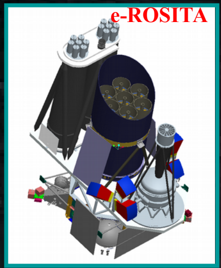
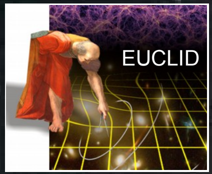
Dark Energy Survey





SPIDERS

The South Pole Telescope (SPT) cluster survey and its cosmological implications

Alex Saro

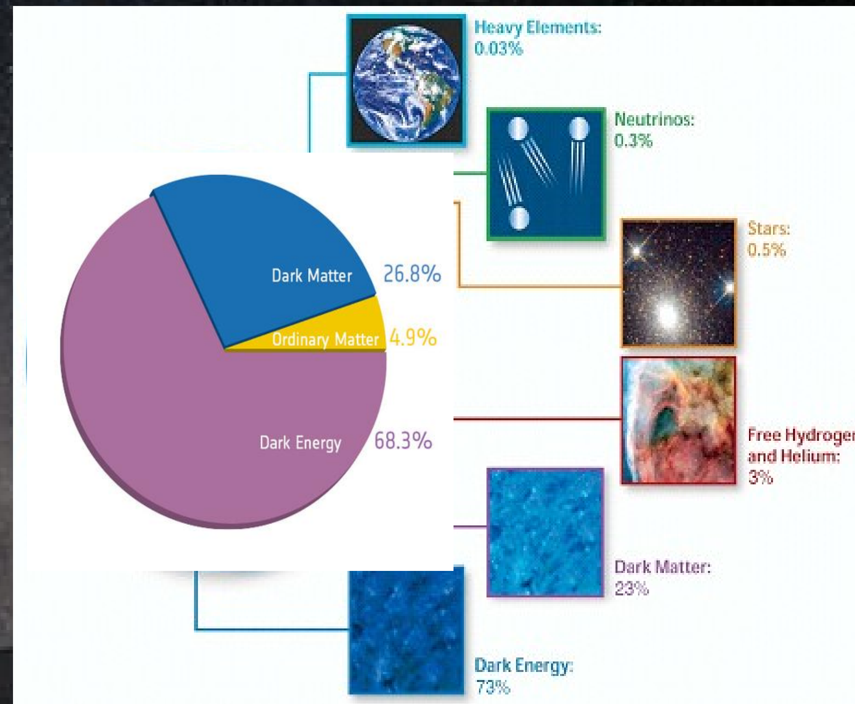
OSSERVATORIO ASTRONOMICO DI TRIESTE · INAF ISTITUTO NAZIONALE DI ASTROFISICA

erc

European Commission

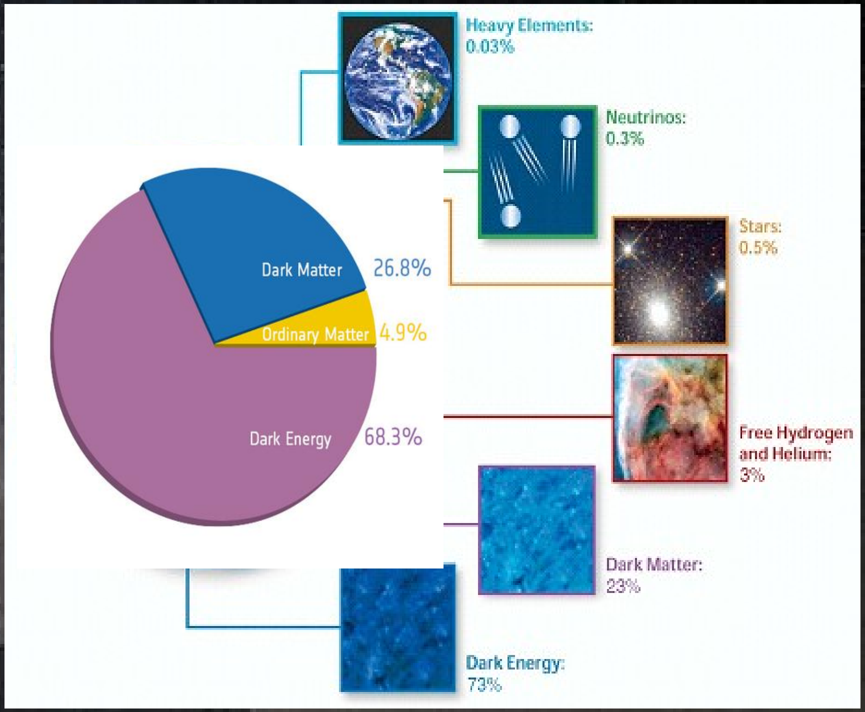
Geometry and Contents of the Universe

- General consensus is that several independent cosmological probes point towards a consistent model of flat LCDM
- A model where ~70% of the energy density is “dark energy” ~25% is “dark matter” and the rest is “normal matter” is consistent with all available data
- Understanding the root cause of the cosmic acceleration is the primary focus of observational cosmology today



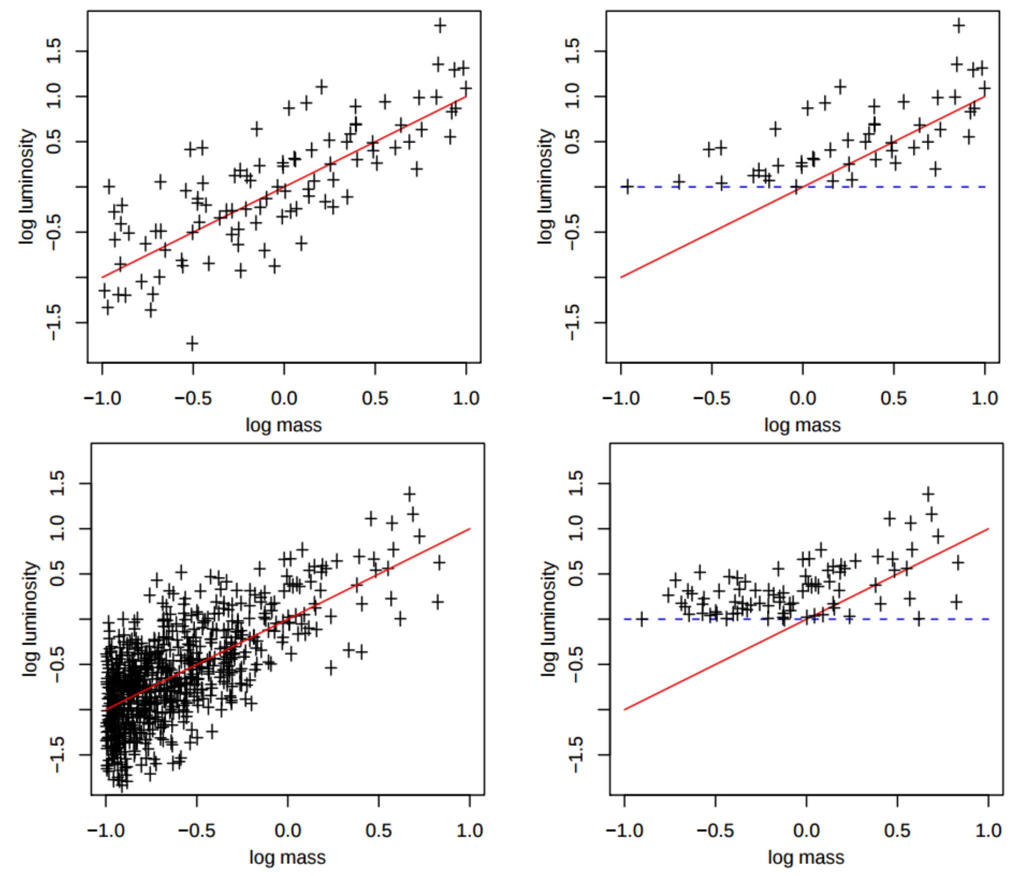
Geometry and Contents of the Universe

- Dominant source of cosmological information is coming from primary CMB fluctuations at z~1100
- Few ≲2σ tensions are present when combining CMB with local probes, e.g.:
  - H_0 (Riess et al. 2016)
  - Cosmic shear (KiDS, CFHTLens, DES)
  - Clusters (e.g., Planck 15)



Cluster Cosmology

- Have a theory prediction for the Halo Abundances
- Find Galaxy Clusters
- Obtain redshifts (distance)
- Mass proxies
- Scaling relations
  - Malmquist bias
  - Eddington bias
  - Selection



Mantz et al. 2010

Cluster Surveys Provide a Rich Source of Information

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

Press & Schechter 72

$$\frac{dn}{dM}(M,z) = -\sqrt{\frac{2}{\pi}}\,\frac{\rho_b}{M}\,\frac{d\sigma(M,z)}{dM}\,\frac{\delta_c}{\sigma^2(M,z)}\exp\left\{\frac{-\delta_c^2}{2\sigma^2(M,z)}\right\}$$

Halo Redshift Distribution

Sensitive to volume-redshift relation and halo abundance evolution

Halo Abundance Evolution

Depends on the amplitude and shape of the power spectrum of density fluctuations

Can be studied directly in N-body simulations; simple “cosmology independent” fitting formulae exist

e.g. Sheth & Tormen 99, Jenkins+01, Warren+05, Tinker+08, Watson+13, Bocquet+16, Despali+16 etc.

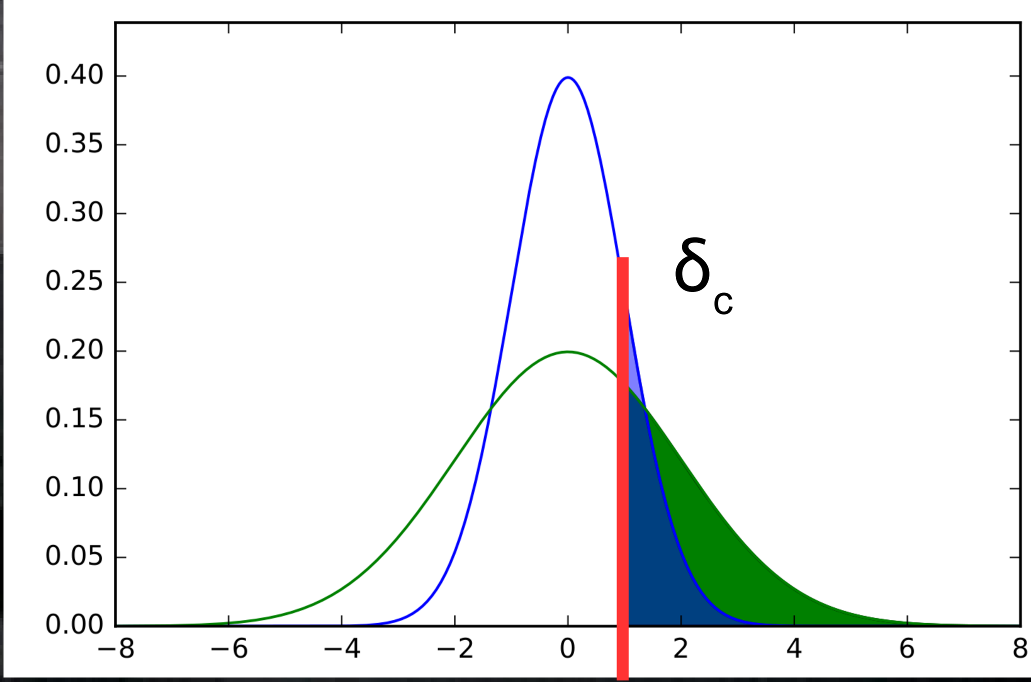
Bottom line: surveys measure

Distances

Characteristics of initial perturbations

Growth rate of density perturbations

But you must know the mass selection of your survey!



Cluster Surveys Provide a Rich Source of Information

Halo Redshift Distribution

Sensitive to volume-redshift relation and halo abundance evolution

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

Press & Schechter 72

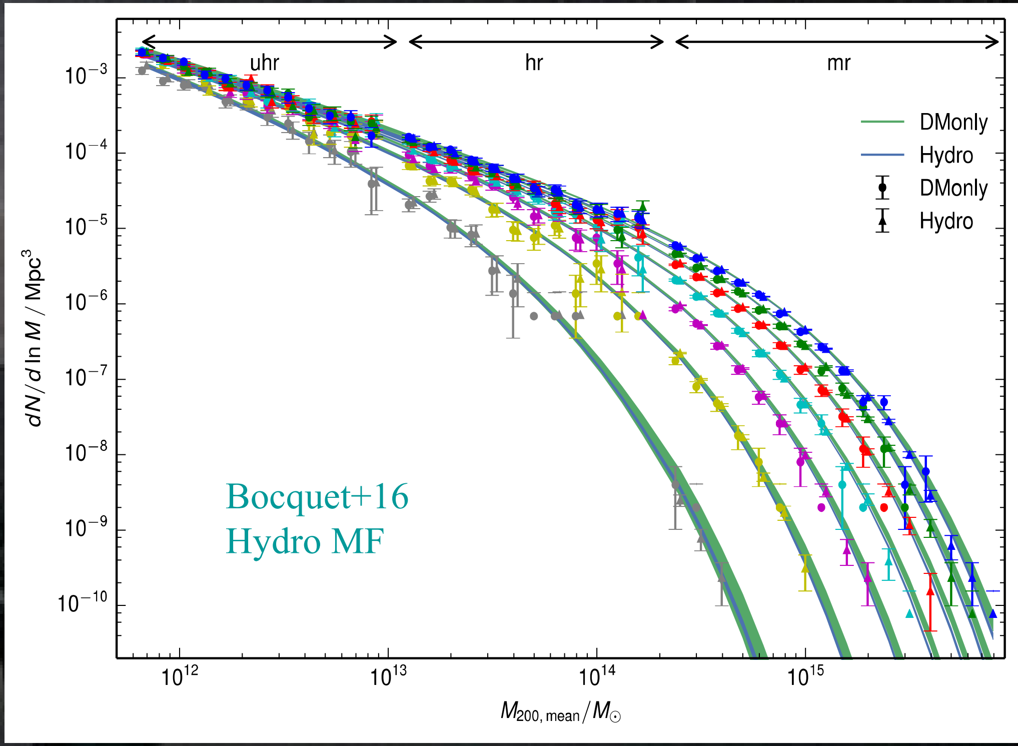
$$\frac{dn}{dM}(M,z) = -\sqrt{\frac{2}{\pi}}\,\frac{\rho_b}{M}\,\frac{d\sigma(M,z)}{dM}\,\frac{\delta_c}{\sigma^2(M,z)}\exp\left\{\frac{-\delta_c^2}{2\sigma^2(M,z)}\right\}$$

Halo Abundance Evolution

Depends on the amplitude and shape of the power spectrum of density fluctuations

Can be studied directly in N-body simulations; simple “cosmology independent” fitting formulae exist

e.g. Sheth & Tormen 99, Jenkins+01, Warren+05, Tinker+08, Watson+13, Bocquet+16, etc



Bottom line: surveys measure

Distances

Characteristics of initial perturbations

Growth rate of density perturbations

But you must know the mass selection of your survey!

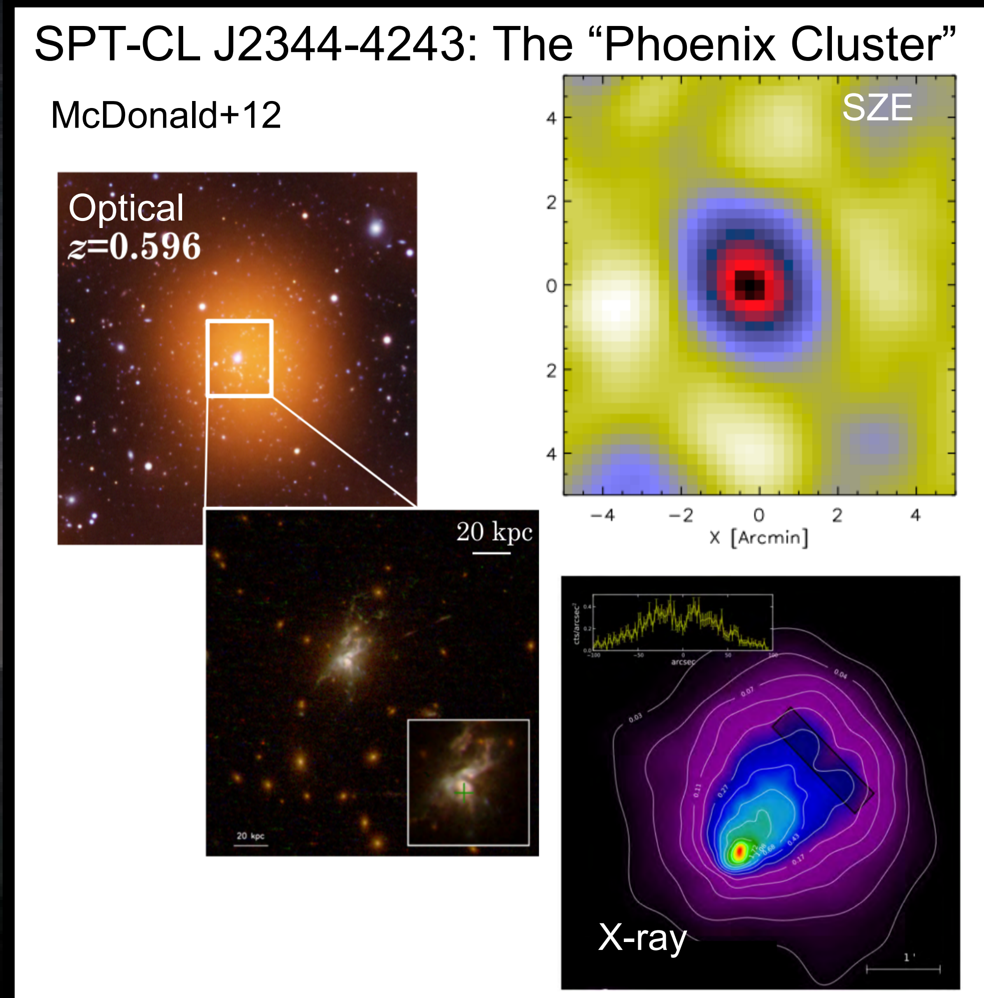
What Are Galaxy Clusters?

Galaxy clusters are the most massive, collapsed structures in the universe. They contain galaxies, hot ionized gas ($10^{7\text{-}8}$K) and dark matter.

In typical structure formation scenarios, low mass clusters emerge in significant numbers at z~2-3

Clusters are good probes, because they are massive and “easy” to detect through their:

- X-ray emission
- Light from galaxies
- Sunyaev-Zel’dovich Effect

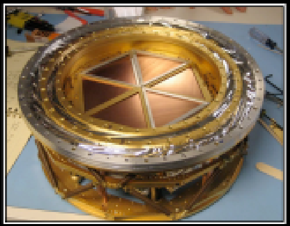


The South Pole Telescope (SPT)

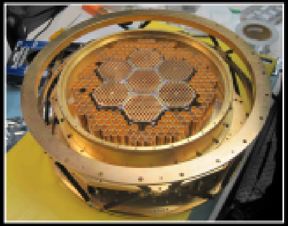
10-meter sub-mm quality wavelength telescope

90, 150, 220 GHz and
1.6, 1.2, 1.0 arcmin resolution

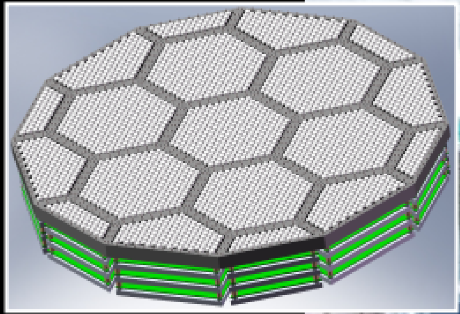
2007: SPT-SZ
960 detectors
90,150,220 GHz

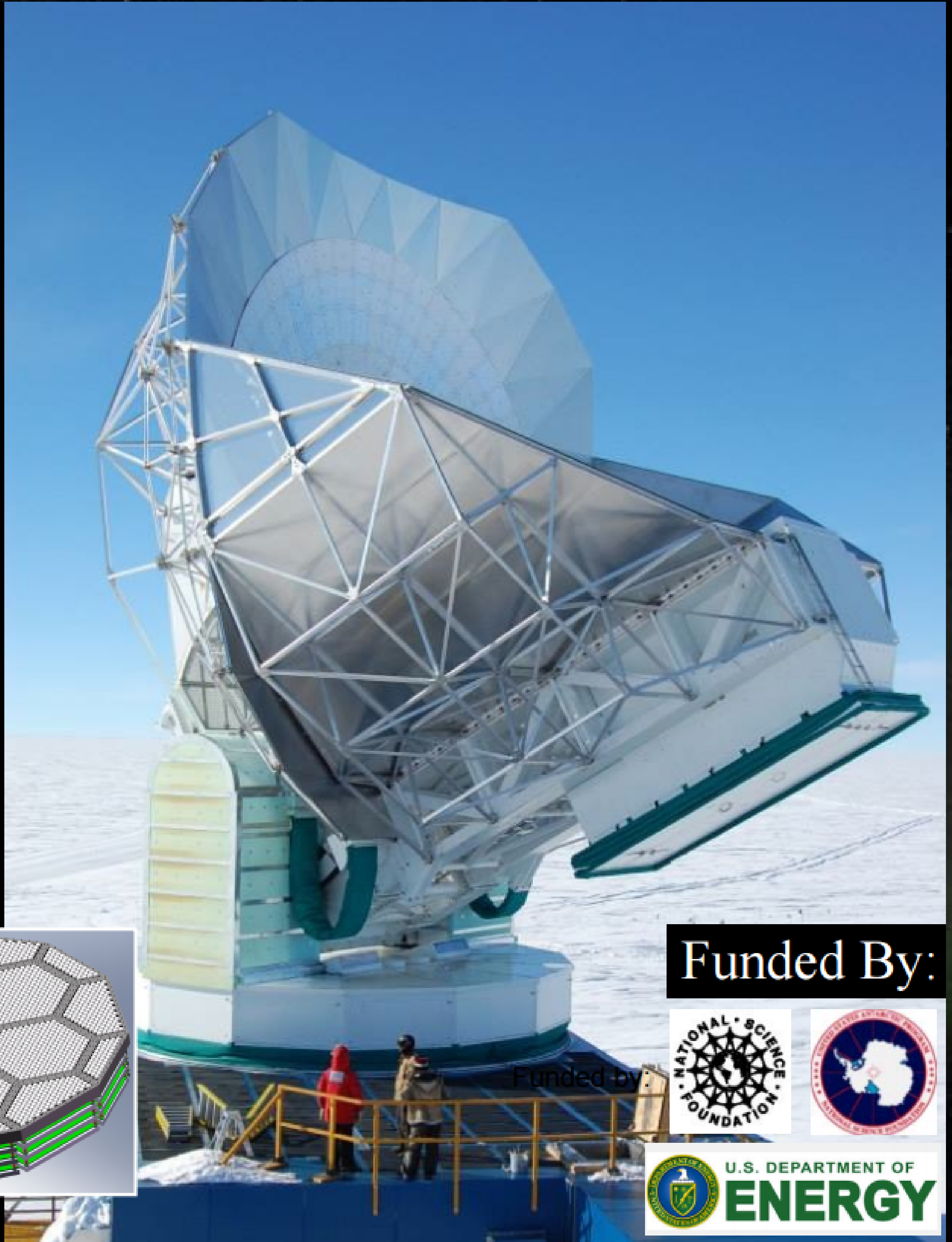


2012: SPTpol
1600 detectors
90,150 GHz
+Polarization



2016: SPT-3G
~15,200 detectors
90,150,220 GHz
+Polarization





Funded By:

NATIONAL SCIENCE FOUNDATION

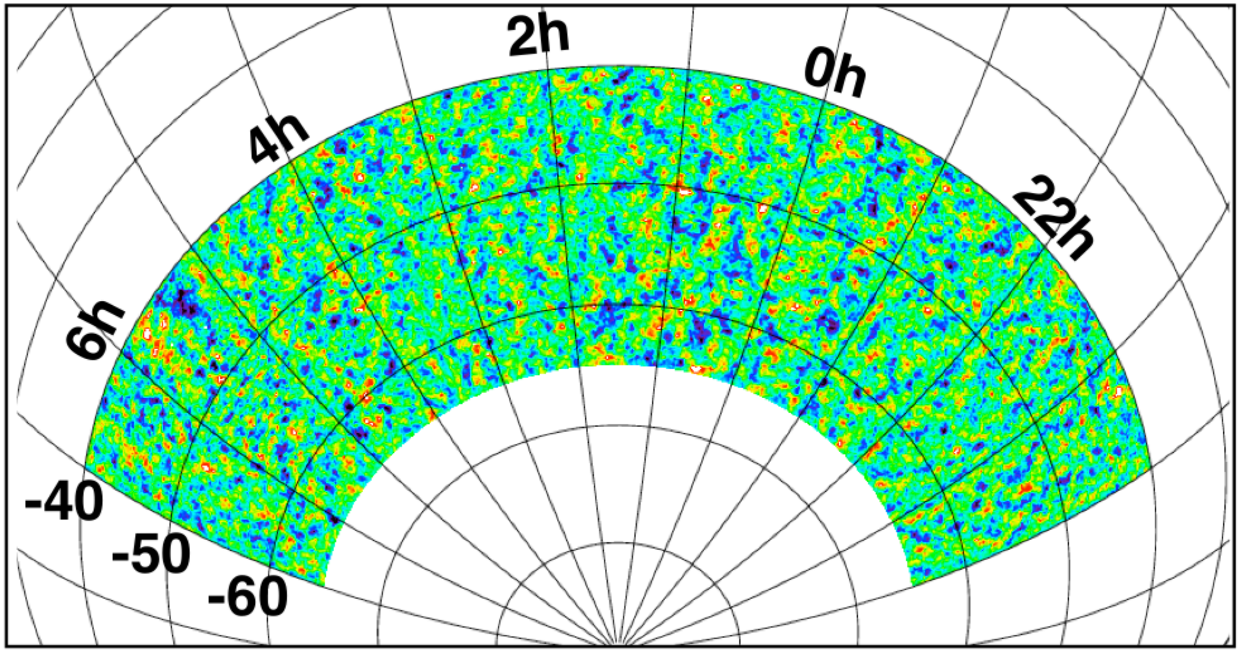
U.S. DEPARTMENT OF ENERGY

1
2

South Pole Telescope

SPT Survey

The 2500 deg² SPT-SZ Survey (2007-2011):

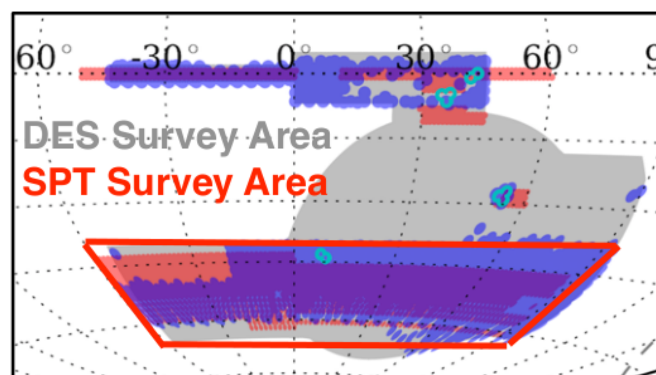


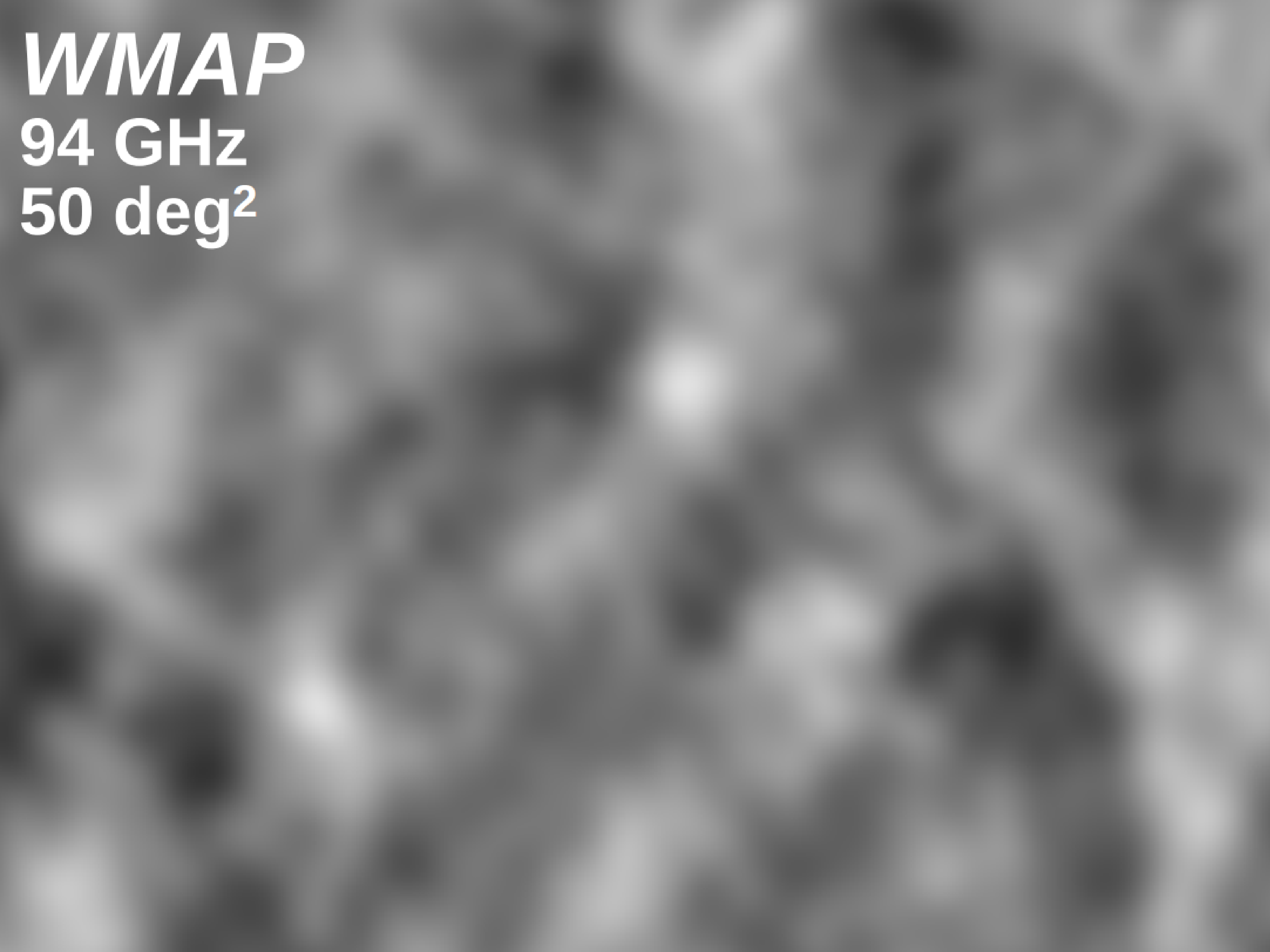
Final survey depths of:

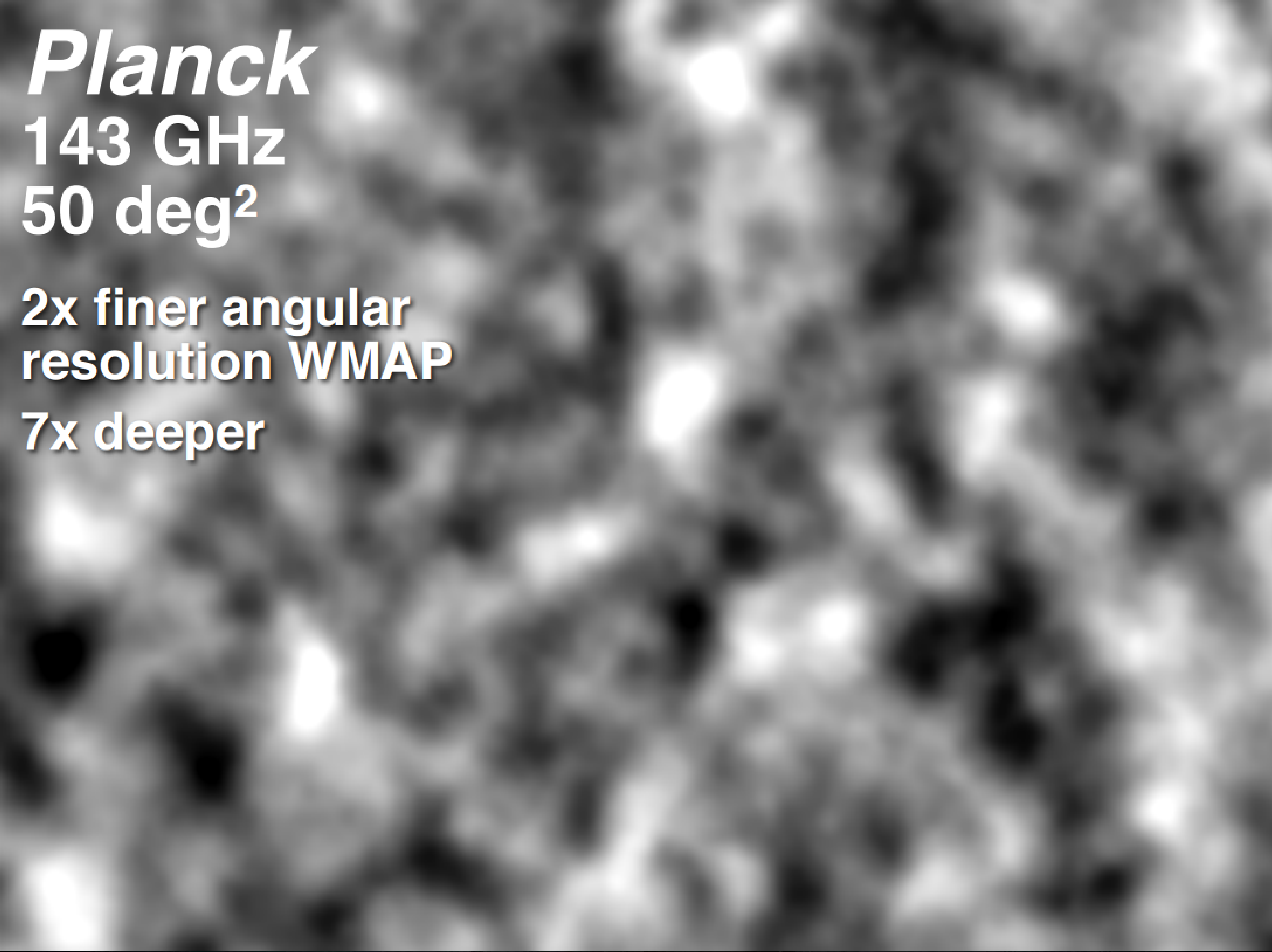
- **90 GHz:** 40 uK_{CMB}-arcmin
- **150 GHz:** 17 uK_{CMB}-arcmin
- **220 GHz:** 80 uK_{CMB}-arcmin

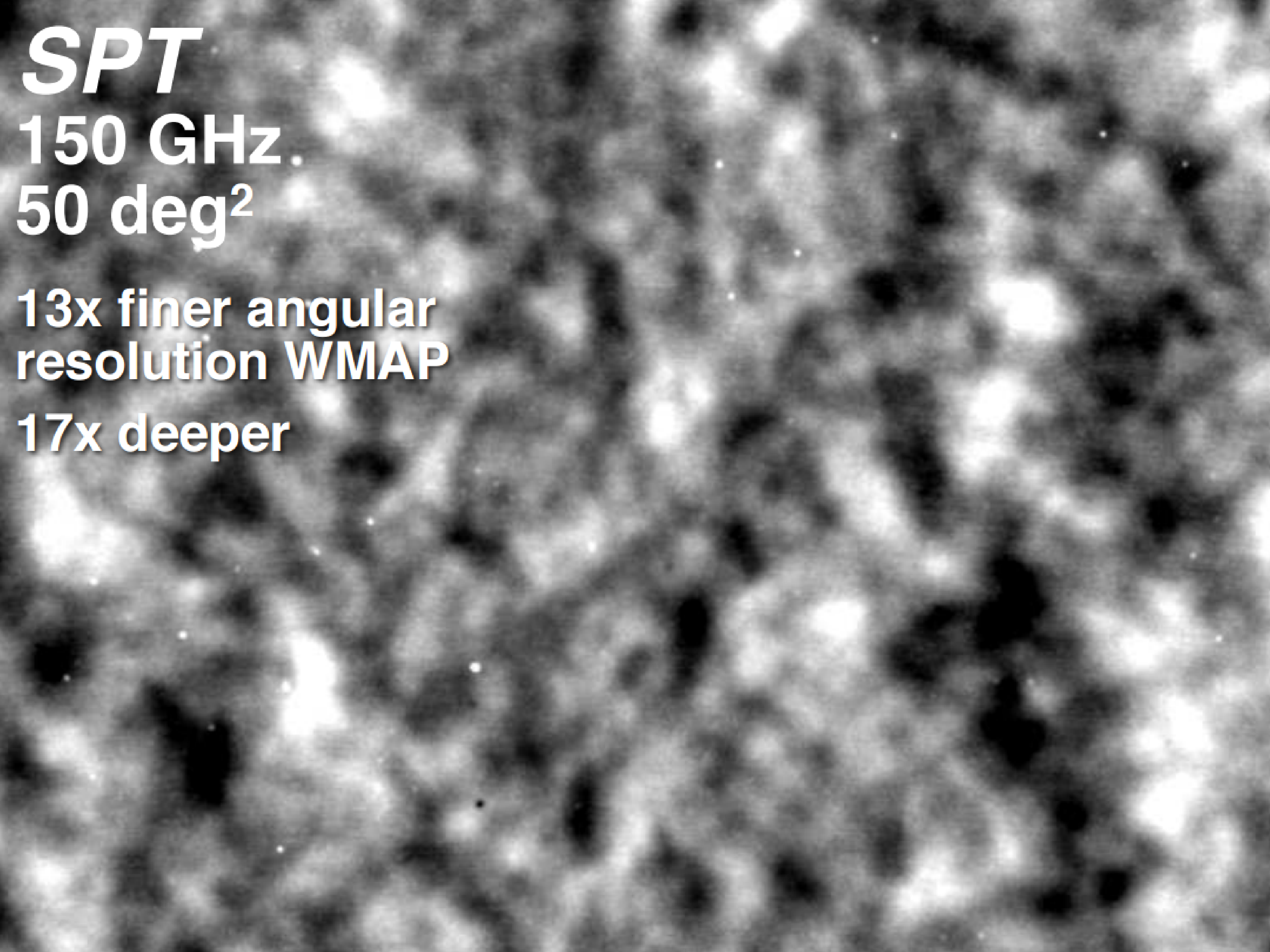
Complete overlap with DES survey

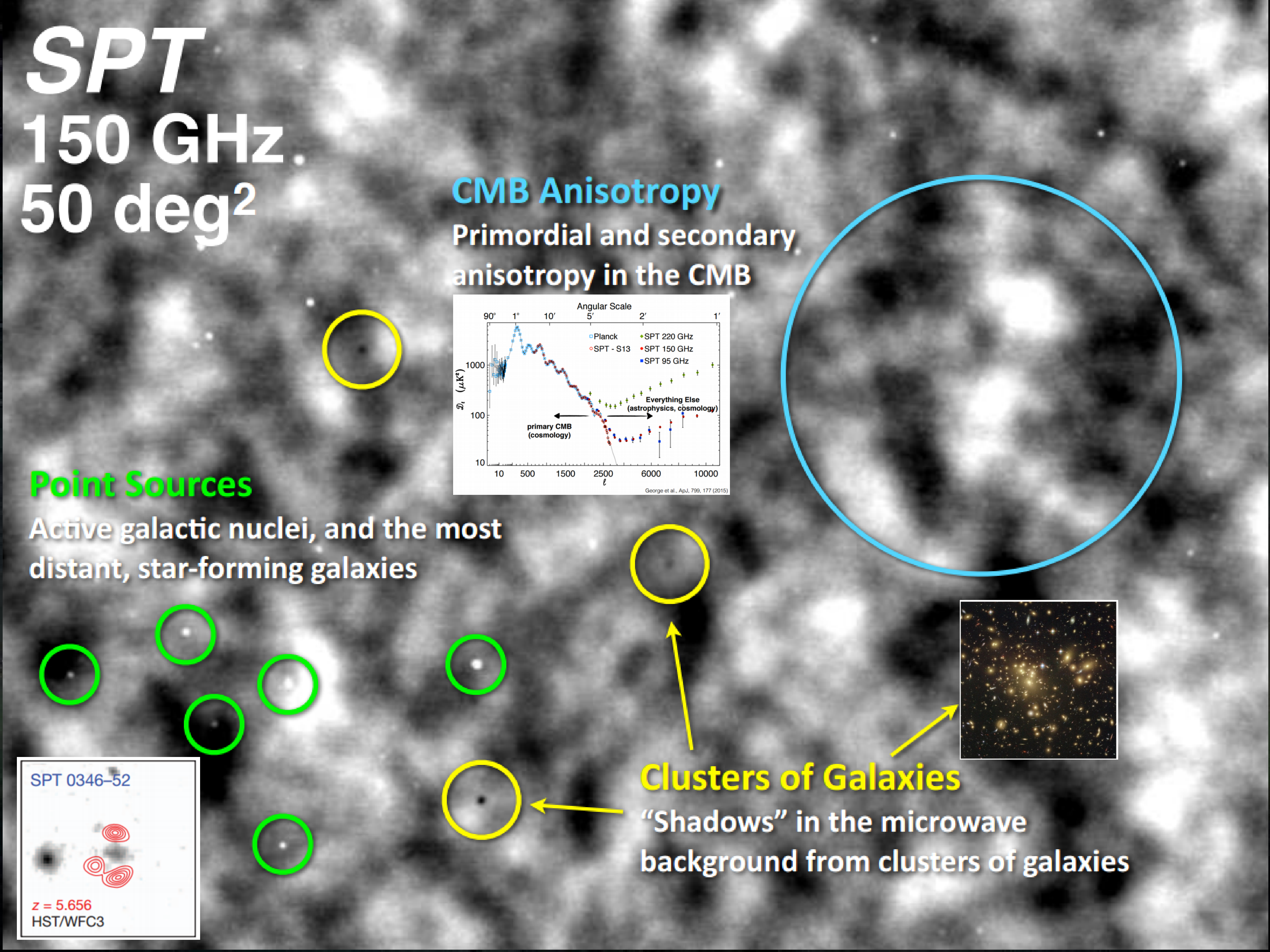
Saro+15, +16



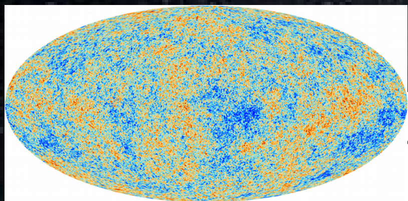

WMAP
94 GHz
50 deg2

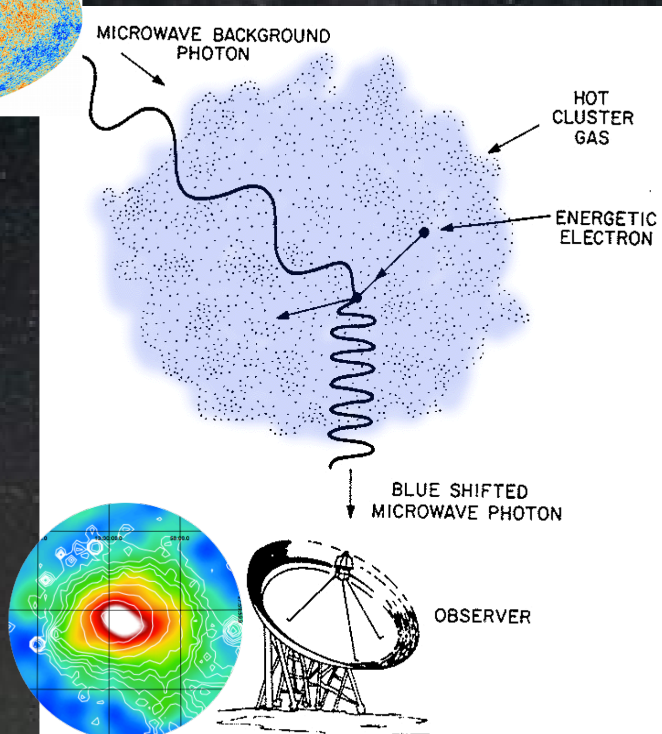

Planck
143 GHz
50 deg^2
2x finer angular resolution WMAP
7x deeper

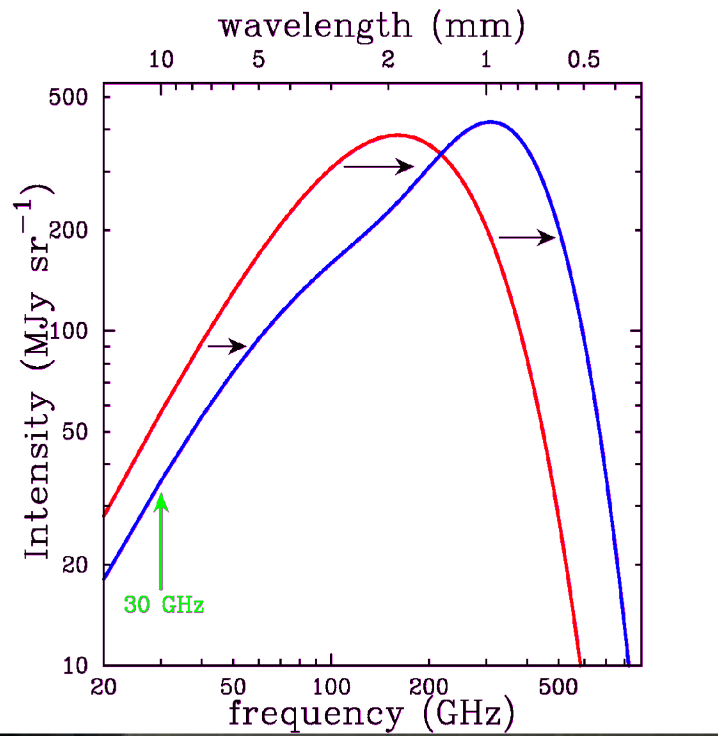

SPT
150 GHz
50 deg2
13x finer angular resolution WMAP
17x deeper


SPT
150 GHz
50 deg^2
CMB Anisotropy
Primordial and secondary anisotropy in the CMB
Angular Scale
90° 1° 10′ 5′ 2′ 1′
Planck
SPT - S13
SPT 220 GHz
SPT 150 GHz
SPT 95 GHz
$\mathcal{D}_\ell$ (μK^2)
1000
100
10
Everything Else
(astrophysics, cosmology)
primary CMB
(cosmology)
10 500 1500 2500 6000 10000
ℓ
George et al., ApJ, 799, 177 (2015)
Point Sources
Active galactic nuclei, and the most distant, star-forming galaxies
SPT 0346–52
z = 5.656
HST/WFC3
Clusters of Galaxies
"Shadows" in the microwave background from clusters of galaxies

Clusters and the Sunyaev-Zel’dovich Effect







Adapted from L. Van Speybroeck   Sunyaev & Zel’dovich 1970, 1972

Spectral Distortion of CMB – redshift independent!

Clusters and the Sunyaev-Zel'dovich Effect

The change of CMB temperature at the position of the the cluster due to the SZE can be expressed as:

$$\frac{T(\hat{n}) - T_0}{T_0} = \int G(\nu)\frac{k_B T_e}{m_e c^2} d\tau = G(\nu) y_c$$

Where: $y_c = (k_B \sigma_T / m_e c^2) \int n_e T_e dl$, $G(x) = x\coth(x/2) - 4$ and $x \equiv h\nu/kT$

If the Universe expands adiabatically we have:

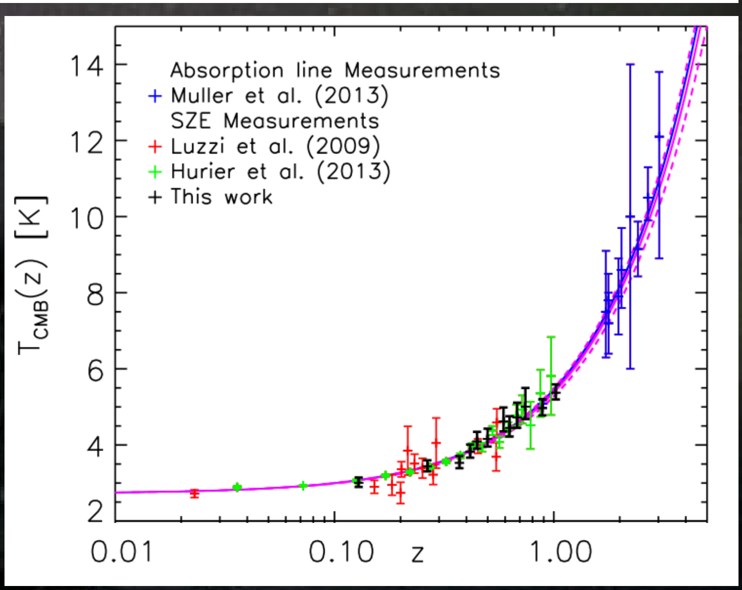
$$T(z) = T_0(1+z) \qquad \nu(z) = \nu_0(1+z)$$

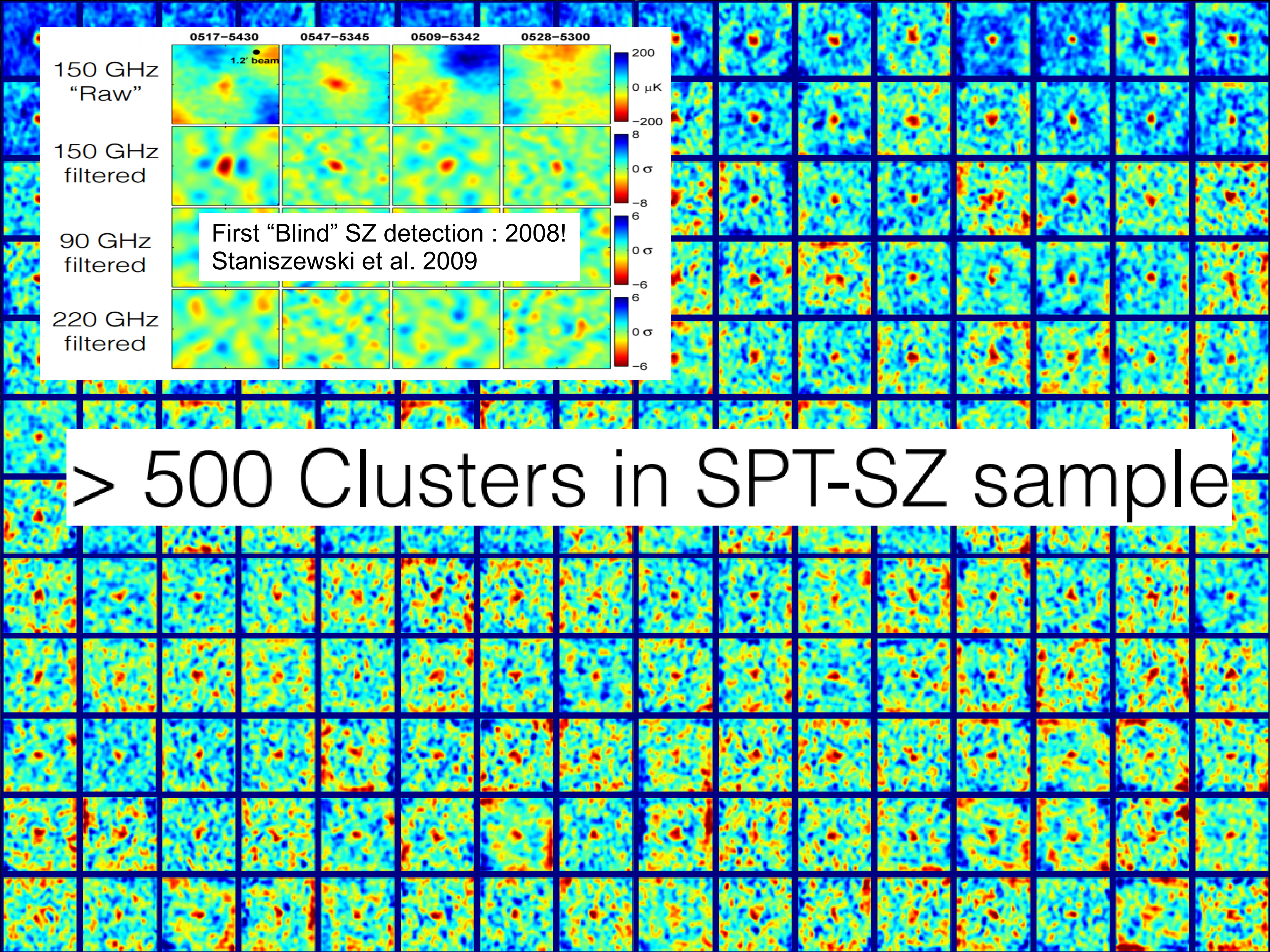
$$\Downarrow$$

$$x = h\nu(z)/kT(z) = h\nu_0/kT_0 = x_0$$

- Redshift independent <=> Allows to test adiabatic expansion of the Universe

  Saro+14



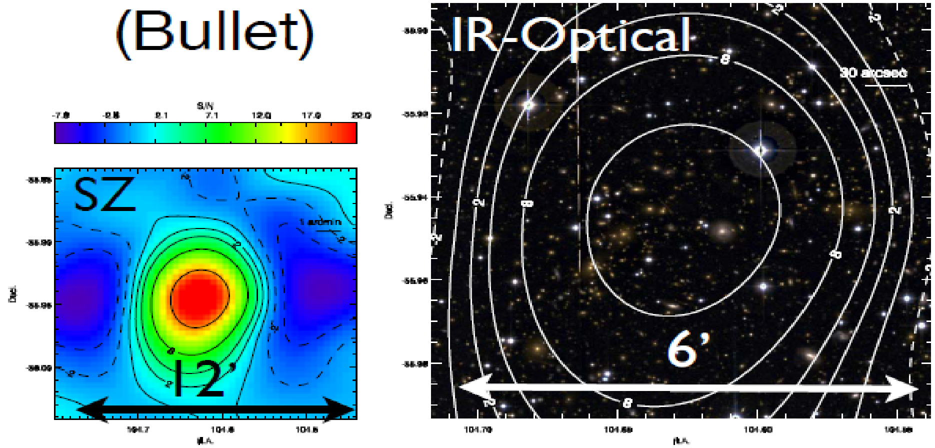


0517−5430
0547−5345
0509−5342
0528−5300
1.2′ beam
150 GHz “Raw”
150 GHz filtered
90 GHz filtered
220 GHz filtered
200
0 μK
−200
8
0 σ
−8
6
0 σ
−6
6
0 σ
−6
First “Blind” SZ detection : 2008!
Staniszewski et al. 2009
> 500 Clusters in SPT-SZ sample

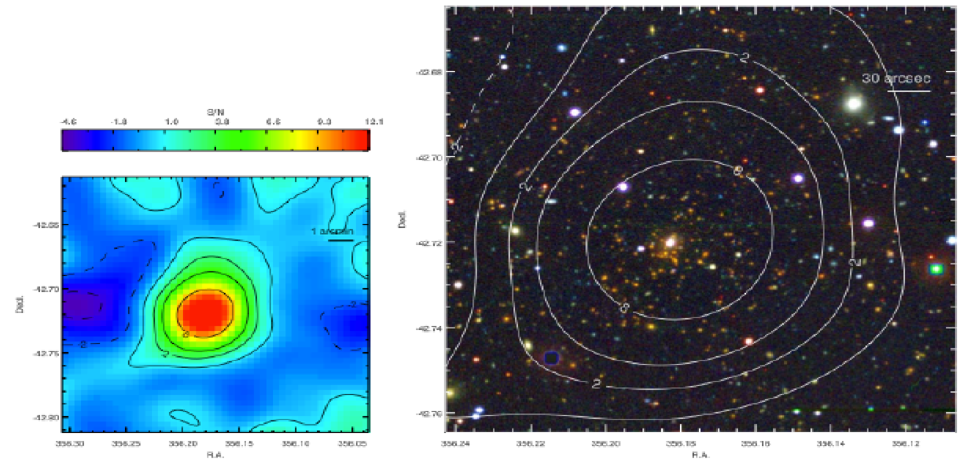
Confirmation of Galaxy Population

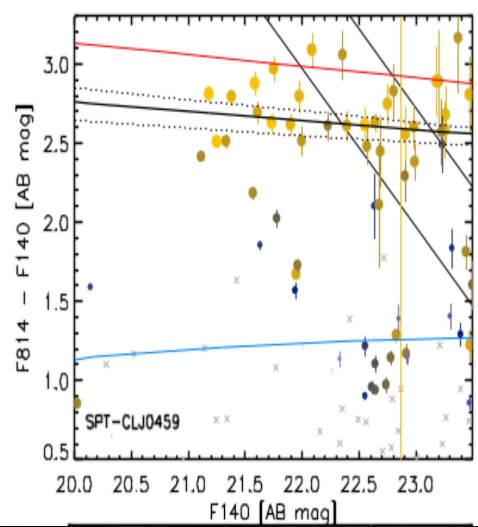
- Over the broad redshift range of the sample, we use optical and NIR imaging to probe for the galaxy population (Strazzullo+)

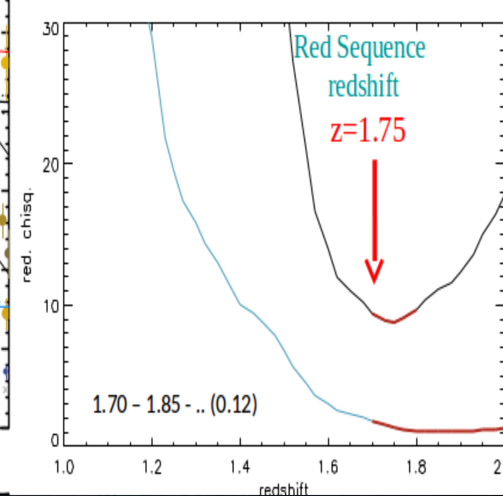
0658-5358 (z=0.30)
(Bullet)



2344-4243 (z=0.62)







SPT-SZ Sample

Song+12, Bleem+15

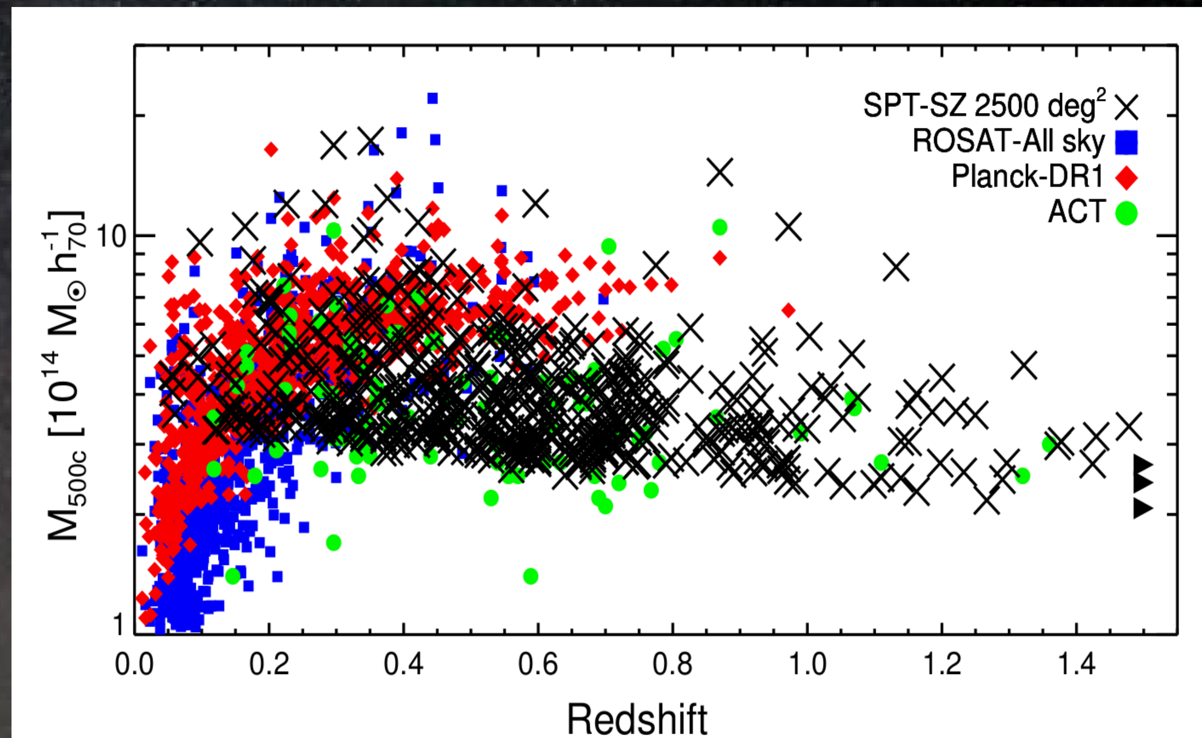
- 2500 deg^2 sample
  - 516 at ξ>4.5
  - 387 at ξ>5.0

    Bleem+15

- High z subsample
  - ~150 (80) > 0.8
  - ~ 70 (40) at z>1
  - Max z_{spec}=1.47

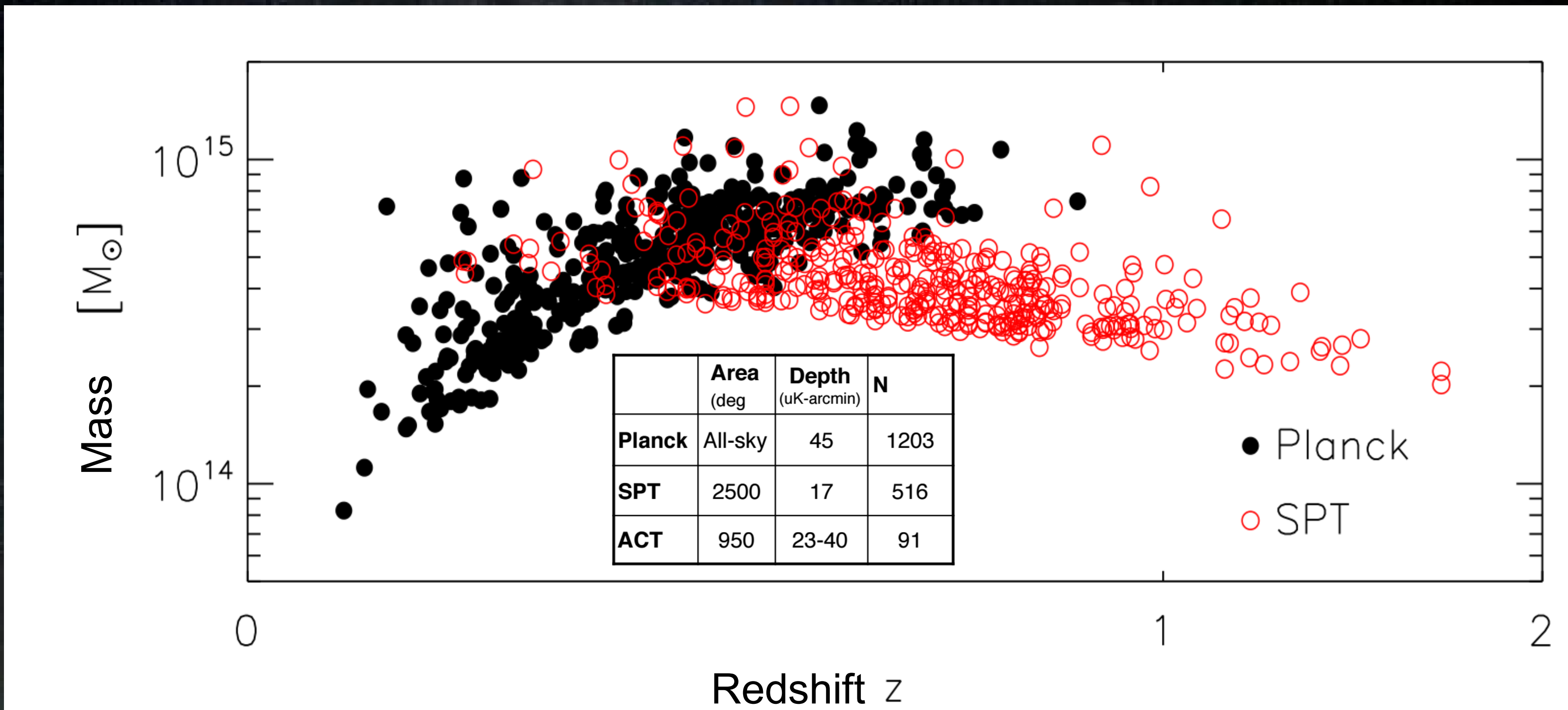
    Bayliss+13
  - Highest phot-z

    Strazzullo+



- Clean sample with M_{500}>3x10^{14} M_o to z~1.7

Planck & SPT



	Area (deg	Depth (uK-arcmin)	N
Planck	All-sky	45	1203
SPT	2500	17	516
ACT	950	23-40	91

- As of today ~ 95% of SZE detected clusters by either Planck or SPT
- Cosmological samples almost equal number: 439 (Planck) vs 377 (SPT)

EXQUISITE COMPLEMENTARITY!!!

Multi-wavelength Observations: Mass Calibration

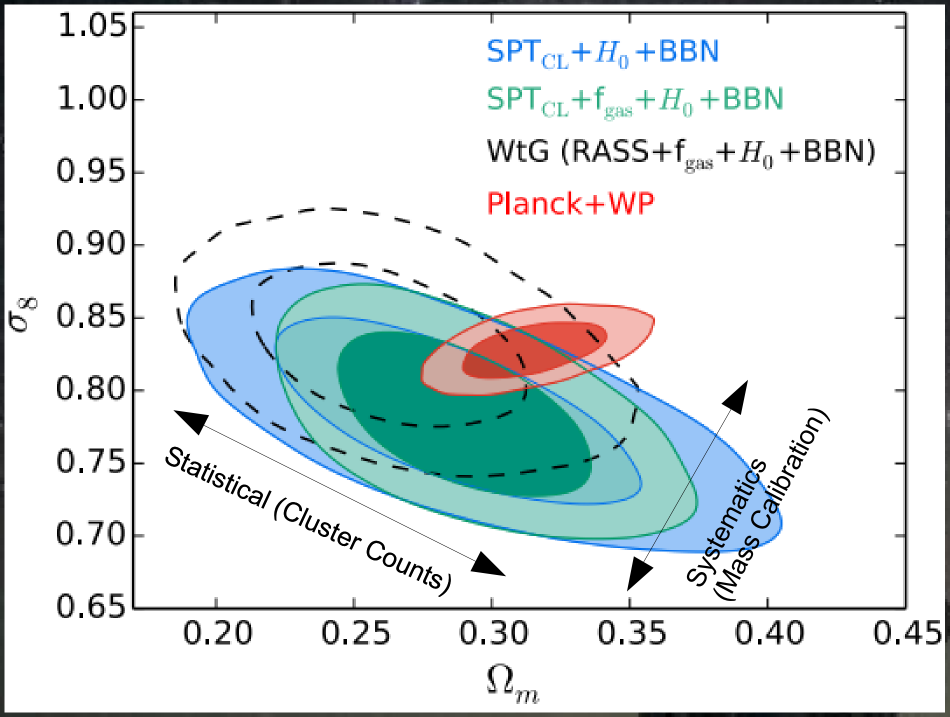
- Multi-wavelength mass calibration campaign, including:
  - X-ray with
    - Chandra
    - XMM
  - Weak lensing from:
    - Magellan ($0.3 < z < 0.6$)
    - HST ($z > 0.6$)
    - DES
  - Dynamical masses from
    - Gemini ($z < 0.8$)
    - VLT ($z > 0.8$)
    - Magellan ($z > 0.8$)

LMU USM

SPT Cluster Cosmology

de Haan+16

- With pure sample, model for selection, and calibration, we can test cosmology:



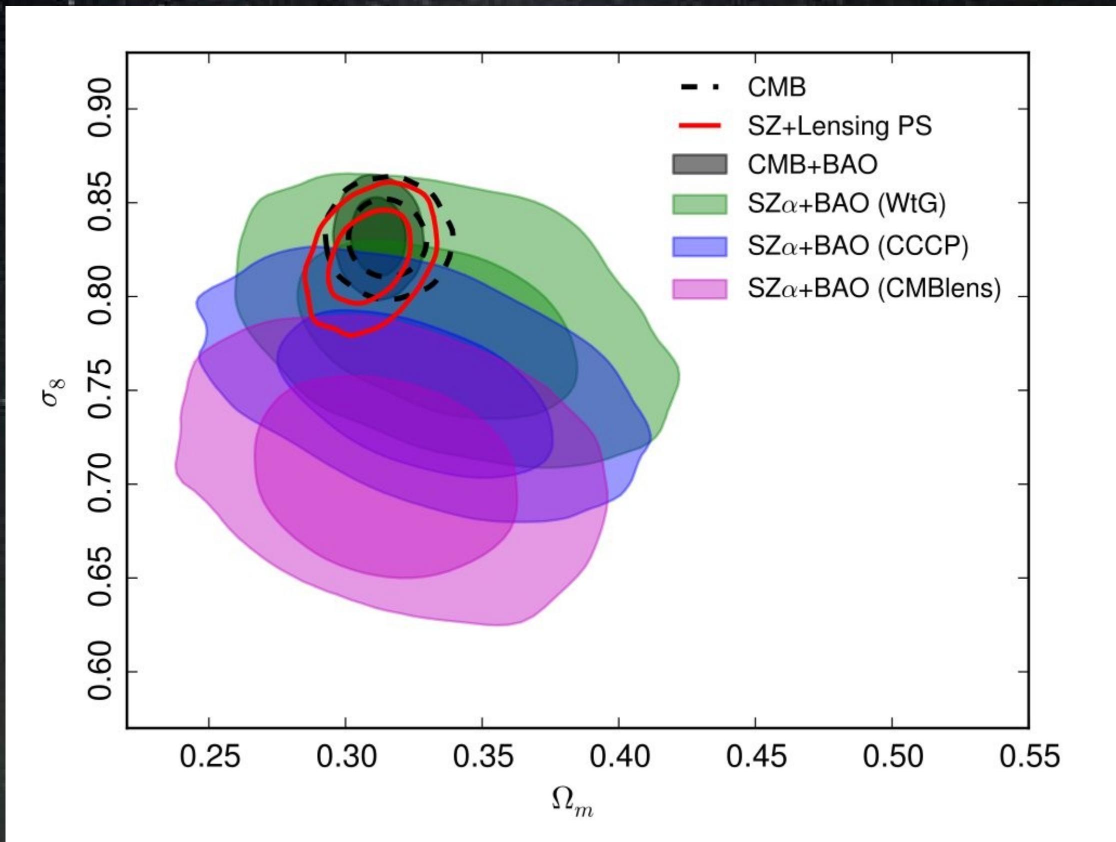
- 387 SPT clusters
- Mass calibration
  - 82 X-ray Y_xs
  - WL prior on Y_x-mass
- 15 parameters
  - 6 cosmological
  - 4 SZ mass-obs
  - 4 X-ray Y_x mass-obs
  - 1 Correlated Scatter
- Tension?
  - Insignificant in ΛCDM
  - Insignificant in wCDM

SPT Cluster Cosmology Constraints in good agreement with other probes within ΛCDM and wCDM models

SPT-SZ: w=-1.28+/-0.31 SPT-SZ++: w=-1.023+/-0.042

Planck Cluster Cosmology

Planck Collaboration XXIV (2015)

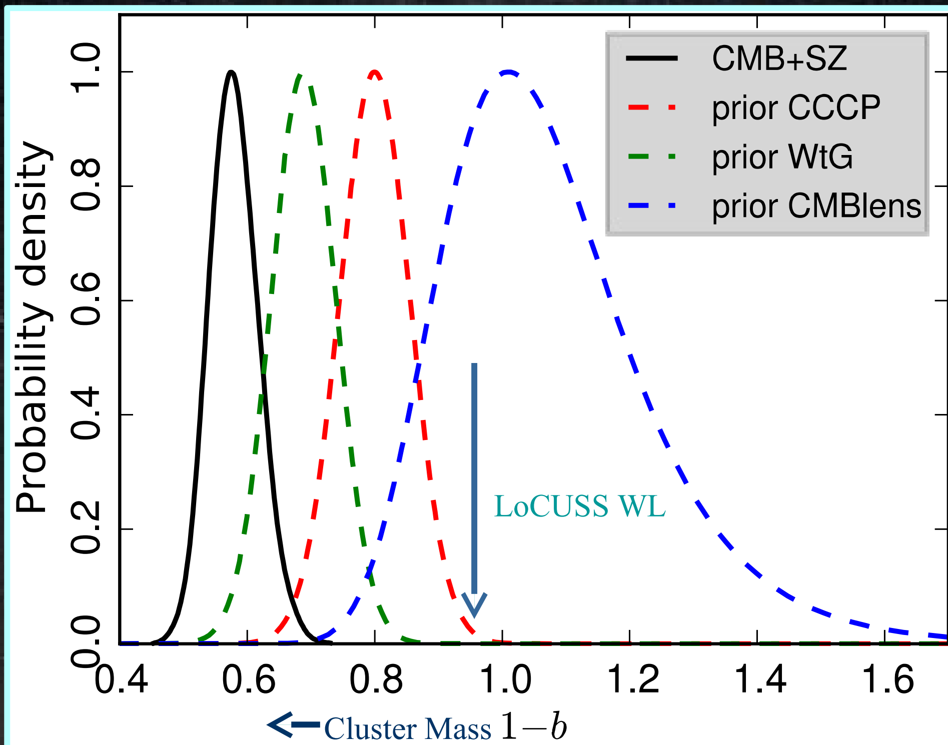


- 439 clusters
- Mass-obs rel'n
  - 3 params
    (C_{sz} fixed)
- Mass calibration
  - WL- WtG
  - WL-CCCP
  - WL-CMB
- Significant tension only if CMB WL used

PlanckSZE+BAO (CCCP): w=-1.00+/-0.18

Planck Cluster Mass Priors

Planck Collaboration XXIV (2015)



- External cosmology priors prefer higher masses than direct measurements
- CMB lensing and LoCUSS WL imply no hydrostatic mass bias
- Some tension among mass priors

WtG: 1-b=0.69+/-0.07
CCCP: 1-b=0.78+/-0.09
CMBLens: 1-b=0.99+/-0.19
LoCUSS: 1-b=0.95+/-0.04

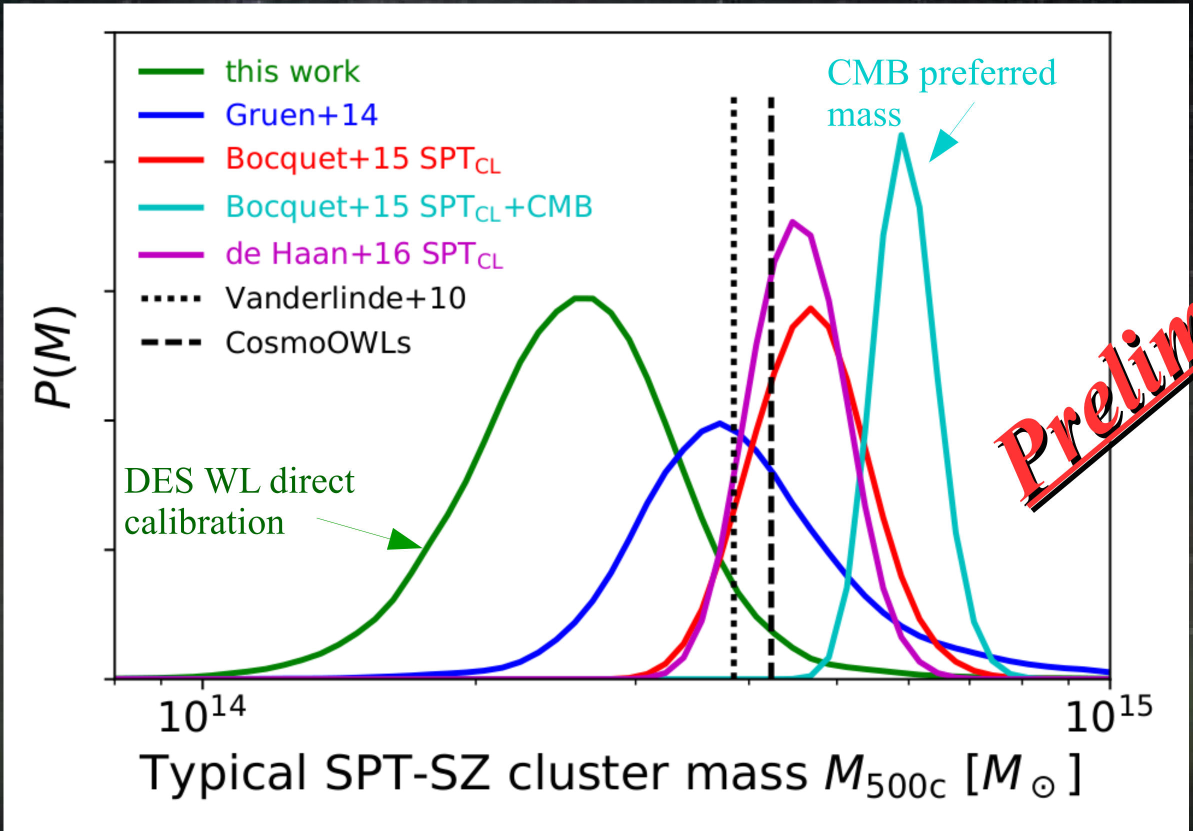
Planck adopts hydrostatic masses as baseline
b is hydrostatic mass bias scale factor

$M_{hydro} = (1\text{-}b)\ M_{true}$

SPT Cluster Masses

Stern+17

- External cosmo priors (also WMAP) tend to prefer higher cluster masses
- Direct constraints (WL, Dyn, Hydro) prefer lower values
- Constraints are still weak- everything statistically consistent



Constraints from 34 clusters in the redshift range $0.25 \leq z \leq 0.8$ using weak lensing shear from DES-SV (Stern et al., in prep.)

SPT Mass Calibration Ongoing

- Direct mass calibration of clusters
  - Dynamical masses:
    - Bocquet+15 (with dispersions)
    - Capasso+ (Jeans analysis)
  - Magnification masses:
    - Chiu+16
  - Shear masses:
    - Dietrich+ (Magellan imaging)
    - Schrabback+ (HST+VLT imaging)
    - Stern+ (DES imaging)

Do External Cosmological Priors Prefer Higher Cluster Masses?

- Evidence is intriguing but not compelling
- What might explain ***if*** future data show it is real?

  - Theoretical mass function wrong? (Bocquet+16)
    - Tinker mass function is biased on high mass end
    - $\Delta\sigma_8(\Omega_m/0.27)^{0.3}\sim+0.02$ (30% of the offset noted in Planck SZE analysis)

  - Unresolved systematics in the CMB data still possible-
    - Tension between base P15 CMB and CMB Lensing (Planck+15, Grandis+16)

  - Could incompleteness in the cluster sample play a role? (Gupta+16)
    - First measurement of 150GHz cluster radio galaxy LF
    - Indicates 2 to 5% incompleteness in SPT-SZ like survey

  - Revision of cosmological model required?