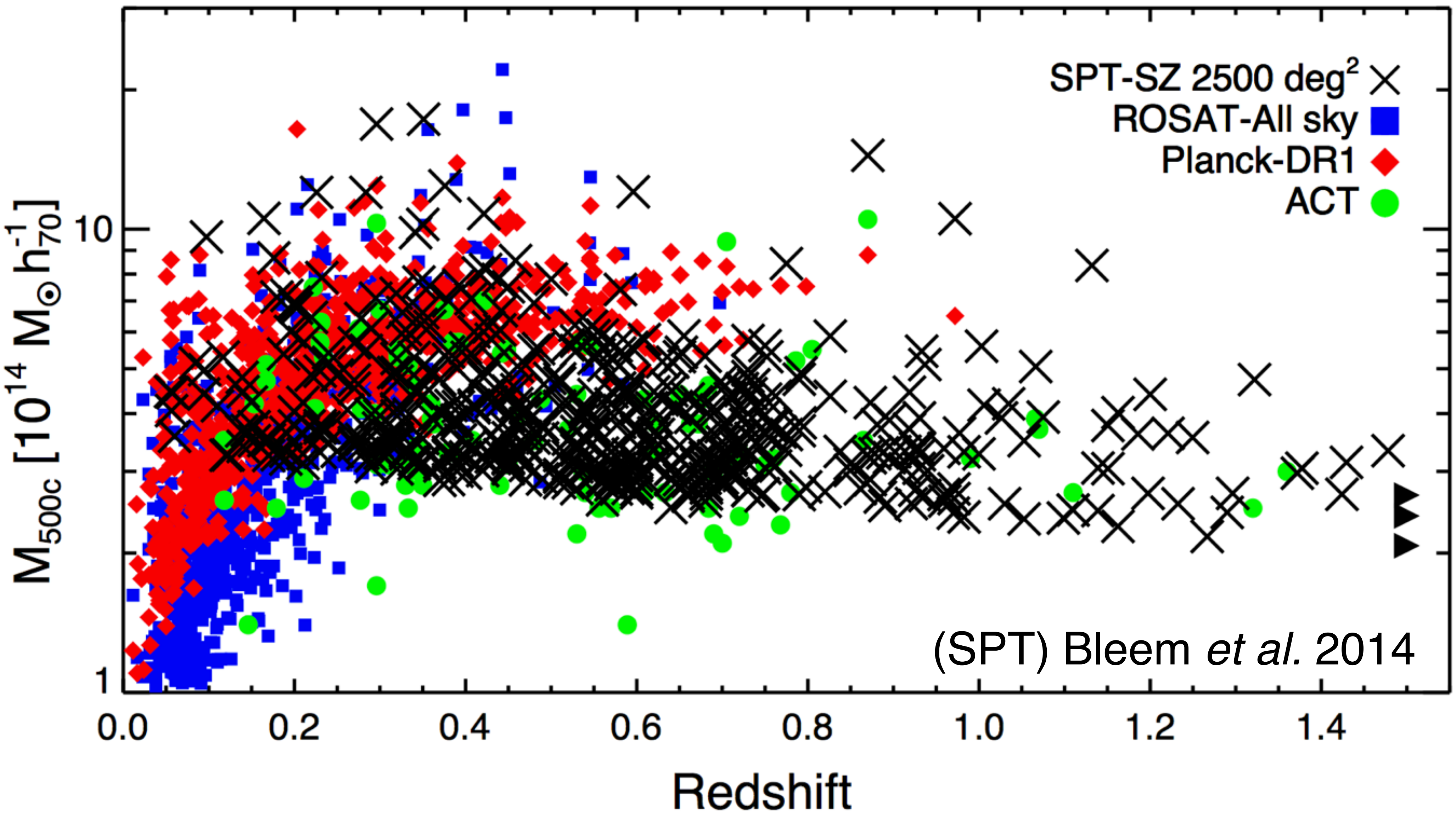
Cluster Cosmology with the South Pole Telescope

Bradford Benson
(Fermilab, U. Chicago)

SZ Cluster Surveys: Mass vs Redshift



	Area (deg²)	**Depth** (uK-arcmin)	$N_{clusters}$
Planck	All-sky	~45	861
SPT	2500	17	516
ACT	950	23-40	91

First SZ-discovered cluster was in 2008** (Staniszewski et al); **6 years later there are > 1300 SZ-identified clusters!

Dark Energy and Cluster Cosmology

- Abundance of clusters is sensitive to the **dark energy equation of state, $w = p / \rho$**

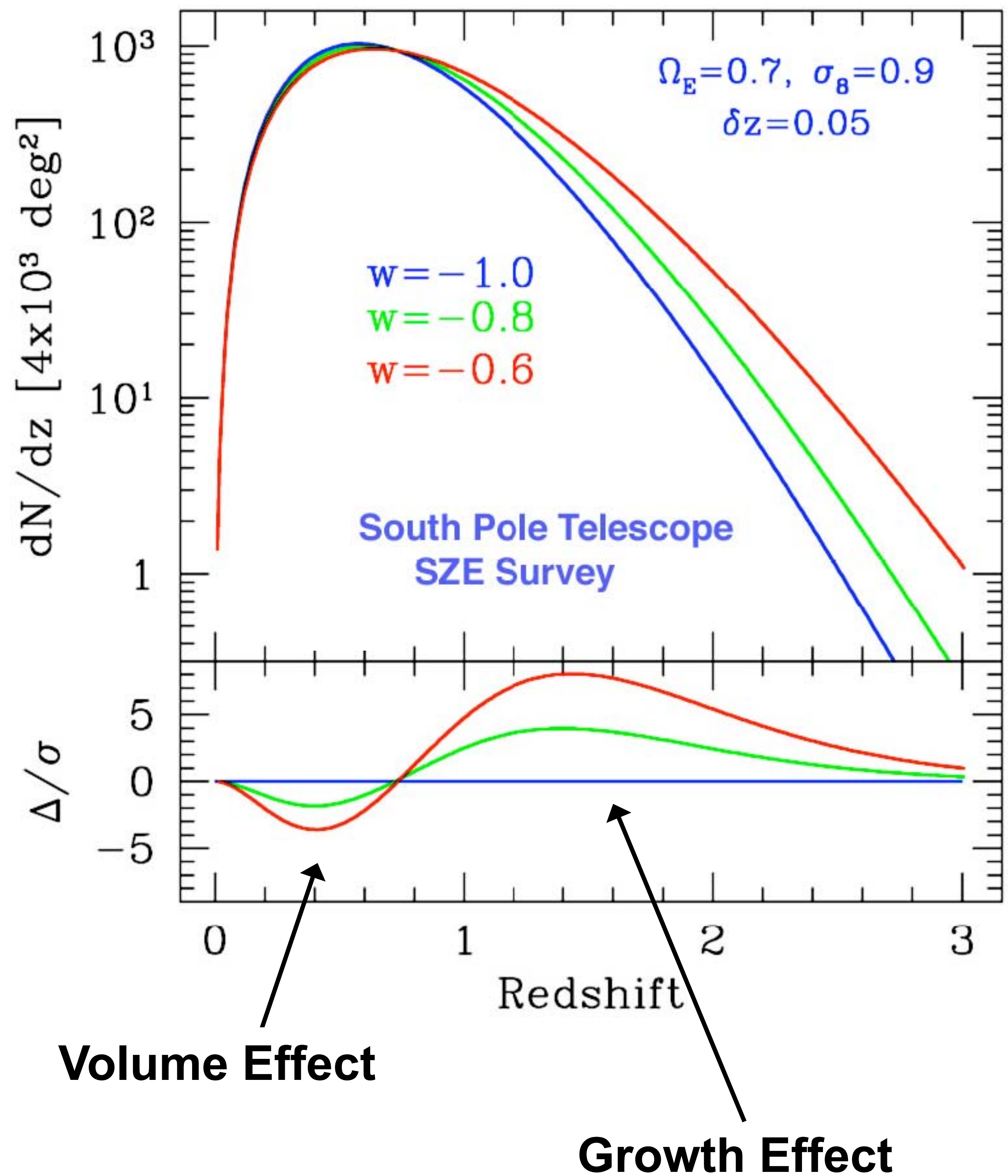
- If dark energy was due to a cosmological constant then w = -1

Cluster Abundance: dN/dz

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

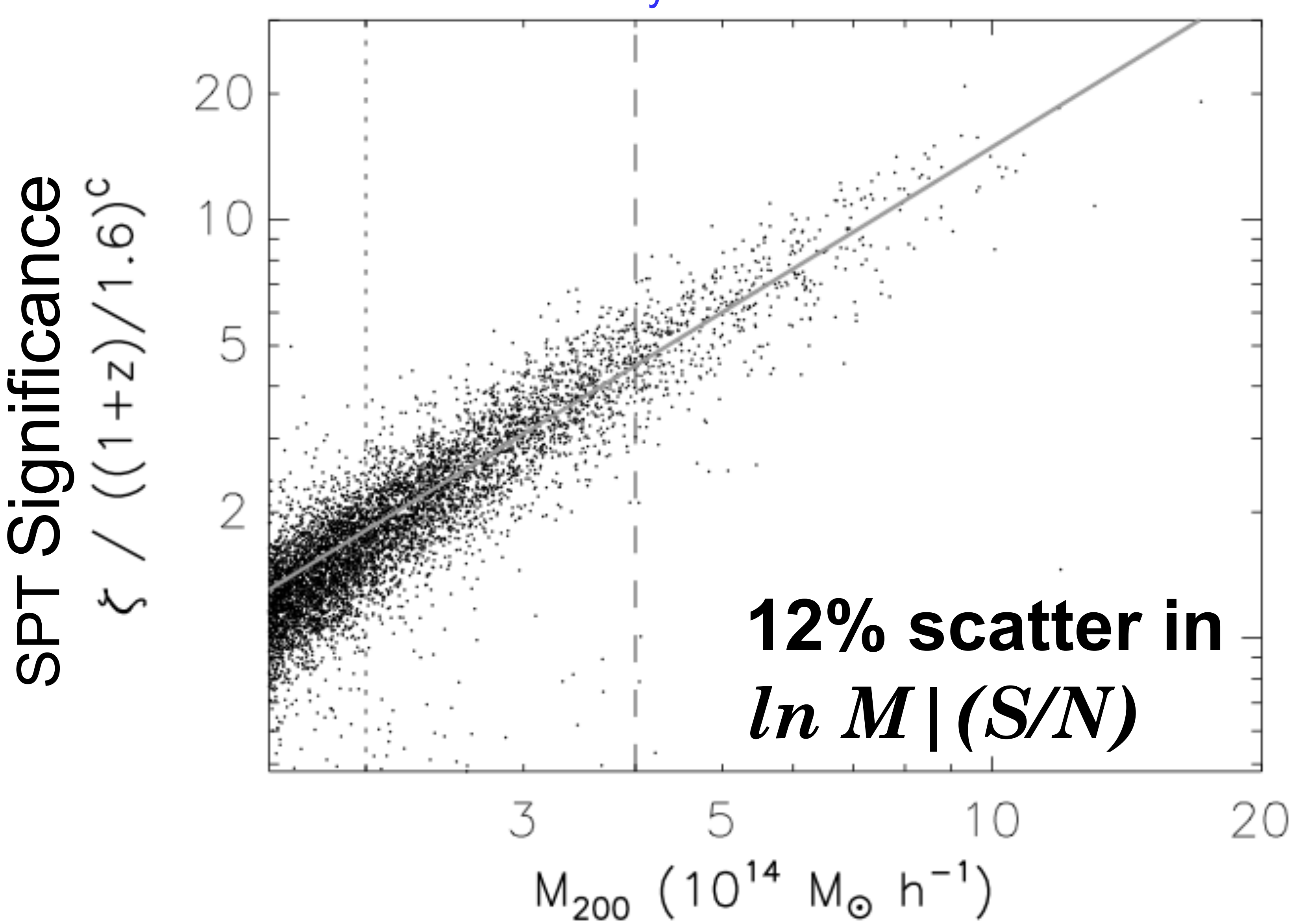
Depends on: (for $n(z)$)
Matter Power Spectrum, σ_8
Growth Rate of Structure, *D(z)*

Depends on: (for $\frac{dV}{d\Omega dz}$)
Rate of Expansion, *H(z)*



SPT Significance as a Mass Proxy

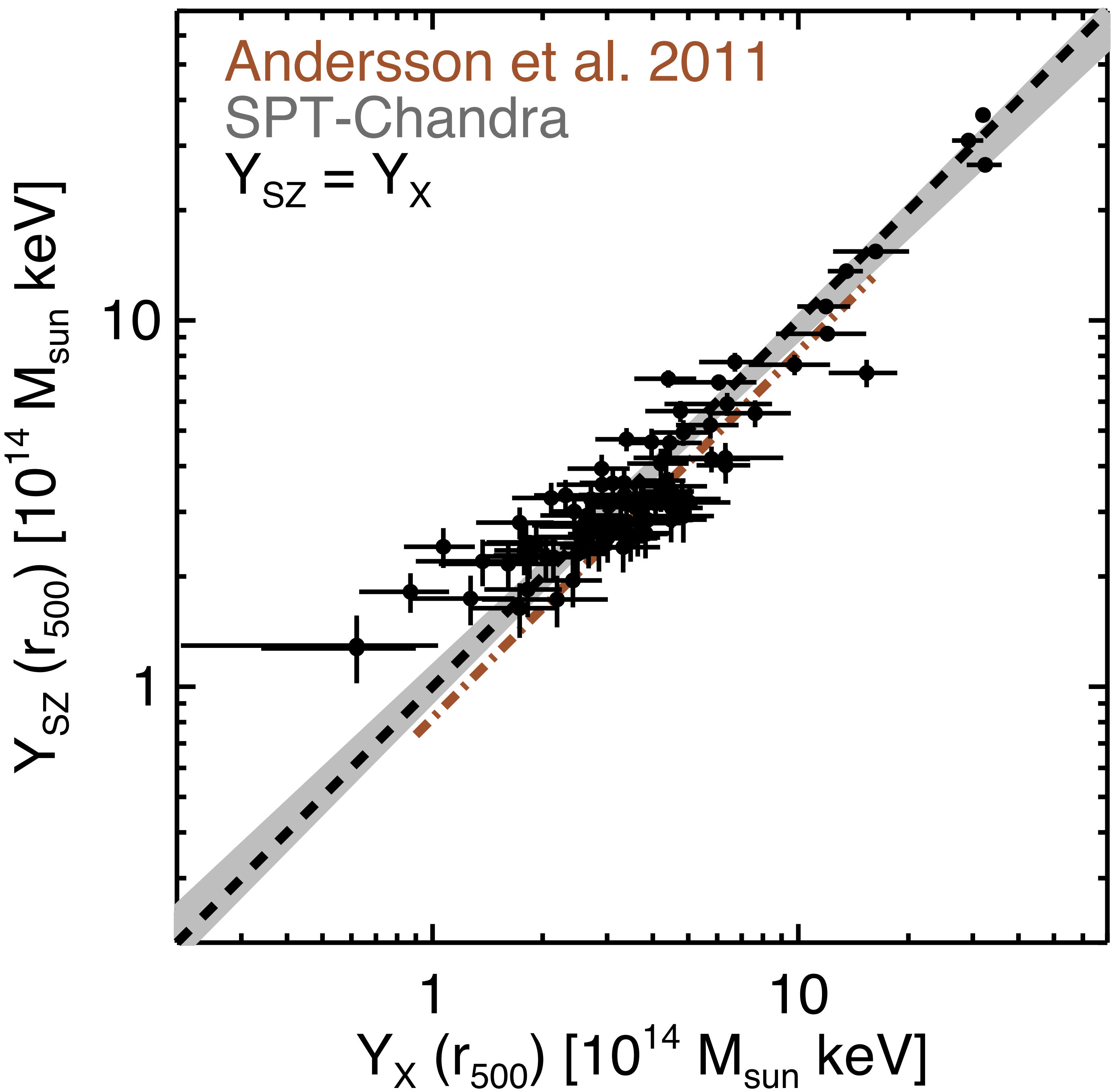
From Simulations by Laurie Shaw



- The challenge for any cluster survey is to link cluster "observable" to cluster mass
- ***The SZ flux is expected to be a low-scatter observable*** (Kravstov 2006, Fabjan 2011, Battaglia 2012)
- S/N in filtered SPT map is a low-scatter mass proxy (Vanderlinde+10)
- **Scatter in $ln(M)$**
  - **7% given Ysz, Yx**
  - ***12% given $SPT\ S/N$***
  - ***~25% given $X\text{-}ray\ Lx$***
  - ***~30% given $Richness$***

Ysz-Yx Relation:

Fit using 83 Clusters with Chandra X-ray Observations



SZ vs X-ray measure of "Compton" Y parameter (density x temperature)

- 1:1 relation with no tilt
- No redshift-evolution
- Low-scatter (~10%)

Benson et al., (2014), in prep

Cosmological Analysis:

Combine X-ray Observables with SPT Cluster Survey

Use Markov-Chain Monte Carlo (MCMC) method to vary cosmology and cluster observable-mass relation simultaneously, while accounting for SZ selection in a self-consistent way

6 Cosmology Parameters (plus extension parameters)

- ΛCDM Cosmology
  - $\Omega_{\rm m}h^2$, $\Omega_{\rm b}h^2$, $A_{\rm s}$, n_s, $\boldsymbol{\theta}_s$
- Extension Cosmology
  - w, Σm_ν, f_{NL}, N_{eff}

9 Scaling Relation Parameters

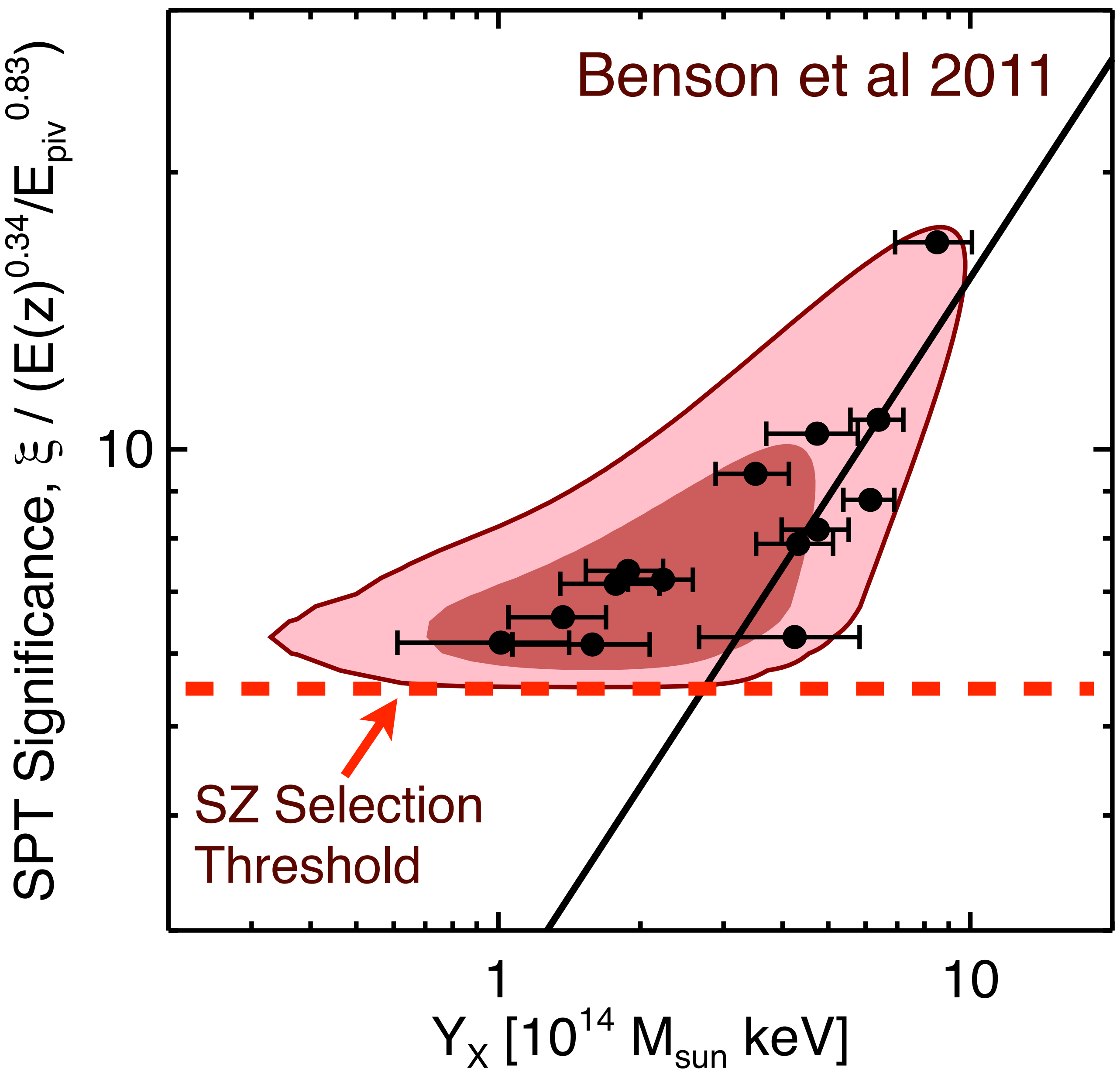
- X-ray (Yx-M) and SZ ($\boldsymbol{\zeta}$-M) relations (4 and 5 parameters):
  - A) normalization,
  - B) slope,
  - C) redshift evolution,
  - D) scatter,
  - F) correlated scatter

Benson et al 2011, arXiv: 1112.5435

SPT Significance-Mass Calibration

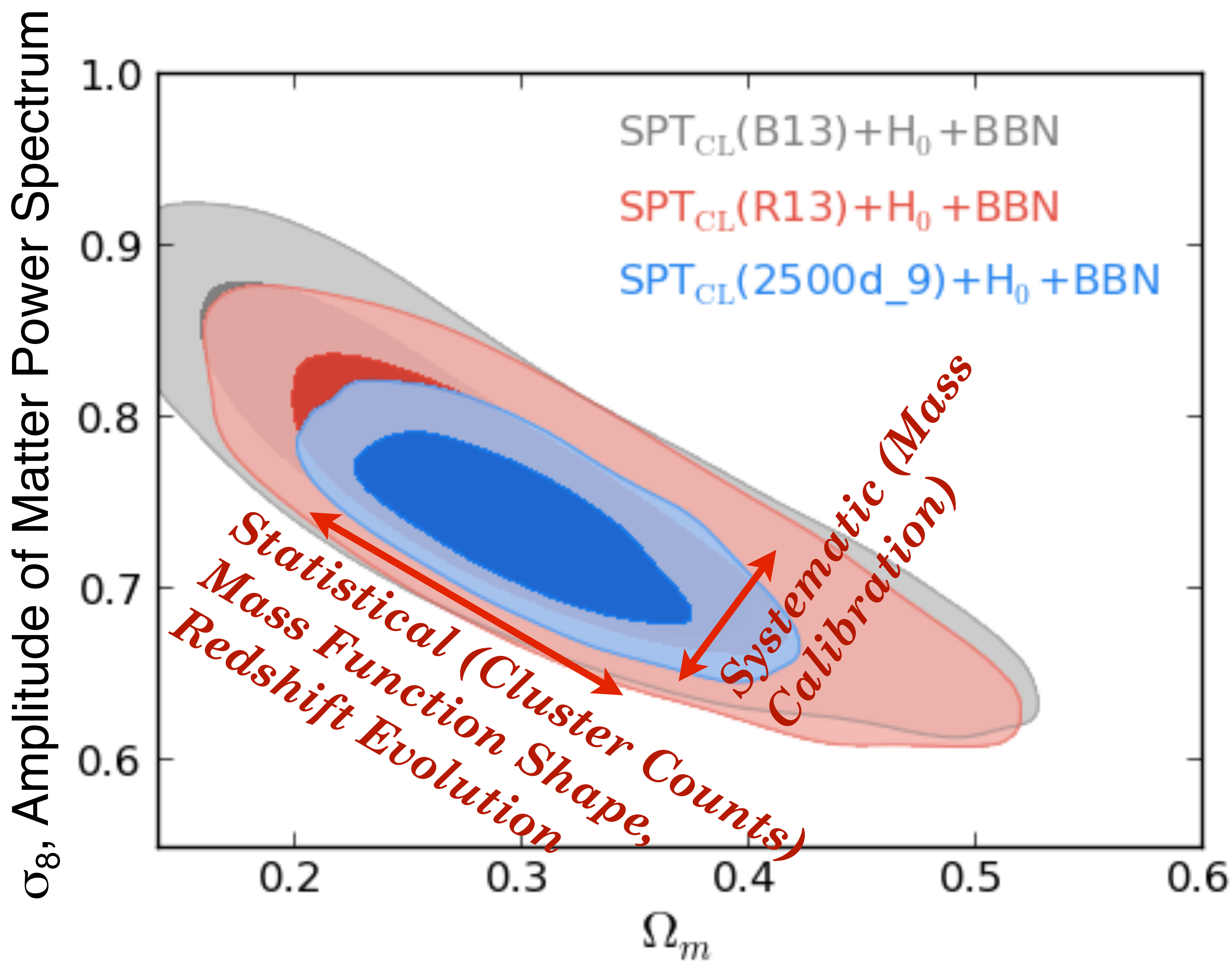
Use X-ray (Yx-M) relation to calibrate SPT significance-mass relation:

- ***X-ray observations calibrate slope, scatter, redshift evolution***
- ***Weak Lensing calibrates mass normalization (~10-15% accuracy)***



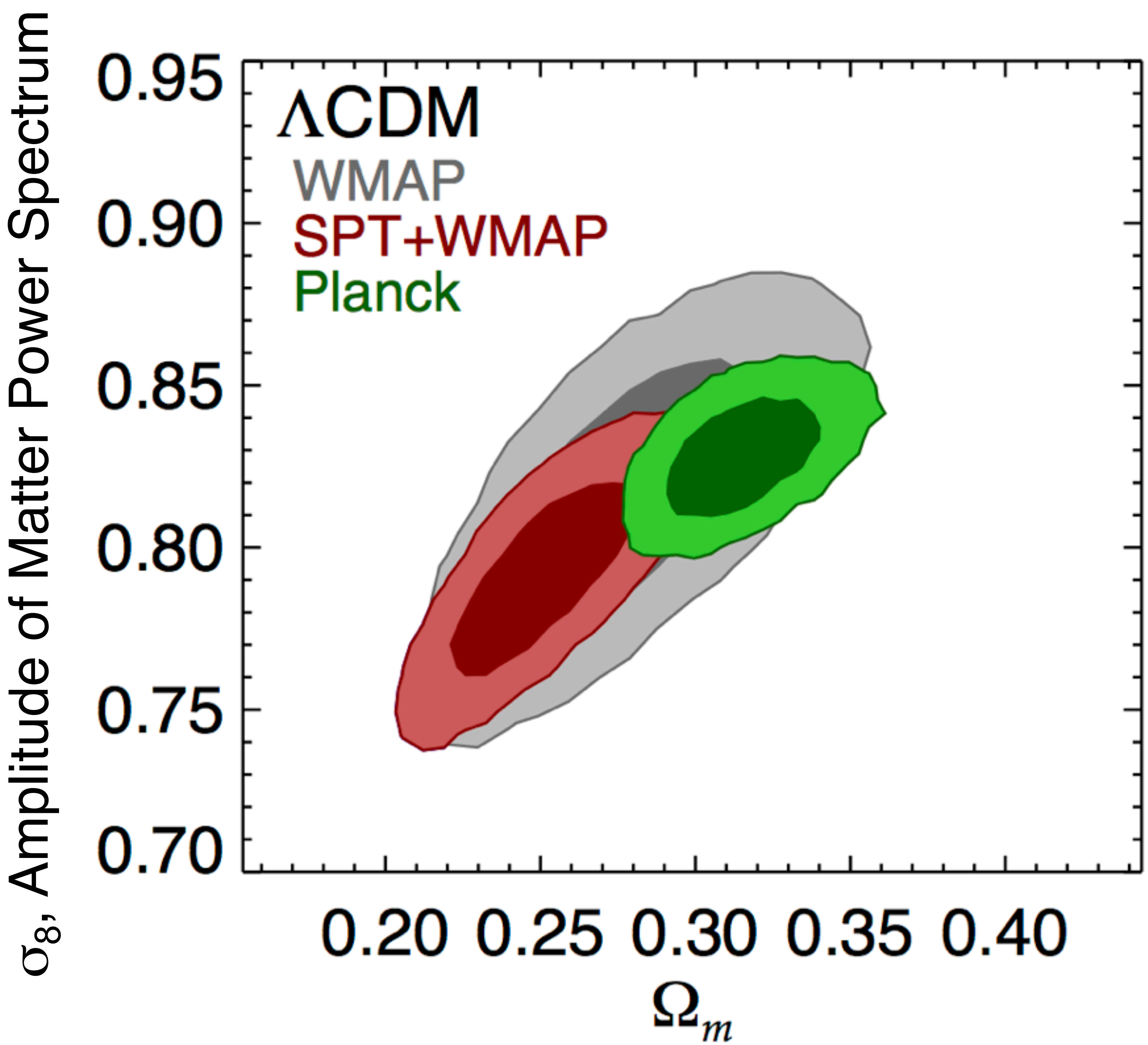
X-ray Pressure, Yx

ΛCDM Constraints:
SPT data using Vikhlinin+09 Yx mass calibration



Benson et al., ApJ 763, 147 (2013)
Reichardt et al., ApJ 763, 127 (2013)
de Haan et al., (2014), in prep

CMB Constraints on σ_8, Ω_m



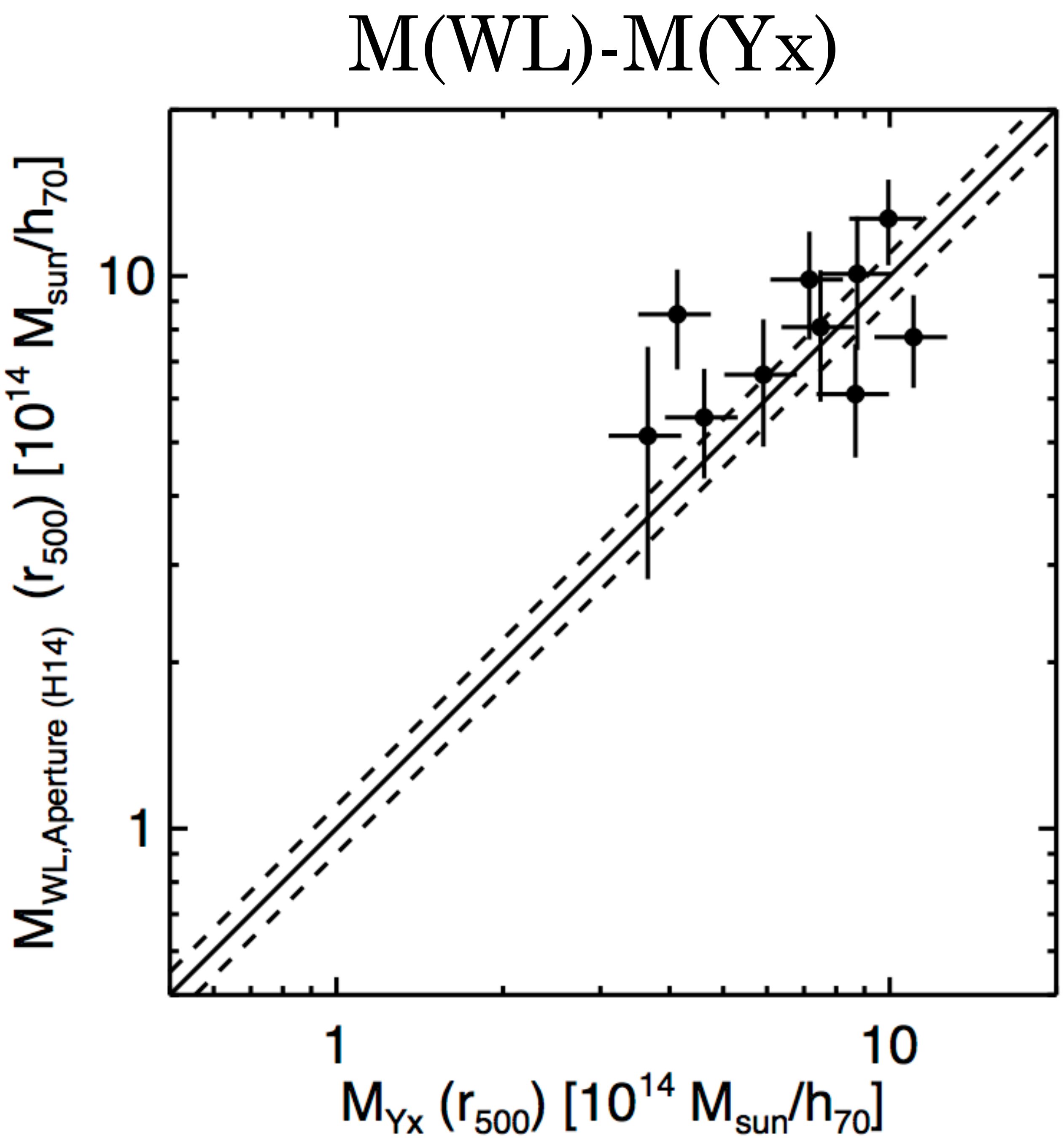
Cluster counts ~ $(\sigma_8)^{10}$

Small but important shift in σ_8 between WMAP and Planck

- Number of clusters goes like $(\sigma_8)^{10}$
- Planck cosmology predicts ~2-3x more clusters than WMAP

(WMAP7) Komatsu+2011
(SPT) Story+2012
Planck XX 2013
Planck XVI 2013

Yx-M Weak Lensing (WL) Calibration:
Updating calibration to new Hoekstra+14 calibration

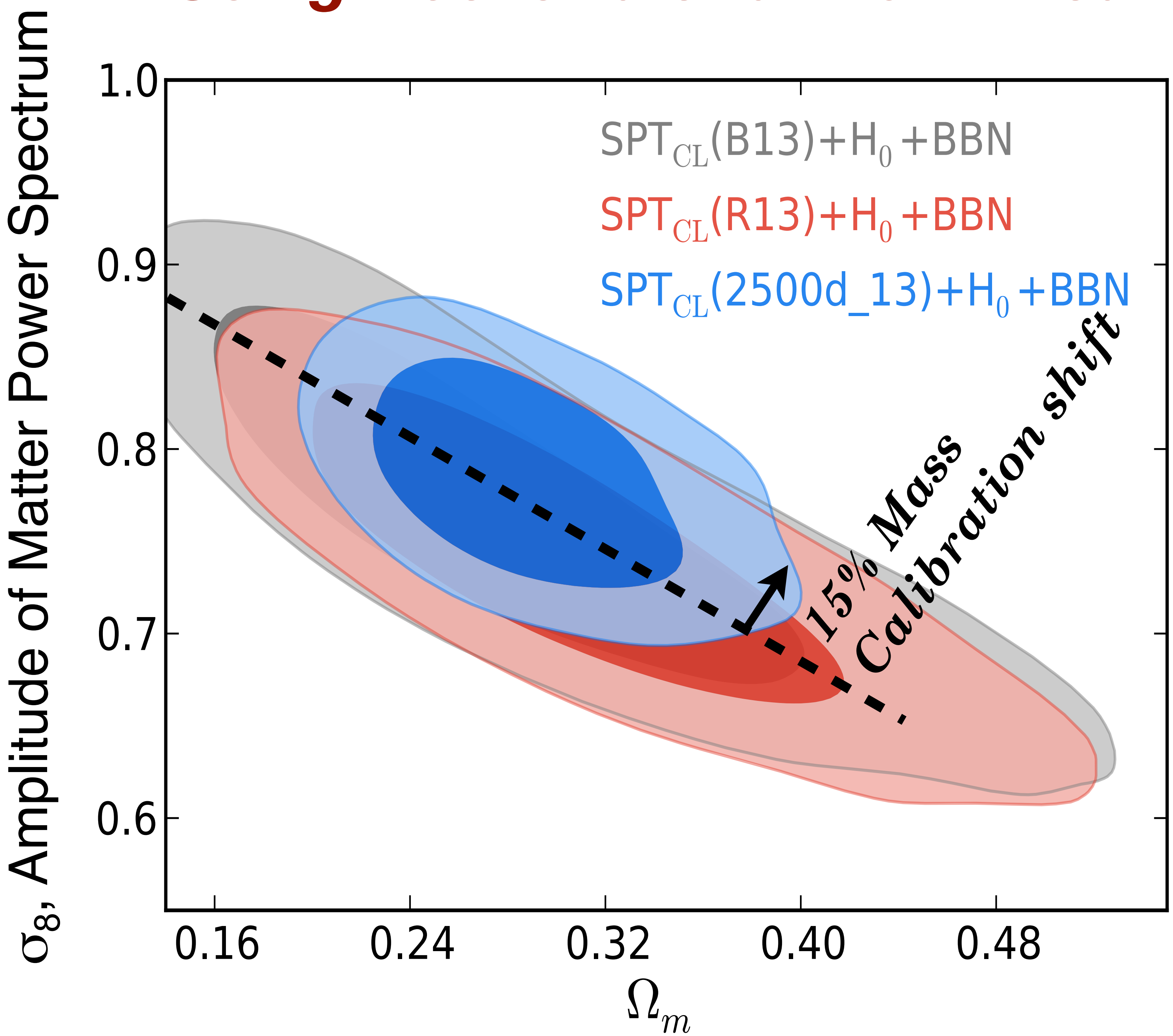


- Updated Yx-M calibration using weak-lensing (WL) masses from Hoekstra+14
- Multiply Vikhlinin+09 Yx-masses by:
  - Hoekstra+12: 1.03+/-0.15
  - Hoekstra+14: 1.15+/-0.16

M(WL, Hoekstra+14) = (1.15+/-0.16) M(Yx)

- ***Caveat****: Reasonable WL people (e.g., Hoekstra, von der Linden) still have ~10-15% offsets in mass estimates even using the same WL / shear data*

ΛCDM Constraints:
Using Hoekstra et al. 2014 Weak Lensing calibration

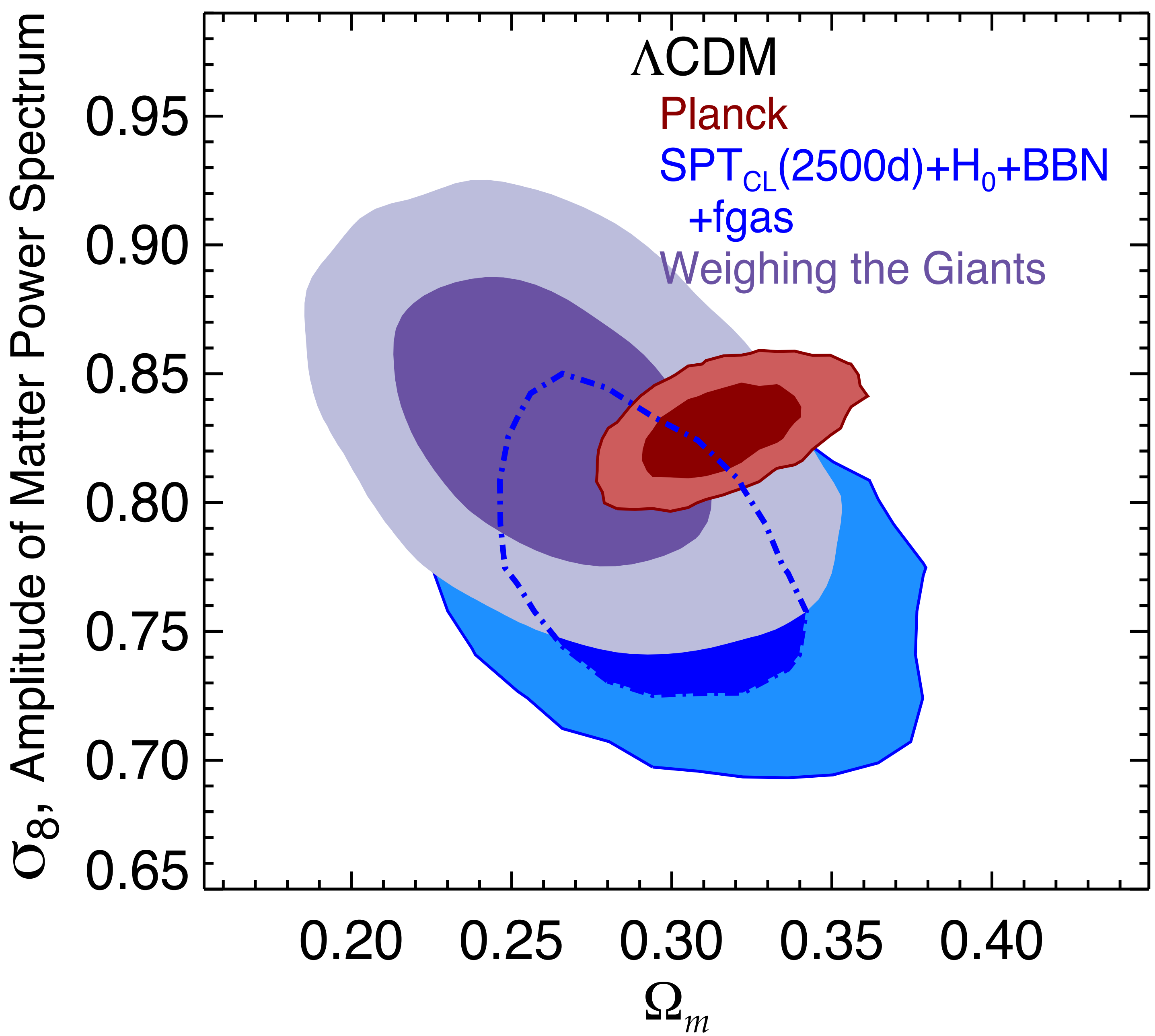


- Weak lensing (WL) is used to calibrate absolute mass scale
- WL techniques and measurements have improved quickly
- Current measurements indicate a 15% increase in mass calibration from Yx-calibration

de Haan et al., (2014), in prep

ΛCDM Constraints: CMB vs Clusters

Updated to Hoekstra et al. 2014 calibration



- **Planck CMB** and **SPT clusters** are statistically consistent
- Relatively good agreement between SPT clusters with "**Weighing the Giants**" (Mantz et al. 2014), based on Rosat all-sky survey

$SPT_{CL}+H_0+BBN+fgas$

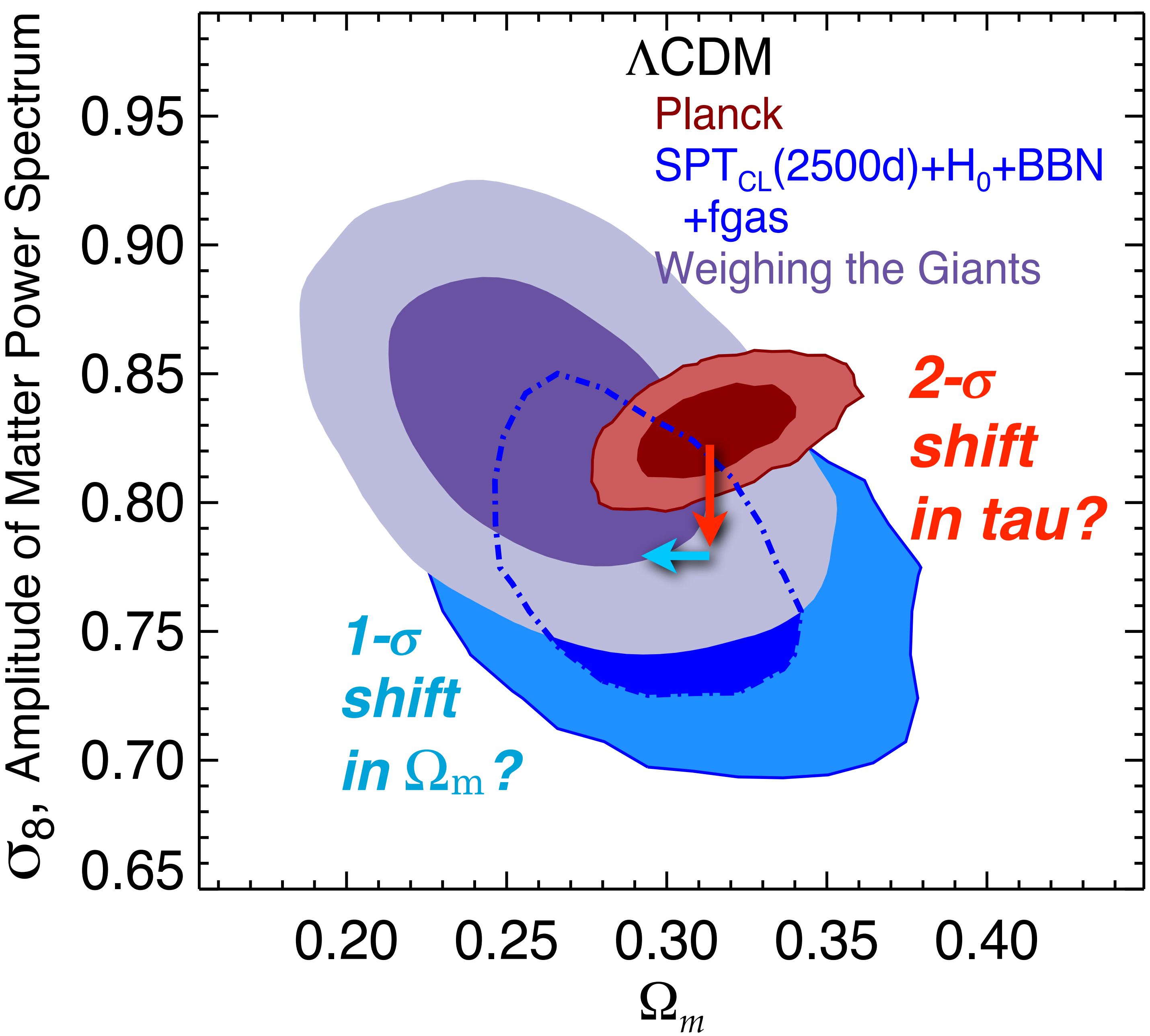
$\sigma_8 = 0.783$ +/- 0.040

$\Omega_m=0.293$ +/- 0.034

de Haan et al., (2014), in prep

ΛCDM Constraints: CMB vs Clusters

How will this change with Planck-CMB 2014 release?



New Planck papers Dec. 22, 2014!

What to look for (aka rumors) regarding σ_8, Ω_m:

1) Reionization optical depth will decrease by >1σ

- *Planck dust measurements impact CMB constraints:* ***δ***(tau) ~ ***δ***(σ_8)

2) Movement back towards WMAP cosmology

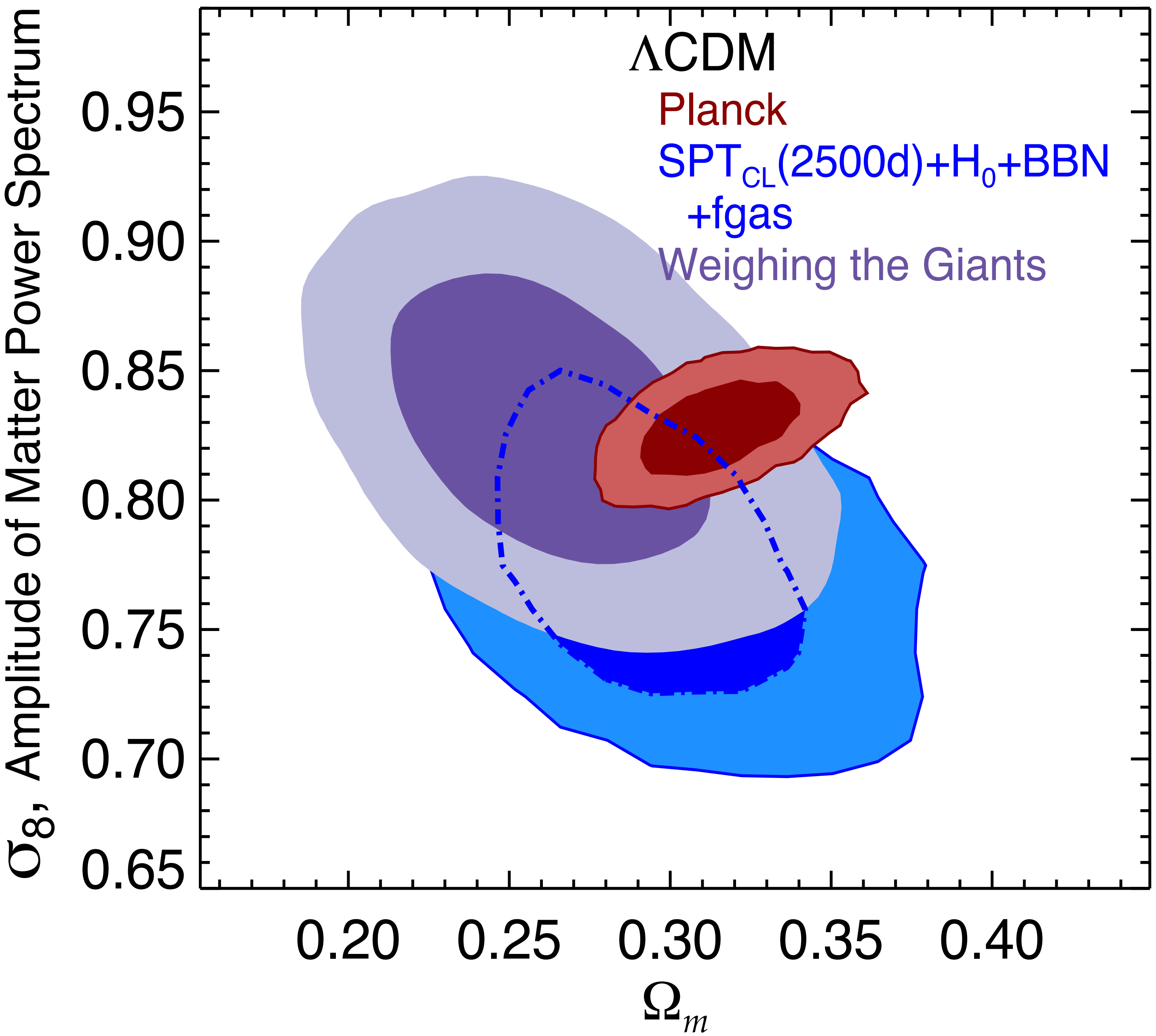
- *Planck 220 GHz had odd pull on Ω_m constraint (Spergel et al. 2014)*

3) Calibration Offset between WMAP and Planck

- *5-sigma (2% power) discrepant between WMAP, Planck*

ΛCDM Constraints: CMB vs Clusters

How will this change with Planck-CMB 2014 release?



New Planck papers Dec. 22, 2014!

What to look for (aka rumors) regarding $\sigma_{8,}\Omega_m$:

1) Reionization optical depth will decrease by

- *Planck dust measurements impact CMB constraints: $\delta(\tau) \sim \delta(\sigma_8)$*

2) Movement back towards WMAP cosmology

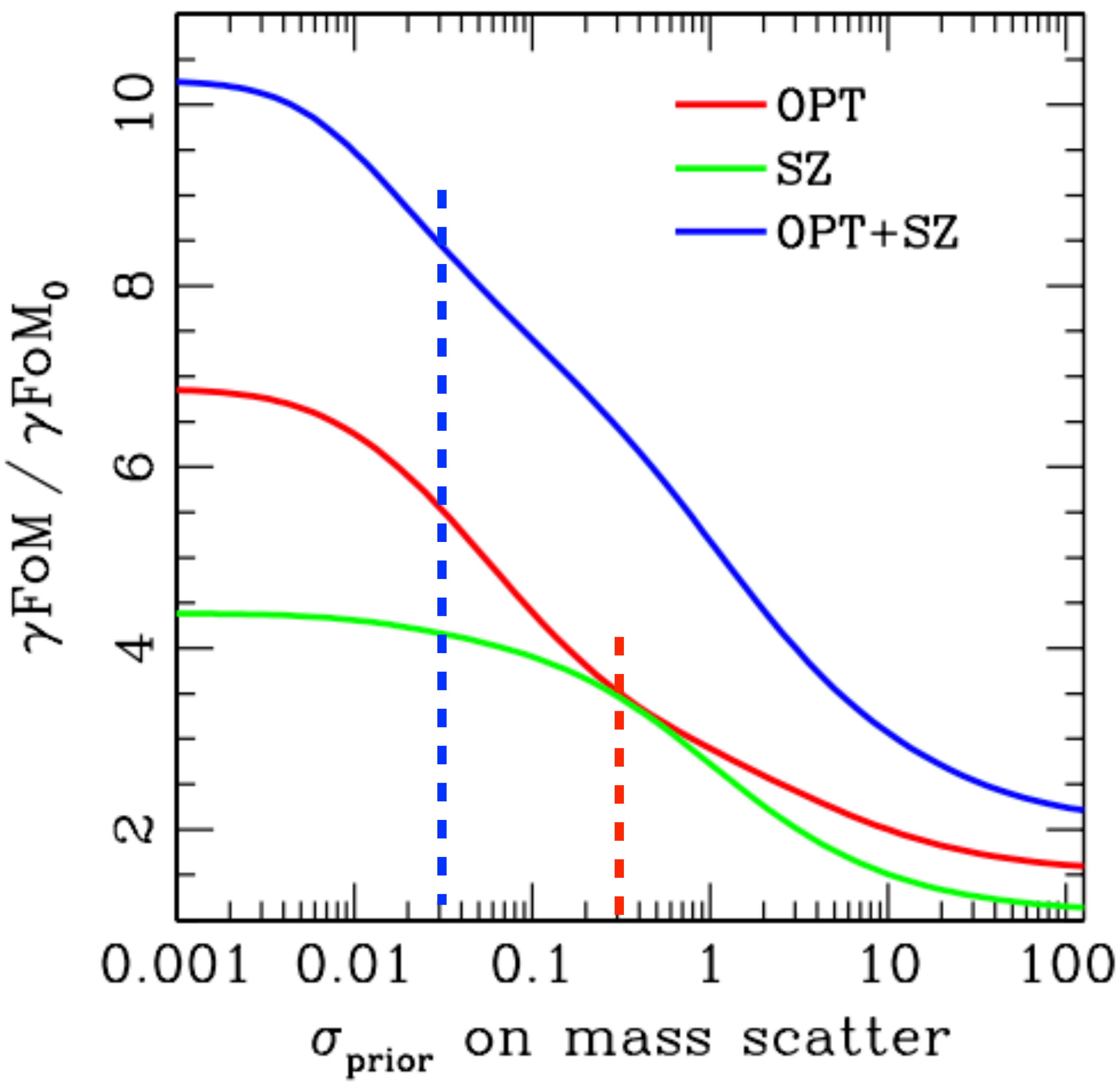
- *Planck 220 GHz had odd pull on Ω_m constraints (Spergel et al. 2014)*

3) Calibration Offset between WMAP and Planck

- *5-sigma (2% power) discrepant between WMAP, Planck*

Planck $\sigma_{8,}\Omega_m$ stayed the same!?!

Joint DES, SPT Cosmology:
Cluster Abundance

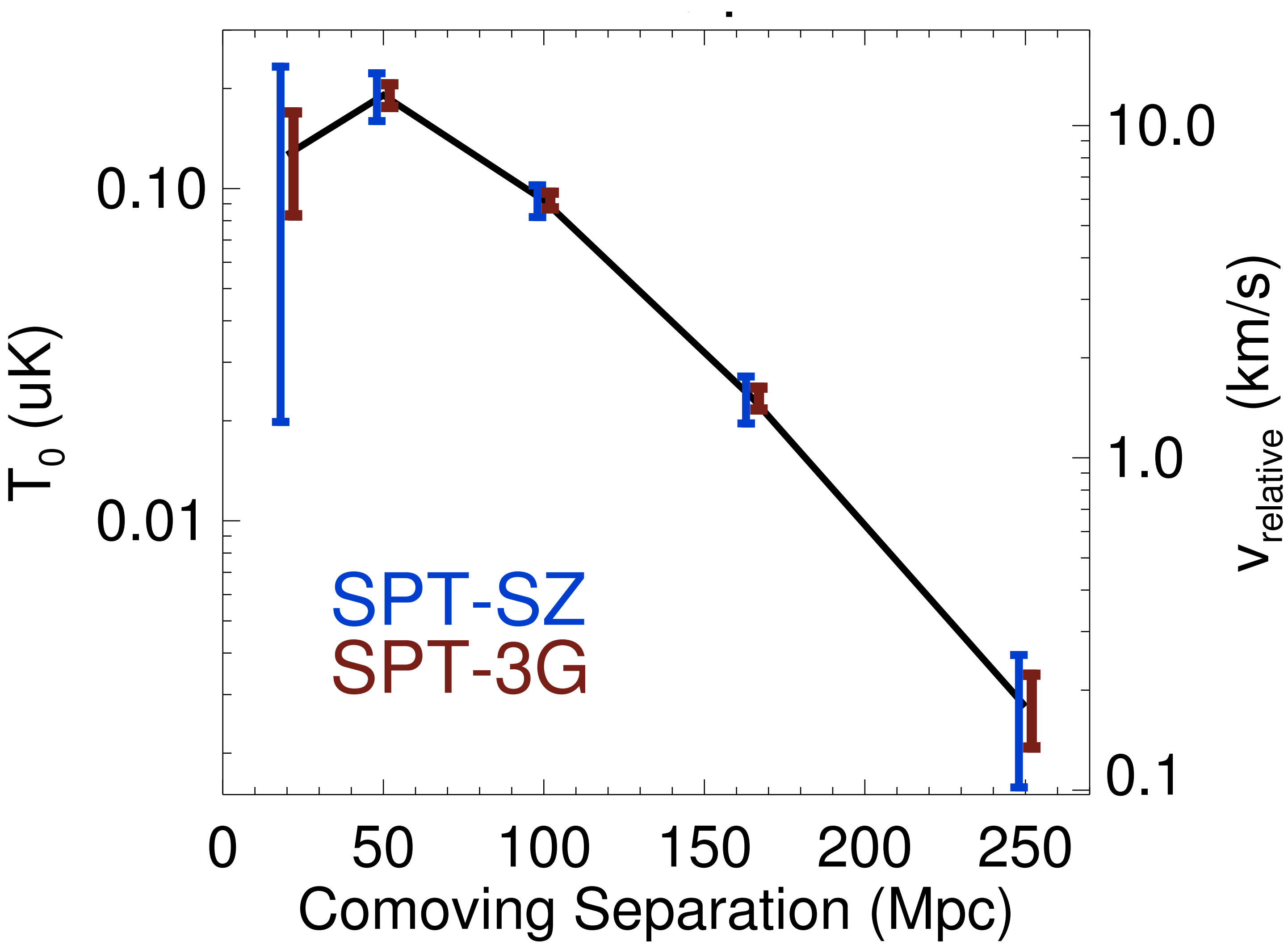


- Same basic likelihood formalism can be applied to joint DES +SPT cluster cosmology
  - *Select on DES richness, SPT is the "follow-up" observable*
- SPT effectively provides the scatter calibration for DES
  - *In Rozo+09 (MaxBCG), scatter prior limited σ_8 to a 4% constraint*
- Synergies between DES, SPT surveys is most evident in growth factor constraint gamma

$$\frac{d\ln D}{d\ln a} \simeq \Omega_m(a)^\gamma$$

Cunha et al., (2009)

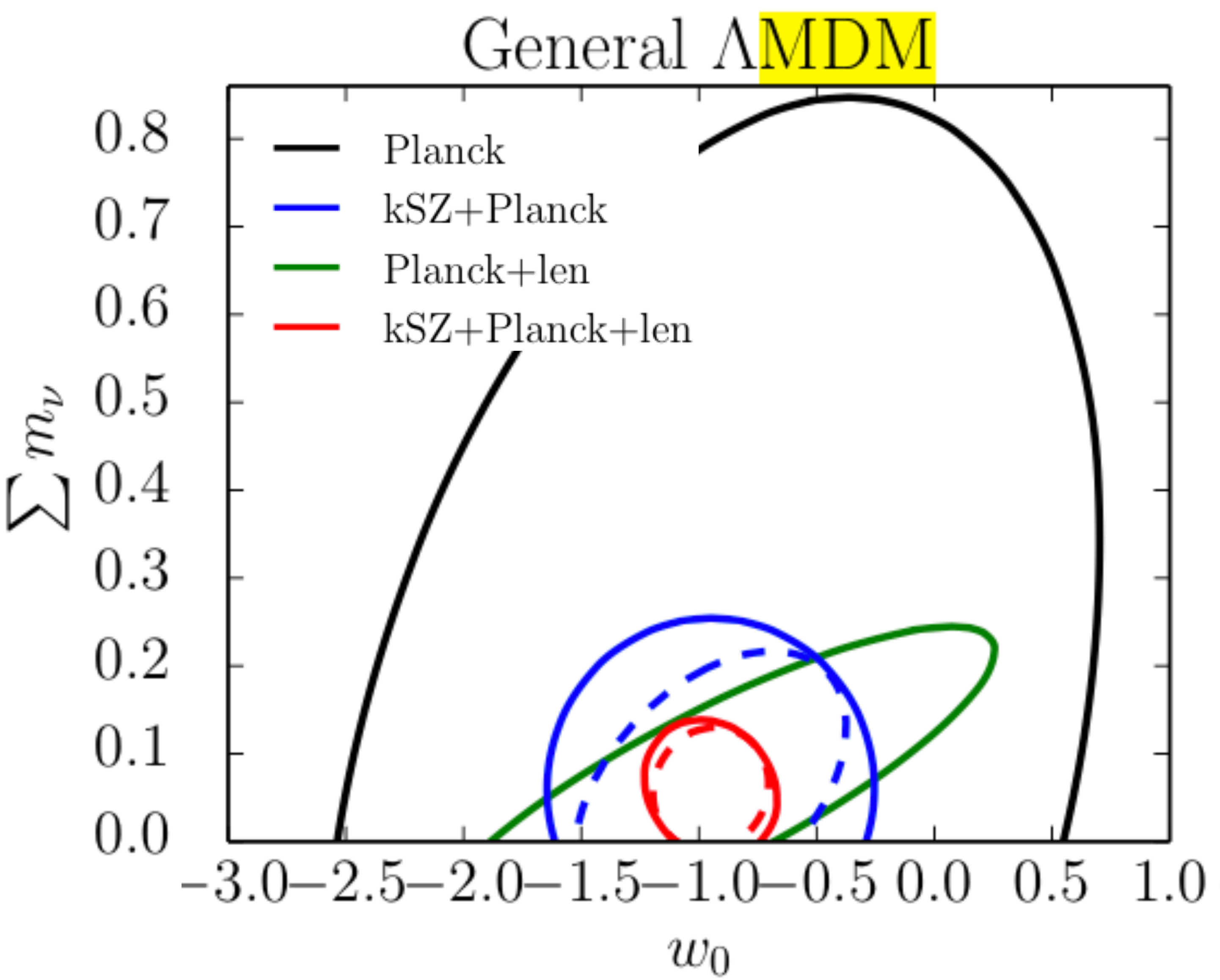
Joint DES, SPT Cosmology:
kinematic Sunyaev-Zel'dovich (kSZ) Pairwise



- kSZ effect imprints peculiar velocity of cluster in CMB (velocity relative to CMB rest frame)
  - *Clusters are test particles which probe the large scale gravitational potential by measuring their "pull" on each other*
- Recently detected at 3-sigma using ACT+SDSS (Hand+12)
- SPT-SZ(3G)+DES expects to detect kSZ at 13 (30) sigma (Keisler+12)

Keisler & Schmidt (2012)
Benson et al. (2013)

Joint DES, SPT Cosmology:
kinematic Sunyaev-Zel'dovich (kSZ) Pairwise



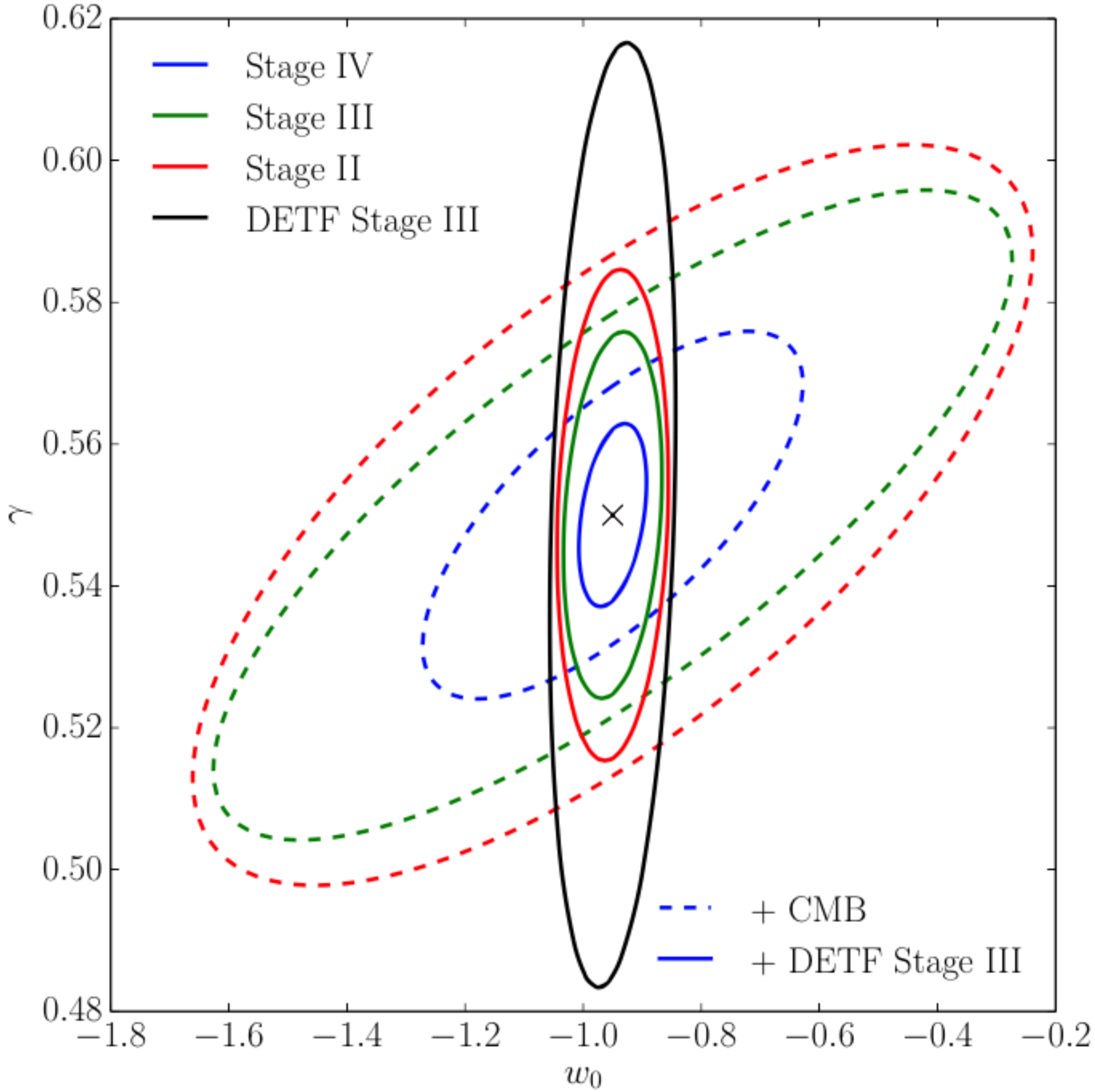
- kSZ potentially powerful probe to break degeneracy between dark energy ("w") and growth ("gamma") constraints
- Interesting constraints on the sum of the neutrino masses
  - *A StageIV CMB experiment kSZ constrains $\sigma(\Sigma m_\nu)$ ~ 30 meV, comparable to LSST, DESI surveys*

Mueller et al. (2014), arXiv: 1408.6248
Mueller et al. (2014), arXiv: 1412.0592

Summary

- Remarkable progress in SZ cluster surveys!
  - Over 1300 SZ identified clusters in less than 6 years
  - Unique massive, high-redshift systems that probe a new epoch of cluster formation
- Multi-wavelength data critical to study cluster evolution and cosmology by leveraging the strengths of different data sets
- SZ surveys are just beginning!
  - Future CMB polarization measurements will increase SZ-cluster samples by orders of magnitude, and enable new physics (e.g., CMB lensing, peculiar velocities, etc.)

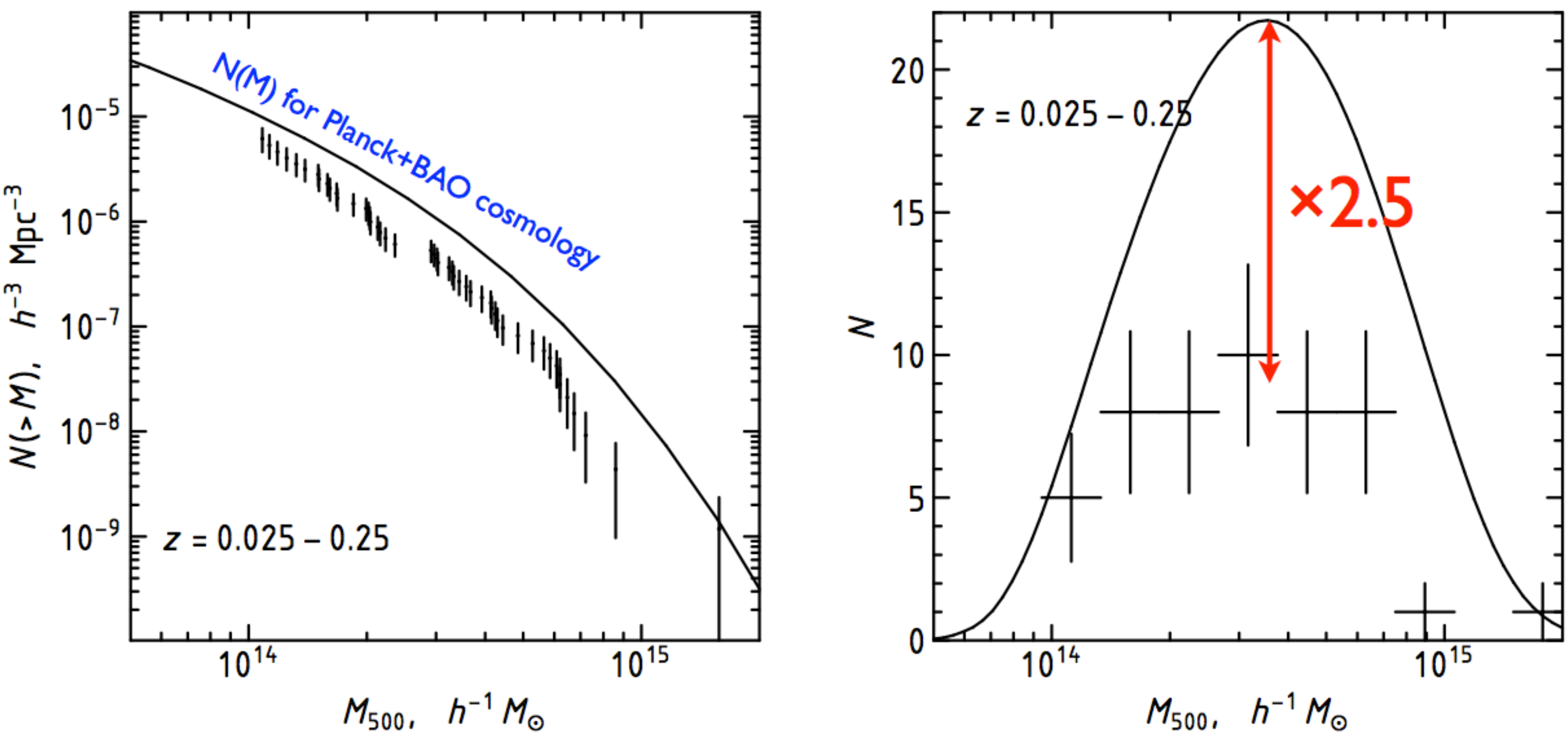
Joint DES, SPT Cosmology:
kSZ Pairwise



- kSZ potentially powerful probe to break degeneracy between dark energy ("w") and growth ("gamma") constraints
- Interesting constraints on the sum of the neutrino masses
  - *A StageIV CMB experiment kSZ constrains $\sigma(\Sigma m_\nu)$~ 30 meV, comparable to LSST, DESI surveys*

Mueller et al. (2014), arXiv: 1408.6248
Mueller et al. (2014), arXiv: 1412.0592

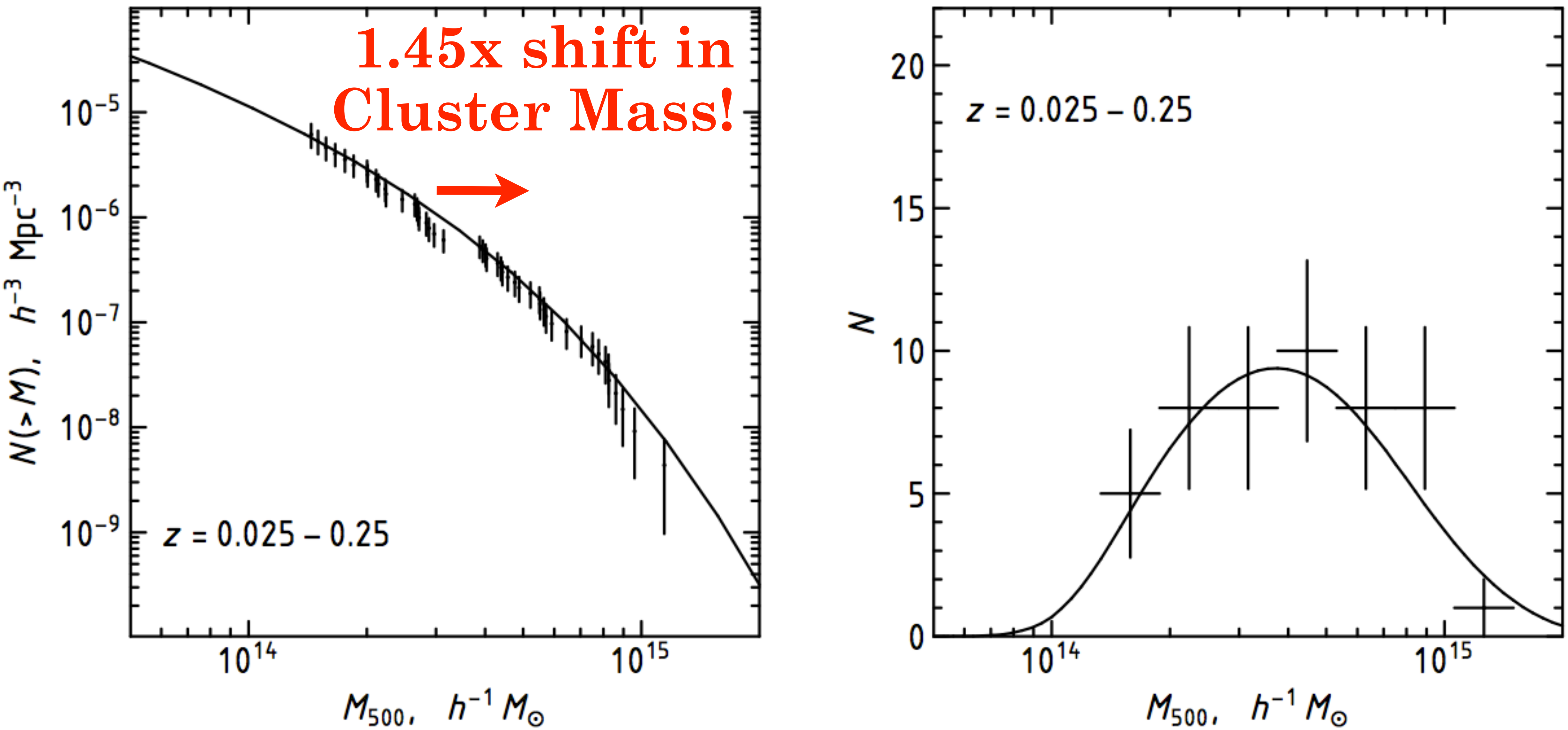
Planck Cosmology has ***profound*** mismatch with Cluster Abundance



Cluster counts ~ $(\sigma_8)^{10}$

Vikhlinin et al. 2009 (CCCP, X-rays)

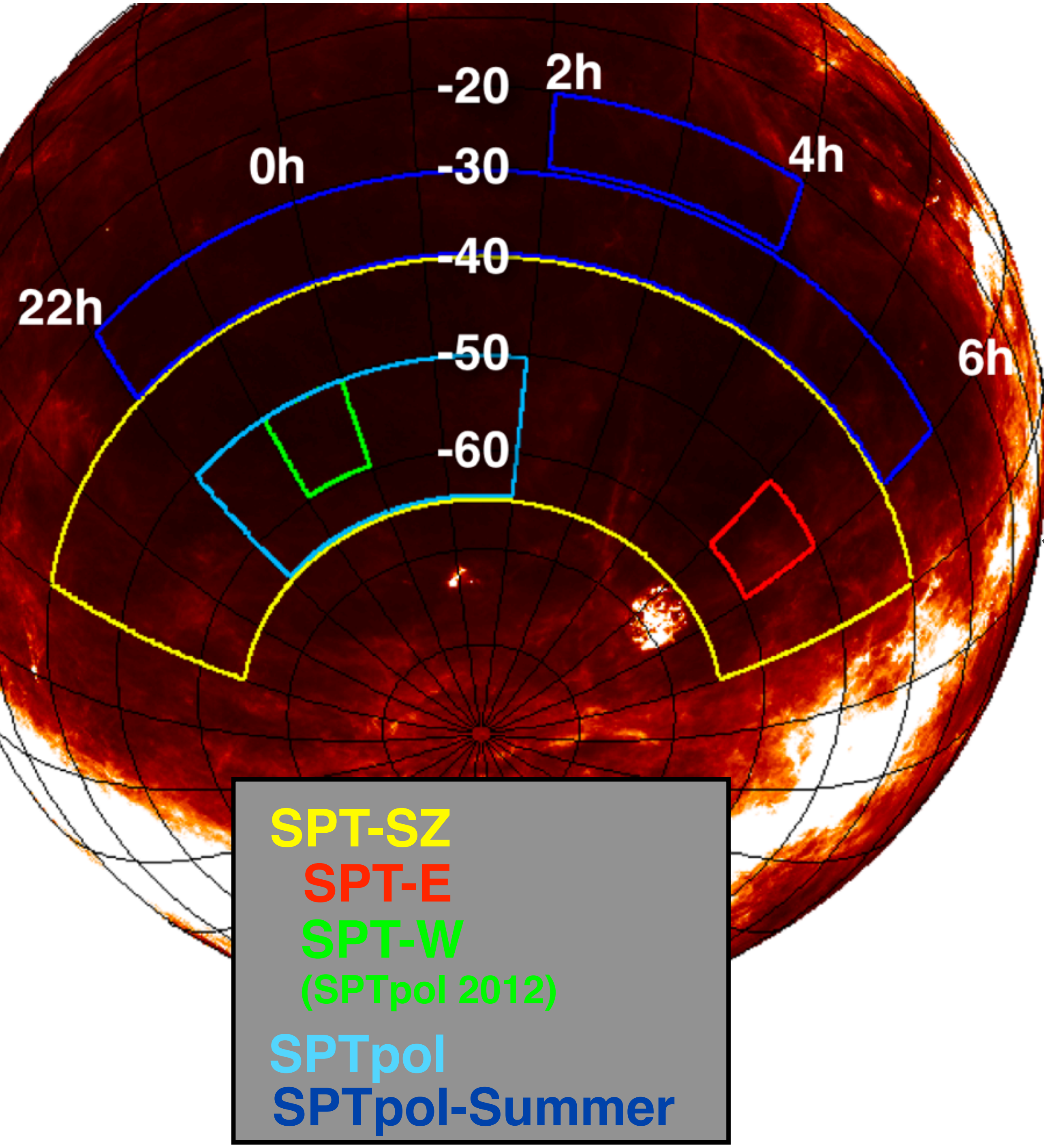
Planck Cosmology has ***profound*** mismatch with Cluster Abundance



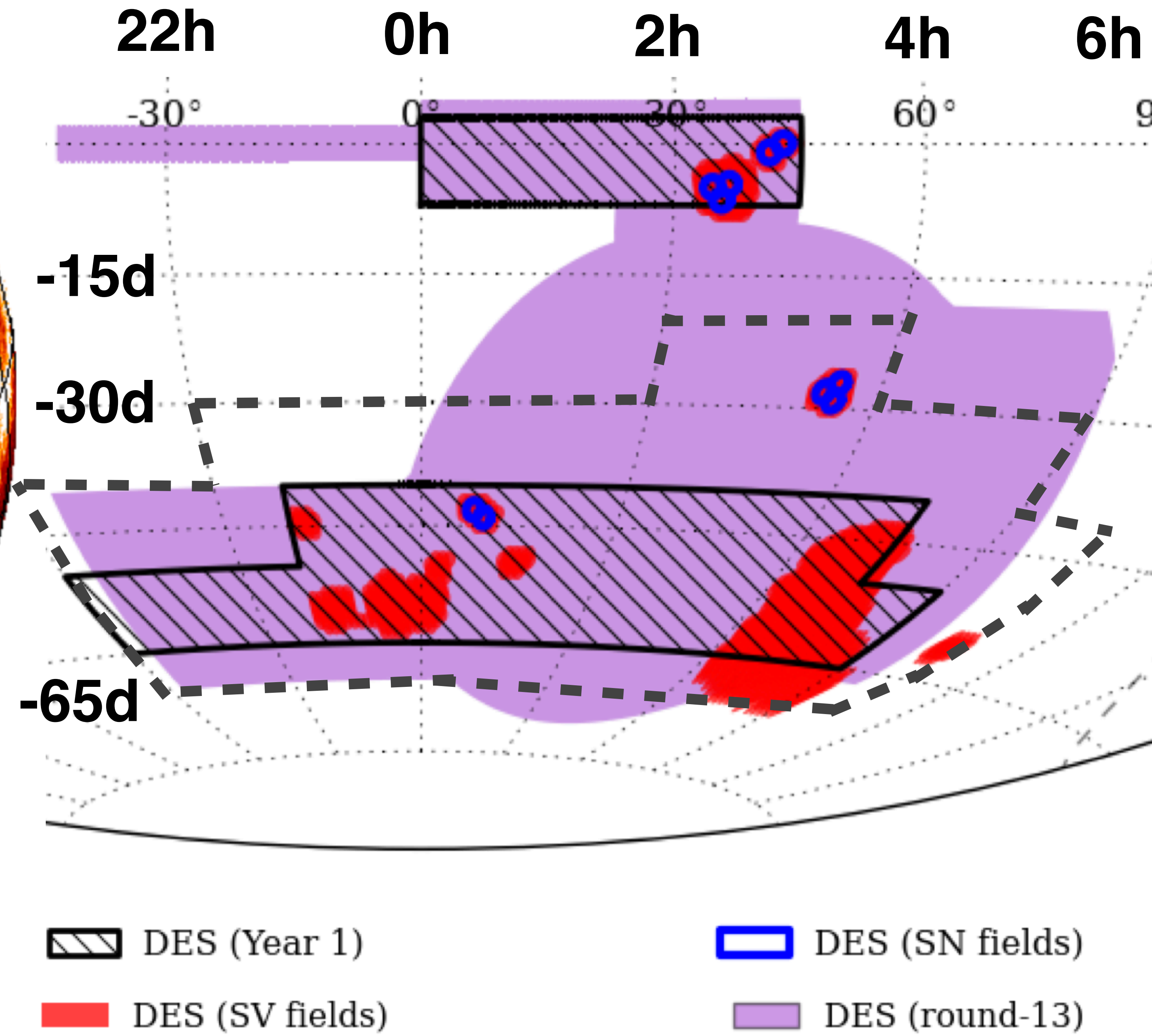
Cluster counts ~ $(\sigma_8)^{10}$

Vikhlinin et al. 2009 (CCCP, X-rays)

SPT Footprints

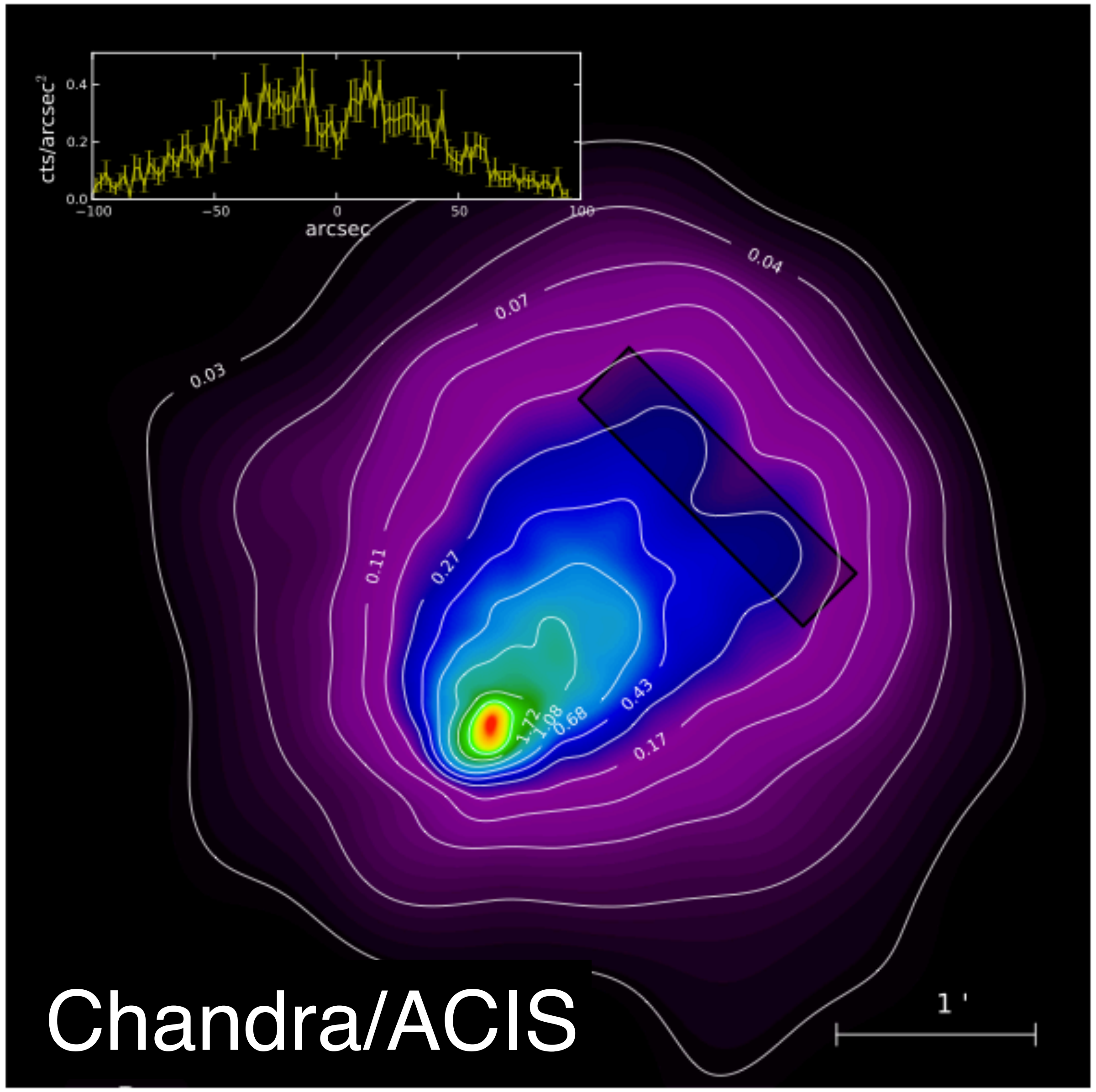


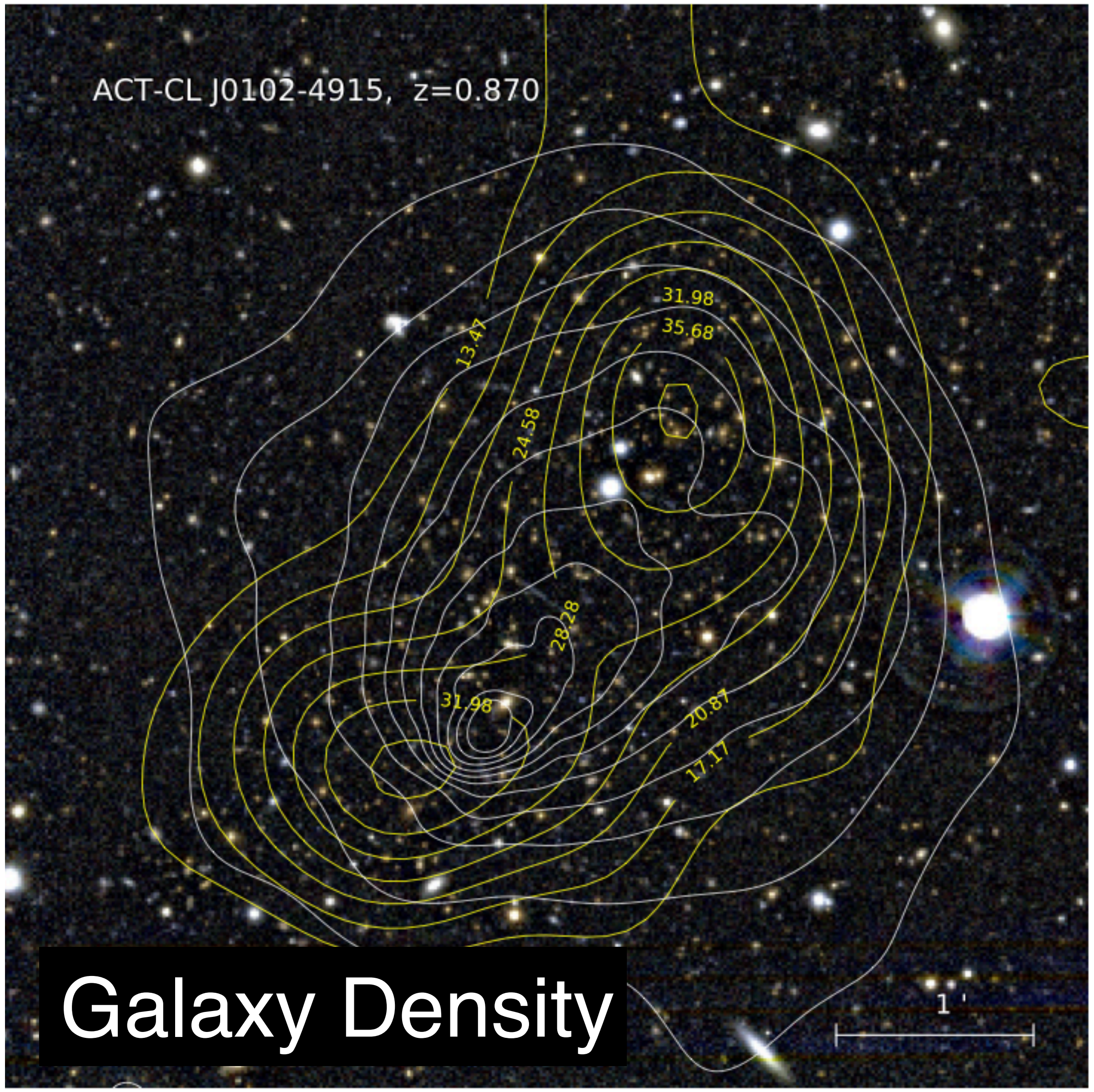
DES Footprint
SPT Footprint



ACT-CL/SPT-CL J0102-4915: *"El-Gordo"*

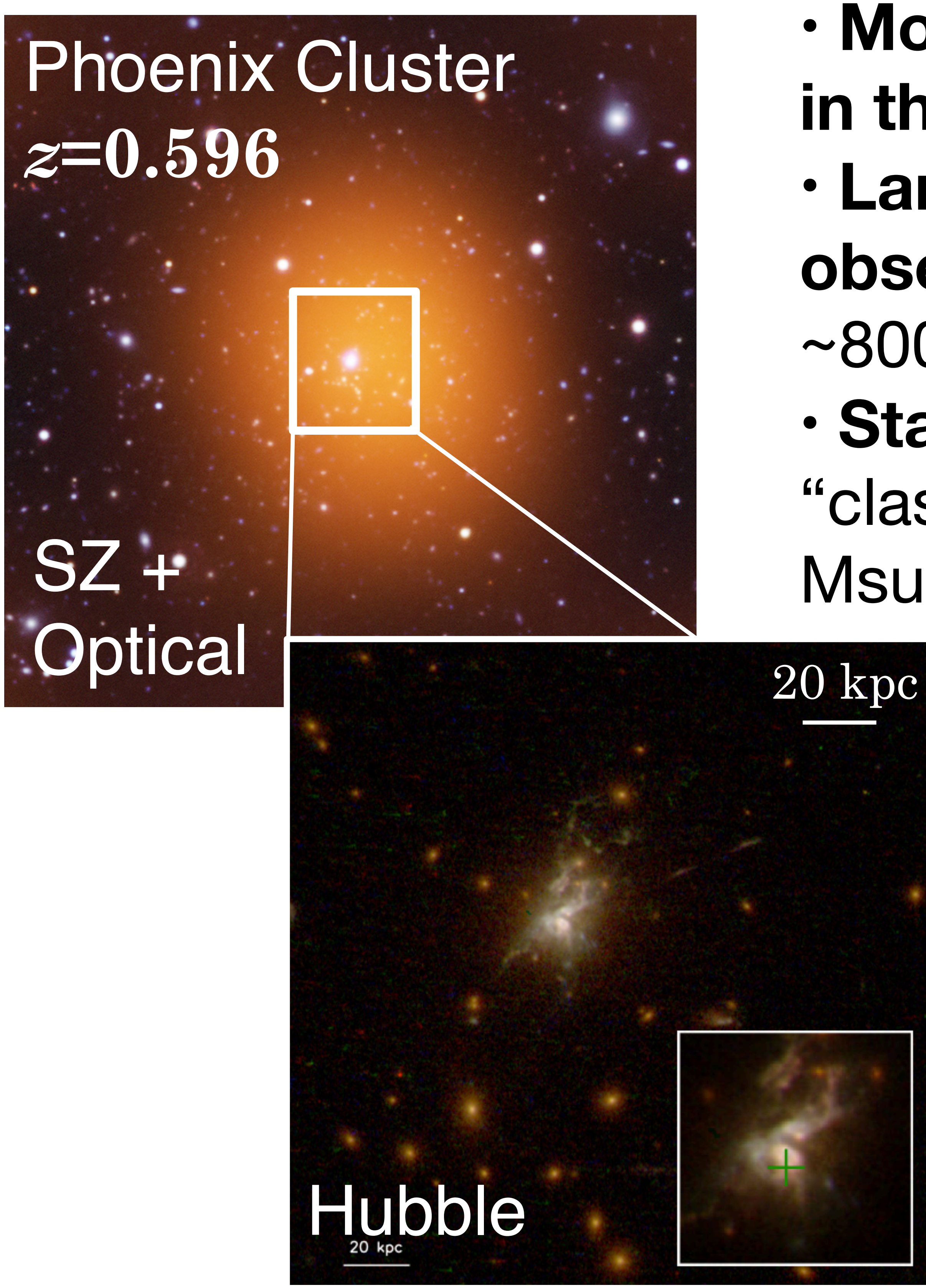
"Rarest" cluster in universe; only ~1 expected in universe above its mass and redshift of $M_{200} \sim 3 \times 10^{15}\ M_{sun}/h_{70}$ at z=0.87



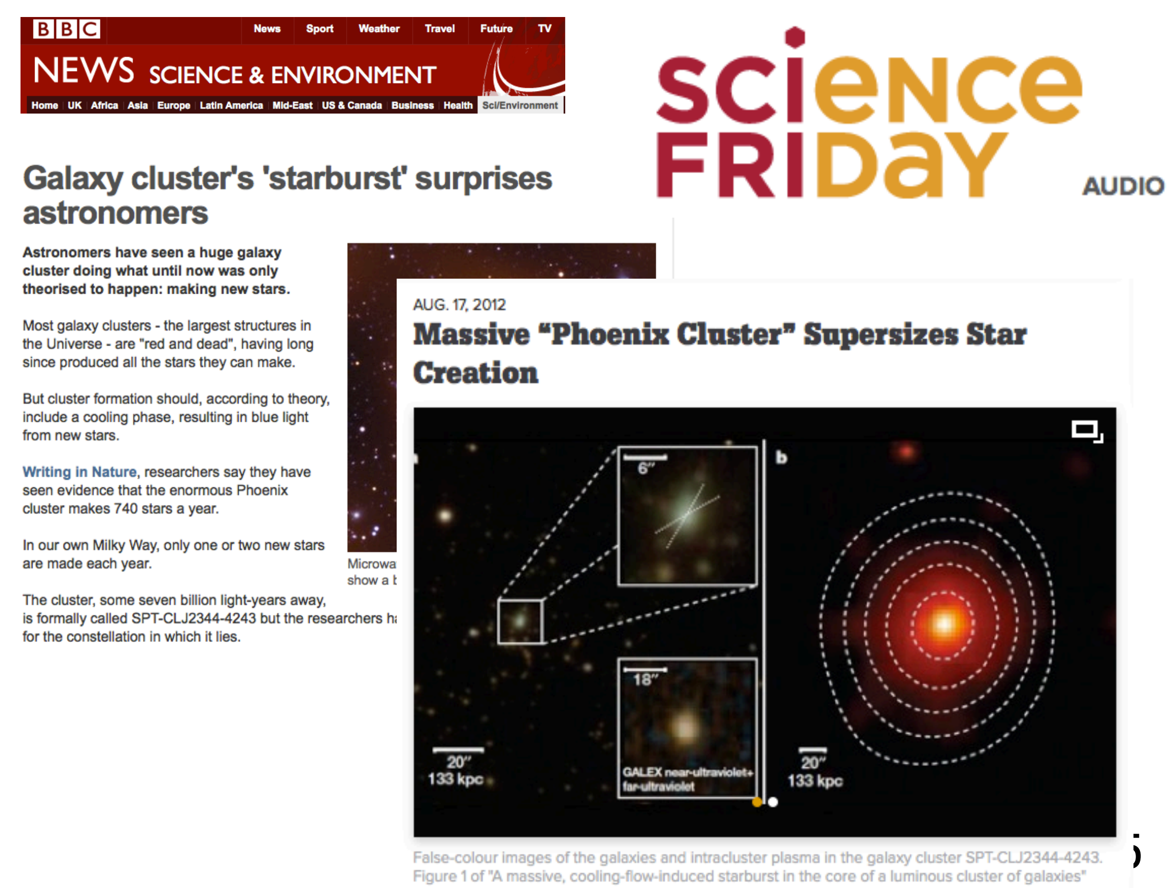


ACT, Menanteau et al. (2011)

SPT-CL J2344-4243: *The "Phoenix Cluster"*



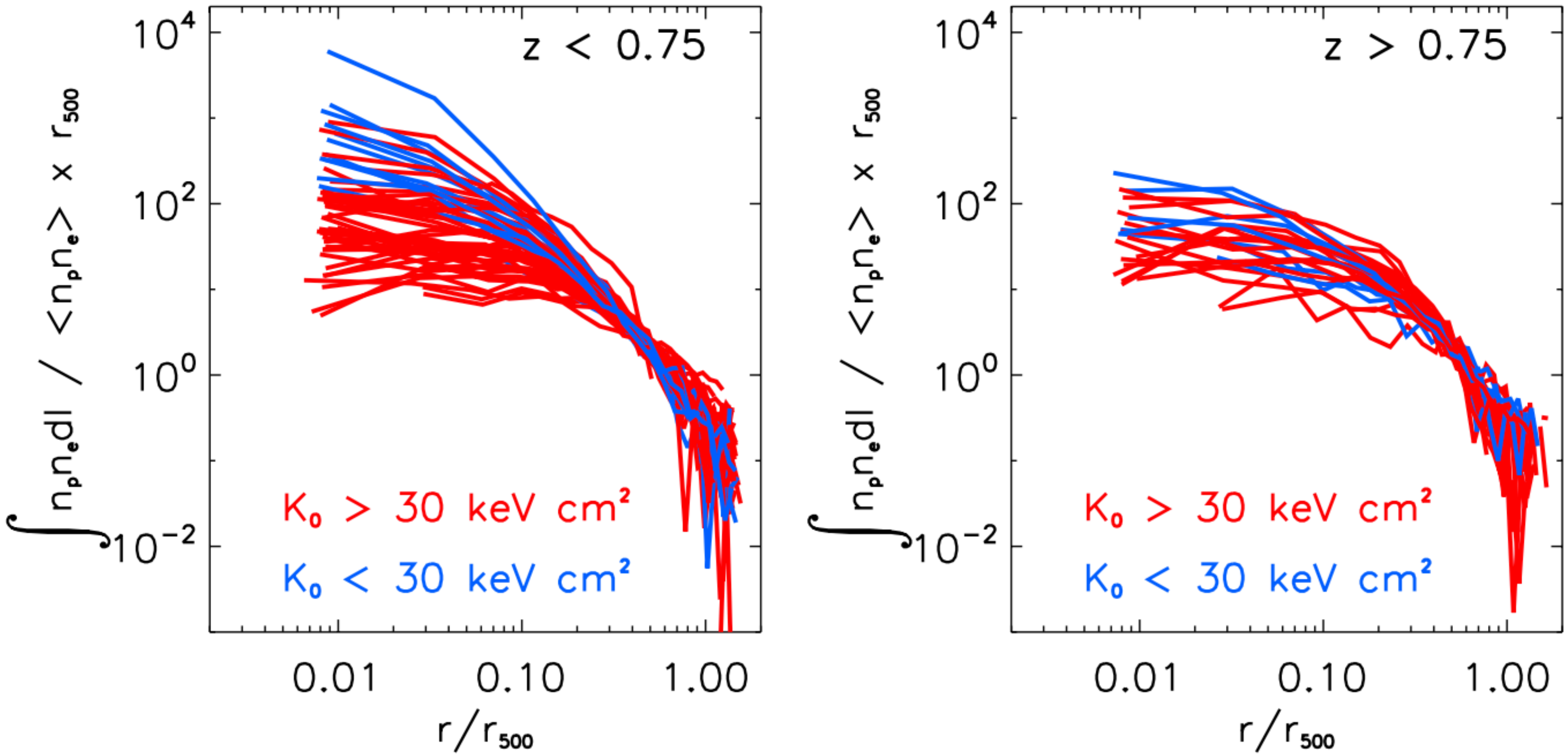
- **Most X-ray luminous cluster known in the Universe**
- **Largest star formation rate observed in a cluster BCG**: ~800 Msun / year
- **Star formation efficiency of ~30%;** "classical" X-ray cooling rate of 2850 Msun / year



McDonald et al. (2012, 2013)

Chandra SPT-XVP (80 clusters at $z > 0.4$):

Central Entropy and Cool Core Evolution



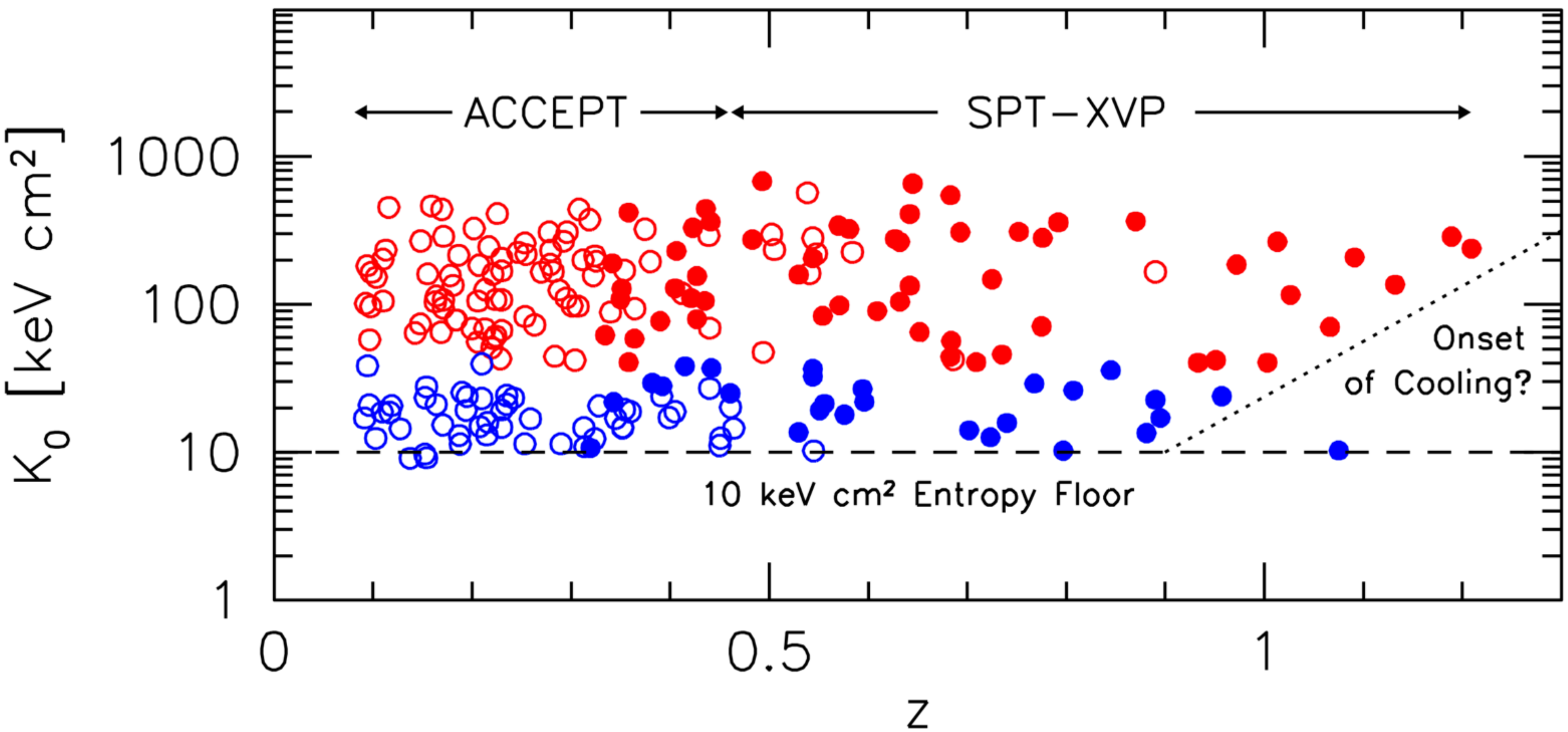
SPT, McDonald et al. (2013)

- While cluster density profiles were found to be less "peaky" at high-redshift (z > 0.6), i.e, no "classical" cool cores
- **There was a persistent floor in the central entropy; whatever mechanism that injects energy / entropy in clusters has been stable since z ~ 1**

Chandra SPT-XVP (80 clusters at $z > 0.4$):

Central Entropy and Cool Core Evolution

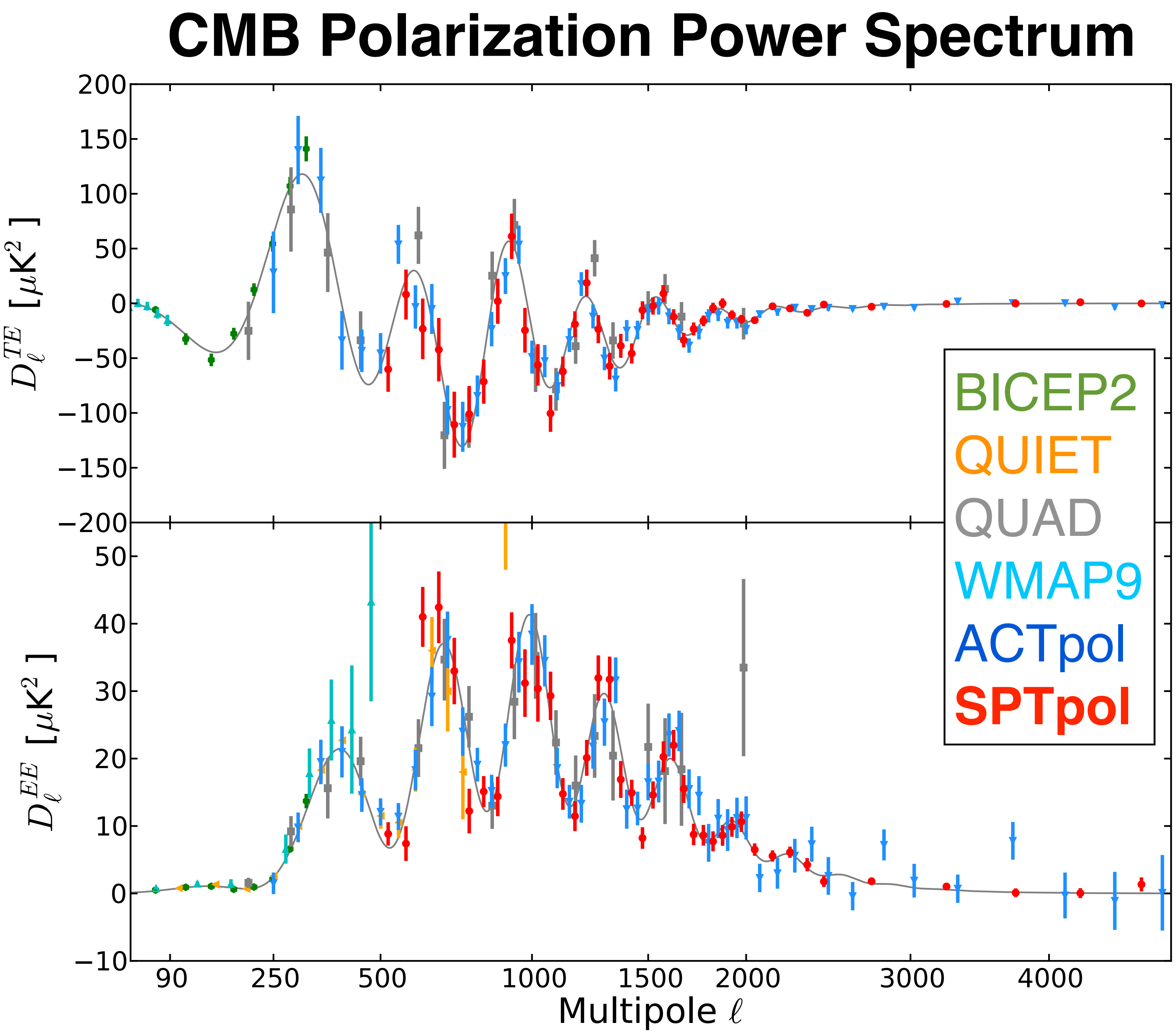
$$K = \frac{kT}{n_e^{2/3}}$$



SPT, McDonald et al. (2013)

- While cluster density profiles were found to be less "peaky" at high-redshift (z > 0.6), i.e, no "classical" cool cores
- **There was a persistent floor in the central entropy; whatever mechanism that injects energy / entropy in clusters has been stable since z ~ 1**

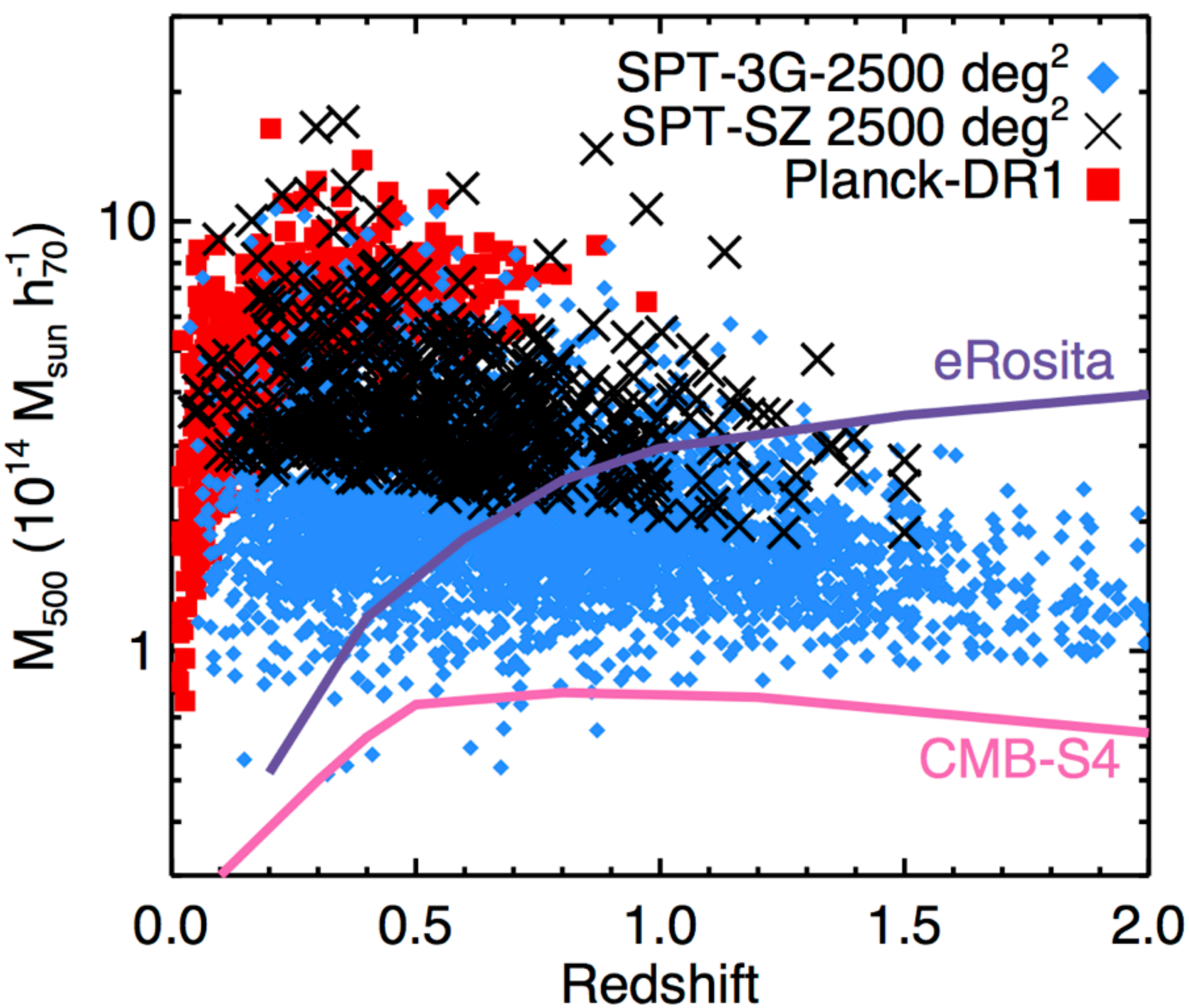
The SPTpol Survey (2012-):



- **SPTpol, 3 years of observations already!**
  - First detection of “B”-modes (Hanson et al. 2013)
  - Most precise constraints at multipoles > 1000 of TE, EE polarization power spectrum (Crites et al. 2014)
- **SPTpol Cluster Survey**
  - Wedding-cake survey: shallow (1000 deg^2) and deep (500 deg^2) regions
  - ***Expect to find ~600 clusters, more than SPT-SZ!***

SPTpol, Hanson et al. (2013)
SPTpol, Crites et al. (2014)
ACTpol, Naess et al. (2014)

Future SPT-3G, CMB-S4 Surveys



SZ cluster counts will increase by orders of magnitude with future surveys:

SPT-SZ/pol: N_{clust} **~ 1,000**

SPT-3G: N_{clust} **~ 10,000**

CMB-S4: N_{clust} **~ 100,000+**

Deep CMB data enables CMB cluster lensing as a mass calibration tool for cluster cosmology:

SPT-3G: σ(M) ~ 3%

CMB-S4: σ(M) < ~0.1%

Especially promising for cluster masses at $z > 1$