Tension between cosmology from galaxy cluster abundance And Planck CMB anisotropy measurements?

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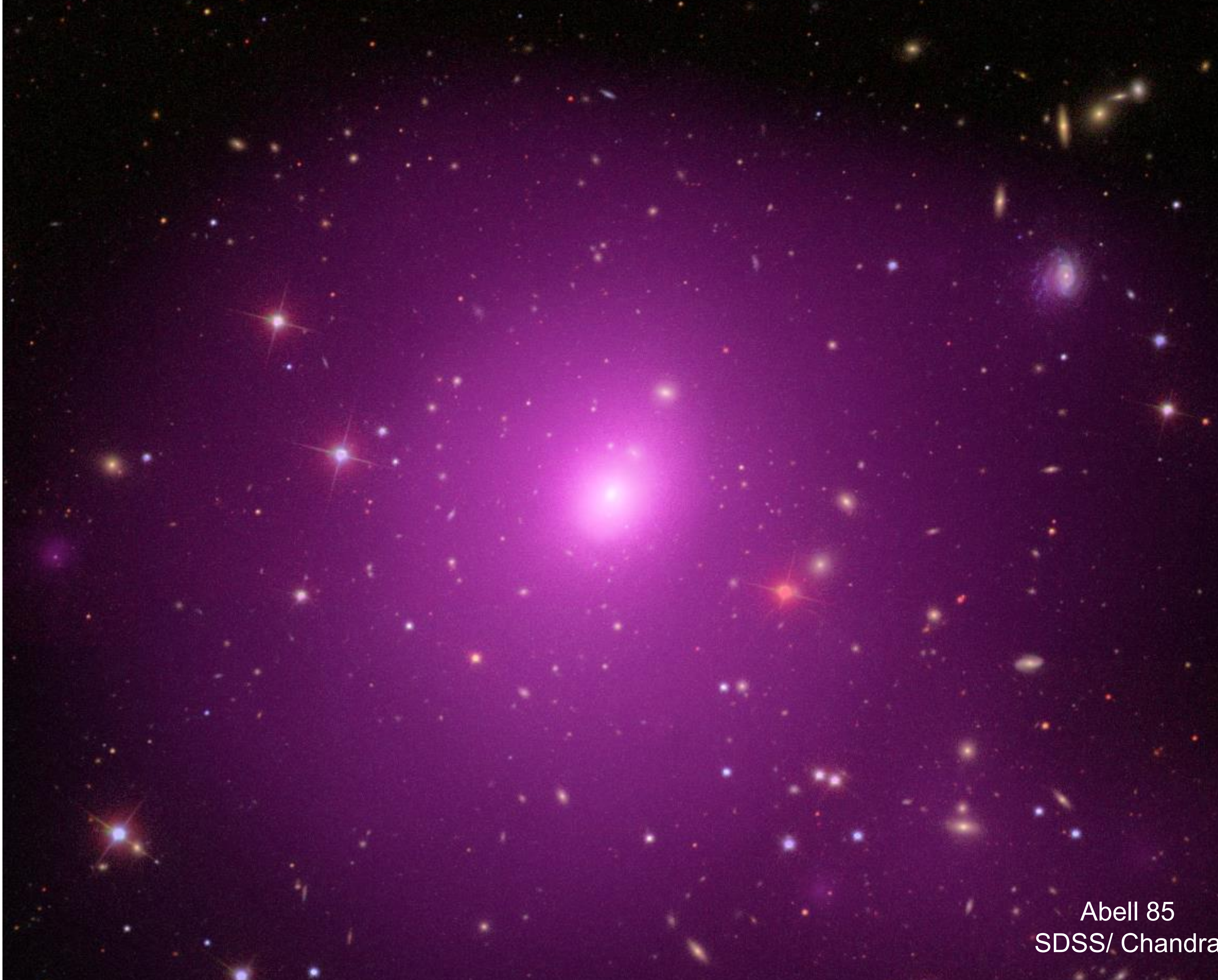
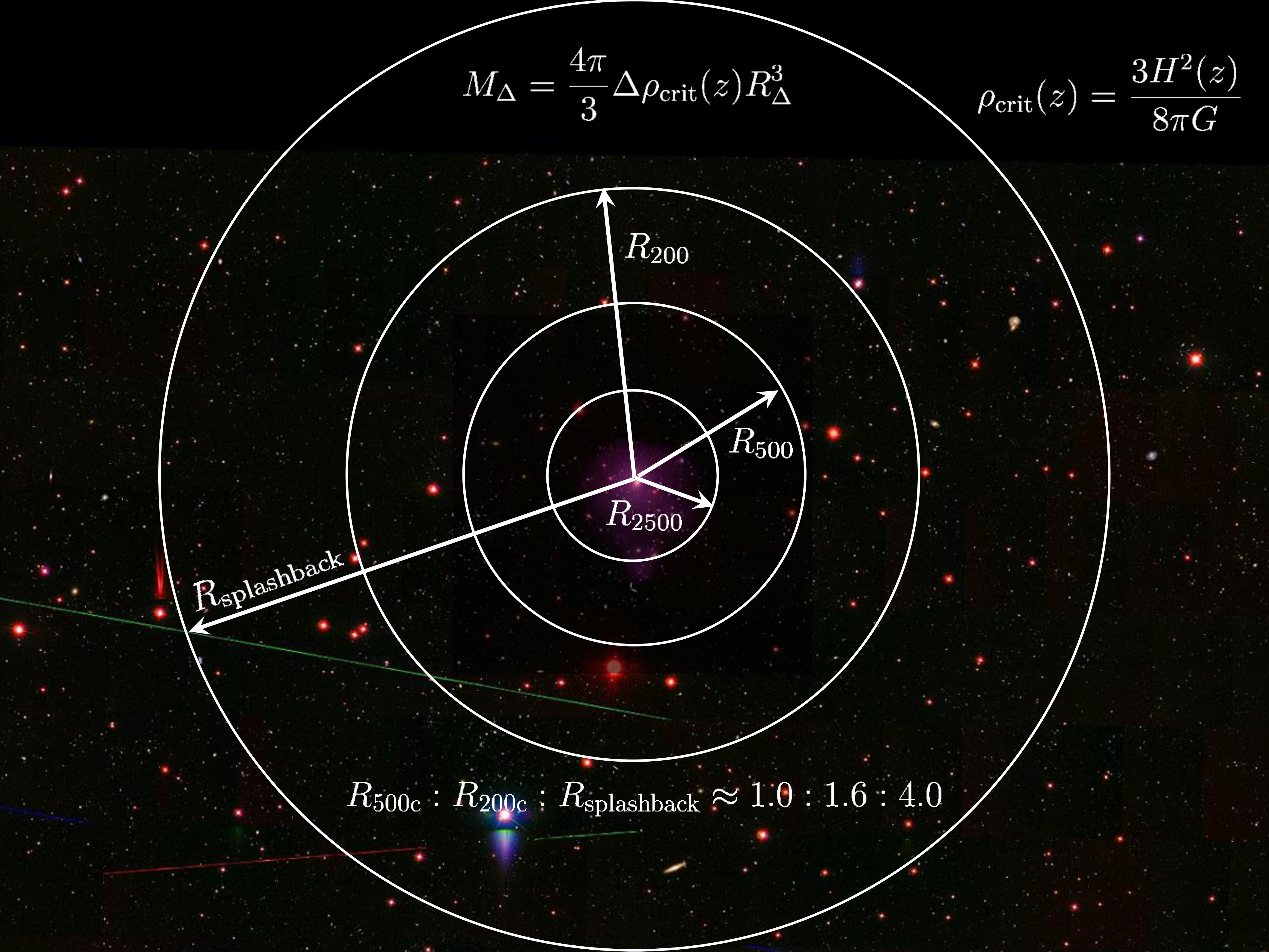
Abell 85
SDSS

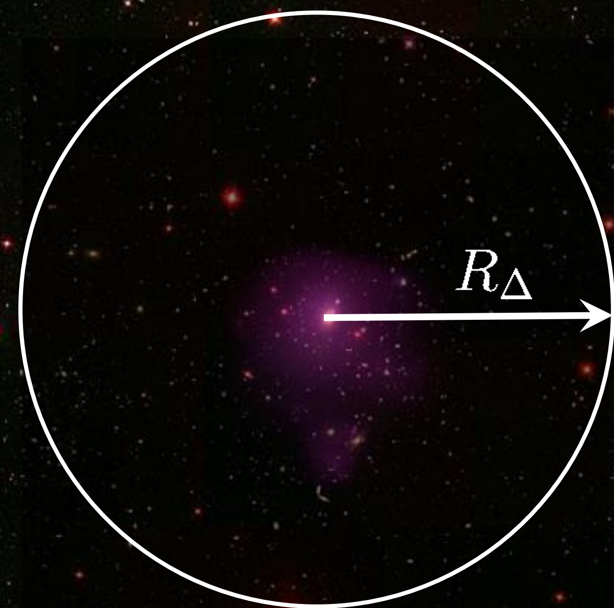

Abell 85
SDSS/ Chandra



$M_\Delta = \frac{4\pi}{3}\Delta\rho_{\rm crit}(z)R_\Delta^3$
$\rho_{\rm crit}(z) = \frac{3H^2(z)}{8\pi G}$
R_{200}
R_{500}
R_{2500}
$R_{\rm splashback}$
$R_{\rm 500c} : R_{\rm 200c} : R_{\rm splashback} \approx 1.0 : 1.6 : 4.0$

$$M_\Delta = \frac{4\pi}{3}\Delta\rho_{\rm ref}(z)R_\Delta^3$$

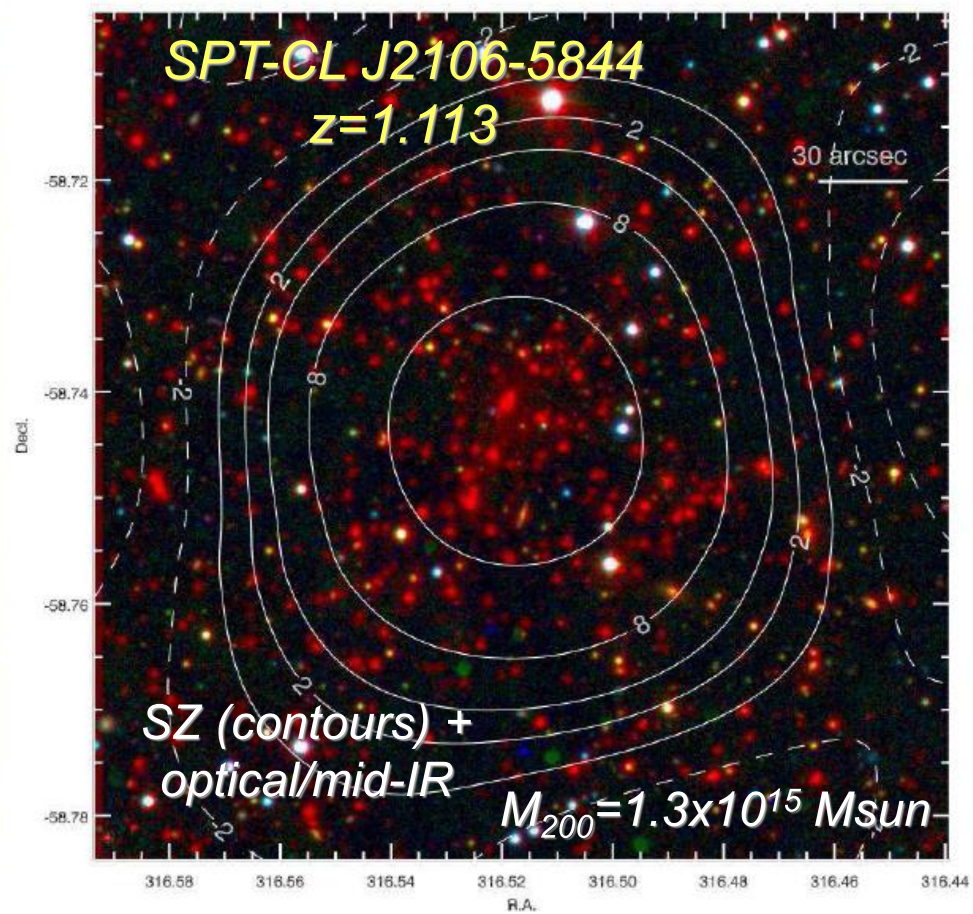
$$T \propto \frac{M_\Delta}{R_\Delta} \propto \Delta^{1/3}\rho_{\rm ref}^{1/3}(z)M_\Delta^{2/3} \begin{cases} \propto \rho_{\rm crit}^{1/3}(z)M_{\Delta \rm c}^{2/3} \propto E^{2/3}(z)M_{\Delta \rm c}^{2/3} \\ \propto \rho_{\rm mean}^{1/3}(z)M_{\Delta \rm m}^{2/3} \propto (1+z)\,M_{\Delta \rm m}^{2/3} \end{cases}$$



$$\mu m_p \frac{GM_{\rm HE}(<R)}{R} = kT(R)\left[-\frac{d\ln\rho_{\rm g}}{d\ln R} - \frac{d\ln T}{d\ln R}\right]$$

$$\frac{GM_{\rm J}(<R)}{R} = \sigma_r^2(R)\left[-\frac{d\ln n_{\rm gal}}{d\ln R} - \frac{d\ln\sigma_r^2}{d\ln R} - 2\beta(R)\right]$$

More recently, weak lensing of background galaxies has become the primary tool of measuring cluster masses

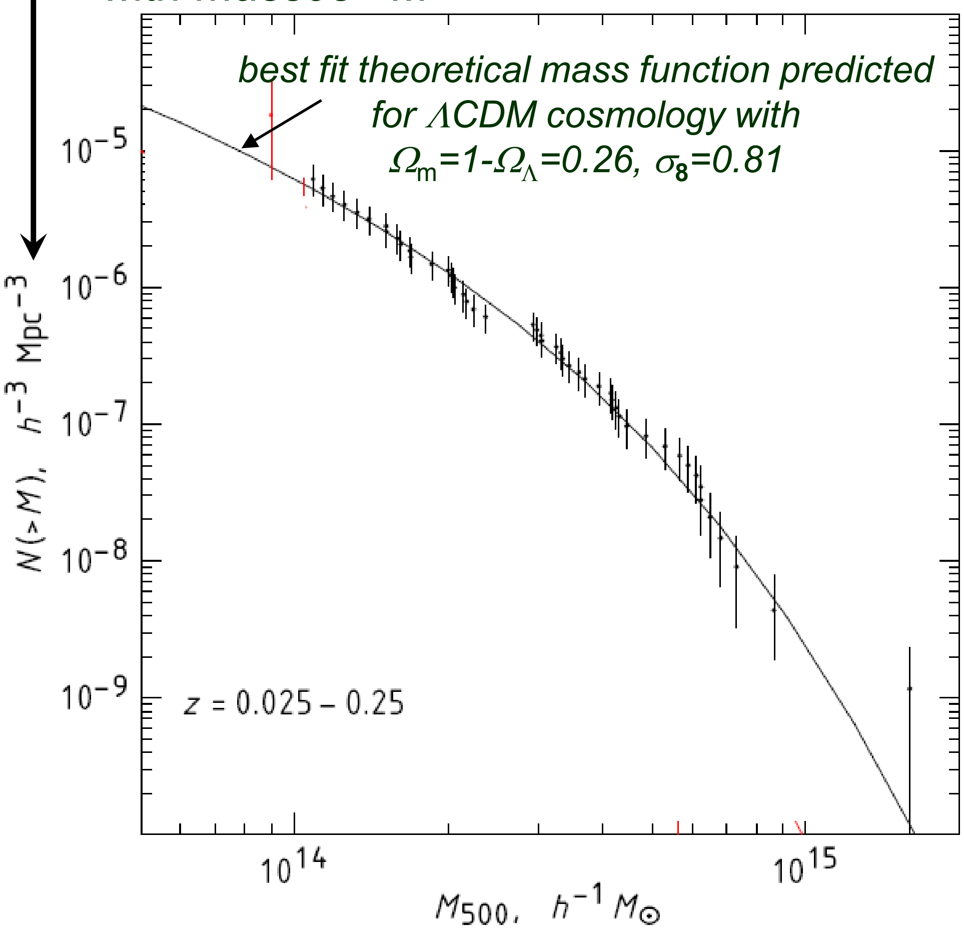


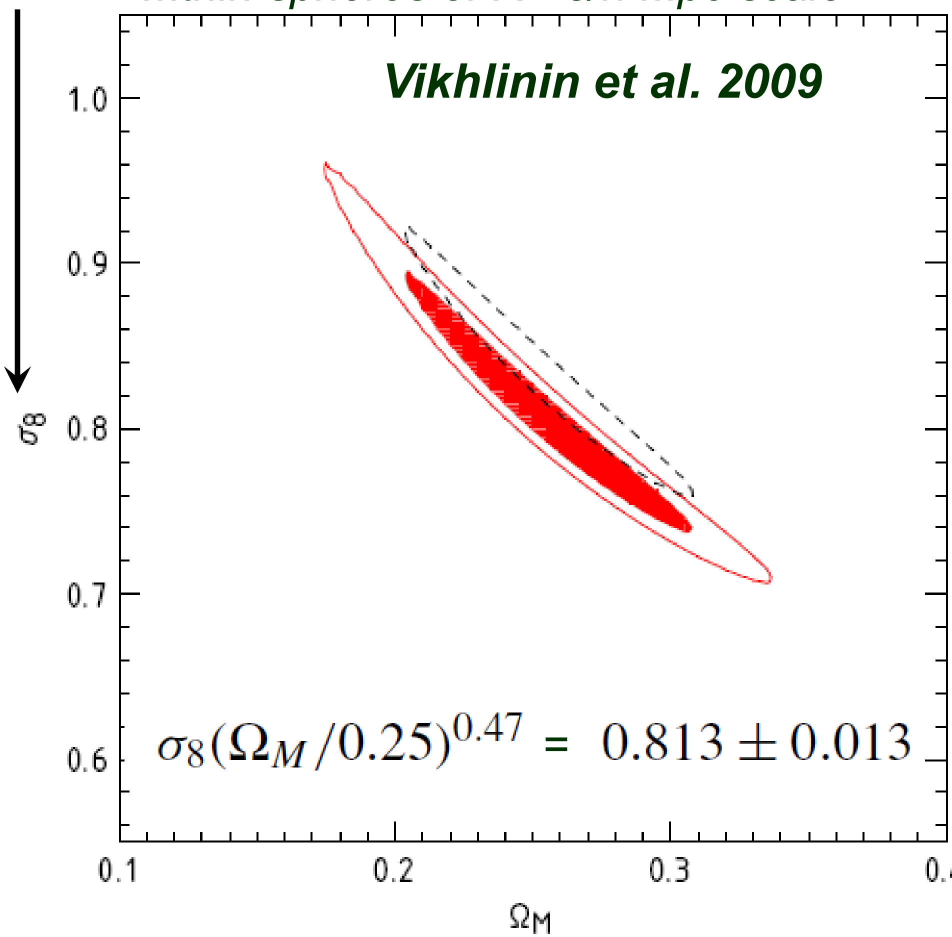
cosmological constraints from cluster abundance

$$\frac{d^2N(z)}{dzd\Omega} = \frac{r^2(z)}{H(z)} \int_0^\infty f(O,z)dO \int_0^\infty p(O|M,z)\frac{dn(z)}{dM}dM$$

number density of clusters with masses >M

aplitude of the rms fluctuations of matter density within spheres of R= 8/h Mpc scale

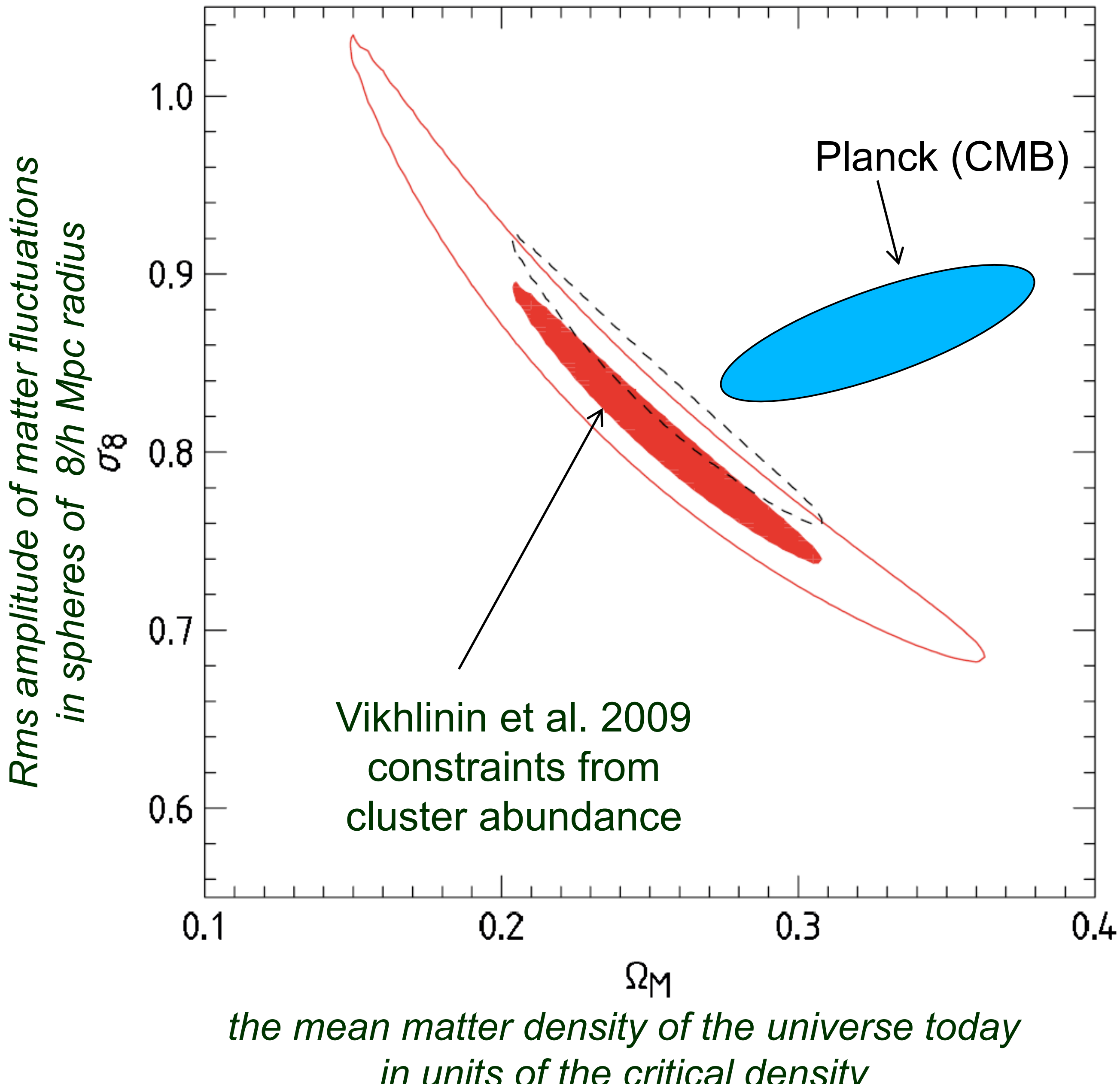




mass within radius enclosing overdensity of 500 times the critical density $\rho_{crit}(z)$

the mean matter density of the universe in units of the critical density

Tension of cluster cosmology constraints and CMB constraints from Planck



Several solutions are discussed:

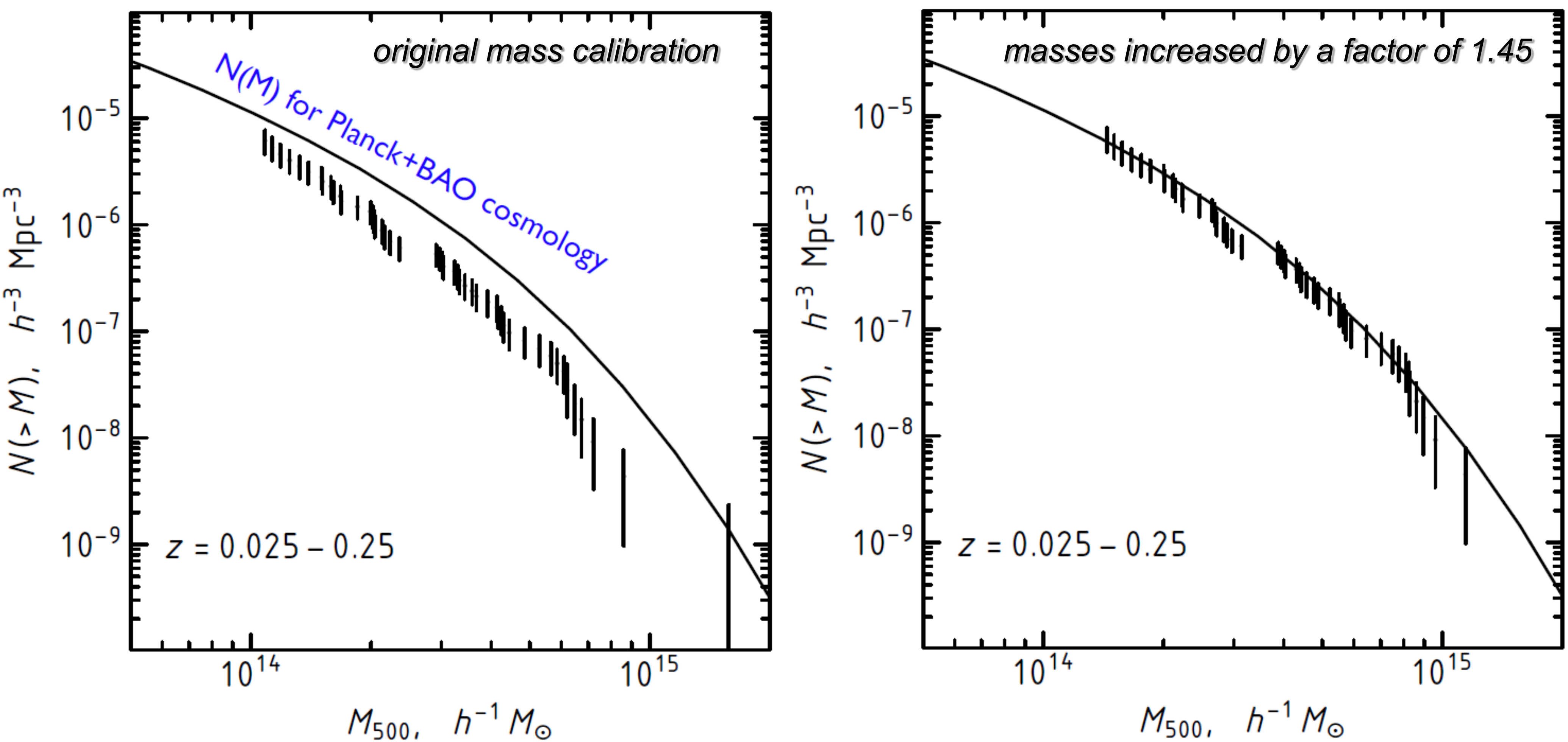
- Non-zero neutrino mass
- CMB constraints biased due to some systematics (e.g., Planck l<1000 constraints are consistent with clusters)
- Cluster masses are miscalibrated. This solution <u>requires ~45% increase of cluster masses</u> to fully reconcile Planck constraints with cluster cosmology constraints

Reconciling discrepancy with Planck by shifting cluster masses

the main source of uncertainty for cluster cosmology is uncertainty in mass calibration of clusters:

- simulations cannot predict observable-mass correlations due to uncertainties in baryonic physics
- current observations have only a limited ability to self-calibrate

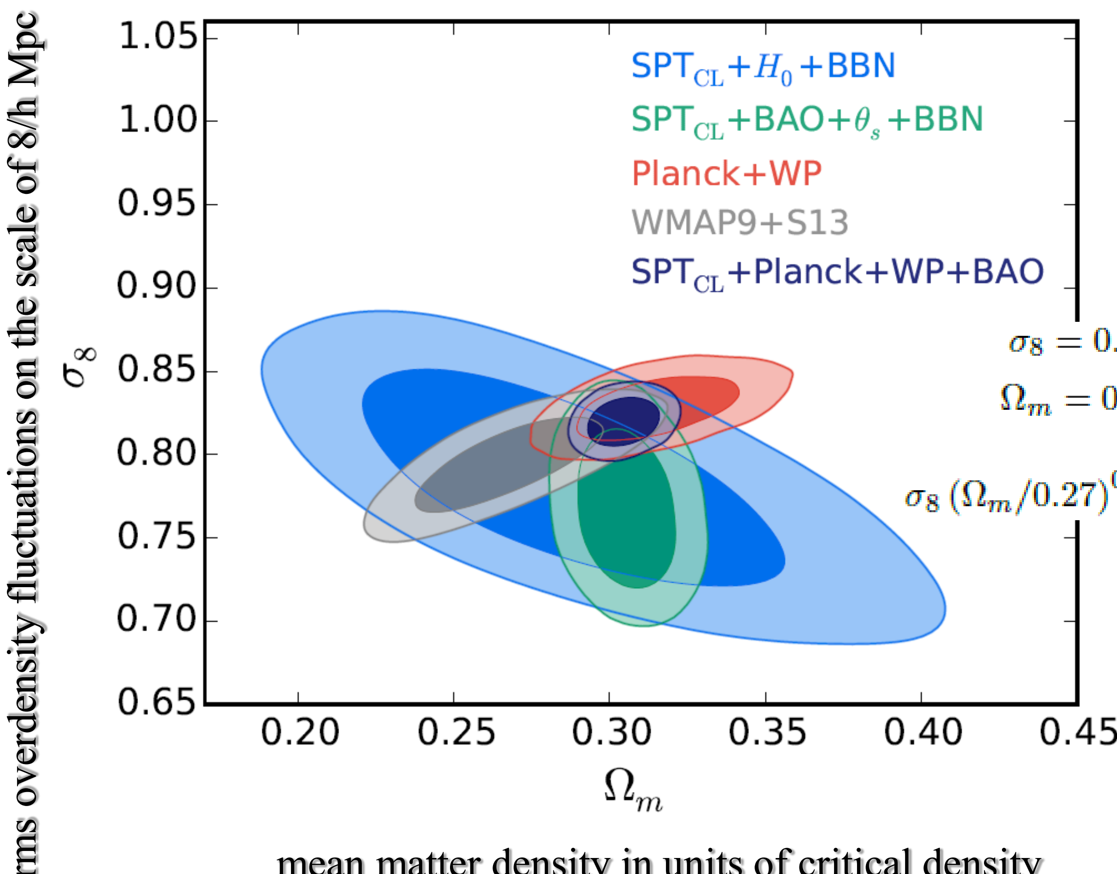
cumulative mass function of clusters at low z from Vikhlinin et al. 2009



current constraints
from the evolution of cluster abundance: all is good?

be correlated between mass proxies. Assuming a spatially flat ΛCDM cosmology, where the species-summed neutrino mass has the minimum allowed value ($\Sigma m_\nu = 0.06$ eV) from neutrino oscillation experiments, we combine the cluster data with a prior on H_0 and find $\sigma_8 = 0.784 \pm 0.039$ and $\Omega_m = 0.289 \pm 0.042$, with the parameter combination $\sigma_8 (\Omega_m/0.27)^{0.3} = 0.797 \pm 0.031$. These results are in good agreement with constraints from the cosmic microwave background (CMB) from SPT, *WMAP*, and *Planck*, as well as with constraints from other cluster datasets. Adding the sum of

de Haan et al.
(the SPT collaboration)
arXiv/1603.06522

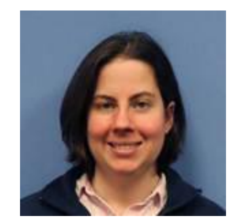


$\sigma_8 = 0.784 \pm 0.039,$

$\Omega_m = 0.289 \pm 0.042,$

$\sigma_8 (\Omega_m/0.27)^{0.3} = 0.797 \pm 0.031.$

with much local involvement

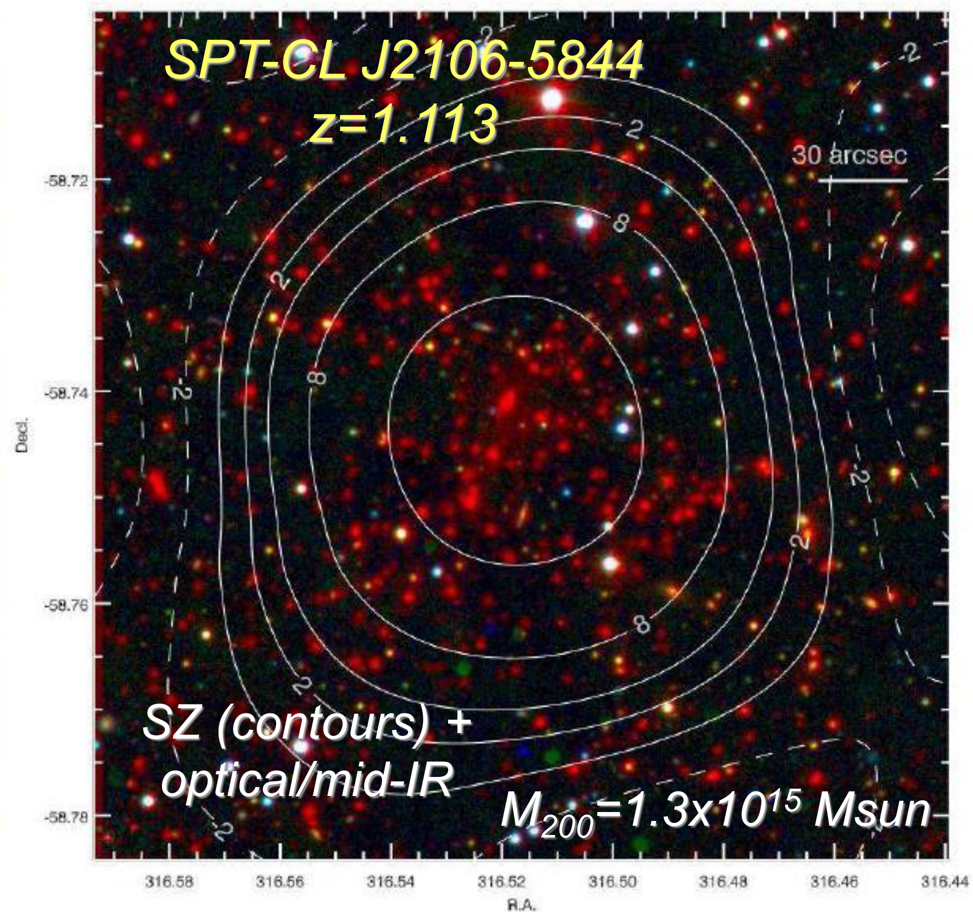


Lindsey Bleem
(U.Chicago -> Argonne)

Brad Benson
(Fermilab/U.Chicago)

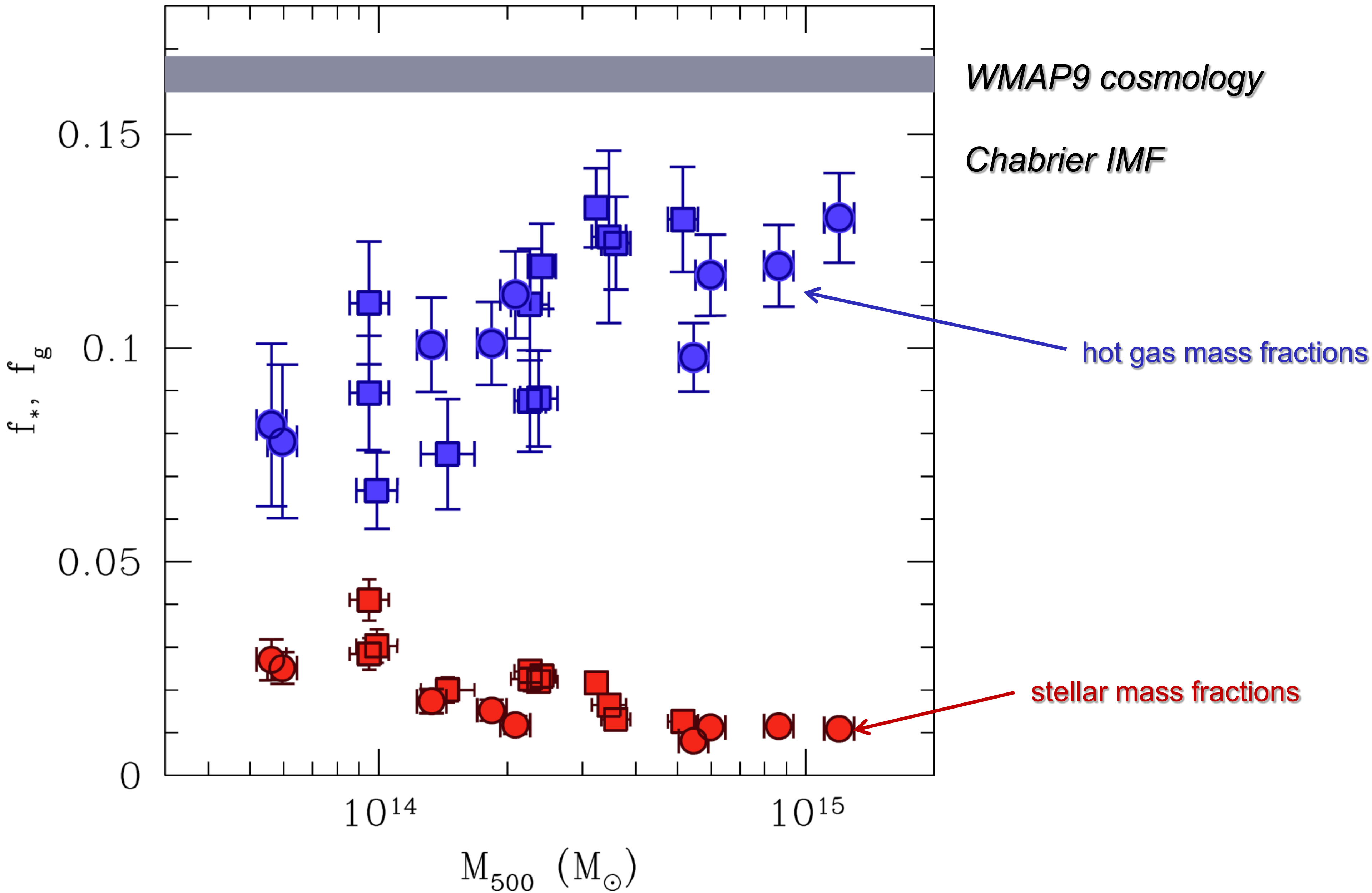
All major mass components of clusters can be probed by modern observations

Unlike galaxies, massive clusters can be reasonably expected to be closed boxes within sufficiently large radius according to simulations. Cosmological simulations of cluster formation can predict baryon mass fraction of clusters within a given radius, at least for massive clusters (>~ 3x10^14 Msun)

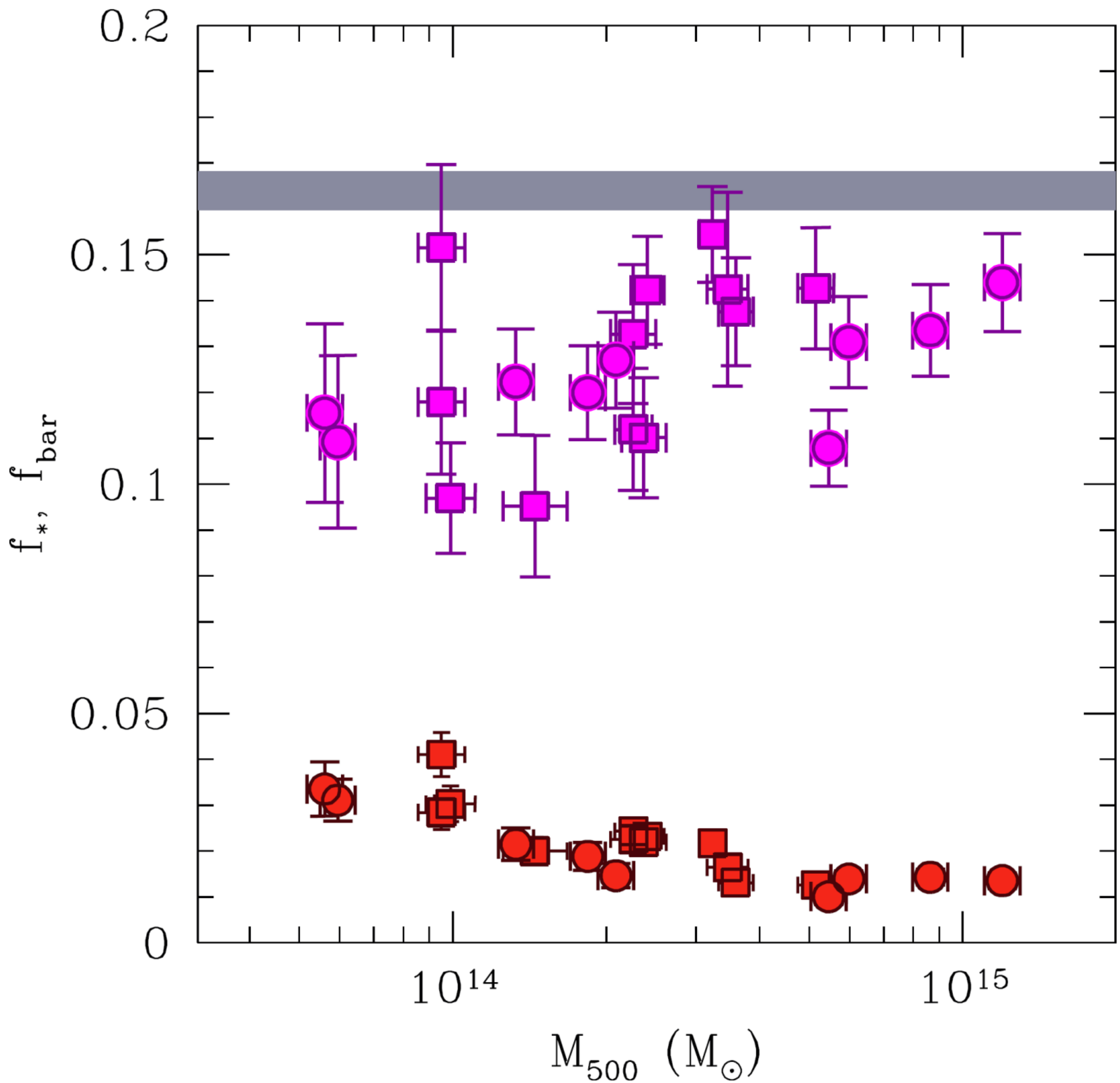


Stellar and gas fractions

A sample of 21 clusters:
12 from Gonzalez et al. 2013; M* from IR, M500 from XMM data
9 new clusters (KVM14); M* from new SDSS photometry, M500 from Chandra data



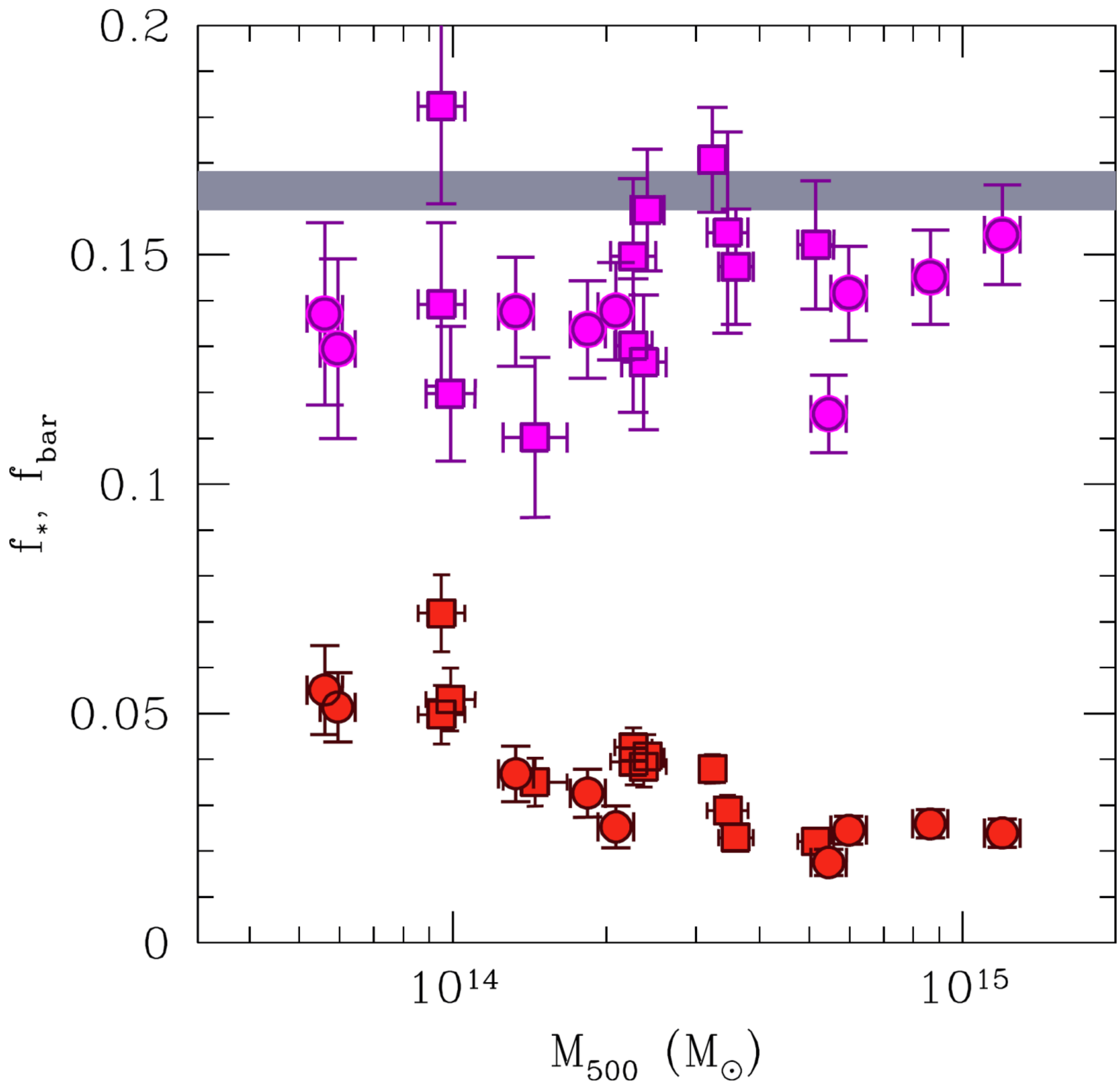
Total baryon (stars+gas) fractions



WMAP9 cosmology

Chabrier IMF

Total baryon (stars+gas) fractions



WMAP9 cosmology

varying IMF (Chabrier at low galaxy masses -> Salpeter at high masses)

Effects of changing cosmology from WMAP to Planck

WMAP: $\Omega_{\rm b}/\Omega_{\rm m} = 0.1667 \pm 0.006$

Planck: $\Omega_{\rm b}/\Omega_{\rm m} = 0.1553 \pm 0.0029$

$$\longrightarrow \frac{f_{\rm b,WMAP}}{f_{\rm b,Planck}} \approx 1.073$$

$$M_{\rm gas} \propto h^{-2.5}$$
$$M_* \propto h^{-2}$$
$$M_{500} \propto h^{-1}$$

$$\longrightarrow$$

$$f_{\rm gas} \propto h^{-1.5}$$
$$f_* \propto h^{-1}$$

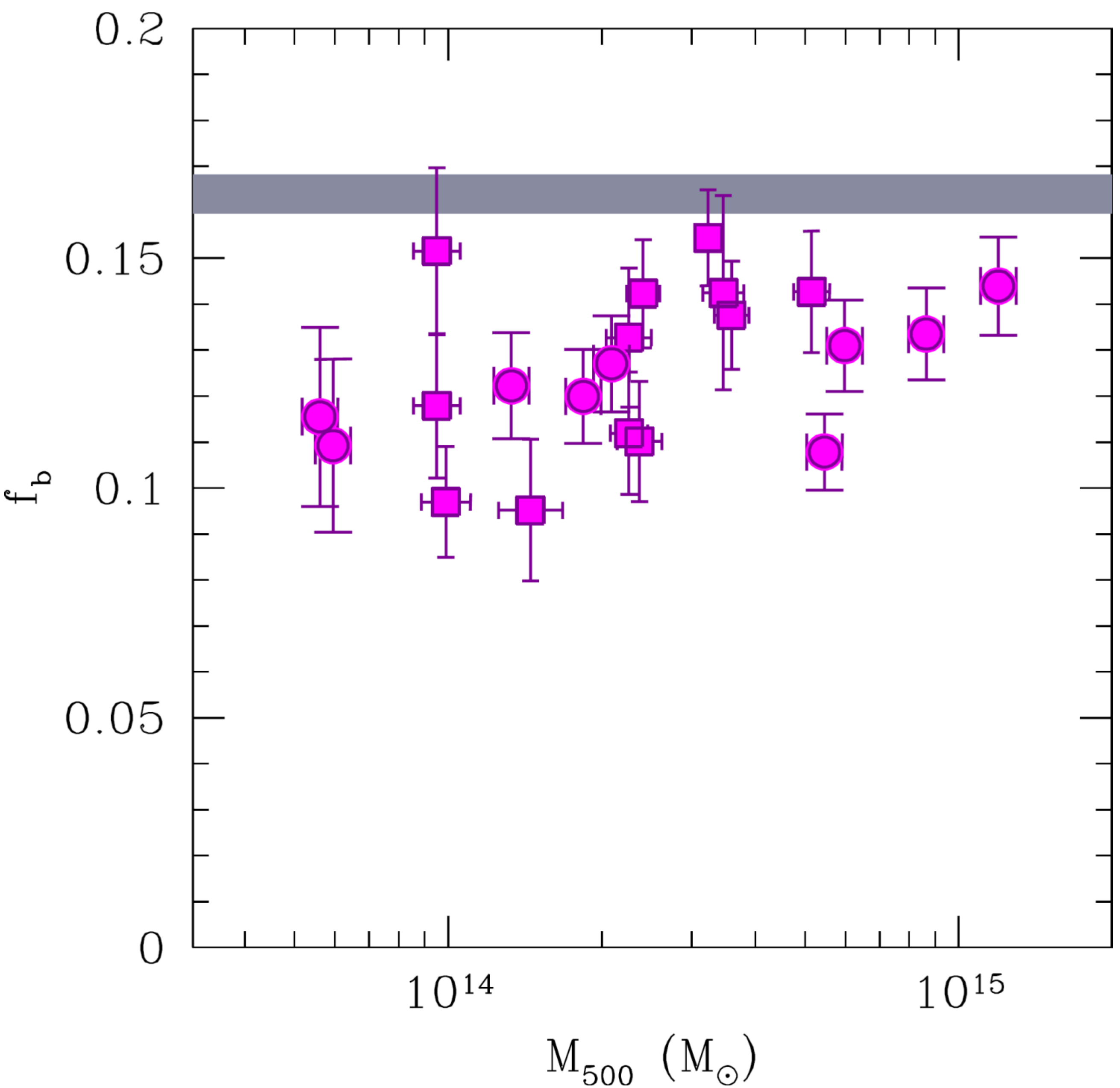
$$h_{\rm WMAP} = 0.703 \pm 0.014$$
$$h_{\rm Planck} = 0.673 \pm 0.012$$

$$\left(\frac{h_{\rm Planck}}{h_{\rm WMAP}}\right)^{-1.5} \approx 1.068$$

$$\left(\frac{h_{\rm Planck}}{h_{\rm WMAP}}\right)^{-1} \approx 1.045$$

the net effect of switching from WMAP to Planck cosmology is <u>to increase</u>
normalized gas fractions by 15%
normalized stellar fractions by 12%
the total baryon fraction by ~14%

Total baryon (stars+gas) fractions

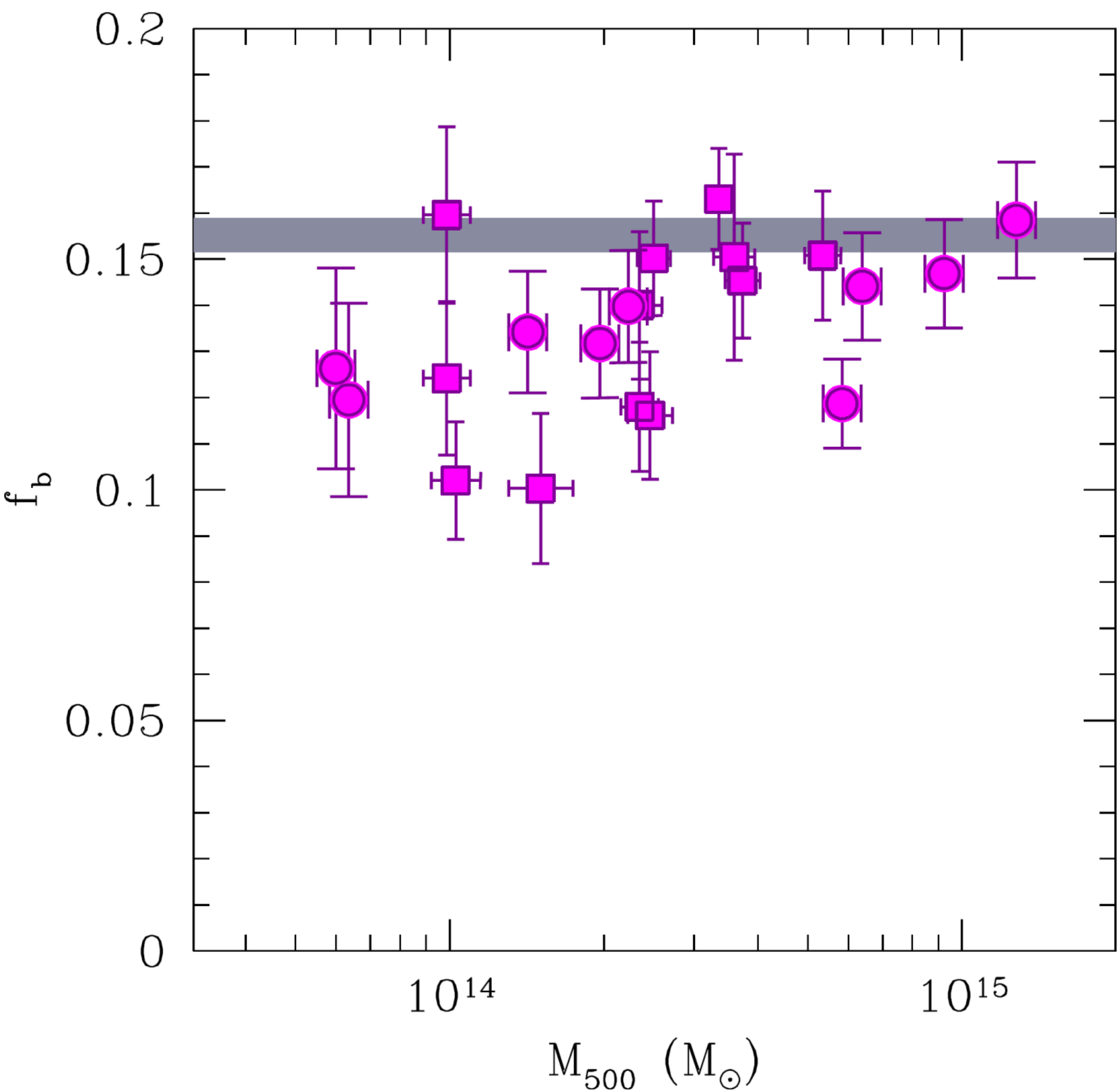


WMAP9 cosmology

Chabrier IMF

Total baryon (stars+gas) fractions

Almost no baryon bias at high masses!

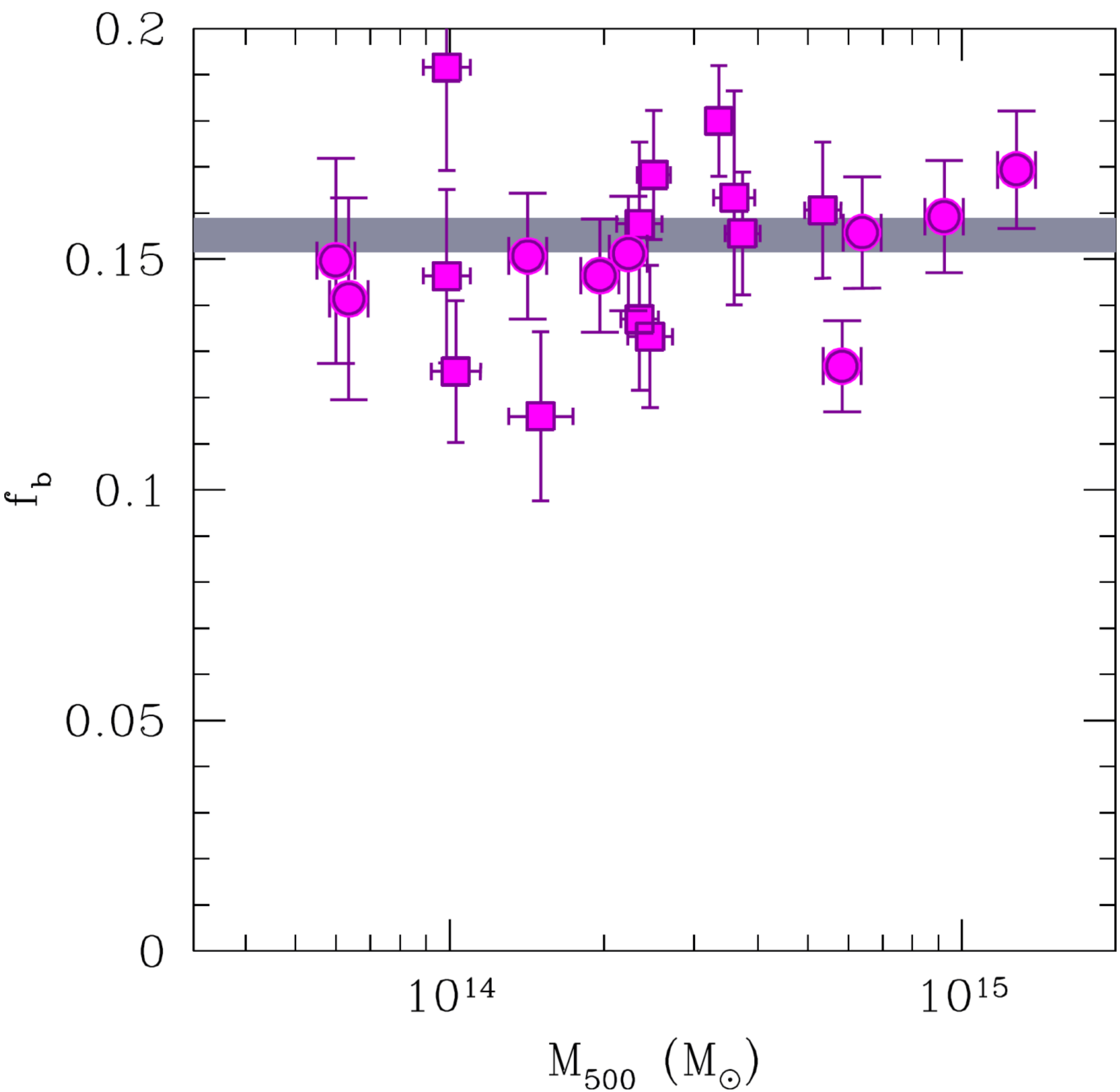


Planck cosmology

Chabrier IMF

Total baryon (stars+gas) fractions

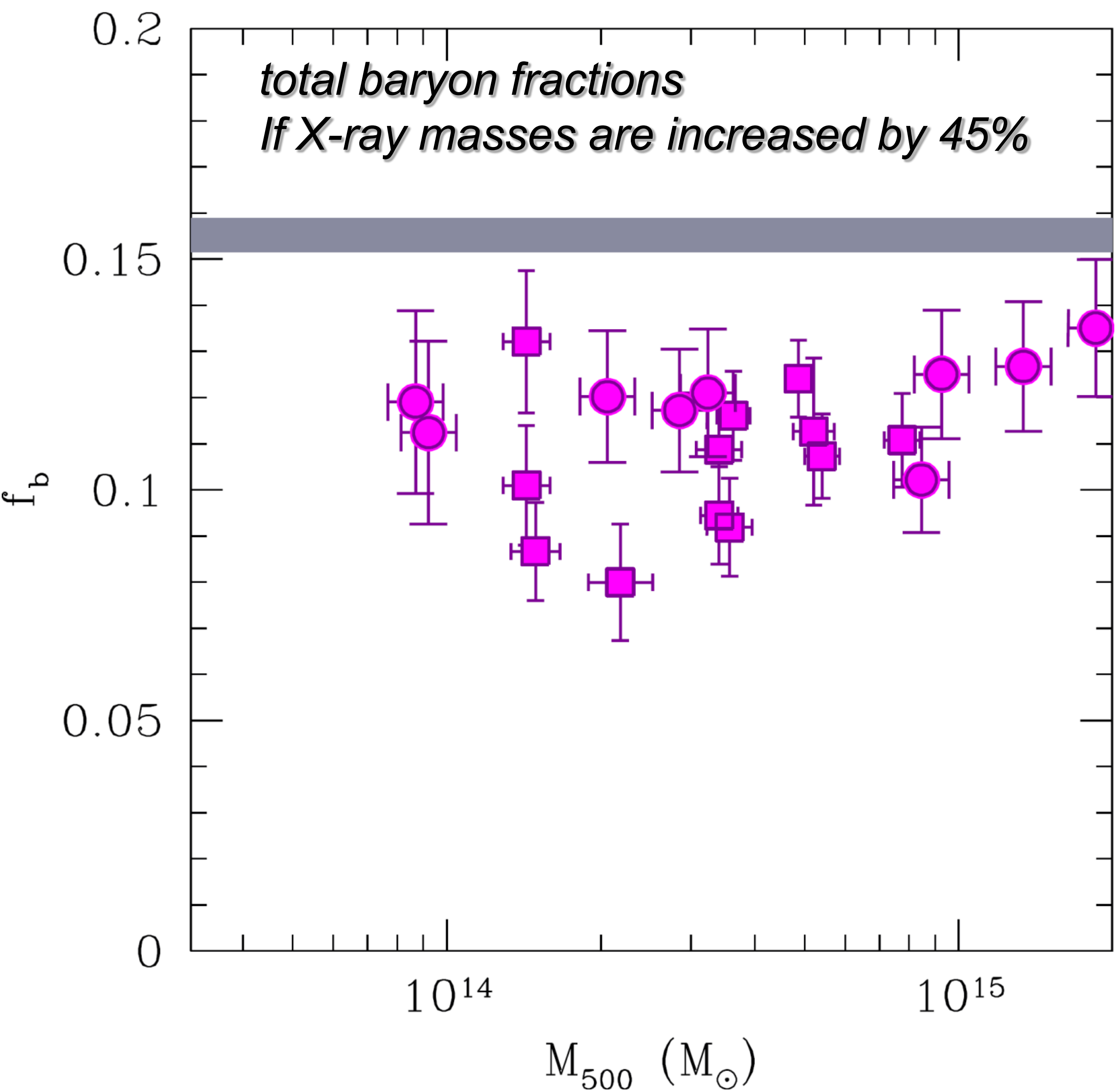
Almost no baryon bias at all masses!



Planck cosmology

varying IMF (Chabrier at low galaxy masses -> Salpeter at high masses)

45% increase in cluster mass would imply
Significant baryon deficiency even in the most massive clusters

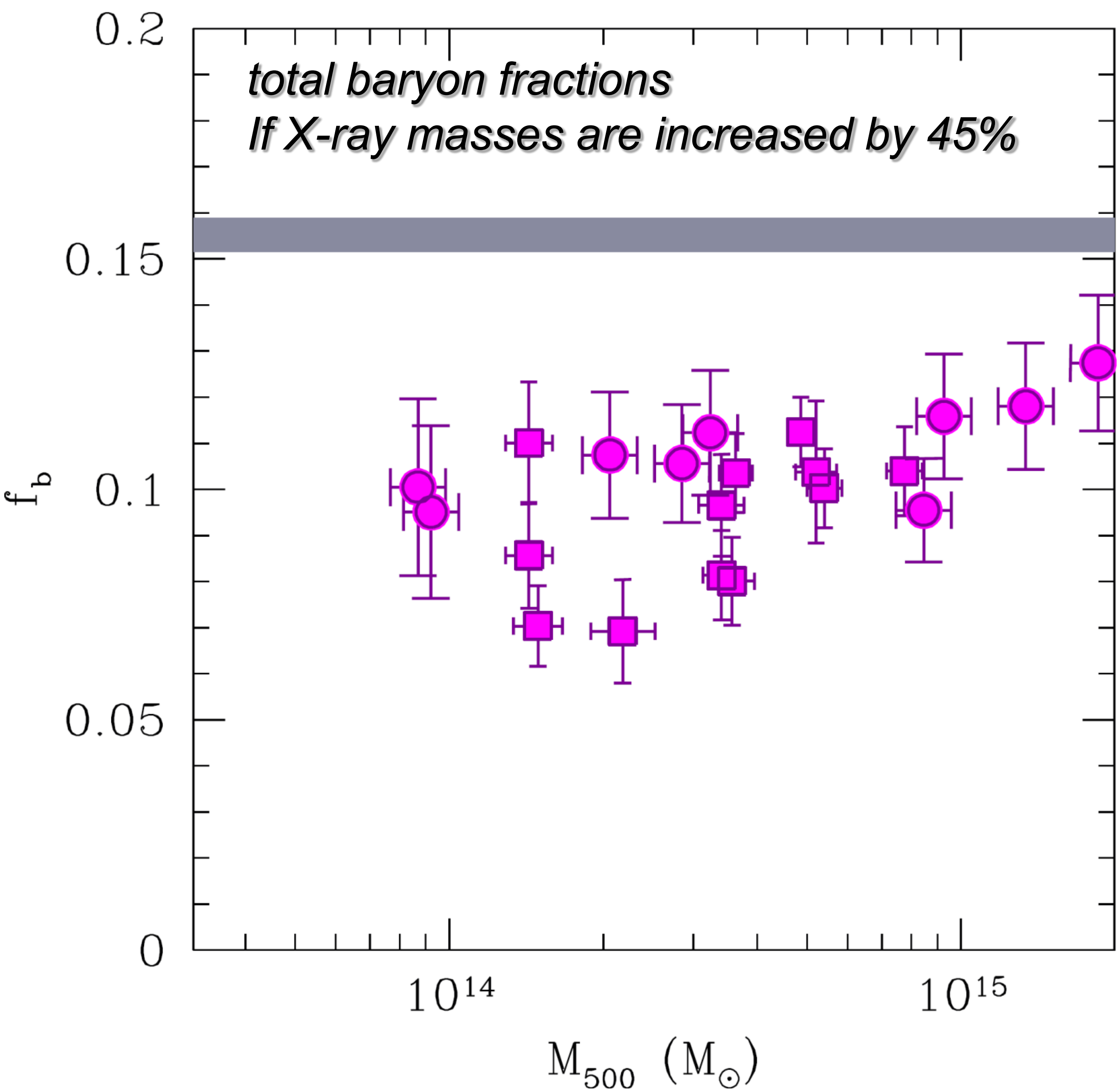


Planck cosmology

variable IMF

M500 is increased by R500
Mgas(<R500) and M(<R500)*
Are adjusted to reflect the corresponding increase of R500

45% increase in cluster mass would imply
Significant baryon deficiency even in the most massive clusters

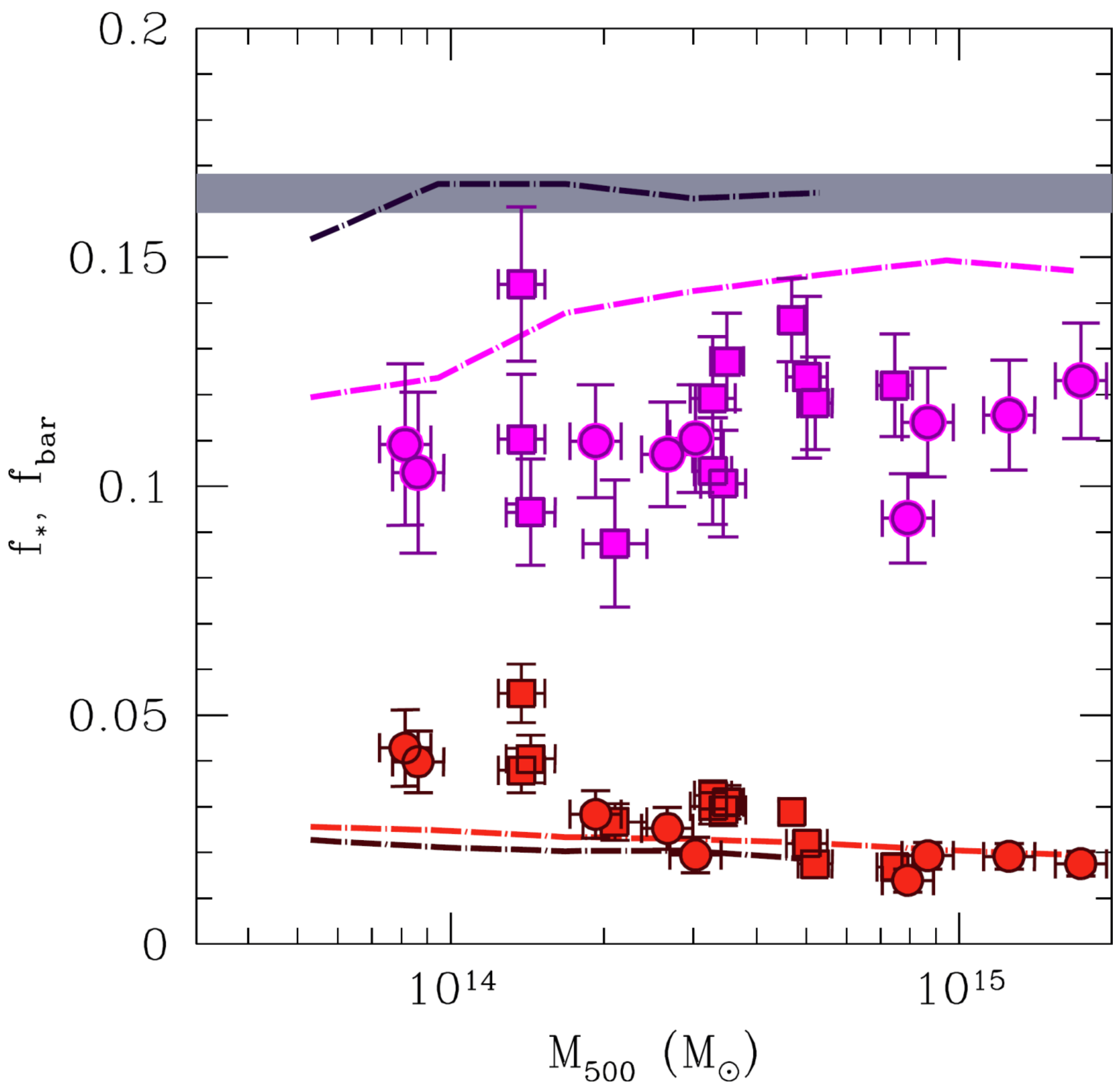


Planck cosmology

Chabrier IMF

M500 is increased by R500
Mgas(<R500) and M(<R500)*
Are adjusted to reflect the corresponding increase of R500

Is such large baryon deficiency expected from cluster models?



WMAP cosmology

varying IMF

45% mass correction

Cluster – Planck summary

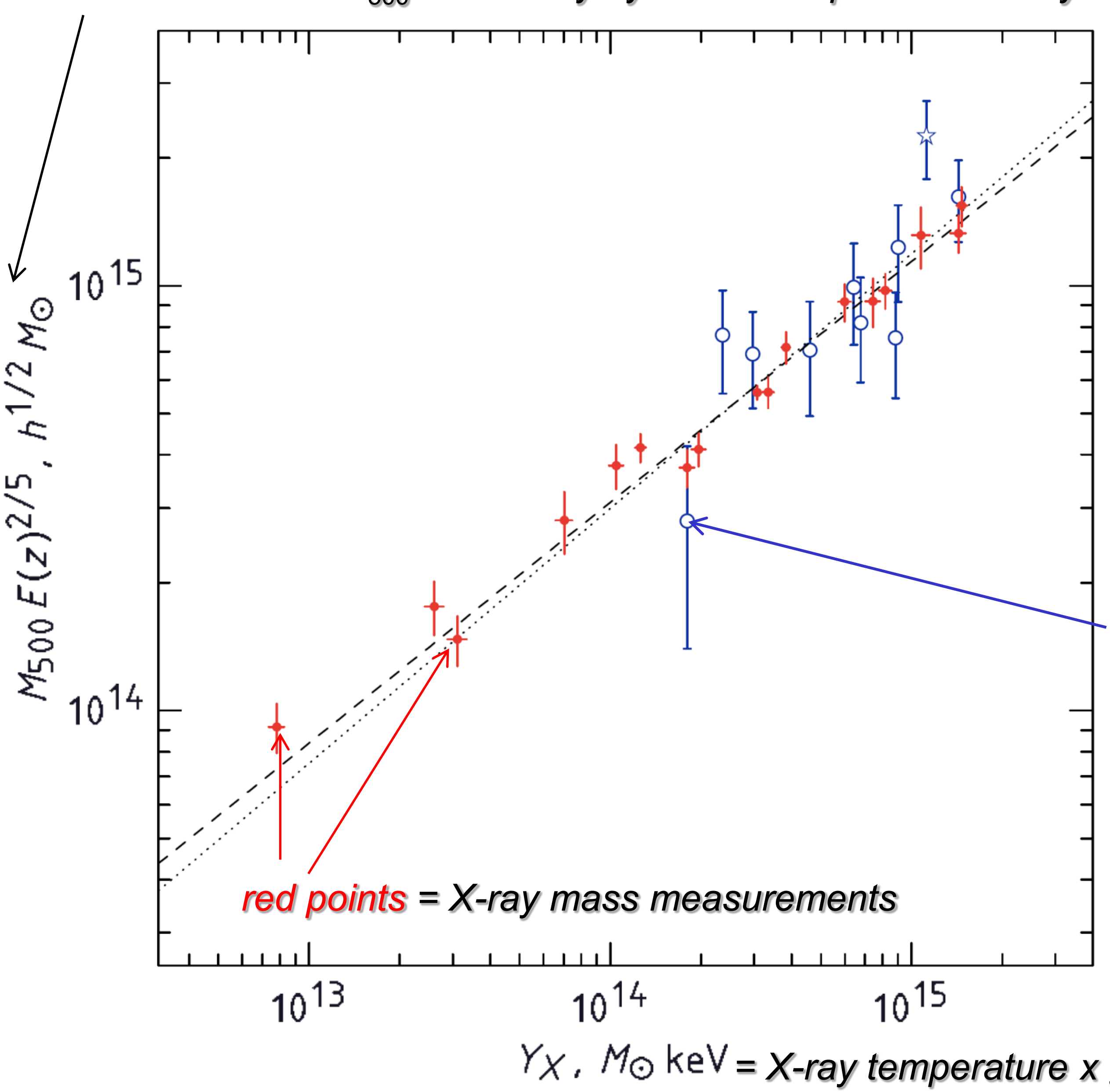
- The original tension between cosmological constraints on s8 and Omega from clusters and Planck CMB anisotropy measurements is weakened by recent cluster analyses which argue for larger uncertainties, and partly by drift of the Planck constraints towards clusters.

- However, explaining the entire difference between peak cluster and Planck likelihood values for s8 and Omega may be problematic, as it would indicate unexpectedly low baryon fractions in massive clusters.

More (and better) data is needed both on cluster masses and on baryon fractions to gauge how much of a problem this is.

Total mass calibration

Total mass within R_{500} from X-ray hydrostatic equilibrium analysis and from weak lensing



= X-ray temperature x gas mass within R_{500}

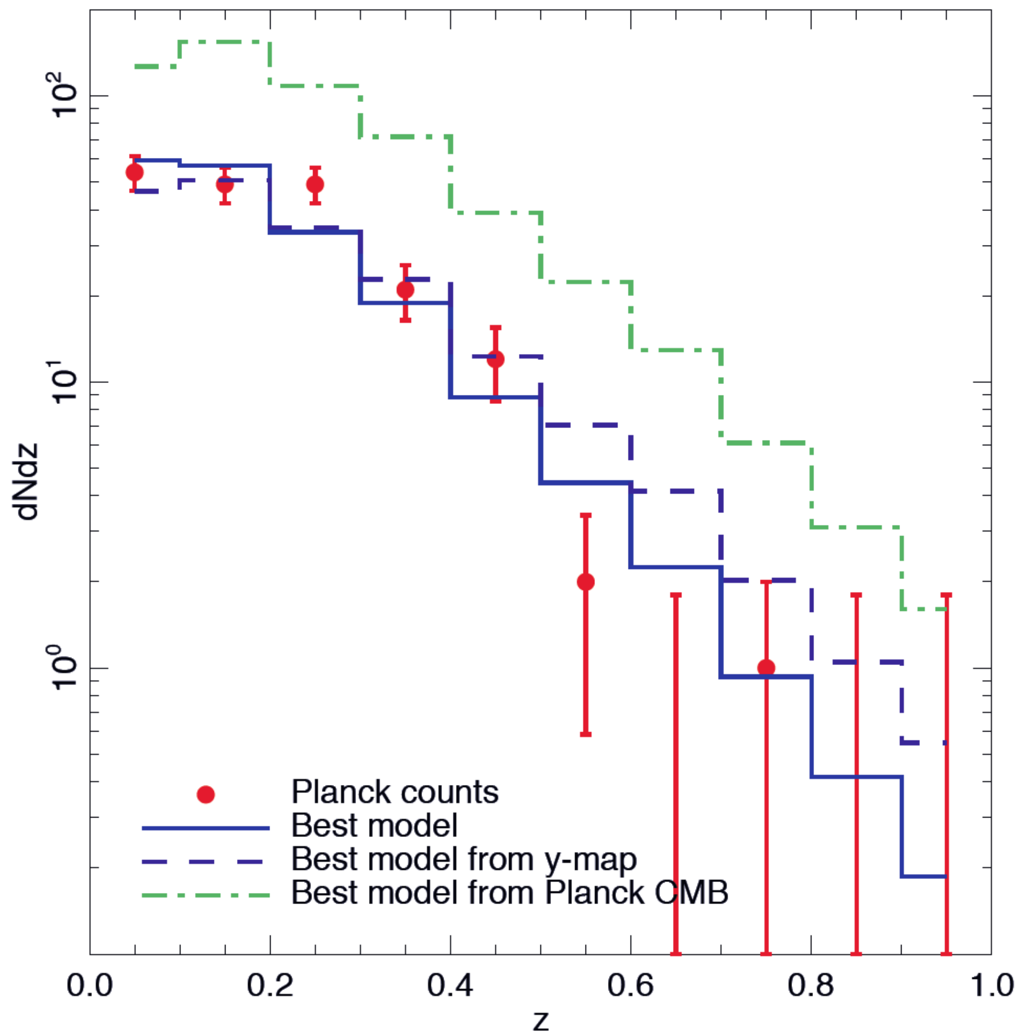
from Vikhlinin et al. 2009

blue points = WL mass measurements (Hoekstra 2007)

Recent weak lensing mass (Hoekstra et al. 2012, Applegate et al. 2012) measurements give masses within +- 10% of the values in this plot

However, Planck cosmology is in strong tension with cluster abundances

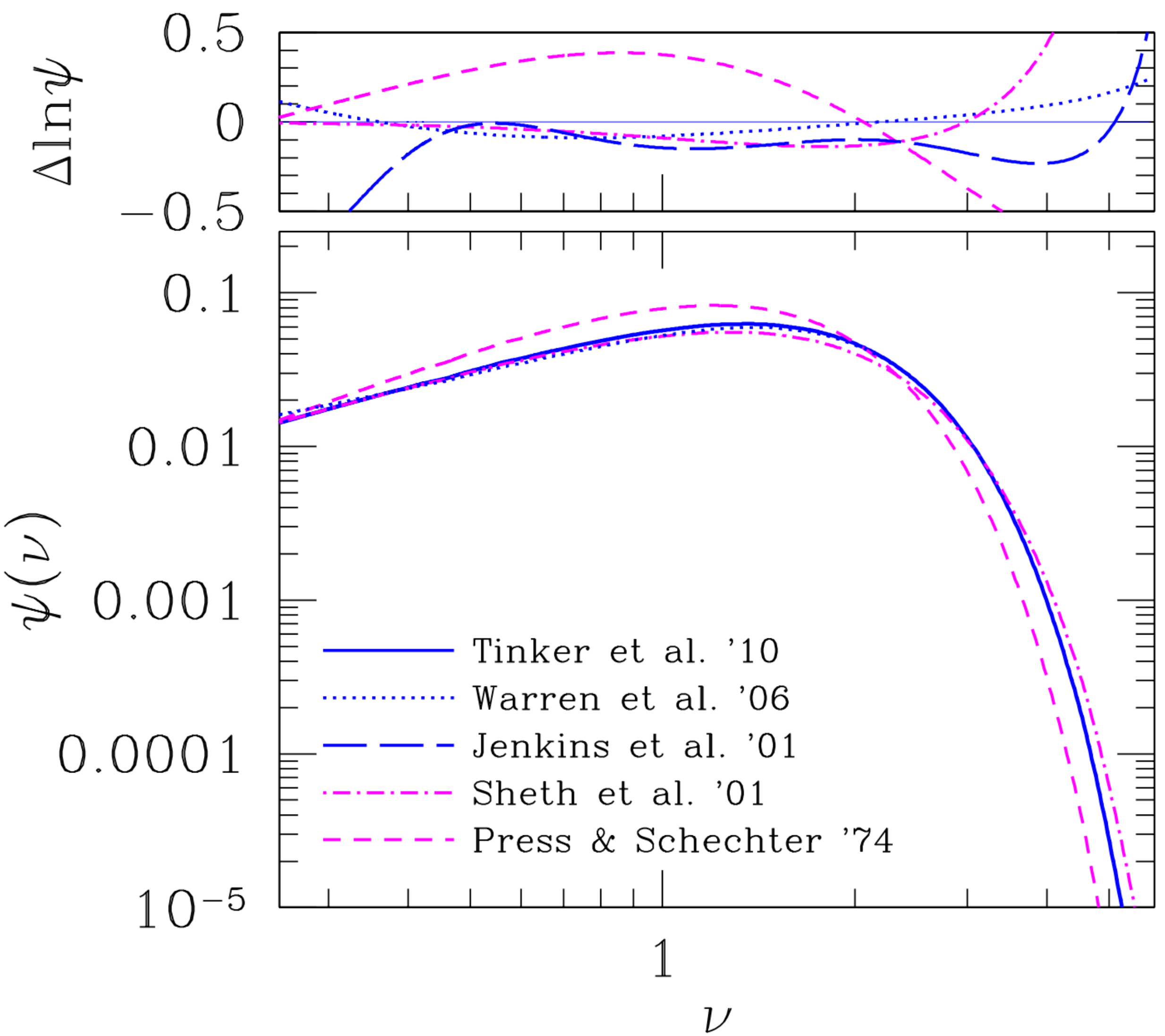
If the discrepancy is to be reconciled by clusters alone, cluster total masses need to be increased by ~45% for a given Y or Yx



Planck 2013, Paper XX

Nevertheless, simple collapse ansatzes make reasonably predictions...

abundance of collapsed halos predicted by the local collapse threshold models vs cosmological simulations



Jeremy Tinker
NYU

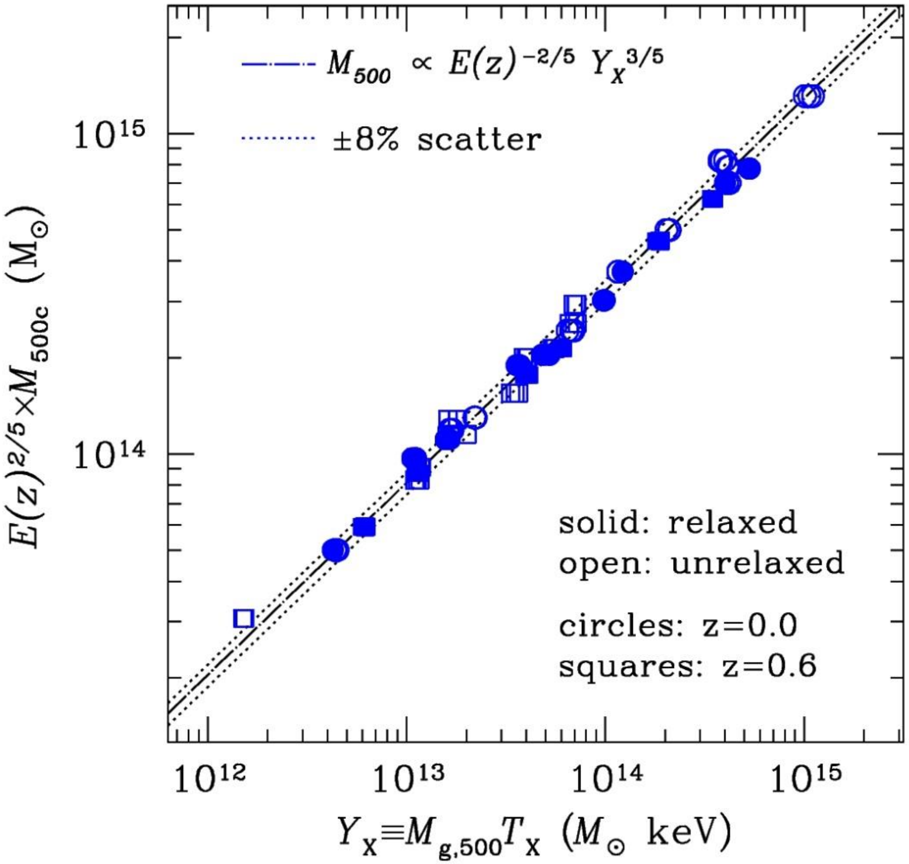
Tinker et al. '08, '10

$$\frac{dn(M)}{d\ln M} = \frac{\bar{\rho}_m}{M}\psi(\nu)$$

$$\nu = \frac{\delta_c}{\sigma(M,z)}$$

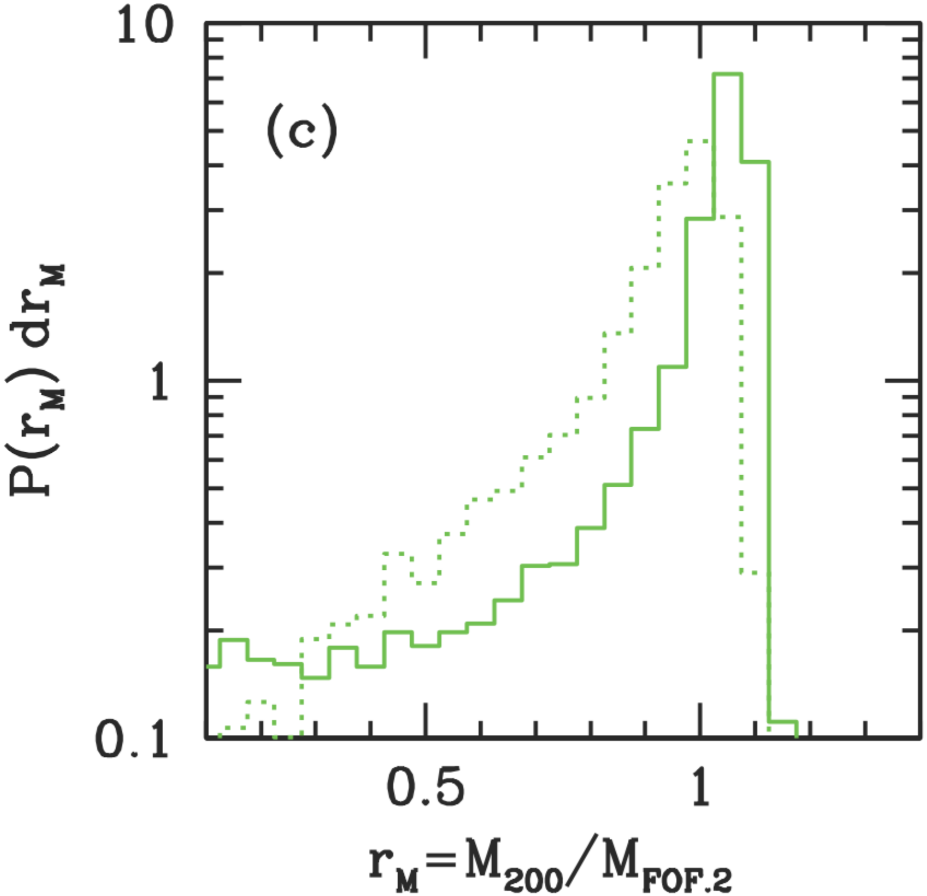
Observable cluster properties such as temperature and integrated Y correlate tightly with Spherical Overdensity mass but not with the FoF mass

→ *strong preference for using the SO mass*



Yx = gas mass x temperature

Kravtsov et al. 2006



Tinker et al. 2008;
Klypin et al. 2011