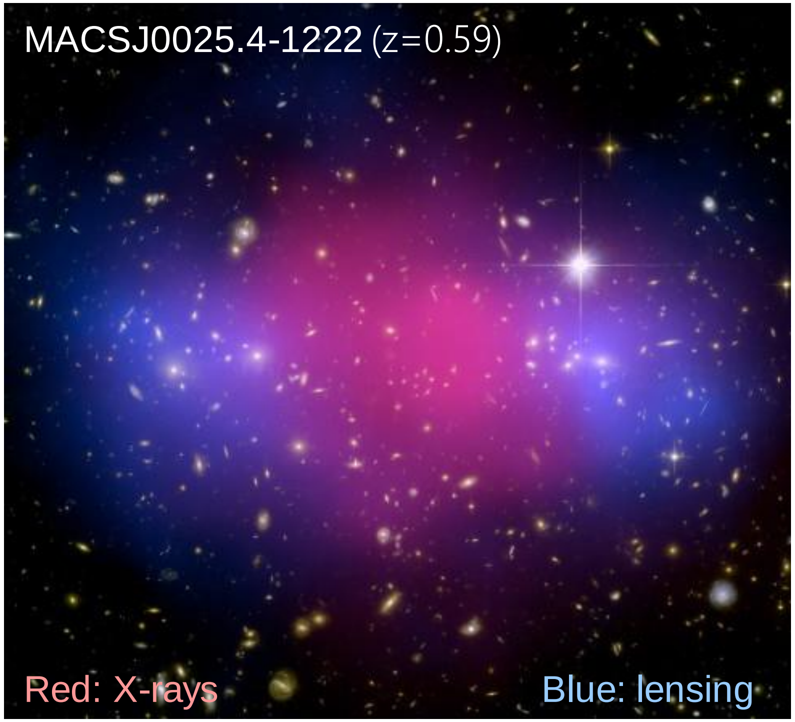
Chandra and Cluster Cosmology

Steve Allen (Stanford/SLAC)



In collaboration with:

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Adam Wright (Stanford/SLAC)

+ many more ...

The largest objects in the Universe

Wu, Hahn & Wechsler 2011

Visualization: R. Kaehler

By comparing the observed internal structure and evolution of galaxy clusters with cosmological model predictions, we can constrain the properties of dark matter and dark energy, as well as gravity, neutrinos, inflation …

1. The fgas test

Featured work: Mantz et al. 2014, MNRAS, 440, 2077
Mantz et al. 2015, MNRAS, 449, 199
Wright et al. 2019, Ph.D. thesis
Baumont et al. 2019, in prep.

See also e.g. White et al '93; David et al. '95; White & Fabian '95; Sasaki '96; Pen '97; Evrard '97; Mohr et al '99; Ettori & Fabian '99; Grego et al '00; Allen et al. '02, '04, '08,'13; Ettori et al. '03, '09; Sanderson et al. '03; LaRoque et al. '06, Rapetti et al. '08, Galli et al. '12, Lagana et al. '13; Landry et al. '13 ...

Constraining cosmology with f_{gas} measurements

<u>BASIC IDEA:</u> galaxy clusters are so large that their matter content should provide an approximately fair sample of matter content of Universe.

Key measurement:

$$f_{gas} = \frac{\text{X-ray gas mass}}{\text{total cluster mass}}$$

From X-ray (+ weak lensing) data

Since clusters provide ~ fair samples of the matter content, and the X-ray gas mass dominates the baryonic mass (~10x), we can also write:

Depletion factor (simulations)

$$f_{gas} = Y \frac{\Omega_b}{\Omega_m}$$

BBNS/CMB

Measure (X-ray data)

First compelling evidence Ω_m<1 (White et al. '93)

Constraining cosmology with f_{gas} measurements

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, need to know *Y(z)* (intuitively expect *Y(z)* ~ constant since massive clusters should provide approx. fair samples at all *z*).

BBNS/CMB

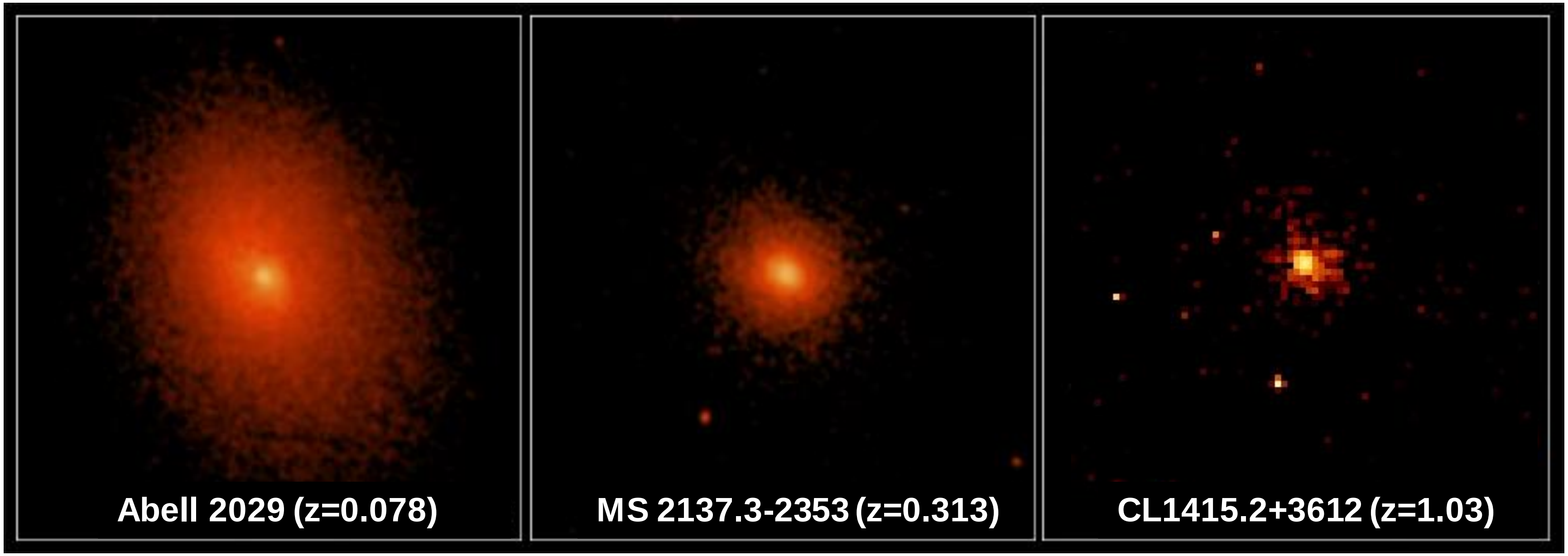
$$f_{gas}^{ref}(z) \propto Y(z)\left(\frac{\Omega_b}{\Omega_m}\right)\left[\frac{d_A^{ref}(z)}{d_A(z)}\right]^{1.5}$$

Measure (X-ray data)

Depletion factor (simulations)

Chandra data → first direct confirmation of SNIa result that expansion of Universe is accelerating (Allen et al. '04)

The observations (X-rays)

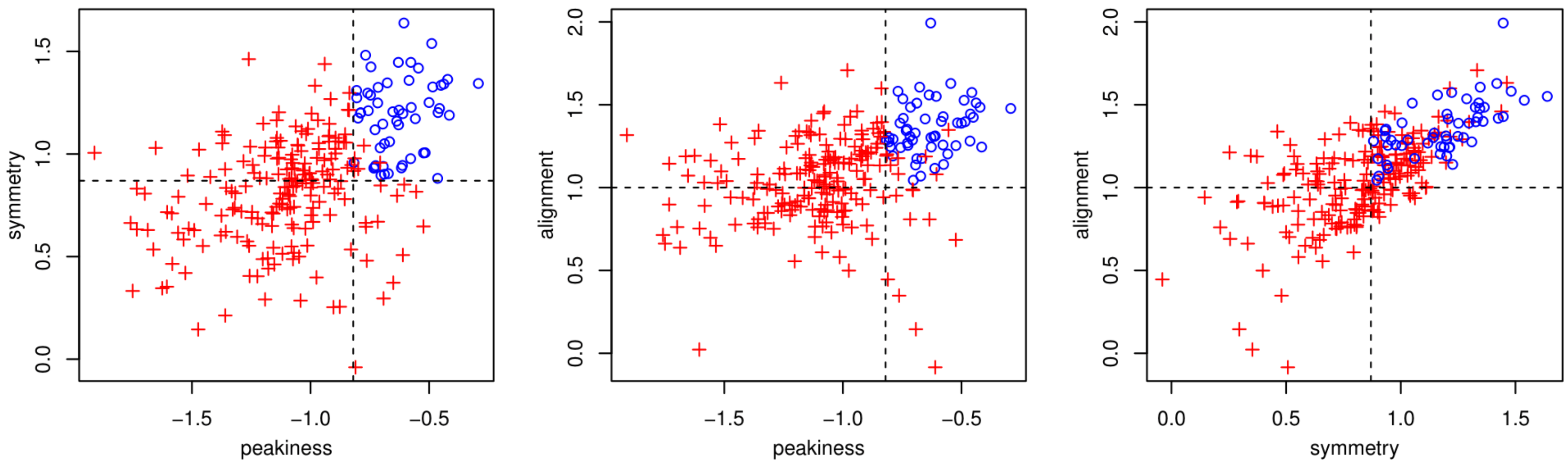


The entire Chandra archive was searched for observations for the hottest (kT>5keV), most dynamically relaxed systems. Determination of relaxation based on soft X-ray morphology. This selection is AUTOMATED, BLIND.

Restriction to hot, relaxed clusters minimizes systematic effects

Looking for relaxation? Try the SPA

Mantz et al. 2016

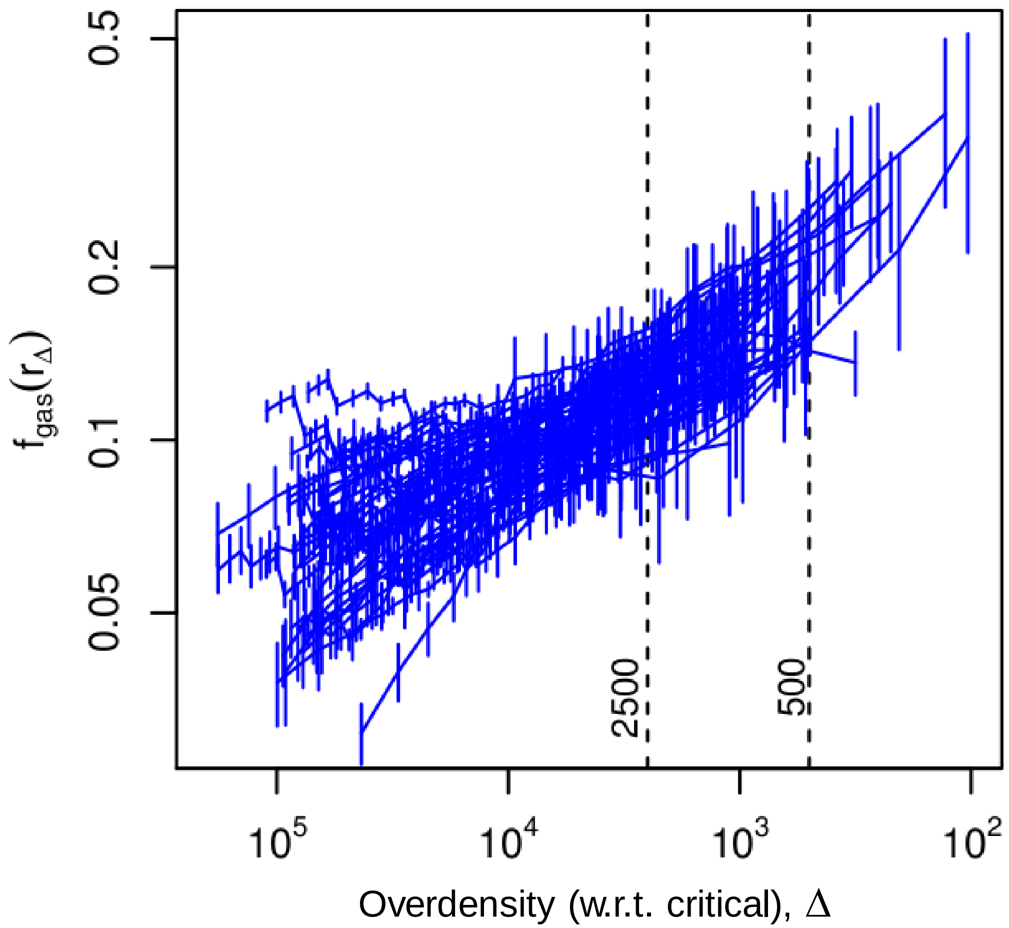


Our identification of the most relaxed systems uses the Symmetry, Peakiness, Alignment (SPA) code. Enables robust comparisons across a range of data quality and redshifts, incorporating rigorous treatment of errors, while avoiding strong assumptions about the cosmological background and cluster masses.

SPA performs better than human experts (lower resultant fgas scatter).

→ 40 systems with kT>5keV simultaneously pass all SPA cuts

Chandra f_{gas} profiles

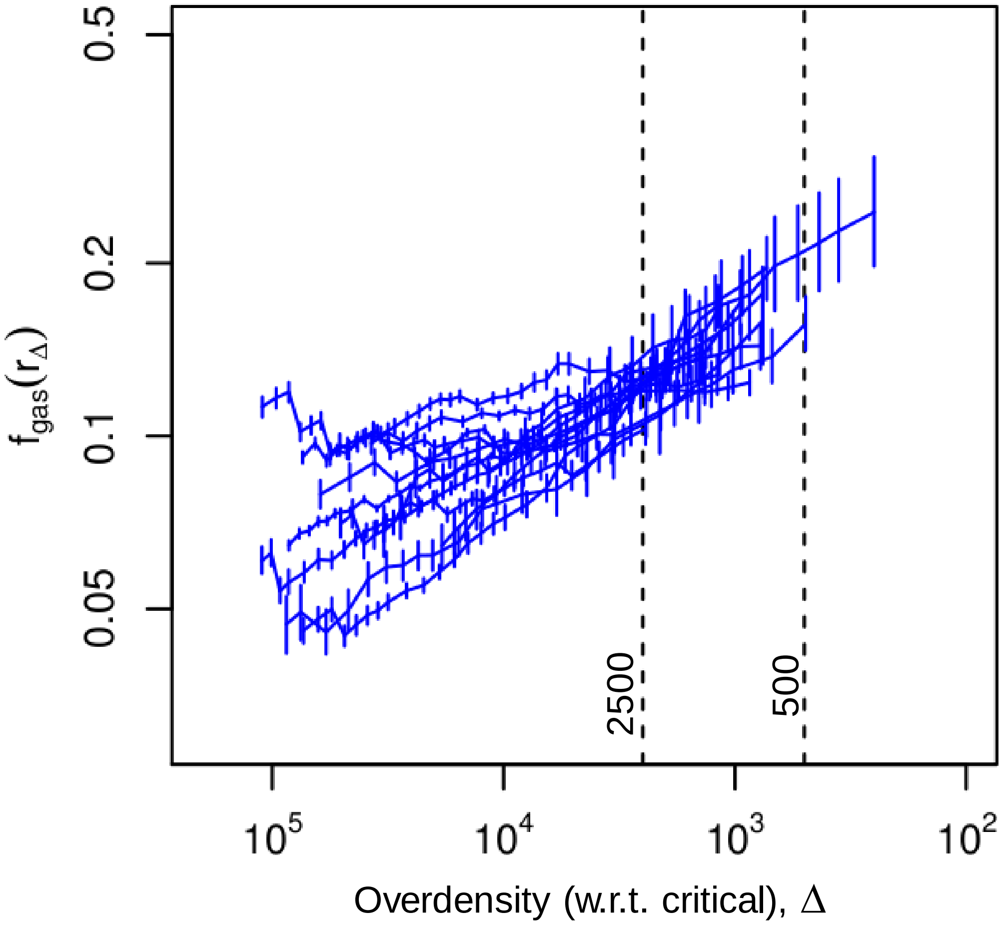


40 clusters

Differential f_{gas} profiles as a function of overdensity, Δ.

Analysis notes: standard assumptions of spherical symmetry and hydrostatic equilibrium employed. NFW mass model assumed (otherwise non-parametric).

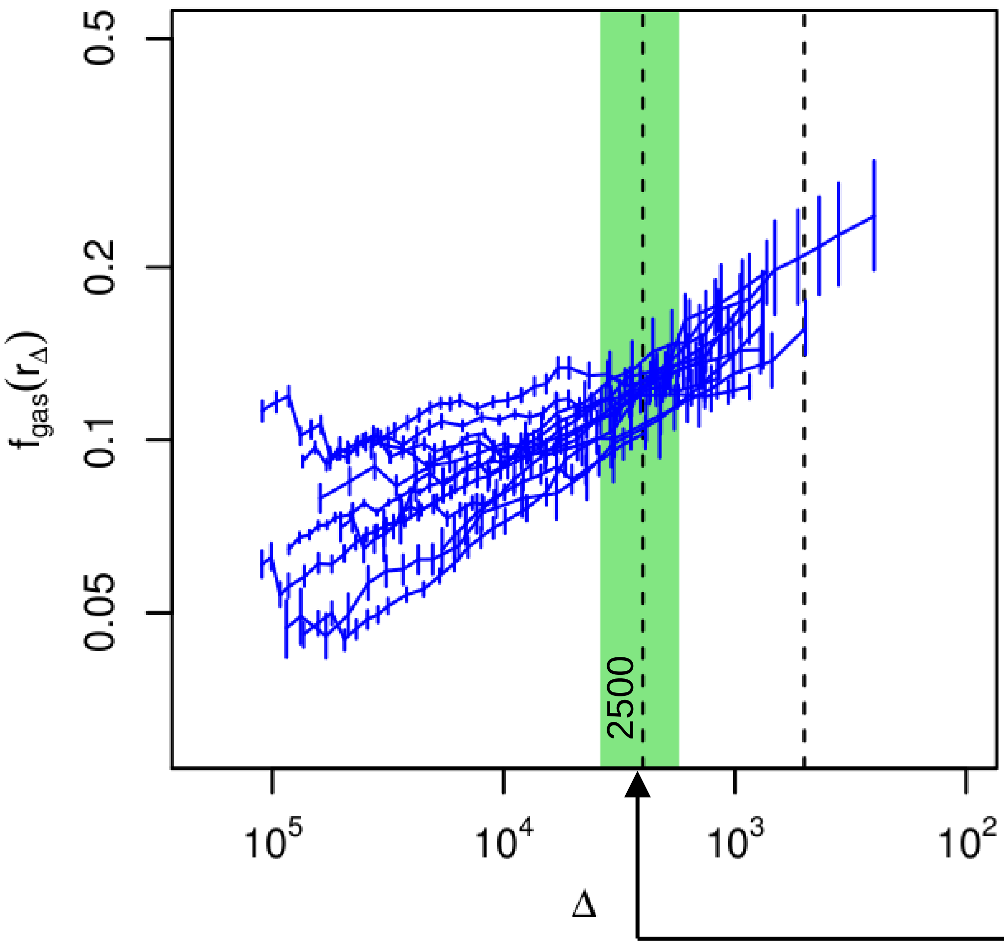
Chandra f_{gas} profiles



12 low-z clusters

Differential f_{gas} profiles as a function of overdensity, Δ.

Chandra f_{gas} profiles



12 low-z clusters

Differential f_{gas} profiles as a function of overdensity, Δ.

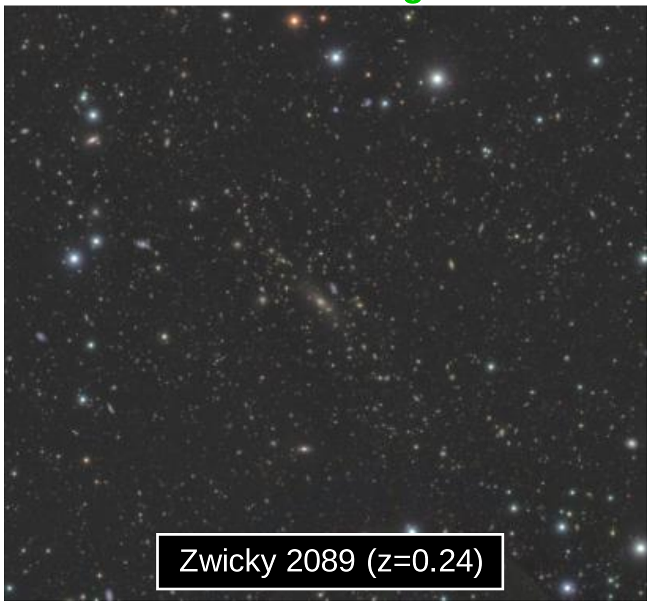
Restricting the analysis to a shell near r_{2500} provides a good compromise between statistical precision and intrinsic scatter in the $f_{gas}(r)$ measurements.

We can also predict the Y(z) robustly at these radii.

Measurement shell (0.8-1.2)r_{2500}

The observations (weak lensing)

Wright et al. 2019



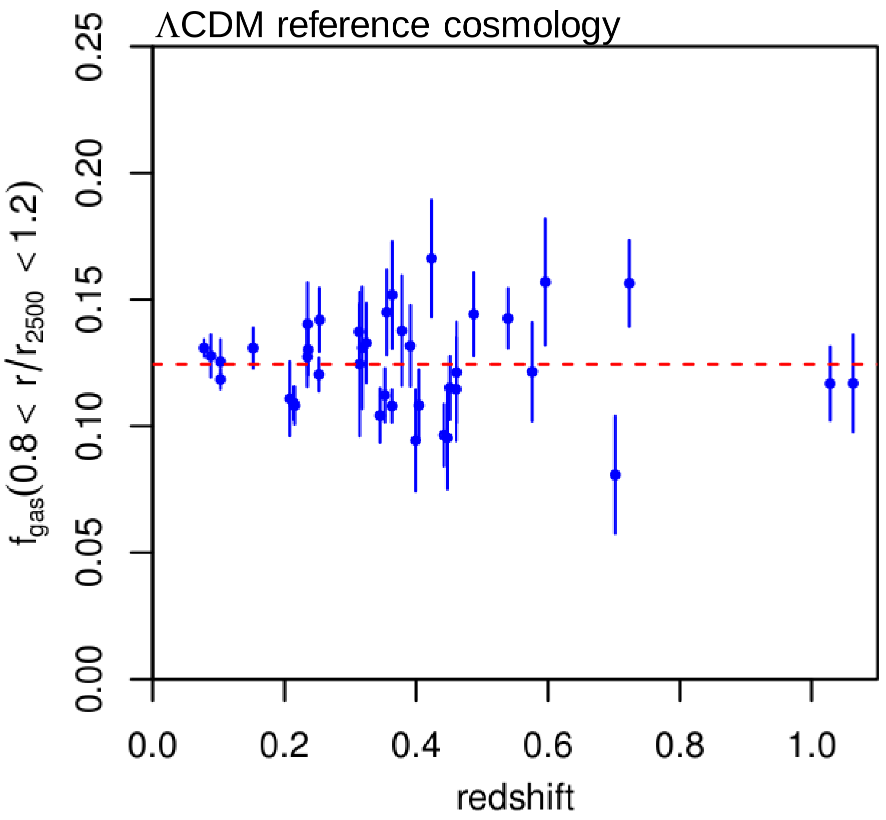
Deep (30-60 min exposures), high quality (0.5-0.7 arcsec seeing), five filter (BVRIZ) Subaru imaging. Updated (WtG2) analysis pipeline uses full photo-z and shape information for individual galaxies → exquisite lensing masses with robust systematic control. (LSST pathfinder study.)

WL data for 10/40 systems used to calibrate absolute mass scale

Fitting the model to the f_{gas} (z) data

$$f_{gas}^{ref}(z) \propto Y(z)\left(\frac{\Omega_b}{\Omega_m}\right)\left[\frac{d_A^{ref}(z)}{d_A(z)}\right]^{1.5}$$

Model includes conservative allowances for systematics (mass calibration and Y(z))



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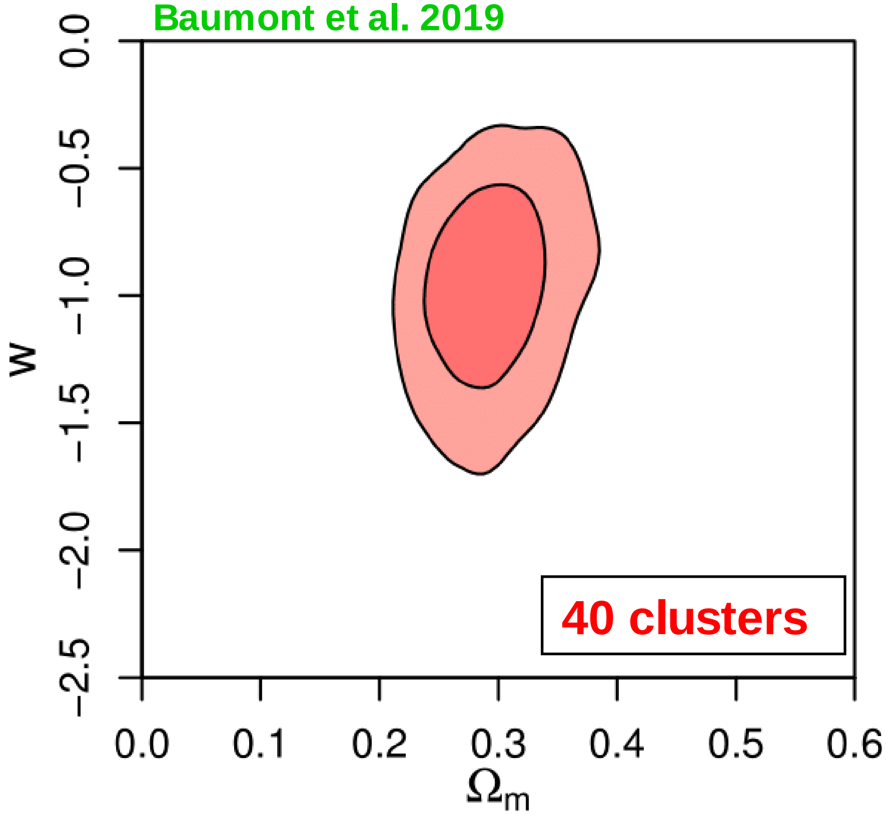
Baumont et al. 2019



Results (flat, constant w)

For (0.8-1.2)r_{2500} shell, including priors on $\Omega_b h^2$ =0.02202±0.00045 (Cooke et al. '13) and h=0.738±0.024 (Riess et al. '11).

Best-fit parameters (ΛCDM):

Ω_m=0.29±0.03, w=-0.93±0.24

Result limited by WL calibration (10/40 clusters).

Result limited by f_{gas} data.

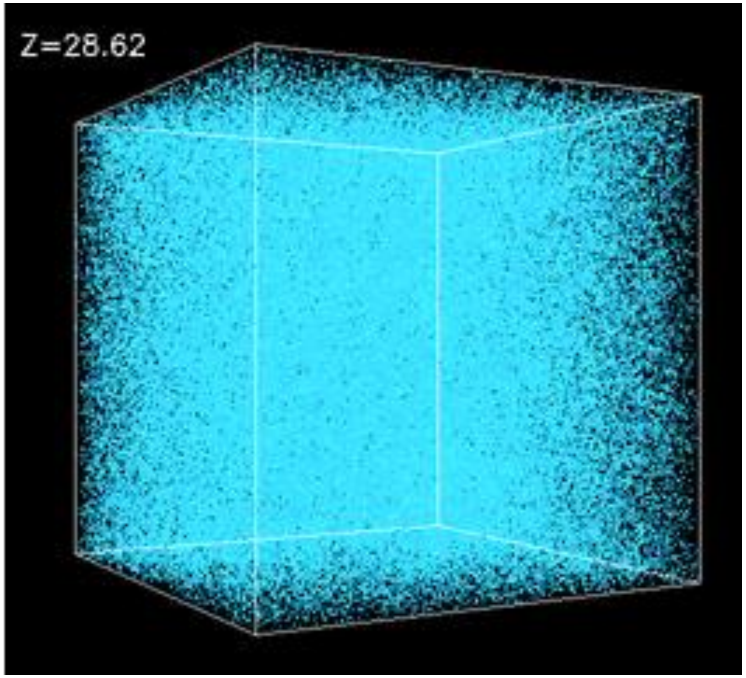
2. Cosmology with Cluster Counts

Featured work: Mantz et al. 2015, MNRAS, 446, 2205
Mantz et al. 2016, MNRAS, 463, 3582
Allen & Mantz, 2019, Chandra e-book

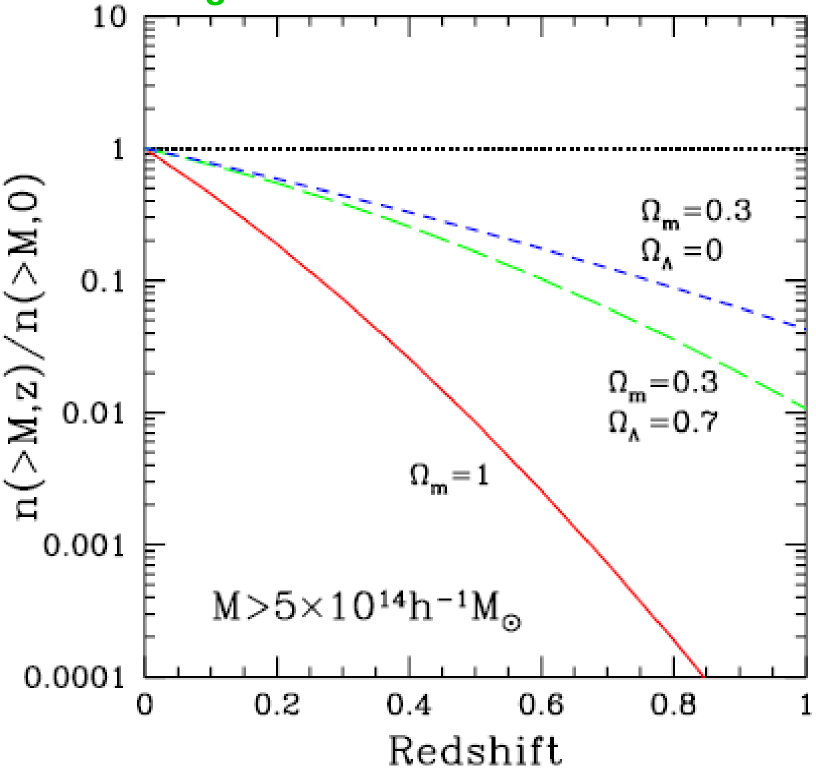
See also e.g. Borgani et al. '01; Reiprich & Bohringer '02; Seljak '02; Viana et al. '02; Allen et al. '03; Pierpaoli et al. '03; Schuecker et al. '03; Voevodkin & Vikhlinin '04; Henry '04; Mantz et al. '08, '10; Vikhilinin et al. 09; Henry et al. '09; Rozo et al. '10; Allen et al. '11; Kravtsov & Borgani '12; Benson et al. '13; de Haan et al. '16; Planck Collaboration et al. '16, '18; Zubelidia & Challinor '19 …

Cosmology with cluster counts

Kravtsov et al.



Borgani '04



Measurements of number counts of galaxy clusters as a function of mass and redshift provide powerful constraints on cosmological parameters ("... galaxy clusters could emerge as the most powerful cosmological probe", DOE Cosmic Visions Dark Energy Science report, arXiv:1604.07626)

Ingredients for cosmology with cluster counts

[THEORY] The predicted mass function of clusters, n(M,z), as a function of cosmological parameters (σ_8,Ω_m,w etc).

[CLUSTER SURVEY] A large, clean, complete cluster survey with a well defined selection function.

Current leading catalogs constructed at X-ray (ROSAT) and mm (SZ) wavelengths (SPT, ACT, Planck).

[MASS-OBSERVABLE RELATION] Well-calibrated scaling relation(s) linking survey observable (e.g. Lx, richness, SZ flux) and mass.

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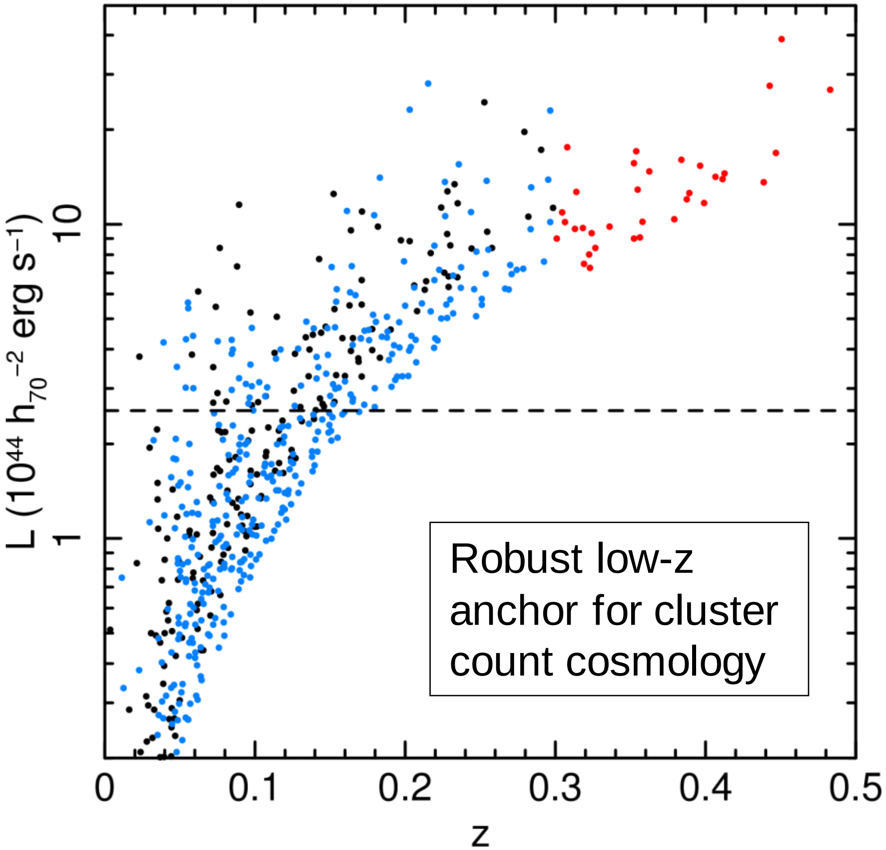
Cluster surveys based on RASS

Mantz et al. 2015



BCS (Ebeling et al. ’98, ’00).
$z<0.3$, $Fx>4.4\times10^{-12}$ ergcm^{-2}s^{-1}
[northern sky: 201 clusters]

REFLEX (Bohringer et al ’04).
$z<0.3$, $Fx>3.0\times10^{-12}$ ergcm^{-2}s^{-1}
[southern sky: 447 clusters]

Bright MACS (Ebeling et al. ’09)
$z>0.3$, $Fx>2.0\times10^{-12}$ ergcm^{-2}s^{-1}.
[all-sky: 34 clusters]

All three surveys based on ROSAT All-Sky Survey (RASS) (0.1-2.4keV).
To minimize systematics, we use conservative flux limits and only the most luminous systems, with $Lx > 2.5\text{x}10^{44}$ h_{70}^{-2} erg s^{-1} (224 clusters total).

Ingredients for cosmology with cluster counts

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[CLUSTER SURVEY] A large, clean, complete cluster survey with a well defined selection function.

Current leading catalogs constructed at X-ray (ROSAT) and mm (SZ) wavelengths (SPT, ACT, Planck).

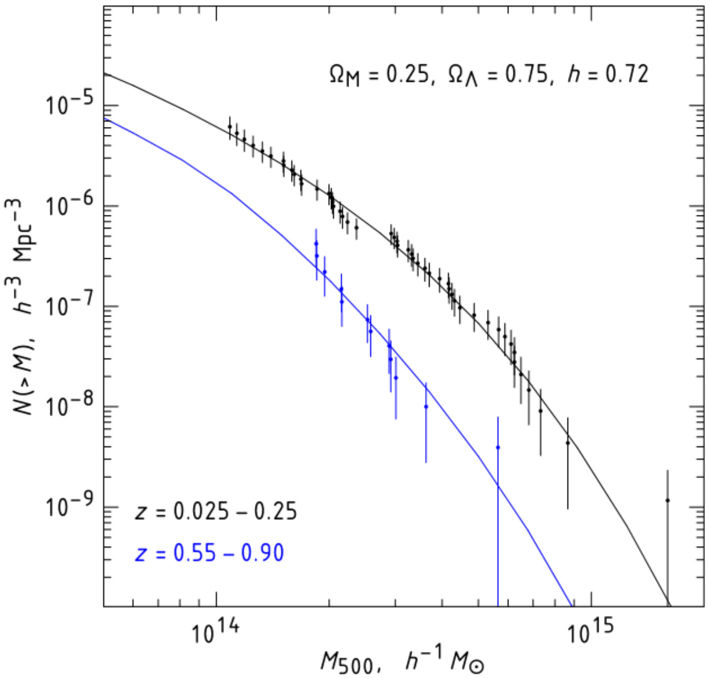
[MASS-OBSERVABLE RELATION] Well-calibrated scaling relation(s) linking survey observable (e.g. Lx, richness, SZ flux) to M,z.

KEYS: gather high quality follow-up data for the clusters in the actual survey, and separate mass calibration into two parts: relative and absolute calibration (Vikhlinin et al. '09, Mantz et al.'10).

Precise relative mass calibration from X-ray data

X-ray measurements provide low-scatter mass proxies (Mgas, Tx, Yx)
→ tight relation between survey observable and relative cluster mass.

Vikhlinin et al. 2009



For massive clusters:

Mgas	Tx	Yx
≤10% scatter	~10-15% scatter	~10-15% scatter

Precise relative mass calibration from X-ray data

X-ray measurements provide low-scatter mass proxies (Mgas, Tx, Yx)
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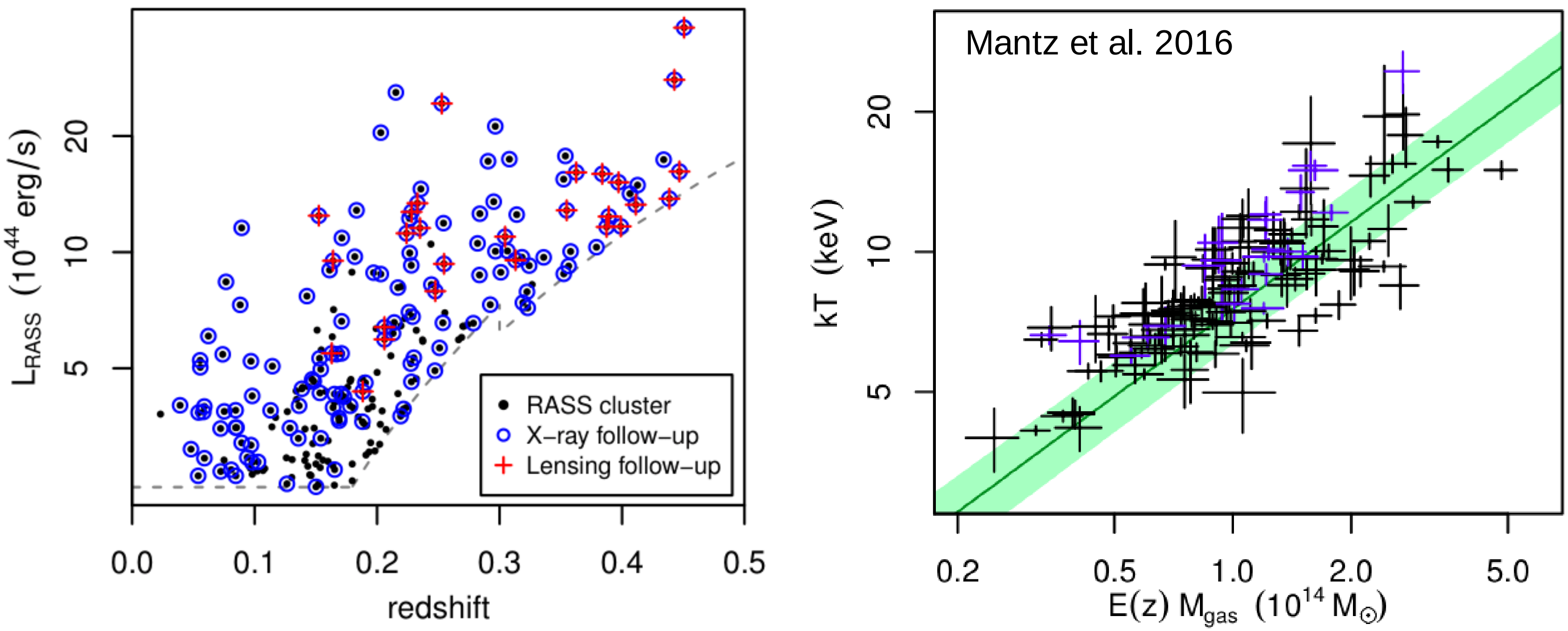
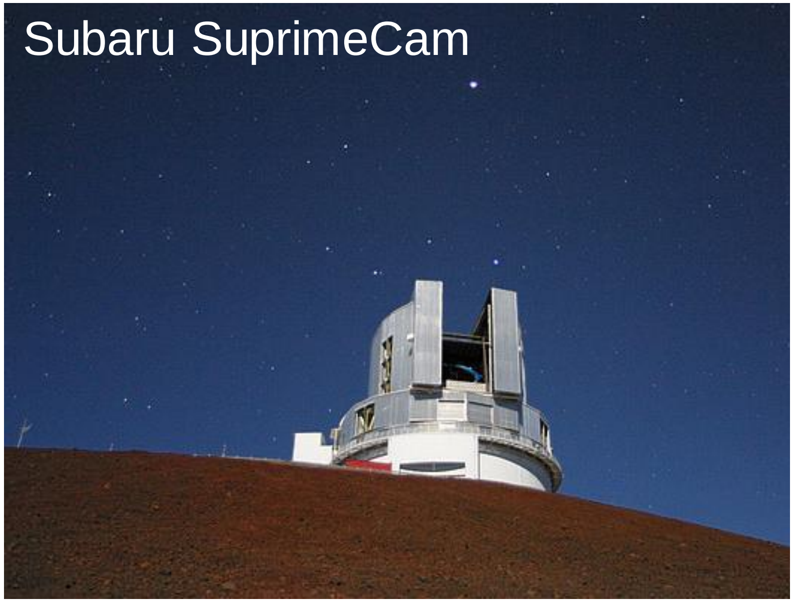


For the RASS surveys: ~10Ms of Chandra and ROSAT observations for 139/224 survey clusters $\rightarrow$ re-measure Lx + measure Mgas, Tx, Yx at r_{500}.

Robust absolute mass calibration from weak lensing

Deep, high quality multi-filter (BVRIZ) Subaru imaging for 27/224 clusters → accurate absolute mass calibration from weak lensing (WL) methods



Weighing the Giants (WtG)

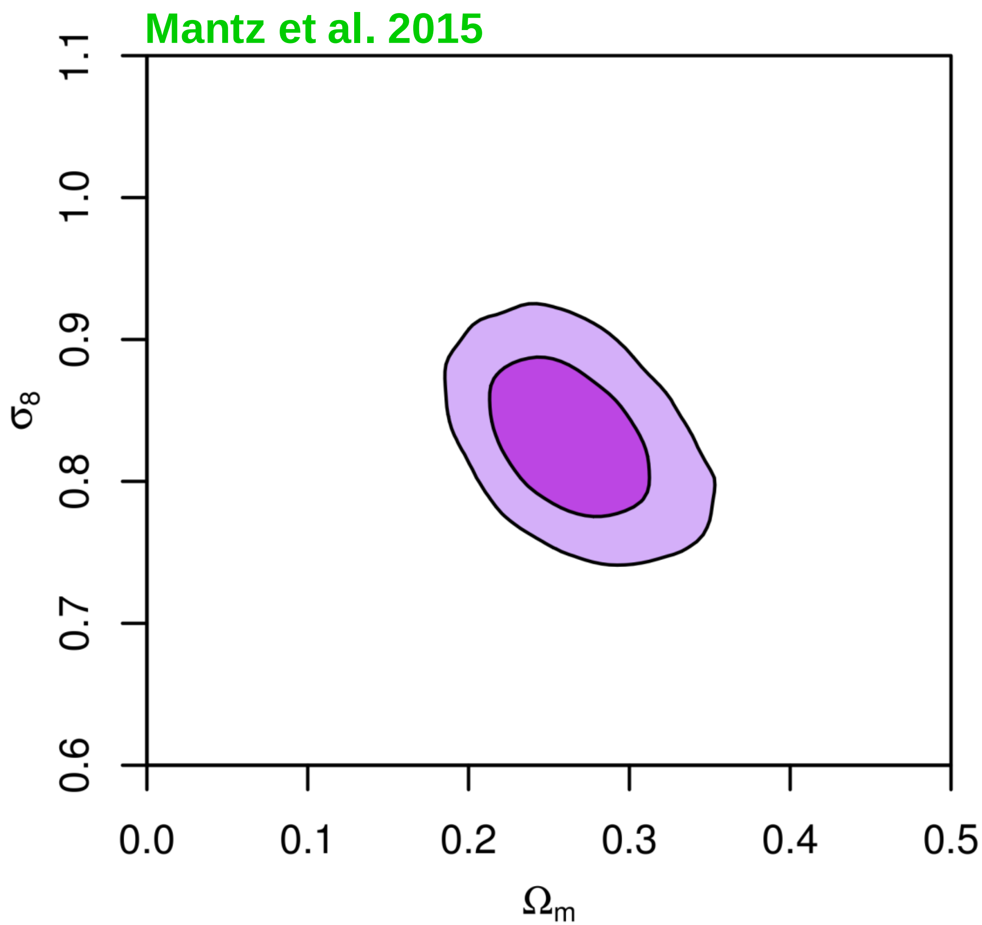
Von der linden et al. 2014
Kelly et al. 2014
Applegate et al. 2014

Improved techniques for cluster WL and (to combat experimenter's bias) BLIND ANALYSIS.

WL masses (measured appropriately) are approximately unbiased on average, with small residual bias being calibrate-able with simulations

WTG → ± 8% absolute mass calibration

Cosmology: results on σ_8, Ω_m



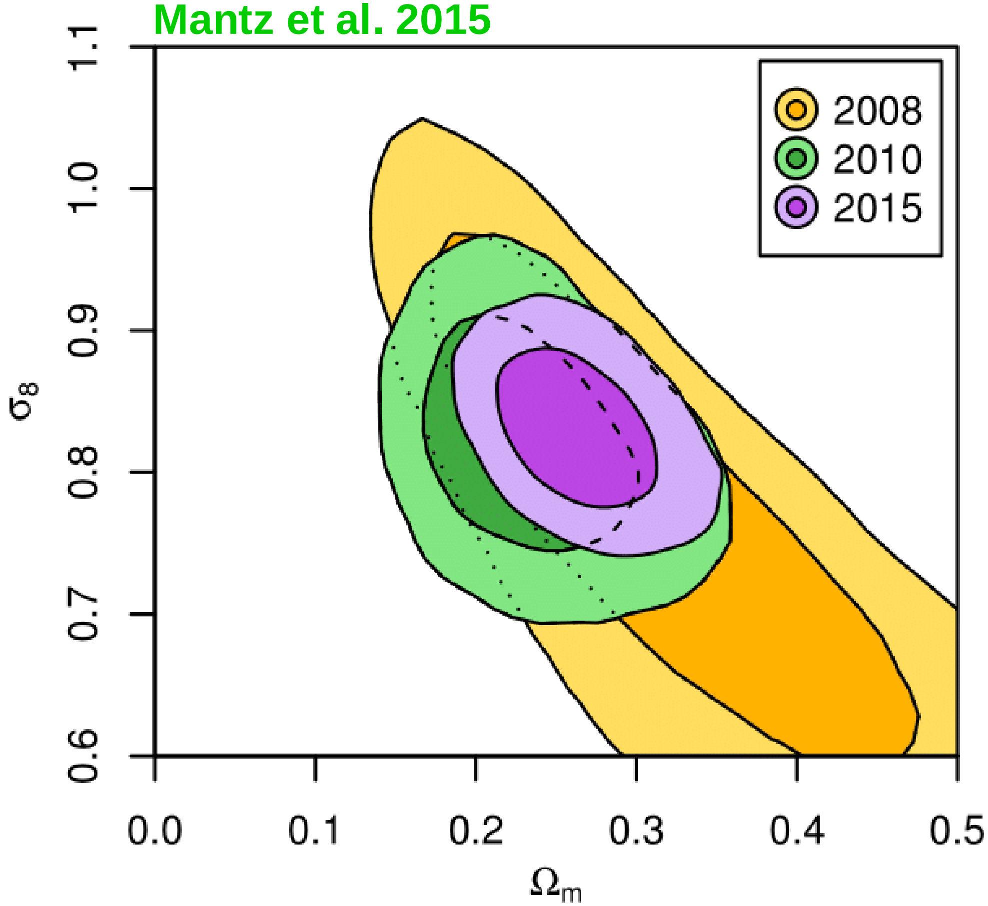
Flat ΛCDM model:

$\Omega_m = 0.260 \pm 0.030$
$\sigma_8 = 0.830 \pm 0.035$

68% confidence limits, marginalized over all systematic uncertainties. (Standard priors on $\Omega_b h^2$ and h included.)

Impact of improved mass calibration

Mantz et al. 2015



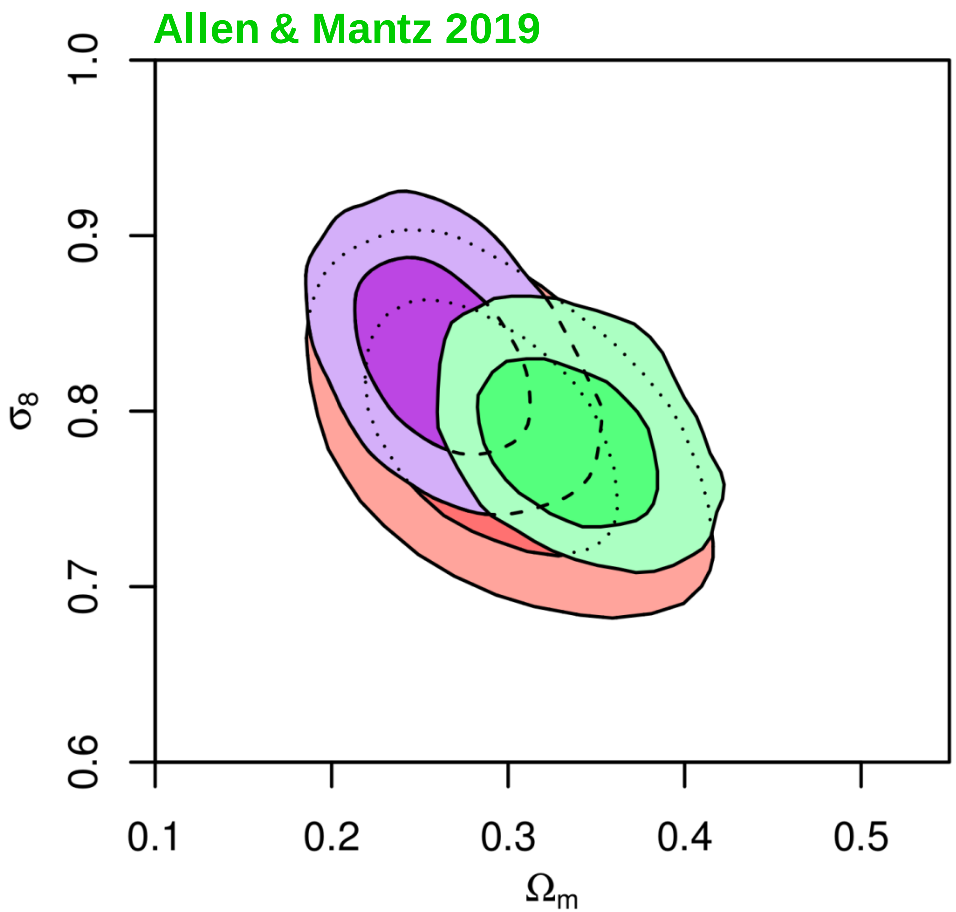
Key advances:

2008→2010: inclusion of low-scatter X-ray mass proxies (+ fgas).

2010→2015: inclusion of Weighing the Giants weak lensing mass calibration.

In combination, X-ray mass proxies + WL mass calibration → substantial boost in cosmological constraining power.

Comparison vs. other cluster experiments



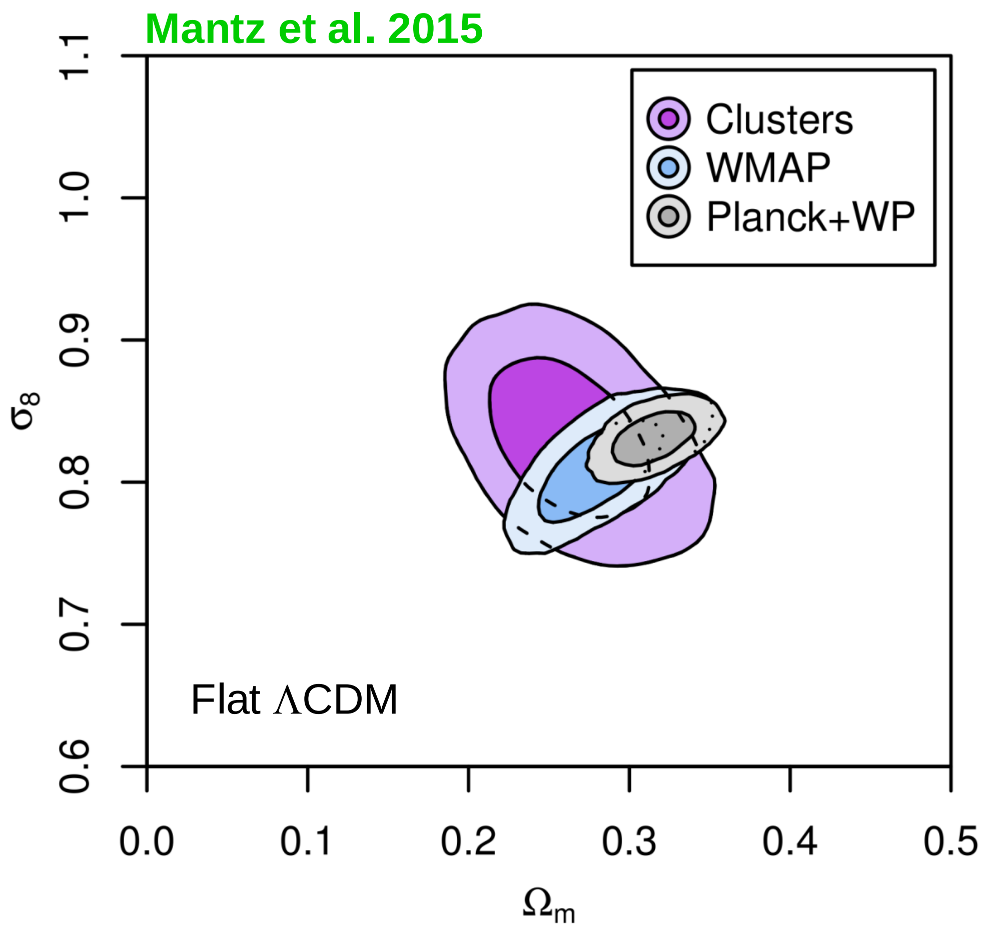
SPT: de Haan et al. '16
Planck Collaboration '16

RASS (Chandra+WTG)
Planck clusters (XMM+WTG)
SPT clusters (Chandra+WL)

Good agreement between X-ray and SZ cluster counts when employing consistent absolute mass calibration.

Consistent results for Planck clusters also obtained using CMB lensing mass calibration (Zubelidia & Challinor '19).

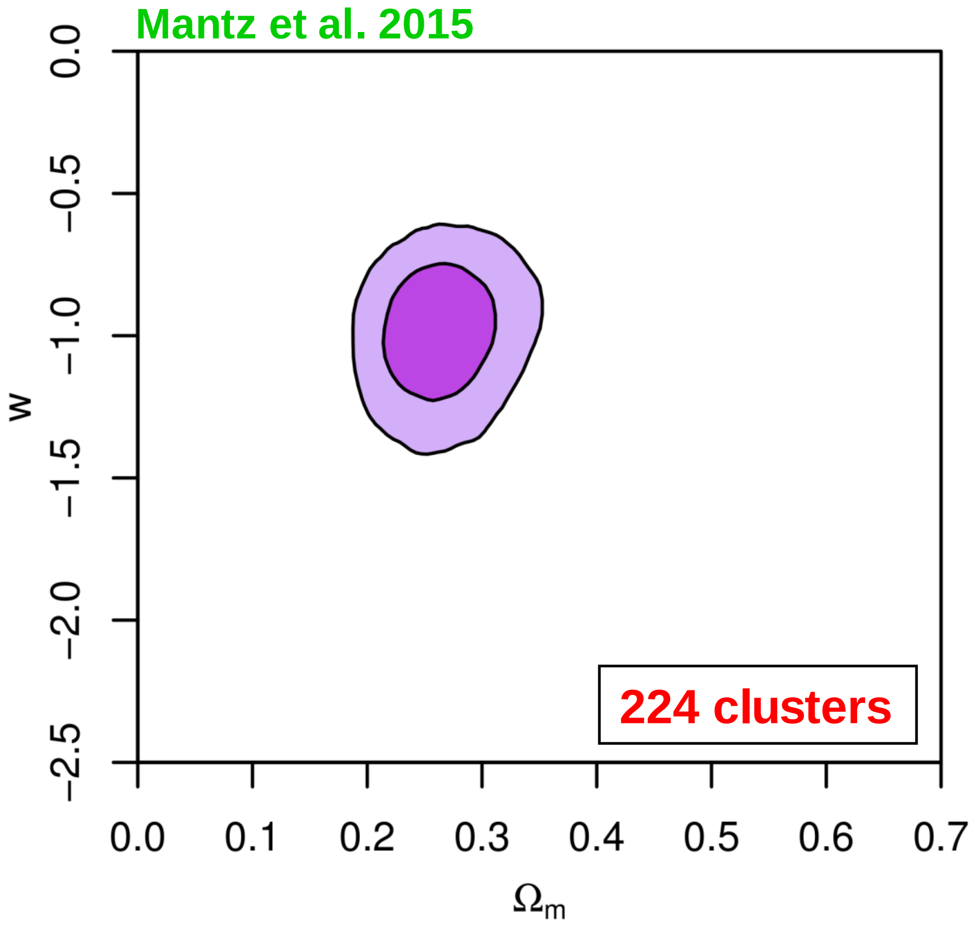
Comparison vs. primary CMB



No tension between constraints from cluster counts and primary CMB (WMAP or Planck) when employing an appropriate statistical framework and robust WL mass calibration.

See also Planck Collaboration '18, Zubelidia & Challinor '19

Results on dark energy (clusters only)



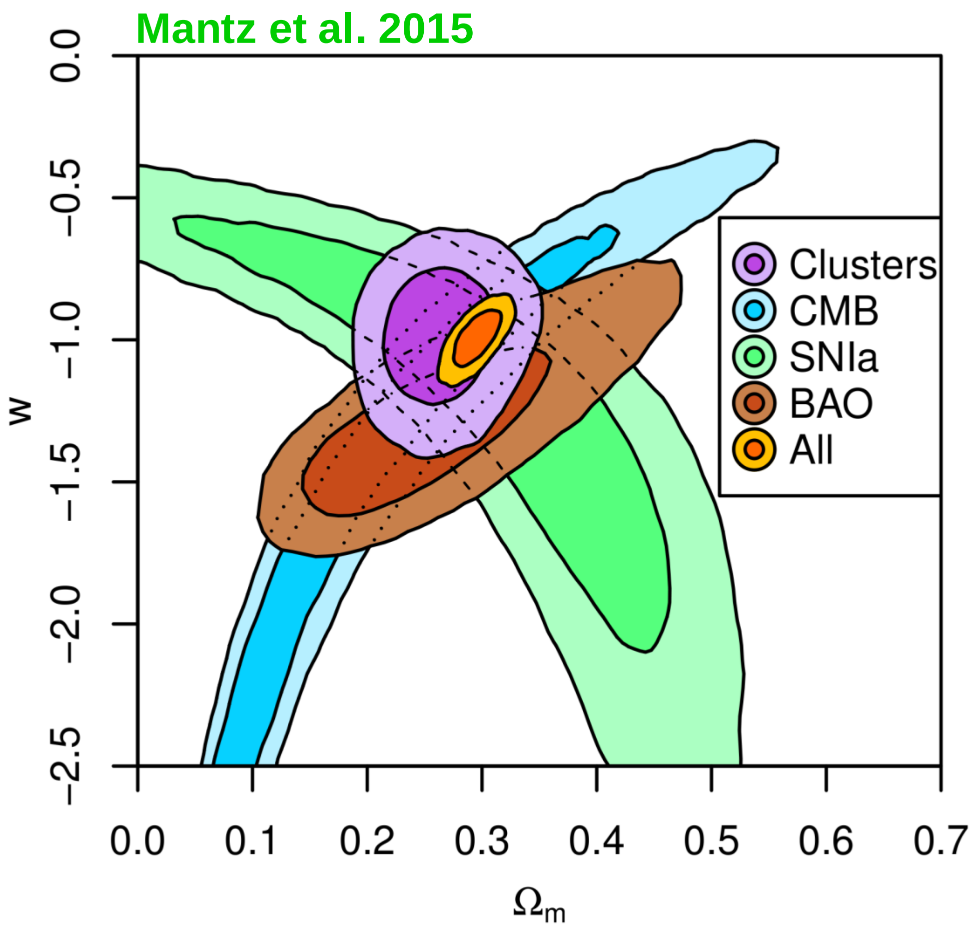
Flat, constant w model:

$\Omega_m = 0.261 \pm 0.031$
$\sigma_8 = 0.831 \pm 0.036$
$w = -0.98 \pm 0.15$

68% confidence limits, marginalized over all systematic uncertainties. (Standard priors on $\Omega_b h^2$ and h included.)

Clear detection of the effects of dark energy on structure growth.

Cluster counts vs. independent techniques



Flat, constant w model:

Clusters (Mantz et al. 15)
CMB (WMAP9+SPT+ACT)
SNIa (Suzuki et al. '12)
BAO (Anderson et al. '14)

Combined constraint (68%)

$\Omega_m = 0.295 \pm 0.013$
$\sigma_8 = 0.819 \pm 0.026$
$w = -0.99 \pm 0.06$

All 4 independent techniques consistent with cosmological constant.
Cluster constraints (highly) competitive with other leading methods.

3. The Road Ahead

Featured work: Mantz et al. 2019, arXiv:1903.05606
Allen & Mantz 2019, Chandra e-book

Surveys on the near and mid-term horizons

Projects:

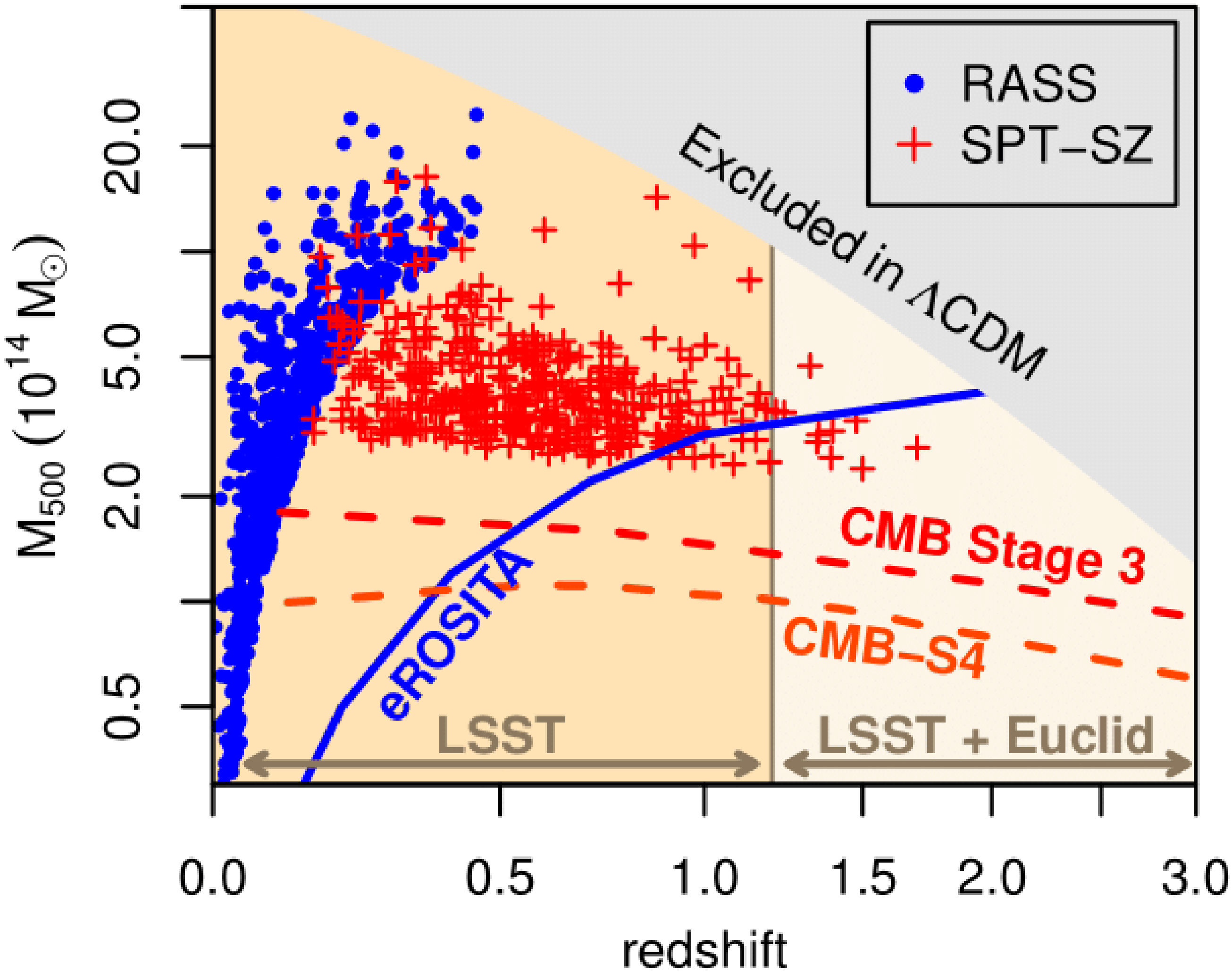
Optical/NIR: DES, HSC, Euclid, LSST
mm: SPT3G, AdvACT, Simons Obs, CMB-S4
X-ray: eROSITA

Strengths:

Optical/NIR: cluster finding, photo-zs, WL mass cal.
mm: high-z cluster finding, CMB-WL mass cal.
X-ray: cluster finding, low-scatter mass proxies.

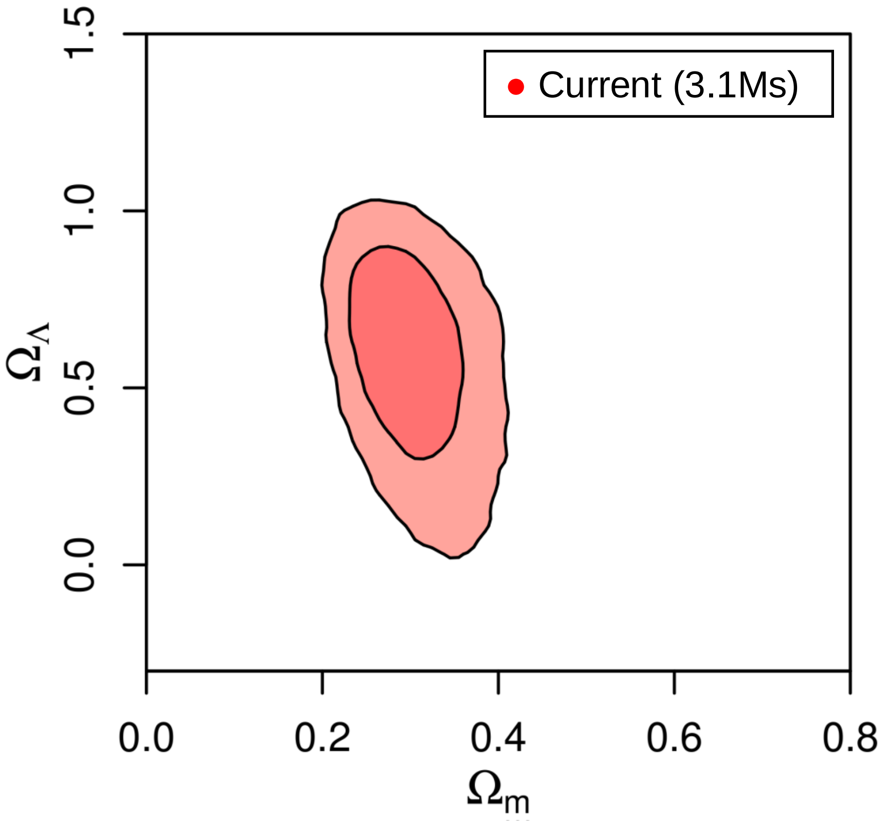
These projects are each powerful (finding 10^5 clusters) but also exceptionally synergistic: **far stronger and more robust in combination than alone.**

The discovery space of near and mid-term surveys



Prospects for the fgas test

Chandra follow-up of newly discovered clusters at intermediate redshifts will enable a powerful extension of the fgas test.



Potential analysis path:

- eROSITA+LSST identifies plausible fgas candidates (SPA)
- Chandra measures fgas(z)
- LSST provides WL mass calib.

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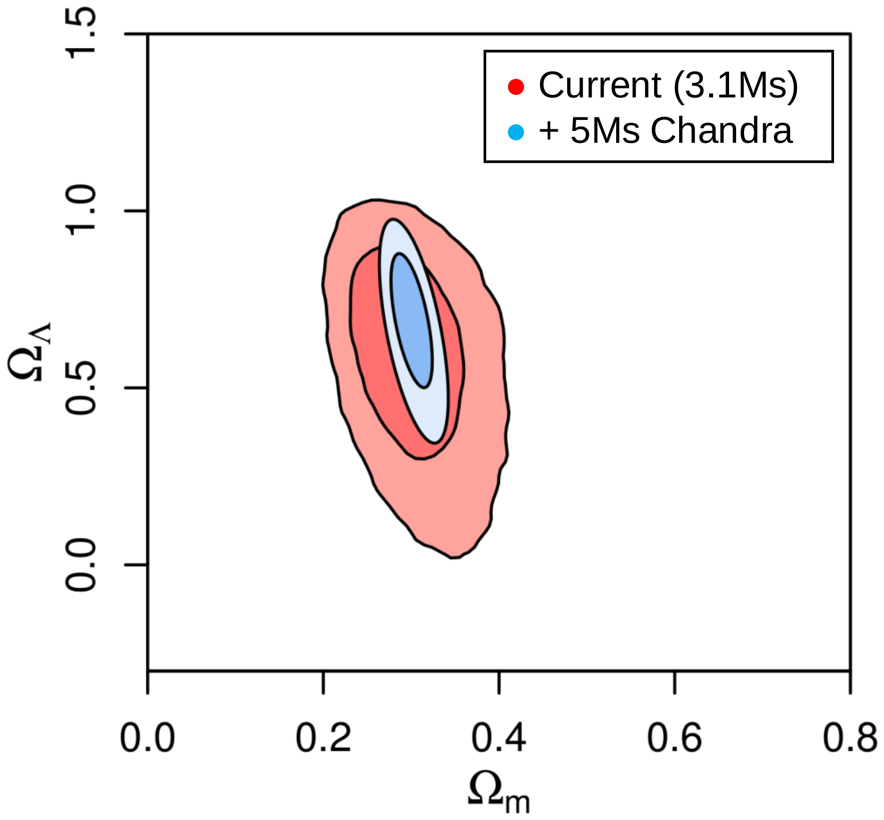


Potential analysis path:

- eROSITA+LSST identifies plausible fgas candidates (SPA)
- Chandra measures fgas(z)
- LSST provides WL mass calib.

Blue contours show improved constraints achievable adding 60 clusters (+5 Ms Chandra time) and complete LSST WL coverage.

Note: fgas measurements with Chandra likely limited to $z \leq 1.0$

Chandra and cluster counts (looking forward)

Measurements of low-scatter X-ray mass proxies will continue to be essential for cosmology with cluster counts at all wavelengths, bringing unique clarity to the key mass-observable scaling relations (form, scatter, evolution).

For surveys at optical wavelengths, X-ray obs. + representative OIR spectroscopy will be vital in quantifying projection effects.

For SZ surveys, X-ray + radio/mm obs. will be needed to model the impact of radio + SF galaxy contamination.

For X-ray surveys, Chandra obs. will be needed to understand the impact of AGN contamination.

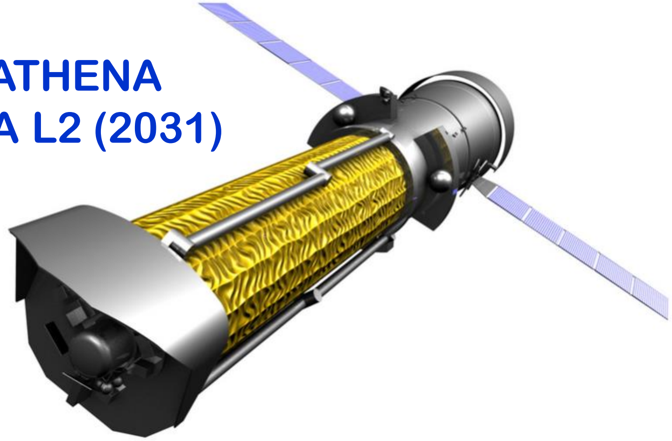
In all cases, the addition of low-scatter X-ray mass proxies will also bring a significant boost in cosmological constraining power

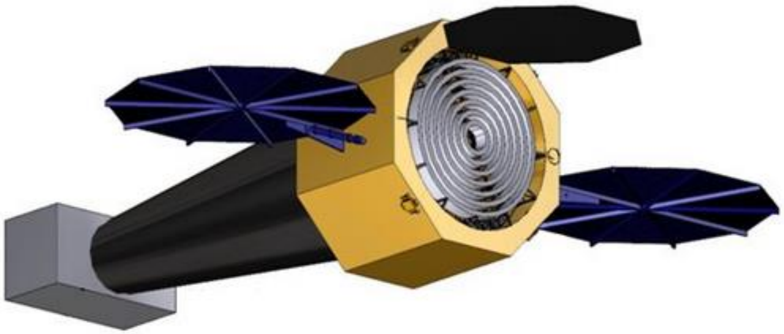
Note: mass proxy measurements with Chandra+XMM effectively limited to $z<1.5$.

Next generation X-ray flagships

The full exploitation of new cluster surveys at the highest redshifts ($z>1.5$) for cosmology and astrophysics will require new flagship X-ray observatories.

ATHENA
ESA L2 (2031)





Lynx (under study for 2020 NRC Decadal Review)

Defining characteristics:

- Large collecting area (≥ 50x Chandra)
- High quality imaging (5” HPD Athena, 0.5” HPD Lynx)
- Wide field imagers + large TES IFUs (+ gratings for Lynx)

Conclusions

Chandra measurements transformed the field of galaxy cluster cosmology.

Chandra fgas measurements $\rightarrow$ robust measurement of Ω_m and interesting constraints on dark energy by tracing the expansion history of the Universe.

Cluster counts $\rightarrow$ robust measurements of Ω_m and σ_8 and tight, independent constraints on dark energy from its effect on the growth of cosmic structure.

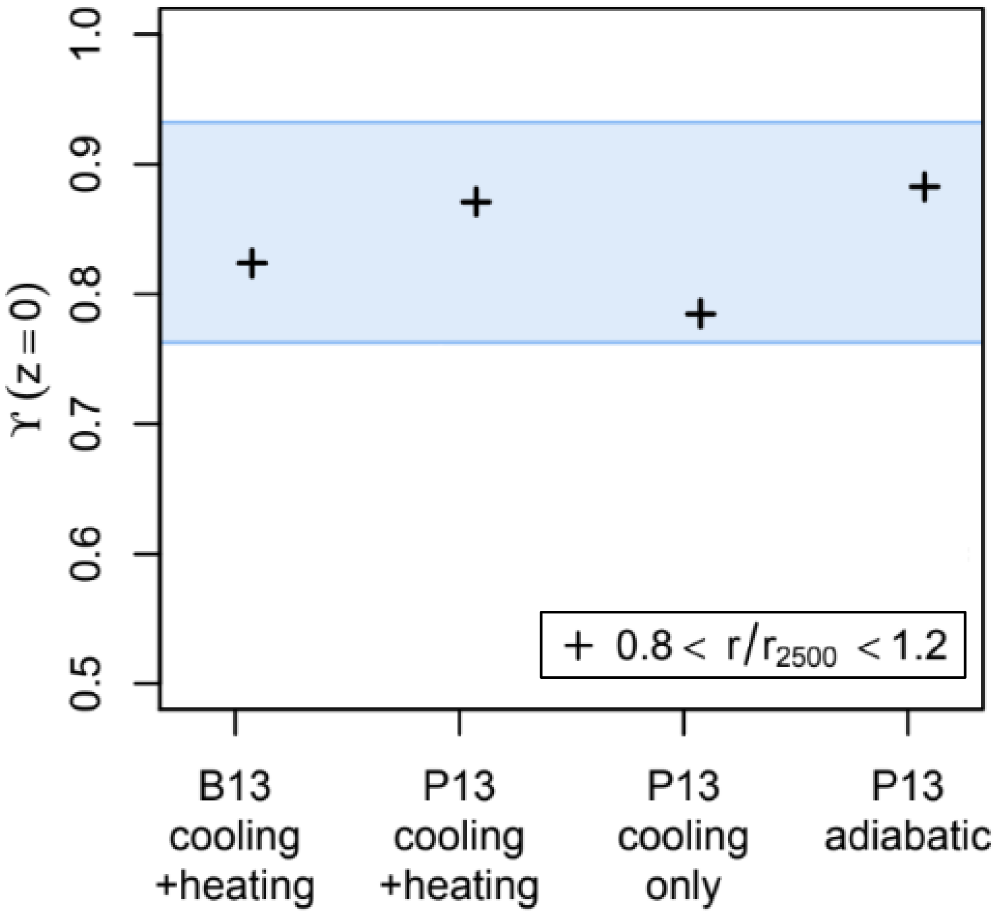
Other studies have provided key insights into the nature of dark matter, gravity, neutrino properties and inflation.

The prospects for improving these constraints with new, multi-wavelength surveys are outstanding. Coordinated analyses, utilizing complementary strengths, will be essential.

Targeted X-ray follow-up with Chandra and XMM-Newton will continue to play a central role throughout the next decade.

Backup slides

The depletion parameter, $\Upsilon(r,z)$



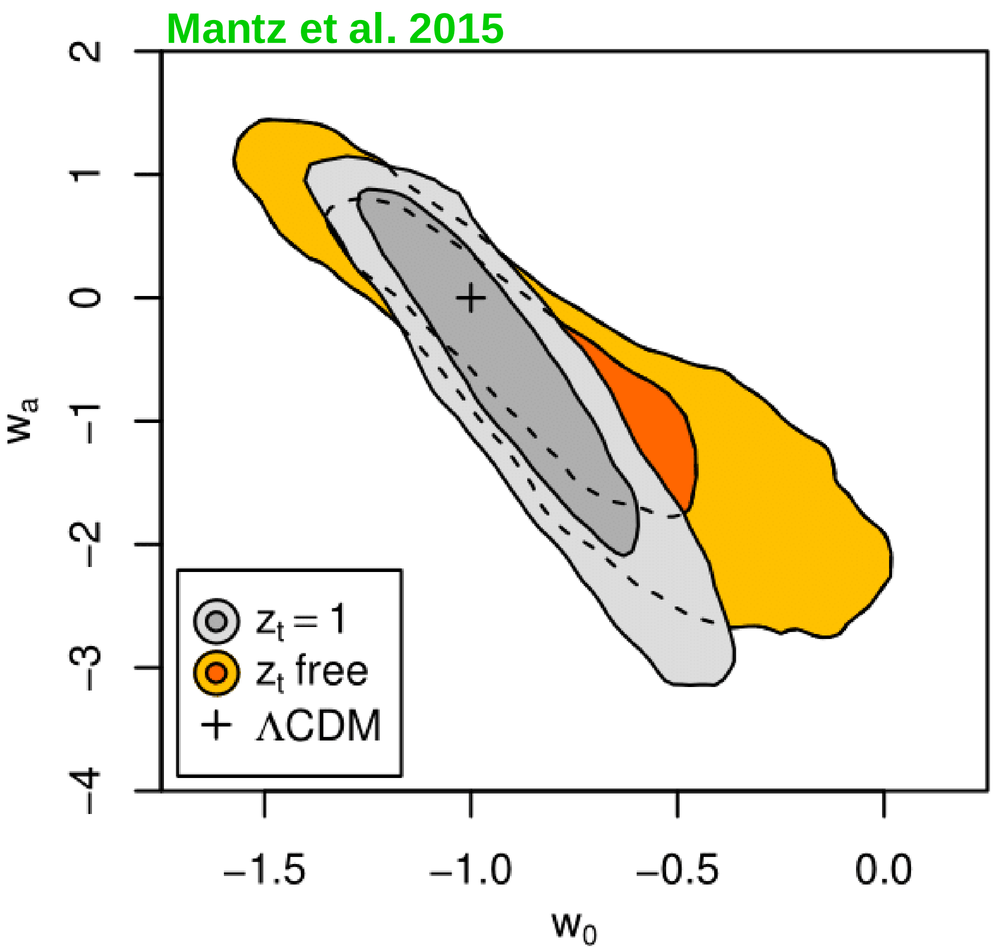
In the centers of clusters, where the effects of gas cooling, star formation and AGN feedback are strong, the gas depletion parameter predicted by hydrodynamical simulations is uncertain.

In the (0.8-1.2) r_{2500} shell, for the hottest (kT>5keV) clusters, the predictions are relatively robust (Planelles et al. '13, Battaglia et al. '13)

Parameterizing $\Upsilon_{2500} = \Upsilon_0(1+\alpha_\Upsilon z)$

$\Upsilon_0 = 0.848 \pm 0.085$, $\alpha_\Upsilon = 0.00 \pm 0.05$

Evolving dark energy models



<u>Standard evolving DE model</u>

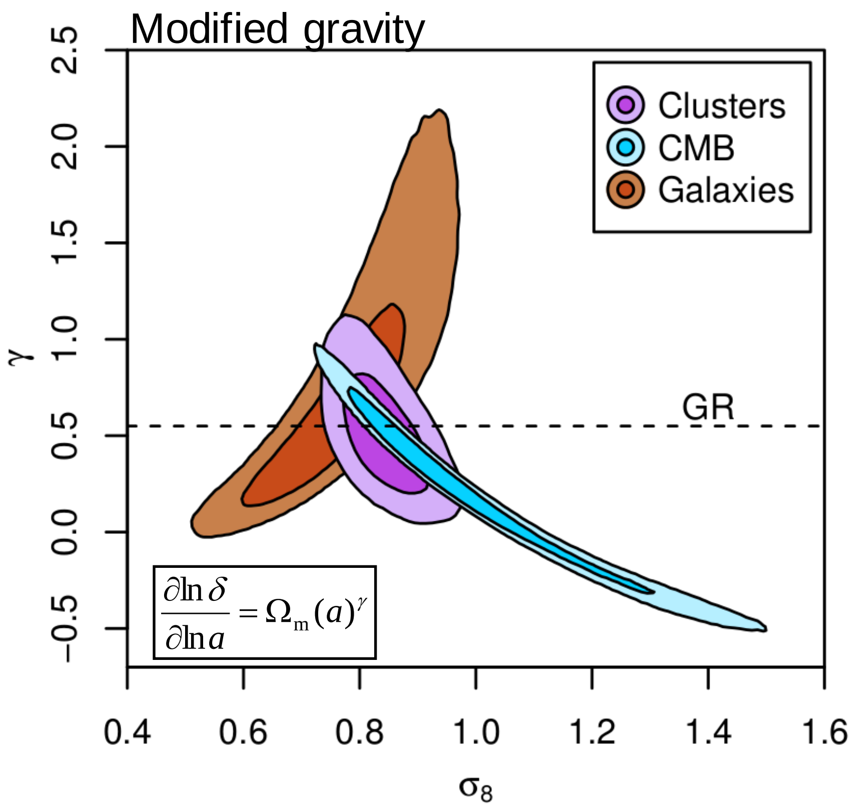
$$w = w_0 + w_a \left(\frac{z}{z + z_{tr}} \right)$$

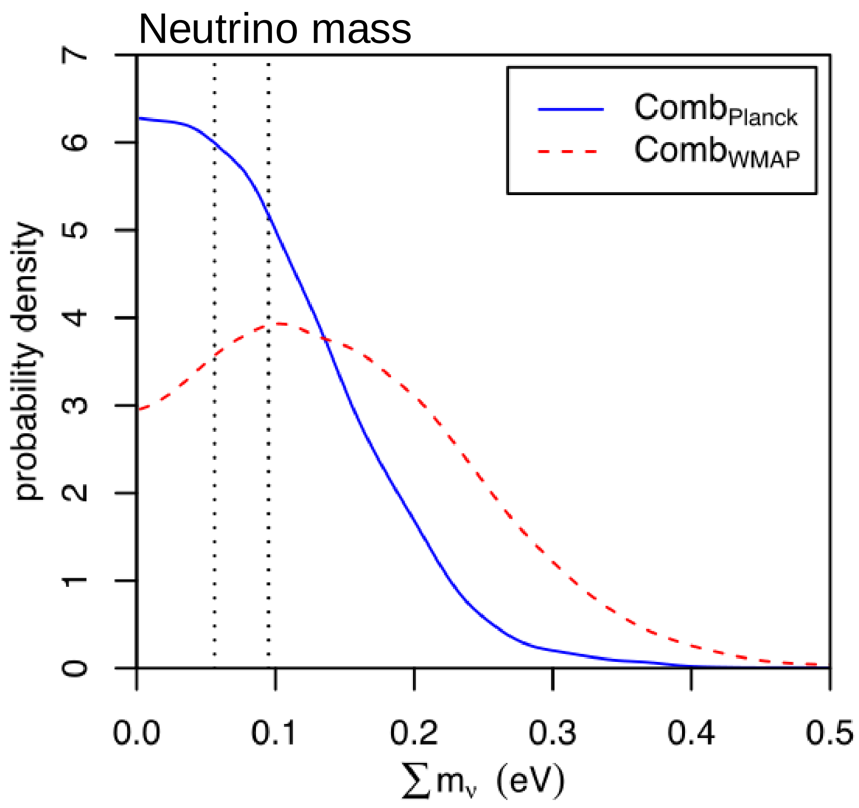
<u>Combined constraint (68%)</u>

$\Omega_m = 0.292 \pm 0.015$
$\sigma_8 = 0.816 \pm 0.027$
$w_0 = -0.93 \pm 0.22$
$w_a = -0.4 \pm 1.0$

Results for evolving DE models consistent with cosmological constant .

Modified gravity and neutrino masses

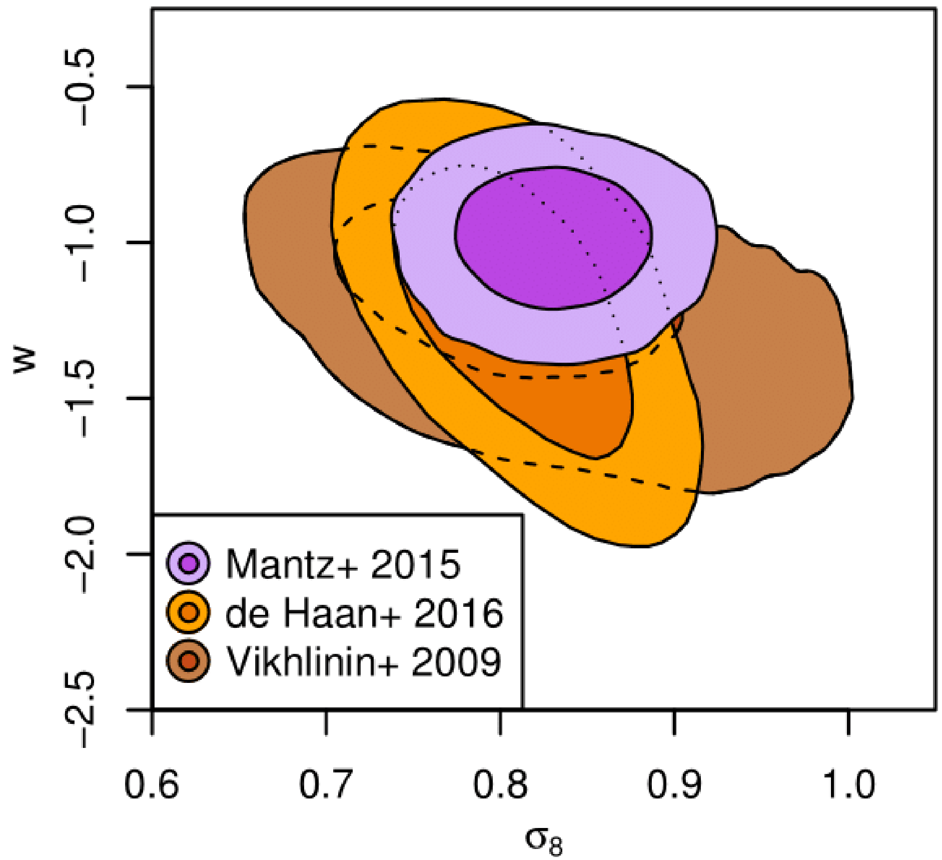




Clusters provide powerful constraints on modified gravity and (together with primary CMB data) the species summed neutrino mass.

Results on dark energy from other cluster experiments

Allen & Mantz 2019



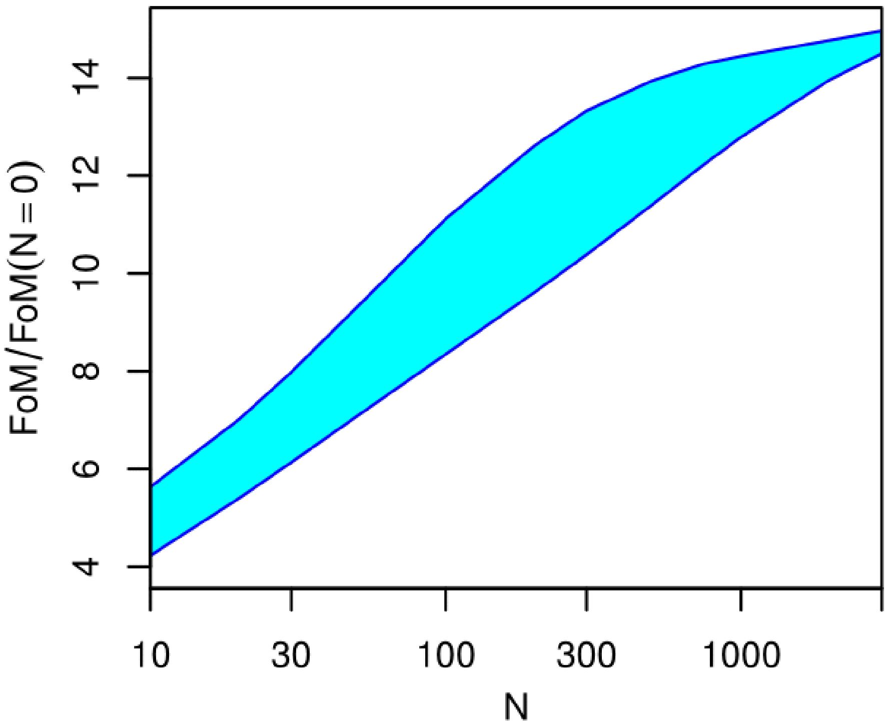
RASS (Mantz et al. ‘10, ’15)
SPT (de Haan et al. ‘16)
400d (Viklinin et al. ‘09)

All three studies to presente results on dark energy from clusters alone consistent with dark energy described by a cosmological constant.

RASS results still provide the tightest constraints to date (sufficient redshift coverage + best mass calibration)

Impact of low-scatter mass proxies on cosmology

X-ray mass proxy measurements will continue to be vital for cosmology with cluster counts, both providing a substantial boost in constraining power and bringing clarity to key mass-observable scaling relations (form, scatter, evolution).



Example analysis path:

- Consider a survey of ~5000 massive clusters @ z<1.5
- New X-ray follow-up obs. sample approximately uniformly in logM,z for 0.4<z<1.5 (archival data at low-z).
- ~5Ms of exposure time per 50 new clusters (approx. equal split of Chandra+XMM).