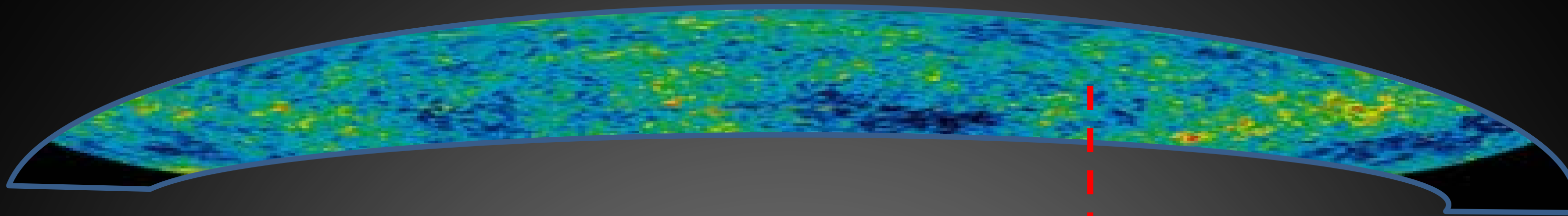


Galaxy Cluster Scaling Relations for Cosmology

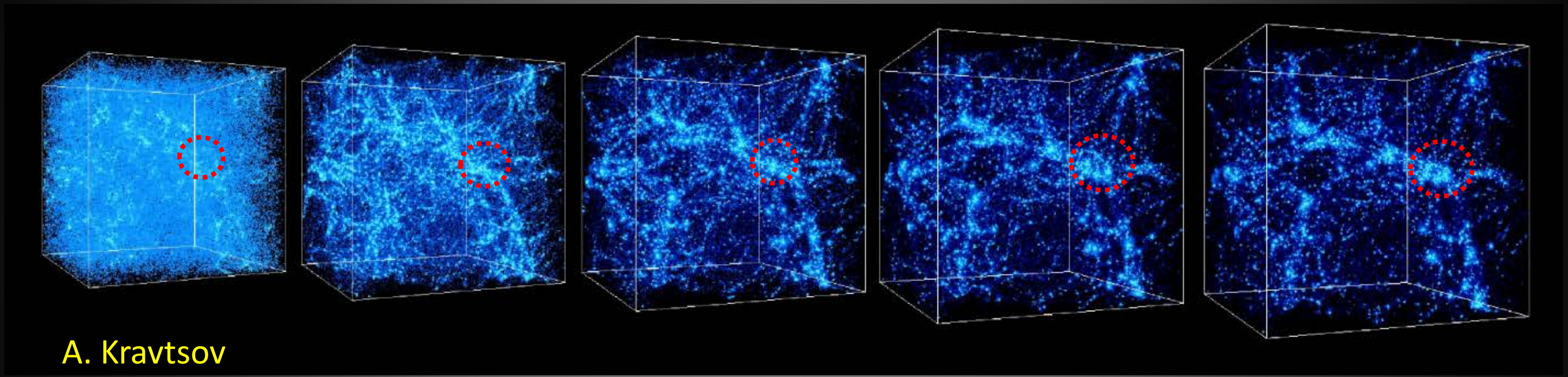
Nicole Czakon (ASIAA)

EAYAM 2015

Galaxy Cluster Cosmology:

How Does Dark Energy Affect The Growth of Large-Scale Structure?

z = 10 z = 3 z = 1 z = 0.5 z = 0.0



http://cosmicweb.uchicago.edu/filaments.html

43 Mpc/h70/side

Freedman Solution

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

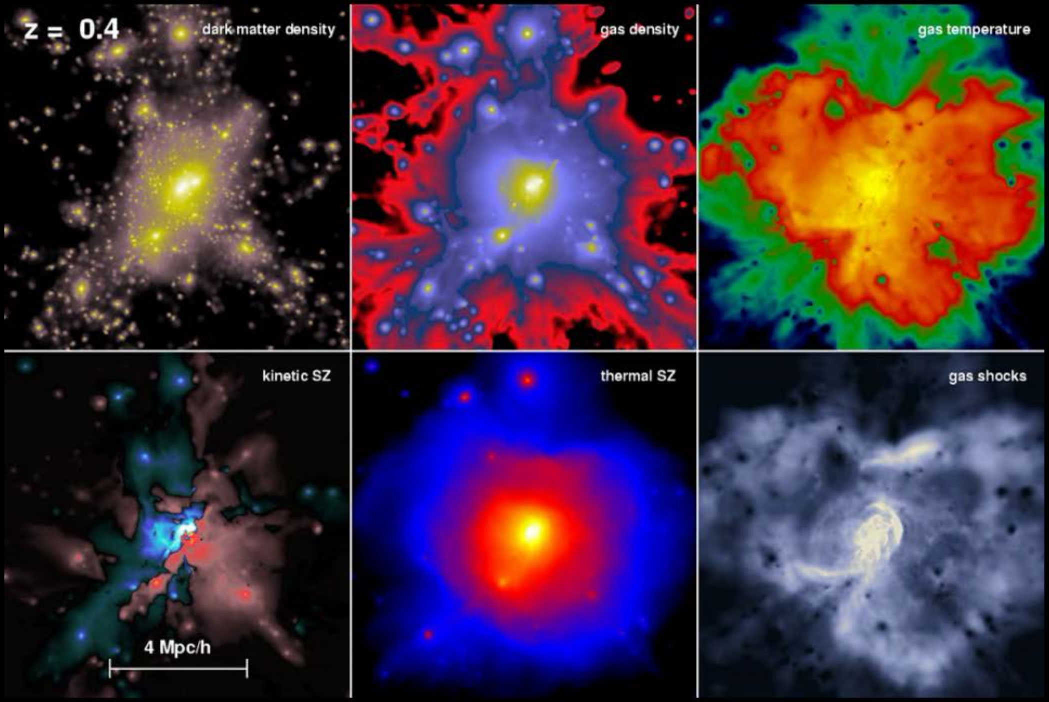
Instead of measuring the rate of recession, measure the rate of growth

→ Galaxy Cluster Mass Function.

From Cosmology to Astrophysics

A rich collection of observables allows for self-calibration…

Credit: Volker Springel
Simulation code: Gadget-2
http://www.mpa-garching.mpg.de/galform/data_vis/



Dark Matter Halo
Significant amount of structure.
Lensing

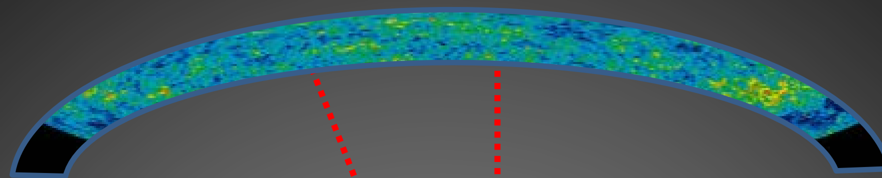
kSZE
Proper velocity.

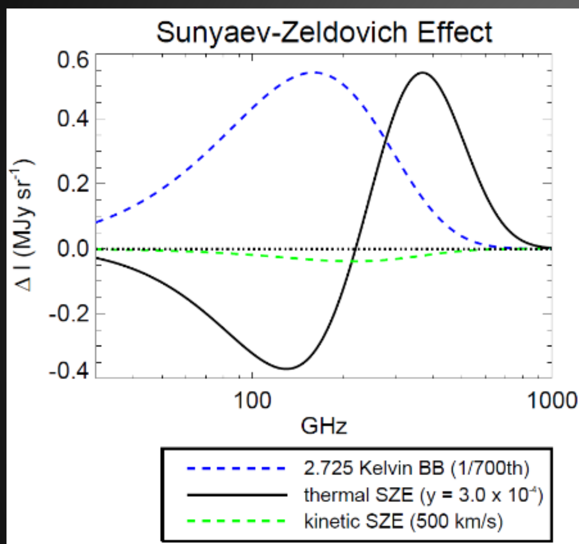
Temperature
Shallow Radial Dependence.

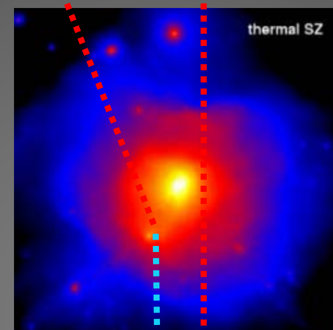
Shocked gas
From merger activity.

tSZE
Smooth and Uniform

The Sunyaev-Zel'dovich Effect





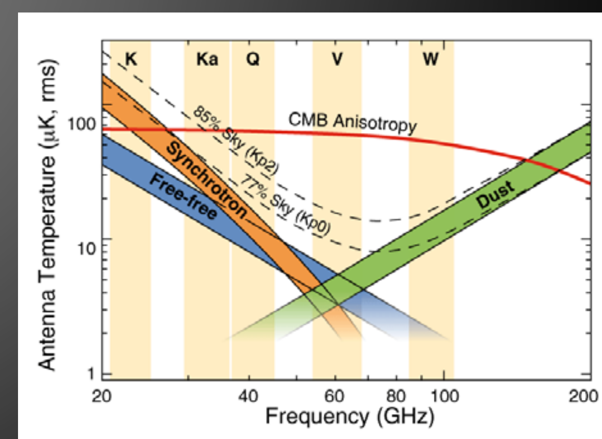


$$Y_{\mathrm{cyl}} = \int y \, d\Omega dl$$

$$d\Omega = \bullet \quad 2 \times \mathrm{R}_{2500}$$

$$Y_{\mathrm{sph}} = \int y \, dV$$

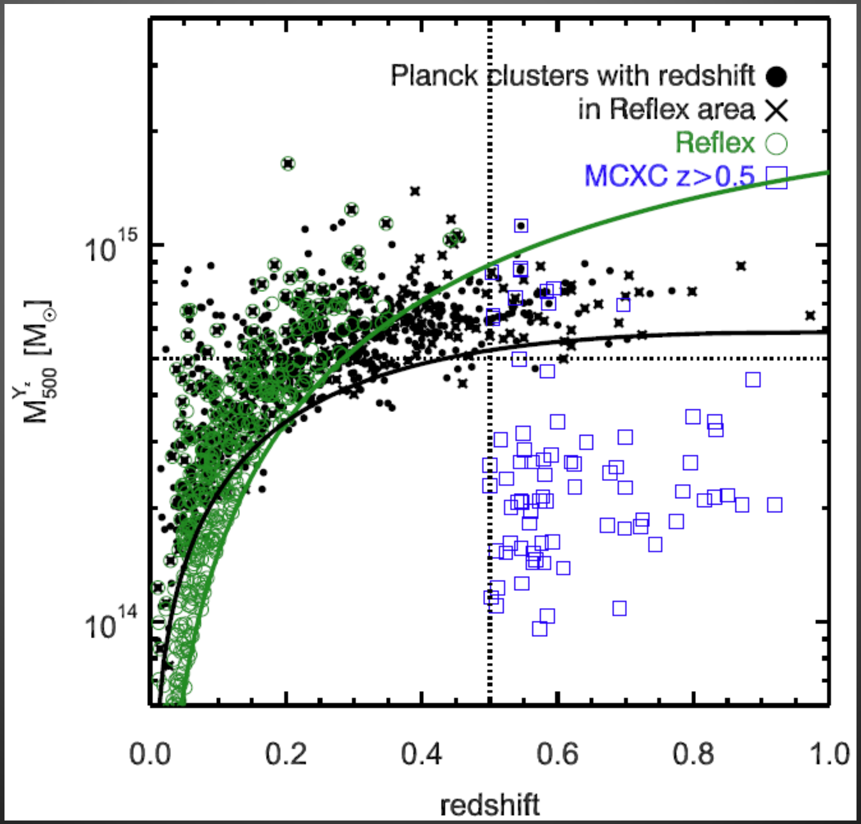
$$\frac{\Delta T_{SZE}}{T_{CMB}} = f(x)\, y = f(x) \int n_e \frac{k_B T_e}{m_e c^2} \sigma_T \, d\ell,$$



http://wmap.gsfc.nasa.gov/mission/observatory_freq.html

Why SZE?
Mass Limit Constant with Redshift

- Lensing can eventually help with calibration
- X-Ray and SZE detect a lot of clusters! More to come with eROSITA!
- Need to find a way to calibrate observables with mass….



Planck 2013 XXIX. SZE Catalog

$M_{500}|Y_{500}$?

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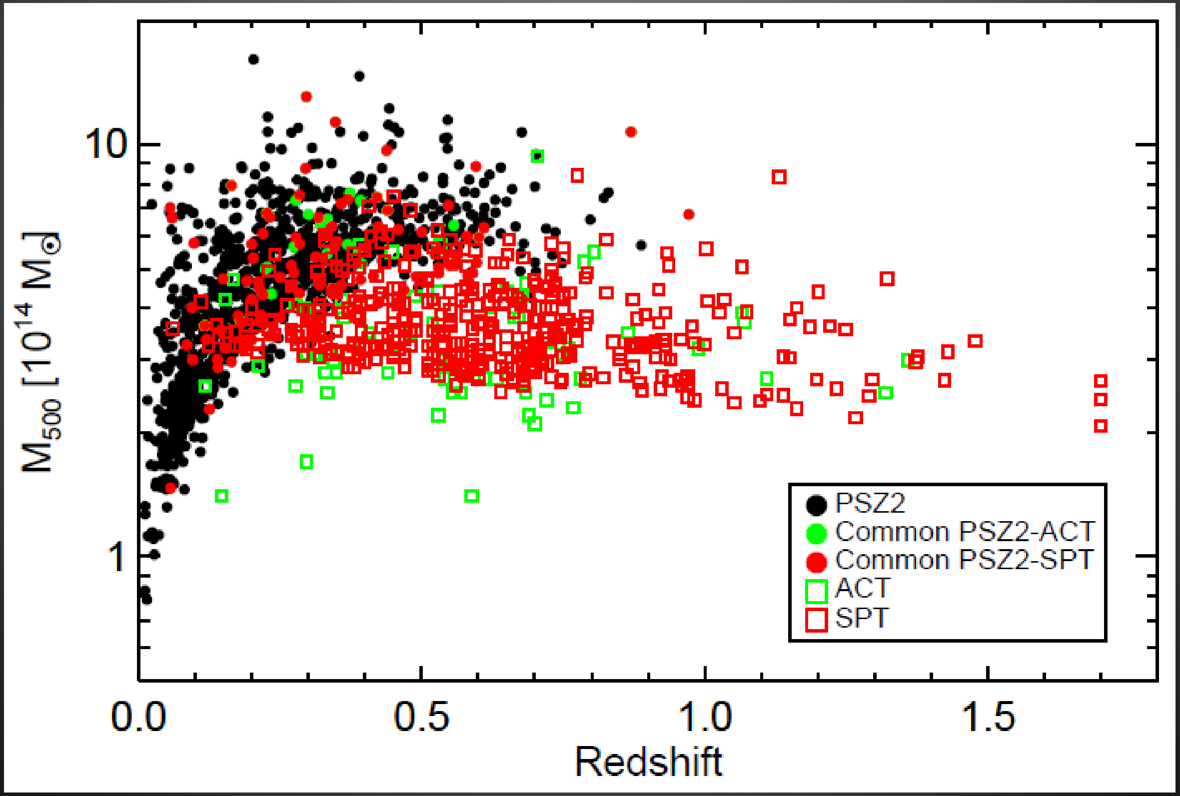
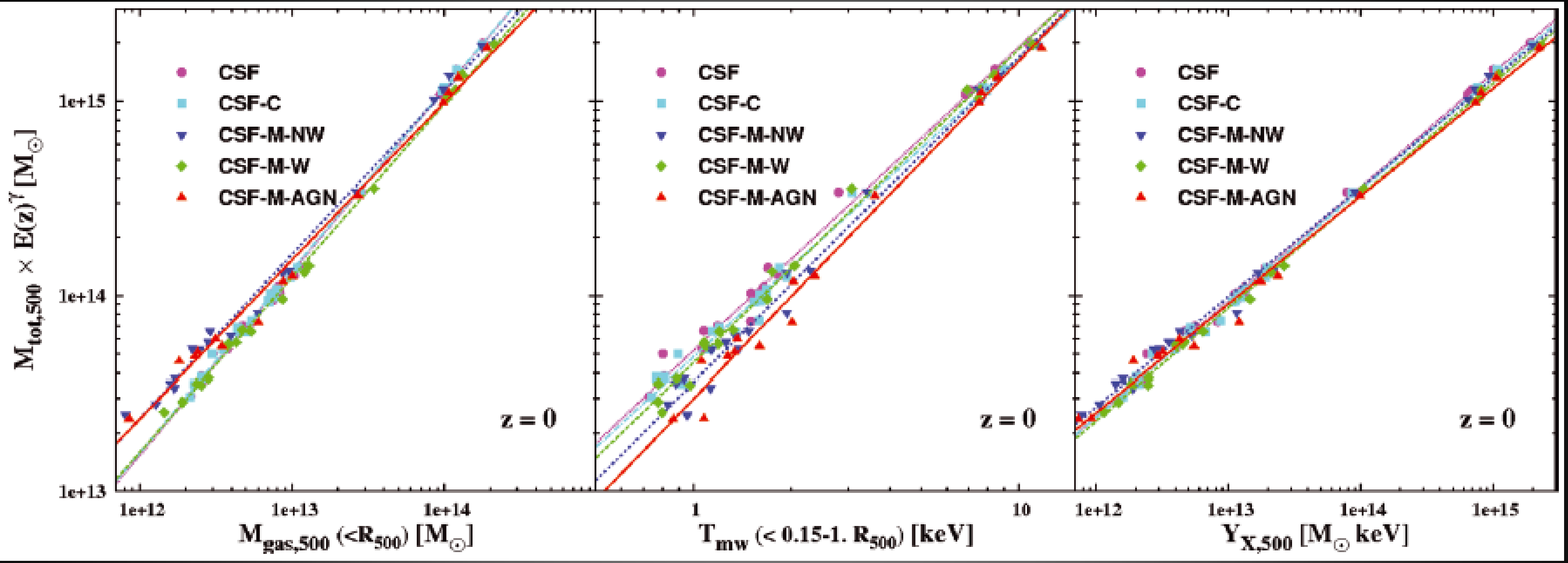


$M_{500}|Y_{500}$?

Planck 2015 XXVII. SZE Catalog

Why SZE? Self-Similarity Seems to Work… Insensitive to Cluster Astrophysics……

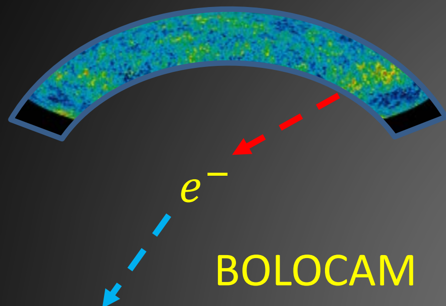


Fabjan, 2011, MNRAS 416:801-816

Simulations and observations agree, Ysz is a low scatter mass proxy.

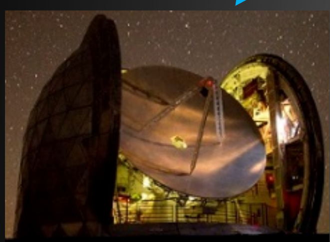
Can make a similar proxy with X-Rays: $Y_X = M_{gas} \times T_X$

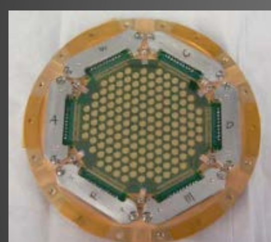
BOXSZ: Bolocam XSZ



CSO

BOLOCAM





12-14'Ø maps 1' PSF

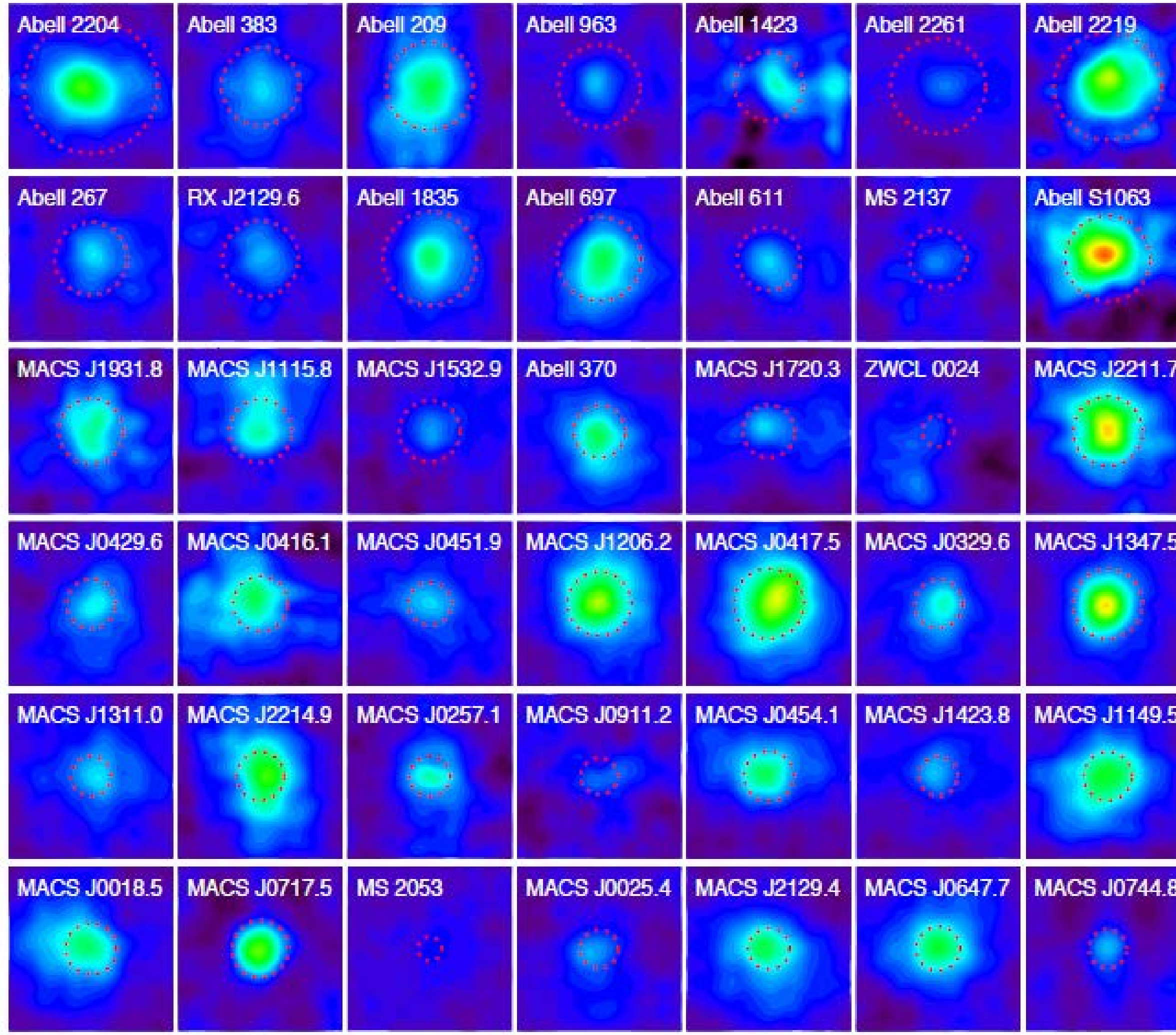
140 GHz (& 268 GHz)

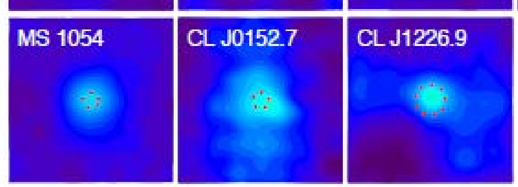
45 clusters, 2006-2012

$\langle z \rangle = 0.4$

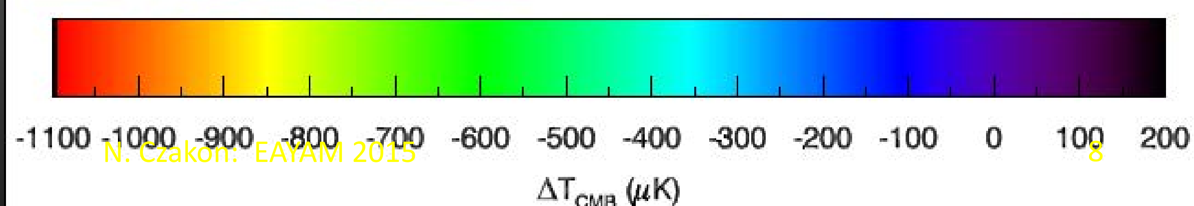
$k_B T > \approx 5$ keV

Decade in mass

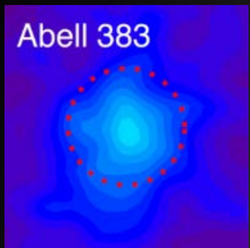


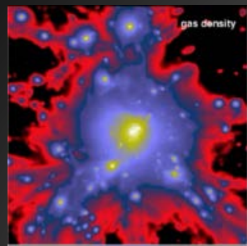


Czakon, 2014, arXiv:1406.2800 (in review)

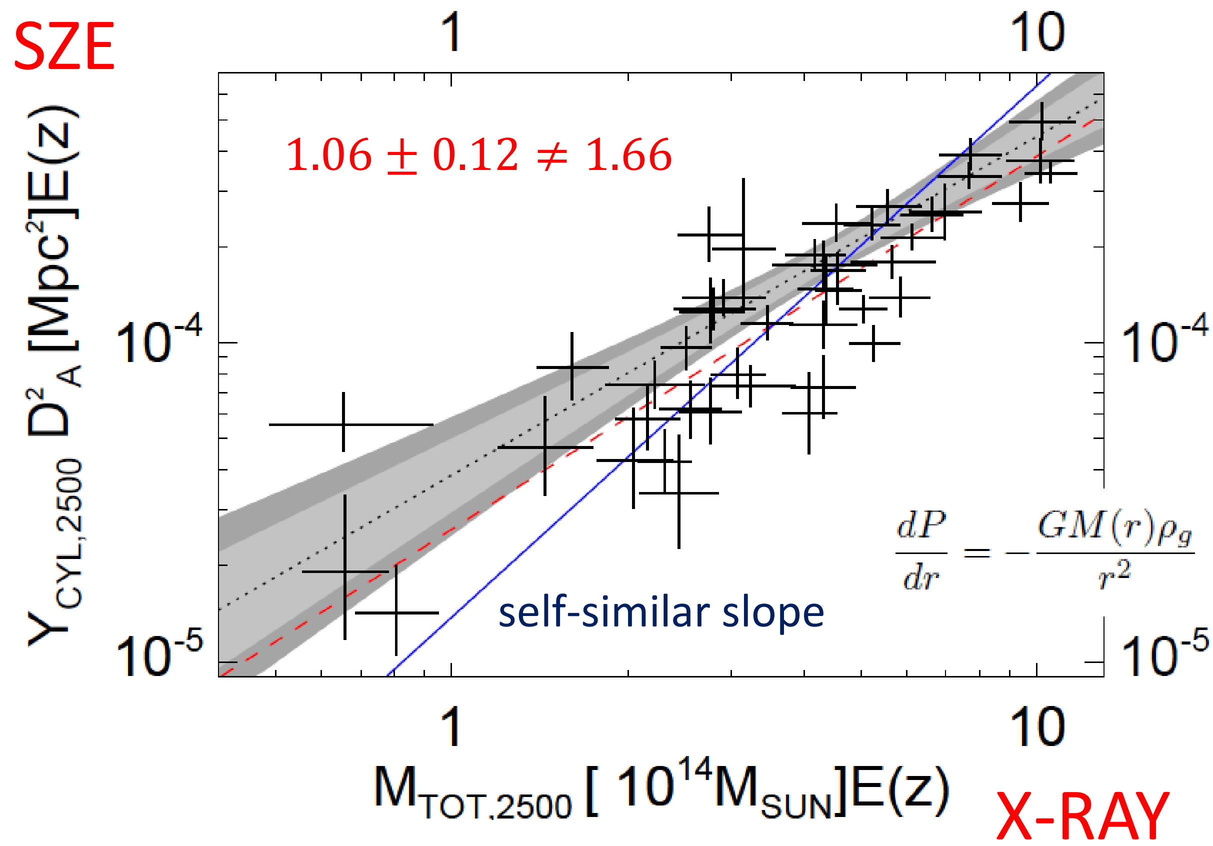


BOLOCAM SZE SCALING RELATIONS

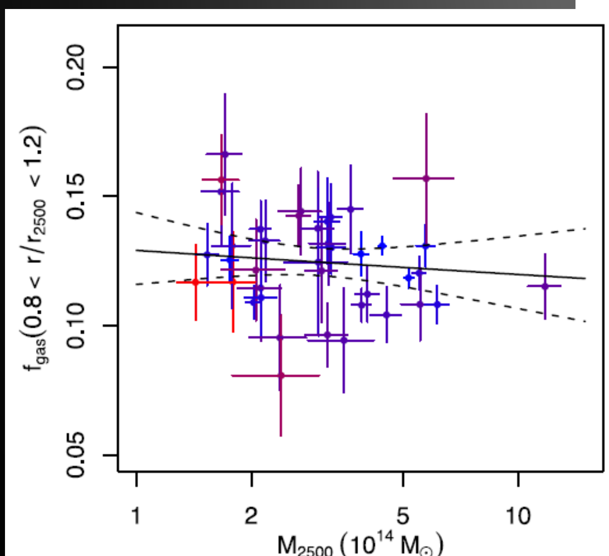




Corrected for selection effects. No redshift, mass, or morphology dependence.....



(Czakon, 2014, arXiv:1406.2800 in review)



(Mantz, 2014, MNRAS 440, 2077-2098)

Y_{sz} vs. M_{tot} : Comparison with Other Analyses

Bender, 2014.
Y_{SZ} : APEX-SZ vs. M_{gas}
P11/B08 measure ~1.4

$1.16^{+0.10}_{-0.17}$

Czakon, 2014

Bonamente, 2008

Andersson, 2011

Planck Early results, 2011

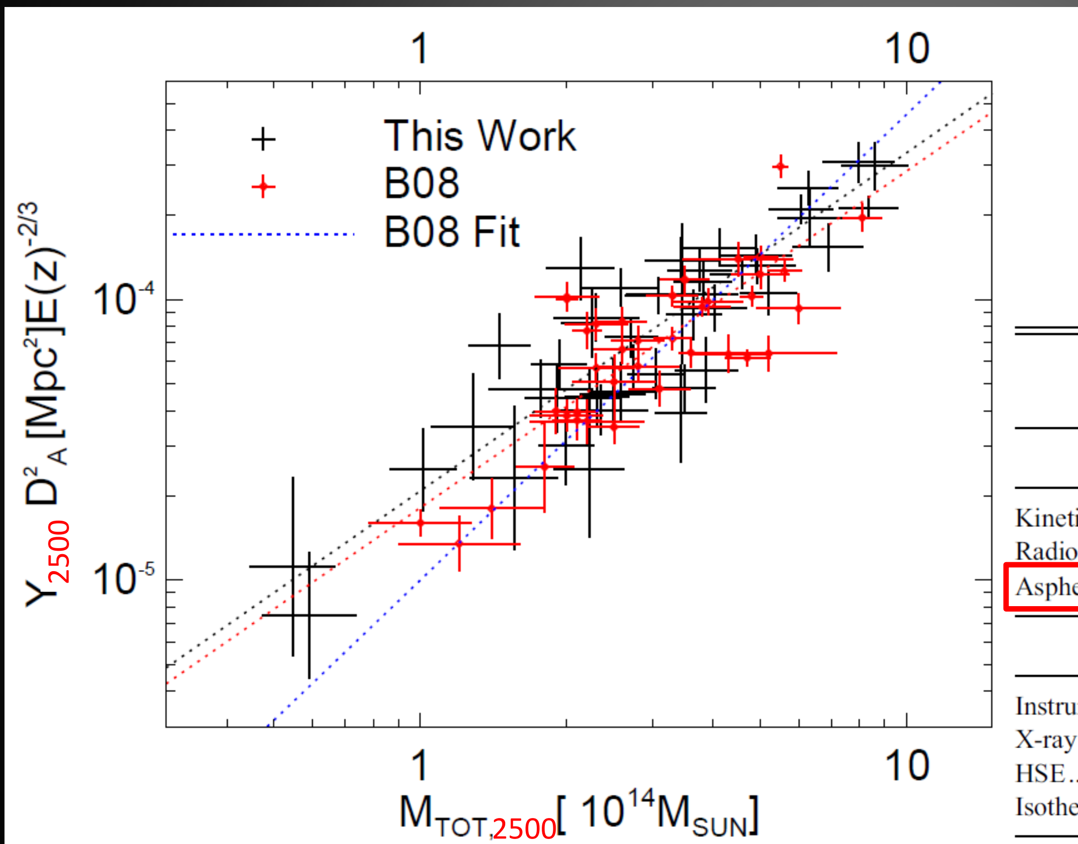
Name	SZE data	X-ray data	Proxy	Δ	$\beta_1^{y\|m}$
this work	Bolocam	CXO	M_{gas}	2500	1.06 ± 0.12
B08	OVRO/BIMA	CXO	HSE	2500	1.66 ± 0.20
A11	SPT	CXO/XMM	Y_X	500	1.67 ± 0.29
P11	*Planck*	XMM	Y_X	500	1.74 ± 0.08

(Czakon, 2014, arXiv:1406.2800)

How can we compare these results independent of M_{tot} ?
Compare the mass proxies directly:

Y_{sz} vs. M_{gas} or Y_{sz} vs. Y_X ……

Systematic Differences in Fit Method
OVRO/BIMA vs. Bolocam



Our Fitting Method

-> Similar Results

B08 Fitting Method

-> B08 Results

Sensitive to assumptions of intrinsic scatter….

Sources of Uncertainty in f_{gas} Measurements

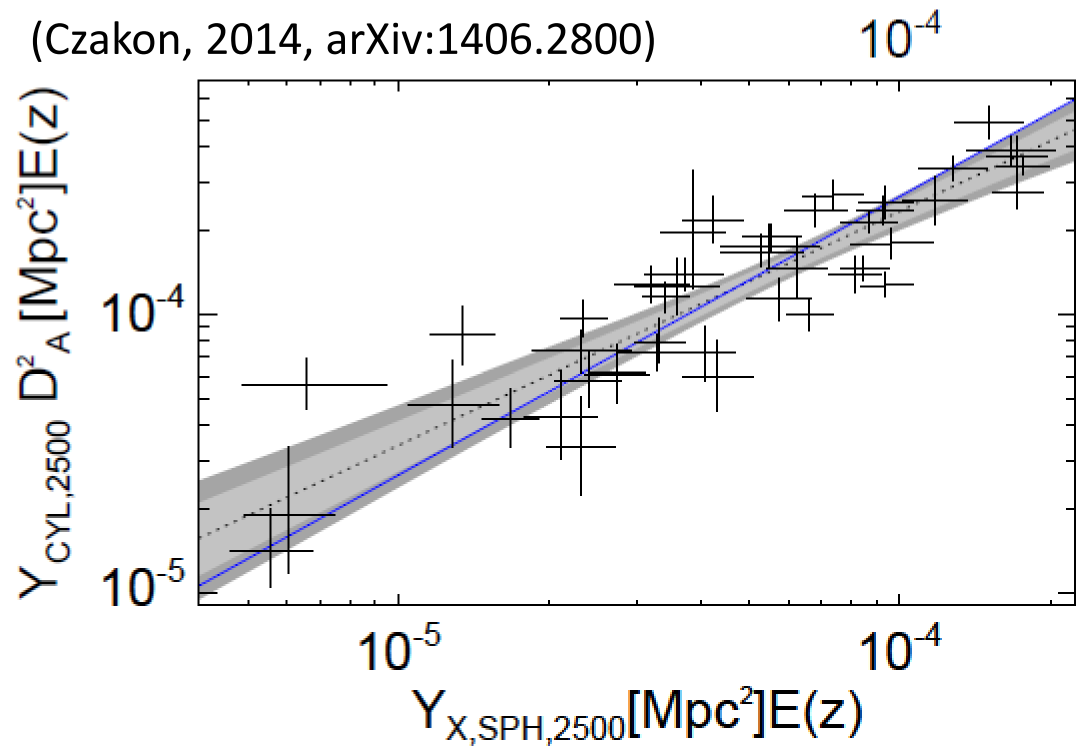
Source	X-Ray f_{gas} (%)	SZE f_{gas} (%)
Statistical Effects[a]		
Kinetic SZE	...	±4
Radio point sources	...	±4
Asphericity	±20	±10
Systematic Effects[b]		
Instrument calibration	±6	±8
X-ray background	+2	...
HSE	−10	−10
Isothermality[c]	−5	−10

Samuel J. LaRoque,[1] Massimiliano Bonamente,[2,] The Astrophysical Journal, 652:917–936, 2006

Y_{sz} vs. $Y_X = M_{gas} T_x$: Consistent Between Analyses

Bender, 2014.
Y_{SZ} : APEX-SZ vs. M_{gas}

$0.98^{+0.07}_{-0.12}$



Czakon, 2014

Bonamente, 2008

Andersson, 2011

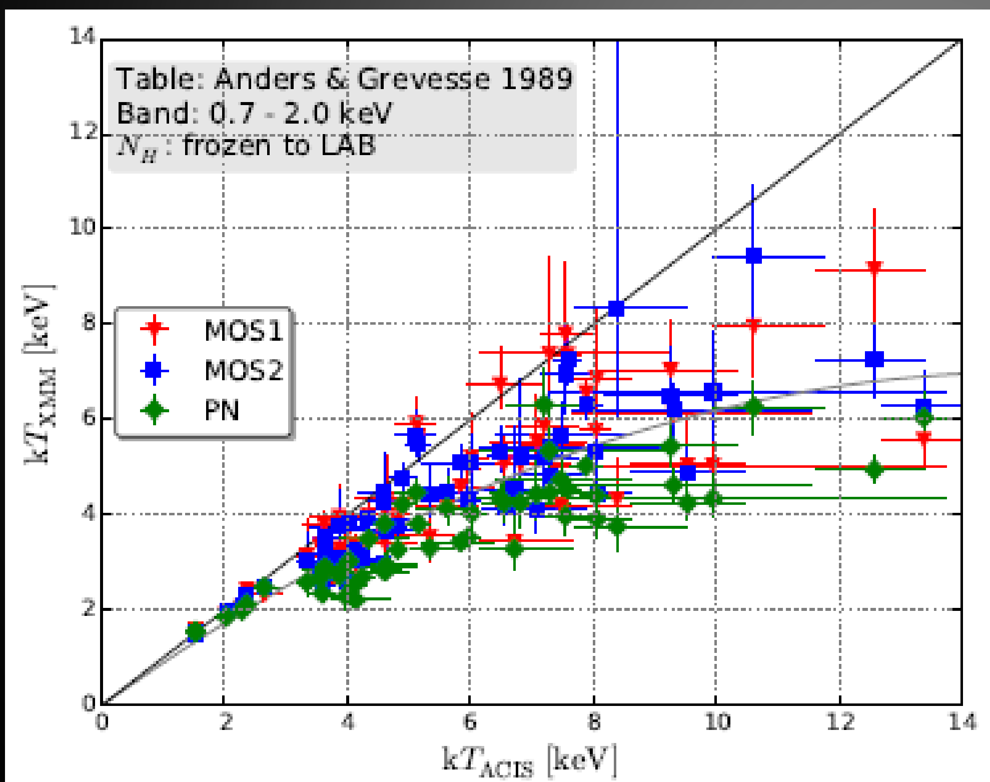
Planck Early results, 2011

Name	Instrum.	$\beta^1_{yy_x}$
This work	*Bolocam*/CXO	0.84 ± 0.07
B08	CXO/OB	$\cdots$
A11	SPT	0.90 ± 0.17
P11	*Planck*/XMM	0.95 ± 0.04

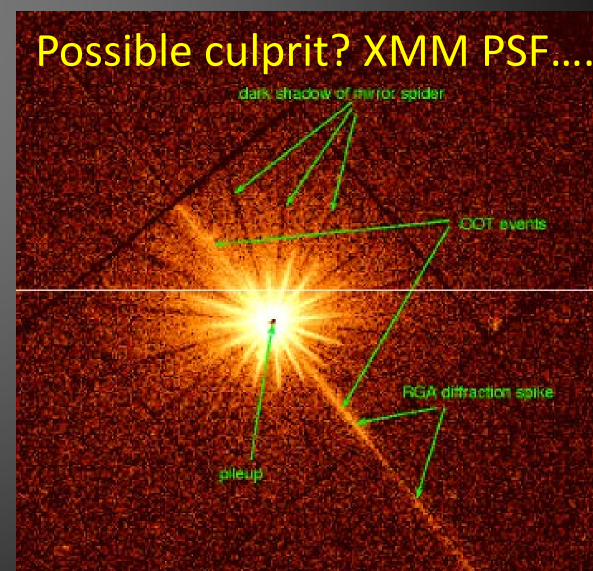
Systematic Differences in the X-ray Data

XMM vs. Chandra

(Schellenberger, 2014, arXiv:140:7130)

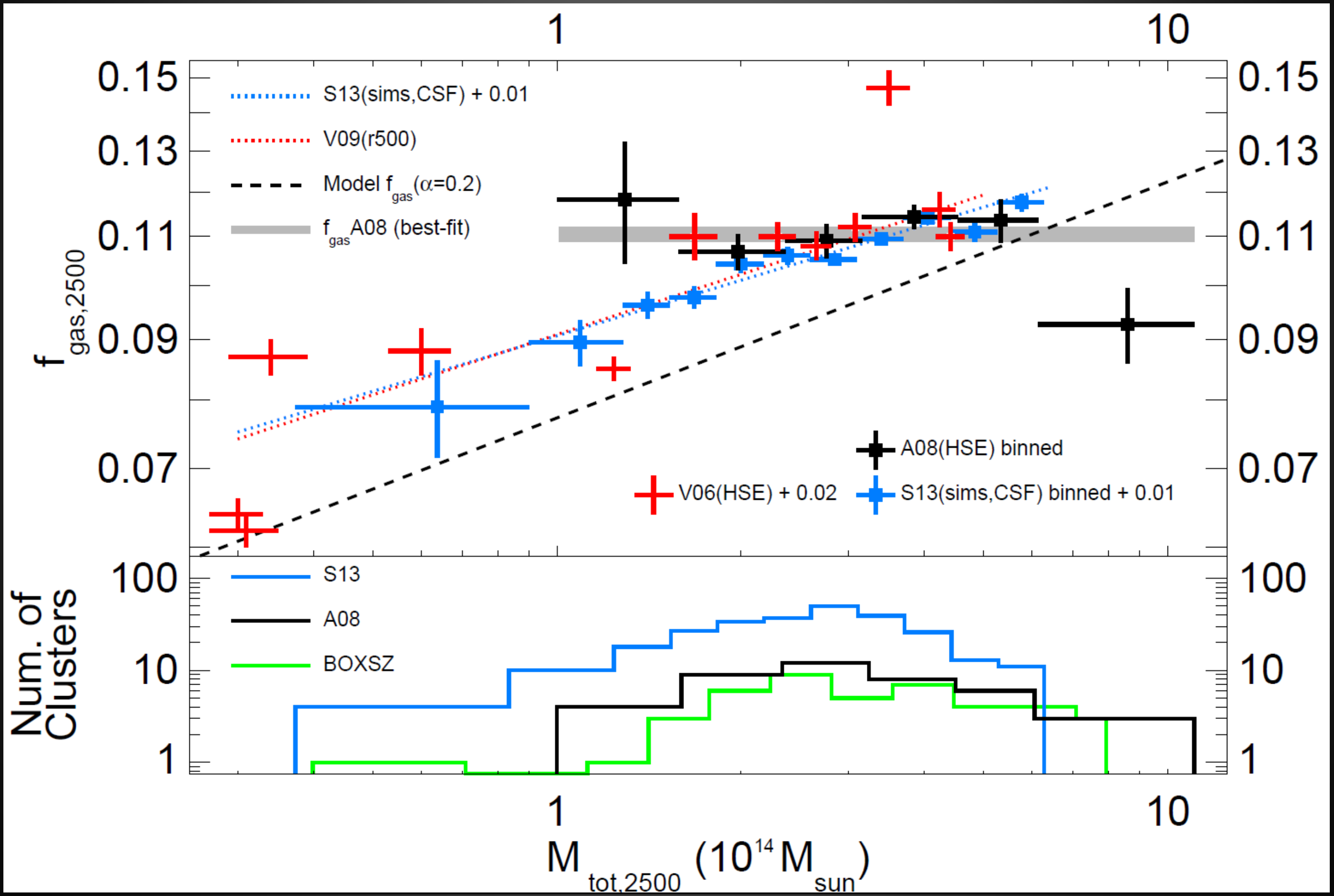


Favors Chandra because of consistent self-calibration and calibration of column density measurements from 21 cm.



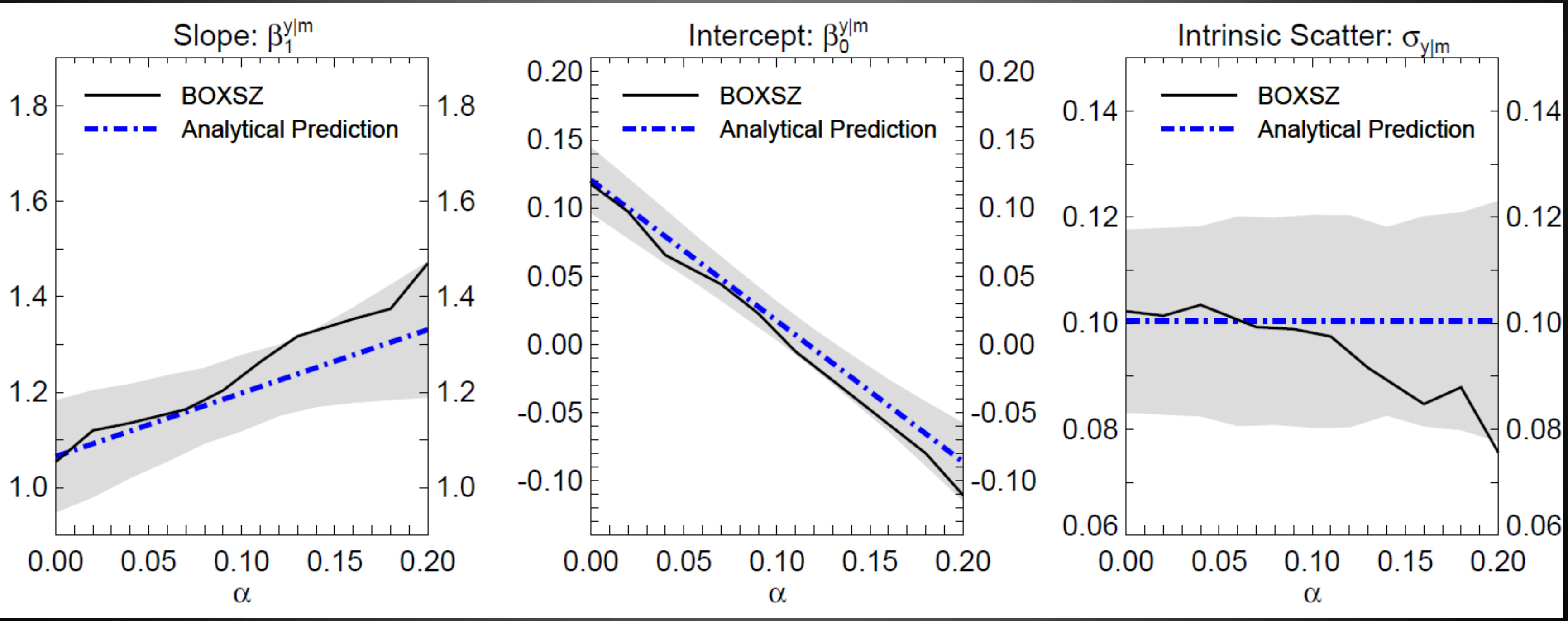
From IM Stewart's website: http://www.ast.uct.ac.za

Broken Power Law in f_{gas}....



Broken Power Law in f_{gas}....

$$f_{\mathrm{gas},2500} = f_0 \left(\frac{M_{2500}}{6 \times 10^{14} M_\odot} \right)^\alpha$$



Conclusion

- We measured the Y_{SZE}—M_{tot} scaling relations for 45 massive clusters using Bolocam SZE data and Chandra X-ray data

  http://irsa.ipac.caltech.edu/Missions/bolocam.html

  - These are much shallower than other observational analyses and predicted by simulations.
- Systematic differences between different analyses make it difficult to get to the root of the problem:
  - Different mass and redshift ranges for various cluster samples.
  - Non-uniform fitting methodologies.
  - Inconsistent Chandra and XMM temperature measurements.
- The inconsistencies between our results and other analyses could be partially explained by an f_{gas}—M_{tot} model with a broken power law…which is not well constrained observationally in the region 10^{14} M_{sun}.
- Possible astrophysics? Too soon to tell…