SPT-3G Experiment Status

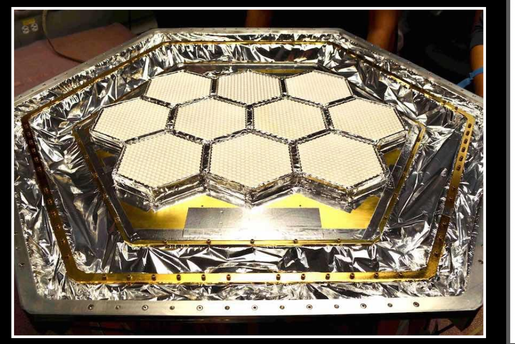
B. Benson
(30-Oct-2023)

Photo: Aman Chokshi

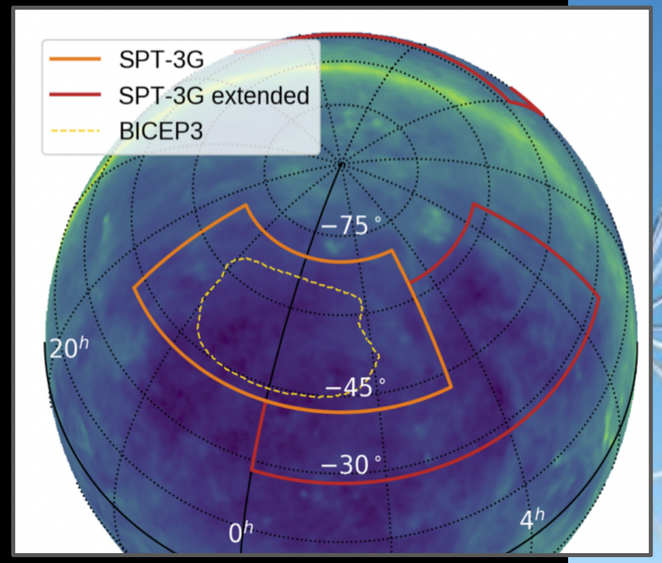
The South Pole Telescope (SPT)

10-meter sub-mm quality telescope

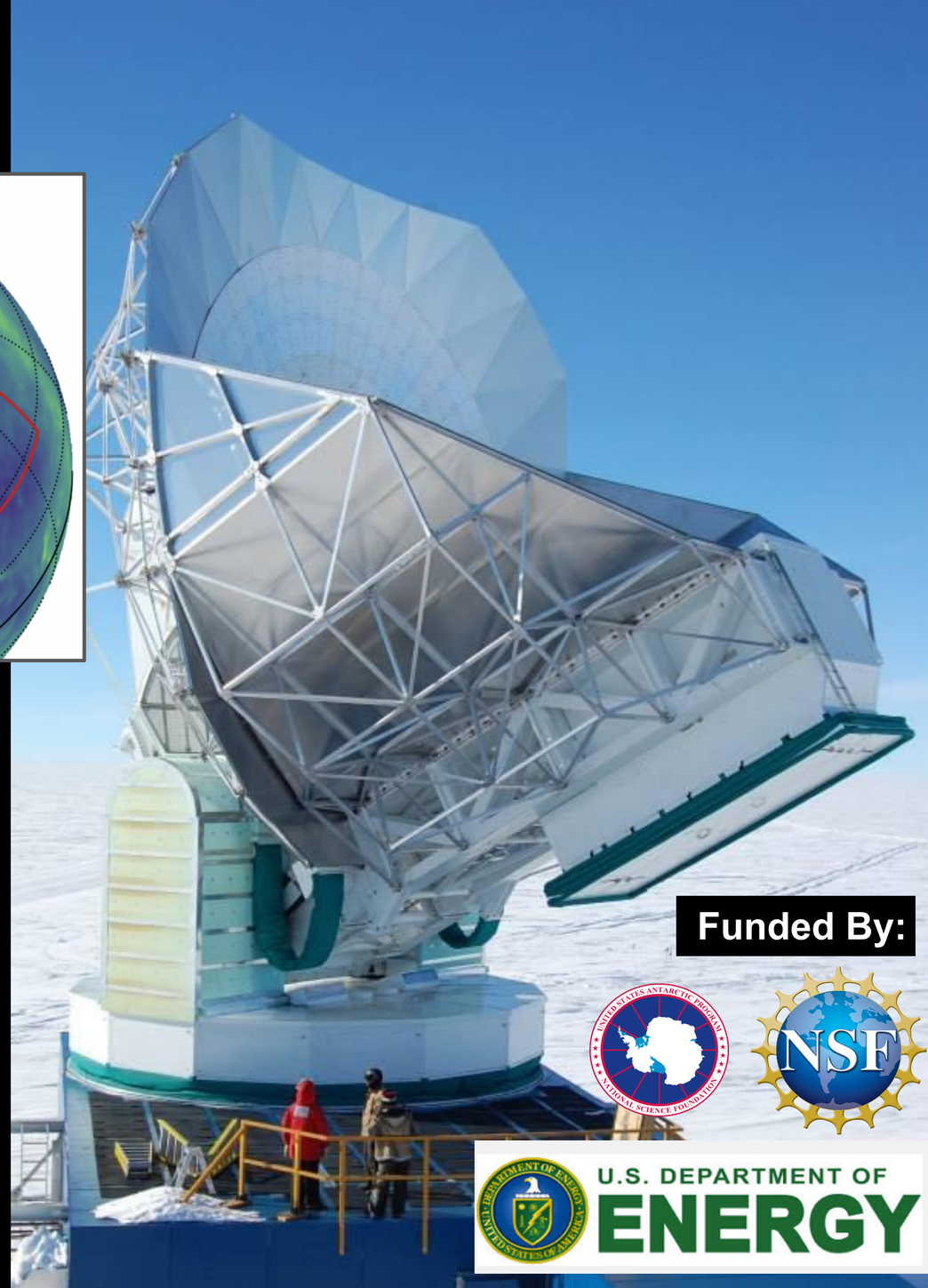
100, **150**, **220** GHz and
1.6, **1.2**, **1.0** arcmin resolution



SPT-3G Camera
~16,200 detectors
100,150,& 220 GHz
+Polarization



- SPT-3G is a NSF & DOE partnered project & experiment
- In 2018, SPT-3G began its main 1500 deg^2 survey, designed to overlap with the BICEP survey
  - *In addition, SPT-3G is doing a 10,000 deg^2 "Wide" survey*
- SPT is key part of the Event Horizon Telescope (EHT)
- SPT is a platform for future experiments, e.g.,
  - *SPT-SLIM (line intensity mapping pathfinder) deploying in 2024 (Karkare et al. 2021, Cecil et at. 2023)*
  - *SPT-3G+ sub-mm camera (Anderson et al. 2022)*

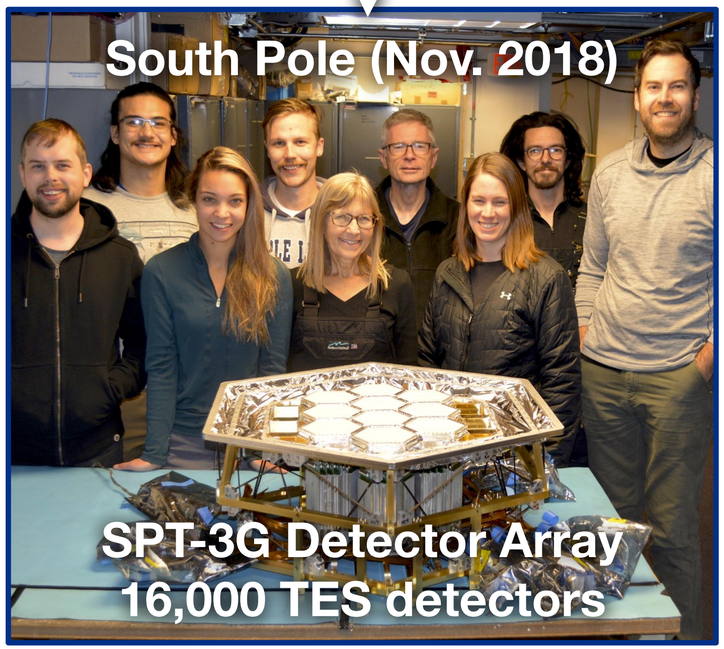


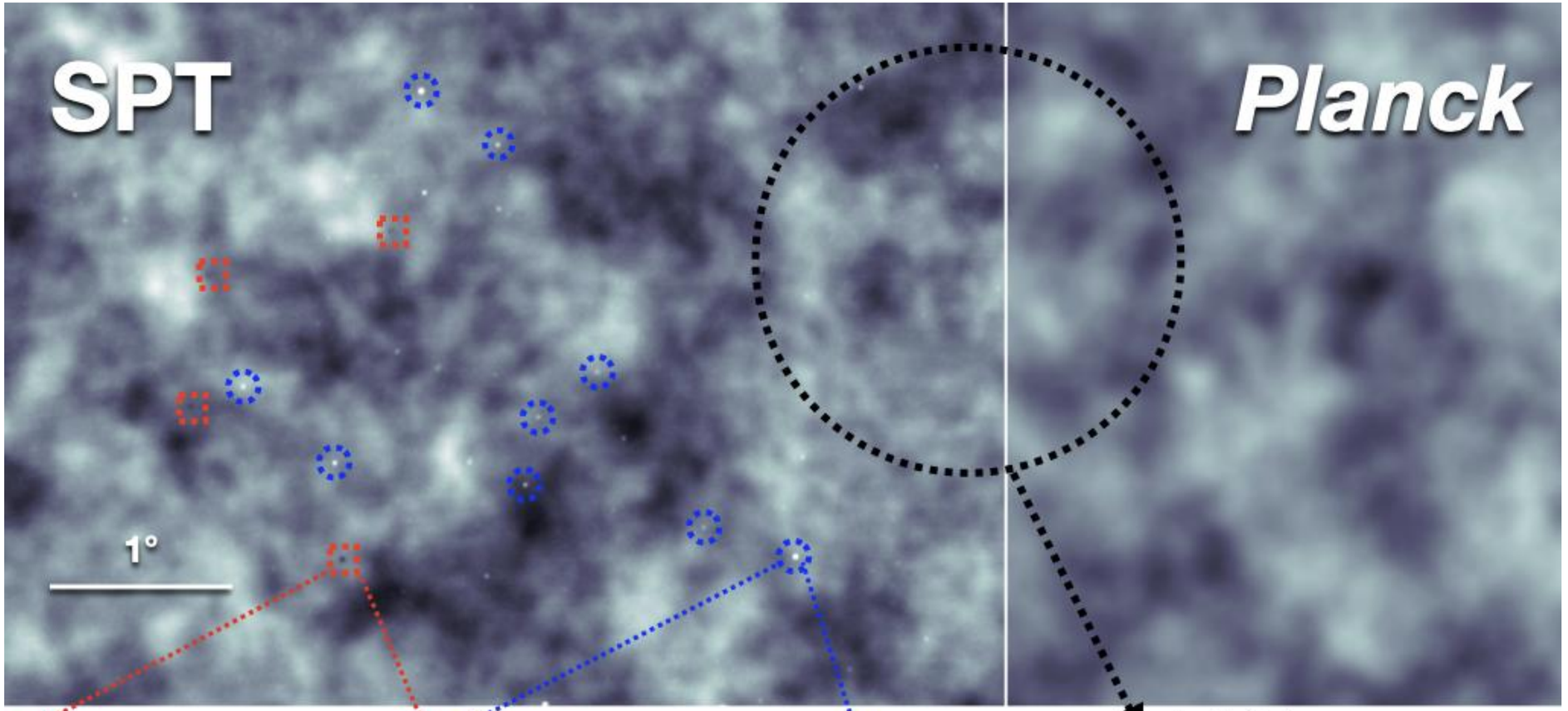
Funded By:

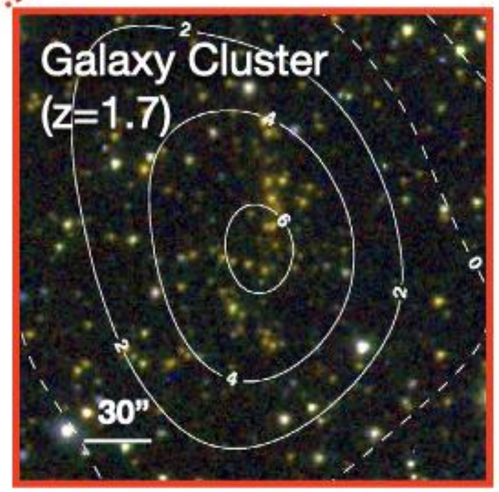
U.S. DEPARTMENT OF ENERGY

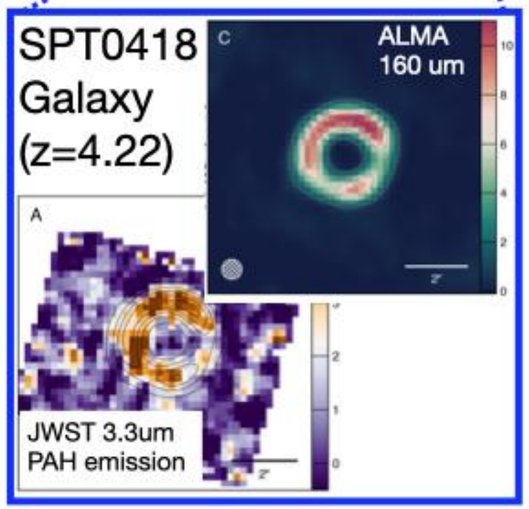
SPT-3G Project Roles

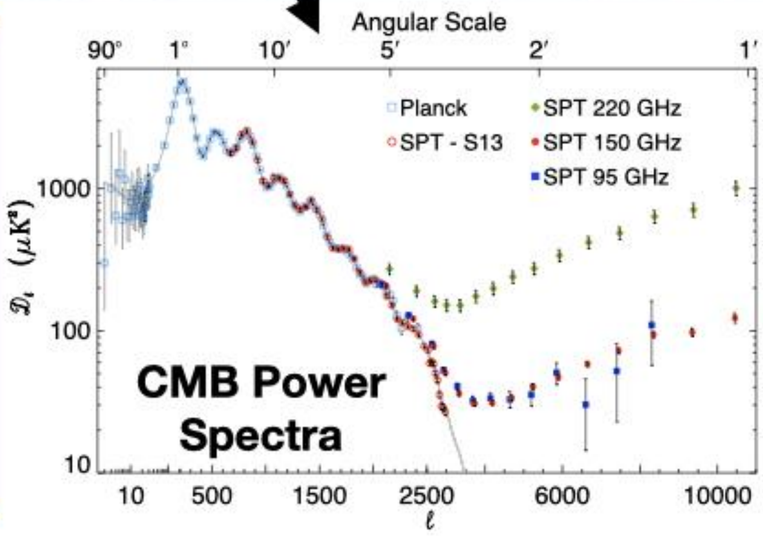
- SPT-3G camera deployed to South Pole in the Jan. 2016.
  - SPT-3G science operations began in 2018, scheduled to continue through 2024, with final results published in ~2026.
- Fermilab team responsible for many critical aspects of the SPT-3G project. Some examples:
  - For all stages of the project (R&D thru Production), Fermilab wirebonded and packaged 100% of the detector modules (~100 total) and cryogenic readout electronics (>100,000 wirebonds total) (**Kubik**, **Jonas**)
  - Fermilab cryogenically tested ~20% (18) of the detector modules produced during R&D and production phases of project (**Anderson**)
  - **Benson** led the camera cryostat design and integration at SiDet; and deployment and commissioning of the SPT-3G camera at the South Pole during three Austral summer seasons.
- Fermilab leading roles in SPT-3G Operations:
  - Associate Director of Operations and Co-PI (**Benson**), Detector and Data Quality (**Anderson**), Data Management (**Rahlin**). **FNAL responsibilities include** day-to-day survey operations and data quality





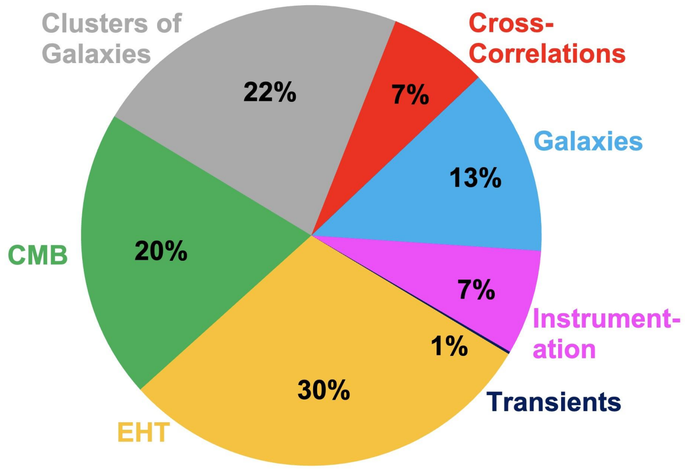






Science Breadth from SPT:

- ***Over 300 science, or technical publications with more than 25,000 citations***



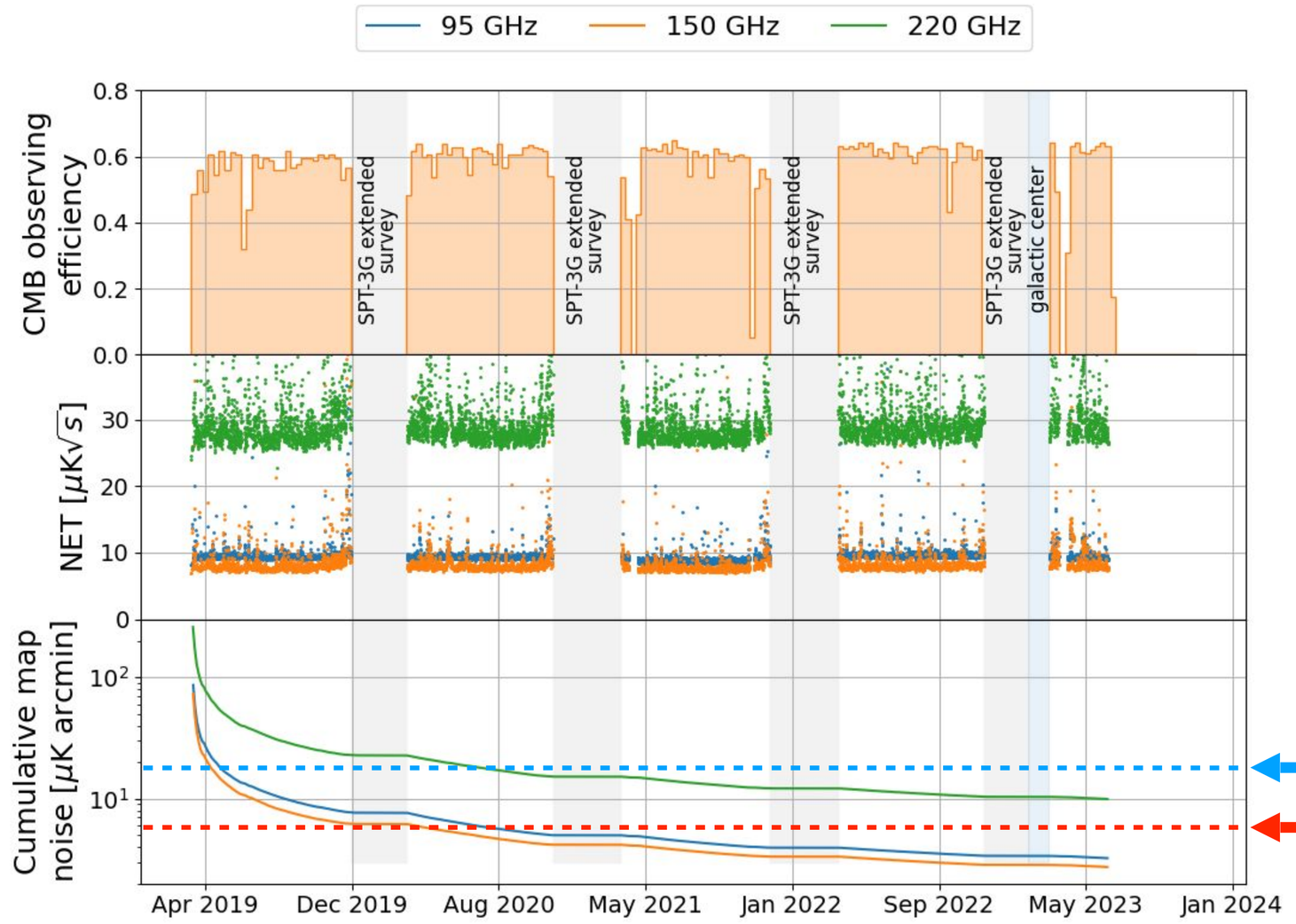
* Citation fraction by topic, for full list see pole.uchicago.edu

SPT Operations: 1500 deg² “Main” SPT-3G Survey

Stable

Operations

Since 2019!



~60% observing efficiency over past 5-observing seasons

Daily camera sensitivity has been stable over past 5-years

SPT-3G Temp. Noise (uK-arcmin)

SPT-SZ 150 GHz Depth

SPTpol (500d)150 GHz Depth

(SO “goal” survey depth, fsky=0.4)

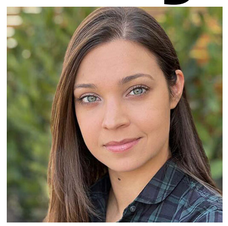
(Figure made by Amy, adapted from the instrument paper!)

Credit: W. Quan

Fermilab-led SPT-3G Analyses

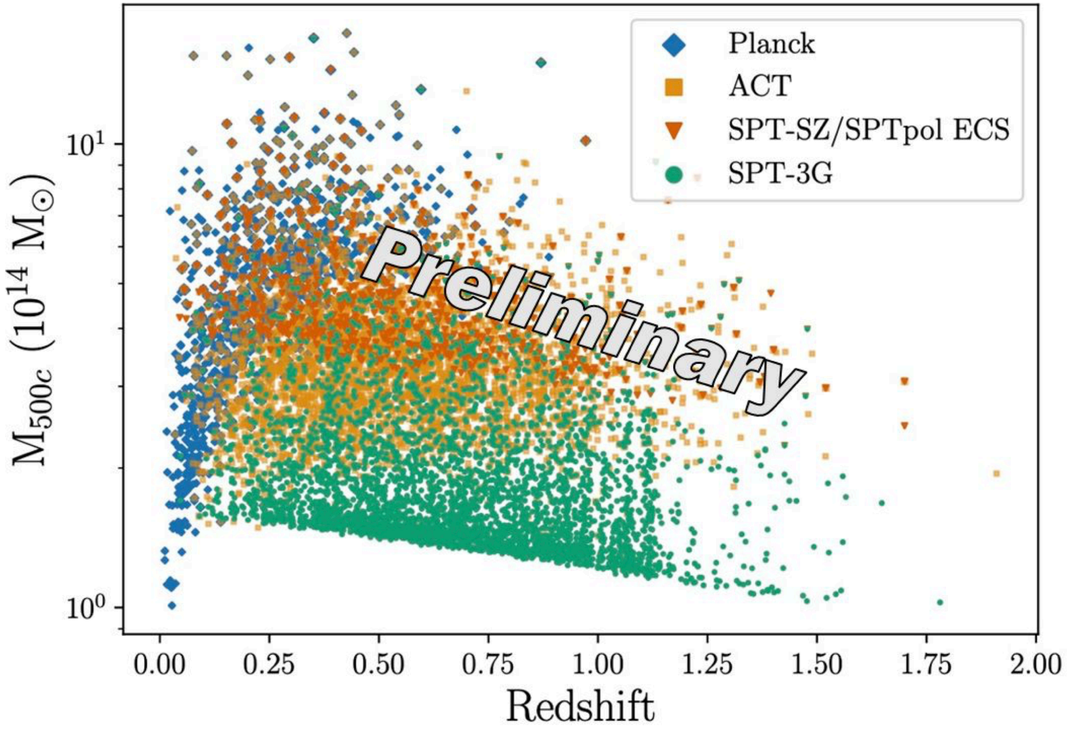
First Catalog of Galaxy Clusters from SPT-3G 1500 deg² Survey

Joshua Sobrin et al.

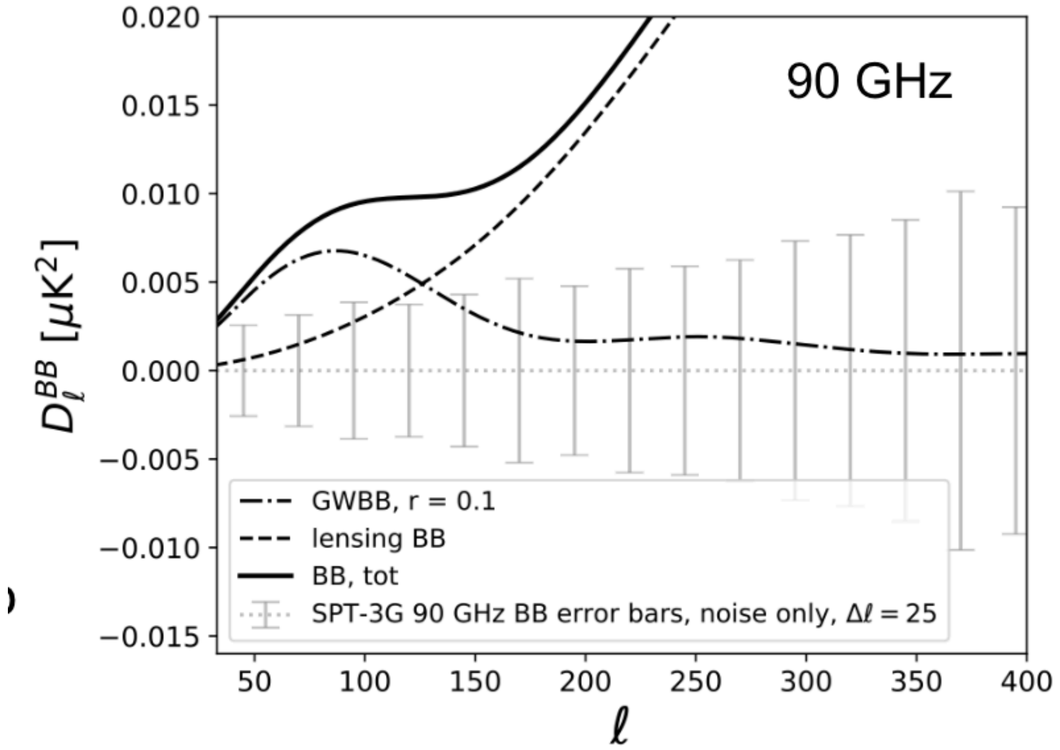


First Inflationary Constraints and B-mode measurements from SPT-3G 1500 deg² Survey

Jessica Zebrowski et al.



- Using 2019-20 SPT-3G data set, nearly 10x larger cluster density than SPT-SZ, with more than 2500 clusters total!

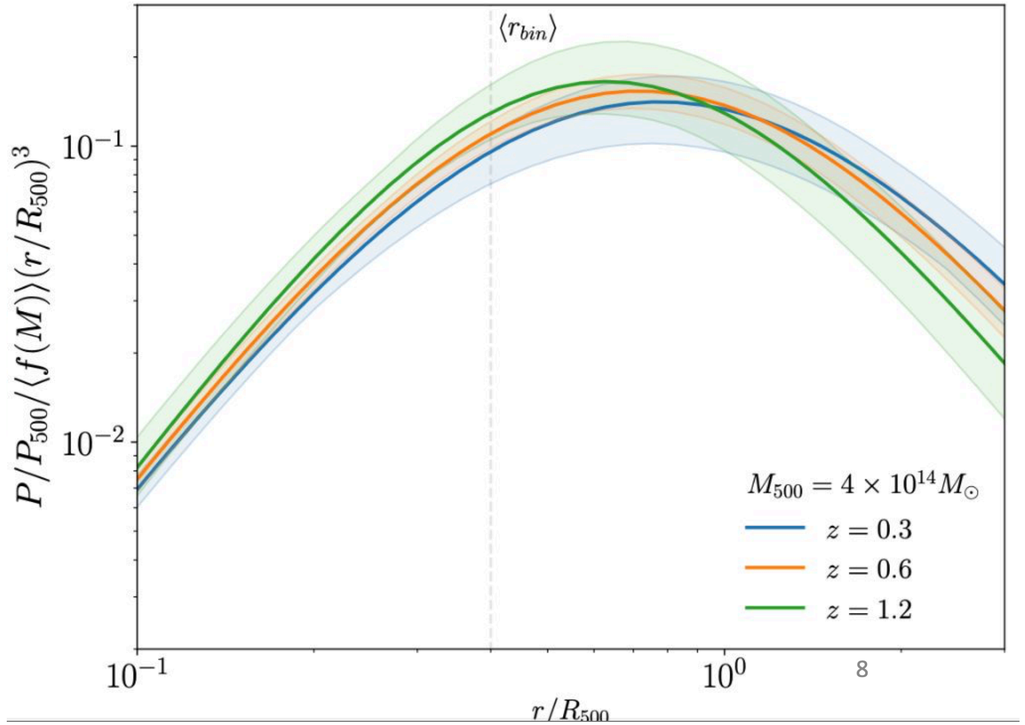


- Using 2019-20 SPT-3G data set, will be “leading” r-constraint, second only to BICEP, but important demo of low-ell B-modes from large aperture telescope

Fermilab-led SPT-3G Analyses

Constraining Cluster Physics in the Outskirts with SPT

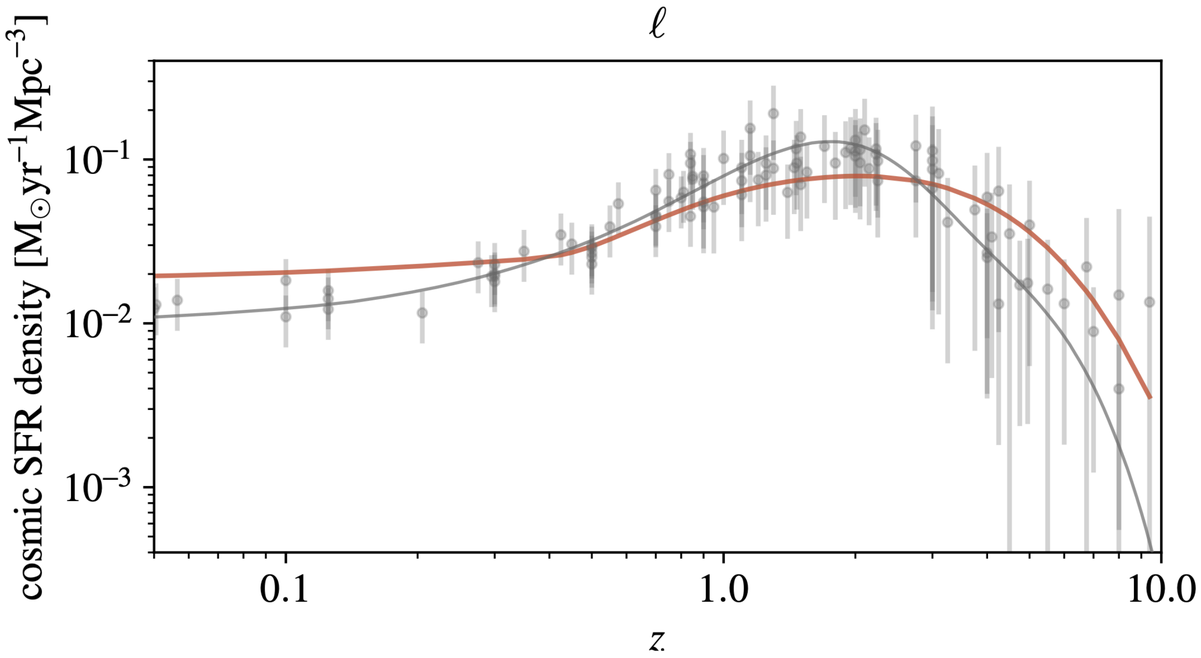
Matt Young et al



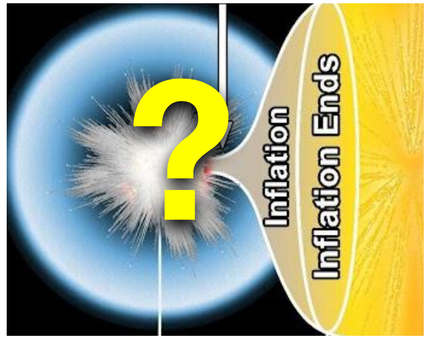
- Developed method to fit SZ pressure profile using SPT-SZ data set, as demo for SPT-3G, to probe new cluster physics in outskirts

A measurement of the Star Formation History and SZ power spectrum with the SPT-3G 1500 deg² Survey

Karia Dibert et al



- Using 2019-20 SPT-3G data set, cross correlation between SPT-3G CMB lensing and high-ell power spectrum to constrain star formation history and tSZ+kSZ power spectrum

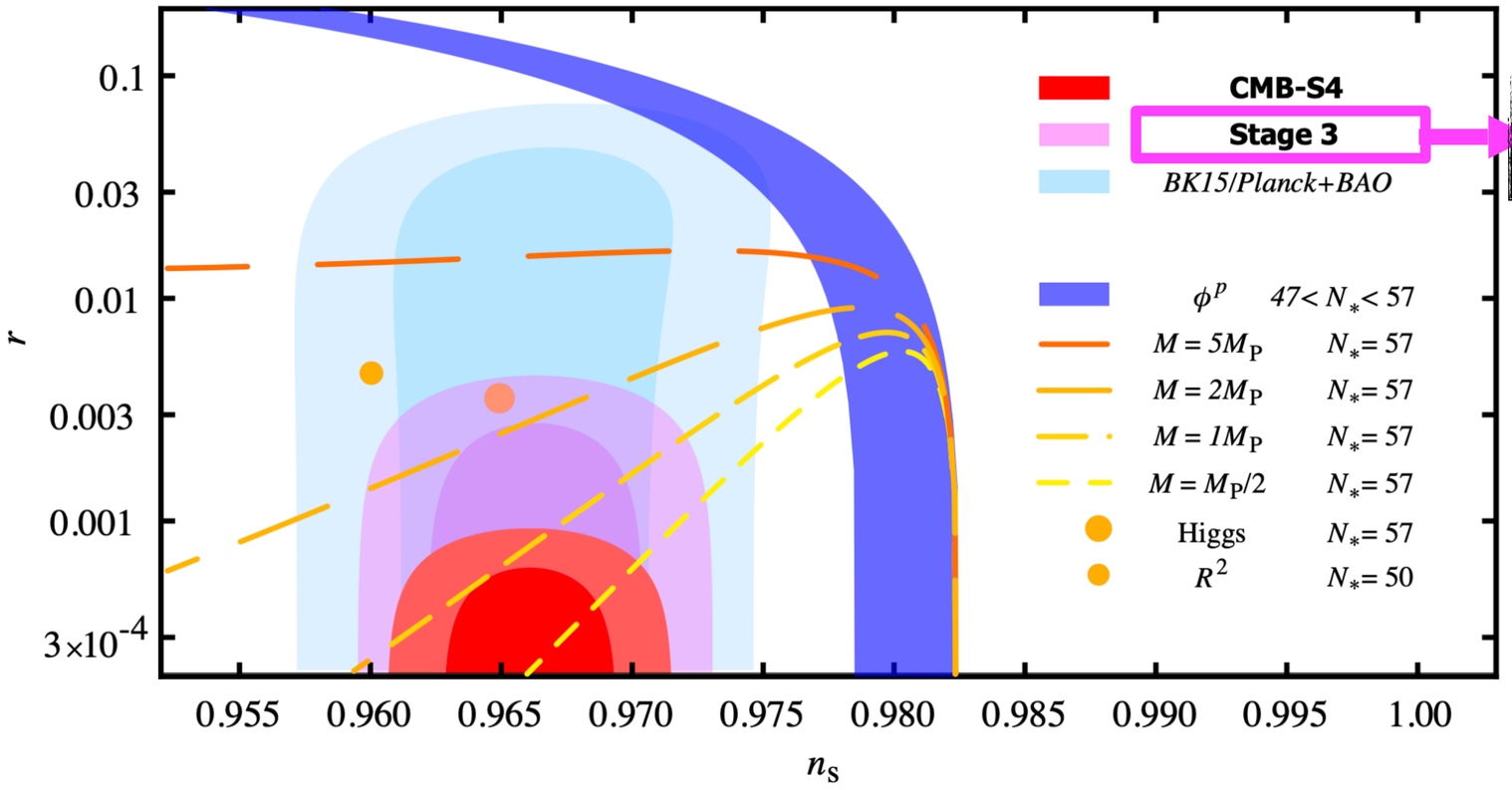


Probing Cosmic Inflation – one of the most important goals in fundamental physics today

$$\text{energy} = 10^{16}\left(\frac{r}{0.01}\right)^{\frac{1}{4}}\ \text{GeV}$$

CMB "r"-measurements explore physics at energies a trillion times beyond the Large Hadron Collider.

South Pole Observatory (SPO)

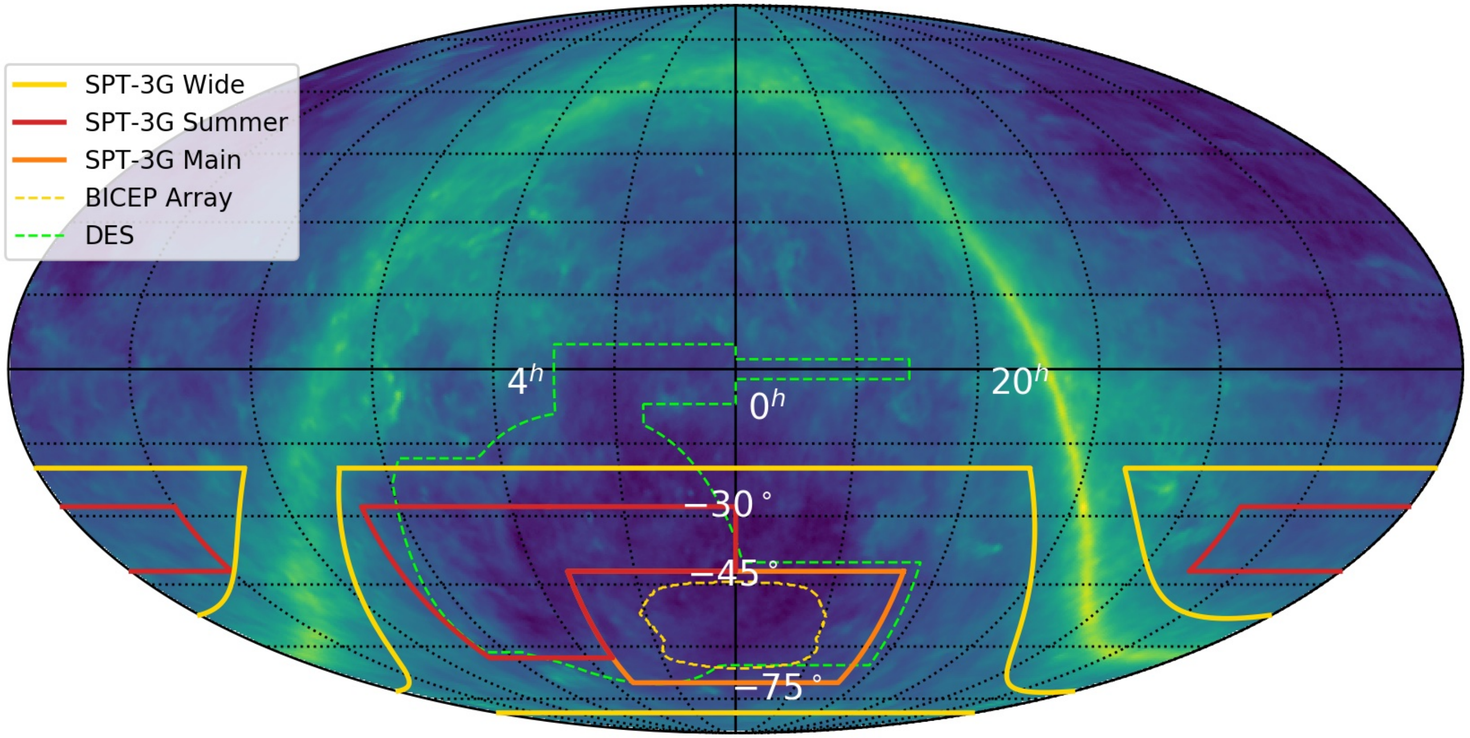


Today: σ(r) = 0.009
By 2026: σ(r) = 0.003

South Pole Observatory (SPO program is providing world leading constraints on Inflation building up to CMB-S4

SPT Operations

- On June 1, submitted a proposal to NSF to fund SPT operations through (+including) through 2028 season
- Proposed to continue SPT-3G observations through (and including) 2026 observing season
- Observations would include a new SPT-3G “Wide” survey during the 2024 observing season
  - ***Wide survey increases total SPT-3G survey area to over 10,000 deg² of relatively clean extragalactic sky***
  - Over 10,000 deg² area, SPT-3G Wide survey would be 4x the area and >2x deeper than SPT-SZ survey.



Survey	Area [deg²]	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

Table 1: Map depths for the three SPT-3G surveys. For comparison, maps in the deepest *Planck* band have a noise level of ∼30 μK-arcmin.

SPT-SZ
Coadded Depth
16.5 uK-arcmin

SPT Operations

- On June 1, submitted a proposal to NSF to fund SPT operations through (+including) through 2028 season
- Proposed to continue SPT-3G observations through (and including) 2026 observing season
- Observations would include a new SPT-3G “Wide” survey during the 2024 observing season
  - ***Wide survey increases total SPT-3G survey area to over 10,000 deg² of relatively clean extragalactic sky***
  - Over 10,000 deg² area, SPT-3G Wide survey would be 4x the area and >2x deeper than SPT-SZ survey.

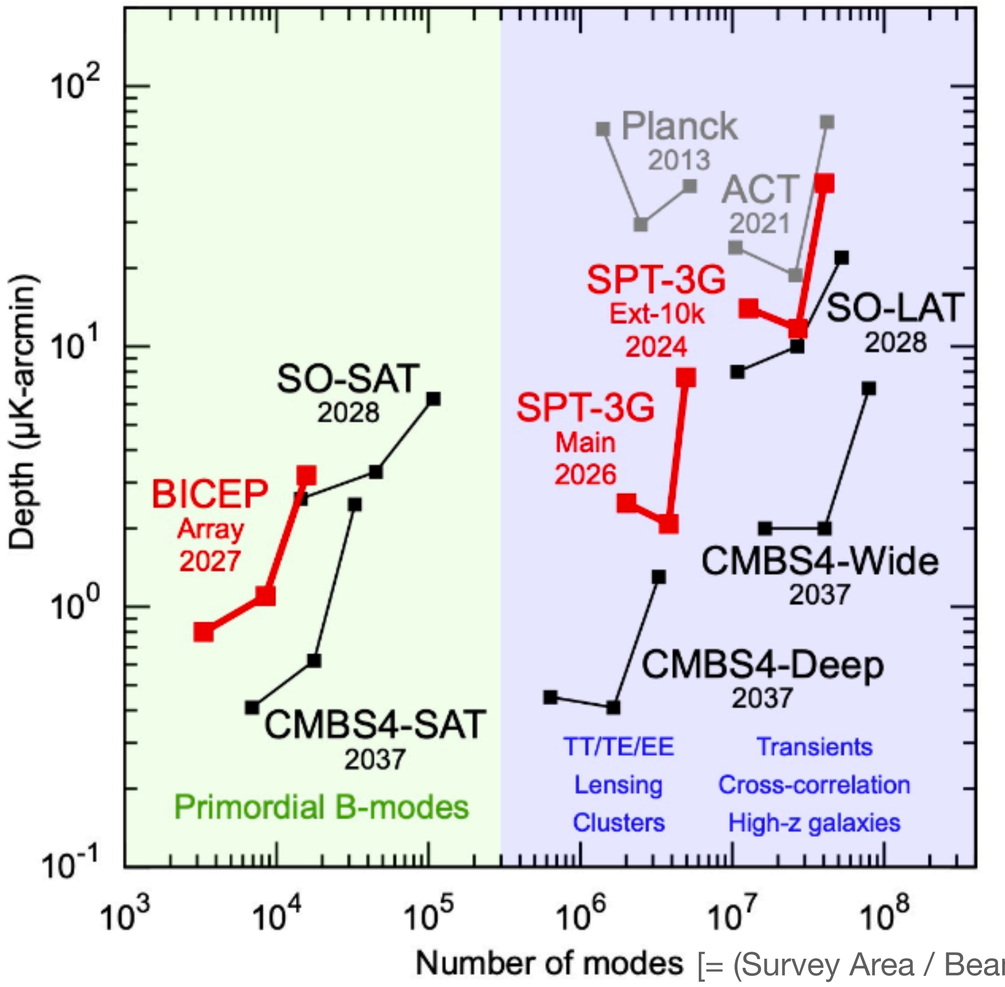


Figure 3: Map noise vs. number of modes measured for ongoing (red), completed (grey), and upcoming (black) CMB surveys. For each survey, the depth is shown for each of the three main CMB bands (95, 150, and 220 GHz), and the expected survey completion date. (Figure adapted from S. Naess, *priv. comm.*.)

SPT-3G “Ext-10k” Survey: CMB Cosmology

- The SPT-3G Ext-10k / Wide survey would fill an interesting region in measurement space.
  - Over similar area, SPT-3G is deeper than ACT-DR6
  - Nearly as deep as SO-LAT Baseline survey, but with on-sky characterized instrument and 4-years earlier
- Combined SPT-3G Ext-10k survey will provide leading CMB cosmological constraints, primarily from CMB polarization information

Added to Planck, SPT-3G Ext-10k data set would reduce LCDM likelihood volume by a factor of 283!

Compared to Planck, SPT-3G will improve LCDM + extension parameter constraints by factors of 2-3, e.g.,

Planck -> Planck+SPT-3G

$\sigma(H_0)$ = 0.54 -> 0.22 km/s/Mpc

$\sigma(N_{eff})$ = 0.18 -> 0.06

	ΛCDM						ΛCDM +1			ΛCDM +2	
	$\Omega_b h^2$	$\Omega_c h^2$	H_0	n_s	A_s	FoM	$N_{\rm eff}$	$Y_{\rm P}$	Ω_K	Σm_ν	$N_{\rm eff}$
$\sigma(Planck)/\sigma(\text{Main})$	1.25	1.28	1.50	0.68	1.17	4.5	–	–	–	–	–
$\sigma(Planck)/\sigma(\text{Ext-10k})$	2.32	1.68	1.96	1.40	1.40	161	–	–	–	–	–
$\sigma(Planck)/\sigma(\text{Ext-10k+}Planck)$	2.72	2.15	2.44	1.83	1.67	283	–	–	–	–	–
$\sigma(Planck)/\sigma(\text{Ext-10k+}Planck)$	–	–	–	–	–	–	2.88	2.99	3.13	2.05	2.93

Table 2: Relative SPT-3G uncertainties on cosmological parameters compared to *Planck*, including $TT/TE/EE$ and lensing data. *First three rows*: Relative ΛCDM parameter uncertainty and the full 6-dimensional parameter volume figure of merit (FoM). *Fourth row*: Relative uncertainty on one- and two-parameter extensions (“ΛCDM+1” and “ΛCDM+2”), including the effective number of relativistic species ($N_{\rm eff}$), the helium abundance ($Y_{\rm P}$), curvature (Ω_K), and the sum of the neutrino masses (Σm_ν). For reference, the Ext-10k forecasted error on H_0 is $0.27\,{\rm km\,s^{-1}\,Mpc^{-1}}$, and the Ext-10k+*Planck* forecasted errors on single-parameter extensions are 0.065, 0.0042, and 0.0021 for $N_{\rm eff}$, $Y_{\rm P}$, and Ω_K, respectively.

SPT-3G “Ext-10k” Survey

Cluster Abundance

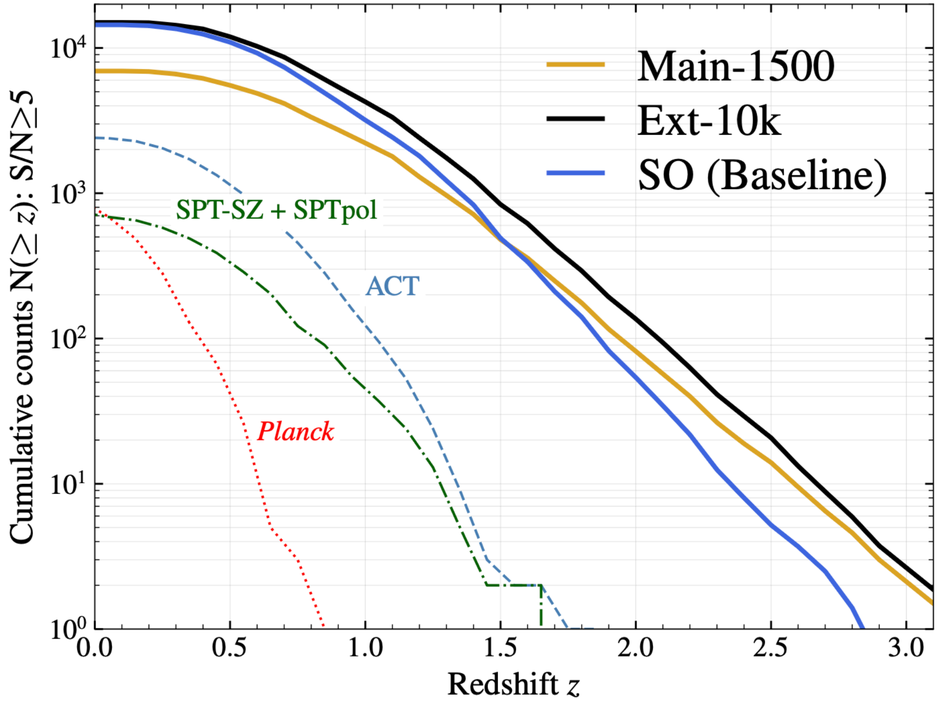


Figure 15: Expected number of clusters detected above a given redshift for the Main and Ext-10k SPT-3G surveys supported by this proposal versus other relevant surveys. The SPT-3G catalog will contain more clusters at high redshift than any currently forecasted pre-CMB-S4 experiment.

Credit: S. Raghunathan

CMB Lensing Cross Correlation

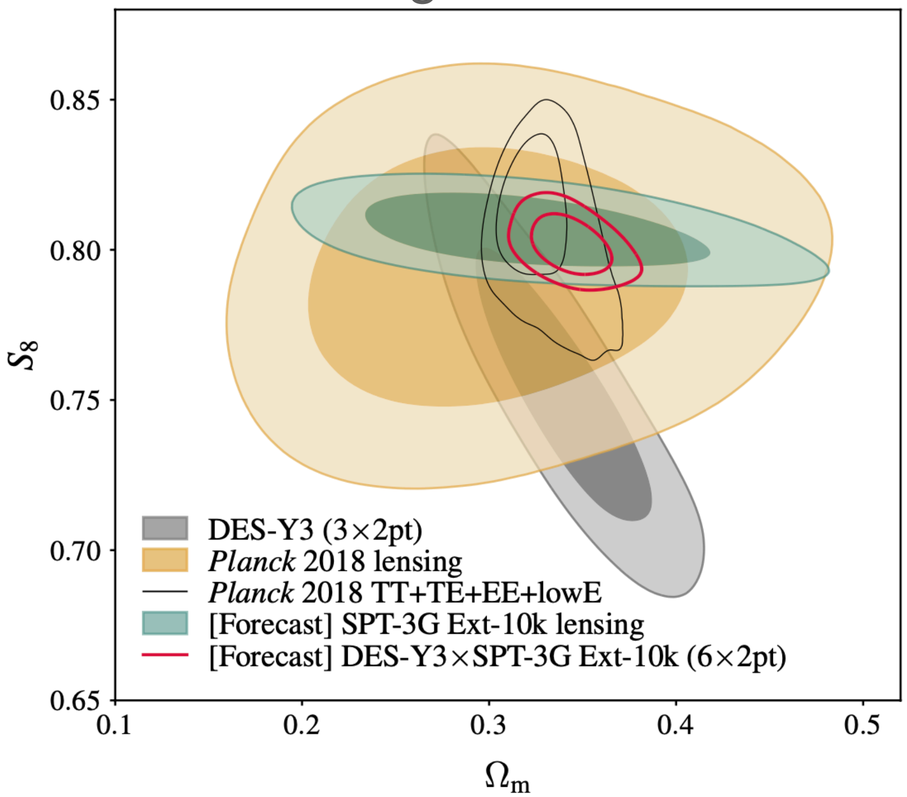
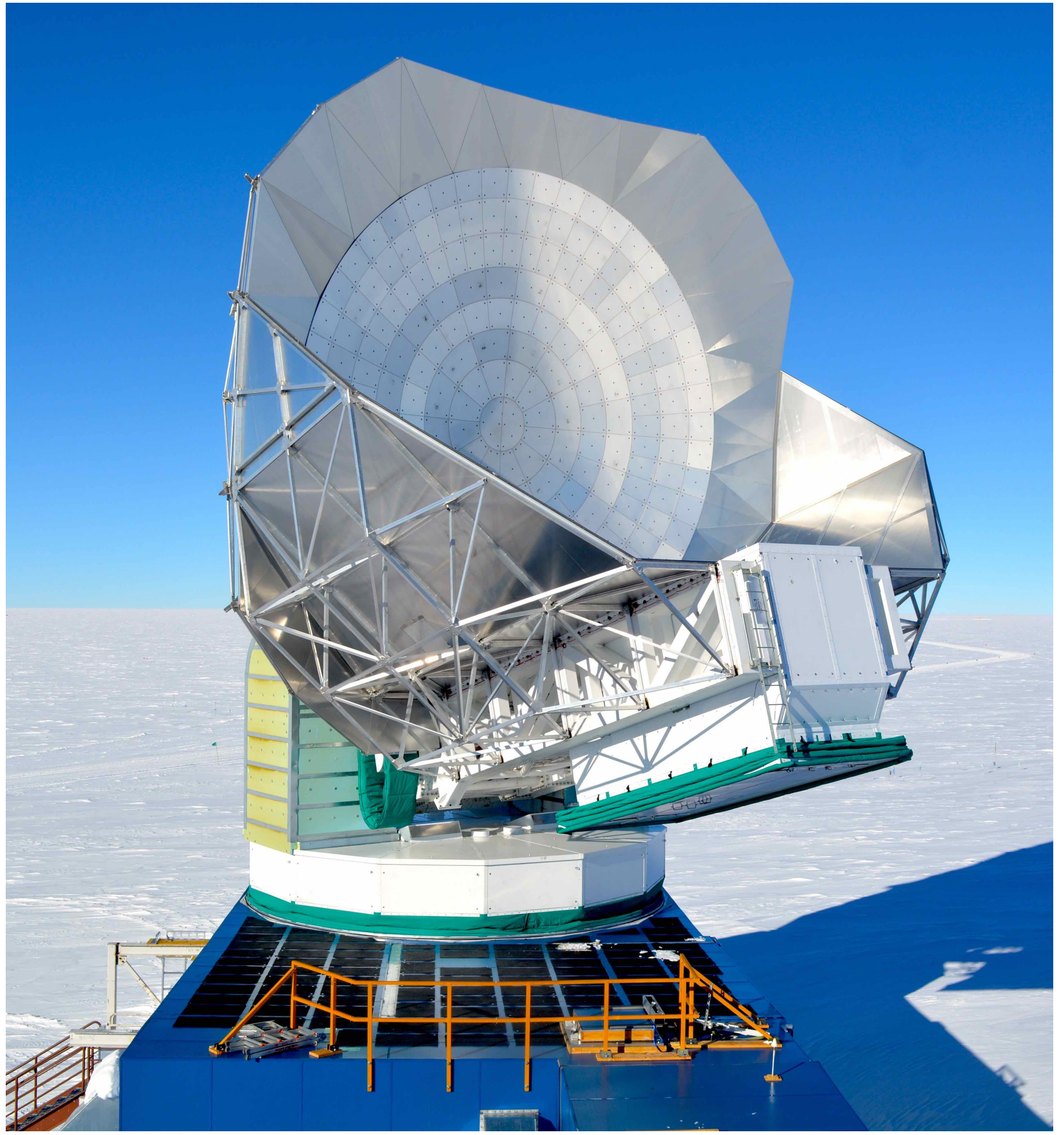


Figure 13: Joint constraints on S_8 and Ω_m from various combinations of galaxy and CMB observables. Forecasted constraints for the DES-Y3+SPT-3G Ext-10k 6×2 analysis (*red*) improve on previous DES-SPT analyses by a factor >2 in S_8, with higher precision than *Planck* primary CMB constraints, providing clarity on the S_8 tension. (Note: forecasts are centered around an arbitrary cosmology.)

Credit: Y. Omori

SPT Strengths



- SPT-3G operating with high-efficiency since 2019
  - Only large aperture CMB telescope currently operating, e.g., SO, CCAT-prime. and CMB-S4 are yet to be built
  - SPT-3G will provide leading CMB cosmological constraints over next 5+ years
- SPT is at the best site for sub-mm/mm-wave observations in the world
  - Astro2000 decadal recommended building SPT, which was intended to have a 20+ year lifetime
- Future opportunities for SPT - ***see Adam's talk!***

1) 10-m aperture, field-of-view, and sub-mm quality is unique combination, even for planned experiments/telescopes

2) Leverage science / observations from 15+ years of SPT surveys, in particular overlap with SPT-3G

3) Overlap with BICEP-Array for CMB de-lensing, world leading r/ Inflation constraints ahead of CMB-S4

4) "Relentless observing" and astrophysical transients; ability to characterize transients from minutes-to-year timescales during VRO/LSST era

5) Geographic importance to EHT network

6) Platform for future technologies (e.g., sub-mm detectors, filled FOV IFU camera) - SPT-3G+ and SPT-SLIM cameras

Extras

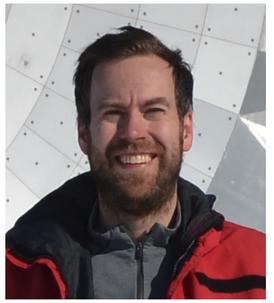
The BICEP/Keck Collaboration

The South Pole Telescope Collaboration

Funded By:

The Fermilab SPT team!

Adam Anderson



Brad Benson

Karia Dibert

Lauren Saunders

Sara Simon

Joshua Sobrin

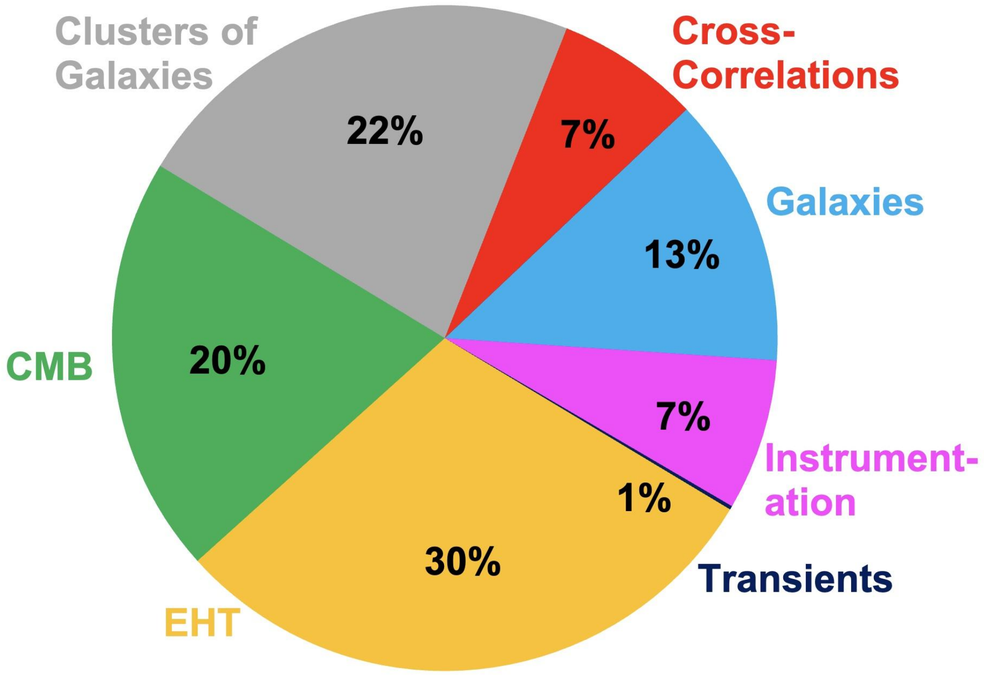
Matthew Young

Jessica Zebrowski

Breadth of SPT results engages a community of > 500 scientists

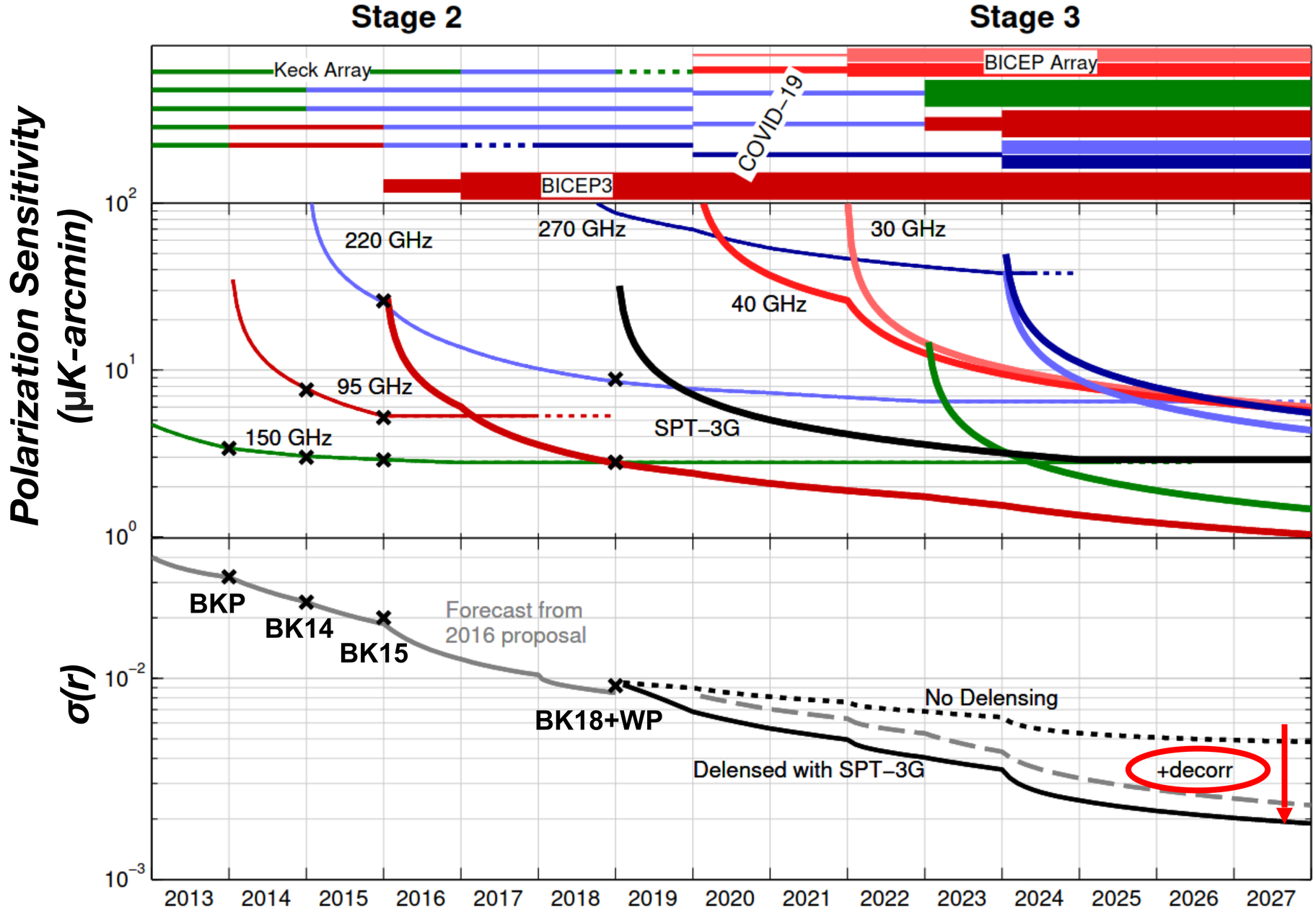
> 300 science or technical publications and > 25,000 citations*

- **SPT & EHT data used by a community of more than 500 scientists!**
  - SPT collaboration and working groups consists of about 200 scientists. EHT collaboration consists of over 350 scientists.
  - SPT operations requires ~10-12 deployments per season, but enables research by a community of several hundred scientists!
- **Broad science reach across cosmology, astronomy, and high-energy physics:**
  - World-leading constraints on cosmic Inflation and the origin of the Universe (with **BICEP** and **South Pole Observatory, SPO**).
  - New constraints on the composition of the Universe, including the density of **dark energy** and **neutrinos**.
  - Discovering the earliest formed **galaxies** and clusters in the Universe, and new classes of **astrophysical transients**.
  - Joint science and observations with many of the biggest facilities in Astronomy (e.g., JWST, Hubble, Chandra, ALMA).
  - Physics of **Black Holes** and general relativity (with **EHT**).



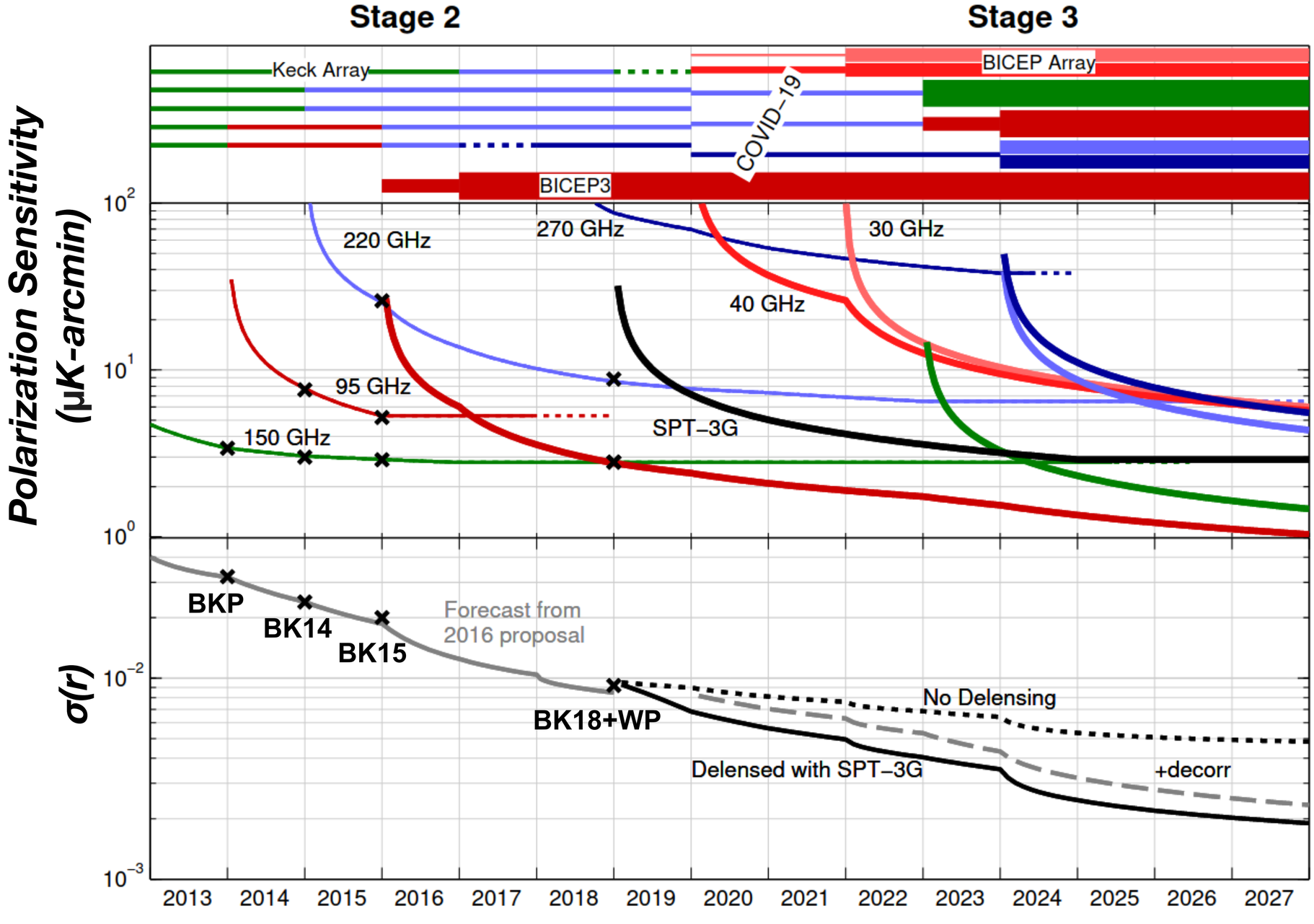
*Publication fraction by topic, for full list see pole.uchicago.edu

SPO (*BICEP+SPT*) Projected Inflationary Constraints



SPT-3G data used to "de-lens" BICEP data to improve constraints by ~3x to $\sigma(r) \sim 0.003$

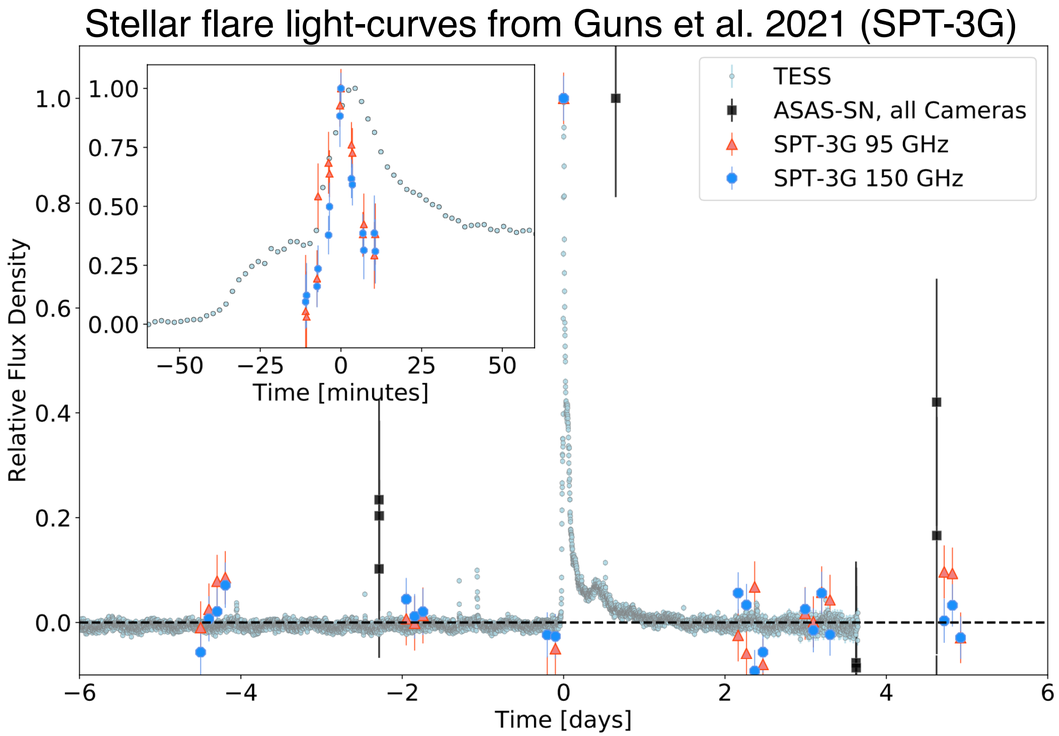
SPO (*BICEP*+*SPT*) Projected Inflationary Constraints



CMB-S4 SAT
95 GHz Depth
0.8 μ*K*-arcmin

CMB-S4 Goal
***σ(r)* = 0.0005**

Transients and the Time-Variable mm-Wave Sky



SPT-3G has made pioneering measurements of the time-variable mm-wave sky;

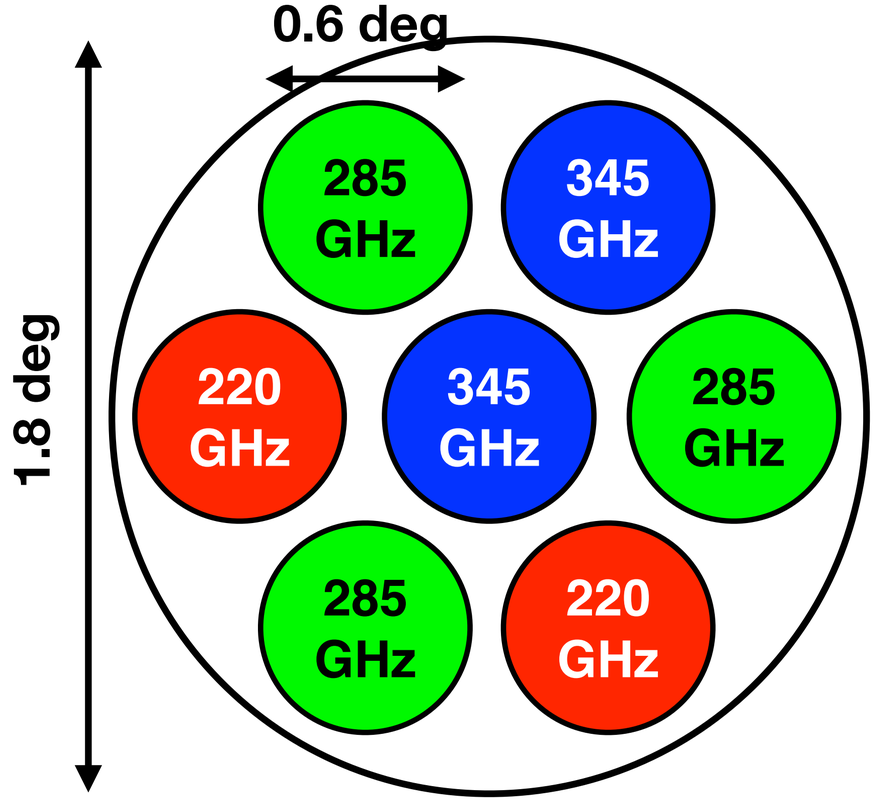
- Guns et al. (2021): **First catalog of 10 transients**, a combination of new stellar and extragalactic sources.
- **Transient alert webpage** to announce quasi-realtime high-confidence astrophysical transients.

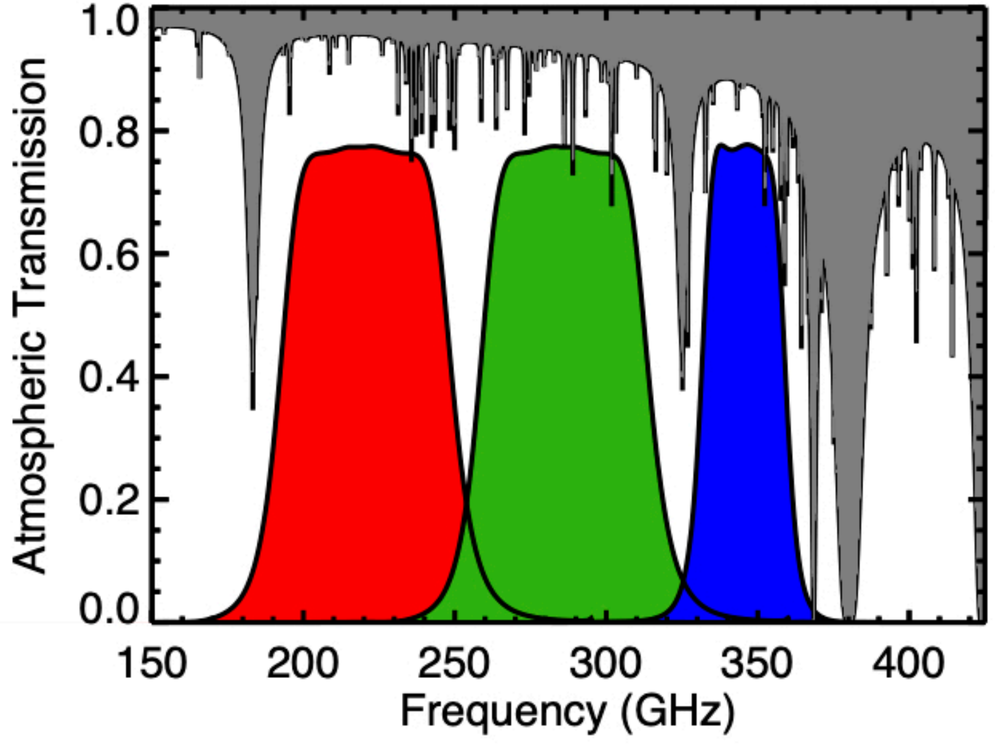
Astro2020: "*An important requirement for our strong endorsement is that the project broadly engage astronomers beyond the traditional CMB community… It is essential that CMB-S4 produce transient alerts…*".

SPT-3G+: A Next-Generation Camera for High-Frequency Surveys with the SPT

- 7x wafers (and optics tubes) with ~4800 det. / wafer, with ~34,000 detectors total
- Polarization-sensitive MKID detectors with 2.2 mm pixels (1.7 F-lambda at 285 GHz)
- Frequency bands at 220, 285, 345 GHz.
- Camera concept allows future (partial or full) expansion to IFU spectrometers for line intensity mapping, by providing swappable single-wafer optics tubes, GHz readout, 100mK base temp.

SPT-3G+ Focal Plane Layout





10/ https://pole.uchicago.edu/spt4/index.php/Receiver_instrument_model

Superconducting Detectors and Readout for Future Cameras

South Pole Telescope is an ideal platform to field-test new mm-wave detector technologies

SPT-SLIM

- ***Intensity mapping*** is a powerful nascent method to measure large-scale structure
- ***On-chip spectrometers*** with kinetic inductance detectors (KIDs) are a highly scalable technology for this measurement
- ***SPT-SLIM*** project, led by FNAL LDRD + UChicago to demo this technique on SPT in 2023!

SPT-3G+

- ***Mapping cosmic velocity fields*** (kSZ) provides powerful constraints on neutrinos, complementary to CMB-S4
- ***Highly multiplexed KID arrays*** enable high sensitivity in a small observing platform