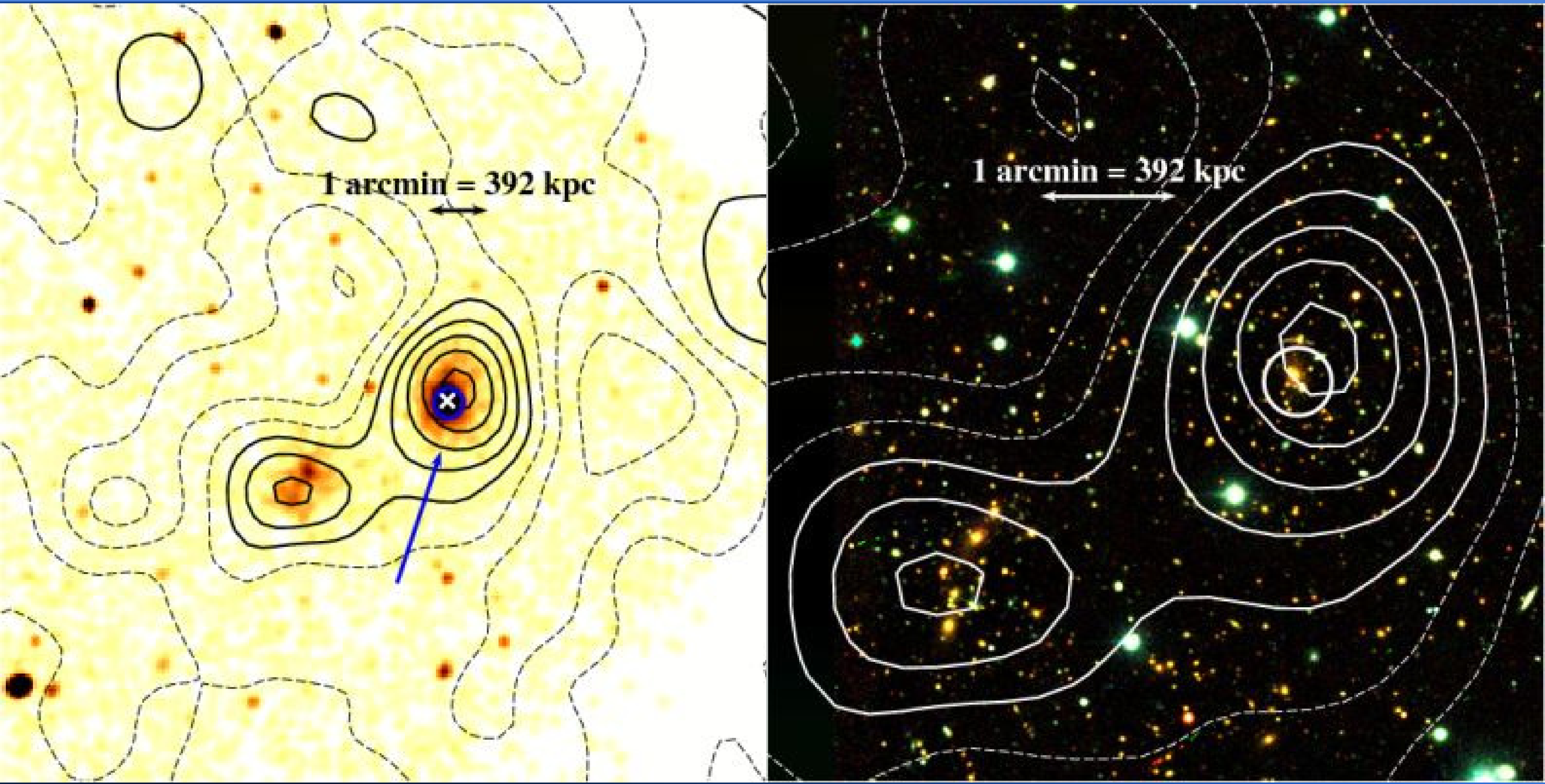
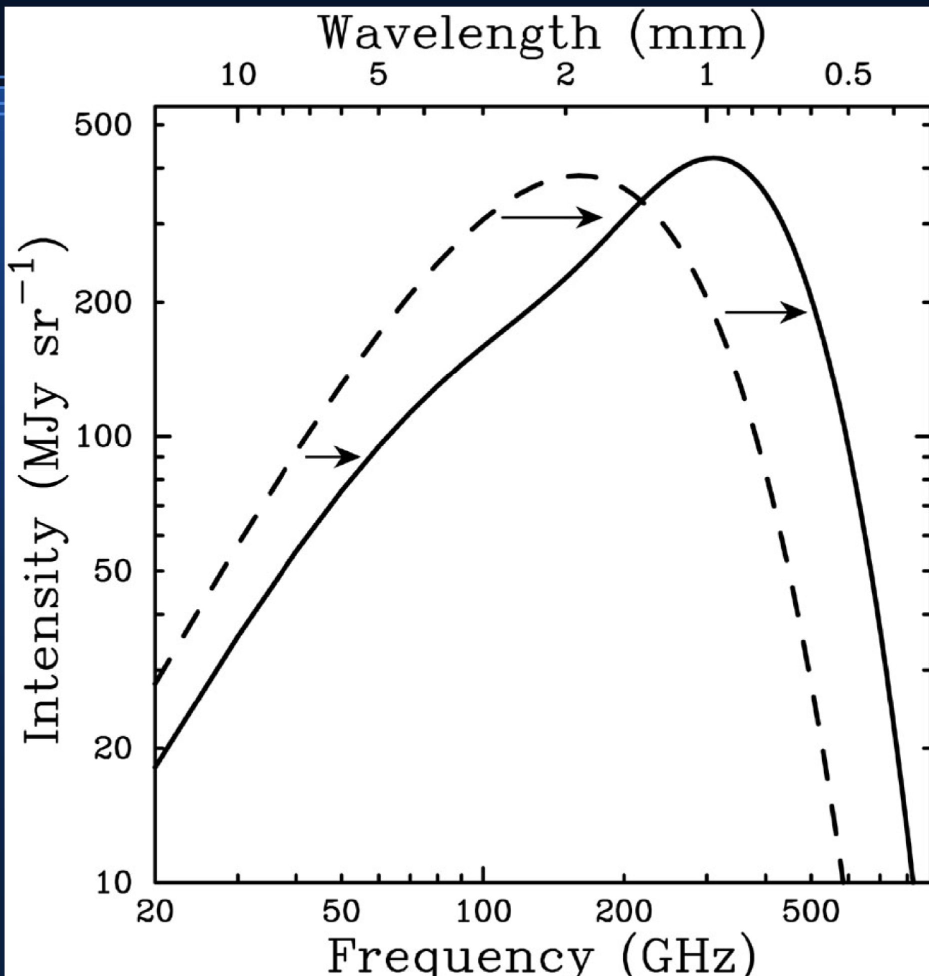
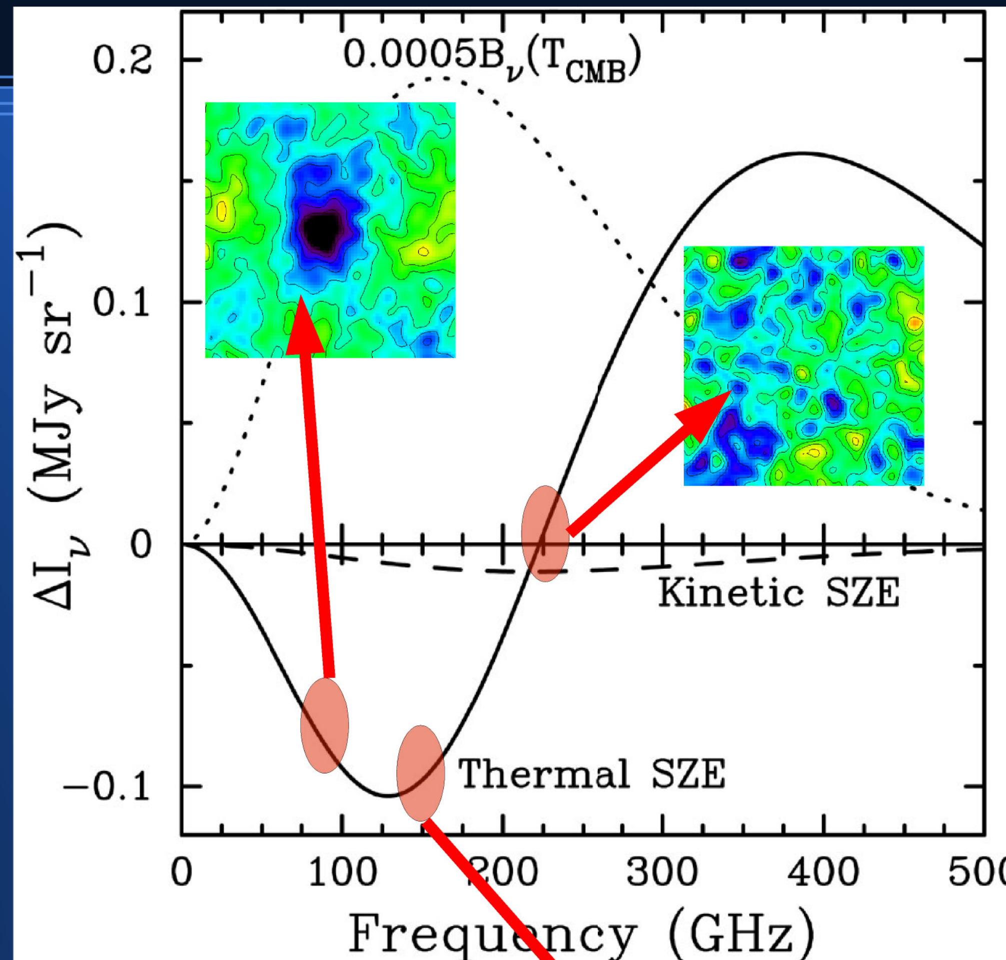
# X-ray properties of SZ selected clusters from the South Pole Telescope



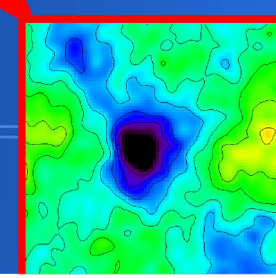
# The Sunyaev-Zel'dovich effect




**SZE distorts CMB spectrum**

$$Y_{SZ} \equiv \int y \, d\Omega \propto M_{gas} T_{mg}$$

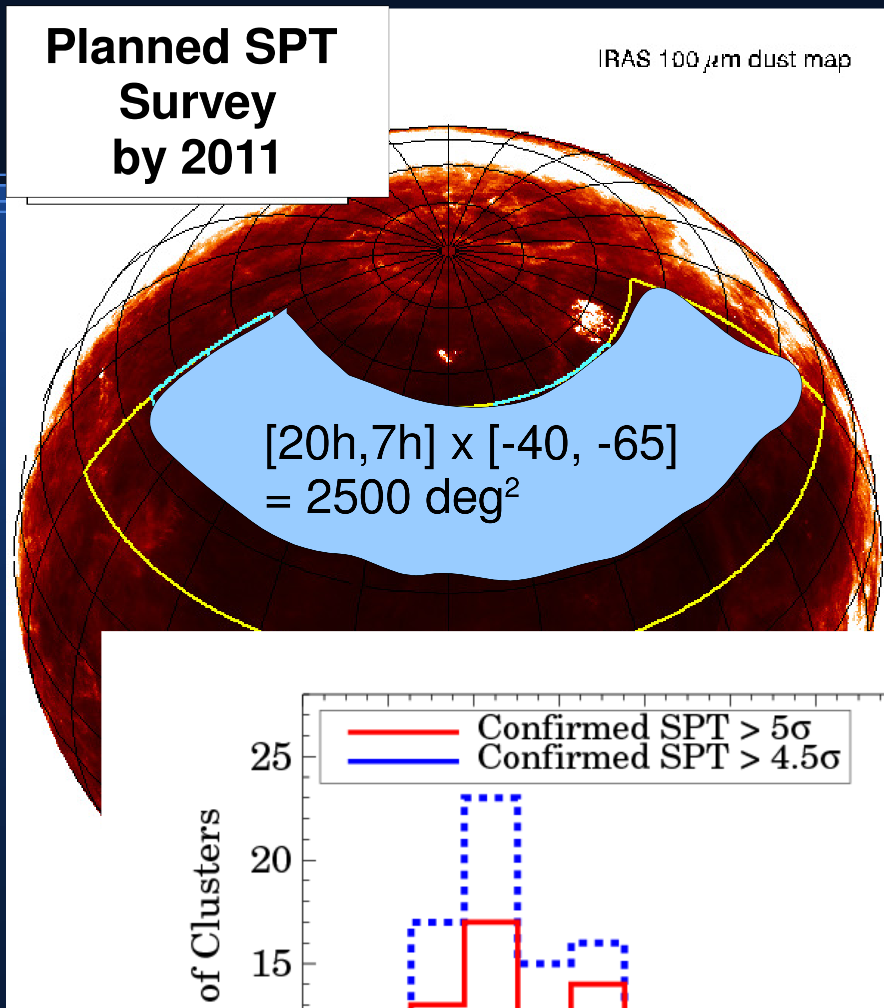


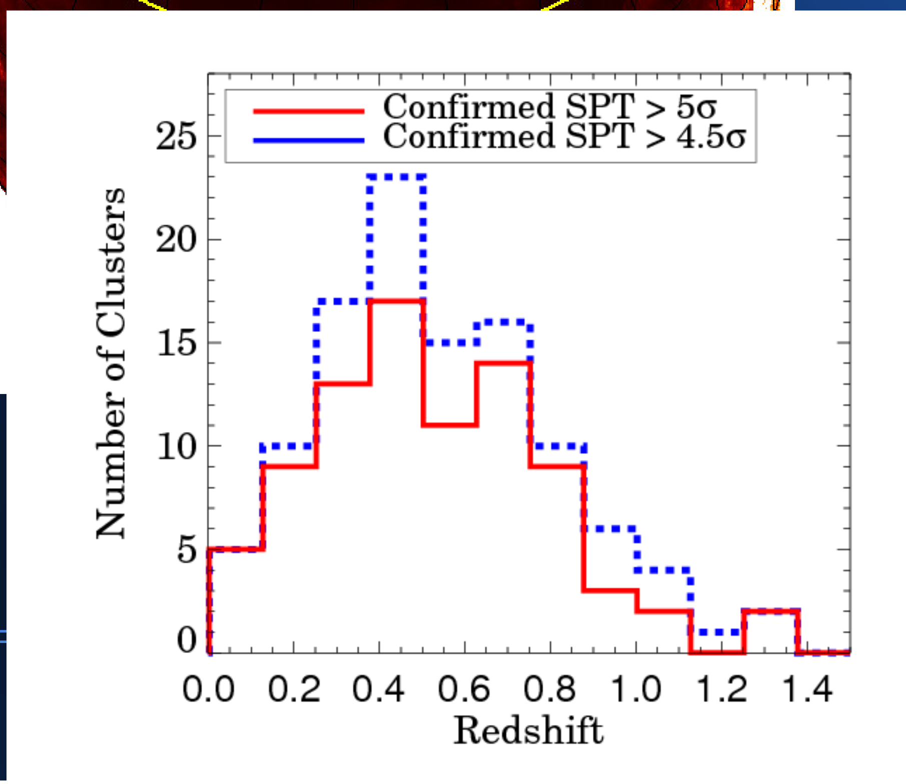
# South Pole Telescope

- 10 meter telescope at the South Pole
- Dry, high alt (2800m) atmosphere is ideal
- Observes the CMB at 95, 150 and 220 GHz
- (WMAP 23,33,41,61,94 GHz)
- Spatial resolution ~1 arcmin
- (WMAP 0.88-0.22 deg)
- (PLANCK 5-10 arcmin)

KICP Kavli Institute for Cosmological Physics at the University of Chicago
Berkeley University of California
Case Western Reserve University
The University of Chicago
UC Davis University of California
Astronomy University of Illinois at Urbana-Champaign
McGill
Harvard-Smithsonian Center for Astrophysics
Cardiff University Prifysgol Caerdydd
Colorado University of Colorado at Boulder
Berkeley Lab

# SPT survey

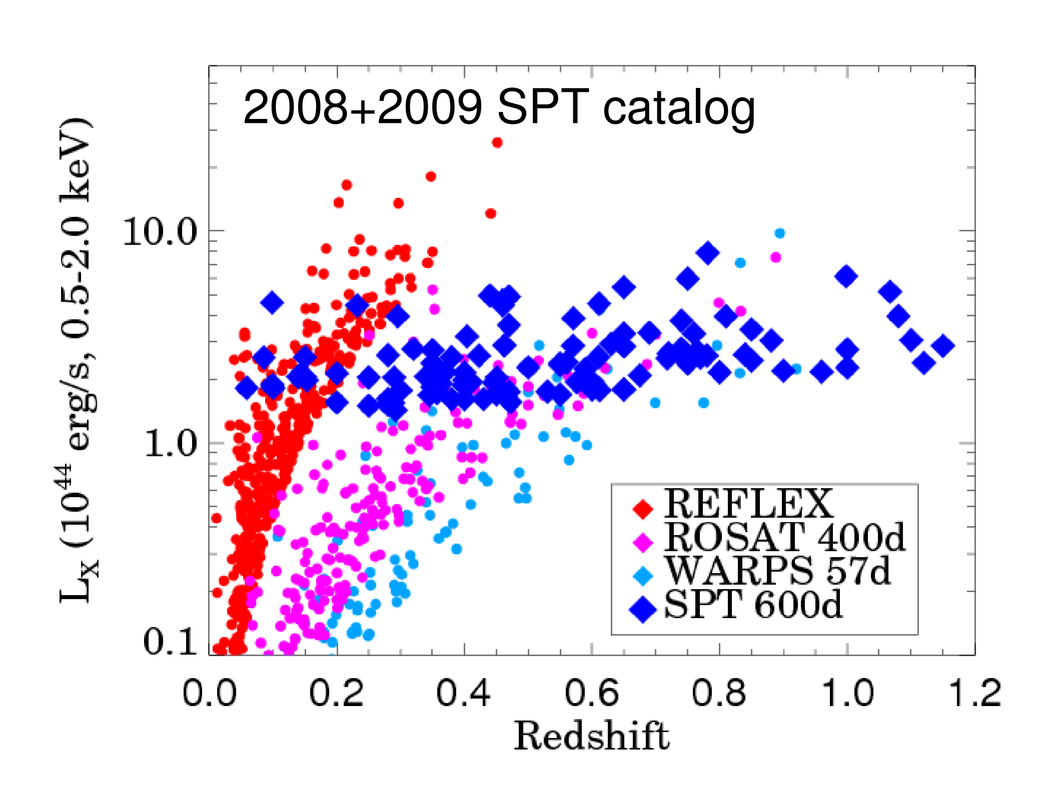


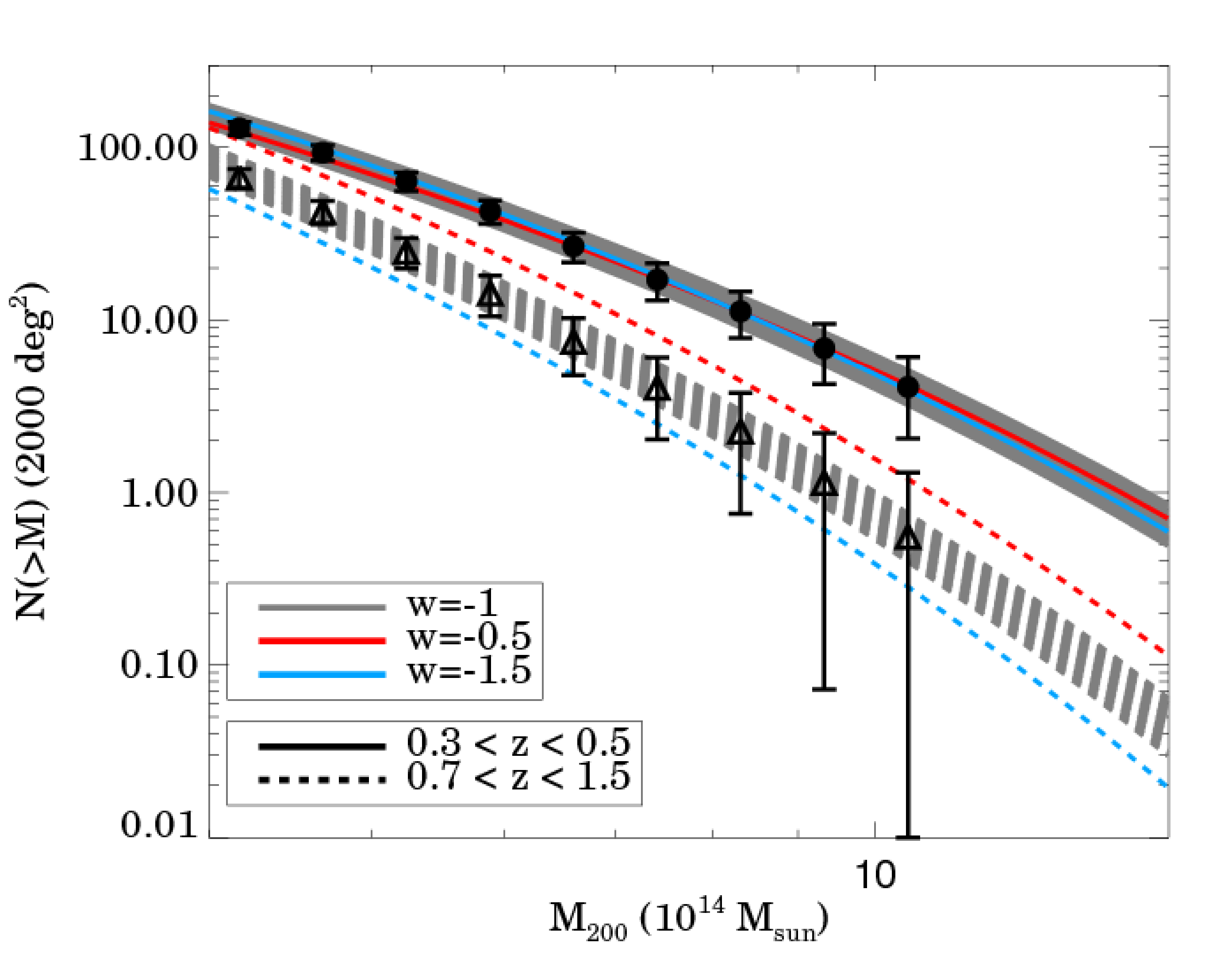

- First clusters detected from an SZ survey, presented in Vandelinde et al. 2010, 21 clusters ~180 $deg^2$
- First cosmological constraints presented
- SPT will cover ~2500 $deg^2$ by 2011
- Goal to constrain cosmological pars through measurement of cluster mass function
- This talk covers only 15 clusters from the first 2008 fields

# SPT clusters

- Currently 1400 deg² observed, over 250 clusters with optical confirmation



# Mass function evolution



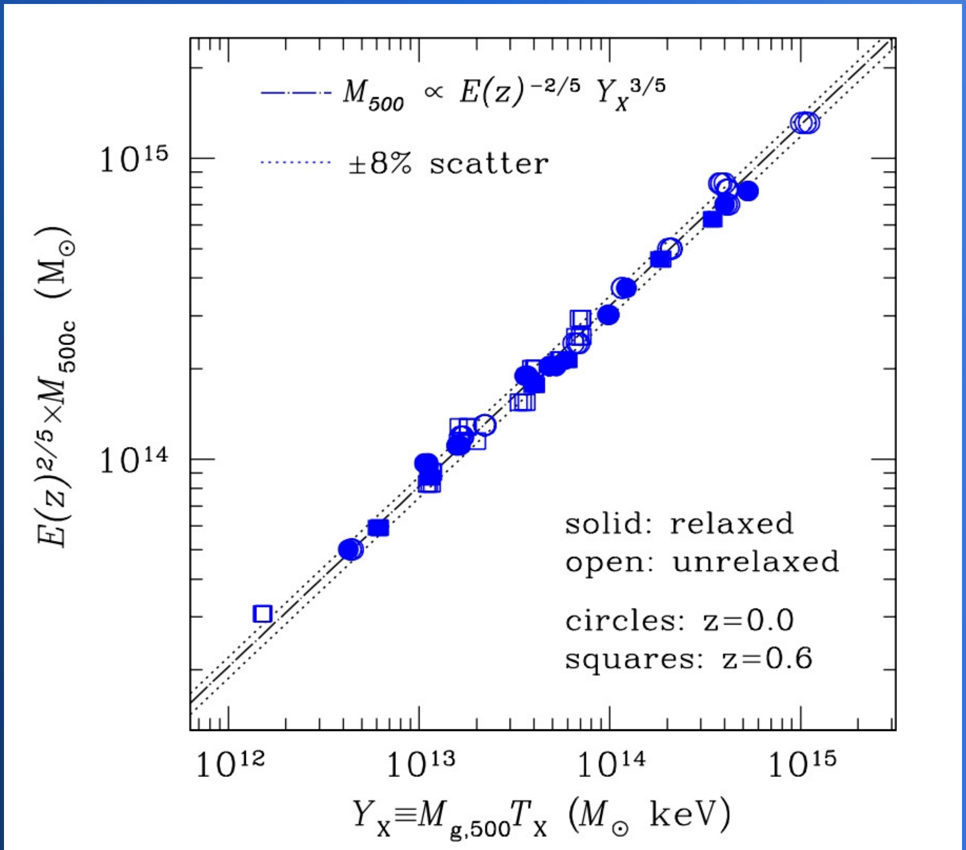

Credit: Brad Benson

# 1st SPT X-ray follow-up program

- 15 highest S/N clusters from 2008 catalog (Vanderlinde et al. 2010)
- Obtain 1500 source cts for ~15% $kT$
- Estimate cluster mass via X-ray calibrated $Y_X$-$M_{500}$ relation
- Observation with both Chandra and XMM
- Results → Andersson et al. 2010, arXiv 1006.3068

# $Y_X$, mass proxy

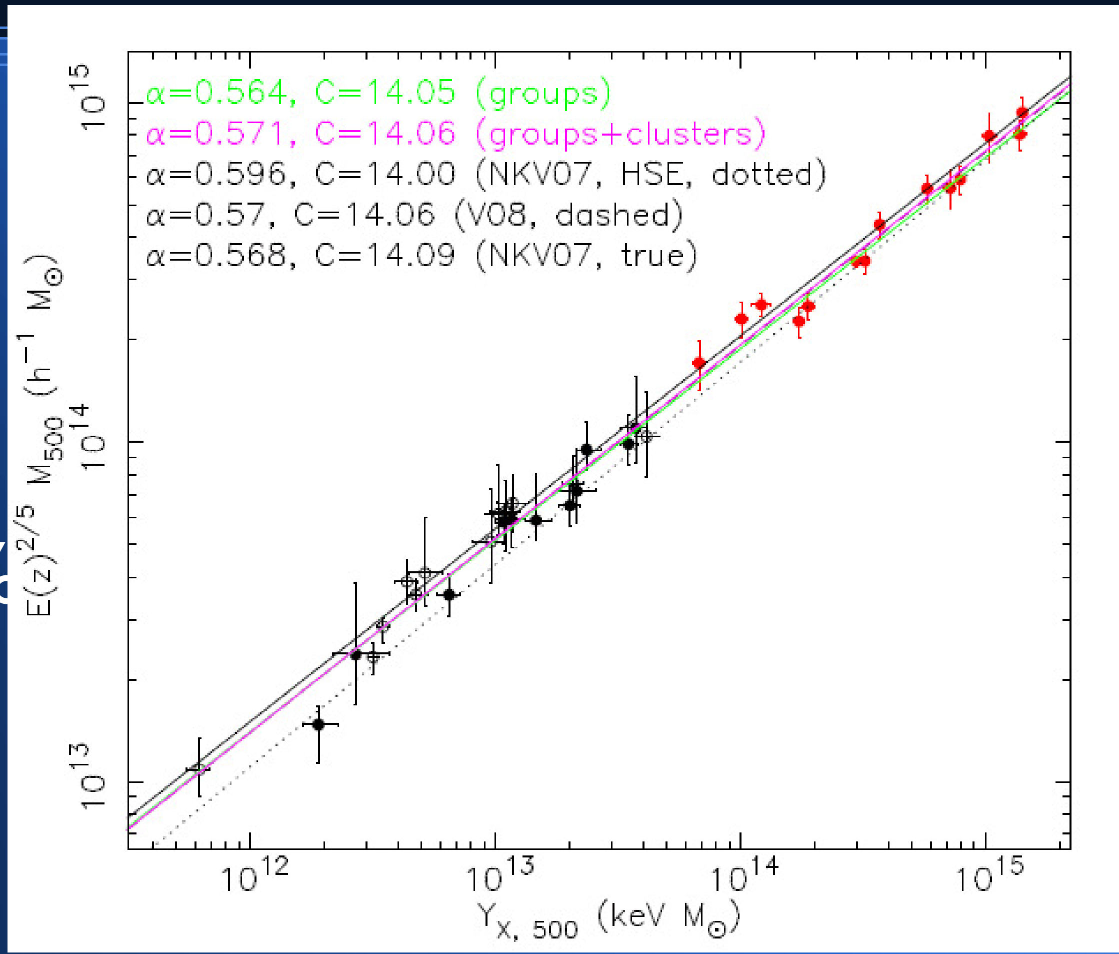
- $Y_X = M_{gas} T_X$
- X-ray mass proxy $Y_X$ has low scatter
- Simulations find < 8%
- Confirmed by observations
- X-ray ~equiv of $Y_{SZ}$




Kravtsov et al. 2006

# $Y_X$, mass proxy

- $Y_X = M_{gas} T_X$
- X-ray mass proxy $Y_X$ has low scatter
- Simulations find < 8%
- Confirmed by observations
- X-ray ~equiv of $Y_{SZ}$



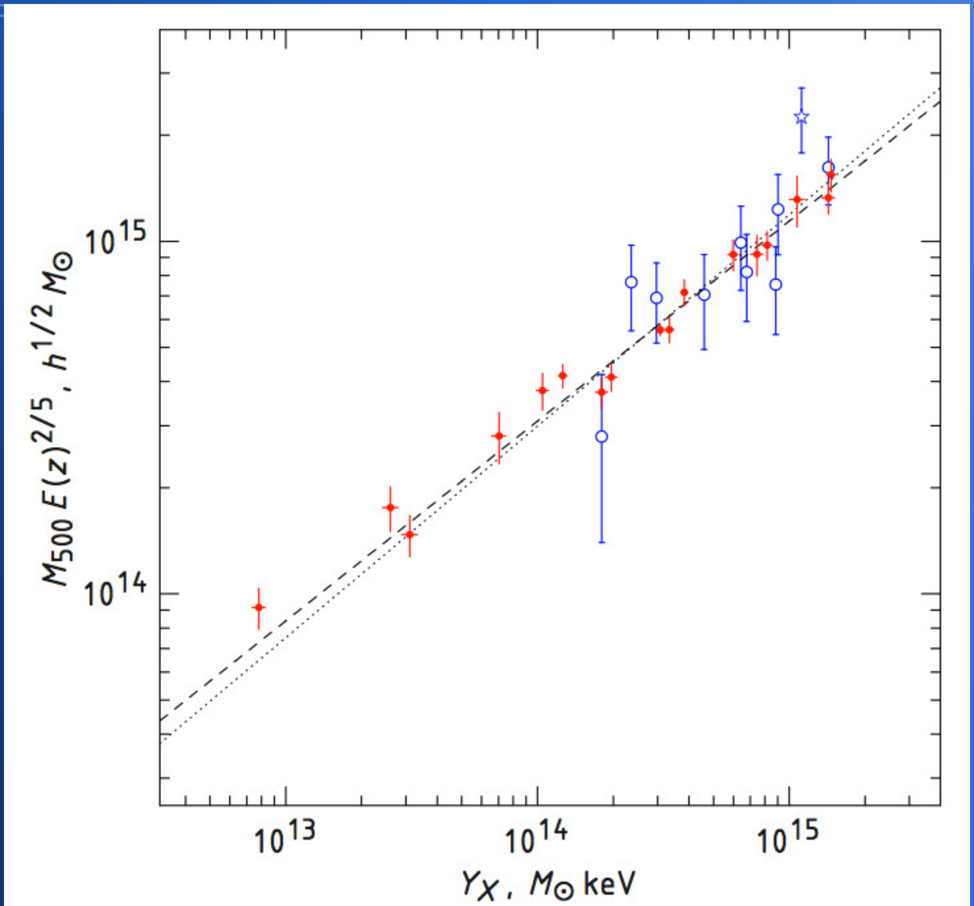

Sun et al. 2009

# $Y_X$ - lensing agreement

- Lensing obs agree with $Y_X$ mass scale within ~9%

  (e.g. Hoekstra+07, Vikhlinin+09)
- Comparisons mostly restricted to z<0.3

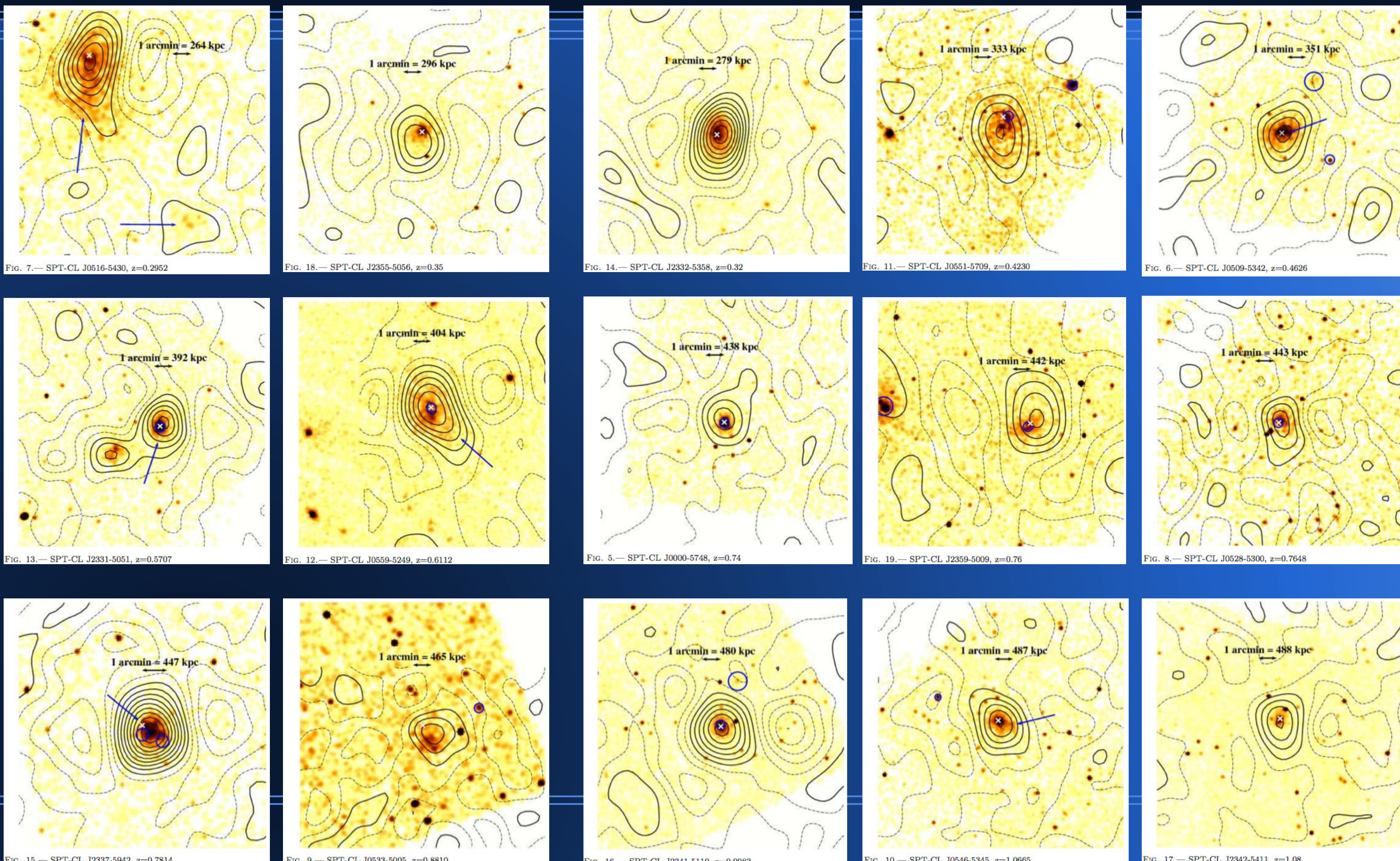
  → propose for more high-z lensing follow-up!




Vikhlinin et al. 2009

# First X-ray study of SZ selected sample

z=0.29




Andersson et al. 2010, 1006.3068

z=1.08

# Cluster modeling → $Y_X$

- Data depth allows for ~1 *kT* measurement
  - No hydrostatic masses
- Model gas density using surface brightness in 0.7-2. keV band
  - Low *kT* dependence
- Can fit variety of cluster morphologies

$$n_e n_p = n_0^2 \frac{(r/r_c)^{-\alpha}}{(1+r^2/r_c^2)^{3\beta-\alpha/2}} \frac{1}{(1+r^\gamma/r_s^\gamma)^{e/\gamma}}$$

**Vikhlinin et al. 2006**

# Spherical $Y_{SZ}$ via deprojection

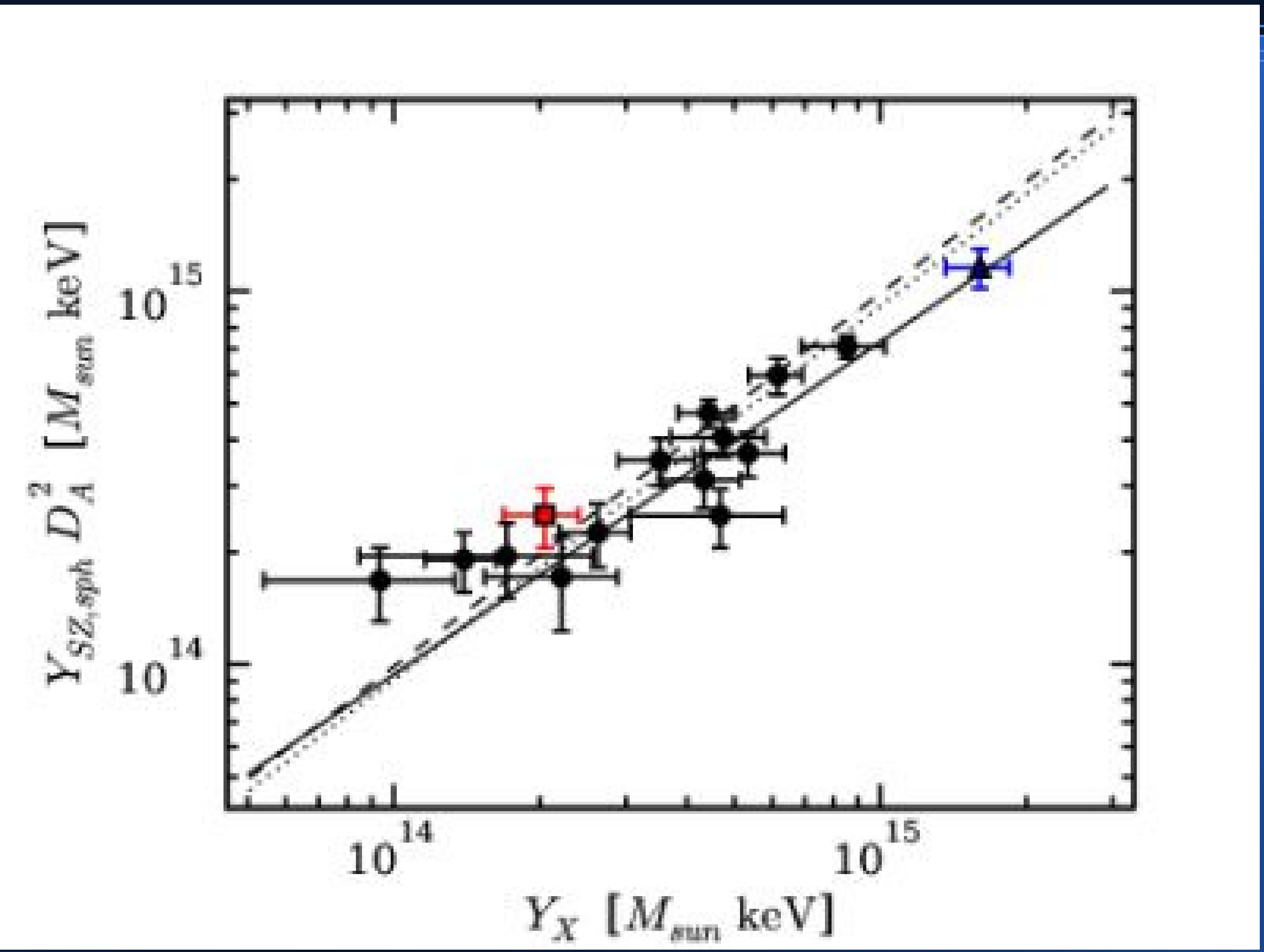
- Vanderlinde et al. 2010, analysis extended
- Spatially filter SPT maps using information from X-ray gas density profile + “universal” temperature profile (also Arnaud+09 pressure)

$$T(r) = T_0 \frac{(x/0.045)^{1.9} + 0.45}{(x/0.045)^{1.9} + 1} \frac{1}{(1 + (x/0.6)^2)^{0.45}}$$

**Vikhlinin et al. 2006**

- De-project $Y_{SZ}$ using these same profiles

# $Y_{SZ}$-$Y_X$ relation



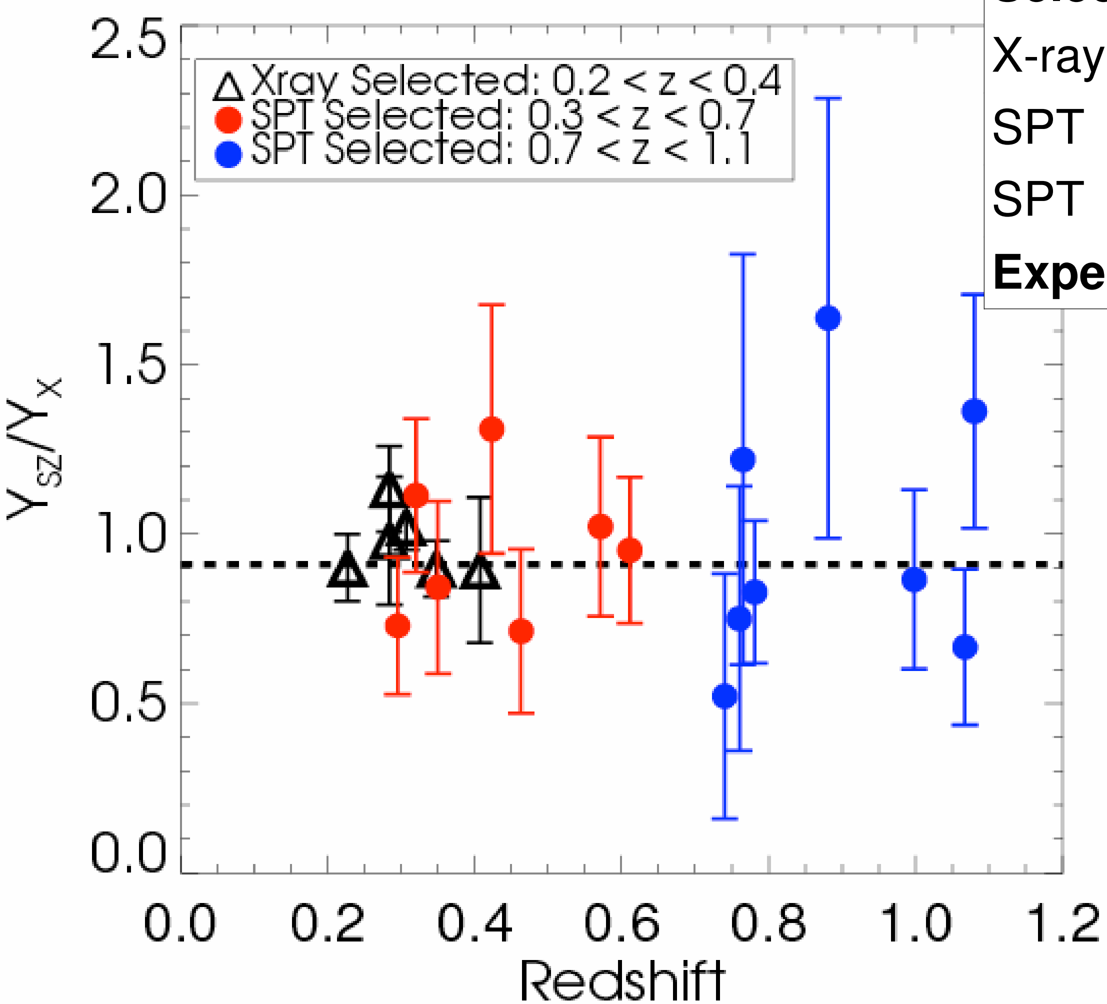

- Slope consistent with expected =1
- Normalization implies $Y_{SZ}$=0.82+-0.07 $Y_X$
- Expected $Y_{SZ}/Y_X$ ratios from different gas models

| | |
|---|---|
| Arnaud+09 | 0.924 |
| Vikhlinin+06 | ~0.91 |
| Suzaku recent | <0.9? |

(Bautz+09 A1795, George+09 PKS 0745-191, Reiprich+09 A2204, Hoshino+10 A1413 ...)

Measuring $T_{mg}/T_X$

# $Y_{SZ}$-$Y_X$ relation evolution?

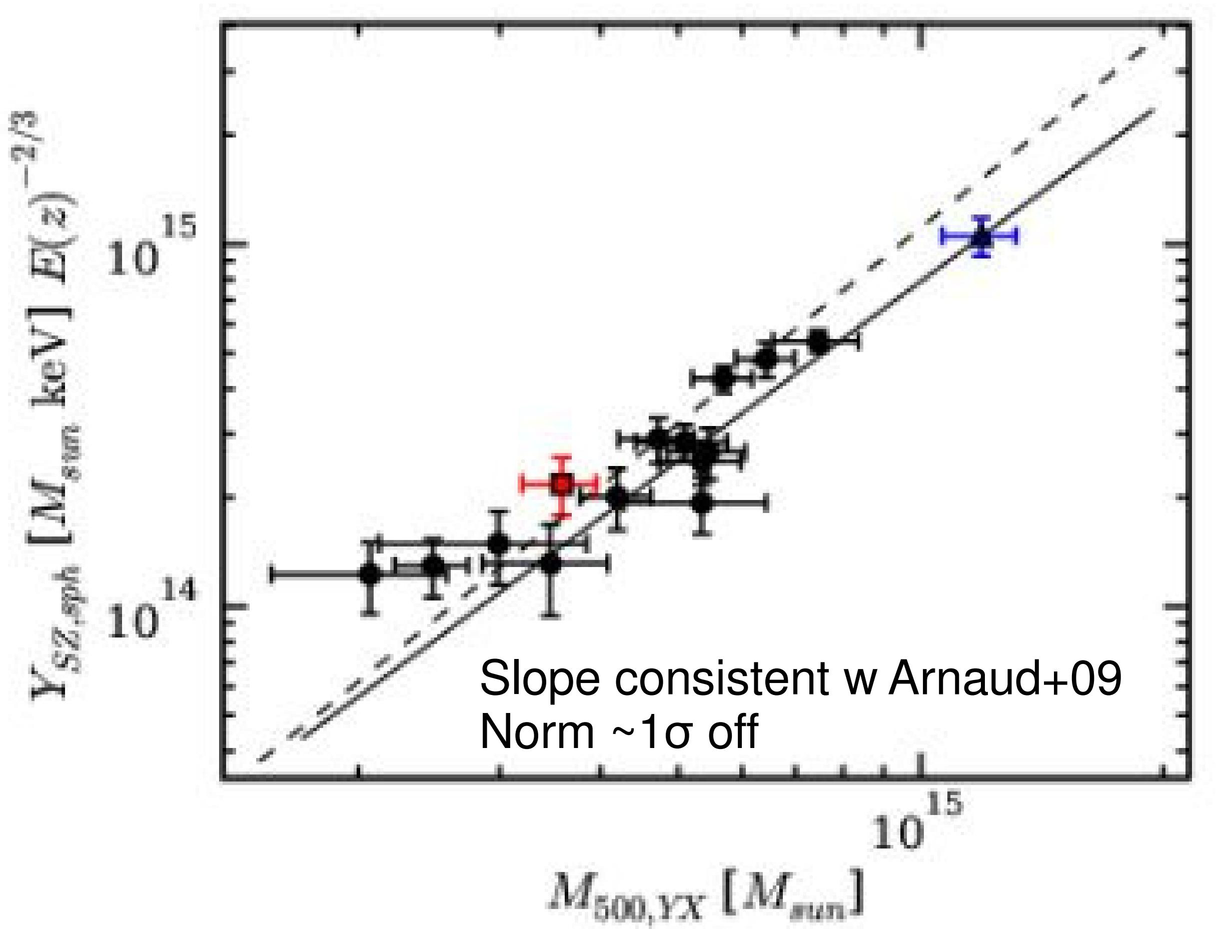



| Selection | Redshift | Ysz/Yx (r500) |
|---|---|---|
| X-ray | 0.2<z<0.4 | 0.95+-0.04 |
| SPT | 0.3<z<0.7 | 0.88+-0.12 |
| SPT | 0.7<z<1.1 | 0.72+-0.14 |
| **Expected** | | **0.91+-0.01** |

- Same conclusion when using Vikhlinin et al. 2006 and Arnaud et al. 2009 profiles
- Good X-ray and SZ agreement at z<0.7
- Some underexposed clusters at high z
- Upcoming observations may resolve this discrepancy

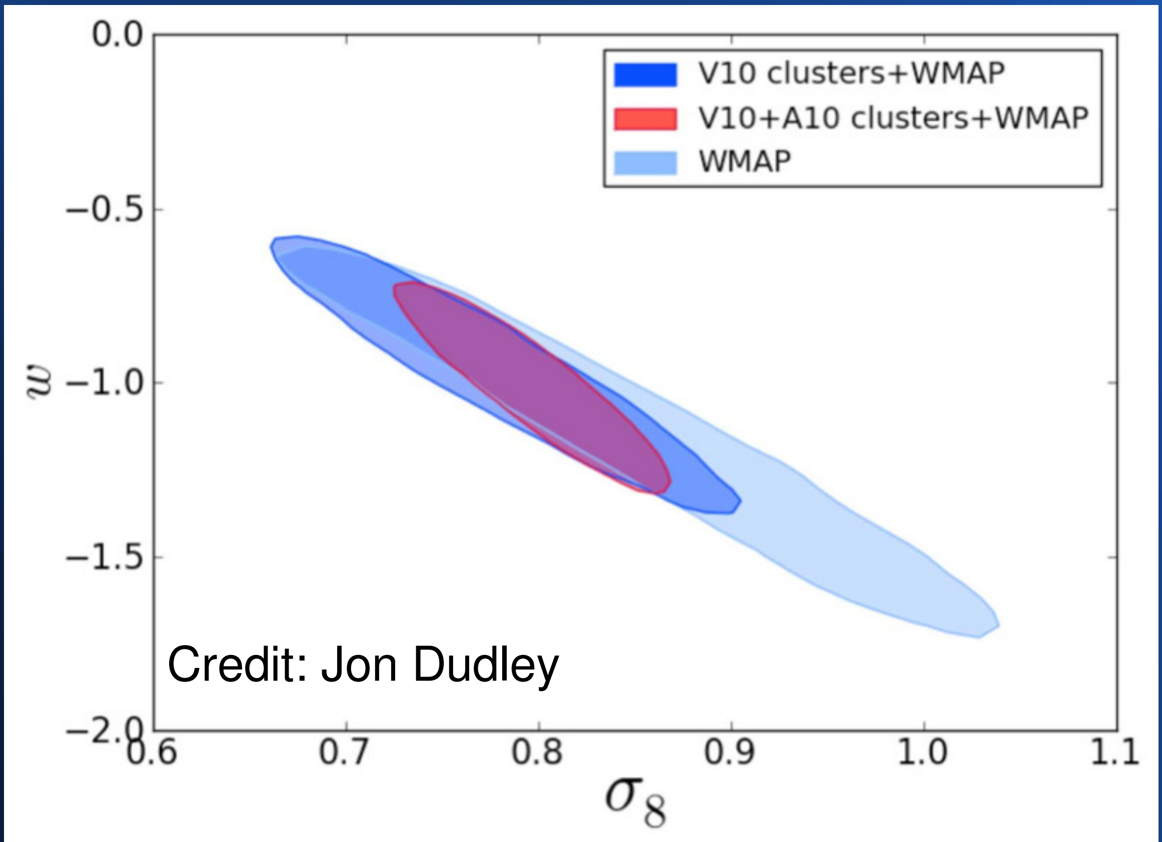
Note: SPT selection function not corrected for in plot, but in SPT selected ratios

# $Y_{SZ}$-$M_{500}$ relation




- Similar to previous plot
- Slope: 1.67+-0.29
- Masses estimated through X-ray calibrated M-$Y_X$ relation
- Can use these masses to calibrate the SZ mass observable relation presented in Vanderlinde et al 2010

# Preliminary: improvement of cosmological constraints




- *w* constraints improved by ~30%
- $\sigma_8$ by ~50%
- More work needed
- Constraints based on just 21 clusters with 15 having (limited) X-ray follow-up
- Full SPT survey will have ~400 clusters
- Separate XMM proposals to constrain low-z and high-z mass-observable norm.

# Summary

- First X-ray follow-up of SZ selected sample
- X-ray mass calibration gives mass-SZ scaling consistent with previous studies
- Improves cosmological constraints of SPT
- SZ and X-ray integrated pressure agree well
- Improvement of SPT results require additional X-ray and optical observations to high-z

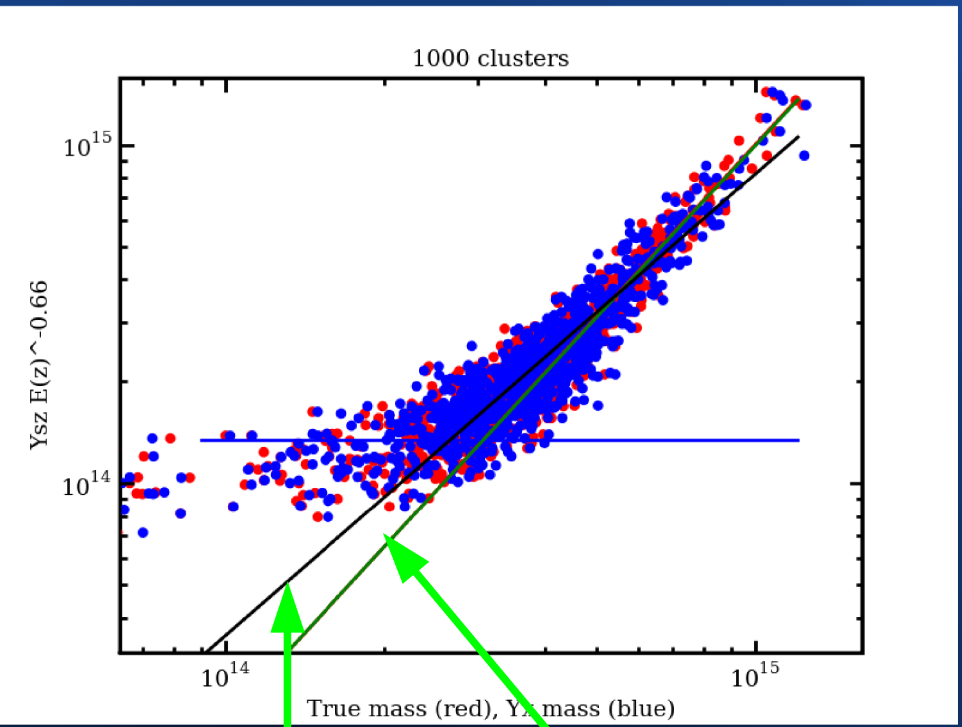
# SZ selection effect

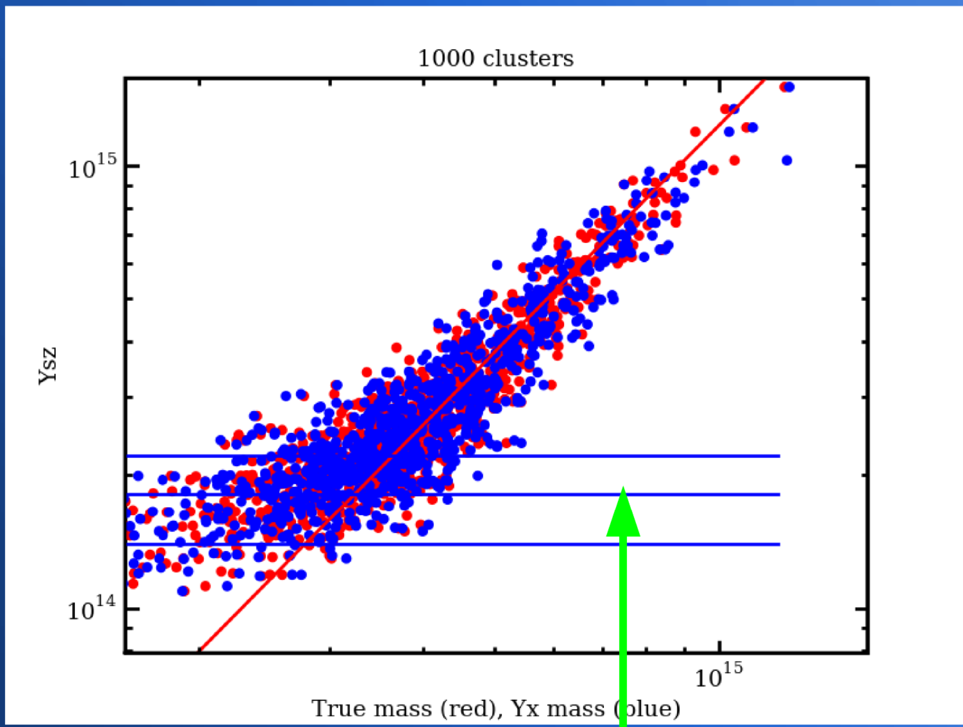
- SZ selection impacts scaling relations
- Selection is applied by truncating probability of Ysz given M and renormalizing
- Here, the \xi=5.5 cut is modeled as an errorfunction in Ysz

$$P_{sel}(\ln Y_{SZ}) = \frac{1}{2}\left(1 + erf\left(\frac{\ln Y_{SZ} - \ln Y_{SZ,\xi-cut}}{\sqrt{2\sigma^2_{\ln Ysz - \ln \xi}}}\right)\right)$$

# SZ selection effect

1000 mock clusters drawn from a mass function



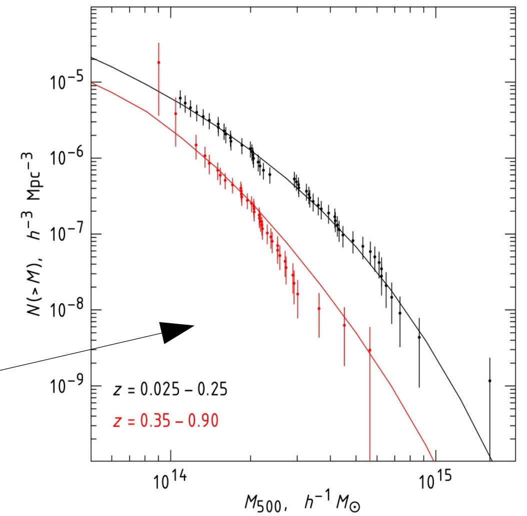




Fit without selection cut applied

Input scaling relation and best fit

Cut threshold, \xi=5.5

# Not quite that simple




**Mass function- and selection effects**

- Cluster mass function is steep!
- Log-normal distribution of intrinsic scatter in Y for given mass
- For a measured Y, distribution is biased towards low mass
- Will tend to find low mass clusters with Y biased high

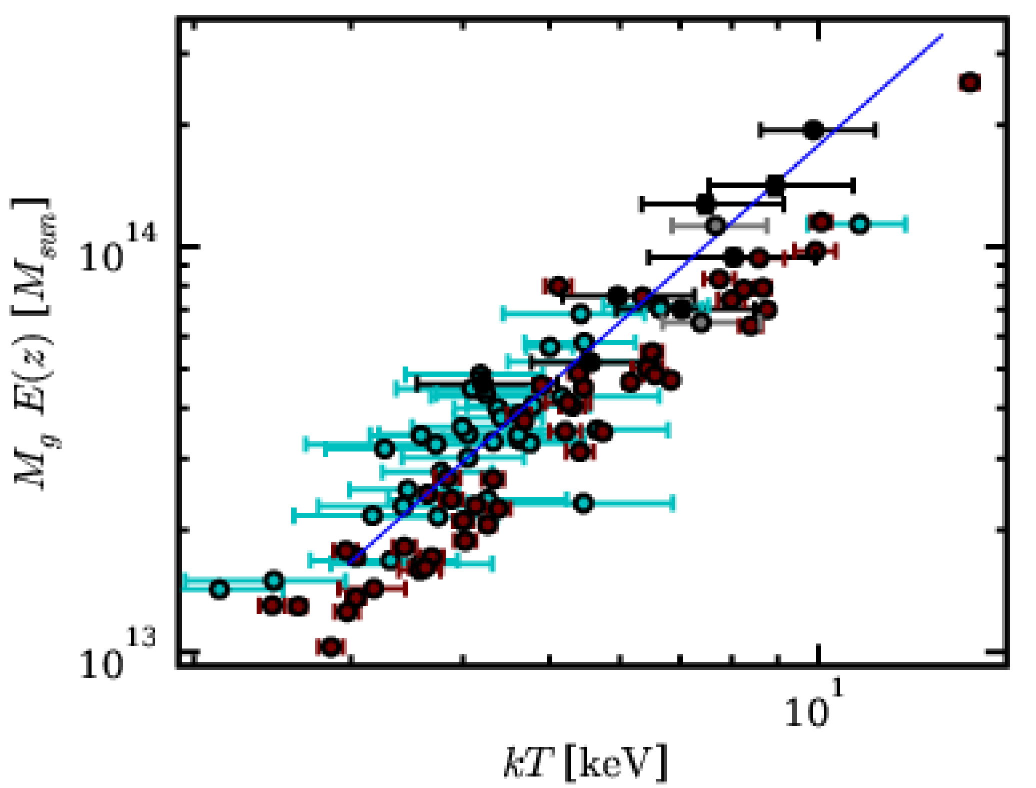
- Similarly, the measured $Y_{SZ}$ is biased high since low signal-to-noise
- Again, will tend to find low mass clusters with $Y_{SZ}$ biased high
- Also selection cut on signal-to-noise, not straightforwardly related to $Y_{SZ}$
- Plan to use Mantz+09 type approach for self-consistency

# SZ mass estimation

- use Bayes theorem, to calculate the probability distribution of M given the SPT significance

$$\frac{dP(\ln M|\xi)}{d\ln M} \propto \frac{dN}{d\ln M} P(\xi|\ln M)$$

# Scaling relations: $M_g$-T

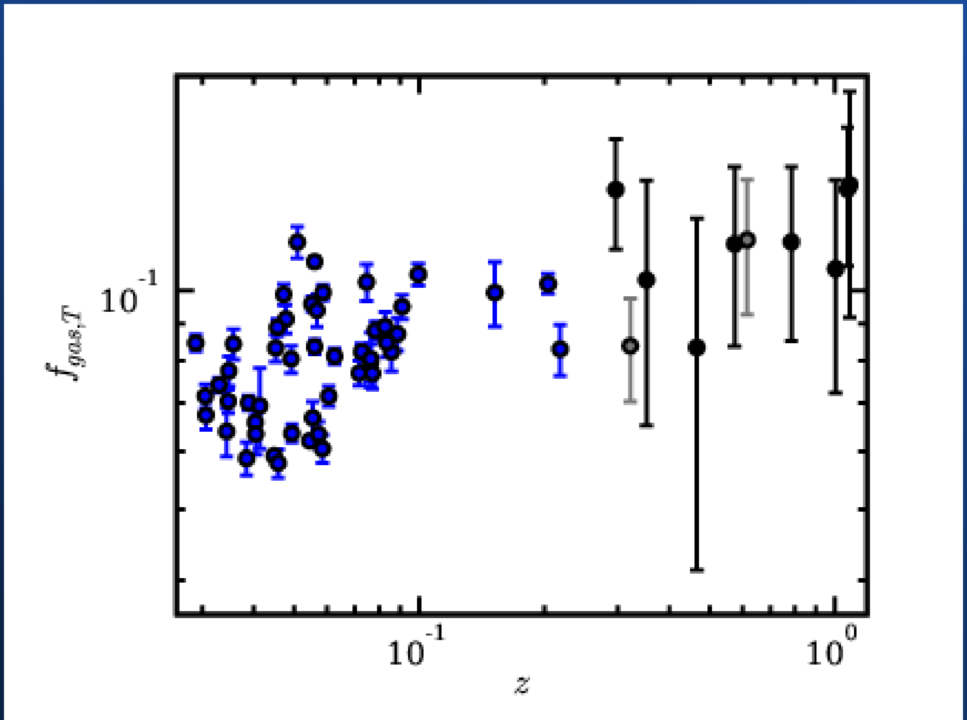


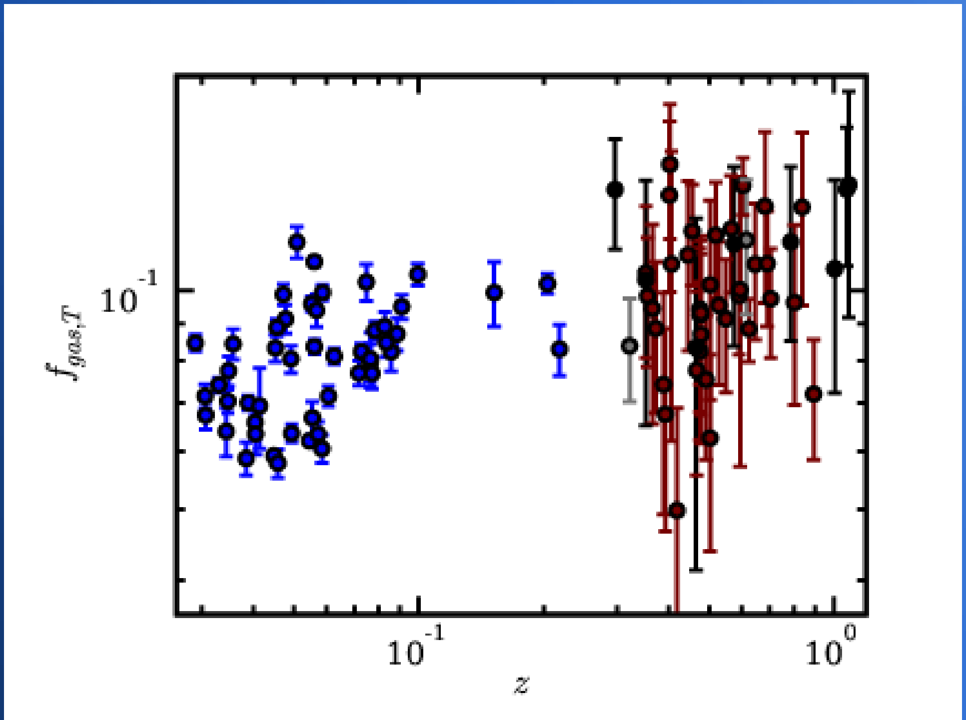

Compared here to local (z<0.2) sample from V09
Offset disappears when the self-similar E(z) scaling is removed

Indicates that $f_{gas}$ is not constant with z

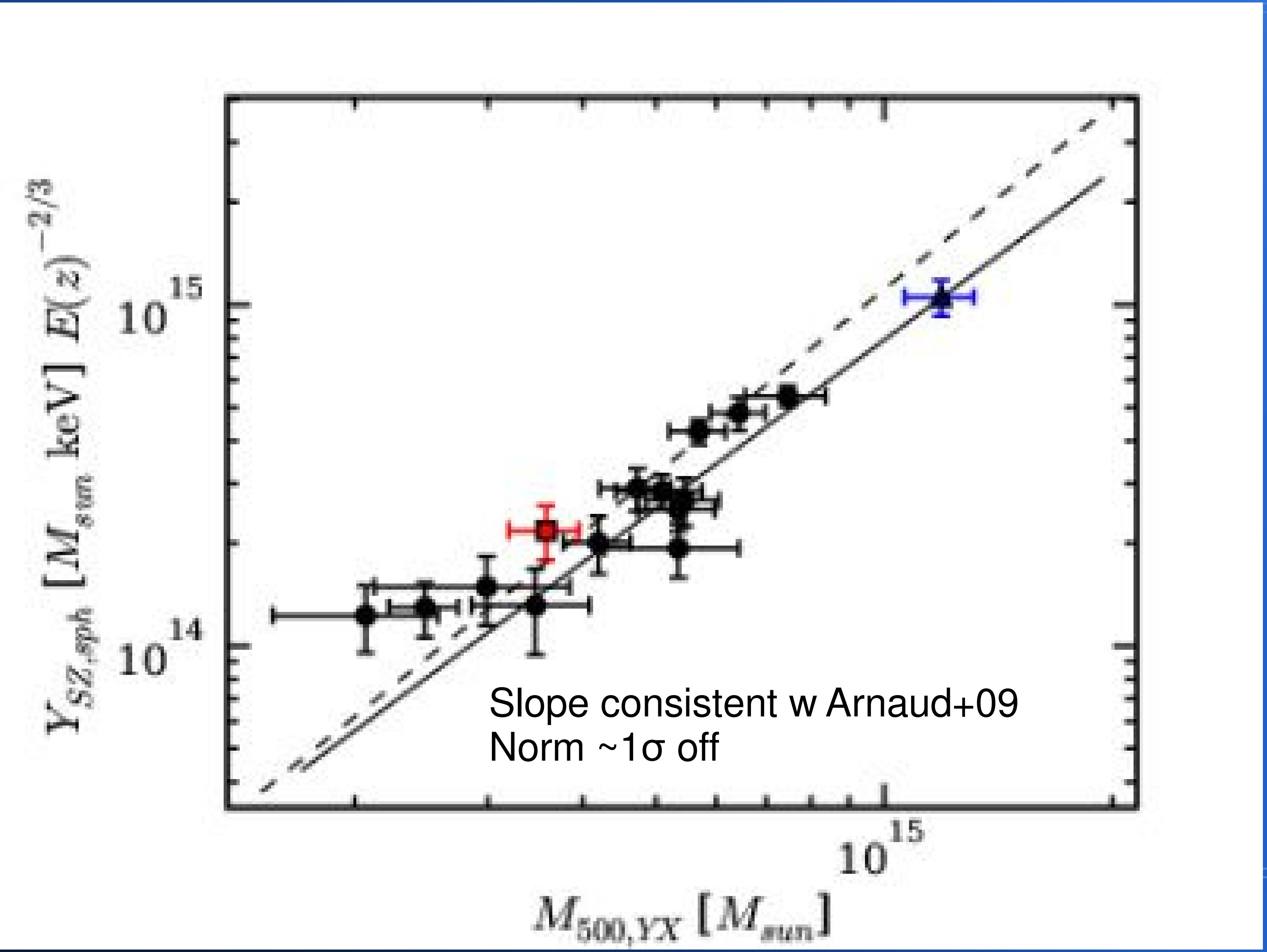
Also powerlaw slope = 1.95+-0.66 > self similar 1.5 → $f_{gas}$ increases with mass

# $f_{gas}$ vs z



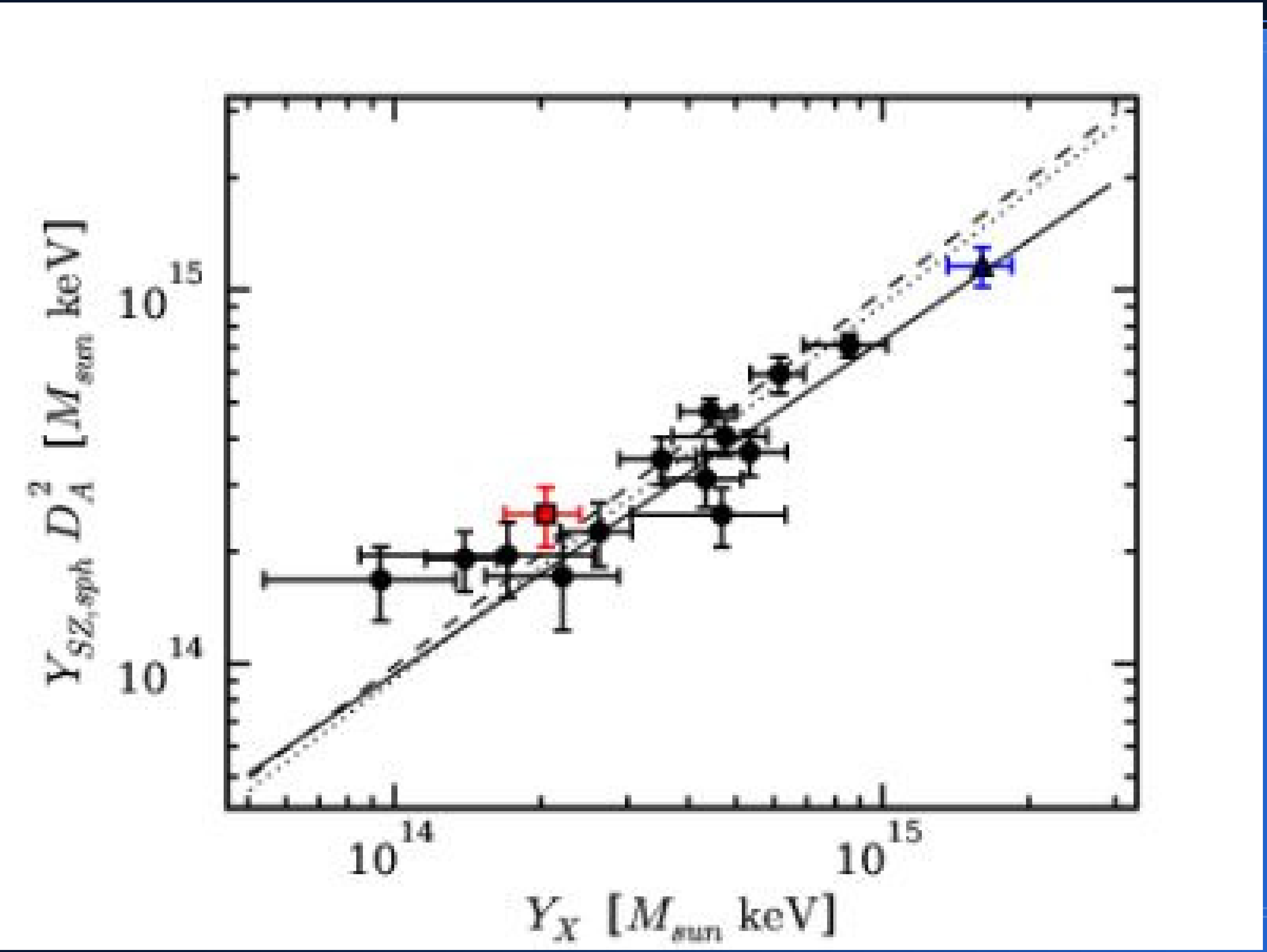



# $Y_{SZ}$ - $M_{500,YX}$



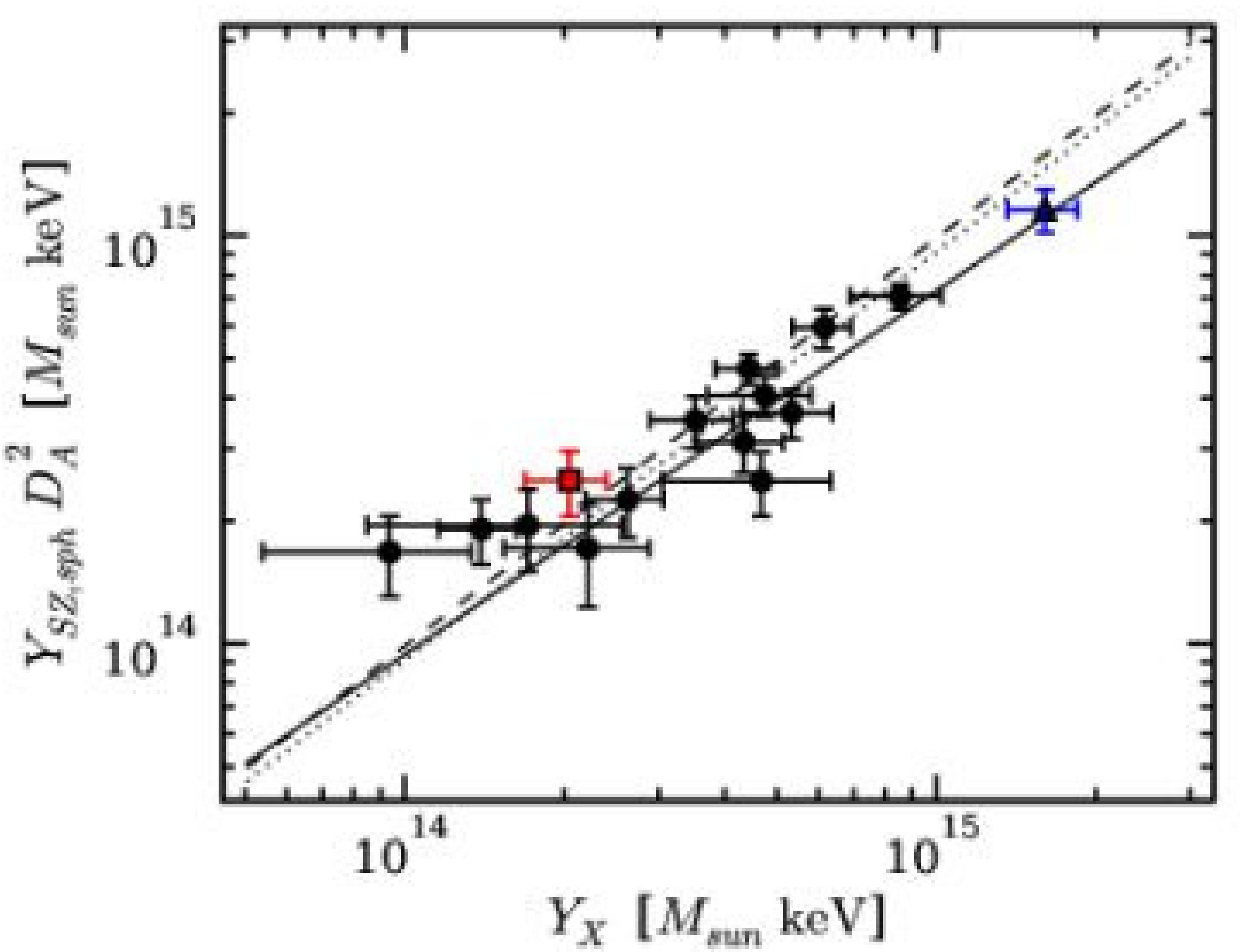
$Y_{SZ,sph}$ [$M_{sun}$ keV] $E(z)^{-2/3}$
$10^{15}$
$10^{14}$
$10^{15}$
$M_{500,YX}$ [$M_{sun}$]
Slope consistent w Arnaud+09
Norm ~1σ off

# $Y_{SZ}$ - $Y_X$



$10^{15}$
$10^{14}$
$Y_{SZ,sph}\,D_A^2\ [M_{sun}\ \mathrm{keV}]$
$10^{14}$
$10^{15}$
$Y_X\ [M_{sun}\ \mathrm{keV}]$

# $Y_{SZ} - Y_X$, z-dependence?




**z<0.7**
**Ysz/Yx = 0.88+-0.12**

**z>0.7**
**Ysz/Yx = 0.72+-0.14**

**More data available on high-z clusters should help shed some light on this**

# XMM analysis, calibration

- 2 clusters have both XMM and Chandra exposures
  - SPT-CL J2337-5942 (z=0.78)
  - SPT-CL J0516-5430 (z=0.295)
- Can check results to confirm XMM pipeline reliability
- Important if we'll have more XMM data in future
- SPT-CL J0516-5430 also analyzed in ACT paper

# XMM analysis, calibration

- SPT-CL J2337-5942 (z=0.78)
- $kT_{XMM} = 9.3^{+1.1}_{-0.8}$, $kT_{Chandra} = 8.9^{+2.0}_{-1.4}$ keV

- SPT-CL J0516-5430 (z=0.295)
- $kT_{XMM} = 9.1^{+0.6}_{-0.5}$, $kT_{Chandra} = 9.8^{+1.7}_{-1.2}$ keV

Something odd with the ACT X-ray analysis, uses 3 Mpc radius for XMM

- ACT-CL J0516-5430 (using same X-ray data)
- $kT_{XMM} = 7.44$+-0.38, $kT_{Chandra} = 13.36^{+3.01}_{-2.28}$ keV

# XMM analysis, calibration

- TODO: Check $M_{gas}$ analysis Chandra v XMM
- Preliminary results show good agreement for 2337 and 0516.
- Chandra density profiles slightly steeper towards center but with small impact on $M_{gas}$
- XMM analysis could potentially benefit from better bkg modeling (e.g. Werner et al)

# Future work

- 15 cluster sample contains many mergers (9/15) but also many sharp central peaks (~6)
- CC fraction at high-z is expected to be low from previous X-ray analyses
- Contradiction?

- Further study $f_{gas}(z)$, compare to low-z X-ray selected samples.

# Future work

- Can we add in the targeted cluster sample to better study z-evolution in Ysz-Yx and Ysz-M relations?
- Could provide a local datapoint
- Is there anything in the SZ observations/ analysis that prevents a direct comparison with the Ysz of survey clusters? Large scale modes?
- Selection of targeted sample?

# Future work

- Tabulate $Y_X$ as function of [E(z,cosmo), $D_A$(z,cosmo)] for a reasonable set of cosmo pars → plug in to Cosmo MC

- Study feasibility of XMM proposal with Chandra snapshots