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

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\[ M_\Delta = \frac{4\pi}{3} \Delta \rho_{\text{crit}}(z) R_\Delta^3 \]

\[ \rho_{\text{crit}}(z) = \frac{3H^2(z)}{8\pi G} \]

\[ R_{500} : R_{200} : R_{\text{splashback}} \approx 1.0 : 1.6 : 4.0 \]
\[ M_\Delta = \frac{4\pi}{3} \Delta \rho_{\text{ref}}(z) R_\Delta^3 \]

\[ T \propto \frac{M_\Delta}{R_\Delta} \propto \Delta^{1/3} \rho_{\text{ref}}^{1/3}(z) M_\Delta^{2/3} \]

\[
\begin{aligned}
&\propto \rho_{\text{crit}}^{1/3}(z) M_{\Delta c}^{2/3} \propto E^{2/3}(z) M_{\Delta c}^{2/3} \\
&\propto \rho_{\text{mean}}^{1/3}(z) M_{\Delta m}^{2/3} \propto (1 + z) M_{\Delta m}^{2/3}
\end{aligned}
\]

\[
\mu m_p \frac{GM_{\text{HE}}(< R)}{R} = k T(R) \left[ -\frac{d \ln \rho_g}{d \ln R} - \frac{d \ln T}{d \ln R} \right]
\]

\[
\frac{GM_j(< R)}{R} = \sigma_r^2(R) \left[ -\frac{d \ln n_{\text{gal}}}{d \ln R} - \frac{d \ln \sigma_r^2}{d \ln R} - 2\beta(R) \right]
\]
More recently, weak lensing of background galaxies has become the primary tool of measuring cluster masses.
cosmological constraints from cluster abundance

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

number density of clusters with masses >M

best fit theoretical mass function predicted for \(\Lambda\)CDM cosmology with \(\Omega_m = 1 - \Omega_\Lambda = 0.26\), \(\sigma_8 = 0.81\)

applitude of the rms fluctuations of matter density within spheres of \(R = 8/h\) Mpc scale

\(\sigma_8(\Omega_M/0.25)^{0.47} = 0.813 \pm 0.013\)

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

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 requires ~45% increase of cluster masses 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**

![Graph showing cumulative mass function](image)

- Original mass calibration
- Masses increased by a factor of 1.45

$N(M)$ for Planck+BAO cosmology

$z = 0.025 - 0.25$
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

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, $M_{500}$ from XMM data
9 new clusters (KVM14); $M^*$ from new SDSS photometry, $M_{500}$ from Chandra data
Total baryon (stars + gas) fractions

![Graph showing total baryon fractions vs. mass]
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: \( \Omega_b/\Omega_m = 0.1667 \pm 0.006 \)  
\( \frac{f_{b,\text{WMAP}}}{f_{b,\text{Planck}}} \approx 1.073 \)

Planck: \( \Omega_b/\Omega_m = 0.1553 \pm 0.0029 \)  
\( \frac{f_{b,\text{Planck}}}{f_{b,\text{WMAP}}} \approx 1.073 \)

\[ \begin{align*}
M_{\text{gas}} & \propto h^{-2.5} \\
M_\ast & \propto h^{-2} \\
M_{500} & \propto h^{-1}
\end{align*} \]

\[ \begin{align*}
f_{\text{gas}} & \propto h^{-1.5} \\
f_\ast & \propto h^{-1}
\end{align*} \]

\[ \begin{align*}
h_{\text{WMAP}} = 0.703 \pm 0.014 \\
h_{\text{Planck}} = 0.673 \pm 0.012
\end{align*} \]

\[ \begin{align*}
\left( \frac{h_{\text{Planck}}}{h_{\text{WMAP}}} \right)^{-1.5} \approx 1.068 \\
\left( \frac{h_{\text{Planck}}}{h_{\text{WMAP}}} \right)^{-1} \approx 1.045
\end{align*} \]

The net effect of switching from WMAP to Planck cosmology is to increase normalized gas fractions by 15%, normalized stellar fractions by 12%, and the total baryon fraction by ~14%.
Total baryon (stars+gas) fractions

$W_{\rm MAP9}$ cosmology

Chabrier IMF
Total baryon (stars+gas) fractions

Almost no baryon bias at high masses!

Planck cosmology
Chabrier IMF
Planck cosmology

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

Almost no baryon bias at all masses!
A 45% increase in cluster mass would imply significant baryon deficiency even in the most massive clusters.

If X-ray masses are increased by 45%, the total baryon fractions would be adjusted to reflect the corresponding increase of $R_{500}$.

Planck cosmology with a variable IMF indicates that $M_{500}$ is increased by $R_{500}$, and $M_{\text{gas}}(<R_{500})$ and $M^*(<R_{500})$ are adjusted to reflect the corresponding increase of $R_{500}$. 

The graph shows the total baryon fractions $f_b$ as a function of $M_{500}$ ($M_\odot$) with error bars.
45% increase in cluster mass would imply significant baryon deficiency even in the most massive clusters.

If X-ray masses are increased by 45%:

- Planck cosmology
- Chabrier IMF

M500 is increased by R500, Mgasm(<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
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

- Red points = X-ray mass measurements
- Blue points = WL mass measurements (Hoekstra 2007)

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

$Y_X, \, M_\odot \, \text{keV} = \text{X-ray temperature} \times \text{gas mass within } R_{500}$
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.
Nevertheless, simple collapse ansatze make reasonably predictions...

_abundance of collapsed halos predicted by the local collapse threshold models vs cosmological simulations_

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

\[
\nu = \frac{\delta_c}{\sigma(M, z)}
\]
Observable cluster properties such as temperature and integrated $Y$ correlate tightly with Spherical Overdensity mass but not with the FoF mass

$Y_x = \text{gas mass} \times \text{temperature}$

*Kravtsov et al. 2006*

$M_{500} \propto E(z)^{-2/5} Y_x^{3/5}$

$\pm 8\%$ scatter

**strong preference for using the SO mass**