Update on the South Pole Telescope Cluster Samples

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Sept 18, 2024

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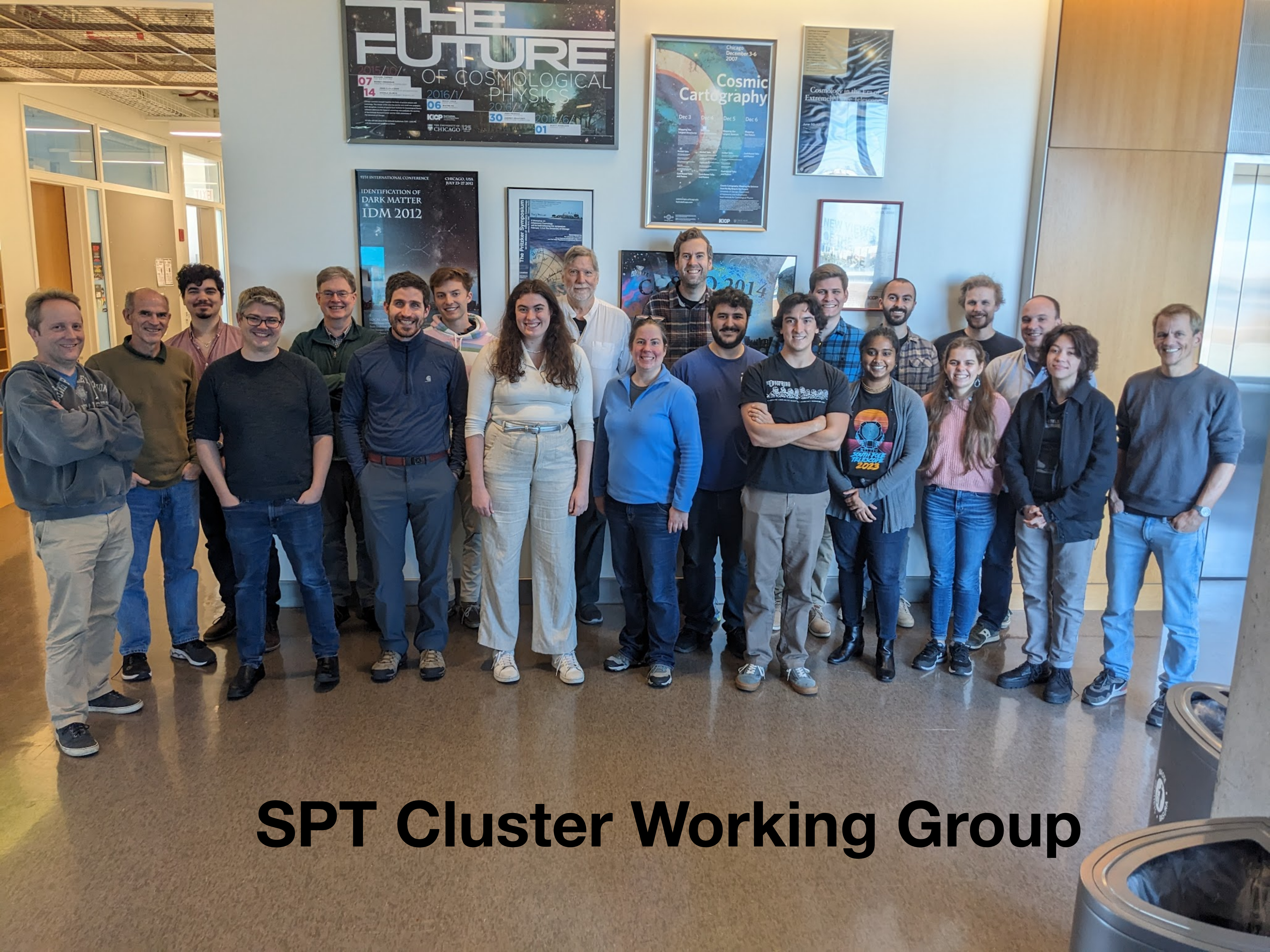
SPT-3G Collaboration



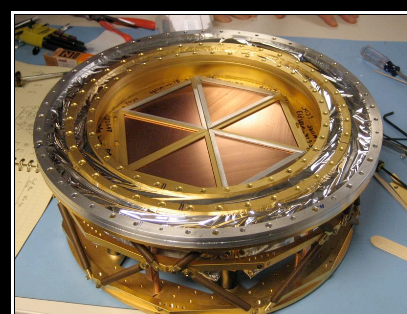
SPT Cluster Working Group

The South Pole Telescope (SPT)

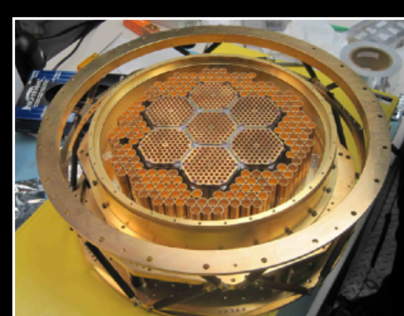
10-meter sub-mm quality wavelength telescope

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

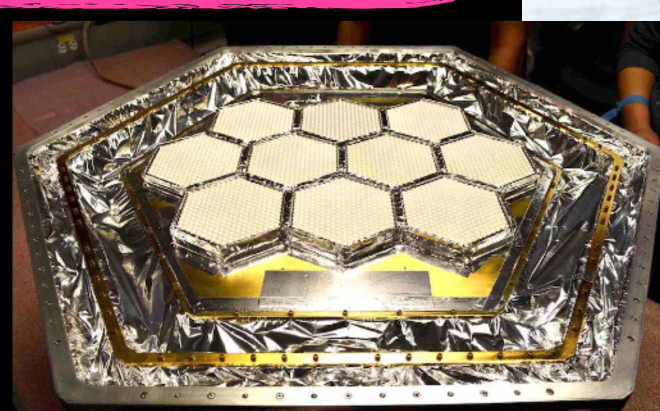
2007: SPT-SZ
960 detectors
90,150,220 GHz

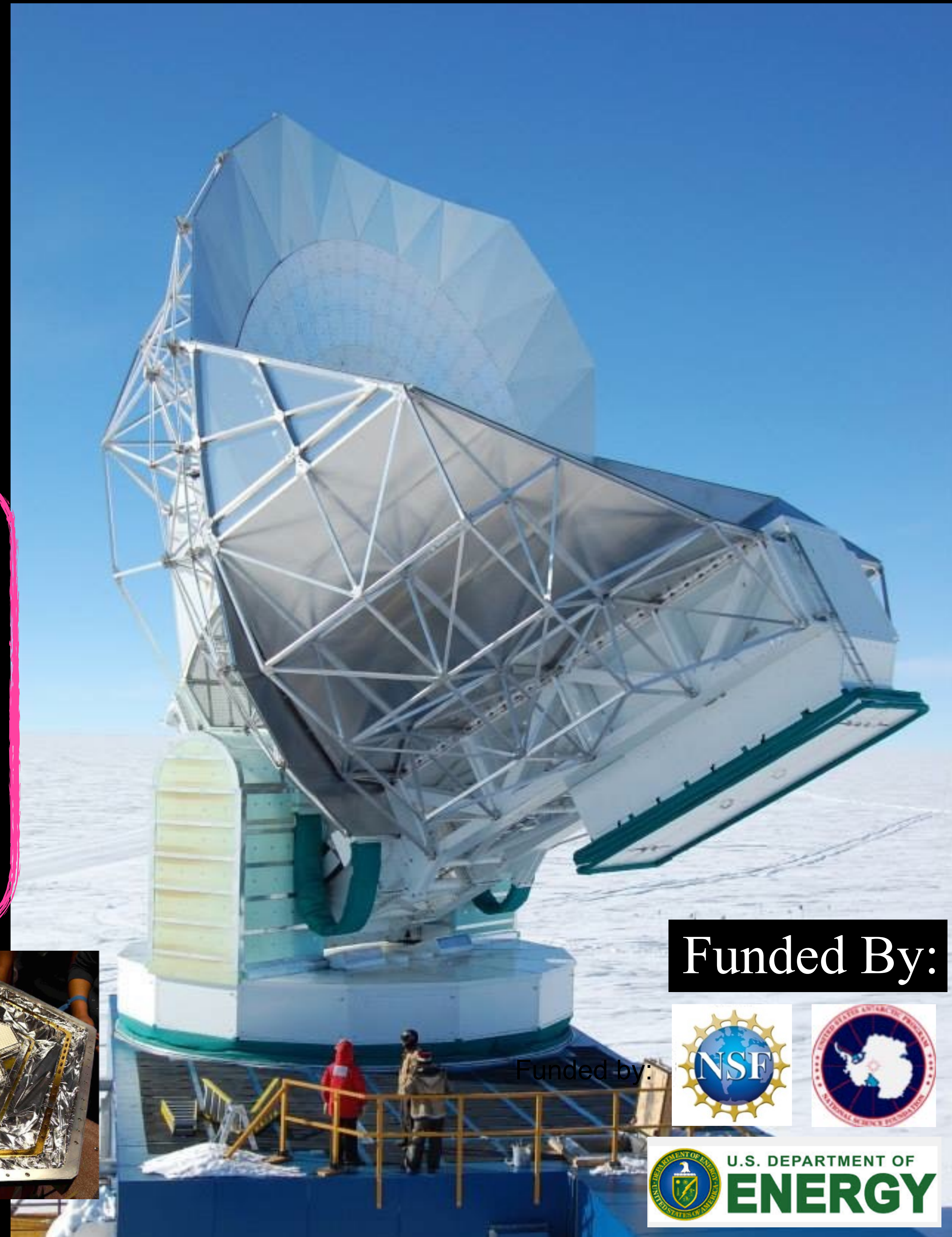


2012: SPTpol
1600 detectors
90,150 GHz
+Polarization

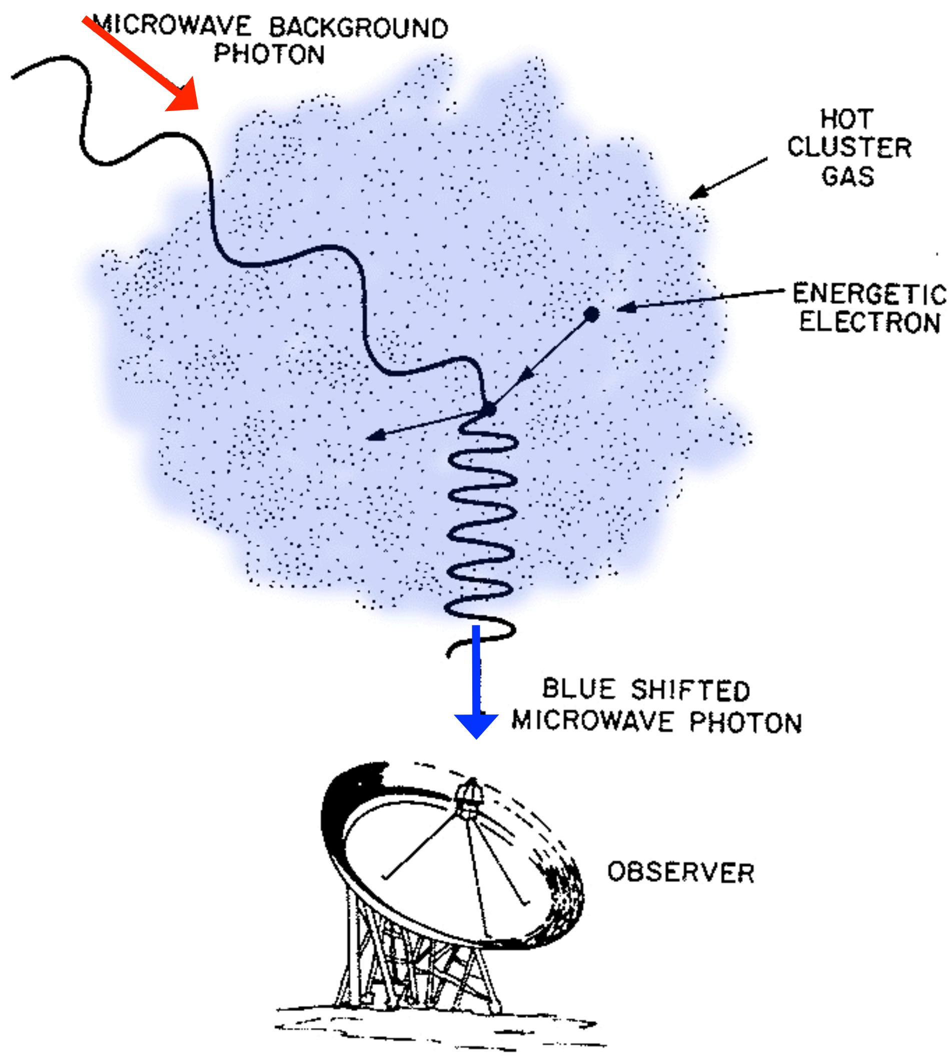


2017: SPT-3G
~15,200 detectors
90,150,220 GHz
+Polarization

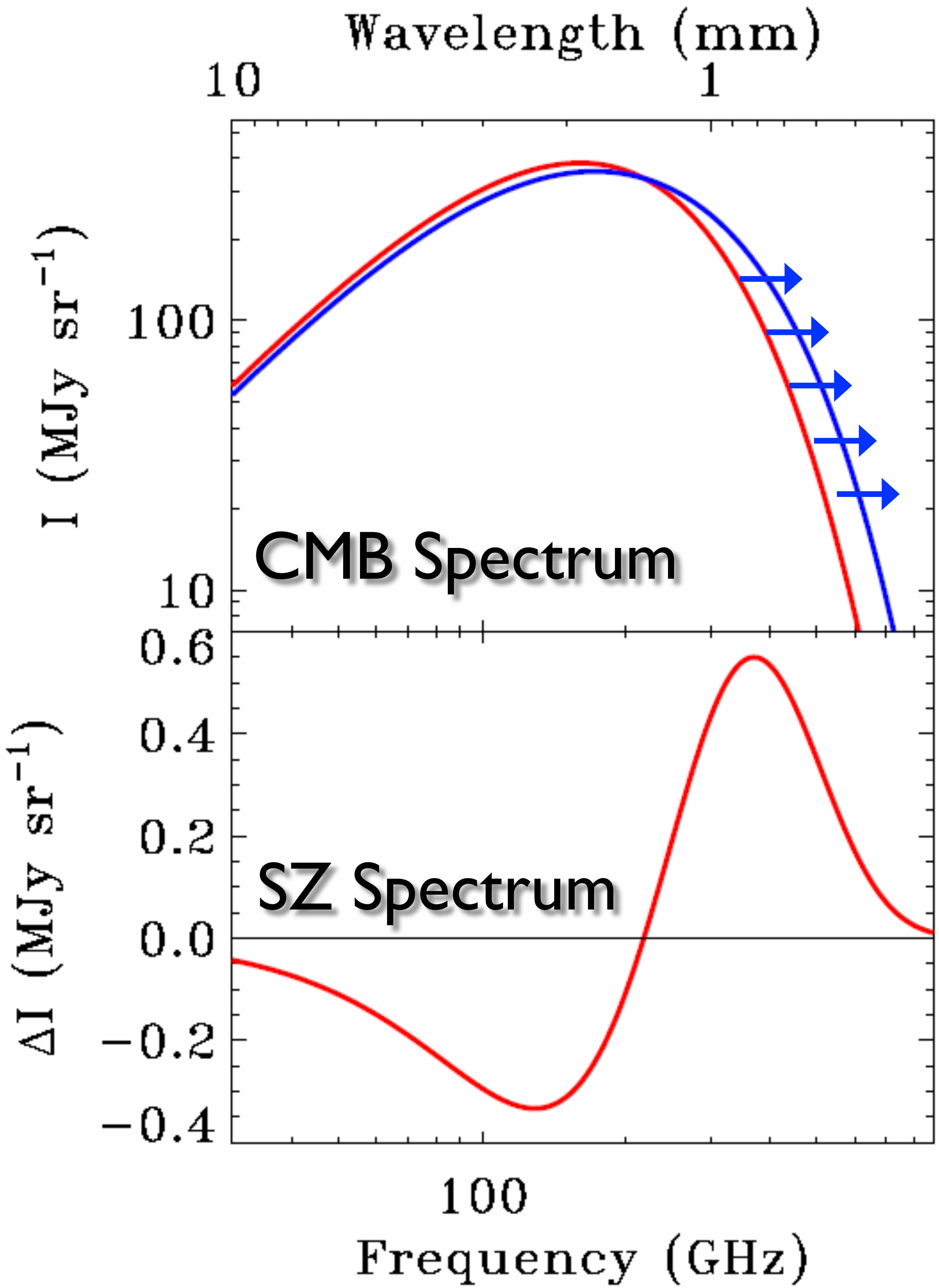




The Sunyaev-Zel'dovich (SZ) Effect

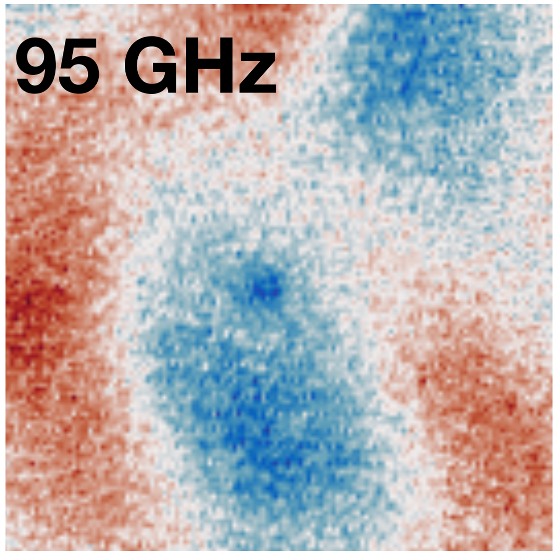


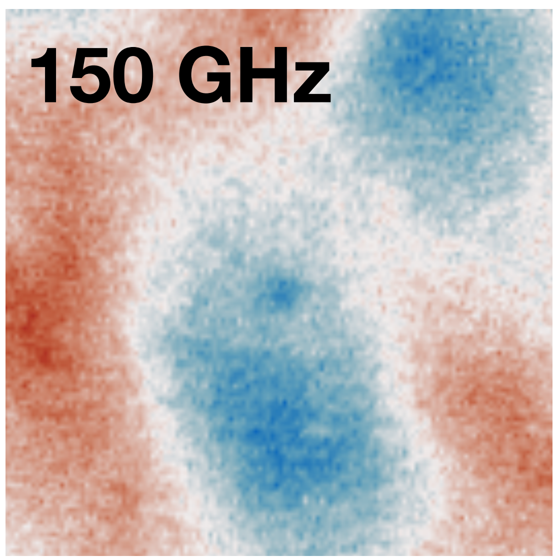
Adapted from L. Van Speybroeck

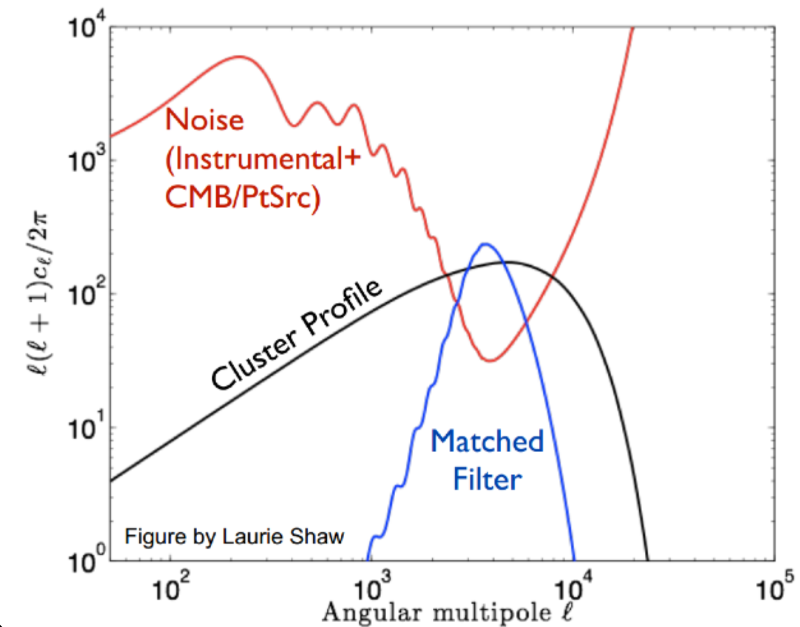


Towards a massive cluster, ~1% of CMB photons scatter off of intra-cluster gas

Finding Clusters in SPT Surveys

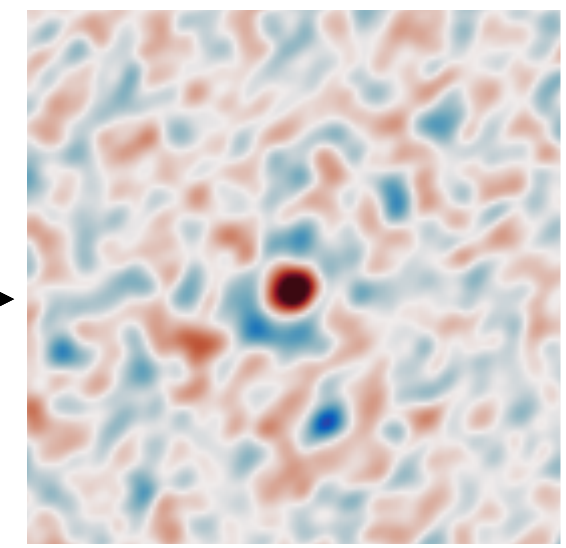






Matched
Filter

$\xi = 12$ **Detection**



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

5,200 deg^2 survey(s) of the southern sky

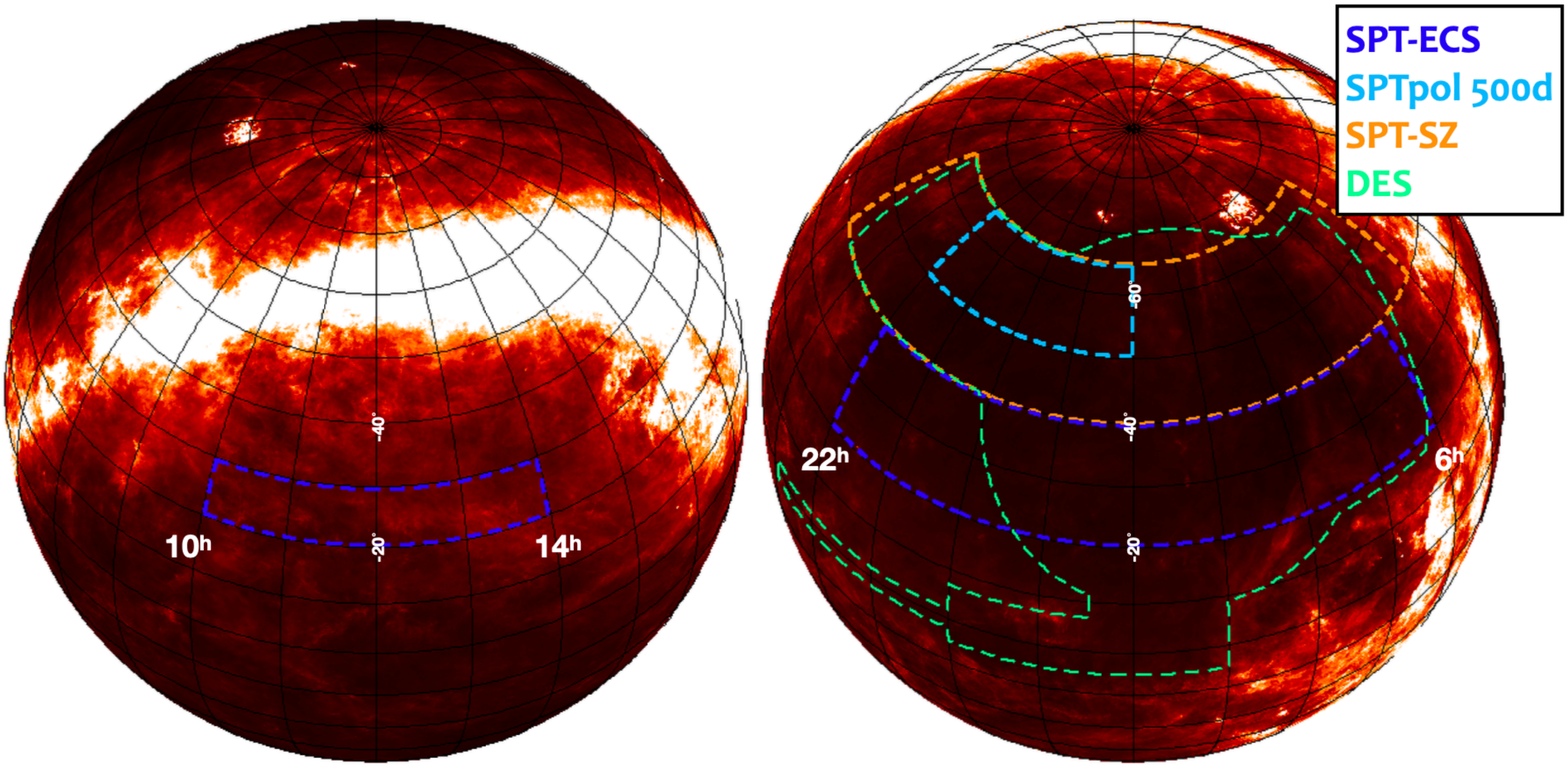
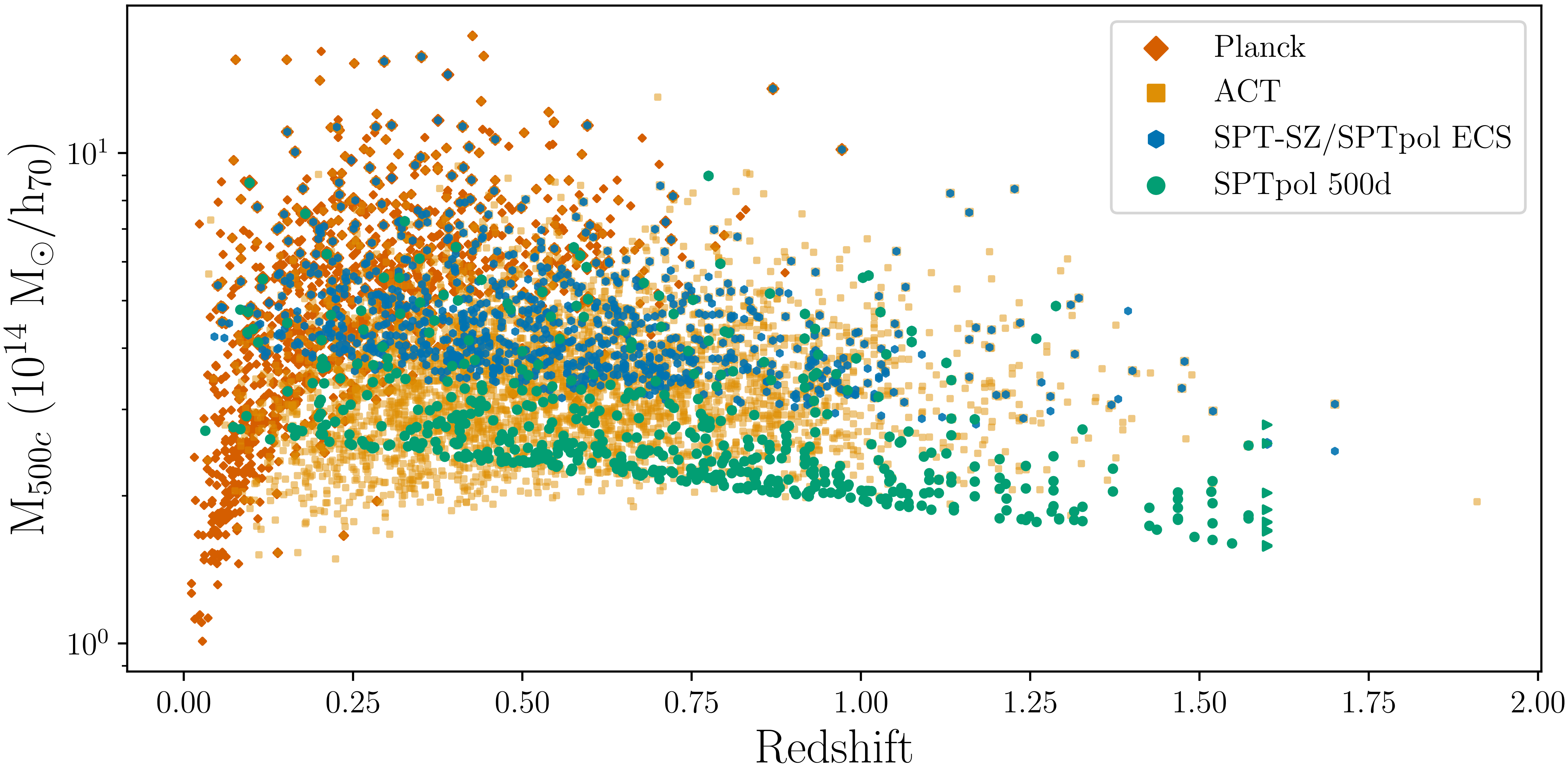


Figure 1. Footprint of the SPTpol Extended Cluster Survey (dark blue) as compared to the SPT-SZ (orange) and SPTpol 500d survey (light blue). Optical-near infrared imaging from the Dark Energy Survey (green-dashed region) covers $\sim 58\%$ of the survey footprint and is used to confirm a significant number of survey clusters presented in this work. The survey outlines are overlaid on the IRAS 100 μm dust map (Schlegel et al. 1998) with the orthographic projection chosen such that the South Celestial Pole is at the top of the globe. Beyond DES, SPT-ECS also has significant overlap with the southern field of the Kilo-Degree Survey, the *Herschel*–ATLAS survey, and the 2dFLenS spectroscopic survey.

SPTpol 500d cluster catalog

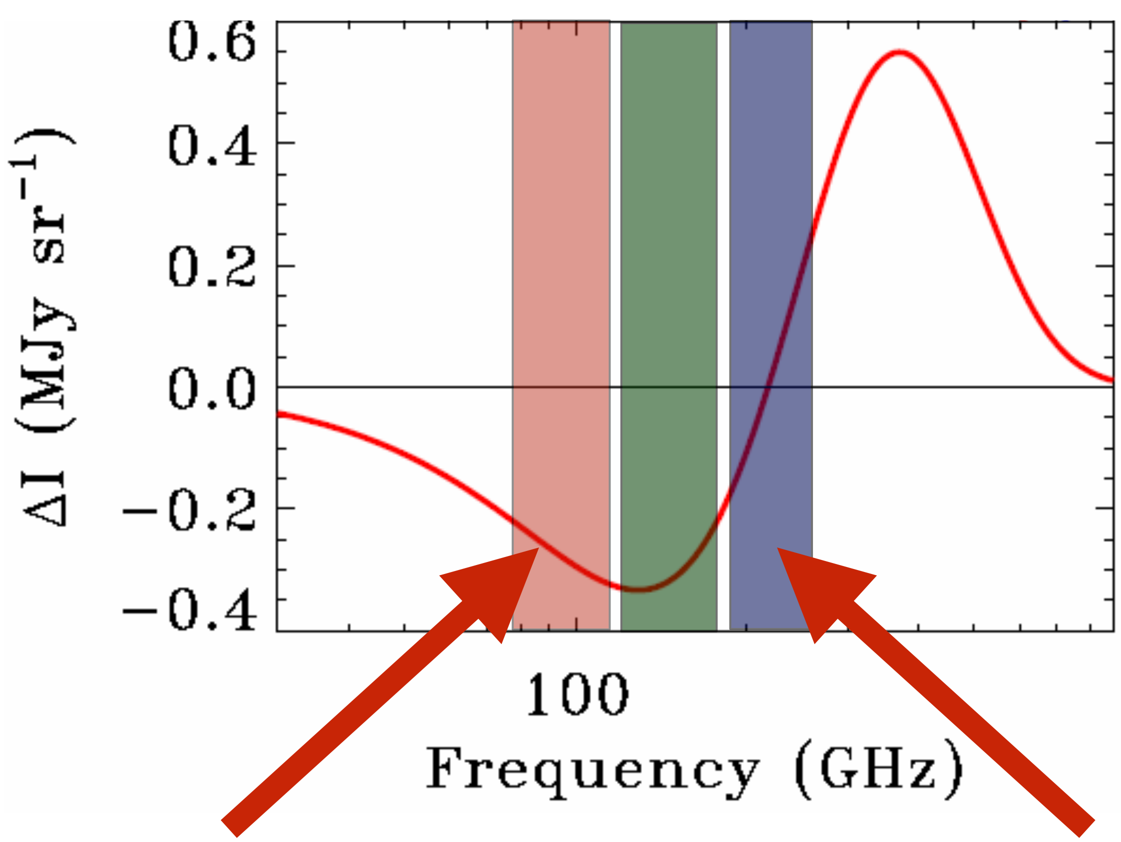


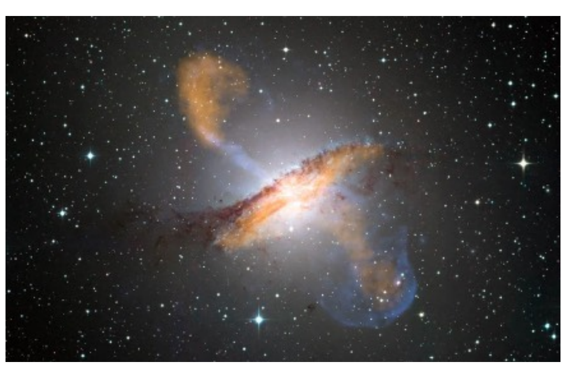
- 689 SZ candidates detected at ξ > 4
- 544 confirmed as galaxy clusters
- 115 at z>1 (21%)
- Cosmology sample (SPT-SZ + SPTpol): 1,005 clusters z > 0.25

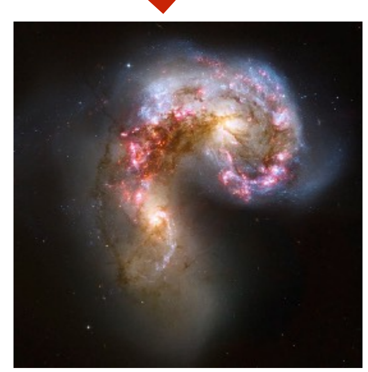
Bleem, Klein et al.
SPTpol & DES Collaborations
OJA 7, 3 (2024)

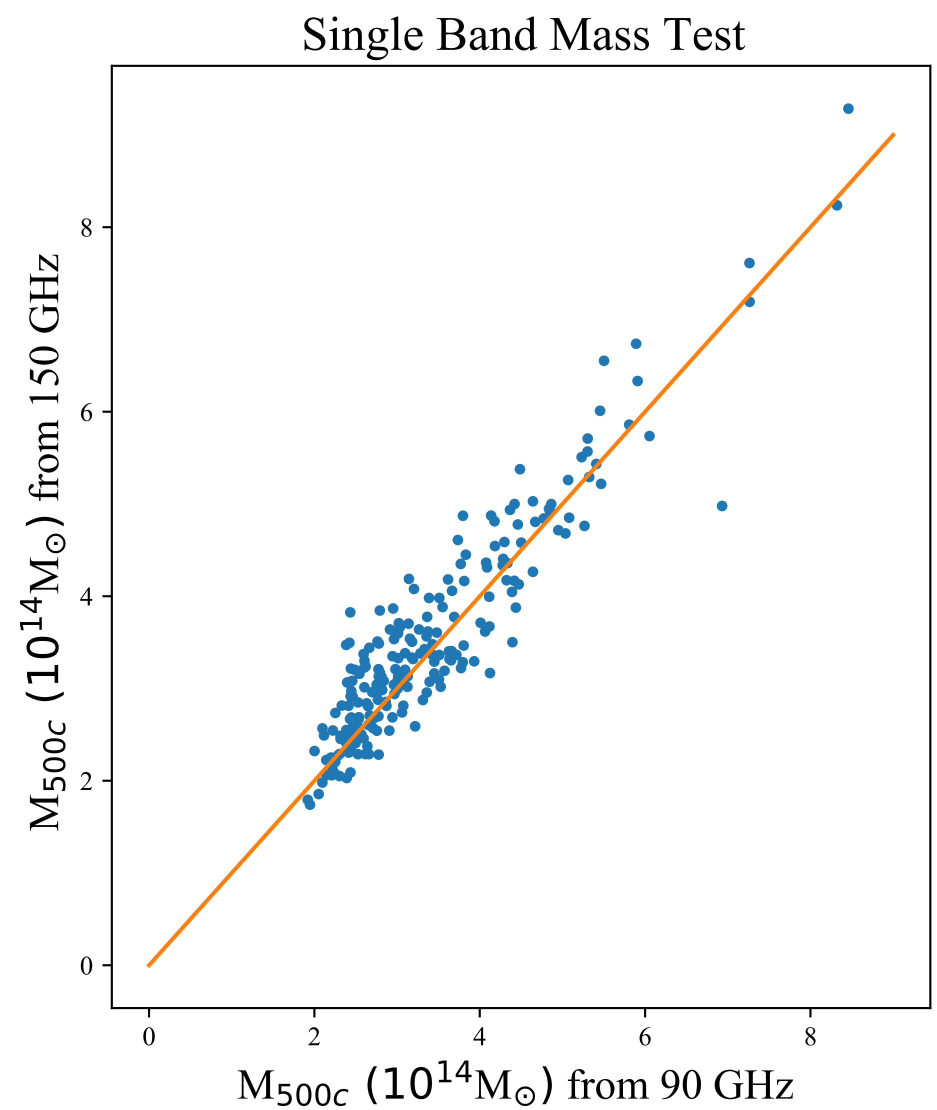
Results: Mass calibration (fixed cosmology)

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





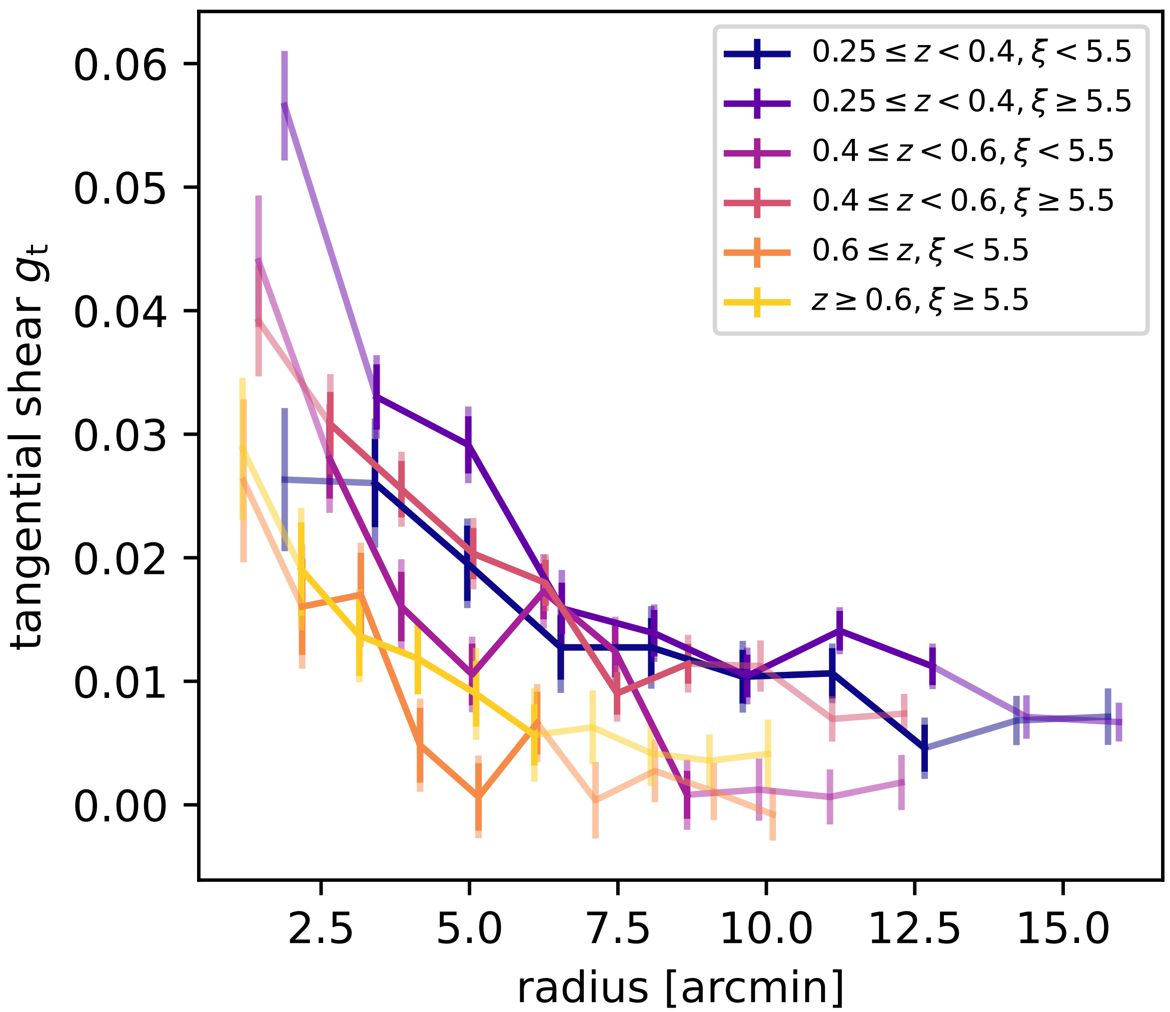




Excellent Consistency between masses derived from 90 and 150 GHz cluster searches alone (221 clusters)

Weak Lensing Mass Calibration

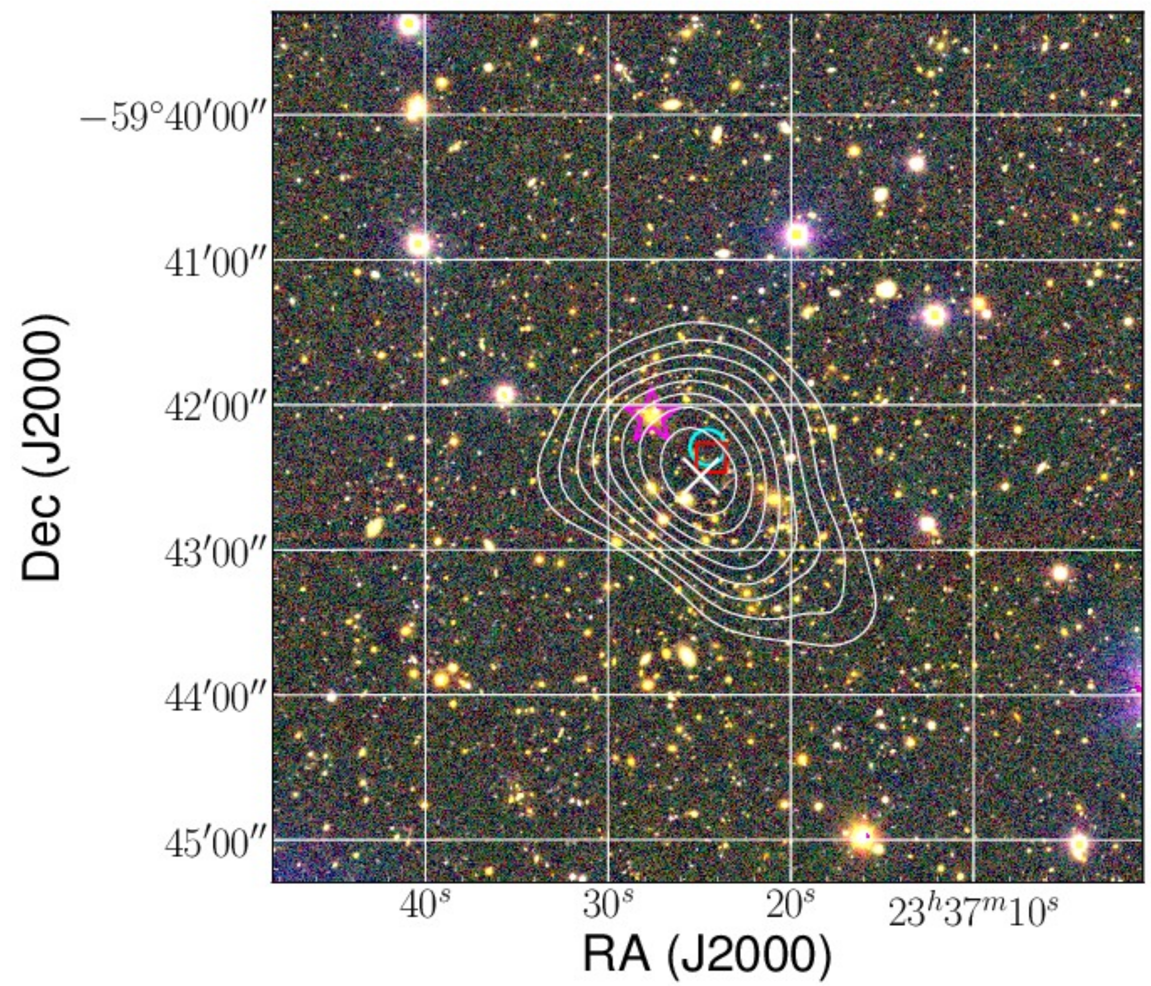
Low redshift



~700 SPT clusters with Dark Energy Survey Year 3 Shear measurements (Bocquet, Grandis, Bleem, Klein, Mohr et al. 2024a, PRD in press)

- DES photo-z and shear calibrations, use tomographic bins [2-4] of DES 3x2 analysis
- Simulation based calibration of shear profile observable -Mhalo relation using hydro sims (Grandis, Bocquet+21 MNRAS, 507, 5671G)

High Redshift



39 high-redshift clusters with

weak lensing mass constraints from HST data

Schrabback et al. (MNRAS 474.2635S, 2018)

Schrabback et al. (MNRAS 505.3923S, 2021)

Zohren et al. (A&A 668, A18, 2022)

Cosmological Analysis:

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.

Scaling Relation Parameters

A) normalization,

B) slope,

C) redshift evolution,

D) scatter,

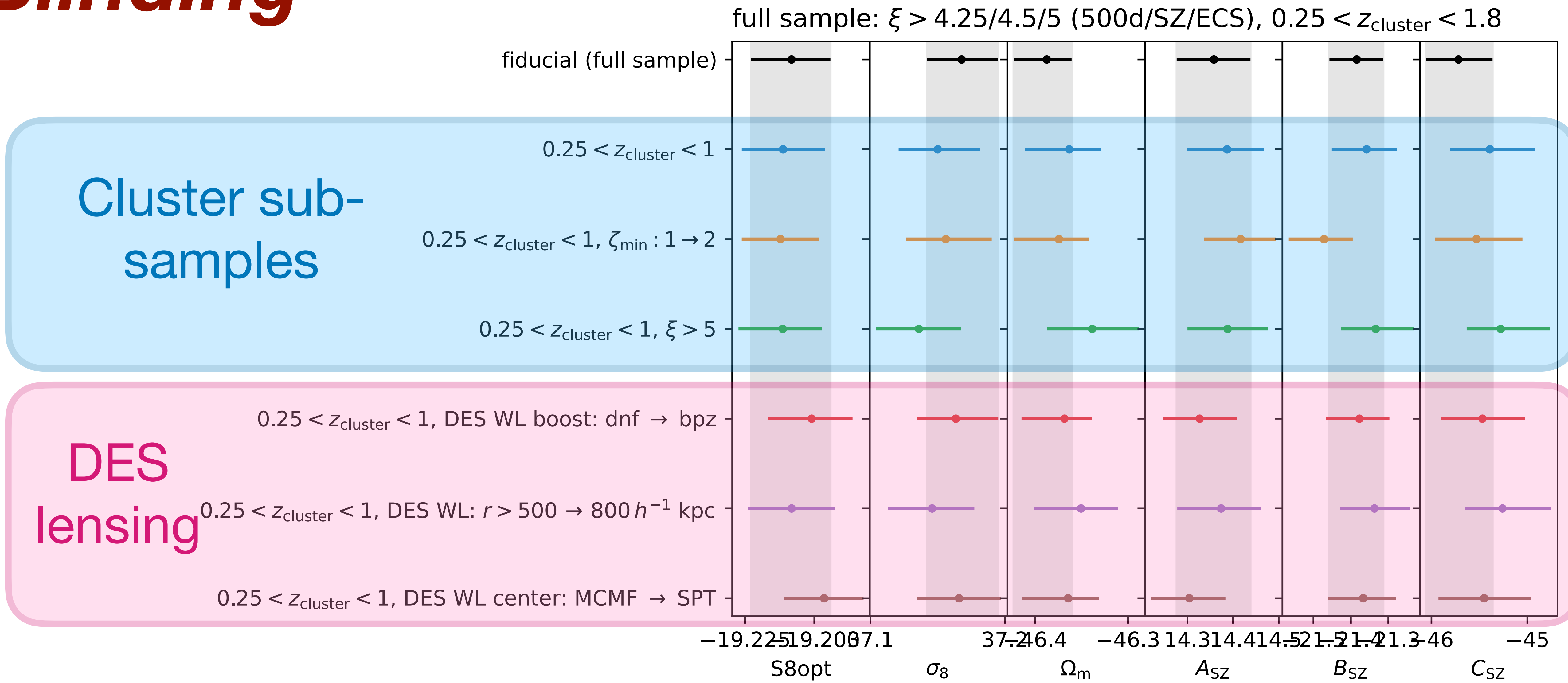
E) correlated scatter

For SZ and optical cluster observables + WL-halo mass calibration parameters for the 3 tomographic bins.

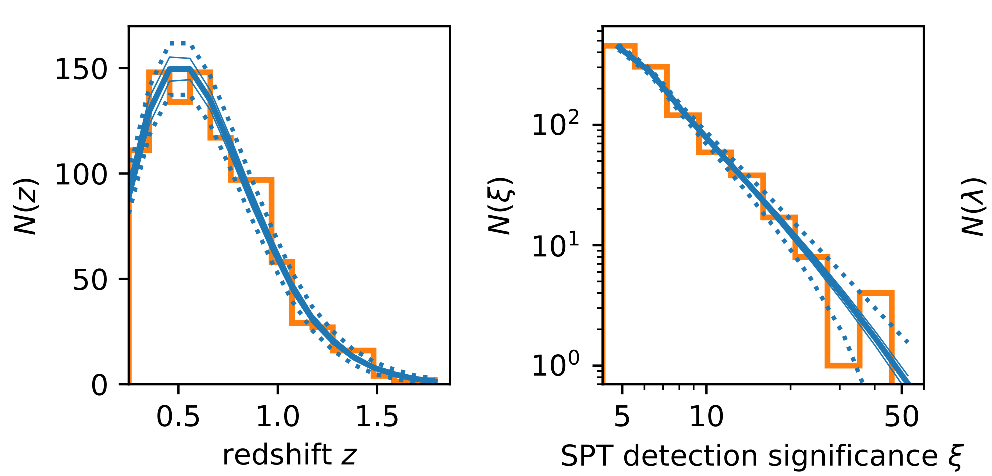
Cosmology Parameters

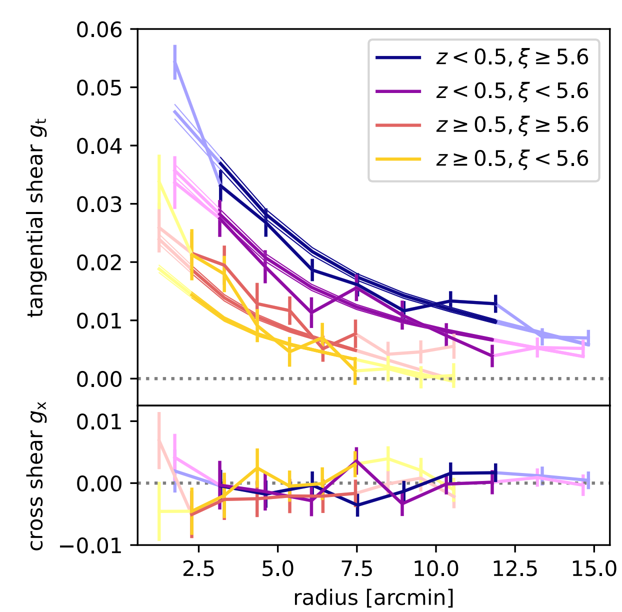
- ΛCDM Cosmology
  - $\Omega_{\mathrm{m}} h^2$, $\Omega_{\mathrm{b}} h^2$, A_{s}, n_s, θ_s
  - $+\Sigma m_\nu$
- Extension Cosmology
  - w, $\sigma_8(z)$

Blinding

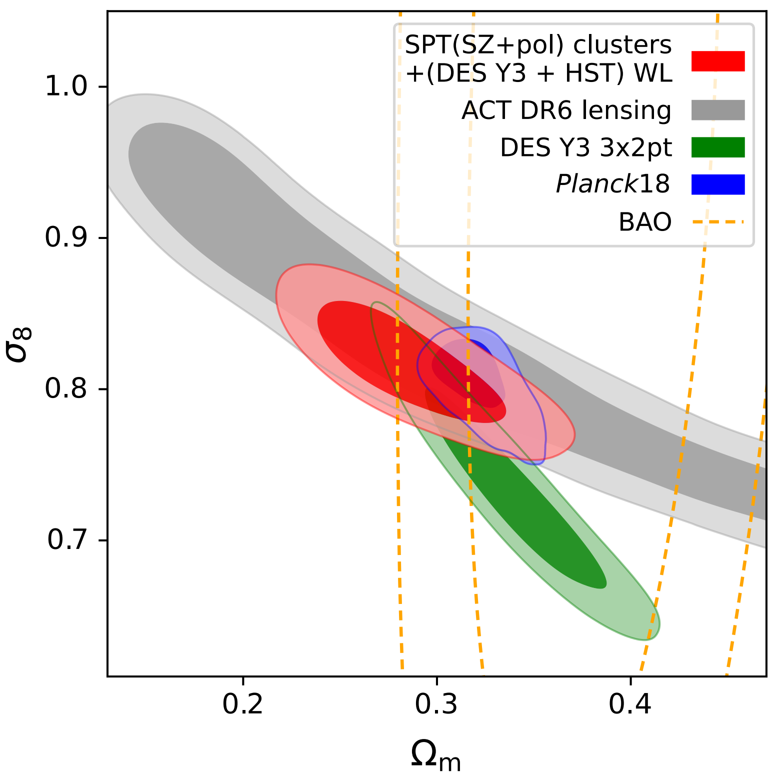


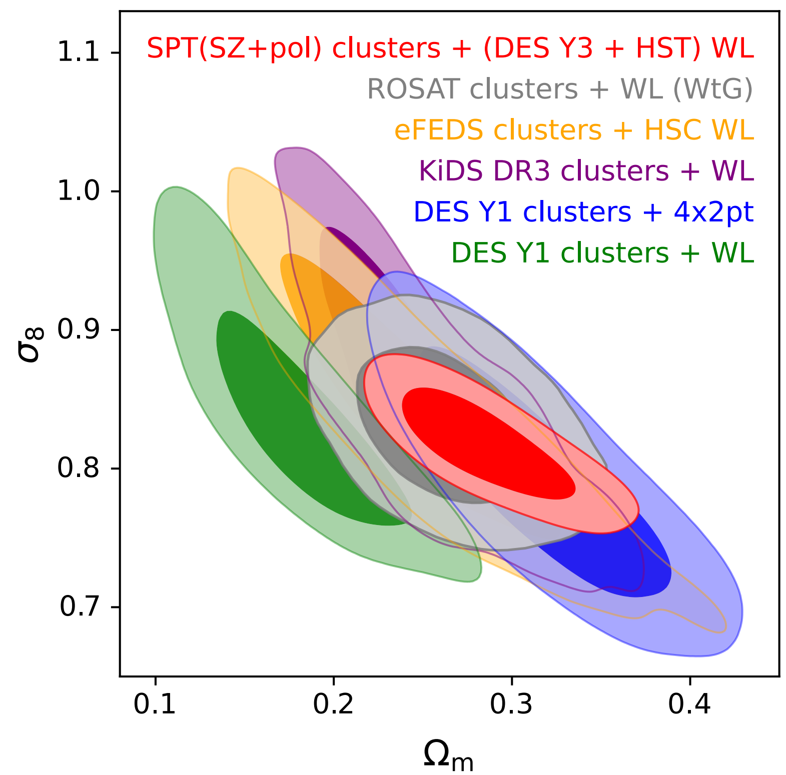
Mean recovered model (with uncertainties) from blinded analysis.

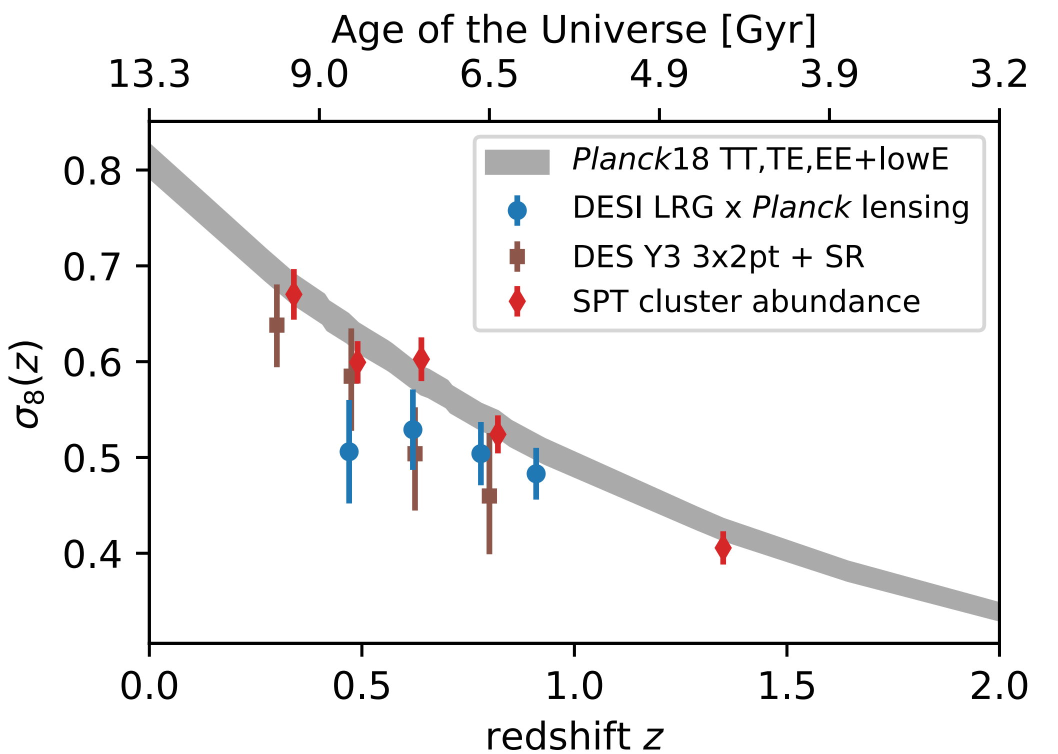




SPT-SZ + SPTpol Clusters w/ DES + HST Weak Lensing

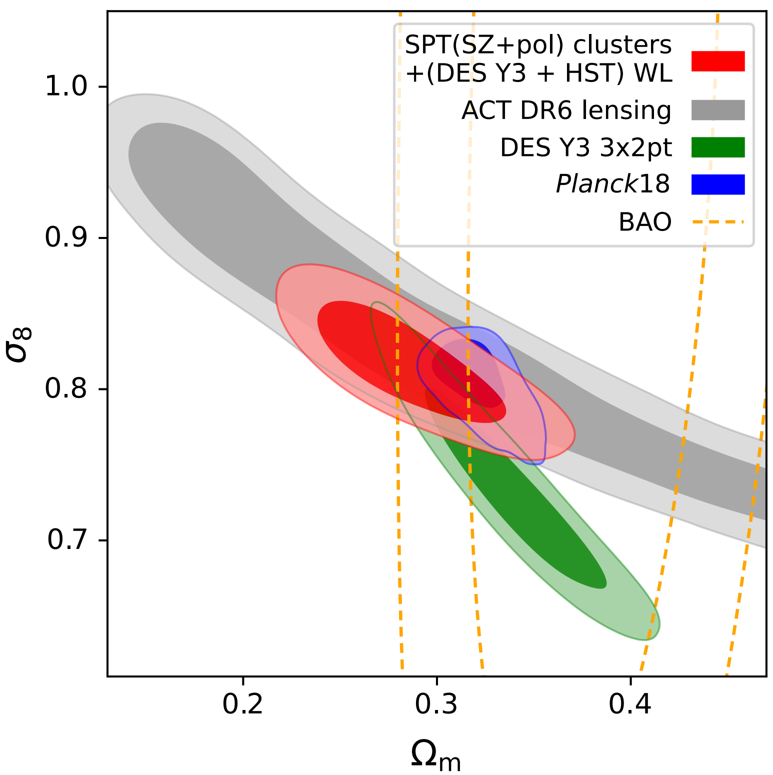




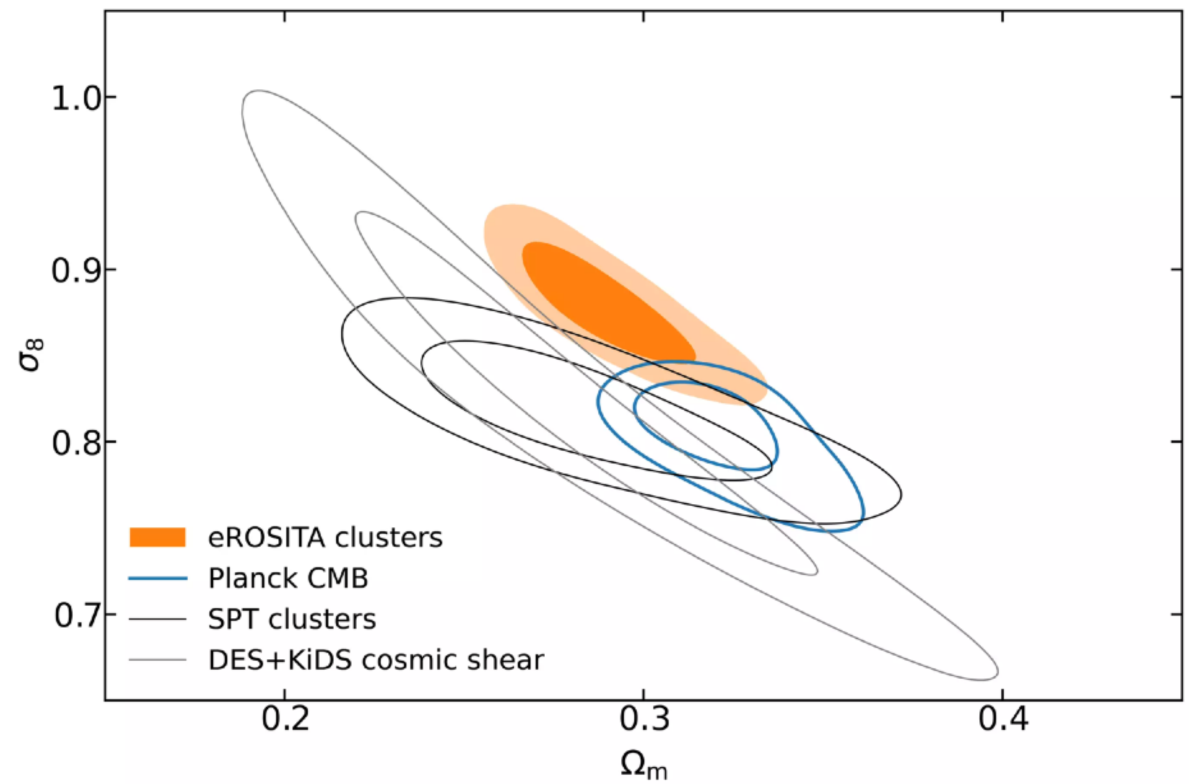


S. Bocquet, S. Grandis, L. Bleem, M. Klein, J. Mohr, T. Schrabback with SPTpol & DES collaborations
arXiv: 2401.02075; PRD in press

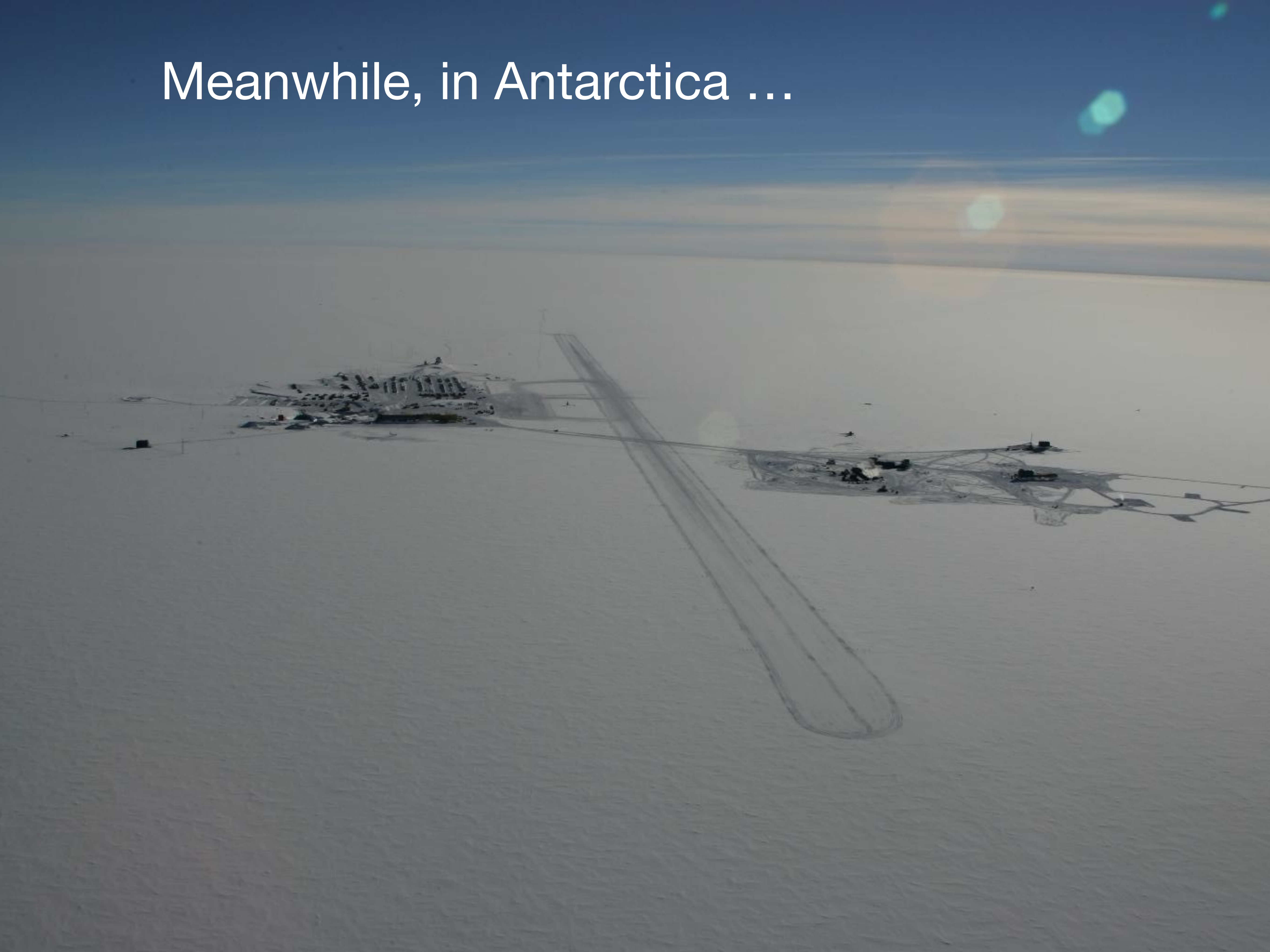
New eROSITA results - Lots more to explore in cluster cosmology!



Ghirardini et al. arXiv: 2402.08458



Meanwhile, in Antarctica …



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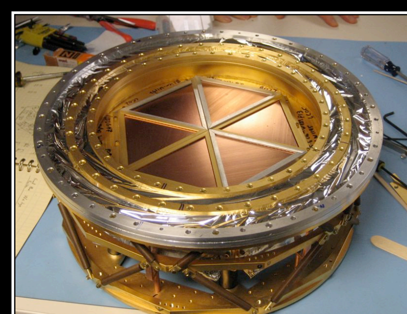

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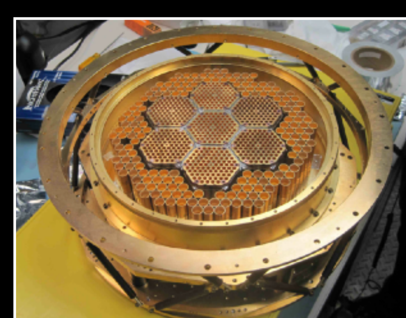

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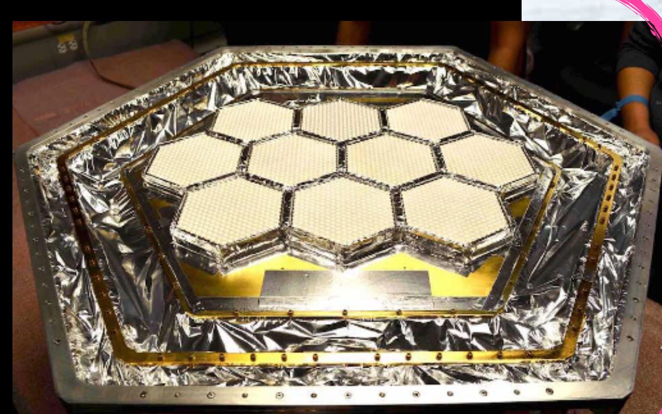

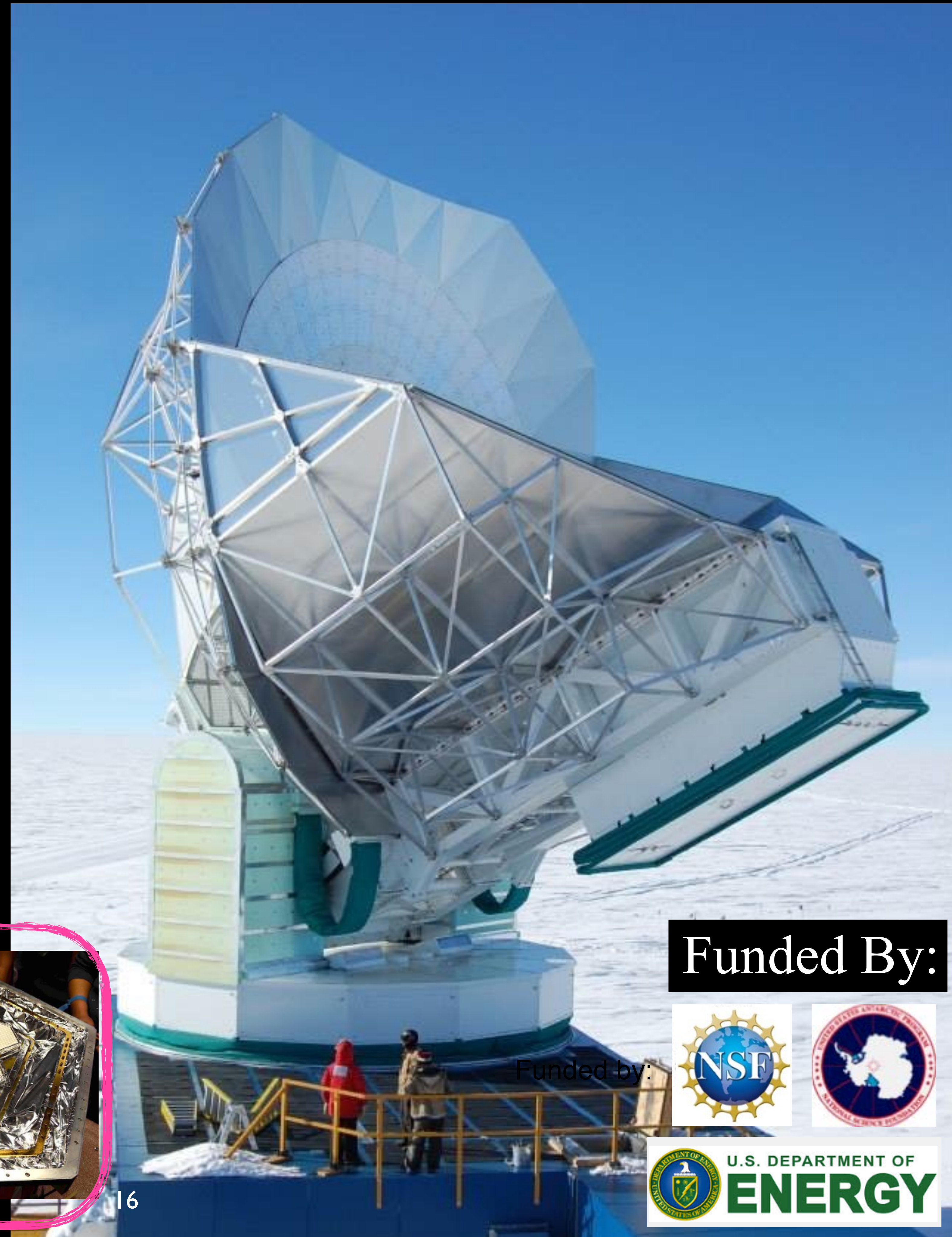

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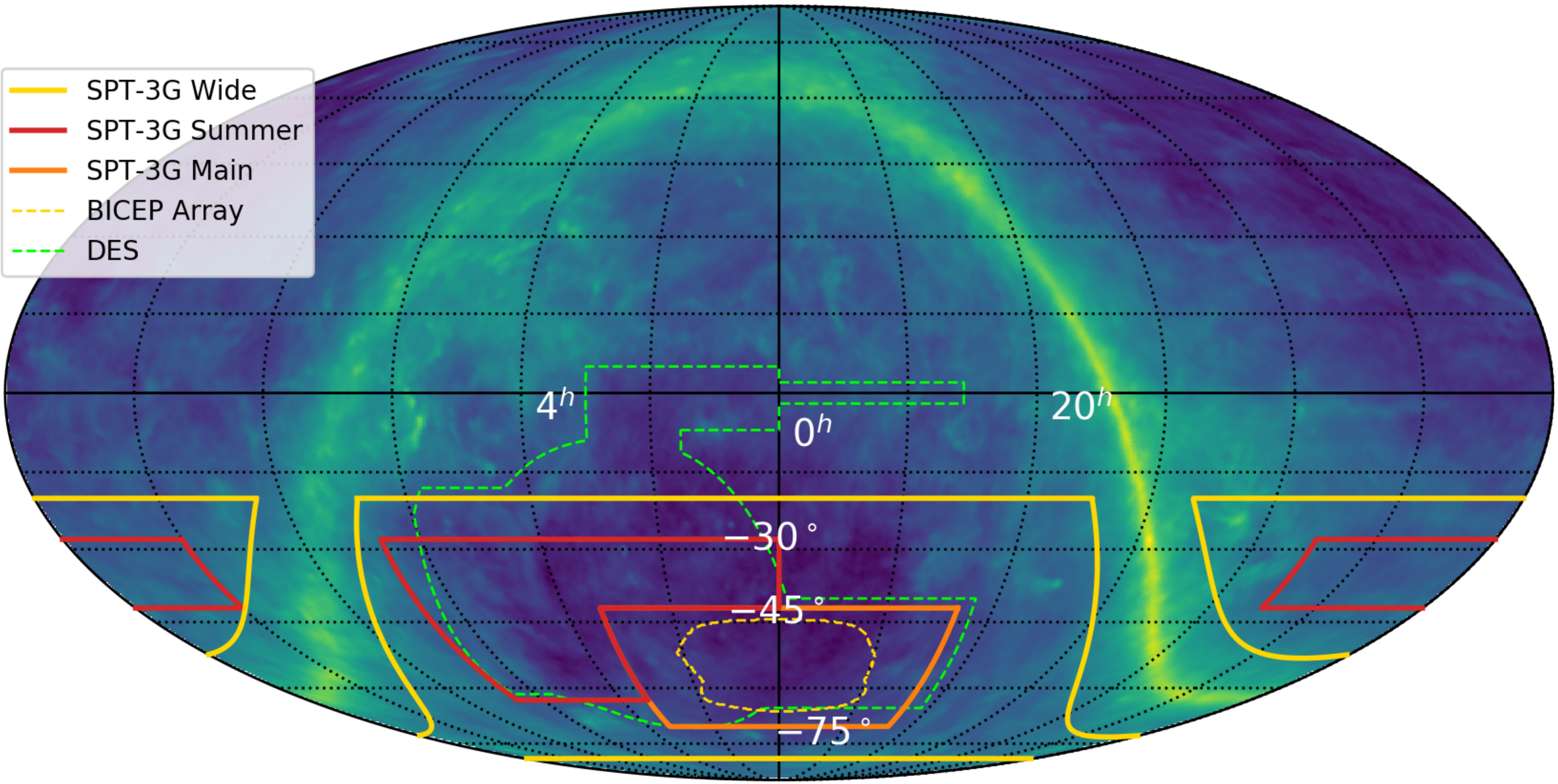
U.S. DEPARTMENT OF ENERGY

The 10,000 square-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

Finishing 10k deg^2 surveyed this month!

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

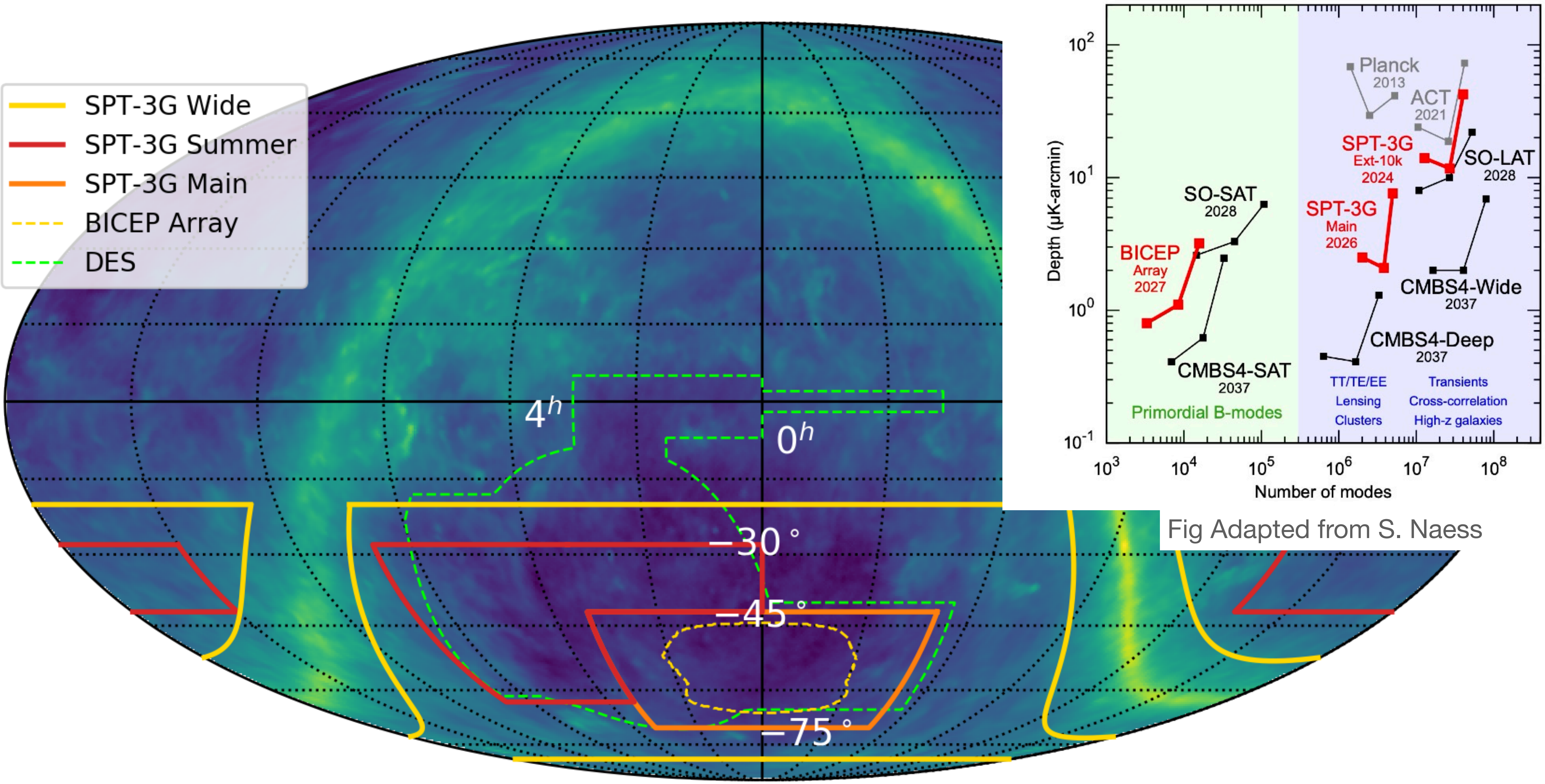


Fig Adapted from S. Naess

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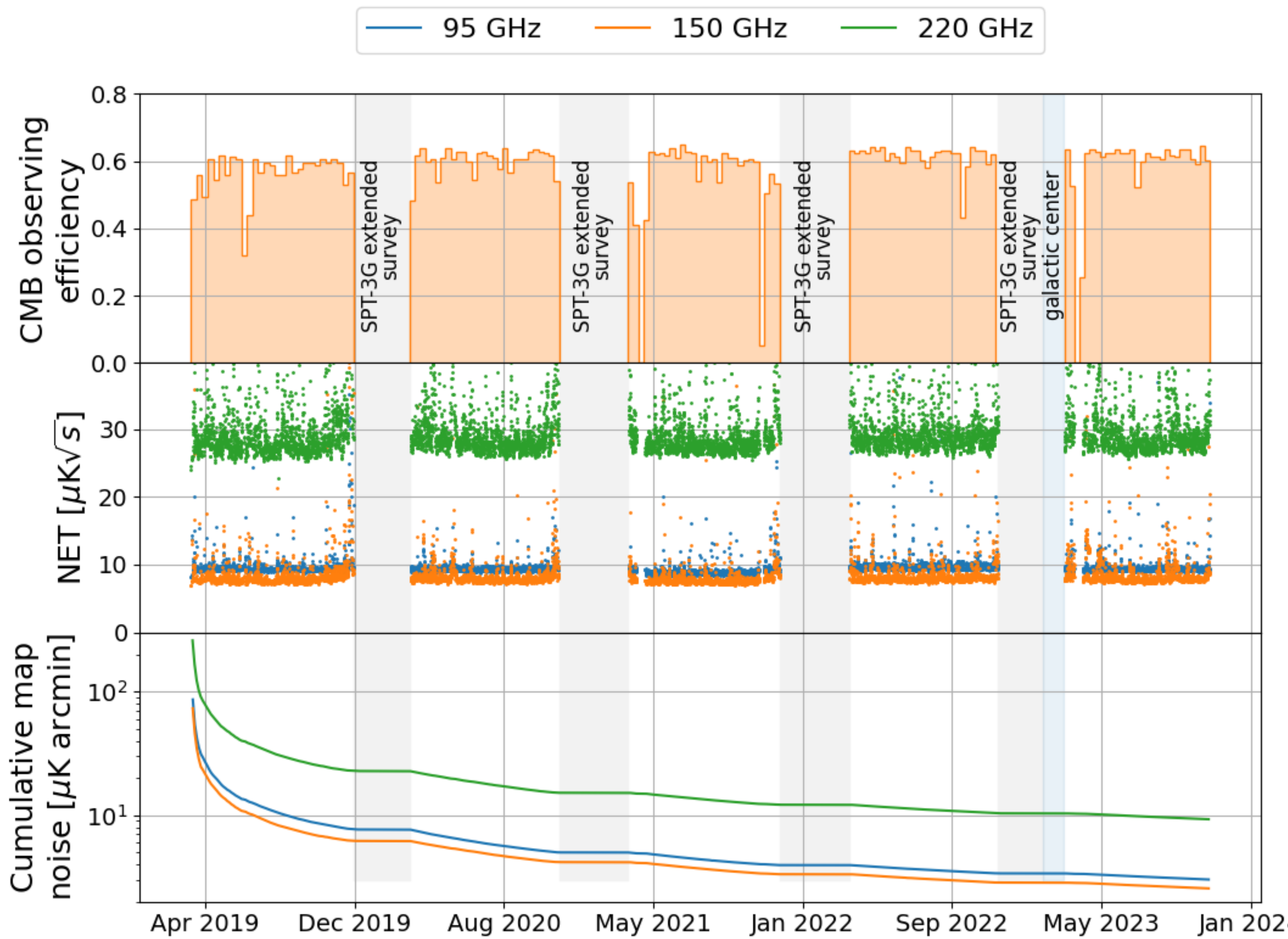
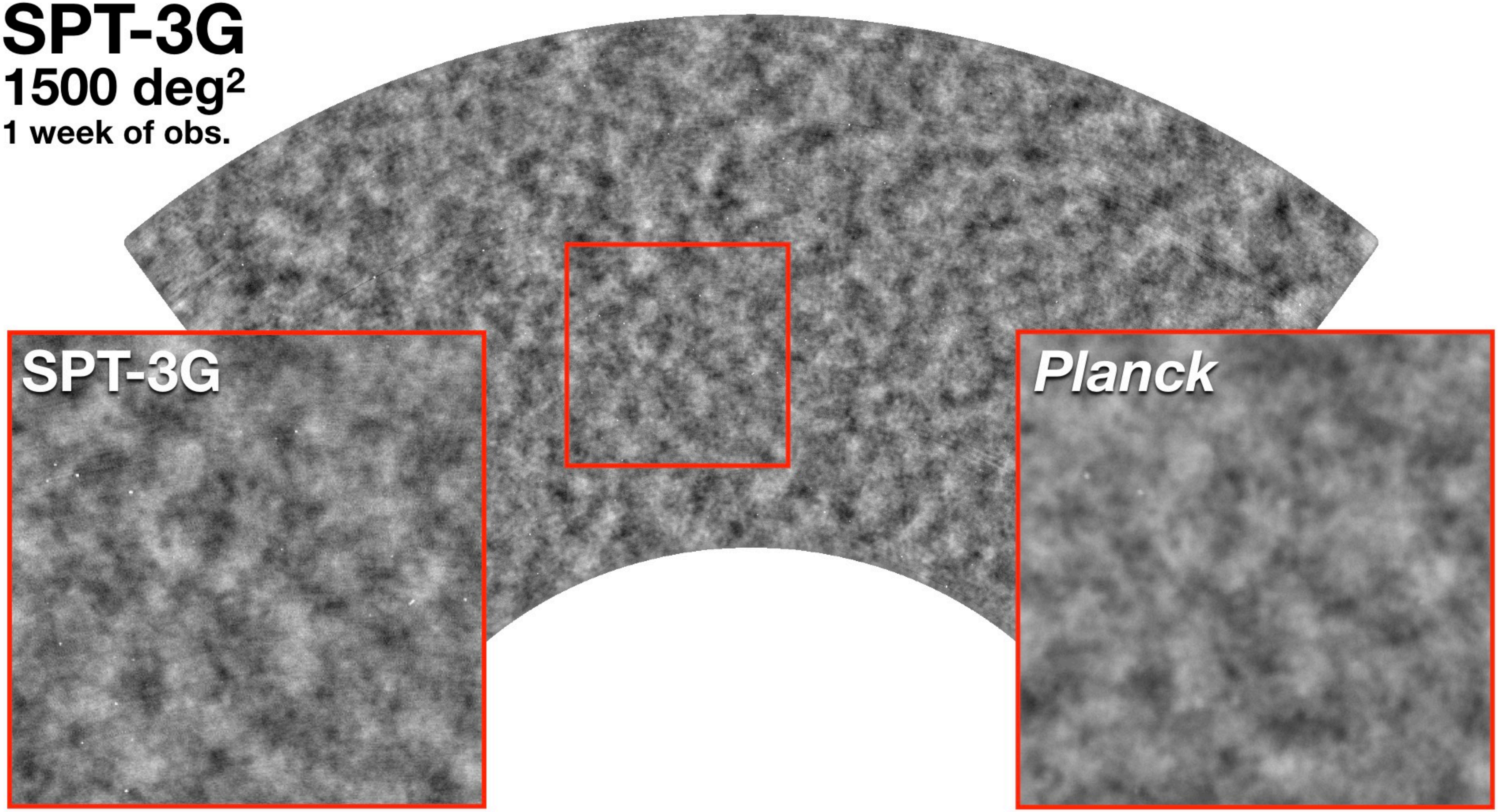
SPT-3G Observations

SPT-3G has thus far achieved nominal observing efficiency and sensitivity over the 2019-2023 observing seasons.

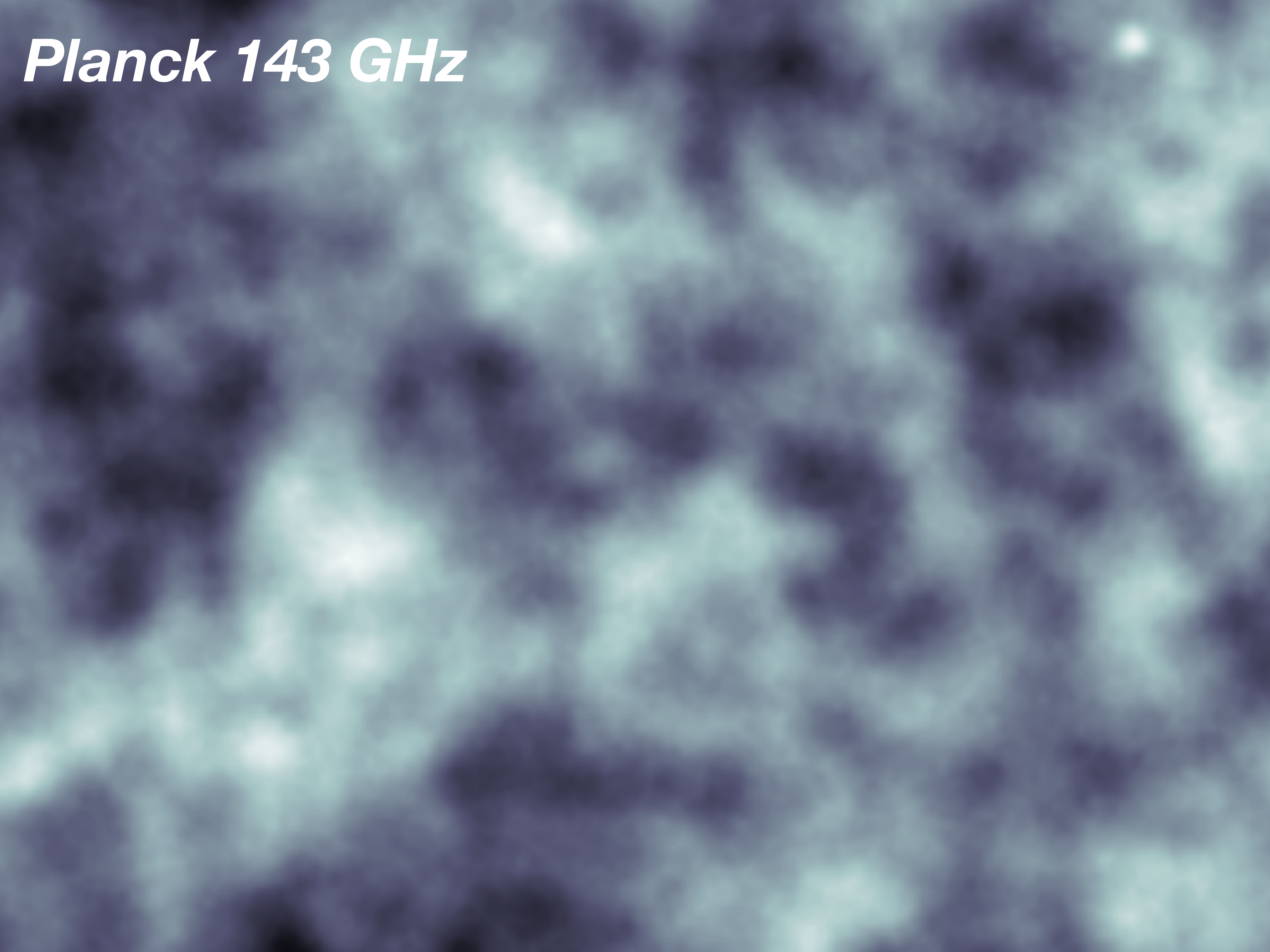


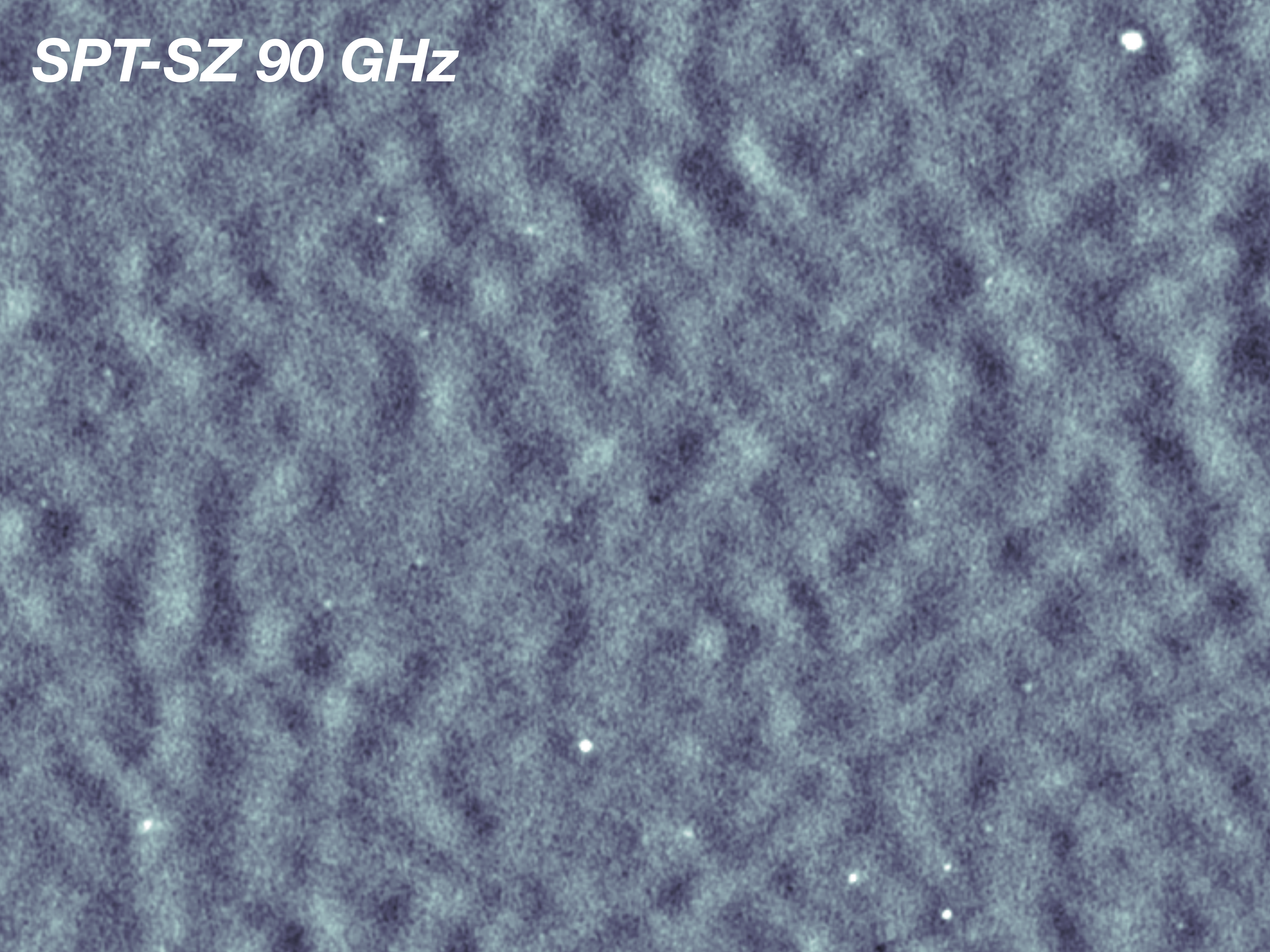
Plot Credit: Amy Bender

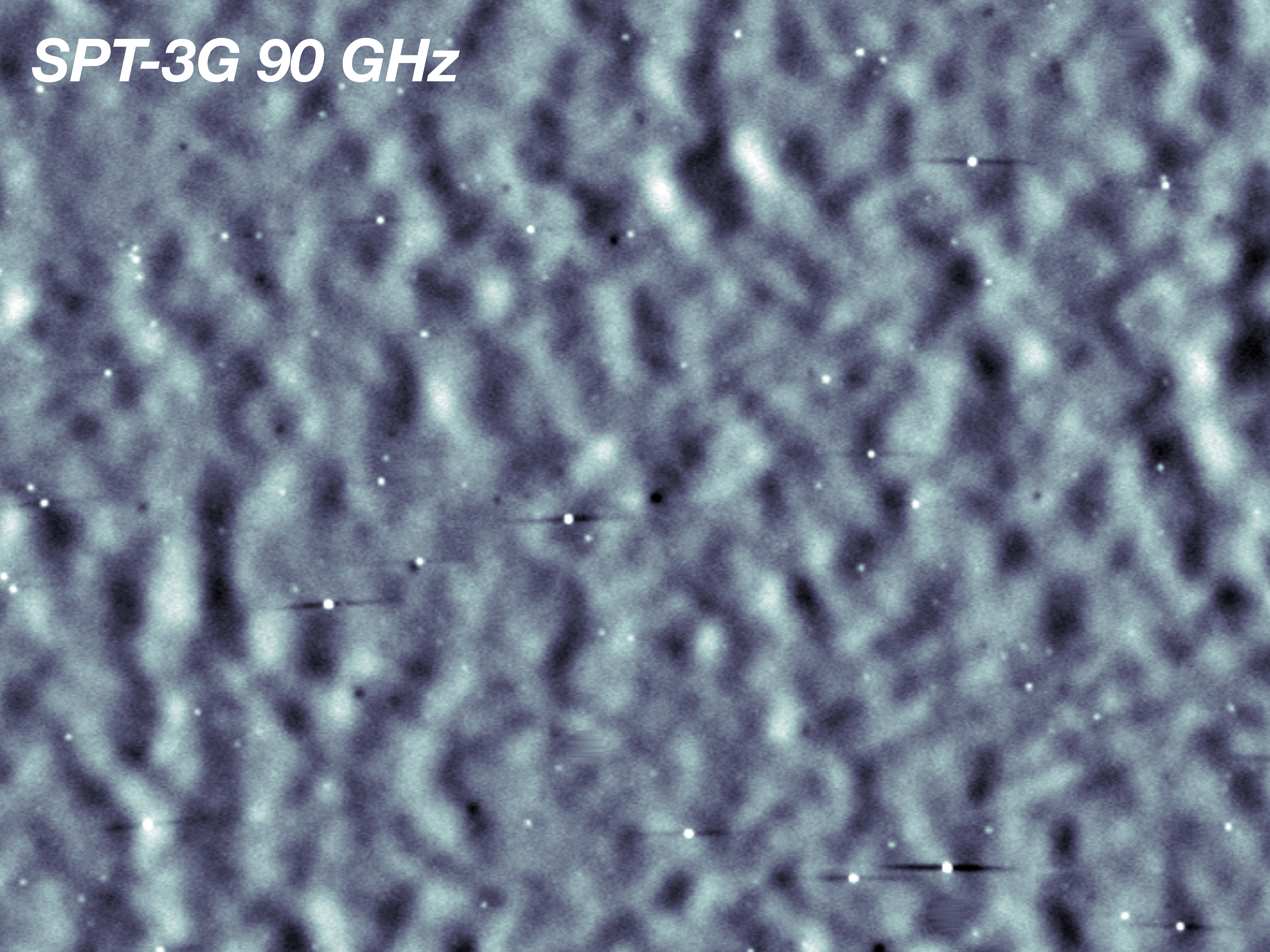
SPT-3G
1500 deg^2
1 week of obs.



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


Planck 143 GHz


SPT-SZ 90 GHz


SPT-3G 90 GHz

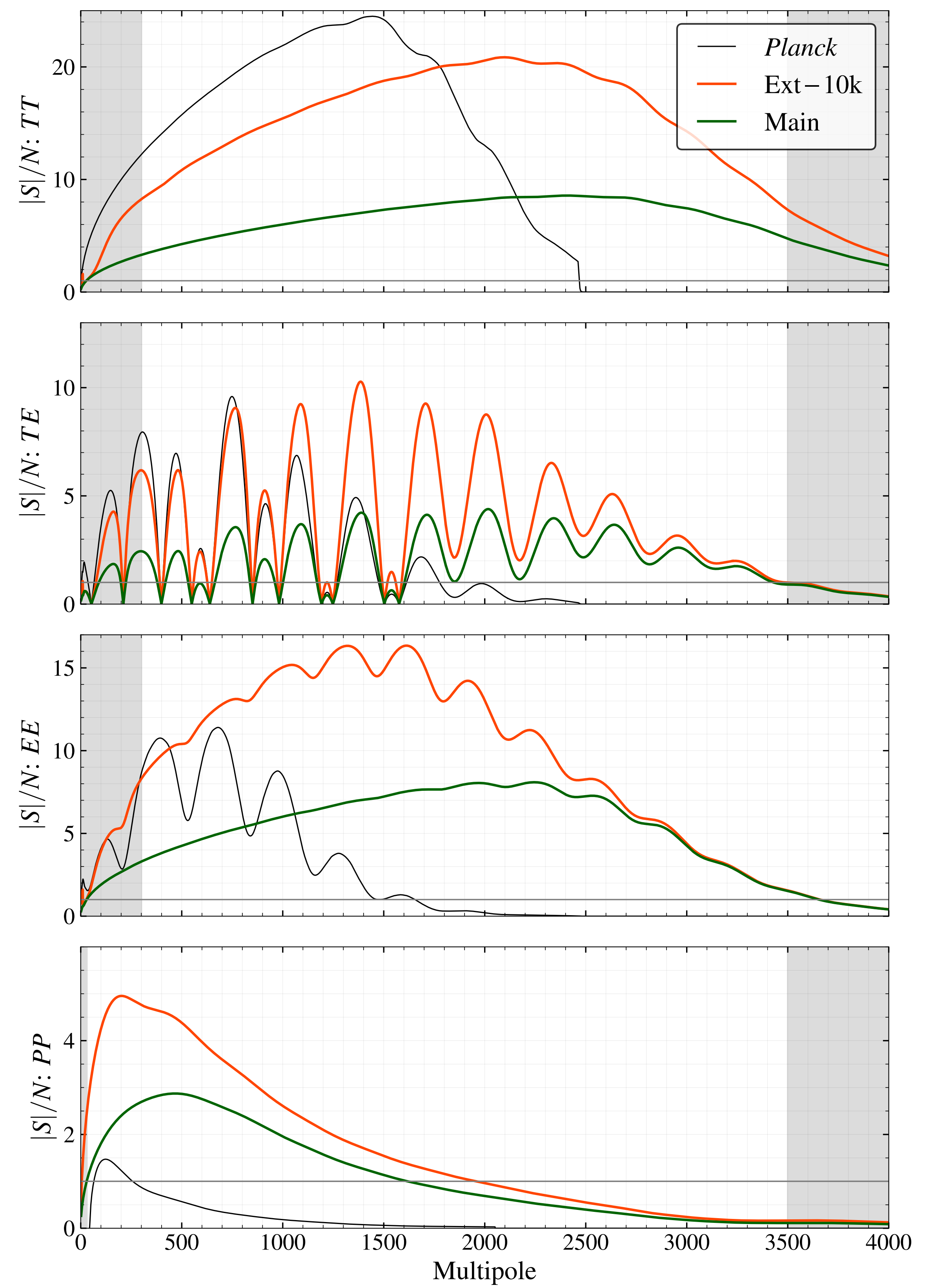

SPT-3G 90 GHz
Clusters of Galaxies
“Shadows” in the microwave background from clusters of galaxies

Forecasts for Full Survey Constraints

Measurements from the SPT-3G 10k survey will enable powerful tests of the ΛCDM cosmological model.

For power spectrum and lensing measurements this constraining power comes from multipoles highly complementary to those that determine *Planck* results.

SPT-3G forecasting paper, Prabhu et al. *arXiv: 2403.17925*



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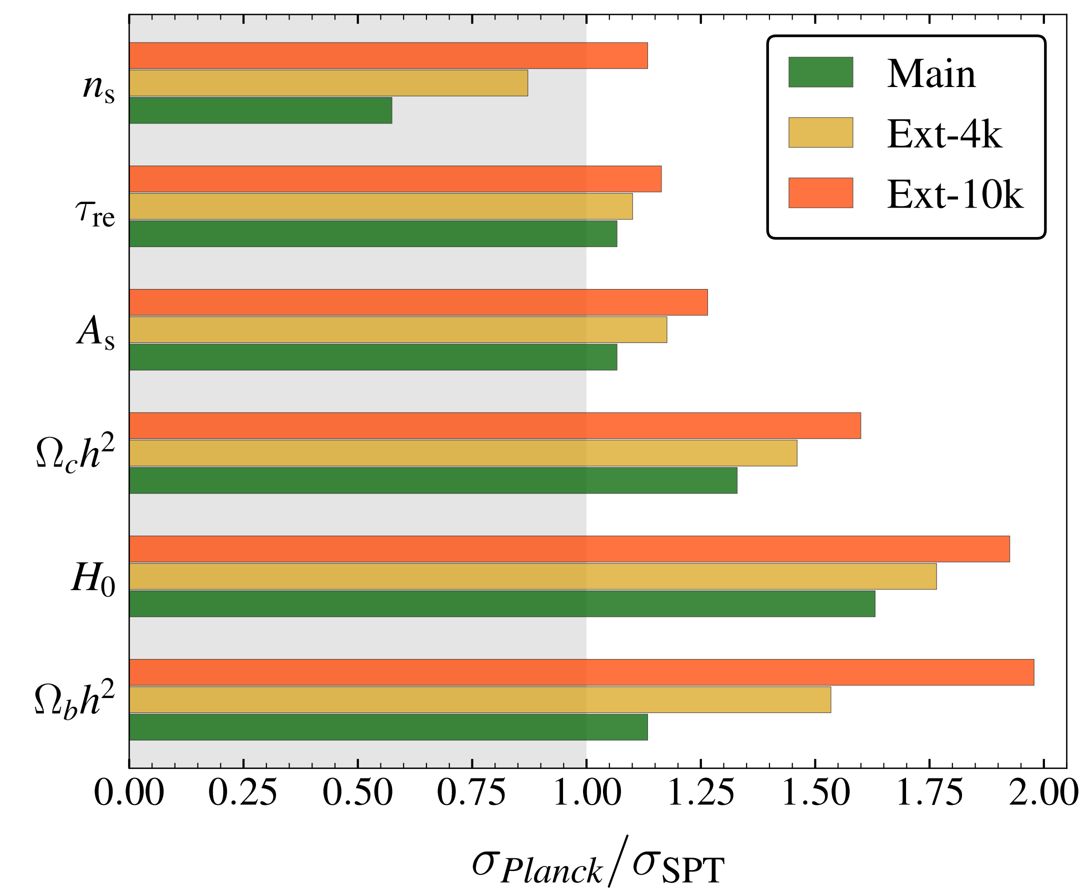
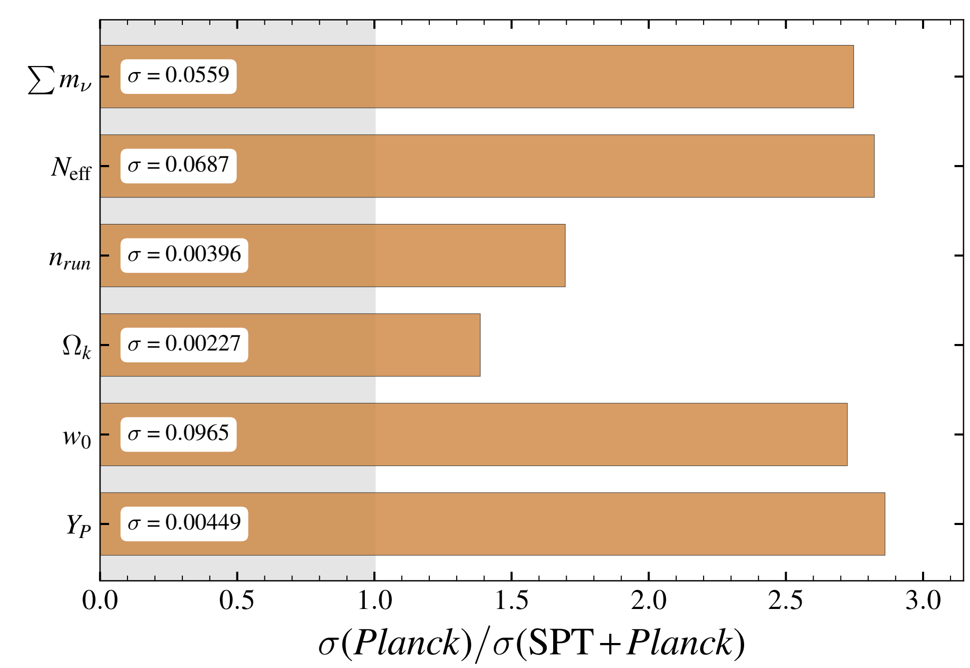
Measurements from the SPT-3G 10k survey will enable powerful tests of the ΛCDM cosmological model.

For power spectrum and lensing measurements this constraining power comes from multipoles highly complementary to those that determine *Planck* results.

- *Independent tests of ΛCDM from CMB of comparable or better constraining power than Planck.*
  - ***~2x better constraints than Planck on H_0.***
- *Significant improvements when combining datasets.*

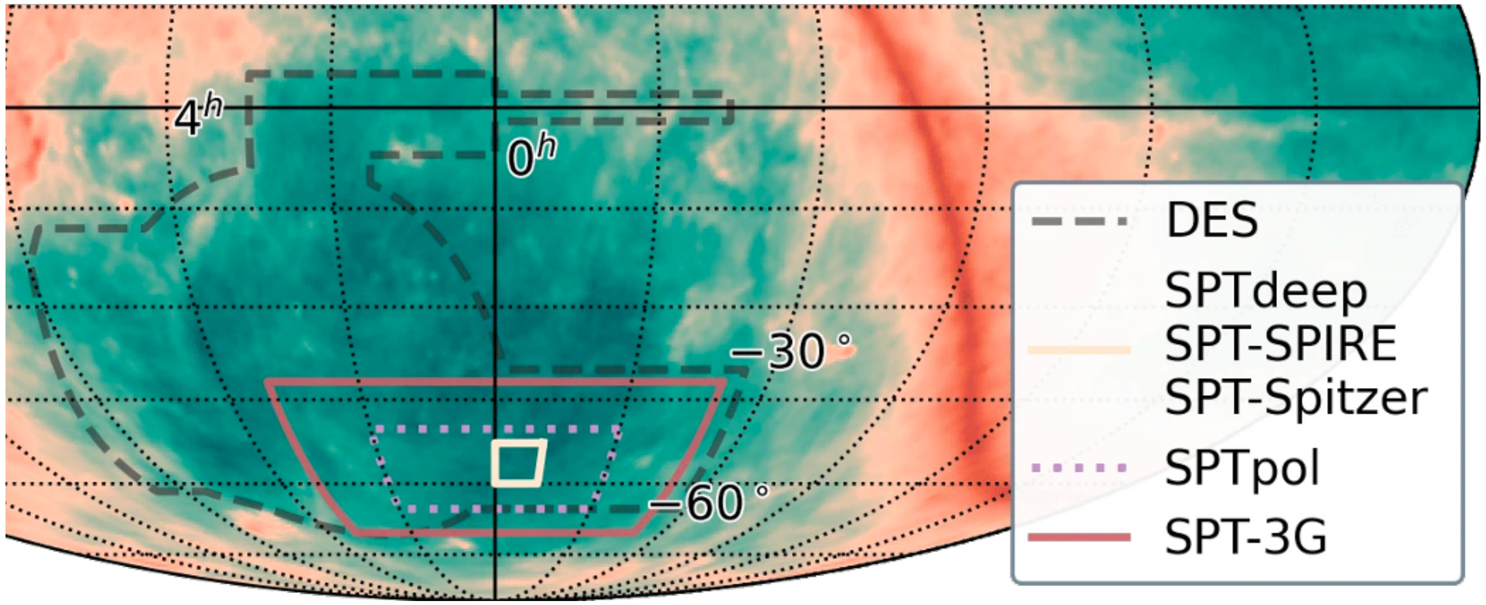
SPT-3G forecasting paper, Prabhu et al. *arXiv: 2403.17925*





The First SPT-3G Cluster Catalog: 100d Deep Field

- The 100d SPT deep field combines data from 5 years of SPT-3G with the SPTpol 100d+ 500d surveys (10 years of CMB observations in total!)
- SPT 100d field overlaps with multi-wave surveys:
  - **Herschel** SPIRE (250, 350, 500 um) (Viero et al., 1810.10643)
  - **Spitzer** SSDF (3.6, 4.5 um) (Ashby et al., 1308.0201)
  - **ATCA** (1.8 GHz)
  - **MeerKAT**
  - **XMM-XXL** (25 deg^2) (Pierre et al.)
  - **Targeted Chandra** (LP PI: McDonald) on 18 clusters at $0.8 < z < 1.4$
  - Wide field surveys from **DES**, **eROSITA**, and (soon) **Euclid**



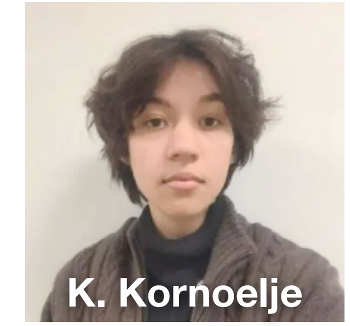
SPT100d Noise Levels

- 90: 3 μK
- 150: 2 μK
- 220: 9 μK

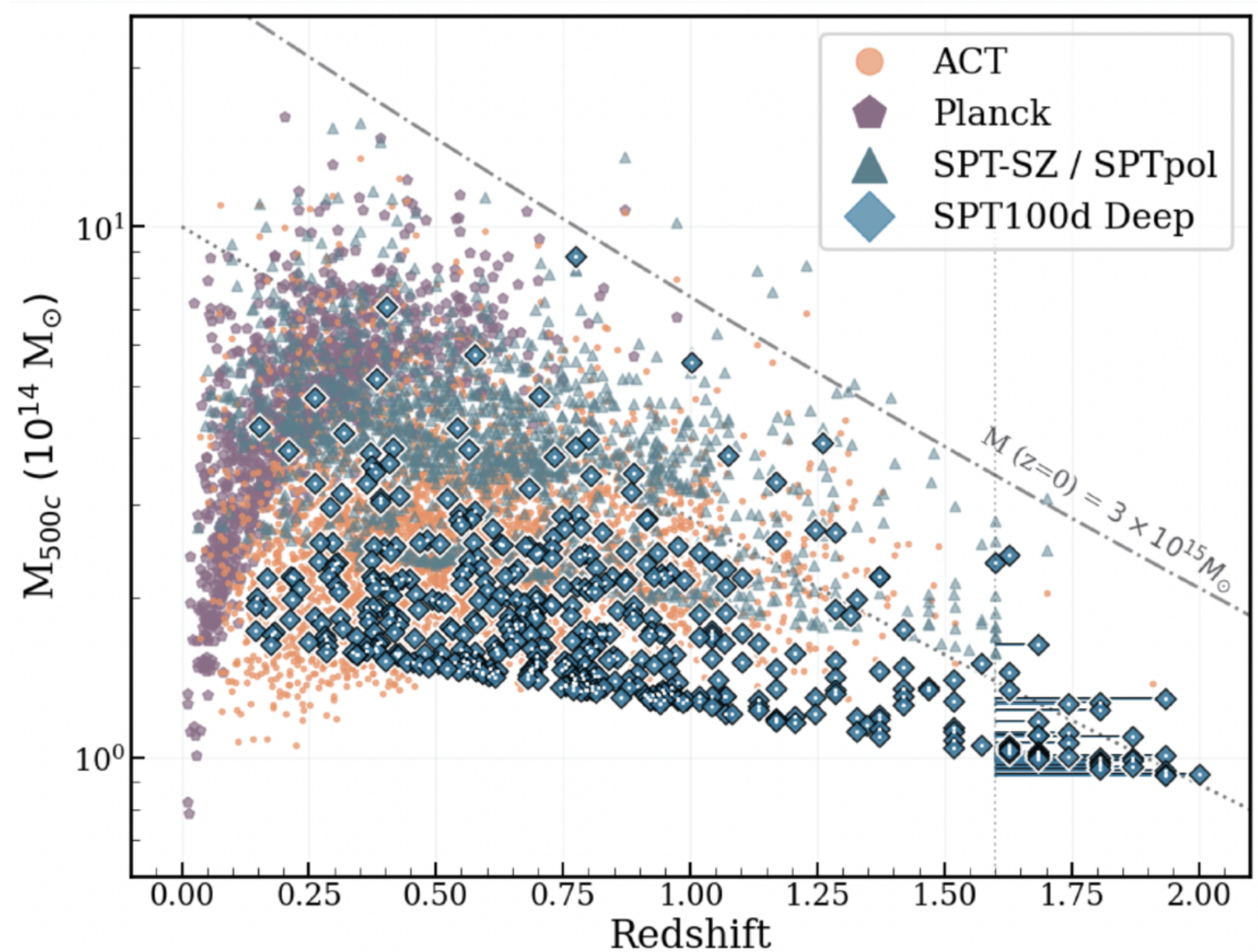
CMB-S4 Wide Noise Levels:

- 93: 1.89 μK
- 145: 2.09 μK
- 225: 6.9 μK

The First SPT-3G Cluster Catalog: 100d Deep Field

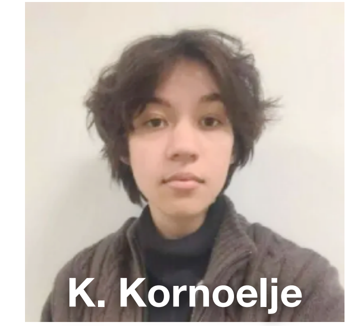


- The 100d SPT deep field combines data from 5 years of SPT-3G with the SPTpol 100d+ 500d surveys (10 years of CMB observations in total!)
- First cluster catalog to be constructed from data at CMB-S4 noise levels.
- Fantastic sample for cluster evolution studies.



	Median Redshift (z)	Median Mass ($M_{500c} \times 10^{14}$)	Cluster Density (deg^{-2})
Planck	0.22	4.74	0.02
ACT	0.52	2.38	0.32
SPT-SZ/SPTpol	0.58	3.72	0.49
SPT100d Deep	0.75	1.48	3.92

The First SPT-3G Cluster Catalog: 100d Deep Field



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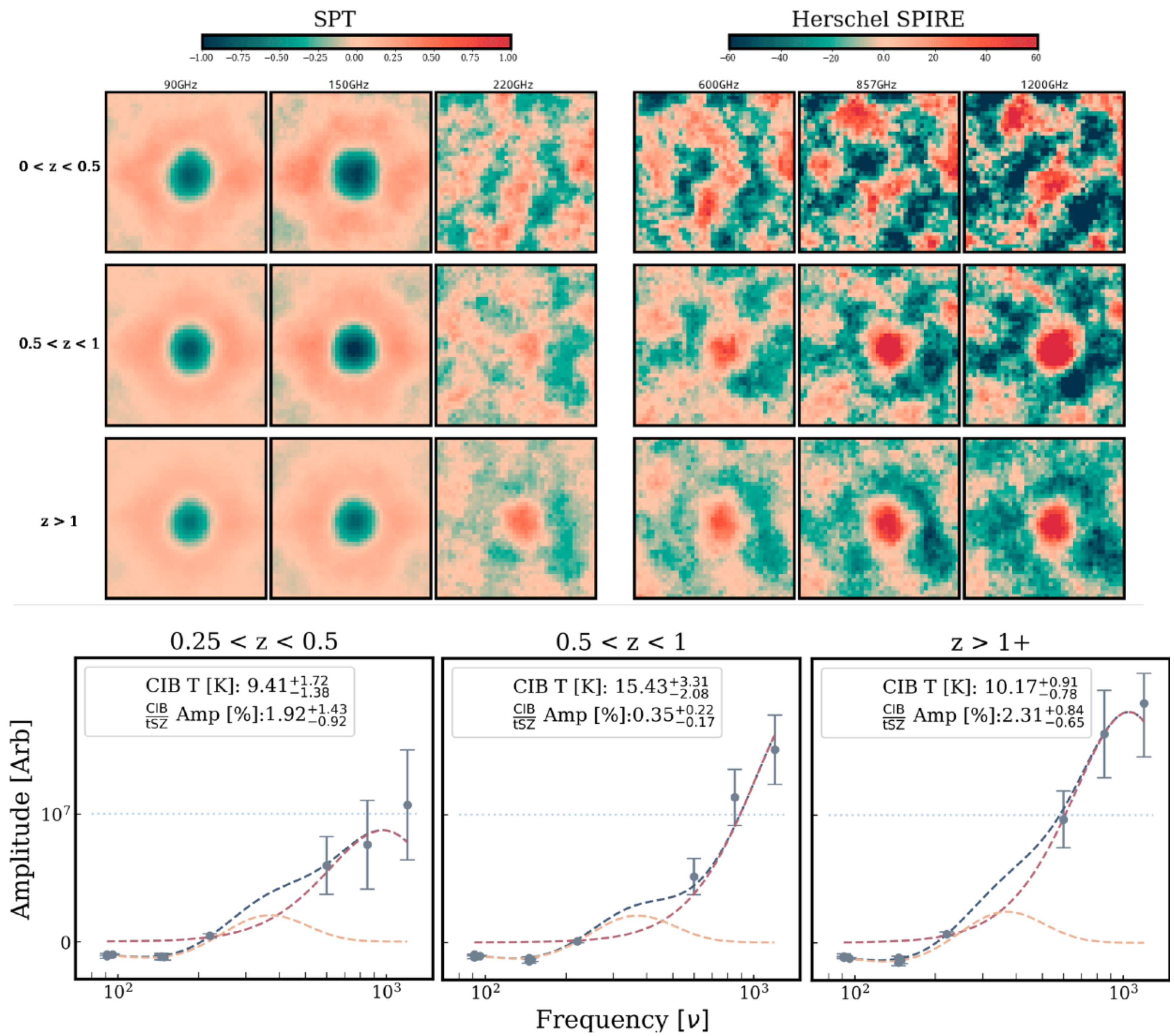
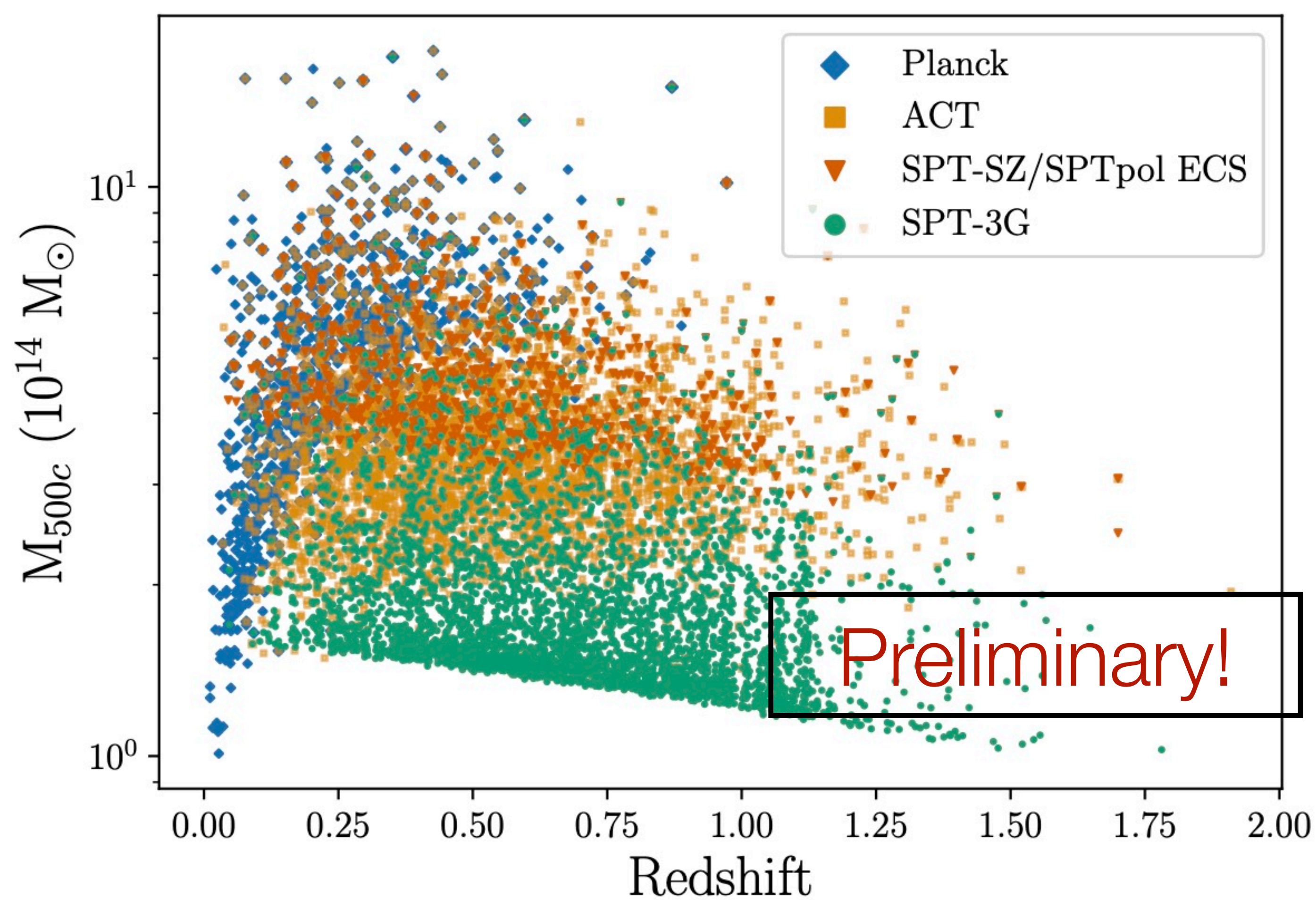
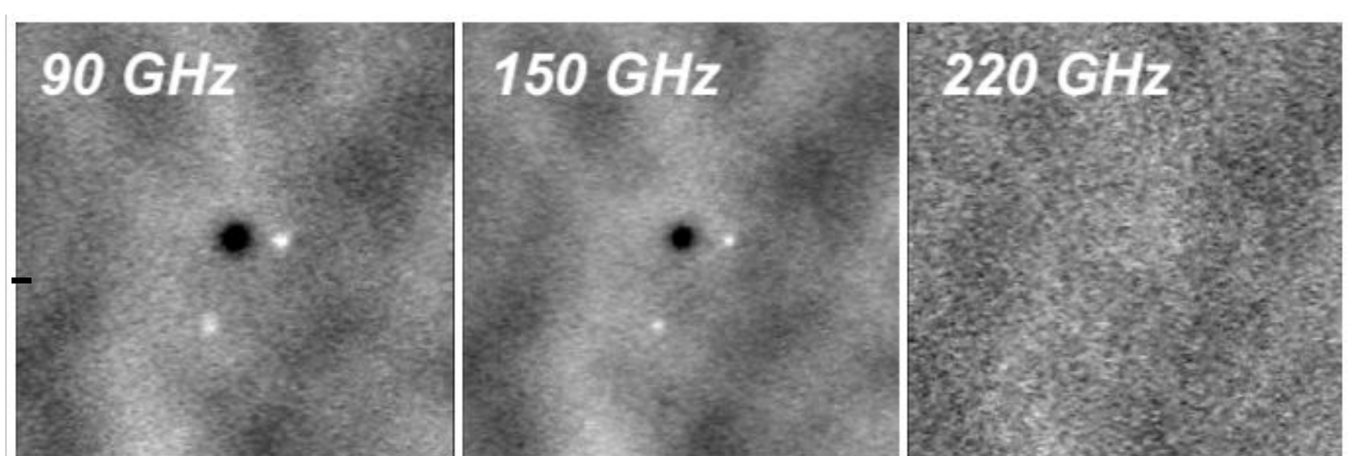
- First cluster catalog to be constructed from data at CMB-S4 noise levels.
- Fantastic sample for cluster evolution studies.
- Enabling us to explore systematics from correlated emission from member galaxies and to build and test robust cluster identification algorithms.



The SPT-3G wide field SZ Catalogs

- SZ candidate lists in progress from 3 SPT surveys (~10,000 deg^2 of sky coverage on disk!)
- Preliminary cluster run on 1500d 5 year data has produced a catalog with 5200 candidates at xi>5 (>99% purity), >9400 candidates at x>4
- Candidates to be confirmed with a combination of DES, DECALS, targeted Magellan 4*, and Euclid data
- 835 matches to eRASS1 Cluster sample
- 2392 matches to eRASS1-m X-ray sources within 1'





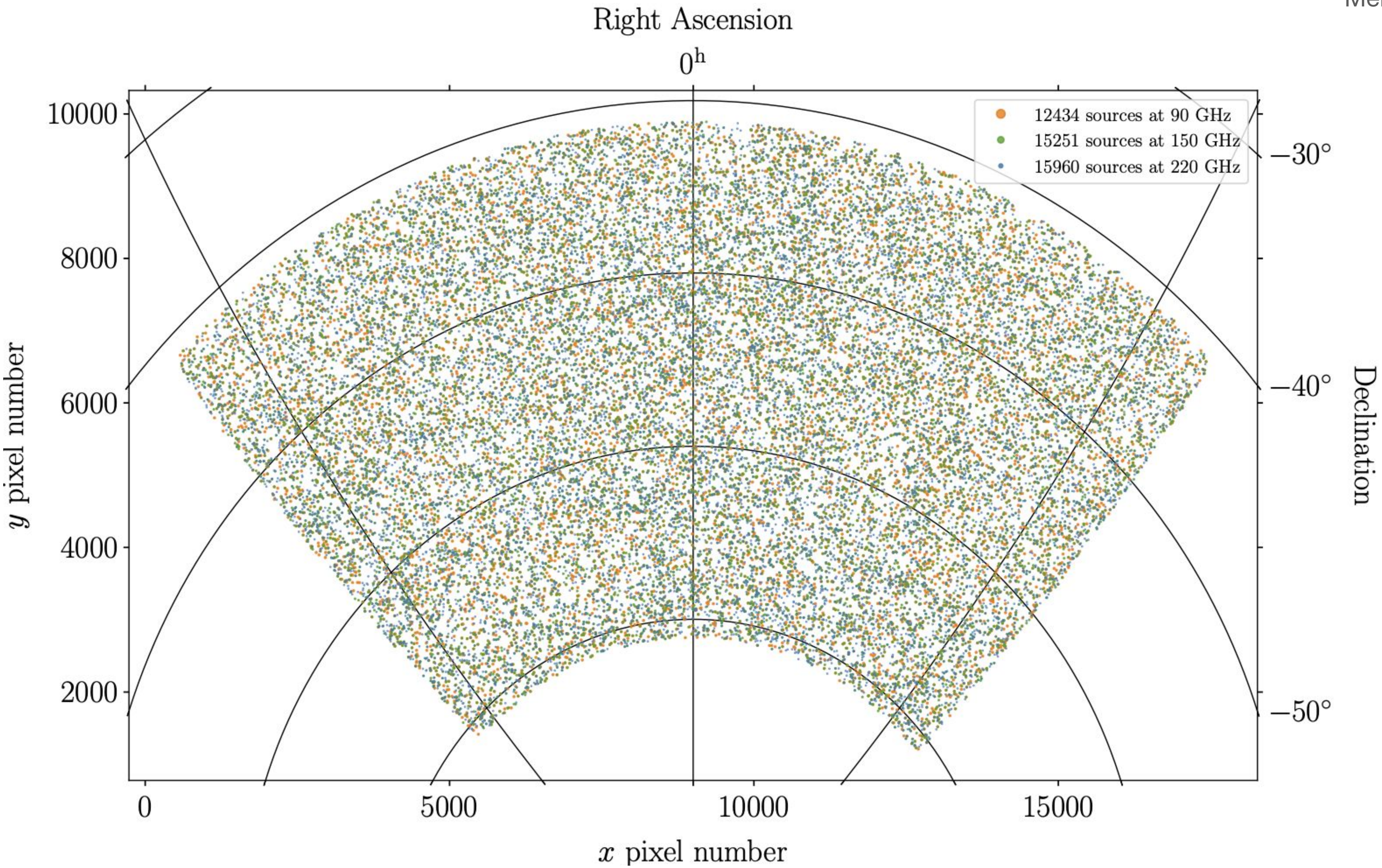
SPT-CL J2344-4243
(Phoenix Cluster, z=0.6) seen in SPT-3G data
at S/N>125 in 5 year data

with L. Bleem, T. de Haan,
F. Kéruzoré, K. Kornoelje, J. Sobrin

Emissive Sources in the SPT-3G Survey - a first look

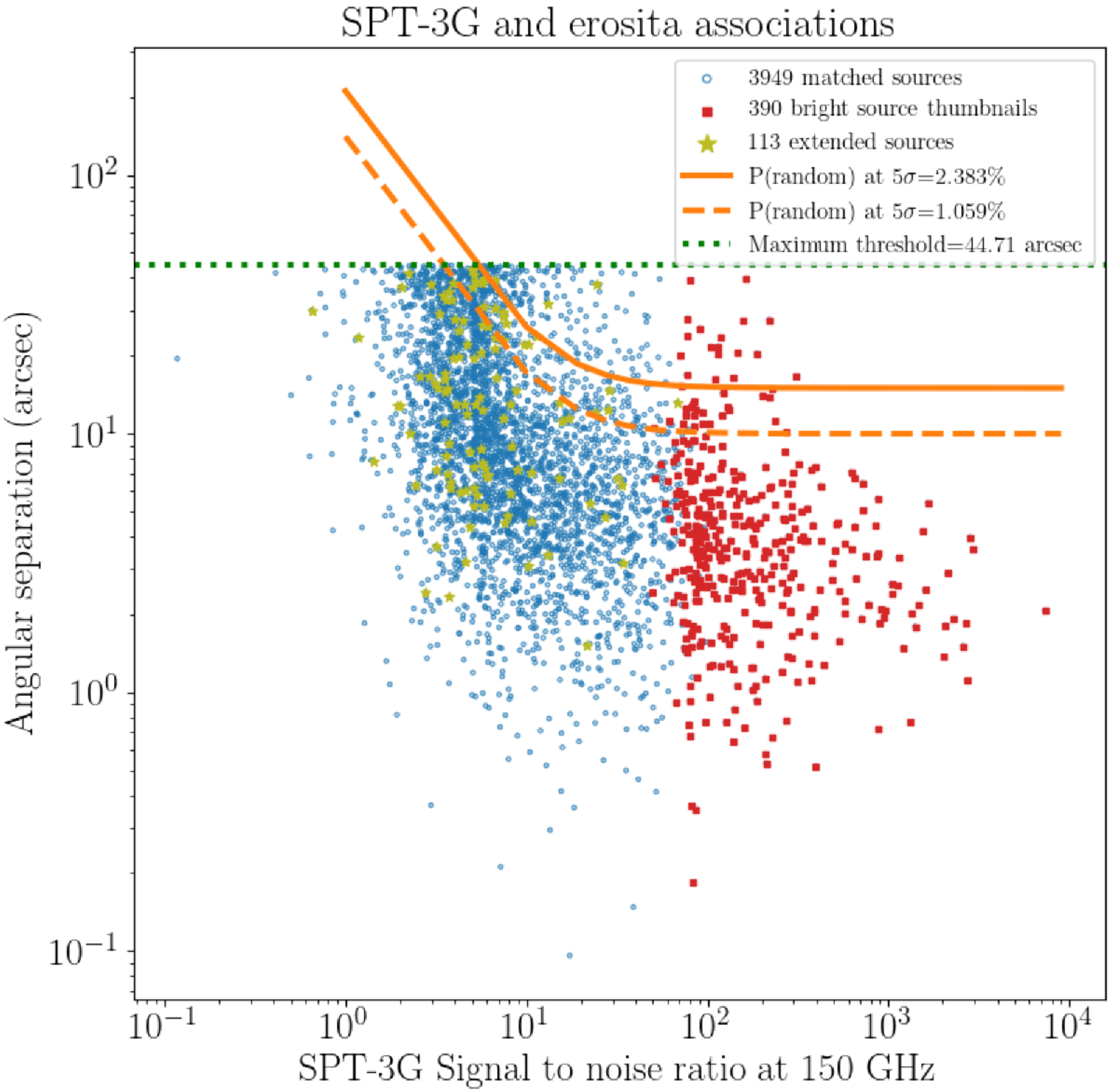
Melanie Archipley

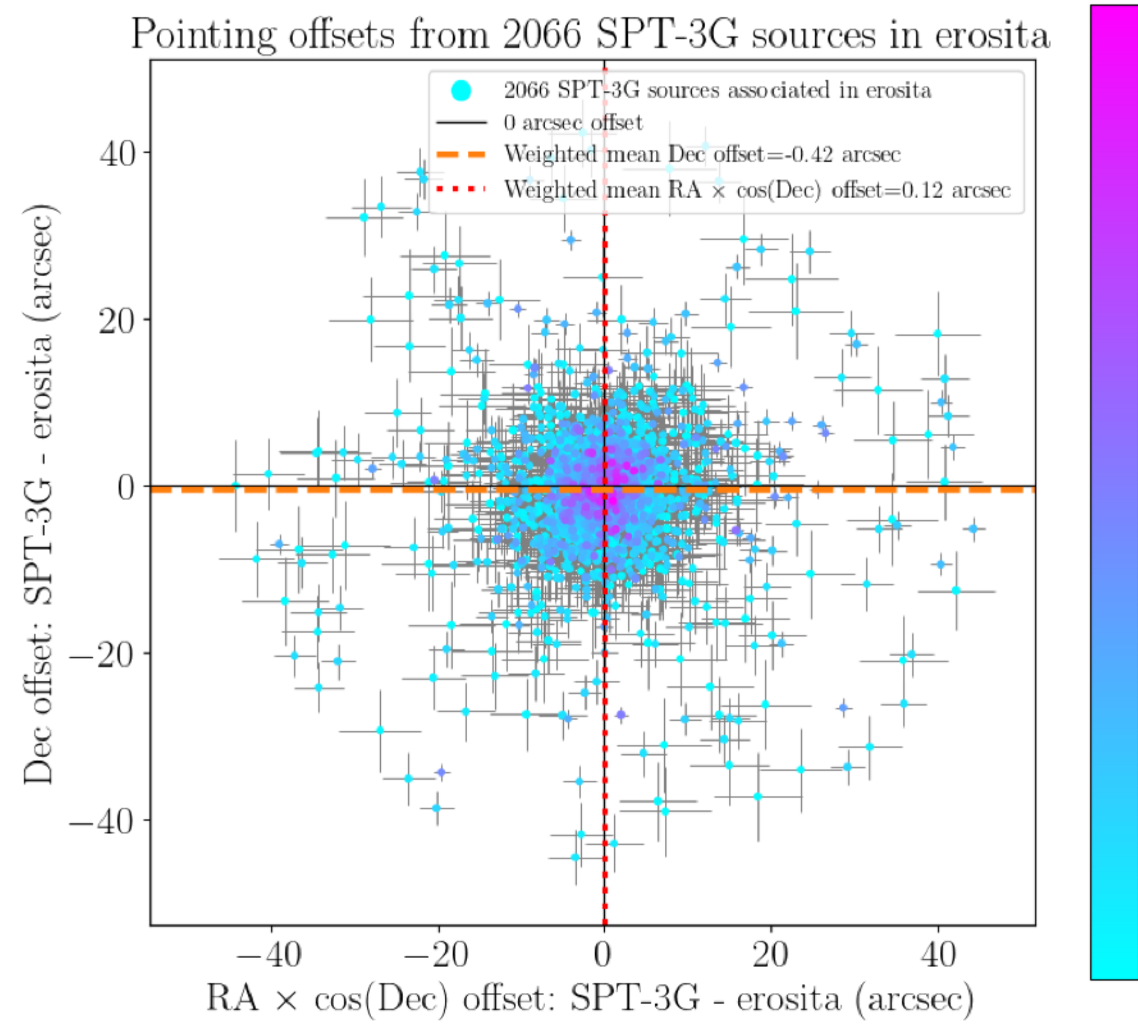
Catalog results: 28736 total sources



Emissive Sources in the SPT-3G Survey - a first look

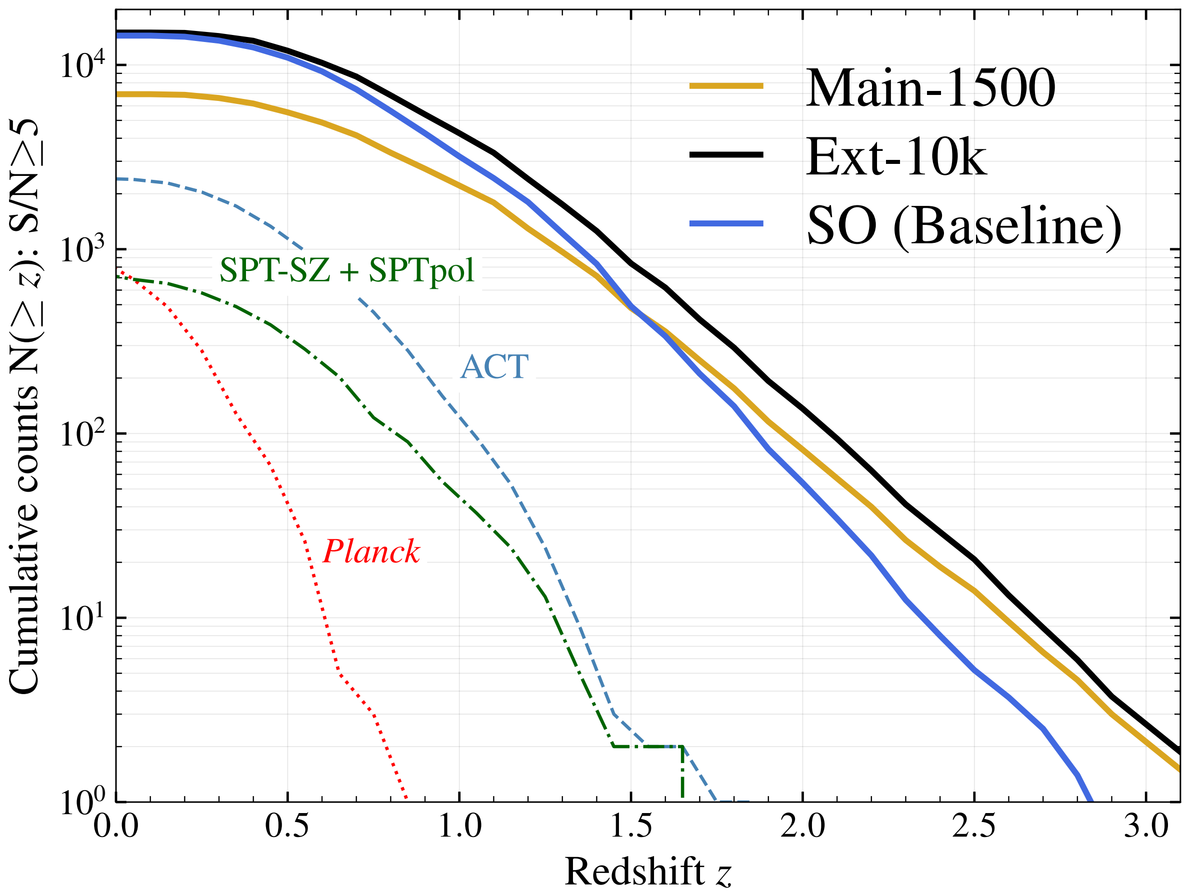
Melanie Archipley

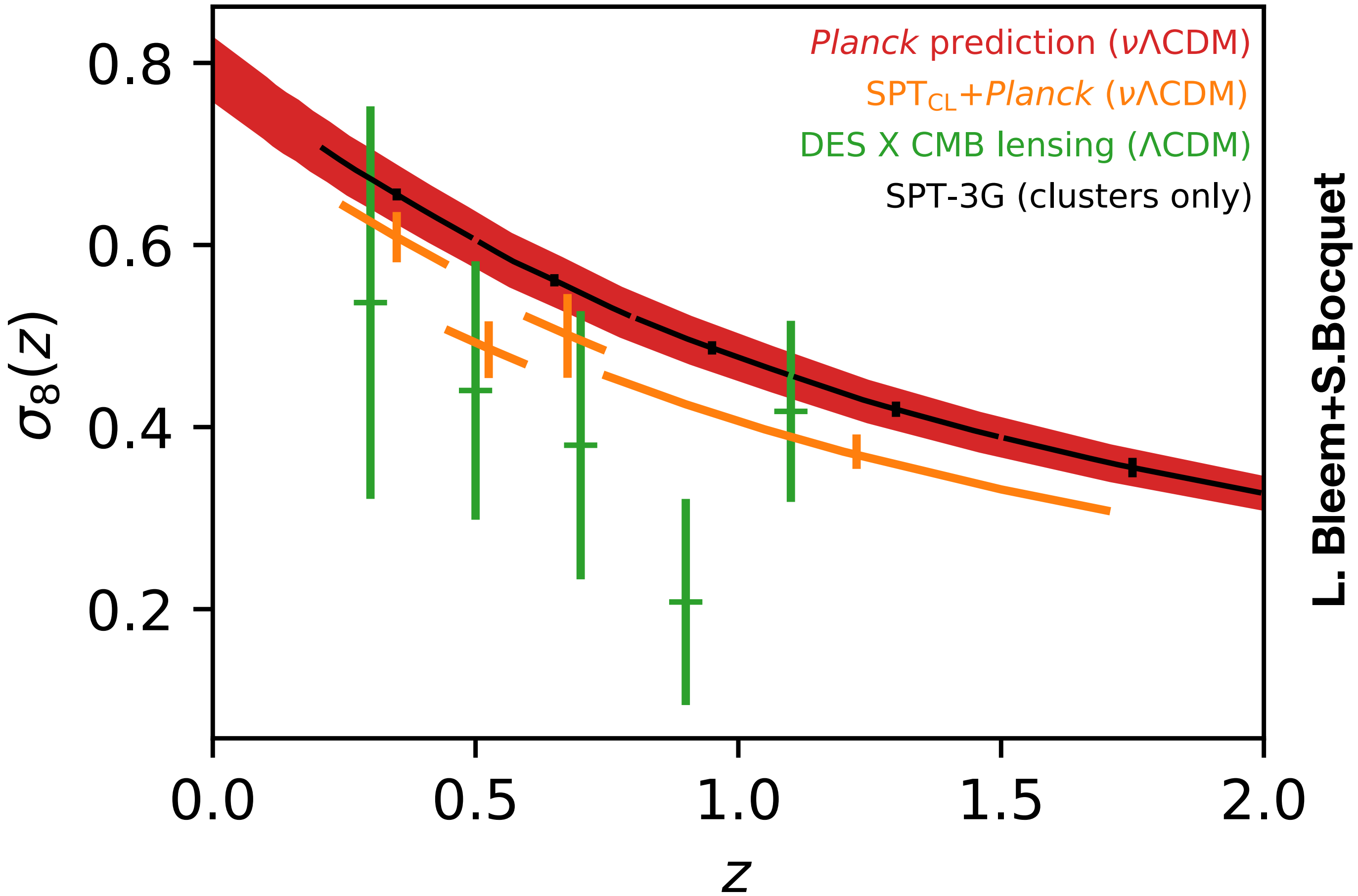


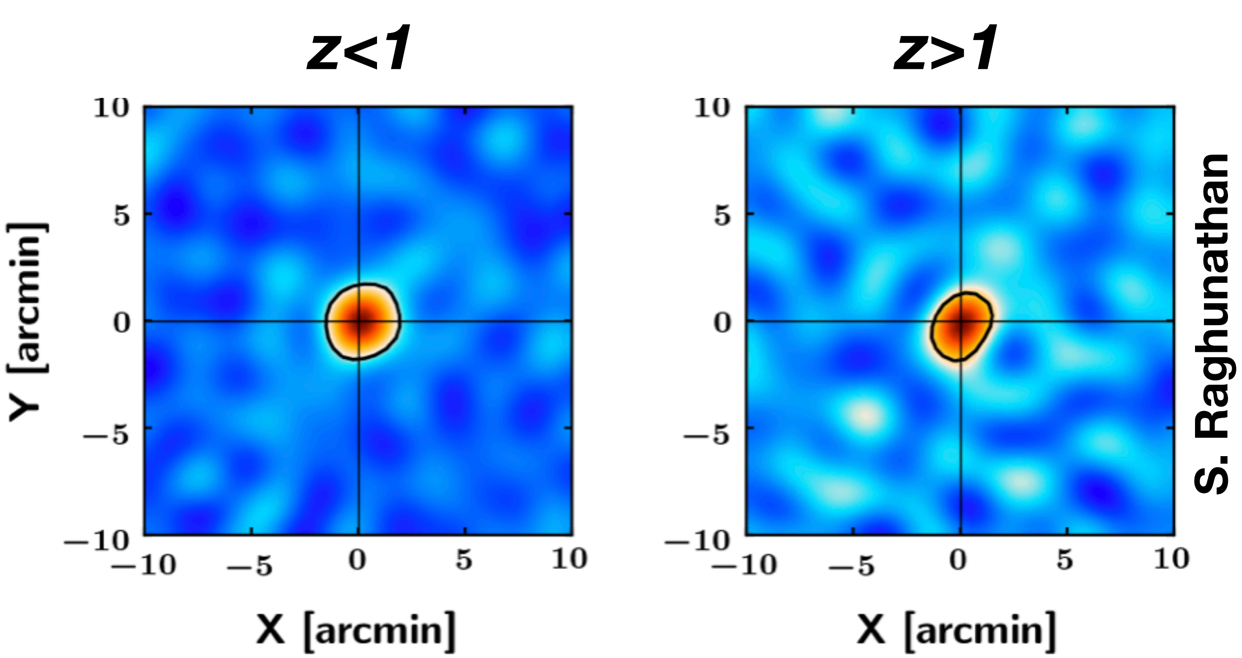


Cluster Forecasts

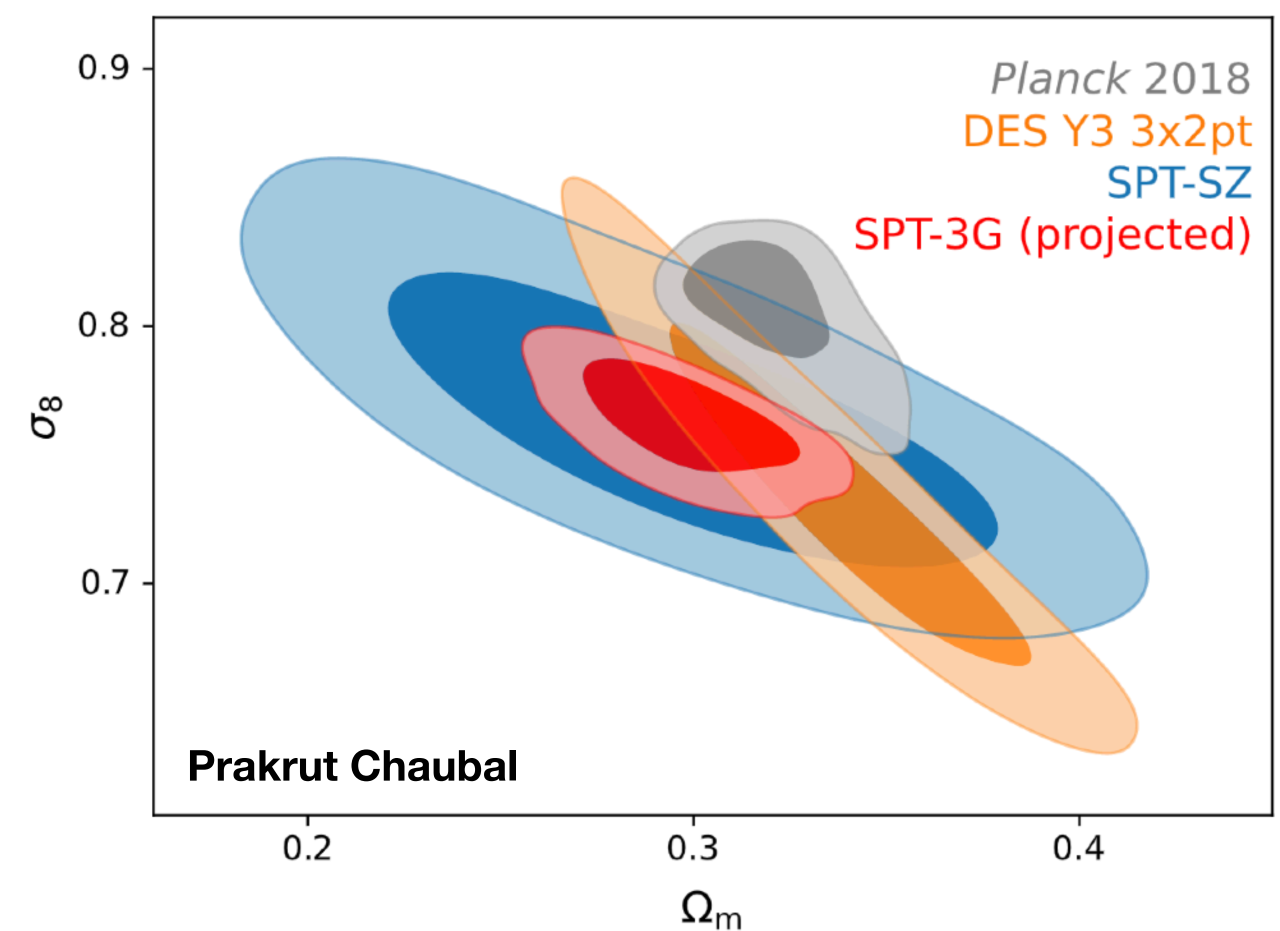
SPT-3G







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



Conclusions

- SPT has found thousands of massive galaxy clusters reaching to z~2 via the SZ effect. This clean, mass-limited selection leads to fantastic samples for cosmological and astrophysical studies.

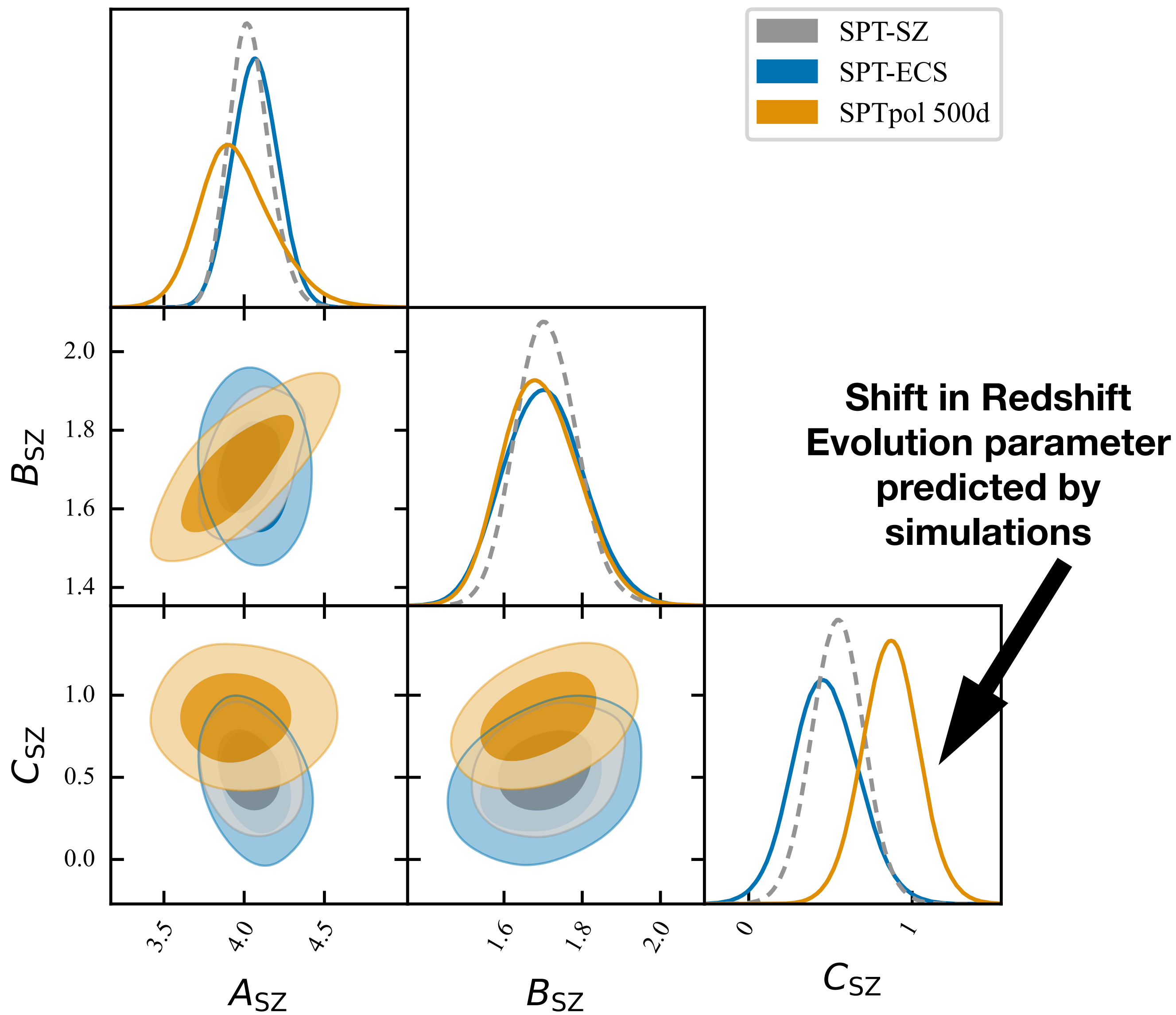
- Clusters from the first two generations of SPT surveys combined with optical weak lensing data from HST and DES are providing powerful tests of the ΛCDM cosmological model. Constraints are consistent with those from primary CMB.

- SPT-3G is in the midst of a 10,000 deg^2 survey of the Southern sky. This survey will enable tests of ΛCDM through a range of probes including TT/TE/EE power spectra, CMB lensing, and galaxy clusters. Stay tuned for upcoming results!

Results: Mass calibration (fixed cosmology)

$$\langle \ln \zeta \rangle = \ln\Big[A_{\rm SZ} \left(\frac{M_{500c}}{3\times 10^{14} M_\odot h^{-1}}\right)^{B_{\rm SZ}} \left(\frac{H(z)}{H(0.6)}\right)^{C_{\rm SZ}}\Big]$$

$$P(\xi|\zeta) = \mathcal{N}(\sqrt{\zeta^2+3}, 1)$$



Excellent Consistency between Mass-ζ Scaling relation
at fixed cosmology across SPT surveys of significantly different depths

The SPT-3G wide field SZ Catalogs

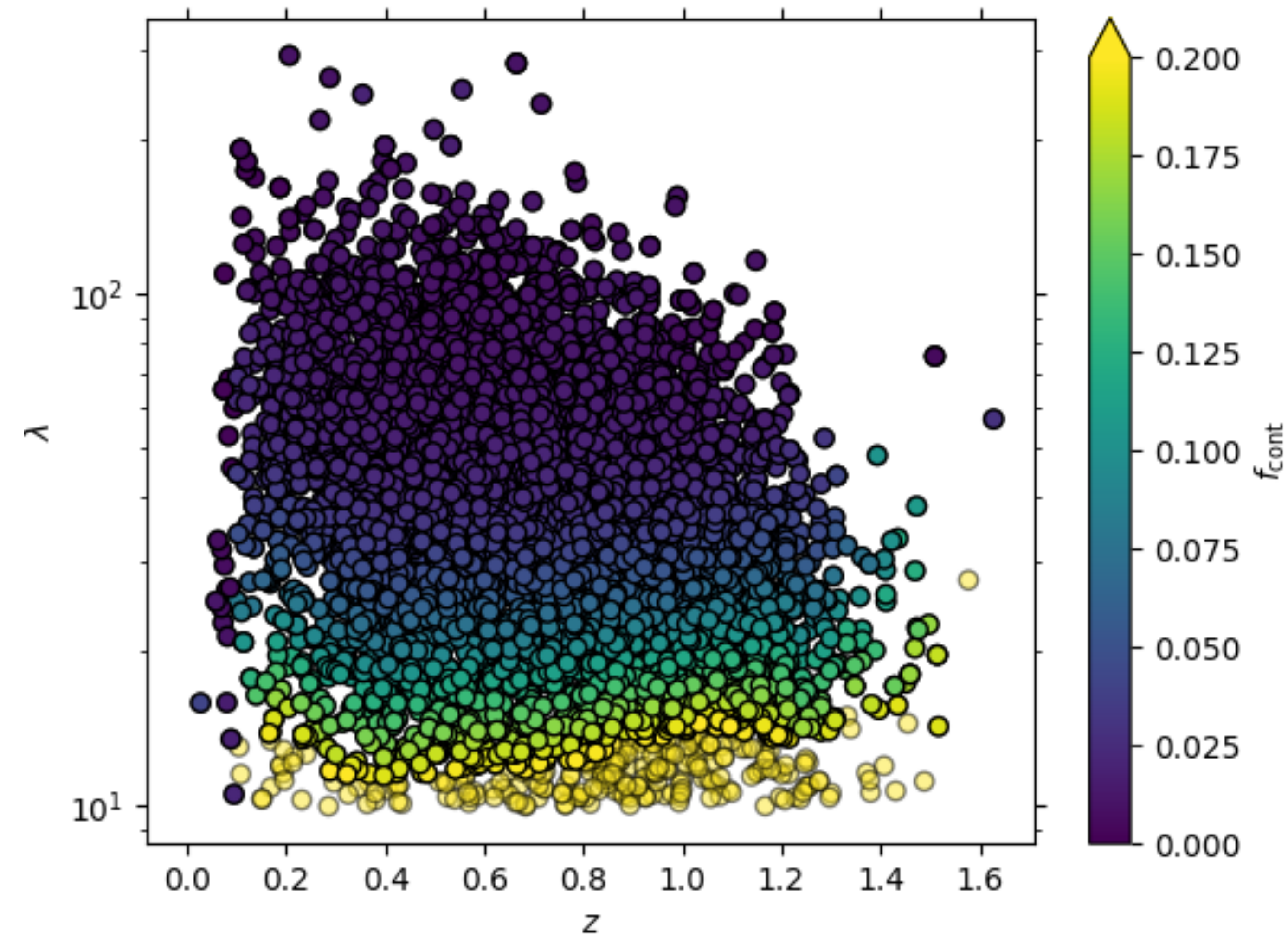
- SZ candidate lists in progress from 3 SPT surveys (~10,000 deg^2 of sky coverage on disk!)

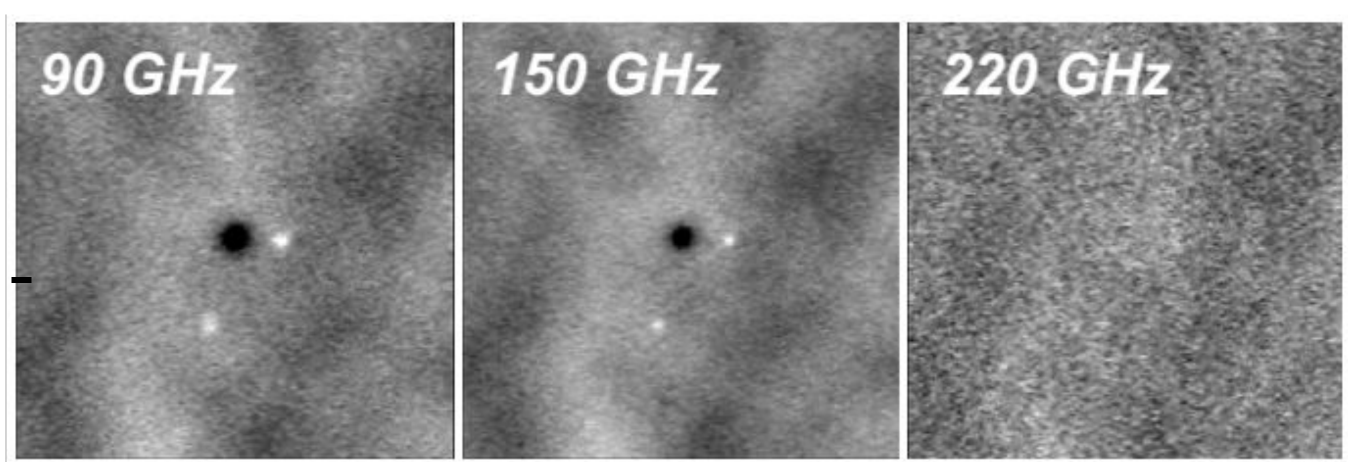
- Preliminary cluster run on 1500d 5 year data has produced a catalog with 5200 candidates at xi>5 (>99% purity), >9400 candidates at x>4

- Candidates to be confirmed with a combination of DES, DECALS, targeted Magellan 4*, and Euclid data

- 835 matches to eRASS1 Cluster sample

- 2392 matches to eRASS1-m X-ray sources within 1'





SPT-CL J2344-4243
(Phoenix Cluster, z=0.6) seen in SPT-3G data
at S/N>125 in 5 year data

with L. Bleem, T. de Haan,
F. Kéruzoré, K. Kornoelje, J. Sobrin