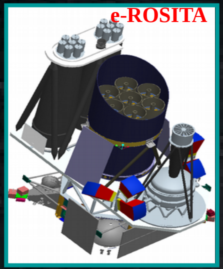
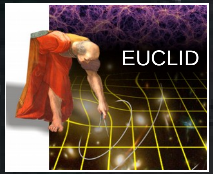
Dark Energy Survey





SPIDERS

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

Alex Saro

OSSERVATORIO ASTRONOMICO DI TRIESTE
INAF ISTITUTO NAZIONALE DI ASTROFISICA

erc

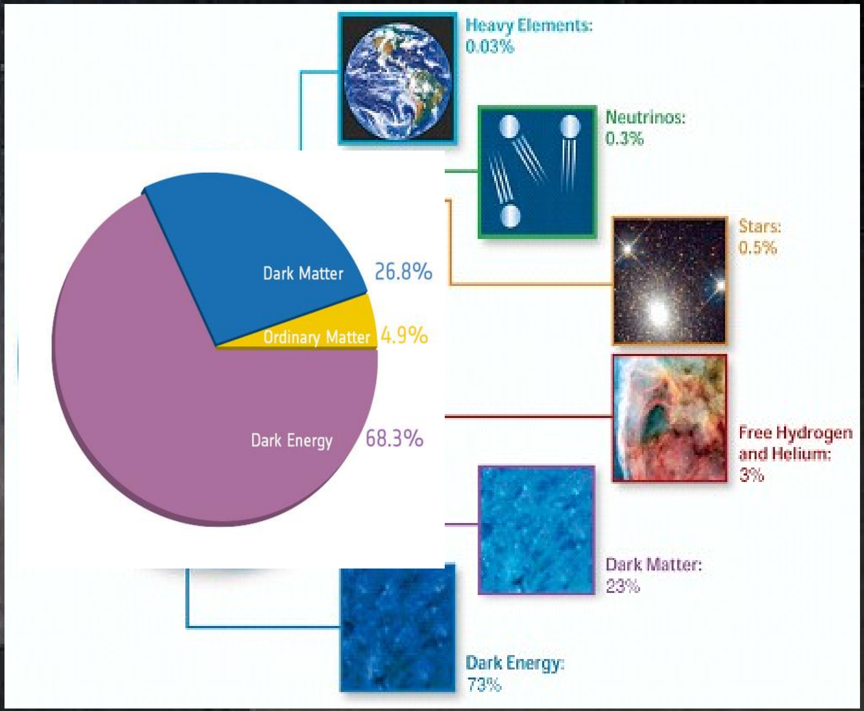
European Commission

Some Outstanding Questions

- What is the nature of Dark Matter?
- What is Dark Energy?
- How does gravity behave on large scales?
- What the sum of the neutrino masses?

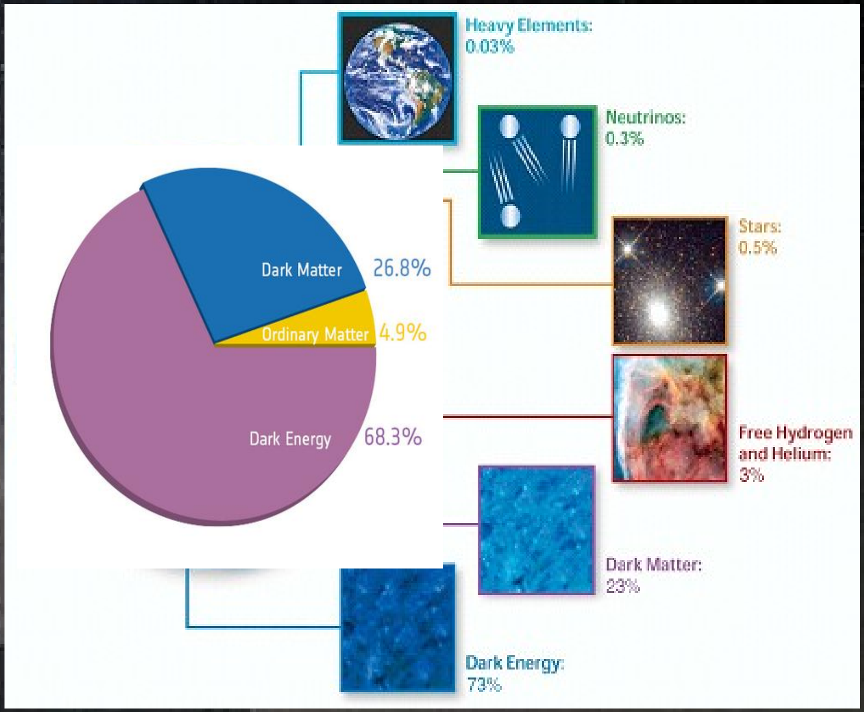
Geometry and Contents of the Universe

- 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

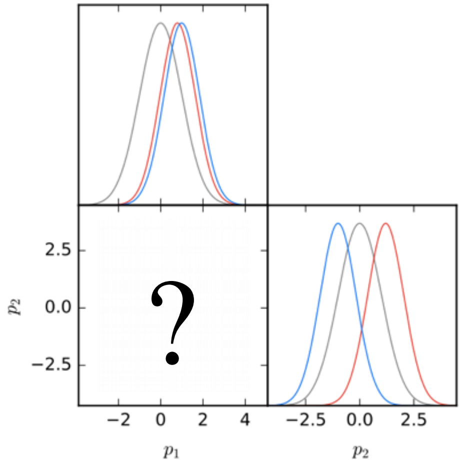
- Dominant source of cosmological information is coming from primary CMB fluctuations at z~1100
- Few ≲2σ tensions are present when combining CMB with local probes, e.g.:
  - H_0 (Riess et al. 2016)
  - Cosmic shear (KiDS, CFHTLens, DES)
  - Clusters (e.g., Planck 15)



What do we mean by tensions?

- Is a model appropriate to describe the data?
- Goodness of the fit test
- For a model M with parameters θ, different data-sets/experiments should provide consistent posterior distributions of θ

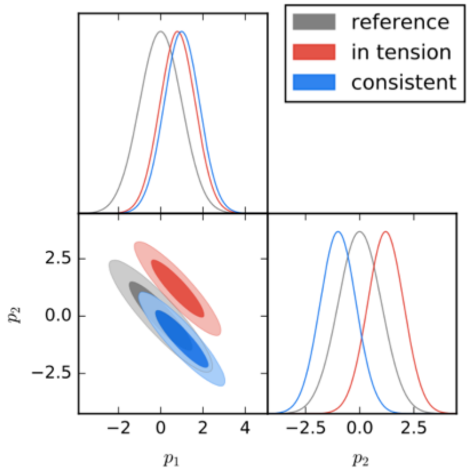
Consistency of data-sets



- Compare blue and red marginalized distributions to compute consistency

  However..

Consistency of data-sets

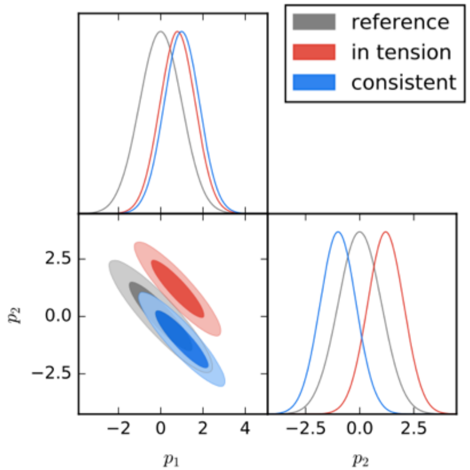


- Compare blue and red marginalized distributions to compute consistency

  However..

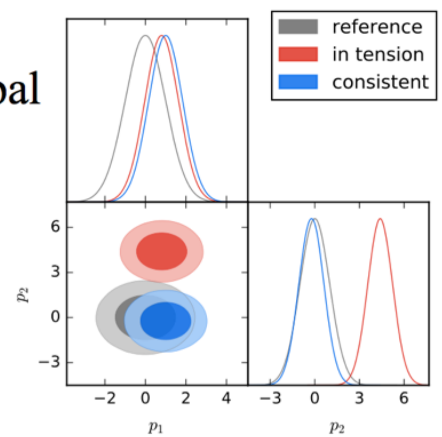
- Projections and marginalized distributions are often misleading!!

Consistency of data-sets



	KL	$\langle KL \rangle$	S	$\sigma(KL)$
red	14.5	0.51	14.0	0.43
blue	0.84	0.51	0.32	0.43

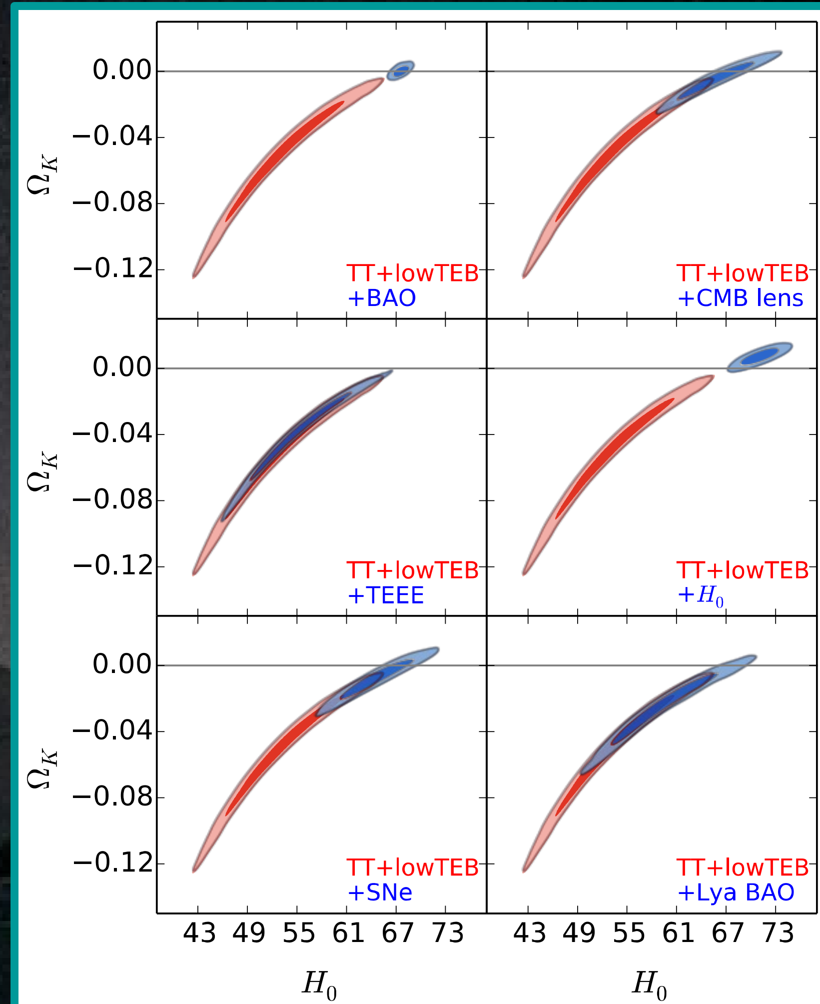
Mapping into Principal Components of prior



Surprise spots "hidden" Tension

The example of flatness

- For example considering flatness: $|\Omega_k|<0.005$ (Planck++15)
- Also a related A_L 2σ tension between Planck TT + low TEB and Lensing constraints
- Consistency with non-CMB data?
- In curved LCDM there is 8σ surprise when adding H_o
- Planck prefers curved Universe at 2.7σ
- In curved LCDM model >3σ surprises exist between Planck TT + low TEB and BAO, SNe, H_o and CMB lensing
- We focus on Galaxy Cluster as Cosmological probes



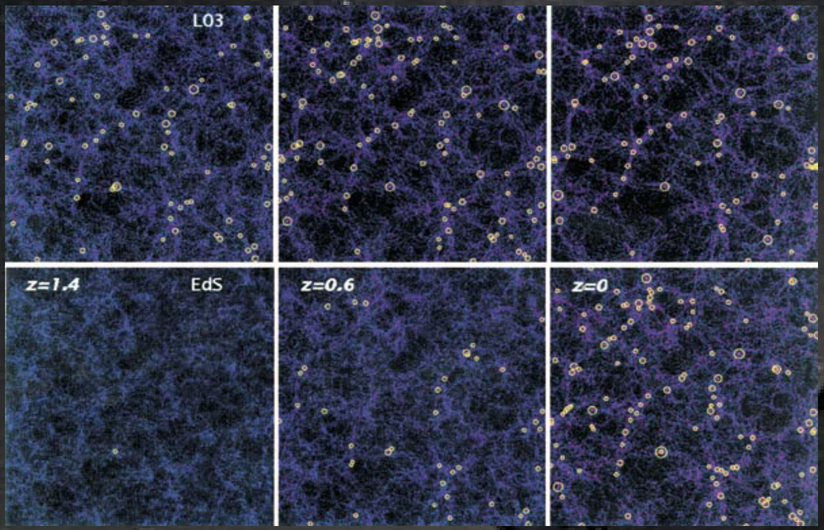
Grandis+ 16

Galaxy Clusters Are Powerful Cosmological Tools

- Sensitive to both **geometry** and **growth of structures**
- Complementary to geometrical probes as CMB, BAO, SNe

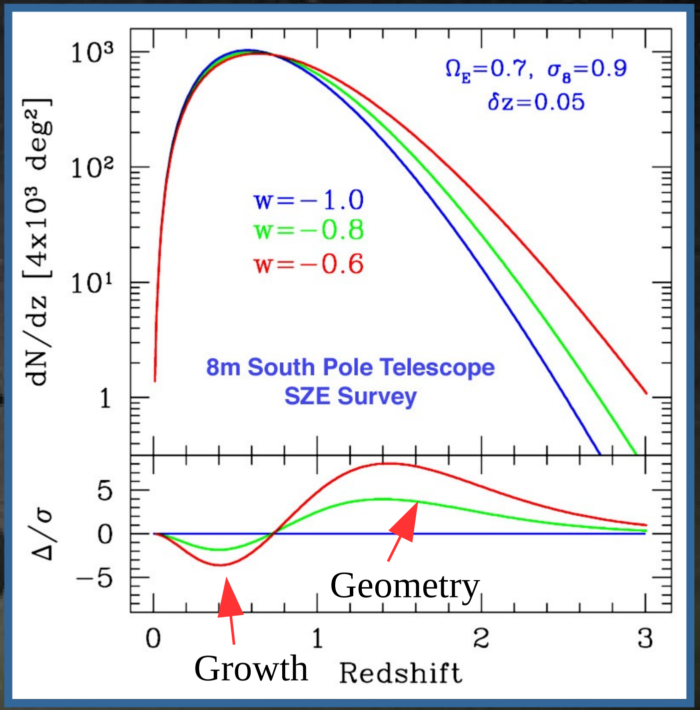
ΛCDM:

EdS:
Ω_Λ=0



Borgani & Guzzo (2001)

- Same distribution at redshift zero
- Completely different redshift evolution



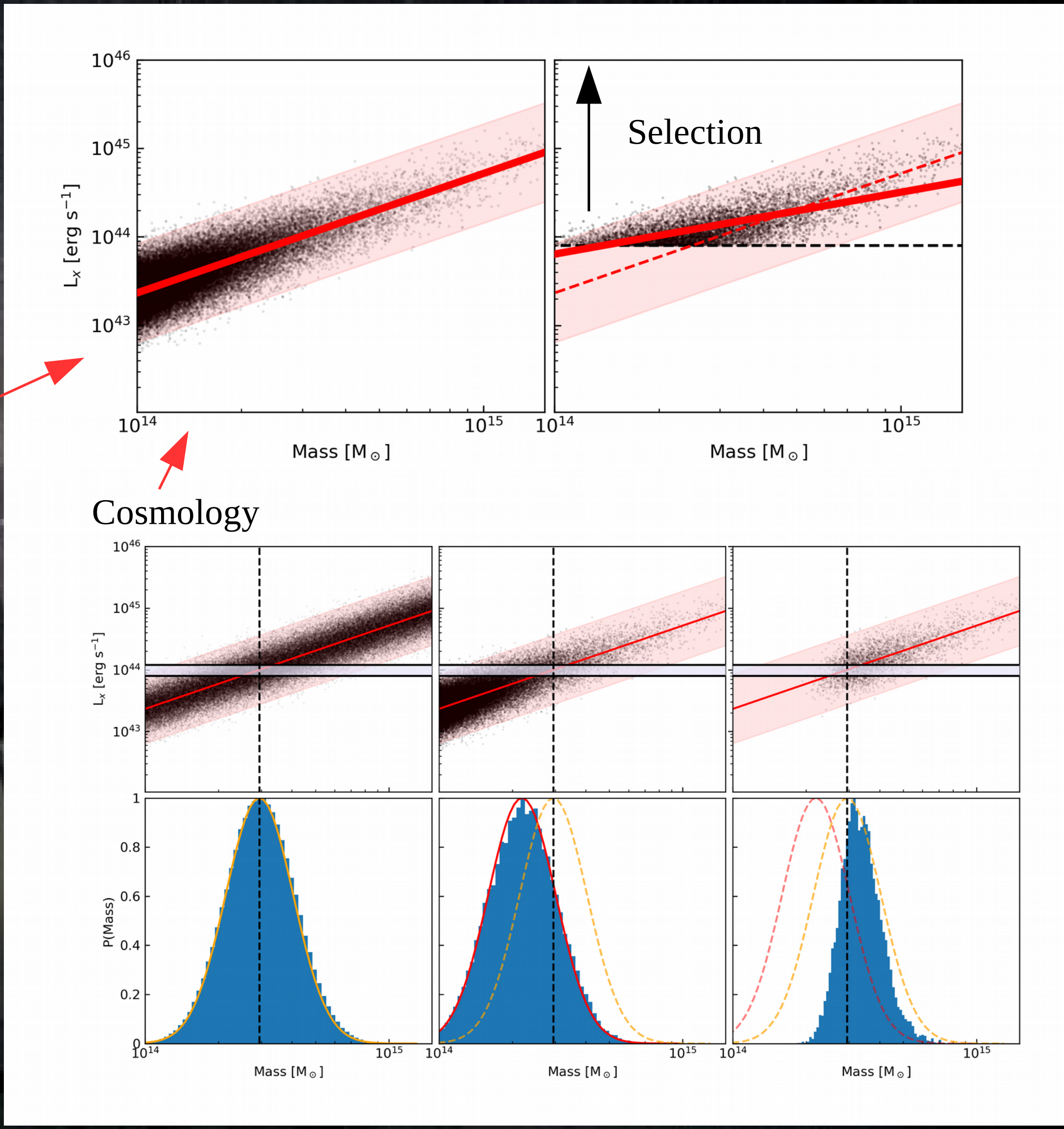
Redshift distribution is sensitive to distance-redshift relation and rate of structure growth
Credit: Joe Mohr

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

Astrophysics



Cluster Surveys Provide a Rich Source of Information

Halo Redshift Distribution

Sensitive to volume-redshift relation and halo abundance evolution

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

Geometry

Growth

Press & Schechter 72

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

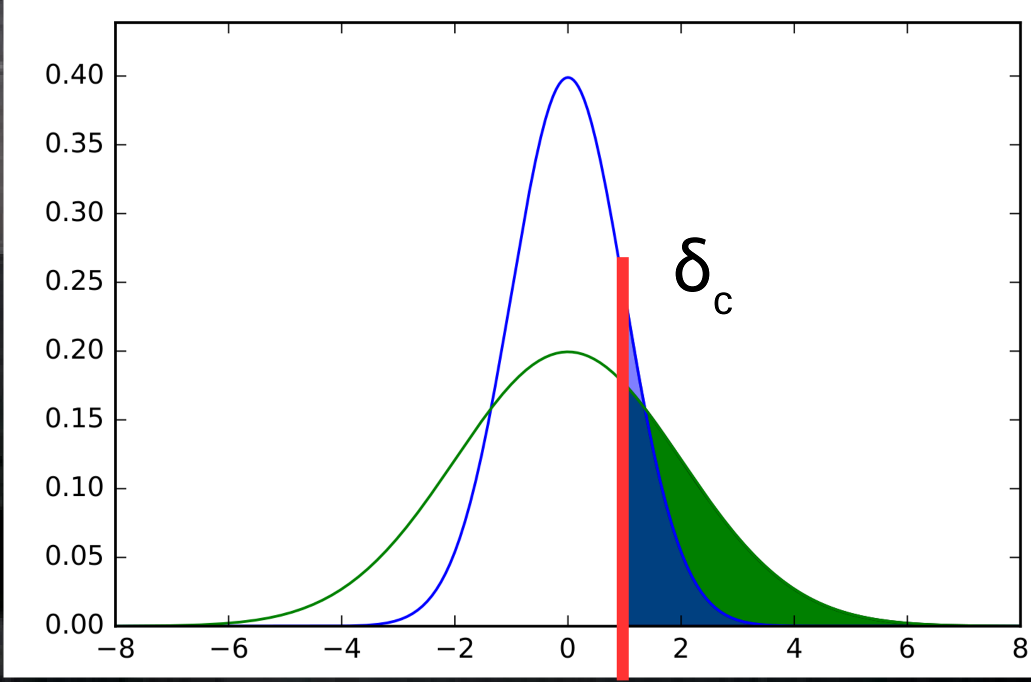
Bottom line: surveys measure

Distances

Characteristics of initial perturbations

Growth rate of density perturbations

But you must know the mass selection of your survey!



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Press & Schechter 72

$$n(M,z) = \frac{\rho_b}{M} \frac{1}{\sqrt{2\pi}\sigma(M,z)} \int_{\delta_c}^{\infty} d\delta \exp\left\{ \frac{-\delta^2}{2\sigma^2(M,z)} \right\}$$

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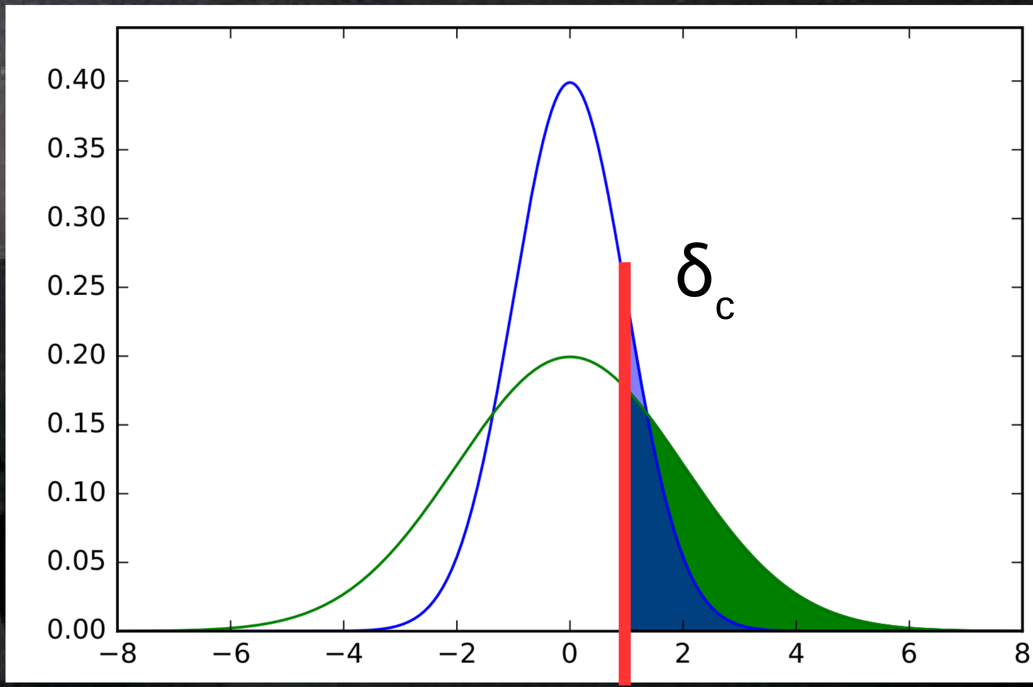

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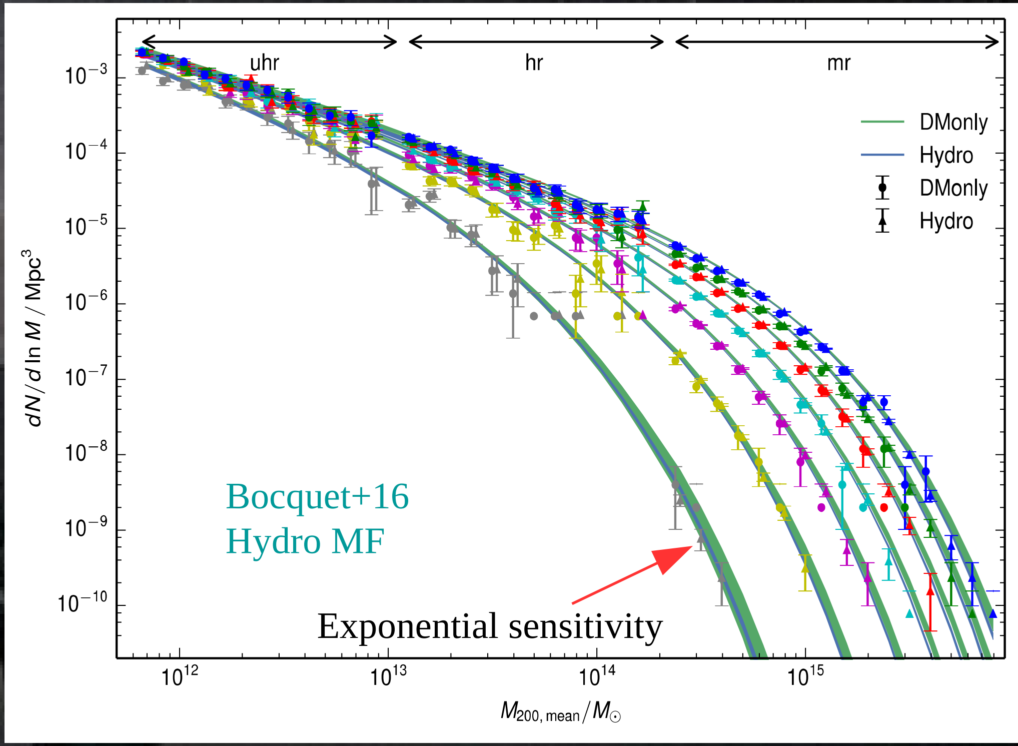
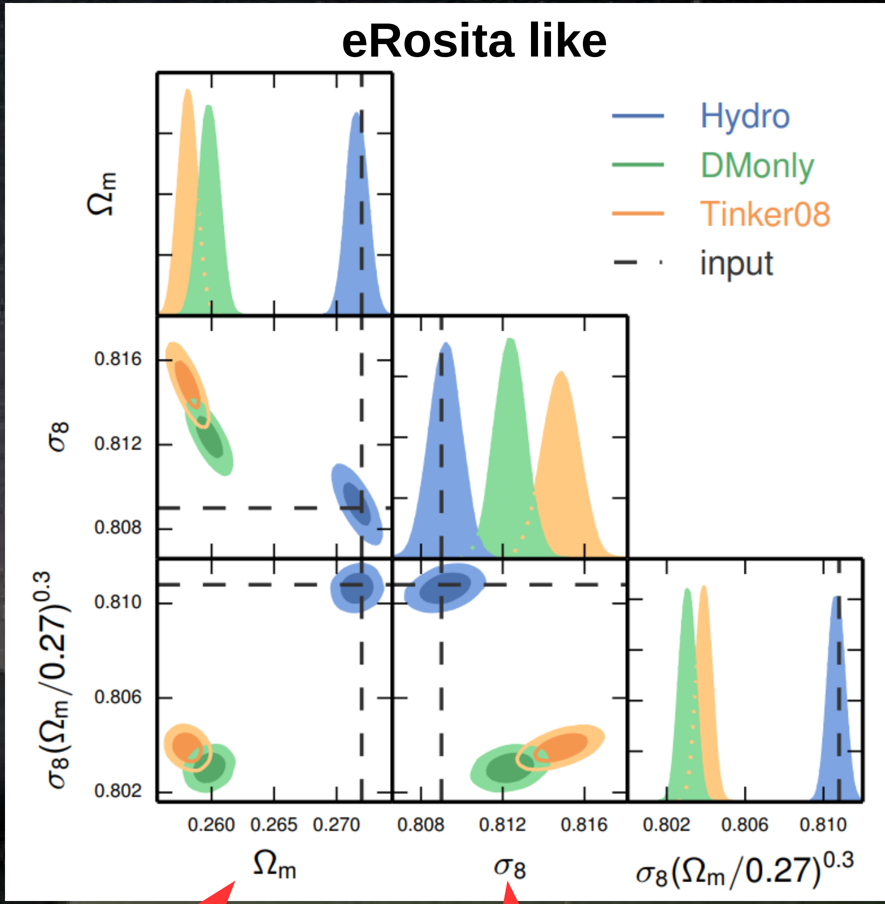


Baryon Impact on Mass Function

Bocquet+16

- For massive cluster surveys like Planck and SPT there is no significant impact of baryon physics on the MF
- Of greater importance is the difference between the Tinker and the Bocquet mass functions!



Matter Density
Dominated by DM

Related to the amplitude
of the primordial fluctuations

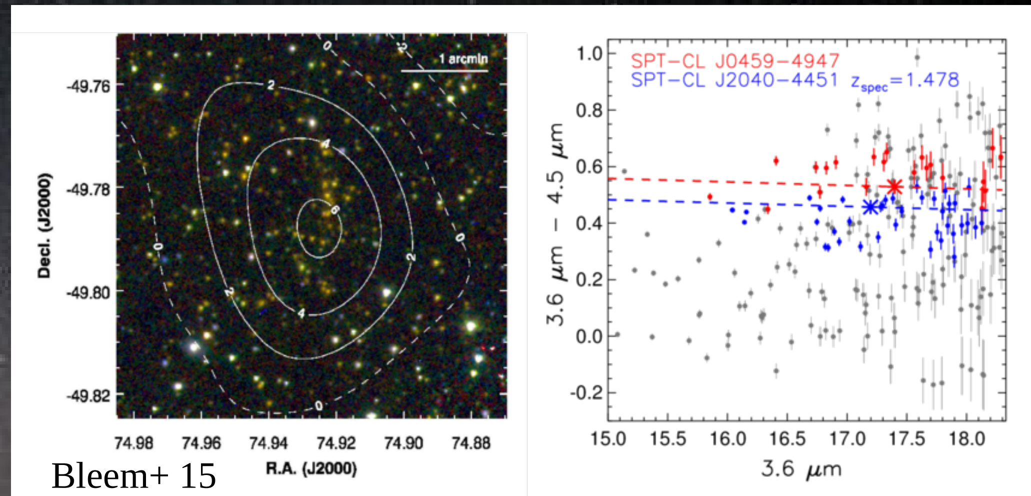
What Are Galaxy Clusters?

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.

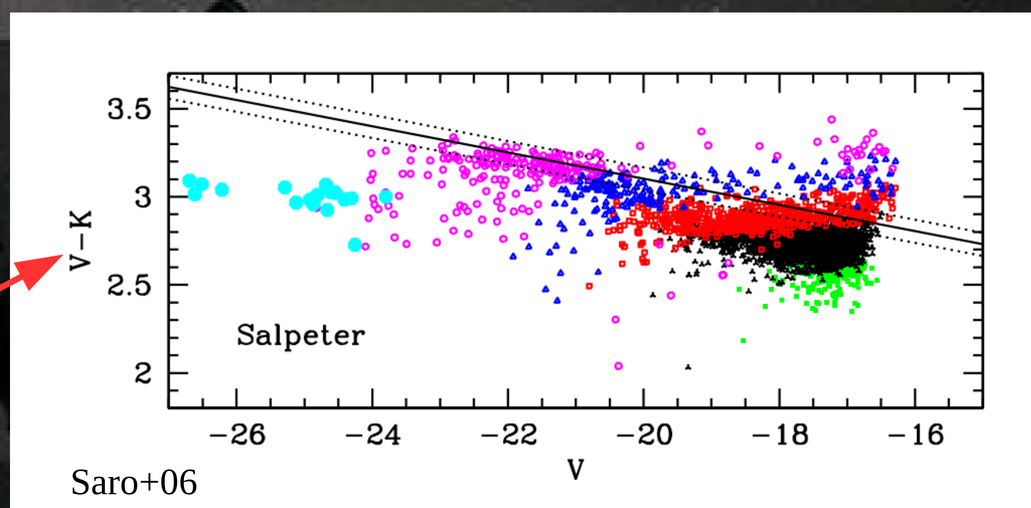
In typical structure formation scenarios, low mass clusters emerge in significant numbers at z~2-3

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

- Light from galaxies



Bleem+ 15



Saro+06

α Ratio of luminosities in different bands

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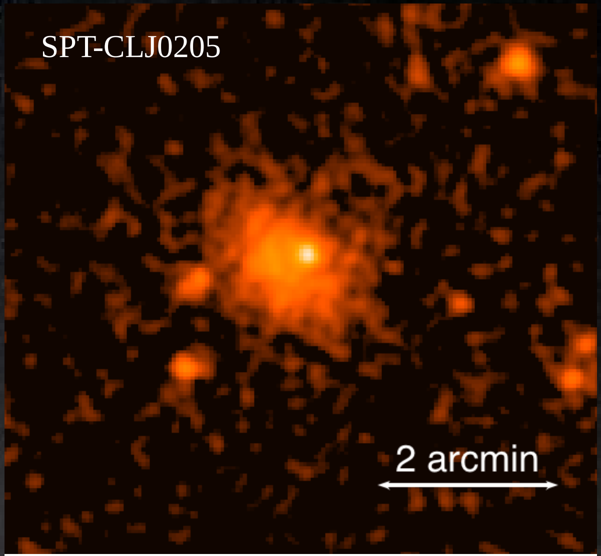
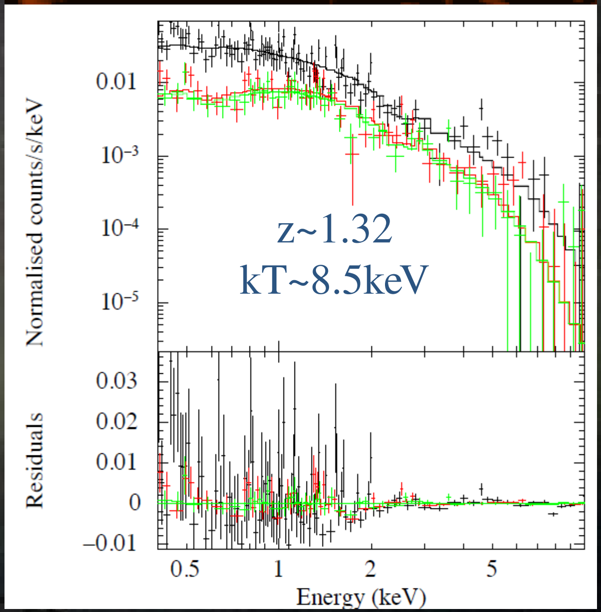
- X-ray emission





Saro+06

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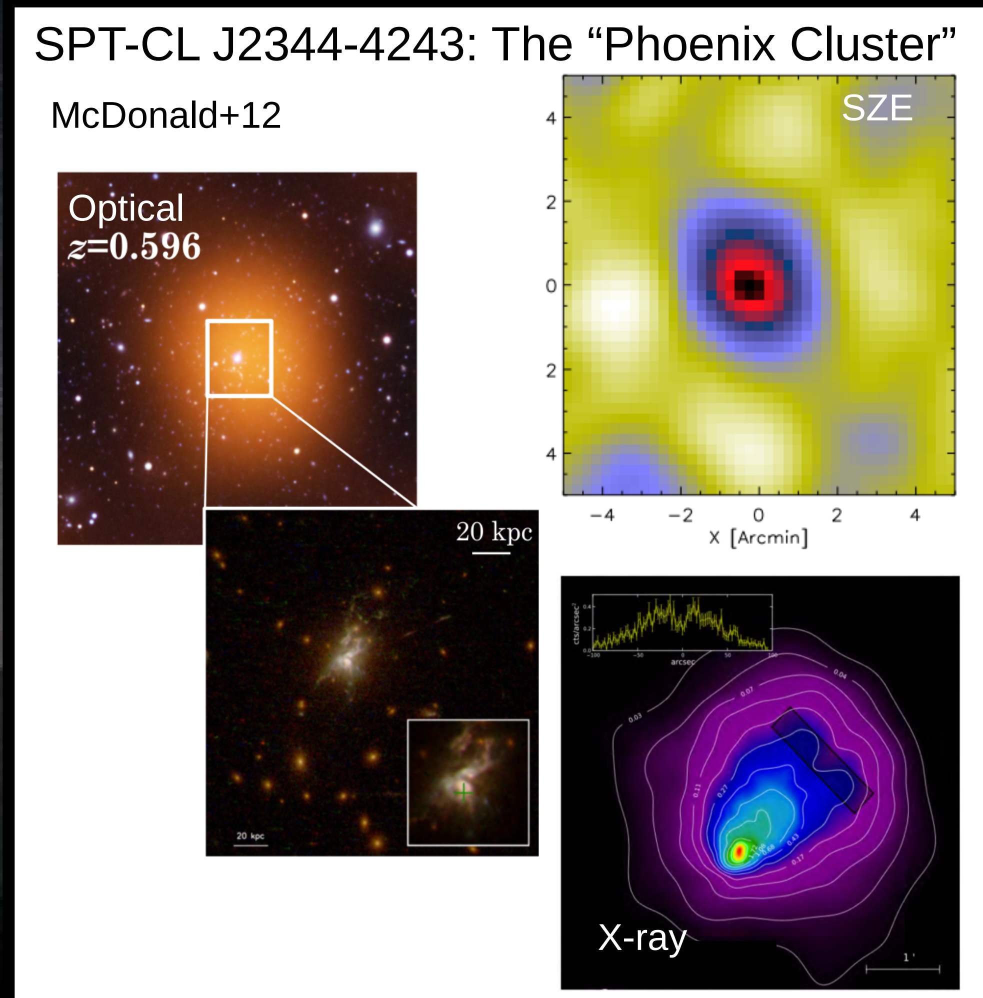
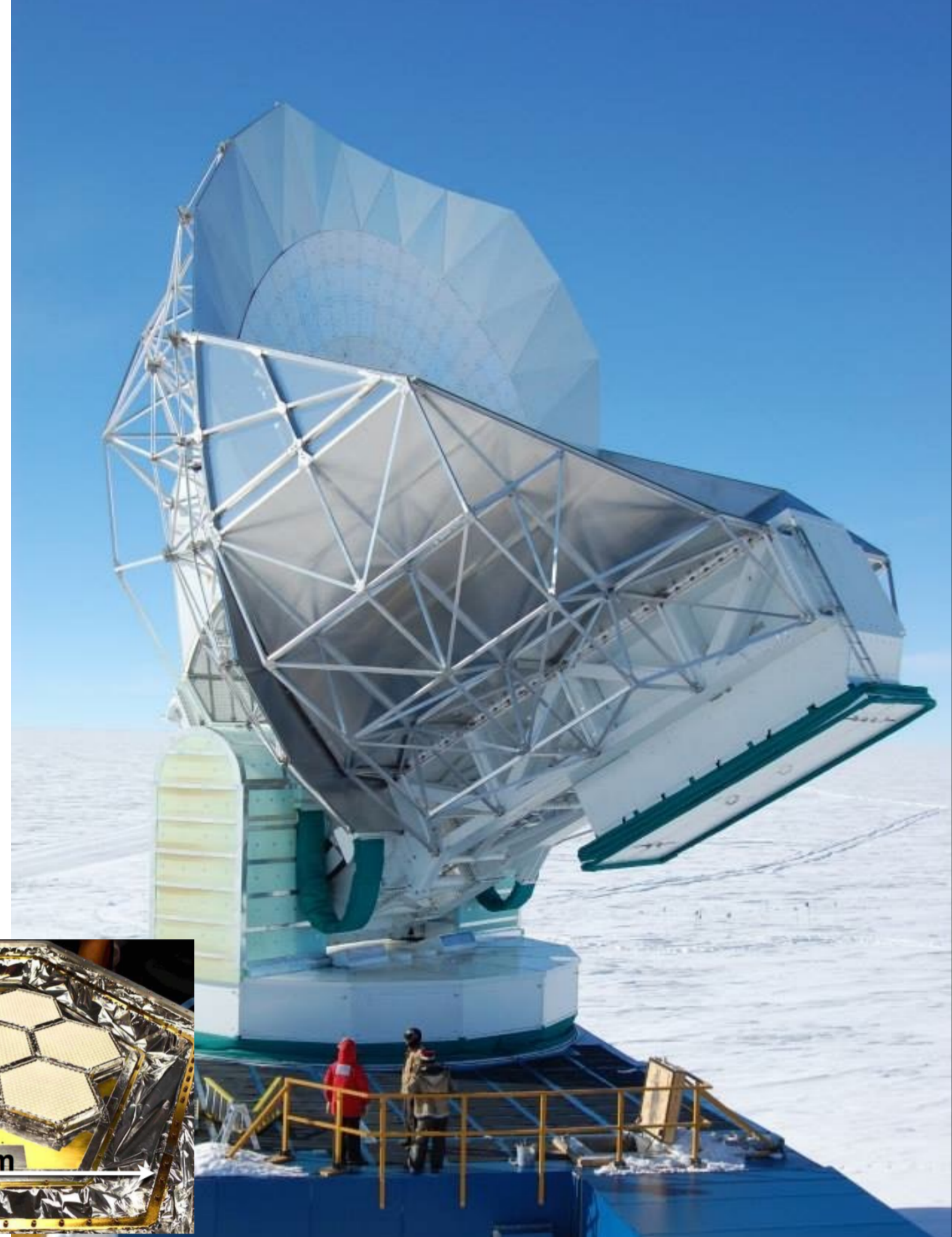
- X-ray emission
- Light from galaxies
- Sunyaev-Zel'dovich Effect



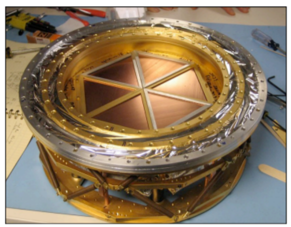
The South Pole Telescope (SPT)

10-meter
submm wave telescope

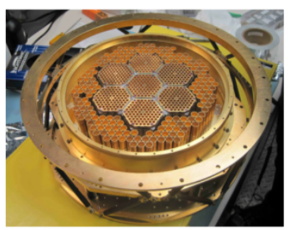
100 150 220 GHz and
1.6 1.2 1.0 arcmin resolution



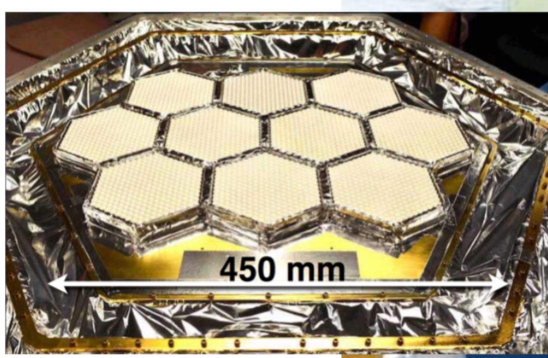
2007: SPT-SZ
960 detectors (UCB)
100,150,220 GHz



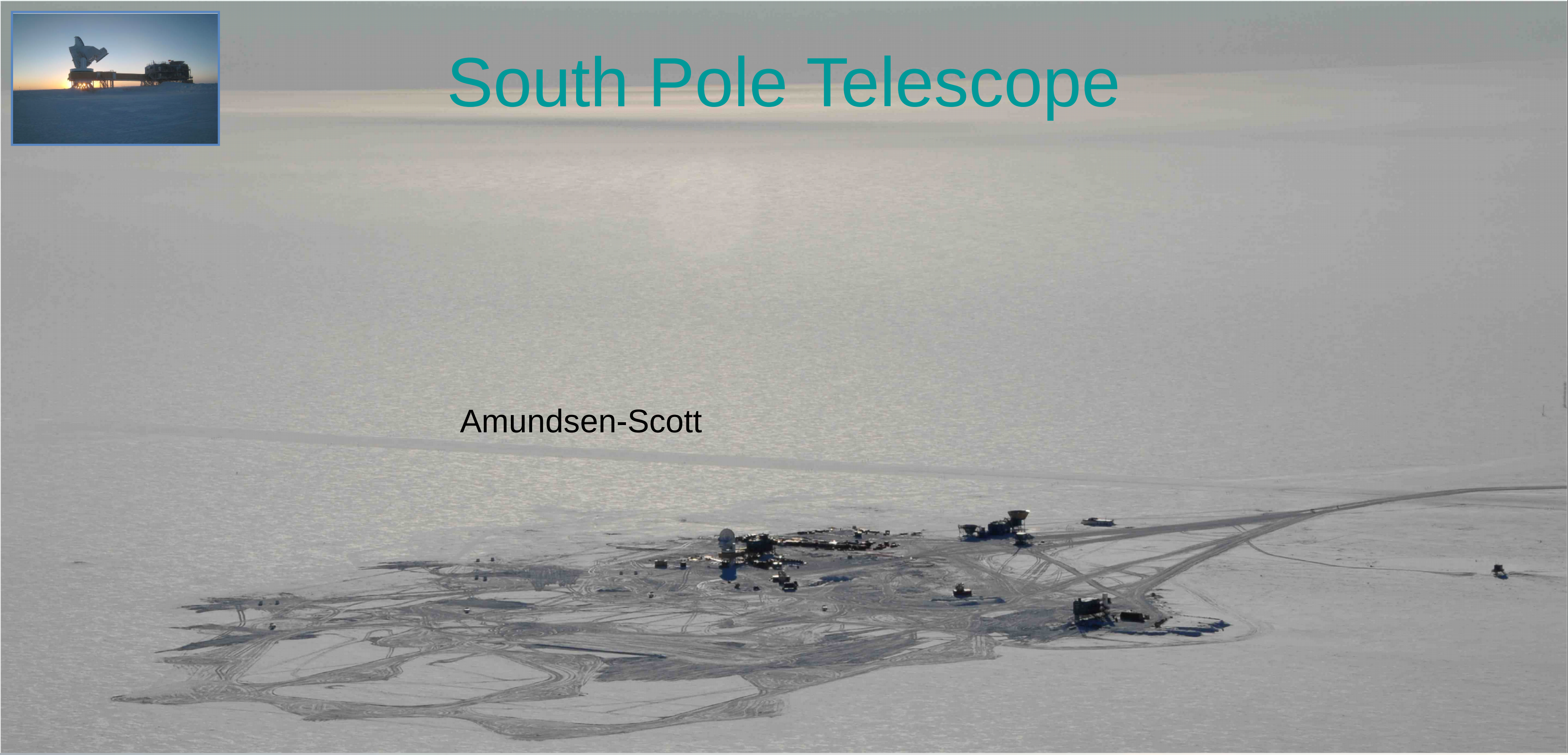
2012: SPTpol
1600 detectors
100,150 GHz
+Polarization



2016: SPT-3G
16,000 detectors
100,150, 220 GHz
+Polarization



South Pole Telescope

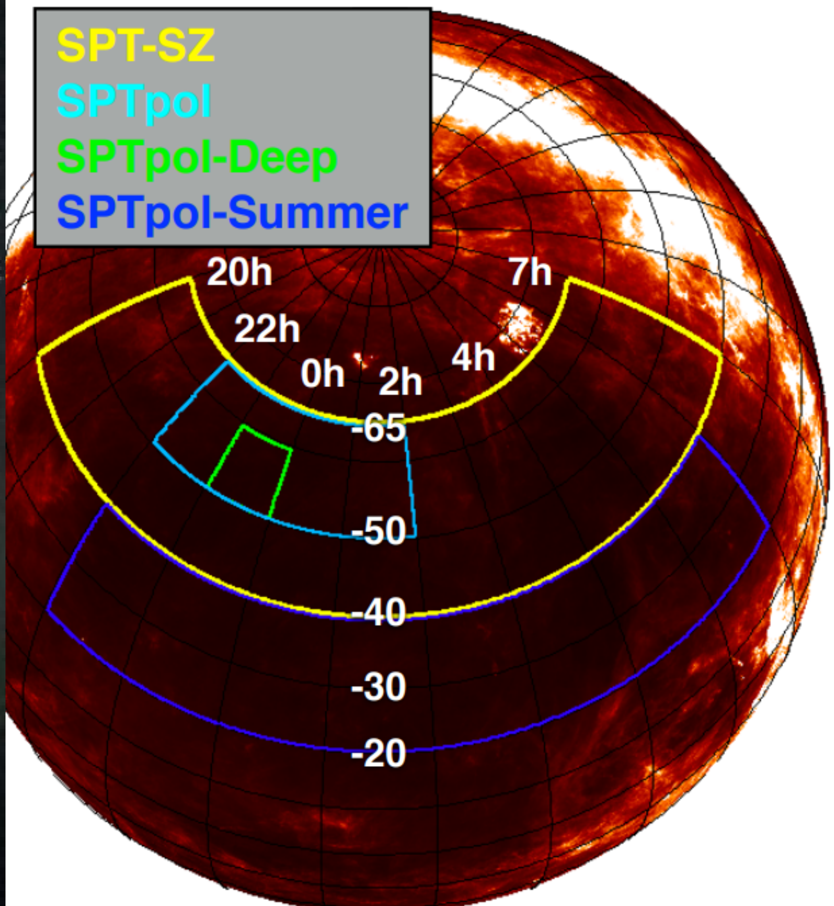


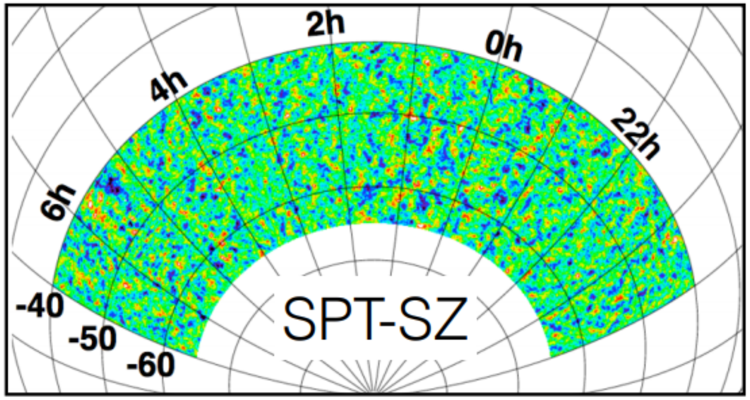
The South Pole Telescope Collaboration

funding:

SPT Survey

The SPT Surveys
5000 deg^2

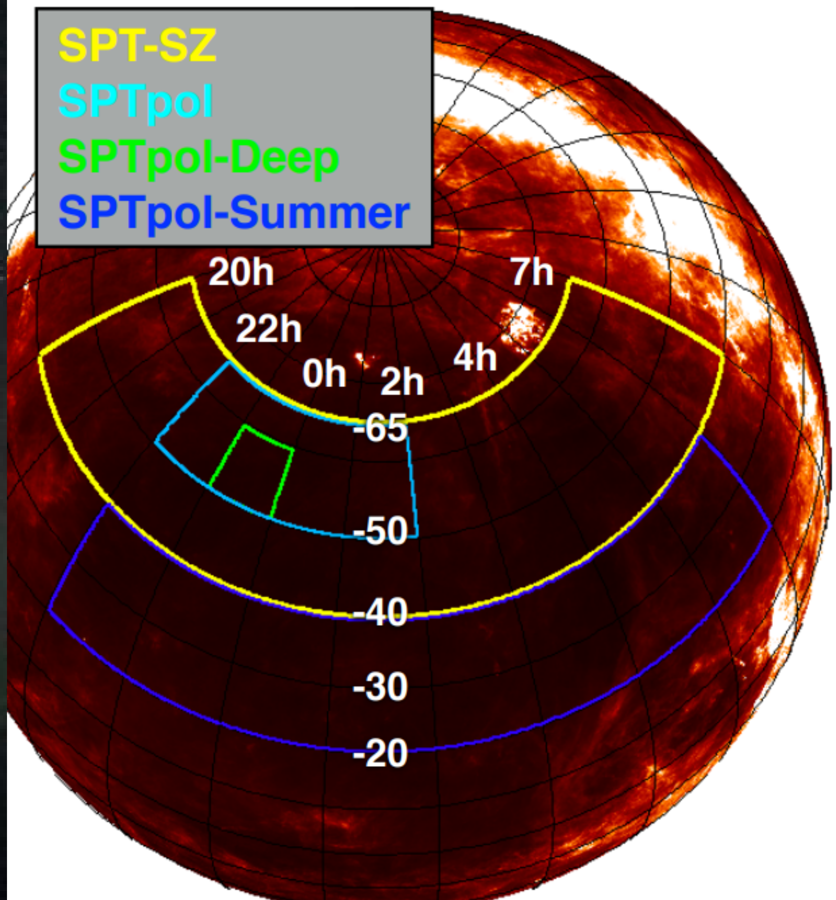


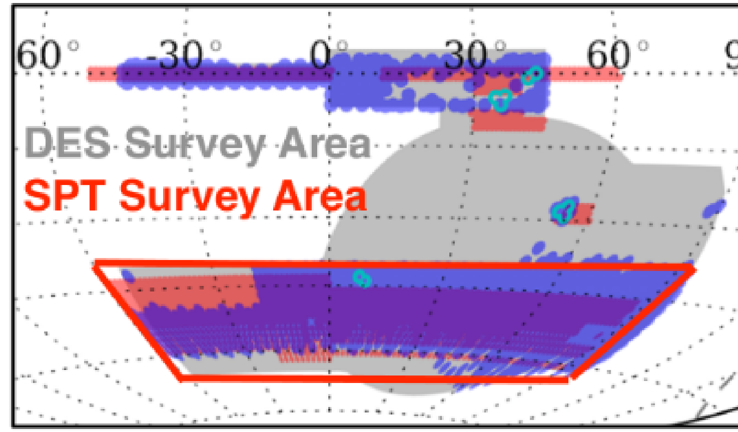


	Obs. Years	Area (deg^2)	95 GHz (uK-arcmin)	150 (uK-arcmin)	220 (uK-arcmin)
SPT-SZ	2007-11	2500	40	17	80
SPTpol-Main	2012-16	500	13	5	-
SPTpol-Deep	2012-16	100	10	3.5	-
SPTpol-Summer	2012-16	2500	47	28	-
SPT-3G *(projected)*	2018-21	1500	2.8	2.6	6.6

SPT Survey

The SPT Surveys
5000 deg²





Complete overlap with DES survey

Saro+15, +16

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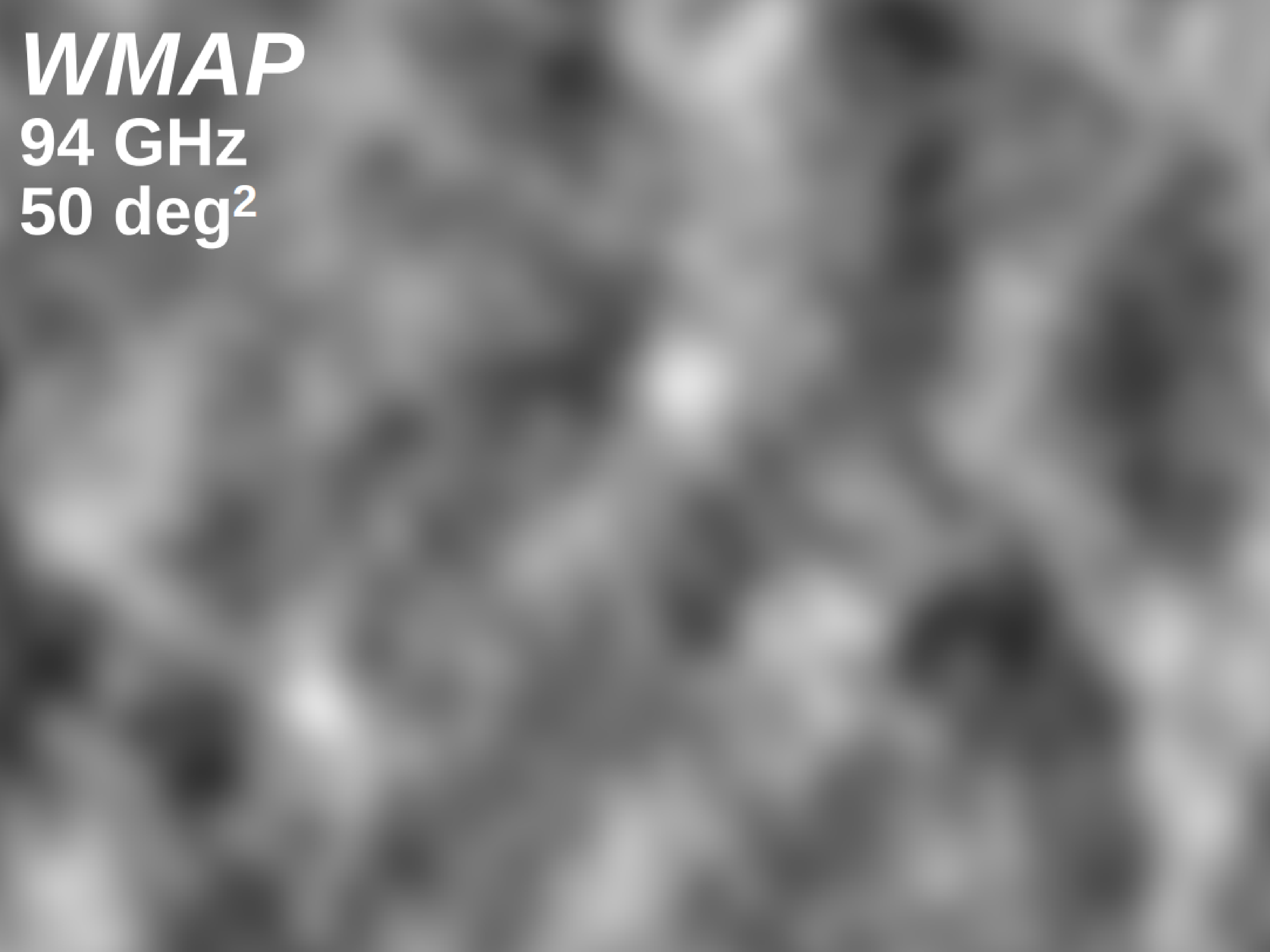
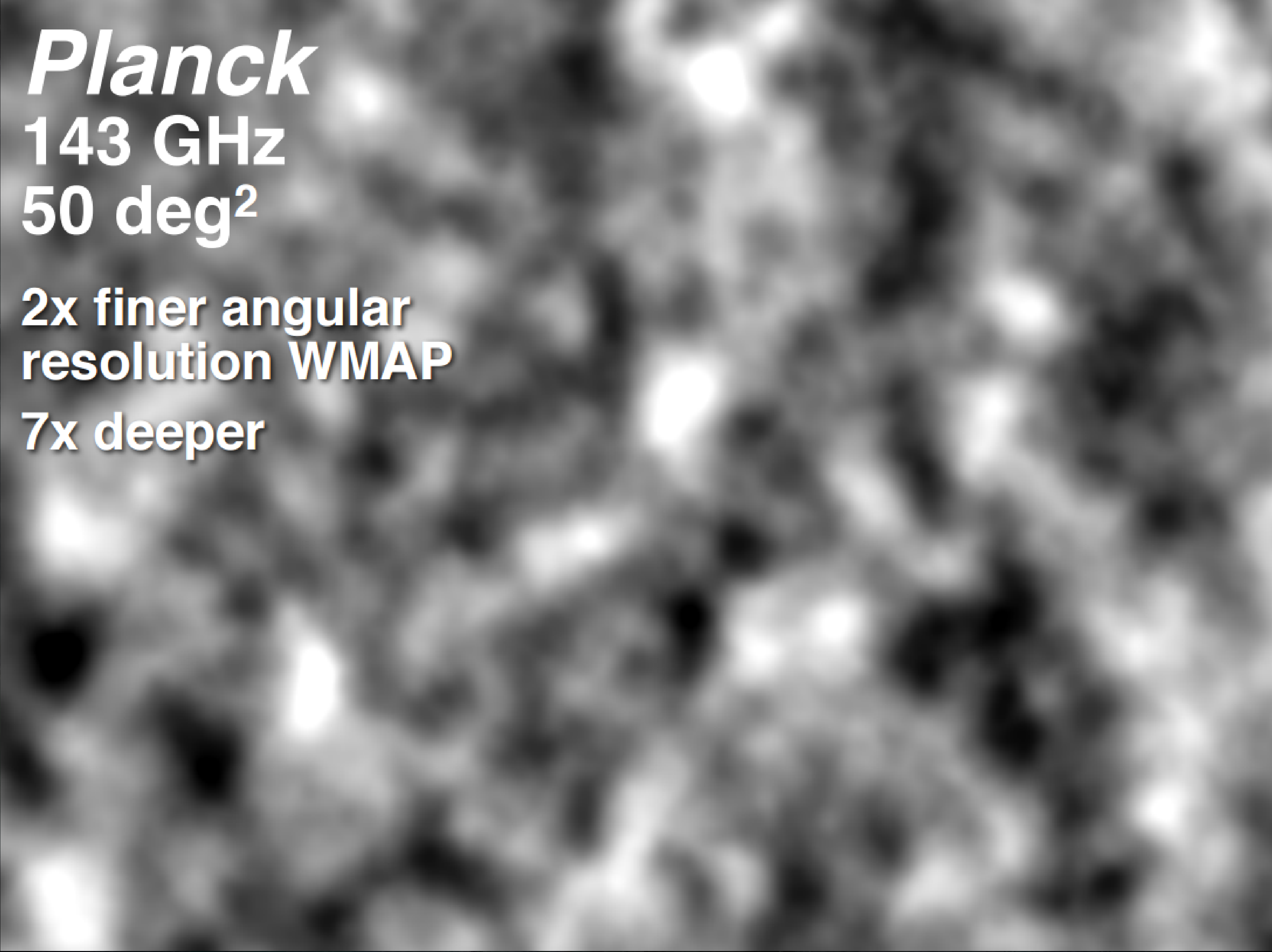
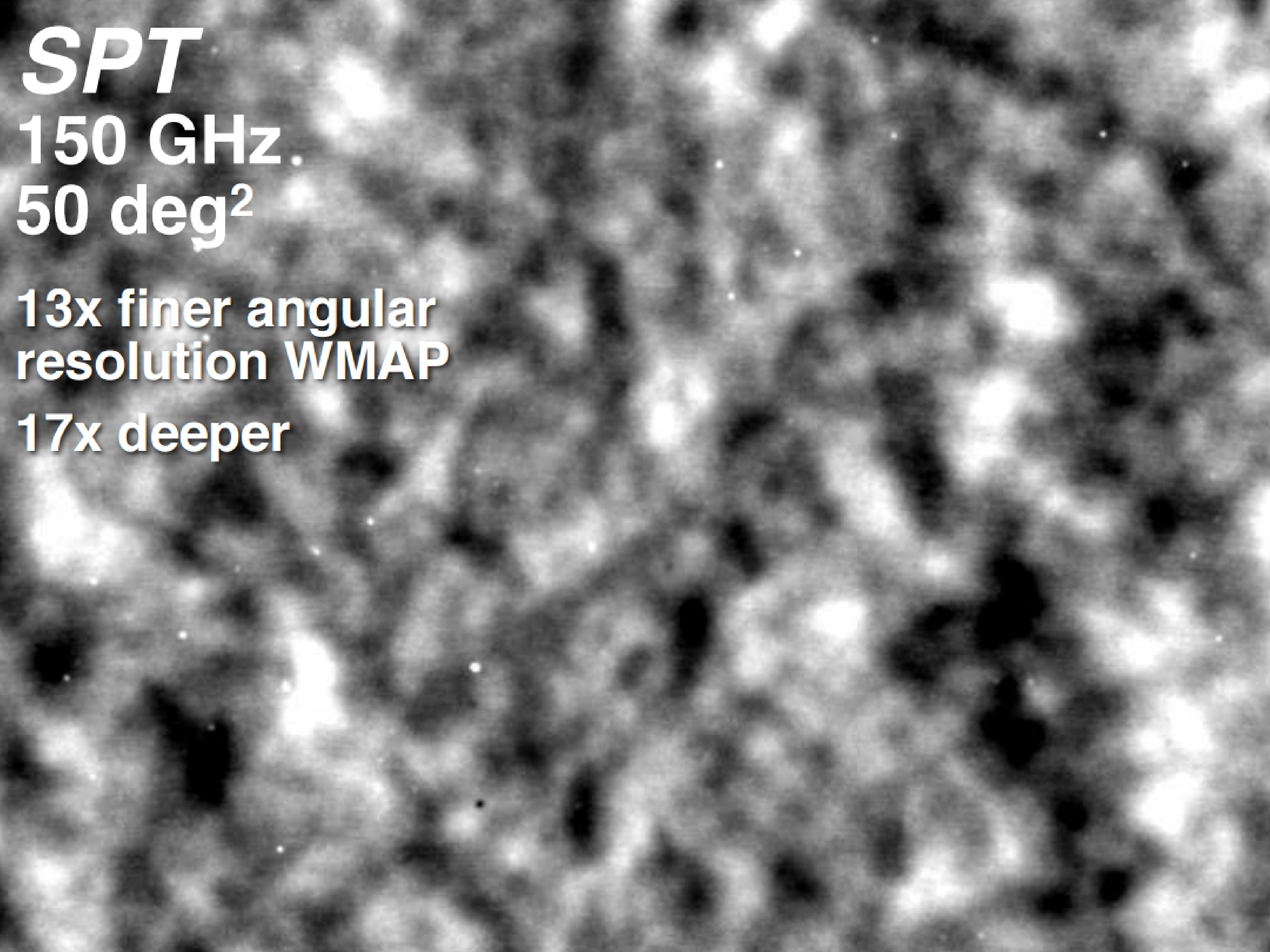
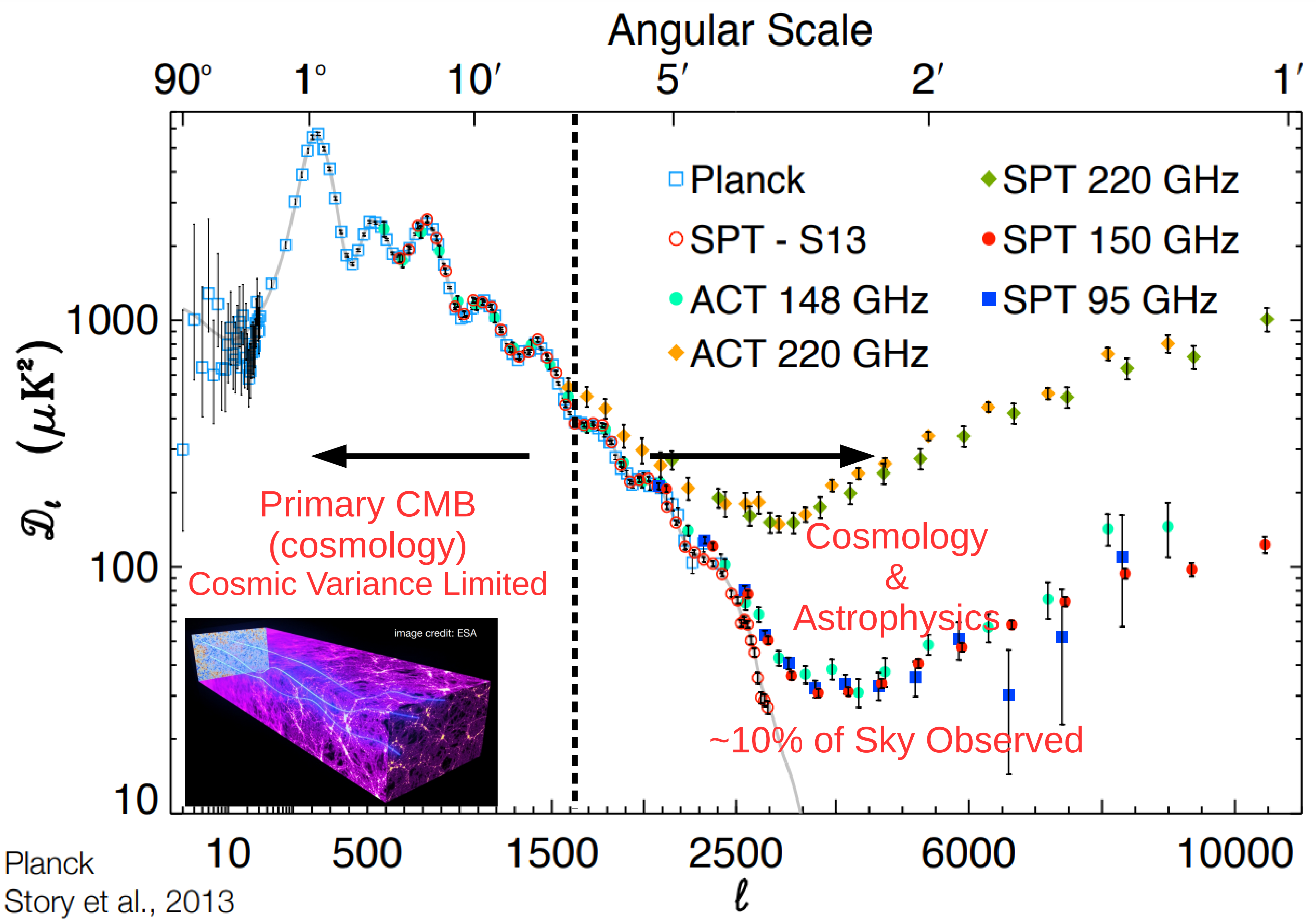

WMAP
94 GHz
50 deg^2


Planck
143 GHz
50 deg2
2x finer angular resolution WMAP
7x deeper


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



Planck
Story et al., 2013
George et al., 2014
Das et al., 2014

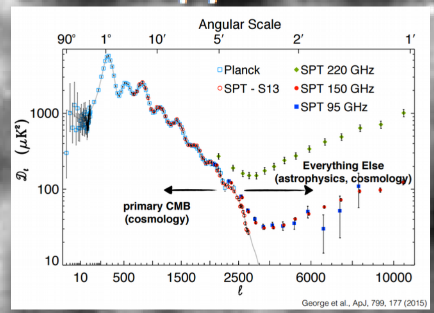
SPT

150 GHz

50 deg²

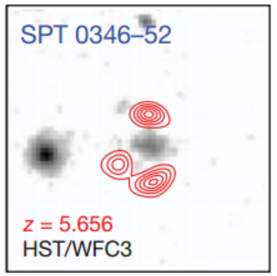
CMB Anisotropy

Primordial and secondary anisotropy in the CMB



Point Sources

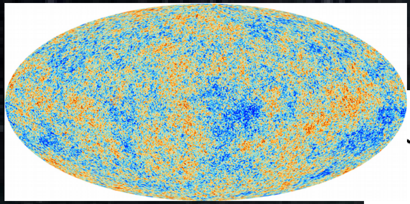
Active galactic nuclei, and the most distant, star-forming galaxies

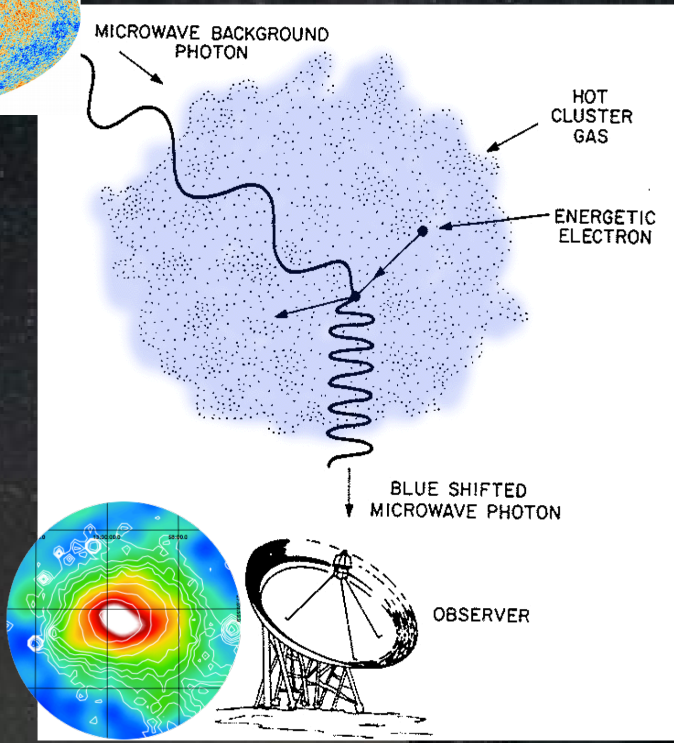


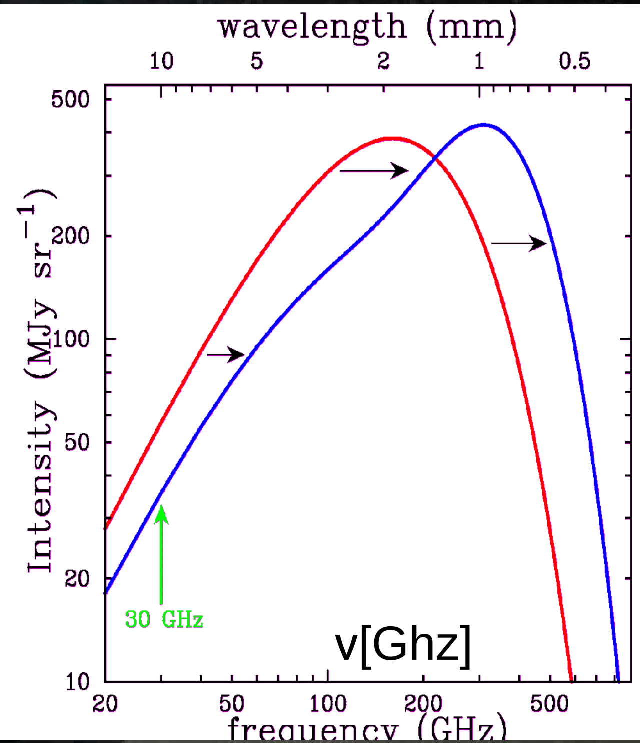
Clusters of Galaxies

"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 $x \equiv h\nu/kT$

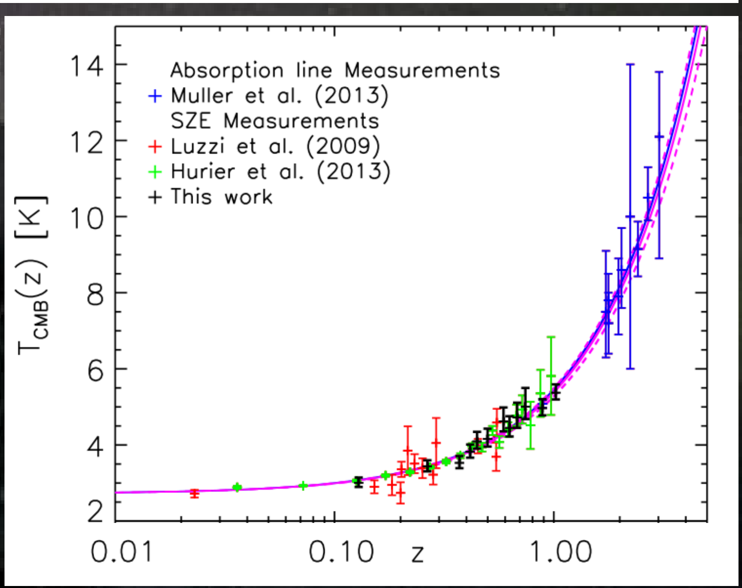
If the Universe expands adiabatically we have:

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

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

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

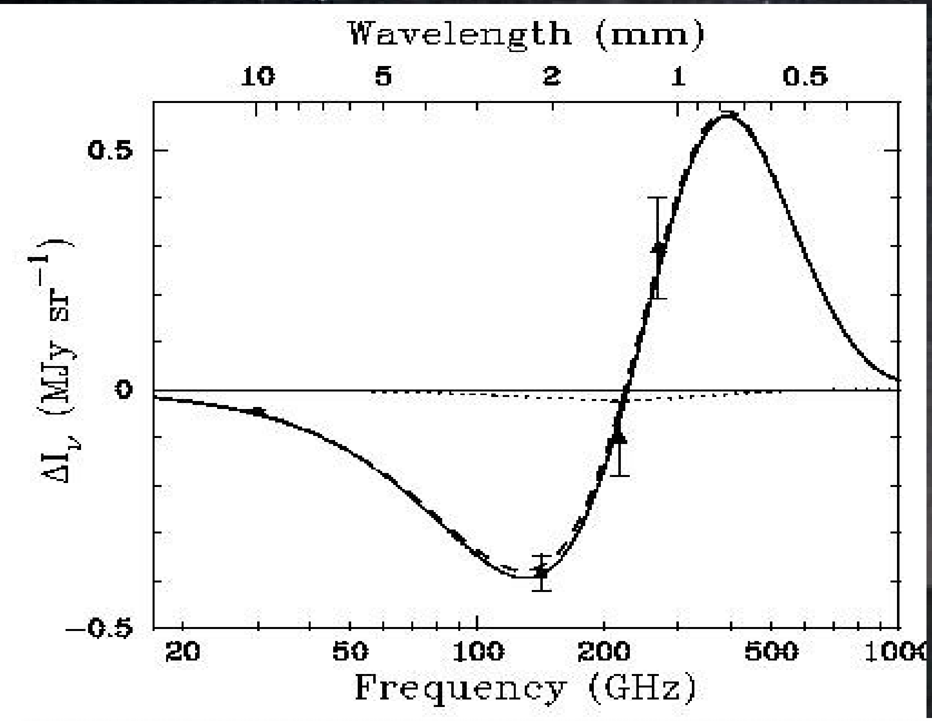
  Saro+14

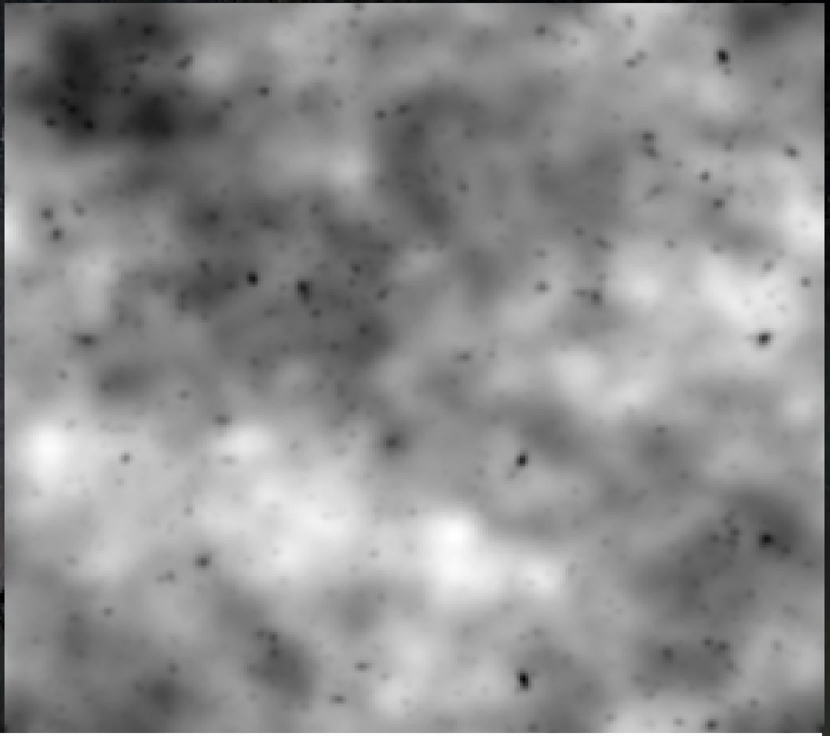


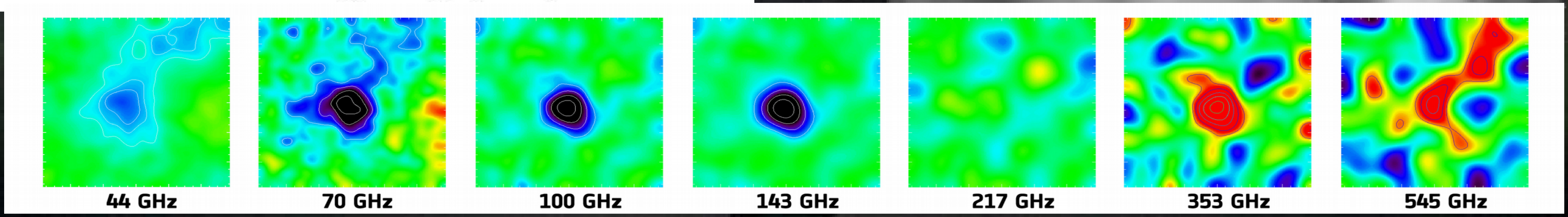
SZE Signature of Galaxy Clusters

Unique spectrum

Unique angular scale

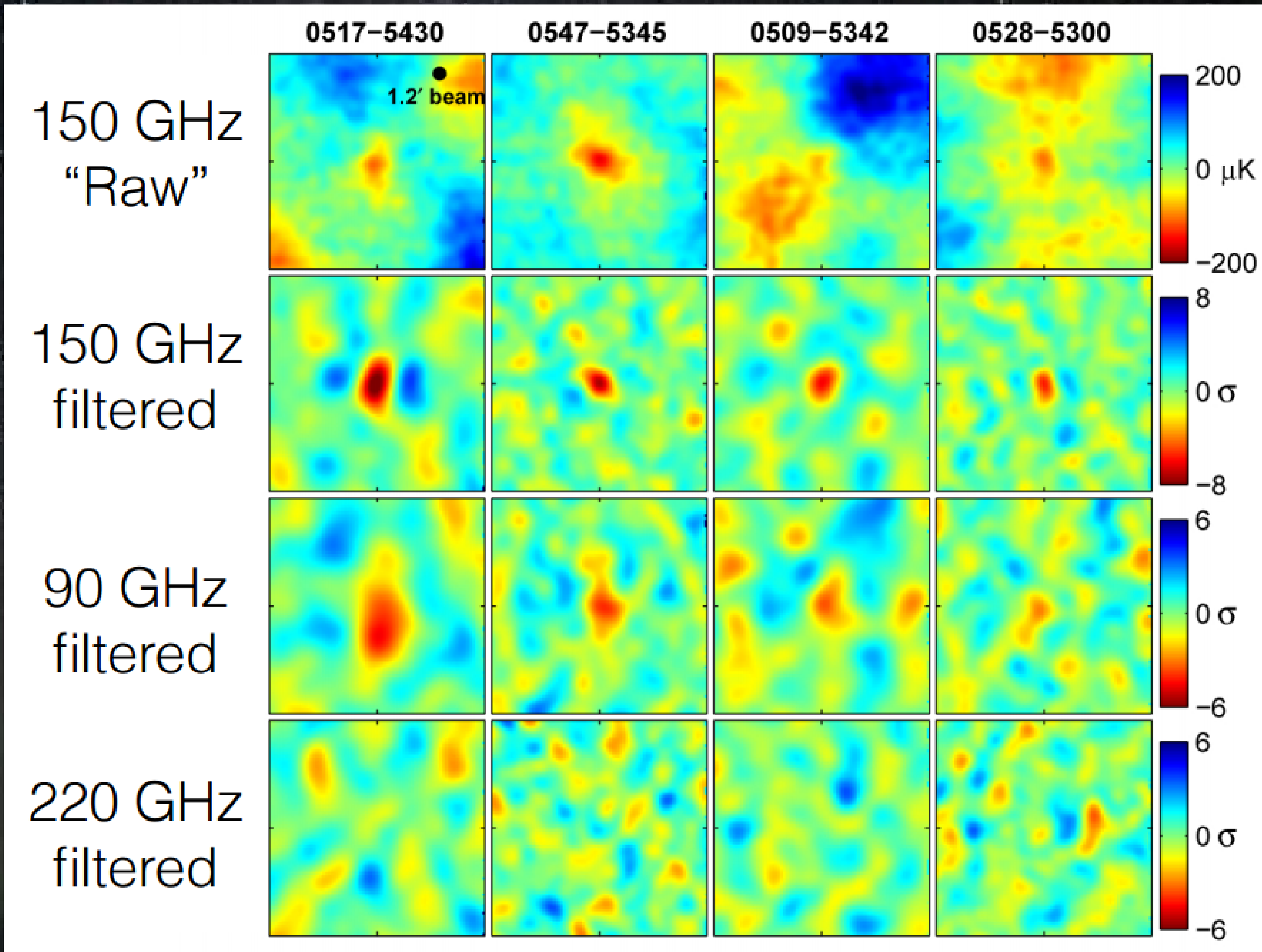






Abell 2319, Planck Collaboration

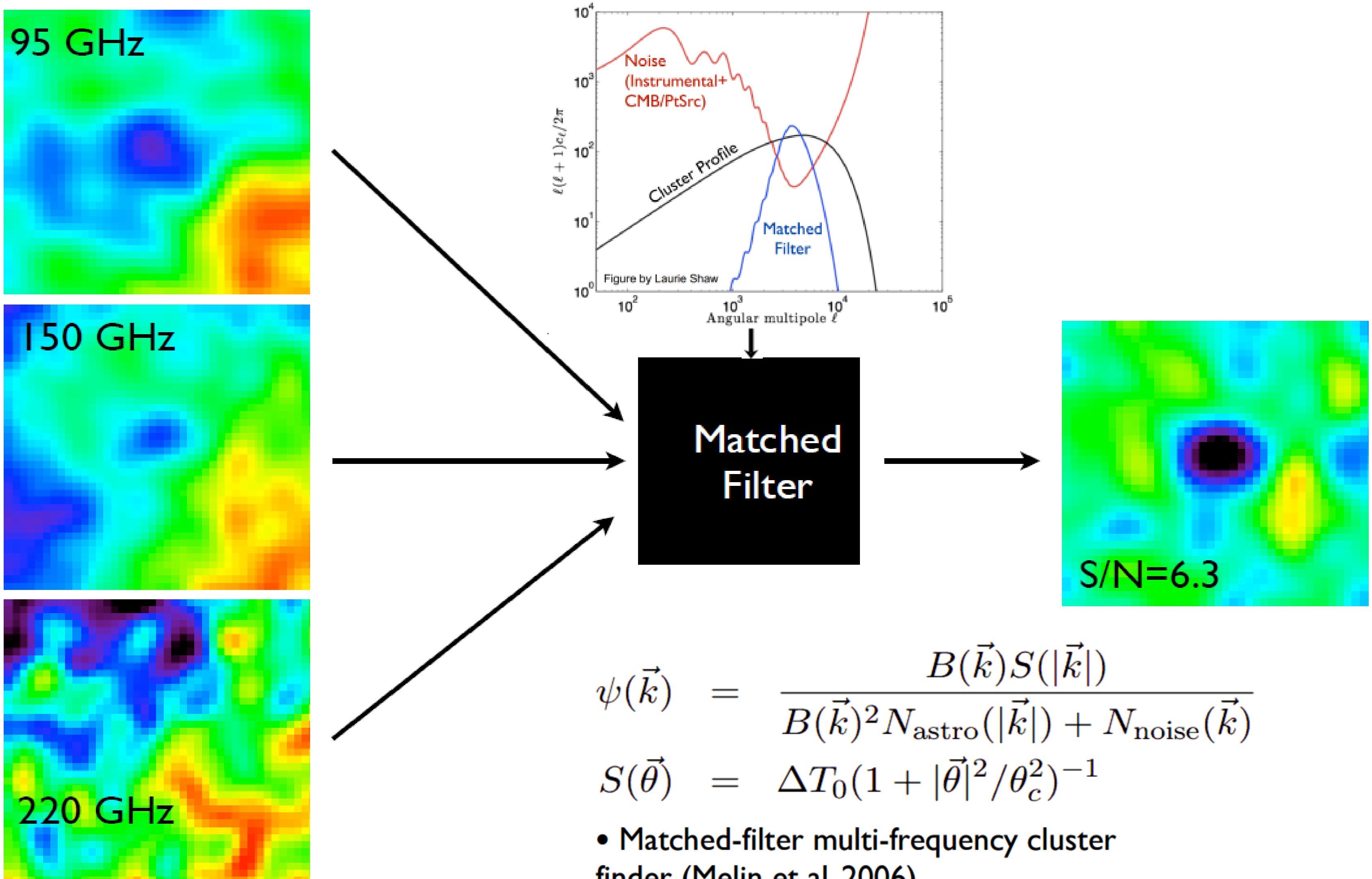
First “Blind” SZ detection : 2008!



Staniszewski et al. 2009

Finding a Cluster in SPT Maps

- Unique signature helps provide pure sample



$$\psi(\vec{k}) = \frac{B(\vec{k})S(|\vec{k}|)}{B(\vec{k})^2 N_{\rm astro}(|\vec{k}|) + N_{\rm noise}(\vec{k})}$$

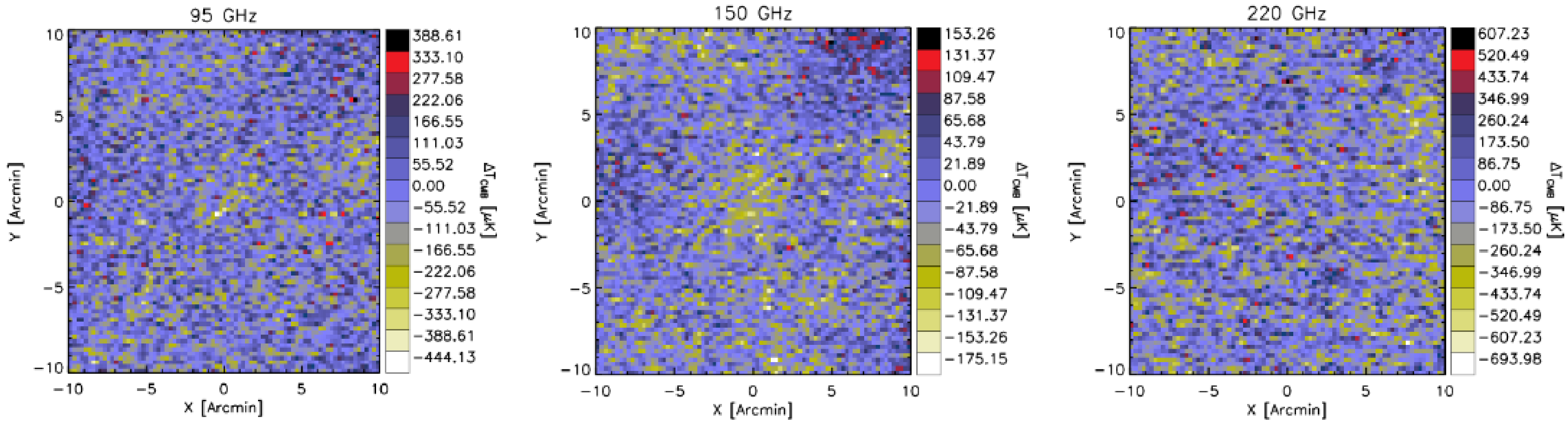
$$S(\vec{\theta}) = \Delta T_0 (1 + |\vec{\theta}|^2/\theta_c^2)^{-1}$$

- Matched-filter multi-frequency cluster finder (Melin et al. 2006)

4
1

Finding a Cluster in SPT Maps

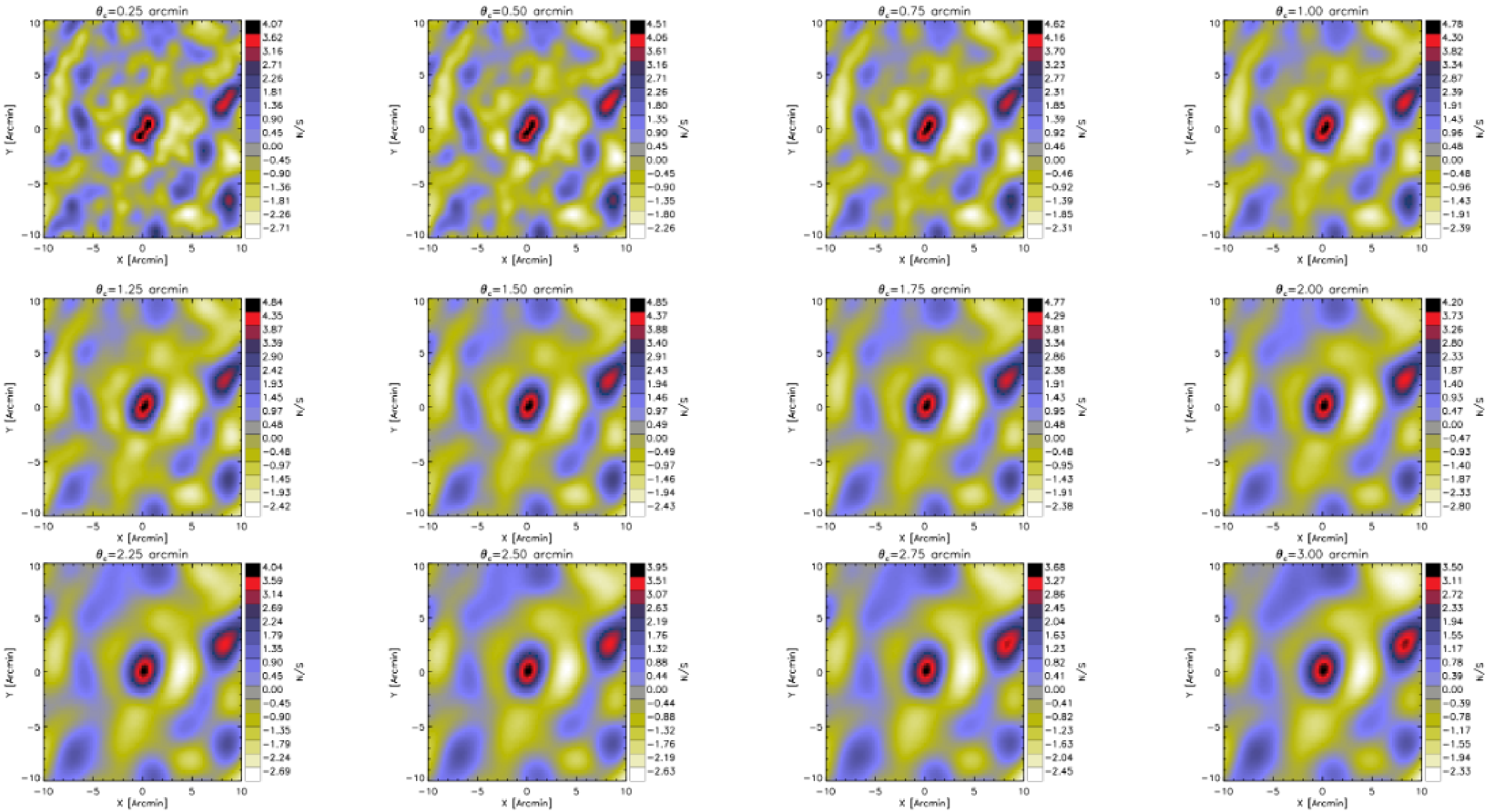
SPT data



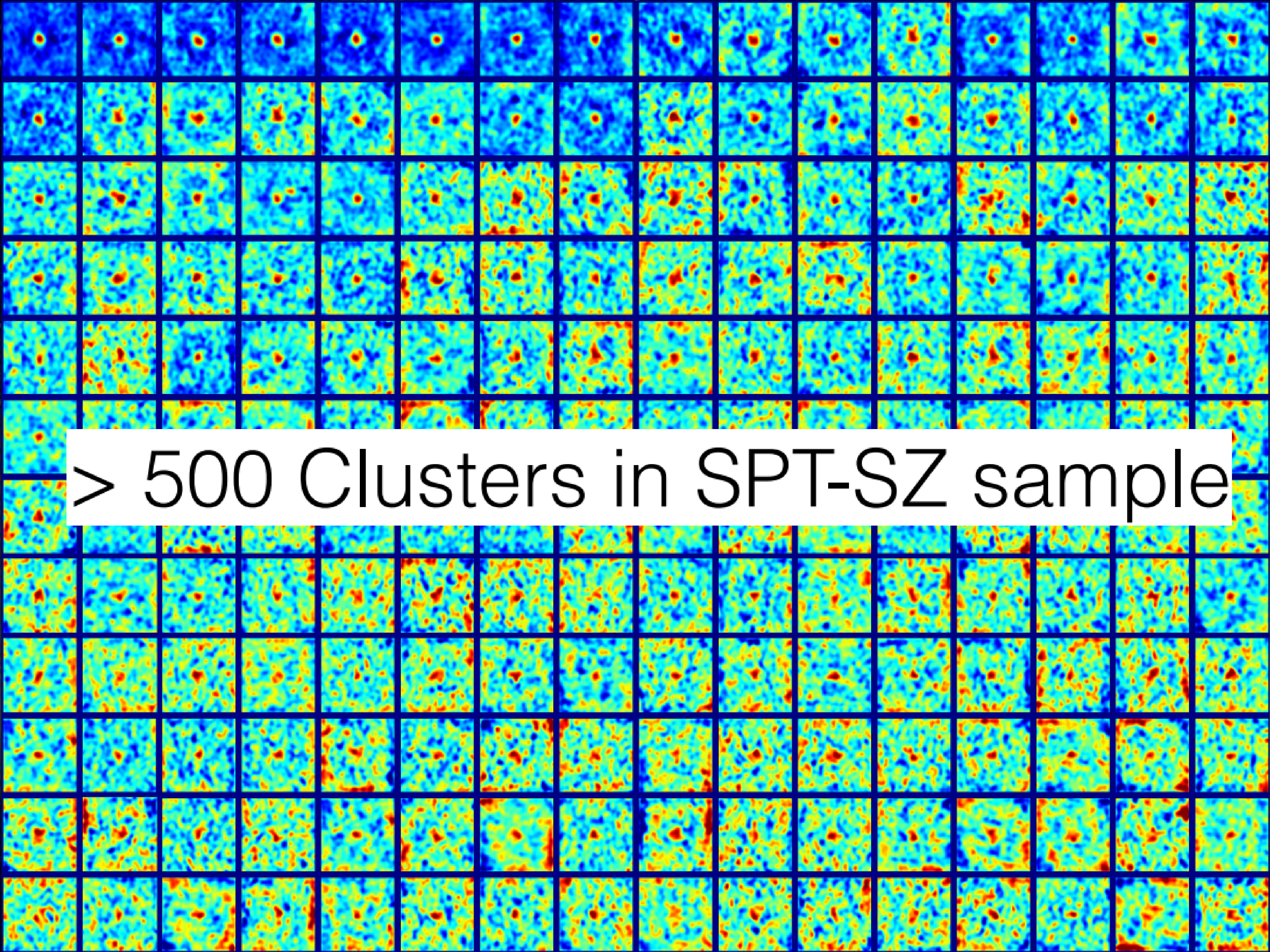
SPT 90 GHz

Finding a Cluster in SPT Maps

SPT filtered maps



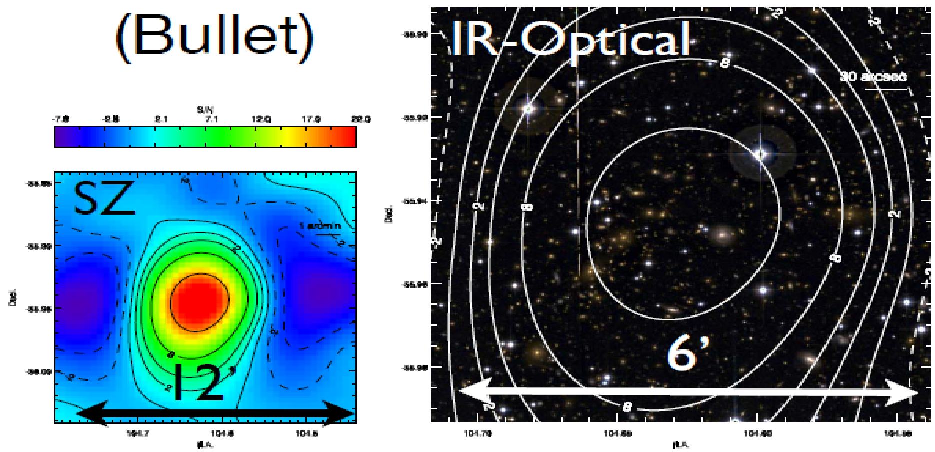
SPT 90 GHz


> 500 Clusters in SPT-SZ sample

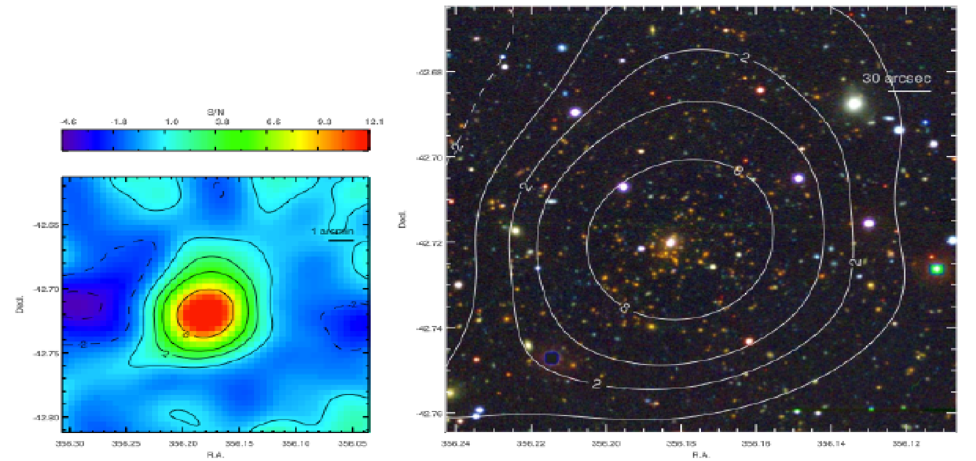
Confirmation of Galaxy Population

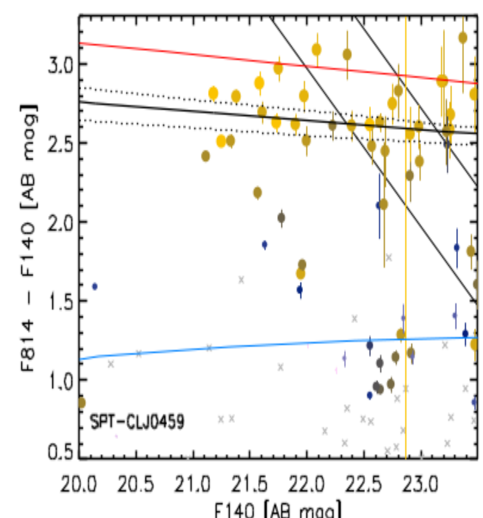
- Over the broad redshift range of the sample, we use optical and NIR imaging to probe for the galaxy population (Strazzullo+)

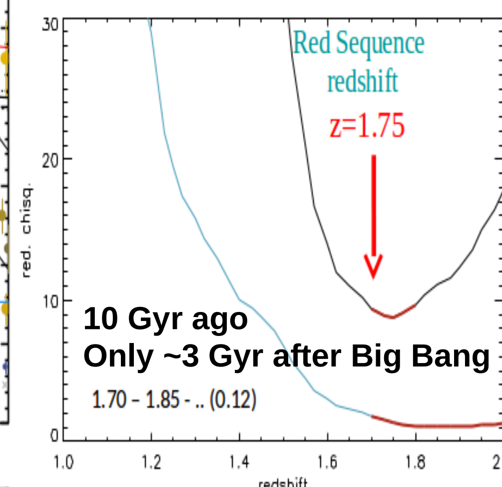
0658-5358 (z=0.30)
(Bullet)



2344-4243 (z=0.62)





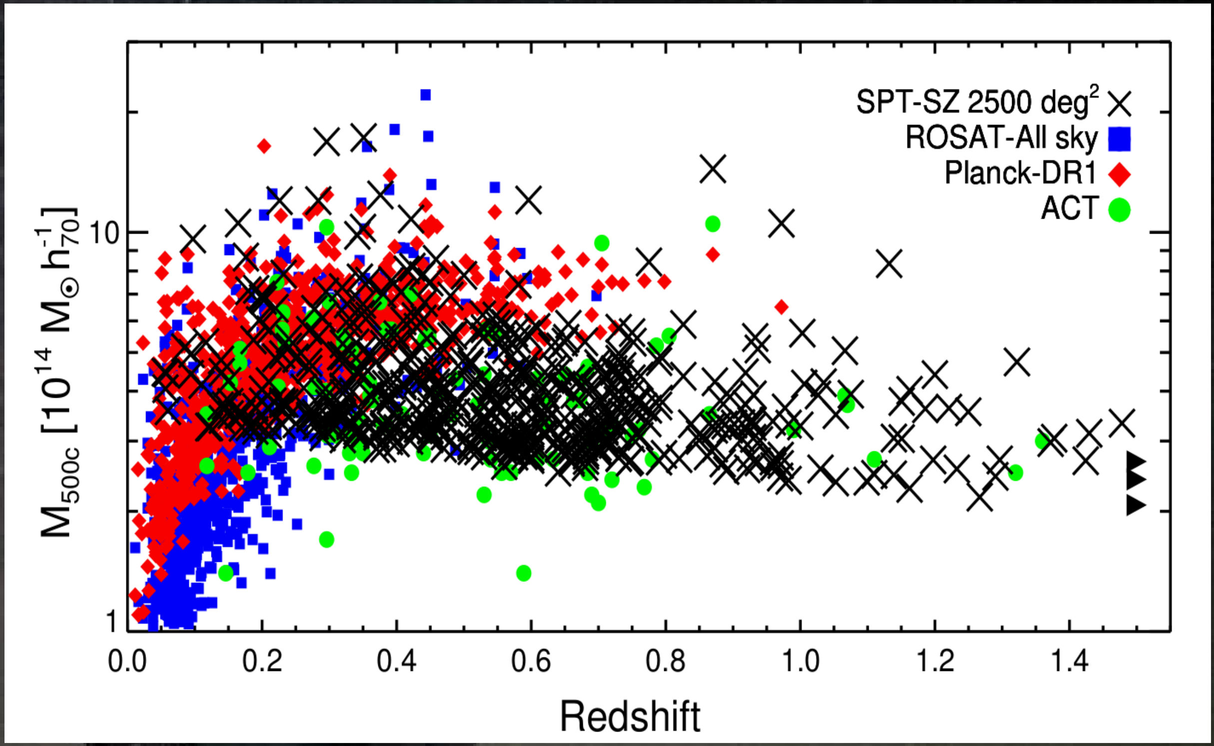


SPT-SZ Sample

Song+12, Bleem+15

- 2500 deg^2 sample
  - 516 at $\xi>4.5$
  - 387 at $\xi>5.0$

    Bleem+15



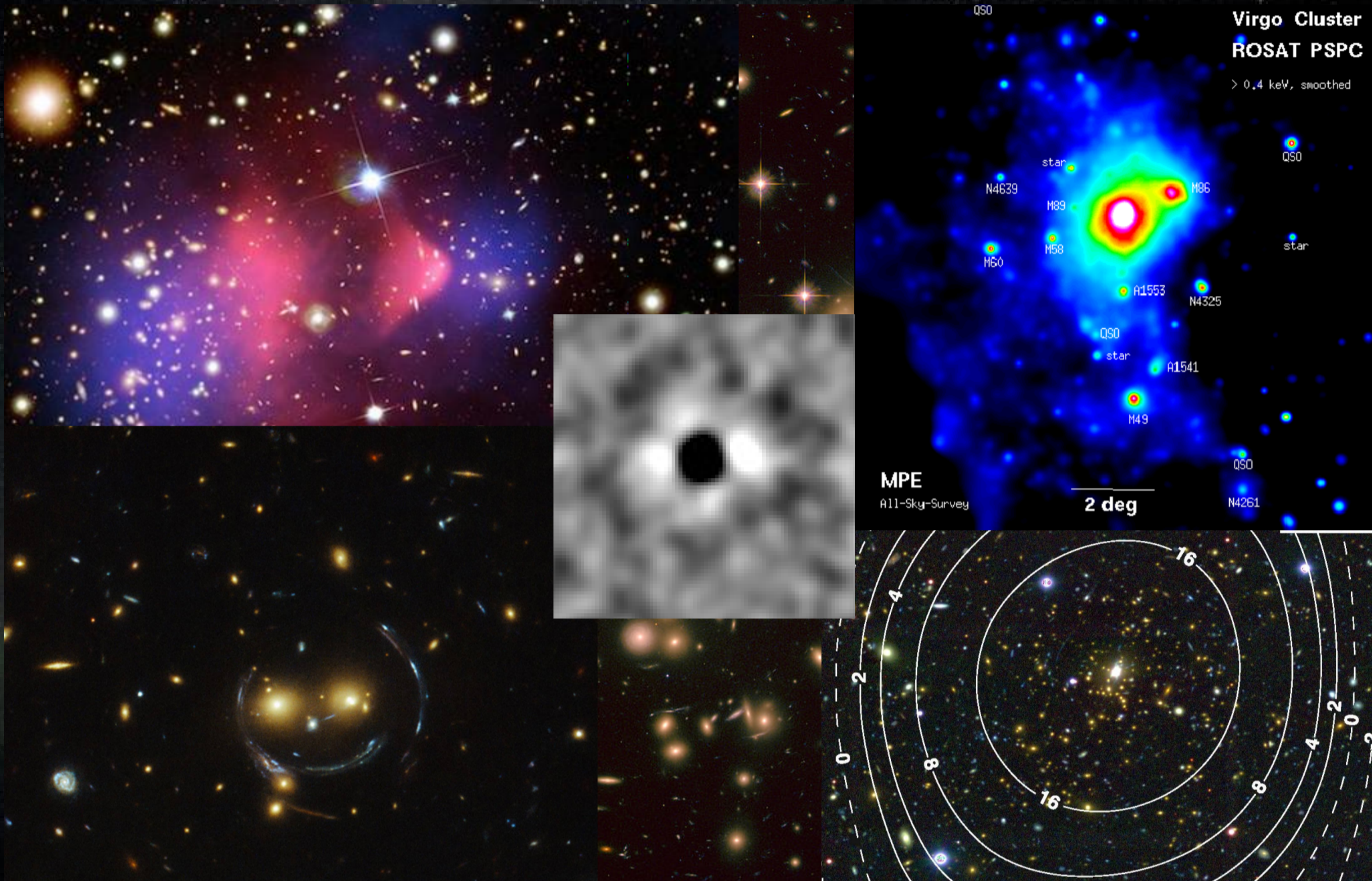
- High z subsample
  - ~150 (80) > 0.8
  - ~ 70 (40) at z>1
  - Max z_{spec}=1.47

    Bayliss+13
  - Highest phot-z

    Strazzullo+

- Clean sample with $M_{500}>3\times10^{14}$ M_o to z~1.8

What is the Mass of this objects?



Multi-wavelength Observations: Mass Calibration

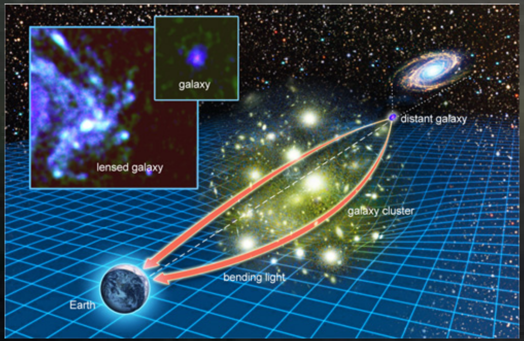
- Multi-wavelength mass calibration campaign, including:
  - **Thermodynamical properties**
  - X-ray with
    - Chandra
    - XMM

Multi-wavelength Observations: Mass Calibration

- Multi-wavelength mass calibration campaign, including:
  - X-ray with
    - Chandra
    - XMM

Gravitational lensing from background galaxies

  - Weak lensing from:
    - Magellan (0.3 < z < 0.6)
    - HST (z > 0.6)
    - DES

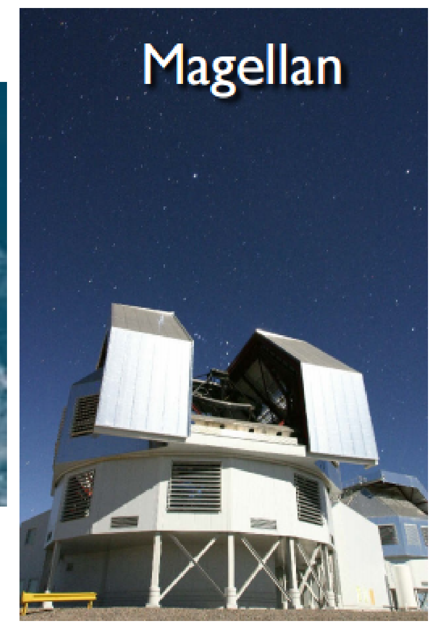


Multi-wavelength Observations: Mass Calibration

- 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

Velocity Dispersion of Galaxies

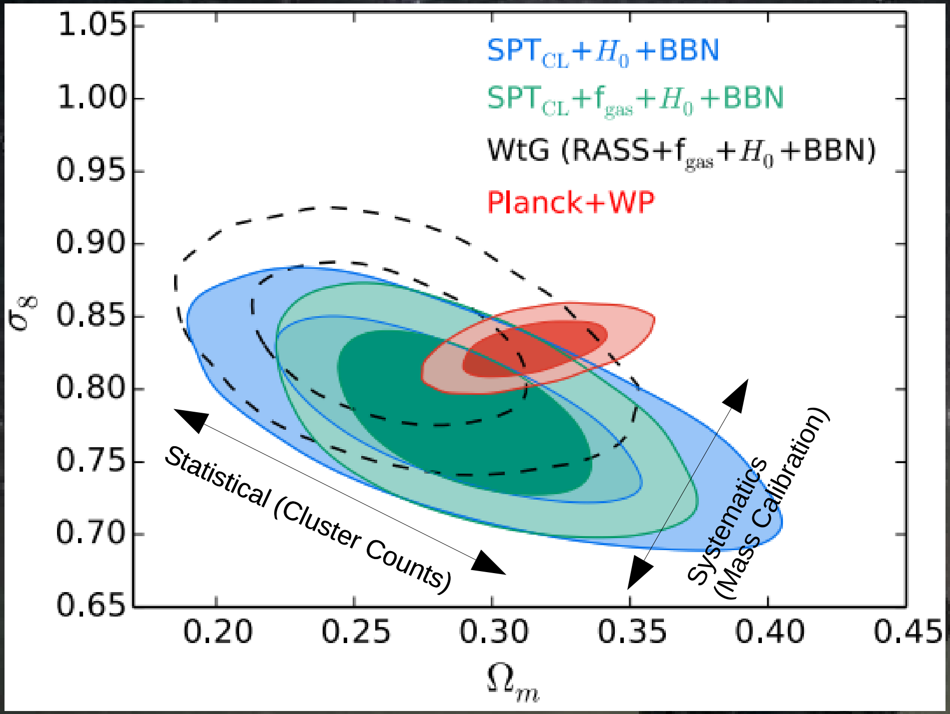
  - Dynamical masses from
    - Gemini (z < 0.8)
    - VLT (z > 0.8)
    - Magellan (z > 0.8)



SPT Cluster Cosmology: ΛCDM

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

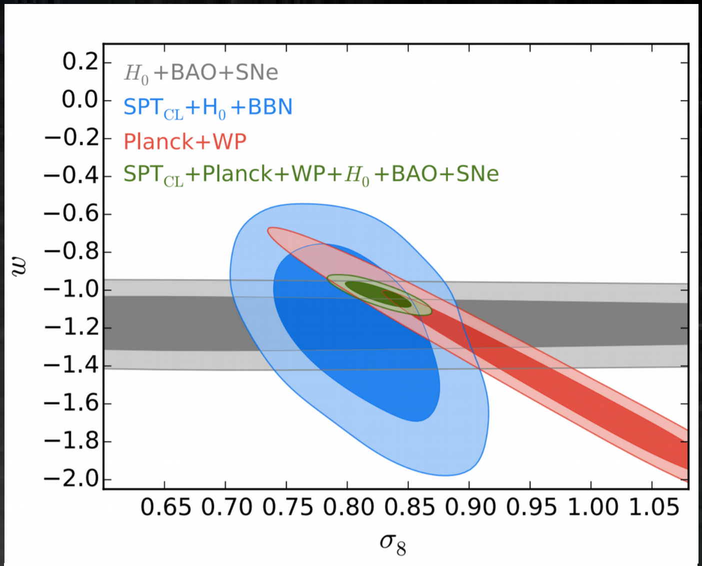
SPT Cluster Cosmology: Extensions

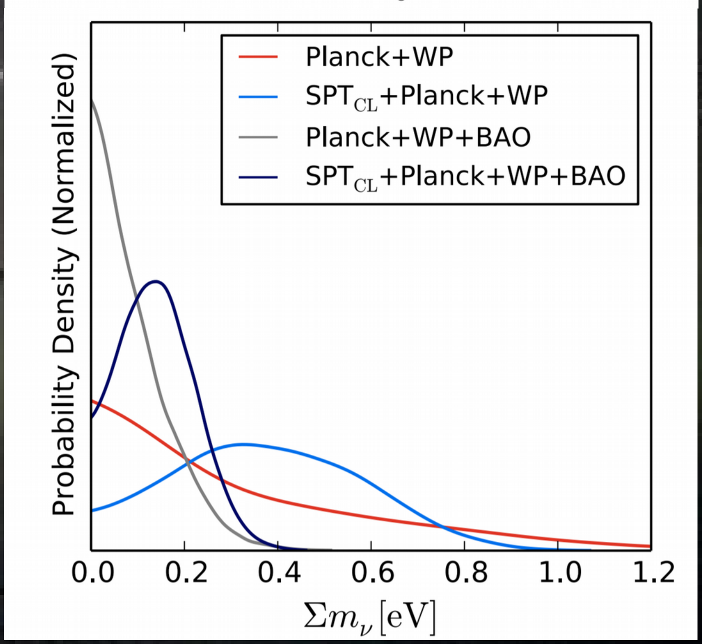
de Haan+16

- Clusters break degeneracies in other data-sets. Combination of Clusters, CMB, geometric probes:

  w = -1.023 +/- 0.042

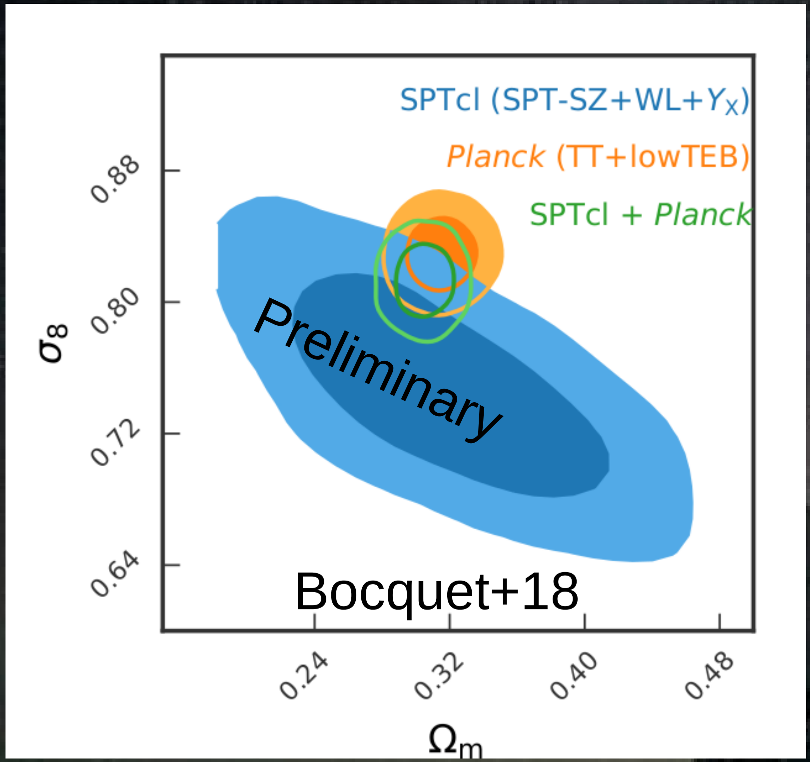
- CMB strong degeneracy σ_8-Σm_ν, so even modest σ_8 can improve constraints

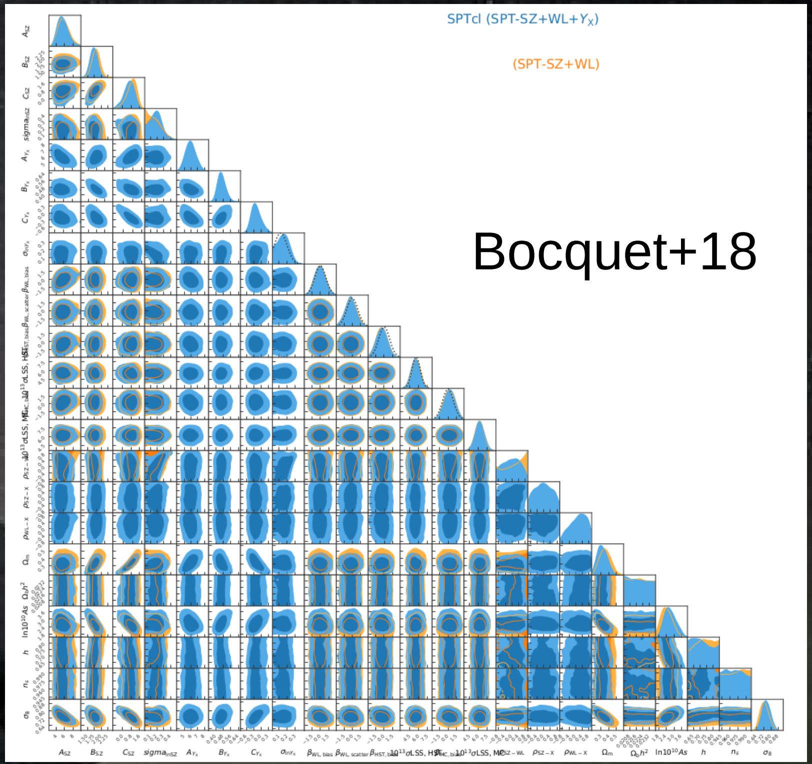




SPT Cluster Cosmology

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





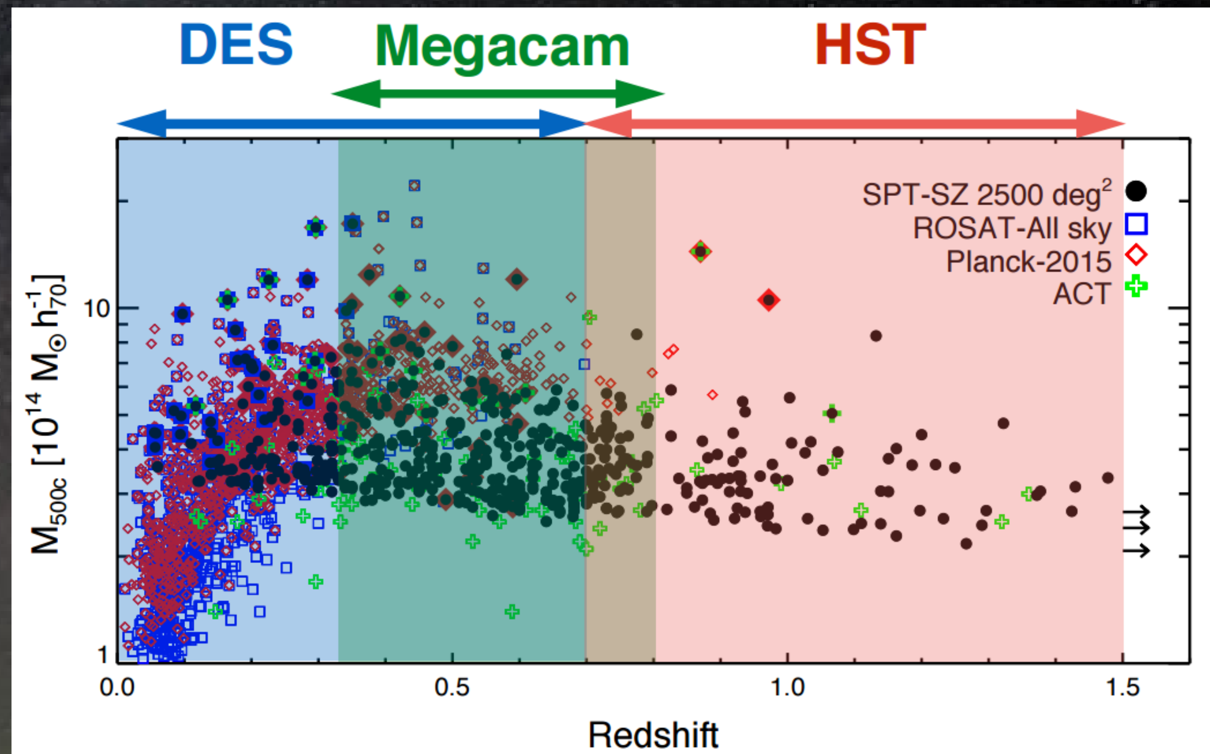
- 387 SPT clusters
- Mass calibration
  - 82 X-ray Y_xs
  - 32 WL
- 22 parameters

Future: More & More calibration

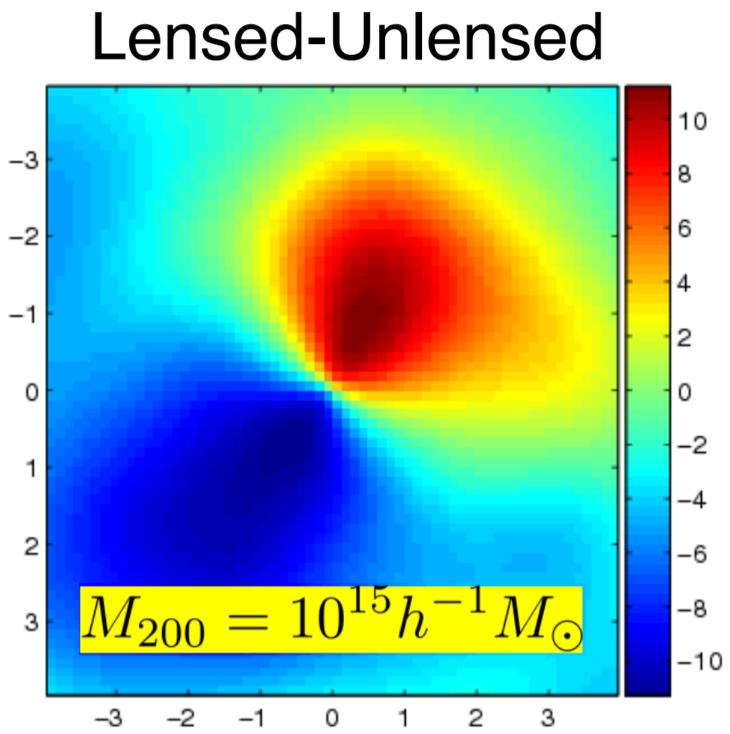
SPT Mass Calibration Ongoing

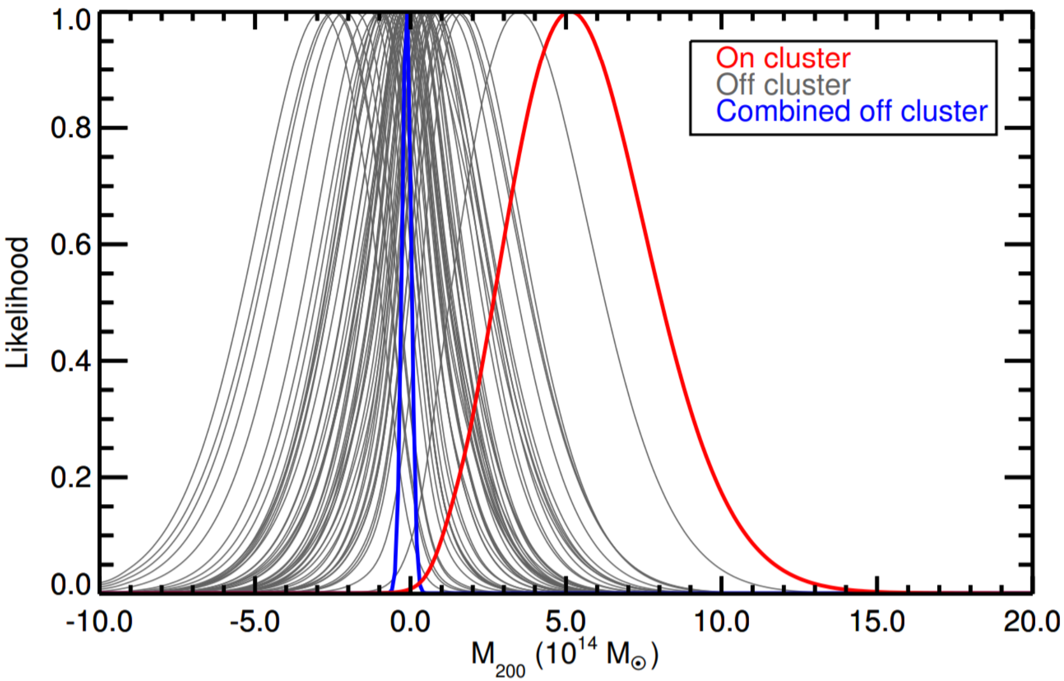
Direct mass calibration of clusters

- Dynamical masses:
  - Bocquet+15: with dispersions
  - Capasso+18: Jeans analysis
- Magnification masses:
  - Chiu+16
- Shear masses:
  - Dietrich+18: Magellan HST imaging
  - Schrabback+18:HST VLT imaging
  - Stern+18: DES imaging



CMB Cluster Lensing with SPT-SZ





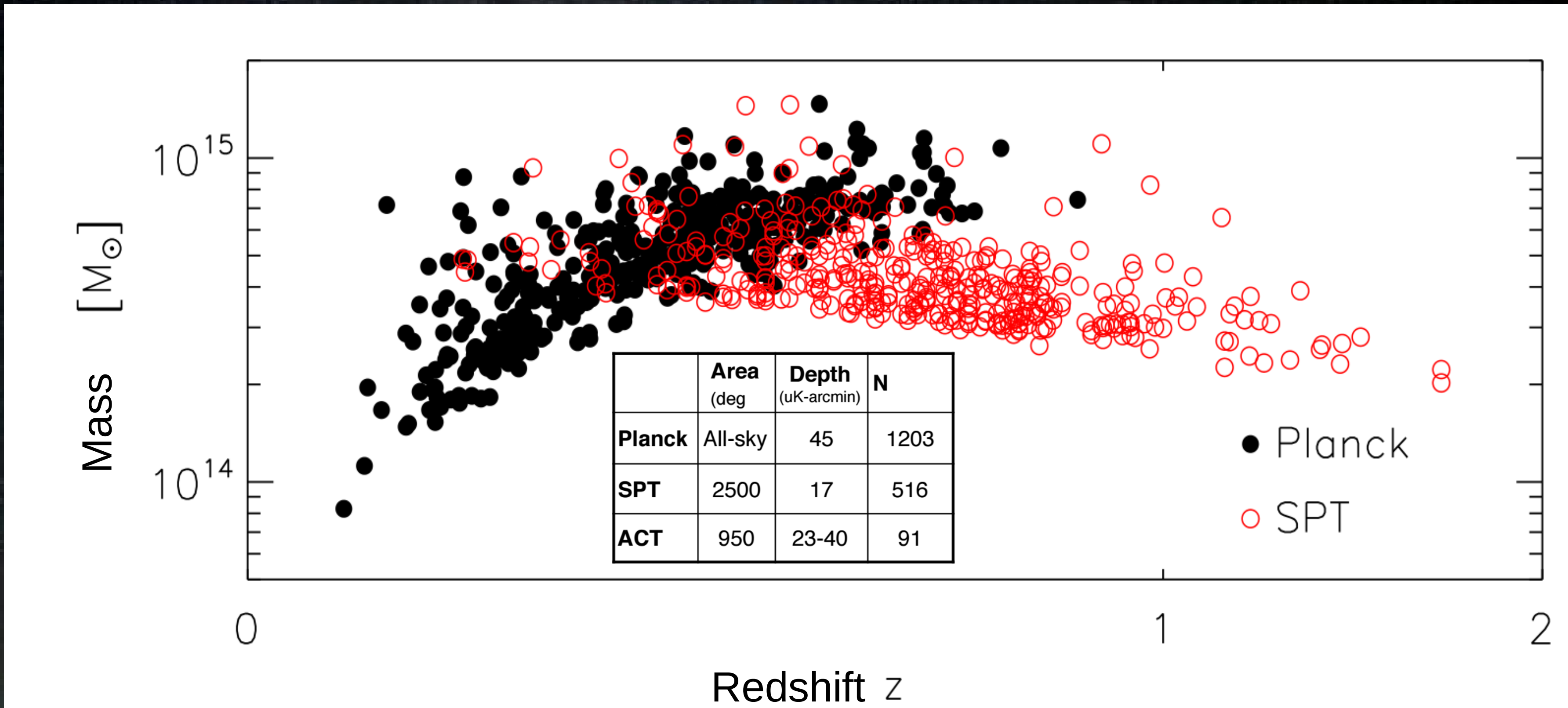
- A ~few uK "dimple" in the CMB caused by lensing of a ~10^{15} solar mass cluster
- A 3.1σ detection of CMB lensing using ~500 clusters measured by SPT-SZ

Baxter et al. 2015, ApJ, 806, 247

See also: Planck Collab. XXIV, 2016 A&A 594, A24 Madhavacheril et al. PRL 114, 15.

Future: More & More clusters

Planck & SPT

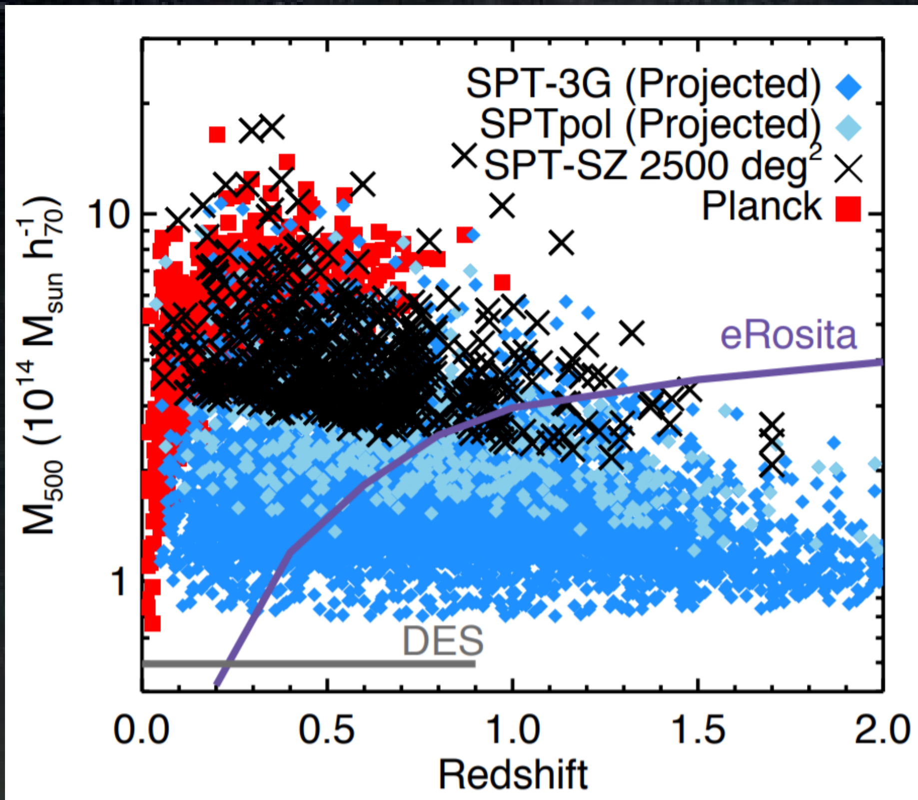


	Area (deg	Depth (uK-arcmin)	N
Planck	All-sky	45	1203
SPT	2500	17	516
ACT	950	23-40	91

- 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!!!

Future: More & More clusters



Deep CMB data also enables CMB cluster lensing as a competitive mass calibration tool for cluster DE science: SPT-3G: σ(M) ~ 3%! CMB-S4: σ(M) < ~0.1%! Especially promising tool for cluster masses at z > 1

South Pole

- SPT-SZ/Pol: Nclus ~ 1000
- SPT-3G: Nclust ~ 10000

Chile

- CCAT-prime
- AdvACT
- Simon's array
- Simons's observatory

CMB S4:

- Nclust ~ 100,000+
- DES: 10,000
- eRosita: 2019
- Euclid: 2021

Summary

- SPT has found hundreds of massive galaxy clusters spanning a redshift range $0.05 < z < 1.7$.
- Clean, mass-limited selection leads to a fantastic sample for cosmological and astrophysical studies.
- Cosmological analysis consistent with other cluster studies & CMB Cosmology
- Better mass calibration required to tighten constraints (and work is ongoing!)
- (Near) future will provide huge samples of clusters with multi-λ observations (astrophysics & cosmology)

Thank you!