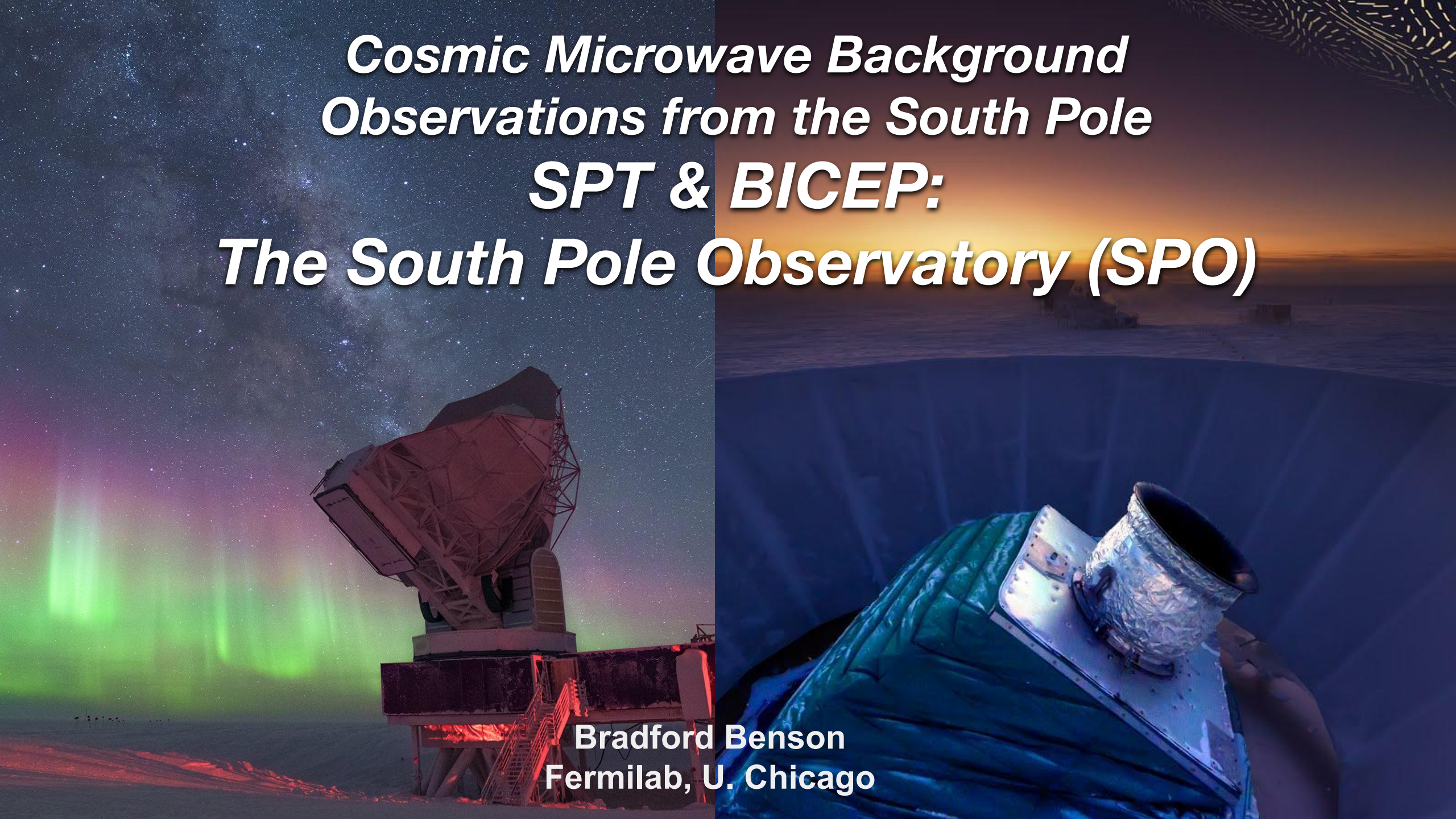
Cosmic Microwave Background Observations from the South Pole

SPT & BICEP:

The South Pole Observatory (SPO)



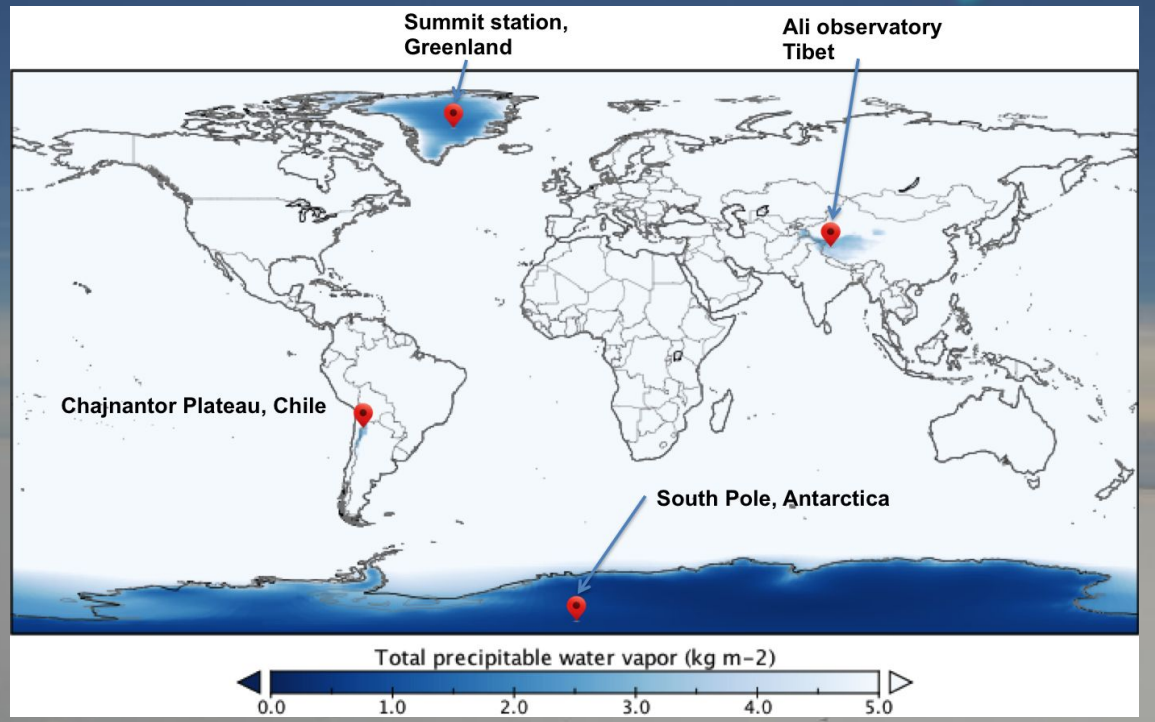
Bradford Benson
Fermilab, U. Chicago

The BICEP/Keck Collaboration

The South Pole Telescope Collaboration

Funded By:

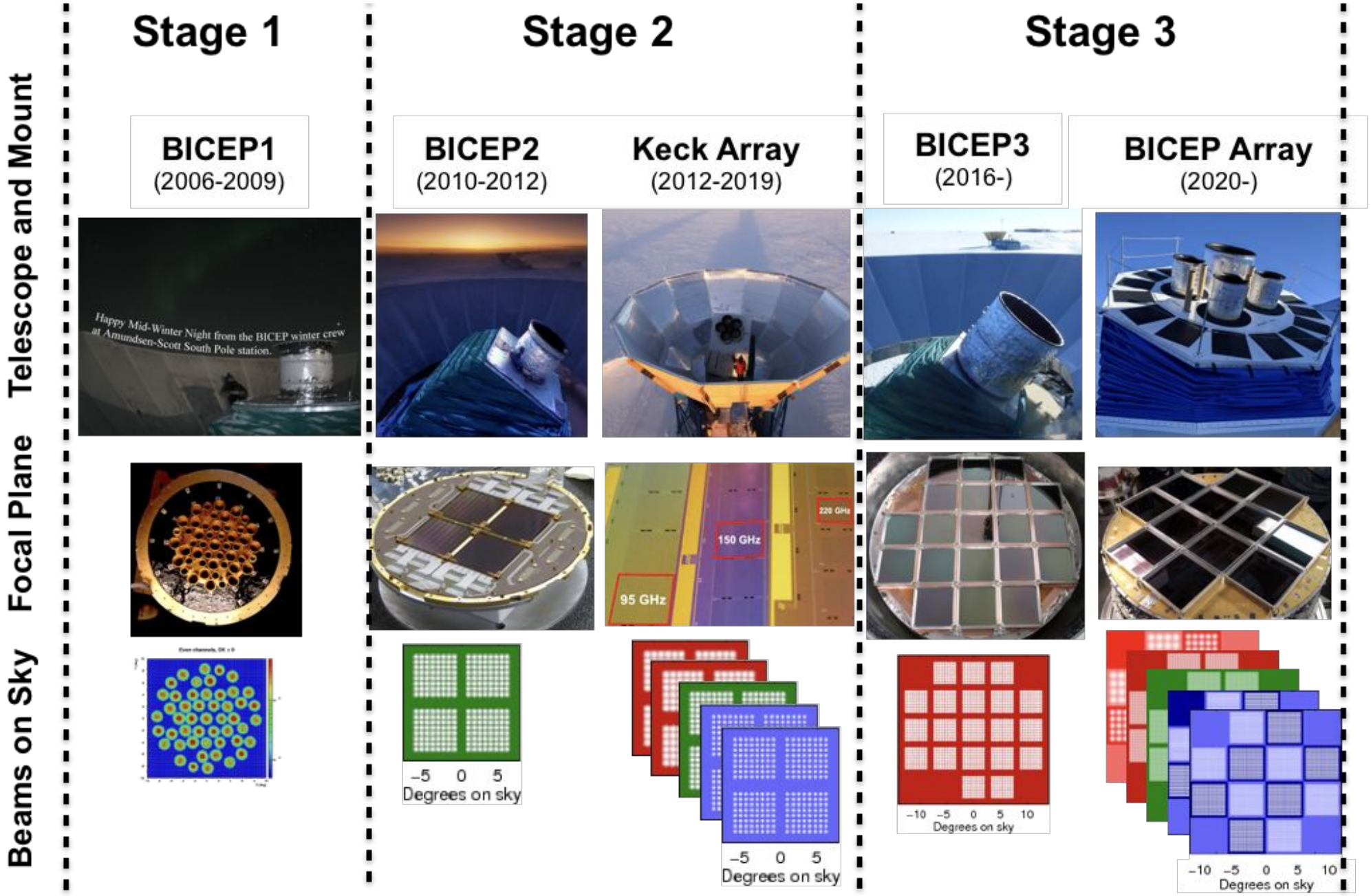
The South Pole is a unique window to the CMB… like being in space!



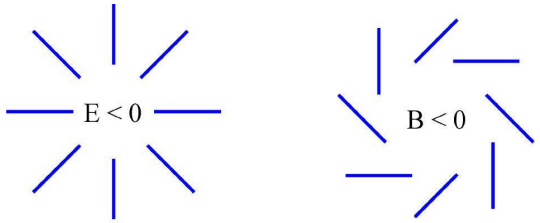
South Pole Environment

- **High Altitude (~10,000 ft) with unique Polar Vortex**
- **Driest desert on Earth with most stable atmosphere**
  - At Pole, the water vapor is 4x lower with a ~30-100x more stable atmosphere than the Chilean Atacama desert.
- **Relentless Observing**
  - 24/7 year-round access to Southern Sky, e.g., including the Black Hole at the Milky Way's center for the Event Horizon Telescope
- **Annual Access for rapid technology deployment**

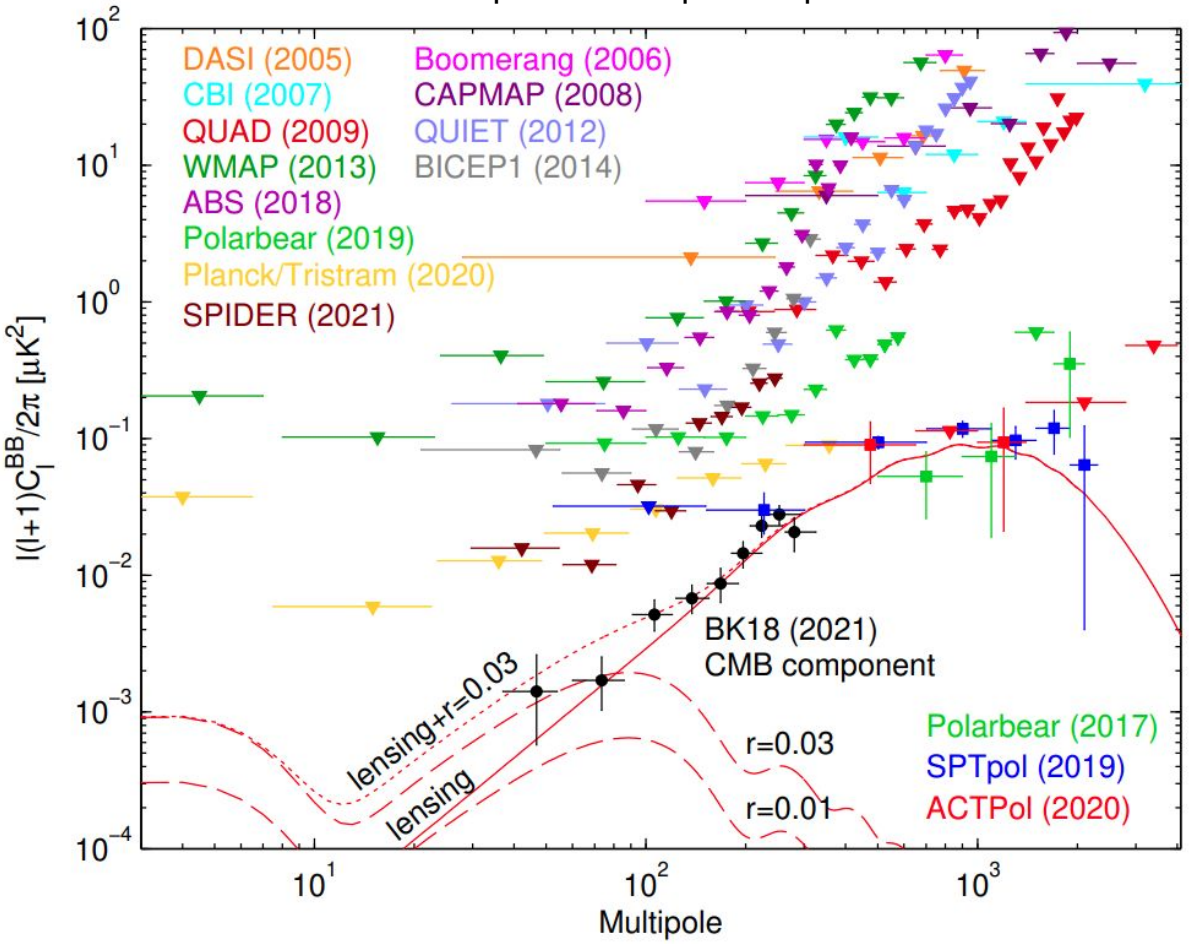
BICEP Experimental Program



Constraints on Inflation to Date



State of B-mode polarization power spectra in 2021



r = tensor to scalar ratio, i.e. amplitude of inflationary gravitational-wave background

Posted B-Mode Sensitivity to r			
Experiment	**arxiv post**	**Bands [GHz]**	**σ(r)**
DASI	0409357	26…36	7.5
BICEP1 2yr	0906.1181	100, 150	0.28
WMAP 7yr	1001.4538	30…60	1.1
QUIET-Q	1012.3191	43	0.97
QUIET-W	1207.5034	95	0.85
BICEP1 3yr	1310.1422	100, 150	0.25
BICEP2	1403.3985	150	0.10
BK13 + Planck	1502.00612	150 + Planck	0.034
BK14 + WP	1510.09217	95, 150 + WP	0.024
ABS	1801.01218	150	0.7
Planck	1807.06209	30...353	0.2
BK15 + WP	1810.05216	95,150,220+WP	0.020
Polarbear	1910.02608	150 + P	0.3
SPTpol	1910.05748	95 + 150	0.22
Planck/Tristram	2010.01139	30...353	0.07
SPIDER	2103.13334	95 + 150	0.13
BK18 + WP	2110.00483	95,150,220+WP	0.009
BK18+Planck PR4	2112.07961	95,150,220+PR4	0.010
Polarbear	2203.02495	150 + P	0.16

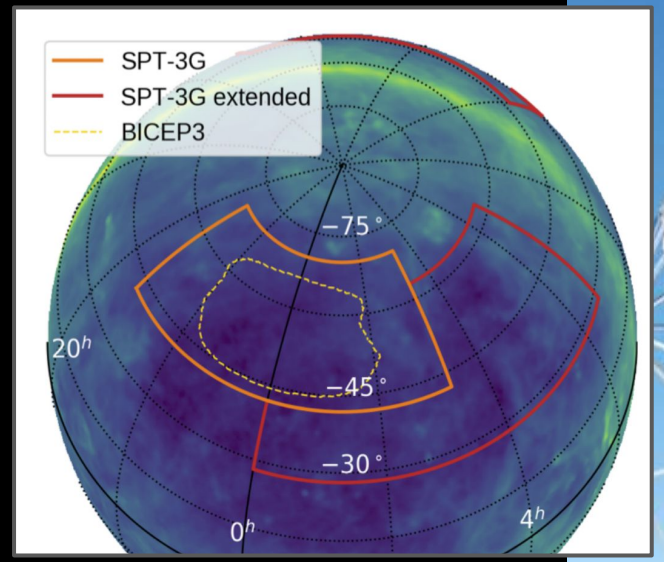
r < 0.036 at 95% conf. (BK18+WP)

The South Pole Telescope (SPT)

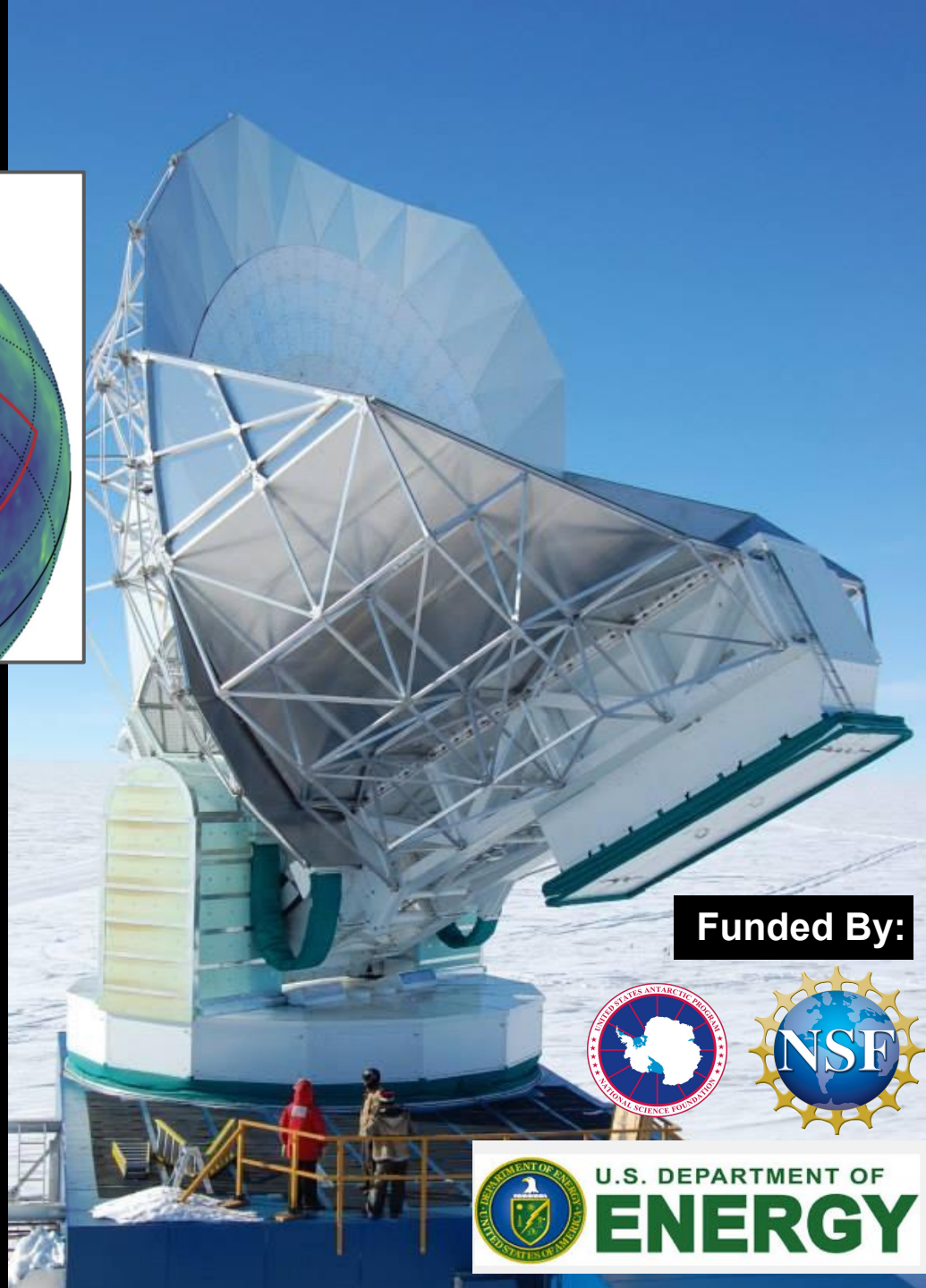
10-meter sub-mm quality telescope

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

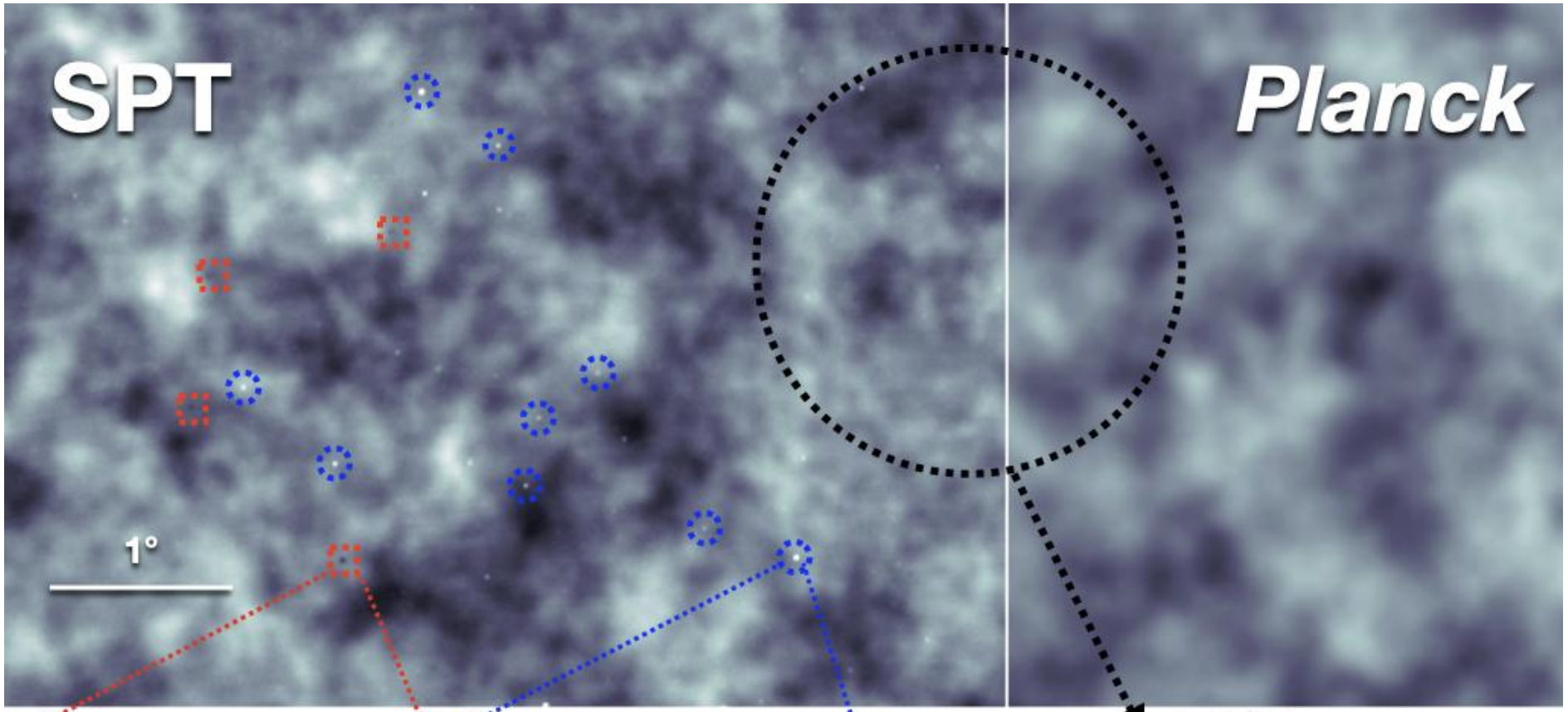
SPT-3G Camera
~16,200 detectors
100,150,& 220 GHz
+Polarization

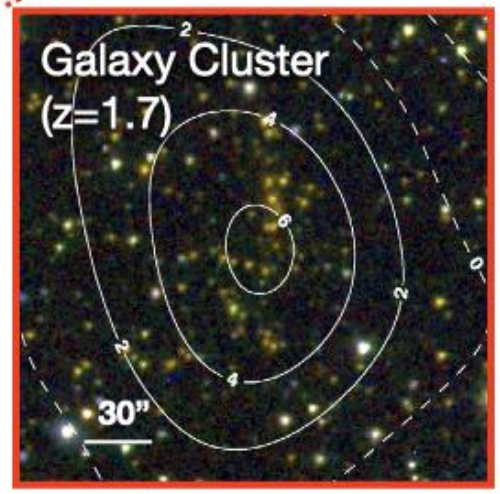


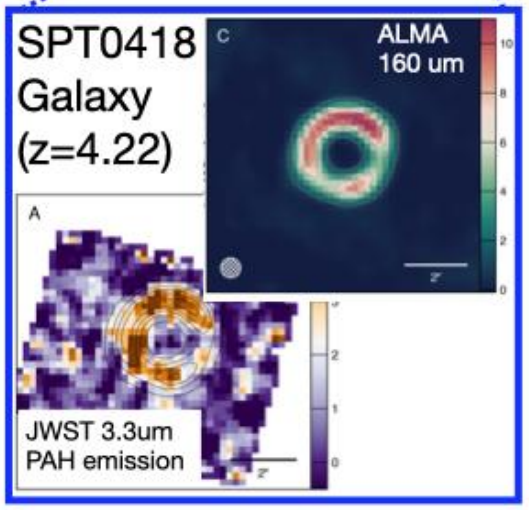
- SPT-3G is a NSF & DOE partnered project & experiment
- In 2018, SPT-3G began its main 1500 deg^2 survey, designed to overlap with the BICEP survey
  - In addition to a 3000 deg^2 "extended" survey
- SPT is key part of the Event Horizon Telescope (EHT)
- SPT is a potential platform for future Line Intensity Mapping (LIM) experiments, e.g.,
  - SPT-SLIM (LIM pathfinder) deploying later this year (Karkare et al. 2021)

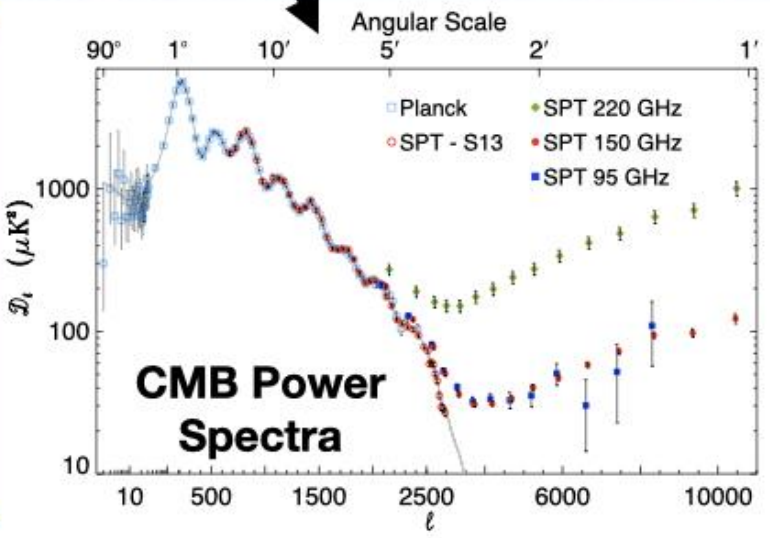


Funded By:
U.S. DEPARTMENT OF ENERGY



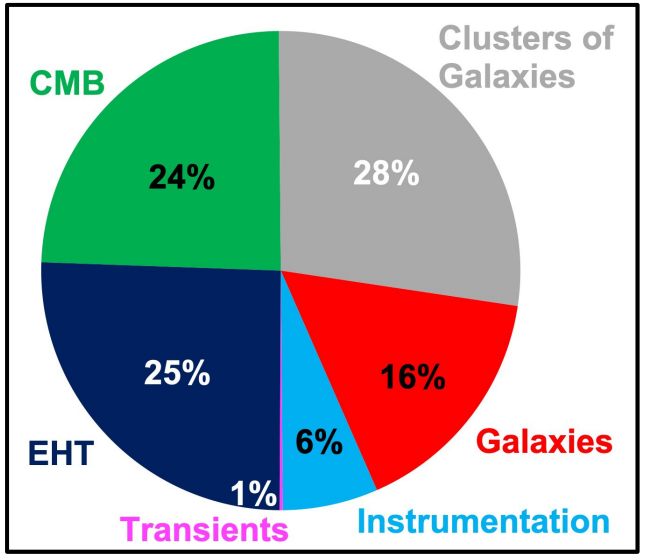






Science Breadth from SPT:

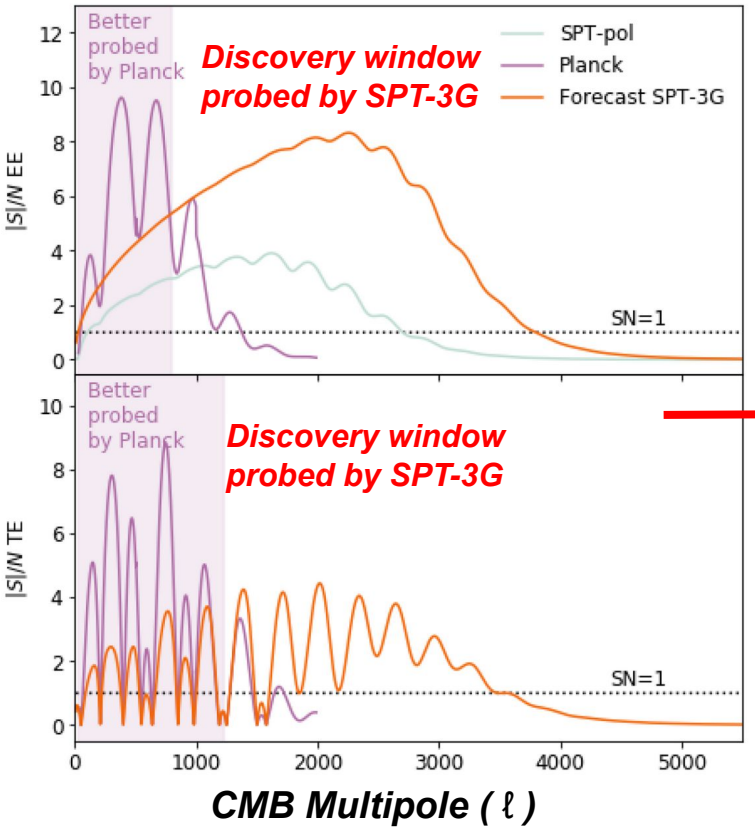
- *Over 300 science, or technical publications with more than 20,000 citations*



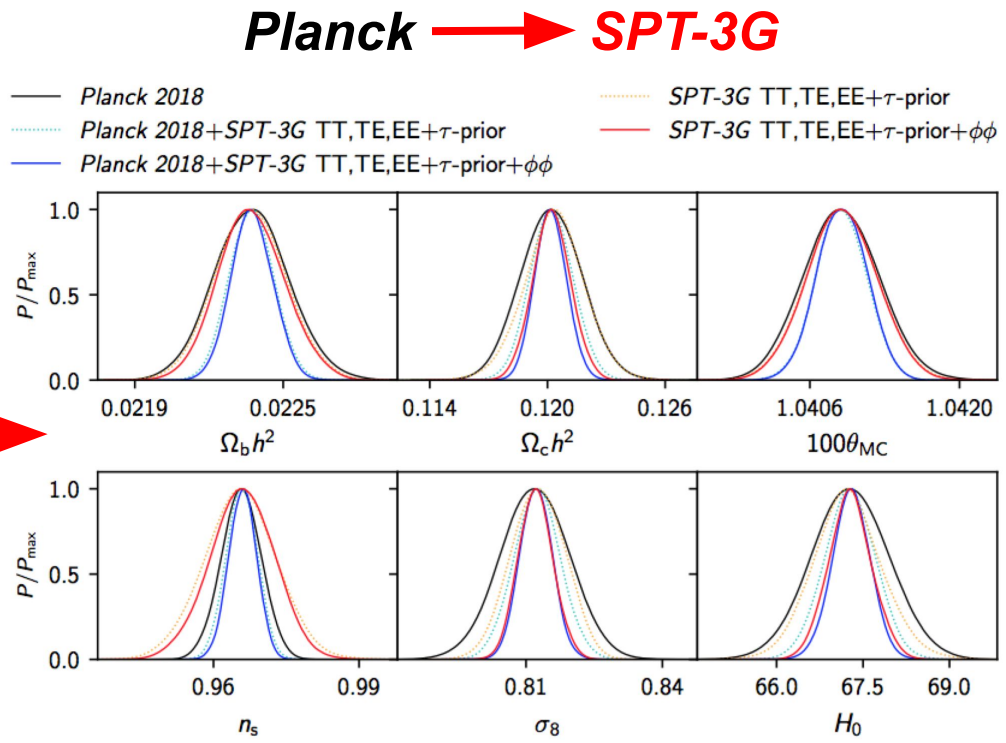
Fraction of total citations by topic

SPT-3G Projected Science Constraints

CMB Power Spectra S/N by Multipole:
Planck vs SPT-3G



Forecasted Cosmology Constraints
(from main SPT-3G 1500 deg^2 survey)



Preliminary
Credit: Silvia Galli

SPT-3G goals through 2024 observing season:

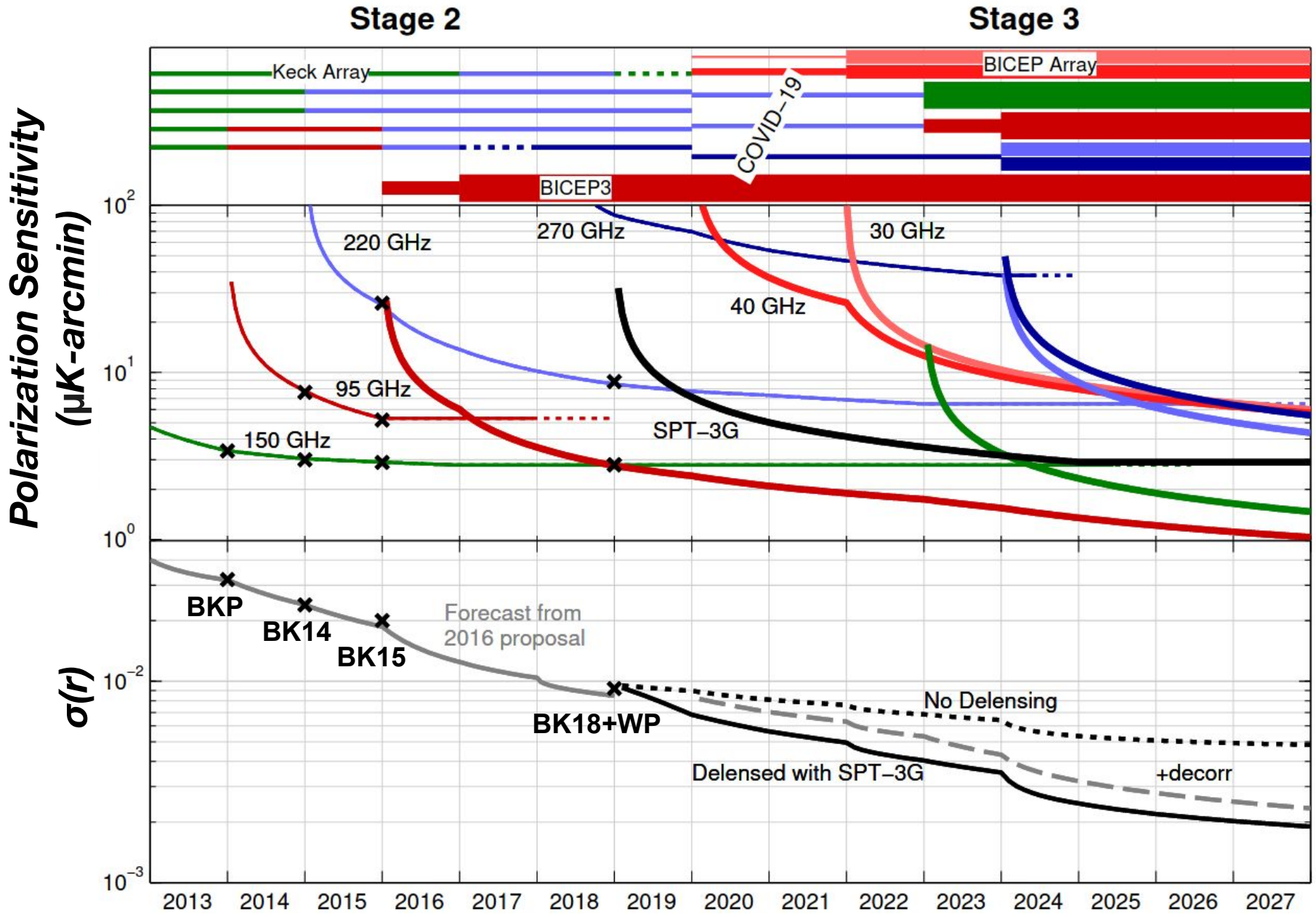
➔ Noise levels:
2.8, 2.6, 6.6 μK-arcmin (T) at 95, 150, 220 GHz

➔ **ΛCDM constraints from SPT-3G TT/EE/TE 1500d survey comparable to Planck !**

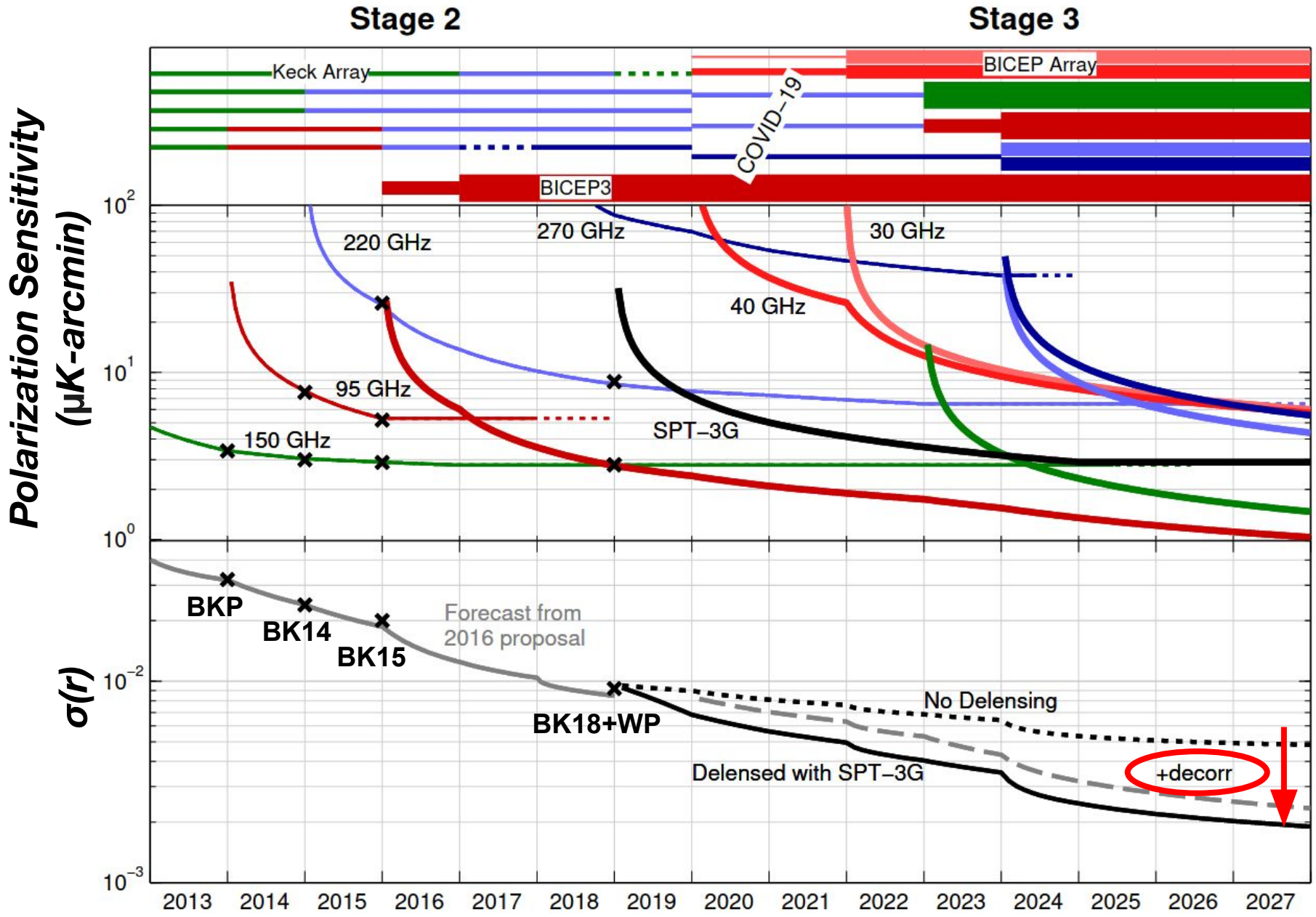
➔ **SPT-3G TT/EE/TE + Planck will improve (most) parameters by a factor 2 !**

- Enabled by deep data, SPT-3G provides new high-ℓ CMB polarization measurements that provide a new test of the ΛCDM model!

SPO (*BICEP+SPT*) Projected Inflationary Constraints

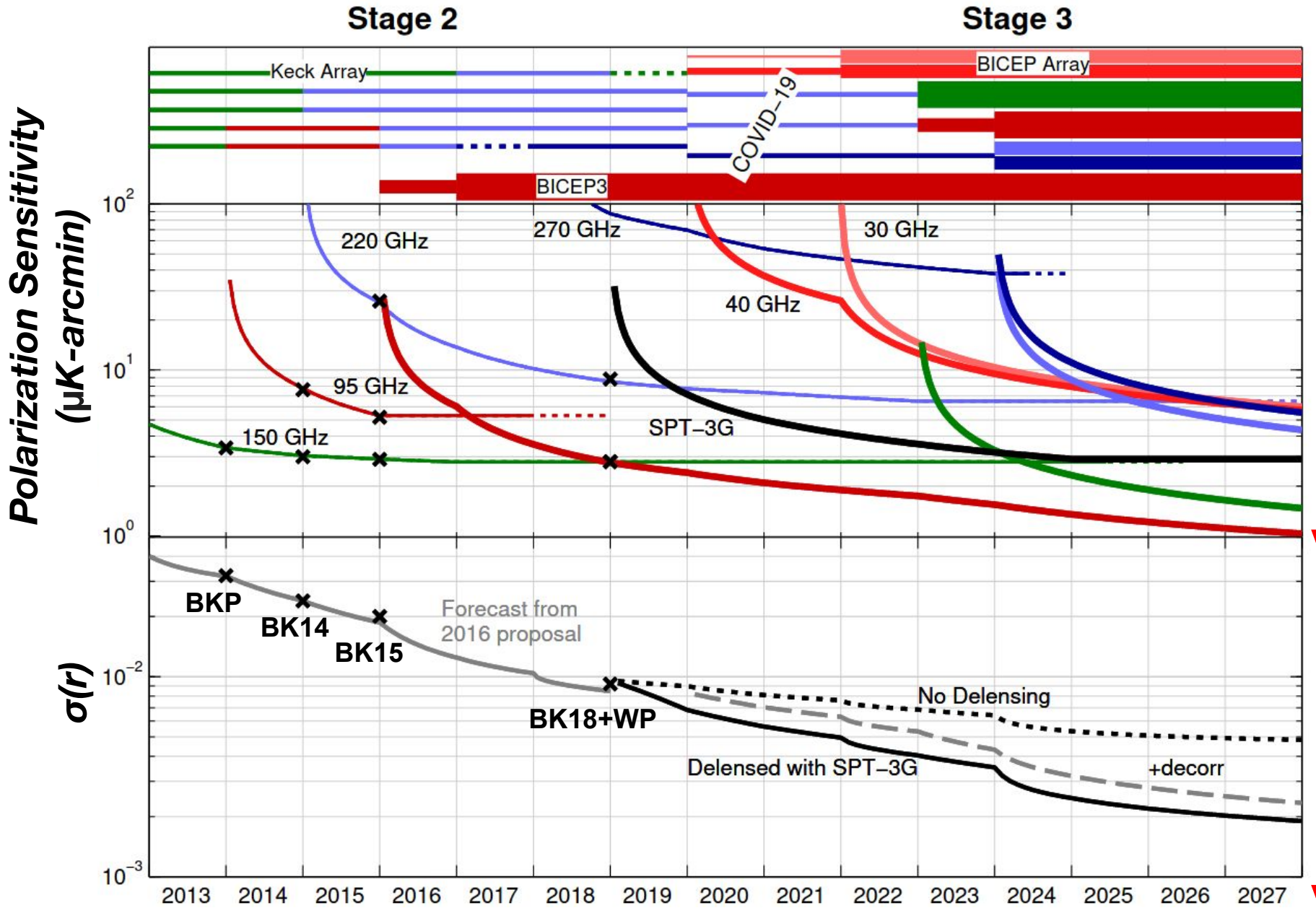


SPO (*BICEP+SPT*) Projected Inflationary Constraints



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

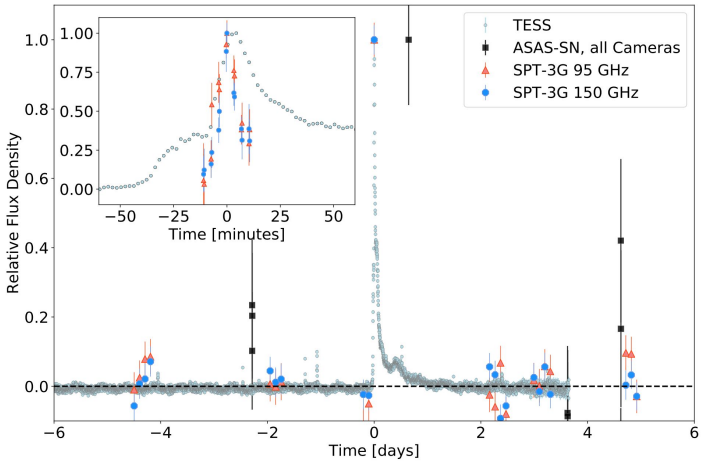
CMB-S4 Goal
***σ(r)* = 0.0005**

BICEP/SPT/SPO informs CMB-S4

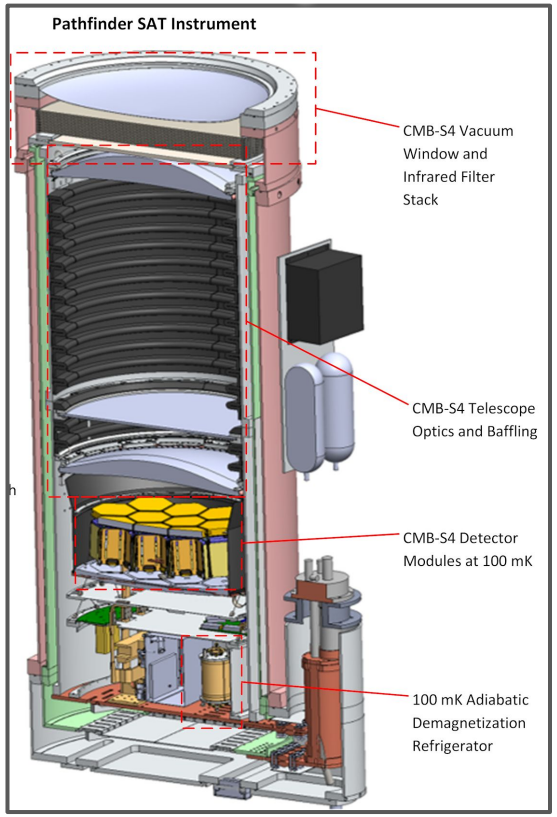
BICEP/SPT/SPO program is providing *demonstrations*, *data sets*, *software*, and *prototype components* relevant for CMB-S4 (S4), e.g.,

- ***Demo*:** BICEP+SPT data set is being used to motivate S4 approach, and is scaled for the LAT+SAT instrument model
- ***Software*:** SPT-3G software and transient analysis pipelines have been provided to (and are used as the baseline) for the S4 pipelines
- ***Data:*** BICEP data are explicitly being included in S4 Inflation/*r* forecasts, to provide additional constraining power on *r*
- ***Proto Components:*** BA Receiver Tower (BART) planned to deploy to Pole as the prototype for S4 SAT tower and mount
- ***Proto Components:*** PSAT planned to deploy on BA at South Pole, to demonstrate S4 detector modules and readout

Stellar flare light-curves from Guns et al. 2021 (SPT-3G)

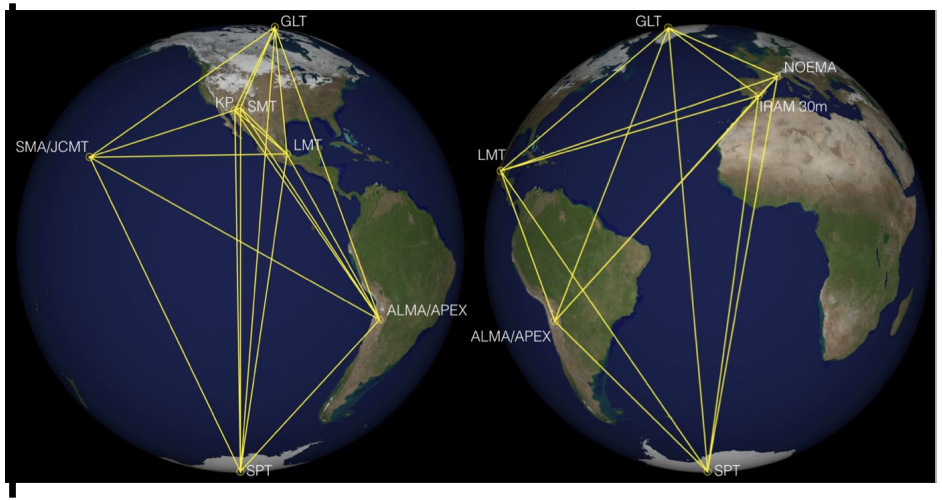


Pathfinder SAT (PSAT) Instrument Design

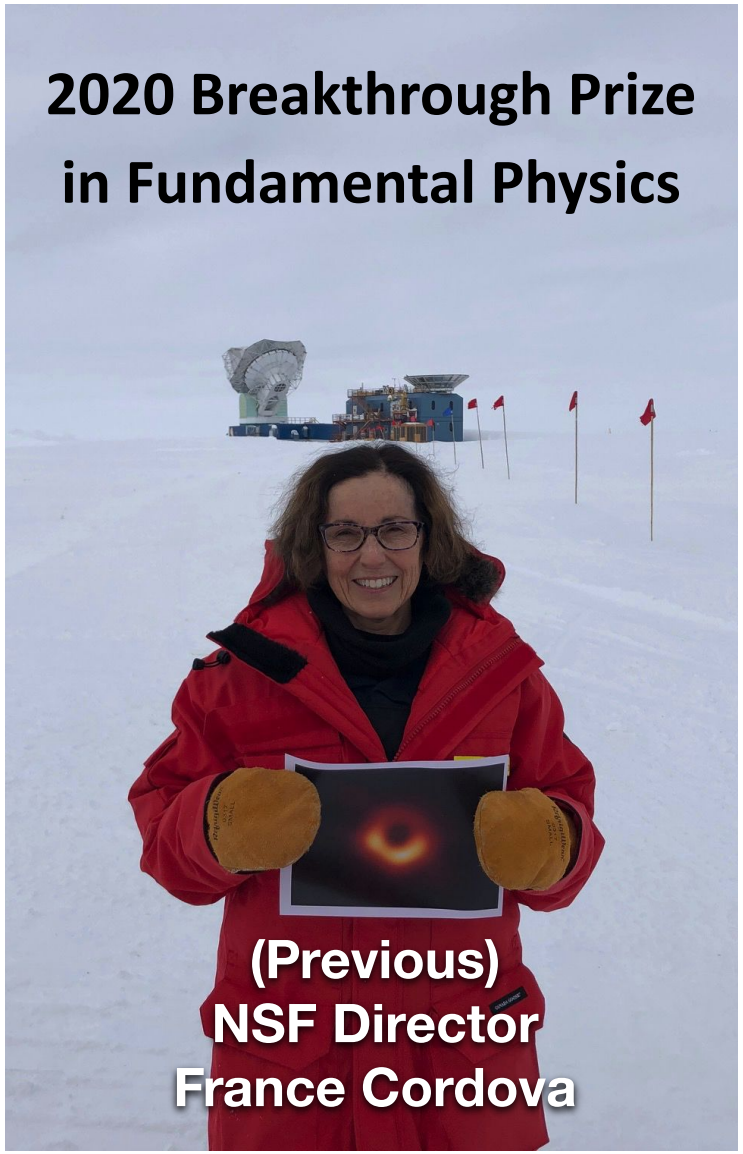


Extras

South Pole is central to the Event Horizon Telescope

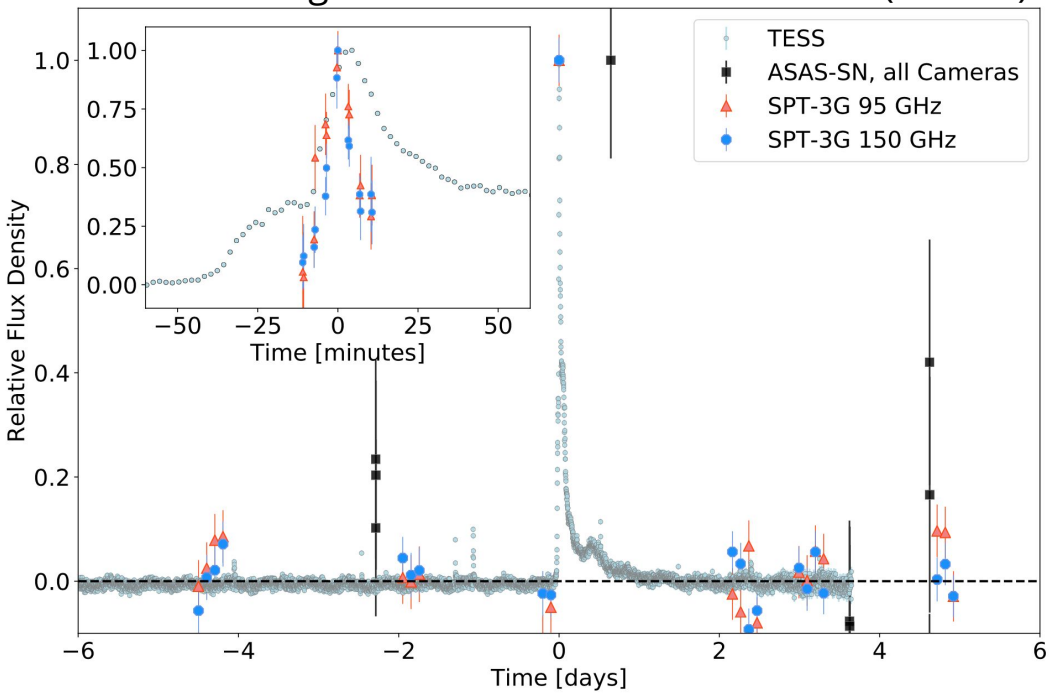


SPT provides 24/7 observing of the Black Hole at the Center of the Milky Way, anchoring the EHT measurements and providing the highest angular resolution.



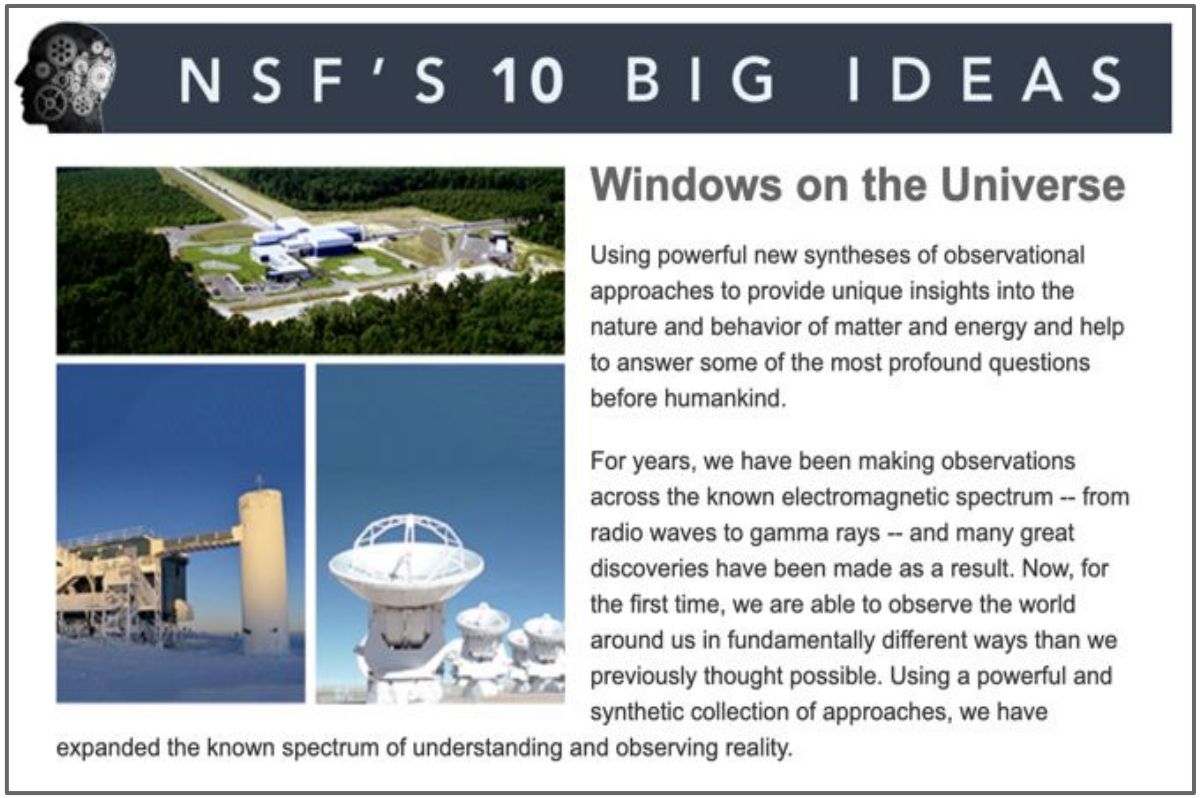
Transients and the Time-Variable mm-Wave Sky

Stellar flare light-curves from Guns et al. 2021 (SPT-3G)



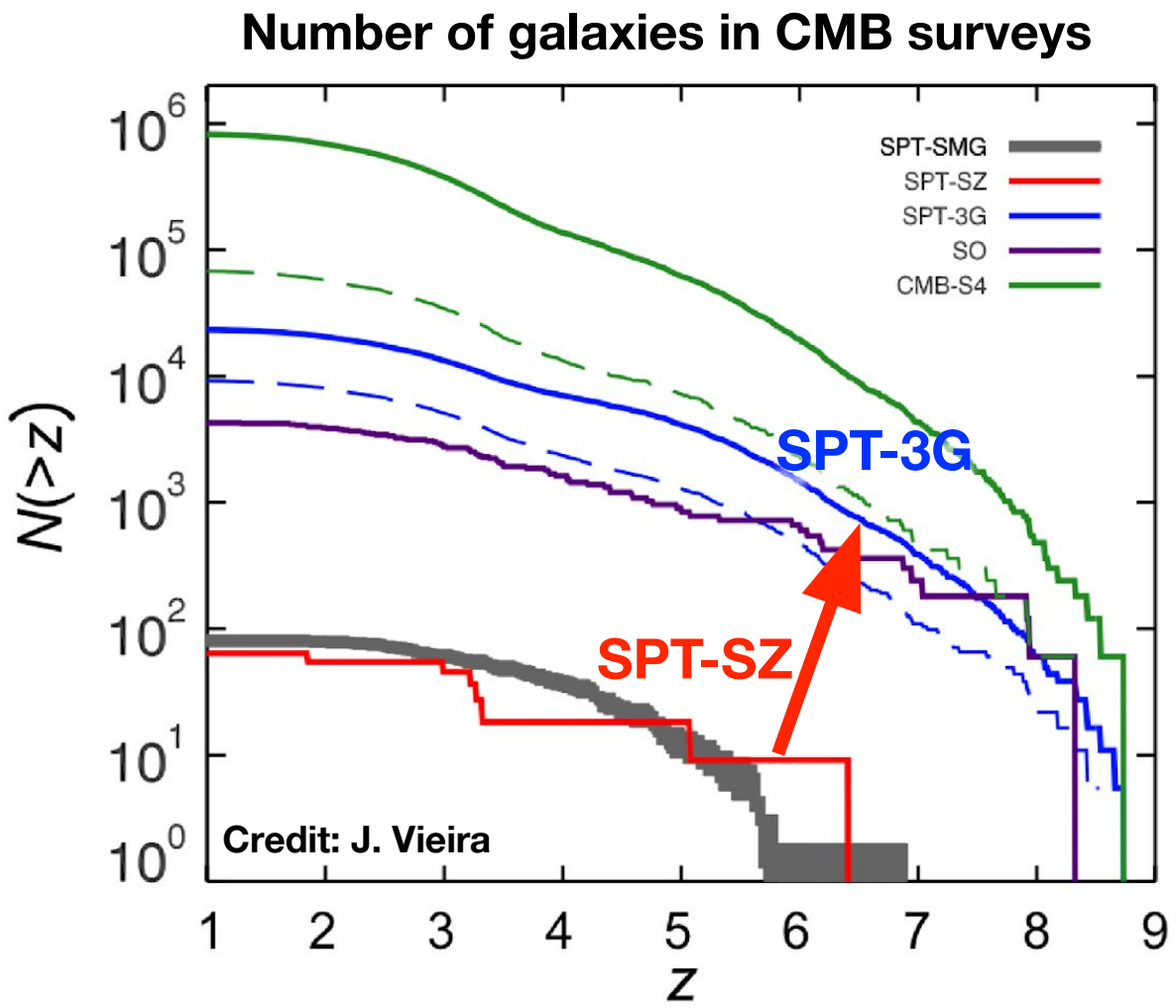
SPT-3G has made pioneering measurements of the time-variable mm-wave sky;

- **Guns et al. (2021): First catalog of 10 transients**, a combination of new stellar and extragalactic sources.
- **Transient alert pipeline (and public webpage)** to produce quasi-realtime high-confidence astrophysical transients.
- **Characterizing** terrestrial (e.g., satellites) and astrophysical **backgrounds** (e.g., flaring stars, variable AGN, etc.)



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…*".

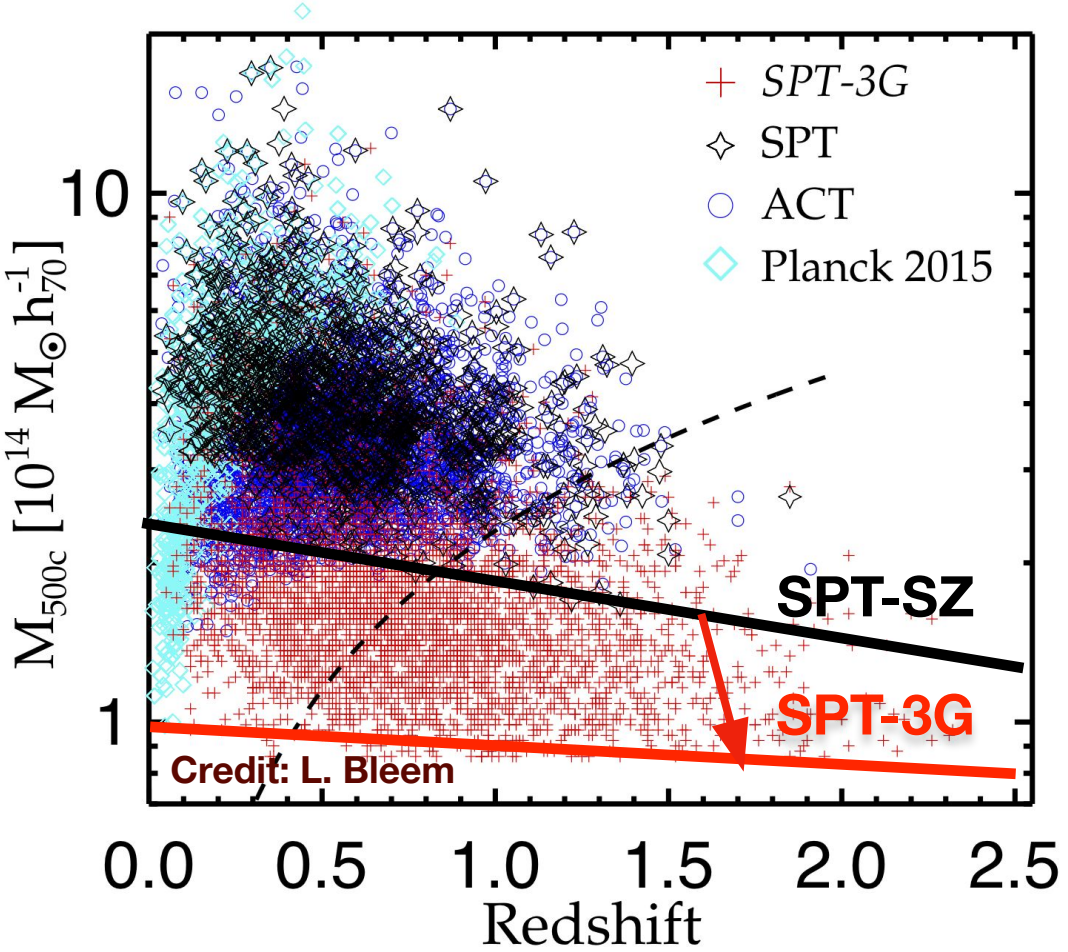
High-z Proto-clusters from CMB surveys

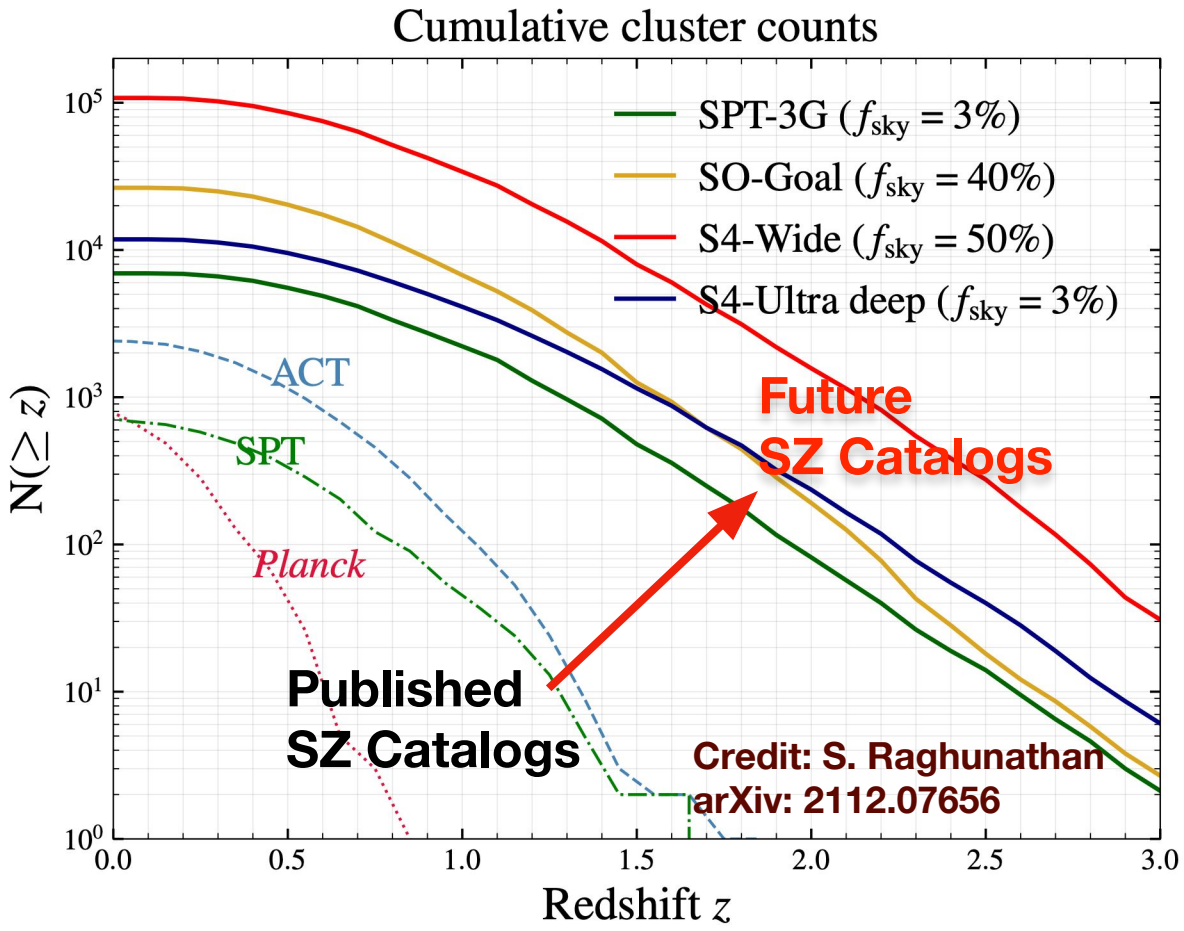


- **SPT-3G will detect ~100x more galaxies than the SPT-SZ survey:**
  - Dusty galaxies to $z \sim 9$
  - 100s of galaxies at $z > 6$
  - ***~100 protoclusters at $z > 4$***
- From detecting SZ and dusty emission, CMB surveys can identify progenitors of most massive clusters from $1 < z < 5$!
  - With multiwave follow-up, can further trace history of gas virialization and infall, stellar quenching, AGN feedback, etc., back to earliest epochs of cluster formation

CMB-S4 Collaboration, arXiv:1907.04473

High-z Galaxy Clusters from CMB surveys





In the near future, SZ surveys will push down a factor of ~3x in mass, below 10^{14} Msun

SZ surveys will extend highest-z reach significantly, by a factor of 1000 at z > 1.5