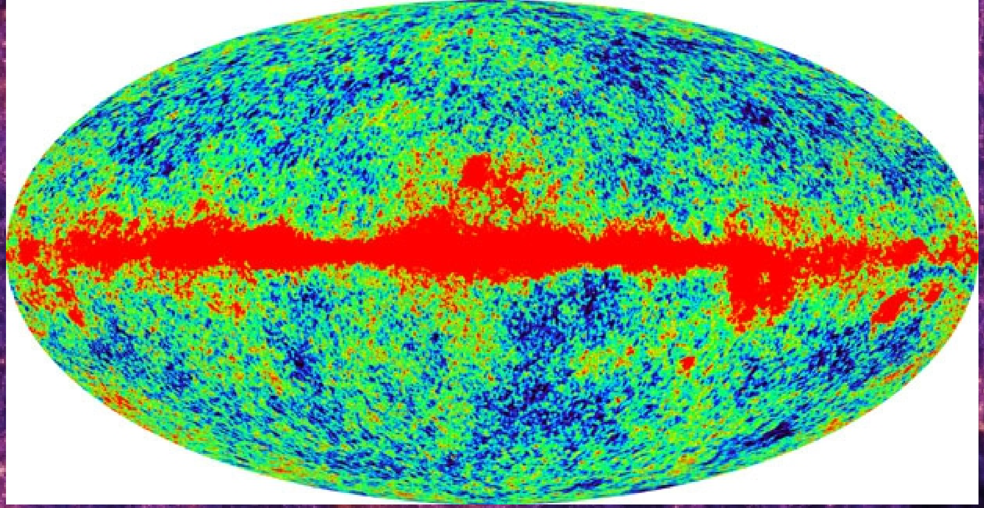
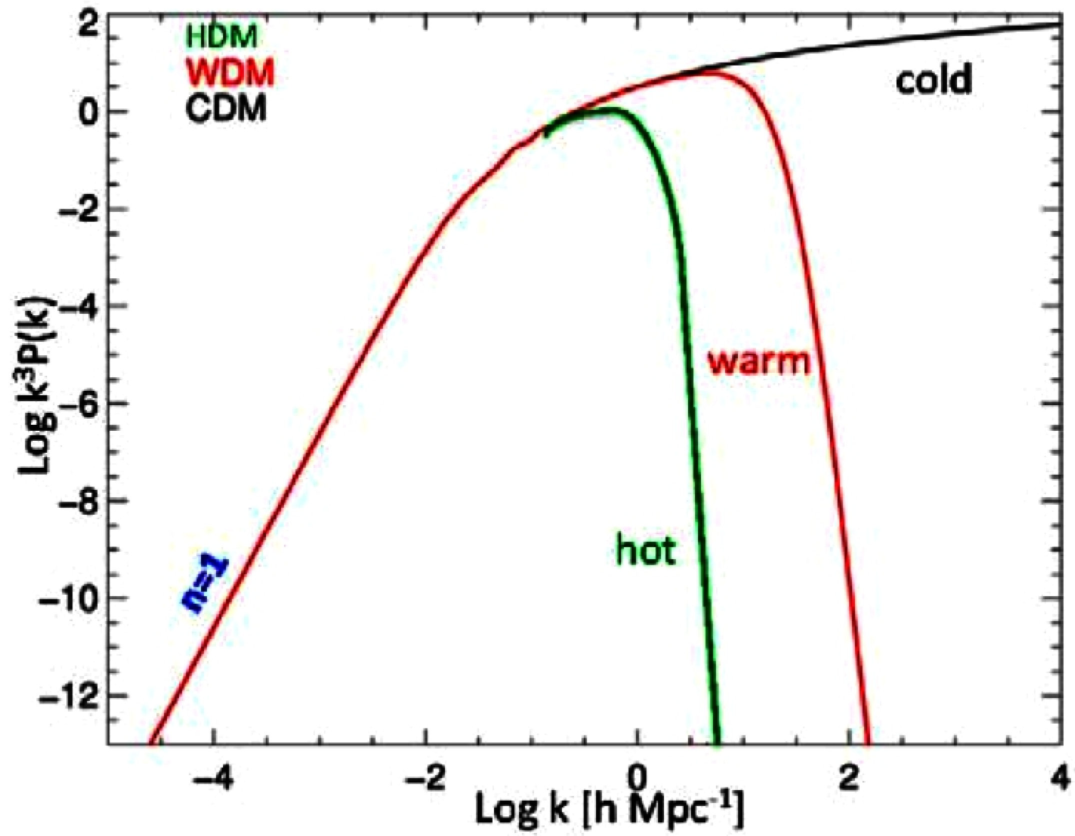


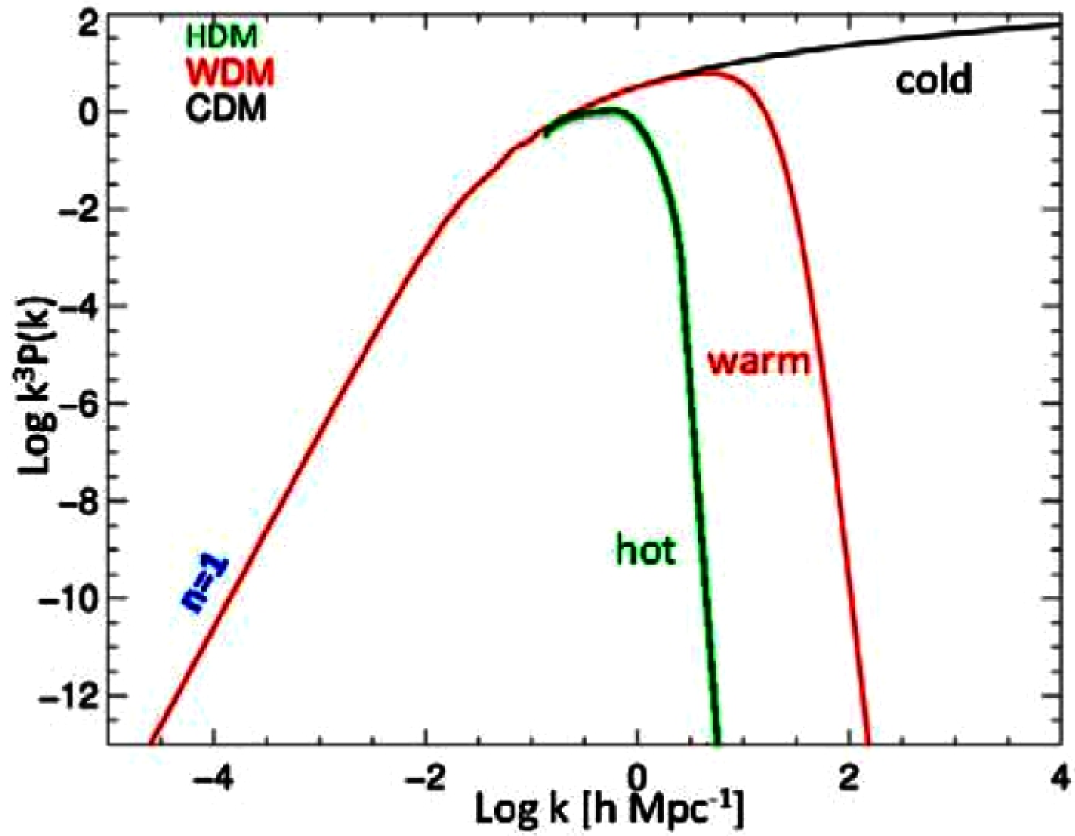
Current status of the ΛCDM structure formation model

Simon White
Max Planck Institut für Astrophysik



The idea that DM might be a neutral, weakly interacting particle took off around 1980, following a "measurement" of the ν_e mass

Hot Dark Matter could be e, μ, or τ neutrinos (10's of eV)
Warm Dark Matter could be a gravitino or sterile neutrino (~1 keV)
Cold Dark Matter could be a neutralino or axion or...



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known to exist!

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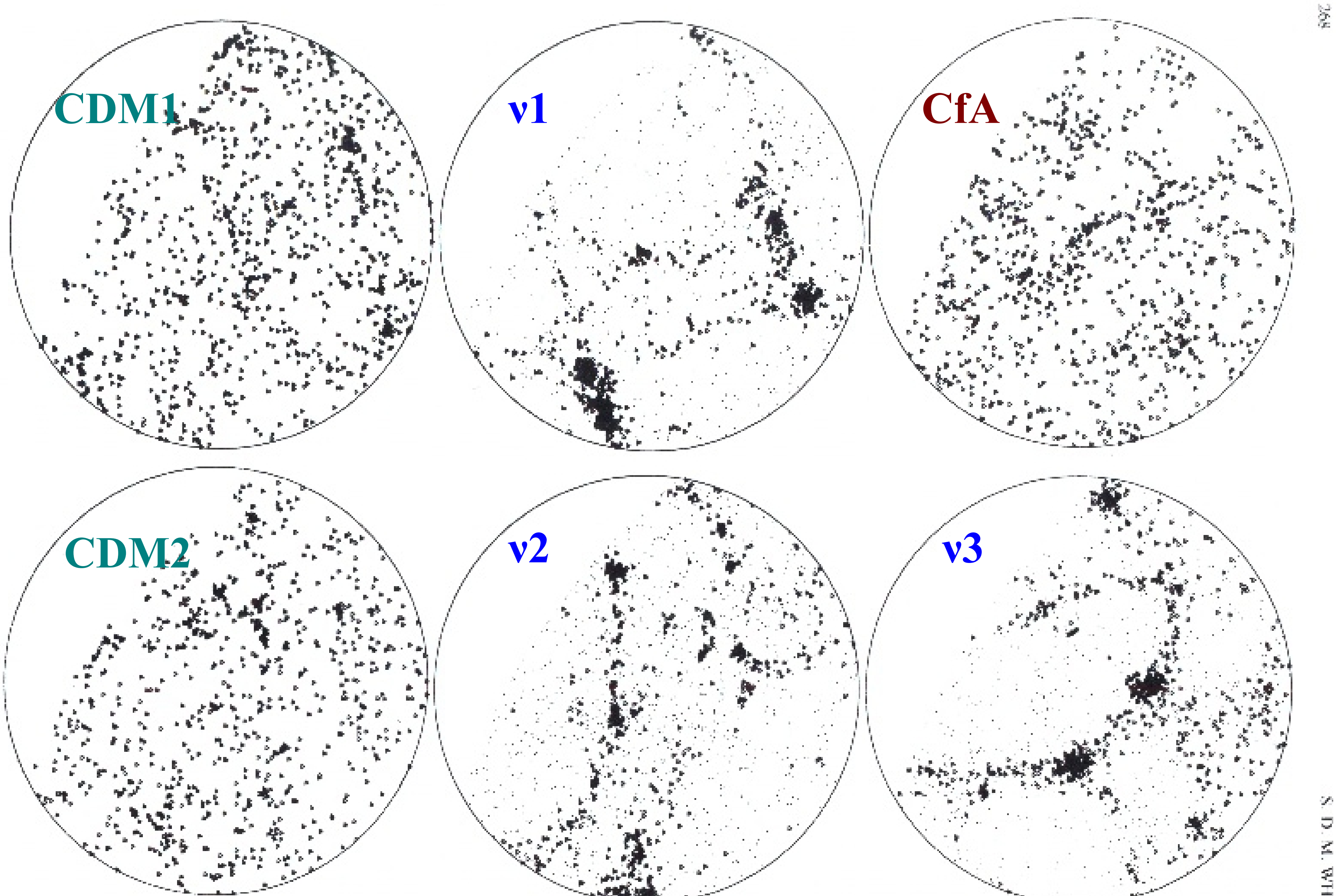
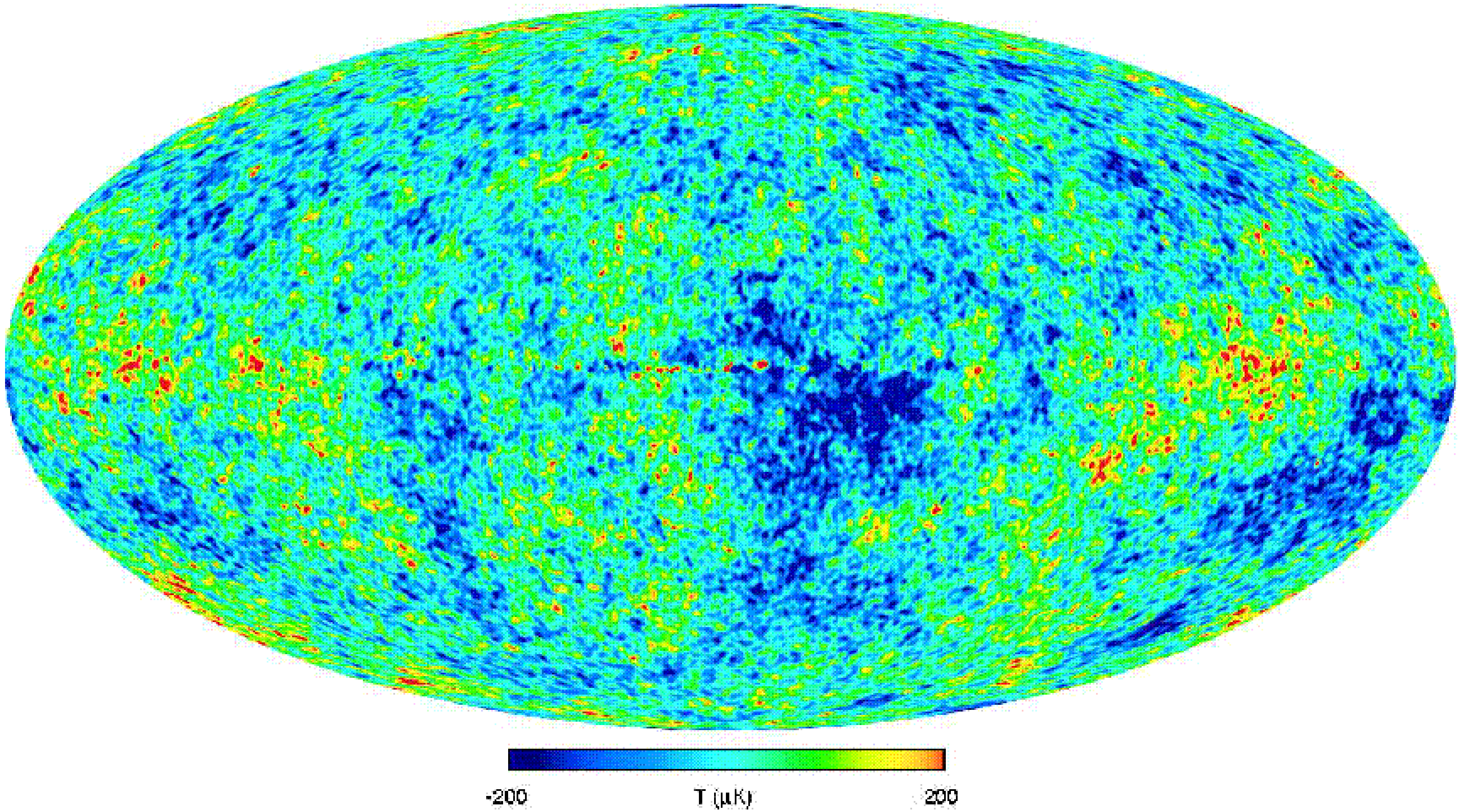
Comparing simulations to the CfA survey excluded HDM and so all <u>known</u> WIMP candidates

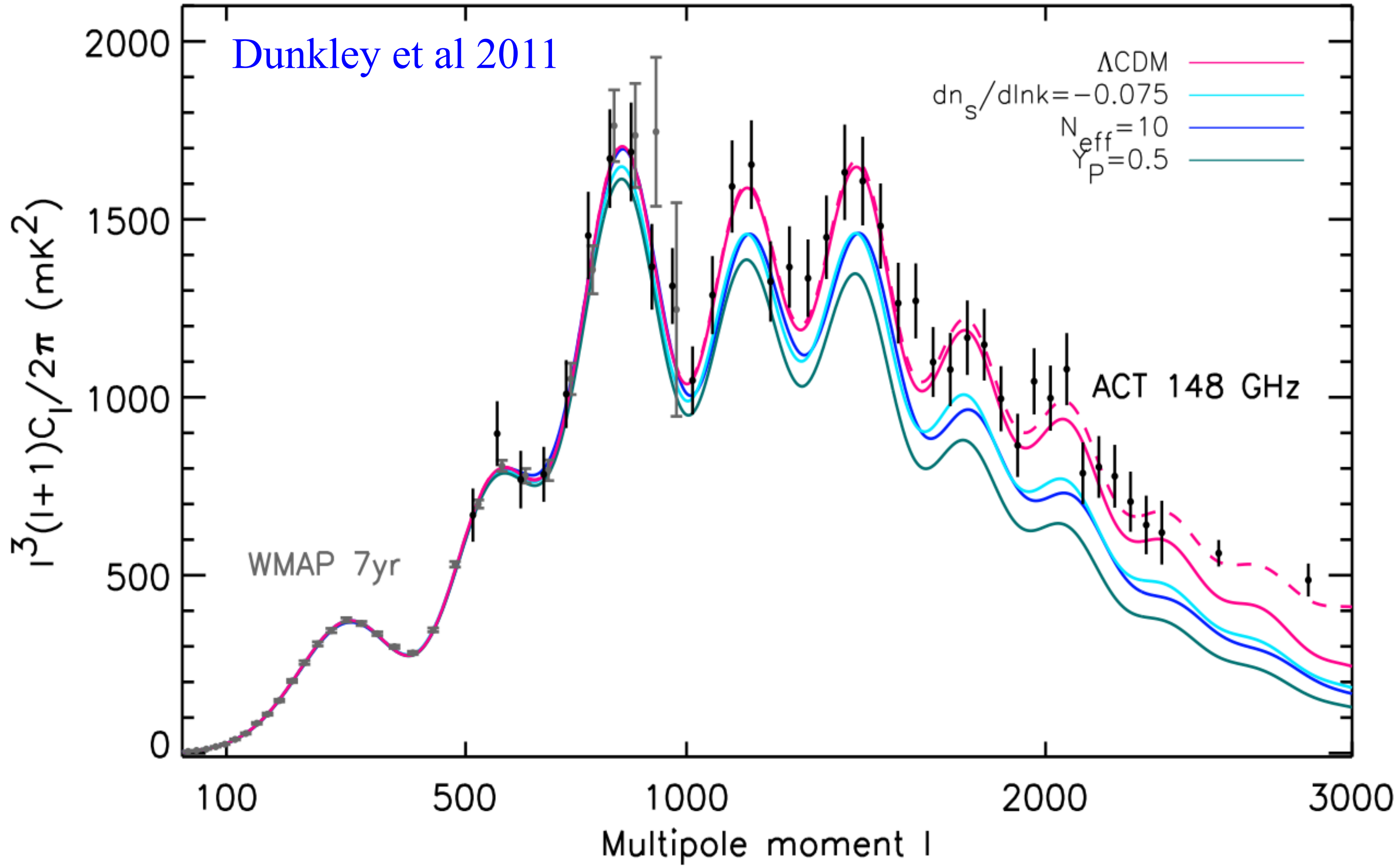


White et al 1983

The *WMAP* of the whole CMB sky



Bennettt et al 2003



Primary	$100\Omega_b h^2$	2.214 ± 0.050
ΛCDM	$\Omega_c h^2$	0.1127 ± 0.0054
	Ω_Λ	0.721 ± 0.030
	n_s	0.962 ± 0.013
	τ	0.087 ± 0.014
	$10^9 \Delta^2_{\mathcal{R}}$	2.47 ± 0.11
Derived	σ_8	0.813 ± 0.028
	Ω_m	0.279 ± 0.030
	H_0	69.7 ± 2.5

a 20σ detection of DM!

Komatsu et al 2010 (WMAP7)

Name	Case	*WMAP* 7-year	*WD*+SN[a]	*WMAP*+BAO+H_0
Grav. Wave[b]	No Running Ind.	$r < 0.36$[c]	0	$r < 0.24$
Running Index	No Grav. Wave	$-0.084 < dn_s/d\ln k < 0.020$[c]	$-0.065 n k < 0.010$	$-0.061 < dn_s/d\ln k < 0.017$
Curvature	$w = -1$	N/A	$-0.0 < 0.0063$	$-0.0133 < \Omega_k < 0.0084$
Adiabaticity	Axion	$\alpha_0 < 0.13$[c]	64	$\alpha_0 < 0.077$
	Curvaton	$\alpha_{-1} < 0.011$[c]	037	$\alpha_{-1} < 0.0047$
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$1 eV	$\sum m_\nu < 0.58$ eV[g]
	$w \neq -1$	$\sum m_\nu < 1.4$ eV[c]	$\sum$1 eV	$\sum m_\nu < 1.3$ eV[h]
Relativistic Species	$w = -1$	$N_{eff} > 2.7$[c]		$4.34^{+0.86}_{[illegible]}$ (68% CL)[i]

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 which interacts purely gravitationally with the baryon-photon fluid.

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

The structure seen in the CMB agrees with that predicted by the concordance ΛCDM model down to scales corresponding to today's groups and clusters of galaxies

Concordance ΛCDM:
- Flat geometry, $\Omega_{tot} \sim 1$
- about 4.5% baryons
- about 23% Cold Dark Matter
- about 72% Dark Energy, $w = -1$
- Gaussian initial density field, $n \sim 0.96$

Structure in pregalactic gas at high redshift

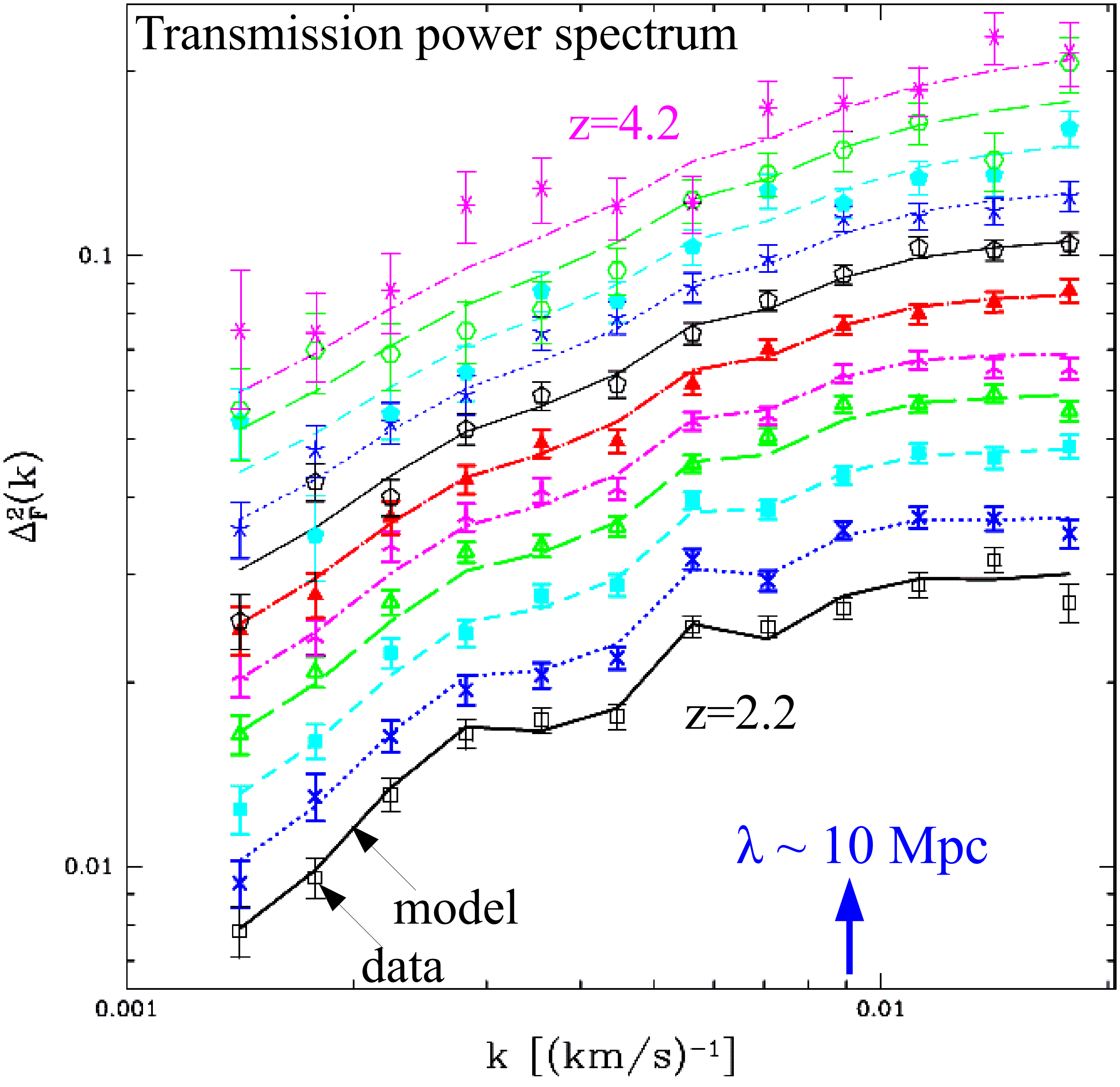
McDonald et al 2005

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 velocities

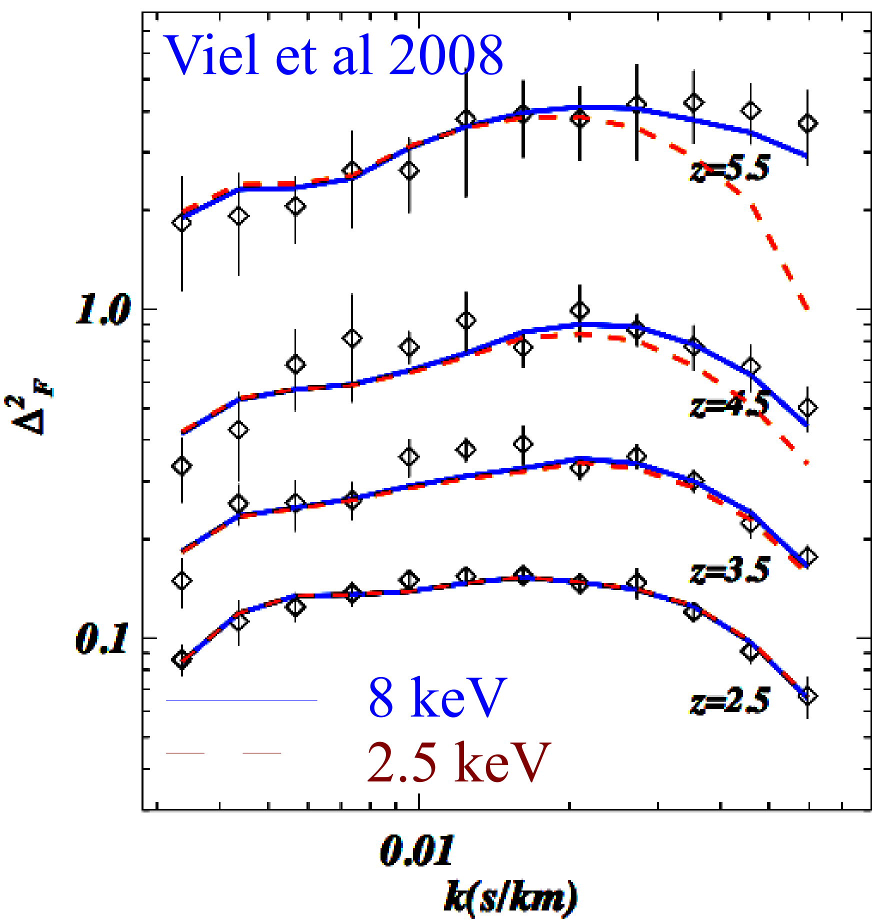
Data - 3300 SDSS quasars

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

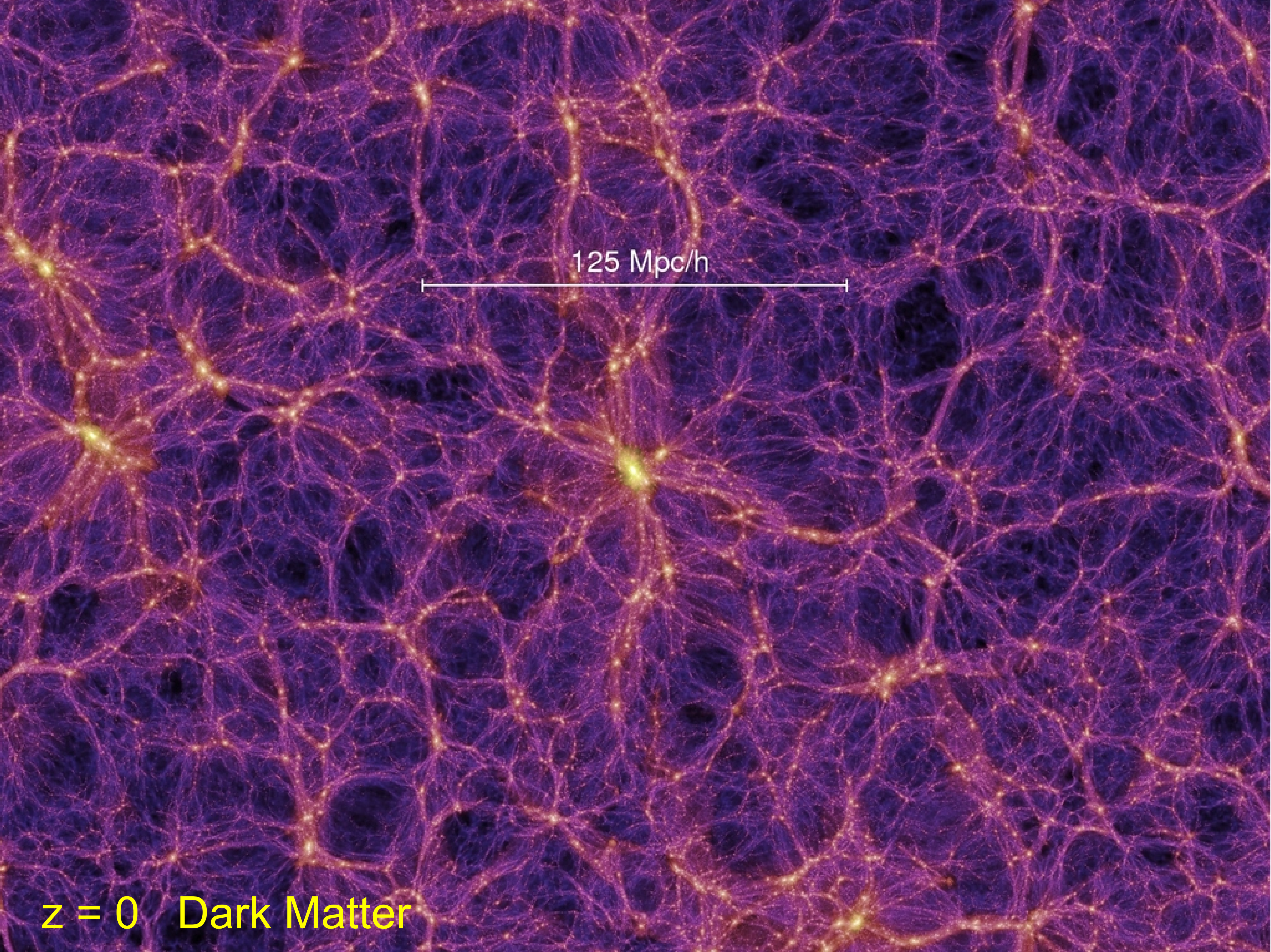
They match ΛCDM predictions down to (Lagrangian) scales corresponding to the smallest dwarf galaxies

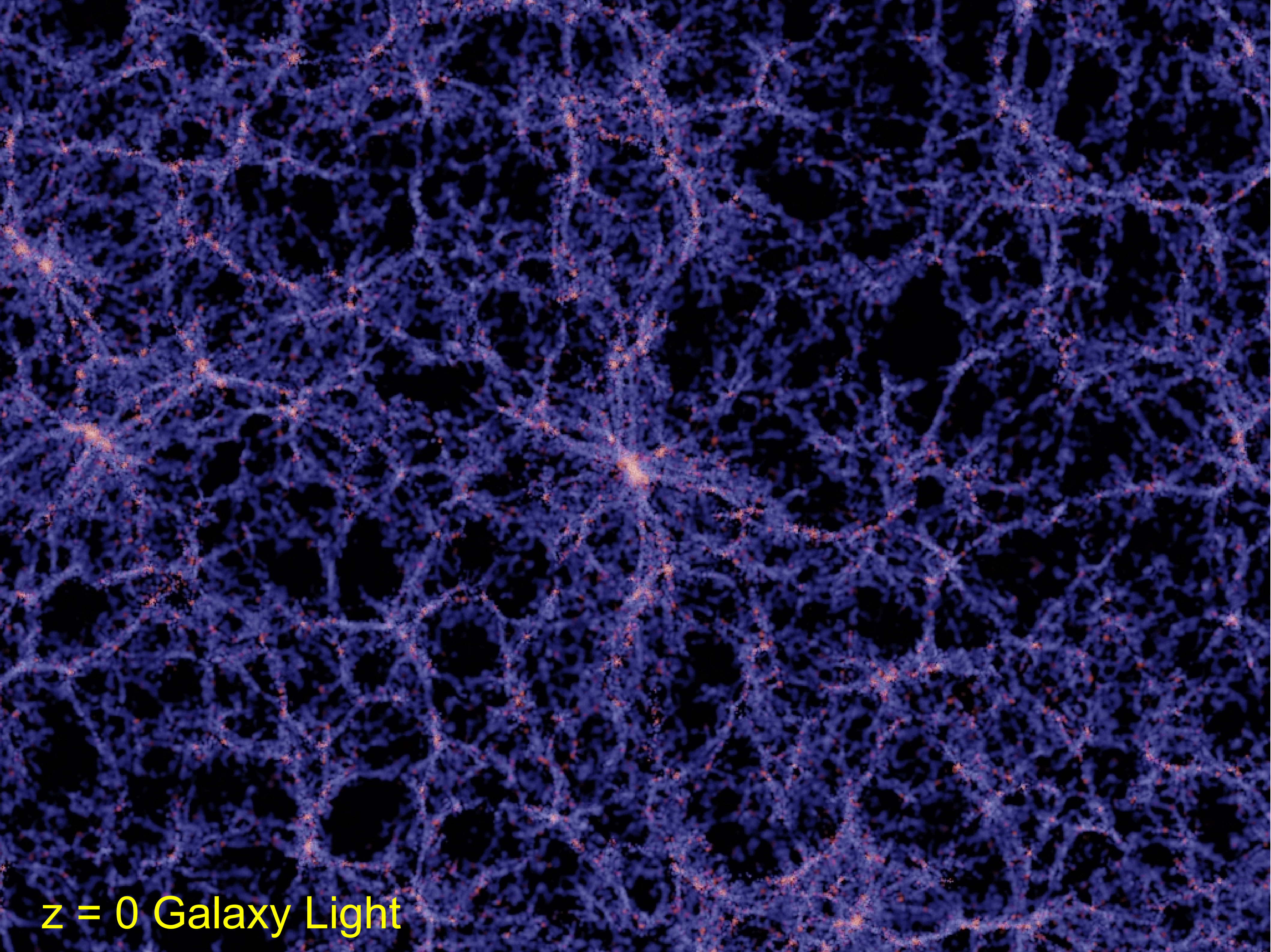


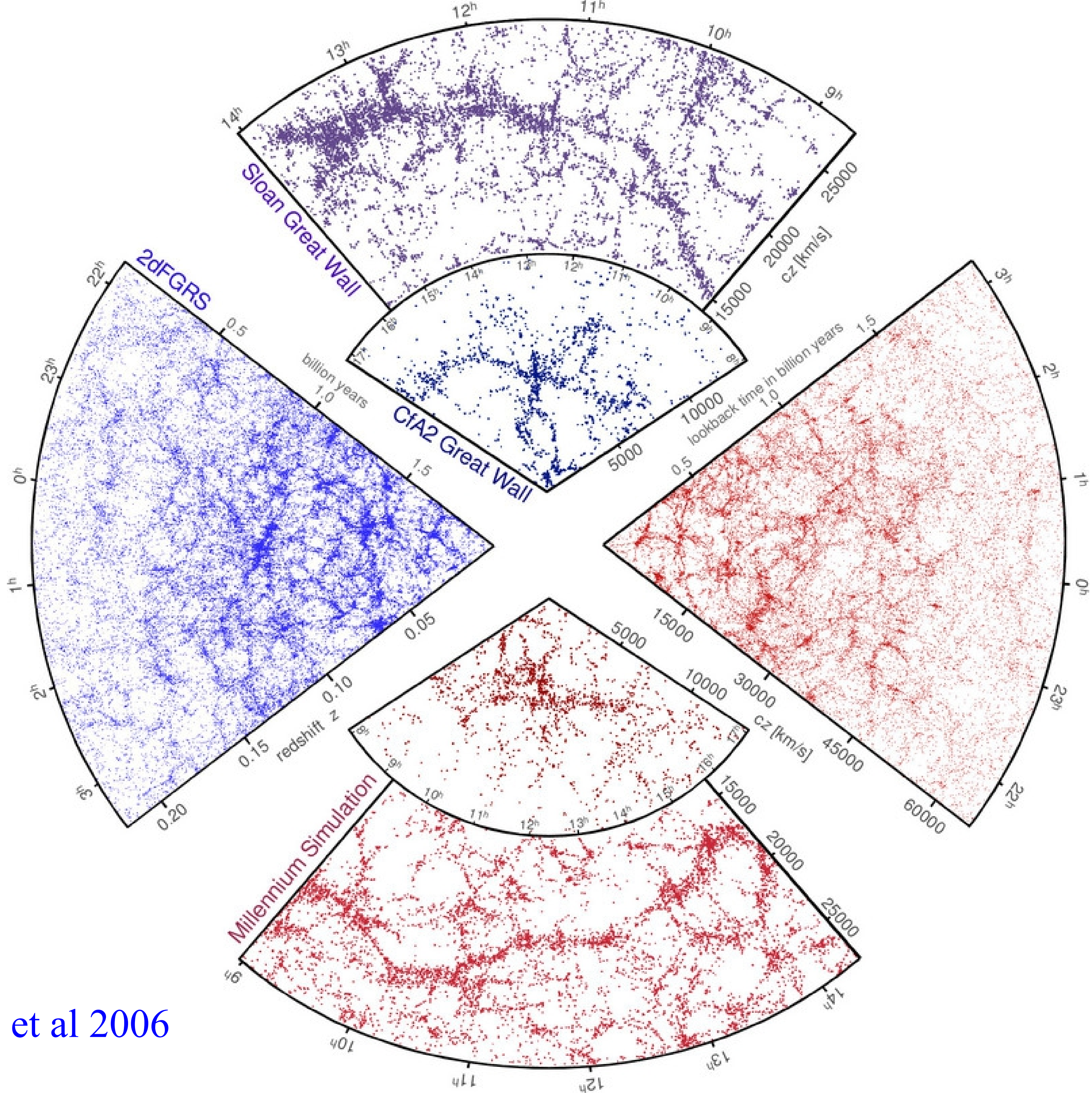
From SDSS+HIRES data 2σ lower limits on WDM particle masses are:

m > 4 keV (early thermal relic)

m > 28 keV (sterile neutrino)


125 Mpc/h
z = 0   Dark Matter

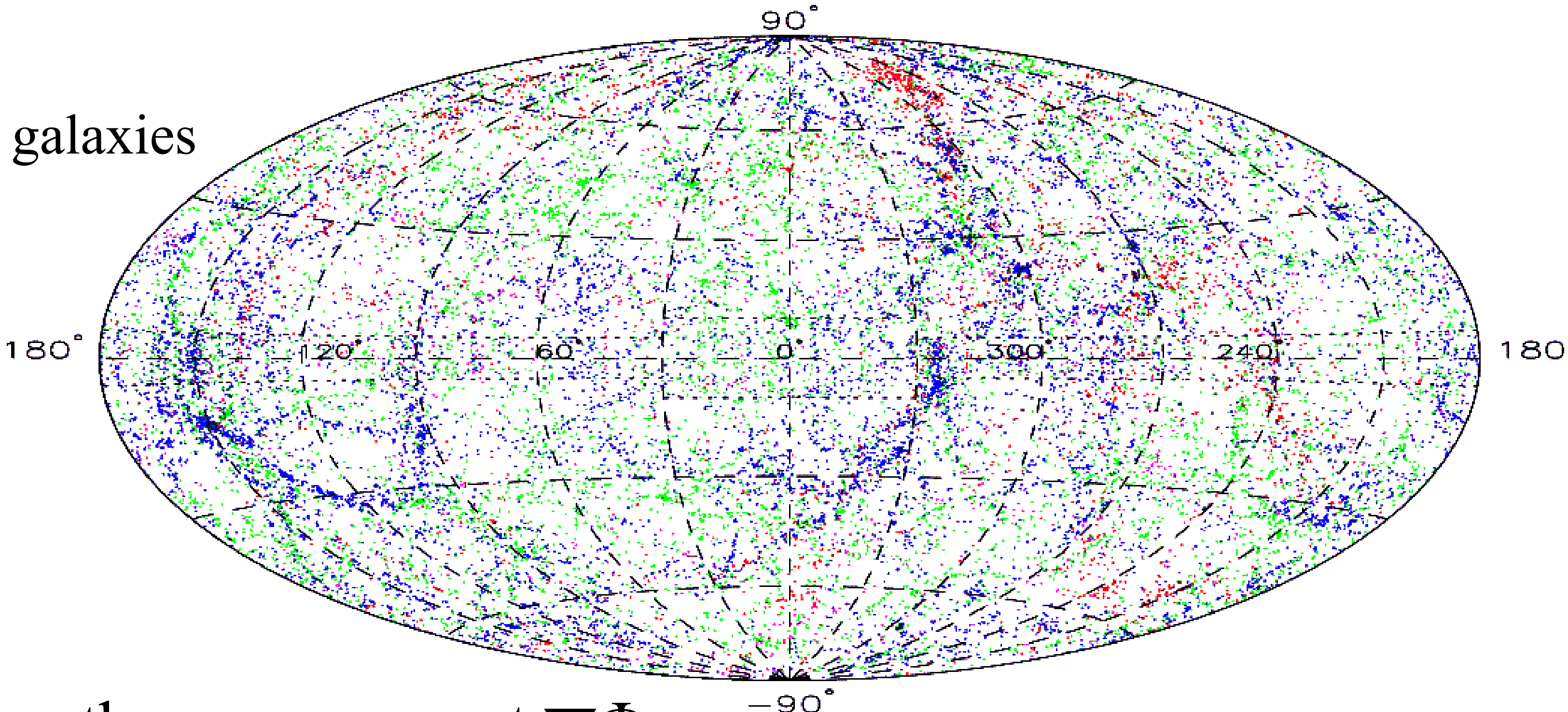

z = 0 Galaxy Light



Springel et al 2006

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

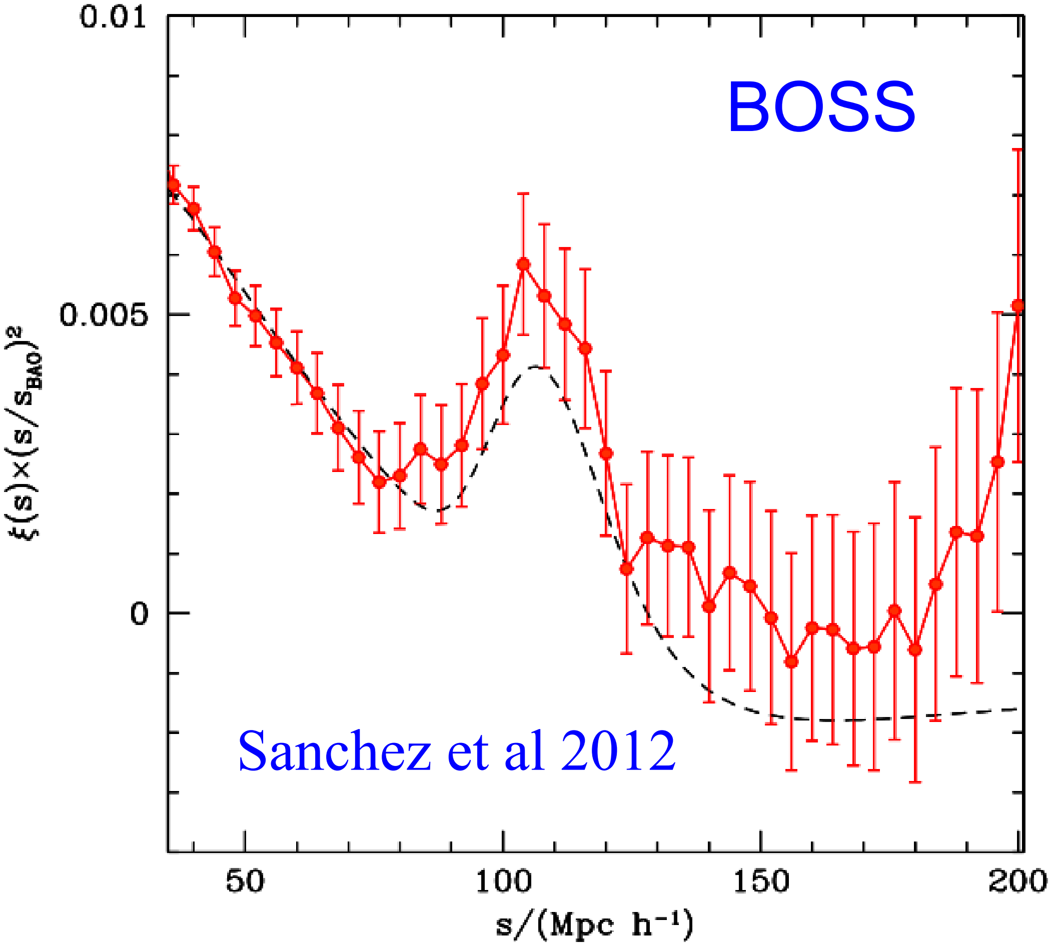
$\nabla\Phi$ can be estimated from the galaxy distribution.

The directions agree to 15 to 20 degrees

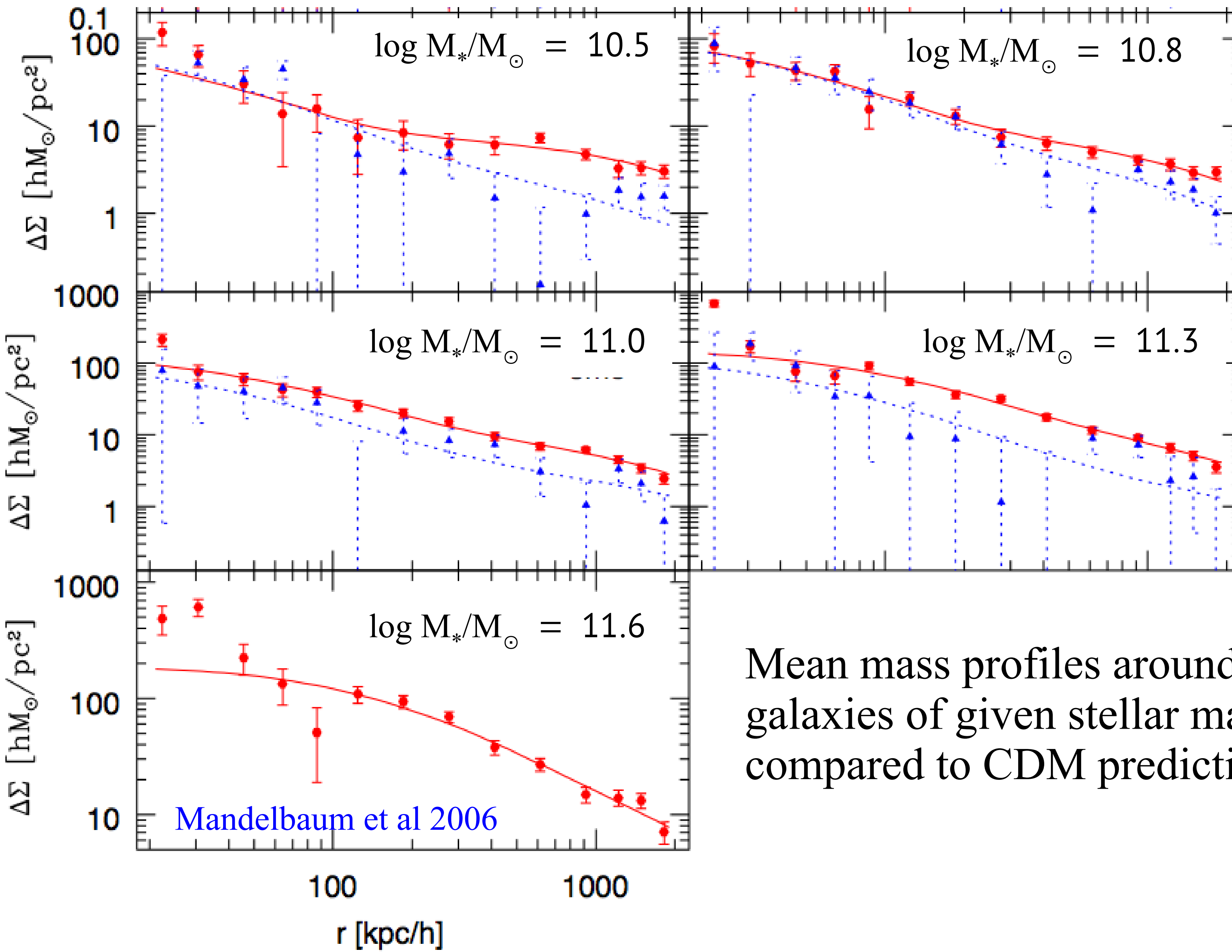
→ $\Omega^{0.6} / b = 0.40 \pm 0.09$ (Erdogdu et al 2006)

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

The 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



Mean halo profiles from gravitational lensing



Mean mass profiles around galaxies of given stellar mass compared to CDM predictions

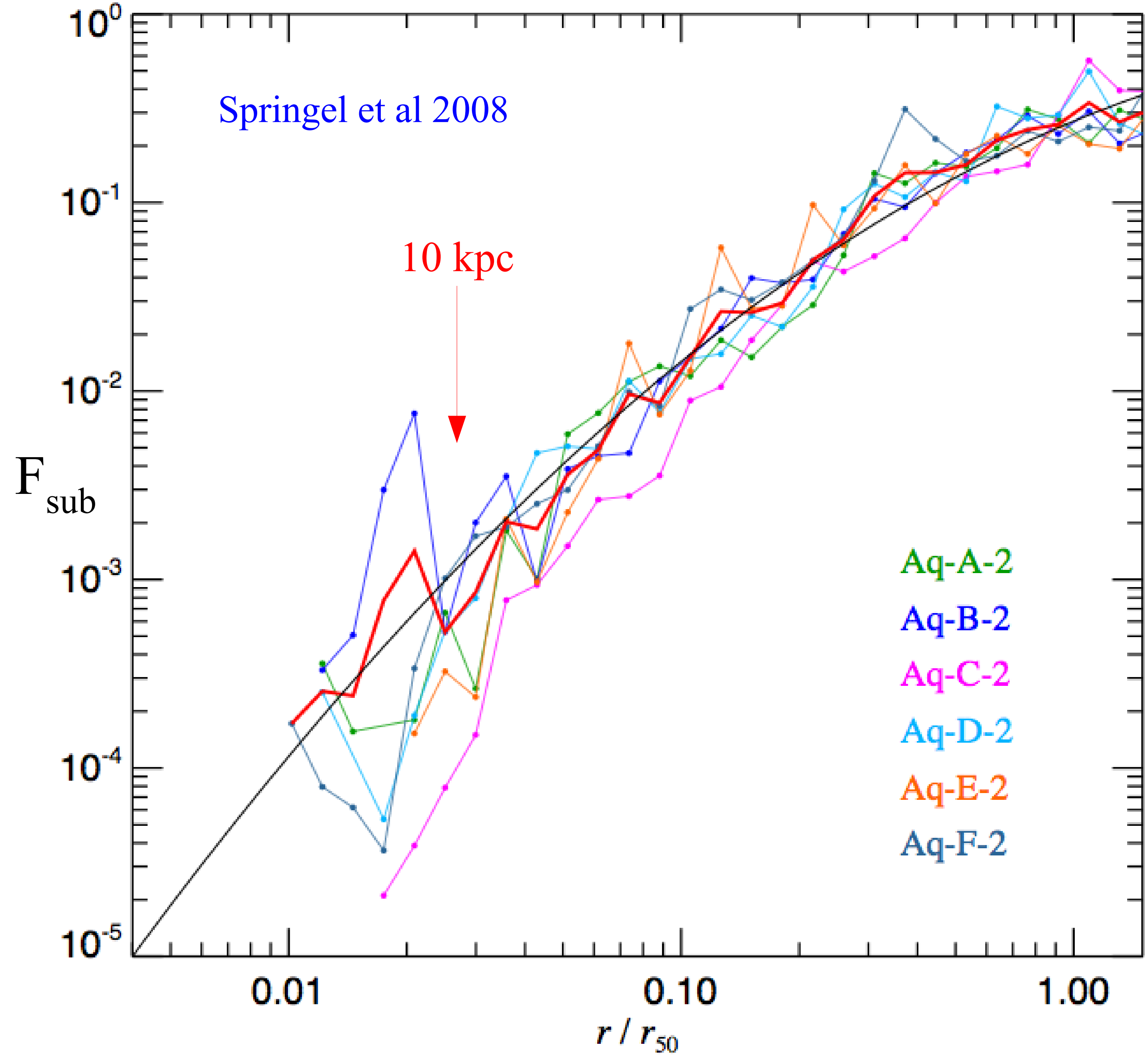
The mean $z = 0$ mass profiles of galaxies of given stellar mass are a good match to the ΛCDM predictions for evolution from the linear initial conditions observed in the CMB at $z = 1000$ and in the Ly α forest at $z = 2.5$

This comparison has, in essence, *no* free parameters because the assignment of galaxies to model halos can be made by matching the observed abundance of galaxies, without reference to the lensing results.

Overall, dark matter is thus the dominant component of galaxies, and is comparable in mass to the stars in the inner visible regions.

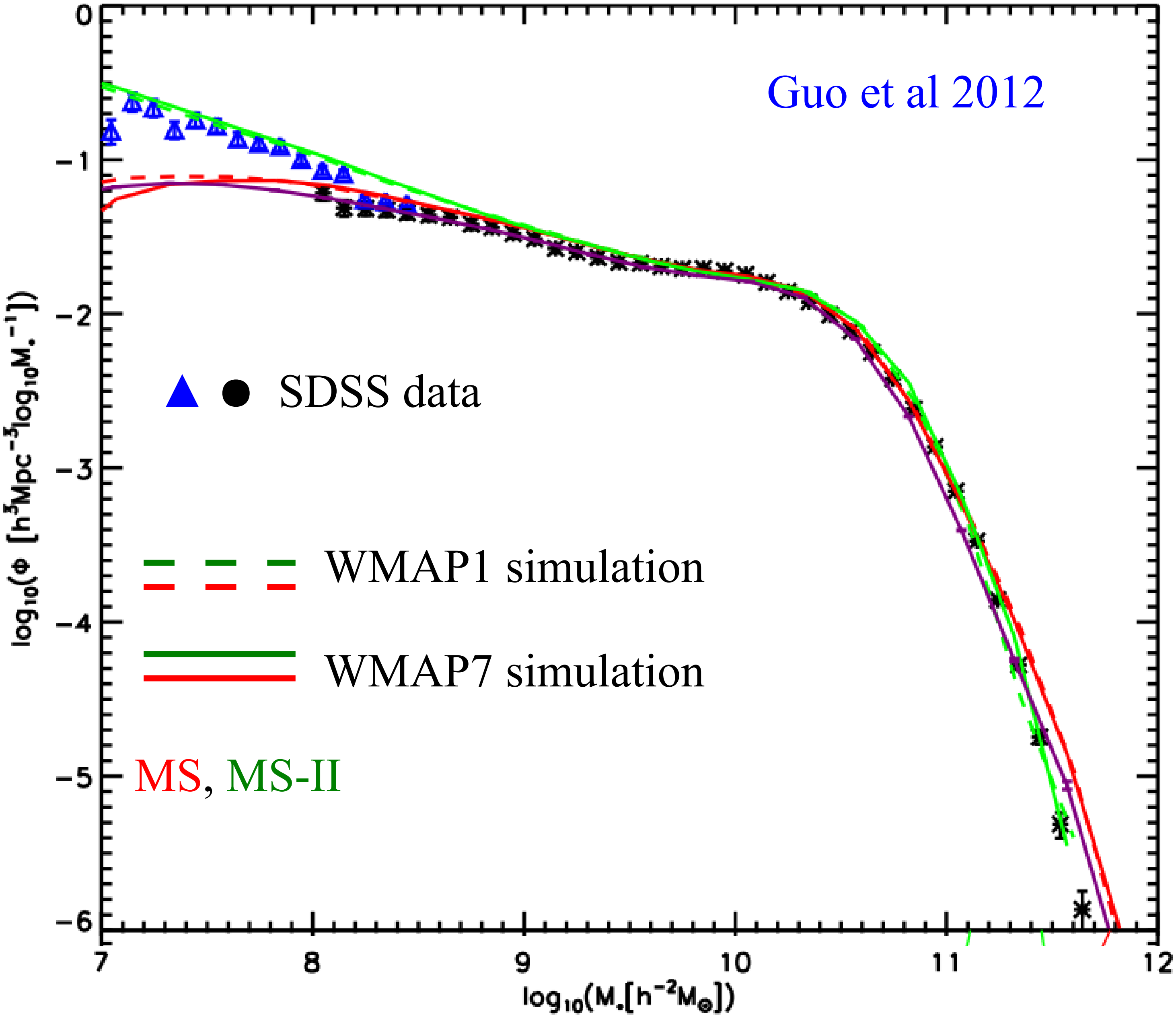
The fine-scale structure of a dark matter halo

Substructure in the inner halo

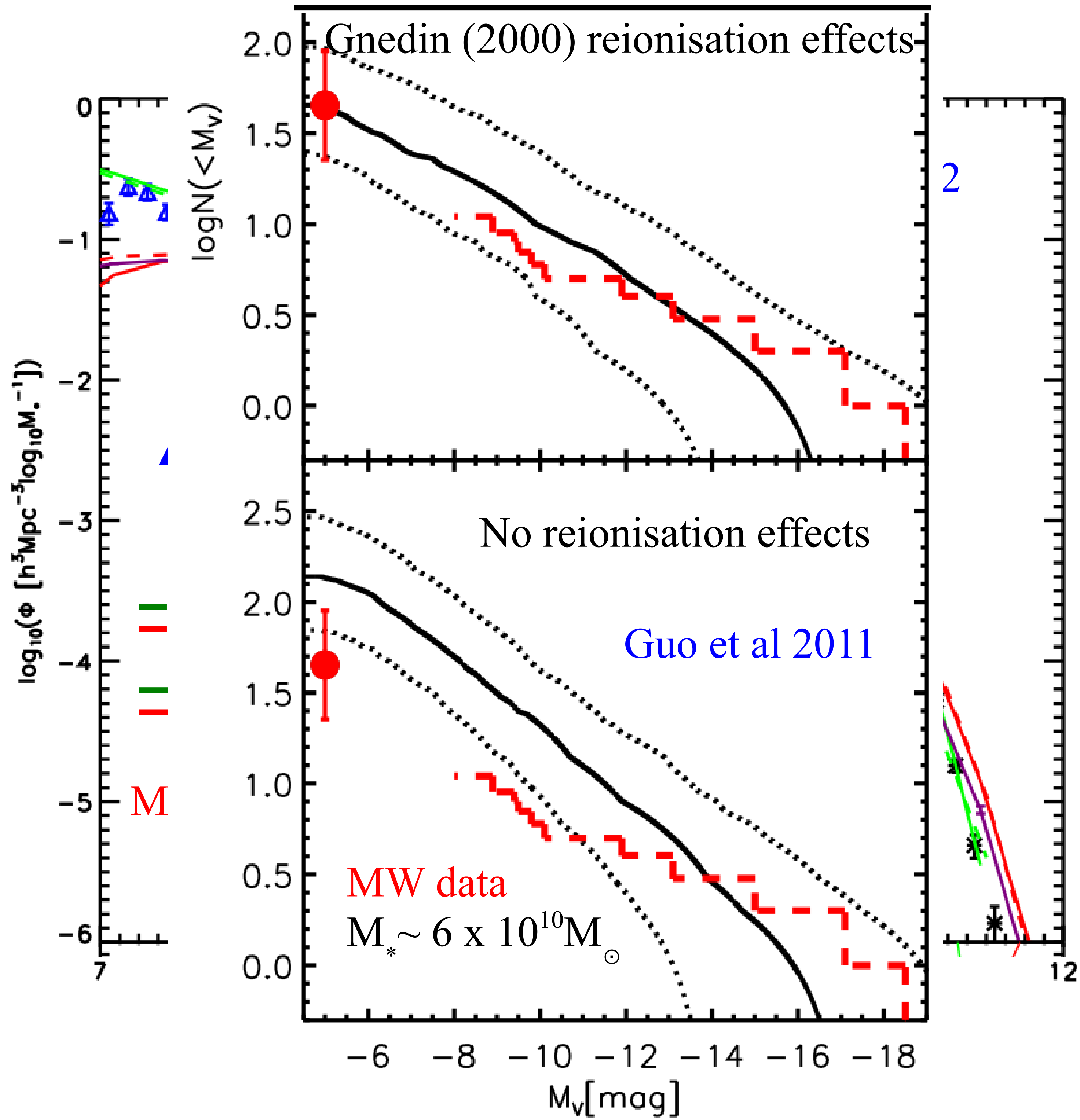


Although the mass fraction in subhalos is ~10% for galaxy halos as a whole, at r=10 kpc subhalos account for only ~10^{-3} of the *local* dark matter density.

DM subhalos have only a weak effect on the stellar dynamics of galaxies or on local DM detection experiments

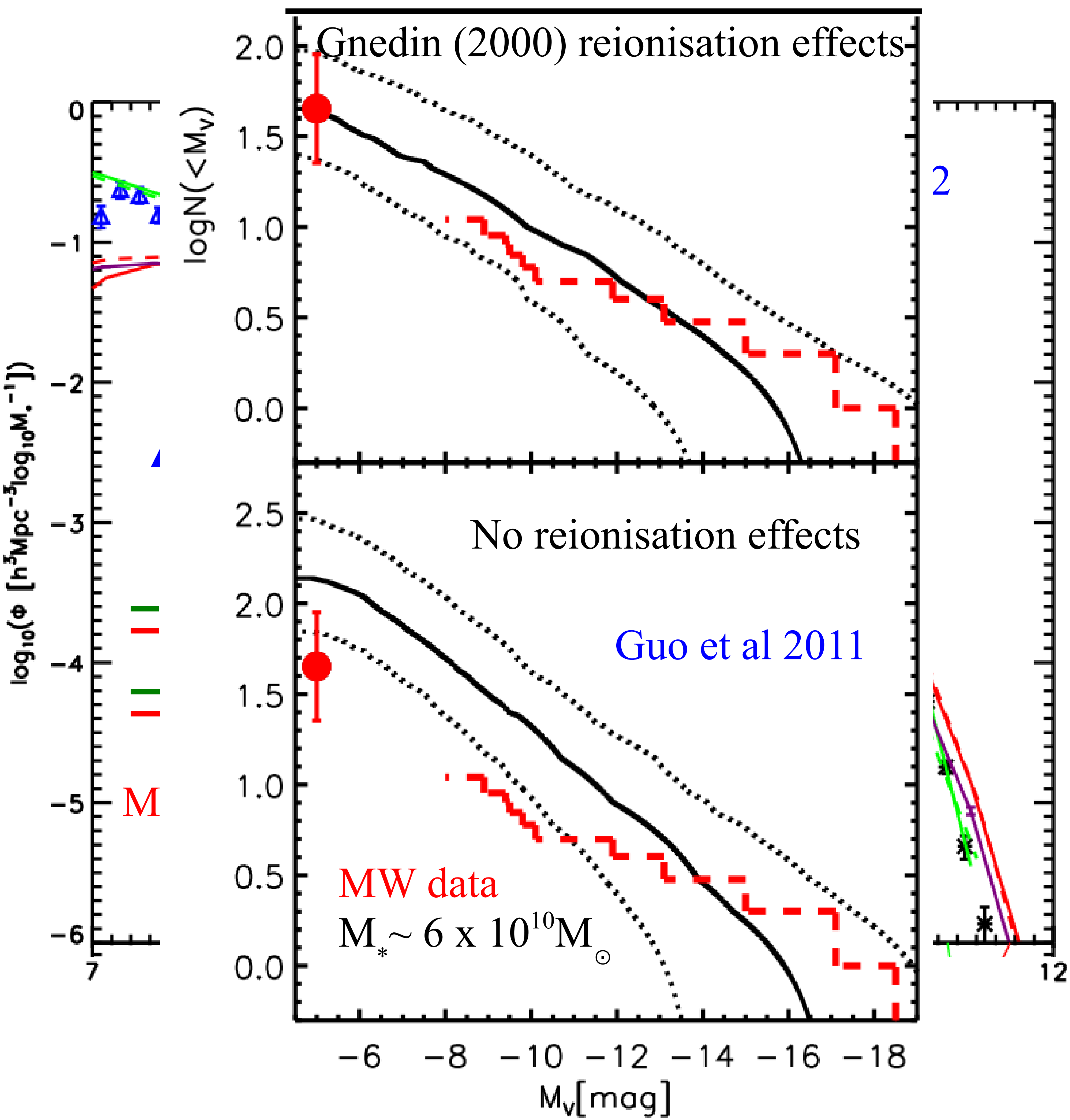


ΛCDM simulations of galaxy formation can match observed galaxy abundances...



ΛCDM simulations of galaxy formation can match observed galaxy abundances...

...and they then <u>also</u> match the observed abundance of MW satellite galaxies, at least if the effects of reionisation are fairly strong

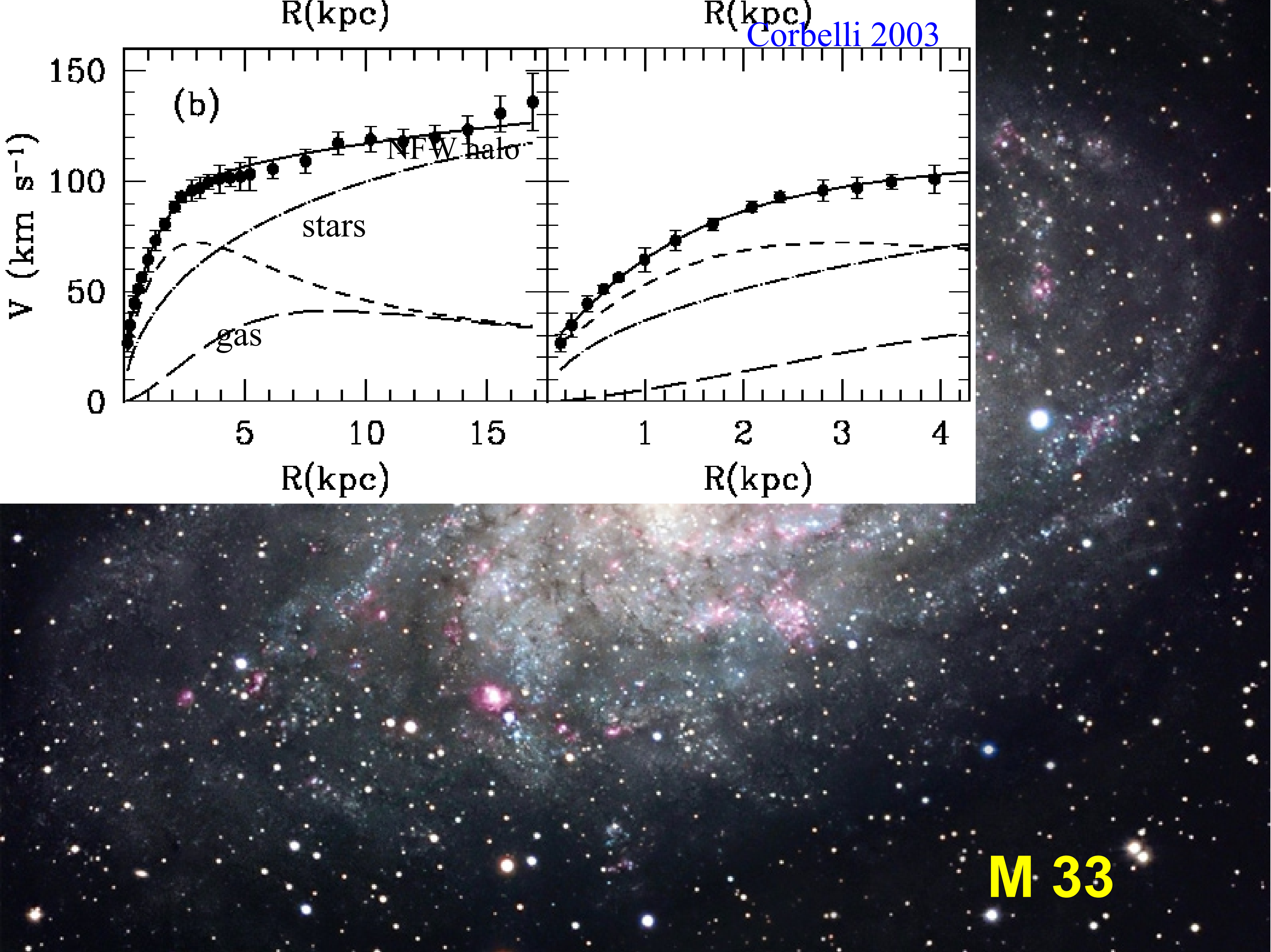


ΛCDM simulations of galaxy formation can match observed galaxy abundances...

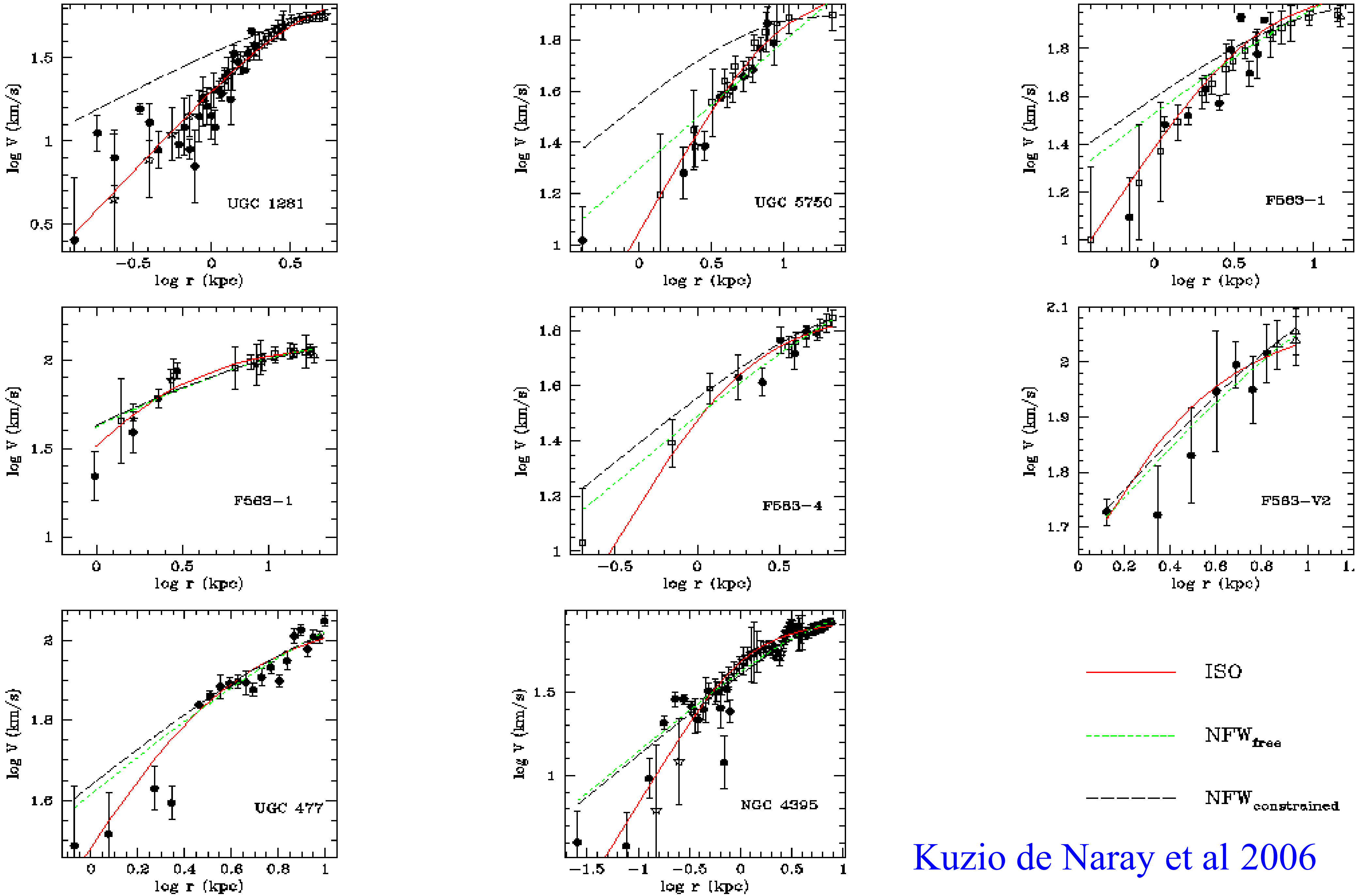
...and they then <u>also</u> match the observed abundance of MW satellite galaxies

Does the structure of the DM in simulated satellites match that observed?

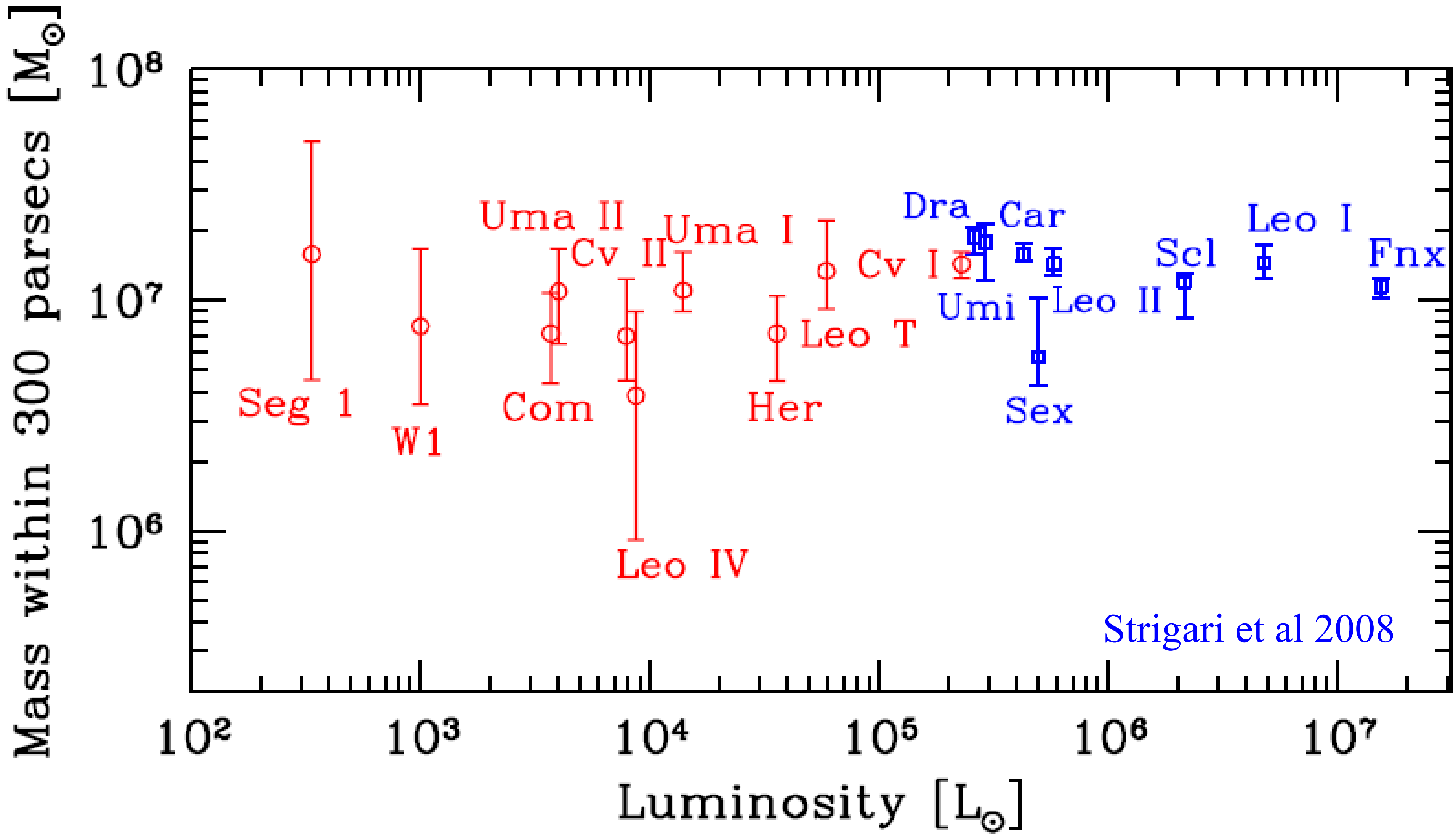

NFW
halo
star
s
gas
M 33


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

Inner rotation curves of low SB galaxies

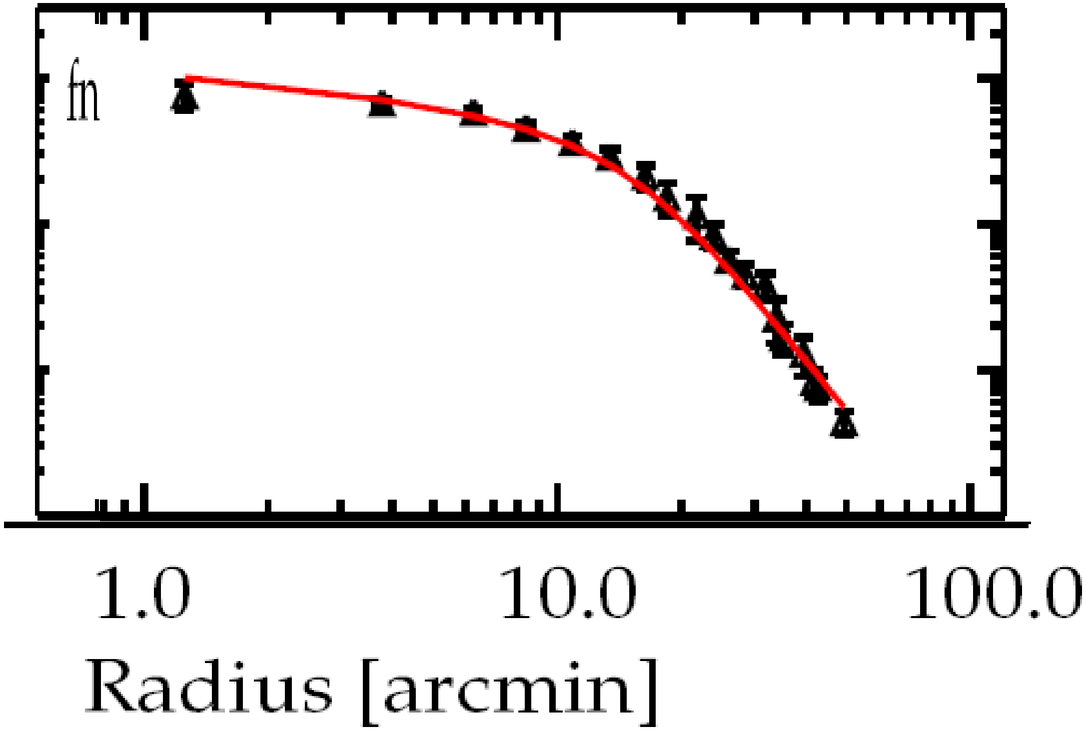


Kuzio de Naray et al 2006

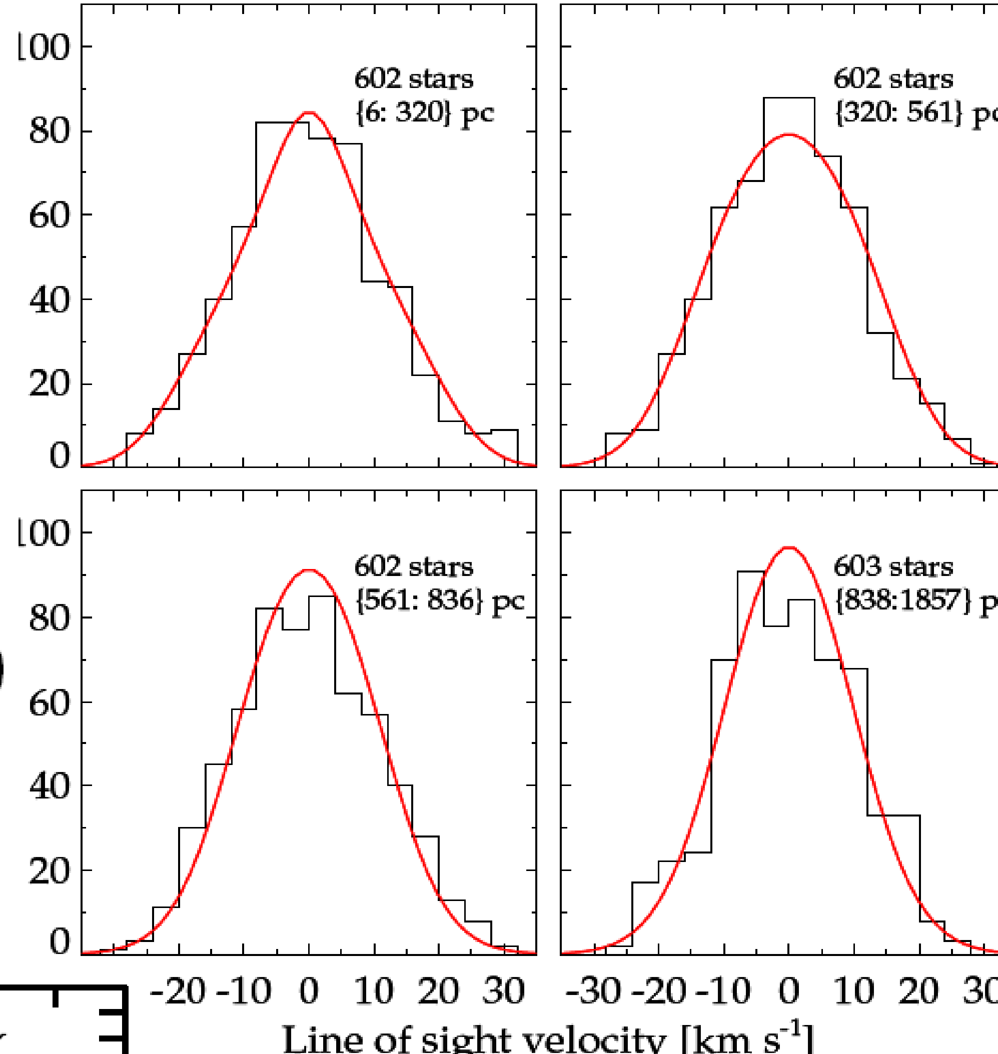


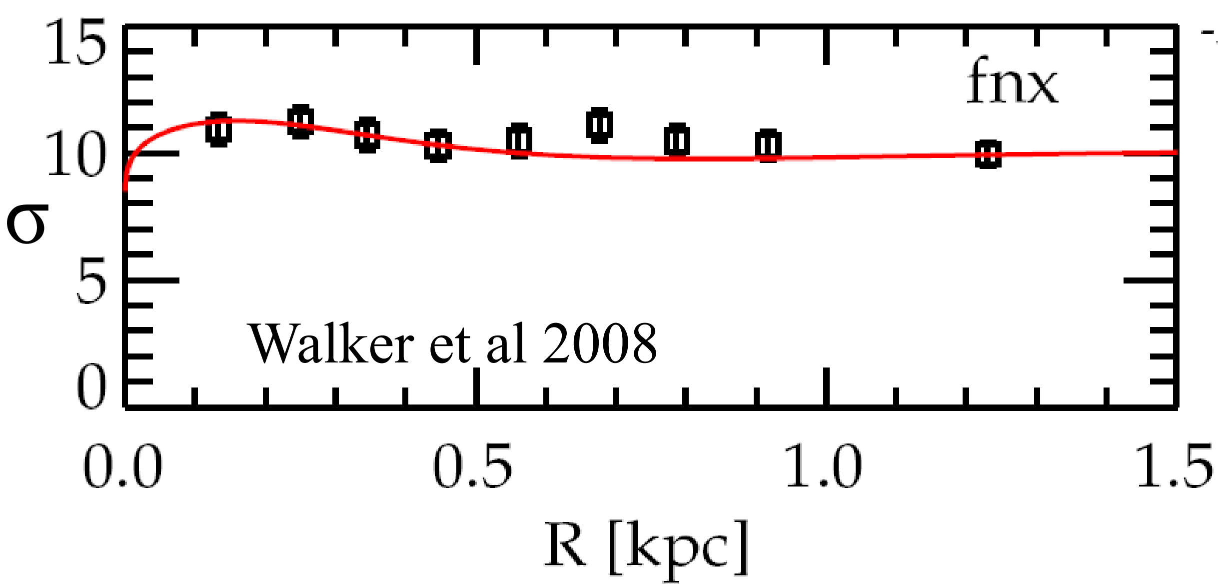
The apparent mass of dwarf galaxies (or equivalently their observed velocity dispersion) is almost independent of their baryonic content

Apparently their gravity is strongly dominated by the DM 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

Currently, the only apparent discrepancy with the ΛCDM model that is clearly established is in the structure of the inner halos of some (but **<u>not</u>** all) dwarf galaxies.

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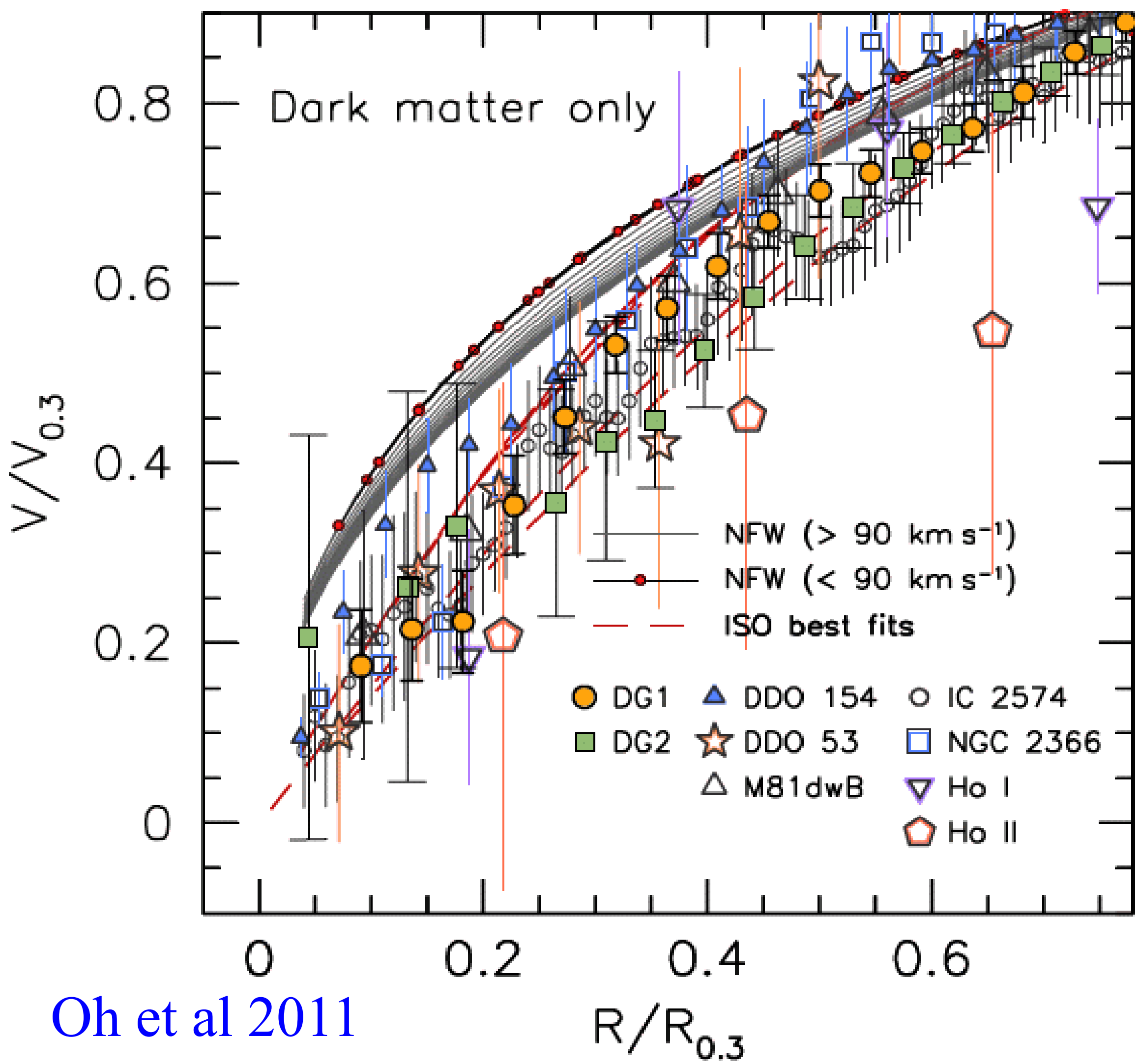
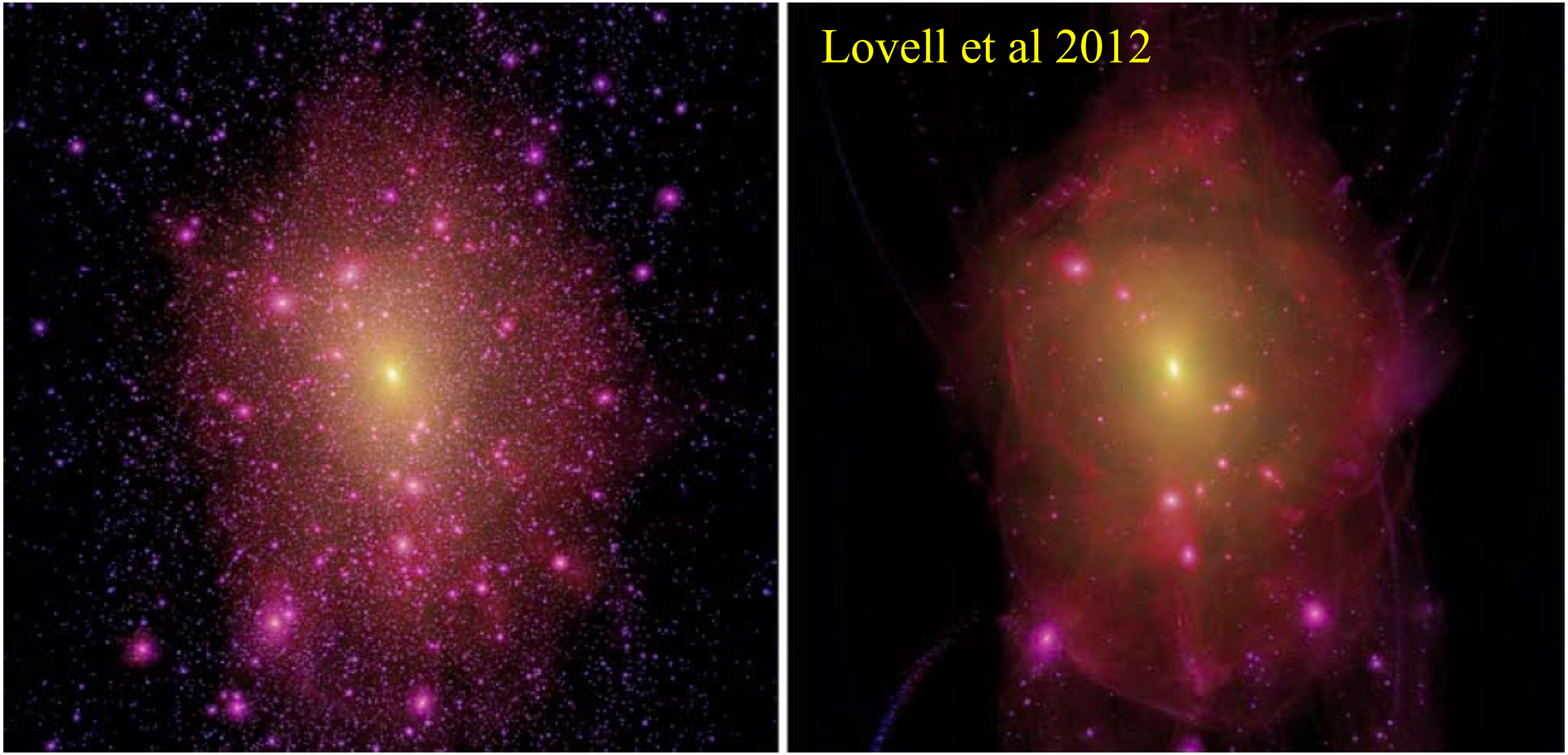


Oh et al 2011

Perhaps this is due to the dynamical effects of the star formation process?

Currently, the only apparent discrepancy with the ΛCDM model that is clearly established is in the structure of the inner halos of some (but **<u>not</u>** all) dwarf galaxies.



Perhaps it is due to WDM removing the smallest halos and reducing the concentration of the rest?