Measuring the CMB from Chile: a look ahead.

L. Page

ICTS, Bengaluru, Jan 2019

ACT/SO neighborhood

Credit: Simons Foundation, Director Debra Kellner, Image Yvan Neault
AdvACT: Suzanne Staggs PI, Mark Devlin co-director
SO Spokesperson: Mark Devlin > Adrian Lee> Suzanne Staggs

Status of activities

- ACT operating. Now has 11 seasons of data taking and 3rd generation of camera, ``AdvACT.”
- Polarbear/Simons array now has 3 telescopes with PB-2 receivers coming on line.
- ABS is done.
- CLASS has been taking data at 40 GHz since 2016 and recently installed a 90 GHz mount and receiver.

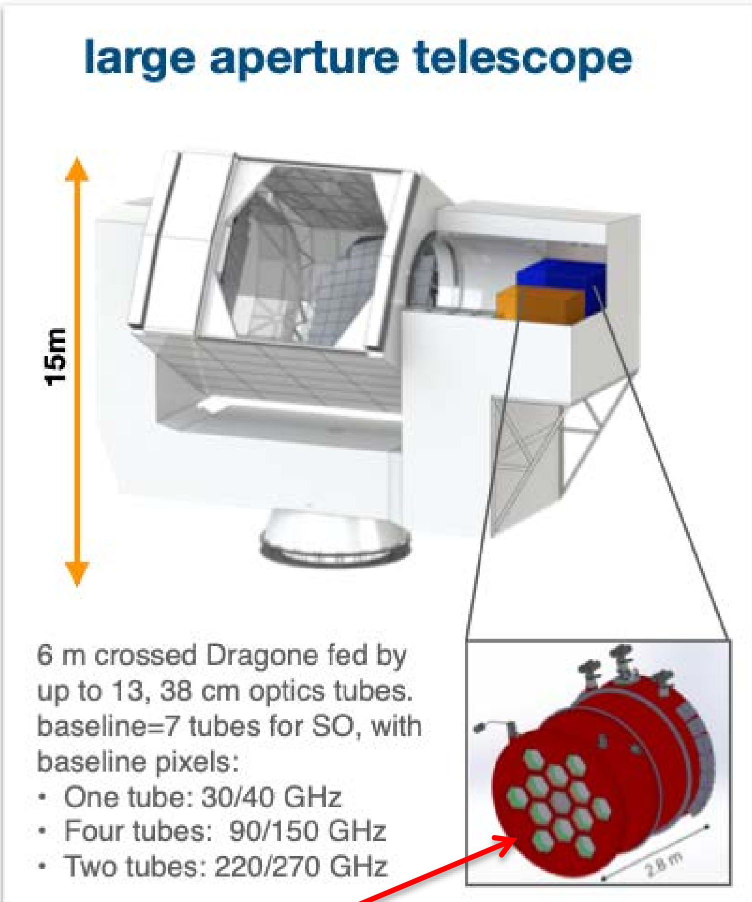
Coming soon…

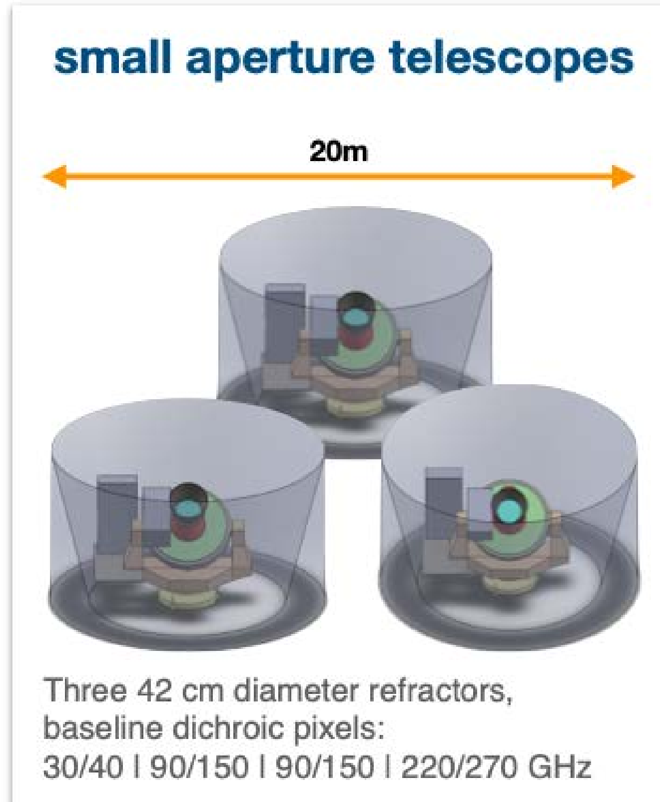
- SO will deploy a 6 m LAT, "Large Aperture Telescope" following the Niemack design (AO, 2016)
- SO will deploy 3-4 SATs, "Small Aperture Telescopes," for B-mode searches.
- CCAT-prime will deploy the same telescope design as SO but at a higher altitude to focus on the CMB and higher frequencies.
- CLASS will finish deploying full suite of receivers at 40,90,150 & 220 GHz.
- Polarbear/Simons Array will finish deploying two more new receivers.

Totals: 3 6m telescopes, 3 2.5m telescopes and 7 ~1/2 m telescopes

Simons Observatory

fully funded (Simons Foundation), **first light**: 2021
location: Atacama (Chile), 60k detectors





Optics tube: ~5000 detectors

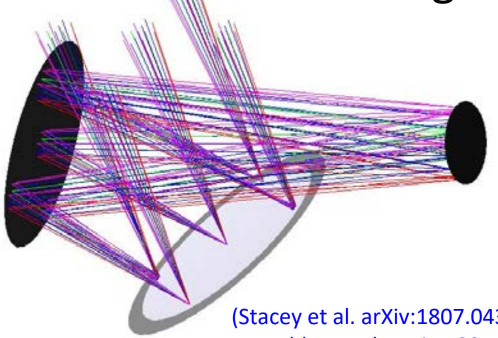
Spokespeople: M. Devlin, **A. Lee**, S. Staggs. Director: B. Keating

CCAT-Prime

6 meter aperture extreme field-of-view sub-millimeter telescope on Cerro Chajnantor at 5600m, Chile

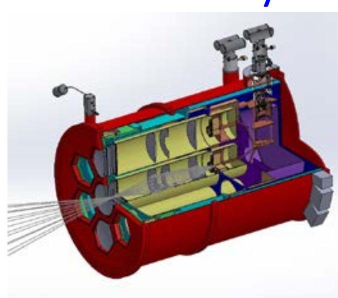
Measurements: Galaxy clusters and CMB polarization, C+ intensity mapping, Dusty galaxies, Galactic emission lines

~8 degree diffraction-limited FOV at 2mm, and ~4 degree at 1mm



(Stacey et al. arXiv:1807.04354, Parshley et al. arXiv:1807.06675 Vavagiakis et al. arXiv: 1807.00058)

Prime-Cam cryostat



Surface accuracy ~10 um at an outstanding sub-mm site with access to 350um – 3mm

Telescope funded, first light 2021

CCAT-prime Collaboration:

CLASS

Cosmology Large Angular Scale Surveyor

fully funded (NSF), **first light**: 2016 (40 GHz), 2018 (90 GHz)
location: Atacama (Chile), 5k detectors

2nd to be deployed in 2020

to be deployed in 2019

4 telescopes: 40 GHz, 2 x 90 GHz, 150/220 GHz (dichroic)

$f_{\rm sky} \sim 75\%$, $2 < \ell < 200$

Rapid front-end modulation alleviates need for large-scale filtering allowing access to lowest multipoles

τ

Large-scale *B*- and *E*-mode experiment

~ sample variance limited ($f_{\rm sky}$ = 75%)

Large angular scale polarization science: GWs and optical depth (τ)

Atmospheric fluctuations are considerable. Need to modulate polarization to get above the atmospheric 1/f. Less of an issue for SP.

ABS showed that rapid modulation with a spinning HWP is effective (Kusaka et al. 2014).

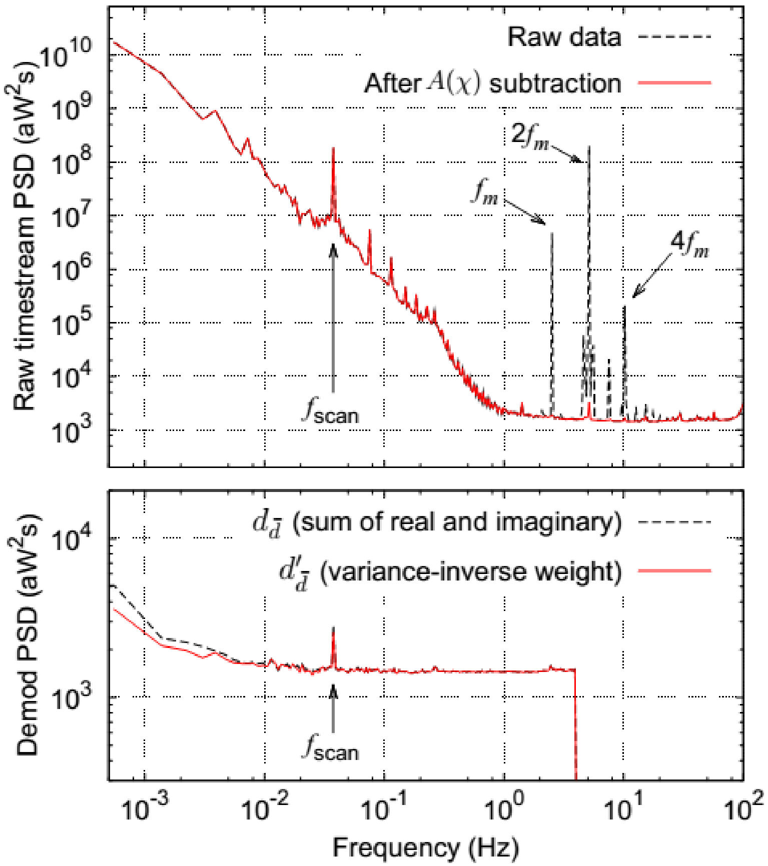
PB/SA will use a spinning cryogenic (50K) HWP. An ambient temp. version was demonstrated (Takakura et al. 2017).

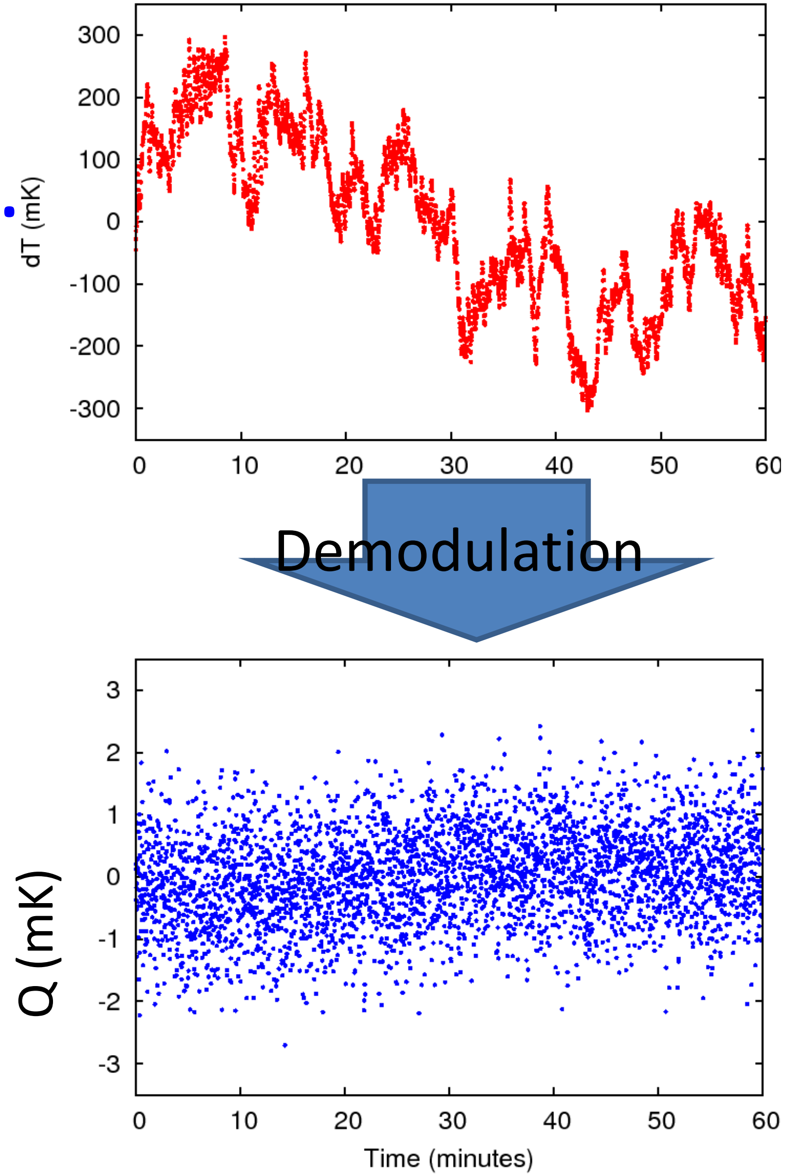
CLASS uses an ambient VPM to modulate between Stokes Q and V. It is unique in its search for circular polarization (Harrington et al. 2018).

SO will use a PB/SA style spinning cryogenic HWP.

A spinning HWP is also beneficial for reducing the effects of beam-related systematic errors and detector 1/f. The **LiteBIRD** satellite plans to use them!

Rapid modulation of incident polarization signal.





Data stable on time scales of 500-1000 seconds (1-2 mHz)

Kusaka et al, RSI 85, 024501 (2014)

Large available sky coverage from Chile is a benefit for B-mode searches.

For four thousand deg^2, f=0.1, you do not need to de-lens to get to r<0.002. **SO SATs** will cover this area.

More low emissions regions available than from SP.

CLASS to cover f=0.75 of sky to measure τ. Lower ell easier at lower frequencies.

Coverage

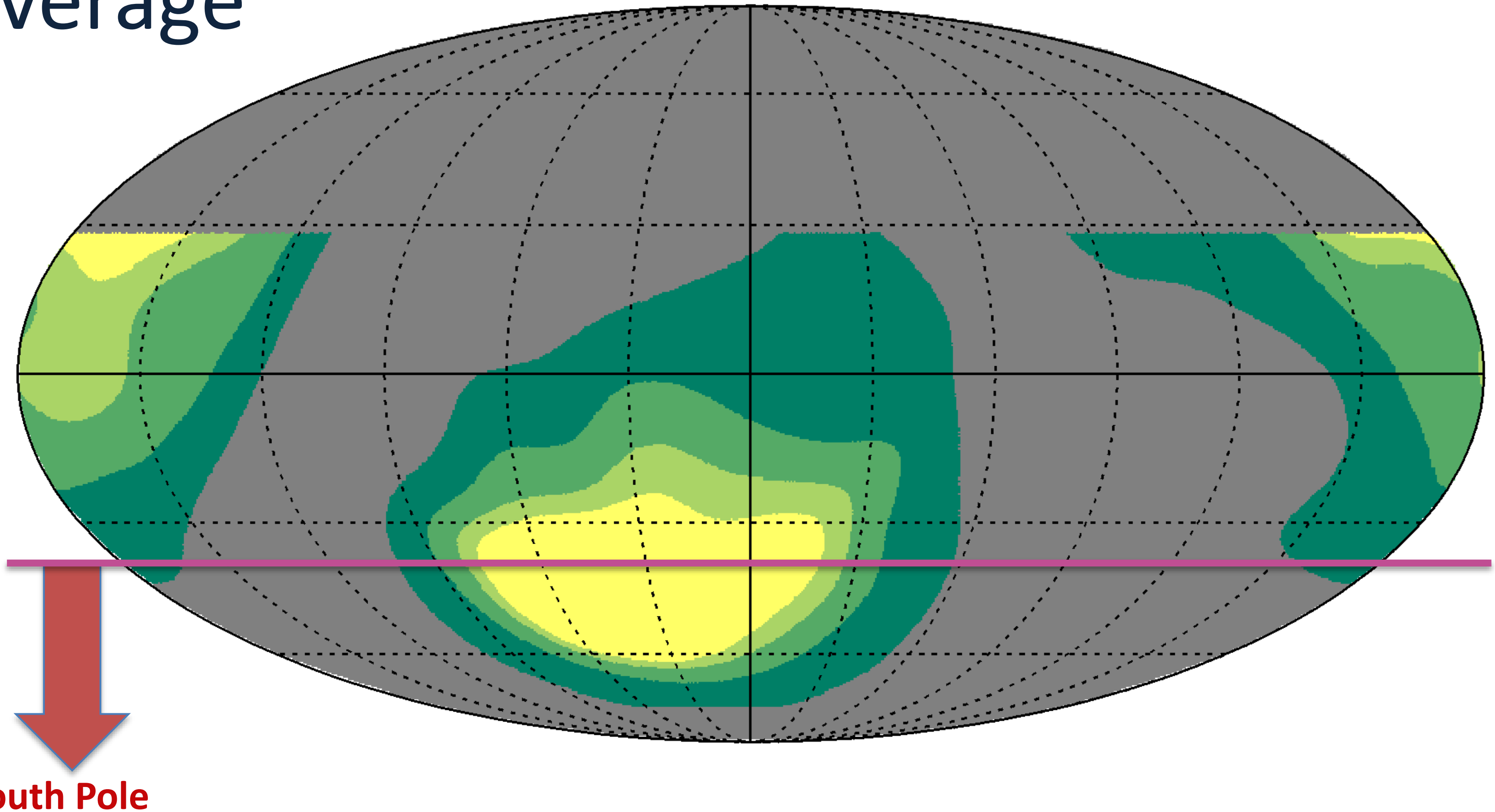


FIG. 3: Sky masks used in the analysis, corresponding to the cleanest 2000, 4000, 8000 and 16000 deg^2 of the sky accessible from Chile in terms of foreground contamination.

All green accessible from Chile

David Alonso, Oxford

Current ACT Coverage

Video from Reily Bova

Coverage

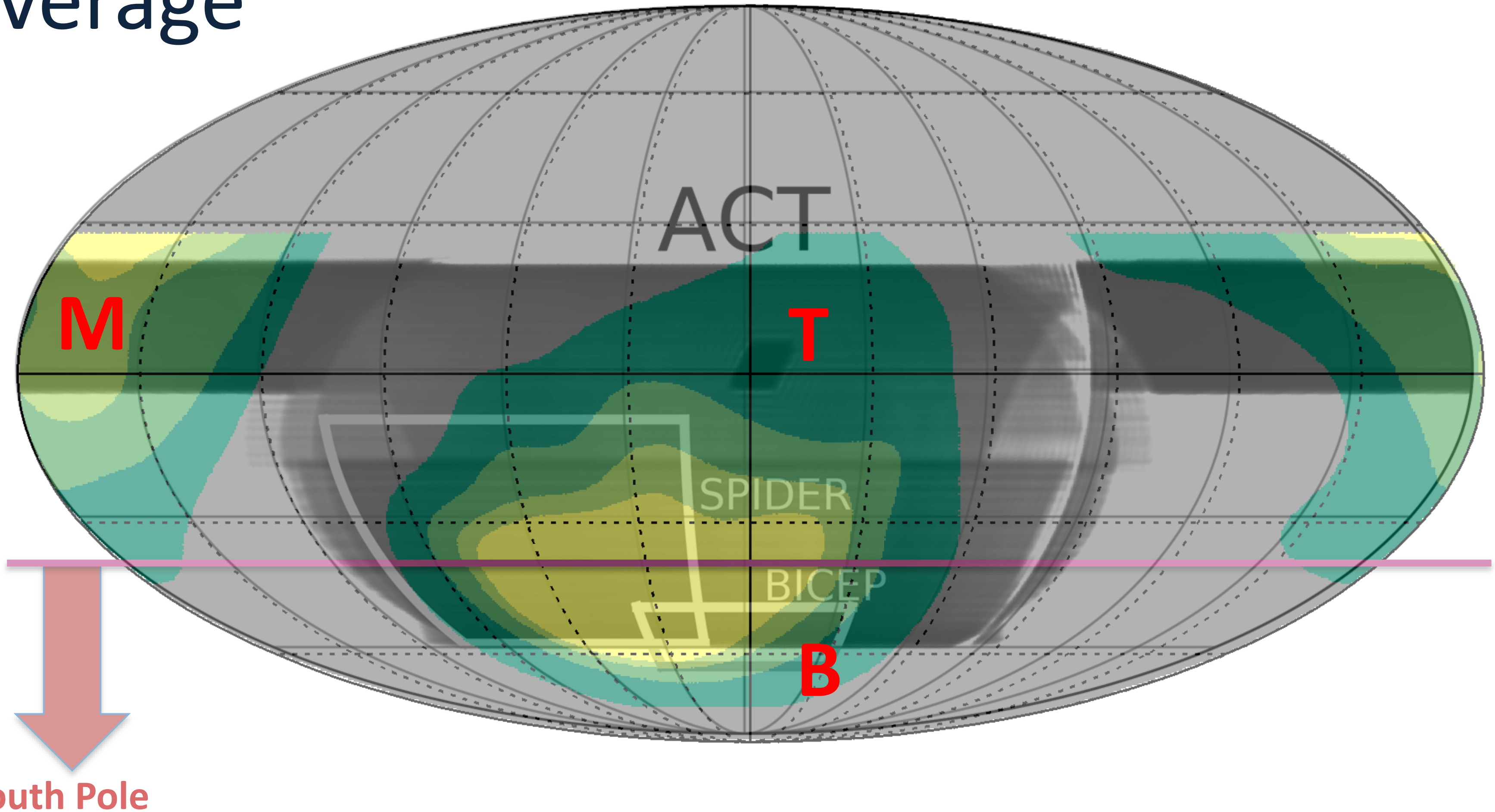
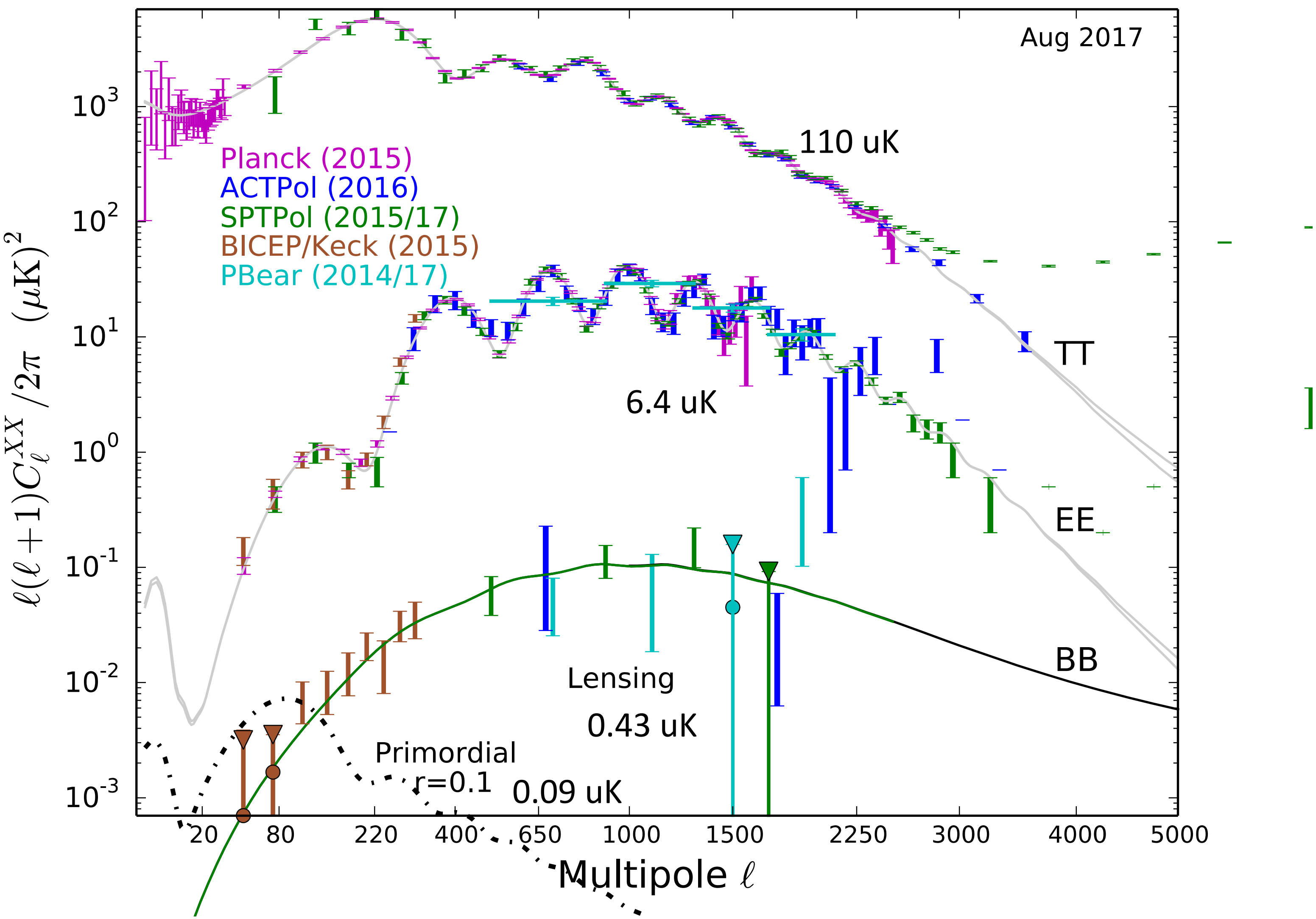


FIG. 3: Sky masks used in the analysis, corresponding to the cleanest 2000, 4000, 8000 and 16000 deg^2 of the sky accessible from Chile in terms of foreground contamination.

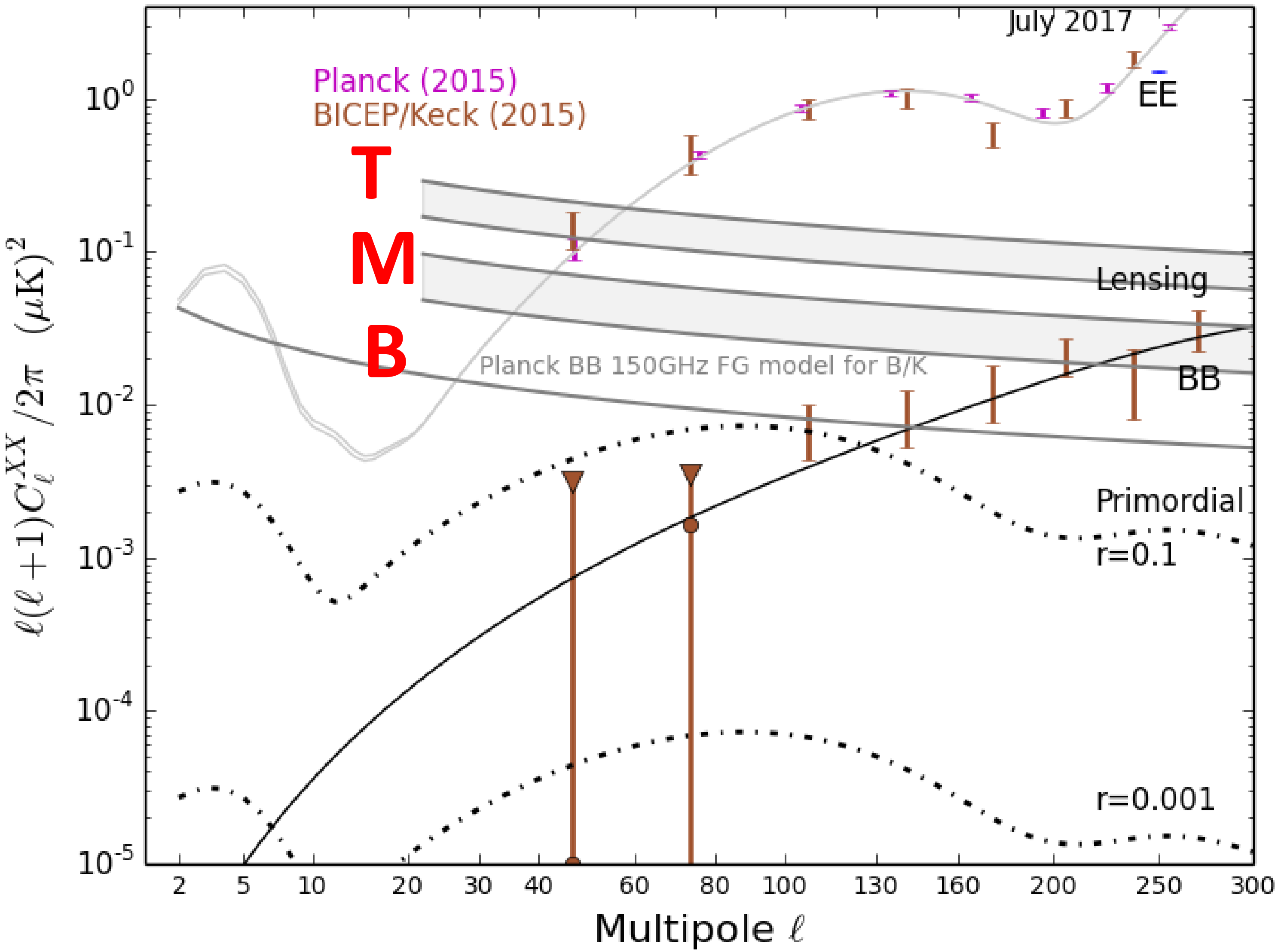
David Alonso, Oxford

At 150 GHz



Aug 2017
Planck (2015)
ACTPol (2016)
SPTPol (2015/17)
BICEP/Keck (2015)
PBear (2014/17)
110 uK
6.4 uK
Lensing
0.43 uK
Primordial
r=0.1
0.09 uK
TT
EE
BB
$\ell(\ell+1)C_\ell^{XX}/2\pi\ \ (\mu\mathrm{K})^2$
Multipole ℓ

At 150 GHz

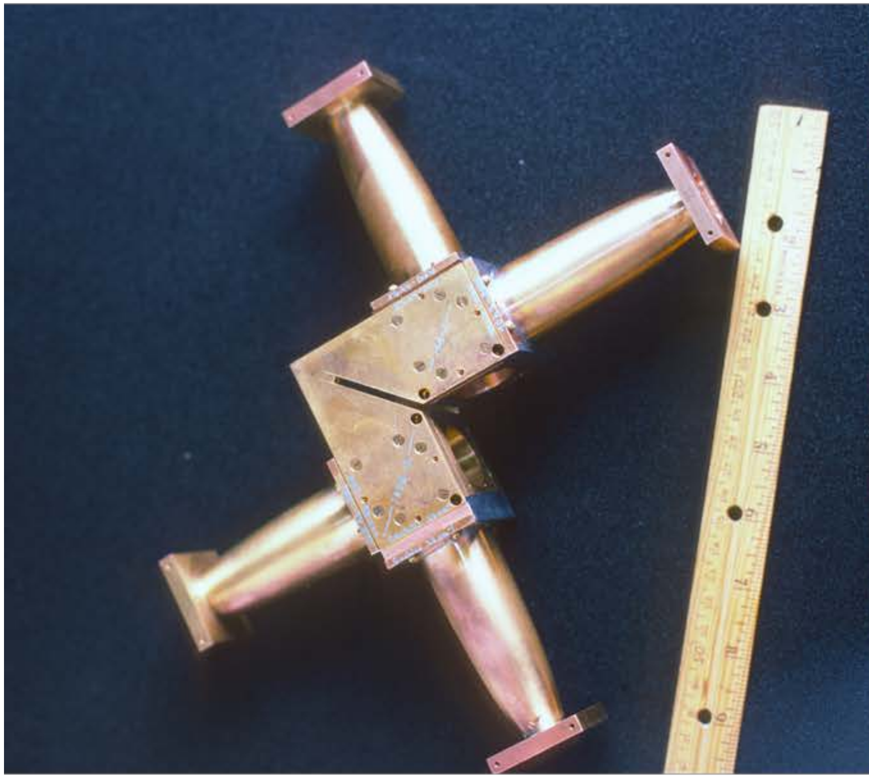

July 2017
Planck (2015)
BICEP/Keck (2015)
T
M
B
EE
Lensing
Planck BB 150GHz FG model for B/K
BB
Primordial
r=0.1
r=0.001
$\ell(\ell+1)C_\ell^{XX}/2\pi \quad (\mu K)^2$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
2 5 10 20 30 40 60 80 100 130 160 200 250 300
Multipole ℓ

For a convincing detection of primordial B-modes I think you will want:

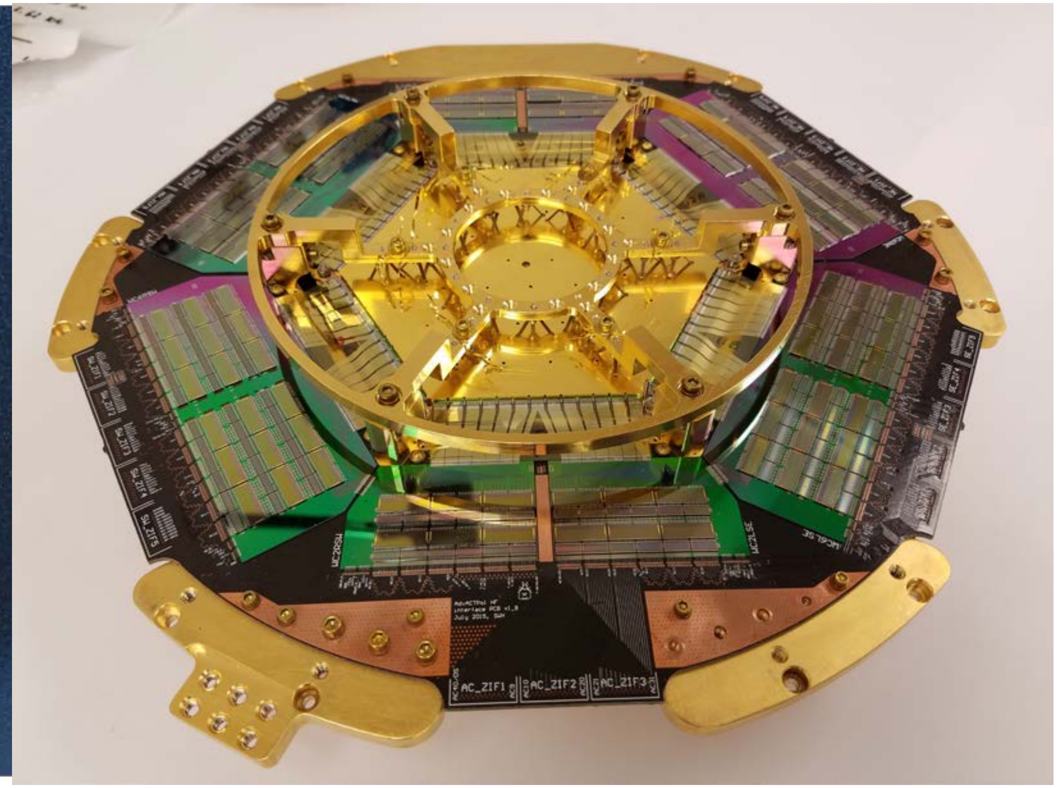
1) Independent detections with independent instruments (e.g., ATLAS and CMS) at the ~5-sigma level.
2) Measurements in multiple regions of sky.
3) An unambiguous frequency spectrum.

Large aperture telescopes will be helpful for foreground cleaning at <90 GHz. To achieve ½ degree resolution at 30 GHz requires a 1.5 meter aperture.

30 years of receiver development



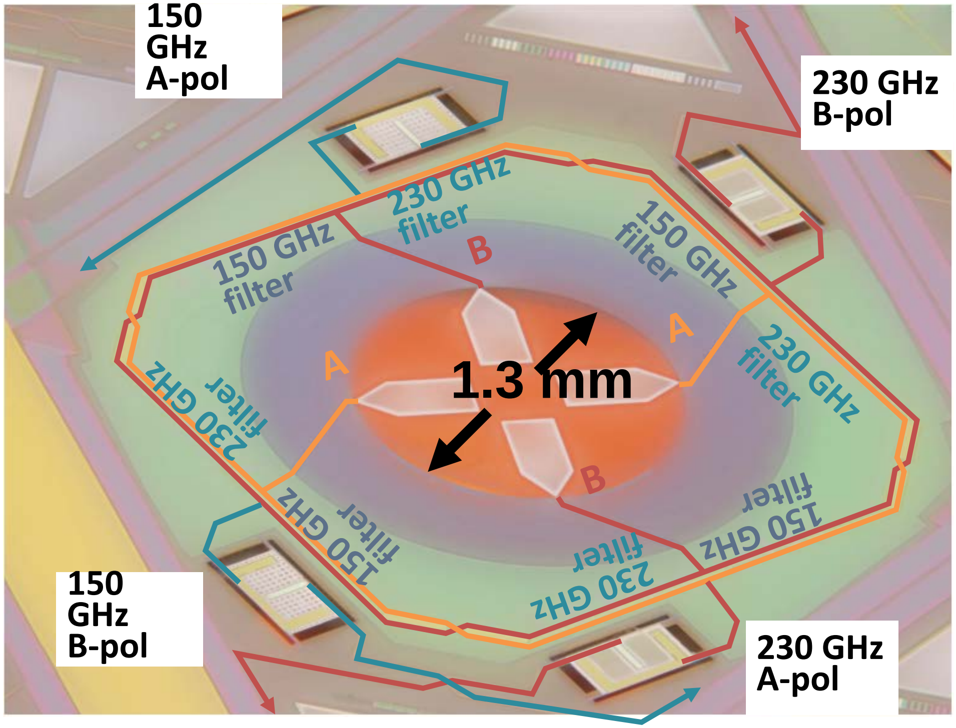
FIRS. First detection of CMB with bolometers. (PI Steve Meyer)

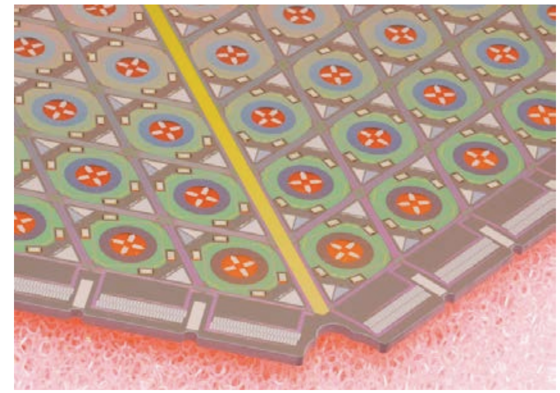


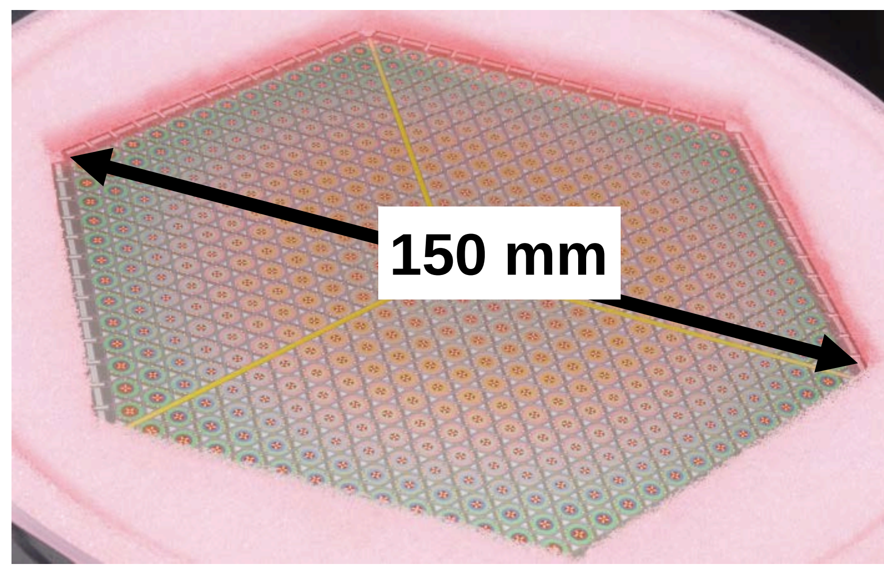
One of three AdvACT array of ~500 feeds. Combination is 3x as sensitive as Planck

AdvACT detector Wafer PA4

NIST







- **506 pixels / 503 horns**
- **2024 TES detectors**
  (1012 each at 150 and 220 GHz)

Figures courtesy of NIST

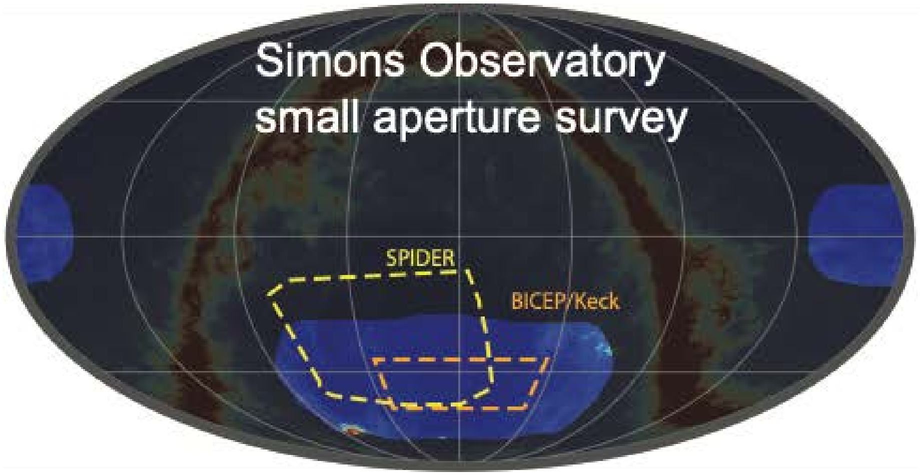
Small angular scales: CMB Smörgåsbord

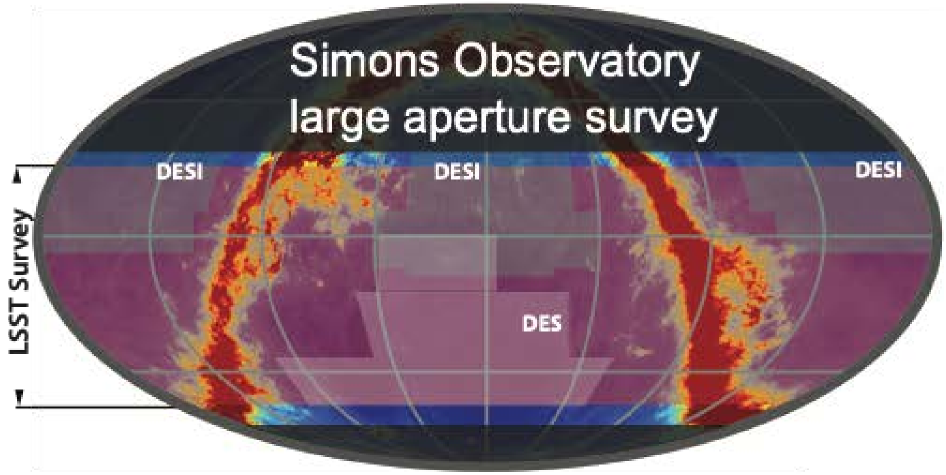
- Independent assessment of cosmological parameters
- H_0 ★
- Neutrino number and mass.
- Isocurvature modes from EE; the lowest hanging fruit?
- Testing GR/equation of state through the growth of structure.
- Calibrating LSST lensing and other surveys.
- Mass bias for quasars, radio sources, through lensing…
- Halo masses through stacking and lensing.
- Cosmic ionization history.
- Find thousands of galaxy clusters.
- Find high redshift dusty galaxies.
- …..
- Something new!

Simons Observatory

Fully funded (Simons Foundation), **first light**: 2021
location: Atacama (Chile), 60k detectors

+ HSC, GAMA, KIDs…





B-mode science

f_{sky} = 10%
@145 GHz: 17' resolution, ~2 μK' *I* noise

Maximizes overlap with LSS surveys

f_{sky} = 40%
@145 GHz: 1.4' resolution, ~6 μK' *I* noise

Science Forecast Matrix

	Simons Observatory	CMB-S4	CLASS	LiteBIRD	PICO
Funded?	yes (Simons Foundation)	no (NSF / DoE)	yes (NSF)	no (phase A) (JAXA)	no (NASA)
Est. first light	2021	2027	2016 (actual)	2027	
Ang. scales	$\ell > 30$	$\ell > 30$	$\ell < 200$	$\ell < 200$	$\ell > 2$
(**B/K**:0.03) $\sigma(r)$	2×10^{-3}	0.5×10^{-3}	6×10^{-3}	1×10^{-3}	0.1×10^{-3}
(**P**:0.4) $\sigma(N_{eff})$	0.05	0.03			0.03
(**P**:0.007) $\sigma(\tau)$			0.003	0.002	0.002
(**P**:240) $\sigma(\Sigma m_\nu)$ [meV]	30	26			15

From Aurelien Fraisse

Sensitivities for f=0.4 per arcmin^2

	90 GHz	150 GHz	
ACT ~B/K ~SPT	19 uK/$(\eta\tau)^{1/2}$	18 uK/$(\eta\tau)^{1/2}$	Notes: Based on measured ACT noise for 50^o elev and for 1.3 mm pwv.* +220,30,40 GHz
SO	7.4-5.3 uK/$(\eta\tau)^{1/2}$ Baseline-goal	9.2-5.8 uK/$(\eta\tau)^{1/2}$ Baseline-goal	Notes: Full atm model, 7/13 OTs. &w/ 30,40,220,270 GHz. From: 1808.07445v1
S4	2 uK/$(\eta\tau)^{1/2}$	2 uK/$(\eta\tau)^{1/2}$	Notes: Based on SO "goal" but with more detectors. Total: 2x19 OT. &w/20,30,40,220 ,280, GHz. From S4 site.

η Is observing efficiency, 20-30%, and τ is duration in years

$*$ The pwv is <1.3 mm 20% of the year, <2 mm 50% of the year

Estimates of ultimate limits

Sensitivity, always important and gains can be made.

For the ground:

Frequency	30 GHz	40 GHz	90 GHz	150 GHz	220 GHz	270 GHz
Achieved ($\mu K\ s^{1/2}$)	[320]	[420] ~200	250	260	780	1100
"Best" possible	…	120	100	170	500	1000

Single detector, single polarization. From J. Gudmundsson & LP

We will ultimately be limited by foreground emission *plus* low-level systematic effects.

There is a lot more exciting science in the CMB!