Constraining dark energy and modified gravity with galaxy clusters

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Full cosmological analysis in this series of papers

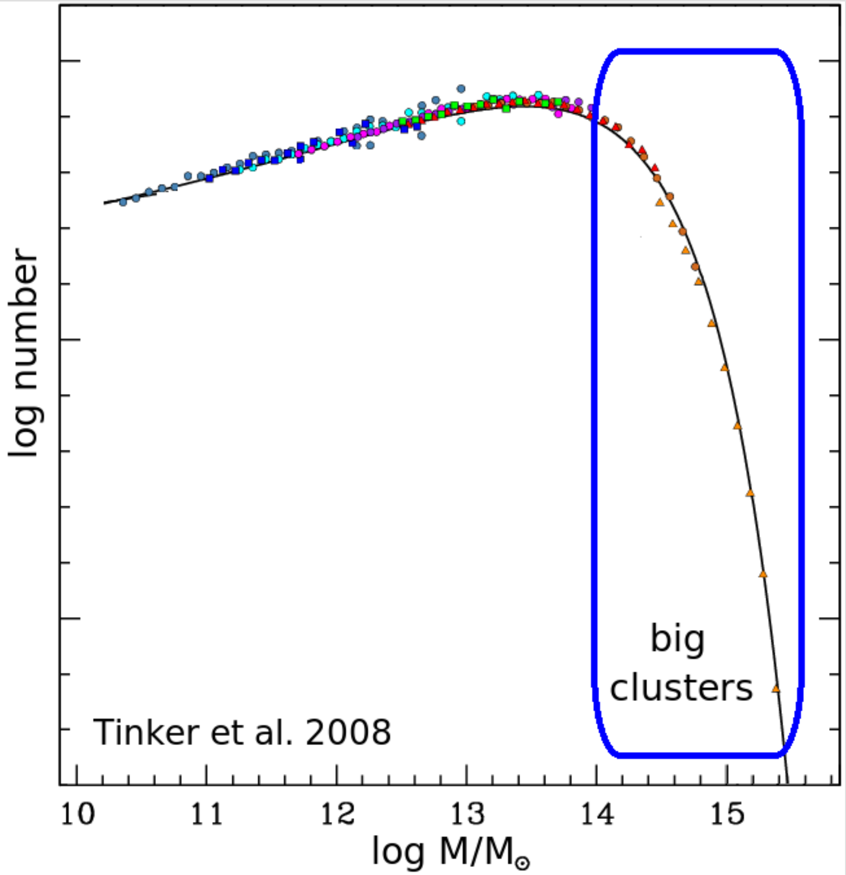
"The Observed Growth of Massive Galaxy Clusters I: Statistical Methods and Cosmological Constraints",
MNRAS 406, 1759, 2010
Adam Mantz, Steven Allen, David Rapetti, Harald Ebeling

"The Observed Growth of Massive Galaxy Clusters II: X-ray Scaling Relations",
MNRAS 406, 1773, 2010
Adam Mantz, Steven Allen, Harald Ebeling, David Rapetti, Alex Drlica-Wagner

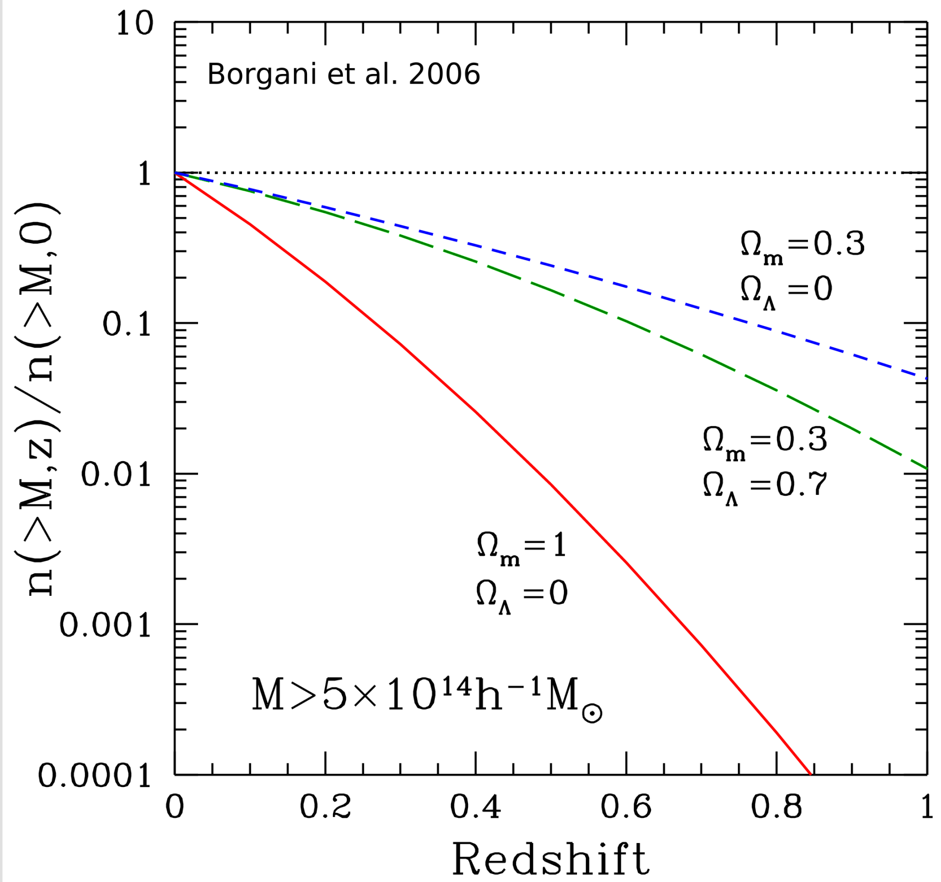
"The Observed Growth of Massive Galaxy Clusters III: Testing General Relativity at Cosmological Scales",
MNRAS 406, 1796, 2010
David Rapetti, Steven Allen, Adam Mantz, Harald Ebeling
(Chandra/NASA press release together with Schmidt, Vikhlinin & Hu 09,
April 14 2010, "Einstein's Theory Fights off Challengers")

"The Observed Growth of Massive Galaxy Clusters IV: Robust Constraints on Neutrino Properties",
MNRAS 406, 1805, 2010
Adam Mantz, Steven Allen, David Rapetti

Cluster abundance as a function of mass and redshift

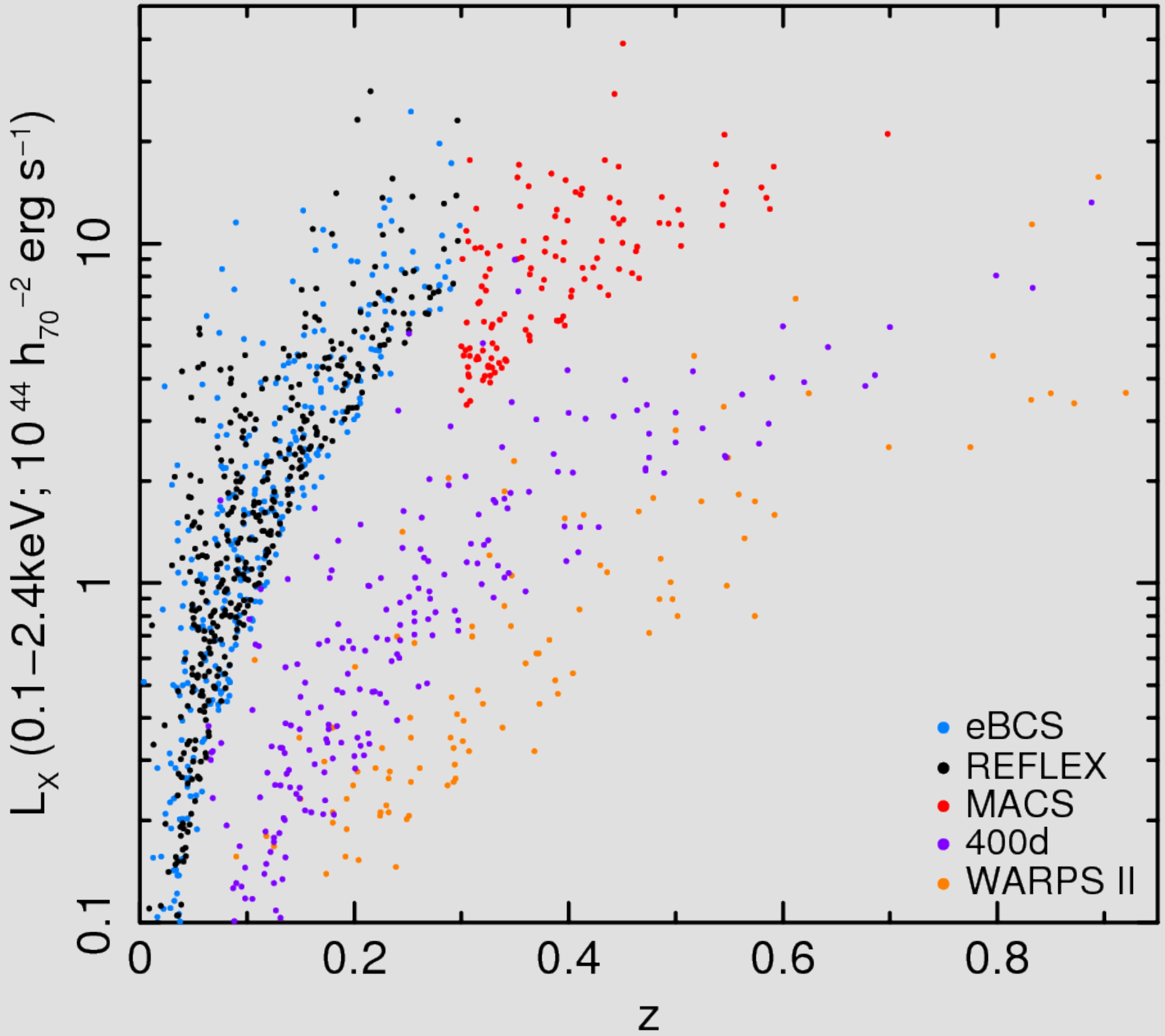


N-body simulations

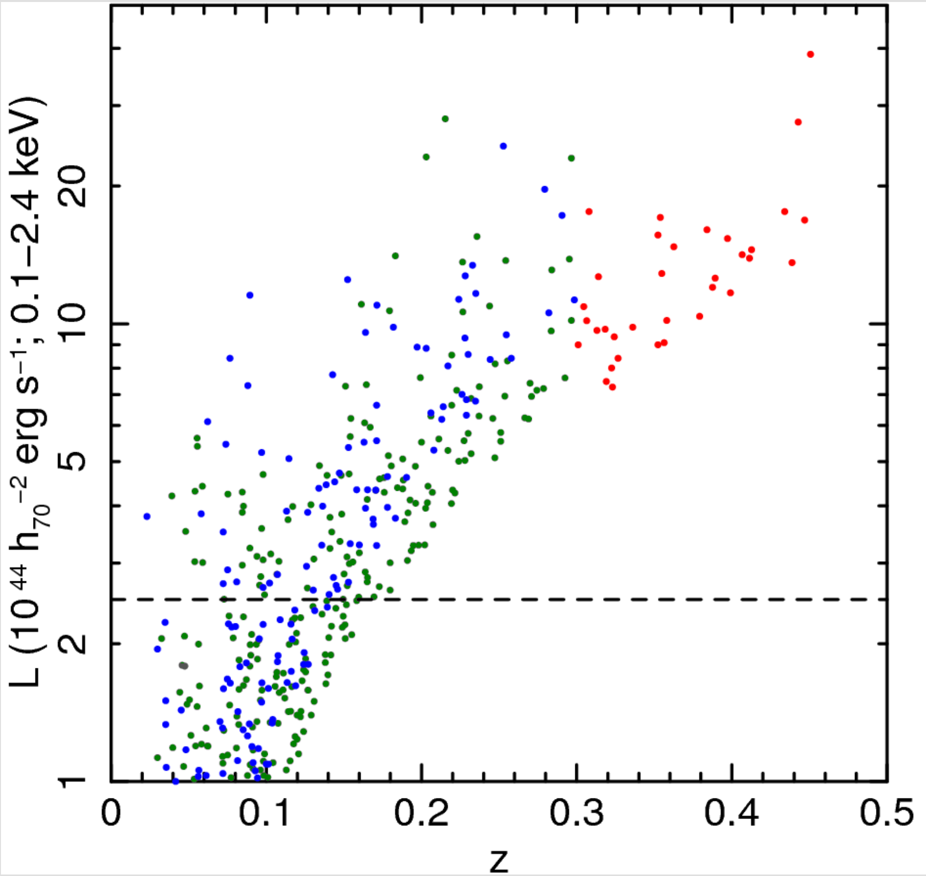


Linear theory

Cluster surveys



Cluster survey data



$L > 2.55\times10^{44}\ h_{70}^{-2}$ erg s^{-1} (dashed line).
Cuts leave 78+126+34=238 massive clusters

Low redshift (z<0.3)

- BCS (Ebeling et al 98, 00)
  F > 4.4 x 10^{-12} erg s^{-1} cm^{-2}
  ~33% sky coverage
- REFLEX (Böhringer et al 04)
  F > 3.0 x 10^{-12} erg s^{-1} cm^{-2}
  ~33% sky coverage

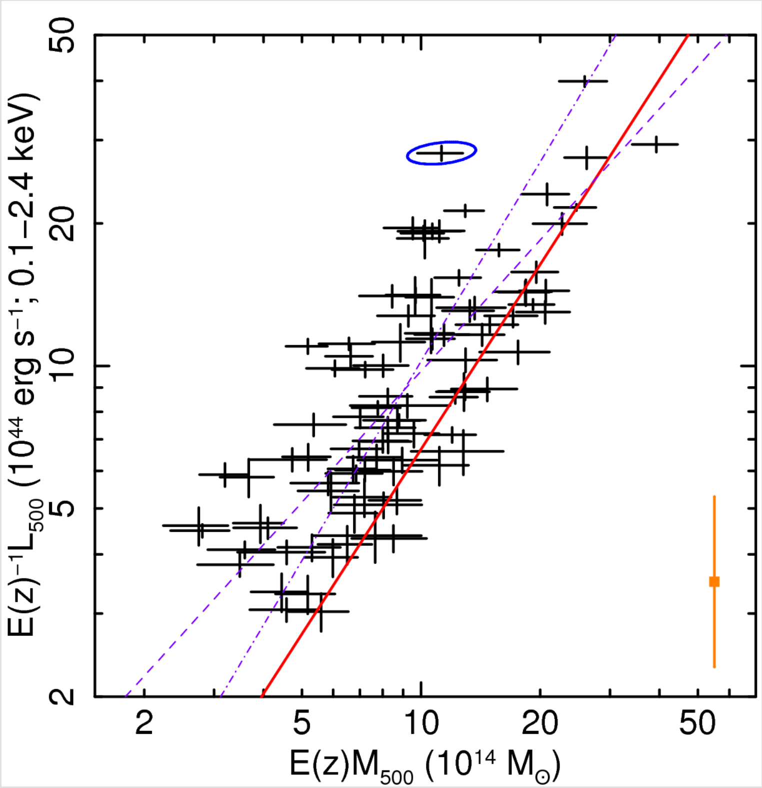
Intermediate redshifts (0.3<z<0.5)

- Bright MACS (Ebeling et al 01, 10)
  F > 2.0 x 10^{-12} erg s^{-1} cm^{-2}
  ~55% sky coverage

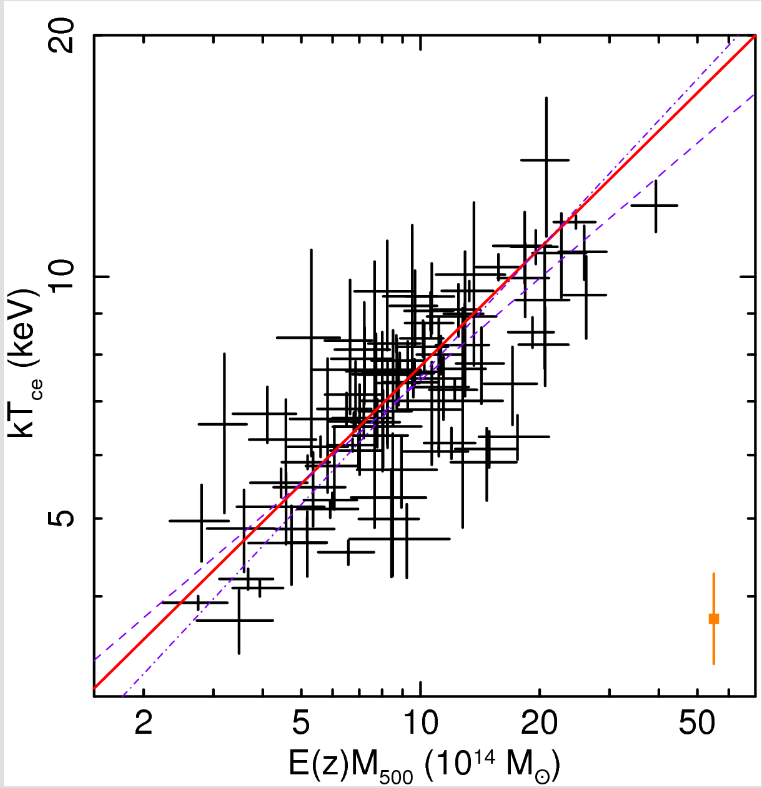
All based on RASS detections. Continuous and all 100% redshift complete.

Scaling relations data: X-ray follow-up for 94 clusters

Mantz et al 10b



Best fit for all the data (survey+follow-up+other data).

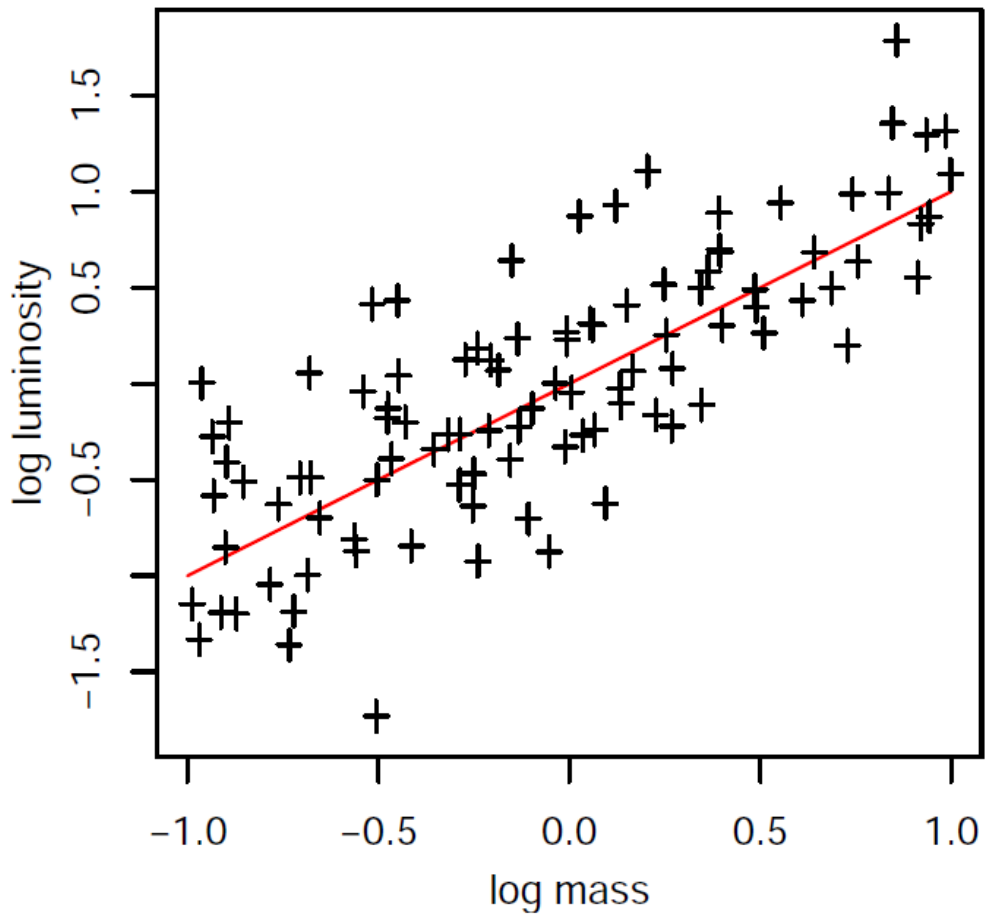


Both, power law, self-similar, constant log-normal scatter.

* Crucial: self-consistent and simultaneous analysis of survey+follow-up data, accounting for selection biases, degeneracies, covariances, and systematic uncertainties.
* Data does not require additional evolution beyond self-similar (see tests in Mantz et al 10b).
* Important cluster astrophysics conclusions (see Mantz et al 10b).

Luminosity-mass scaling relation: selection biases

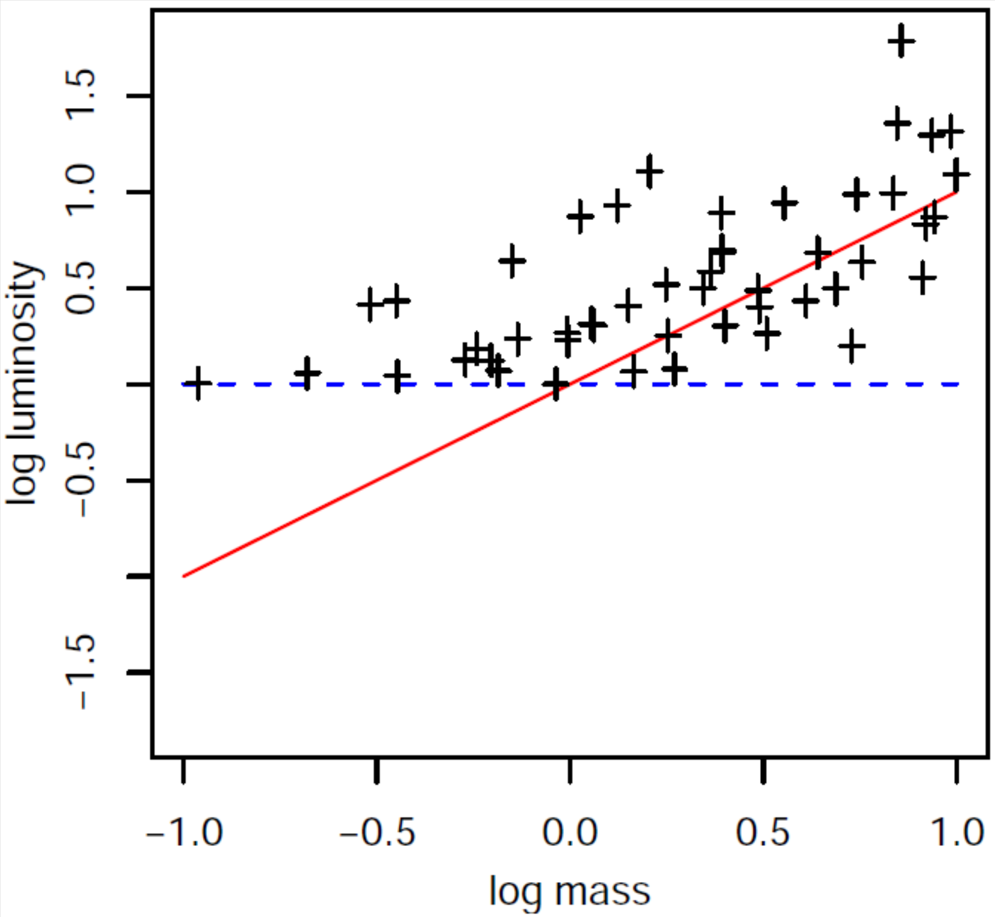
Mantz et al 10b



For illustration purposes: Uniform distribution of simulated data and fictitious luminosity-mass relation (red line).

Luminosity-mass scaling relation: selection biases

Mantz et al 10b



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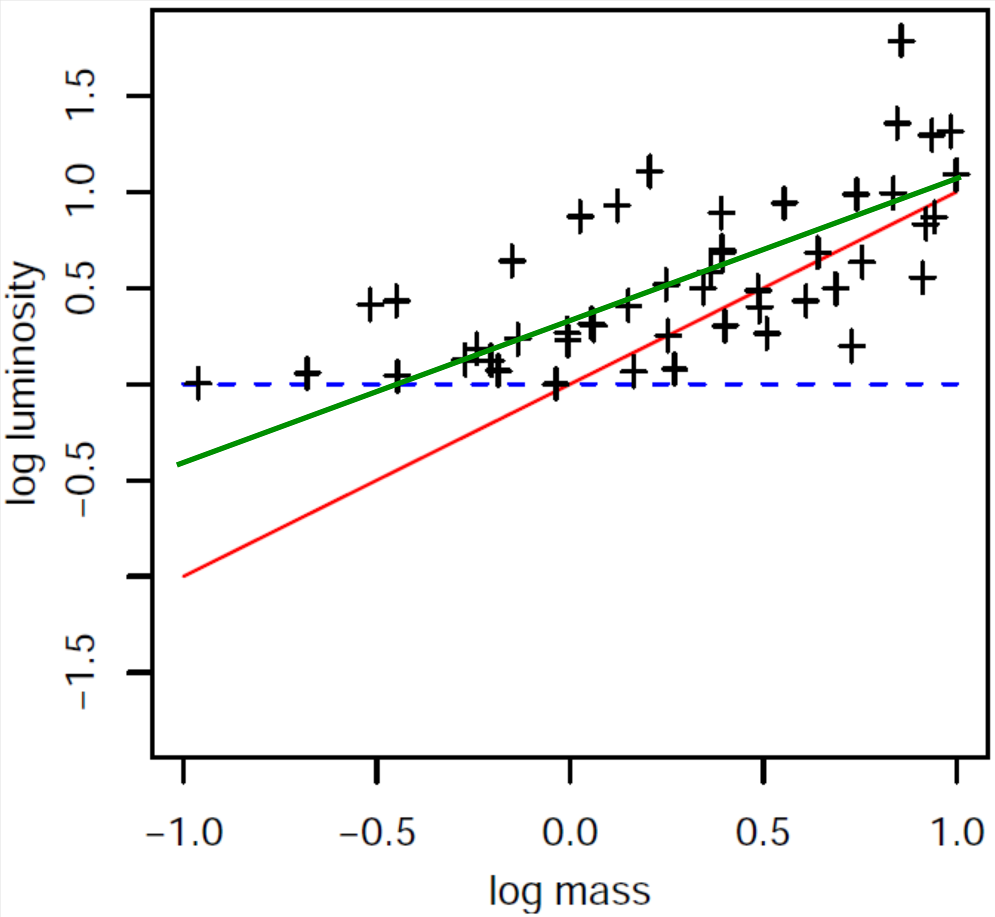
* The luminosity-mass relation has intrinsic scatter (~40%), which leads to Malmquist bias: brighter cluster are easier to find.

Luminosity-mass scaling relation: selection biases



For illustration purposes: Uniform distribution of simulated data and fictitious luminosity-mass relation (red line).

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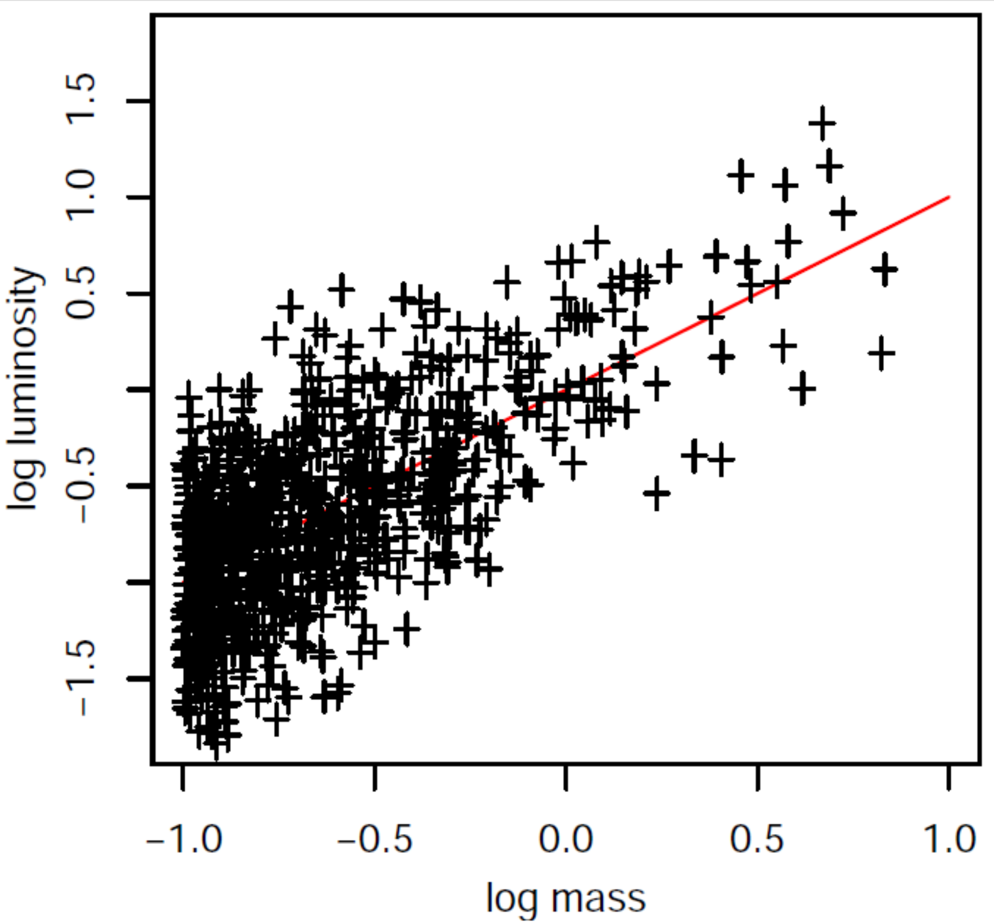
* For illustration purposes: fitting (by eye, green line) these data alone is clearly wrong.

Luminosity-mass scaling relation: selection biases

Mantz et al 10b



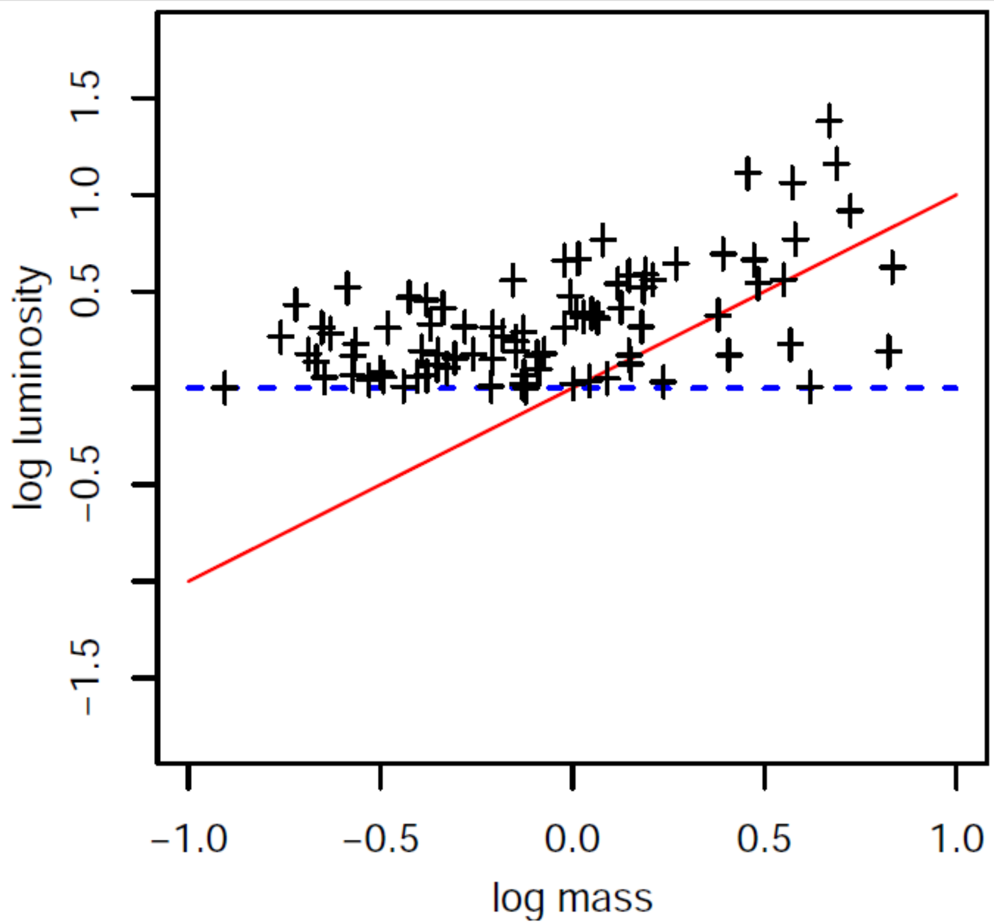
For illustration purposes: Exponential distribution of simulated data and fictitious luminosity-mass relation (red line).

* The luminosity-mass relation has intrinsic scatter (~40%), which leads to Malmquist bias: brighter cluster are easier to find.

* The shape of the mass function leads to Eddington bias: much more low-mass clusters

Luminosity-mass scaling relation: selection biases

Mantz et al 10b



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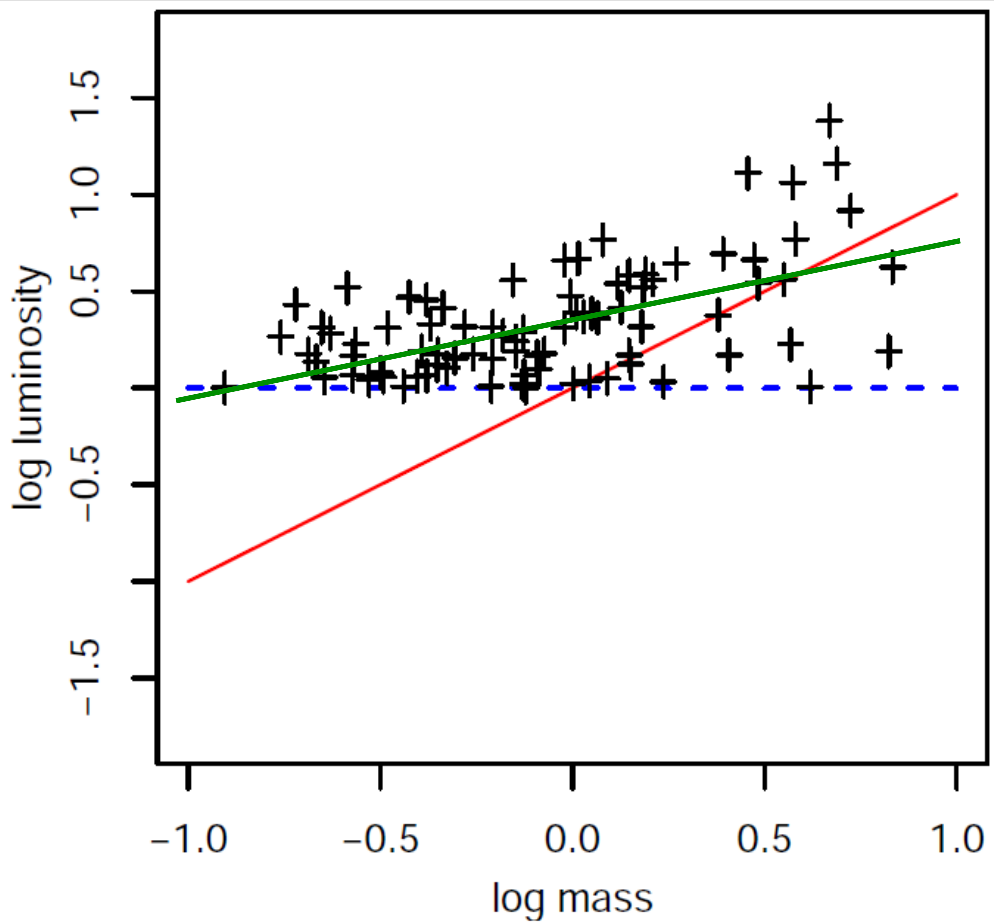

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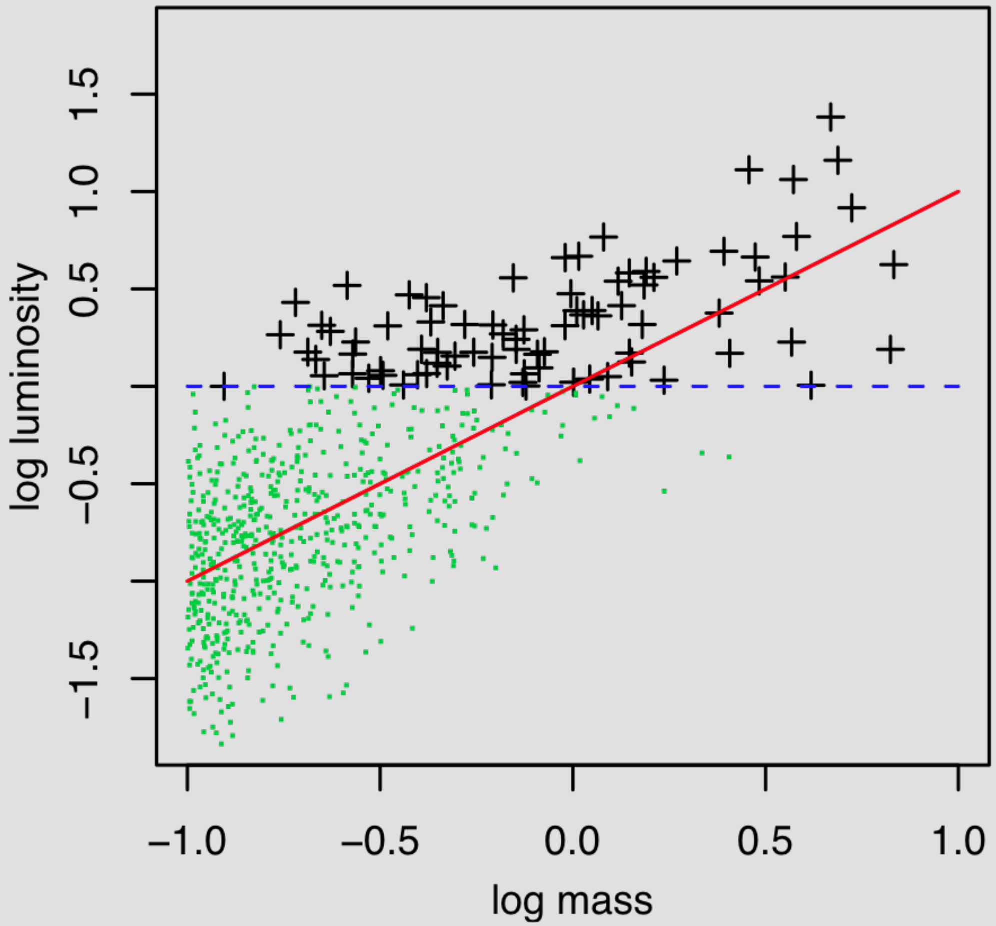
Luminosity-mass scaling relation: selection biases

Allen, Evrard, Mantz 11



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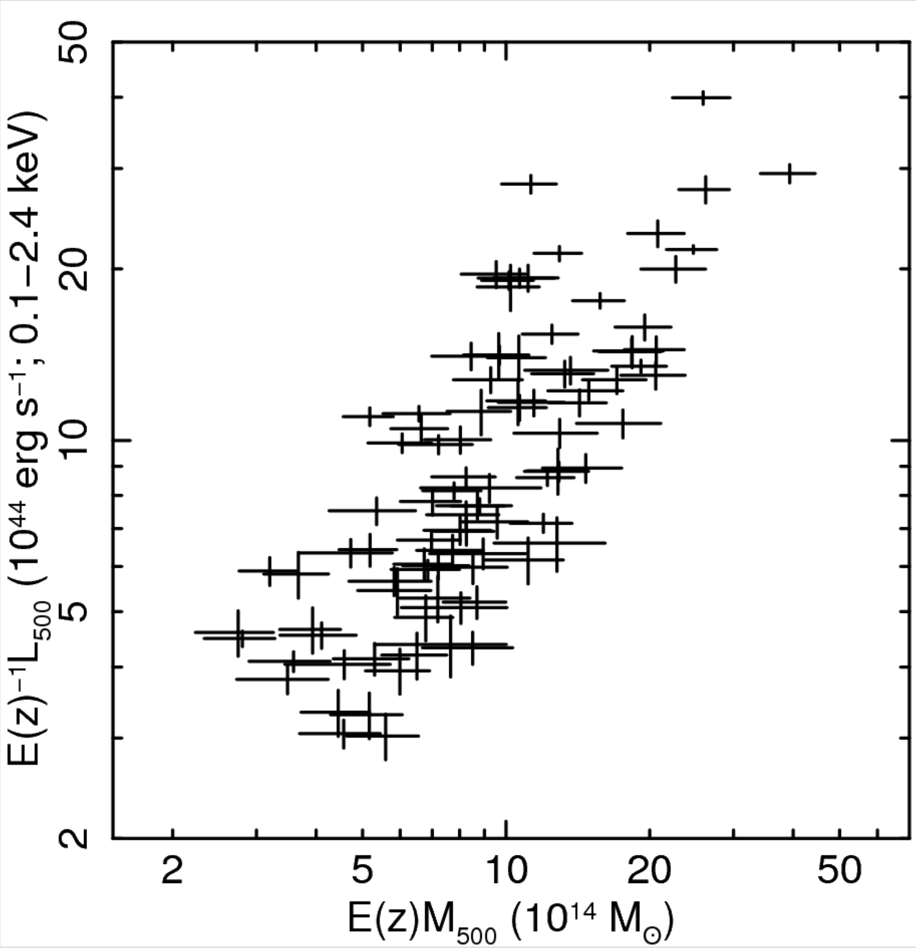
X-ray luminosity-mass relation



Fitted with simple power law model, self-similar evolution and constant log-normal scatter σ_{lm}

$$\langle l(m) \rangle = \beta_0^{lm} + \beta_1^{lm} m$$

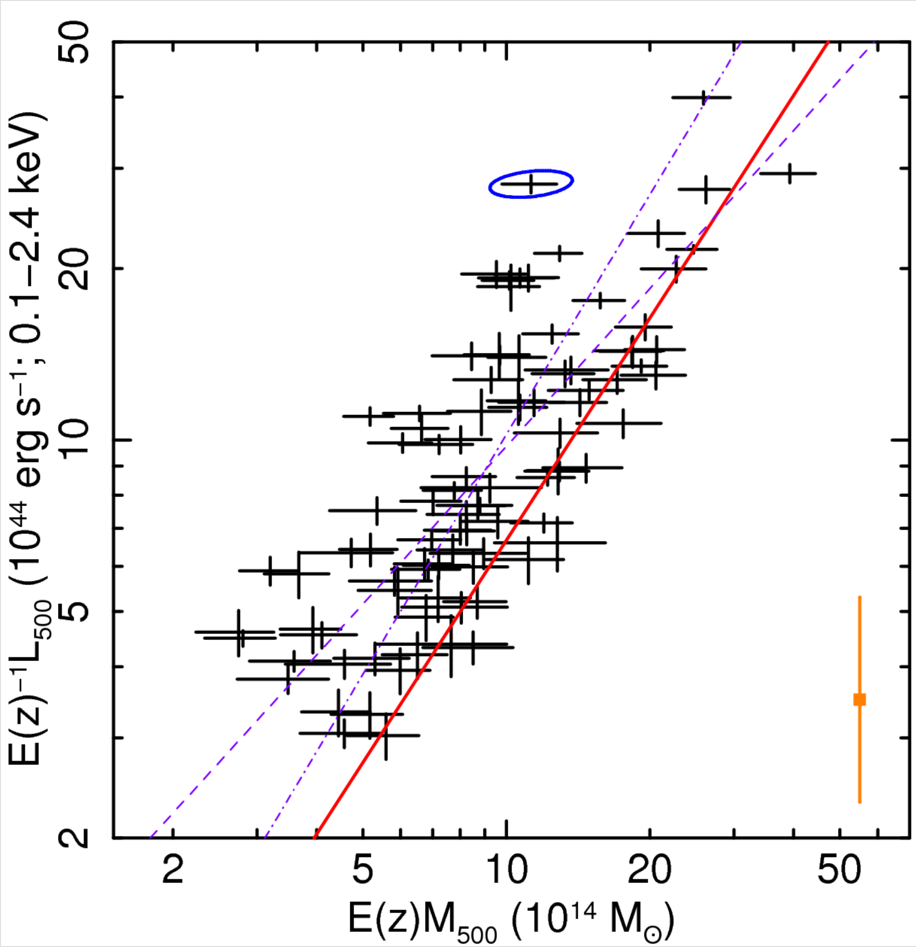
Using the definitions

$$l = \log_{10}\left(\frac{L_{500}}{E(z)10^{44}\, erg\, s^{-1}}\right)$$

$$m = \log_{10}\left(\frac{M_{500}E(z)}{10^{15}\, M_{solar}}\right)$$

Current data do not require (i.e. acceptable fit) neither additional evolution beyond self-similar and constant scatter or asymmetric scatter (see details in Mantz et al 10b).

X-ray luminosity-mass relation



For bolometric luminosities, the best fit using all the data (survey+follow-up+other cosmological data sets):

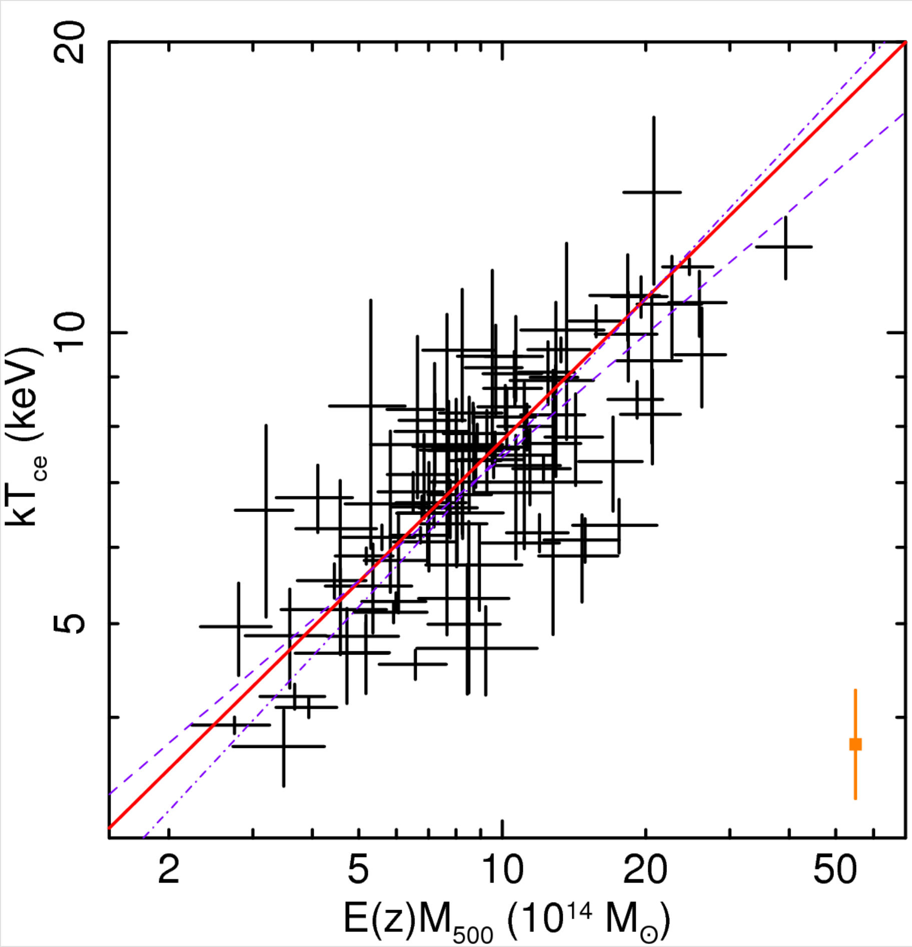
norm.	$\beta_0^{lm} = 1.23 \pm 0.12$
slope	$\beta_1^{lm} = 1.63 \pm 0.06$
scatter	$\sigma_{lm} = 0.185 \pm 0.019\ (\sim 40\%)$

Slope steeper than the simple virial prediction: $\beta_1^{lm} = 1.33$

Consistent with excess heating

Energy injection heats (e.g. AGN) the gas raising the temperature, decreasing the density and therefore the luminosity, being more important for less massive systems.

Temperature-mass relation



Again, simple power law, self-similar, constant log-normal scatter. Best fit for all the data:

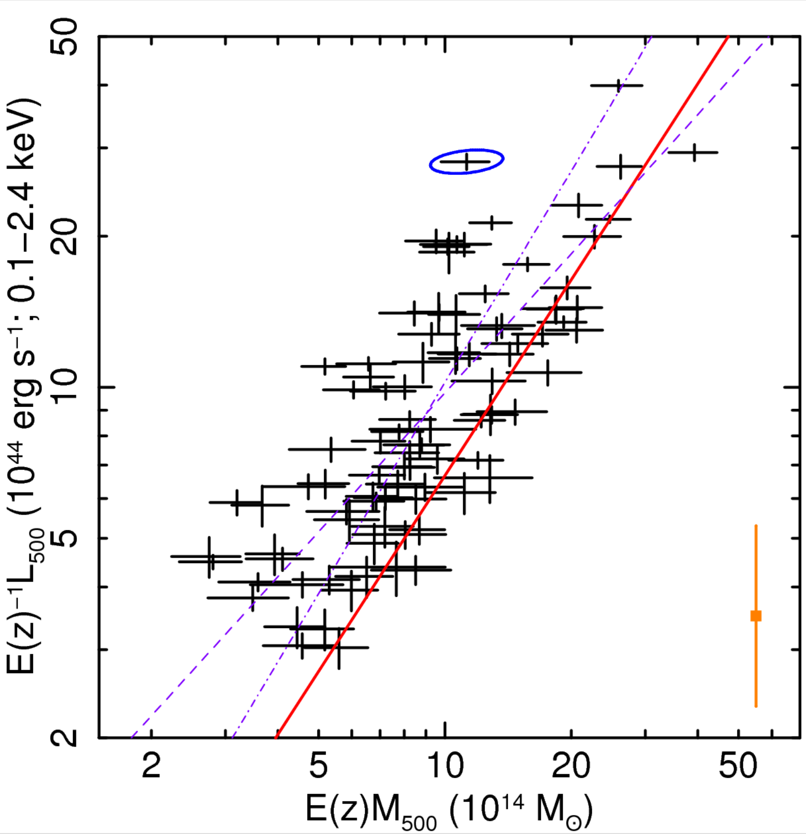
norm.	$\beta_0^{tm} = 0.89 \pm 0.03$
slope	$\beta_1^{tm} = 0.49 \pm 0.04$
scatter	$\sigma_{tm} = 0.055 \pm 0.008\ (\sim 15\%)$

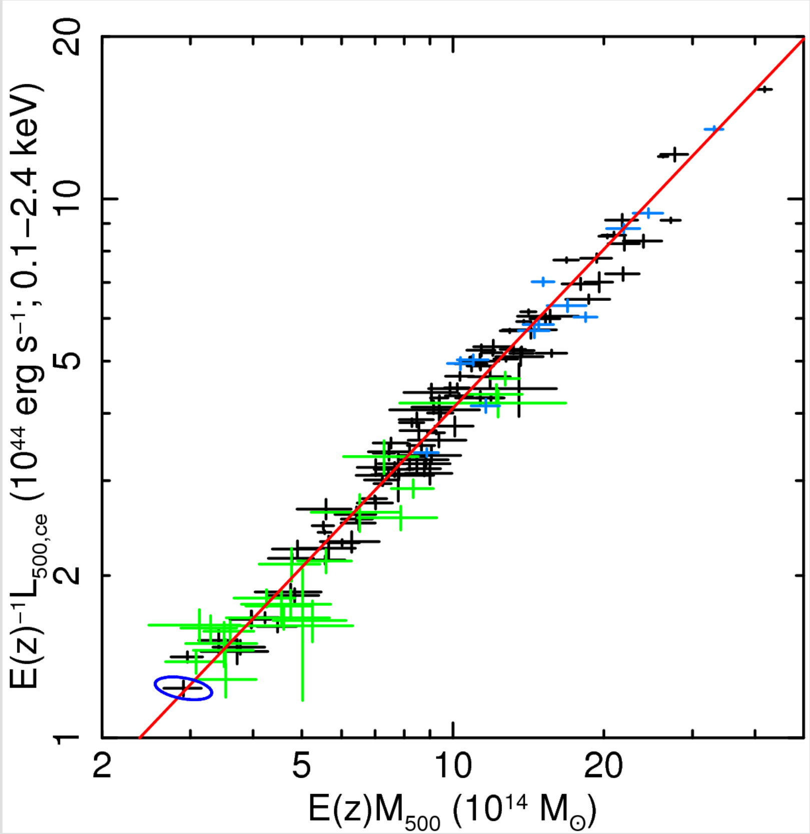
Slope shallower than the simple virial prediction: $\beta_1^{tm} = 0.67$

Consistent with excess heating

Energy injection heats (e.g. AGN) the gas raising the temperature, decreasing the density and therefore the luminosity, being more important for less massive systems.

X-ray luminosity-mass relation





Core-included: scatter ~40%

Data consistent with self-similar evolution suggesting that excess heating occurred at z>0.5

Core-excised $r<0.15r_{500}$.

Scatter undetected <5%.

$\beta_1^{lm} = 1.30 \pm 0.05$ Consistent with the virial th.

Excess heating limited to the centers / effective mass-limited cluster sample could be possible

Constraints on dark energy

All data sets

1. Abundance of massive clusters (X-ray Luminosity Function, XLF) to measure cosmic expansion and growth of matter fluctuations with respect to the mean density.

$$D(z) \equiv \frac{\delta(z)}{\delta(z_{\rm t})} = \frac{\sigma(M,z)}{\sigma(M,z_{\rm t})}$$

$$\delta = (\rho_{\rm m} - \bar{\rho}_{\rm m})/\bar{\rho}_{\rm m}$$

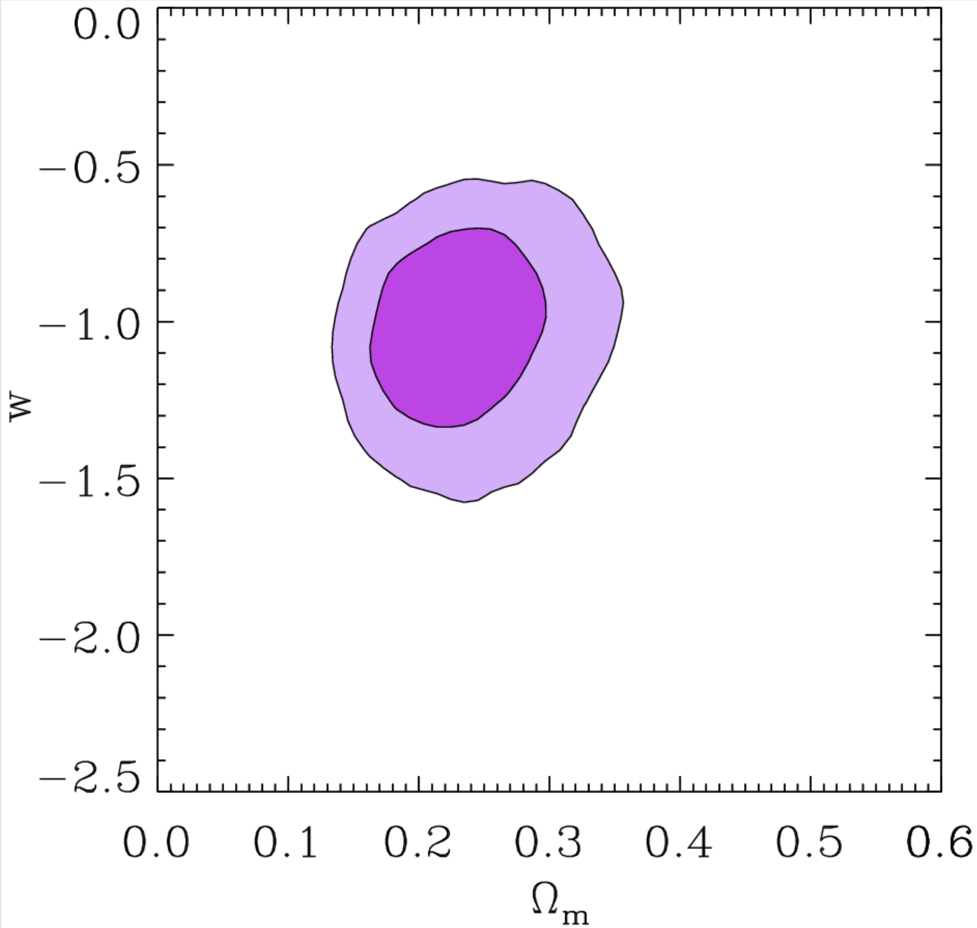
2. SNIa, f_{gas}, XLF, CMB, BAO to measure the cosmic expansion of the background density. We use three expansion histories well fitted by these data sets.

$$E(a) = \left[\Omega_{\rm m}\, a^{-3} + \Omega_{\rm de}\, a^{-3(1+w)} + \Omega_{\rm k}\, a^{-2}\right]^{1/2}$$

i) flat ΛCDM w=-1, Ω_k=0
ii) flat *w*CDM w constant, Ω_k=0
iii) non-flat ΛCDM w=-1, Ω_k constant

Dark Energy results: flat wCDM

Mantz et al 10a

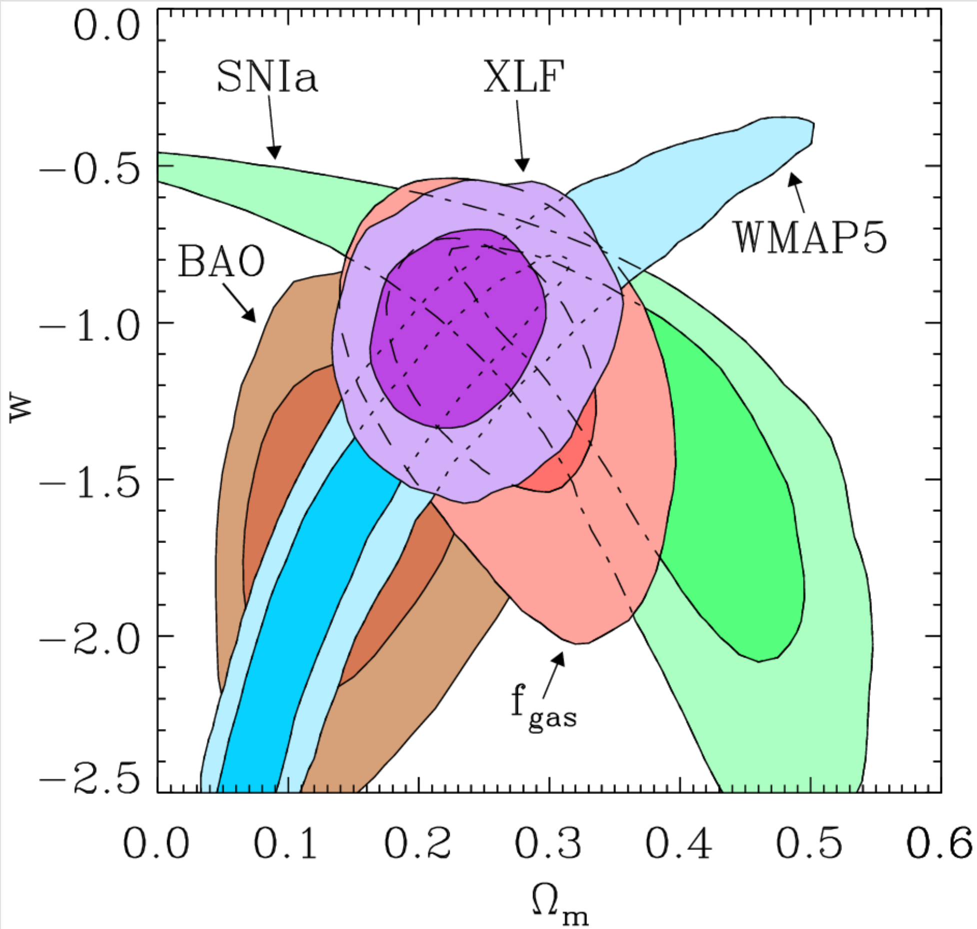


XLF(survey+follow-up data): BCS +REFLEX+MACS (z<0.5) 238 clusters (Mantz et al 10a). Including systematics.

Ω_m = 0.23 +- 0.04
σ_8 = 0.82 +- 0.05
w = -1.01 +- 0.20

Dark Energy results: flat wCDM

Mantz et al 10a



Green: SNIa (Kowalski et al 08, Union)

Blue: CMB (WMAP5)

Red: cluster f_{gas} (Allen et al 08)

Brown: BAO (Percival et al 07)

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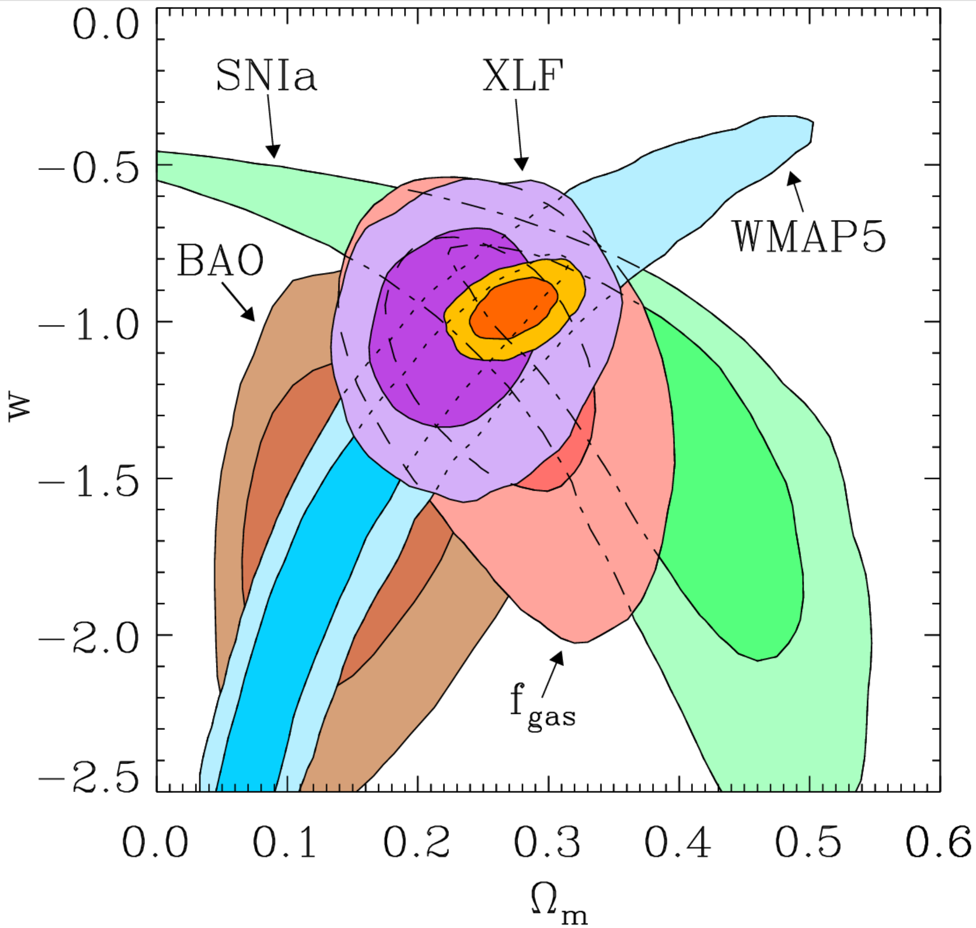

Good mass proxy at all z

Green: SNIa (Kowalski et al 08, Union)

Blue: CMB (WMAP5)

Red: cluster f_{gas} (Allen et al 08)

Brown: BAO (Percival et al 07)

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

XLF(survey+follow-up data): BCS +REFLEX+MACS (z<0.5) 238 clusters (Mantz et al 10a). Including systematics

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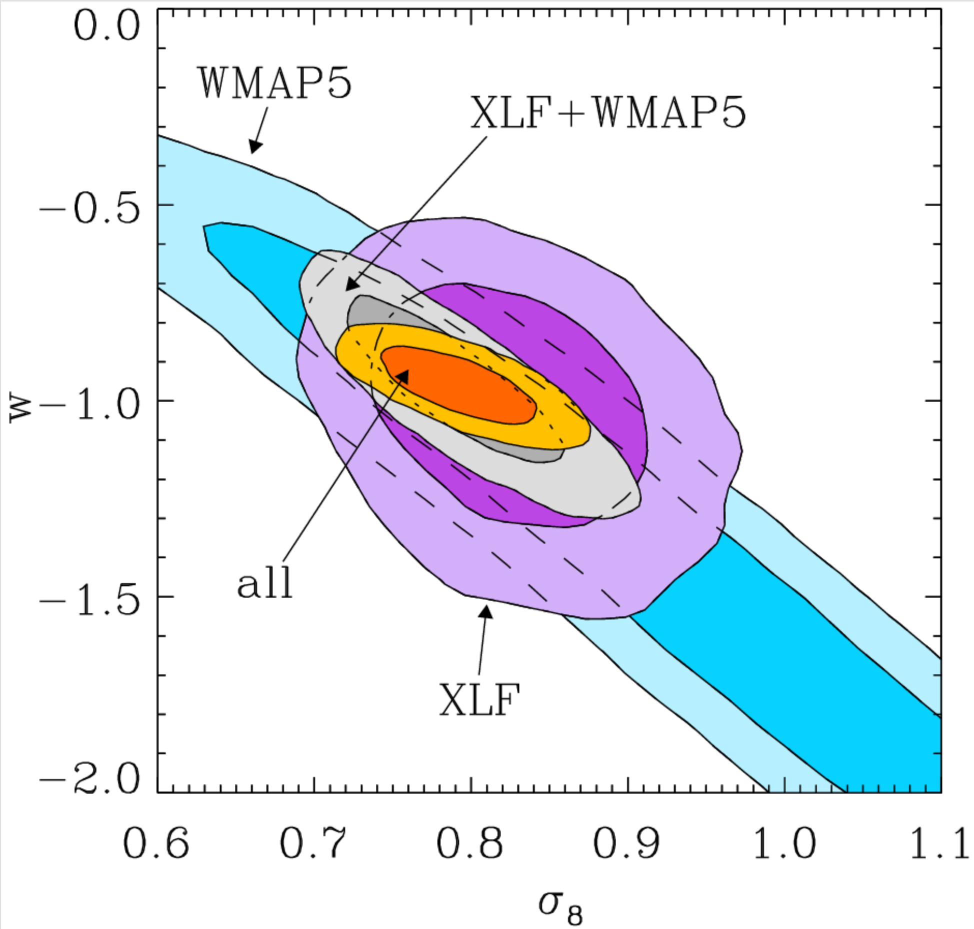
Dark Energy results: flat wCDM

Mantz et al 10a



Grey: XLF+WMAP5

Blue: CMB (WMAP5)

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

Ω_m = 0.272 +- 0.016
σ_8 = 0.79 +- 0.03
w = -0.96 +- 0.06

XLF(survey+follow-up data): BCS +REFLEX+MACS (z<0.5) 238 clusters (Mantz et al 10a). Including systematics

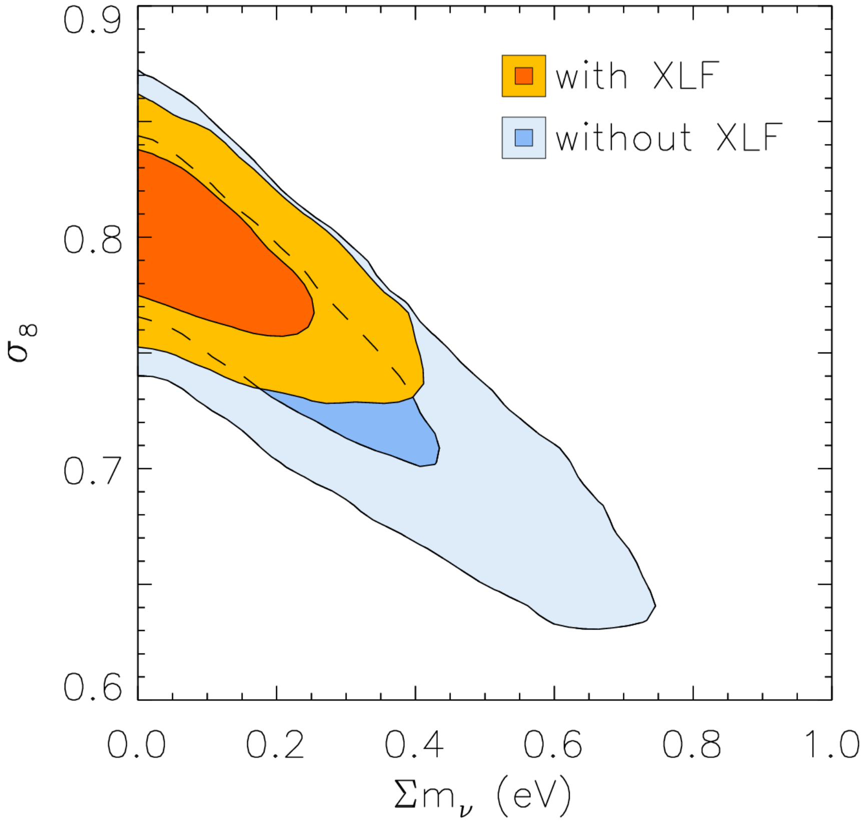
Ω_m = 0.23 +- 0.04
σ_8 = 0.82 +- 0.05
w = -1.01 +- 0.20

Constraints on neutrino properties

Robust constraints on neutrino properties

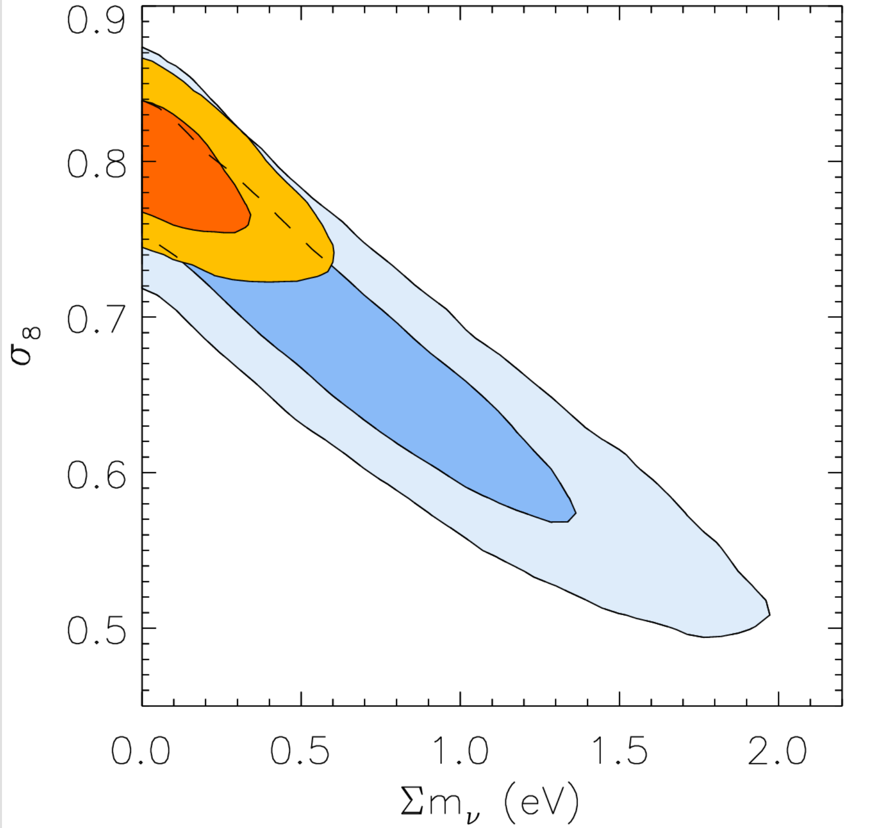
ΛCDM+Σm_ν: Breaking the degeneracy in the Σm_ν, σ_8 plane

Σm_ν<0.33eV (95.4%)



Even more useful when allowing N_{eff}, Ω_k, r, n_t (tensors) to be free

Σm_ν<0.7eV (95.4%) N_{eff}=3.7+-0.7 (68.3%)



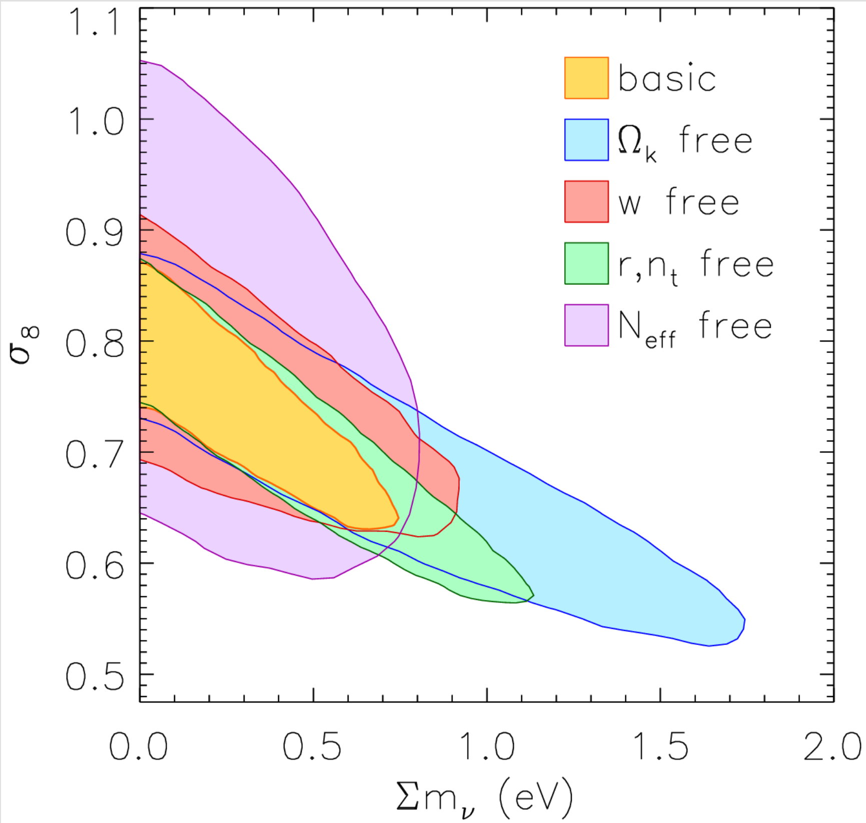
Note differences in scale between panels

Mantz et al 10c

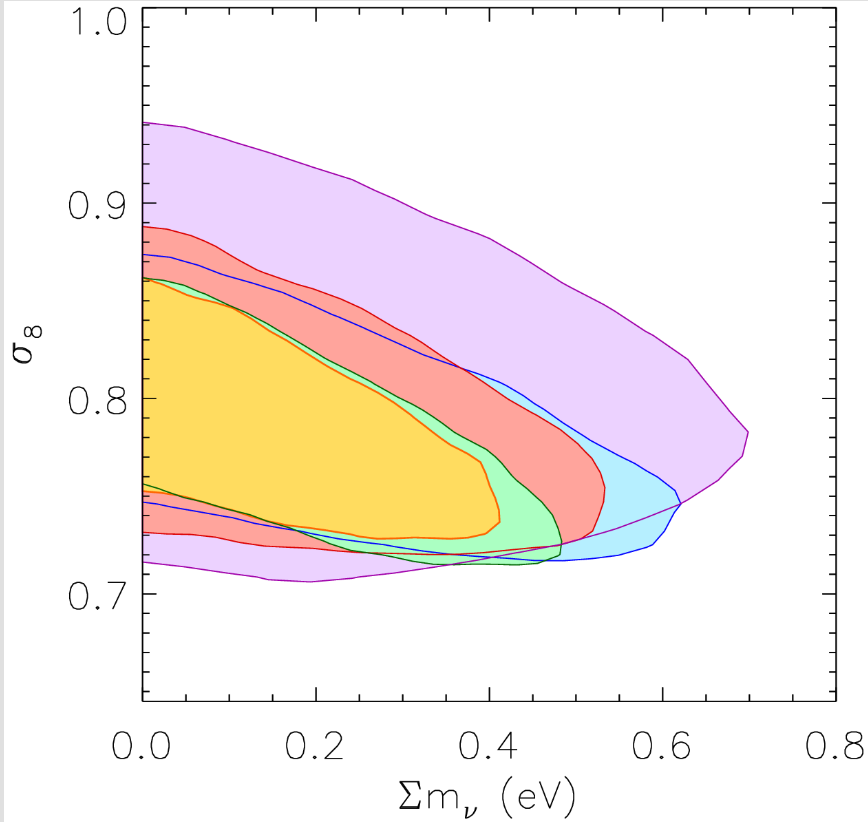
Robust constraints on neutrino properties

Basic: ΛCDM+Σm_ν

CMB+fgas+SNIa+BAO



CMB+fgas+SNIa+BAO+XLF



Mantz et al 10c

Testing gravity at large scales

Testing GR on cosmic scales

1. From the evolution of the cluster abundance (XLF) we directly measure linear cosmic expansion and growth.

2. From a variety of measurements we find cosmic acceleration and face the cosmological constant problems.

3. We can either include a new energy component, dark energy, or modify the theory of gravity.

4. We test General Relativity (GR) for consistency.

5. GR has been very well tested from small to Solar system scales. Here we test modifications of GR at cosmological scales.

Ingredients to test a given theory of gravity with cluster abundance data

1. Cosmic expansion model / mean matter density (theory).

2. Matter power spectrum / linear density perturbations (theory).

3. Halo mass function / nonlinear structure formation (N-body simulations for f(R) or DGP: e.g. Schmidt et al 2009, Schmidt 2009a/b, Chan & Scoccimarro 2009, Zhao, Li & Koyama 2011).

4. Relation between the observed mass (e.g. “dynamical”) and the true mass (e.g. “lensing”) (Theory/N-body simulations: Schmidt 2010a).

Consistency test of the growth rate of General Relativity

1. We use a phenomenological time-dependent parameterization of the growth rate and of the expansion history.

2. We assume the same scale-dependence as GR.

3. We test only for linear effects (not for non-linear effects). We use the "universal" dark matter halo mass function (Tinker et al 2008). Note that the relevant scales for the cluster abundance experiment are at the low end of the linear regime.

4. We match GR at early times and small scales.

Modeling linear, time-dependent departures from GR

$$n(M,z) = \int_0^M f(\sigma)\,\frac{\bar{\rho}_{\rm m}}{M'}\,\frac{d\ln\sigma^{-1}}{dM'}\,dM'$$

Number density of galaxy clusters

$$\sigma^2(M,z) = \frac{1}{2\pi^2}\int_0^\infty k^2 P(k,z)|W_M(k)|^2 dk$$

Variance of the density fluctuations

$$P(k,z) \propto k^{n_{\rm s}} T^2(k,z_{\rm t})\,D(z)^2$$

Linear power spectrum

General Relativity

$$\ddot{\delta} + 2\frac{\dot{a}}{a}\dot{\delta} = 4G\pi\bar{\rho_{\rm m}}\delta$$

Scale independent in the synchronous gauge

Phenomenological parameterization

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

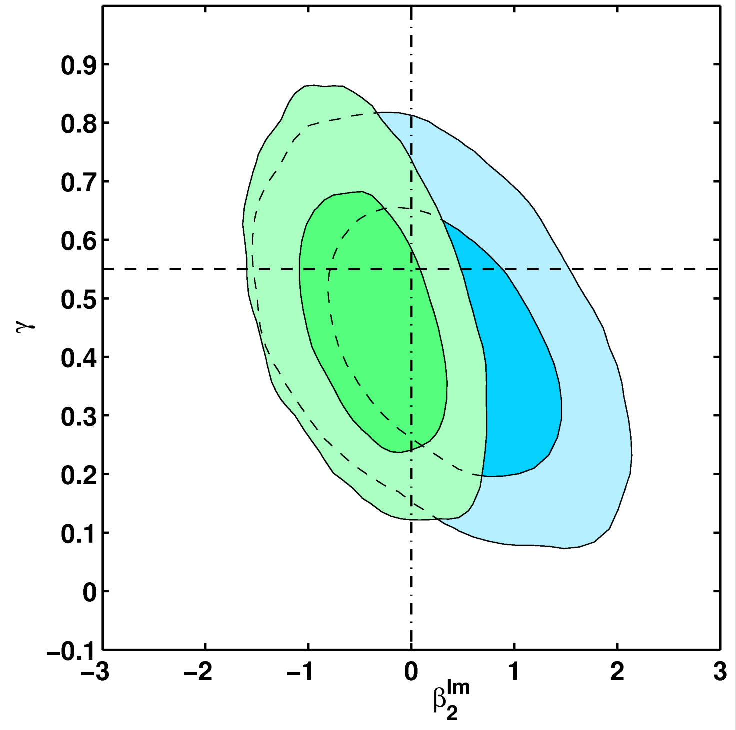
GR γ~0.55

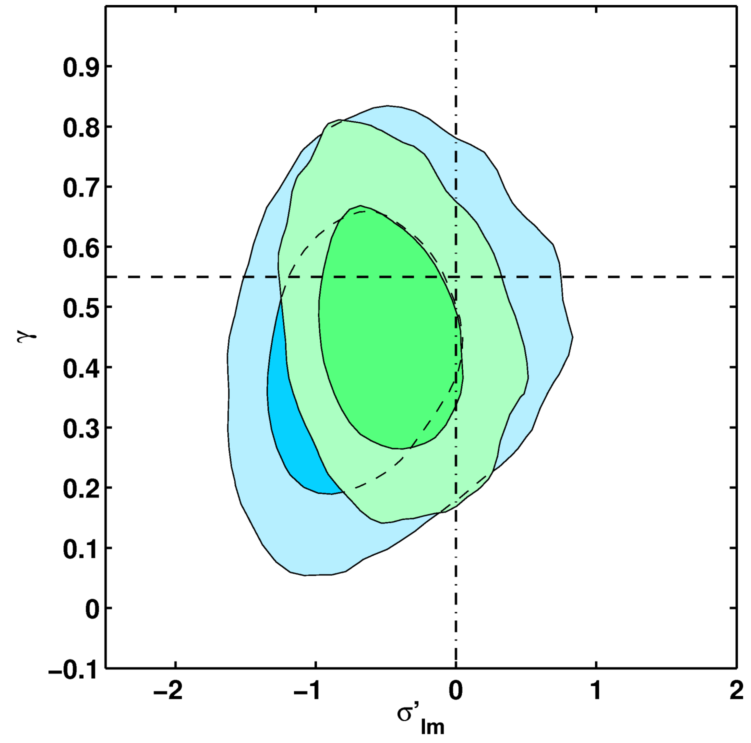
$$f(a) \equiv d\ln\delta/d\ln a = \Omega_{\rm m}(a)^\gamma$$

Growth rate

Test of GR robust w.r.t evolution in the l-m relation

Rapetti et al 10





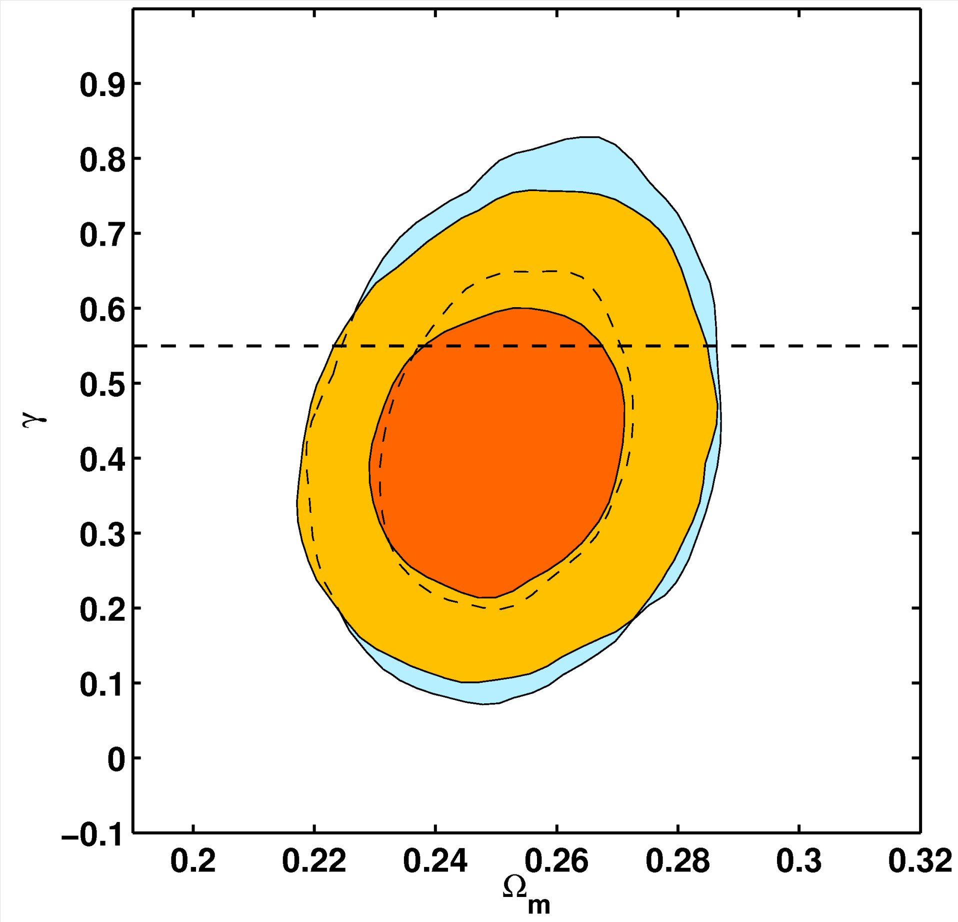
$$\langle l(m)\rangle = \beta_0^{lm} + \beta_1^{lm} m + \beta_2^{lm}\log_{10}(1+z)$$

$$\sigma_{lm}(z) = \sigma_{lm}(1 + \sigma'_{lm} z)$$

Current data do not require (i.e. acceptable fit) additional evolution beyond self-similar and constant scatter nor asymmetric scatter (Mantz et al 2010b).

flat ΛCDM + growth index γ

Rapetti et al 10



XLF: BCS+REFLEX+MACS (z<0.5)

238 survey with 94 X-ray follow-up

CMB (WMAP5)

SNIa (Kowalski et al 2008, UNION)

cluster f_{gas} (Allen et al 2008)

For General Relativity γ~0.55

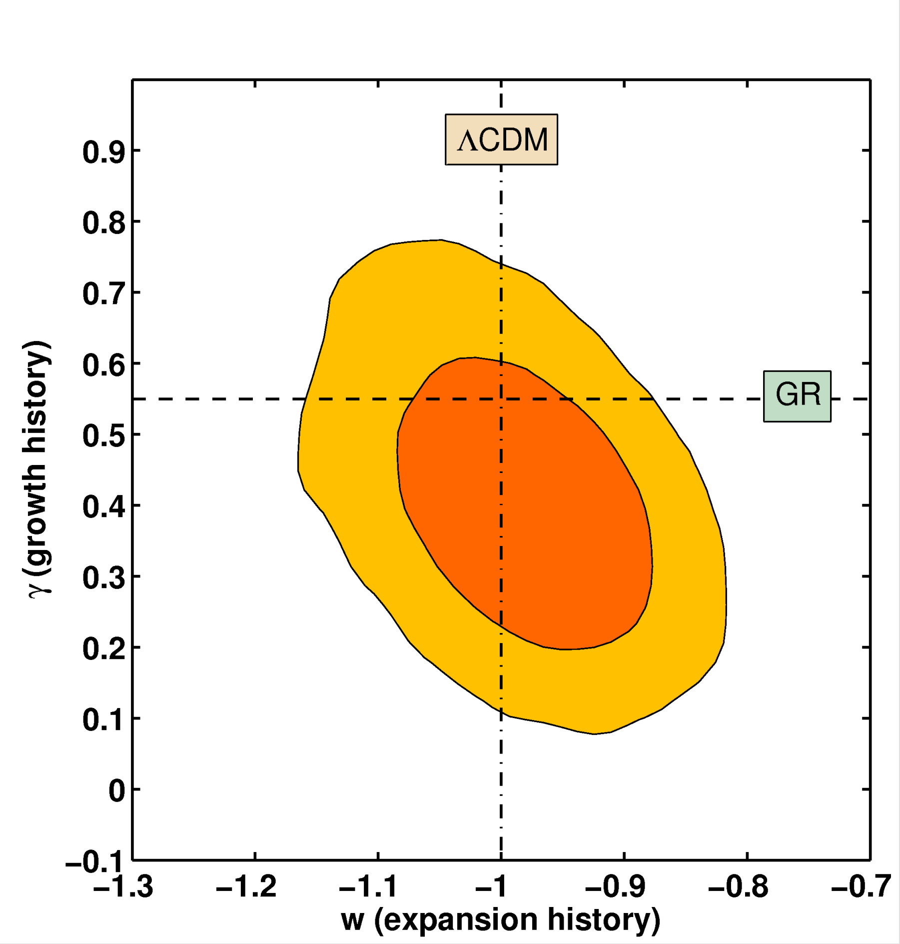
Gold: Self-similar evolution and constant scatter

Blue: Marginalizing over β^{lm}_2 and σ'_{lm} (only ~20 weaker: robust result on γ).

Remarkably these constraints are only a factor of ~3 weaker than those forecasted for JDEM/ WFIRST-type experiments (e.g. Thomas et al 2008, Linder 2009).

flat wCDM + growth index γ

Rapetti et al 10



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238 survey with 94 X-ray follow-up

CMB (WMAP5)

SNIa (Kowalski et al 2008, UNION)

cluster f_{gas} (Allen et al 2008)

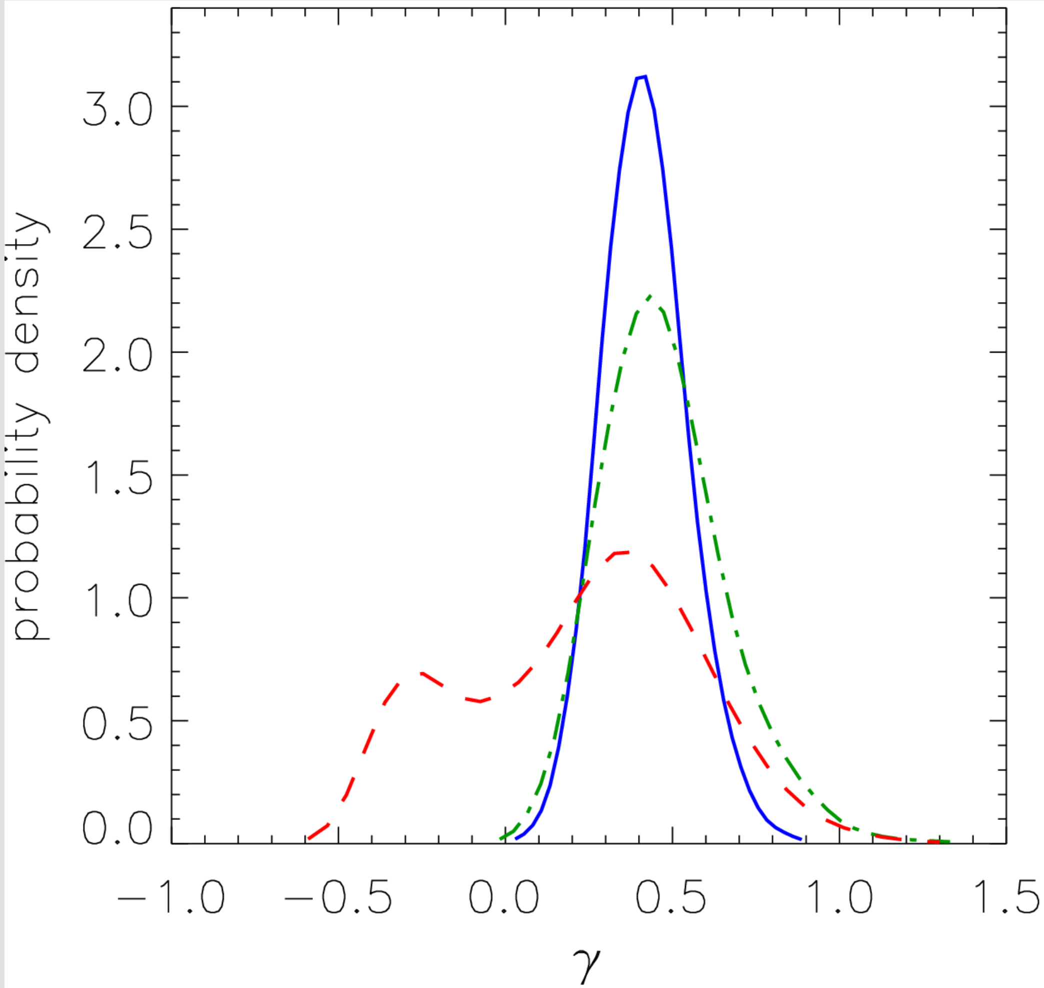
For General Relativity $\gamma \sim 0.55$

Gold: Self-similar evolution and constant scatter

Simultaneous constraints on the expansion and growth histories of the Universe at late times: Consistent with GR+ΛCDM

The impacts of the different data sets

Rapetti et al 10



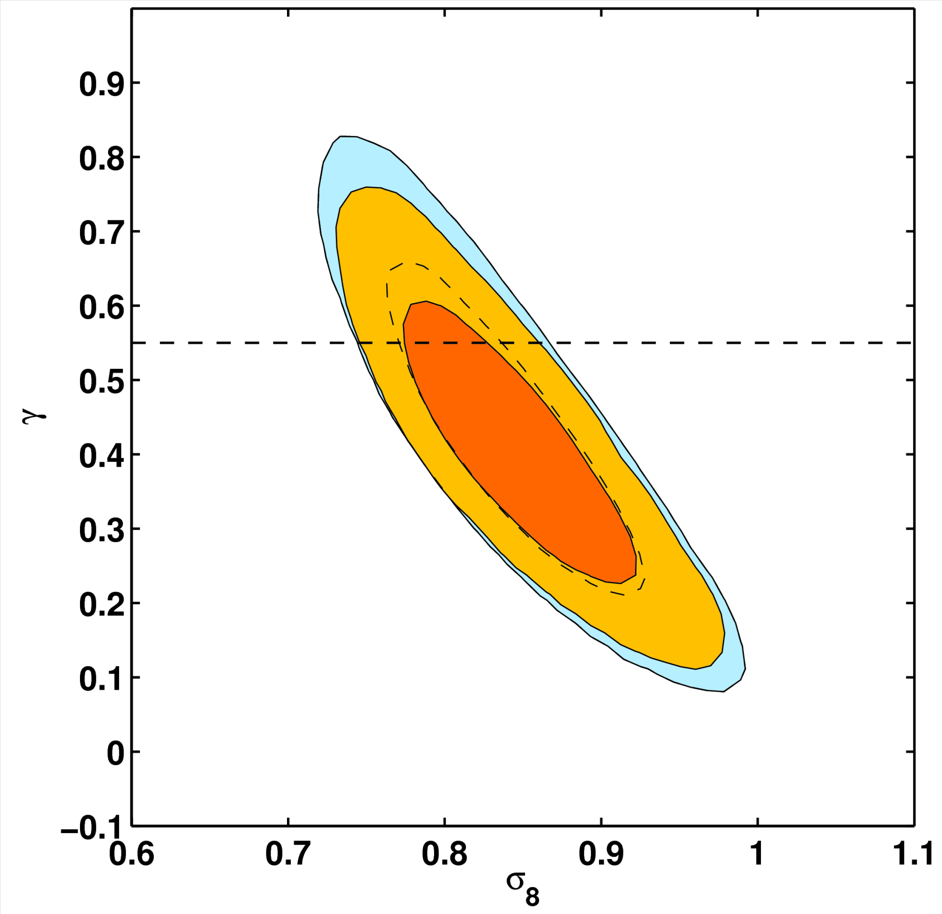
Green, dotted-dashed line:
XLF alone

Red, dashed line:
SNIa+fgas+BAO+CMB(ISW)

Blue, solid line:
XLF+SNIa+fgas+BAO+CMB(ISW)

flat ΛCDM + growth index γ

Rapetti et al 10



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238 survey with 94 X-ray follow-up

CMB (WMAP5)

SNIa (Kowalski et al 2008, UNION)

cluster f_{gas} (Allen et al 2008)

For General Relativity γ~0.55

Gold: Self-similar evolution and constant scatter

Blue: Marginalizing over β^{lm}_2 and σ'_{lm}

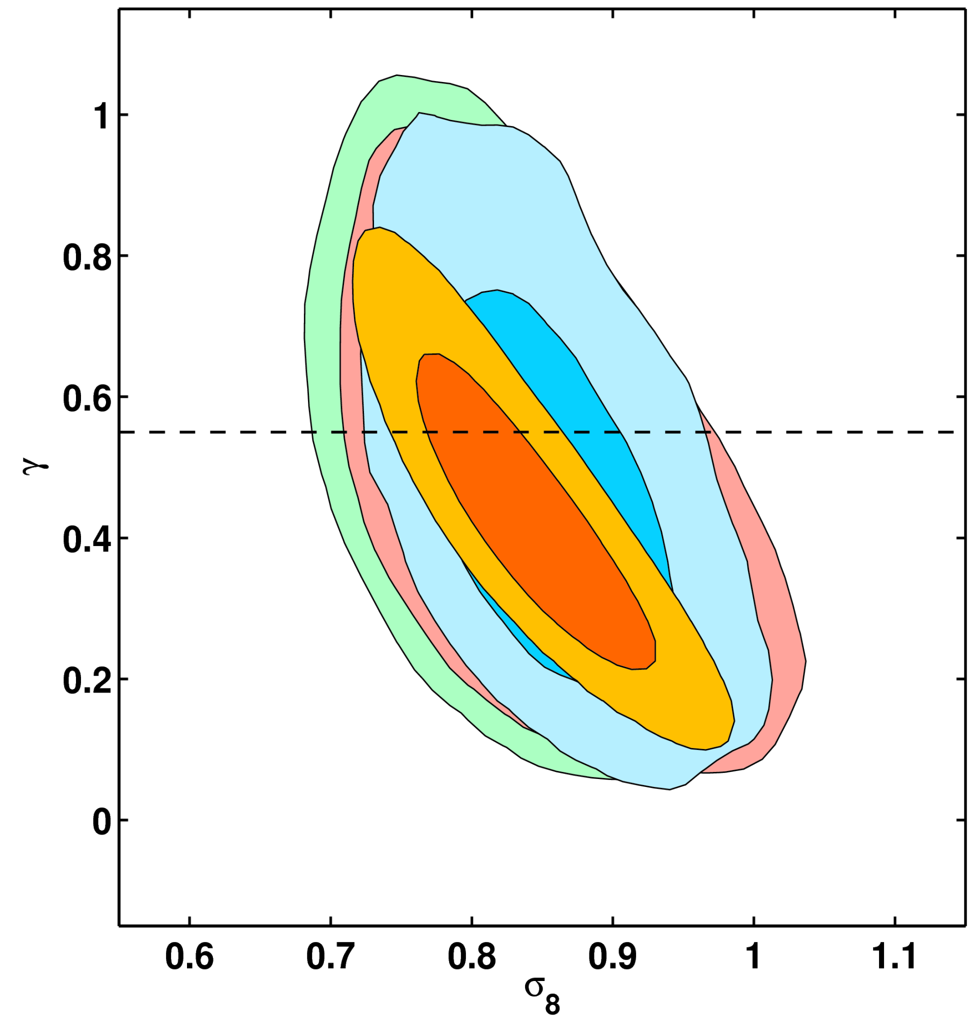
$$\gamma\left(\frac{\sigma_8}{0.8}\right)^{6.8} = 0.55^{+0.13}_{-0.10}$$

Tight correlation between σ_8 and γ:

$$\rho = -0.87$$

The impacts of the different data sets

Rapetti et al 10



Red: clusters (XLF+fgas)

Green: clusters+SNIa

Blue: clusters+SNIa+BAO

Gold: clusters+SNIa+BAO+CMB

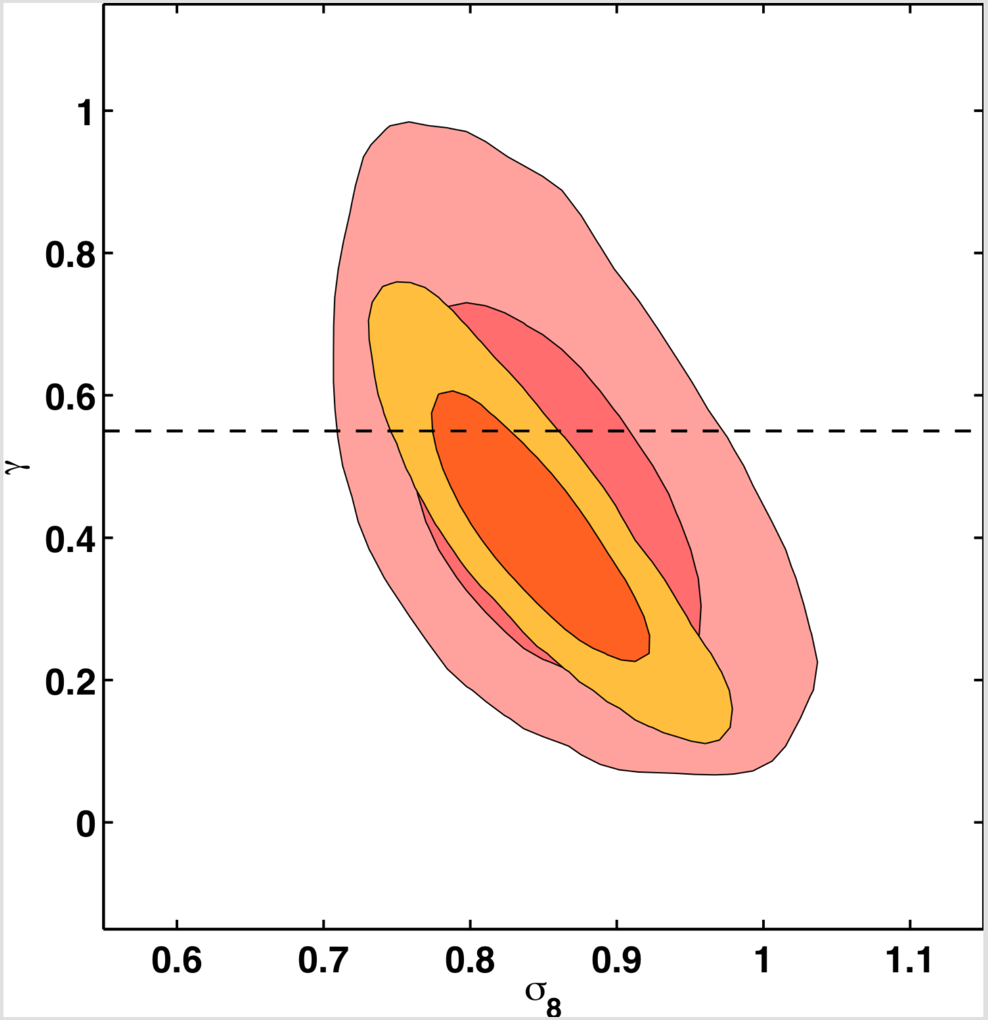
Adding the CMB leads to a tight correlation between σ_8 and γ thanks to the constraints on several cosmological parameters:

$$\gamma\left(\frac{\sigma_8}{0.8}\right)^{6.8} = 0.55^{+0.13}_{-0.10}$$

Strong correlation between σ_8 and γ:

$$\rho = -0.87$$

The impacts of the different data sets



Red: clusters (XLF+fgas)

Gold: clusters+SNIa+BAO+CMB

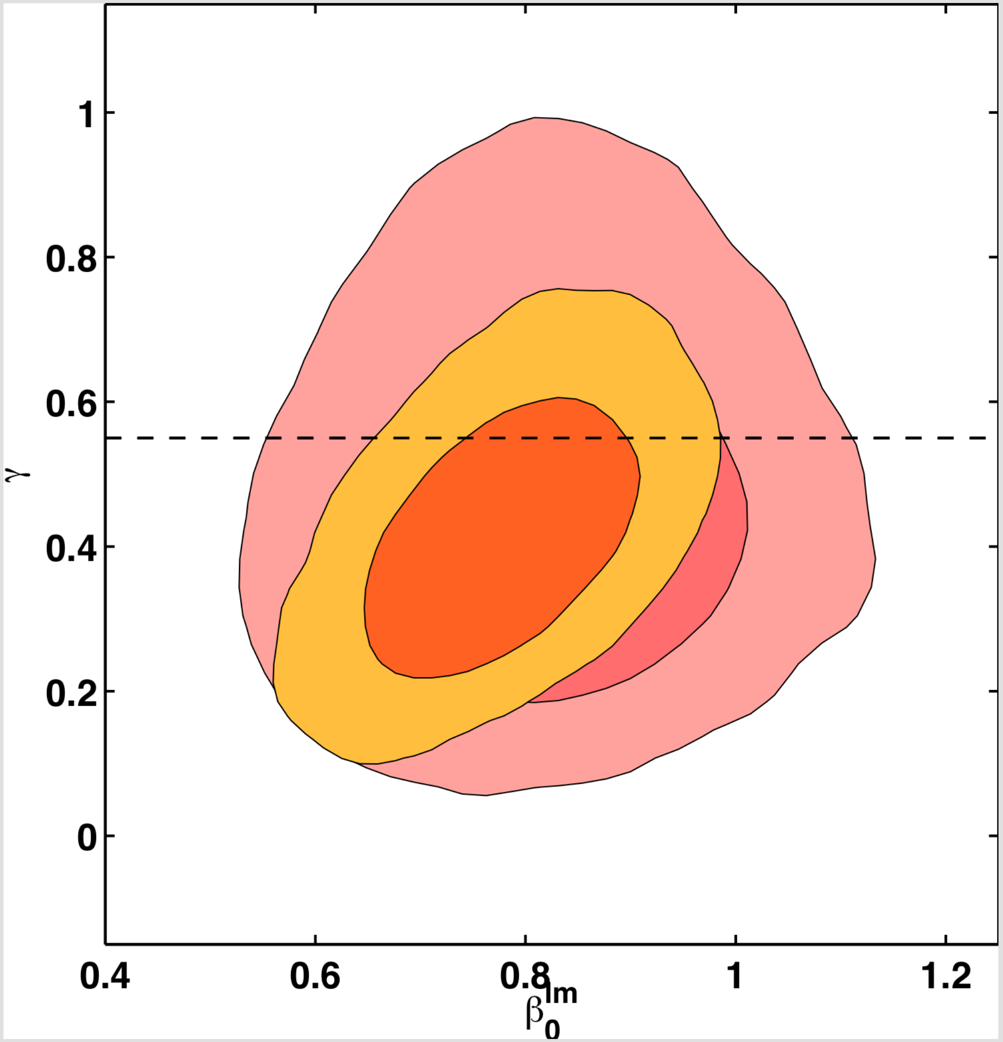
Adding the CMB leads to a tight correlation between σ_8 and γ thanks to the constraints on several cosmological parameters:

Strong correlation between σ_8 and γ:

$$\rho = -0.87$$

Note also the reduction in the area contained by the contours in this plane (this area could be defined as a Figure of Merit in the same fashion as the DETF did for the w_0-w_a plane).

The impacts of the different data sets



Red: clusters (XLF+fgas)

Gold: clusters+SNIa+BAO+CMB

Adding the CMB leads to another (less tight) correlation between β^{lm}_0 and γ thanks to the constraints on several cosmological parameters:

Correlation between β^{lm}_0 and γ:

$$\rho = 0.52$$

Note also the reduction in the area contained by the contours in this plane (this area could also be defined as another FoM).

Conclusions

- For the first time, we present a simultaneous and self-consistent analysis of cluster survey plus follow-up data accounting for survey biases, systematic uncertainties and parameter covariances. This kind of analysis is essential for both cosmological and scaling relation studies.

- We obtain the tightest constraints on w for a single experiment from measurements of the growth of cosmic structure in clusters (flat wCDM): w = -1.01+-0.2. We use follow-up Chandra and ROSAT data for a wide redshift range and gas mass as total mass proxy (f_{gas} has low scatter), which is crucial to obtain such tight constraints.

- We have performed a consistency test of General Relativity (growth rate) at large scales using cluster growth data: BCS+REFLEX+Bright MACS, Tinker et al 2008 mass function, 94 clusters with X-ray follow-up observations as well as other cosmological data from f_{gas}+SNIa+CMB+BAO.

- We obtain a tight correlation $\gamma(\sigma_8/0.8)^{6.8}$=0.55+0.13-0.10 for the flat ΛCDM model. This promises significant improvements on γ by adding independent constraints on σ_8.

- Our results are robust when allowing additional evolution in the luminosity-mass relation and its scatter thanks to the wide redshift range covered by the follow-up data.

- Simultaneously fitting γ and w, we find that current data is consistent with GR+ΛCDM.

- Our results highlight the importance of X-ray cluster data to test dark energy and modified gravity models as well as neutrino properties. The same techniques developed here can be applied to SZ and optical surveys. Future: more MACS and Chandra data, XCS, XXL, Astro-H, eROSITA, WFXT, Athena.