South Pole

U.S. CMB Stage 3 Efforts

John Carlstrom
CMB-S4 Co-Spokesperson
U.Chicago / Argonne

Photo credit Cynthia Chiang

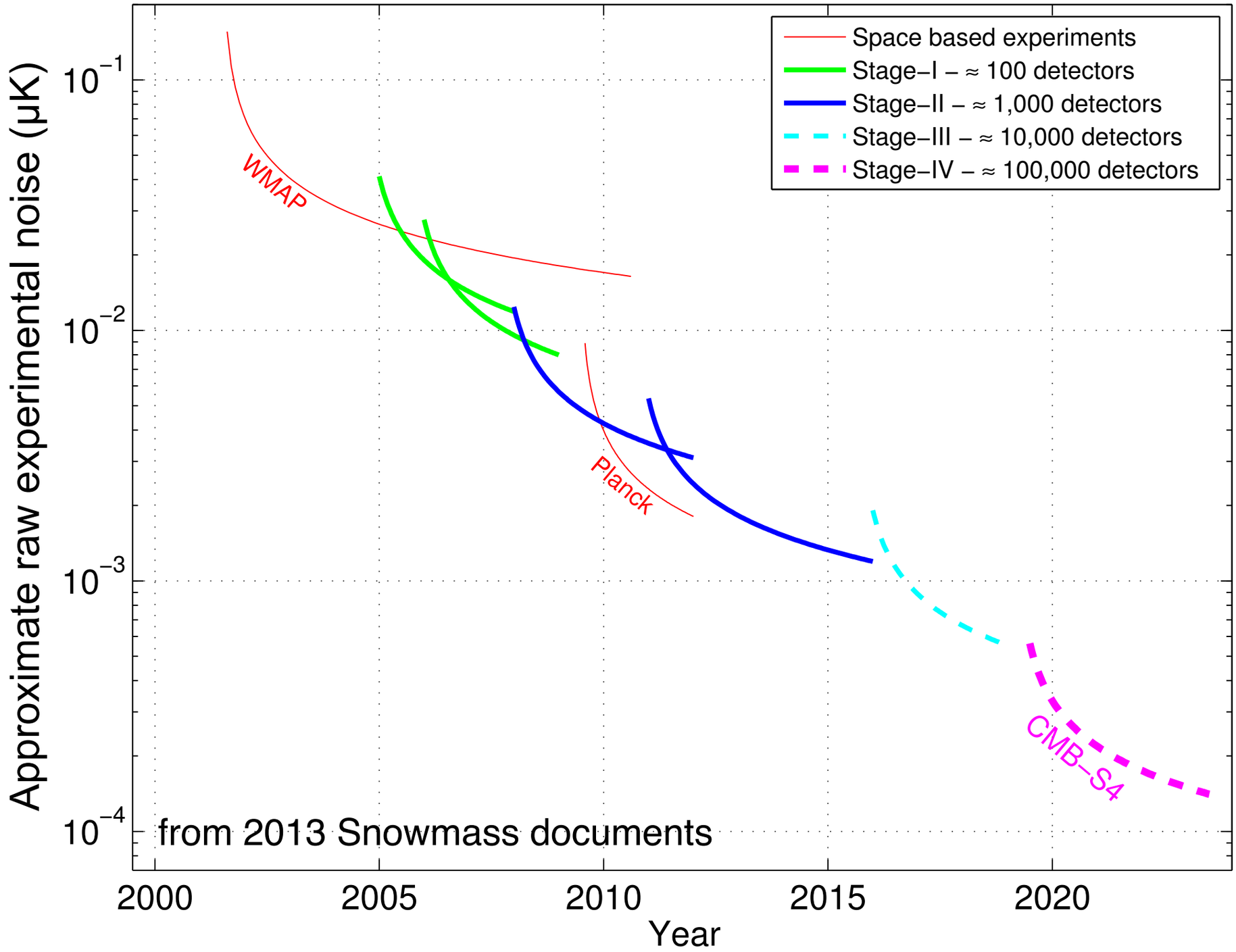
Atacama, Chile

Photo provided by Mark Devlin

Long history of US ground-based CMB experiments

- We've been at this for decades
- Many lessons learned
- Highly complementary to Space and Balloon experiments
- Effort has consolidated on two sites:
  South Pole & Atacama Plateau in Chile
- Produced a lot of science, with the best yet to come.
  Stage 3 results coming over next 5 years.
- Efforts are all leading to CMB-S4

"Moore's Law" of CMB sensitivity



But need more than detectors…

South Pole CMB efforts started in 1980's

Python CMB Telescope

1994 Winter-over
John Kovac

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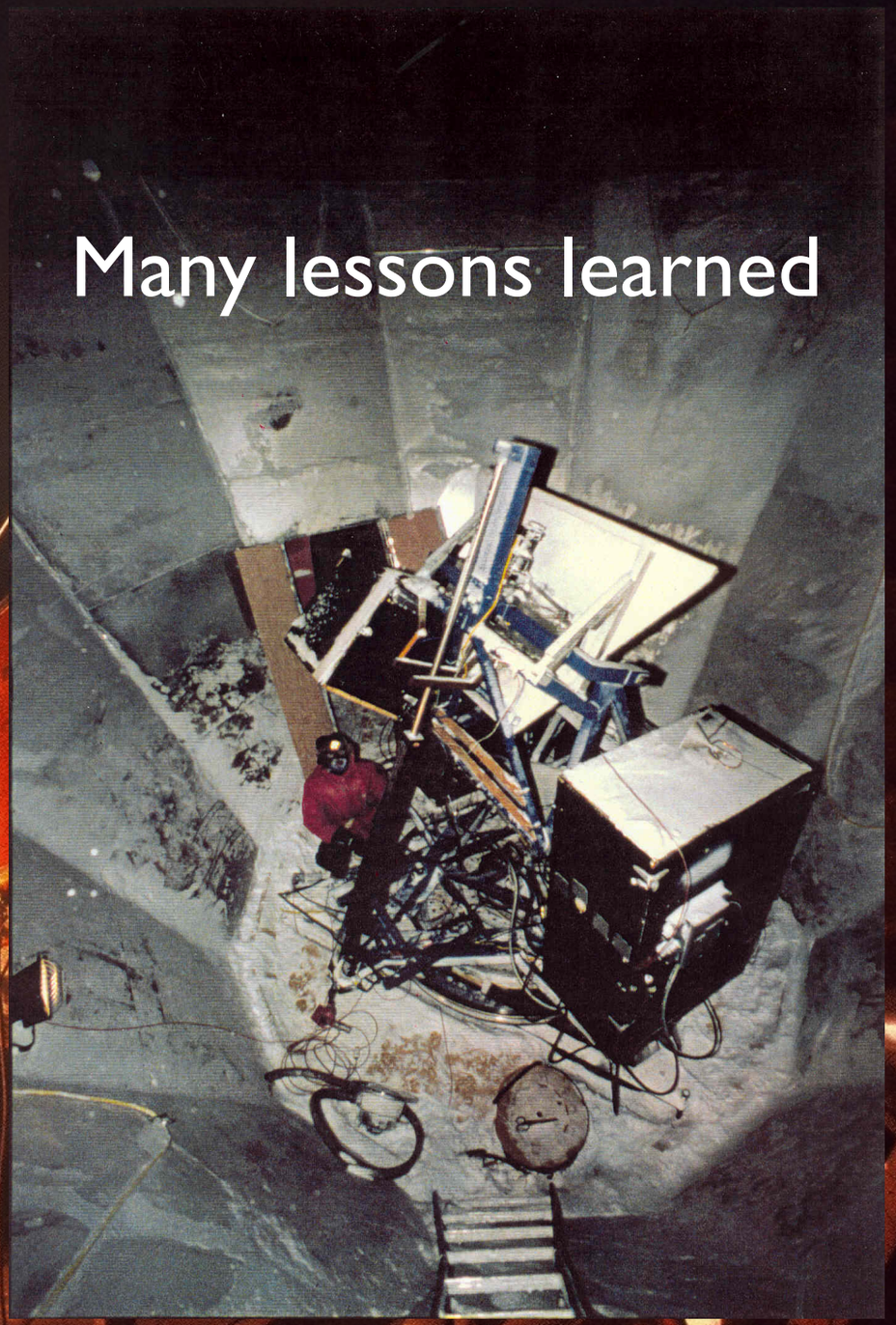
Many lessons learned



Atacama, Chile efforts started in late 90's

from Lyman Page

Amber Miller
Mark Devlin
Randy Doriese

it's been a busy and exciting couple of decades

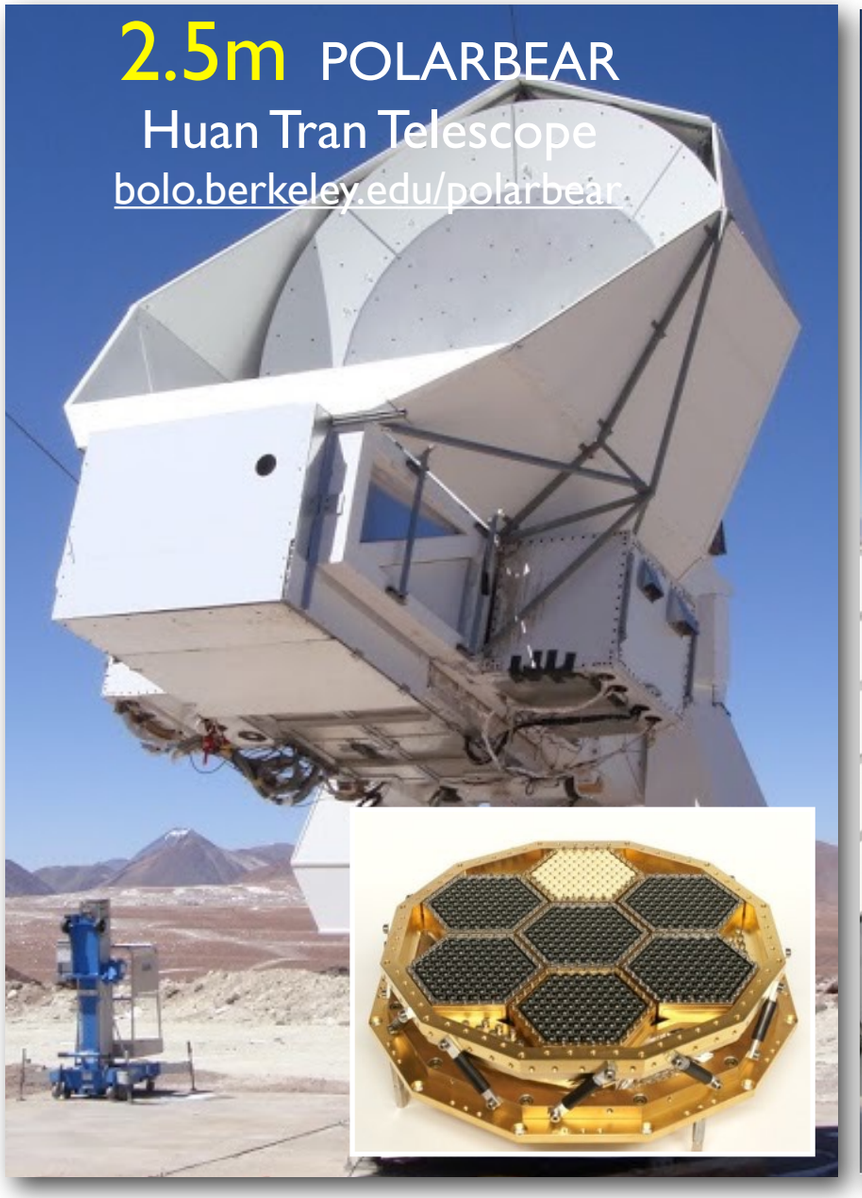
- Detector and readout technology greatly advanced, especially multiplexed, background-limited TES detectors

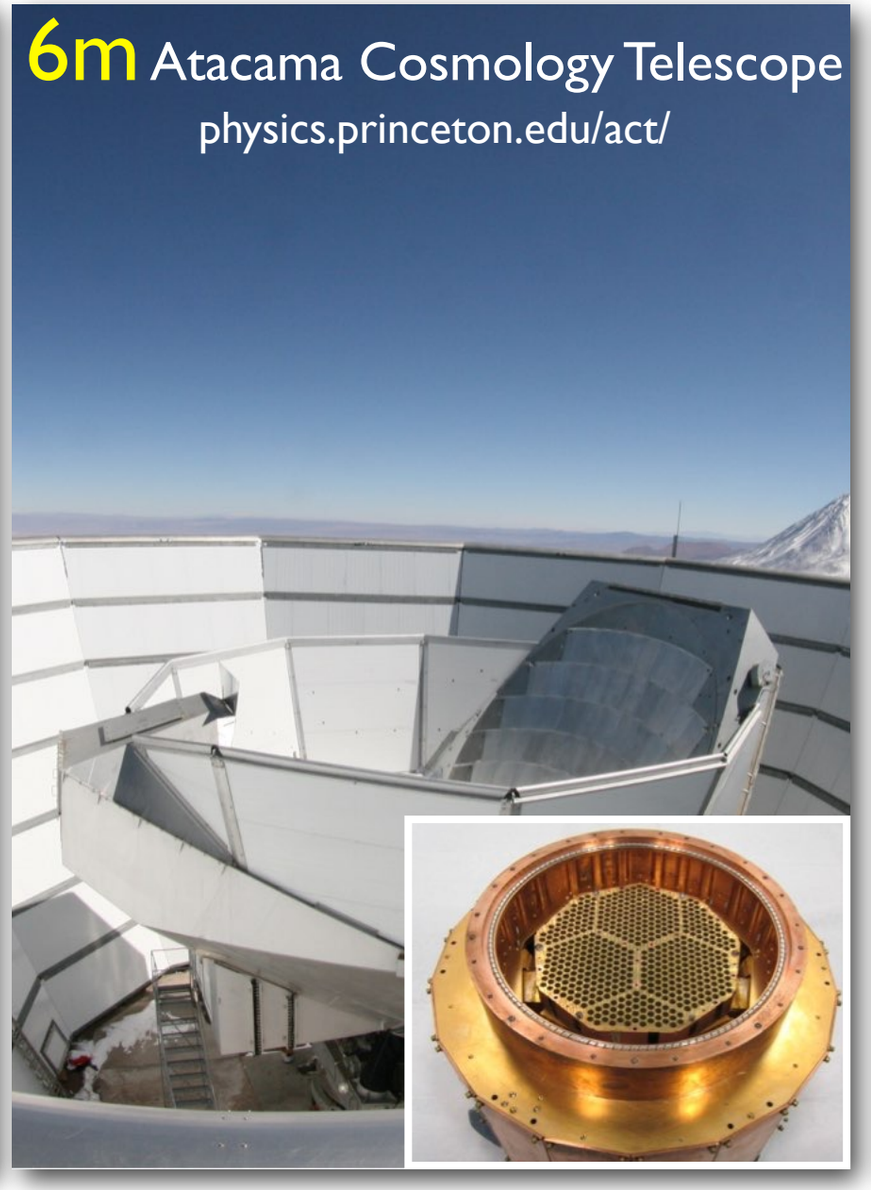
- Telescopes have advanced

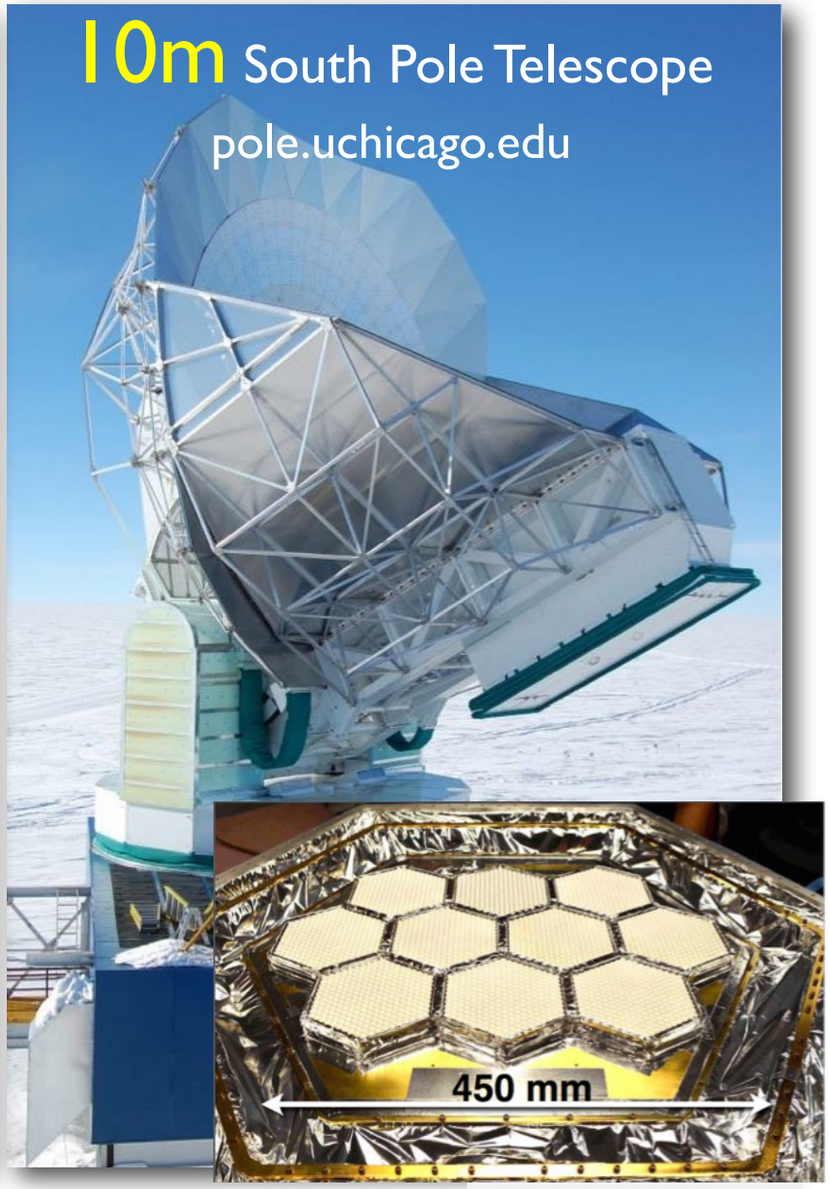
- Data sets and analyses have advanced; theory has advanced

- Teams have coalesced and grown

High resolution CMB experiments



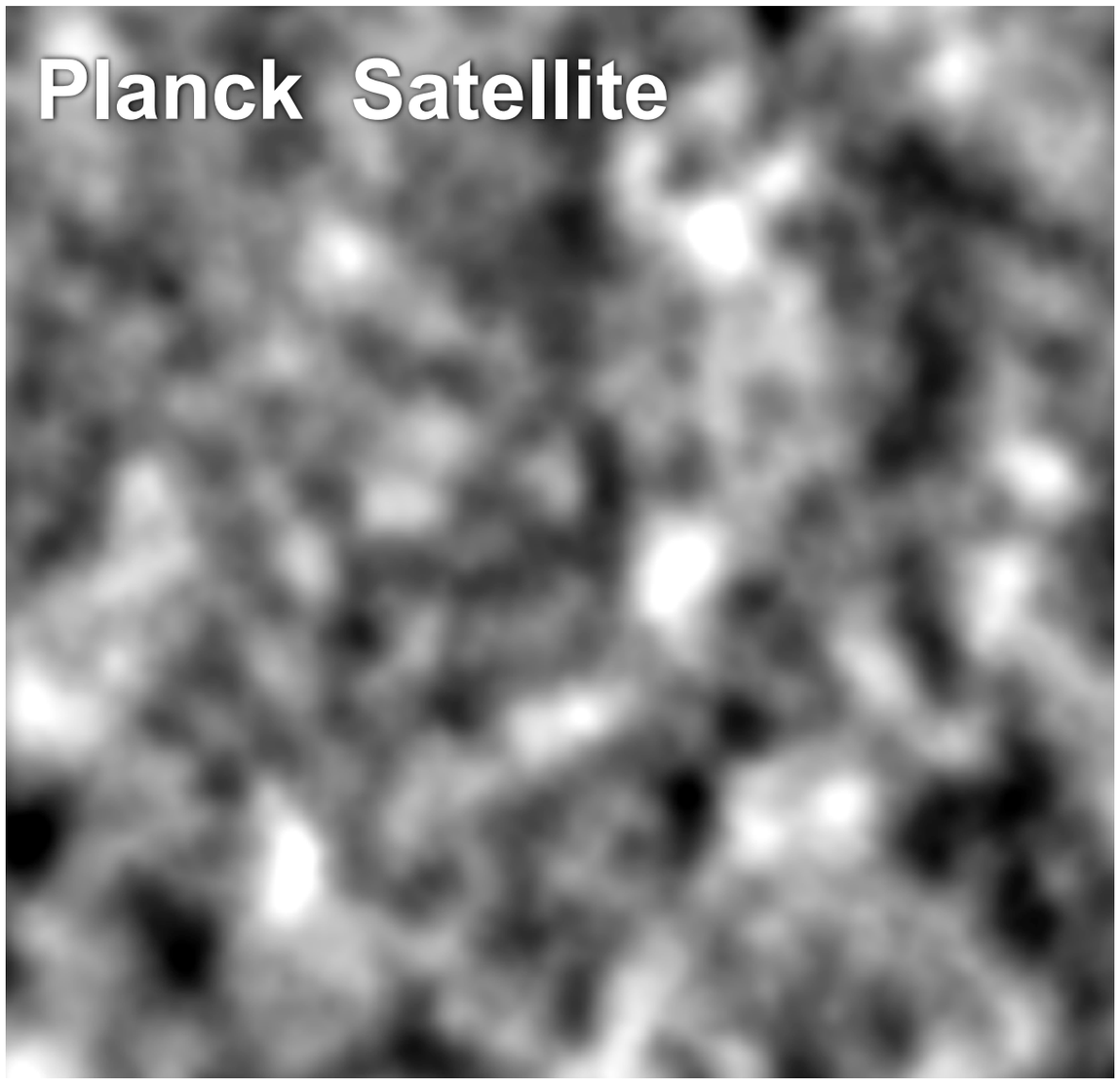


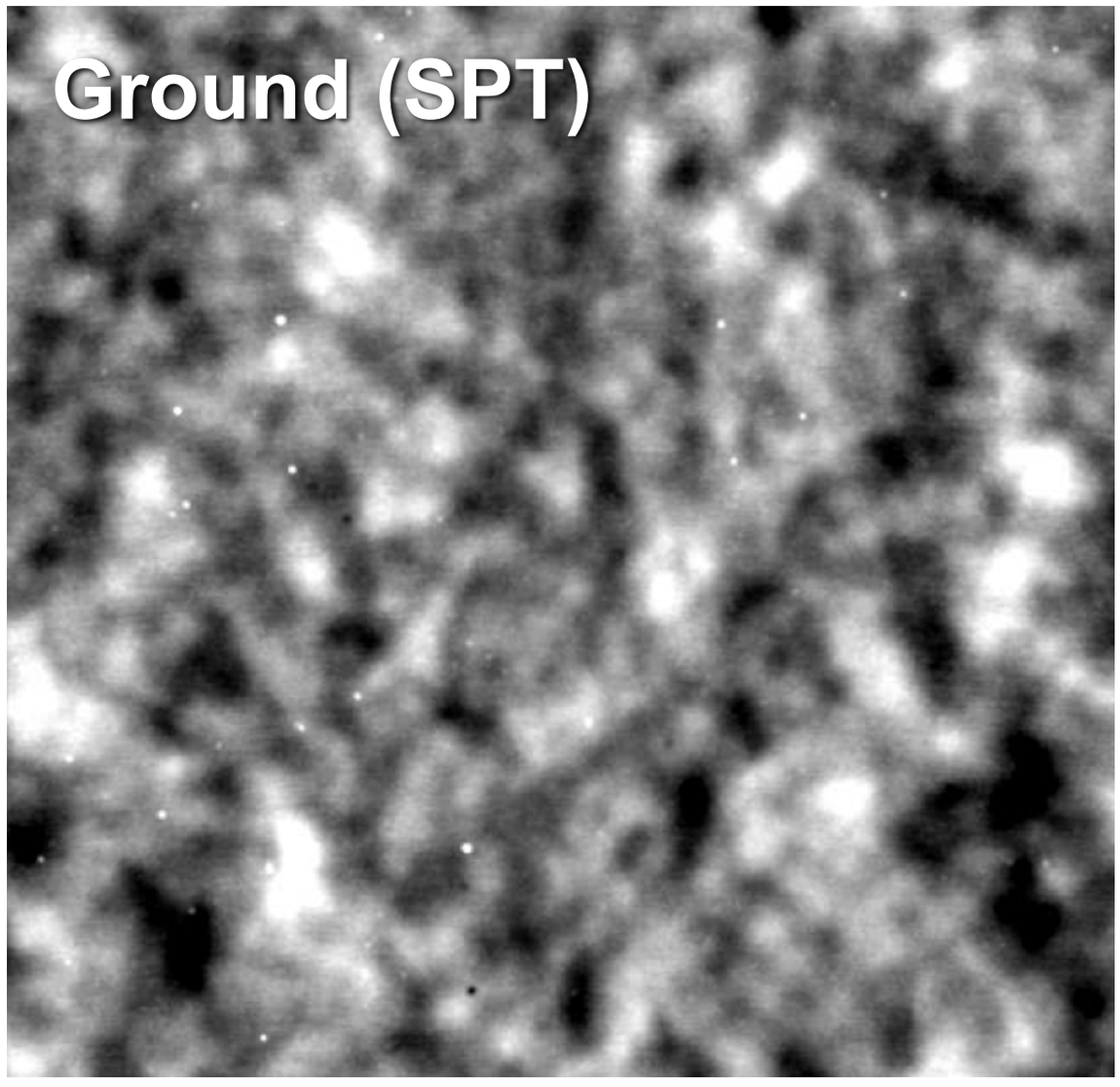


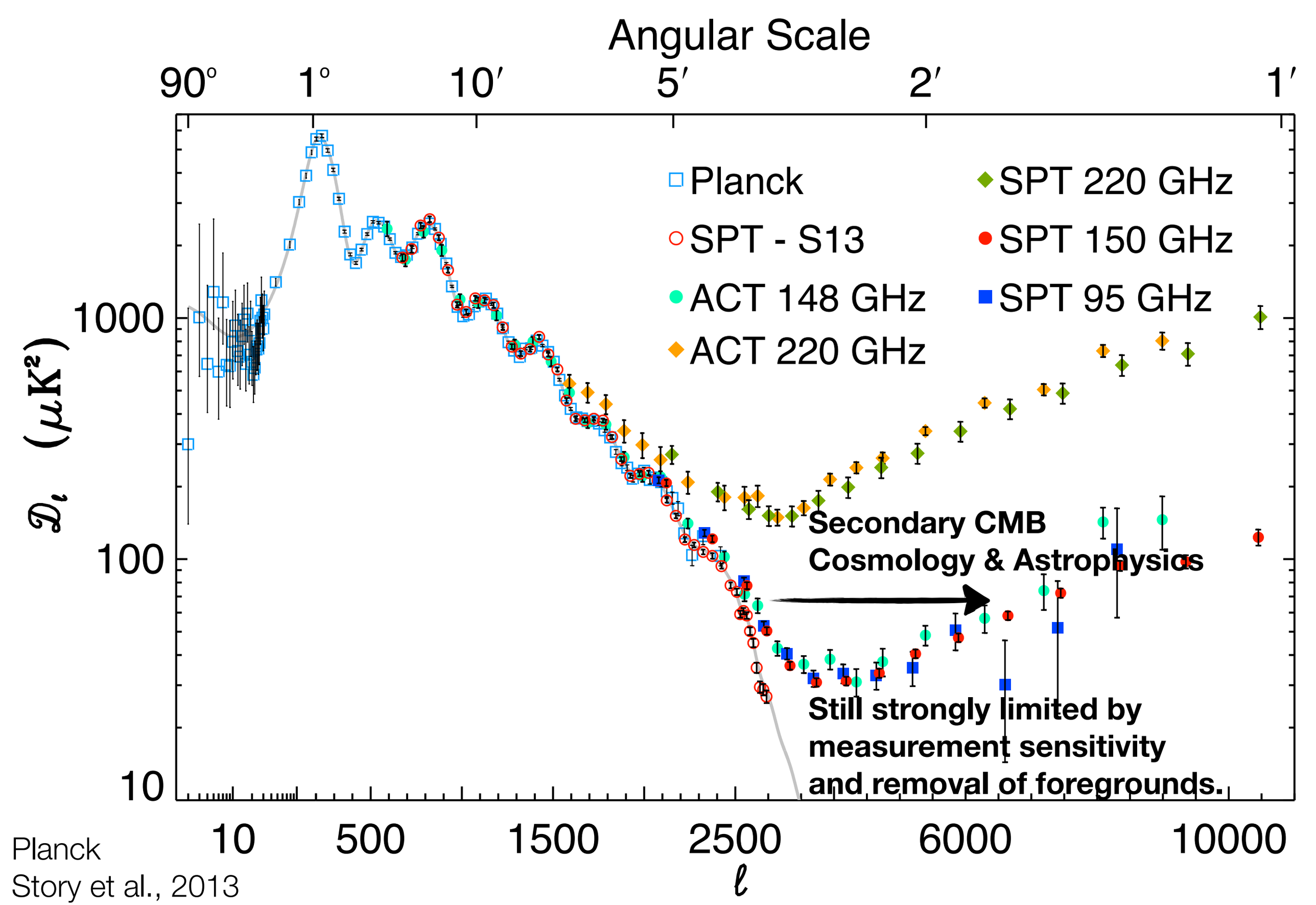
NIST U.S. DEPARTMENT OF ENERGY

Exceptional high and dry sites for dedicated CMB observations.
Exploiting and driving ongoing revolution in low-noise bolometer cameras

high angular resolution from the ground

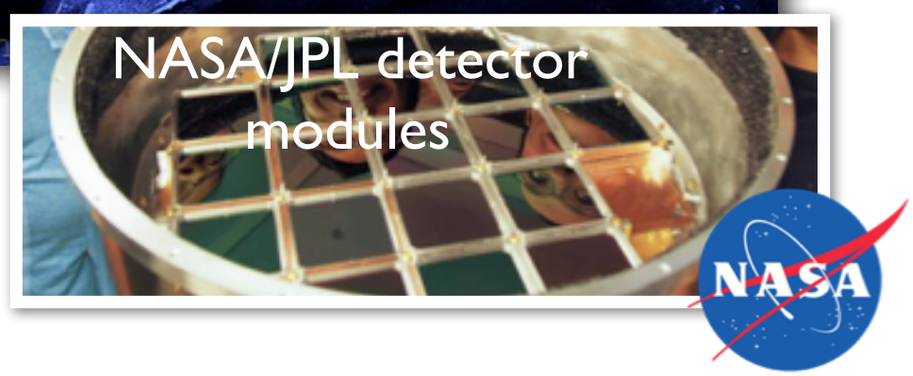




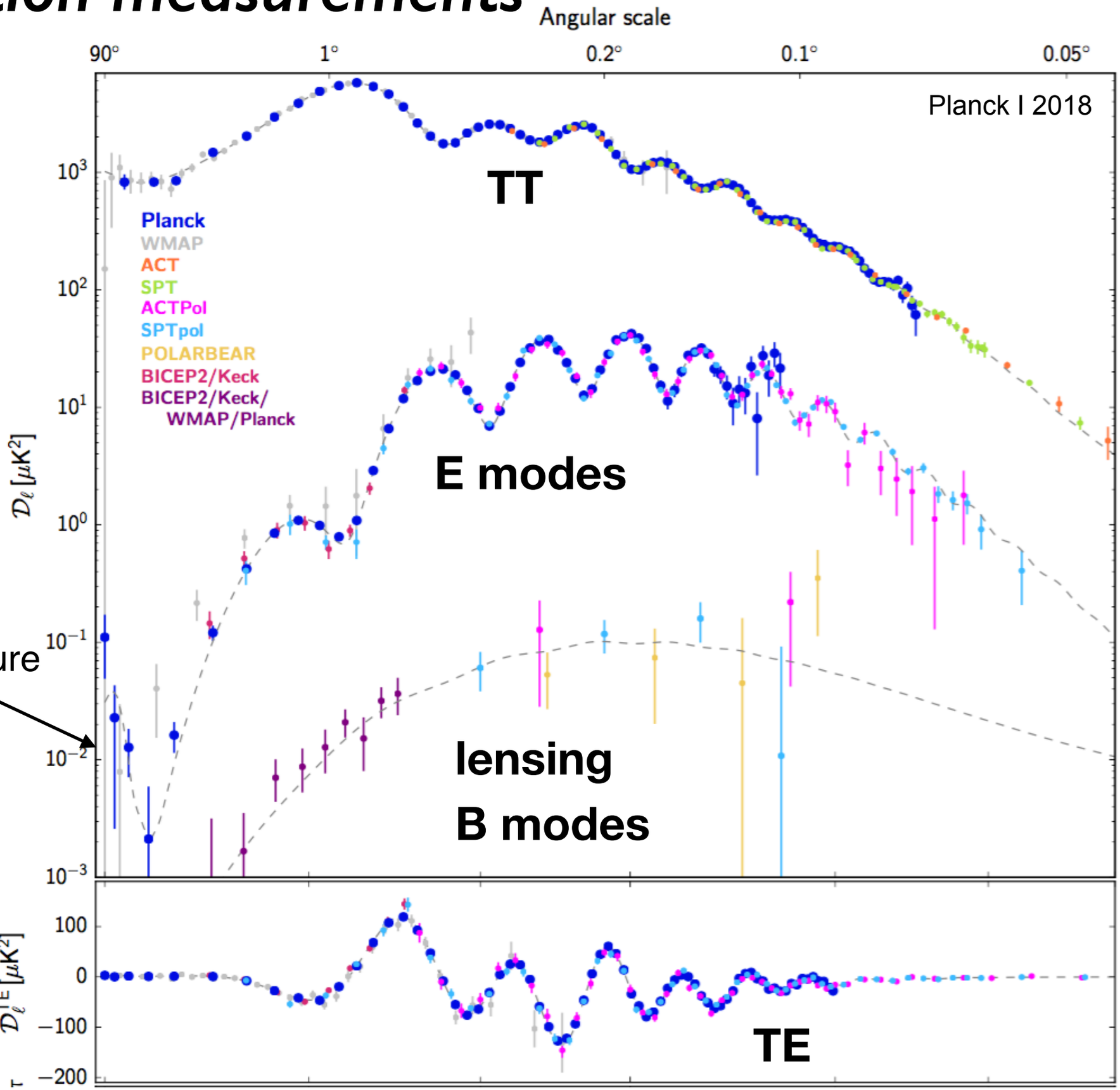


Planck
Story et al., 2013
George et al., 2014
Das et al., 2014

Small aperture (big beam) CMB telescopes



Status of CMB primary anisotropy temperature and polarization measurements

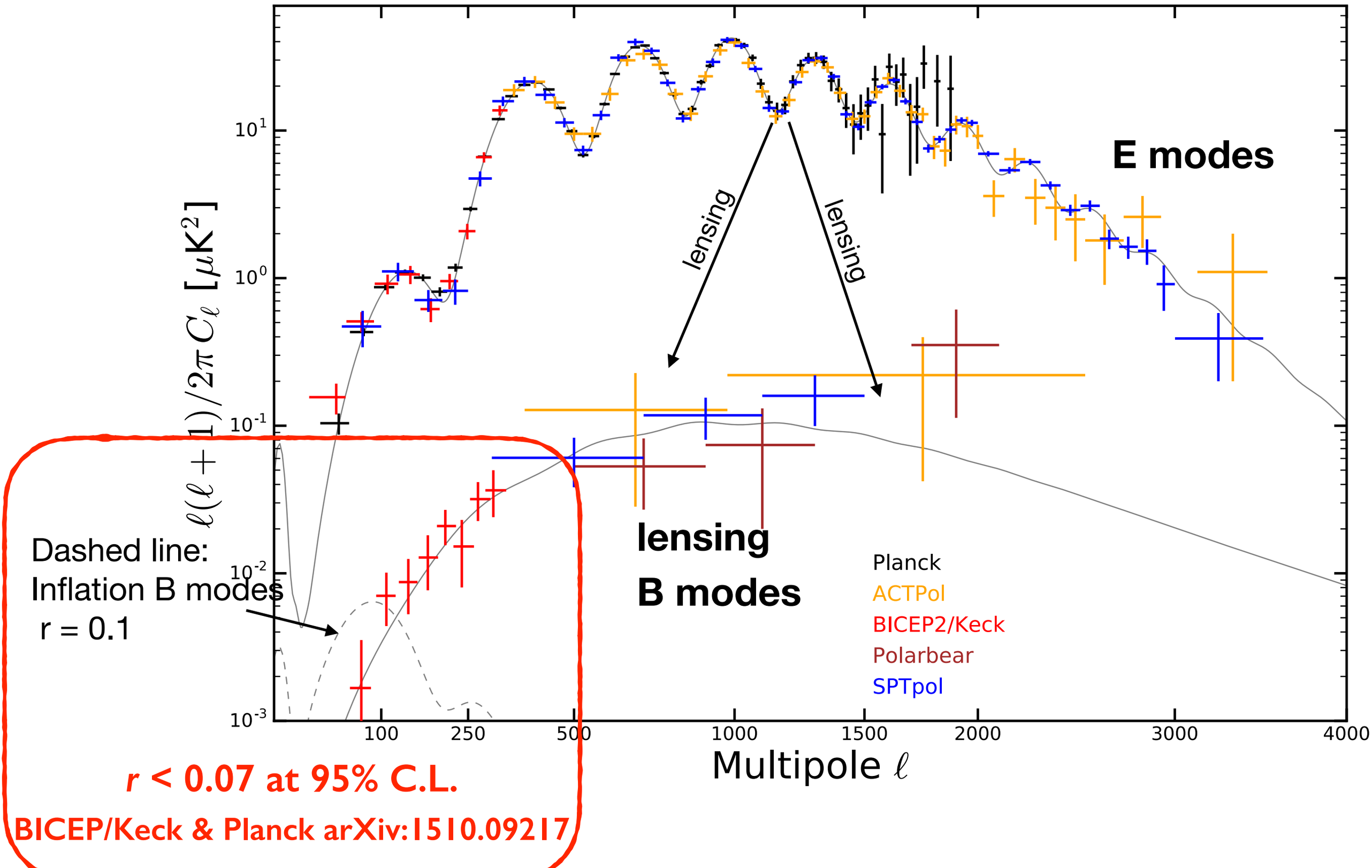


Planck 2018 EE

τ_e=0.054 ± 0.007

from reionization feature

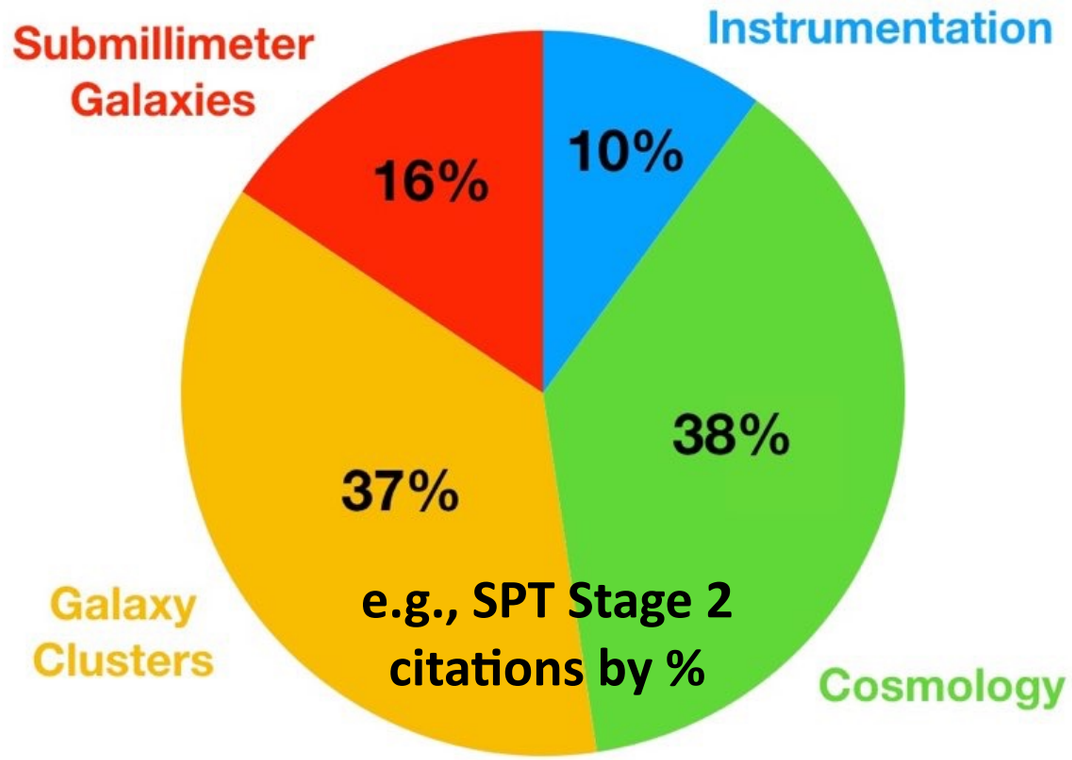
Status of CMB polarization measurements



***r* < 0.07 at 95% C.L.**

BICEP/Keck & Planck arXiv:1510.09217

Broad Science Reach



- **Cosmological model and parameters** (Temperature and Polarization power spectra)
- **Primordial gravitational waves** (B-mode polarization)
- **Determine neutrino mass scale** (CMB lensing & Clusters)
- **Light relic particles**
- **Dark Energy/non-GR**: CMB lensing correlation with galaxy density & shear maps; cluster CMB lensing mass calibration; kSZ large scale flows
- **Reionization**: When and how? optical depth τ_e, diffuse kSZ, bi-spectrum
- **Galaxy cluster astrophysics and cosmology:** redshift independent SZ discovered clusters catalogs; intracluster medium measurements
- **Galaxy formation and evolution**: unique handle on baryonic feedback via stacked SZ effects on galaxy populations; catalogs of high-z lensed dusty star forming galaxies, and high-z protoclusters
- *and much more…*

POLARBEAR / Simons Array

Key Technologies:

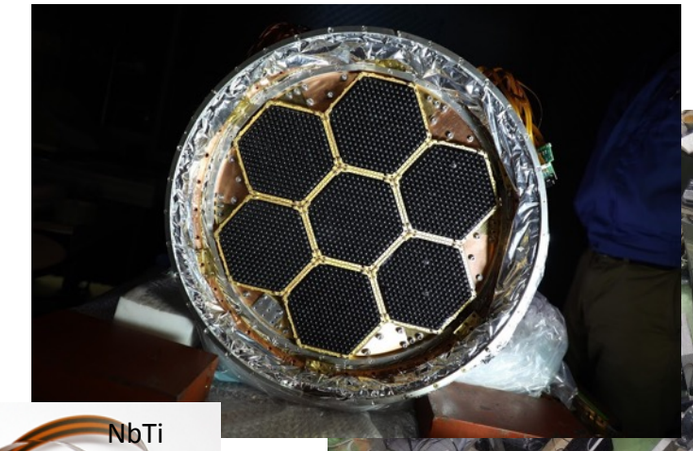
- frequency domain multiplexing (fdm)
- PB: **Continuous half-wave plate modulation**
- SA: **Lenslet coupled sinuous planar antennas, dual polarization, two freq band pixels**

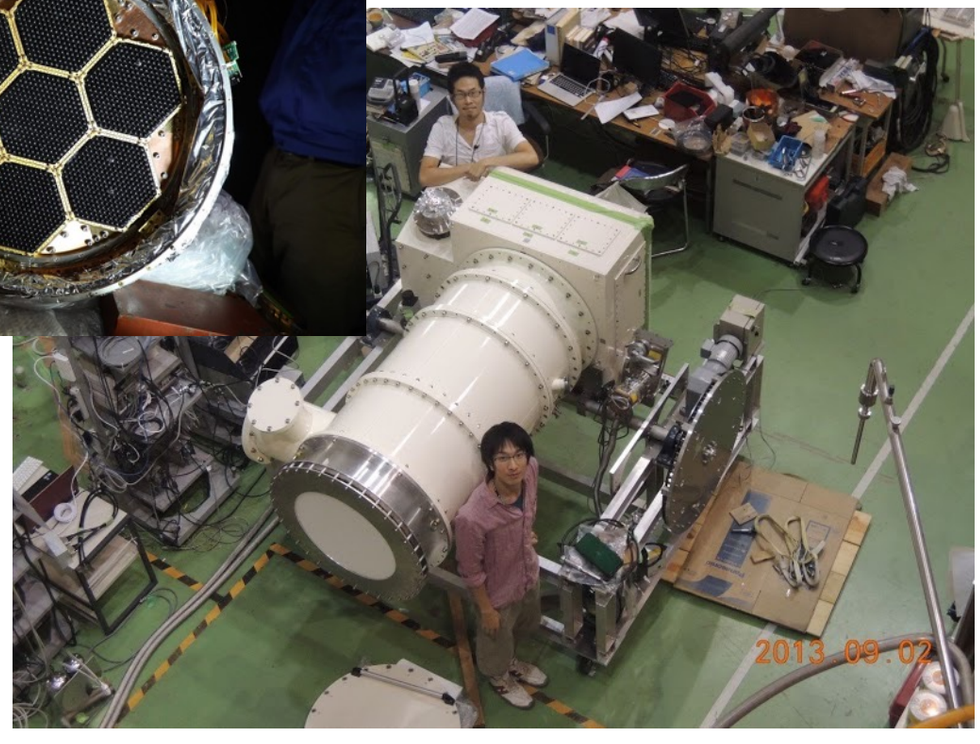
Polarbear:

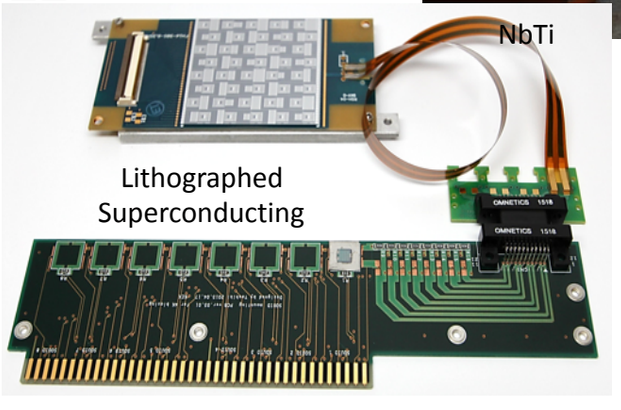
- 150 GHz array
- 2 seasons of 700 deg^2 on BICEP field at 20 uK arcm

Simons Array (3 PB telescopes):

- 22,764 bolometers in total
- 4 frequency bands (95/150/220/270 GHz)
- Single survey (fsky=10%)
- Schedule:
  - PB-2a: Deploy 11/18
  - PB-2b: Deploy 7/19
  - PB-2c: Deploy 12/19
  - **Observations through 2022**







SQUID Printed Circuit

Slide material from A. Lee

POLARBEAR / Simons Array Collaboration

MEXT

SIMONS FOUNDATION
Advancing Research in Basic Science and Mathematics

CONICYT Ministerio de Educación Gobierno de Chile

NSF

NASA

UC Berkeley
Brian Barch
Yuji Chinone
Ari Cukierman
Tijmen de Haan
Josquin Errard
Neil Goeckner-Wald
John Groh
Grantland Hall
Charles Hill
William Holzapfel
Yasuto Hori
Oliver Jeong
Adrian Lee
Mike Myers
Chris Raum
Paul Richards
Blake Sherwin
Ian Shirley
Bryan Steinbach
Aritoki Suzuki
Nathan Whitehorn
Oliver Zahn

CU Boulder
Nils Halverson
Greg Jaehnig
David Schenck

UC San Diego
Chris Aleman
Matt Atlas
Darcy Barron
Tucker Elleflot
George Fuller
Logan Howe
Jon Kaufman
Kavon Kazemzadeh
Brian Keating
David Leon
Lindsay Lowry
Frederick Matsuda
Martin Navaroli
Hans Paar
Gabriel Rebeiz
Praween Siritanasak
Nathan Stebor
Grant Teply
Alex Zahn

UW-Madison
Kam Arnold
Anh Phan

U. Melbourne
Christian Reichardt

KEK
Yoshiki Akiba
Takaho Hamada
Masaya Hasegawa
Kaori Hattori
Masashi Hazumi
Yuki Inoue
Haruki Nishino
Yuuko Segawa
Jun-ichi Suzuki
Osamu Tajima
Satoru Takakura
Sayuri Takatori
Takayuki Tomaru

Laboratoire Astroparticule & Cosmologie
Maude Le Jeune
Julien Peloton
Davide Poletti
Radek Stompor

Imperial College
Anne Ducout
Stephen Feeney
Andrew Jaffe

McGill University
Matt Dobbs
Adam Gilbert
Josh Montgomery
Graeme Smecher

Dalhousie
Scott Chapman
Colin Ross
Kaja Rotermund
Alexei Tikhomirov

Lawrence Berkeley NL
Julian Borrill
Reijo Keskitalo
Theodore Kisner
Akito Kusaka
Eric Linder

Kavli IPMU
Takuro Fujino
Fumiya Irie
Nobuhiko Katayama
Kuniyoshi Mizukami
Tetsu Yamashita

Argonne NL
Amy Bender

SISSA
Carlo Baccigalupi
Giulio Fabbian
Giuseppe Puglisi

JAXA
Tomotake Matsumura

UC Irvine
Chang Feng

National Institute for Fusion Science
Suguru Takada

Cardiff University
Peter Ade

NASA Goddard
Nathan Miller

Princeton
Zigmund Kermish

Católica (PUC)
David Boettger
Rolando Dunner

And many more in years past…

Slide from A. Lee

Atacama Cosmology Telescope (ACT)

Key Technologies:

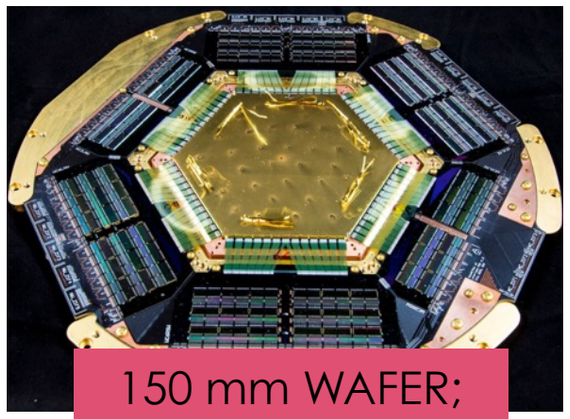
- **Three optics tubes, one cryostat**
  ~ 1000 TES detector array / tube
- NIST Feedhorn coupled arrays
  & dichroic arrays
- 90 mK dilution fridge
- large silicon AR machined lenses

ACTPol (2013-2017):

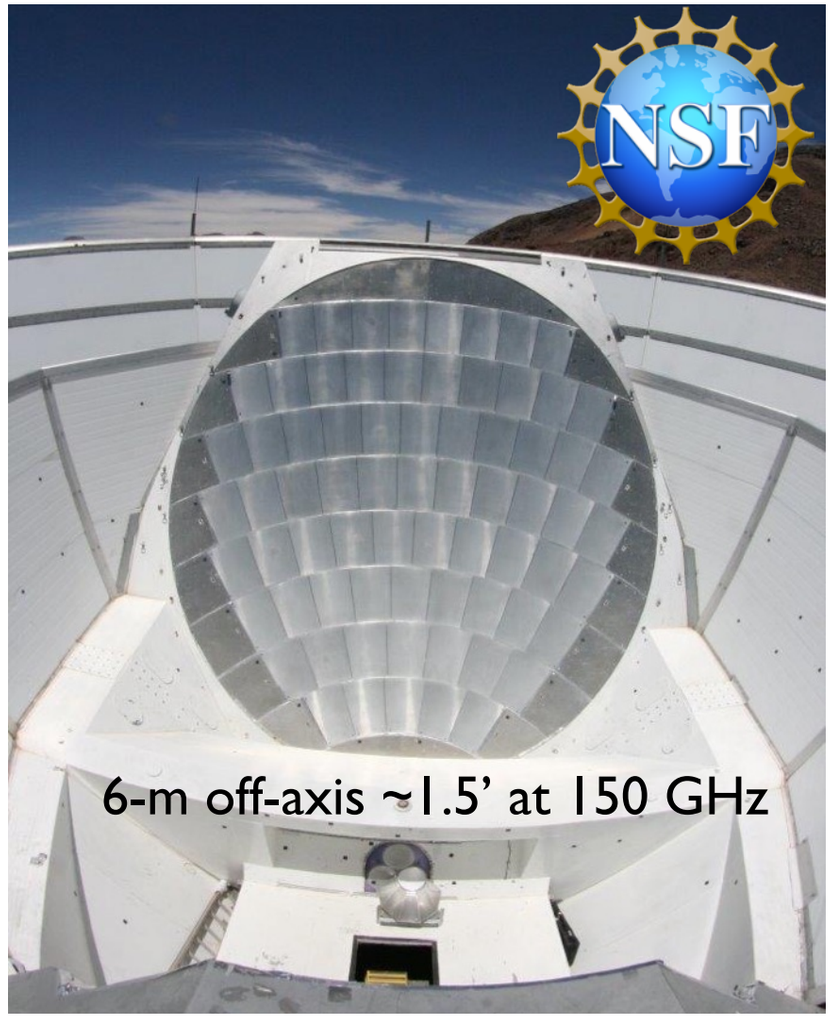
- 2 arrays @ 150 GHz and one dichroic
  90 & 150 GHz array

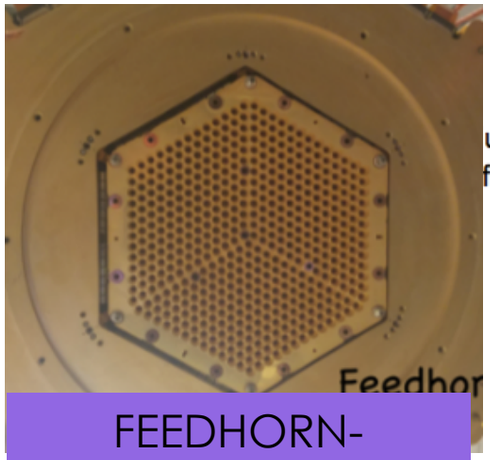
ADVACT (2017 - 2021):

- 2 multifreq arrays @ 90 & 150 GHz;
  1 array at 150 & 220 GHz
- Swap out 90 & 150 GHz array for
  30 & 40 GHz array next year
- **Wide survey: ~17,000 deg² (Fsky 0.4)**
- **Plan to observe to 2021**

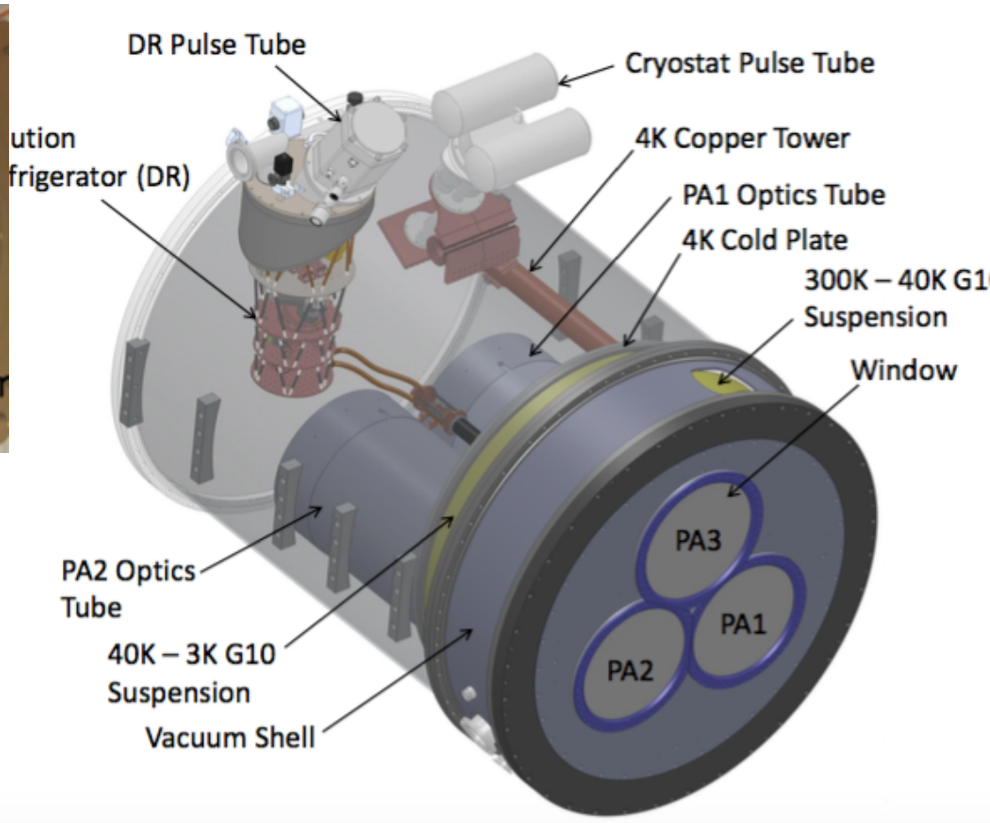


150 mm WAFER; SQUID-BASED TDM READOUT





FEEDHORN-COUPLED



Slide material from S. Staggs

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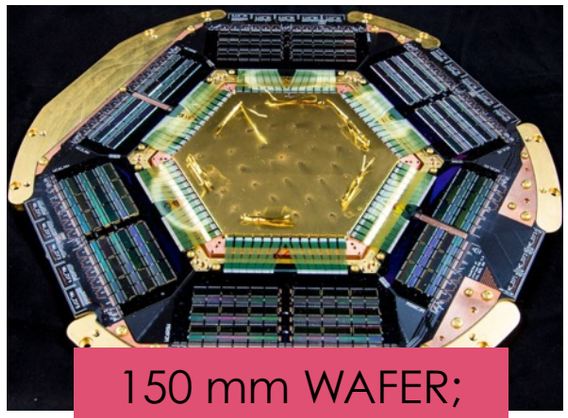

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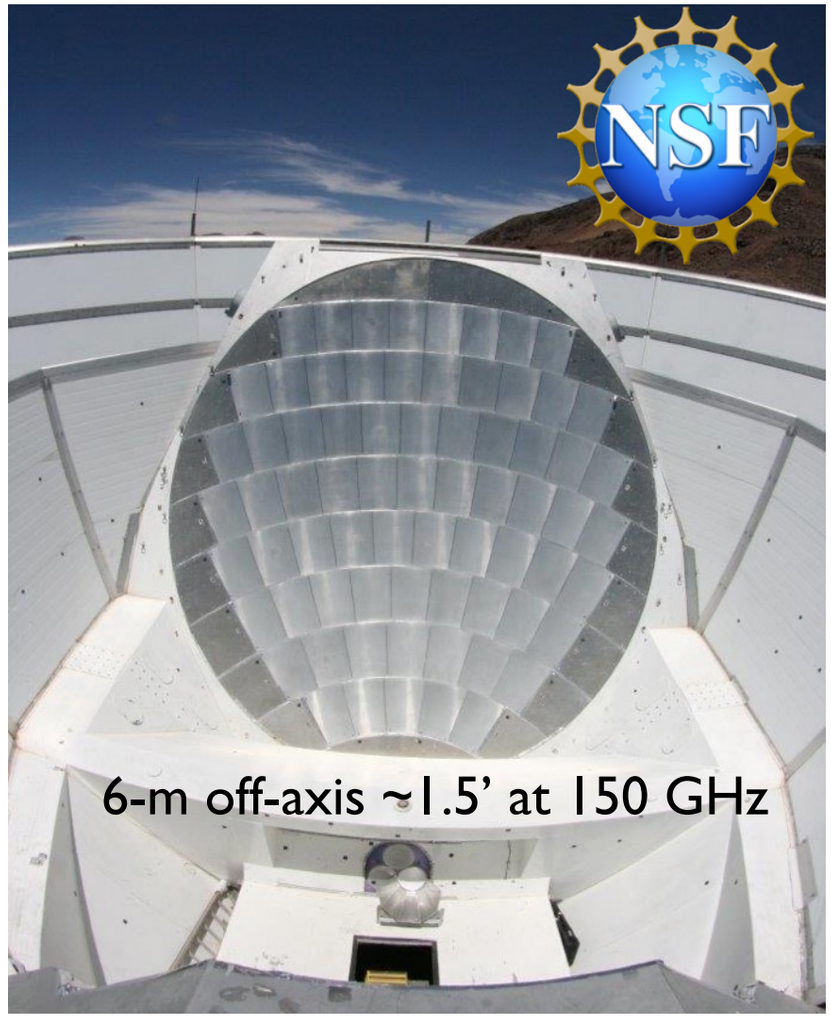

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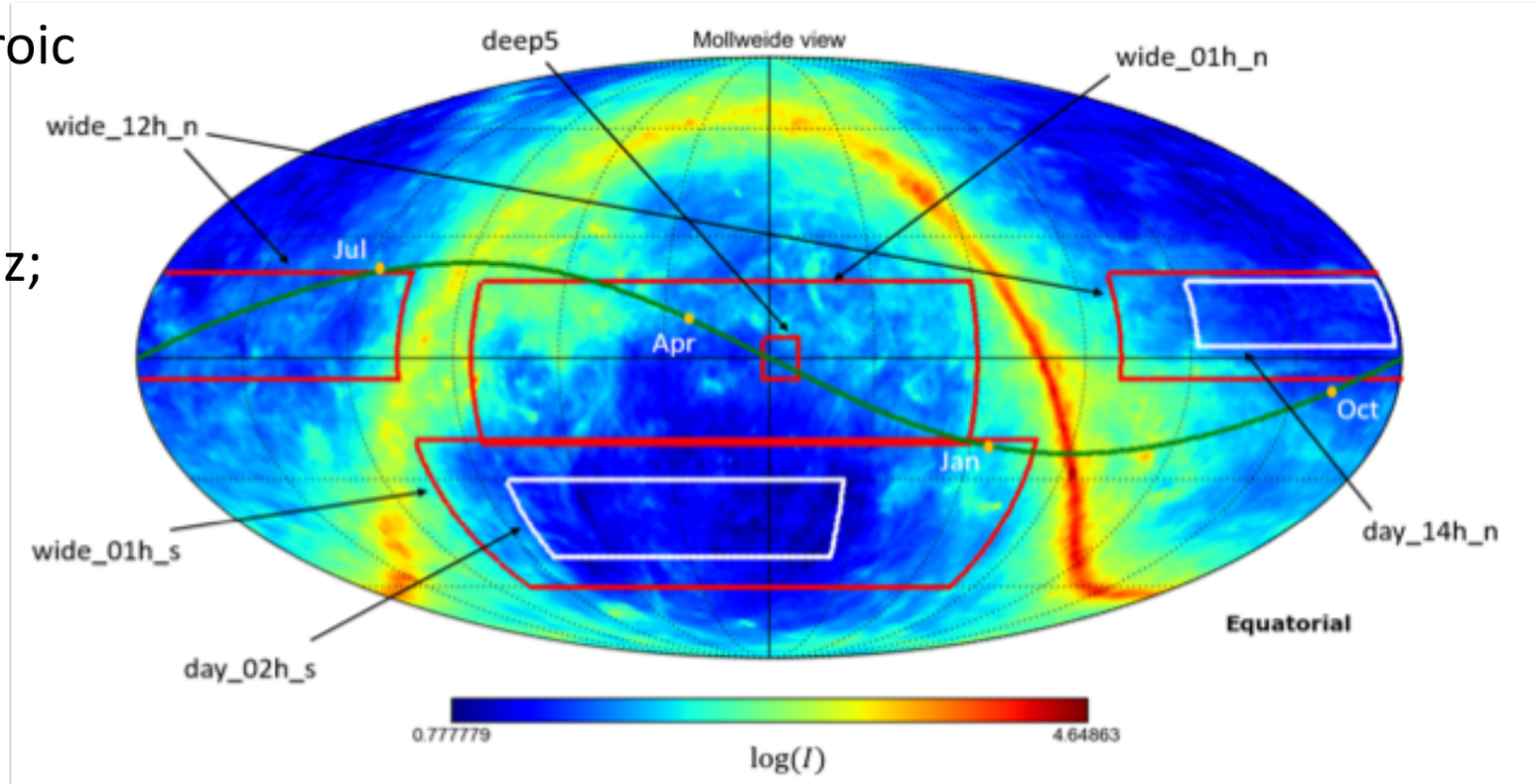


de Bernardis , Stevens, Hasselfield, et al, 2016; arXiv: 1607.02120

Slide material from S. Staggs

Atacama Cosmology Telescope Collaboration

ACT MEETING JANUARY 2018

22 institutions & ~80 collaborators

Slide material from S. Staggs

Cosmology Large Angular Scale Surveyor (CLASS)

Targeting the reionization feature at 2 < l < 10 from the ground!

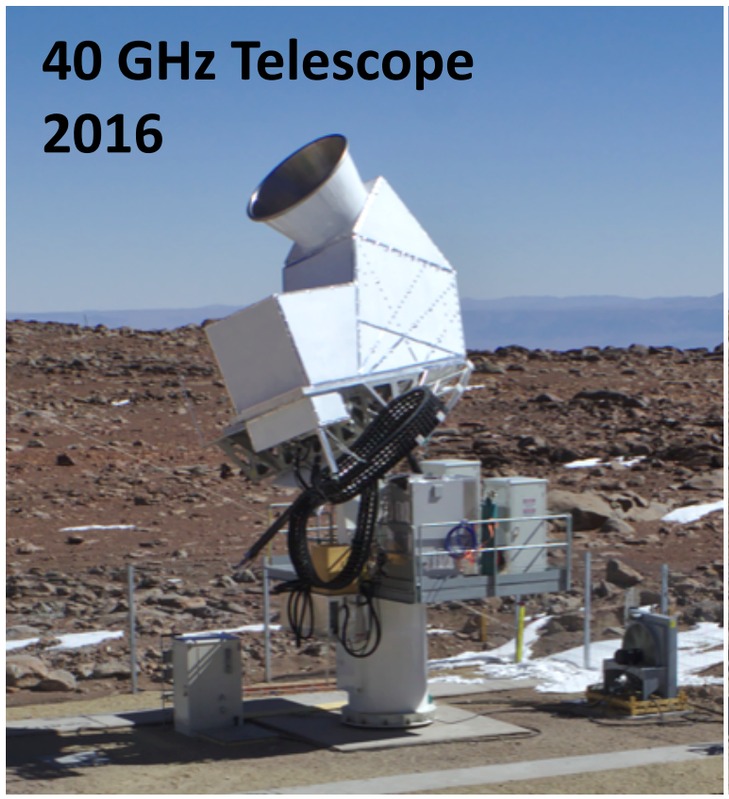
(covering 75% of sky)

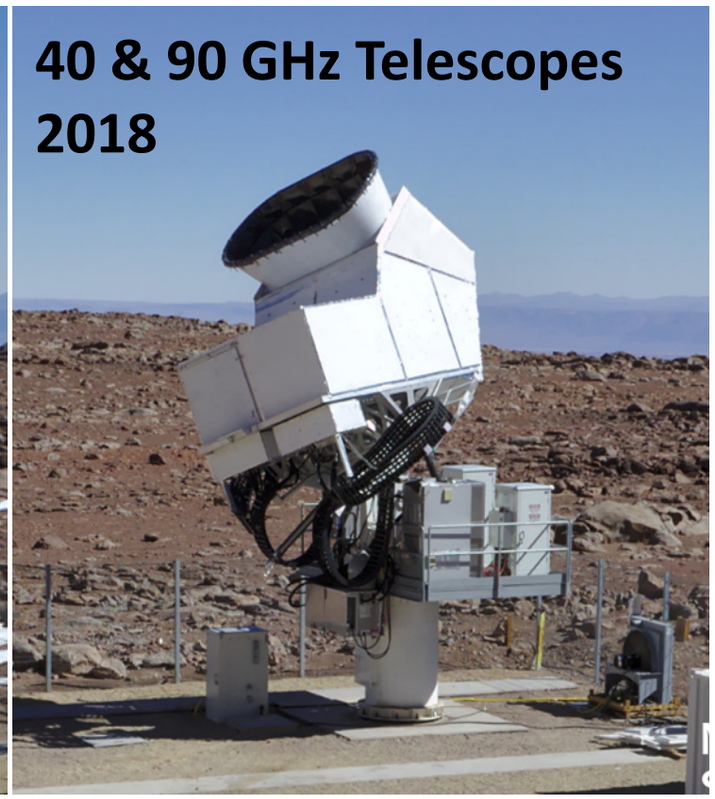
Key Technologies:

- **Rapid front-end polarization modulation**
- Horn-coupled 150 mK TES bolometers (Goddard)
- boresight rotation and comoving forebaffles
- Four telescopes: 40 GHz, 2x90 GHz, 150/220 GHz (dichroic) in Atacama Desert

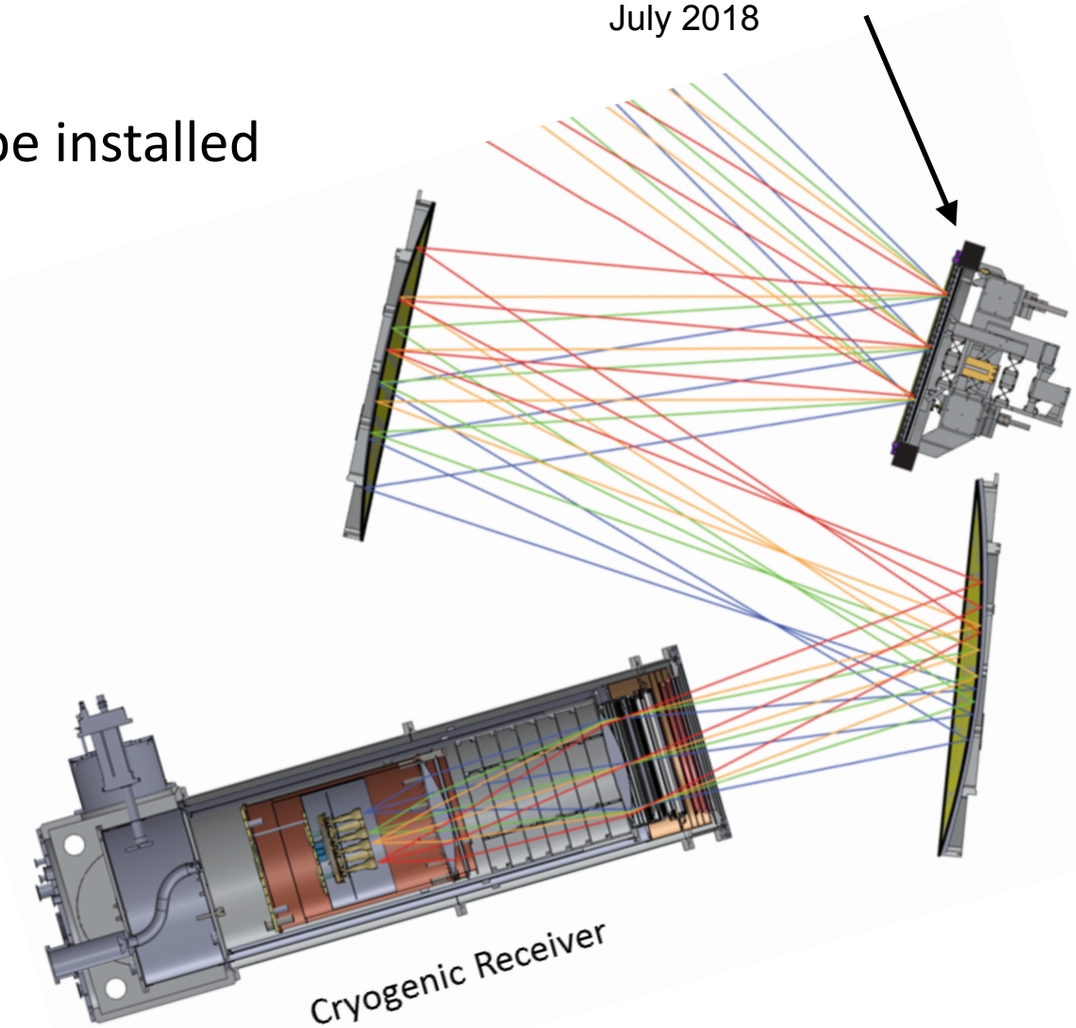
Schedule:2016: 40 GHz Telescope installed

- 2016: 40 GHz Telescope installed
- 2018: 90 GHz Telescope installed
- 2019: Second 90 GHz and 150/220 GHz Telescopes to be installed
- **Observing planned through Sept 2021**





"**Variable-delay Polarization Modulators for the CLASS Telescopes,"** ArXiv e-prints, July 2018



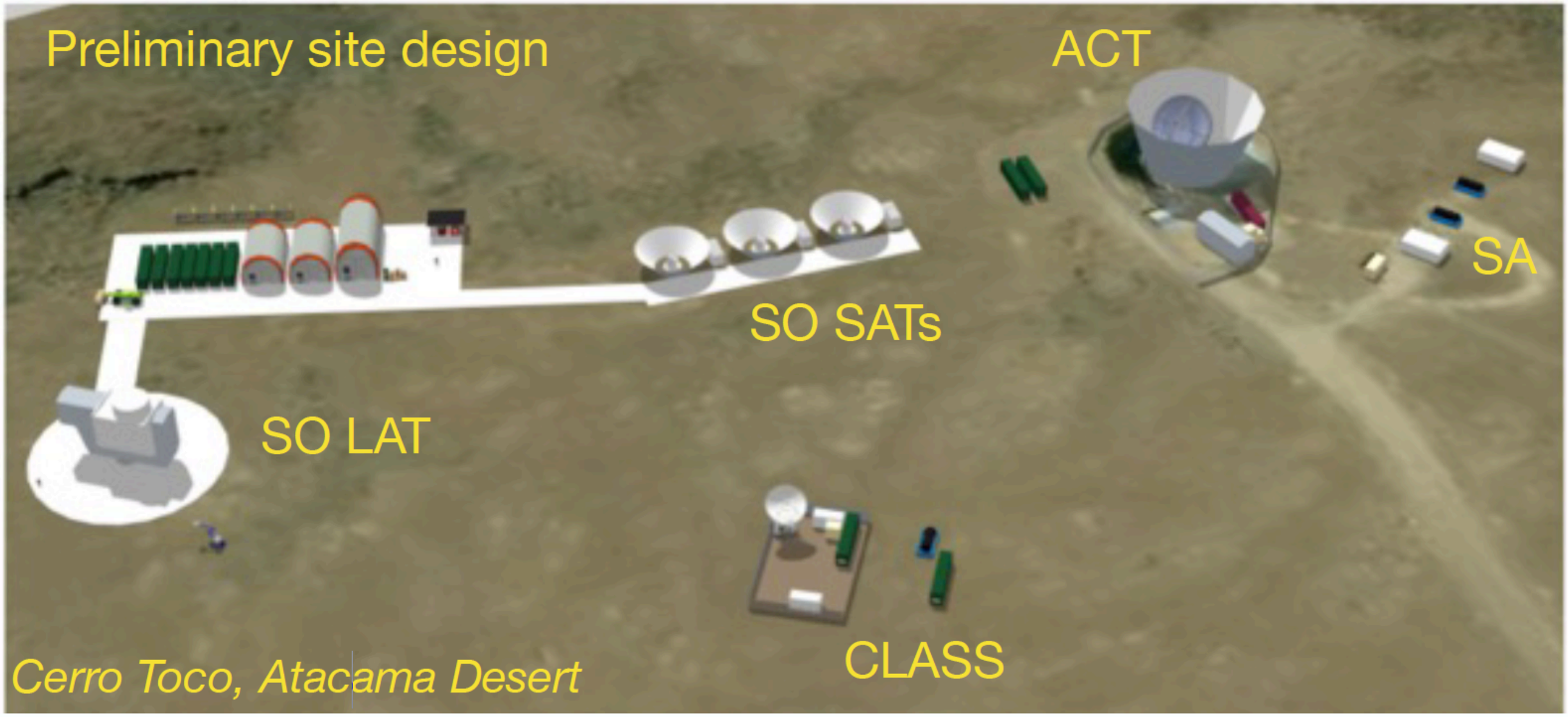
Slide material from T. Marriage

Class Collaboration
~ 50 people

Slide from J. Appel

Simons Observatory

One 6m Large Aperture Telescope
Three 0.5m Small Aperture Telescopes
Five-year survey planned 2021-26, six frequencies 30-280 GHz



Large telescope: resolution needed for all science goals except tensor-to-scalar ratio
Small telescopes: lower noise at the few-degree-scale B-mode signal, for tensor-to-scalar ratio

slide from J. Dunkley

Simons Observatory

Key Technologies:

- uMux readout
- 100 mK dilution fridge
- Mix of SA (sinuous) and ACT (feedhorn) coupled TES detectors — **60,000 total detectors**
- 1 large **6m high throughput 6m Cross Dragone Telescope** (LAT) with one cryostat containing up to 13 optics tubes, 7 in baseline design:
  - 1 x 27/39 GHz
  - 4 x 90/150 GHz
  - 2 x 220/270 GHz
- 3 small 42cm degree scale telescopes (SAT) baseline dichroic pixels arrays:
  - 27/39 GHz, 90/150 GHz & 220/270 GHz

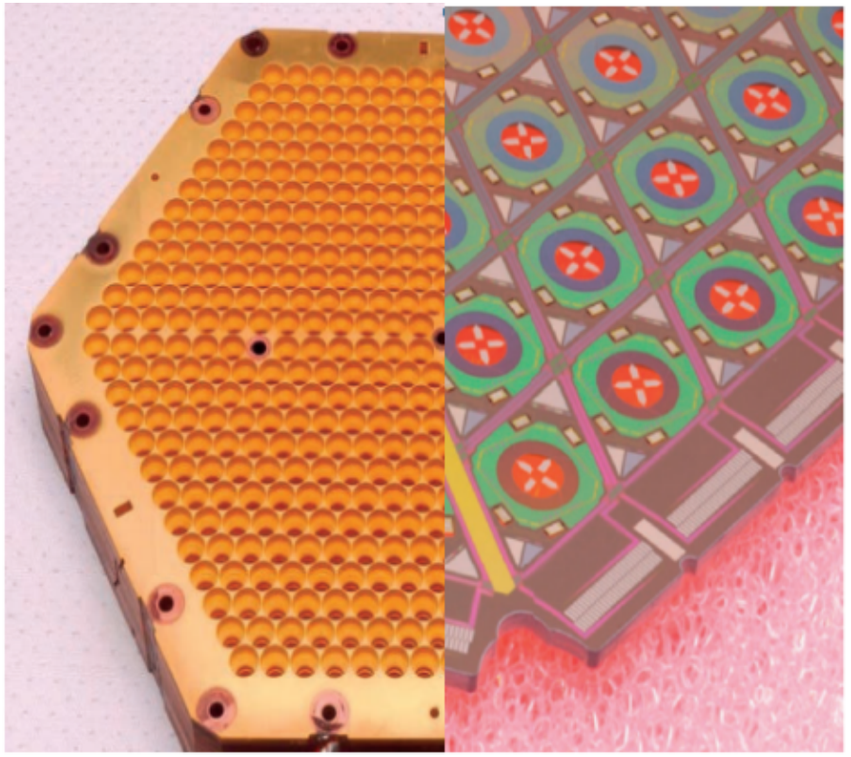
Two Surveys

- **Broad LAT survey f_{sky} = 0.4** with 90+150 -> ~6uK arcm
- **Deep SAT survey f_{sky} = 0.1**, with 90+150 -> ~2uK arm **targeting σ(r) = 0.003**

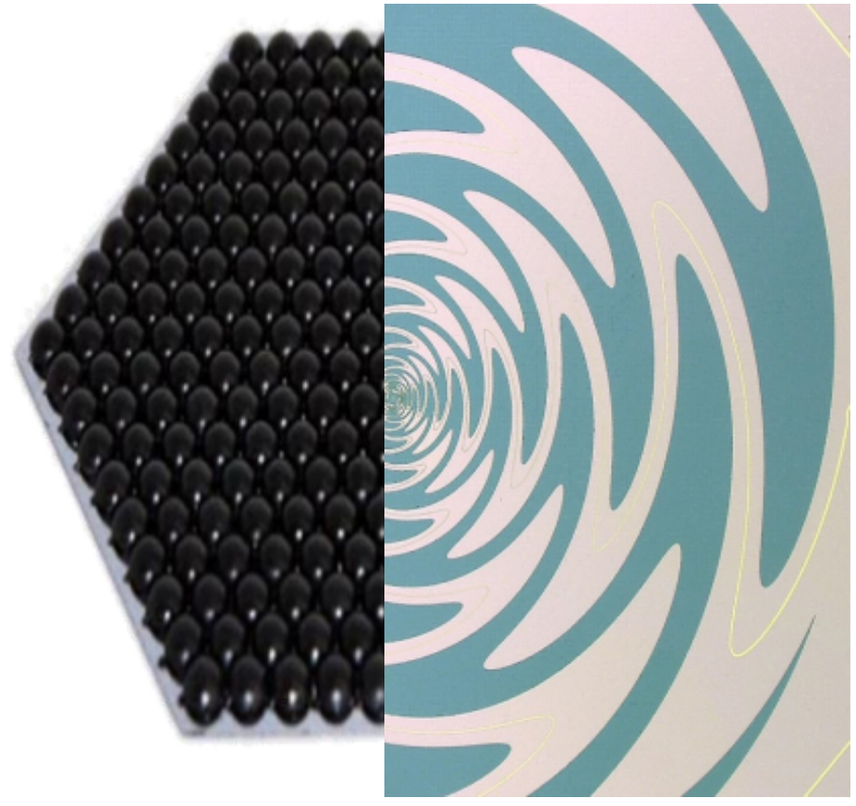
Schedule:

- Construction now though 2021
- **Observations 2022 - 2026**

slide info from A. Lee

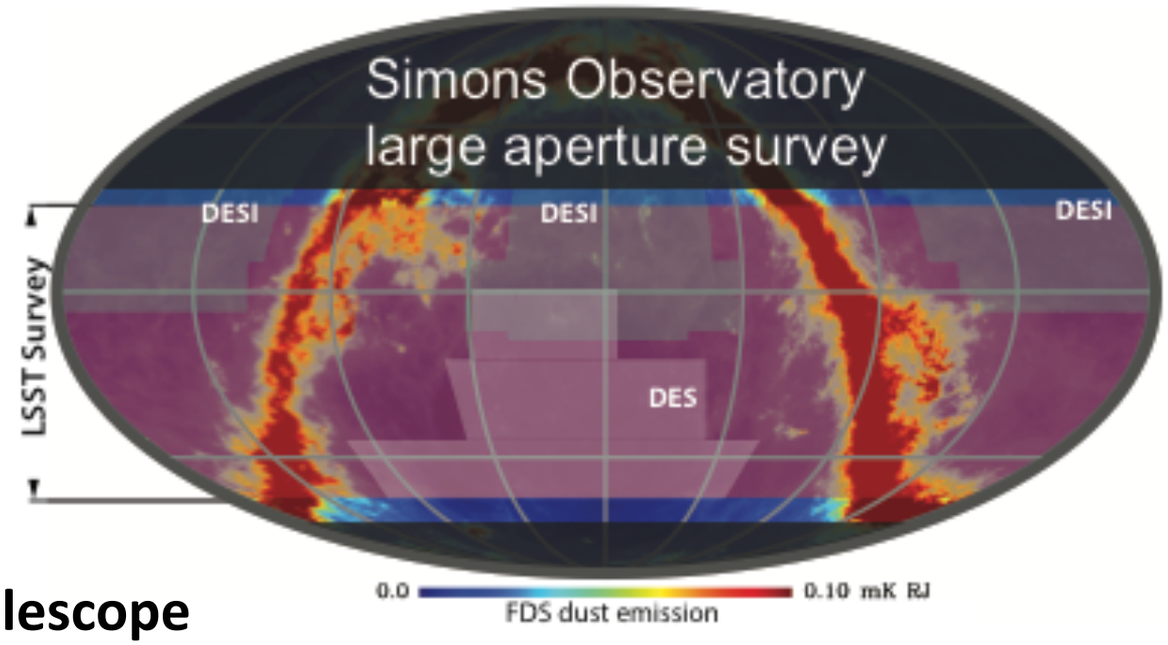


Spline feed horns coupled to OMT detectors (NIST)



Anti-reflection coated silicon lenslets coupled to sinuous detectors (Berkeley)

Simons Observatory



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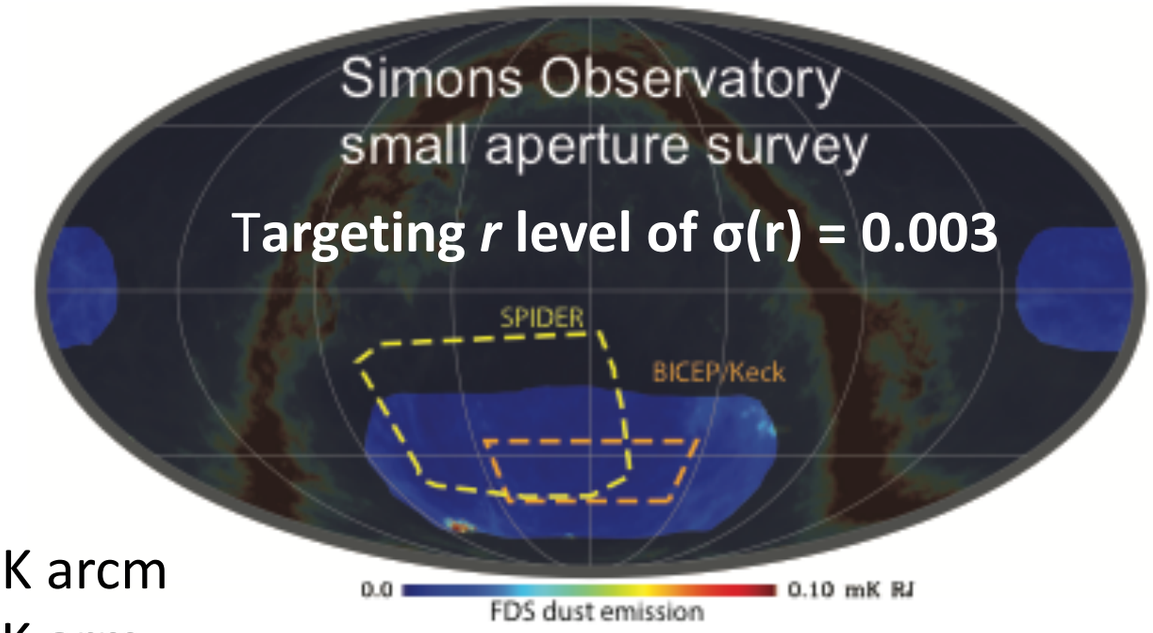

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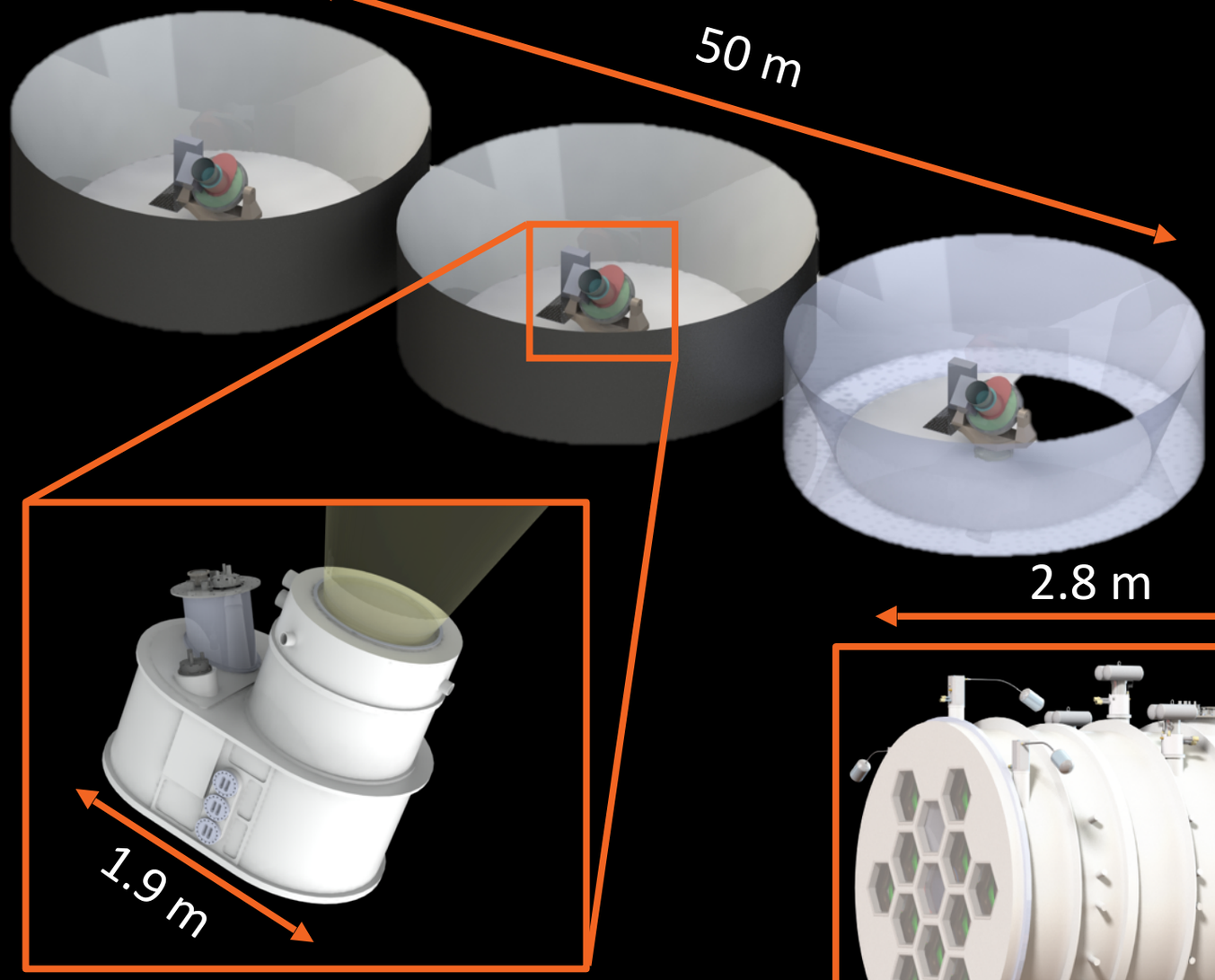
slide info from A. Lee

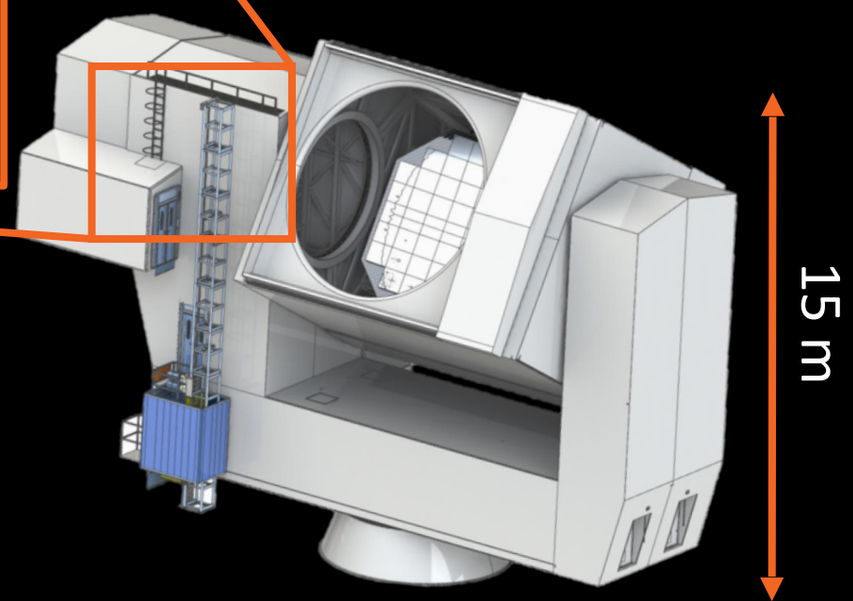
SO – Instruments and Technology



<u>Large Aperture Telescope</u>

6 m crossed Dragone telescope coupled to up to 13, 36 cm optics tubes.
SO baseline has 7 tubes populated with baseline dichroic pixels:

- 1 x 27/39 GHz
- 4 x 90/150 GHz
- 2 x 220/270 GHz



<u>Small Aperture Telescopes</u>

Three 42 cm aperture refractors,
baseline dichroic pixels:
27/39 90/150 90/150 220/270 GHz

slide from A. Lee

The Simons Observatory collaboration

- **10 Countries**
- **40+ Institutions**
- **160+ Researchers**

United States

- Arizona State University
- Carnegie Mellon University
- Center for Computational Astrophysics
- Cornell University
- Florida State
- Haverford College
- Lawrence Berkeley National Laboratory
- NASA/GSFC
- NIST
- Princeton University
- Rutgers University
- Stanford University/SLAC
- Stony Brook
- University of California - Berkeley
- University of California – San Diego
- University of Michigan
- University of Pennsylvania
- University of Pittsburgh
- University of Southern California
- West Chester University
- Yale University

Japan

- KEK
- IPMU
- Tohoku
- Tokyo

Canada

- CITA/Toronto
- Dunlap Institute/Toronto
- McGill University
- Simon Fraser University
- University of British Columbia

Chile

- Pontificia Universidad Catolica
- University of Chile

Europe

- APC – France
- Cambridge University
- Cardiff University
- Imperial College
- Manchester University
- Oxford University
- SISSA – Italy
- University of Sussex

South Africa

- Kwazulu-Natal, SA

Australia

- Melbourne

Middle East

- Tel Aviv

slidefrom A. Lee

The South Pole Telescope (SPT)

Key Technologies:

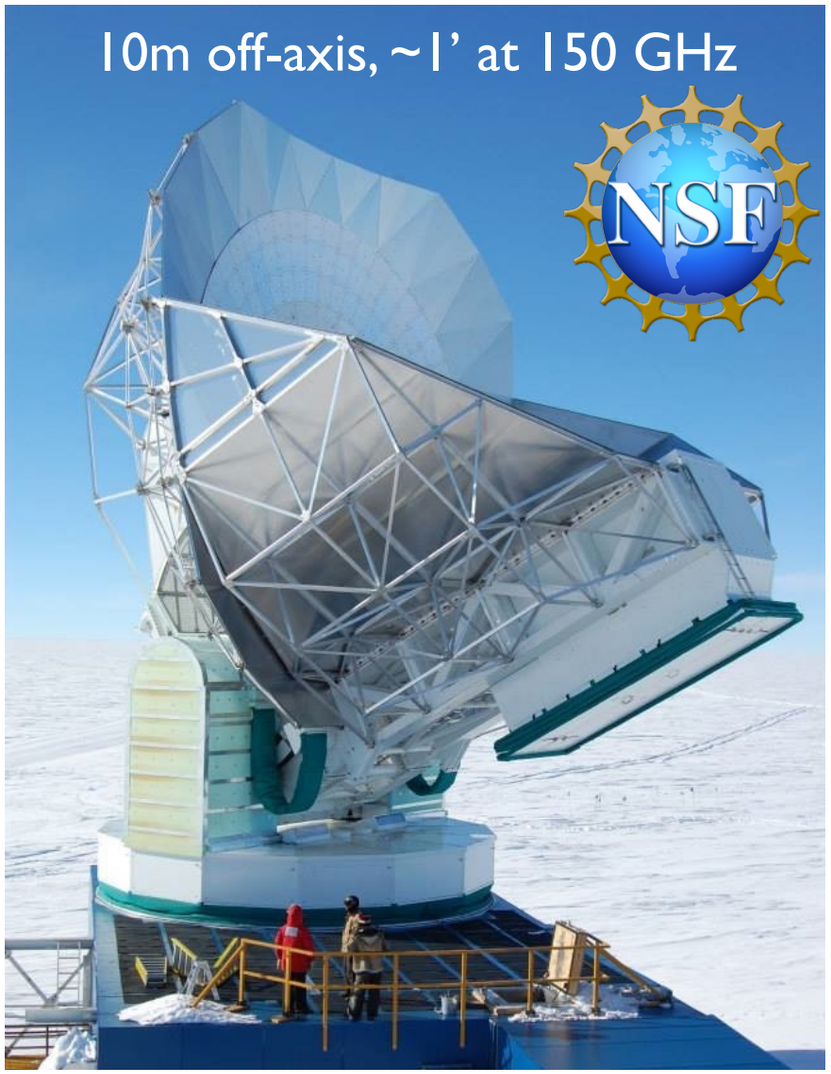
- Precision 10m CF supported primary (< 20 um rms)
- Adaptation to extreme thermal environment
- Large (700mm) 3-layer AR coated alumina lens
- 3-layer AR coated lenslet coupled antennas
- Sinuous planar antenna (Berkeley design)
  3 band dual polarization TES pixels (fabricated at Argonne)
- 68x freq domain (fdm) readout

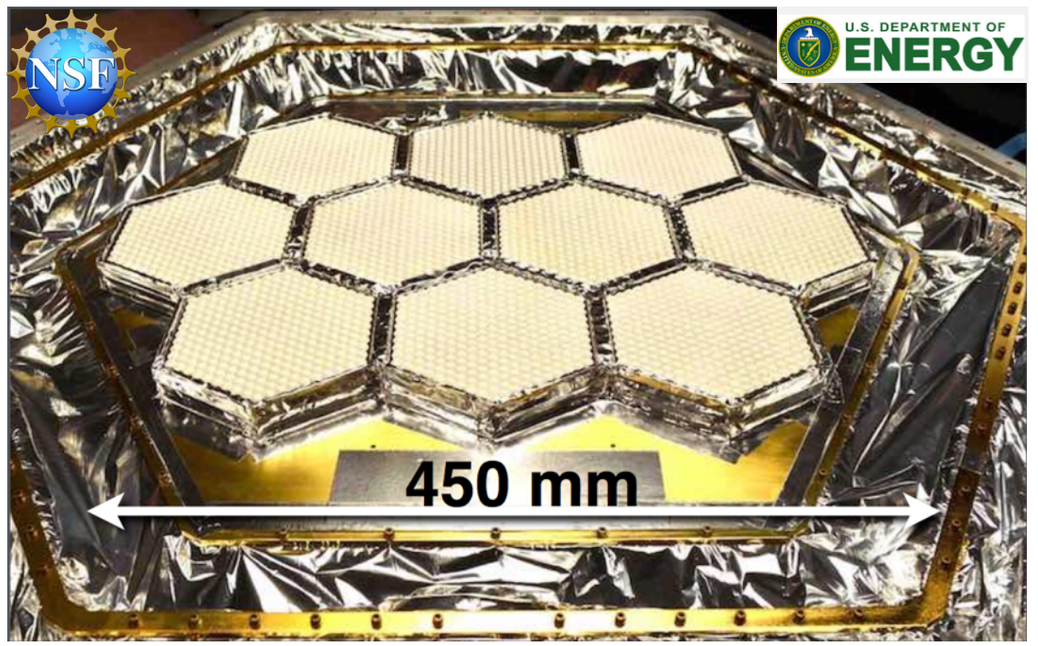
SPTpol (2012 - 2016):

- 1600 detectors: 90 GHz and 150 GHz
- 500 deg^2 survey at 6uK arcm at 150 GHz
- 100 deg^2 survey at 4uK arcm at 150 GHz

SPT-3G (2017 - 2023):

- **16,000 detectors**; 90 GHz, 150 GHz and 220 GHz
- **Deep 1500 deg^2 survey**
  - 2.2 uK arcm at 150 GHz
  - Same field as BICEP Array field to allow de-lensing and joint analysis
- **Observations planned through 2023**





SPT-3G Stage 3 (10x SPT pol)
16,000 detectors at T = 250mK

The South Pole Telescope (SPT)

Key Technologies:

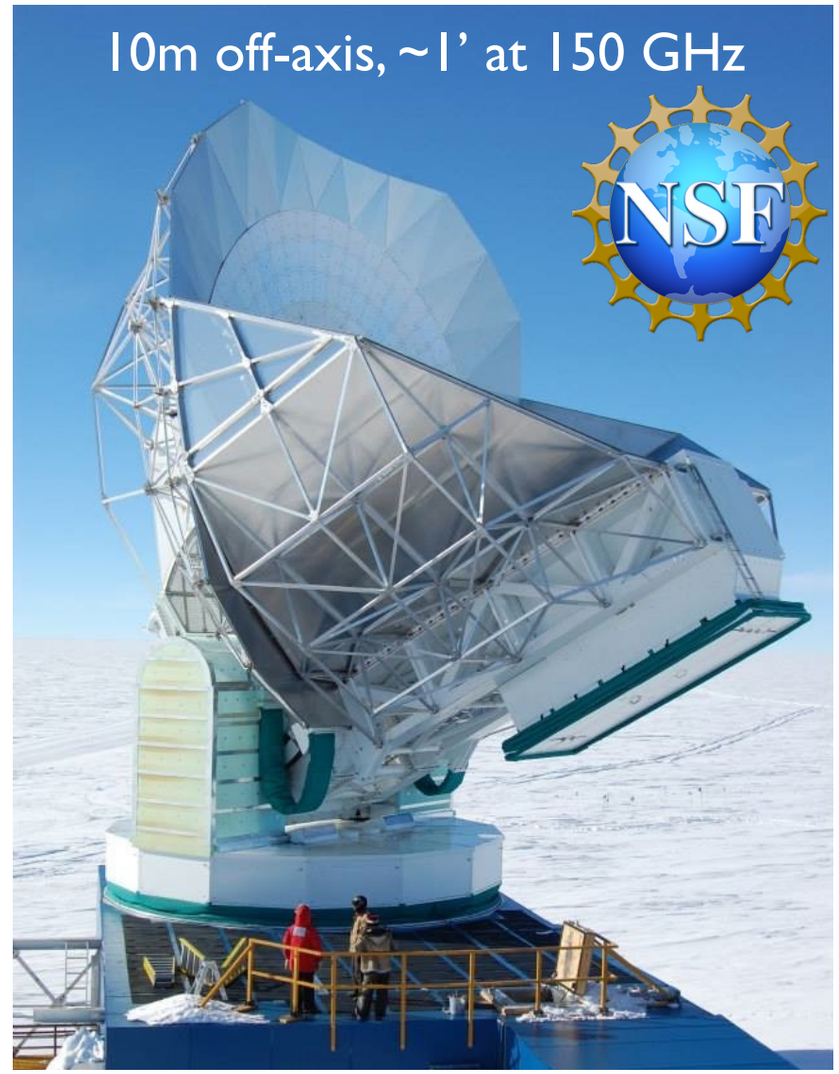
- Precision 10m CF supported primary (< 20 um rms)
- Adaptation to extreme thermal environment
- Large (700mm) 3-layer AR coated alumina lens
- 3-layer AR coated lenslet coupled antennas
- Sinuous planar antenna (Berkeley design)
  3 band dual polarization TES pixels (fabricated at Argonne)
- 68x freq domain (fdm) readout

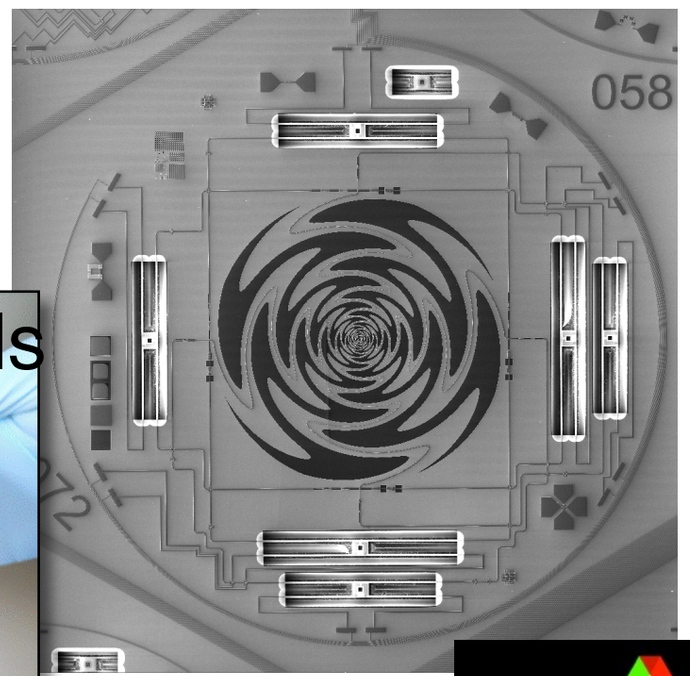
SPTpol (2012 - 2016):

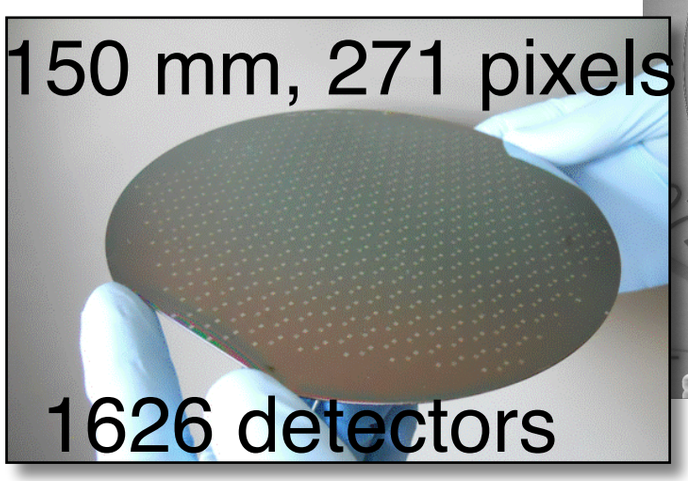
- 1600 detectors: 90 GHz and 150 GHz
- 500 deg^2 survey at 6uK arcm at 150 GHz
- 100 deg^2 survey at 4uK arcm at 150 GHz

SPT-3G (2017 - 2023):

- **16,000 detectors**; 90 GHz, 150 GHz and 220 GHz
- **Deep 1500 deg^2 survey**
  - 2.2 uK arcm at 150 GHz
  - Same field as BICEP Array field to allow de-lensing and joint analysis
- **Observations planned through 2023**







Argonne NATIONAL LABORATORY

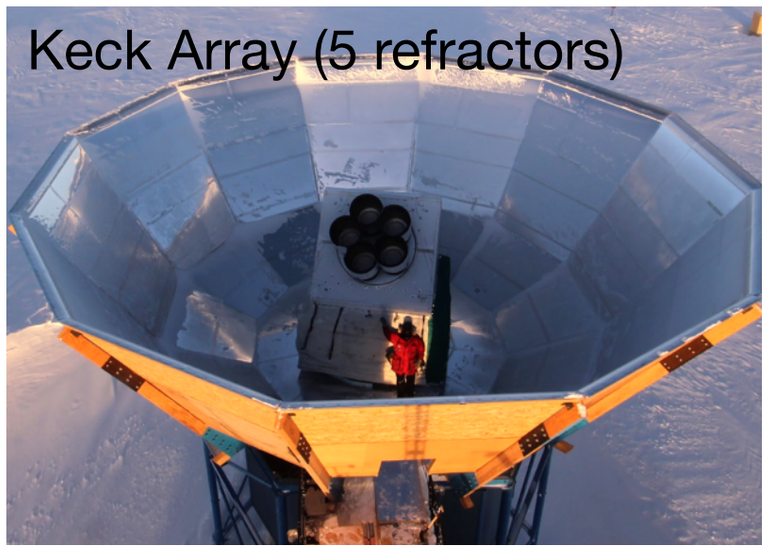
The South Pole Telescope Collaboration

23+ institutions **80+ people**

funding:

Argonne NATIONAL LABORATORY
Berkeley Lab
Cardiff University / Prifysgol Caerdydd
NIST
MIT
SLAC
McGill
U.S. Department of Energy
KICP Kavli Institute for Cosmological Physics at the University of Chicago
Berkeley University of California
Case Western Reserve University
Colorado University of Colorado at Boulder
Stanford University
KAVLI
The University of Chicago
LMU Ludwig-Maximilians-Universität München
Harvard-Smithsonian Center for Astrophysics
UC Davis University of California
Fermilab
Gordon and Betty Moore Foundation

BICEP3, BICEP Array



Key Technologies:

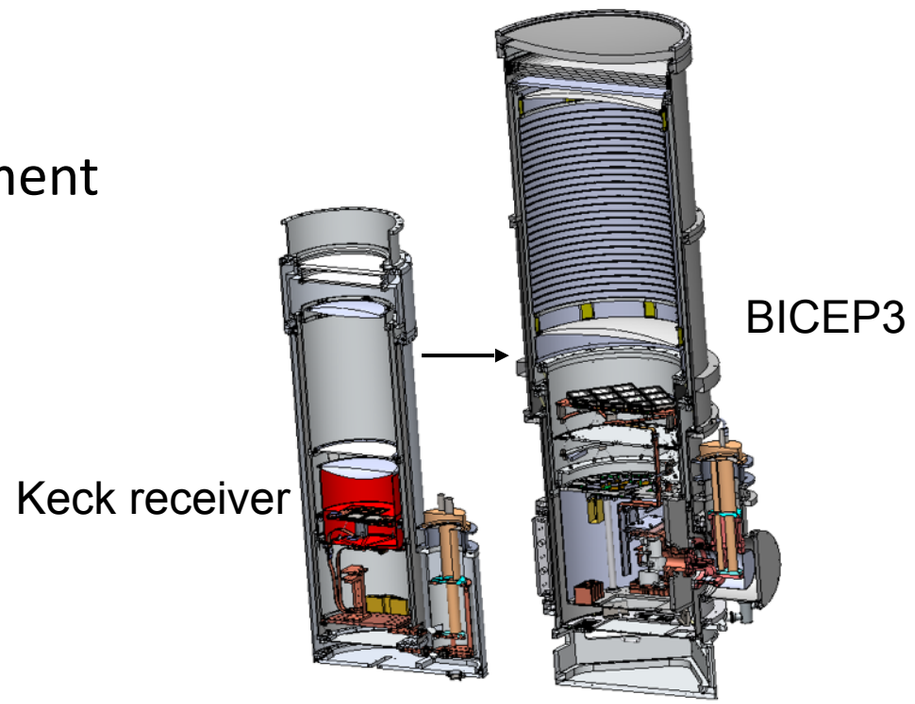
- **Pioneered degree-angular scale refractor telescopes**
- **Large alumina cooled lenses (550 mm)**
- **dual-pol planar "patch" antennas coupled TES (JPL)**
- **precision beam measurements / calibration to control systematics**
- **boresight rotation (from DASI), no λ/2 pol modulation**
- **comoving forebaffle and fixed ground shield**

BICEP/KECK program (2006 -)

- deep 90 GHz, 150 GHz, 220 GHz and 270 GHz measurements of ~500 deg^2 field

BICEP3 and BICEP Array:

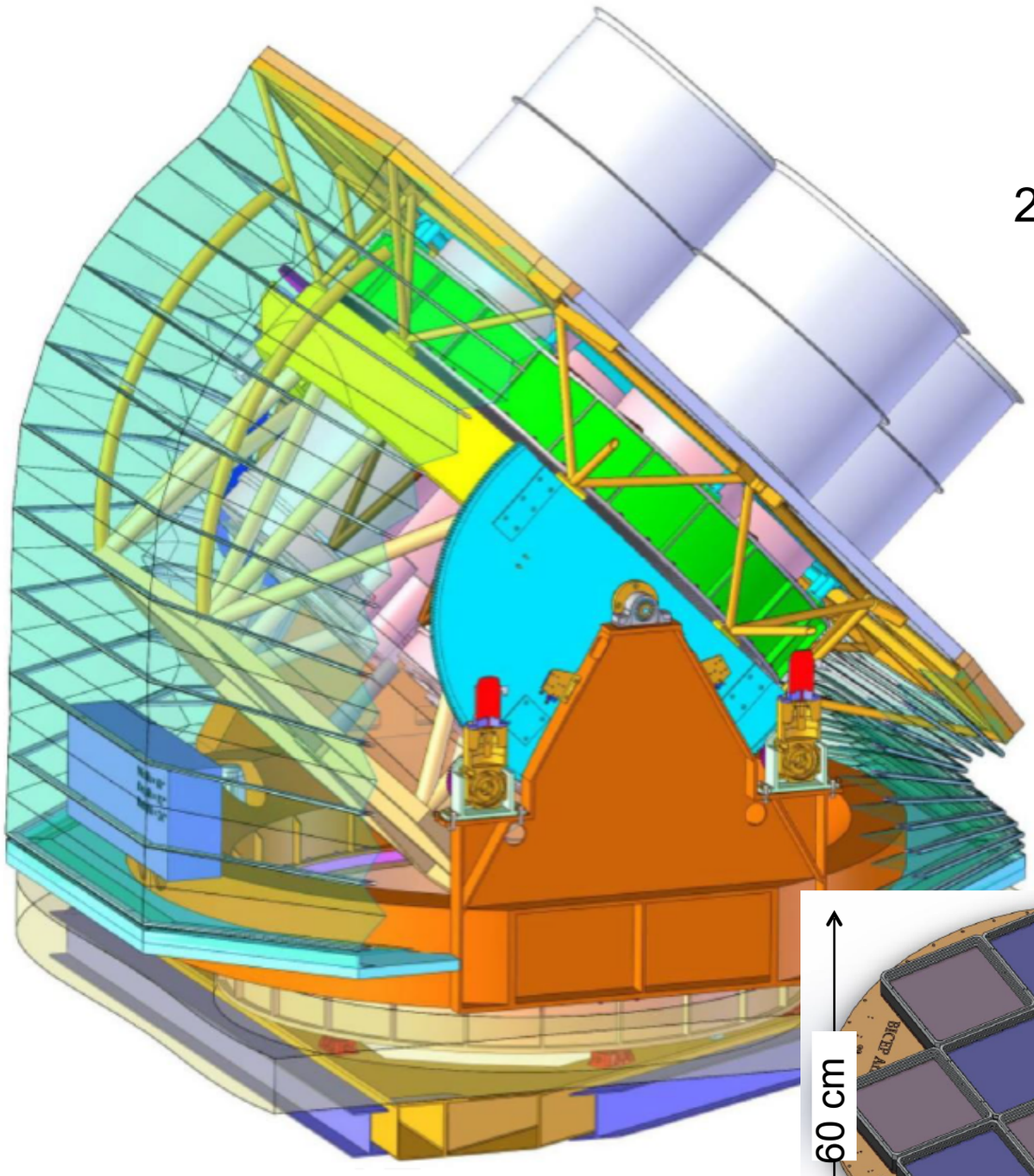
- 2015: BICEP3 replaced BICEP2; 2560 detectors at 95 GHz (10x BICEP2); Shifted to **larger 1500 deg^2 field**
- 2020: BICEP Array mount with staged BICEP3-like replacement of Keck Array receivers:
  - 2020: 30/40 GHz rx and 150 GHz rx
  - 2021: Second 95 GHz rx and 220/270 GHz rx
- **Observations planned through 2023**



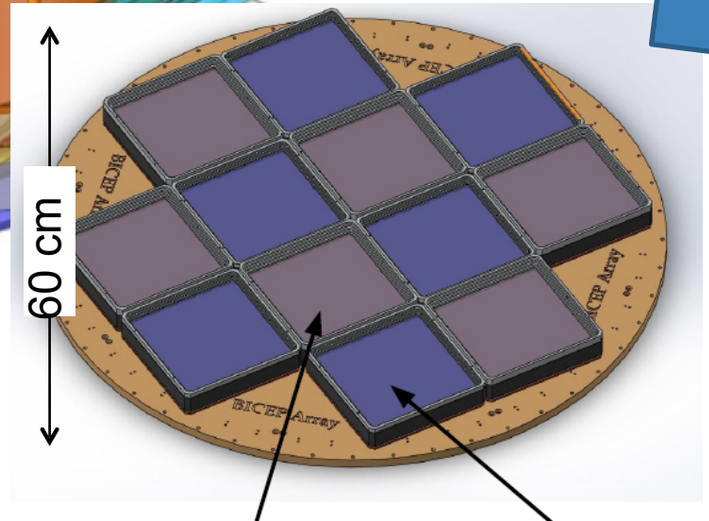
Slide material from J. Kovac

BICEP Array Under Construction

4 wide-field receivers
30/40 GHz
95 GHz
150 GHz
220/270 GHz



Wide-field cryogenic receiver



Focal plane layout

Stage 2

Stage 3

Keck Array

BICEP Array

BICEP3

10^2

10^1

10^0

Map Sensitivity [μK–arcmin]

270 GHz

40 GHz

30 GHz

220 GHz

95 GHz

150 GHz

BKP

BK14

BK15

10^{-2}

10^{-3}

σ(r)

No Delensing

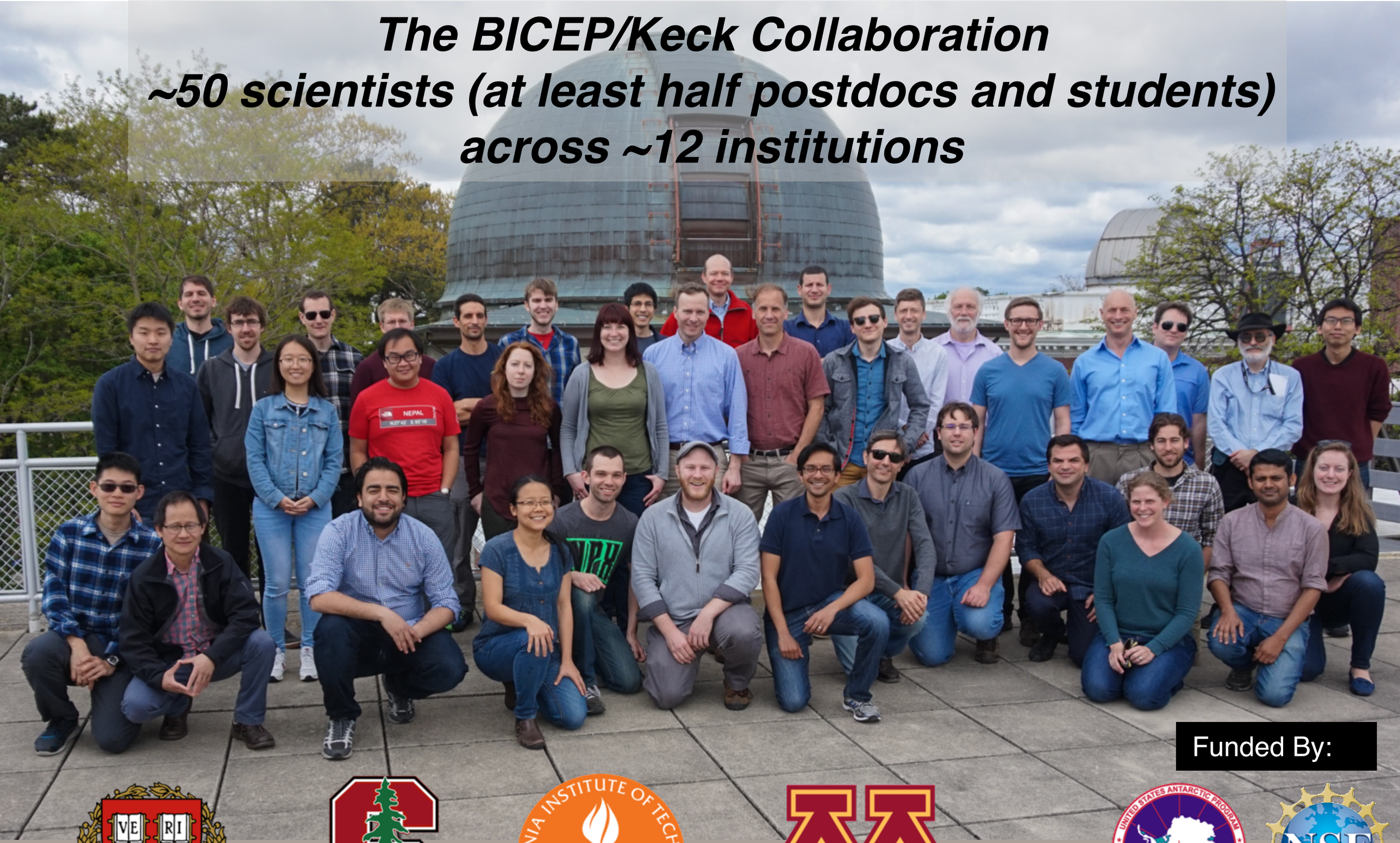
Delensed w/ SPT–3G

Raw Sensitivity

σ(r) < 0.01 w/ data through 2017;
σ(r) < 0.003 w/ data through 2023
& SPT-3G delensing

2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023

The BICEP/Keck Collaboration
~50 scientists (at least half postdocs and students)
across ~12 institutions



Funded By:

HARVARD

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

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NSF

cea

UCSD

JPL

NIST

CARDIFF UNIVERSITY

UNIVERSITY OF TORONTO

UBC

		Sensitivity (μK^2)	$\sigma(r)$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	Dark Energy F.O.M
2015	Stage 2 1000 detectors					
2016					Boss BAO prior	DES+BOSS SPT clusters
2017		$\approx 10^{-5}$	0.035	0.14	0.15eV	~180
2018	Stage 3 10,000 detectors					
2019						
2020						
2021					Boss BAO prior	DES + DESI SZ Clusters
2022						
2023		10^{-6}	0.003	0.06	~0.06eV	~300-600
2024						
2025						
2026					DESI BAO +τ_e prior	DESI +LSST S4 Clusters
2027/34	**CMB-S4**	**10^{-8}**	**0.0005**	**0.03**	**0.015eV**	**1250**

2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027

Stage 2
1000
detectors

Stage 3
10,000
detectors

SPTpol

SPT-3G

BICEP3
&
Keck
Array

BICEP3
& BICEP
Array

joint S.Pole
10m + 5 x 0.5m
52,000 detectors

?

POLAR-
BEAR

Simons
Array
(3x PB)

ACTPol

ADV-
ACT

Simons Observatory
6m + 3 x 0.4m
60,000
detectors

CLASS

Stage 4: CMB-S4 Start operations

2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027

Stage 2
1000
detectors

Stage 3
10,000
detectors

SPTpol

SPT-3G

BICEP3
&
Keck
Array

BICEP3
& BICEP
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joint S.Pole
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CLASS

Stage 4: CMB-S4 Start operations

2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027

Stage 2
1000 detectors

Stage 3
10,000 detectors

SPTpol

SPT-3G

BICEP3 & Keck Array

BICEP3 & BICEP Array

joint S.Pole
10m + 5 x 0.5m
52,000 detectors

SPT high-v survey? Or repurpose SPT for submm survey with KID IFU?

POLAR-BEAR

Simons Array (3x PB)

ACTPol

ADV-ACT

CLASS

Simons Observatory
6m + 3 x 0.4m
60,000 detectors

Stage 4: CMB-S4 Start operations

2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027

Stage 2
1000 detectors

Stage 3
10,000 detectors

SPTpol

SPT-3G

BICEP3 & Keck Array

BICEP3 & BICEP Array

joint S.Pole
10m + 5 x 0.5m
52,000 detectors

SPT high-v survey? Or repurpose SPT for submm survey with KID IFU?

High throughput CMB telescope suitable for CMB-S4 at S. Pole?

POLAR-BEAR

Simons Array (3x PB)

ACTPol

ADV-ACT

Simons Observatory
6m + 3 x 0.4m
60,000 detectors

CLASS

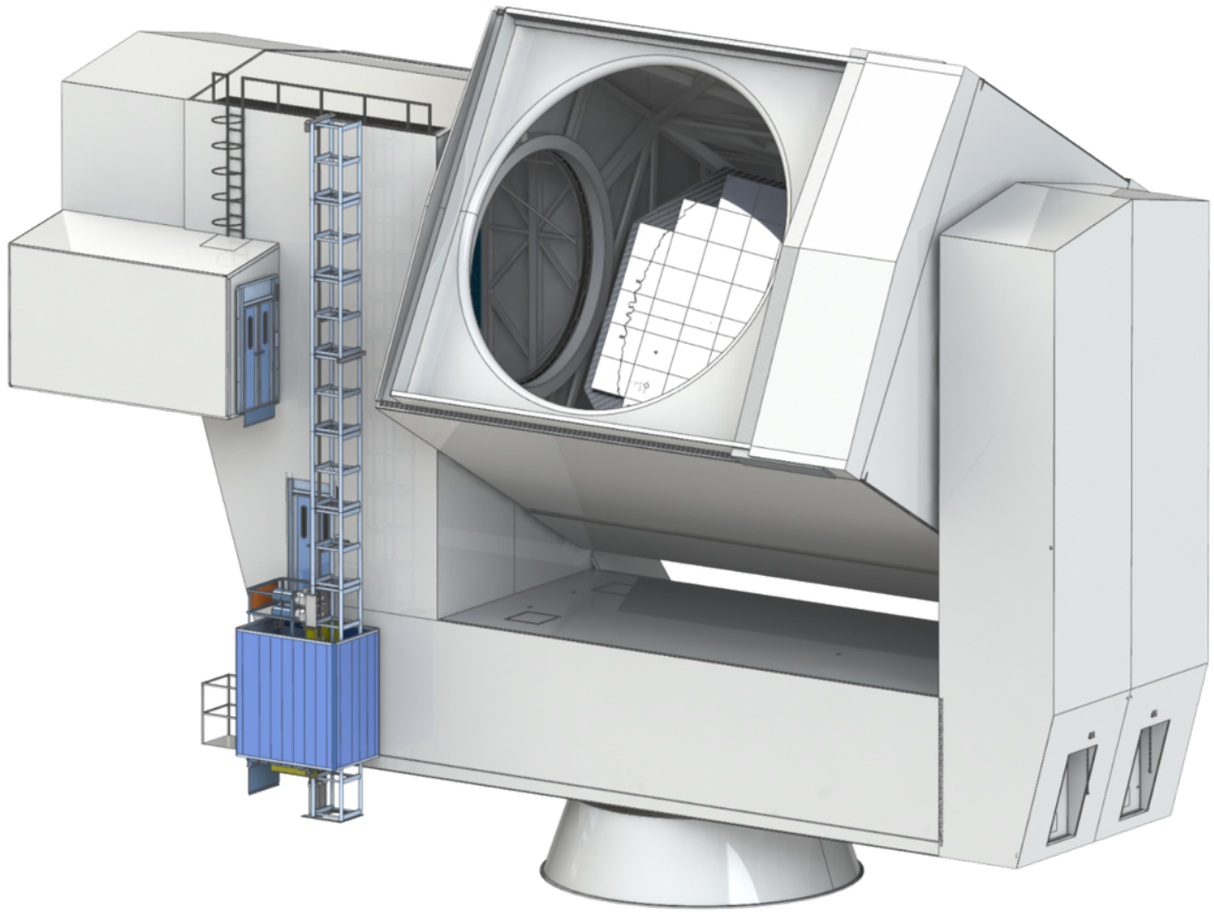
Stage 4: CMB-S4 Start operations

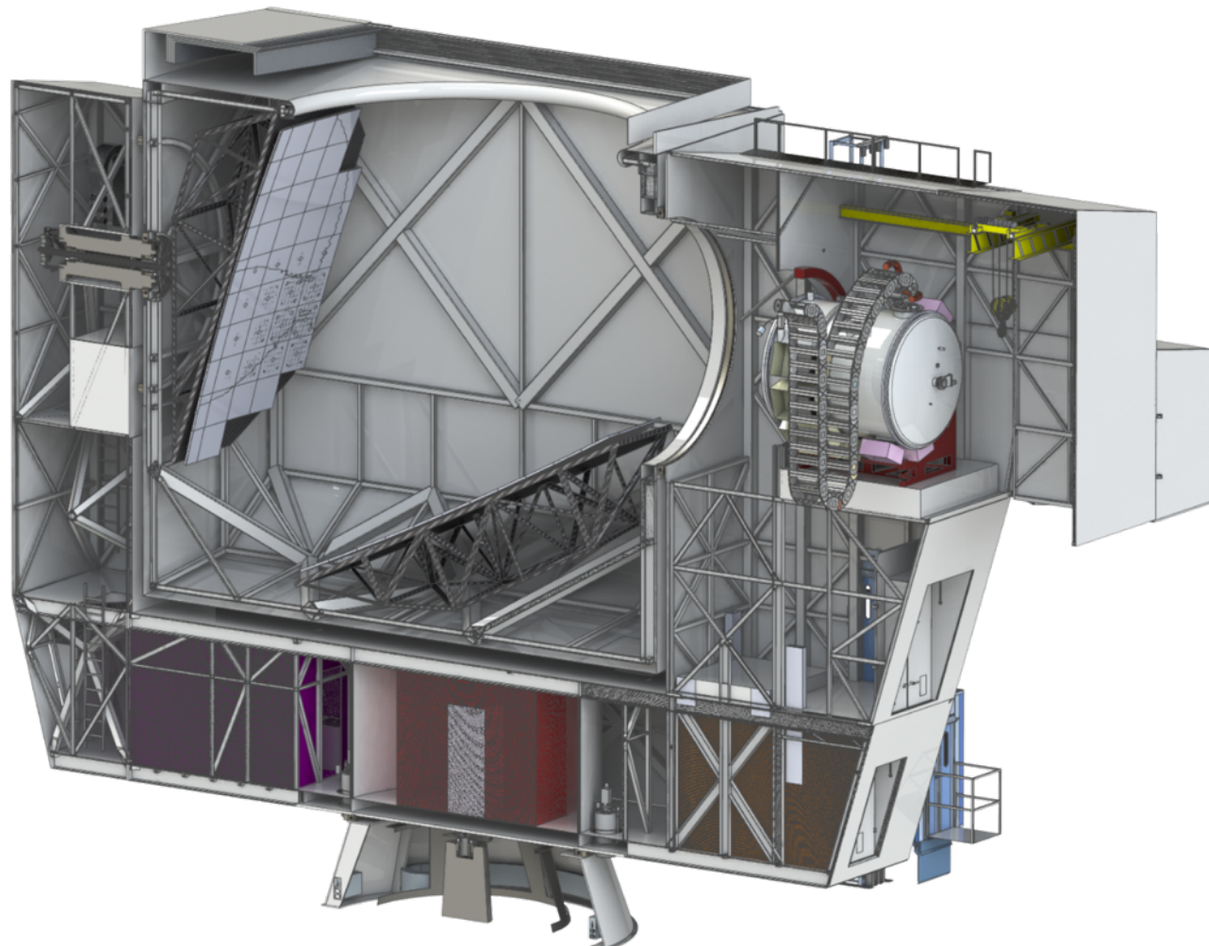
One Option: Modified Simons Obs 6-m Cross Dragone telescope

Arc minute resolution with high throughput.

For 6-m design:

- 80 deg^2 field of view at λ 3mm
- 1.7’ resolution at 150 GHz





SO and CCAT developing for use in Chile, raising Technical Readiness Level (TRL)

Currently the “reference design” for CMB-S4 large aperture telescope (LAT).

For South Pole will need significant modifications primarily for thermal issues.

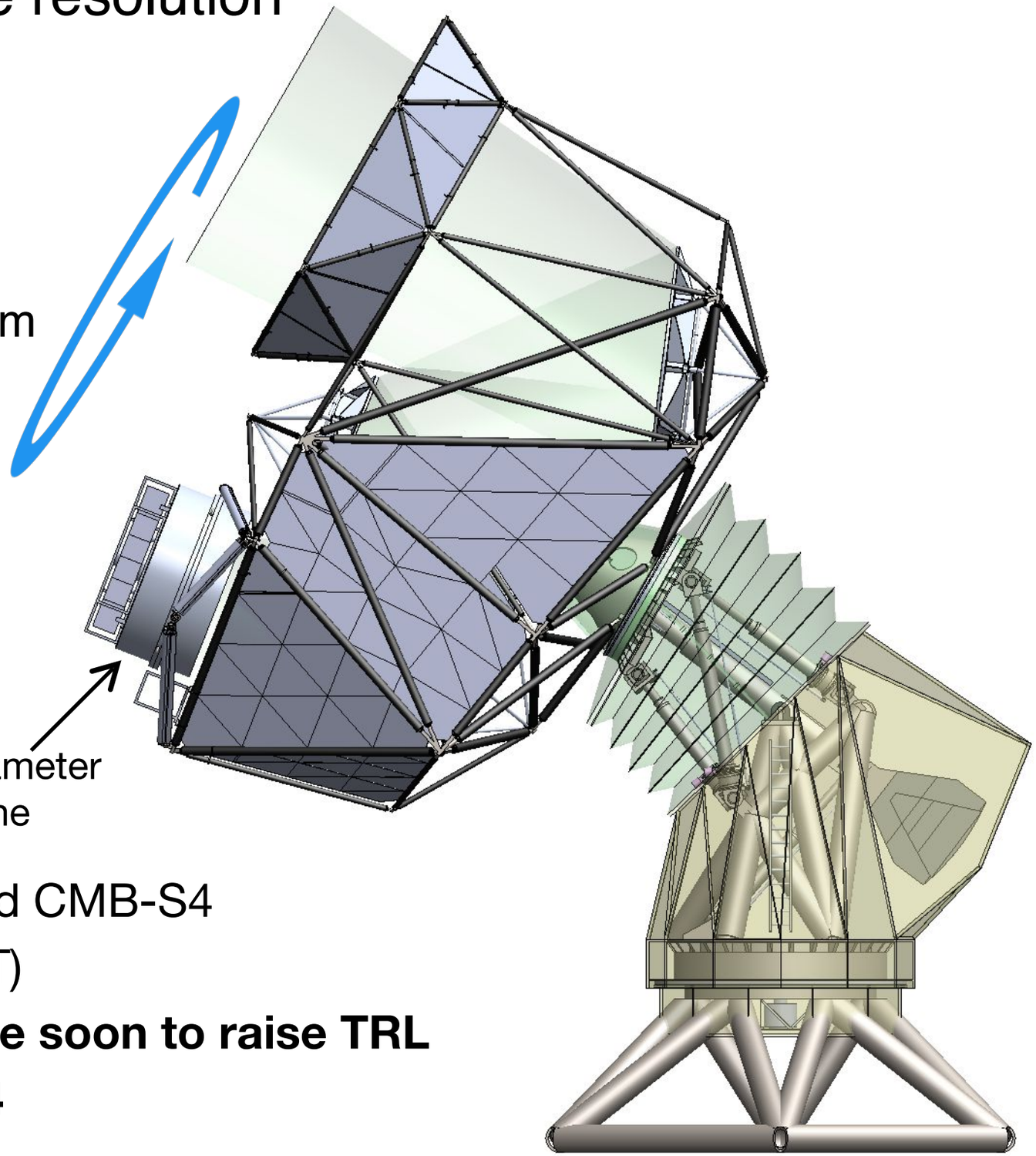
Niemack, Appl. Opt. 55, 1688–1696 (2016).

2nd Option: Three Mirror Anastigmat for CMB observations

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 for polarization modulation
- 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)

Need to further develop and prototype soon to raise TRL so it can be viable option for CMB-S4

Padin, Applied Optics, 57, 9, 2314 2018
https://www.osapublishing.org/ao/upcoming_pdf.cfm?id=320108

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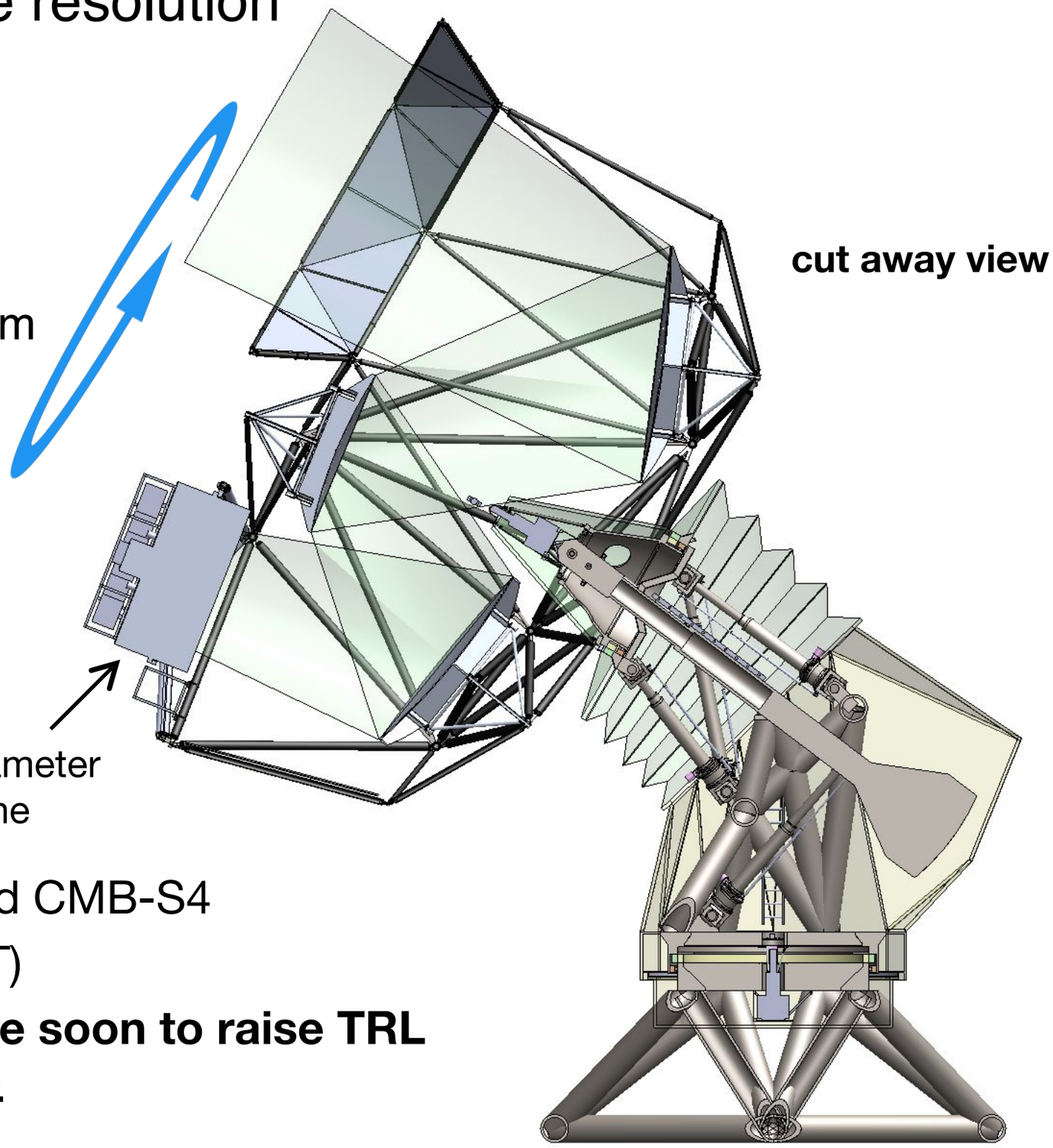

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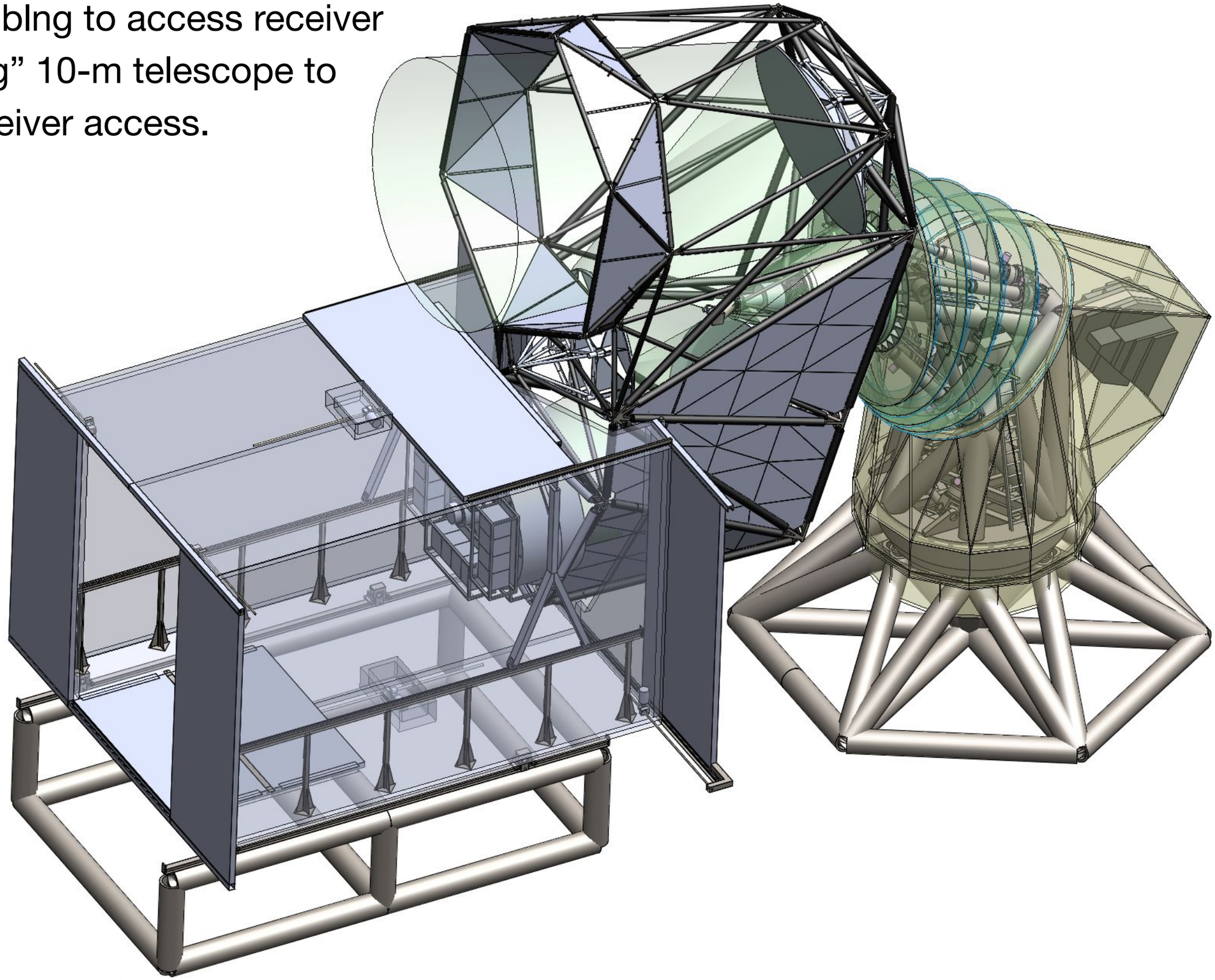
Padin, Applied Optics, 57, 9, 2314 2018
https://www.osapublishing.org/ao/upcoming_pdf.cfm?id=320108

2nd Option: Three Mirror Anastigmat for CMB observations

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



Wrap up U.S. Stage 3

- U.S. Stage 3 is making substantial progress, with experiments deployed and science results coming
- Stage 3 is field testing Stage 4 technology and methods
- Stage 3 is training the next generation for CMB-S4
- The best is yet to come, and that is CMB-S4
- We are all headed toward CMB-S4