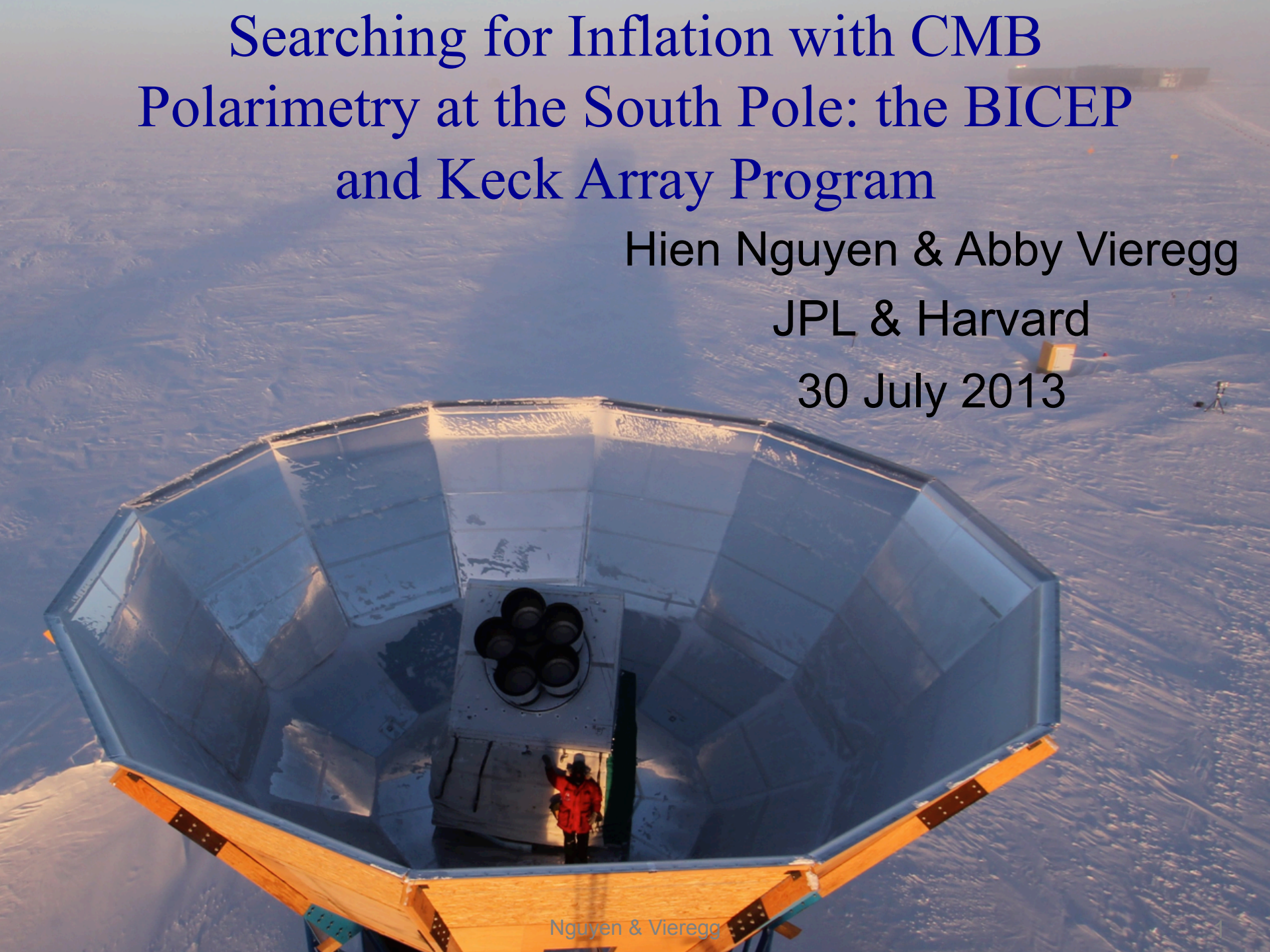
Searching for Inflation with CMB Polarimetry at the South Pole: the BICEP and Keck Array Program

Hien Nguyen & Abby Vieregg

JPL & Harvard

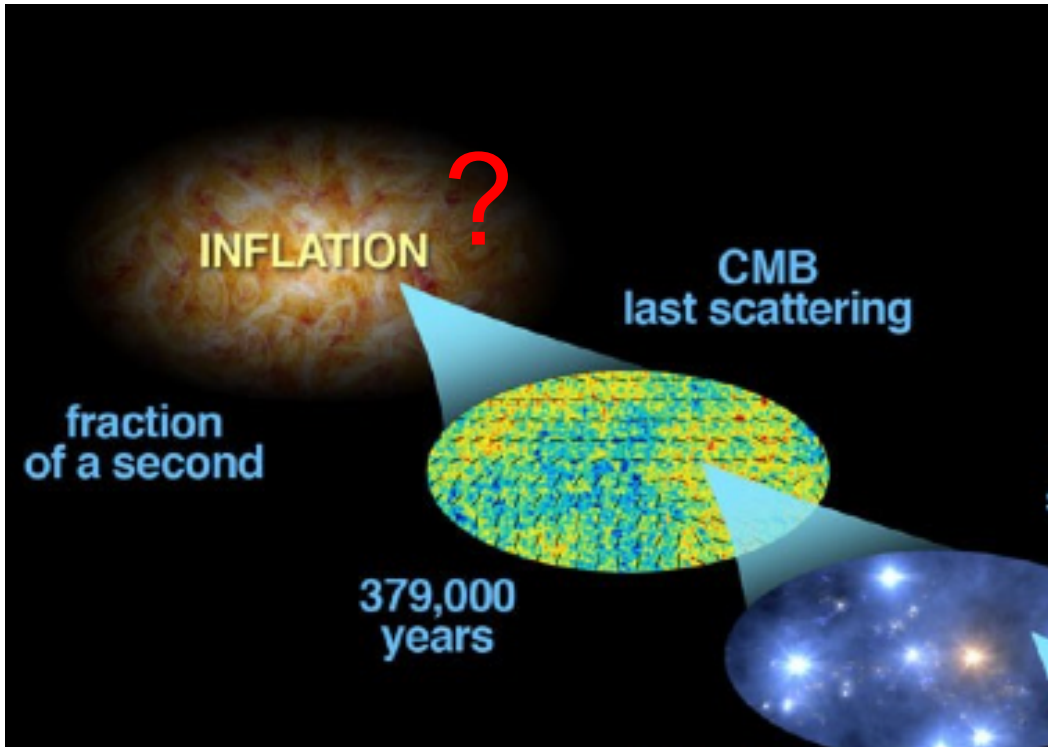
30 July 2013

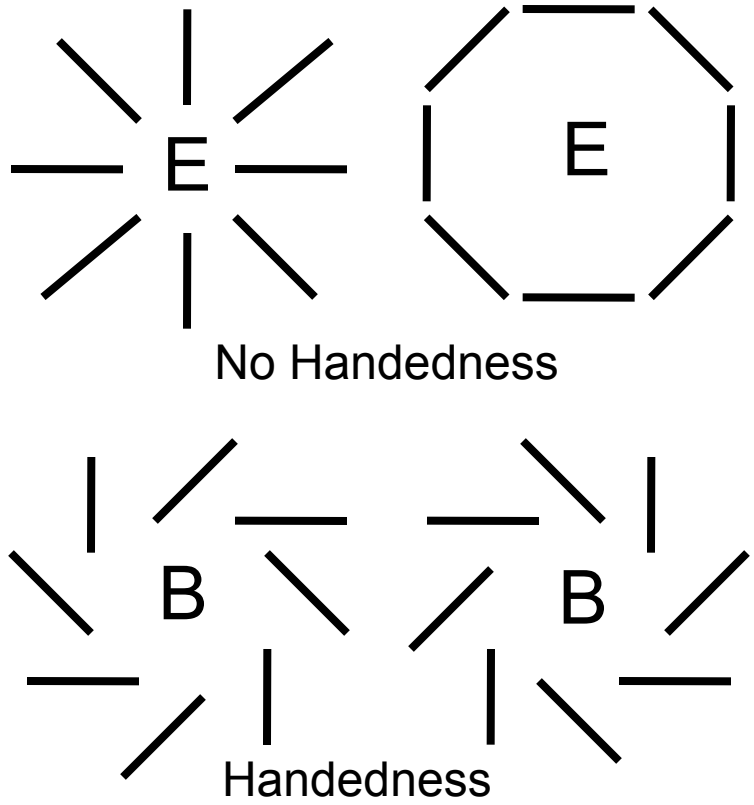


Direct Evidence for Inflation?

- Generic prediction of Inflation: primordial gravitational waves
- CMB Polarization:
  - "E-modes" from density fluctuations (first seen by DASI 2002)
  - "B-modes" a signature of gravitational waves

  → Strength scales with energy scale of Inflation





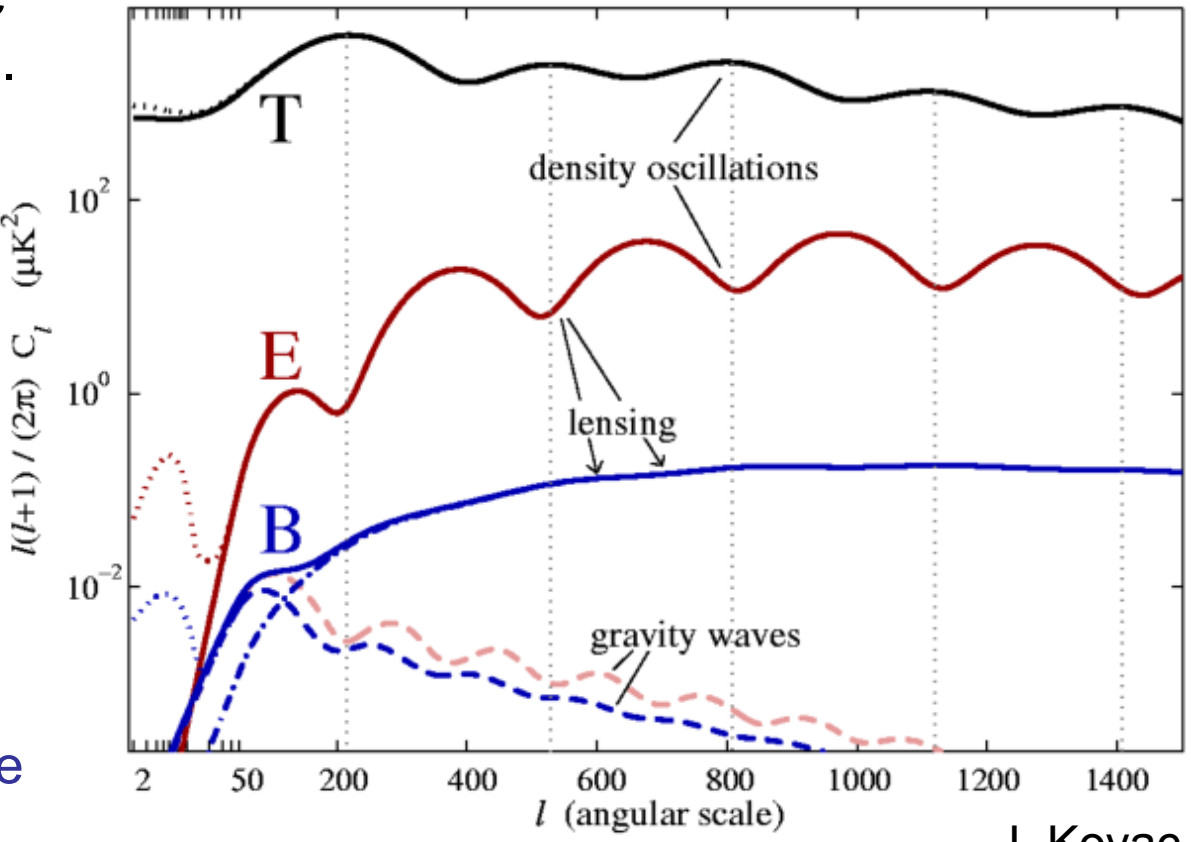
Features of the CMB Spectrum

Temperature spectrum traces density evolution of acoustic oscillations in early universe.

E-polarization spectrum:
- 10^2 lower
- correlated with T
  but out of phase

B-polarization spectrum:
- 10^2 - 10^3 lower still!
- gravitational waves:
  large angular scale
- lensing: small angular scale

B-modes are a teeny signal! Hard to detect!



J. Kovac

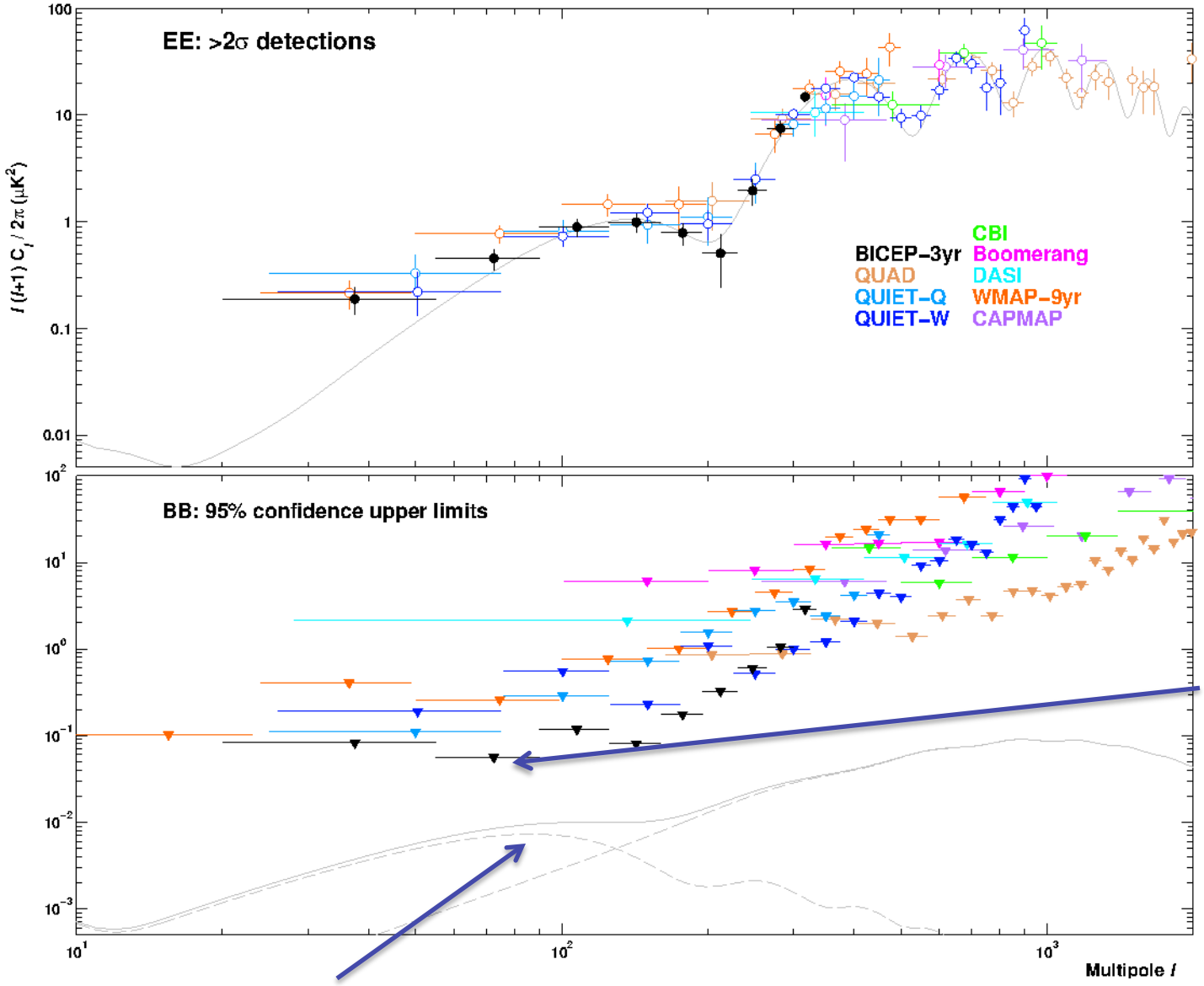
Why Bother with B-modes?

We need CMB polarization measurements to push deeper on the tensor-to-scalar ratio r!

- SPT + WMAP7 + BAO + H_0: $r < 0.11$
  (Story et al., 2012)
- Planck + WMAP (pol.): $r < 0.12$
  (Planck Collab. XXII, 2013)
- Theoretical limit from sample variance for CMB temperature measurements: $r < 0.1$
  (Knox & Turner, 1994)

→ Can't do better with temperature alone

Published CMB Polarization Results to Date



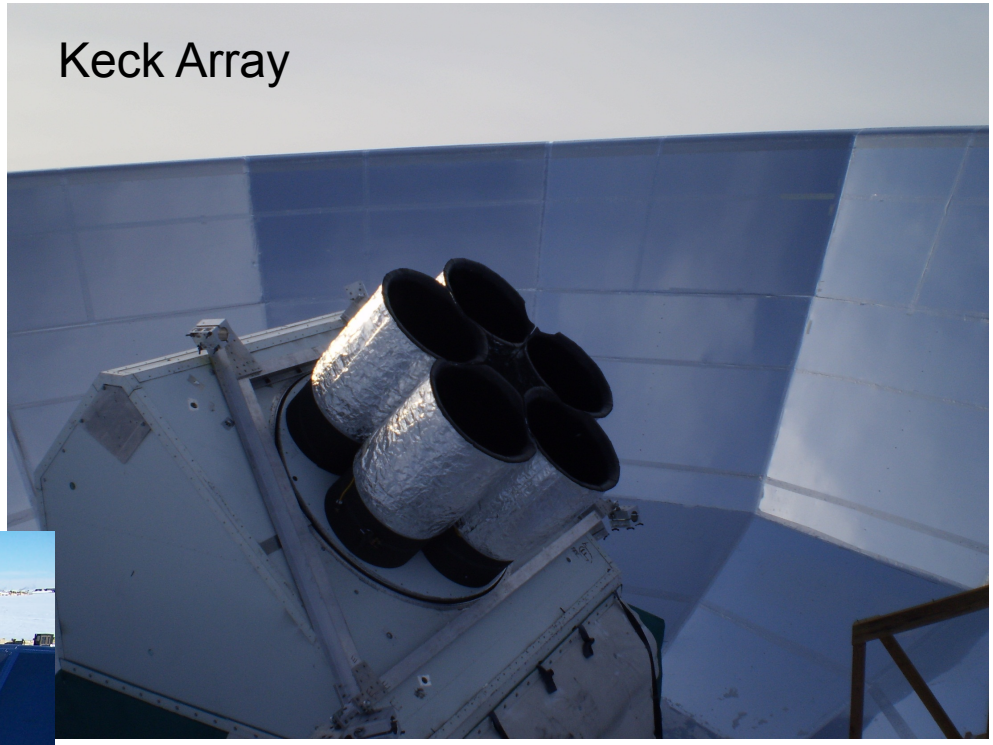
Barkats et al. 2013, in Prep

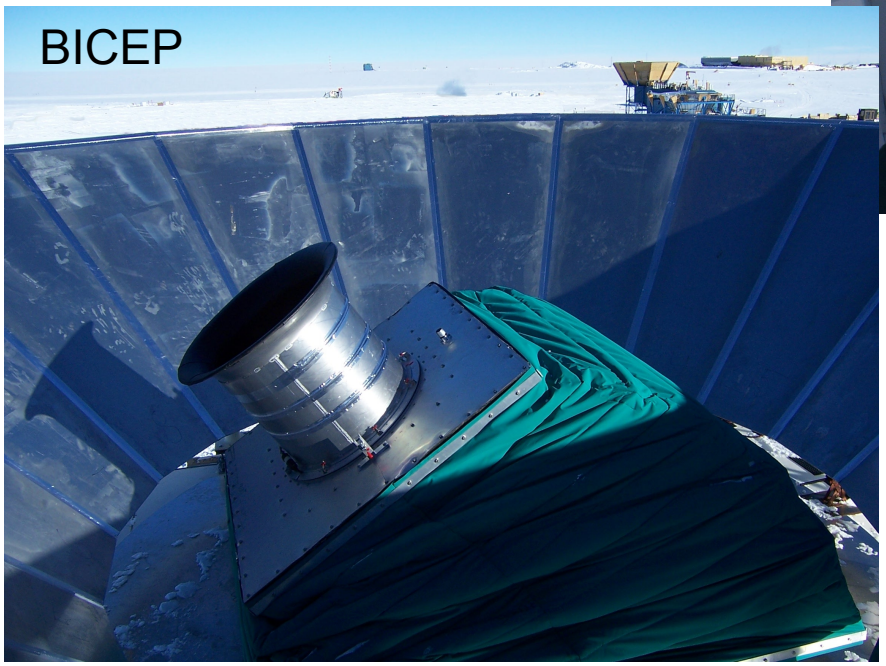
Best limit on r (tensor-to-scalar ratio) is from BICEP1!

$\ell = 100$ peak, r=0.1

BICEP/Keck Array Program

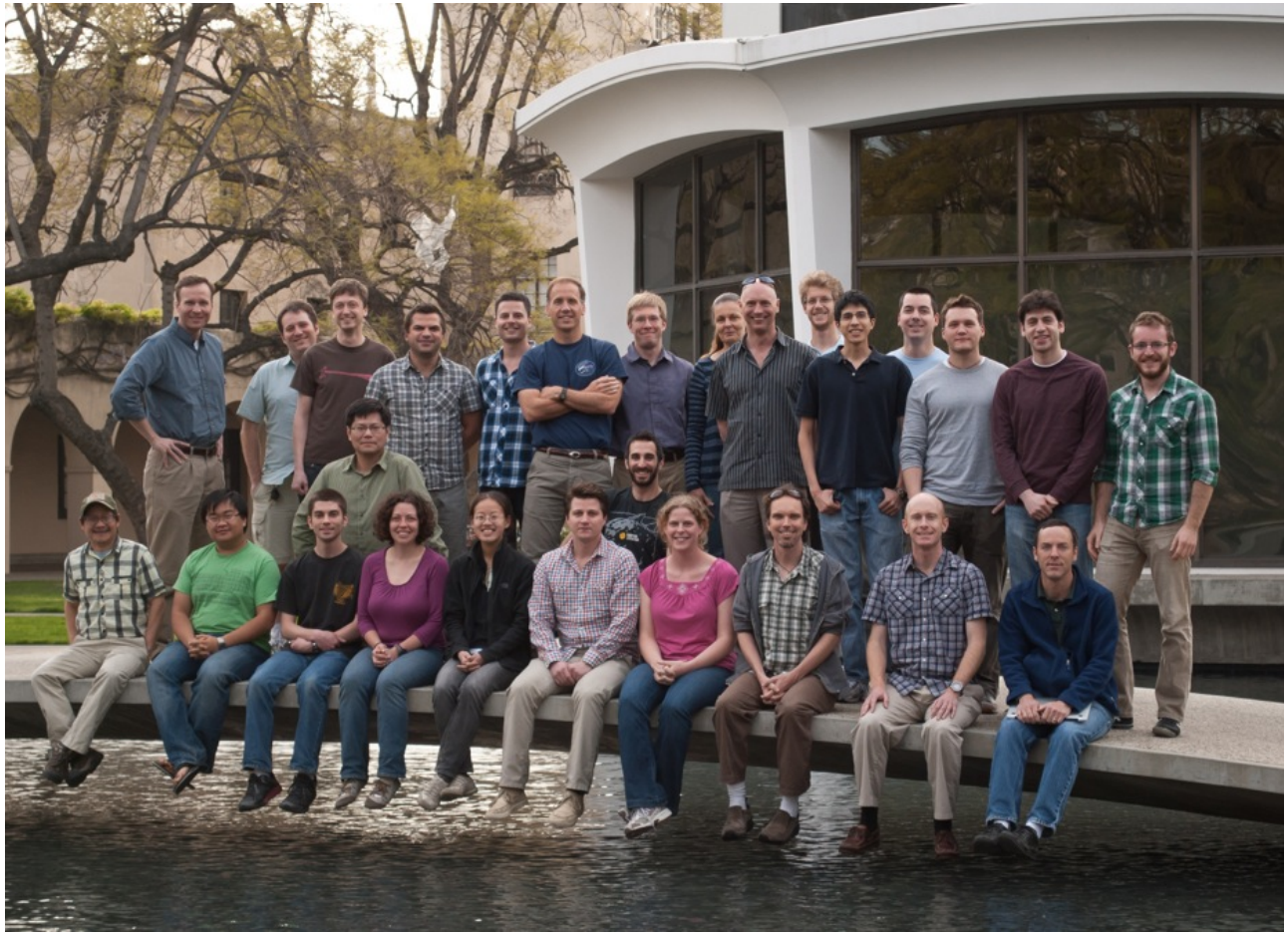
Purpose-built machines targeted to look for the inflationary B-mode polarization signature in the CMB





→ With BICEP/Keck Array program, we have the sensitivity and systematics control to get to r=0.01

The BICEP/Keck Array Collaboration



- British Columbia
- Caltech
- CEA Grenoble
- Chicago
- Harvard
- JPL
- Minnesota
- NIST
- Stanford
- Toronto
- Wales Cardiff

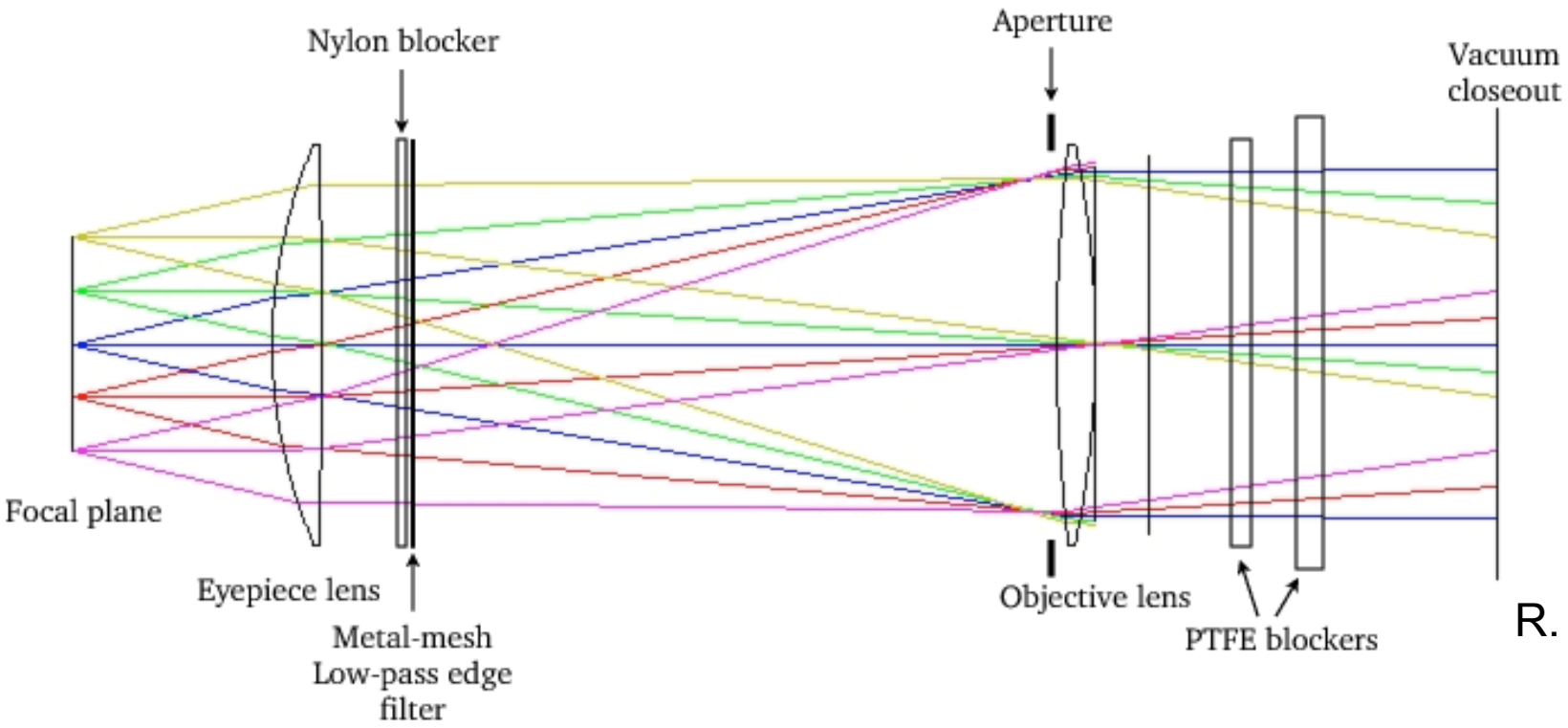
The BICEP/Keck Array Strategy

- Small Aperture
- Compact, single-frequency, refractive telescopes
- Stare deep into clean patch of sky
- Start with 150 GHz until you see B-modes
- Observe from the best high, dry, stable site
- Lots of detectors & tight control of systematics

Small Aperture Telescopes

12” aperture defines half degree beams
→ target peak of inflationary B-mode spectrum

BICEP/Keck Array Optical Design



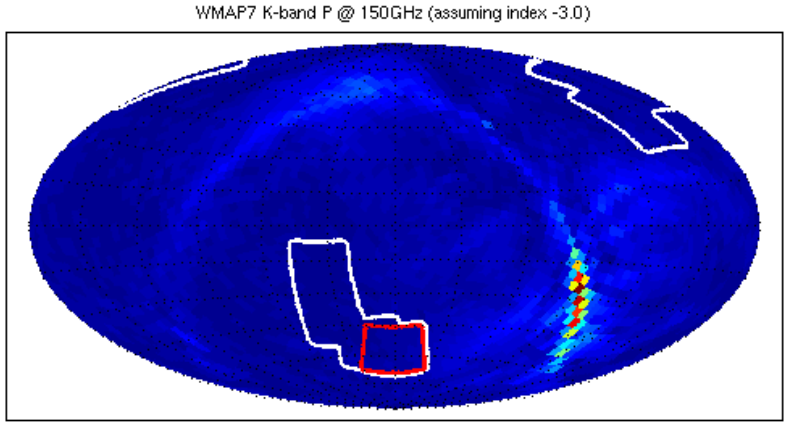
R. Aikin

- On-axis, refractive telescope
- Large field of view
- High throughput
  - Compact, co-mount five telescopes

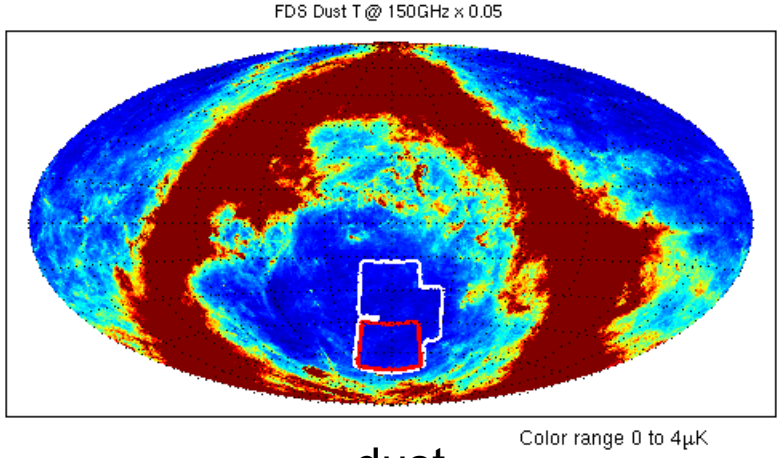
- Good control of systematics
  - All cold optics (4K)
  - Multiple stages of baffling
  - Rotation about boresight

Observe Where Foregrounds are the Smallest

"Southern Hole"

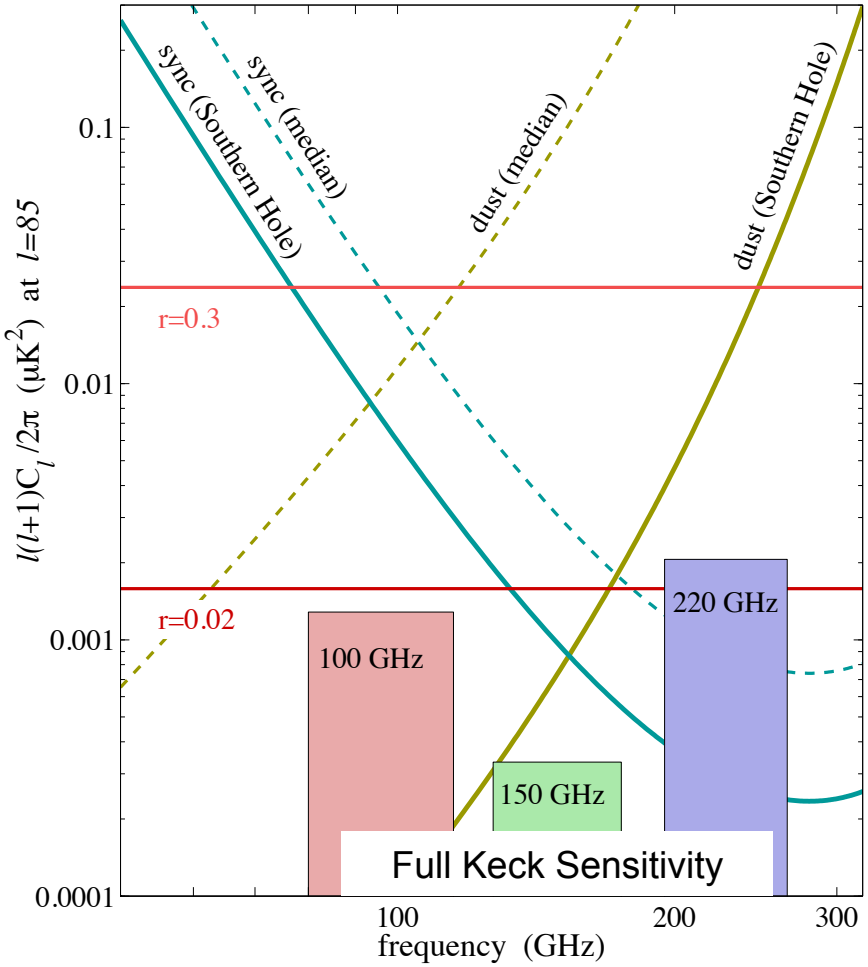


synchrotron



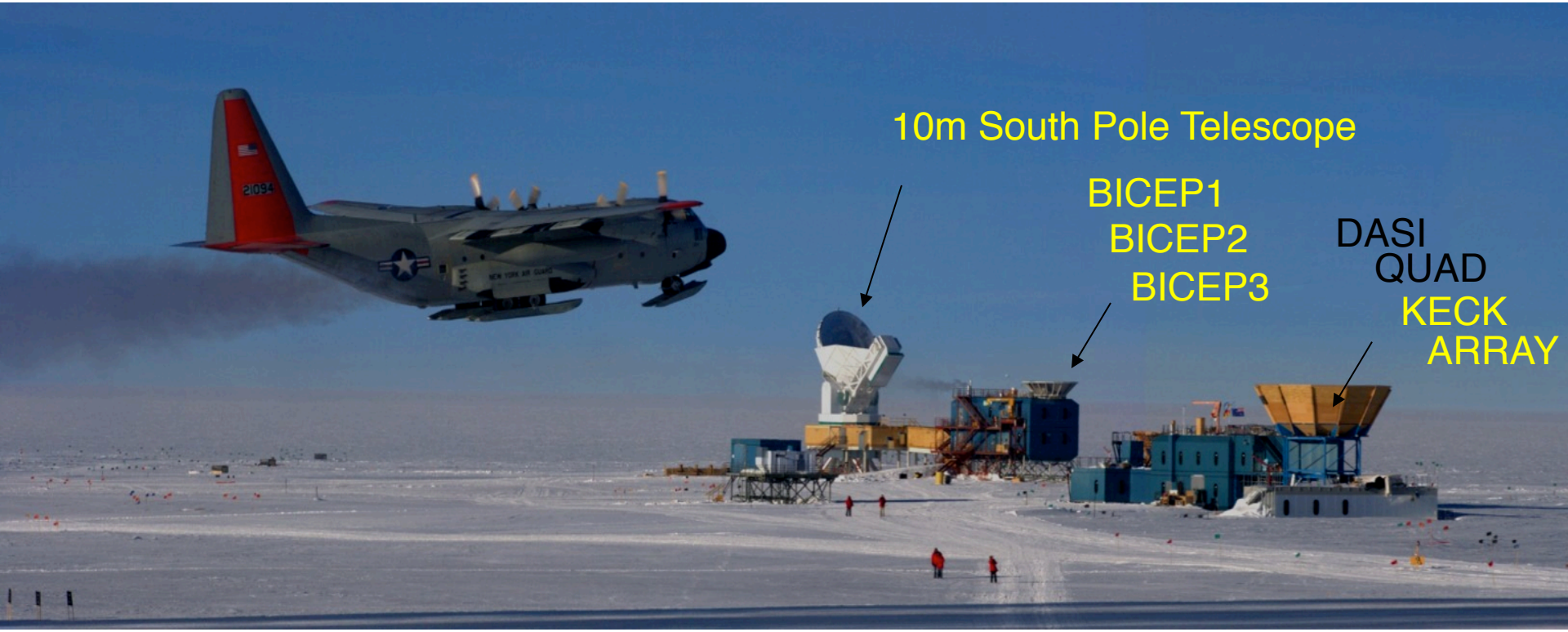
dust

@ 150 GHz (until you see B-modes)



Pryke & Kovac

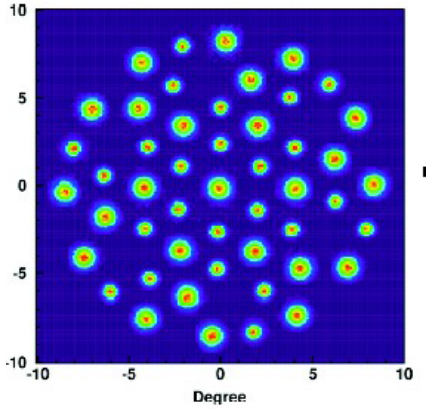
Observe from the South Pole



- Extremely stable, dry atmosphere
- Pressure altitude: 10,500 ft
- One night and one day per year
- High Observing Efficiency
  - “Southern Hole” visible 24/7

The Quest for More Sensitivity

BICEP1
2006-2008

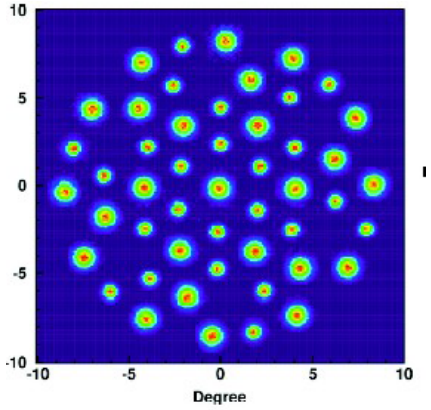


50 @ 100 GHz
48 @ 150 GHz

Current best limits on Inflationary polarization

The Quest for More Sensitivity

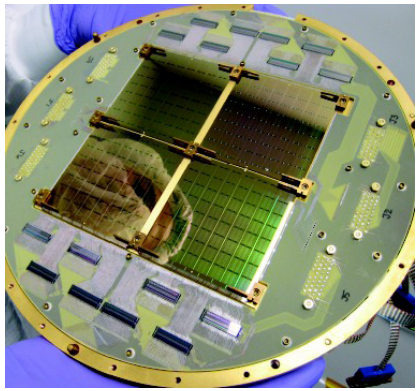
BICEP1
2006-2008

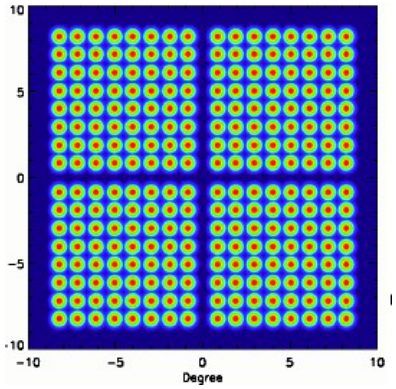


50 @ 100 GHz
48 @ 150 GHz

Current best limits on Inflationary polarization

BICEP2
2010-2012





512 @ 150 GHz

x10 mapping speed

The Quest for More Sensitivity

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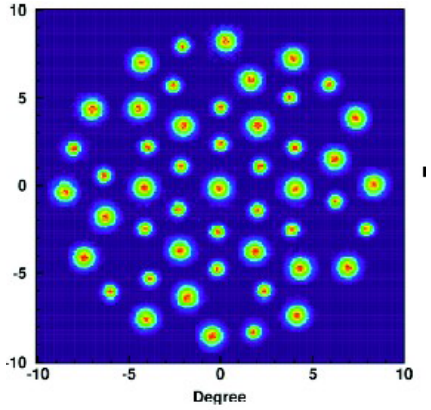
2006-2008



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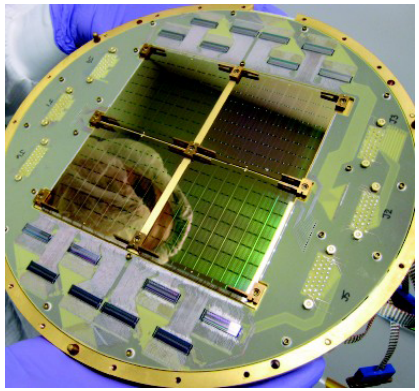
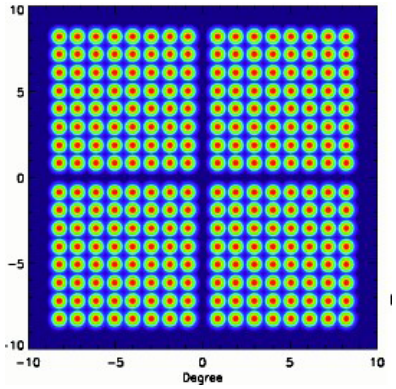
Current best limits on Inflationary polarization

BICEP2
2010-2012

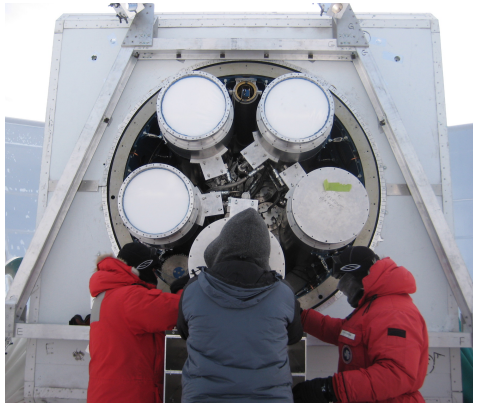


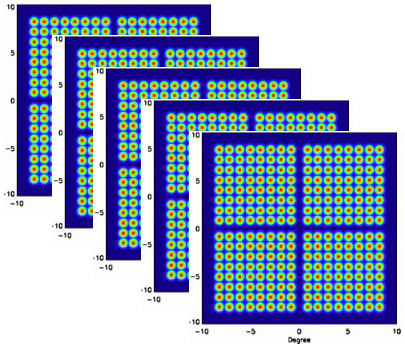


512 @ 150 GHz

x10 mapping speed

Keck Array
3 x deployed Jan 2011
2 x deployed Jan 2012
4 Years of Observation



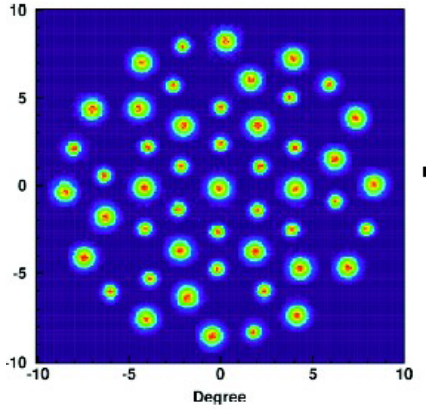


5 x 512 @ 150 GHz
(plans for 100 GHz and 220 GHz)

x50 mapping speed

The Quest for More Sensitivity

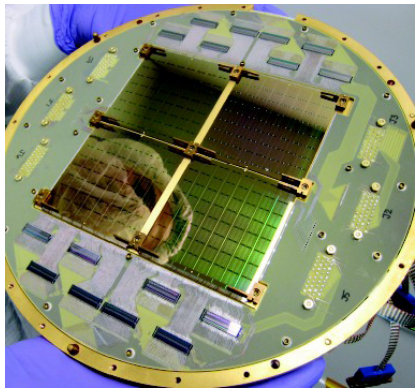
BICEP1
2006-2008

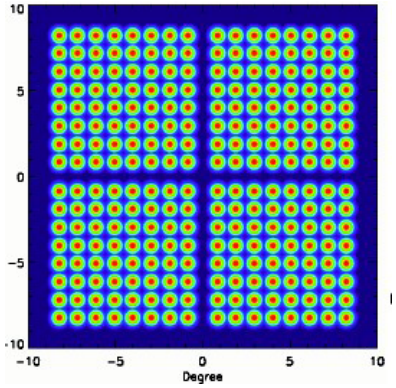


50 @ 100 GHz
48 @ 150 GHz

Current best limits on Inflationary polarization

BICEP2
2010-2012





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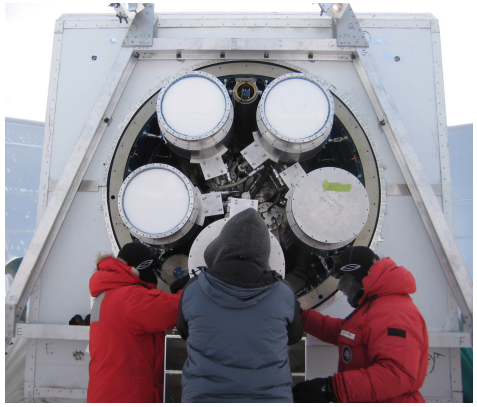
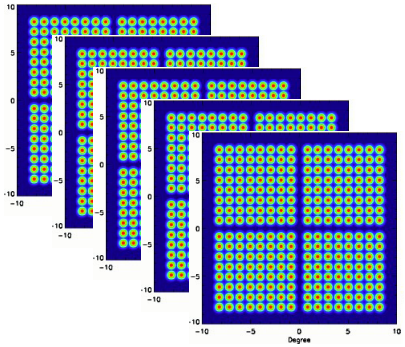
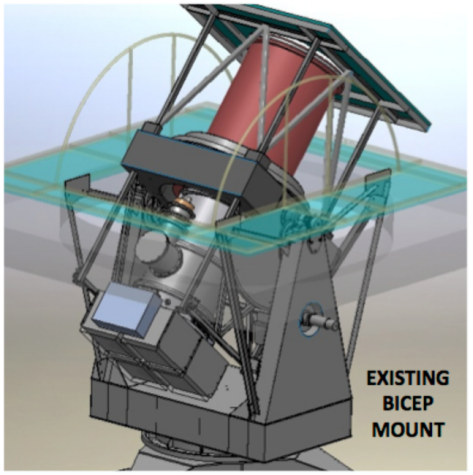


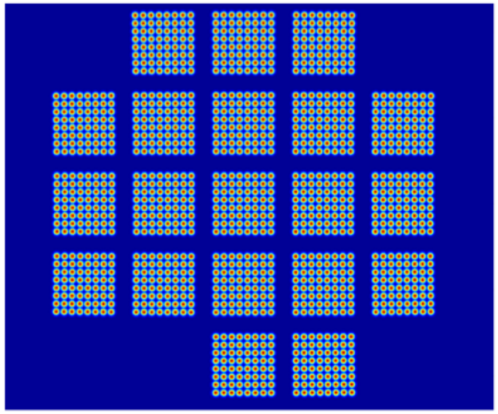


5 x 512 @ 150 GHz
(plans for 100 GHz and 220 GHz)

x50 mapping speed

BICEP3
Will Deploy in 2014

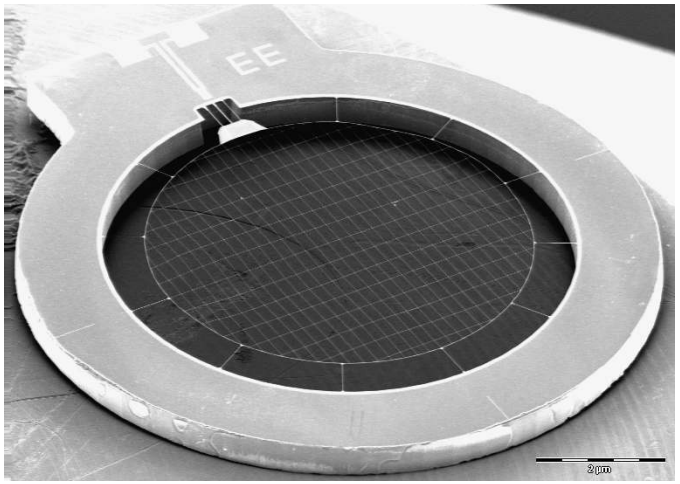


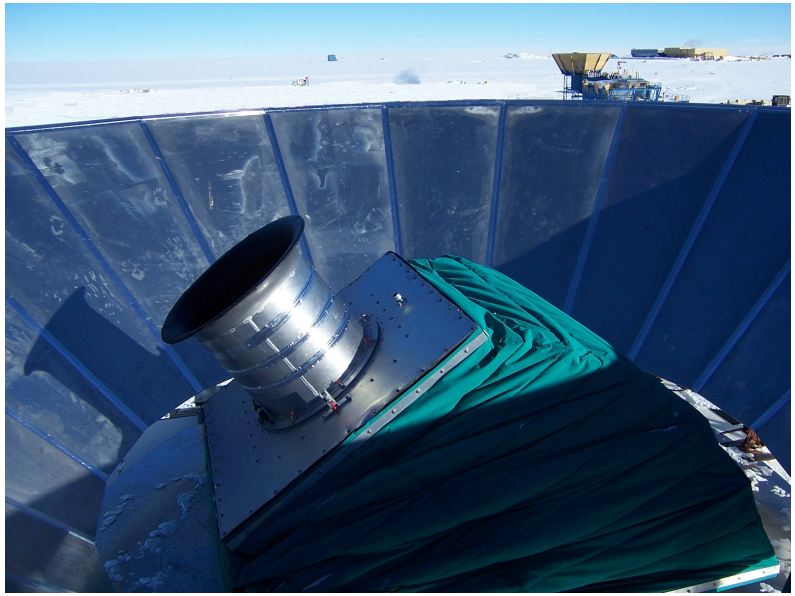


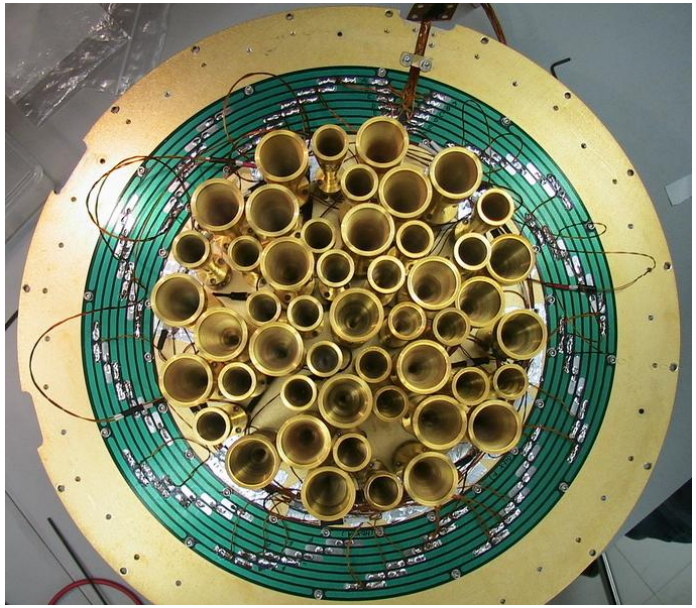
2056 @ 100 GHz

BICEP1 (2006-2008)

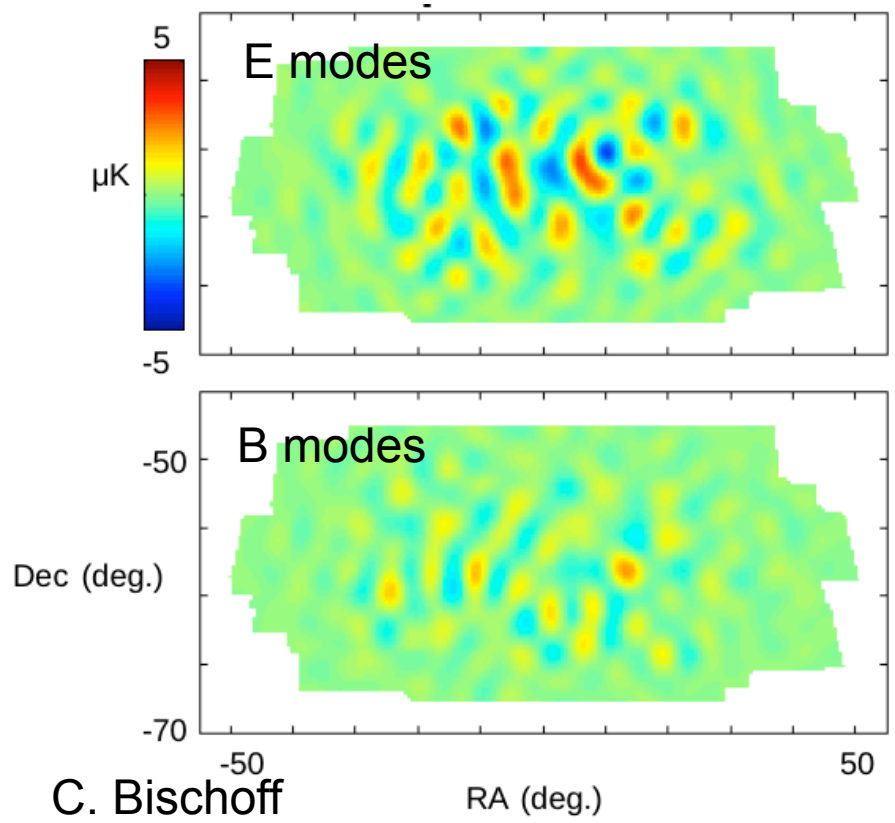
- 49 pairs of feed horn-coupled polarization sensitive NTD bolometers
- 100 & 150 GHz
- 2 year results: r < 0.72 (Chiang et al. 2009)



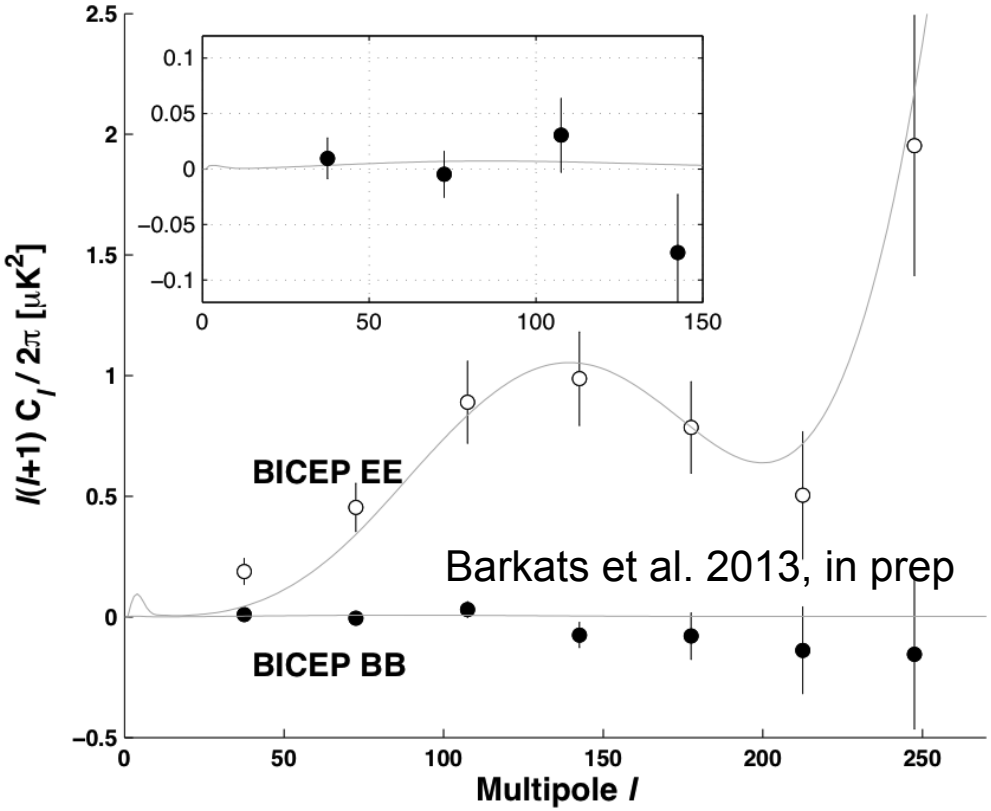




BICEP1 New 3-Year Result



C. Bischoff



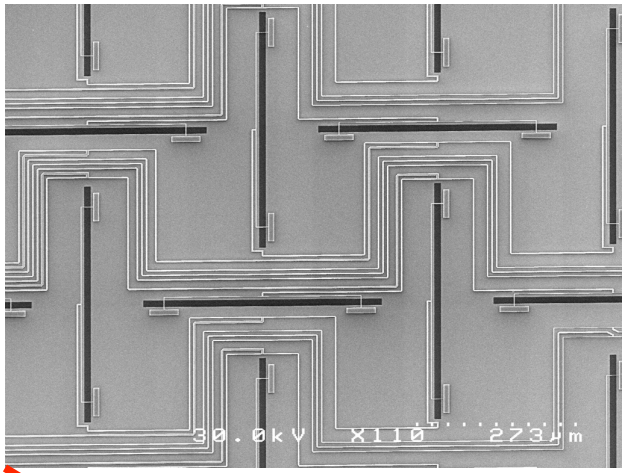
BICEP1 did not find B modes.

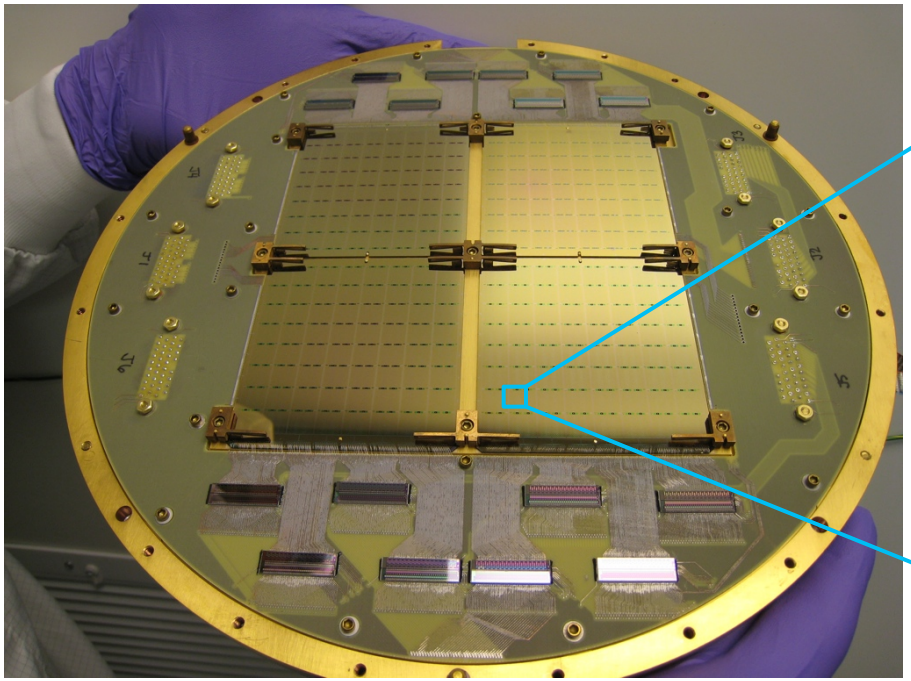
3-year map depth: 500 nK-deg

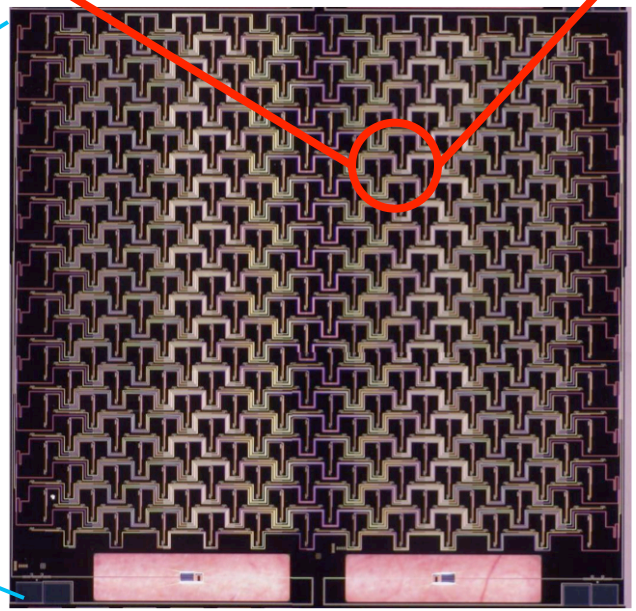
New world's best limit from polarization measurements: tensor-to-scalar ratio r < 0.70 @ 95% CL

BICEP2 (2010-2012)

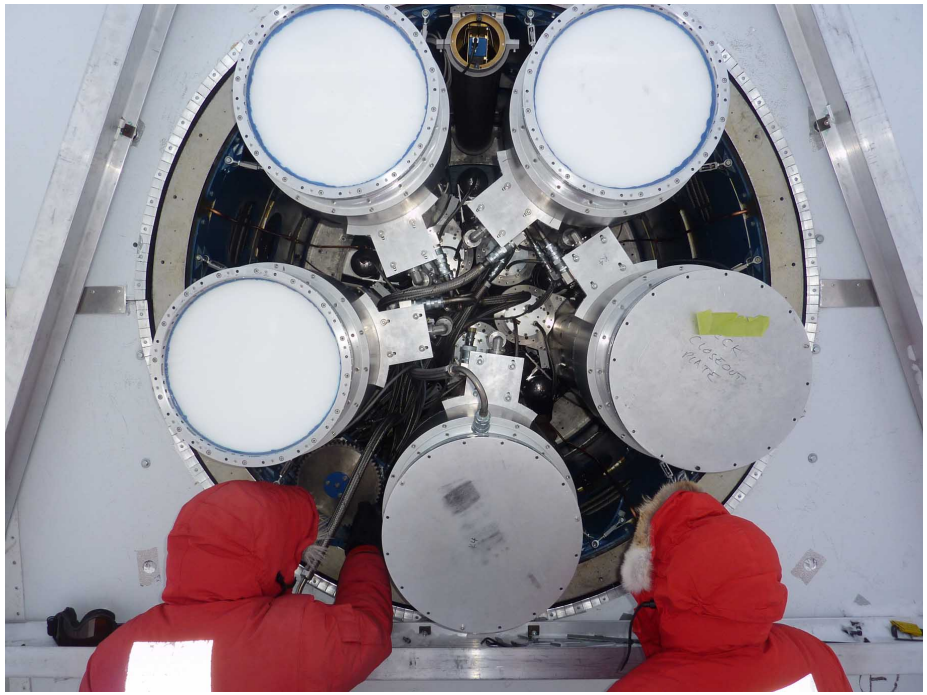
- 512 dual-polarization slot antenna coupled Transition Edge Sensor (TES) Bolometers at 150 GHz
- 10x BICEP1 mapping speed

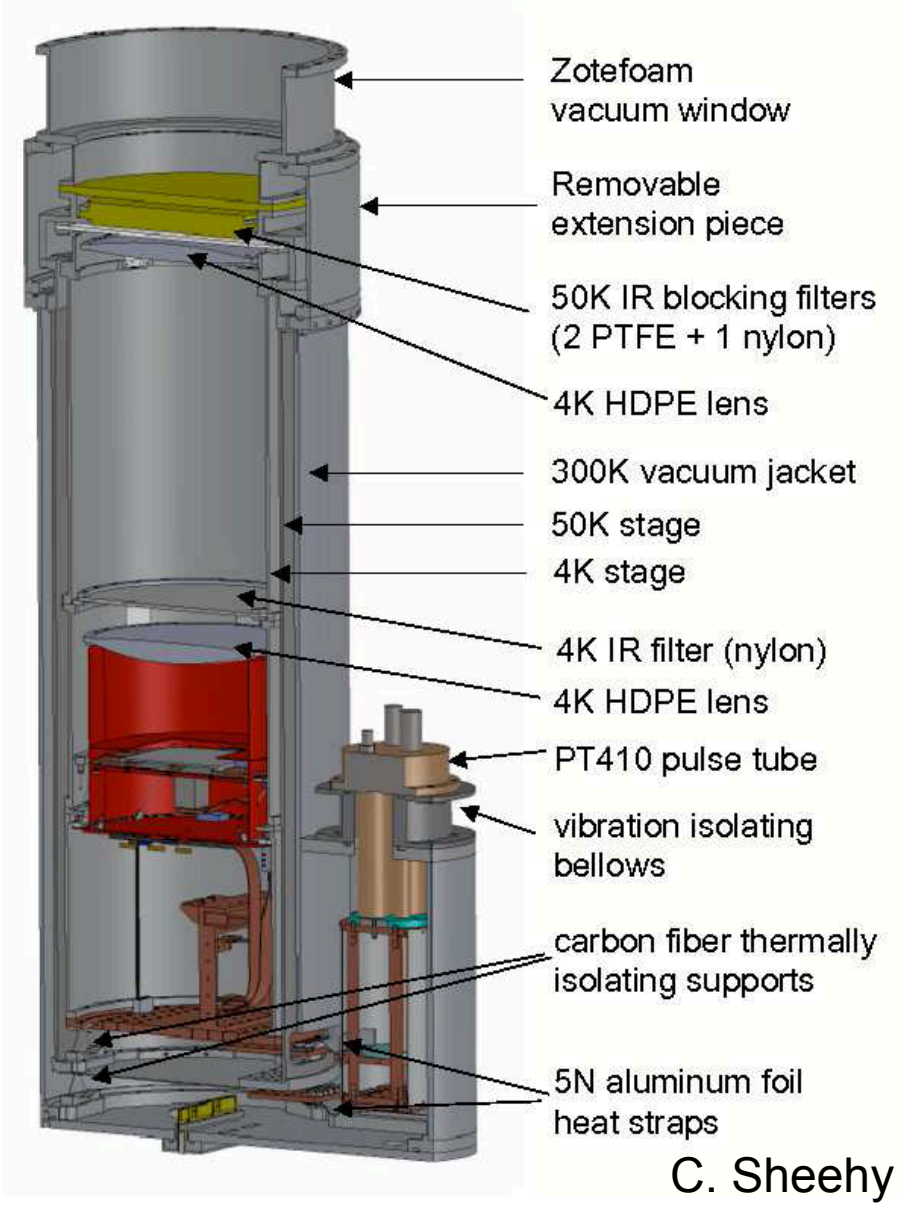






The Keck Array (2011-)

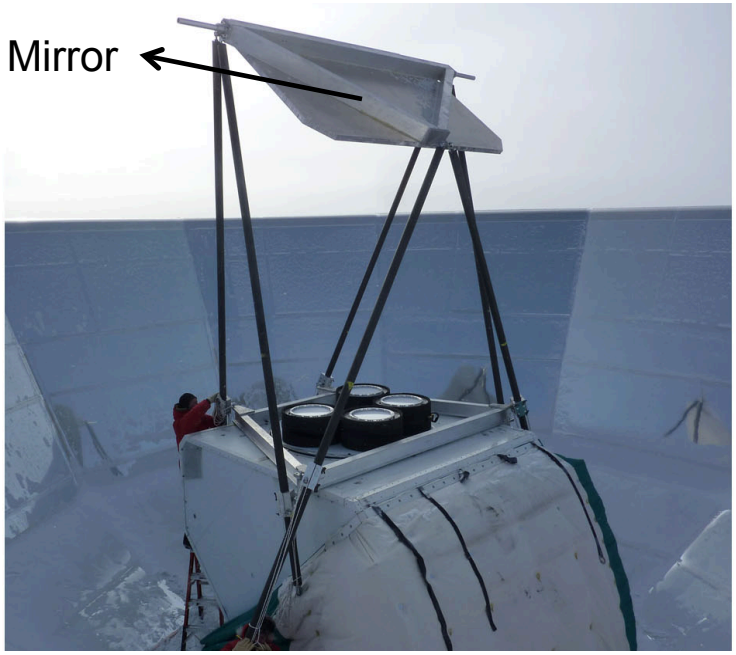


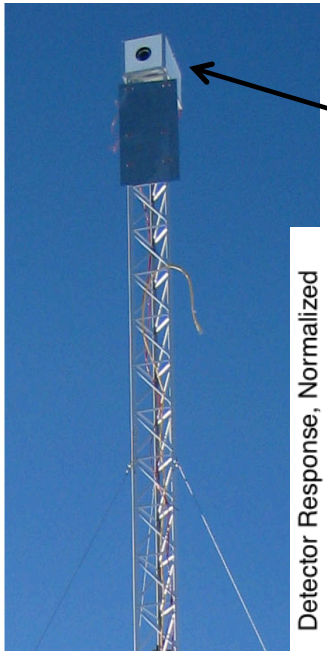


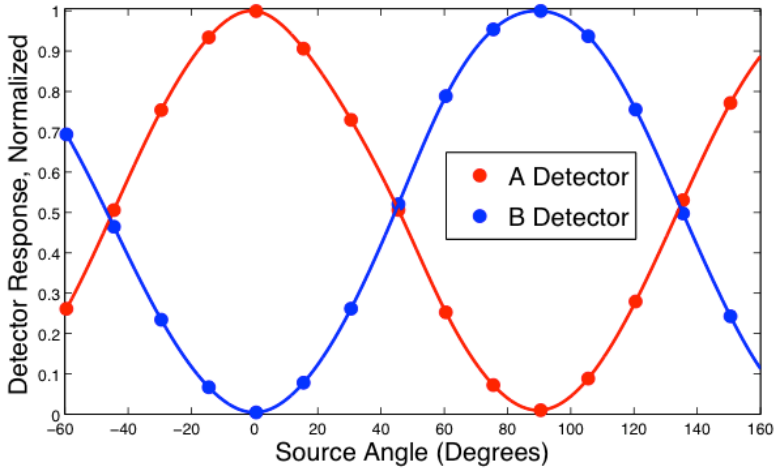
- 5x BICEP2
- New: pulse tube coolers
- Currently 5 @ 150 GHz
- This year: 100, 220 GHz

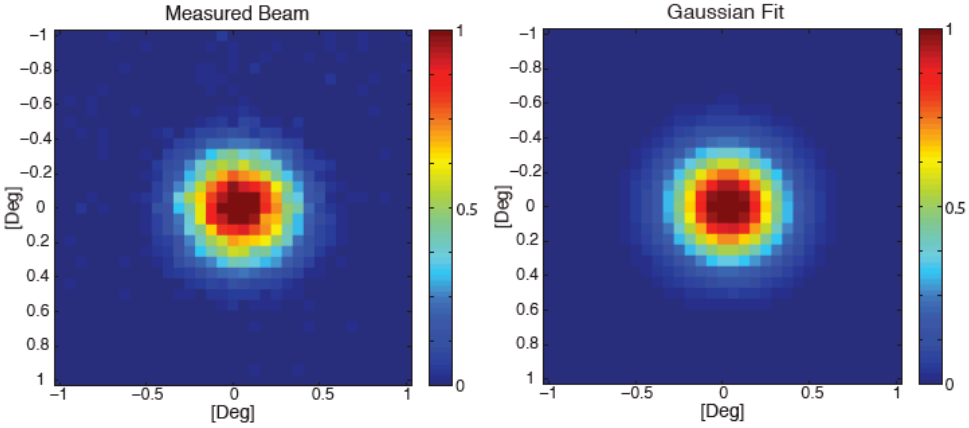
C. Sheehy

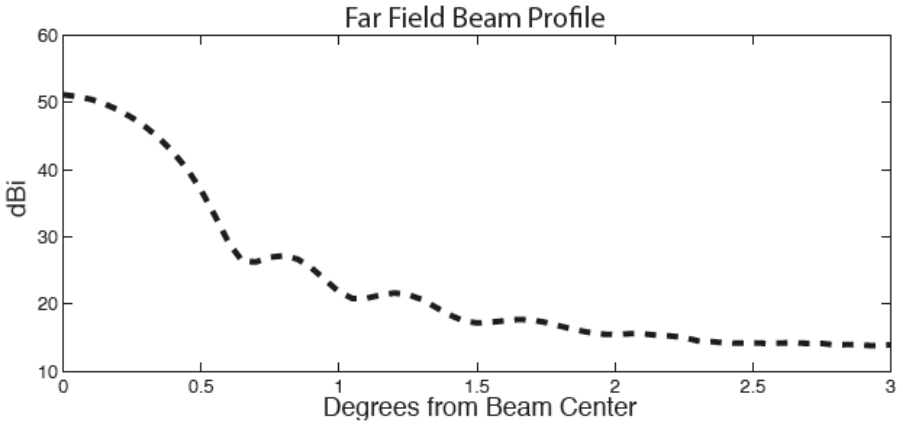
Verifying Keck and BICEP2 Optical Performance





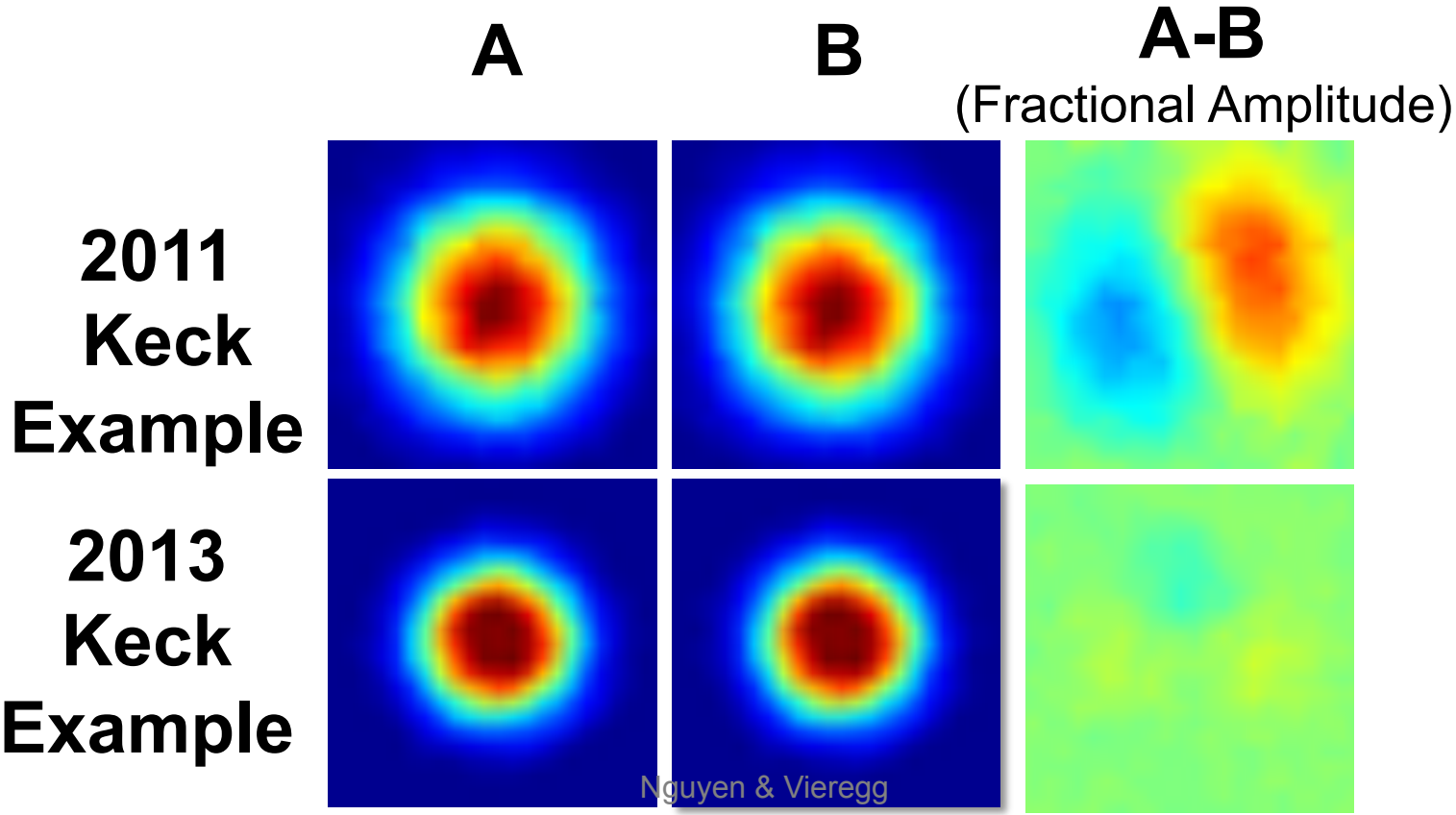






Beam Mismatch and Mitigation

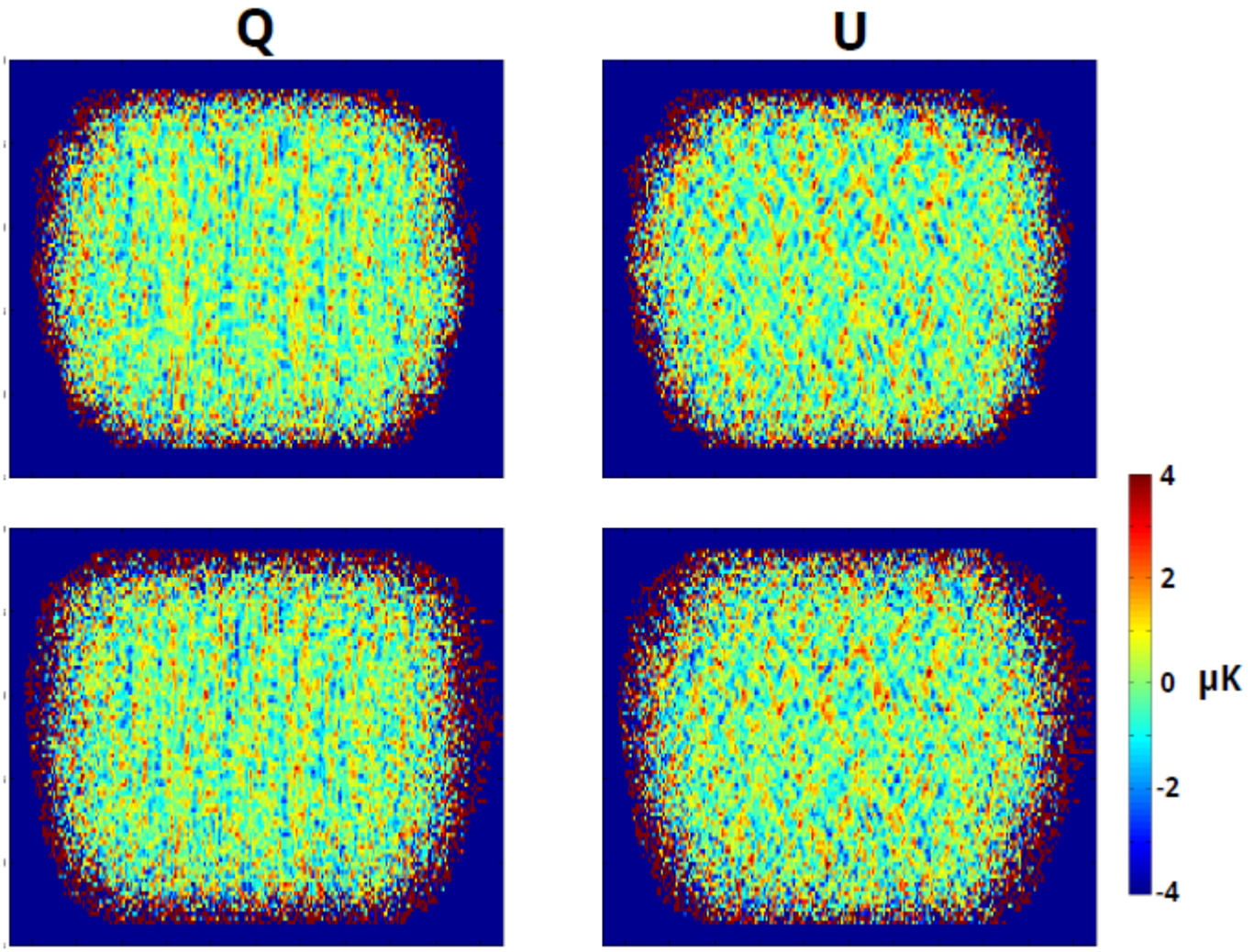
- Beam pointing mismatch observed between orthogonally-polarized detectors in a pair
- Much improved in recent focal planes (now observing at Pole)
- T→P leakage can be mitigated in analysis (Aikin et al., in prep)
- Sufficient control of beam systematics to achieve sensitivity goal



BICEP2 and Keck Array: The Deepest Maps at Degree Angular Scales

BICEP2 3-year:
128 nK-deg

Keck 2012 only:
170 nK-deg



C. Bischoff

Achieved Program Sensitivity

	Sensitivity (uK √s)
BICEP 1	54
BICEP 2	16
Keck Array 2011	20
Keck Array 2012	11
Keck Array 2013	9.5

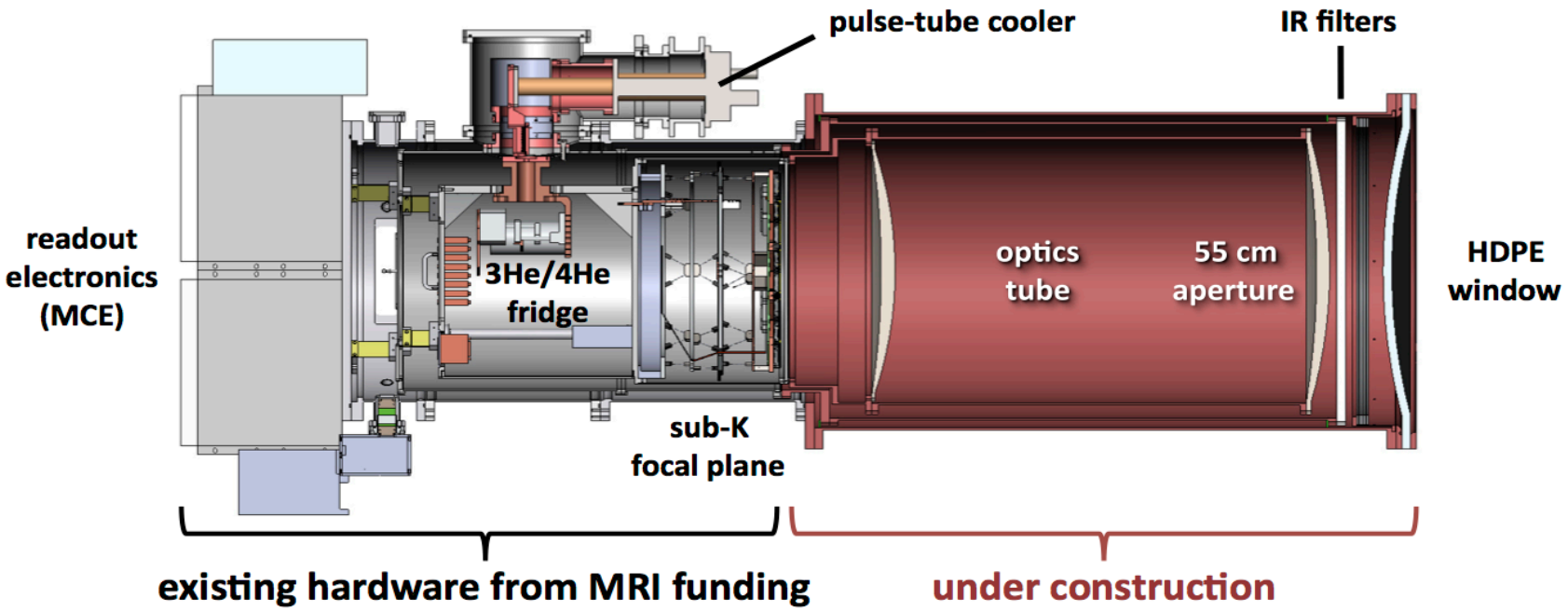
3 receivers only in 2011

All 5 receivers deployed, 1 focal plane with improved sensitivity

5 receivers, 2 more focal planes with improved sensitivity

BICEP3 (2015-)

- 2560 detectors at 100 GHz
- Larger aperture, faster optics → 10x BICEP2's optical throughput
- Doubles the program's survey speed
- Important for foreground separation



Summary

- BICEP1: final results in preparation, still the best constraint on B modes from inflation
- BICEP2/Keck Array: first results soon
- BICEP3: double our mapping speed
- We can reach r=0.01, and we are improving every year!
- Careful analysis is critical and new techniques have been developed(deprojection of beam systematics)
- With our achieved sensitivity, we fully expect that foreground separation and delensing will become critical soon