Probing the Galaxy Cluster Population to High Redshift with the Sunyaev-Zel’dovich Effect

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7th KIAS Workshop on Cosmology and Structure Formation

Sunyaev-Zel’dovich Effect Galaxy Cluster Selection

Cluster SZE Signature

- Measures total thermal energy in ICM
- Strongly correlated with mass (low scatter)
- Signature at fixed mass is ~independent of redshift!
**SPT-SZ 2500 deg² Survey**

Carlstrom+ 2010

- Maps produced from bolometer time stream of $\sim 10^5$ T measurements/s integrated over 4 years with $\sim 65\%$ efficiency

- Matched filter selection
- Painstaking optical followup

First SZE selected clusters pulled from first year SPT data (Staniszewiski+09)

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**SPT-SZ Sample**

Song+12, Bleem+15

- 2500 deg² sample
  - 516 at $\xi>4.5$
  - 387 at $\xi>5.0$
    - Bleem+15

- High z subsample
  - 36 at $z>1$
  - Max $z_{\text{spec}}=1.47$
    - Bayliss+13
  - Highest phot-z
    - Strazzullo+

- Clean sample with $M_{500}>3\times10^{14}$ $M_\odot$ to $z\sim1.7$
Sure:
- (see Haiman, Mohr & Holder 2001)
- Observable distribution $d^2N/dzd\xi$ must be mapped to cosmology dependent hydro mass function $d^2N/dzdM$
- Need observable-mass relation
Observable-Mass Relation
Bocquet+15

- Statistical relationship between observable and underlying halo mass
  - Clusters are young, merging objects
  - Crucial for selection observable (S/N, Y, L_x)
  - Include lower scatter mass proxies (Y_x, M_micm)

- SZE Observable-Mass relation
  - Minimum of four free parameters: power law plus (log-normal) intrinsic scatter
    \[ \zeta = A_{SZ} \left( \frac{M_{500}}{3 \times 10^{14} h^{-1} M_\odot} \right)^{B_{SZ}} \left( \frac{E(z)}{E(0.6)} \right)^{C_{SZ}} \]
    4 params: A_{SZ}, B_{SZ}, C_{SZ} and D_{SZ}
  - Parametrization allows systematic uncertainties to be included
  - Mass information added through weak lensing, galaxy kinematics, external priors

SPT Cluster Cosmology
de Haan+16

- 387 SPT clusters
- Mass calibration
  - 82 X-ray Y_x s
  - WL prior on Y_x-mass
- 14 parameters
  - 6 cosmological
  - 4 SZ mass-obs
  - 4 X-ray Y_x-mass-obs
- Tension?
  - Insignificant in $\Lambda$CDM
  - Insignificant in wCDM

SPT Cluster Cosmology Constraints in good agreement with other probes within $\Lambda$CDM and wCDM models

SPT-SZ: w=-1.28+/-0.31 SPT-SZ++: w=-1.023+/-0.042
Planck Cluster Cosmology
Planck Collaboration XXIV (2015)

- 439 clusters
- Mass-obs rel’n
  - 3 params
    (C_{w} fixed)
- Mass calibration
  - WL- WtG
  - WL-CCCP
  - WL-CMB
- Significant tension only if CMB WL used

PlanckSZE+BAO (CCCP): w=-1.00+/-0.18

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Planck Cluster Mass Priors
Planck Collaboration XXIV (2015)

- External cosmology priors prefer higher masses than direct measurements
- CMB lensing and LoCUSS WL imply no hydrostatic mass bias (in conflict with simulations)
- Some tension among mass priors
  - WtG: 1-b=0.69+/-0.07
  - CCCP: 1-b=0.78+/-0.09
  - CMBlens: 1-b=0.99+/-0.19
  - LoCUSS: 1-b=0.95+/-0.04

Planck adopts hydrostatic masses as baseline
b is hydrostatic mass bias scale factor
M_{hydro} = b M_{true}
SPT Cluster Masses
Bocquet+15

- External cosmo priors (also WMAP) tend to prefer higher cluster masses
- Direct constraints (WL, Dyn, Hydro) prefer lower values
- Constraints are still weak - everything statistically consistent

\[
\zeta = A_{SZ} \left( \frac{M_{500}}{3 \times 10^{15} h^2 \, M_\odot} \right) \frac{E(z)}{E(0.6)}
\]

SPT Mass Calibration Ongoing

- Direct mass calibration of clusters
  - Dynamical masses:
    - Bocquet+15 (with dispersions)
    - Capasso+ (Jeans analysis)
  - Magnification masses:
    - Chiu+16
  - Shear masses:
    - Dietrich+ (Magellan imaging)
    - Schrabback+ (HST+VLT imaging)
    - Stern+ (DES imaging)
Do External Cosmological Priors Prefer Higher Cluster Masses?

- Evidence is intriguing but not compelling
- What might explain if future data show it is real?
  - Theoretical mass function wrong? (Bocquet+16)
    - Tinker mass function is biased on high mass end
    - $\Delta \sigma_8(\Omega_m/0.27)^{0.3} = +0.02$ (30% of the offset noted in Planck SZE analysis)
  - Unresolved systematics in the CMB data still possible-
    - Tension between base P15 CMB and CMB Lensing (Planck+15, Grandis+16)
  - Could incompleteness in the cluster sample play a role? (Gupta+16)
    - First measurement of 150GHz cluster radio galaxy LF
    - Indicates 2 to 5% incompleteness in SPT-SZ like survey
  - Revision of cosmological model required?

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Baryon Impact on Mass Function
Bocquet+16

- For massive cluster surveys like Planck and SPT there is no significant impact of baryon physics on the MF
- Of greater importance is the difference between the Tinker and the Bocquet mass functions!
- Watson MF is parametrized incorrectly and has “artificial” cosmological sensitivity
External Cosmo Priors Push Masses Higher?

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Systematics in CMB?

- We heard yesterday (from Karim) about high-l vs. low-l 2\( \sigma \) tension
- Also a related \( A_L \) 2\( \sigma \) tension between Planck TT + low TEB and Lensing constraints
- Consistency with non-CMB data?
  - In flat \( \Lambda \)CDM there is 8\( \sigma \) surprise when adding \( H_0 \)
  - Planck prefers curved Universe at 2.7\( \sigma \)
    - In curved \( \Lambda \)CDM model >3\( \sigma \) surprises exist between Planck TT + low TEB and BAO, SNe, \( H_0 \) and CMB lensing

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**Cluster Radio Galaxies at 150GHz**

_Gupta+16_

- Study the overdensity of high frequency radio galaxies 95, 150, 220GHz toward clusters
- Centrally concentrated
  - consistent with 1.4GHz- see Lin & Mohr 2007
- High-$\nu$ sources 10X rarer at a given luminosity
- Mock SPT-SZ samples with radio galaxies are incomplete at 2 to 5%
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Future SZE Surveys

- SPTpol + SPT-3G + AdvACT underway
- CORE space mission proposed for ESA M5
- CMB-S4 ground based (US coordinated, seeking European participation)
- Large cluster samples:
  - $z>1.5$: 500, 5000, 20,000 clusters
- Exquisite mass constraints

Melin+16 forecasts for CORE

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Summary

SPT Cluster Cosmology
- Good agreement with CMB++ datasets and other probes in $\Lambda$CDM/wCDM
- WL and dynamical mass calibration ongoing- first wave of papers imminent
- Planck: Mixed story on agreement with CMB++ datasets in $\Lambda$CDM/wCDM
  - + WL mass constraints from WtG or CCCP
  - - CMB lensing constraints and Smith WL masses provide tension

Cluster mass measurements
- Improved direct measurements with WL and dynamical data needed
- Additional hydro simulation studies of MF needed

Larger samples and better calibration on the way
- SPT-3G, Core, CMB-S4
- And don’t forget about eROSITA!!!

LMU Cosmology and Structure Formation Group

- Focus:
  Observational cosmology and structure formation studies

- Survey Projects
  South Pole Telescope
  Dark Energy Survey
  D-MeerKAT
  eROSITA
  Euclid
  LSST

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