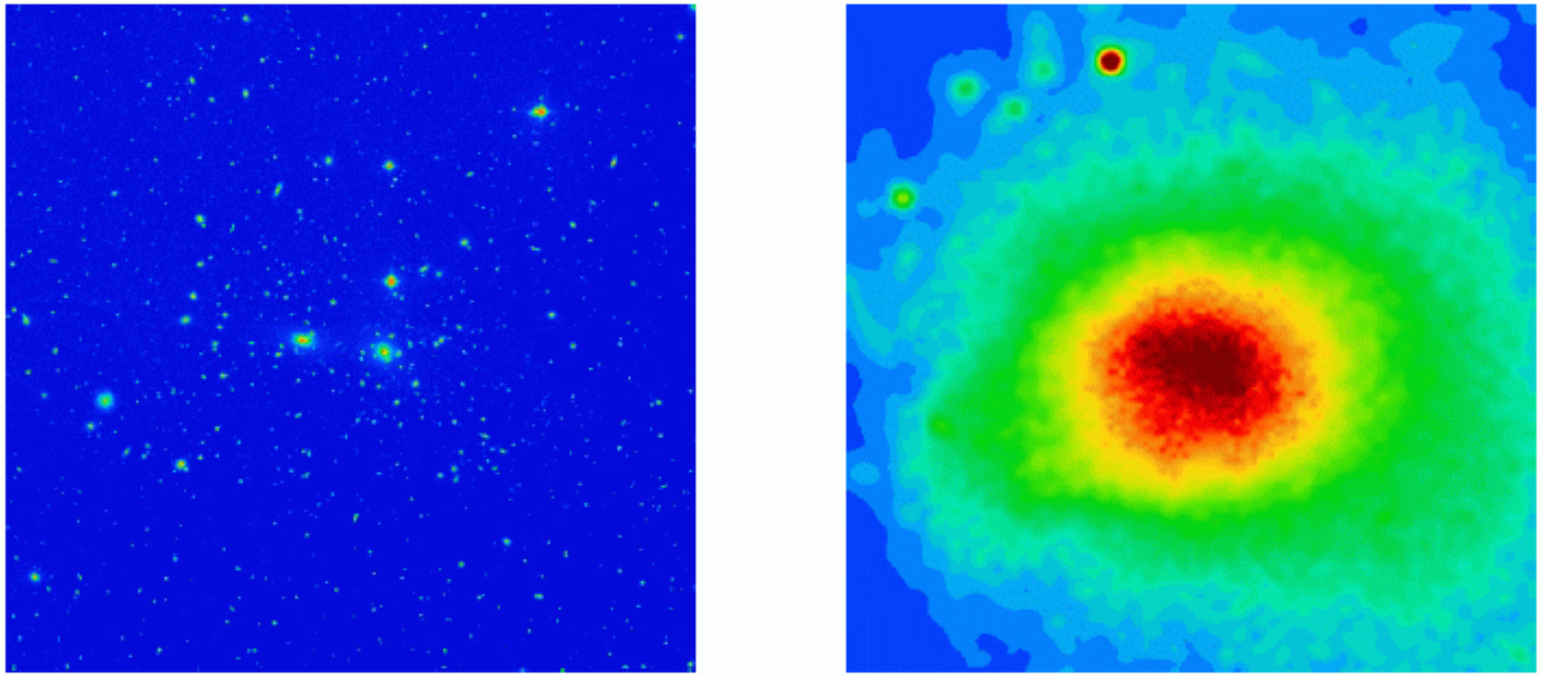
X-RAY SCALING RELATION OF GALAXY CLUSTERS

Qinxun Li

Clusters are among the most luminous x-ray sources in the sky. This X-ray emission comes from hot intracluster gas.

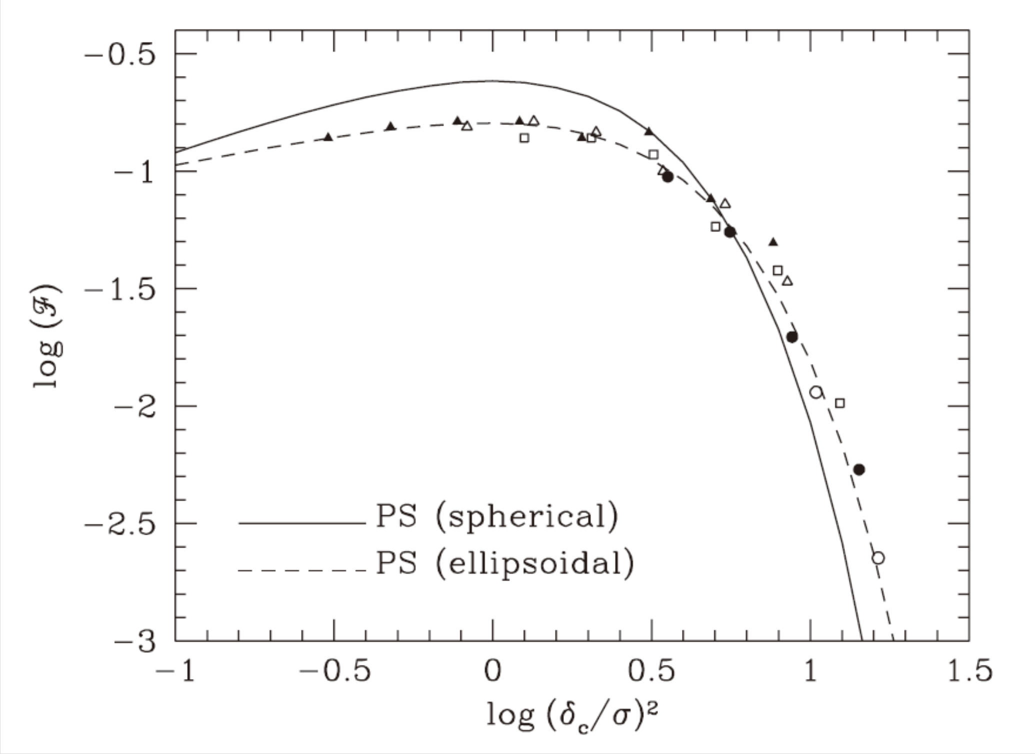


Coma cluster

X-ray observations provide information on the amount, distribution, temperature and chemical composition of the Intracluster gas

MOTIVATION

CLUSTER COSMOLOGY

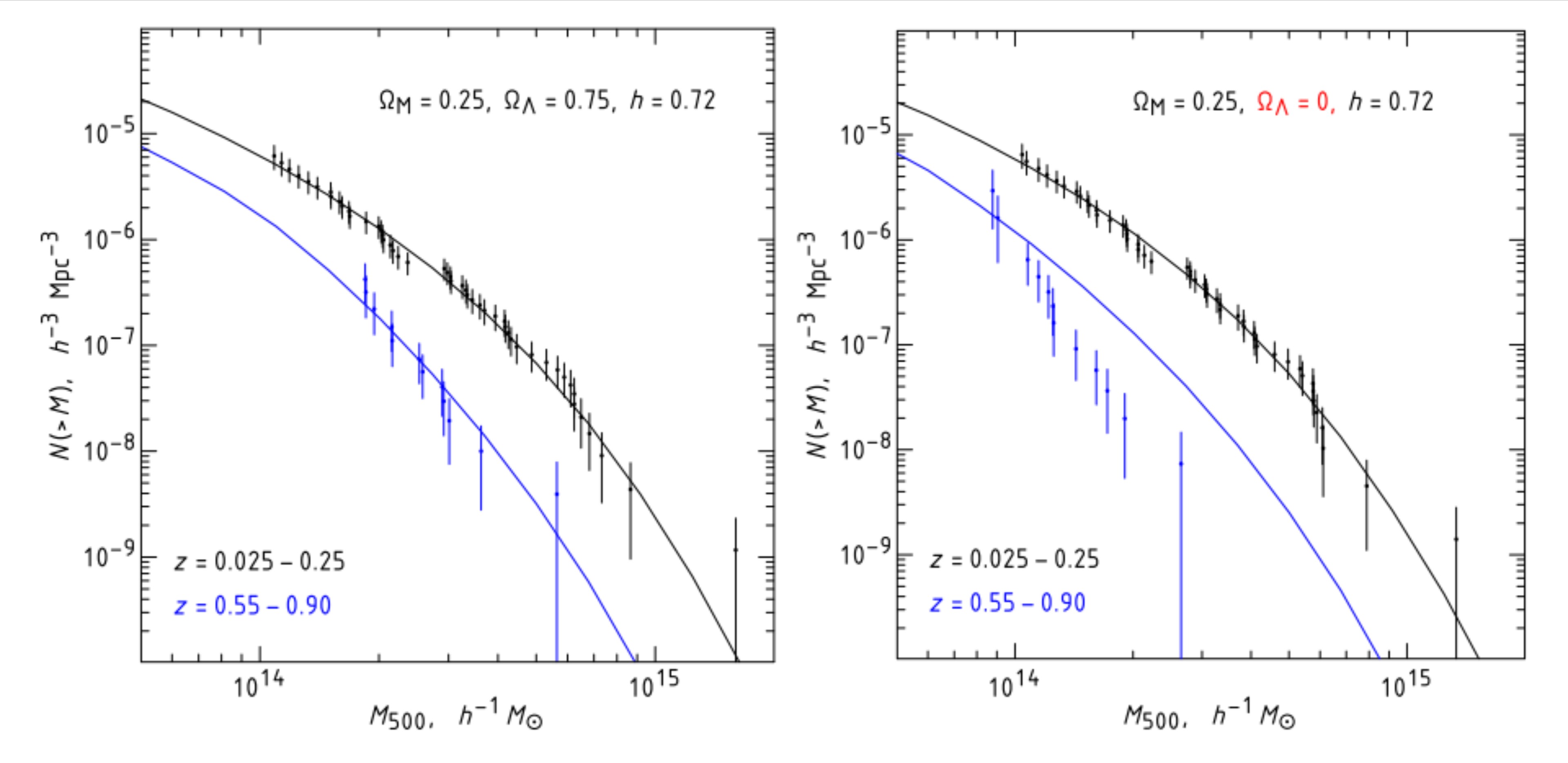


- The number of galaxy clusters above halo mass M_A can be predicted from halo mass function:

$$N(M_{\mathrm{A}}) = \frac{4\pi r_8^3}{3}\int_{M_{\mathrm{A}}}^{\infty} n(M,t_0)\,\mathrm{d}M$$
$$\approx \frac{2}{\sqrt{\pi}}\left(\frac{\delta_{\mathrm{c}}}{\sqrt{2}\sigma_8}\right)^{3/\beta}\int_{y_{\min}}^{\infty} y^{-3/\beta}\exp(-y^2)\,\mathrm{d}y,$$

- So, measuring halo mass of massive cluster can be a probe to HMF and cosmology
- X-ray observation is powerful to find clusters.

CLUSTER COSMOLOGY

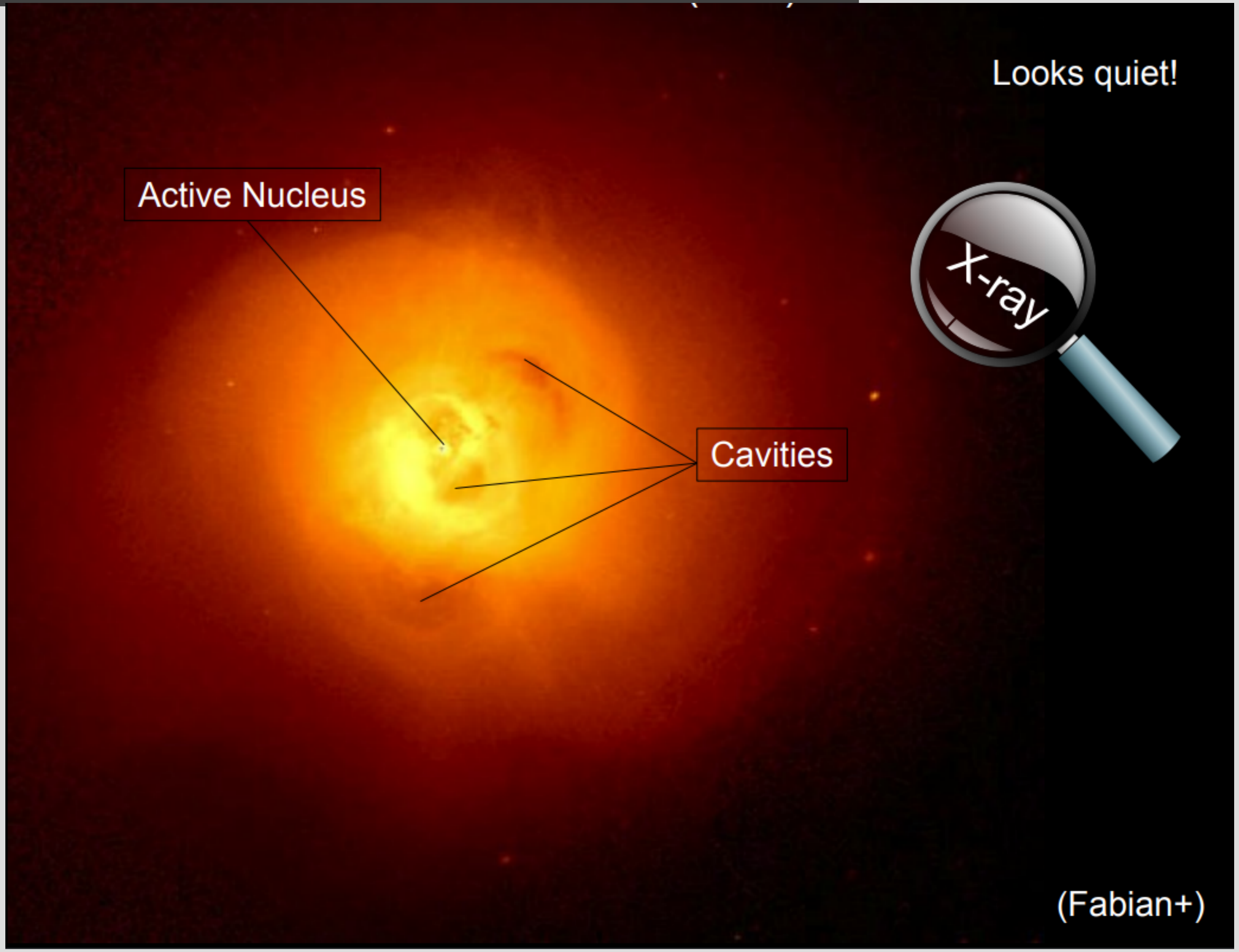


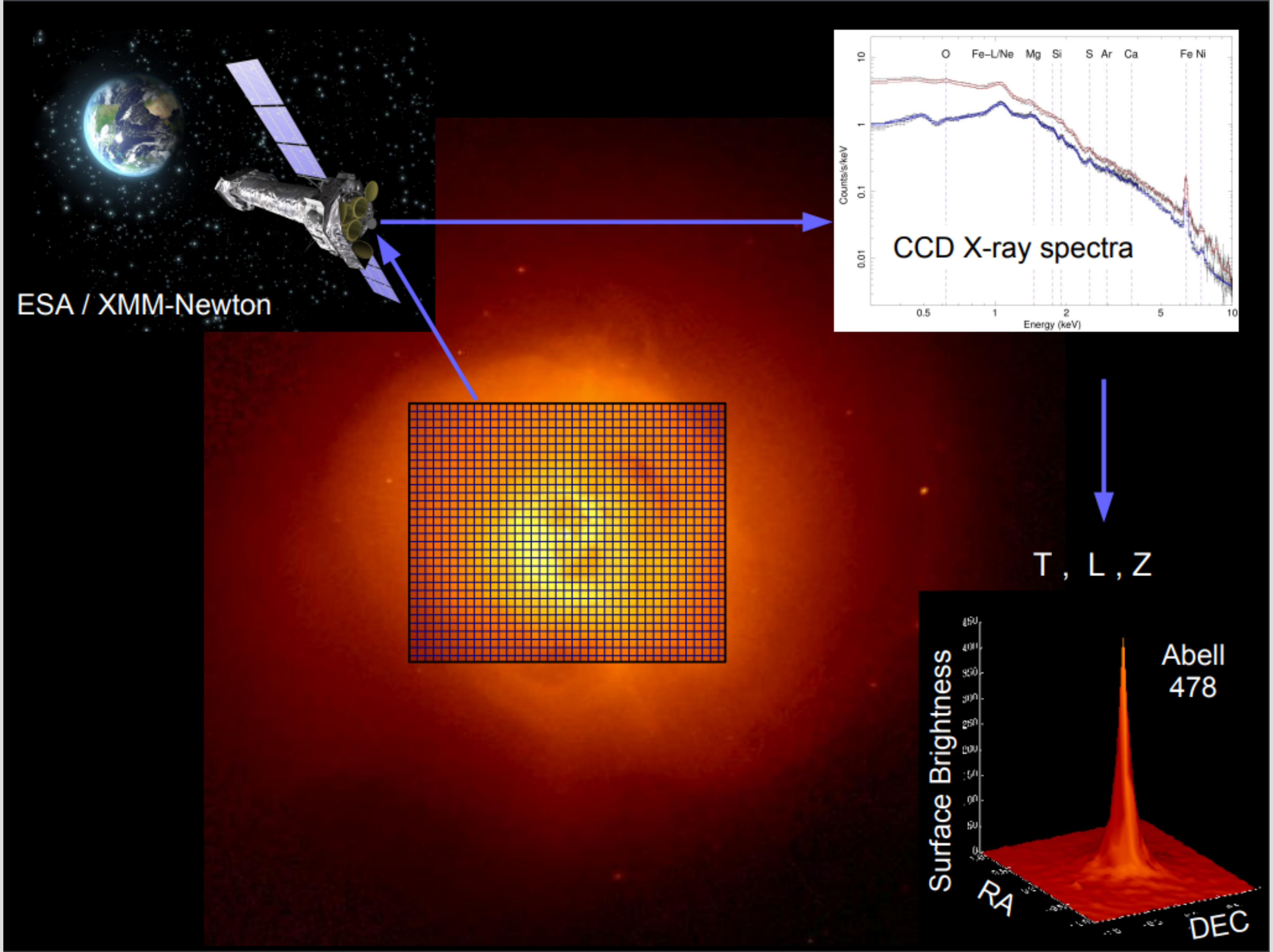
CLUSTER COSMOLOGY

- ✓ Advantages
  - ✓ Clusters provide an efficient way of surveying a large volume of space
  - ✓ Cluster distribution provides information about conditions in the early universe
  - ✓ Clusters can be seen at great distances
- ✓ Disadvantages
  - ✓ Their low space density makes clusters sparse tracers of the large scale structure
  - ✓ Results may depend on the chosen cluster sample
  - ✓ Redshifts of many clusters are still unmeasured

BARYONIC FEEDBACK

- Feedback heats ICM
- Feedback blows gas away
- Change the shape of scaling relation

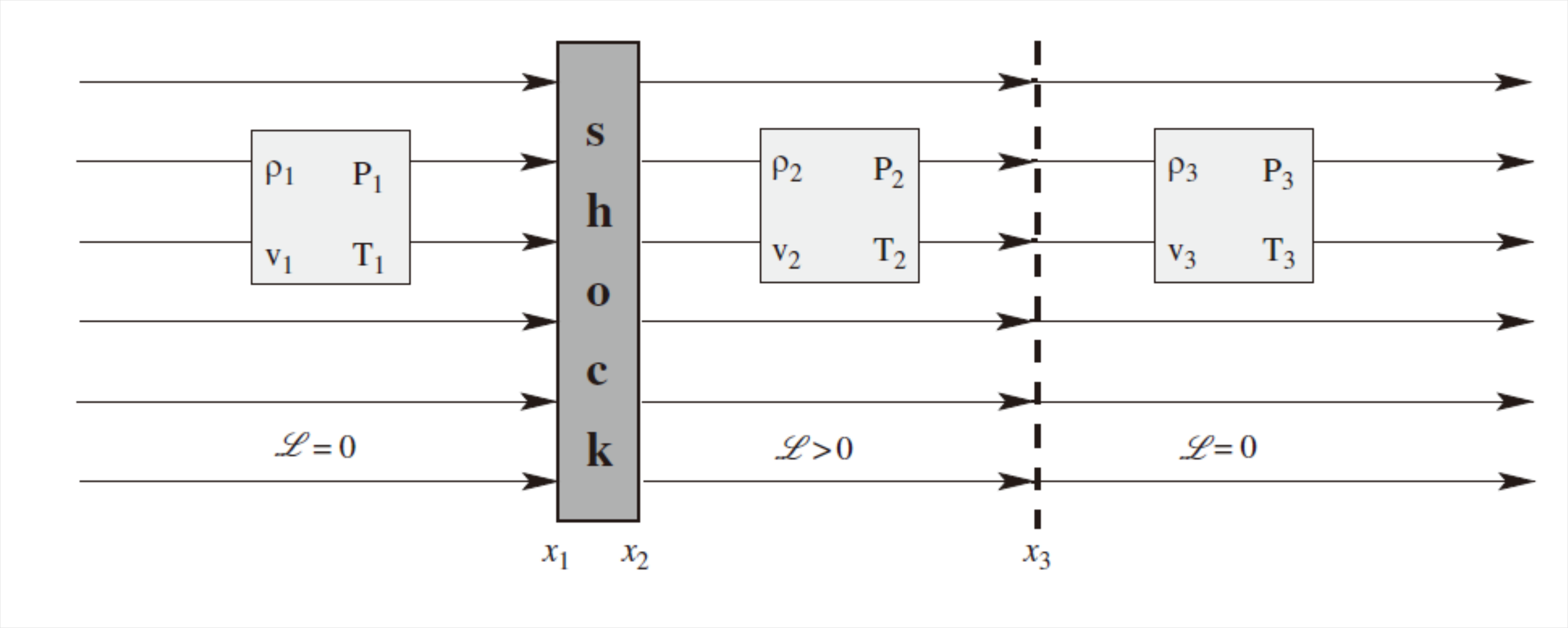


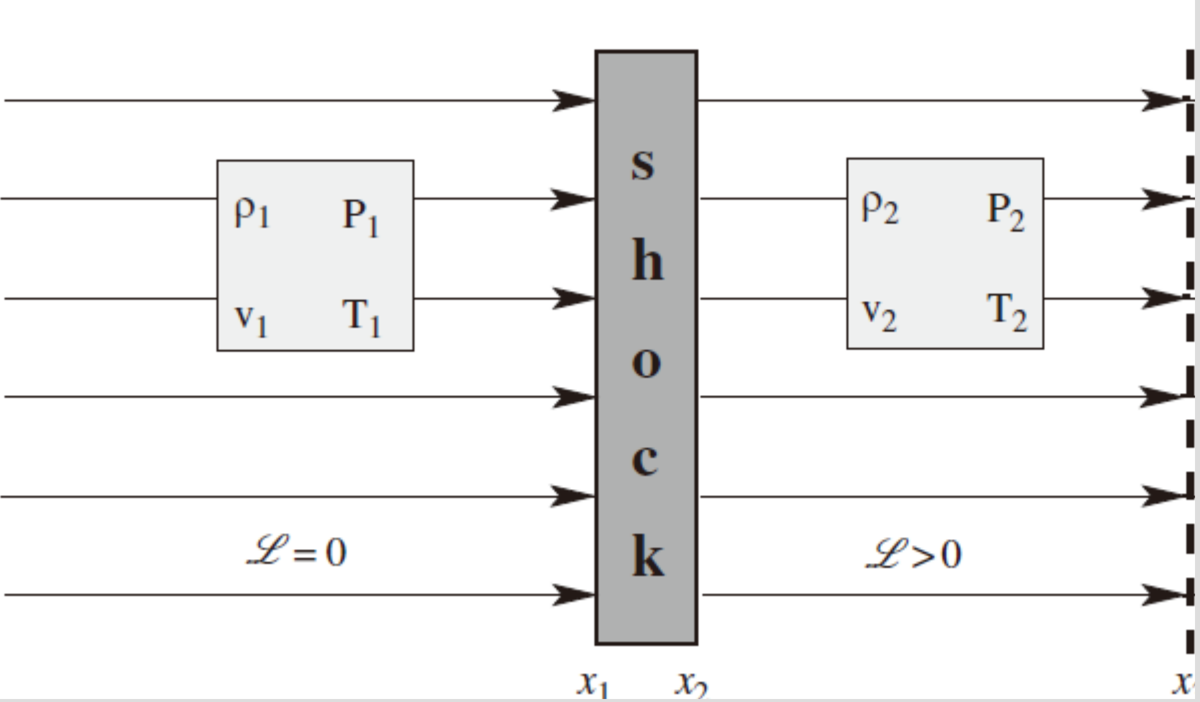


ESA / XMM-Newton
O
Fe–L/Ne
Mg
Si
S
Ar
Ca
Fe Ni
Counts/s/keV
Energy (keV)
CCD X-ray spectra
T , L , Z
Abell 478
Surface Brightness
RA
DEC

I. THEORY

SHOCK HEATING OF ICM





$$\rho_2 v_2 = \rho_1 v_1,$$

$$\rho_2 v_2^2 + P_2 = \rho_1 v_1^2 + P_1,$$

$$\frac{1}{2}v_2^2 + \frac{P_2}{\rho_2} + \mathscr{E}_2 = \frac{1}{2}v_1^2 + \frac{P_1}{\rho_1} + \mathscr{E}_1,$$

$$\frac{\rho_2}{\rho_1} = \frac{v_1}{v_2} = \left[\frac{1}{\widehat{M}_1^2} + \frac{\gamma-1}{\gamma+1}\left(1 - \frac{1}{\widehat{M}_1^2}\right)\right]^{-1},$$

$$\frac{P_2}{P_1} = \frac{2\gamma}{\gamma+1}\widehat{M}_1^2 - \frac{\gamma-1}{\gamma+1},$$

$$\frac{T_2}{T_1} = \frac{P_2}{P_1}\frac{\rho_1}{\rho_2} = \frac{\gamma-1}{\gamma+1}\left[\frac{2}{\gamma+1}\left(\gamma\widehat{M}_1^2 - \frac{1}{\widehat{M}_1^2}\right) + \frac{4\gamma}{\gamma-1} - \frac{\gamma-1}{\gamma+1}\right],$$

v_1大于声速(激波后方马赫数 $\hat{M}_1$大于1)时, 气体被压缩、减速、加热

SELF-SIMILAR MODEL

Mon. Not. R. astr. Soc. (1986) **222,** 323–345

Evolution and clustering of rich clusters

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- Assume pure gravitational heating
- Prove that in this case,

$M \propto T^{3/2}$

$$\frac{M_{\Delta_z}}{R^3_{\Delta_z}} = \text{constant},$$

$$T_{\rm gas} \propto \frac{GM}{R} \propto R^2_{\rm vir},$$

$$M_{\Delta_z} \propto T_{\rm gas}^{\frac{3}{2}},$$

Why hydrostatic equilibrium?

– The intracluster gas will respond to changes at a rate determined by the sound speed.

– The sound speed in an ideal monatomic gas is

$$v_{sound} \sim \sqrt{\frac{5k_BT}{3\mu m_H}} \tag{11}$$

where μ = mean molecular weight of gas and m_H = mass of proton

– The time for a sound wave to cross a cluster of diameter d is

$$t_{sound} \sim \frac{d}{v_{sound}} \sim 7 \times 10^8 \left(\frac{T}{10^8 K}\right)^{-1/2} \left(\frac{d}{1 Mpc}\right)^{-1} years \tag{12}$$

– Because $t_{sound} << t_{cool}$ the gas will be in hydrostatic equilibrium (gas pressure balances gravity). For a spherical mass distribution,

$$\frac{1}{\rho_{gas}}\frac{dP}{dr} = -\frac{d\Phi}{dr} = -\frac{GM(r)}{r^2} \tag{13}$$

Because the gas is in hydrostatic equilibrium in the cluster potential well, its distribution maps the cluster's mass distribution.

X-RAY HALO MASS

Assuming that the intracluster gas is in hydrostatic equilibrium in the cluster potential well, the **total** cluster mass can be found:

$$\frac{1}{\rho_{gas}}\frac{dP}{dr} = \frac{d\phi}{dr} = -\frac{GM_{cl}(r)}{r^2} \tag{5}$$

Substituting the ideal gas law, P=$\rho k_b T/\mu m_H$ and solving for M(R)

$$M_{cl}(< R) = -\frac{k_b T_{gas}}{\mu m_H G}\left(\frac{\delta ln\rho_{gas}}{\delta lnr} + \frac{\delta lnT_{gas}}{\delta lnr}\right) \tag{6}$$

Note that M_{cl} depends sensitively on T_{gas} but weakly on ρ_{gas}. In principle, radial gradients in ρ_{gas} and T_{gas} are observable. In reality, temperature gradients are very difficult to detect.

A simplifying assumption is that the gas is **isothermal**, then

$$\frac{\delta lnT_{gas}}{\delta lnr} = 0 \tag{7}$$

$$M(< R) = -\frac{k_b T_{gas}}{\mu m_H G}\left(\frac{\delta ln\rho_{gas}}{\delta lnr}\right) \tag{8}$$

DYNAMICAL HALO MASS

$$\frac{1}{2}M_{cl}\sigma^2 - \frac{\alpha G M_{cl}^2}{R} = 0$$

where α depends on the matter distribution

$\alpha = 3/5$ for a uniform sphere

$\alpha \sim 1$ for typical profiles

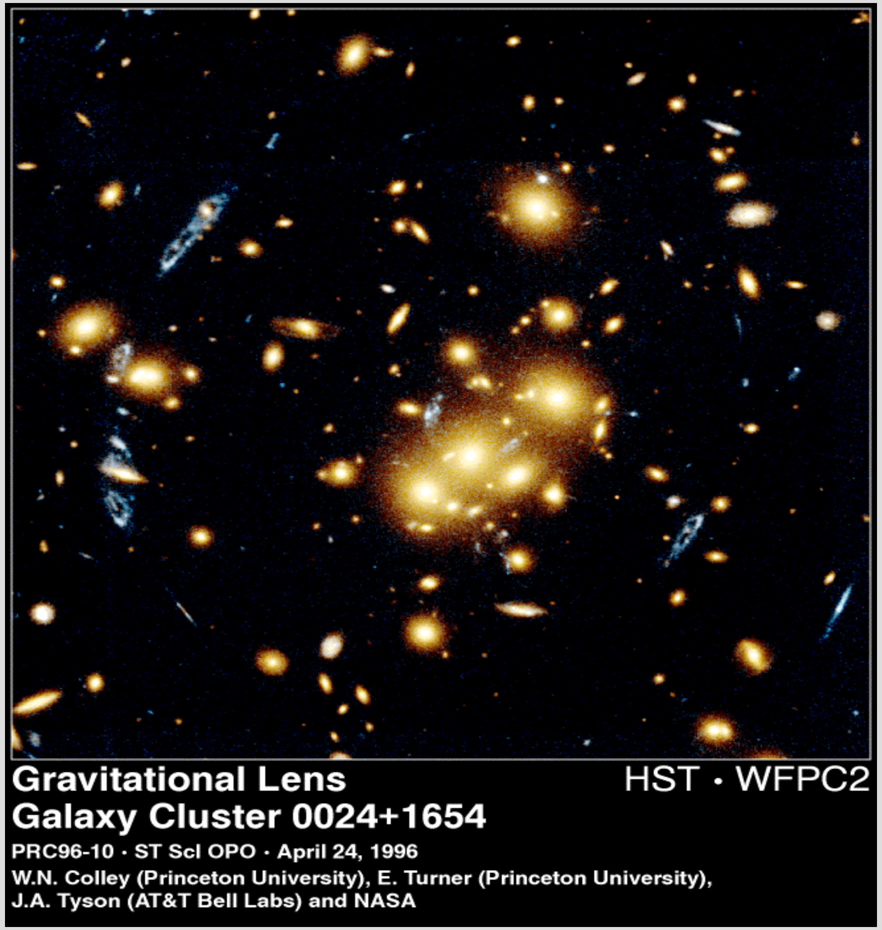
This yields,

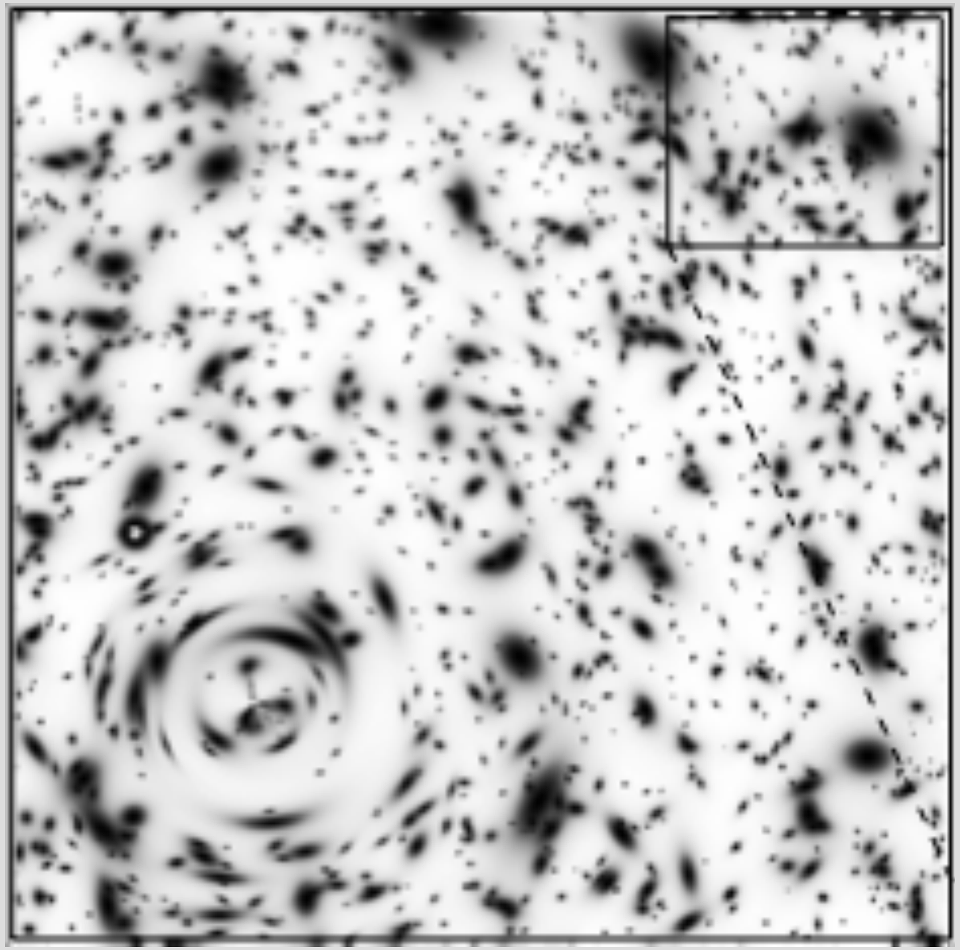
$$M_{cl} \sim 10^{15} M \odot \left(\frac{\sigma_{los}}{10^3 km/s}\right)^2 \left(\frac{R}{1Mpc}\right)$$

– Virial estimates indicate total cluster masses $\mathrm{M}_{cl} \sim 10^{13}$–$10^{15}$ $\mathrm{M}\odot$

– Visible galaxies account for only $\sim 5 - 10\%$ of M_{cl}

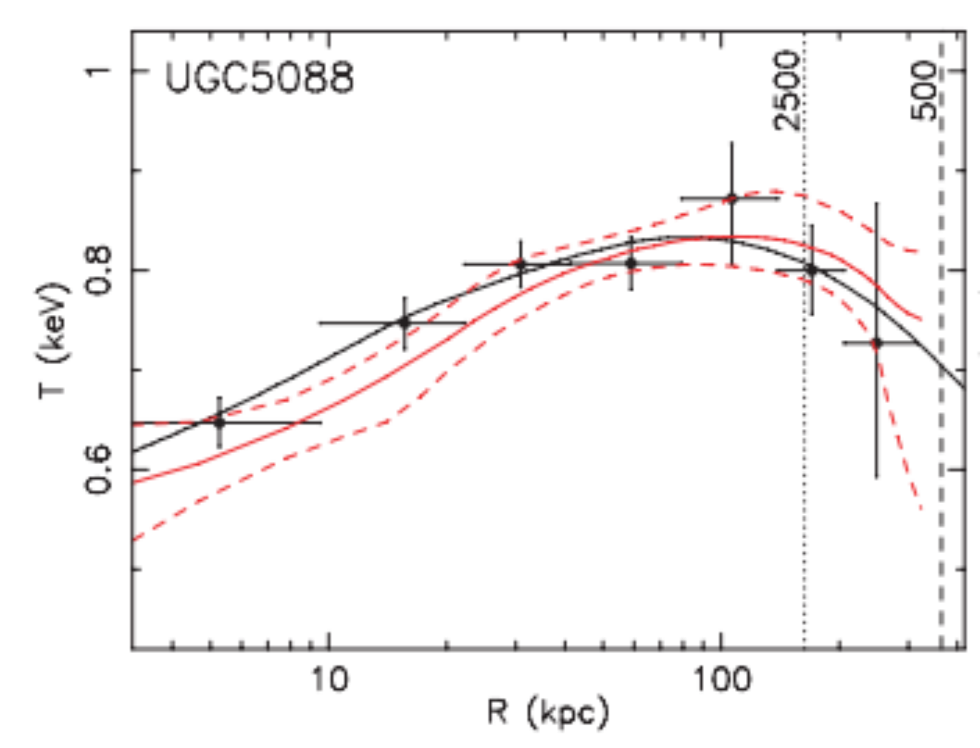
LENSING HALO MASS

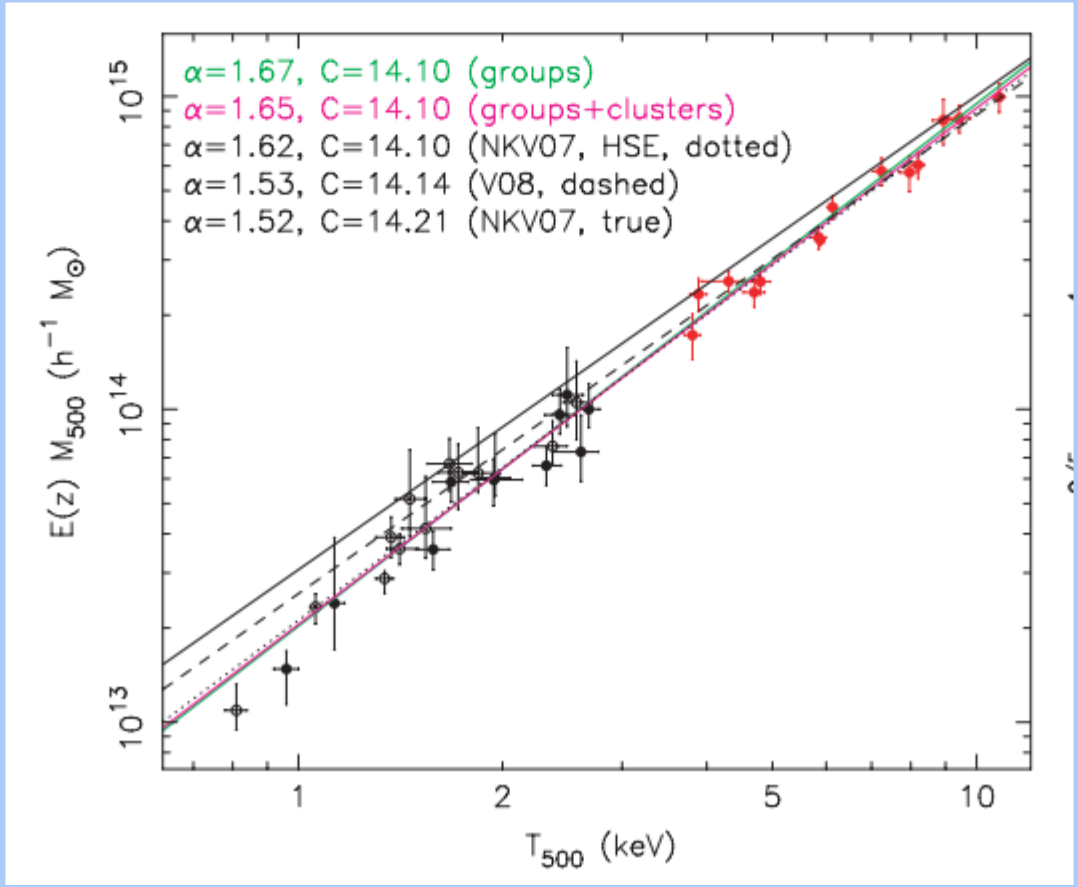




II. OBSERVATION

M(T) RELATION: X-RAY MASS





M(T) RELATION: X-RAY MASS

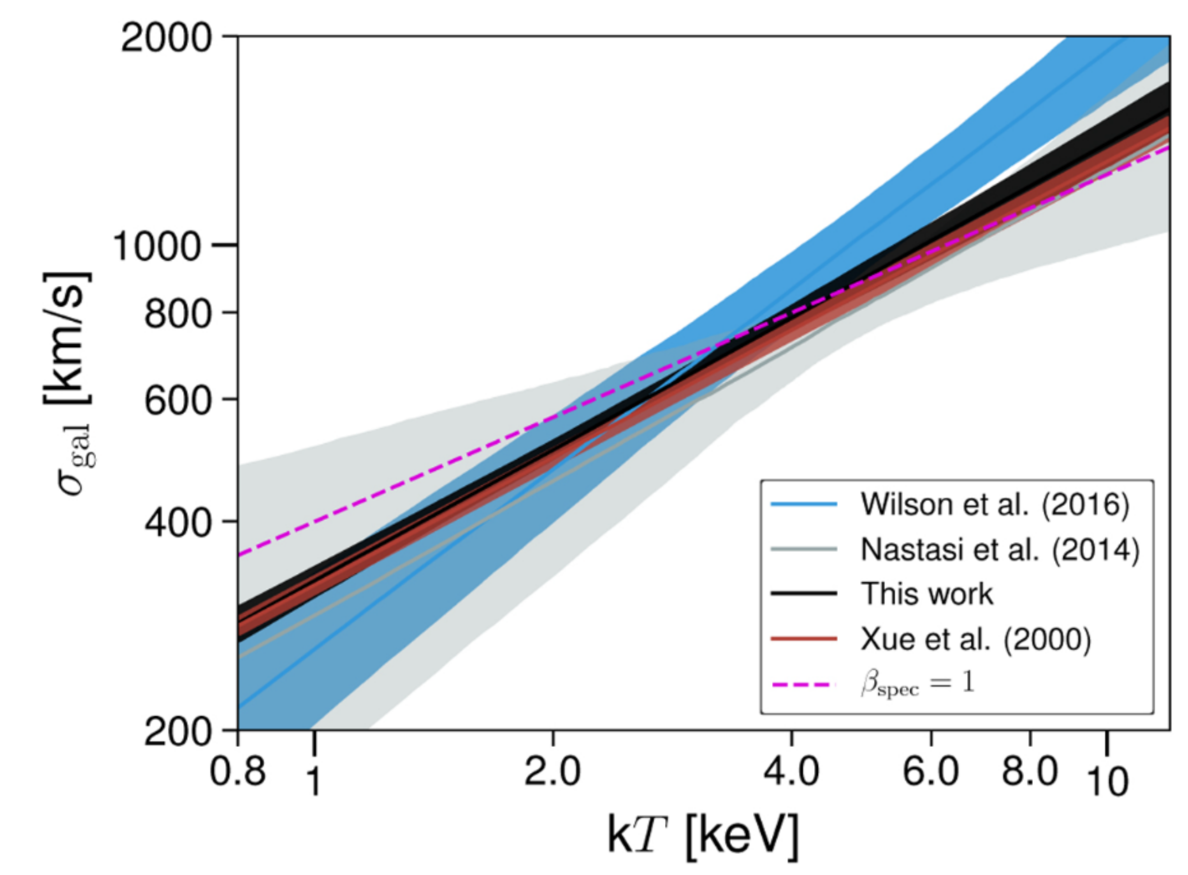
X-Rays

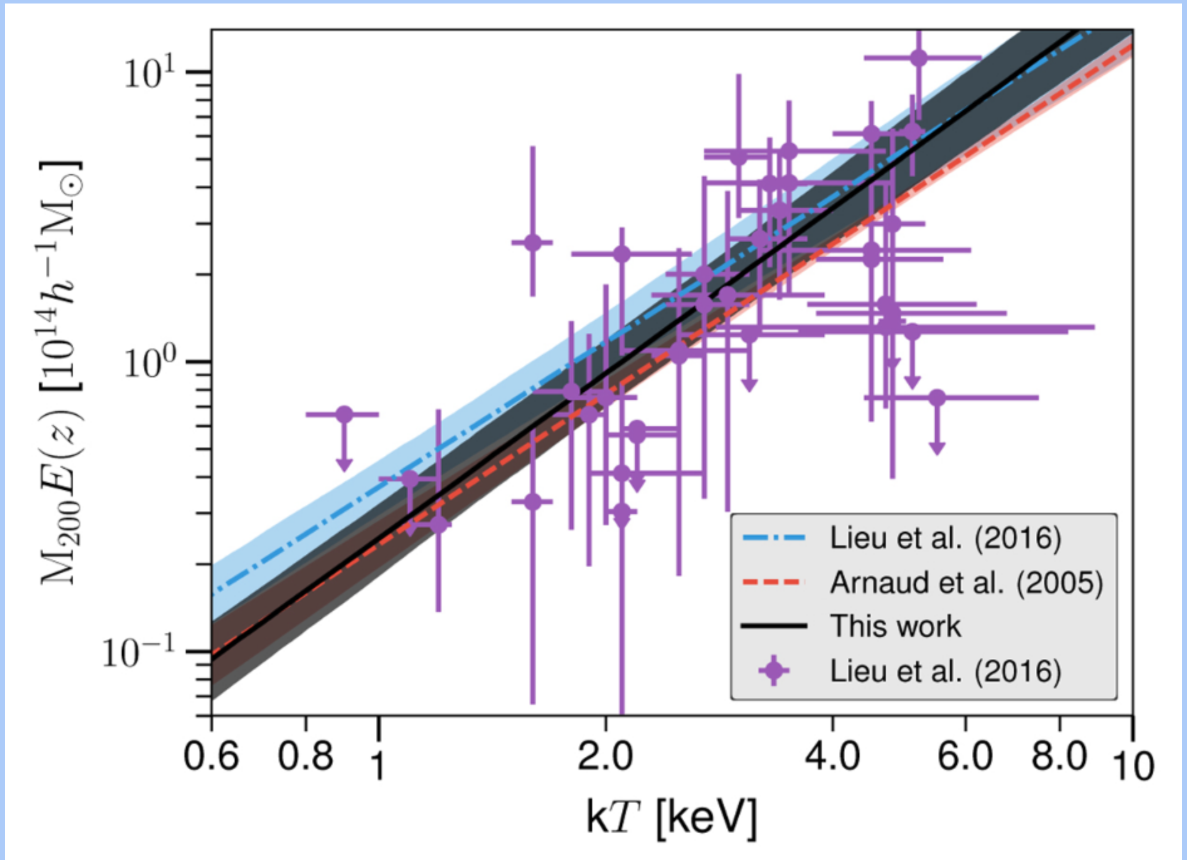
☹ **Depend of thermal/dynamical state of the ICM**

☹ **Cannot separate components along the line of sight.**

☺ **All Sky Surveys (e.g. ROSAT) can provide large and homogeneous samples**

M(T) RELATION: DYNAMICAL MASS





M(T) RELATION: X-RAY MASS

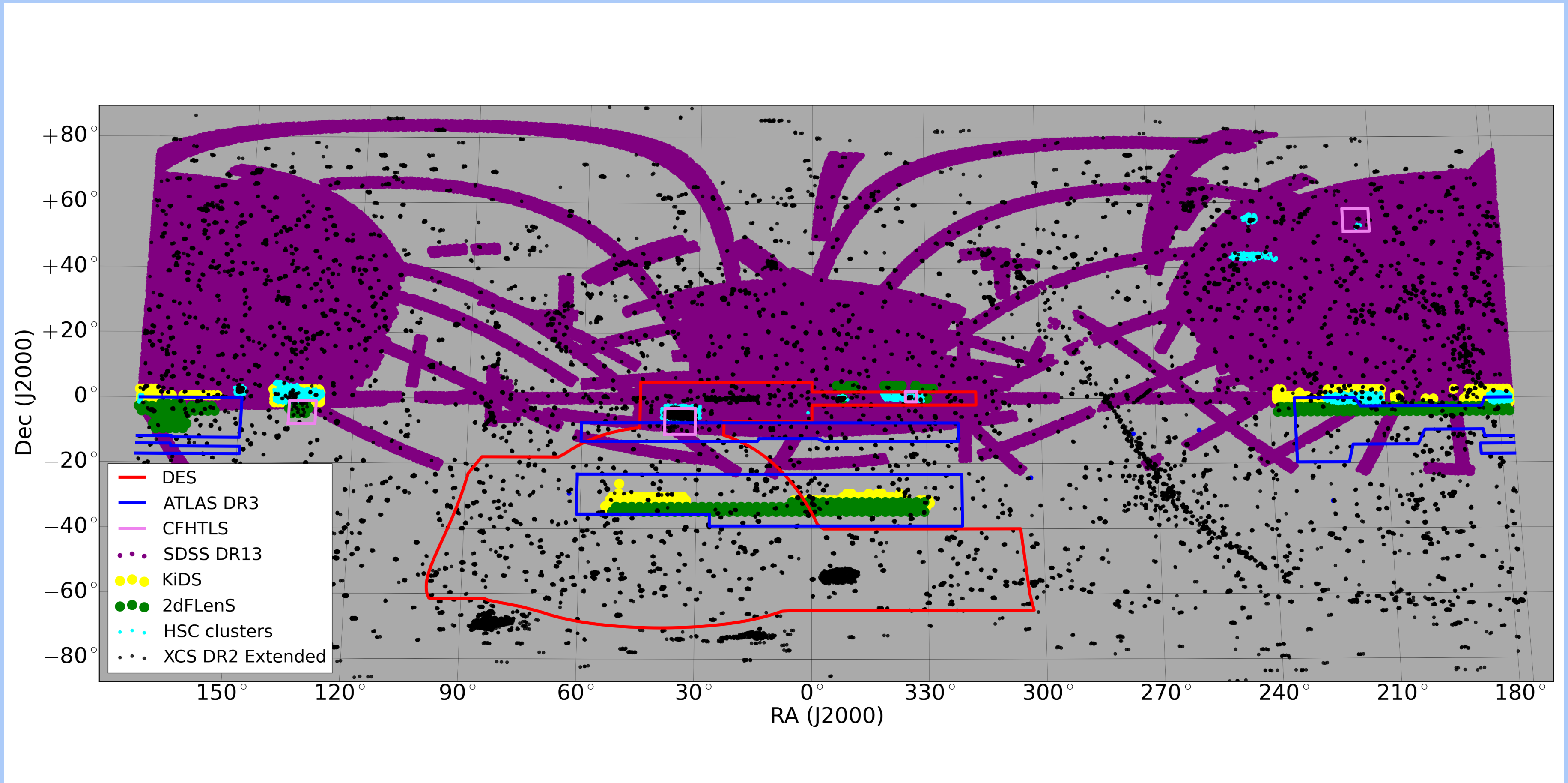
Dynamics of galaxies

☹ Depend on the dynamical state of the cluster galaxies (galaxies relaxes later than the ICM)

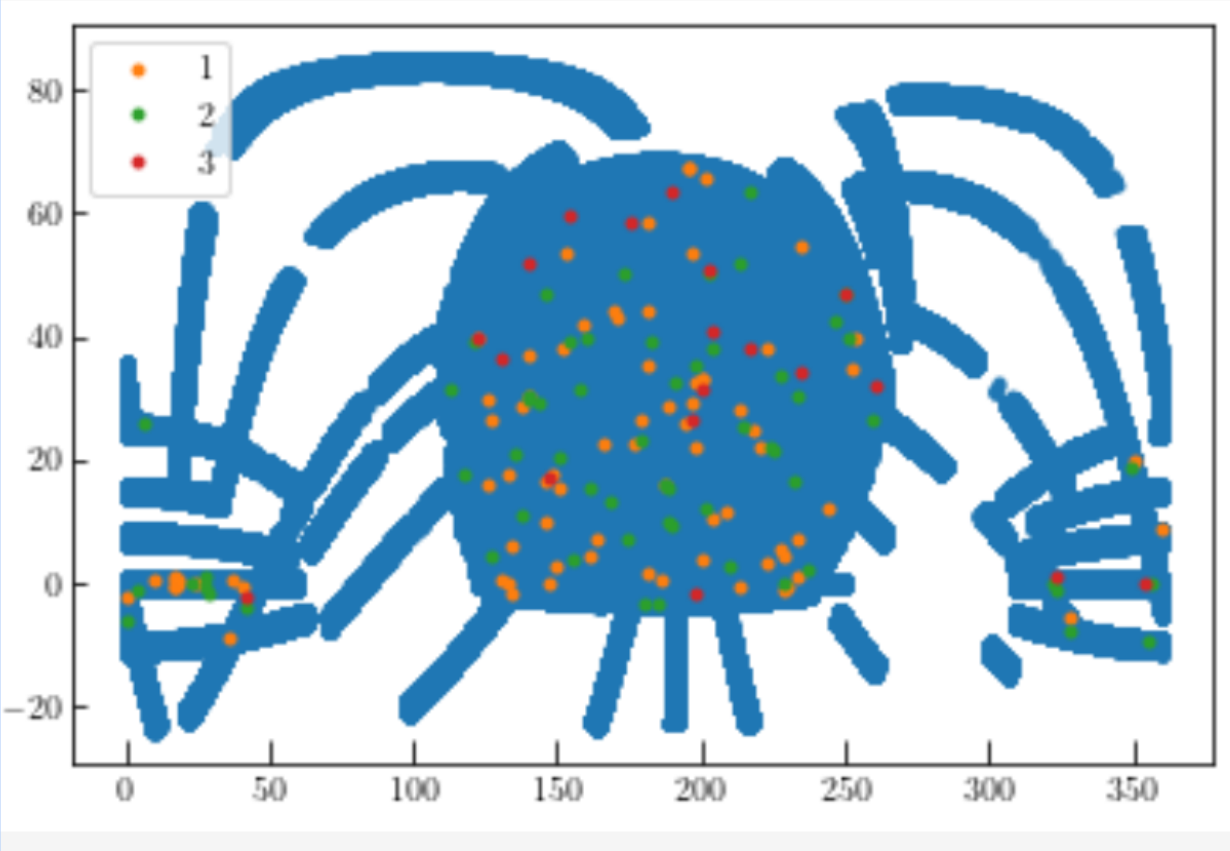
☹ Reliable results depends on a large number of galaxy velocities over a large area (e.g. Czoske et al. 2002)

☺ Can separate structures along the line of sight

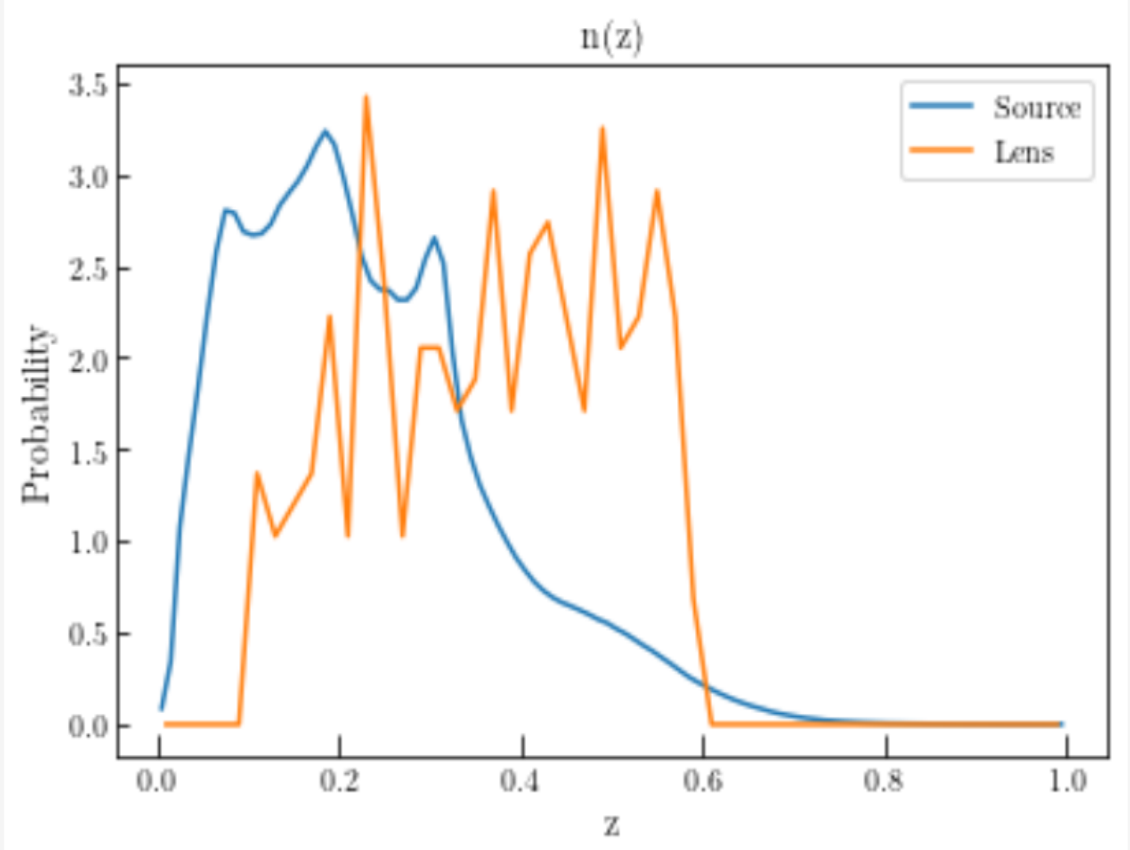
XMM CLUSTER SURVEY



SDSS SHAPE CATALOG

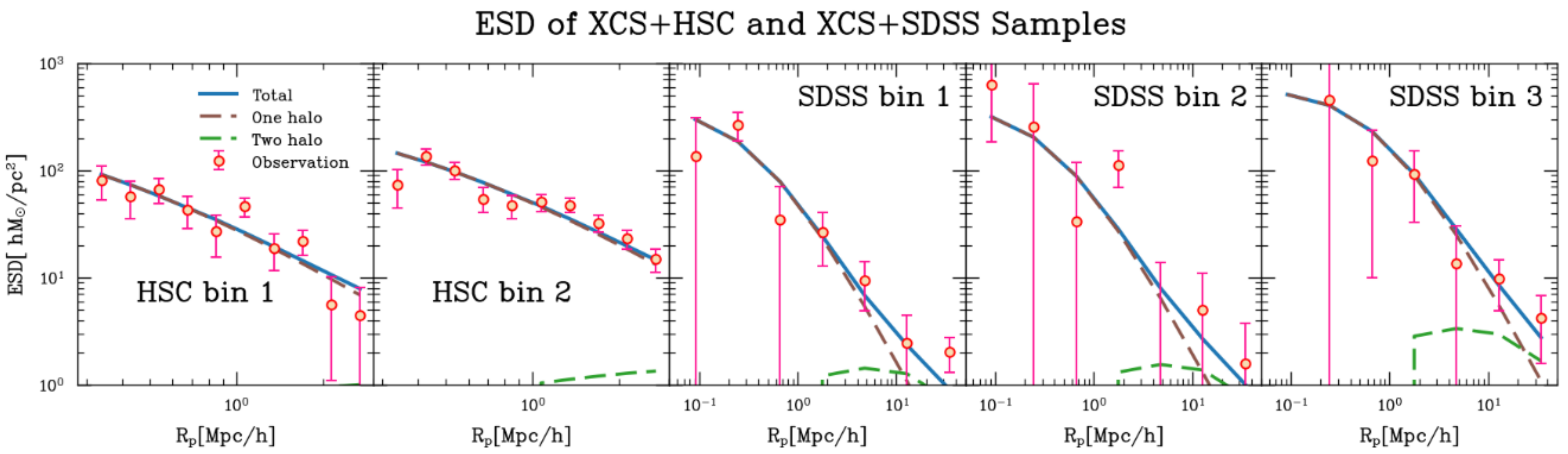


SDSS DR7 footprint

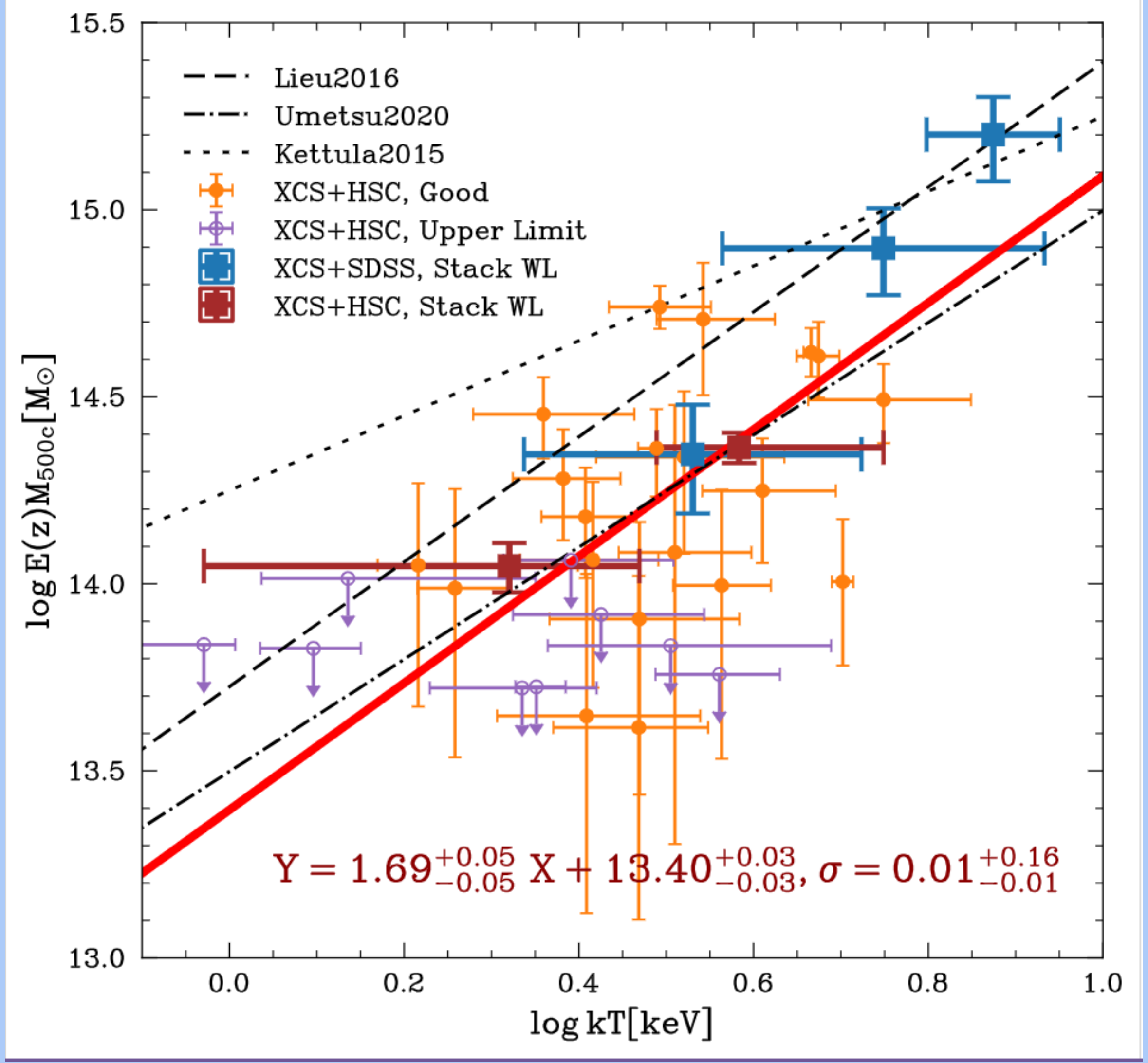


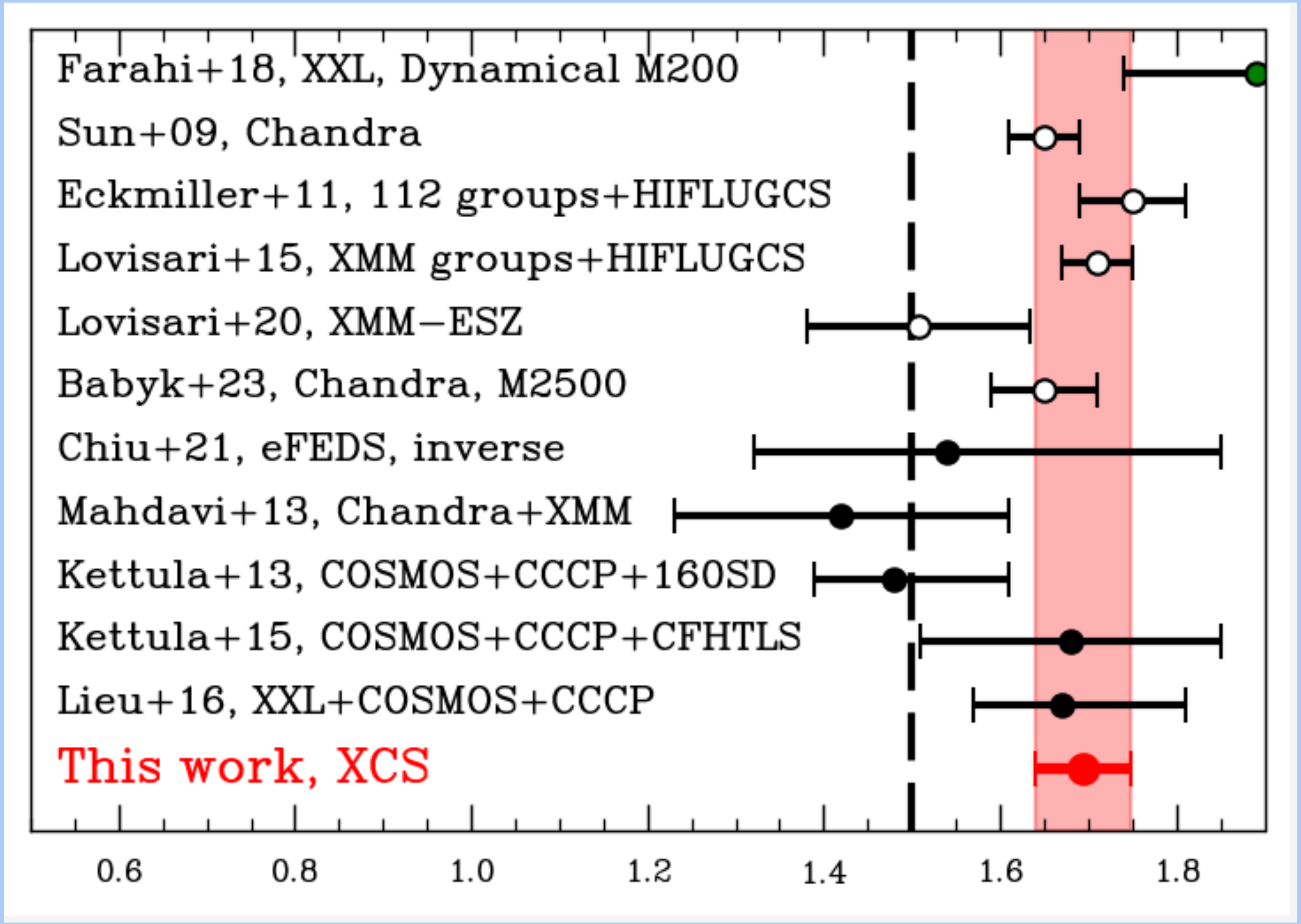
Redshift distribution

LENSING SIGNAL



OUR CONSTRAINT





Farahi+18, XXL, Dynamical M200
Sun+09, Chandra
Eckmiller+11, 112 groups+HIFLUGCS
Lovisari+15, XMM groups+HIFLUGCS
Lovisari+20, XMM−ESZ
Babyk+23, Chandra, M2500
Chiu+21, eFEDS, inverse
Mahdavi+13, Chandra+XMM
Kettula+13, COSMOS+CCCP+160SD
Kettula+15, COSMOS+CCCP+CFHTLS
Lieu+16, XXL+COSMOS+CCCP
This work, XCS
0.6
0.8
1.0
1.2
1.4
1.6
1.8