Cosmology with *Planck* SZ cluster counts

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The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.
Planck 2013 results. XX. Cosmology from Sunyaev–Zeldovich cluster counts

Typical properties

- 100 – 1000 galaxies
- Mass : $10^{14-15} \, M_{\text{sun}}$
- Temperature : 1-10 keV
- Electron number density : 0.01 cm$^{-2}$
Sunyaev-Zeldovich Effect

\[
\frac{\Delta T}{T} \propto \sigma_T \int n_e T_\text{edl}
\]

= integrated gas pressure along the line of sight

\[
\frac{\Delta T}{T} = g(\nu)y(\theta) \quad Y = \int d\Omega y(\theta)
\]

Compton $y$ parameter

Cluster

CMB photons

Compton scattering

$e^- + \gamma \rightarrow e^- + \gamma$

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Frequency dependence

![Graph showing frequency dependence](image)
The image shows a comparison of the Cosmic Microwave Background (CMB) at different redshifts (z) for two different cosmological models: ACDM (open universe) and SCDM (closed universe).

- **ACDM (Open Universe):**
  - **z=3:** The universe is highly structured with a lot of large-scale fluctuations.
  - **z=1:** The structure appears less pronounced than at z=3.
  - **z=0:** The structure is less visible, indicating a more uniform state.

- **SCDM (Closed Universe):**
  - **z=3:** The CMB shows significant structure, similar to ACDM at z=3.
  - **z=1:** The structure is less pronounced than at z=3.
  - **z=0:** The structure is barely visible, similar to ACDM at z=0.

The Planck Collaboration logo is present, indicating that these images are related to the Planck satellite mission.
Cluster number counts

\[
\frac{dN}{dz} = \Delta \Omega \frac{dV}{dz d\Omega} \int_{M_{\text{lim}}}^{\infty} \frac{dN}{dV dM} dM
\]

Survey area
Cosmological volume element
Reference mass function: Tinker et al. 2008
Limiting mass determined from flux limit
key unknown
\[
\left[ \frac{E(z)}{D_A(z)} \right]^{2/3} \left[ \frac{D_A(z)}{10^{-4} \text{ Mpc}^2} \right]^2 = Y_* \left( \frac{h}{0.7} \right)^{-2+\alpha} \left[ \frac{(1-b)M_{500}}{6 \times 10^{14} M_{\text{sun}}} \right]^\alpha
\]

Calibrated on 71 clusters with Planck SZ data and X-ray XMM-Newton data

\[
\log Y_* = -0.19 \pm 0.02
\]

\[
\alpha = 1.79 \pm 0.08
\]

\[
\sigma_{\log Y} = 0.075 \pm 0.01
\]
Y-M bias

• We have hidden the astrophysics in 1-b
  - it parameterizes the extent to which X-rays don’t measure the true mass!

• We argue that
  - 1-b=0.8 is the best value
  - with a range of [0.7,1.0] being reasonable

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SZ clusters detection

see Planck 2013 XXIX paper

• Matched Multi Filter (MMF)
  – exploits frequency dependence of SZ effect and information on cluster profiles
  – applied to 100-857 GHz maps

• 1227 clusters and candidates
  – 683 known
  – 178 new - confirmed
  – 366 candidates
  – \( z \text{ in } [0,1], \ M \text{ in } [1,20] \times 10^{14} \ M_{\odot} \)
Examples from Planck
Selection function

- Noise map from MMF for all detection patches
- Threshold in S/N
• 65% of sky
• 189 clusters at S/N>7
Dependence on cosmological parameters

$\Omega_m = 0.3, \sigma_8 = 0.8$

$\sigma_8 \pm 0.02$

$\Omega_m \pm 0.02$
Dependence on cosmological parameters

$\sigma_8 \pm 0.02$
$\Omega_m \pm 0.02$
$\Omega_K \pm 0.2$
$w = \pm 0.2$
Likelihood

• Cash-C statistics (based on Poisson statistics)

\[
\ln L = \ln \mathcal{P}(N_i|n_i) = \sum_{i=1}^{N_b} \left[ N_i \ln(n_i) - n_i - \ln(N_i!) \right],
\]

- predicted counts
- catalogue counts
Additional information used

• BBN
  - $\Omega_b h^2 = 0.022 +/- 0.002$

• BAO or HST
  - BAO from SDSS, 6dF, WiggleZ & BOSS
  - HST prior on $H_0 = (73.8 +/- 2.4) \text{ km sec}^{-1} \text{ Mpc}^{-1}$

• Planck CMB prior on $n_s = 0.963 +/- 0.009$

• Fix: $1-b=0.8$
Constraints from SZ+priors

- $\Omega_m = 0.29 \pm 0.02$
- $\sigma_8 = 0.77 \pm 0.02$
Constraints from SZ+priors

\[ \sigma_8 \left( \frac{\Omega_m}{0.27} \right)^{0.3} = 0.764 \pm 0.025 \]
### Comparison with CMB

#### TT from Planck + WP

**SZ+BAO+BBN+n_s prior with 1-b=0.8**
Comparison to other measurements

![Graph showing comparison to other measurements]

**Fig. 10.** Comparison of constraints at 95% confidence interval on $\sigma_8(\Omega_\Lambda^{0.77})^{0.3}$ from various methods.

- **LSS**
- **Clusters**
- **CMB**
- **Planck**
- **WMAP**
- **SPT**
- **WL**
- **MaxBCG**
- **X-rays**
- **ACT**

Details on the graph:
- The graph compares different methods of measuring cosmological parameters, such as LSS, Clusters, and CMB, with Planck and WMAP.
- Each method is represented by a data point, with error bars indicating the uncertainty.
- The X-axis represents $\sigma_8(\Omega_\Lambda^{0.77})^{0.3}$, while the Y-axis represents the confidence interval.

**Key Notes**:
- Strong constraints on cosmological parameters have been obtained.
- Comparison to other methods shows the robustness of the techniques used.
- The graph highlights the importance of cross-calibration and the need for improved mass calibrations.

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**Reichardt et al.**

- Used this to improve on the statistical uncertainties.
- Restricted comparison to some recent analyses exploiting a large mass sample.

**Watson et al.**

- Slightly enhanced the constraints from SPT surveys.
- Followed the bias in the mass function of galaxy clusters.

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**Planck Collaboration**

- Used a large cluster sample and reported constraints on cosmological parameters.
- Used galaxy clusters in the first 36 months of the mission.

**Watson et al.**

- Slightly enhanced the constraints from SPT surveys.
- Followed the bias in the mass function of galaxy clusters.

**Tinker et al.**

- Followed the bias in the mass function of galaxy clusters.

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**Cosmological Parameters**

- The dark energy equation of state is constrained to $w = -1$.
- Mass calibrations are necessary to determine the true mass for a given sample.

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**6.1. Comparison with other cluster constraints**

- The best value and errors are quoted for a spatially flat model.
- The constraints perpendicularly reflect the uncertainty in the possible bias between the X-ray and optical richness.

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**Discussion**

- The comparison of outcomes using the mass functions of various surveys highlights the importance of cross-calibration.
- The constraints on the evolution of the scaling law with redshift are not trivial and show large scatter amongst simulations.

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**Equations**

- $\Omega_m = \sum_i \omega_i$ (where $\omega_i$ represents the density of each component).
- $\Omega_\Lambda = 1 - \Omega_m$ (for a flat universe).
- $\sigma_8 = \frac{M}{\Delta M}$ (where $M$ is the mass and $\Delta M$ is the mass difference for a given sample).

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**Marked with an asterisk**

- Indicates data points that might have an original power of 5, 36, and 35, respectively, instead of 24 as they are used for more details.

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**Figures and Tables**

- Figures and tables are used to summarize current constraints.
- Table (not shown) summarizes some of the current constraints, marked with an asterisk, with an original power of 5, 36, and 35, respectively, instead of 24.
Impact of hydro mass bias

$1 - b = 0.59 \pm 0.05$

Low compared to expectations from X-rays

$\sigma_8$ vs. $\Omega_m$

TT from Planck + WP

TT + SZ with free (1-b)

SZ+BAO+BBN+$n_s$ prior with 1-b=0.8

Fiducial value

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CMB: Large scales

LSS: Small scales

Matter power spectrum

\[ P(k) \]

\[ 10^0 \quad 10^1 \quad 10^2 \quad 10^3 \quad 10^4 \quad 10^5 \]

\[ 0.001 \quad 0.010 \quad 0.100 \quad 1.000 \quad 10.000 \]

8 Mpc h^{-1}
Impact of massive neutrinos

- $\Sigma m_\nu = 0.0$ eV: $\sigma_8 = 0.67$
- $\Sigma m_\nu = 0.2$ eV: $\sigma_8 = 0.70$
- $\Sigma m_\nu = 0.5$ eV: $\sigma_8 = 0.80$

CMB scales

- 8 Mpc h$^{-1}$

SZ scales
Fit for massive neutrinos

CMB+SZ (1-b=0.8): (527+/−191)meV
CMB+SZ (1-b=[0.7,1.0]): (402+/−211)meV
CMB+SZ (1-b=[0.7,1.0])+BAO: (203+/−94)meV
CMB alone: < 933 meV
Conclusions

• Cosmology with 189 SZ clusters
• In agreement with other cluster studies
• In agreement with Planck SZ power spectrum
• Tension with primary CMB on $\sigma_8$
  – Astrophysics: mass bias
  – Physics: massive neutrinos
Recent developments: mass function

- Cusworth, Kay, Battye & Thomas (2014)
  - mass function is modified downwards by the inclusion of baryons
  - not enough to explain the tension but in the right direction
Recent developments: mass bias

• Von der Linden et al. (2014)
  – Weak lensing WtG masses vs Planck X-rays masses; find (1-b)~0.7 that would reduce the tension

• Applegate et al. (2014)
  – WtG masses are 20-25% higher than other WL masses (e.g. Okabe et al. 2010, Hoekstra et al. 2012)

• Israel et al. (2014)
  – weak lensing 400d masses vs X-ray masses; good agreement, no evidence for a strong bias
Recent developments: LSS and neutrinos

- Supporting evidence for low $\sigma_8$ from LSS or massive neutrinos:
  - lensing (Battye & Moss 2014, covered by Adam’s talk)
  - redshift space distortions (Macaulay, Wehus & Eriksen 2013)
  - BOSS data (Beutler et al. 2014)
  - etc
Conclusions

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• Tension with primary CMB on $\sigma_8$
  – Astrophysics: mass bias
  – Physics: massive neutrinos
• Triggered work supporting both mass bias and neutrinos explanations
• New Planck SZ analysis to come, using lower S/N catalogue