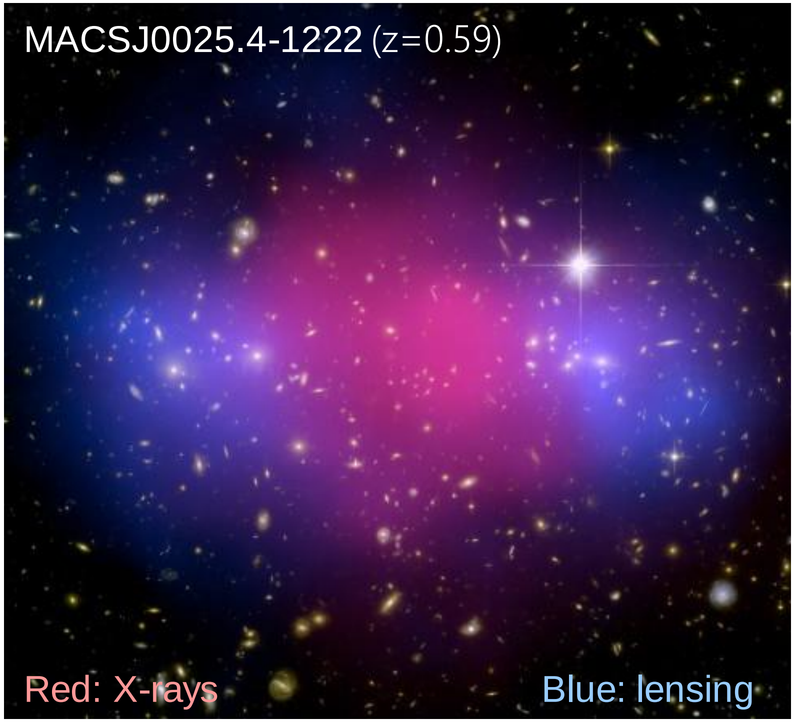
The Landscape of Galaxy Cluster Cosmology

Steve Allen (KIPAC)



In collaboration with:

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David Rapetti (UC Boulder)
Adam Wright (KIPAC)

+ many more ...

1. The fgas test

Featured work: Mantz et al. 2014, MNRAS, 440, 2077
Mantz et al. 2015, MNRAS, 449, 199
Adam Wright, Ph.D., Stanford 2019
Lucy Baumont, Ph.D., SUNY, 2020

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

BASIC IDEA: 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).

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

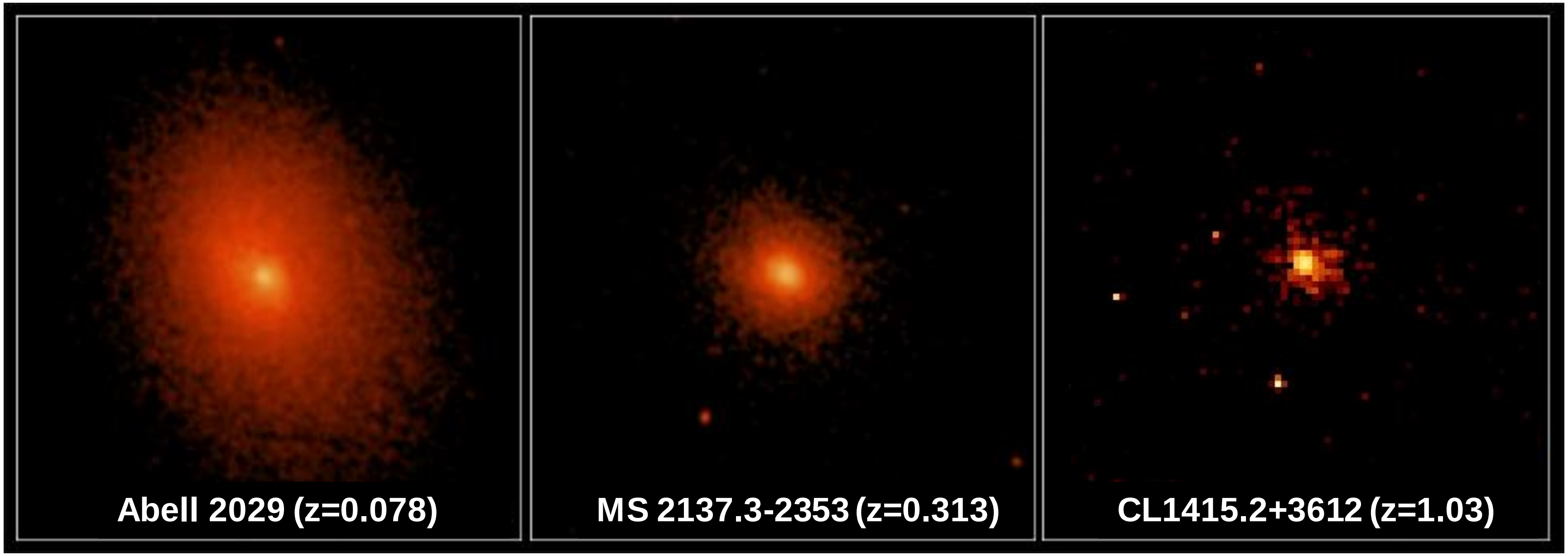
BBNS/CMB

Measure (X-ray data)

Depletion factor (simulations)

First direct confirmation of SNIa result that expansion of Universe is accelerating (Allen et al., '04)

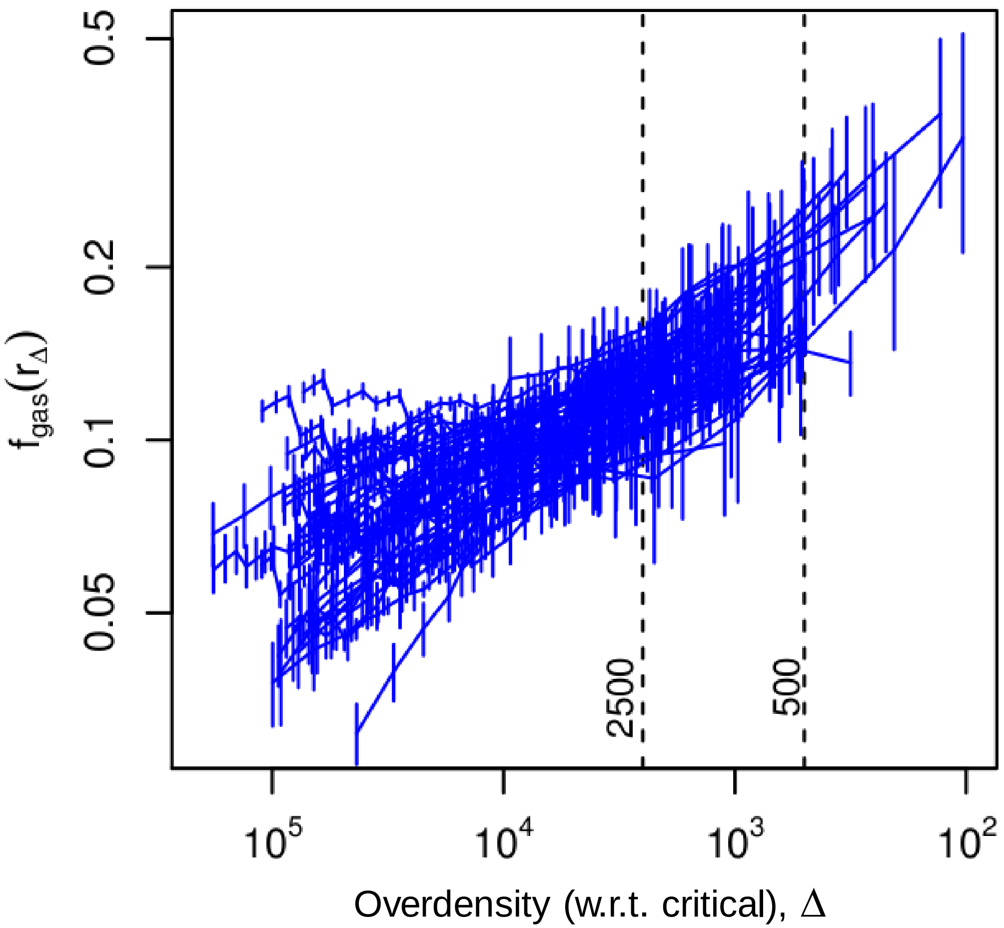
The observations (X-rays)



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

Chandra f_{gas} profiles

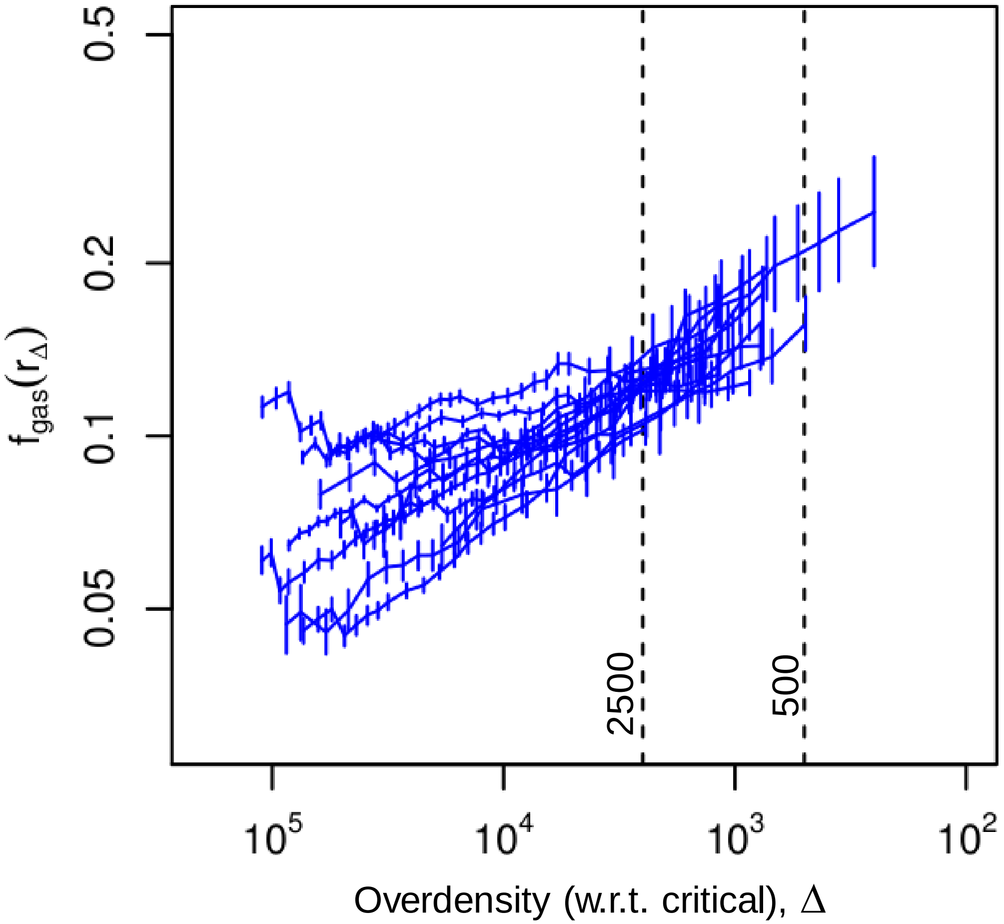


40 clusters

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).

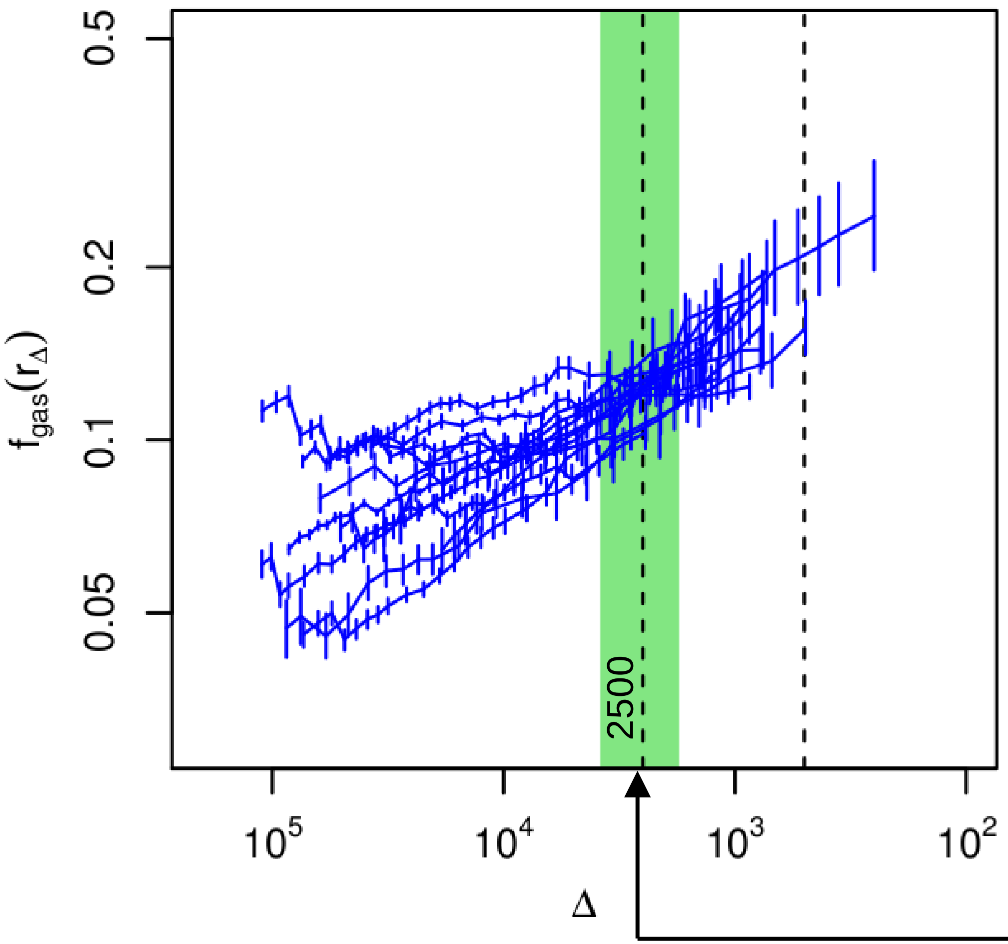
Chandra f_{gas} profiles



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.

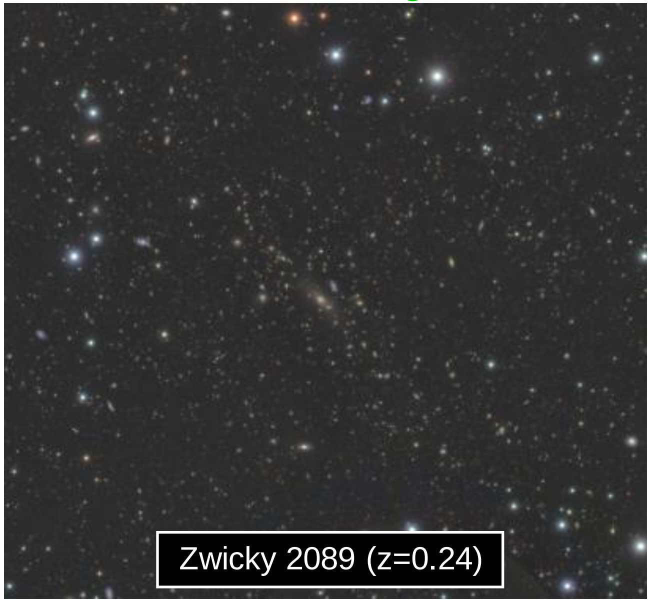
Restricting the analysis to a shell near r_{2500} provides a good compromise between statistical precision and intrinsic scatter in the $f_{gas}(r)$ measurements.

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



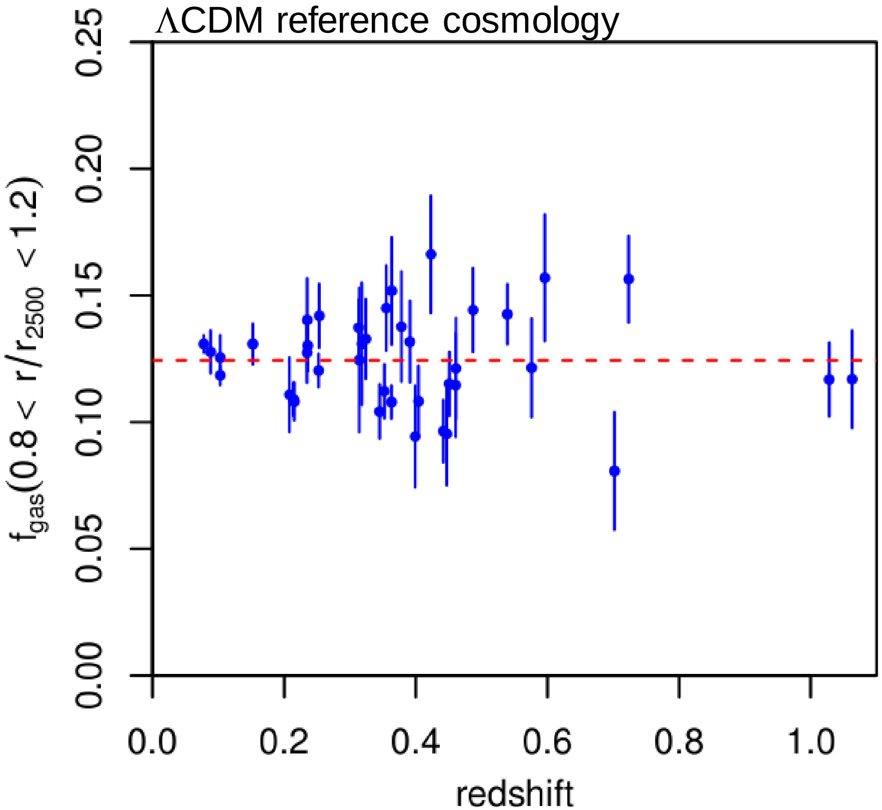
Deep (30-60 min exposures), high quality (0.5-0.7 arcsec seeing), five filter (BVRIZ) Subaru imaging. WtG2 pipeline uses full photo-z and shape information for individual galaxies → exquisite lensing masses with precise systematic control. (LSST pathfinder study.)

WL data for 10 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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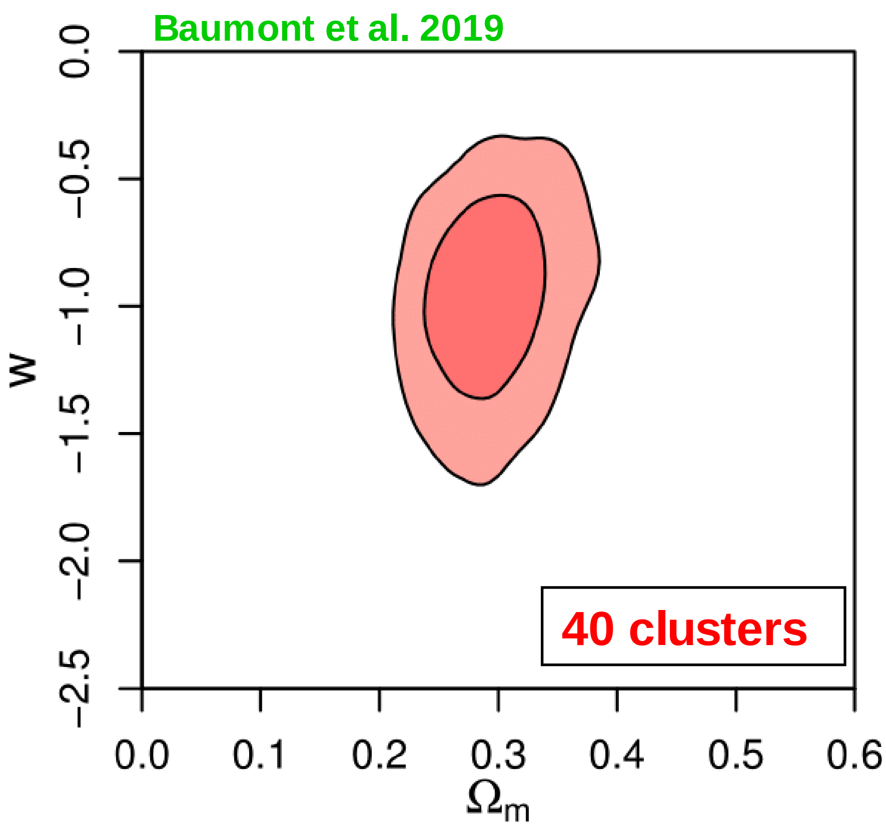


Results (flat, constant w)

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.

Result limited by f_{gas} data.

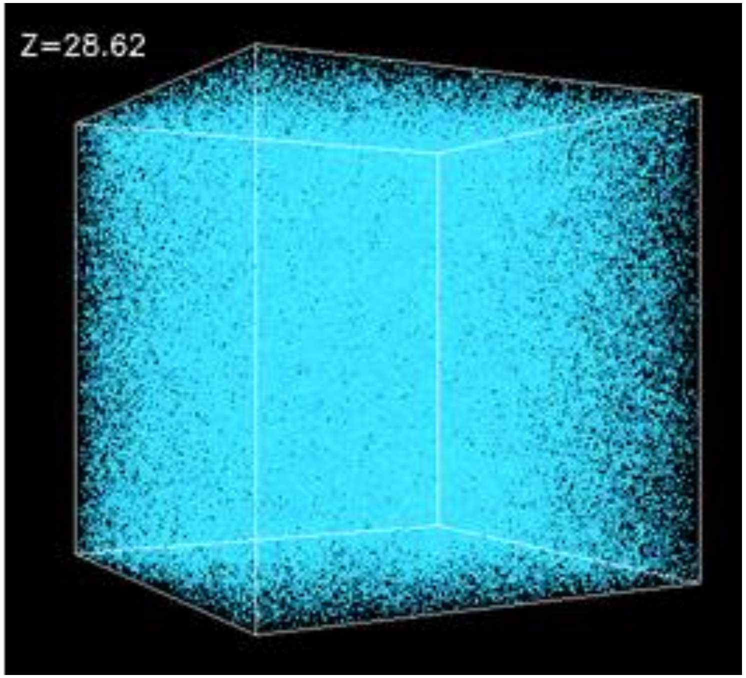
2. Cosmology with Cluster Counts

Featured work: Mantz et al. 2015, MNRAS, 446, 2205
Mantz et al. 2016, MNRAS, 463, 3582
Allen & Mantz, 2019, in press

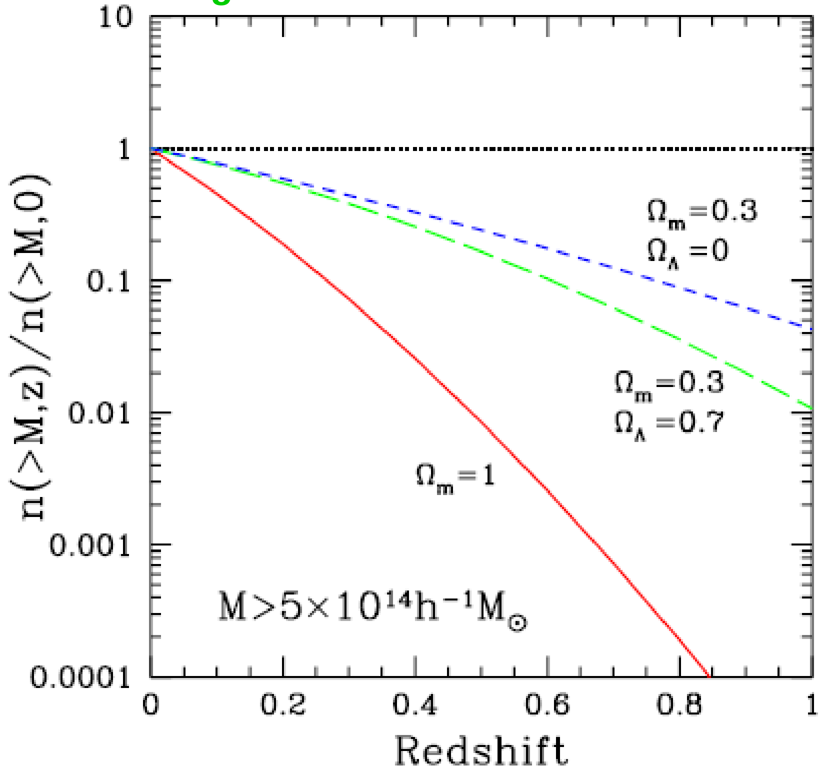
See also e.g. Borgani et al. ’01; Reiprich & Bohringer ’02; Seljak ’02; Viana et al. ’02; Allen et al. ’03; Pierpaoli et al. ’03; Schuecker et al. ’03; Voevodkin & Vikhlinin ’04; Henry ’04; Mantz et al. ’08, ‘10; Vikhilinin et al. 09; Henry et al. ’09; Rozo et al. ’10; Allen et al. ’11; Kravtsov & Borgani ’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), optical (SDSS, DES) 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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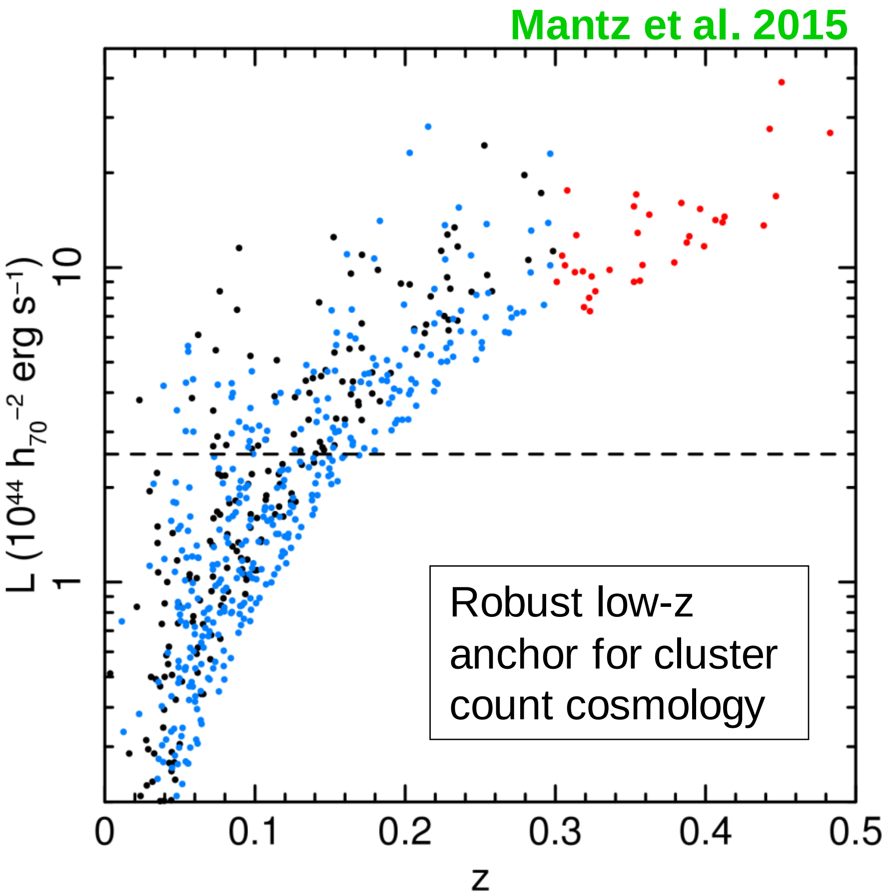
Cluster surveys based on RASS



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 $Lx > 2.5\times10^{44}$ 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.

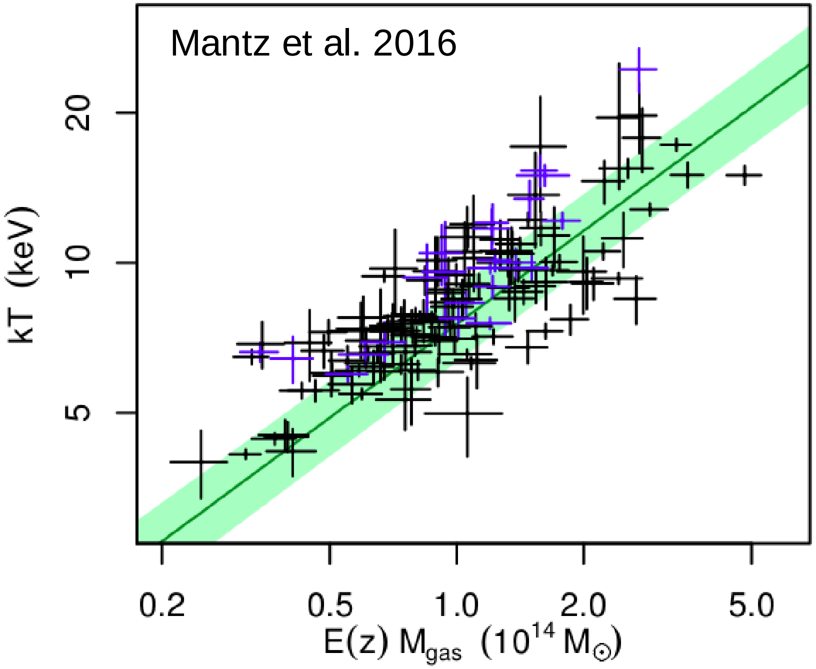
Current leading work based on X-ray (ROSAT), optical (Sloan Digital Sky Survey) and SZ surveys (SPT, ACT, Planck).

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

KEY: gather high quality follow-up data for the clusters in your survey and separate into two parts: relative and absolute mass calibration.

Precise relative mass calibration from X-ray data

10Ms of pointed Chandra and ROSAT observations for 139/224 survey clusters
→ re-measure Lx + measure Mgas, Tx, Yx at r_{500} (<15% scatter mass proxies)

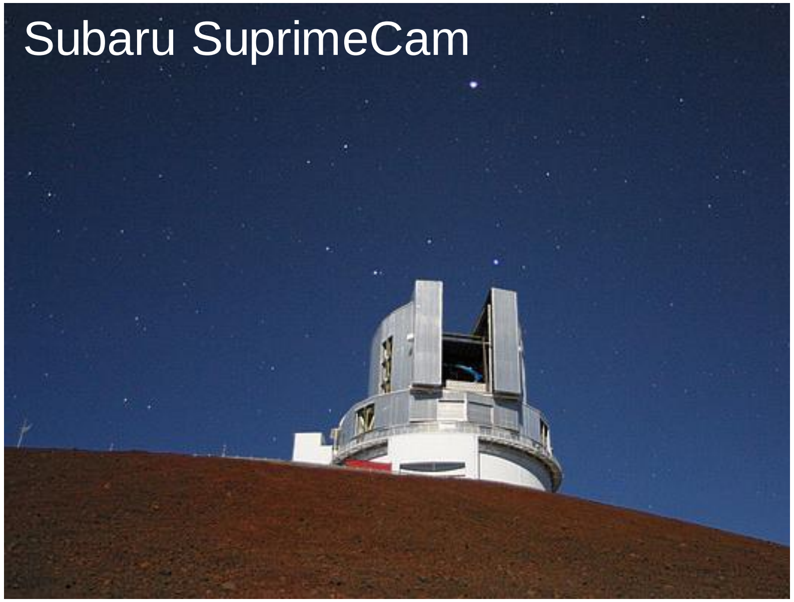


Low scatter mass proxies → tight relation between survey observable and mass.

Lx-M	Mgas-M	Tx-M
~40% scatter	≤10% scatter	~10-15% scatter

Robust absolute mass calibration from weak lensing

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



Weighing the Giants (WtG)

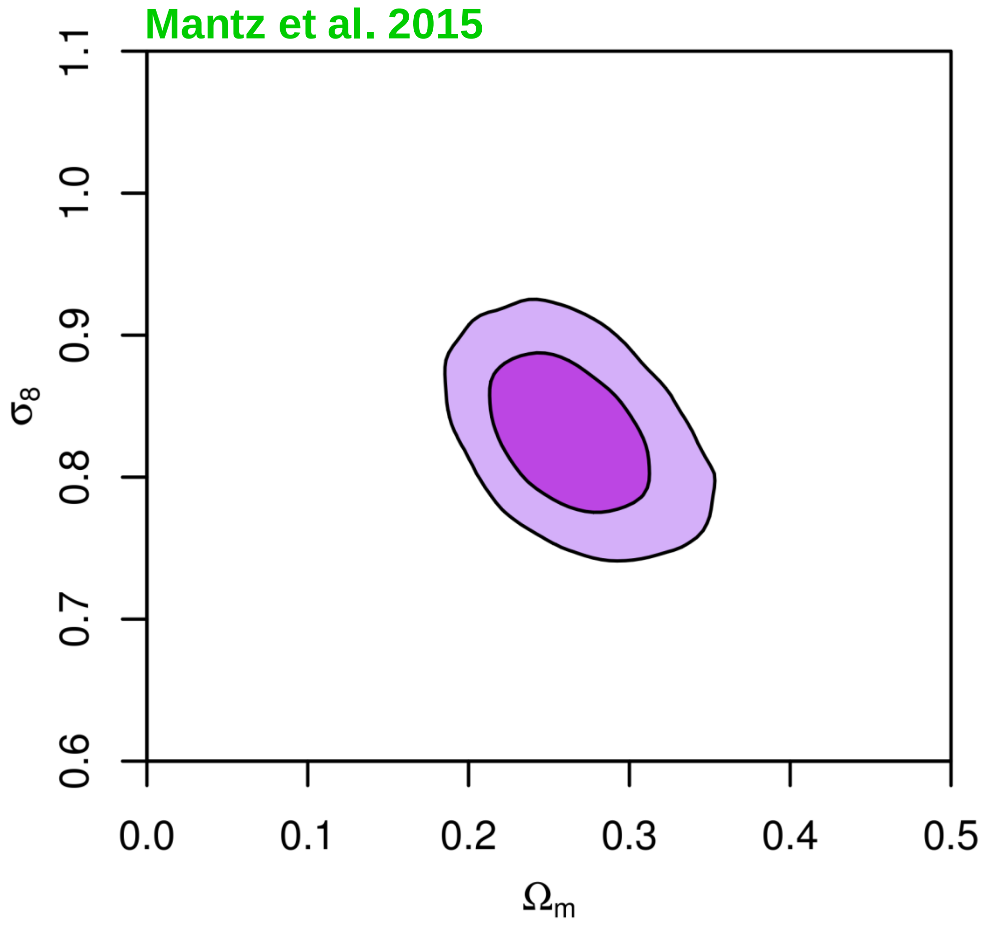
Von der linden et al. 2014
Kelly et al. 2014
Applegate et al. 2014

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

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

WTG $\rightarrow \pm$ 8% absolute mass calibration

Cosmology: results on σ_8, Ω_m

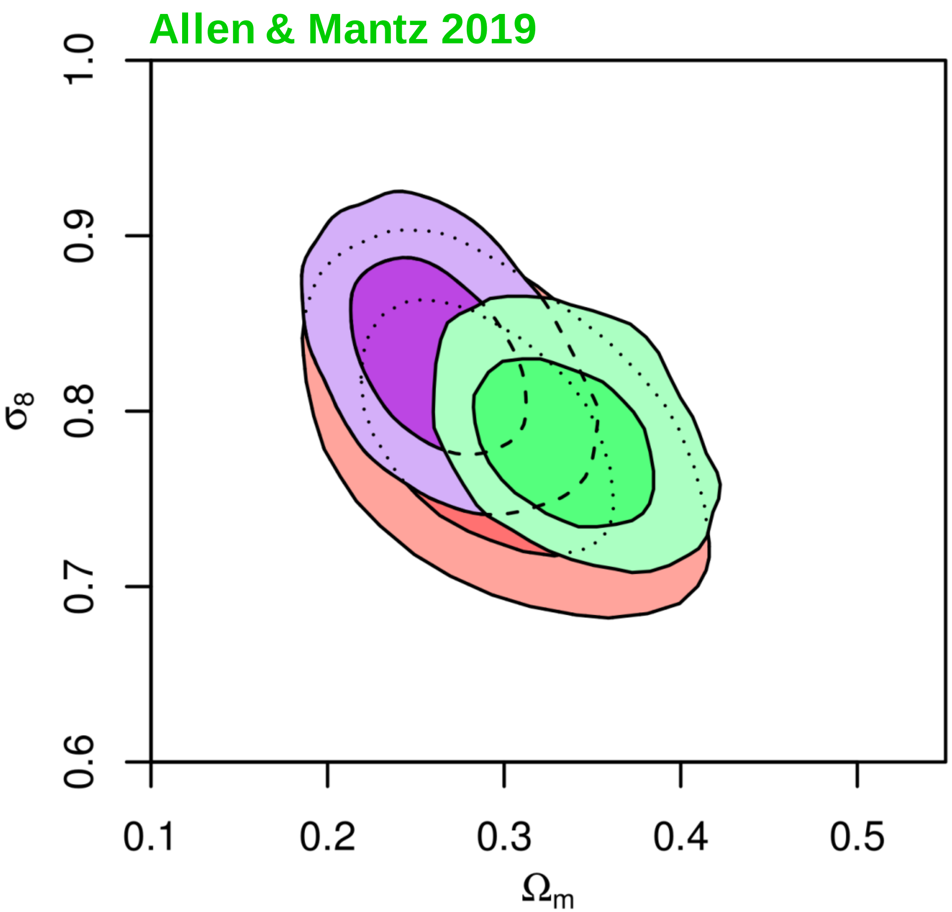


Flat ΛCDM model:

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

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

Comparison vs. other cluster experiments



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

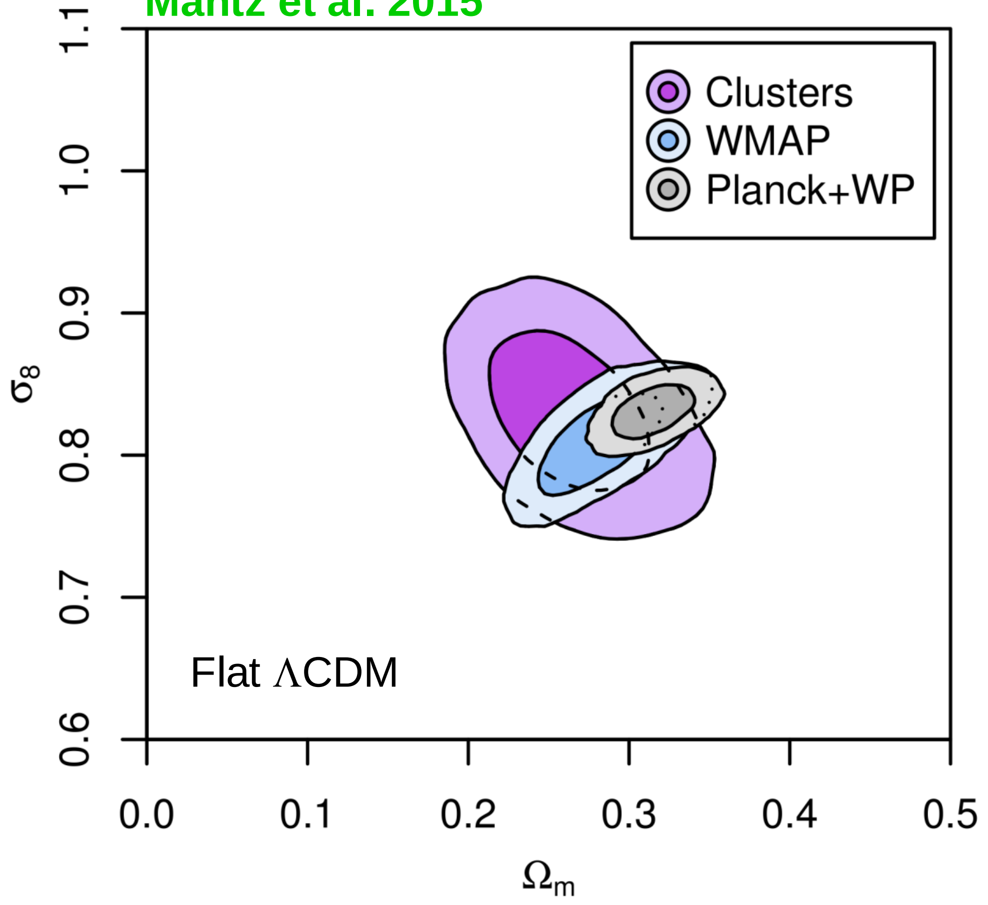
RASS (WTG)
Planck clusters (WTG)
SPT clusters (WTG+H15)

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

Also consistent with recent results for ACT+HSC (Miyatake et al. ‘19) and Planck clusters using CMB lensing (Zubelidia & Challinor ‘19).

Comparison vs. primary CMB

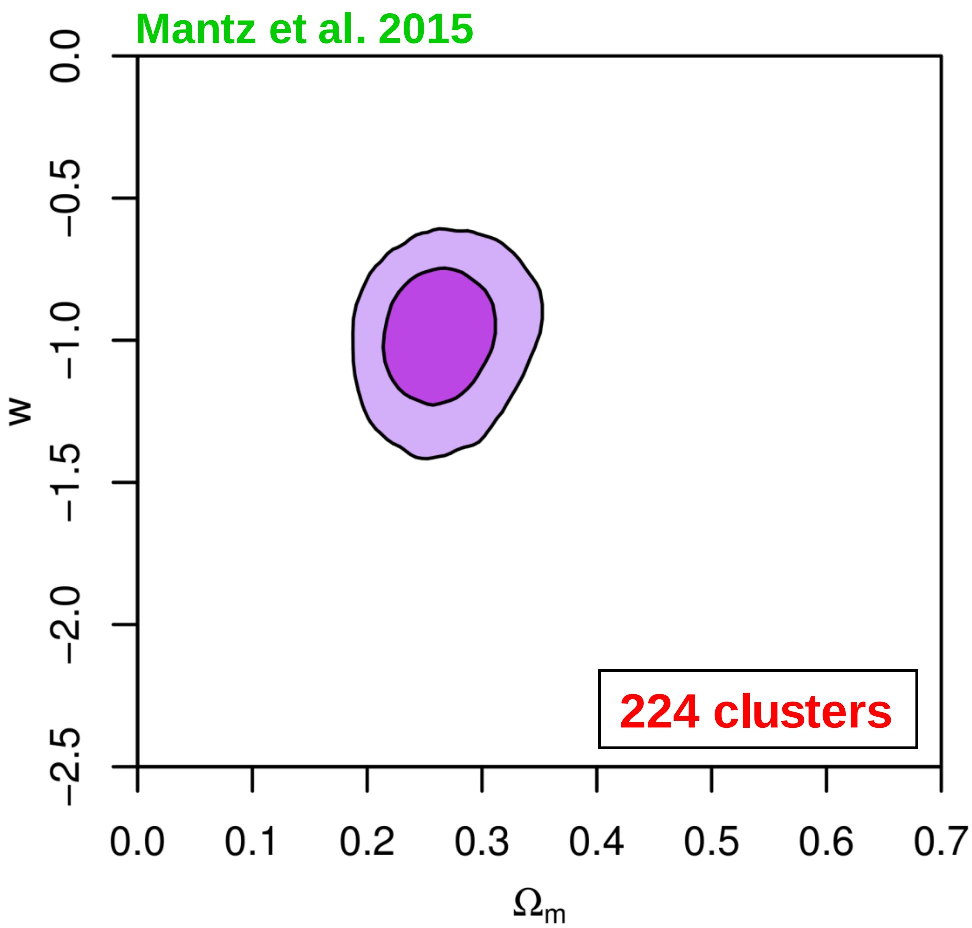
Mantz et al. 2015



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 cluster growth.

3. The Road Ahead
Opportunities and Challenges

Featured work: Mantz et al. 2019, arXiv:1903.05606
Myles et al. 2019, in prep.

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.

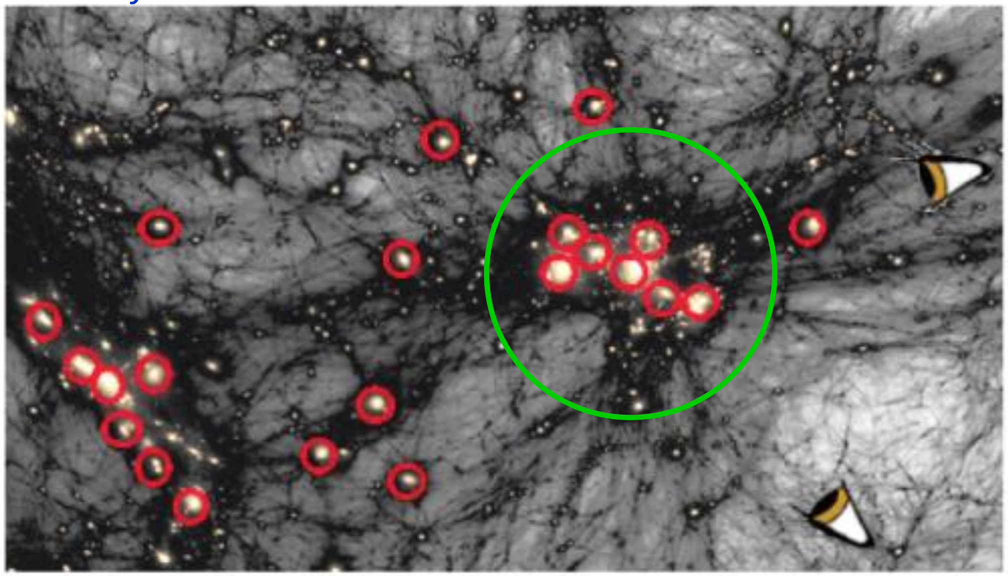
These projects are each powerful (finding 10^5 clusters) but also exceptionally synergistic: **far stronger and more robust in combination than alone.**

Example: optical cluster cosmology

LSST will deliver exquisite photo-zs and weak lensing constraints, and aid in the construction of large cluster catalogs at all wavelengths.

However, the identification of clusters at optical wavelengths (alone) is hard and complicated by projection effects. Simulations cannot yet predict these effects with sufficient fidelity for precision cosmology.

DarkSky simulations / SLAC visualization team



Galaxy clusters are embedded in surrounding large scale structure.

The same cluster can be assigned a different richness (and have a different projected matter density profile) depending on the viewing angle.

Calibrating projection effects with observations

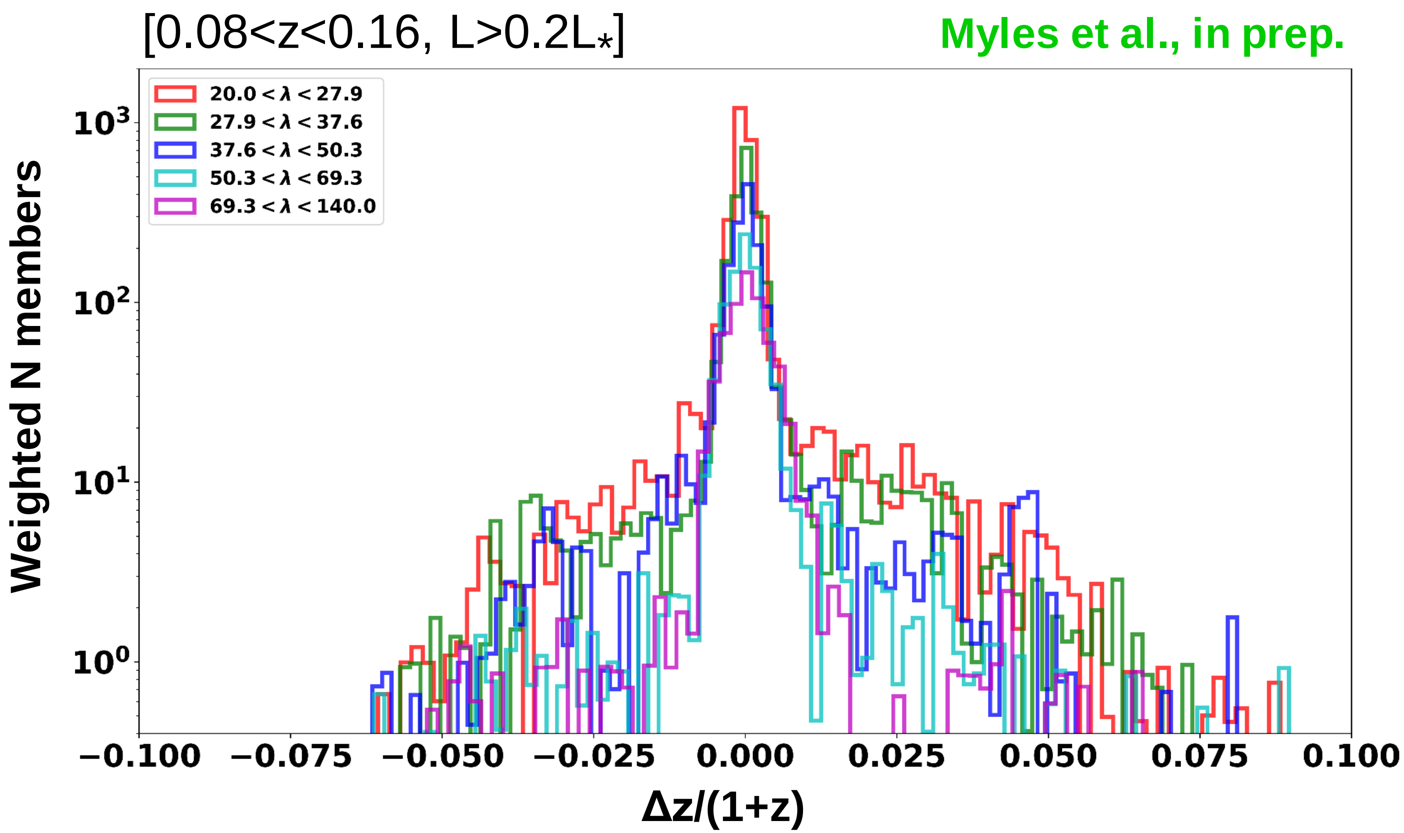
Fortunately multi-wavelength observations provide an empirical route to calibrate projection effects. We have two main complementary tools:

X-ray observations: X-ray measurements are essentially immune to projection effects $\rightarrow$ precise, relative 3D masses.

Optical spectroscopy: spectroscopic coverage can reveal which nominal member galaxies are physically within the 3D halos, and which are viewed in projection.

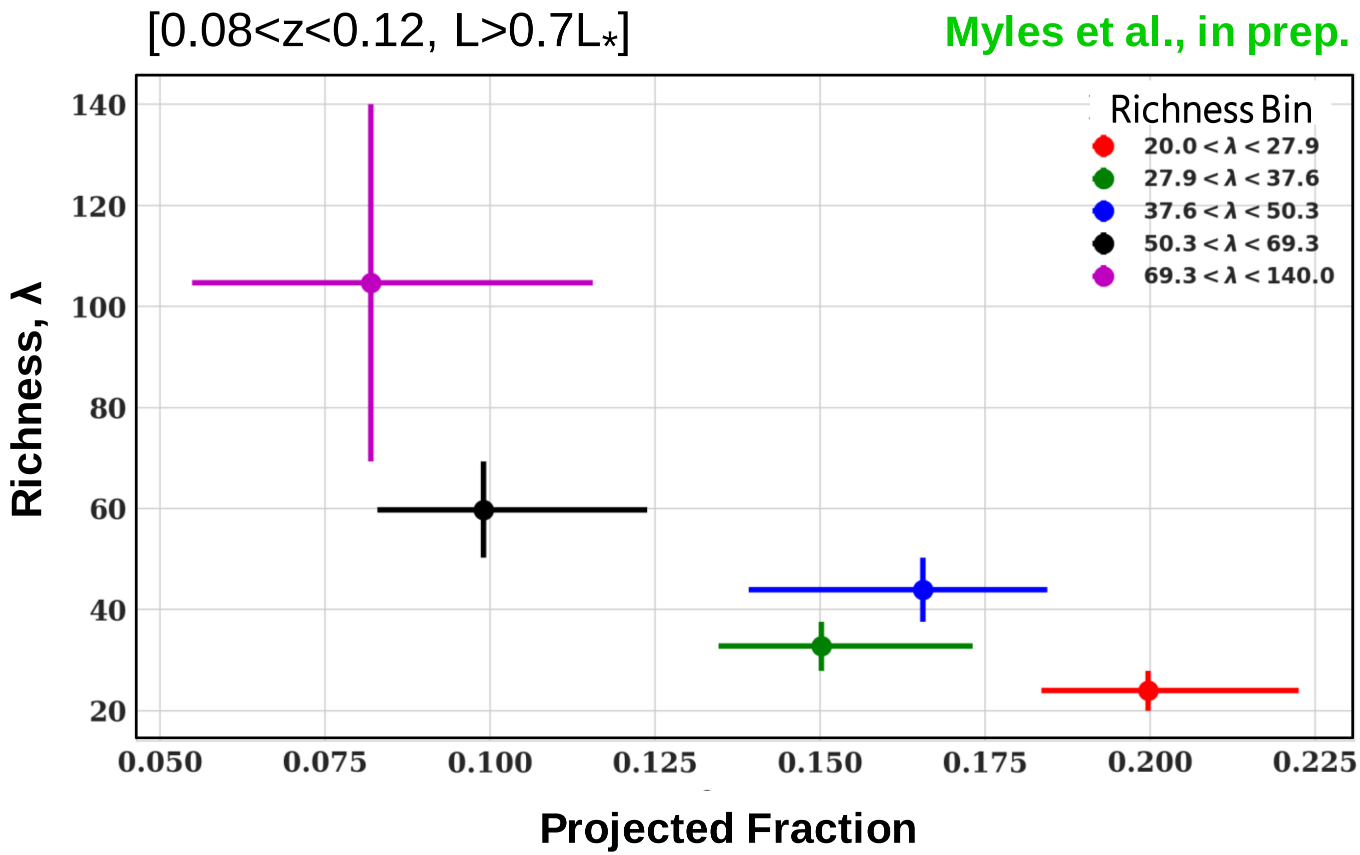
By obtaining representative X-ray and spectroscopic follow-up of optically selected cluster samples, we can build an empirical model for projection effects, as function of (λ,z).

Projection effects in redMaPPer clusters (SDSS)



The spectral data clearly show the narrow, central virialized components of the clusters but also broad wings (projection effects).

Projection effects in SDSS redMaPPer clusters



Projection effects in optically-selected clusters are **significant** and **richness dependent**. Work is now underway to gather similar data across the full richness and redshift range of the SDSS and DES catalogs.

Conclusions

Galaxy clusters offer multiple ways to probe cosmology.

The fgas method provides a robust measurement of Ω_m and interesting constraints on dark energy by tracing the expansion history of the Universe.

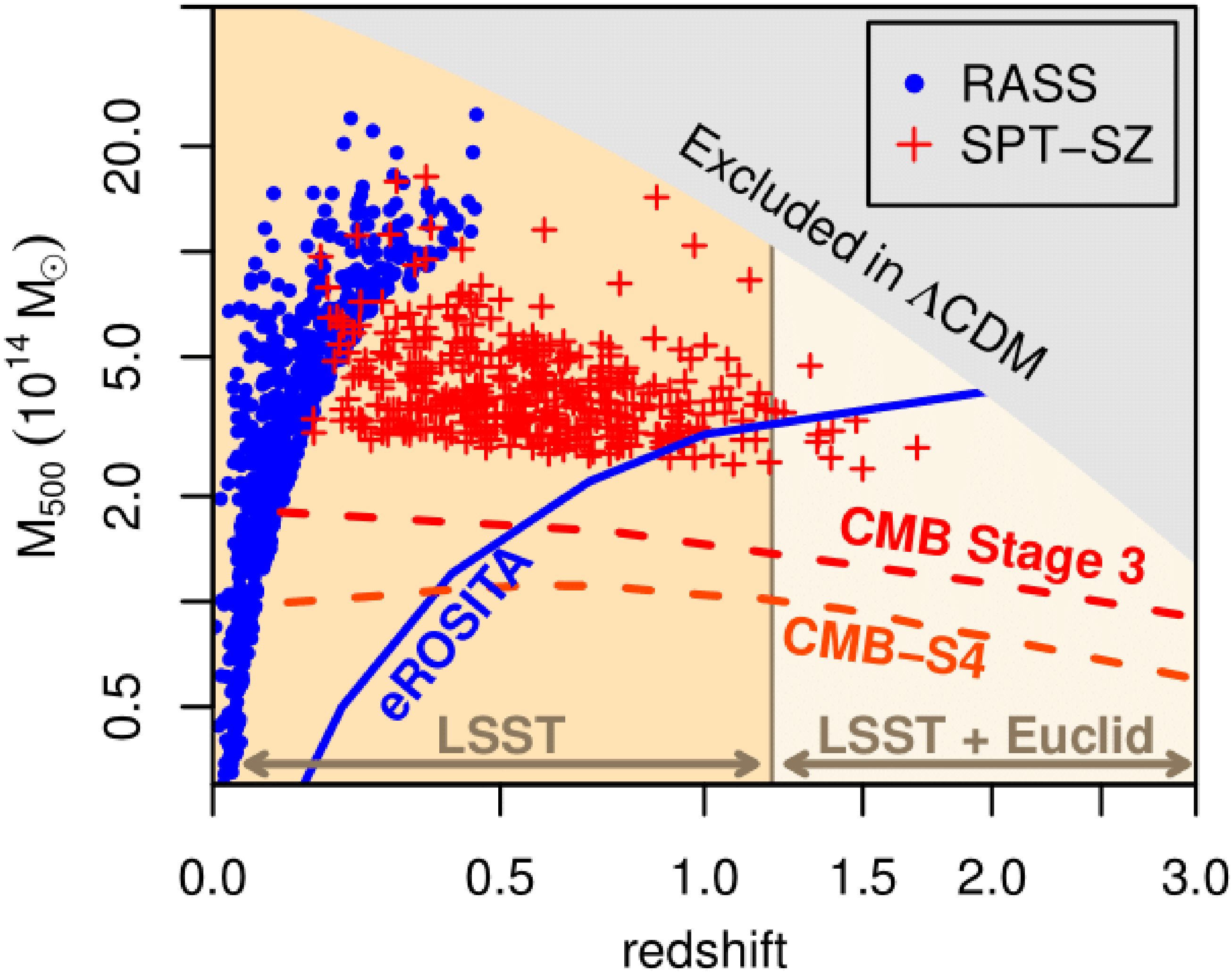
Cluster counts provide robust measurements of Ω_m and σ_8 and tight, independent constraints on dark energy from its effect on the growth of cosmic structure.

The prospects for improving these constraints using new, multi-wavelength surveys are outstanding, although challenges remain.

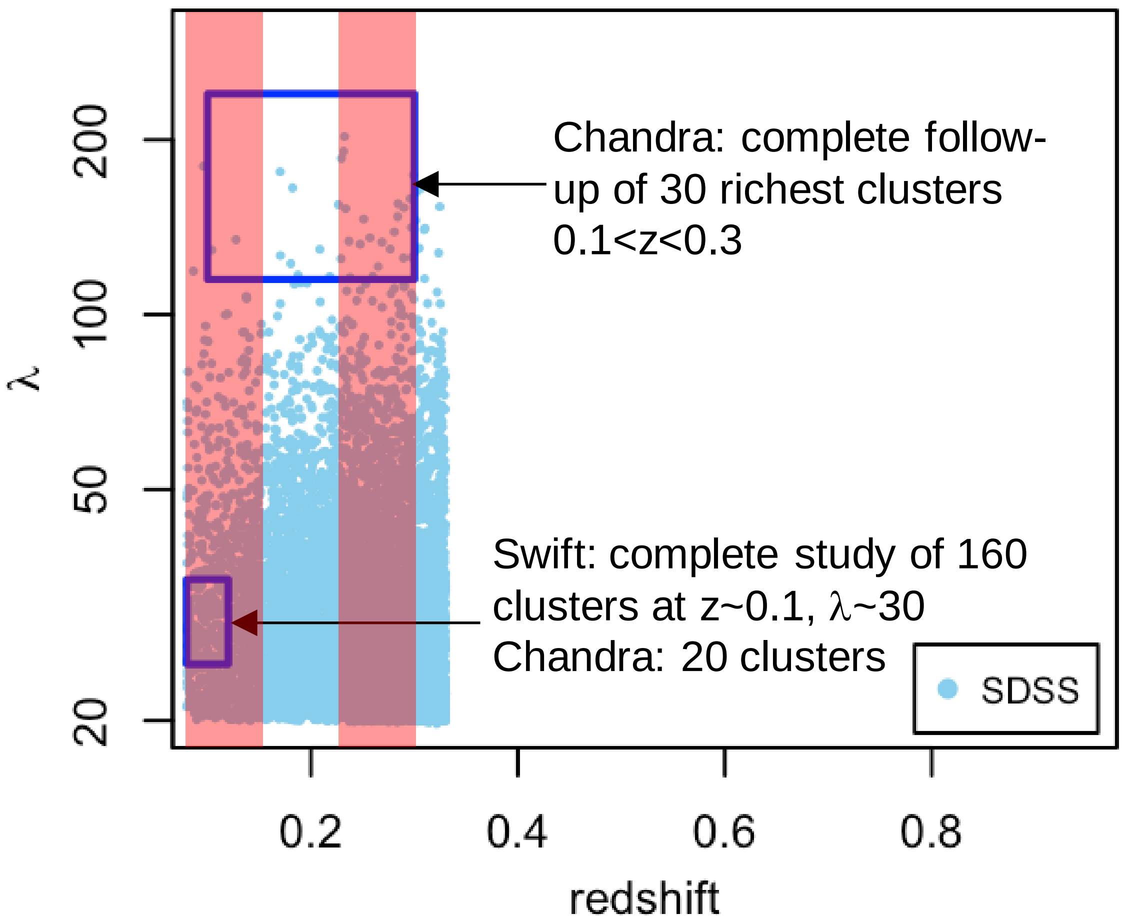
Coordinated analyses, utilizing the complementary strengths of these surveys and targeted, multi-wavelength follow-up observations will be essential.

Backup slides

The discovery space of near and mid-term surveys



Quantifying projection effects in SDSS clusters

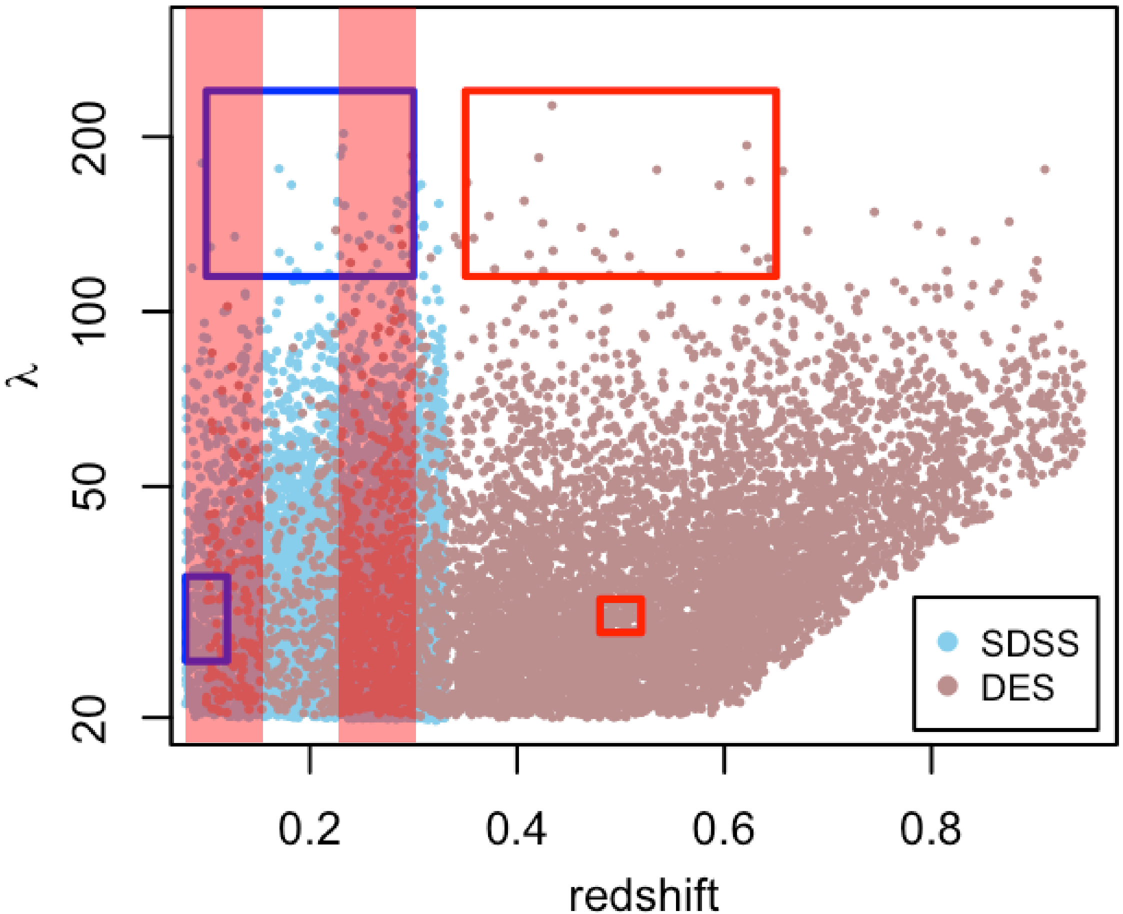


SDSS redMaPPer catalog (Rykoff et al. '14)

3 X-ray follow-up programs completed (von der Linden et al. '19, Myles et al. '19)

2 complete optical spectroscopic data sets in hand (Myles et al. '19)

Quantifying projection effects in DES clusters



Illustrative DES catalog

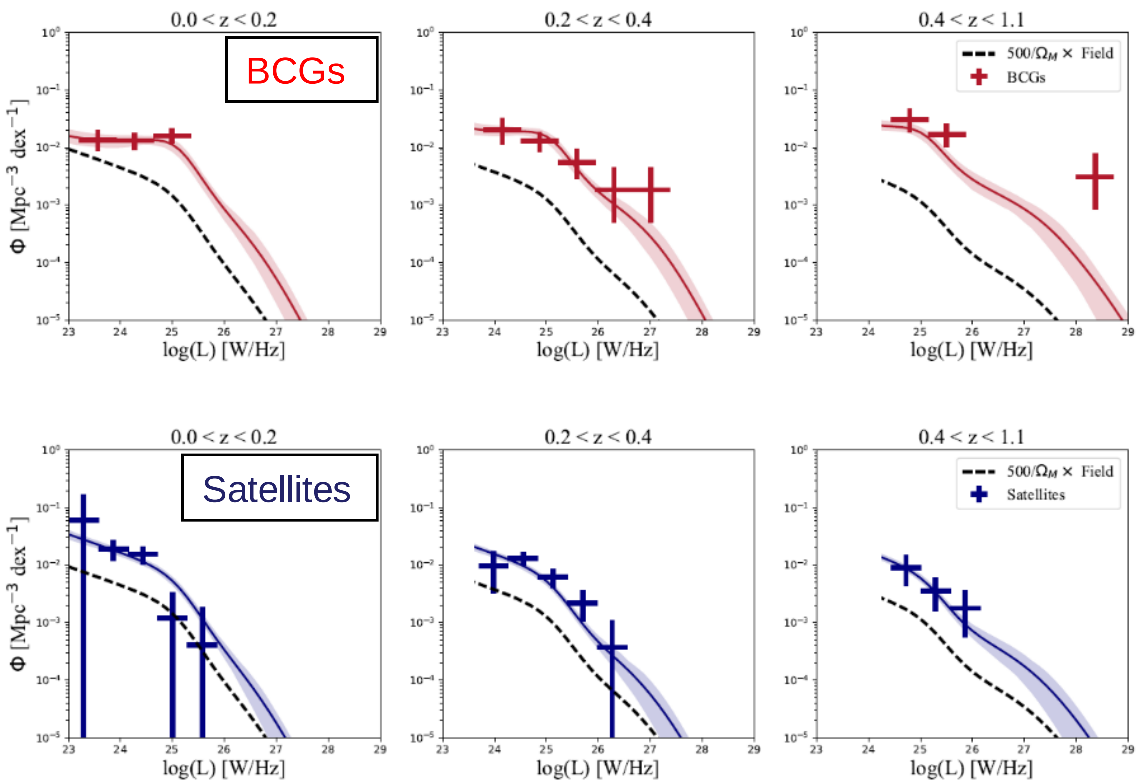
2 pathfinder X-ray programs accepted (data collection underway).

Initial proposals for spectroscopic coverage submitted.

Extension to DES, LSST will require significant investments of telescope time

Example challenge 2: AGN contamination of SZ signal

The emission from radio AGN contaminates (reduces) the cluster SZ signal. Unfortunately the probability of finding a 1.4GHz radio AGN of a given luminosity is enhanced in cluster environments (King et al. 2019).

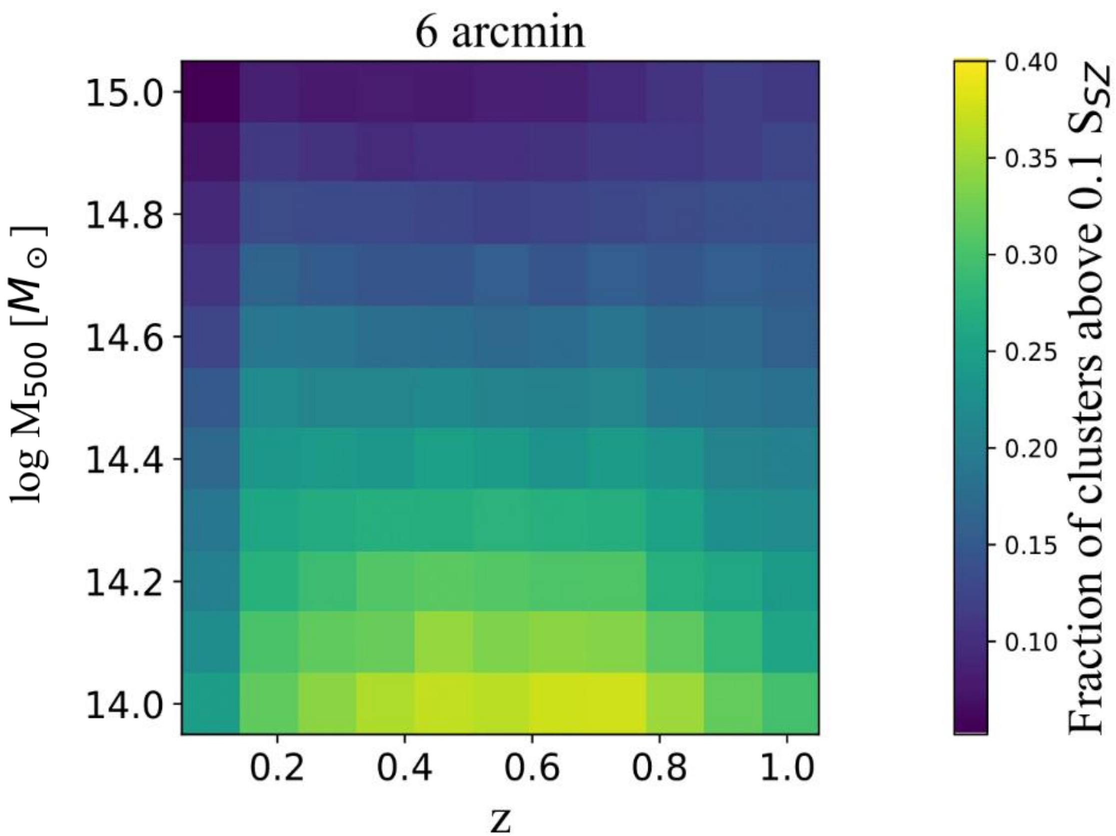


The enhancement of AGN in clusters is particularly strong for BCGs at higher-z (and especially for relaxed clusters).

Good `low frequency' (30, 40 GHz) coverage of SZ survey fields will be important to model such contamination.

Is this a problem for SZ cluster selection?

Taking the RCATS cluster radio AGN luminosity function and adopting the 1.4-150 GHz spectral index distribution of Gupta et al. '17 …



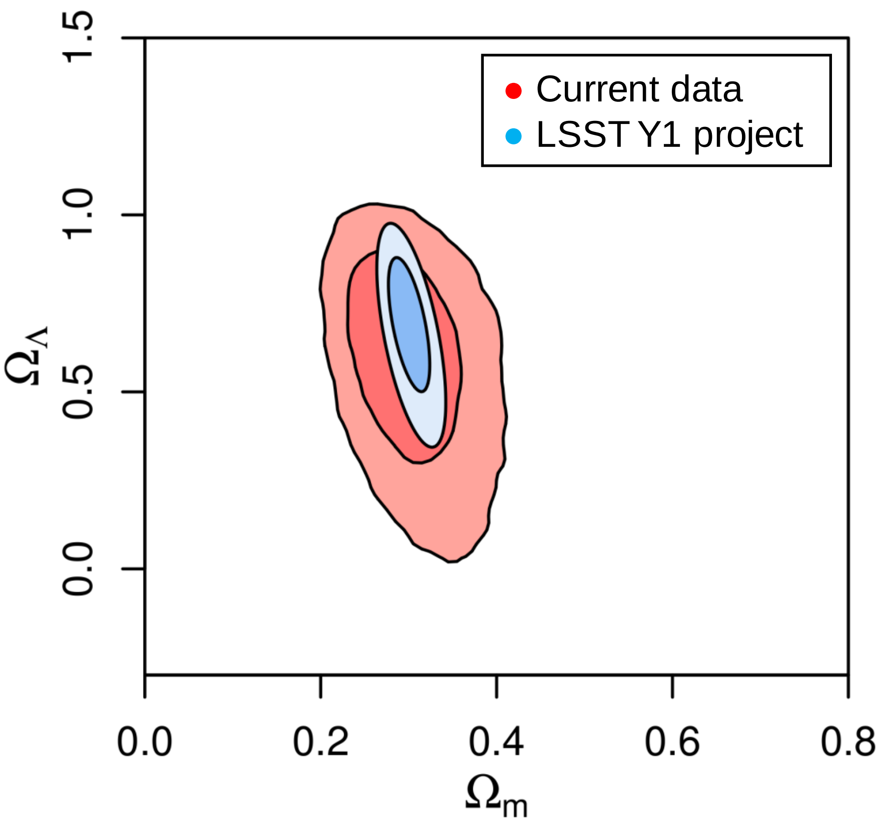
… implies that a substantial fraction of SZ clusters may have their 150 GHz signals contaminated (reduced) by ≥ 10%.

Adequate low-freq. coverage (30,40 GHz) essential for future mm-wave cluster surveys.

Radio CATS (King et al. '19)

The future of the fgas test

In combination with LSST and Chandra follow-up, eROSITA and SPT-3G should enable a rapid extension of the fgas test.



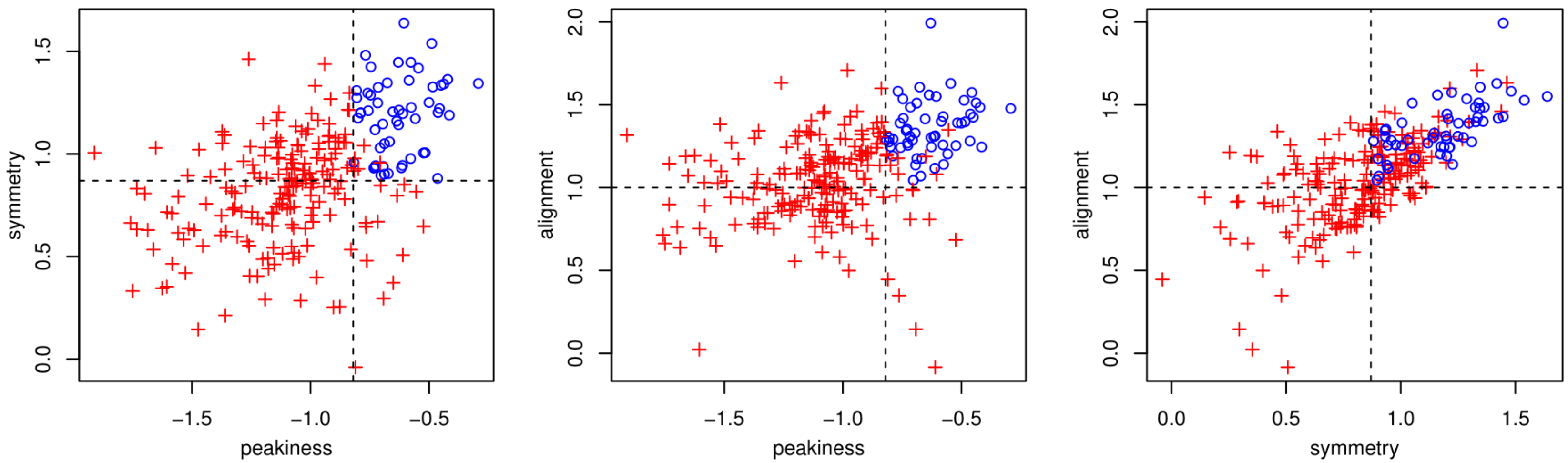
Potential analysis path:

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

Fig. shows improved constraints achievable adding 60 clusters (+5−10 Ms Chandra time) and complete LSST WL coverage.

Looking for relaxation? Try the SPA

Mantz et al. 2016

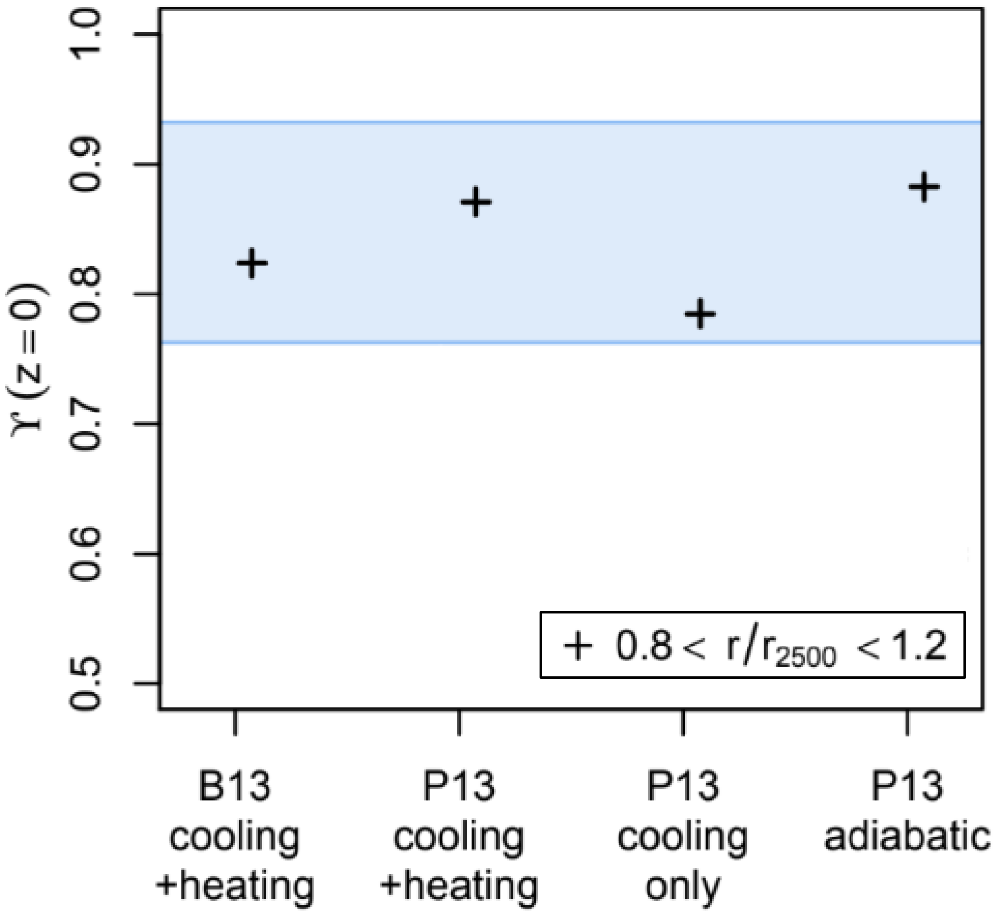


Our identification of the most relaxed systems uses the Symmetry, Peakiness, Alignment (SPA) code. Enables robust comparisons across a range of data quality and redshifts, incorporating rigorous treatment of errors, while avoiding strong assumptions about the cosmological background and cluster masses.

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

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

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)

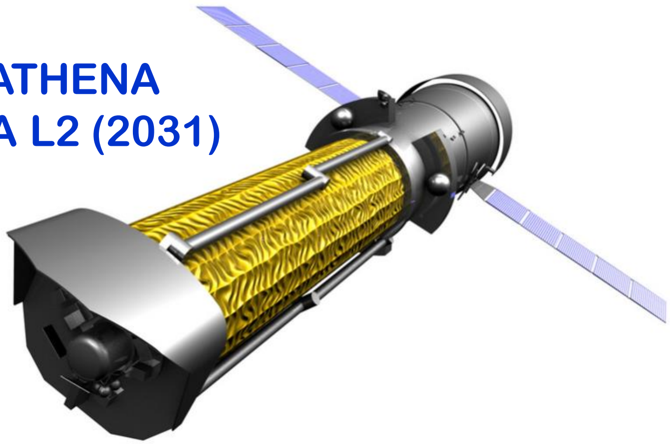
Parameterizing $\Upsilon_{2500} = \Upsilon_0(1+\alpha_\Upsilon z)$

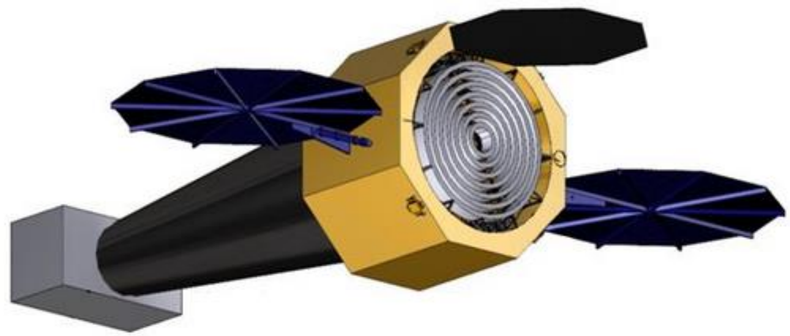
$\Upsilon_0 = 0.848 \pm 0.085$, $\alpha_\Upsilon = 0.00 \pm 0.05$

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)



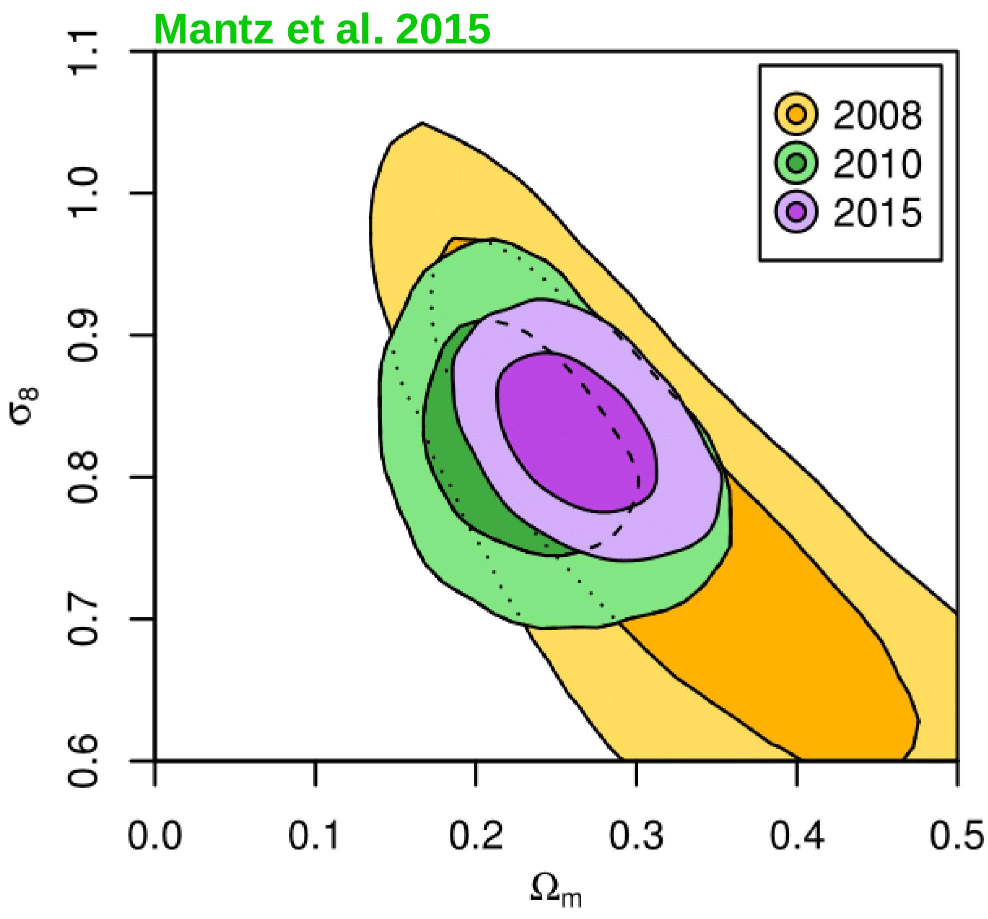


Lynx (under study for
2020 NRC Decadal Review)

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)

Impact of improved mass calibration



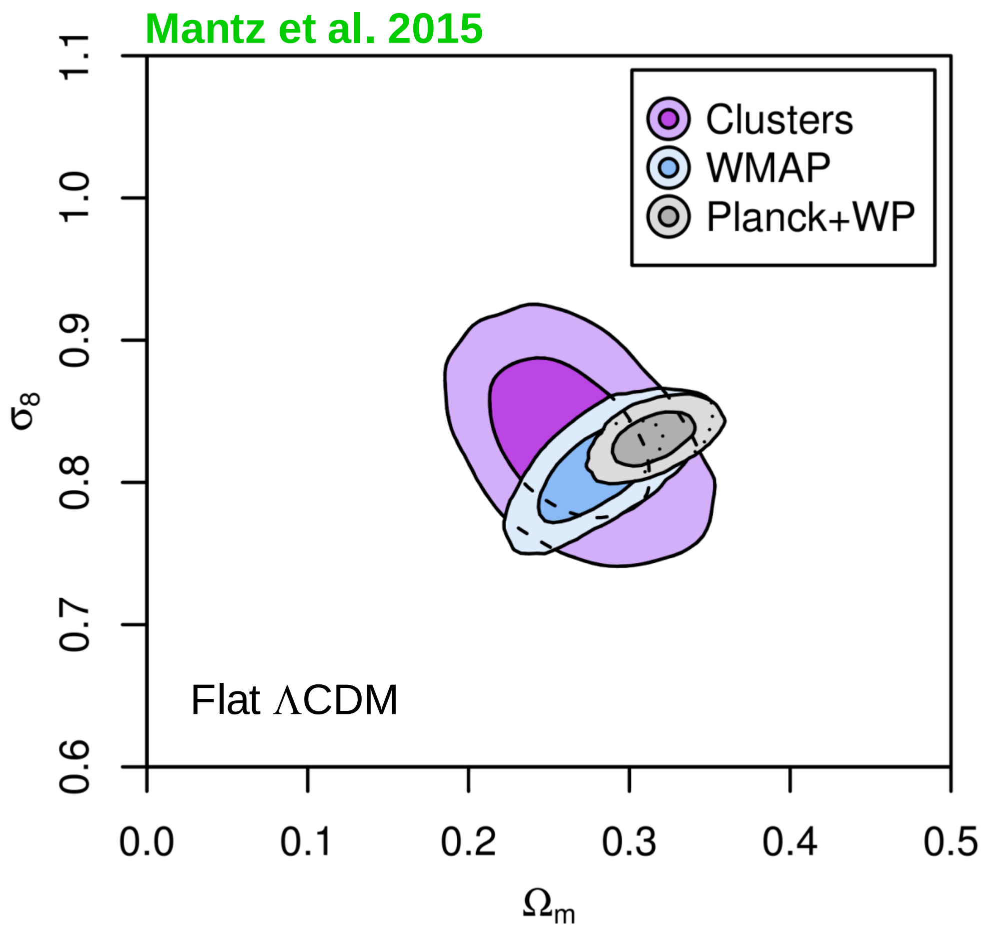
Key advances:

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

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

In combination, Chandra + WTG mass calibration → substantial boost in cosmological constraining power.

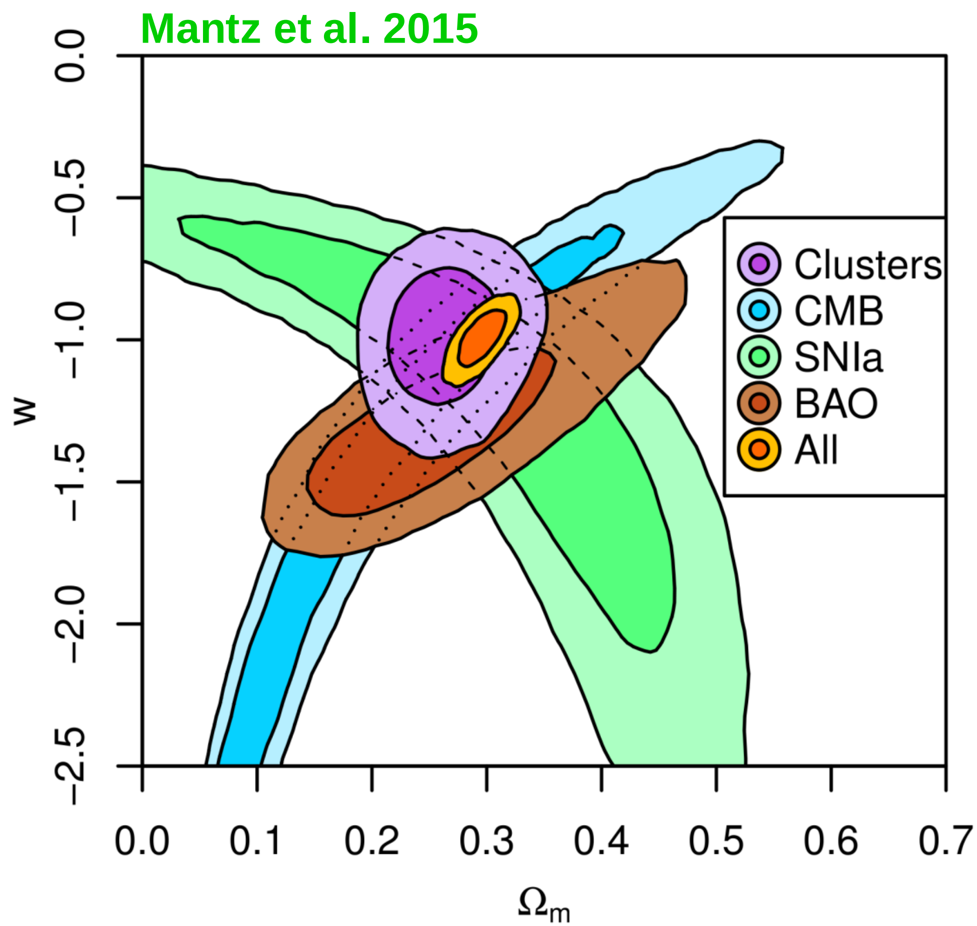
Comparison vs. primary CMB



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

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%)

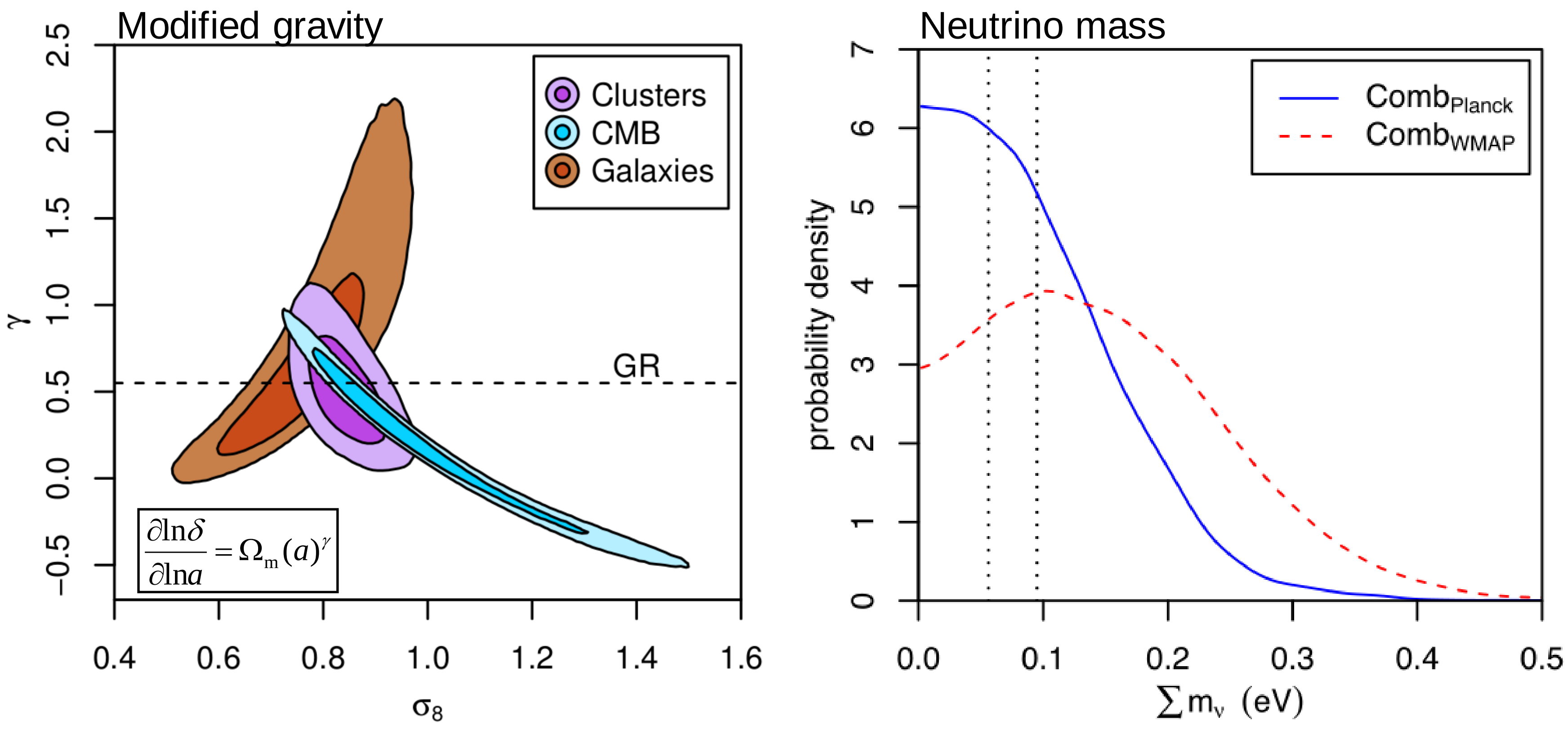
$\Omega_m = 0.295 \pm 0.013$

$\sigma_8 = 0.819 \pm 0.026$

$w = -0.99 \pm 0.06$

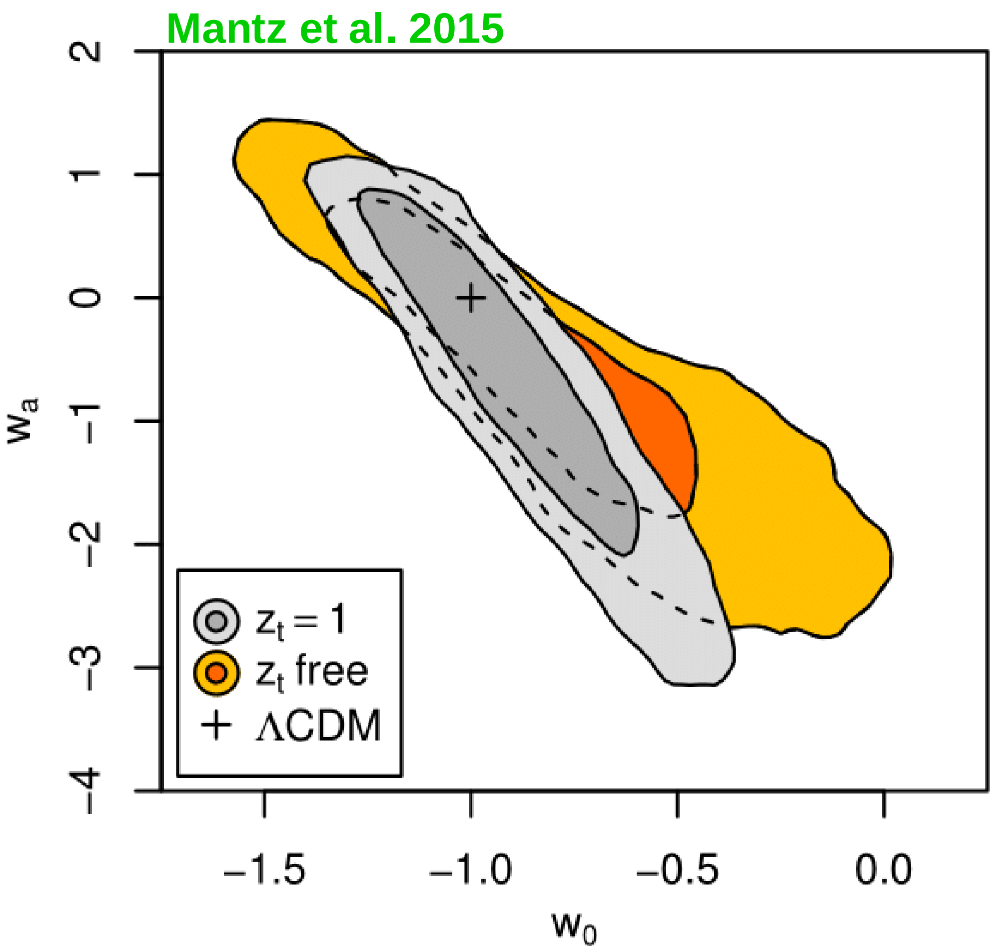
All 4 independent techniques consistent with cosmological constant.
Cluster constraints (highly) competitive with other leading methods.

Modified gravity and neutrino masses



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

Evolving dark energy models



Standard evolving DE model

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

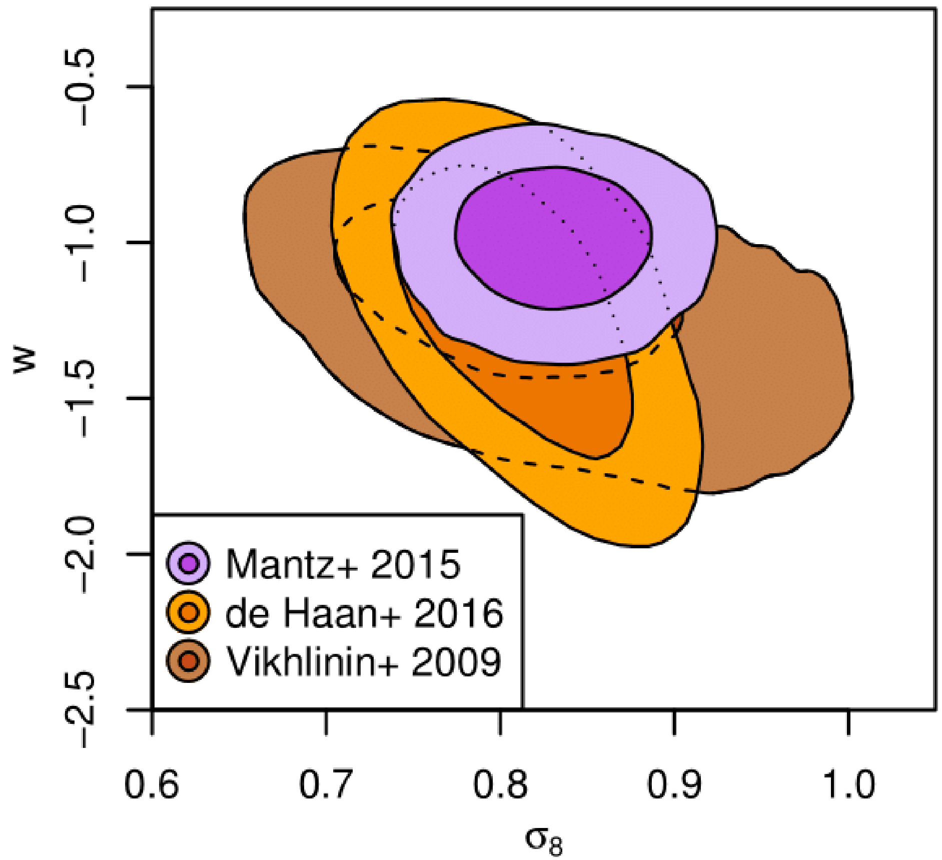
Combined constraint (68%)

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

Results for evolving DE models consistent with cosmological constant .

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)