Galaxy Cluster Cosmology with SPT

Mass Calibration from Velocity Dispersions and X-ray Y_X's

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South Pole Telescope

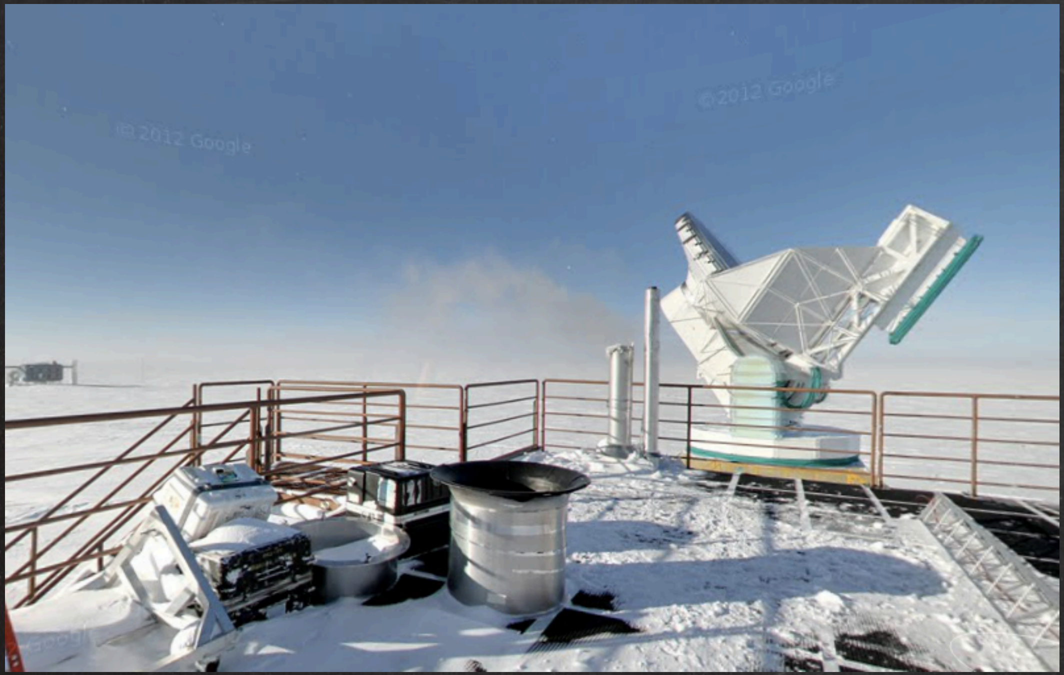
Overview

- Galaxy Clusters
- South Pole Telescope
- SPT SZ-selected Sample
- Galaxy Cluster Cosmology
- Mass Calibration
- Combining Velocity Dispersions with X-ray Y_X's
- Outlook

Galaxy Clusters

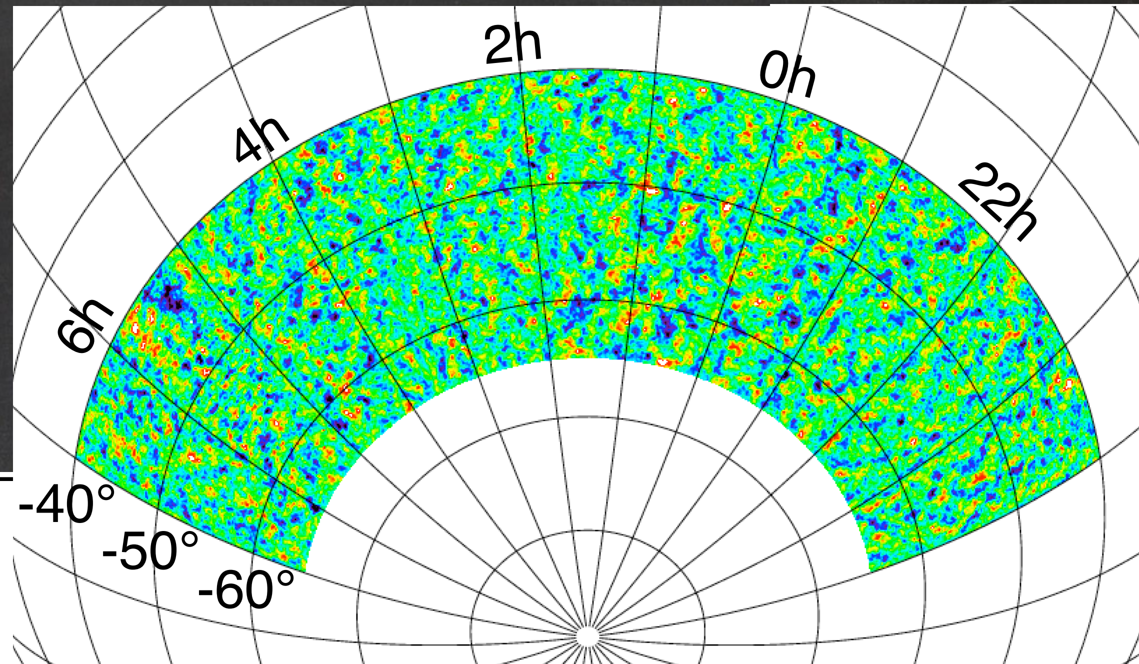
- Most massive collapsed objects in the Universe
- Content:
  - 87% dark matter
  - 11% hot gas, the intra cluster medium (ICM)
  - 2% galaxies
- Infalling gas is heated to O(keV) temperatures and emits X-ray Bremsstrahlung
- Number of member galaxies varies between a few and thousands
- Mass range: $10^{13} – 10^{15}$ M_{solar}

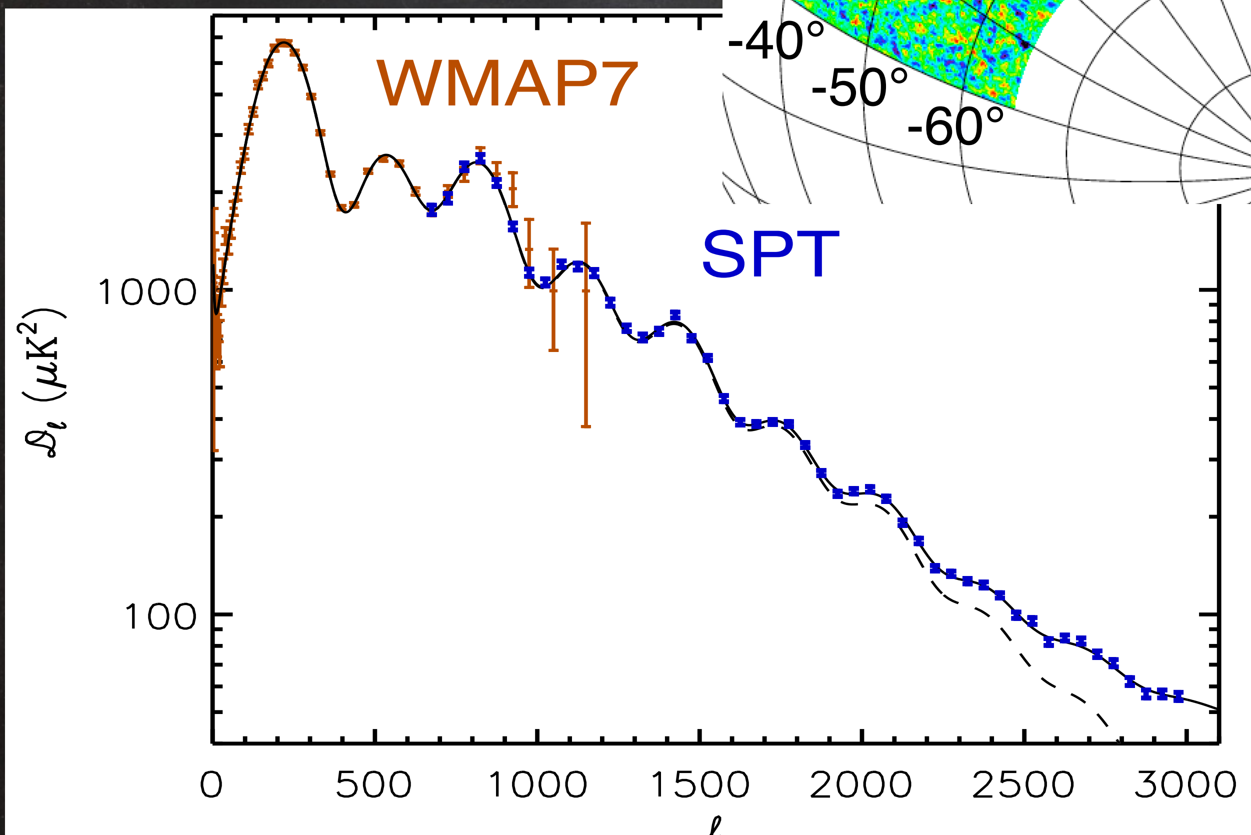
South Pole Telescope



- (Sub) millimeter wavelength telescope
  - 10 meter aperture
  - 1’ FWHM beam at 150 GHz
  - 5 arcsec astrometry
- mm-wave receiver
  - 1 deg^2 FOV
  - 3 bands: 95 GHz, 150 GHz, 220 GHz
  - Depth ~ 15-60 μK-arcmin

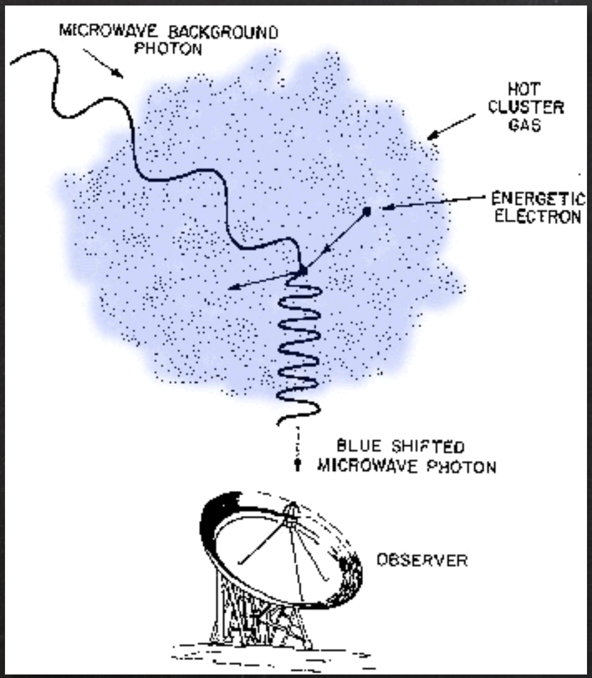
SPT survey 2500 deg^2



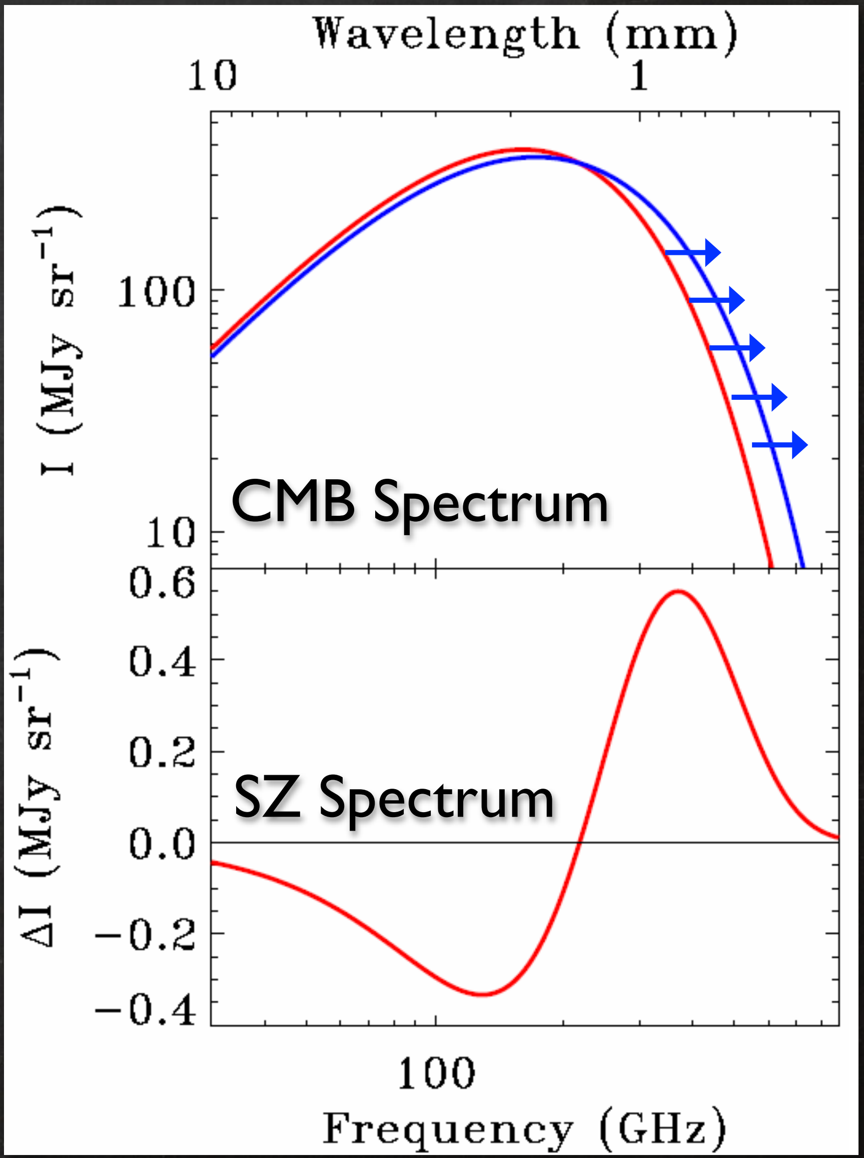


Story et al. 2012
astro-ph/1210.7231

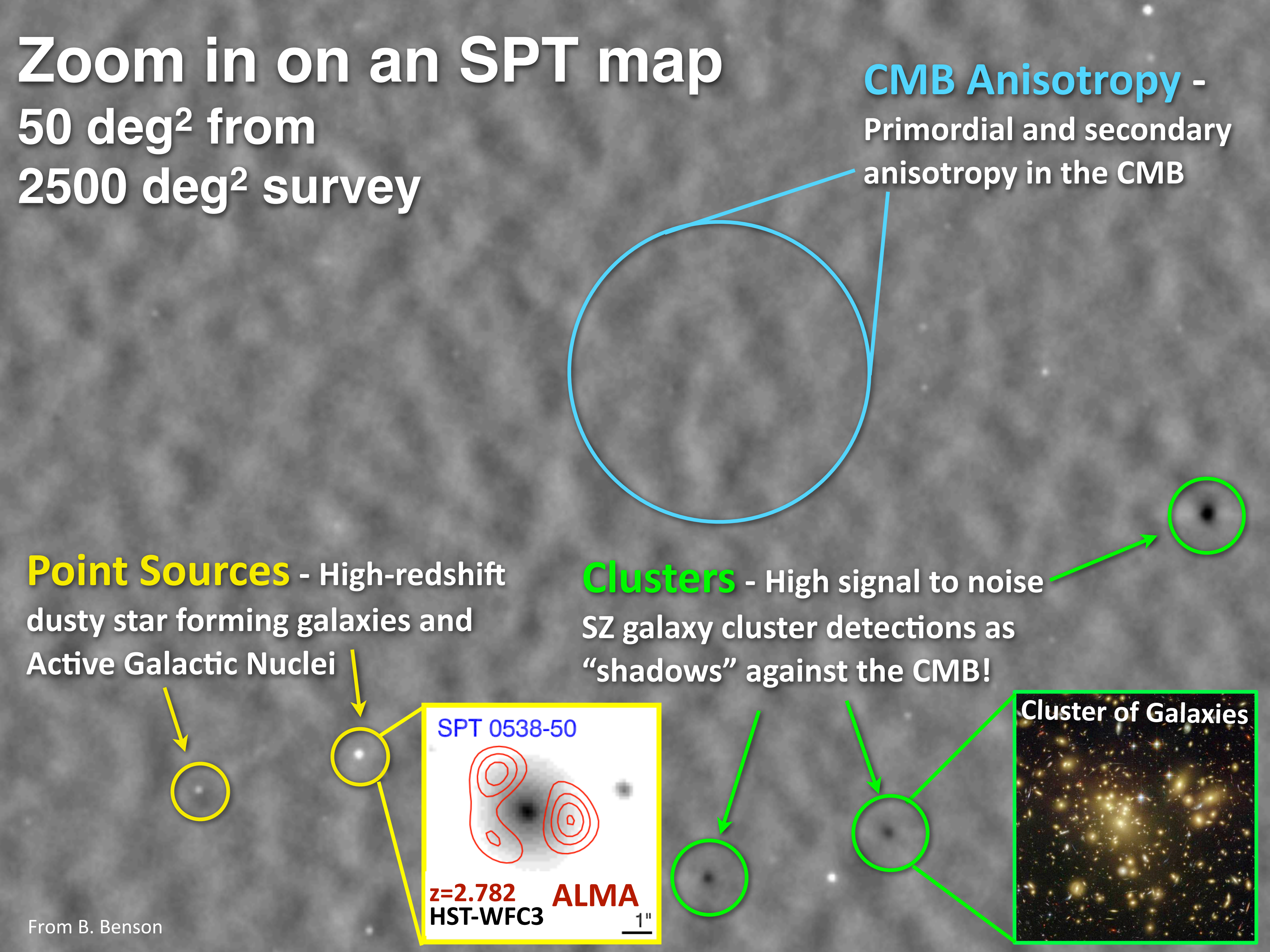
Sunyaev-Zel'dovich effect



from L. Van Speybroeck



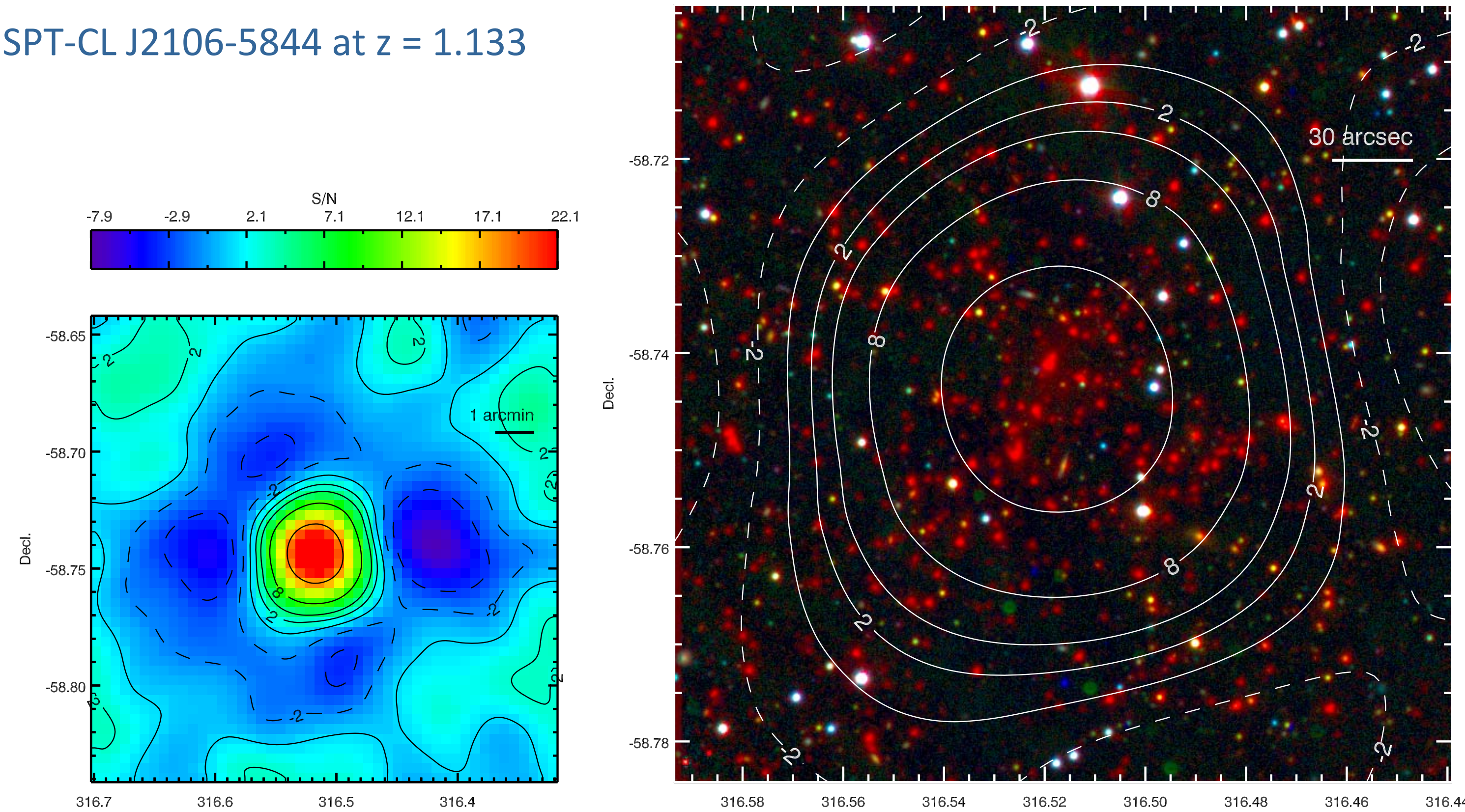
- About 1% of CMB photons scatter
- SZ flux proportional to total thermal energy in the electron population
- SZ surface brightness is independent of redshift



Zoom in on an SPT map
50 deg² from
2500 deg² survey
CMB Anisotropy -
Primordial and secondary
anisotropy in the CMB
Point Sources - High-redshift
dusty star forming galaxies and
Active Galactic Nuclei
Clusters - High signal to noise
SZ galaxy cluster detections as
“shadows” against the CMB!
SPT 0538-50
z=2.782
HST-WFC3
ALMA
1"
Cluster of Galaxies
From B. Benson

Optical / NIR follow-up

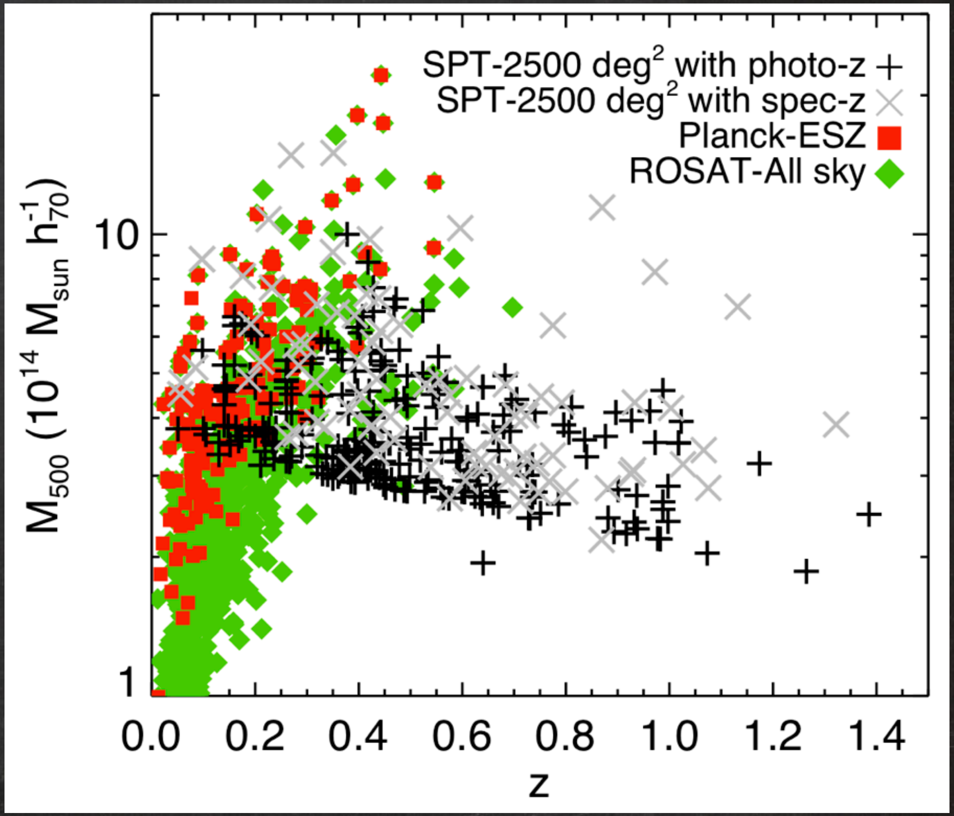
SPT-CL J2106-5844 at z = 1.133



Most massive cluster known at z > 1, Foley et al 2013

SPT SZ-selected Sample

- Clean and nearly redshift-independent selection
- 2500 deg^2 sample:
  - ~600 candidates at S/N > 4.5
  - Confirmation underway
  - 85% new discoveries
  - 95% pure at S/N > 5
  - ~450 clusters at S/N > 5
  - Median z = 0.55
  - ~100% complete above 5×10^{14} M_{solar}/h



Galaxy Cluster Cosmology

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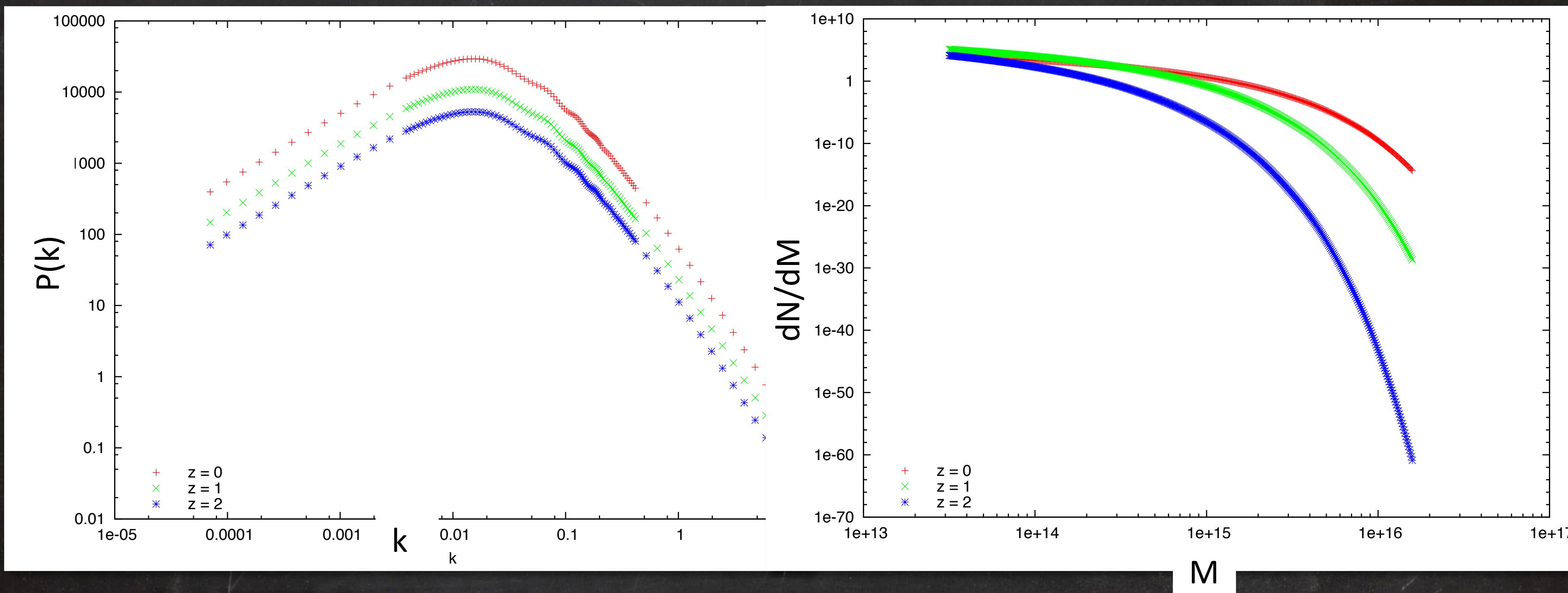


- Start with linear matter power spectrum
- Simulation-calibrated cluster mass function (Tinker et al., 2008)
- Exponential sensitivity
- Probe growth of structure in the late time Universe
- Need accurate knowledge of cluster masses

Cluster Mass Function

- Variance of the matter power spectrum

$$\sigma^2 = \frac{1}{2\pi^2}\int P(k)\left|W_k\right|^2 k^2 dk$$

- Probability that region of mass M exceeds collapse threshold

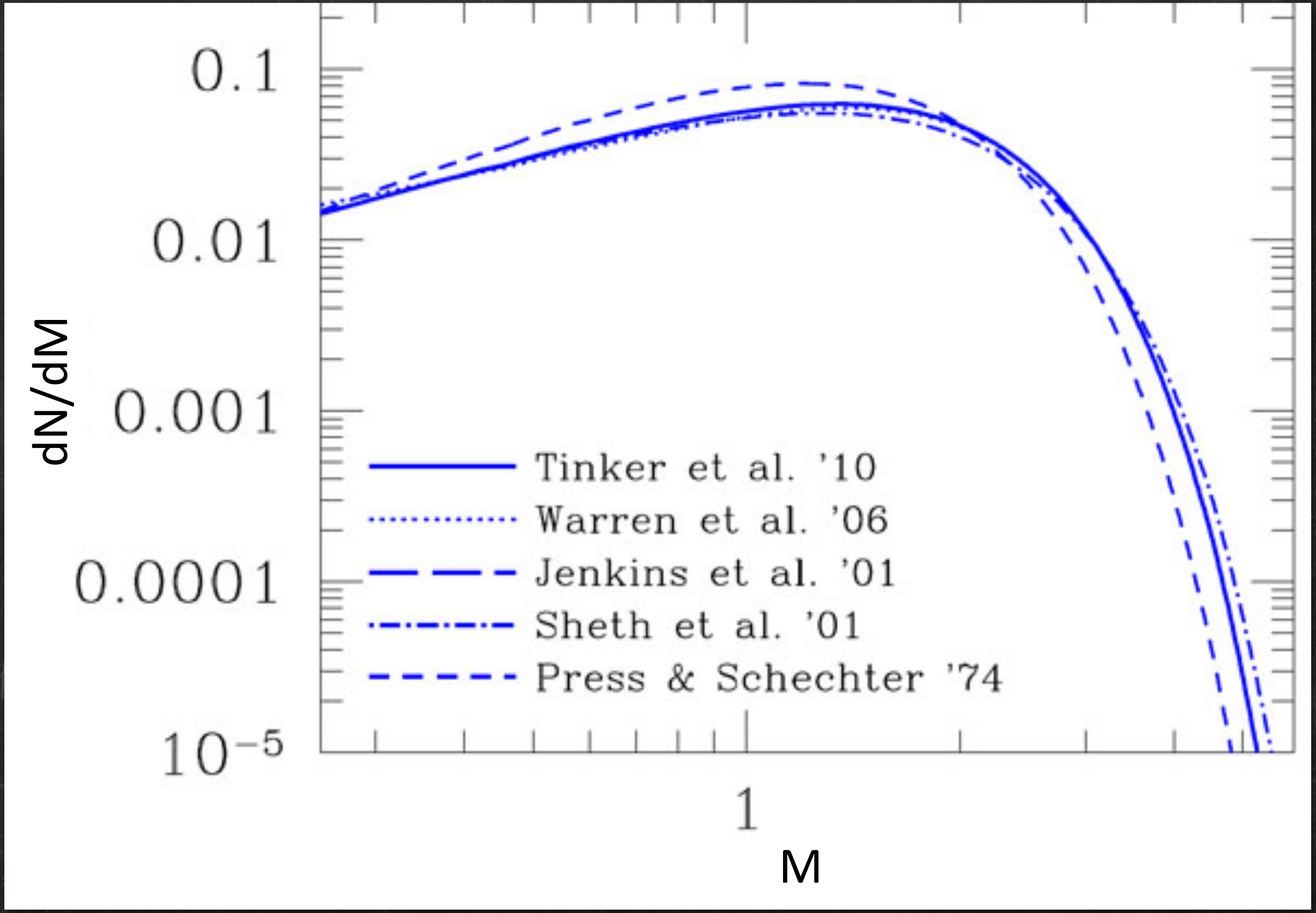
$$P(M,z) = erfc\left(\delta_c / \sqrt{2}\sigma(M,z)\right)$$

- Cluster Mass Function (Press & Schechter 1974)

$$n(M,z) = \frac{\rho_M}{M} P(M,z)$$

- Increase accuracy with numerical simulations

Cluster Mass Functions



http://ned.ipac.caltech.edu/level5/Sept12/Kravtsov/Kravtsov3.html

Mass observables

- Mass function provides prediction as a function of cluster mass
- What do we actually observe?
  - ~~Mass~~
  - SZ flux / SZ significance
  - X-ray luminosity / X-ray $Y_x = M_g T_x$
  - Velocity dispersion σ_v
- Scaling relations

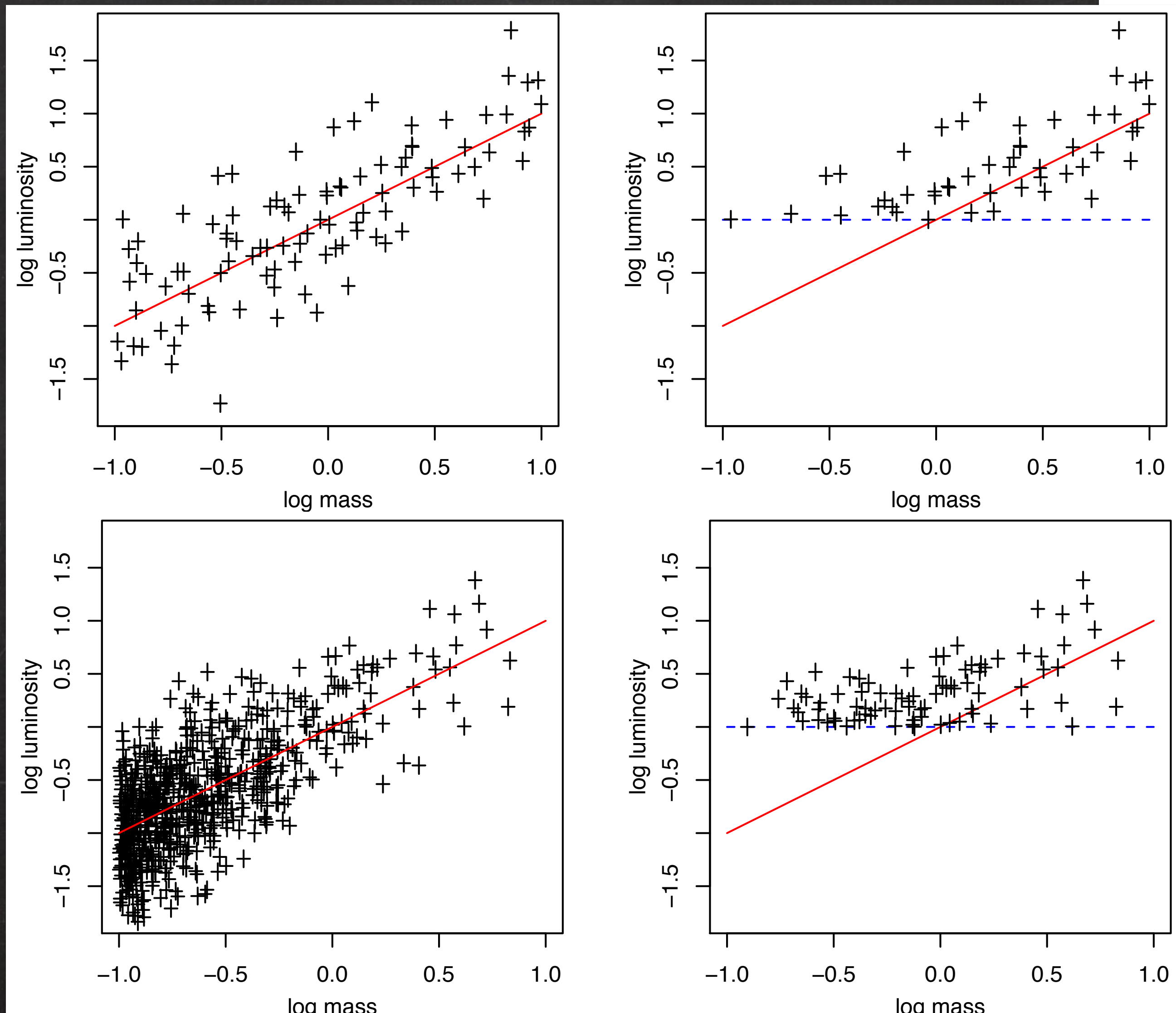
$$\zeta = A_{SZ}\left(\frac{M_{500}}{3\times10^{14}h^{-1}M_\odot}\right)^{B_{SZ}}\left(\frac{E(z)}{E(0.6)}\right)^{C_{SZ}}$$

$$M_{500c} = A_X h^{1/2} M_\odot \left(\frac{Y_X}{3\times10^{14}M_\odot keV}\right)^{B_X} E(z)^{C_X}$$

$$\sigma_v = A_\sigma \left(\frac{M_{200c}}{10^{15}M_\odot}\right)^{B_\sigma} h(z)^{C_\sigma}$$

- Each comes with an (unknown) intrinsic scatter
- … and (known) observational uncertainty

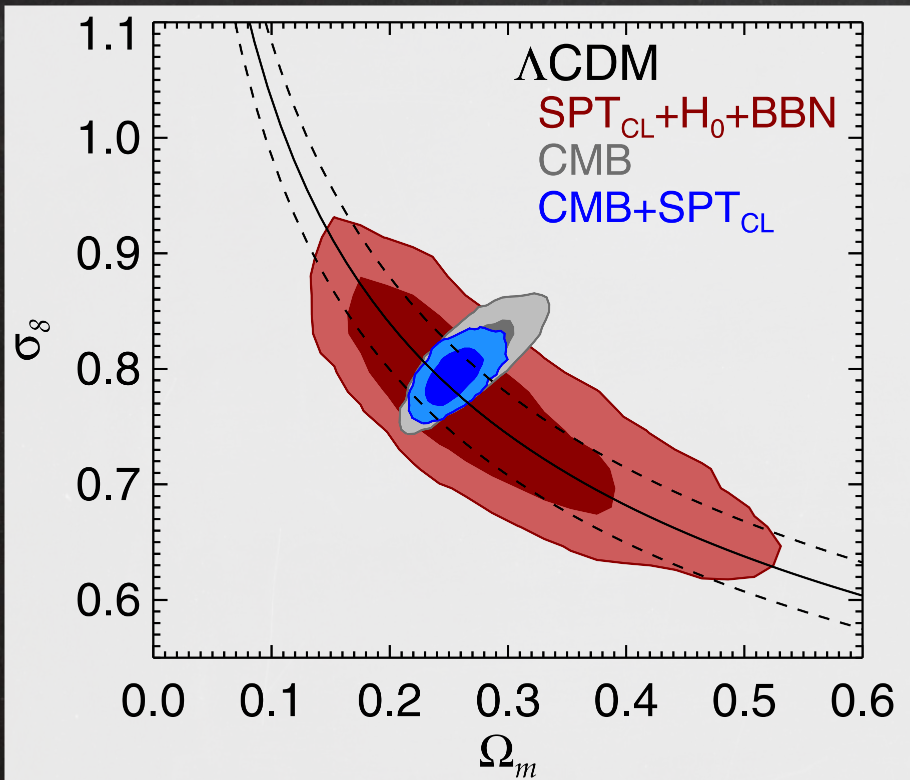
Selection and Scatter



Mantz et al 2010

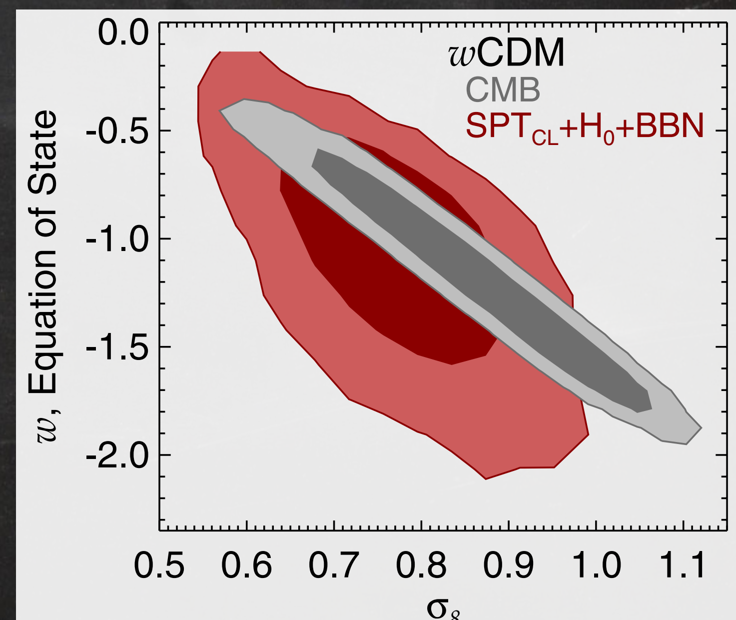
Let’s do cosmology!

Chapter 1 (oans)

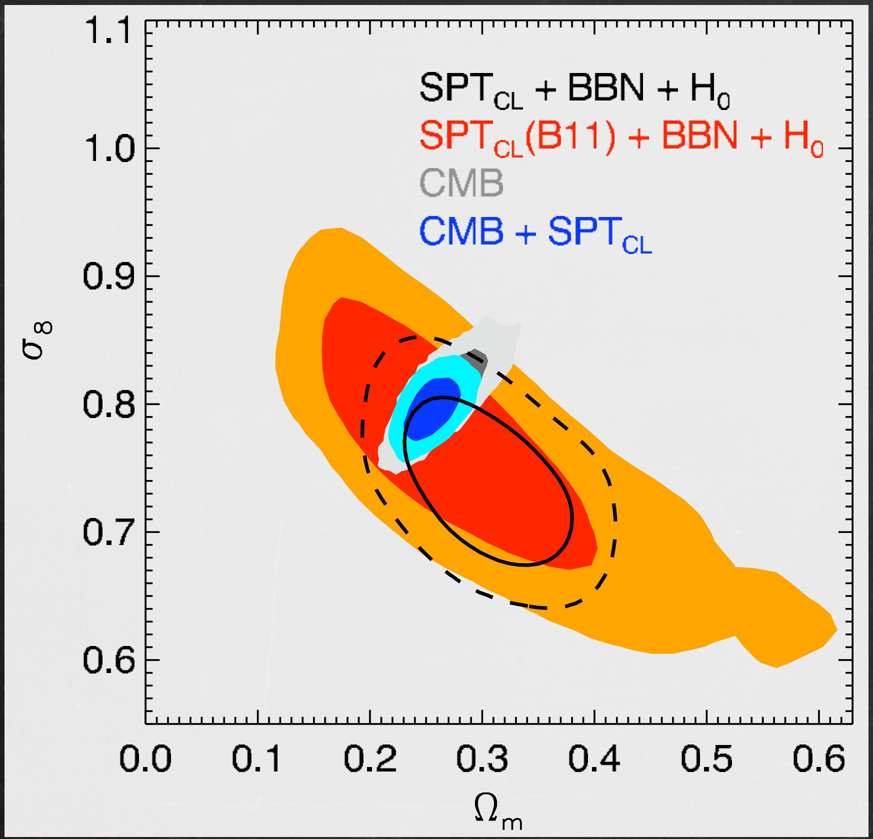


- 18 SZ clusters, of which
- 14 with X-ray Yx measurement
- Consistent with other cosmological probes

Benson et al 2013



Chapter 2 (zwoa)

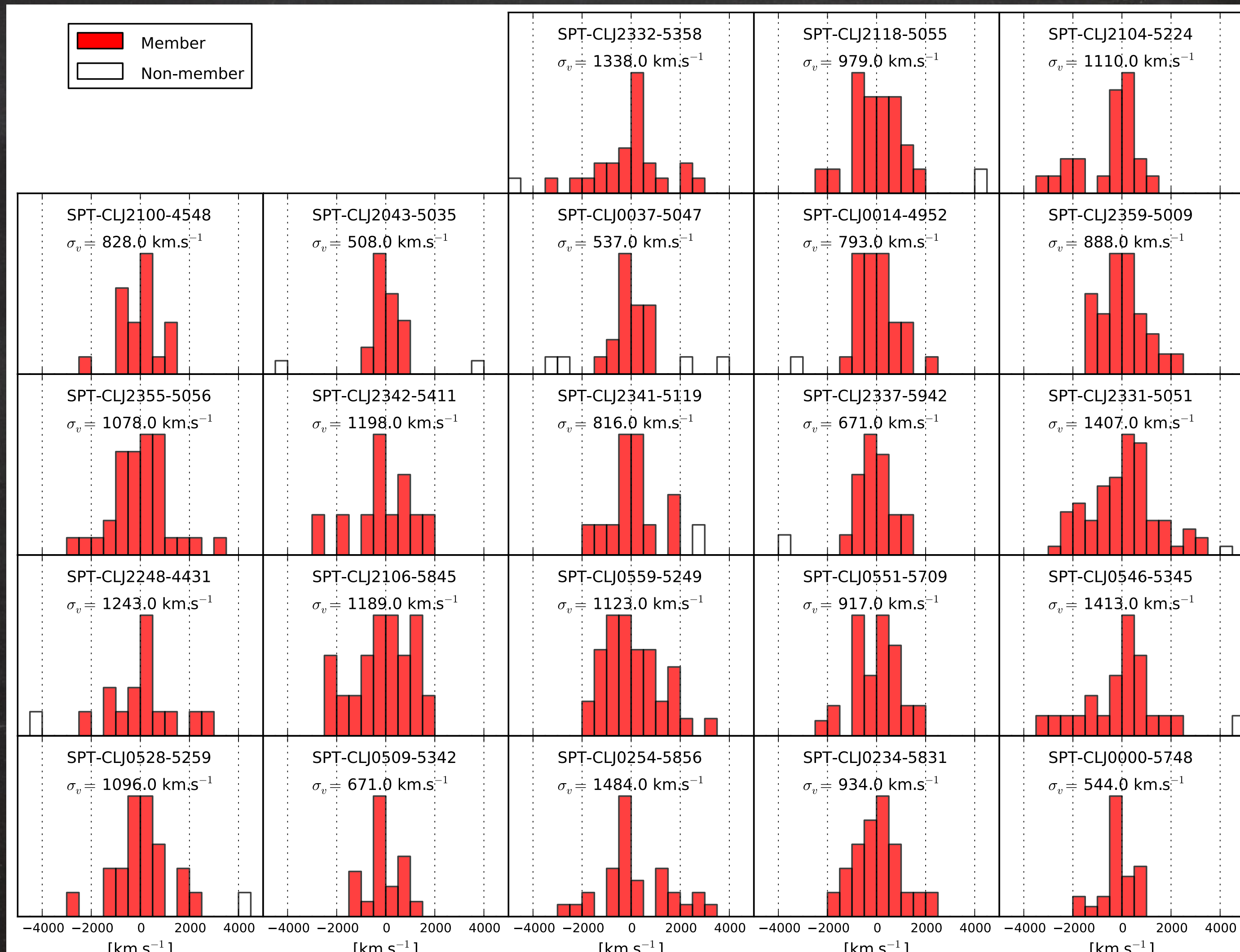


Reichardt et al 2013

- 100 SZ clusters, of which
- 14 with X-ray Y_x measurement
- Constraints in Ω_m-σ_8 plane improve by 1.8x in area
- Still limited by SZ accuracy of the SZ normalization parameter

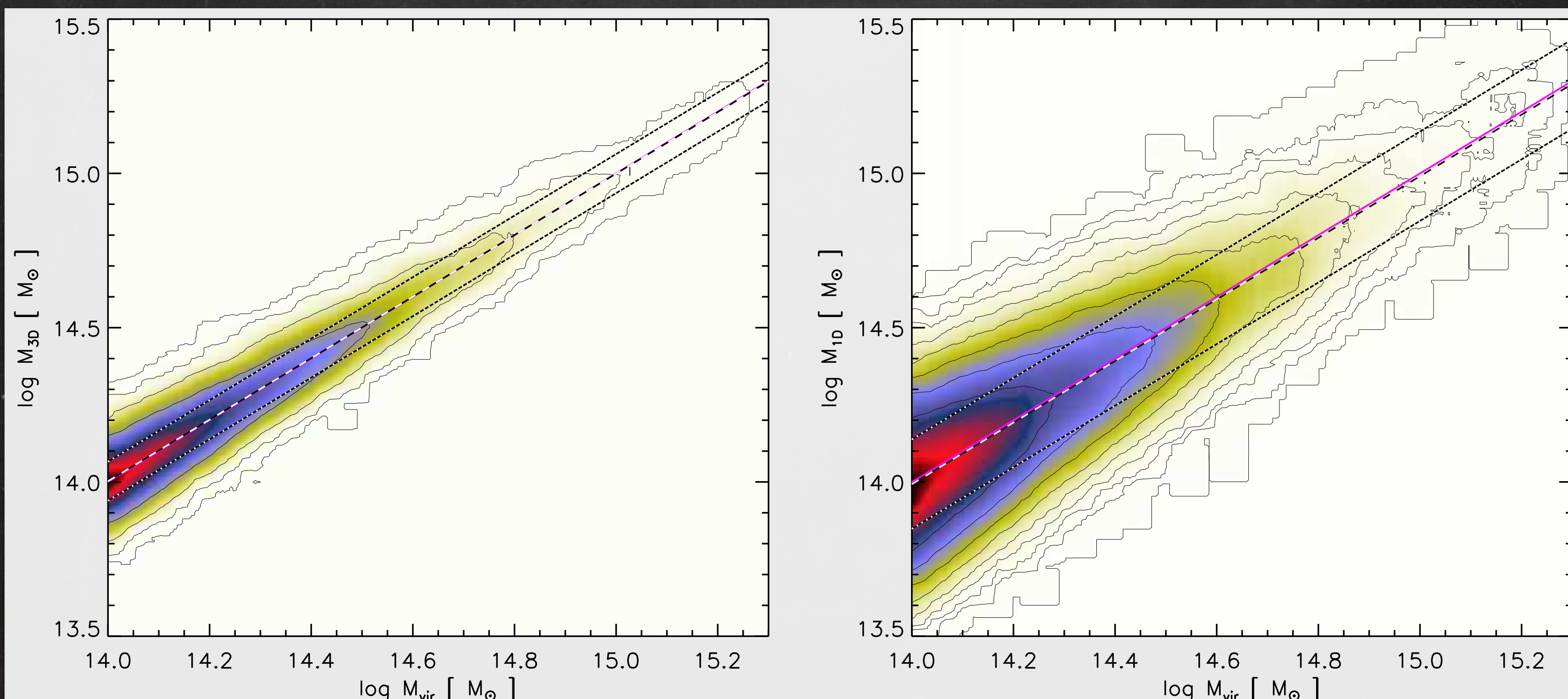
Galaxy Velocity Dispersion

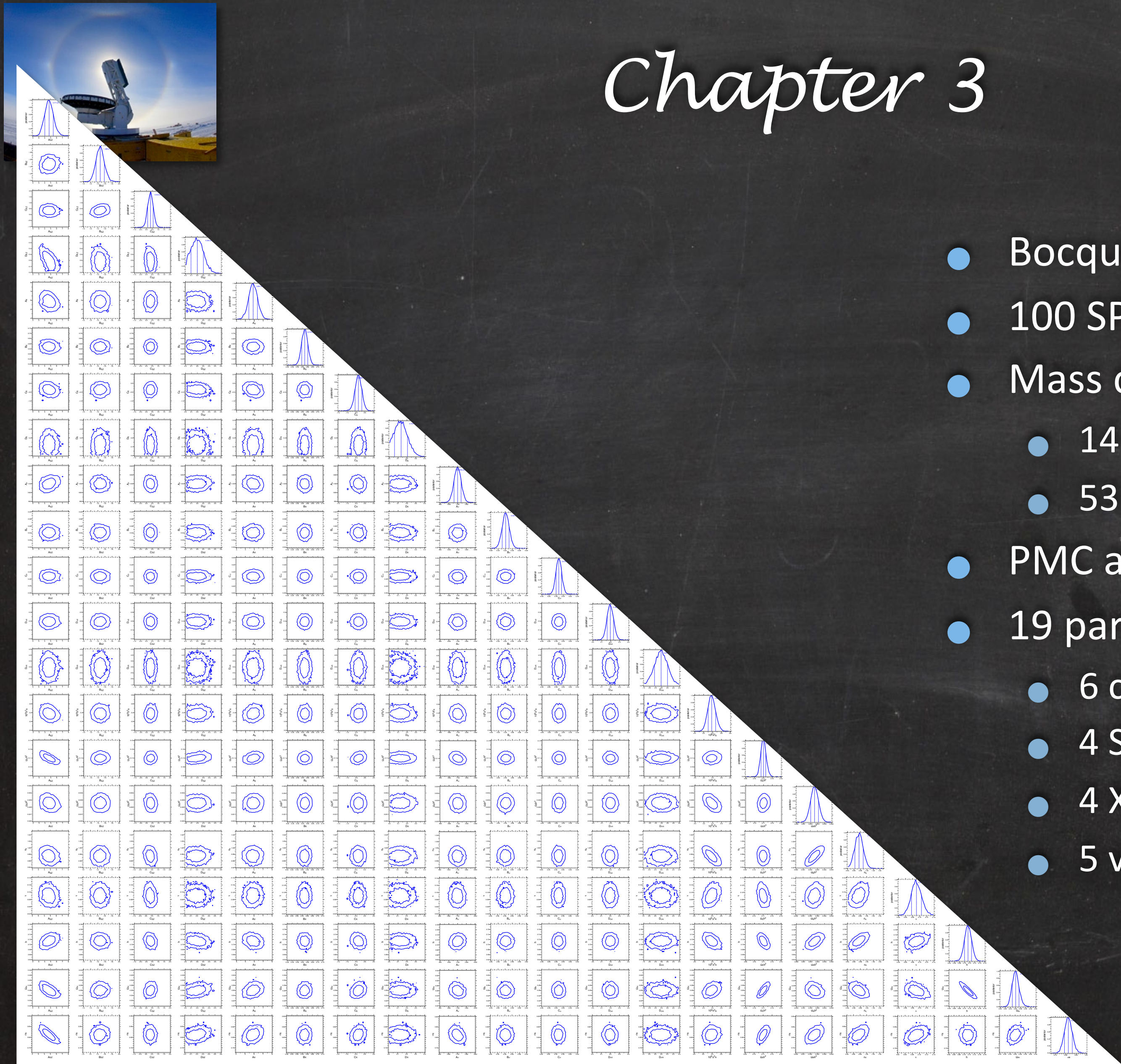
Gemini South, Magellan, VLT: Ruel et al. in prep.



Galaxy Velocity Dispersion

- Include velocity dispersion as a mass calibrator
  - Not affected by gas physics, does not rely on hydrostatic equilibrium
  - Independent cross-check of the X-ray mass calibration
- Numerical calibration by Saro et al 2013, arXiv 1203.5708





Chapter 3

- Bocquet et al in prep
- 100 SPT clusters (720 deg^2)
- Mass calibration
  - 14 X-ray Y_xs
  - 53 velocity dispersions
- PMC algorithm
- 19 parameters
  - 6 cosmological
  - 4 SZ
  - 4 X-ray Y_x
  - 5 velocity dispersion

Mass Calibration with Y_X and σ_v, ΛCDM Cosmology, no CMB data

	Prior	SPT$_{\rm CL}$+BBN+H$_0$+ Y_X	σ_v	Y_X+σ_v
$A_{\rm SZ}$	6.24 ± 1.872	$5.36^{+1.42}_{-1.20}$	$4.62^{+1.44}_{-1.09}$	$4.60^{+1.09}_{-0.97}$
$B_{\rm SZ}$	1.33 ± 0.266	1.58 ± 0.13	1.60 ± 0.13	1.60 ± 0.13
$C_{\rm SZ}$	0.83 ± 0.415	0.69 ± 0.35	0.75 ± 0.36	0.74 ± 0.39
$D_{\rm SZ}$	0.24 ± 0.16	0.25 ± 0.12	0.22 ± 0.13	0.23 ± 0.12
A_X	5.77 ± 0.56	5.60 ± 0.54	$\cdots$	5.77 ± 0.51
B_X	0.57 ± 0.03	0.57 ± 0.03	$\cdots$	0.57 ± 0.03
C_X	-0.40 ± 0.20	-0.46 ± 0.20	$\cdots$	-0.39 ± 0.18
D_X	0.12 ± 0.08	0.13 ± 0.07	$\cdots$	0.14 ± 0.08
A_{σ_v}	1048 ± 53	$\cdots$	1080 ± 48	1083 ± 44
B_{σ_v}	0.34 ± 0.01	$\cdots$	0.34 ± 0.01	0.34 ± 0.01
C_{σ_v}	0.32 ± 0.02	$\cdots$	0.32 ± 0.02	0.32 ± 0.02
$D_{\sigma_v 0}$	0.2 ± 0.04	$\cdots$	0.20 ± 0.04	0.20 ± 0.04
$D_{\sigma_v N}$	3 ± 0.6	$\cdots$	2.97 ± 0.59	2.97 ± 0.58
$100\Omega_b$	$\cdots$	4.1 ± 0.5	4.0 ± 0.5	4.1 ± 0.5
Ω_m	$\cdots$	$0.34^{+0.13}_{-0.06}$	$0.37^{+0.16}_{-0.07}$	$0.37^{+0.22}_{-0.07}$
σ_8	$\cdots$	0.73 ± 0.05	0.74 ± 0.06	0.74 ± 0.06
H$_0$	73.8 ± 2.4	73.1 ± 2.4	73.5 ± 2.4	73.4 ± 2.4

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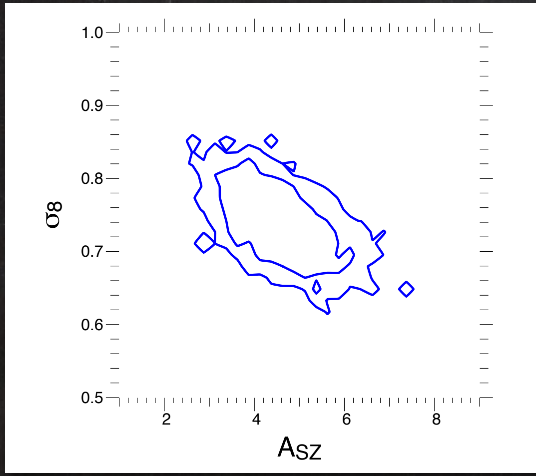
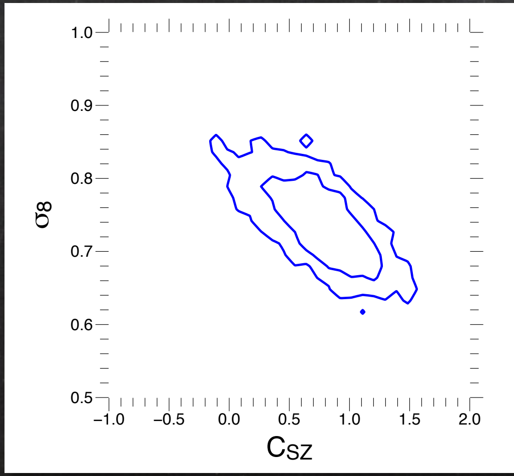
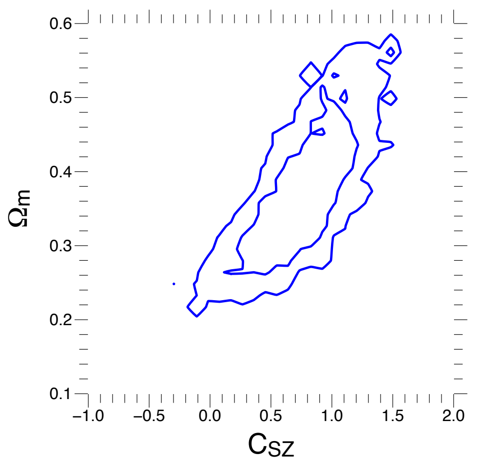
Bocquet et al in prep

Parameter	SPT_{CL}+BBN+H_0	CMB	SPT_{CL}+CMB
A_{SZ}	$4.60^{+1.09}_{-0.97}$	$\cdots$	$4.33^{+0.76}_{-0.71}$
B_{SZ}	1.60 ± 0.13	$\cdots$	1.52 ± 0.12
C_{SZ}	0.74 ± 0.35	$\cdots$	0.36 ± 0.24
D_{SZ}	0.23 ± 0.13	$\cdots$	0.23 ± 0.12
n_s	0.971 ± 0.013[a]	0.970 ± 0.014	0.969 ± 0.014
Ω_m	$0.37^{+0.22}_{-0.07}$	0.276 ± 0.030	0.262 ± 0.015
σ_8	0.74 ± 0.06	0.818 ± 0.030	0.799 ± 0.019
H_0	73.4 ± 2.4	70.1 ± 2.4	71.0 ± 1.6







Growth Rate of Structure

- Parametrized matter power spectrum (Peebles 1980, Wang&Steinhardt 1998)

$$\frac{d^2 \ln \delta}{d \ln a^2} + \left(\frac{d \ln \delta}{d \ln a}\right)^2 + \frac{d \ln \delta}{d \ln a}\left[\frac{1}{2} - \frac{3}{2} w(1-\Omega)\right] = \frac{3}{2}\Omega$$

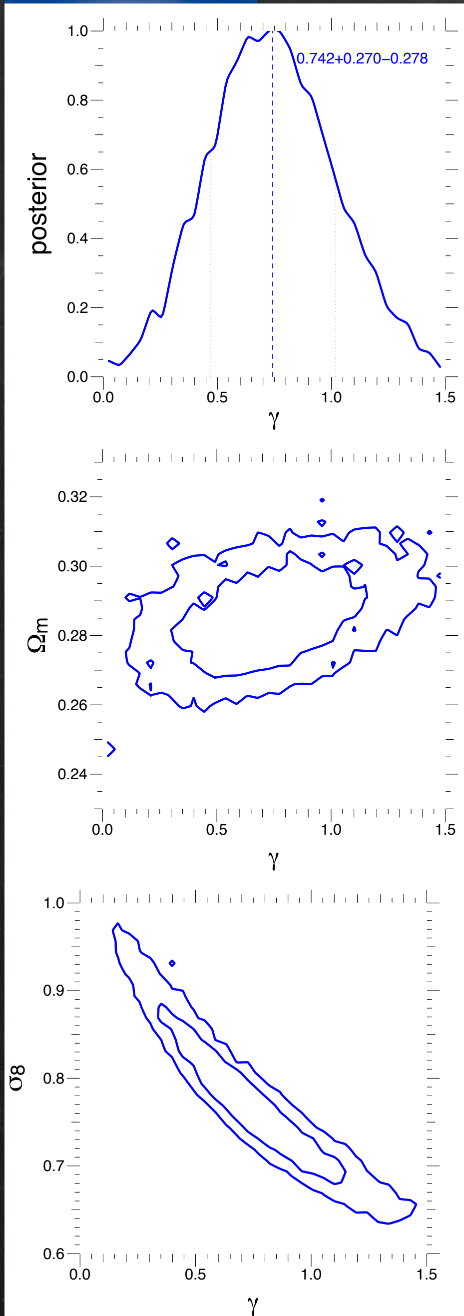
$$f \equiv \frac{d \ln \delta}{d \ln a} \equiv \Omega^\gamma$$

$$\gamma \approx \frac{6 - 3(1+w)}{11 - 6(1+w)}$$

- Parametrized matter power spectrum

$$\mathrm{P}_{\mathrm{norm}}(k, z) = \mathrm{P}(k, z_{\mathrm{ini}}) D^2_{z_{\mathrm{ini}}}(z)$$

- Assume standard expansion history
- GR predicts γ=0.55
- Consistency test of the cosmic growth history



Cosmic Growth Index

- GR predicts γ=0.55
- Bocquet et al in prep

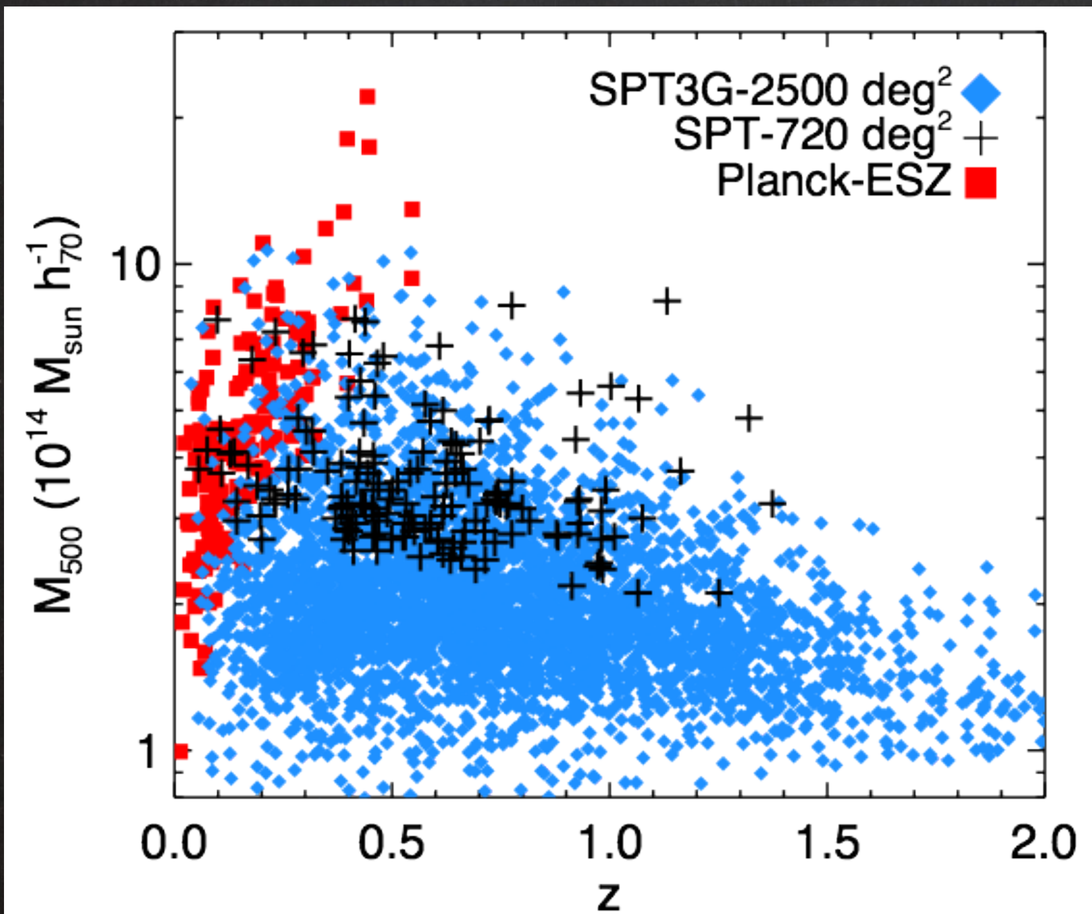
Dataset:
STPcl+Y_X+σ_v+WMAP7+BAO+SNIa+H_0

Parameter	Prior	Result
$\Omega_c h^2$	...	0.114 ± 0.003
$100\Omega_b h^2$	...	2.23 ± 0.05
$10^9 \Delta_R^2$	...	2.44 ± 0.09
n_s	...	0.966 ± 0.012
τ	...	0.082 ± 0.13
H_0	73.8 ± 2.4	69.1 ± 0.9
γ	...	0.74 ± 0.27
Ω_m	...	0.286 ± 0.011
σ_8	...	0.770.07

Outlook: Mass Calibration

- Full SPT-SZ sample coming soon
- X-ray
  - XVP with Chandra to get Y_xs of ~80 high ξ clusters
  - XMM obs of ~30 clusters (Magellan WL and high-z)
- Velocity dispersions
  - ~100 cluster velocity dispersions from ~25 member velocities using Gemini GMOS-S at z<0.8, VLT FORS2 at z>0.8 and MagellanIMACS as available
- Weak Lensing
  - 18 z~0.3-0.4 clusters with Magellan Megacam
  - HST Snapshot observations of ~60 clusters underway

Outlook: SPT-3G



- Starting 2016
- 10X more clusters than SPT-SZ
- Expect 4000 clusters
- Purity 99%

Thank you for your attention!