Galaxy Clusters:
Mass Estimates & Substructures

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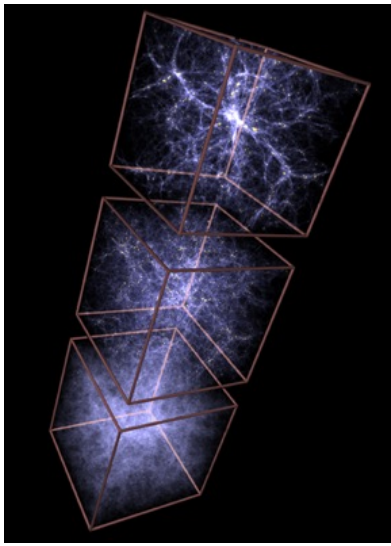
Overview

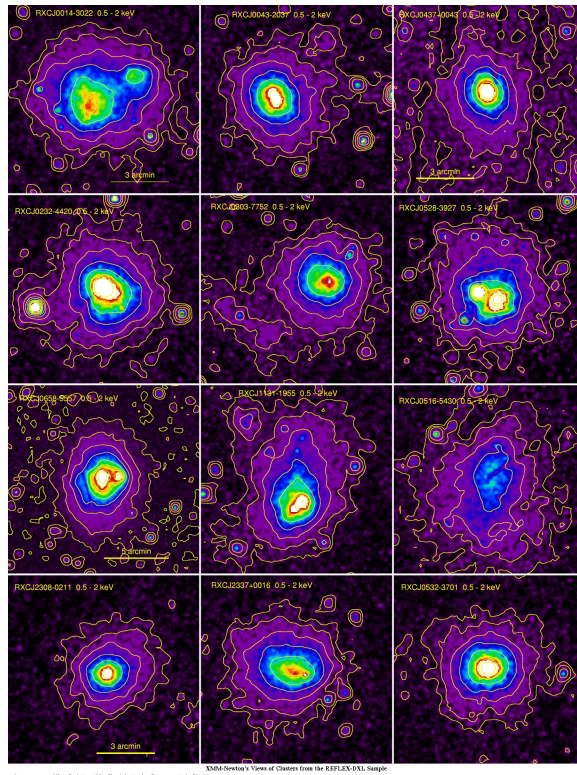
- Clusters of galaxies
- Cluster cosmology using mass function
- Mass – observable scaling relations
- X-ray vs. weak lensing masses
- X-ray mapping intracluster medium
- Summary
- Future perspective

Clusters of galaxies

V. Springel



- Formed very recently, dynamically young
  some showing evident substructures
- Largest virialized systems:
  ~$10^{14\text{-}15}$ solar mass
- 6-10% matter of the Universe, in clusters
- ~85% bayons in clusters being
  hot intracluster medium, 2-20keV, X-rays
- X-ray surveys – wide-area, clean, complete
  ROSAT: ~2000 clusters
  eROSITA: ~100,000 clusters (launch-2011)

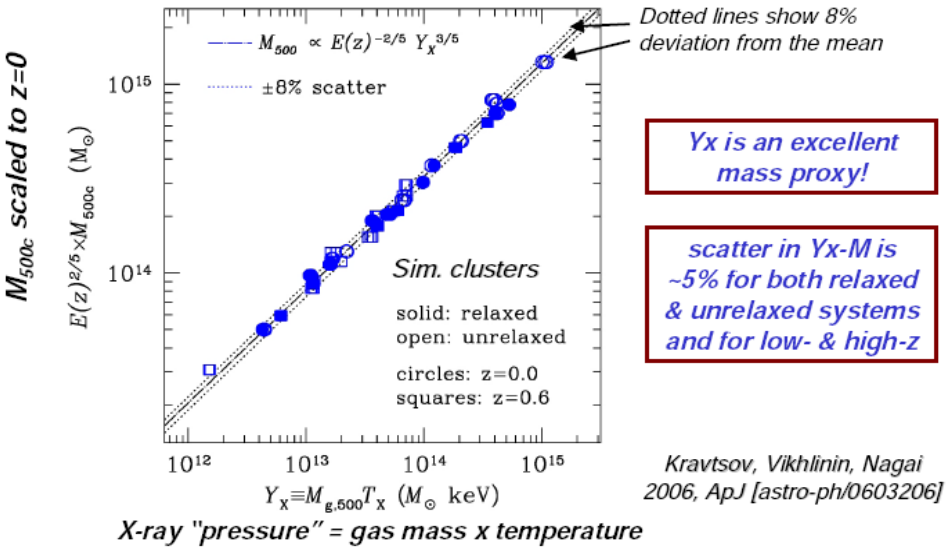


Zhang et al. 05a

Clusters of galaxies

- ***Tight mass - observable scaling relations***

Simulations, 5% scatter in
mass - Mgas: gas mass
&
mass - Y: integrated pressure



X-ray "pressure" = gas mass x temperature

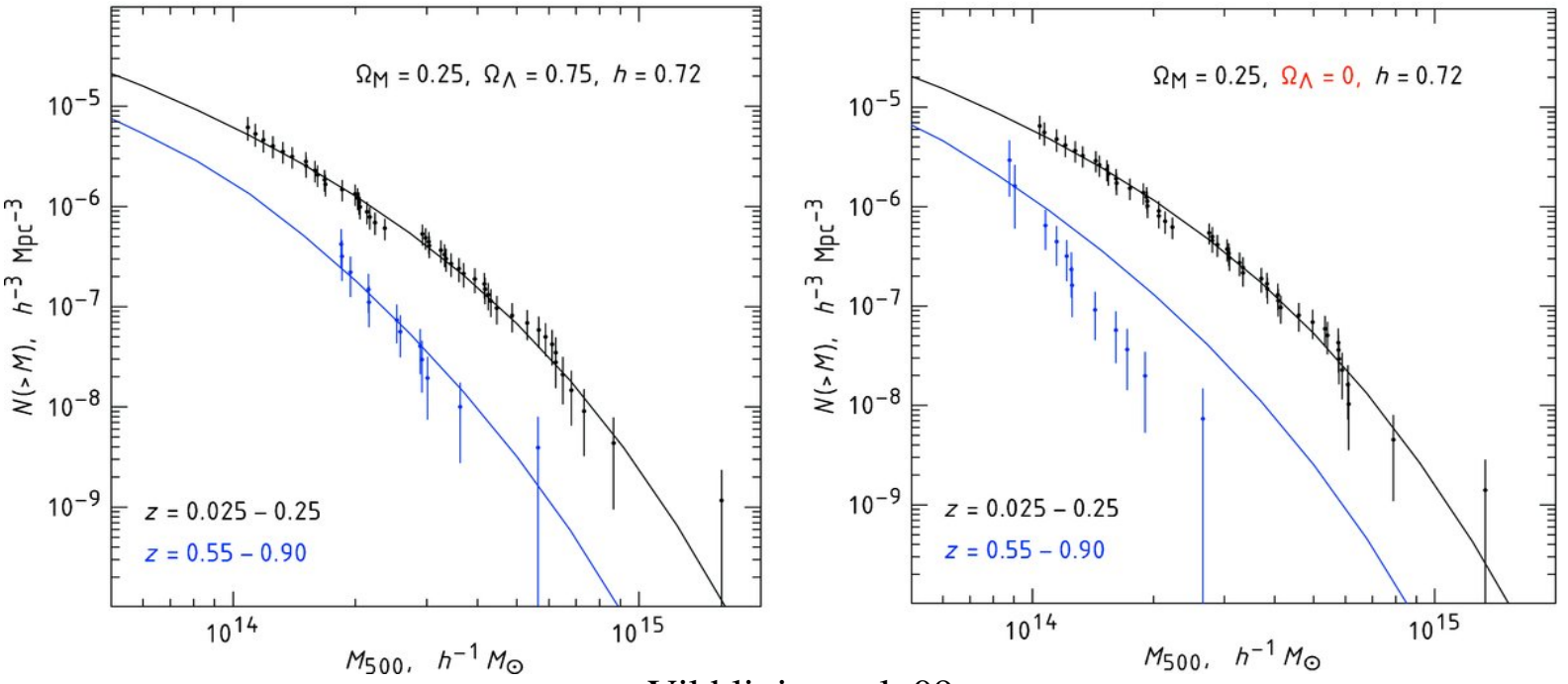
X-ray data, 10% scatter in
mass - gas mass & mass - Y
Note: Shape/normalization in agreement within 2% between different data sets.

e.g. Vikhlinin et al. 06; Zhang et al. 06, 08;
Arnaud et al. 07; Pratt et al. 09

Cluster cosmology using mass function

- Cluster mass function:
  In principle:
  Counting clusters as a function of mass & redshift N(M,z)
  - distance measurements of the cosmology

Mass function N(M,z)



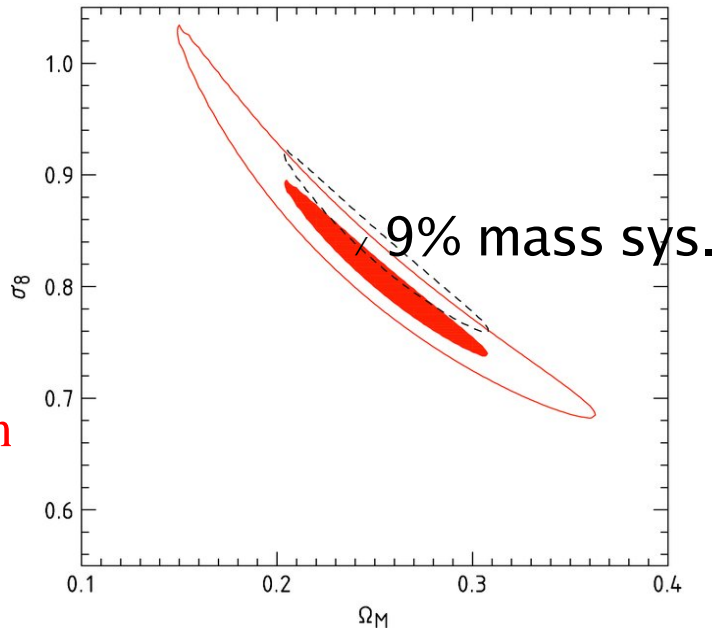
Vikhlinin et al. 09

Cluster cosmology using mass function

- In practice:
  Counting clusters as a function of observable & redshift
  ⇩ ⇦ ***Mass – observable relation***
  ⇩ observable as a mass proxy
  Mass function N(M,z)

- Mass systematics:
  Recent results: ~ 10-20% in cosmo. param
  40 clusters, ΔM/M ~ 9% ---------->
  Coming results:
  100 clusters, ΔM/M ~ 5%
  Future results:
  100,000 clusters, ΔM/M ~ 0.5%, 1% precision on cosmological parameters
  eROSITA (2011)

Vikhlinin et al. 09



σ_8

Ω_m

Mass – observable scaling relations

- Possible biases in the mass – observable relations:
  1) X-ray mass and X-ray observables
     Not completely independent
  2) Limit of X-ray mass estimates - substructures
     Physics effects, e.g. non-thermal pressure

$$M_{\rm tot} = -\frac{r^2}{G}\frac{\nabla P_g}{\rho_g} \propto T(r)\, r \left(\frac{d\ln\rho_g}{d\ln r} + \frac{d\ln T}{d\ln r}\right)$$

e.g. Churazov et al. 07, ~10% in a nearby galaxy

$$P = P_{thermal} + \underbrace{P_{CR} + \frac{B^2}{8\pi} + P_{turb}}_{\text{Non-thermal pressure}}$$

Geometric effects, e.g. asymmetry

In the extreme case, a line-of-sight merger: by a factor of 2

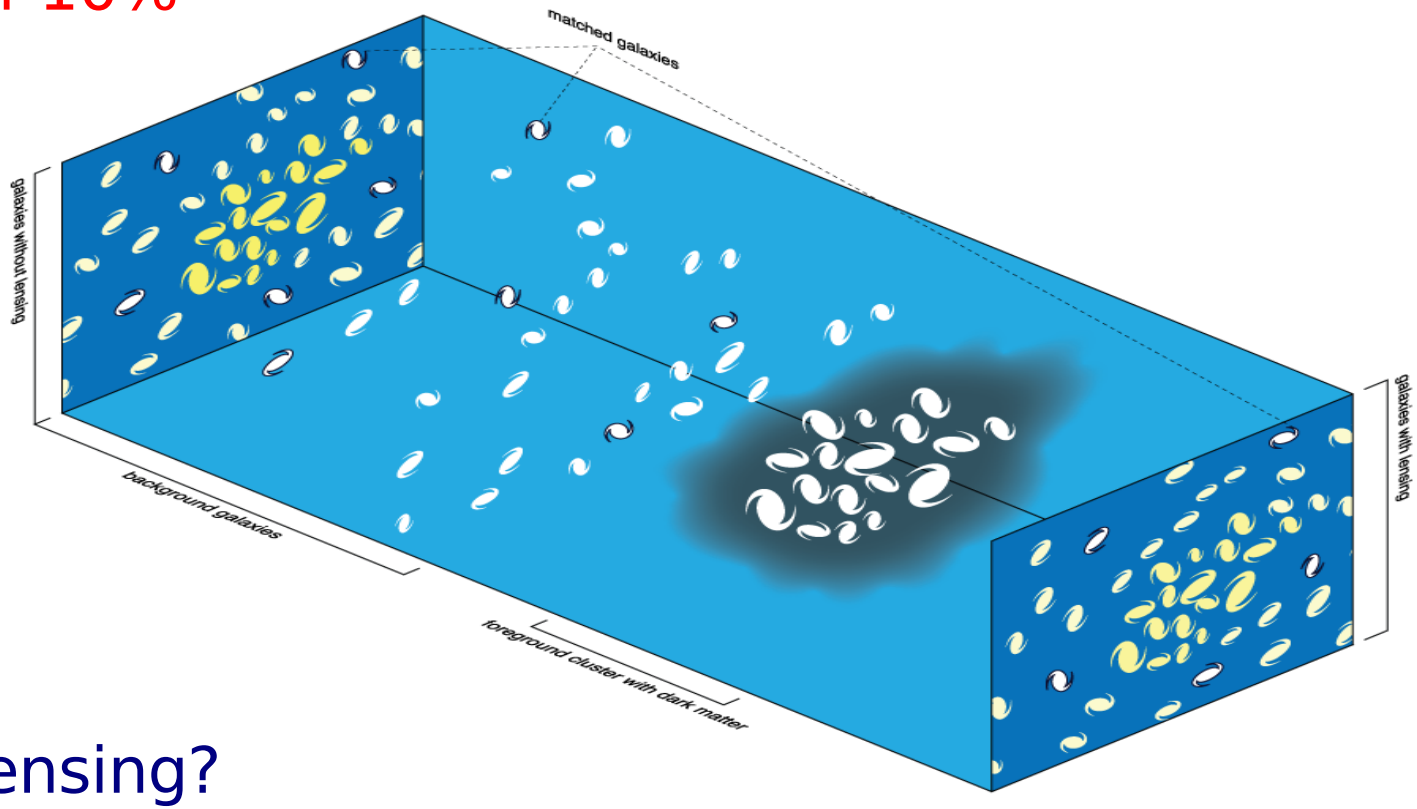
e.g. Zhang et al. 05, CL0024+17; Prat et al. 05, A2218

- Approach:
  Calibrate the observational bias
  Weak lensing vs. X-ray masses
  X-ray mapping intracluster medium
  Correct the 1st order bias in mass-observable relations

X-ray vs. weak lensing masses

- What is weak lensing?
  Statistically coherent distortions of background galaxies, on the order of 10%

Schindler et al. 08

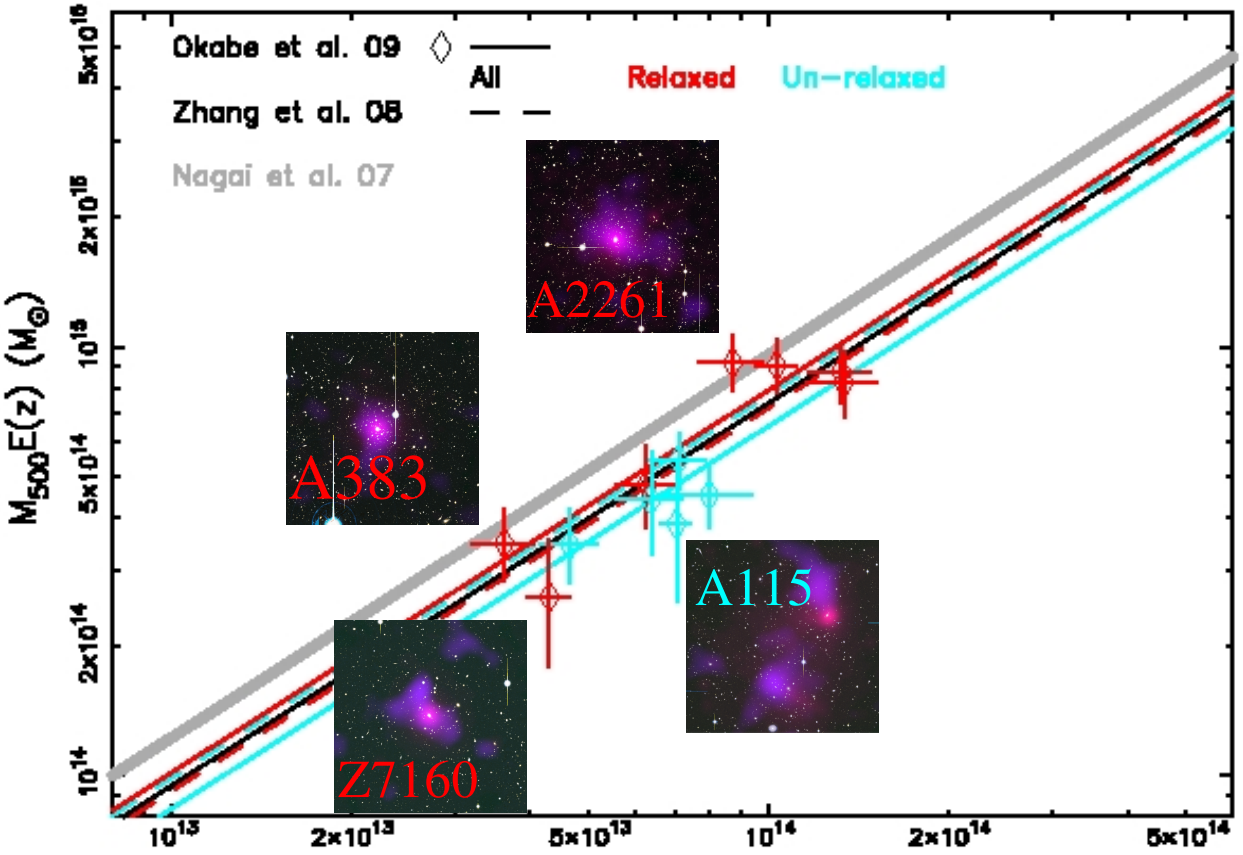


- Why is weak lensing?
  Independent of cluster dynamical state & evolution history
  Independent mass estimate from the X-ray approach

X-ray vs. weak lensing masses

- Weak lensing mass vs. X-ray mass, in agreement statistically
- Observational bias due to significant substructure

Subaru
0.25sq.deg fov

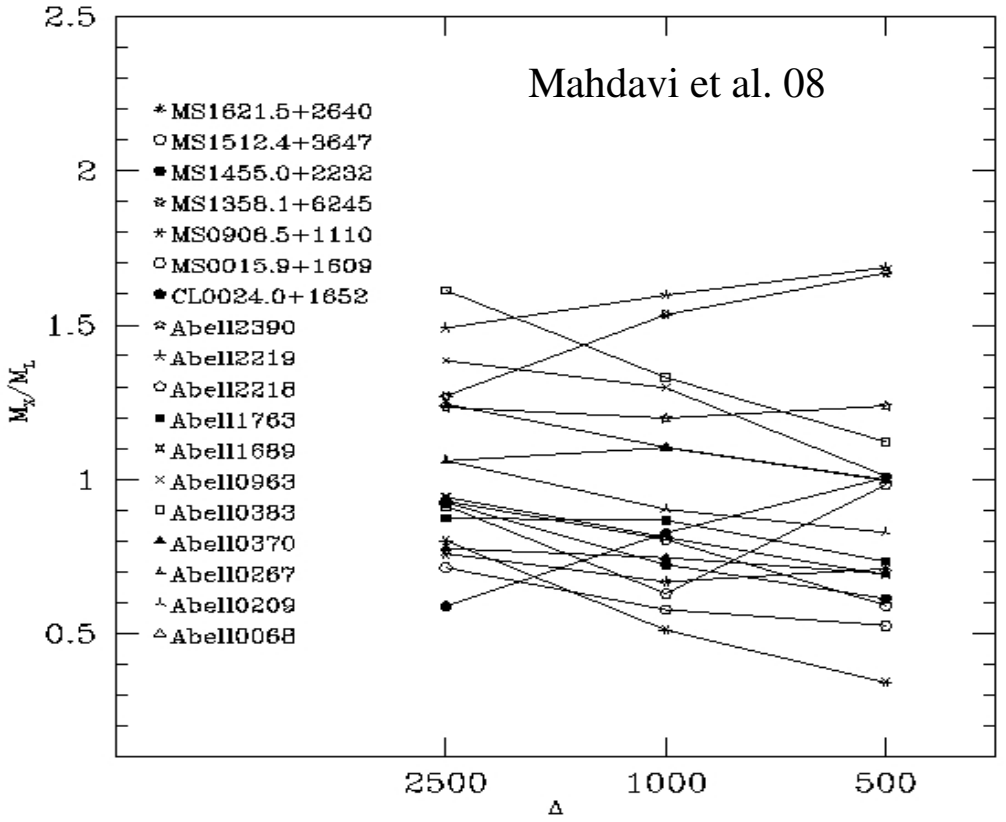


XMM-Newton
0.2sq.deg fov

X-ray vs. weak lensing masses

- X-ray to weak lensing mass ratio is 0.78+/-0.09 @r500
  1.03+/-0.07@r2500

  Radial dependence of the mass bias?!
  Sampling bias?!

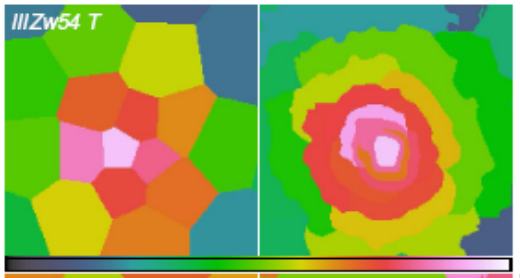


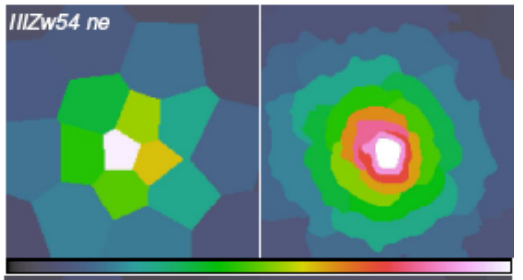
X-ray mapping intracluster medium

Zhang et al. 09

- Relaxed

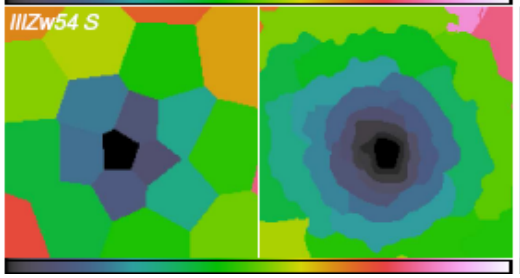
Temperature ->

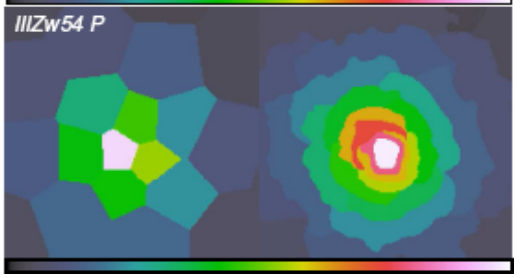




<- Density

Entropy ->

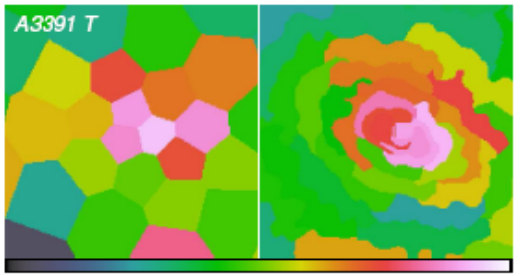


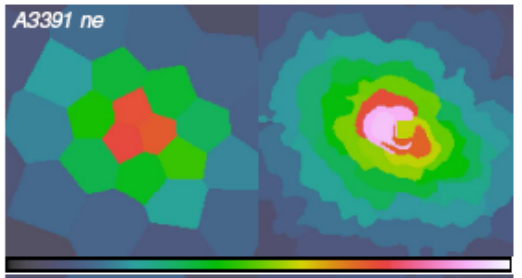


<- Pressure

- Unrelaxed

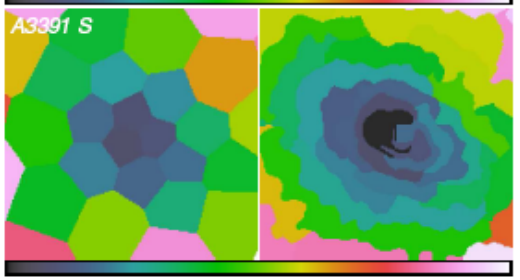
Temperature ->

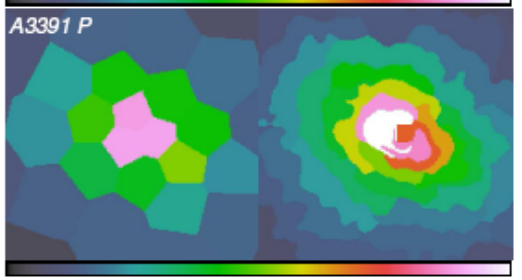




<- Density

Entropy ->





<- Pressure

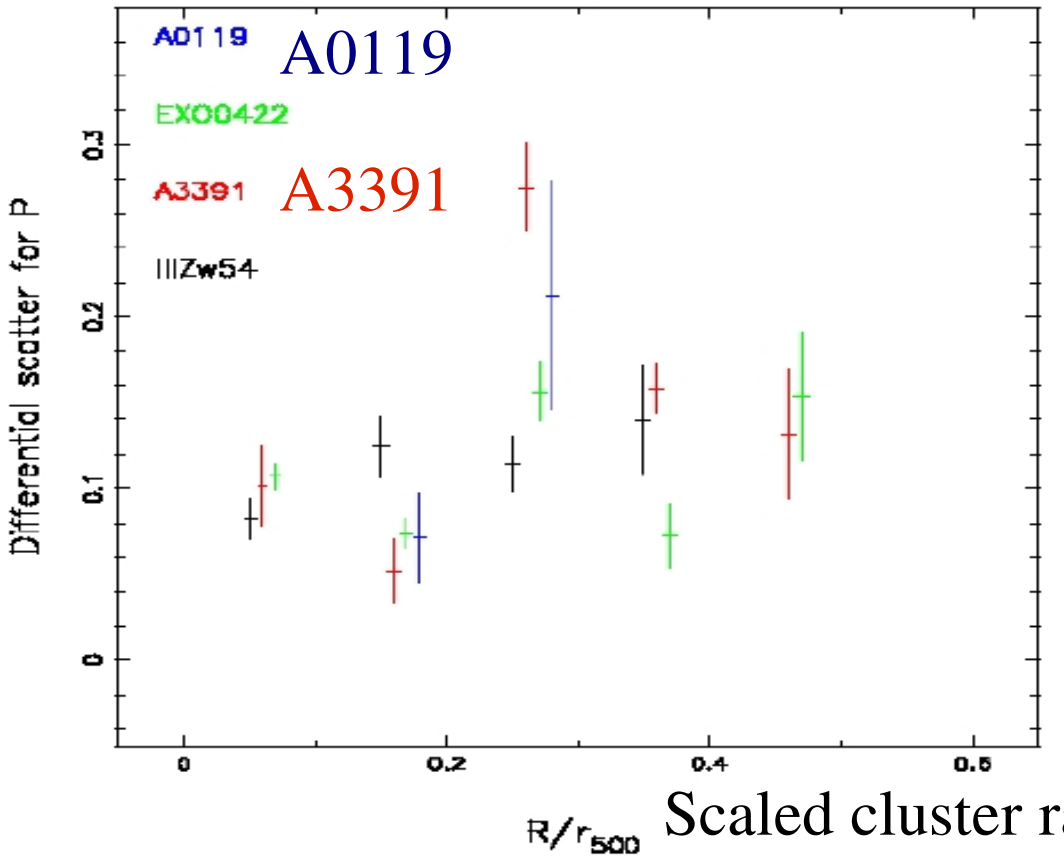
X-ray mapping intracluster medium

- Scatter profile of fluctuations

$$\sqrt{\Sigma F_i^2 w_i}/\sqrt{\Sigma w_i} \qquad F = |D(d,\theta)/\langle D(d)\rangle - A|$$

- Substructure diagnostics: high amplitude discontinuities

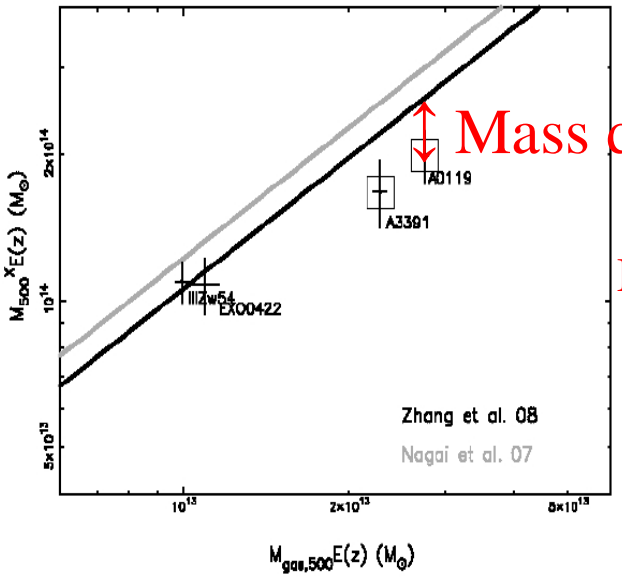
e.g. Scatter of pressure fluctuations



Zhang et al. 09

X-ray mapping intracluster medium

- High correlation coefficient between substrucure indicator- scatter of pressure/P & entropy/S fluctuations
  &
  mass bias- the scaled mass deviation



Mass deviation

Mass bias

Bias	Scatter	*Mask-V*			*Mask-S*		
		A	B	coeff.	A	B	coeff.
$B^{Y_X}_{M_{500}}$	S	1.28 ± 0.36	-13.3 ± 3.0	-0.98	0.50 ± 0.20	-6.2 ± 1.6	-0.80
	P	0.92 ± 0.28	-7.4 ± 1.7	-0.97	0.98 ± 0.29	-8.6 ± 2.0	-0.97
$B^{M_{gas}}_{M_{500}}$	S	0.92 ± 0.39	-9.2 ± 3.4	-0.95	0.33 ± 0.22	-3.7 ± 1.8	-0.69
	P	0.67 ± 0.30	-5.1 ± 1.9	-0.94	0.65 ± 0.30	-5.5 ± 2.2	-0.90

$$Y = A + BX$$

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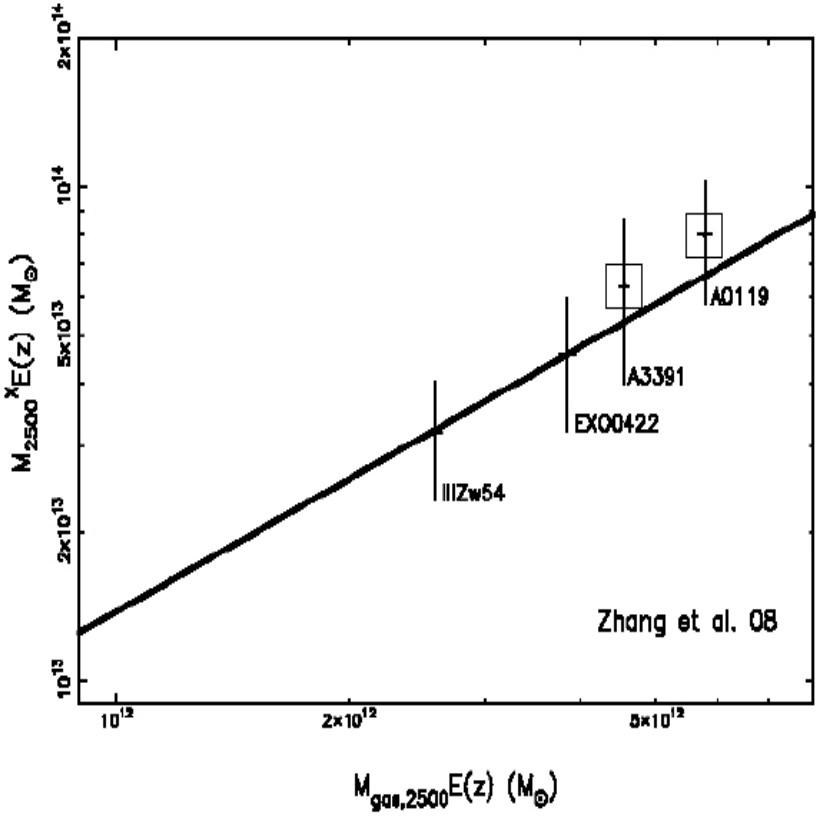
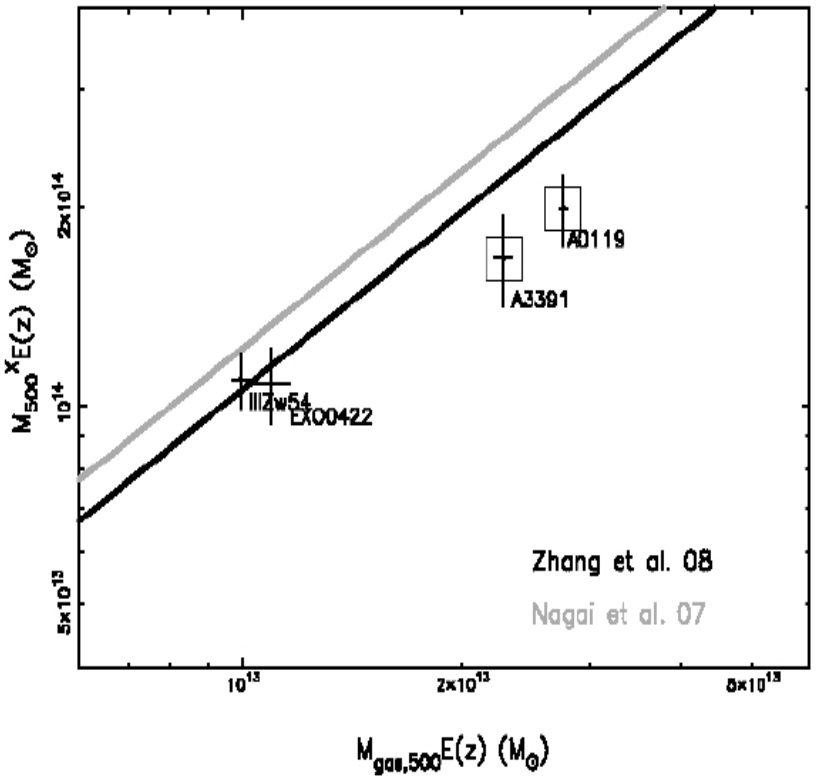
X-ray mapping intracluster medium

- Mass bias, radial dependence or extrapolation bias?!
  linking to substructure diagnostics – scatter prof.

Mass vs. Gas mass at inner (left) and outer (right) radii





Zhang et al. 09

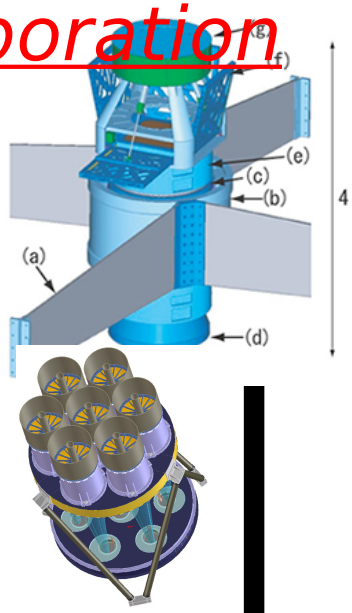
Summary

- X-ray surveys provide wide-area, clean and complete cluster catalogs for cosmological tests.
- Mass and observable bias could be better understood to control the systematics of the cosmological constraint using the cluster mass function.
- Mass and observable bias may be radial dependent, and could be quantified using the presented two methods ***giving a large sample***
  1. X-ray vs. weak lensing masses
  2. X-ray mapping intracluster medium

Future perspective

- *Such a large sample (~100 cluster)*
  Statistically complete, no sample bias
  with data of X-ray: XMM - 0.2 sq.deg fov
  &
  weak lensing: Subaru - 0.25 sq.deg fov
  Covering the whole cluster, no extrapolation bias

- *A possibility of much more powerful collaboration*
  between
  Hyper-Suprime-Cam: 1.5 sq.deg fov
  (Weak lensing 2000 sq.deg survey 2011-)
  &
  e-ROSITA, 1.0 sq.deg fov
  (All sky survey, 100,000 cluster, 2011-)



Thank you!