Acceleration and Modified Gravity Constraints from X-ray Galaxy Clusters

Adam Mantz (U. Chicago)

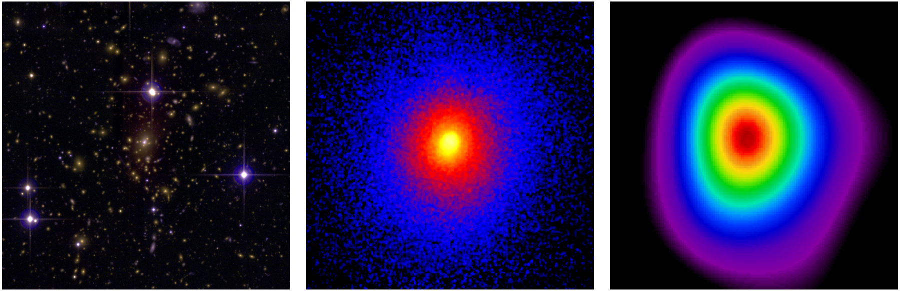
with

David Rapetti, Steve Allen,
Harald Ebeling, and Glenn Morris

Workshop on Cosmic Acceleration

August 26, 2012

Warning: data



Abell 1835 in optical (Subaru), X-ray (Chandra), SZ (SZA)

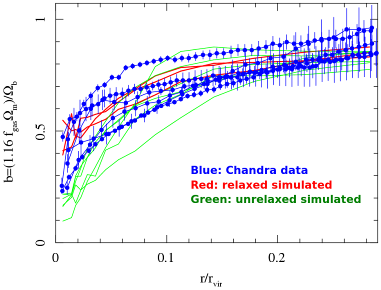
Outline

- Constraining acceleration at late times
  - Cluster f_{gas} (Allen+ 2008)
  - Growth of structure (AM+ 2010)
- Constraining gravity late times (Rapetti+ 2012)

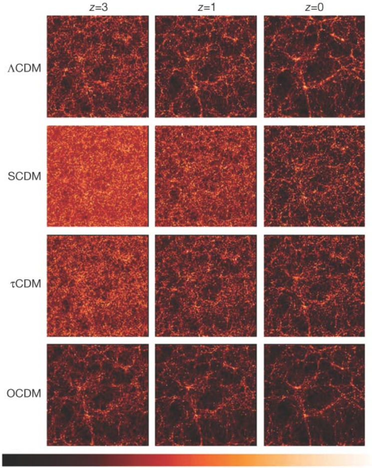
Constraining dark energy (acceleration)

Clusters provide multiple probes:

Standard gas fraction ($f_{\rm gas}$)

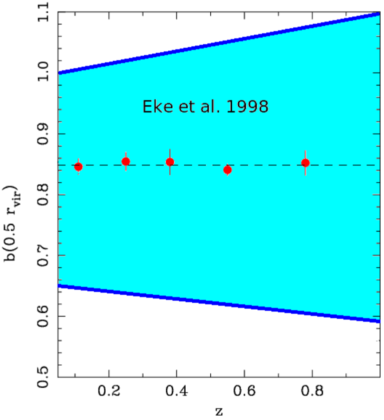


Growth of structure



Cosmic acceleration from $f_{\rm gas}$

- Exploits the small scatter in $f_{\rm gas} = M_{\rm gas}/M_{\rm tot}$ at intermediate radii, and the prediction of little to no evolution.
- X-ray data can measure $f_{\rm gas}(r)\,d(z)^{-3/2}$ for sufficiently massive, dynamically relaxed clusters.



(simulations and prior)

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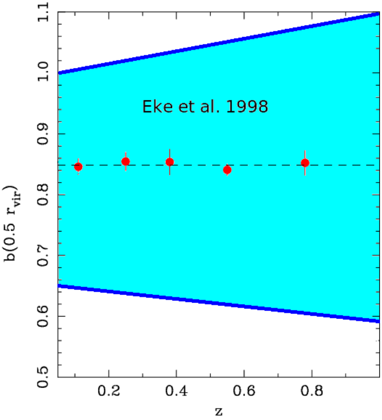

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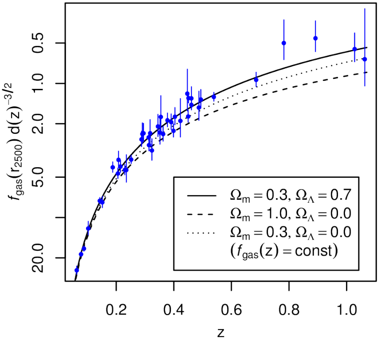

(Data from Allen et al. 2008)

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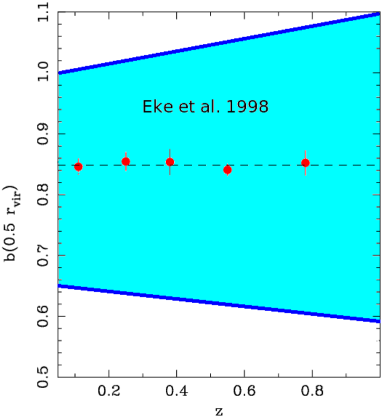

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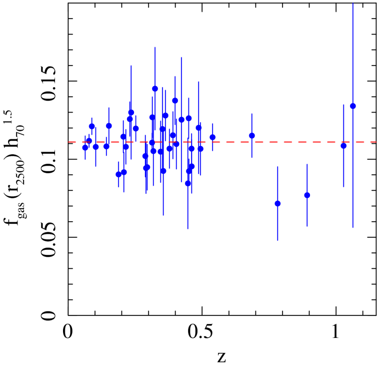

(Data from Allen et al. 2008)

$d(z)$ for $\Omega_{\rm m} = 0.3$, $\Omega_\Lambda = 0.7$

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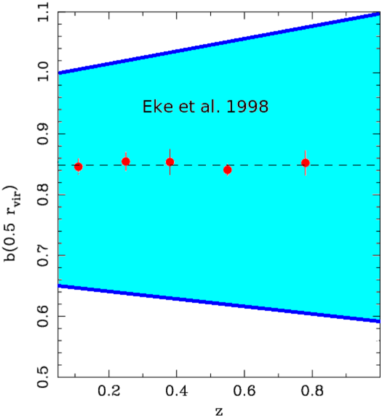

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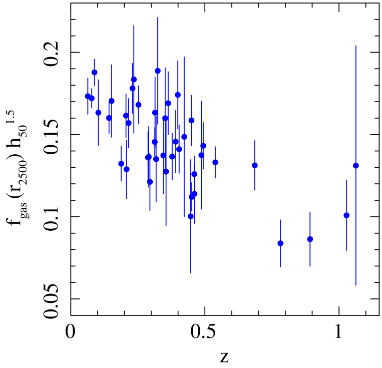
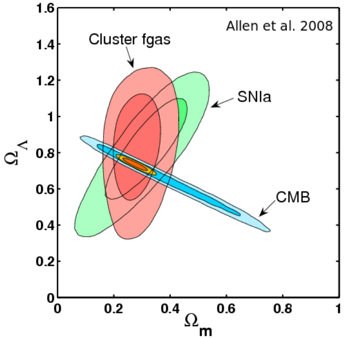


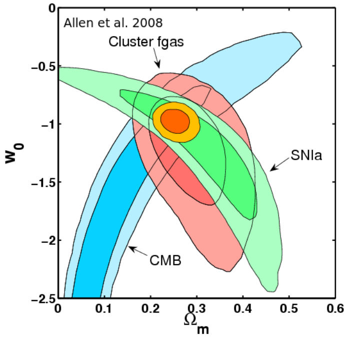
(Data from Allen et al. 2008)

$d(z)$ for $\Omega_{\rm m} = 1.0$, $\Omega_\Lambda = 0.0$

Results

Chandra data for 42 massive, relaxed clusters at $0.05 < z < 1.1$ provided strong confirmation of cosmic acceleration.





Cluster $f_{\rm gas}$ (incl. systematics):

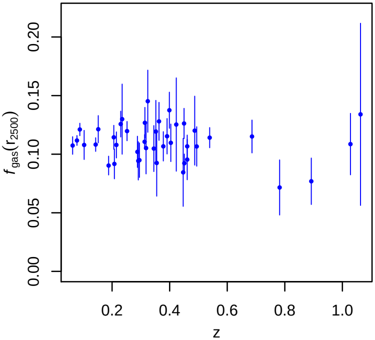
$$\Omega_{\rm m} = 0.27 \pm 0.06$$
$$\Omega_\Lambda = 0.86 \pm 0.19$$

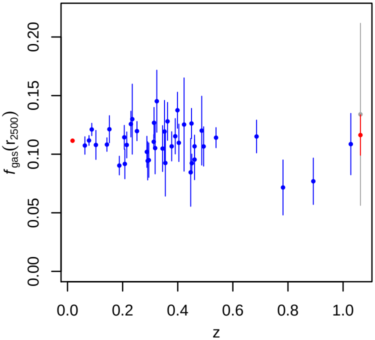
$$\Omega_{\rm m} = 0.28 \pm 0.06$$
$$w = -1.14 \pm 0.31$$

Teaser

A new analysis with 100% more data should be finished soon (still blinded).

e.g. New Perseus data point from Suzaku ($z = 0.018$), updated value for 3c186 ($z = 1.06$) from 100ks Chandra observation.





2008 results, new/updated

$f_{\rm gas}(r_{2500})$ for $\Omega_{\rm m} = 0.3$, $\Omega_\Lambda = 0.7$

Outline

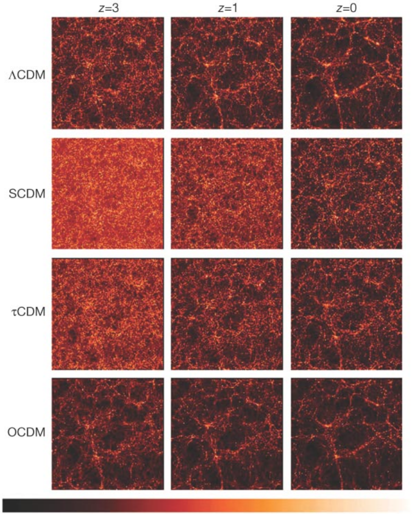
Constraining acceleration at late times

- Cluster $f_{\rm gas}$ (Allen+ 2008)
- Growth of structure (AM+ 2010)

Constraining gravity late times (Rapetti+ 2012)

Cluster growth

Cluster abundance as a function of mass and redshift is sensitive to the

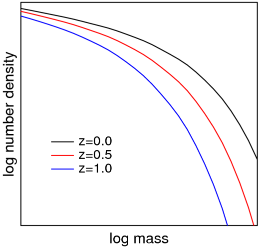


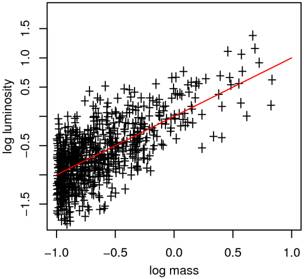
- Amplitude and growth of density perturbations
- Cosmic expansion history

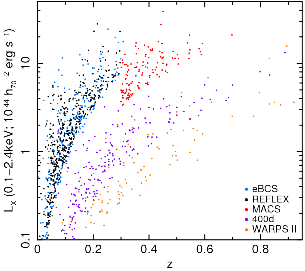
(Image from Cole 2005)

Theoretical and observational ingredients

$$\frac{dN}{dzdM} + P(L|M,z) \rightarrow \frac{dN}{dzdF}$$







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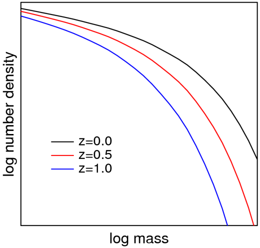
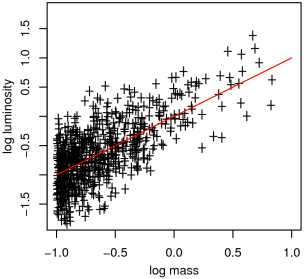
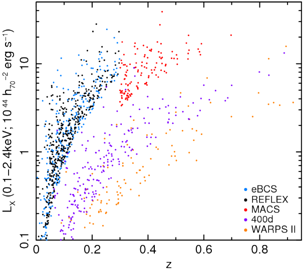
$$\frac{dN}{dzdM} + P(L|M,z) \rightarrow \frac{dN}{dzdF}$$







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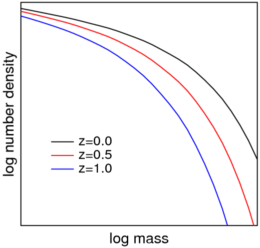
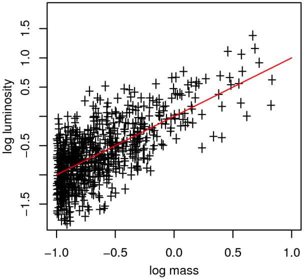
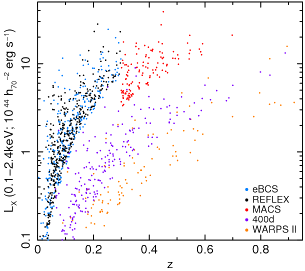
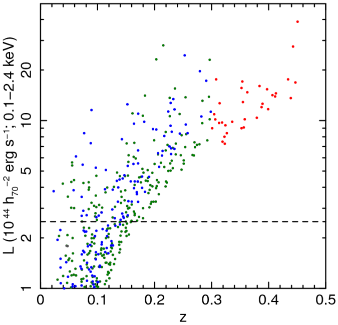






Survey data



Continuous and complete redshift coverage for $z < 0.5$

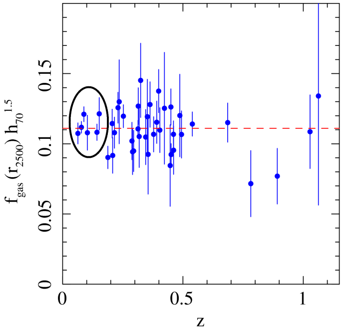
X-ray flux limited cluster samples from the ROSAT All-Sky Survey:

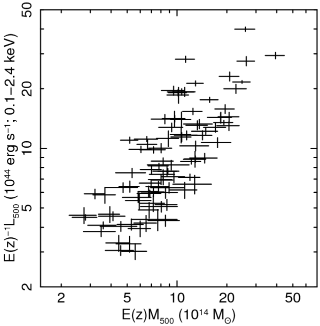
- BCS (Ebeling et al. '98)
  $z < 0.3$
  $\sim 33\%$ sky coverage
  $F > 4.4 \times 10^{-12}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$
- REFLEX (Böhringer et al. '04)
  $z < 0.3$
  $\sim 33\%$ sky coverage
  $F > 3.0 \times 10^{-12}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$
- Bright MACS (Ebeling et al. '10)
  $0.3 < z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

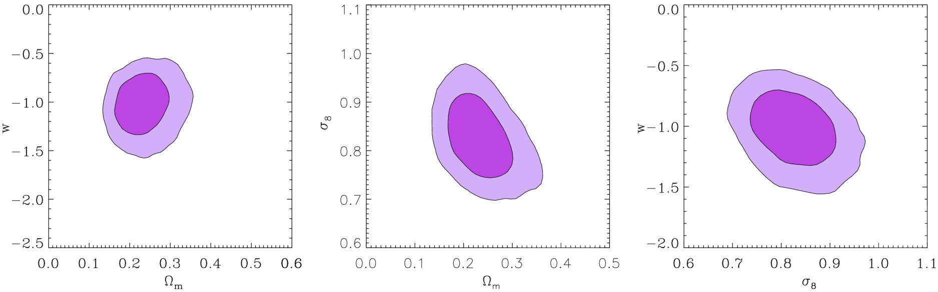
Mass calibration

For this work we simply took advantage of the low-scatter $M_{\rm gas}$ vs. $M_{\rm tot}$ calibration from earlier, and targeted Chandra or ROSAT observations of 94 of the survey clusters.





Results

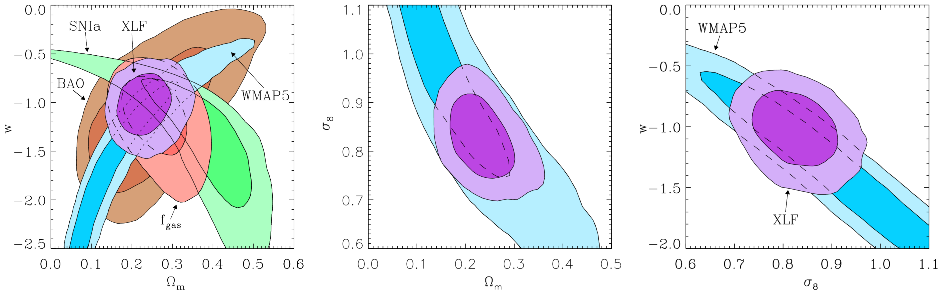


238 clusters, $z < 0.5$
Including systematics

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

(AM+ 2010)

Results



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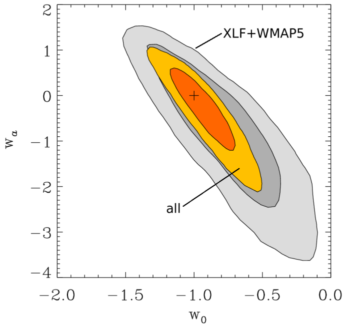
(AM+ 2010)

Evolving w models



$$w(a) = w_0 + w_a(1 - a)$$

Clusters + WMAP5:

$$w_0 = -0.77 \pm 0.31$$
$$w_a = -0.34^{+0.72}_{-1.42}$$

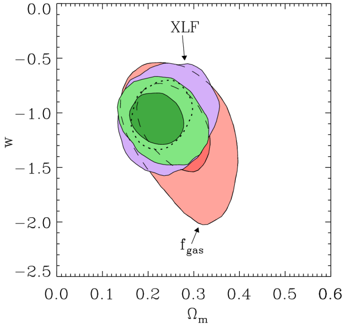
$\ldots +$ SNIa + f_{gas} + BAO:

$$w_0 = -0.93 \pm 0.16$$
$$w_a = -0.13^{+0.47}_{-0.73}$$

(AM+ 2010)

Summary of cluster DE results

Complementary probes providing independent confirmation of acceleration and dark energy.



Combined cluster data: $w = -1.06 \pm 0.15$

(AM+ 2010)

Outline

Constraining gravity

Cosmological data now probe both the expansion and the direct action of gravity at late times. This permits:

- More complete constraints on real dark energy and modified gravity models.
- Independent consistency tests of expansion and growth against the concordance model prediction.

Constraining gravity

Cosmological data now probe both the expansion and the direct action of gravity at late times. This permits:

- More complete constraints on real dark energy and modified gravity models.

  Challenging, but being worked on.
- Independent consistency tests of expansion and growth against the concordance model prediction.

  Rapetti et al. '09, '10, '12.

The basic idea

In the concordance flat ΛCDM model, $\Omega_{\rm m}$, Ω_Λ etc. determine

1. the average expansion

$$H^2(z) = H_0^2 \left[\Omega_{\rm m}(1+z)^3 + \Omega_\Lambda\right]$$

2. growth of density perturbations

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

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In the concordance flat ΛCDM model, $\Omega_{\rm m}$, Ω_Λ etc. determine everything, but we can always generalize somehow.

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$$H^2(z) = H_0^2\left[\Omega_{\rm m}(1+z)^3 + \Omega_{\rm de}(1+z)^{3(1+w)}\right]$$

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$$\frac{d\delta}{da} \approx \frac{\delta}{a}\Omega_{\rm m}(a)^{0.55}$$

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2. growth of density perturbations (Peebles c. 1980)

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

Constraining γ (or γ and w) provides a test of the late-time, scale-independent growth, independent of the expansion history.

Types of data

- Clusters probe the amplitude of the density field at one scale, as a function of z.
- The CMB has some sensitivity due to the ISW effect.
- Galaxy redshift space distortions probe a combination of the density and velocity fields.

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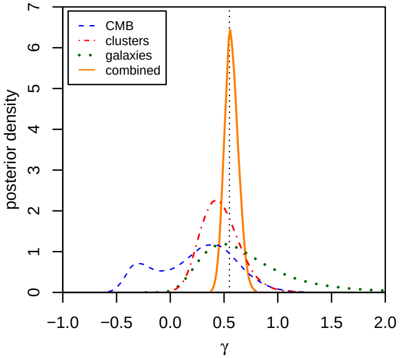
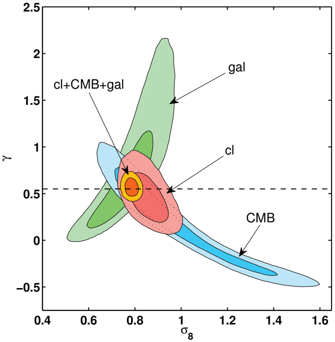
- Clusters probe the amplitude of the density field at one scale, as a function of z.
  $f_{\rm gas}$ + growth data from earlier, plus H_0 and BBN priors
- The CMB has some sensitivity due to the ISW effect.
  WMAP 5 year data set
- Galaxy redshift space distortions probe a combination of the density and velocity fields.
  RSD and AP from WiggleZ, 6df and BOSS ($+H_0$ prior)

Results

Marginalizing over a ΛCDM expansion model:





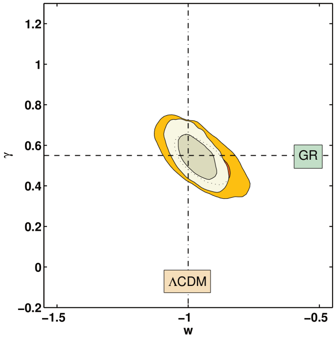
Combined data:

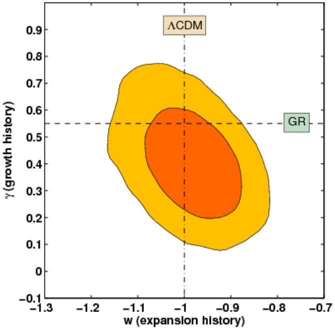
$$\sigma_8 = 0.784 \pm 0.019$$
$$\gamma = 0.561 \pm 0.061$$

(Rapetti+ 2012)

Results

Marginalizing over a constant-w expansion model:





Combined data (plus snIa, BAO):

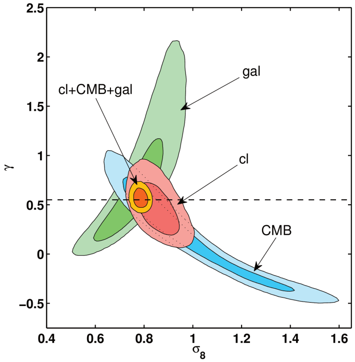
$$\begin{aligned} \sigma_8 &= 0.783 \pm 0.019 \\ \gamma &= 0.546 \pm 0.072 \\ w &= -0.97 \pm 0.05 \end{aligned}$$

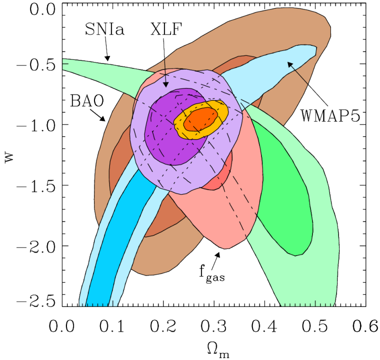
Rapetti 2010
(w/o galaxy survey data)

(Rapetti+ 2012)

Summary

Growth index constraints are getting there!





Joint constraints on $\gamma \sim 10\%$

Joint constraints on $w \sim 5\%$