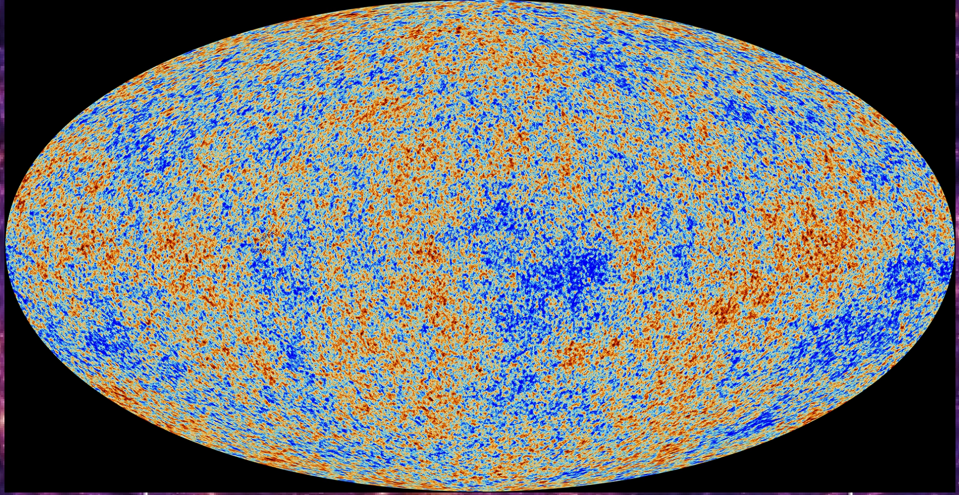
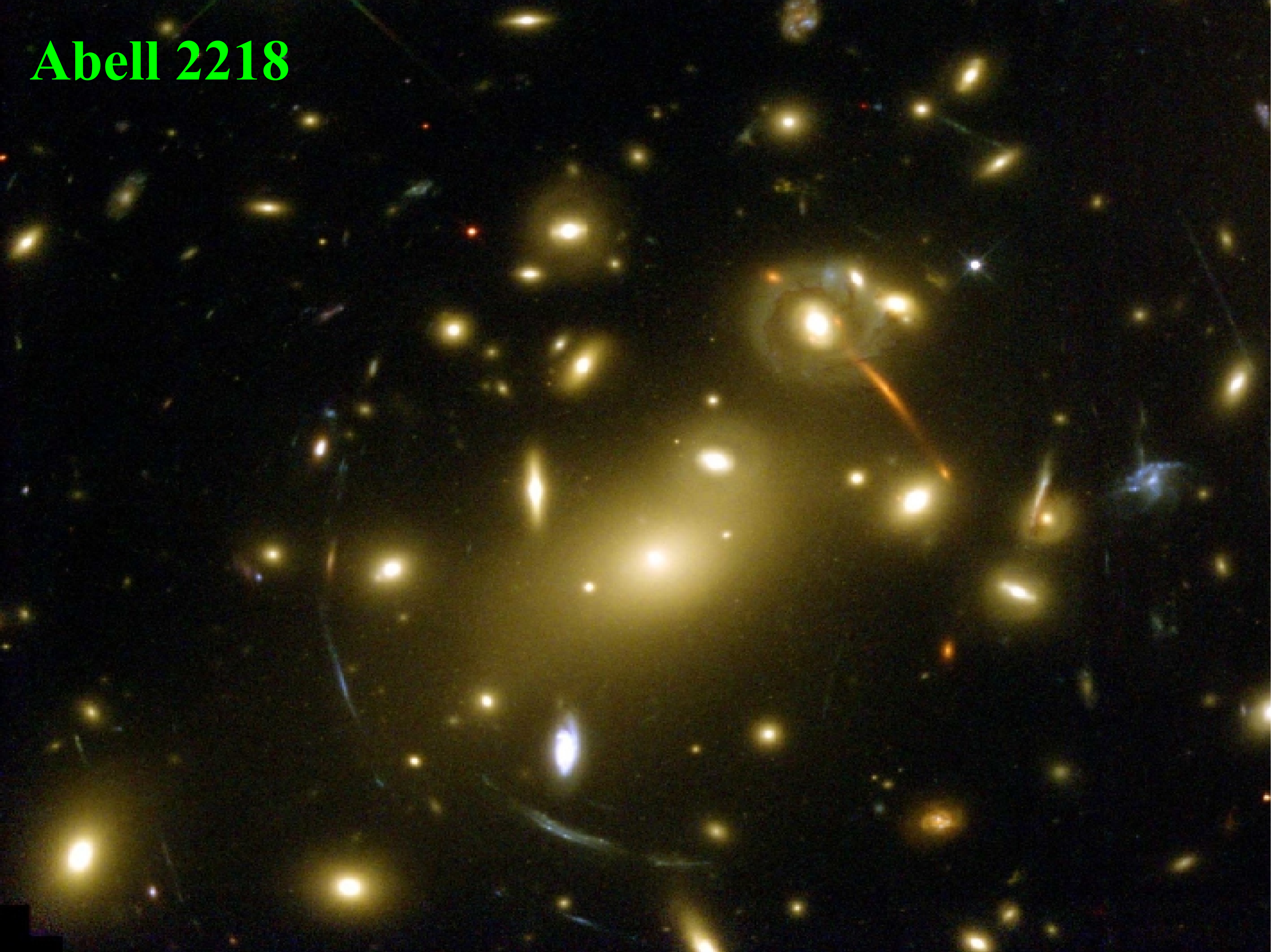


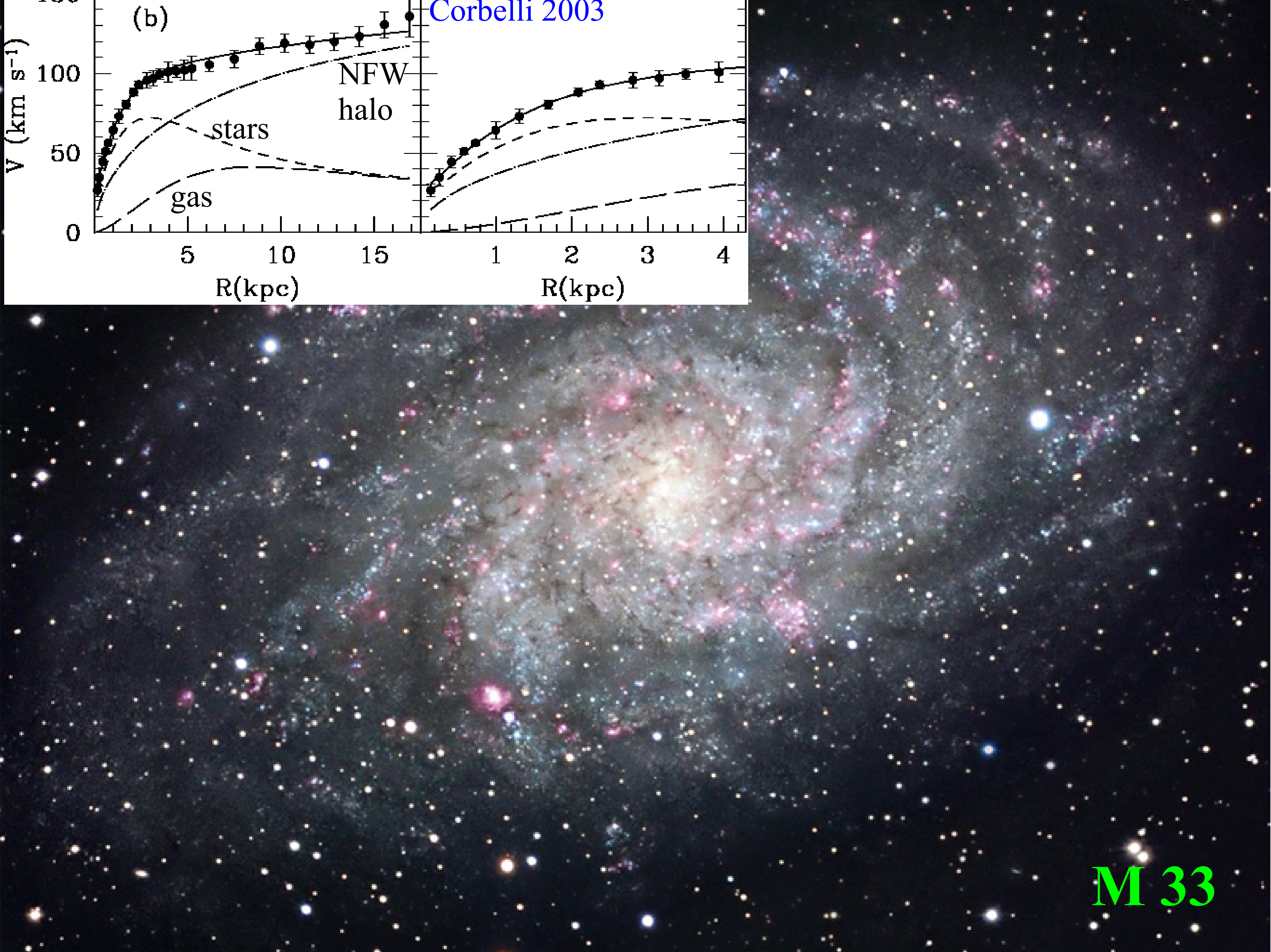
PLANCK 2014
Ferrara

Dark matter from cosmological probes

Simon White
Max Planck Institute for Astrophysics

Dark matter was "discovered" in the Coma Cluster by Zwicky (1933)


Abell 2218



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

P2013 parameters for the minimal ΛCDM model

	Planck+WP	
Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063
τ	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$

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A 40σ detection of nonbaryonic DM using *only* z ~1000 data!

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86σ in 2014 using *Planck* data alone!!

P2013 parameters for the minimal ΛCDM model

Direct constraints are on relatively large scales

$\Omega_b h^2$)28

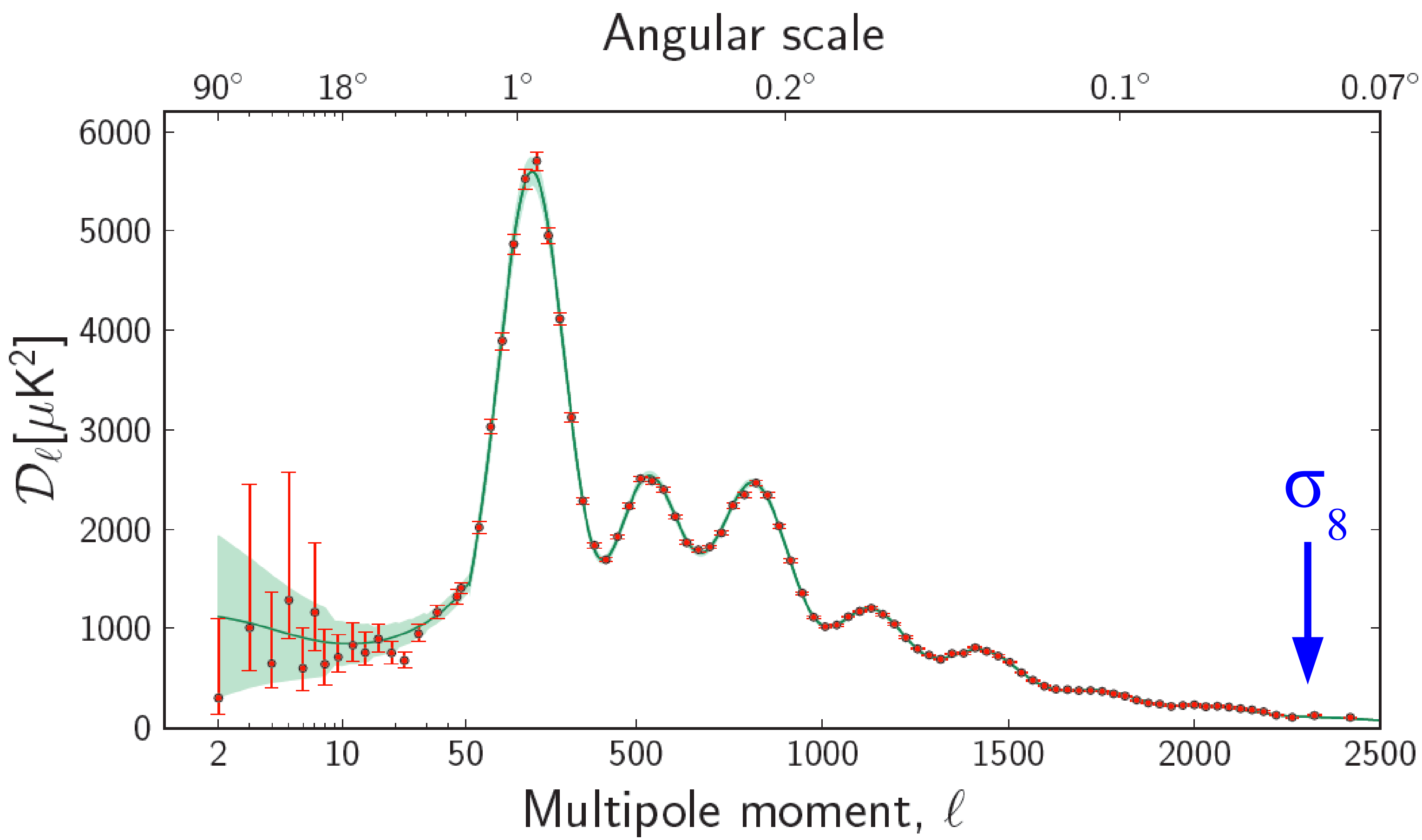
$\Omega_c h^2$ '27

$100\theta_M$

τ . .

n_s . '3

data!

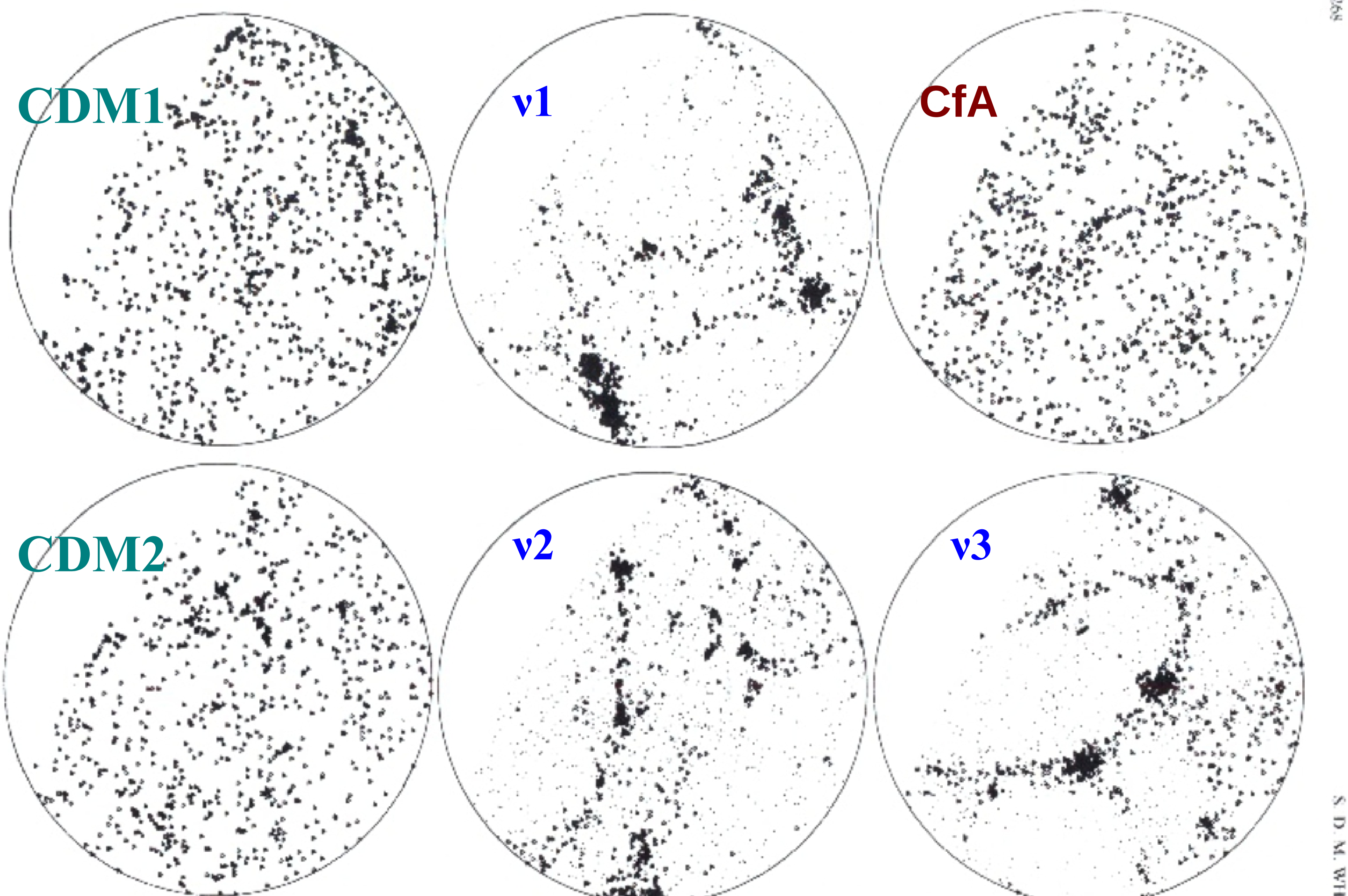


$\ln(10^{10} A_s)$ . . . . 3.0980 $3.089^{+0.024}_{-0.027}$

CMB constraints on Dark Matter

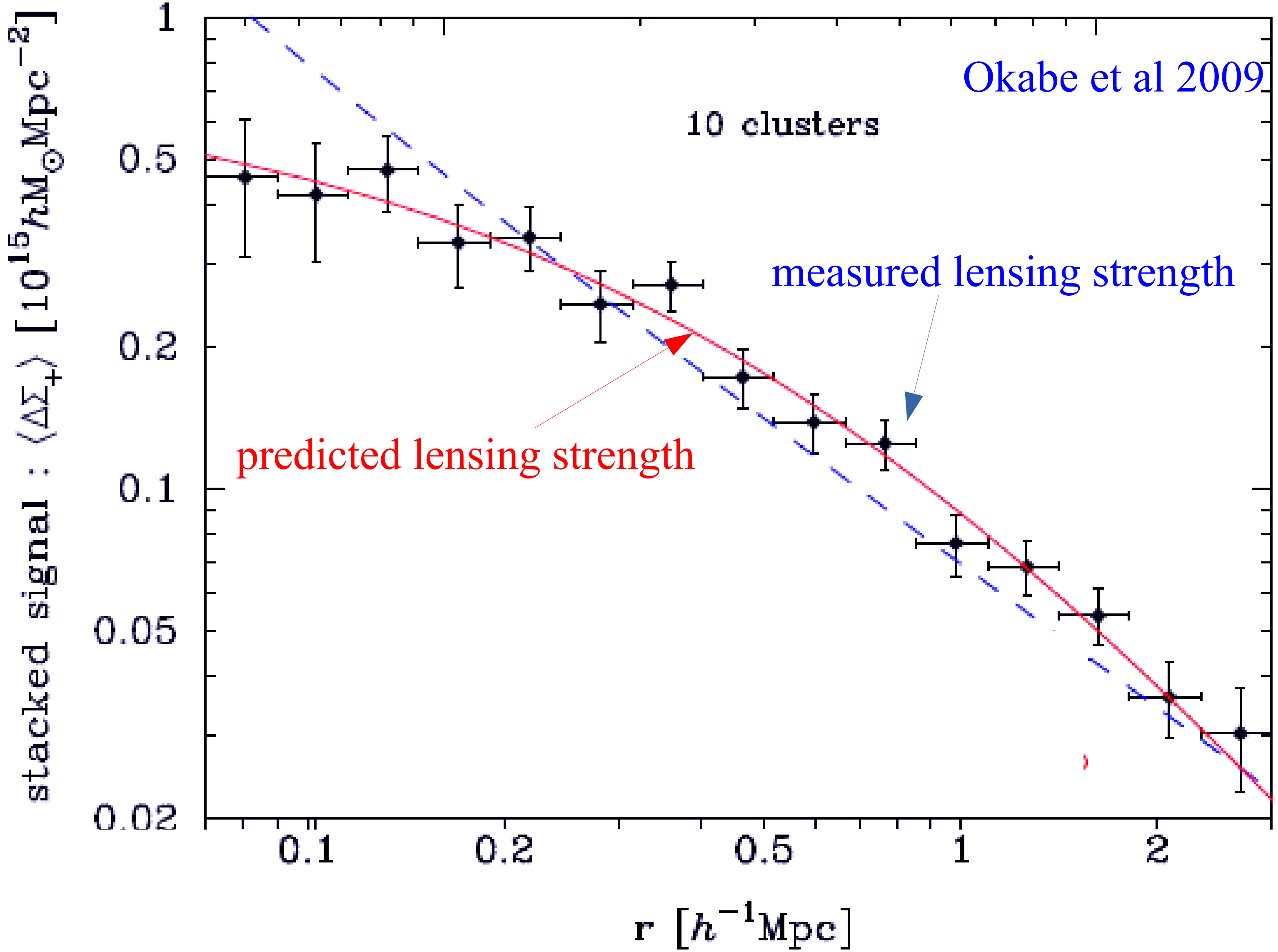
- The density of DM at z=1000 is 5.4 times that of baryonic matter
  → already present as DM at nucleosynthesis
- It is smooth with weak fluctuations paralleling those of the coupled baryon/photon fluid (e.g. “adiabatic” initial conditions)
- Non-gravitational interactions with the photon/baryon fluid are weak
- Its “thermal” motions were nonrelativistic at z=1000 – it's not “hot”
- Decay/annihilation rates into “visible” channels are low, $\ll 1/t_H$
- At most a small fraction can be any known particle (e.g. neutrinos)

Large-scale structure measurements excluded υ's as dark matter about two decades <u>before</u> direct mass limits or CMB fluctuations

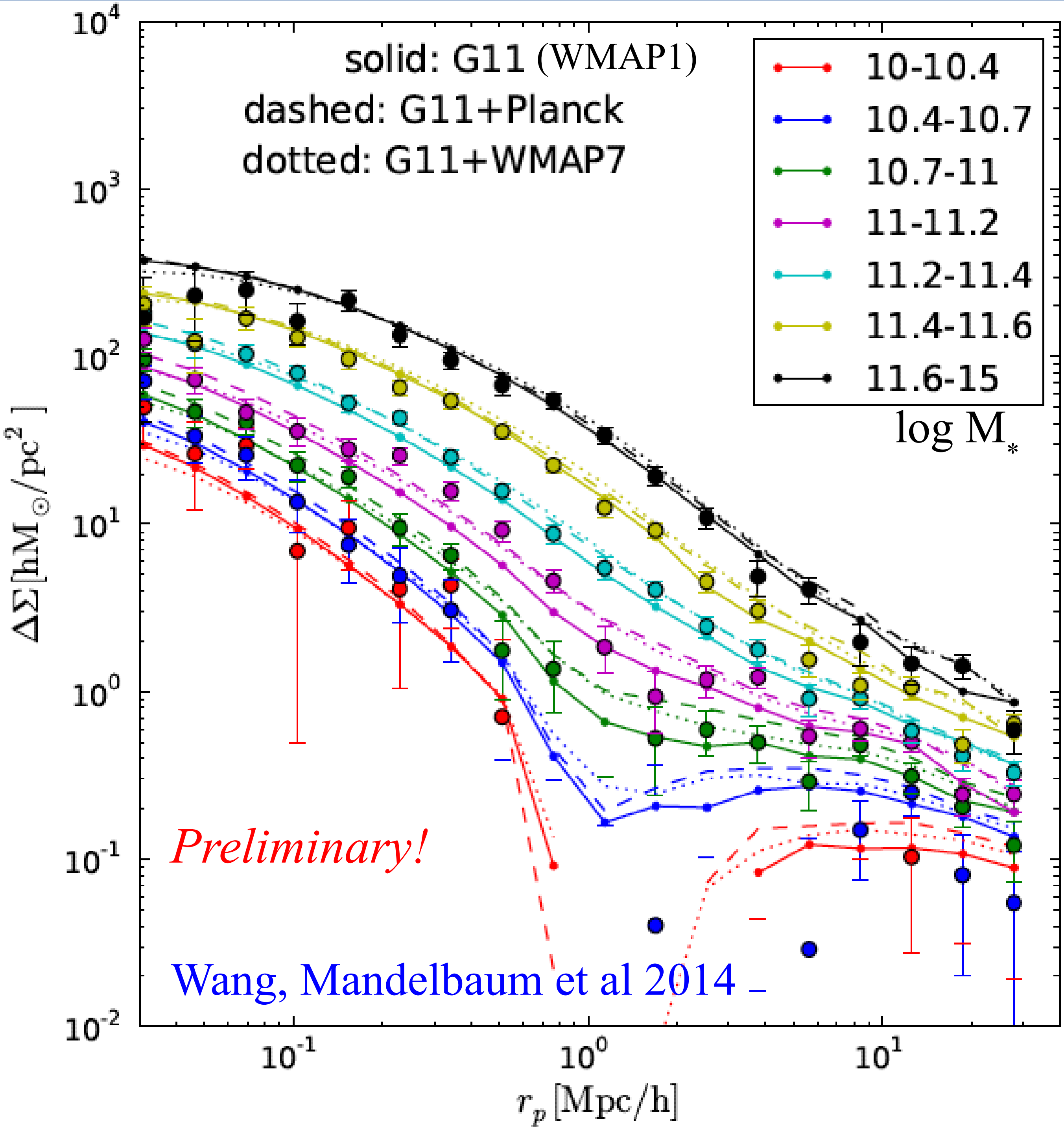


White et al 1983

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



Mean mass profiles around Locally Brightest Galaxies in SDSS

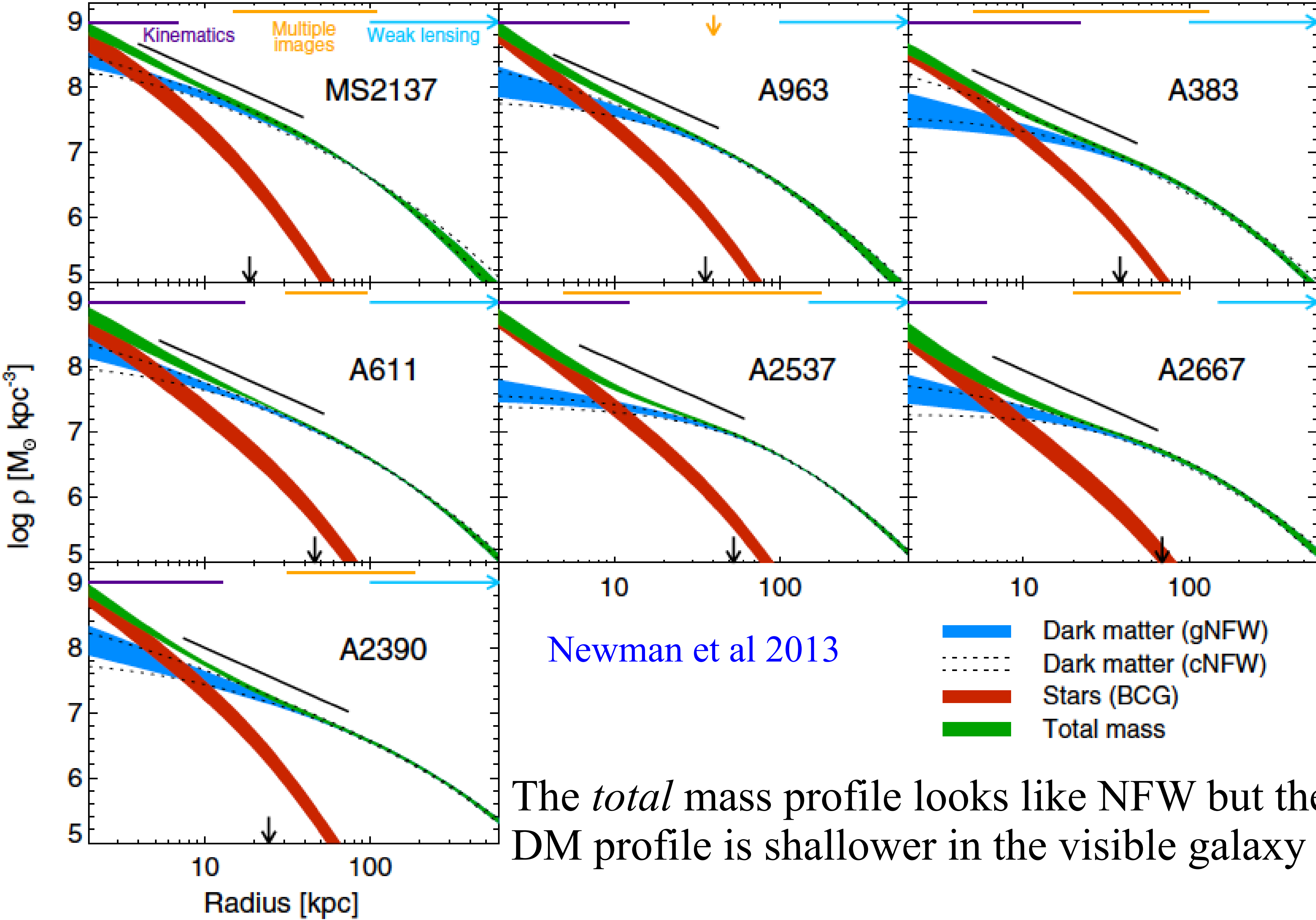


Stacking of the weak lensing signal around 260,000 locally brightest SDSS galaxies measures a good signal over a range of ~1000 in radius and 30 in stellar mass or ~300 in halo mass.

Comparison is with simulations which reproduce the observed stellar mass function in different cosmologies

Effectively a zero parameter comparison!

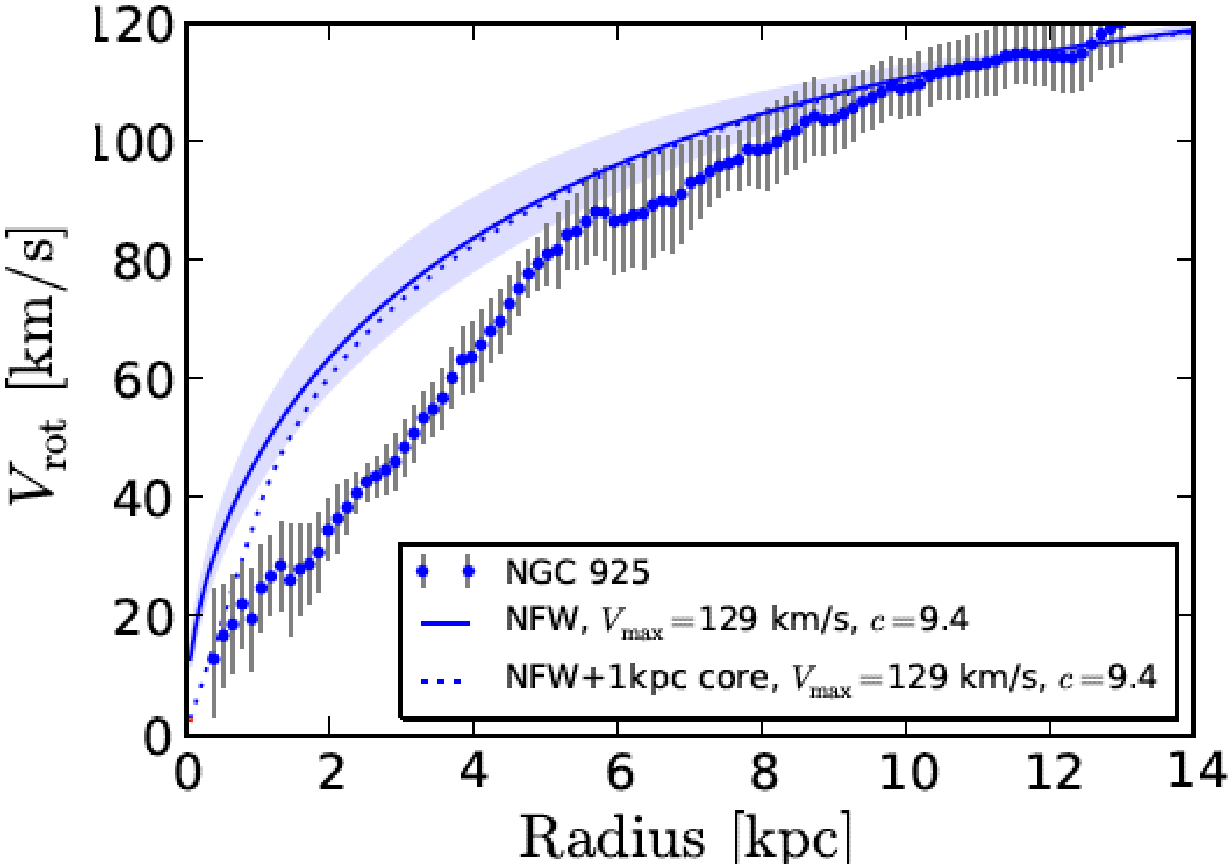
Innermost DM profiles of rich, relaxed clusters



Newman et al 2013

The *total* mass profile looks like NFW but the DM profile is shallower in the visible galaxy

Apparent cores in dwarf galaxies



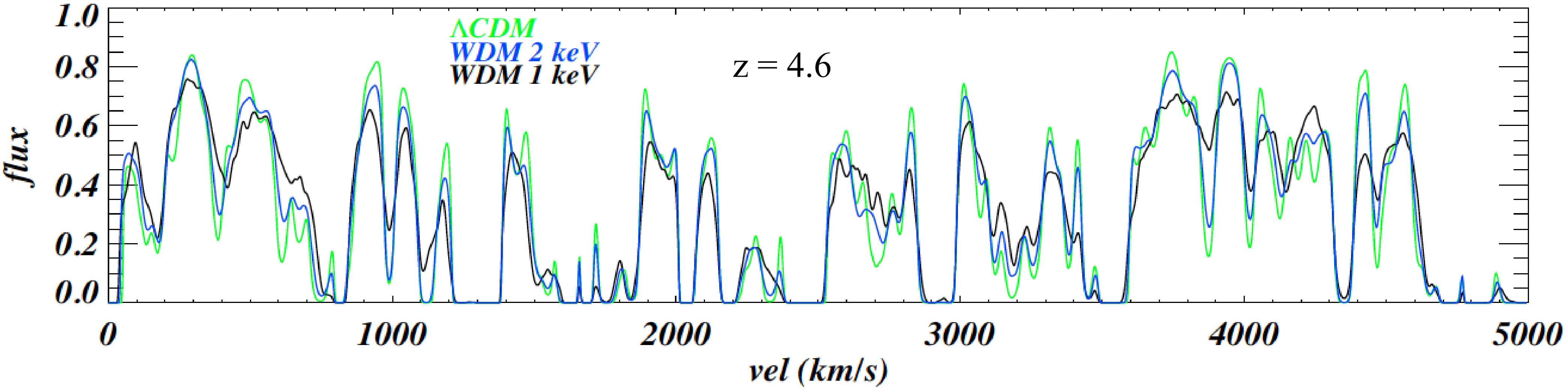
Unlike in M33, the rotation curves of many dwarfs rise slowly, indicating the presence of DM cores and inconsistent with NFW.

Baryonic effects during galaxy formation?

A reflection of the nature of DM? (WDM? SIDM?)

Ly α forest spectra and small-scale initial structure

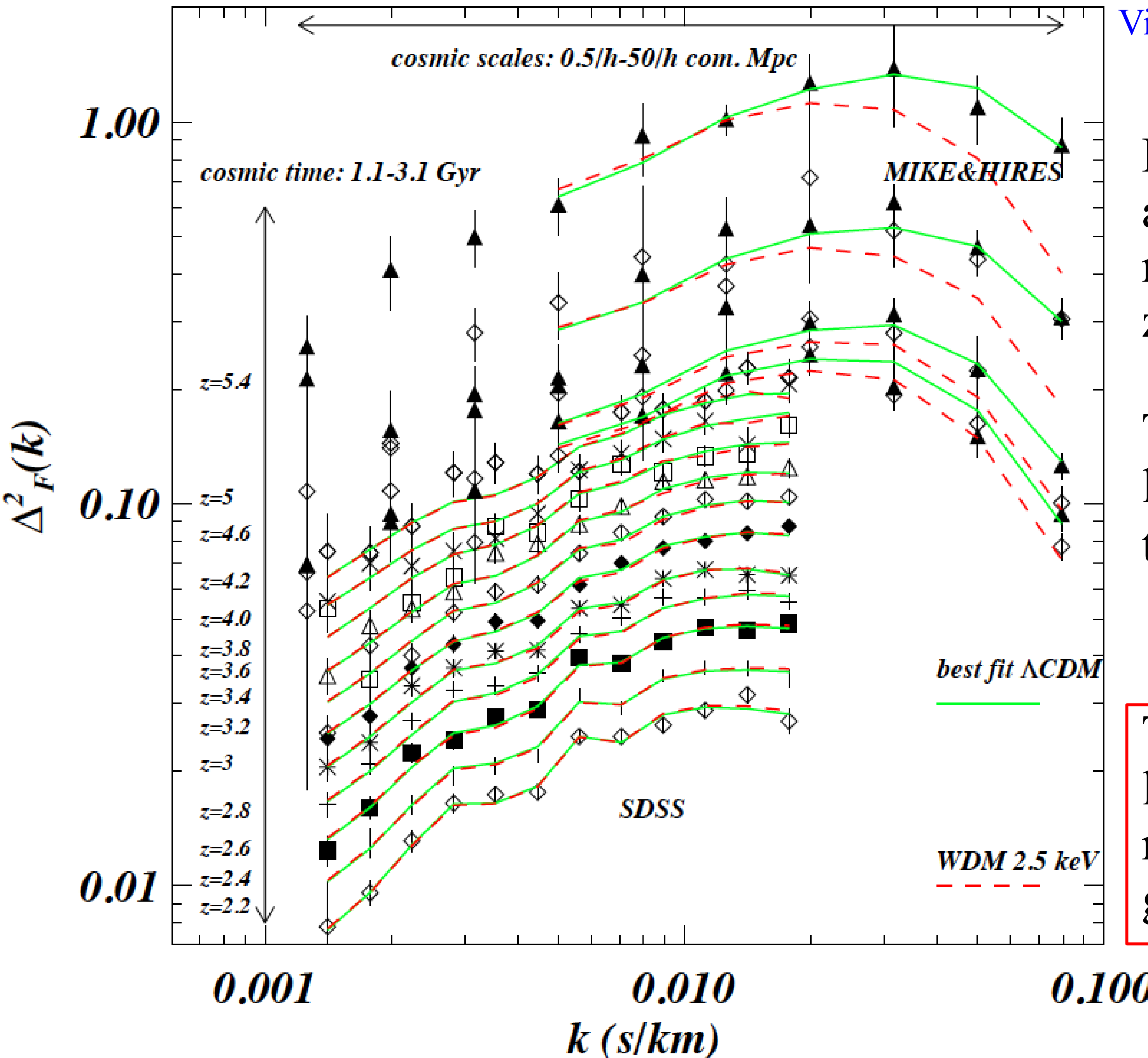
Viel, Becker, Bolton & Haehnelt 2013



Transmitted quasar flux in hydrodynamic simulations of the intergalactic medium in ΛCDM and WDM models.

High-frequency power is missing in the WDM case

Lyman α forest spectra for WDM relative to CDM



Viel, Becker, Bolton & Haehnelt 2013

High-resolution Keck and Magellan spectra match ΛCDM up to z = 5.4

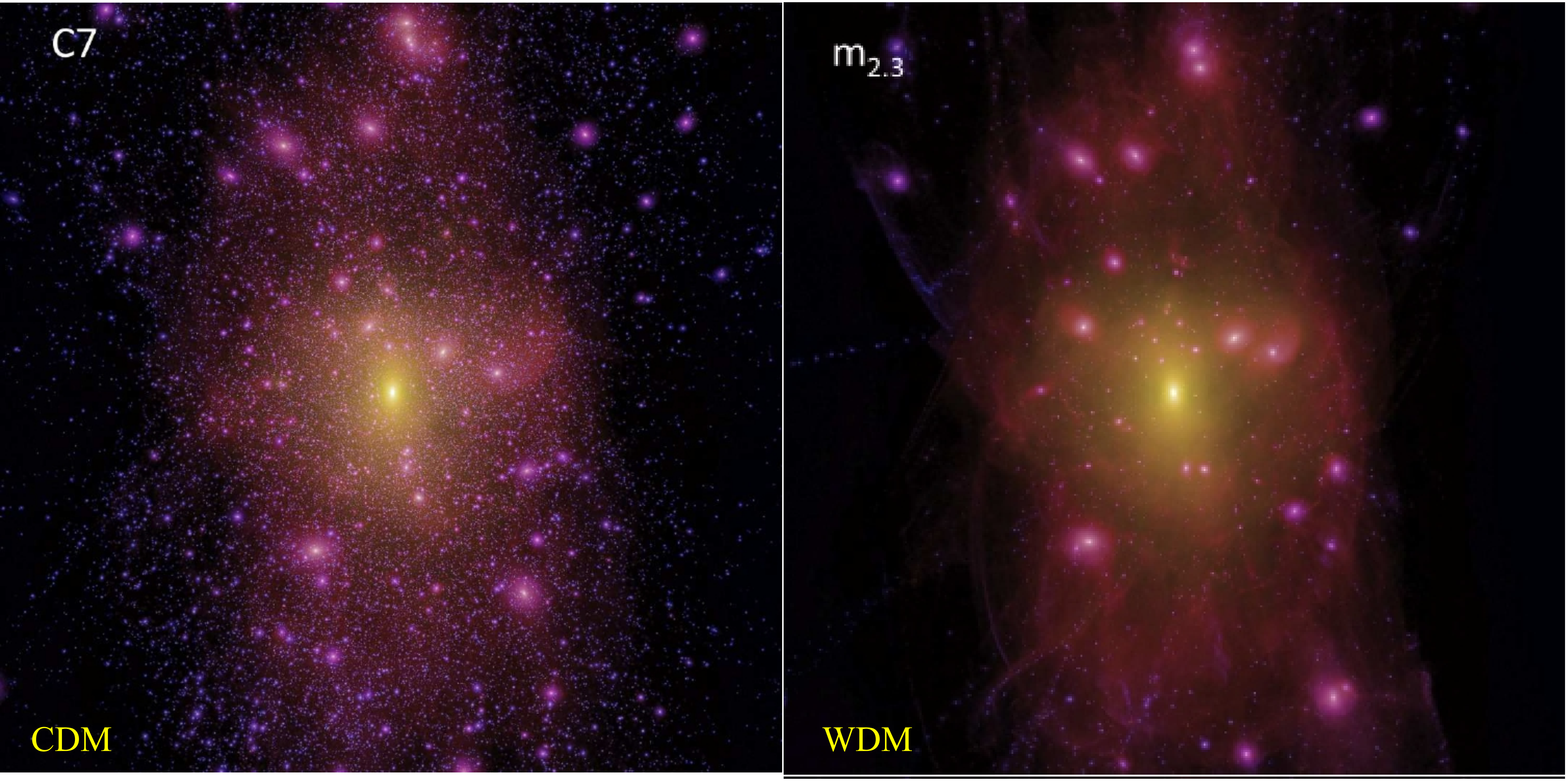
This places a 2σ lower limit on the mass of a thermal relic

$m_{WDM} > 3.3$ keV

This lower limit is too large for WDM to have much effect on dwarf galaxy structure

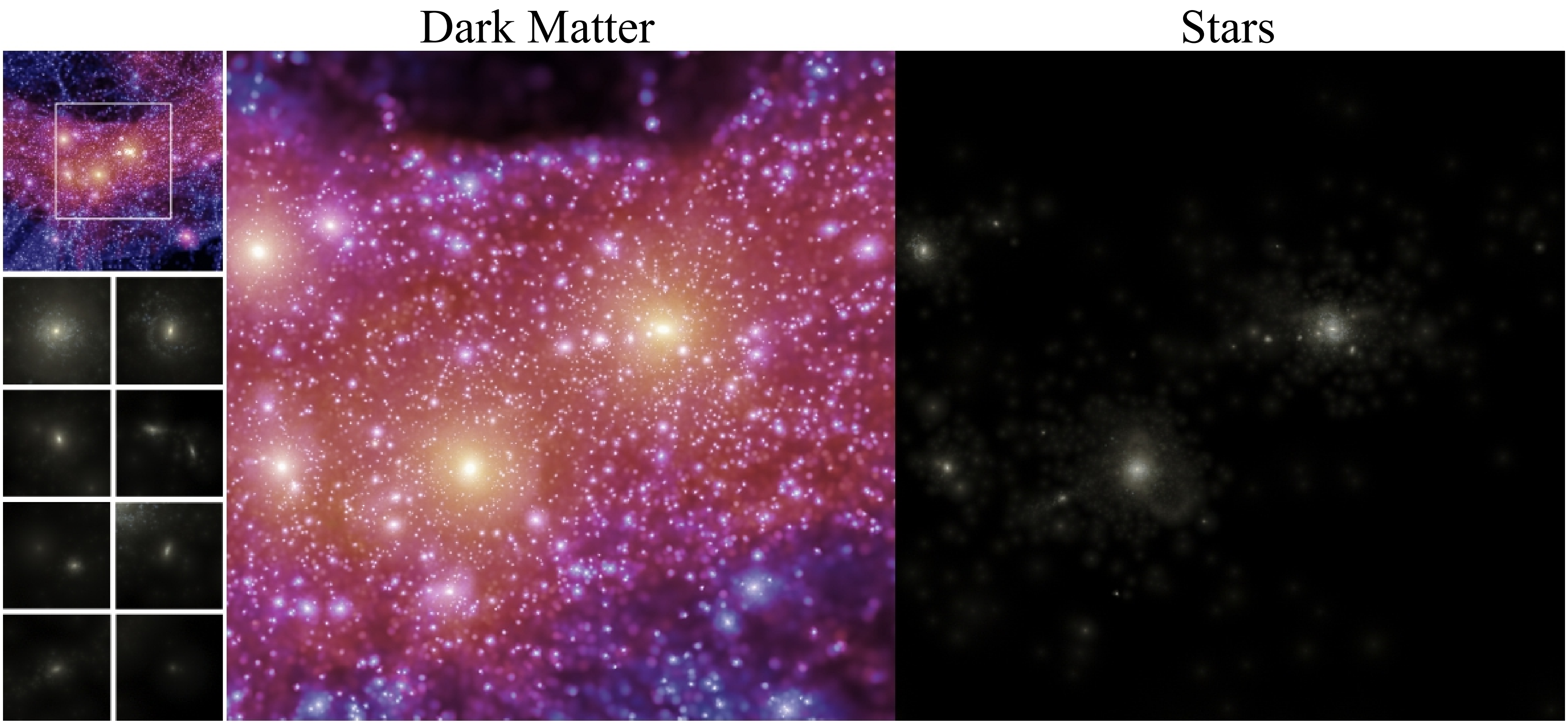
Dark matter effects on galaxy formation?

Lovell et al 2013.



"Milky Way" halos in CDM and WDM. Note, the Ly α forest 2σ lower limit gives a limiting halo mass 3 times *smaller* than assumed here. The IC's are ~ΛCDM on essentially all scales relevant to galaxies

Galaxy formation may hide the small substructures

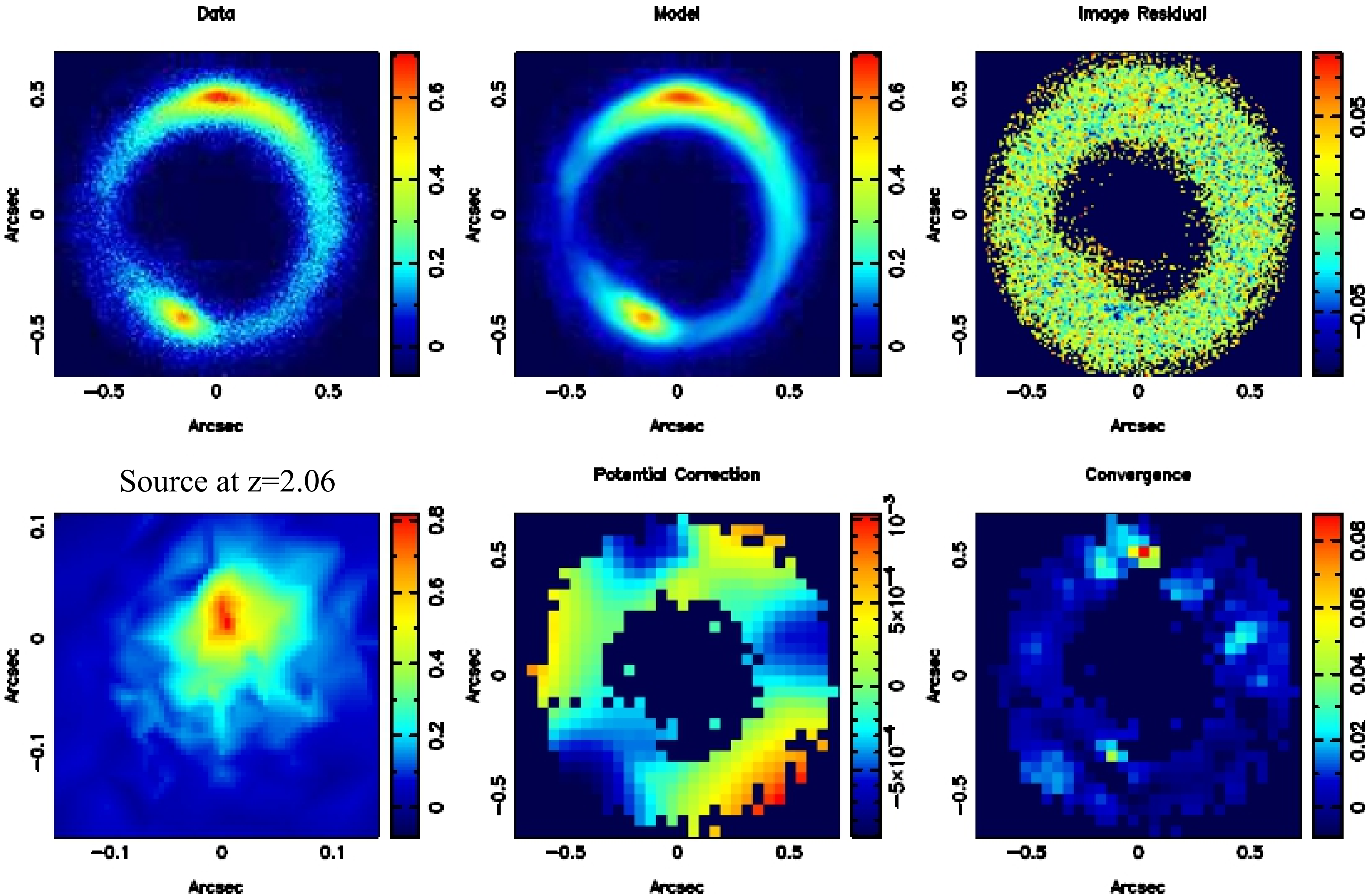


High-resolution hydrodynamics simulation of a “Local Group”

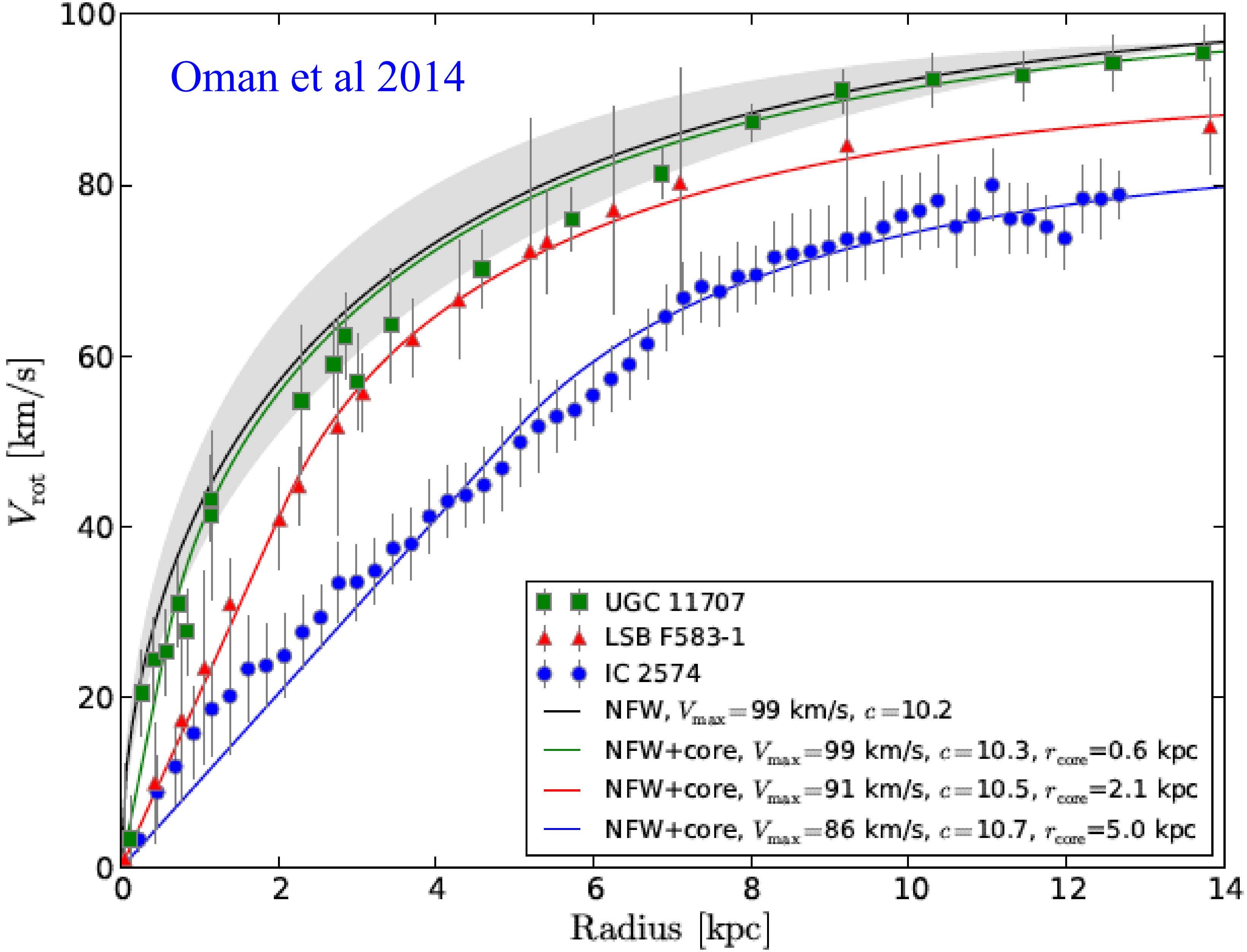
Sawala et al 2014

Detection of a $2x10^8 M_\odot$ “dark” substructure in a z=0.88 halo

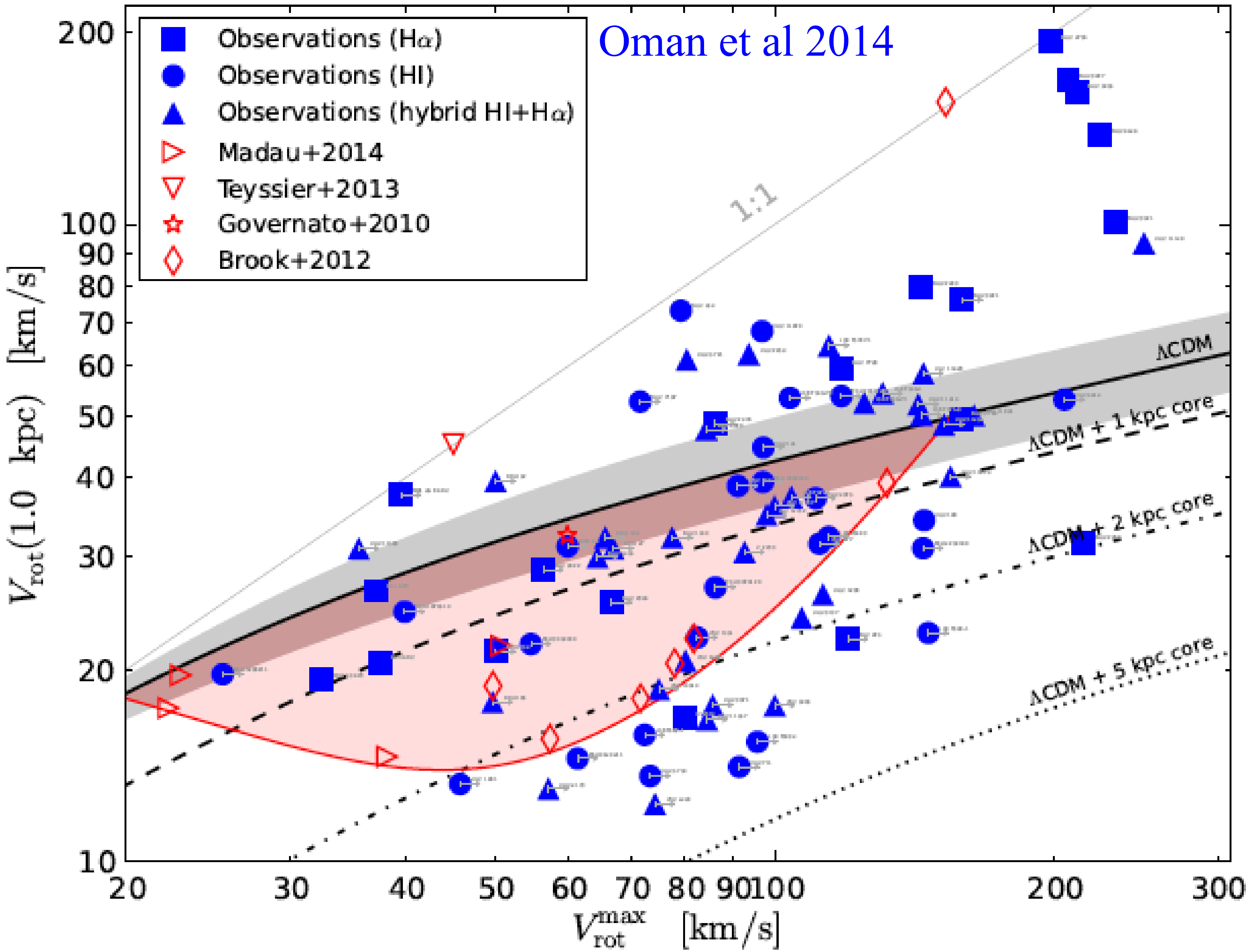
Vegetti et al 2012



Not all dwarf galaxy cores look the same...



..indeed, the diversity is so large it seems inconsistent both with a dark matter origin, and with current models of baryonic effects!



- The CMB now provides a precise and robust demonstration of the existence of DM based on data from z=1000 alone.
- Only a small fraction of the DM is made of known particles
- Evolution from the ΛCDM initial conditions seen in the CMB reproduces the structure and abundance of z=0 halos
- Ly α forest data are close to excluding all WDM models which have significant effects on the structure of observed galaxies
- The core structure of many dwarf galaxies differ from simple ΛCDM predictions in ways that are still not well understood