Total masses from X-ray analyses

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Dissecting Cluster Cosmology: toward a roadmap for forthcoming cluster surveys

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Cluster surveys & cosmology

The key ingredients to use cluster number counting to constrain the cosmological parameters are:

- **Well defined selection function**
- **Precise and accurate total cluster mass (M_{tot}) estimates**

✗ **We do not know the "true" cluster population**

✗ **We cannot measure M_{tot} for all clusters**

➡ **crucial to establish the correct (& tight) relation between M_{tot} and observables**

➡ **observables calibrated to M_{tot} using an unbiased mass estimator (with large scatter)**

For all this chain to work one needs to:

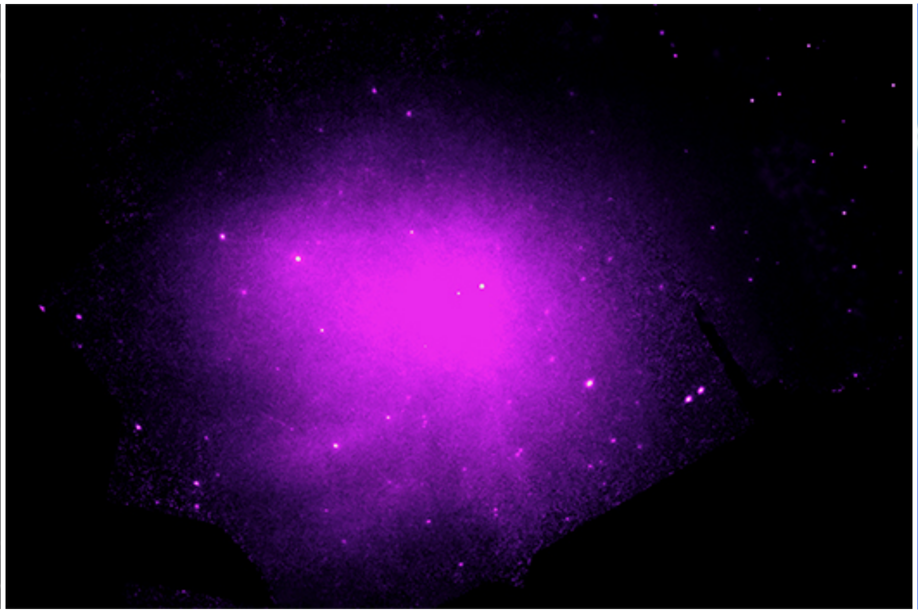
(i) understand how survey samples map the underlying cluster population

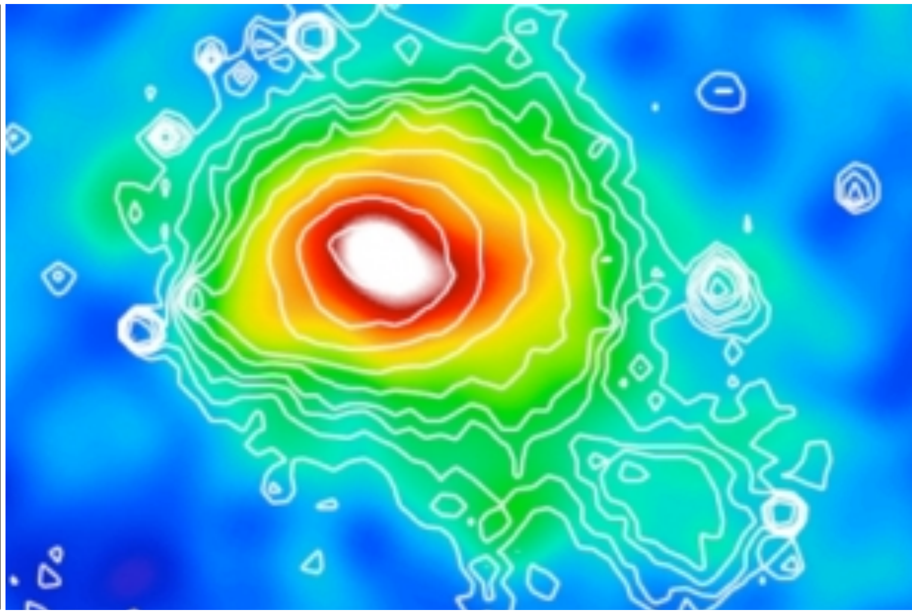
(ii) homogeneously determine accurate masses

(iii) calibrate the mass-observable relations

“True” cluster population

Optical | **X-ray** | **SZ**





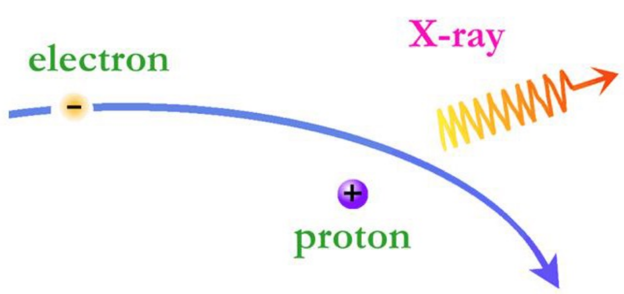
Clusters detected as high concentrations of galaxies in the sky

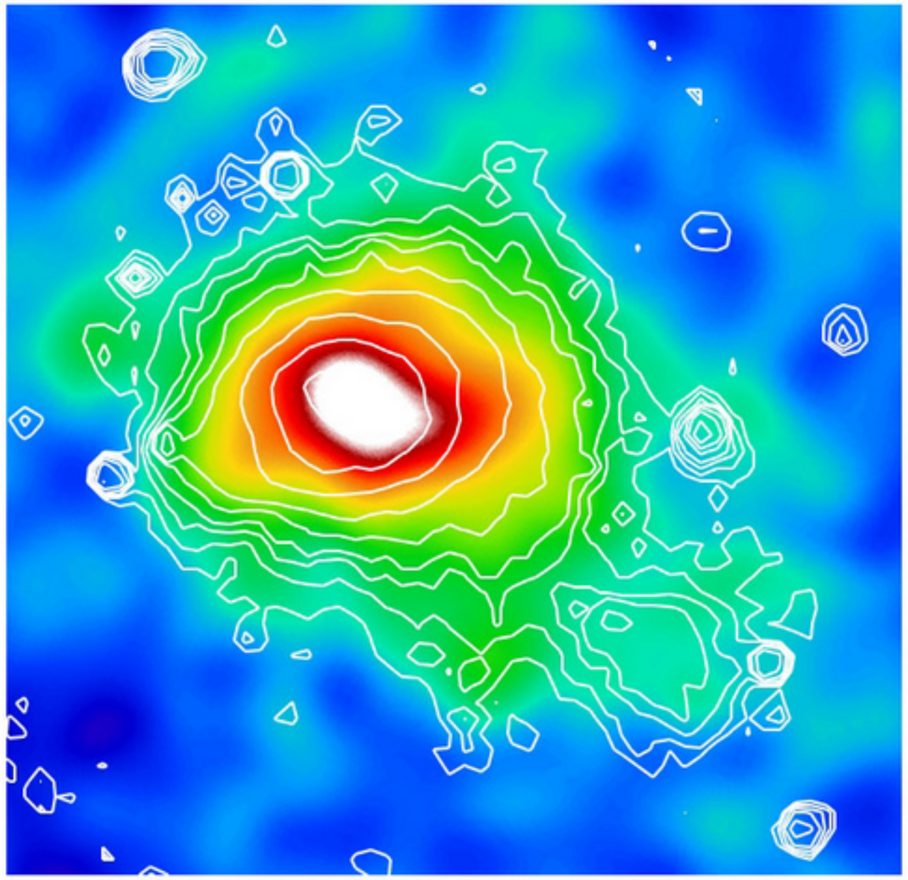
The hot plasma (accounting for ~85% of the cluster baryons) is responsible for the X-ray light through thermal bremsstrahlung and line emission, and to the scatter of the CMB photons, causing the SZE

likely NOT detecting the same clusters

ICM emission

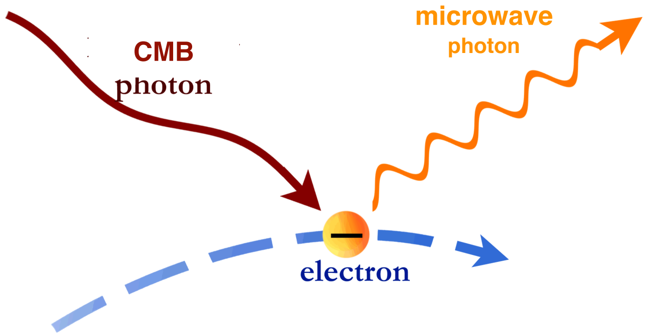
Bremsstrahlung





Coma cluster - Planck image & X-ray contours

Inverse Compton scattering



$$E_X \propto \int_V n_e^2 \Lambda(T) dV$$

→ X-ray emission

$$F_\nu \propto \int_\Omega (P = n_e T) d\Omega$$

→ Sunyaev-Zeldovich effect

Two independent probes of the same physical component

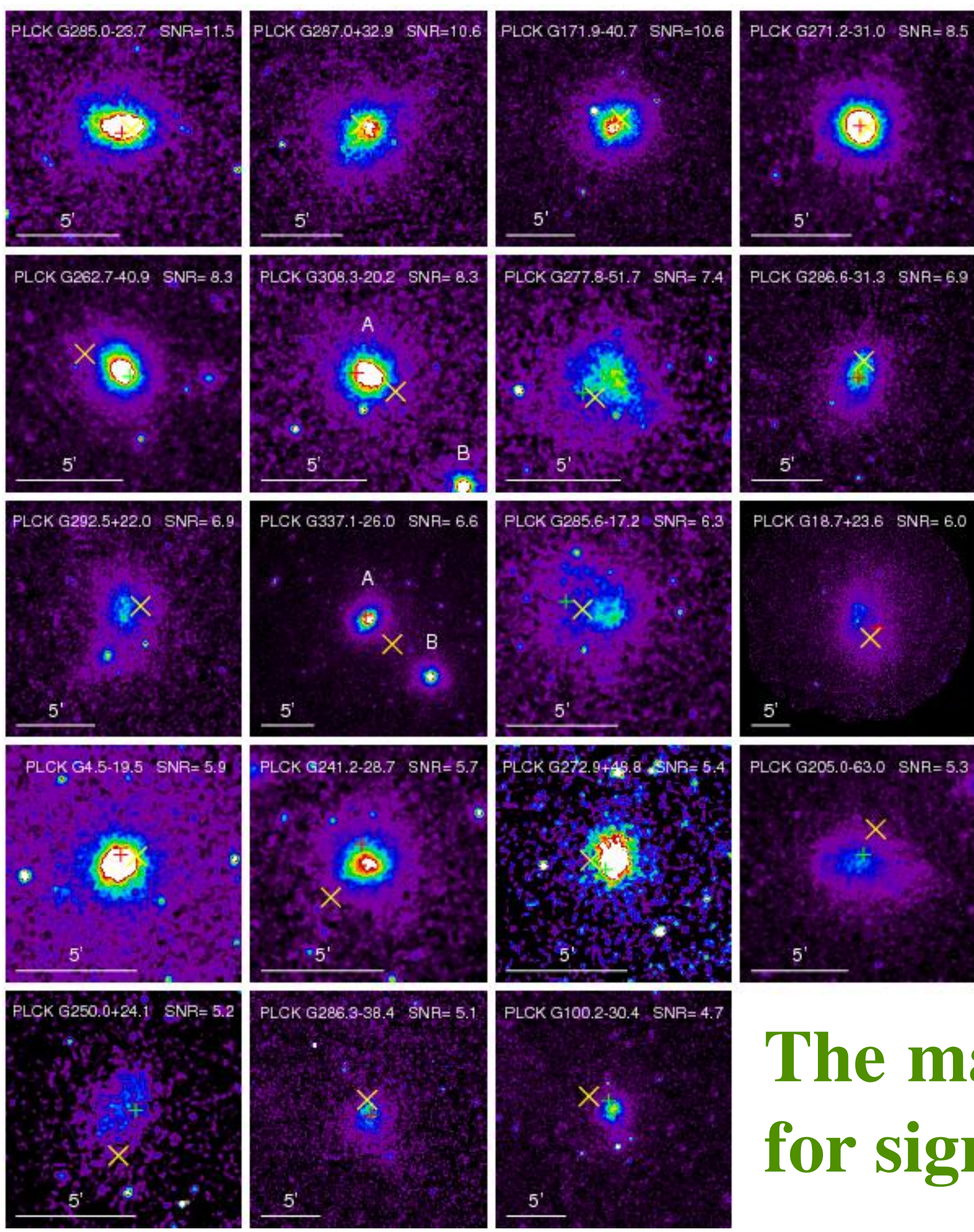
Different cluster detectability

X-ray surveys provide us with large GC catalogs but…

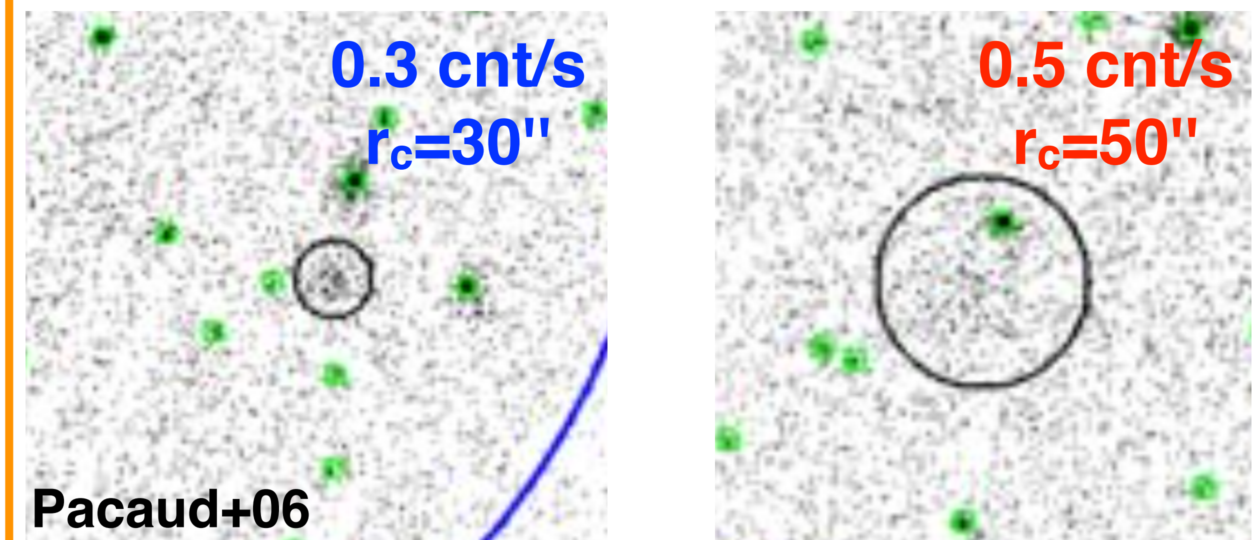
detectability (may) depend on the morphology

SZ

Planck Collaboration 2011, Planck Early results IX



X-ray



a cluster with a large core radius is much harder to be seen that a more compact object

The majority of the objects show evidence for significant morphological disturbance.

ESZ vs REXCESS

Concentration

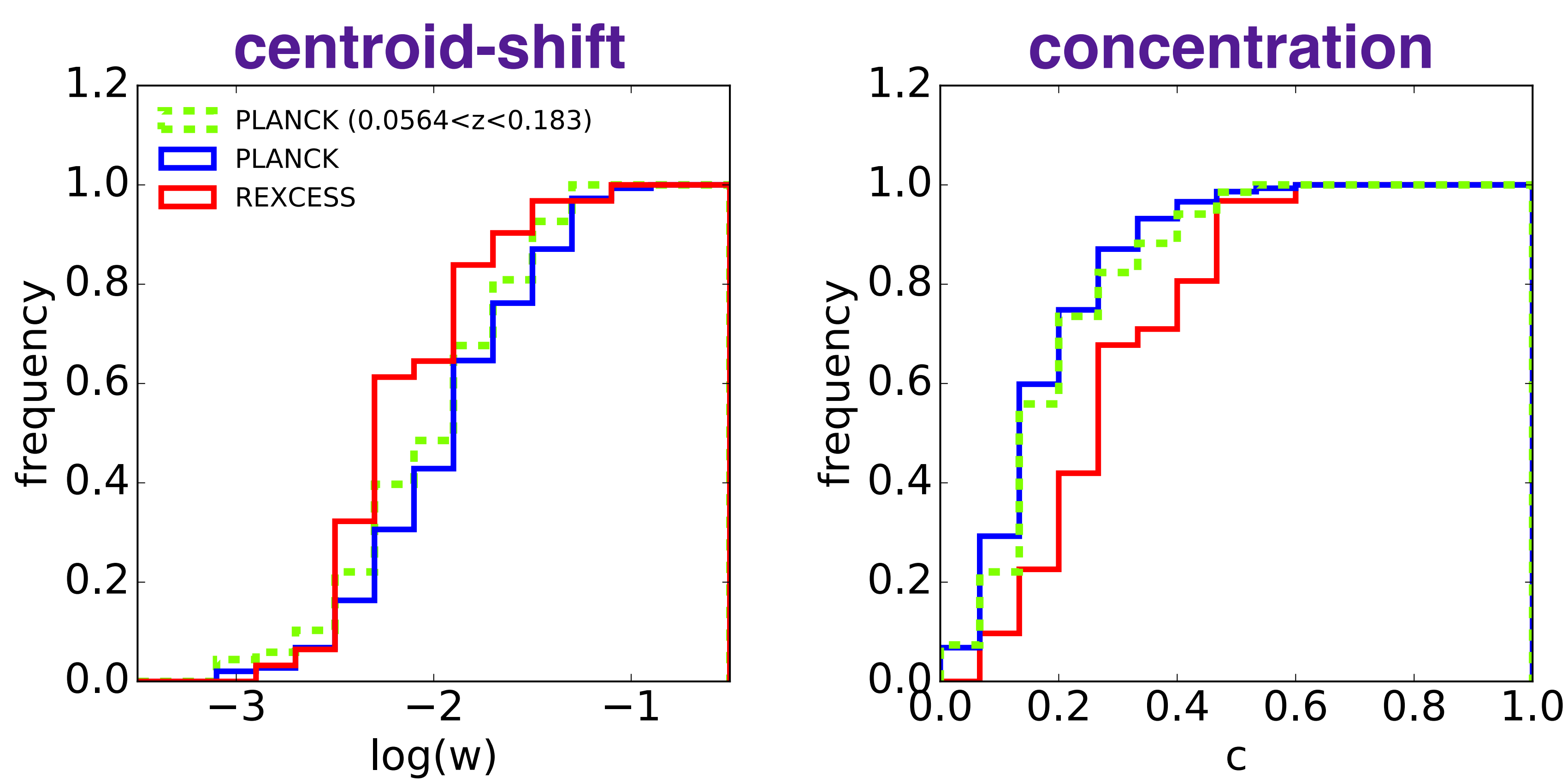
$$c = \frac{SB(< 0.1R_{500})}{SB(< R_{max})}$$

Discriminate clusters with a compact core (i.e., no recent merger event) from cluster with a more diffuse X-ray emission (i.e., disturbed from a recent merger episode)

Centroid-shift

$$w = \left[\frac{1}{N-1}\sum_i(\Delta_i - \overline{\Delta})^2\right]^{\frac{1}{2}} \frac{1}{R_{max}}$$

Sensitive to the presence of X-ray bright clumps (unless they are in symmetric geometry)

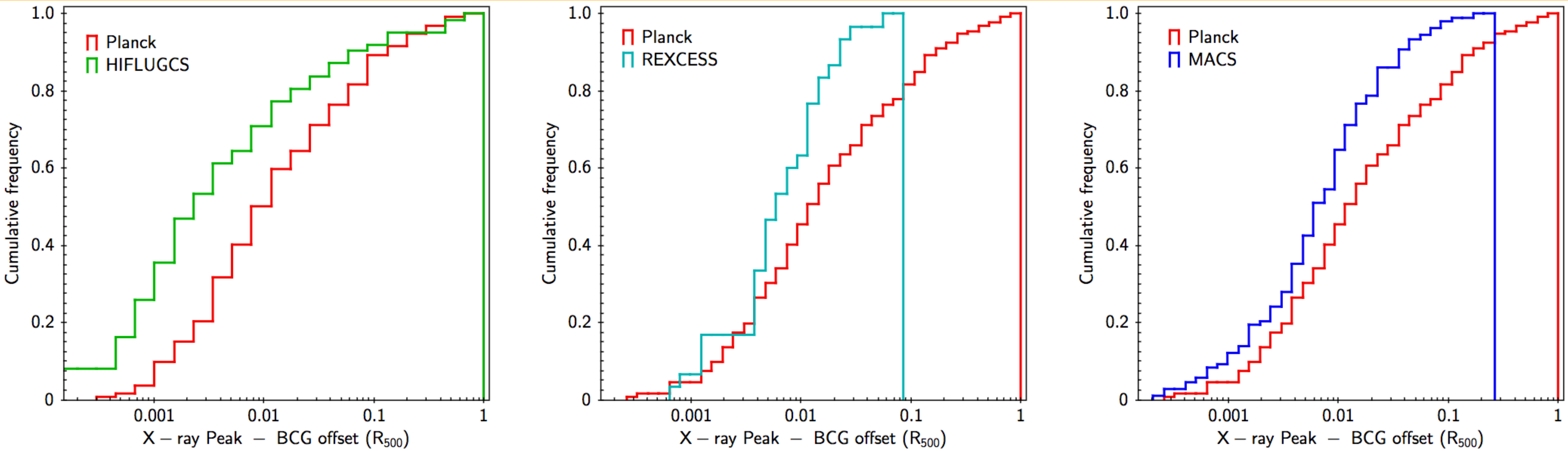


Lovisari+17

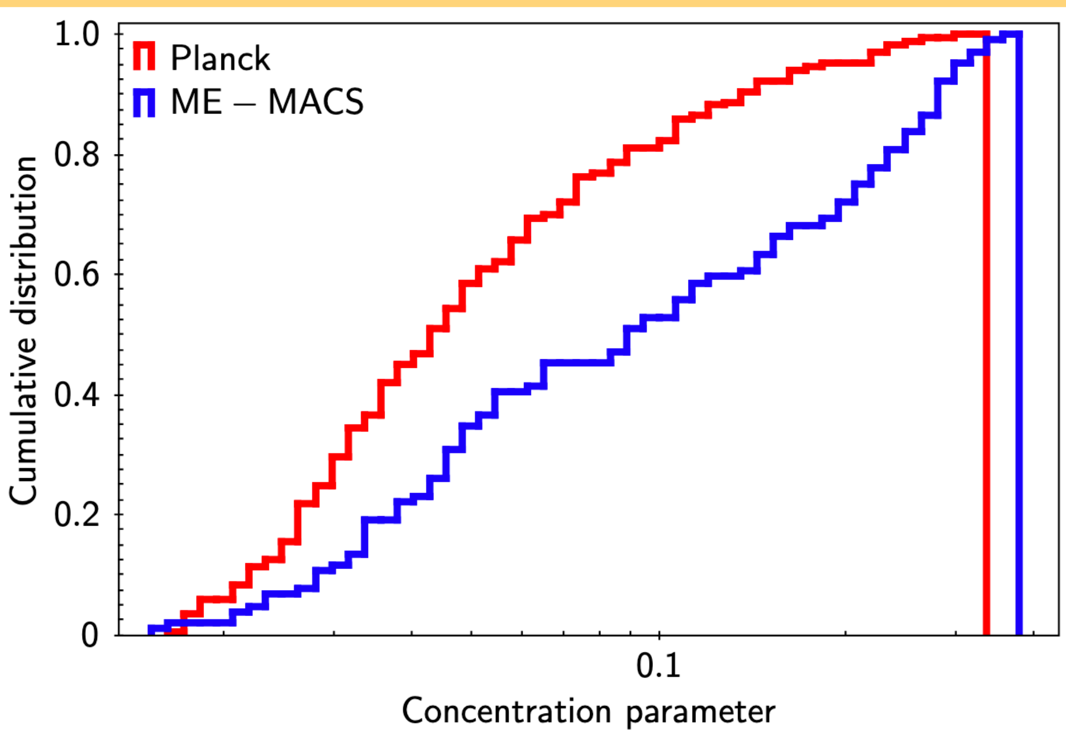
KS test

D=0.33 (w) and D=0.36 (c) --> p<0.01%

Consistent results (I)



"The distributions are significantly different and the fraction of relaxed objects is smaller in the Planck sample than in X-ray samples" **Rossetti+16**



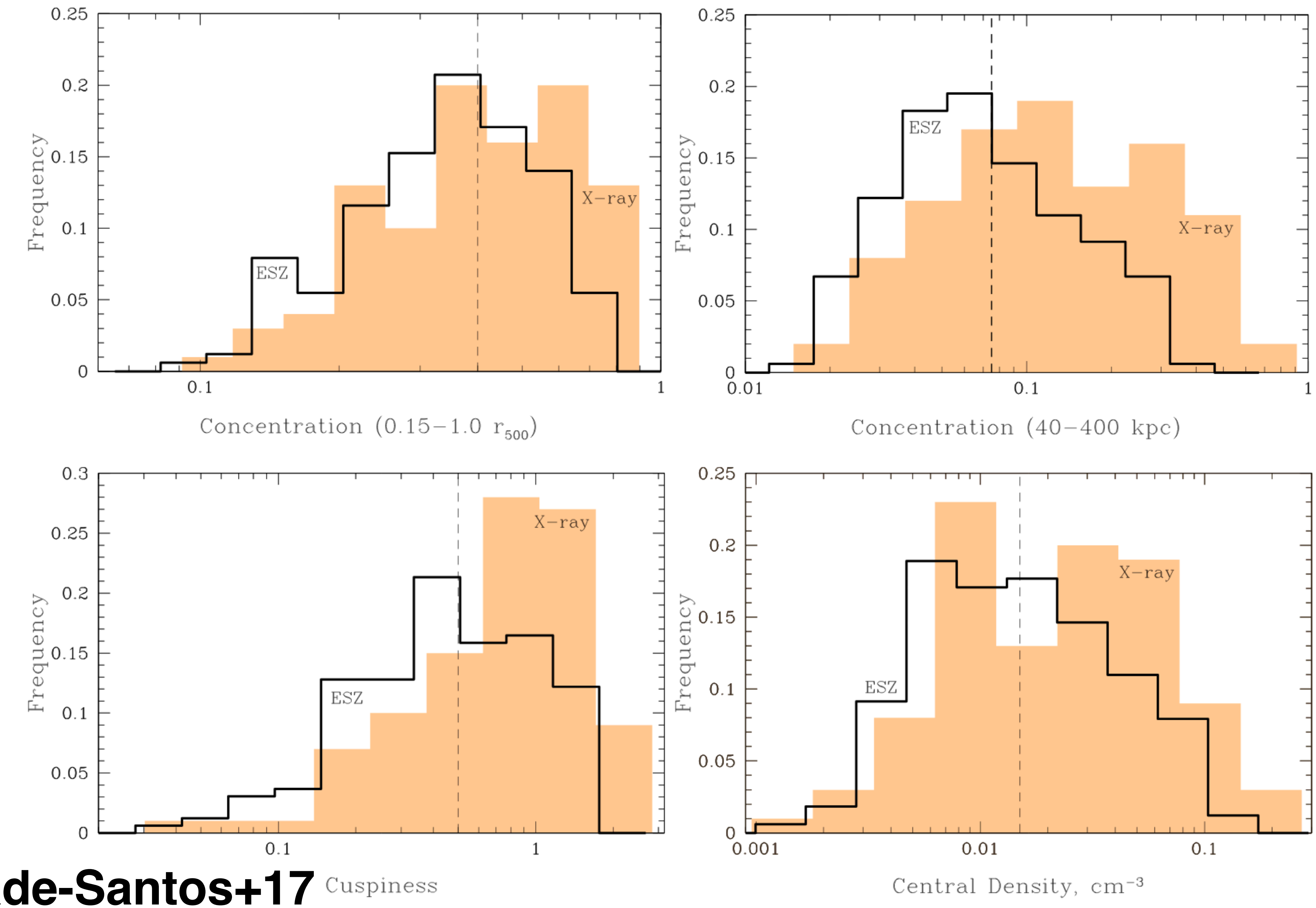
"the distributions are significantly different and the cool core fraction in MACS is much higher than in Planck."

KS test D=0.22 p<0.01

Rossetti+17

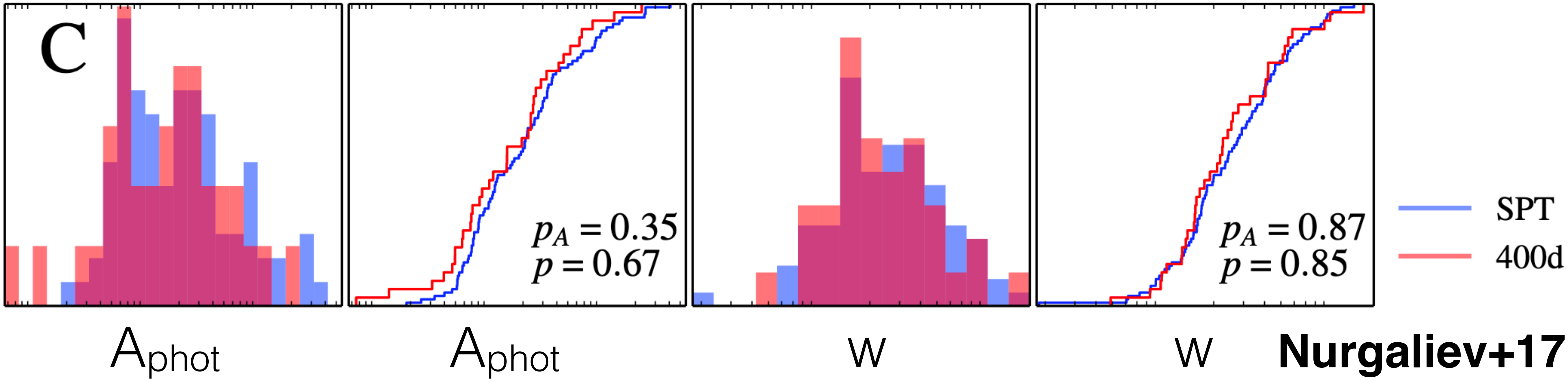
Consistent results (II)

"Our X-ray flux limited sample, compared to approximately mass-limited SZ selected sample is over-represented with CC"



Andrade-Santos+17

Inconsistent results? (I)



Nurgaliev+17

Sample	CC fraction %
Planck	29 ± 4
Planck $z > 0.15$	29 ± 5
ME-MACS	59 ± 5
HIFLUGCS (X)	56 ± 6
V09 low-z (X)	58 ± 10
V09 high-z /400d (X)	31 ± 8
Pascut15 (X)	74 ± 5
Santos10 (X)	60 ± 13
SPT all (SZ)	29 ± 5
SPT low-z (SZ)	29 ± 7

Rossetti+17

400d - the only X-ray selected sample apparently unaffected by the CC-bias

NOT FLUX LIMITED

but LUMINOSITY-LIMITED

X-ray selection

Luminosity limited sample can be less affected by CC-bias (Vikhlinin et al 2009)

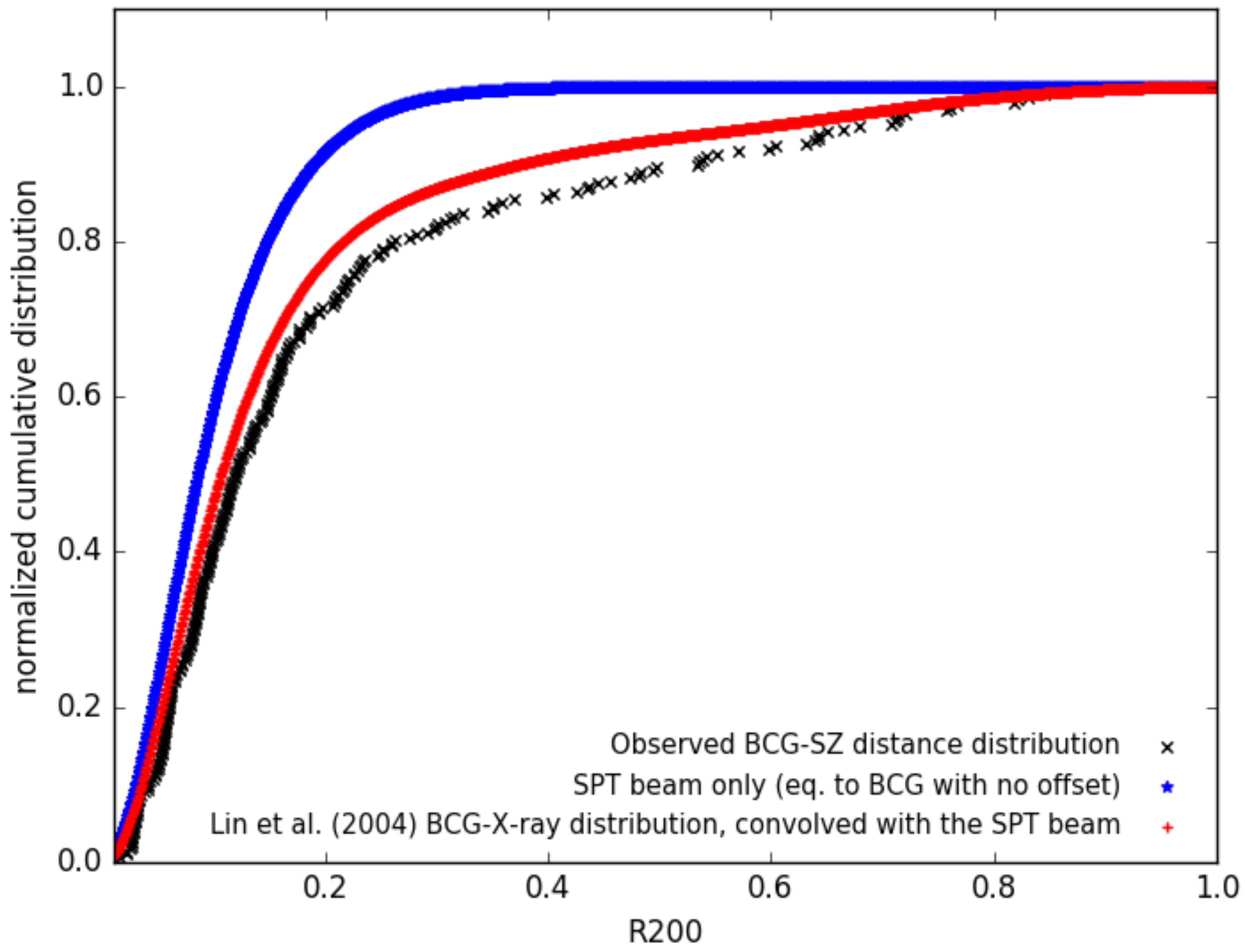
Chon & Bohringer (2017): comparison of a parent luminosity-limited sample with flux-limited subsamples

	luminosity limit	flux limit	
	VLS	FLS1	FLS2
Non-CC	57	27	22
Cool Core	36	24	20
Total	93	51	42
cc fraction	39%	47%	48%

Not all the X-ray selections are the same

Inconsistent results? (II)

"We show that the radial distribution of offsets provides no evidence that SPT SZ-selected cluster samples include a higher fraction of mergers than X-ray-selected cluster samples."



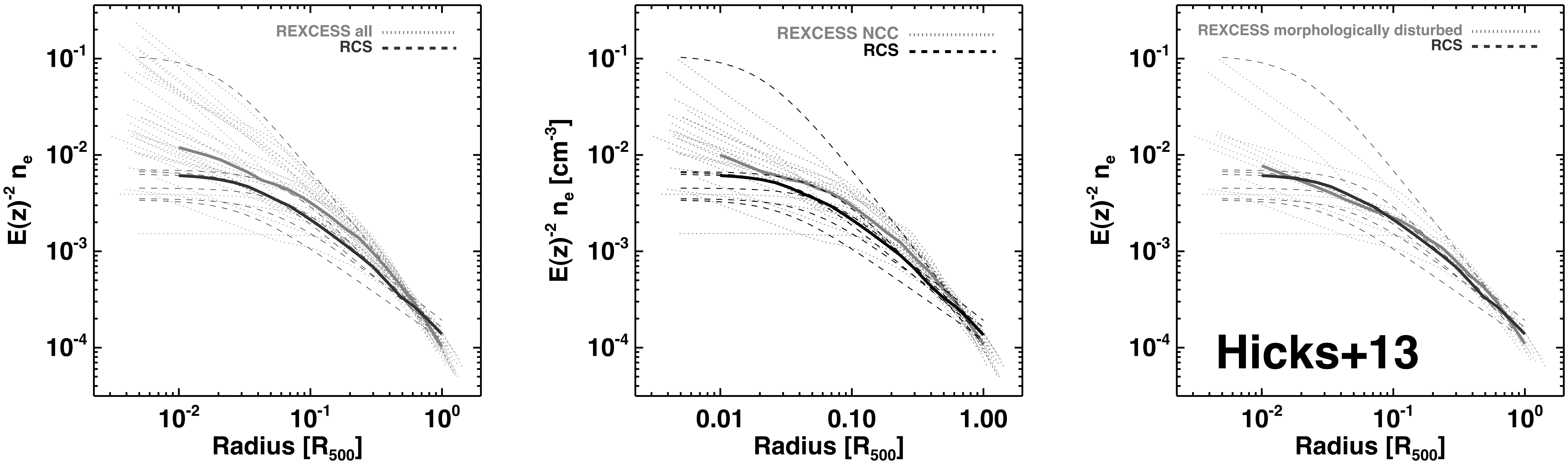
KS test shows a p=0.094 (at D = 0.072 r200) between X-ray and SPT-SZ selected clusters providing no evidence that SZ clusters are richer in disturbed systems

Zenteno+20

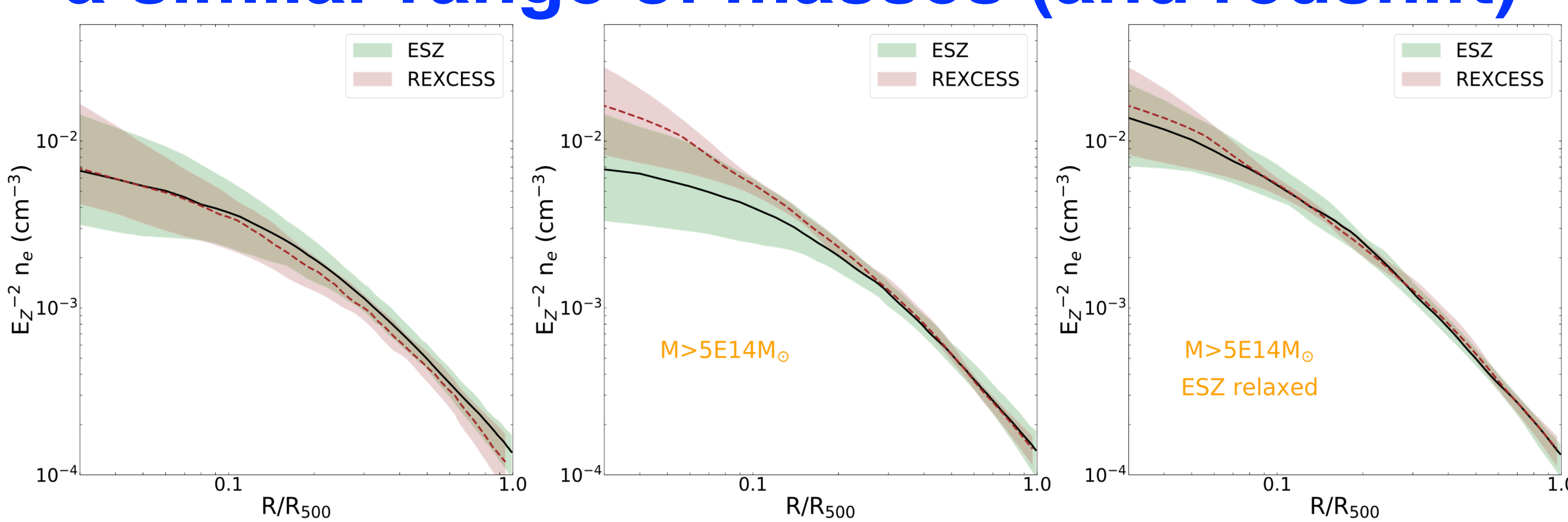
However, the X-ray selected clusters used in the analysis from Lin&Mohr+04 are an inhomogeneous selection from several catalogs and are spanning a significantly different redshift and mass range than the SPT sample

What about optically-selected?

Not aware of a comparison of X-ray morphological parameters for optically-selected samples vs X-ray or SZ, but central ne suggests they are more disturbed than X-ray-selected



however, to use n_e one must assure they span a similar range of masses (and redshift)

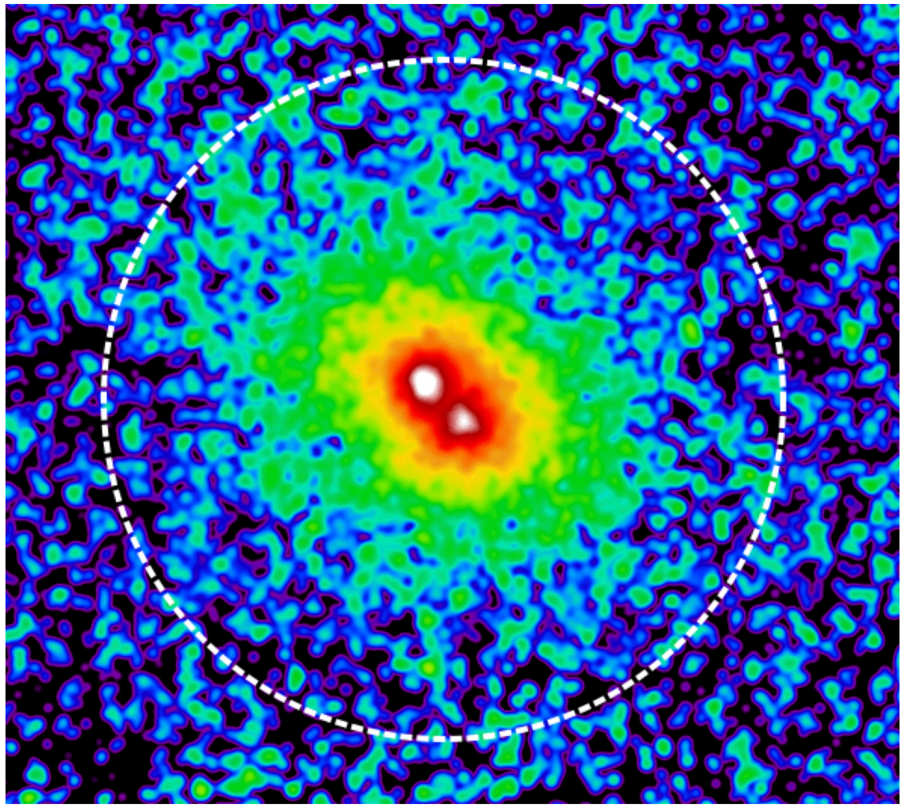


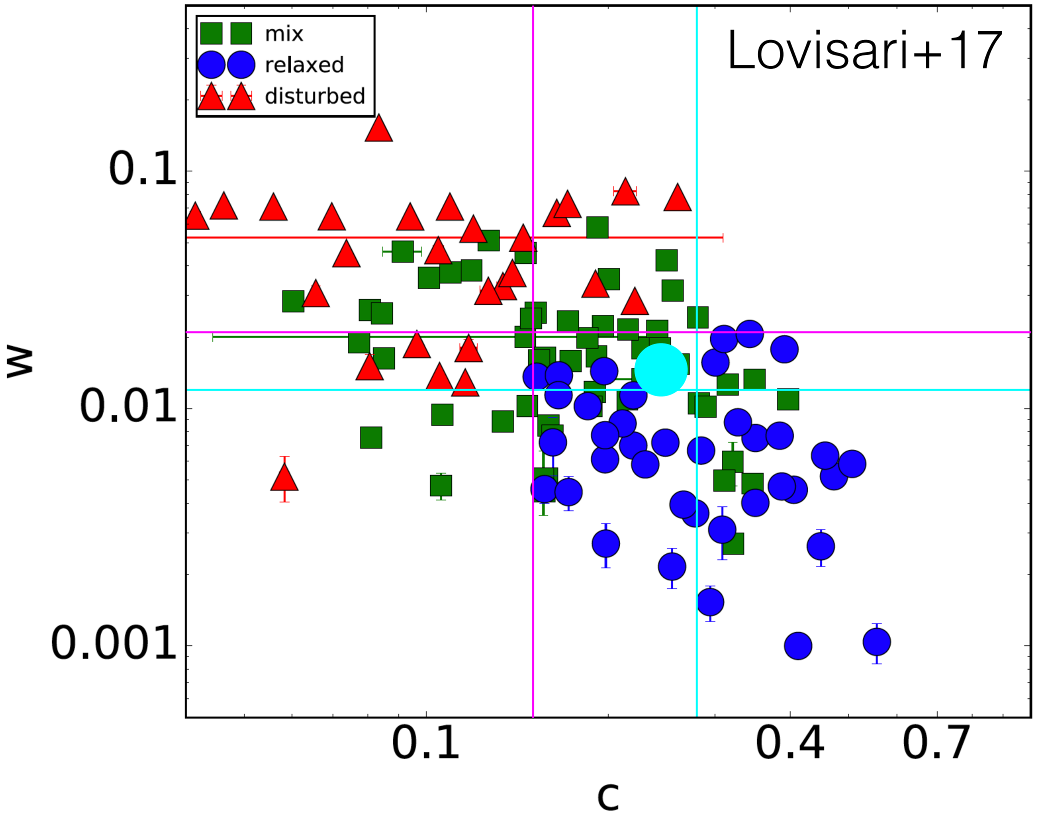
Lovisari+20

Dynamical state

Morphological parameters are very powerful (and cheap) tools to identify very relaxed and very disturbed systems

G036.72+14.92





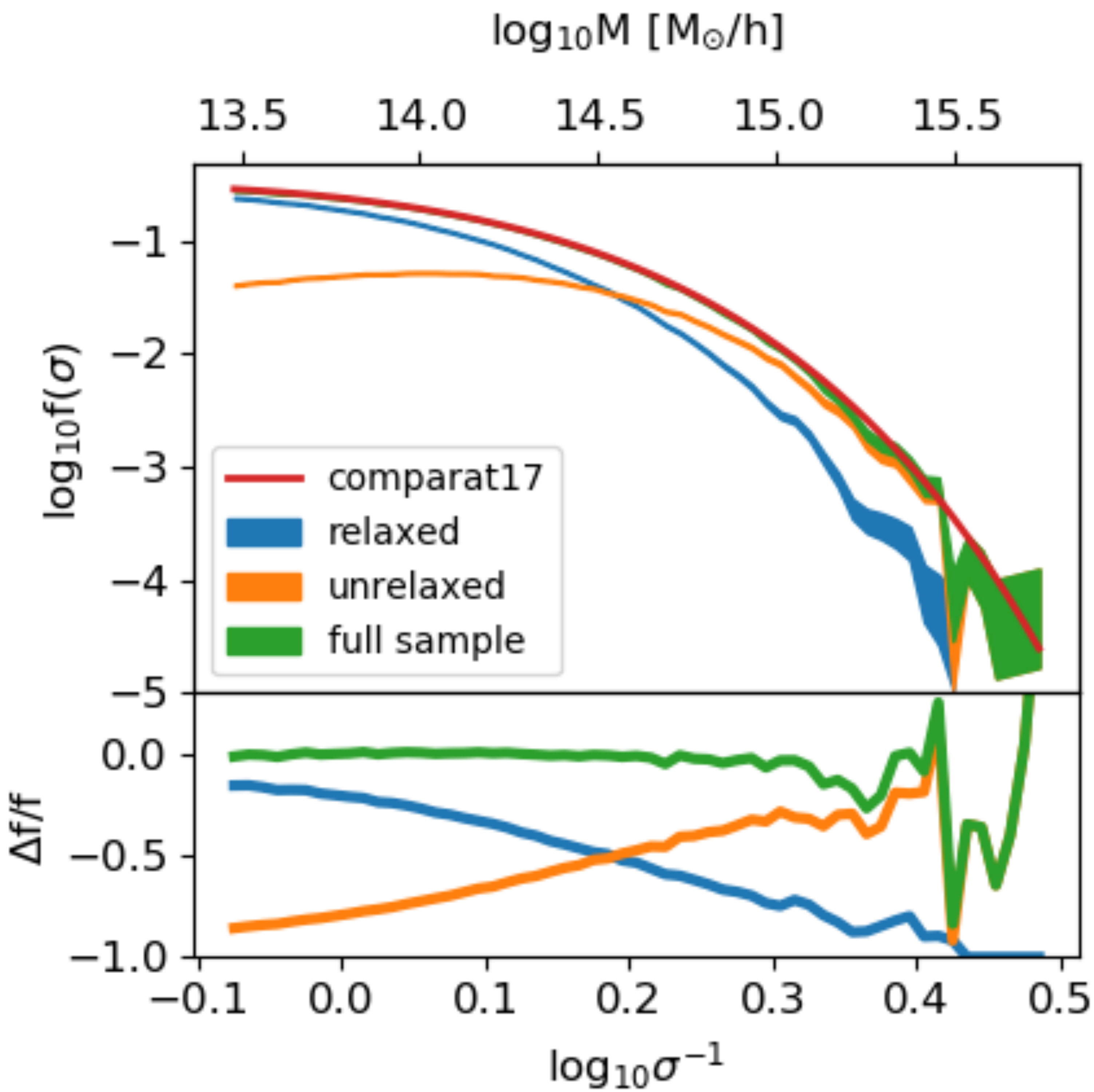
Because of projection effects they are not a flawless indicator of the dynamical state of the cluster

(My) Take-home messages

- SZ (& optically) selected clusters are(?) on average more disturbed than X-ray selected samples (but X-ray selections are not all the same!)
- SZ selection often assumed to be representative of the underlying population: is it true? What if baryon poor systems exist? Or if we are missing a particular class of systems?

Mass function

The shape of the mass function depends on the dynamical state



Seppi+21

Self-similarity

The assumption that gravity is the dominant (scale free) process leads to simple power-law correlations between different observable properties of clusters, known as **scaling relations**.

Clusters should be self-similar objects (kaiser,1986)

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

$$T \propto \frac{GM_{\Delta_z}}{R_{\Delta_z}} \propto R^2_{\Delta_z}$$

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

Very important relation because kT is one of the direct observables with X-ray data!

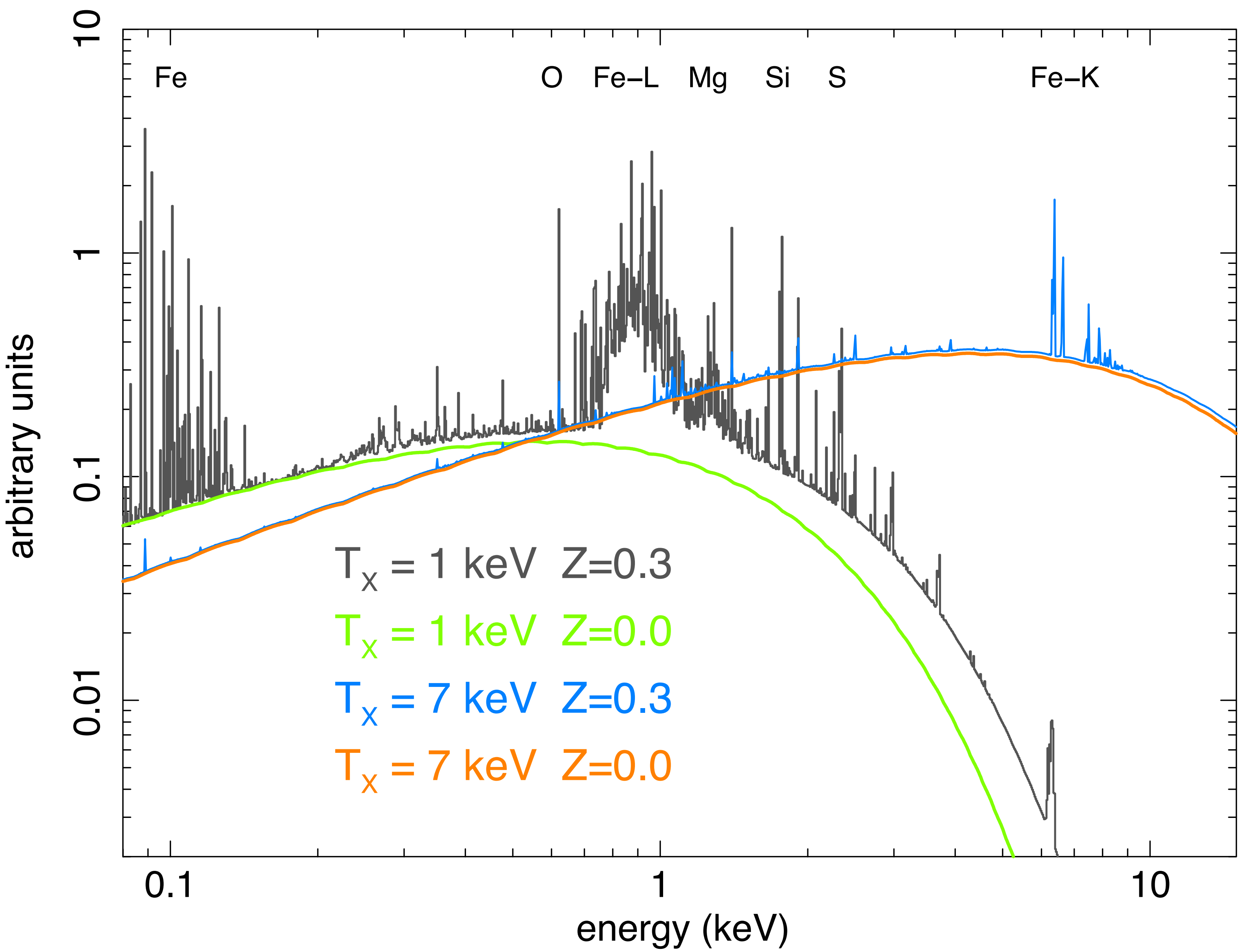
X-ray emission of GGs & GCs

The fundamental physical properties of the ICM are its temperature, density, and abundance of heavy elements

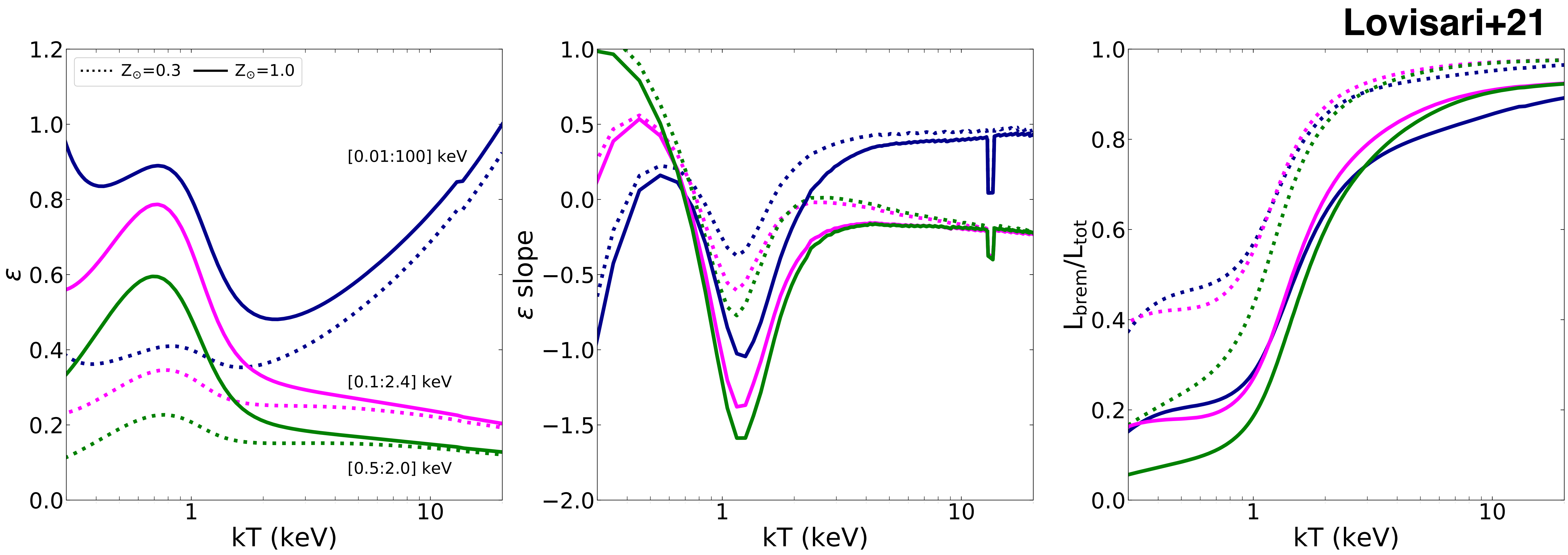
$$\epsilon \propto n_e n_p \boxed{\Lambda(T_X, Z)}$$

$\sim$

thermal bremsstrahlung
+
emission lines

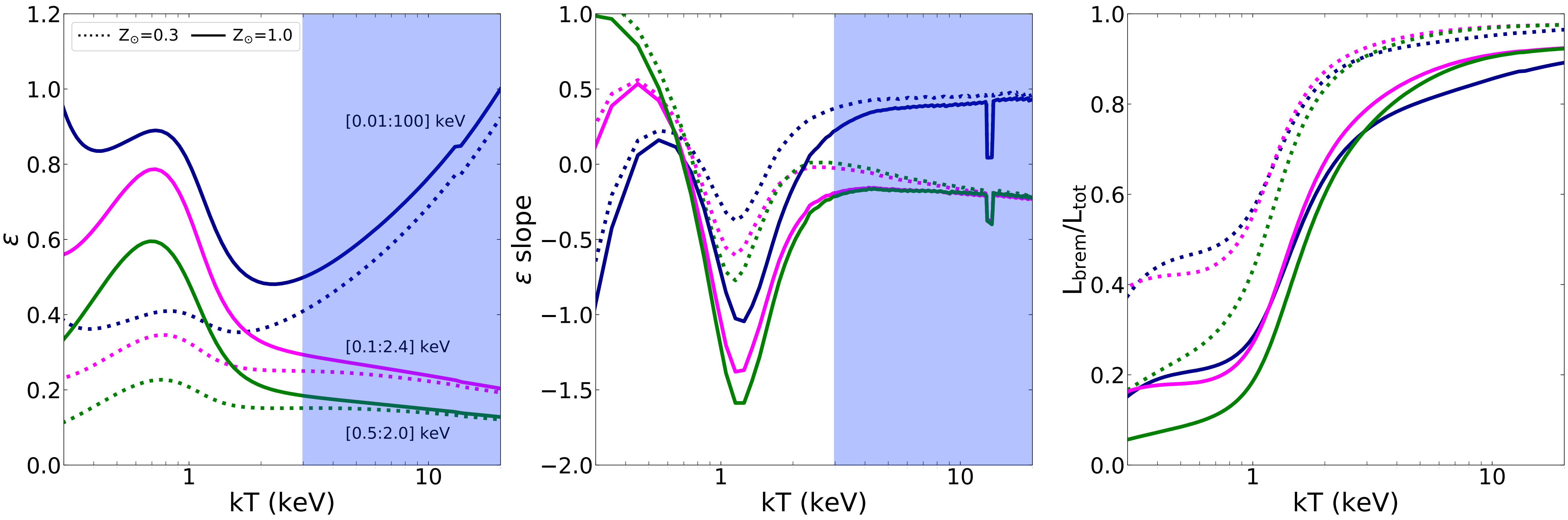


X-ray emissivity



- ★ for massive systems with typical cluster abundance the X-ray emissivity in soft band is almost independent of the system temperature
- ★ at low masses the abundance change significantly the emissivity
- ★ increasing contribution of line emission to the total luminosity for low-temperature plasmas

self-similar L-M & L-T (clusters)



$$L \propto \int \epsilon dV$$

bolometric

$$\Lambda(T,Z) \propto T^{1/2} \qquad L \propto \rho^2 R^3 T^{1/2} \qquad L \propto T^2 \qquad L \propto T^{1.9}$$

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

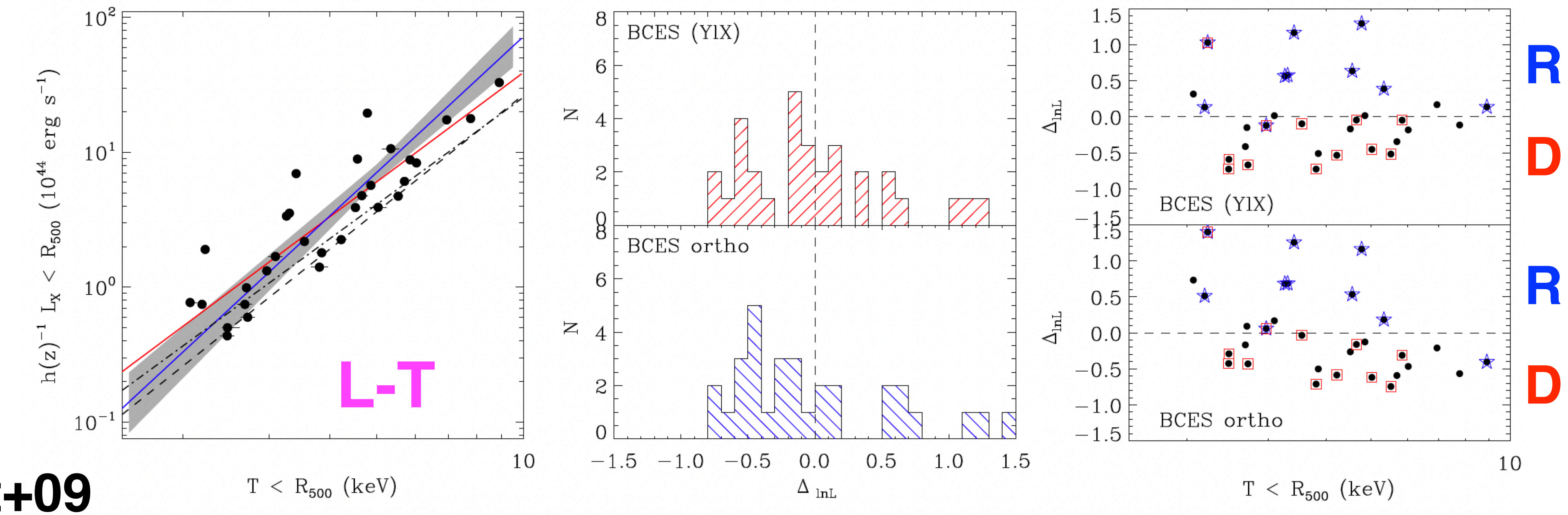
soft band

$$\Lambda(T,Z) \propto T^0 \qquad L \propto \rho^2 R^3 \qquad L \propto T^{3/2} \qquad L \propto T^{1.4}$$

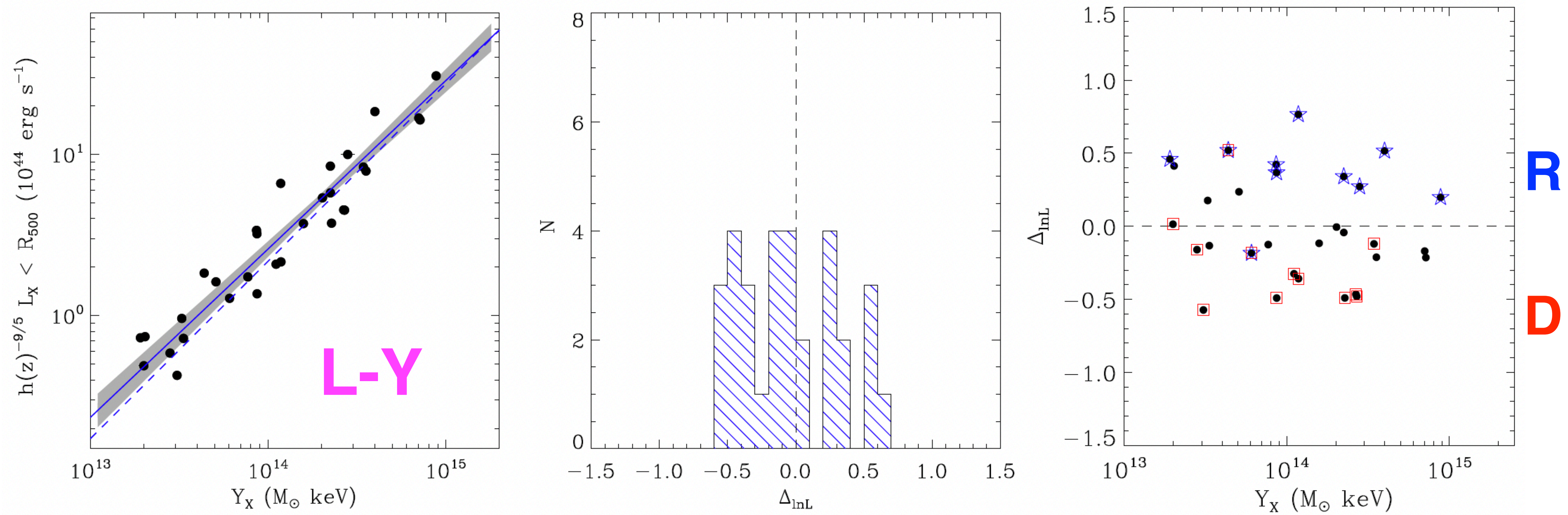
The "true" self-similar slopes are slightly shallower than traditionally assumed

Importance of finding the true population

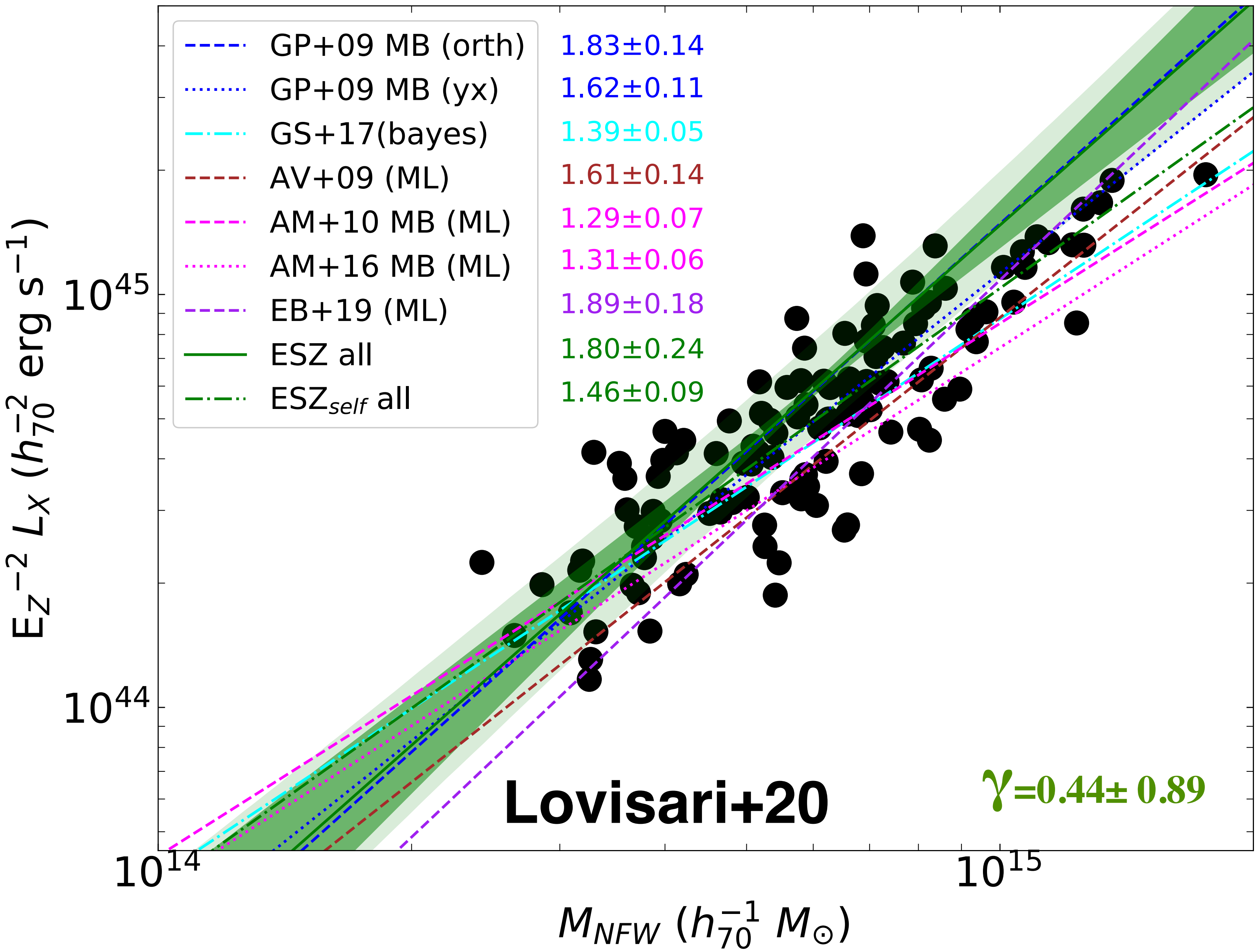
Different scaling relations for relaxed & disturbed clusters



Pratt+09



L_X-M relation



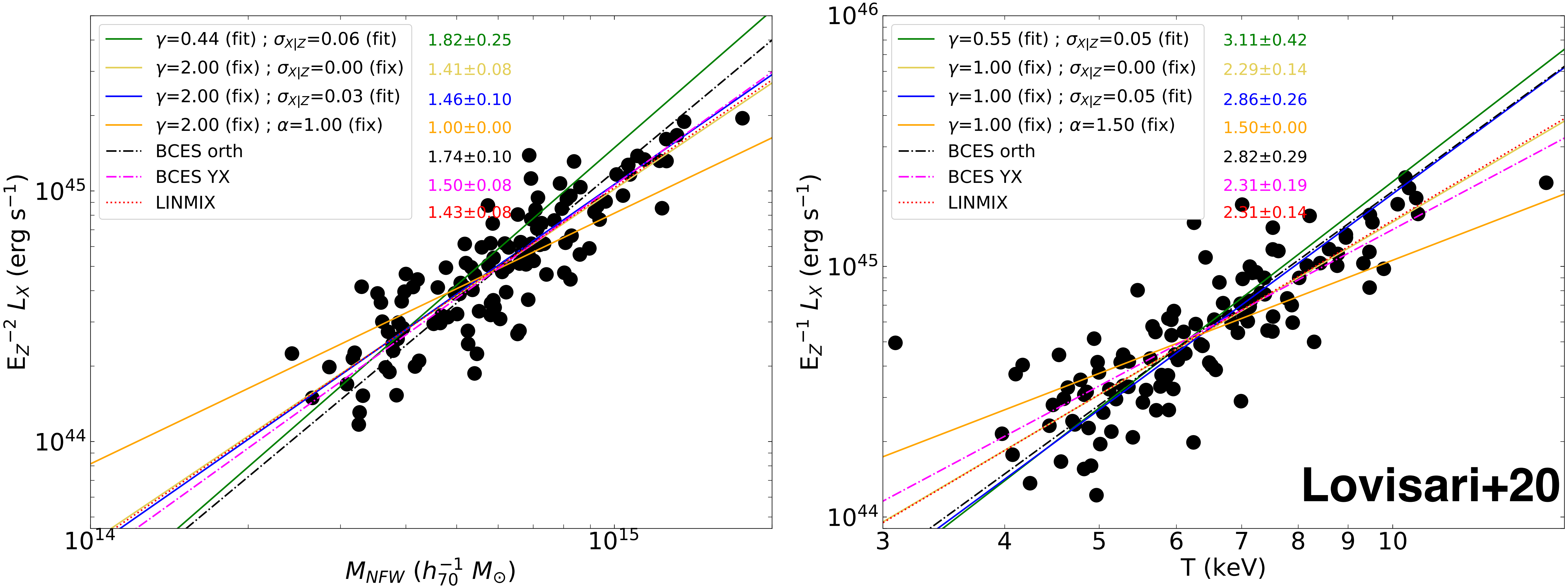
REXCESS (GP+09)
HIFLUGCS (GS17)
400d survey (AV+09)
AM+10 & AM+16
SPT (EB+19)

with the exception of REXCESS, X-ray selected samples have a lower normalization

redshift evolution at ~2σ level

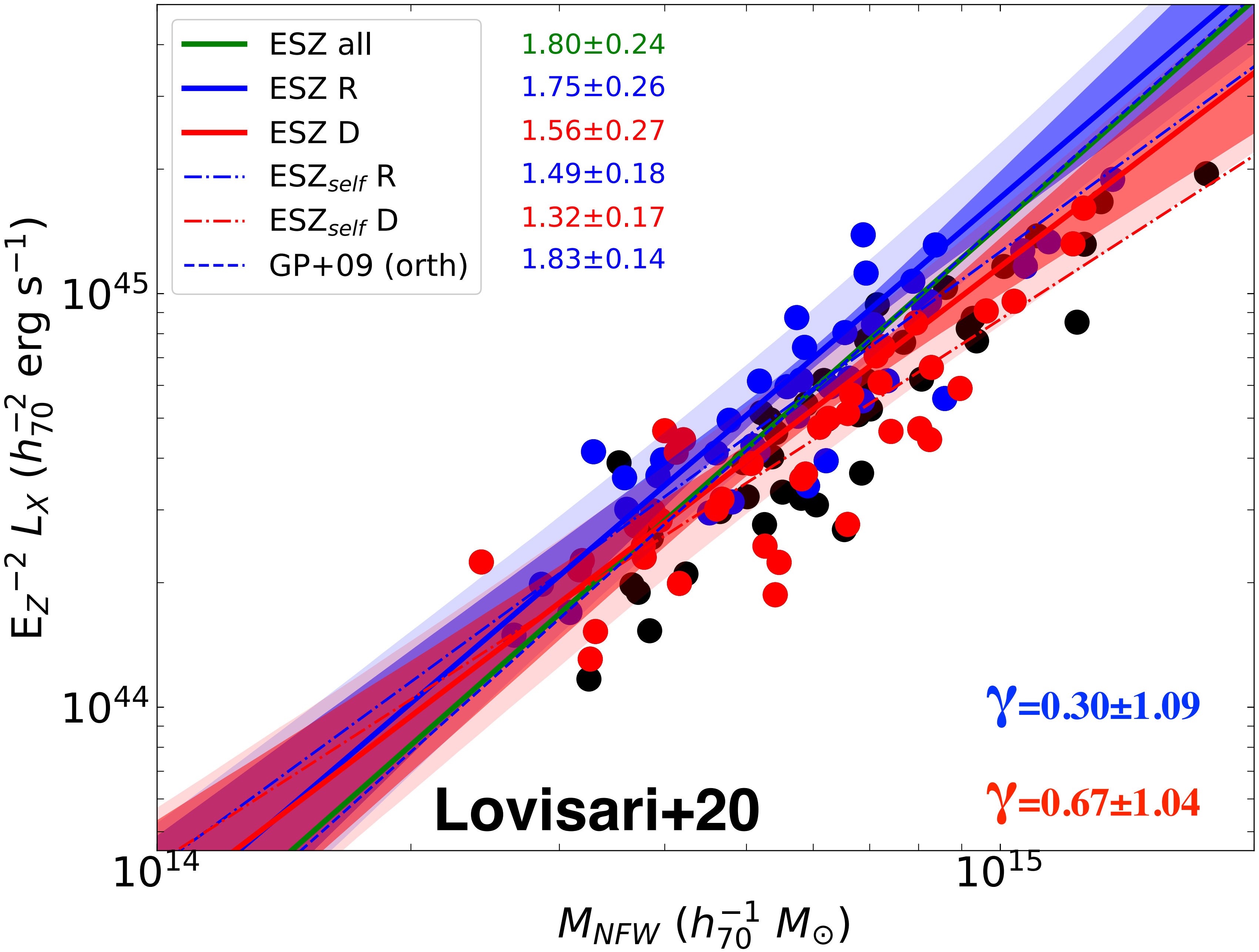
ESZ & SPT slopes agree but ~45% norm offset
if γ=2 offset reduce to ~20% but slopes disagree
…but better agreement with X-ray selected samples

Fitting algorithms



Comparing the best-fit relations from different works is not straightforward because of the different linear regression techniques (how one treats the measurement errors, which may be heteroscedastic and correlated, and the intrinsic scatter) used in the analysis.

L_X-M & morphology

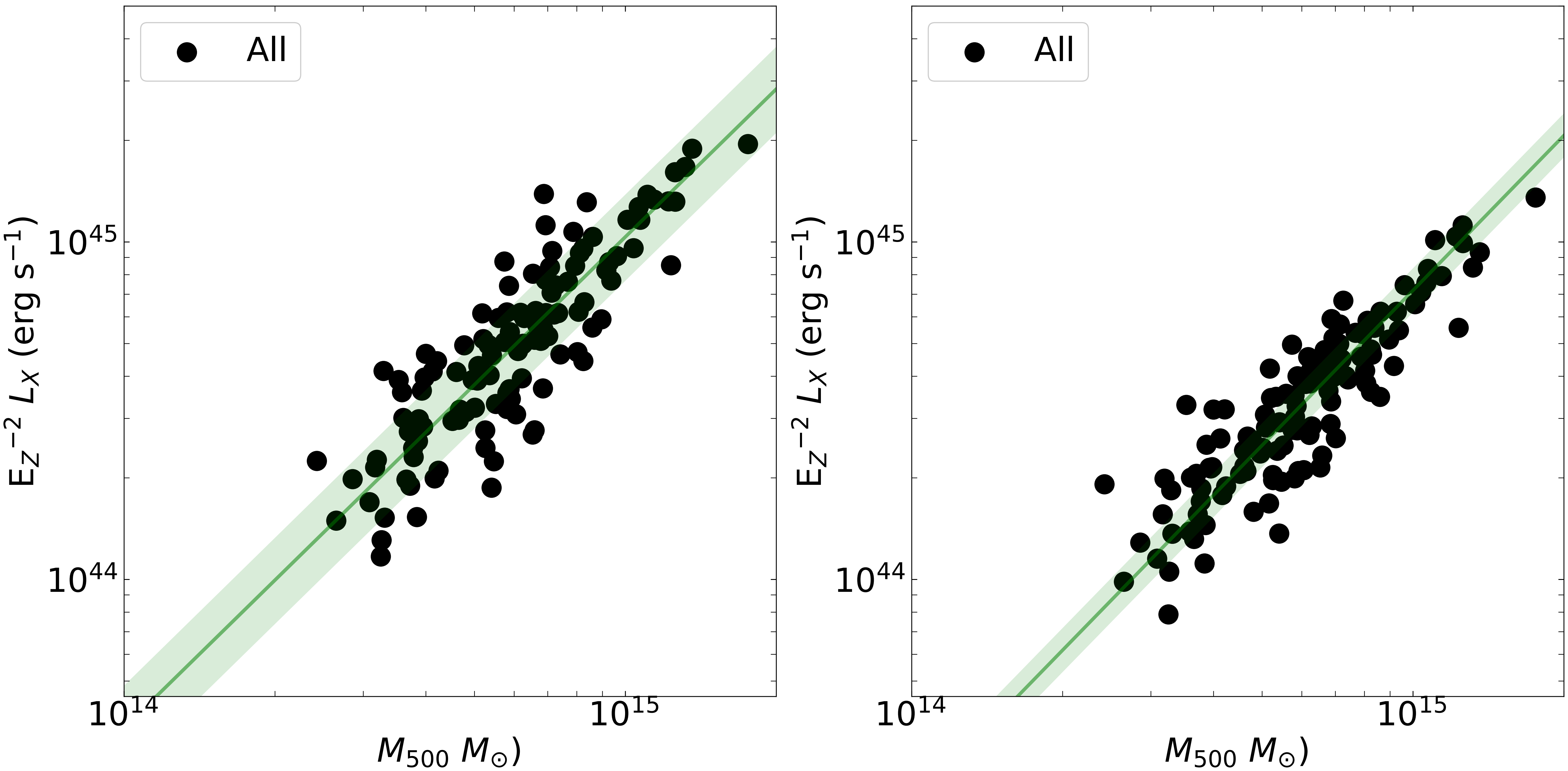


- **relaxed clusters on average above the relation**
- **disturbed clusters below the relation**

At M=6E14 $M_\odot$

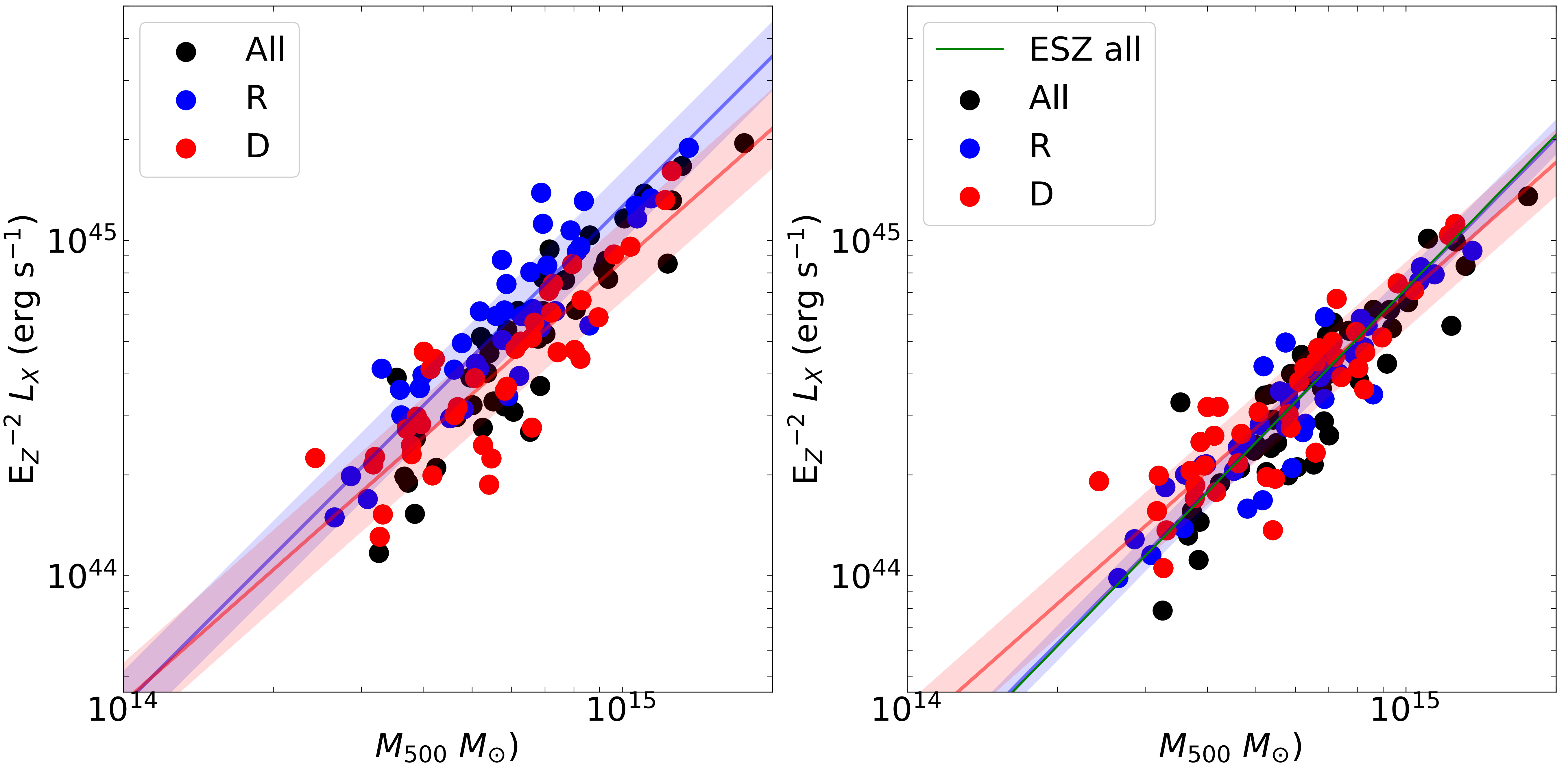
- **norm ~20% > best fit**
- **norm ~10% < best fit**

core-excised L_x



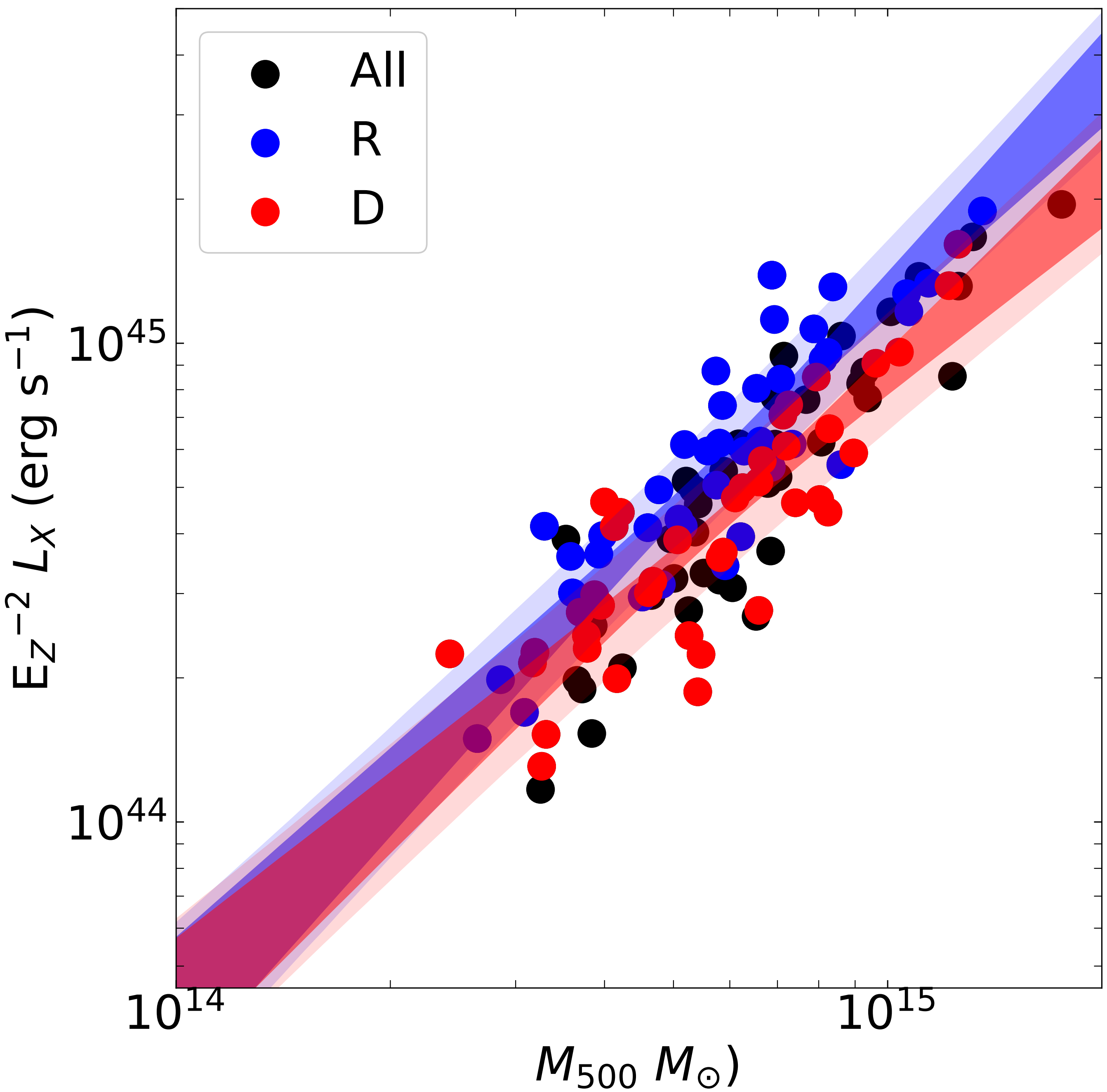
- **intrinsic scatter reduced by ~40%**

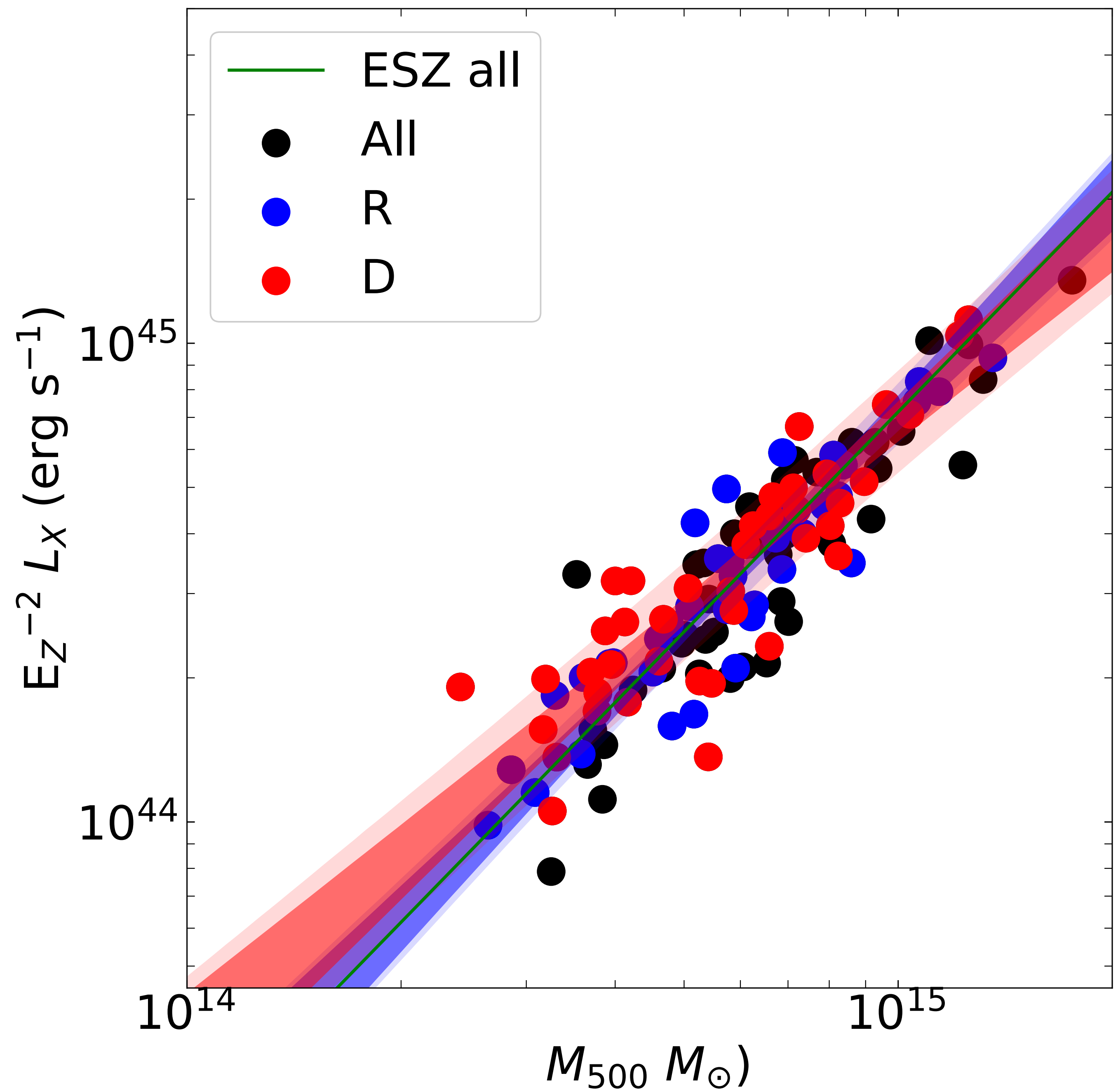
core-excised L_X



- **intrinsic scatter reduced by ~40%**
- **scatter reduced only marginally for disturbed clusters**

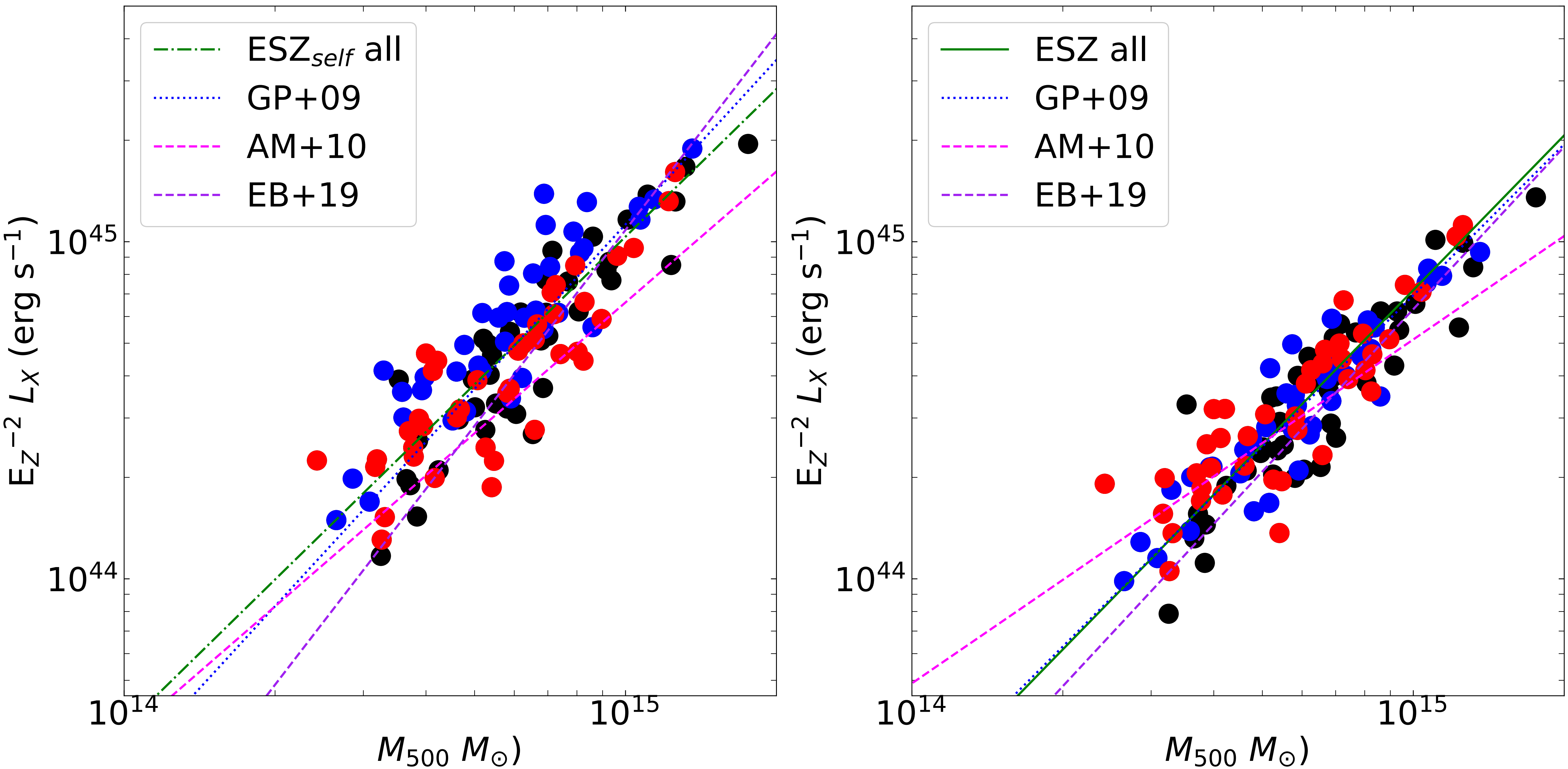
core-excised L_X





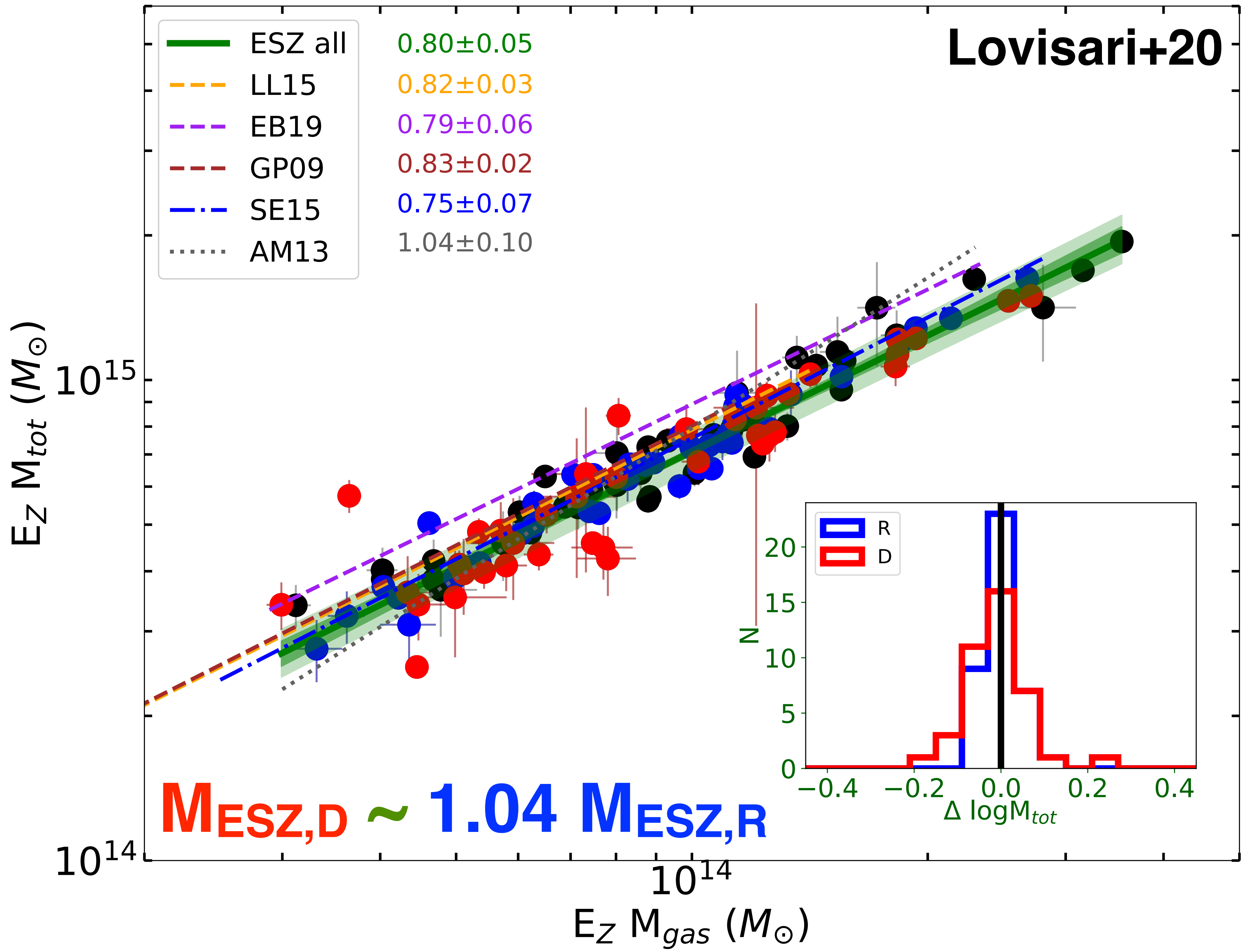
- **intrinsic scatter reduced by ~40%**
- **scatter reduced only marginally for disturbed clusters**
- **relaxed and disturbed systems sharing the same LM**

core-excised L_X



- **intrinsic scatter reduced by ~40%**
- **relaxed and disturbed systems sharing the same LM**
- **scatter reduced only marginally for disturbed clusters**
- **convergence between X-ray and SZ selected samples**

mass proxy: M_{gas}



$M_{ESZ,D} \sim 1.04\ M_{ESZ,R}$

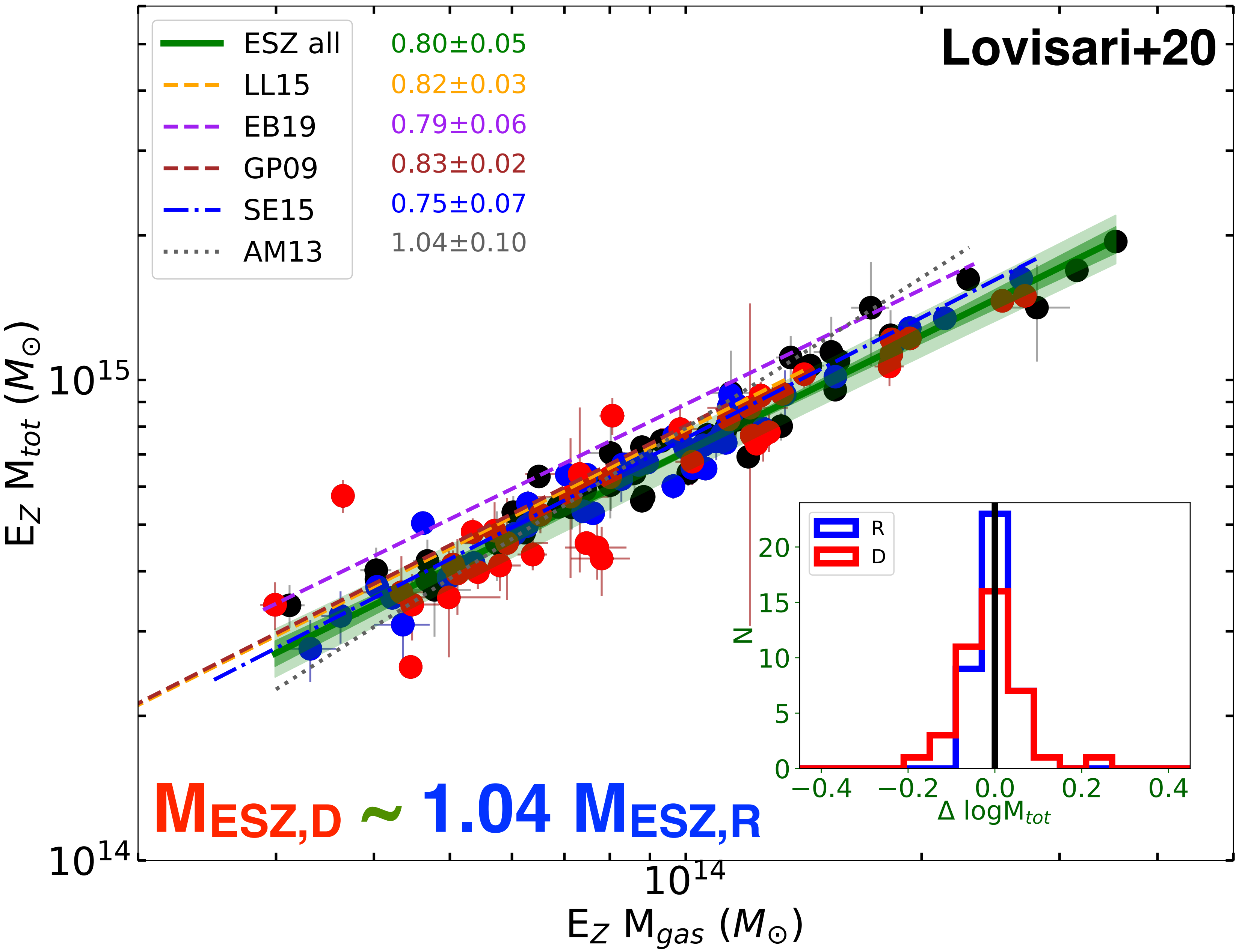
- slopes agree
- normalization offset
- tension between the relation derived using ESZ and SPT samples

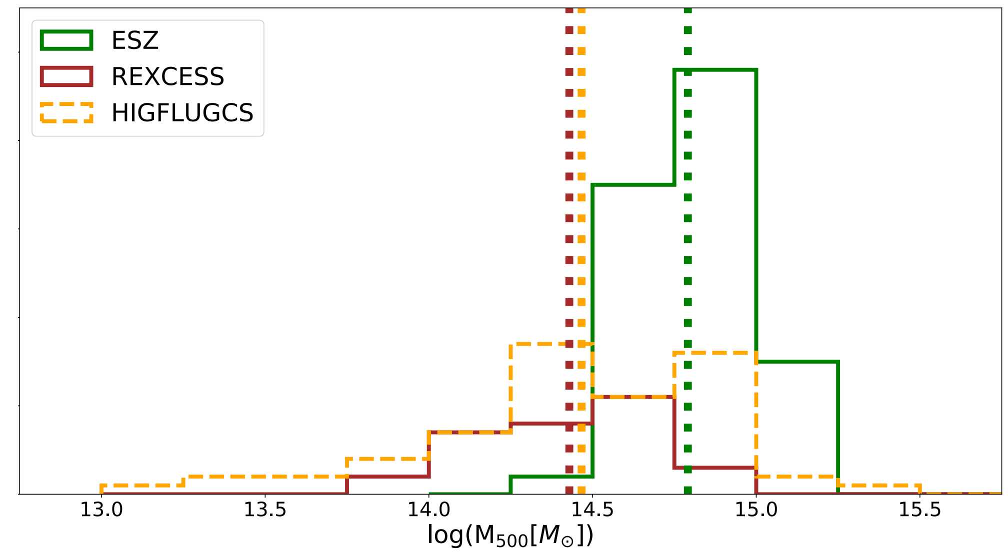
At M_{gas}=1E14 $M_\odot$

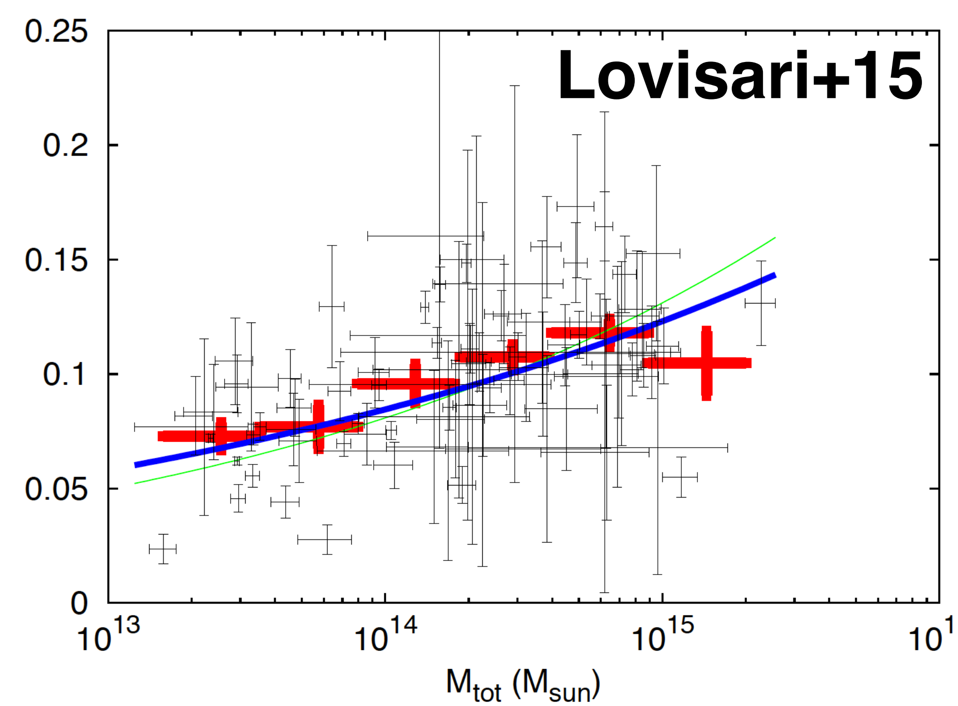
- $M_{SE+15} \sim 1.05\ M_{ESZ}$
- $M_{GP+09} \sim 1.10\ M_{ESZ}$
- $M_{EB+19} \sim 1.20\ M_{ESZ}$

~insensitive to the dynamical state of the objects…

mass proxy: M_{gas}

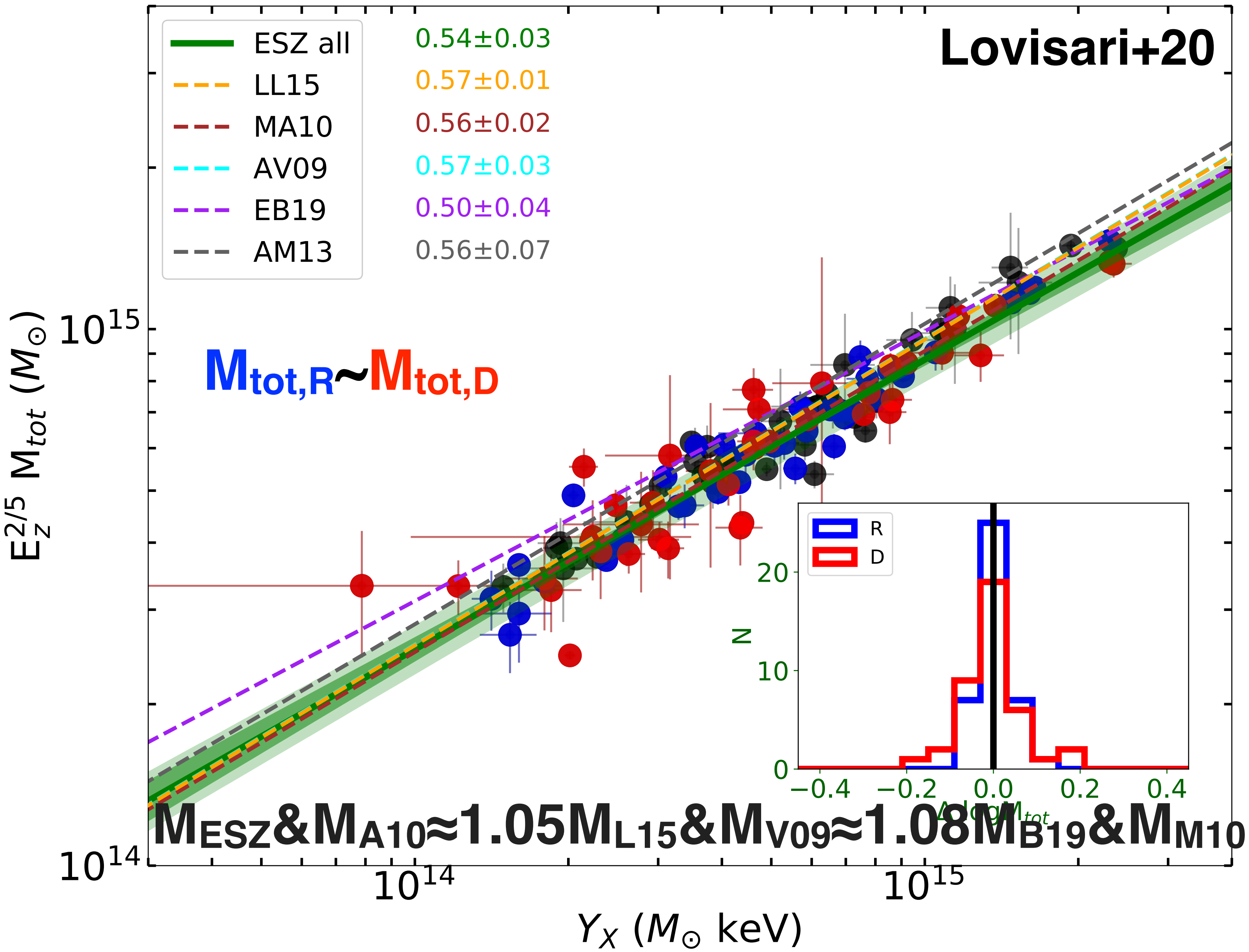






~insensitive to the dynamical state of the objects…
but dependent on the mass range investigated

mass proxy: Y_X



slope in agreement between the different studies, independently on the sample

offset in the norm probably connected with the differences in M_{gas}

insensitive to the dynamical state of the objects but the f_{gas} dependence may also play a role

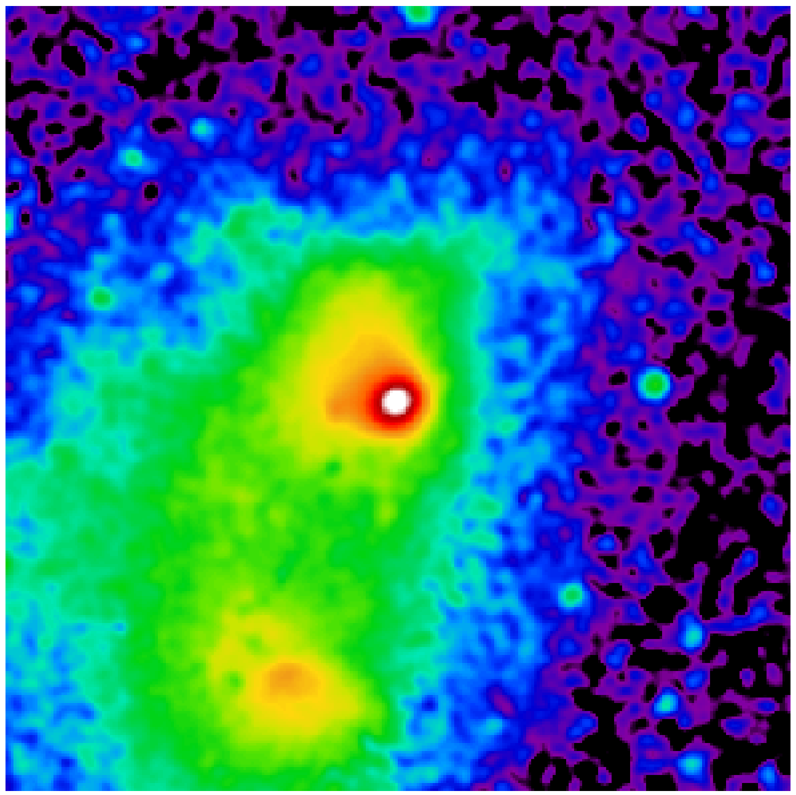
(My) Take-home messages

- SZ (& optically) selected clusters are(?) on average more disturbed than X-ray selected samples (but X-ray selections are not all the same!)
- SZ selection often assumed to be representative of the underlying population: is it true? What if baryon poor systems exist? Or if we are missing a particular class of systems?
- The different fraction of relaxed/disturbed systems strongly impact the L-M (& L-T) relation but excising the core make the relation insensitive to the dynamical state of the clusters
- M_{gas} and Y_X also show little dependence on the clusters dynamical state but the range of masses investigated may play an important role

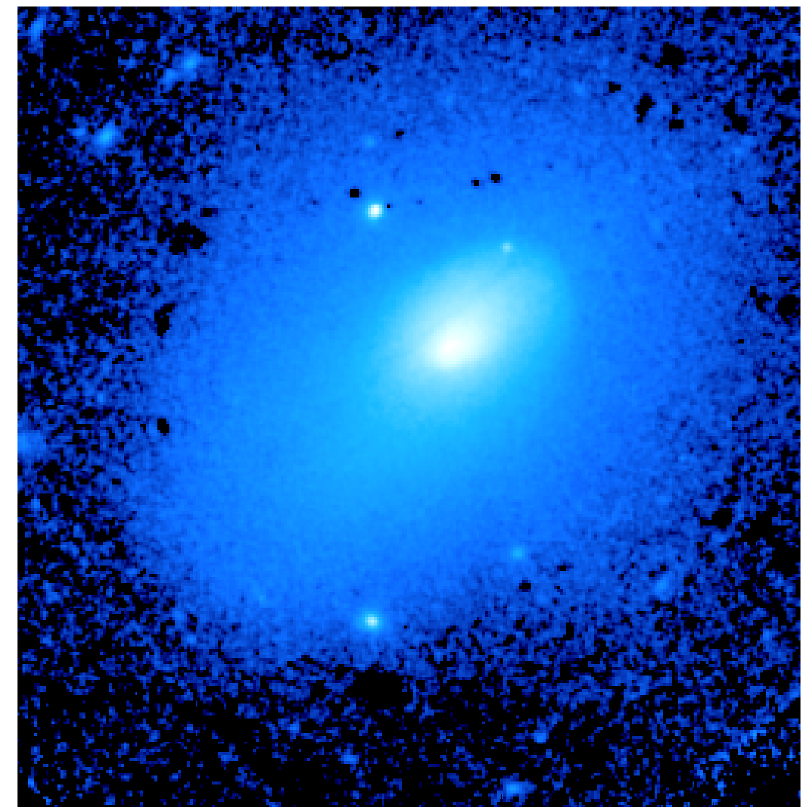
What is the cluster mass scale?

The route to accurate total masses is complicated

mergers



gas motions



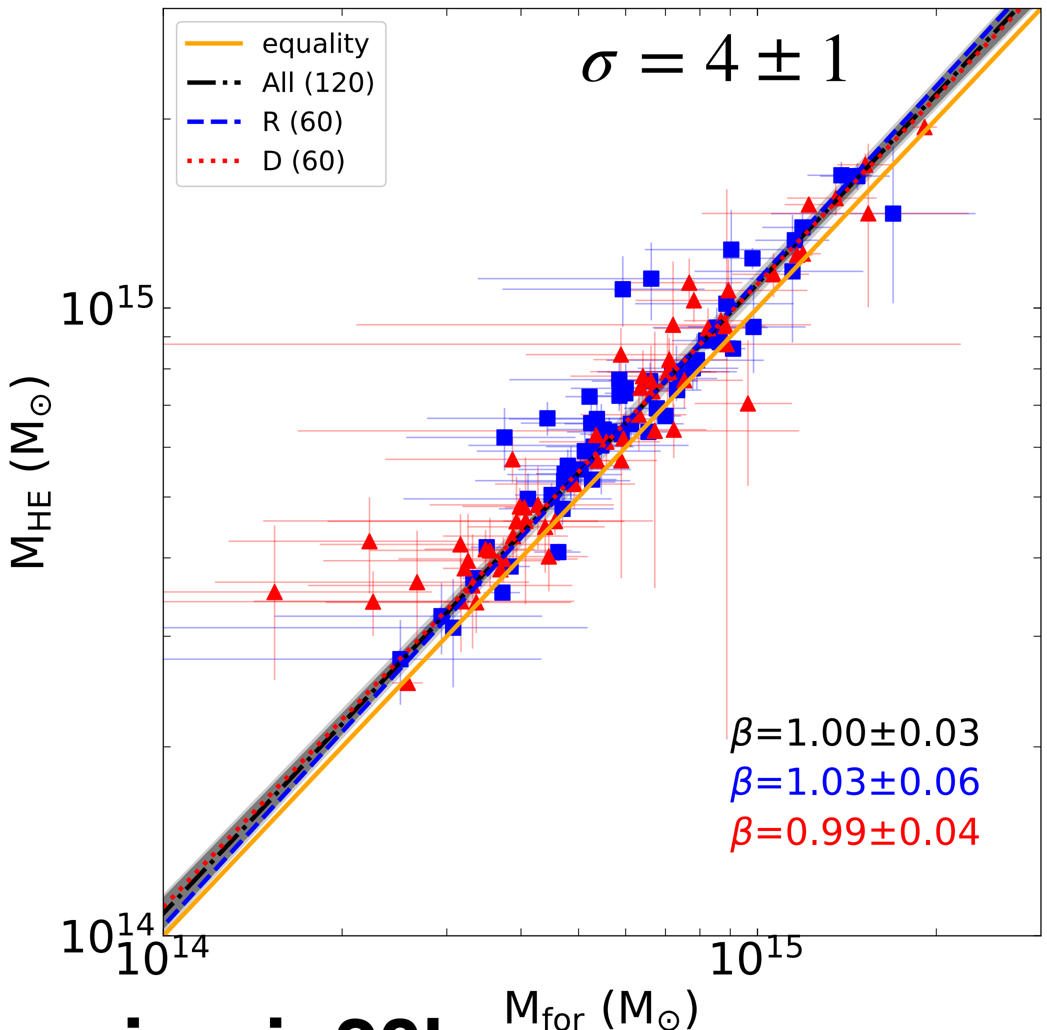
$$\frac{GM_{HE}(<r)}{r^2} = -\frac{dP_g}{dr}\frac{1}{\rho_g}$$

$$\frac{GM_{tot}(<r)}{r^2} = -\frac{d(P_g + P_{NT})}{dr}\frac{1}{\rho_g}$$

What is the magnitude of the mass bias?
And its dependence on the dynamical state?

X-ray mass reconstruction

Do the different methodologies (e.g., NFW vs fitting functional forms) returning the same masses?



Lovisari+20b

M_{for} ~9% < than M_{HE} masses, independently of the dynamical state

BUT

data quality matters, if last T bin at:

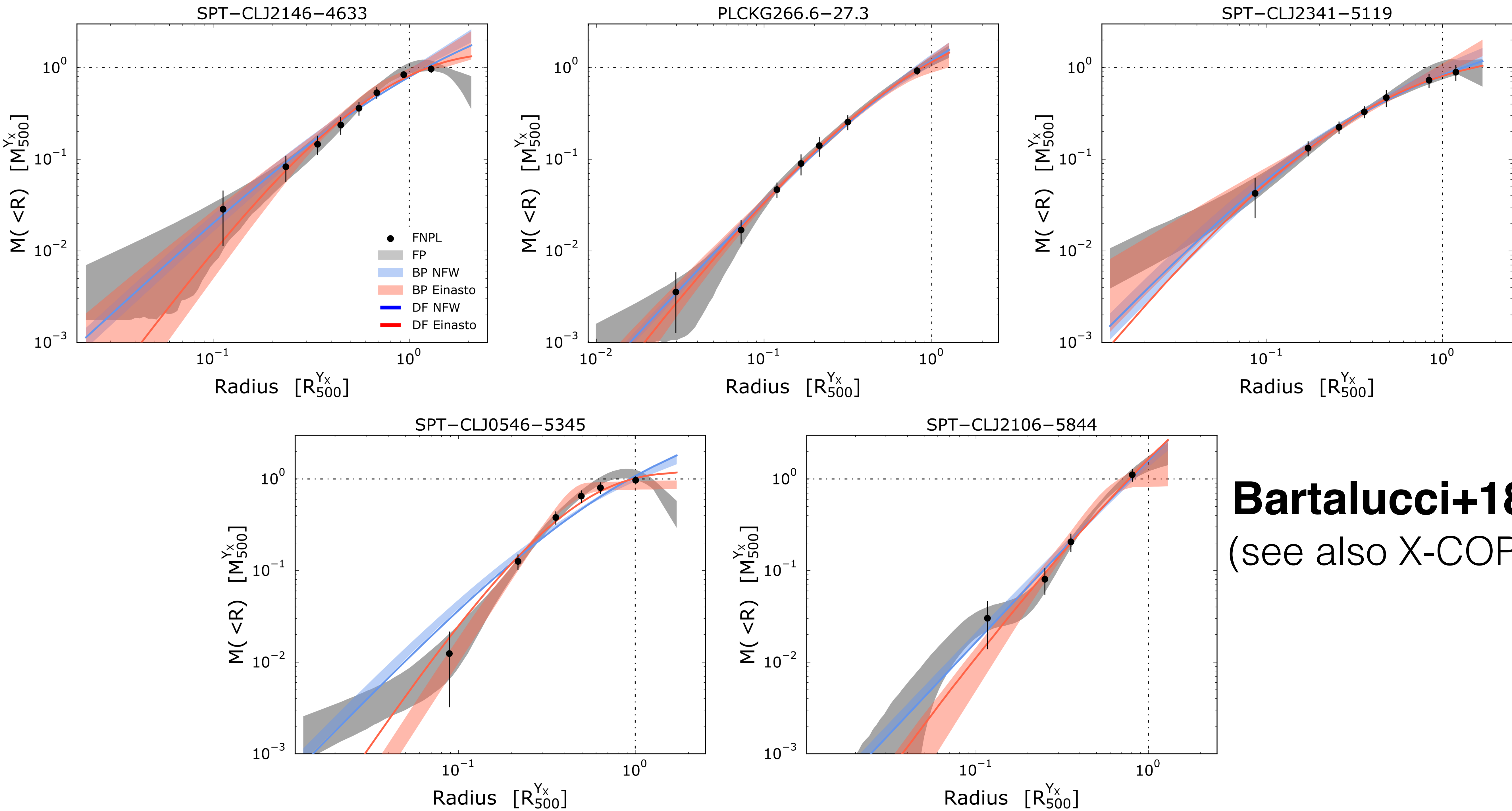
$r<0.6R_{500}$	13%
$r<0.6$–$0.8R_{500}$	9%
$r>0.8R_{500}$	7%

the smaller the extrapolation required, the better the two estimates agree

High-z clusters have on average lower quality data, so that usually the difference between the two methods is higher

Temperature sampling

M_{500} ~indipendent of the method



Bartalucci+18

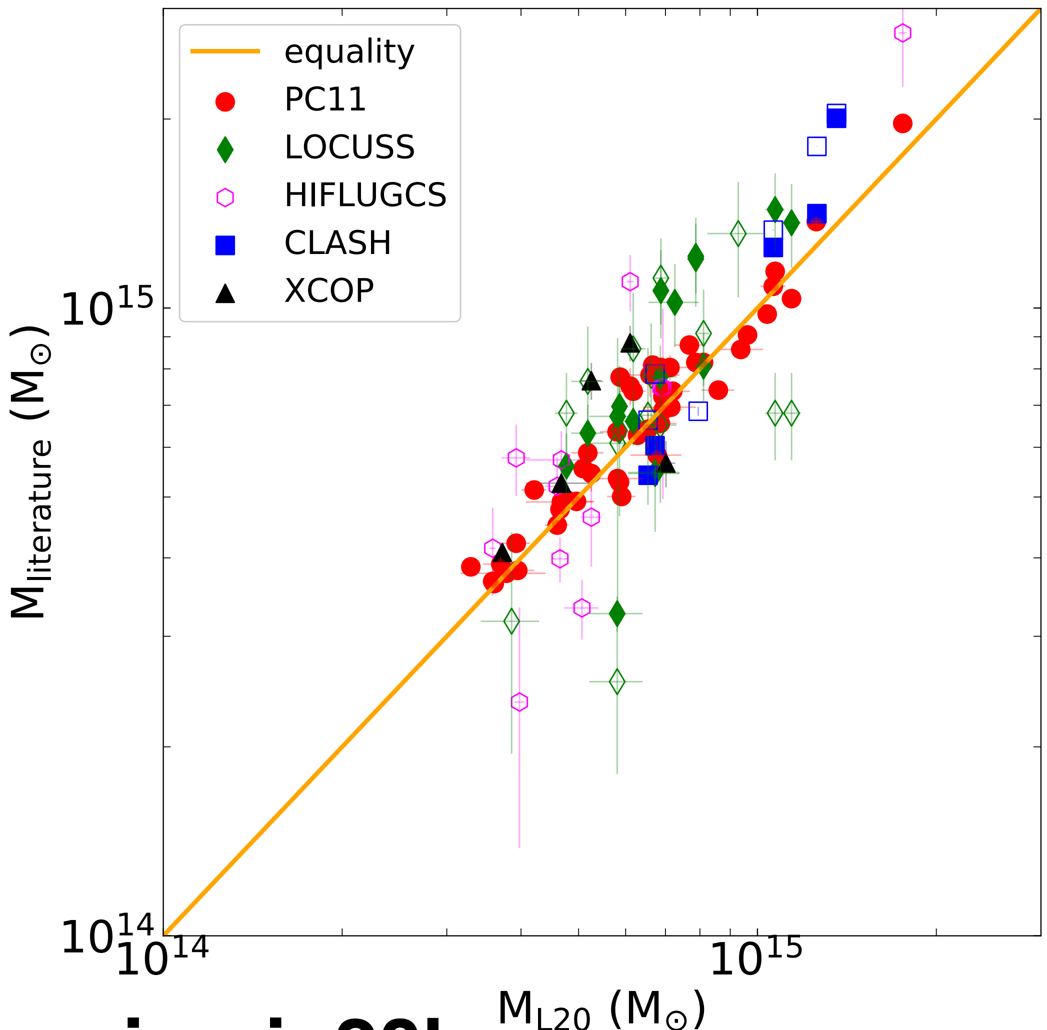
(see also X-COP)

if good temperature sampling (N>8)

then M_{for} & M_{HE} masses agree at ~1%

Different X-ray pipelines

Several studies (e.g. Rozo+14, Sereno+15) reported that M_{tot} can differ by a factor of two (even for relaxed clusters) between different X-ray analyses



Lovisari+20b

discrepancy up to ~30% for individual clusters

average difference in sample pairs <10%

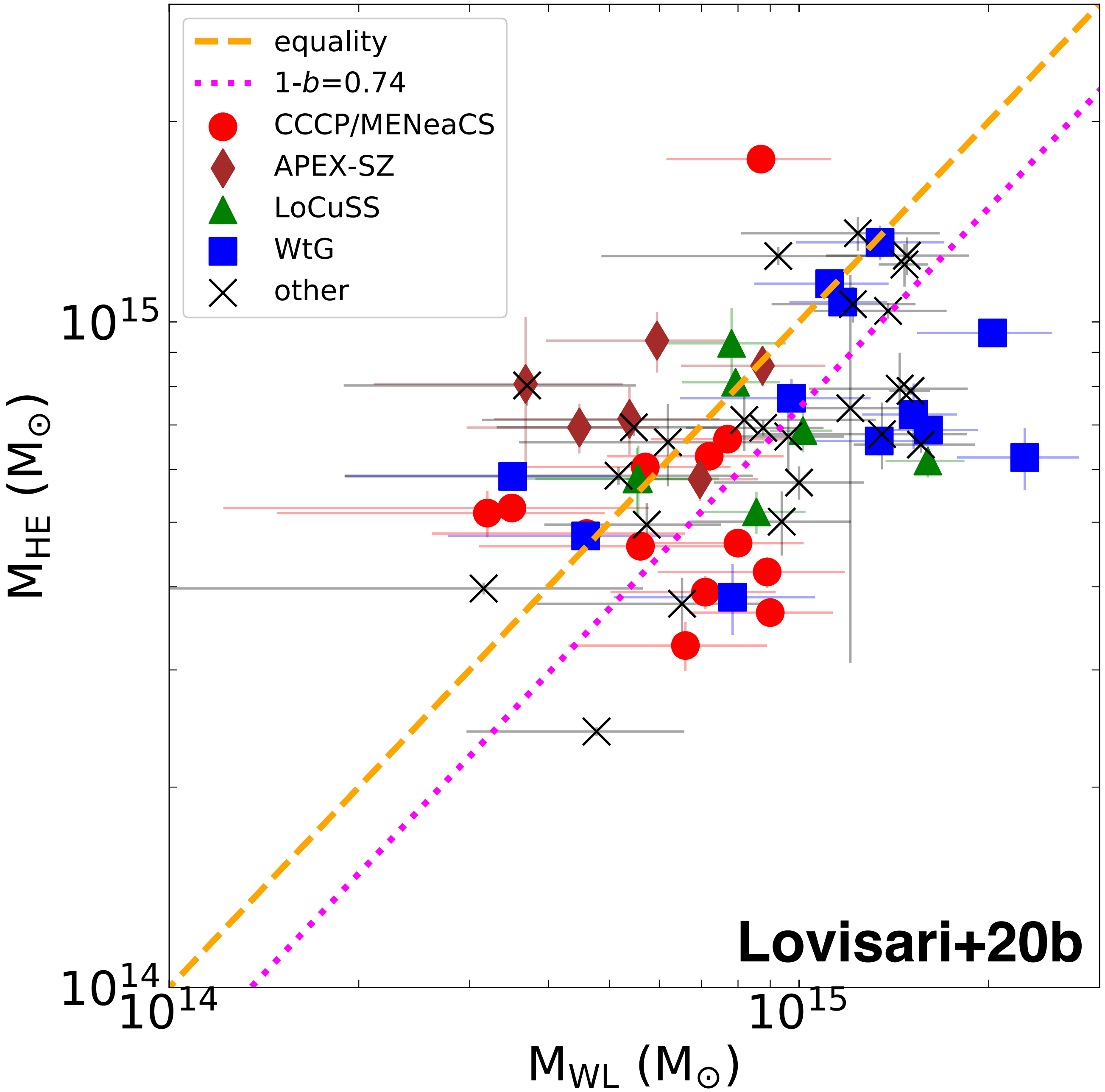
Some differences can be attributed to cross-calibration difference between X-ray detectors

Bkg treatment and R_{500} coverage play also a crucial role

If data quality is good, and the background properly treated the differences between masses of individual clusters is probably <10%

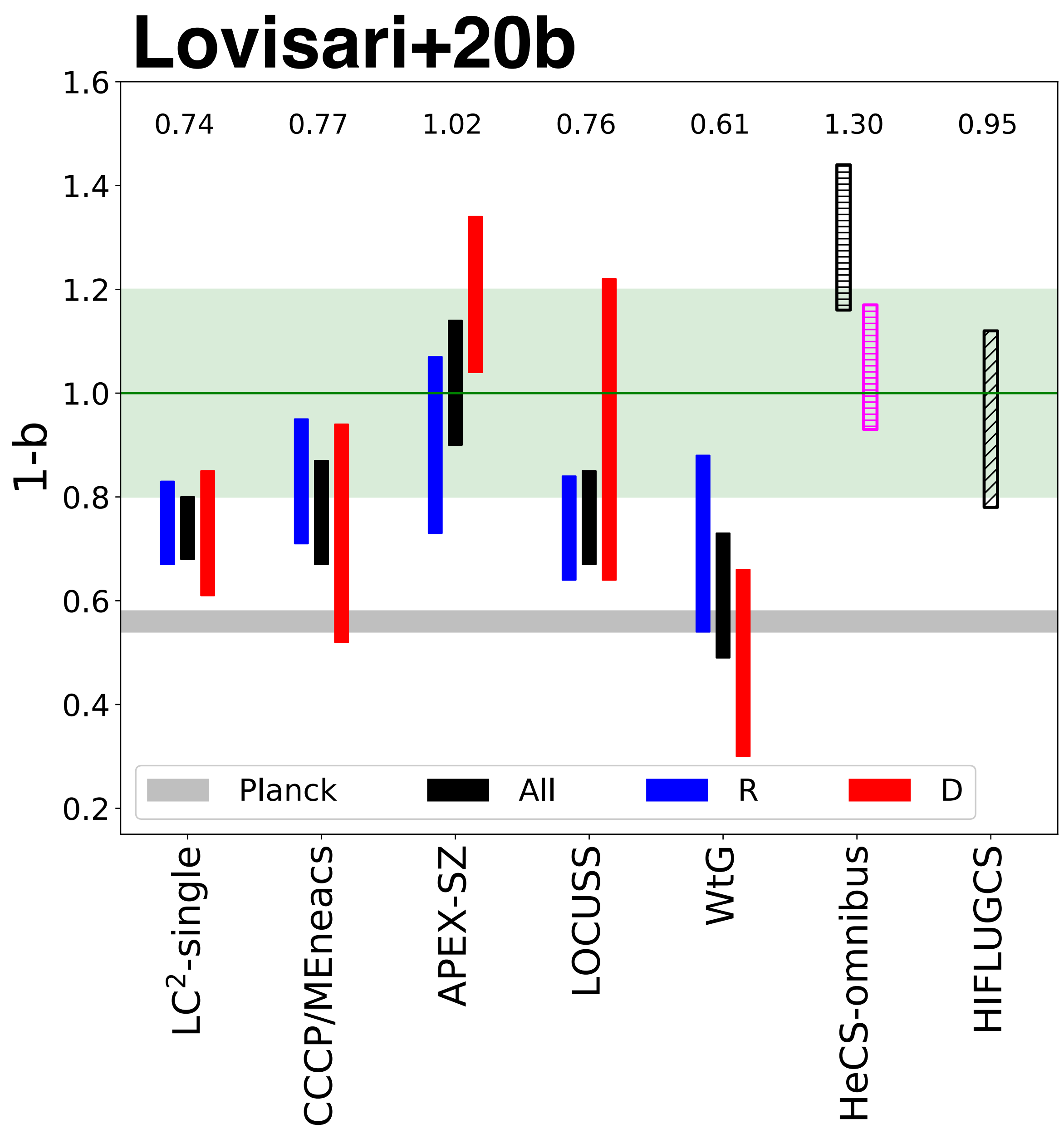
X-ray vs WL

For WL masses, we used LC2 (Literature Catalogs of Weak Lensing Clusters, Sereno 2015), a meta-catalog with 800+ unique entries. When multiple analyses per cluster are available, preference is given to studies exploiting the deeper observations and multiband optical coverage for optimal galaxy background selection.



Sample	N	$\tilde{M}_{WL}$	$\tilde{z}$	1-b	σ_{WL}	σ_{HE}
All						
LC^2-*single*	62	8.37	0.21	0.74±0.06	27±8	30±6
CCCP/MENeaCS	27	7.40	0.18	0.77±0.10	10±9	40±8
APEX-SZ	19	8.51	0.28	1.02±0.12	37±10	28±10
LoCuSS	18	8.24	0.22	0.76±0.09	23±9	24±8
WtG	17	11.73	0.29	0.61±0.12	31±15	26±11
Relaxed						
LC^2-*single*	34	8.65	0.21	0.75±0.08	27±9	18±8
CCCP/MENeaCS	17	7.10	0.17	0.83±0.12	21±13	25±10
APEX-SZ	11	8.75	0.27	0.90±0.17	42±14	27±13
LoCuSS	14	9.42	0.22	0.74±0.10	20±10	26±8
WtG	10	11.46	0.23	0.71±0.17	22±18	32±14
Disturbed						
LC^2-*single*	28	8.09	0.29	0.73±0.12	31±14	45±10
CCCP/MENeaCS	10	8.35	0.19	0.73±0.21	10±13	61±17
APEX-SZ	8	7.57	0.30	1.19±0.15	14±15	15±14
LoCuSS	4	5.89	0.24	0.93±0.29	9±20	22±29
WtG	7	15.20	0.41	0.48±0.18	16±17	18±16

Mass bias

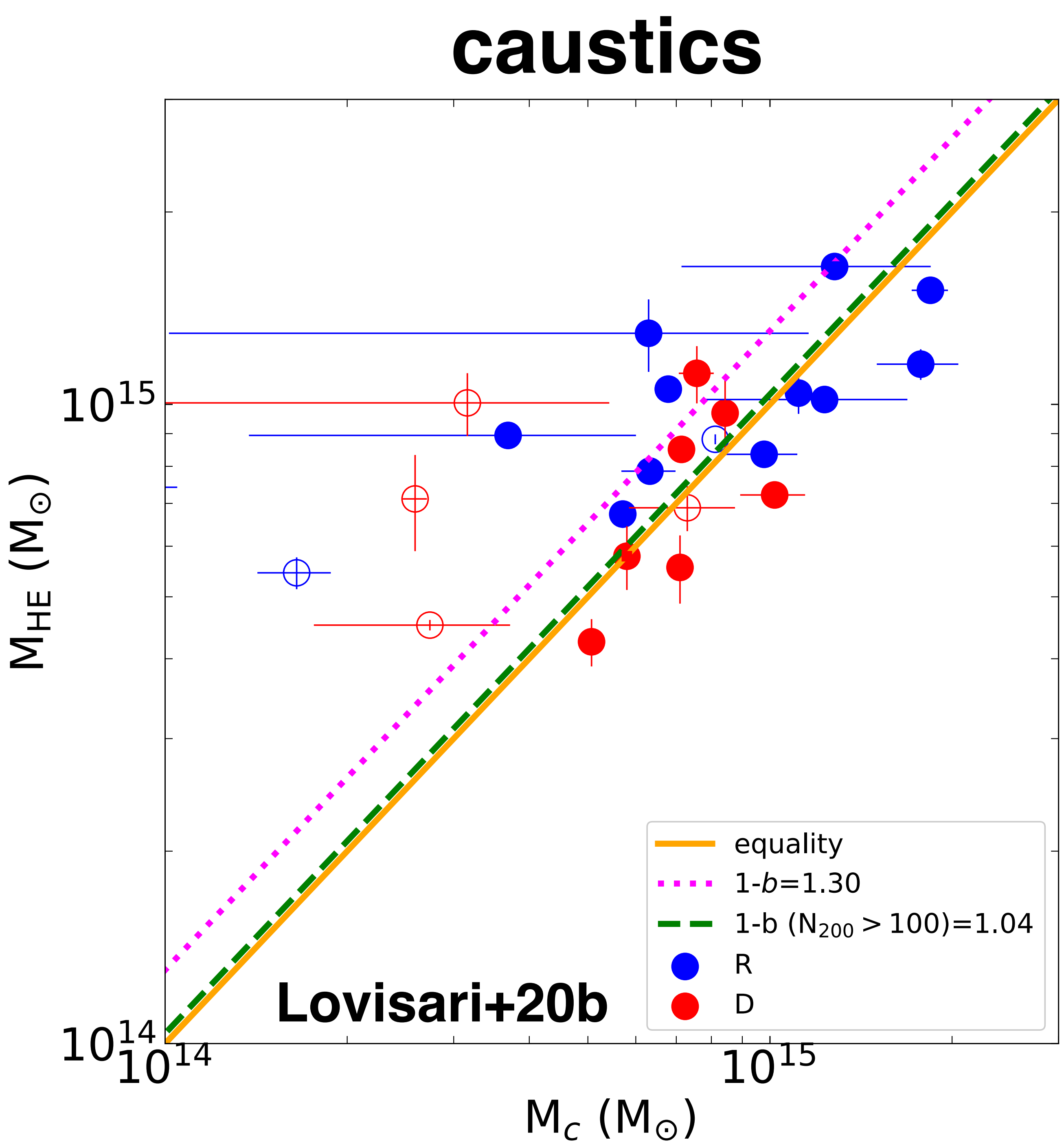


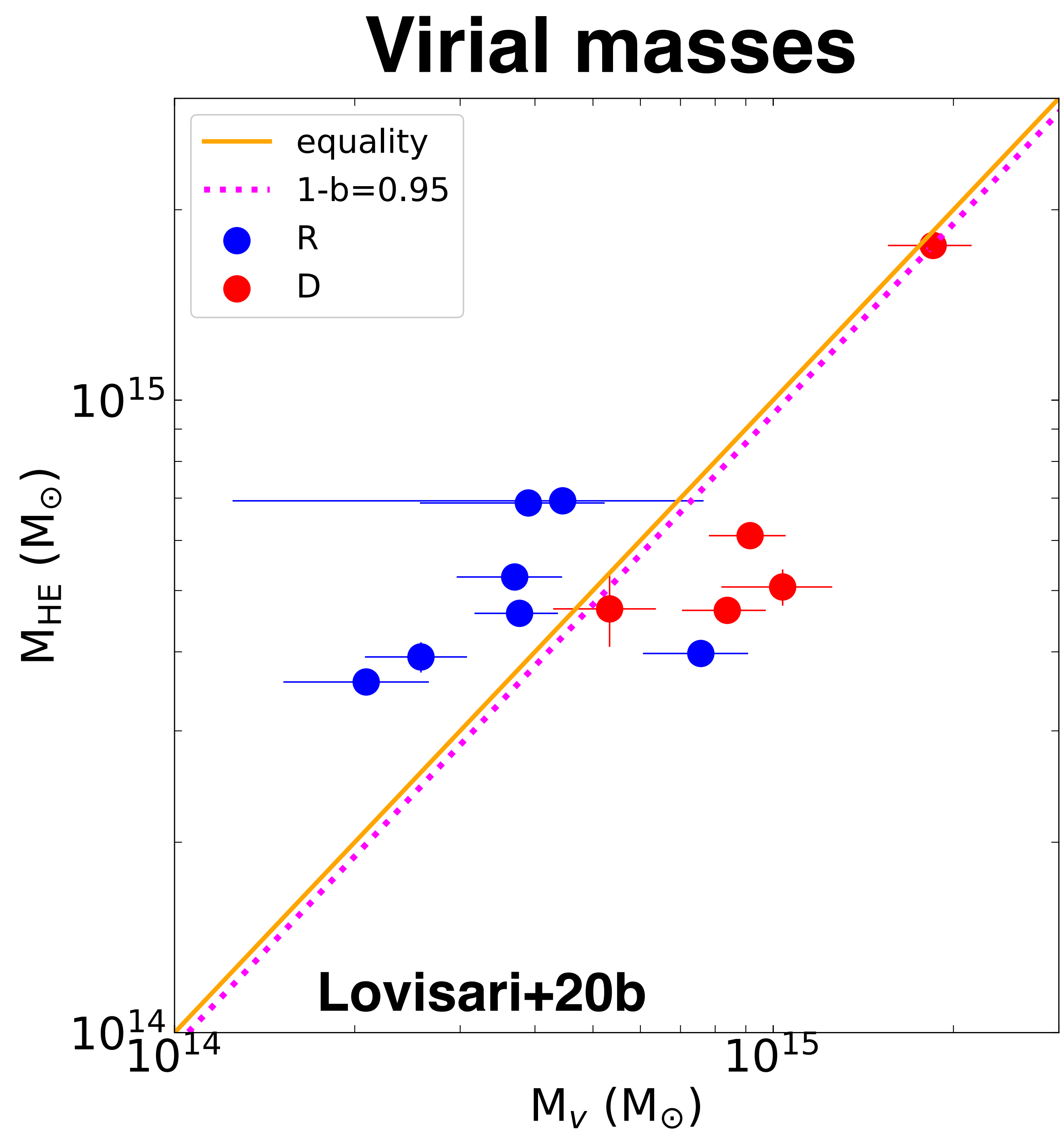
All						
Sample	N	$\tilde{M}_{WL}$	$\tilde{z}$	1-b	σ_{WL}	σ_{HE}
LC^2-*single*	62	8.37	0.21	0.74±0.06	27±8	30±6
CCCP/MENeaCS	27	7.40	0.18	0.77±0.10	10±9	40±8
APEX-SZ	19	8.51	0.28	1.02±0.12	37±10	28±10
LoCuSS	18	8.24	0.22	0.76±0.09	23±9	24±8
WtG	17	11.73	0.29	0.61±0.12	31±15	26±11
Relaxed						
Sample	N	$\tilde{M}_{WL}$	$\tilde{z}$	1-b	σ_{WL}	σ_{HE}
LC^2-*single*	34	8.65	0.21	0.75±0.08	27±9	18±8
CCCP/MENeaCS	17	7.10	0.17	0.83±0.12	21±13	25±10
APEX-SZ	11	8.75	0.27	0.90±0.17	42±14	27±13
LoCuSS	14	9.42	0.22	0.74±0.10	20±10	26±8
WtG	10	11.46	0.23	0.71±0.17	22±18	32±14
Disturbed						
Sample	N	$\tilde{M}_{WL}$	$\tilde{z}$	1-b	σ_{WL}	σ_{HE}
LC^2-*single*	28	8.09	0.29	0.73±0.12	31±14	45±10
CCCP/MENeaCS	10	8.35	0.19	0.73±0.21	10±13	61±17
APEX-SZ	8	7.57	0.30	1.19±0.15	14±15	15±14
LoCuSS	4	5.89	0.24	0.93±0.29	9±20	22±29
WtG	7	15.20	0.41	0.48±0.18	16±0.17	18±16

the mass bias inferred from the WL masses of different projects vary by a large amount

however, WtG is the only sample that show the expected correlation between mass bias and dynamical state

X-ray vs dynamical masses





Good agreement between X-ray and caustic measurements after removing the clusters with fewer member galaxies

On average good agreement but with significant differences when relaxed and disturbed clusters are considered

(My) Take-home messages

- SZ (& optically) selected clusters are(?) on average more disturbed than X-ray selected samples (but X-ray selections are not all the same!)
- SZ selection often assumed to be representative of the underlying population: is it true? What if baryon poor systems exist? Or if we are missing a particular class of systems?
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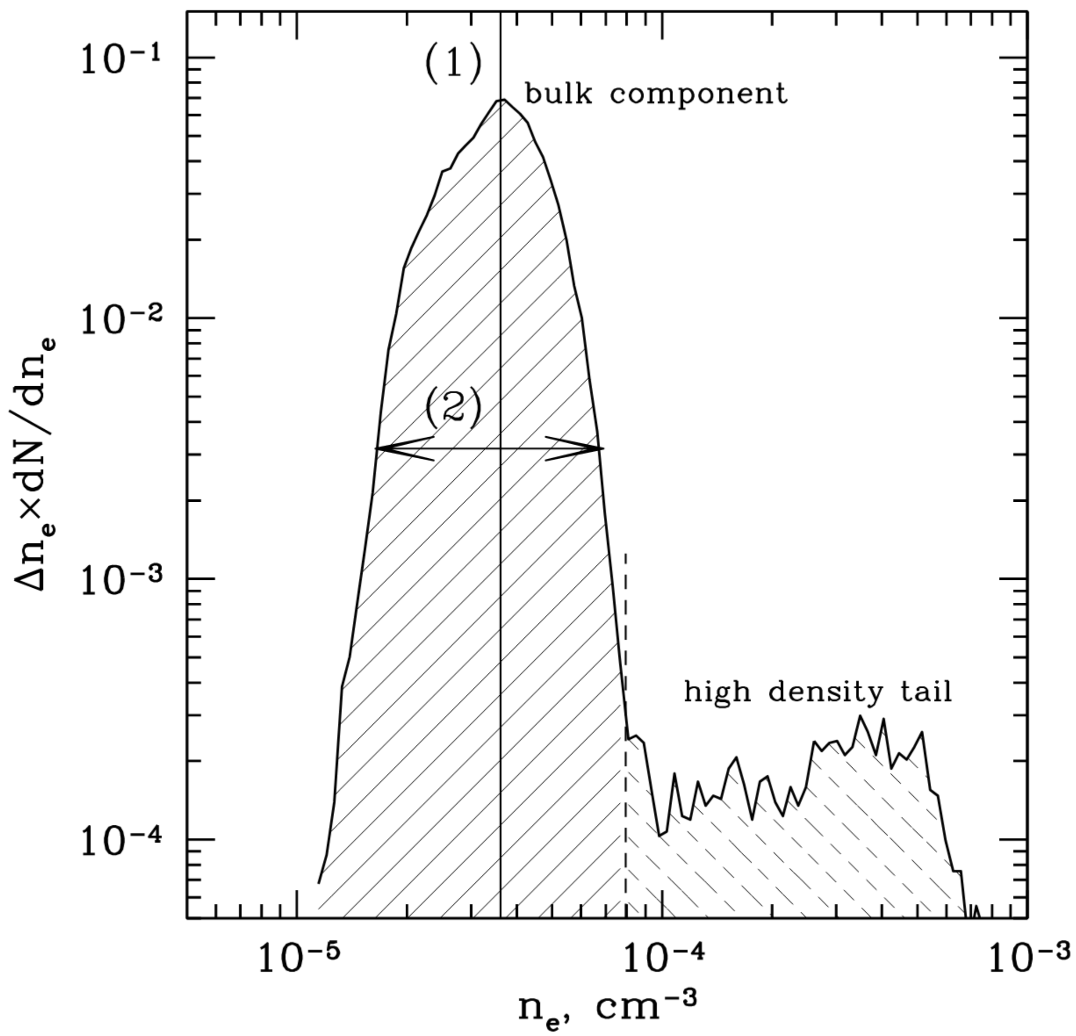
- Unlike the WL masses, the dynamical masses, either from caustic or velocity dispersion, favor a scenario where X-ray hydrostatic masses have little or no bias

M_{tot} & ICM inhomogeneities

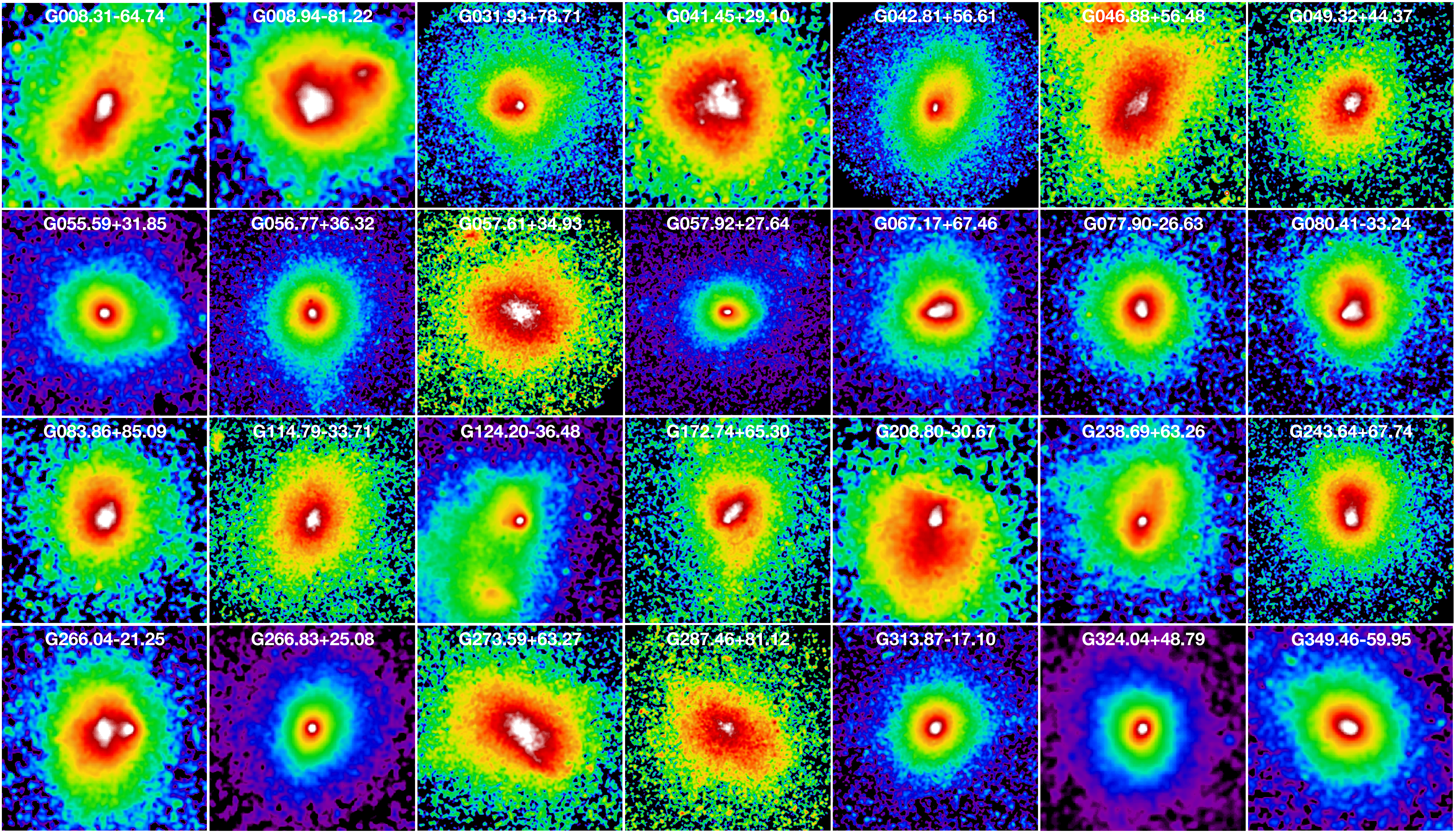
Zhuravleva+13

the presence of temperature and density inhomogeneities can cause biases in the determination of the azimuthal profiles (key inputs in the mass estimate from X-ray analysis), and so on the X-ray measured mass distribution.

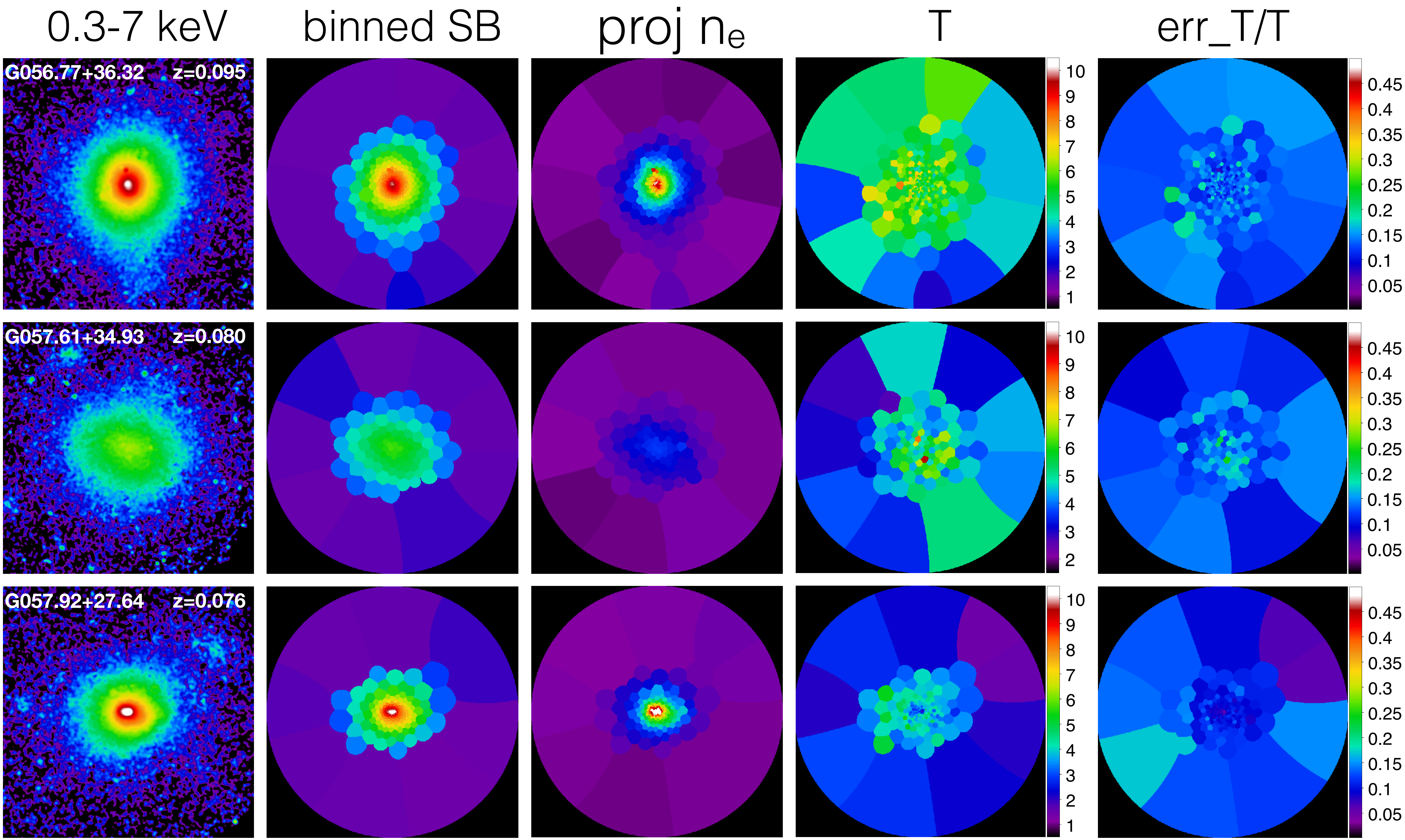


Can we remove the kT inhomogeneities and improve or homogenize the cluster mass estimate?

28 CHEX-MATE clusters



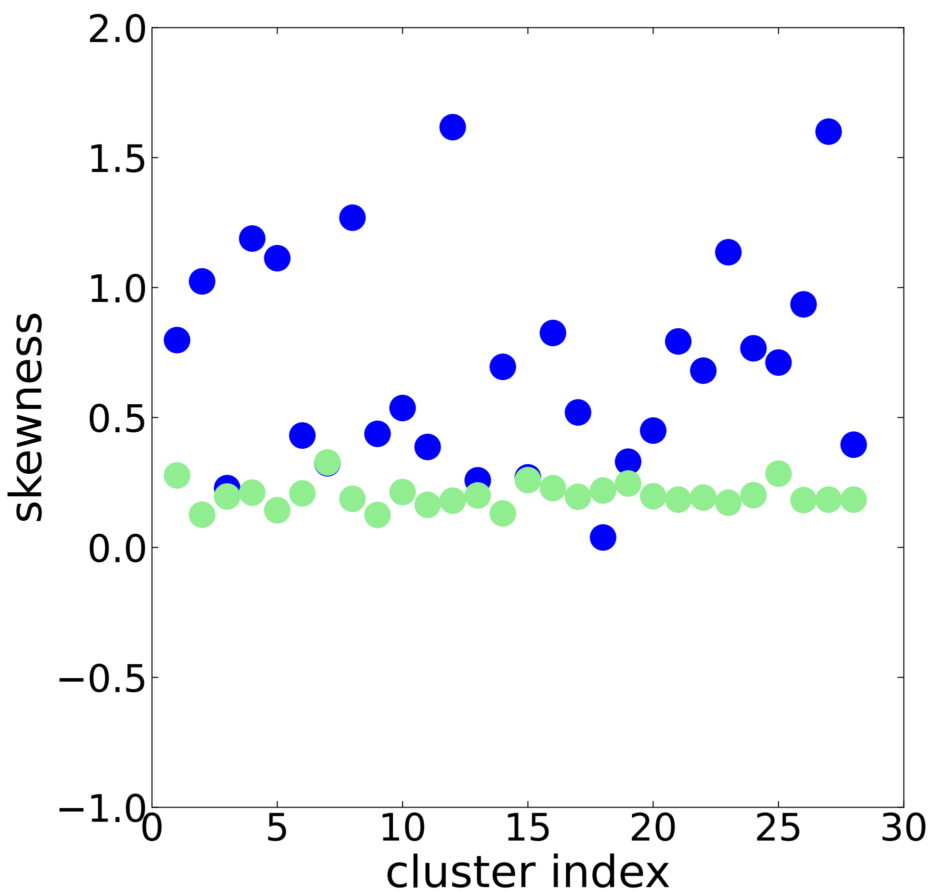
Maps in the paper

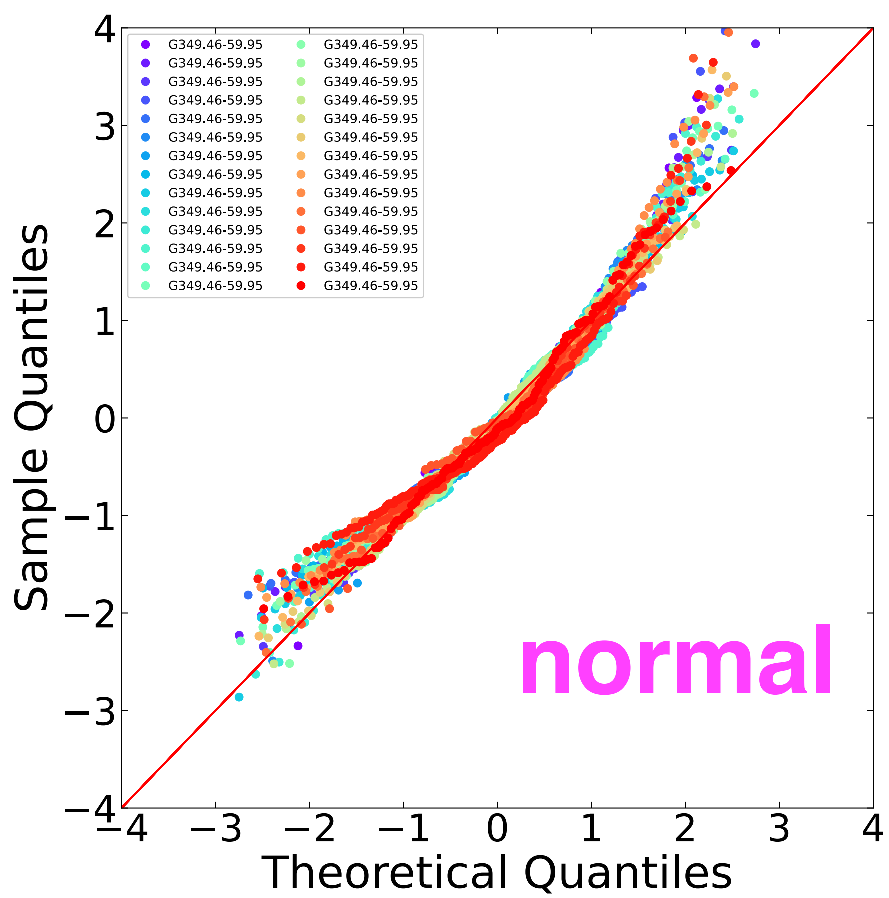


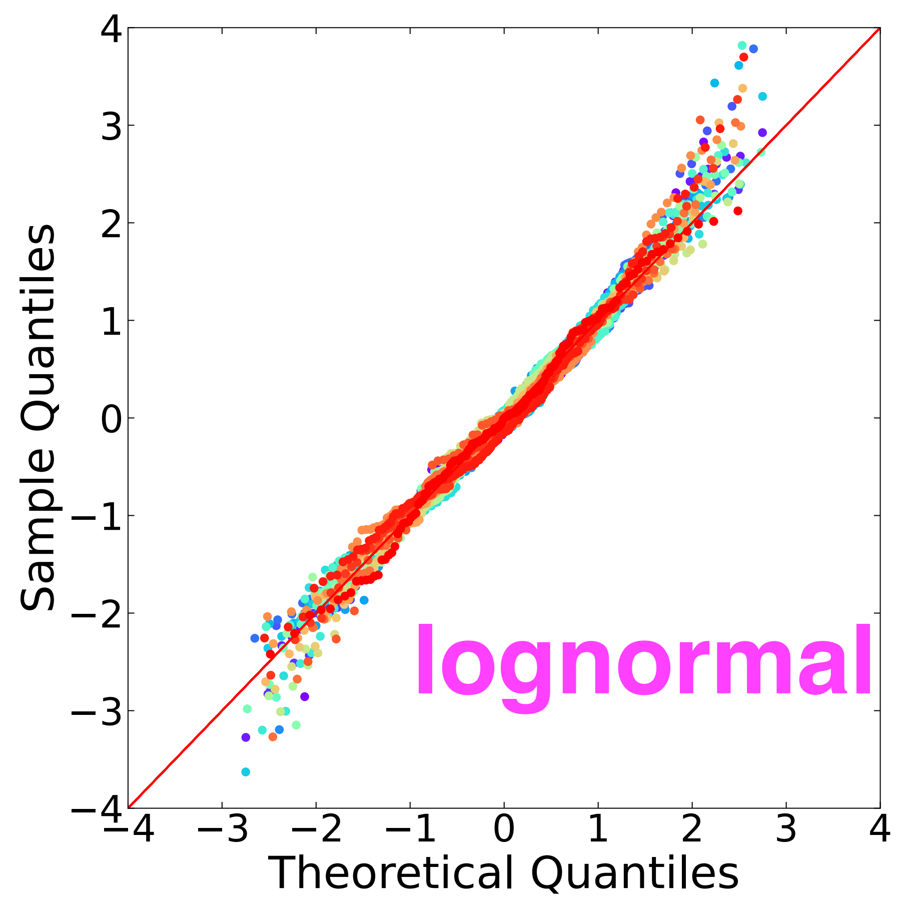
Properties of the 2D distribution

N_{bins} —-> 50 - 300

Most of the maps show a positive skewness







the skewness measured in presence of a low number of bins can be quite uncertain: however the green point indicate the expected skewness value using the N bins of each map and confirm that the skewness is real

heavily right-skewed (i.e. hot clumps)

gaussianity can be rejected at a s.l. of 5% (1%) for 20 (14) objects

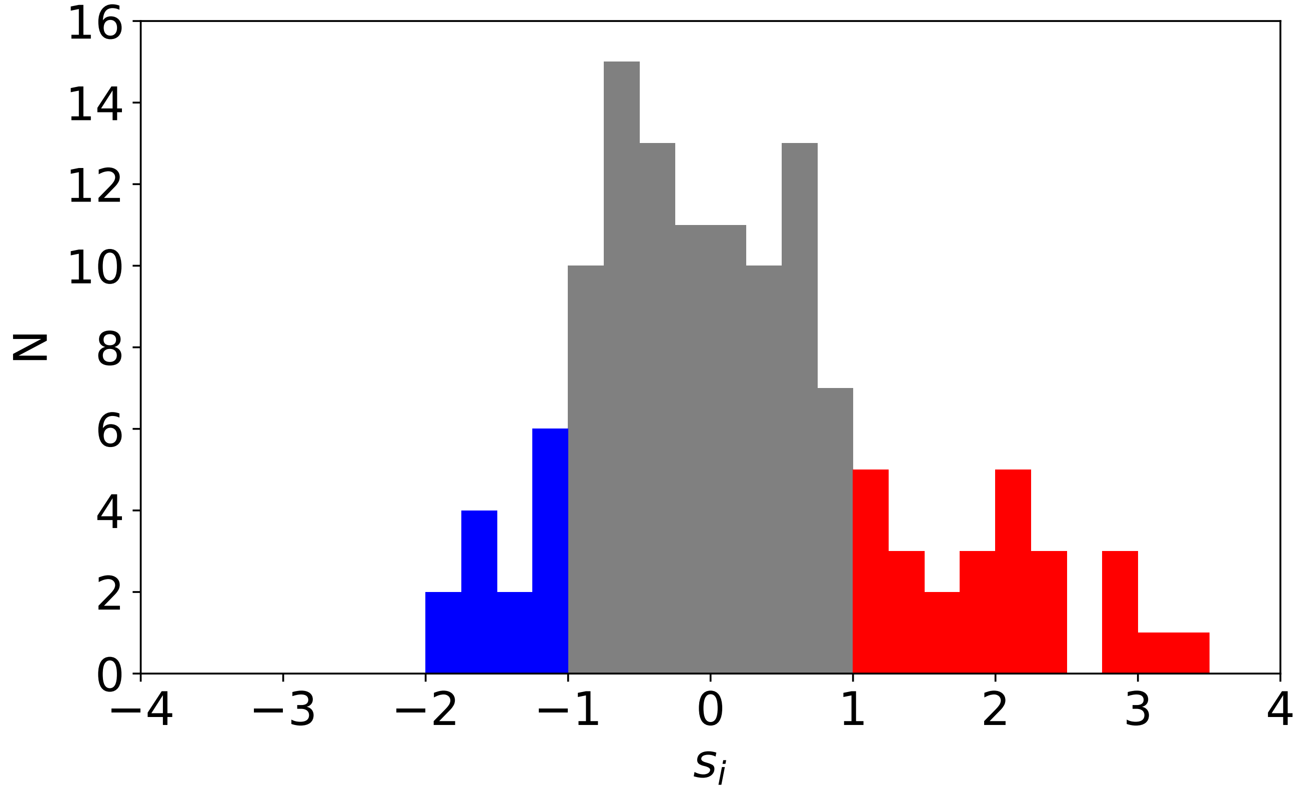
light left tail (partially associated with the core region)

temperatures are roughly log-normally distributed

Lovisari+(subm)

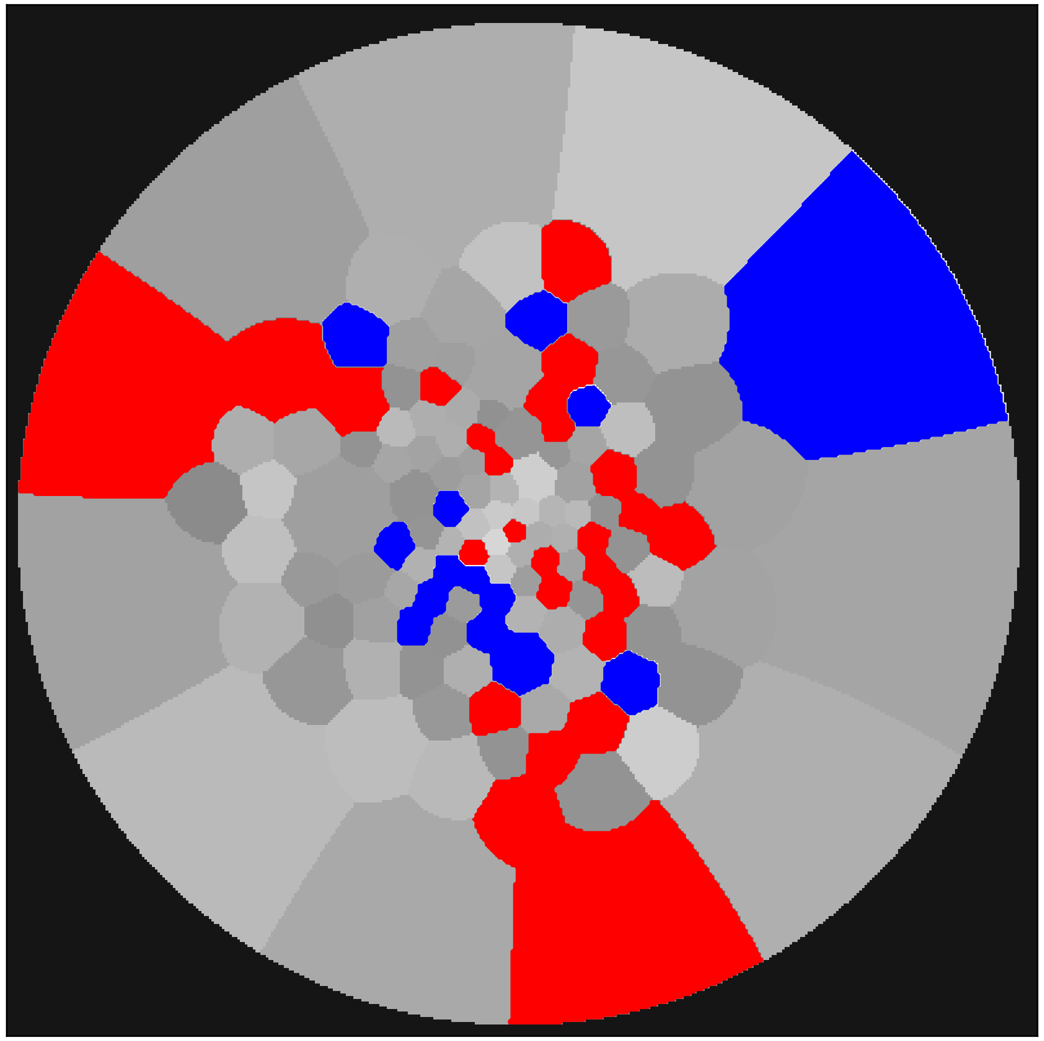
Example of clipping

$$s_i = \frac{T_{2D,i} - T_{1D,j}}{\left(\epsilon^2_{T_{2D,i}} + \epsilon^2_{T_{1D,j}}\right)^{1/2}}$$



distribution of s_i values with the ones in red and blue being the bins deviating more than 1σ from the azimuthal value

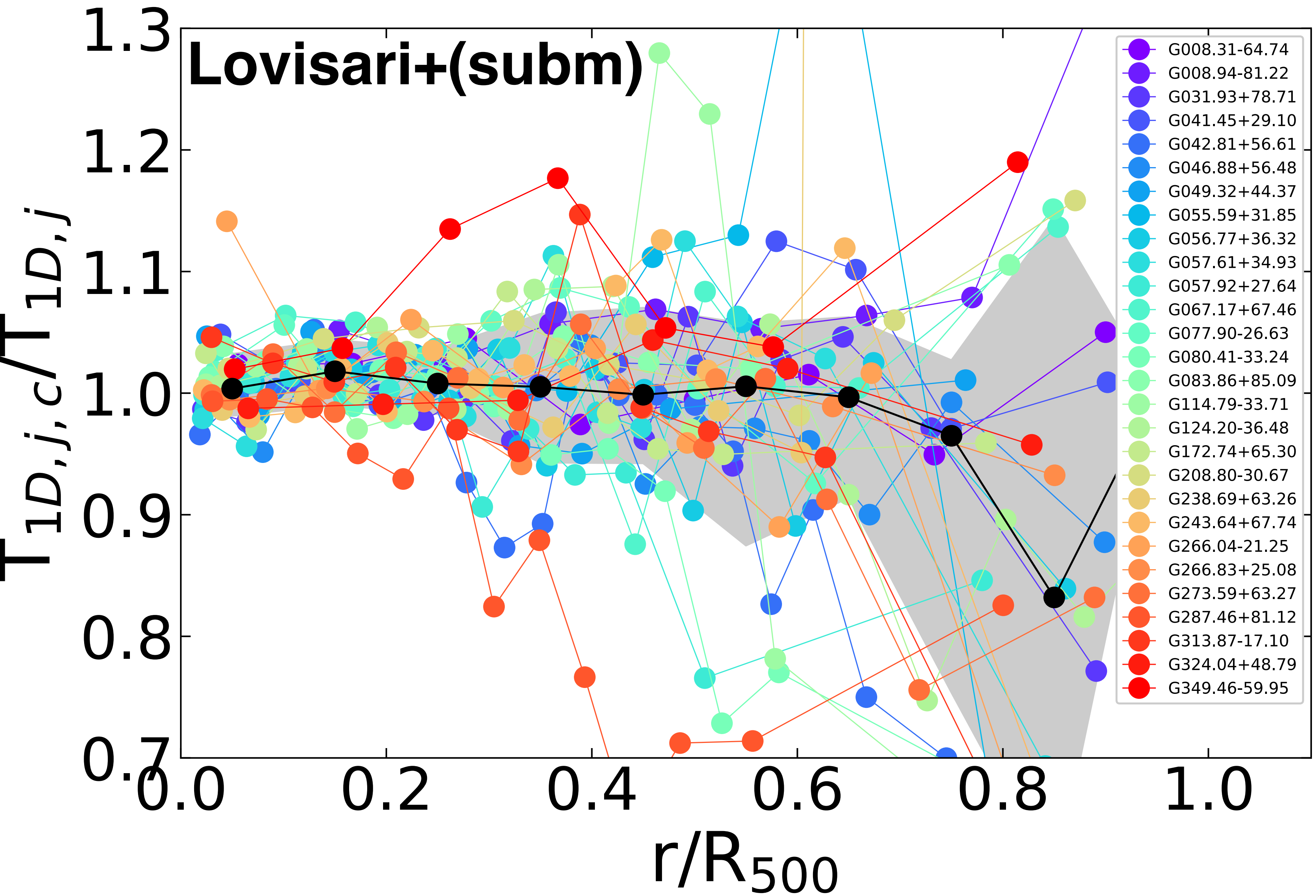
G041.45+29.10

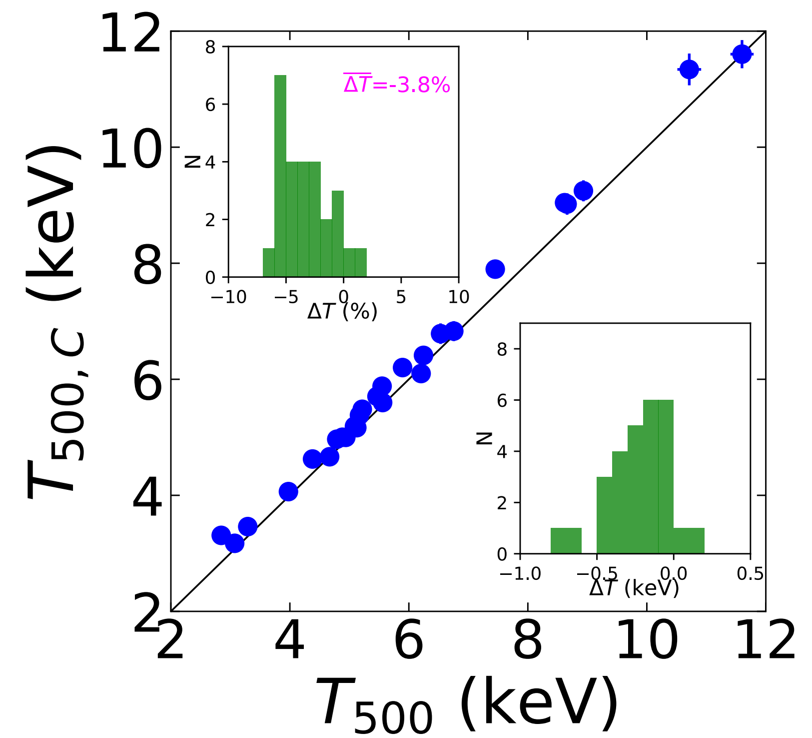


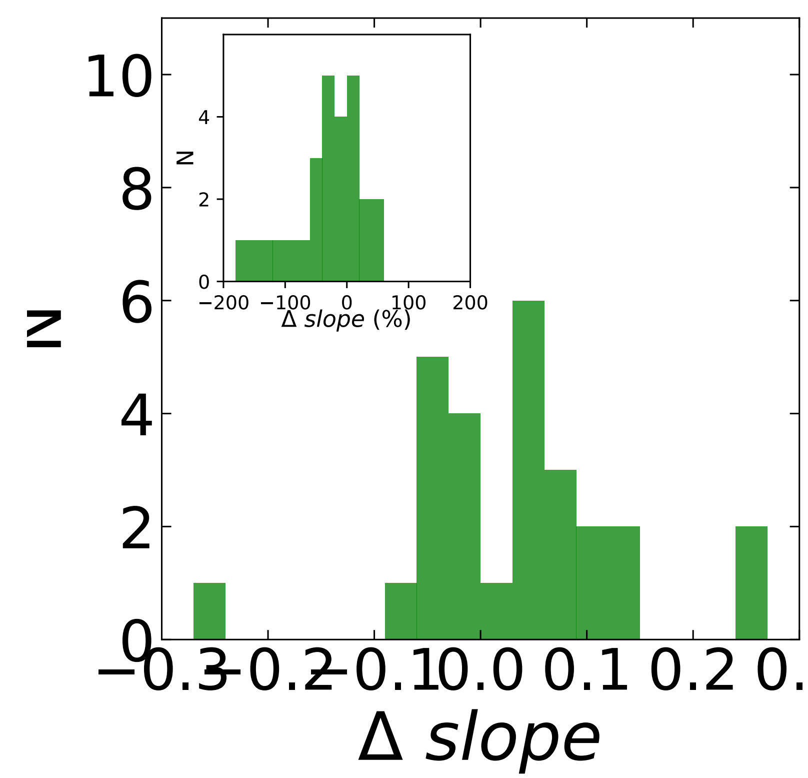
distribution of the clipped regions

Lovisari+(subm)

Impact of the T fluctuations on the profiles



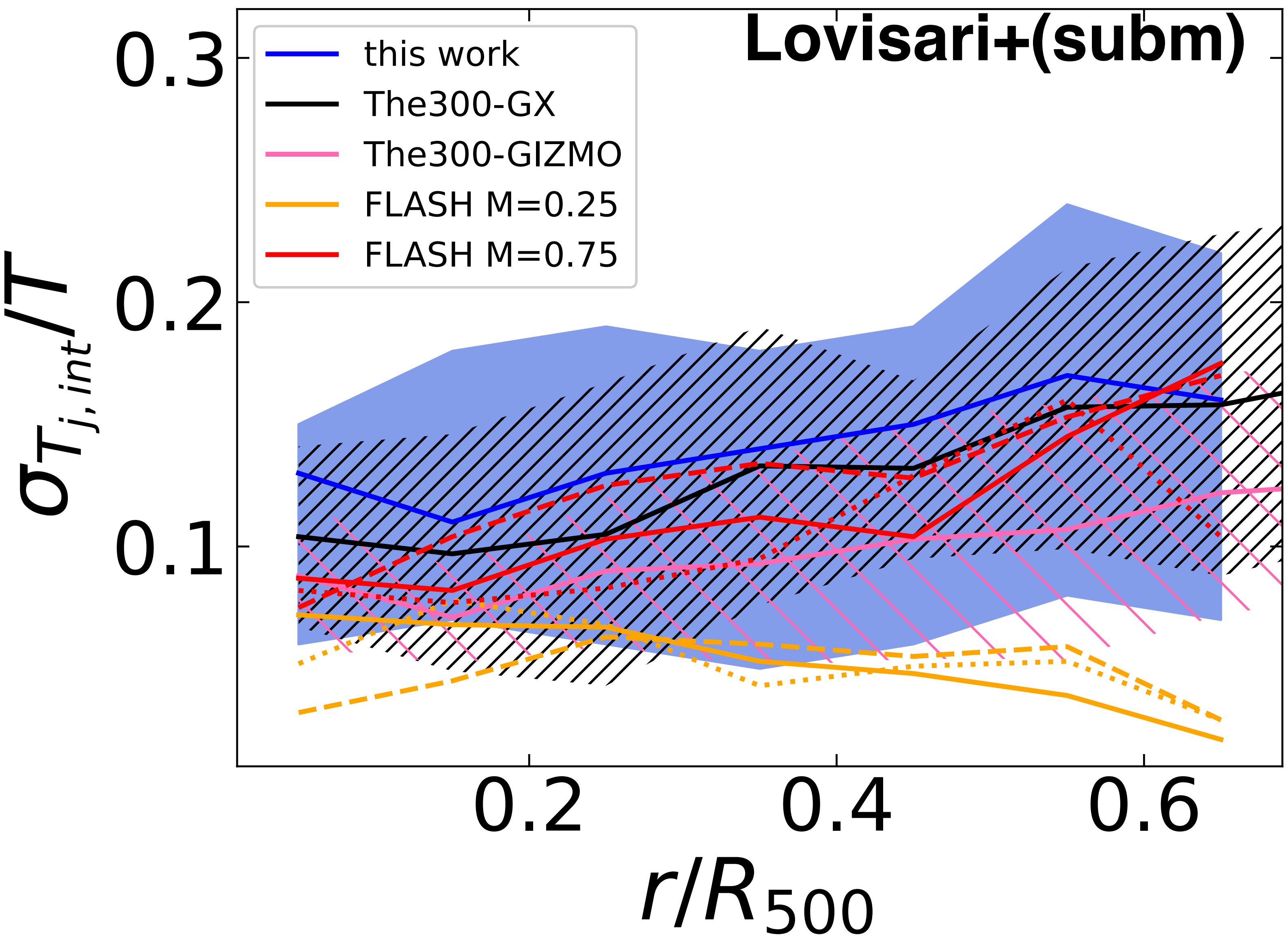




even the morphologically relaxed systems (i.e. high c and low w) do not have $T_{clip}/T_{prof} \sim 1$

Within $\sim 0.3R_{500}$, the effect is somehow small (i.e. <5%) but at larger radii the effect can be of 10% or more.

Comparison with simulations



There is a general agreement on the trend with the radius between the constraints obtained by observations and simulations, with a very weak increase ratio moving outwards.
There is also a good agreement in the level of the temperature dispersion measured in observations and simulations.

From temperature fluctuations to turbulence and mass bias

$$\sigma_T^2 \propto E_{turb} \propto \int P(k)k^2 dk = \int E(k)dk,$$

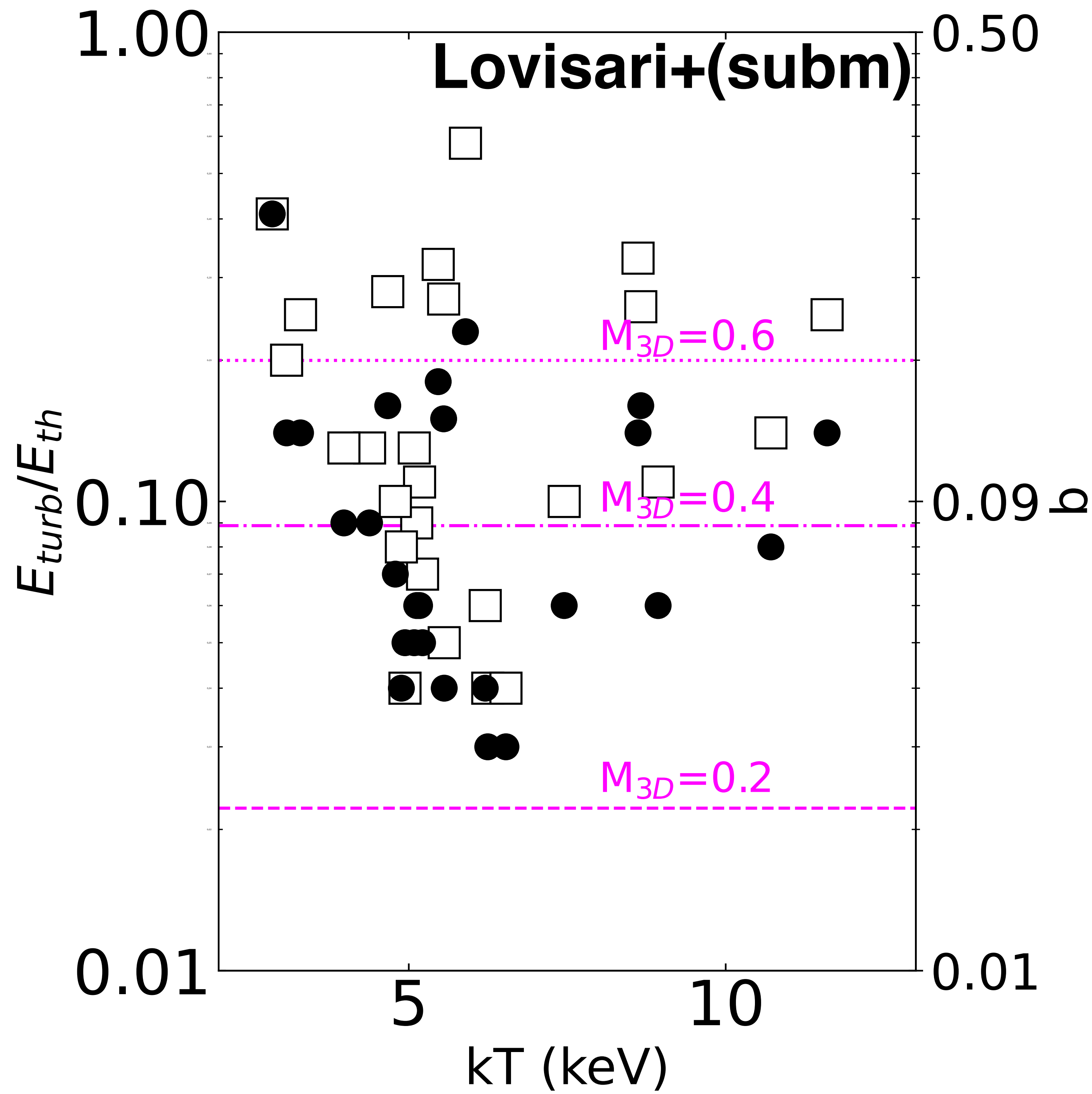
Gaspari+13

$$M_{1D} = \frac{M_{3D}}{\sqrt{3}} \sim \frac{\sigma_{n_e}}{n_e} \sim \frac{1}{\gamma - 1}\frac{\sigma_{T,int}}{T}$$

$$\frac{E_{turb}}{E_{th}} = 0.5\gamma(\gamma - 1)M_{3D}^2$$

Ettori+22

$$b = \left(\frac{E_{th}}{E_{turb}} + 1\right)^{-1}$$



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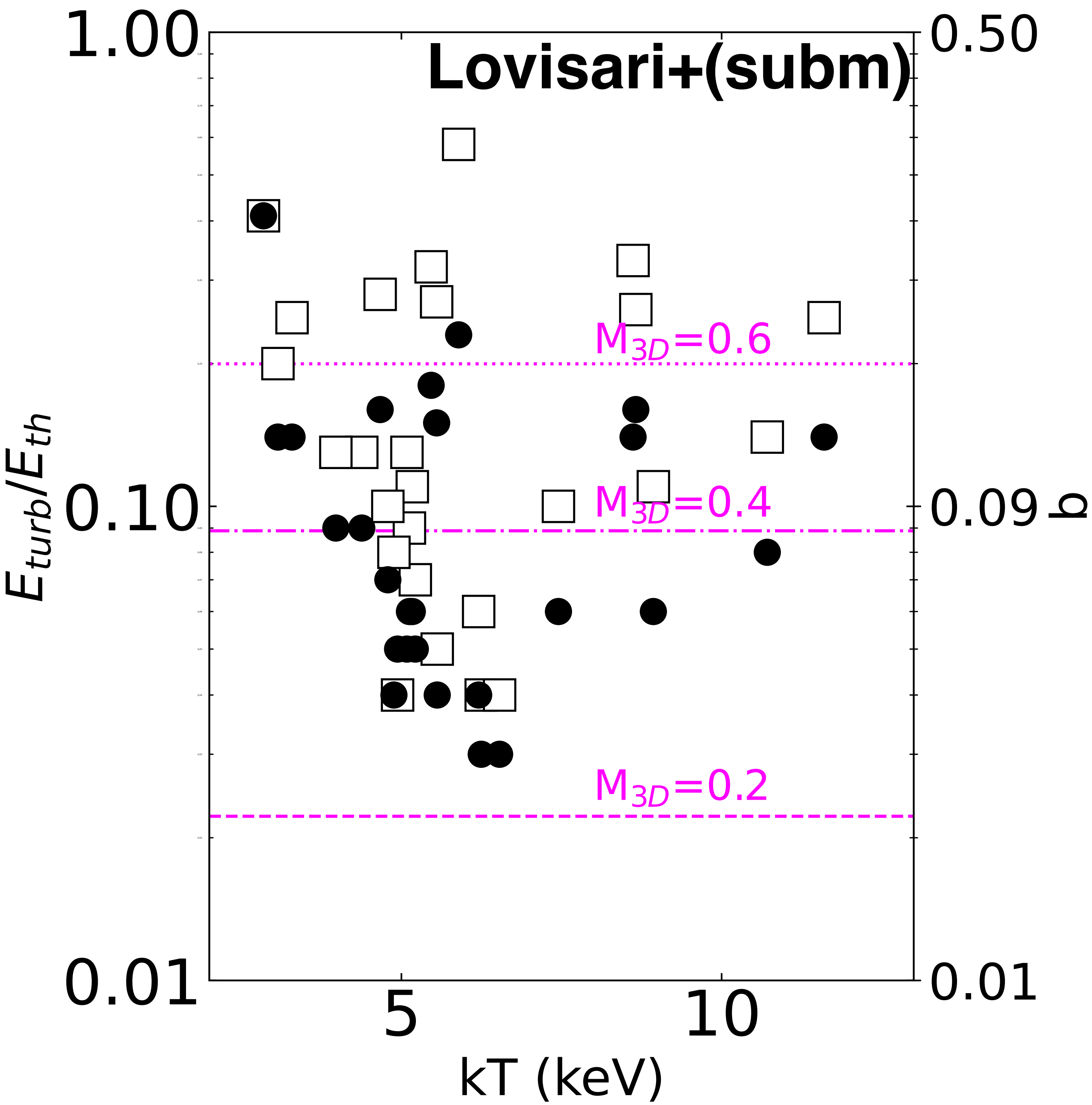
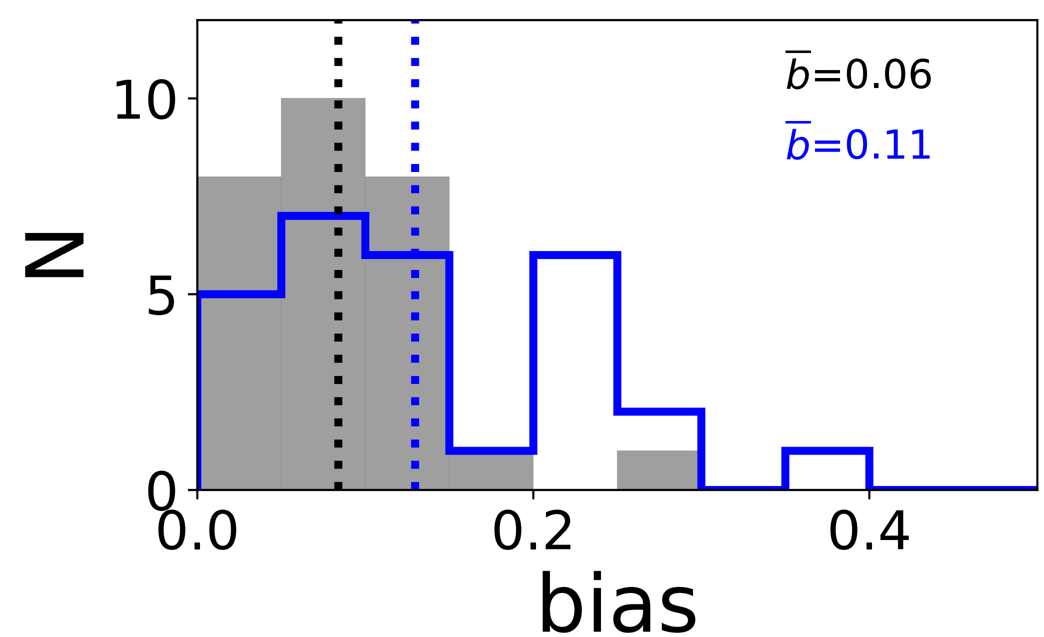


we have estimated a correction to E_{turb} by integrating an assumed Kolmogorov spectrum over the scale range [10kpc, 0.5R_{500}]



The correction increases the average b to ~0.11 ([0-37]%)

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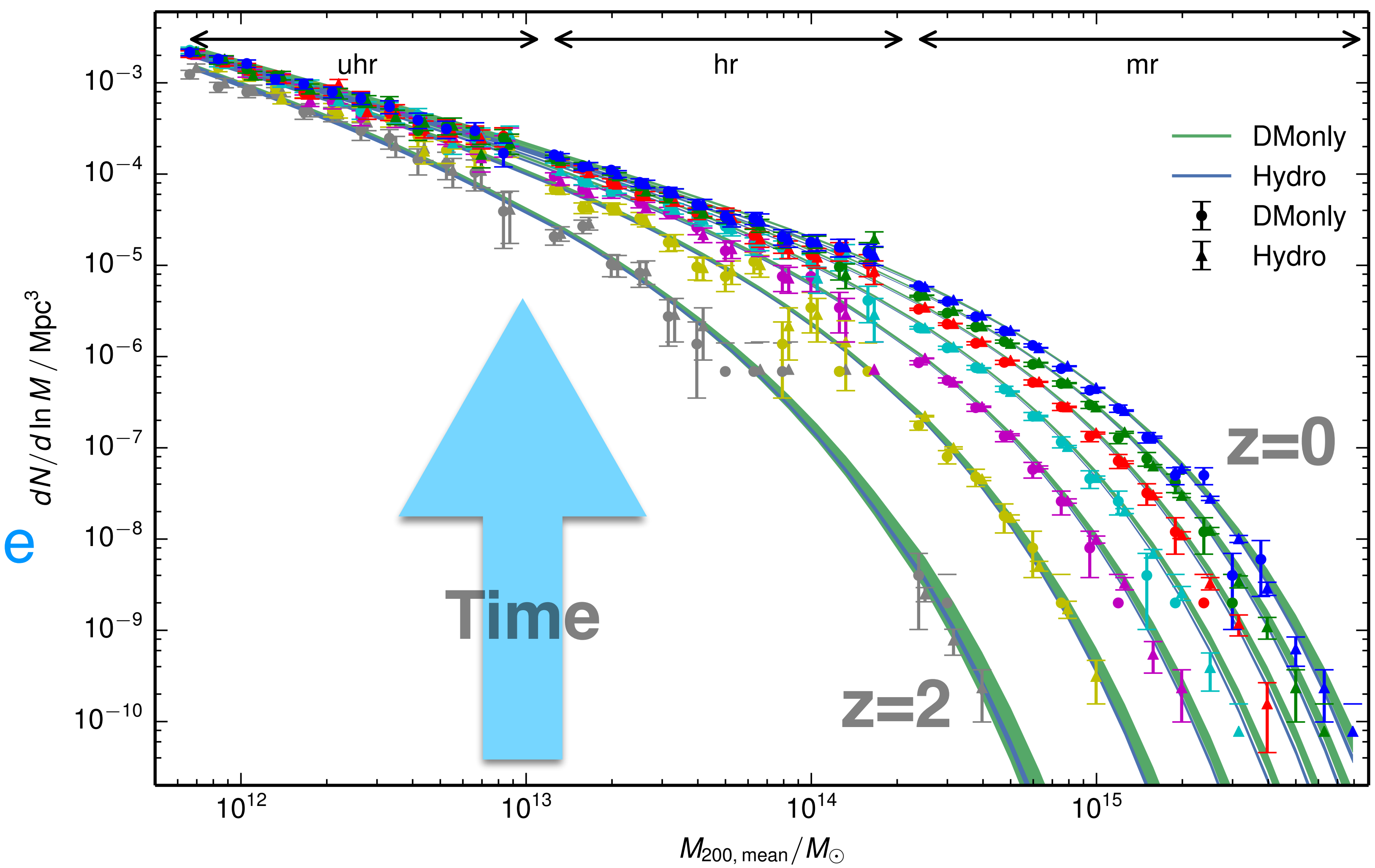
What about groups?

Low mass systems more common than rich clusters

~30/210/1500 more objects in the mass range $M_{500}=10^{13}\,M_{sun}$-M_1 than in $M_{500}>M_1$, and M_1=1/2/5x$10^{14}\,M_{sun}$ at z=0

Bocquet+16



Galaxy groups contain the bulk of all galaxies and baryonic matter in the local Universe, and they have a key role to both cosmological and astrophysical studies

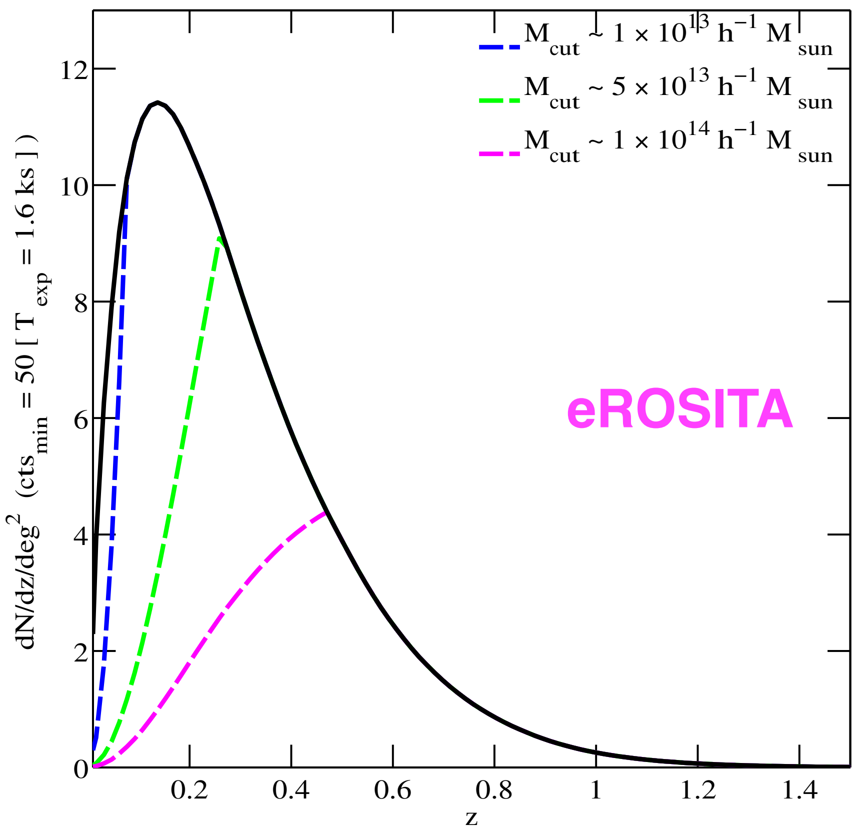
Role of groups in the near future

Despite the crucial role played by groups in cosmic structure formation and evolution, they have received less attention compared to massive clusters

Over the next decade, dedicated surveys (e.g., eROSITA in X-rays, Vera Rubin Observatory and Euclid in the Optical/Infrared, and several “Stage 3” ground-based mm-wave observatories) will increase the number of known groups (and clusters) out to high-z, constraining the scenario for their formation and evolution.

Almost all groups (and clusters) detected with eROSITA will lack sufficient X-ray photons to accurately constrain temperature and mass profiles. Thus, cosmological studies will rely heavily on a detailed understanding of the scaling relations.

Pillepich+12



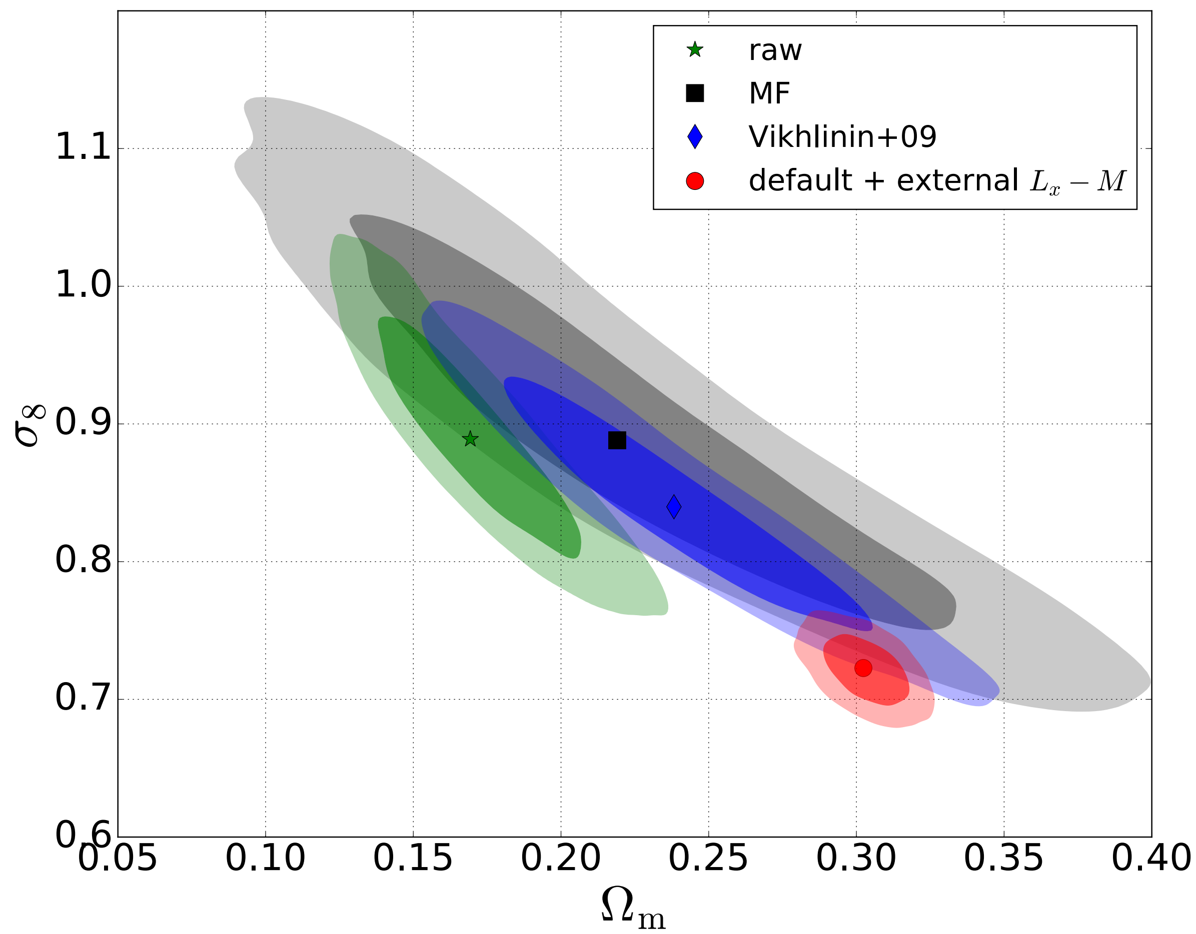
Cosmology

Galaxy groups and clusters are important tools to constrain the cosmological parameters

The cluster MF is a sensitive probe of Ω_M and σ_8

but there is a large degeneracy for high-mass systems

Schellenberger+17



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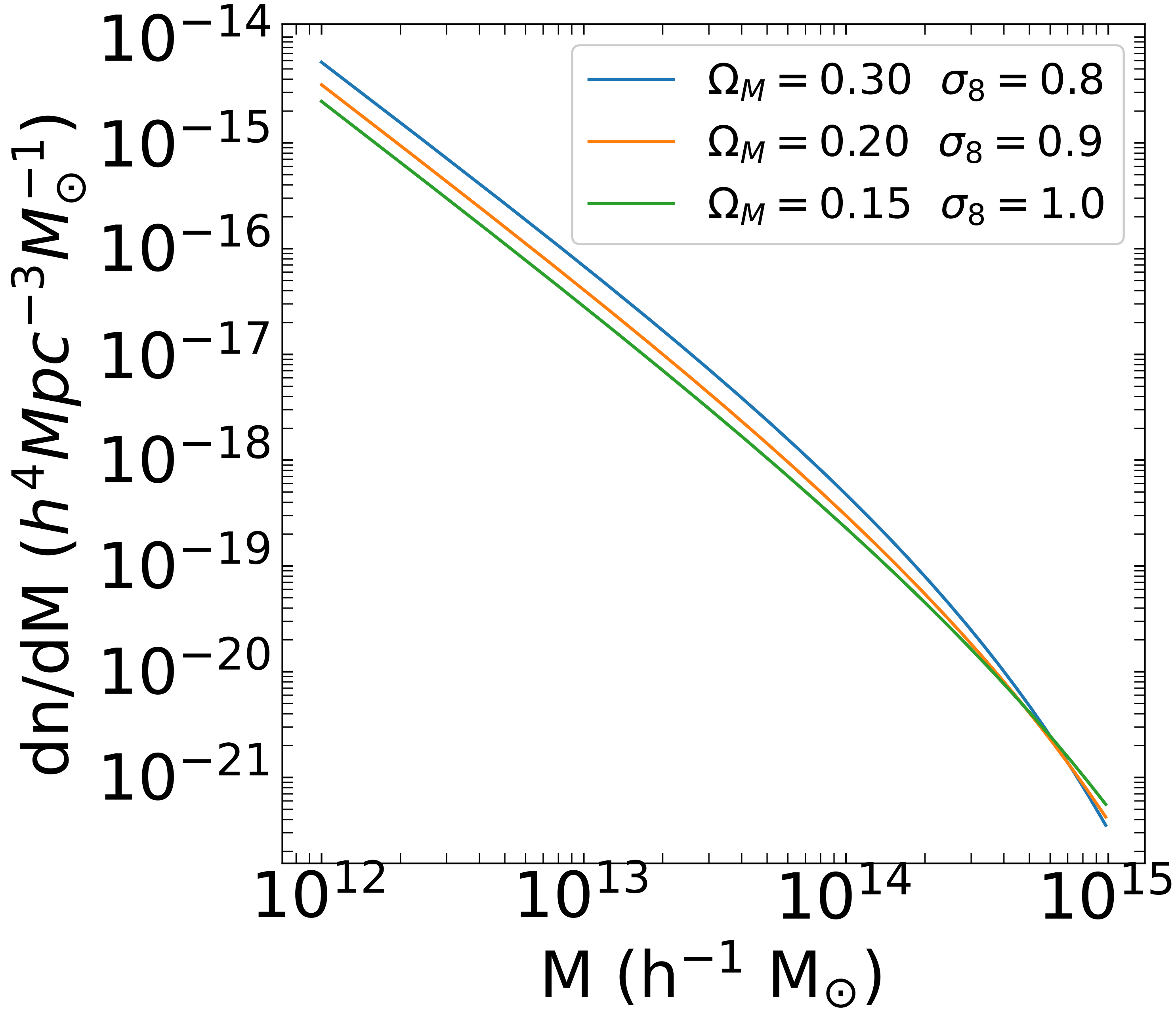
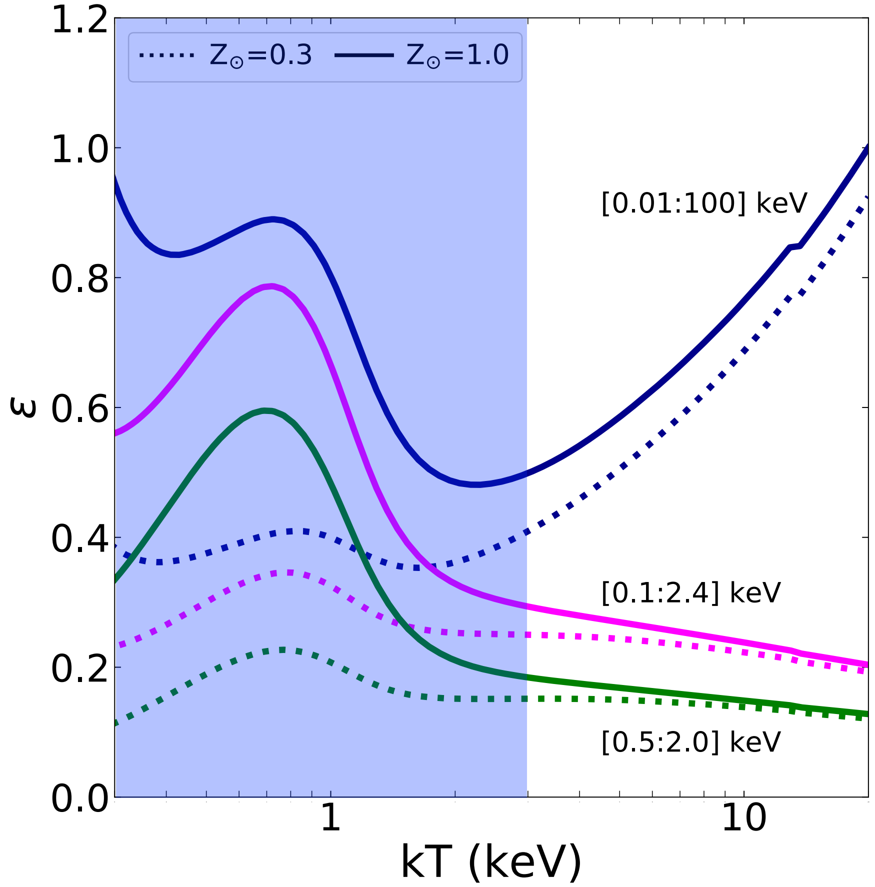
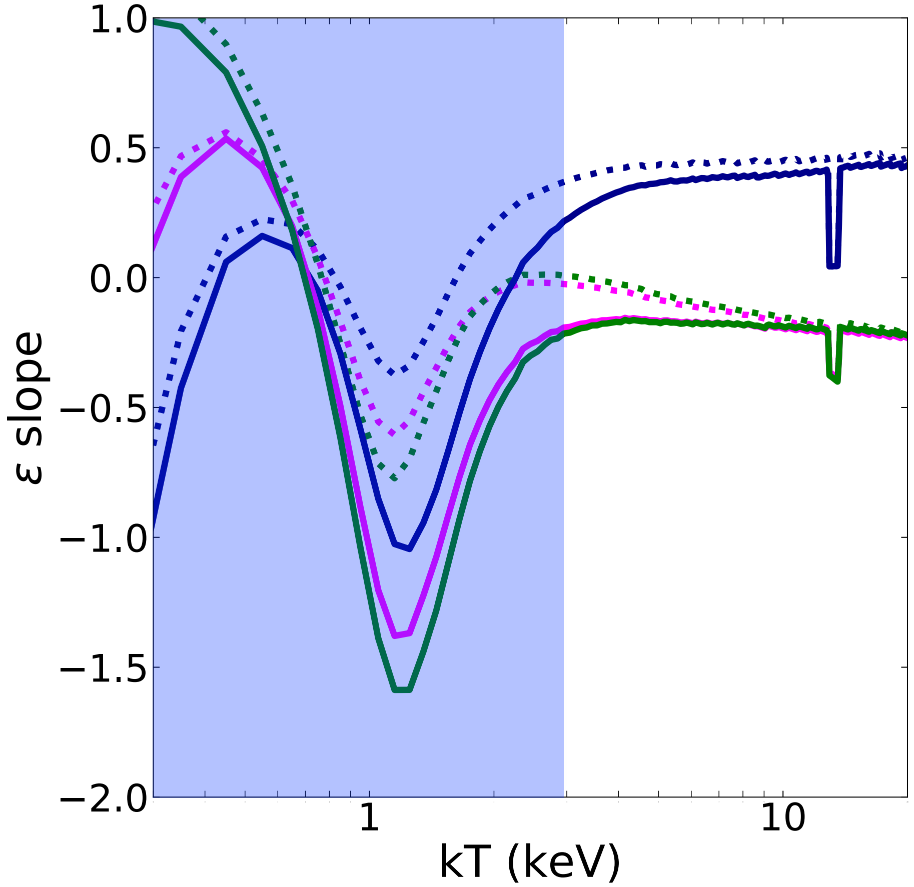
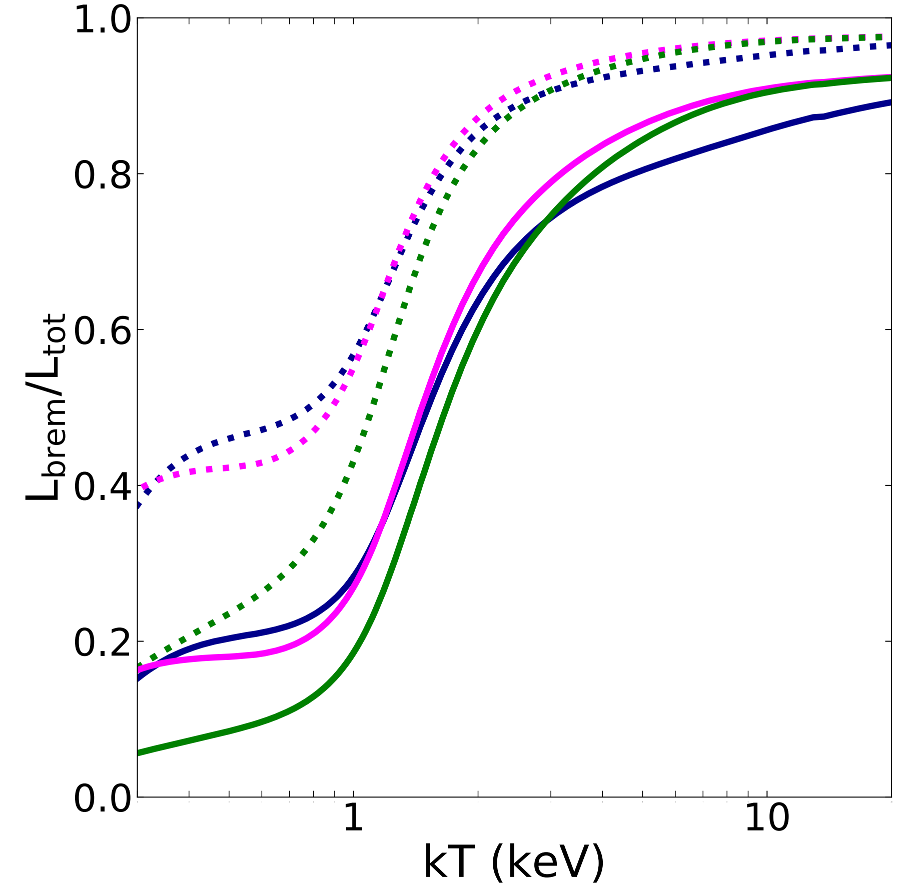


the degeneracy between Ω_M and σ_8 can be broken by probing not just the amplitude of the MF, but also its shape

self-similar L-M & L-T (groups)

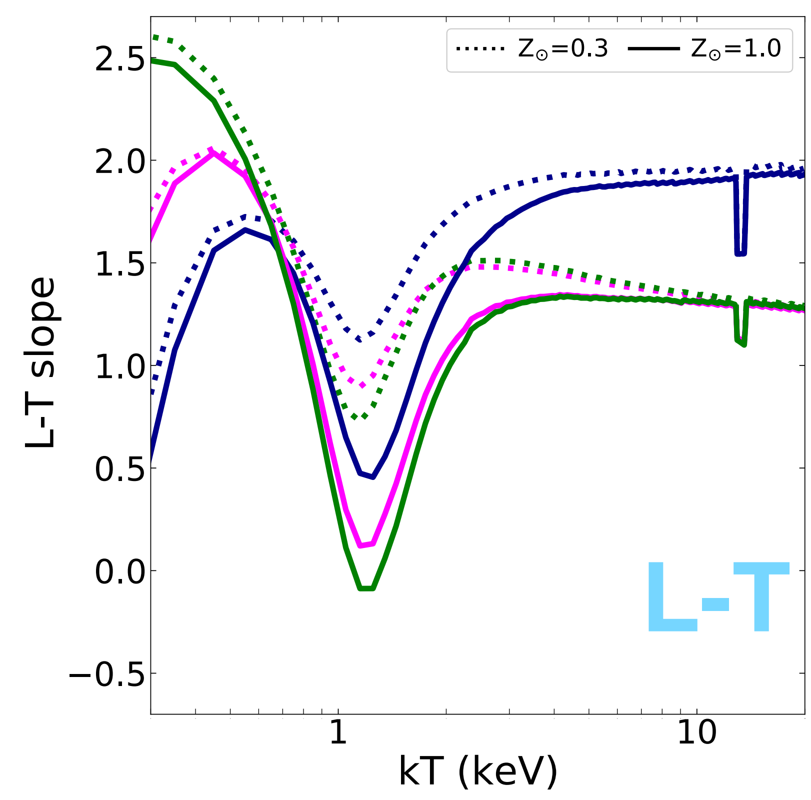


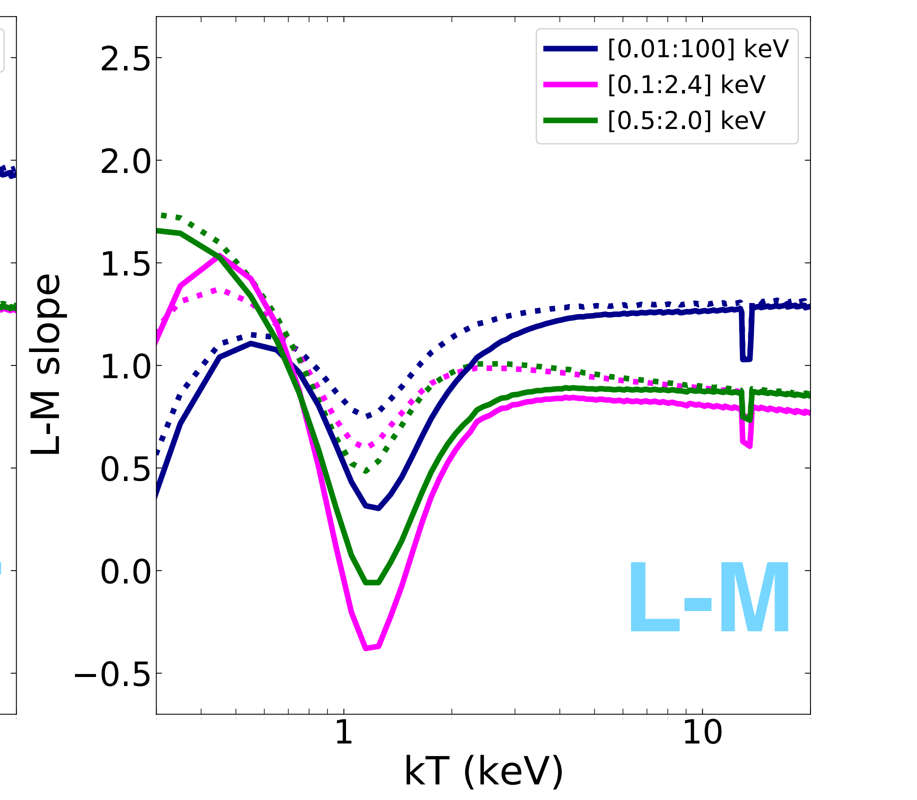




$$\Lambda(T_X, Z) \propto T^{\gamma}$$

$$L \propto T^{1.5+\gamma} \qquad L \propto M^{1+\frac{\gamma}{1.5}}$$





Sample selection

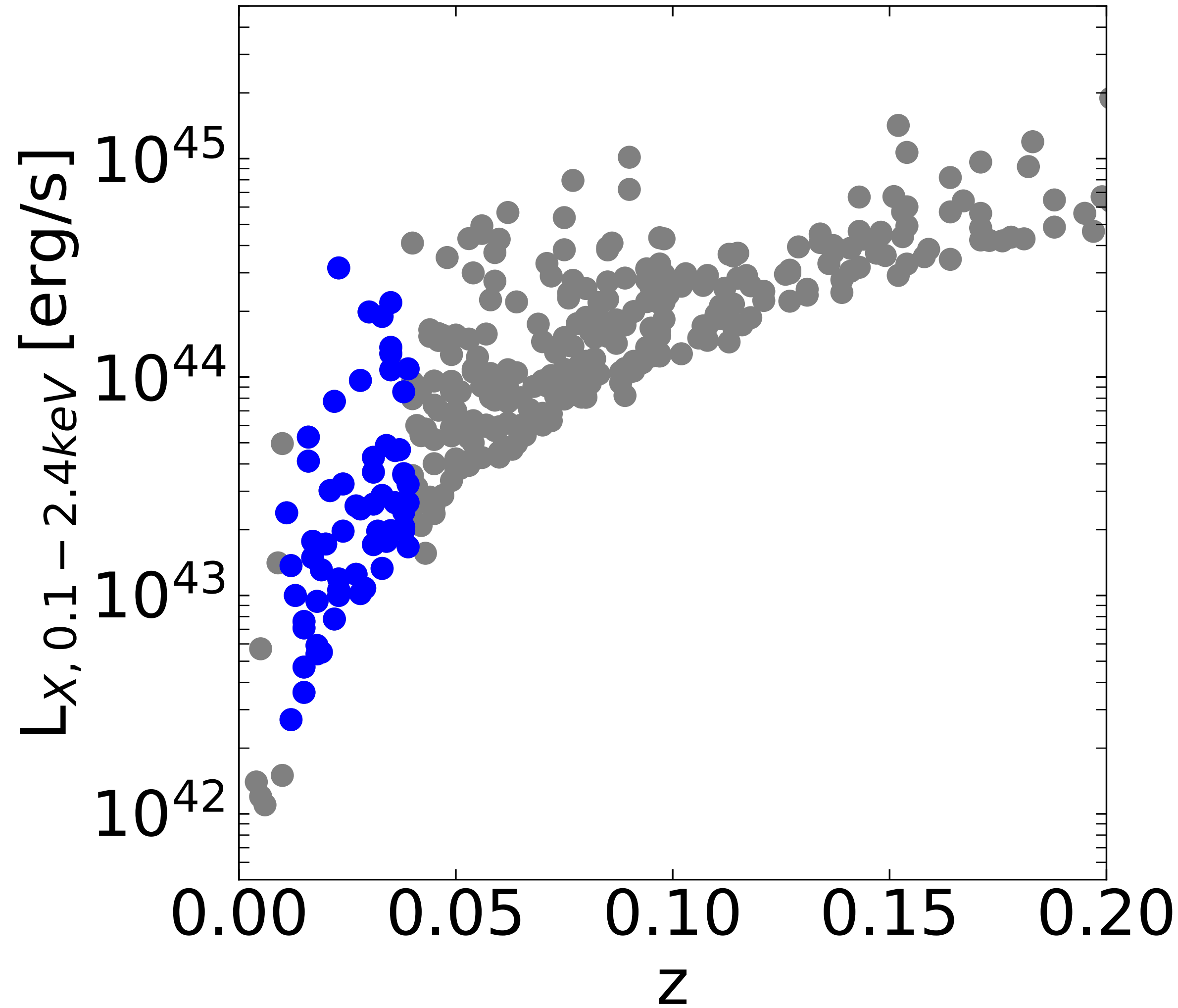
Large & well defined sample

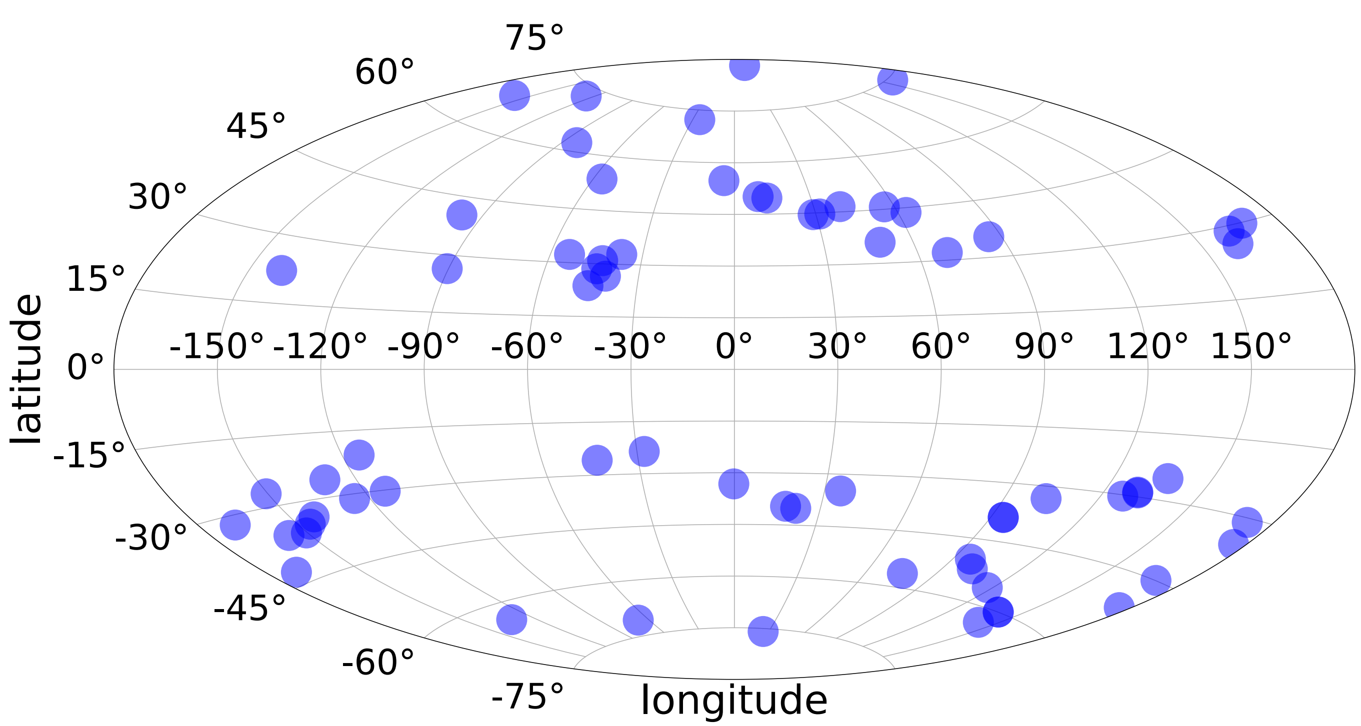
- Flux cut at 5×10^{-12} erg/s/cm² to NORAS, REFLEX, and BCS catalogs
- Two redshift cuts ($0.01<z<0.04$)

66 systems

All observed with XMM with >150 pointings for a total of ~3.5 Ms of cleaned MOS data

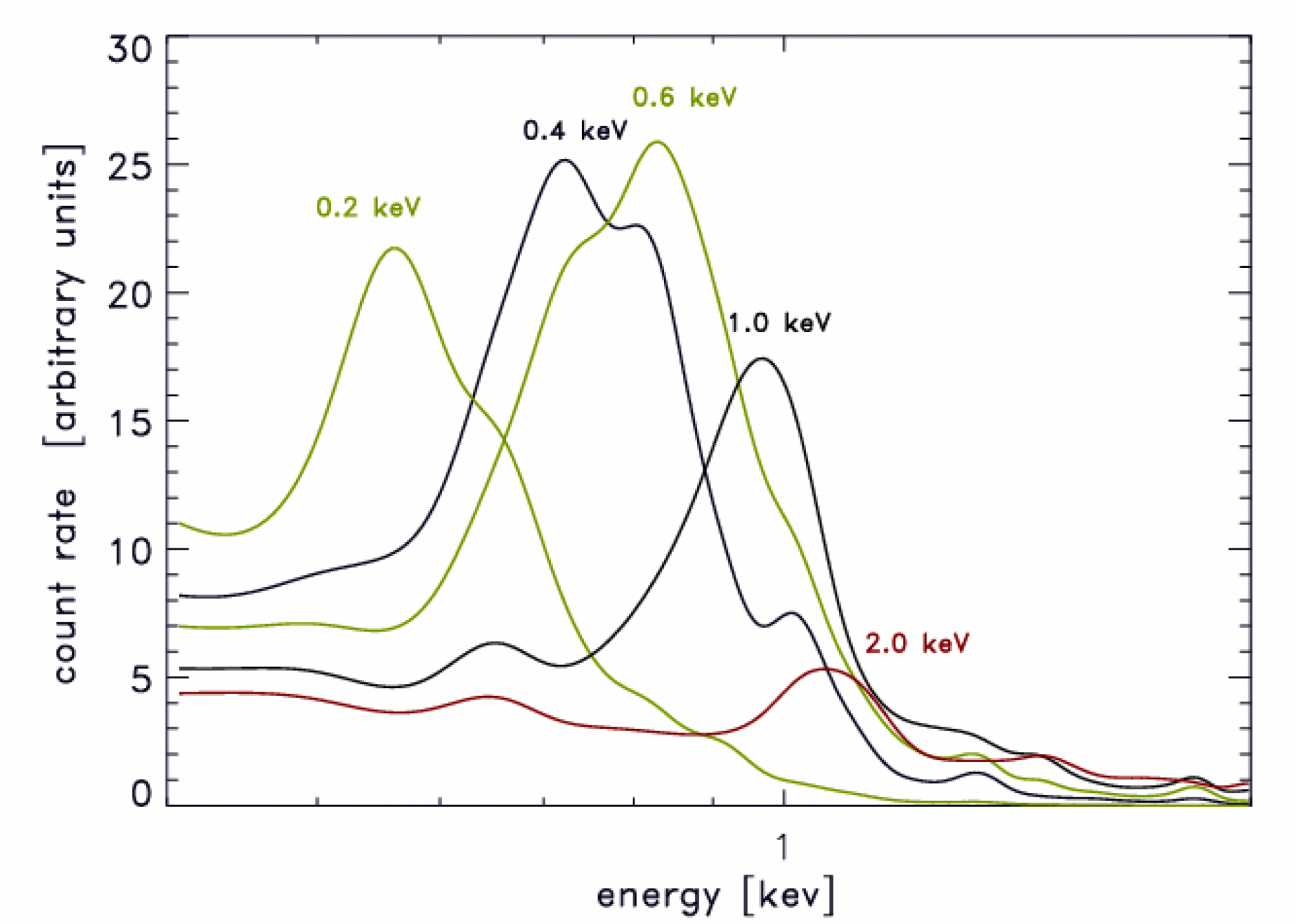
A few groups have flared obs



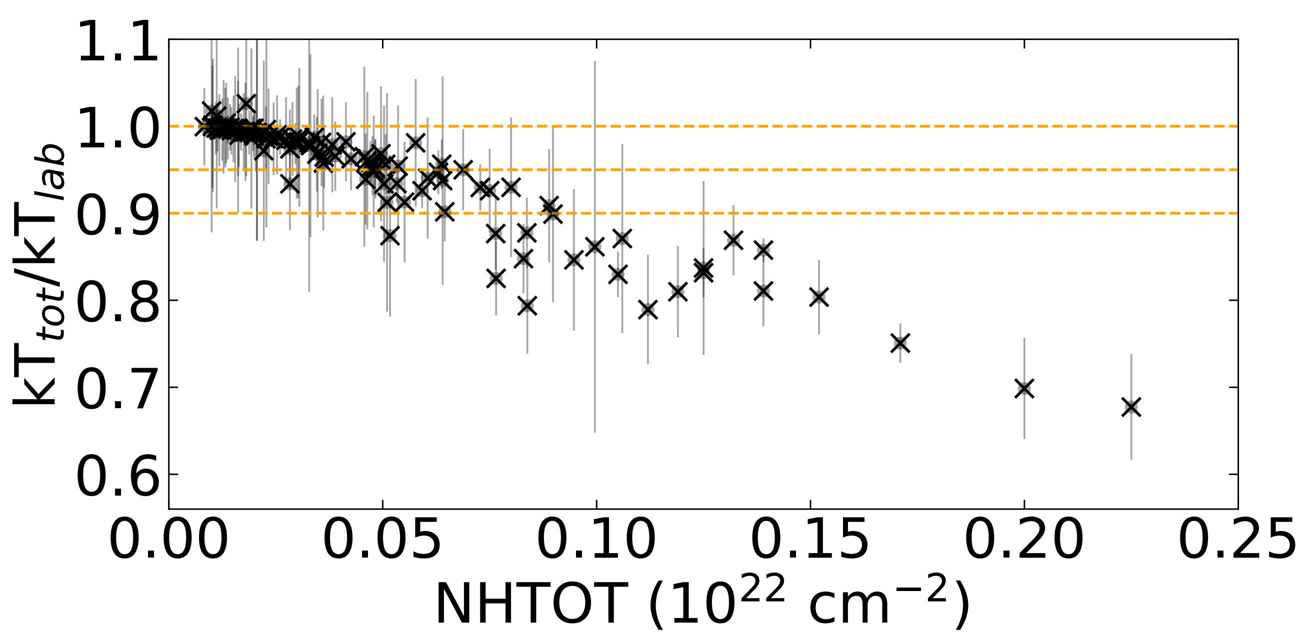


Issues with low-mass systems

Groups are in a regime where there is a strong degeneracy between temperature, metallicity, normalization, & N_H

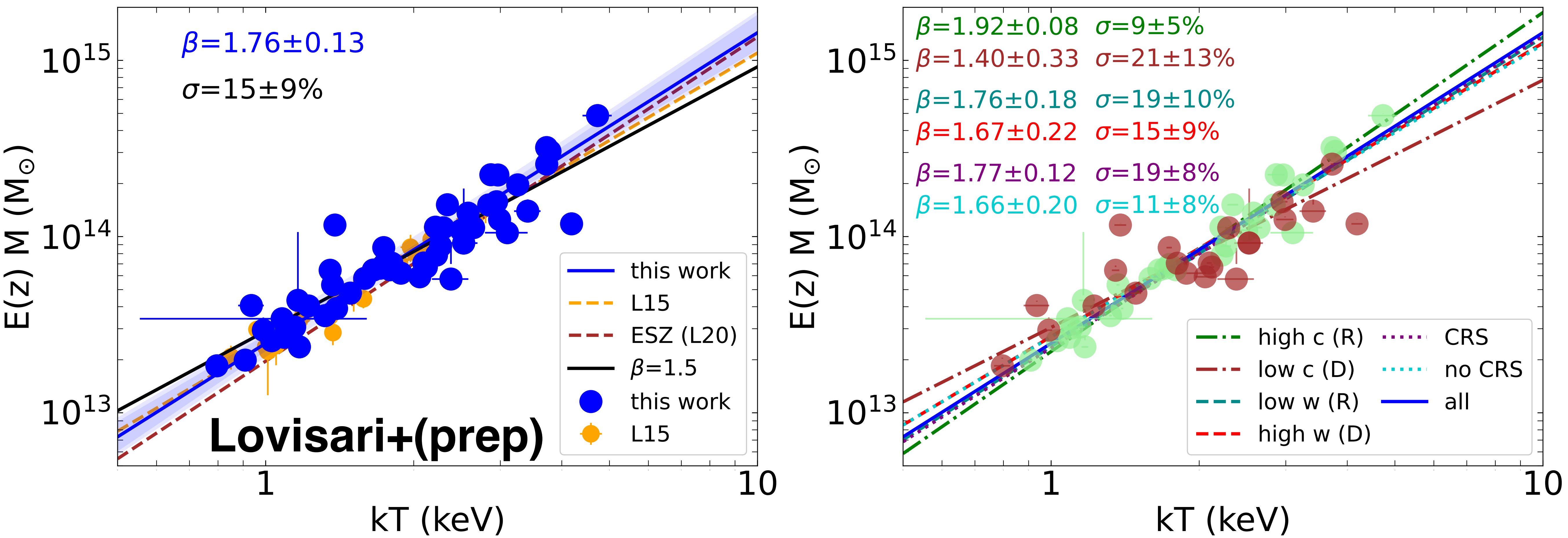


Fe-L line shift with T



Molecular hydrogen contribute to the absorption and impact the T (& Z & N) measurements

M-T relation for groups

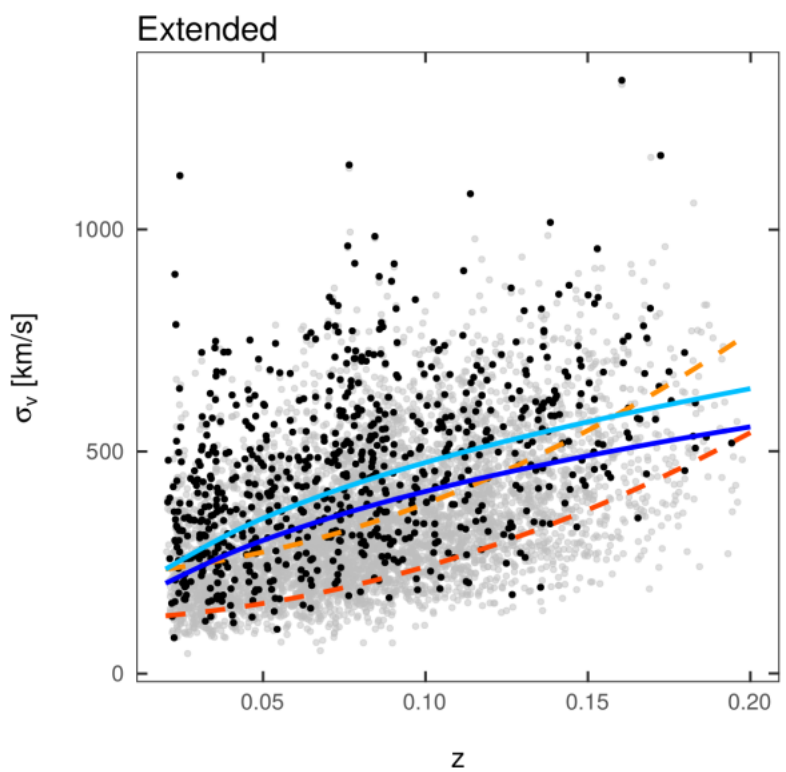


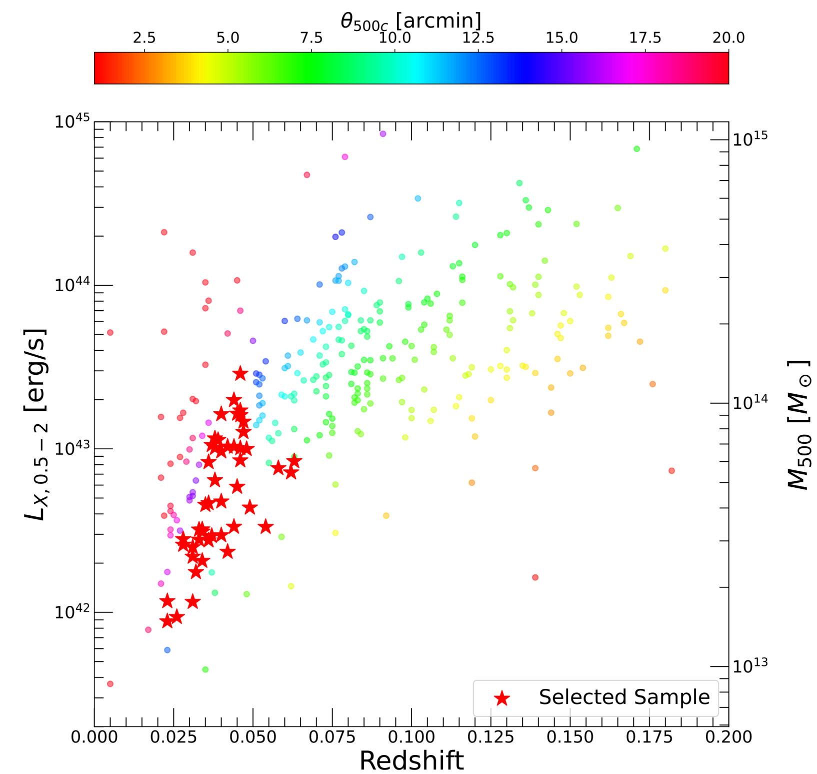
- the gas temperature reflects the depth of the underlying potential well
- higher scatter (15-18%) compared to clusters (8-10%)
- Hints of flatter slope and higher scatter for flat SB systems

X-GAP

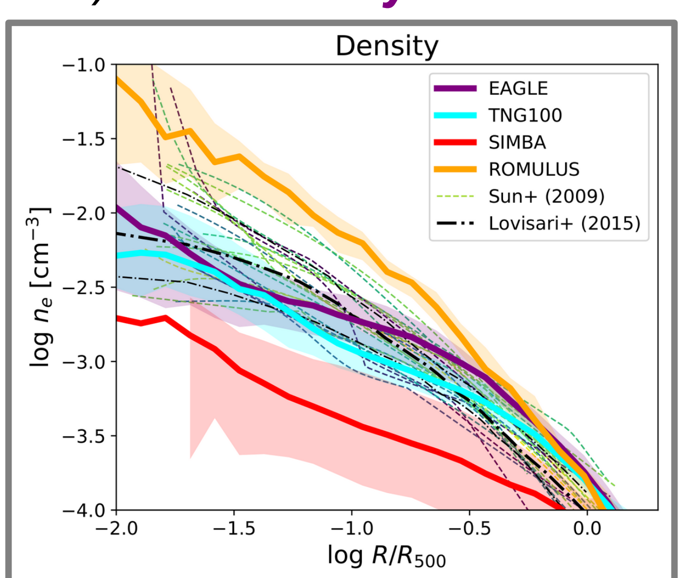
XMM-Newton Group AGN (PI: Eckert)

Cross-correlation of spectroscopic Friends-of-Friends groups from the Sloan Digital Sky Survey with extended X-ray sources selected from the ROSAT all-sky survey

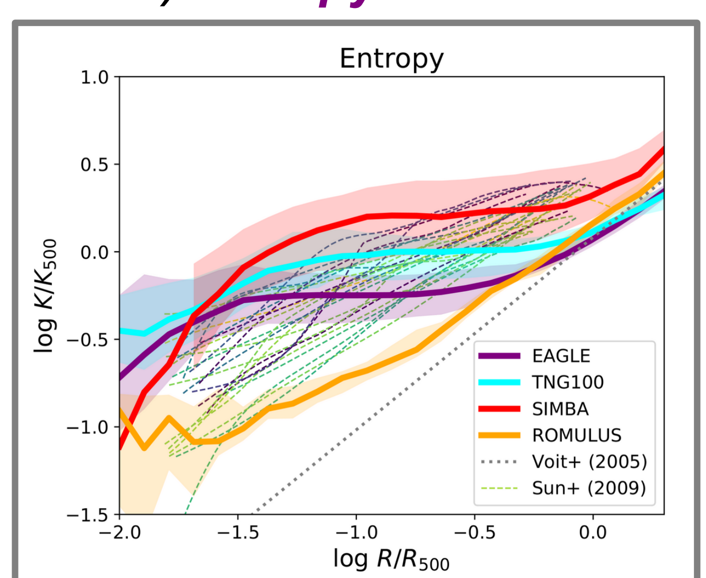




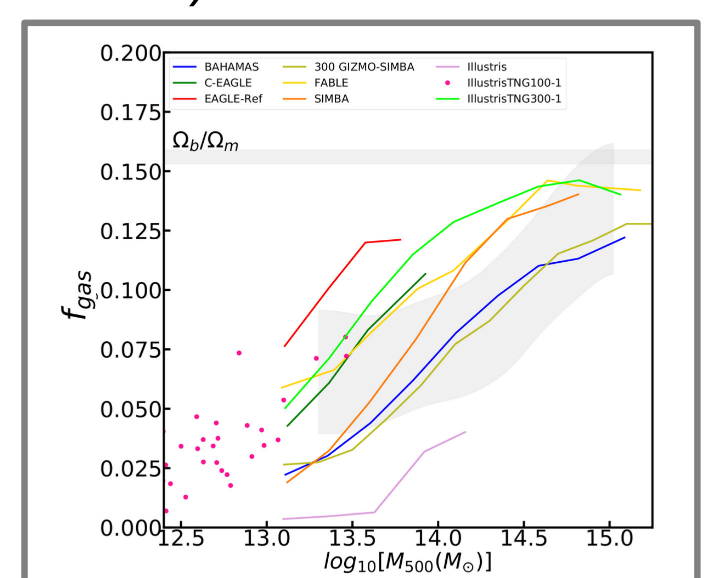
a) *Gas Density Profiles*



b) *Entropy Profiles*



c) *Gas fraction*



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- T is a robust proxy to estimate the total mass down to the low-mass regime