Reliability of galaxy clusters as cosmological probes

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SZ map of RX J1347-1145
Upper: submm (350GHz) with SCUBA at JCMT
Lower: mm (150GHz) with NOBA at Nobeyama
(Komatsu et al. 1999, 2001)
**Precision cosmology with clusters**

- Power spectrum from cluster distribution (c.f., talk by Schuecker)
- $\Omega_8 - \Omega_0$ relation from cluster abundance
- consistent with CMB, SN and galaxy surveys (c.f., talk by Boehringer).
- Certainly useful and complementary, but can it be precise enough to be competitive with the other probes, especially in the next generation?
- Or, have we understood what are the clusters?
What is the definition of galaxy clusters?

**Abell (optical) clusters**
- The Abell radius
- \( m_3 < m < m_3 + 2 \)
- Richness class

**Press-Schechter halos**
- Spherical collapse
- \( \rho_{\text{vir}} = 18 \rho_c^2 \)

**SZ clusters**
- \( I_{\text{SZ}} \)
- \( n_e T_e \)

**X-ray clusters**
- \( S_x \propto n_e^2 T_e^{1/2} \)

**Halos in N-body simulations**
- Friend-of-friend
- Linking length = 0.2

Definitely they are closely related, but the exact one-to-one correspondence is unlikely....
Globally similar distribution, but their precise relation is unclear because definitions of clusters (especially at high $z$) are very ambiguous.

A cluster-size halo ($8 \times 10^{14} M_{\text{sun}}$ at $z=0$)

- Dark matter
- Hot gas
- DM core
- Cold Gas
- galaxy

SPH simulations in LCDM: $N=128^3$ boxsize: 75 $h^{-1}$Mpc
(Yoshikawa, Taruya, Jing & Suto 2001)
An example; substructure of RXJ1347-1145 (z=0.45) detected via SZ map at 150 GHz

150GHz with NOBA (Nobeyama Bolometer Array) at Nobeyama 45m telescope in March, April, 1999 and February 2000

\[ \theta_{\text{FWHM}} = 13'' \]

- Globally similar morphology to the X-ray image
- Substructure in the South-East direction

Komatsu et al. PASJ 53(2001)57

central source subtracted (3.8mJy assumed)
Confirmed by Chandra and BIMA observations

RXJ1347-1145

BIMA@30GHz
63”x80” beam
(10.3mJy point source removed)

Carlstrom et al. (2001)

- non-spherical modeling is crucial, perhaps at high z in particular.
- Clusters are not so simple as we have pretended to believe (c.f., talk by Briel)
The first SZ map of a cluster in the submm band with SCUBA, JCMT. (contours: Chandra X-ray map)

The highest angular resolution SZ map of a cluster in the mm band with NOBA, Nobeyama

Spherically averaged SZ surface brightness profile at 350GHz. Globally consistent with the X-ray observation.

Komatsu et al. 
PASJ 53(2001)57
$\delta_8$ from cluster abundances and lensing


More recent estimate of $\Omega_8$

Bahcall et al. (SDSS)
astro-ph/0205490

Brown et al.
astro-ph/0210213
COMBO-17 survey
Systematic uncertainties

Theoretical modeling of X-ray clusters

**Halo density profile**

\[
\rho(r) = \frac{\delta_c \rho_{\text{crit}}}{(r / r_s)^\alpha (1 + r / r_s)^{3-\alpha}}
\]

\[
c_{\text{vir}}(M) \equiv \frac{r_{\text{vir}}(M)}{r_s(M)} = \frac{9}{1 + z} \left( \frac{M}{2 \times 10^{13} h_{70}^{-1} M_{\text{Sun}}} \right)^{-0.13}
\]

**Hydrostatic equilibrium gas distribution**

\[
\rho_{\text{gas}}(r) = \rho_{\text{gas},0} \exp \left[ \frac{2 c_{\text{vir}} T_{\text{vir}}}{m(c_{\text{vir}} T_{\text{gas}})} f(x) \right]
\]

\[
f(x) = 1 - \frac{\ln(1 + x)}{x} \quad (\alpha = 1)
\]

\[
= 2\sqrt{\frac{1 + x}{x}} - 2\frac{\ln(\sqrt{x} + \sqrt{1 + x})}{x} \quad (\alpha = 3/2) \Rightarrow \text{analytic!}
\]

Mass – temperature relation to X-ray luminosity

- Convert the observed MT relation (\(M_{500}\) and \(M_{2500}\) to \(M_{\text{vir}}\) in our adopted dark matter halo profile):
  - **Finoguenov et al. (2001)**
    
    \[
    T_{\text{gas}} = (1.92 \pm 0.06) \text{keV} \left( \frac{M_{\text{vir}}}{10^{14} h^{-1}_7 M_{\odot}} \right)^{0.54 \pm 0.02} \quad (\alpha = 1)
    \]
  - **Allen et al. (2001)**
    
    \[
    T_{\text{gas}} = (1.53 \pm 0.56) \text{keV} \left( \frac{M_{\text{vir}}}{10^{14} h^{-1}_7 M_{\odot}} \right)^{0.57 \pm 0.12} \quad (\alpha = 1)
    \]

- Gas mass fraction (Mohr et al. 1999)
  
  \[
  f_{\text{gas}} = \min \left[ 0.92 h^{-3/2}_7 \left( \frac{T_{\text{gas}}}{6 \text{keV}} \right)^{0.34}, 1 \right]
  \]

- Compute the X-ray luminosity
  
  \[
  L_X = 4\pi \int_0^{r_{\text{vir}}} \Lambda(T_{\text{gas}}, Z) \left( \frac{\rho_{\text{gas}}(r)}{\mu m_{\text{proton}}} \right)^2 r^2 dr
  \]
From the observed mass-temperature relation to the luminosity-temperature relation

L-T relation is sensitive to M-T relation
Limits on a parameterized M-T relation from the observed L-T relation

\[ T_{\text{gas}} = T_{\text{gas}, 0} \left( \frac{M_{\text{vir}}}{10^{14} h_7^{-1} M_{\odot}} \right)^p \]
Limit on gas mass fraction from the observed L-T relation

\[ f_{\text{gas}}(T_{\text{gas}}) = f_{\text{gas},0} \left( \frac{T_{\text{gas}}}{1 \text{ keV}} \right)^{p_{\text{gas}}} \]

c.f., Mohr et al. (1999)

\[ f_{\text{gas}} = 0.92 h_{70}^{-3/2} \left( \frac{T_{\text{gas}}}{6 \text{ keV}} \right)^{0.34} \]

Limits on a parameterized M-T relation from the observed L-T relation and XTF

$\Delta \chi^2$ from the observed X-ray temperature function
Conclusions

- One can perform statistical analysis of X-ray clusters, provided a good physical model for halo-cluster connection beyond the unrealistic one-to-one correspondence.

- From dark halos to visible objects:
  - halo mass -- cluster gas temperature relation
  - non-gravitational effects inside dark halos (cooling, star/galaxy formation, preheating, supernova feedback, etc.)

- The goal of the next generation cluster surveys is not precision cosmology, but is to understand "what are the clusters of galaxies".