The South Pole Telescope Cluster Samples

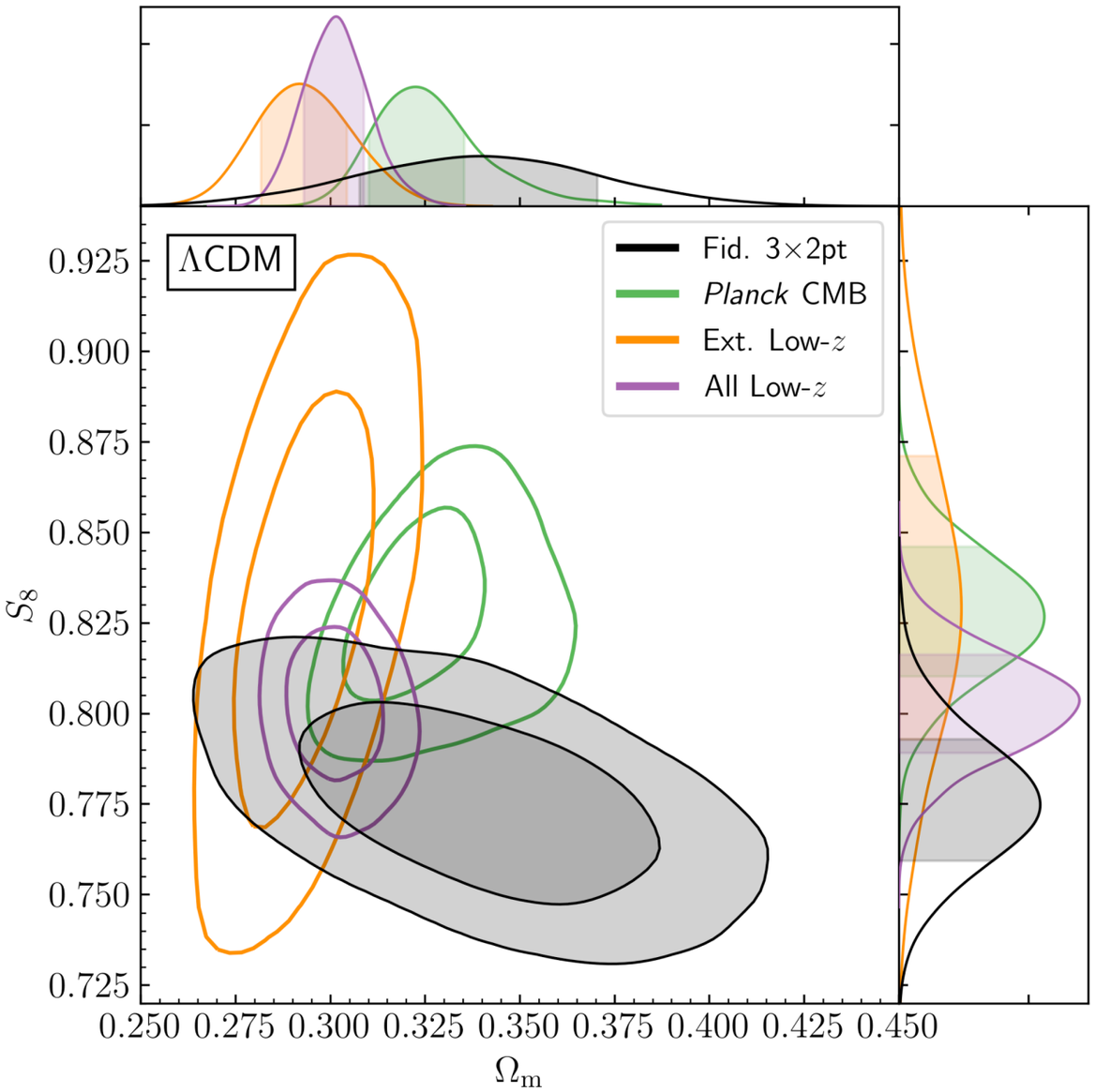
mm Universe 2023

Lindsey Bleem
Argonne National Laboratory
June 26, 2023

Overview

- Brief Introduction
- Status of the Current SPT SZ samples
  - Sample Construction
  - Confirmation
  - Validation
- SPT Compton-y map
- Coming soon from SPT-3G

Cosmic Concordance

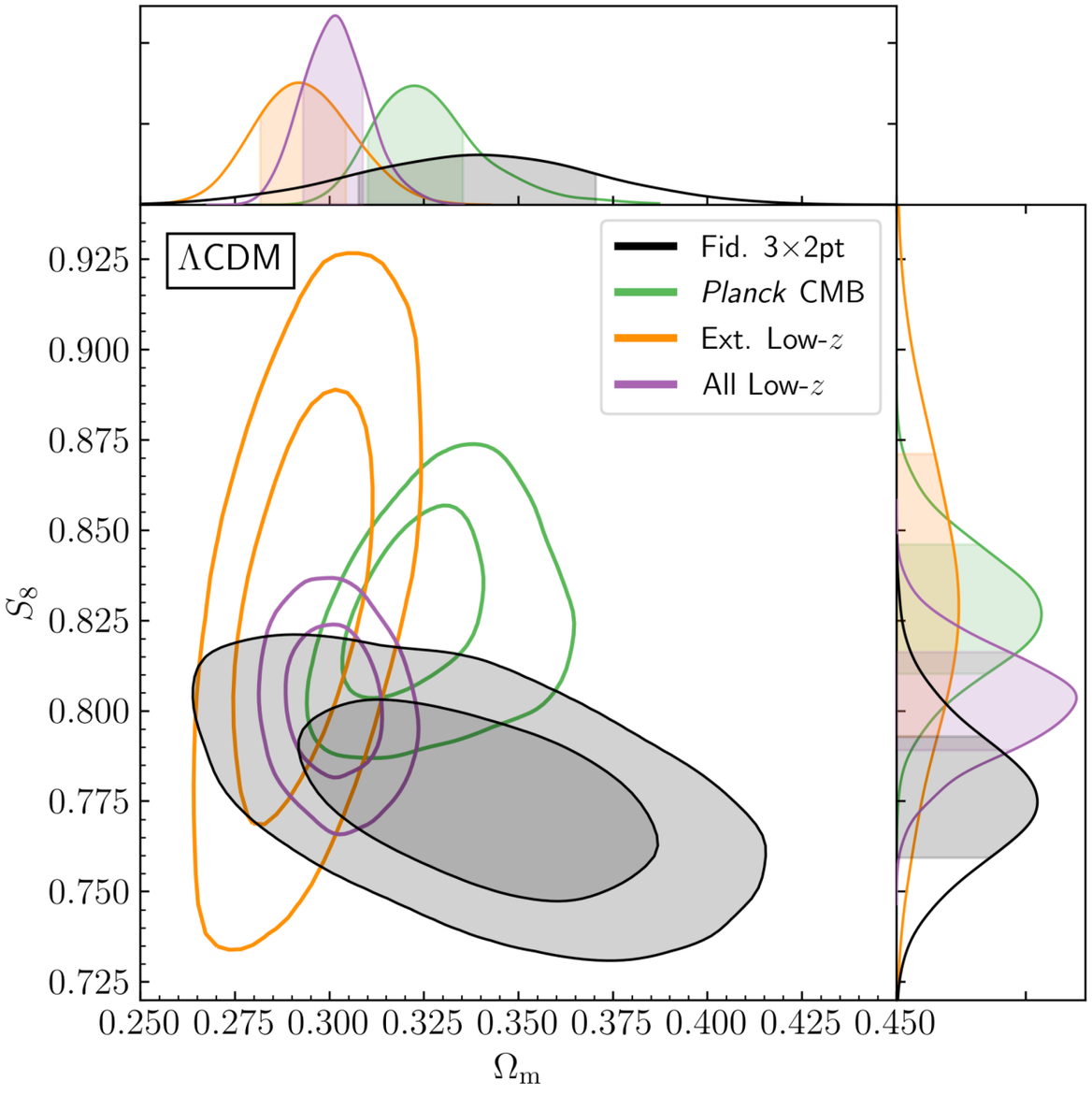


DES Collaboration;
PhysRevD 105.023520,2022

Cosmic Concordance

or

Cosmic Controversy?



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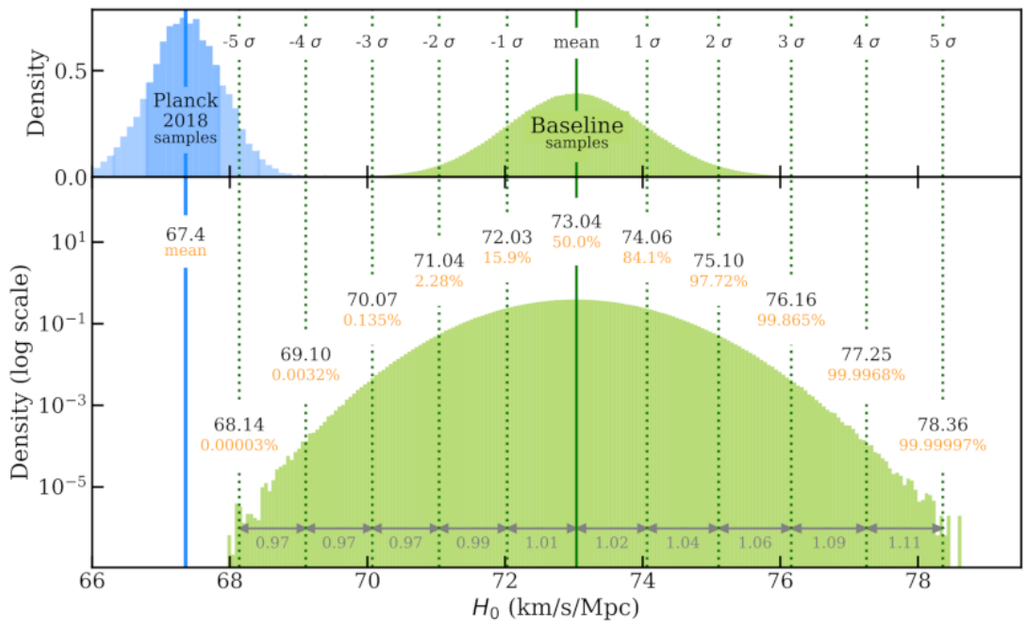
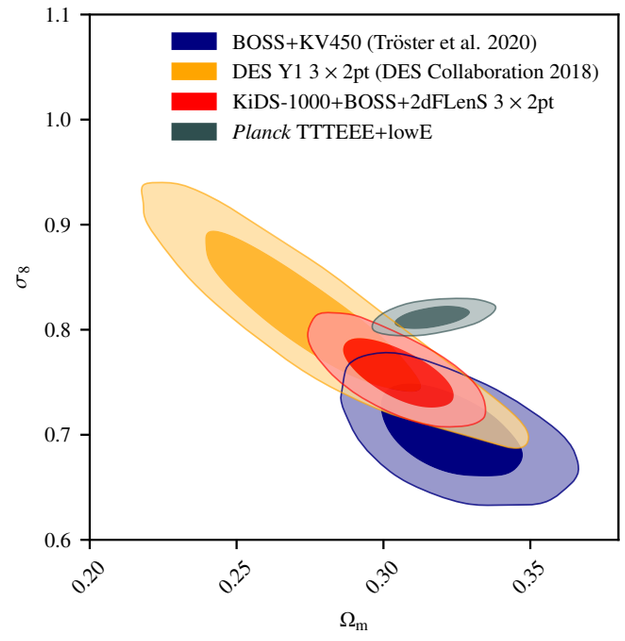
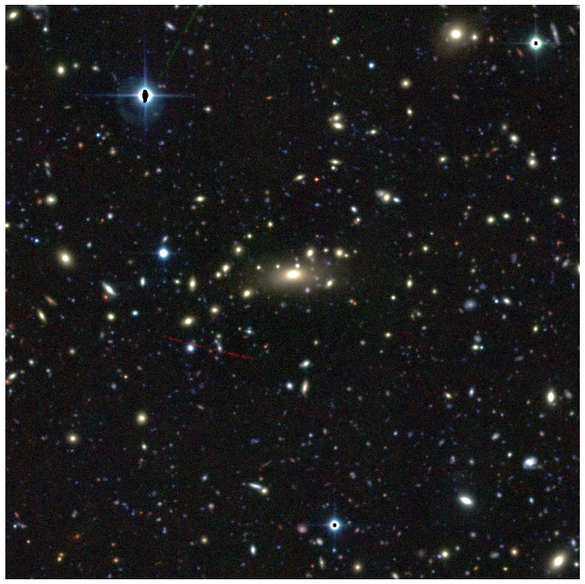
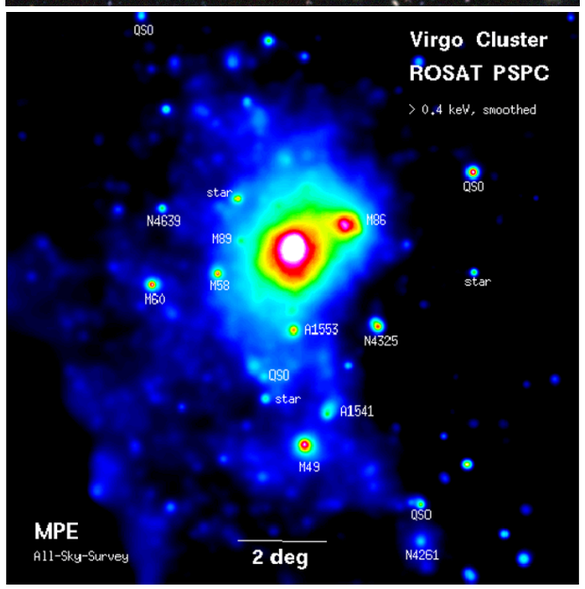


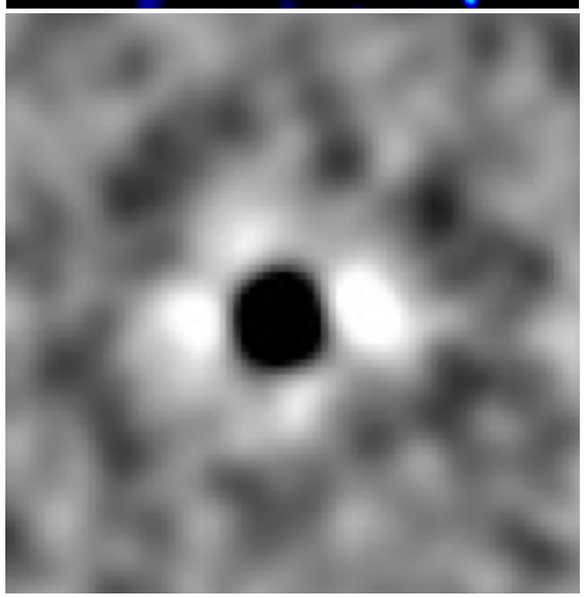


Riess et al. arXiv: 2112.04510
Heymans et al. A&A 646, A140 (2021)

Clusters as Cosmological Probes





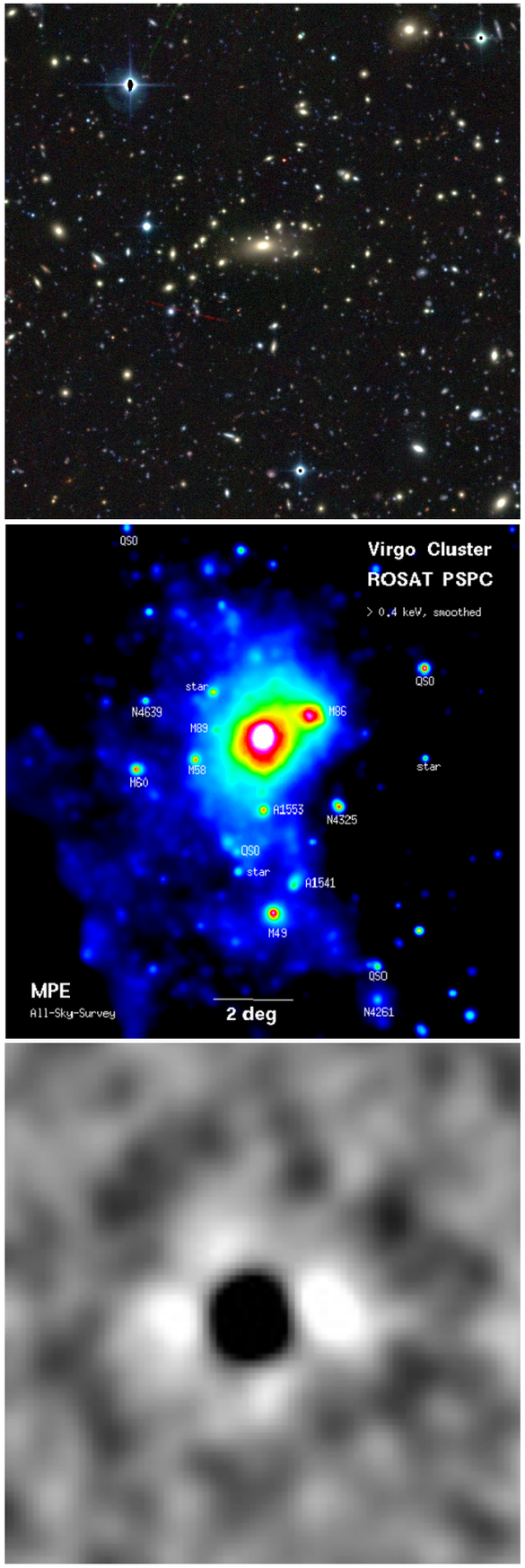


Cosmic Visions Dark Energy: Science

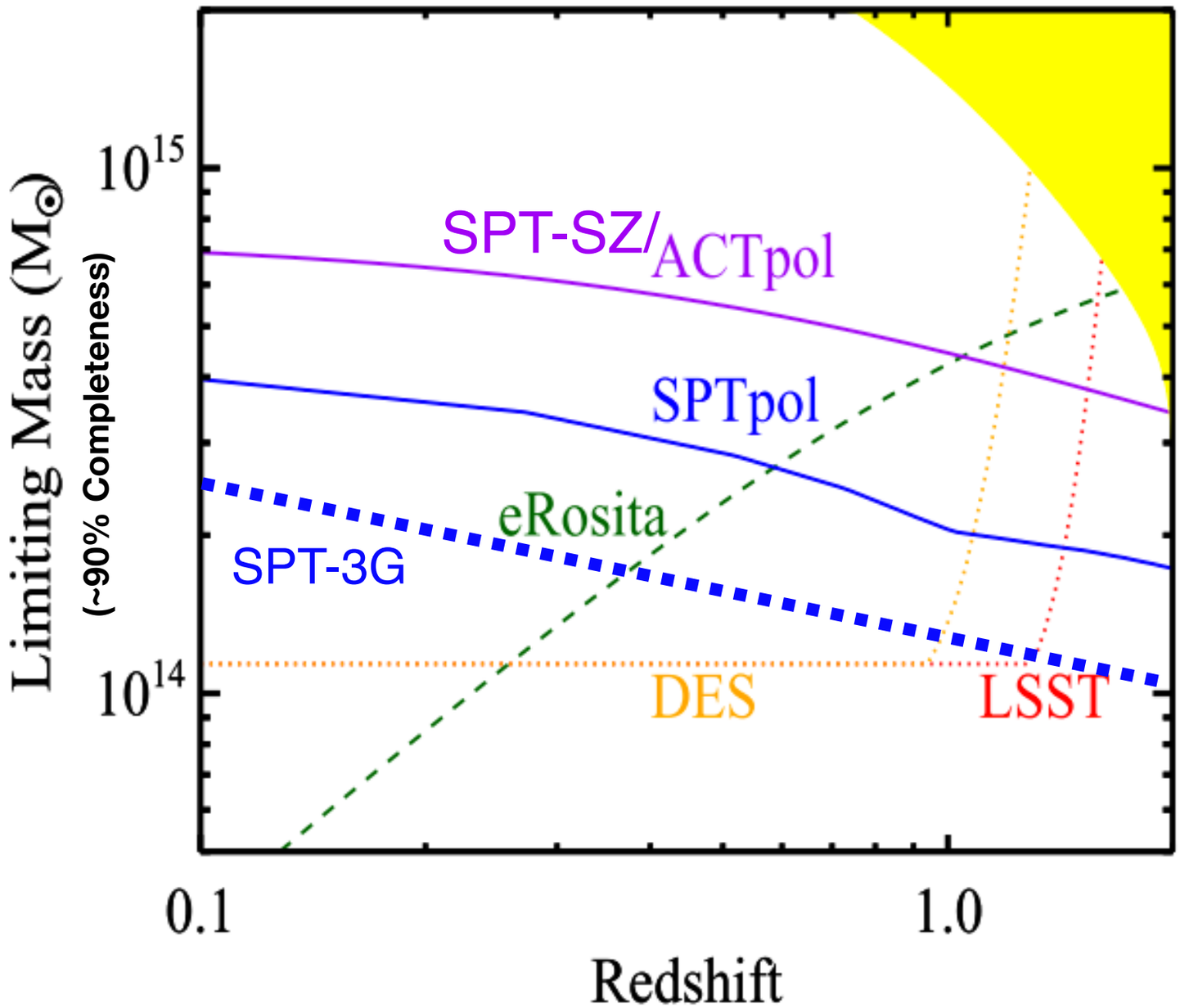
Scott Dodelson, Katrin Heitmann, Chris Hirata, Klaus Honscheid, Aaron Roodman, Uroš Seljak, Anže Slosar, Mark Trodden

The number of massive galaxy clusters could emerge as the **most** powerful cosmological probe ***if*** masses of the clusters can be accurately measured.

3 Approaches: Optical, X-ray, SZ



Range of Multi-wavelength Cluster Surveys



Weinberg et al. PhR 520, 87W (2013)

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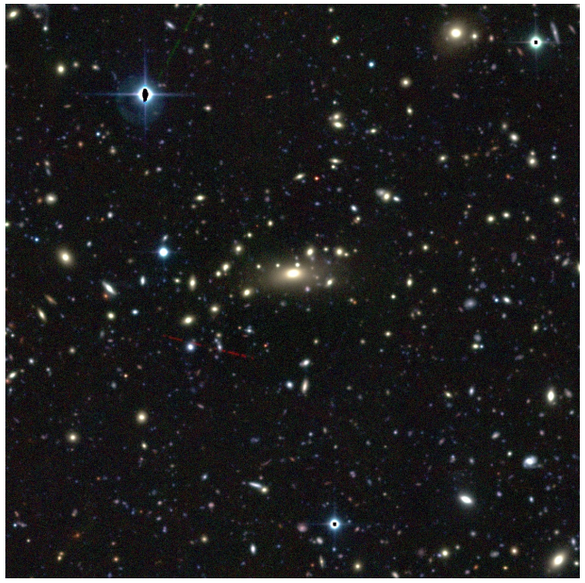

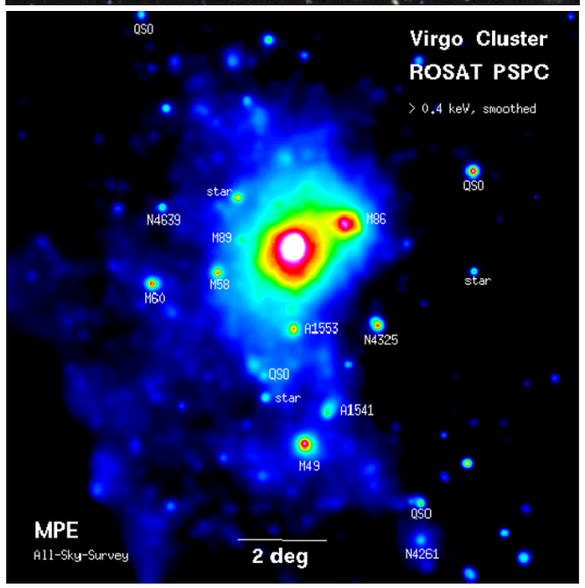

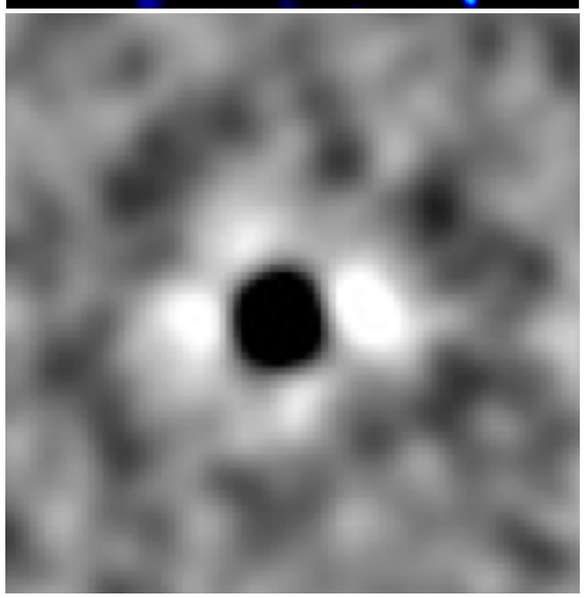

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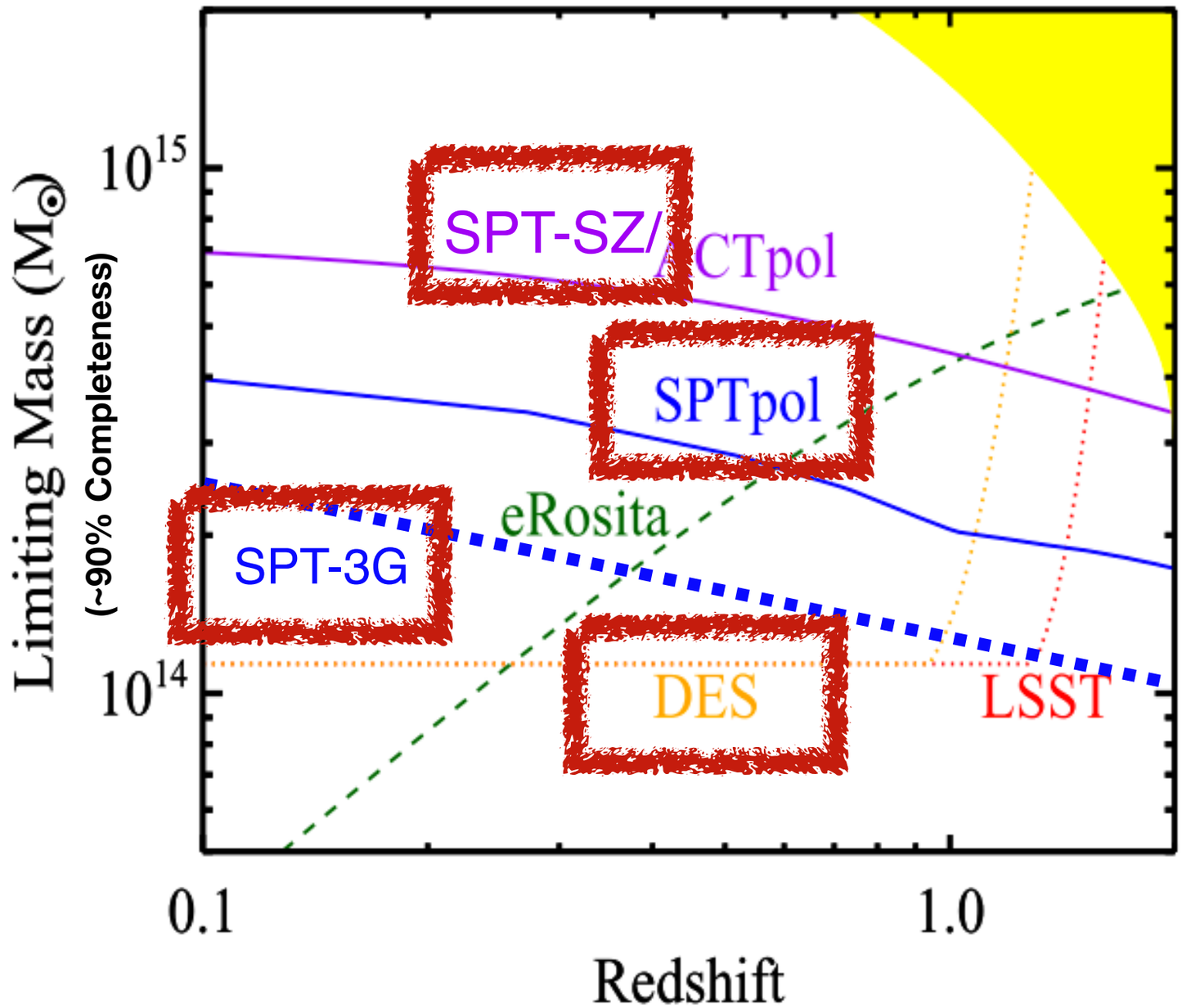
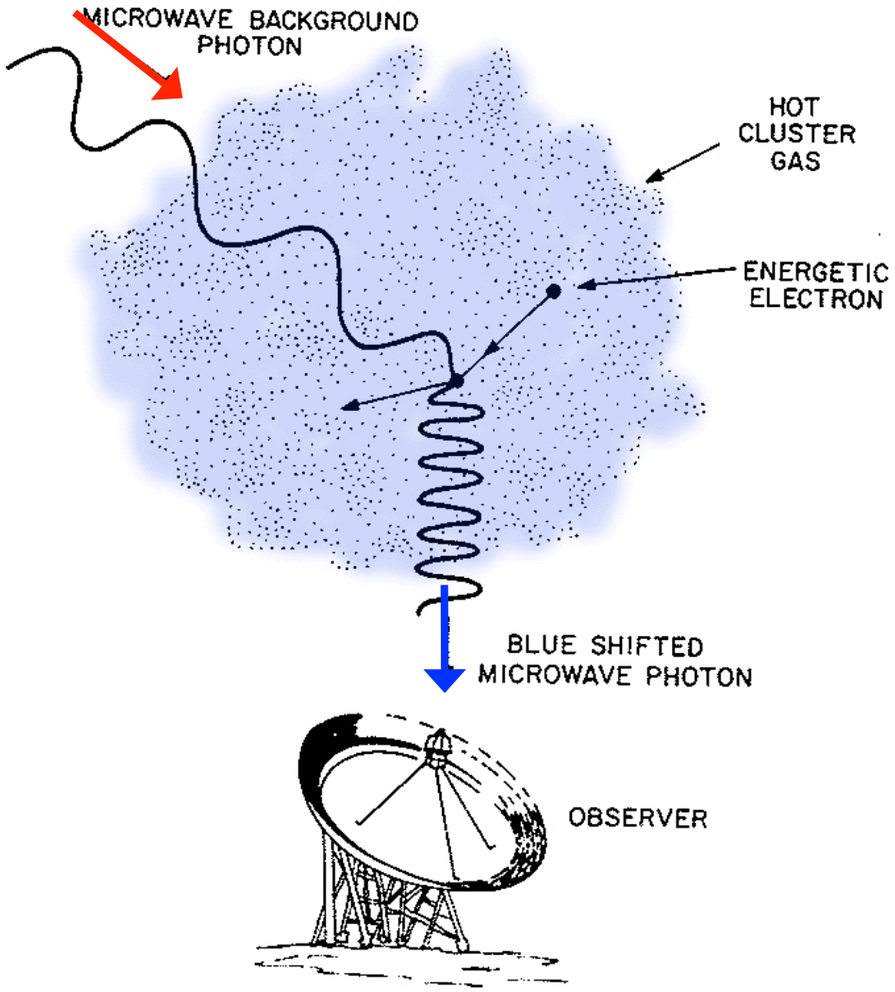


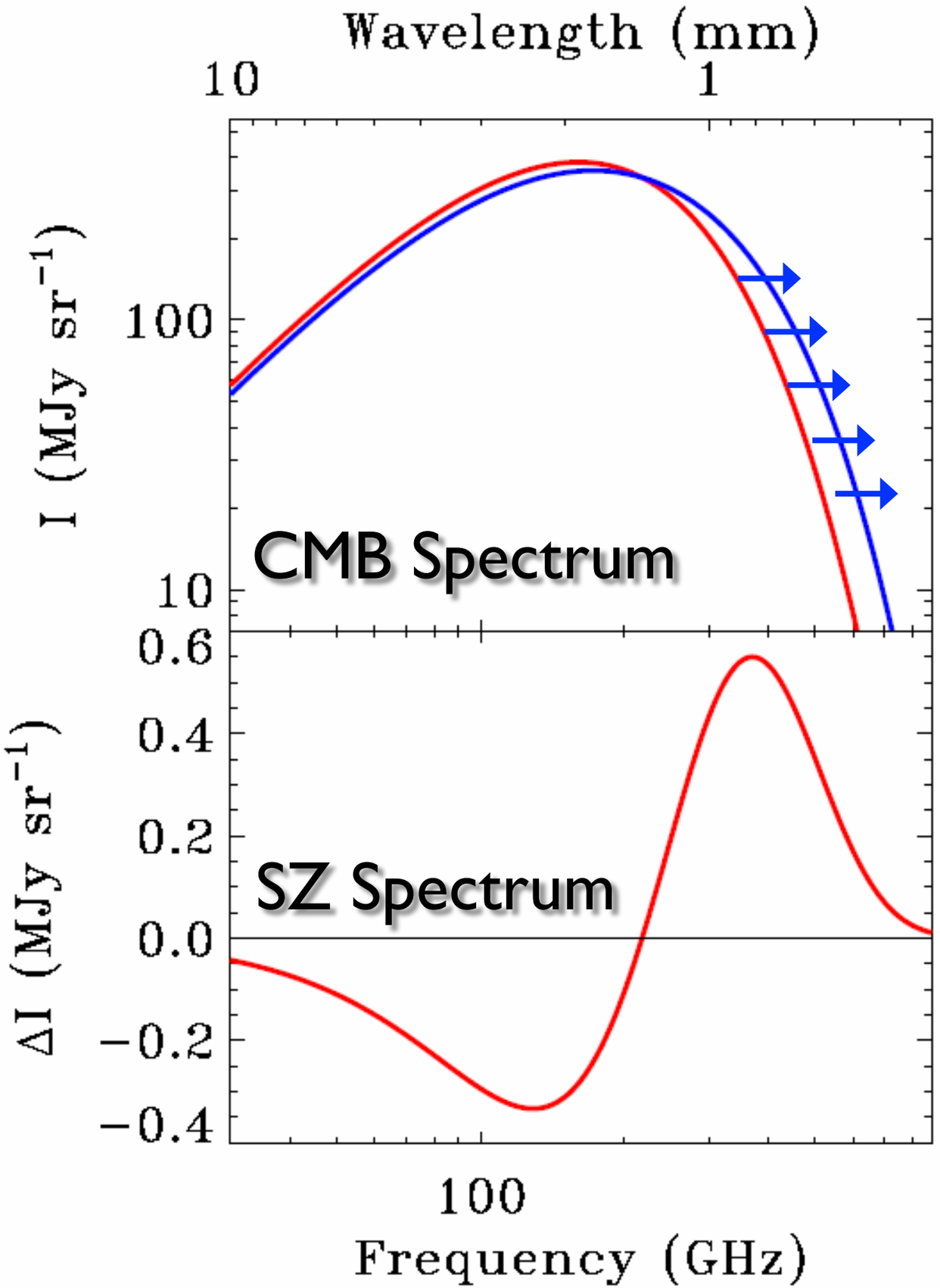
Weinberg et al. PhR 520, 87W (2013)

The Sunyaev Zel'dovich (SZ) Effect



Adapted from L. Van Speybroeck

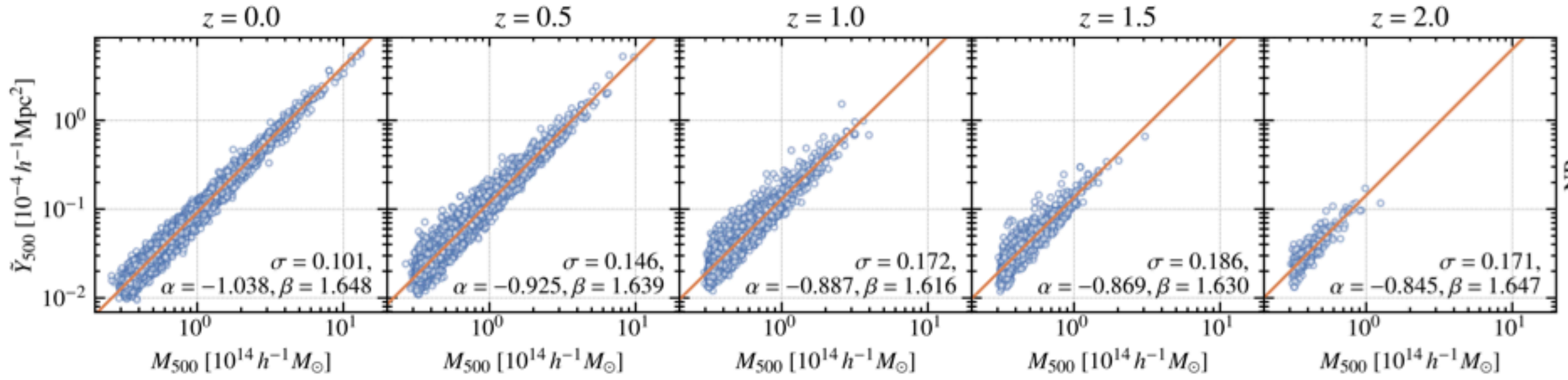
Towards a massive cluster,
~1% of CMB photons scatter
off of intra-cluster gas



The SZ-observable is tightly correlated with mass.

$$\int y d\Omega \propto \frac{k_B T_e}{m_e c^2} \sigma_T \frac{N_e}{D_a^2}$$

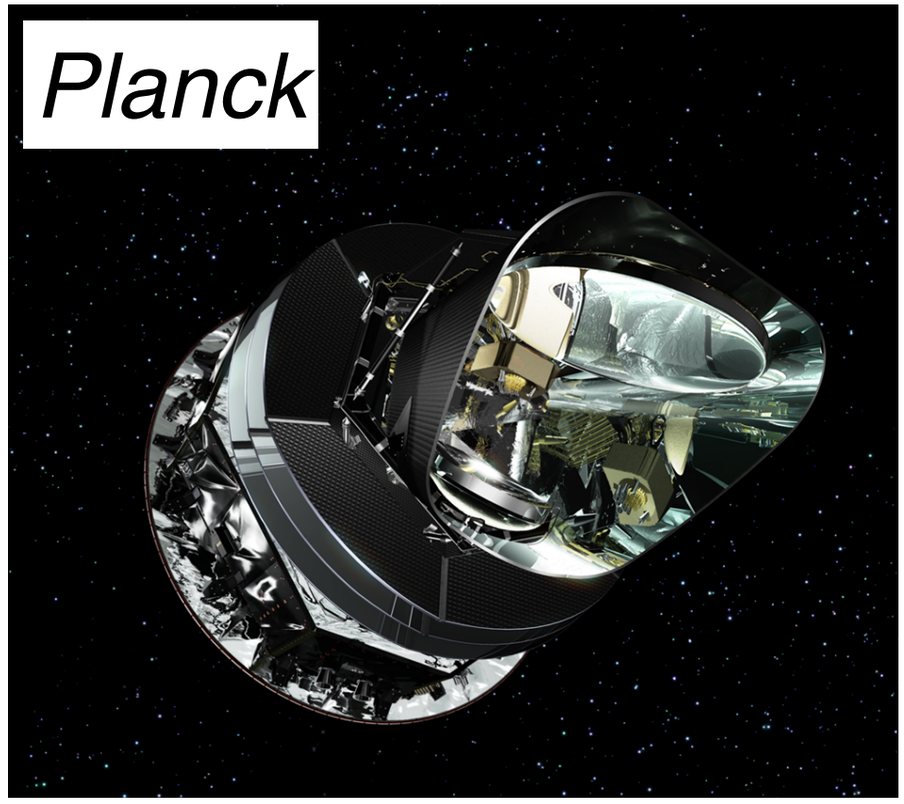
Integrated Signal proportional to total thermal energy, should faithfully track cluster mass



Kéruzoré et al. (on the arXiv tonight!)

We require high-resolution, wide-area surveys to discover significant numbers of clusters.

Atacama Cosmology Telescope



South Pole Telescope

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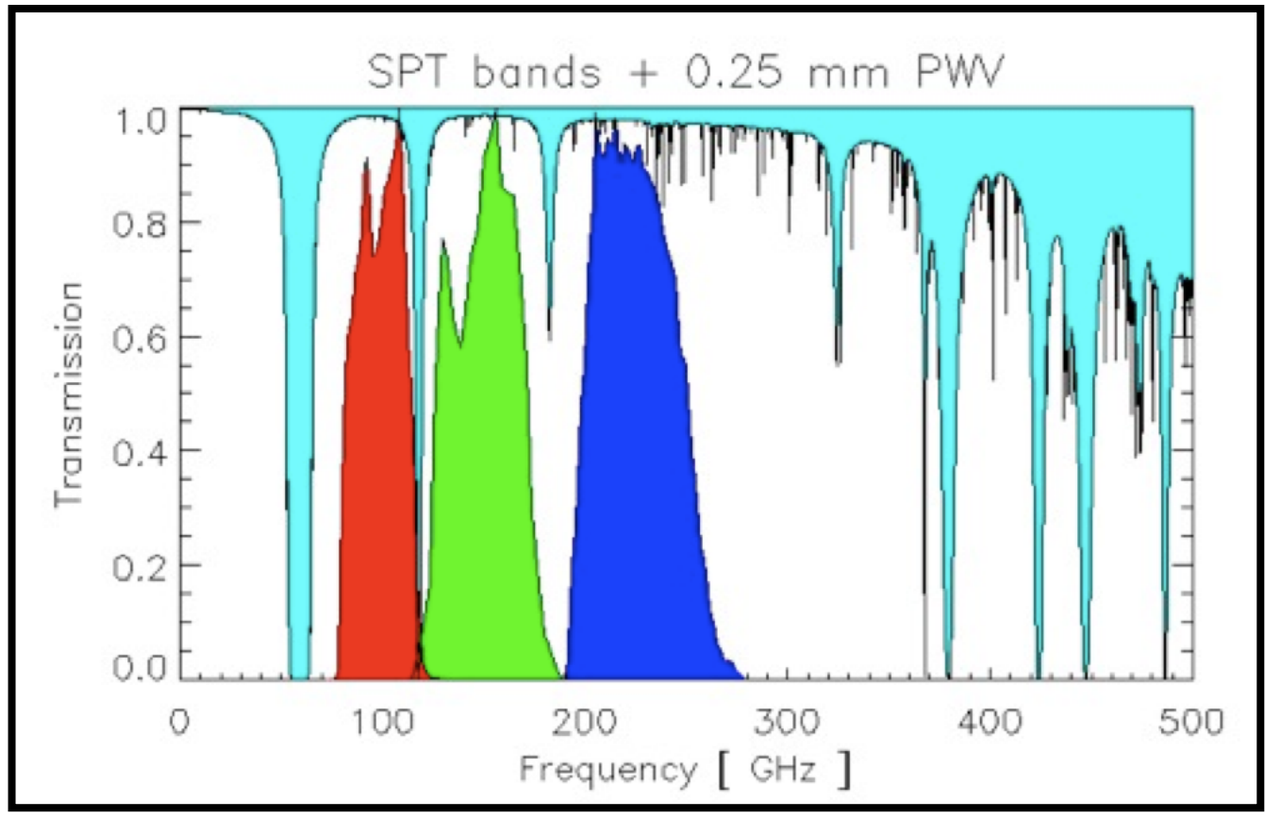
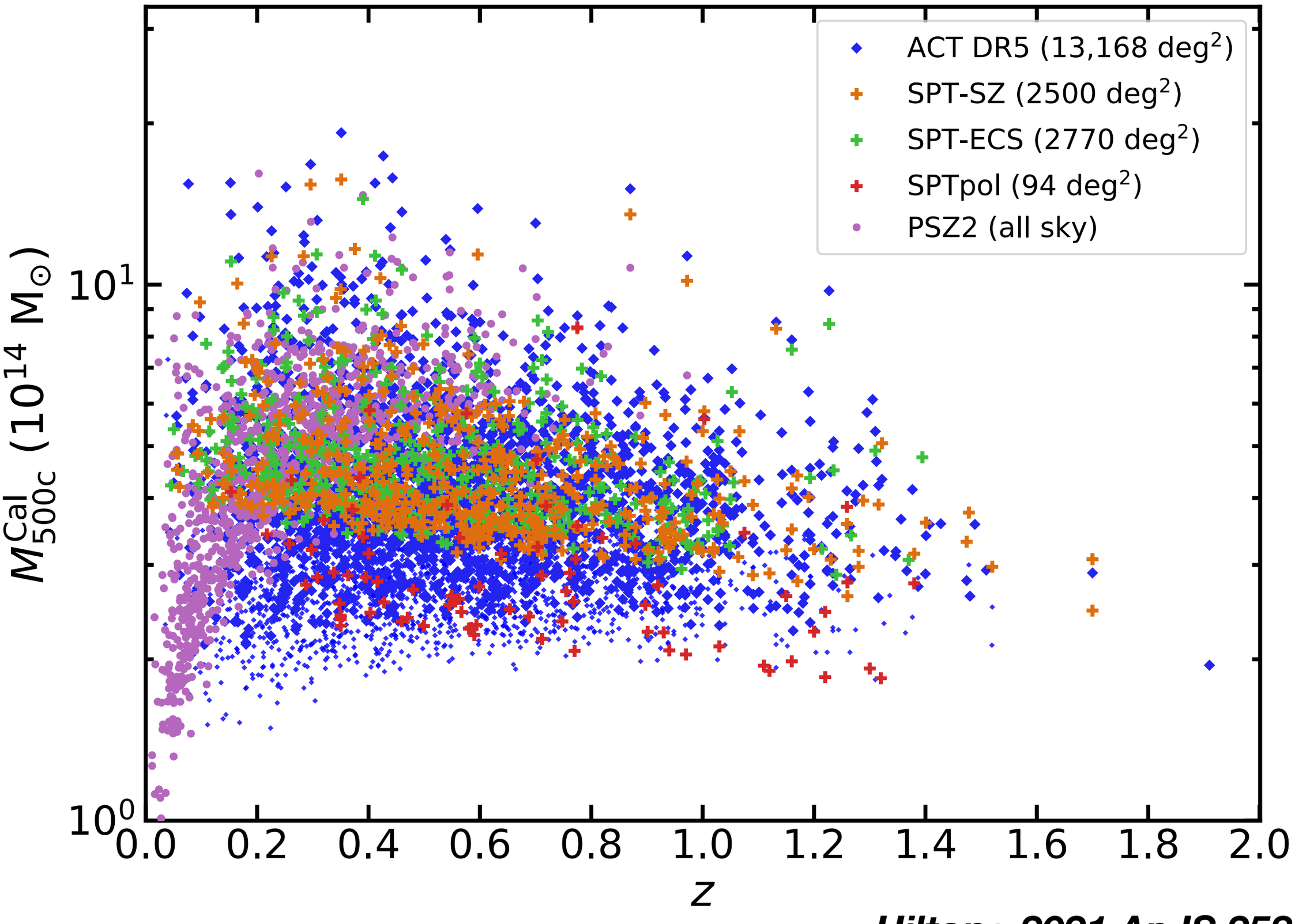


South Pole Telescope

> 4000 Massive Clusters published from SZ surveys



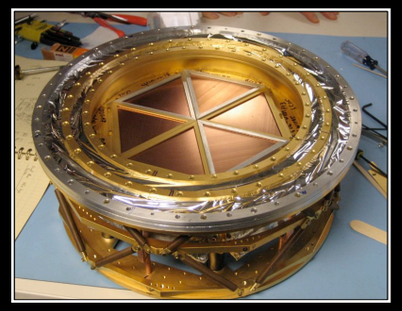
Hilton+ 2021 ApJS,253, 3H

The South Pole Telescope (SPT)

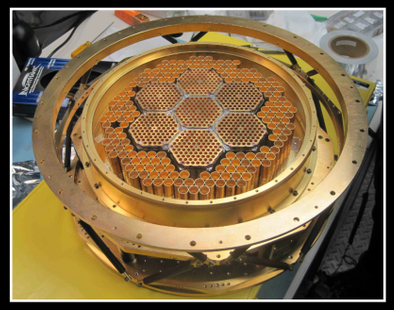
10-meter sub-mm quality wavelength telescope

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

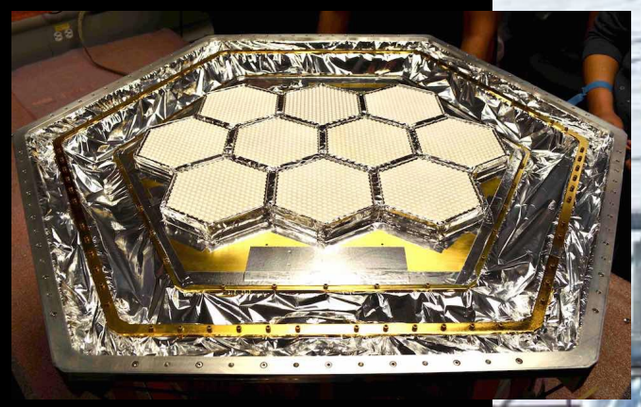
2007: SPT-SZ
960 detectors
90,150,220 GHz

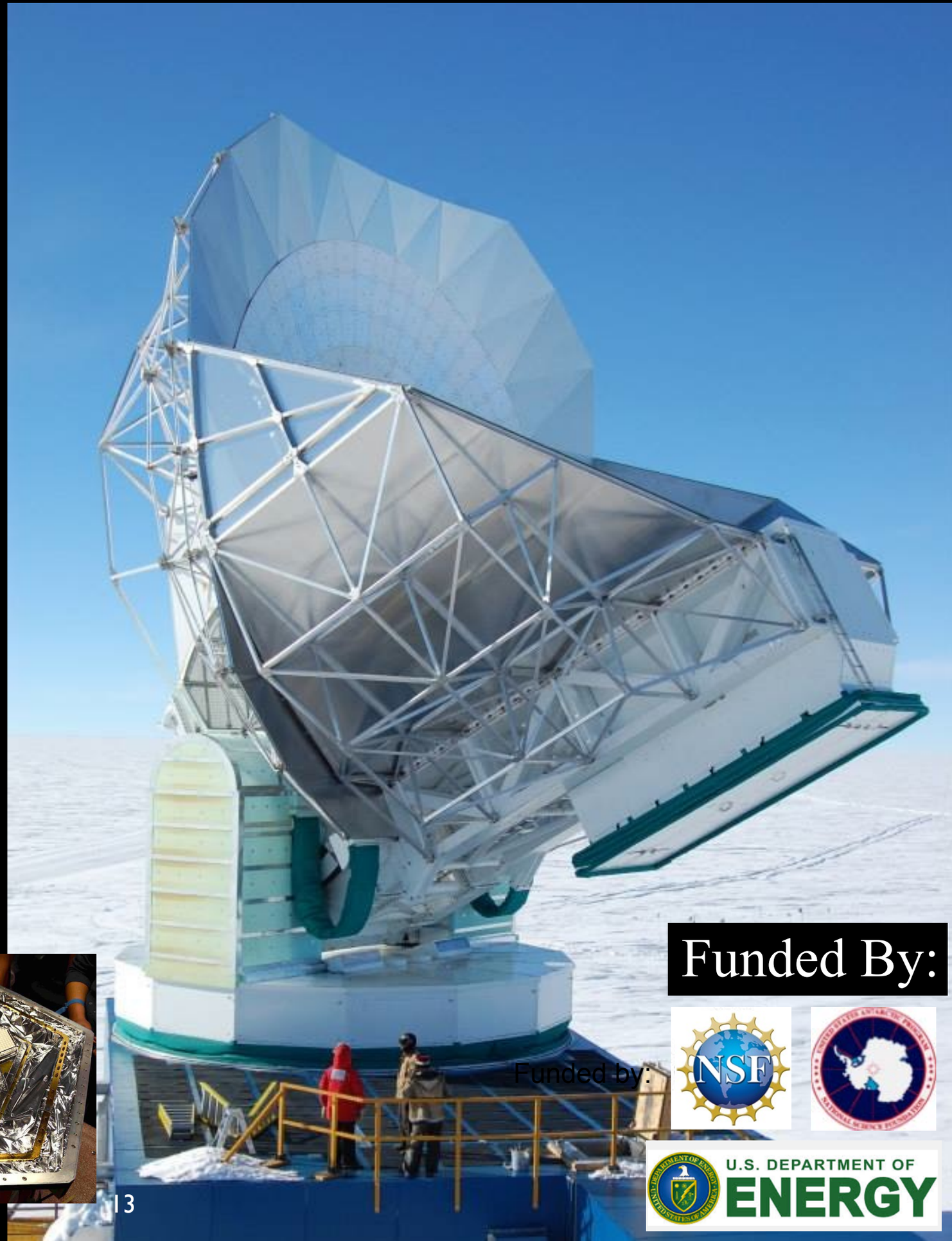


2012: SPTpol
1600 detectors
90,150 GHz
+Polarization



2017: SPT-3G
~15,200 detectors
90,150,220 GHz
+Polarization

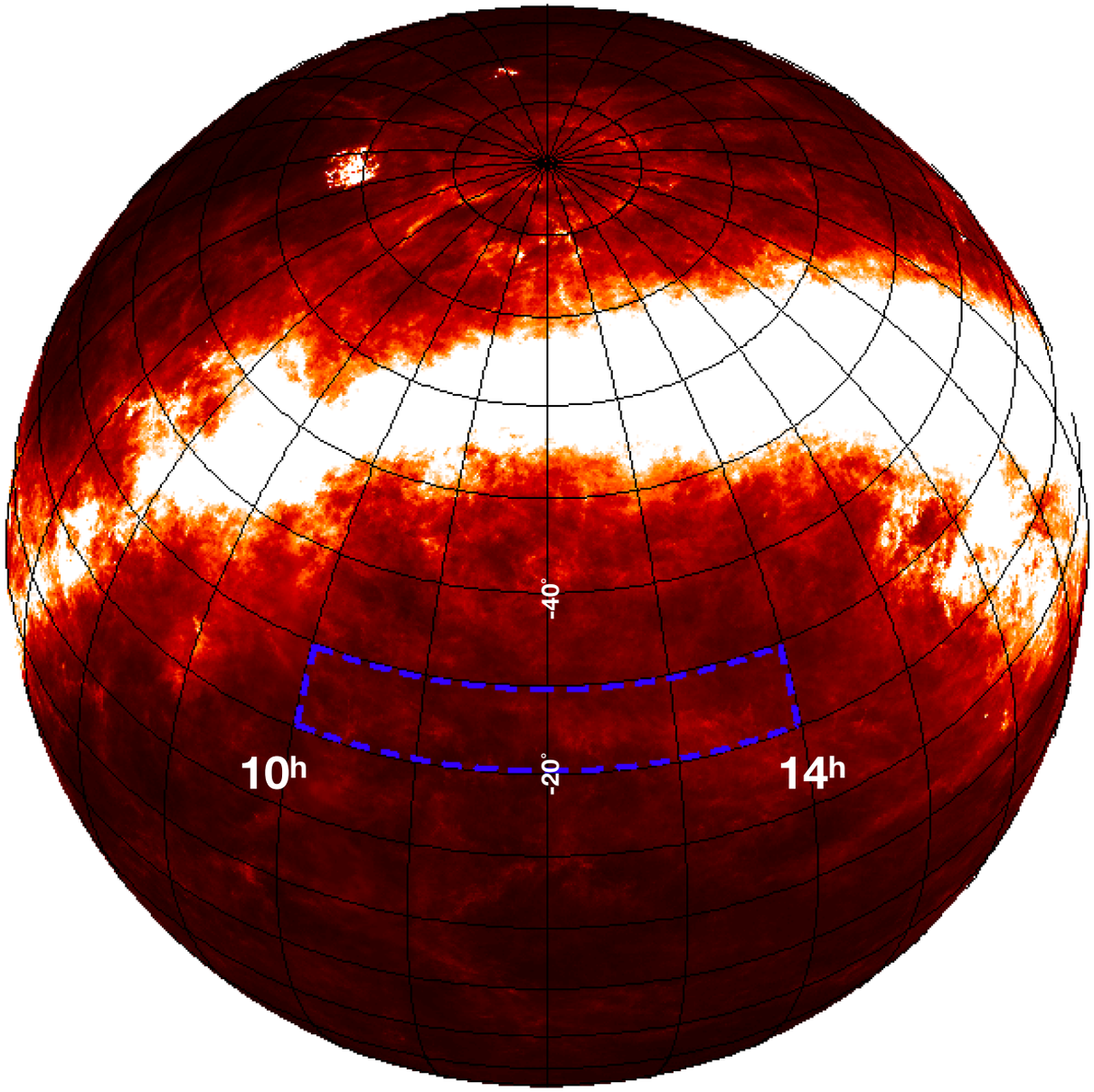


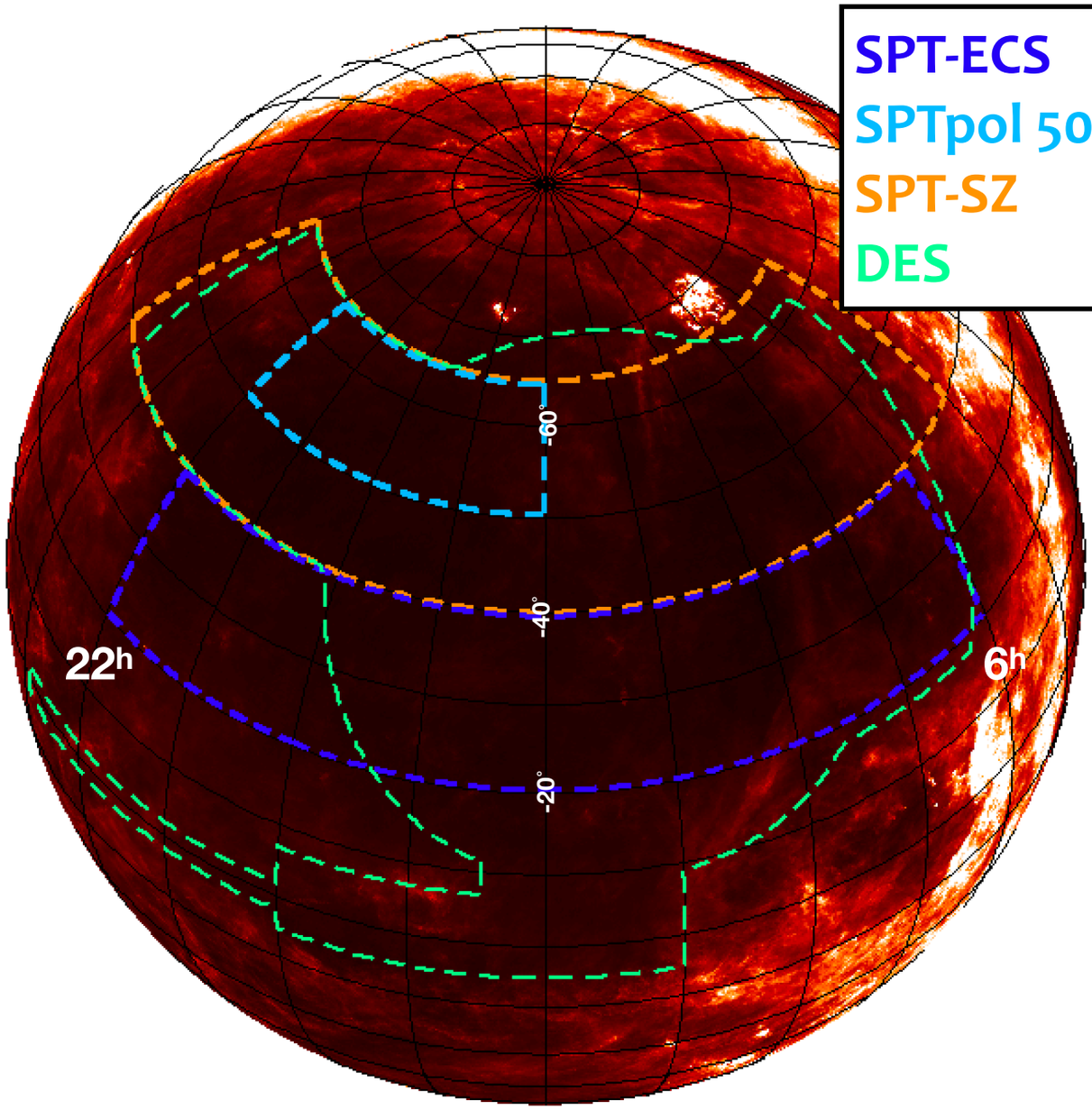


Funded By:

Funded by:

SPT-3G Collaboration





Survey	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**	**12**	**5**	**-**
SPTpol-Deep	2012-16	100	10	3.5	-
SPT-ECS	2012-16	**2770**	**47**	**28**	-

Planck

143 GHz

50 deg²

2x finer angular resolution WMAP

7x deeper

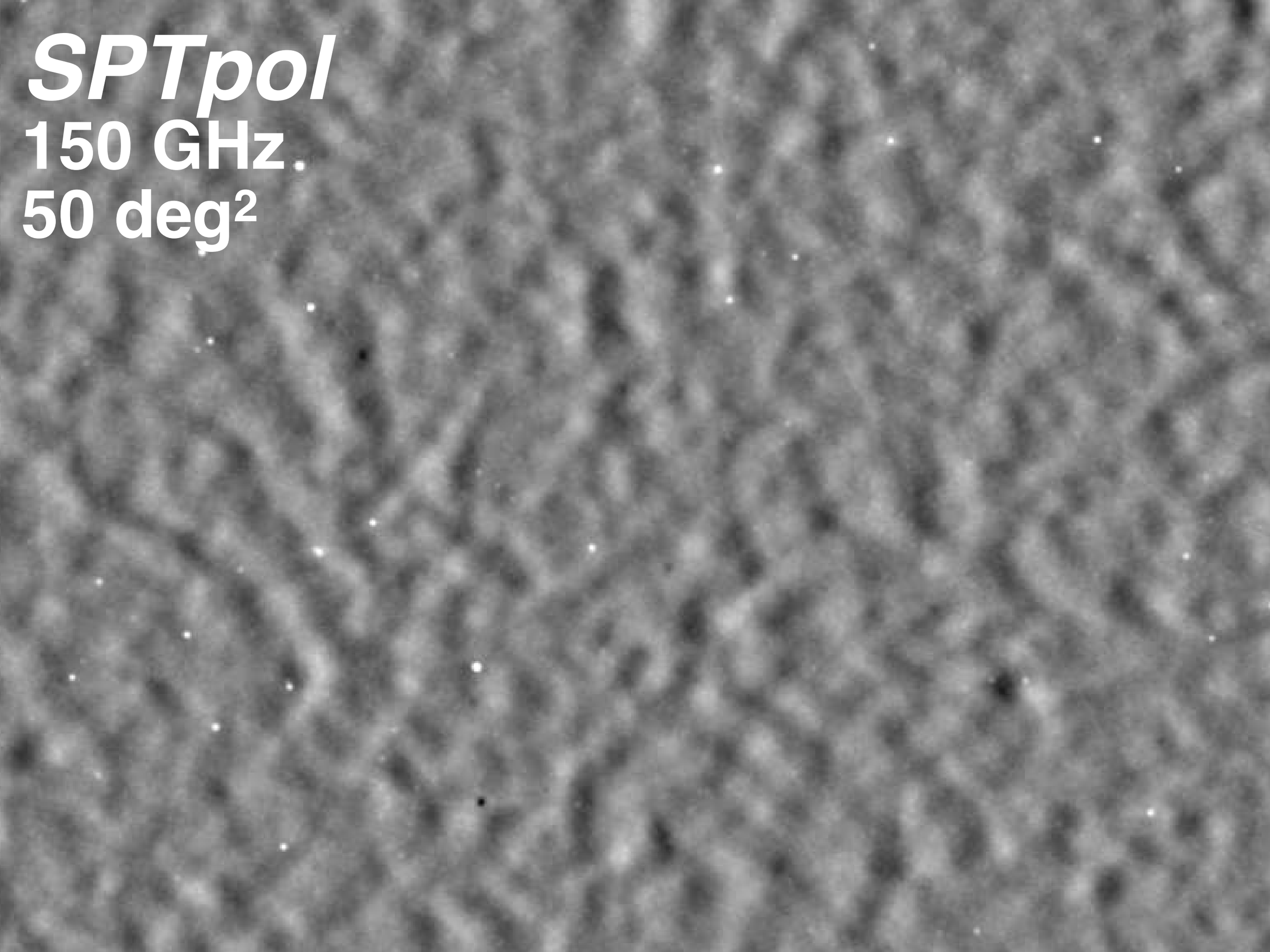
SPTpol

150 GHz

50 deg^2

6.5x finer angular resolution Planck

5x deeper


SPTpol
150 GHz
50 deg²

SPTpol
150 GHz
50 deg^2

CMB Anisotropy

Primordial and secondary anisotropy in the CMB

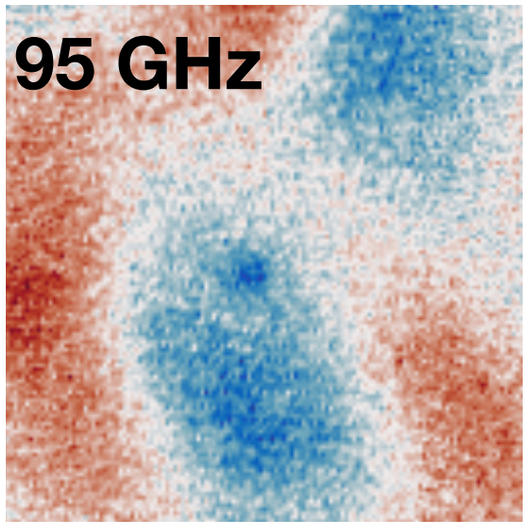
Point Sources

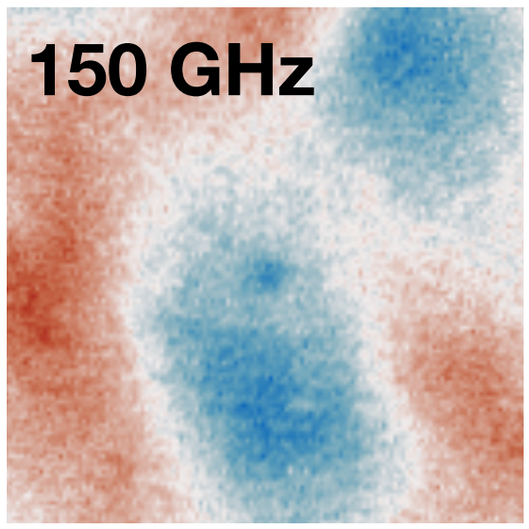
Active galactic nuclei, and the most distant, star-forming galaxies

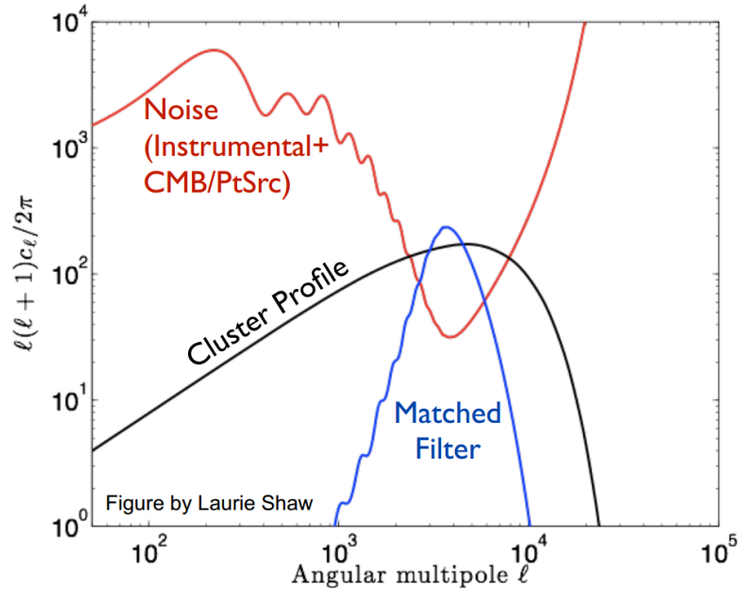
Clusters of Galaxies

"Shadows" in the microwave background from clusters of galaxies

Finding Clusters in SPT Surveys

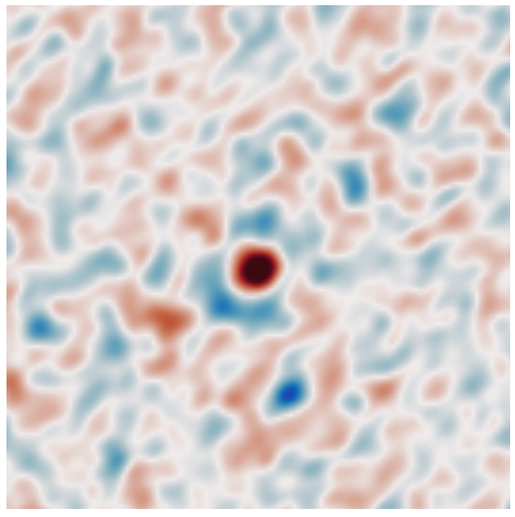






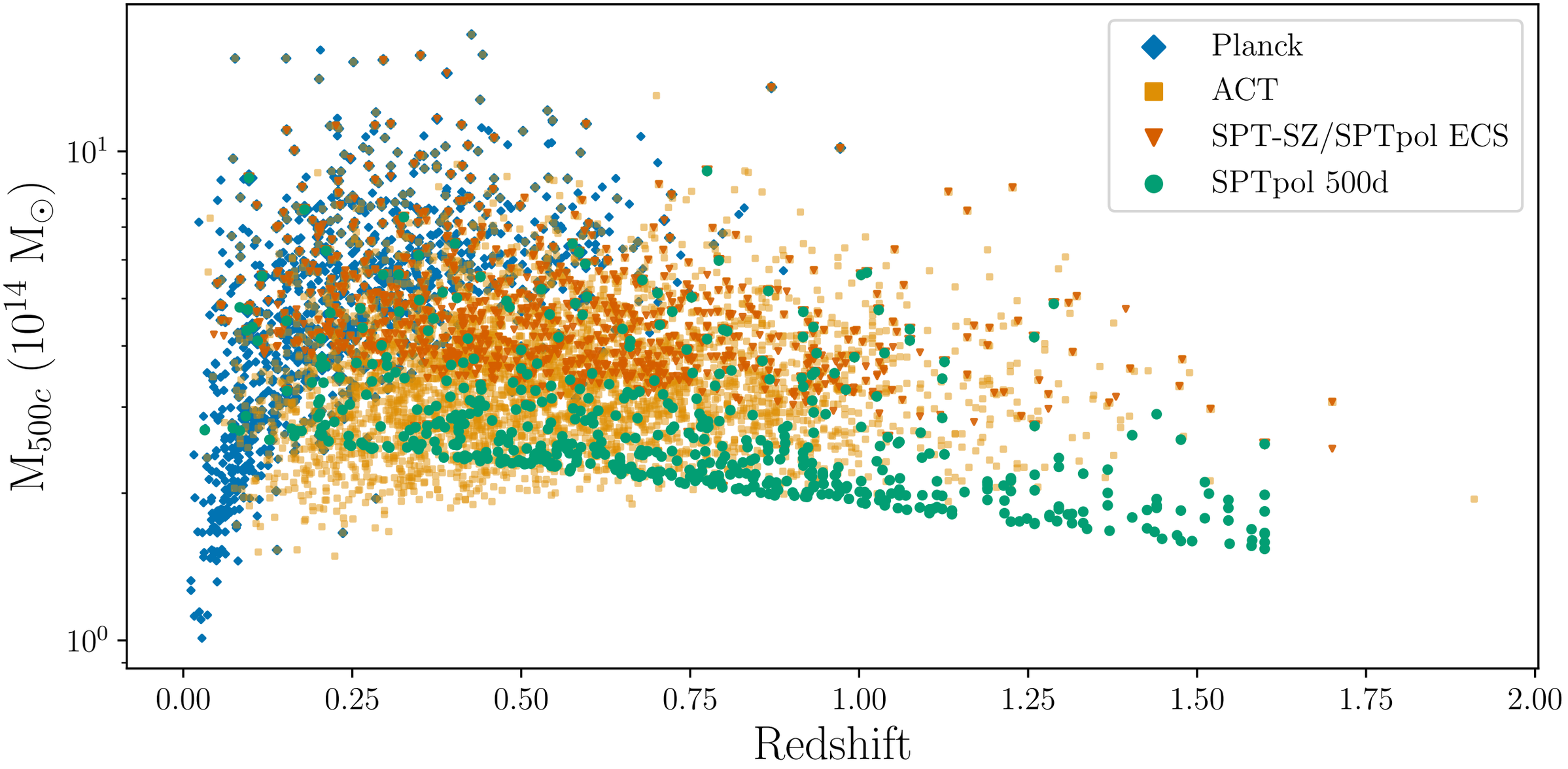
Matched Filter

$\xi = 12$ **Detection**



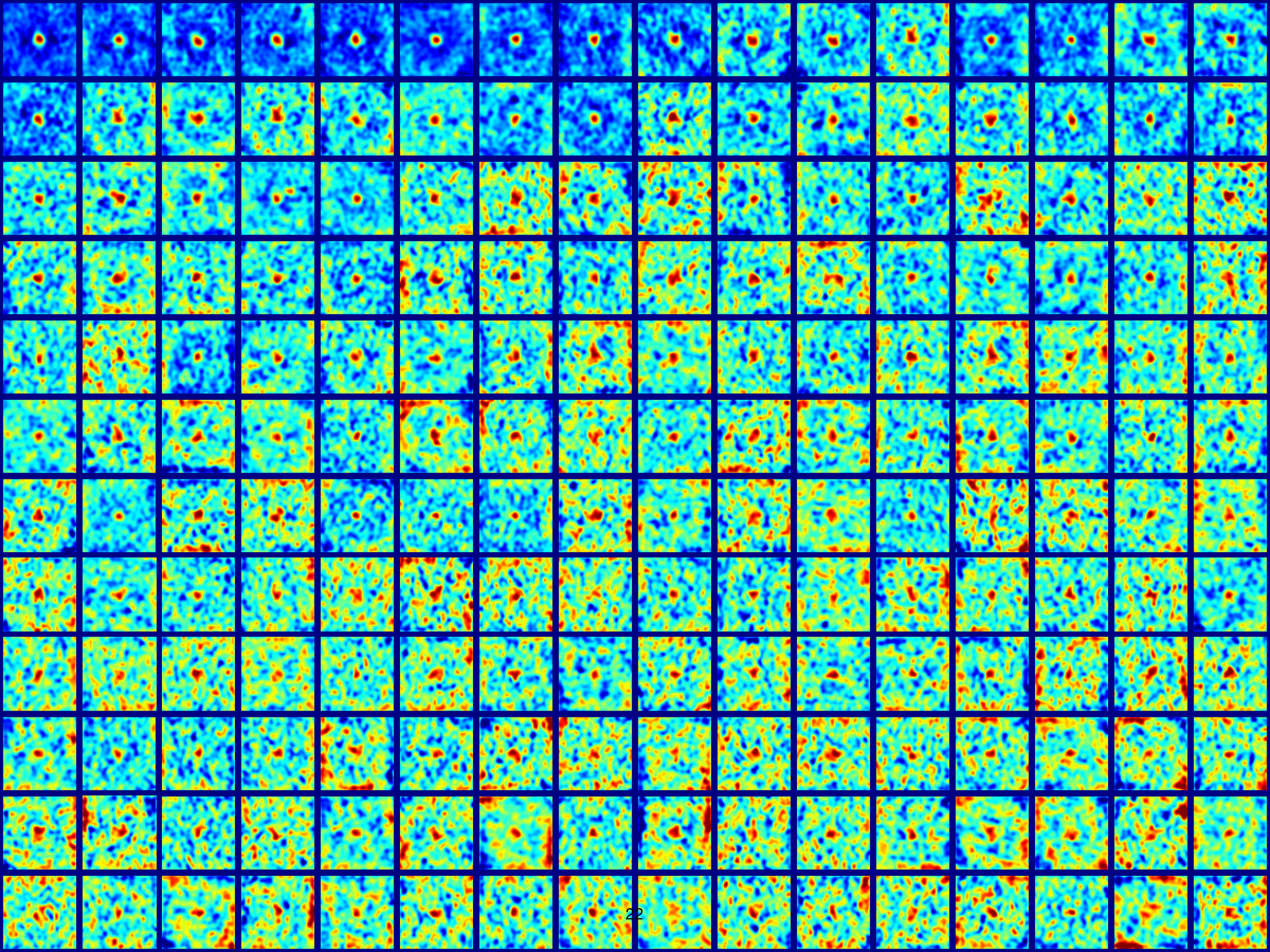
- Matched-filter multi-frequency cluster finder (Melin et al. 2006)

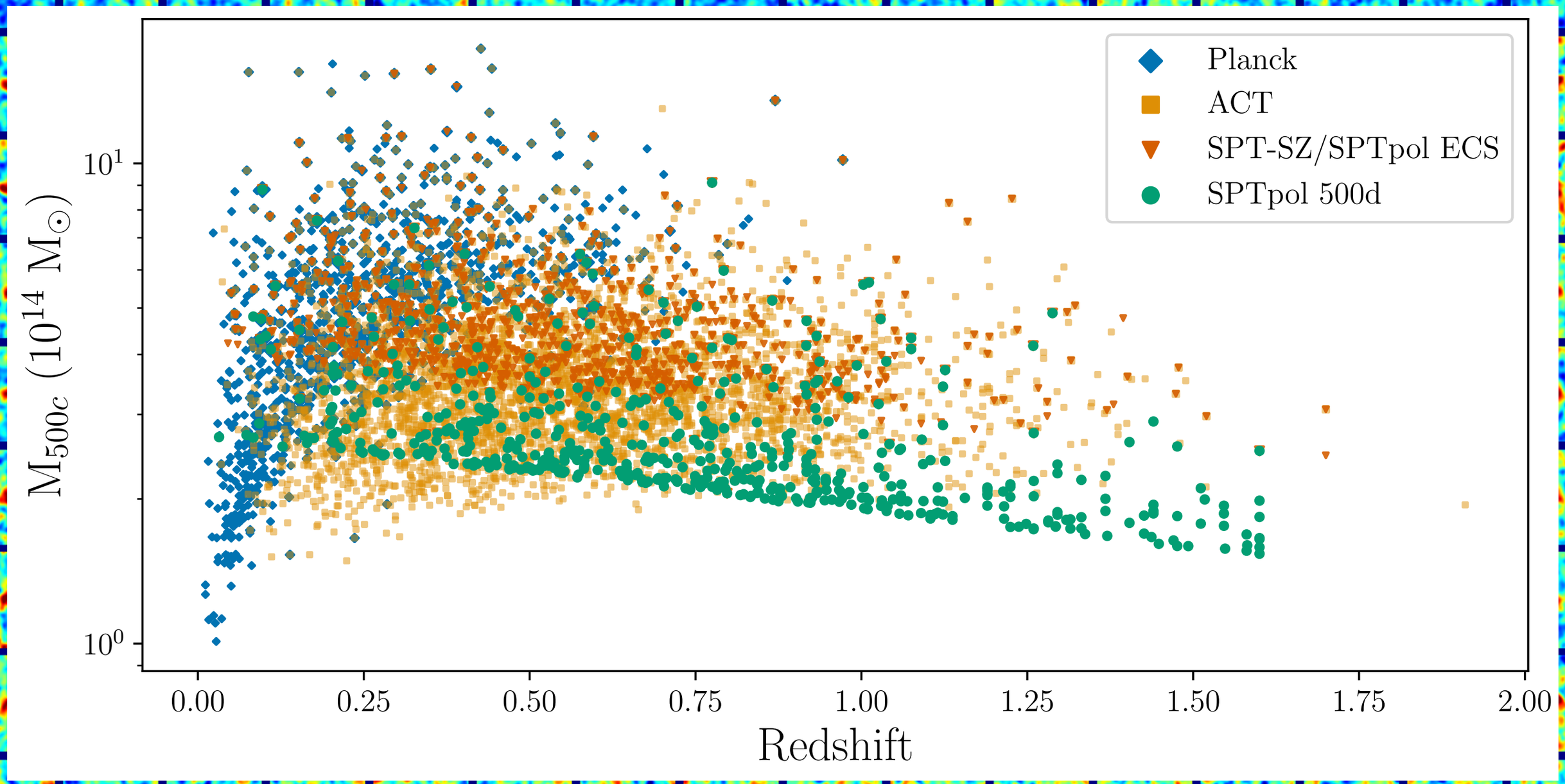
SPTpol 500d Cluster catalog



- 689 SZ candidates detected at ξ > 4
- 544 confirmed as galaxy clusters
- 115 at z>1 (21%)

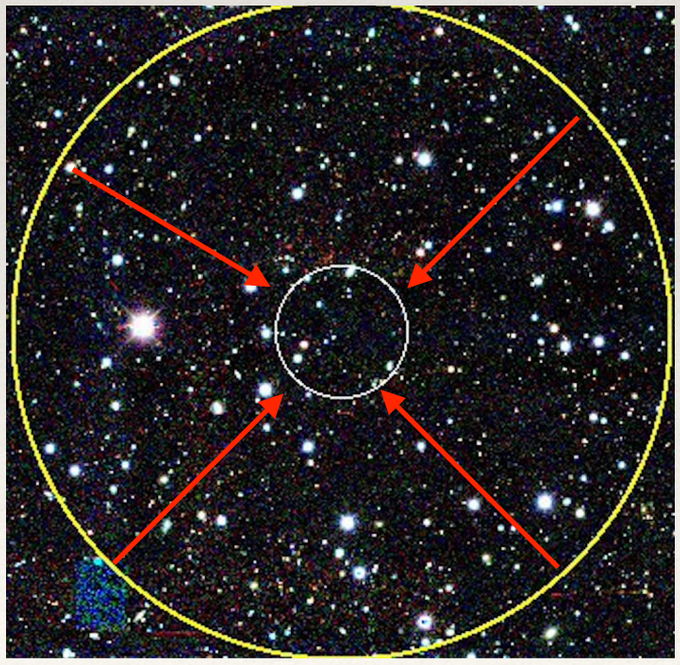
Bleem et al (in prep),
with M Klein, S Bocquet
and the SPTpol Collaboration

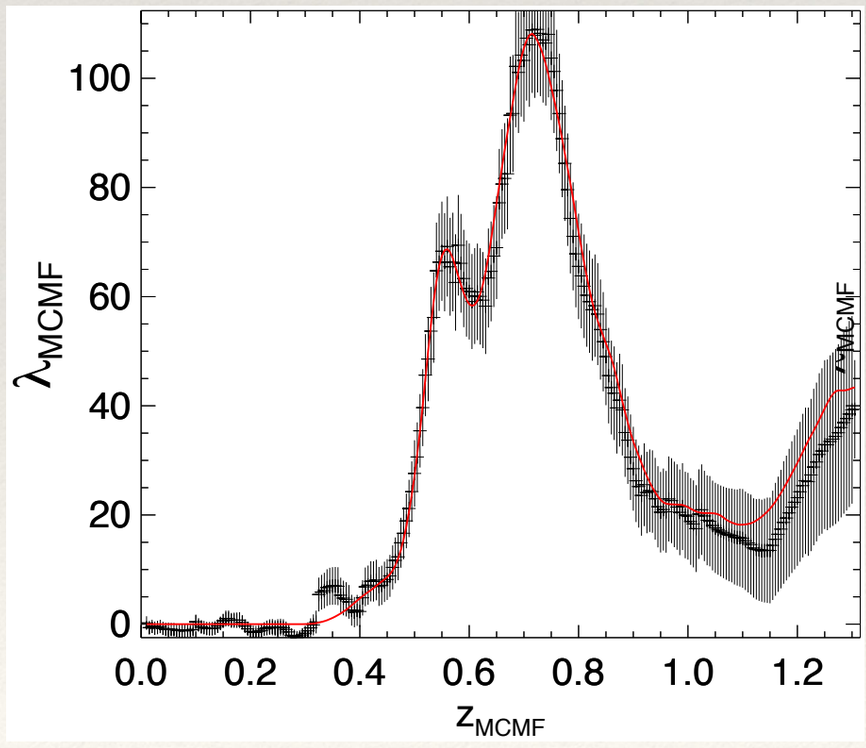


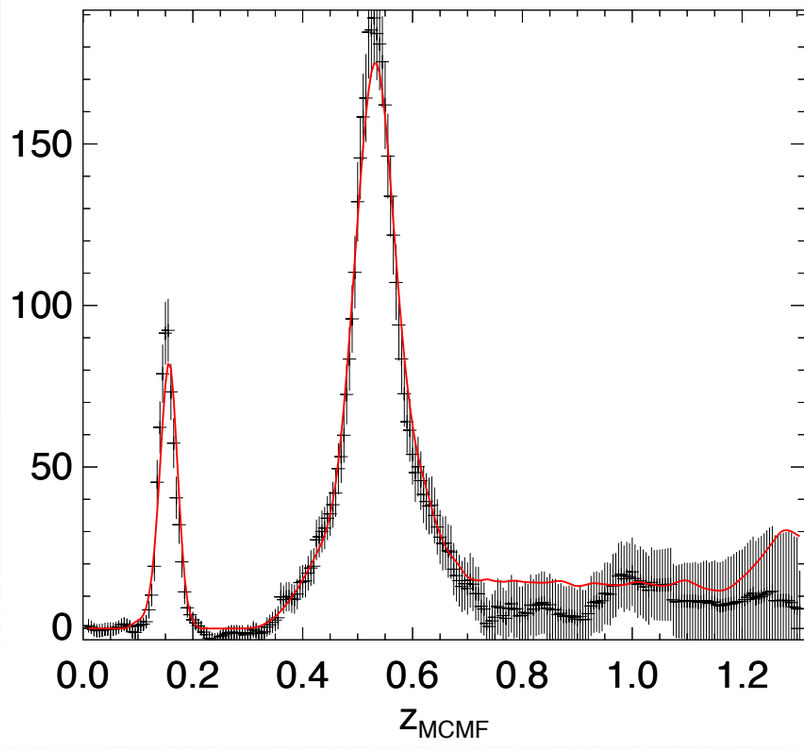

Planck
ACT
SPT-SZ/SPTpol ECS
SPTpol 500d
10^1
10^0
M_{500c} $(10^{14}$ $M_\odot)$
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
Redshift

Multi-Component Matched Filter (MCMF) cluster confirmation tool (Klein+18,19)

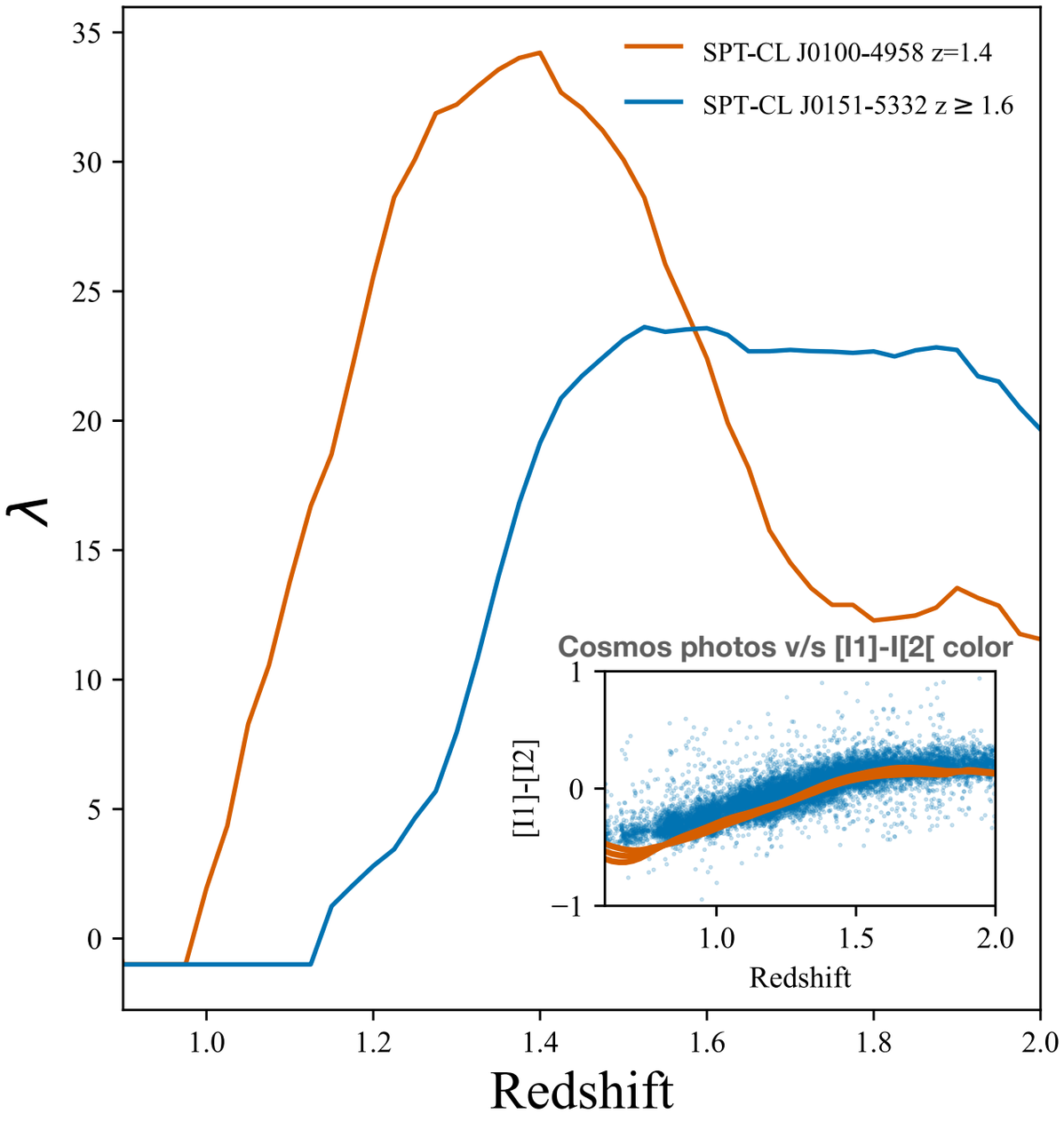
- uses **red-sequence** to obtain richness & redshift with DES *griz* data
- use ICM based information (flux, S/N) to obtain estimate of r_{500} given redshift
- scans through redshift and calculates richness within apertures of r_{500} around ICM based position
- peak identified and fit by calibrated peak profiles to get redshifts & richness of potential counter parts

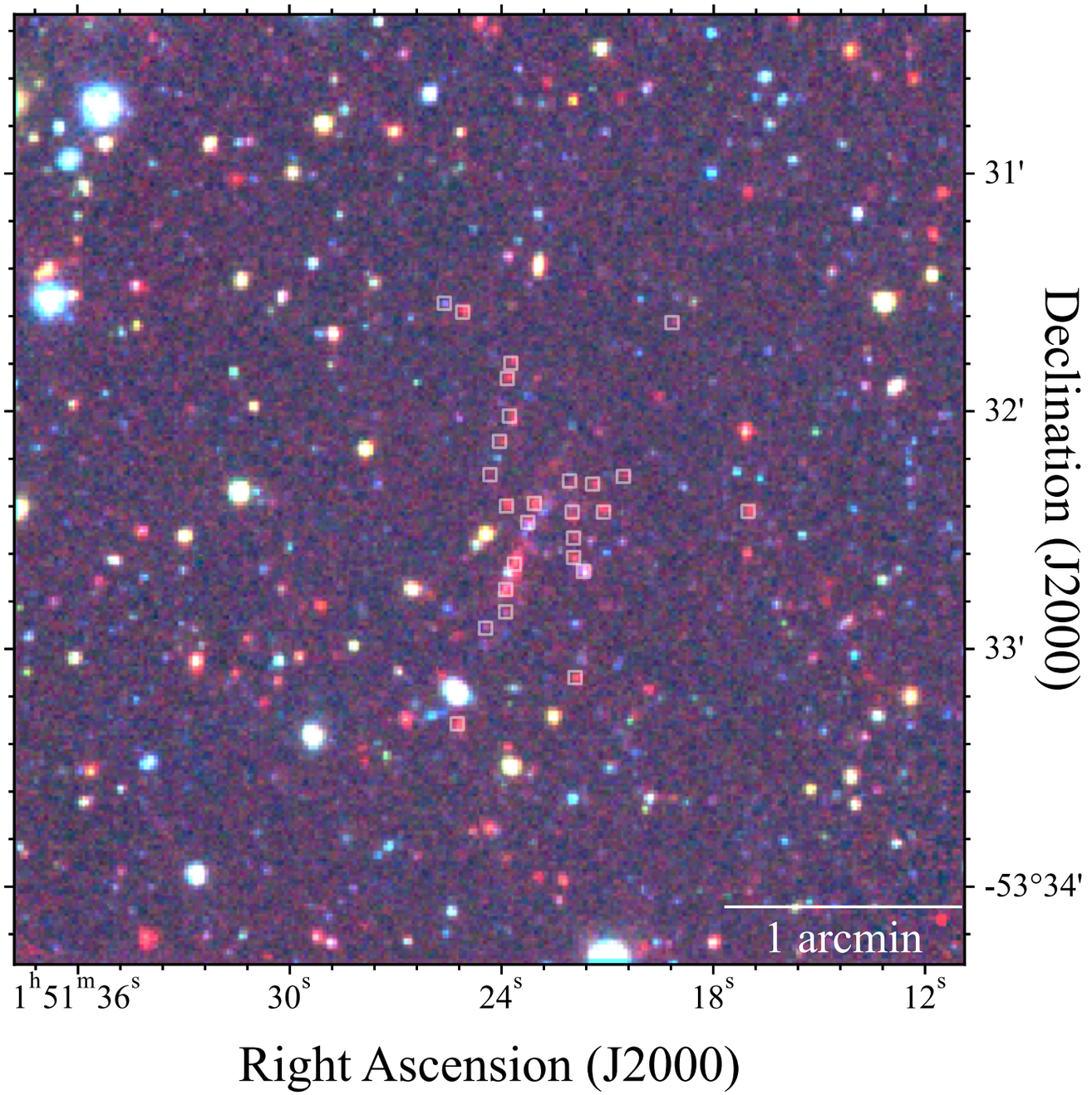


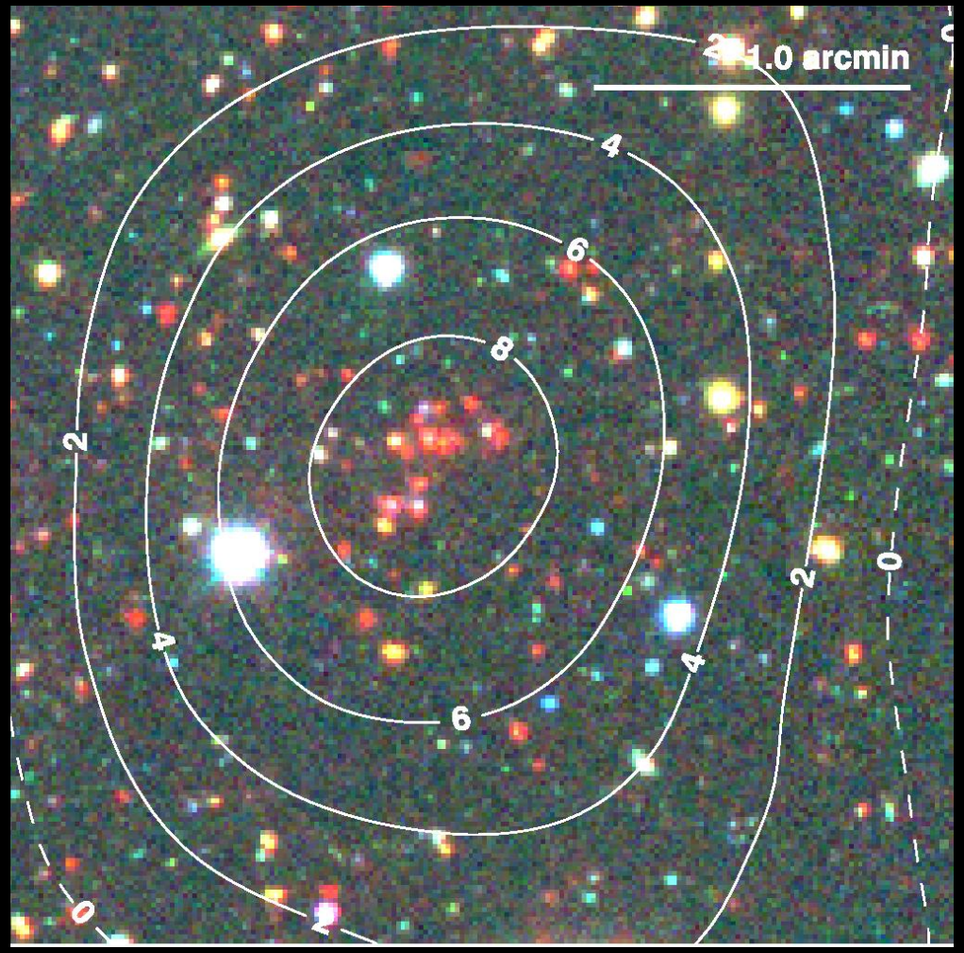


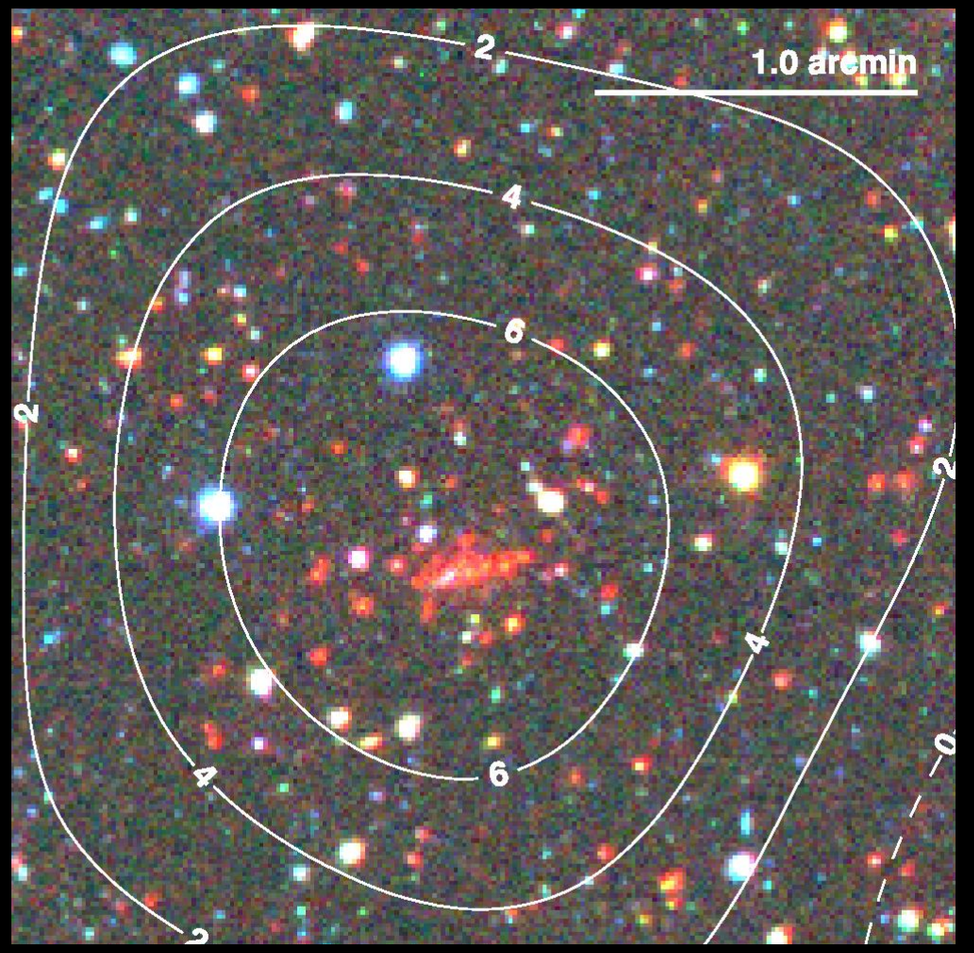


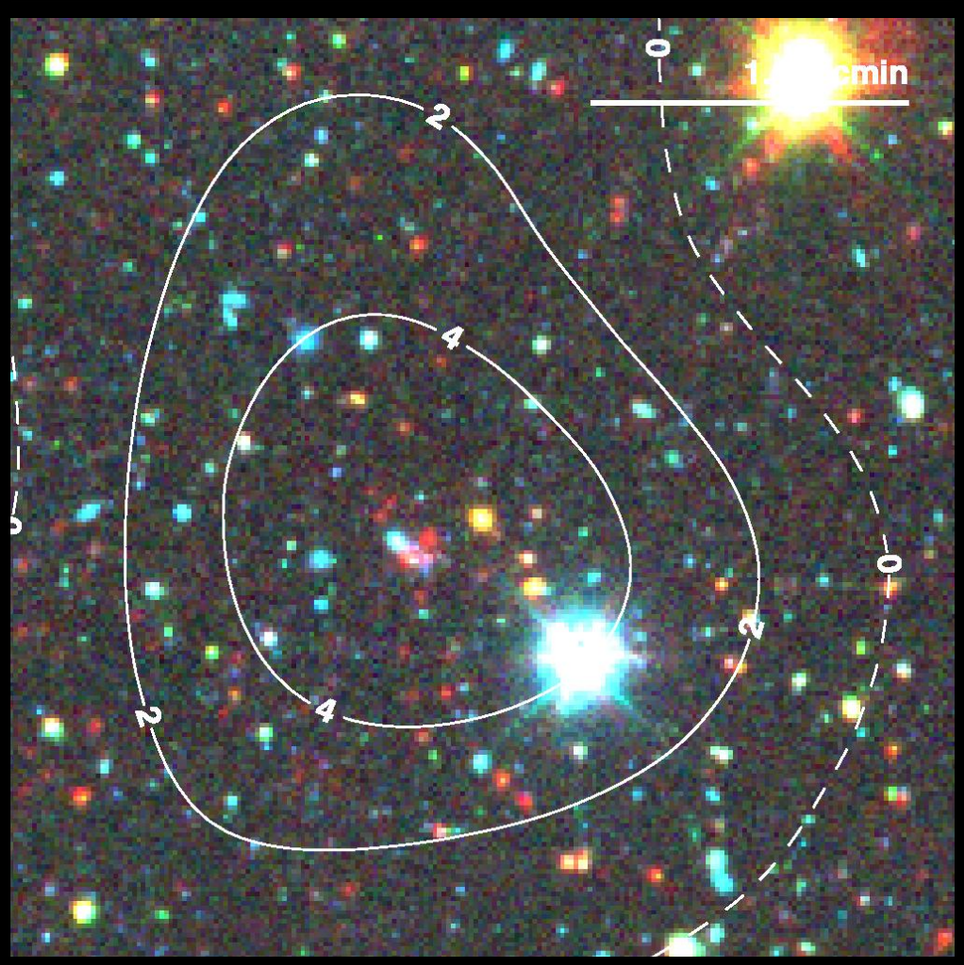
At high-redshifts we leverage the 1.6 μm stellar bump feature






1.0 arcmin


1.0 arcmin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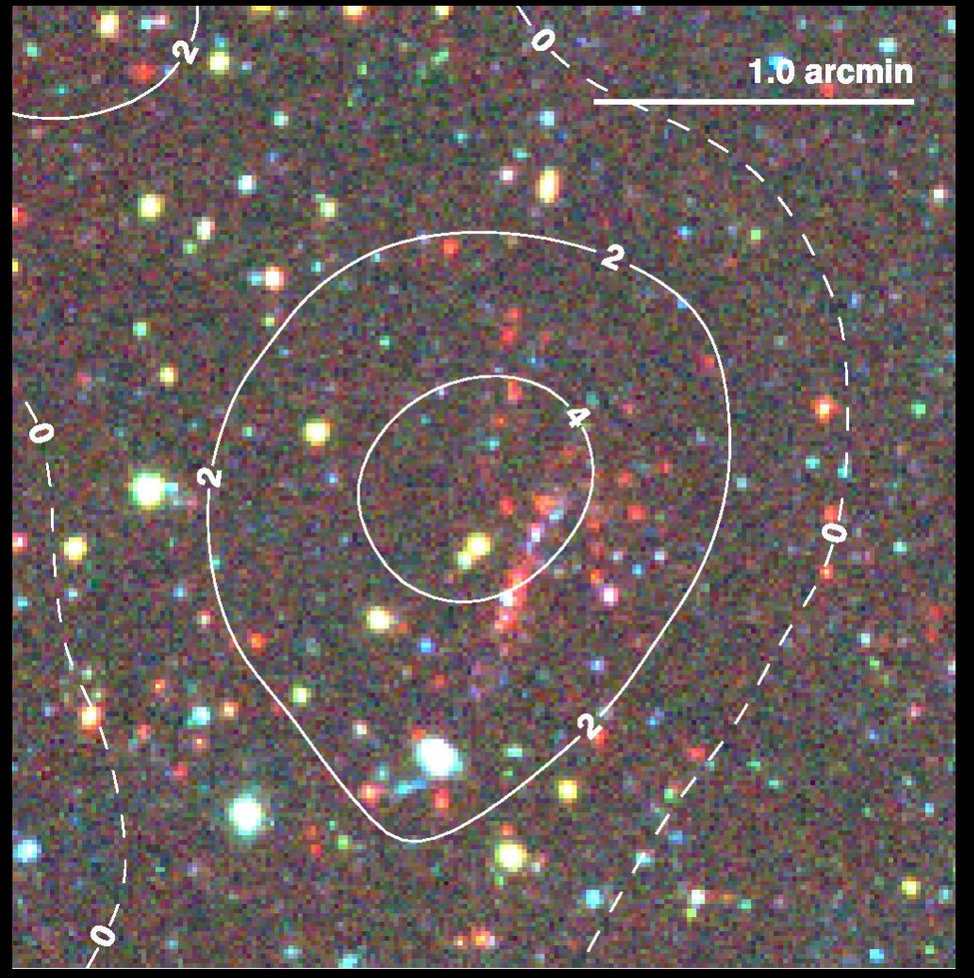
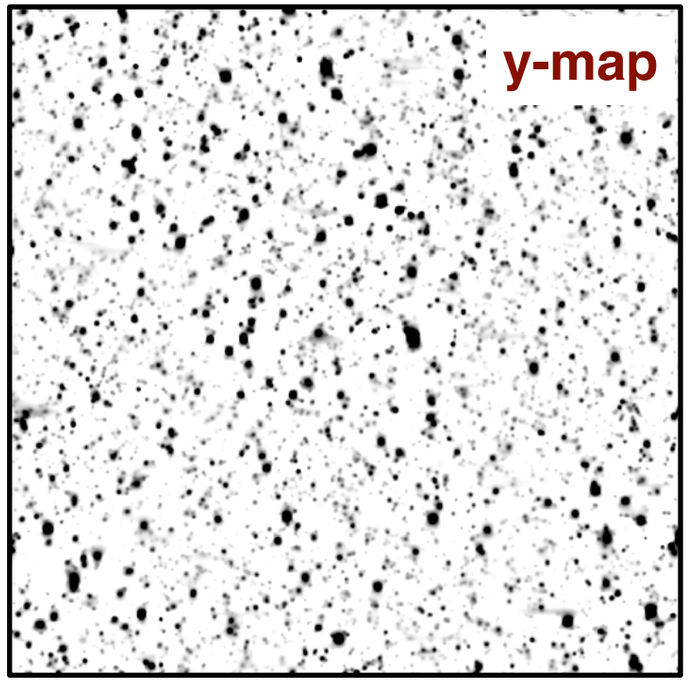
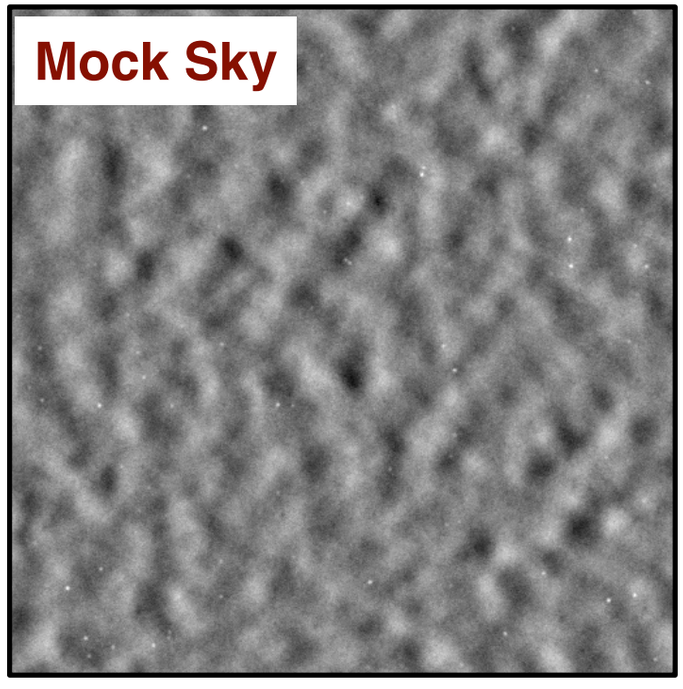
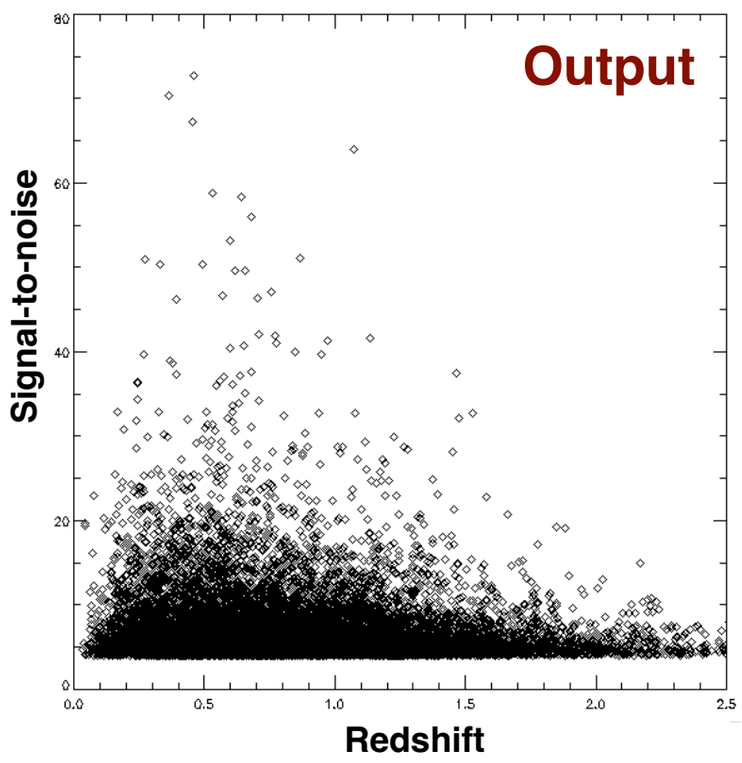

1.0 arcmin

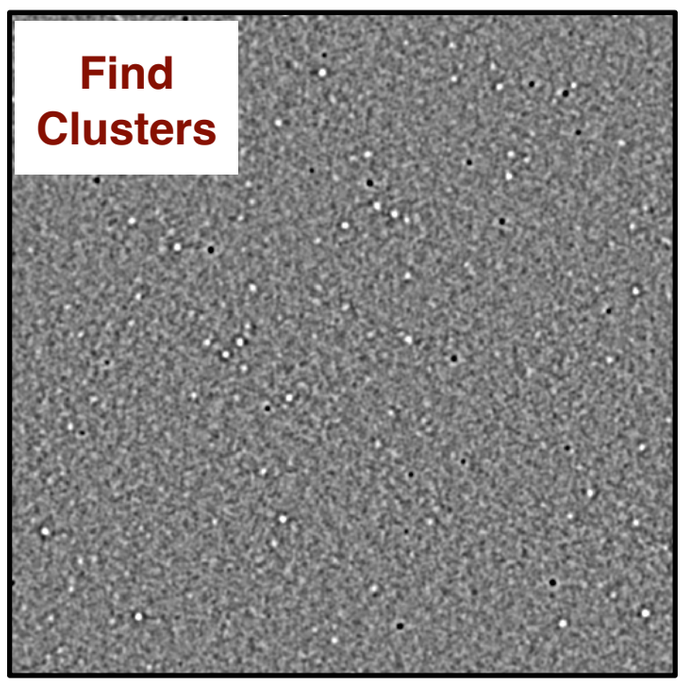
Simulation-based calibration

- Used to calibrate relative masses of SPT samples as well as to estimate sample purity.
- Based upon HACC OuterRim simulation; tSZ+kSZ added in post processing (with simplified "baryon-painting" of Flender+16 for tSZ)
- Instrumental noise models based on realized SPTpol performance at 90,150
- CMB, CIB, uncorrelated radio sources foreground power added to match observations
- In parallel development/analysis of other cluster observables:
  - Significantly refined baryon pasting
    - (**See F. Kéruzoré's talk Wednesday!**)
  - Optical Strong + Weak Lensing



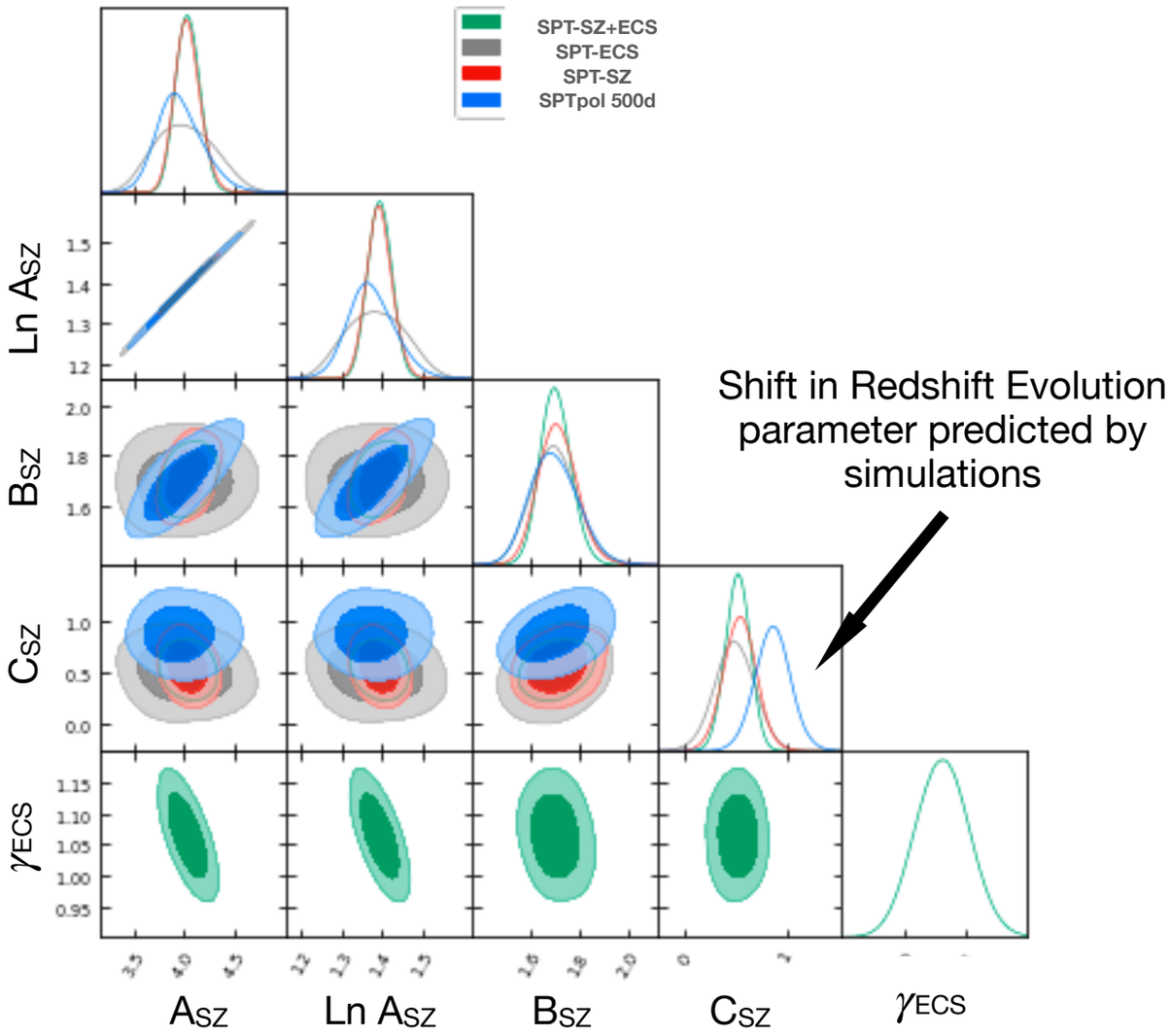




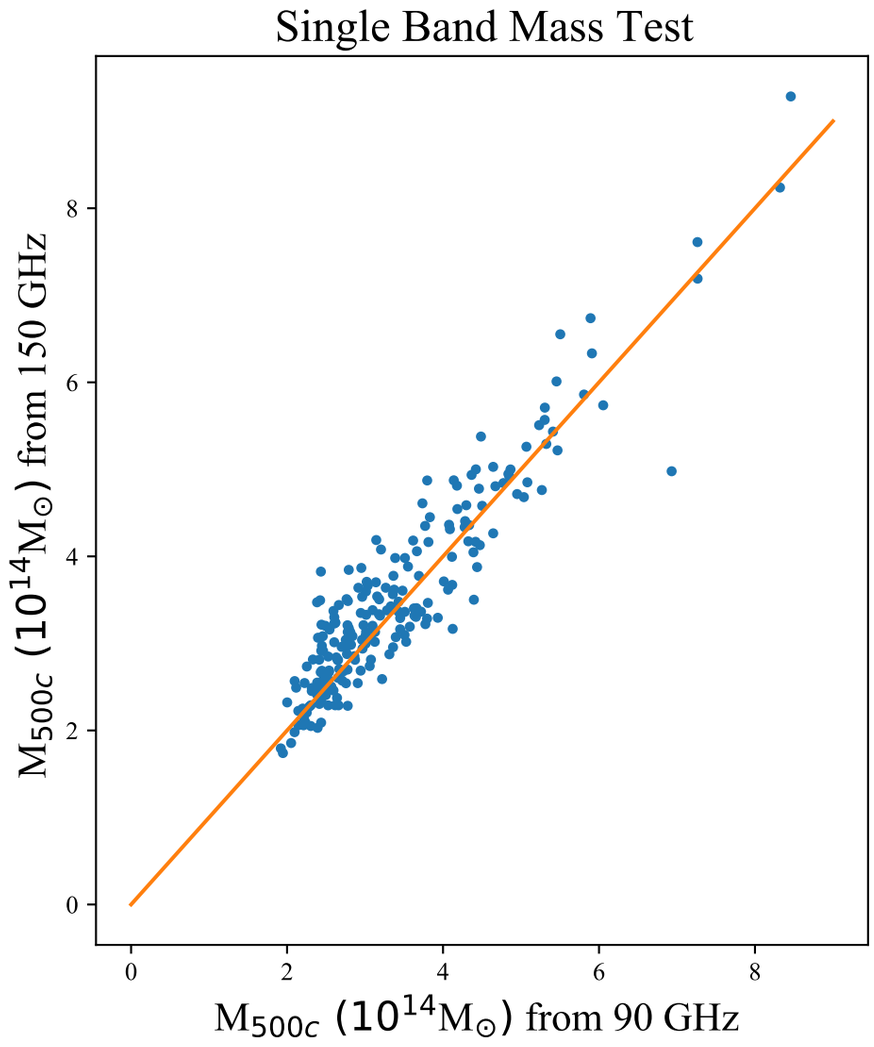


Results: Mass calibration (fixed cosmology)

$$\langle \ln \zeta \rangle = \ln\left[A_{\rm SZ}\left(\frac{M_{500c}}{3\times10^{14}M_{\odot}h^{-1}}\right)^{B_{\rm SZ}}\left(\frac{H(z)}{H(0.6)}\right)^{C_{\rm SZ}}\right] \qquad P(\xi|\zeta) = \mathcal{N}(\sqrt{\zeta^2+3},1)$$

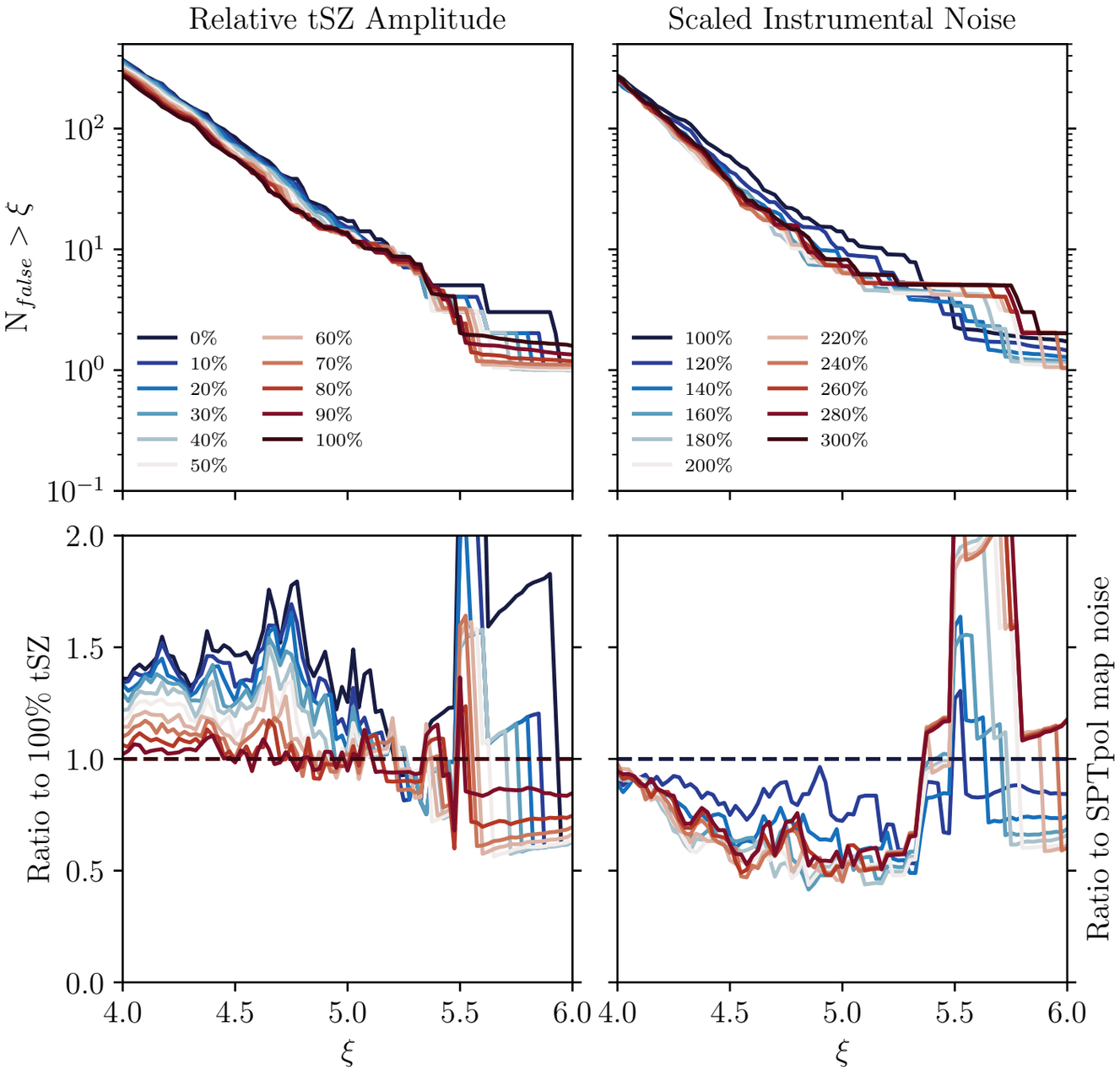


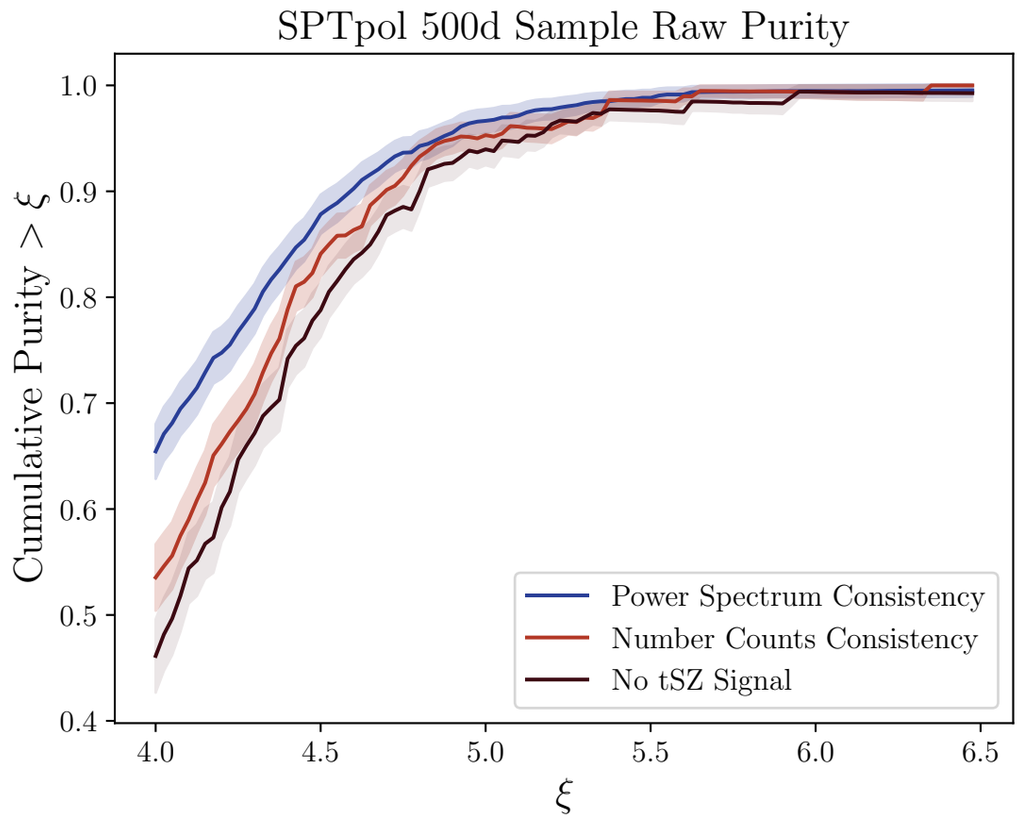
Excellent Consistency between Mass-ζ Scaling relation at fixed cosmology across SPT surveys



Excellent Consistency between Masses derived from 90 and 150 GHz cluster searches alone (221 clusters)

Results: Sample Purity

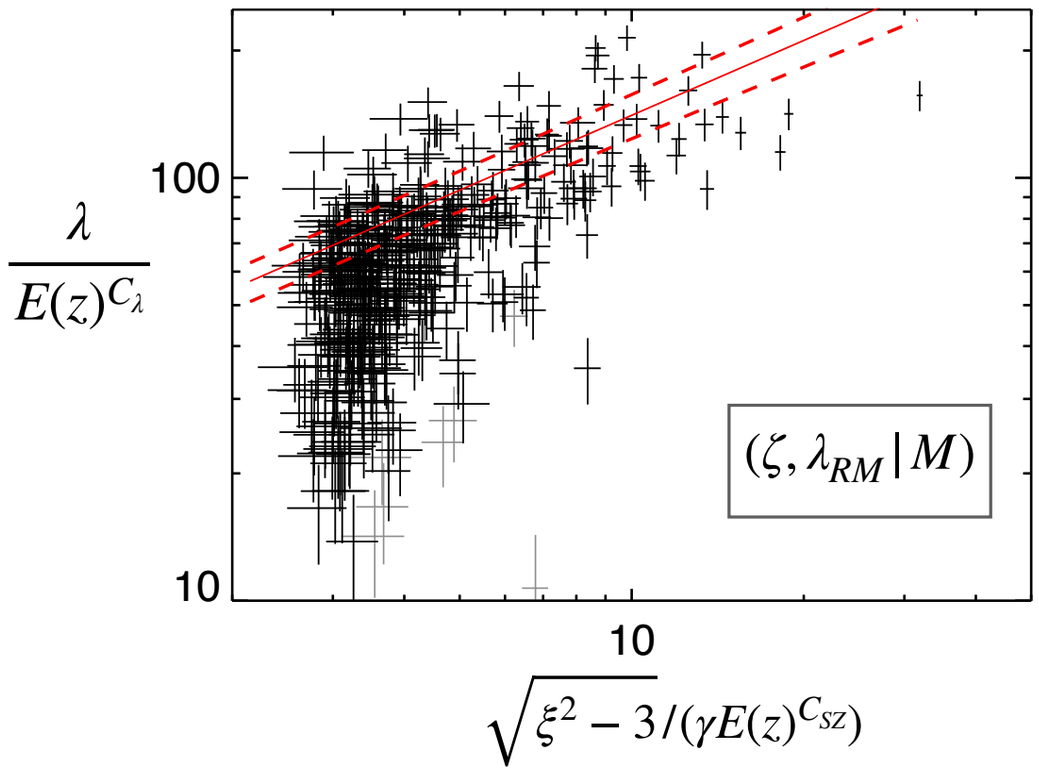


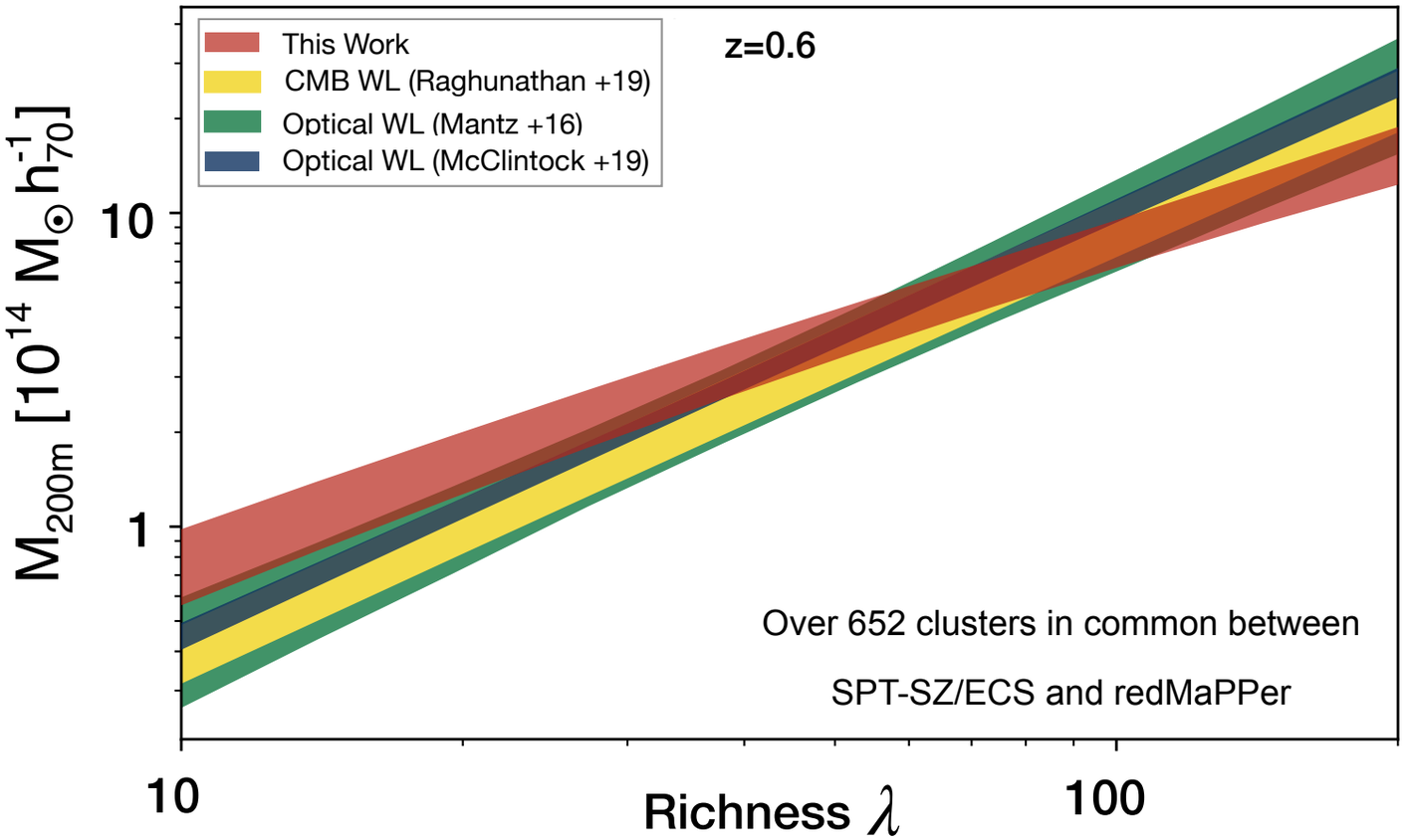


As the instrumental noise drops, and foregrounds + tSZ signal become more important in the total noise sum important to properly includes these signals in map-based purity simulations to capture non Gaussian components of these signals.

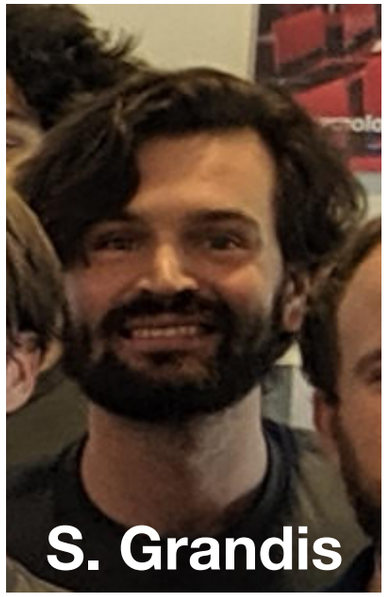
Comparisons across wavelength provide powerful tests of systematics control.

Bleem et al. ApJS 247,25, 2020

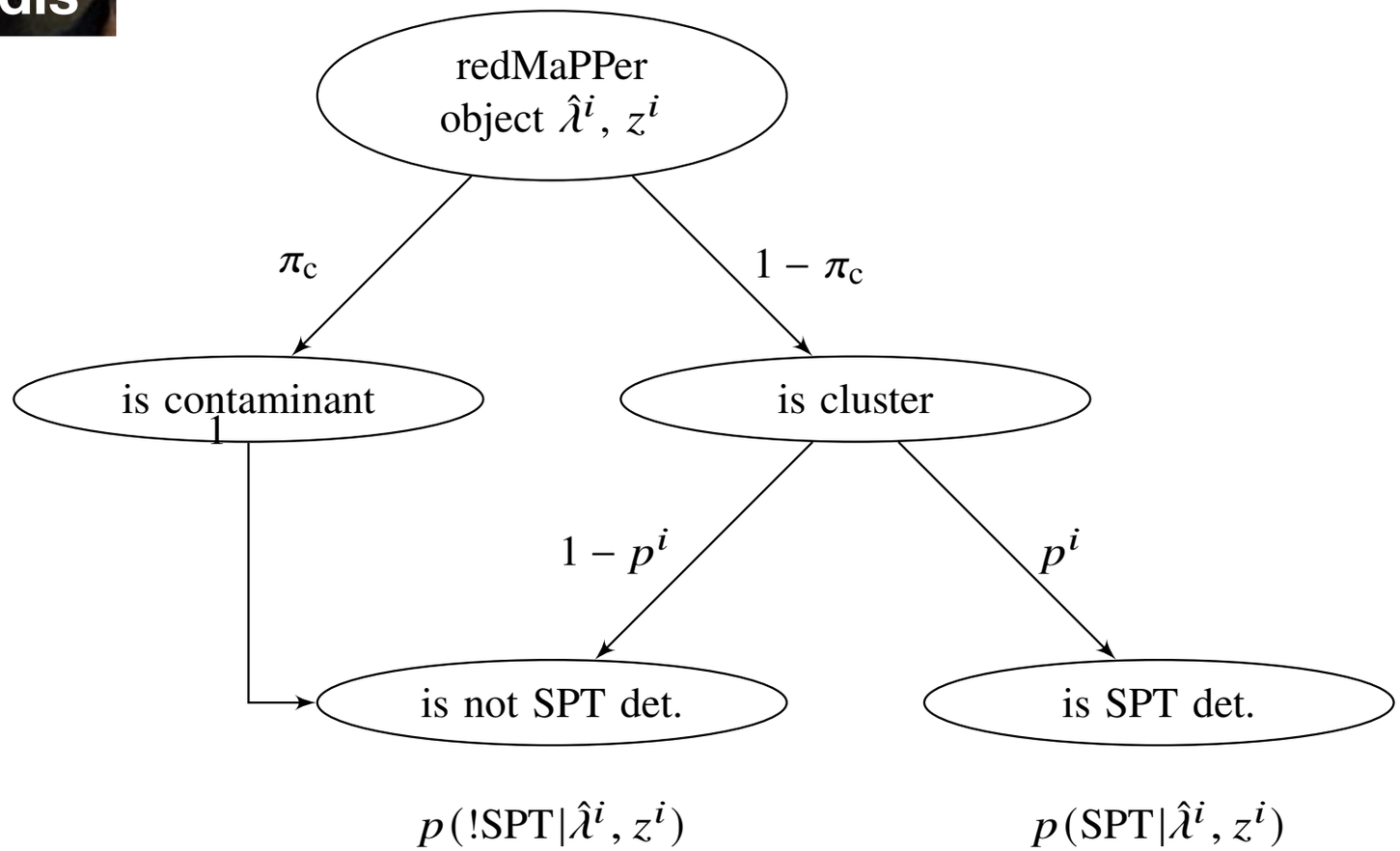


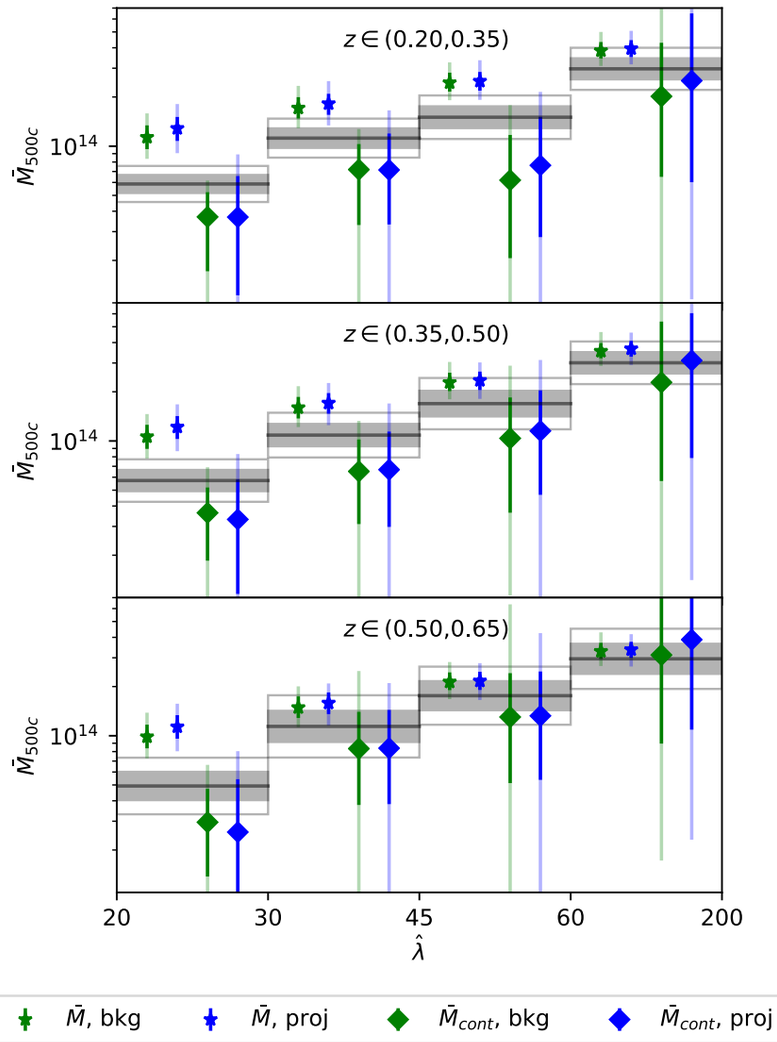


4 σ tension between the slope of the Mass-Richness Relation inferred from SPT calibration versus optical weak lensing



Modeling the composition of the redMaPPer Sample



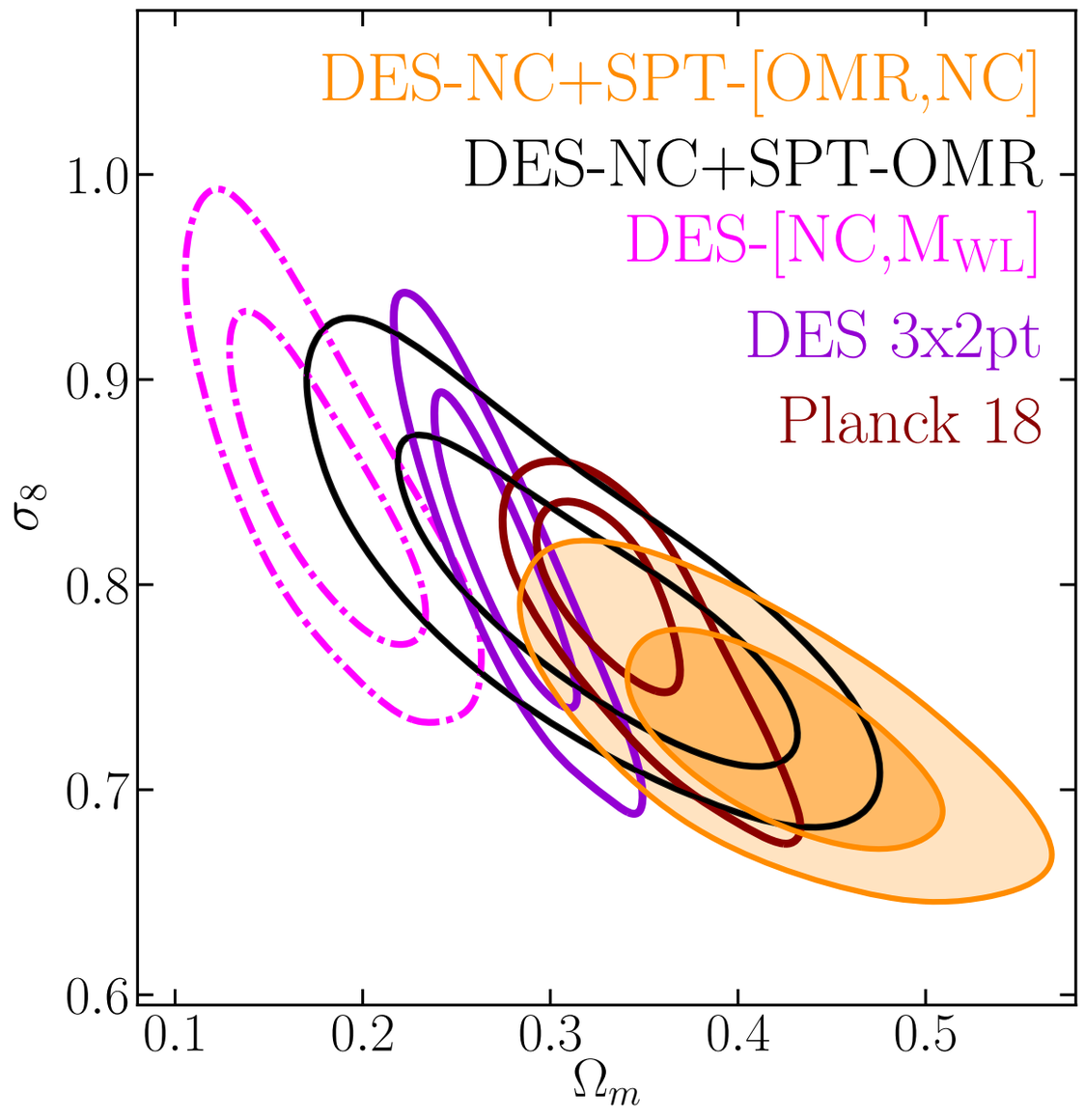


Using the Matched SPT-RM sample can explore the fractional contamination of the optically-selected cluster sample by correlated structures along the line-of-sight

Grandis et al. MNRAS 504, 1253G (2021)

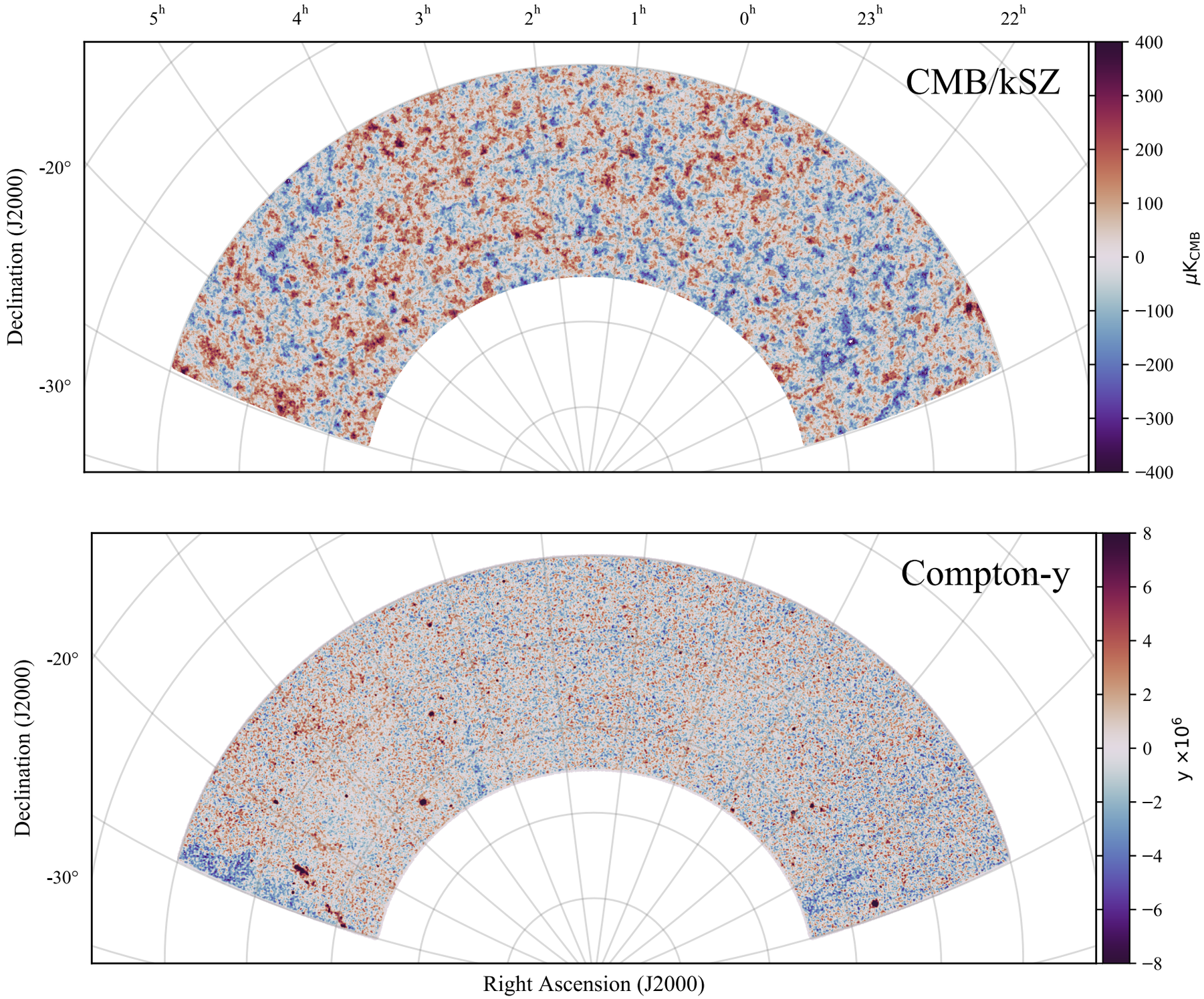
Joint SPT-DES Analyses enable robust cosmological constraints.

M. Costanzi



Costanzi et al Phys RevD, 103, 043522 (2021)
DES Collaboration Phys RevD, 102, 023509 (2020)

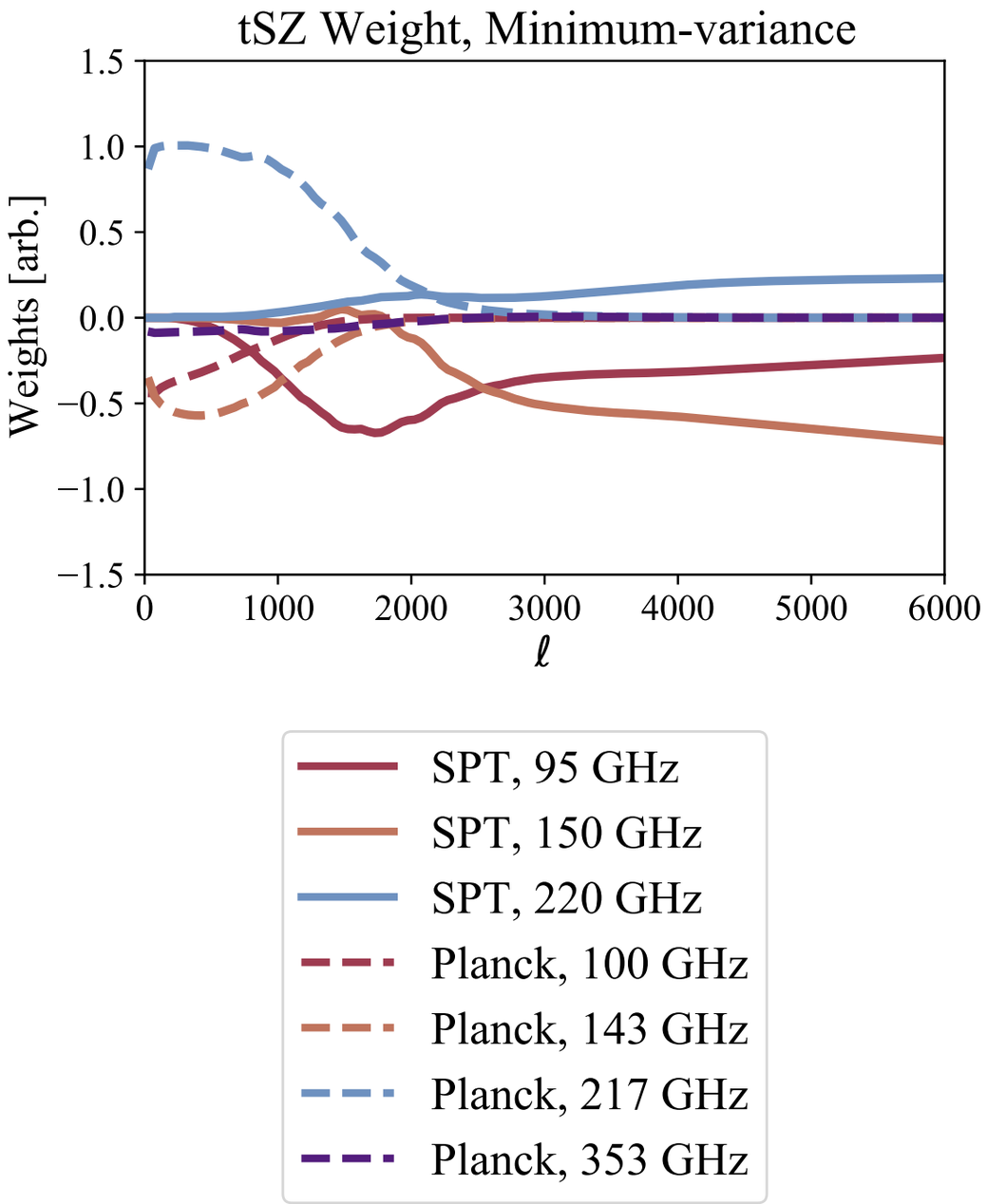
Multifrequency CMB Data can be Combined to Isolate Cluster Signals

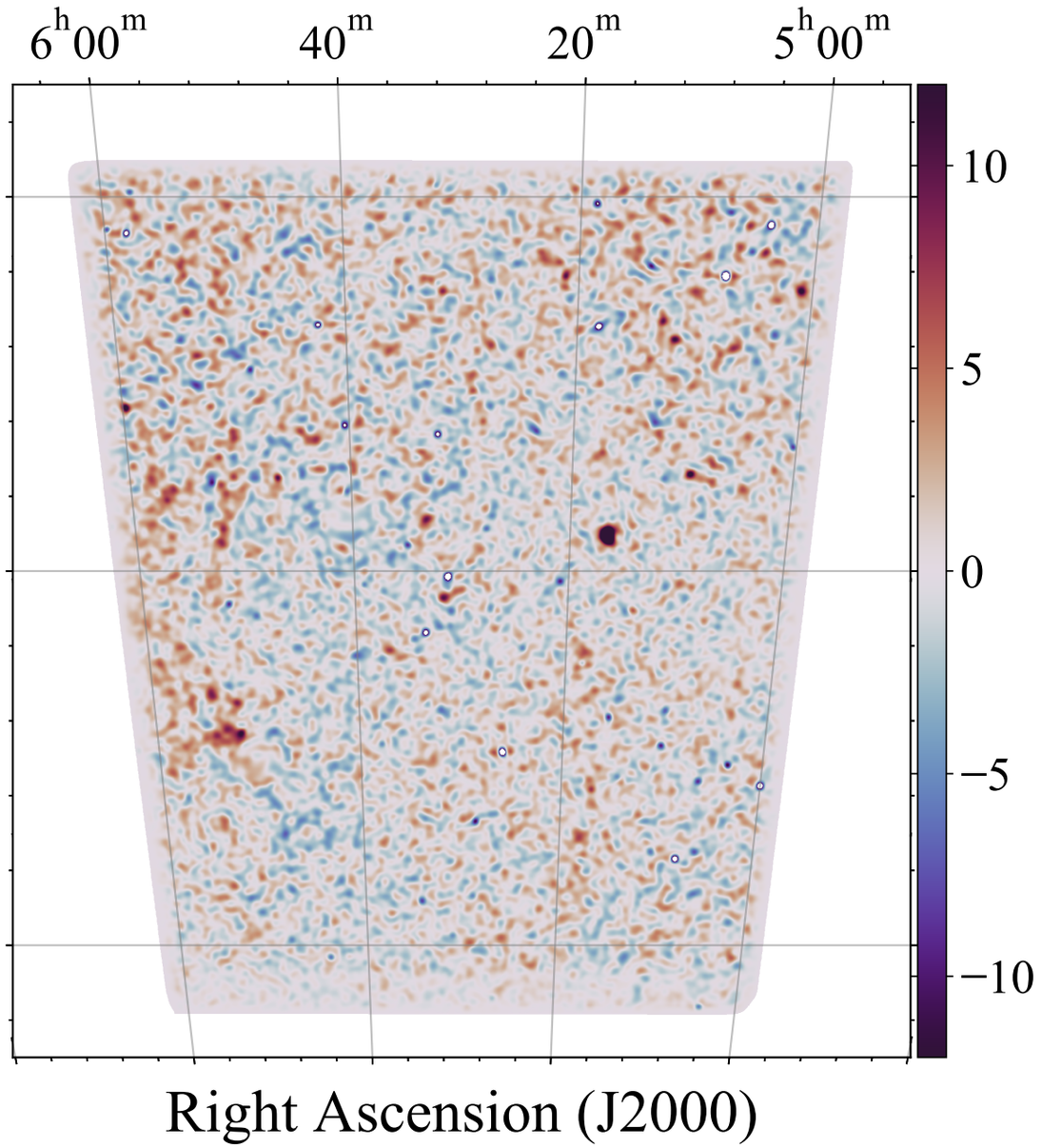


Combined analysis of SPT + Planck data to isolate both CMB and SZ signals

Bleem+ ApJ 258, 36B (2022)

Multifrequency CMB Data can be Combined to Isolate Cluster Signals



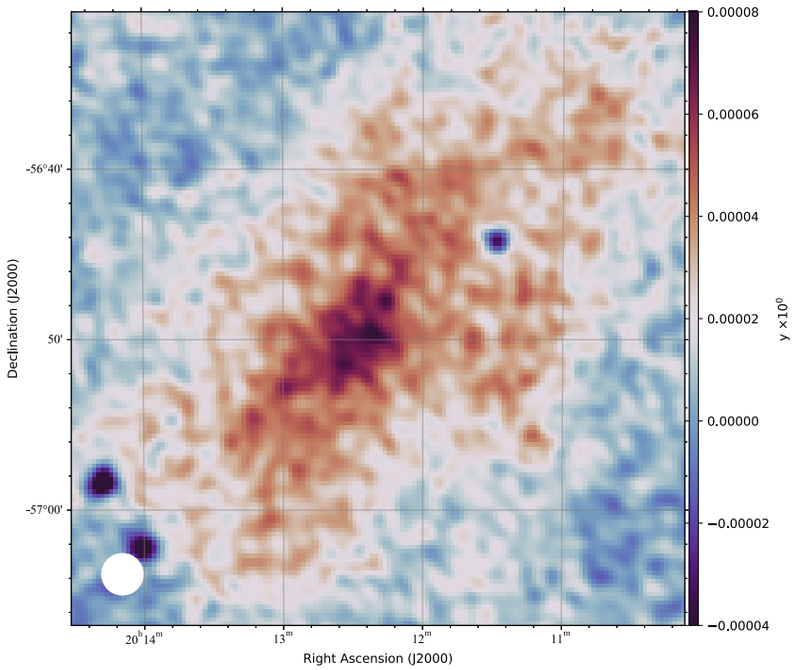


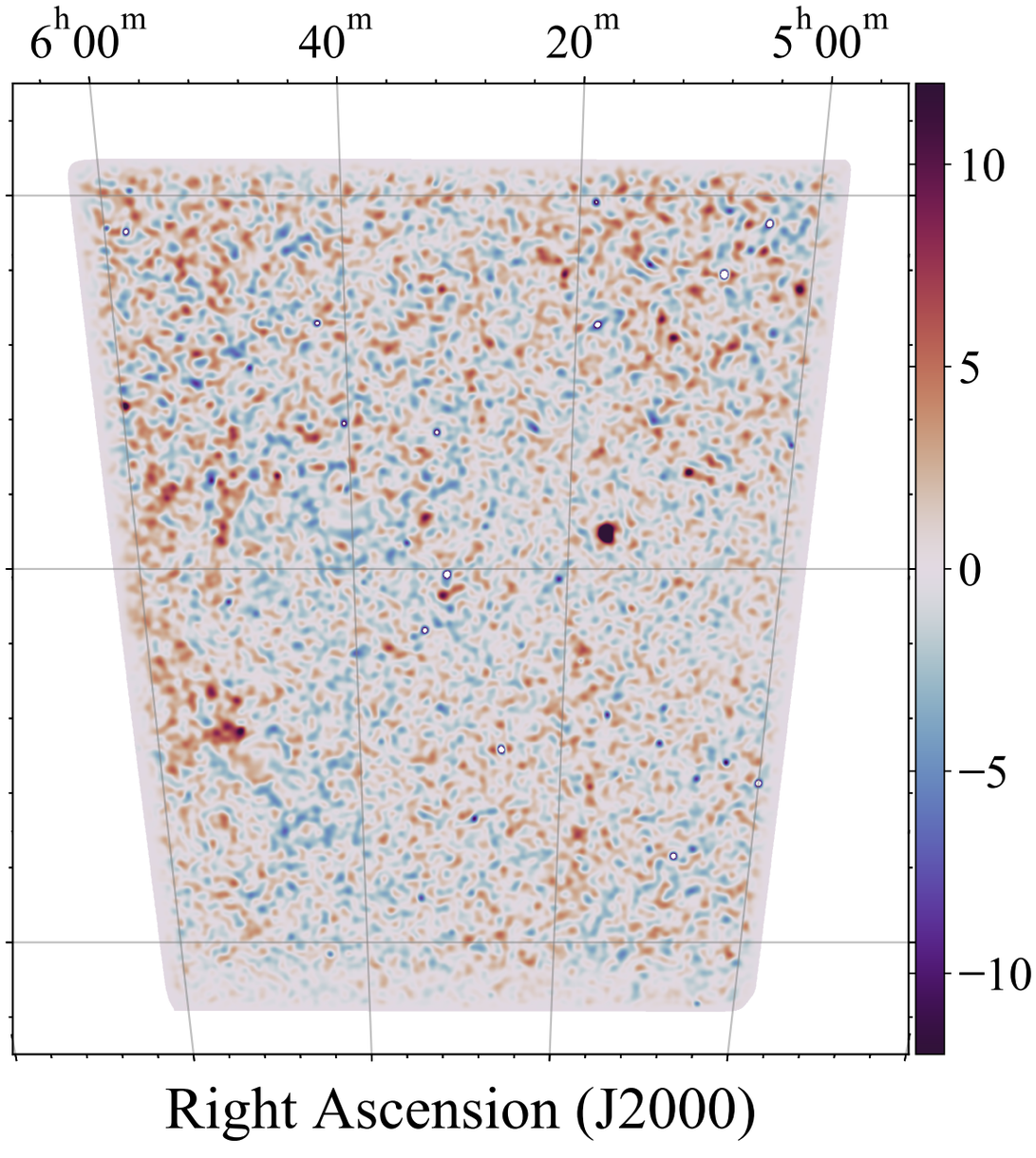
Combined SPT + *Planck* maps isolating tSZ signals 1/19 SPT-SZ fields

Bleem+ ApJ 258, 36B (2022)

See Also Madhavacheril et al. Phys. Rev. D 102, 023534 , 2020
Planck 2015 results. XXII.

Multifrequency CMB Data can be Combined to Isolate Cluster Signals





Combined SPT + *Planck* maps isolating tSZ signals 1/19 SPT-SZ fields

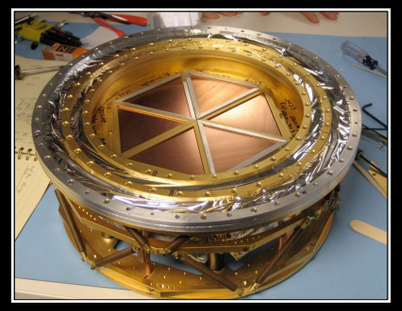
Bleem+ ApJ 258, 36B (2022)

The South Pole Telescope (SPT)

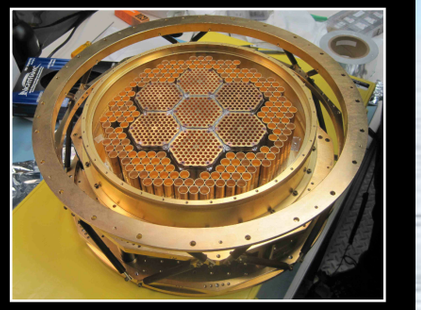
10-meter sub-mm quality wavelength telescope

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

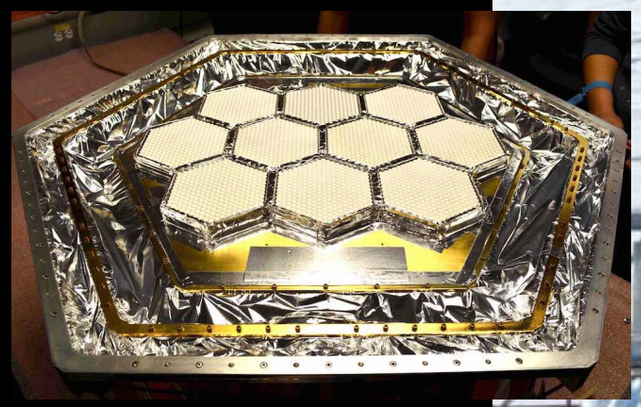
2007: SPT-SZ
960 detectors
90,150,220 GHz



2012: SPTpol
1600 detectors
90,150 GHz
+Polarization



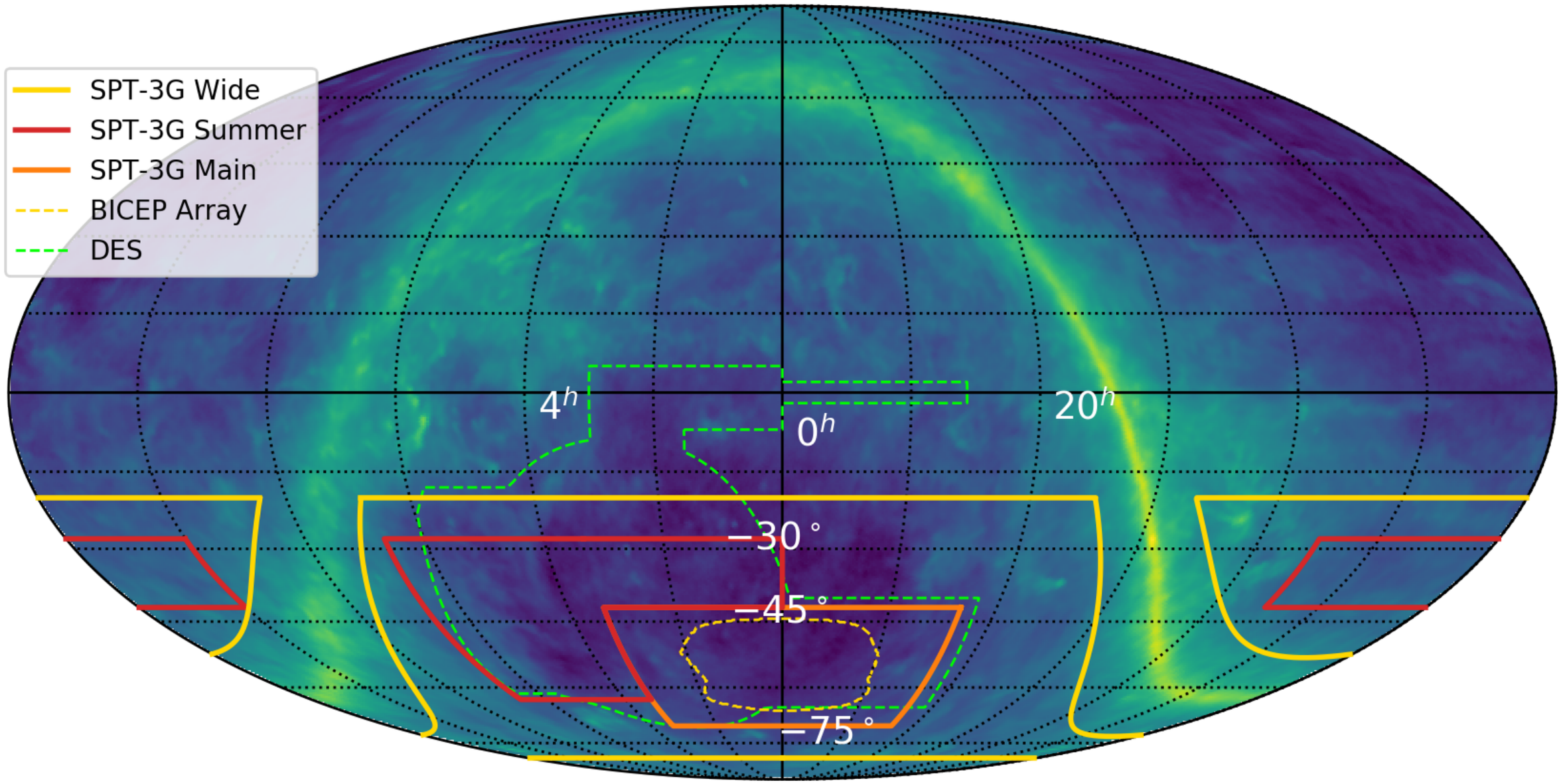
2017: SPT-3G
~15,200 detectors
90,150,220 GHz
+Polarization



Funded By:

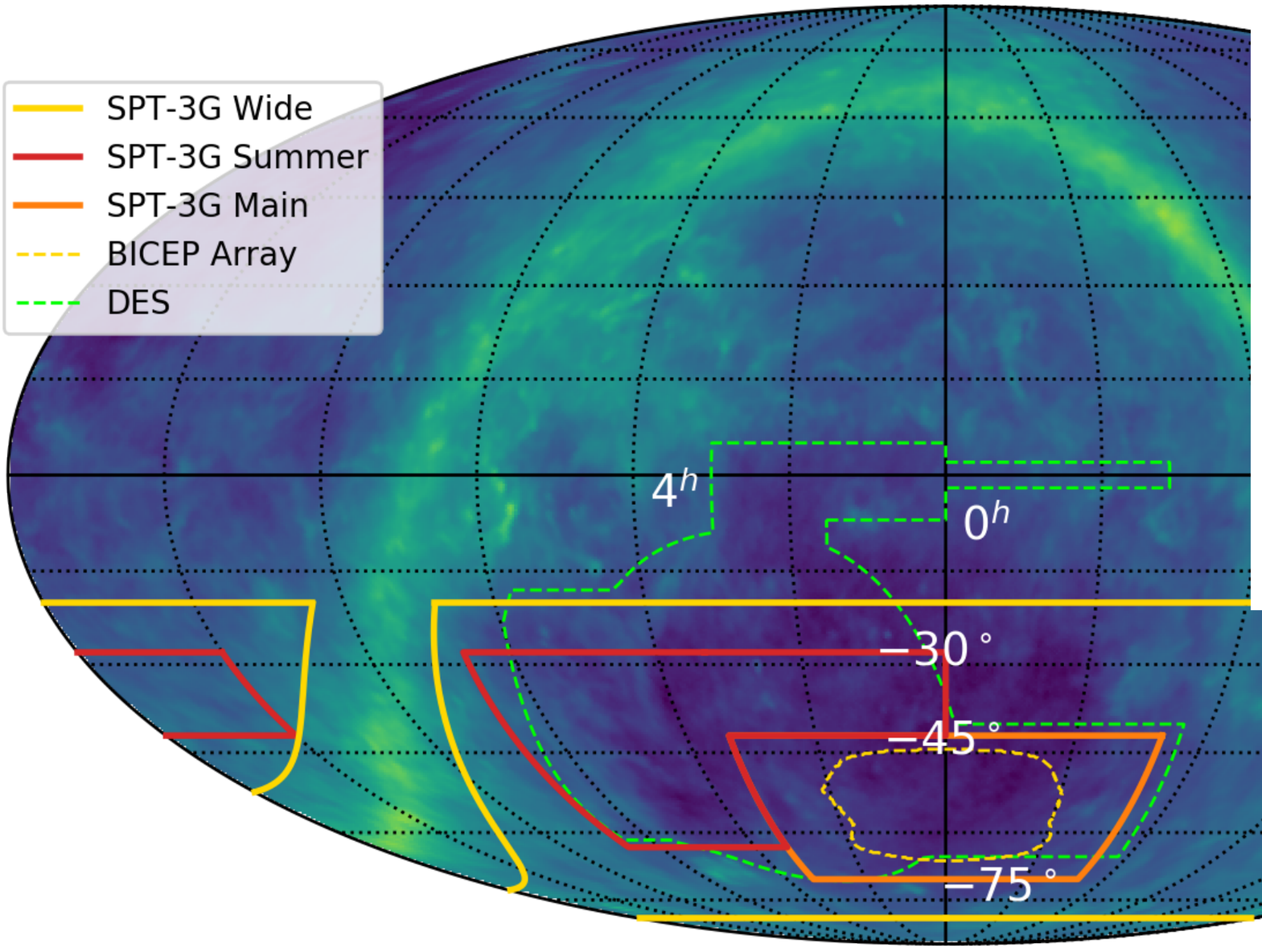
Funded by:
NSF
U.S. DEPARTMENT OF ENERGY

The 10,000 sq-degree SPT-3G Survey(s)



Survey	Area [deg^2]	Years observed	Noise level (T) [μK-arcmin]			
			95 GHz	150 GHz	220 GHz	Coadded
SPT-3G Main	1500	2019-2023, 2025-2026	2.5	2.1	7.6	1.6
SPT-3G Summer	2600	2019-2023	8.5	9.0	31	6.1
SPT-3G Wide	6000	2024	14	12	42	8.8

The 10,000 sq-degree SPT-3G Survey(s)



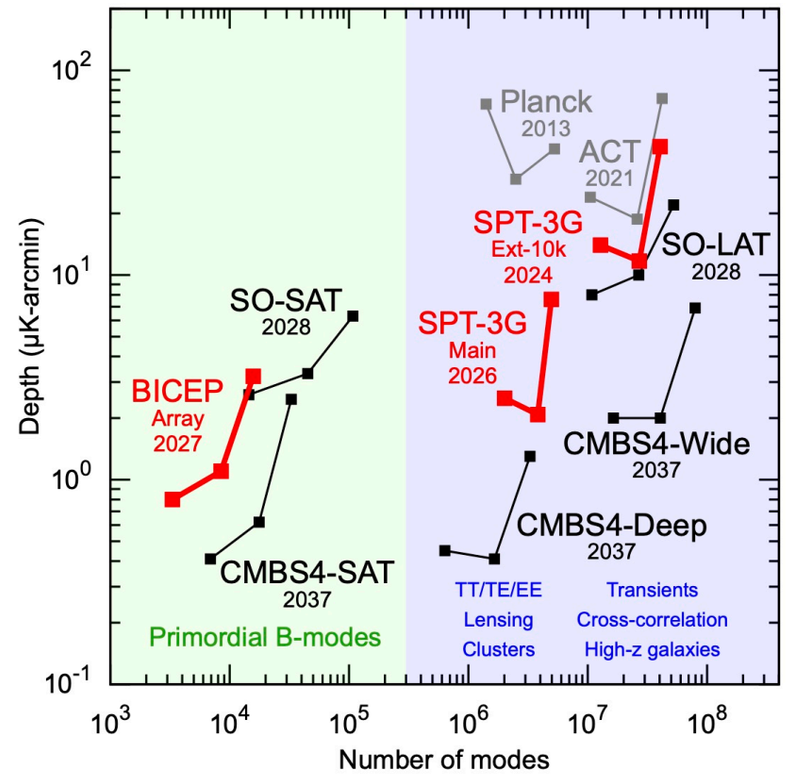


Fig Adapted from S. Naess

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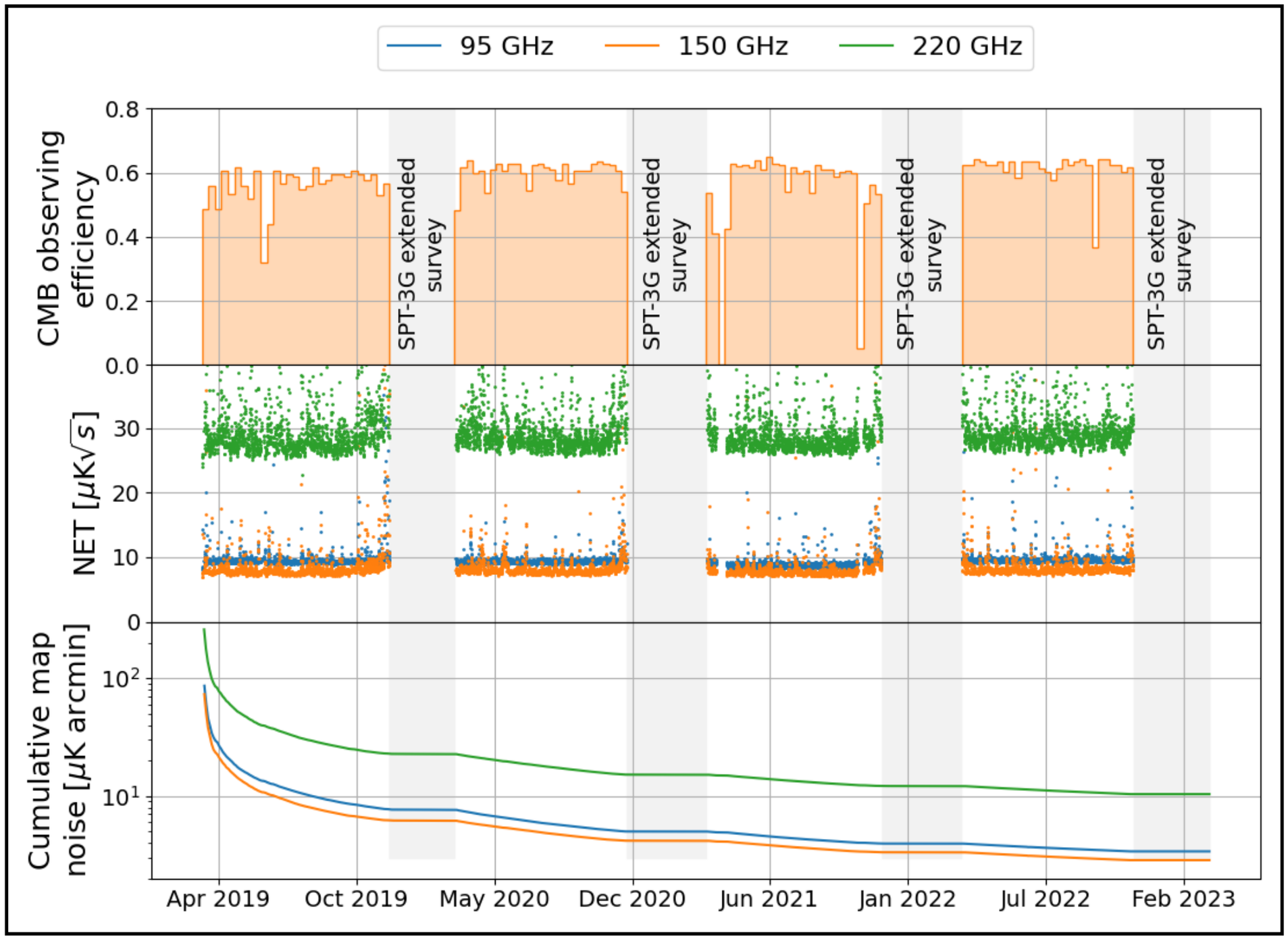
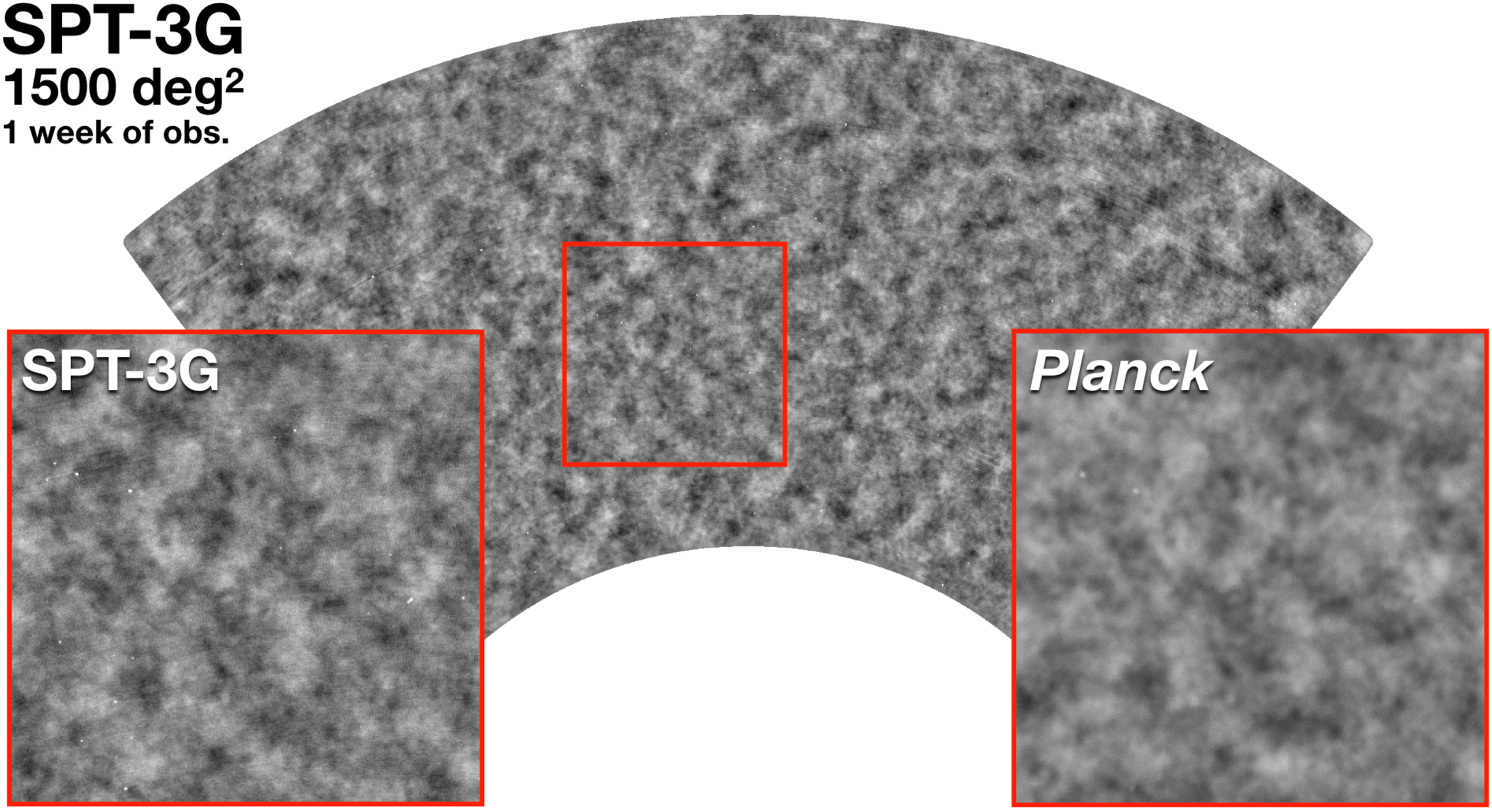
SPT-3G Observations

- SPT-3G has thus far achieved nominal observing efficiency and sensitivity over the 2019 thru 2022 observing seasons.



Plot Credit: Amy Bender

SPT-3G
1500 deg²
1 week of obs.



- ***SPT-3G data gets to ~Planck depth on 1500d field with a ~week of data.***
- ***Observe 1500d field every ~2 days for 6 years***

SPT-3G (2019+2020)
50 deg^2 of 95 GHz Map

Galaxy Clusters

Point Sources

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

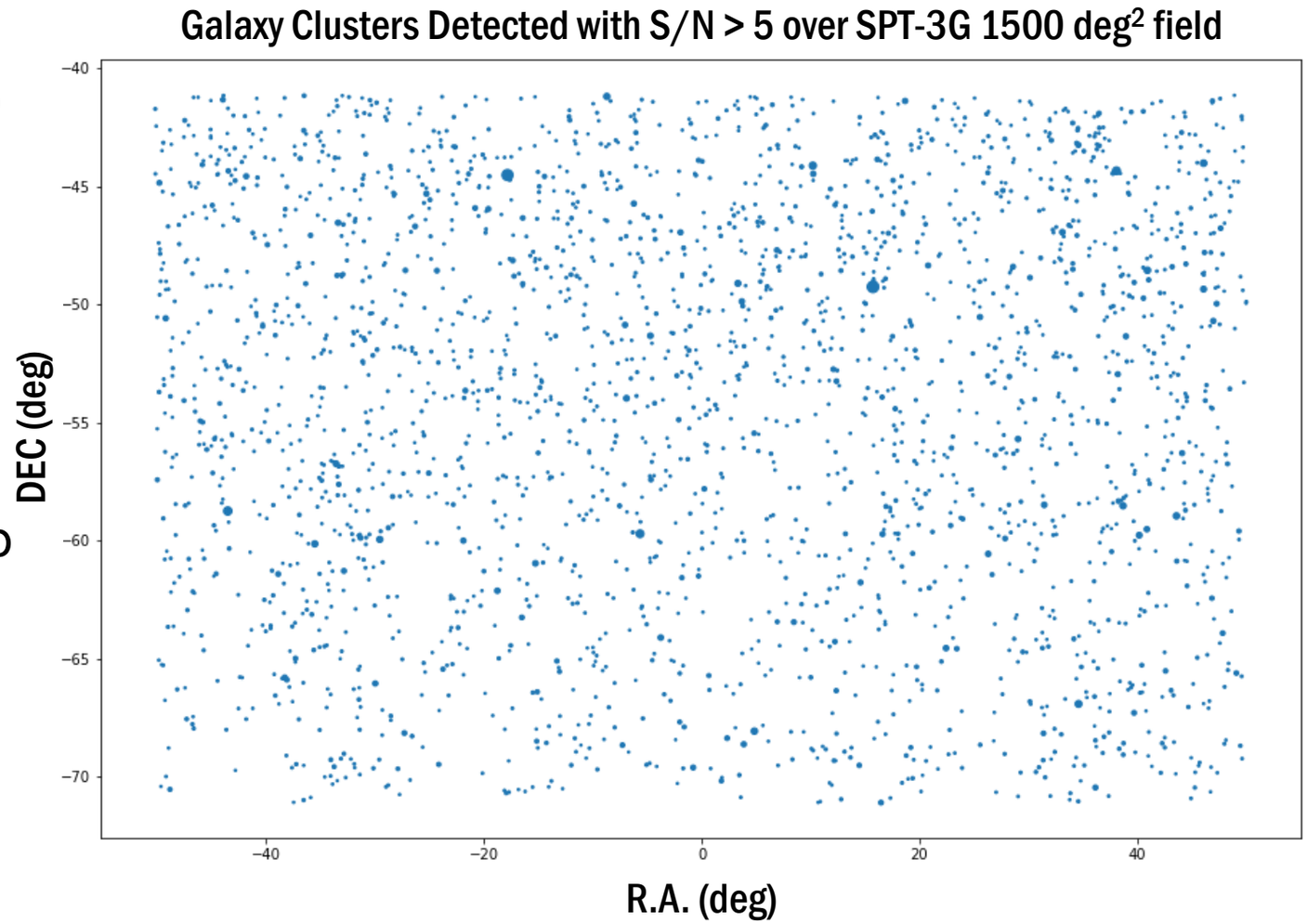
The SPT-3G SZ Catalog

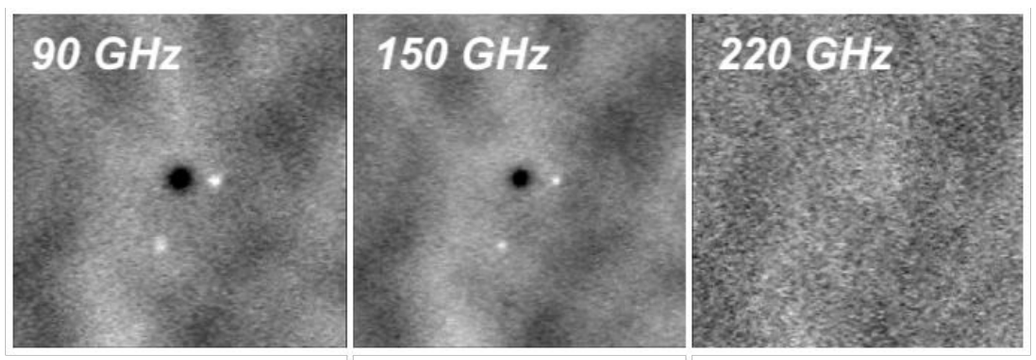
- First catalog being produced from 2019-2020 data

- Preliminary cluster run has produced a catalog with 2457 cluster candidates at xi>5 (>99% purity)

- 5891 candidates at 3.85 < xi < **130.2**(!)

- Candidates screened through DES, promising targets flagged for additional followup. A total of 12 nights of NIR followup with Magellan/FourStar of SPTpol 500d/ SPT-3G cluster candidates has resulted in 124 SPT-3G cluster candidates with NIR imaging [2 more nights coming this July!], analysis of these systems is ongoing





SPT-CL J2344-4243 (Phoenix Cluster, z=0.6) see in SPT-3G data at S/N>120

with L Bleem, F Kéruzoré

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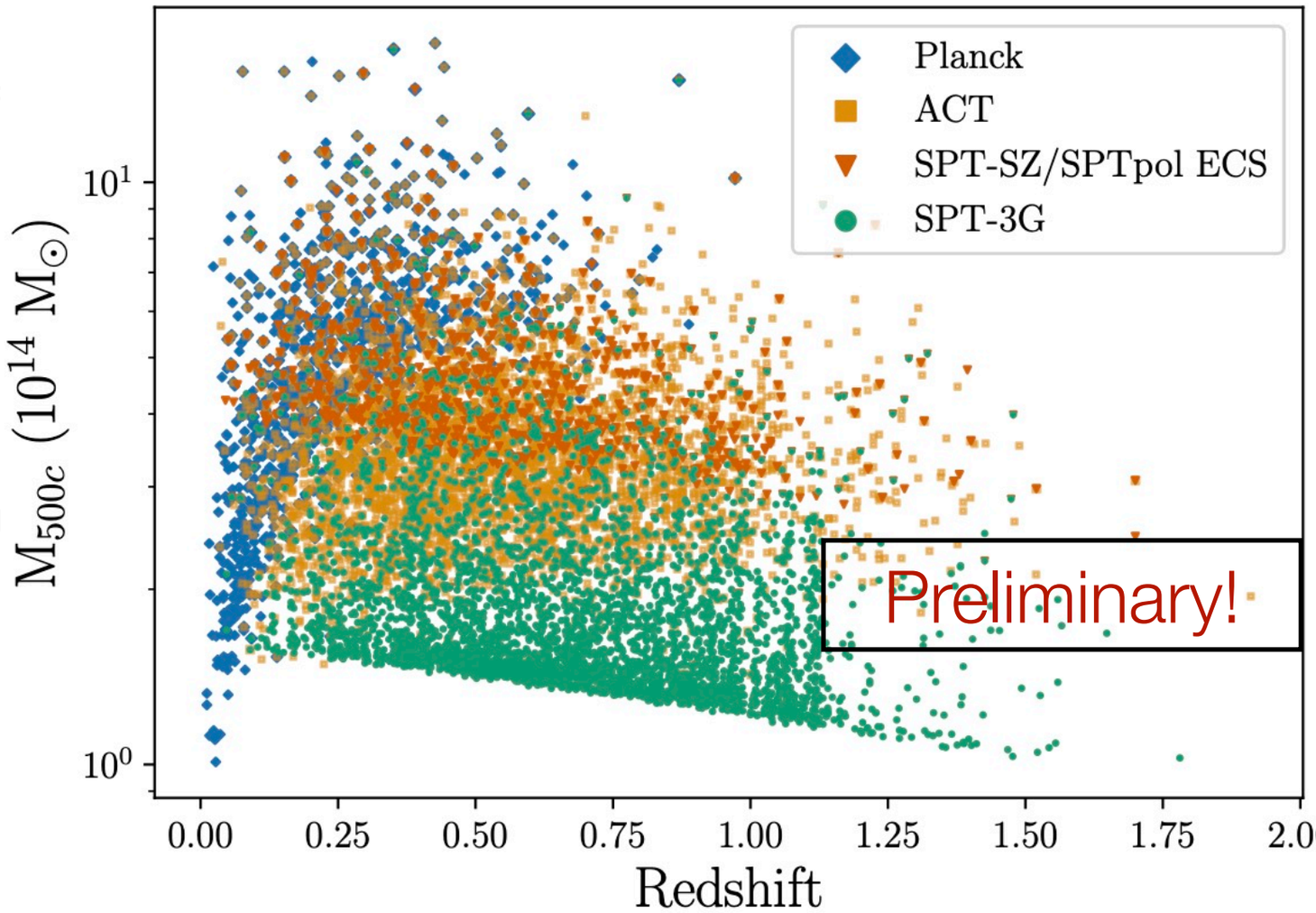
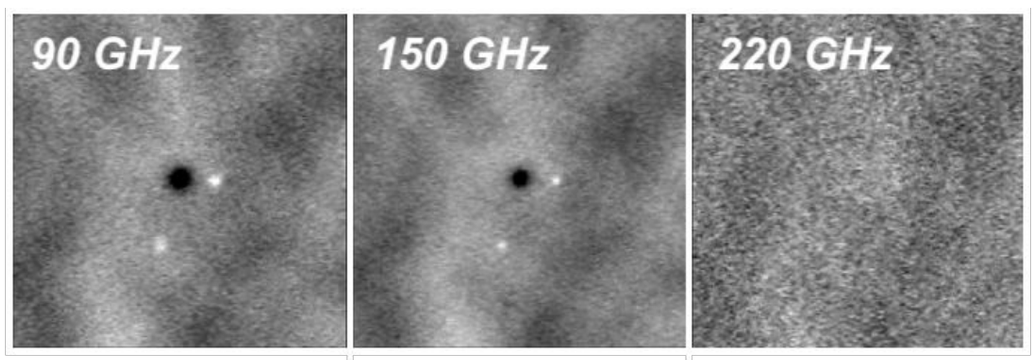


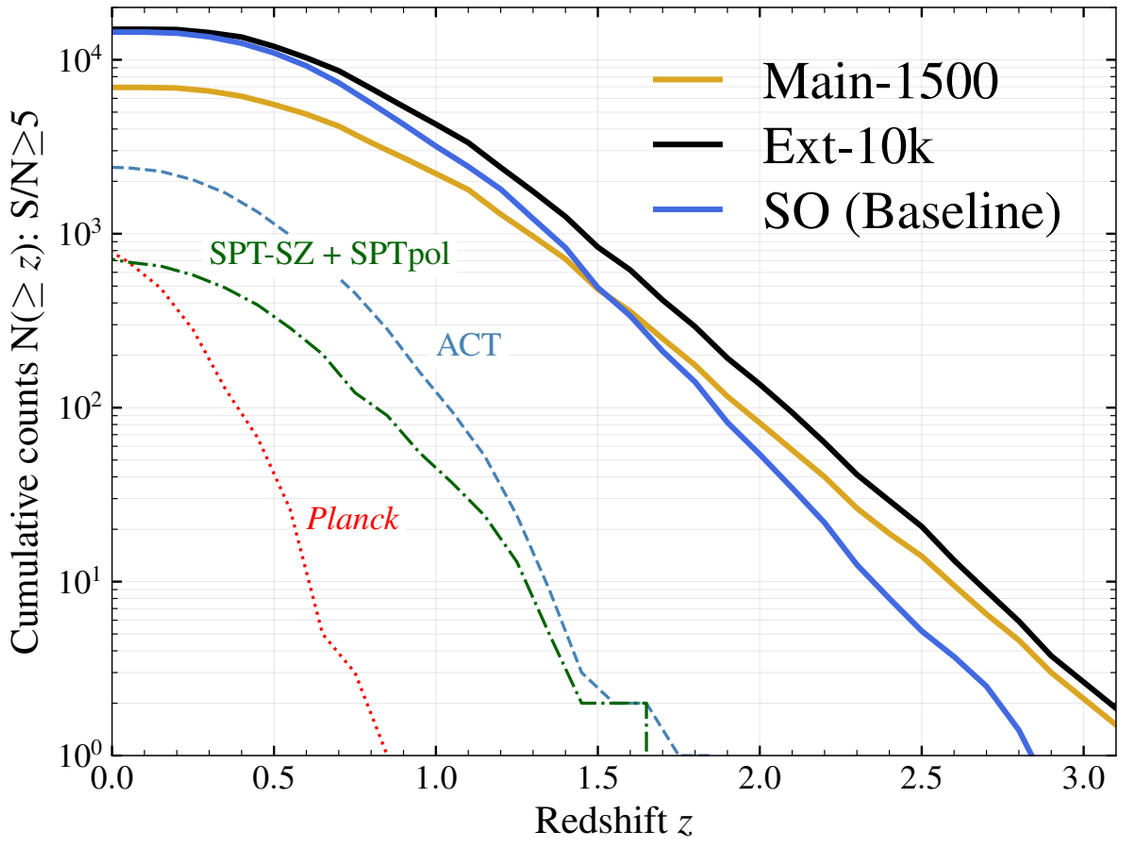


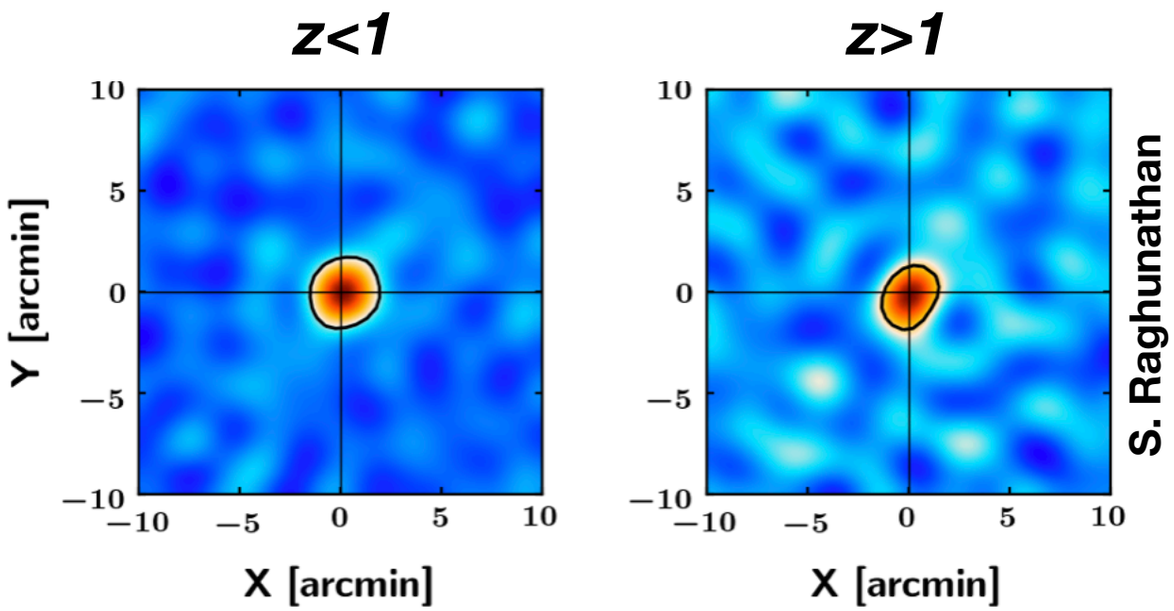
SPT-CL J2344-4243 (Phoenix Cluster, z=0.6) see in SPT-3G data at S/N>120

with L Bleem, F Kéruzoré

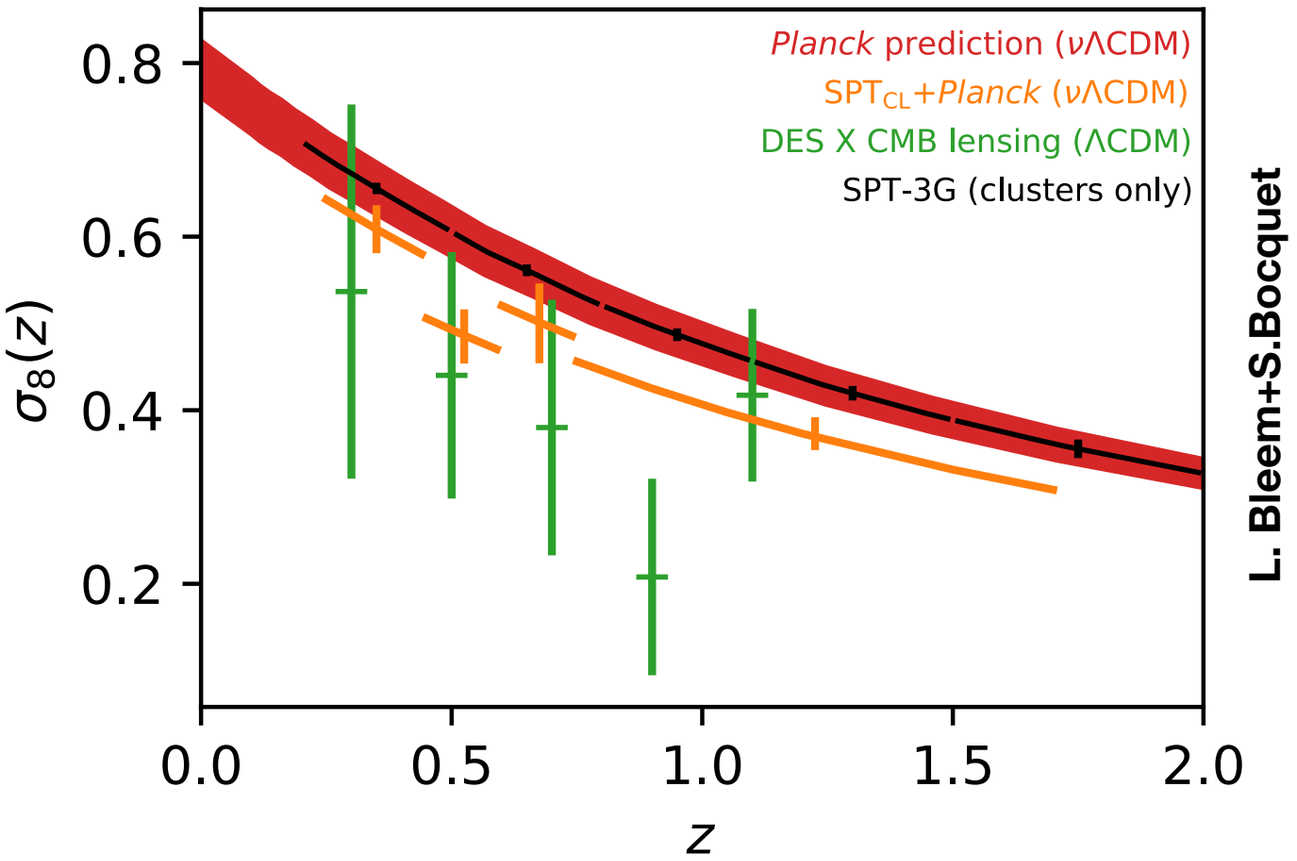
Cluster Forecasts

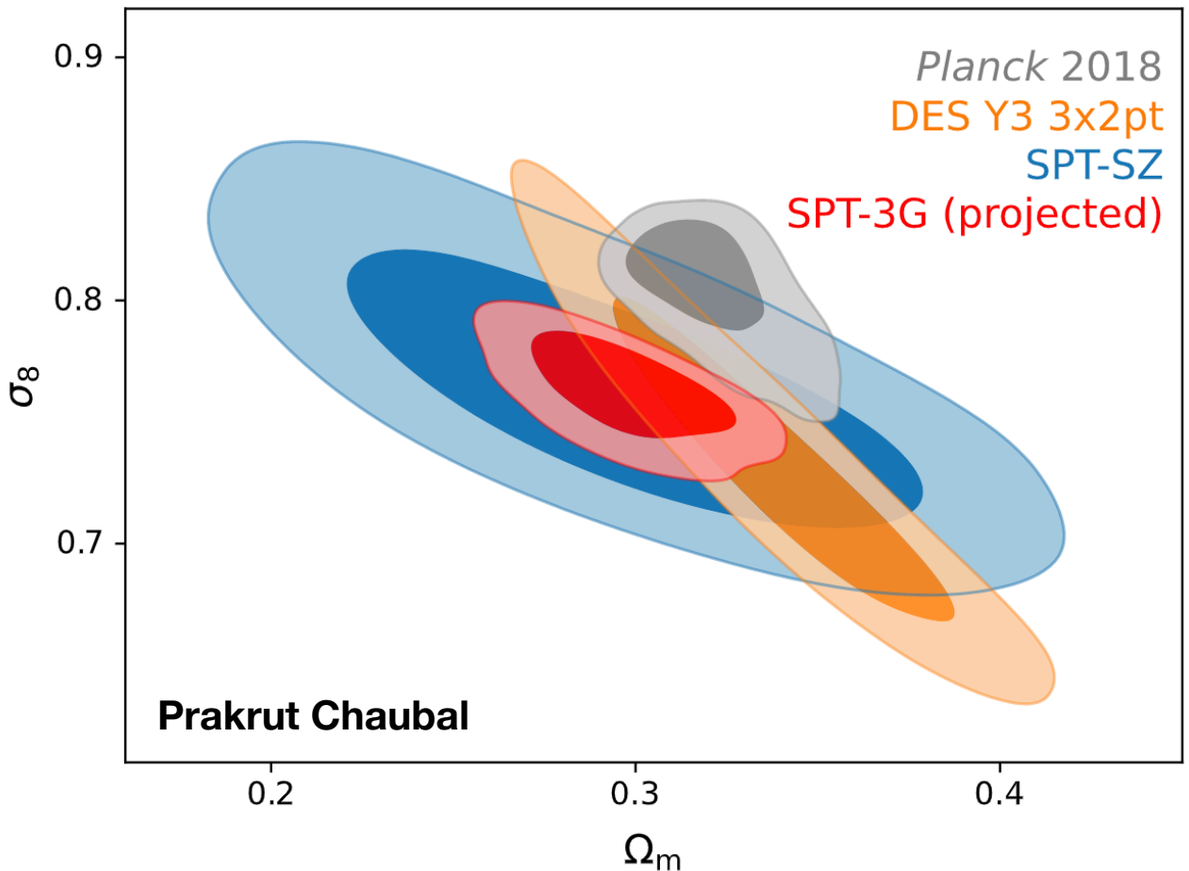
SPT-3G





High S/N (>30σ) detection of CMB cluster lensing!





Conclusions

- SPT has found thousands of massive galaxy clusters reaching to z~1.9 via the SZ effect.

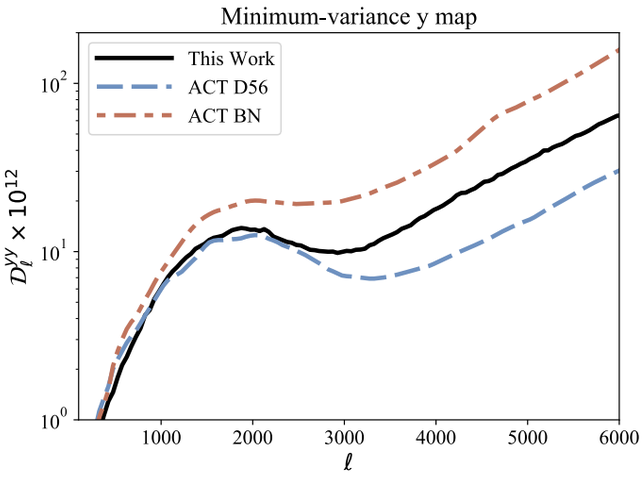
- Clean, mass-limited selection leads to fantastic samples for cosmological and astrophysical studies. They also enable important tests of systematics control in multi-wavelength cluster studies.

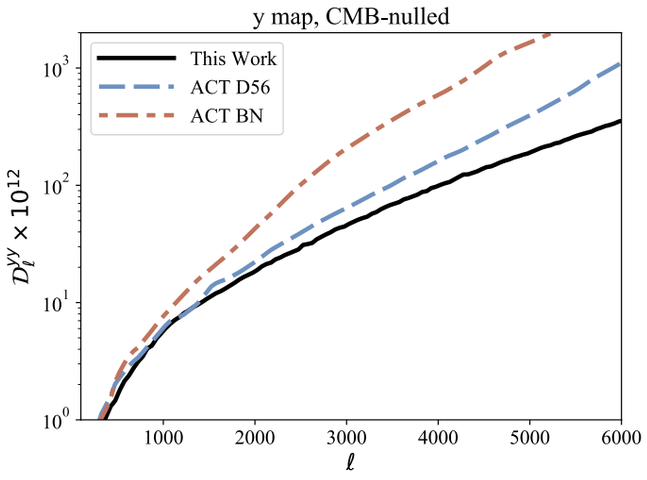
- A new cluster catalog from SPTpol is coming this summer along with high-resolution CMB maps and associated data products.

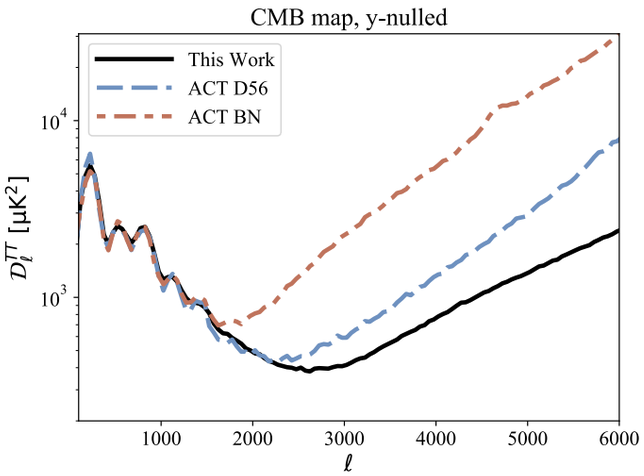
- SPT-3G is in the midst of a 10,000 square degree survey of the Southern sky that will detect $>10^4$ SZ clusters. Progress on the first SPT-3G sample is well underway!

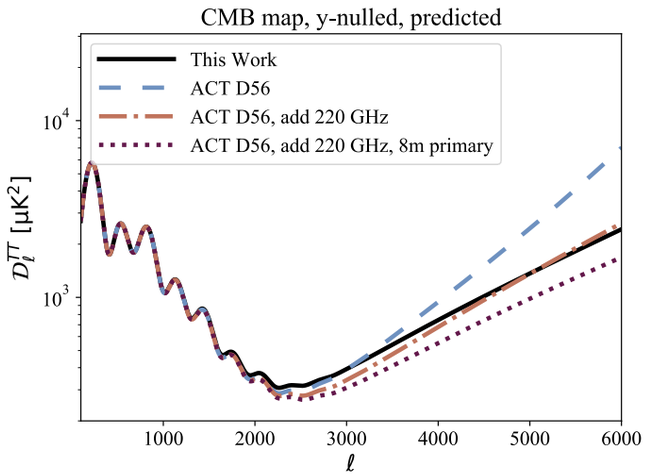
Extra Slides

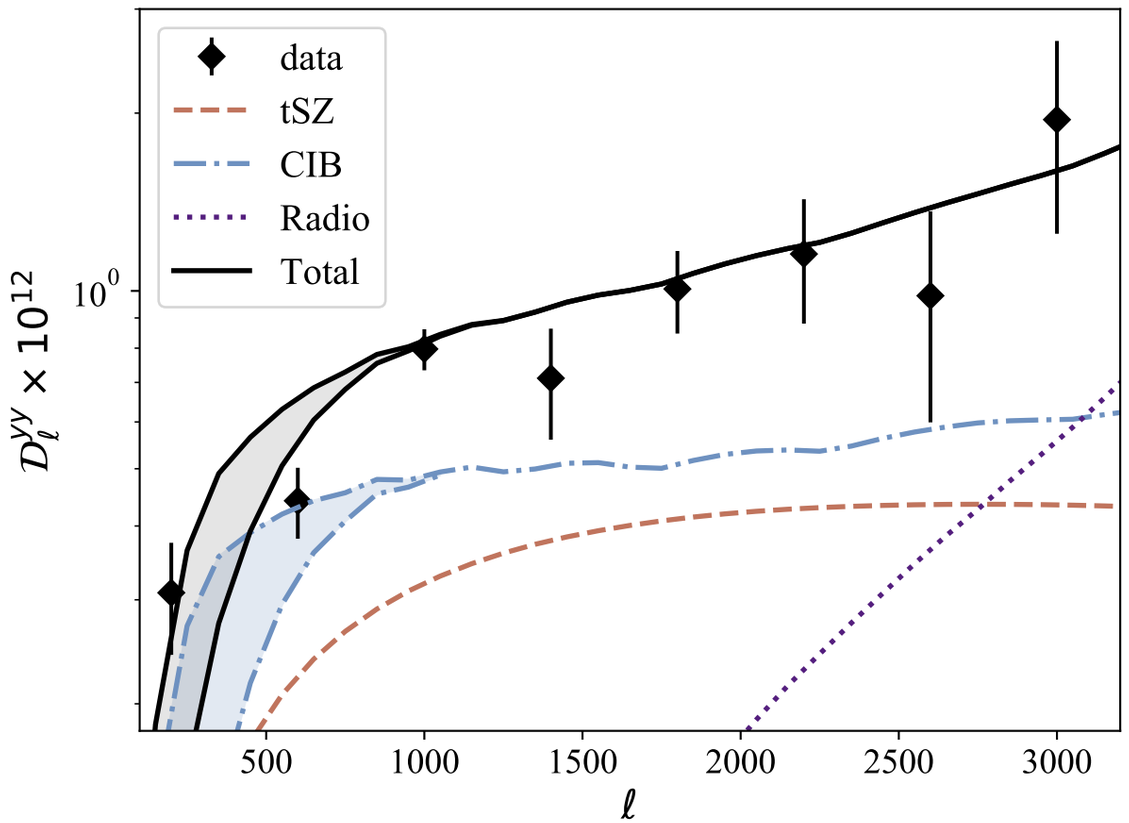
Multifrequency CMB Data can be Combined to Isolate Cluster Signals



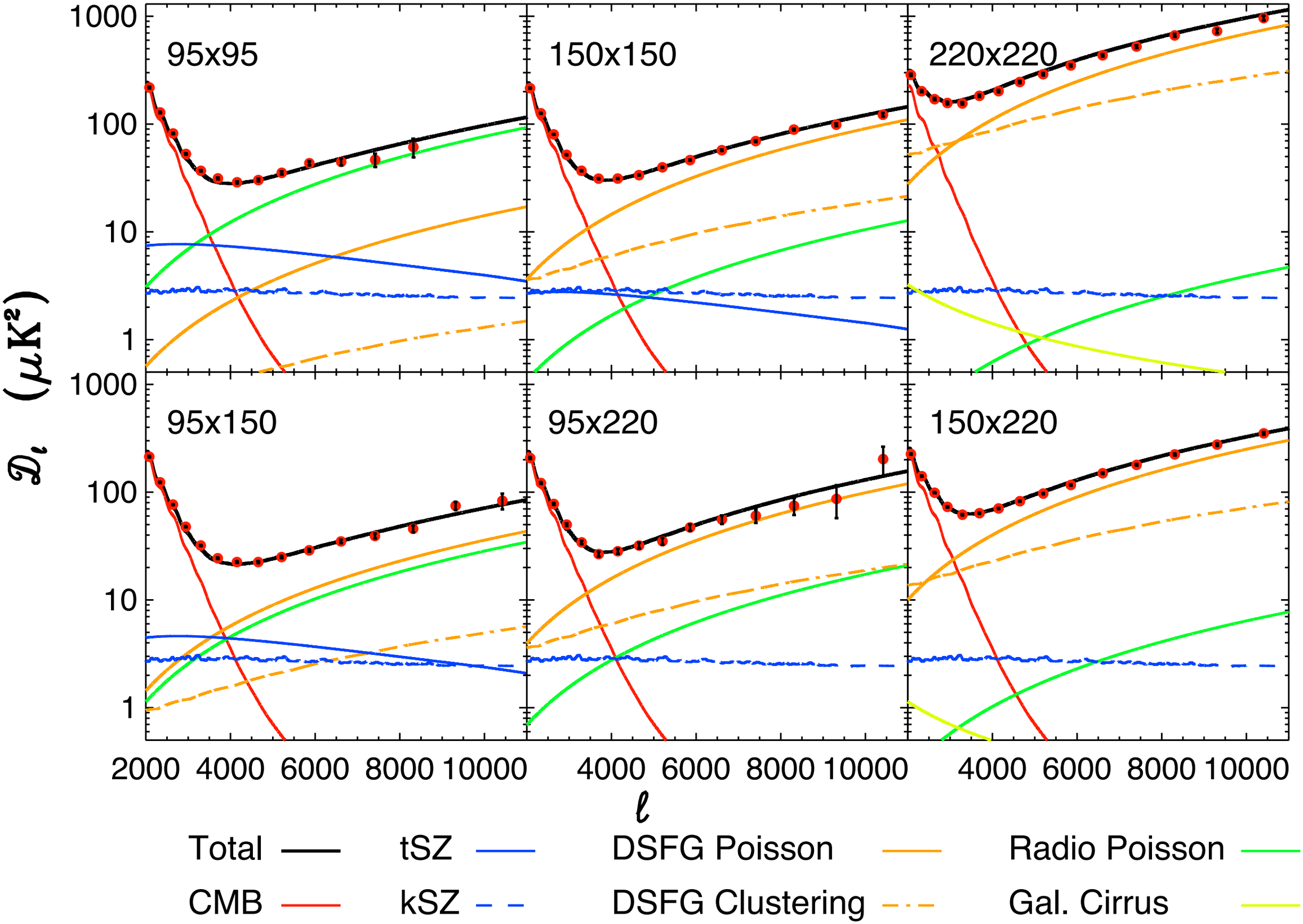








Bleem+ ApJ 258, 36B (2022)

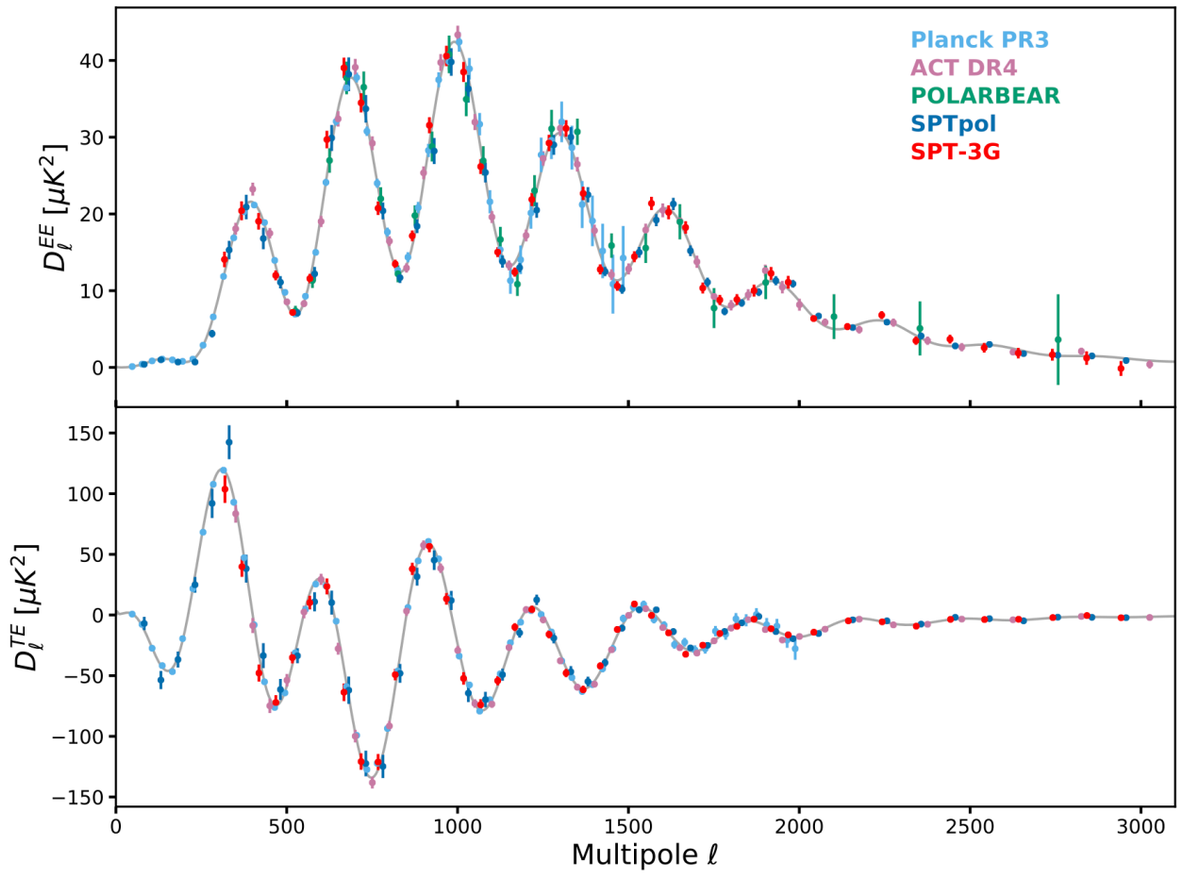


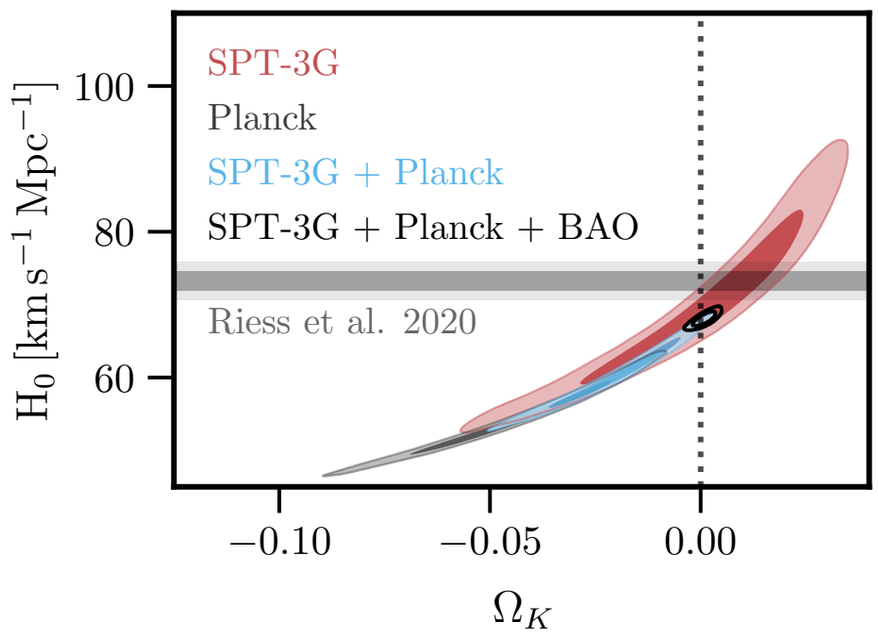
Reichardt et al, 2021; ApJ 908, 199R

First SPT-3G Science

2018 survey data

- ~7000 detectors for 4 months
- 1500 sq deg
- Similar sensitivity to multi-year SPTpol survey
- Most sensitive measurement from SPT in $300 < \ell < 1400$ for EE
- Maps from 2019-2020 are 3-4x deeper
- SPT-3G 2018 EE data does not resolve H_0 tension between CMB & local probes





Dutcher et al. Physical Review D, 104, 2, 022003 (2021)
Balkenhol et al. Physical Review D, 104, 8, 083509 (2021)

Contamination suppression factor f_cont

- run MCMF on random lines of sight ("randoms")
- do the richness histograms of candidates and randoms for sources within small redshift slices
- calculate f_cont for each counter part for cluster candidate

$$f_{\mathrm{cont},i} = \frac{\int_{\lambda_i}^{\infty} f_{\mathrm{rand}}(\lambda)d\lambda}{\int_{\lambda_i}^{\infty} f_{\mathrm{obs}}(\lambda)d\lambda}$$

- a sample selected by f_cont< x has x times the contamination of the original ICM sample (e.g. x=0.1 -> 10% of the contamination of the original ICM sample)
- by construction the contamination is held constant over redshift.