Cluster Cosmology in the *Chandra* Era: Potential, Problems & Prospects

An incomplete & biased sampling

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Overview

- Cosmology & clusters in principle
- The real world according to *Chandra*
- Dealing with it
- Where we stand
- Prospects

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Leon van Speybroeck

Cosmological Observables

Two paths to knowledge of recent cosmic history:

- Geometry:
  - * Measure (something that depends on) coordinate distance vs. redshift: $D(z) \sim \int dz'/H(z')$
  - * Examples: Standard candle, ruler, baryon fraction
- Growth:
  - * Measure rate of growth of cosmic structure:

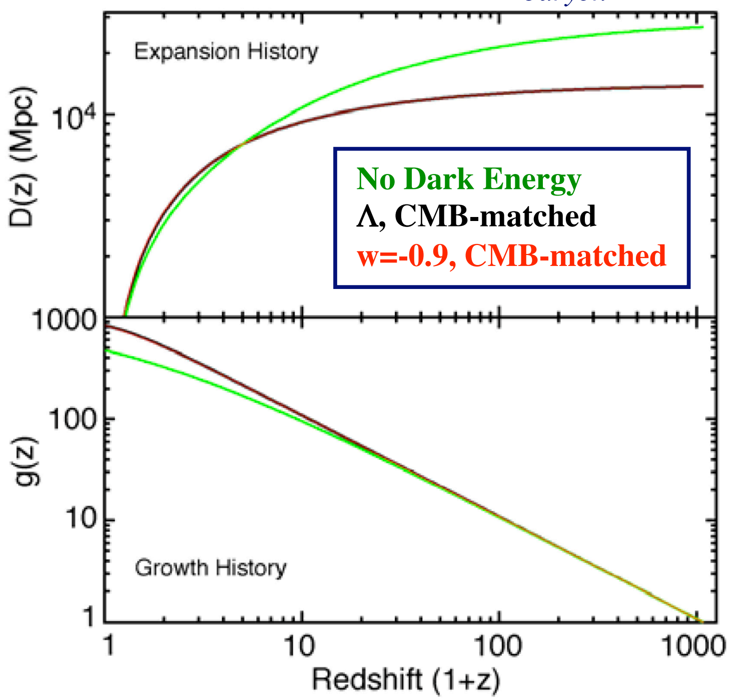
    $$\delta_0 = g(a)\,\delta_a \,; \quad g(a) \sim \Omega_m H(a) \int da'/\{a'H(a')\}^3 \;\; (a = 1/(1+z))$$

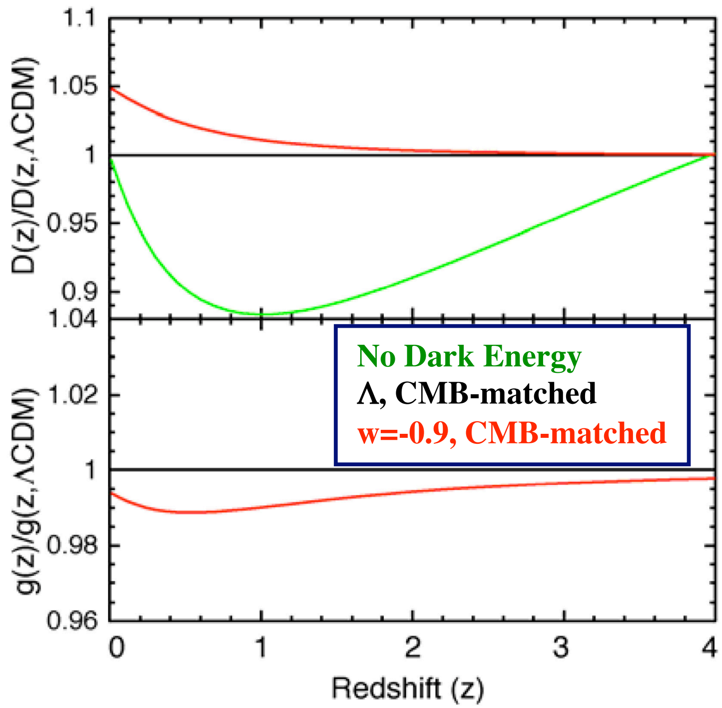
  - * Examples: Cosmic shear, Cluster abundance

Cosmological Observables

Distance: $D(z) \sim \int dz'/H(z')$

e.g.: SNe, BAO, Cluster f_{baryon}





Growth: $g(a) \sim \Omega_m H(a) \int da'/\{a'H(a')\}^3$

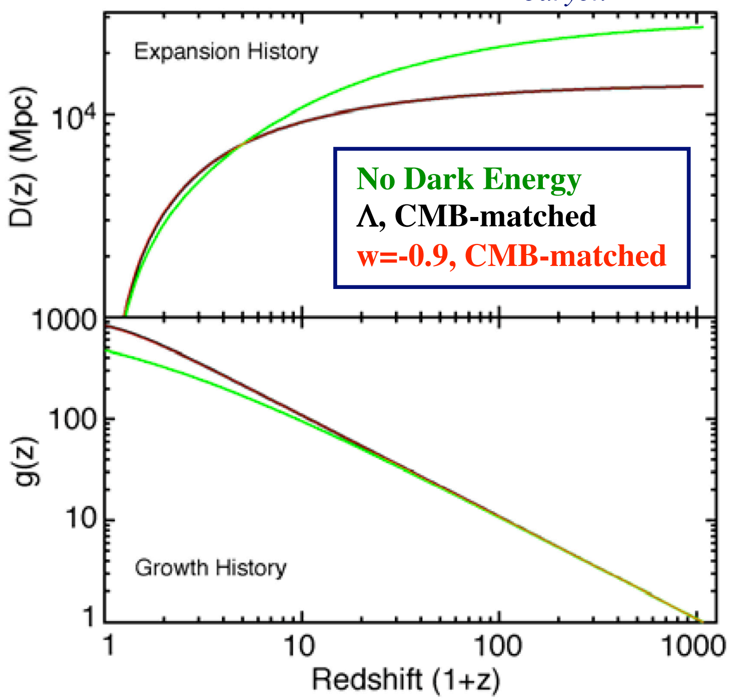
e.g: cluster abundance, cosmic shear

Figures: DETF Report Albrecht, Kolb et al., 2006

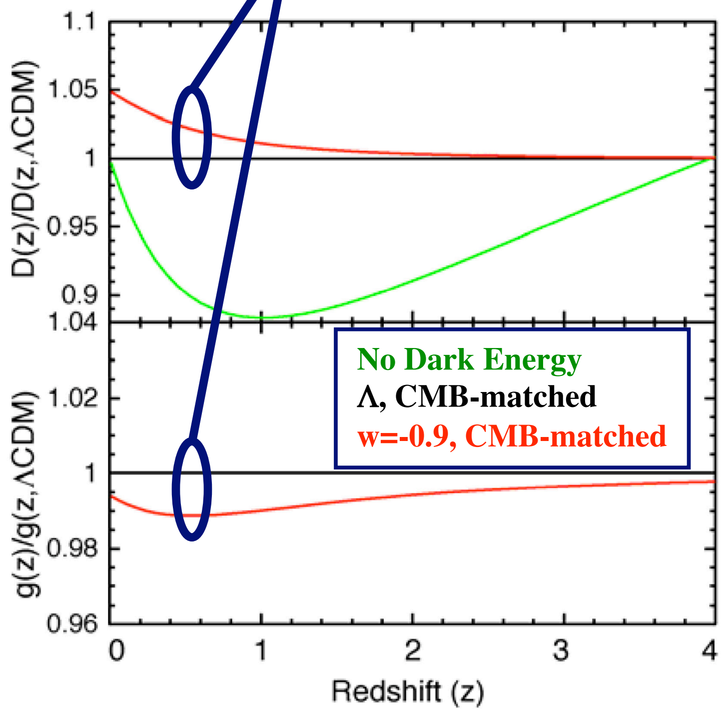
Cosmological Observables

Distance: D(z) ~ ∫dz'/H(z')

e.g.: SNe, BAO, Cluster f_{baryon}



Extreme Precision Required!



Growth: g(a) ~ $\Omega_m H(a) \int da'/\{a'H(a')\}^3$

e.g: galaxy clusters, cosmic shear

Figures: DETF Report
Albrecht, Kolb et al., 2006

Why Clusters for Cosmology?
(The Elevator Pitch)

- Selected clusters can be geometric standards (SZE, f_{baryon})
- Cluster distribution (dN/dz & P(k)) is sensitive to both distance (via dV/dΩdz) and growth history:
  * Physically independent of "distance-only" metrics
  * In principle allows test of GR: D(z) & g(z) should match
- Clusters are 'easy' to find (*if* you know how to look)
- Cluster physics is relatively simple (just ask McNamara & Burns!):
  * Dominated by gravity
  * Amenable to simulation
- Complementary to other cosmological probes

The Cluster Hubble Diagram

Two measures of cluster distance:

- X-ray (S_X) + Microwave SZE (ΔT_0):

  $d \sim \Delta T_0^2 / S_x$ [Bonamente, Joy et al.]

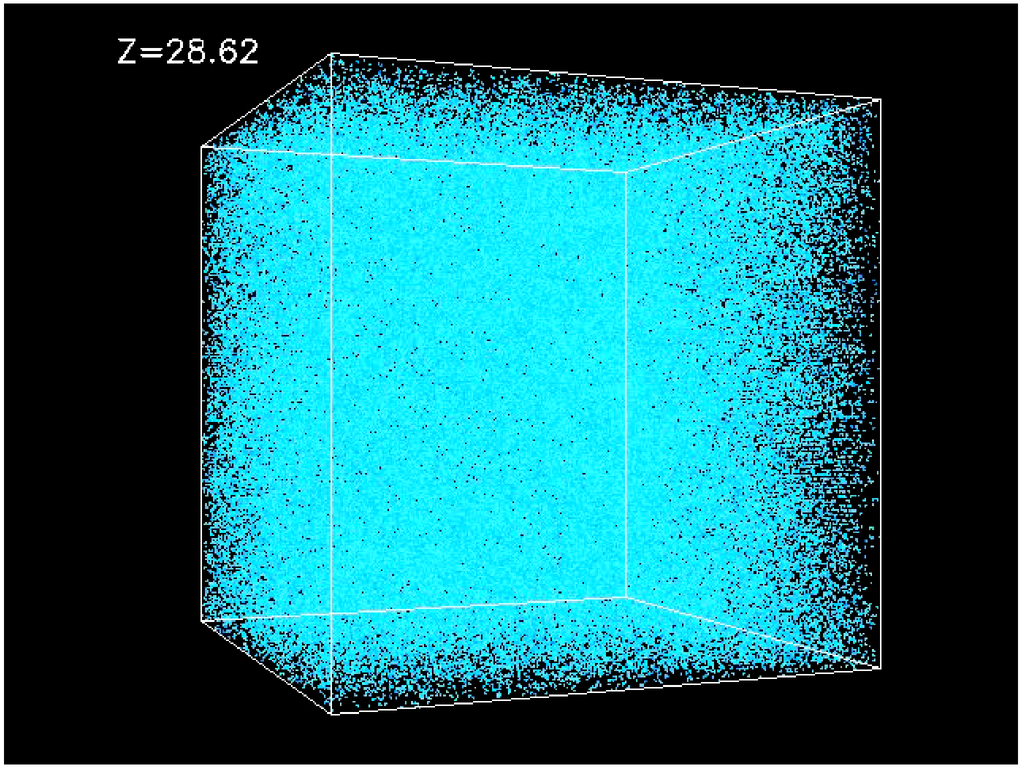
- Baryon fraction:

  $d \sim f_{gas}^{2/3}$; $(f_{gas} + f_{stars}) = \Omega_b / \Omega_m = \text{constant}$

  NB: also yields Ω_b / Ω_m [Allen et al.]

Andrei Kravtsov

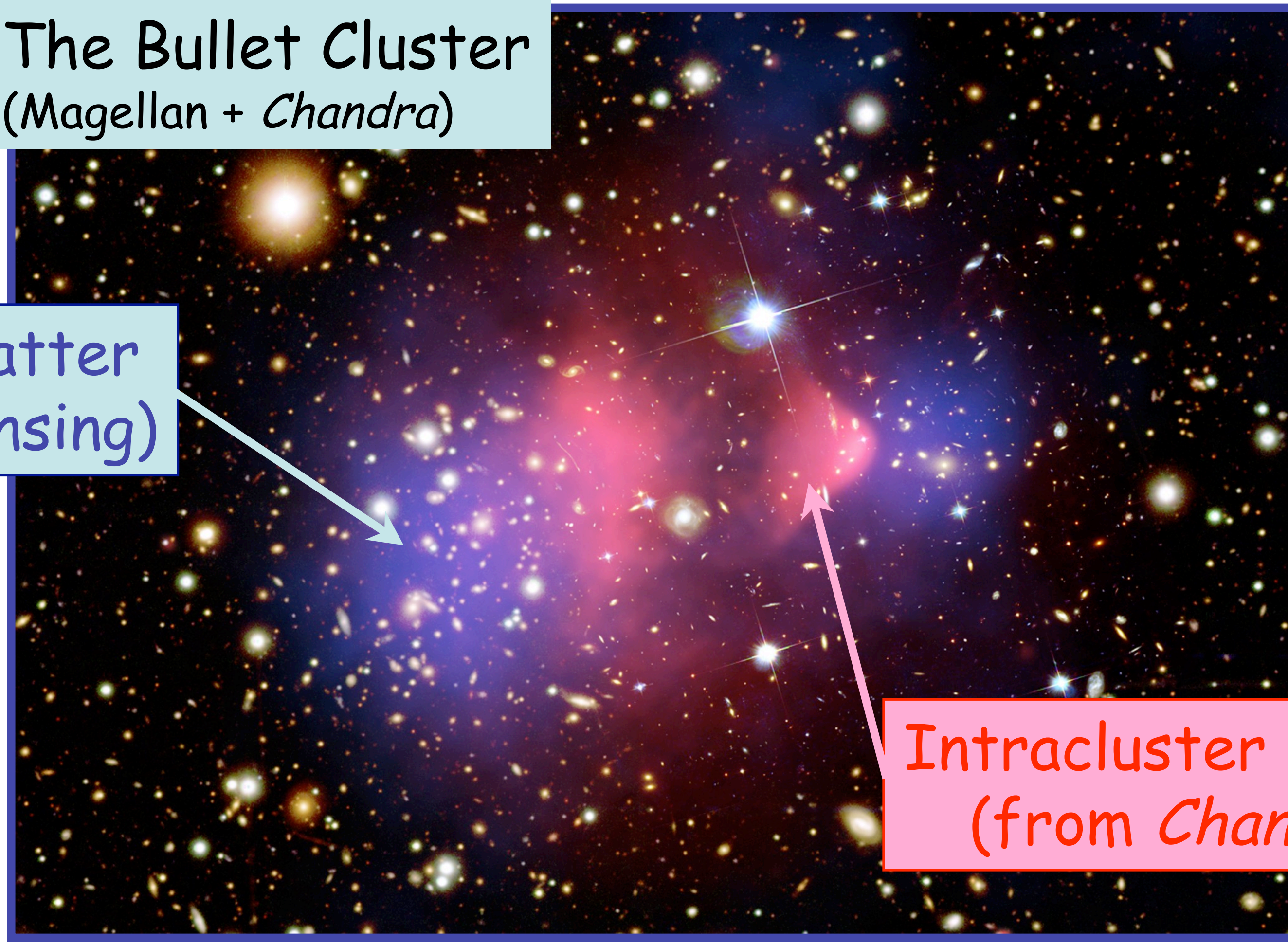
Clusters Trace Structure Formation



- Cosmic structure grows via gravitational instability
- The rate of growth is sensitive to the cosmic expansion history & thus to the cosmological model
- The cluster population (e.g. dN/dVdM) is sensitive to cosmology
- Key observational requirement: **measure cluster masses**
  [Henry, Reiprich & Boehringer, Mohr et al., Vikhlinin et al., Allen & Mantz...]

Cluster complexity: merging

Clowe, Markevtich et al. 2006



Cluster complexity: AGN heating

The Perseus cluster
as seen by *Chandra* (Fabian et al. 2006)

Clusters in reality according to Chandra

Chandra (& XMM) have shown that clusters aren't so simple:

- Both subtle & spectacular complexity in ICM density
  - ==> mergers, fronts & AGN heating (Markevitch, Vikhlinin, McNamara. Fabian...)
  - ==> evolution of spatial structure (Jeltema, Maughan)
  - ==> 'absence' of high-z 'bright' (cool) cores (Vikhlinin)
- Spectral evidence against simple cooling models
  - ==> AGN heating (Peterson...)
- Confirmation of 'non-self-similar' scaling relations (e.g. L_X *vs* T)
  - ==> (e.g.) non-gravitational thermodynamics (Vikhlinin,Markevitch,Allen, Ettori..)
- Scatter in mass/observable relations (Maughan, Mantz, O'Hara)
- Variation of f_{baryon} with cluster mass/ temperature (Allen, Vikhlinin)

The message from Chandra

In sum:

- Gravity is *not* solely responsible for cluster structure & evolution
- Clusters are not, in general, 'relaxed'

So, can we deal with this?:

Can we measure cluster masses well enough to do cosmology?

M. Bautz / MIT Kavli Institute

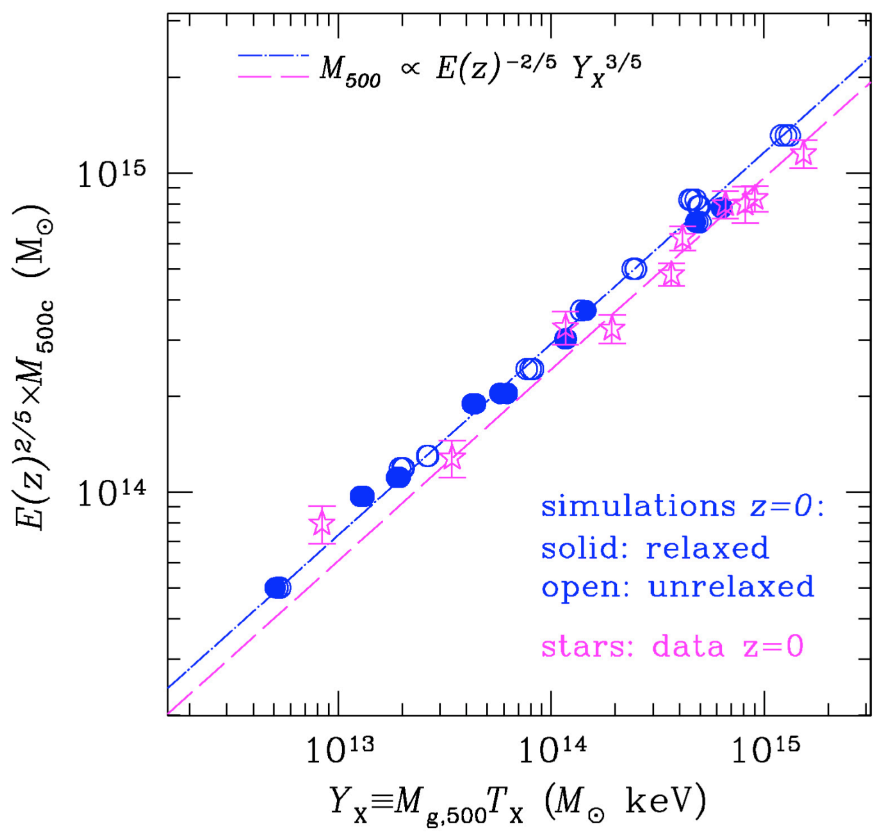
Cluster Mass Proxies

- Mass is not directly observable, so use observable proxies: N_{gal}, $\sigma_{opt,}$ Y_{SZE}, L_X, $T_{x,}$ M_{gas}, Y_X ...
- One must know both evolution & scatter in mass-observable relations to do cosmology (& knowing physics would also help!)
- So far, evolution in X-ray observables seems modest, generally consistent with 'gravity only' self-similar picture
- Until recently, scatter seemed large:
  - * Optical richness: ~x2 scatter at fixed mass (SDSS better?)
  - * Millimeter: Y_{sze} ~30% (est.)
  - * Weak lensing: ~40% (est)
  - * X-ray: $\delta M/M$ from L_X ~50%; T_X ~15%
- Refined X-ray mass proxies show much lower scatter

Accurate & Precise Mass Estimator
(Kravtsov, Vikhlinin & Nagai 2006)

- In N-body+hydro simulations, $Y_X = M_{gas}(r_{500}) T_x$ is accurate mass proxy
- Scatter σ_M = 7%, *including unrelaxed clusters*
- Must ignore core (<$0.15 r_{500}$)
- Observed M-Y relation ~15% lower than simulated (non-thermal pressure)
- In simulations, z- evolution close to self-similar

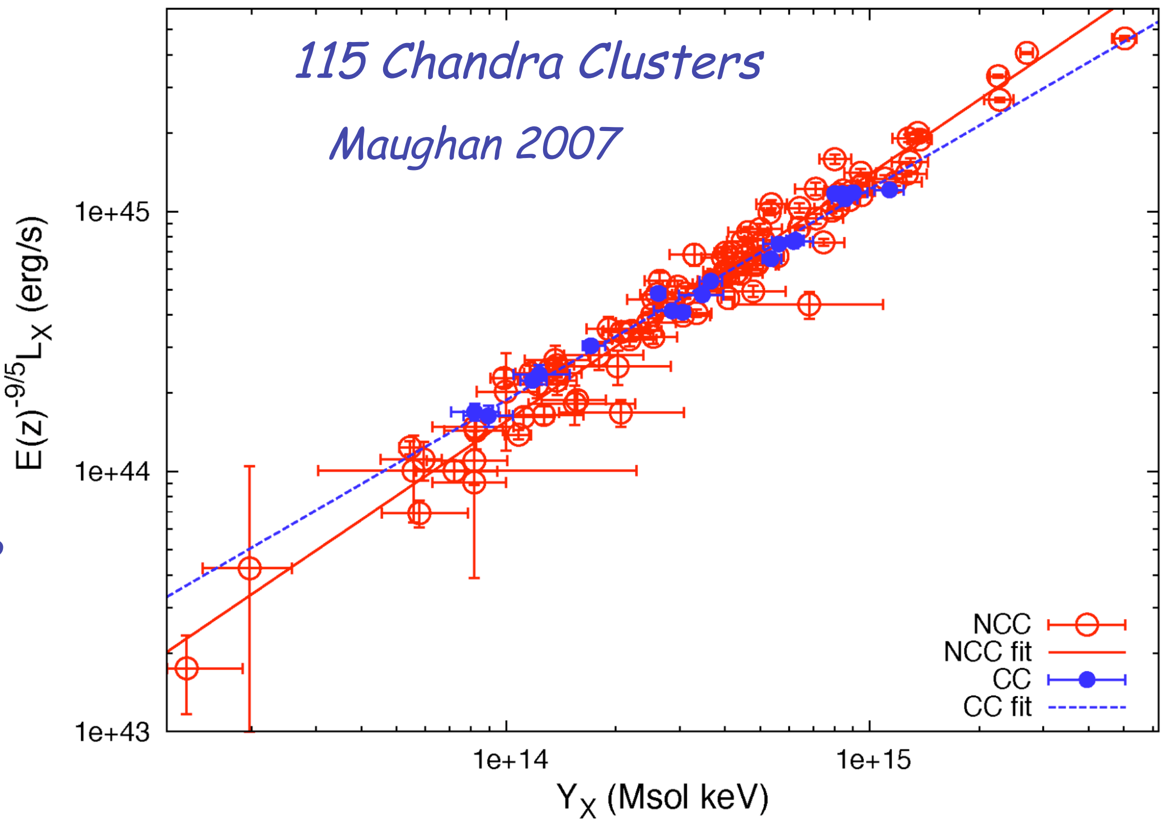
Kravtsov et al. 2006



L_X as a Mass Estimator
(Maughan 2007)

- Conventional L_x/M relation shows large scatter (σ_M ~40-60%)
- Excluding cluster core ($r<0.15r_{500}$) yields tight L_X/Y_X rel'n, & σ_y ~12%
- Even *without* accurate kT measure, expect L_X to measure mass to 16% if core is excluded

(cf O'Hara et al. 2006)



Recent Cosmological Results from Clusters

- Improved constraints on σ_8
  - Fine-tuning WMAP results (Henry, Evrard et al.)
- Lastest from geometric methods
  - CXO/SZE (Bonamente, Joy et al)
  - F_{gas} (Allen, Rapetti et al.)
- Latest on growth of structure
  - Mantz et al. (next talk)
  - Vikhlinin et al. (coming soon)

Results from SZE & Chandra

Bonamente, Joy et al. 2006

H_0 =77.6±4±9 km s^{-1} Mpc^{-1} (ΛCDM Ω_m = 0.3)

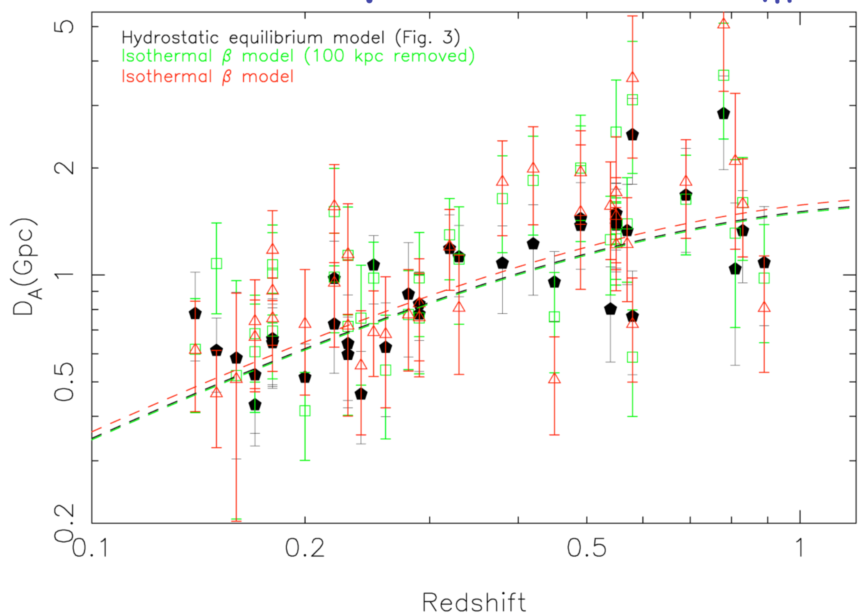


Fig. 4.— Angular diameter distances of the 38 clusters, using the simple r <100 kpc-cut isothermal β model (green) and the isothermal β model (red) described in Section 4.2. The error bars are the total statistical uncertainties, obtained by adding the X-ray and SZE data modelling uncertainties (Table 4, Table 5) and the additional sources of random error described in Section 3.3 and Table 3. The systematic errors of Table 3 are not shown. Dashed lines are the best-fit angular diameter curves using the best-fit Hubble constant H_0=77.6 km s^{-1} Mpc^{-1} (green) and H_0=73.7 km s^{-1} Mpc^{-1} (red) and $\Omega_M = 0.3$, for $\Omega_\Lambda = 0.7$. In black are the distances obtained with the hydrostatic equilibrium model of Section 4.1 (Figure 3).

Read the fine print!

Results from Cluster f_{gas}

Allen et al. astro-ph/0706.0033

$\Omega_\Lambda>0$ @ 99.99% confidence, f_{gas} + priors

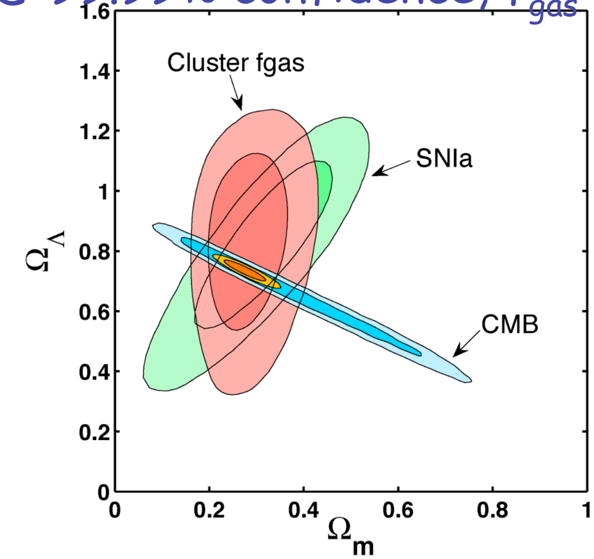


Figure 6. The 68.3 and 95.4 per cent (1 and 2 σ) confidence constraints in the Ω_m, Ω_Λ plane for the Chandra f_{gas} data (red contours; standard priors on $\Omega_b h^2$ and h are used). Also shown are the independent results obtained from CMB data (blue contours) using a weak, uniform prior on h ($0.2 < h < 2$), and SNIa data (green contours; the results for the Davis *et al.* 2007 compilation are shown). The inner, orange contours show the constraint obtained from all three data sets combined (no external priors on $\Omega_b h^2$ and h are used). A ΛCDM model is assumed, with the curvature included as a free parameter.

$\sigma_w = 0.07$ ($\Omega_K=0$ assumed)

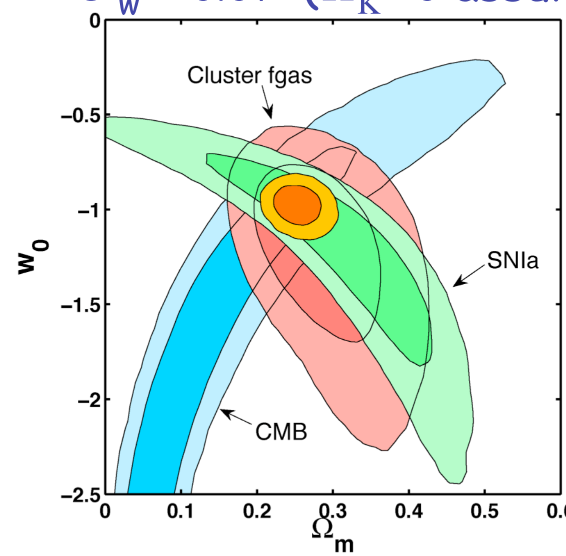


Figure 8. The 68.3 and 95.4 per cent (1 and 2σ) confidence constraints in the Ω_m, w plane obtained from the analysis of the Chandra f_{gas} data (red contours) using standard priors on $\Omega_b h^2$ and h. Also shown are the independent results obtained from CMB data (blue contours) using a weak, uniform prior on h ($0.2 < h < 2.0$) and SNIa data (green contours; Davis *et al.* 2007). The inner, orange contours show the constraint obtained from all three data sets combined: $\Omega_m = 0.253 \pm 0.021$ and $w = -0.98 \pm 0.07$ (68 per cent confidence limits). No external priors on $\Omega_b h^2$ and h are used when the data sets are combined. A flat cosmology with a constant dark energy equation of state parameter w is assumed.

Read the fine print!

Key Questions

- How good are absolute mass estimates?
  * e. g., X-ray/weak-lensing comparison
- Are X-ray selected samples fair?
  * e. g., compare to SZE- and optical selection
- How do we tell which clusters are 'relaxed'?
- How do mass-observable relations evolve?
- How do mergers & feedback affect scatter & evolution of mass-observable relations?

More data coming soon

- SZ surveys for clusters:
  - * SPT: 4000 deg^2, > 10^4 clusters, 1^{st} light '07
  - * ACT: ~1000 deg^2, 1^{st} light '07
  - * Planck: All-sky, launch 2008
  - * ALMA:
- X-ray surveys:
  - * SRG-e-ROSITA: ~half-sky, S_X >4e-14 cgs, >8 x 10^4 clusters, launch 2011
  - * Others?
- Optical surveys:
  - * LST: all-sky, 1^{st} light ~2014

Future X-ray Observations

Near-term:

- *Chandra* observations of ~100 higher-z clusters (~5 Ms) from, e.g., SZ survey) can:
  - * Measure evolution & scatter of mass proxies
  - * Improve cosmological constraints from growth-of structure (better masses)
- e-ROSITA will provide ~x100 more X-ray selected clusters than we have now (most @ z < 1)

Future X-ray Observations

Longer term:

- Constellation-X is essential to resolve bulk motions & turbulence in the ICM to z=1:
  - * Size (collecting area) matters!
  - * Reduce mass systematics in f_{gas} samples
  - * Improve mass-observable relations for structure growth experiments
- Future low-background, high-angular-resolution mission would reveal very first clusters at z ~2+

Conclusions

- Cluster studies have already contributed to our knowledge of cosmology & structure formation.
- As with every cosmological measurement, systematic errors dominate; progress is rapid:
  * Chandra has vastly improved cluster mass metrics
  * Better absolute normalization of mass-obs. rel'n is needed & coming (lensing, SZE, future observatories)
- Chandra has shown us clusters are complicated, but (so far, it seems) not too complicated.
  * We now know mergers AGN feedback affect ICM
  * We need to understand the physics & quantify effects on mass estimates