Opportunity for
European involvement in a Large Aperture Telescope:

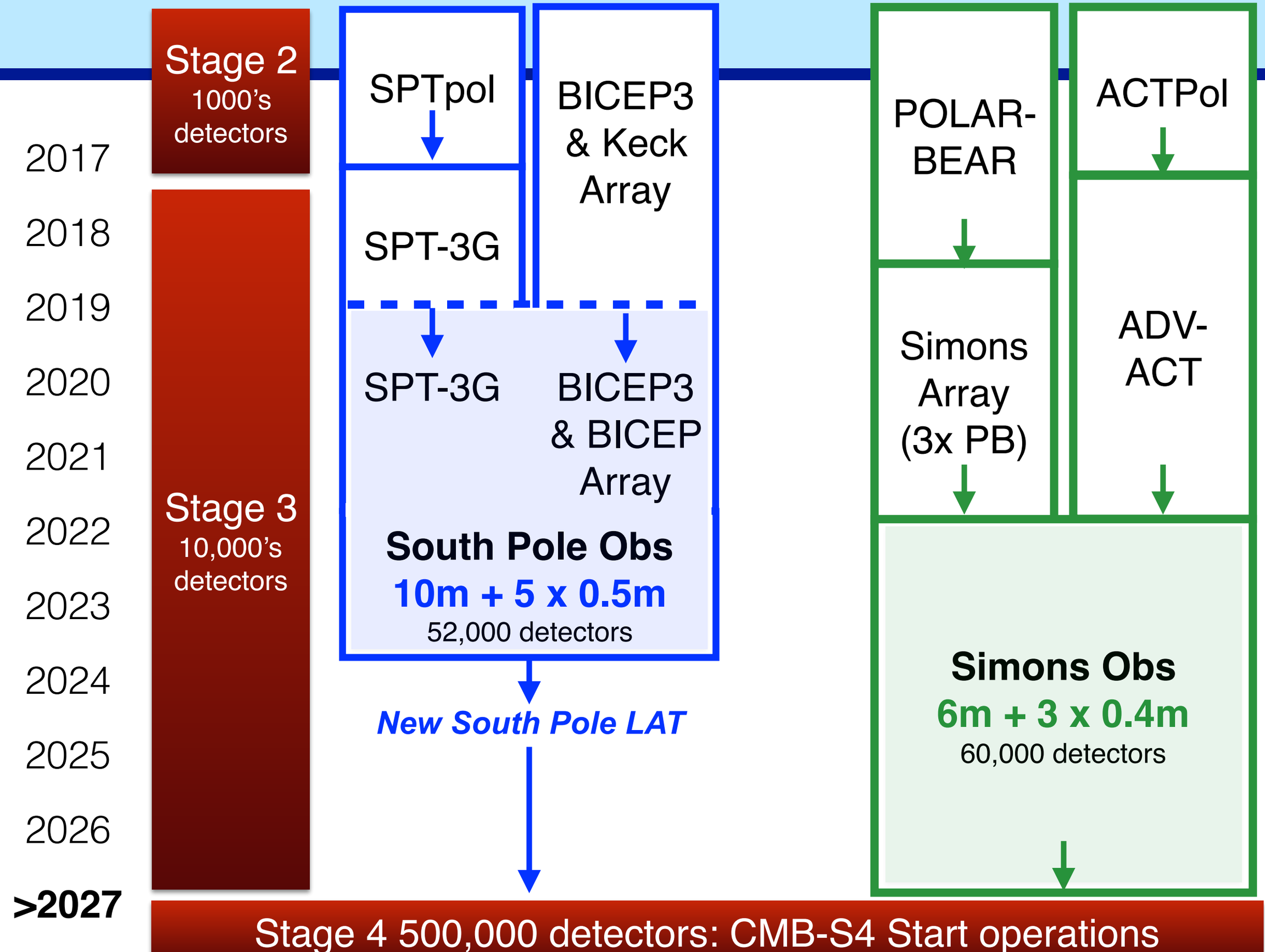
A new South Pole high throughput Large Aperture CMB Telescope (LAT)

John Carlstrom

Big picture

- SPT-3G and BICEP3/BICEP Array SPO program observing through 2023 (Clem Pryke's talk).
- CMB-S4 is gearing up, DOE and NSF are investing (Julian Borrill's talk).
- SPO and SPT are planning next step beyond SPT-3G at South Pole with a high throughput large aperture telescope (LAT) for de-lensing and high-ℓ science.
- Plan is for South Pole LAT to meet or exceed CMB-S4 requirements.

Evolution and timelines

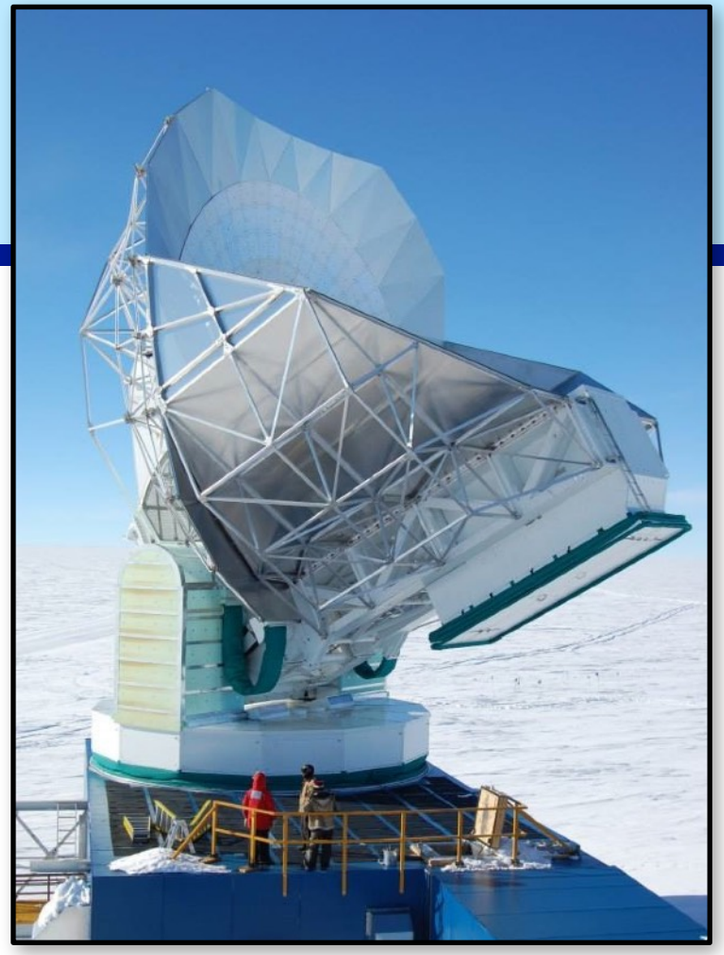


The South Pole site

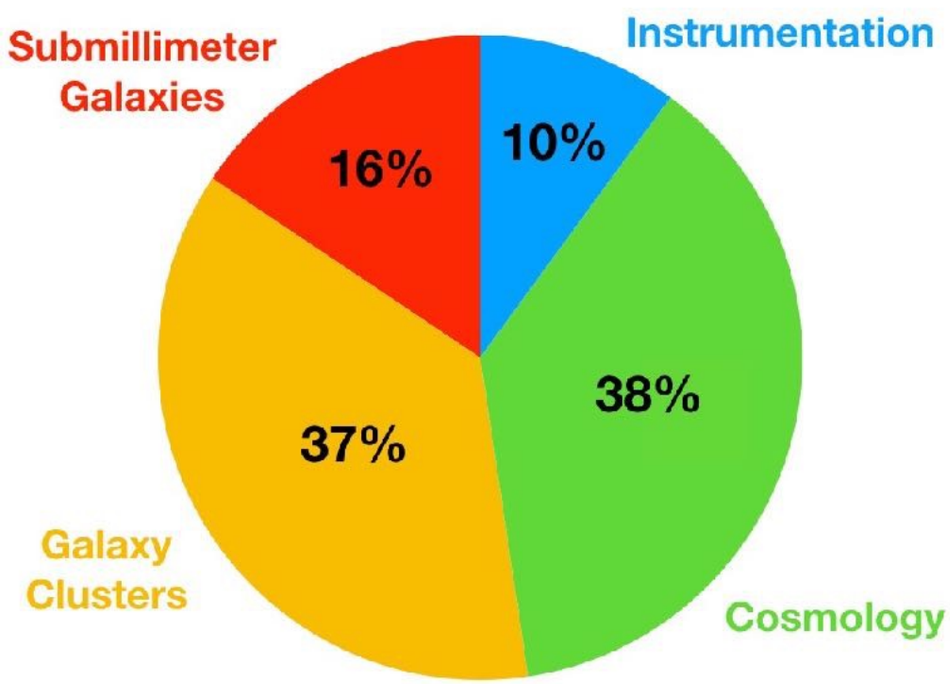
- Extremely dry & stable atmosphere
  *sky noise power is ~100x less than Atacama at mm-wavelengths**
- High altitude ~ 2900 m
- Sun below horizon for 6 months.
- Relentless observing of low-foreground sky
- Limited sky coverage
- Best developed site for ultra-deep, low-foreground measurements of up to 10% of the sky.

* Bussmann et al. ApJ 622 1343 (2005); Lay & Halverson ApJ 543, 787 (2000): Kuo arXiv 1707.08400

Breadth of SPT results
(> 130 science publications*)

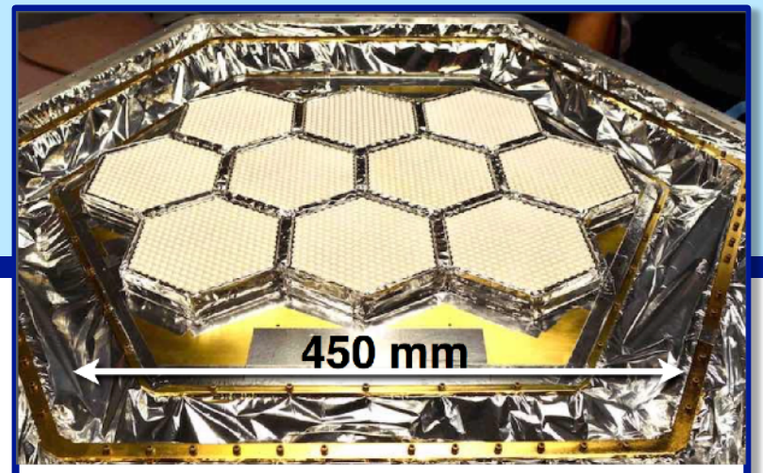


- Temperature and polarization power spectra and cosmological parameters
- Diffuse kinematic and thermal SZ effect constraints: bi-spectrum, pairwise kSZ, patchy reionization
- CMB lensing: power spectra; cross-correlations; cluster-lensing mass calibration
- First SZ discovery of galaxy clusters, SZ cluster catalog and cosmology
- Discovered population of high redshift lensed dusty star forming galaxies
- First detection of lensing B-mode polarization; demonstrating of de-lensing
- Participating in the Event Horizon Telescope
- much more…



*For publications see pole.uchicago.edu

SPT-3G is working extremely well!



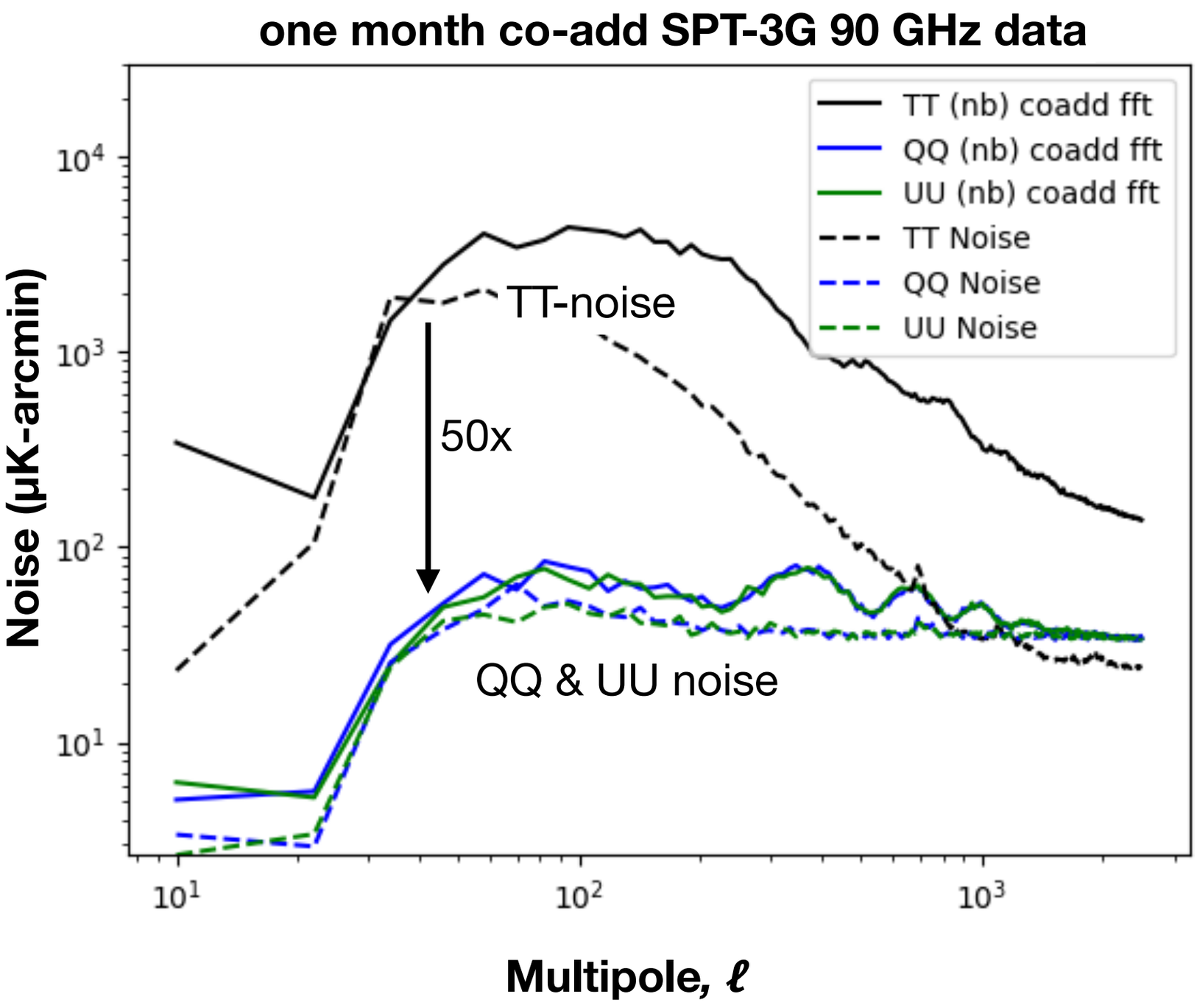
SPT-3G 16,000 detectors
100,150, 220 GHz

2018 SPT-3G 150GHz EE power spectrum
Equivalent to 1.5 months 2019 SPT-3G data.

PRELIMINARY

From Daniel Dutcher Jan 2019 AAS talk

SPT-3G is working well at degree scales



- South Pole atmosphere has relatively low-fluctuation power and is unpolarized
- SPTpol low-ℓ noise was limited by temperature sensitivity of electronics
- SPT-3G has improved low-ℓ performance:
  - Electronics ℓ_{knee}=24 (Bender et al, arxiv:1907.10947)
  - ***1500 deg² survey QU-noise has a $\ell_{knee} < 50$ at 90 GHz***
    (Using out-of-box RCW38 calibration, 1 deg/sec scanning, scans poly filtered with $\ell_{knee} < 40$, no additional modulation)

from Jessica Avva

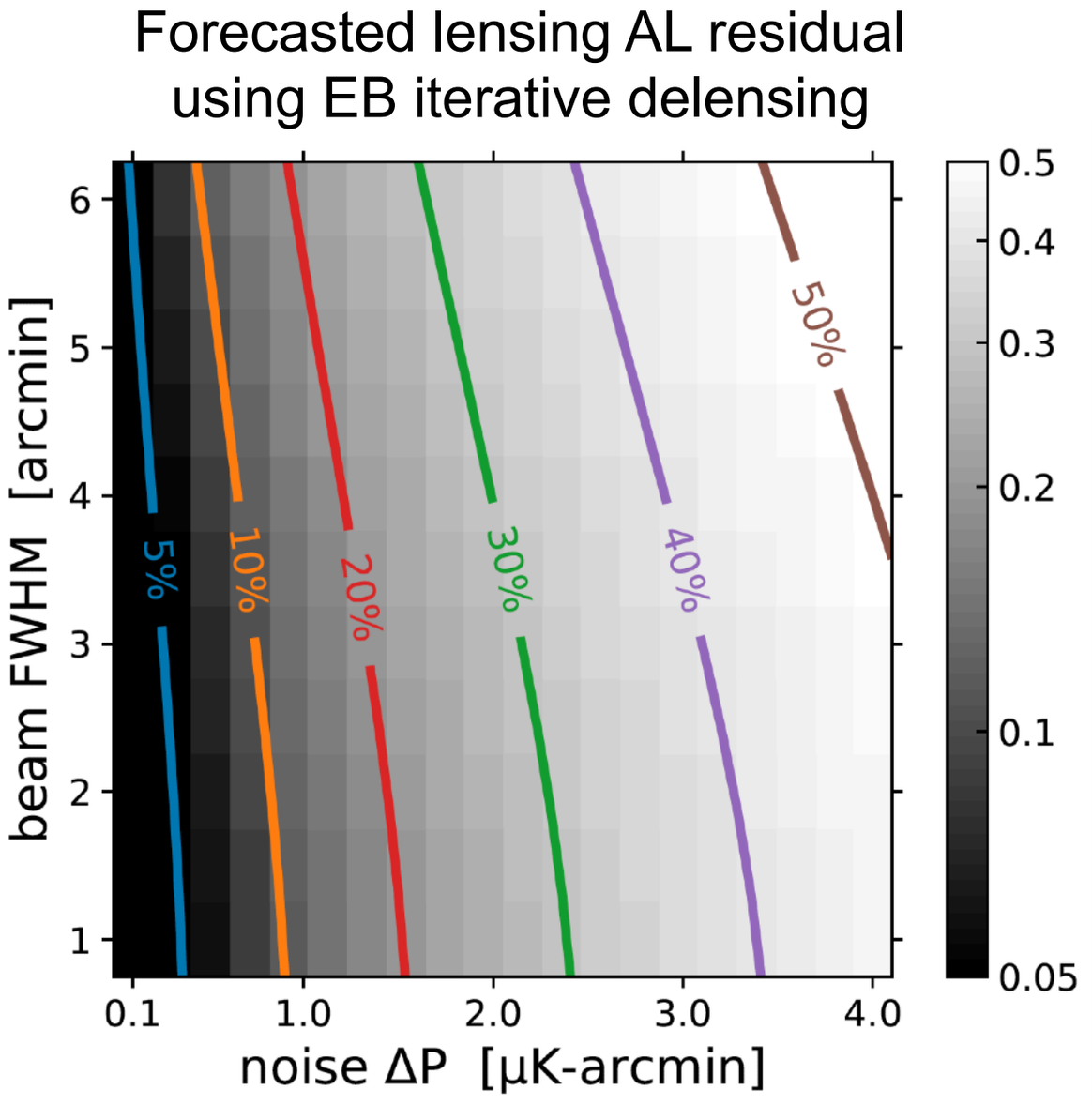
The case for a new South Pole LAT

- SPT-3G camera already saturates the throughput of SPT
- We need more sensitivity (10x) for de-lensing to meet our ultimate “r” goal.
- We are confident that a South Pole LAT could also contribute B-mode sensitivity at degree scales (low ℓ).
- So, we plan to build LAT to conduct an ultra-deep, narrow field complement (f_{sky} ~ 3%) to Simons Observatory wide-field (f_{sky} ~ 40%)
  - higher s/n maps, although higher sample variance for cosmo parameters
  - deeper CMB-lensing maps, including cluster lensing
  - lower mass SZ clusters and therefore higher redshift reach
  - kSZ, tSZ, reionization measurements, bi-spectra, etc.
  - daily time series for mm-wave transients at mJy level.

De-lensing requires high angular resolution and sensitivity

Inflationary B modes search requires exquisite sensitivity at recombination bump at degree scales (ℓ ~100) and at arc minute scales (ℓ ~5000) for de-lensing.

South Pole LAT target $\Delta P \lesssim 0.5$ μK-arcm, eventually, as per CMB-S4 specification



From: *CMB-S4 Science Case, Reference Design, and Project Plan* arXiv:1907.04473

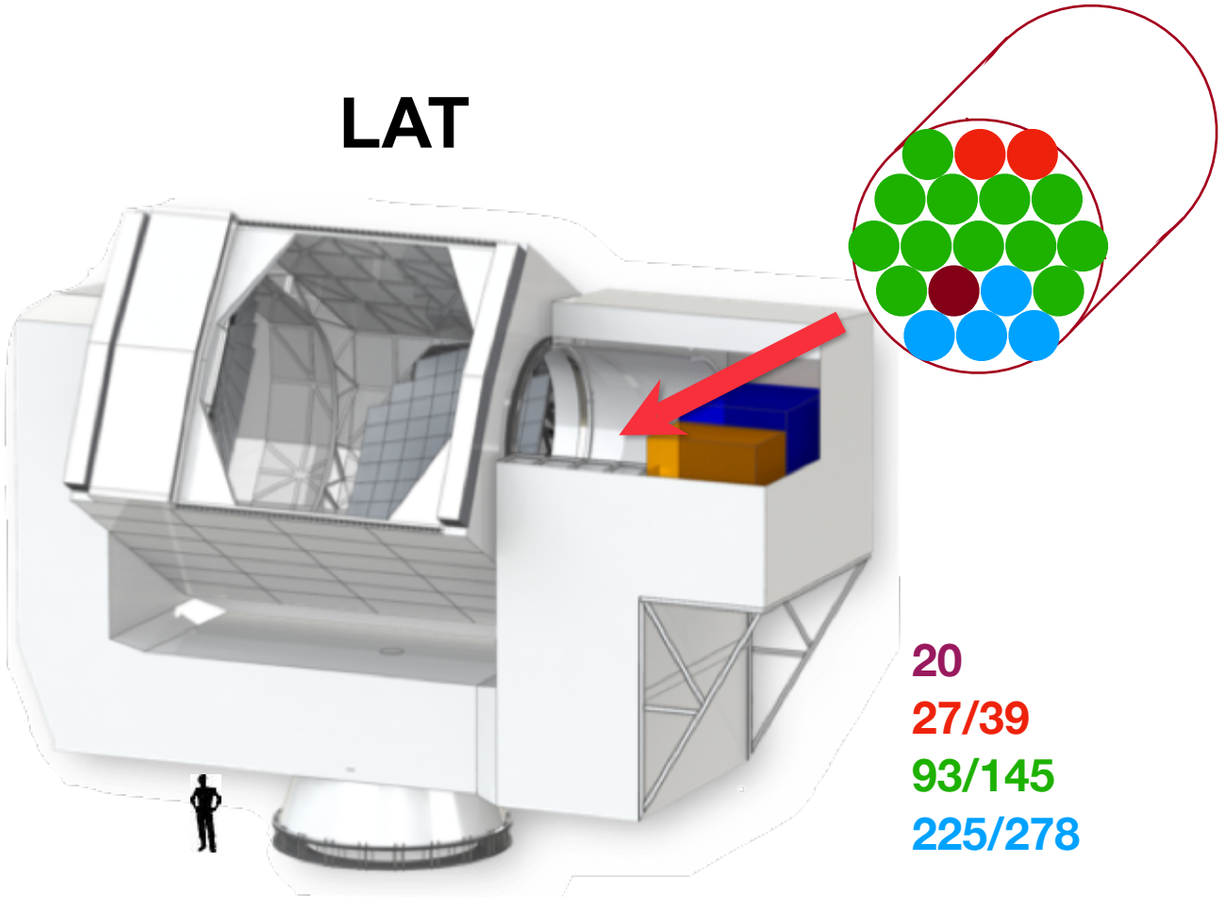
South Pole LAT should be a stepping stone to CMB-S4

- LAT should meet or exceed the specifications for the CMB-S4 de-lensing LAT required to conduct the ultra-deep narrow survey for the search for primordial gravitational waves, i.e., with SATs to achieve **$\sigma(r) = 5 \times 10^{-4}$**

Specifically, the CMB-S4 ultra-deep “r” survey requires seven years of observing with 18 x 0.55m small refractor telescopes targeting ≥ 3% of sky with 150,000 detectors over 8 bands and **a dedicated de-lensing large aperture telescope with ≥ 120,000 detectors.**

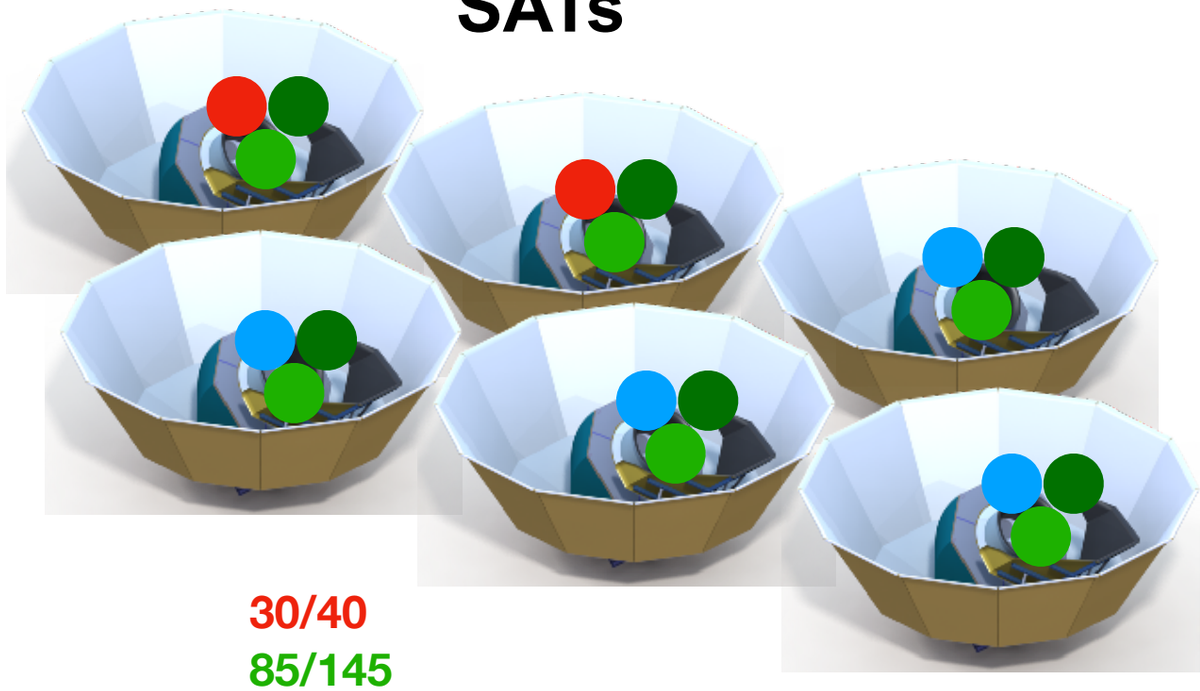
CMB-S4 “Reference Design” for ultra-deep, narrow *r* survey

LAT



20
27/39
93/145
225/278

SATs



30/40
85/145
95/155
220/270

Simons Observatory LAT Concept
(not designed for low ℓ or for South Pole)

New high throughput South Pole telescope: Three Mirror Anastigmat design

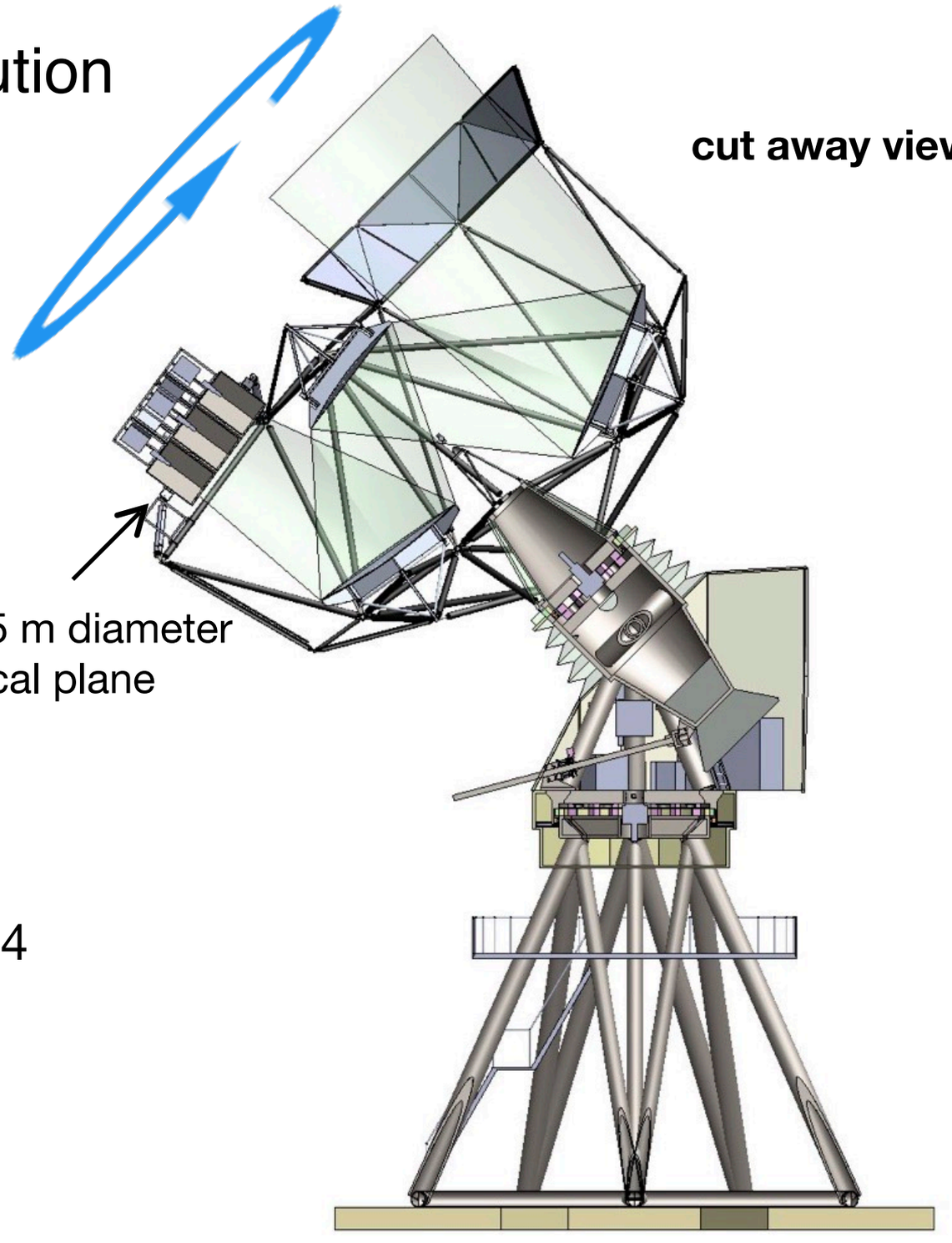
Degree B-modes ***and*** arc minute resolution with extremely high throughput.

For 5-m design:

- 100 deg^2 field of view, could support 424k/136k/63k Fλ pixels at λ=1/2/3mm
- Monolithic mirrors (low scattering)
- Boresight rotation (investigate and mitigate potential systematics in polarization and sidelobe response)
- Comoving baffle (low pickup)
- 1.6’ resolution at 150 GHz

Designed compatible for South Pole and CMB-S4 (similar in cost and scope to 10-m SPT)

Now working to design fully and prototype, targeting 2024 deployment



Padin, Applied Optics, 57, 9, 2314 2018

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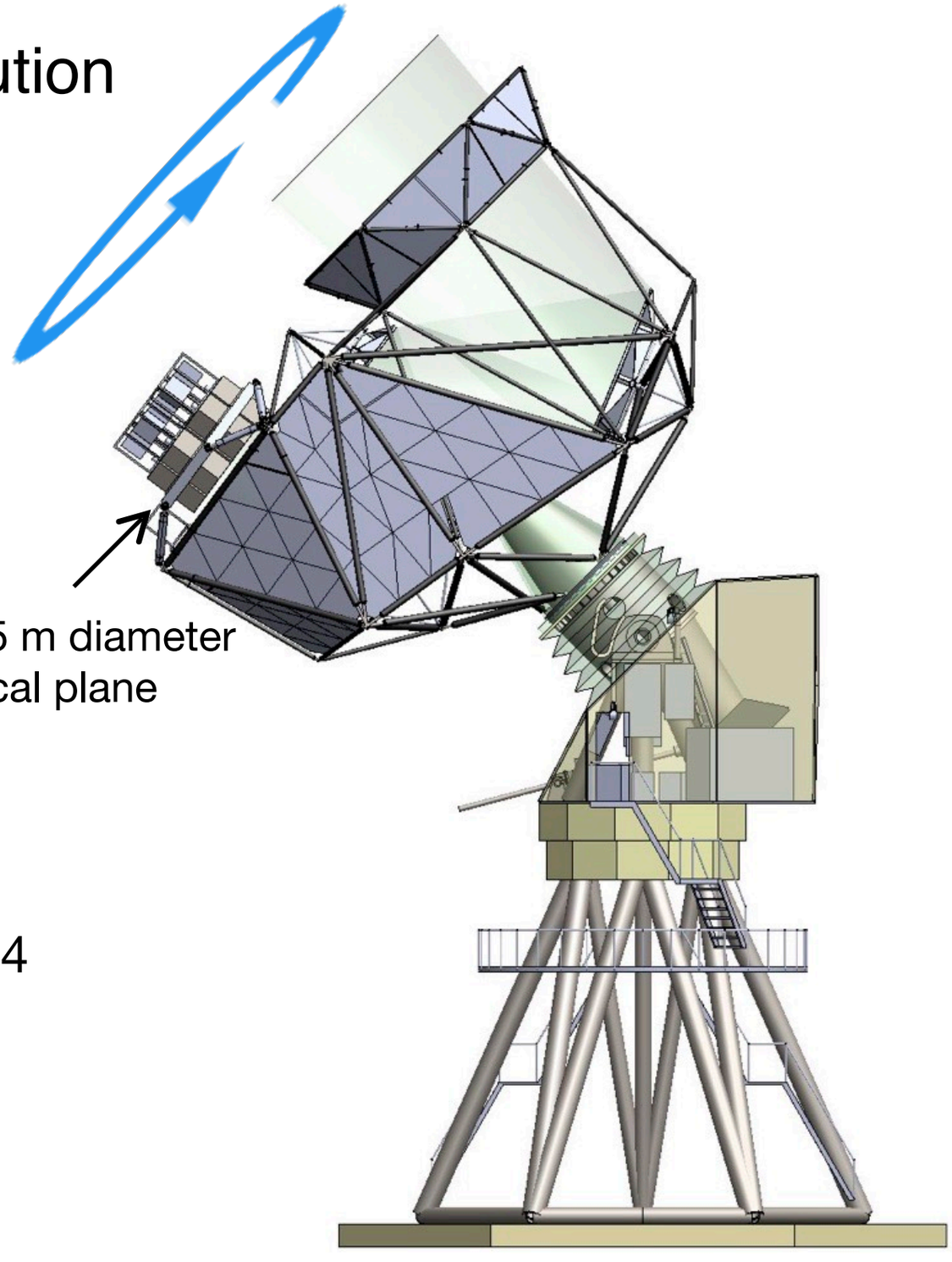

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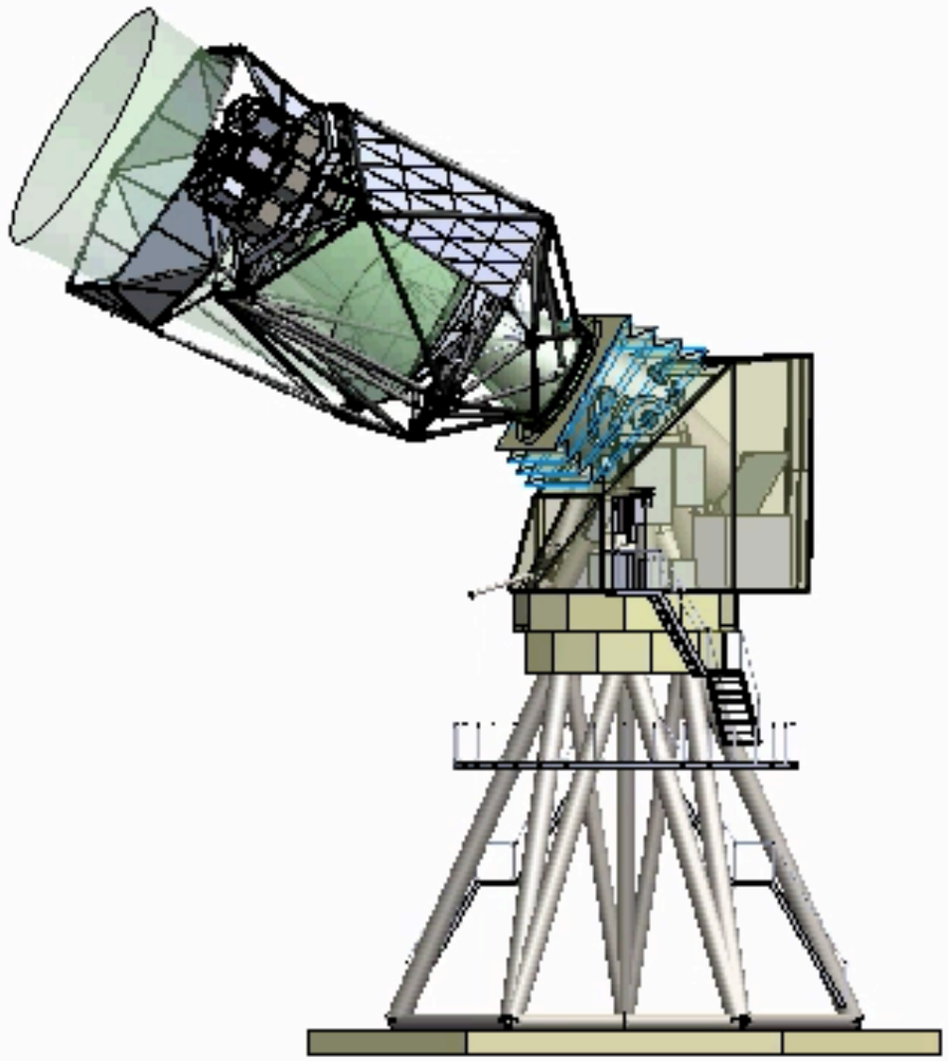
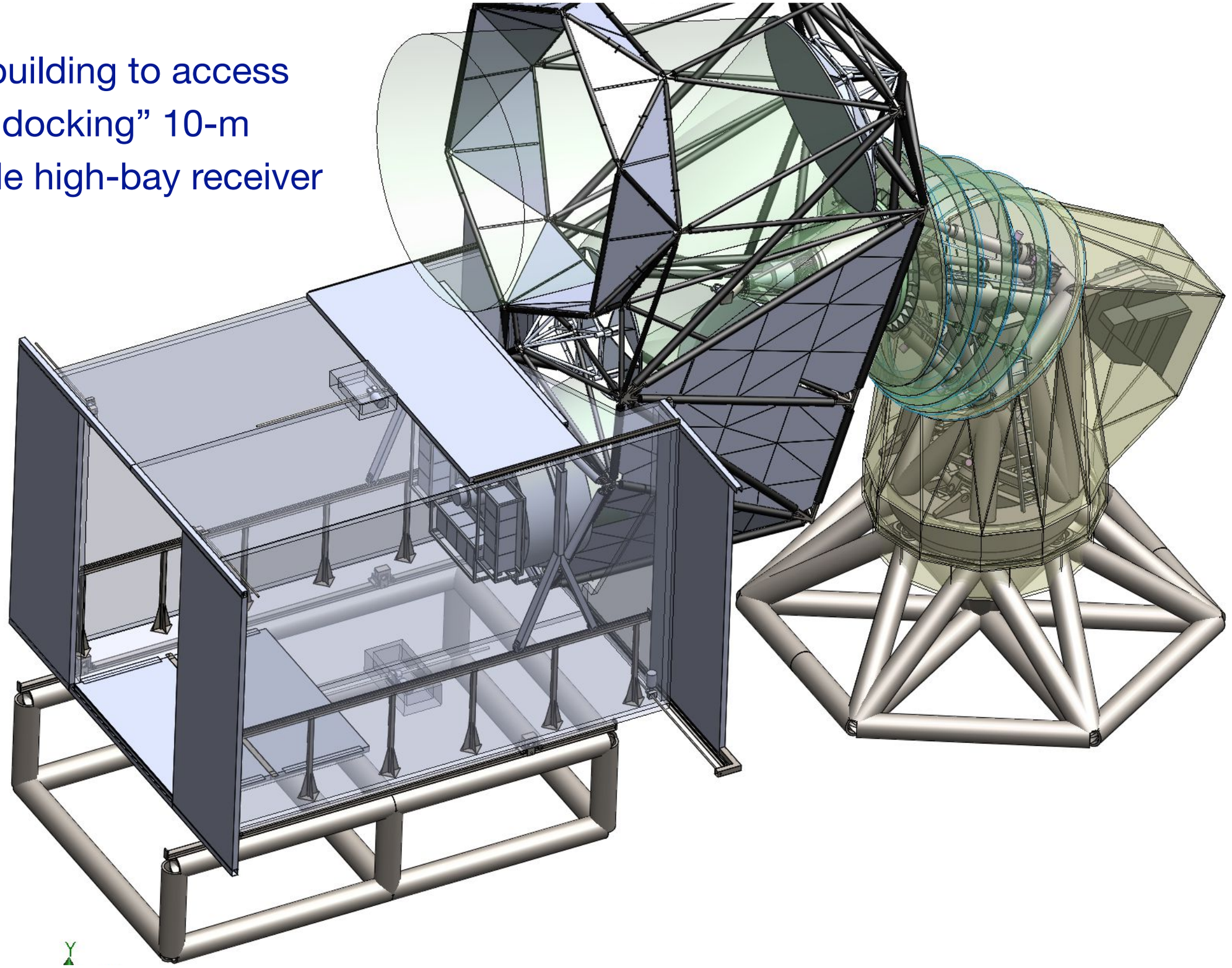


New high throughput South Pole telescope: Three Mirror Anastigmat design

High-bay support building to access receiver similar to “docking” 10-m telescope to provide high-bay receiver access.

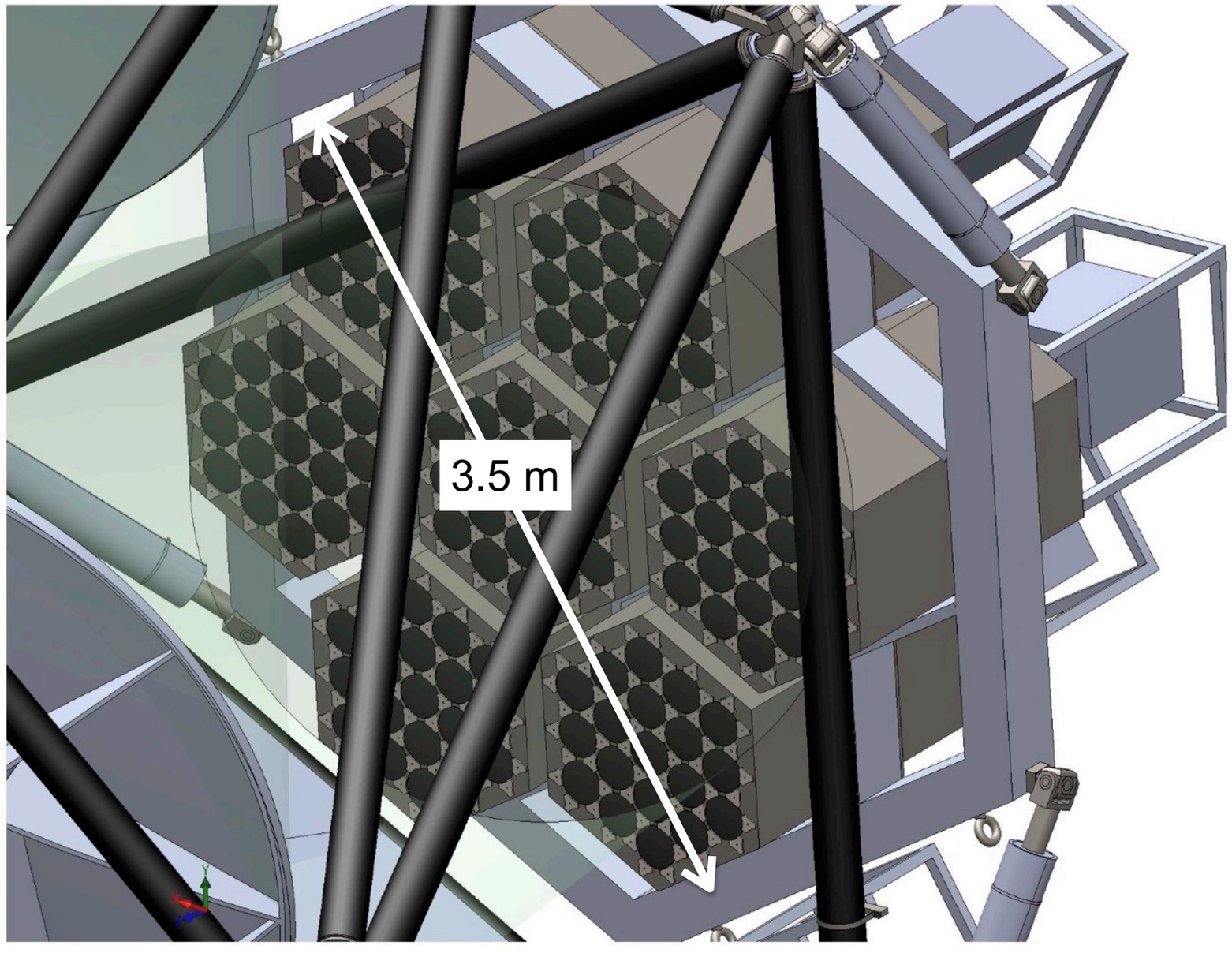


(figure not updated)

New high throughput South Pole telescope: Three Mirror Anastigmat design

Seven cryostat camera concept

- quick thermal cycling
- risk mitigation
- staged deployments with off-site testing
- standard modules integrated from the start with the telescope design
- allow separate camera efforts



from Steve Padin

What about 10 meter SPT after SPT-3G in 2024?

- It is a beautiful sub-millimeter telescope, with high precision surface (surface rms < 20 um).
- We are targeting to submit proposal this Fall for either
  - high frequency extension to SPT-3G (220, 270 and 350 GHz), or
  - kilopixel mKiD spectrometer intensity mapping experiment, or
  - possibly a combination of both of the above.
- We are interested in partners.

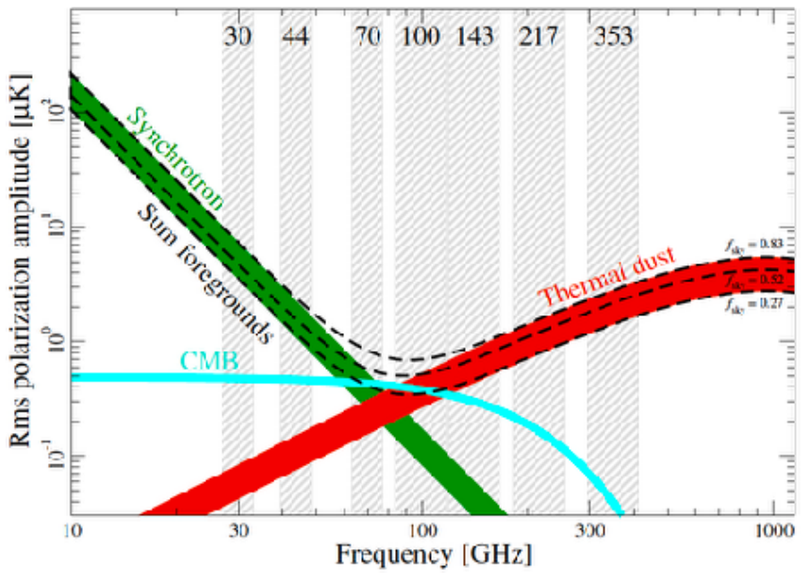
Last comments

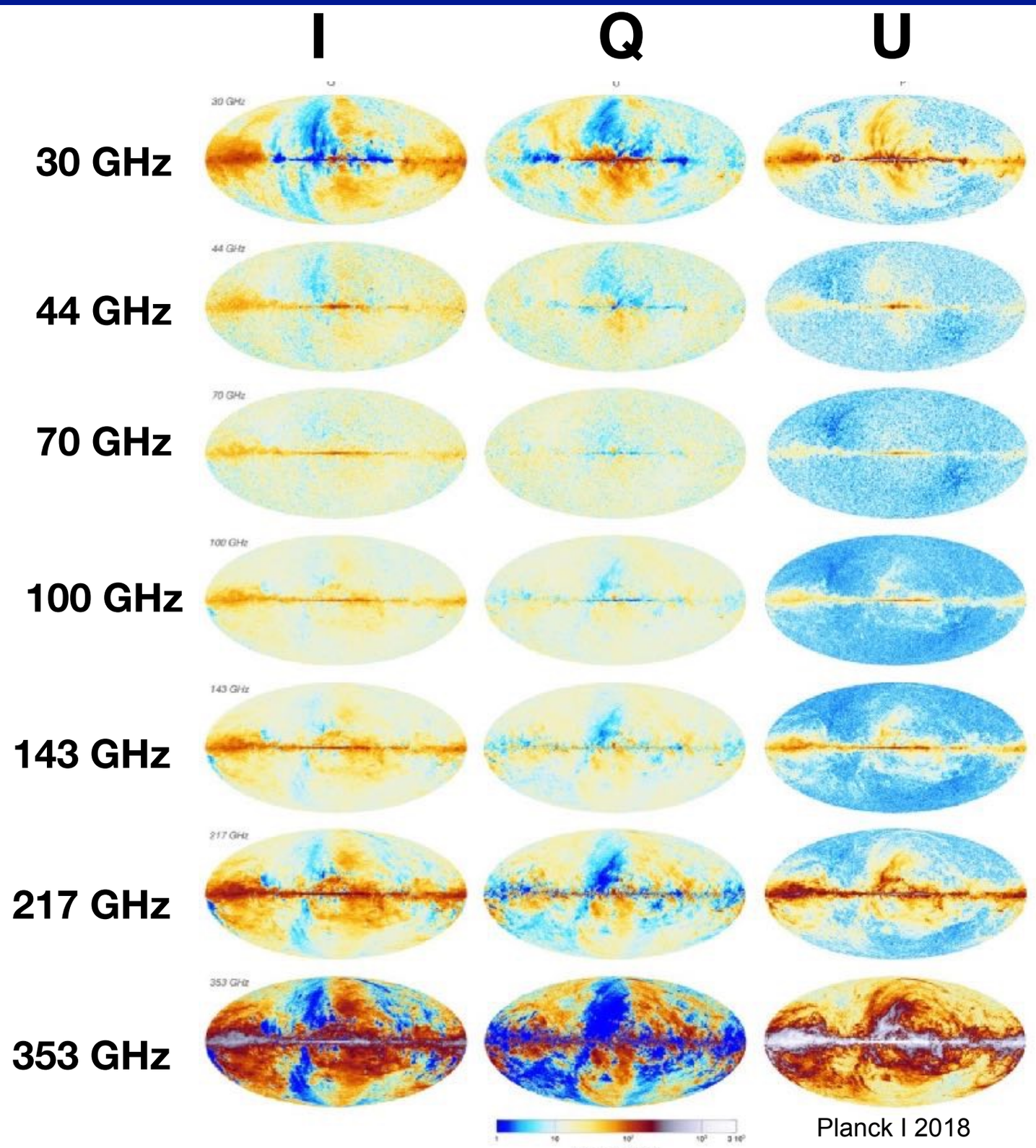
- South Pole LAT team assembled with initial funding (private & inkind) to go from current advanced concept to final design and start of construction, < 2 yr design phase.
- Three year construction and deployment timeline; cost estimate $16M includes the support building, but not camera.
- US agency funding opportunities and timing:
  - NSF MSIP expected call for proposals in Fall 2019
  - NSF MSRI expected call for proposals in Fall 2020
- We are interested in partners who are also enthusiastic about SPO and CMB-S4.
- We are also interested in possible partners for next SPT experiment, post SPT-3G.

back up slides

Multiple frequency channels to remove foregrounds

Planck polarized all sky maps at seven frequencies





Planck I 2018

CMB detector requirements and specifications:

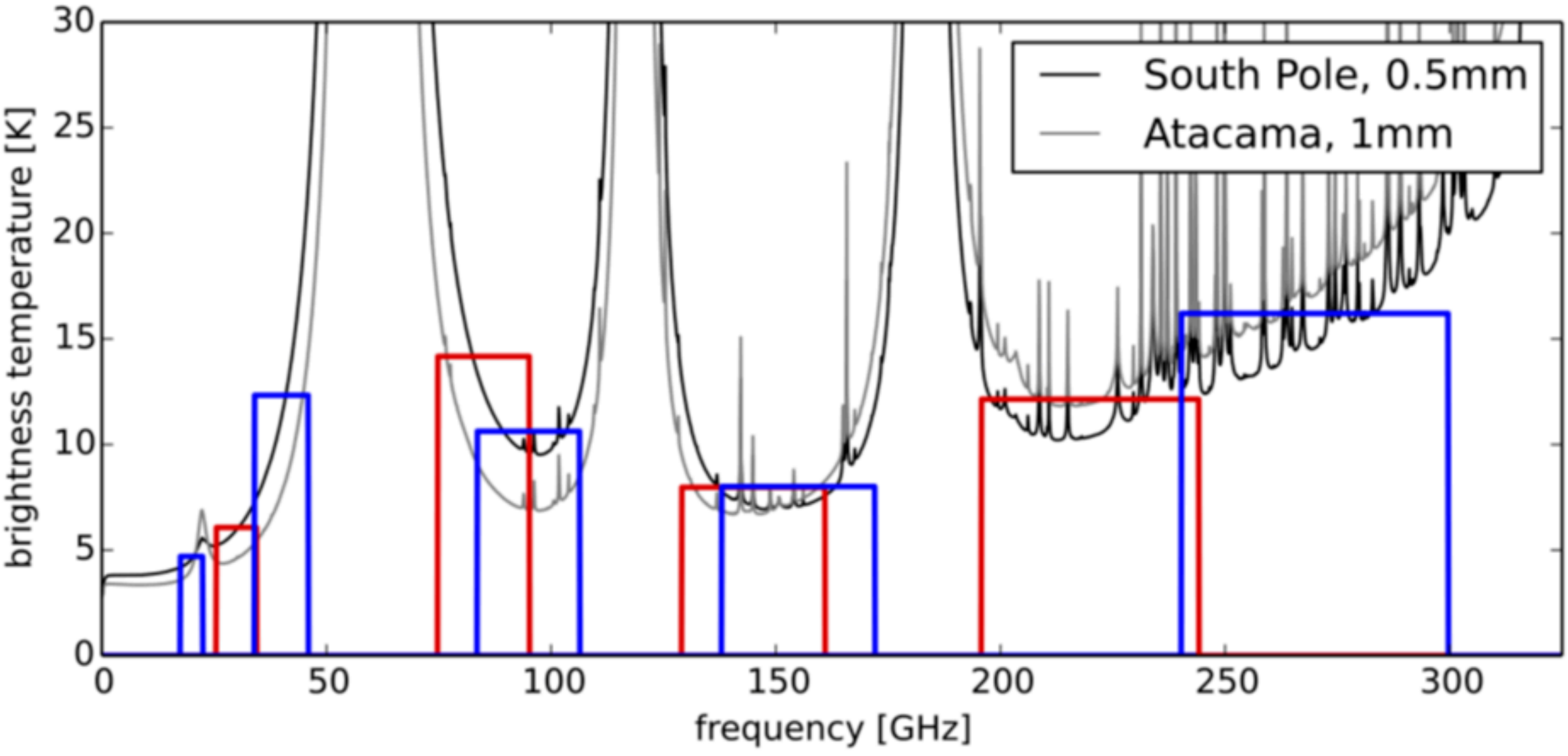
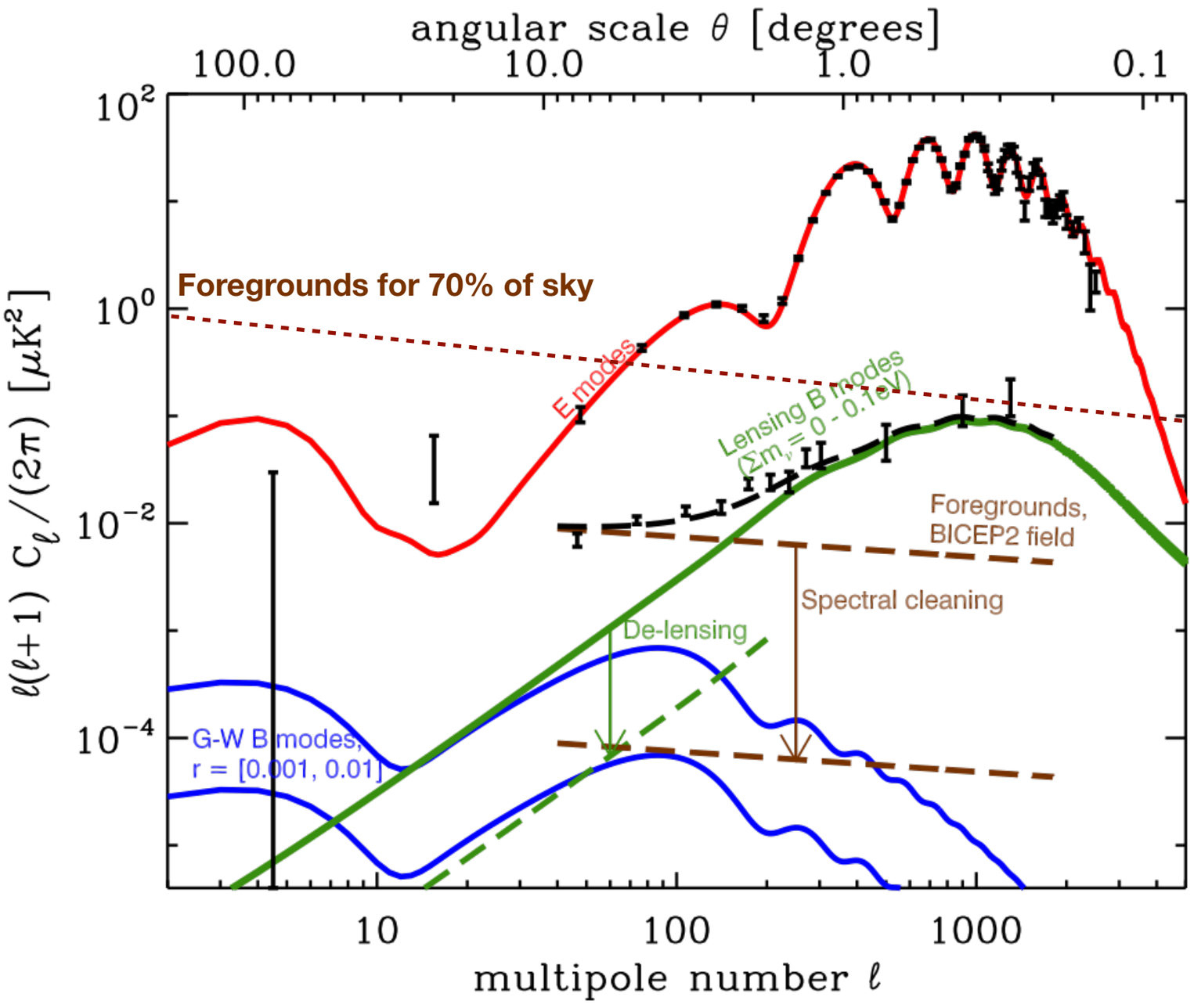


Figure 67. *Calculated atmospheric brightness spectra (at zenith) for the South Pole at 0.5 mm PWV and Atacama at 1.0 mm PWV (both are near median values). Atmospheric spectra are generated using Ref. [563]. The tophat bands are plotted on top of these spectra, with the height of each rectangle equal to the band-averaged brightness temperature using the South Pole spectrum.*

The path forward is through extremely challenging multi-frequency polarization measurements



E modes

lensing B modes

inflationary gravity wave B modes

CMB detector requirements and specifications:

The DSR presents the required detectors and sensitivity required to meet CMB-S4 science goals with 7 years of observations, based on performance achieved or extrapolated from previous measurements:

Small-aperture telescopes requirements: 4 different dichroic pixel designs => 4 wafer designs

Property	LF		CF High		CF Low		HF	
Center frequency (GHz)	30	40	85	145	95	155	220	270
Primary lens diameter (cm)	55	55	55	55	55	55	44	44
FWHM (arcmin)	72.8	72.8	25.5	25.5	22.7	22.7	13	13
Fractional bandwidth	0.3	0.3	0.24	0.22	0.24	0.22	0.22	0.22
NET (μK$\sqrt{\text{s}}$) per detector	177	224	270	238	309	331	747	1281
N_{det} per optics tube	288	288	3524	3524	3524	3524	8438	8438
N_{tubes}	2		6		6		4	
N_{wafers}	24		72		72		36	
N_{wafers} total	204							
$N_{\text{detectors}}$	576	576	21144	21144	21144	21144	33752	33752
$N_{\text{detectors}}$ total	153232							
Data rate (18 optics tubes)	1.7 TB/day							

Table 3-1. *Small-aperture telescope (SAT) receiver properties.*

Large-aperture telescopes requirements: 4 different dichroic pixel designs => 4 wafer designs

Property	ULF	LF		MF		HF	
Center frequency (GHz)	20	27	39	93	145	225	278
FWHM (arcmin)	10.0	7.4	5.1	2.2	1.4	1.0	0.9
Fractional bandwidth	0.25	0.22	0.46	0.38	0.28	0.27	0.16
NET (μK$\sqrt{\text{s}}$) per detector	438	383	250	302	356	737	1840
$N_{\text{detectors}}$ per tube	160	320	320	3460	3460	3744	3744
N_{wafers} per tube	4	4		4		4	

Chile (Wide Field Survey – 2 LATs

N_{tubes} per LAT	0	2	12	5
Data rate (2 LATs)	10.8 TB/day			

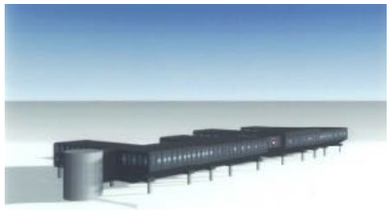
South Pole (Delensing Survey – 1 LAT)

N_{tubes}	1	2	12	4
Data rate (1 LAT)	5.0 TB/day			

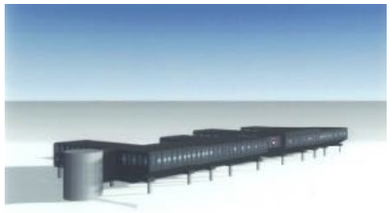
Total (3 LATs)

$N_{\text{detectors}}$	160	1920	1920	124560	124560	52416	52416
$N_{\text{detectors}}$ total	357952						
N_{wafers}	4	24		144		56	
N_{wafers} total	228						

Table 3-2. *Large-aperture telescope (LAT) receiver properties.*



Amundsen-Scott South Pole Research Station



Station Features

Kitchen

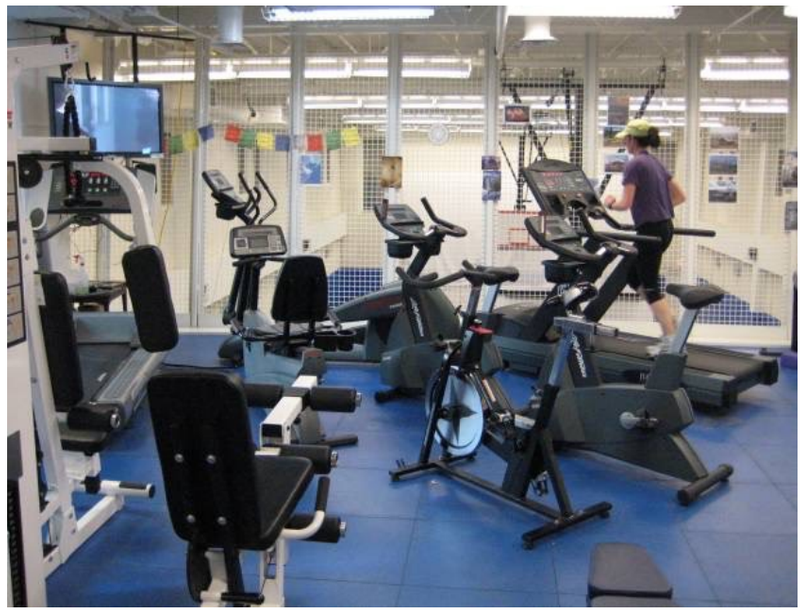
Communications

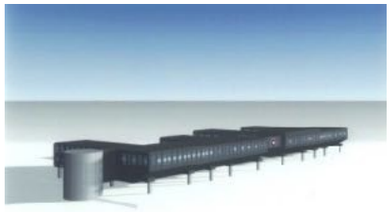
Berthing

Dining Area

Medical

Recreation





Power Plant

1 Megawatt Power Capacity