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Clusters of Galaxies - Lecture 3

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Cosmological Constraints from Cluster Surveys

Over the past several years cluster surveys have begun yielding samples that provide significant cosmological constraints that are in general in good agreement with other independent cosmological probes. Interesting cluster specific applications have emerged, too.

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Outline

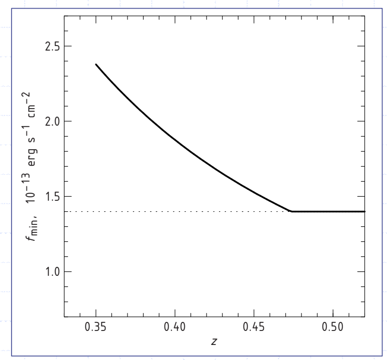
- Halo abundance as cosmological constraints
- Galaxy clusters and galaxy cluster surveys
- Cosmological constraints from cluster surveys
- Future Prospects

Overview: Cosmological Constraints from Cluster Surveys

- Examination of two ROSAT selected cluster surveys
  - Using low scatter mass proxies
- A cluster cosmology primer- a closer look at the SPT analyses
  - A closer look at mass-observable calibration
- Non-gaussianity and rare clusters

Sample Selection for Vikhlinin Sample

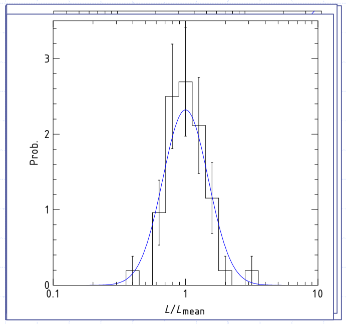
- Vikhlinin et al 2009:
  - Sample:
    - 49 “local” clusters discovered pre-ROSAT- “Edge sample”
    - 37 clusters from 400d ROSAT pointed survey at z>0.35
      - Characteristic X-ray image quality ~0.5 arcmin FWHM
      - This sample targeted by Chandra to get better X-ray data
- Samples reflect selection by L_x (or f_x) as mass proxy
  - Note redshift dependent flux limit- keeps sample small for Chandra



Vikhlinin et al 2009

Mass Information for Vikhlinin Sample

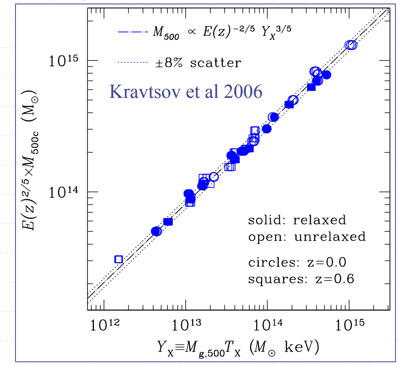
- Targeted 37 ROSAT clusters with Chandra to get improved gas masses and temperatures
- Used hydrostatic masses of 17 relaxed clusters to calibrate the Y_x-mass scaling relation
  - Demonstrate consistency with weak lensing masses using analyses from Hoeksta 2007
- Bootstrapped using Y_x to calibrate L_x-mass (including scatter) relation
  - Allows for clean model of L_x selection
  - Power law: Amplitude, Slope, z-evolution, log-Normal scatter (48%)



Vikhlinin et al 2009

Why Bother with Y_x?

- The SZE observable Compton Y is proportional to the total thermal energy in the cluster electron population
  - This quantity Y_{SZ} is well correlated to cluster virial mass and proportional to M_g * T_m, the gas mass X the mass weighted electron temperature
- X-ray observables offer a similar quantity- it also seems to correlate well with cluster mass
  - T_x is the (core excluded) X-ray emission weighted mean temperature

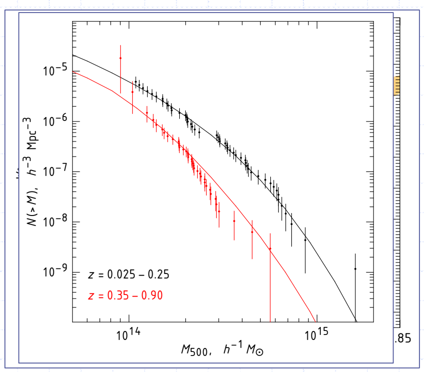


$$Y_{SZ} = \frac{\sigma_T}{m_e c^2} \int dV\, n_e k_B T_e \propto M_g T_m$$

$$Y_X = M_g T_X$$

400d ROSAT Sample Interpretation

- Analysis:
  - 49 "local" + 37 z>0.35 clusters
  - Mass functions using Y_x masses
  - Cycle through cosmological parameters, refitting mass-obs relations and comparing consistency of cluster mass and redshift distributions to theoretical expectation
- Results:
  - 12 clusters at z>0.55 require Lambda
  - Independent constraints in good agreement with WMAP+ cosmology
  - w constrained to 0.2(clus)/0.05(all)

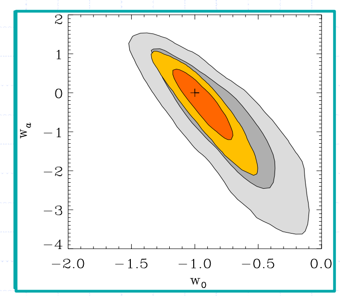


Vikhlinin et al 2009

: Interesting constraints from small sample using low scatter mass proxy Y_x
: Underlying mass calibration comes from hydrostatic equilibrium – validated with WL

Mantz et al Sample Selection and Masses

- Sample:
  - 238 clusters from the ROSAT All Sky Survey at z<0.5 for mass function
    - Characteristic X-ray image quality ~2 arcmin FWHM
  - Use M_{ICM} as mass proxy (assume constant f_{ICM}) for 94 with followup observations
  - +42 "relaxed" clusters with direct f_{ICM} measurements used
- Sample reflects selection by L_x (or f_x)
- Results
  - Independent: σ_8 = 0.82 (0.05) and w=-1.01 (0.20)
  - WMAP+SNe+BAO+Clusters+f_{ICM}:
    - σ_8 = 0.79 (0.03)
    - w=-0.96 (0.06)
  - DETF FOM =15.5 (~2x improvement)
    - w_o=-0.93 (0.16), w_a=-0.16 (+0.47,-0.73)



Mantz et al 2010

: The mass proxy is M_{icm} (M_g), which behaves similarly to Y_x
Underlying mass calibration uses hydrostatic equilibrium masses

Overview- X-ray Cluster Cosmology

- Samples of ~10^2 clusters used to extract competitive cosmological constraints – no current evidence of significant disagreement with other probes
- Rely on L_x selection (~45% scatter with mass)
- Use other lower scatter X-ray observables (M_{icm}, T_x) to build mass function when available
- Both currently rely on masses from hydrostatic equilibrium, which is known from simulations to introduce biases at the ~10% level
- Next step is to increase samples, adopt weak lensing mass calibration

Focus on SZE Cluster Cosmology – with SPT

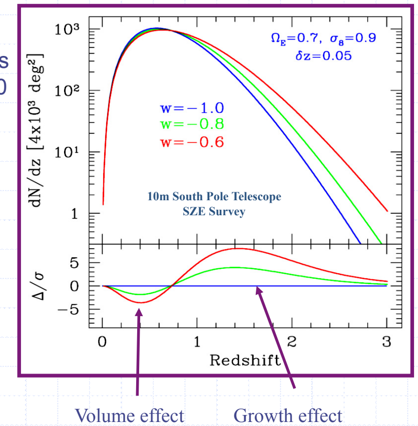
- We designed SPT in hopes of selecting ~10^4 clusters over all redshifts
- In the end we will have ~500 high mass clusters uniformly selected from a 2500 deg^2 survey region
- Cosmology and mass-calibration machinery provide an interesting test case

$$\frac{dN(z)}{dz\,d\Omega} = \frac{dV}{dz\,d\Omega}\,n(z)$$

Raising **w** at fixed Ω_E:

- Decreases volume surveyed
- Decreases growth rate of density perturbations

Redshift Distribution Sensitive to DE Equation of State Parameter



South Pole Telescope (SPT)

- This is a dedicated cluster survey and CMB anisotropy mission- finds clusters over broad redshift range using the SZE
- (Sub) millimeter wavelength telescope:
  - 10 meter aperture
  - 1' FWHM beam at 150 GHz
  - 20 micron RMS surface
  - 5 arcsec astrometry
- SZ Receiver:
  - 1 sq. deg FOV
  - Observe in 3 bands between 95-220 GHz simultaneously
  - Sensitivity ~ 15-60 μK-arcmin

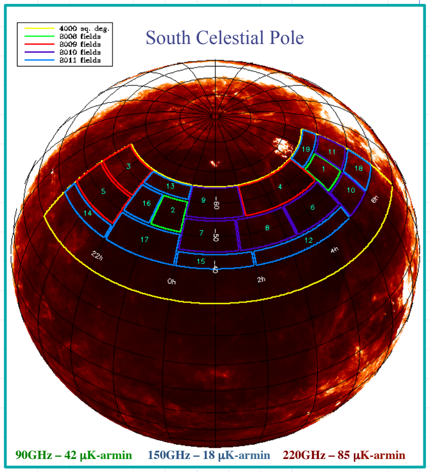
In comparison to Planck:
Smaller beam (1’ vs 8’)
Fewer bands (3 vs 9)
Deeper observations at 150GHz

South Pole Telescope

SPT Survey Sky Coverage

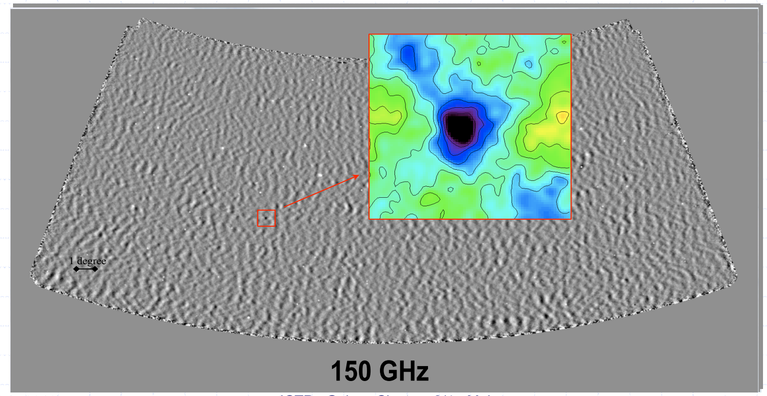
- Survey 2008-2011
  2491deg^2 complete
- Data used to study CMB anisotropy
- Select clusters through Sunyaev-Zel'dovich Effect
  Redshift independent
  Tied closely to cluster mass
- Cluster candidates found:
  657 at S/N>4.5

SZE work by Planck, ACT, and other experiments ongoing



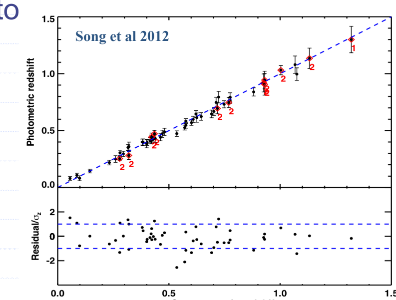
Finding a Cluster in mm-wave Sky Maps

- Unique SZE signature helps provide pure sample, use matched filter
- No redshift information – requires multi-λ followup



SPT Optical Followup

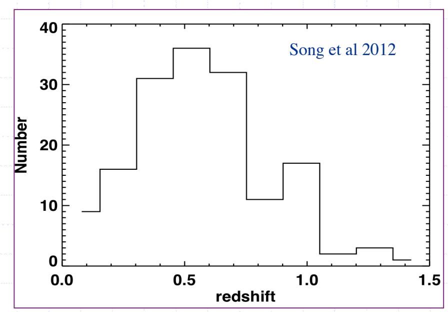
- We use multiband photometry to get red sequence cluster redshifts
- Began with dedicated survey
  Blanco Cosmology Survey –
  60 nights/ 80 deg^2/*griz*
  Desai et al 2012
- Now go cluster by cluster
  - ~100 nights on the telescope so far
  - Over 500 candidates imaged to date
  - Goal: finish by end of year



Characteristic scatter δz~0.017 for 0<z<1.32
For 56 clusters with spec-z's

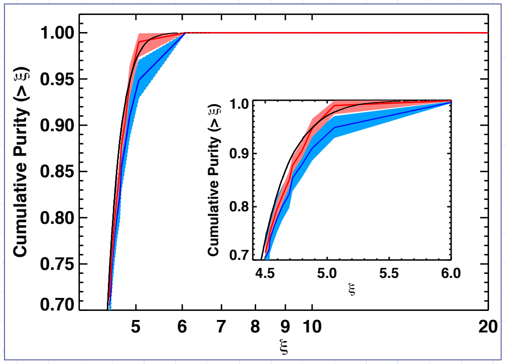
SPT Clusters: Redshift Distribution

- Statistics of 750 deg^2 sample:
  - 224 candidates
  - 158 with measured photo-z's
  - Median redshift is ~0.57
  - 18% of sample at z>0.8
  - 9 clusters with no photo-z, but with significant NIR/IR overdensities- high-z systems that need more attention



SPT Clusters: Contamination

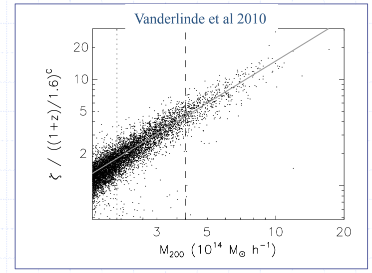
- Negative noise peaks *can* masquerade as clusters
  - Stay at high S/N!
- Optical confirmation allows us to measure the contamination



SPT-only selection produces >95% pure sample at S/N>5
SPT+optical followup produces ~100% pure sample at S/N>4.5

So How Do We Do Cosmology?

- Sample selection is with ξ, the matched filter signal to noise of the detected cluster
  - We model the ξ-mass relation as power law: Amplitude, slope, redshift evolution
  - Scatter: log-normal intrinsic plus normal measurement scatter
- Mass calibration currently comes from Y_x calibration (Vikhlinin 2007 hydrostatic equilibrium masses)



SPT Mass-Observable Relation

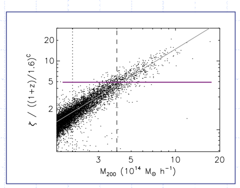
- Observed S/N ξ is pulled from the filtered maps for each cluster
  - Filters built to suppress power on scales dominated by noise (shot noise + CMB anisotropy) compared to modes of cluster signal (β=1 model)
    (see Melin et al 2006)

$$\zeta = \sqrt{\langle \xi \rangle^2 - 3}$$

$$\zeta = A_{SZ}\left(\frac{M_{500}}{3x10^{14}h^{-1}M_\odot}\right)^{B_{SZ}}\left(\frac{E(z)}{E(0.6)}\right)^{C_{SZ}}$$

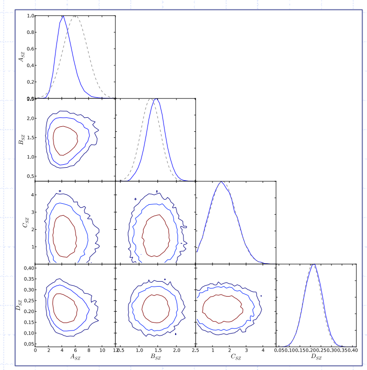
- Observed S/N ξ is different from unbiased underlying ζ-mass relation, because of maximization bias
  - We search position (two dimensions) plus scale (12 core radii) to assign maximum observed S/N x
- Selection in log(mass) is like error function due to log-normal scatter around ζ-mass relation

Scatter: log-normal in ζ-mass
normal in ξ-ζ (σ=1)



Extracting Constraints

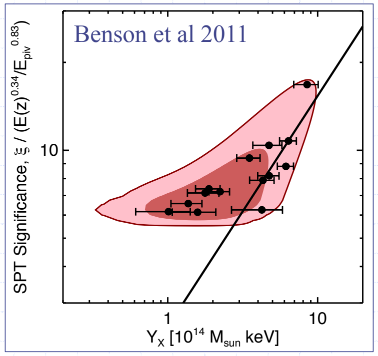
- Define inputs:
  - Choose ξ>5, z>0.3 (100 systems)
  - Adopt priors on nuisance params
  - Adopt external constraints (or not)
- Cycle through Markov Chain:
  - Select cosmological and nuisance parameters
  - Calculate cluster abundance as function of mass+redshift
  - Use ξ-M relation (with scatter) and Y_x-M relation to transform mass function dn/dMdz(M,z) to ξ−Y_x function dn/dξd$Y_x$dz(ξ,Y_x,z)
  - Evaluate likelihood of sample
  - Iterate until chain converges



Bazin et al 2012

Mass-Obs Calibration in Given Selection

- Selection effects must be correctly accounted for in calibrating scaling relations
  - Malmquist bias with scatter
  - Eddington bias with scatter
  - Both with scatter
    (see Mantz et al 2010!)

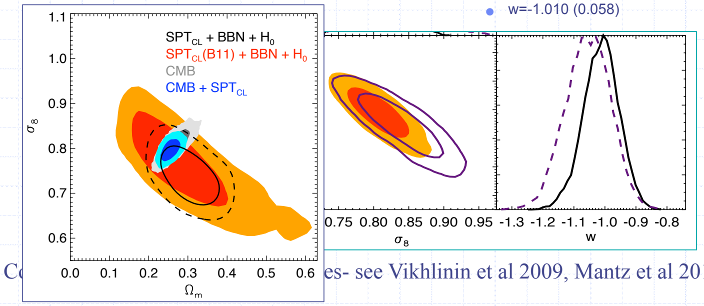


- The scaling relation calibration is carried out simultaneously with cosmology
  - Distances, E(z), mass function
  - 14 clusters with Y_x

SPT Constraints on Dark Energy

- 100 Clusters from 750 deg^2
  - Mass calibration from X-ray
- Cosmology limited by mass uncertainties
- Cosmological constraints:
  - WMAP+SNe+BAO+H0:
    - σ_8 = 0.84 (0.04)
    - w=-1.054 (0.073)
  - Above + SPT Clusters
    - σ_8 = 0.81 (0.03)
    - w=-1.010 (0.058)

Reichardt et al 2012



Co… es- see Vikhlinin et al 2009, Mantz et al 2010

Non-Gaussianity and Halo Abundance

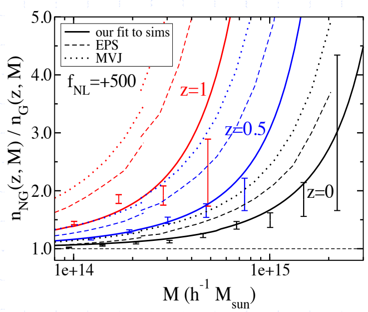
- In some models of inflation the resulting density perturbations have significant non-Gaussianity
  - For local non-Gaussianity parameter f_{NL} the perturbed gravitational potential takes the form

$$\Phi_{NG}(\vec{x}) = \phi(\vec{x}) + f_{NL}\left(\phi^2(\vec{x}) - \langle\phi^2\rangle\right)$$

  - Positive f_{NL} leads to an enhanced overdensity relative to the corresponding Gaussian case

$$\delta_{NG} \approx \delta + 2 f_{NL} \phi_p$$

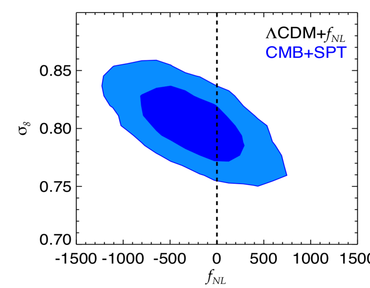
- Studies have revealed how this non-Gaussianity affects the mass function
  - Positive f_{NL} enhances the number of haloes in the rare tails of the probability distribution at high mass and/or at high redshift



Dalal et al 2008

SPT Constraints on Non-Gaussianity

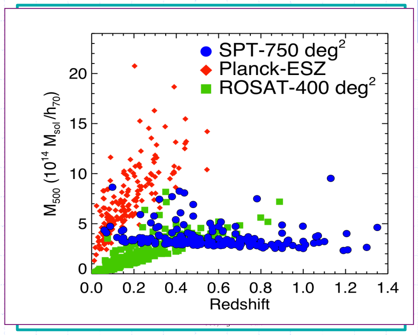
- SPT constraints on non-Gaussianity
  - f_{nl}=-192+/-310, 20+/-450
    (from full likelihood analysis including selection function of SPT sample)
  - For comparison, -10<f_{NL}<74 (95%) from CMB
    Komatsu et al 2011
    But this is on much larger scales
- Interesting thread- combination of cluster counts and power spectrum greatly enhances constraints on f_{nl}
  (i.e. see Sartoris et al 2010 for discussion)



Williamson et al 2011
Benson et al 2011

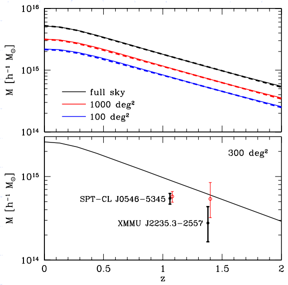
SZE Signature is Good Mass Indicator

- We have leveraged X-ray mass indicators to calibrate our sample
  - Direct mass calibration underway
    weak lensing and velocity dispersions
- High-z massive SPT clusters are unique population
  - M_{200}>4x10^{14} M_o even at highest z
  - Large solid angle survey (2500 deg^2) allows us to find very rare objects
  - ~100 of these clusters over full survey



Tests of ΛCMD and *w*CDM Paradigm

- The combination of CMB, SNe, BAO and H_o constraints are already quite restrictive even without the additional of galaxy cluster survey constraints
- Mortonson and collaborators explored this available parameter space in the standard, ΛCMD and wCDM models
  - Flat geometry
  - Gaussian density perturbations
  - General relativity
  - Dark energy with equation of state param w
- They determined regions in mass and redshift where the existence of even a single galaxy cluster would rule out the paradigm

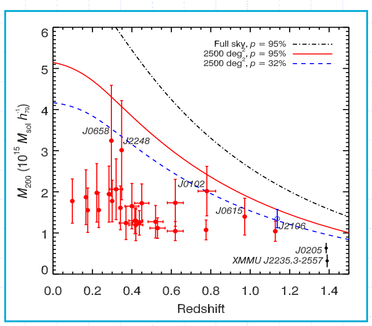


Mortonson et al 2011

The Rarest, Most Massive Clusters

- In late 2010 SPT finished shallow "preview" scans of the full 2500deg^2
  - Adequate to select the 26 most massive clusters, independent of redshift
- Mortonson analysis suggests no single cluster in tension with ΛCMD
  - Explore the full range of models consistent with current cosmological constraints from CMB, BAO, SNe
  - Define a region beyond which even a single cluster would cause problems for the a Dark Energy model, requiring either modified gravity of non-Gaussianity
- More precise statements require improved mass measurements

Williamson et al 2011

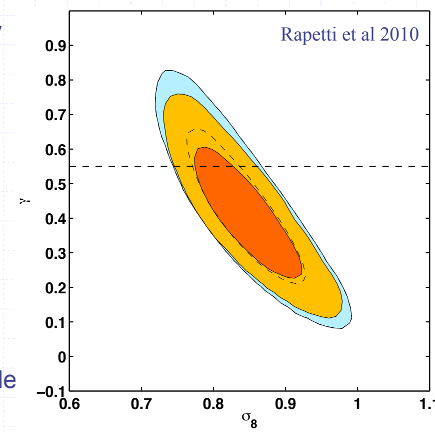


Tests of Growth Rate of Structure

- One can carry out a consistency test of General Relativity by allowing the growth rate of structure to deviate from the GR expectation
  (e.g. Wang & Steinhardt 1999)

$$\frac{d\ln\delta}{d\ln a} = \Omega_m^\gamma(a)$$

- Current results are not very constraining, and certainly observed cluster samples provide no evidence of problems for GR
  (see recent combined cluster, CMB galaxy clustering analysis- Rapetti 2012)



Remaining Challenges

- Cluster mass measurements:
  - Need methods that don't require equilibrium assumption
    - Weak lensing and galaxy kinematics
- Clean selection techniques
  - X-ray and SZE well understood
  - Optical understood, but there are challenges to be met
- Large surveys like eROSITA will push the limits
  - It's not clear yet where the systematics floor will be, so it's difficult to project accurate cosmological constraints from this mission.

Summary

- X-ray and SZE cluster survey cosmology results encouraging
  - Small samples, low scatter mass proxies, high purity, completeness well understood
  - Samples used to examine non-Gaussianity, test wCDM paradigm, carry out consistency test of GR
- Mass calibration is the current weak point
  - All analyses currently relying on hydrostatic equilibrium mass calibration (at z~0.3 and below)
  - The uncertainties (~10%-15%) on the calibrating relations are too large to enable the full use of the datasets
- Next steps include improved weak lensing and dispersion calibration together with acquiring more low scatter X-ray mass proxies (Y_x or M_{icm}) to understand scatter

References

- *Articles from the current literature*