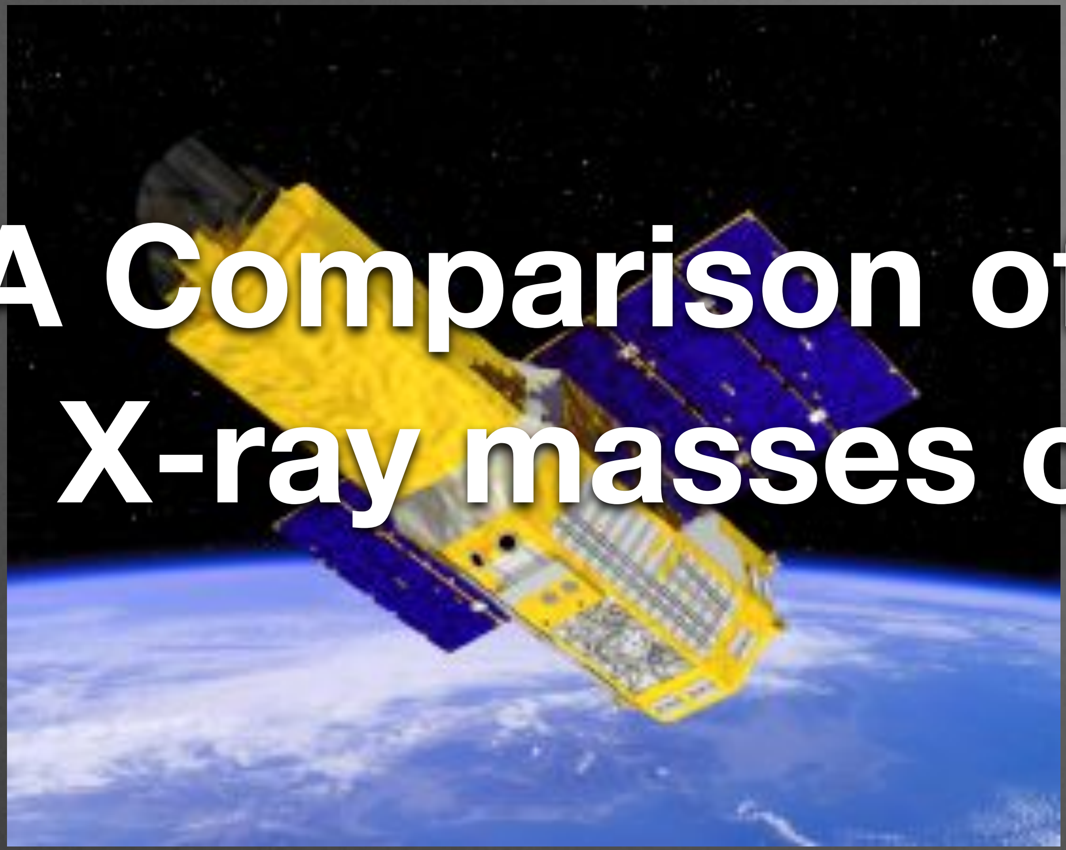
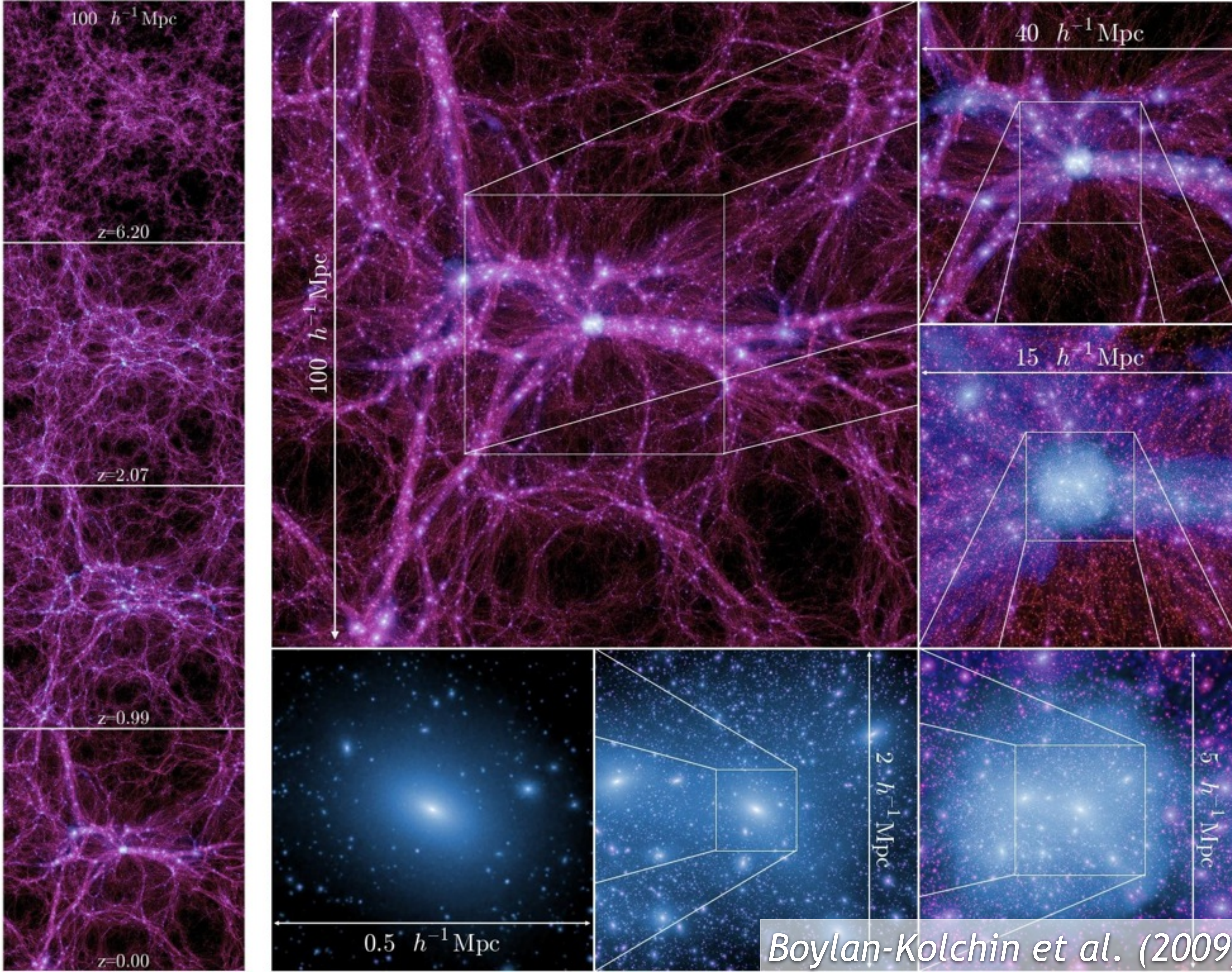
 

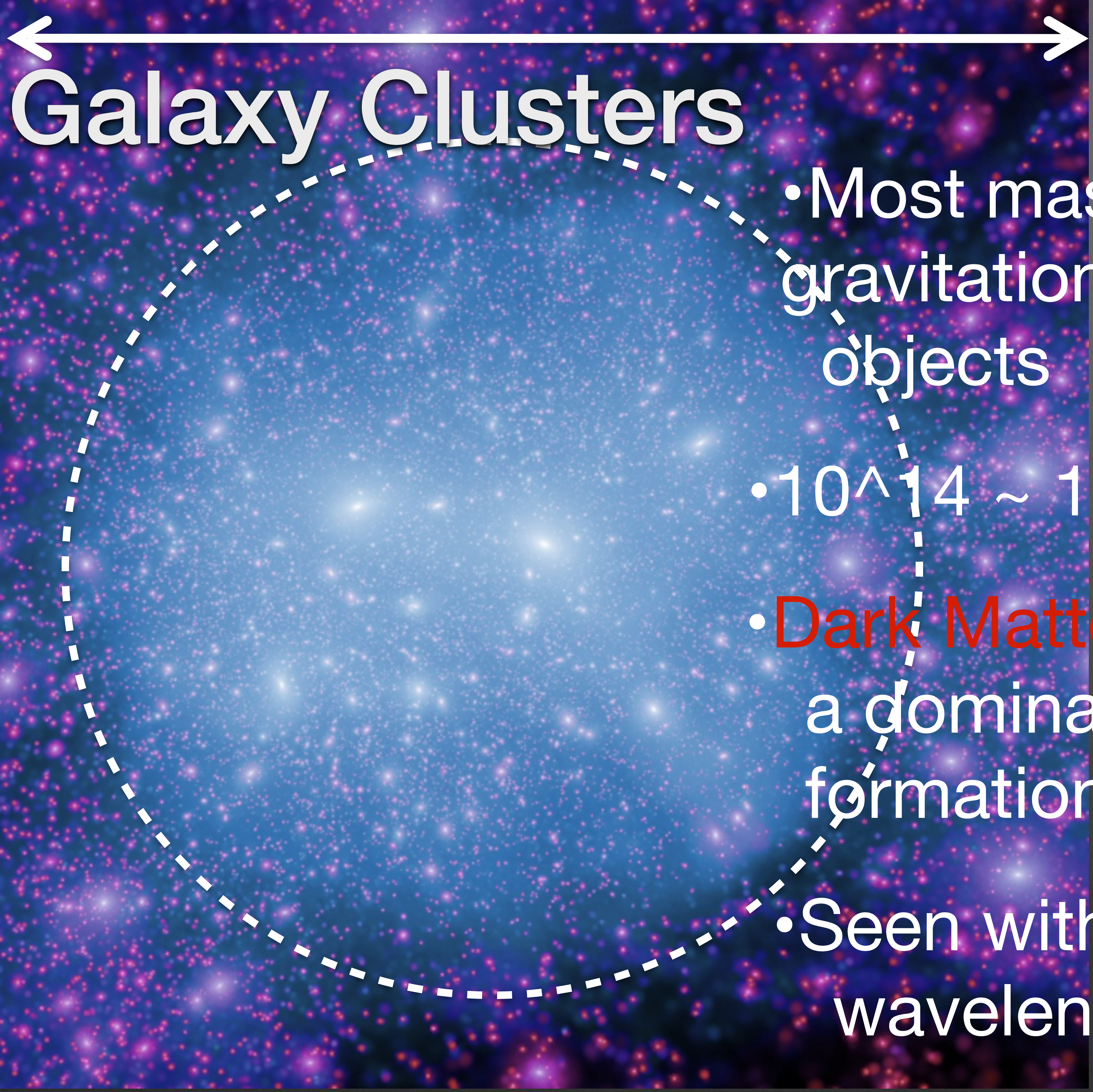
A Comparison of Weak-lensing and X-ray masses of Galaxy Clusters

Nobuhiro Okabe

Kavli IPMU (Univ. of Tokyo)

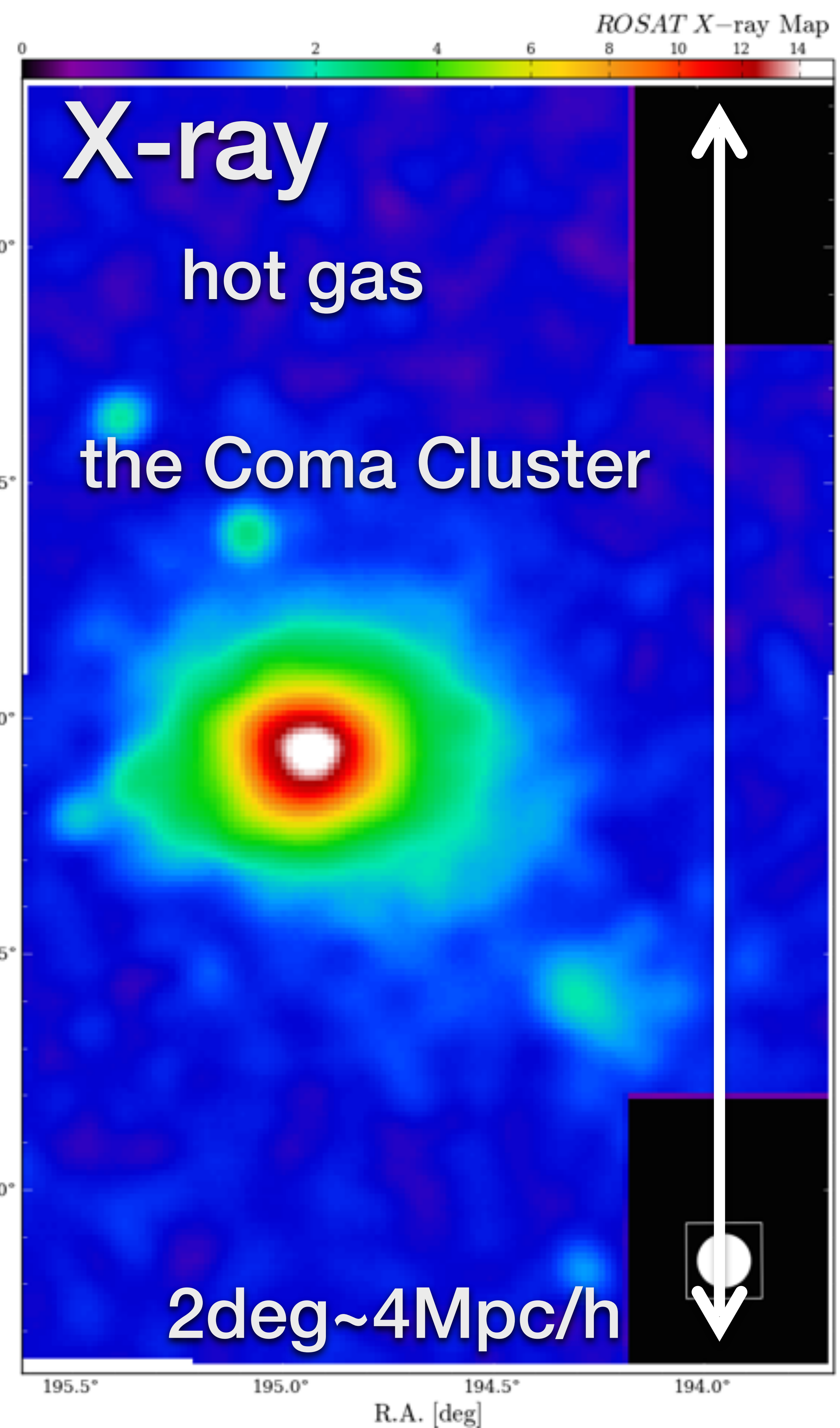

100 h^{-1} Mpc
z=6.20
z=2.07
z=0.99
z=0.00
100 h^{-1} Mpc
40 h^{-1} Mpc
15 h^{-1} Mpc
5 h^{-1} Mpc
2 h^{-1} Mpc
0.5 h^{-1} Mpc
Boylan-Kolchin et al. (2009)

Galaxy Clusters

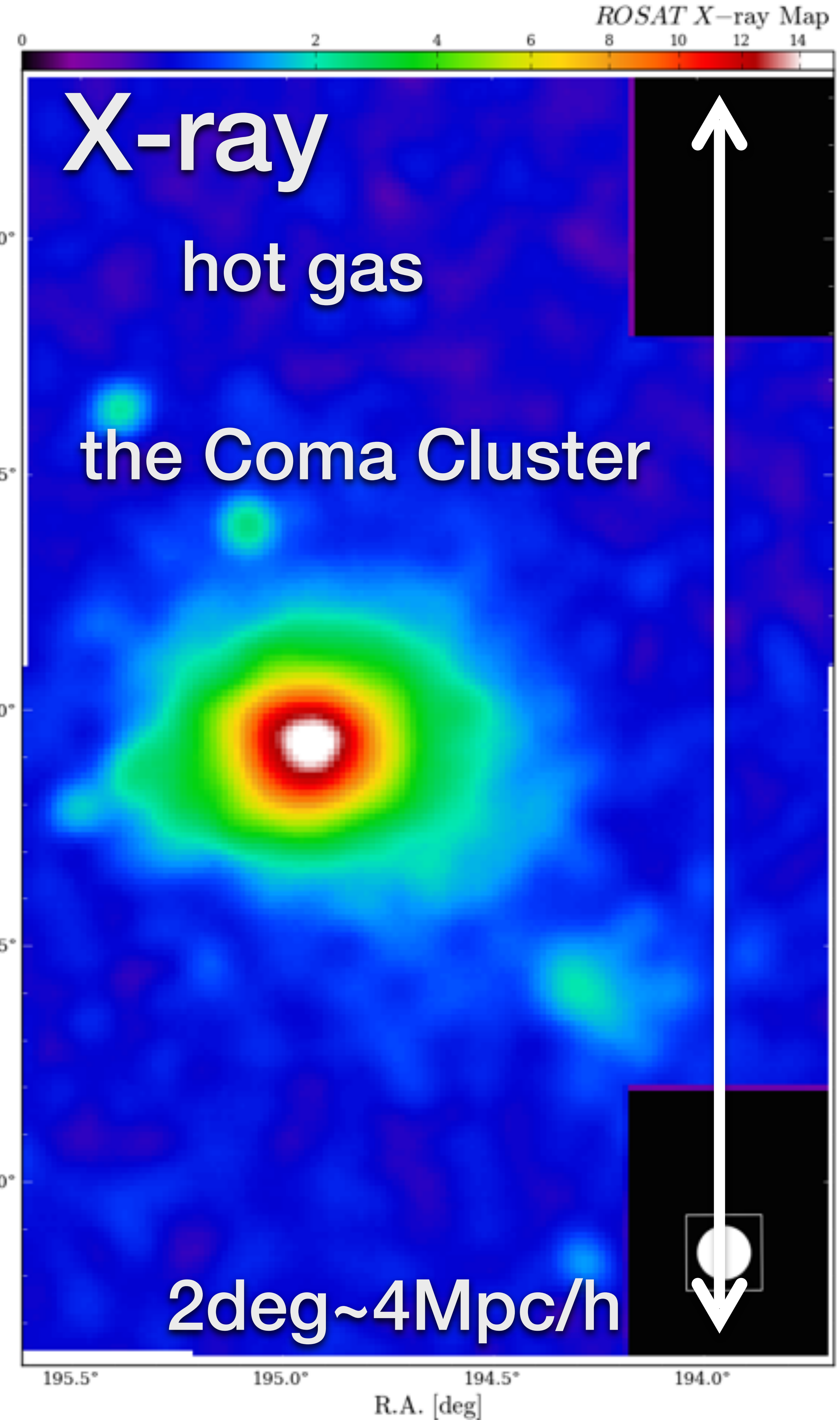


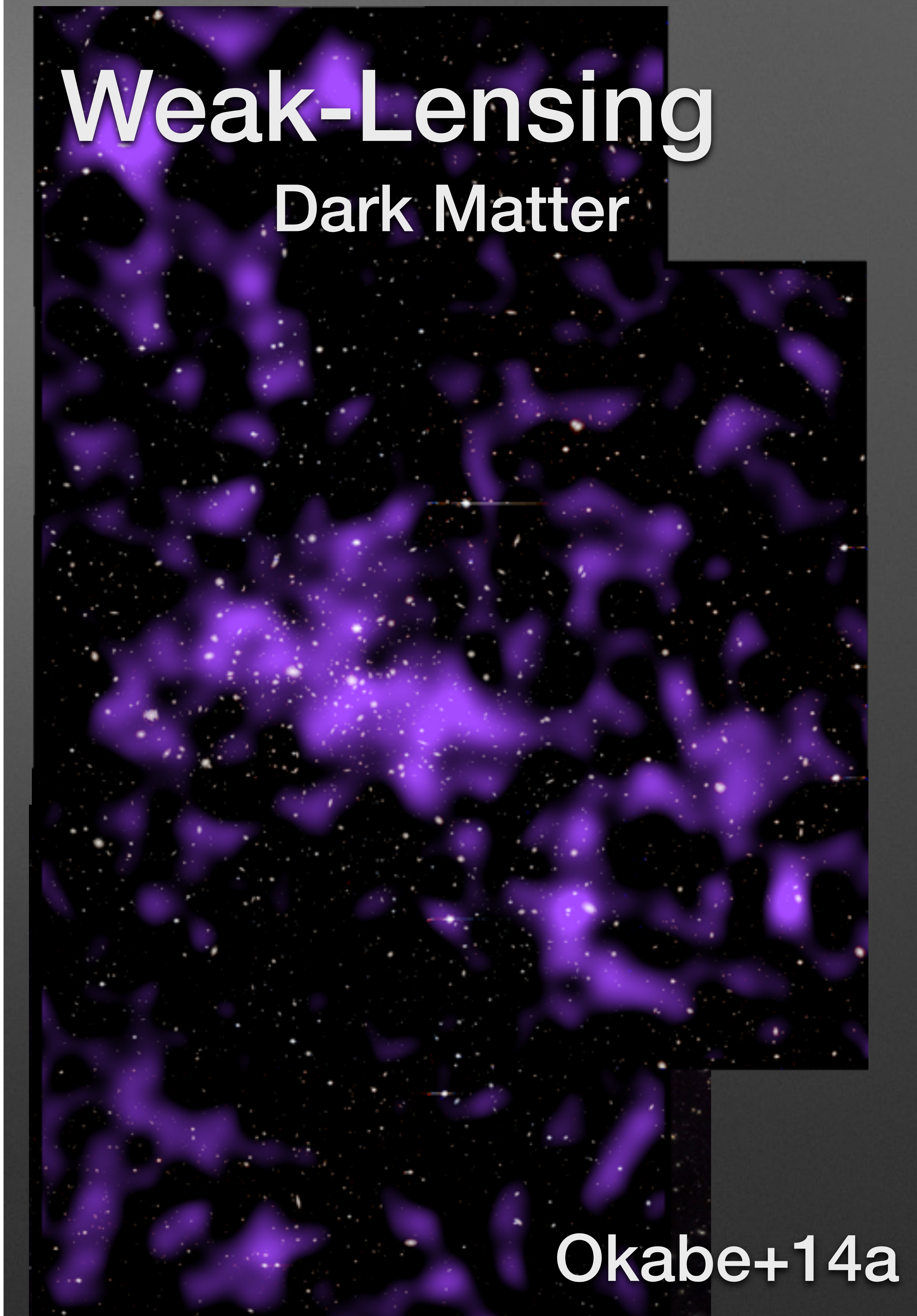
- Most massive gravitationally bound objects
- 10^14 ~ 10^15 M_sun
- Dark Matter (DM) plays a dominant role to the formation
- Seen with various wavelengths

Boylan-Kolchin+09

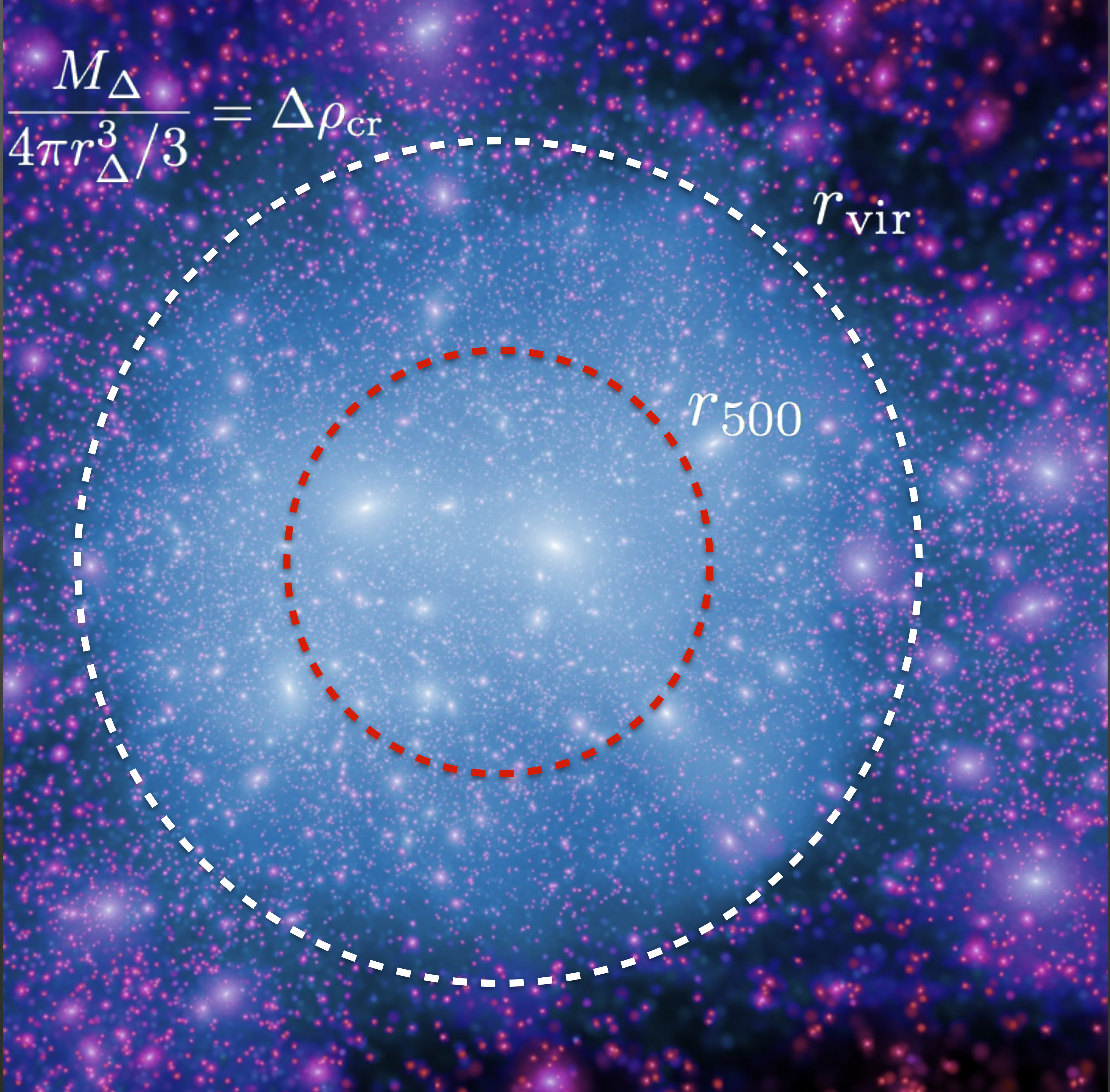

ROSAT X−ray Map
0
2
4
6
8
10
12
14
X-ray
hot gas
the Coma Cluster
2deg~4Mpc/h
195.5°
195.0°
194.5°
194.0°
R.A. [deg]

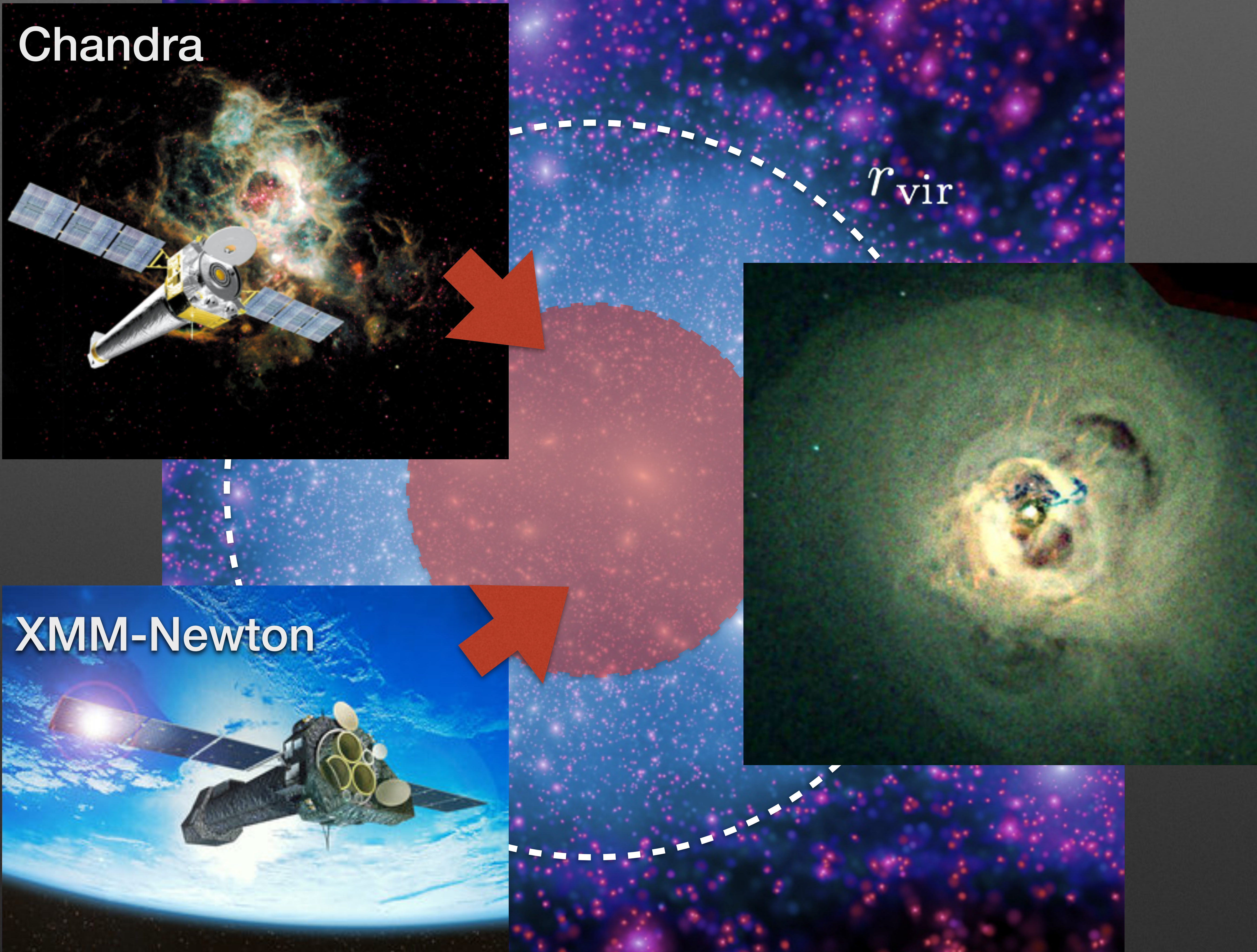
Optical
Galaxies
Okabe+14a

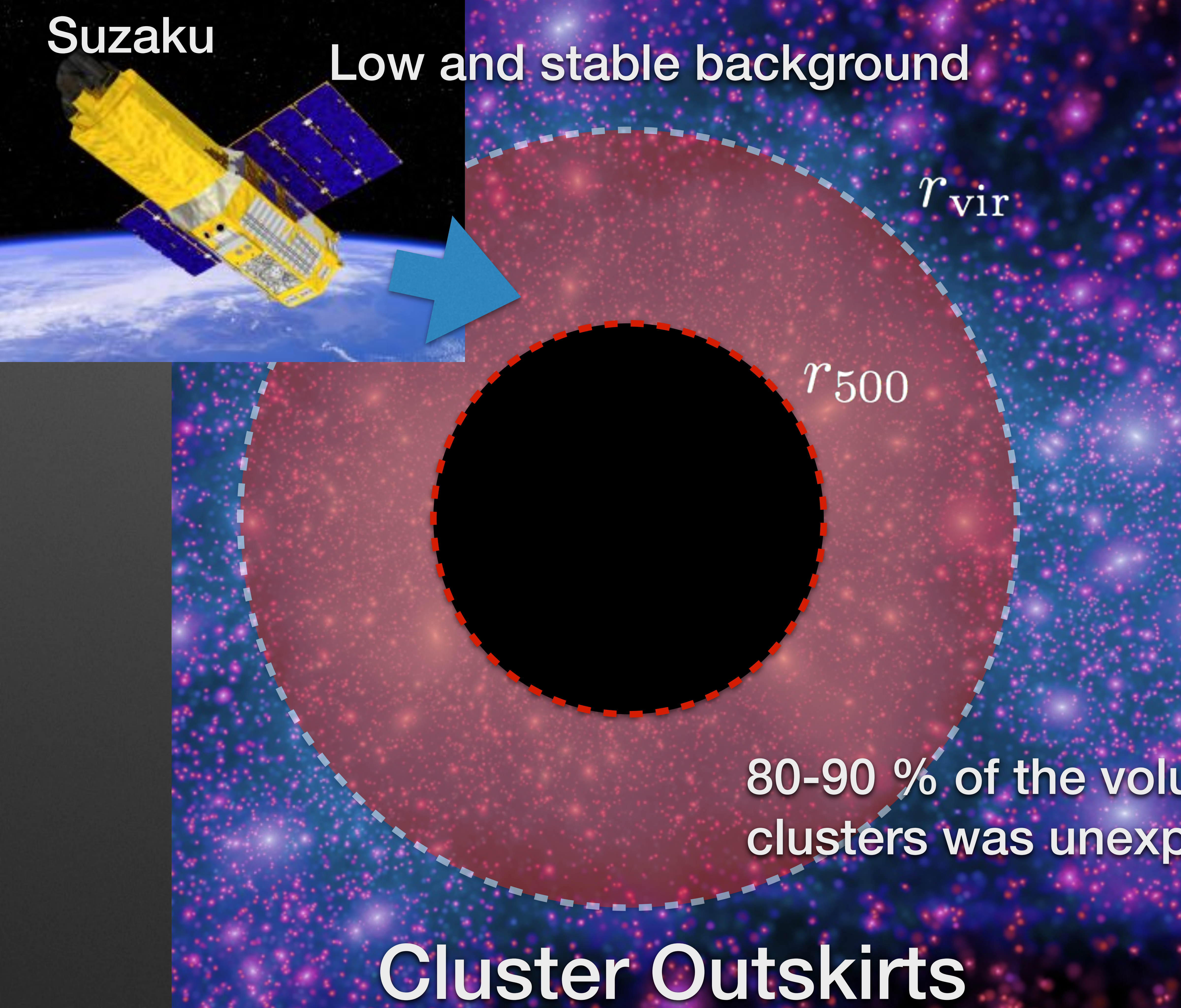

ROSAT X−ray Map
0
2
4
6
8
10
12
14
X-ray
hot gas
the Coma Cluster
2deg~4Mpc/h
195.5°
195.0°
194.5°
194.0°
R.A. [deg]


Weak-Lensing
Dark Matter
Okabe+14a

$$\bar{\rho}_m = \frac{M_\Delta}{4\pi r_\Delta^3/3} = \Delta \rho_{\rm cr}$$




Chandra
XMM-Newton
r_{vir}

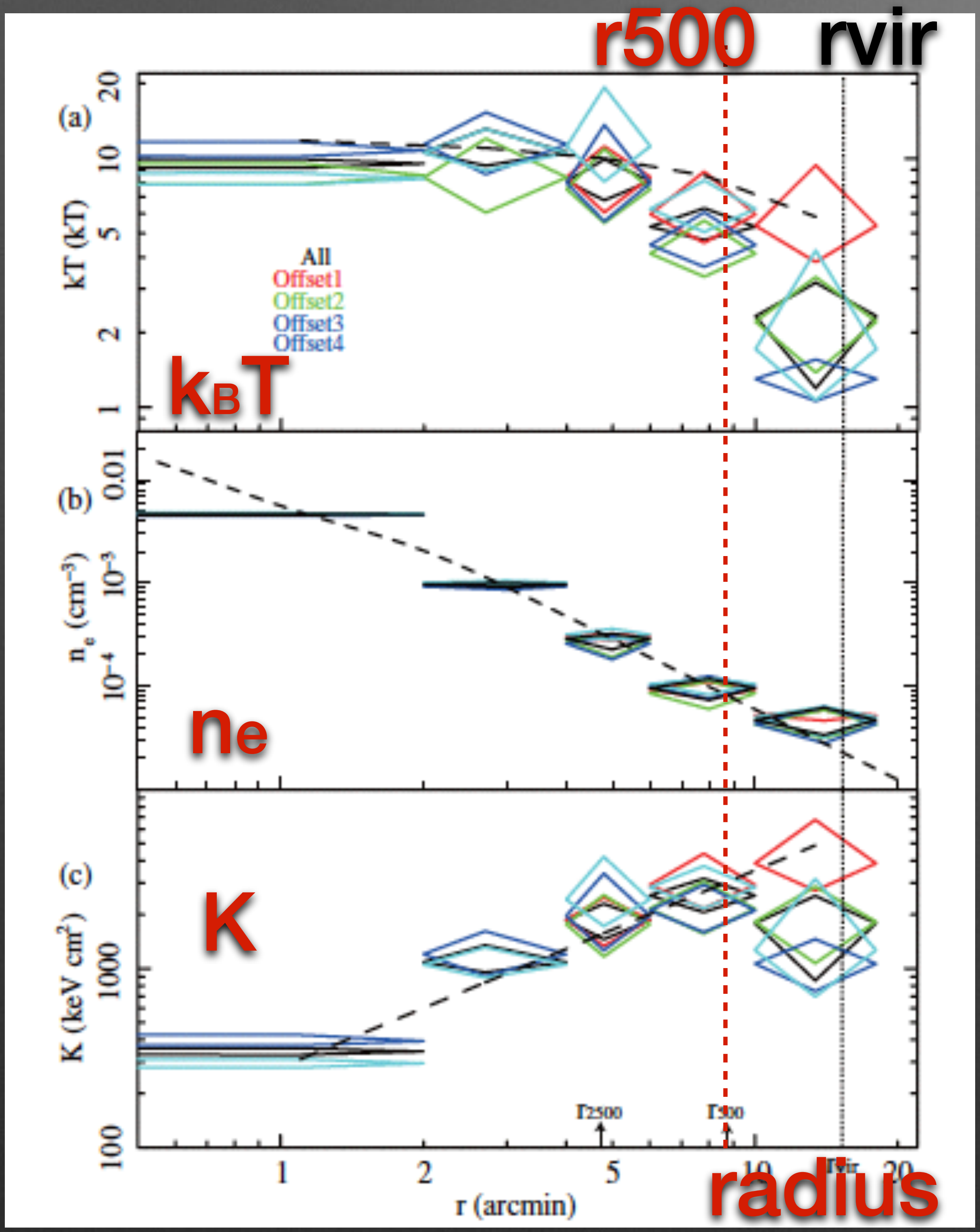


Low and stable background

80-90 % of the volume of clusters was unexplored.

Cluster Outskirts

Unexpected Feature of the ICM in Cluster Outskirts



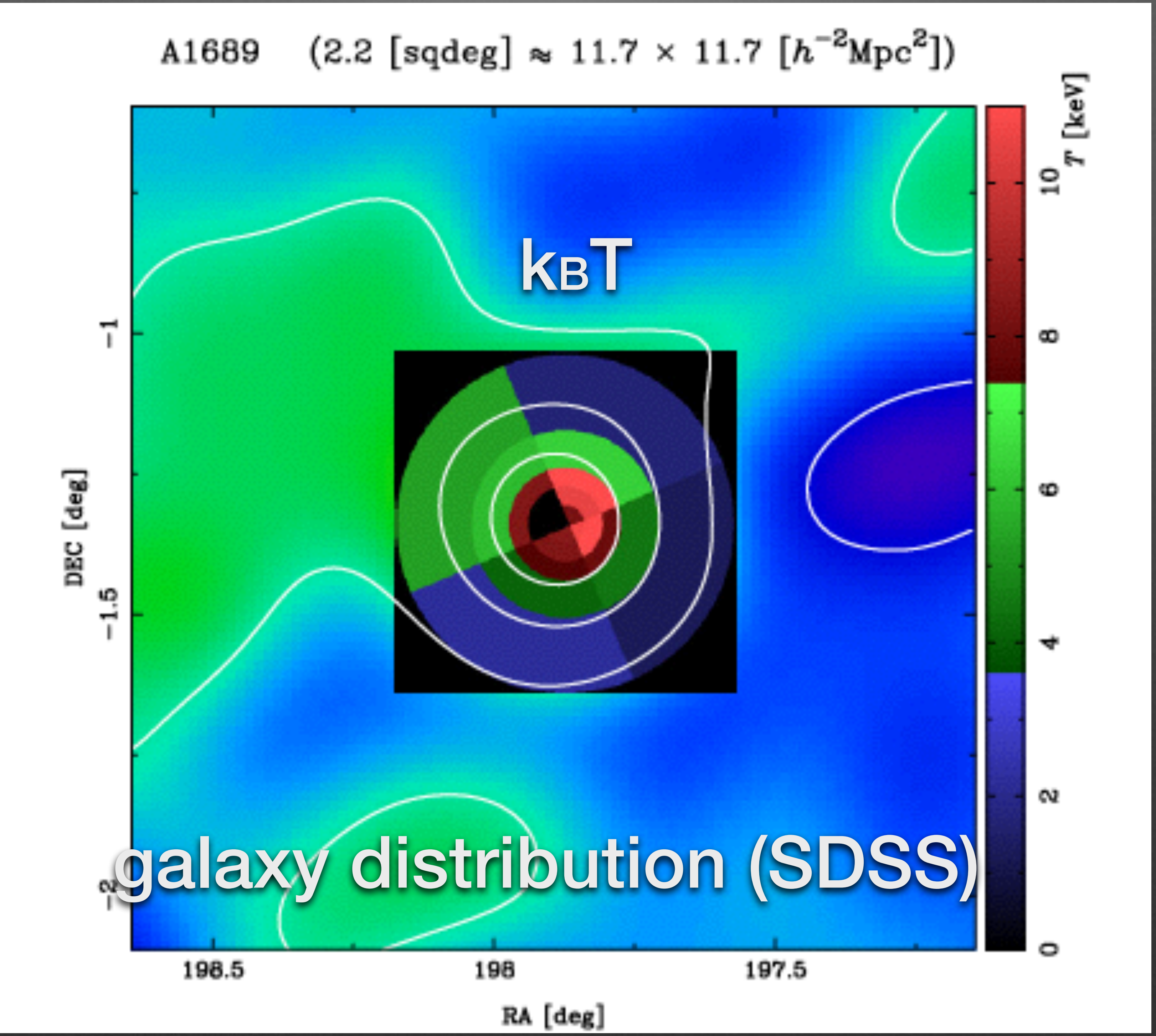
A1689: Kawaharada+10

Temperature drops at $r > r_{500}$.

density (monotonously) decreases.

Entropy flattens at $r > r_{500}$.

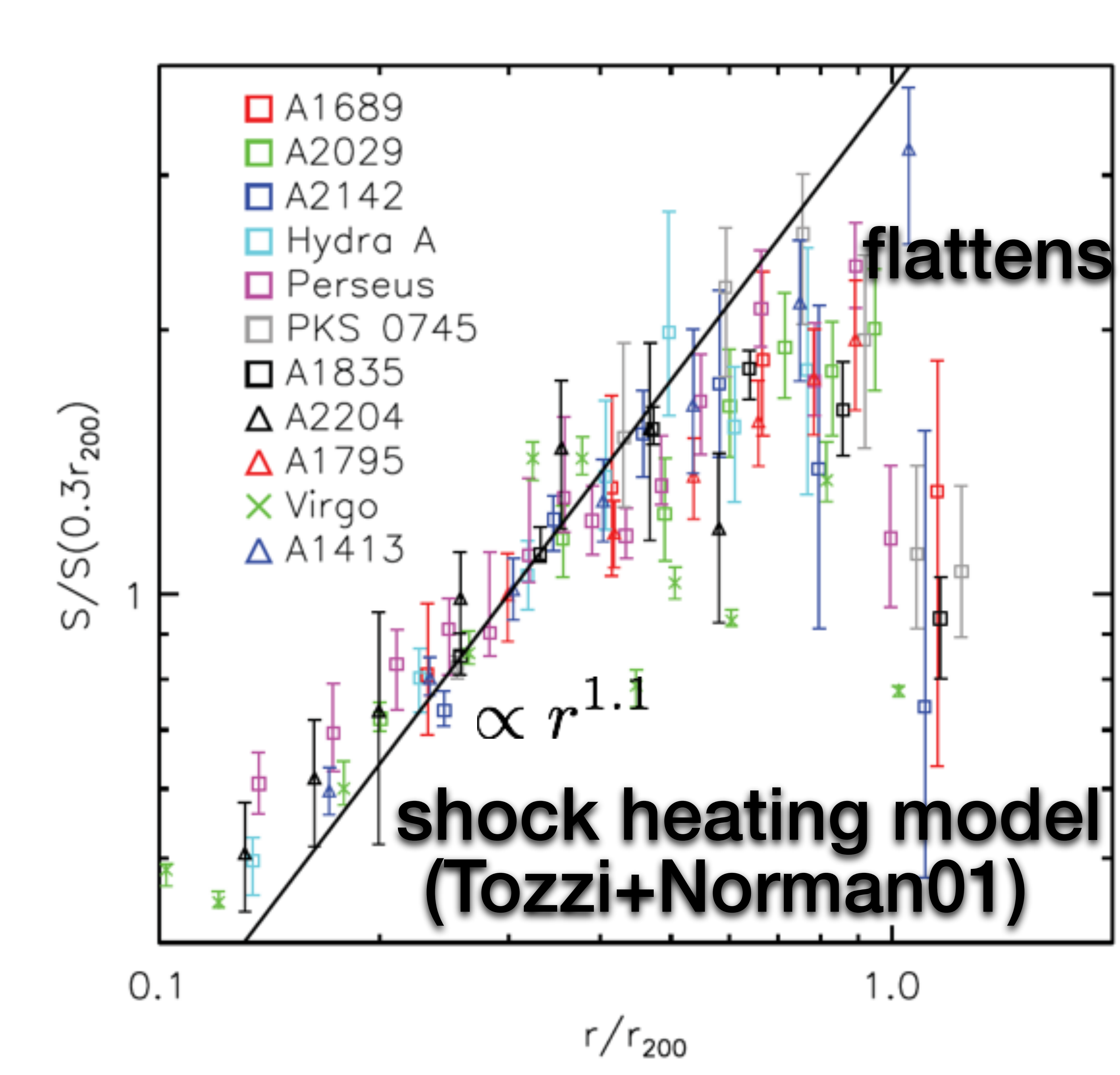
Correlation between the outskirts temperature (or density) and surrounding large scale structure is found in several clusters.



A1689 : Kawaharada+10

Entropy Profile

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



Walker+2012

Possible interpretations

- Temperature drops

  1: non-thermal pressure (Kawaharada+10)

  2: $T_i \neq T_e$ (Hoshino+10)

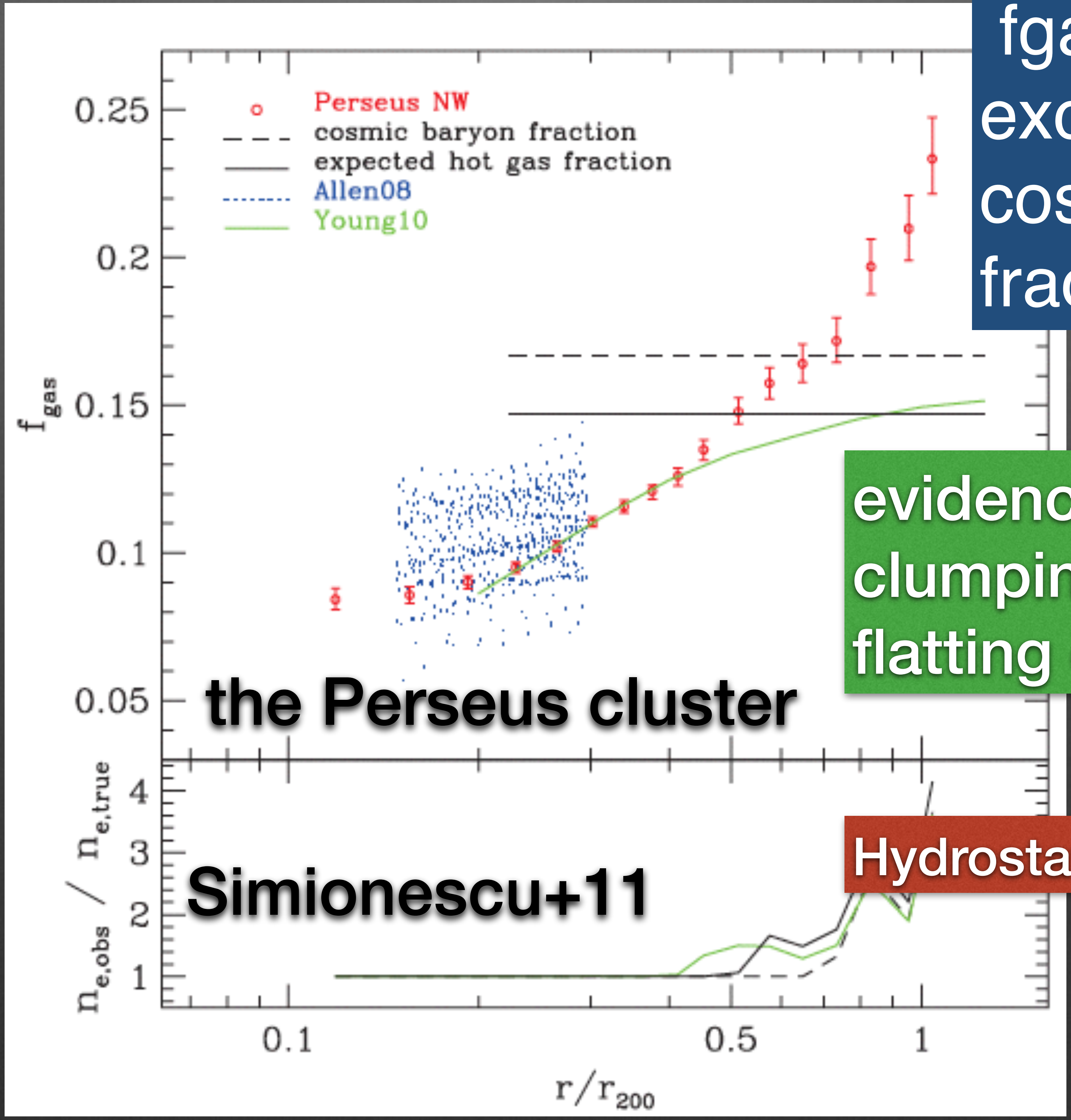
  3: the efficiency of accretion shock heating is weakened due to cosmic expansion (Lapi+10)

- Number density

  overestimated by gas clumpiness (Nagai+Lau11)

Gas fraction

$$f_{\text{gas}} = \frac{M_{\text{gas}}}{M_{\text{H.E.}}}$$



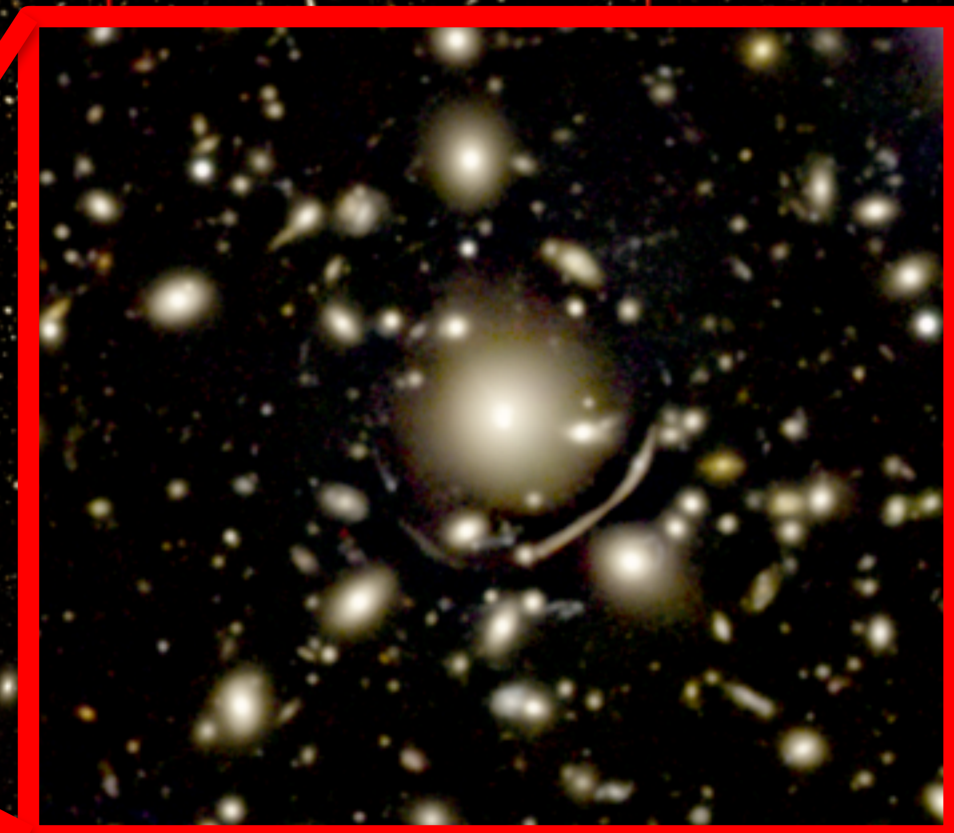
fgas extremely exceeds the cosmic baryon fraction

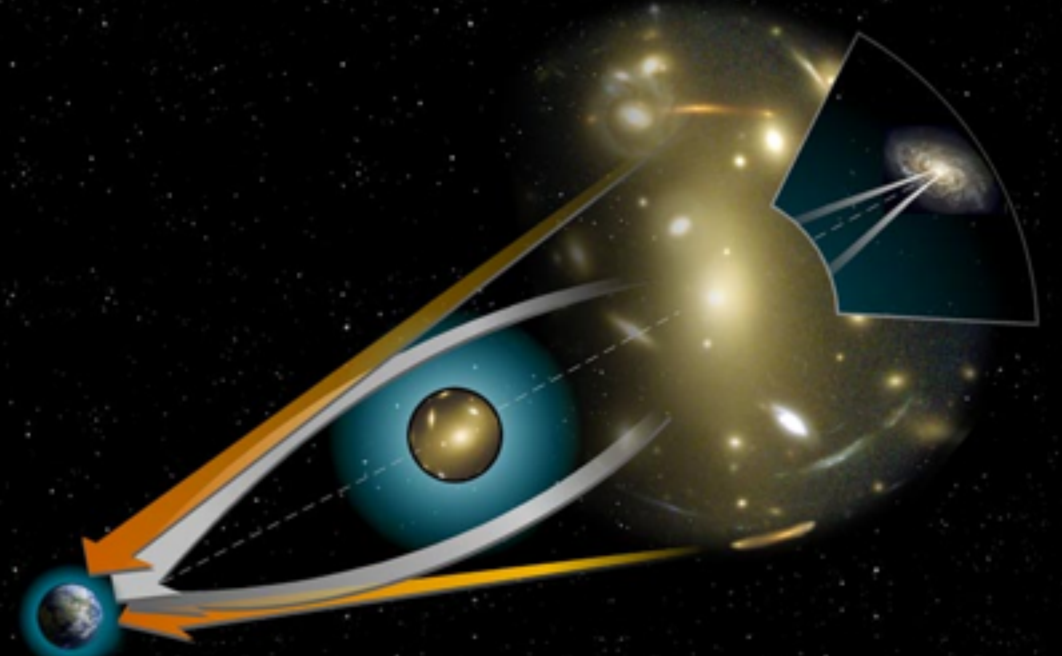
evidence of gas clumpiness and flatting entropy ?

Hydrostatic mass bias?

based on hydrostatic mass $M_{\text{H.E.}}$

Gravitational Lensing Effect
=directly "see" invisibles





- independent of dynamical state
- complementary to X-ray studies

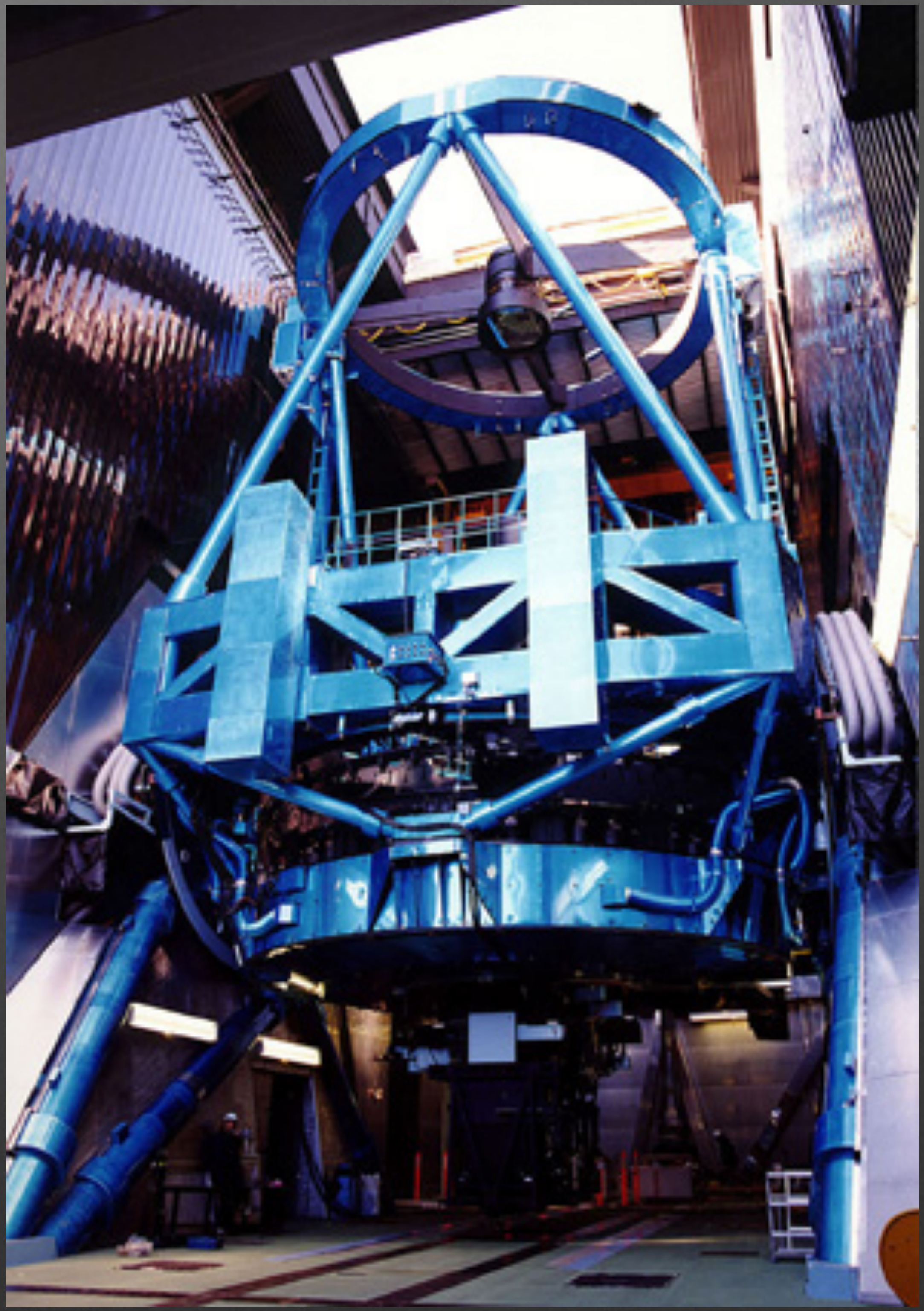
Subaru Telescope:
Best facility for WL measurement

1. High photon collecting power
   (8.2 m mirror)
   (limitting mag ~26ABmag
   with short exposure ~30 min)

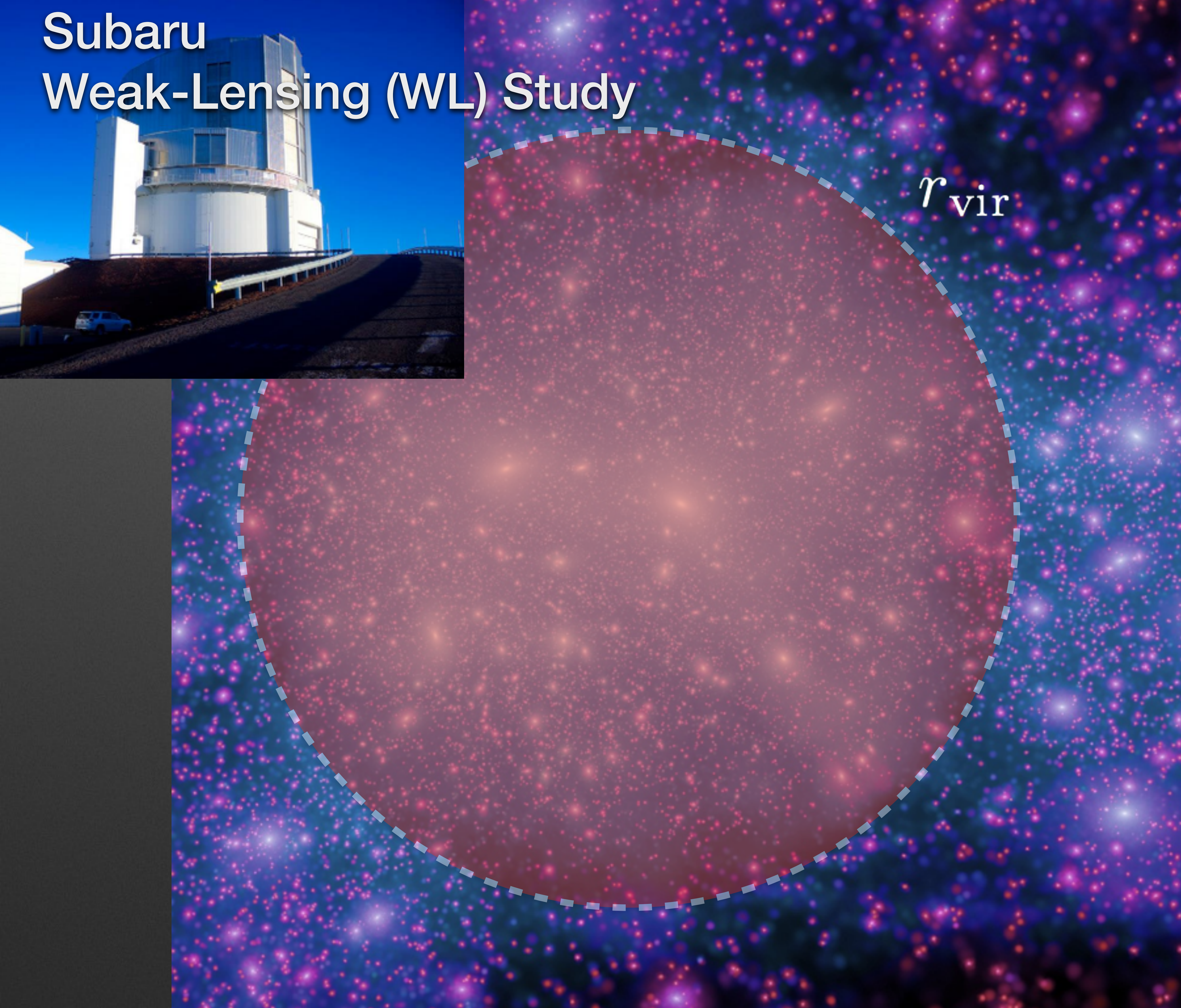
2. Good seeing (~0.7”)

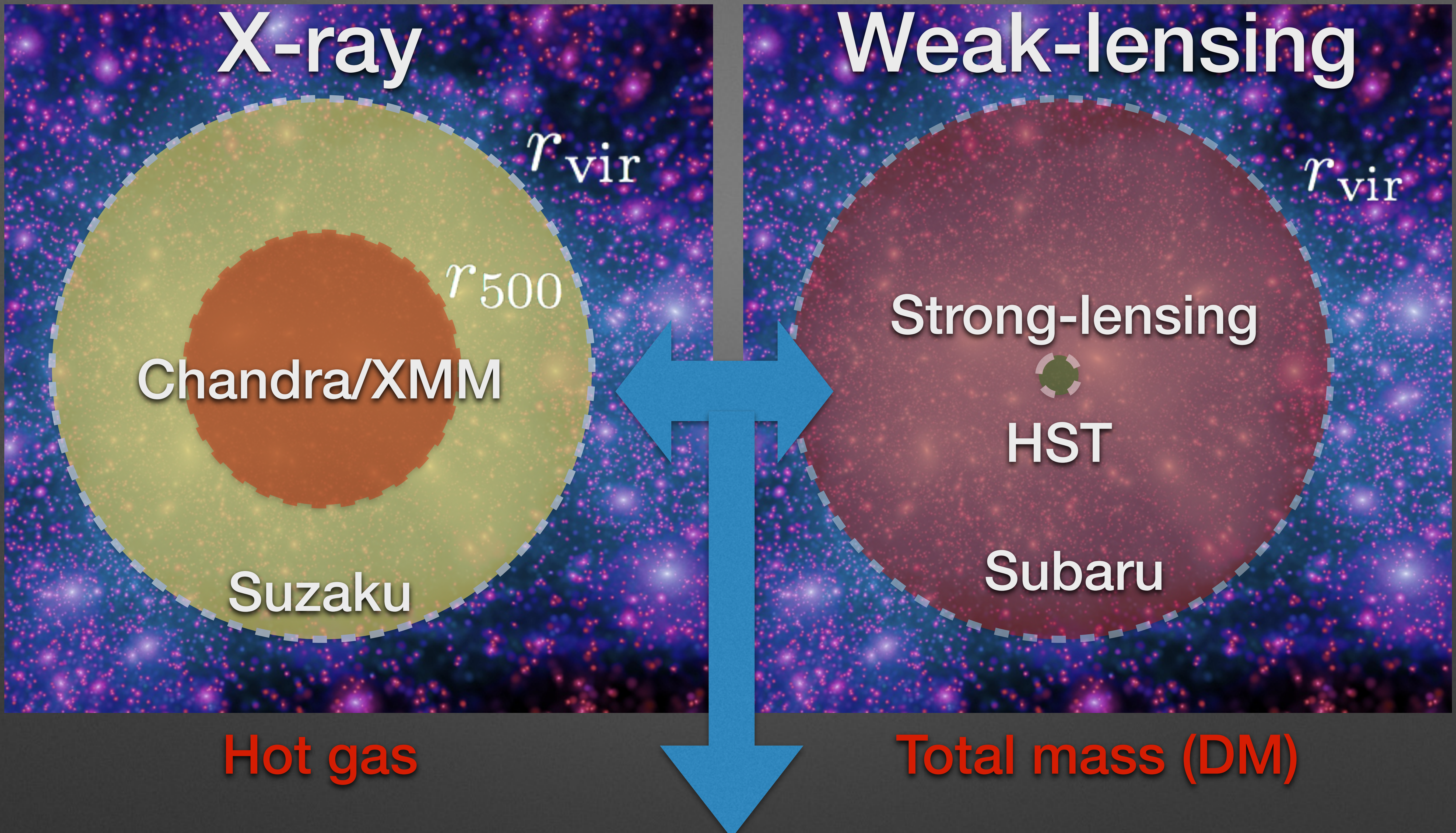
3. High imaging quality

4. Large Field-of-view
   (0.25 sqdeg ~ 1 pointing
   covers virial radius of clusters
   @ z > 0.15)



Subaru
Weak-Lensing (WL) Study

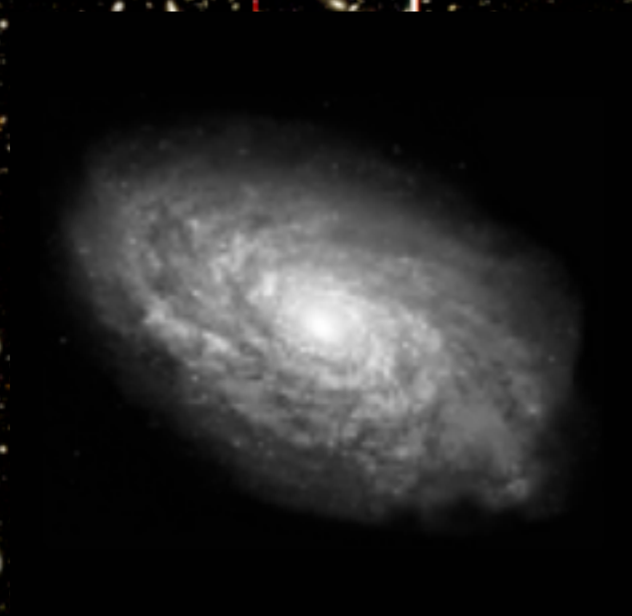


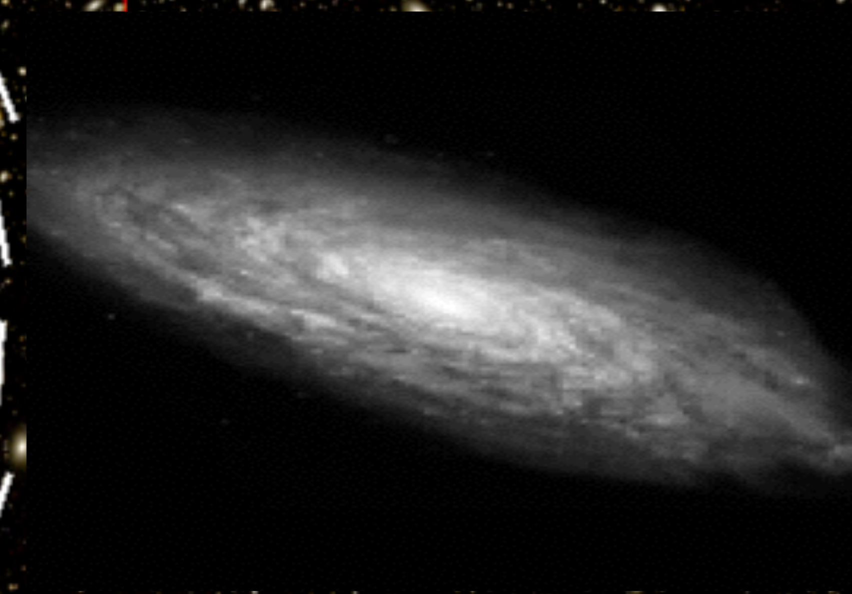


A comparison of X-ray and weak-lensing cluster mass estimates provides a stringent test of the level of hydrostatic equilibrium out to viral radius.

Weak Gravitational lensing Distortion

Intrinsic shape of a background galaxy





$$\varepsilon \sim 0.3$$

$$\varepsilon^{\mathrm{obs}} \simeq \varepsilon + \gamma^{\mathrm{GL}}$$

Step 1: Quantify the shape of each galaxy in terms of its surface brightness profile

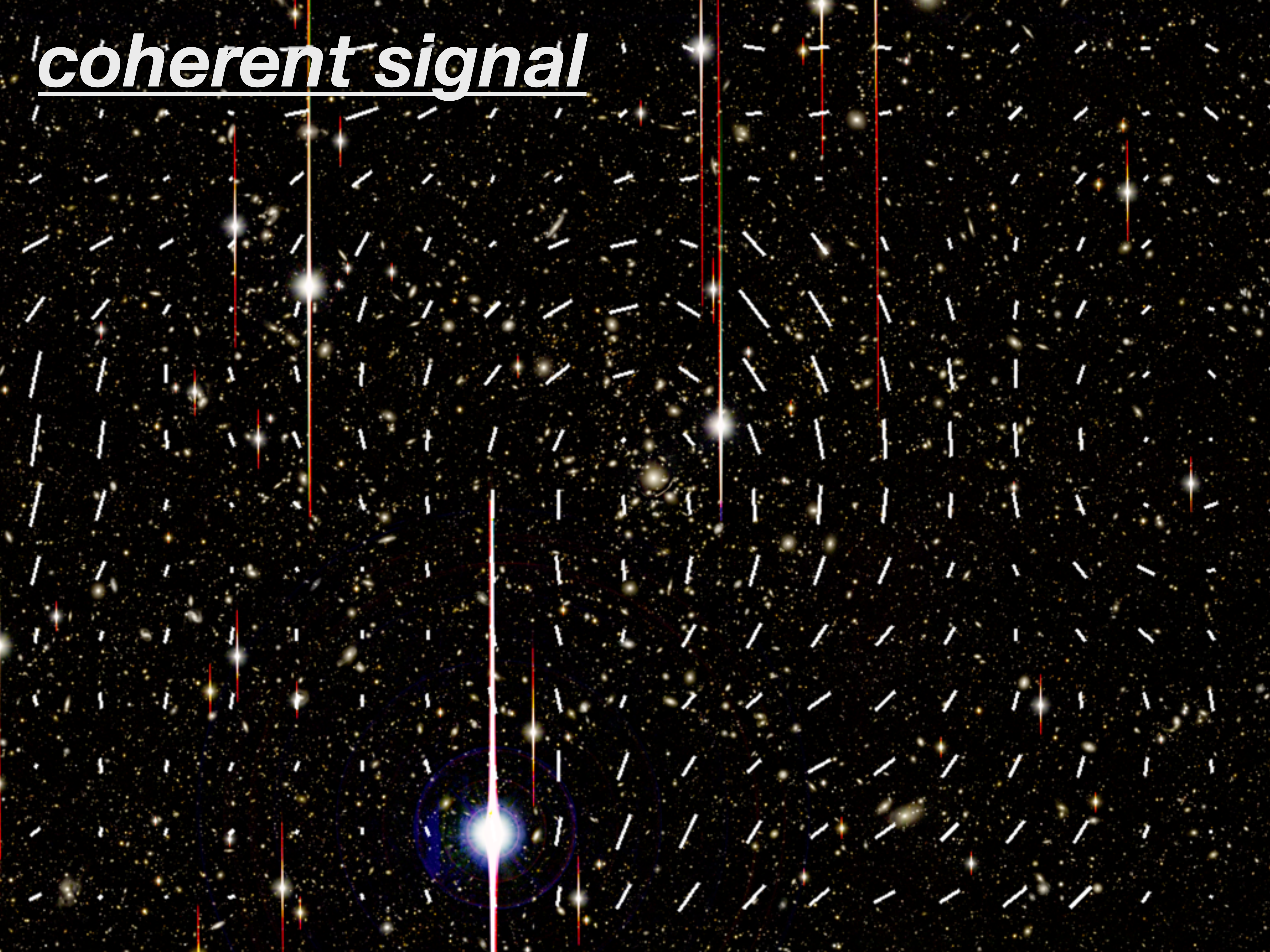
Weak Lensing = A statistical lensing

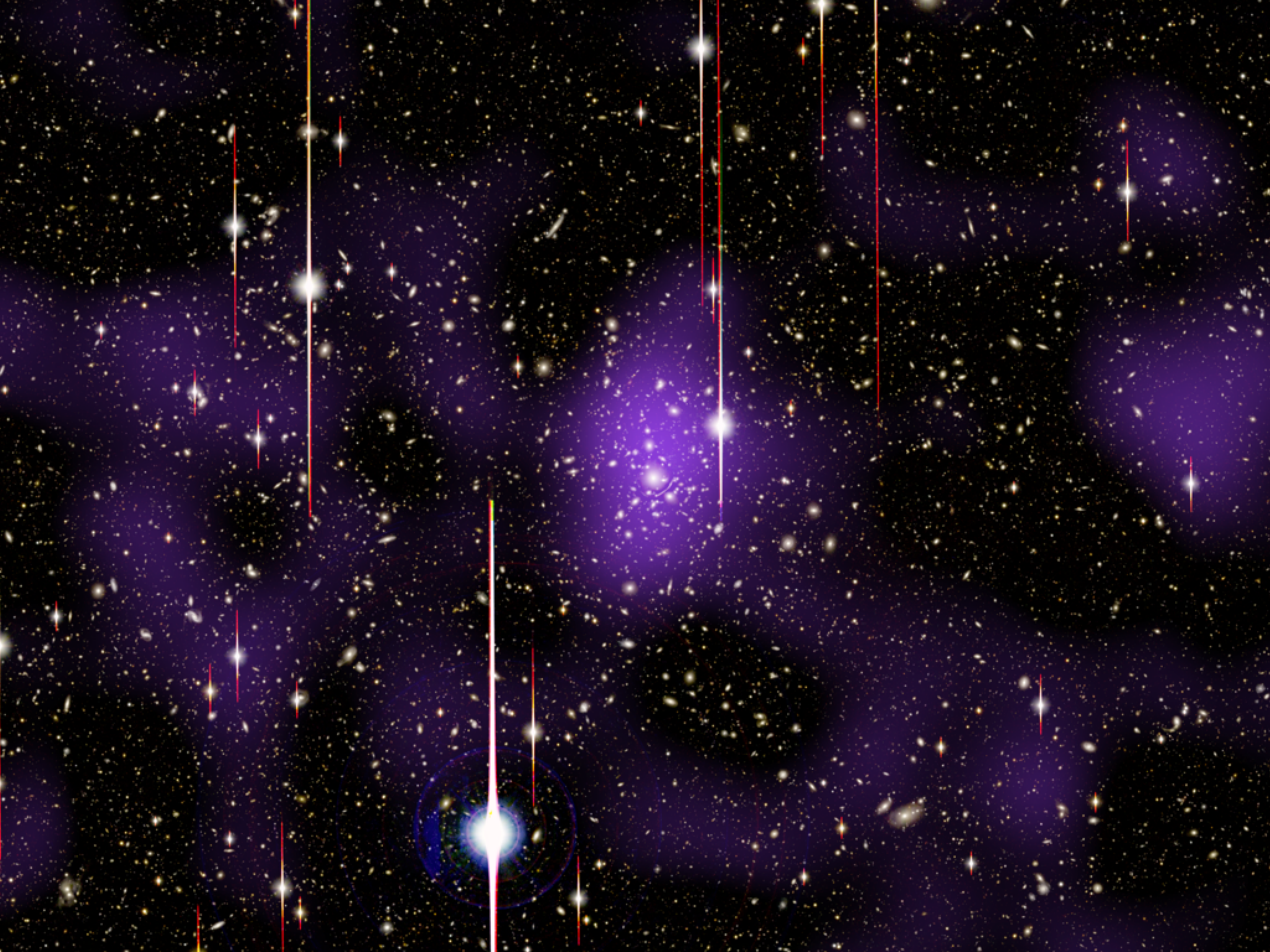
Step 2: Assumption of random orientation of intrinsic ellipticity $\Rightarrow$ Averaging over galaxies

<u>*coherent signal*</u>

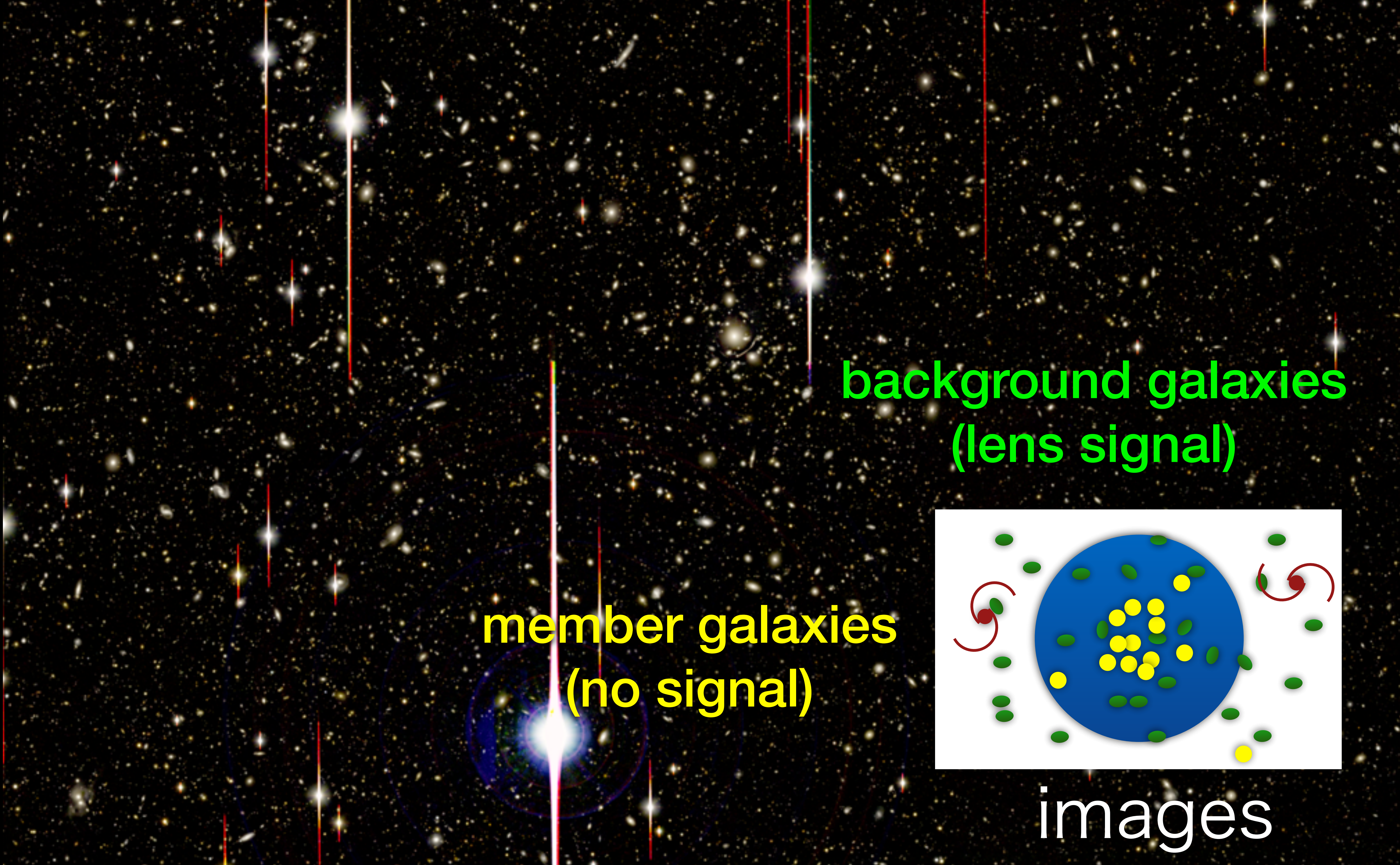
$$\langle \varepsilon_i^{\mathrm{obs}} \rangle \simeq \langle \gamma_i^{\mathrm{GL}} \rangle \pm \cancel{\langle \varepsilon_i \rangle}$$

$$S/N \simeq \gamma^{\mathrm{GL}}(M)\sqrt{N_g}$$


coherent signal



Importance of a secure background selection

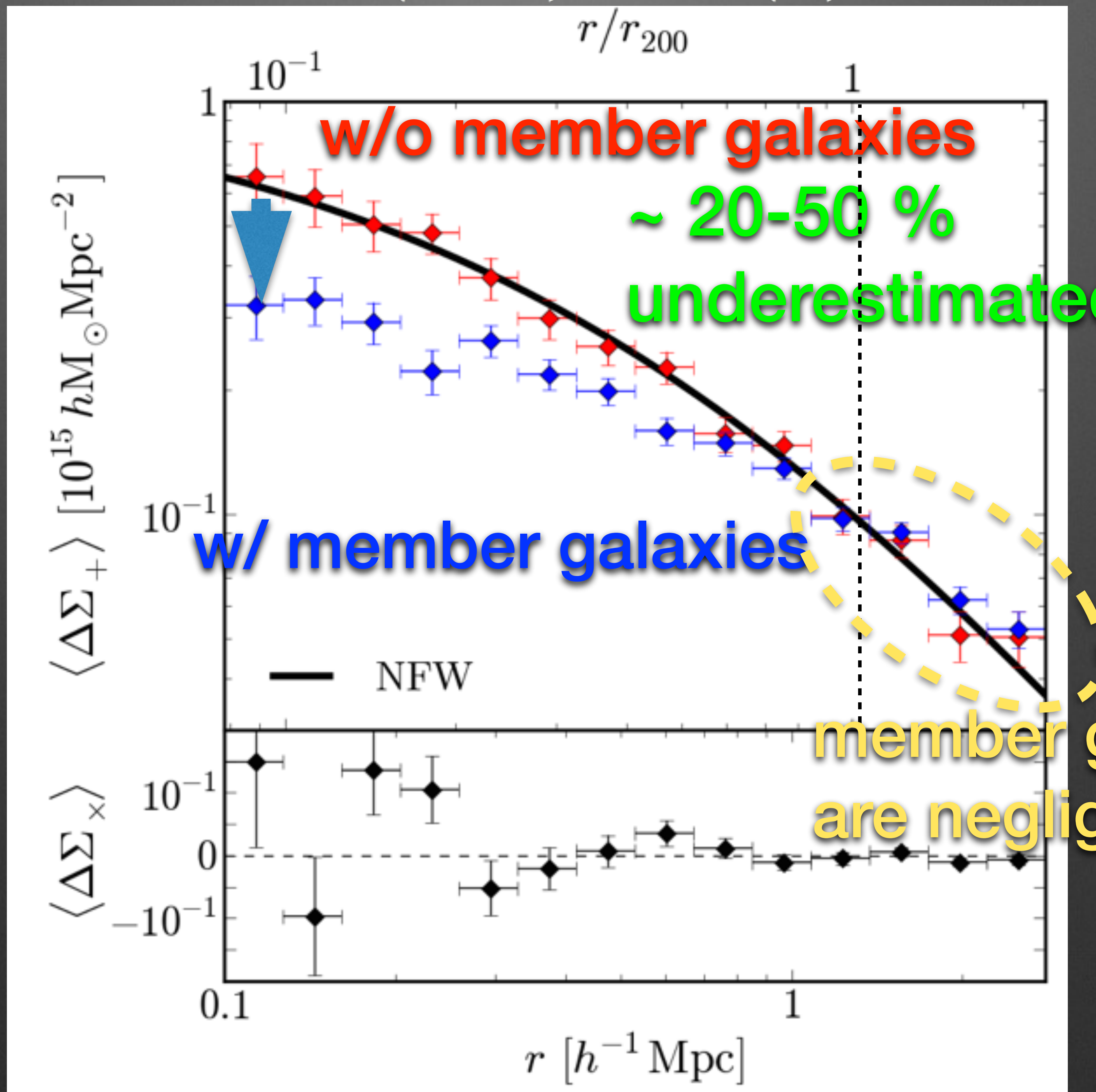


Contamination of member galaxies

$$\Delta\Sigma_+ \simeq \gamma_+\Sigma_{\rm cr} = \bar{\Sigma}(<r) - \Sigma(r)$$

Lens Signal

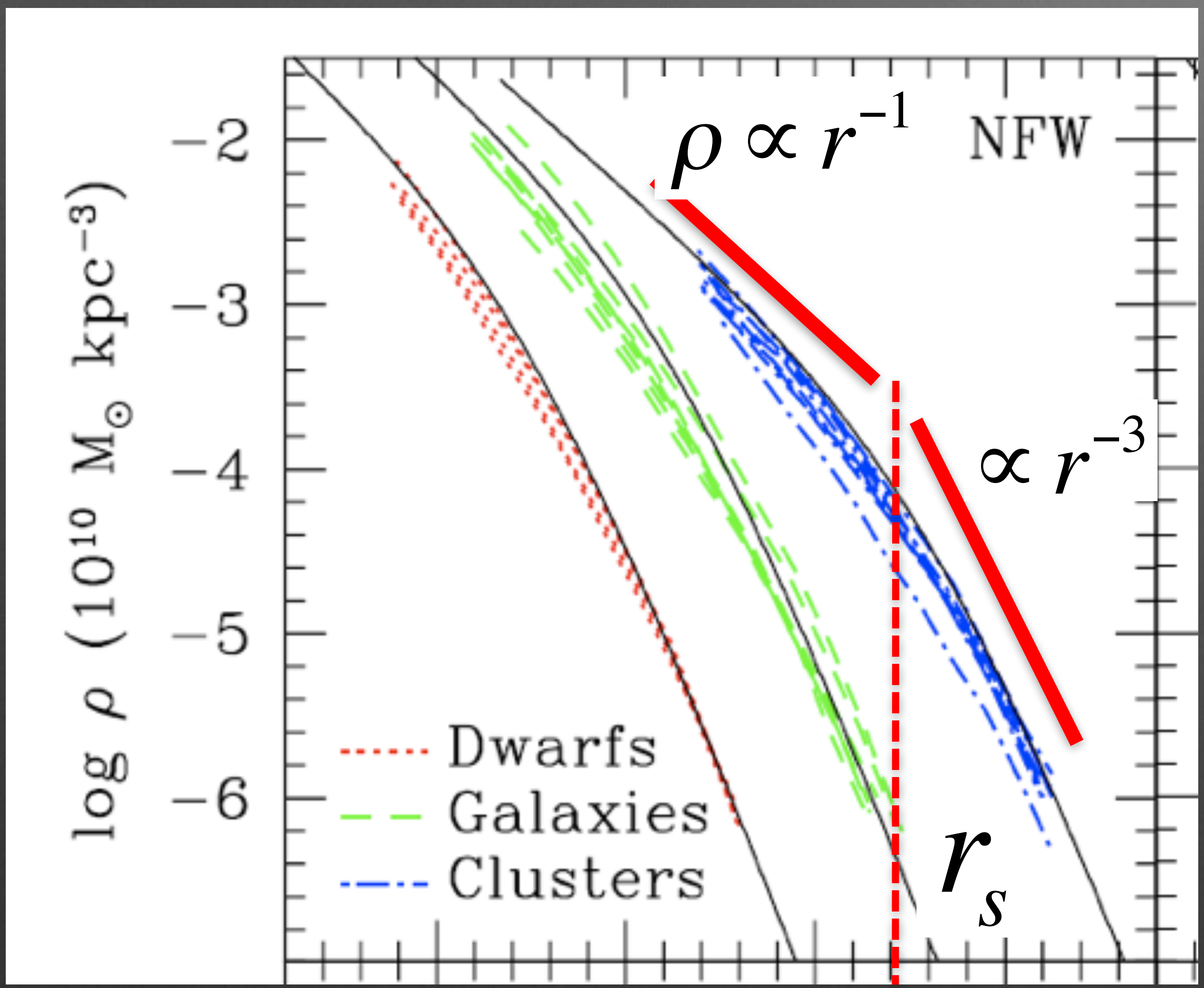
B-mode



An average mass profile for clusters

Universal Mass Profile

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



Navarro+04

$$\rho_{\rm NFW}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

Cluster Mass $M_{\rm vir}$

Concentration parameter

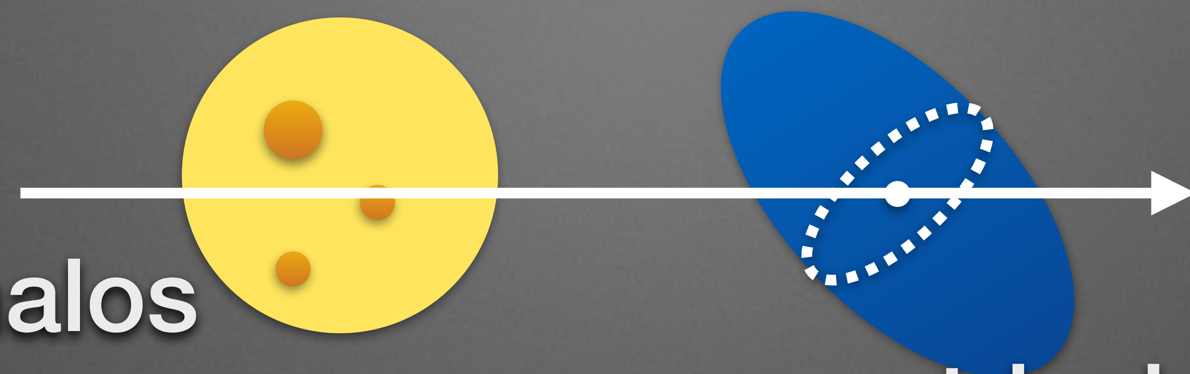
$$c_{\rm vir} = r_{\rm vir}/r_s$$

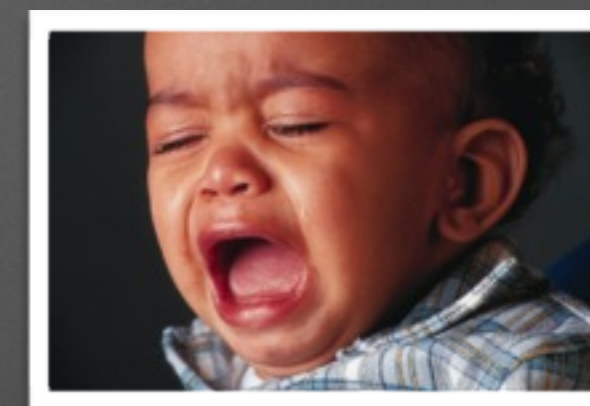
The mass and concentration are correlated.

A test of the CDM hierarchical structure formation scenario

Stacked Weak-lensing analysis for *50 clusters (LoCuSS)*

intrinsic properties = Mass, Concentration, subhalos, triaxiality….

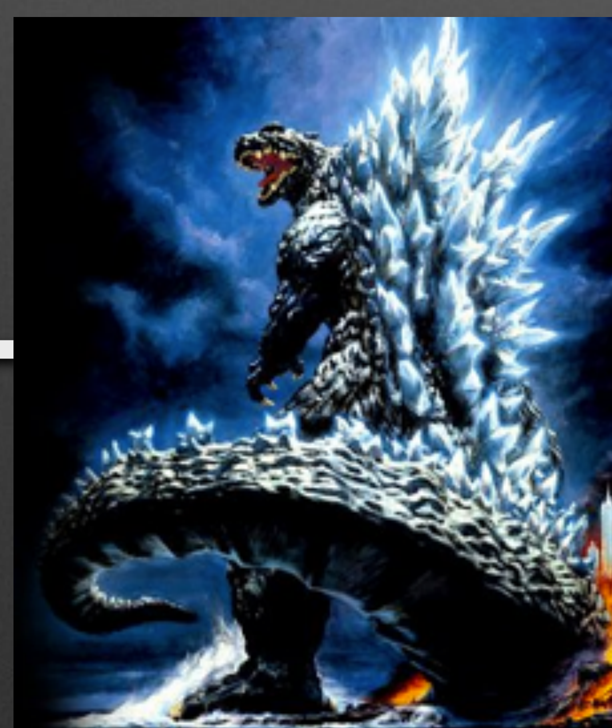




Stacking lens signals

=less sensitive to individual properties.

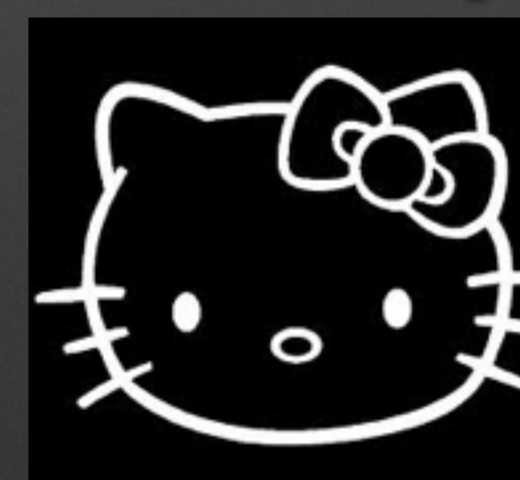
+



+

..=

“dark“halo” kitty

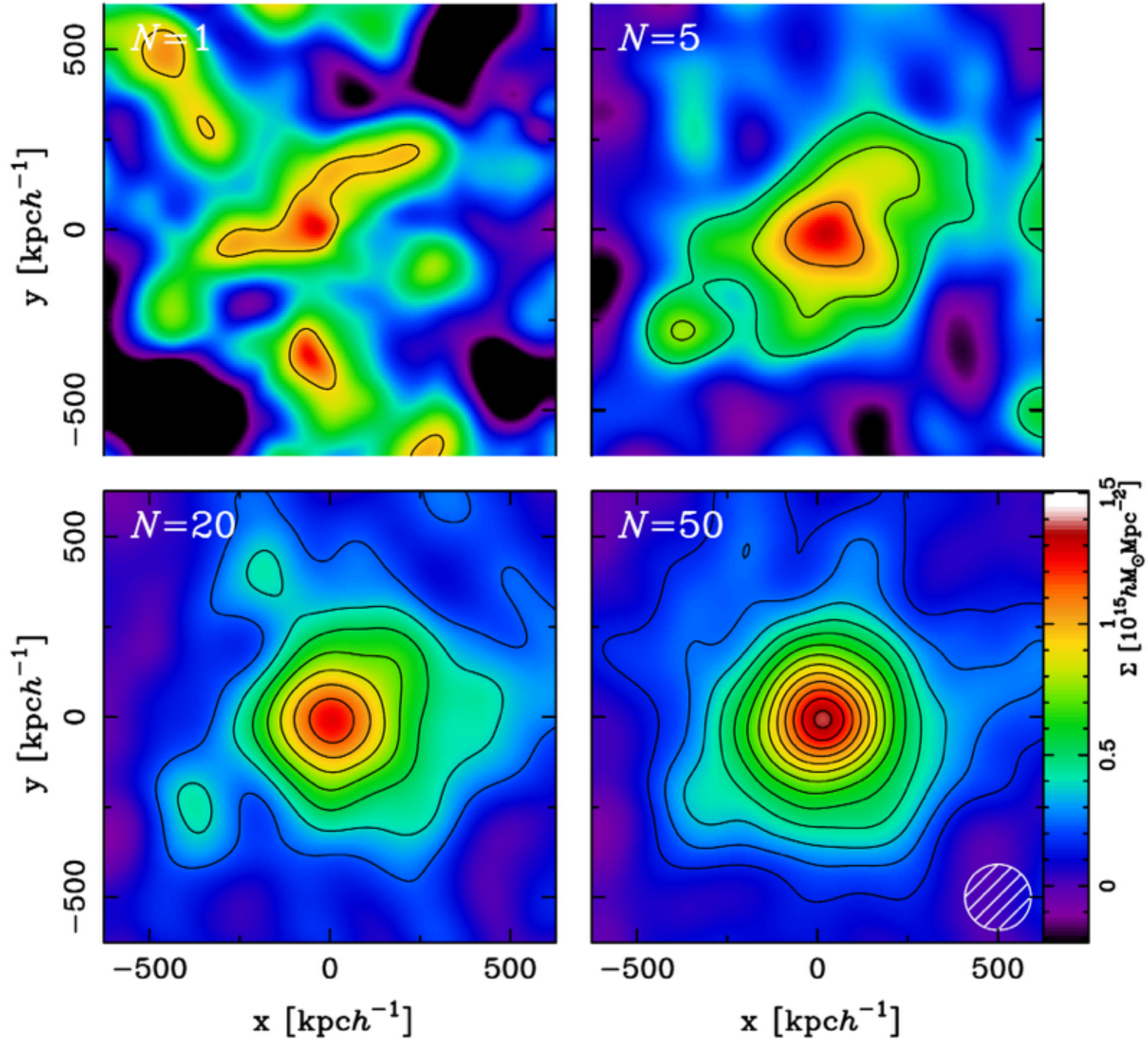


cluster 1

cluster 2

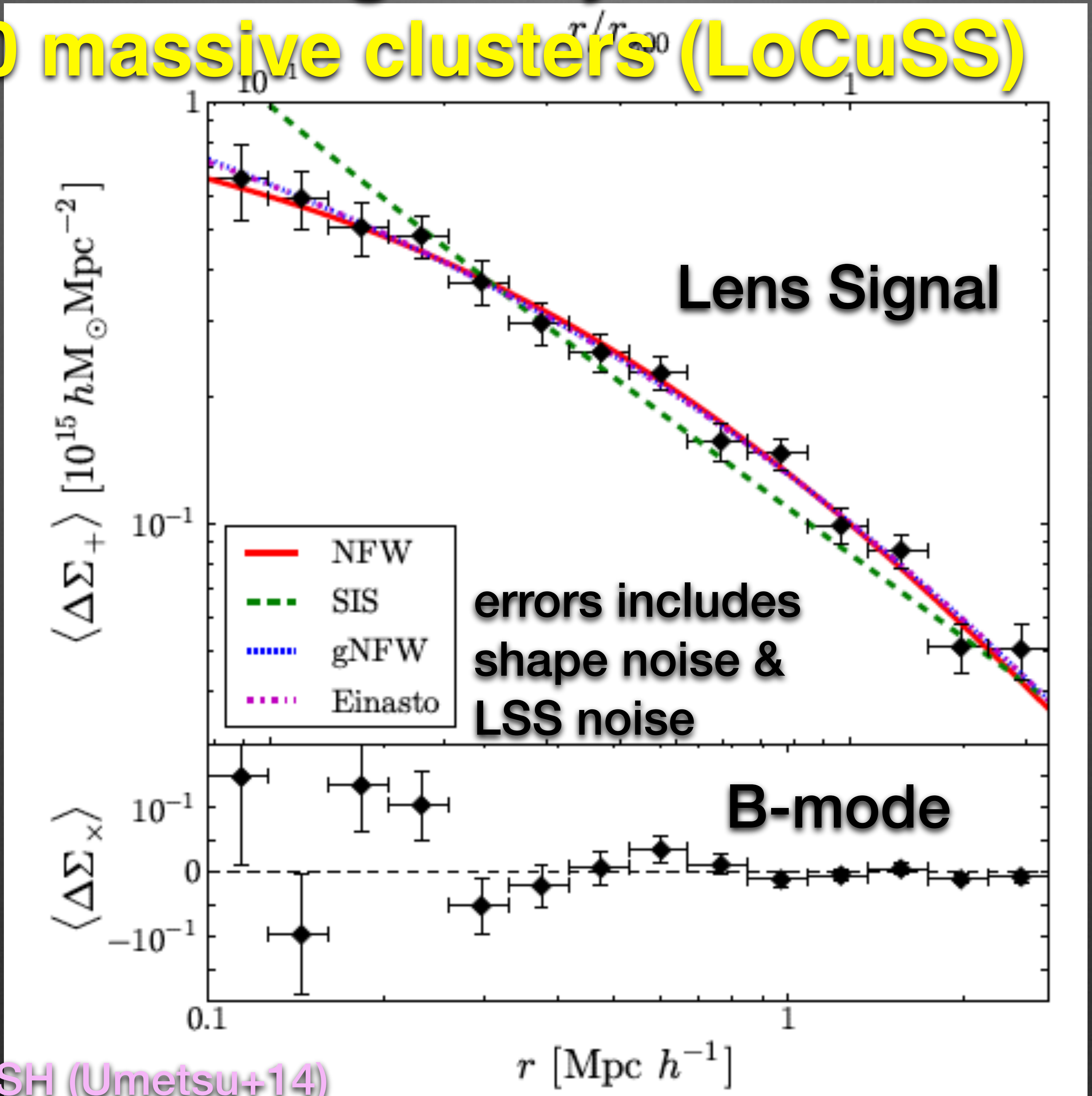
cluster 3

average



N=1
N=5
N=20
N=50
500
0
−500
y [kpch^{-1}]
x [kpch^{-1}]
Σ [$10^{15}h$M$_\odot$Mpc^{-2}]
0
0.5
1
1.5

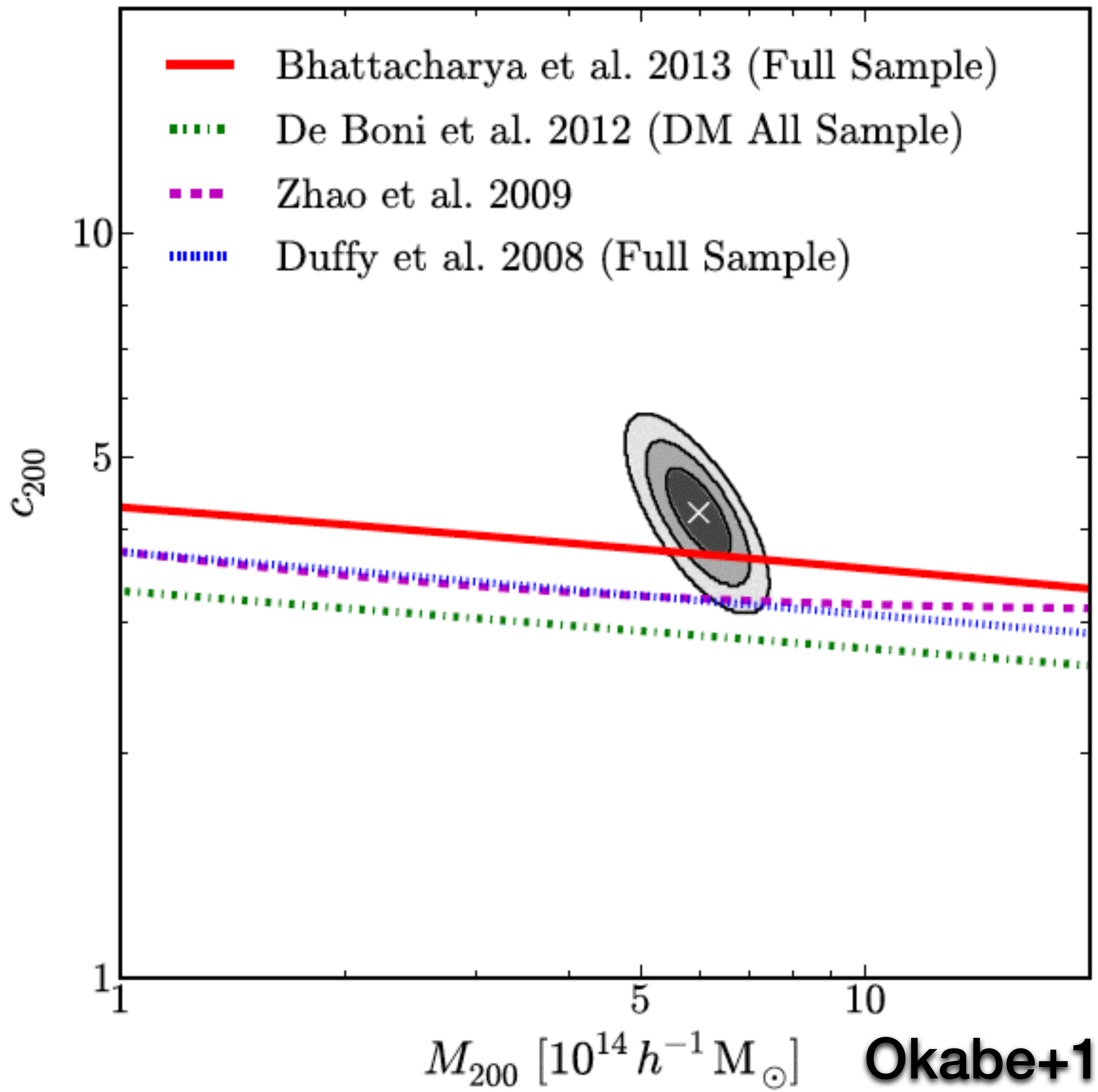
Stacked lensing Analysis for 50 massive clusters (LoCuSS)



z~0.2

Okabe+13

e.g. CLASH (Umetsu+14)



Bhattacharya et al. 2013 (Full Sample)
De Boni et al. 2012 (DM All Sample)
Zhao et al. 2009
Duffy et al. 2008 (Full Sample)
10
5
1
c_{200}
1
5
10
M_{200} [$10^{14}\,h^{-1}\,\mathrm{M}_\odot$]

Okabe+13

Joint Suzaku X-ray and Subaru Weak-Lensing Analysis

Observations are expensive!!

- X-ray : typical integration time of outskirts

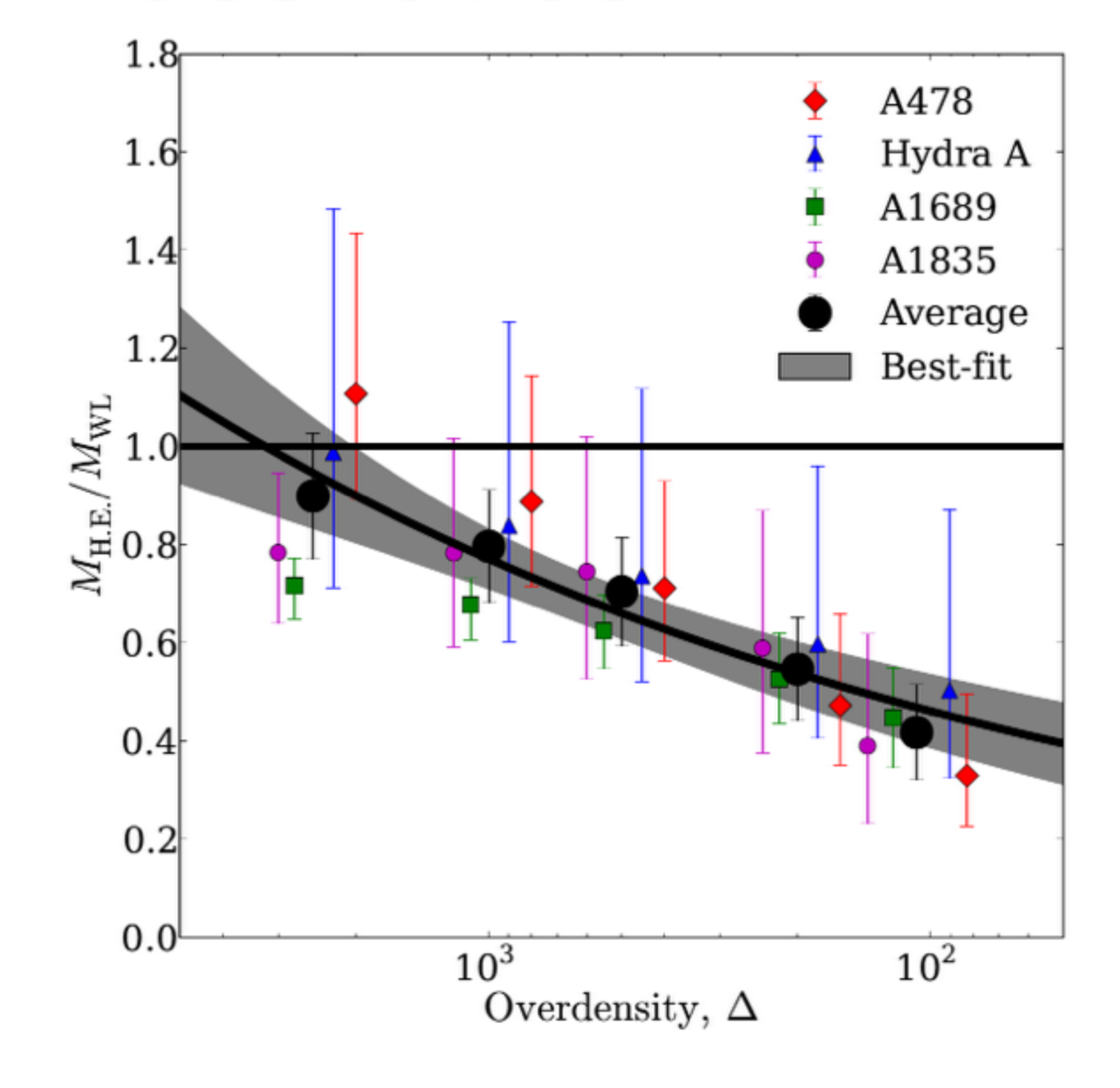
> 200 ksec ⟷ ~20 - 50 ksec ($<r_{500}$)

- WL : Subaru observation of very nearby clusters (z<0.1 : ~4 deg^2)

~ 4 hours ⟷ ~ 1 hour (z~0.2)

Name	z	L_X $[10^{45}\mathrm{ergs}^{-1}]$	$\langle k_B T \rangle$ [keV]	M_{200} $[h_{70}^{-1} 10^{14} M_\odot]$
Hydra A	0.0538	0.27	3.0	$3.72^{+2.11}_{-1.44}$
A 478	0.0881	0.72	7.0	$13.05^{+4.12}_{-3.30}$
A 1689	0.1832	1.25	9.3	$16.73^{+4.88}_{-3.44}$
A 1835	0.2528	1.97	8.0	$10.35^{+2.80}_{-2.40}$

X-ray hydrostatic to WL total mass ratios



MH.E. < MWL

at $\Delta > 1000$

MH.E.~70% MWL

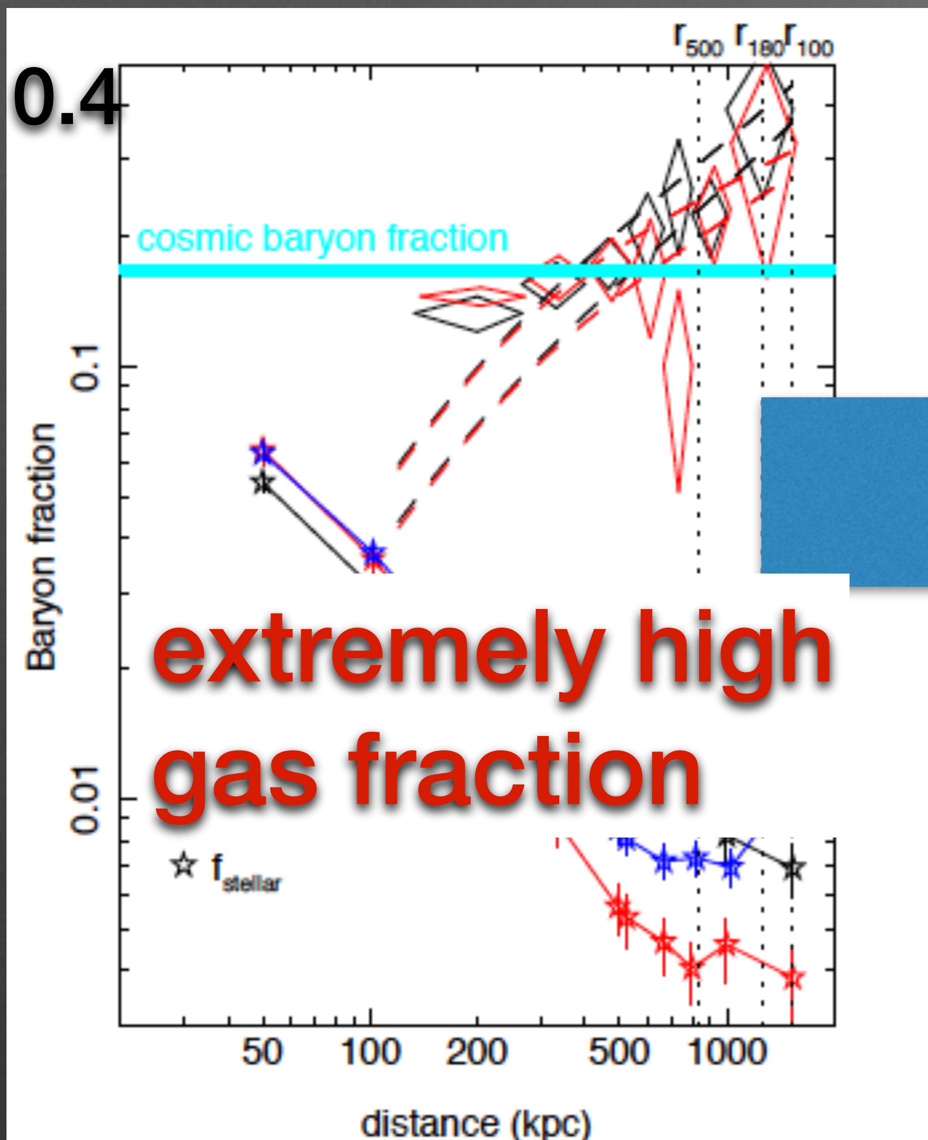
at $\Delta = 500$

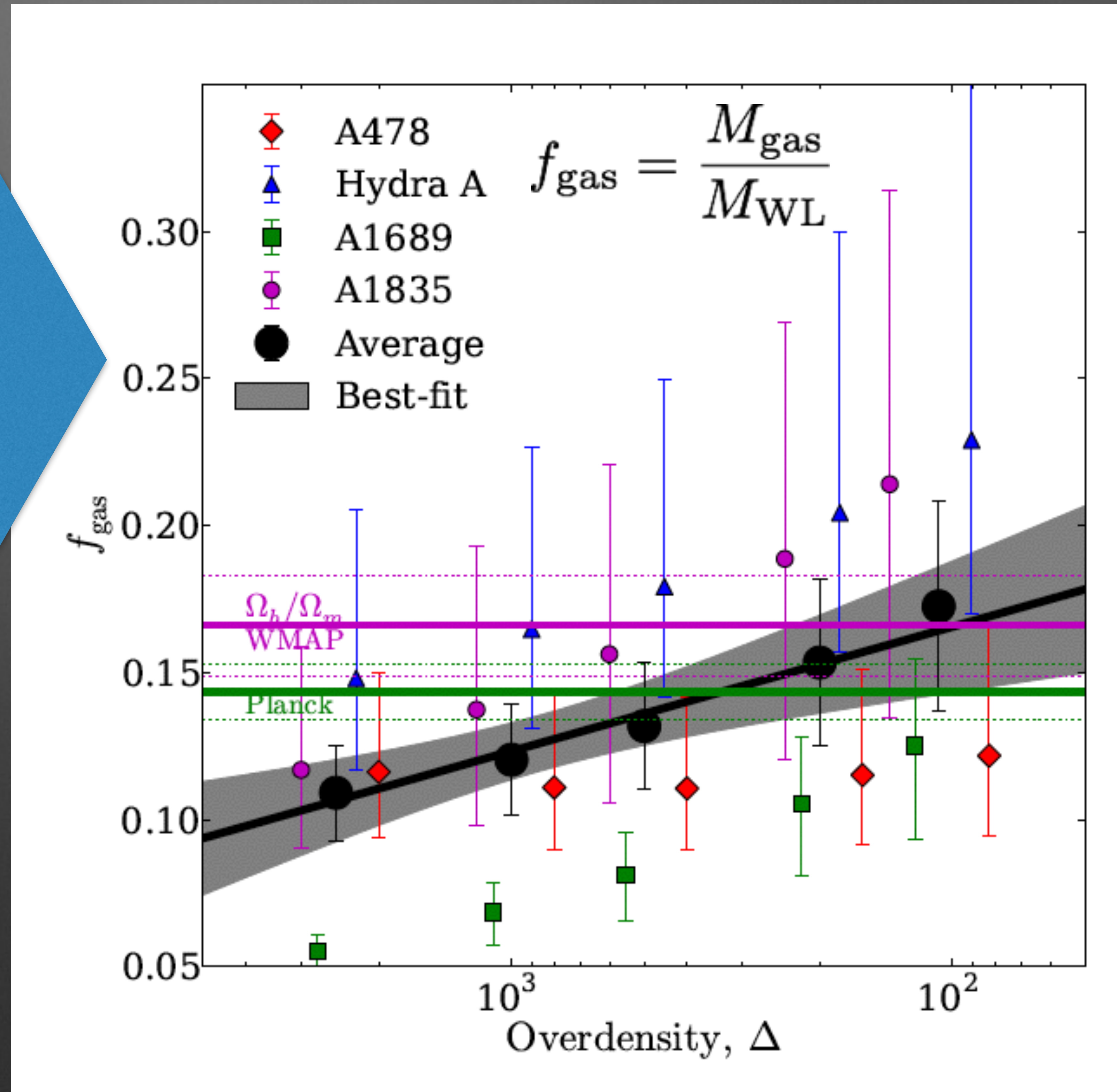
Radial dependence (3 sigma)

important for cluster cosmology.

Okabe+14b
arXiv:1406.3451

Gas Mass Fraction

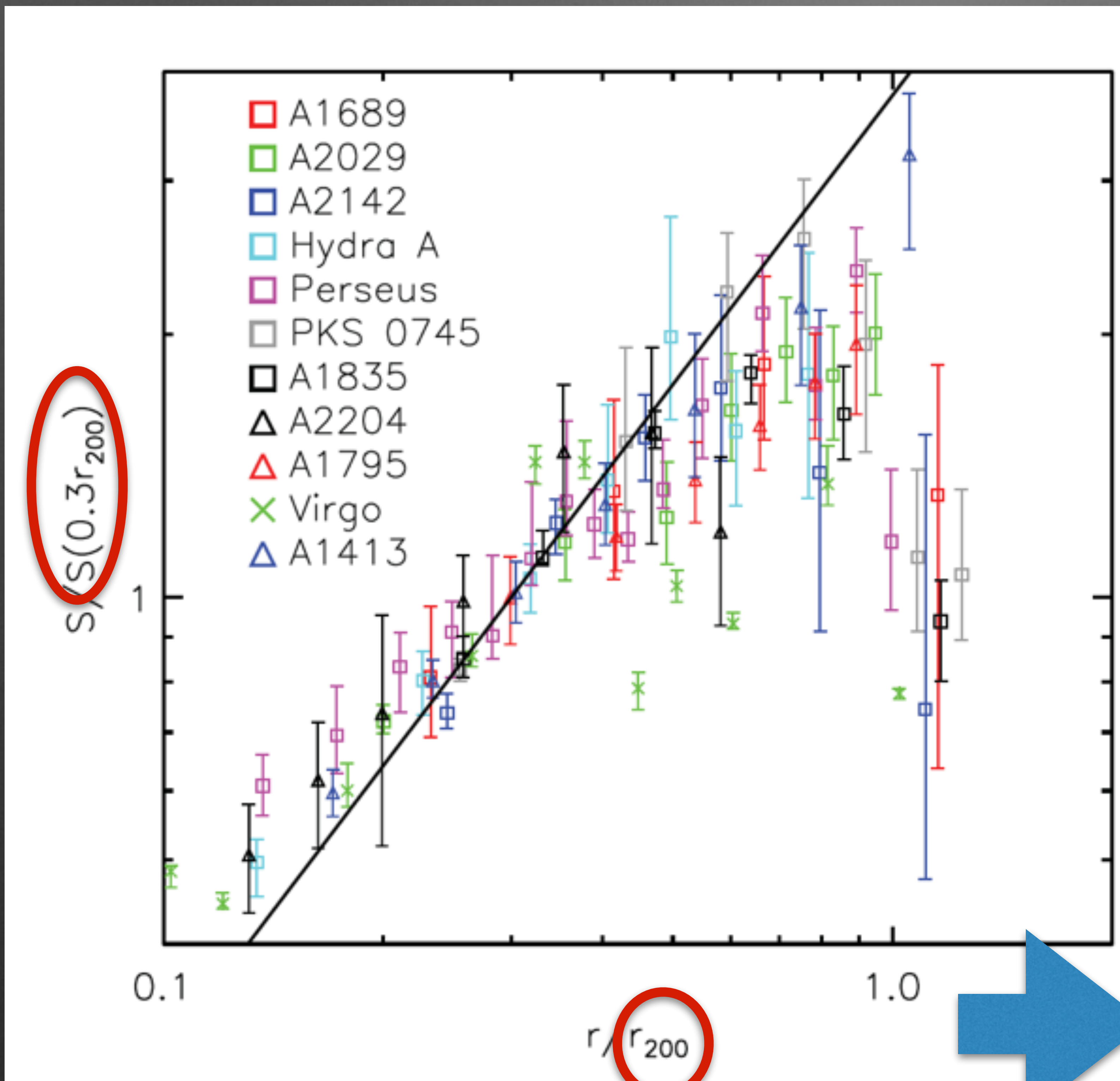




e.g. : Sato+12
Hydra A

based on $M_{H.E.}$ mass

Normalized Entropy Profile



Traditional method

Step 1 :

Estimates normalization factors using scaling relation.

Step 2 :

Normalized the profile to unity at a pivot radius.

Step 3 :

Fitting the normalized profile with given function.

Error propagation becomes very difficult.

New method

Mass-observable scaling relation
X
radial profile

$$f_K(M_\Delta, \tilde{r}) = K_0 E(z)^{-4/3} \left(\frac{M_\Delta E(z)}{10^{14} h_{70}^{-1} M_\odot} \right)^a \times (\tilde{r}/\tilde{r}_0)^\alpha \left(1 + (\tilde{r}/\tilde{r}_0)^\beta\right)^{-\alpha/\beta}$$

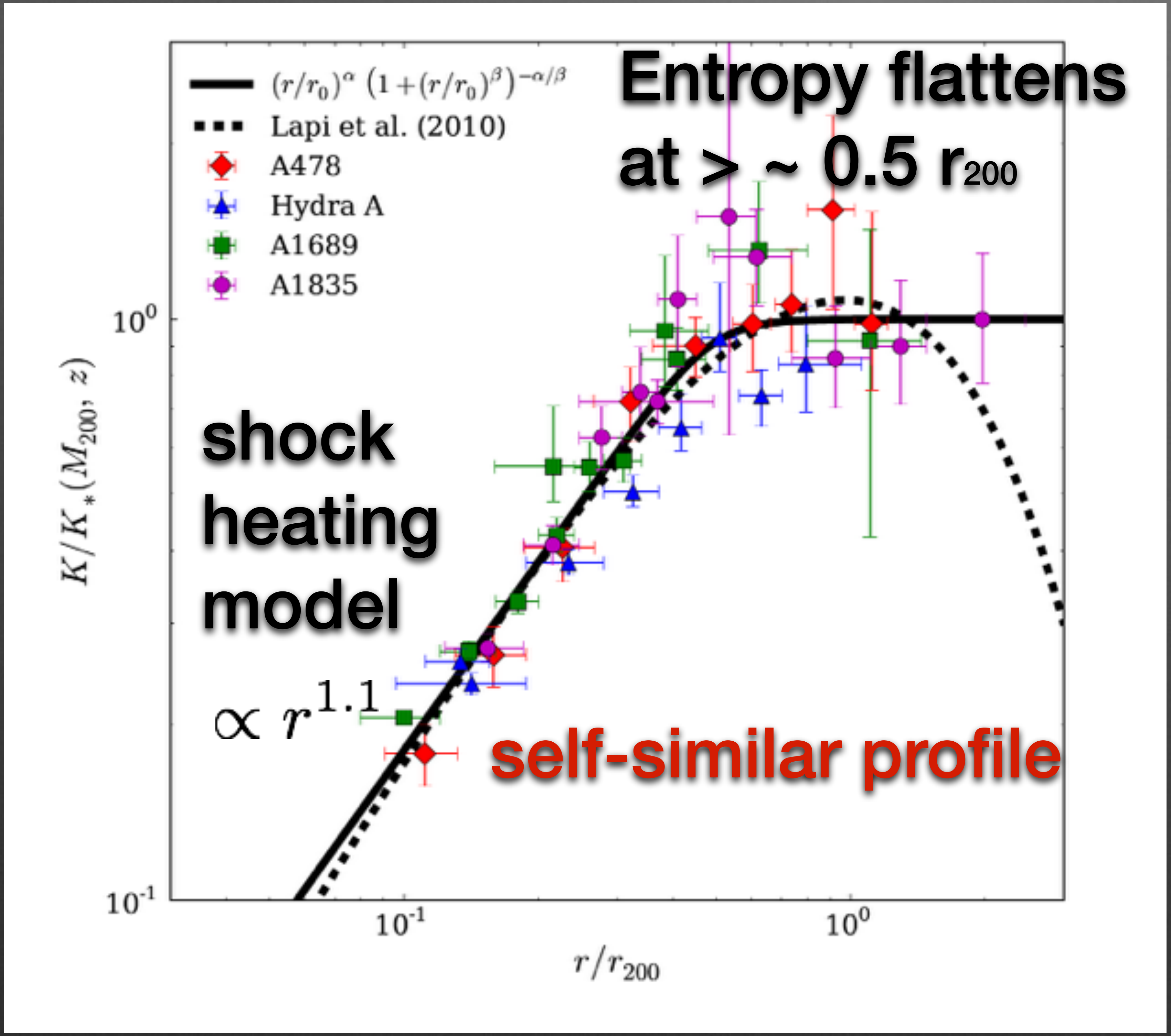
scaling relation　　　radial profile

Simultaneously fitting multiple data points of all clusters with WL mass and overdensity radius.

All errors from X-ray observables and WL masses are considered.

This new method enables us to measure an average profile, which is complementary to the stacked method (we don't need re-analysis of stacked X-ray profile).

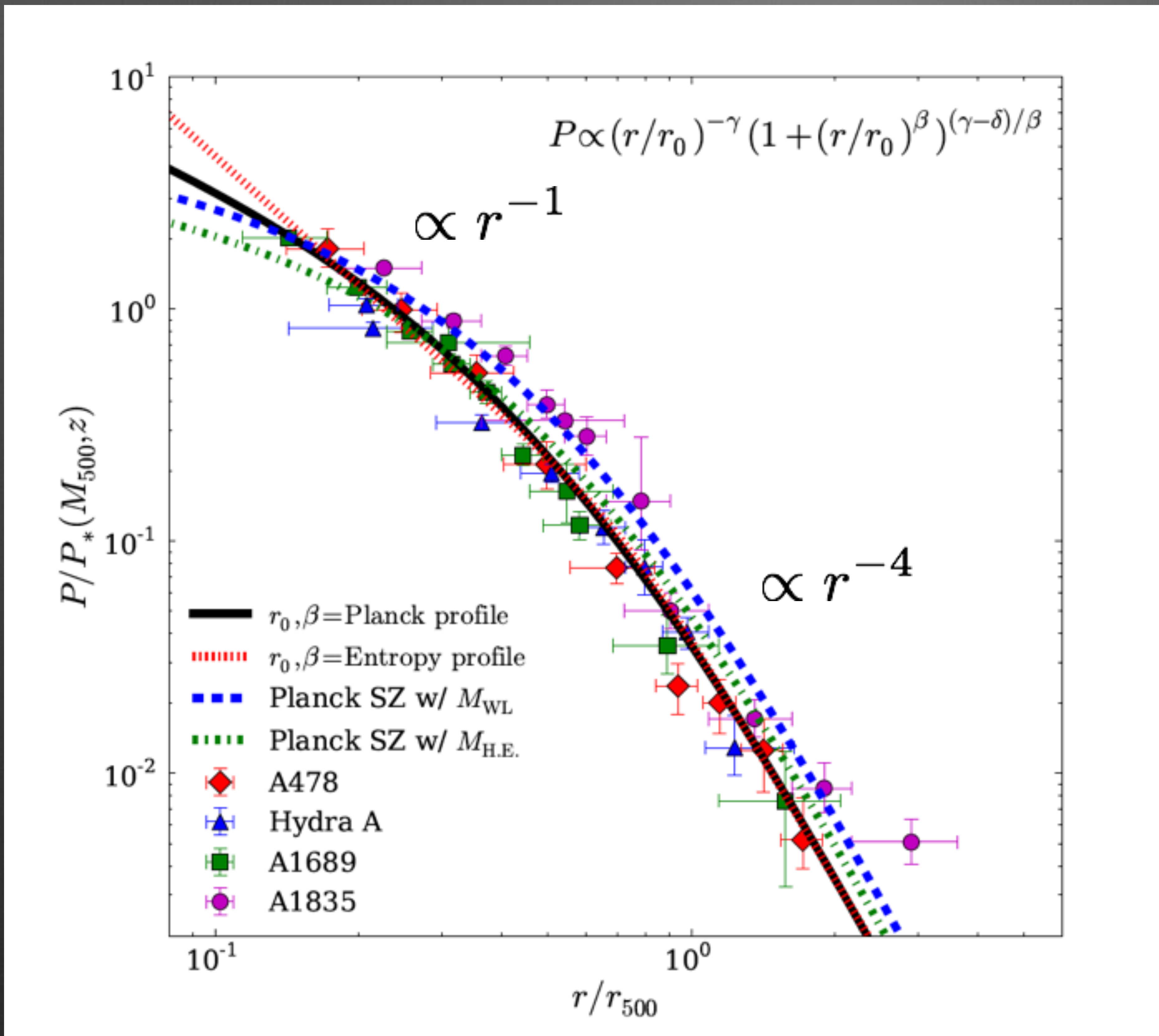
Normalized Entropy Profile



- Thermalization mechanism over the entire cluster region is controlled by the gravity.
- Heating efficiency in cluster outskirts needs to be modified from the standard law.

Okabe+14b arXiv:1406.3451

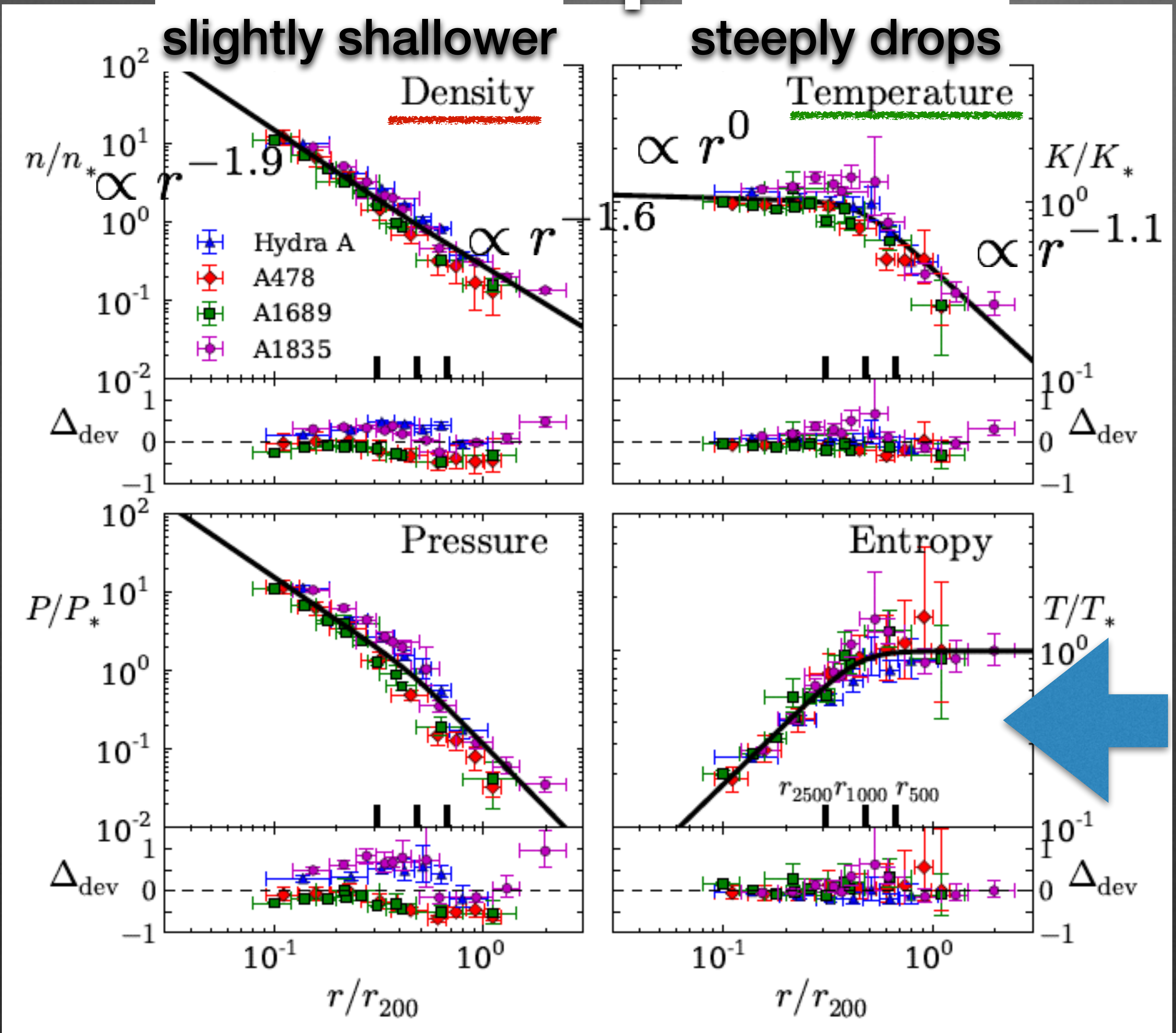
Normalized Pressure Profile



Pressure slope steepens

Consistent with the average Planck SZ profile

Joint fit with Number Density and Temperature Profiles



Caused by the steeping T profile, rather than the flattening n profile.

Summary

1. Several research groups reported that outskirts entropy flattens beyond ~0.5 r_{vir}.

2. Weak-lensing mass is a key to understand the ICM in cluster outskirts.

3. $M_{H.E.}/M_{WL}$ is decreasing from 70% (r_{500}) to 40% (r_{vir}).

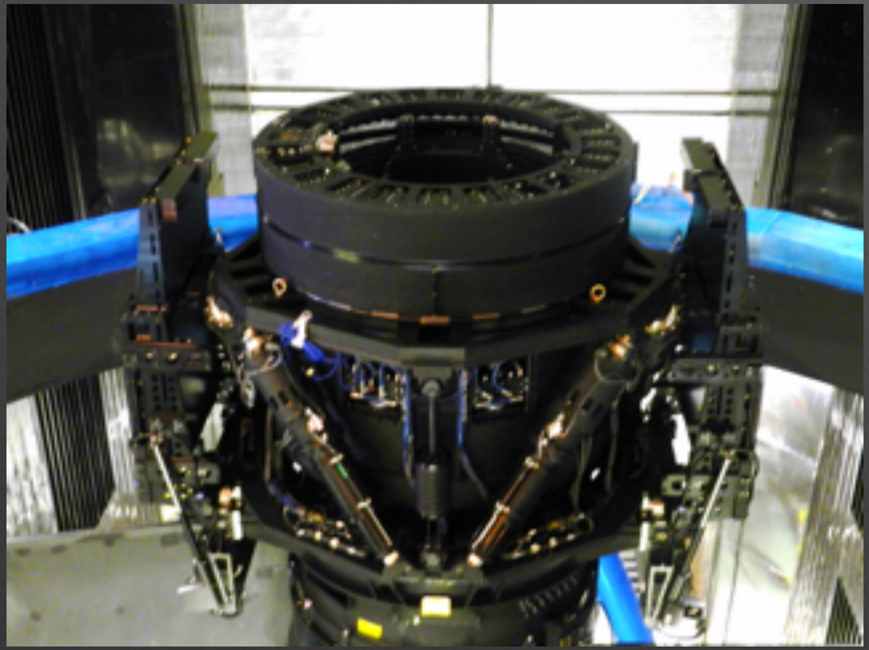
4. Gas profiles normalized by the weak-lensing mass and over-density radius are surprisingly self-similar.

5. The flattening entropy is caused by the steeping of the temperature profile, rather than by the flattening of the density profile.

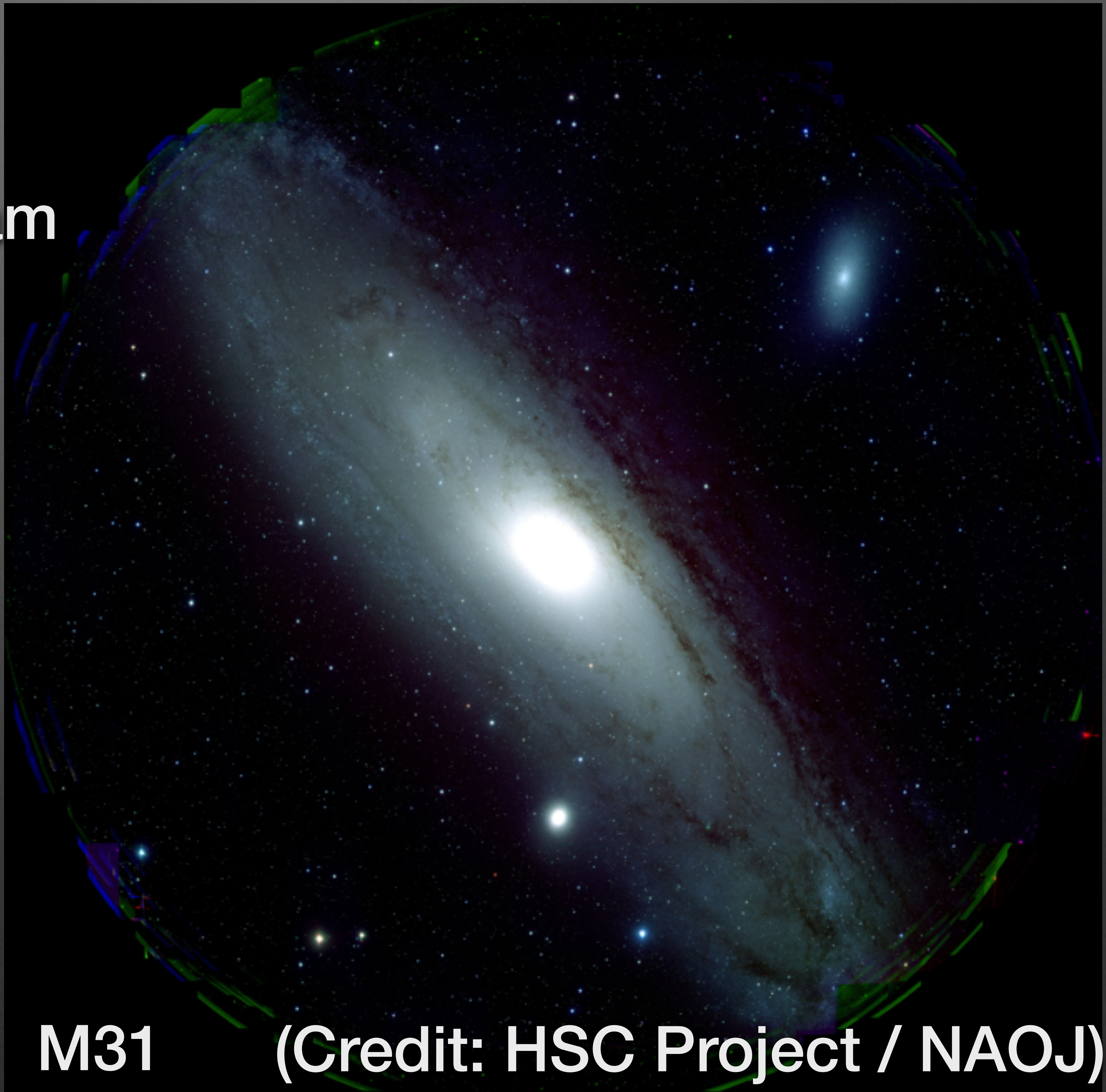
6. Future……

Subaru New Prime Focus Camera

Hyper Suprime-Cam
(HSC)

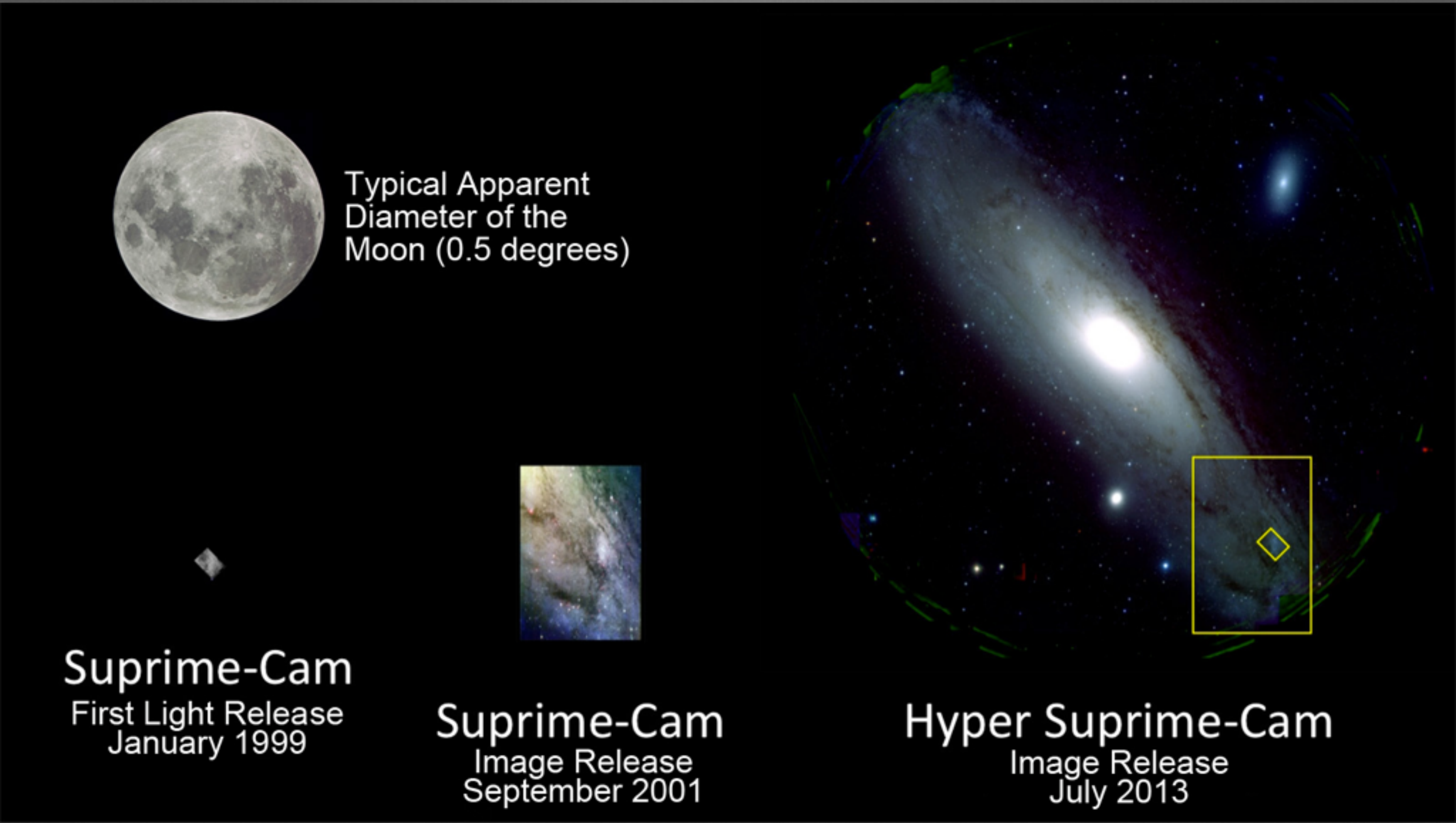


FoV : 1.5 sqdeg



M31 (Credit: HSC Project / NAOJ)

Subaru/HSC



(Credit: HSC Project / NAOJ)

HSC Survey started !

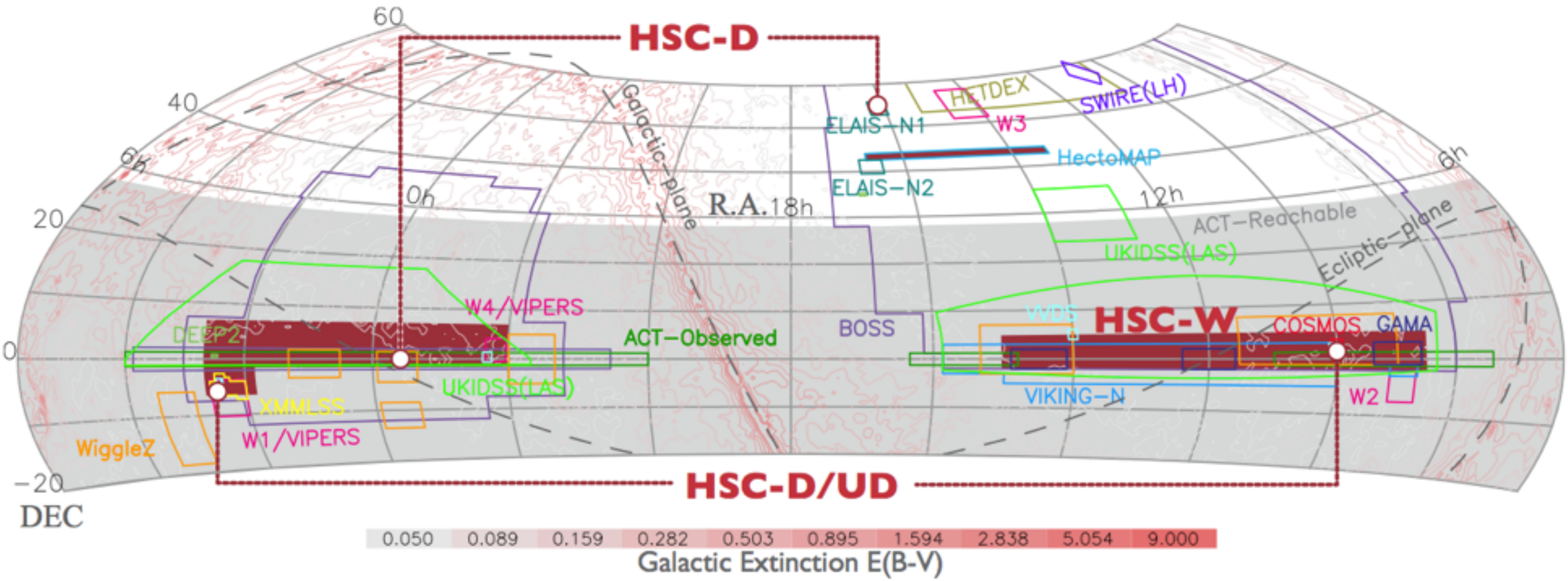
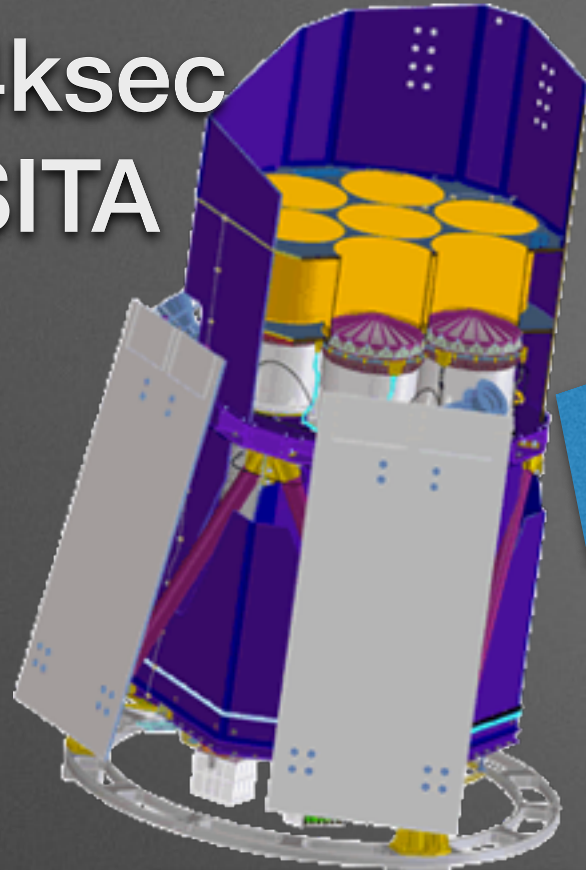


Figure 11: The location of the HSC-Wide, Deep (D) and Ultradeep (UD) fields on the sky in equatorial coordinates. A variety of external data sets and the Galactic dust extinction are also shown. The shaded region is the region accessible from the CMB polarization experiment, ACTPol, in Chile.

- 1400 sqdeg
- full 5-bands : g'r'i'z'y'
- good seeing : ~0."7
- 2014-2019 (300 nights)
- overlapped with ACT (ACT-pol: SZ) region

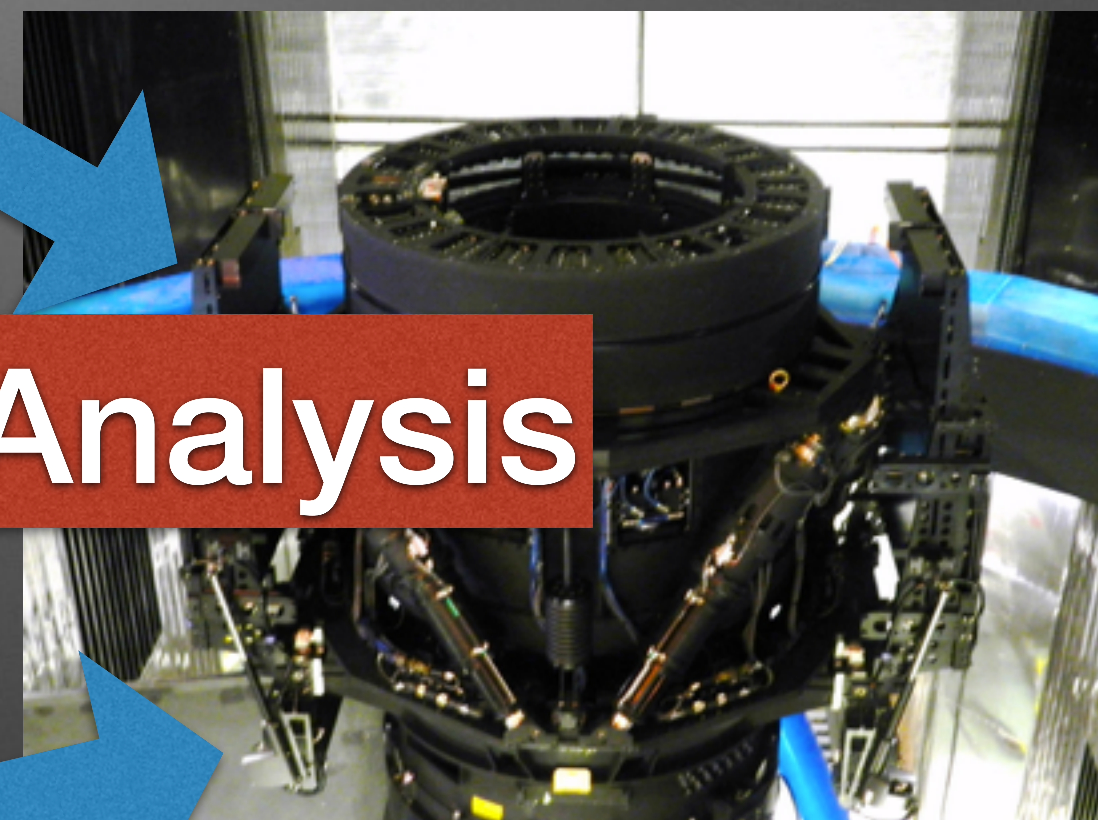
reconstruct DM distirubtion up to z ~1.5

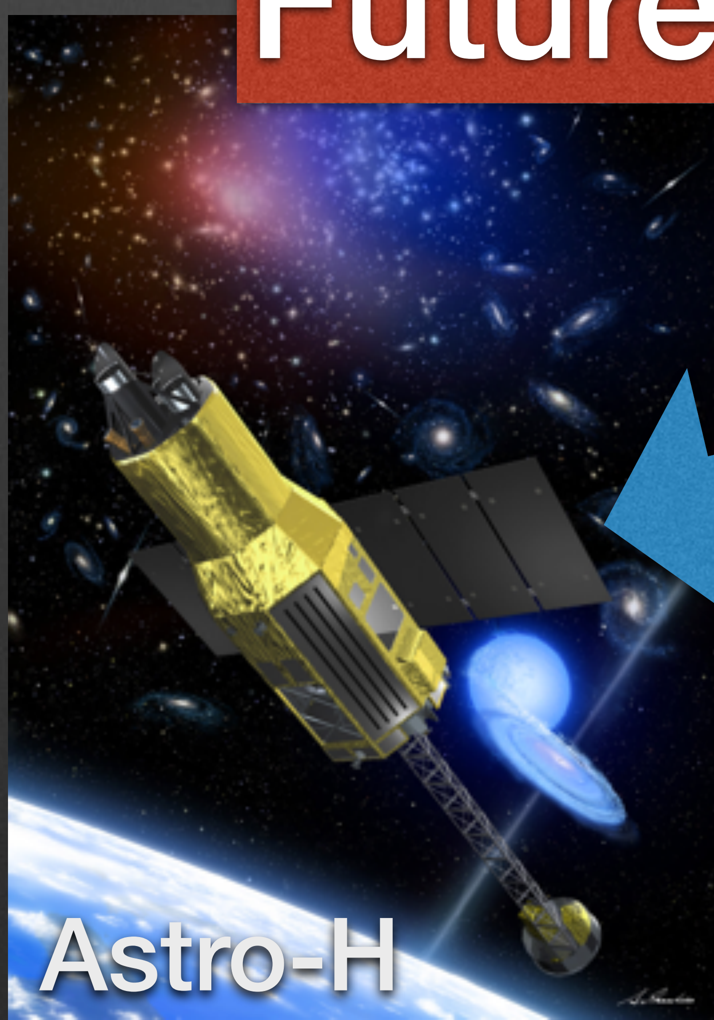
~ 2-4ksec
eROSITA



A joint study will encourage the X-ray, optical and WL community.

Future Joint Analysis





Subaru/HSC

1: high quality photometric data
2: optical-identified cluster sample
3: WL masses