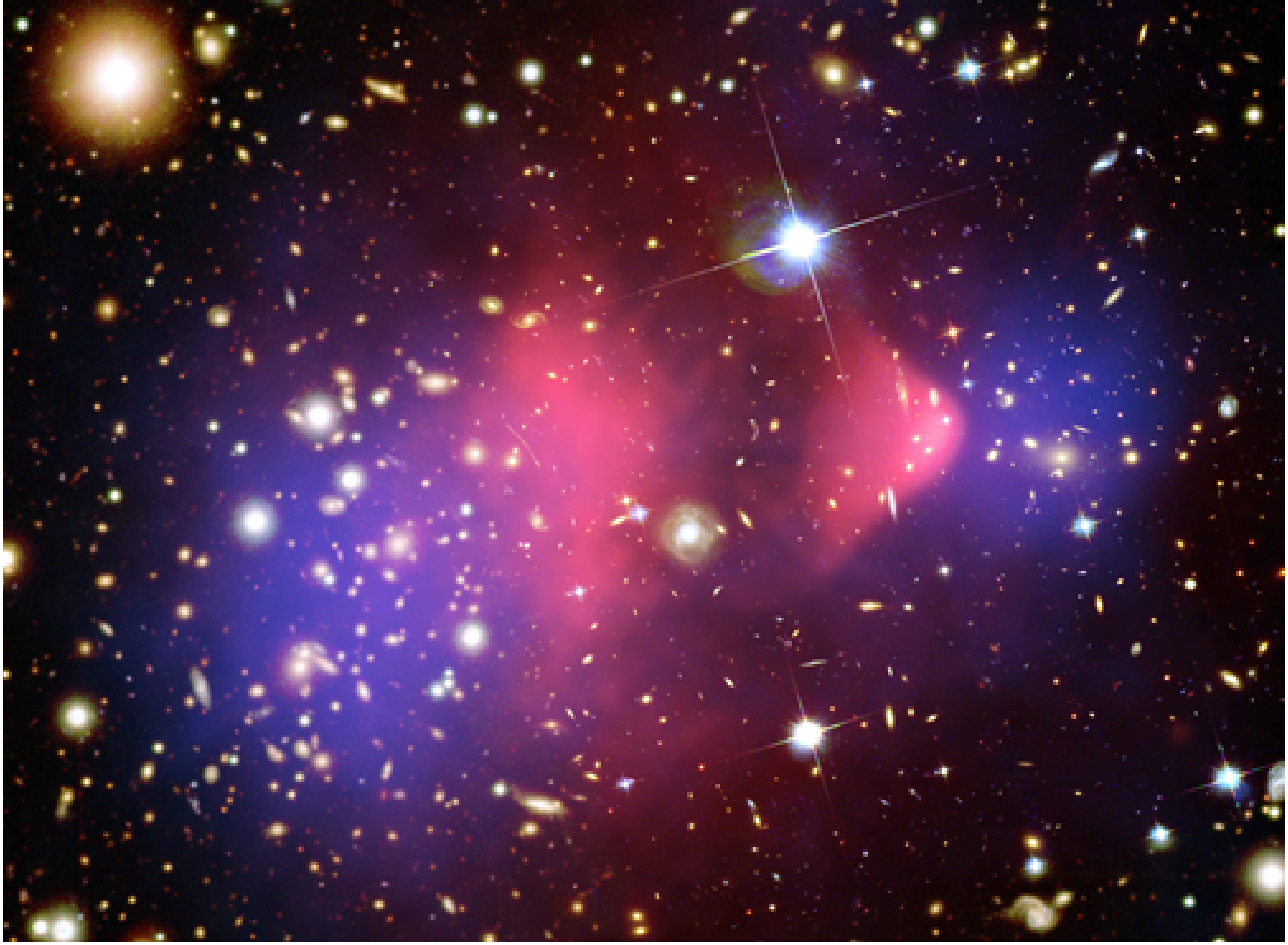
$$10^{13}\ M_\odot \le\ M_{200}\ \le\ 10^{15}\ M_\odot$$

Lensing data from SDSS/maxBCG (Sheldon et al 2007)

The mass structure of galaxy clusters inferred using standard gravity agrees *in detail* with that predicted by the WMAP/ΛCDM cosmology

This is true whether one uses galaxy motions, hydro-static equilibrium of the gas, or gravitational lensing to infer the mass distribution

Both photons and nonrelativistic particles are affected by the unseen mass exactly as predicted by GR

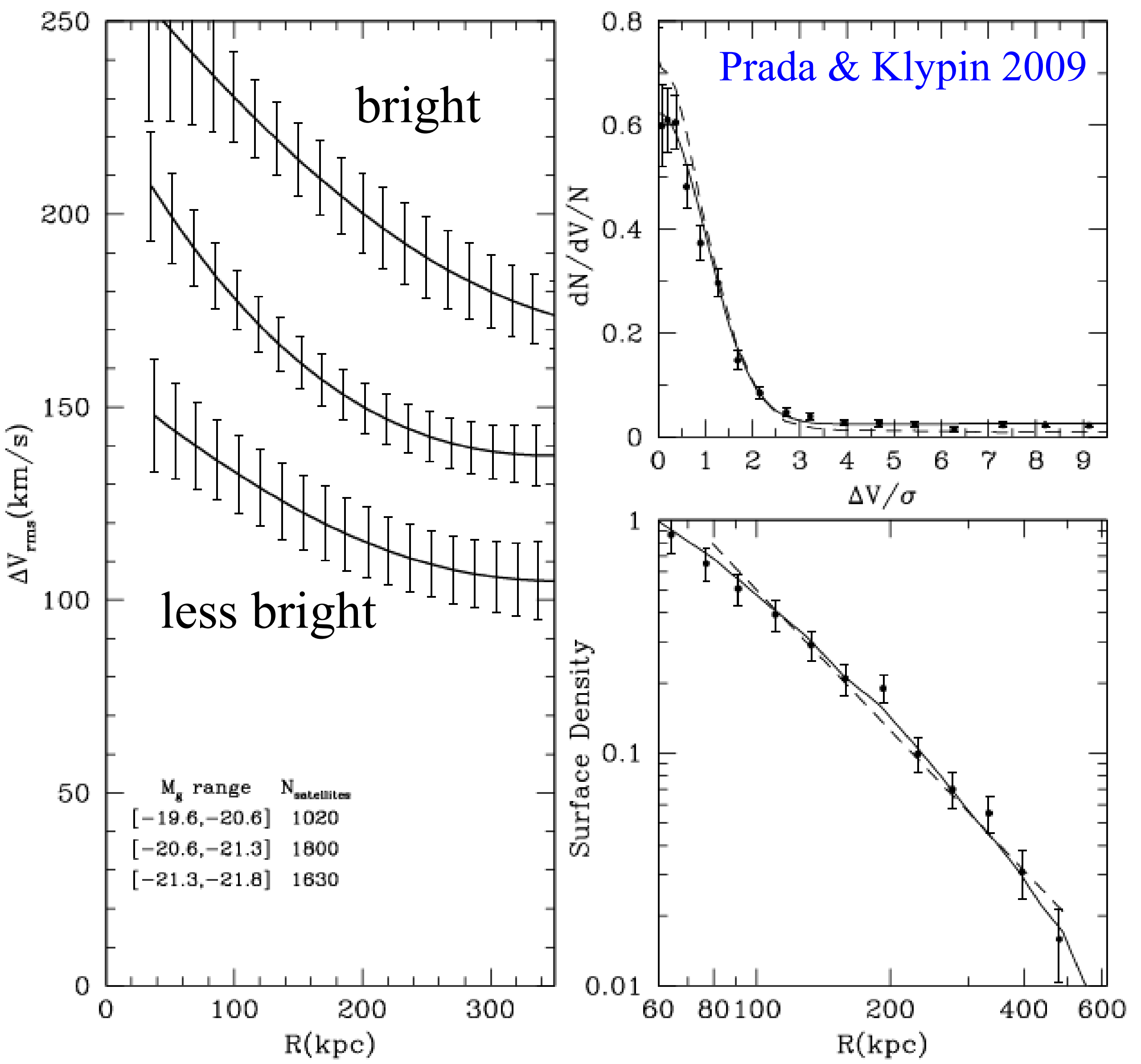


In the “Bullet Cluster” the mass detected by lensing agrees with the positions of the (subdominant) galaxy clumps and *not* with the position of the dominant baryonic component, the X-ray gas

Another, more massive, component must surround the galaxies

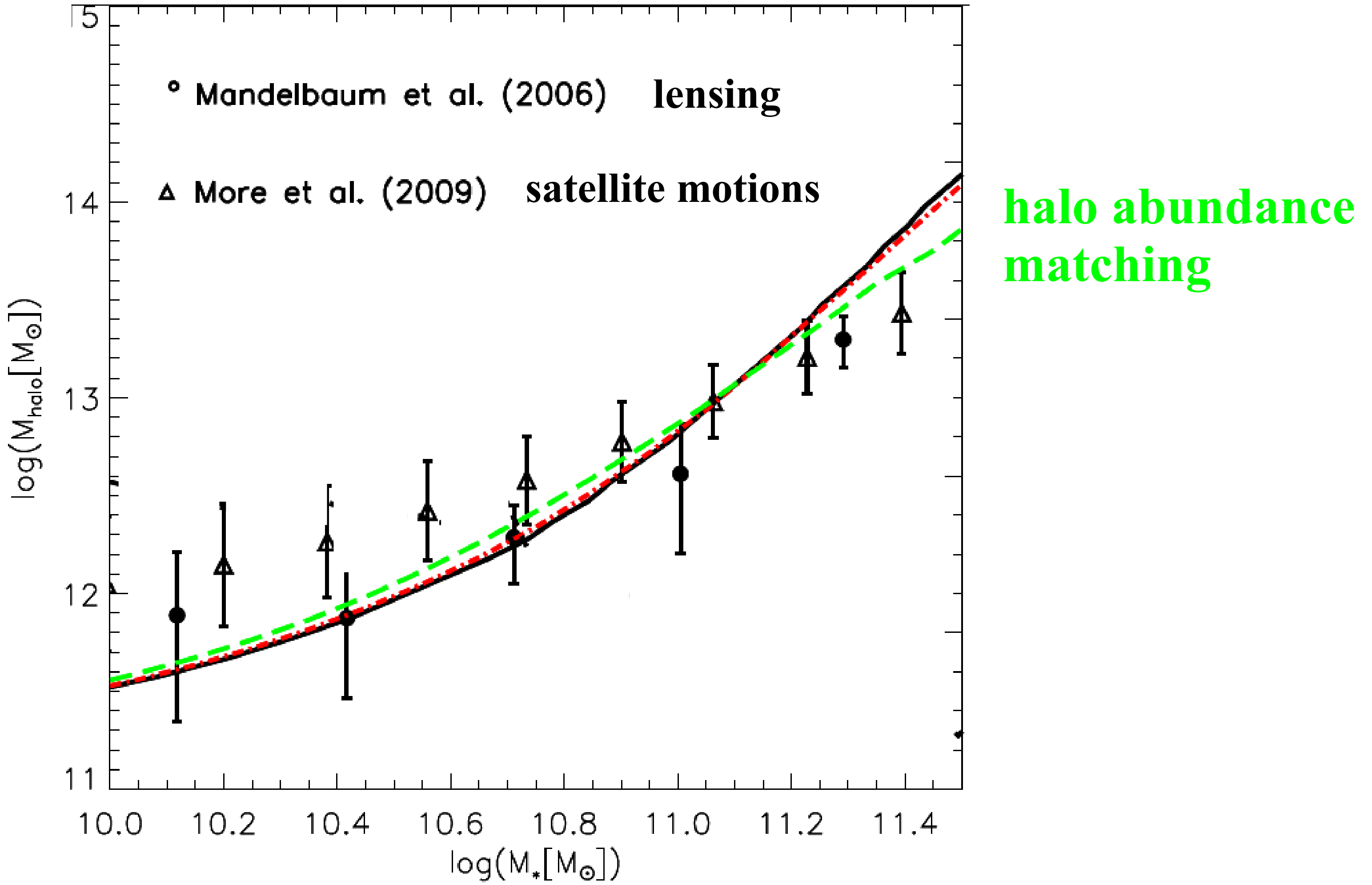
Satellite motions around isolated galaxies

- Motions of faint satellites relative to isolated bright host galaxies
- Orbital motions increase with host luminosity
- Orbital motions decrease with distance from host
- Radial distribution of satellites is similar to the prediction for dark matter
- Velocities are consistent with ΛCDM predictions



Consistency of ΛCDM for galaxy halos

Guo et al 2009



Relations between dark halo mass and galaxy stellar mass inferred

(i) from the motions of satellite galaxies

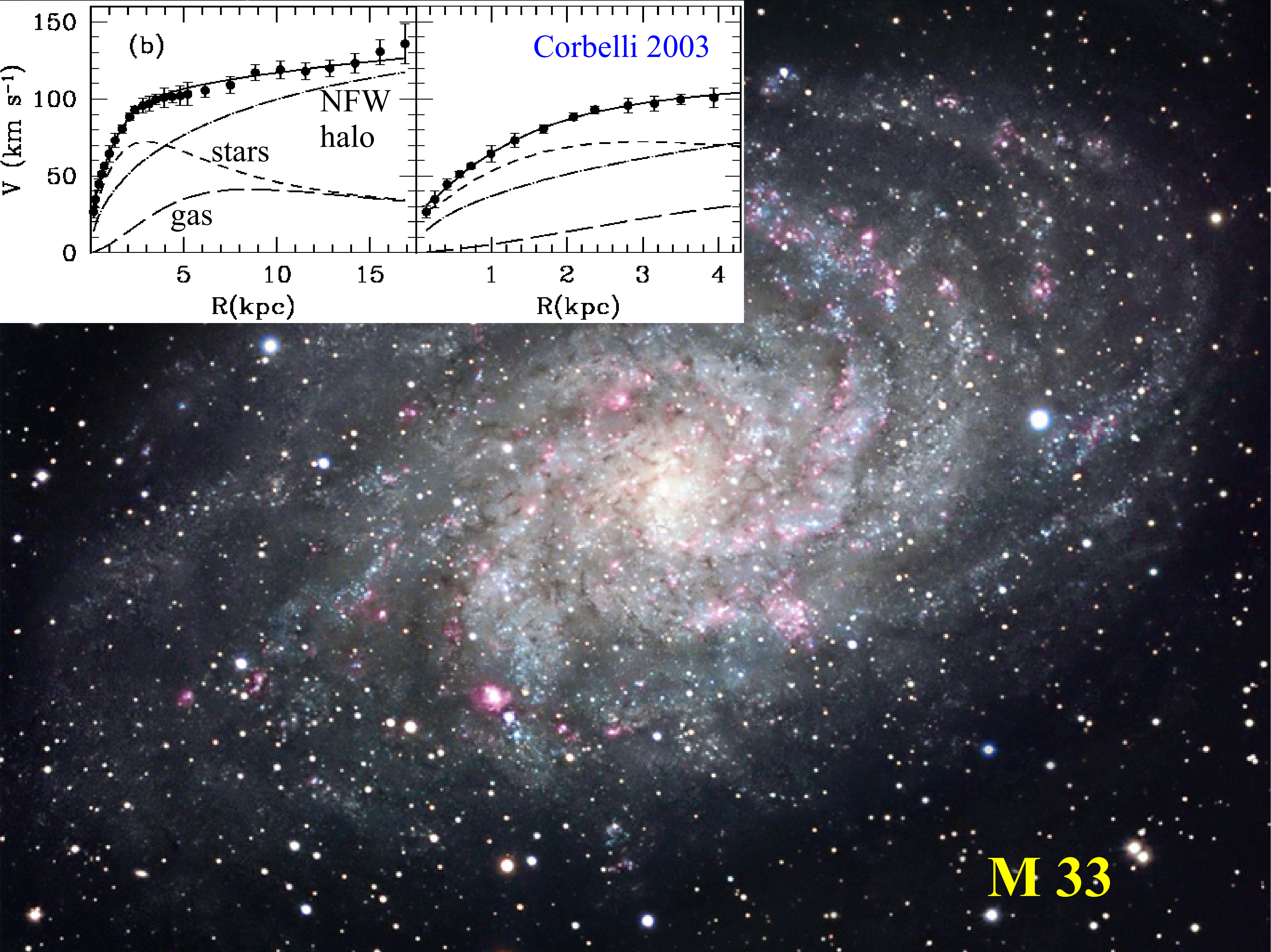
(ii) from gravitational lensing

(iii) from matching predicted halo count to observed galaxy count

all agree!

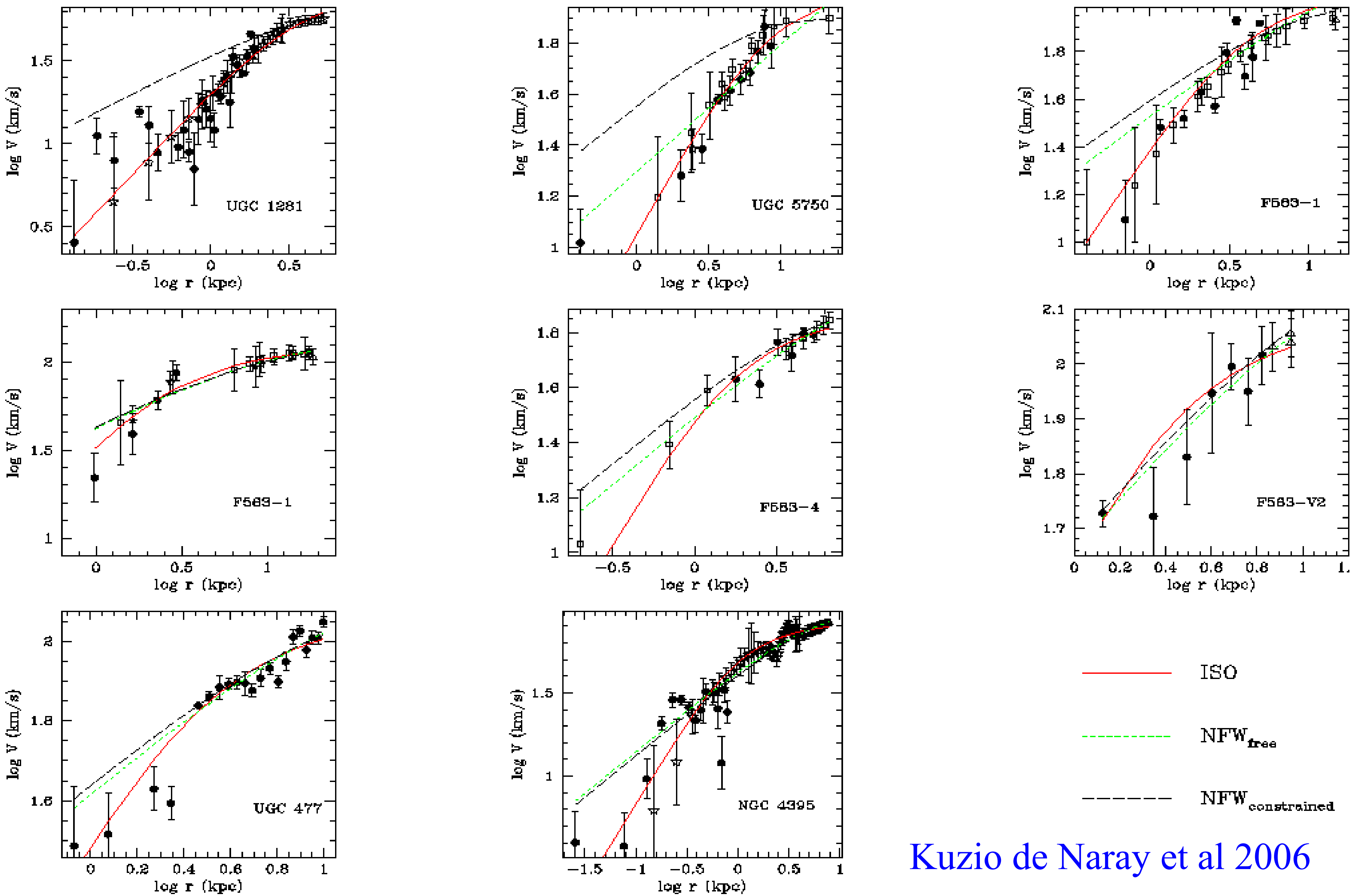
The mass structure predicted by the WMAP/ΛCDM cosmology for the dark halos of isolated galaxies agrees as a function of their stellar mass with that inferred directly from lensing and dynamical data

This comparison has *no* free parameters



150
100
50
0
V (km s^{-1})
(b)
NFW
halo
stars
gas
5
10
15
R(kpc)
Corbelli 2003
1
2
3
4
R(kpc)
M 33

Inner rotation curves of low SB galaxies

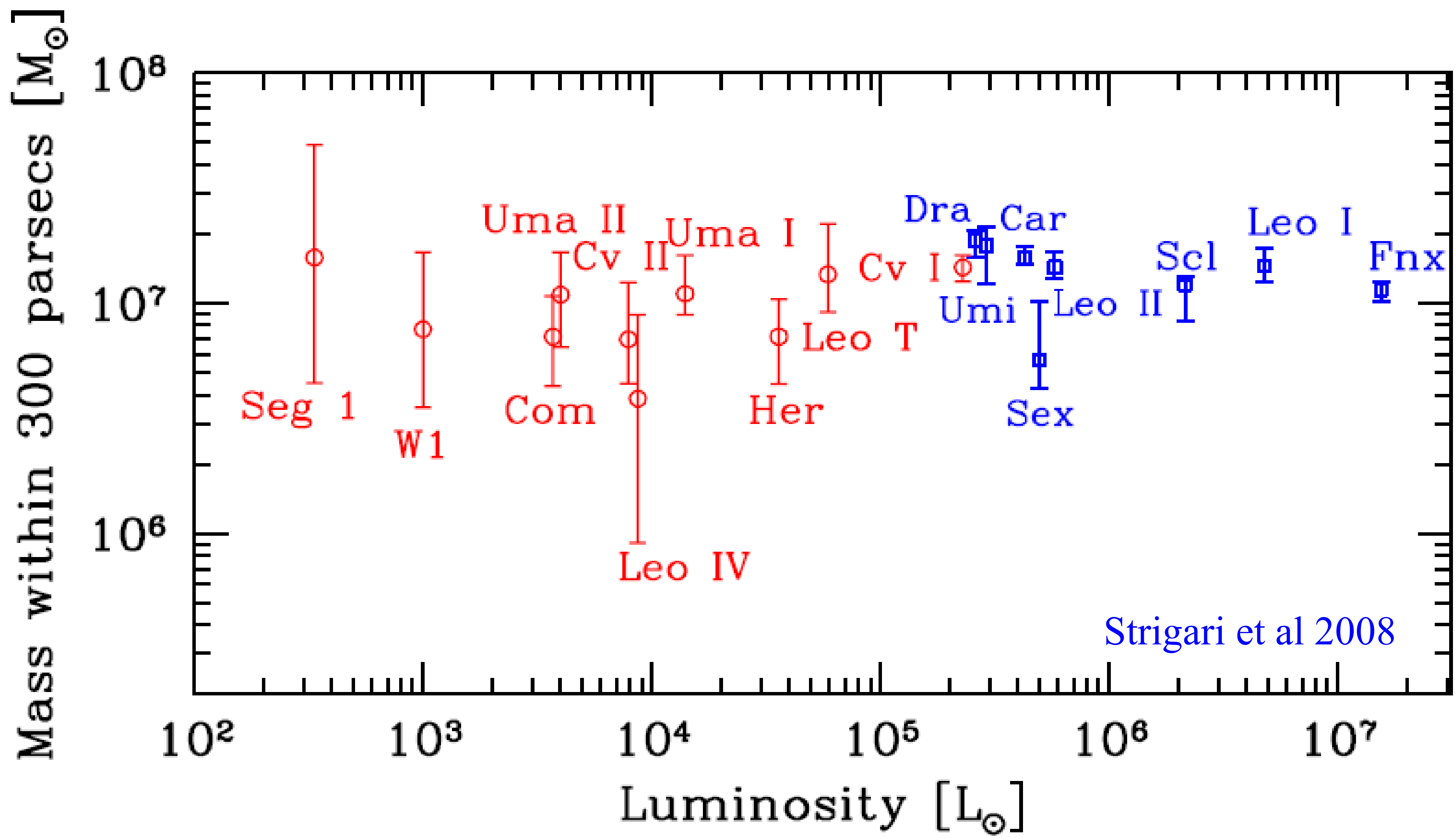


Kuzio de Naray et al 2006

The rotation curves of most bright galaxies can be fit by combining the observed stellar mass with a ΛCDM halo

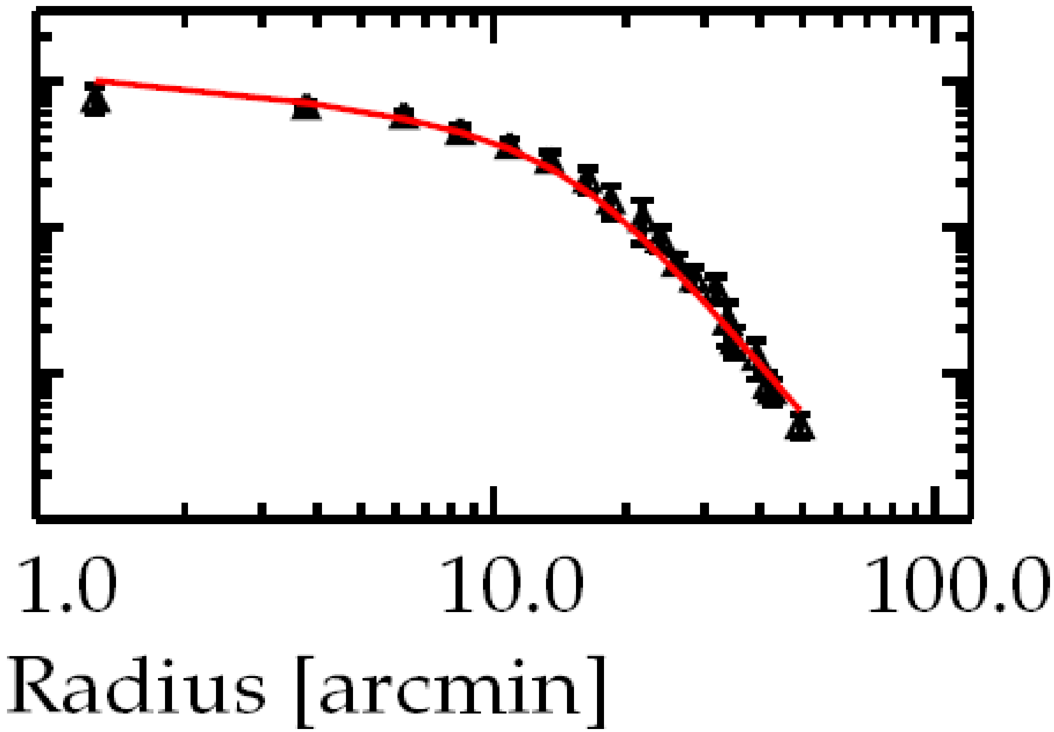
There are difficulties in the core of some dwarf galaxies where the theory predicts too much dark matter

The difficulties occur in regions where highly nonlinear *baryonic* astrophysics is important

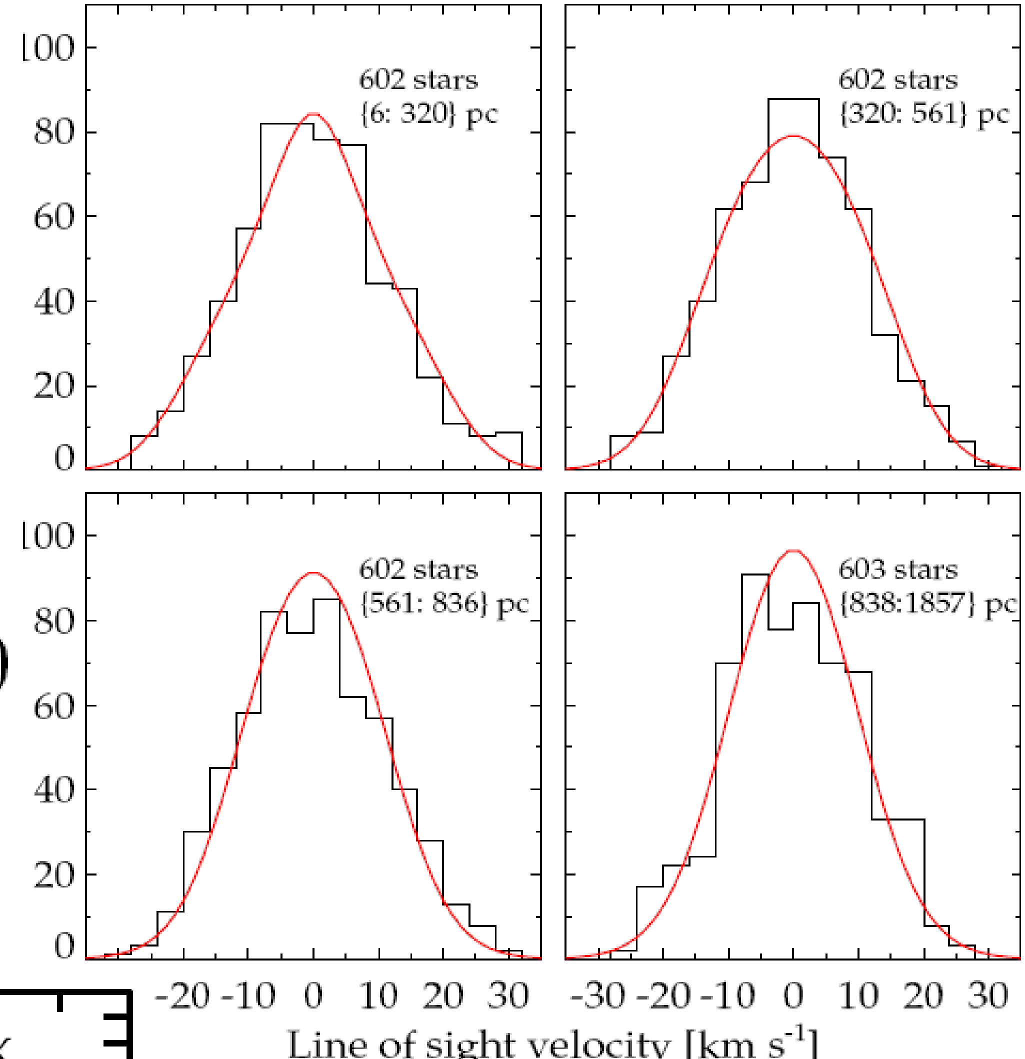


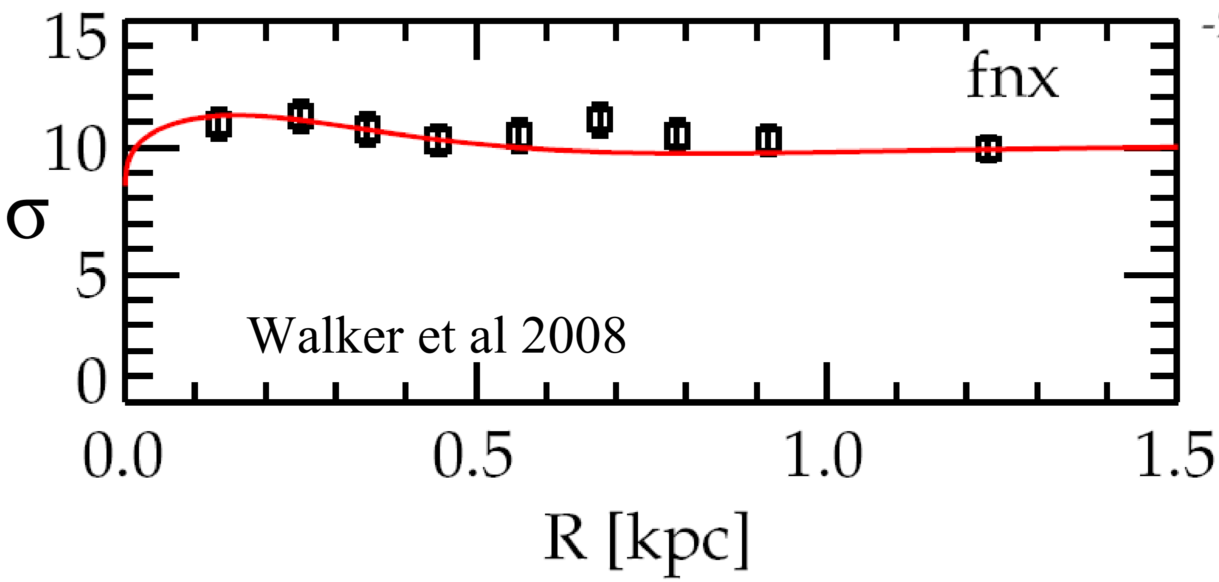
The apparent mass of dwarf galaxies (or equivalently their observed velocity dispersion) is almost independent of their baryonic content

Apparently their gravity is dominated by a different component



Strigari, Frenk & White 2010





Fornax data are **consistent** with living in an Aquarius CDM subhalo with isotropic velocity dispersions

→ a cusp is not excluded

Dark matter has NOT yet been seen directly, thus its existence is a hypothesis to be tested

There is observational evidence for an unseen source of gravity at times between 380,000 and 13.7 billion years, and on scales from 10^7 to 10^{18} $M_\odot$

A new Weakly Interacting Massive Particle (WIMP) is currently the only hypothesis that is demonstrably and quantitatively consistent with the data

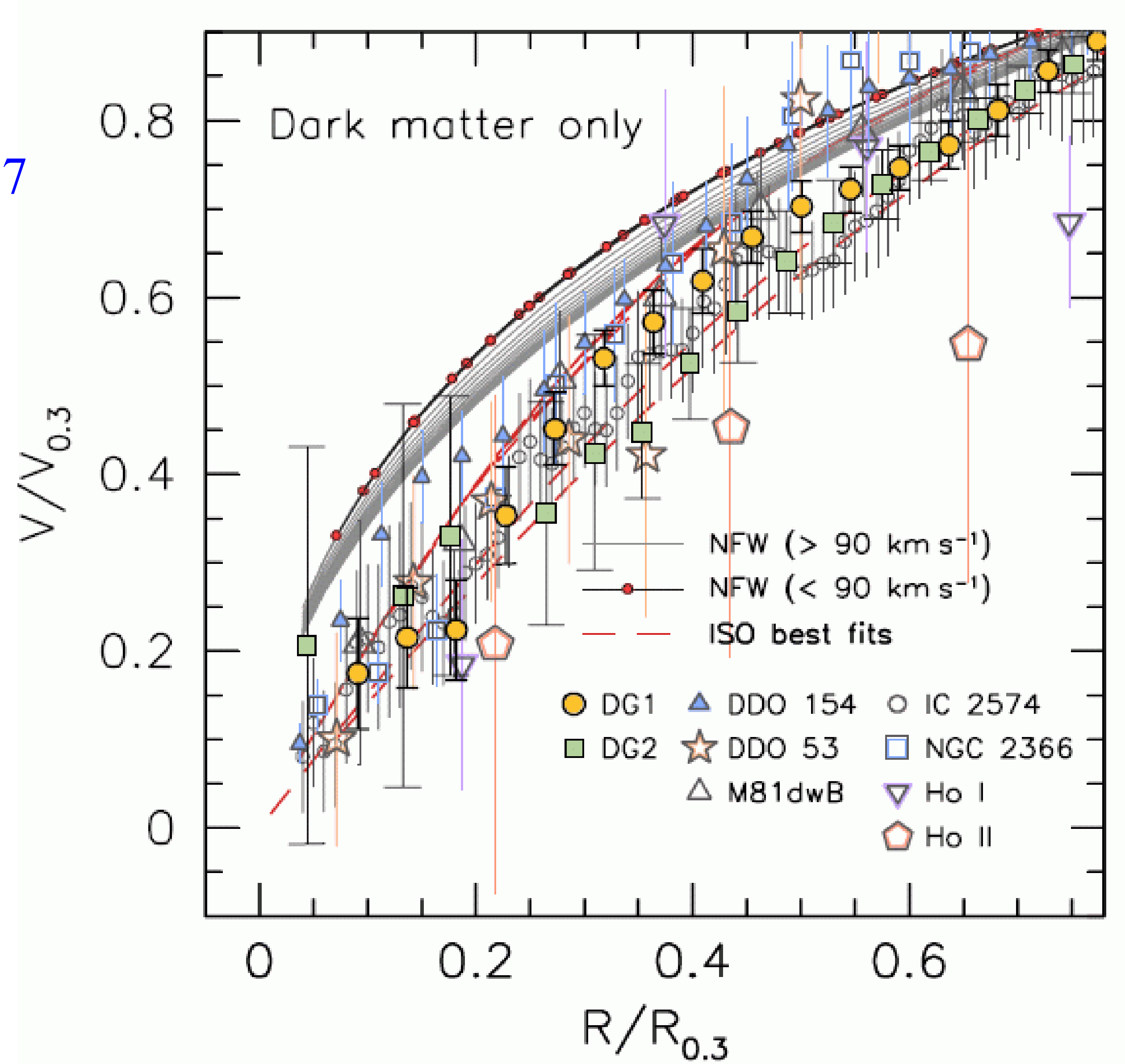
6 NOVEMBER 2009 VOL 326 SCIENCE

Problem of Missing Mass

Pedro G. Ferreira[1]* and Glenn D. Starkman[2]*

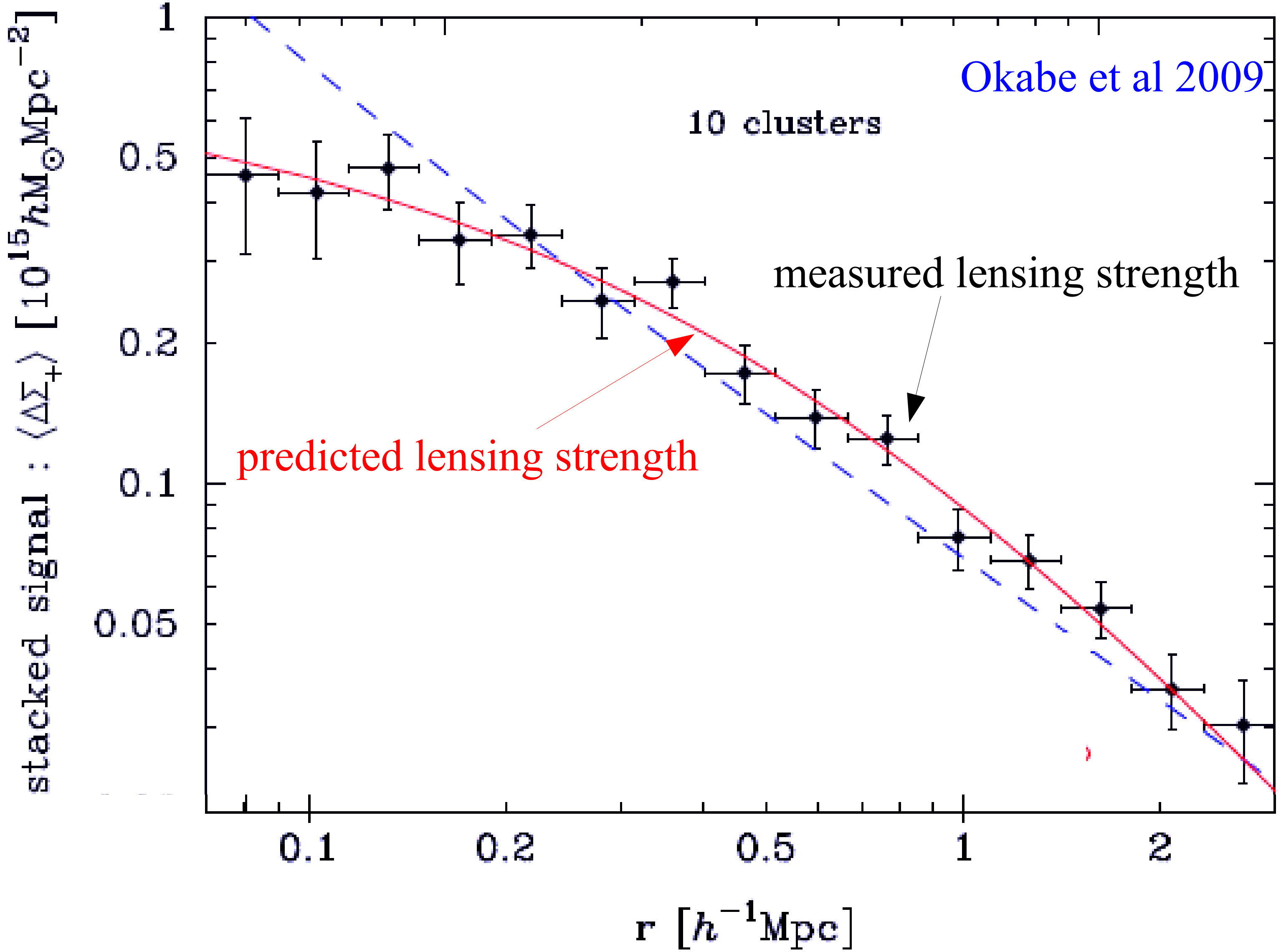
The observed matter in the universe accounts for just 5% of the observed gravity. A possible explanation is that Newton's and Einstein's theories of gravity fail where gravity is either weak or enhanced. The modified theory of Newtonian dynamics (MOND) reproduces, without dark matter, spiral-galaxy orbital motions and the relation between luminosity and rotation in galaxies, although not in clusters. Recent extensions of Einstein's theory are theoretically more complete. They inevitably include dark fields that seed structure growth, and they may explain recent weak lensing data. However, the presence of dark fields reduces calculability and comes at the expense of the original MOND premise, that the matter we see is the sole source of gravity. Observational tests of the relic radiation, weak lensing, and the growth of structure may distinguish modified gravity from dark matter.

Oh et al 2010
arXiv:1011.2777

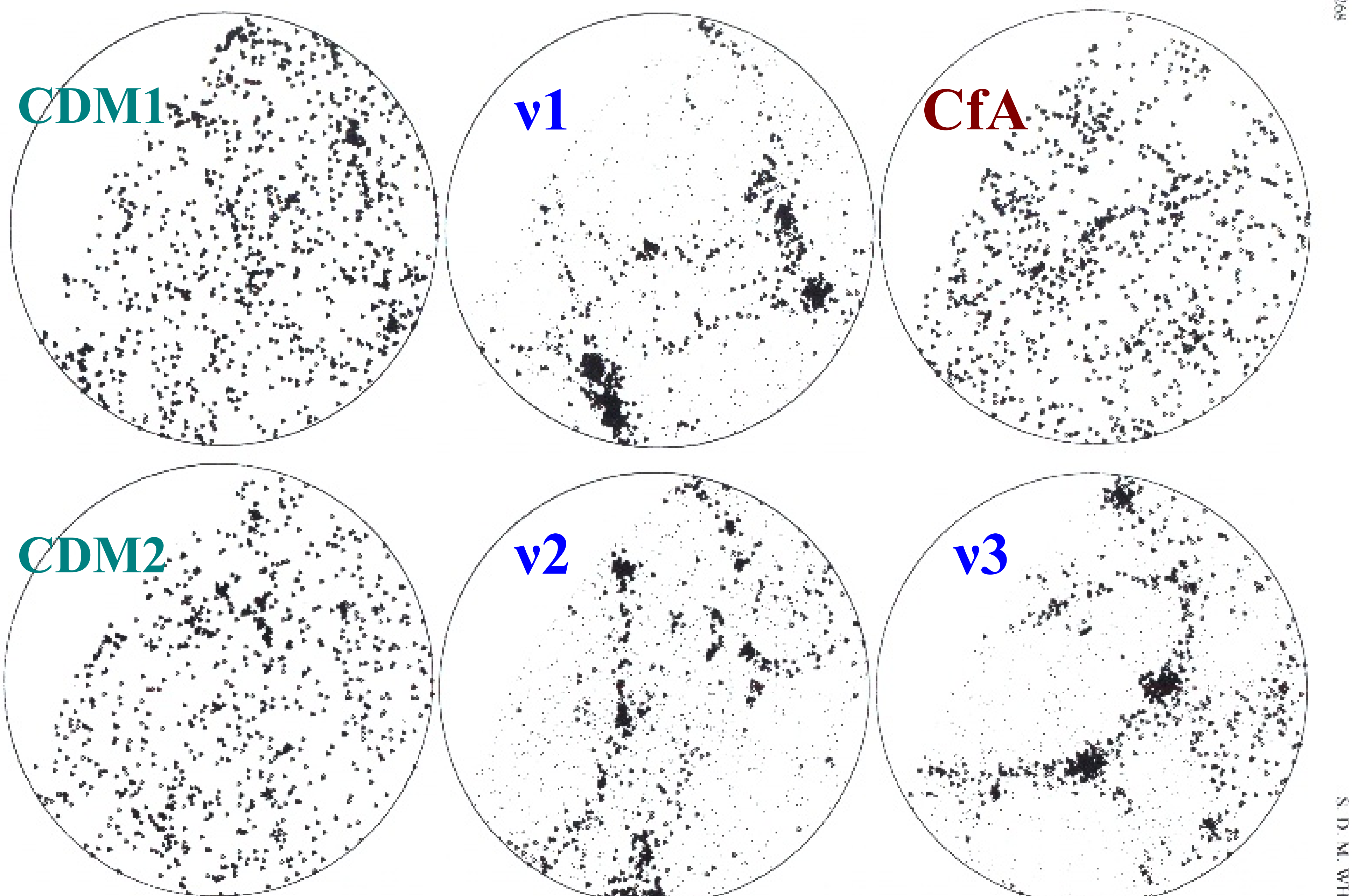


Comparison of the rotation curves of two simulated ΛCDM dwarf galaxies (DG1 and DG2) with seven nearby dwarfs from the THINGS survey. Simulated dwarfs are *less* concentrated than DM only halos.

Comparison of lensing strength measured around real galaxy clusters to that predicted by simulations of structure formation



Excluding massive neutrinos as the Dark Matter



White et al 1983