

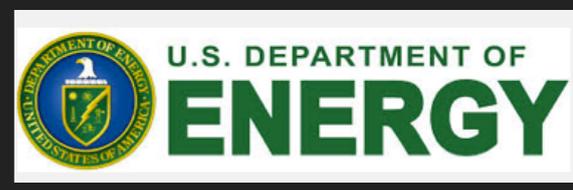
# EXPLORING THE MICROWAVE SKY WITH THE SOUTH POLE TELESCOPE

SASHA RAHLIN

UNIVERSITY OF CHICAGO



# SPT3G COLLABORATION

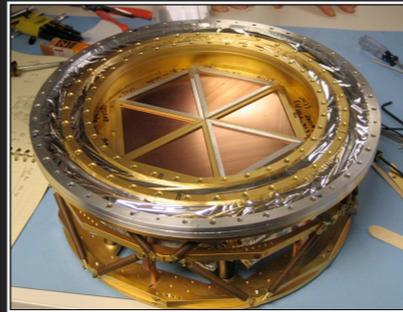


# THE SOUTH POLE TELESCOPE

- ▶ 10-m submm-quality wavelength telescope
  - ▶ 90, 150, 220 GHz
  - ▶ 1.6, 1.2, 1.0 arcmin resolution

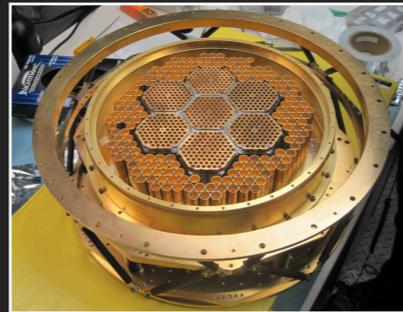
- ▶ **2007: SPT-SZ**

- ▶ 960 detectors
- ▶ 90, 150, 220 GHz



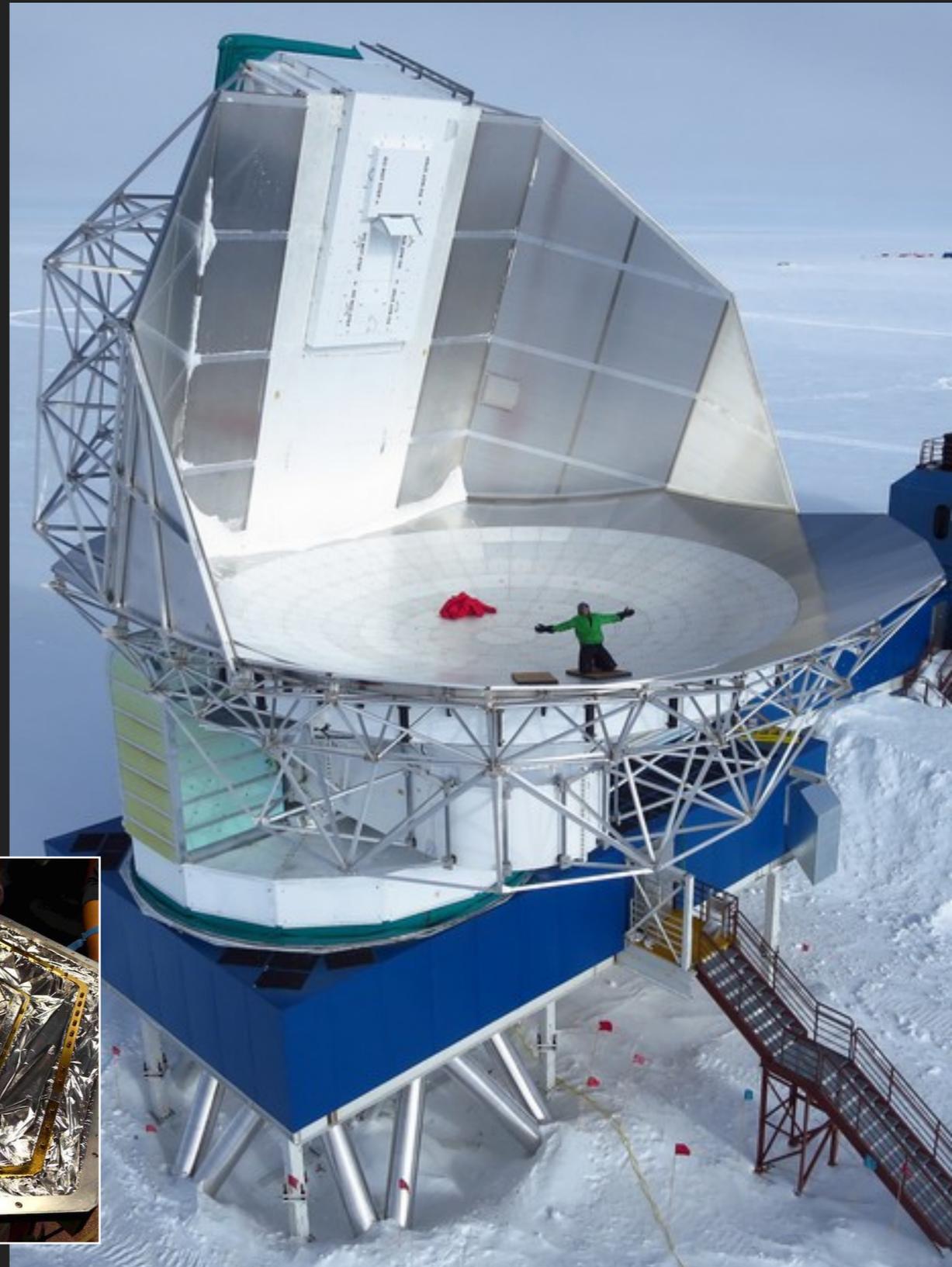
- ▶ **2012: SPTpol**

- ▶ 1600 detectors
- ▶ 90, 150 GHz
- ▶ +polarization



- ▶ **2017: SPT-3G**

- ▶ ~16,200 detectors
- ▶ 90, 150, 220 GHz
- ▶ +polarization

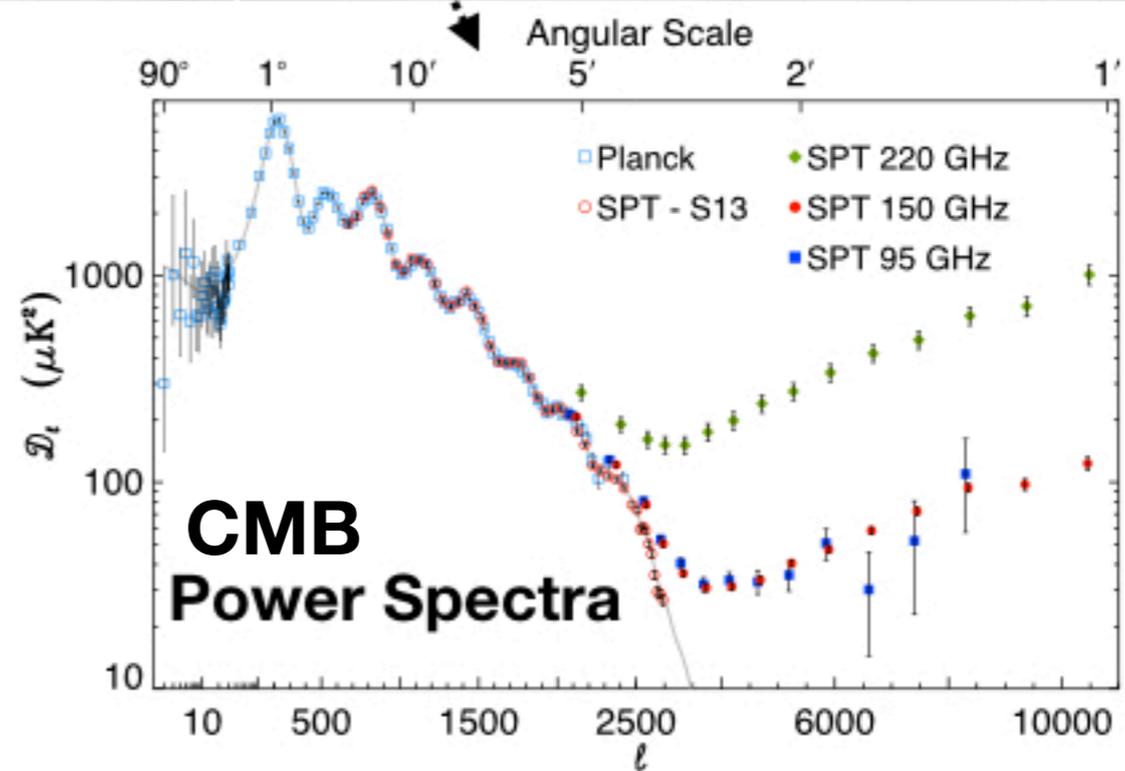
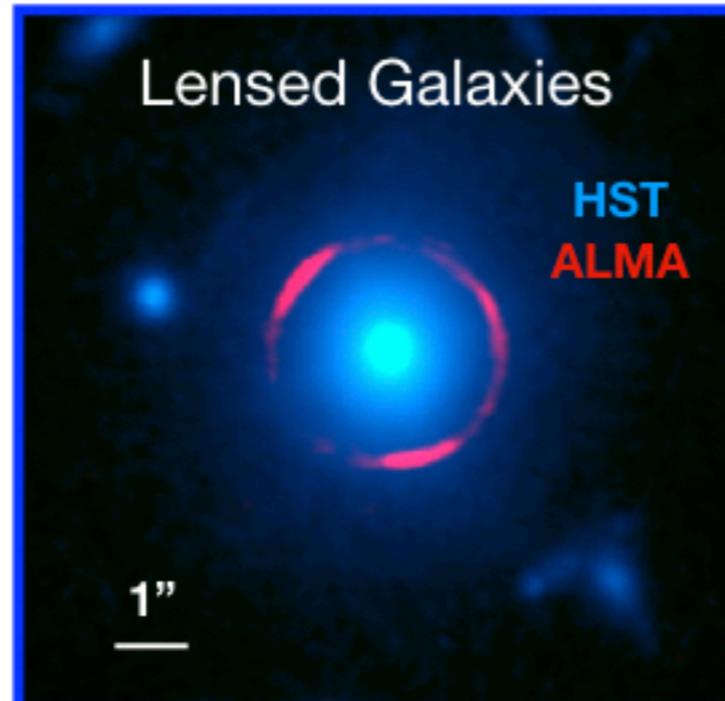
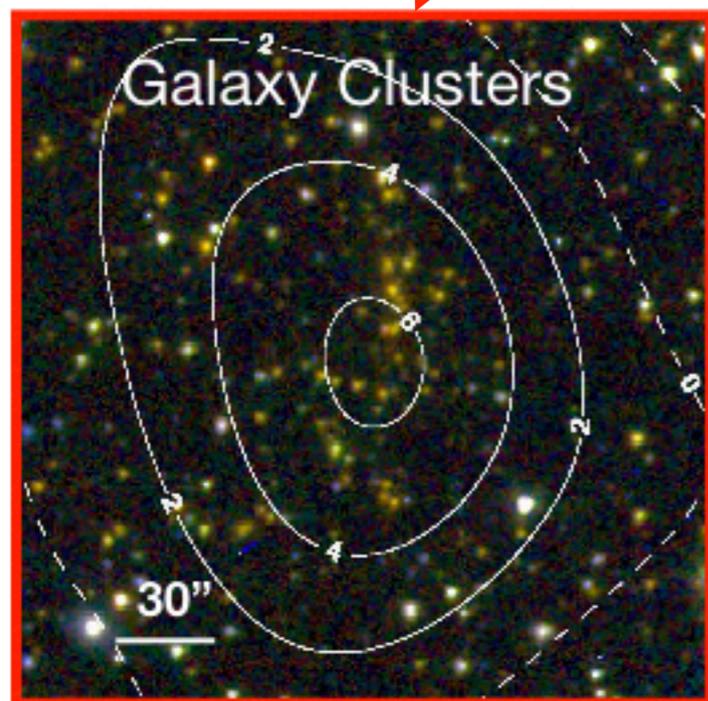


# SPTpol

6x deeper  
6x finer angular  
resolution

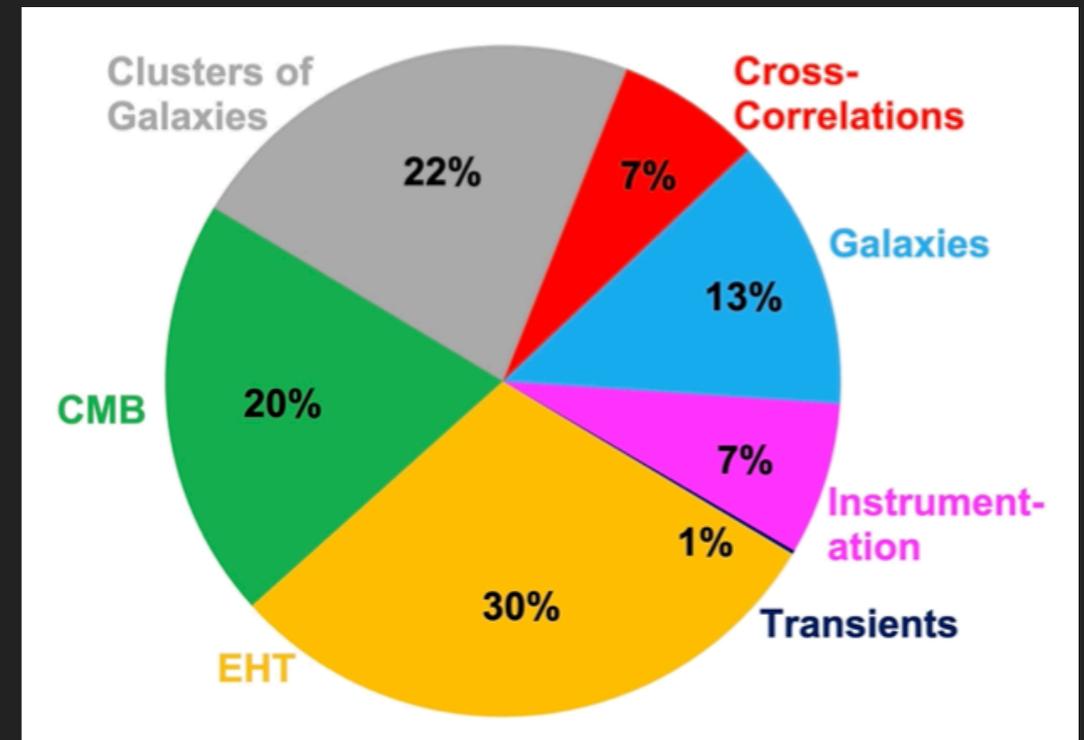
# Planck

1°



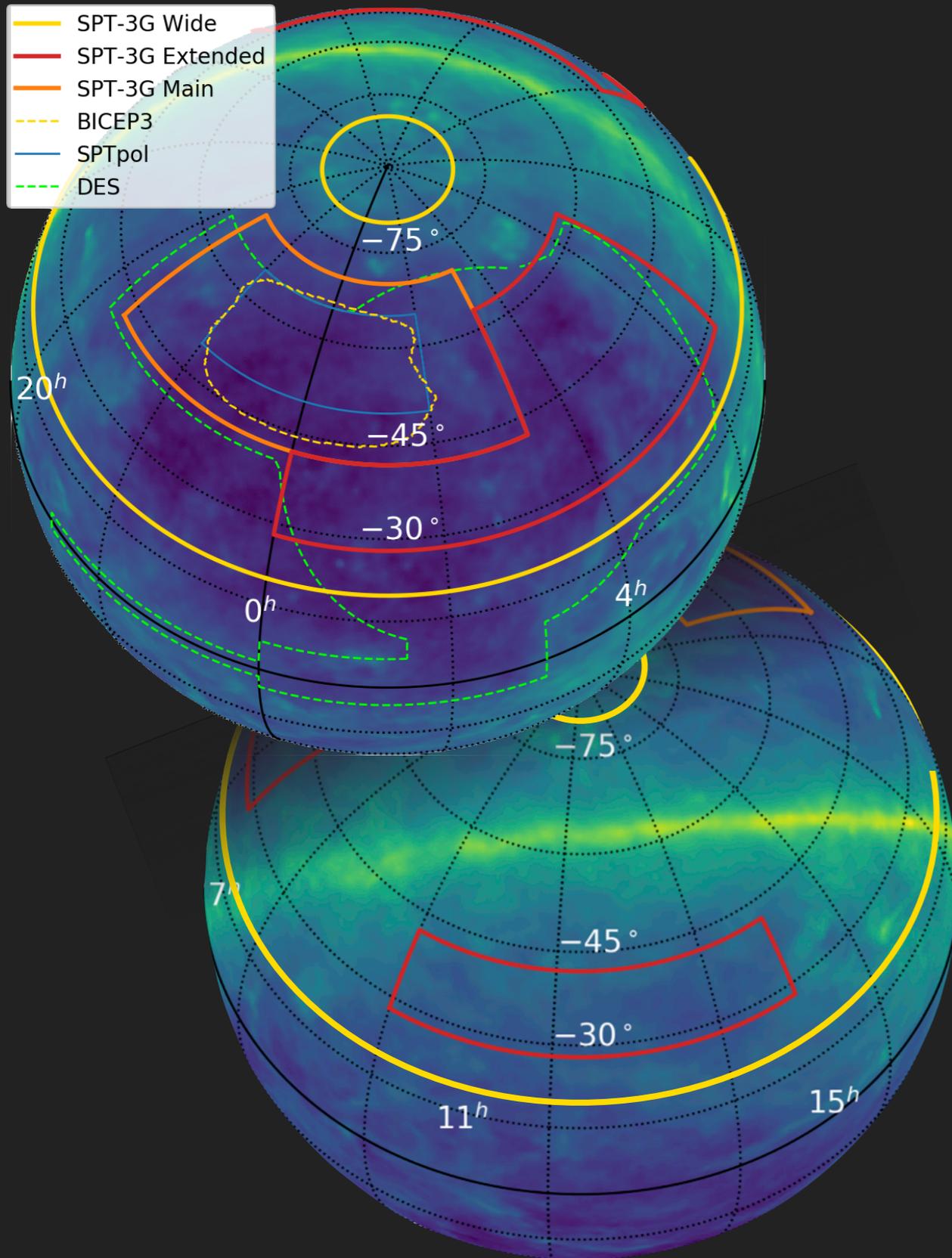
# BREADTH OF SPT RESULTS

- ▶ **CMB anisotropy:** Power spectra and cosmological parameters
- ▶ **CMB B-Modes:** First detection of lensing B-mode polarization; demonstration of delensing for improved constraints on inflationary tensor-to-scalar ratio
- ▶ **CMB lensing:** power spectra; cross-correlations; cluster-lensing mass calibration
- ▶ **Sunyaev-Zel'dovich (SZ):** Diffuse kinematic and thermal SZ effect constraints: bispectrum, pairwise kSZ, patchy reionization
- ▶ **Galaxy Clusters:** First SZ discovery clusters, SZ cluster catalog and cosmology
- ▶ **High-Redshift Galaxies:** Discovered population of lensed dusty star forming galaxies
- ▶ **Transients:** mm-wave phenomena (GRBs, FRBs), mJy-level monitoring of 1000s of blazars, AGNs
- ▶ Participating in the **Event Horizon Telescope**
- ▶ ...



*Publications: [pole.uchicago.edu](http://pole.uchicago.edu)*

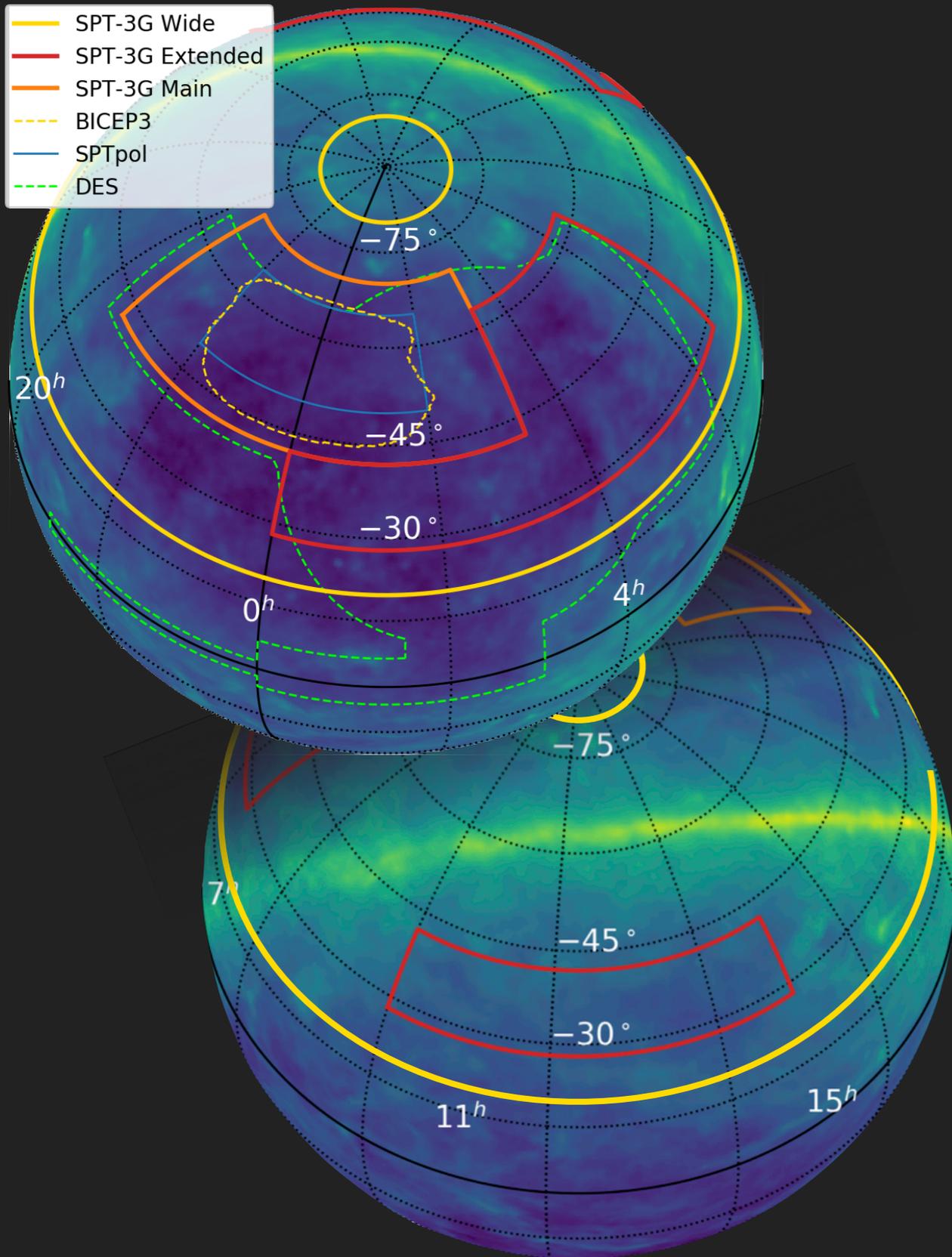
# THE SPT-3G 1500 DEG<sup>2</sup> SURVEY



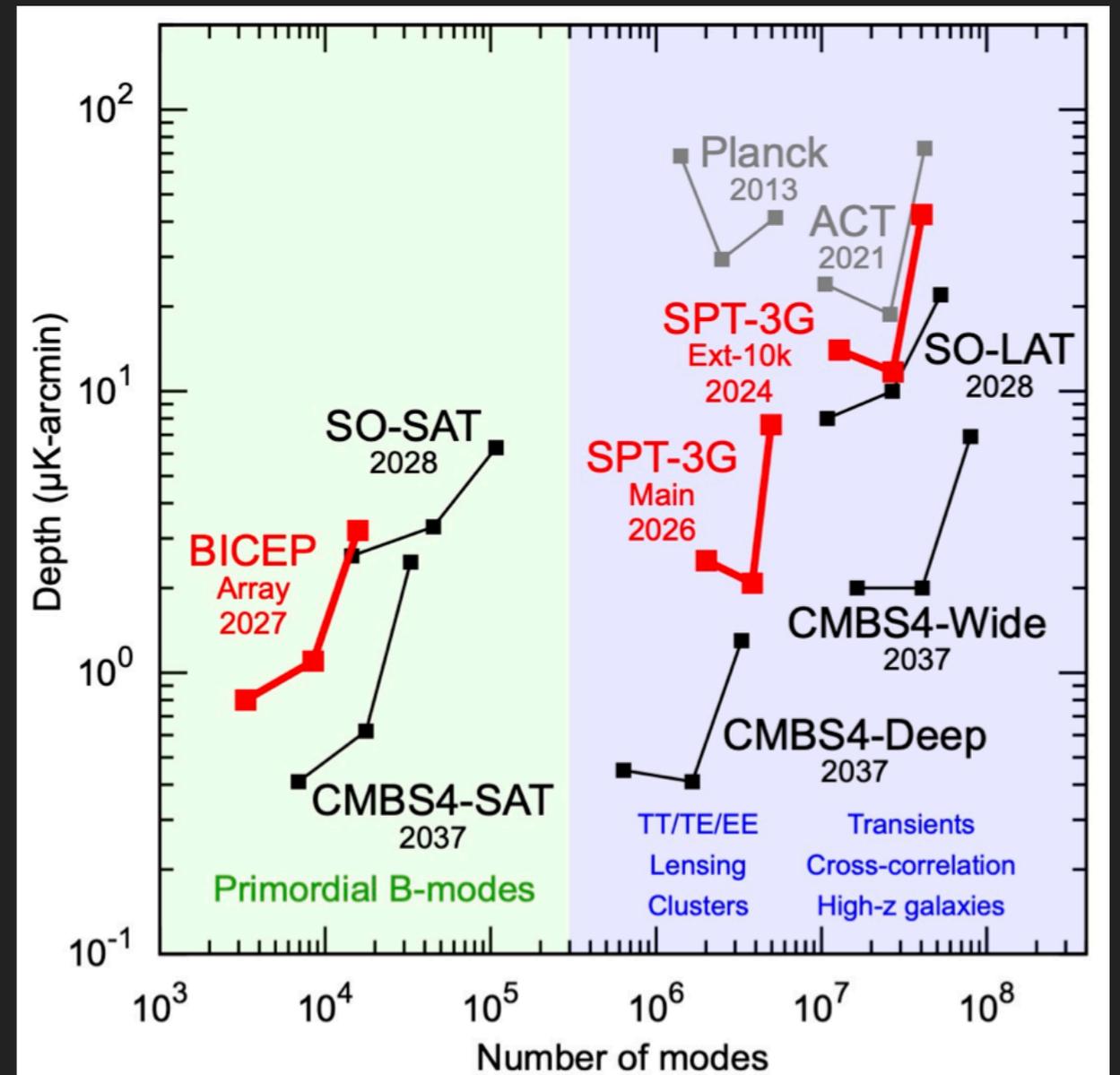
- ▶ SPT-3G 1500 deg<sup>2</sup> survey will be ~10x deeper than SPT-SZ
- ▶ Overlaps BICEP Array, to optimize inflationary constraints from CMB delensing

	Obs. Years	Area (deg <sup>2</sup> )	95 GHz (uK-)	150 (uK-)	220 (uK-)
<b>SPT-SZ</b>	2007-11	2500	40	17	80
<b>SPTpol-500d</b>	2012-16	500	13	6	-
<b>SPTpol-100d</b>	2012-16	100	10	5	-
<b>SPTpol-2700d</b>	2012-16	2700	47	28	-
<b>SPT-3G Main</b>	<b>2018-23 2025-26</b>	<b>1500</b>	<b>2.5</b>	<b>2.1</b>	<b>7.6</b>
<b>SPT-3G Extended</b>	<b>2019-23</b>	<b>2600</b>	<b>8.5</b>	<b>9.0</b>	<b>31</b>
<b>SPT-3G Wide</b>	<b>2024</b>	<b>6000</b>	<b>14</b>	<b>12</b>	<b>42</b>

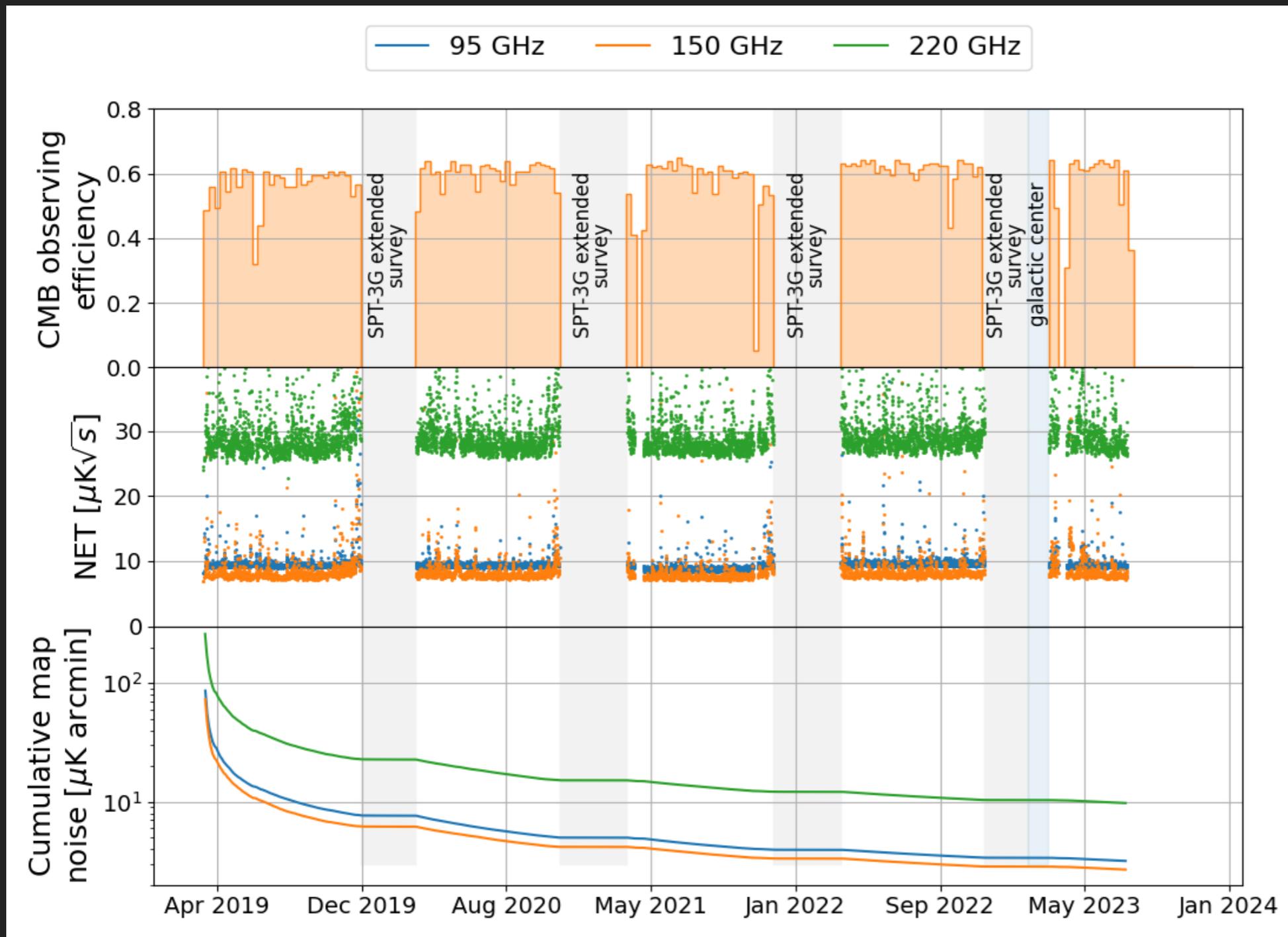
# THE SPT-3G EXTENDED SURVEY



- ▶ Additional one-year wide survey to cover all remaining visible sky area (10K total area with existing surveys)
- ▶ Overlap with ACT/Planck, mode-by-mode cross checks



# SPT-3G: DATA QUALITY



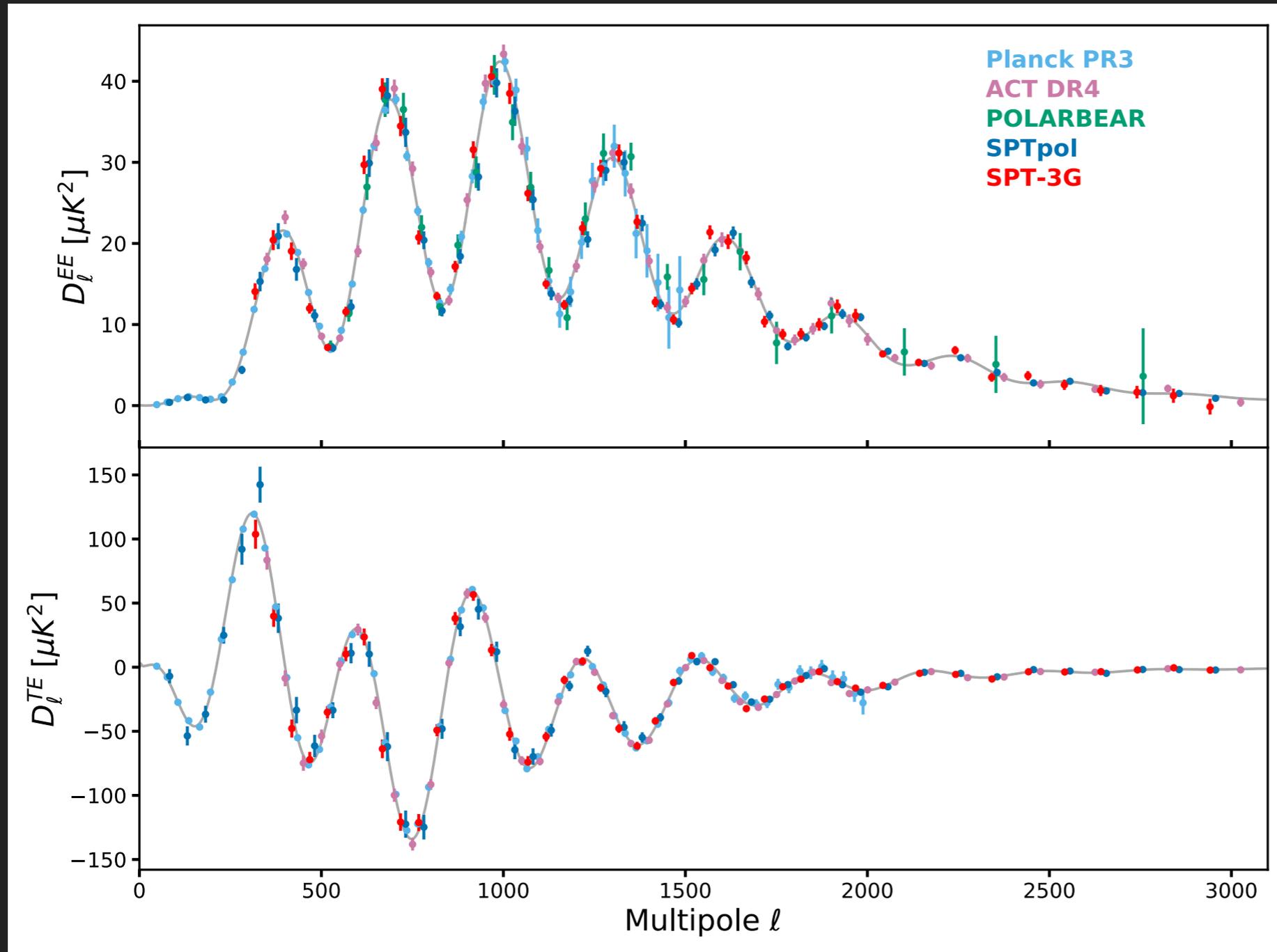
~60% observing efficiency in 9-month observing season

Daily camera sensitivity is stable over season

Expect to reach CMB-S4 wide survey depth by end of 2023

*A. Anderson, W. Quan, A. Bender*

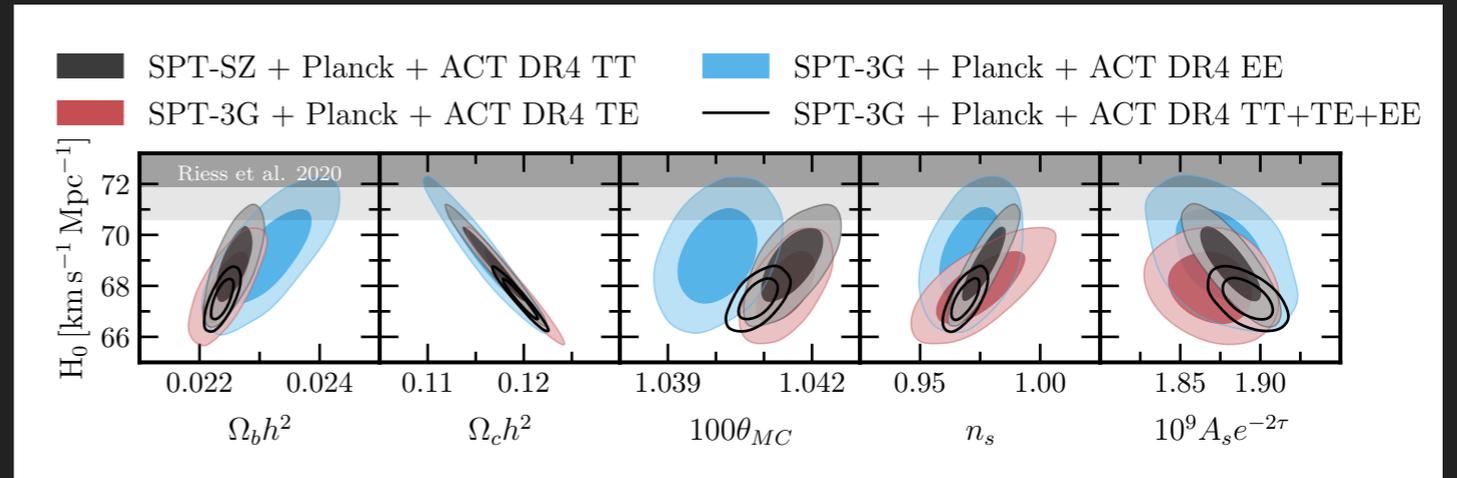
# SPT3G: 2018 CMB POWER SPECTRA



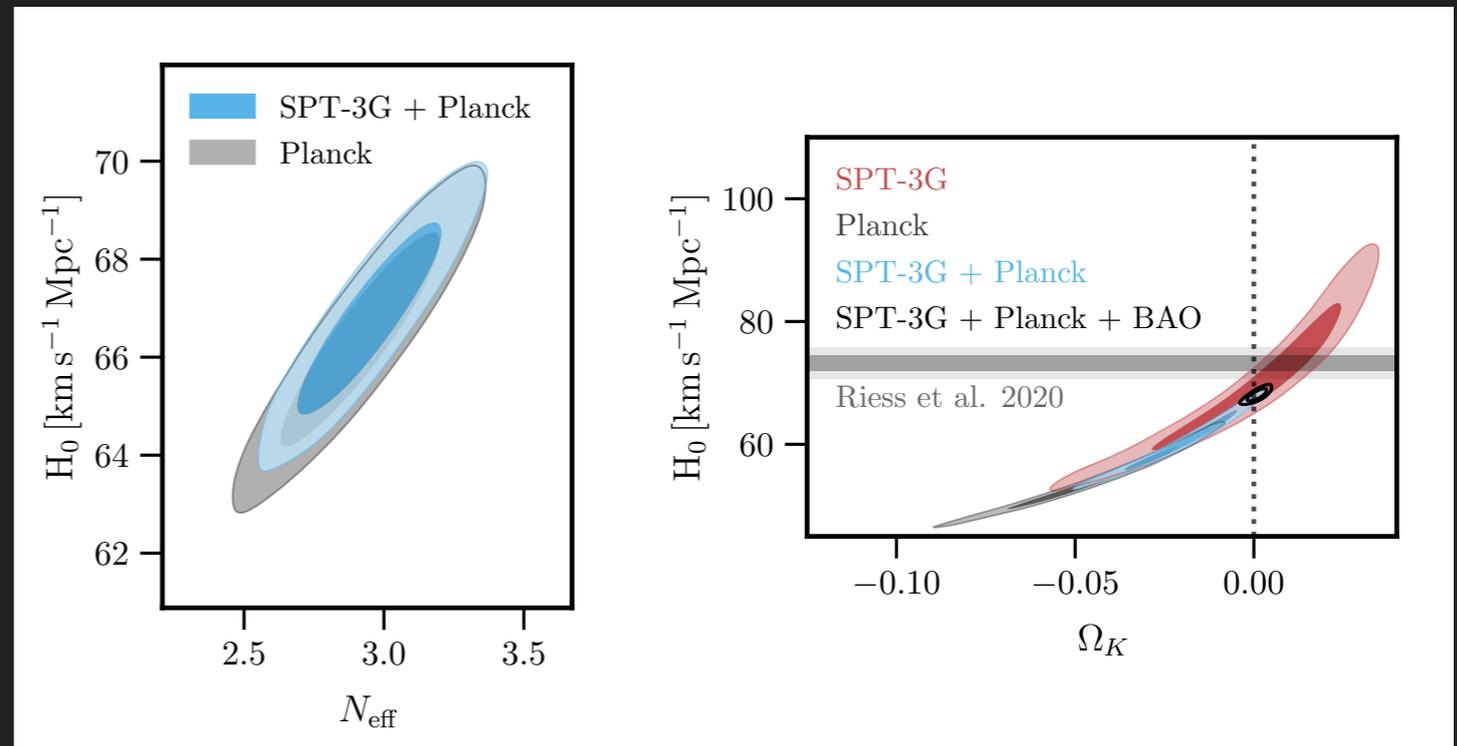
- ▶ 2018: half season with half of full detector count
- ▶ Constraints already comparable to or exceed leading measurements at intermediate scales

# SPT3G: 2018 $\Lambda$ CDM CONSTRAINTS

- ▶ Consistent  $H_0$  values between T and P spectra when evaluated across experiments
- ▶ Tightest constraint on  $H_0$  to date
  - ▶ 4.1  $\sigma$  tension with Riess et al
- ▶ Further model extensions:  $N_{\text{eff}}$ ,  $Y_p$ ,  $\sum m_\nu$ ,  $\Omega_K$ 
  - ▶ No clear evidence for any extensions
  - ▶ with Planck, reduce volume of parameter space by 1.3-2x

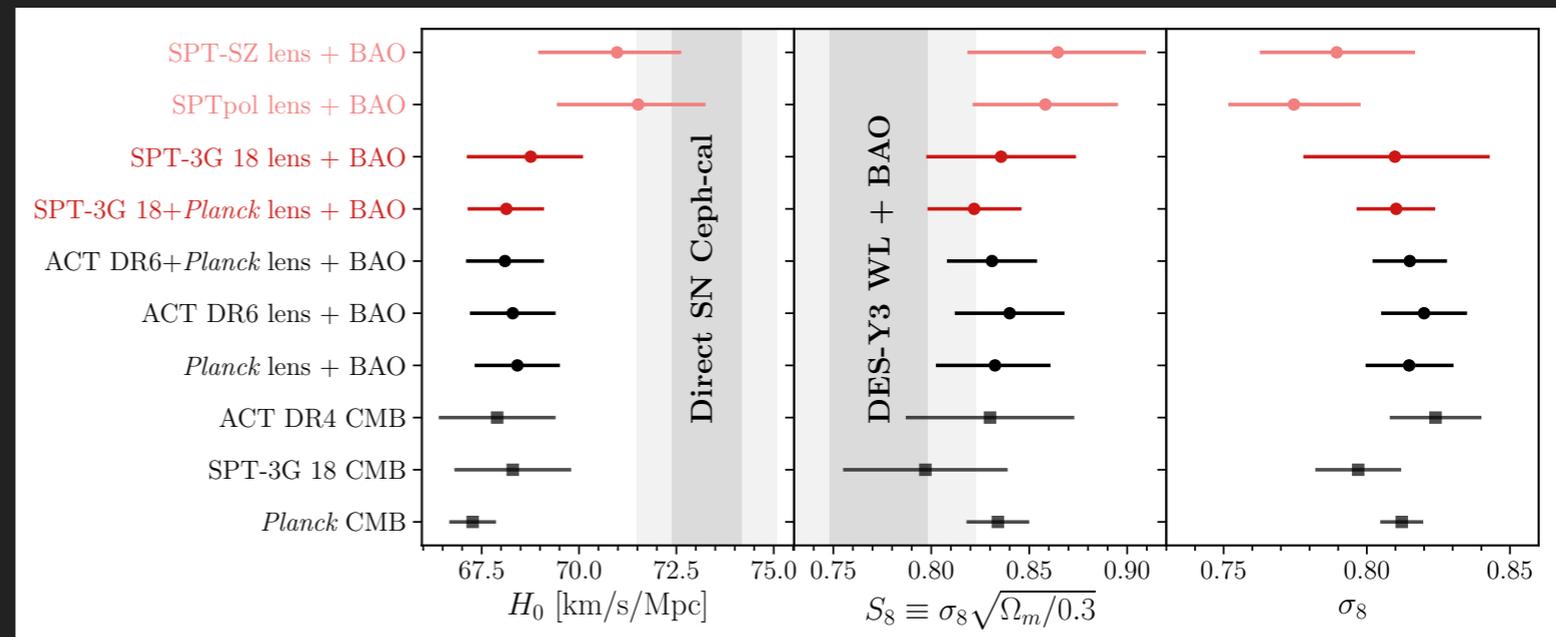
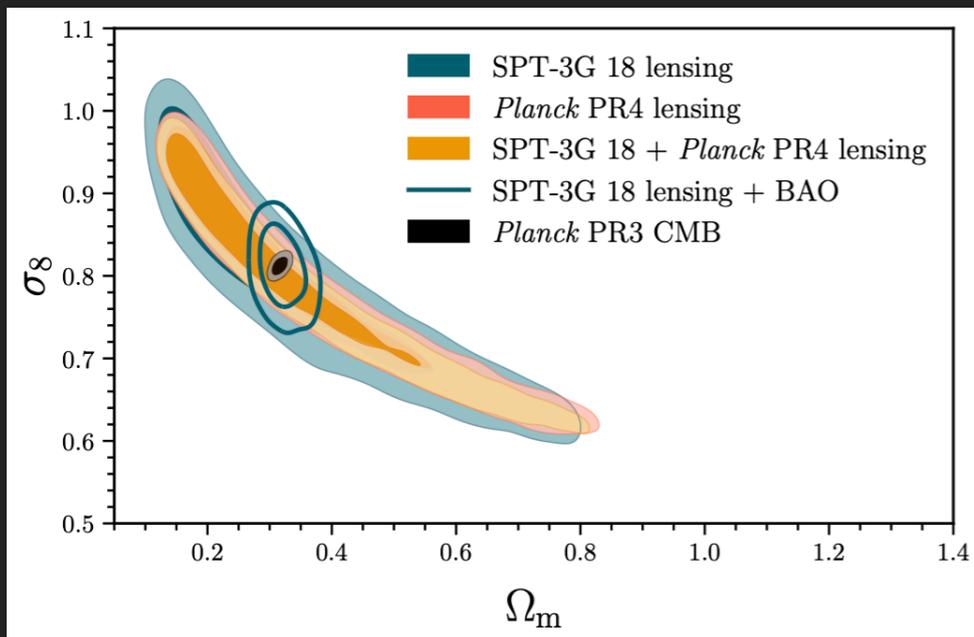
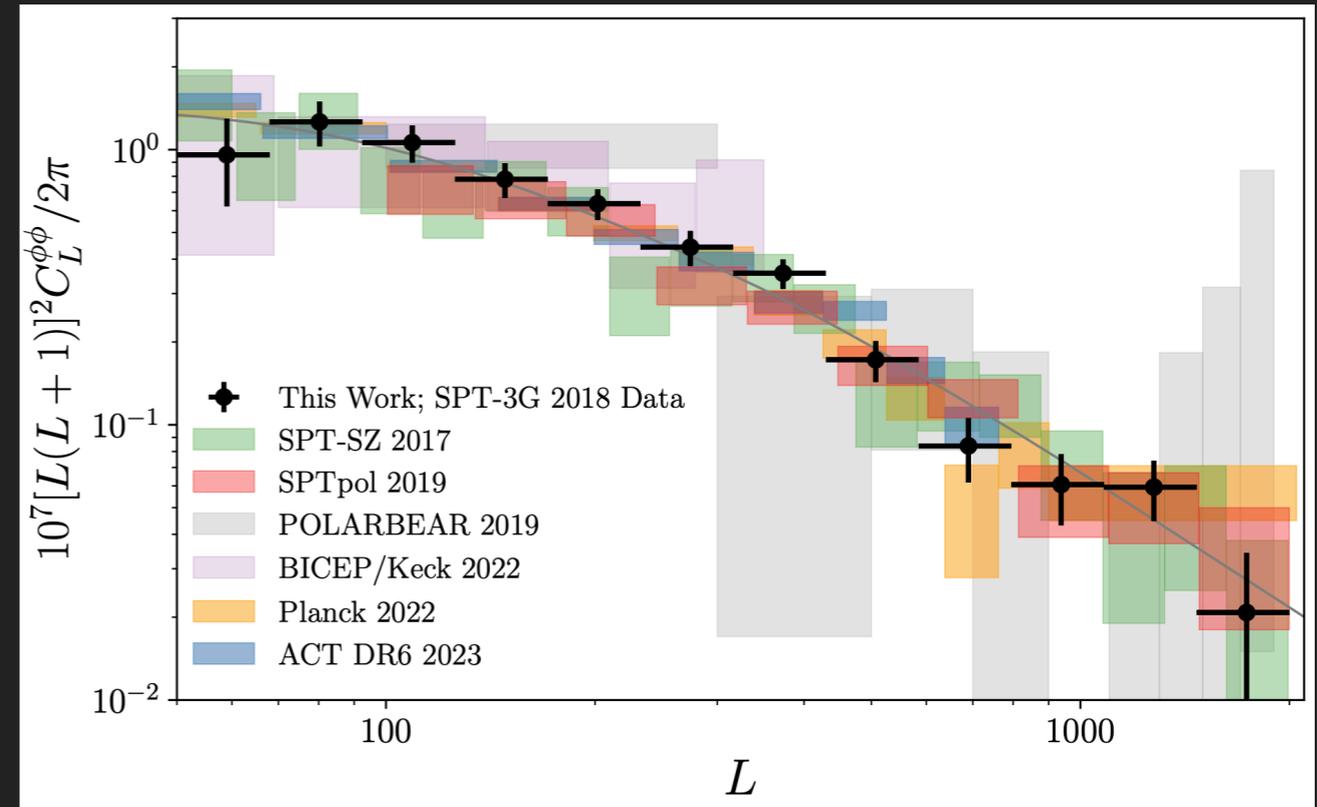


Spectra	Datasets	$H_0$ [ $\text{km s}^{-1} \text{Mpc}^{-1}$ ]
<i>TT</i>	SPT-SZ + <i>Planck</i> + ACT DR4 ( $\ell > 1800$ )	$68.85 \pm 0.97$
<i>TE</i>	SPT-3G 2018 + <i>Planck</i> + ACT DR4	$67.95 \pm 0.94$
<i>EE</i>	SPT-3G 2018 + <i>Planck</i> + ACT DR4	$69.2 \pm 1.2$
<i>TT + TE + EE</i>	SPT-3G 2018 + <i>Planck</i> + ACT DR4	$67.49 \pm 0.53$

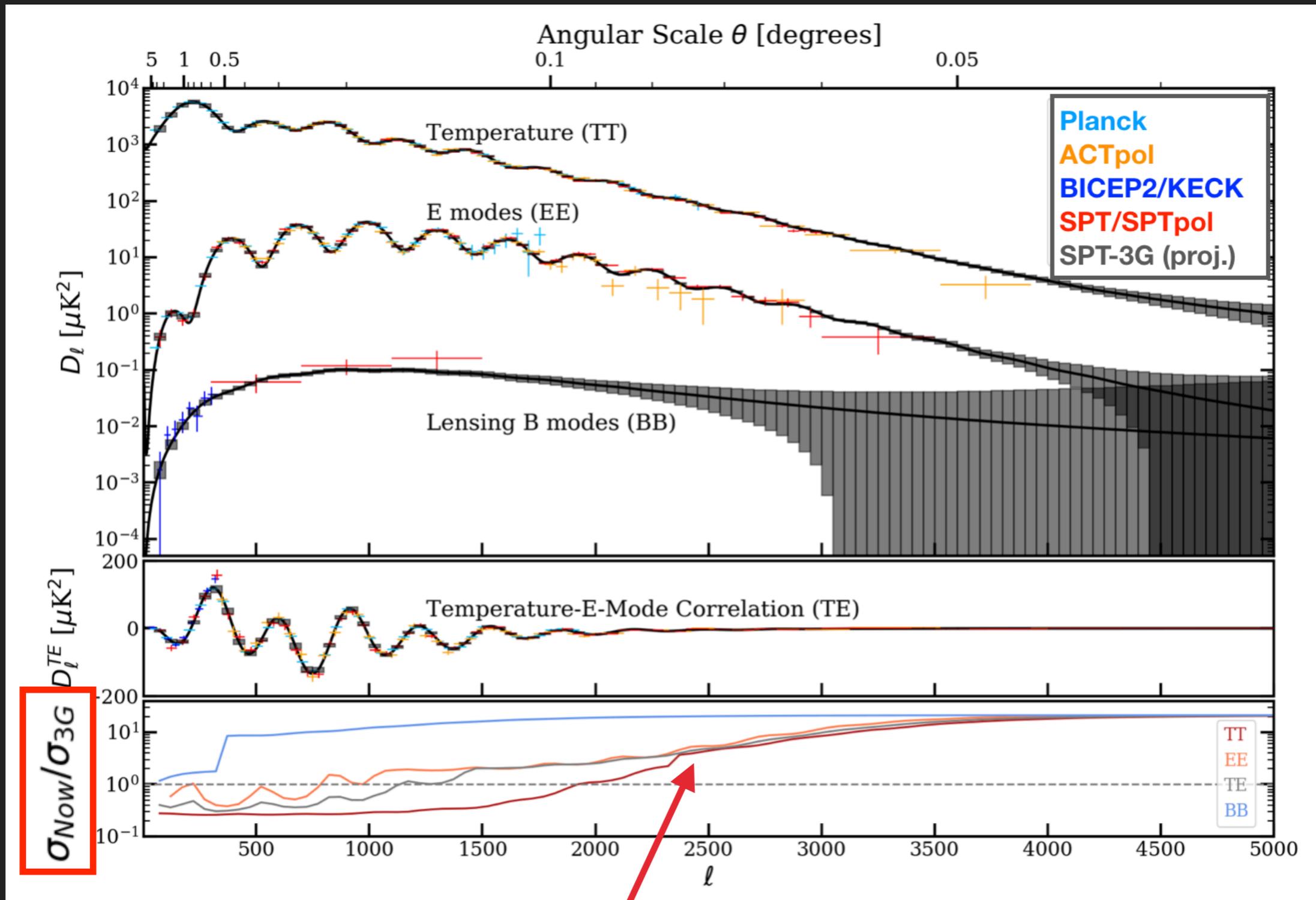


# SPT3G: 2018 CMB LENSING CONSTRAINTS

- ▶  $A_L = 1.020 \pm 0.060$ , consistent with others and  $\Lambda$ CDM
- ▶ Constraint on  $\sigma_8$  consistent with Planck and SPT-SZ/SPTpol
- ▶ With BAO, 1.6-1.8 $\sigma$  tension in  $S_8$  with low-redshift surveys
- ▶ Independent SPT3G-only constraints on  $\Omega_K, \Omega_\Lambda, \sum m_\nu$



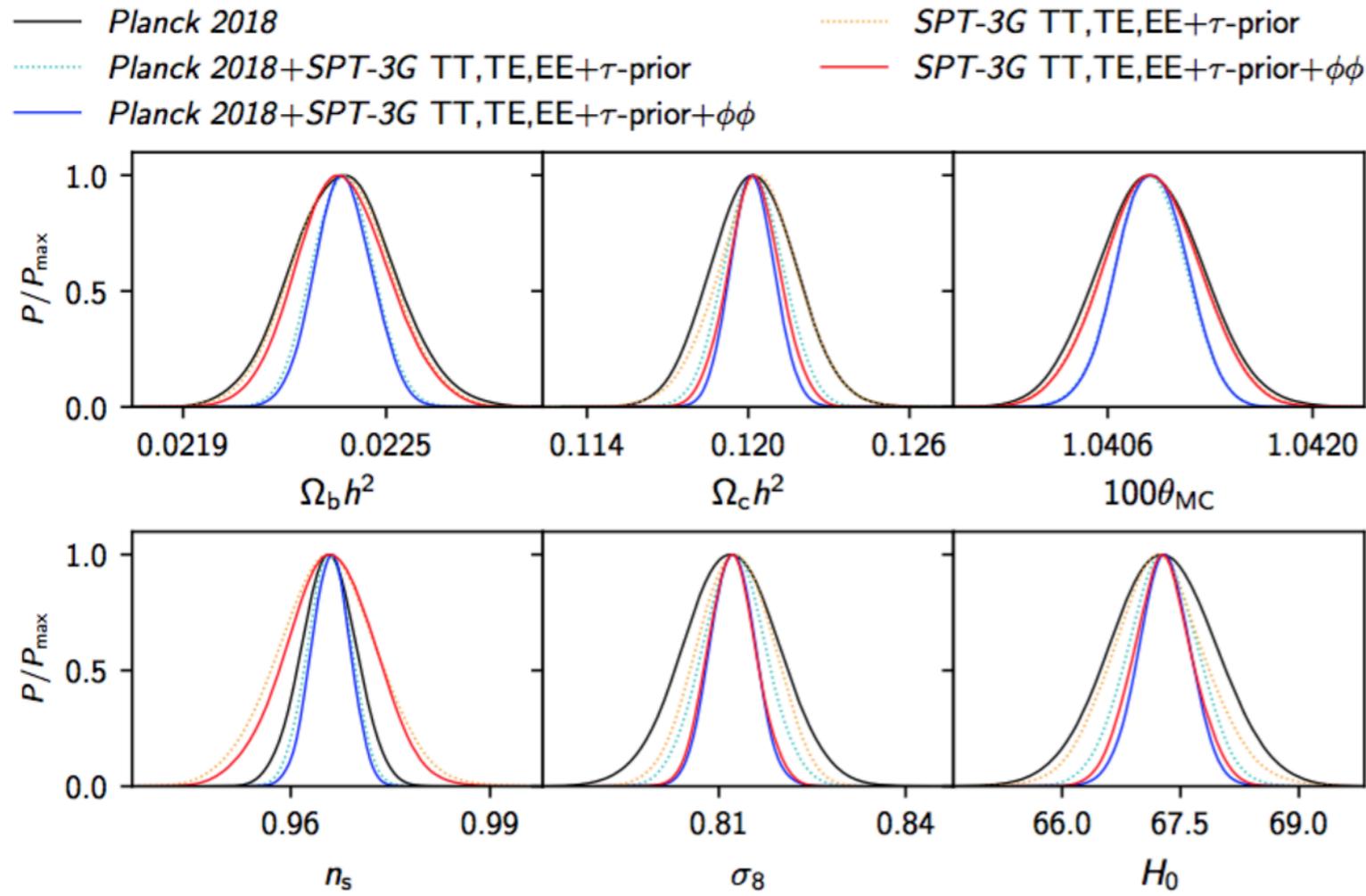
# SPT3G FORECAST: CMB POWER SPECTRUM



Improve S/N of CMB power spectra by factors of  $> \sim 10$  at  $l > 2500$  over current constraints

# SPT3G FORECAST: $\Lambda$ CDM CONSTRAINTS

## Planck $\longrightarrow$ SPT-3G Main

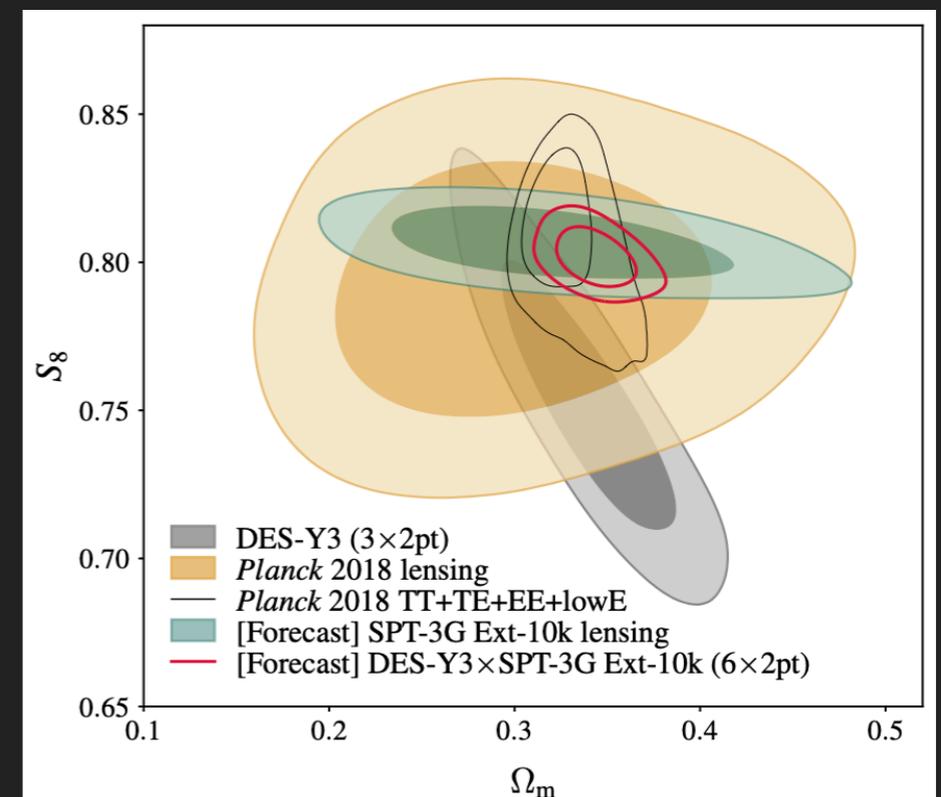
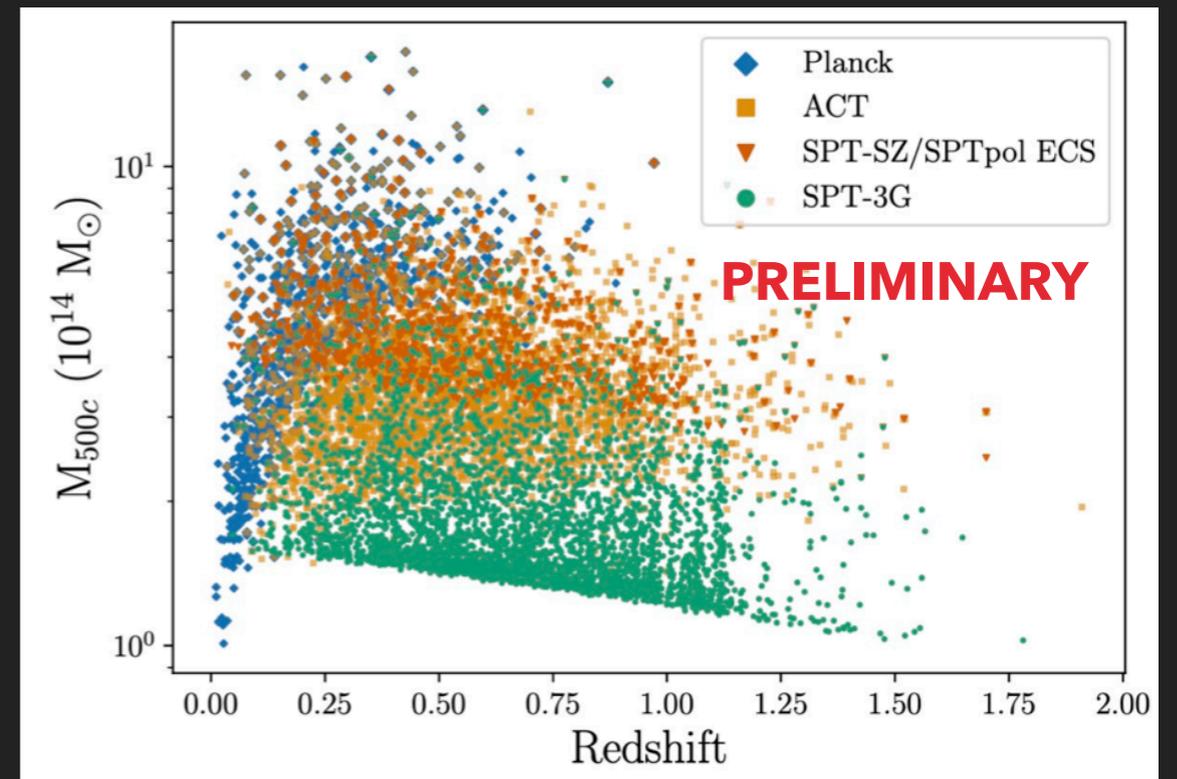


- ▶ SPT-3G alone will do as well as Planck on most parameters
  - ▶ e.g.,  $\sigma(H_0) = 0.27$  km/s/Mpc from SPT-3G-Ext-10K lensed TT,TE,EE spectra
- ▶ SPT-3G gives  $\sim$ independent cosmological information from high- $\ell$  CMB polarization spectrum
- ▶ SPT-3G Main + Planck will improve most parameters  $>2x$  over Planck alone
- ▶ Extended survey provides  $>3x$  improvement over Planck alone

	$\Lambda$ CDM						$\Lambda$ CDM +1			$\Lambda$ CDM +2	
	$\Omega_b h^2$	$\Omega_c h^2$	$H_0$	$n_s$	$A_s$	FoM	$N_{\text{eff}}$	$Y_P$	$\Omega_K$	$\Sigma m_\nu$	$N_{\text{eff}}$
$\sigma(\text{Planck})/\sigma(\text{Main})$	1.25	1.28	1.50	0.68	1.17	4.5	–	–	–	–	–
$\sigma(\text{Planck})/\sigma(\text{Ext-10k})$	2.32	1.68	1.96	1.40	1.40	161	–	–	–	–	–
$\sigma(\text{Planck})/\sigma(\text{Ext-10k+Planck})$	2.72	2.15	2.44	1.83	1.67	283	–	–	–	–	–
$\sigma(\text{Planck})/\sigma(\text{Ext-10k+Planck})$	–	–	–	–	–	–	2.88	2.99	3.13	2.05	2.93

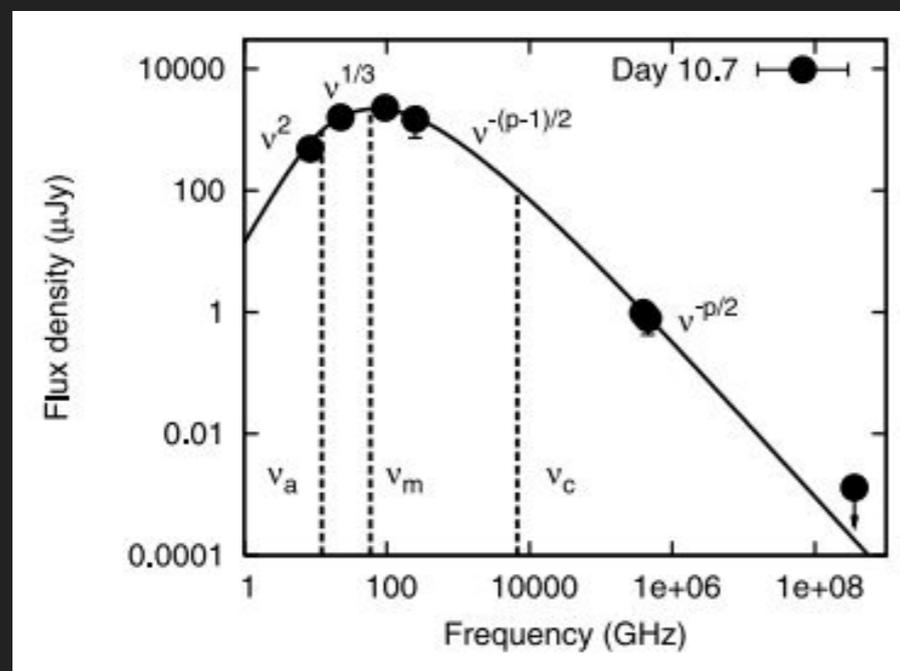
# SPT3G FORECAST: CLUSTER COSMOLOGY

- ▶ SPT was first to discover high-redshift clusters via thermal SZ effect
- ▶ SPT3G cluster survey extends to higher redshift and lower mass
  - ▶ >4000 confirmed clusters
  - ▶ >500 high- $z$  clusters detected at >99% purity
- ▶ Probe tension in  $S_8$  between local measurements and inference from CMB
- ▶ Cross-correlation with DES (VRO-LSST) will improve constraints on  $S_8$  by 2x (3x)

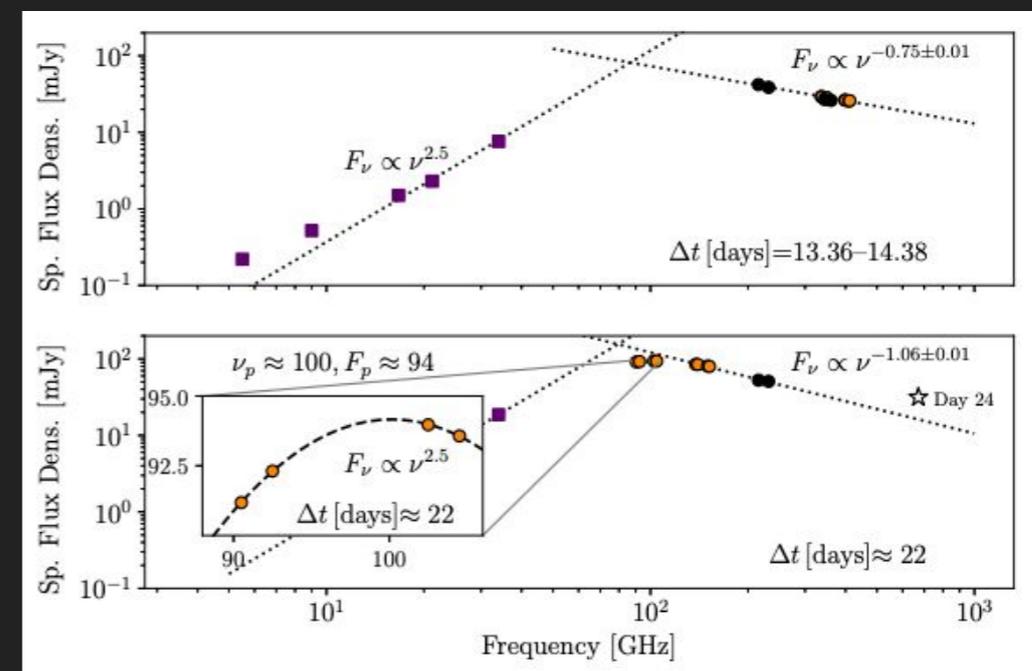


# SPT3G: ASTROPHYSICAL TRANSIENTS

- ▶ Exploit CMB observing cadence: repeated daily imaging of large sky area at multiple frequencies
- ▶ Provide useful probe of high-energy astrophysics (AGN, GRB, FRB, stellar flares, ...)
- ▶ No dedicated transient surveys exist between 10GHz and IR frequencies
- ▶ Large discovery potential with online alert system



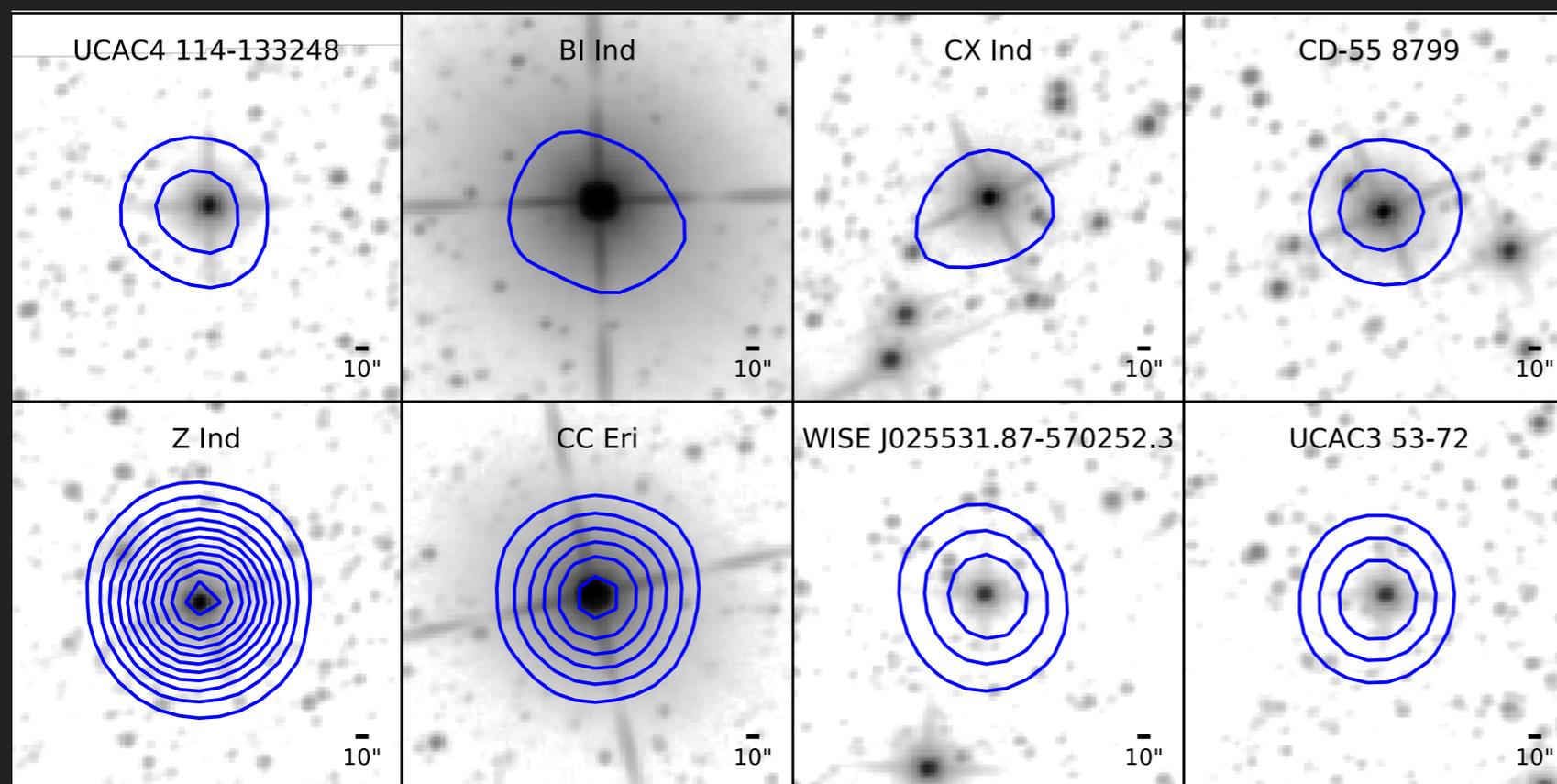
*Spectrum of GRB 070125  
(Chandra et al 2008)*



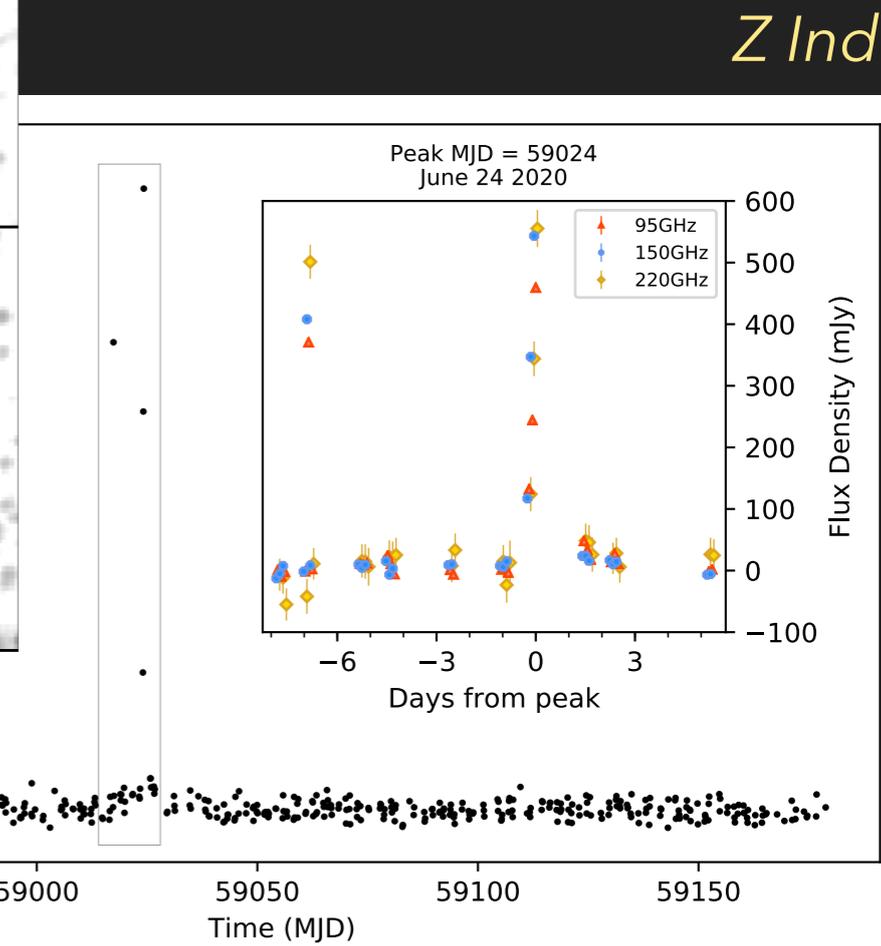
*New type of transient: FBOT  
(AT2018cow, Ho et al 2019)*

# SPT3G: ASTROPHYSICAL TRANSIENTS

- ▶ First results: 15 transient events in 2019 dataset
- ▶ Most are stellar flares (likely magnetic reconnection events?)
  - ▶ up to 2 Jy in brightness, flares as short as 20 min, some flare more than once

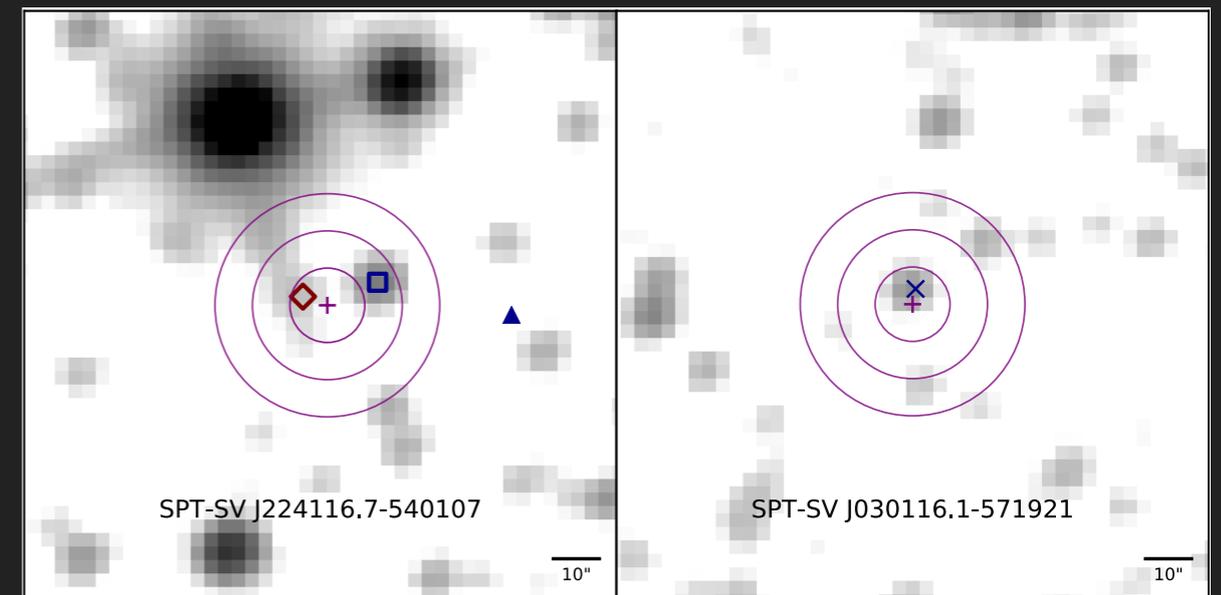
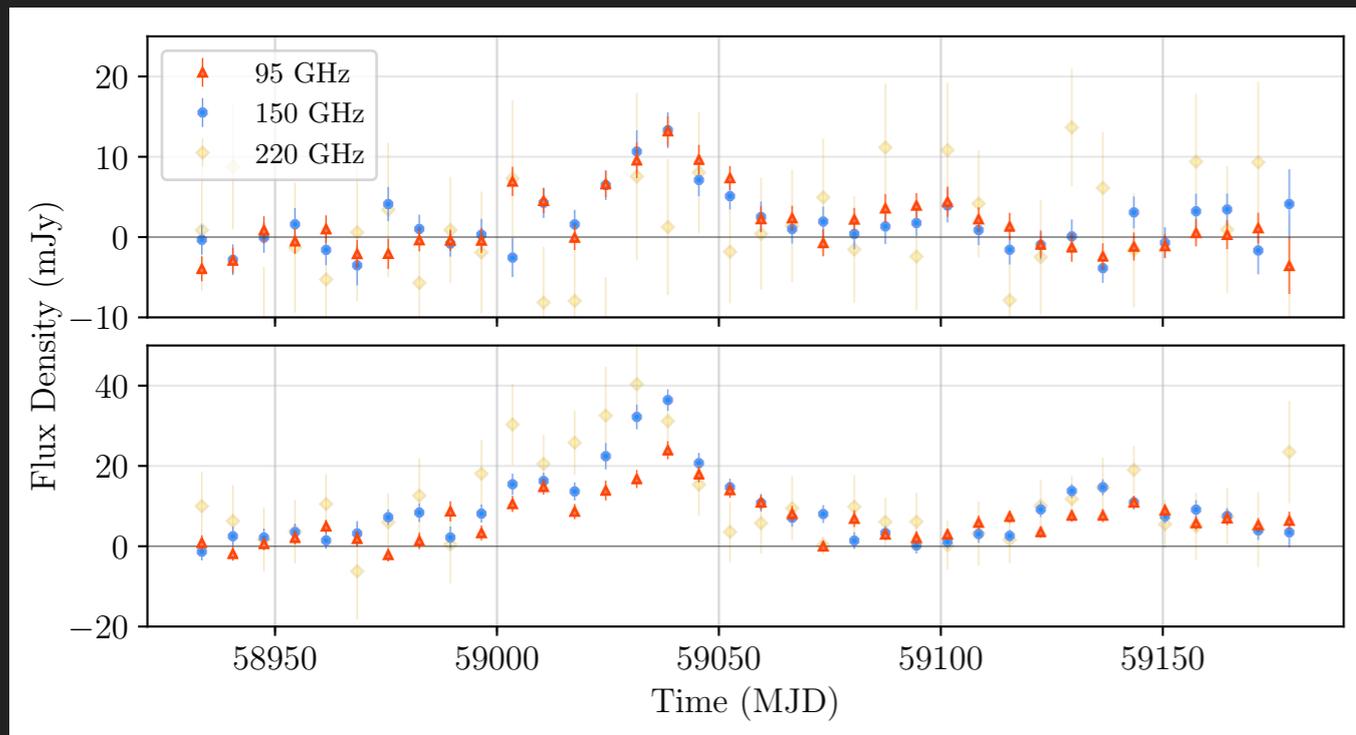


*unWISE 3.4um W1*



# SPT3G: ASTROPHYSICAL TRANSIENTS

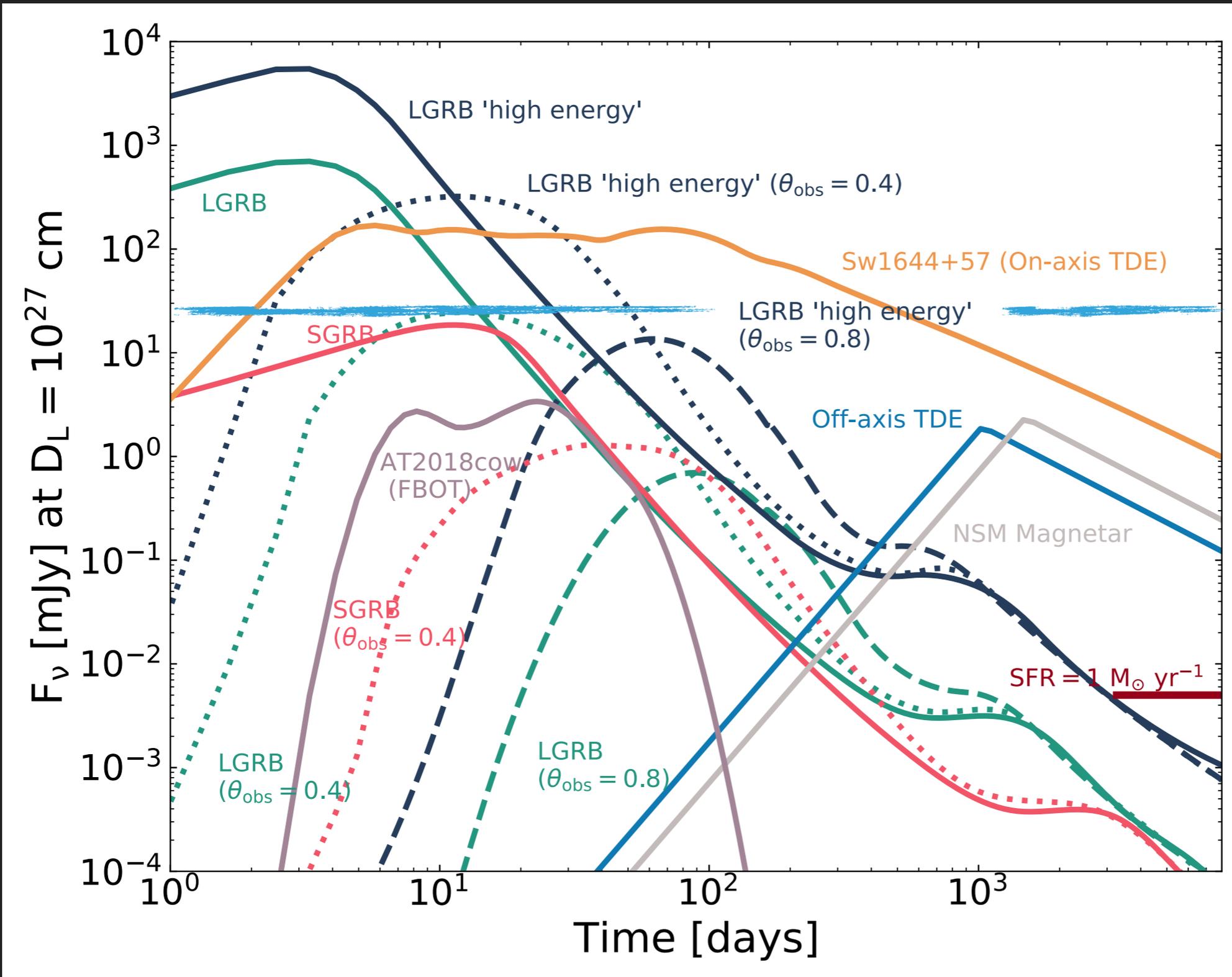
- ▶ First results: 15 transient events in 2019 dataset
- ▶ Two extragalactic long-duration flares
  - ▶ Super variable AGN? Something else? Follow-up in progress



*unWISE 3.4um W1*

*4x / 15x increased flux relative to 2019 average*

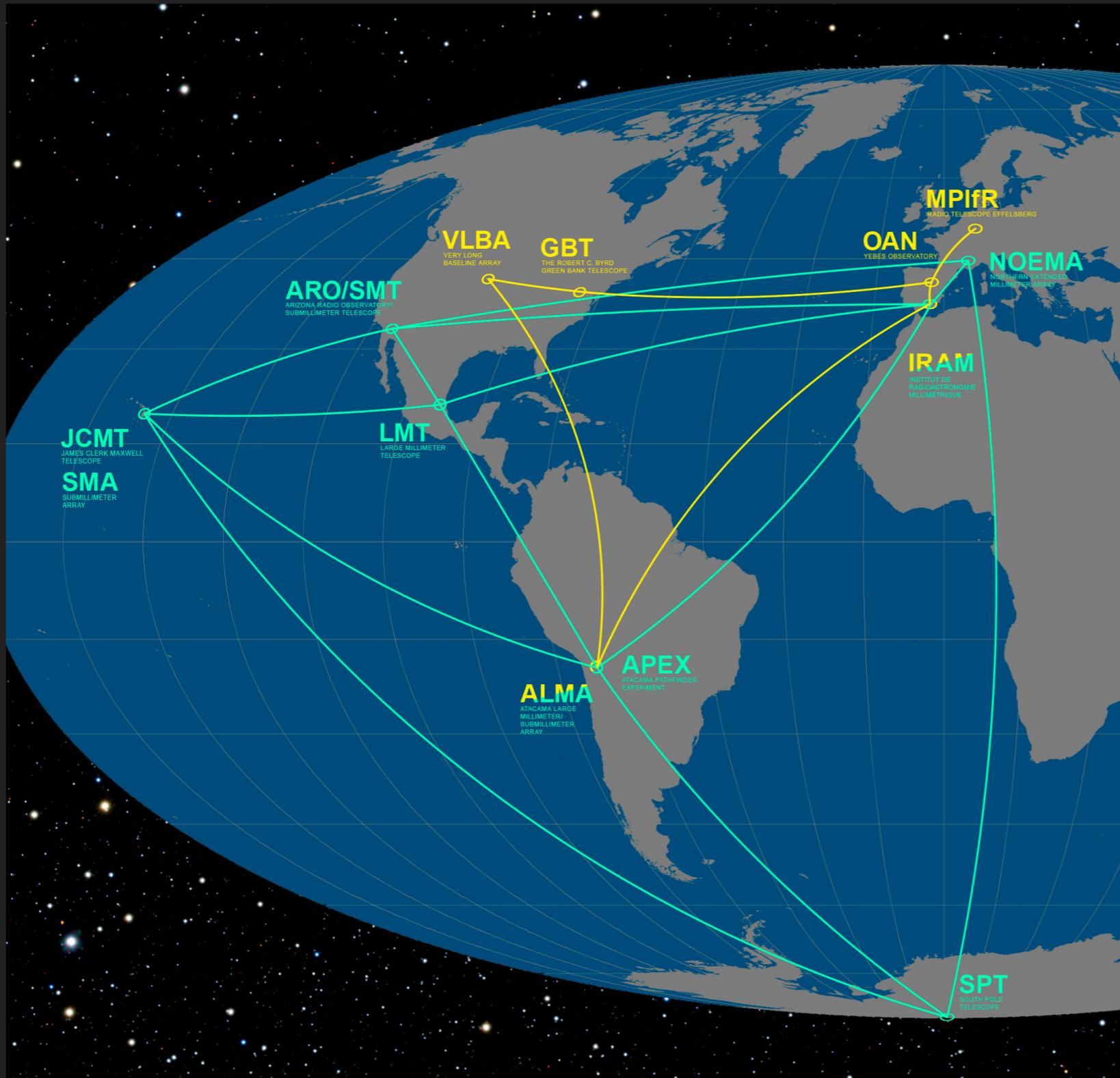
# SPT3G: ASTROPHYSICAL TRANSIENTS



CMB-S4 Deep / SPT-3G  
10 $\sigma$  daily limit

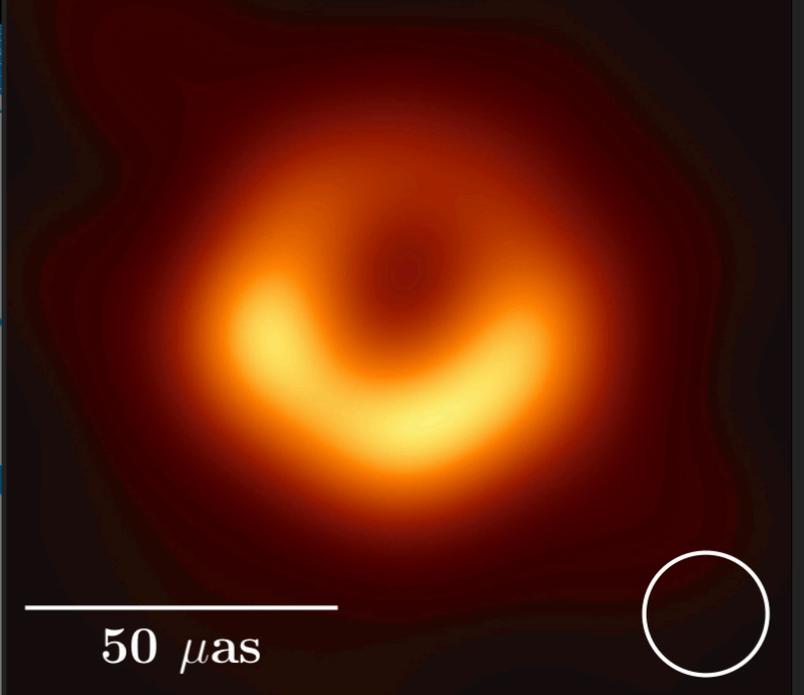
► Lots of  
discovery  
potential!

# EVENT HORIZON TELESCOPE



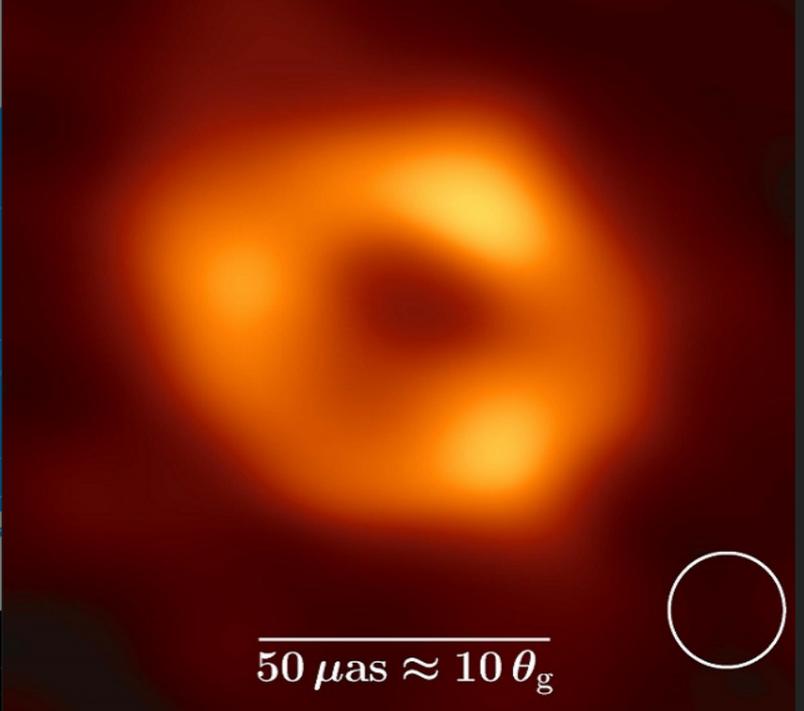
M87\*

April 11, 2017

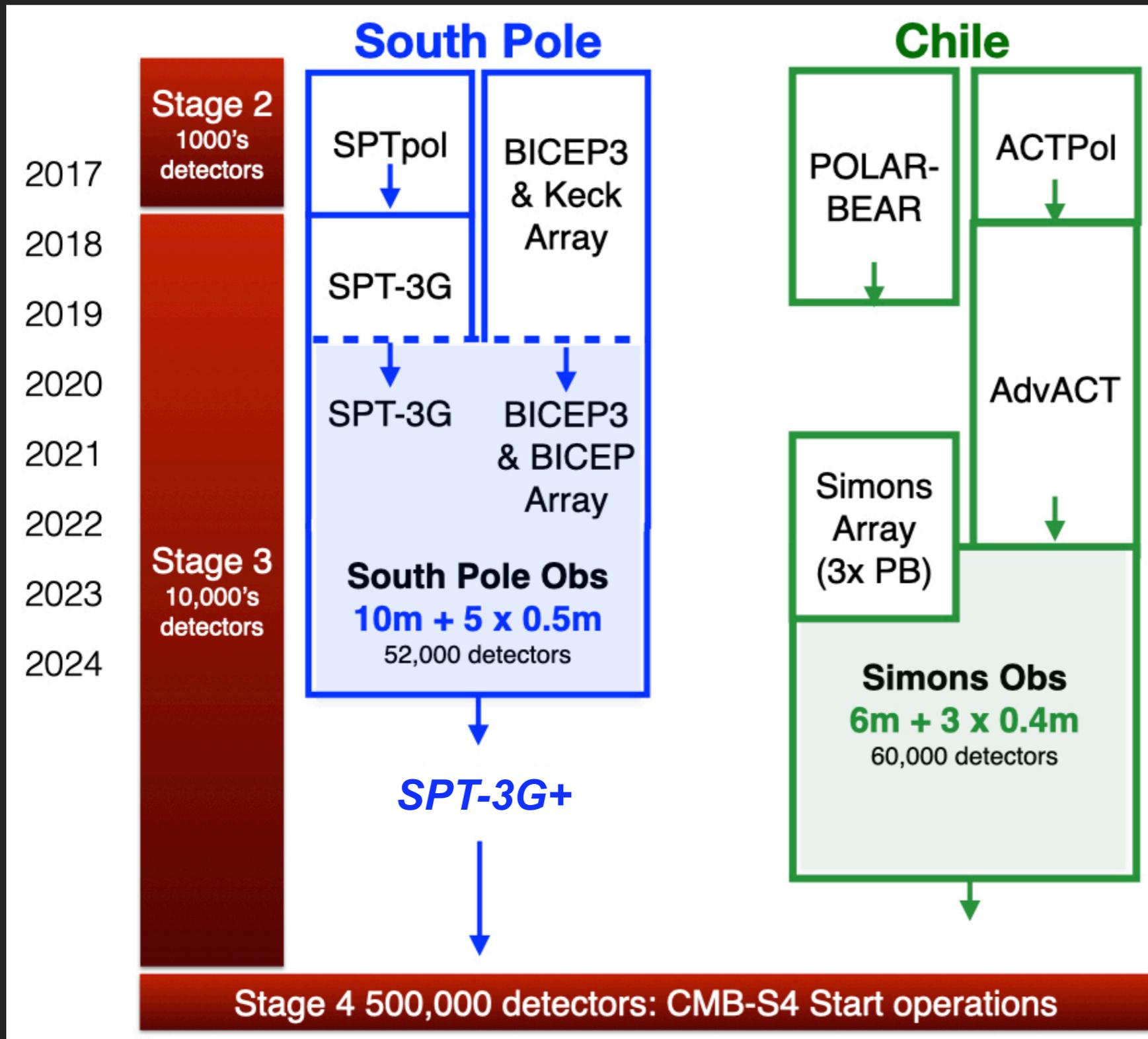


Sgr A\*

April 7, 2017

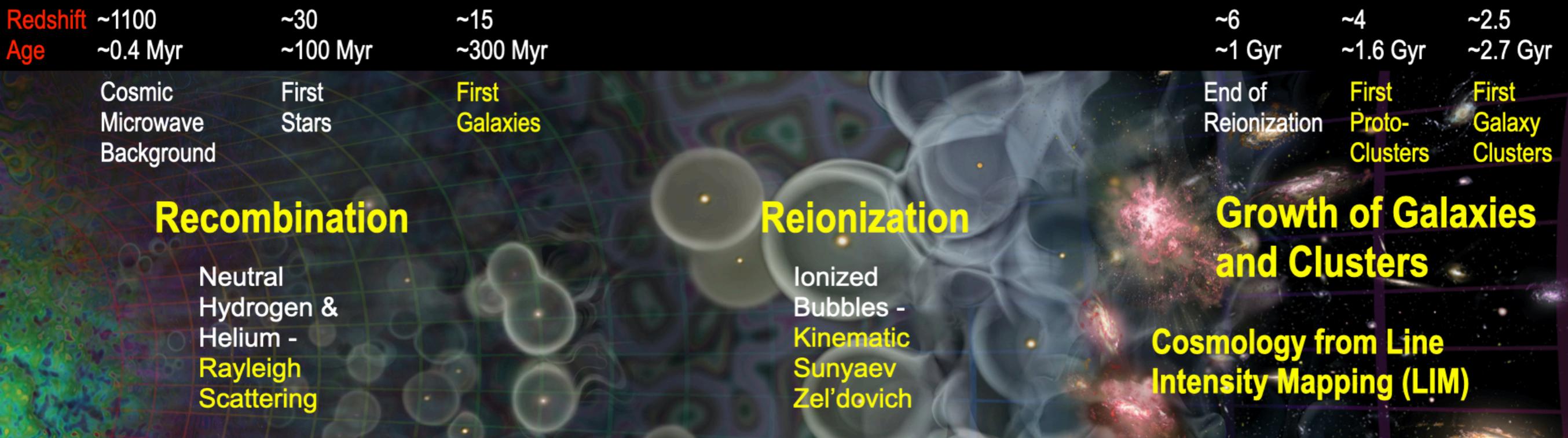


# FUTURE DIRECTIONS



- ▶ ~5-year gap between end of SPT3G and start of CMB-S4
- ▶ SPT3G+ proposed to utilize the SPT submm-quality telescope during the gap
- ▶ Focus on higher frequencies

# SPT3G+ SCIENCE



## ▶ Recombination

- ▶ First detection of CMB Rayleigh Scattering, new probe of cosmic expansion history, and cosmology. (Dibert et al [2205.04494], Zhu et al [2205.04496])

## ▶ Reionization

- ▶ Constrain duration and redshift of reionization via kSZ

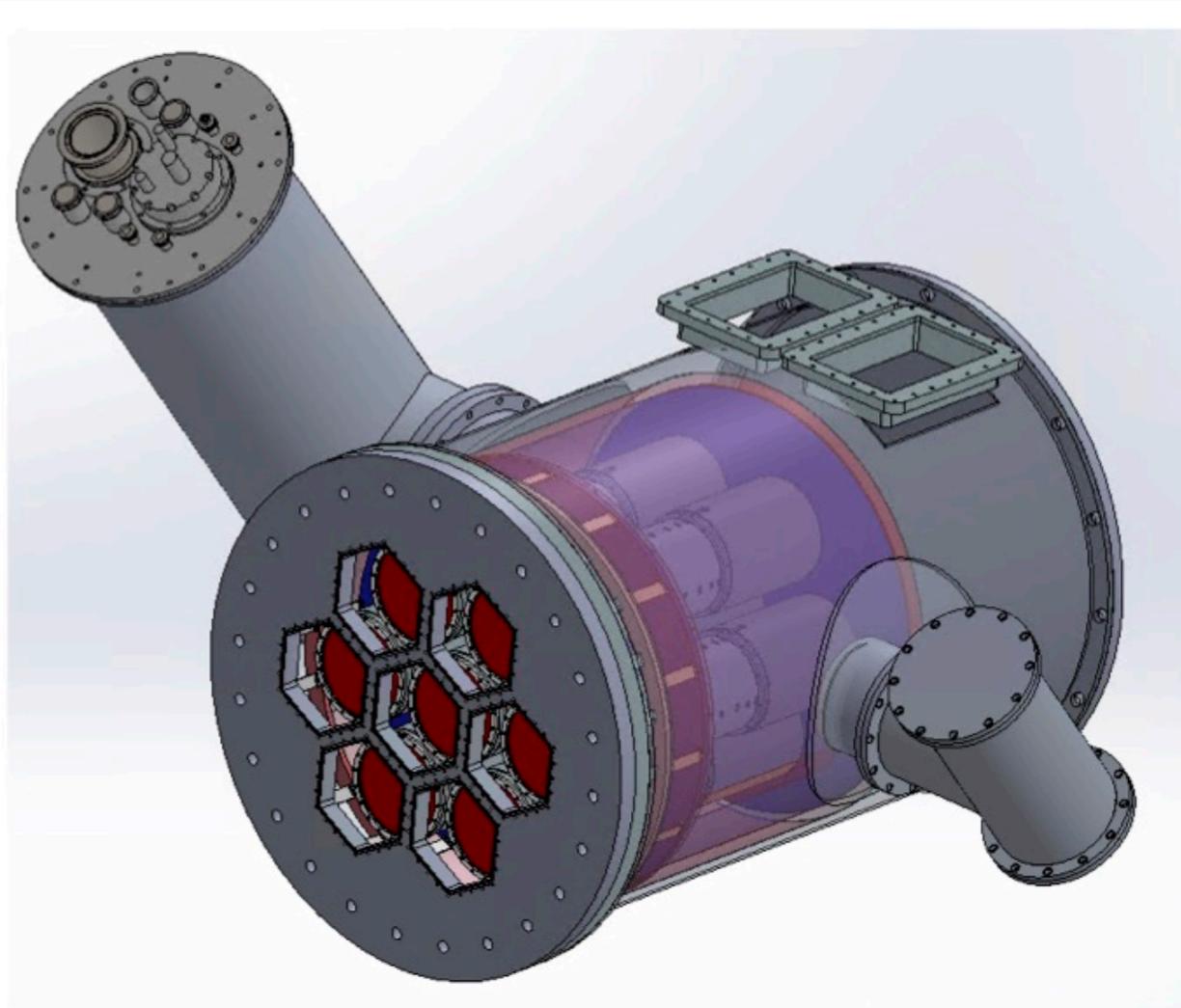
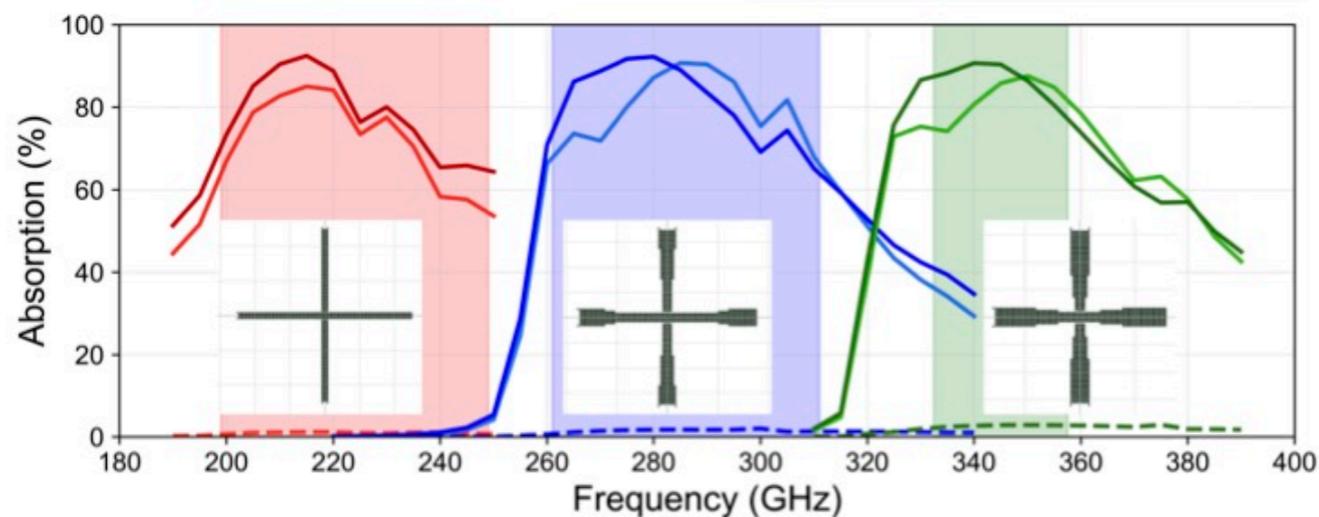
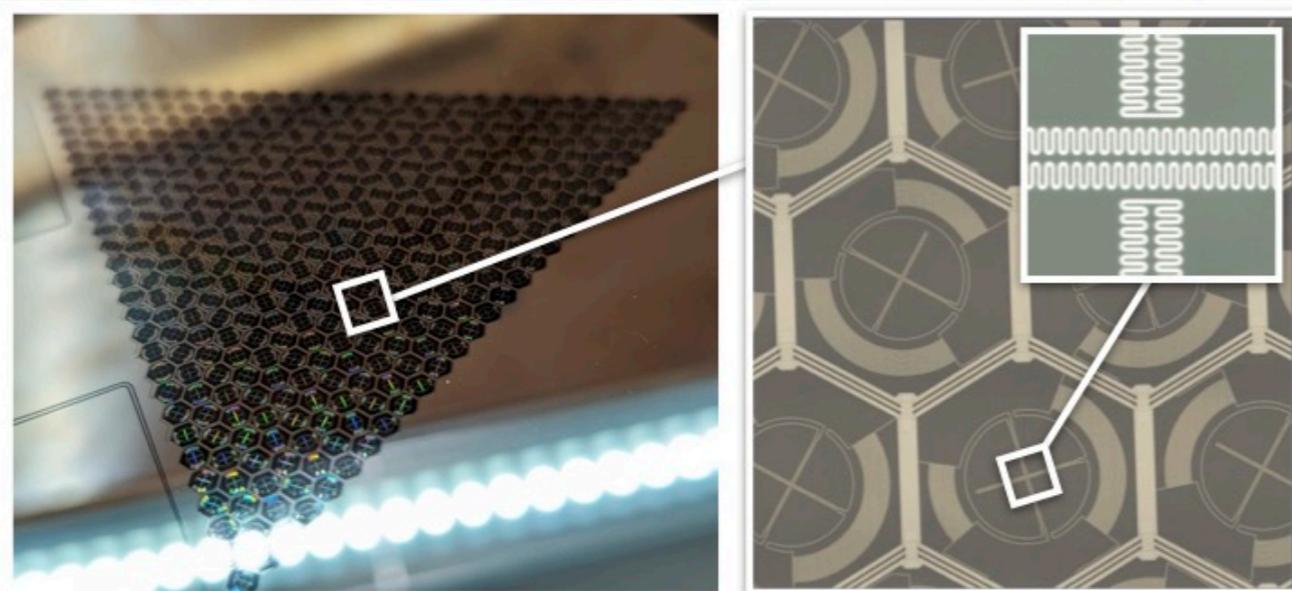
## ▶ Growth of galaxies and clusters

- ▶ Detect growth of massive galaxies and clusters from  $1 < z < 9$

## ▶ Dust and star formation in the galaxy

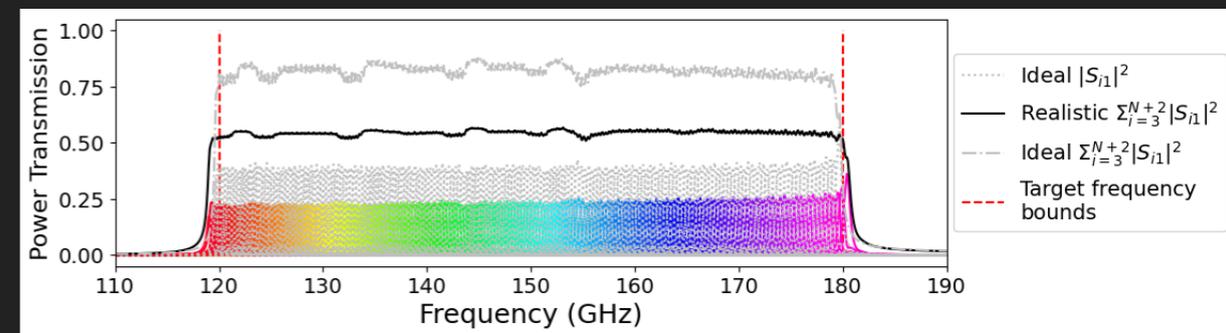
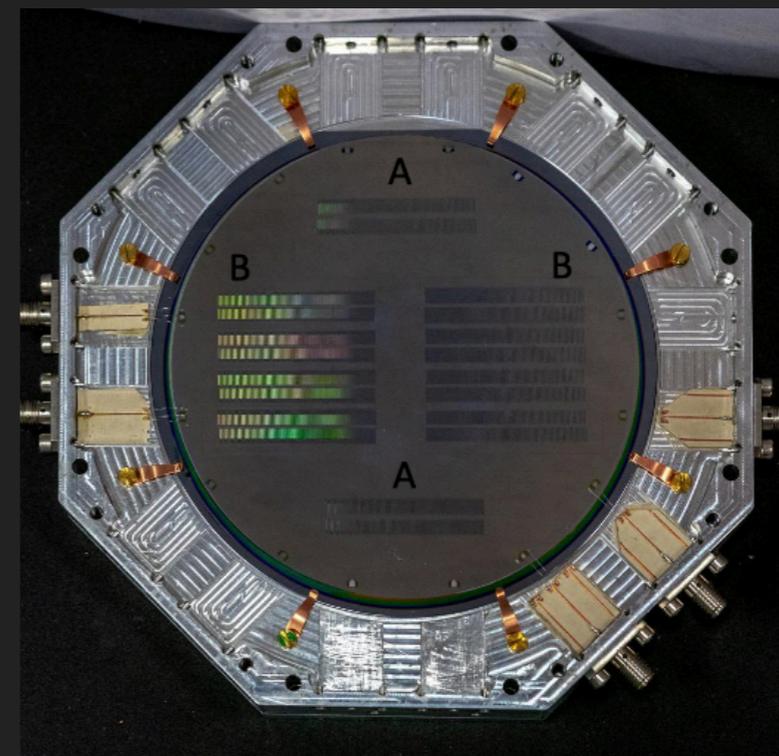
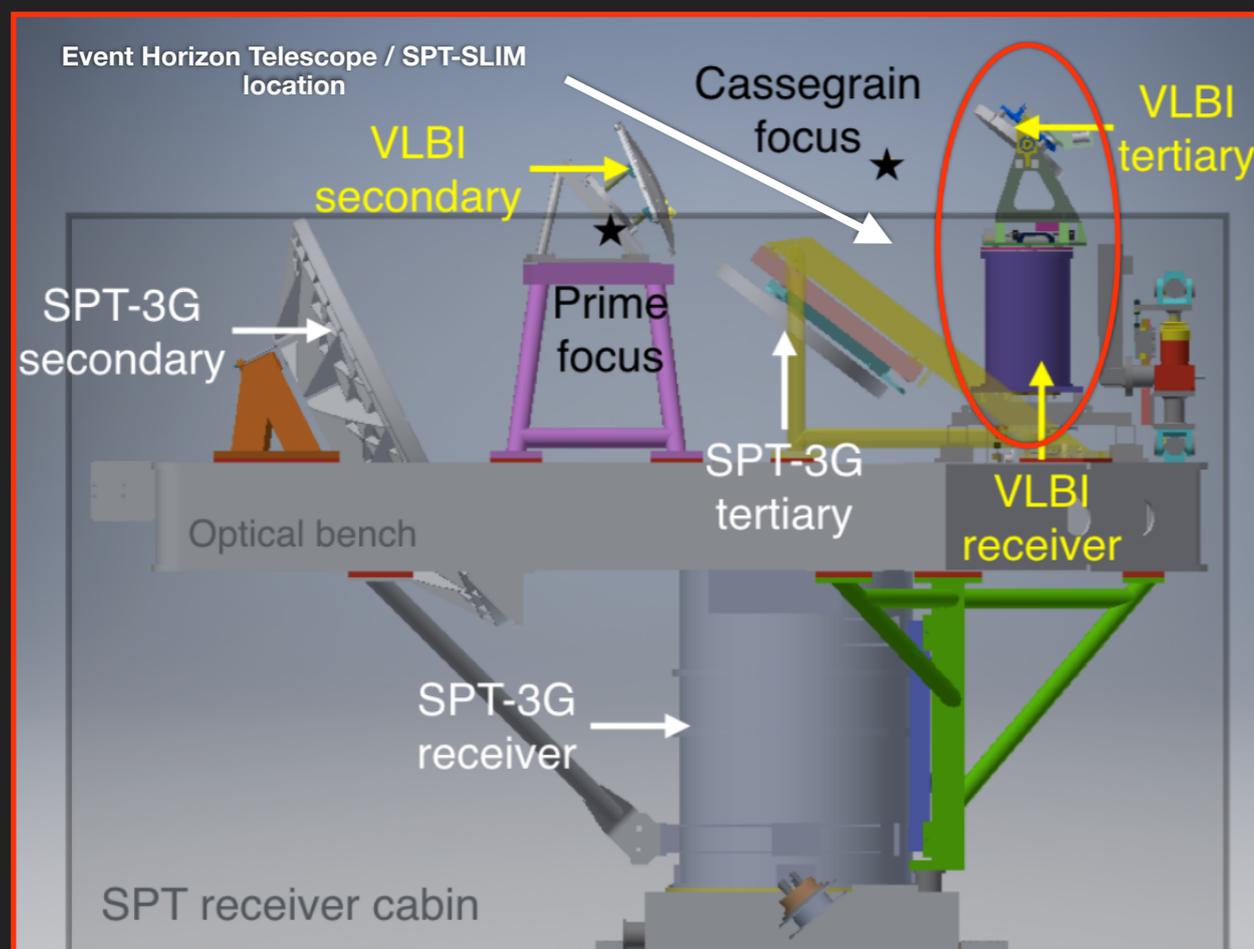
# SPT3G+ INSTRUMENT

- ▶ High-frequency (220/280/350 GHz) receiver of MKIDS



# SPT-SLIM: LINE INTENSITY MAPPING PATHFINDER

- ▶ On-chip spectrometers
- ▶ Install on secondary mount point
- ▶ Observe for one austral summer season



- ▶ Prototype filter banks fabricated at Argonne

*J. Kim, et al. 1805.09346*

# SUMMARY

- ▶ SPT-3G survey is ongoing
  - ▶ First results from 2018 season published, with impressive CMB sensitivity and performance at large scales
  - ▶ SPT-3G science publications from 2019-2020 seasons coming soon
  - ▶ Rich astrophysical transient program
- ▶ SPT-3G science forecasts through 2026 season
  - ▶  $\Lambda$ CDM constraints at least as good as Planck on most cosmological parameters
  - ▶ With Planck, factor of  $\sim 2$ - $3$ x improved constraints on  $N_{\text{eff}}$  and neutrino mass
  - ▶ With BICEP Array, factor of  $\sim 10$ x improvement on current BK15 tensor-to-scalar ratio constraint
- ▶ Future plans for CMB science at the South Pole
  - ▶ SPT3G+ to enable first detection of CMB Rayleigh Scattering, and to constrain reionization via the kSZ effect
  - ▶ CMB-S4 coming online at the end of the decade