IV. Baryon Fraction Tests

Course Overview

Observations of galaxy clusters (primarily in X-rays) for cosmological tests

- ★ Cosmological primer
  - incomplete overview of parts of cosmology important for cluster studies
- ★ Galaxy clusters and their observation
  - mass determinations
- ★ Cluster baryon fraction tests
  - constraints on matter density and standard bucket
- ★ Cluster mass function
  - growth of structure and volume tests

Baryon Fraction Tests

- ★ Early constraints on Ω_M
- ★ Clusters as a “standard bucket”
- ★ Observational results
- ★ Caveats

Constraining Ω_M

Standard big bang theory accurately predicts abundances of light elements produced in first few minutes via nucleosynthesis

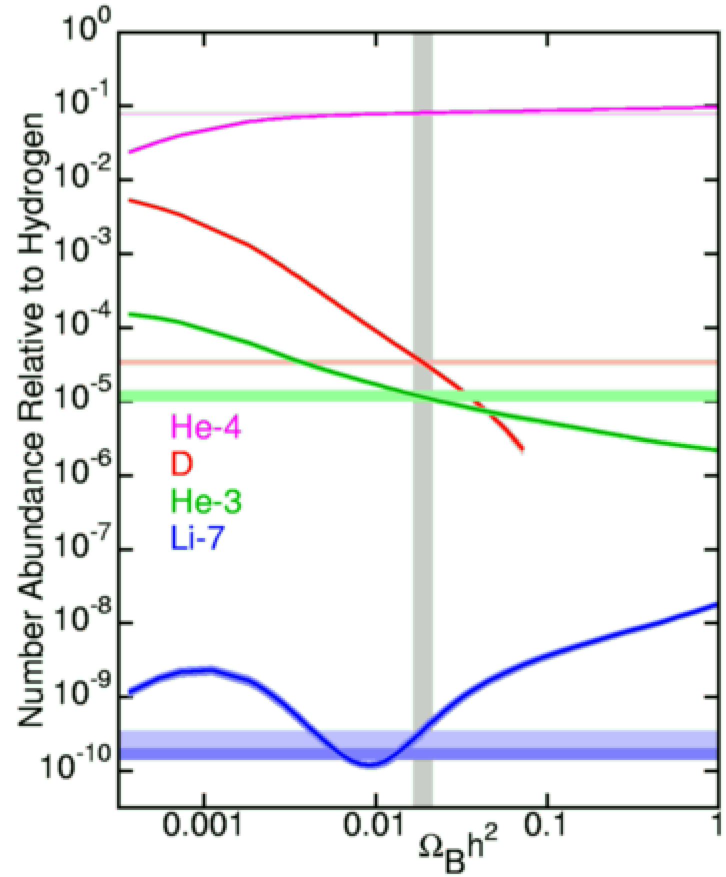
- ★ Tight theoretical and observational constraints on Ω_b
  - ratio of baryon density to critical density

$$\Omega_b = \frac{\rho_b}{\rho_c}$$

Constraining Ω_M

Present abundances of light element isotopes depends on Ω_b

- ★ curves show theoretical dependence
- ★ lines show measured abundances
- ★ current best estimate $\Omega_b = 0.044$ (e.g. Kirkman et al, 2003, ApJS, 149



Constraining Ω_M

Theory + observations strongly suggest Universe is flat (Ω_{tot} = 1)

★ Ω_b << 1 so majority of matter/energy density is non-baryonic

Matter density comprises baryonic and dark matter:

$$\Omega_M = \Omega_b + \Omega_{dark}$$

In early 1990's, flat models with Ω_{tot} = Ω_M = 1 popular

Constraining Ω_M

Galaxy clusters are largest objects for which masses determined

- ★ large enough to assume enclose representative volume of Universe

This means ratio of baryonic mass to total mass in cluster (f_b) should match universal ratio:

$$f_b = \frac{M_b}{M_{tot}} = \frac{\Omega_b}{\Omega_M}$$

Thus can attempt to measure f_b and use Ω_b to determine Ω_M

Constraining Ω_M

White et al (1993, Nature, 366) made one of first attempts to measure Ω_M using f_b

- ★ used X-ray surface brightness profile to estimate gas mass

$$M_{gas} = 1.3 \times 10^{14} M_\odot$$

- ★ used total optical luminosity, and mass to light ratio to estimate stellar mass

$$M_{stars} = 1.4 \times 10^{13} M_\odot$$

- ★ used various methods (velocity dispersion, kT) to estimate total mass

$$M_{tot} = 1.6 \times 10^{15} M_\odot$$

Constraining Ω_M

$$f_b = \frac{M_b}{M_{tot}} = \frac{M_{gas} + M_{stars}}{M_{tot}}$$

This gave $f_b \sim 0.1$

- ⋆ implied $\Omega_M \sim 0.15$
- ⋆ strong evidence to abandon $\Omega_M = 1$

"Either the density of the Universe is less than that required for closure, or there is an error in the standard interpretation of element abundances."

(White et al 1993; Nature, 366, 429)

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(White et al 1993; Nature, 366, 429)

More recently, similar tests give $\Omega_M \sim 0.3$ (e.g. Sanderson & Ponman 2003, MNRAS, 345)

Constraining Ω_M

In 1930's, galaxy cluster observations showed

★ $M_b << M_{tot}$

i.e. dark matter required

★ $\Omega_b << \Omega_M$

In 1990's cluster observations showed

★ $\Omega_M < 1$

i.e. open Universe, or cosmological constant

In 2000's clusters used as standard buckets...

Standard Buckets

Assuming that clusters large enough to be representative, expect f_b to be same at all z

- ★ at least until reach z clusters forming
- ★ "standard bucket"
- ★ observational determination of f_b depends on distance to cluster
  - sensitive to E(z)

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- ★ observational determination of f_b depends on distance to cluster
  - ▸ sensitive to E(z)

If we know f_b, and measure z, then infer distance to cluster

- ★ constrain E(z), hence $\Omega_M, \Omega_\Lambda, w$

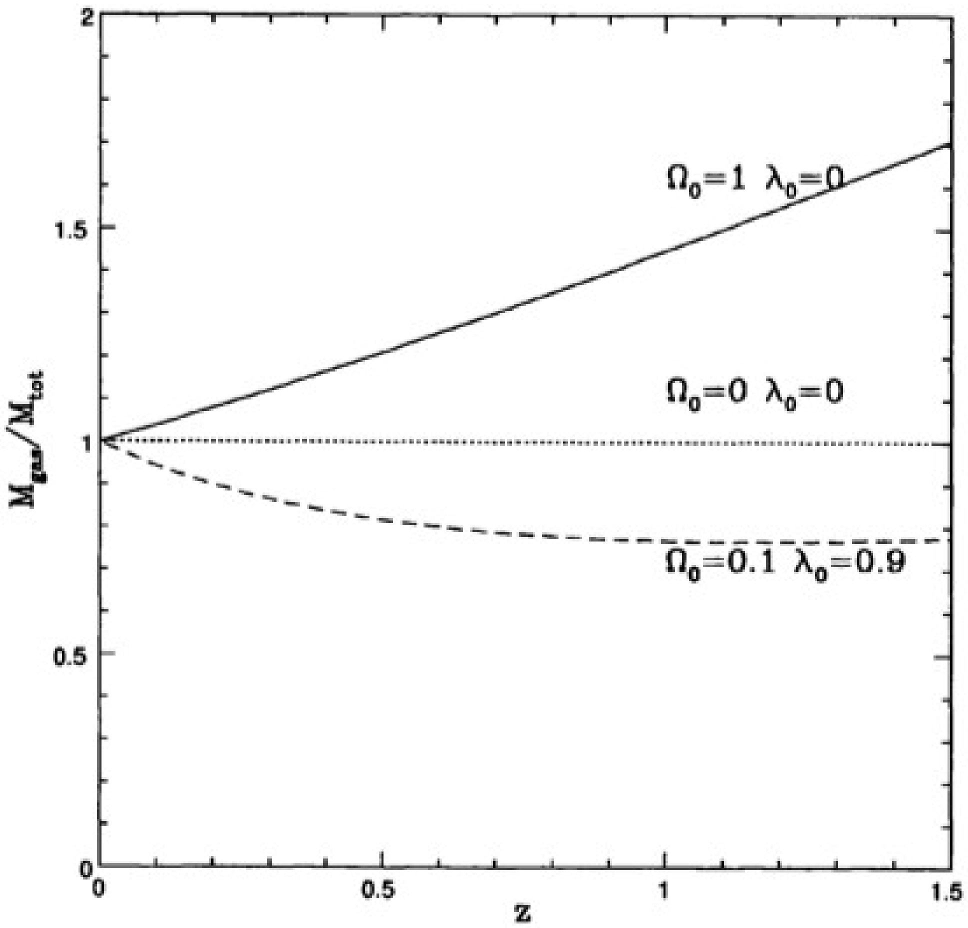
For strongest constraints, measure f_b for set of clusters at different z

Standard Buckets

Method first proposed by Sasaki (1996, PASJ, 48)

Artificial evolution in f_{gas} for different cosmologies

Only get constant f_{gas} with z if using correct cosmology



Distance Dependance of f_b

$$f_b = \frac{M_b}{M_{tot}} = \frac{M_{gas} + M_{stars}}{M_{tot}}$$

- ★ Measure M_{stars} from optical and M_{gas} from X-ray
- ★ Dominated by M_{gas} – measured value depends on d

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Consider spherical region of cluster, angular radius θ

- Physical (proper) radius of region is

$$R = \theta d_A$$

where d_A is angular diameter distance.

- The proper volume of the region is just

$$V = \frac{4}{3}\pi(\theta d_A)^3$$

Distance Dependance of f_b

Now M_{gas} is given by

$$M_{gas} = \rho_{gas} V$$

so

$$M_{gas} \propto \rho_{gas} (\theta d_A)^3$$

Distance Dependance of f_b

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so

$$M_{gas} \propto \rho_{gas} (\theta d_A)^3$$

and recall that gas density is related to the X-ray luminosity

$$L \propto \int n_p n_e dV \propto \rho_{gas}^2 V$$

and we can relate L to the observed flux F:

$$L = F \times 4\pi d_L^2$$

where d_L is the luminosity distance to the cluster

Distance Dependance of f_b

$$L \propto \int n_p n_e dV \propto \rho_{gas}^2 V \qquad L = F \times 4\pi d_L^2$$

Rearrange for ρ in terms of observables F and θ

$$\rho_{gas} \propto (L/V)^{1/2}$$

$$\rho_{gas} \propto \left(\frac{F d_L^2}{\theta^3 d_A^3}\right)^{1/2}$$

and finally

$$M_{gas} \propto \rho_{gas}(\theta d_A)^3 \propto (F\theta^3)^{1/2} d_L d_A^{3/2}$$

Distance Dependance of f_b

$$M_{gas} \propto (F\theta^3)^{1/2} d_L d_A^{3/2}$$

For a cluster with observed F within angular radius θ

$$M_{gas} \propto d_L d_A^{3/2}$$

Distance Dependance of f_b

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For a cluster with observed F within angular radius θ

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Can also show that if total mass is determined from X-ray hydrostatic analysis

$$M_{tot} \propto d_A$$

so the **estimated** value of the baryon fraction depends on distance as

$$f_{gas} = \frac{M_{gas}}{M_{tot}} \propto d_L d_A^{1/2}$$

Distance Dependance of f_b

$$f_{gas} = \frac{M_{gas}}{M_{tot}} \propto d_L d_A^{1/2}$$

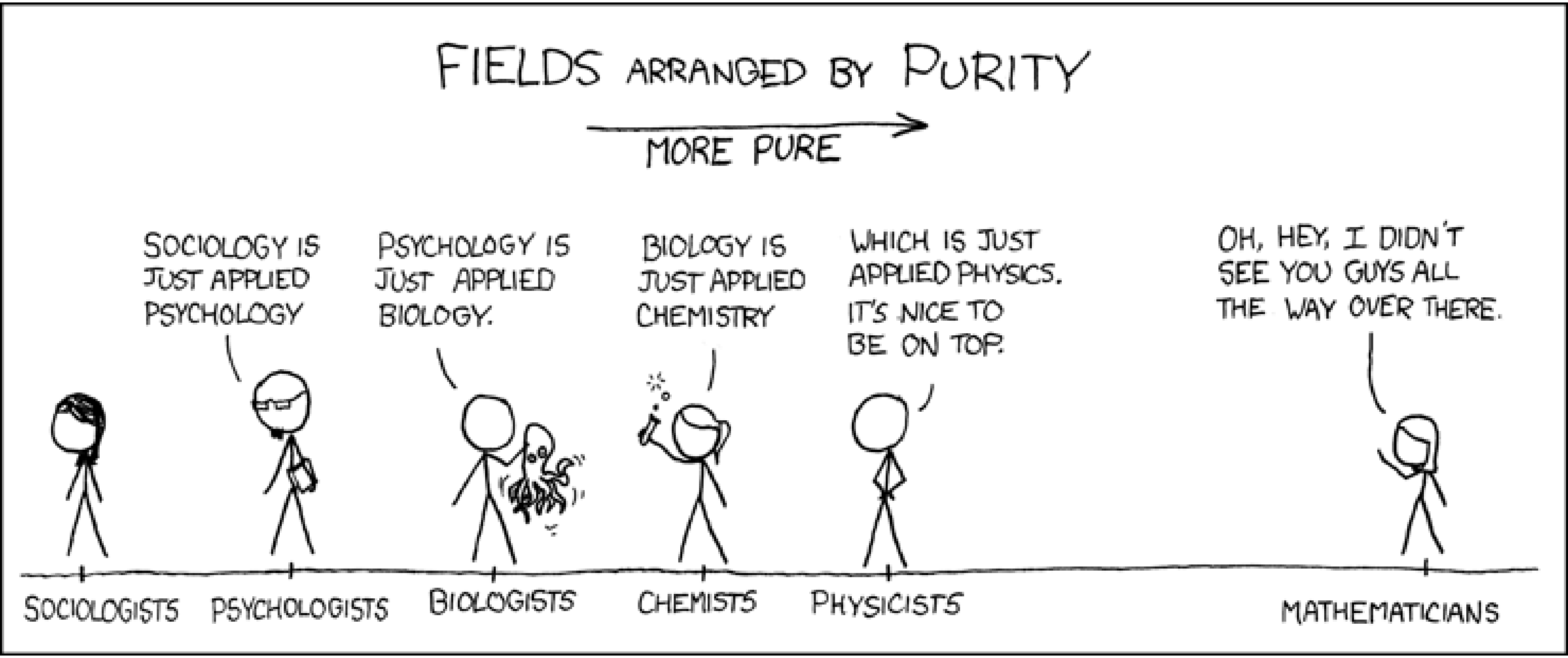
So to determine f_{gas} (or f_b) from X-ray observation of cluster at redshift z

★ need to know d_A, d_L to z

Instead, if we know f_b from theory, can determine d_A, d_L to z

★ constrain E(z)

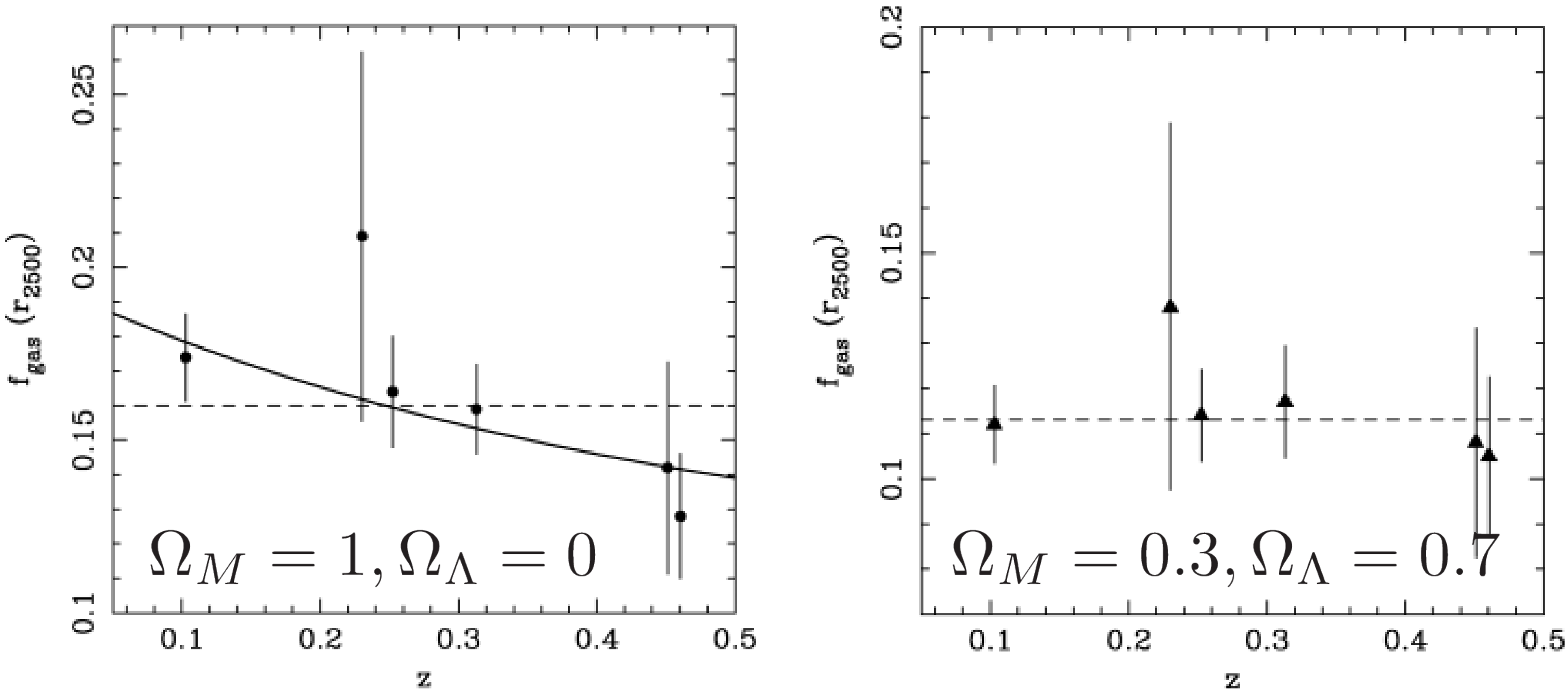
xkcd break



FIELDS ARRANGED BY PURITY
MORE PURE
SOCIOLOGY IS JUST APPLIED PSYCHOLOGY
PSYCHOLOGY IS JUST APPLIED BIOLOGY.
BIOLOGY IS JUST APPLIED CHEMISTRY
WHICH IS JUST APPLIED PHYSICS. IT'S NICE TO BE ON TOP.
OH, HEY, I DIDN'T SEE YOU GUYS ALL THE WAY OVER THERE.
SOCIOLOGISTS
PSYCHOLOGISTS
BIOLOGISTS
CHEMISTS
PHYSICISTS
MATHEMATICIANS

Experimental Results

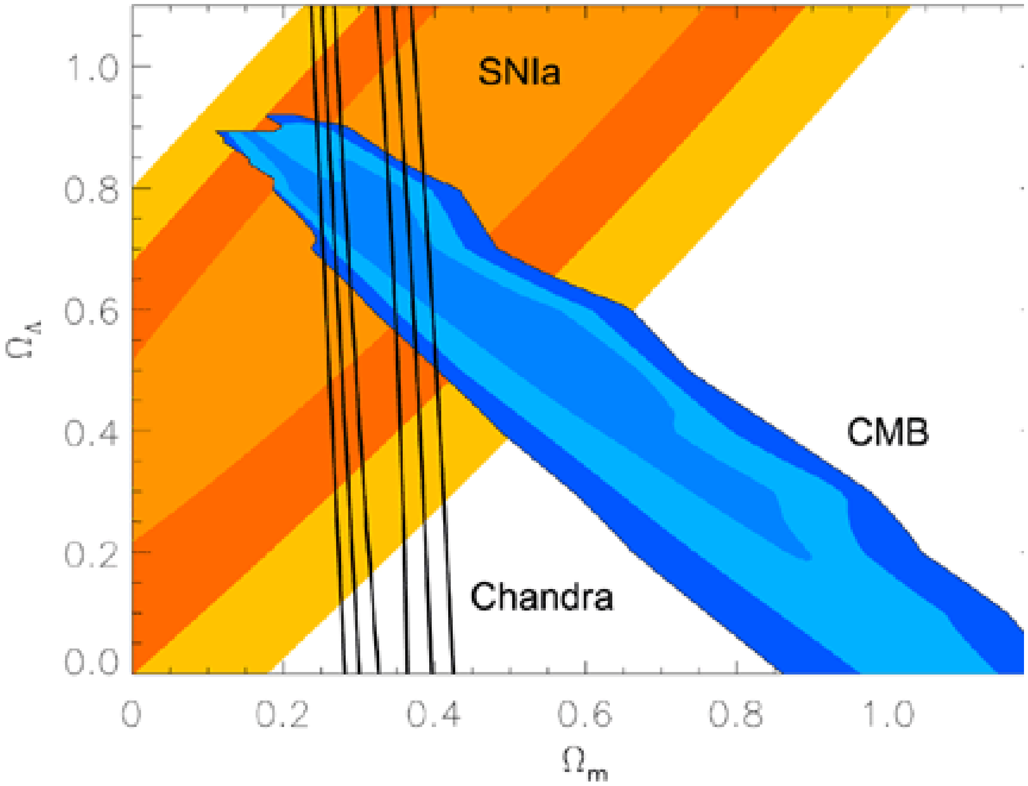
Allen et al. (2002) used 6 clusters for first study of $f_{gas}(z)$



Data favour $\Omega_M = 0.3, \Omega_\Lambda = 0.7$

Experimental Results

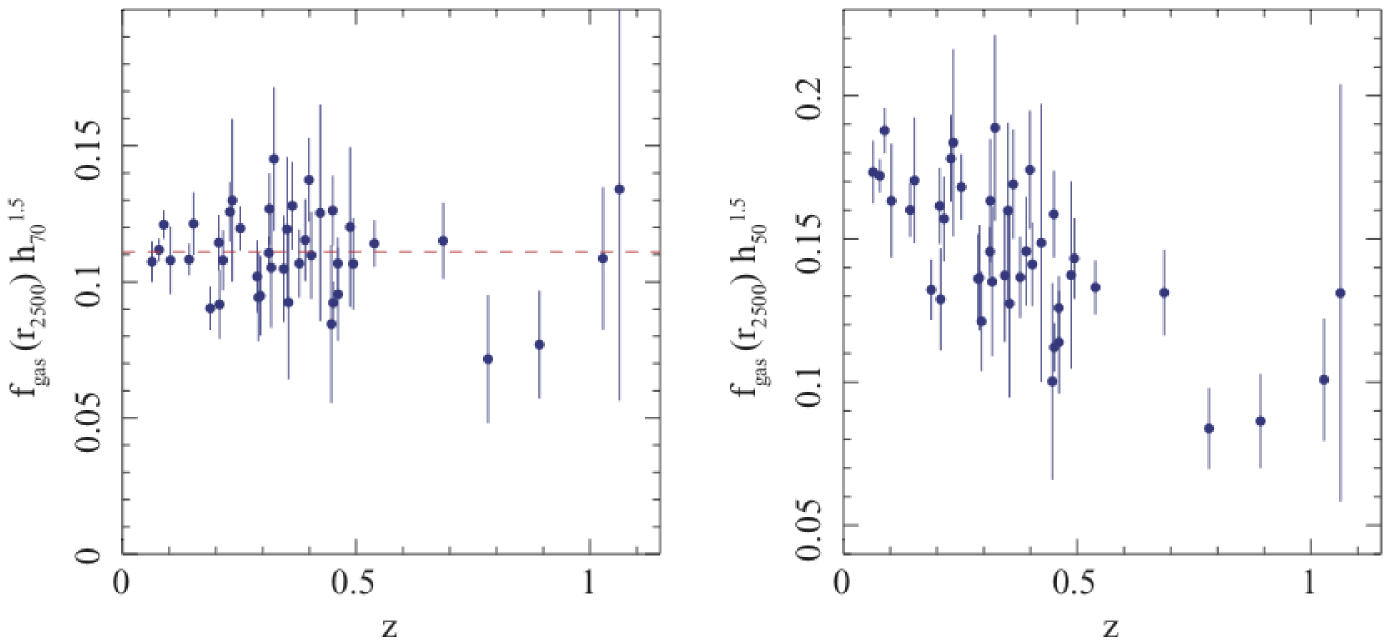
Solve for cosmological parameters that give constant $f_{gas}(z)$



$$\Omega_M = 0.30 \pm 0.04, \Omega_\Lambda = 0.95^{+0.48}_{-0.72}$$

Experimental Results

More recently Allen et al (2008) used 42 clusters at 0.05 < z < 1.1



$$\Omega_M = 0.3, \Omega_\Lambda = 0.7 \qquad \Omega_M = 1, \Omega_\Lambda = 0$$

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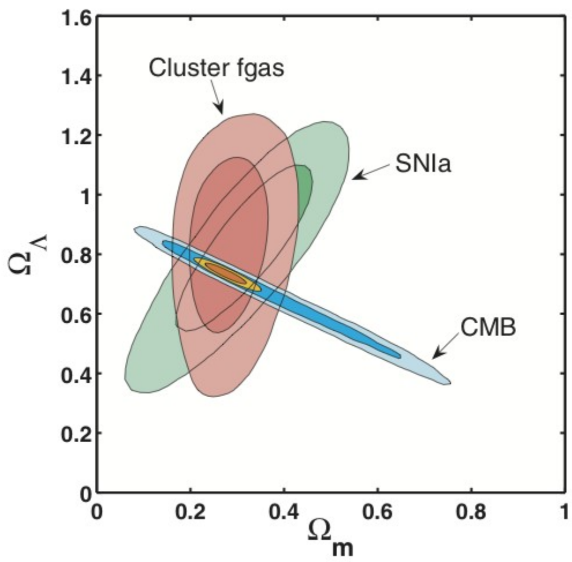
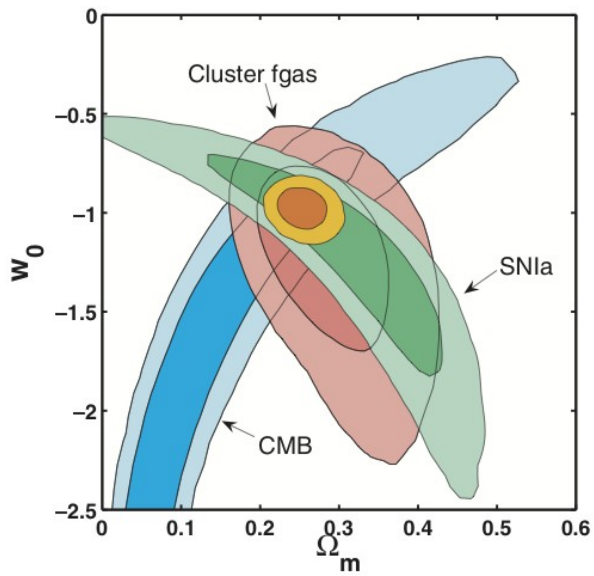




$$\Omega_M = 0.28 \pm 0.06$$
$$\Omega_\Lambda = 0.86 \pm 0.21$$
$$w = -1.14 \pm 0.31$$

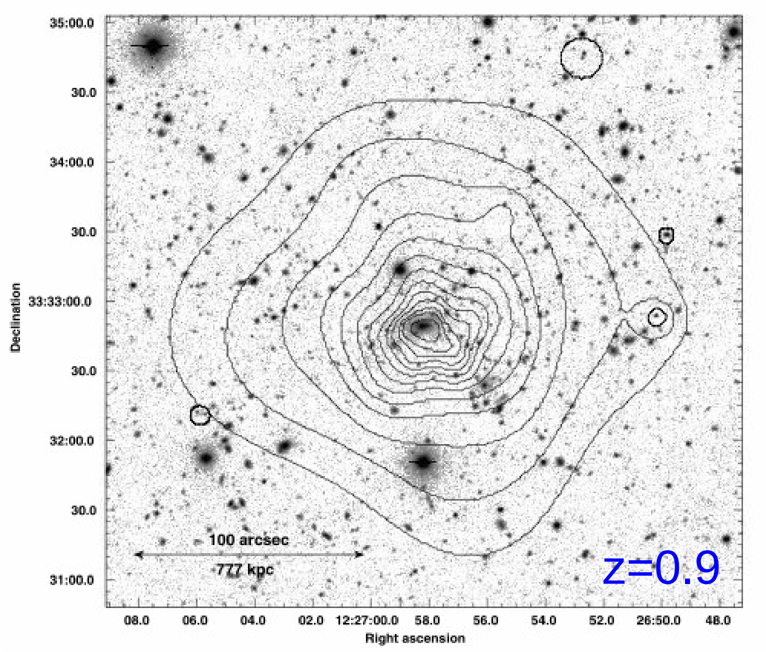
$$w = -0.98 \pm 0.07$$

- ★ N.B. Ω_M also constrained by overall fgas
  - ‣ improves constraints from fgas(z)
- ★ best constraints if combine with SNIa and CMB data

Cautions & Caveats

Method relies on determination of M_{tot}

★ hydrostatic masses – are clusters really relaxed?



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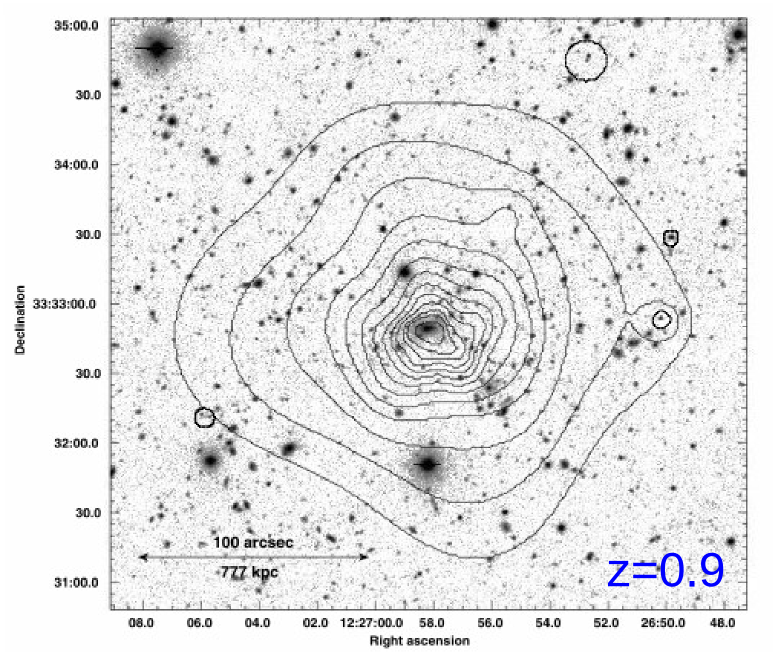
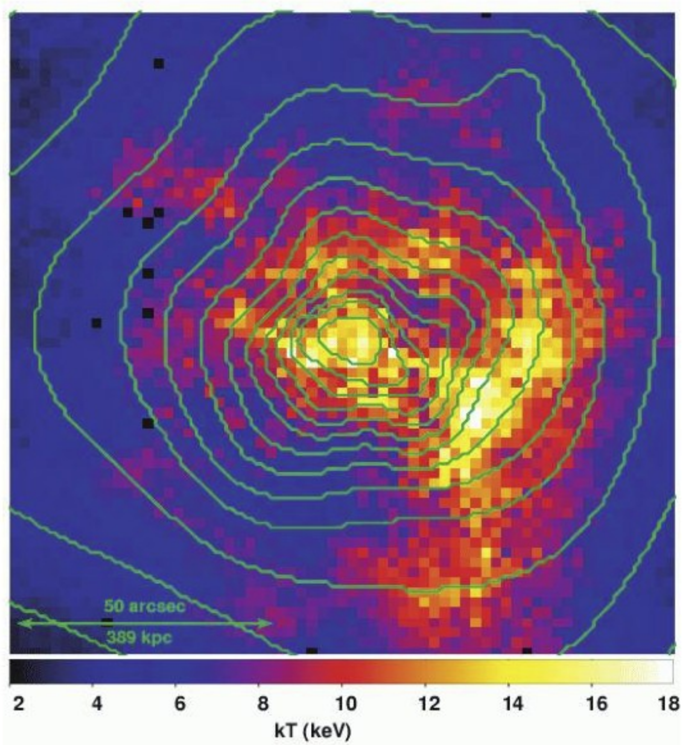




★ Hard to tell for distant clusters

- bright relaxed clusters biased towards line of sight mergers?

Maughan et al. (2007) ApJ, 659

Cautions & Caveats

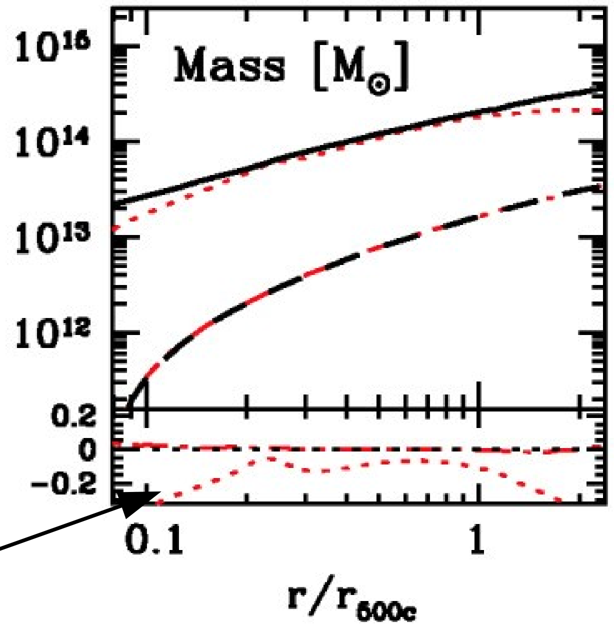
Method relies on determination of M_{tot}

★ are X-ray masses accurate?

Nagai et al (2007) analysed mock X-ray observations of simulated clusters

★ for relaxed clusters M_{gas} fine

★ M_{tot} underestimated by ~10%



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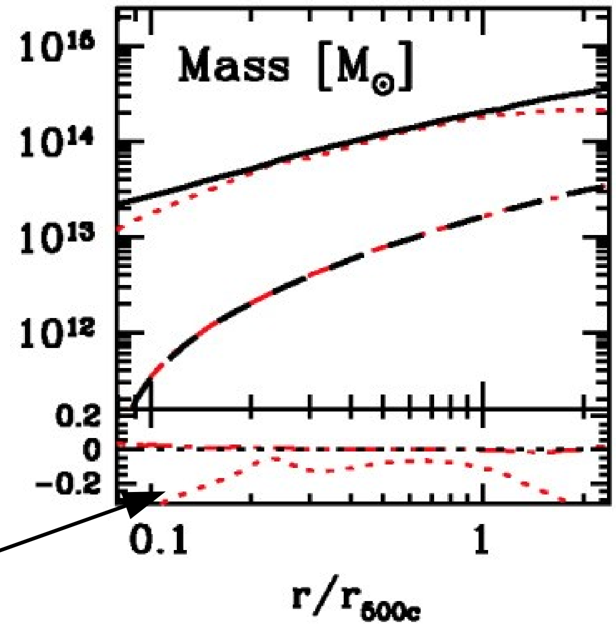


Due to **non-thermal pressure support**

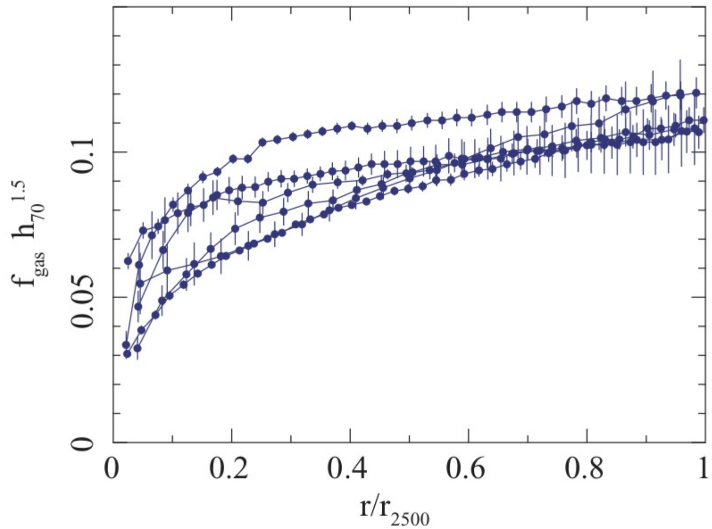
$$M(r) = \frac{-r^2}{G\rho(r)}\frac{dP}{dr}$$

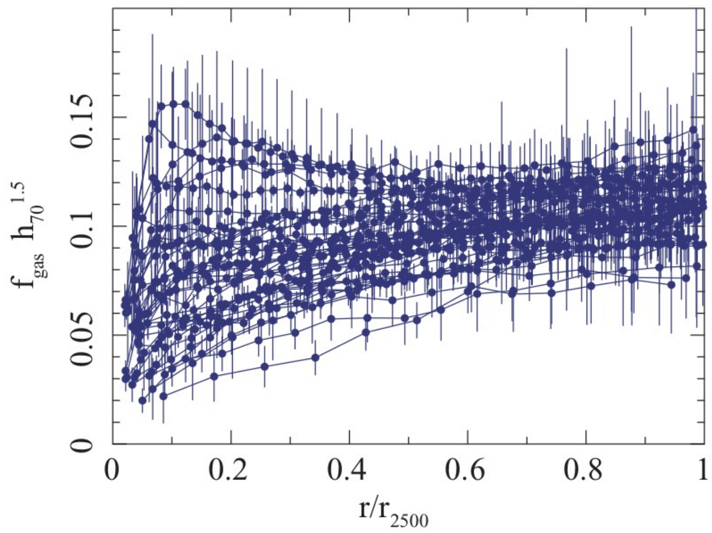
- ★ thermal pressure observed in X-ray
- ★ extra pressure from bulk motions allows for larger M

Cautions & Caveats

Is f_{gas} the same for all clusters?

★ radial profiles of f_{gas}





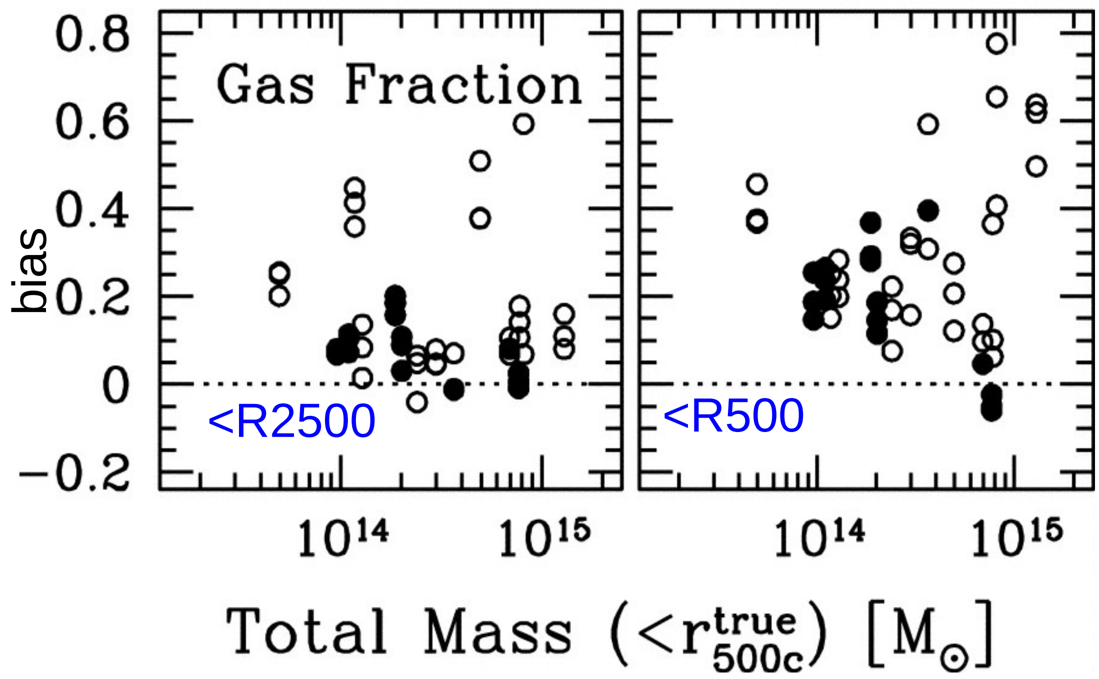
★ some variation at small radius, but consistent with same value at R2500

- **statistical** variation at R2500 gives 5% distance uncertainty
- c.f. 7% **intrinsic** distance uncertainty from SNIa

Cautions & Caveats

Is f_{gas} the same for all clusters?

★ simulations also support small variation in f_{gas} (Nagai et al 2007)



★ variation <6% for **relaxed** clusters

★ lower still for more massive clusters

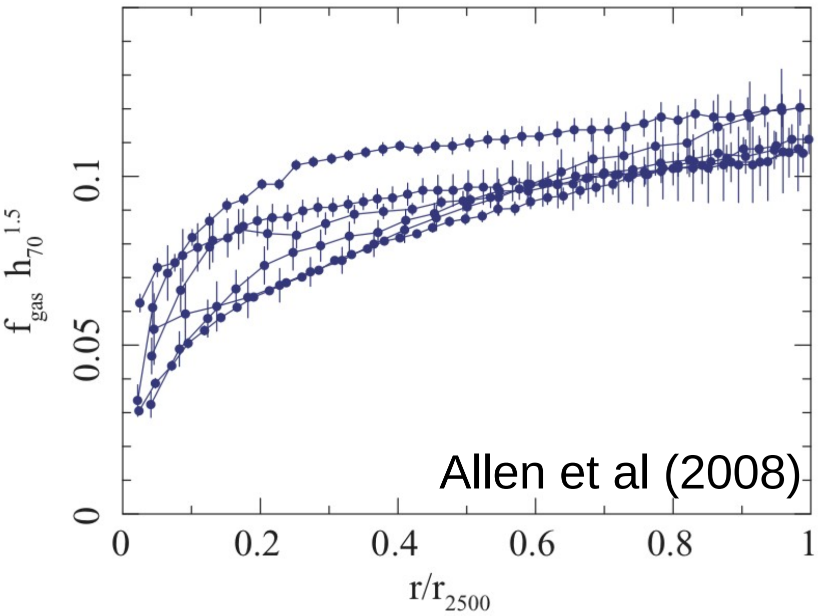
Cautions & Caveats

Allen et al. derived f_b in R2500

- ★ is this large enough to be a standard bucket?

Assumed clusters large enough that ratio of mass components is universal

- ★ but f_{gas} increases with R
- ★ still increasing at R2500



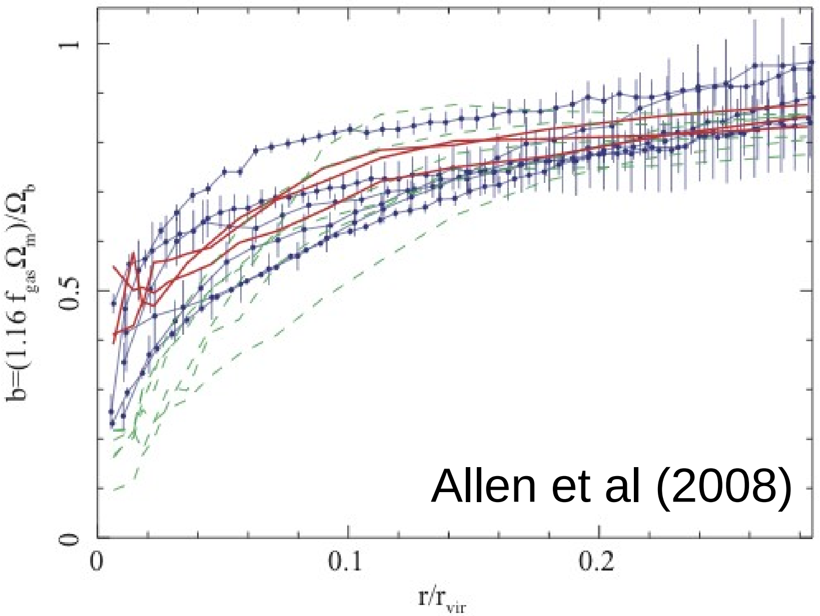
Cautions & Caveats

Allen et al. derived f_b in R2500

- ⋆ is this large enough to be a standard bucket?

Simulations used to estimate bias factor b

- ⋆ ratio of enclosed f_b to universal value
- ⋆ relaxed clusters in sims agree with observed f_{gas}



Use sims to correct f_b at R2500 by bias factor b~0.8

- ⋆ does b vary with z?
- ⋆ sims suggest not, but could be important

Summary

Assuming clusters large enough to be representative, mass composition should match Universe

$$f_b = \frac{M_b}{M_{tot}} = \frac{\Omega_b}{\Omega_M}$$

★ observe f_b and constrain Ω_M

Assuming f_b redshift independent, any observed variation with z due to assumed cosmology

$$f_{gas} = \propto d_L d_A^{1/2}$$

★ constrain E(z) and from observed $f_b(z)$

★ combined with CMB and SNIa and including possible sytematics:

$$\Omega_M = 0.253 \pm 0.021 \qquad w = -0.98 \pm 0.07$$