Galaxy clusters, in the light of Planck

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Galaxy clusters in the cosmic web

CLEF-SSH hydro simulation, Kay et al. '06
Cluster components

Dark matter → 85%  
Observed in optical

Galaxies → 2%  
Observed in optical and IR

Diffuse hot gas → 13%  
Emitting in X-ray, observed in SZ
Observing the hot intra-cluster gas

Bremsstrahlung $\to$ X-ray emission

Inverse Compton $\to$ SZ effect

$E_X \propto \int_V n_e^2 \Lambda(T) dV$

$F_\nu \propto \int_\Omega (P = n_e T) d\Omega$

Total SZ “flux” proportional to $M_{\text{gas}}/d_A^2(z)$

Two independent probes of the same physical component
The Sunyaev-Zel'dovich (SZ) effect

Abell 2319 across Planck channels

SZ, Comments on Astr. and Space Physics 1972
Detection of new clusters with SZ

From first blind detections by SPT (Staniszewski et al' 09)

SPT \([\sim 1.1' @150\text{GHz}]\)

244 SZ sources
Williamson et al '10, Reichardt et al '13

ACT \([\sim 1.4' @148\text{GHz}]\)

91 SZ sources
Marriage et al '10, Menanteau et al '11, Hasselfield et al. '13

To Planck catalogue of SZ sources (Planck 2013 results XXIX)

ACT \([\sim 5' @100 \text{ to } 857\text{GHz}]\)

1227 SZ sources

~200 newly discovered clusters
683 known clusters
~344 candidate clusters
Planck early results VIII, Planck 2013 results XXIX
Cluster number counts are sensitive to the growth rate and to the volume element.

Number counts and evolution of mass function provide powerful cosmological constraints.

Nunes et al '09

Borgani '06

Nunes et al '09
Analyses with X-ray surveys, SDSS (optical) and more recently SZ surveys.
Cosmology from cluster number counts

Probability of observed number counts given those predicted from theory

\[
\frac{dN}{dz} = \int d\Omega \int dM_{500} \chi(z, M_{500}, l, b) \frac{dN}{dz dM_{500} d\Omega}
\]

**Reference mass function** → from numerical simulations, function of cosmological parameters (e.g., Tinker et al. '08)

**Reference selection function** → accounting for survey properties, counting clusters & measuring their redshifts

**Reference scaling relation** → from observable to mass
Sky coverage vs survey depth →
Planck detects the rarest high-mass clusters
SPT and ACT detect higher-z lower mass clusters

Quasi mass-limited selection →
SZ shows no redshift dimming
X-ray surveys more sensitive to low mass systems

Planck catalogue: Largest catalogue of massive clusters (up to $1.5 \times 10^{15}$ $M_{\odot}$)
From observable to mass: Scaling relations

Complex physics but simple assumptions for cluster mass determination:
- Hydrostatic equilibrium (no turbulence, bulk motion, convection, major mergers, etc)
- No other forces (magnetic fields, etc)
- No pressure from relativistic particles
- No multi-temperature structure

\[ E_X \propto \int_V n_e^2 \Lambda(T) dV \quad F_\nu \propto \int_\Omega (P = n_e T) d\Omega \]

Stanek et al '11

SZ signal more directly related to the mass \(\rightarrow\) less scatter

Planck 2013 results XXIX
SZ-X scaling relation

Subsample of 71 clusters in the Planck cosmo-sample with XMM-Newton data

$Y_{sz}$ measured with X-ray size and at position $Y_{X}$ derived from X-ray data

$Y_{X} \rightarrow M_{X}$ and $Y_{X} \rightarrow Y_{sz}$ \rightarrow $Y_{sz} - M_{X}$

Ratio between observed mass and true mass from numerical simulation $b$

$$E^{-\beta(z)} \left[ \frac{D_{A}(z) \bar{Y}_{500}}{10^{-4} \text{ Mpc}^2} \right] = Y_{*} \left[ \frac{h}{0.7} \right]^{-2+\alpha} \left[ \frac{(1-b)M_{500}}{6 \times 10^{14} \text{ M}_{\odot}} \right]^\alpha$$

$(1-b) = 0.8 \text{ in } [0.7 - 1.0]$
Cosmology from SZ-cluster counts in Planck

Well characterised sample (189 clusters @S/N ≥ 7 on 65% cleanest part of sky) Completeness function of filter size & position on the sky

Tension at ~3σ level on $\sigma_8$ from SZ counts vs CMB

To bring clusters and CMB to agree:
- Missing ~half of the massive clusters, NO
- $(1-b)\sim 0.55$, i.e. true mass higher by ~50%, unlikely
- More complex bias dependence
- Massive neutrino $\Sigma m_\nu \sim 0.2$ ev
- Combination (calibration, high $b$, $\Sigma m_\nu > 0$)
Comparison with other constraints

*Planck*: 189 clusters, 71 with $Y_x$

*SPT*: 100 clusters, 14 with $Y_x$

*ACT*: 22 clusters, 7 with $M_{\text{dyn}}$

Systematic effects start dominating over statistics

→ Characterise the cluster population

→ Understand cluster physics
Statistical properties of cluster population: 
SZ-X scaling relation

- **Consistent overall view of ICM** properties from X-rays and SZ
  - SZ & X-ray luminosities agree down to lowest luminosity bins
  - SZ & X-ray pressure measurements agree within $R_{500}$
- Error dominated by systematics, low scatter → $Y_{SZ} - Y_X$ good mass proxy

\[ Y_{SZ} - L_X \]

\[ Y_X = M_{\text{gas}} T_X \]
Hot-gas content of DM halos

• Hot gas statistically measured in large halos $\geq 5 \times 10^{13} \, M_{\odot}$

• SZ derived from stellar mass of locally brightest galaxies from SDSS

SZ signal statistically detected from largest halos $\sim 2 \times 10^{15} \, M_{\odot}$ to $\sim 4 \times 10^{12} \, M_{\odot}$

25% of the total amount of missing baryons detected in form of hot gas in halos!
Statistical properties: SZ-optical scaling relation

Predicted SZ disagrees with measurement: Deficit of SZ signal as function of richness

Combination of:
- Calibration, scatter...
- Centering, orientation...
- Selection effect
Statistical properties:
SZ-Optical scaling relation

LOCUSS: SZA – Subaru

Planck – Subaru

ACT – $M_{\text{dyn}}$

$D_A Y_{\text{SZ}}$

$E(z)^{2/3} D_A Y_{500}$ [Mpc$^2$]

$M_{WL, 500}$ [M$_{\odot}$]

Planck Collaboration 2011
(X-ray HE mass)

Marrone et al. 2011

Overall agreement within 20% between $M_{WL}$ and $M_{HE}$

Marrone et al '11

Planck intermediate results '13

Sifon et al '13
Cluster physics with multi-wavelength approach

New high quality cluster samples require addressing some of the complex physics:
- Hydrostatic equilibrium (turbulence, bulk motion, convection, major mergers, etc)
- Other forces (magnetic fields, etc)
- Pressure from relativistic particles
- Multi-temperature structure

Radio observation (e.g., LOFAR) key to probe dynamical state and non thermal phenomena
- Probe non-gravitational processes (e.g., galaxy feedback)
- Probe merging history (e.g., thermal vs non-thermal processes)

SZ observation key to probe gas pressure
Follow up: more than 300 Planck sources followed up in X-rays (XMM-Newton DDT), optical (WFI, RTT150, ENO, etc), IR (Spitzer)
Density profiles **shallower than X-ray selected clusters** → under-luminous for their masses → under-represented at the X-ray detection limit

- Large variety of dynamical state → 70% new clusters have **disturbed morphologies** (compared to 30% in X-ray selected clusters e.g. REXCESS) including **multiple systems**
Exploring the cluster content/properties
e.g. Coma

Resolved SZ signal → Probing complex cluster physics
Measured shock fronts, pressure “jump”:
- Independent measure of western jump in Planck & X-rays & radio
- Indication of new south-eastern jump

SZ pressure profile out to $3-4 \ R_{500}$ “flatter” at large radii than GNFW → Non-thermal pressure? Contamination?
• Good agreement between GNFW X-ray and SZ pressure profiles within \( R_{500} \)

• Pressure profile slightly "flatter" than GNFW and than simulation at large radii → Non-thermal pressure?

62 high S/N clusters from Early SZ sample with high quality X-ray data

SZ signal detected out to \( 3R_{500} \)

\[
F_\nu \propto \int_\Omega (P = n_e T) d\Omega
\]

Deconvolution & deprojection → from SZ to pressure profile

\[
P(r) = \frac{m_e c^2}{\sigma_T} \frac{1}{D_A(z)} \frac{1}{y(\theta)} \frac{d\theta}{dr}
\]

Good agreement with BOLOCAM (Sayers et al. '13)
Radio emission probes mergers

→ 80% massive clusters host a radio halo in Planck SZ-selected sample versus ~40% in X-ray selected sample (from Sommer & Basu '13)

Selection effect? SZ intrinsic effect?

Probing dynamics:
Some exceptional objects e.g., giant arcs evidence of past mergers in PLCK G287.0+32.9

Bagchi et al., 2011

PLCK G287.0+32.9 z=0.39 kT ~13 keV

See also PLCK- ESZ G241.97+14.85 ; van Weeren et al. '13
Towards future routine radio observation
With LOFAR and SKA

LOFAR OBSERVATIONS OF ABELL 2256

LOFAR @ 61-67 MHz

Robust -0.1:
Mean rms ~ $10 \times 10^{-3}$ J y/beam
FWHM: 22'' x 26''

Robust 0.5:
Mean rms ~ $25 \times 10^{-3}$ J y/beam
FWHM: 52'' x 62''

van Weeren +12

Courtesy C. Ferrari
“New frontier”, high redshift clusters: Multi-wavelength synergy

Most distant cluster @z=2.07
Overdensity in Spitzer

Spitzer/IRAC IDCS J1426.5+3508 z=1.75

CL J1449+0856 z=2.07
$M_{200} \sim 5 \times 10^{13}$

Brodwin et al 12

Spitzer & XMM

Gobat et al, 11

NOAO

CARMA
Conclusions and challenges

→ **New clusters** (e.g. SZ) with new selection criteria and biases
→ **New data** and observational windows with new instruments (e.g. LOFAR)

→ Probe cluster formation with multi-wavelength studies
  - New probe of outskirt physics
  - New insight on merger physics from radio/X-ray/high resolution SZ/lensing
→ Much more on cosmology (distant clusters to challenge theory, follow-up of complete SZ samples)

Some Challenges for future cluster surveys:
  Understand cluster physics details thanks to radio (beat systematics)
  Optimise detection techniques in the optical (beat chance alignment and low-mass system contamination)
  Follow-up for redshift and confirmation of thousands of future clusters

Synergies with large surveys: Euclid, SKA, eROSITA, Planck, LOFAR
Synergies with other facilities: ESO, XMM, Chandra, Spitzer, etc