NECSUS: SUBARU/HSC WEAK-LENUSING ANALYSIS OF VERY NEARBY GALAXY CLUSTERS

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Weak-Gravitational lensing study is a direct probe to reconstruct cluster mass distribution. Complementary to X-ray analysis.
Universal Mass Profile

Simulation-based predictions: the appearance of a characteristic, universal density profile (Navarro, Frenk & White 96, 97; **NFW profile**)

\[ \rho \propto r^{-1} \]

\[ \rho_{\text{NFW}}(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2} \]

- \( \rho \propto r^{-3} \)
- Dwarfs
- Galaxies
- Clusters

**Cluster Mass** \( M_{\text{vir}} \)  

**Concentration parameter** \( c_{\text{vir}} = \frac{r_{\text{vir}}}{r_s} \)
Weak-lensing studies of “massive” clusters in recent 10 years

Massive clusters beyond redshift ~ 0.15

Redshift range are selected by the FoV (~full moon size) of Subaru/Suprime-cam

- exquisite imaging quality
- 8.2 diameter mirror
- one pointing covers viral radii

LoCuSS, CLASH, CCCP, wtG and so on
LoCuSS (Local Cluster Substructure Survey) multi-wavelength survey for ~ 80 clusters at $z = 0.15-3.0$, unbiasedly selected from X-ray luminosity.

Subaru, Chandra, XMM-Newton, SZA, Spitzer, GALEX, Herschel.
**LoCuSS** \((0.15 < z < 0.3; \text{50 clusters})\)

Lensing signal agrees well with NFW/Einasto profiles. Mass-concentration relation a good agreement with numerical simulations.

Okabe+Smith16

**Stacked lensing profile**
Next Decade: Hyper Suprime-Cam (HSC)

FoV: 7 times larger

Full moon

Suprime-Cam
Image Release
September 2001

Hyper Suprime-Cam
Image Release
July 2013

(Credit: HSC Project / NAOJ)
HSC is the best interment for clusters at $z < \sim 0.1$

Suprime-Cam Era

HSC Era

Frontier of WL studies

HSC SSP Survey

Matched with the performances of Suzaku, XMM–Newton, Chandra and Hitomi satellites
NEarby Cluster Survey with Subaru

Advantages of WL analysis for very nearby clusters

- no (less) contamination of member galaxies
  (contamination is a critical issue at $z \sim 0.2$)
- the enormous number of background galaxies reduce the statistical shape noise and thus compensates for the low lensing efficiency of the nearby cluster.
  ($N_g$ is 20-60 times higher than that at $z \sim 0.2$)
- large apparent size resolve less massive subhalos.
  (down to $\sim 5 \times 10^{12} - 10^{13}$ $M_{\odot}$)
  (massive subhalos in meting clusters at $z \sim 0.2$)
Overall Mass Profile (main=smooth mass component)

Internal Structure (clumpy subhalos)
Mass map (Coma)

Pilot Study with Suprime-Cam

32 cluster subhalos detected by WL signals

Associated with known optical groups/galaxies

X-ray emission detected from some massive subhalos

FWHM = 4 arcmin

Okabe+14a
Stacked Lensing Analysis:

The Stacked lensing signals for 50 massive clusters show sharply truncated features. The NFW model is rejected for these clusters. The profiles of subhalos (21 subhalos, 8 subhalos, 3 subhalos) do not exhibit any feature of truncation.

The equation for the TNFW model is given by:

\[
\rho_{\text{TNFW}} = \begin{cases} 
\rho_{\text{NFW}} & (r < r_t) \\
0 & (r > r_t) 
\end{cases}
\]

where \(\rho_{\text{TNFW}}\) is the density of the TNFW model, \(\rho_{\text{NFW}}\) is the density of the NFW model, and \(r_t\) is the truncation radius.
Consistent with CDM predictions: slope $\sim 0.9-1$

Two orders of the magnitude in mass
the Perseus Cluster with HSC

One of primary targets of cluster sciences.

GT target of Hitomi X-ray satellite to directly measure gas motions.

Chandra

z=0.0178
Overlaid with mass contours
HSC : ReGauss
Okabe : KSB+
Joint constraints by WL and BCG stellar kinematics

\[ \langle \Delta \Sigma_+ \rangle \left[ 10^{15} h_{70} M_\odot \text{Mpc}^{-2} \right] \]

\[ \chi^2 = \chi_g^2 + \chi_{\text{dyn}}^2, \]

\[ \Sigma_* \sigma_{1, \text{os}}^2 (R) = 2G \int_{R}^{\infty} \frac{\nu_* (r) M(r) F(r)}{r^{2-2\beta}} dr \]

Projected velocity dispersion

\[ \sigma_{v_\star} \left[ \text{km/s} \right] \]

\[ r \left[ h_{70}^{-1} \text{Mpc} \right] \]

\[ \theta \left[ \text{arcsec} \right] \]
Joint X-ray and HSC-WL analysis

1: Indirect Constraint of Non-thermal Pressure vs Hitomi/SXS measurement of gas motion

Importance for cluster cosmology

2: Suzaku Cluster Outskirts Problem
Total Pressure v.s. Thermal Pressure v.s. Non-thermal Pressure

XMM/Chandra/Suzaku

X-ray

Thermal pressure

$P_{th}$

Non-thermal pressure

Subaru

WL

total pressure

$P_g = \int_{r}^{\infty} \frac{GM\rho_g}{r^2} dr$

X-ray

Hitomi

“direct” observation of non-thermal pressure.
Non-thermal pressure at small radii is negligible.

Consistent with Hitomi result
Outskirts Entropy Problem

\[ K = \frac{k_B T}{n_e^{2/3}} \]

Possible interpretations:

- Temperature drops
  - Non-thermal pressure (Kawaharada+10, Sato+12, Ichikawa+13, Okabe+14c)
- Number density excess
  - Overestimated by gas clumpiness (Nagai+Lau11, Simionescu+11, Urban+14)

Walker+2012
Clumpiness interpretation

**Nagai+Lau 11**

Entropy flattering is found beyond $r_{200}$.

Observations are within $r_{200}$.

Clumpiness within $r_{200}$ are negligible.

Consistent with gas physics.

Lifetime of gas clumpy structures is very short due to ram-pressure/hydro-instability.

**Suzaku Observation**

Density excess is reported only in the Perseus cluster.

We now have WL and X-ray data for the cluster.
Simultaneous fit of X-ray and WL data

- Do NOT assume existing scaling relations/base-lines to understand the data.
Since we don’t know whether the assumption is true or not, we may misunderstand causes.

Self-Consistent Analysis

\[
 f_n(\tilde{r} = r/r_\Delta) = \frac{n_0 E(z)^2}{10^{14} h^{-1}_7 M_\odot} \left( \frac{M_{\Delta} E(z)}{10^{14} h^{-1}_7 M_\odot} \right)^a \left( \frac{\tilde{r}}{r_0} \right)^{-\alpha} \left( 1 + \left( \frac{\tilde{r}}{r_0} \right)^\beta \right)^{-\gamma/\beta}
\]

\[
 f_T(\tilde{r} = r/r_\Delta) = \frac{T_0}{10^{14} h^{-1}_7 M_\odot} \left( \frac{M_{\Delta} E(z)}{10^{14} h^{-1}_7 M_\odot} \right)^b \left( \frac{\tilde{r}}{r_0} \right)^{-\delta} \left( 1 + \left( \frac{\tilde{r}}{r_0} \right)^\beta \right)^{-\eta/\beta}
\]

\[
 -2 \ln \mathcal{L} = \sum_{i,j} \ln(\det(C_{ij})) + v_{ij}^{T} C_{ij}^{-1} v_{ij},
\]

\[
 v = \left( \begin{array}{c}
 \ln(n(\tilde{r})) - \ln(f_n(M_{\Delta}, \tilde{r})) \\
 \ln(T(\tilde{r})) - \ln(f_T(M_{\Delta}, \tilde{r})) 
\end{array} \right),
\]

\[
 C = C_{\text{stat}} + C_{\text{int}}
\]
Entropy decreasing caused by $T$ drop

Density

Temperature

Pressure

Entropy

$\delta \left( \frac{d \ln T}{d \ln r} \right) \sim -1$

$K = \frac{k_B T}{n_e^{2/3}}$

$\frac{r}{r_{200}}$

$\Delta_{\text{dev}}$

slope

$\frac{n}{n_*}$

slope

$\frac{P}{P_*}$

$\Delta_{\text{dev}}$

$\frac{T}{T_*}$

$\frac{K}{K_*}$

$\Delta_{\text{dev}}$

slope

$\frac{1}{n}$

$\frac{1}{T}$

$\frac{1}{P}$

$\frac{1}{K}$

$\frac{1}{r}$

$\frac{1}{r_{200}}$
Summary

- New project for very nearby clusters using Subaru/HSC is launched.
- Indirect constraint of non-thermal pressure agrees well with the quiescent gas by Hitomi’s direct observation.
- X-ray gas profiles (n, T, P, and K) scaled by weak-lensing mass and over-density radius have universal forms out to ~ virial radius.
- Low entropy in cluster outskirts is caused by temperature drops rather than gas clumpiness.