Cluster Astrophysics in the Era of Multi-Wavelength Cosmological Surveys

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Multi-wavelength Cluster Surveys

**eROSITA**

- All-sky survey for 4 yrs + targeted obs.
- Science Goals: Study the LSS and Dark Energy
- >100,000 clusters up to z~1.5
- $A_{\text{eff}} \sim 1500 \text{ cm}^2$ @ 1.5keV; $\Theta_{\text{eff}} \sim 25-40$ arcsec

**SPT-3G**

- SPT+Chandra
  - $z>0.3$, $>3 \times 10^{14} M_\odot$
- $z<0.5$, $>10^{14} M_\odot$
- $z>0.5$, $>4 \times 10^{14} M_\odot$

**eROSITA**

- $z<0.5$, $>10^{14} M_\odot$

**SPT3G/Adv-ACT/SO**

+ Athena/Lynx

**LSST**

**Adv-ACT**

**Future opportunities: many surveys coming online**
Cluster Cosmology in the Stage IV Era

eROSITA

Galaxy Clusters are powerful cosmological probes
Cluster Cosmology Today

X-ray Cluster Cosmology

Mantz+15
also Vikhlinin+09, Benson+13

Planck Cosmological Constraints
from CMB vs. Cluster counts

Systematic uncertainties are already comparable to statistical uncertainties

Possible Solutions:
- Cluster mass calibration is biased by 45%
- Planck CMB results may be biased
- Sum of the neutrino masses is ~0.2eV
- Combination of the above

Challenge #1: Mass Calibration (+Selection Function)
Key: Cluster Astrophysics
Alternative Probe: SZ power spectrum

Thermal SZ power spectrum from Planck

Cosmological constraints from SZ power spectrum

Challenge #2: Calibrating Pressure Profiles in Groups & Clusters (+foreground)
Cross-correlation of Planck and RCSLens data shows tensions with the Planck tSZ power spectrum result, indicating possible systematics in lensing measurements and/or ICM physics in low-mass clusters at z>0.2

van Waerbeke+14, Hill & Spergel+14, Hojjati+17
**Pairwise kSZ signal:**

- CMB pattern caused by the kSZ effect + pairwise motion of clusters (improve statistics by summing over many cluster pairs):

\[
\frac{\Delta T_{\text{pkSZ}}(r,z)}{T_{\text{CMB}}}(r,z) = \frac{\nu_{12}(r,z)}{c} \Rightarrow \frac{\nu_{12}(r,z)}{c} = \frac{\Delta T_{\text{pkSZ}}(r,z)}{T_{\text{CMB}}}
\]

- at large scales:

\[
\nu_{12} \sim \xi_v \delta \sim f \sigma_8^2
\]

- therefore the signal is of fundamental cosmological interest:

\[
\Delta T_{\text{pkSZ}} \sim \bar{\tau}_{\text{eff}} f \sigma_8^2
\]

Illustration by Sudeep Das
Previous pairwise kSZ measurements

![Graph showing pairwise kSZ measurements](image)

- **ACT+BOSS Hand+12**
- **SPT+DES Soergel+16**
- **Planck+SDSS Ade+15**
- **ACTPol+BOSS DeBernadis+16**

**Equation:**

$$\xi(r) = (3.75 \pm 0.89) \cdot 10^{-3}$$

**Data Points:**

- **HFI-217 GHz SEVEM**
- **Planck+SDSS Ade+15**
- **ACTPol+BOSS DeBernadis+16**
Cosmology with pairwise kSZ signal

Sugiyama+16: improved constraints on H, $D_A$, f by adding kSZ information

Keisler & Schmidt+13: dependence of $\xi_{\delta v}$ on the gravity model

Challenge #3: External prior of the optical depth ($\tau$) to better than 20% can be a big help!
**SOLUTION: Hybrid Approach**

**Hydro Simulations + Semi-Analytic Model**

**Goal:** Maximize the scientific return of LSS & CMB surveys

**Strategies:**

1. Cosmological hydro. simulations to gain physical insights into cluster astrophysics

2. Physically-motivated, computationally efficient Semi-Analytic Model (SAM) of gas + N-body simulations for modeling cosmological surveys
Lessons from Hydro Simulations after some rigorous comparisons with observations

✦ Cluster Core \( (r<0.2R_{500c}) \)

- Heating, Cooling, & Plasma physics
  1. AGN feedback (Mechanical/CR heating)
  2. Dynamical Heating, Gas sloshing
  3. Thermal Conduction, Magnetic Field, He sedimentation

  Outstanding Challenge - especially critical for X-ray surveys (e.g., eROSITA)

✦ Beyond Core \( (r=[0.2,3]R_{500c}) \)

- Gas Accretion & Non-equilibrium phenomena
  1. **Non-thermal pressure due to gas motions**
  2. Shapes of Gas & DM
  3. **Splashback & Shock Radii**
  4. Gas clumping/inhomogeneities
  5. Non-equilibrium electrons

Sweet Spot for Cluster Cosmology!
Non-thermal Pressure
Analytical Model vs. Hydro Simulations

Shi & Komatsu 2014 (analytical model)

\[ \frac{d\sigma^2_{\text{nth}}}{dt} = -\frac{\sigma^2_{\text{nth}}}{t_d} + \eta \frac{d\sigma^2_{\text{tot}}}{dt} \]

Time Change in Turbulence Energy per unit mass
Dissipation of Turbulence
Generation of Turbulence sourced by mass accretion

Semi-analytic model can match the results of hydrodynamical simulations remarkably well
Accretion shock radius is $\sim 1.5$ times larger than the Splashback radius, eliminating the uncertainties associated with the outer boundaries of DM and gaseous halos.
Multiwavelength lightcone simulations with Semi-Analytic Model of the ICM

- Develop a spherical SAM model of the ICM (Shaw et al. 2010; Flender et al. 2017)
- Paint them on the N-body simulations with $N=2048^3$ in volume of $480^3$ and $960^3$ [Mpc/h]$^3$ in the WMAP 9yr cosmology
- Create mock lensing, tSZ and X-ray sky mocks in a 10x10 sq. deg. sky

Shirasaki et al. in prep.
Constraining the SAM with X-ray observations

Gas density profile from extended Shaw Model from Flender+17

McDonald+2013: Chandra measurements of gas density profiles of SPT-selected clusters

Vikhlinin+06, Sun+09, Lovisari+15: measurements of the $M_{\text{gas}}$-$M$ relation

Vikhlinin+06, Sun+09, Lovisari+15: measurements of the $M_{\text{gas}}$-$M$ relation
Constraints on the ICM parameters

AGN feedback

dynamical friction heating

breaking point

broken polytropic exponent

stellar fraction

slope in stellar model

z-evolution of cooling

scatter in $M_{\text{gas}}$-$M$

Constraints on the ICM parameters
Impact of ICM physics on τ of galaxy clusters

Dynamical heating of the ICM

Energy feedback from stars and AGN

Normalization of the $M^*$-$M_{\text{halo}}$ relation

Slope of the $M^*$-$M_{\text{halo}}$ relation

Our model is computationally efficient and suitable for parameter estimation

Flender+17
Our SAM can reproduce the results of hydro simulations by Battaglia+16 (see also Soergel+17).
Better than 12% constraints on the $\tau$ profile

$M_{500} = 5 \cdot 10^{13} \, M_\odot$
$\tau_0 = 2.91 \pm 0.35 \, (12\%)$

$M_{500} = 10^{14} \, M_\odot$
$\tau_0 = 4.04 \pm 0.29 \, (7.2\%)$

$M_{500} = 5 \cdot 10^{14} \, M_\odot$
$\tau_0 = 7.47 \pm 0.27 \, (3.6\%)$

$M_{500} = 10^{15} \, M_\odot$
$\tau_0 = 9.43 \pm 0.36 \, (3.8\%)$
Painting Galaxies onto Dark Matter Halos

- **Bolshoi-Planck simulation**
  - Box size = 250/h Mpc
  - DM particle mass = $1.9 \times 10^8$ Msun
  - Spatial resolution = 1.5 kpc
  - Planck Cosmology

- **Universe Machine Galaxy Mock**
  (Behroozi et al. in prep)
  - reproduce both $M^*$ and SFR of galaxies
  - paint galaxies onto the Bolshoi-Planck N-body simulation
Velocity Dispersion for Cluster Cosmology

\[ b(r) = \frac{\sigma_{\text{gal,LOS}}(r)}{\sigma_{\text{DM,LOS}}(r)} \]

Velocity bias is unity across \([0.3-3]R_{200m}\) in projection in different models.

Aung, Nagai, Rozo, Hearin, Behroozi, in prep.
Cluster Cosmology with DESI

$$b(r_1, r_2) = \frac{\sigma_{gal,LOS}(r_1 < r < r_2)}{\sigma_{DM,LOS}(r_1 < r < r_2)}$$

Velocity bias in $[0.3-1]R_{200m}$ can be controlled below 2% across redshift range $z$ in $[0,1]$. 
Cosmology & Astrophysics in the Era of Multi-wavelength Cosmological Surveys

Goal: Maximize the scientific return of LSS & CMB surveys

Challenge
Non-linear astrophysics of both gas and stars on small scales (<a few Mpc)

Methodology
Hybrid approach: hydro sim + SAM
Cluster astrophysics is tractable down to 10% the viral radius (r>0.1R\text{vir}~100kpc)

Modeling Challenges
• Develop a unified SAM of gas & stars
• Create realistic multi-wavelength extragalactic sky mocks (e.g., cross-correlation)
• Impact of baryonic physics on mass profile & shape of DM halos