The Latest Cosmological Results from X-ray Galaxy Clusters

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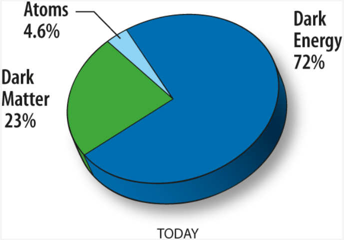
15 Years of Chandra

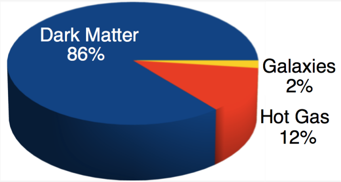
November 20, 2014

References: 1402.6212, 1407.4516

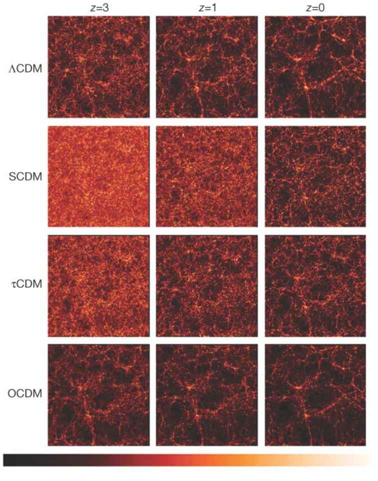
Two cosmological tests using clusters

1. $f_{\rm gas}$





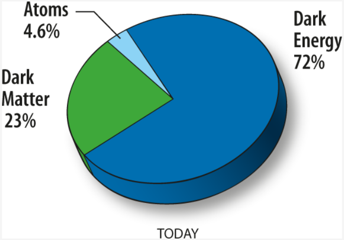
2. counts/growth



Cluster $f_{\rm gas}$

1. Gas mass fractions ($f_{\rm gas}$): uses a "gold" set of the most massive, dynamically relaxed clusters, for which $f_{\rm gas}$ measurements and predictions are most reliable.

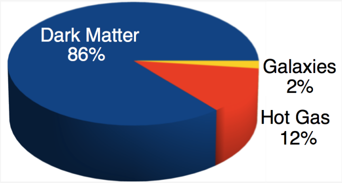
Universe:



Questions:

- How much dark matter is there? ($\Omega_{\rm m}$)
- How strongly is the cosmic expansion accelerating? (aka dark energy; Ω_Λ, w)

Clusters:



Cluster $f_{\rm gas}$: ingredients

1. Hydro simulations to predict the depletion factor ($f_{\rm gas}\,\Omega_{\rm m}/\Omega_{\rm b}$) and its evolution with redshift.
    - Current state-of-the-art includes radiative cooling, star formation, and feedback.
    - We marginalize over a range $4\times$ wider than the latest such work spans.

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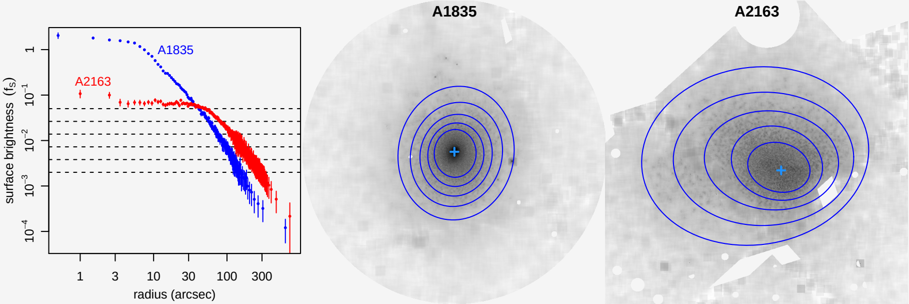
2. $f_{\rm gas}$ measurements for the most massive, relaxed clusters.
   - Sample is identified based on X-ray morphology and a temperature cut.
   - Contains 40 clusters spanning $0.07 < z < 1.1$ (3.1 Ms of Chandra).
   - Measurements in a shell (excluding the core) to minimize scatter and theoretical uncertainty.

$f_{\rm gas}$: identifying a relaxed sample

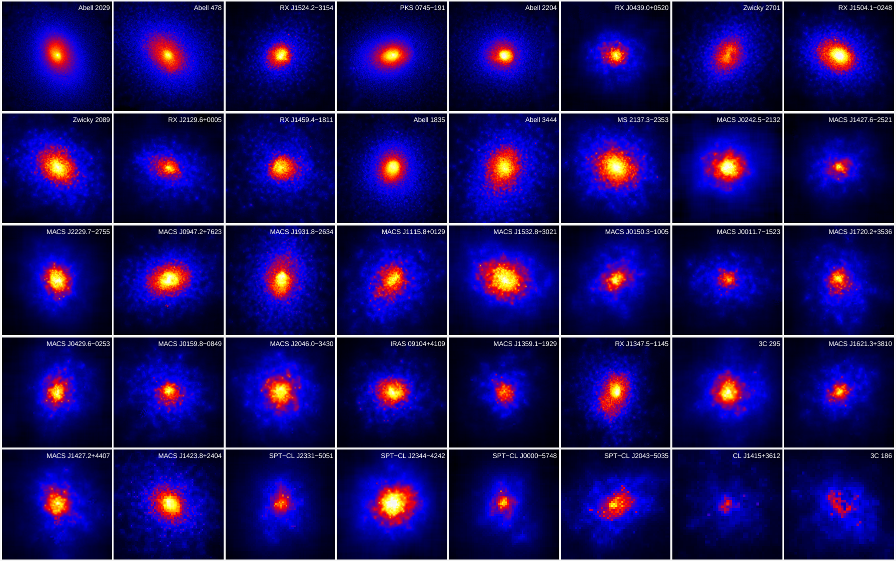


We searched through > 20 Ms of the Chandra archive.

Relaxation was determined using automated measurements of morphological features (Peak brightness, isophote Symmetry and Alignment): the SPA method for finding relaxed clusters.

Final sample has 40 clusters with $0 < z < 1.1$ and $kT > 5$ keV.

f_{gas}: the relaxed (SPA) sample



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   - Based on sub-sample of 12 relaxed clusters overlapping with WtG.

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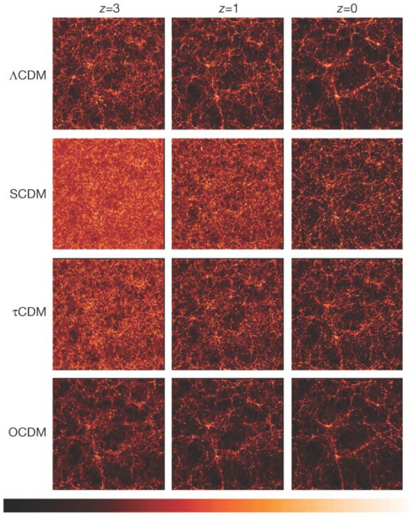
   - Corrects both non-thermal pressure and Chandra calibration.
   - Based on sub-sample of 12 relaxed clusters overlapping with WtG.
4. External priors on h and $\Omega_{\rm b}h^2$ (i.e. on $\Omega_{\rm b}$).
   - Allows us to focus on constraining $\Omega_{\rm m}$ and dark energy.

Growth of Structure

2. Abundance/growth: uses the statistical properties of the population.



(Image from Cole 2005)

Questions:

- How inhomogeneous is the universe? (σ_8)
- How much dark matter is there? (Ω_m)
- How massive are neutrinos? (Ω_ν)
- How much dark energy is there, and is it a cosmological constant? (Ω_Λ, w)
- Should we modify General Relativity instead?
- What drove inflation?

Growth of Structure: ingredients

1. Predicted mass function of halos (number density as a function of redshift, mass).
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    - Complete spectroscopic redshifts.
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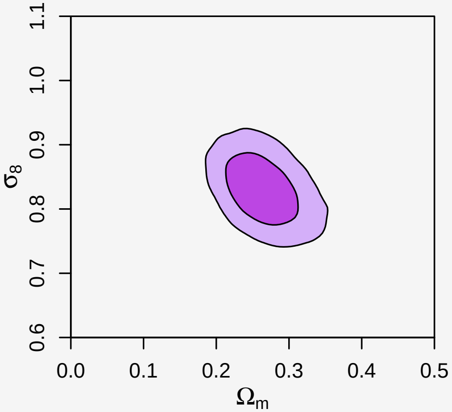
3. Mass estimates to empirically constrain scaling relations between mass and X-ray luminosity (or the SZ effect, or richness. . .).
   - Additional mass proxies (e.g. ICM temperature, $M_{\rm gas}$) also useful.
   - We use Chandra/PSPC data for ~ 90 clusters and weak lensing for 50.

Quick aside

1. To achieve useful precision, the $f_{\rm gas}$ test needs X-ray data.
2. Counts/growth experiments are not intrinsically wavelength-specific, but X-ray mass proxies (at minimum) are invaluable (e.g. Benson/SPT talk).
3. Optical/NIR gravitational lensing data now plays a critical role in both, providing unbiased total mass estimates.
   (See Weighing the Giants papers by von der Linden, Kelly, Applegate 2014)

f_{gas} + growth: constraints on Ω_{m} and σ_8



Latest constraints:

$$\Omega_{\text{m}} = 0.26 \pm 0.03$$

$$\sigma_8 = 0.83 \pm 0.04$$

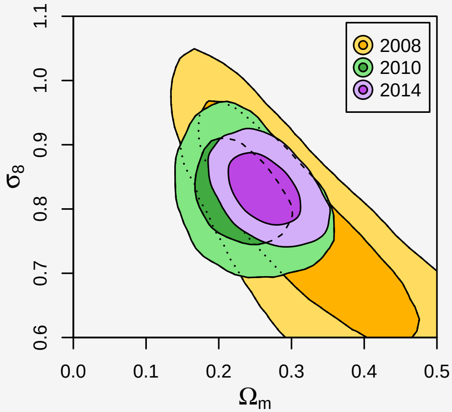
$$\sigma_8 \left(\frac{\Omega_{\text{m}}}{0.26}\right)^{0.17} = 0.83 \pm 0.03$$

Both these parameters limited by the mass calibration (lensing).

Note: growth and f_{gas} both constrain Ω_{m}, f_{gas} slightly more.
σ_8 comes only from the counts/growth.

Cluster constraints on these are essentially model independent.

$f_{\rm gas}$ + growth: constraints on $\Omega_{\rm m}$ and σ_8



Improvements in mass estimation and analysis:

2008: Relatively crude analysis, hydrostatic masses used regardless of dynamical state.

2010: Complete analysis, inclusion of $f_{\rm gas}$ data and low-scatter mass proxies.

2014: WtG lensing mass calibration.

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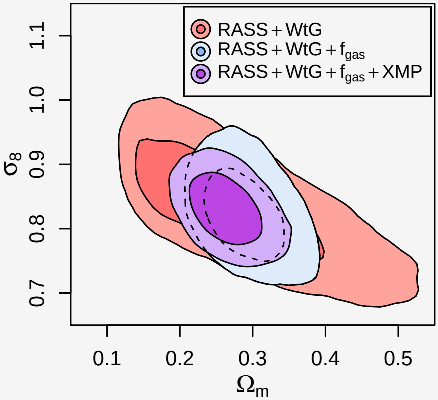

Even with lensing, X-ray mass proxies (kT, $M_{\rm gas}$) boost our constraining power noticeably.

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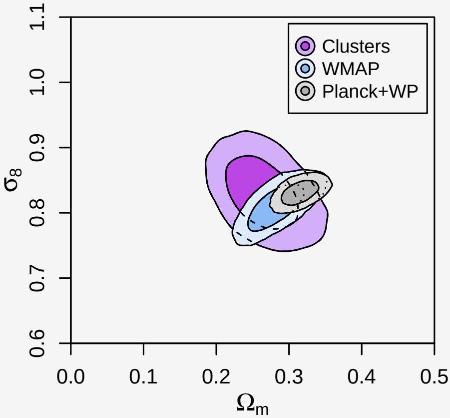
$f_{\rm gas}$ + growth: constraints on $\Omega_{\rm m}$ and σ_8



(CMB constraints assume flat ΛCDM, minimal neutrino mass)

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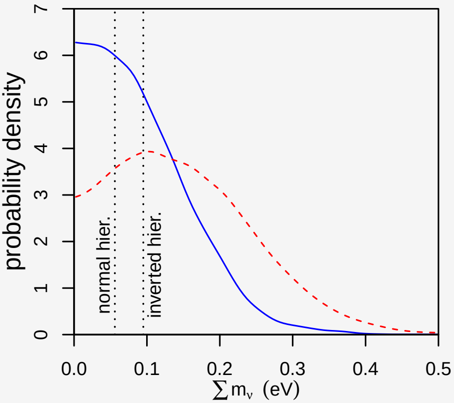
σ_8 comes only from the counts/growth.

Cluster constraints on these are essentially model independent.

$f_{\rm gas}$ + growth: constraints on neutrino mass

Cosmological currently data provide the tightest constraints on $\sum m_\nu$, but require an accurate measurement of σ_8.



Clusters+SN+BAO+ACT+SPT

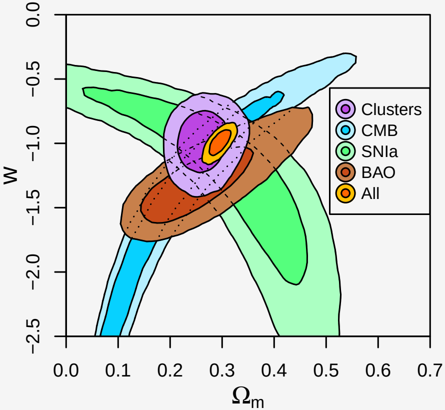
+Planck+WP:
$\sum m_\nu < 0.22\,\mathrm{eV}$

+WMAP:
$\sum m_\nu < 0.33\,\mathrm{eV}$

No cosmological signal for non-minimal neutrino mass (yet)!
(Laboratory limit is $\lesssim 6\,\mathrm{eV}$.)

$f_{\rm gas}$ + growth: constraints on dark energy

flat, constant-w models:



Clusters:

$$\Omega_{\rm m} = 0.261 \pm 0.031$$
$$\sigma_8 = 0.831 \pm 0.036$$
$$w = -0.98 \pm 0.15$$

CMB: WMAP, ACT, SPT

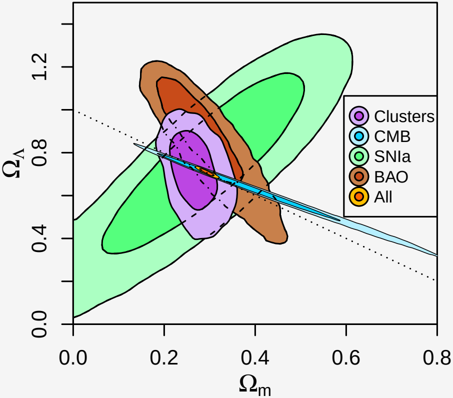
SNIa: Union 2.1

BAO: 6df, SDSS, BOSS

Note: growth and $f_{\rm gas}$ both constrain $\Omega_{\rm m}$ and w.
$f_{\rm gas}$ dominates the $\Omega_{\rm m}$ constraint, and growth dominates w.

$f_{\rm gas}$ + growth: constraints on dark energy

non-flat ΛCDM models:



Clusters:

$$\Omega_{\rm m} = 0.261 \pm 0.032$$
$$\sigma_8 = 0.830 \pm 0.035$$
$$\Omega_\Lambda = 0.728 \pm 0.115$$

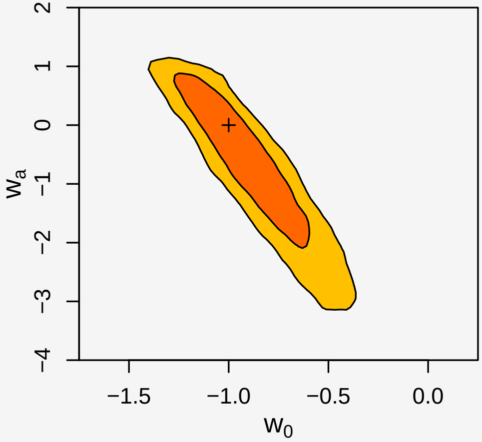
CMB: WMAP, ACT, SPT
SNIa: Union 2.1
BAO: 6df, SDSS, BOSS

Note: growth and $f_{\rm gas}$ both constrain $\Omega_{\rm m}$ and Ω_Λ.
$f_{\rm gas}$ dominates the $\Omega_{\rm m}$ constraint, and growth dominates Ω_Λ.

Combined constraints on evolving dark energy

evolving-w plus free curvature:

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



Clusters+CMB+SN+BAO:

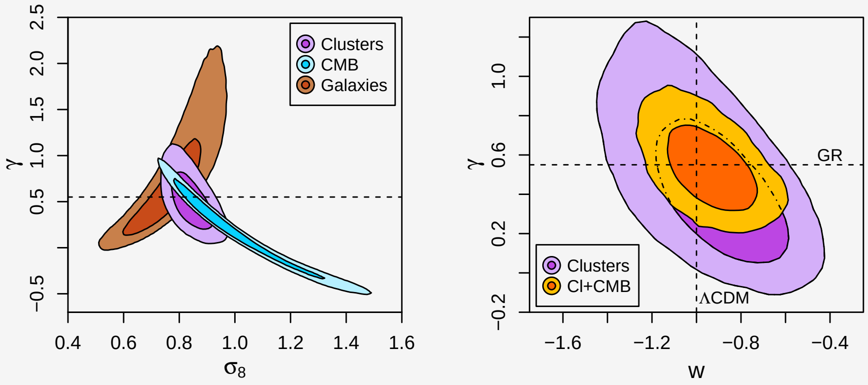
$$w_0 = -0.93 \pm 0.22$$
$$w_a = -0.4 \pm 1.1$$

(consistent with a cosmological constant and spatial flatness)

$f_{\rm gas}$ + growth: constraints on gravity

"Growth index" as a consistency test of GR: $\frac{d\delta}{da} = \frac{\delta}{a}\Omega_{\rm m}(a)^{\gamma}$

Clusters + CMB: $\gamma = 0.52 \pm 0.14$, $w = -0.94 \pm 0.13$



Coming soon: constraints on $f(R)$ models from Cataneo et al.

Summary

- Cluster $f_{\rm gas}$ and growth provide tight constraints on $\Omega_{\rm m}$, σ_8 and dark energy parameters – arguably the tightest of any single probe.
- Ongoing and planned surveys will capitalize on the extensively studied, massive, low-z clusters used here to provide even tighter constraints and test a wider range of models.