Testing gravity on cosmological scales using X-ray luminous galaxy clusters

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Full cosmological analysis in this series of papers

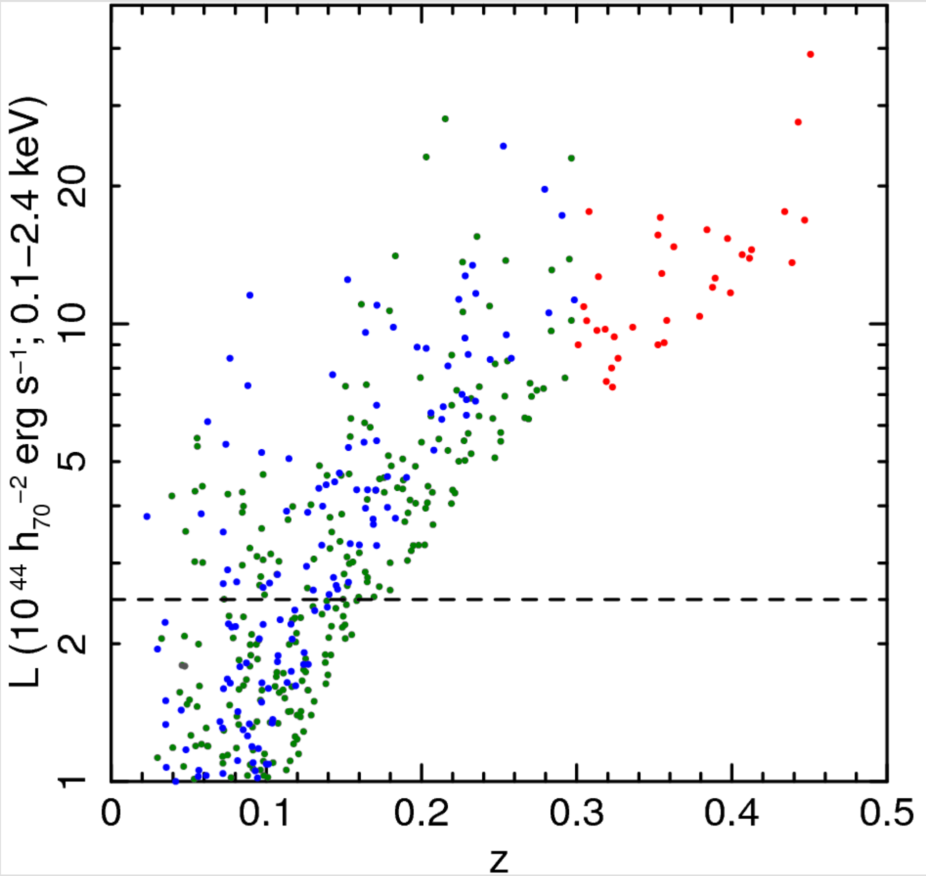
"The Observed Growth of Massive Galaxy Clusters I: Statistical Methods and Cosmological Constraints",
MNRAS 406, 1759, 2010
Adam Mantz, Steven Allen, David Rapetti, Harald Ebeling

"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 surveys



$L > 2.55\times10^{44}\ h_{70}^{-2}$ erg s^{-1} (dashed line).

Cuts leave 78+126+34=238 massive clusters

Low redshift (z<0.3)

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

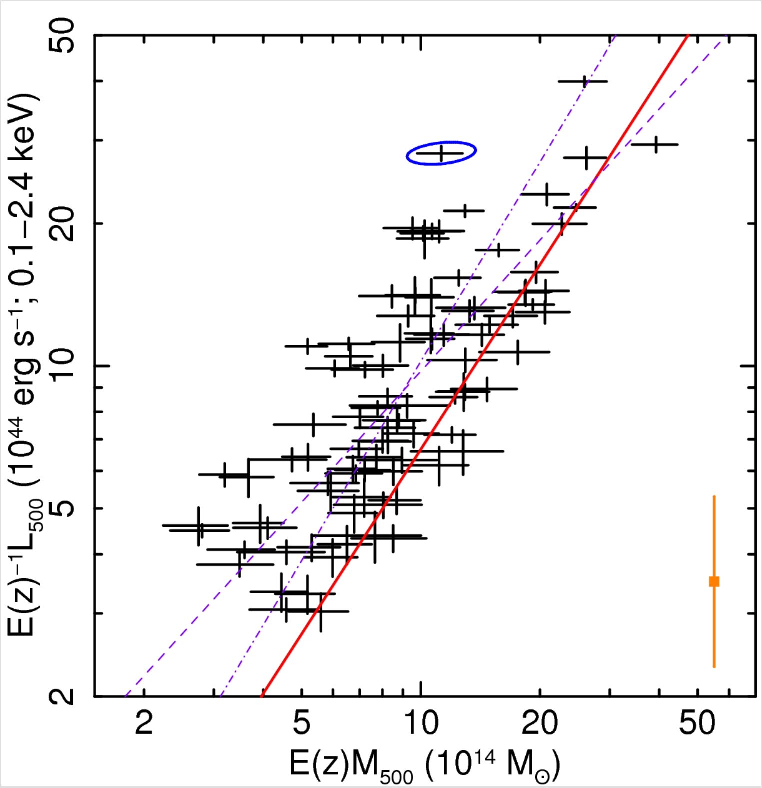
Intermediate redshifts (0.3<z<0.5)

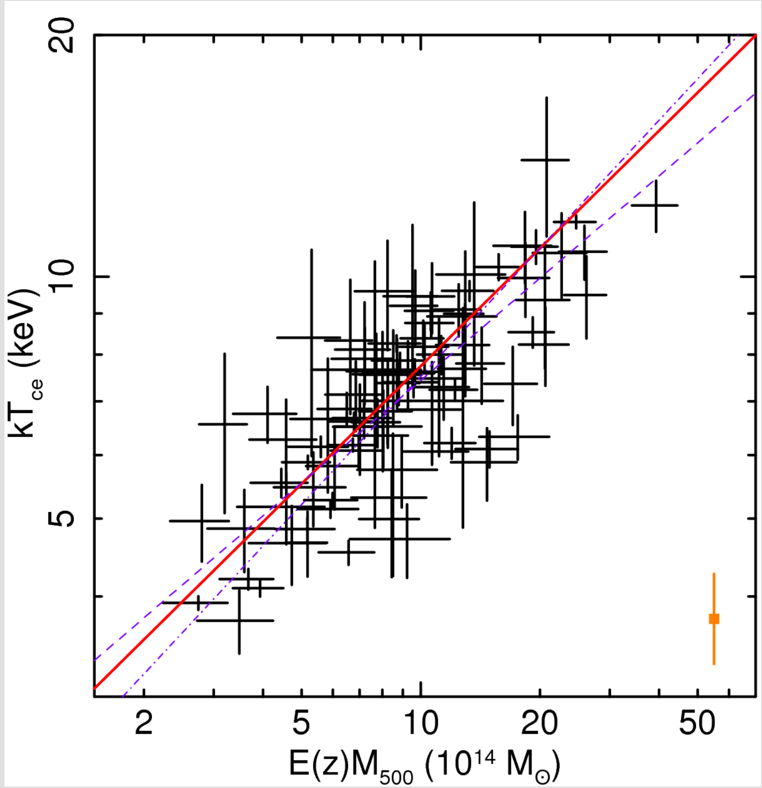
- Bright MACS (Ebeling et al 01, 10)
  $F > 2.0 \times 10^{-12}$ erg s^{-1} cm^{-2}
  ~55% sky coverage

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

Scaling relations data

Mantz et al 10b





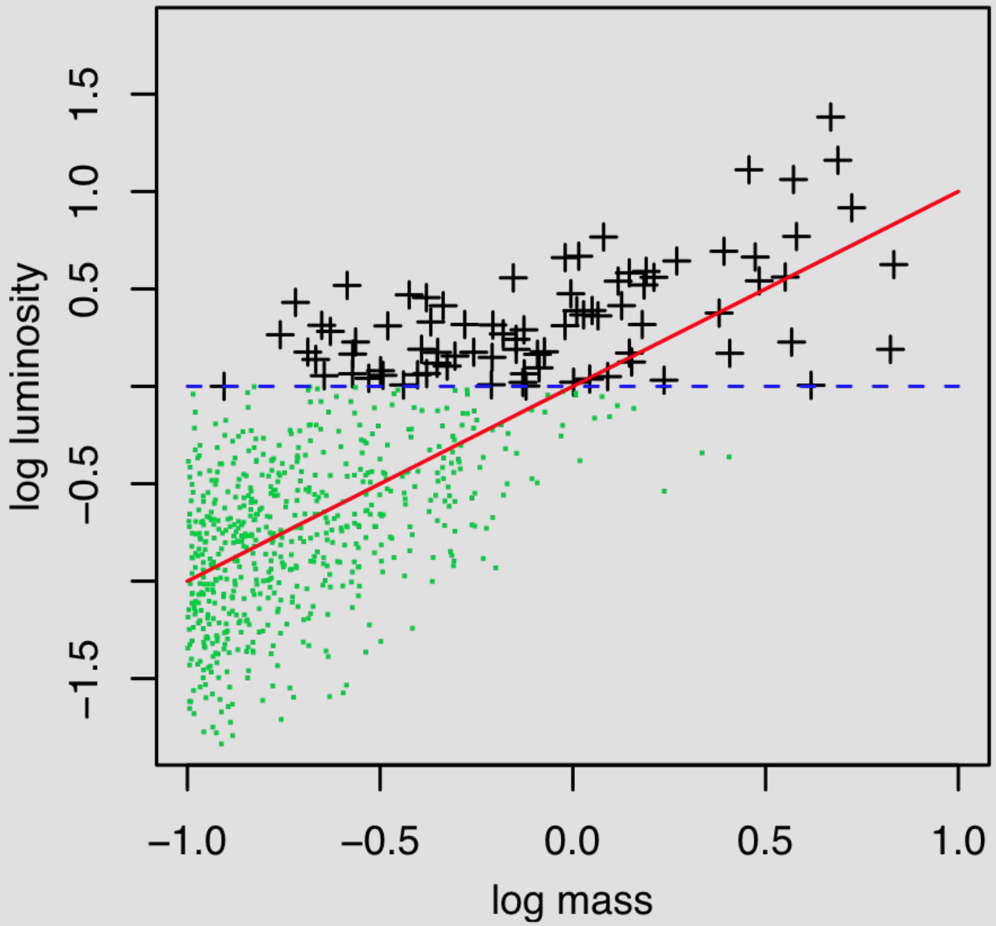
Best fit for all the data (survey+follow-up+other data).

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

Allen, Evrard, Mantz 11



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

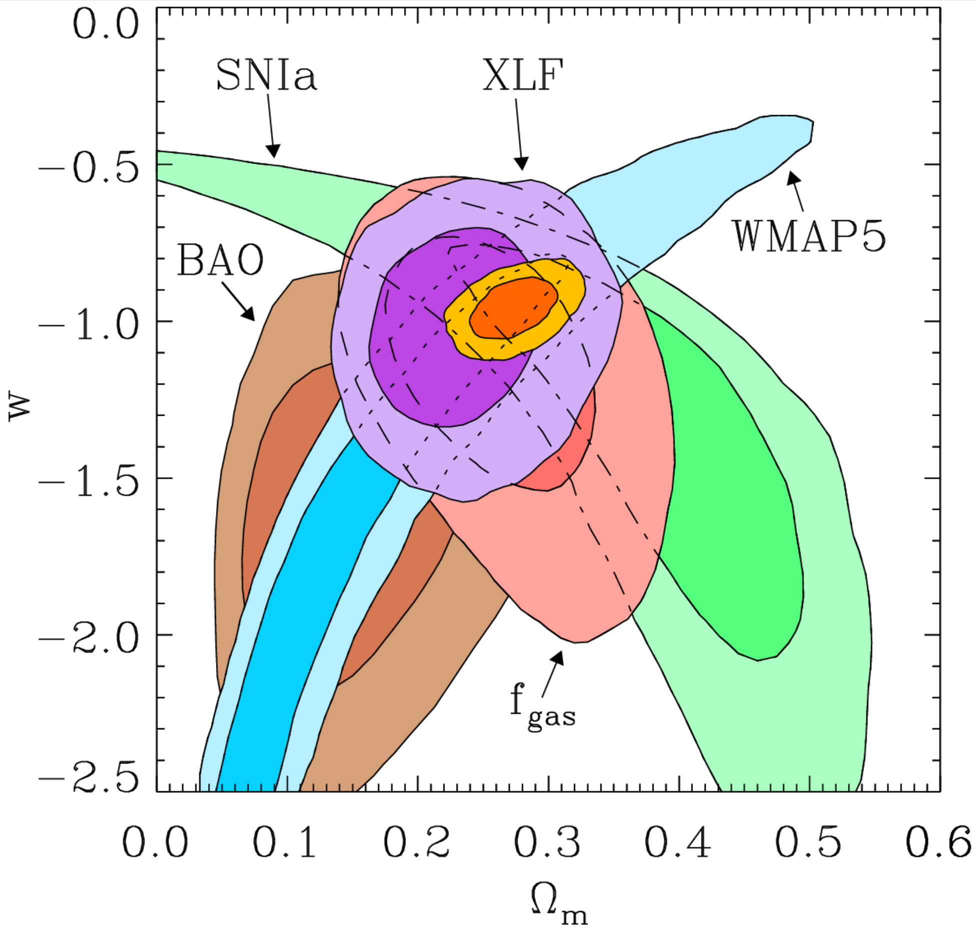
* The luminosity-mass relation has intrinsic scatter (~40%), which leads to Malmquist bias: brighter cluster are easier to find.

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

Dark energy constraints

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)

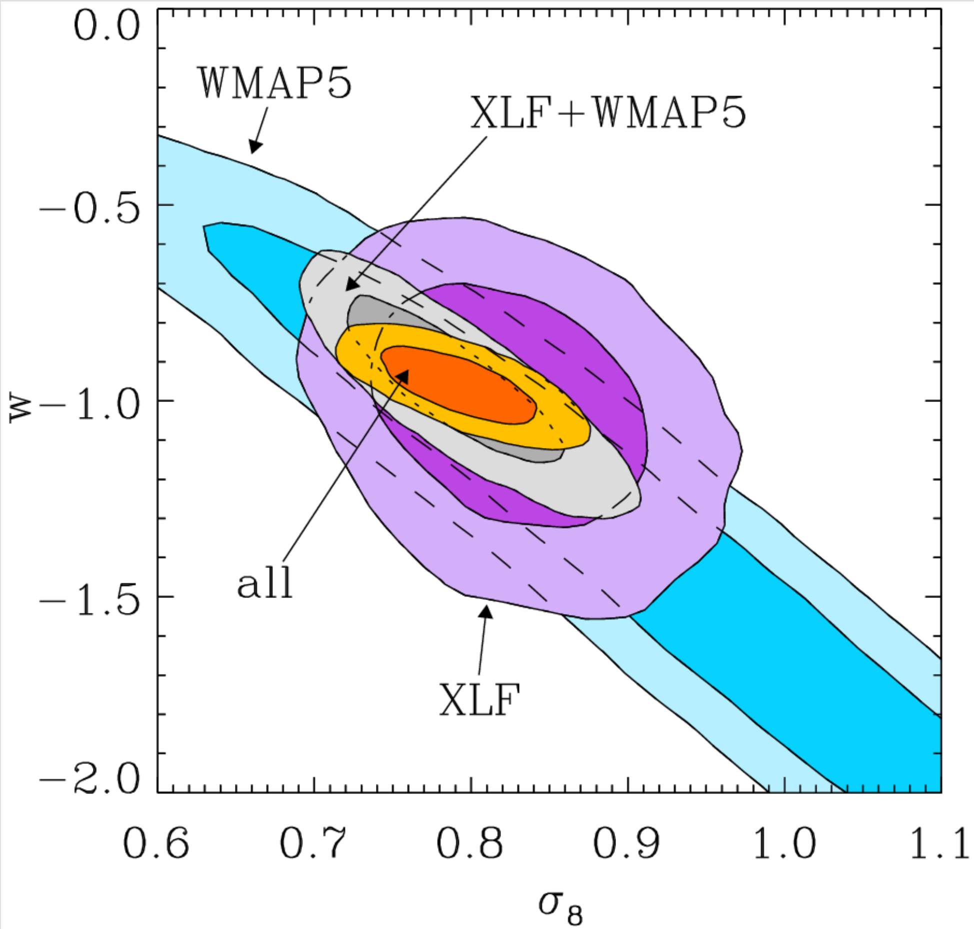
Gold: XLF+f_{gas}+WMAP5+SNIa+BAO

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

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

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

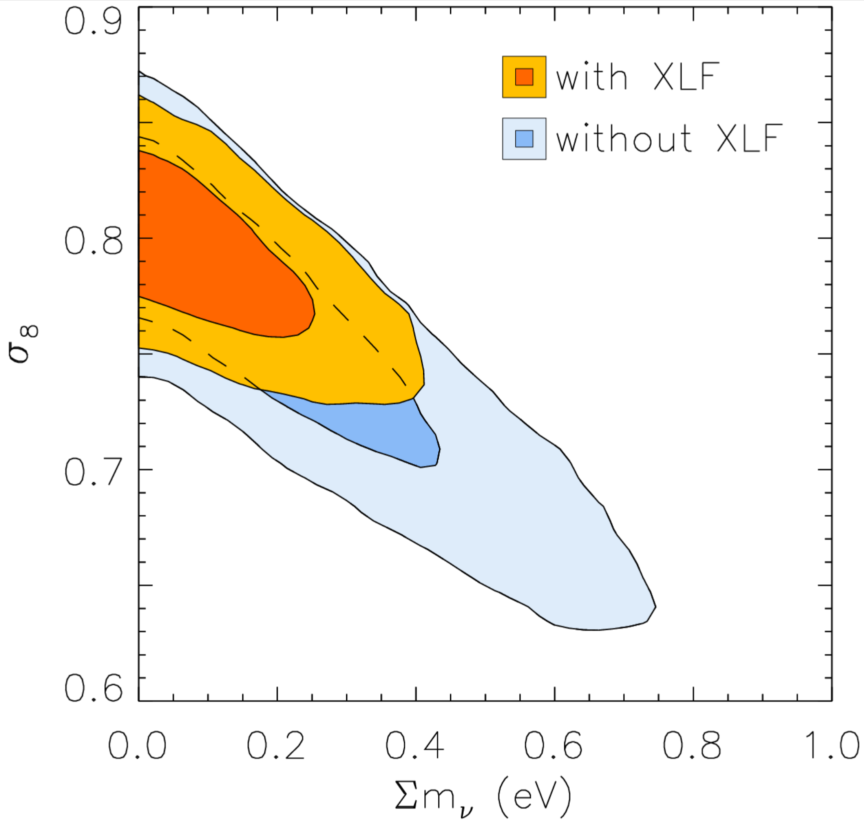
Ω_m = 0.23 +- 0.04
σ_8 = 0.82 +- 0.05
w = -1.01 +- 0.20

Constraints on neutrino properties

Robust constraints on neutrino properties

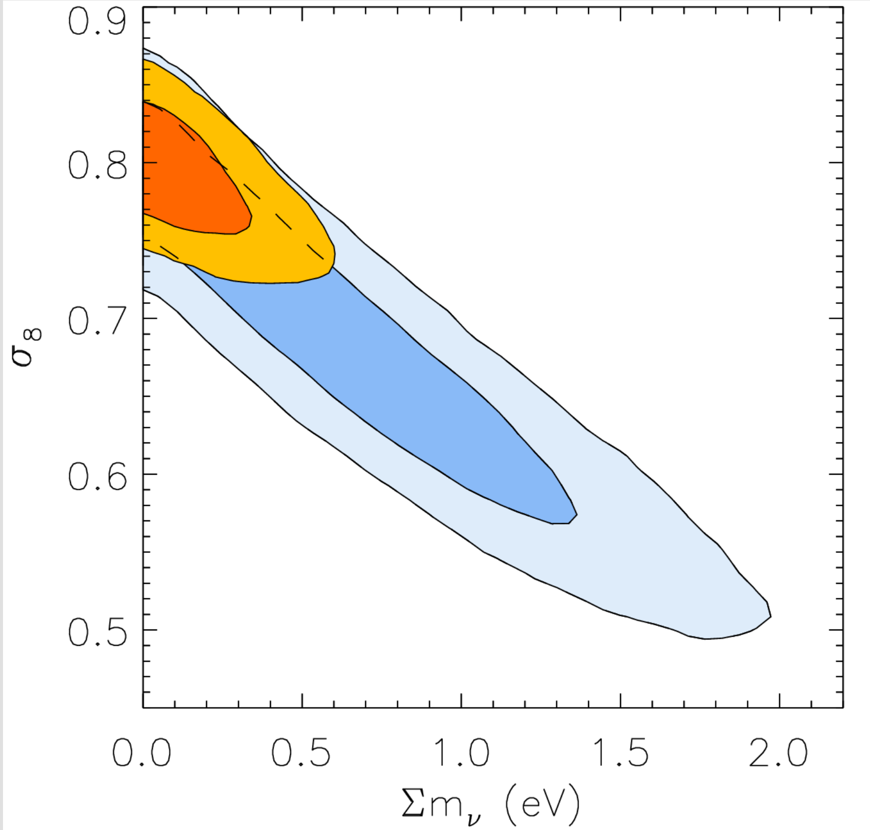
ΛCDM+Σm_ν: Breaking the degeneracy in the Σm_ν, σ_8 plane

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

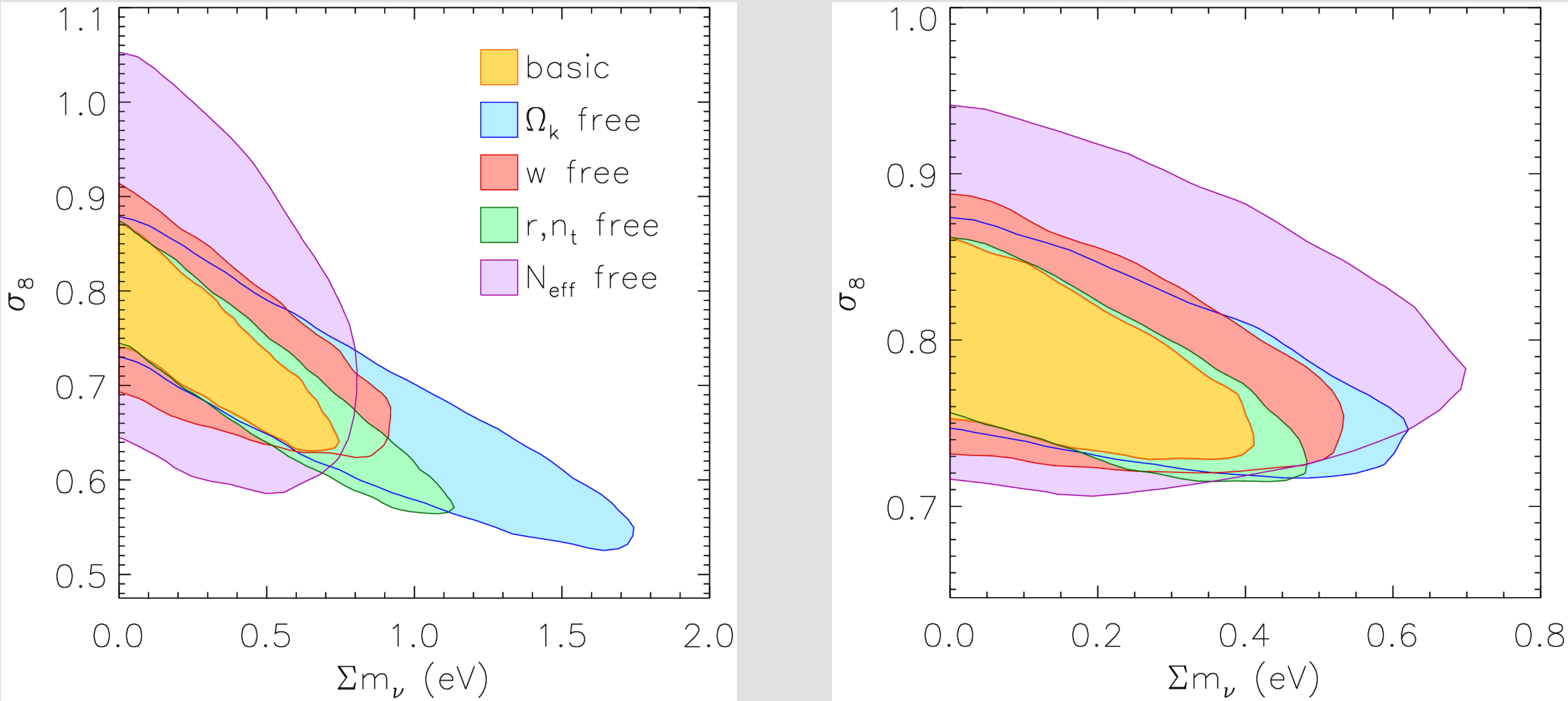
Mantz et al 10c

Robust constraints on neutrino properties

Basic: ΛCDM+Σm_ν

CMB+fgas+SNIa+BAO

CMB+fgas+SNIa+BAO+XLF



Mantz et al 10c

Testing General Relativity

Motivation

1. Cosmic acceleration measurement + cosmological constant problem (from fundamental theory) + not solved with quintessence

2. In the Friedmann equation: we can either include a new component, dark energy, or modify the theory of gravity [such as using extra dimensions (e.g. DGP), f(R) models, etc.]. (There are also other possibilities such as non-FRW metrics, etc.)

3. Test General Relativity (GR) for consistency.

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

5. From the evolution of the cluster abundance (XLF) we can directly measure cosmic growth.

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. Fabian et al 2009, Fabian 2009a/b, Chan & Scoccimarro 2009, Zhao, Li & Koyama 2011).

4. Relation between the so-called "dynamical" and "lensing" masses (Theory/N-body simulations: Fabian 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).

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

Modeling linear, time-dependent departures from GR

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

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

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

Linear power spectrum

General Relativity

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

Scale independent in the synchronous gauge

Phenomenological parameterization

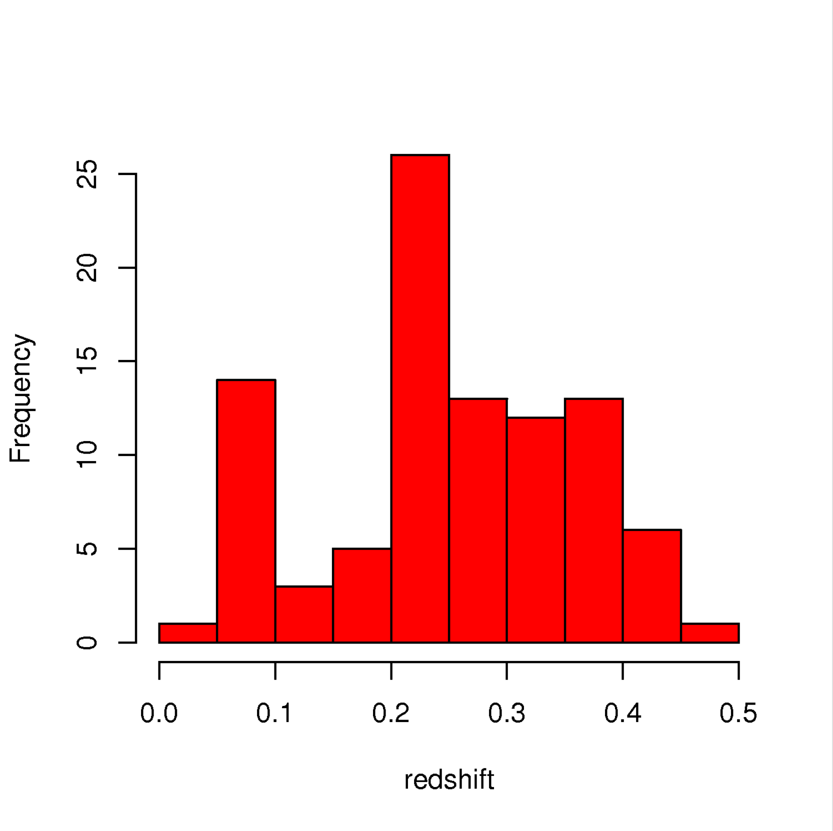
$$\frac{d\delta}{da} = \frac{\delta}{a}\Omega_\mathrm{m}(a)^\gamma$$

GR $\gamma \sim 0.55$

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

Growth rate

Investigating luminosity-mass evolution



Within the 238 flux-selected clusters we used pointed observations for

23 clusters (z<0.2) from ROSAT
71 clusters (z>0.2) from Chandra

Mass-luminosity and its intrinsic scatter

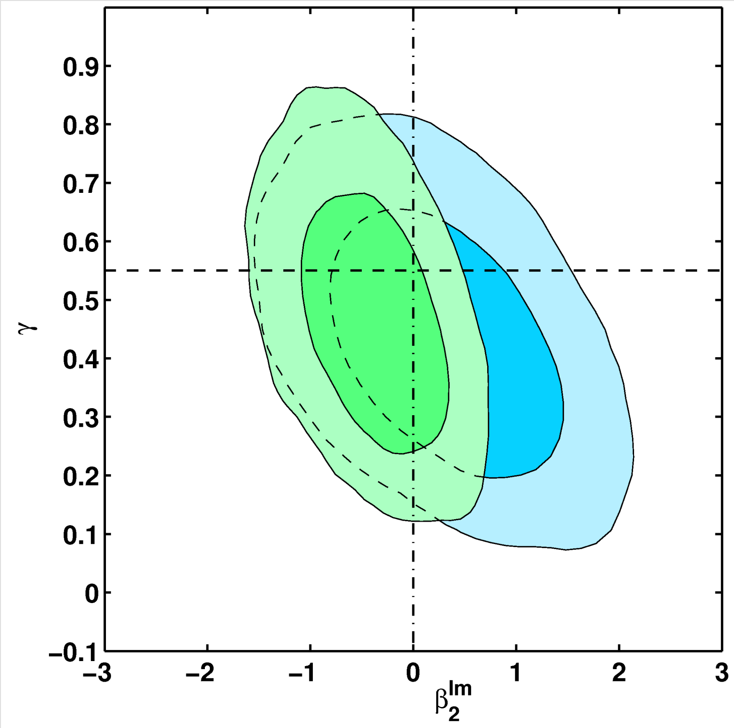
$$\langle l(m) \rangle = \beta_0^{lm} + \beta_1^{lm} m + \beta_2^{lm} \log_{10}(1+z)$$

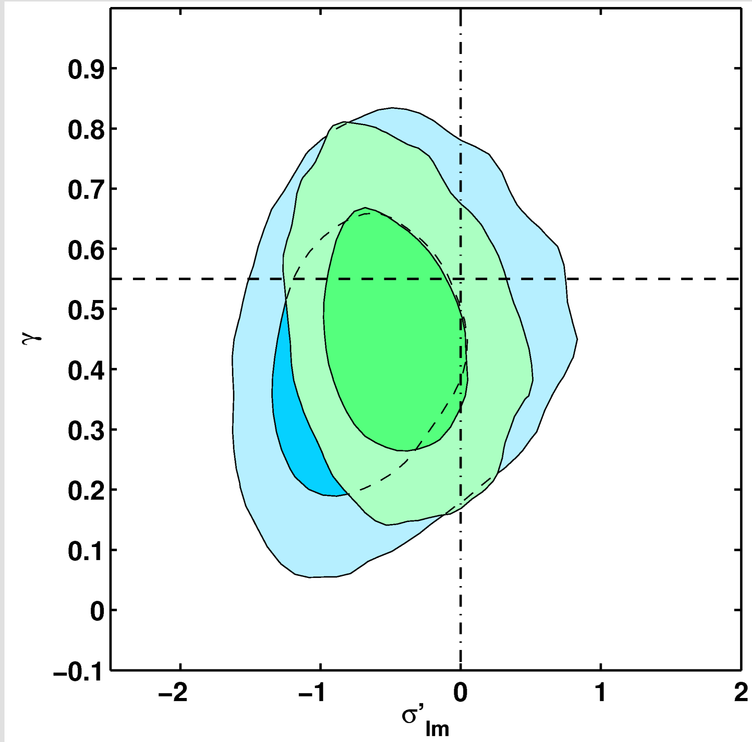
$$\sigma_{lm}(z) = \sigma_{lm}(1 + \sigma'_{lm} z)$$

$$l = \log_{10}\left(\frac{L_{500}}{E(z) 10^{44}\, erg\, s^{-1}}\right); \quad m = \log_{10}\left(\frac{M_{500} E(z)}{10^{15} M_{solar}}\right)$$

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

Rapetti et al 10





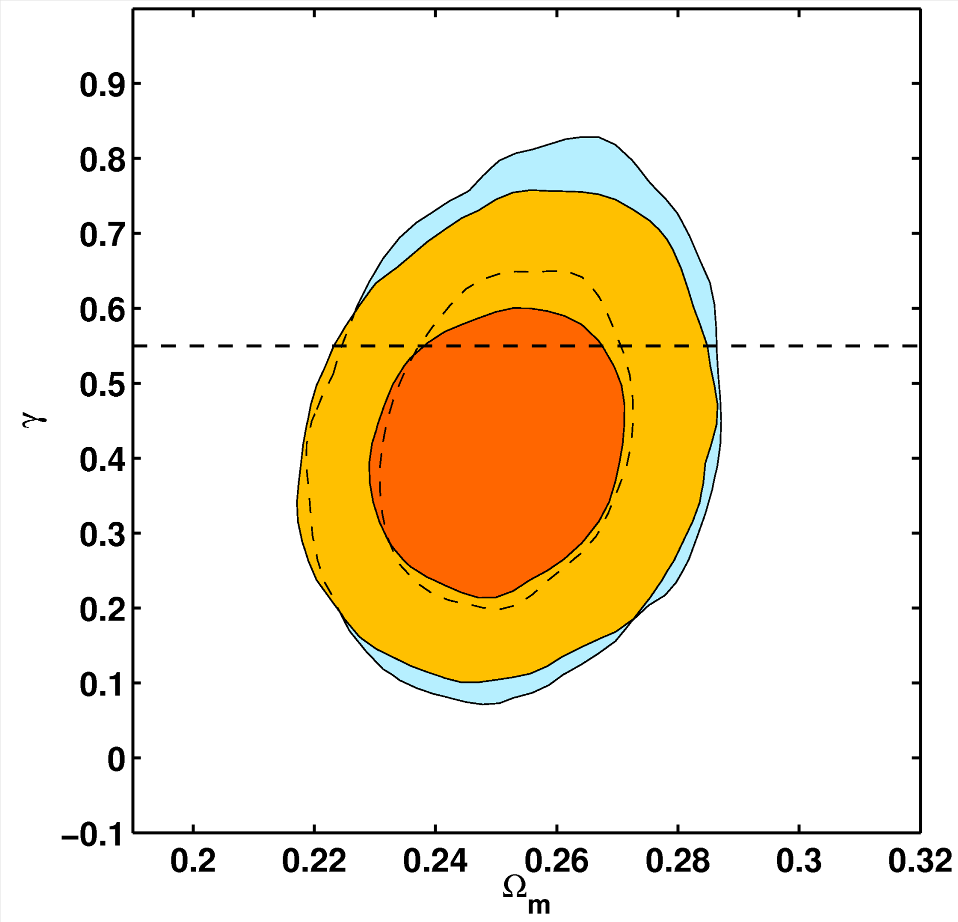
$$\langle l(m)\rangle = \beta_0^{lm} + \beta_1^{lm} m + \beta_2^{lm}\log_{10}(1+z)$$

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

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

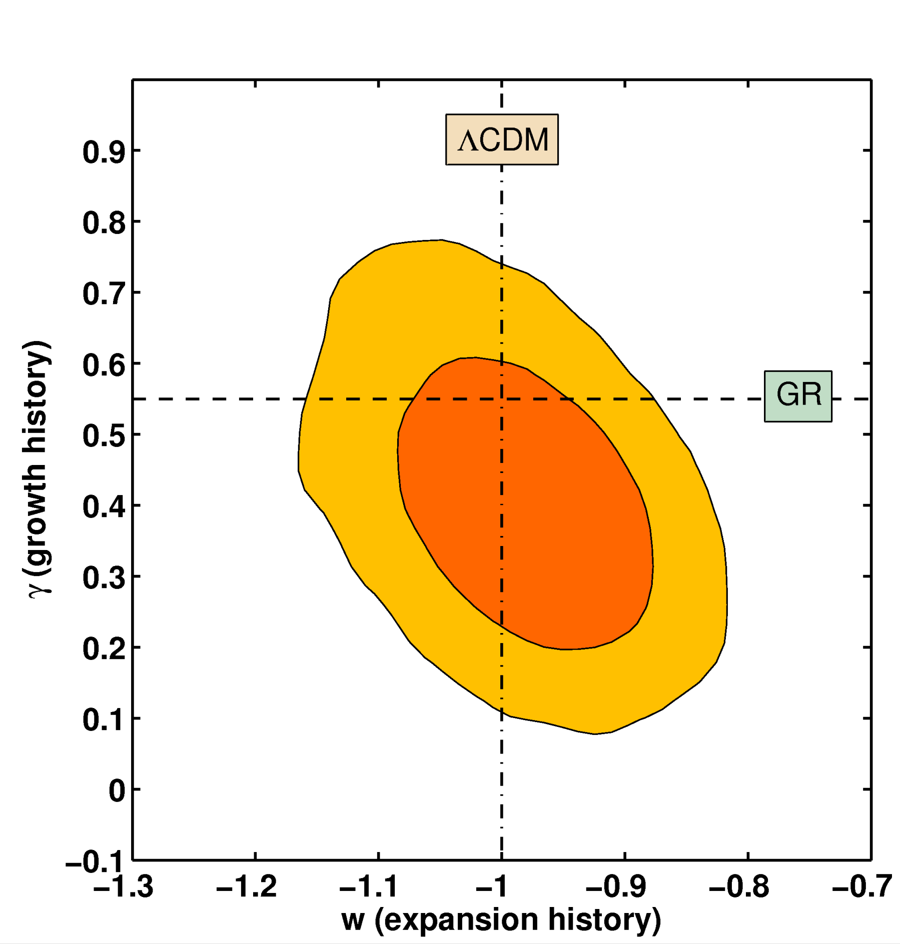
Gold: Self-similar evolution and constant scatter

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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cluster f_{gas} (Allen et al 2008)

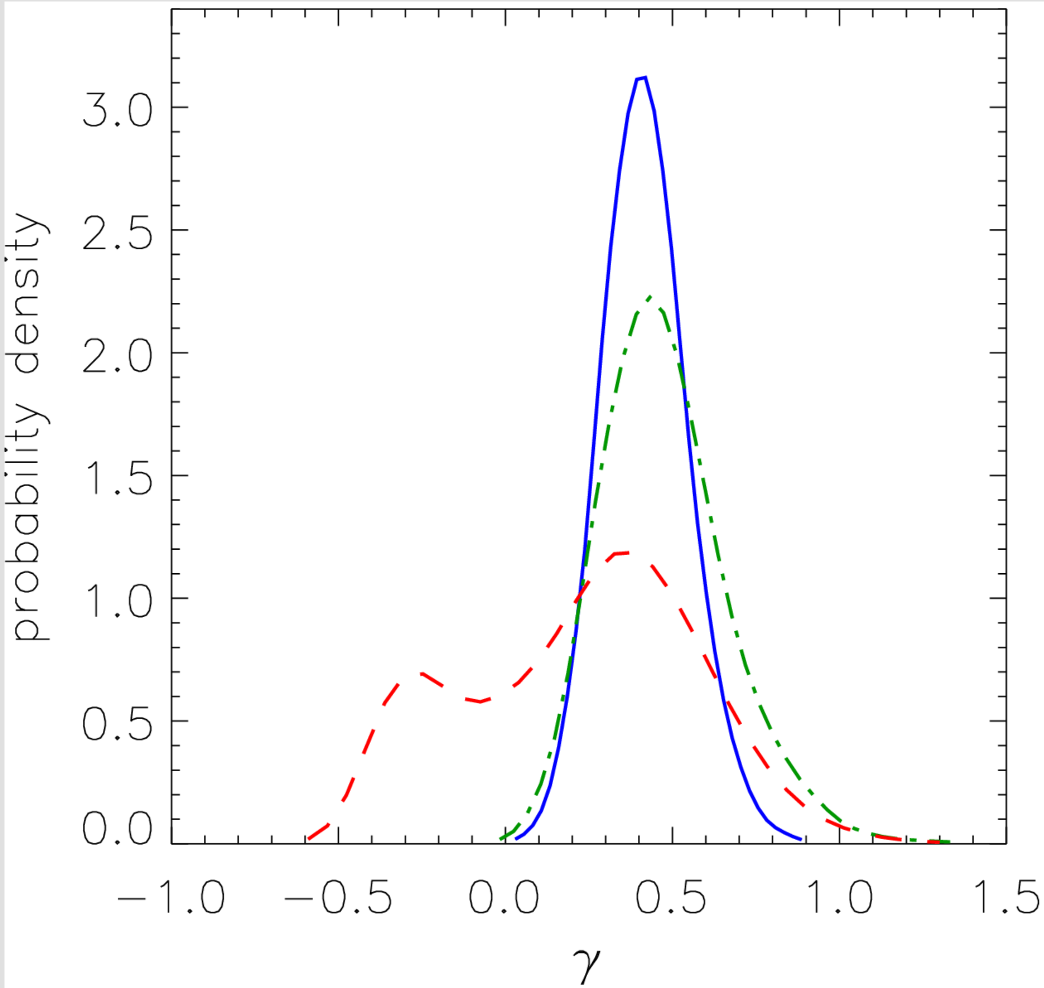
For General Relativity γ~0.55

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



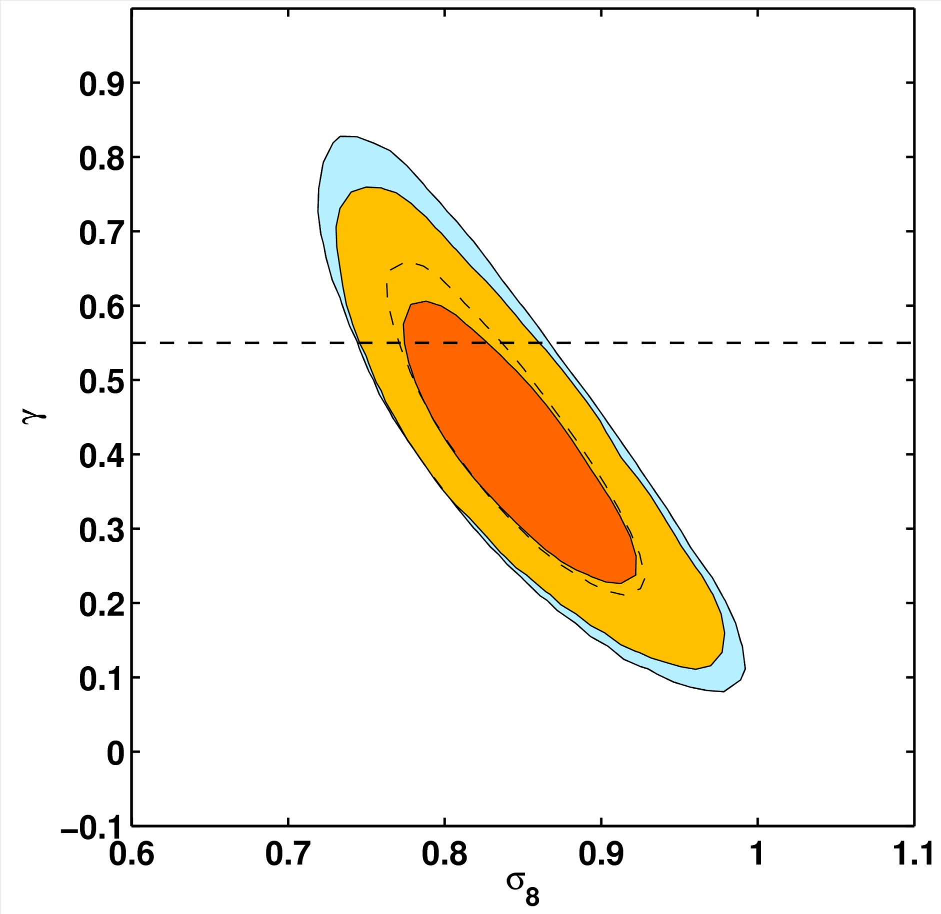
Green, dotted-dashed line:
XLF alone

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



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}

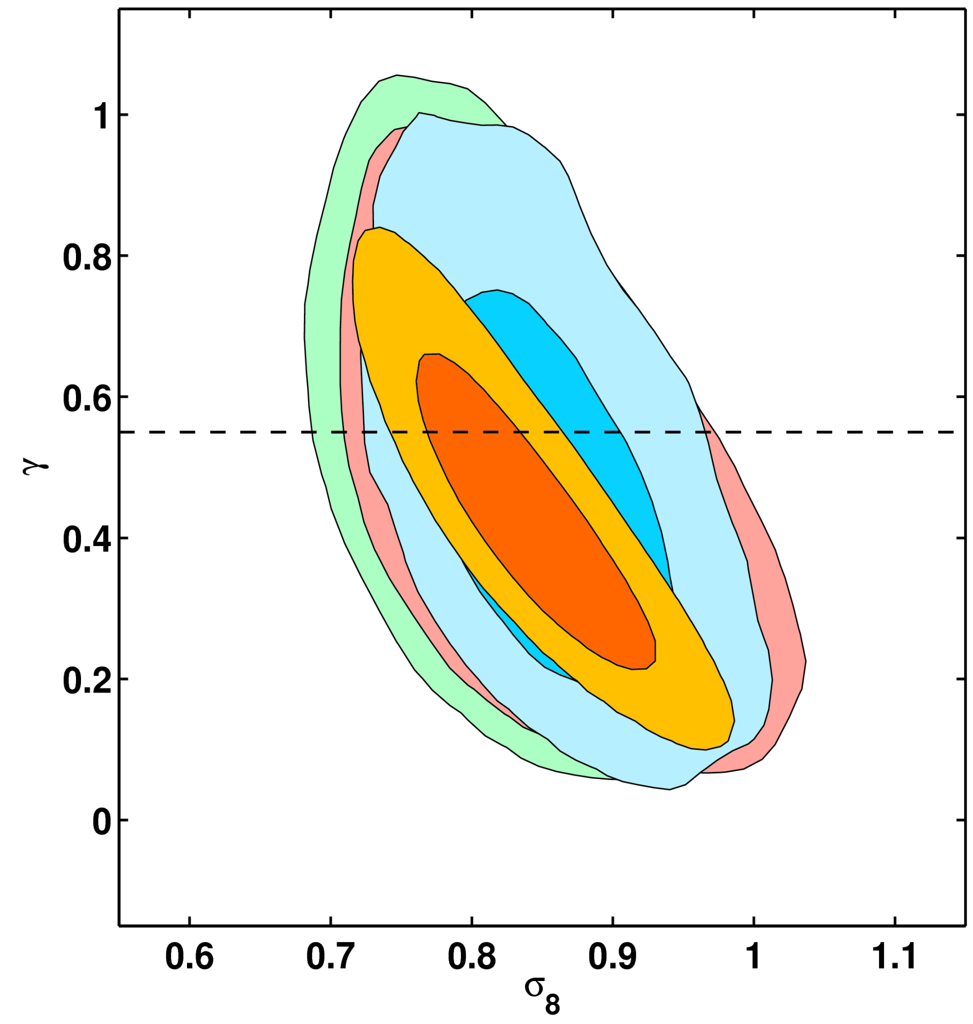
$$\gamma\left(\frac{\sigma_8}{0.8}\right)^{6.8} = 0.55^{+0.13}_{-0.10}$$

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:

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

Tight correlation between σ_8 and γ:

$$\rho = -0.87$$

Conclusions

- For the first time, we present a simultaneous and self-consistent analysis of a 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} low scatter), which is crucial to obtain such tight constraints.

- We have performed a consistency test of General Relativity (growth rate) 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, Astro-H, eROSITA, WFXT, Athena.