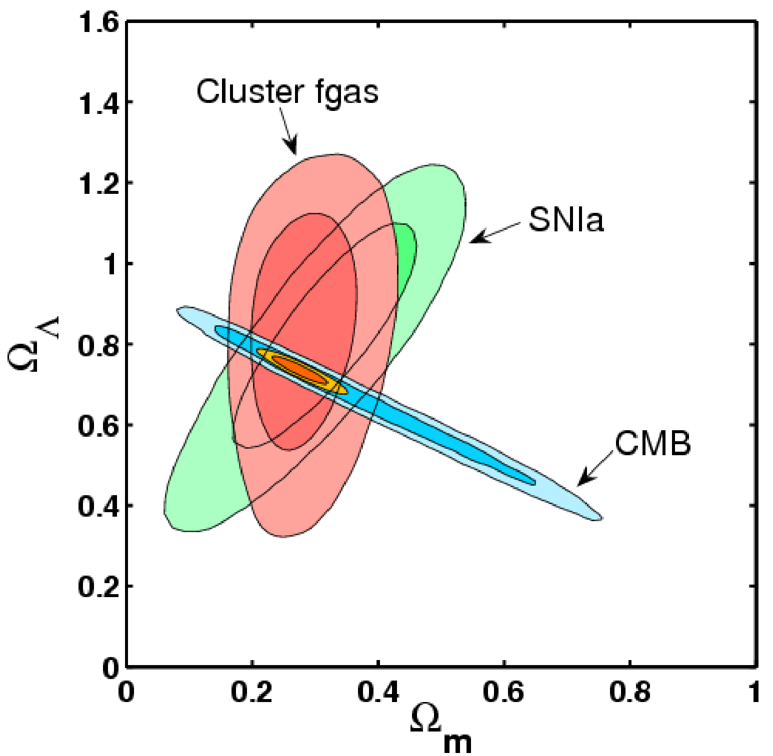
Cluster Distance Measurements

Steve Allen (Stanford/SLAC)



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(+ many more)

Outline of talk:

I will discuss two ways to measure distances with galaxy clusters.

These are complementary to the more familiar tests based on cluster counts, i.e. the mass function and clustering.

1) Measurements of the baryonic mass fraction in the largest dynamically relaxed clusters (a.k.a. the fgas test).

2) Combined X-ray and SZ measurements of the Compton y-parameter (a.k.a. the XSZ test).

For further info: Allen, Evrard & Mantz, 2011, ARA&A, 49, 409.

Cluster Distance Measurements

1. The fgas experiment

Featured work: Allen et al. 2008, MNRAS, 383, 879

See also e.g. White & Frenk ’91; Fabian ’91; Briel et al. ’92; White et al ’93; David et al. ’95; White & Fabian ’95; Evrard ’97; Mohr et al ’99; Ettori & Fabian ’99; Roussel et al. ’00; Grego et al ’00; Allen et al. ’02, ’04; Ettori et al. ’03, ‘09; Sanderson et al. ’03; Lin et al. ’03; LaRoque et al. ’06 …

Constraining cosmology with f_{gas} measurements

BASIC IDEA: galaxy clusters are so large that their matter content should provide a ~ fair sample of matter content of Universe.

Define: $$f_{gas} = \frac{\text{X-ray gas mass}}{\text{total cluster mass}}$$ and $$f_{star} = \frac{\text{stellar mass}}{\text{total cluster mass}}$$

Then: $$f_{baryon} = f_{star} + f_{gas} = f_{gas}(1+s)$$

Since clusters provide ~ fair sample of Universe: $$f_{baryon} = b\,\frac{\Omega_b}{\Omega_m}$$

Simulations

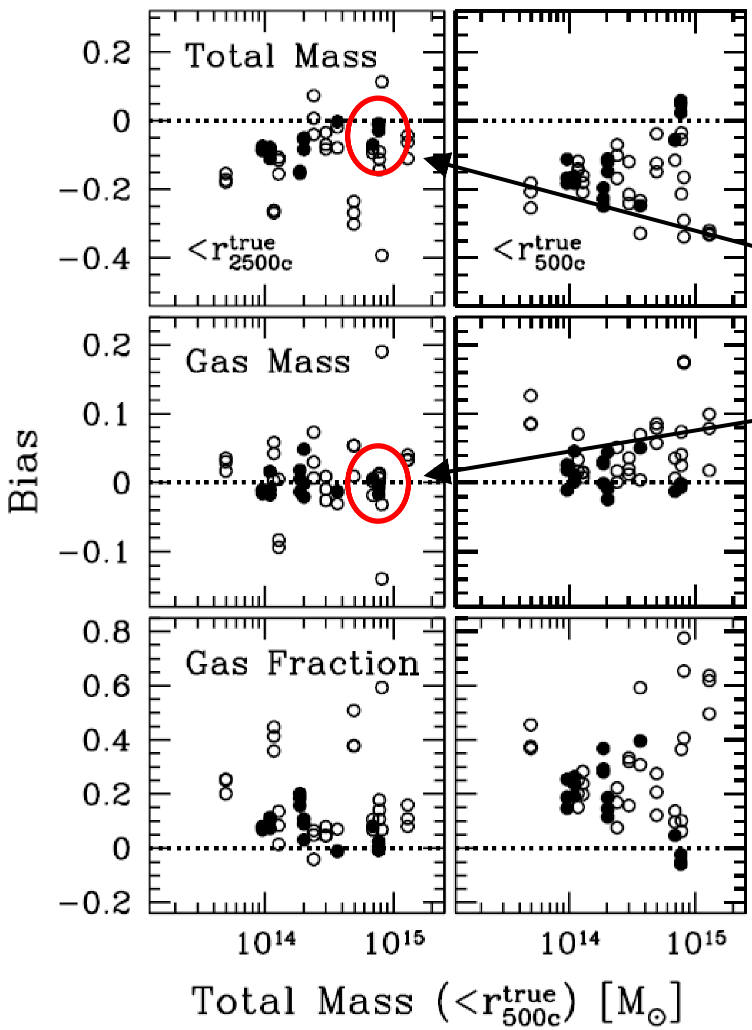
$$f_{gas} = \frac{b}{(1+s)}\,\frac{\Omega_b}{\Omega_m}$$

BBNS/CMB

Measure

For relaxed clusters, HSE modeling → precise masses

Nagai, Vikhlinin & Kravtsov '07



Relaxed clusters (filled circles)

For <u>largest, relaxed clusters</u> (selected on X-ray morphology) measured at r_{2500}

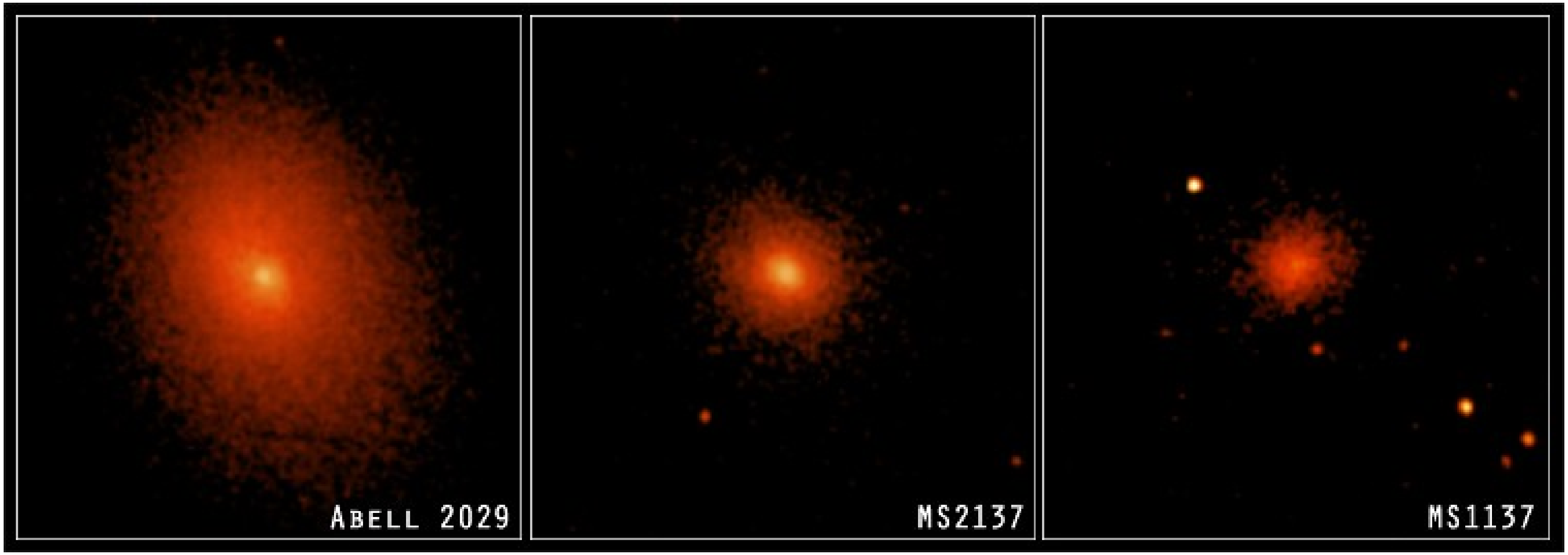
X-ray data + hydrostatic eq. →

Total mass and fgas to better 10 % accuracy (both bias and scatter).

X-ray gas mass to few % accuracy.

Note: weak gravitational lensing data can in principle also aid absolute mass calibration for ensembles of clusters.

The observations

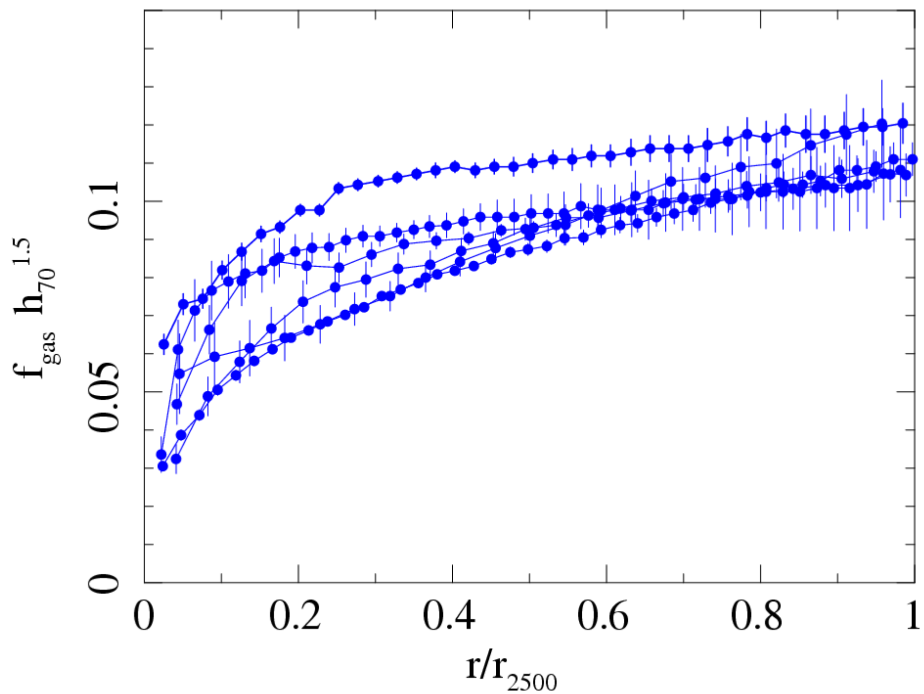


1.6Ms of Chandra data for 42 hot (kT>5keV), dynamically relaxed clusters spanning redshift range 0<z<1.1.

Selected on X-ray morphology: sharp central X-ray surface brightness peaks, minimal X-ray isophote centroid variations and high overall symmetry.

Restriction to hot, relaxed clusters minimizes all systematic effects.

Chandra results on f_{gas}(r)



6 lowest redshift relaxed clusters ($0<z<0.15$) :

f_{gas}(r) → approximately universal value at r_{2500}

Fit constant value at r_{2500}

$f_{gas}(r_{2500})=(0.113\pm0.003)h_{70}^{-1.5}$

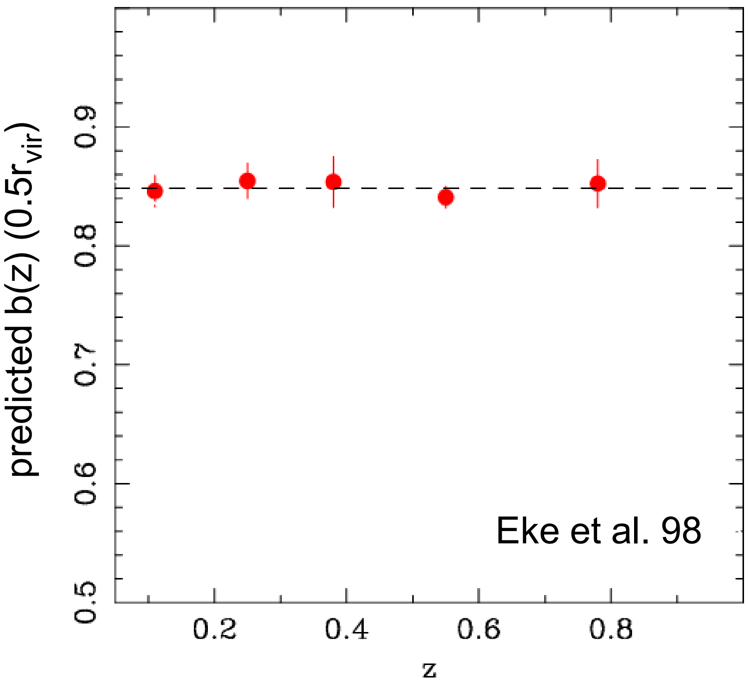
For $\Omega_b h^2=0.0214\pm0.0020$ (Kirkman et al. '03), $h=0.72\pm0.08$ (Freedman et al. '01), $s=0.16\pm0.05$ (Lin & Mohr '04) and $b=0.83\pm0.09$ (Eke et al. '98 +10% systematics)

$$\Omega_m = \frac{(0.83\pm0.09)(0.0437\pm0.0041)h_{70}^{-0.5}}{(0.113\pm0.003)(1+[0.16\pm0.05]h_{70}^{0.5})} = 0.27\pm0.04$$

Distances and dark energy with $f_{gas}(z)$

The measured f_{gas} values depend upon the assumed distances to clusters as $f_{gas} \propto d^{1.5}$, which brings sensitivity to dark energy through the *d(z)* relation. To use this information, we need to know the expected $f_{gas}(z)$.

What do we expect to observe?

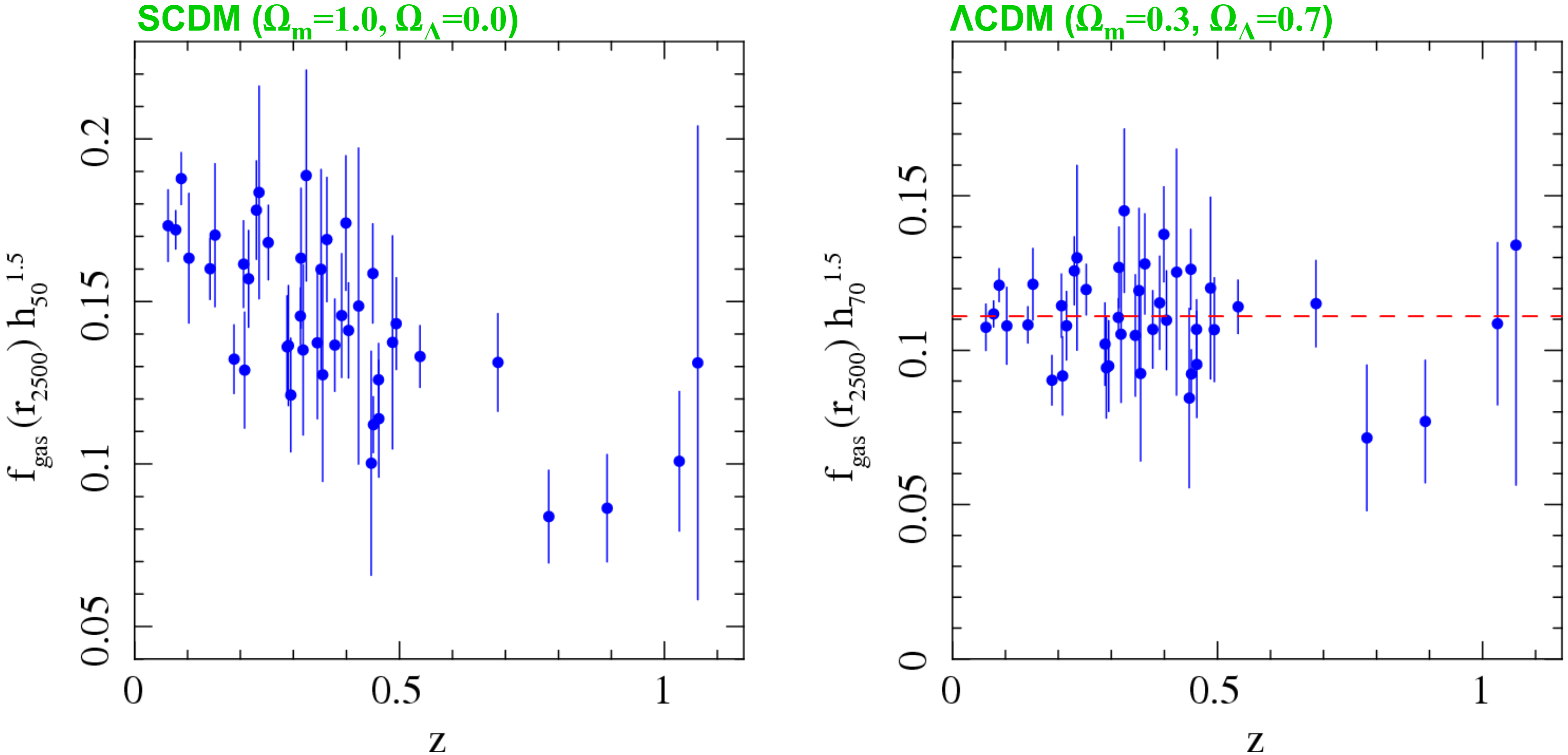


Simulations:

For large (kT>5keV) clusters, we expect b(z) and therefore $f_{gas}(z)$ to be approximately constant with z.

The precise prediction of b(z) is a key task for hydro. simulations. See e.g. Battaglia et al. 2013, Planelles et al. 2013.

Chandra results on $f_{gas}(z)$ at r_{2500}



Brute-force determination of $f_{gas}(z)$ for two reference cosmologies:

→ Inspection clearly favours ΛCDM over SCDM cosmology.

To quantify: fit data with model which accounts for apparent variation in $f_{gas}(z)$ as underlying cosmology is varied → find best fit cosmology.

$$f_{\mathrm{gas}}(\mathrm{z}) = \frac{KA\beta b(z)}{1+s(z)} \left(\frac{\Omega_{\mathrm{b}}}{\Omega_{\mathrm{m}}} \right) \left[\frac{d_{\mathrm{A}}^{\mathrm{LCDM}}(z)}{d_{\mathrm{A}}^{\mathrm{model}}(z)} \right]^{1.5}$$

For details see Allen et al. (2008).

Allowances for systematic uncertainties

Our analysis includes a conservative treatment of potential sources of systematic uncertainty (marginalized over in analysis).

1) The depletion factor (simulation physics, feedback processes etc.)

$b(z)=b_0(1+\alpha_b z)$ ± 20% uniform prior on b_0 (simulation physics)
±10% uniform prior on α_b (simulation physics)

2) Baryonic mass in stars: define $s= f_{star}/f_{gas} =0.16h_{70}^{0.5}$

$s(z)=s_0(1+\alpha_s z)$ ± 30% Gaussian uncertainty in s_0 (observational uncertainty)
± 20% uniform prior on α_s (observational uncertainty)

3) Non-thermal pressure support in gas: (primarily bulk motions)

$\beta = M_{true}/M_{X\text{-}ray}$ 10% (standard) or 20% (weak) uniform prior [$1<\gamma<1.2$]

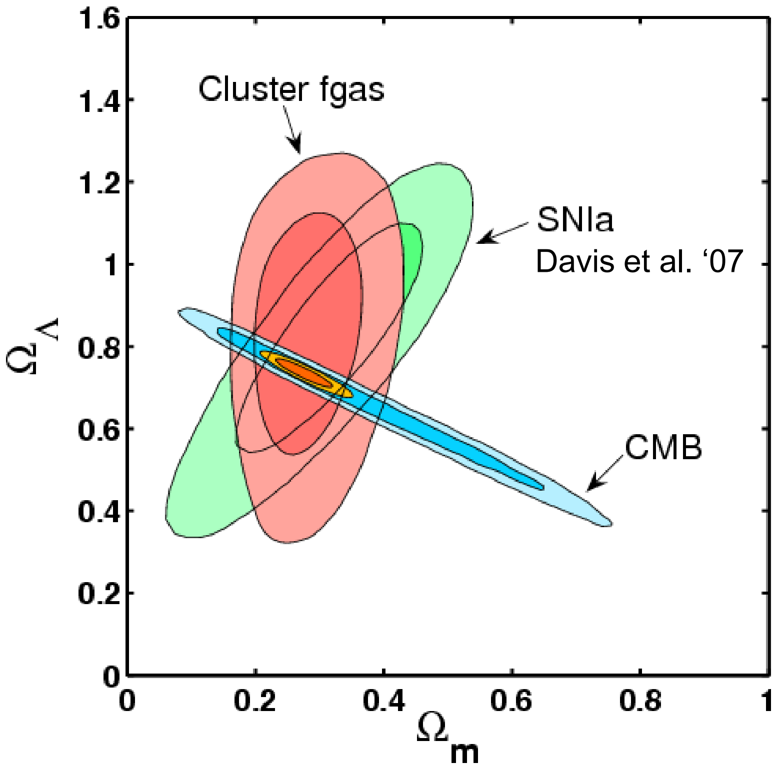
4) Instrument calibration, X-ray modelling

K ± 10% Gaussian uncertainty

With these (conservative) allowances for systematics

Model:

$$f_{\mathrm{gas}}(z) = \frac{KA\beta b(z)}{1+s(z)} \left(\frac{\Omega_b}{\Omega_m} \right) \left[\frac{d_A^{\mathrm{LCDM}}(z)}{d_A^{\mathrm{model}}(z)} \right]^{1.5}$$



Results (ΛCDM)

Including all systematics + standard priors:
($\Omega_b h^2$=0.0214±0.0020, h=0.72±0.08)

Best-fit parameters (ΛCDM):

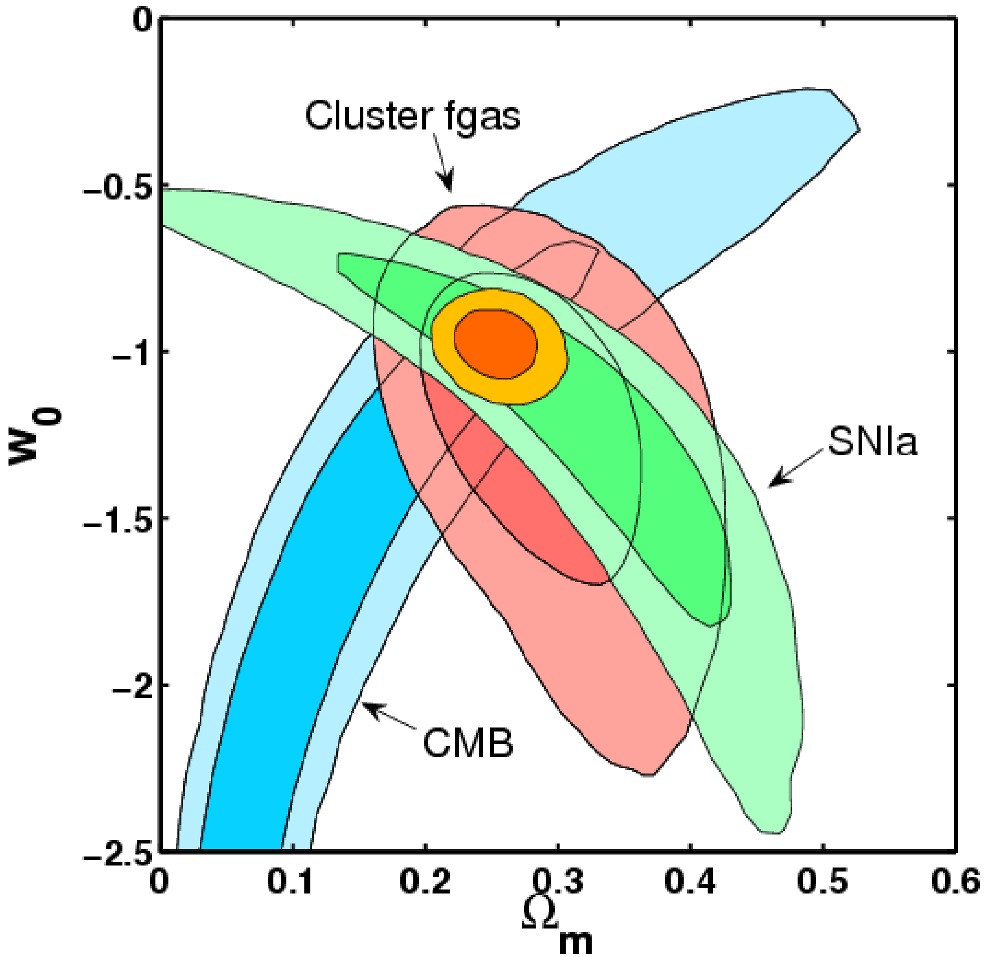
Ω_m=0.27±0.06, Ω_Λ=0.86±0.19

(Note also good fit: χ^2=41.5/40)

Result limited by b(z),K priors

Important

Dark energy equation of state



Constant w model (flat):

68.3, 95.4% confidence limits for all three data sets consistent with each other.

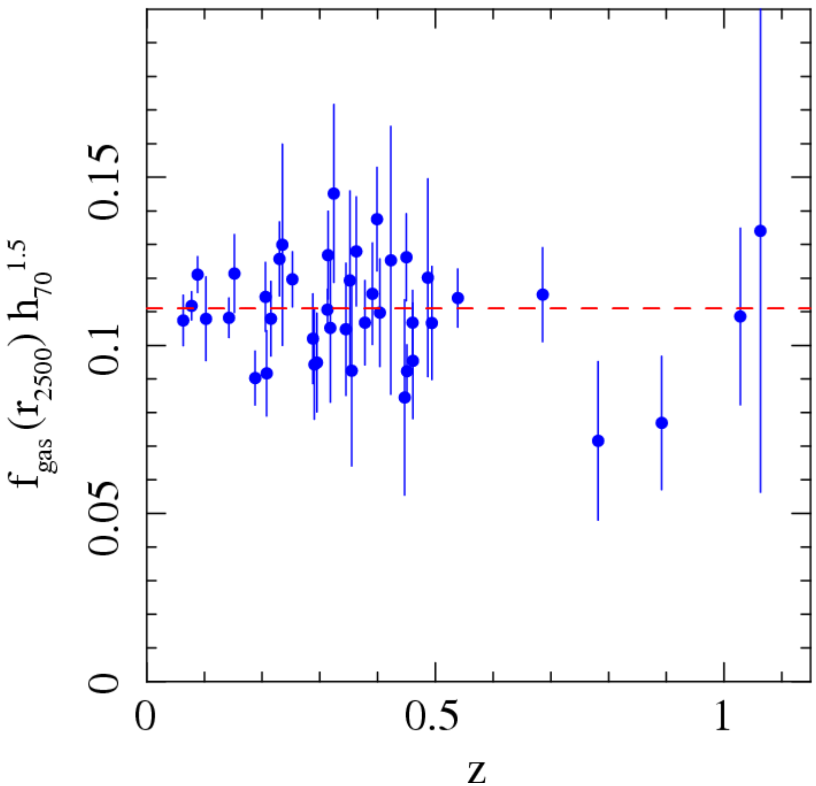
Combined constraints (68%)

$$\Omega_m = 0.253 \pm 0.021$$
$$w_0 = -0.98 \pm 0.07$$

Results marginalized over all systematic uncertainties.

Note: combination with CMB data removes the need for $\Omega_b h^2$ and h priors.

f_{gas}(z) distances have low systematic scatter.



χ^2 for best fit acceptable.
Intrinsic scatter is undetected.

68% upper limit on fgas scatter
σ_{fgas}~10% (7% in distance).

(Consistent with expectations from hydro. simulations)

fgas $\rightarrow$ precise tracer of expansion history (individually, better than SNIa?).

Mgas $\rightarrow$ excellent mass proxy for hot, massive clusters.

Mantz et al., in preparation.

(5 year project, just unblinded.)

Expanded sample: 3x more fgas data.

Automated target selection applied to archives (20Ms of observations).

Optimized X-ray analysis engine.

Improved external priors.

Blind analysis: fgas(r) measurements unblinded Feb 2013.

Cluster Distance Measurements

2. The XSZ experiment

See also e.g. Silk & White 1978, Cavaliere et al. 1979, Myers et al. 1997, Mauskopf et al. 2001, Mason et al. 2001, Jones et al. 2001, Carlstrom et al. 2002, Reese et al. 2002, Schmidt et al. 2004, Bonamente et al. '06 …

X-ray+SZ distance measurements

The thermal SZ effect is a modification to the CMB spectrum caused by Compton scattering by hot electrons in the ICM.

BASIC IDEA: The SZ flux measured at mm wavelengths can be expressed in terms of the Compton y-parameter. For a given reference cosmology, the y-parameter can also be determined independently from X-ray observations.

$$\boxed{y_{\mathrm{ref}}^{\mathrm{X\text{-}ray}} \propto \int n_e T dl}$$

For the correct reference cosmology, the X-ray and mm values should be equal. Expressing the distance dependence of the X-ray measurement we have

$$\boxed{\left(\frac{d_{\mathrm{true}}}{d_{\mathrm{ref}}}\right)^{0.5} = k(z)\,\frac{y^{\mathrm{SZ}}}{y_{\mathrm{ref}}^{\mathrm{X\text{-}ray}}}}$$

Systematics (geometry, calibration, clumping etc)

X-ray+SZ distance measurements

Note 1: the best clusters to observe for the XSZ experiment are the *same clusters* * used for the fgas experiment, i.e. the largest, most dynamically relaxed clusters (strongest SZ signals and minimal systematics associated with thermodynamic structure and geometry).

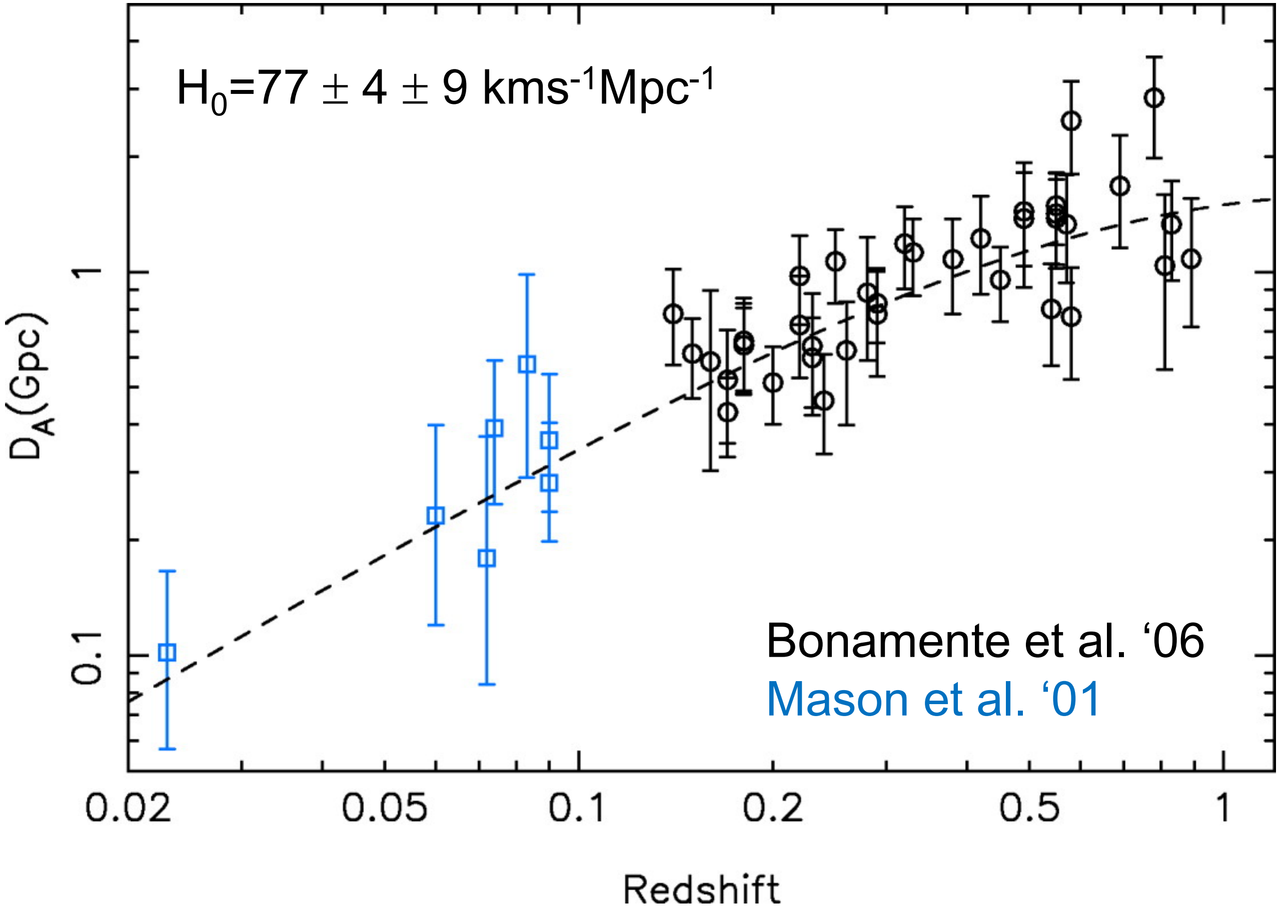
Note 2: since the distance dependence for the XSZ experiment is weaker than for the fgas experiment ($d^{0.5}$ vs. $d^{1.5}$) it has less intrinsic cosmological constraining power.

However, the XSZ experiment has different systematic uncertainties and used in combination with fgas data brings enhanced robustness and some degeneracy breaking power.

* The same X-ray data can (should) be utilized by both experiments.

X-ray+SZ distance measurements

Bonamente et al. '06



Prospects

Featured work: Rapetti et al. 2008, MNRAS, 388, 1265

Longer term prospects

Assuming that Chandra/XMM-Newton are extended into 2020s, one can envisage a program like the following. (For a next generation X-ray mission the plans would be more ambitious.)

STAGE 1:

Short X-ray exposures of the ~thousand hottest, X-ray brightest or highest SZ flux clusters detected in surveys like eROSITA and SPT-3G.

→ mass proxy information for standard cluster tests: Lx, gas mass, gas temperature, Yx (product of gas mass and mean temperature).

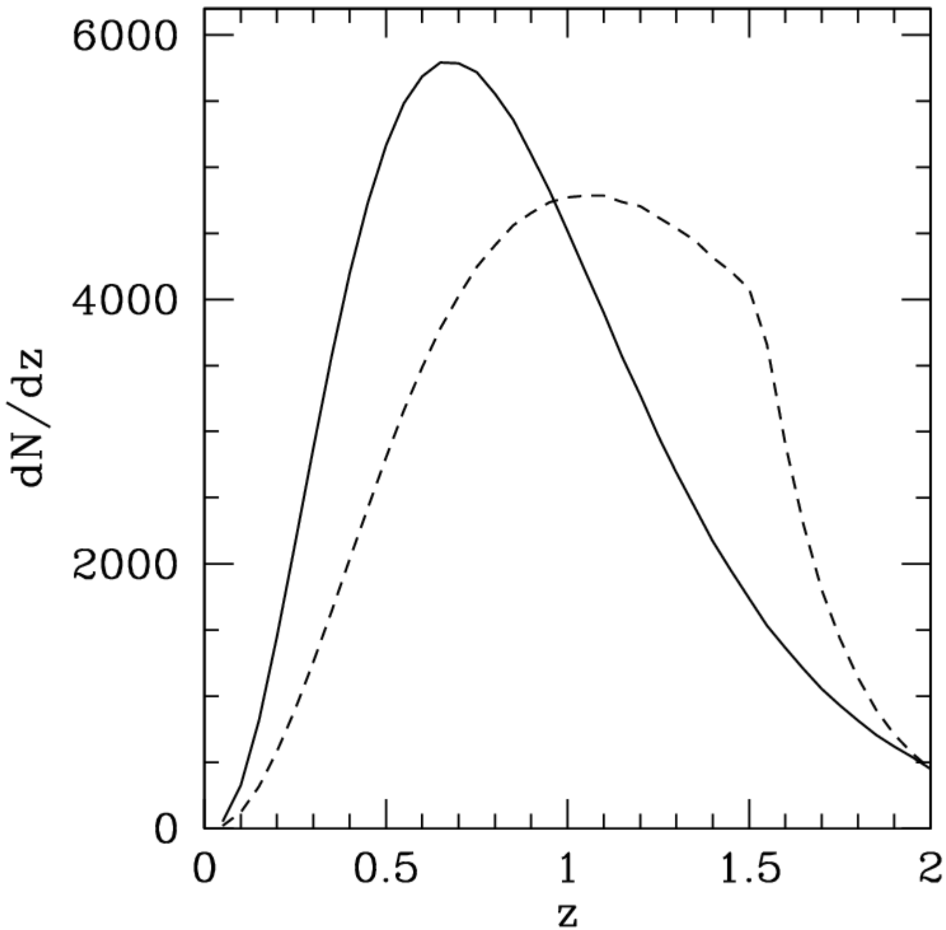
→ identify ~200 most relaxed systems (morphology + velocity width).

STAGE 2:

Deeper follow-up of ~200 most relaxed clusters.

→ sufficient to measure fgas(r) and predict Compton y-parameter to ~10% precision (~7% in distance).

Redshift distribution of target clusters



Target clusters provided by eROSITA flux limited X-ray survey.

Solid curve shows >5 keV clusters (same kT range used with present data).

Density of target clusters peaks at z~0.7.

Rapetti et al. 2008, MNRAS, 388, 1265

DETF figure of merit for cluster distance measurements.

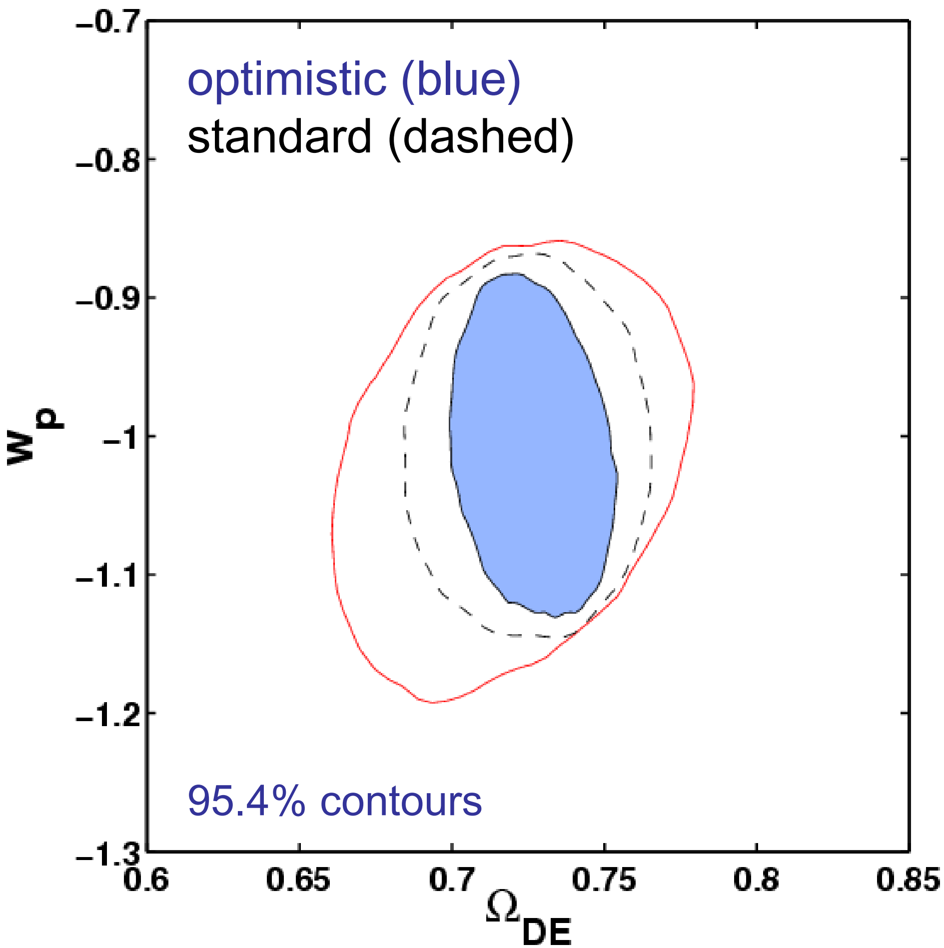
FoM calculations in the style of the Dark Energy Task Force (DETF).

A next generation (IXO-like) X-ray experiment with 500 clusters observed to 5% fgas precision is assumed. Following the DETF, `Planck priors' and `optimistic', `standard' and `pessimistic' systematics are allowed. Results shown are based on full MCMC simulations.

Cluster	Parameter	Allowance (optimistic/standard/pessimistic)	Type
$f_{\rm gas}$ EXPERIMENT			
Calibration/Modelling	K	$1.0 \pm 0.02/\pm 0.05/\pm 0.10$	Gaussian
Non-thermal pressure	γ	$0.96 < \gamma < 1.04/0.92 < \gamma < 1.08$	uniform
Gas depletion: norm.	b_0	$0.82 \times (1 \pm 0.02/\pm 0.05/\pm 0.10)$	uniform
Gas depletion: evol. (linear)	$\alpha_{\rm b}$	$\pm 0.02/\pm 0.05/\pm 0.10$	uniform
Gas depletion: evol. (quadratic)	$\beta_{\rm b}$	$\pm 0.02/\pm 0.05/\pm 0.10$	uniform
Stellar mass: norm.	s_0	$0.16 \times (1 \pm 0.02/\pm 0.05/\pm 0.10)$	Gaussian
Stellar mass: evol. (linear)	$\alpha_{\rm s}$	$\pm 0.02/\pm 0.05/\pm 0.10$	uniform
Stellar mass: evol. (quadratic)	$\beta_{\rm s}$	$\pm 0.02/\pm 0.05/\pm 0.10$	uniform
XSZ EXPERIMENT			
Calibration/Modelling	k_0	$1.0 \pm 0.02/\pm 0.05$	Gaussian
evolution (linear)	$\alpha_{\rm k}$	$\pm 0.02/\pm 0.05/\pm 0.10$	uniform

Rapetti et al. 2008, MNRAS, 388, 1265

DETF figure of merit for cluster distance measurements.



$$FoM=[\sigma(w_p) x \sigma(w_a)]^{-1}$$

$w_p=w(a_p)$; minimal $\sigma(w(a))$.

	$\sigma(\Omega_{DE})$	$\sigma(w_p)$	FoM
Optim.	0.009	0.044	38.5
Pessim.	0.023	0.058	25.2

Comparable to constraints for other methods: DETF (opt./pes.)

Rapetti et al. 2008, MNRAS, 388, 1265