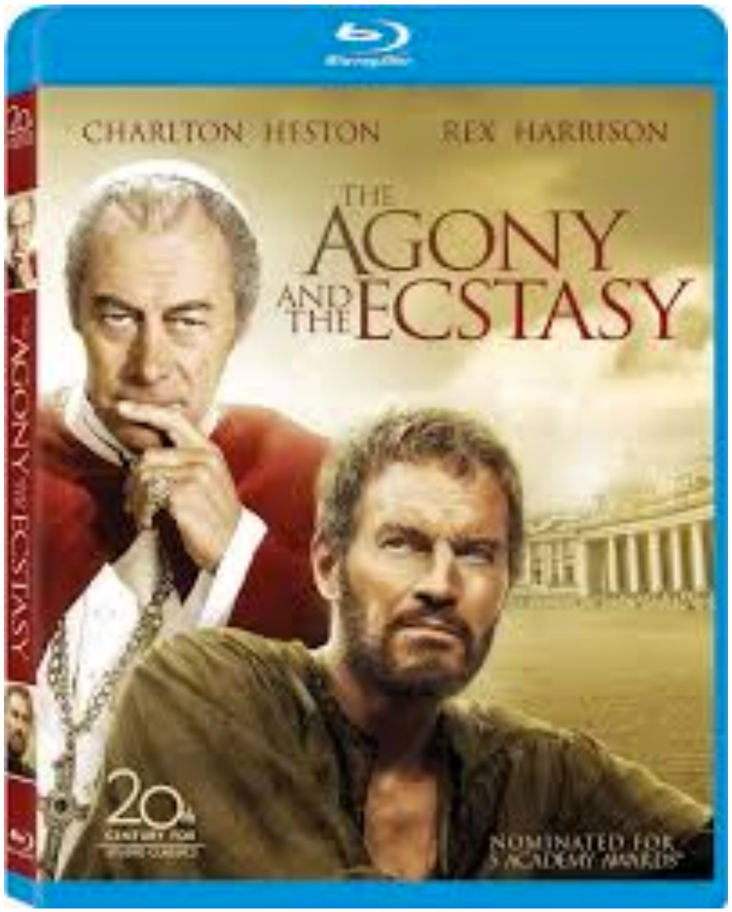


Cluster Cosmology
+
Property Covariance
of Massive Halos

August (Gus) Evrard

Arthur F. Thurnau Professor
Departments of Physics and Astronomy
Michigan Center for Theoretical Physics
University of Michigan

outline

- opportunities / challenges
- recent work on MORs and property covariance : simulations + observations
- speculations on **CLUSTERS 2032**…

Opportunities

opportunities I

- gas fraction as a standard ruler: wCDM GEOMETRY (dV/dz) only

physical basis: Massive halos contain ~constant fraction of mass in hot gas.

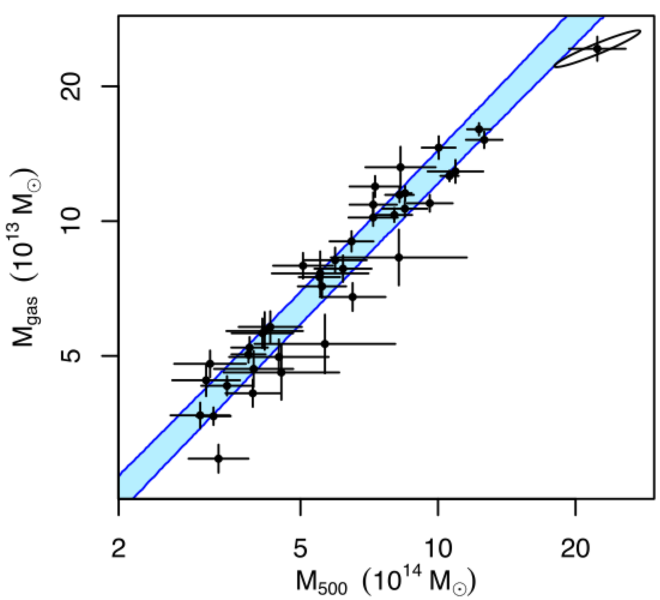
methodology:

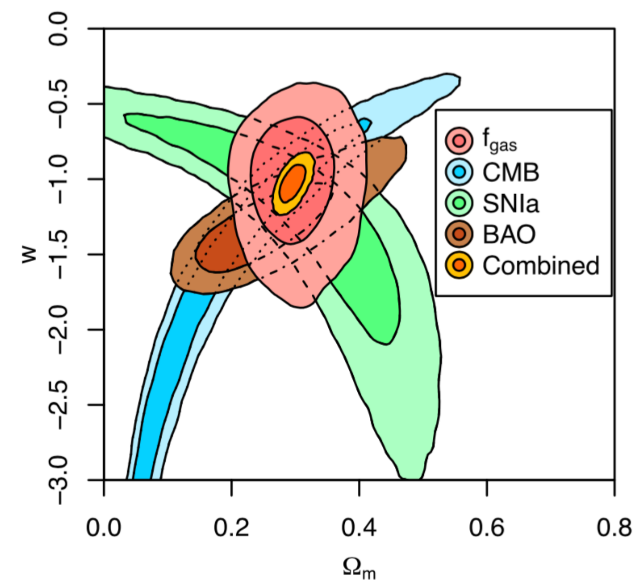
– use (typically X-ray) observations to estimate Mgas, Mtot

– assume <fgas(z)> = constant to constrain H(z), thereby wCDM parameters

Opportunity: Apply to larger, deeper samples with ongoing/future X-ray and SZ data

Mantz et al, 2016





early version of this idea…

August E. Evrard[1,2]★

[1]Physics Department, University of Michigan, Ann Arbor, MI 48109-1120, USA
[2]Institut d'Astrophysique, 98 bis Boulevard Arago, F75014 Paris, France

1997 (pre-SN 1a)

$\Omega_m\, h^{2/3} = 0.30 \pm 0.07$

Accepted 1997 July 3. Received 1997 June 30; in original form 1997 January 27

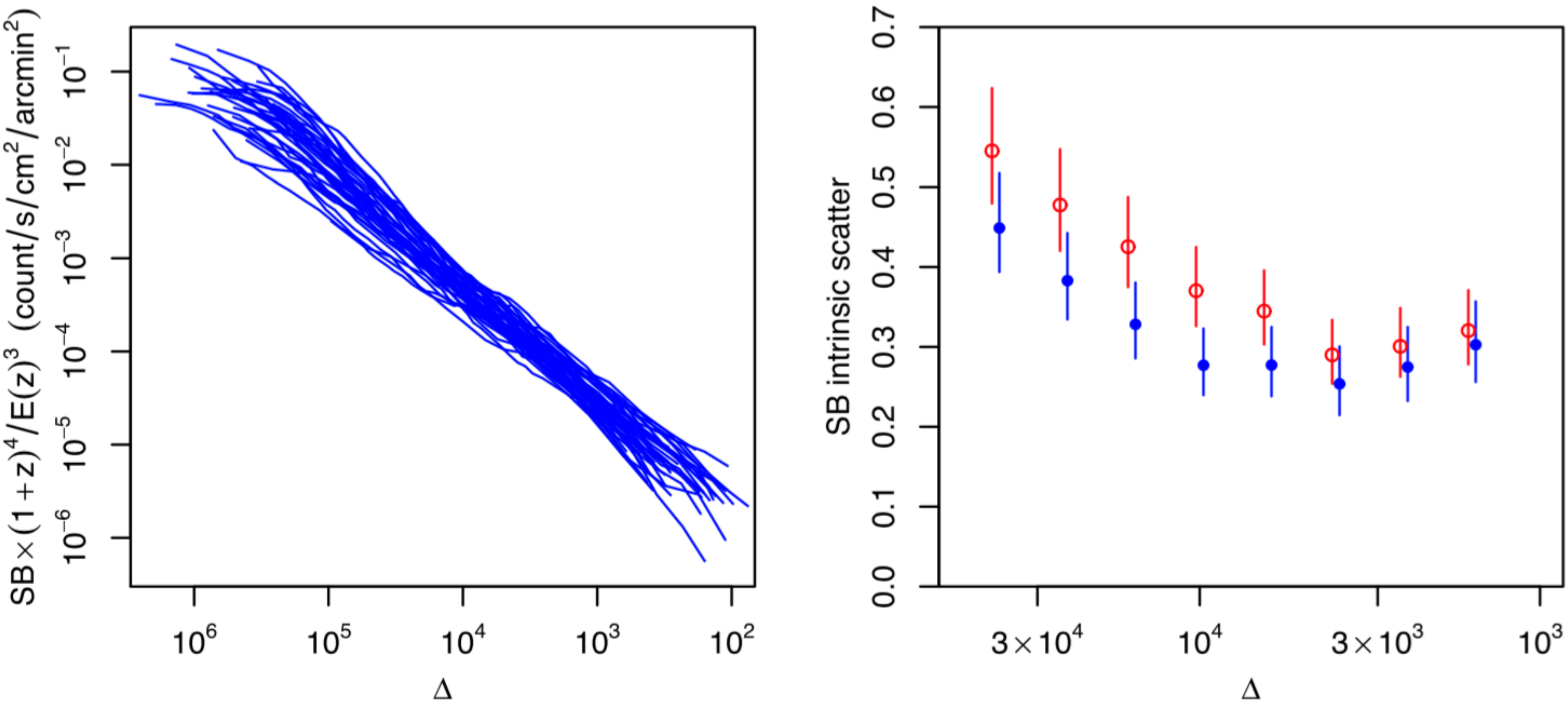
ABSTRACT

The mean intracluster gas fraction of X-ray clusters within their hydrostatic regions is derived from recent observational compilations of David, Jones & Forman and White & Fabian. At radii encompassing a mean density 500 times the critical value, the individual sample bi-weight means are moderately (2.4σ) discrepant; revising binding masses with a virial relation calibrated by numerical simulations removes the discrepancy and results in a combined sample mean and standard error $\bar{f}_{gas}(r_{500}) = (0.060 \pm 0.003)\, h^{-3/2}$. For hierarchical clustering models with an extreme physical assumption to maximize cluster gas content, this value constrains the universal ratio of total, clustered-to-baryonic mass $\Omega_m/\Omega_b \leq 23.1\, h^{3/2}$. Combining this with a maximal value of Ω_b from primordial nucleosynthesis results in $\Omega_m\, h^{1/2} < 0.76$. A more physically plausible approach based on low deuterium abundance inferences from quasar absorption spectra and accounting for baryons within cluster galaxies yields an estimate of $\Omega_m\, h^{2/3} = 0.30 \pm 0.07$, with sources of systematic error involved in the derivation providing approximately 30 per cent additional uncertainty. Other effects which could enhance the likelihood of the Einstein–de Sitter case $\Omega_m = 1$ are presented, and their observable signatures discussed.

self-similarity in Tx-selected sample of relaxed clusters

Mantz et al, 2014, 2016

sample of 40 ***dynamically relaxed***, hot (kT>5 keV) clusters spanning 0 < *z* < 1

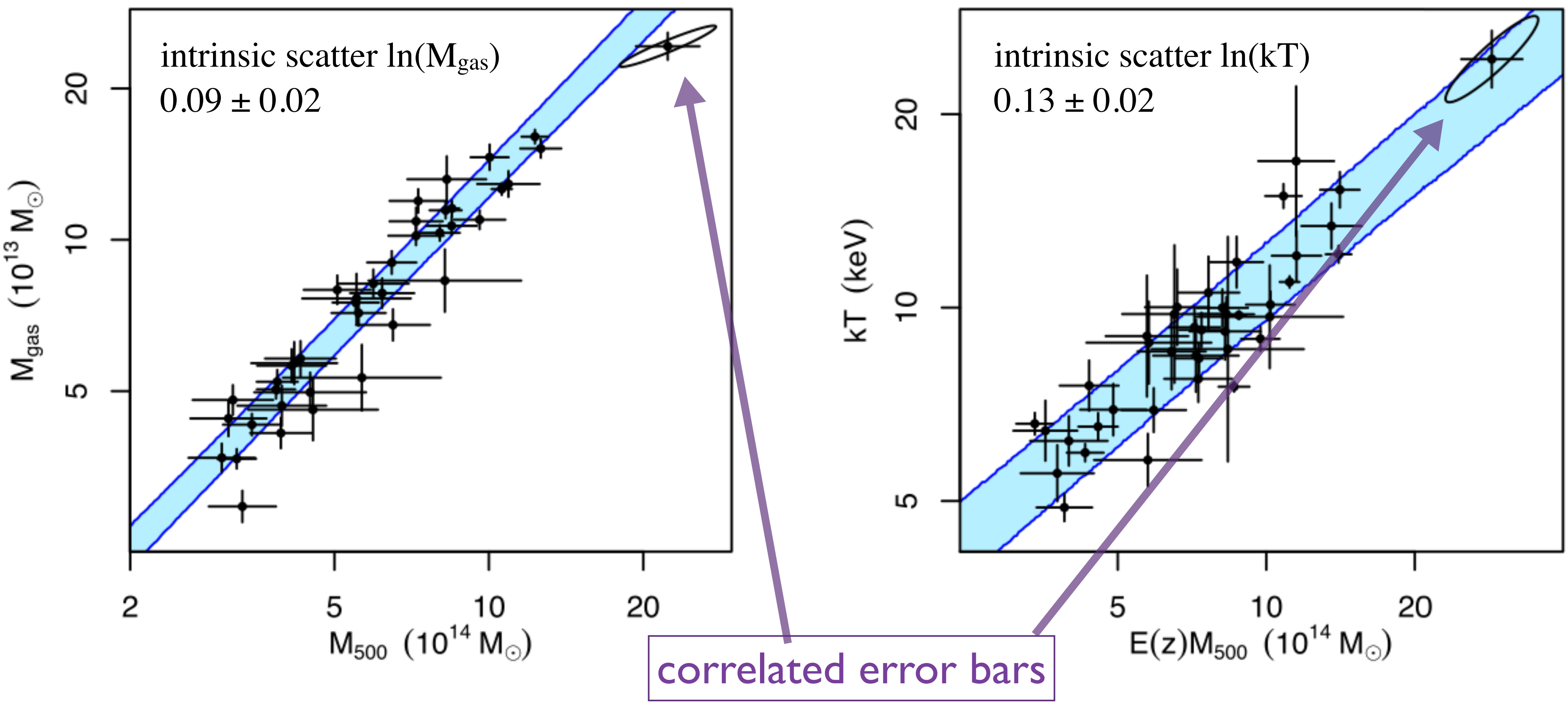


MOR analysis of relaxed clusters

Mantz et al, 2014, 2016

– MOR of Mgas and Tx are consistent with simple self-similarity

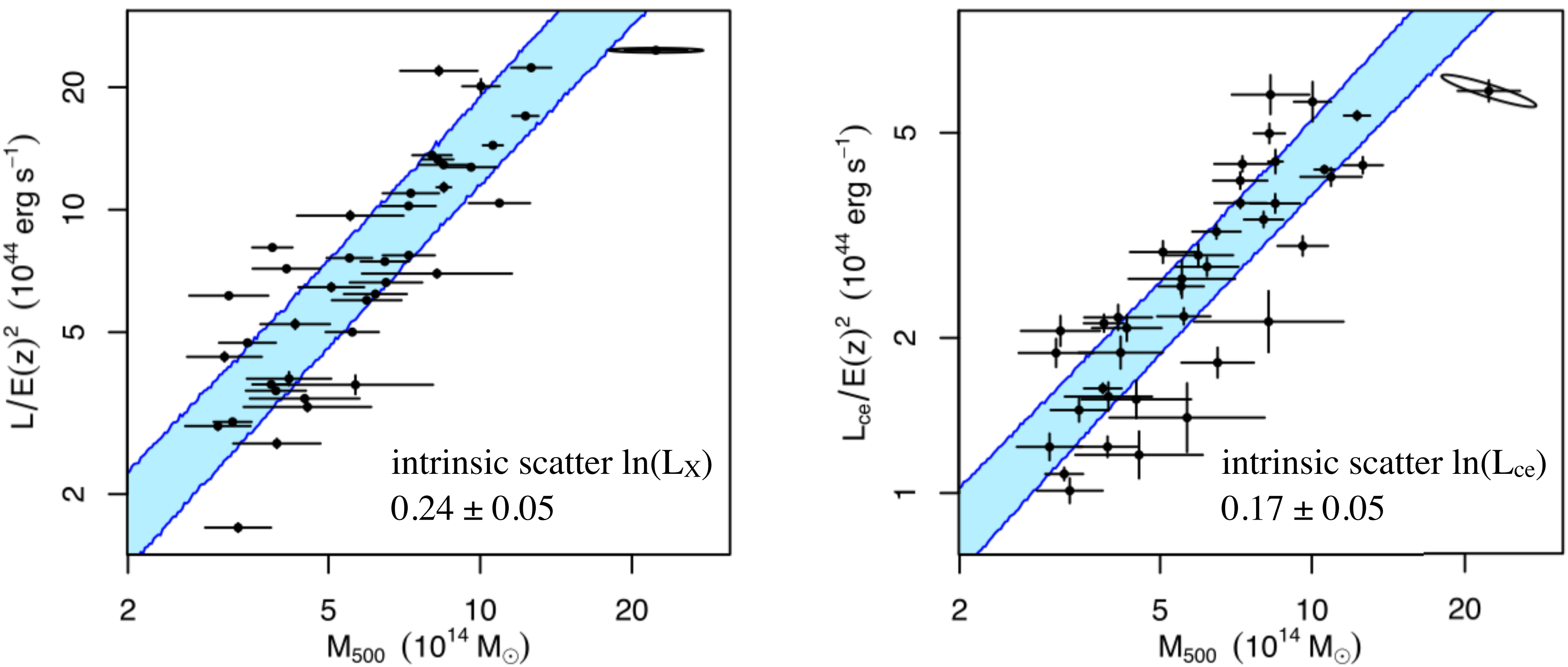
– total masses, M500, are X-ray hydrostatic estimates (~OK for relaxed systems?)



MOR analysis of relaxed clusters

Mantz et al, 2016

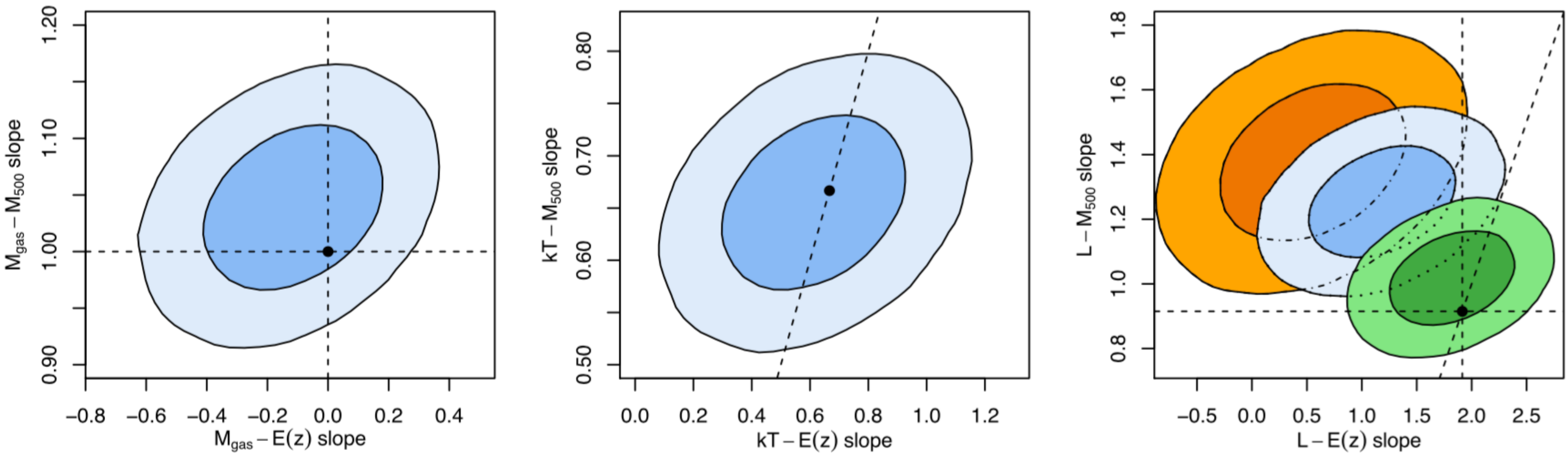
– Lx looks better when you put your thumb over the core



MOR analysis of relaxed clusters

Mantz et al, 2016

– slopes in mass and redshift are consistent with self-similarity (dashed lines)

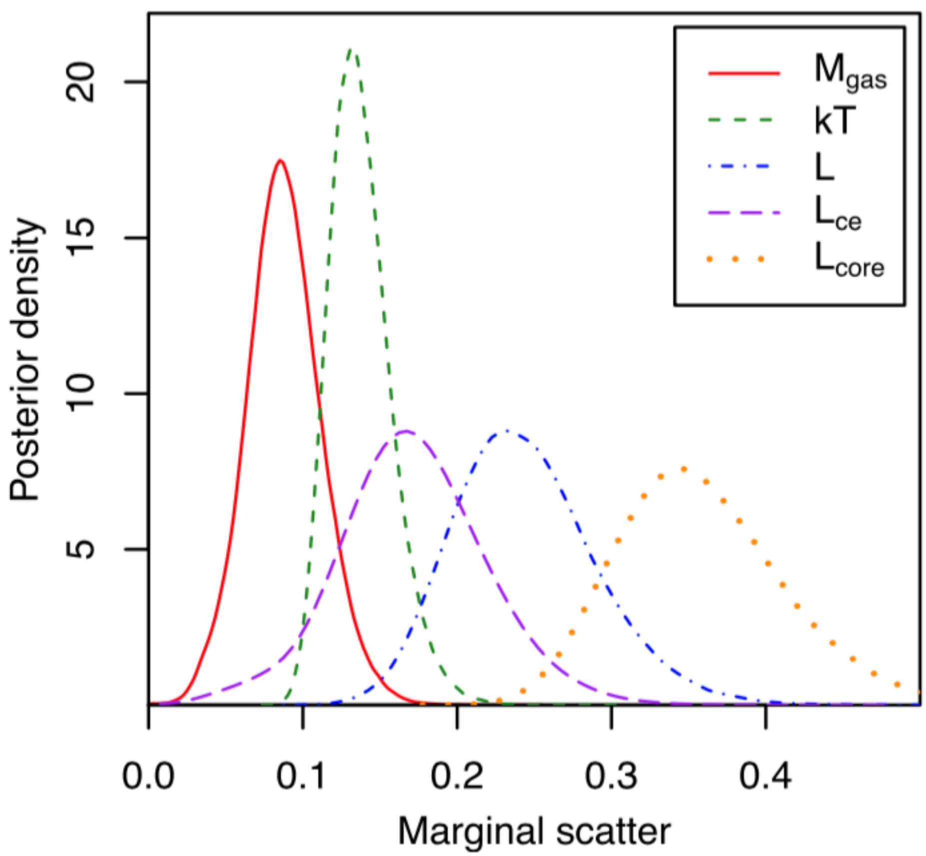


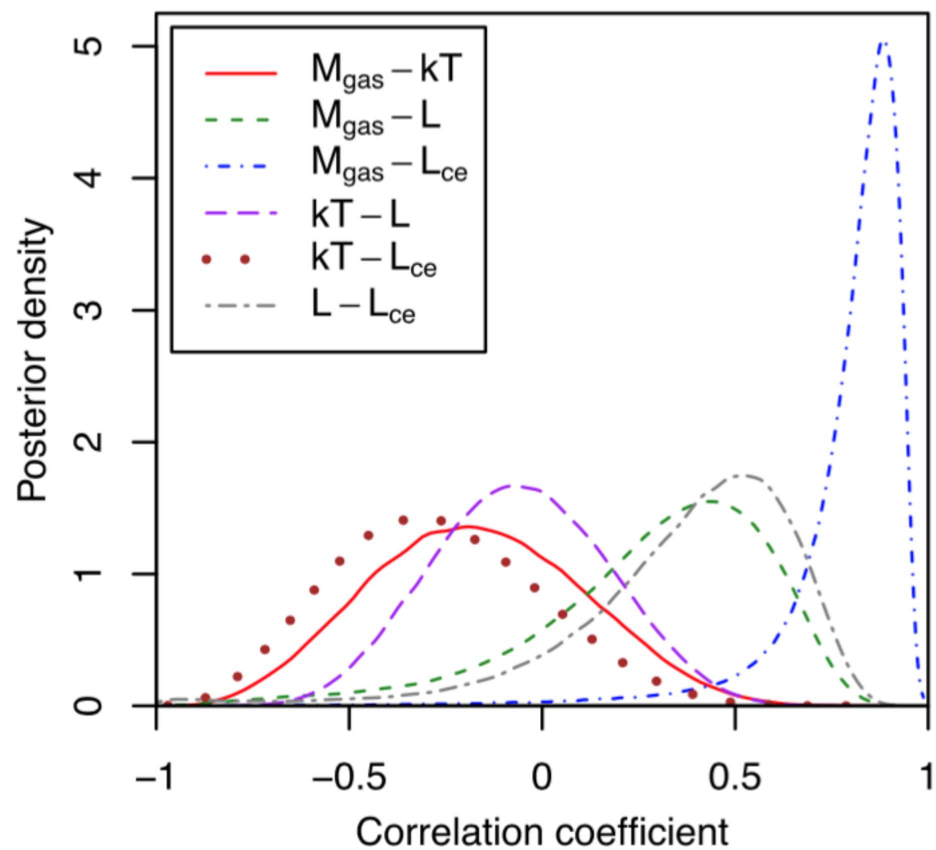
MOR analysis of relaxed clusters

Mantz et al, 2016

– intrinsic scatter in $\ln(S_i)|M_{500}$; S = { M_{gas}, kT, L, L_{ce}, L_{core} } ; gas mass is best

– first estimates of property covariance at fixed total mass





MOR analysis of relaxed clusters

Mantz et al, 2016

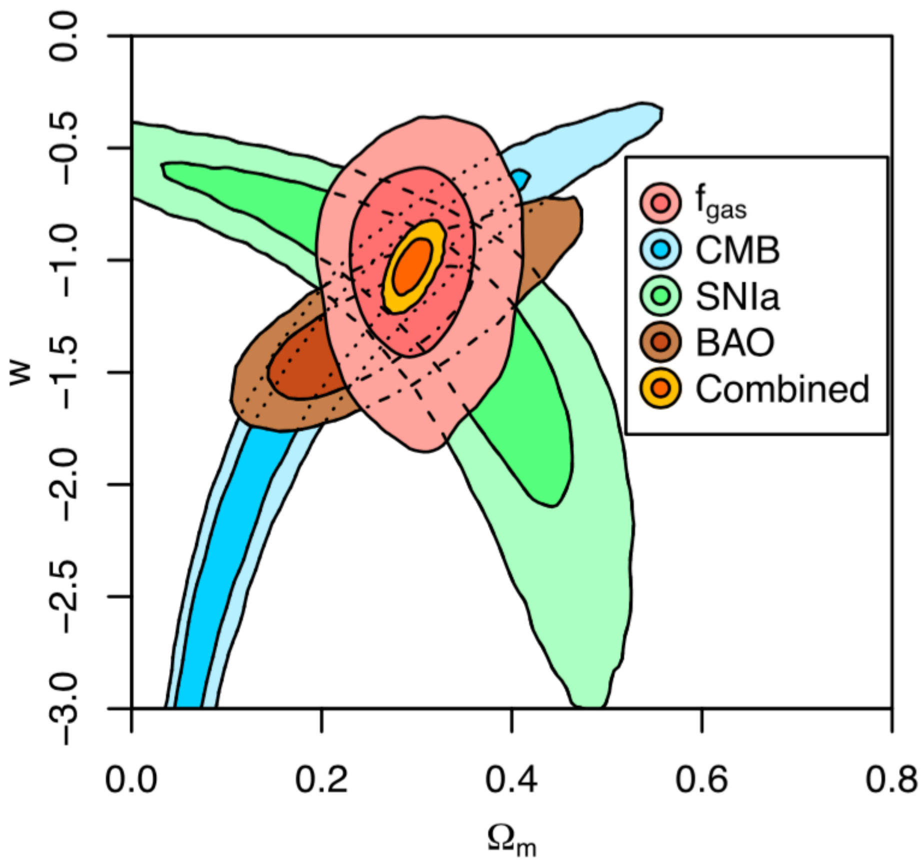
Type	Symbol	Meaning	Prior
Cosmology	h	Hubble parameter	$\mathcal{N}(0.738,\ 0.024)$
	f_b	Cosmic baryon fraction, Ω_b/Ω_m	
	Ω_m	Total matter density normalized to ρ_{cr}	
	Ω_{DE}	Dark energy density normalized to ρ_{cr}	
	w_0	Present-day dark energy equation of state	
	w_a	Evolution parameter for $w(a)$	
	a_{tr}	Transition scalefactor for $w(a)$	$\mathcal{U}(0.5,\ 0.95)$
Derived	$100\,\Omega_b h^2$	Baryon density	$\mathcal{N}(2.202,\ 0.045)$
	Y_{He}	Primordial helium mass fraction	
	w_{et}	Early-time dark energy equation of state	
Clusters	Υ_0	Gas depletion (f_{gas}/f_b) normalization	$\mathcal{U}(0.763,\ 0.932)$
	Υ_1	Gas depletion evolution	$\mathcal{U}(-0.05,\ 0.05)$
	η	Power-law slope of shell f_{gas}	$\mathcal{N}(0.442,\ 0.035)$
	σ_f	Intrinsic scatter of shell f_{gas} measurements	
	K_0	Mass calibration at $z=0$	
	K_1	Mass calibration evolution	$\mathcal{U}(-0.05, 0.05)$
	σ_K	Intrinsic scatter of lensing/X-ray mass ratio	

"nuisance" parameters
- local gas depletion
- bias/scatter in total mass

MOR analysis of relaxed clusters

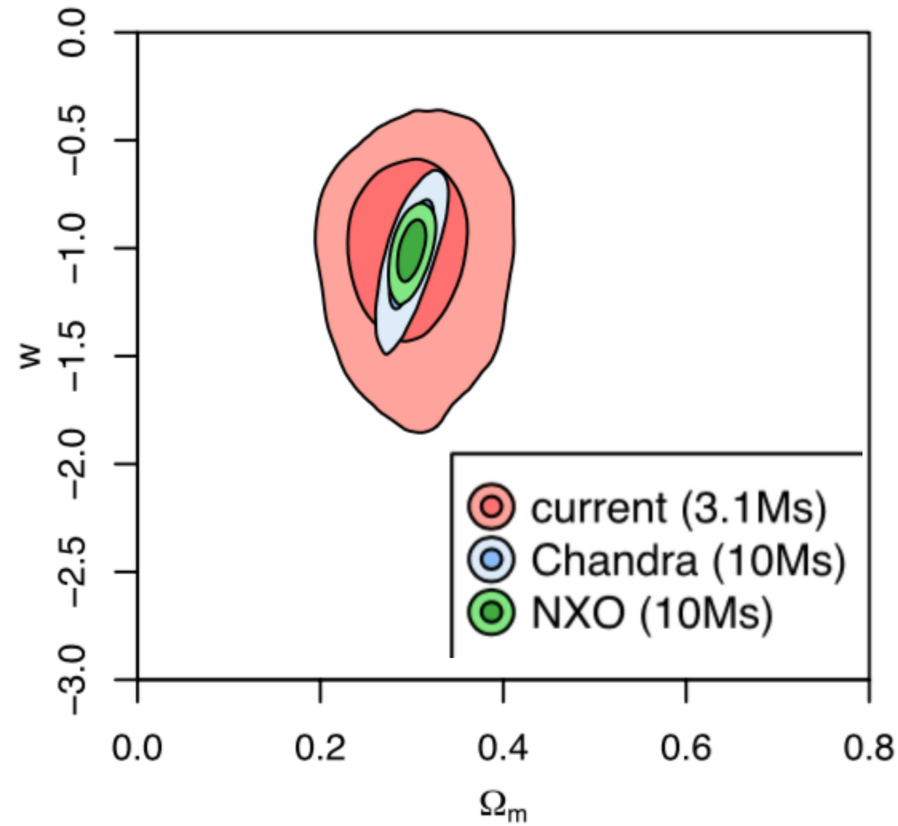
Mantz et al, 2014

– complementary with other methods for w-constraints



– forecast improvements

NXO = 400 clusters, 7.5% fgas error



opportunities II

- counts and clustering (canonical): wCDM GEOMETRY + GROWTH, D(z)

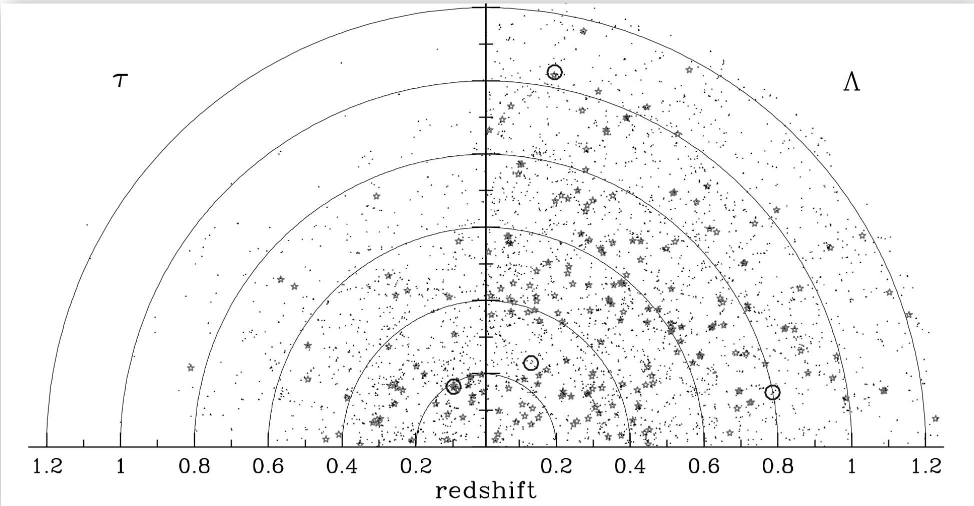
physical basis: The space density of massive halos is exponentially sensitive to cosmological parameters.

methodology:

– use sky surveys to find clusters via an observable, S, and determine redshifts, z

– employ mass function, dn/dlnM, and mass-observable relation (MOR), p(S | M,z), to constrain wCDM parameters

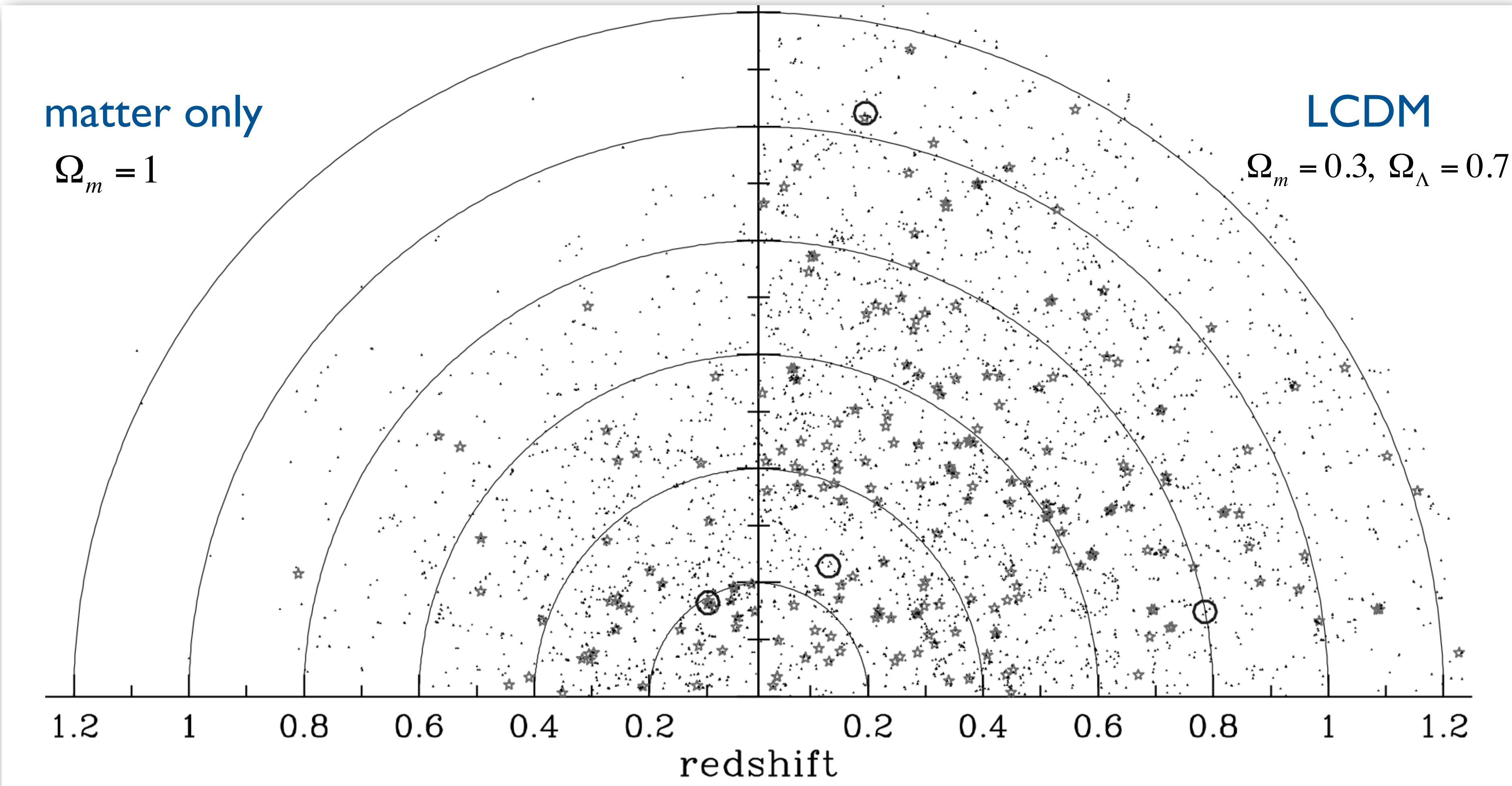
Opportunity: Apply to larger, deeper samples with **multi-wavelength** data



counting experiment version of cluster cosmology

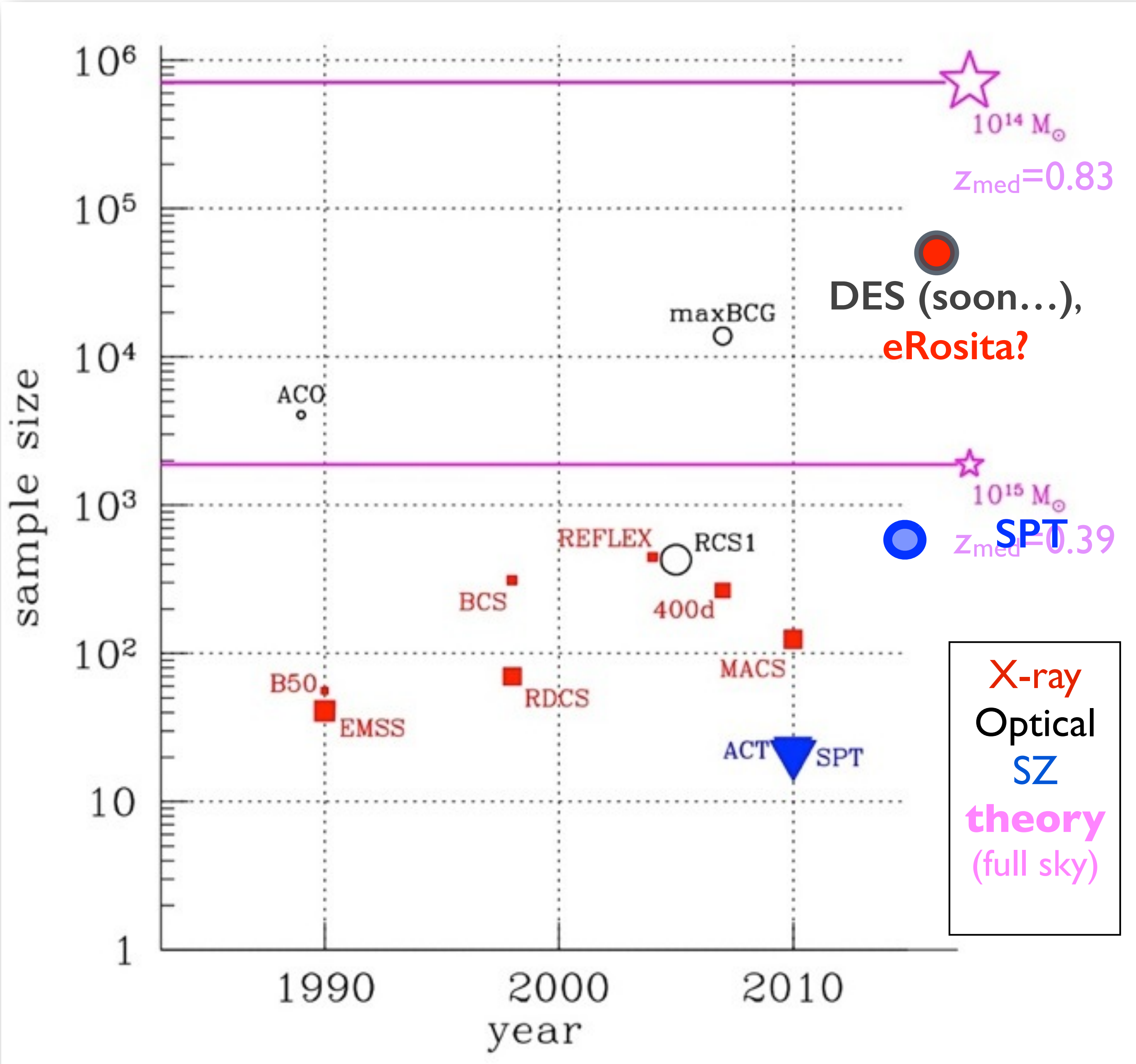
Evrard et al. (Virgo Consortium) 2002

- massive halos in lightcone outputs of Hubble Volume simulations (DM only)
  - symbols: log10(M) > 14 (dots), 14.5(stars), 15(circles)
  - virtual observer at bottom center of graphic (z=0)
  - P(k) amplitudes chosen to yield same "near field" population (z<0.2)



cluster surveys today sample small fraction of massive halos on the sky

Allen, Evrard & Mantz 2011, ARAA



Near-term experiments will discover most of the massive halo population.

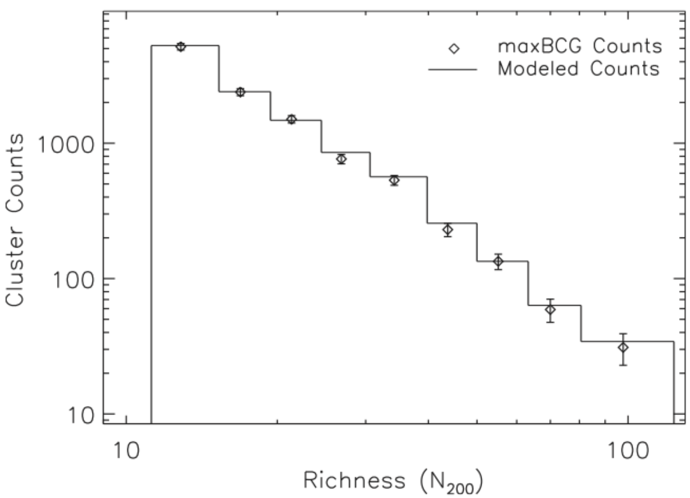
Next generation (Euclid, WFIRST, etc.) will be **universally** complete.

symbol size scales with median redshift

Halo mass scale is M_{200m} (h = 0.7)

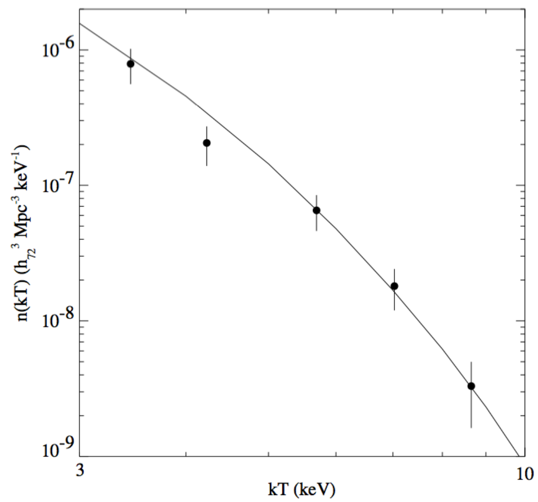
published results using optical, X-ray and SZ selection

– **systematic uncertainties** dominate cosmological parameter posteriors



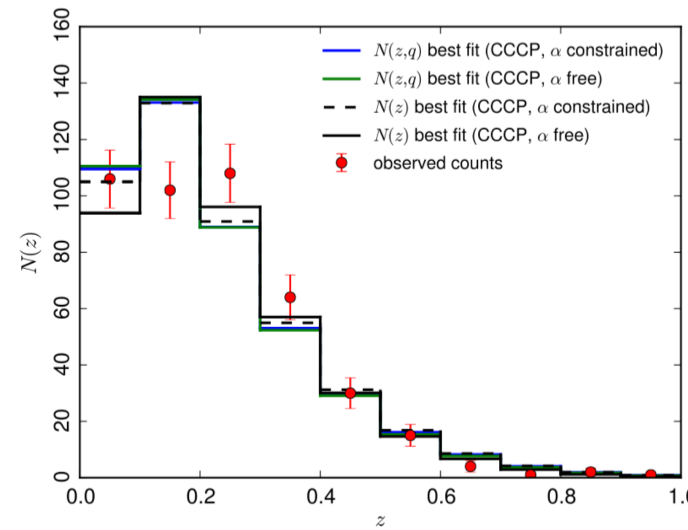
Rozo et al 2010; SDSS optical

~10,000 clusters



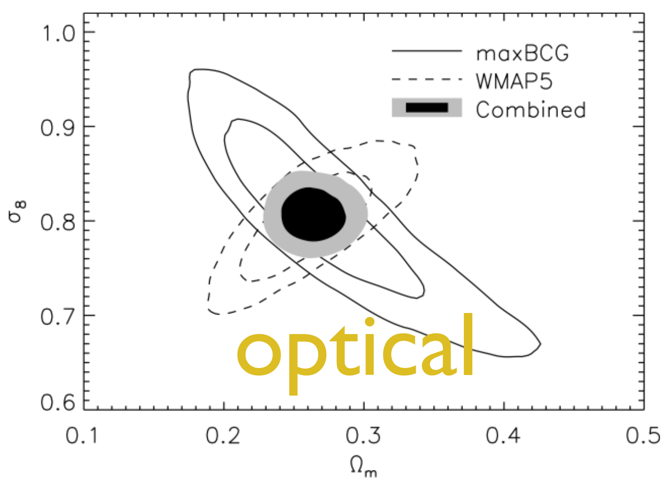
Henry et al 2009; Chandra

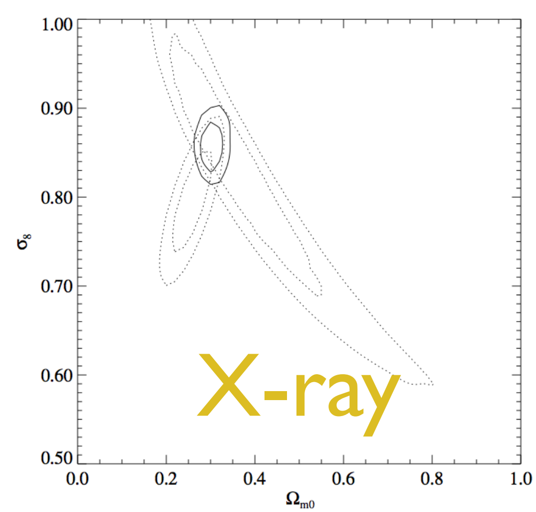
~50 clusters

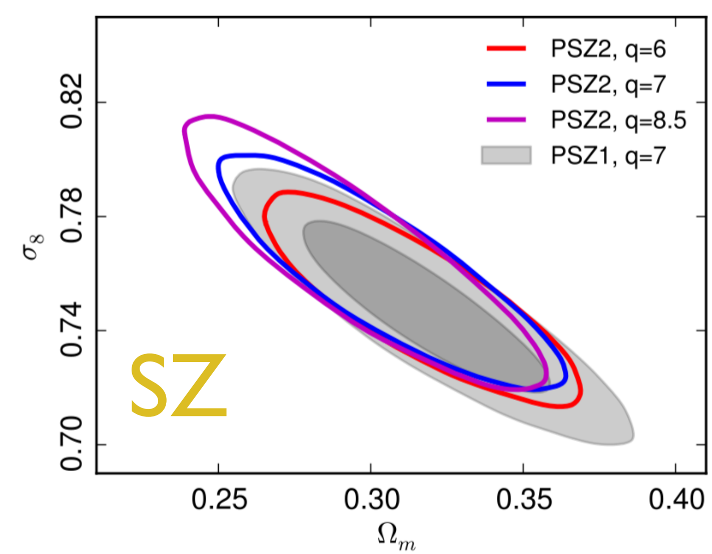


Planck XXIV, 2015

~450 clusters

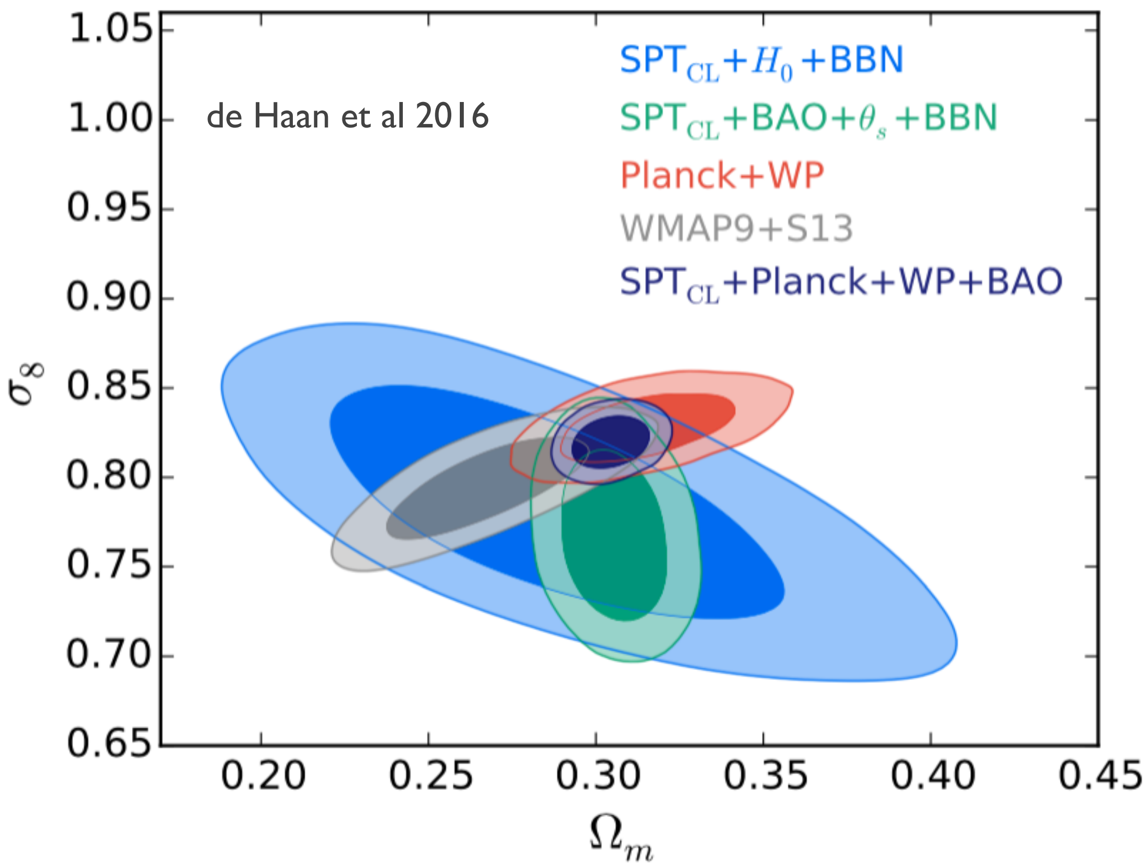






SPT 2016 results

– 377 clusters, z>0.25 (significance > 5)
– includes prior on Yx-M relation from WL analysis of X-ray sub-sample



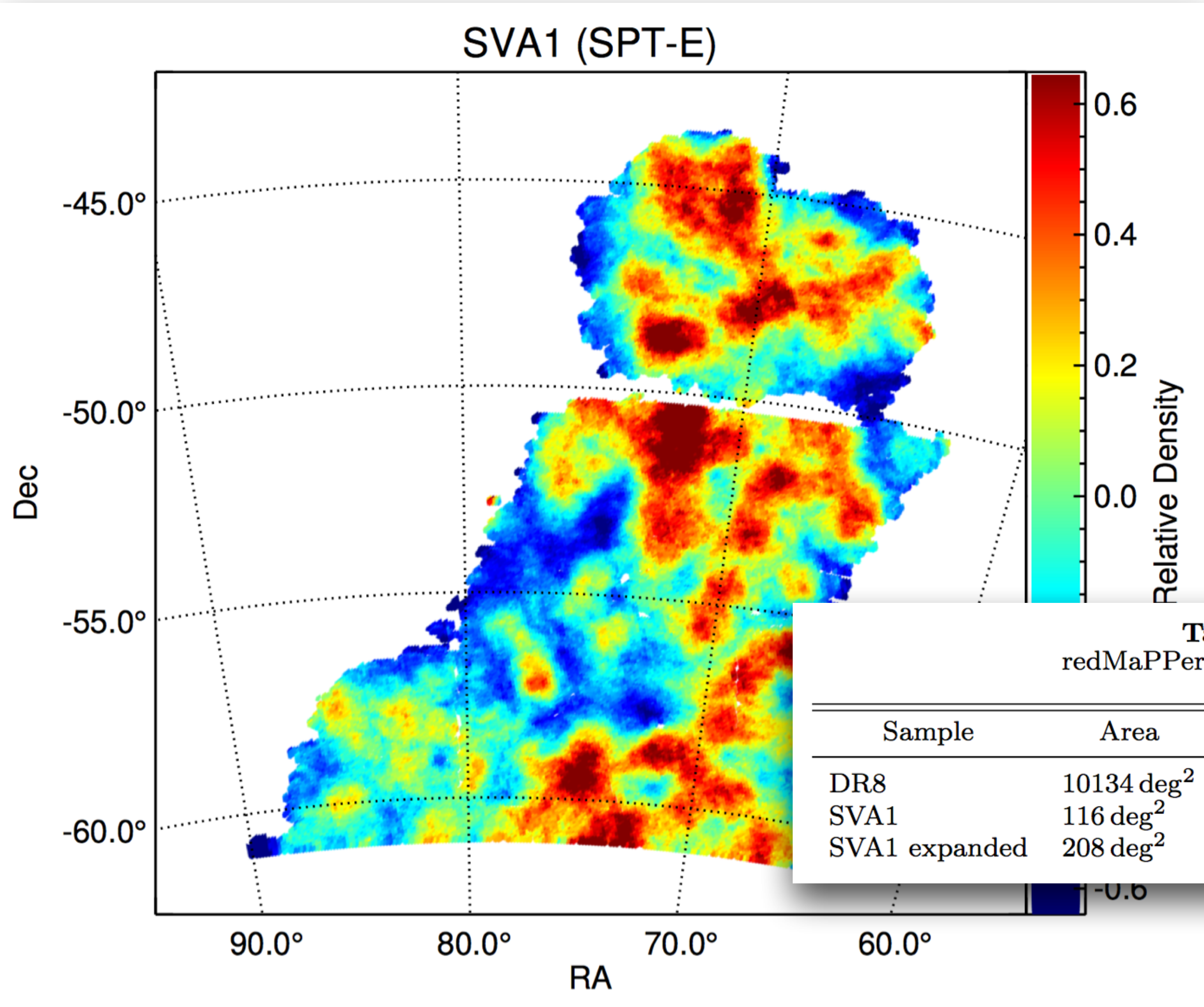
SPT + H0 + BBN result:

$$\sigma_8 = 0.784 \pm 0.039,$$
$$\Omega_m = 0.289 \pm 0.042,$$

$$\sigma_8 \left(\Omega_m/0.27\right)^{0.3} = 0.797 \pm 0.031.$$

DES redMaPPer SVA1 cluster sample

Rykoff, Rozo + DES, 2016



redMaPPer – a matched-filter likelihood method

small training set of spectroscopic redshifts sets the red sequence location

DES-SV samples

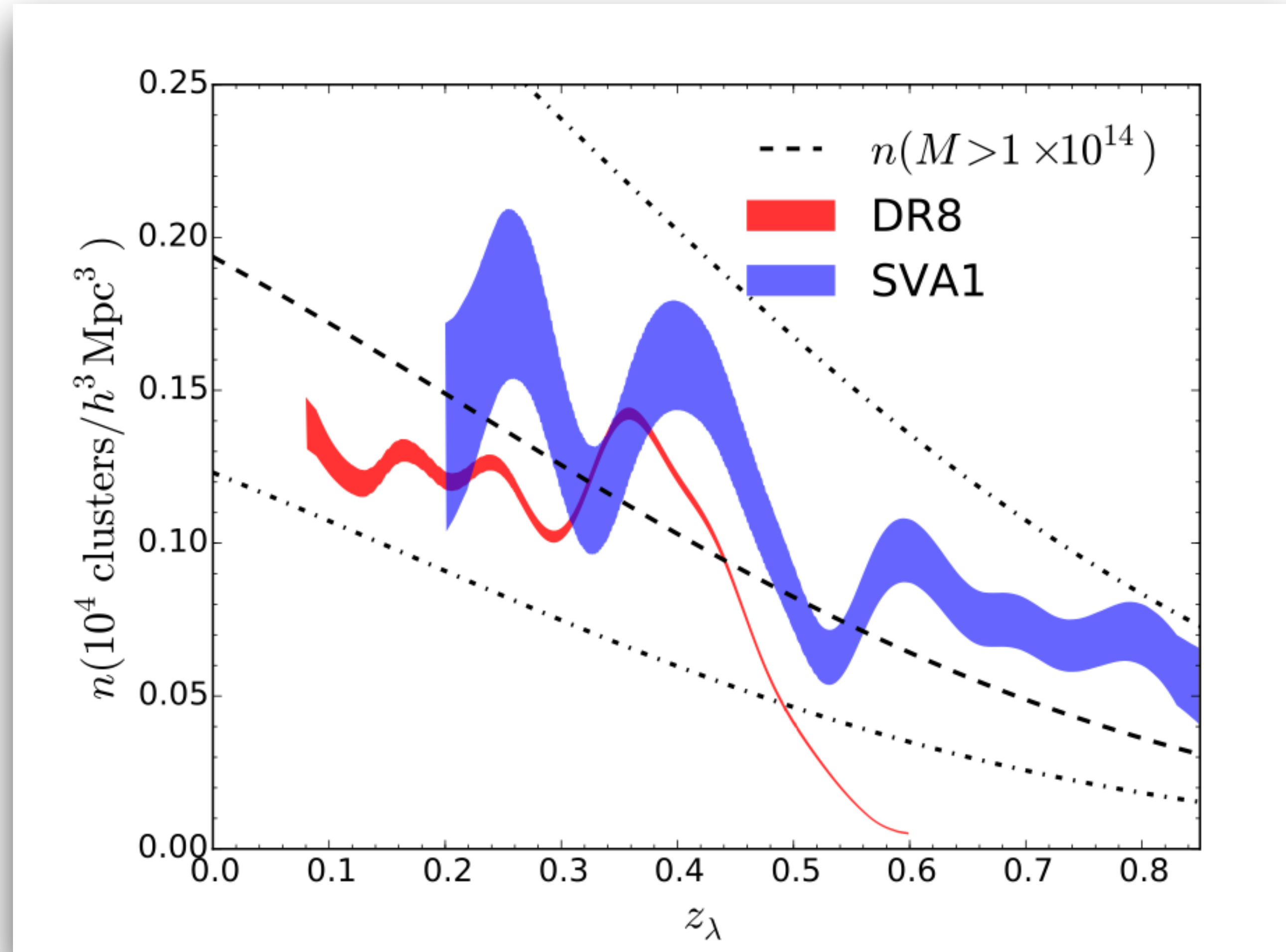
Table 1
redMaPPer Cluster Samples

Sample	Area	Redshift Range	No. of Clusters
DR8	10134 deg^2	$0.08 < z_\lambda < 0.6$	26308
SVA1	116 deg^2	$0.2 < z_\lambda < 0.9$	804
SVA1 expanded	208 deg^2	$0.2 < z_\lambda < 0.9$	1414

rogue's gallery of DES-SV clusters - *many more where these came from!*

redMaPPer: DES-SVA1 + SDSS-DR8 cluster number densities

Rykoff, Rozo + DES, 2016



clusters with λ>20

~follow the space density of 10^{14} Msun halos in LCDM cosmology

local variations from cosmic variance (DES 100 sq deg) and Malmquist bias in color space

opportunities III

- non-standard stuff

physical basis: Canonical model (GR, Gaussian fluctuations, …) is incomplete/ wrong

methodology:

– method depends on type of deviation being searched for…

Opportunity: Fame, glory, and maybe…

Challenges

challenges : observations + data modelling

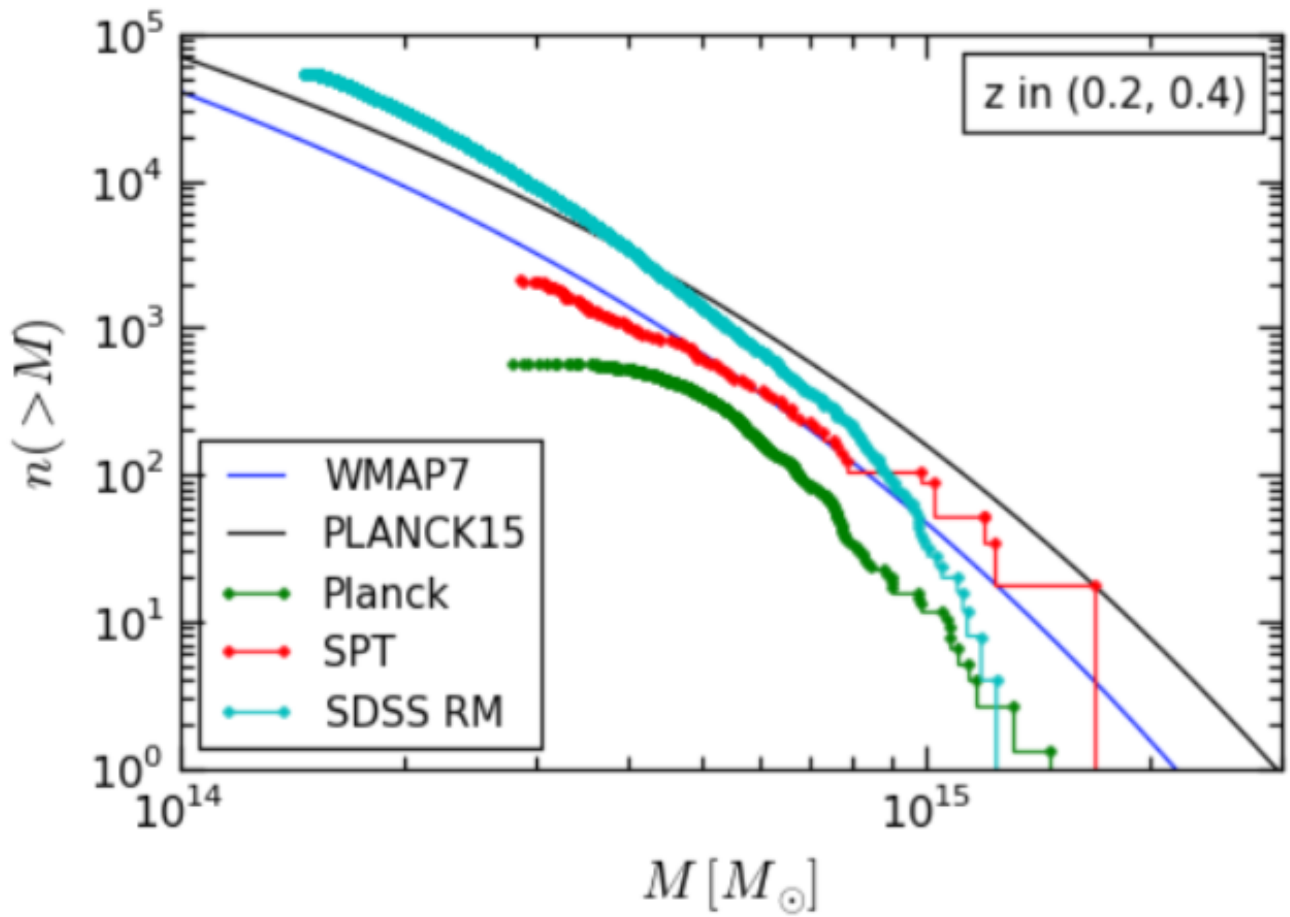
- assembling the evidence
  - characterising and evaluating sample selection functions
  - obtaining group/cluster redshifts
  - data quality (angular resolution, S/N, …)

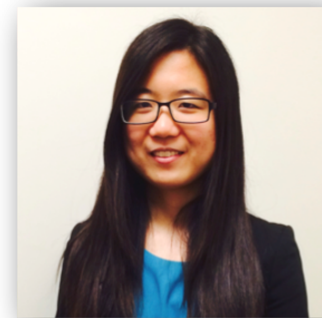
- one cluster ≠ one halo
  - projection effects
  - mis-centering / sharding / blending of extended objects
    - R200 areas of M>1e14 Msun clusters cover ~10% of sky

- total system mass on an absolute scale
  - modelling framework given that one cluster ≠ one halo

surveys must ultimately find the same high-mass halos

current SZ and optical surveys don't "abundance match" in mass





Xinyi Chen (Michigan)

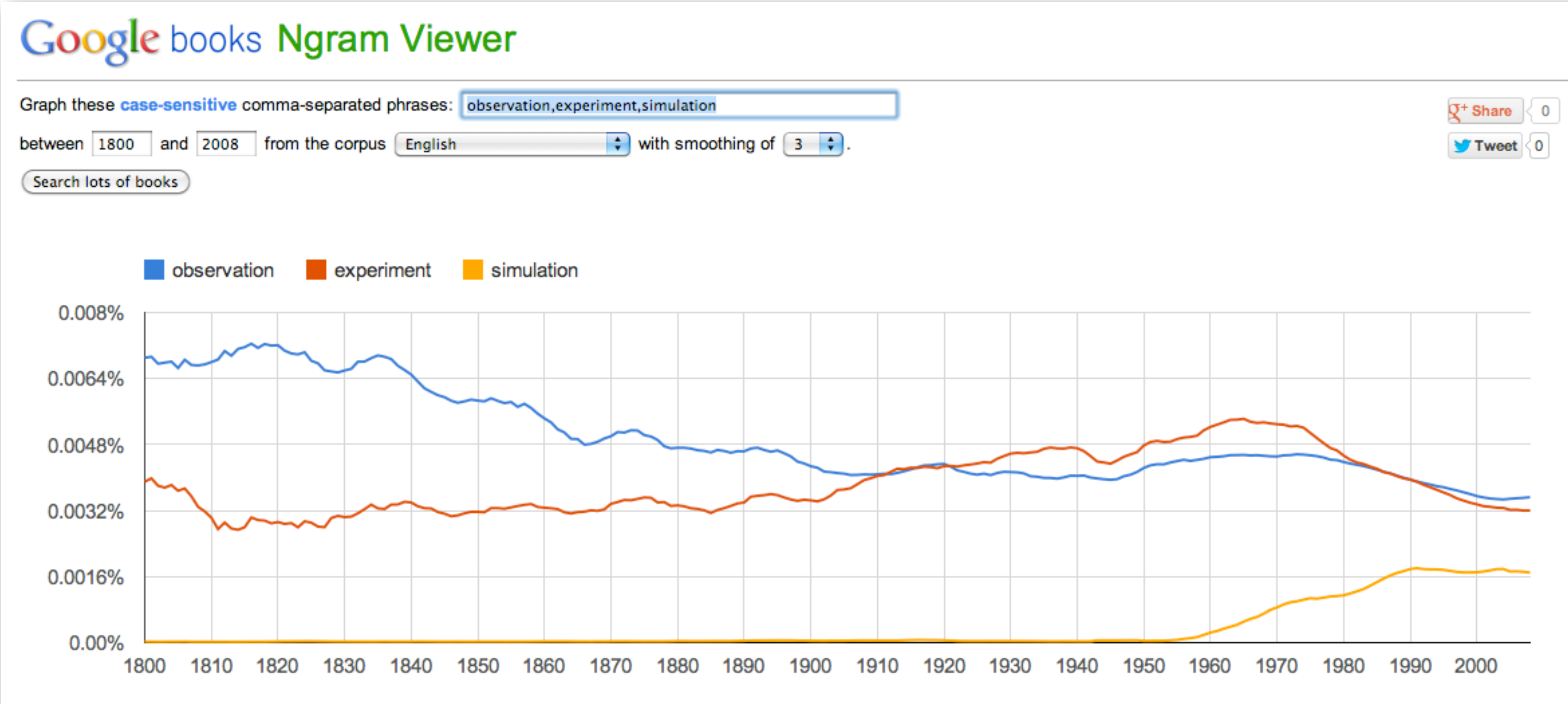
now Yale graduate school

challenges : simulation + theory

- halos manifest the strongly non-linear regime of large-scale cosmic structure
  - unlike CMB or BAO, linear theory does not apply :-(
  - must do expensive numerical simulations :-) :-/

- forward modelling the (massive) halo population
  - space density (mass function) of halos as a function of M,z
  - internal composition and structure => MORs, Pr(**S** | M,z)
  - solving (or at least mitigating) the galaxy formation bottleneck

challenges IV : cultural evolution

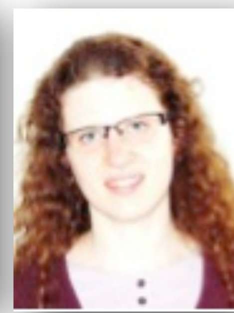


Relative to observation and experiment, simulation is in an adolescent phase.

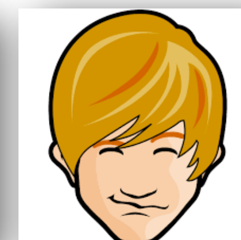
Mass-Observable Relations (MORs) and Property Covariance:

BAHAMAS+MACSIS simulations

Arya Farahi (Michigan)



Ian McCarthy (LJMU) +
Amandine Le Brun (Saclay)
Bahamas



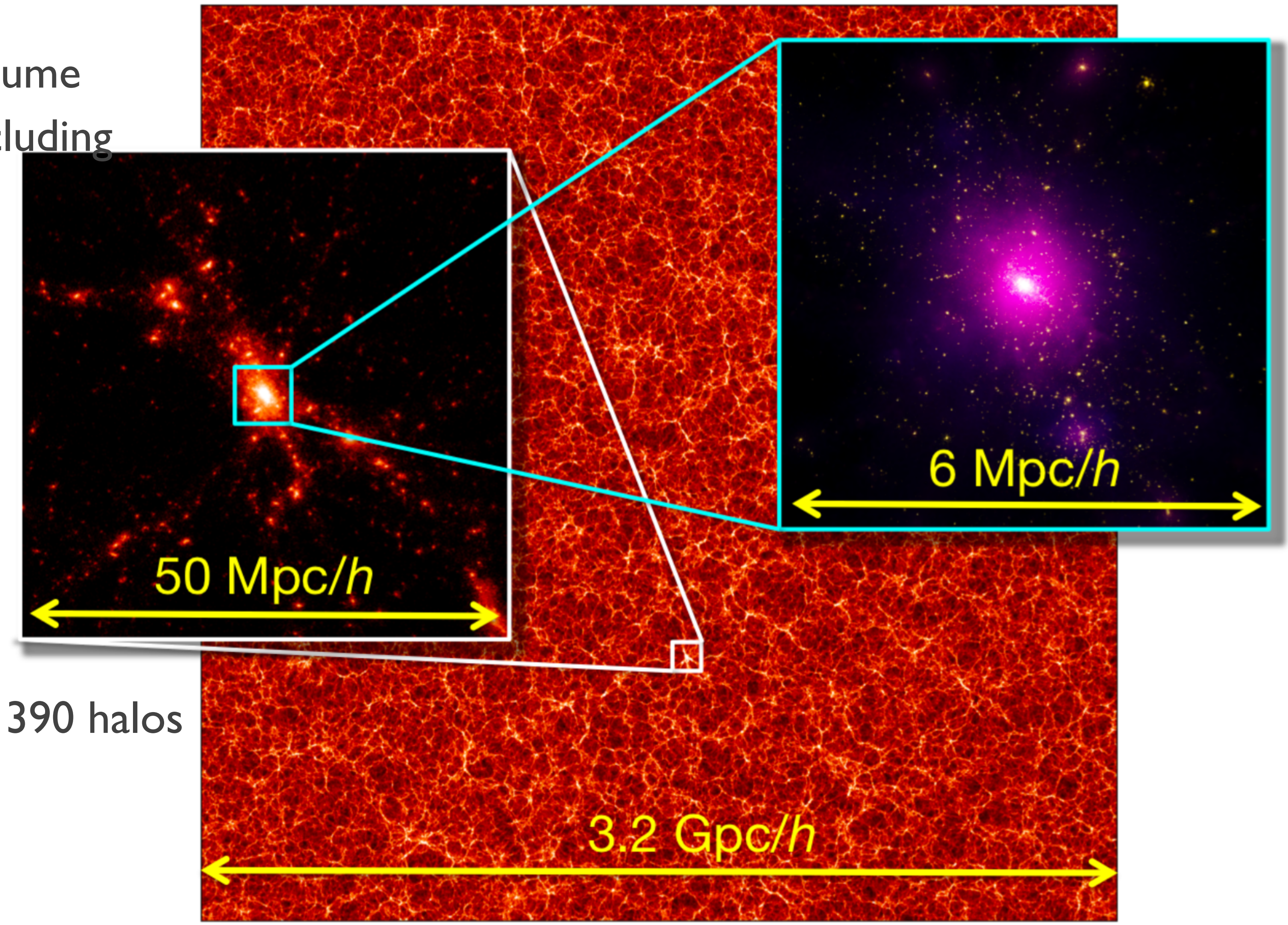
Scott Kay + David Barnes
(Manchester)
MACSIS

BAHAMAS + MACSIS simulations w/ AGN feedback

McCarthy et al 2016
Barnes et al 2016

<u>BAHAMAS</u>

– 400 Mpc full volume
– "full physics" including AGN feedback



<u>MACSIS</u>

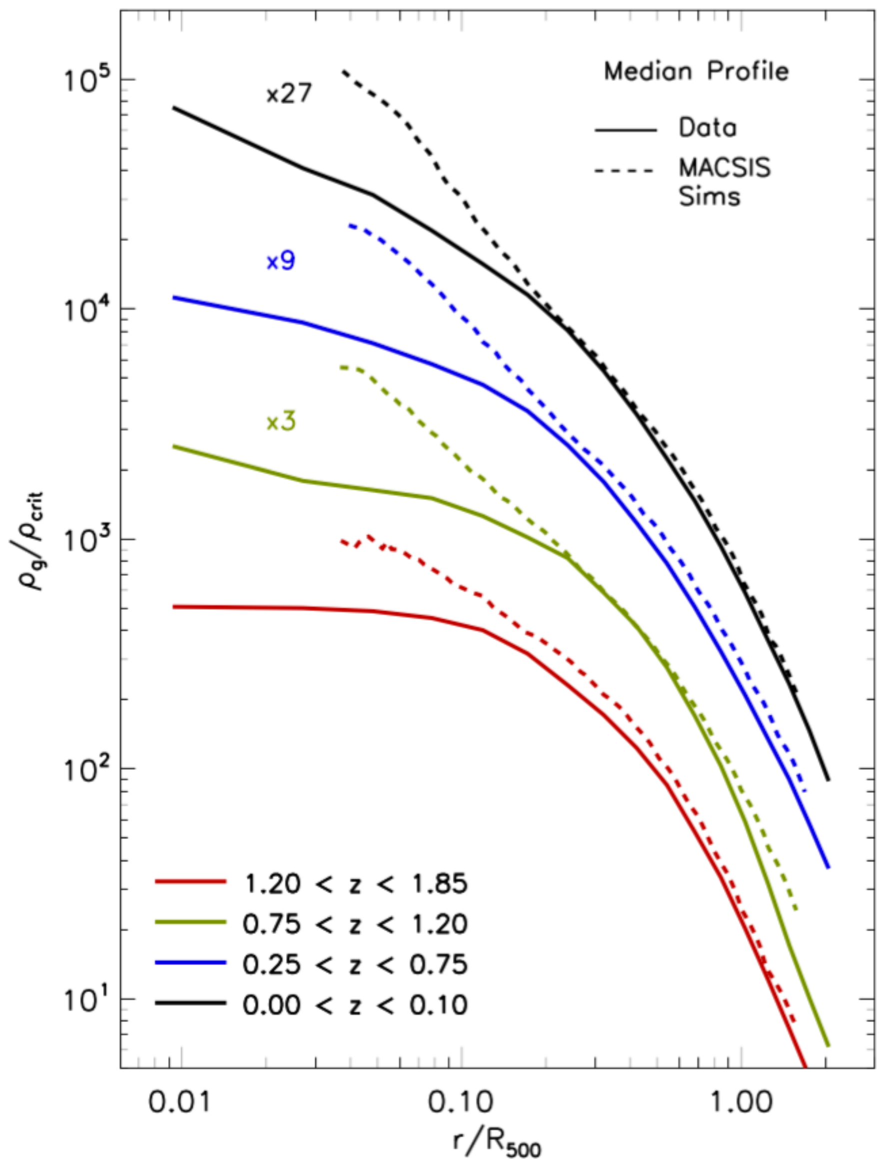
– zoom resims of 390 halos
– same physics as BAHAMAS

BAHAMAS + MACSIS simulations w/ AGN feedback

McDonald et al, 2017

– reasonable match to observed SPT gas profiles outside the core

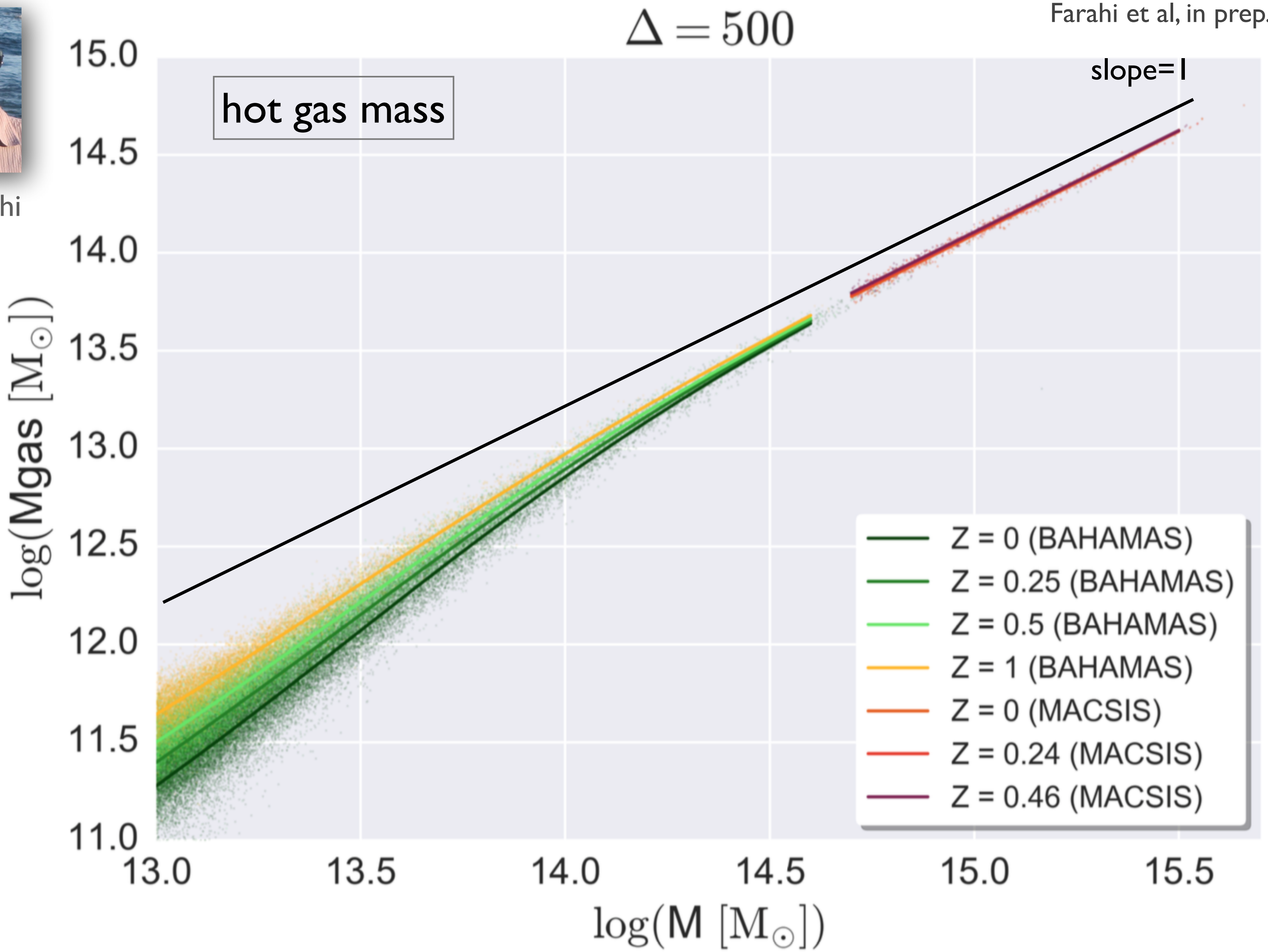
NOT a sim. design requirement!



Bahamas + MACSIS simulations w/ AGN feedback

McCarthy et al 2016
Barnes et al 2016

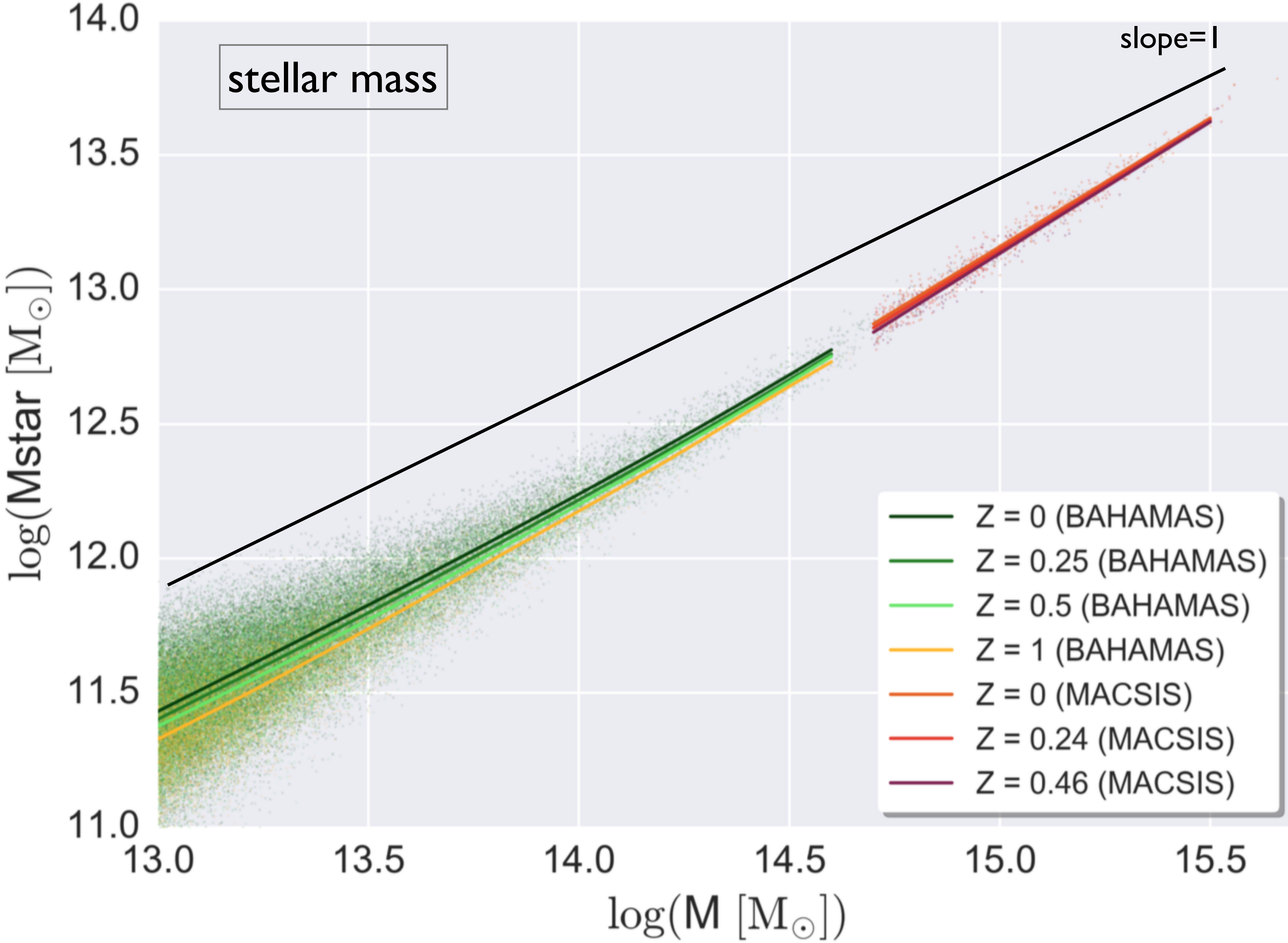

Arya Farahi



Bahamas + MACSIS simulations w/ AGN feedback

McCarthy et al 2016
Barnes et al 2016

Farahi et al, in prep.

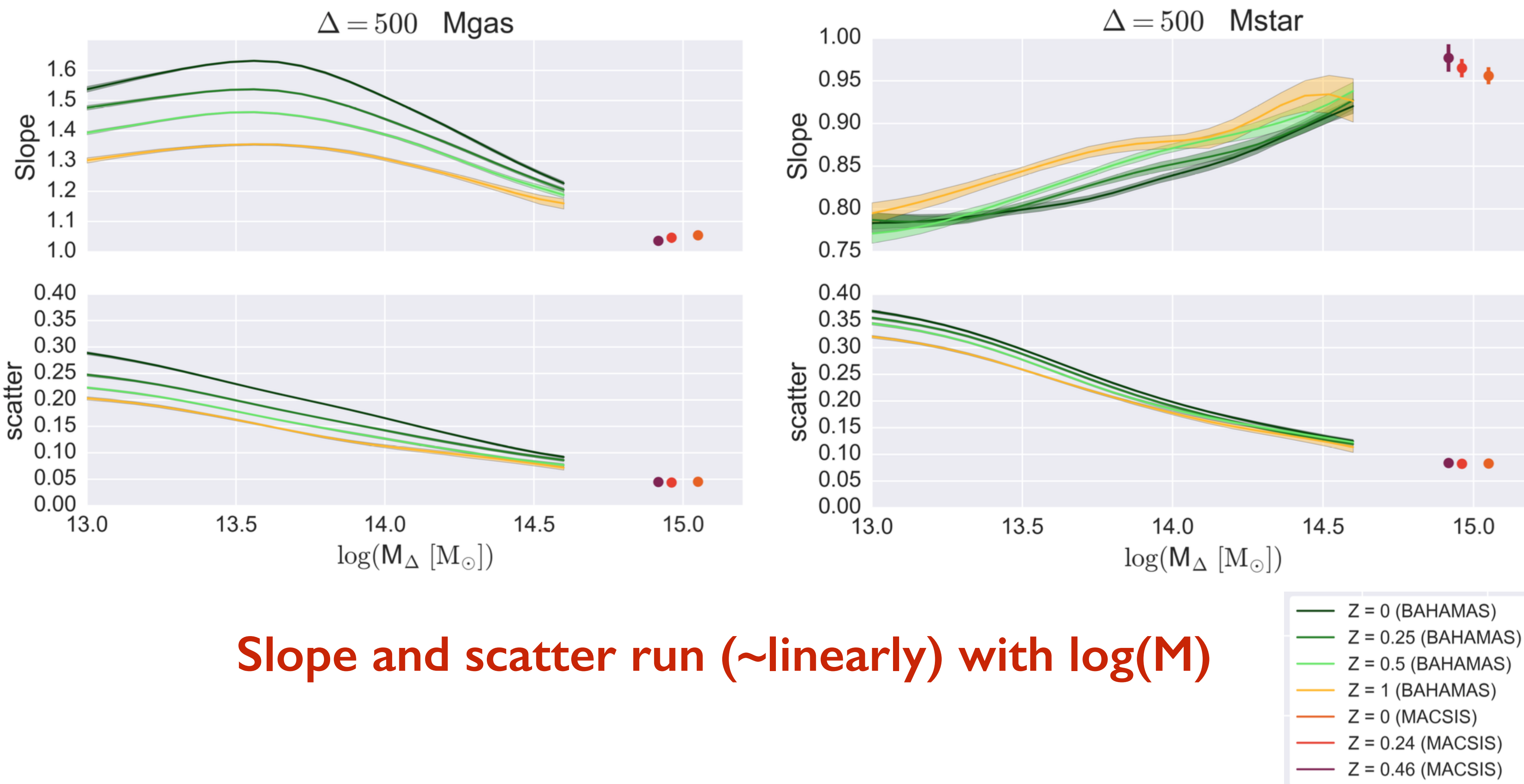


Bahamas + MACSIS simulations w/ AGN feedback

McCarthy et al 2016
Barnes et al 2016

Farahi et al, in prep.

localized, linear regression (0.2 dex gaussian in halo mass)



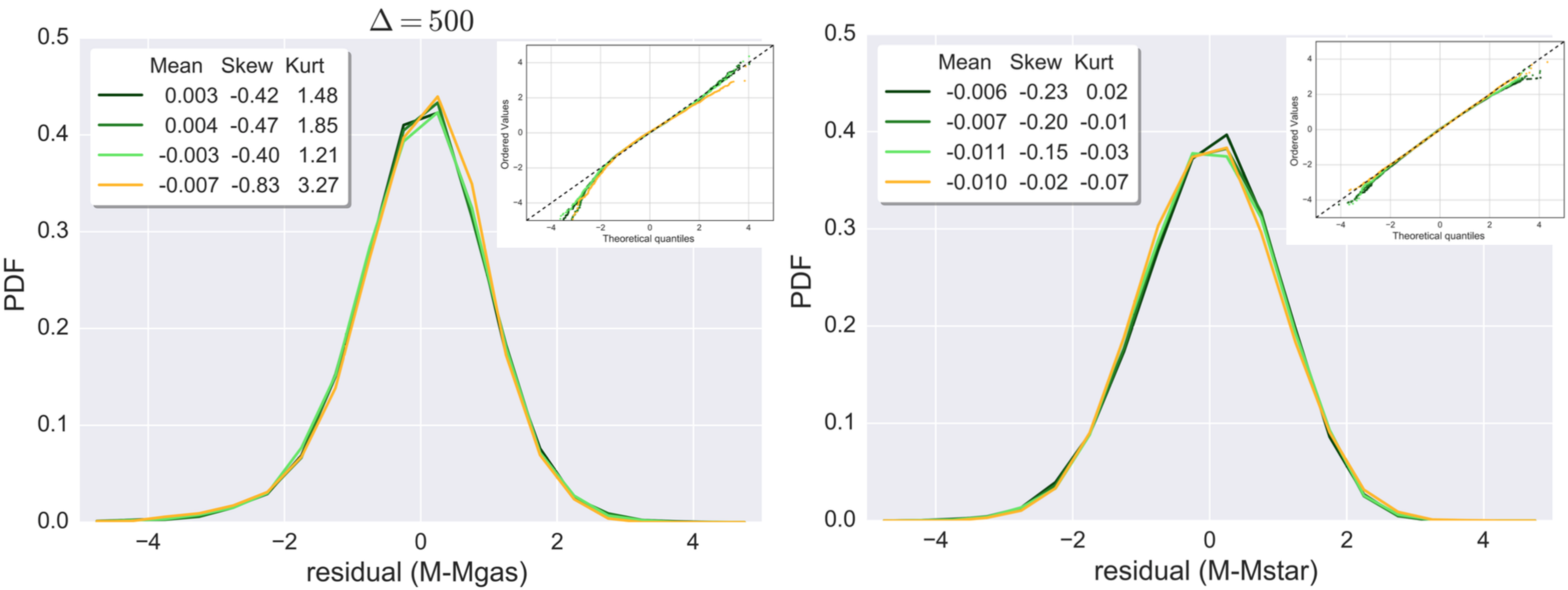
Slope and scatter run (~linearly) with log(M)

Bahamas + MACSIS simulations w/ AGN feedback

McCarthy et al 2016
Barnes et al 2016

Farahi et al, in prep.

log-normal PDFs of properties around their means



~60,000 halos !

Bahamas + MACSIS simulations w/ AGN feedback

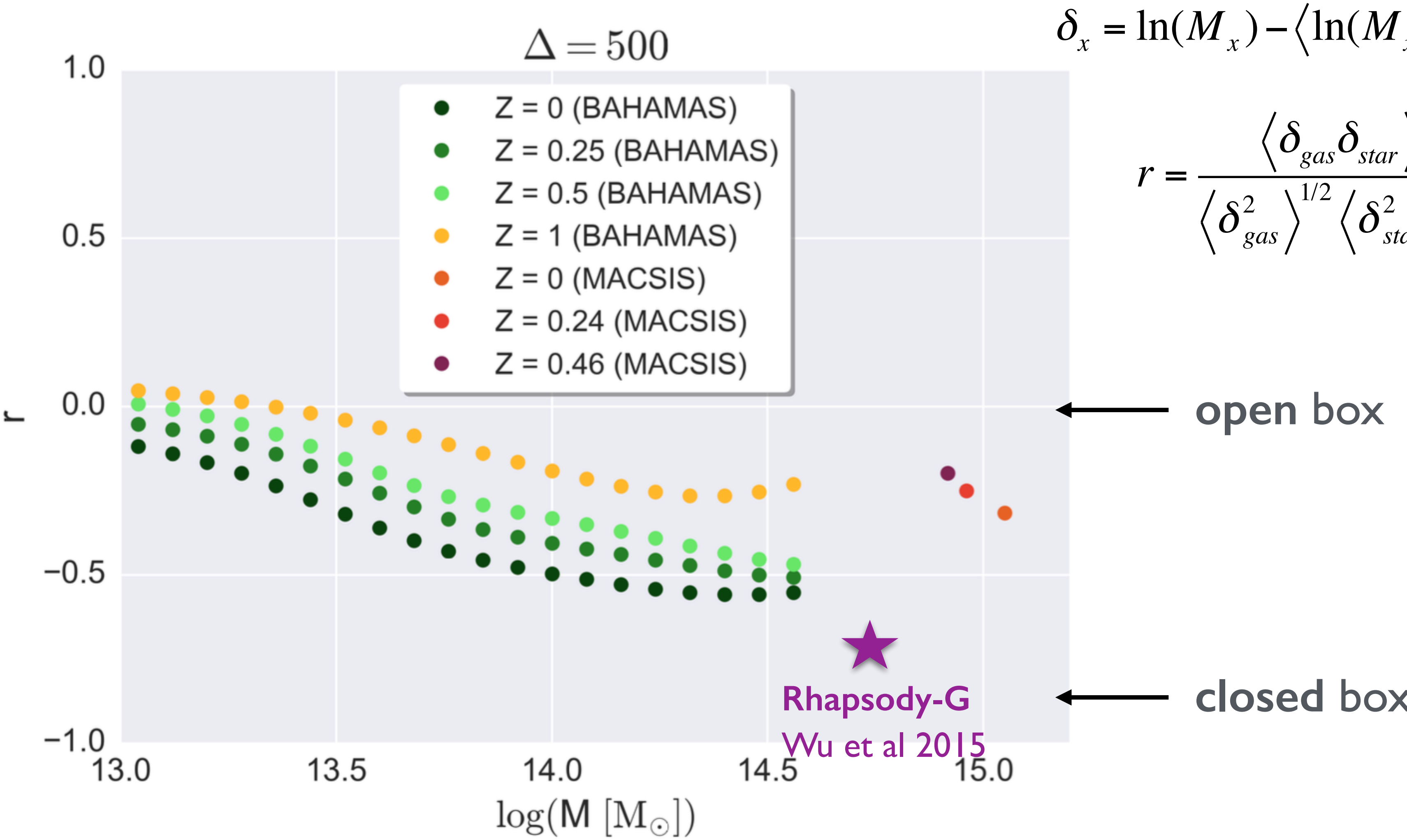
McCarthy et al 2016
Barnes et al 2016

Farahi et al, in prep.

covariance of hot gas + stellar mass at *fixed halo mass*

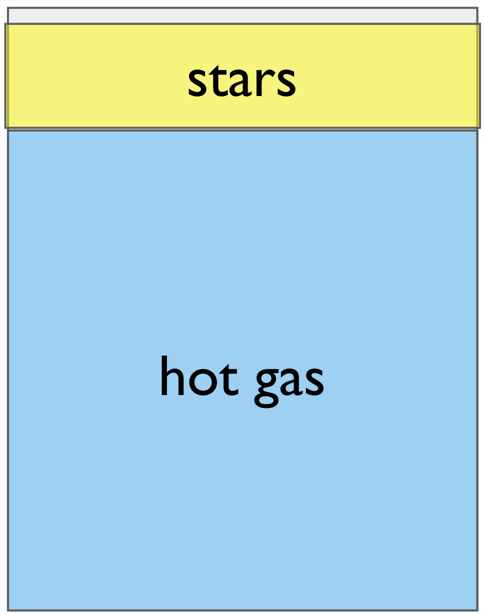
$$\delta_x = \ln(M_x) - \langle \ln(M_x) \mid M_{500} \rangle$$

$$r = \frac{\langle \delta_{gas}\delta_{star} \rangle}{\langle \delta_{gas}^2 \rangle^{1/2} \langle \delta_{star}^2 \rangle^{1/2}}$$



should cold and hot mass fractions anti-correlate in halos?

$$f_{\text{gas}} + f_{\text{star}} \cong C (= \Omega_b / \Omega_m)$$
$$\Rightarrow \delta f_{\text{gas}} \cong -\delta f_{\text{star}}$$



"closed box"

$$f_{\text{gas}} + f_{\text{star}} \cong f_{\text{retain}} C$$
$$\Rightarrow \delta f_{\text{gas}} + \delta f_{\text{star}} = \delta f_{\text{retain}}$$

"open box"

recent comparison of different “full physics” numerical methods (single halo)

Sembolini et al 2016

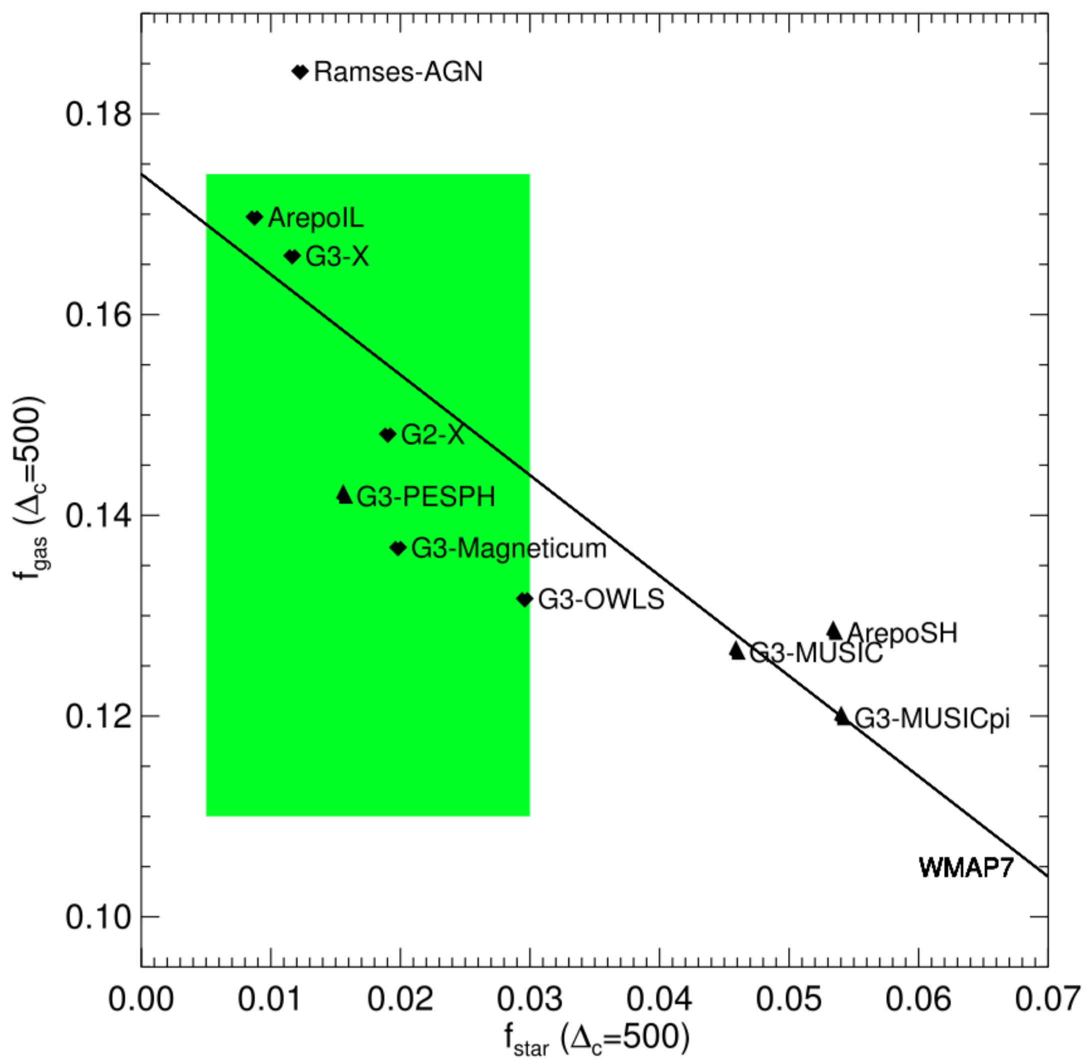


Figure 1. Values of $f_{\rm gas}$ and $f_{\rm star}$ as calculated at $\Delta_c = 500$ for the different codes. The green area corresponds to the phase space supported by observations. Codes including AGN feedback are represented as diamonds, codes not including AGN feedback as triangles. The diagonal line shows the relation $f_{\rm gas}+f_{\rm star} = 0.174$, the value of the cosmic ratio according to *WMAP7*.

collective behaviour of multiple codes follows a simple “closed box” expectation

High mass halos are cosmic baryon reservoirs!

White et al. 1993

Q. for the 300:

Is the *form* of the halo property covariance PDF consistent among the sims?

And is that form log-normal?

How does gas-stellar covariance run with mass?

Mass-Observable Relations (MORs) and Property Covariance:

LoCuSS Sample Analysis

Arya Farahi (Michigan)

Sarah Mulroy + Graham Smith (Birmingham)
LoCuSS

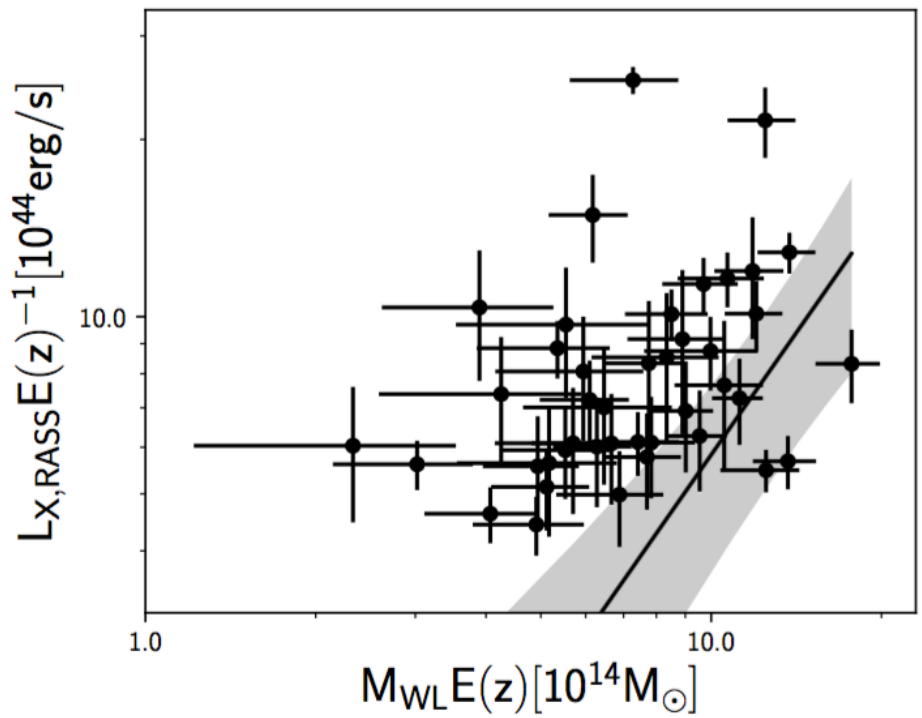
LoCuSS: 42 (RASS-selected) clusters w/ multi-wavelength follow-up

Mulroy, Smith, Farahi et al, in prep.

Lx RASS selected (1990's BCS+)

high quality follow-up data:

- Subaru weak lensing
- Chandra, XMM imaging + spectra
- multi-band galaxy photometry
- Planck Ysz
- (some) spectroscopy



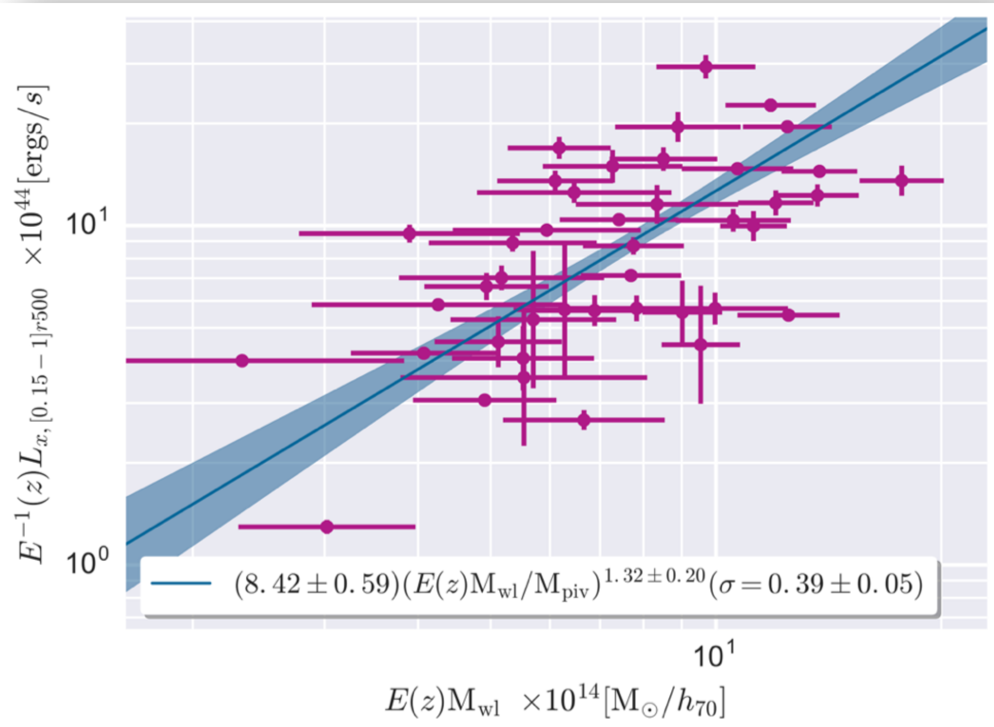
fit to likelihood model with:

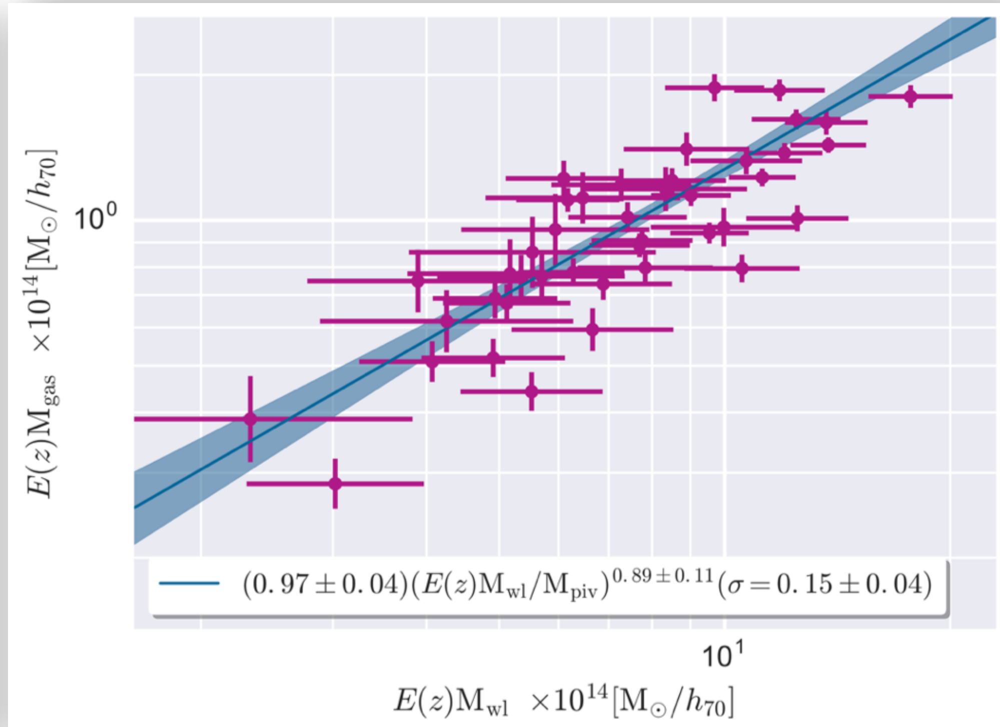
- LxRASS selection
- halo population model with
  - mass function prior
  - power-law mean scaling
  - log-normal property covariance at fixed halo mass

LoCuSS: 42 (RASS-selected) clusters w/ multi-wavelength follow-up

Mulroy, Smith, Farahi et al, in prep.

Hot gas – weak lensing mass relations





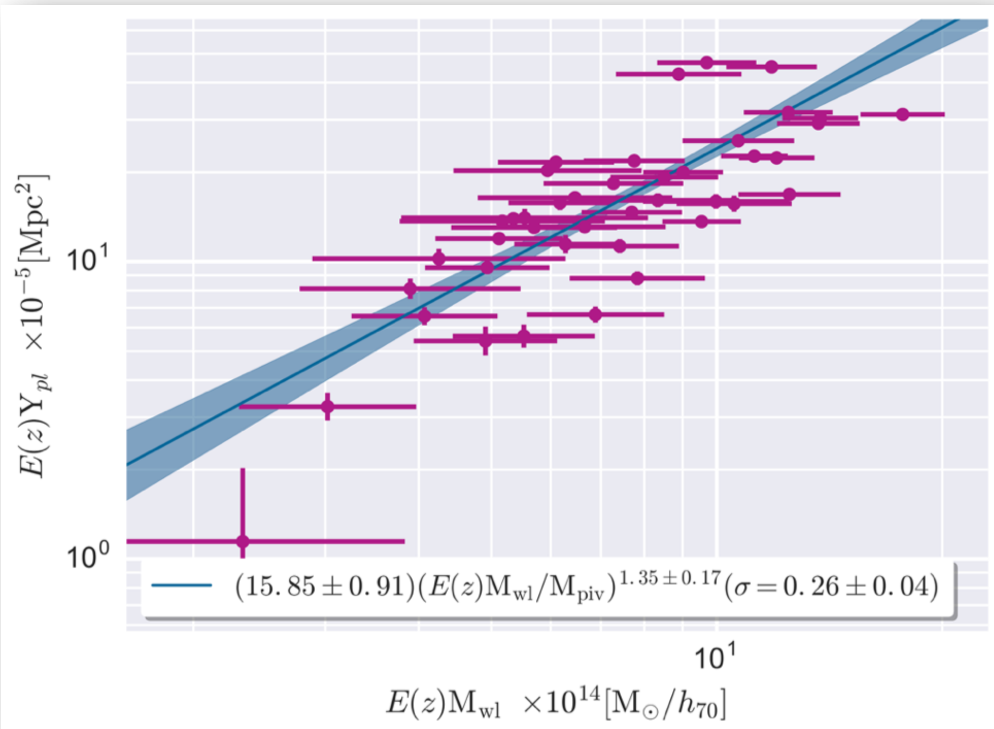
Lx : slope 1.32 ± 0.20
scatter 0.39 ± 0.05

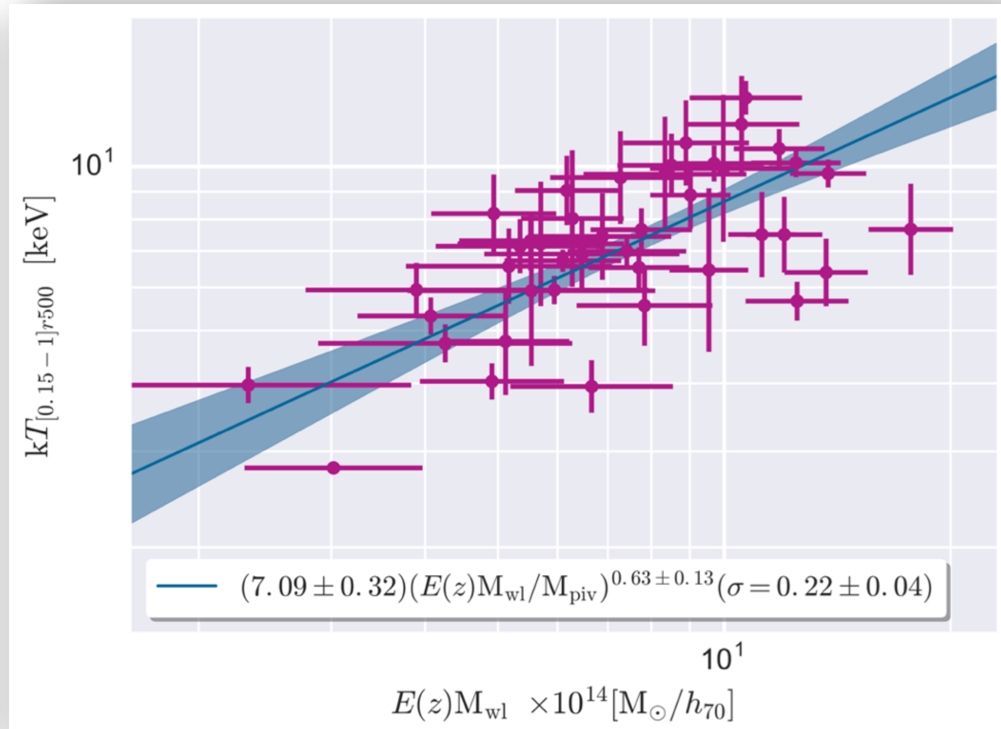
Mgas : slope 0.89 ± 0.11
scatter 0.15 ± 0.04

LoCuSS: 42 (RASS-selected) clusters w/ multi-wavelength follow-up

Mulroy, Farahi et al, in prep.

Hot gas – weak lensing mass relations





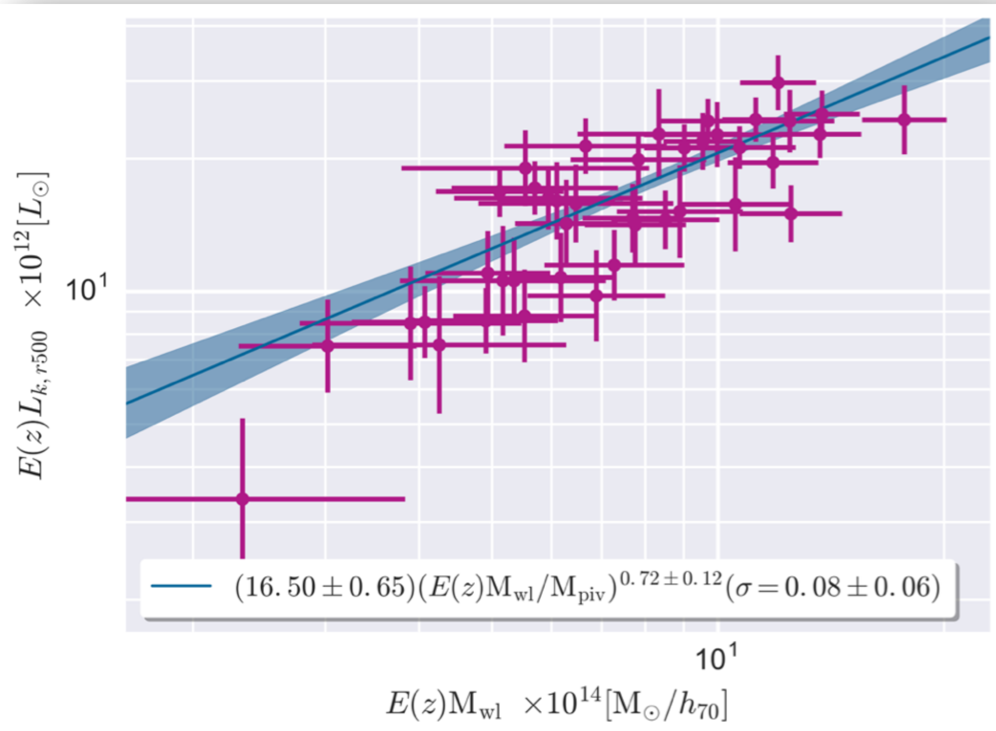
Ypl : slope 1.35 ± 0.17
scatter 0.26 ± 0.04

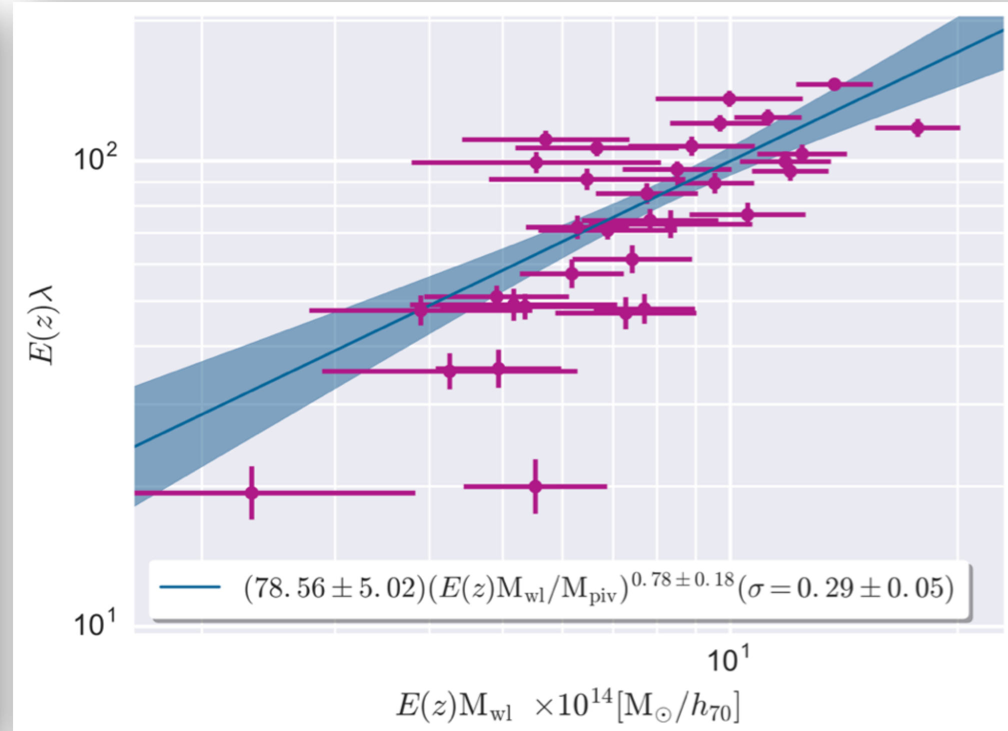
kT : slope 0.63 ± 0.13
scatter 0.22 ± 0.04

LoCuSS: 42 (RASS-selected) clusters w/ multi-wavelength follow-up

Mulroy, Farahi et al, in prep.

Galaxy – weak lensing mass relations





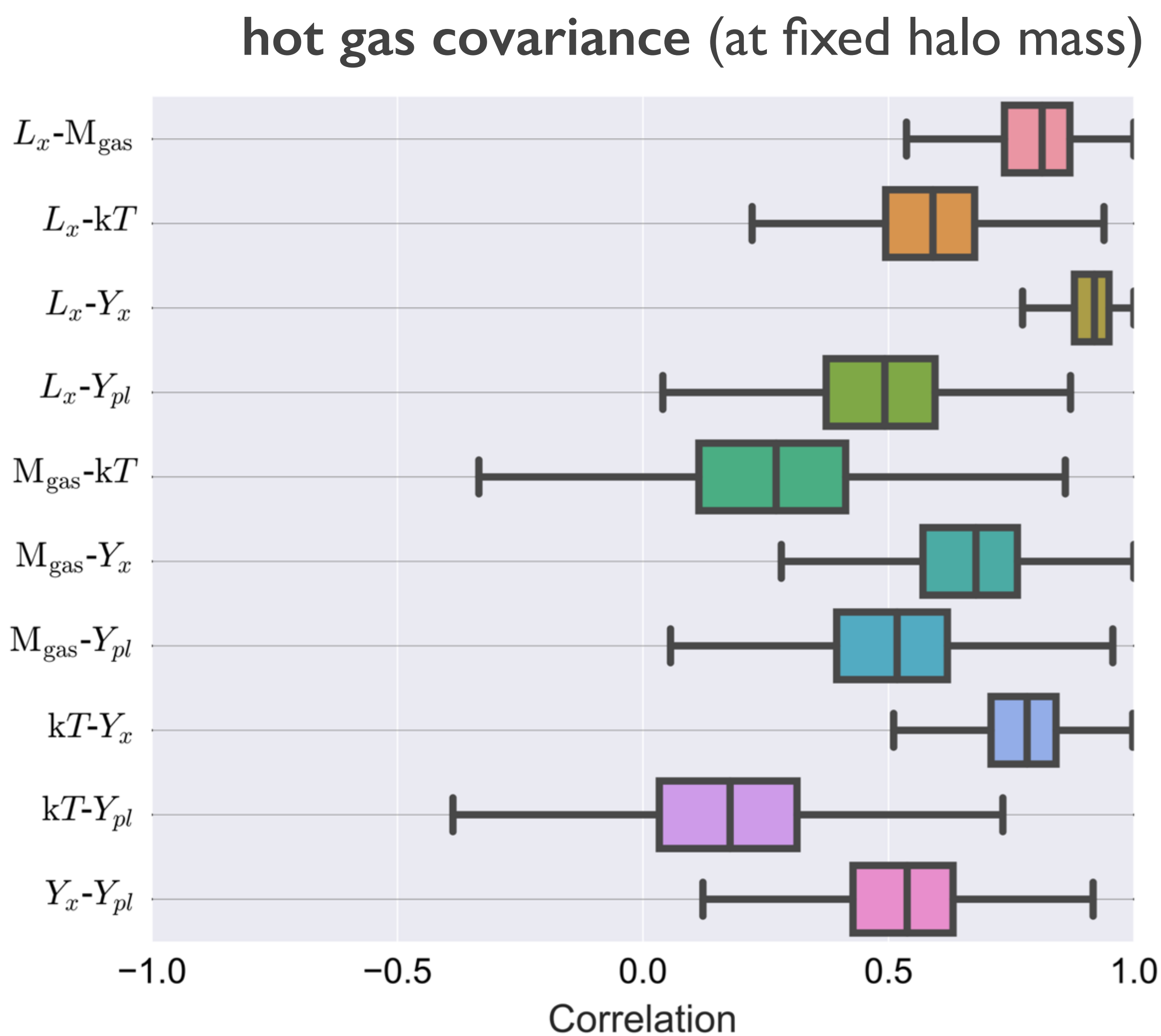
Lk : slope 0.72 ± 0.12
scatter 0.08 ± 0.06

λ : slope 0.78 ± 0.18
scatter 0.29 ± 0.05

see Mulroy et al (2014)

off-diagonal correlation coefficients

Mulroy, Farahi et al, in prep.

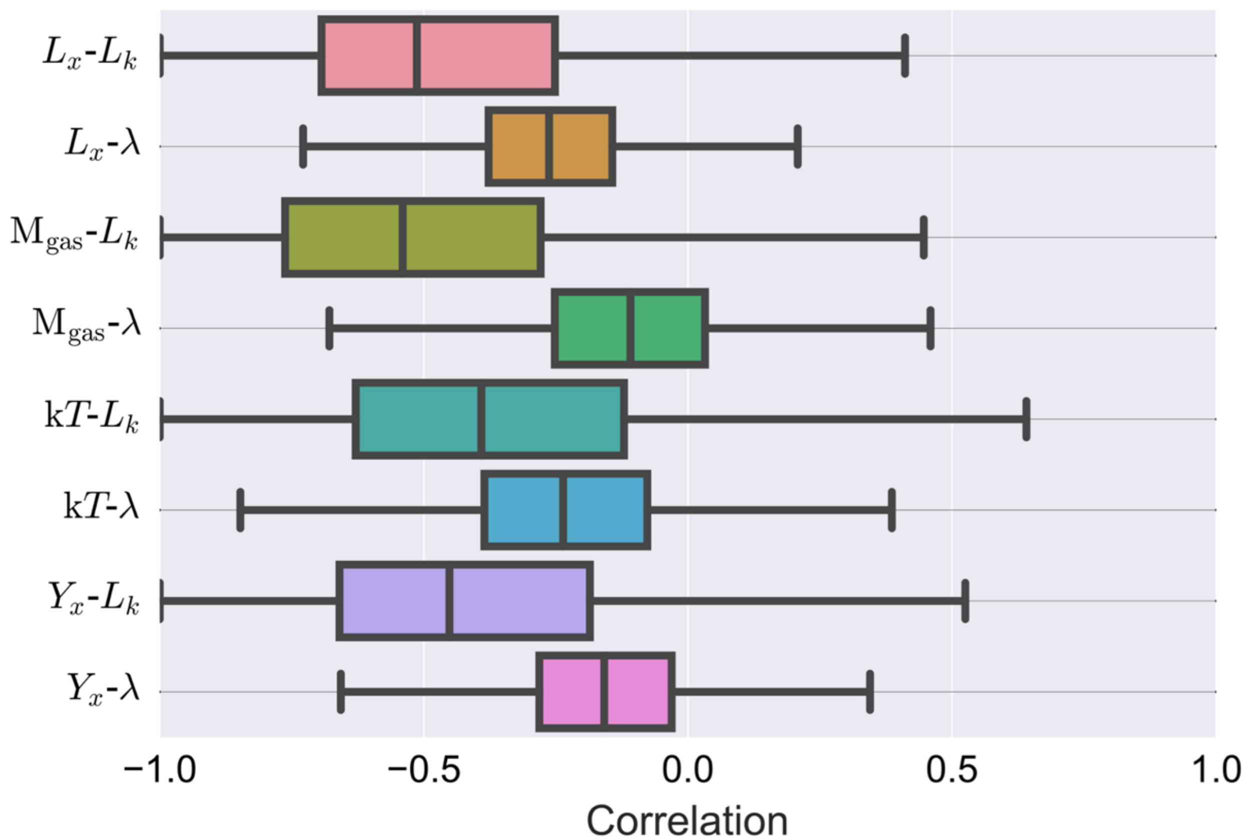


mostly positive correlations (see Mantz et al 2016)

off-diagonal correlation coefficients

Mulroy, Farahi et al, in prep.

hot gas – galaxy covariance (at fixed halo mass)

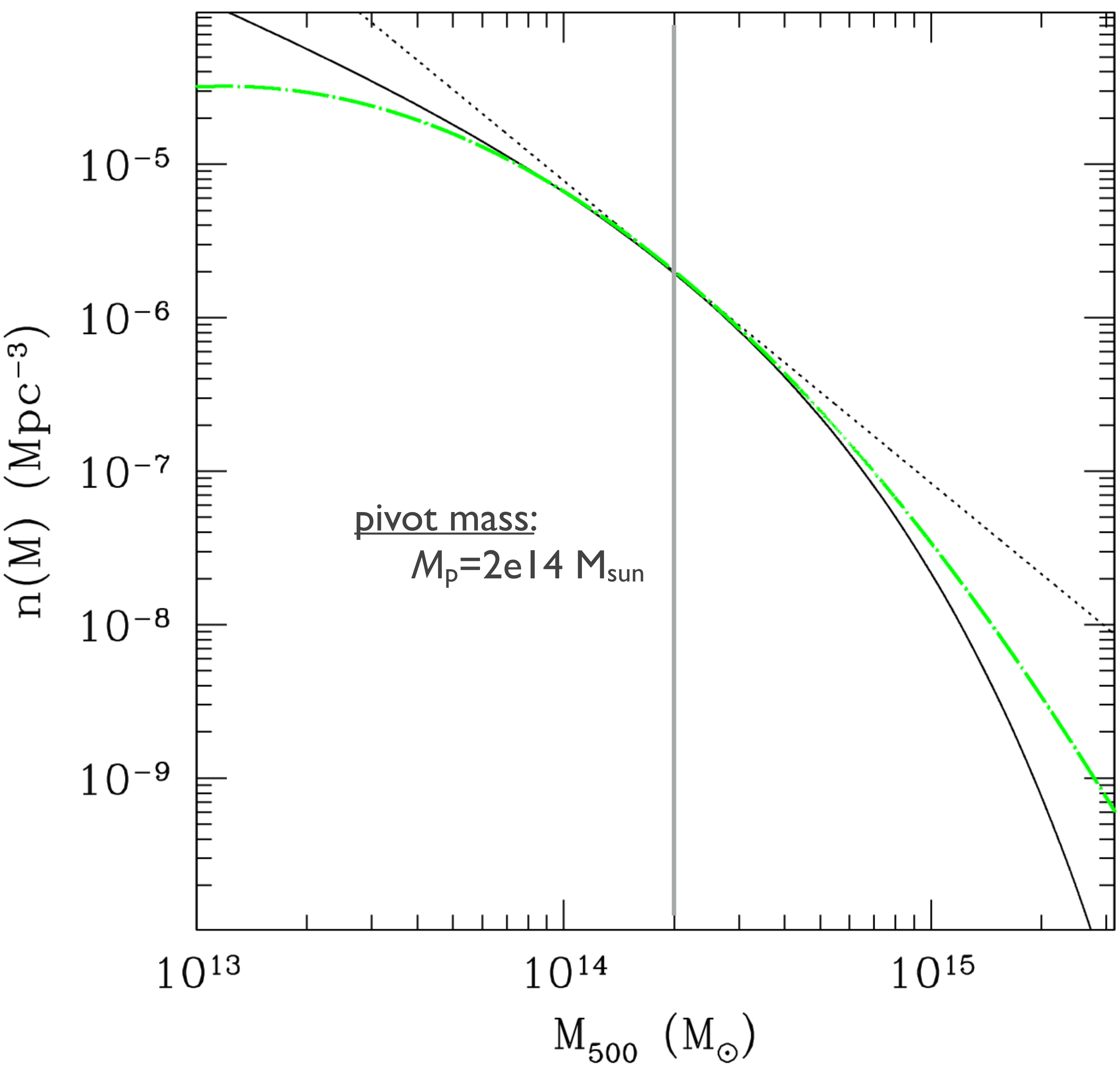


preliminary evidence for **anti-correlation** of hot and cold phase baryons

supports ~closed box baryonic nature of high mass halos predicted by simulations

local mass function shape is **~polynomial** in log

Evrard et al 2014



$$\log(n_1(M)) = \log(A) - \beta_1 \log(M/M_p) - \beta_2/2\,(\log(M/M_p))^2$$

Tinker MF (z=0.2)

~local **quadratic** (running power-law)

convolution with log-normal MOR PDF has ANALYTIC form

compactifying the notation…

Evrard et al 2014

scaling relation inputs: $\langle \mathbf{s} | \mu \rangle = \boldsymbol{\pi} + \boldsymbol{\alpha} \mu$ log-means (vector)

$C_{ab} = \langle (s_a - \langle s_a | \mu \rangle)(s_b - \langle s_b | \mu \rangle) \rangle$ covariance of log-observables deltas

joint, multi-observable space density

$\mu = \ln M$

$s_i = \ln(\text{observable}_i)$

$$n_1(\mathbf{s}) = A'_1 \exp\left[-\frac{1}{2} \left((\mathbf{s} - \boldsymbol{\pi})^T \mathbf{C}^{-1} (\mathbf{s} - \boldsymbol{\pi}) - \frac{\langle \mu | \mathbf{s} \rangle_1^2}{\sigma^2_{\mu|\mathbf{s},1}} \right) \right]$$

$$A'_1 = A \; \sigma_{\mu|\mathbf{s},1} \; \left((2\pi)^{N-1} |\mathbf{C}| \right)^{-1/2}$$

$$\langle \mu | \mathbf{s} \rangle_1 = \left[\boldsymbol{\alpha}^T \mathbf{C}^{-1} (\mathbf{s} - \boldsymbol{\pi}) - \beta_1 \right] \sigma^2_{\mu|\mathbf{s},1}$$

mean selected mass

$$\sigma^2_{\mu|\mathbf{s},1} = (\boldsymbol{\alpha}^T \mathbf{C}^{-1} \boldsymbol{\alpha})^{-1}.$$

variance in selected mass

log-normal form of property-conditioned samples, $\Pr(s_b \mid s_a)$

$$\langle s_b | s_a \rangle_1 = \pi_b + \alpha_b [\langle \mu | s_a \rangle_1 + \beta_1 \, r_{ab} \, \sigma_{\mu|a,1} \, \sigma_{\mu|b,1}]$$
mean s_b for s_a selection

$$\sigma^2_{b|a,1} = \alpha_b^2 \, [\sigma^2_{\mu|a,1} + \sigma^2_{\mu|b,1} - 2 r_{ab} \, \sigma_{\mu|a,1} \sigma_{\mu|b,1}]$$
variance ”

$\mu = \ln M$

$s_i = \ln(\text{property}_i)$

Note: Variance is maximized when a+b are ***anti-correlated*** at fixed halo mass.

These are what we actually measure in survey samples!

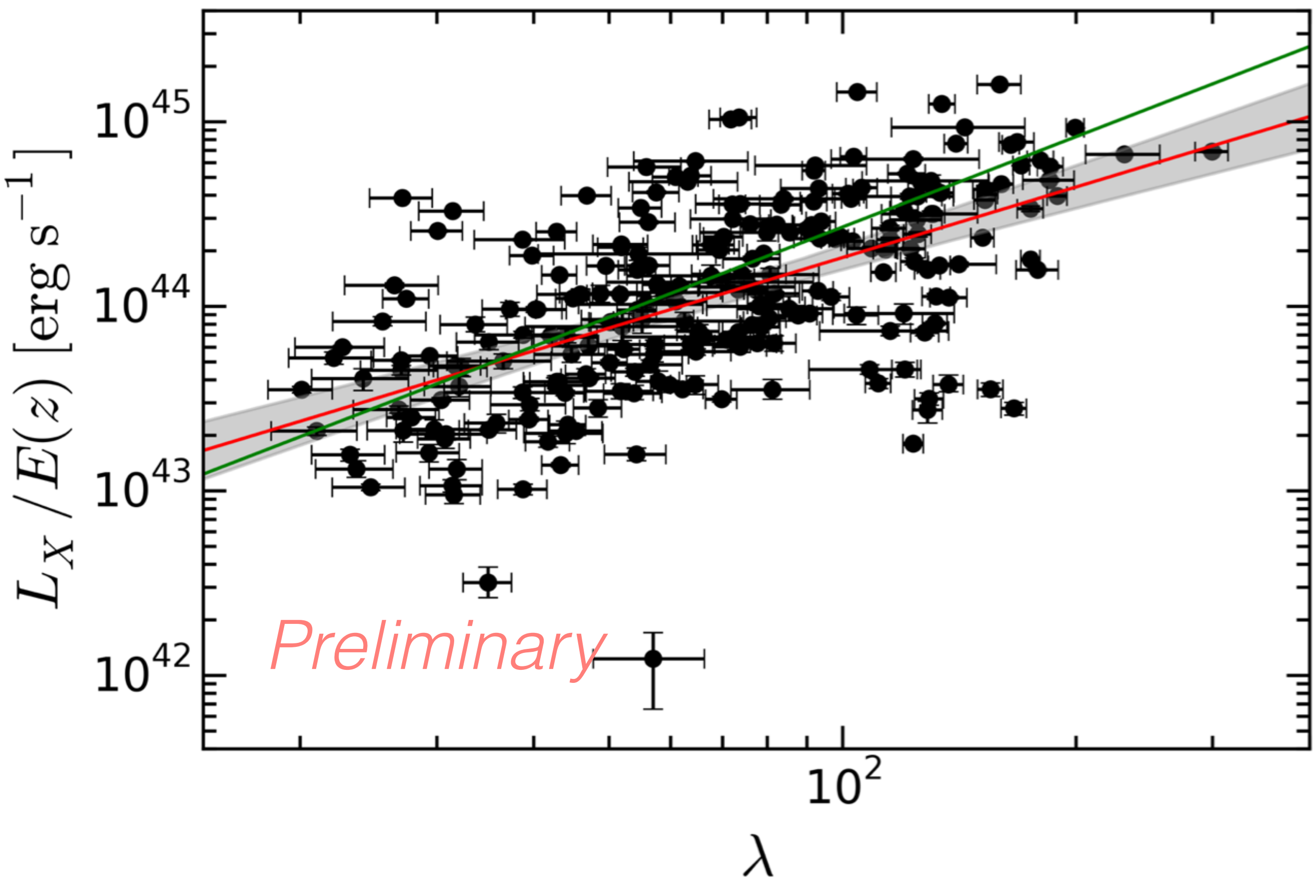
SDSS RedMaPPer
X-ray – optical scaling


Arya Farahi + Xinyi Chen (Michigan)


Devon Hollowood + Tesla Jeltema (UCSC)

SDSS redMaPPer + Chandra archive search

Hollowood + DES, in prep.



Tx-detected systems

235 objects

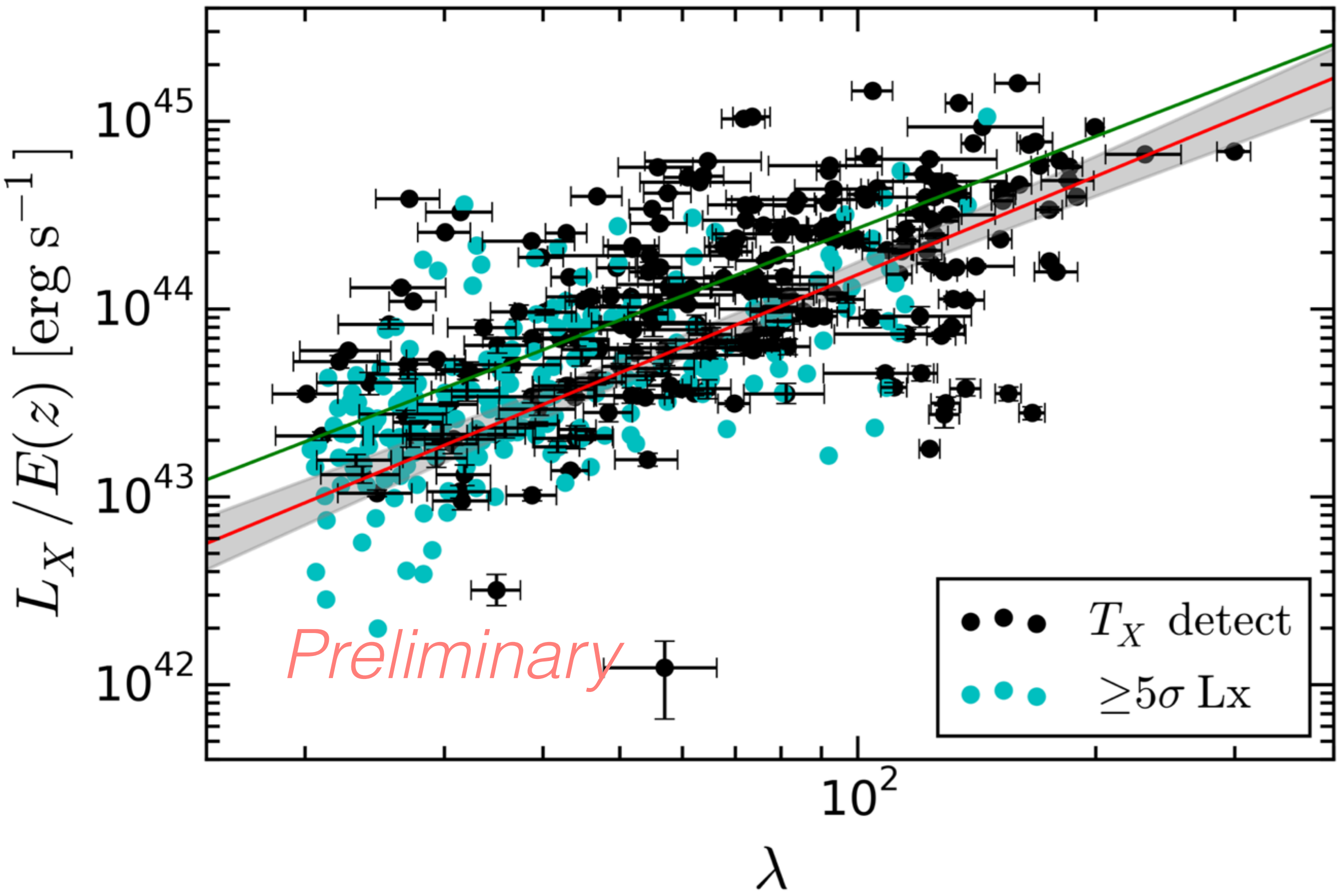
Lx– λ

slope 1.29 ± 0.10

scatter 0.87 ± 0.04

SDSS redMaPPer + Chandra archive search

Hollowood + DES, in prep.



Tx-detected systems

Lx detected (5sigma)

408 objects

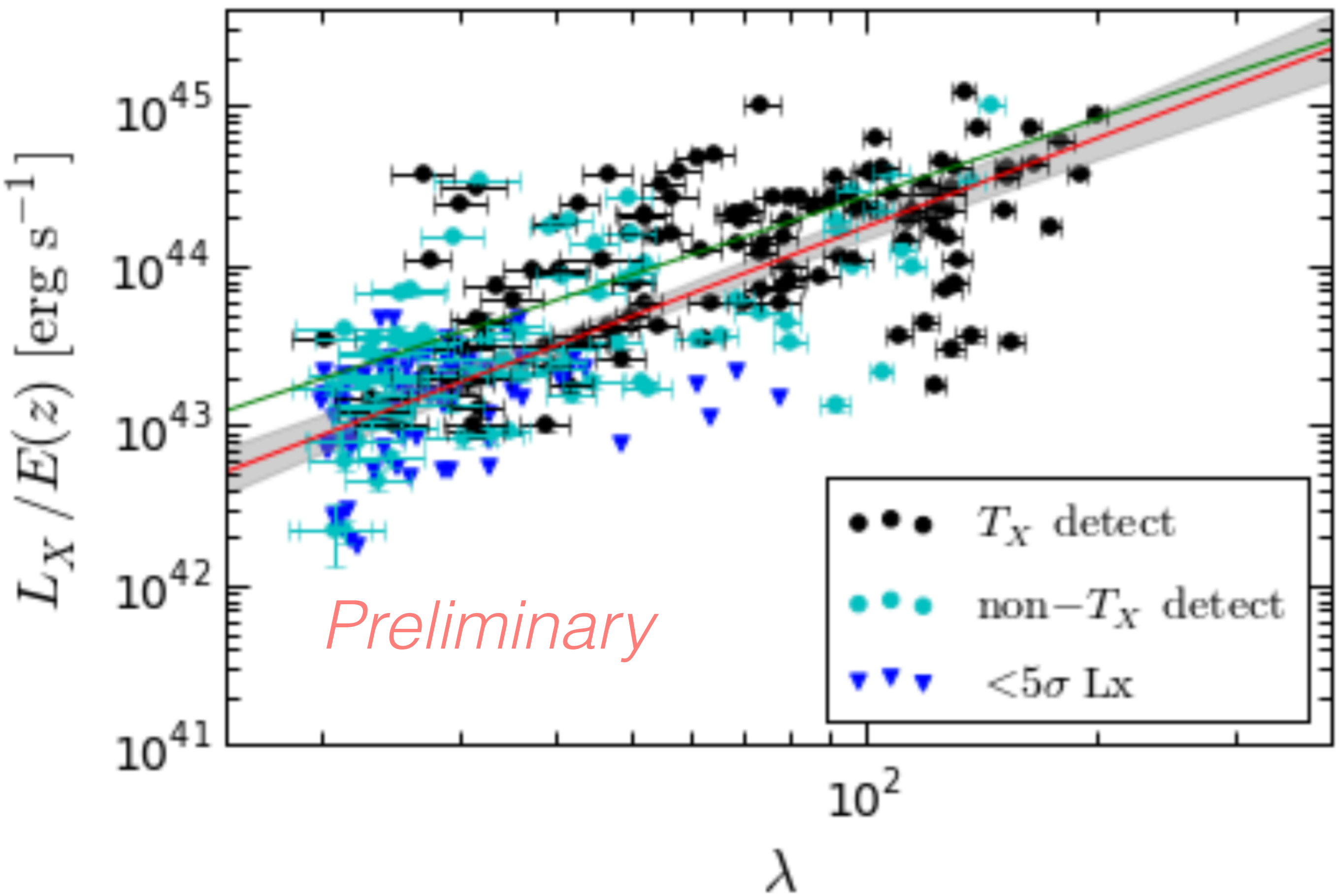
Lx– λ

slope 1.46 ± 0.08

scatter 0.82 ± 0.03

SDSS redMaPPer + Chandra archive search

Hollowood + DES, in prep.



Tx-detected systems

Lx detected (5sigma)

Lx upper limit (<5sigma)

484 objects

Lx– λ

slope 1.71 ± 0.08

scatter 0.87 ± 0.04

What will we be talking about?

Mean halo mass scaling for X-ray, SZ, optically selected samples (M>1e14):
- sub-percent for z<1 (see Henk…), percent-level for 1< z <2

Hot gas in cluster samples at z > 3

Debating the 2nd significant digit in the sum of the neutrino masses.

z > 20 Pop III stars in strong lensing clusters.

Precise measurements of running in the MOR slope and covariance.

Multi-dimensional HOD models of cluster galaxy populations.

Public services for data analysis including multi-wavelength simulated skies.

The latest "full physics" sub-grid models for Enzo / Arepo / Gizmo / etc.

Fourth significant digit in DE equation of state parameter, w = –1.00x…

The End