Toward understanding mass proxies of galaxy clusters for modern cosmology

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The results presented here are in collaboration with H. **Andernach**, A. **Babul**, H. **Böhringer**, C. **Caretta**, C. **Collins**, A. **Evrard**, A. **Finoguenov**, T. **Futamase**, M. **Girardi**, L. **Guzzo**, Y. **Ikebe**, T. **Laganá**, D. **Marrone**, K. **Matsushita**, P. **Mazzotta**, N. **Okabe**, F. **Pace**, D. **Pierini**. R. **Piffaretti**, E. **Puchwein**, T. **Reiprich**, A. **Sanderson**, P. **Schneider**, P. **Schuecker**, D. **Sijacki**, G. **Smith**, M. **Takada**, K. **Umetsu**, R. **Valdarnini**, X.-P. **Wu**

Outline

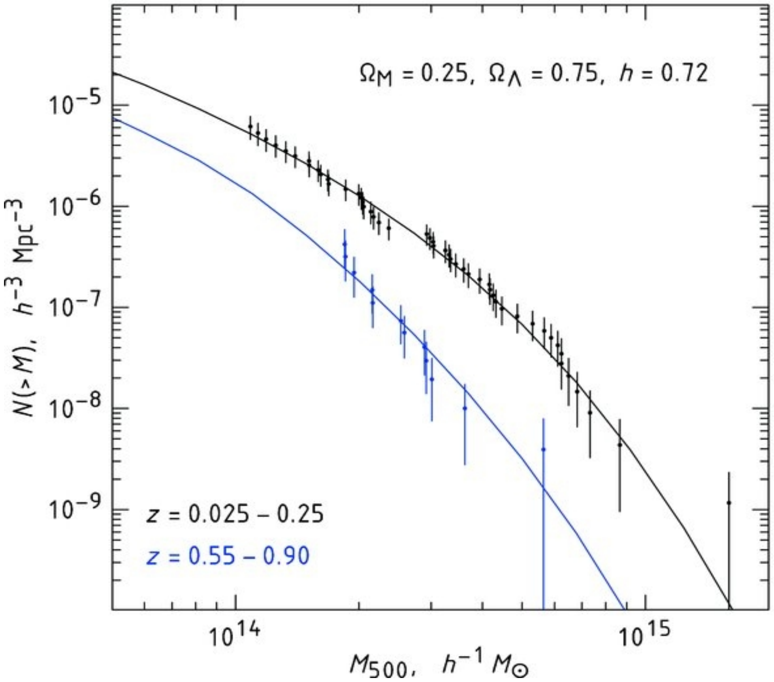
- Galaxy clusters as cosmological tools

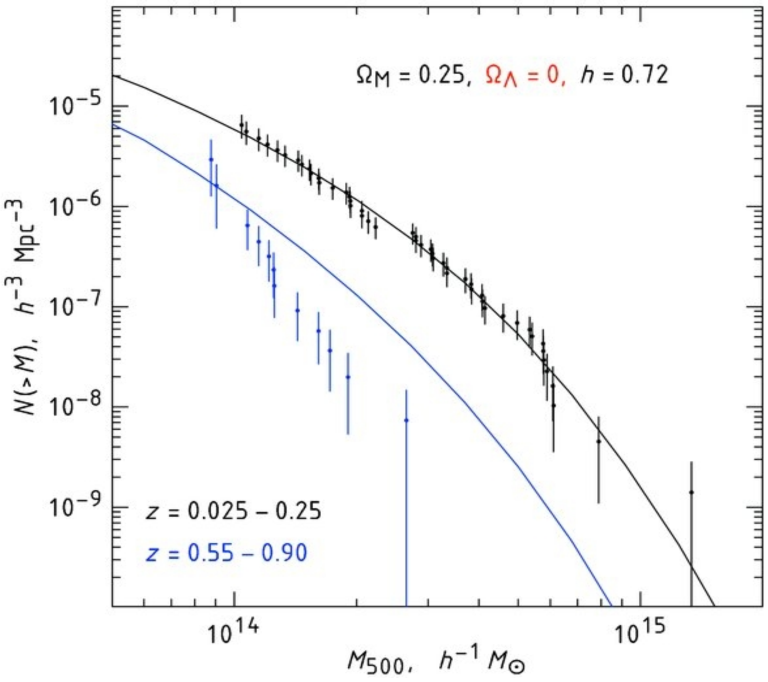
- Calibrating mass and mass proxies

- Summary

Galaxy clusters as cosmological tools

- Evolution of the mass function

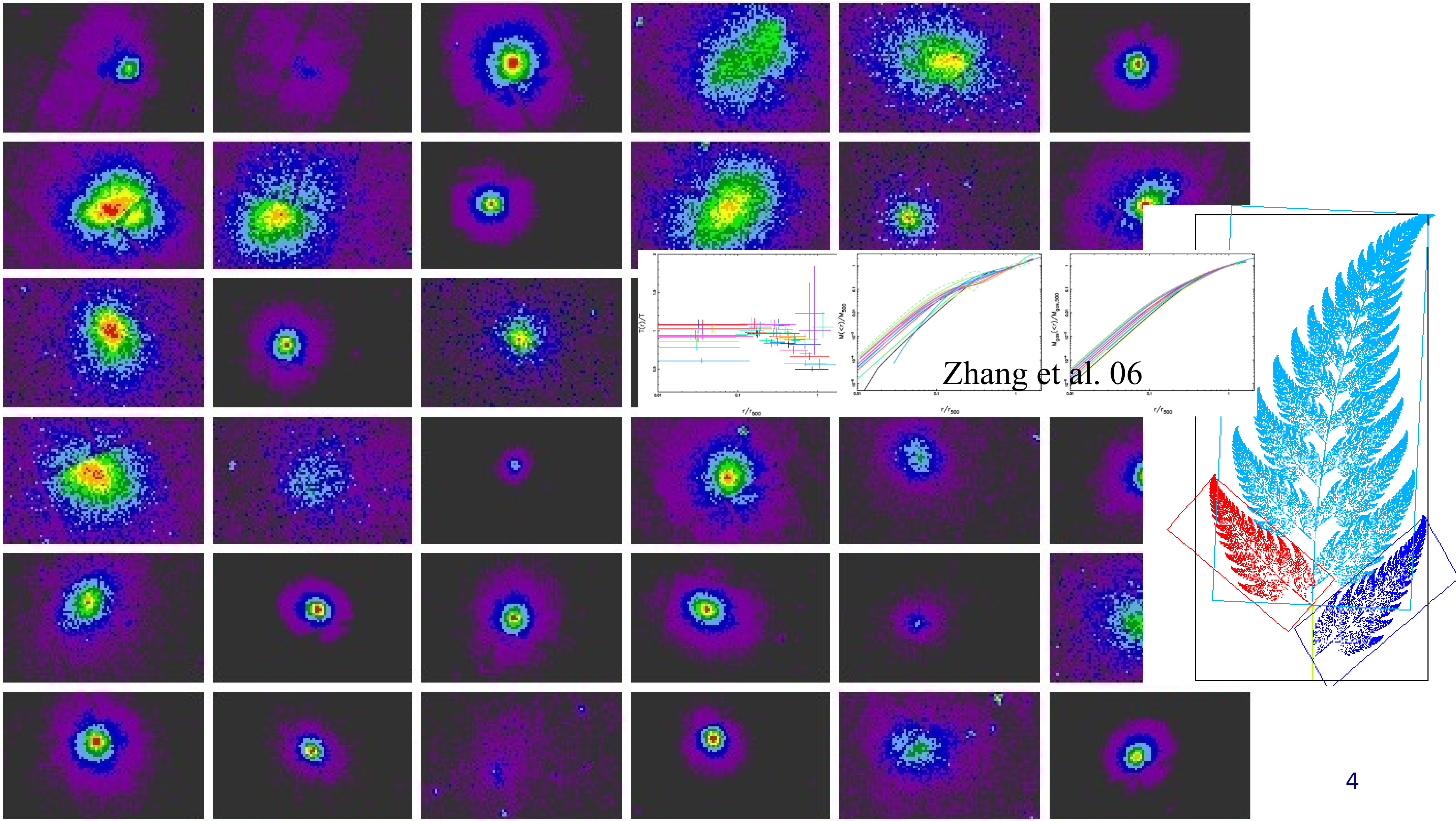




Galaxy clusters provide a powerful and well-established cosmological probe. Historically, galaxy clusters provided some of the first evidence for a low density universe (White et al. 93, Nat., 336, 429). Clusters currently receive much more attention as a potential probe of the dark energy (DE) equation of state parameter w. The evolution of the mass function for the sample in Vikhlinin et al. (09) constrains w=-1.14 ± 0.21 assuming a constant w and flat universe. The combination of the mass function and gas mass fraction of galaxy clusters, as well as CMB, SNIa, and BAO, can constrain w at late and early times, w_0=-0.88 ± 0.21 and $w_{\rm et}$=$-1.05^{+0.20}_{-0.36}$ (Mantz et al. 10). Current results remain statistically limited.

Galaxy cluster as cosmological tools

- Self-similarity & mass proxies (more references in the next page)



Galaxy clusters as cosmological tools

- References calibrating their self-similarity and mass proxies
  - Before X-ray satellites: Mitchen et al. 77; Mushotzky et al. 78; Henry & Tucker 79; etc.
  - EXOSAT, Einstein, & Ginga X-ray data: Edge & Stewart 91; Henry & Arnaud 91; David et al. 93; etc.
  - ROSAT X-ray data: White et al. 97; Markevitch 98; Markevitch et al. 98; Arnaud & Evrard 99; Mohr et al. 99; Vikhlinin et al. 99, 02; Xue & Wu 00; Finoguenov et al. 01; Horner 01; Xu et al. 01; Ikebe et al. 02; Reiprich & Böhringer 02; Sanderson et al. 03; Ettori et al. 04; Ota & Mitsuda 05; O'Hara et al. 06; Chen et al. 07; etc.
  - Chandra & XMM-Newton data: Ettori et al. 04; Arnaud et al. 05, 07; Kotov & Vikhlinin 05; Pratt & Arnaud 05; Maughan et al. 06, 07, 08; Zhang et al. 04, 06, 07, 08, 09; Vikhlinin et al. 06, 09a, 09b; Pacaud et al. 07; Pratt et al. 09, 10; Sun et al. 09; etc.
  - Lensing + X-ray: Miralda-Escude et al. 95; Squires et al. 96; Wu & Fang 96, 97, Wu et al. 98; Allen 98; Smith et al. 05; Zhang et al. 05, 07, 08, 10; Bardeau et al. 07; Mahdavi et al. 08; Vikhlinin et al. 09; Leauthaud et al. 10; Richard et al. 10; Okabe et al. 10; etc.
  - X-ray + optical: Girardi et al. 96; Wu et al. 99; Popesso et al. 2005; Zhang et al. 11; etc.

Galaxy cluster as cosmological tools

- Scaling relation uncertainty is the dominant source of systematic error in dark energy studies
  - High-precision cosmology with the mass function and baryon-mass fraction of galaxy clusters requires the knowledge of the normalization, slope, intrinsic scatter and evolution of the mass vs. mass proxy relations (e.g., Smith et al. 2003; Zhang & Wu 2003; Stanek et al. 2009, 2010; Cunha & Evrard 2009)

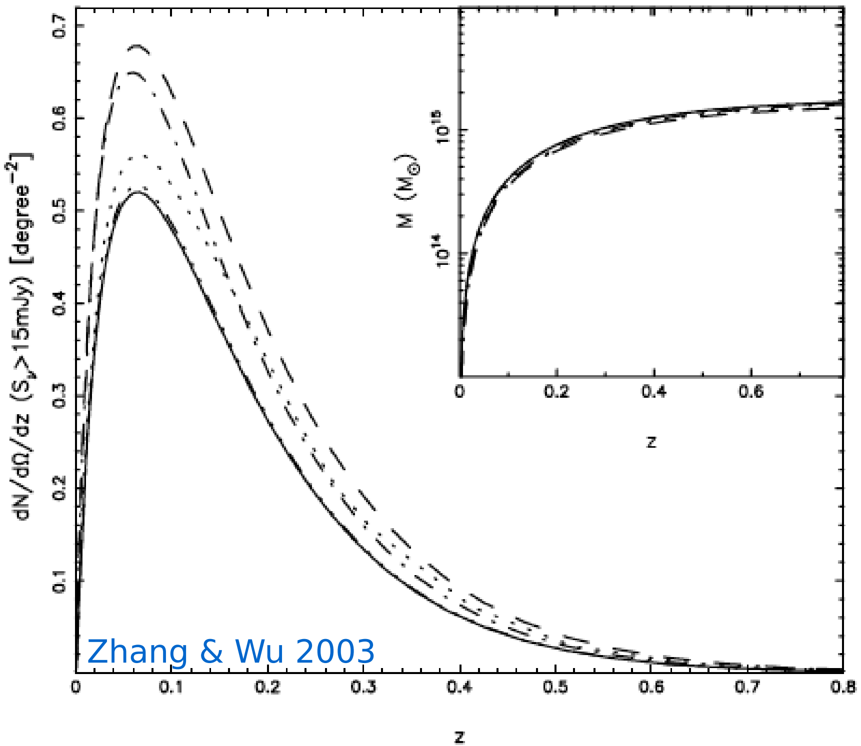


FIG. 1.—Expected redshift distribution of SZ cluster counts with $S_\nu = 15$ mJy at frequency 30 GHz. Results for five models with and without radiative cooling and under different assumptions of the intracluster gas in Table 1 are shown. *Inset*: Minimum mass threshold against cluster redshift.

TABLE 1

PARAMETERS AND LEGEND FOR THE MODELS OF GAS DISTRIBUTION

Model	Cooling	n_e	T	Metallicity ($Z_\odot$)	Line Style
I	No	Gas-traces-mass	e.h.e.[a]	0.3	Dot-dashed
II..........	No	e.h.e.	Isothermal	0.3	Dashed
III	Yes	e.h.e.	Isothermal	0.3	Dotted
IV	Yes	Gas-traces-mass	e.h.e.	0.3	Solid
V..........	Yes	Gas-traces-mass	e.h.e.	$0.3(t/t_0)$	Dash-dot-dot-dotted

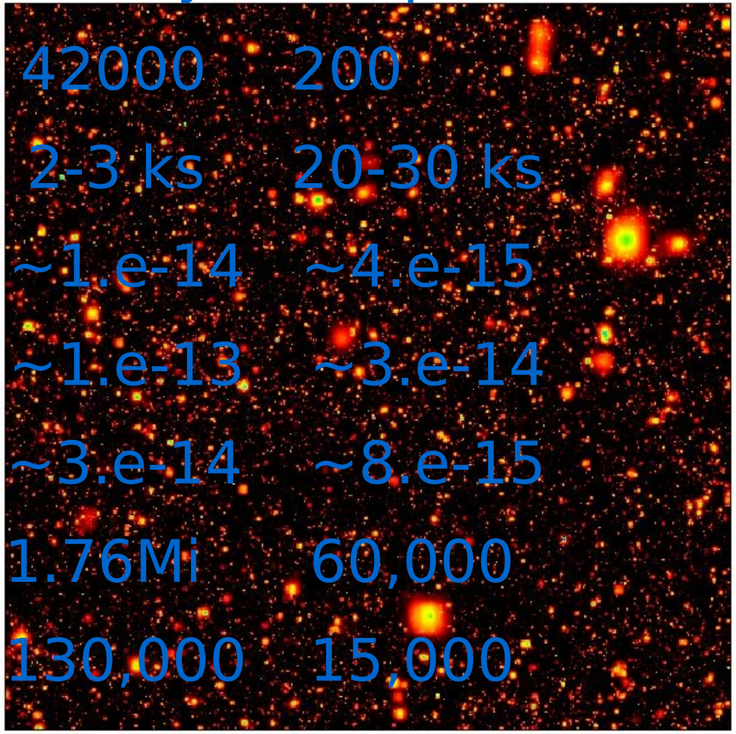
[a] Obtained by solving the equation of hydrostatic equilibrium.

Galaxy cluster as cosmological tools

- The eROSITA Surveys (4 yrs)

  Predehl et al. 2009

Survey	All-Sky	Deep
Solid Angle (sq.deg)	42000	200
Exposure time (average)	2-3 ks	20-30 ks
0.5-2 keV flux limit (AGN)	~1.e-14	~4.e-15
2-10 keV flux limit (AGN)	~1.e-13	~3.e-14
0.5-2 keV flux limit (Clusters)	~3.e-14	~8.e-15
Expected AGN (0.5-2 keV)	1.76Mi	60,000
Expected AGN (2-10 keV)	130,000	15,000
Expected **Clusters** (0.5-2 keV)	**72,000**	6,500



Credit: F. Pace

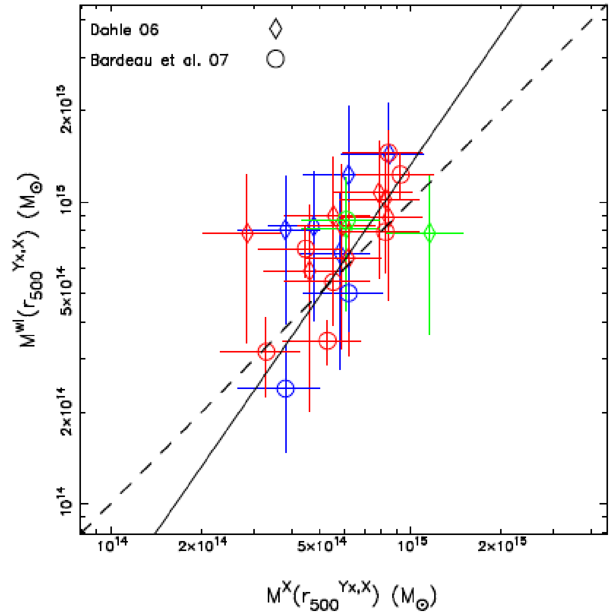
Calibrating mass and mass proxies

- WL-to-X-ray mass ratio of
  1.09+/-0.08 (Zhang et al. 08)
- An X-ray selected, volume-limited (via the L-M relation in Zhang et al. 08) sample of 67 massive clusters @z~0.2
  - XMM-Newton X-ray data (PI: Zhang)
  - Subaru weak lensing data (PI: Smith)

  - HST (PI Smith)
  - SZA (PI: Marrone)

  - Chandra
  - GALEX
  - Hectospec
  - Spitzer
  - Herschel

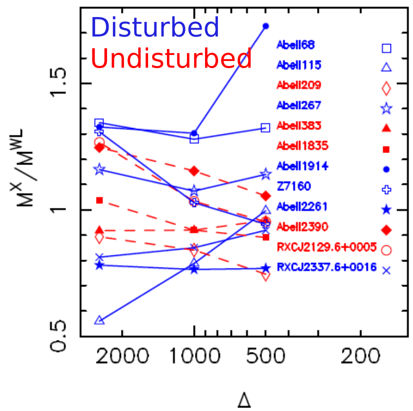
For a pioneer sample of ~30 clusters in the Local Cluster Substructure Survey

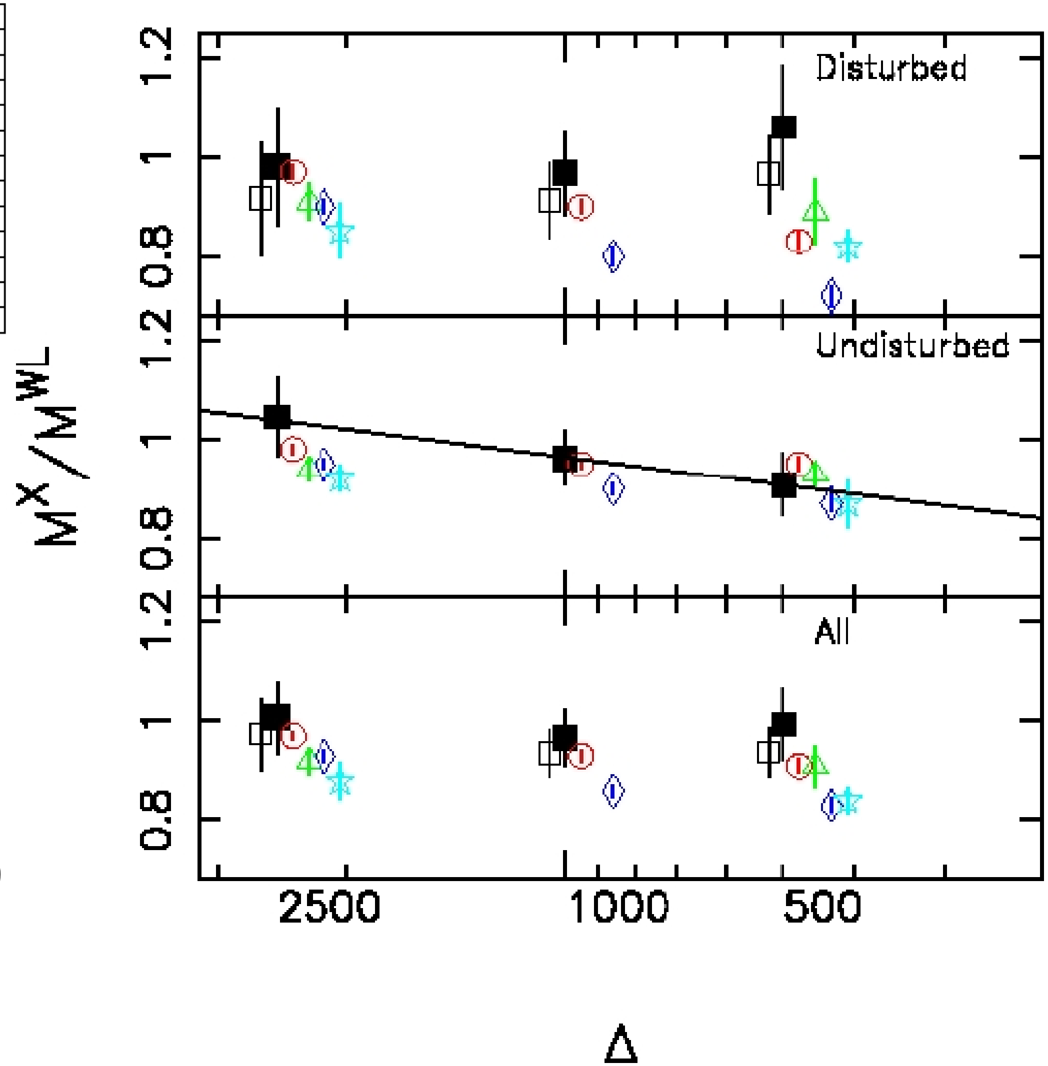


Calibrating mass and mass proxies

- X-ray to weak lensing mass ratios

Zhang et al. 10





■ All 7 disturbed clusters
1.06±0.12

□ 6 disturbed ones (~~A1914~~)
0.97±0.08

■ All 5 undisturbed ones
0.91±0.06

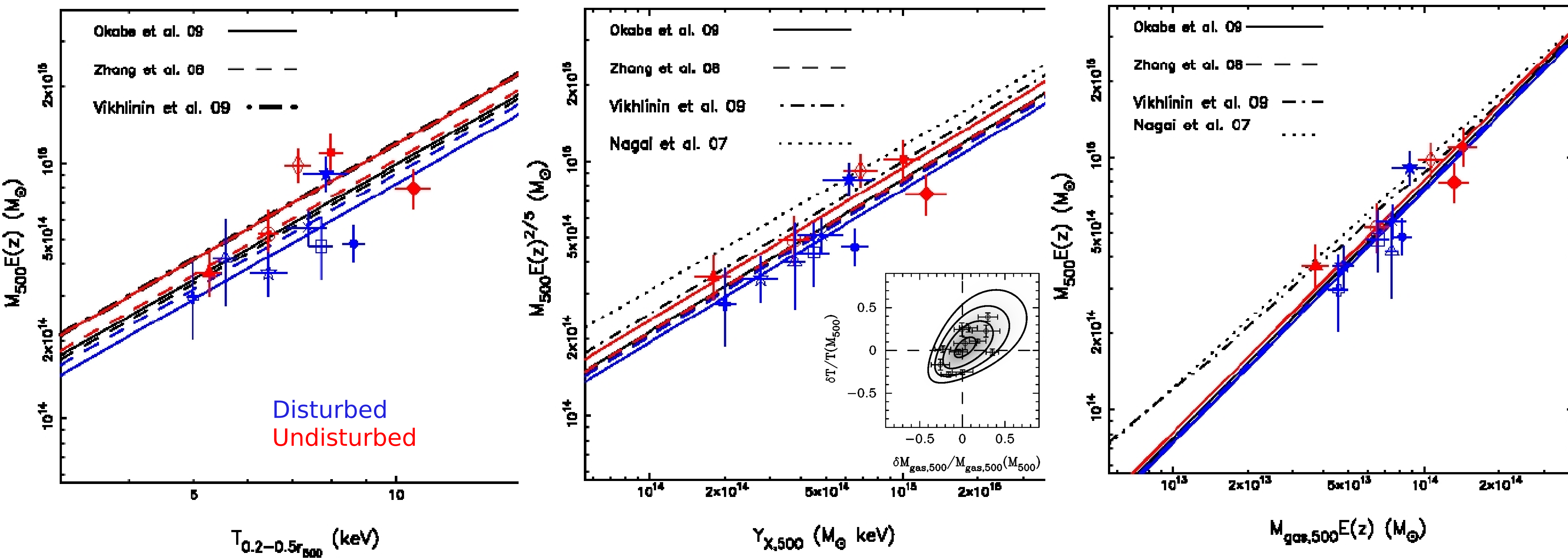
$M^X/M^{WL}=(0.908\pm0.004)+(0.187\pm0.010)*\log_{10}(\Delta/500)$

■ All 12
0.99±0.07

□ 11 clusters (~~A1914~~)
0.94±0.05

Calibrating mass and mass proxies

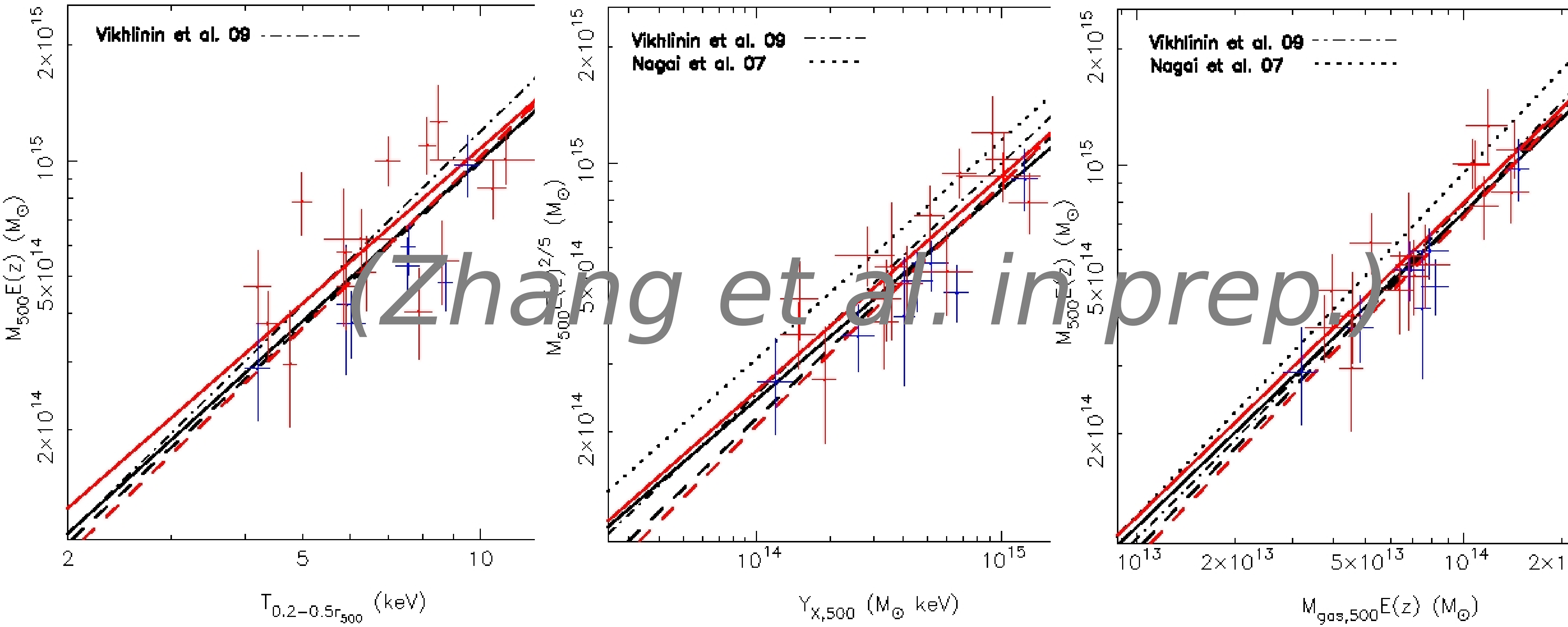
- Weak lensing mass vs. T / Y_X / M_{gas}
  - Intrinsic scatter σ_{lnM}, M-T>M-Y_X>M-M_{gas} ($8.3^{+6.3}_{-4.6}$%)
  - Anti-correlation (also found in simulations in Stanek et al. 10)



Okabe, Zhang et al. 10, red – undisturbed, blue – disturbed;
solid – WL mass vs. X-ray mass proxies;
dashed – X-ray mass vs. X-ray mass proxies

Calibrating mass and mass proxies

- Fitting the slopes: M vs. L / M_{gas} / Y
  - M-T, σ_{int}=?, slopes: ?, ?
  - M-Y, σ_{int}=?, slopes: ?, ?
  - M-M_{gas}, σ_{int}=?, slopes: ?, ?

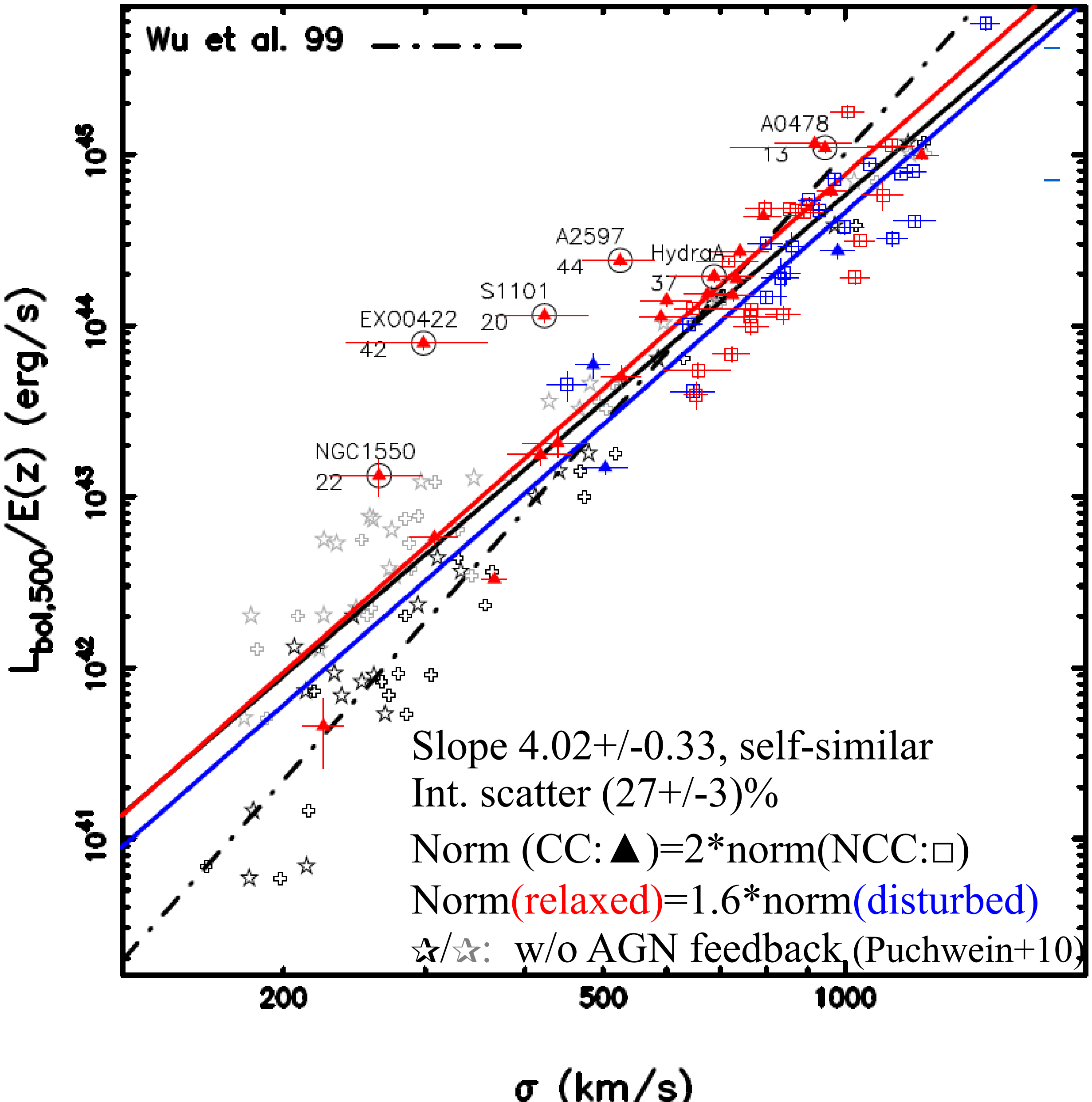


(Zhang et al. in prep.)

Disturbed
Undisturbed

Calibrating mass and mass proxies

- Probing biases in the mass proxies: AGN feedback & substructures



AGN feedback biases ***X-ray luminosity*** toward low values at different levels
Substructure biases ***velocity dispersion*** toward higher values

Zhang et al. 2011

Calibrating mass and mass proxies

- Probing biases in the mass proxies: SF & SN / radio-galaxy feedback
  - heating from merging quenches the star-formation activity of galaxies in massive systems or feedback from SN and radio galaxies drives a significant amount of ***gas (gas mass)*** beyond r_{500}

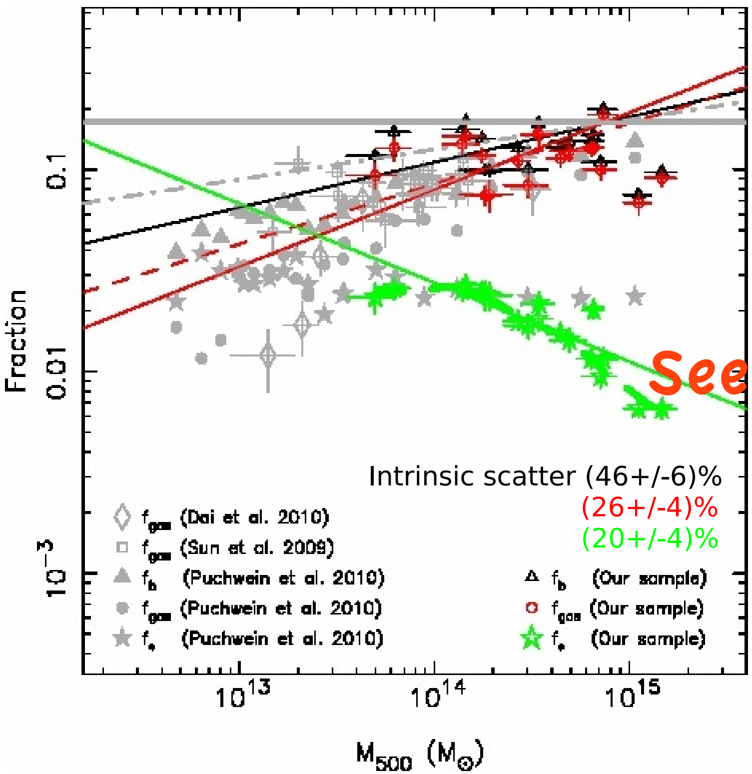
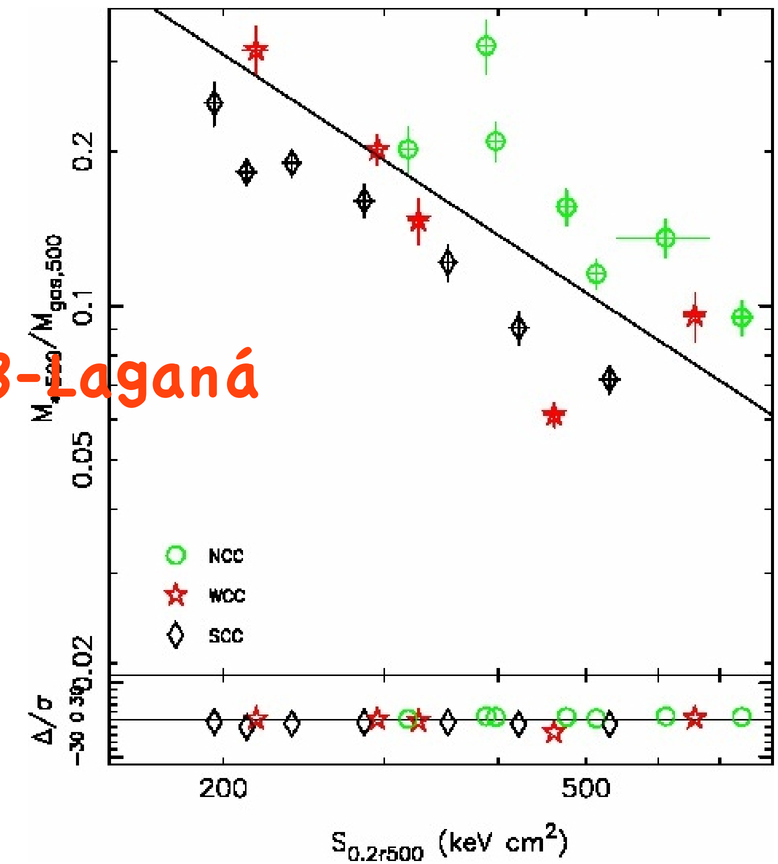


Fig. 2. Gas-mass fraction (red, open circles), stellar mass fraction (green, open stars), and baryon-mass fraction (black, open triangles) as a function of the total mass and the best fits excluding A2065 and A2029 in the same colors. For comparison, we also show the gas-mass fraction (gray, solid circles), stellar mass fraction in galaxies (gray, solid stars), and the sum of these two fractions (gray, solid triangles) for the simulated sample of 21 clusters with AGN feedback in Puchwein et al. (2010) as well as the gas mass fractions of the X-ray selected groups in Sun et al. (2009; gray, open boxes) and near-infrared selected groups in Dai et al. (2010; gray, open diamonds). The best fit of the baryon-mass fraction as a function of the total mass of the observational sample in Lin et al. (2003) is shown in gray, dot-dashed line. The gray band shows the 1σ measurement from the WMAP 5-year result (Dunkley et al. 2009). **A2142 displays a baryon-mass fraction of** 0.198 ± 0.008**, which exceeds the WMAP result with a** 3σ **significance.** The best fit of the gas-mass fractions combining our clusters and the clusters in Sun et al. (2009) is shown in red, dashed line.

See poster H08-Laganá



Zhang et al. submitted

Summary

- For relaxed clusters
  - WL-to-X-ray mass ratio of 0.91+/-0.06 at r500
  - Mass bias increasing with the radius, $M^{X}/M^{WL}=(0.908\pm0.004)+(0.187\pm0.010)*\log_{10}(\Delta/500)$
- Fixing the slope, gas mass has the lowest intrinsic scatter as the mass proxy
  - $\sigma_{\ln M(T)} > \sigma_{\ln M(Yx)} > \sigma_{\ln M(Mgas)} = 8.3^{+6.3}_{-4.6}\%$ @r_{500}
  - Correlation between the temperature vs. gas mass deviations as mass proxies, $r=\sigma_{TMg}/\sigma_{T}\sigma_{Mg}=0.575\pm0.224$, in agreement with Stanek+09's Millennium gas simulations
- Slopes of the WL mass vs. X-ray observable relations may be less dependent on the cluster dynamics then predicted
- Mass bias can be probed regarding cluster dynamics and physics
  - Substructures
  - Star formation
  - AGN, SN & radio-galaxy feedback

Thank you