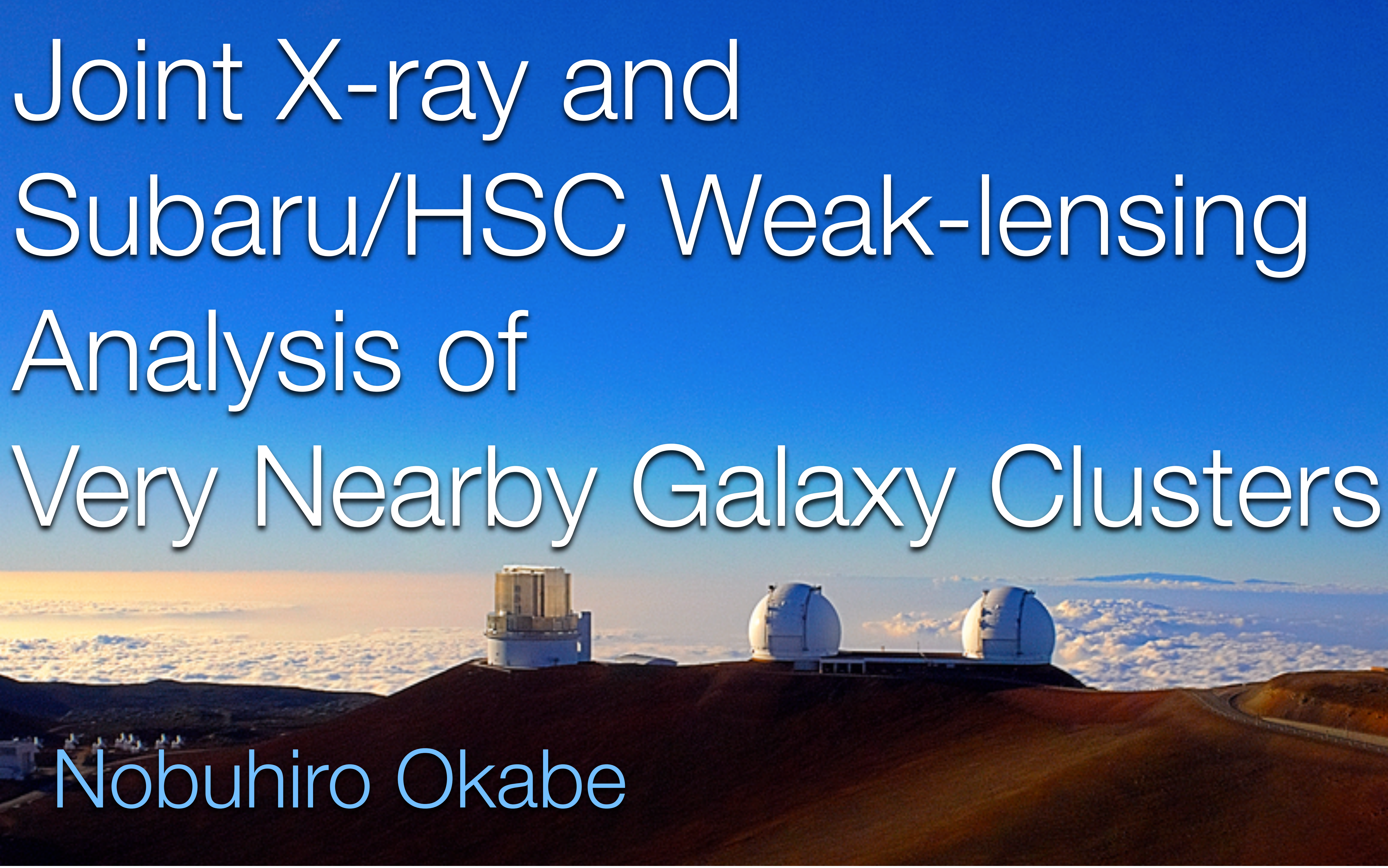
Joint X-ray and Subaru/HSC Weak-lensing Analysis of Very Nearby Galaxy Clusters



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CORE-U
Core of Research for the Energetic Universe
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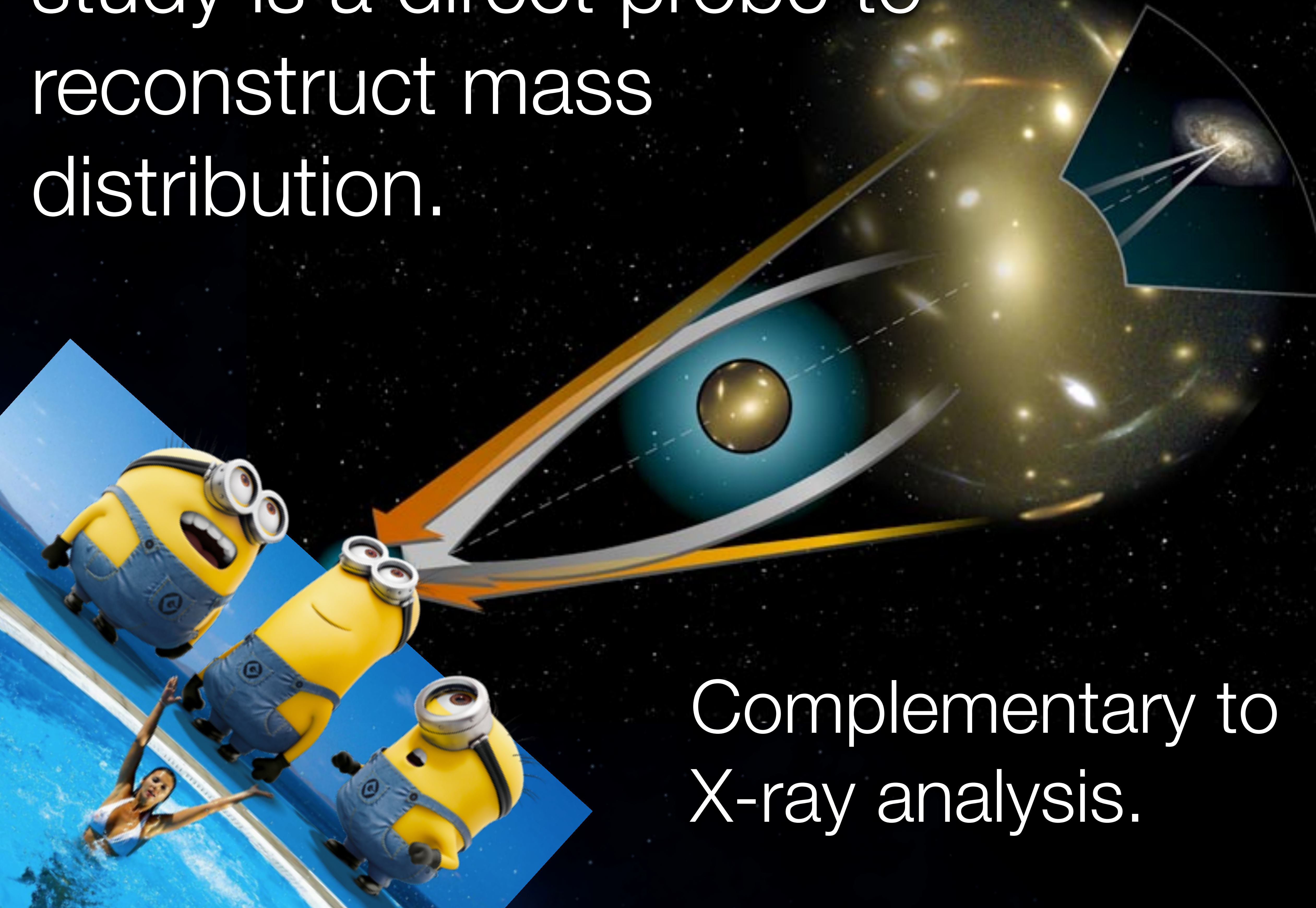
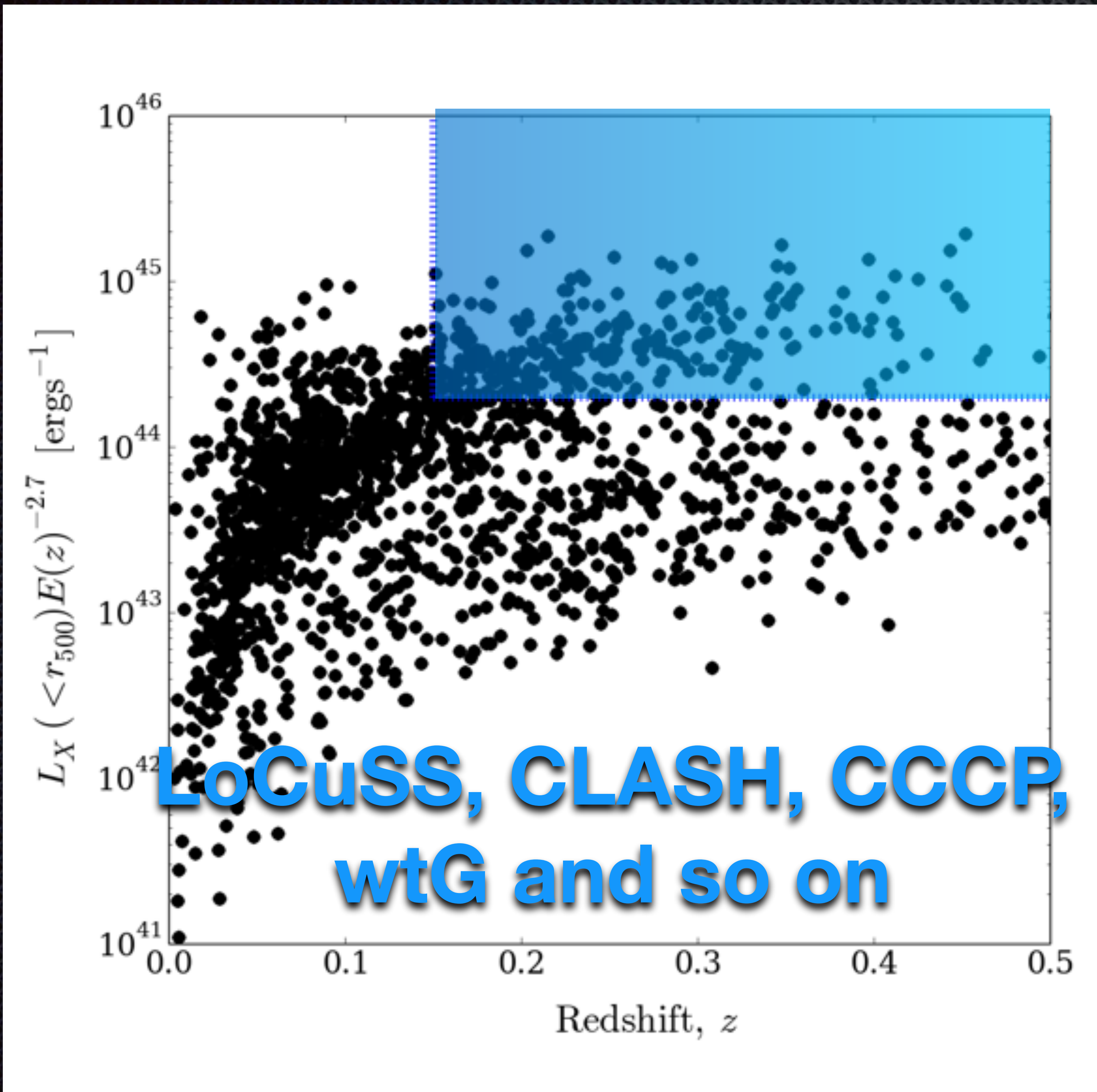
Weak-Gravitational lensing

study is a direct probe to reconstruct mass distribution.



Complementary to X-ray analysis.

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

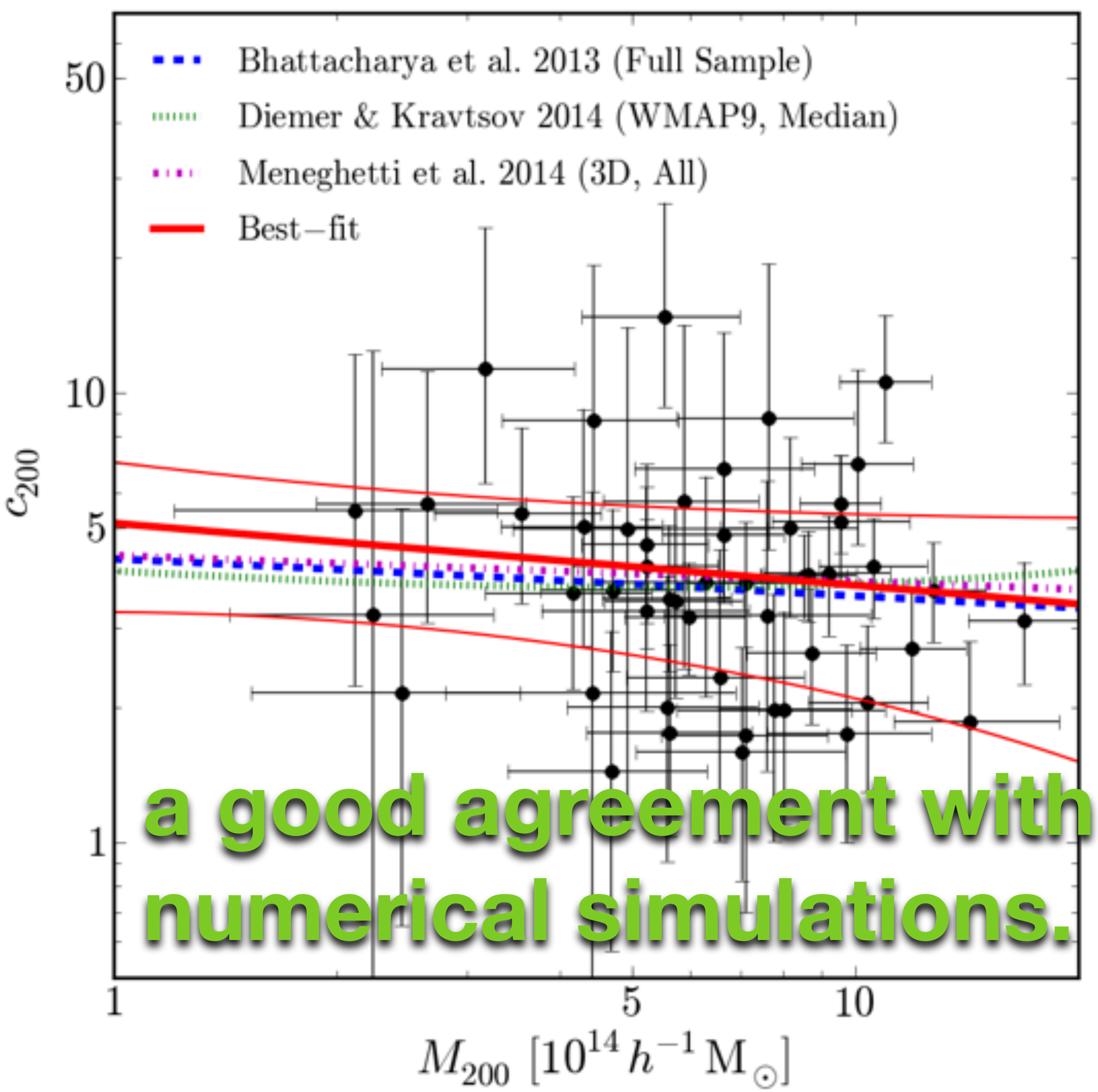
LoCuSS(0.15<z<0.3)

Okabe+Smith16

- secure background selection is primarily important.

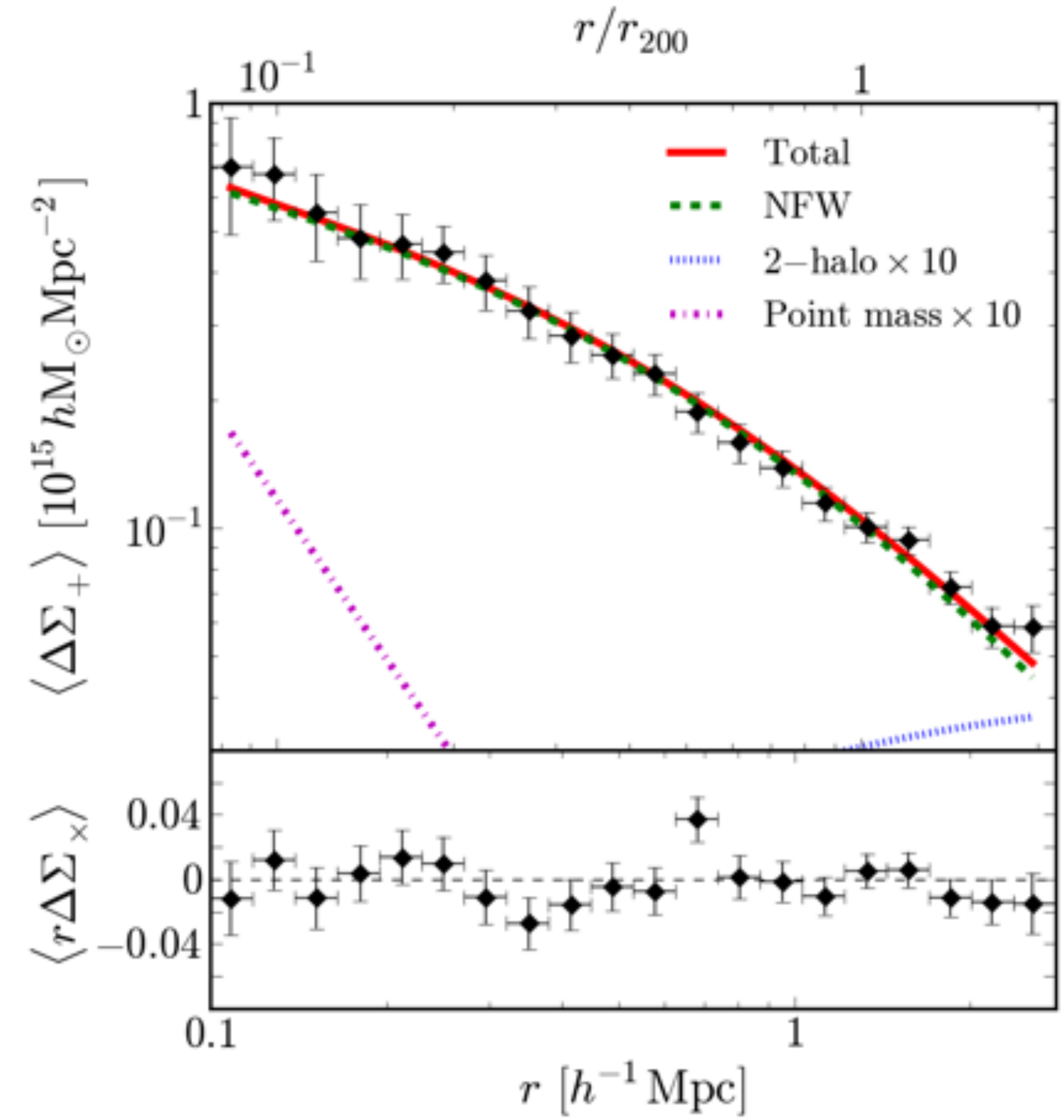
agree well with NFW/Einasto profiles.

mass-concentration relation



a good agreement with numerical simulations.

stacked lensing profile



Next Decade :
Hyper Suprime-Cam (HSC)

FoV : 7 times larger

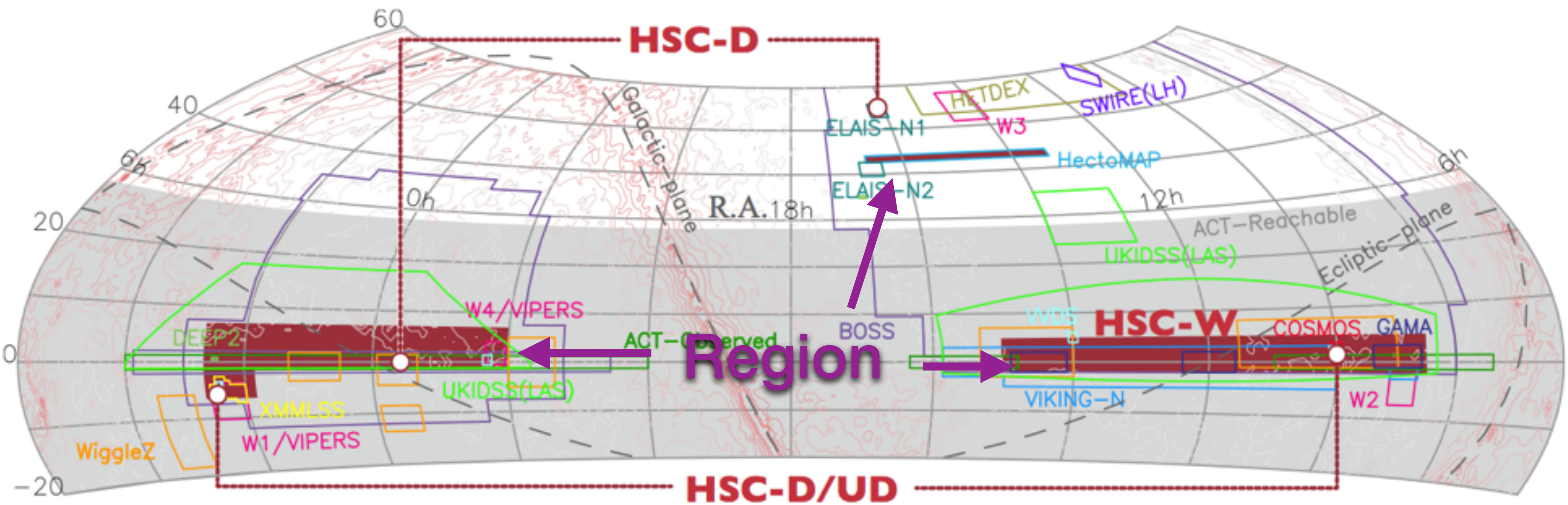
Full moon

Suprime-Cam
Image Release
September 2001

Hyper Suprime-Cam
Image Release
July 2013

(Credit: HSC Project / NAOJ)

HSC Survey



1400sqdeg grizy bands

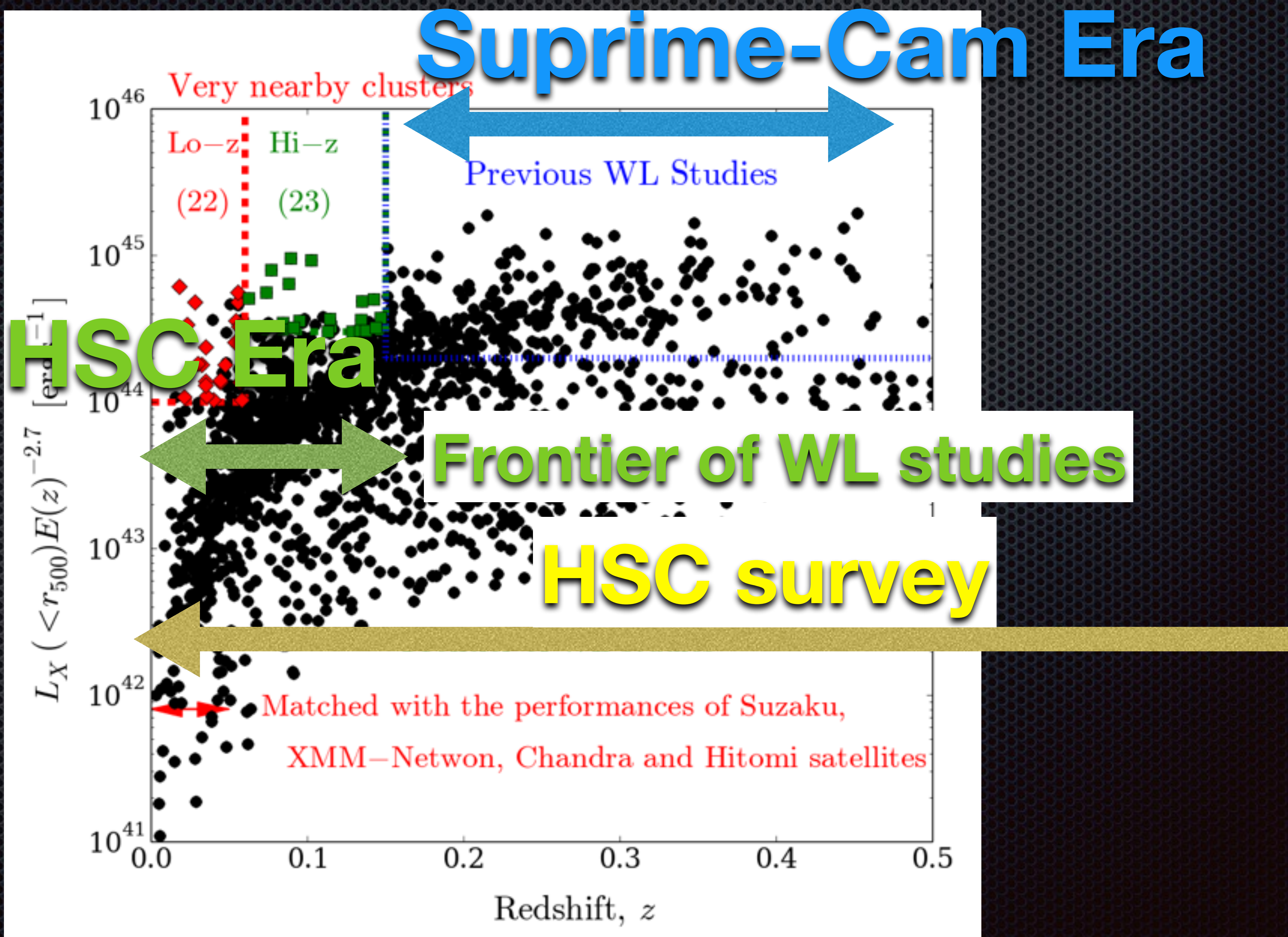
Japan + Taiwan + Prinston Univ. collaboration.

Dark matter distribution up to z~1.

> 10,000 clusters and groups

Will unveil an average mass profile of galaxy clusters and its evolution with high accuracy.

HSC is the best interment for clusters at z < ~ 0.1



NECSUS

low-z sample :
22 clusters at z < 0.06

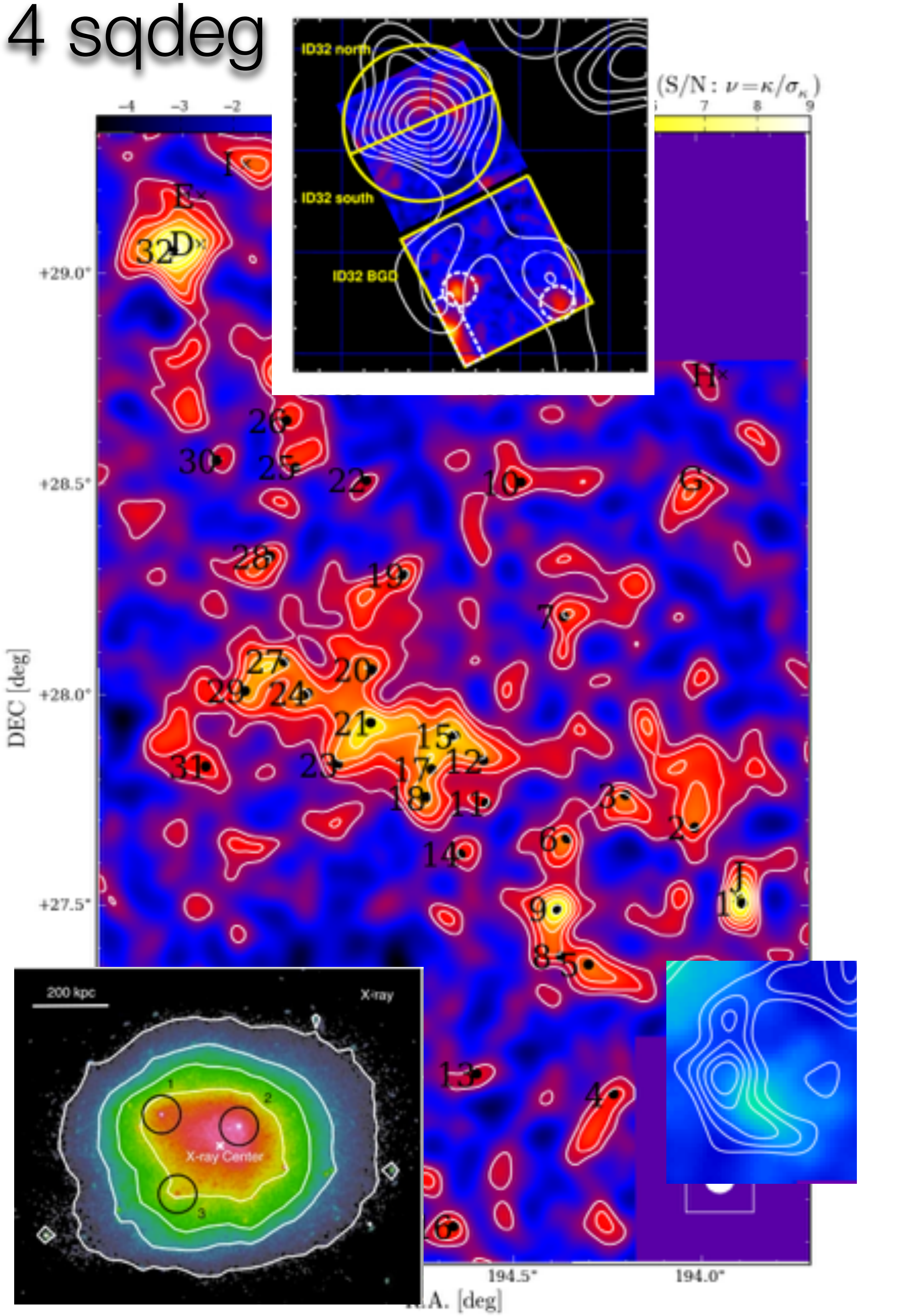
NEarby Cluster SUrvey with Subaru

Advantages of WL analysis for very nearby clusters

- no (less) contamination of member galaxies
  (contamination is a critical issue at z~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~0.2)
- large apparent size resolve less massive subhalos.
  (down to ~ 5×10^{12}-10^{13} Msun)
  (massive subhalos in meting clusters at z~0.2)

The pilot study : the Coma cluster (Okabe+14a) w/ Suprime-cam

4 sqdeg

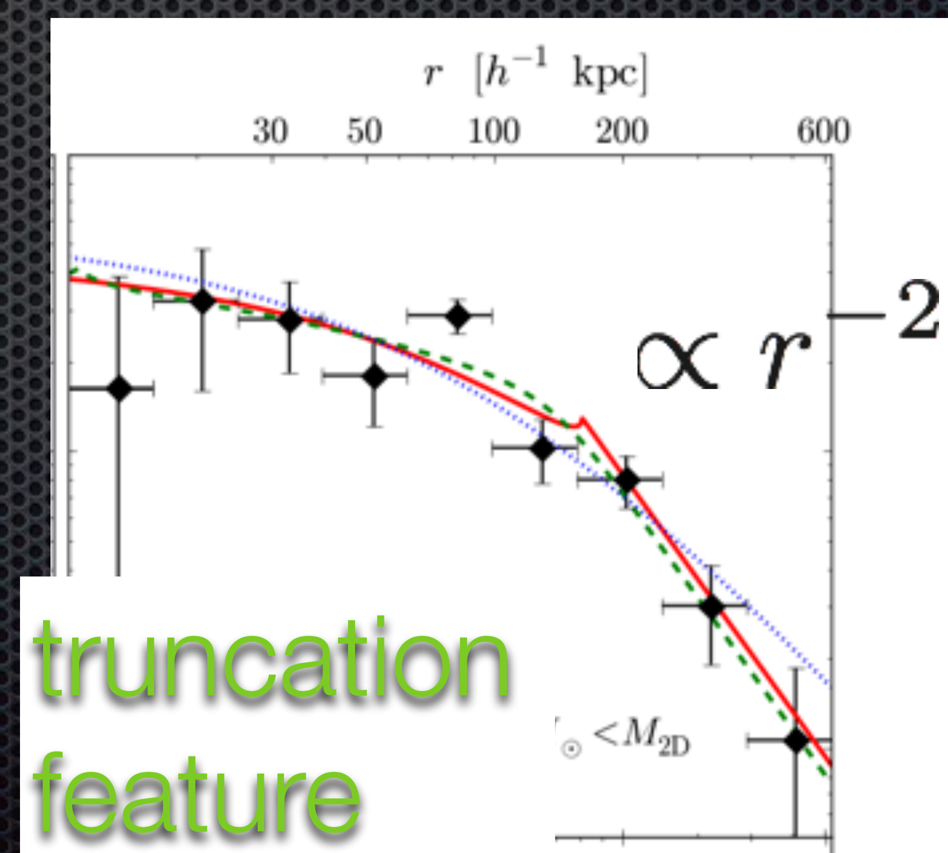


32 subhalos are detected.

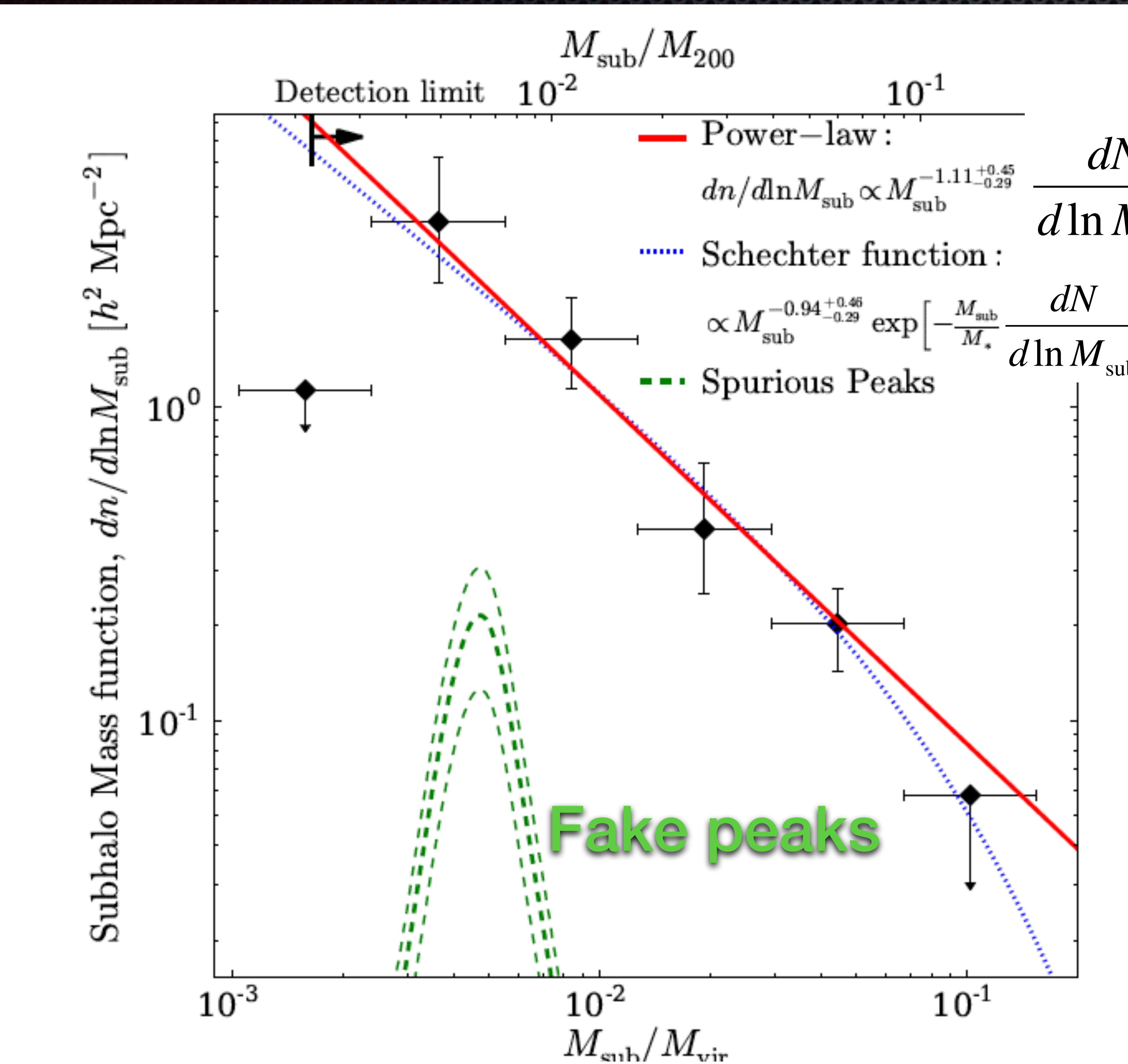
- associated with known optical groups

- X-ray groups for some subhalos

Stacked lensing profile



Subhalo mass function



$$\frac{dN}{d\ln M_{sub}} \propto \left(\frac{M_{sub}}{M_{vir}}\right)^{-1.11^{+0.45}_{-0.29}}$$

$$\frac{dN}{d\ln M_{sub}} \propto \left(\frac{M_{sub}}{M_{vir}}\right)^{-0.94^{+0.46}_{-0.29}} \mathrm{Exp}\left[-\frac{M_{sub}}{M_*}\right]$$

Consistent with CDM predictions : slope ~0.9-1

Two orders of the magnitude in mass

the Perseus Cluster z=0.0178

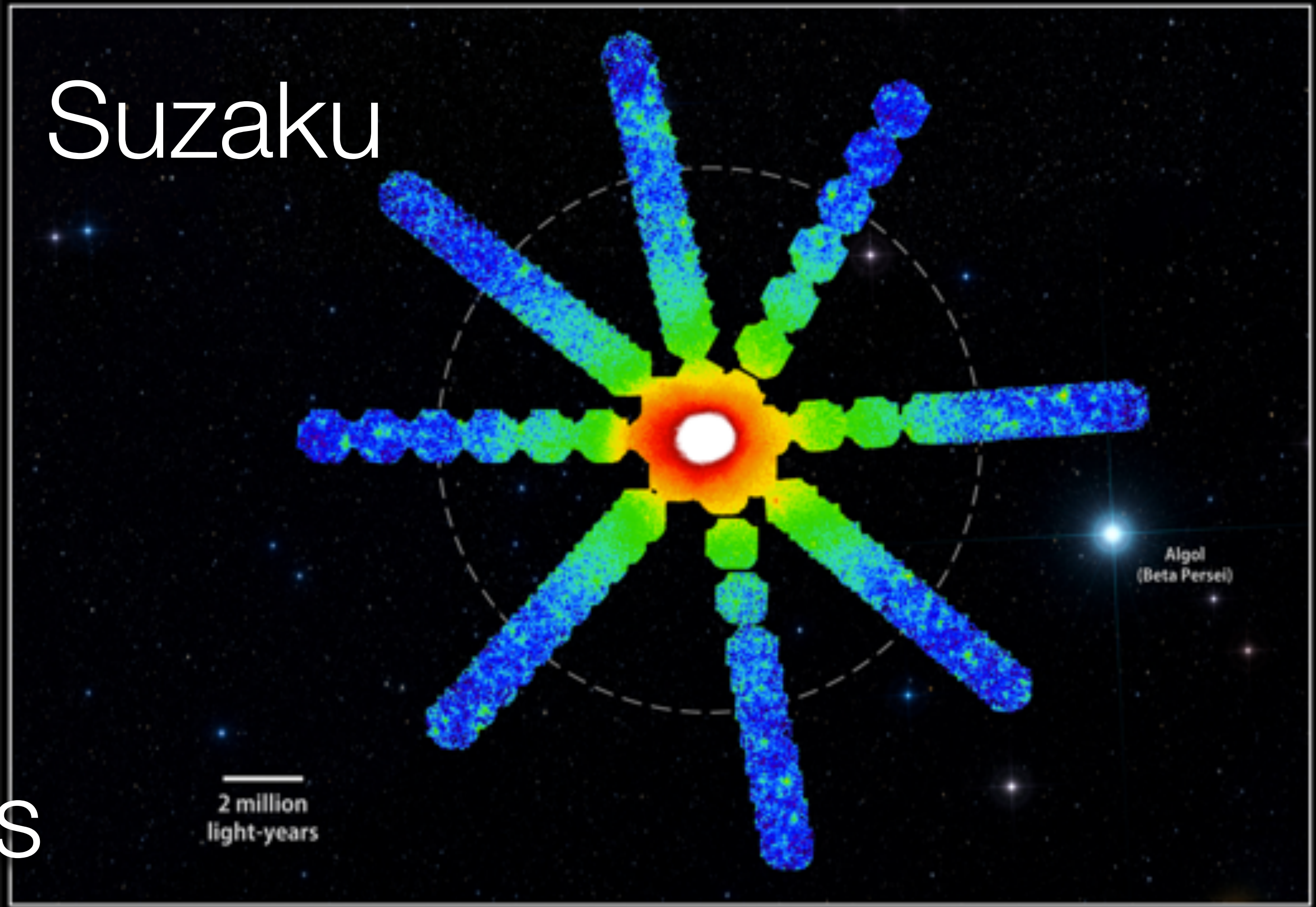
the core region

Chandra

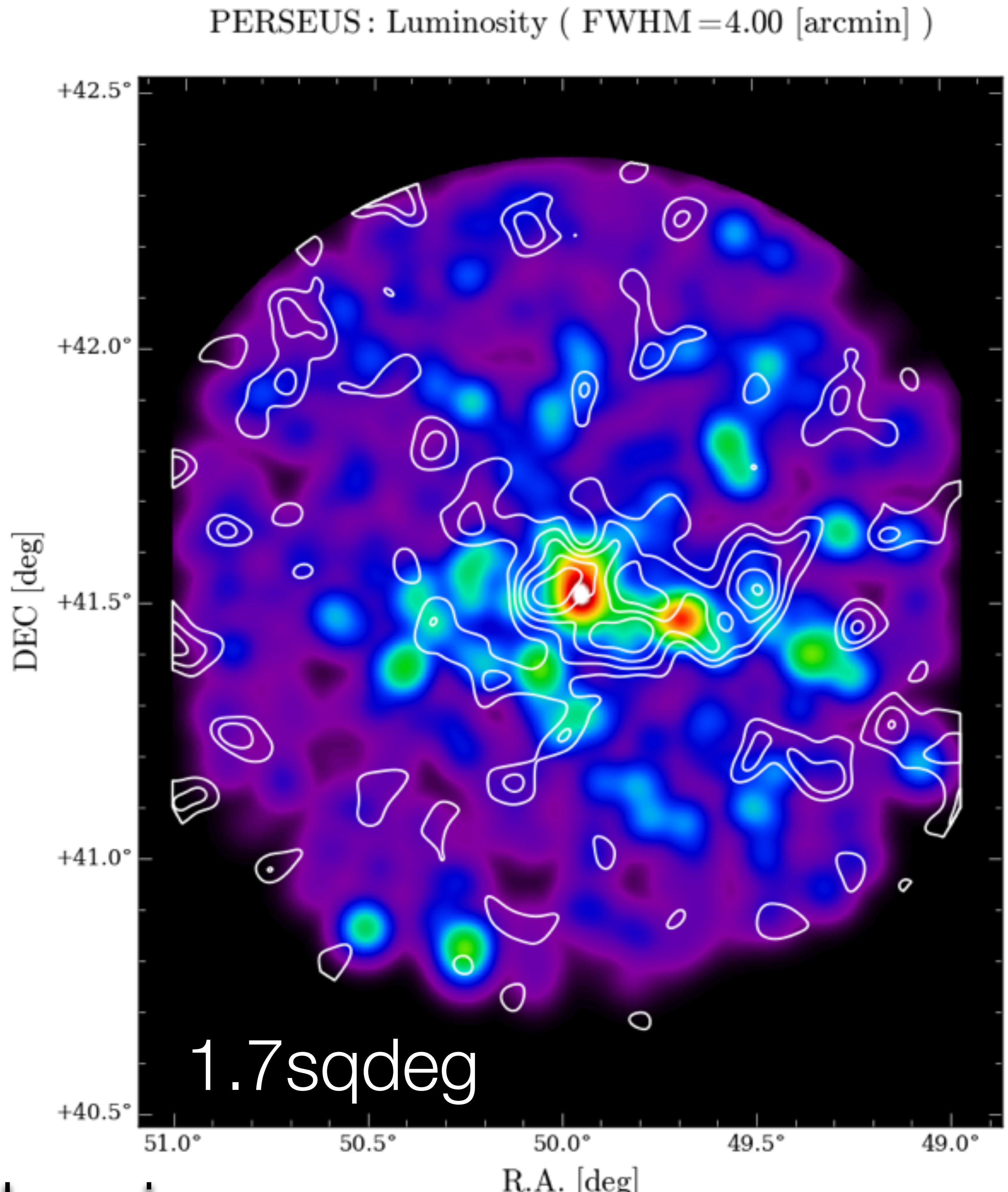
One of primary target of cluster sciences.

Hitomi's target to measure gas motions.

Suzaku

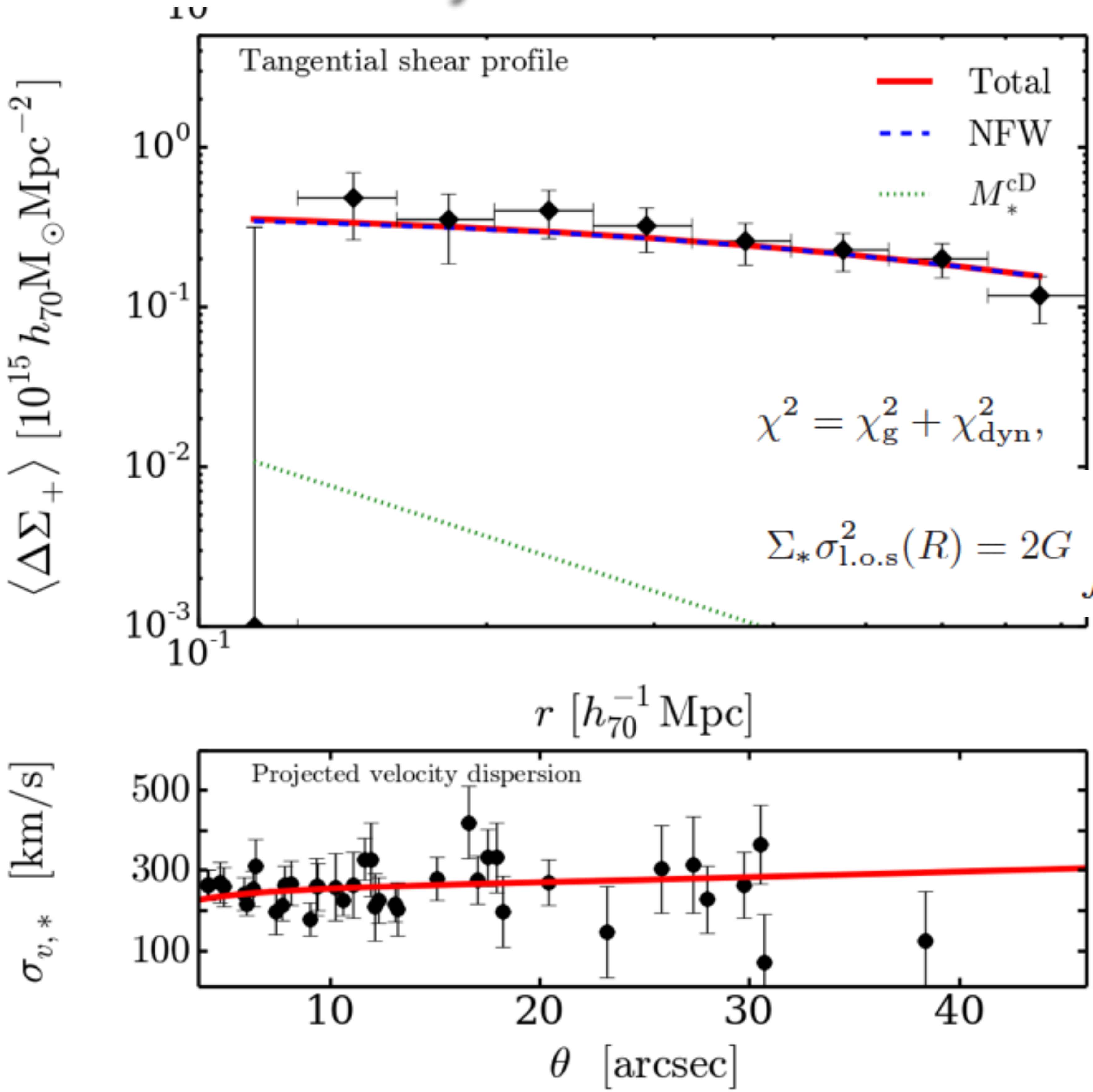


outskirts



Okabe+ in prep

Joint constraints by WL and BCG stellar kinematics



$$\chi^2 = \chi^2_{\mathrm{g}} + \chi^2_{\mathrm{dyn}},$$

$$\Sigma_* \sigma^2_{\mathrm{l.o.s}}(R) = 2G \int_R^\infty \frac{\nu_*(r) M(r) F(r)}{r^{2-2\beta}} dr$$

Joint X-ray and HSC-WL analysis

1: Indirect Constraint of Non-thermal Pressure

2: Suzaku Cluster Outskirts Problem

Total Pressure derived from WL Mass v.s. Thermal Pressure

total pressure

$$\frac{1}{\rho_g}\frac{dP_g}{dr} = -\frac{GM}{r^2},$$

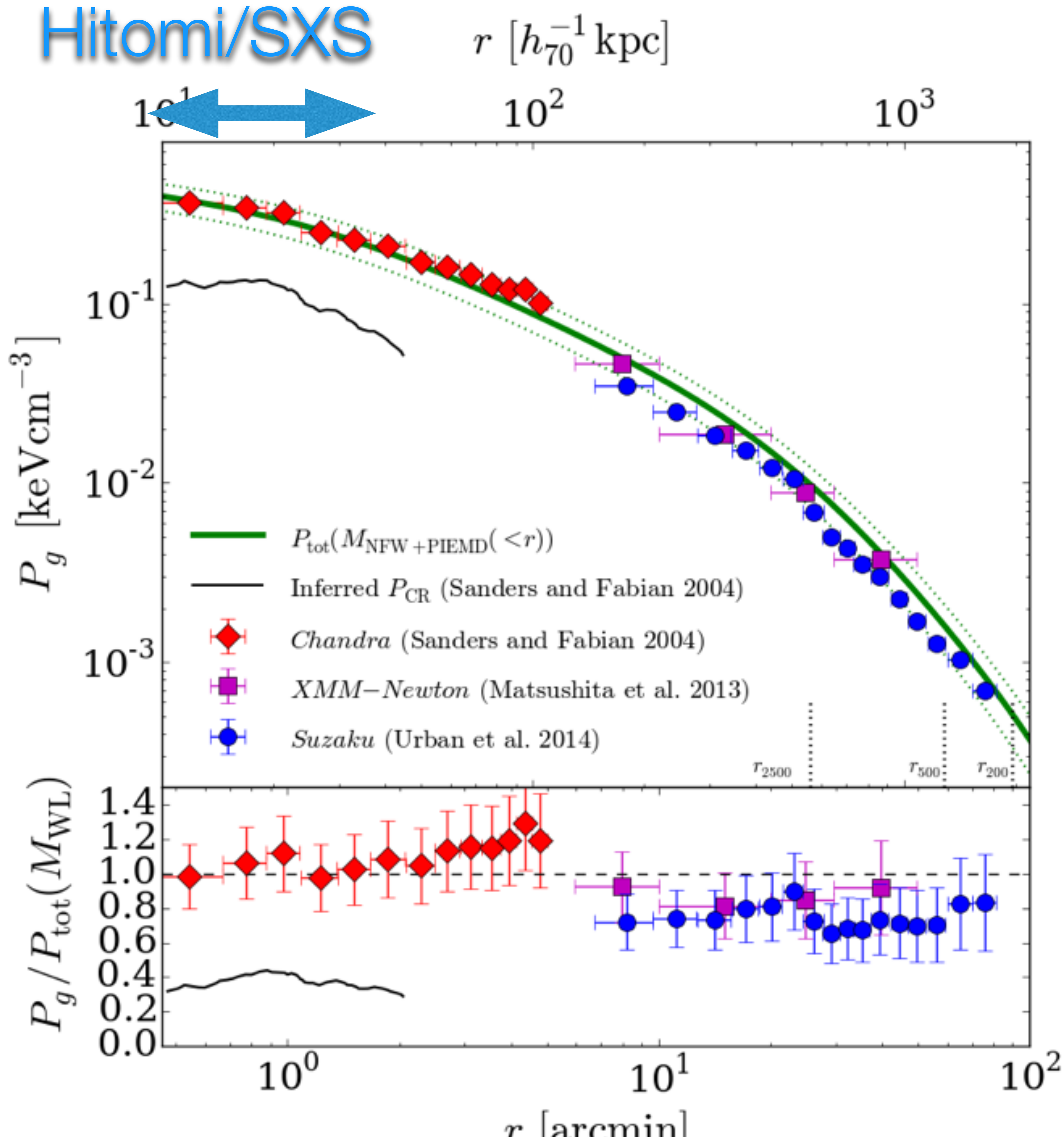
X-ray

WL

WL mass does not assume dynamical states.

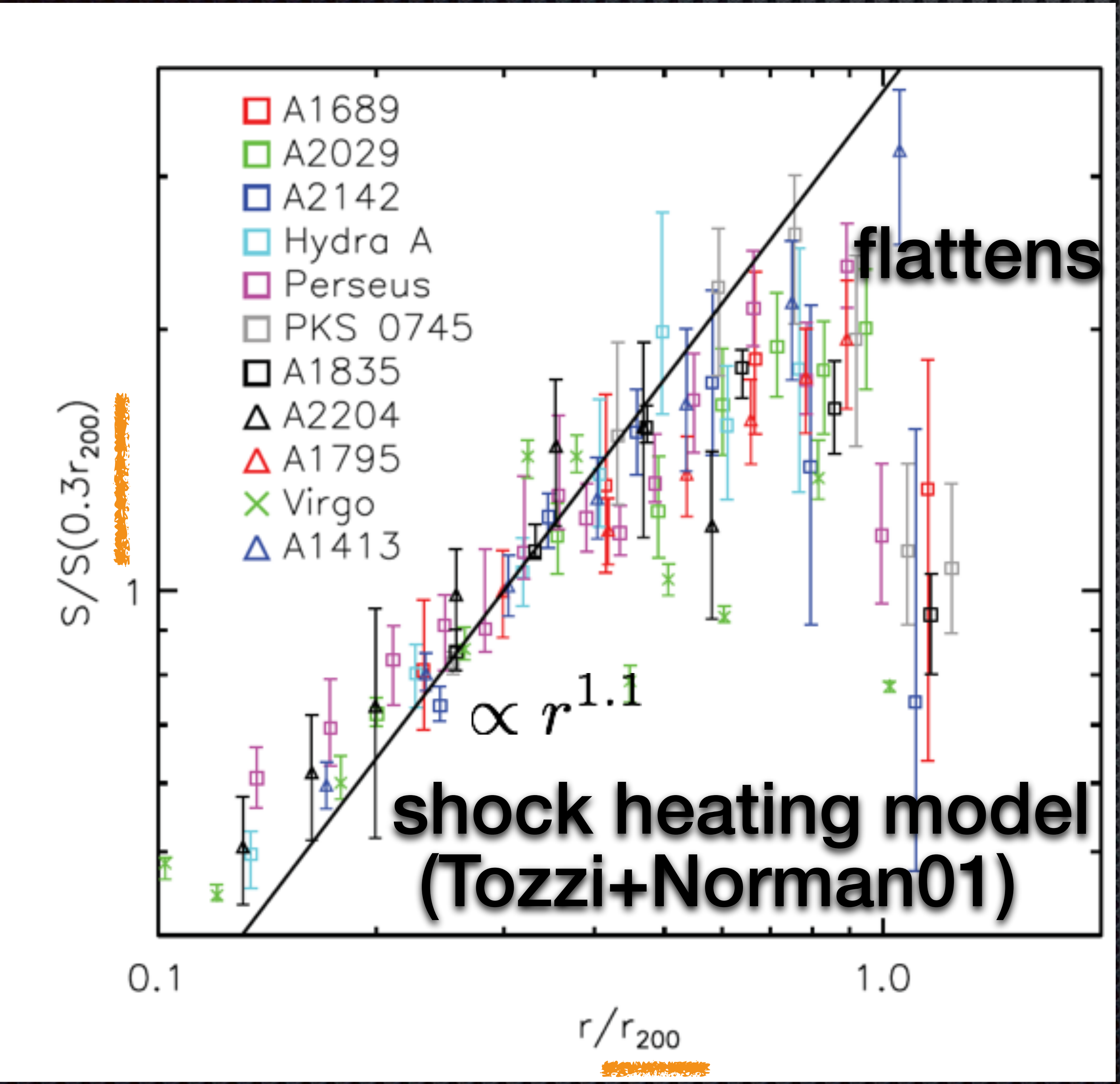
A comparison of total pressure and thermal pressure enables us to conduct a “indirect” test of the validity of hydrostatic assumption.

Hitomi/SXS : direct observation of non thermal pressure.



Non-thermal pressure at small radii is negligible.

Outskirts Entropy Problem



Walker+2012

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

Possible interpretations

- Temperature drops

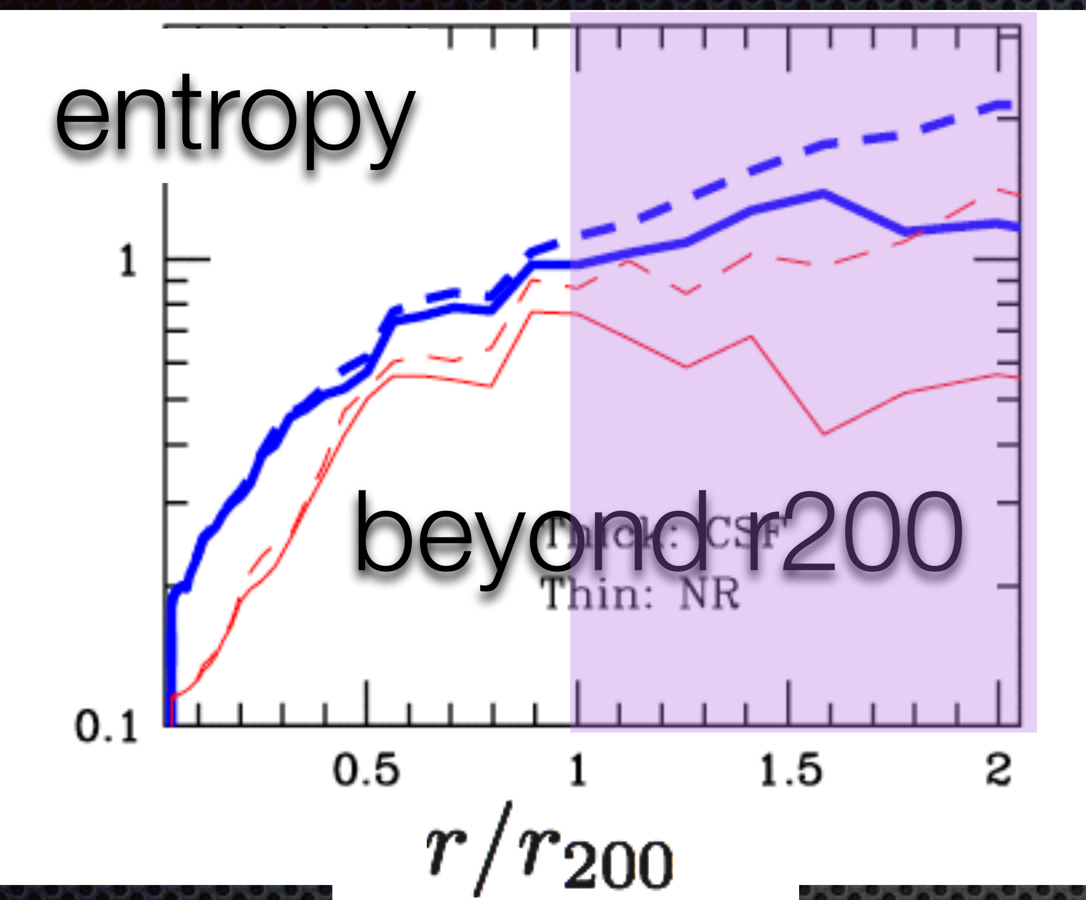
  Non-thermal pressure (Kawaharada+10, Sato+12, Ichikawa+13, Okabe+14c)

- Number density excess

  Overestimated by gas clumpiness (Nagai+Lau11, Simionescu+11, Urban+14)

Clumpiness interpretation

Nagai+Lau 11



[sim]

- Entropy flatting is found beyond r200.

Observations are within r200.

[sim]

- Clumpiness within r200 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

Okabe+14c

X-ray WL

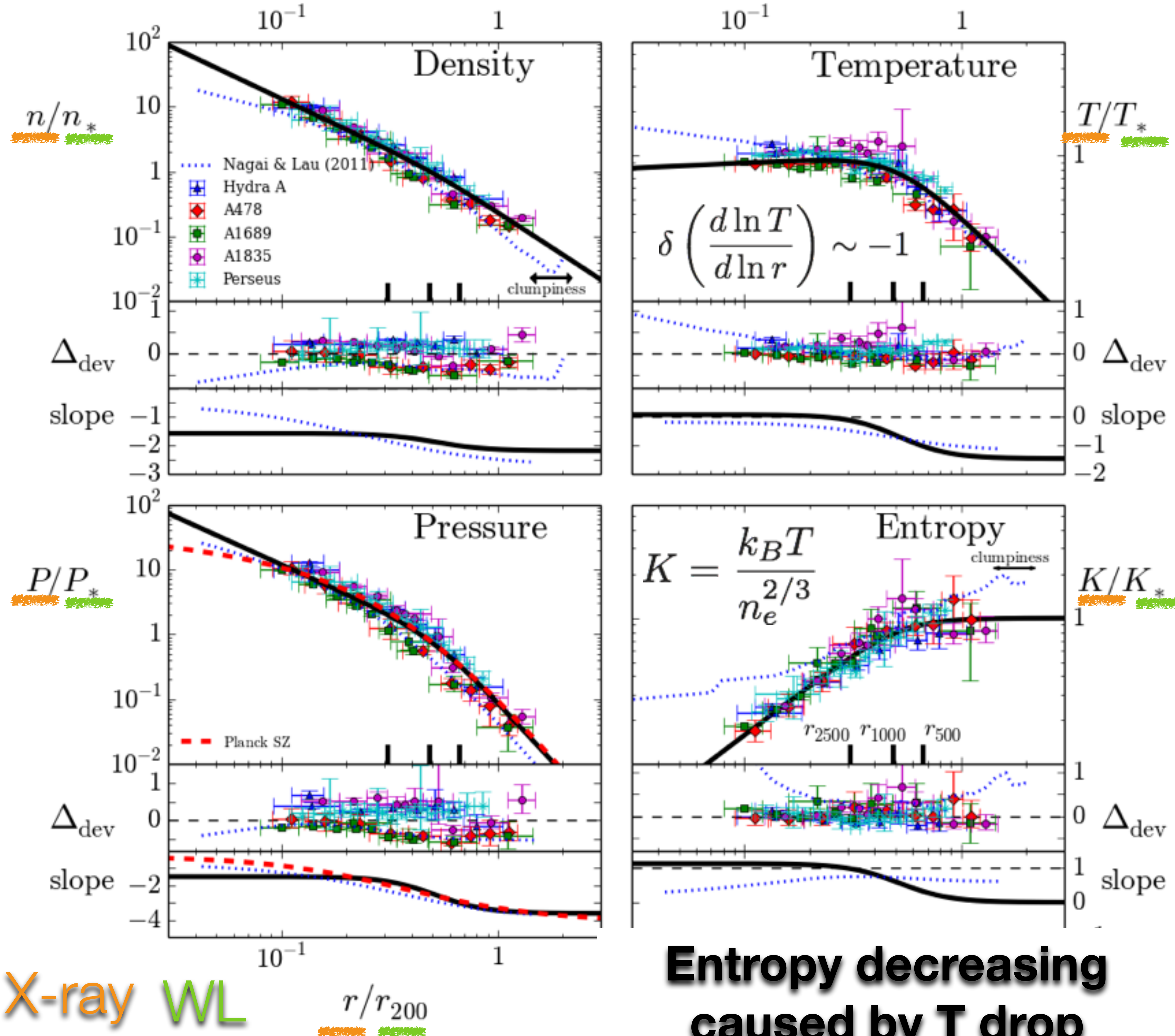
$$f_n(\tilde{r} = r/r_\Delta) = n_0 E(z)^2 \left(\frac{M_\Delta E(z)}{10^{14}\ h_{70}^{-1} M_\odot}\right)^a \left(\frac{\tilde{r}}{\tilde{r_0}}\right)^{-\alpha} \left(1 + \left(\frac{\tilde{r}}{\tilde{r_0}}\right)^\beta\right)^{-\gamma/\beta} \quad (10)$$

$$f_T(\tilde{r} = r/r_\Delta) = T_0 \left(\frac{M_\Delta E(z)}{10^{14}\ h_{70}^{-1} M_\odot}\right)^b \left(\frac{\tilde{r}}{\tilde{r_0}}\right)^{-\delta} \left(1 + \left(\frac{\tilde{r}}{\tilde{r_0}}\right)^\beta\right)^{-\eta/\beta} \quad (11)$$

$$-2\ln\mathcal{L} = \sum_{i,j} \ln(\det(\boldsymbol{C}_{ij})) + \boldsymbol{v}_{ij}^T \boldsymbol{C}_{ij}^{-1} \boldsymbol{v}_{ij},$$

$$\boldsymbol{v} = \begin{pmatrix} \ln(n(\tilde{r})) - \ln(f_n(M_\Delta, \tilde{r})) \\ \ln(T(\tilde{r})) - \ln(f_T(M_\Delta, \tilde{r})) \end{pmatrix},$$

$$\boldsymbol{C} = \boldsymbol{C}_{\rm stat} + \boldsymbol{C}_{\rm int}$$



Entropy decreasing caused by T drop

Summary

- New project for very nearby clusters using Subaru/HSC is launched.
- Indirect constraint of non-thermal pressure suggests that Hitomi/SXS observation will not significantly detect non-thermal pressure component.
- 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.

$$T_{3D}(r) = T_0 \frac{\left(\frac{r}{r_{cool}}\right)^{a_c} + \frac{T_{min}}{T_0}}{1 + \left(\frac{r}{r_{cool}}\right)^{a_c}} \frac{\left(\frac{r}{r_t}\right)^{-a}}{\left[1 + \left(\frac{r}{r_t}\right)^b\right]^{c/b}}.$$

Urban+14

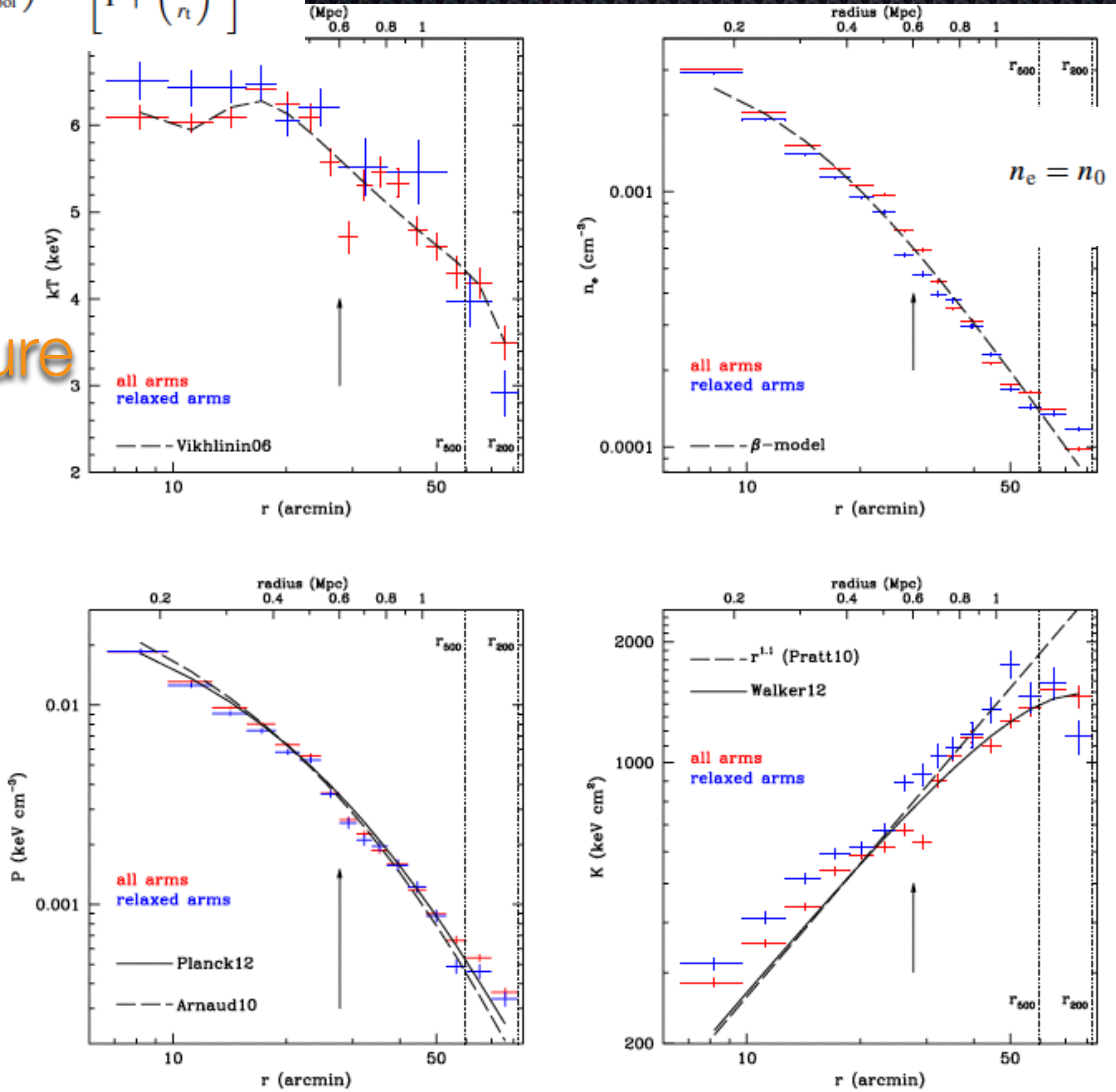
$$n_e = n_0 \left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-3\beta/2}.$$

Temperature

Density

Pressure

Entropy



Deviations from Expectations

Urban+14

$$kT^{\text{expected}}(r) = P(r)^{2/5} K(r)^{3/5},$$

$$n_e^{\text{expected}}(r) = P(r)^{3/5} K(r)^{-3/5}.$$

T/T_{exp} n/n_{exp}

$$\frac{P(r)}{P_{500}} = \frac{P_0}{(c_{500}x)^\gamma \left[1 + (c_{500}x)^\alpha\right]^{(\beta-\gamma)/\alpha}},$$

Arnaud+10 :
XMM observations

$$\frac{K}{K_{500}} = 1.47 \left(\frac{r}{r_{500}}\right)^{1.1},$$

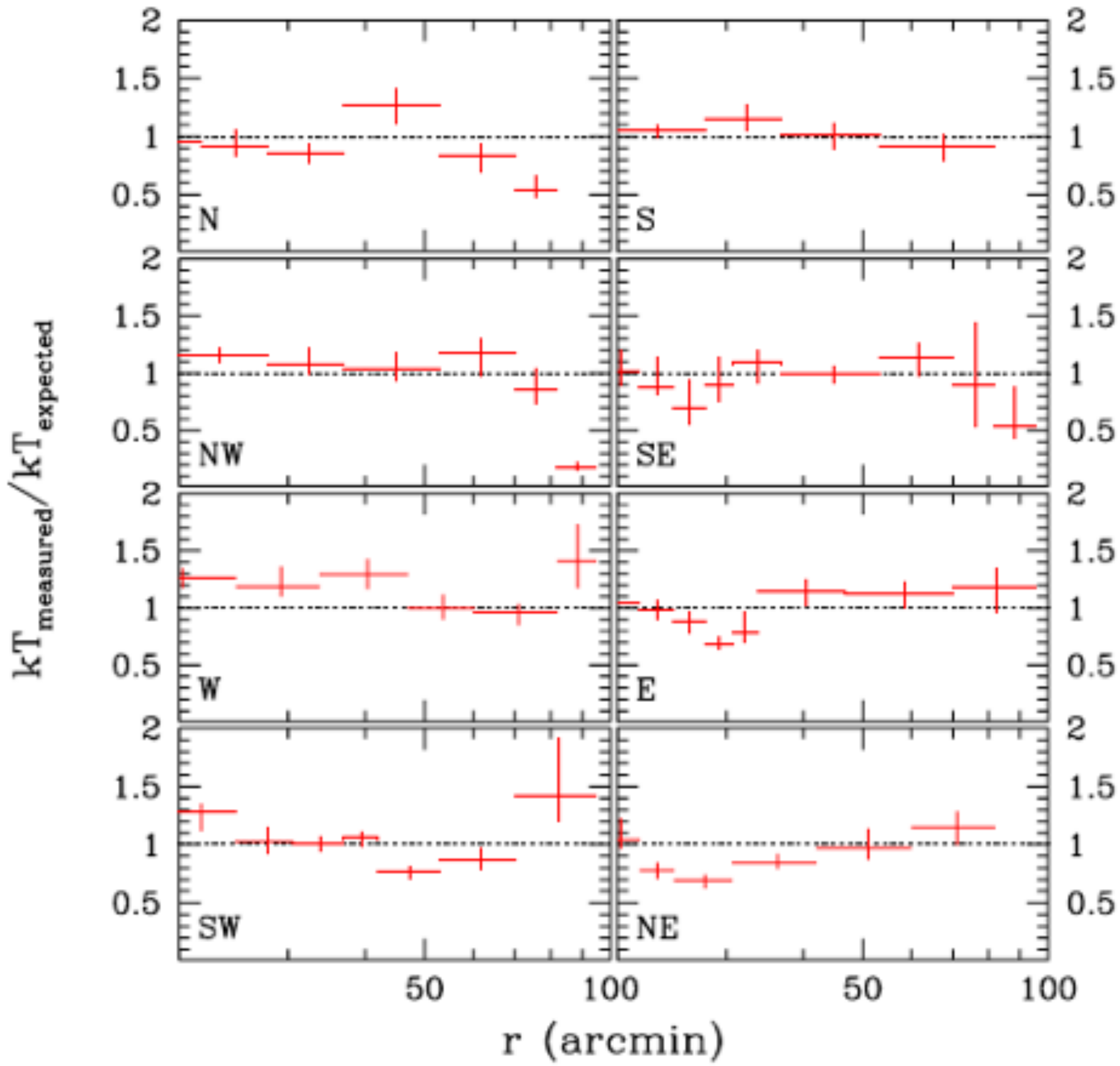
Voit+05
Numerical simulations

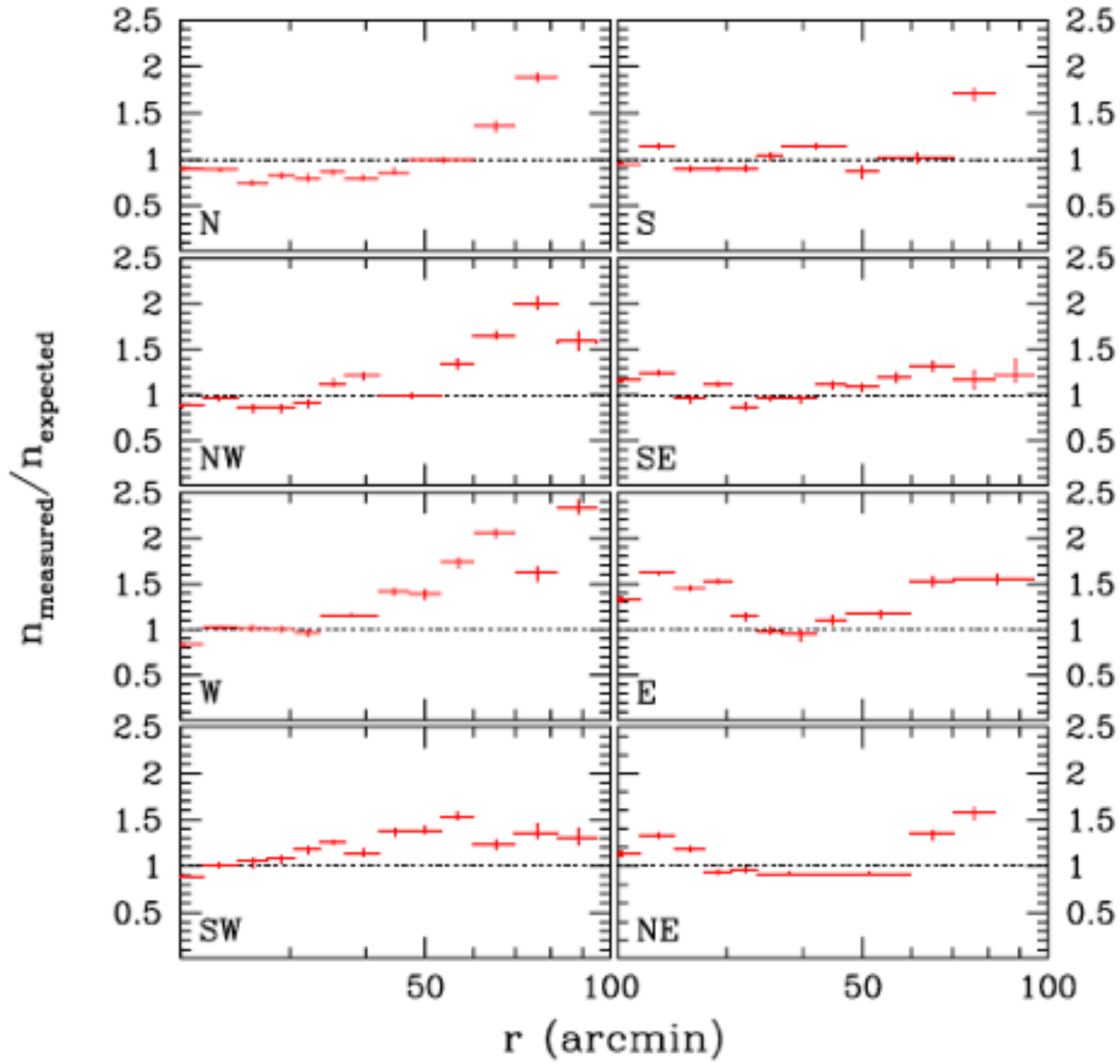
- They adopted inconsistent base-lines for Pressure and Entropy profiles.
- They are also different from Nagai+Lau's functional form.

Baseline gives bias on their interoperation.

Temperature

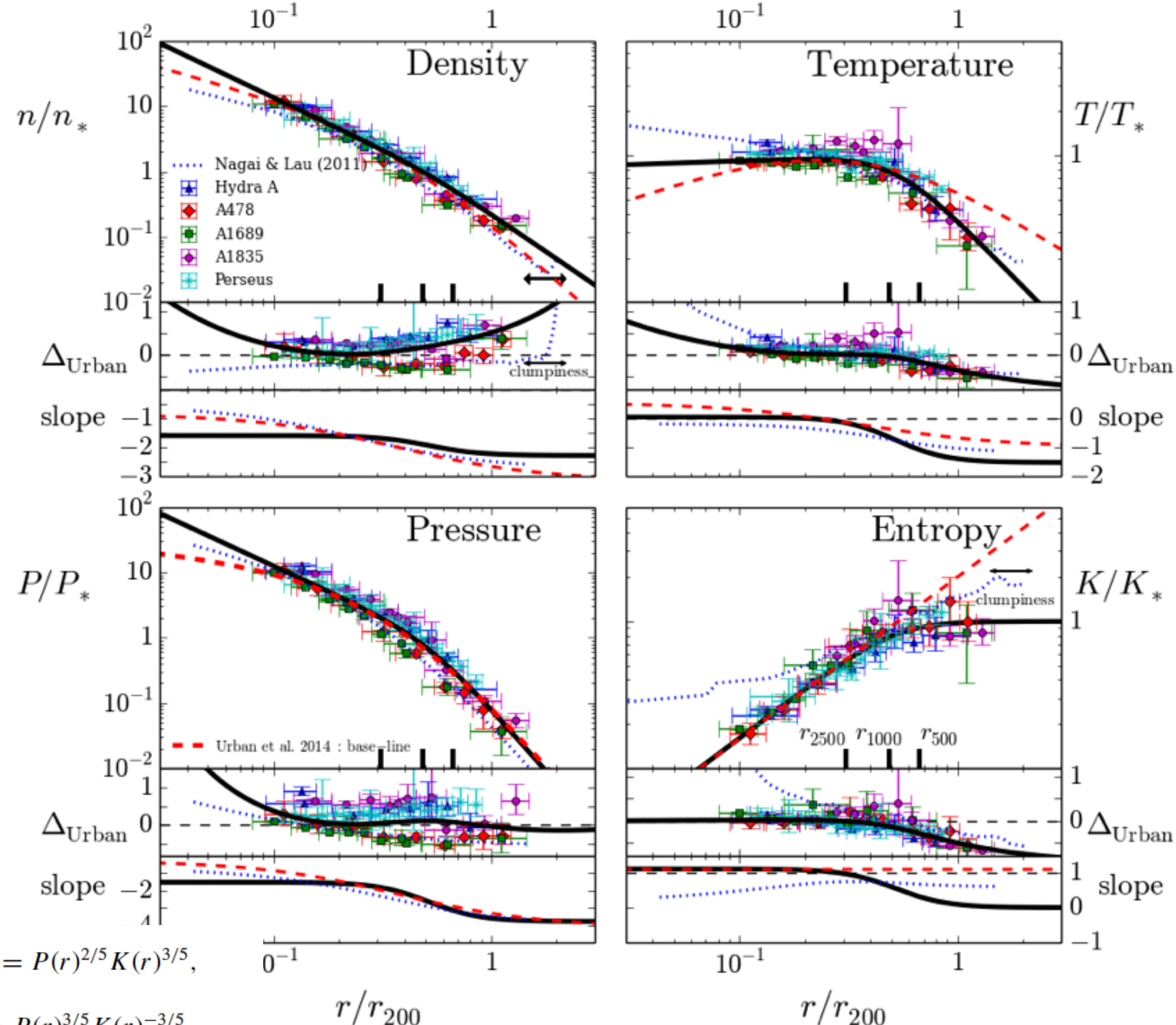
Density





Entropy flattning is caused by density excess

Urban+14



$$kT^{\rm expected}(r) = P(r)^{2/5} K(r)^{3/5},$$

$$n_{\rm e}^{\rm expected}(r) = P(r)^{3/5} K(r)^{-3/5}.$$

Nagai+Lau withdrew their original idea

arXiv:1605.01723

STIRRED, NOT CLUMPED: EVOLUTION OF TEMPERATURE PROFILES IN THE OUTSKIRTS OF GALAXY CLUSTERS

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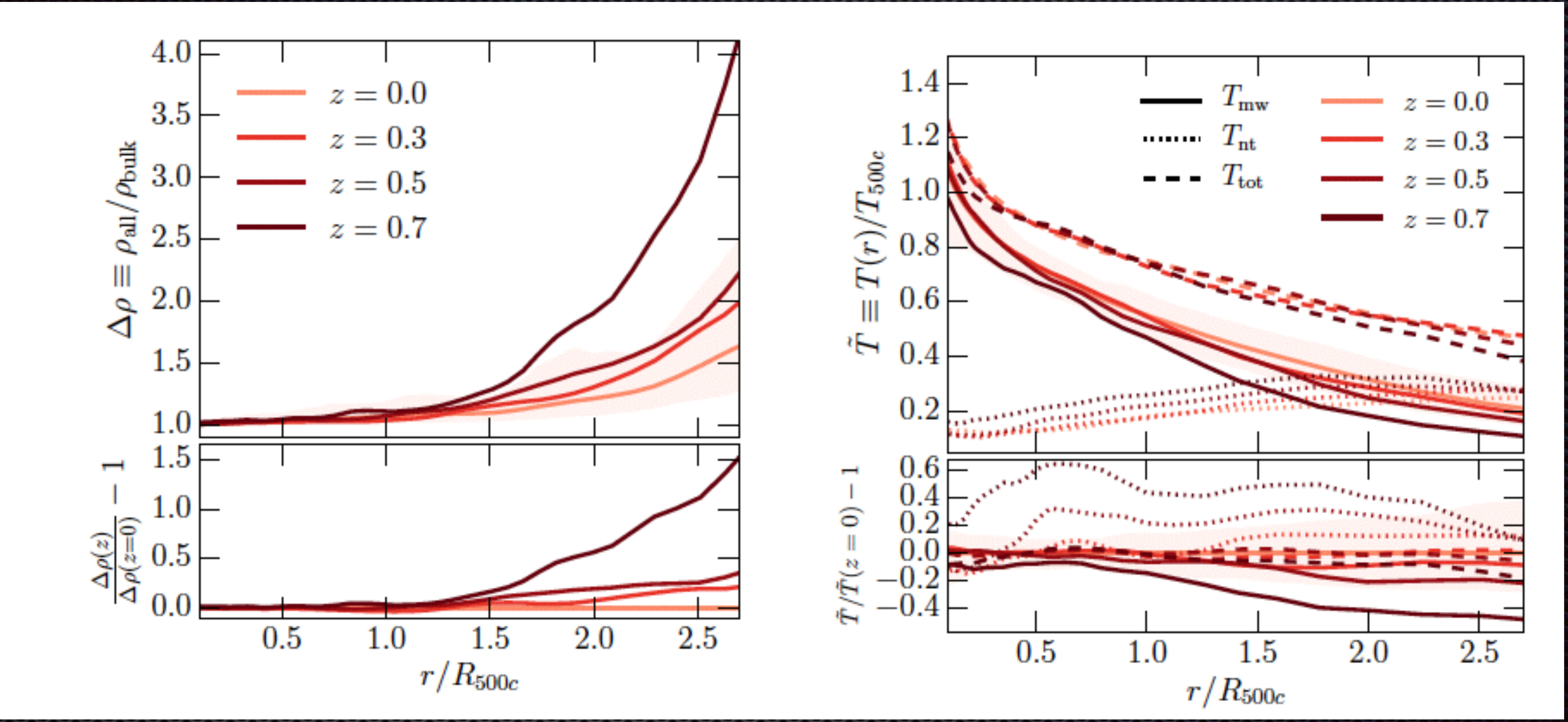
The Astrophysical Journal, submitted

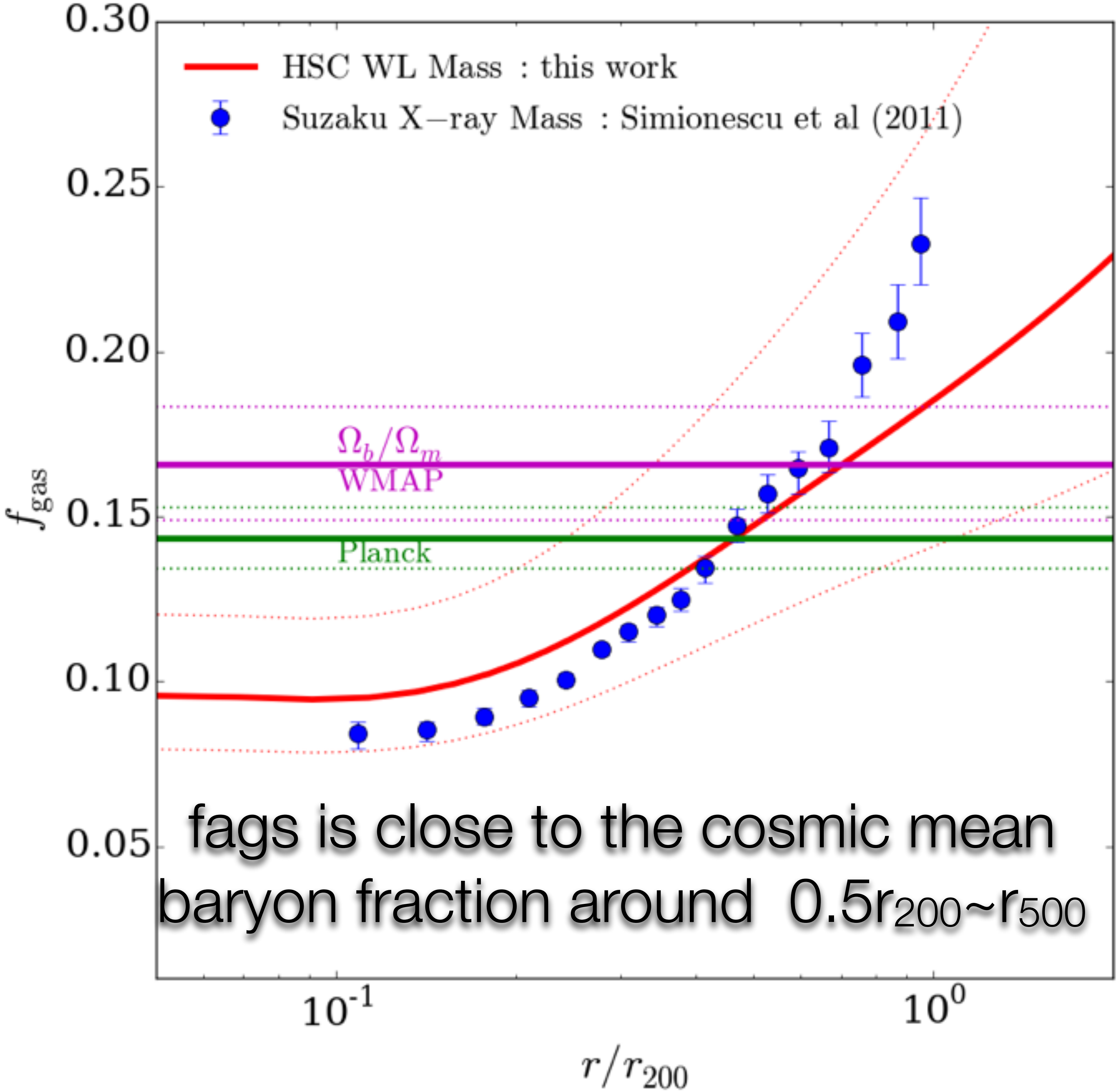
ABSTRACT

Recent statistical X-ray measurements of the intracluster medium (ICM) indicate that gas temperature profiles in the outskirts of galaxy clusters deviate from self-similar evolution. Using a mass-limited sample of galaxy clusters from cosmological hydrodynamical simulations, we show that the departure from self-similarity can be explained by non-thermal gas motions driven by mergers and accretion. Contrary to previous claims, gaseous substructures only play a minor role in the temperature evolution in cluster outskirts. A careful choice of halo overdensity definition in self-similar scaling mitigates these departures. Our work highlights the importance of non-thermal gas motions in ICM evolution and the use of galaxy clusters as cosmological probes.

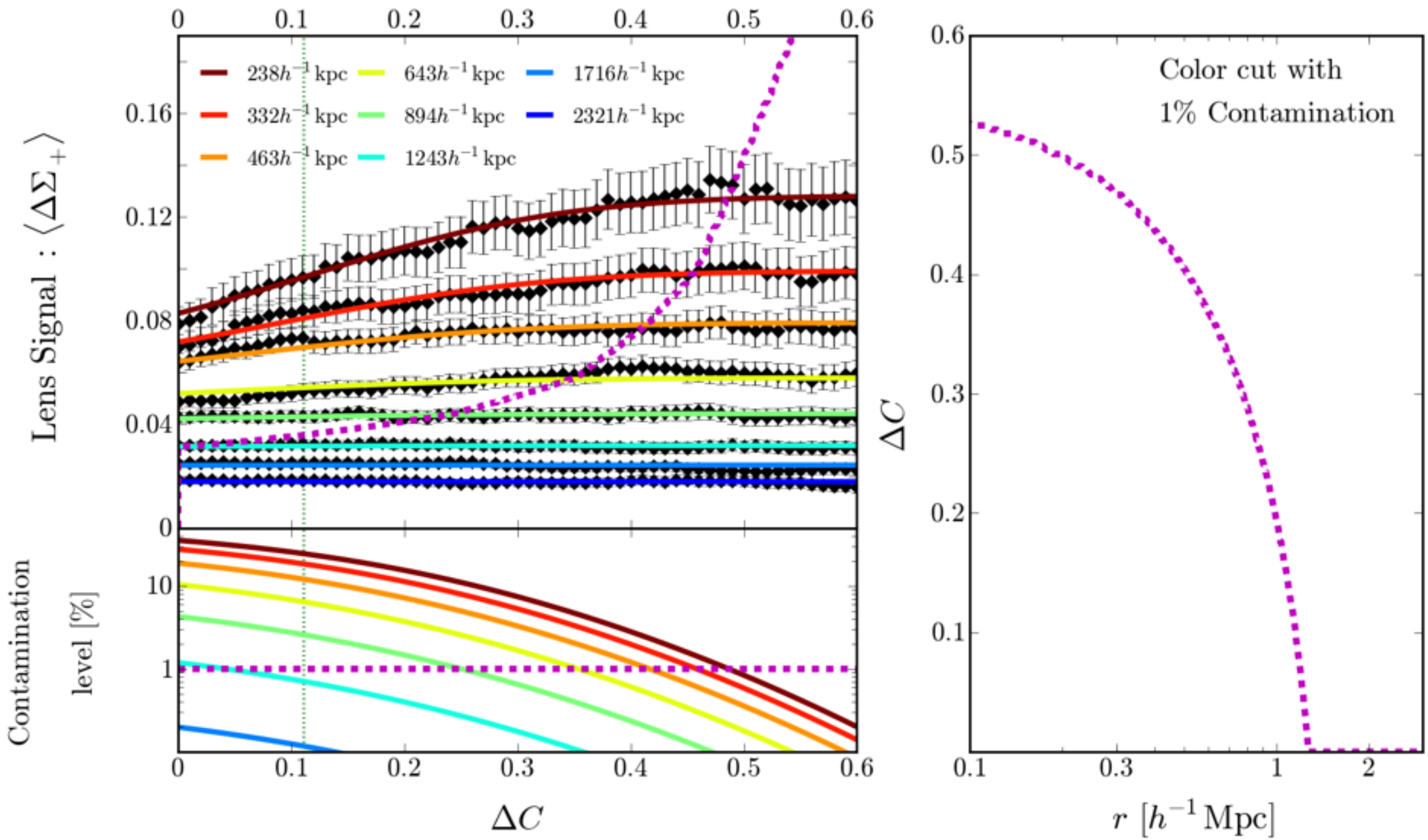
Subject headings: cosmology: theory — galaxies: clusters: general — galaxies: clusters : intracluster medium — methods : numerical — X-rays:galaxies:clusters



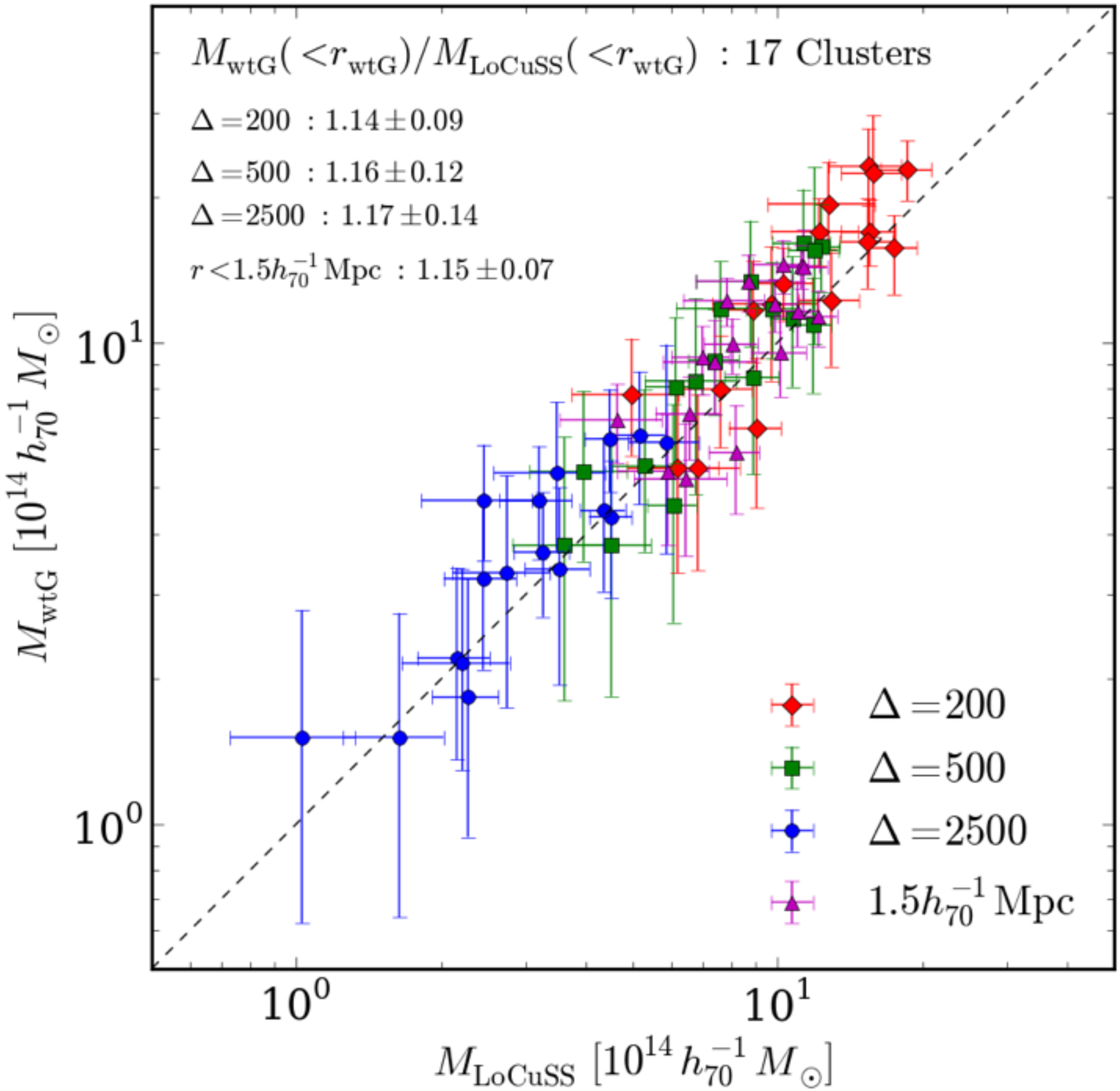
$\Delta\rho \equiv \rho_{\rm all}/\rho_{\rm bulk}$
$z = 0.0$
$z = 0.3$
$z = 0.5$
$z = 0.7$
$\frac{\Delta\rho(z)}{\Delta\rho(z=0)} - 1$
r/R_{500c}
$\tilde{T} \equiv T(r)/T_{500c}$
$T_{\rm mw}$
$T_{\rm nt}$
$T_{\rm tot}$
$\tilde{T}/\tilde{T}(z=0) - 1$

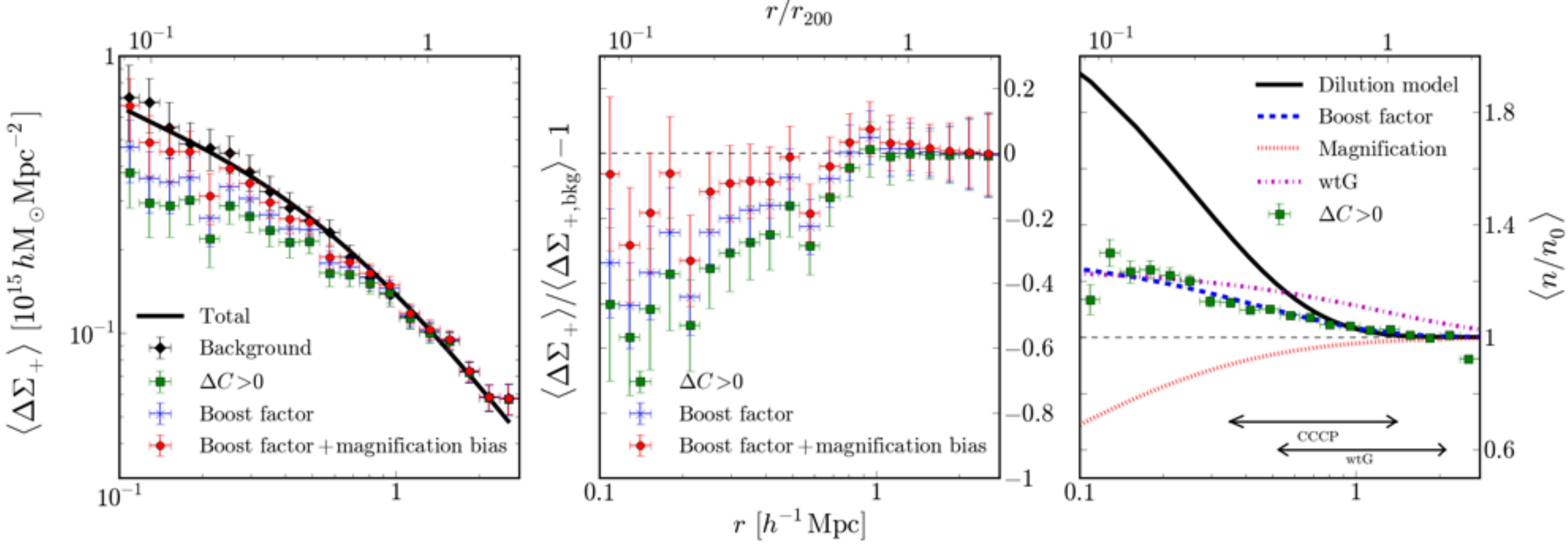


HSC WL Mass : this work
Suzaku X−ray Mass : Simionescu et al (2011)
Ω_b/Ω_m
WMAP
Planck
0.30
0.25
0.20
0.15
0.10
0.05
f_{gas}
10^{-1}
10^{0}
r/r_{200}
fags is close to the cosmic mean
baryon fraction around 0.5r200~r500

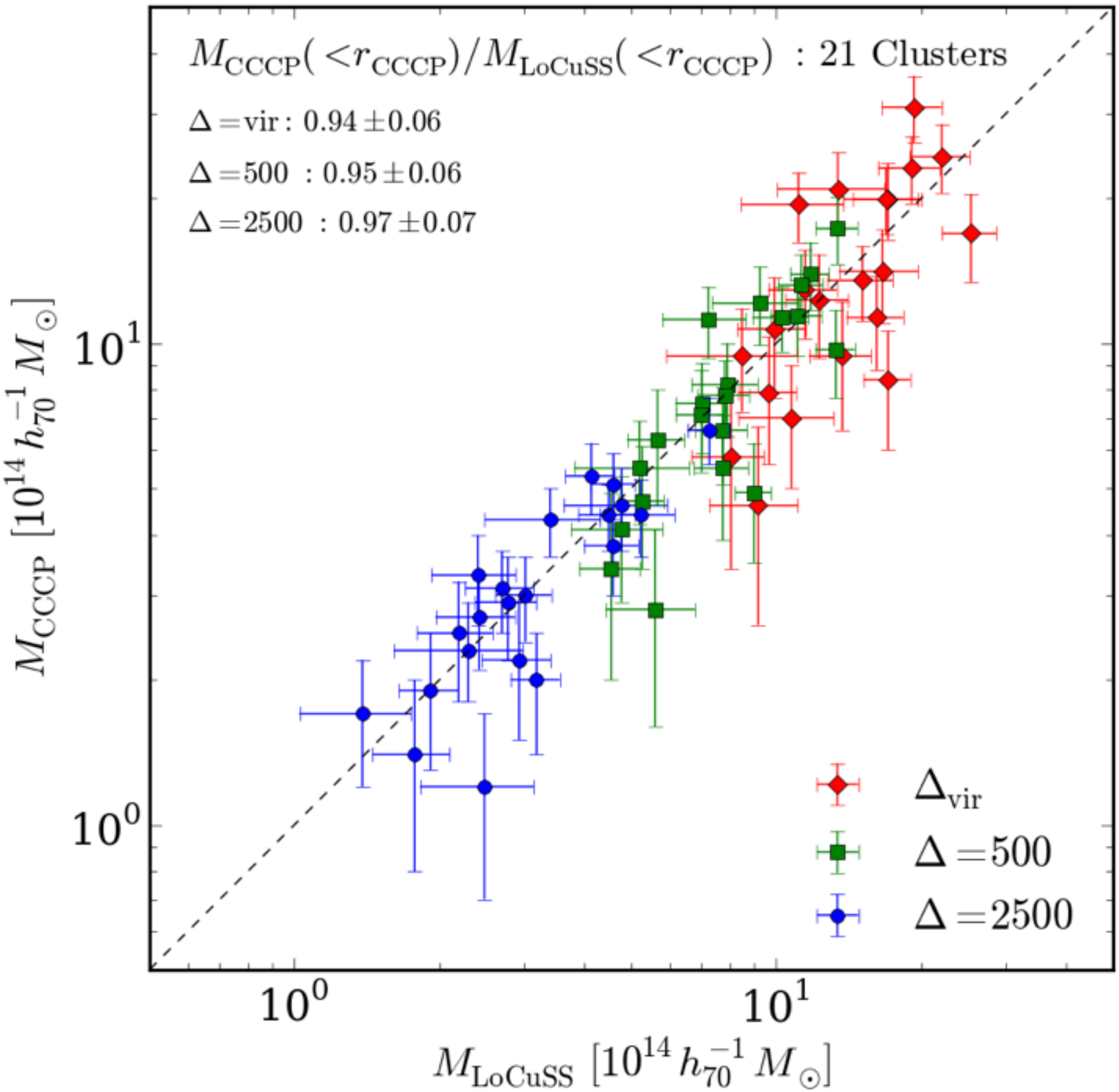


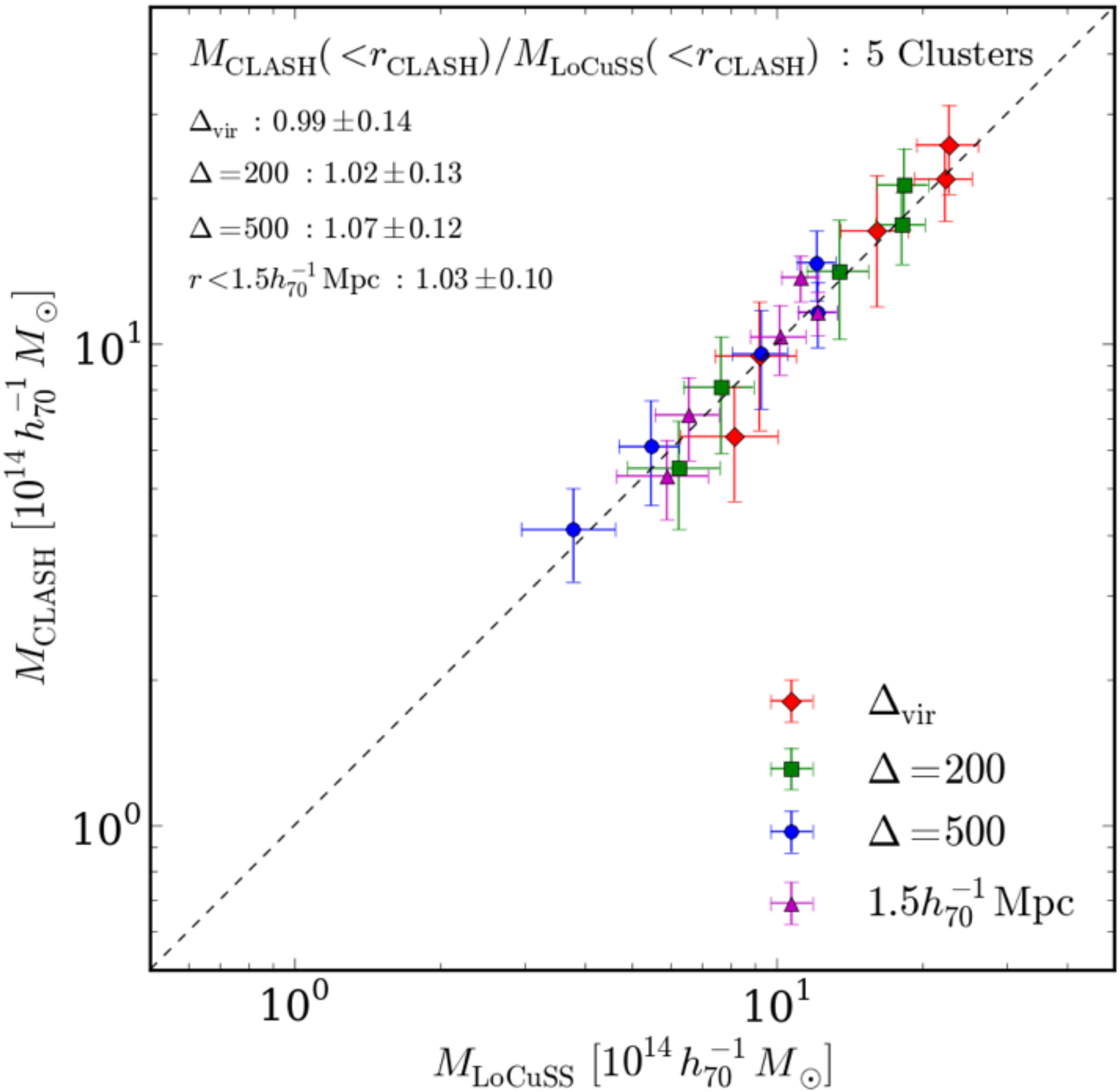
$238h^{-1}$ kpc
$332h^{-1}$ kpc
$463h^{-1}$ kpc
$643h^{-1}$ kpc
$894h^{-1}$ kpc
$1243h^{-1}$ kpc
$1716h^{-1}$ kpc
$2321h^{-1}$ kpc
Lens Signal : $\langle \Delta\Sigma_+ \rangle$
Contamination level [%]
ΔC
Color cut with
1% Contamination
$r\ [h^{-1}\,\mathrm{Mpc}]$


$M_{\rm wtG}(<r_{\rm wtG})/M_{\rm LoCuSS}(<r_{\rm wtG})$: 17 Clusters
$\Delta = 200$: 1.14 ± 0.09
$\Delta = 500$: 1.16 ± 0.12
$\Delta = 2500$: 1.17 ± 0.14
$r < 1.5 h_{70}^{-1}$ Mpc : 1.15 ± 0.07
$\Delta = 200$
$\Delta = 500$
$\Delta = 2500$
$1.5 h_{70}^{-1}$ Mpc
10^{0}
10^{1}
$M_{\rm wtG}\ [10^{14}\, h_{70}^{-1}\, M_\odot]$
$M_{\rm LoCuSS}\ [10^{14}\, h_{70}^{-1}\, M_\odot]$



r/r_{200}
$\langle \Delta\Sigma_+ \rangle$ [$10^{15} h \mathrm{M}_\odot \mathrm{Mpc}^{-2}$]
Total
Background
$\Delta C > 0$
Boost factor
Boost factor + magnification bias
$\langle \Delta\Sigma_+ \rangle / \langle \Delta\Sigma_{+,\mathrm{bkg}} \rangle - 1$
$\Delta C > 0$
Boost factor
Boost factor + magnification bias
r [h^{-1} Mpc]
Dilution model
Boost factor
Magnification
wtG
$\Delta C > 0$
CCCP
wtG
$\langle n/n_0 \rangle$


$M_{\mathrm{CCCP}}(<r_{\mathrm{CCCP}})/M_{\mathrm{LoCuSS}}(<r_{\mathrm{CCCP}})$: 21 Clusters
$\Delta = \mathrm{vir}: 0.94 \pm 0.06$
$\Delta = 500 : 0.95 \pm 0.06$
$\Delta = 2500 : 0.97 \pm 0.07$
Δ_{vir}
$\Delta = 500$
$\Delta = 2500$
10^{0}
10^{1}
$M_{\mathrm{CCCP}}\ [10^{14}\, h_{70}^{-1}\, M_\odot]$
$M_{\mathrm{LoCuSS}}\ [10^{14}\, h_{70}^{-1}\, M_\odot]$



$M_{\rm CLASH}(<r_{\rm CLASH})/M_{\rm LoCuSS}(<r_{\rm CLASH})$: 5 Clusters
$\Delta_{\rm vir}$: 0.99 ± 0.14
$\Delta = 200$: 1.02 ± 0.13
$\Delta = 500$: 1.07 ± 0.12
$r < 1.5 h_{70}^{-1}$ Mpc : 1.03 ± 0.10
$\Delta_{\rm vir}$
$\Delta = 200$
$\Delta = 500$
$1.5 h_{70}^{-1}$ Mpc
$M_{\rm CLASH}$ $[10^{14}\, h_{70}^{-1}\, M_\odot]$
$M_{\rm LoCuSS}$ $[10^{14}\, h_{70}^{-1}\, M_\odot]$
10^0
10^1