GALAXY CLUSTER COSMOLOGY

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http://chandra.harvard.edu/photo/2006/1e0657/
OVERVIEW

• Cluster Cosmology in a Nutshell
• The Halo Mass Function
• How do we Measure Cluster Properties?
• Scaling Relations
• Recent results (with a focus on SPT)
THE UNIVERSE

CONTENT

- Dark energy: 69%
- Dark matter: 25%
- Atomic matter: 5%

Others:
- Neutrinos: 0.1%
- Photons: 0.01%
- Black holes: 0.005%
The Q Continuum Simulation: Heitmann et al., 2015 (arXiv:1411.3396)

1. Predict abundance of halos as a function of cosmology using numerical simulations
2. Measure number of galaxy clusters in a given survey as a function of mass and redshift
3. Learn about cosmology at $z=0$ and $z=2$

![Image of dark matter halo evolution over time](image)

**Figure:** Evolution of dark matter halo from $z=4.0$ to $z=0.0$.
Cluster masses usually defined as $M_\Delta$, which is mass enclosed within a sphere of radius $r_\Delta$, whose average density is $\Delta^* \rho$

- defined with respect to $\rho_{\text{mean}}$ or $\rho_{\text{critical}}$
- $\Delta = 500c$ used for X-ray because only inner part is bright
- $\Delta = 200c$ used for weak grav. lensing and velocity dispersions
- In simulations, also consider friend-of-friend (FoF) masses with linking length $b \sim 0.2$
CONSTRAINTS ON FLAT LCDM MODEL

DE HAAN ET AL. 2016 (SPT COLLABORATION)
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Structure formation in numerical simulations

N-BODY VS. HYDRODYNAMIC SIMULATIONS

- gravity-only
- (relatively) cheap
- no free parameters
- gravity & gas
- more expensive
- complicated sub-grid physics such as star formation, feedback from active galactic nuclei
HALO MASS FUNCTION

SB ET AL. 2016 (ARXIV:1502.07357)
**IMPACT OF BARYONS ON THE HMF**

*Magneticum Hydrodynamic Simulations: up to (3.8 Mpc)$^3$ (K. Dolag+)*

SPT-like (high-mass > ~3e14 $M_{\text{sun}}$)  
eROSITA-like (all masses > ~5e13 $M_{\text{sun}}$)

blue vs. green contours: impact of baryons on the HMF

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HMF - OUTLOOK

CALIBRATE THE COSMOLOGICAL DEPENDENCE

• Run simulations for a range of different cosmologies and mass definitions
• Use emulator to interpolate to desired cosmology

Mass function

26 model emulator

55 model emulator

FoF HMF emulator (Heitmann et al. 2016)
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THESE ARE GALAXY CLUSTERS...

... SO WHAT ARE THEIR MASSES?

Credit: NASA, ESA, and J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI)
http://www.spacetelescope.org/images/heic1401a/

Credit: NASA, ESA, the Hubble Heritage Team (STScI/AURA), J. Blakeslee (NRC Herzberg Astrophysics Program, Dominion Astrophysical Observatory), and H. Ford (JHU) http://www.spacetelescope.org/images/heic1317a
WHAT IS A GALAXY CLUSTER?

- thermal Bremsstrahlung (X-ray)
- weak gravitational lensing (optical / mm)
- Sunyaev-Zel’dovich effect (mm)
SZ / NIR OBSERVATIONS
MOST MASSIVE CLUSTER KNOWN AT Z > 1, FOLEY ET AL. 2013

SPT-CL J2106-5844 at z = 1.133
The South Pole Telescope

- (Sub) millimeter wavelength telescope
  - 10 meter aperture
  - 1' FWHM beam at 150 GHz
  - 5 arcsec astrometry
- mm-wave receiver
  - 1 deg² FOV
  - 3 bands: 95 GHz, 150 GHz, 220 GHz
  - Depth ~ 15-60 µK-arcmin
- Observed the CMB over >2500 deg²

Image credit: Nicholas Huang & Robert Citron
Sunyaev-Zel’dovich Effect (SZE)

- About 1% of CMB photons scatter
- SZE flux proportional to total thermal energy in the electron population
- SZE surface brightness is independent of redshift
Zoom in on an SPT map
50 deg$^2$ from
2500 deg$^2$ survey

CMB Anisotropy - Primordial and secondary
anisotropy in the CMB

Point Sources - High-redshift
dusty star forming galaxies and
Active Galactic Nuclei

Clusters - High signal to noise
SZ galaxy cluster detections as
“shadows” against the CMB!

From B. Benson
SZ AND X-RAY SURVEYS

Fig. 6.—Comparison of the 2500 deg$^2$ SPT-SZ cluster catalog to other X-ray and SZ-selected cluster samples. Here we plot the estimated mass versus redshift for the 516 optically confirmed clusters from the SPT catalog, 91 clusters from the ACT survey (Marriage et al. 2011; Hasselfield et al. 2013), 809 SZ-selected clusters from the Planck survey (Planck Collaboration et al. 2014a), and 740 X-ray clusters selected from the ROSAT all-sky survey (Piacentini et al. 2011) with $M_{500c} = 10^{14} M_{\odot} h^{-1}$. We mark 68% confidence lower limits for the redshifts of the three high-redshift SPT systems for which the Spitzer redshift model is poorly constrained (right arrows). We plot clusters in common between SPT and the other datasets (see e.g., Table 5) at the SPT mass and redshift and, for common clusters in the other datasets, at the mass and redshift of the dataset in which the cluster was first reported. While the SPT data provides a nearly mass-limited sample, the cluster samples selected from ROSAT and Planck data are redshift-dependent owing to cosmological dimming of X-ray emission and the dilution of the SZ signal by the large Planck beams, respectively.

We search the literature for counterparts to SPT candidates. We query the SIMBAD and NED databases as well as the union catalog of SZ sources detected by Planck (Planck Collaboration et al. 2014a) for counterparts. For confirmed clusters with $z \leq 0.3$ we utilize a $500$ kpc association radius; otherwise we match candidates within a $200$ kpc radius. All matches are listed in Table 5; we discuss potential false associations in the footnotes of this table. Additionally, we associate the brightest cluster galaxies in two clusters (SPT-CL J0249+5658 and SPT-CL J2254+5805) with spectroscopic galaxies from the 2dF Galaxy Redshift Survey (Colless et al. 2003) and the 6dF Galaxy Survey (Jones et al. 2009), respectively.

In total, 115 of the SPT candidates are found to have counterparts in the literature (14 of these clusters were first discovered in SPT data). We report the new discovery of 251 clusters here, increasing the number of clusters first discovered in SPT data to 415. We highlight particularly noteworthy systems below, and a subset of the SPT cluster catalog is shown in Figure 8.


We provide estimated masses for all confirmed clusters in Table 4. These estimates, determined from each cluster's $c^{+}$ and redshift, are based upon the methodology presented in Benson et al. (2013) and R13 but are reported here for a fixed flat $\Lambda$CDM cosmology—with $8=0.80$, $\Omega_b=0.046$, $\Omega_m=0.30$, $h=0.70$, $\mu=0.089$. X-ray
(SOME OF THE) UPCOMING SURVEYS
SPT-3G, EROSITA

Benson et al. 2014
CLUSTER RED SEQUENCE
USEFUL FEATURE IN COLOR-MAGNITUDE SPACE
RED-SEQUENCE MATCHED-FILTER PROBABILISTIC PERCOLATION
CLUSTER FINDER (REDMAPPER, RYKOFF ET AL.)

Stott et al. 2009
RED SEQUENCE OF SPT CLUSTERS IN DES

0.07 < z < 1.12 (Hennig et al. 2016)
EXAMPLE OPTICAL SURVEYS

• Sloan Digital Sky Survey (SDSS): 14,000 deg$^2$, 26,311 clusters with richness $\lambda > 20$, $0.08 < z < 0.6$

• Dark Energy Survey (DES): 5,000 deg$^2$; currently: 150 deg$^2$ Science Verification Data, 786 clusters with $\lambda > 20$, $0.2 < z < 0.9$

• Large Synoptic Survey Telescope (LSST, ~2020): 18,000 deg$^2$
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SCALING RELATIONS
RELATE OBSERVABLES TO MASS

• Assume there is a mean relation $<\text{Obs}> = f(\text{Mass})$ with scatter

• self-similar model for virialized objects (Kaiser 1986)
  
  • $M_{\text{gas}} = C_{\text{gas}} \, M_{\Delta_c}$
  
  • $T^{3/2} = C_T \, E(z) \, M_{\Delta_c}$
  
  • $Y_{sz}^{3/5} = C_{SZ} \, E(z)^{2/5} \, M_{\Delta_c}$
  
  • $E(z) = H(z)/H_0$

• In practice, allow for more freedom $<\text{Obs}> = A \, M^B \, E(z)^C$
SCALING RELATIONS IN SIMULATIONS

Gupta et al. 2016

Le Brun et al. 2016
X-RAY - WL CALIBRATION

weak lensing mass

de Haan et al. 2016

Mantz et al. 2016
weak lensing

dynamical mass

Accuracy

Precision

SZ effect  Yx

good

bad
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Observed Cluster Mass Function
Flat LCDM Cosmology
Neutrino Sector
Dark Energy
Equation of State
PARAMETRIZED GROWTH OF STRUCTURE

\[ f(a) \equiv \frac{d \ln \delta}{d \ln a} \equiv \Omega_m^\gamma(a) \]

\[ D_{\text{ini}}(z) \equiv \frac{\delta(z)}{\delta(z_{\text{ini}})} = \delta(z_{\text{ini}})^{-1} \exp \left( \int_{a_{\text{ini}}}^{a} d \ln a' \Omega_m^\gamma(a') \right) \]

\[ P(k, z) = P(k, z_{\text{ini}}) D_{\text{ini}}^2(z) \]

GR predicts \( \gamma = 0.55 \)
RESULTS FROM CLUSTERS TO DATE

Weighing the Giants IV: Mantz et al. 2015
RESULTS FROM CLUSTERS TO DATE

SPT-SZ 720 deg$^2$: SB et al. 2015