Constraints on Cosmology and X-ray Scaling Relations from the Growth of Massive Galaxy Clusters

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Chandra's First Decade of Discovery

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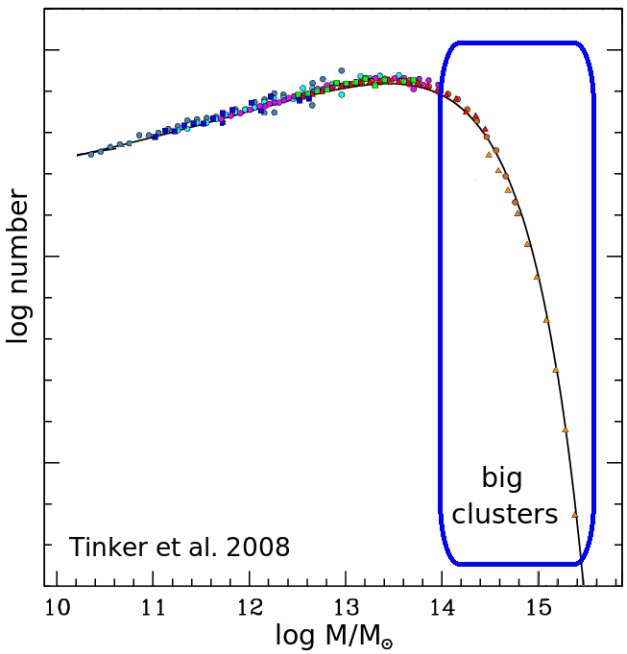
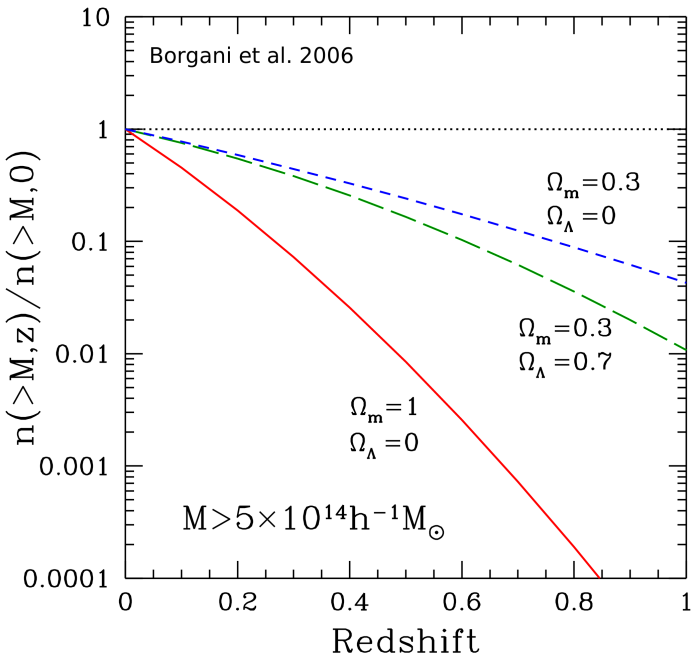
Clusters and the growth of structure

Cluster abundance as a function of mass and redshift probes the mass function and expansion history.

- Low redshift clusters $\longrightarrow \Omega_{\rm m}$, σ_8
- Evolution $\longrightarrow$ dark energy





Ingredients

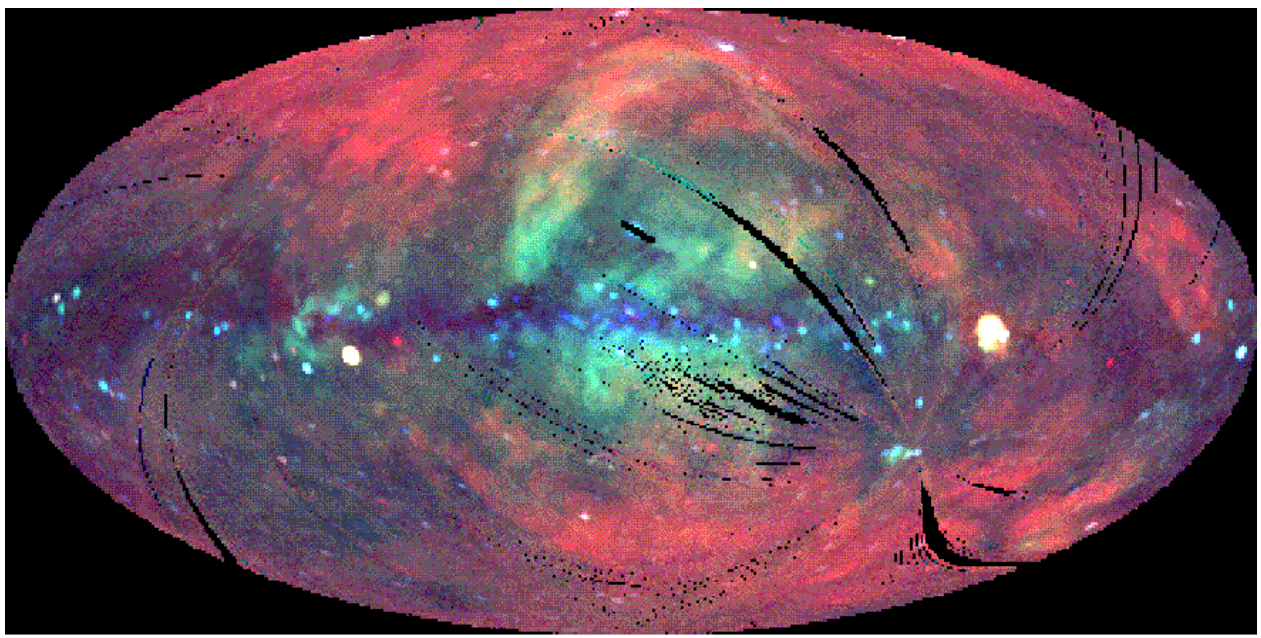
To do this, we need

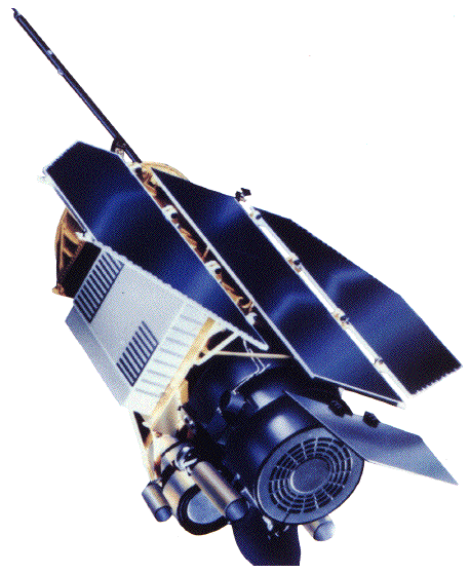
- a cluster survey with a well-understood selection function
- an observable–mass scaling relation

In X-rays, we have the *ROSAT* All-Sky Survey.

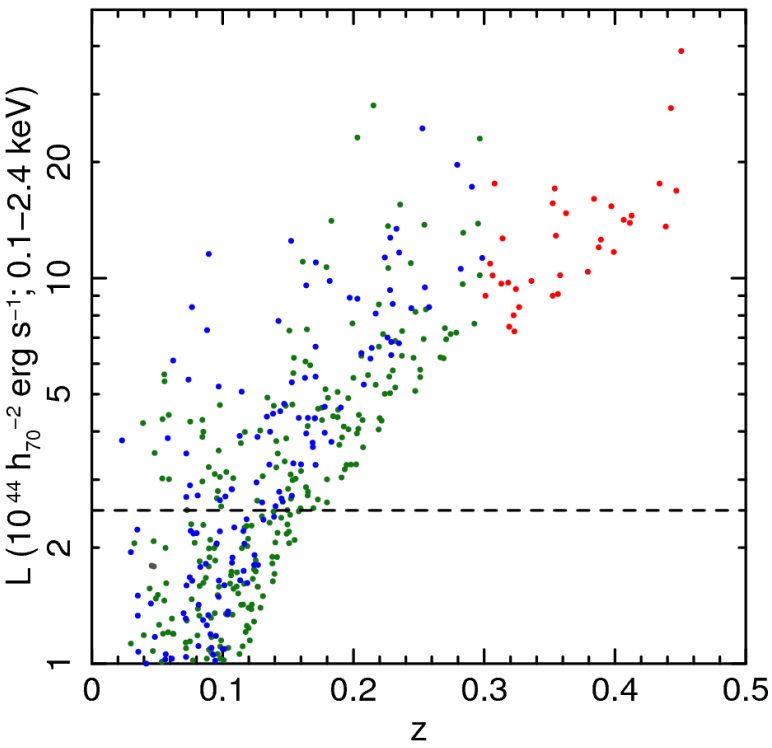
Clusters are found based on their X-ray flux.

The relevant scaling relation is X-ray luminosity–mass.





Data: cluster survey



Continuous and complete redshift coverage

X-ray flux limited cluster samples from the ROSAT All-Sky Survey:

- BCS (Ebeling et al. '98)
  $z < 0.3$
  $\sim 33\%$ sky coverage
  $F > 4.4 \times 10^{-12}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$
- REFLEX (Böhringer et al. '04)
  $z < 0.3$
  $\sim 33\%$ sky coverage
  $F > 3.0 \times 10^{-12}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$
- Bright MACS (Ebeling et al. '01)
  $0.3 < z < 0.5$
  $\sim 55\%$ sky coverage
  $F > 2.0 \times 10^{-12}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$

Luminosity cut at $2.5 \times 10^{44} h_{70}^{-2}\,\mathrm{erg\,s^{-1}}$
leaves $78 + 126 + 34 = 238$ massive clusters.

Data: X-ray follow-up observations

Of the 238 flux-selected clusters, there are pointed observations of

- 23 at $z < 0.2$ with *ROSAT*
- 71 at $z > 0.2$ with *Chandra*

For dated reasons, we call the complete data set the cluster X-ray Luminosity Function (XLF).

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Measure average properties (within r_{500})

- luminosity
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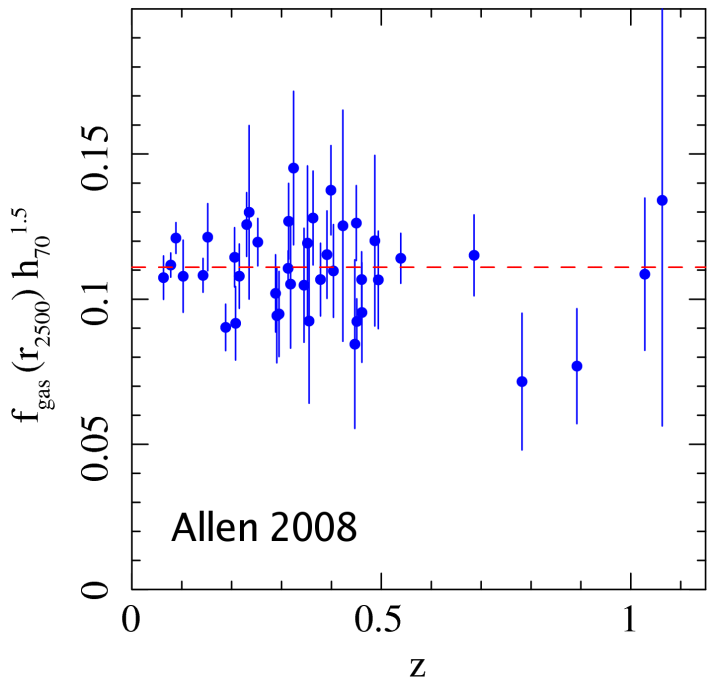

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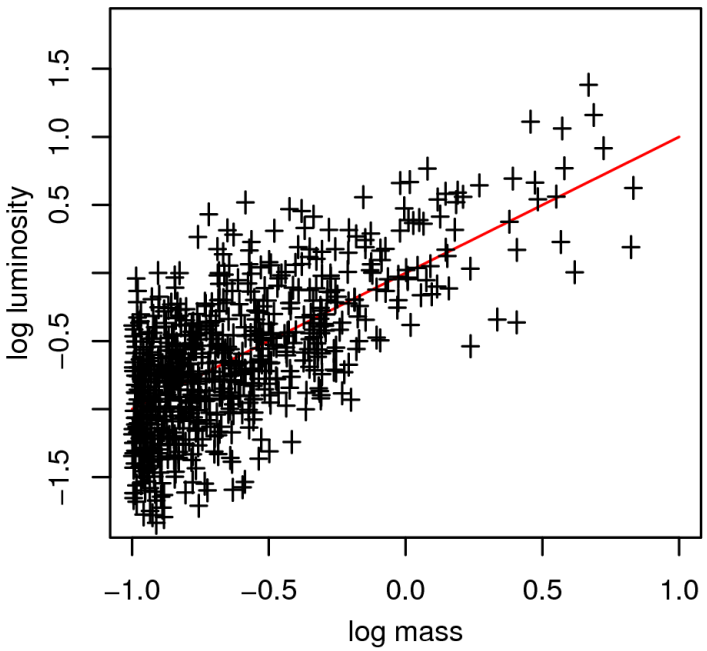
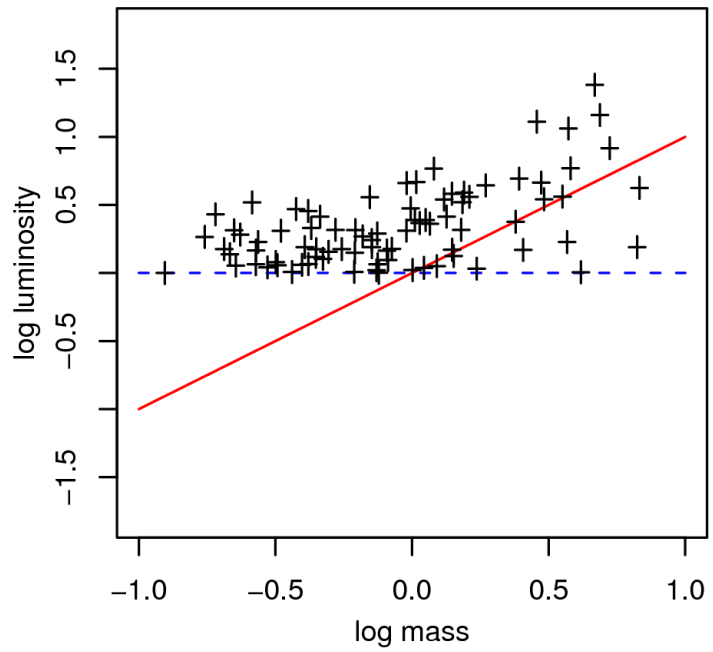
Analysis (briefly)

The mass–luminosity relation has intrinsic scatter ($\sim 40\%$).

$\Rightarrow$ significant bias compared with a mass-limited sample.





For internal consistency, the analysis of the cosmology and scaling relations *must* be fully simultaneous.

Priors and systematic allowances

Cosmological parameters		
Hubble constant, h	0.72 ± 0.08	Hubble Key Project
Baryon density, $\Omega_{\rm b} h^2$	0.0214 ± 0.0020	BBN
Mass function		
normalization/shape	10%	Tinker et al.
evolution	10%	2008
Survey		
incompleteness/contamination	5%	
Mass measurement		
$f_{\rm gas}(r_{500})$	0.12 ± 0.04	6 clusters ($z < 0.15$) (Allen et al. 2008)

These allowances are included in all cluster results shown later.

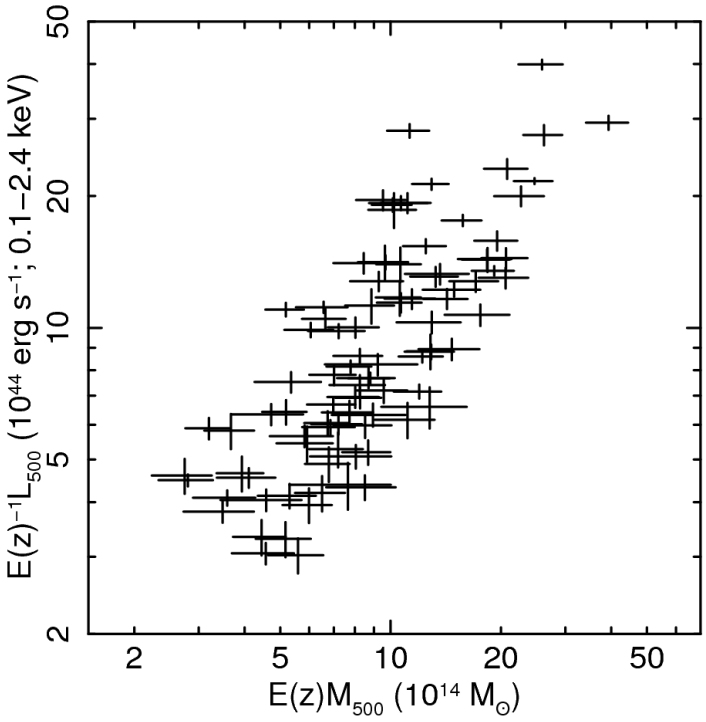
Scaling relation model

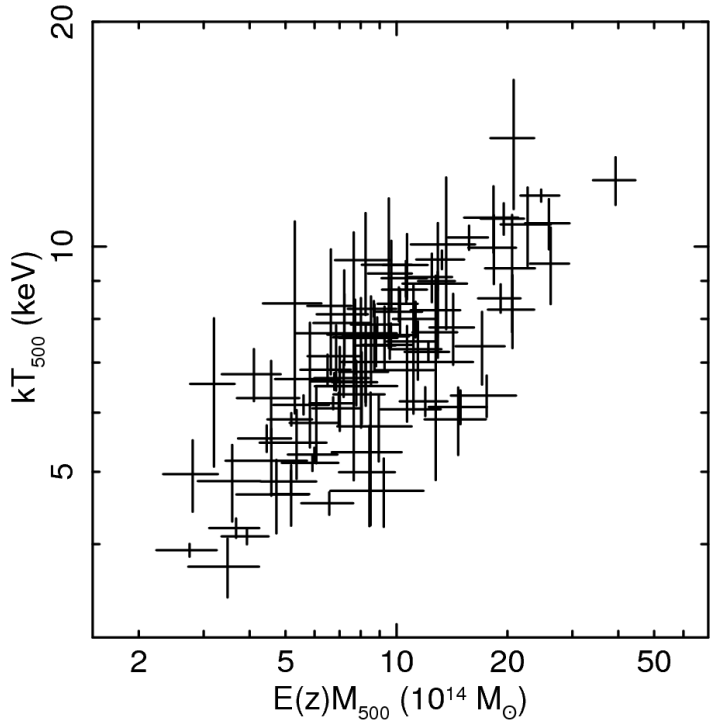
Nominal M–L and M–T relations as power laws with self-similar evolution:

$$\frac{L_{500}}{E(z)} \propto [E(z)M_{500}]^{\beta_L} \qquad kT_{500} \propto [E(z)M_{500}]^{\beta_T} \qquad E(z) = H(z)/H_0$$

Intrinsic scatter in L and T at fixed M modeled as bivariate log-normal.

Scaling relation results





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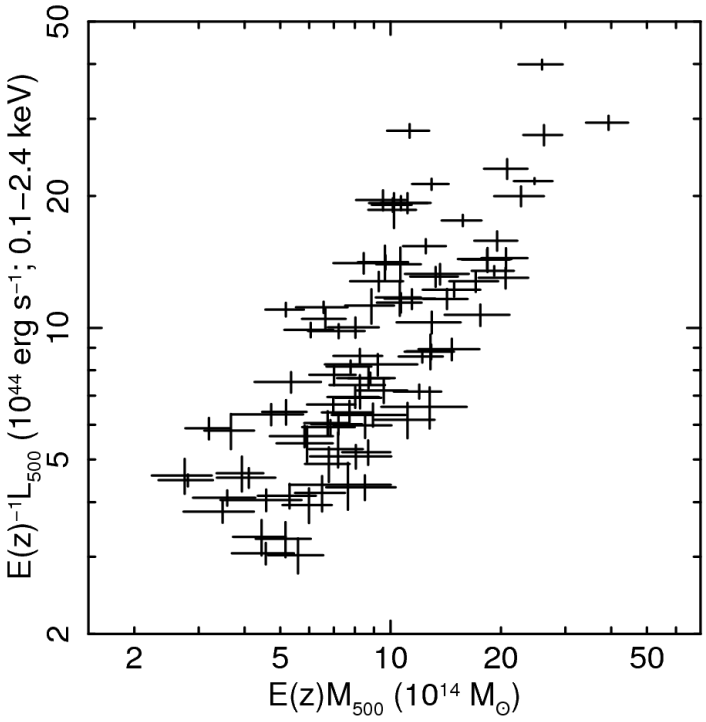

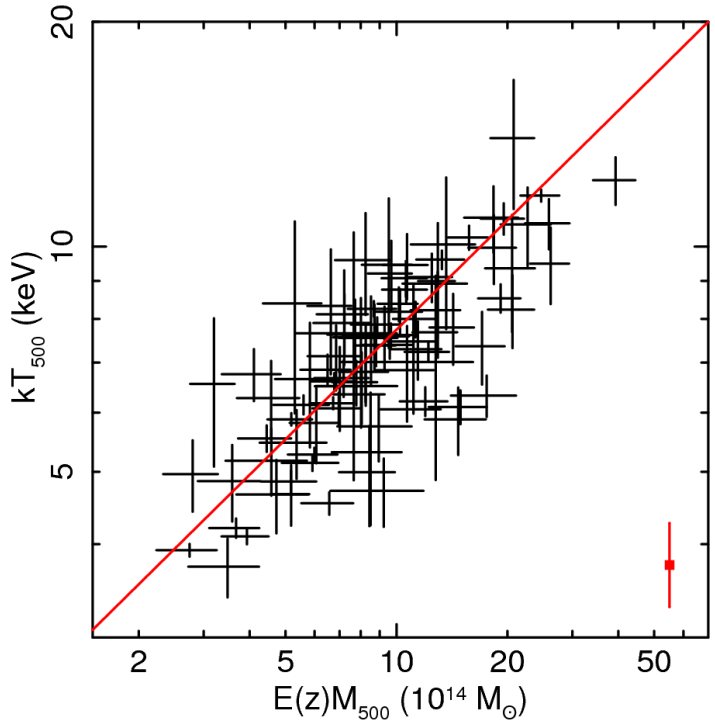

Intrinsic scatter: $\sim 15\%$

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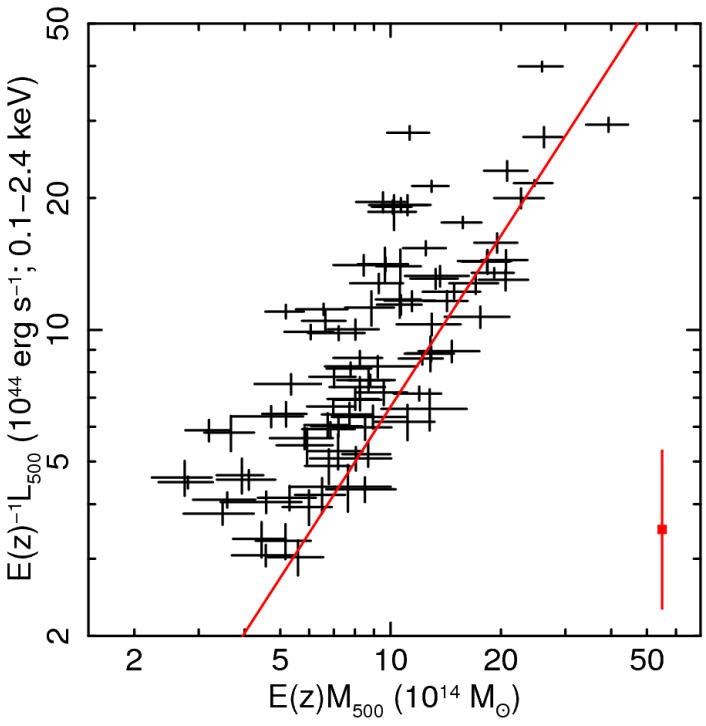

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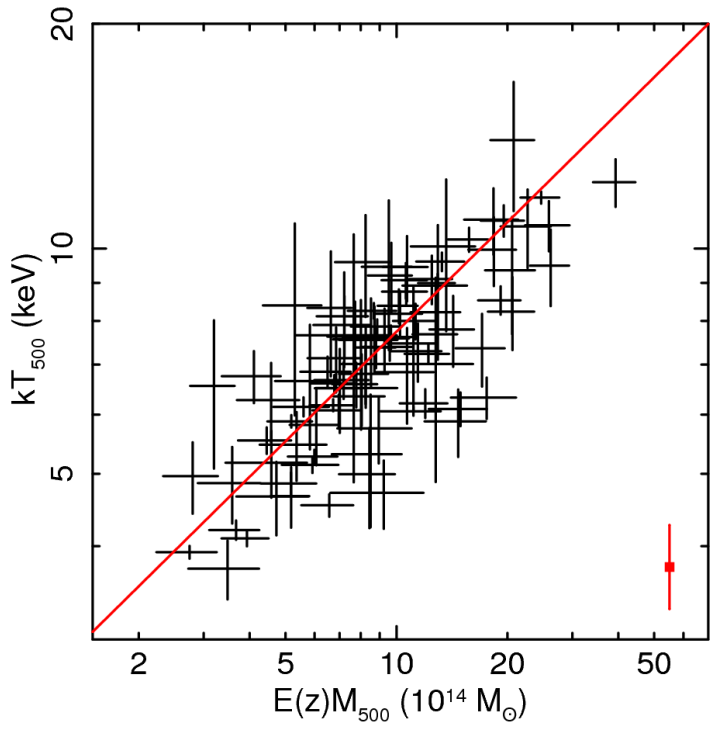
Note selection bias!



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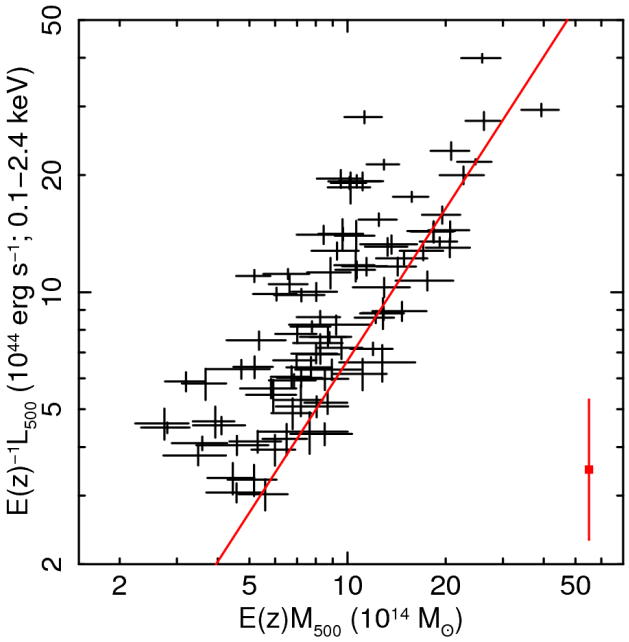

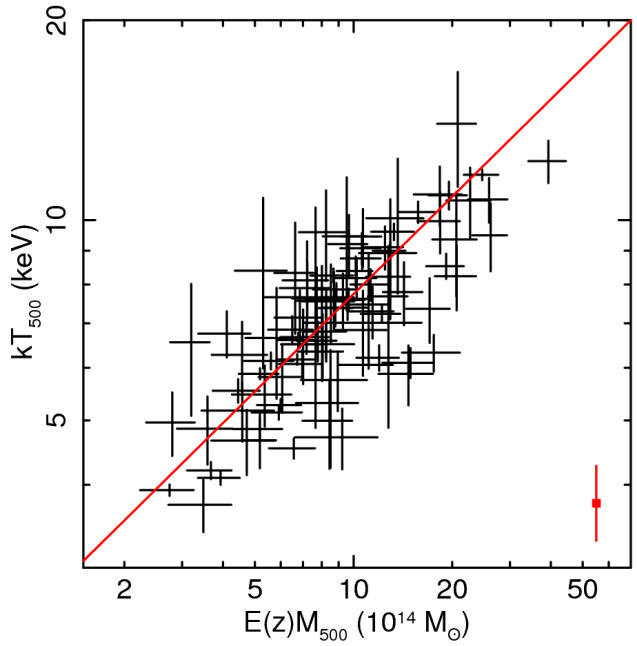

Is this simple model sufficient?

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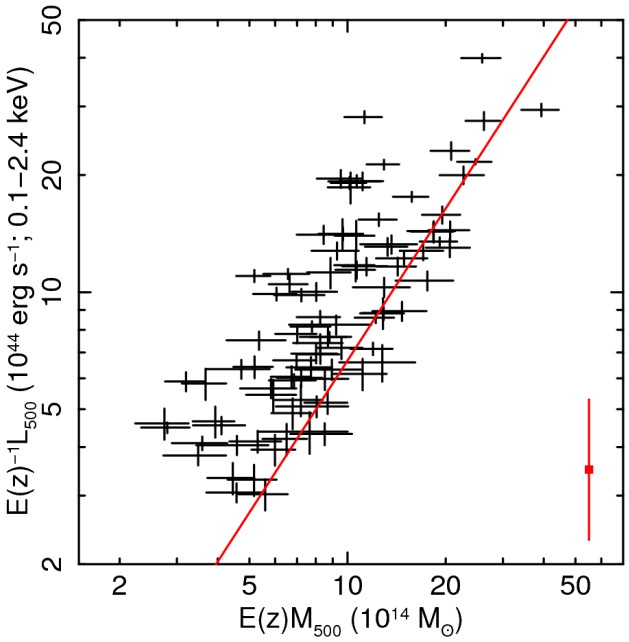

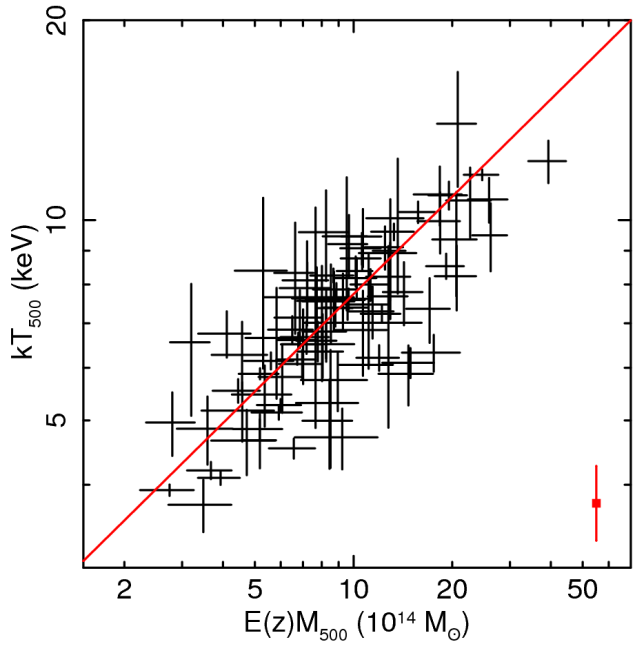

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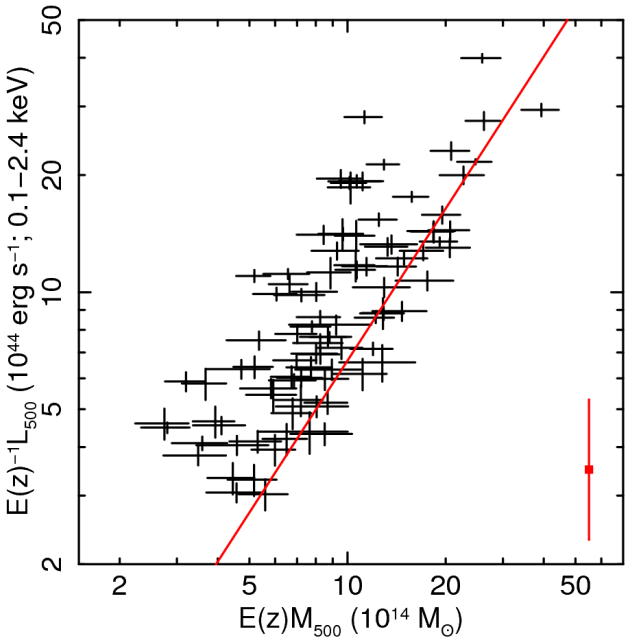

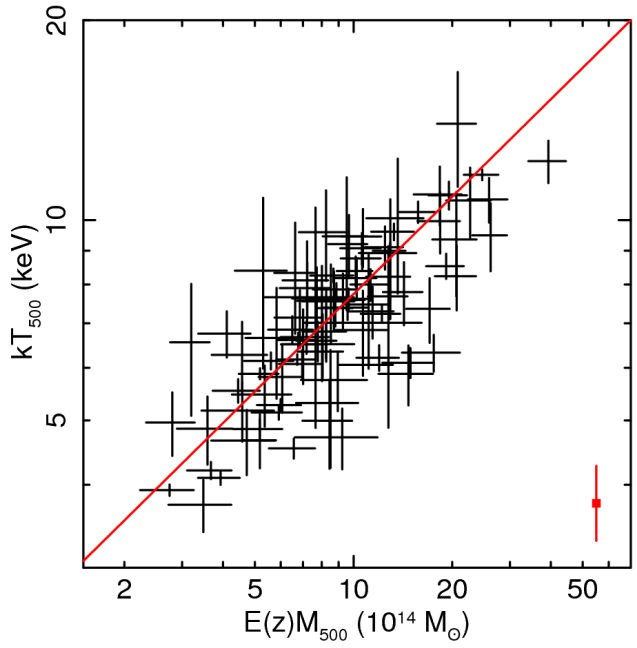

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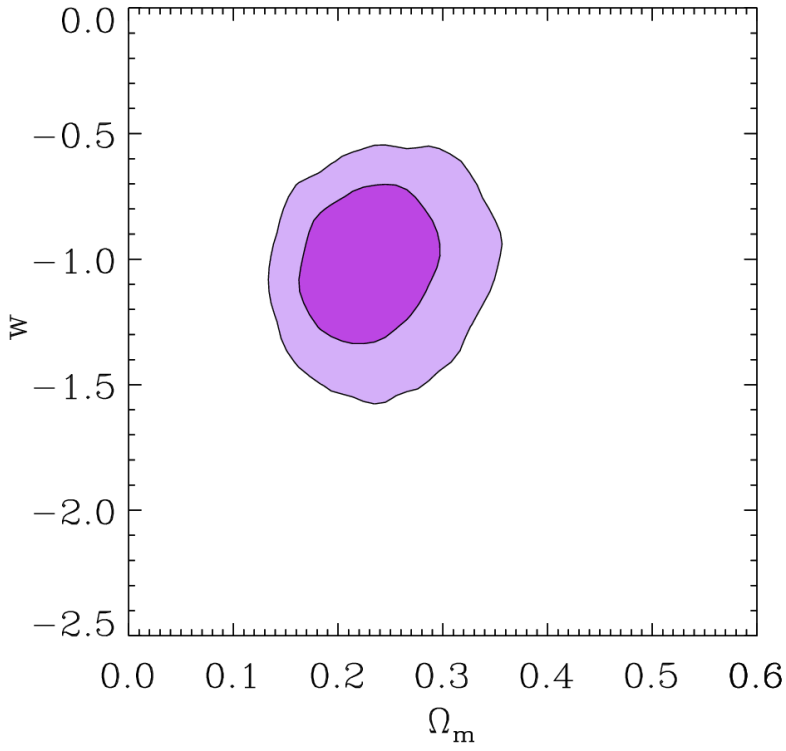
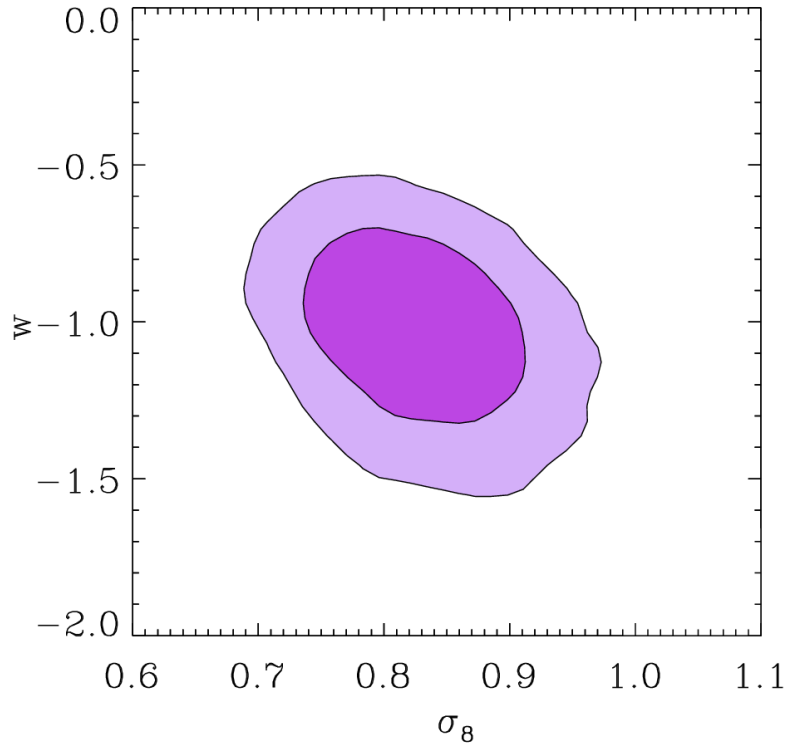
The data do not prefer

- departures from self-similar evolution
- evolution in the intrinsic scatter
- asymmetry in the intrinsic scatter

Cosmological results for flat, constant-w models





238 clusters, $z < 0.5$ (XLF)
Including systematics

$$\begin{aligned} \Omega_{\rm m} &= 0.23 \pm 0.04 \\ \sigma_8 &= 0.82 \pm 0.05 \\ w &= -1.01 \pm 0.20 \end{aligned}$$

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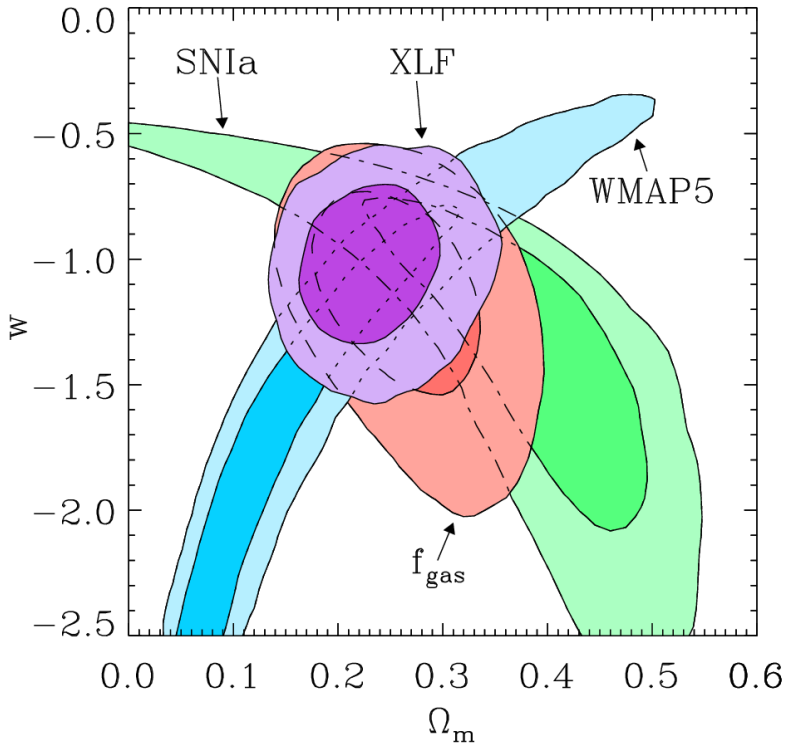

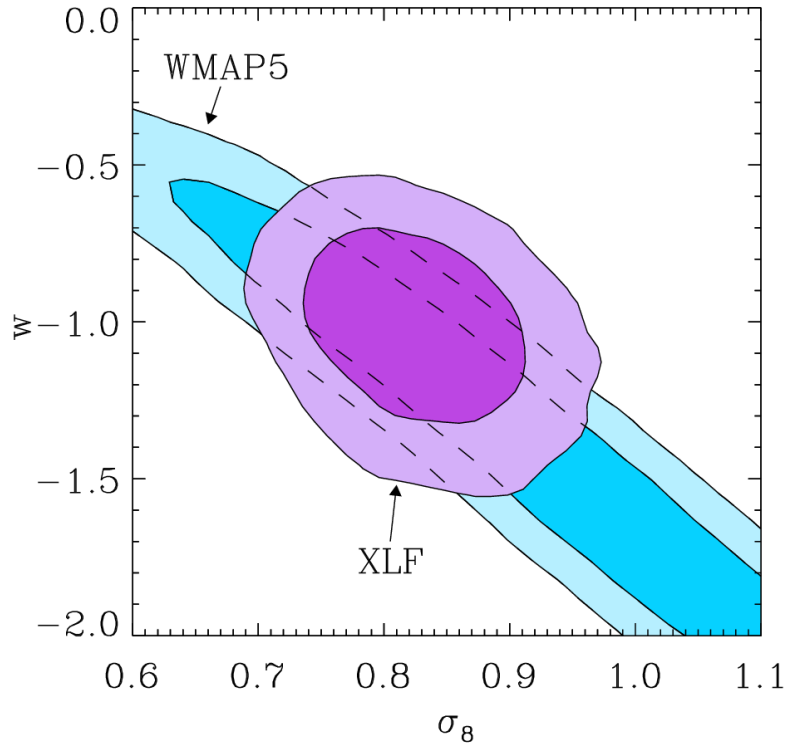

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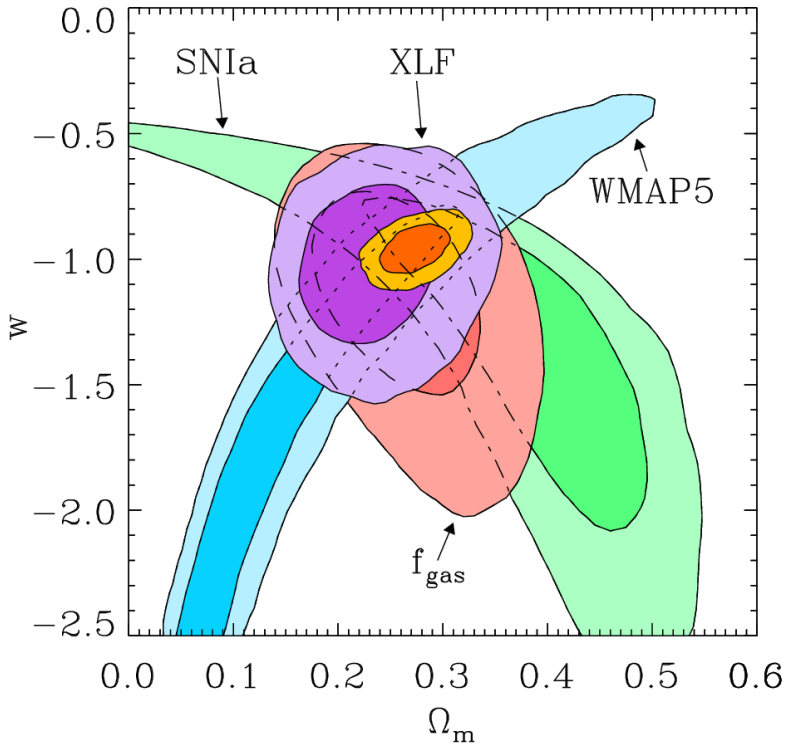

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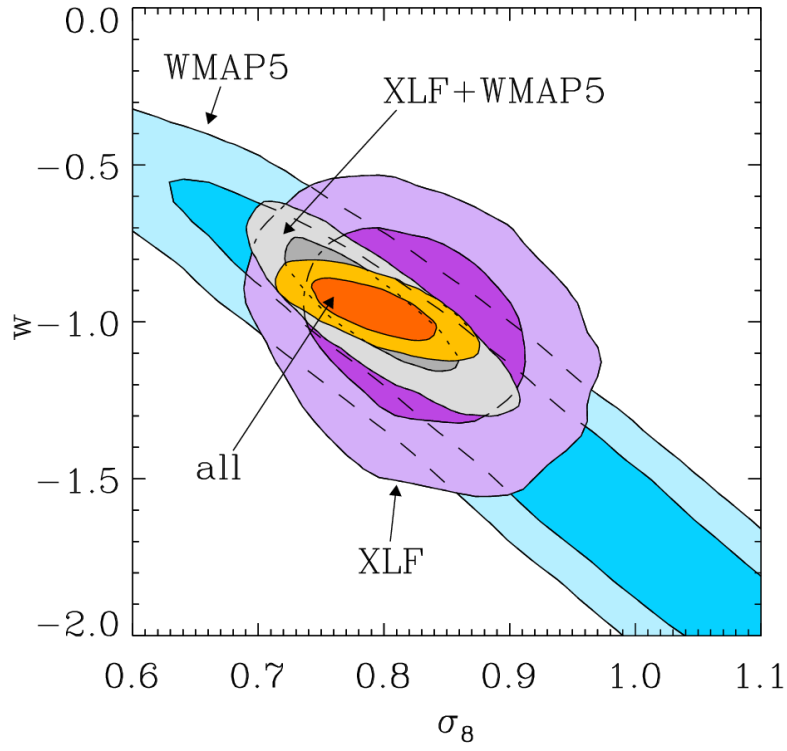

XLF+WMAP5+SNIa+$f_{\rm gas}$+BAO

$$\begin{aligned} \Omega_{\rm m} &= 0.272 \pm 0.016 \\ \sigma_8 &= 0.79 \pm 0.03 \\ w &= -0.96 \pm 0.06 \end{aligned}$$

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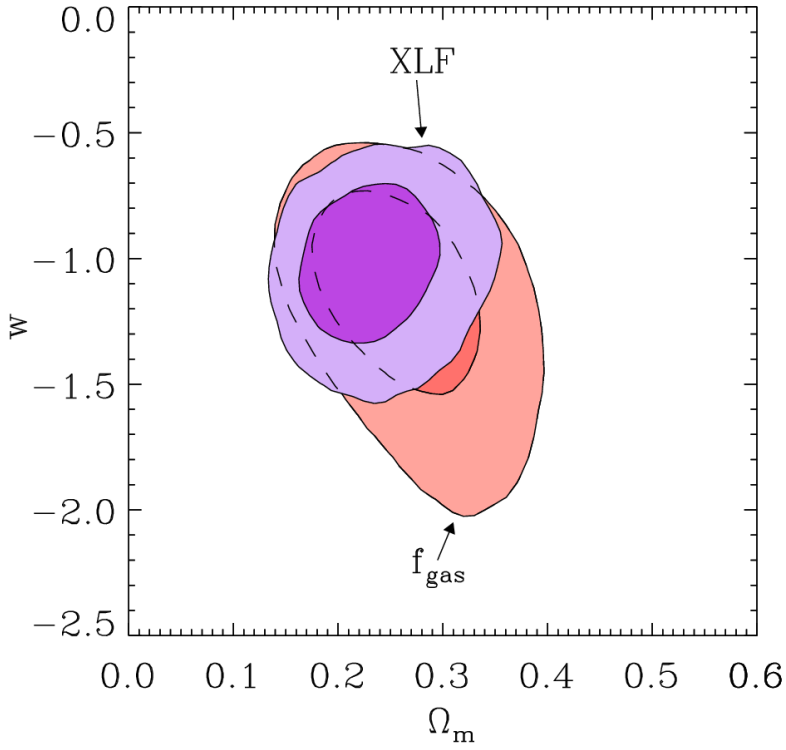

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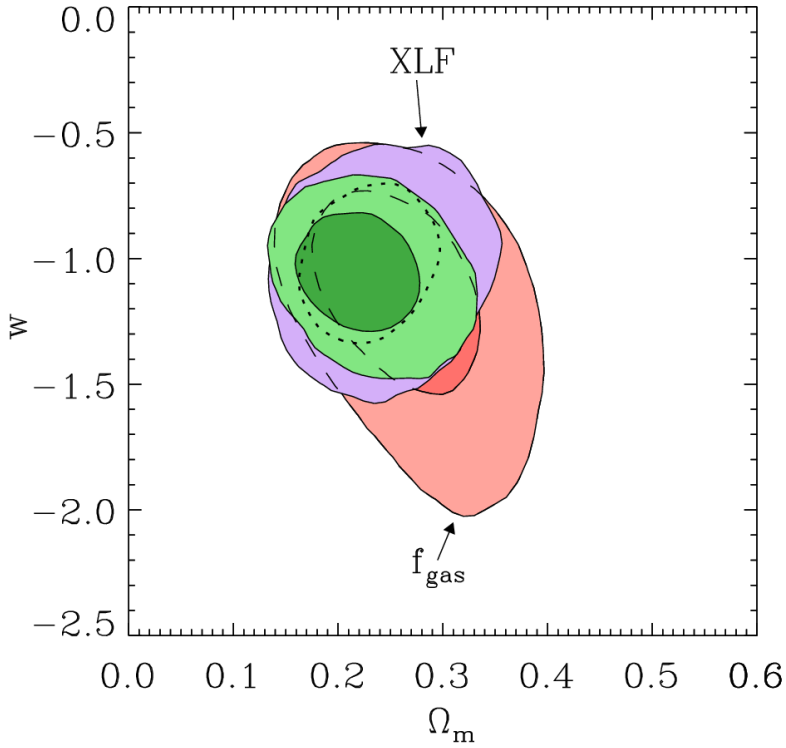

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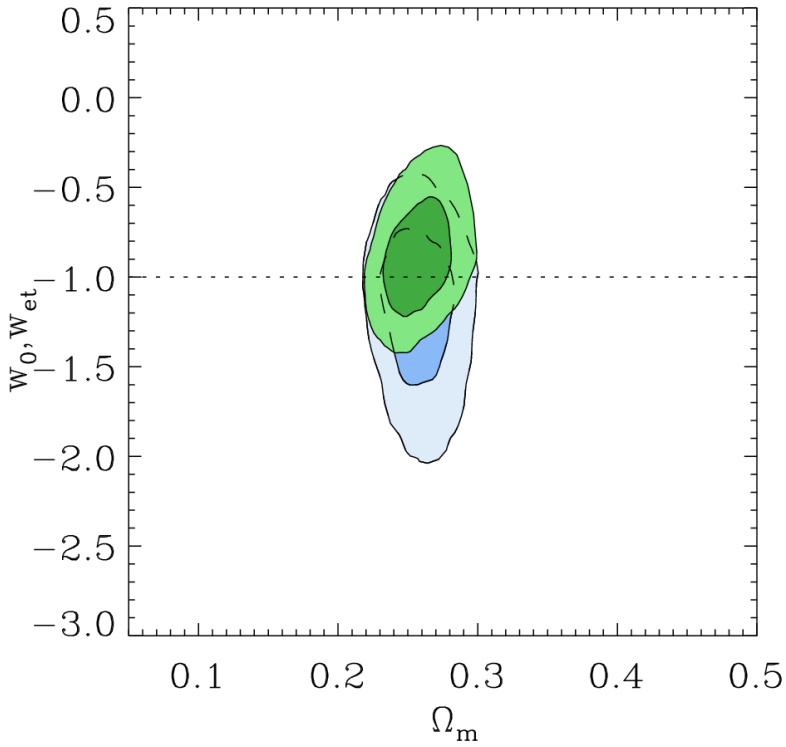

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$$w(z) = \frac{w_0 z_t + w_{et} z}{z_t + z}$$

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XLF+WMAP5+SNIa+f_{gas}+BAO:

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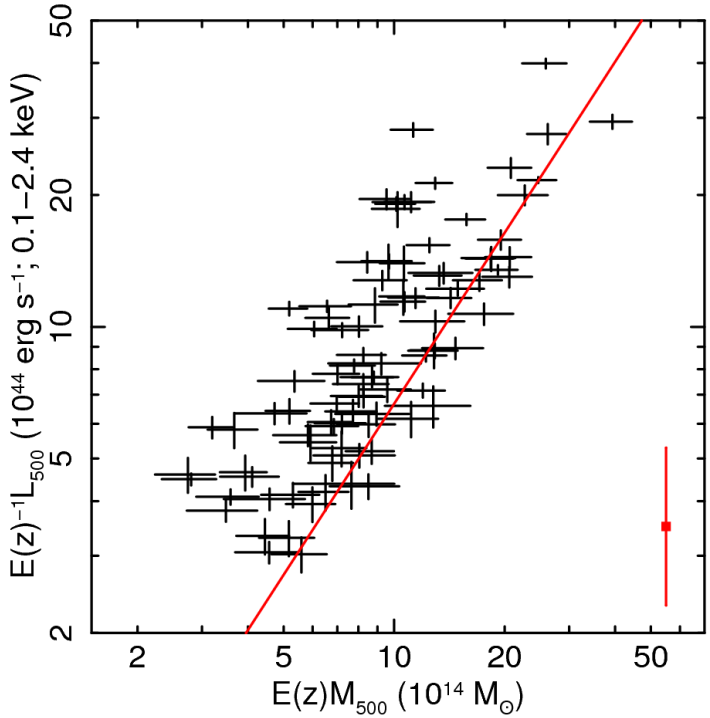
Current data are still consistent with the simple ΛCDM picture.

The core-excised mass–luminosity relation



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Exclude the central $0.15 r_{500}$ from L ...

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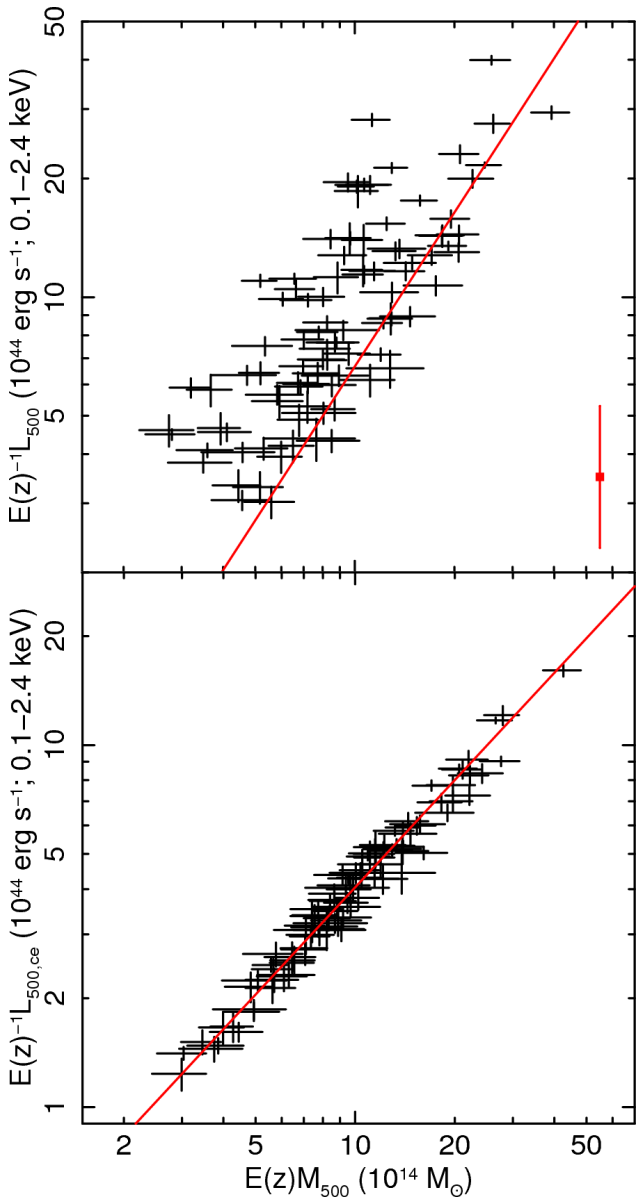

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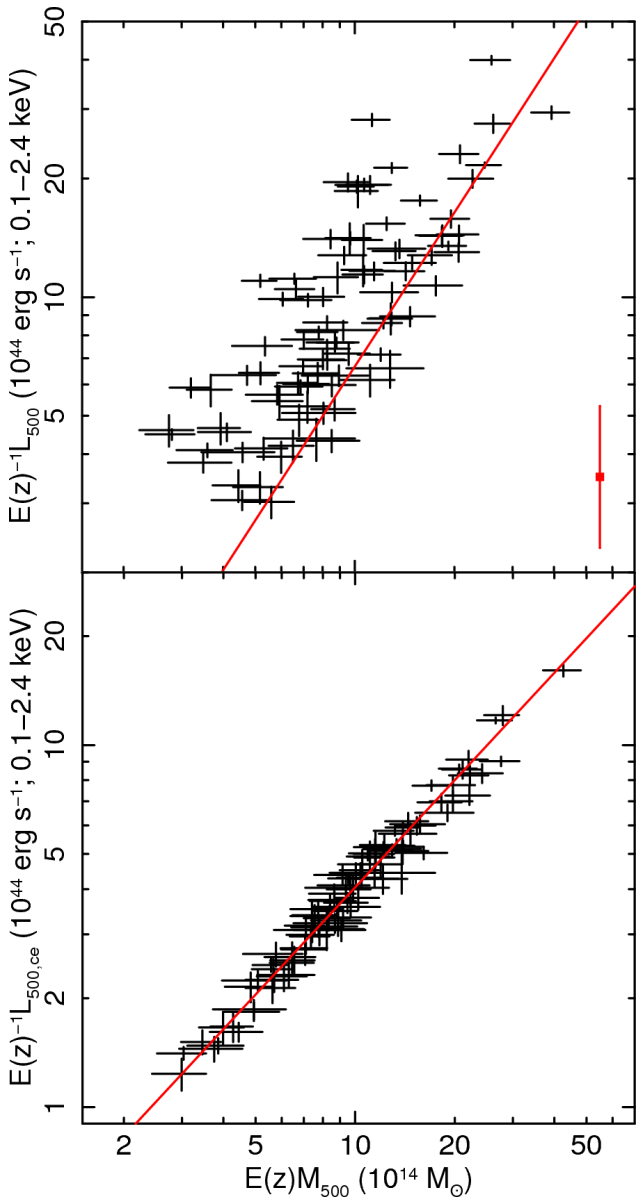

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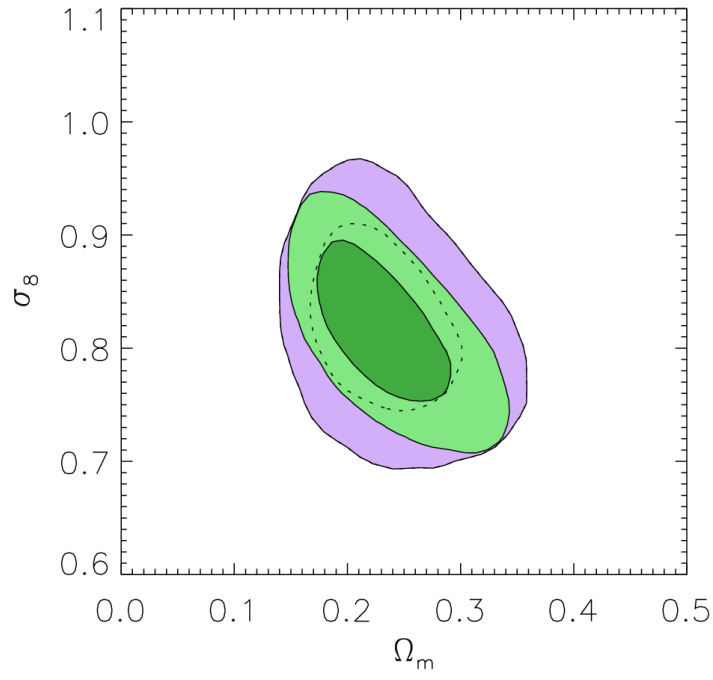
Suggests that

- excess heating limited to centers
- gas outside centers is simpler
- an X-ray survey could produce an effectively mass-limited cluster sample! (given enough resolution)

But wait, there's more!

Stay put to hear about multiwavelength/lensing data for our clusters . . .


1.1
1.0
0.9
0.8
0.7
0.6
σ_8
0.0
0.1
0.2
0.3
0.4
0.5
Ω_m

Testing general relativity with the growth of structure

Parametrize the growth through

$$\frac{d\delta}{da} = \frac{\delta}{a}\Omega_{\rm m}(a)^{\gamma}$$

with $\gamma \sim 0.55$ corresponding to GR.

Constraints on γ test the time dependence of the growth at large scales and late times.

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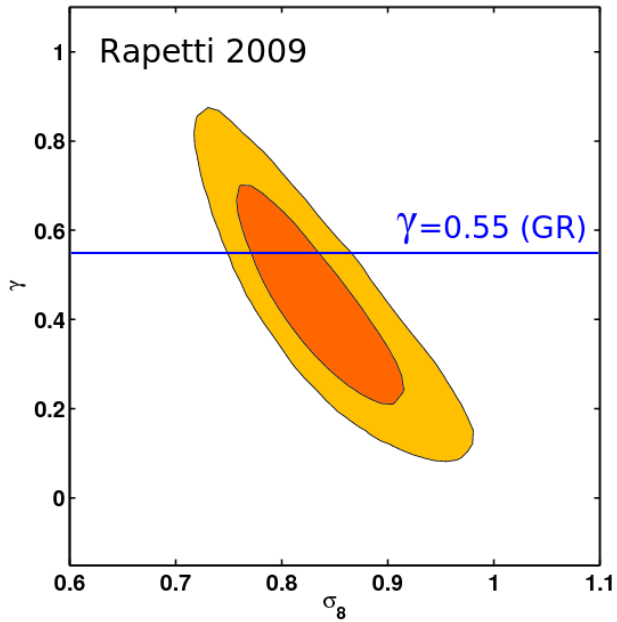
submitted



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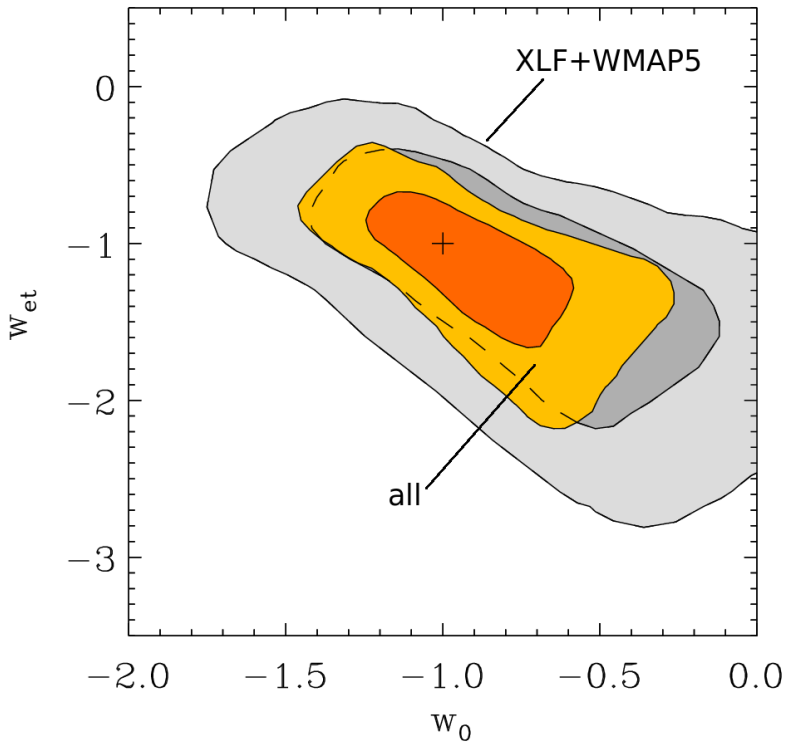

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