Allowances for systematic uncertainties

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

1) The depletion factor (simulation physics, gas clumping 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)

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

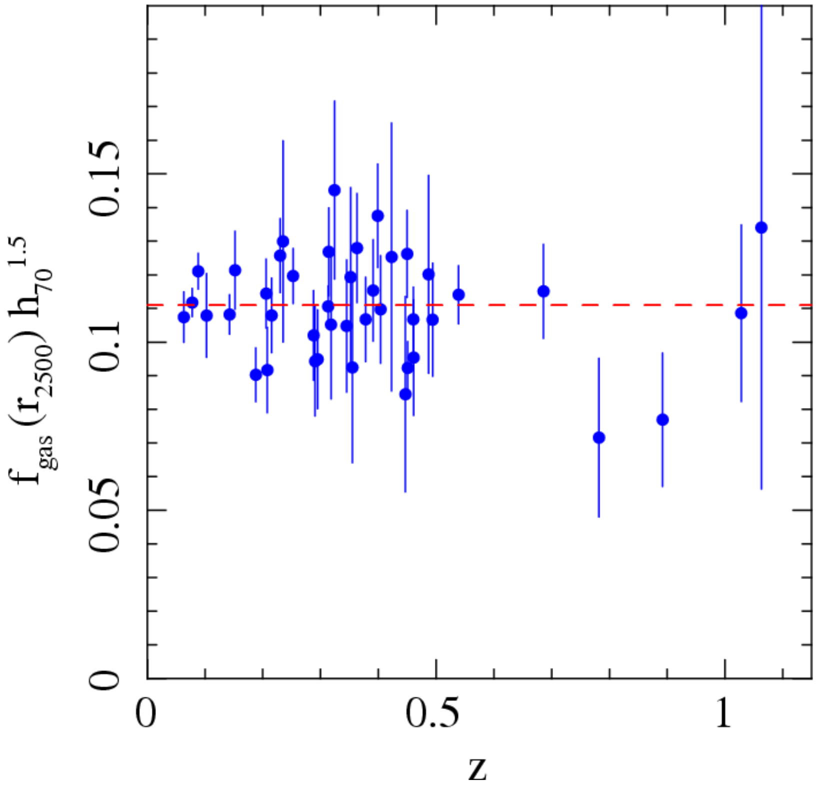
4) Instrument calibration, X-ray modelling

K 10% Gaussian uncertainty

With these (conservative) allowances for systematics

Model:

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



Results (ΛCDM)

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

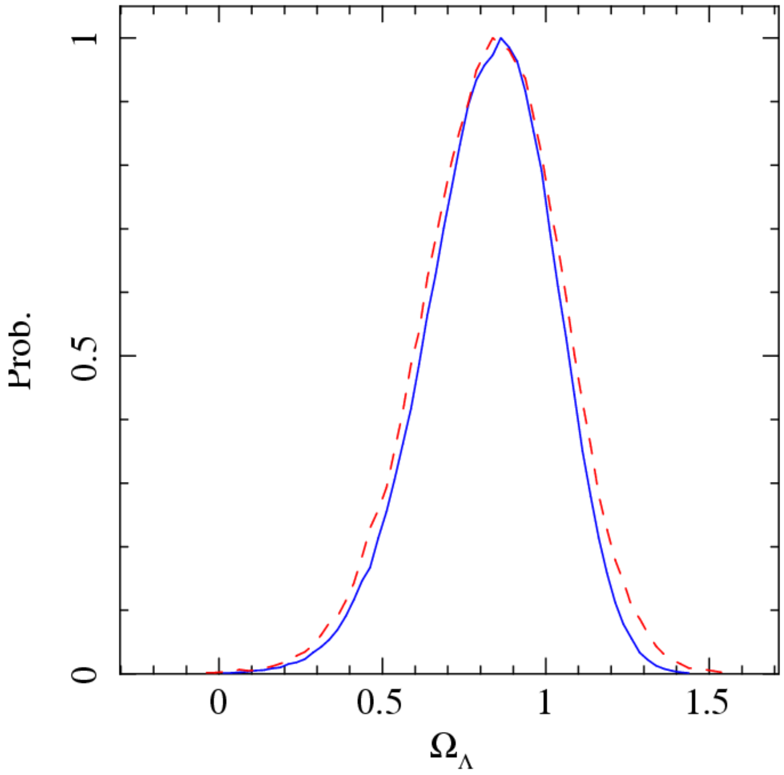
Best-fit parameters (ΛCDM):

Ω_m=0.27±0.06, Ω_Λ=0.86±0.19

(Note also good fit: χ^2=41.5/40)

Important

Marginalized results on dark energy (ΛCDM)



Blue: standard priors on $\Omega_b h^2$,h.

$\Omega_\Lambda = 0.86 \pm 0.19$

Red: weak (3x) priors on $\Omega_b h^2$, h.

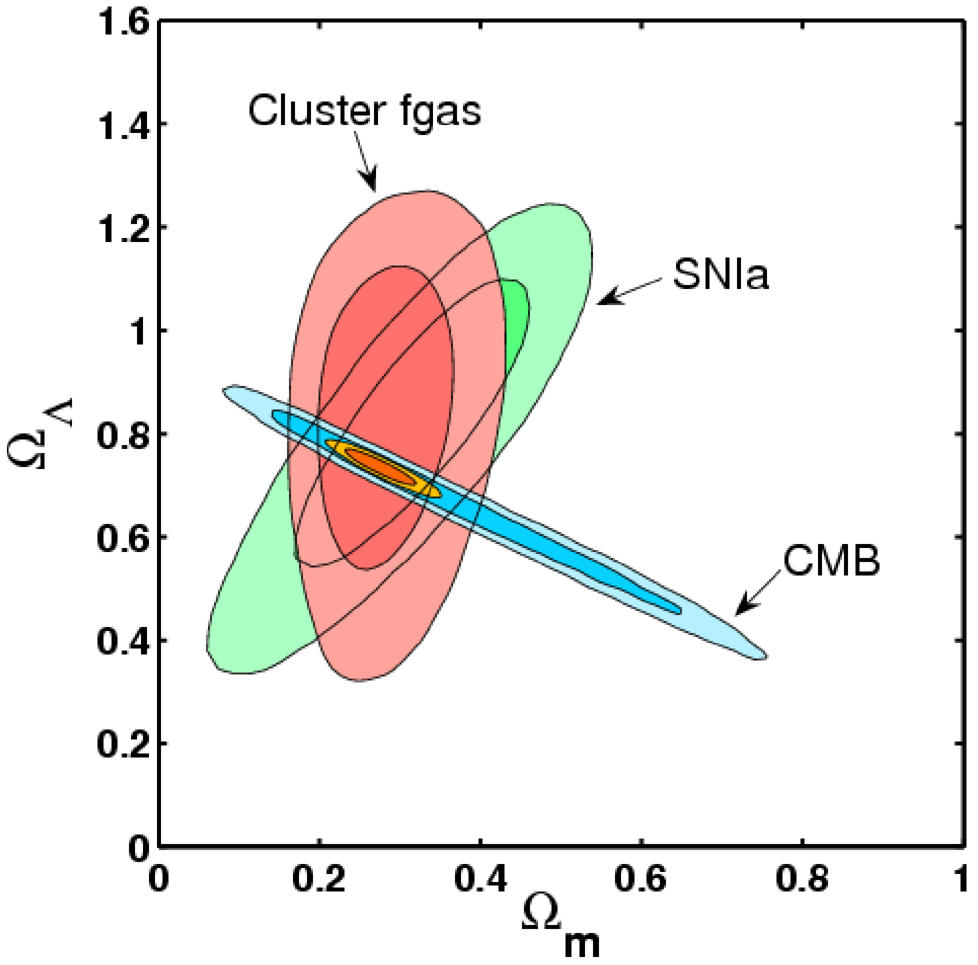
$\Omega_\Lambda = 0.86 \pm 0.21$

$\Omega_\Lambda > 0$ at 99.99% significance
(comparable to SNIa studies).

Cluster $f_{gas}(z)$ data confirm that the Universe is accelerating.

Like SNIa, this result is based on distance measurements to individual objects (but very different objects subject to very different astrophysics)

Comparison of independent constraints (ΛCDM)



f_{gas} analysis: 42 clusters including standard $\Omega_b h^2$, and h priors and full systematic allowances

CMB data (WMAP-3yr +CBI+ACBAR + prior $0.2<h<2.0$)

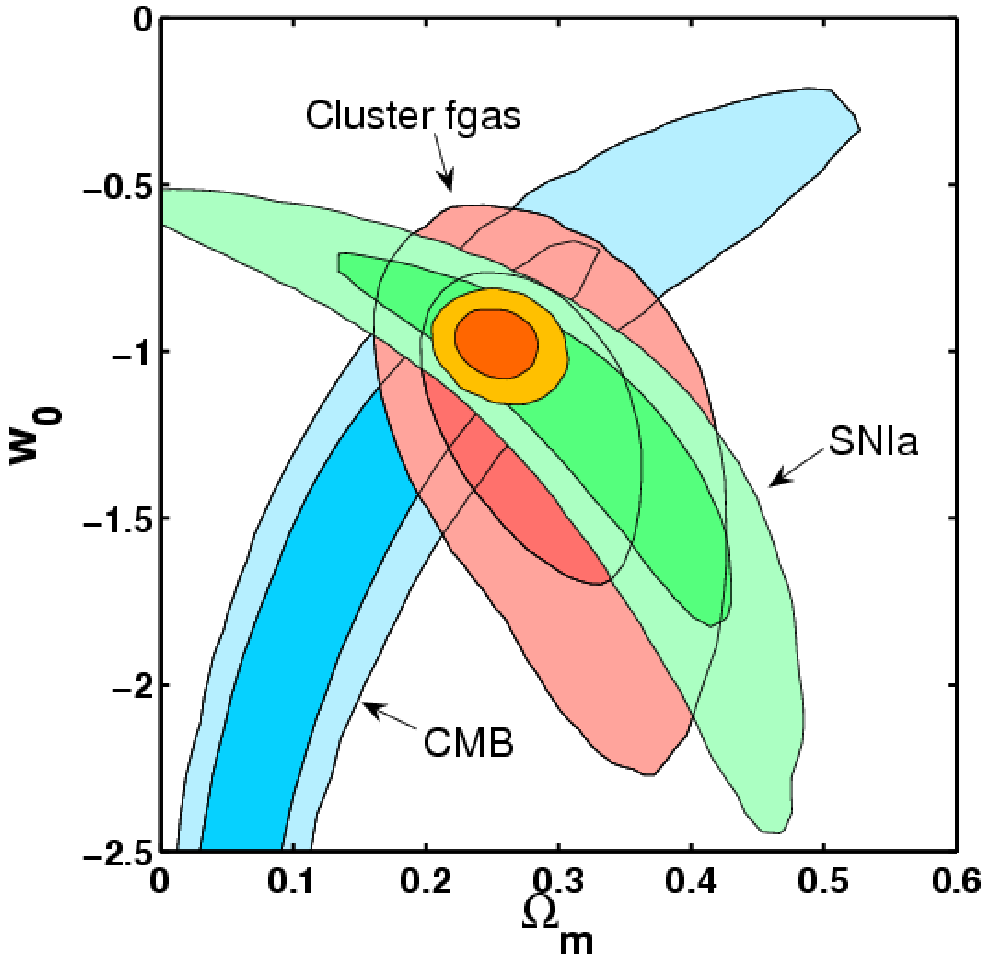
Supernovae data from Davis et al. '07 (192 SNIa, ESSENCE+ SNLS+HST+nearby).

Combined constraint (68%)

$$\Omega_m = 0.275 \pm 0.033$$
$$\Omega_\Lambda = 0.735 \pm 0.023$$

Allen et al 2008

Dark energy equation of state:



Constant w model (flat):

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

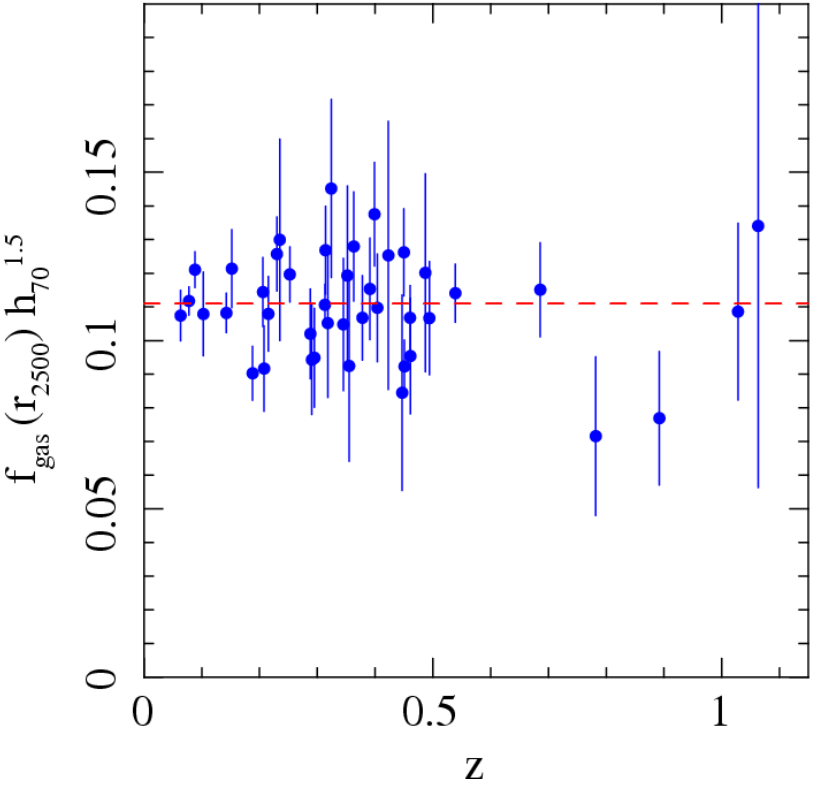
Combined constraints (68%)

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

Results marginalized over all systematic uncertainties.

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

The low systematic scatter in the $f_{gas}(z)$ data



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

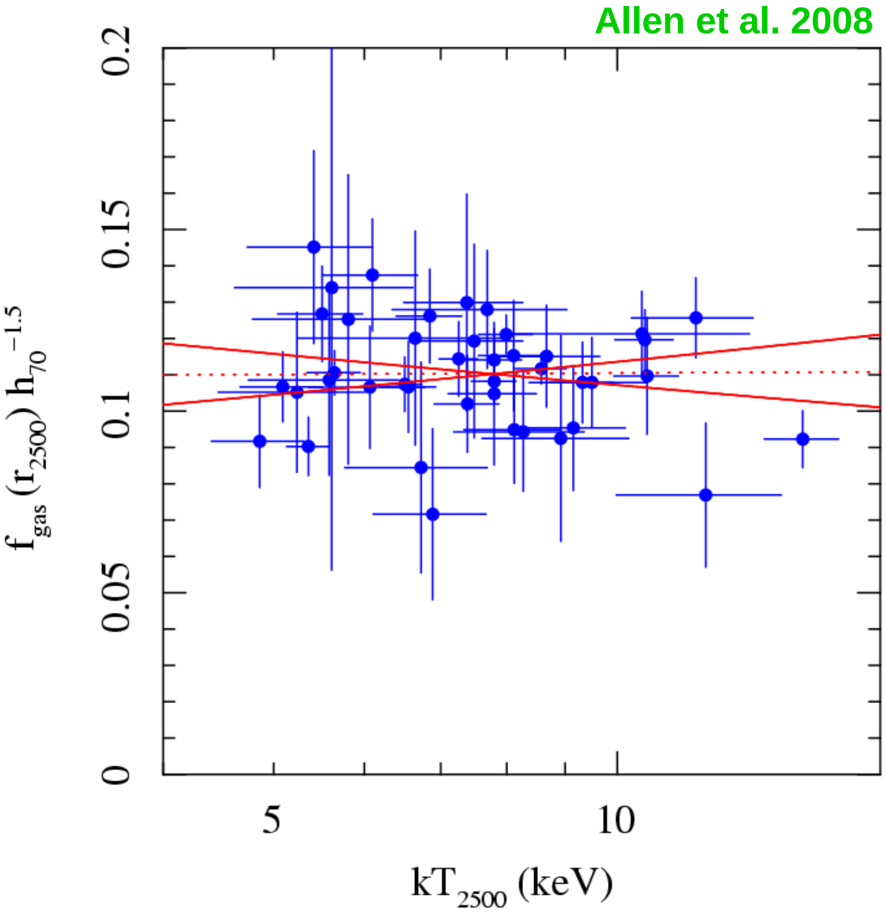
Formal 68% upper limit on fgas scatter 8% (5% in distance).

(Consistent with expectations from hydro. simulations)

In other words, for hot, massive clusters, the X-ray gas mass indeed provides an excellent, low-scatter proxy for the total gravitating mass.

Check and check again …

The trend of f_{gas} with temperature.

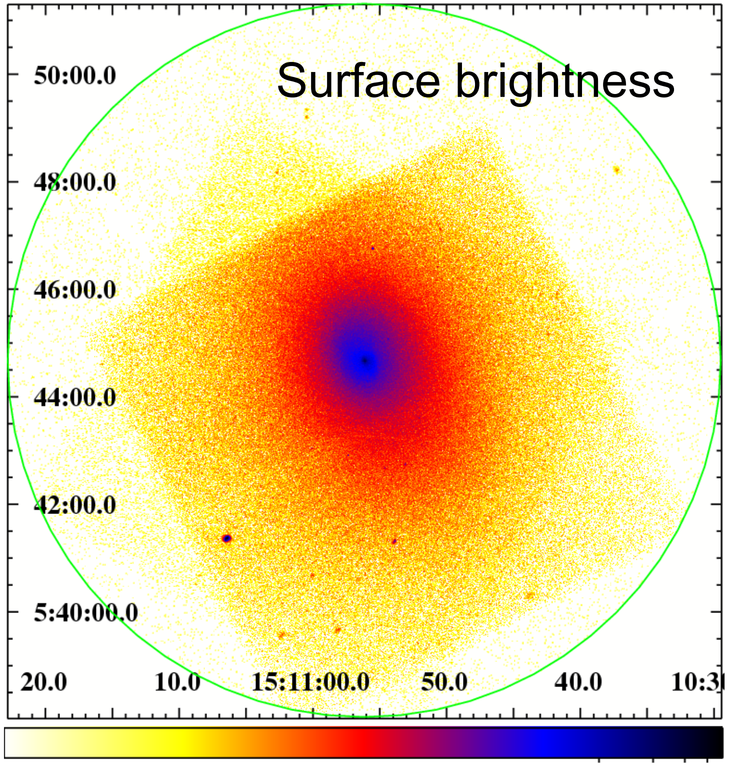


For the hottest, most massive clusters we find no evidence for a trend of fgas with kT.

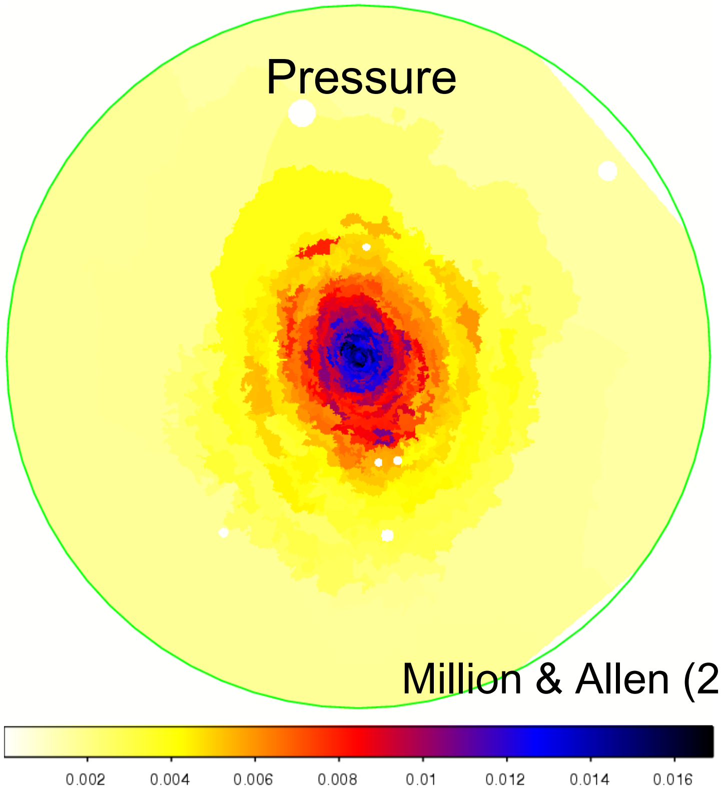
Best-fit power-law model is consistent with a constant. (plot shows 2-sigma limits).

Checks on hydrostatic assumption

X-ray pressure maps: (from projected kT and emission measure)



A2029 (z=0.078)

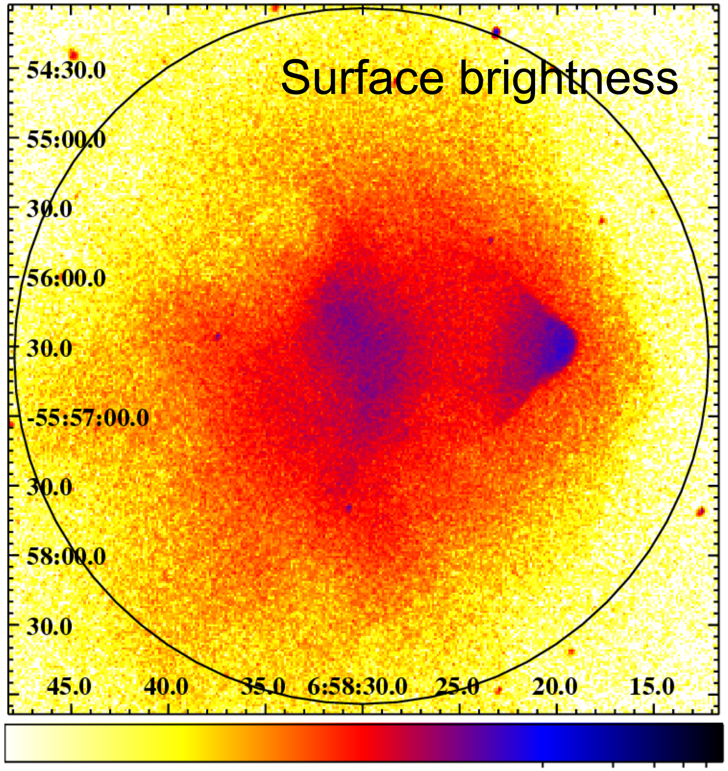


Million & Allen (2009)

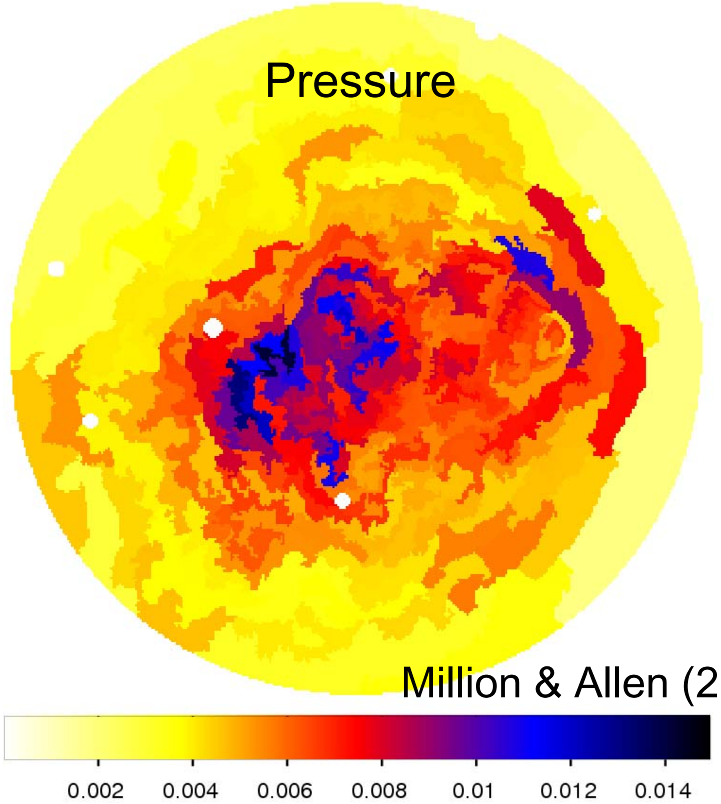
Analysis confirms effectiveness of morphological X-ray selection criteria.

Checks on hydrostatic assumption

X-ray pressure maps: (from projected kT and emission measure)



1E0657-56 (z=0.31)



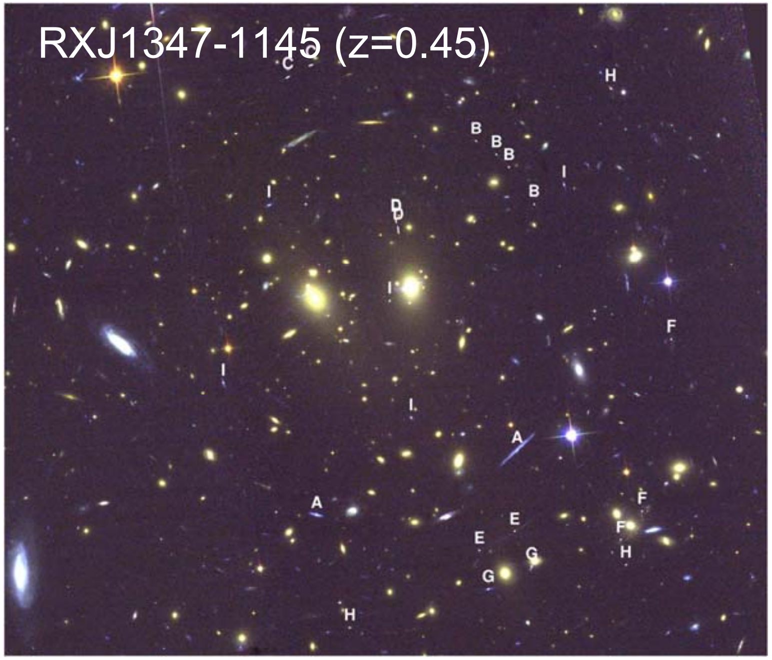
Million & Allen (2009)

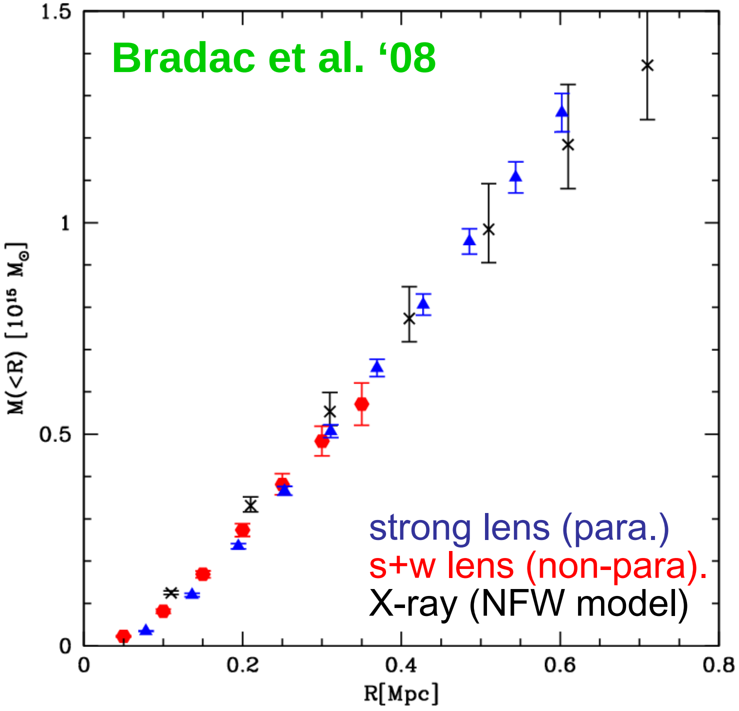
Analysis confirms dynamically complex nature of merging clusters.

Comparison vs. lensing masses

Gravitational lensing: provides a way to measure cluster masses that is independent of the dynamical state of the matter.

Extensive multi-color ground+space-based optical imaging+spectroscopy programs underway. State-of-the-art strong+weak lensing analysis.





Excellent agreement. See also Newman et al. '09 study of Abell 611 (z=0.29)

Comparison vs. lensing masses

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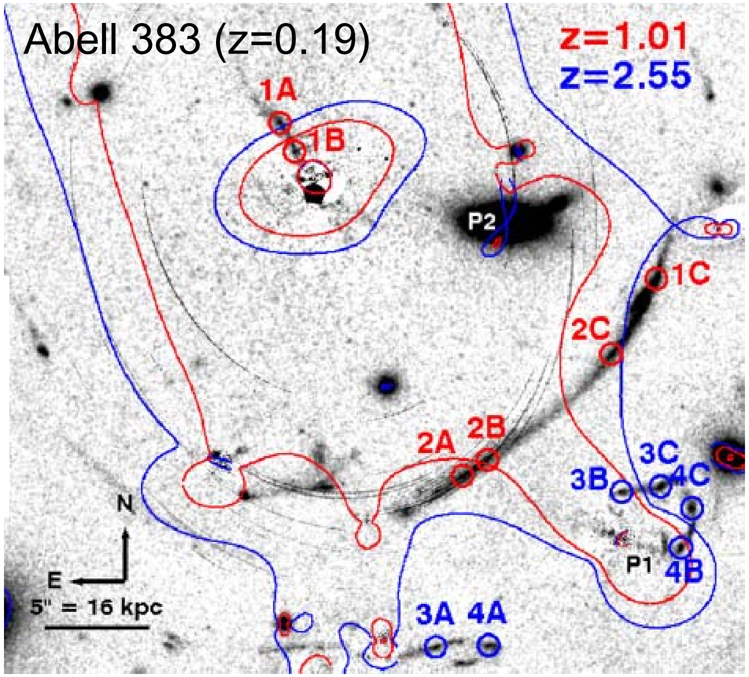
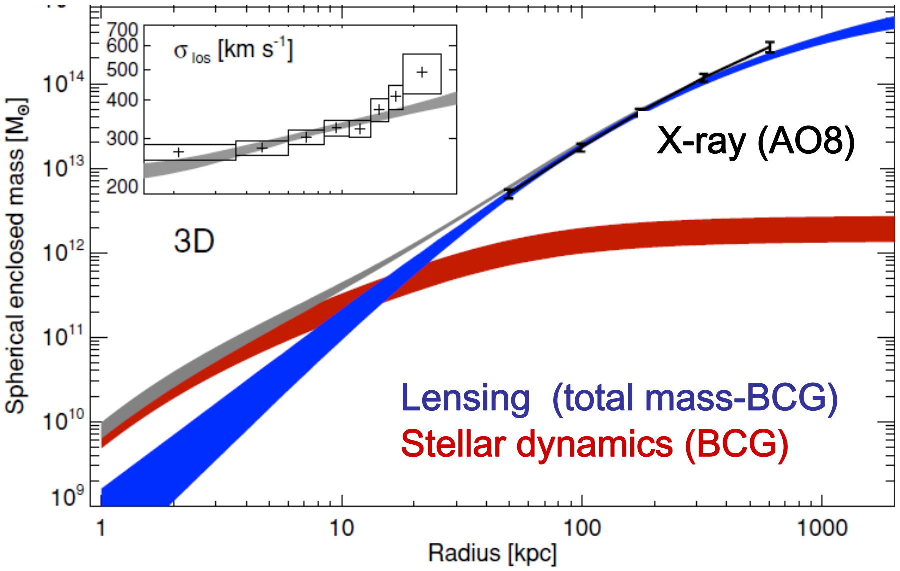


Newman et al. 2011

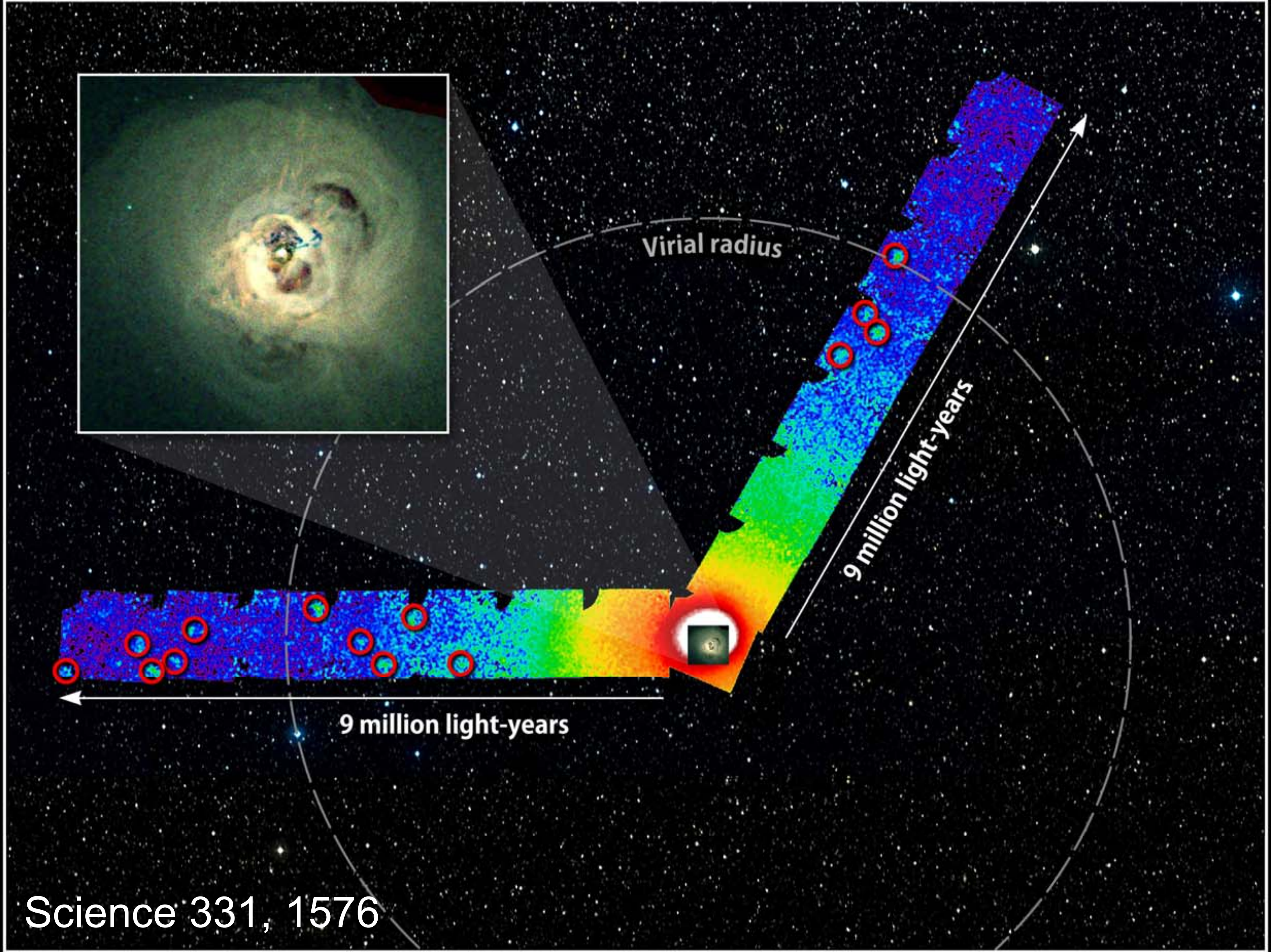


For A383, data combination reveals significant line-of-sight elongation.

fgas at larger radii

Suzaku imaging of the Perseus Cluster

Simionescu et al. 2011

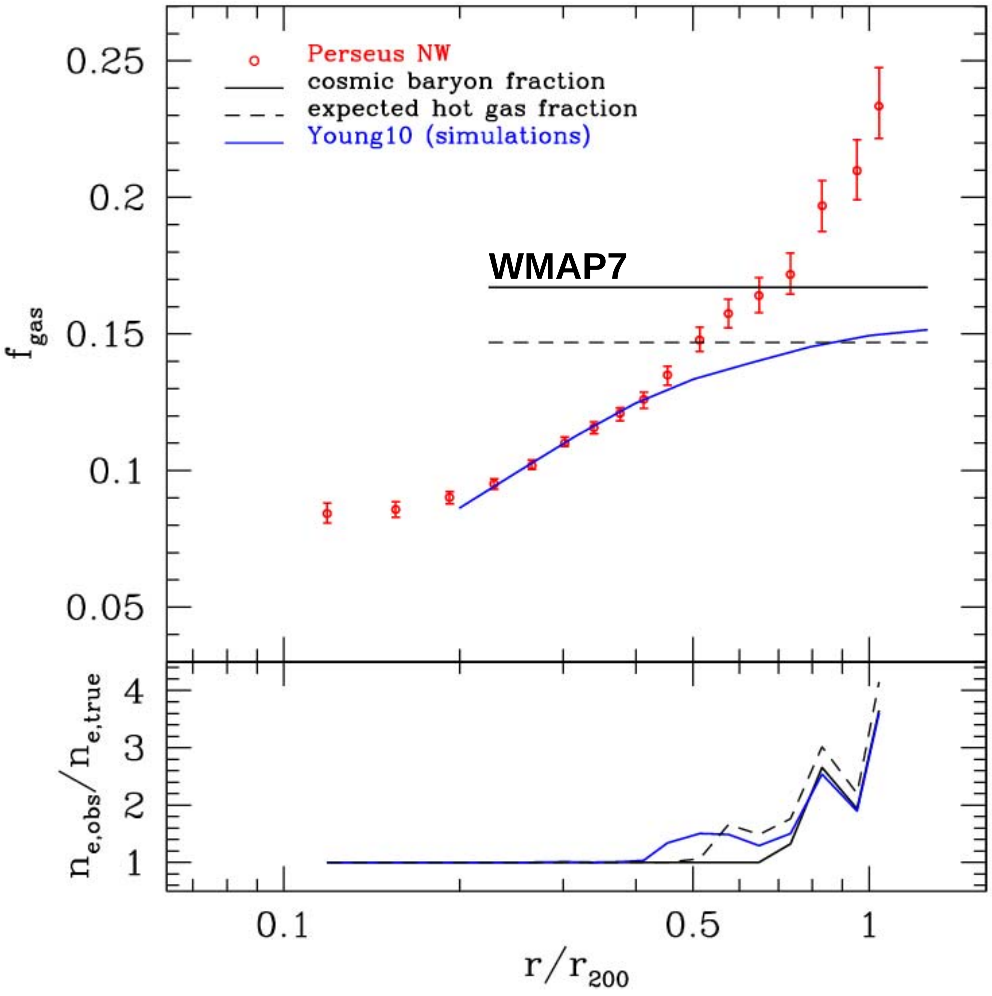


Science 331, 1576

Credit: NASA/ISAS/DSS/A. Simionescu et al.

Suzaku fgas(r) for the Perseus Cluster

Simionescu et al. 2011



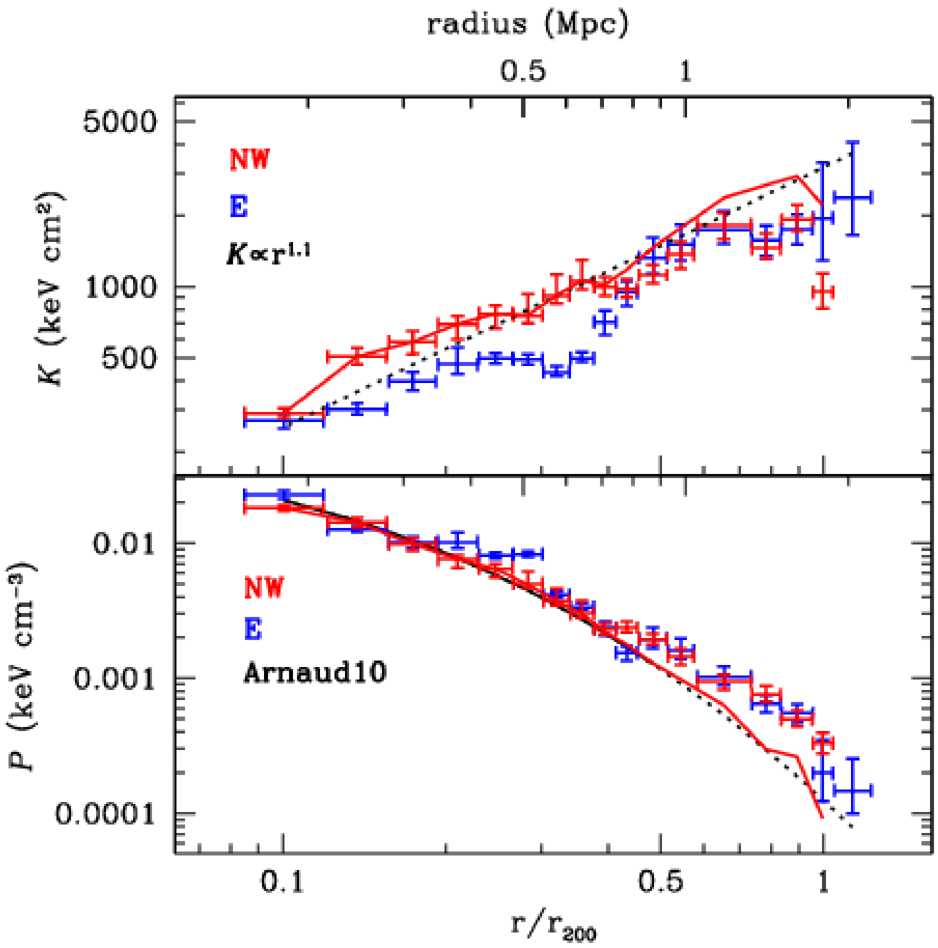
Best fgas measurements for any individual cluster to date.

Good agreement with hydro. simulations (blue curve) out to intermediate radii ($r \leq 0.45 r_{200}$).

In contrast to some previous claims, no `missing baryons' at large radii ($r \sim 0.5 r_{200}$).

Clumping makes apparent fgas exceed universal value at very large radii ($r > 0.5 r_{200}$).

Thermodynamics at large radii

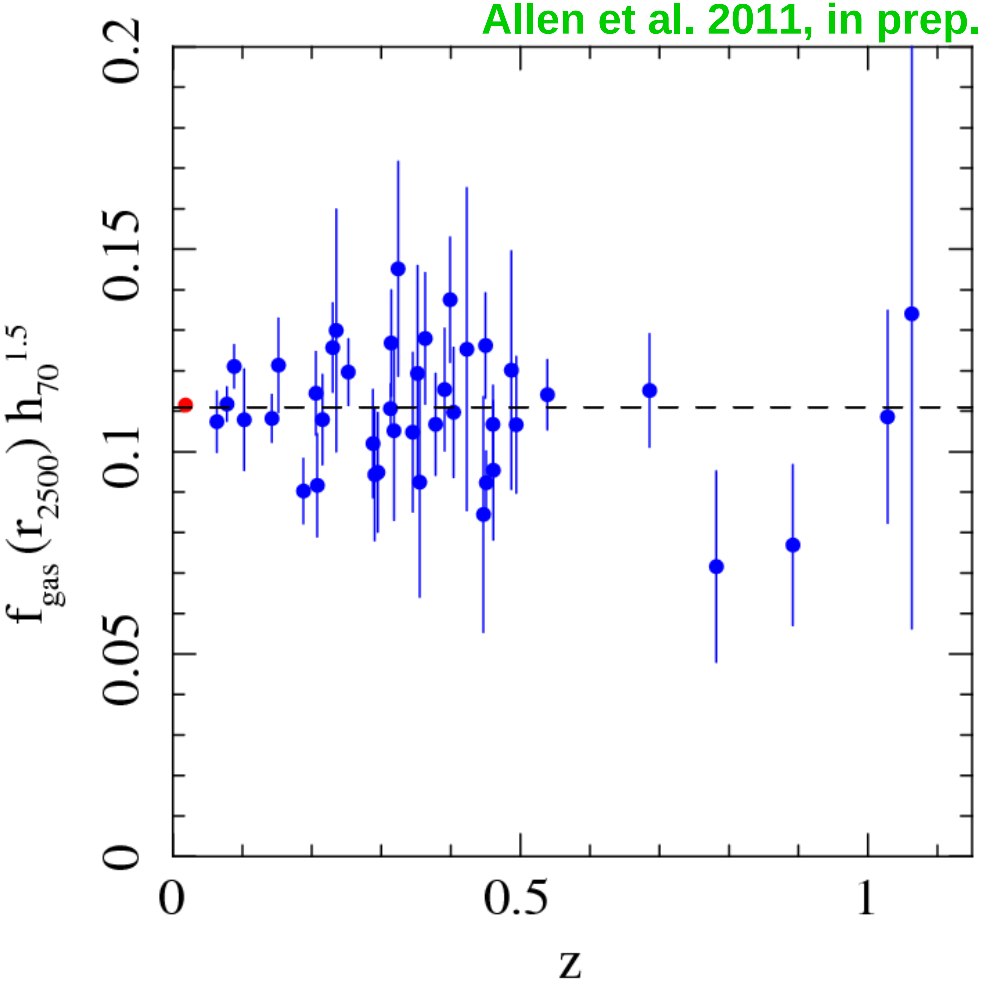


Gas clumping at $r \geq 0.5 r_{200}$ is confirmed by measurements of other thermodynamic properties.

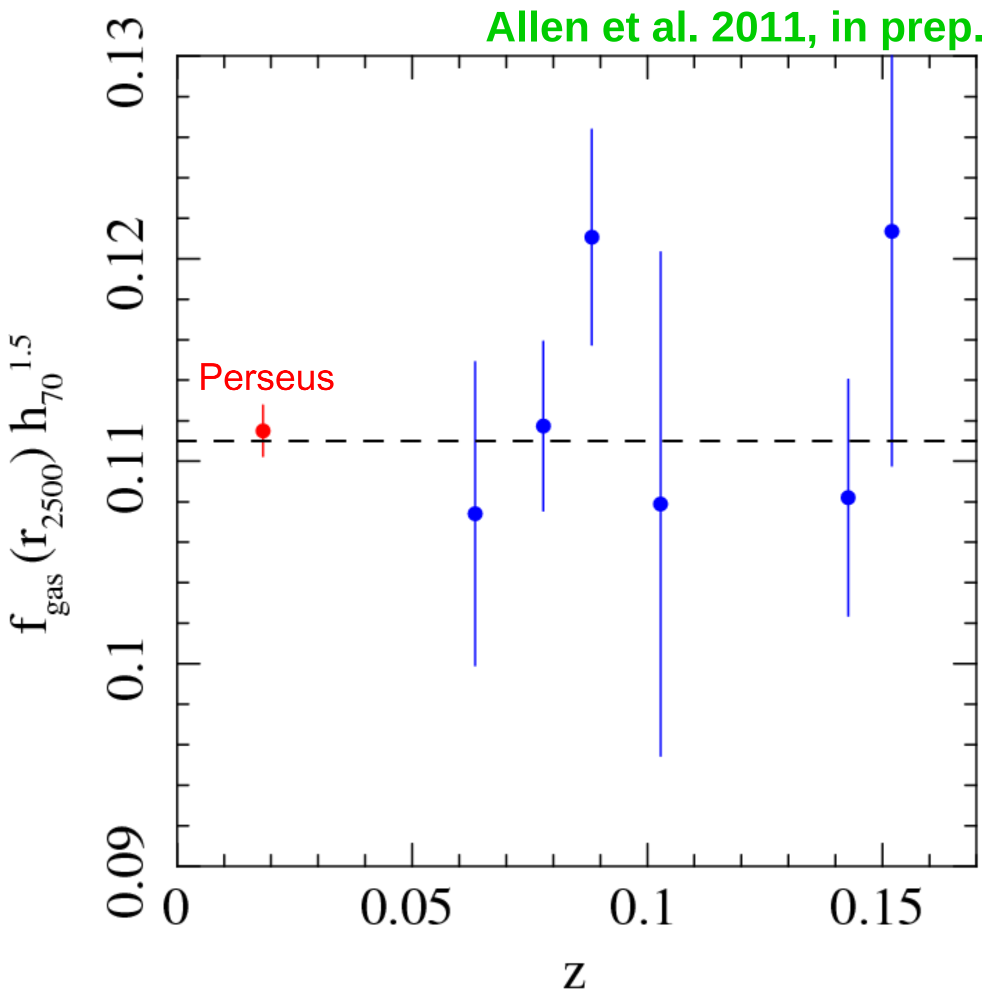
Clumping-corrected profiles (solid red curves) show good agreement with hydro. model predictions (dashed curves)

Suzaku vs Chandra f_{gas} measurements

Allen et al. 2011, in prep.



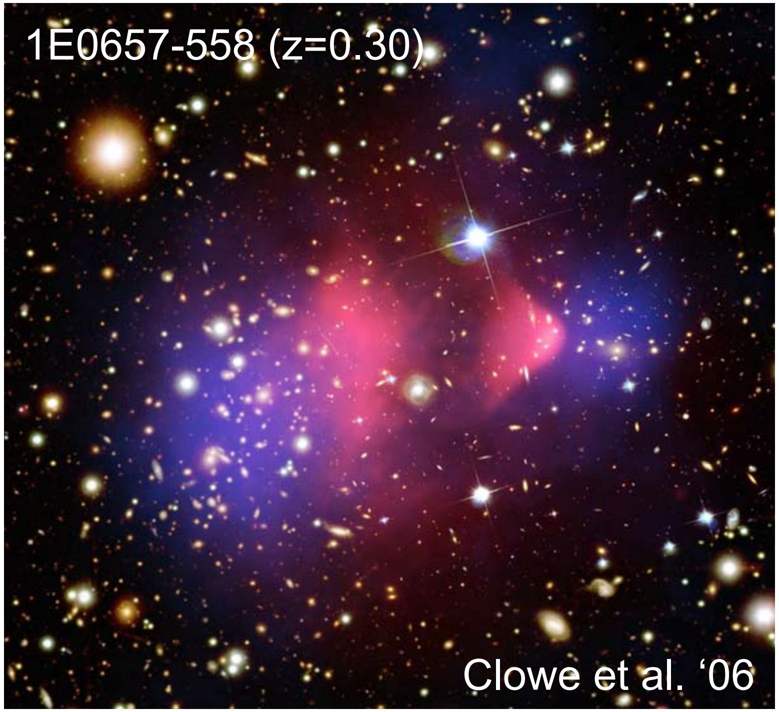
Suzaku vs Chandra f_{gas} measurements

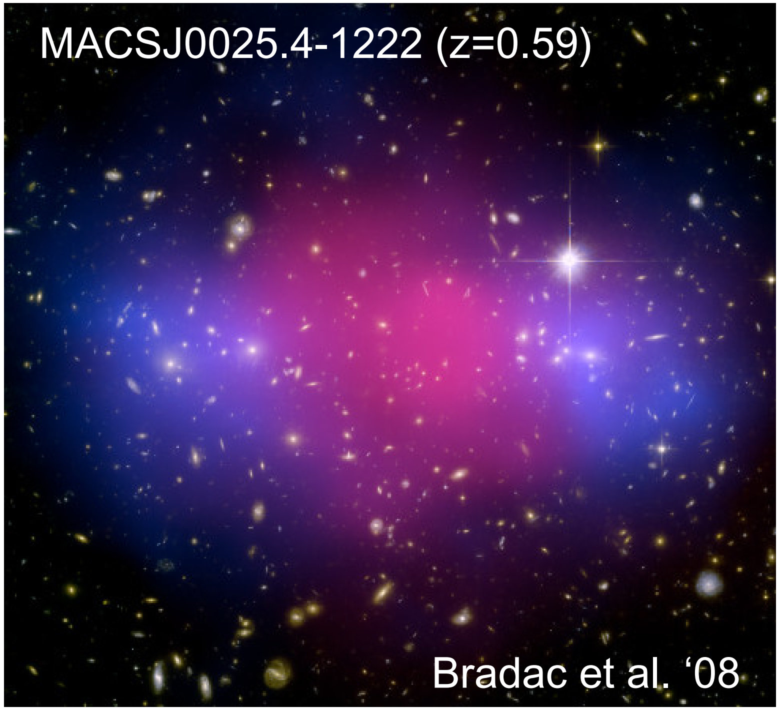


Excellent agreement with Chandra measurements at higher redshifts,

Testing the CDM paradigm

Tesing CDM with merging clusters





Cluster mergers provide interesting constraints on the dark matter self-interaction cross section. During mergers, the X-ray emitting gas (red) experiences ram pressure drag whereas the dark matter (blue) and galaxies do not.

$$\sigma / m < 1.5\ \mathrm{cm}^2\,\mathrm{g}^{-1}$$

Consistent with CDM

Testing CDM with relaxed clusters

The CDM paradigm predicts that the density profiles of relaxed dark matter halos follow a simple, universal profile (Navarro, Frenk & White ’97).

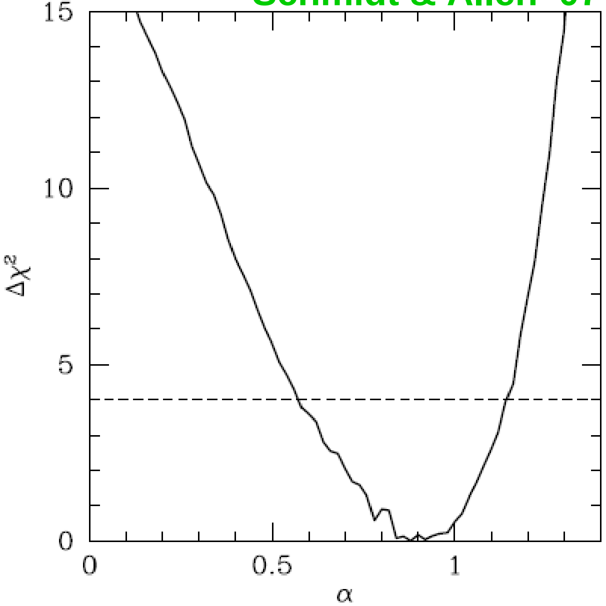
$$\rho(r) = \frac{\rho_0}{(r/r_s)(1+r/r_s)^2}$$

Q: Does this model provide an acceptable description of the data?

A: Yes, for > 80% of clusters with high quality Chandra data.

Q: DM models with significant self-interaction cross sections predict flattened, quasi-isothermal density cores. Are the observed central density slopes consistent with CDM (α=1)?

A: Yes, down to scales of tens of kpc ($0.02r_{200}$). Consistent with CDM.



Schmidt & Allen ‘07

Self-interaction cross sections from relaxed clusters

Q: How do such constraints translate into limits on σ/m?

A: Initial result of $\sigma/m < 0.1\ \mathrm{cm}^2\mathrm{g}^{-1}$ (Arabadjis et al. 2002) based on absence of DM core in X-ray and lensing data for MS1358+6245.

Q: A significant DM self-interaction cross section would reduce the central ellipticities of relaxed clusters. What limits have been placed?

A: Initial result $\sigma/m < 0.02\ \mathrm{cm}^2\mathrm{g}^{-1}$ (Miralda-Escude 2002) based on lensing data for the relaxed cluster MS2137.3+2353.

To improve these constraints, multiwavelength measurements for statistical samples of clusters, coupled with improved simulations (modeling the interactions between dark matter and baryons) are required.

Conclusions to lecture 1

Measurements of fgas for massive, dynamically relaxed clusters provide powerful constraints on Ω_M and dark energy, comparable to and consistent with those from SNIa and other leading methods.

Combined X-ray and lensing data for galaxy clusters provide interesting limits on the dark matter self-interaction cross section. Current results remain consistent with the standard cold dark matter (CDM) paradigm.

The prospects for near-term improvements are strong but will require coordinated efforts, involving deep, multiwavelength observations and enhanced numerical simulations.

Glossary of relevant cosmological parameters

$\Omega_{\mathrm{m}} = \rho_{\mathrm{m}}/\rho_{\mathrm{crit}}$	is the mean matter density in units of the critical density
$\Omega_{\mathrm{de}} = \Omega_{\Lambda} = \rho_{\mathrm{de}}/\rho_{\mathrm{crit}}$	is the dark energy density …
$\mathrm{w} = p_{\mathrm{de}}/\rho_{\mathrm{de}}$	is the dark energy equation of state. $w = -1$ for cosmological constant
σ_8	is the amplitude of matter fluctuations in $8h^{-1}$Mpc spheres (linear theory)
γ	is the gravitational growth index. $\gamma \sim 0.55$ for General Relativity
$\sum m_\nu$	is the species-summed neutrino mass