

BICEP Array: a next-generation CMB polarimeter to probe the primordial universe from the South Pole

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for the BICEP/Keck Collaboration

June 7th, 2019

Photo credit: R. Schwarz

mm Universe @NIKA2
Grenoble, France

NIKA2

- mm-camera Imager
- 150GHz, 260GHz (260GHz pol)
- Large FPU arrays of MKID detectors
- Optimize: sensitivity, resolution, FOV
- Shared Observatory
- Multiple science goals: SZ effect, galaxy cluster, galaxy formation, nearby galaxies, dust/planets and star formation
- Challenges: weather and water-vapor, mm-wave optics (dichroic, lenses), beam effects

BICEP Array

- mm-camera Imager
- 30, 40, 95, 150, 220, 270 GHz
- Large FPU arrays of polarization-sensitive TES detectors
- Optimize: sensitivity, systematics control, continuous observations
- Dedicated instrument
- One science goal: signal from primordial gravitational waves in CMB pol (r)
- Challenges: water-vapor, mm-wave optics (lenses, AR-coating), cryostat IR loading, beam effects, yearly upgrades, south pole schedule

The Big Bang Theory

what's
Big Bang Theory,
You've Got To Be Kidding.

-God

EMAR

INFLATION

fraction
of a second

**CMB
last scattering**

379,000
years

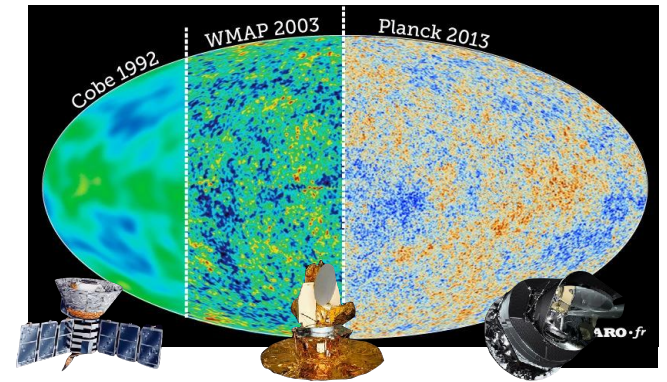
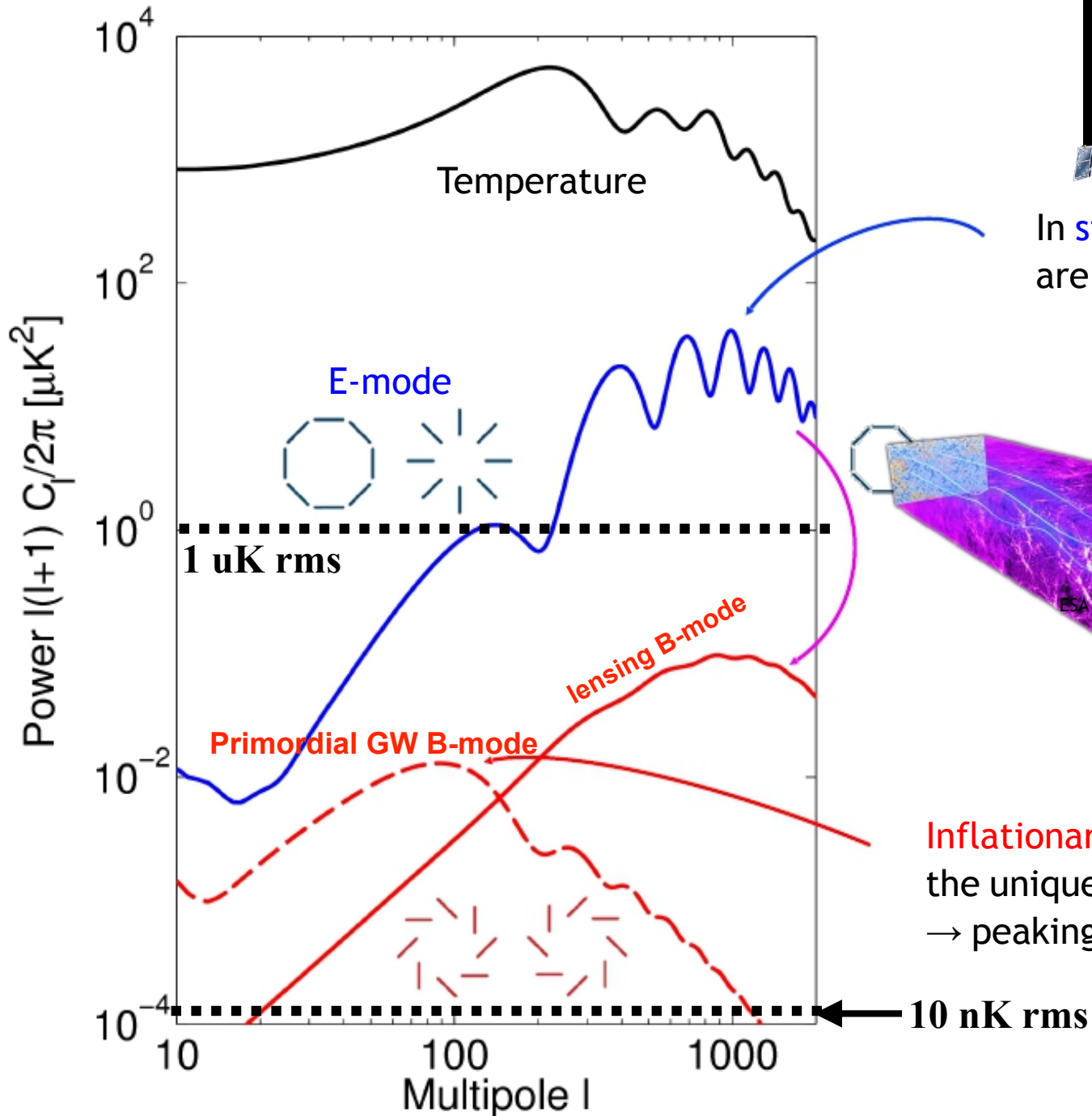
**first
stars**

~200 million
years

**present
day**

13.7 billion
years

CMB Polarization



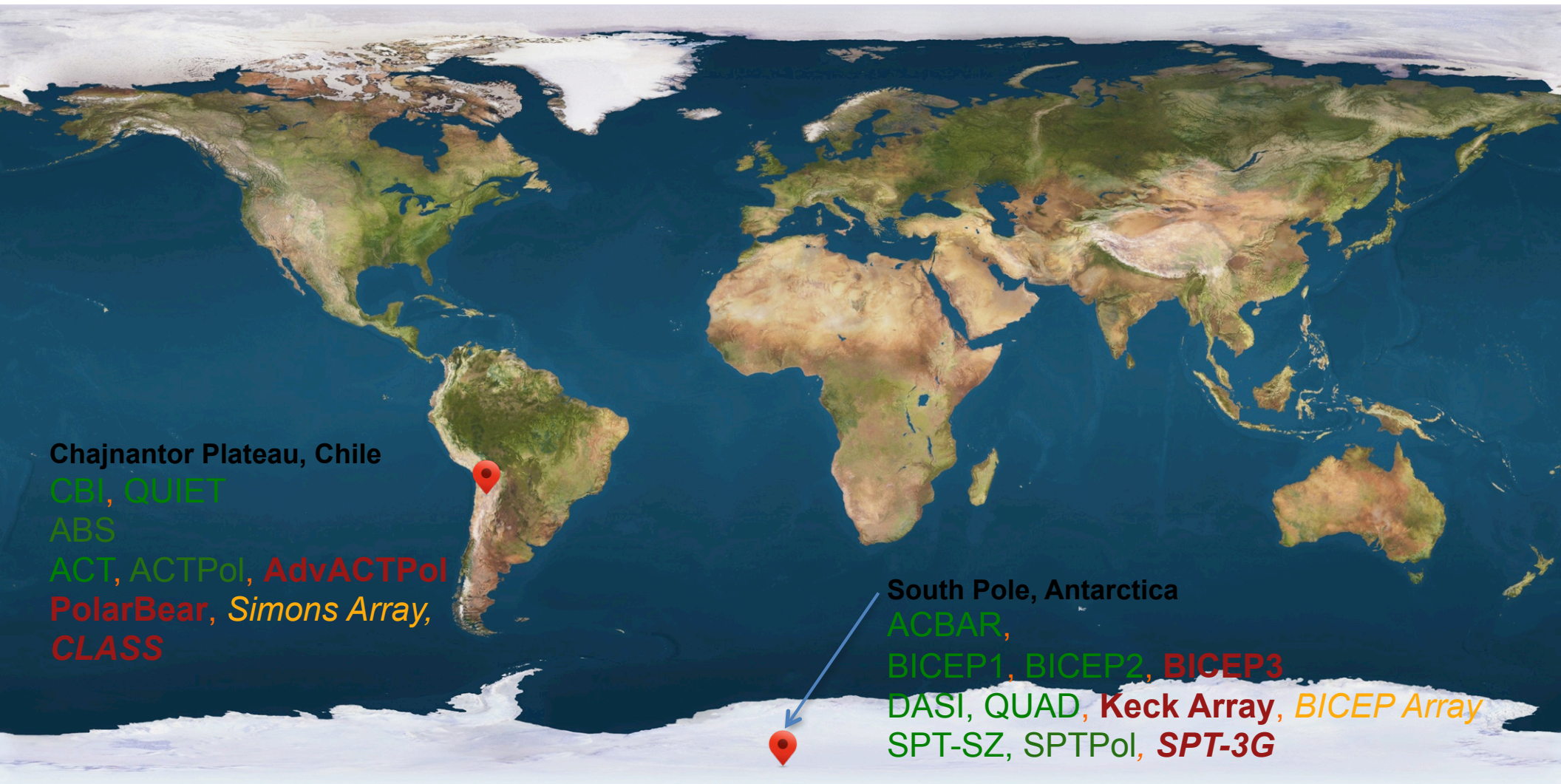
In standard ΛCDM only E-modes are present at last scattering

During propagation some of the E-modes are transformed into B-modes by lensing

Inflationary gravitational waves are the unique source of B-modes
 → peaking at $l \approx 100$: degree scales

Last Decade of ground-based CMB polarization telescopes

high precision/accuracy CMB temperature and polarization measurements



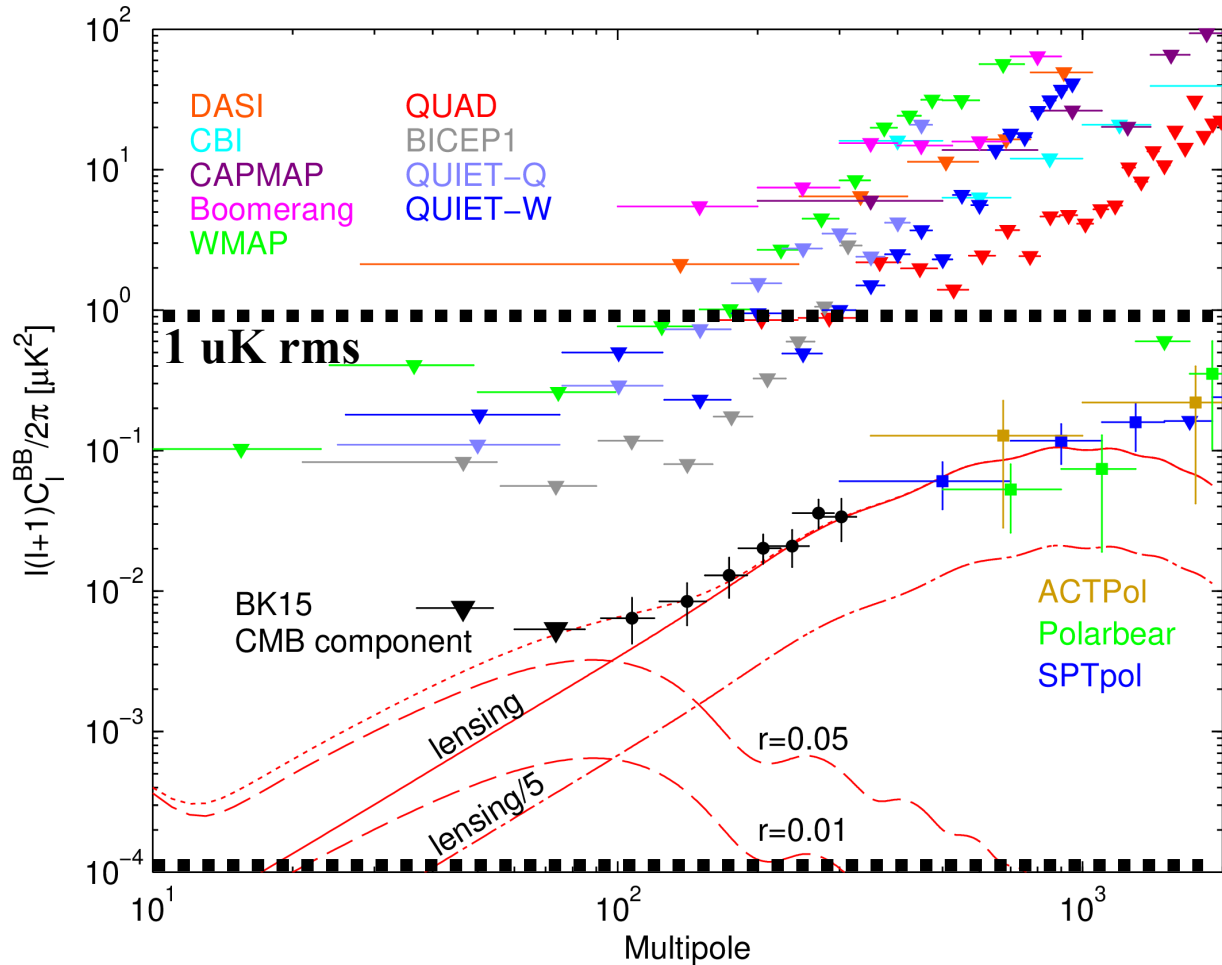
Also: QUBIC, QUIJOTE, GroundBird

Past, Current, Future

BICEP-Keck Constraints on Inflation to Date

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

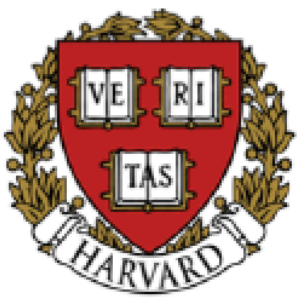
State of B-mode polarization power spectra in 2018



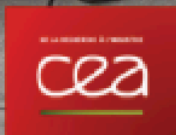
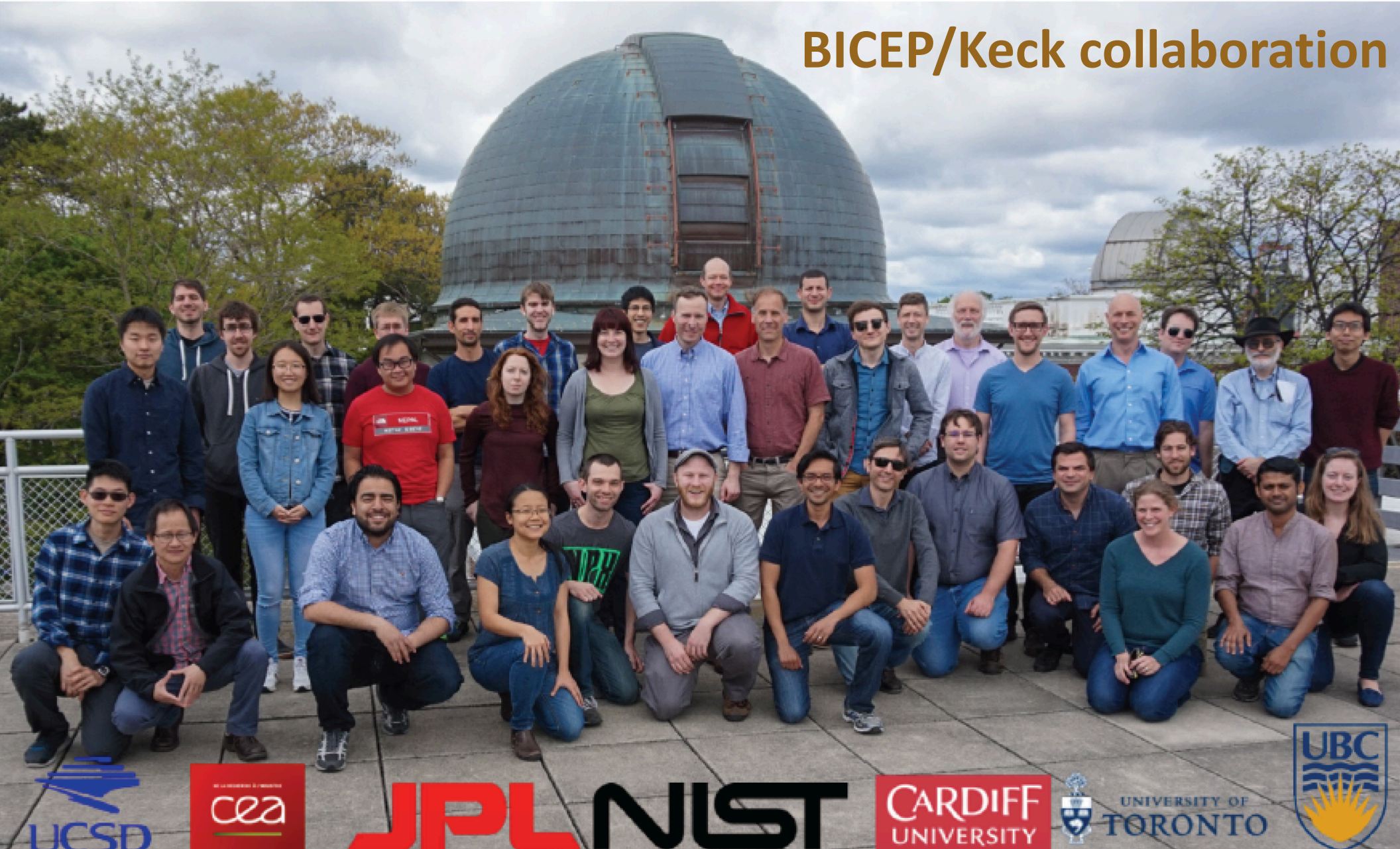
Published B-Mode Sensitivity to r

Experiment	Year	Bands [GHz]	$\sigma(r)$
DASI	2004	26...36	7.5
BICEP1 2yr	2009	100, 150	0.28
WMAP 7yr	2010	30...60	1.1
QUIET-Q	2010	43	0.97
QUIET-W	2012	95	0.85
BICEP1 3yr	2013	100, 150	0.25
BICEP2	2014	150	0.10
BK + Planck	2015	150 + Planck	0.034
BK14	2015	95, 150 + P	0.024
ABS	2018	150	0.7
Planck	2018	30 ... 353	~0.2
BK15	2018	95,150,220 + P	0.020
BK18	2019?	95,150,220 + P	0.010 (ongoing analysis)

10 nK rms



BICEP/Keck collaboration



BICEP/Keck Experimental Strategy

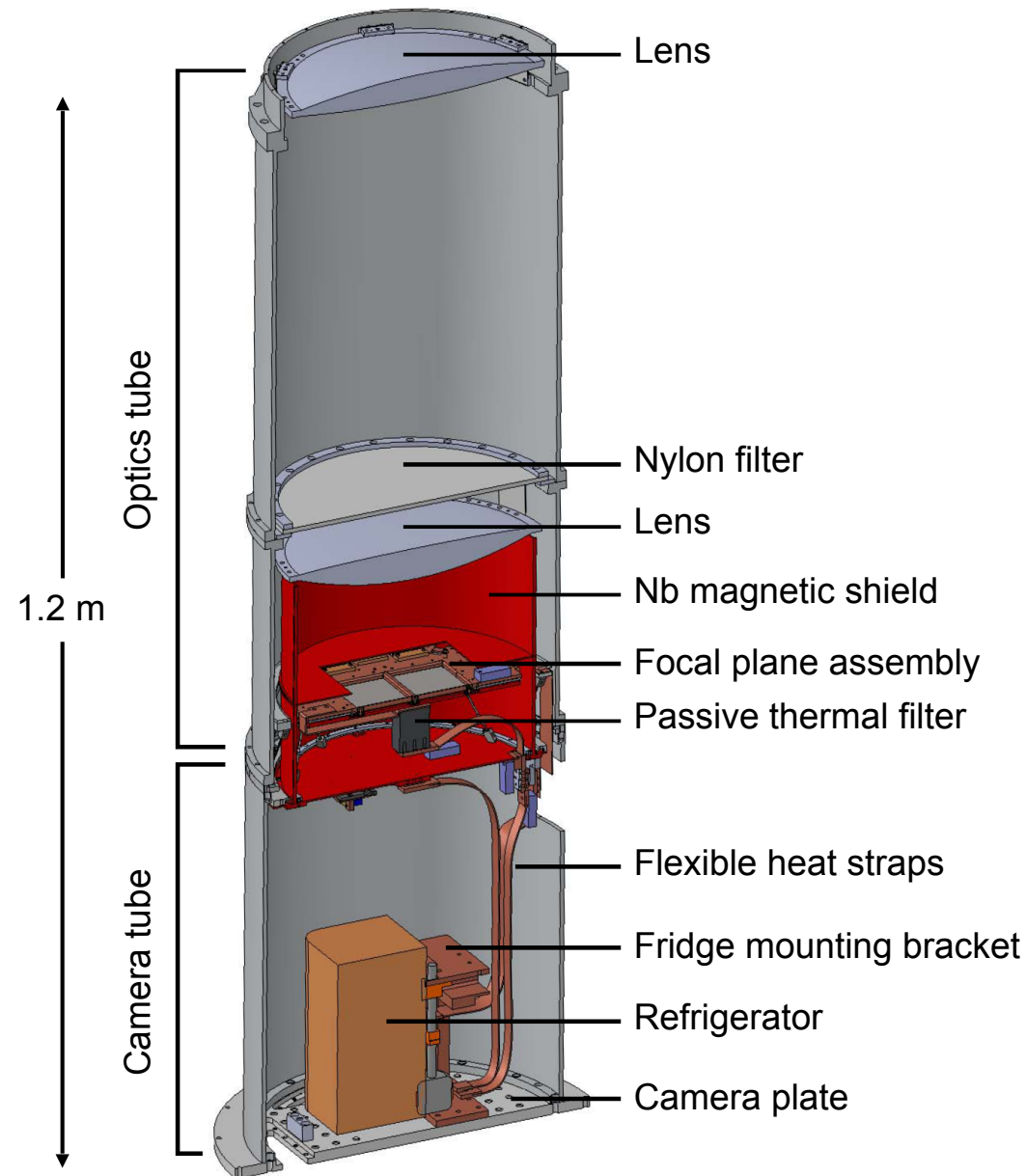
Optimize sensitivity: Large focal plane arrays, photon-limited TES bolometers, large FOV

Target 2-deg B-mode signal: aperture as compact as possible while still having the angular resolution to observe degree-scale features.

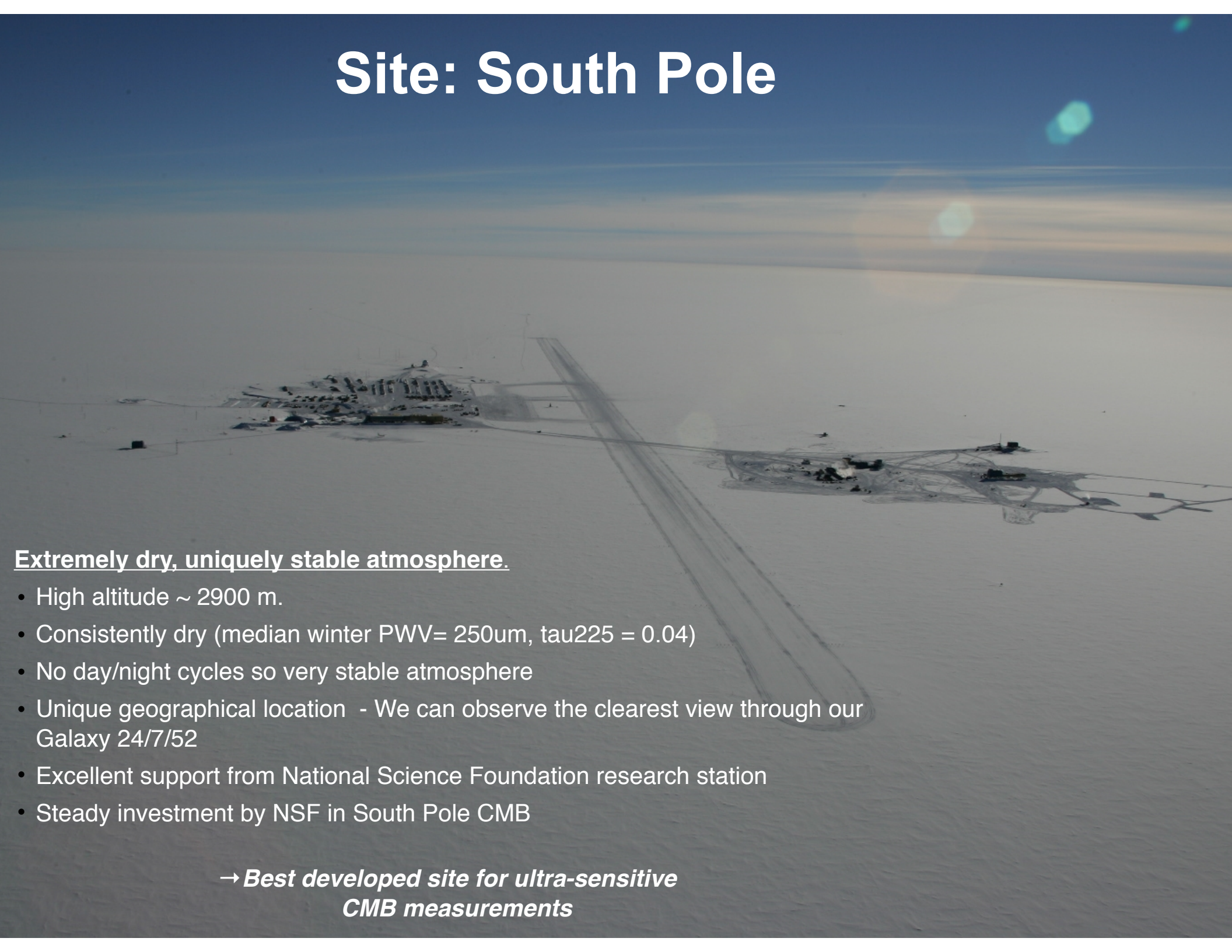
Control systematics: On-axis, refractive optics allow the entire telescope to rotate around boresight for polarization modulation. (+ easy baffling)

Minimize instrumental noise: Optics cooled to 4K, detectors cooled to 250mK

Ultra-deep mapping: continuous integrations over many South Pole winters.



Site: South Pole

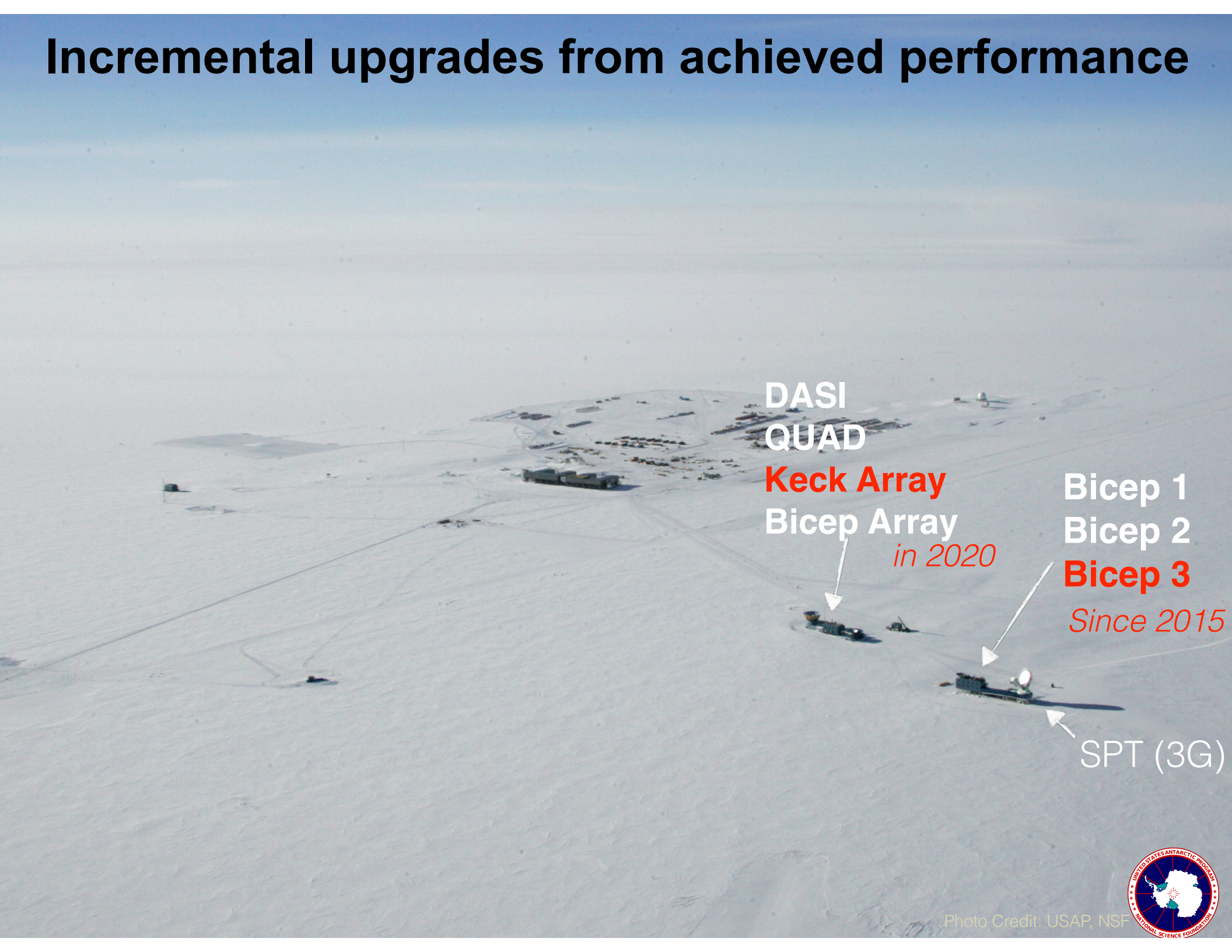


Extremely dry, uniquely stable atmosphere.

- High altitude ~ 2900 m.
- Consistently dry (median winter PWV= $250\mu\text{m}$, $\tau_{225} = 0.04$)
- No day/night cycles so very stable atmosphere
- Unique geographical location - We can observe the clearest view through our Galaxy 24/7/52
- Excellent support from National Science Foundation research station
- Steady investment by NSF in South Pole CMB

→ ***Best developed site for ultra-sensitive
CMB measurements***

Incremental upgrades from achieved performance



DASI
QUAD

Keck Array

Bicep Array
in 2020

Bicep 1

Bicep 2

Bicep 3

Since 2015

SPT (3G)

Incremental upgrades from achieved performance

Telescope and Mount

Focal Plane

Beams on Sky

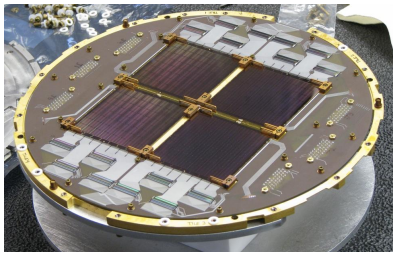
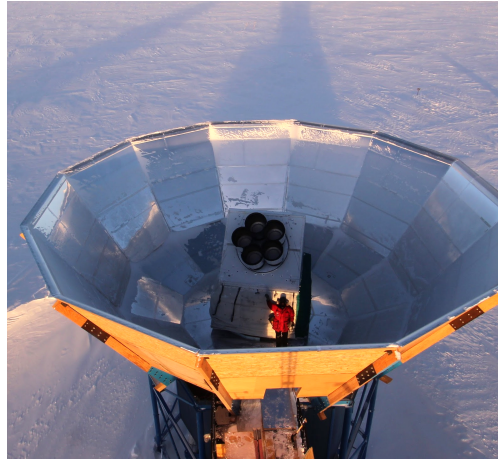
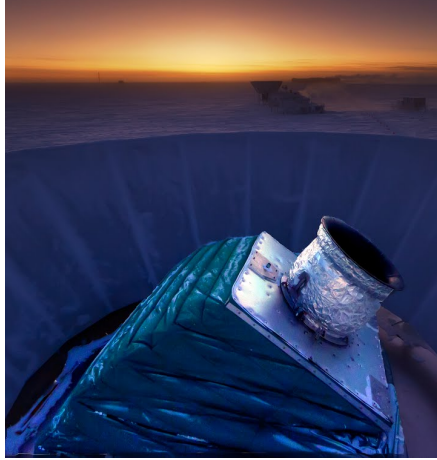
Detectors

Stage 2

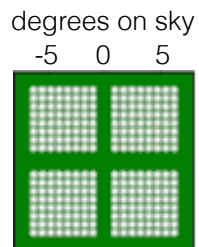
BICEP2
(2010-2012)

$\times 5 =$

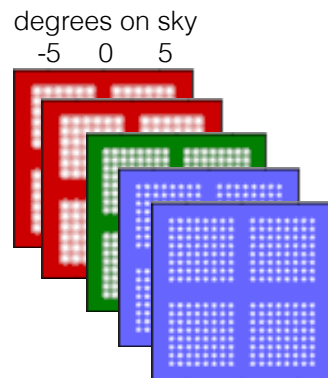
Keck Array
(2012-2019)



integrated FPU



500



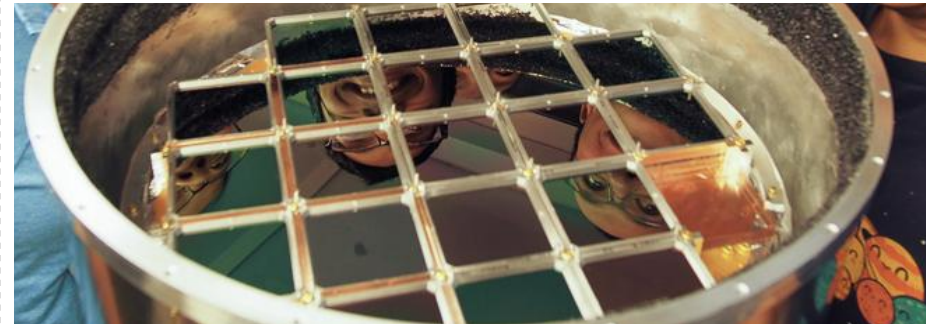
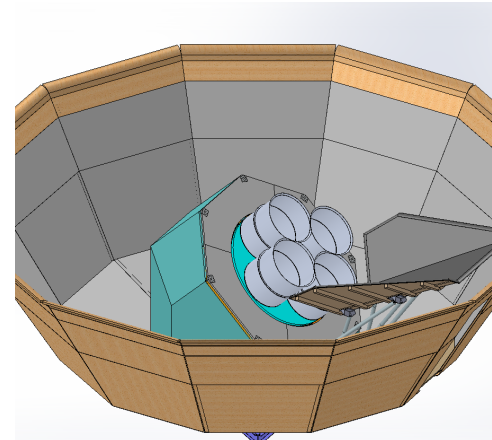
2500

Stage 3

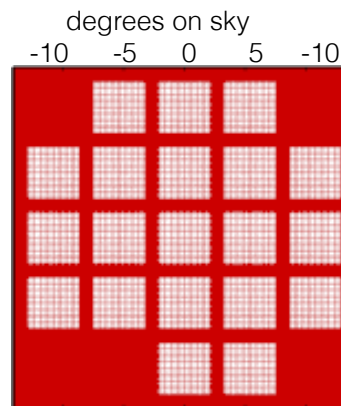
BICEP3
(2015-)

$\times 4 =$

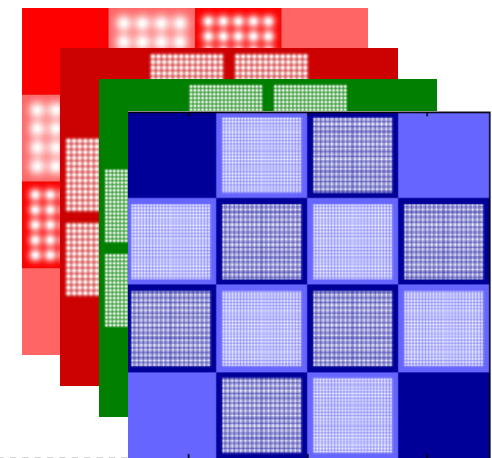
BICEP Array
(2020-)



FPU modules

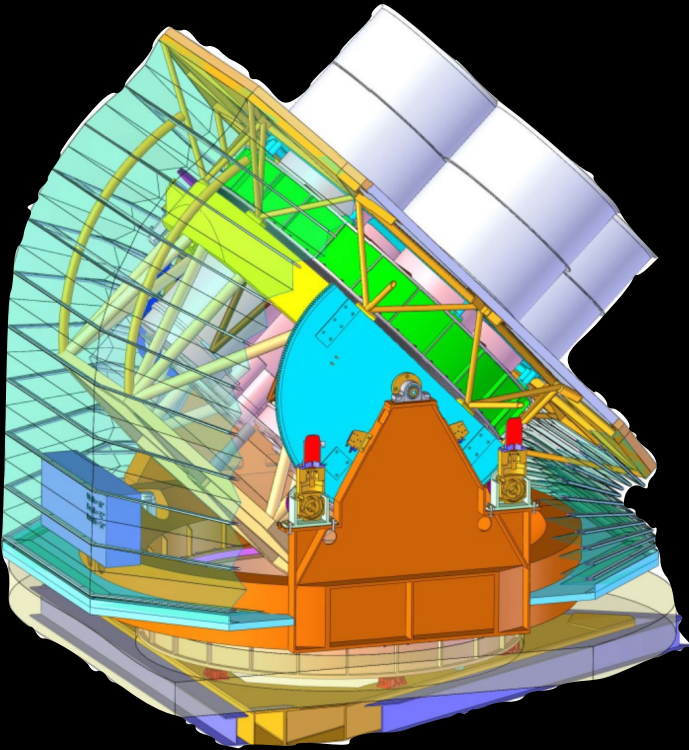


2500



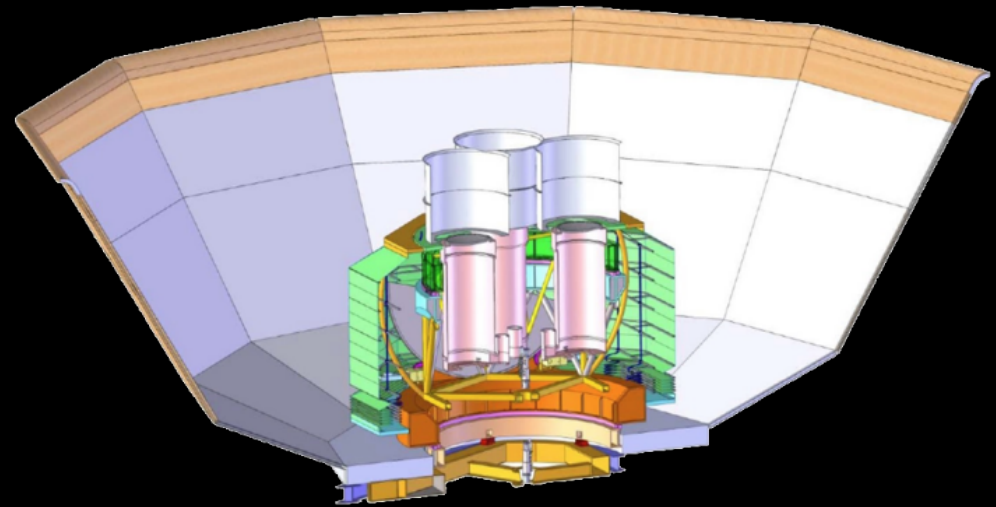
30000

BICEP Array: instrument overview



Replace Keck Array in 2019, new mount

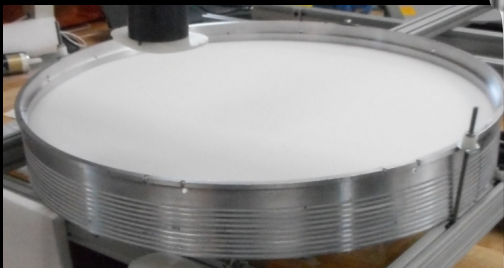
- 4 receivers
- 30, 40 GHz
- 95 GHz
- 150 GHz
- 220, 270 GHz
- 55 cm aperture
- 30 degree FOV
- f/1.55 optics
- arXiv:1808.00569, 1808.00568



Receiver Observing Band (GHz)	Nominal Number of Detectors	Nominal Single Detector NET ($\mu\text{K}_{\text{cmb}}\sqrt{\text{s}}$)	Beam FWHM (arcmin)	Survey Weight Per Year ($\mu\text{K}_{\text{cmb}})^{-2} \text{ yr}^{-1}$)
<i>Keck Array</i>				
95	288	288	43	24,000
150	512	313	30	30,000
220	512	837	21	2,000
270	512	1310	17	800
<i>BICEP3</i>				
95	2560	288	24	200,000
<i>BICEP ARRAY</i>				
30	192	221	76	19,500
40	300	301	57	20,500
95	4056	288	24	338,000
150	7776	313	15	453,000
220	8112	837	11	37,000
270	13068	1310	9	15,000

BICEP Array Cryostat

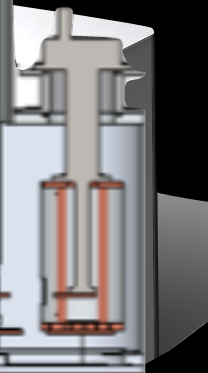
Zotefoam filters



Alumina lens + filters



He fridge



BICEP2/Keck Array



BICEP3

lens

filter

HDPE window
(at 30/40 GHz only)

Zotefoam IR filters

50K alumina filter

300K shell

50K shield

4K shield

Niobium Flared
Magnetic Shield
(aka "spittoon")

Pulse Tube
Cryocooler

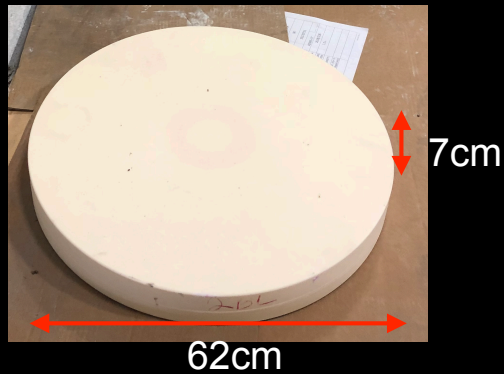
2m

1m

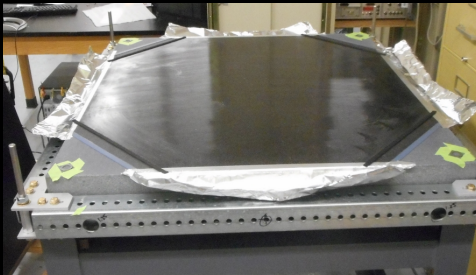
BICEP Array Refractive Optics



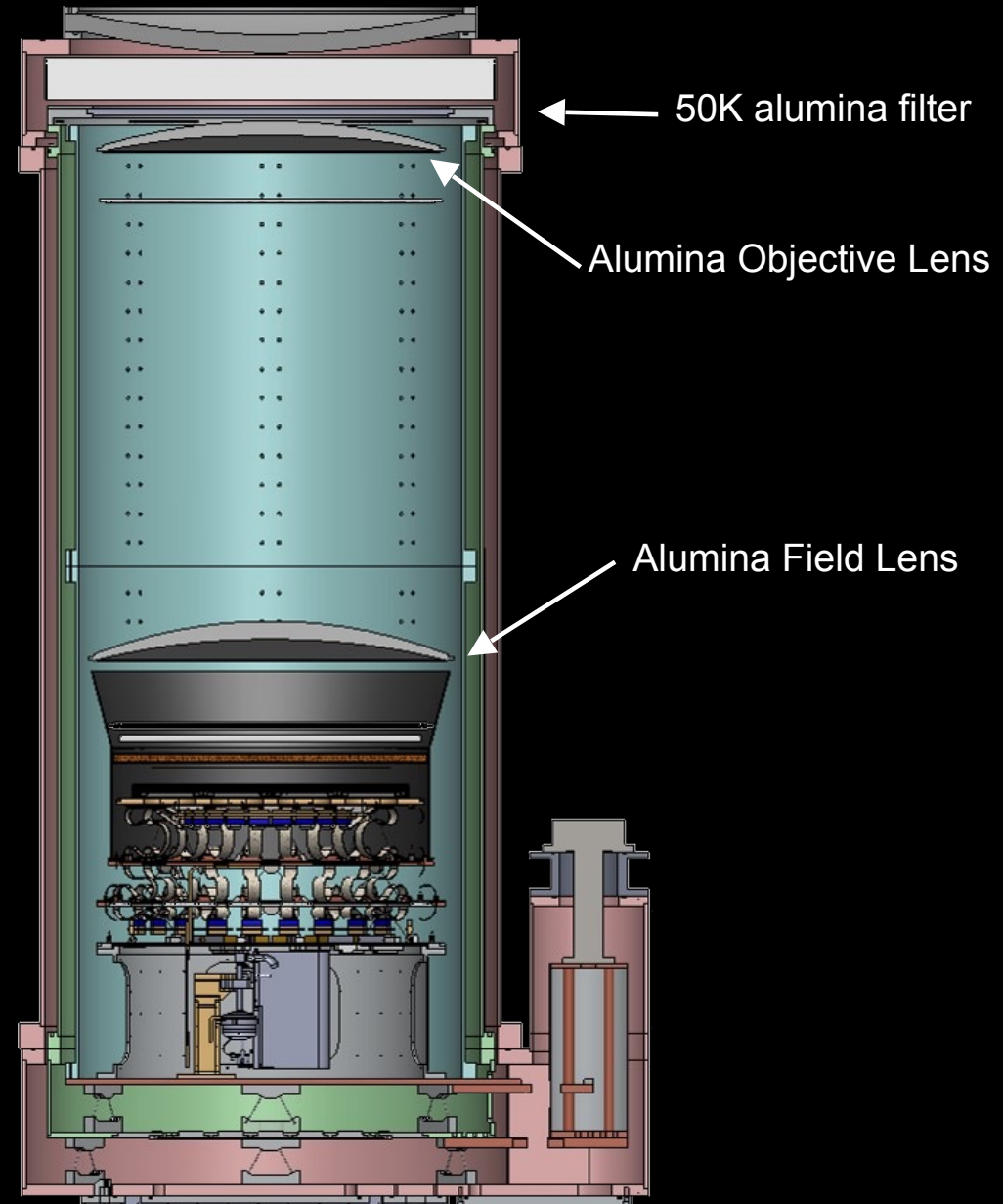
Hi purity (99.5%) fired Alumina blanks



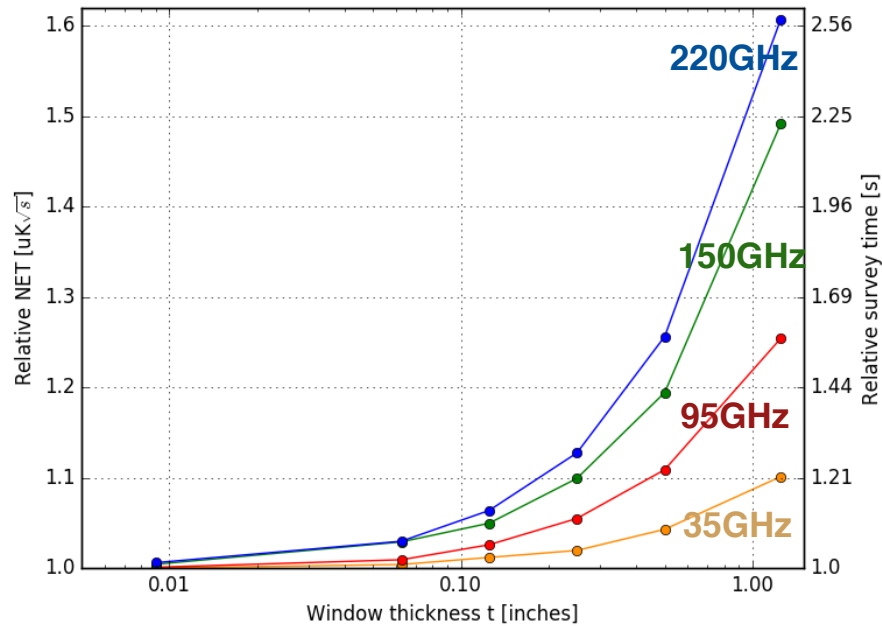
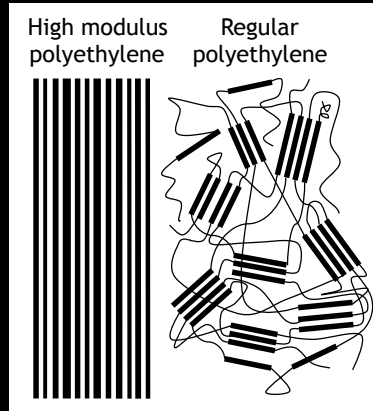
Cast large sheet of Stycast epoxy mix .
Control index of refraction and thickness



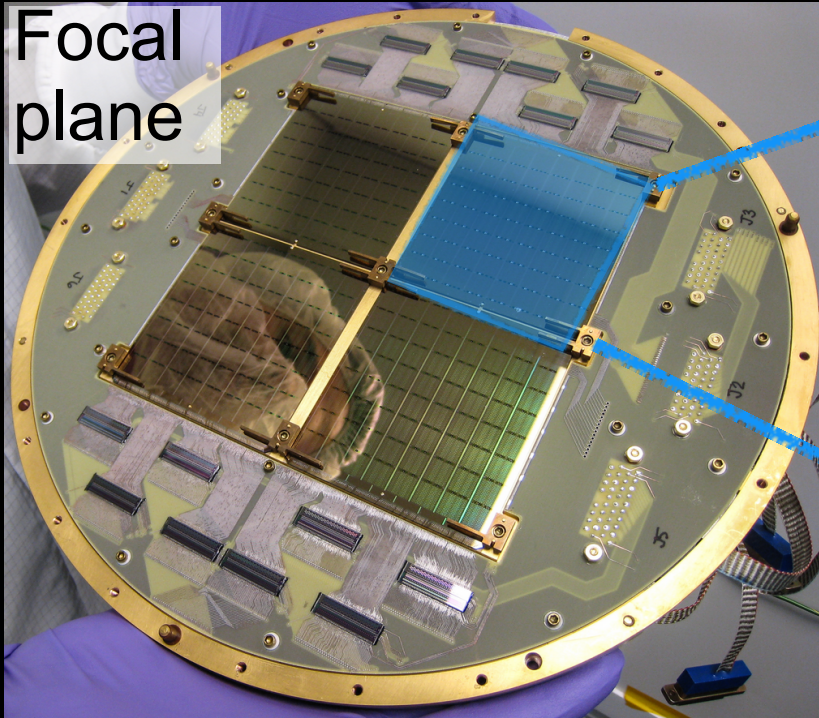
“Slump” onto machined Alumina lens
Heat- vacuum lamination
Stress relieve with laser dicing



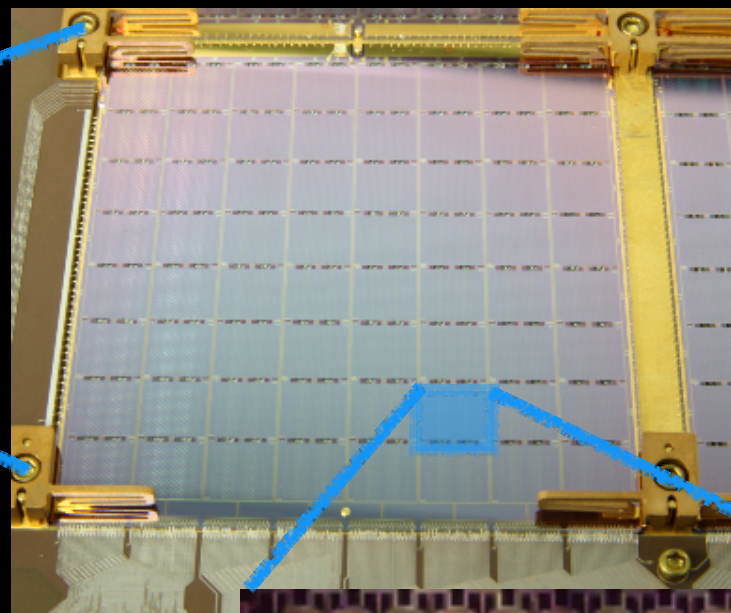
BICEP Array Vacuum window



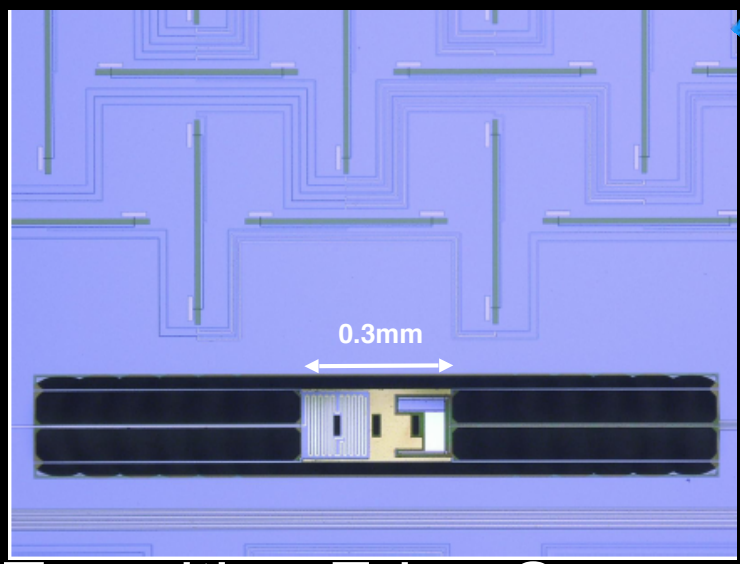
Mass-produced Superconducting Detectors



JPL



Planar antenna array



Slot antennas



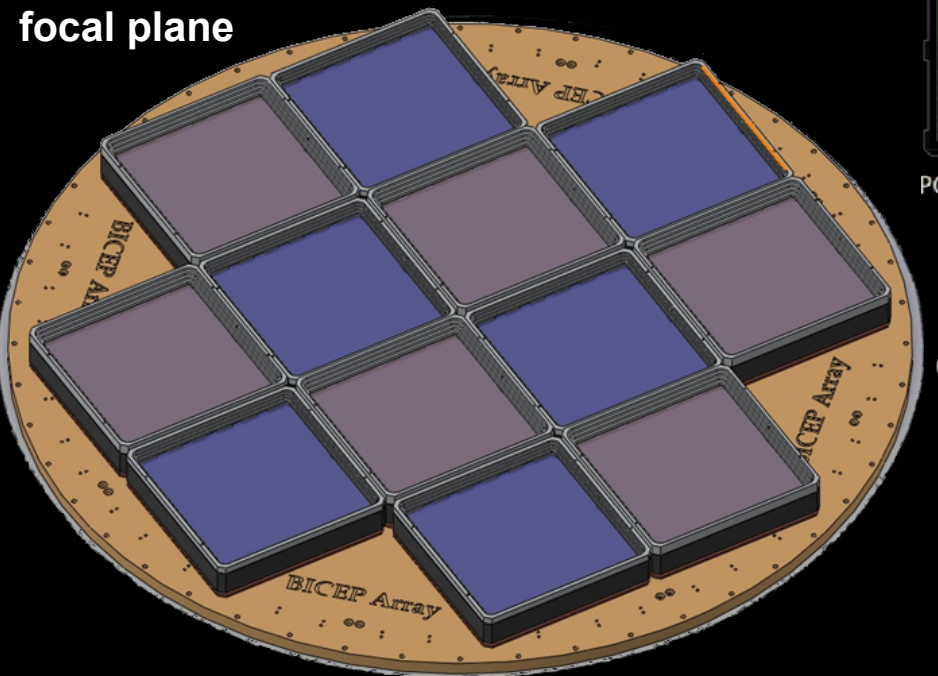
Transition Edge Sensor



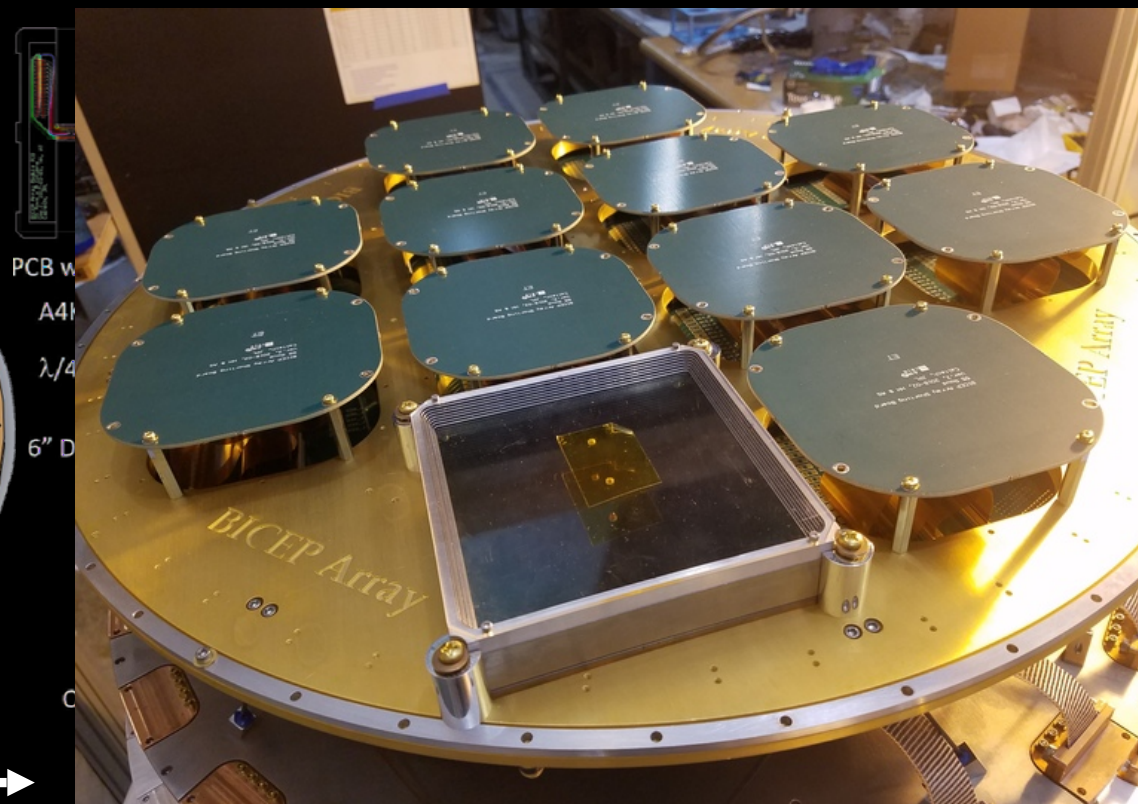
Microstrip filters

Focal plane & modules

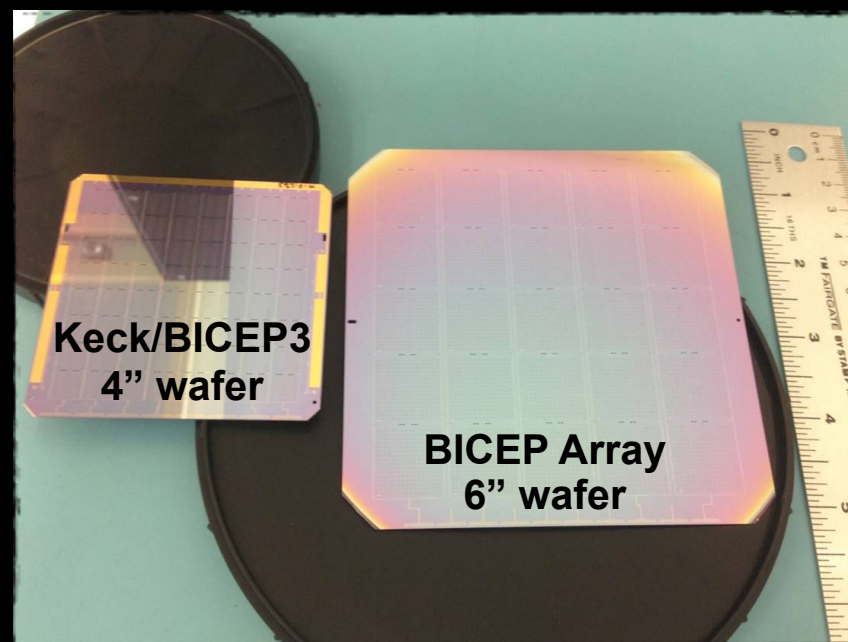
30/40 GHz
focal plane



~500 mm

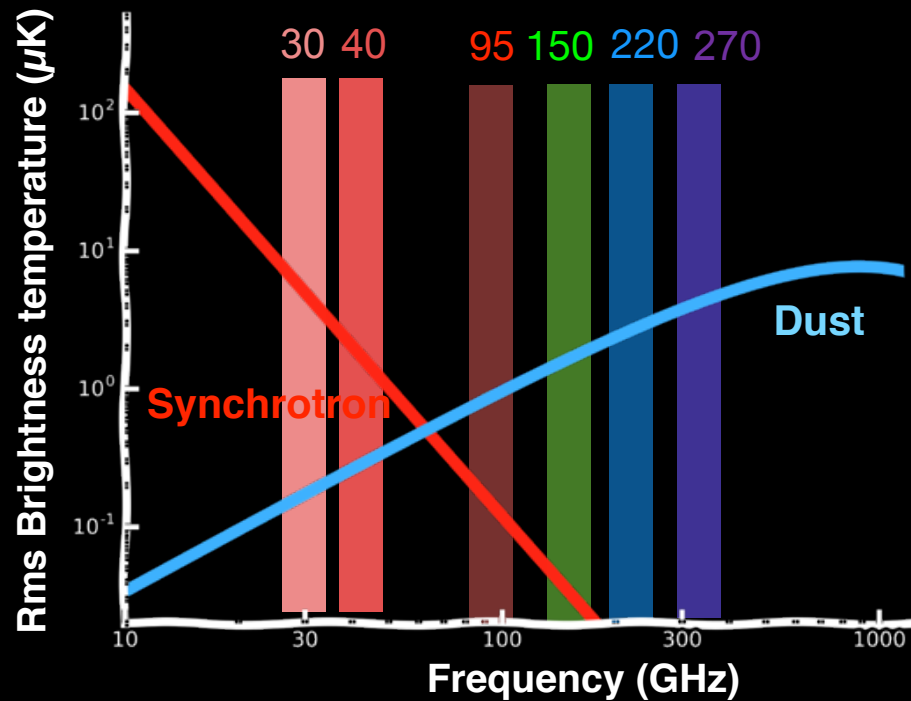


Frequency	30/40 GHz	95 GHz	150 GHz
# Detector Tiles	12	12	12
# Detectors	192 + 300	4056	7776
# Detectors/Tile	32 + 50	338	648
# SQUID MUX11 chips/Tile	6	32	64
# MCE	1	3	6
# Columns/module	2	8	16
# Rows (multiplexing factor)	33	43	42

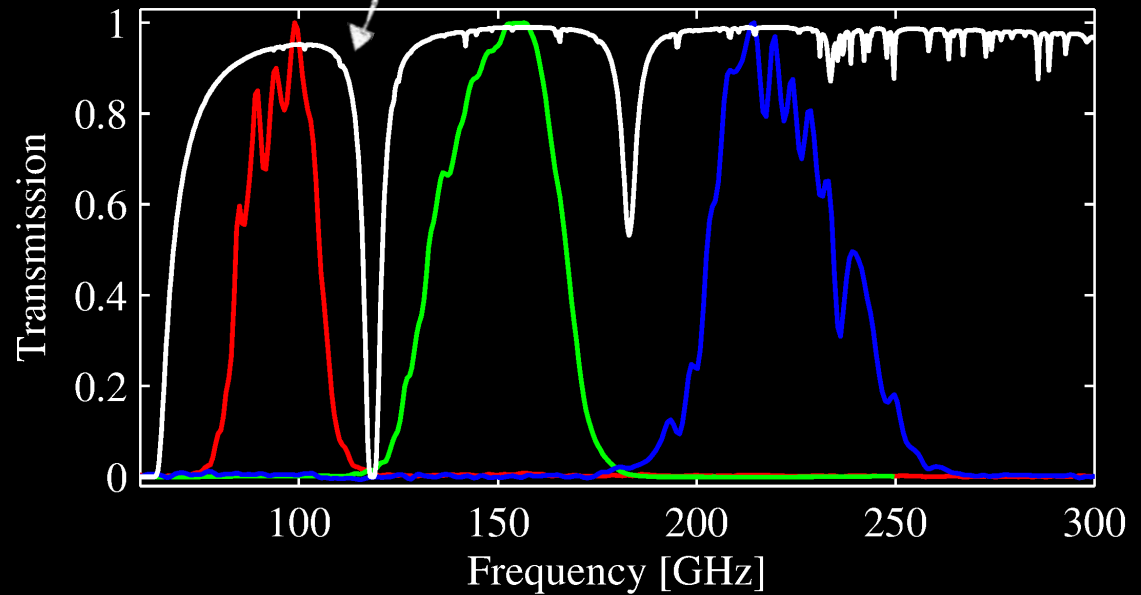


Band Response

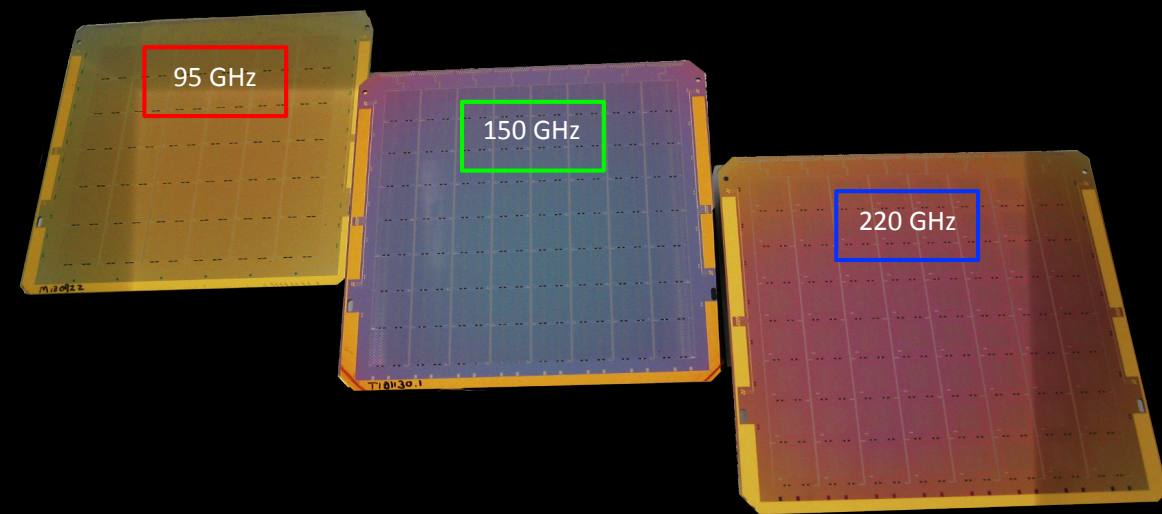
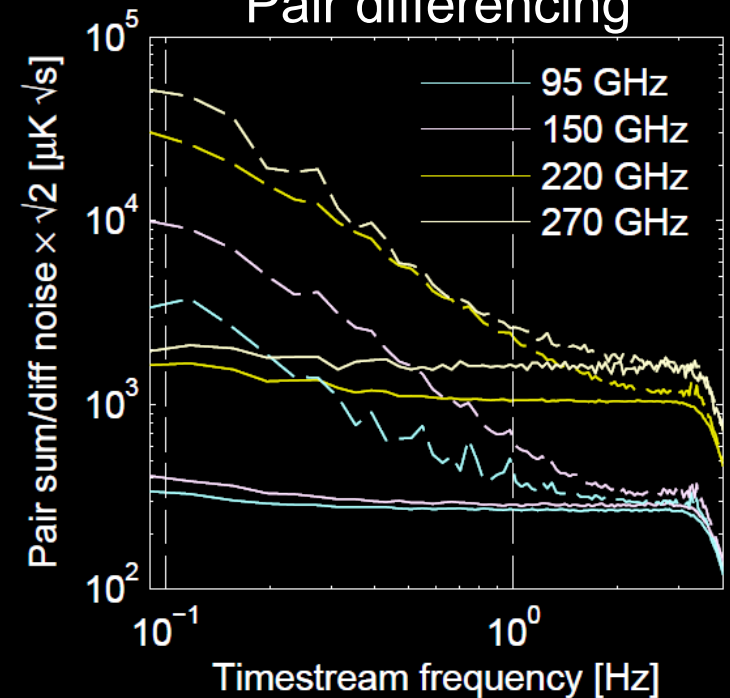
Polarized foregrounds



South Pole atmospheric transmission



Pair differencing



JPL detectors designed to scale with frequency

BICEP Array Mount under construction



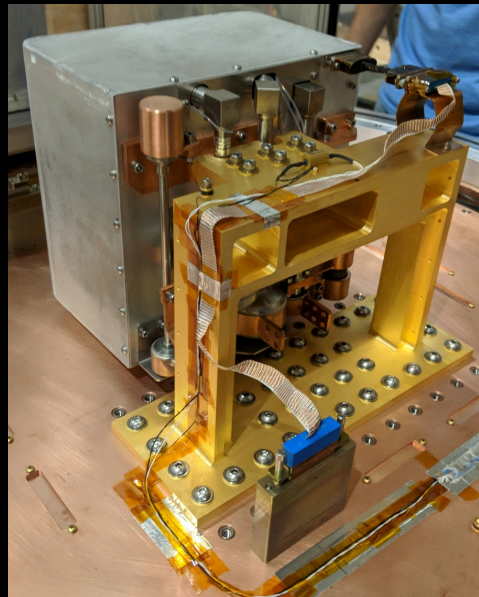
- New BK mount since BICEP1 (2005)
- 3-axis rotation:
- azimuth
 - elevation
 - boresight (for polarization modulation and systematics control)





BICEP Array under construction

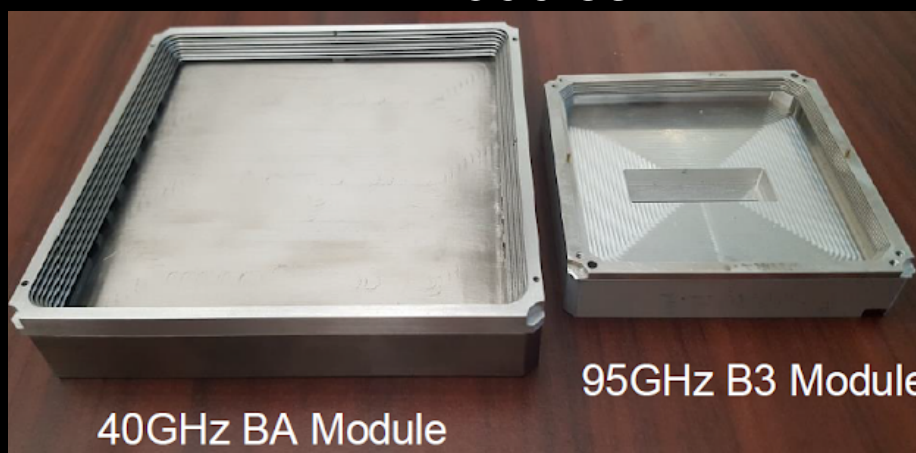
300mK sorption fridge



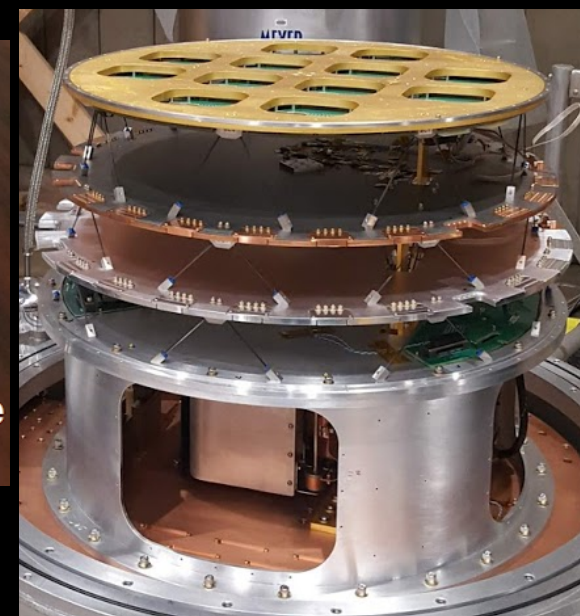
FPU & niobium magnetic shield



Modules

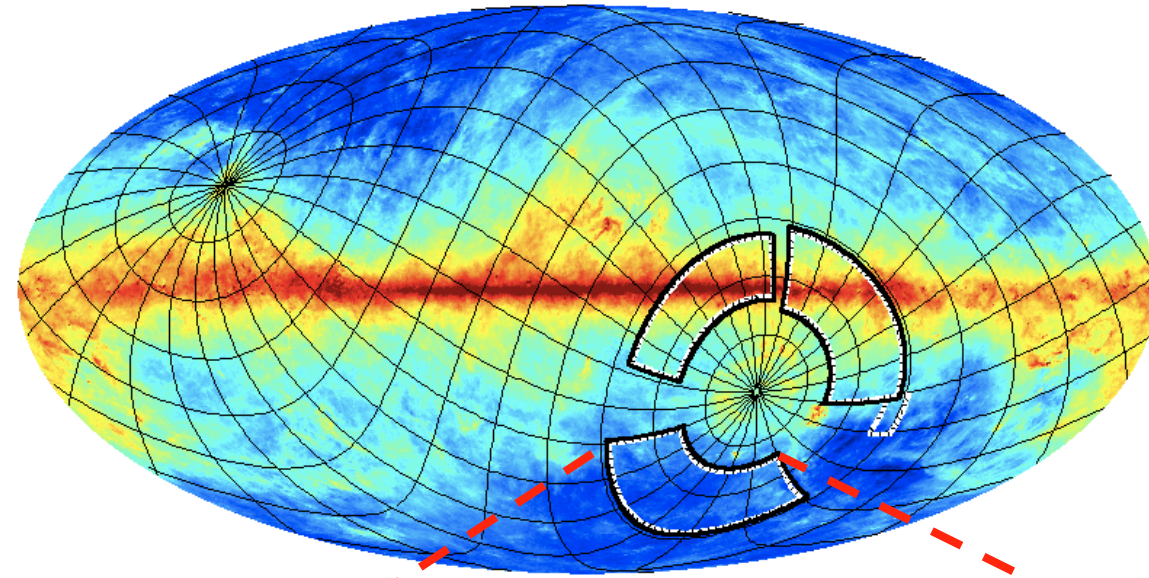


Insert truss

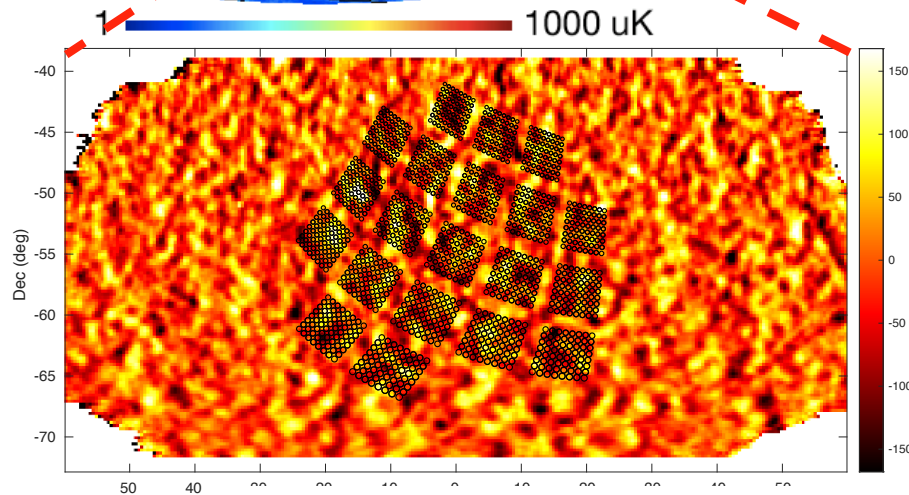


Observed Field

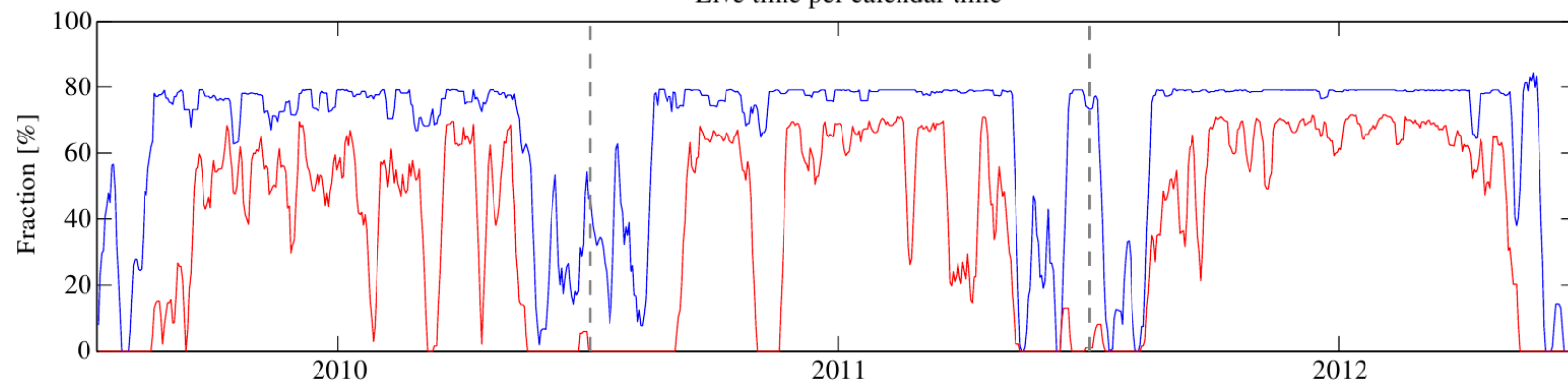
100 GHz FDS Dust Model



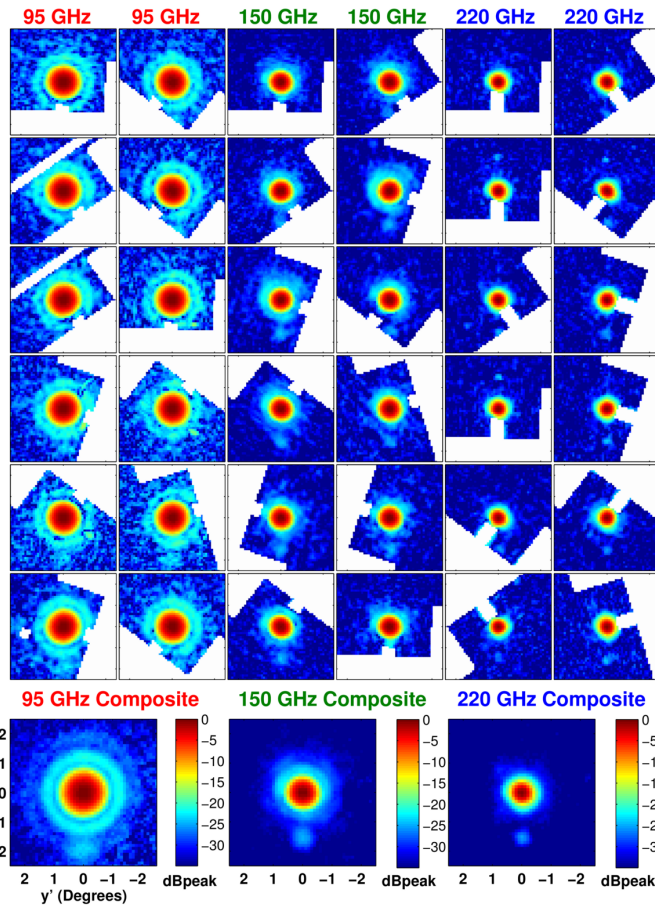
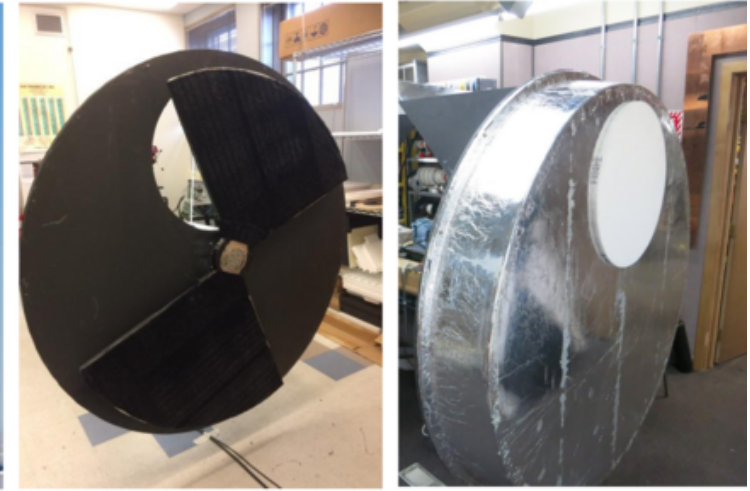
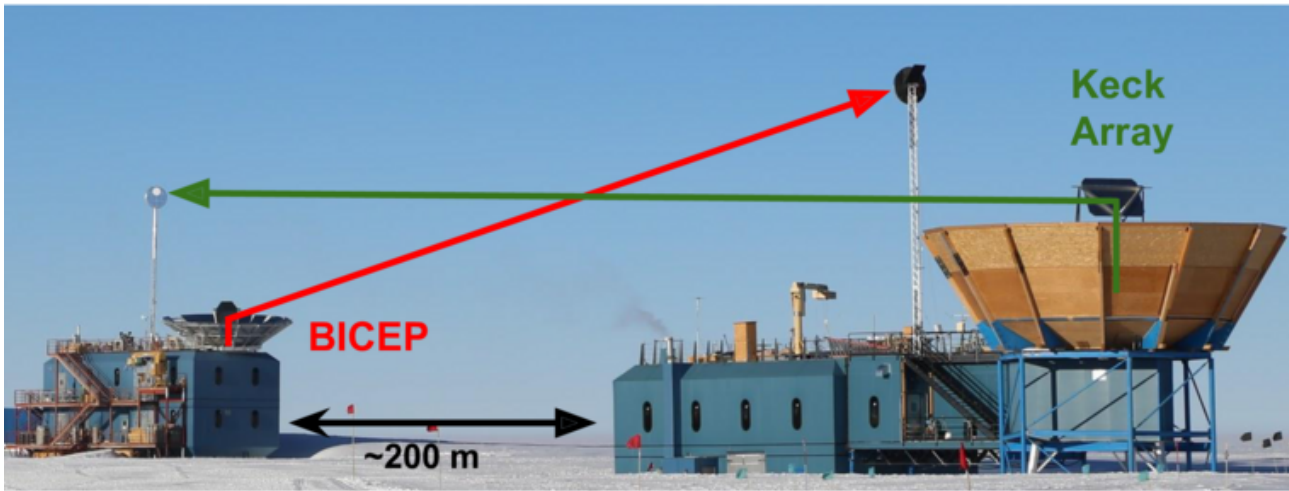
- 30deg FOV
- 400 deg² patch in Southern Galactic Hole
- Chosen in 2004 to to minimize dust and synchrotron foreground intensity emission in that small patch of sky
- Continuous azimuth raster scans
- 1 full map every 18hours.
- Repeat at 8 different dk angles.
- High efficiency integration



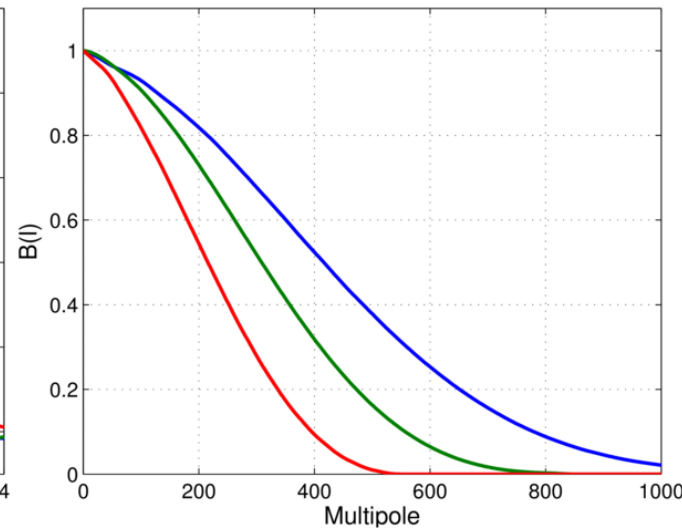
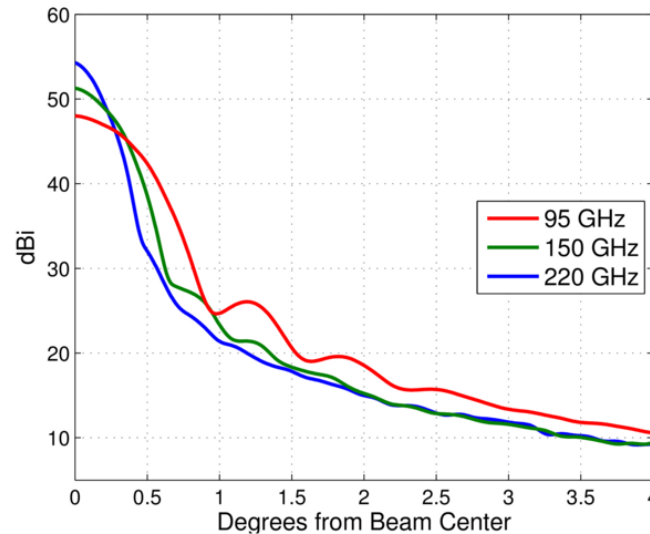
Live time per calendar time



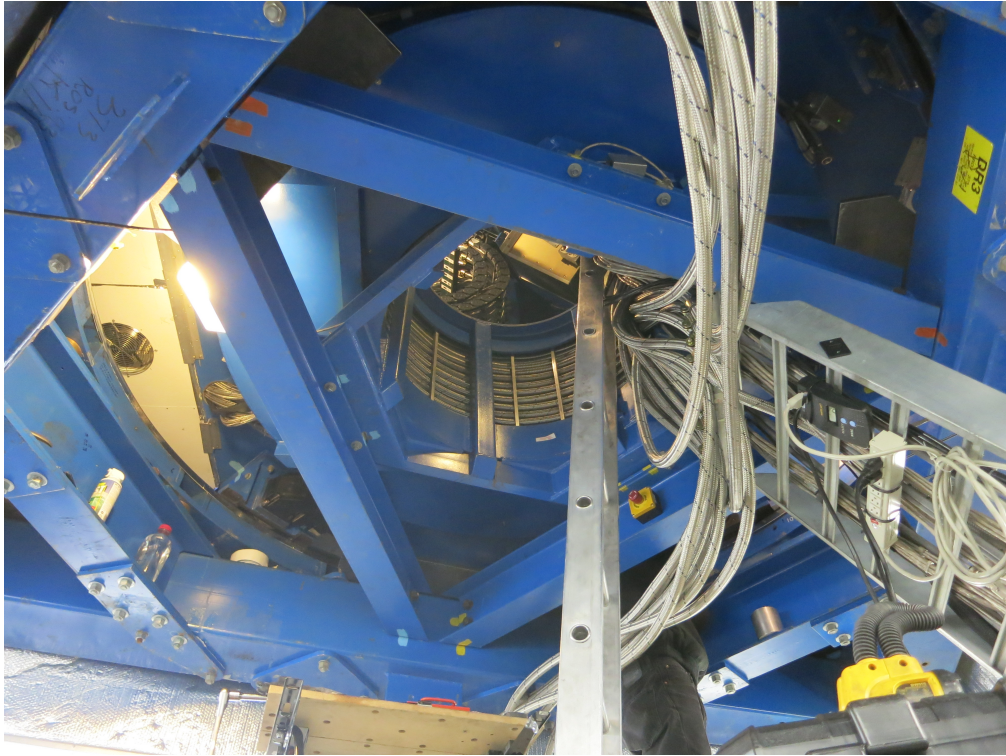
Precision Beam Measurements *in situ* at South Pole



Small aperture \rightarrow far field close by
 Chopped blackbody source, 24" aperture spinning at 16 Hz
 Scan across source at multiple boresight angles
 Mask out ground-fixed contamination and coadd to form composite
 From 2010-2015, measured 10368 distinct beam patterns
 arXiv:1904.01640



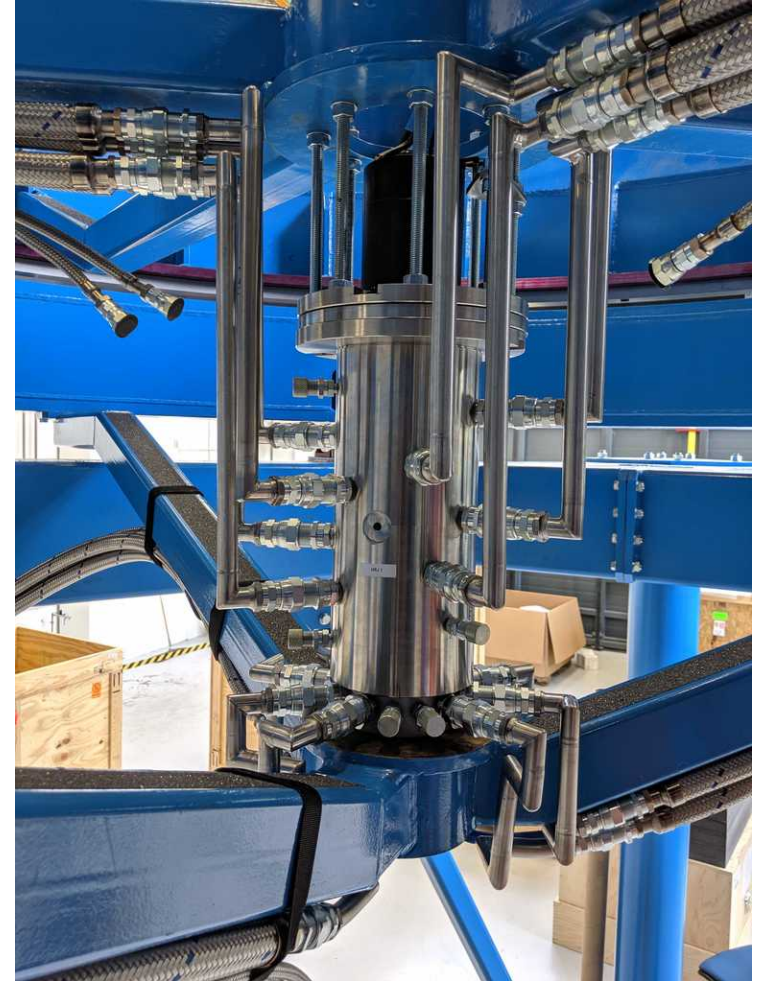
Pulse tube cryocooler on a 3-axis mount



Keck array mount:

12 Helium flex lines in large 3m-diam azimuth cable wrap.

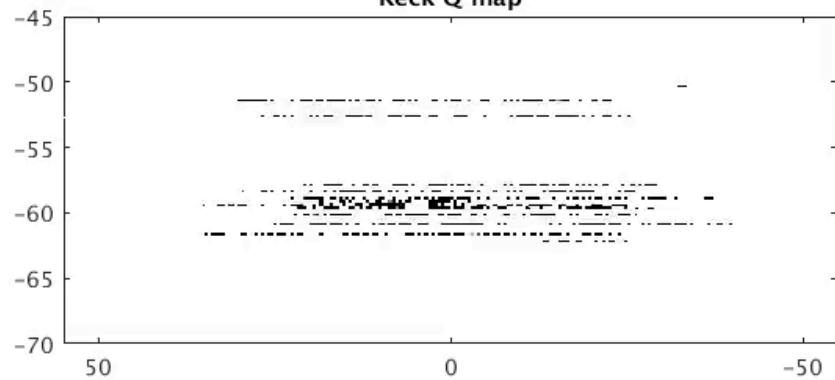
- Space consuming
- He flex line failures due to metal fatigue (10 failures/year)



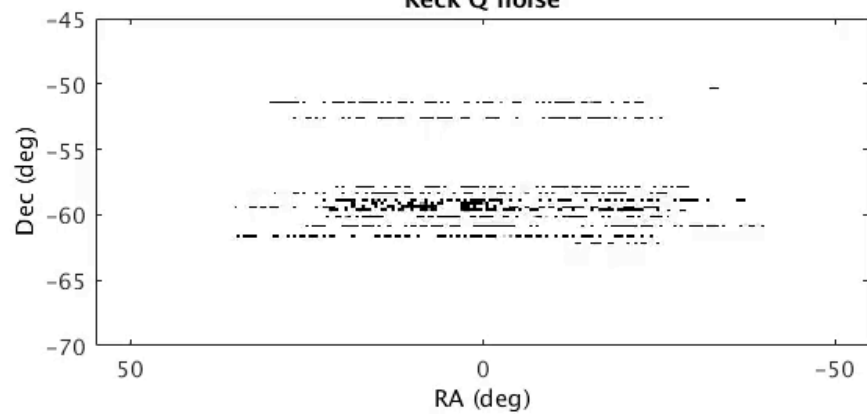
Bicep array mount: Helium rotary joint

- 12 individual passages through stator/rotor for hydraulic fluids.
- Customization for He gas
- Space efficient
- Pioneered and tested with 4way HRJ on B3.

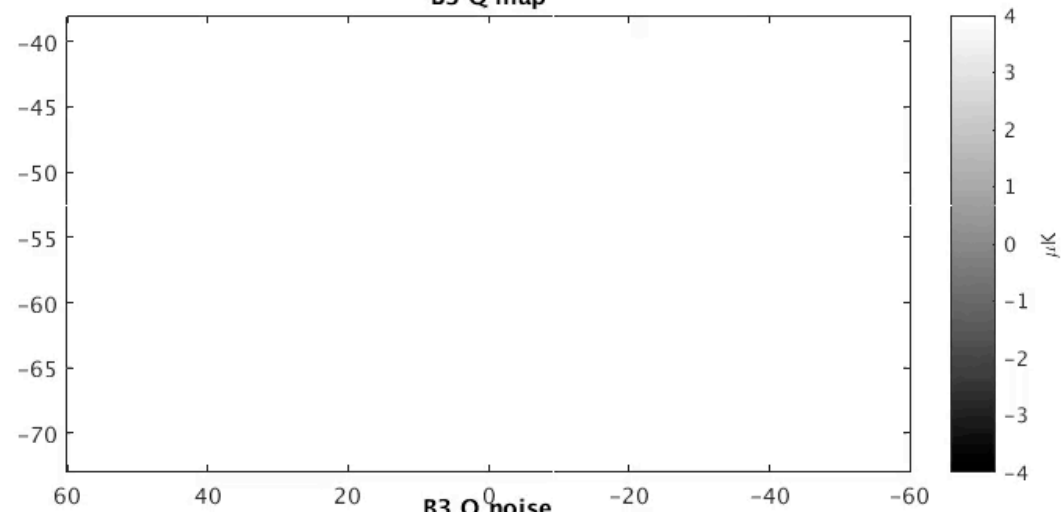
Keck Q map



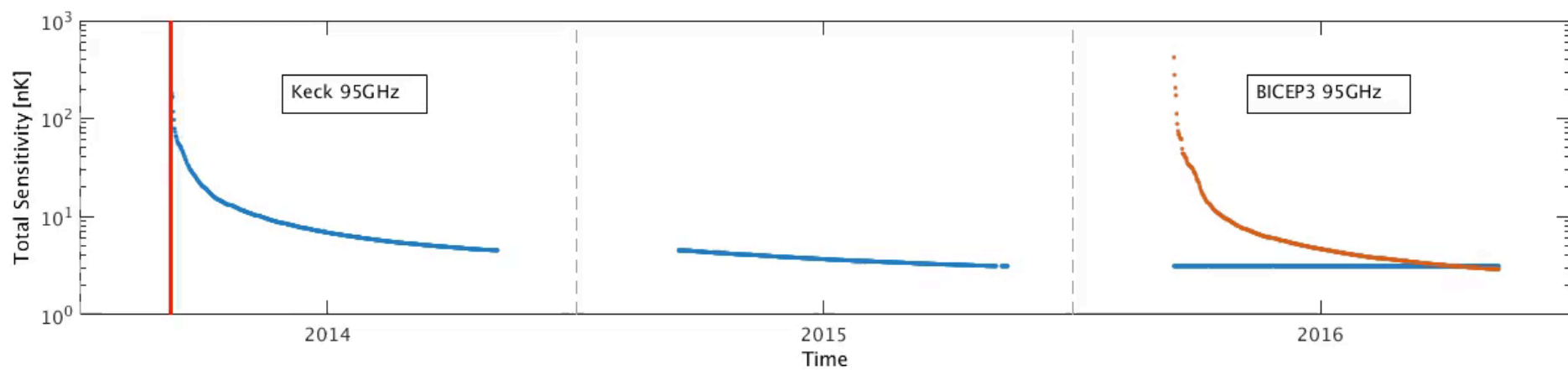
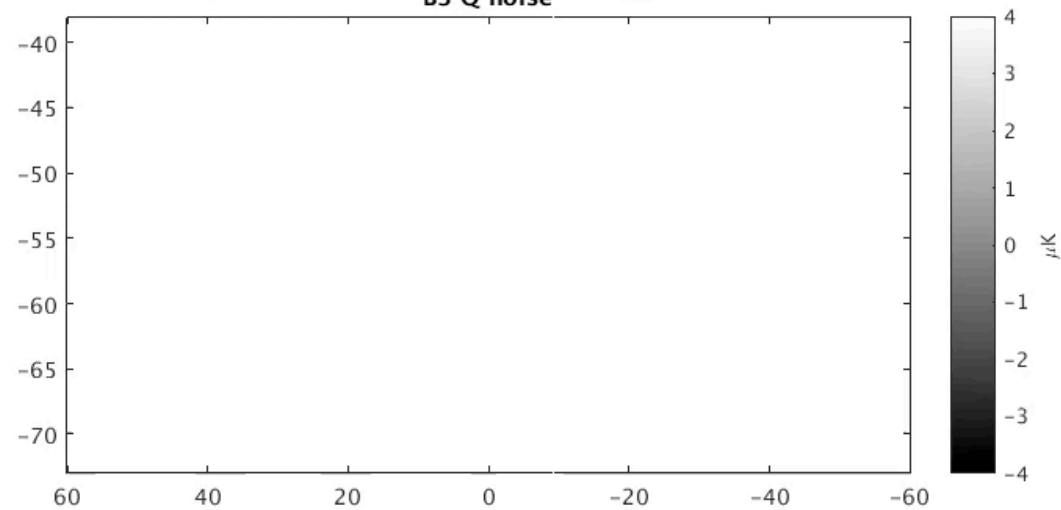
Keck Q noise



B3 Q map

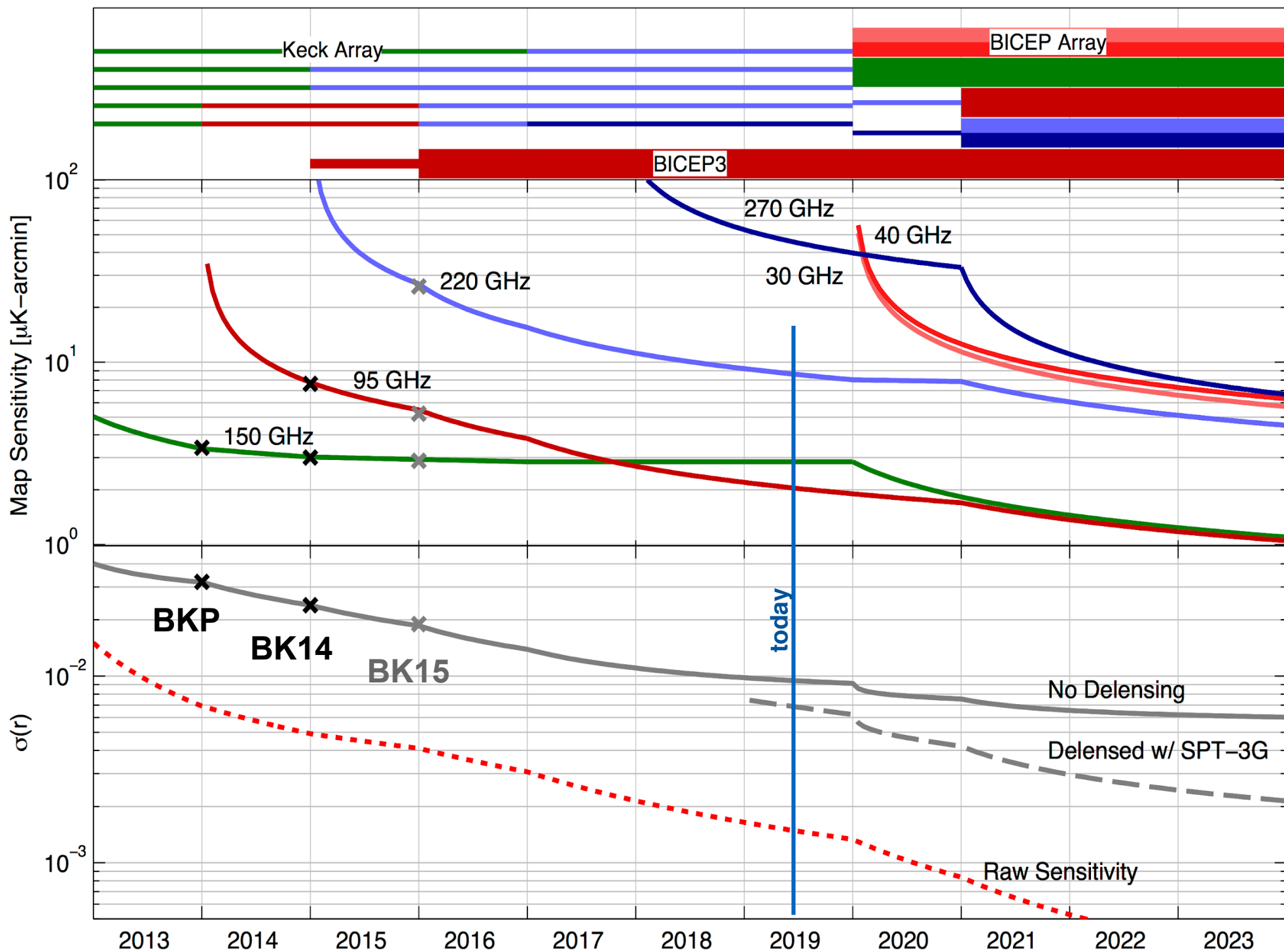


B3 Q noise



Stage 2

Stage 3





- A next generation, Stage 4, ground-based experiment to pursue **inflation**, **relic particles**, **neutrino properties**, **dark energy**, galaxy and structure evolution and new discoveries.
- Enormous increase in sensitivity over the combined Stage-3 experiments now being deployed ($>100\times$ current Stage 2) to enable CMB-S4 to cross critical science thresholds.
- $O(400,000)$ detectors spanning **20 - 270 GHz** using multiple telescopes, large and small, at **South Pole and Chile** to map most of the sky, as well as deep targeted fields.
- Broad participation of the CMB community, including those on the existing CMB experiments (e.g., ACT, BICEP/Keck, CLASS, POLARBEAR/Simons Array, Simons Obs & SPT), U.S. National Labs and the High Energy Physics community.



Thank you!

