Advancing Polarization in the US

CMB

Advancing Polarization in the US


Advancing CMB Polarization in the US
…over 20+ years with KICP
John Kovac, KICP Brood -1 / 0
Chicago →Caltech →Harvard
June 2024 — KICP 20th Anniversary!

1994: getting to Chicago the hard way

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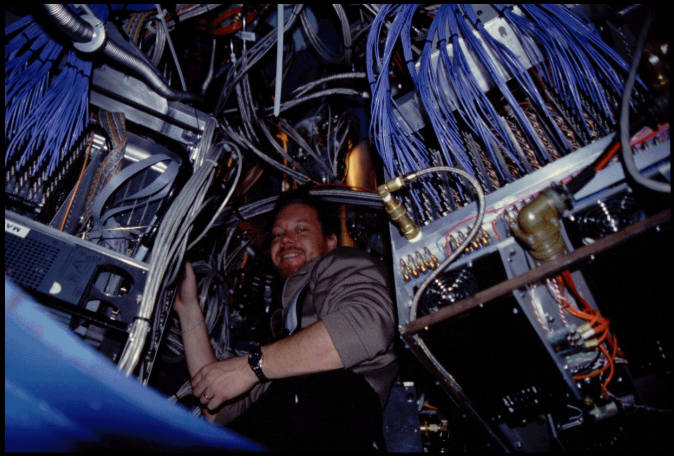
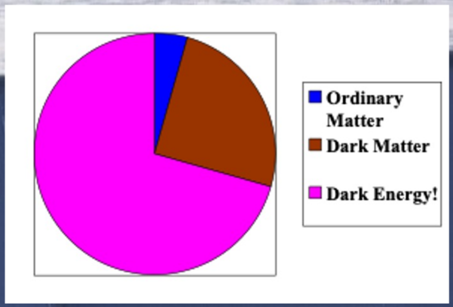
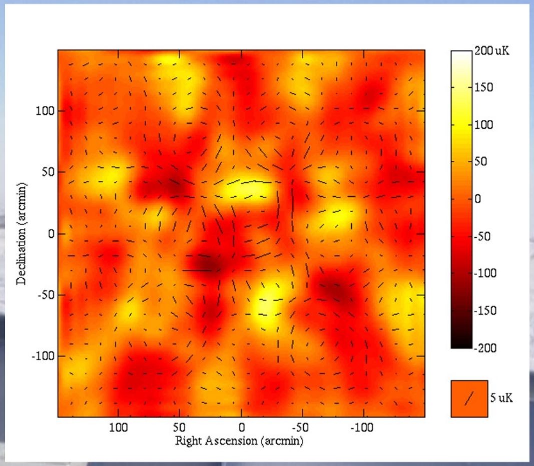
1995-1999: learning from John Carlstrom

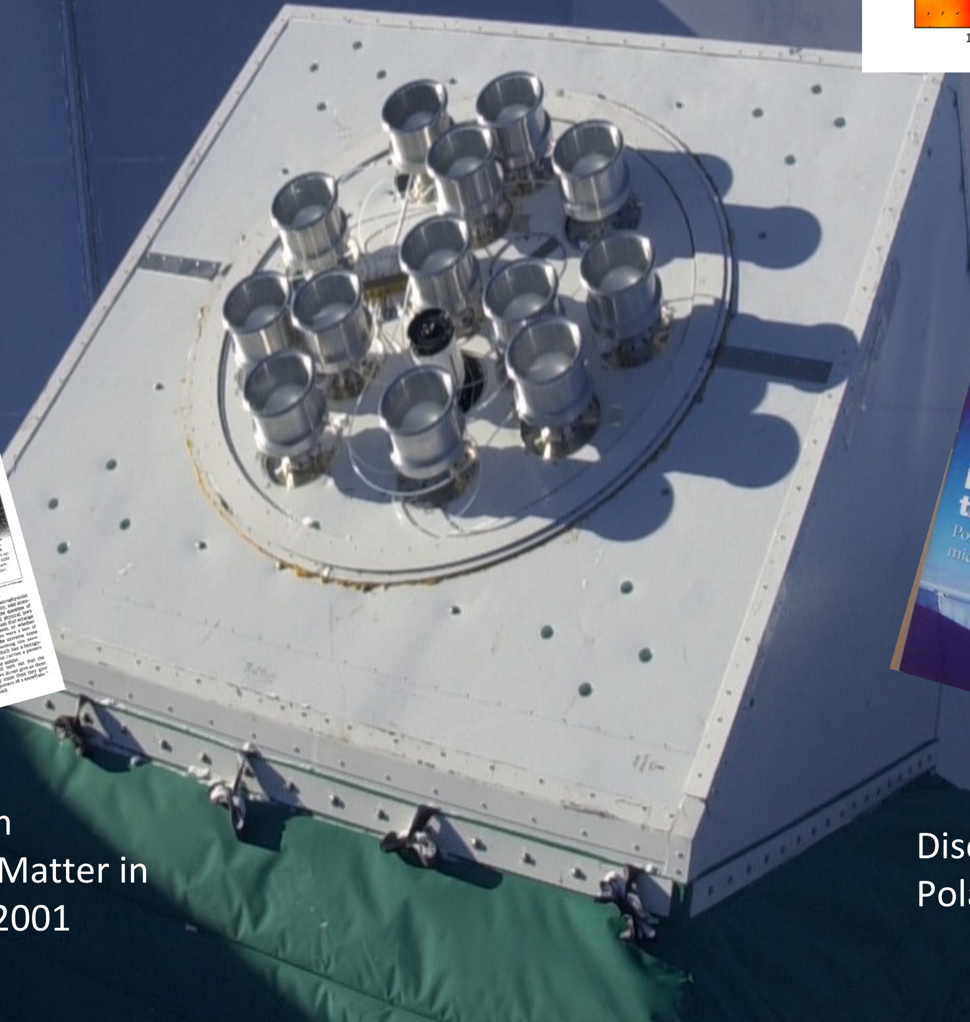
… as DASI takes shape



~2001: South Pole established as leading platform for CMB discovery







Power Spectrum indicating Dark Matter in early universe, 2001

Discovery of CMB Polarization, 2002

Sep 2002 DASI detection of E-mode Polariation
CfCP / Cosmo2002 @ Adler

(Scott: 6 co-authors, 5 sigma…not the other way around)

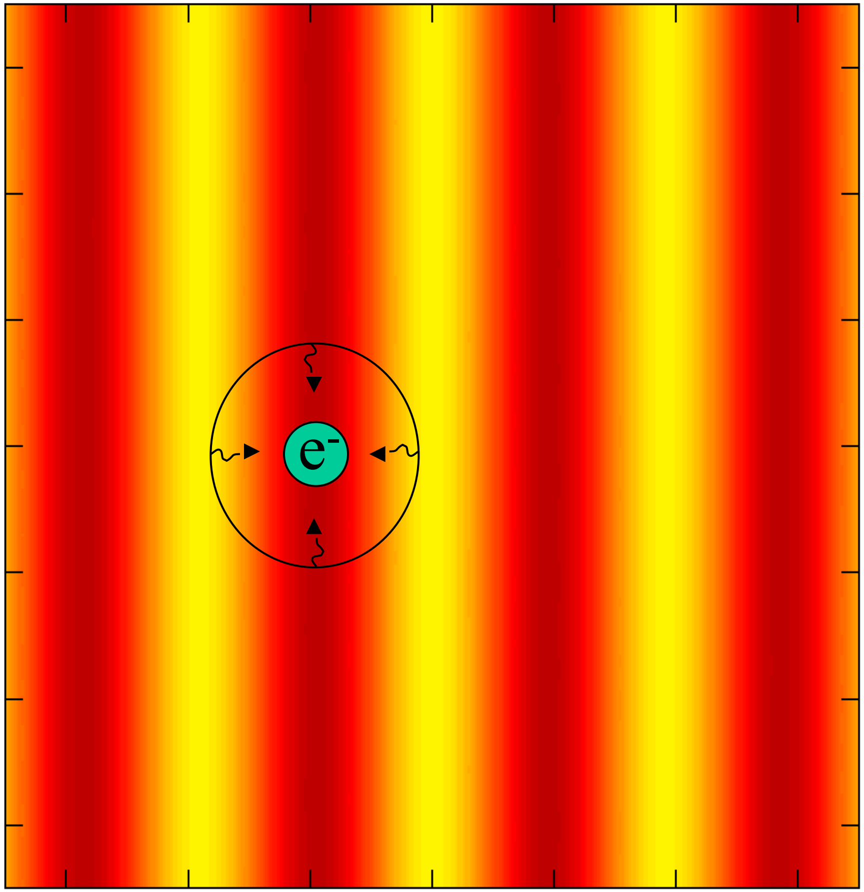
"Acoustic" standing waves

Photon-baryon fluid oscillates,
photon pressure gives
restoring force

Seeded by primordial fluctuations
density (scalar)

Linear regime: Fourier modes
evolve independently

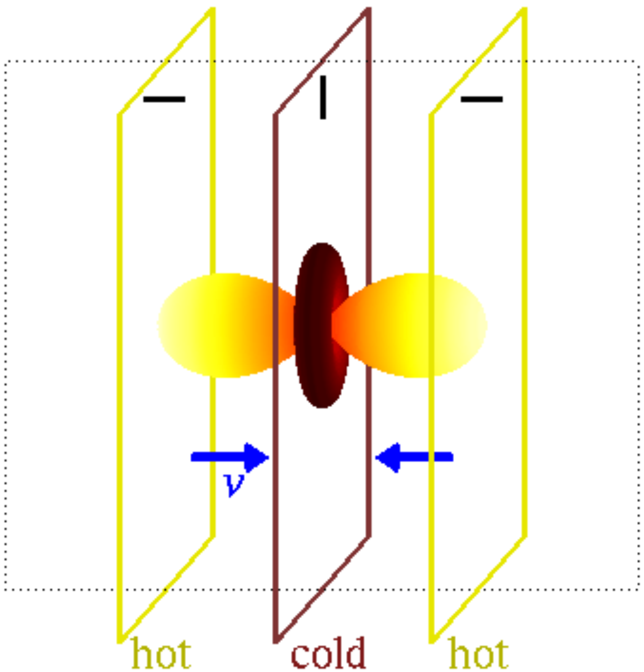
Pattern is frozen at last scattering
(z ~ 1100, t ~ 380,000 yrs.)

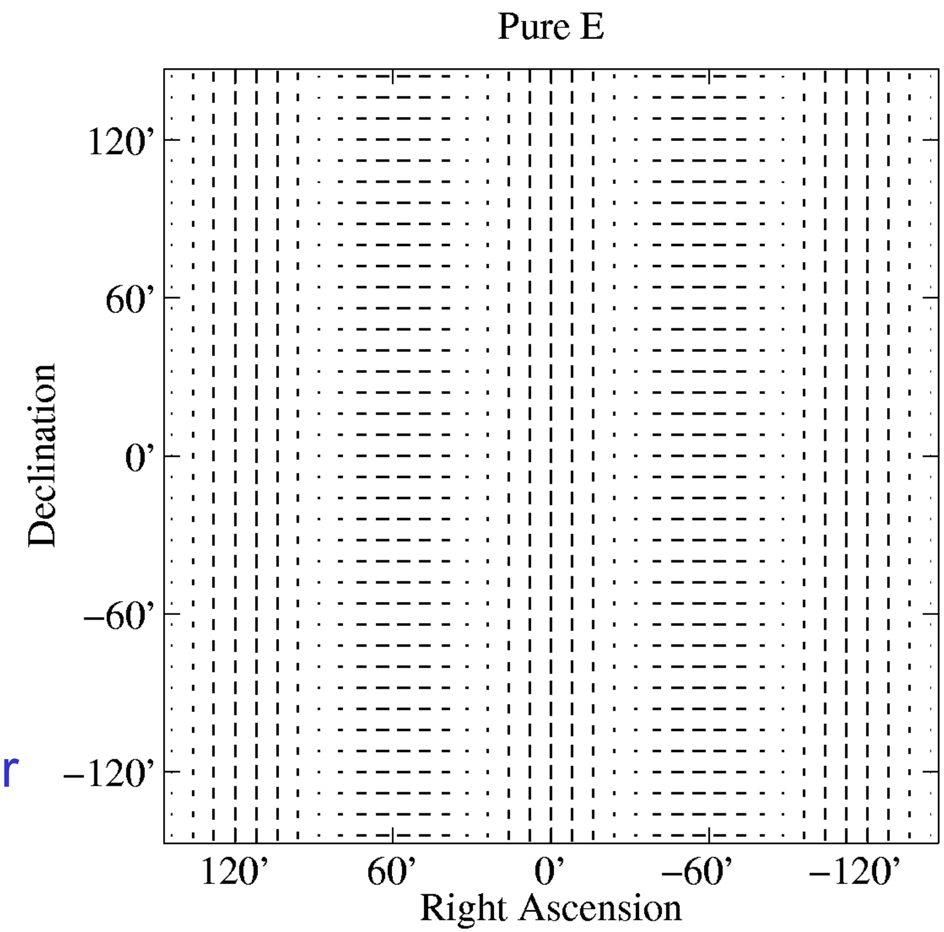


Thompson Scattering give rise
to Polarization

Only while mean free path is growing!

E-mode Polarization (curl free)

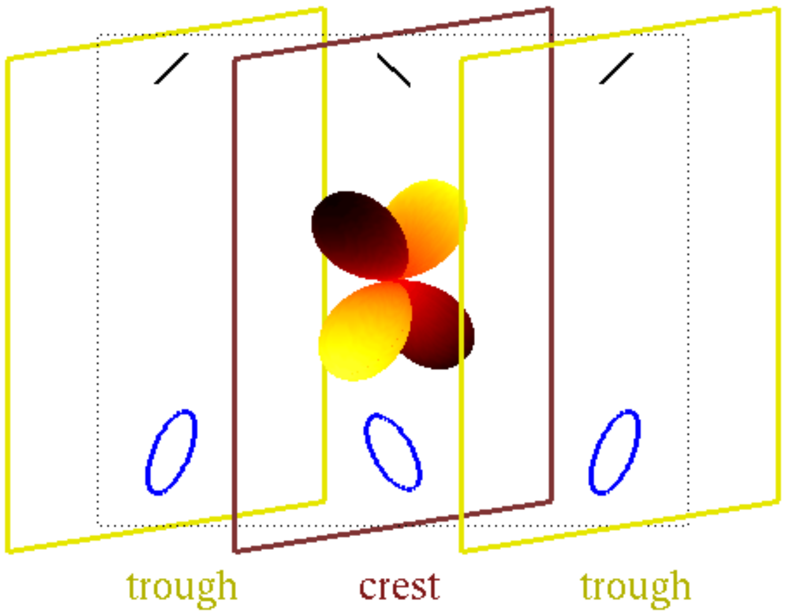


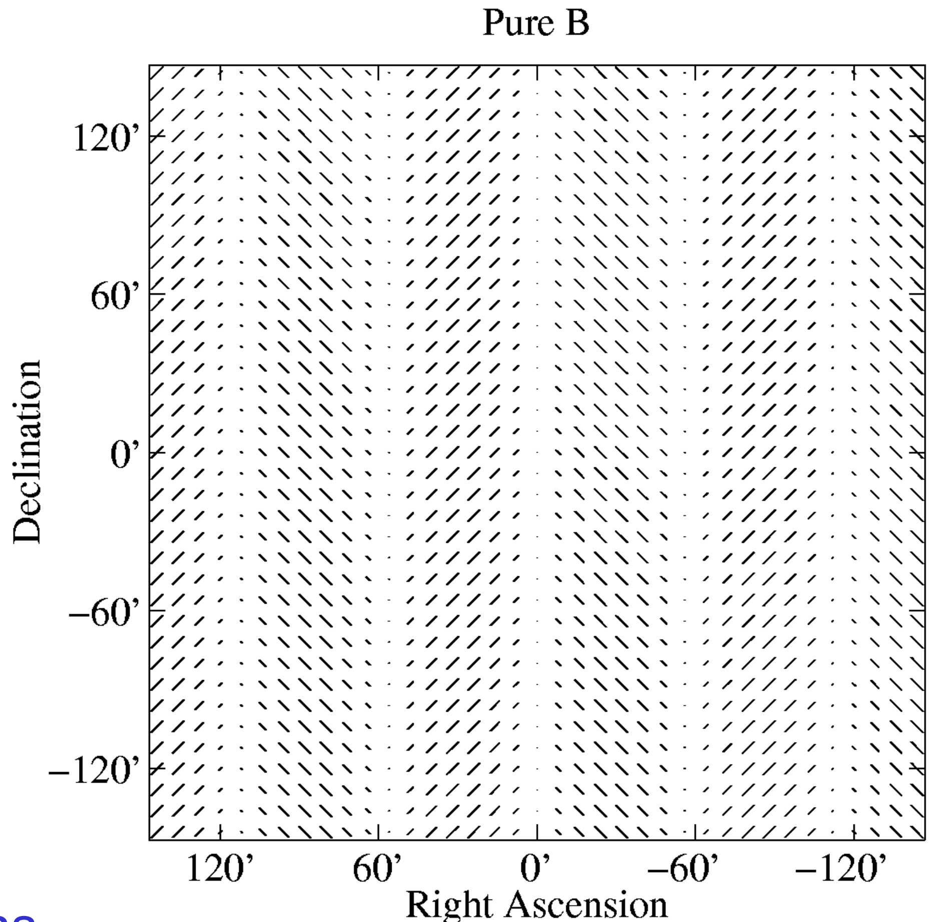


Polarization parallel or perpendicular to wave vector

Density (scalar) fluctuations generate only E-Polarization

B-mode Polarization (curl component)

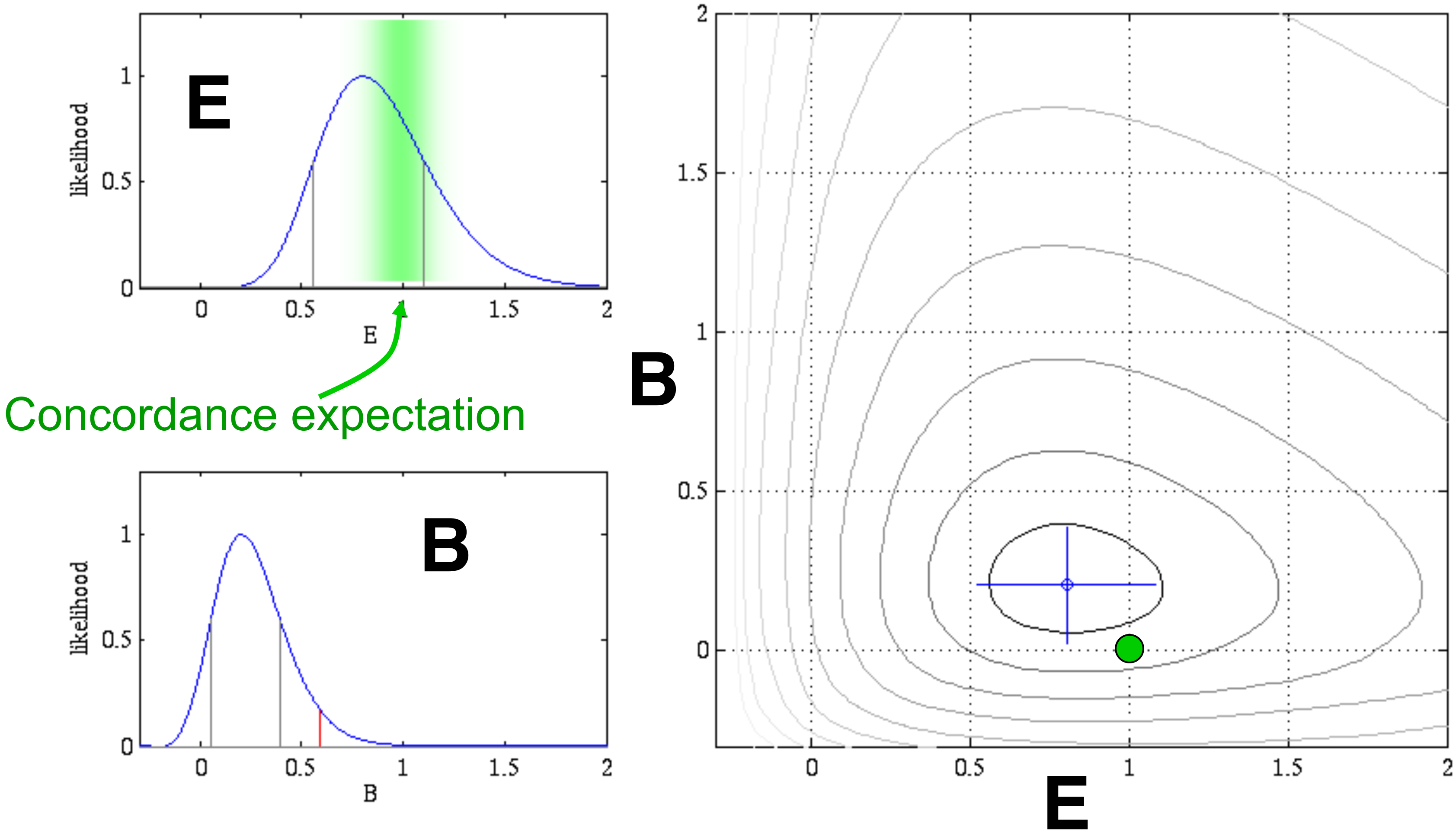




Polarization oriented at 45 degrees
to wave vector

Not generated by density oscillations
(only primordial source: inflationary gravity waves)

DASI Constraint on Scalar E-mode Polarization

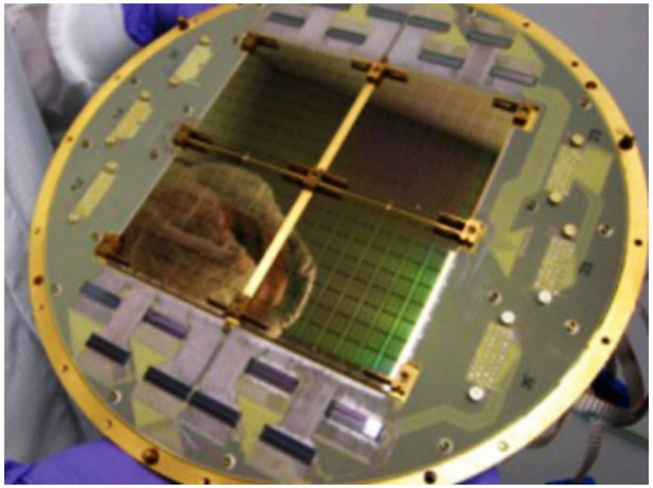


“The greatest pleasure a scientist can experience is to encounter an unexpected discovery.” — Jim Cronin (quoted by Toshihiro on Thursday)

onwards to Cosmology's greatest wild goose chase

The Search for Inflationary B-Modes

Andrew Lange
Caltech Marvin L. Goldberger Professor of Physics
1957 - 2010



Antenna-coupled transition-edge superconducting (TES) bolometer arrays.

CMB Polarization Workshop, 2009

We are holding a workshop on CMB polarization experiment in Chicago on July 1-3. There is currently great scientific excitement surrounding the push to detect gravitational wave induced B-mode polarization of the Cosmic Microwave Background. The purpose of this meeting is to review and discuss the fast moving ground based and sub-orbital experimental program, and to get an update on the evolving plans for a next generation satellite mission.

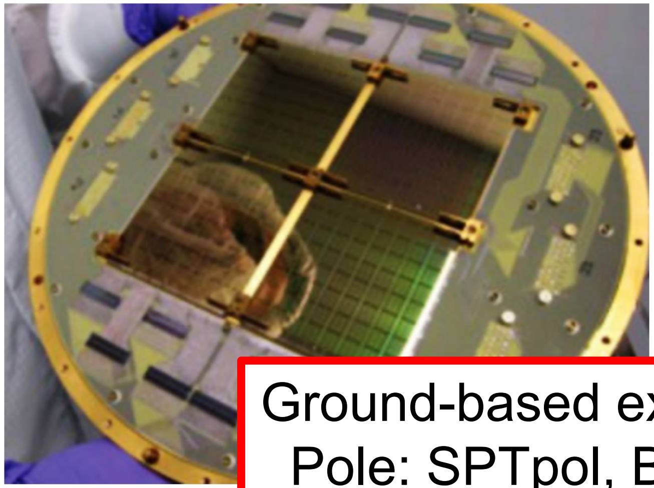
Path to CMBPolarization
Chicago
July 2009

The Path to CMBPol - Upcoming Measurements of CMB Polarization

July 1 - 3, 2009 ✦ Chicago, Illinois

CMB Polarization Workshop

HOME   OVERVIEW   PROGRAM   PRESENTATIONS   LOGISTICS   CONTACT US



Antenna-coupled tra
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Ground-based experiments at Workshop:
- Pole: SPTpol, BICEP/Keck
- Chile: QUIET, ABS, ACTpol, Polarbear
  - (CLOVER, QUBIC, QUIJOTE…)

…+ balloons, satellites…

RELATED WORKSHOPS ▶▶ CMBPol Theory and Foregrounds, 2008   CMBPol Technology, 2008   CMBPol Systematic, 2008

KICP

THE UNIVERSITY OF CHICAGO

From BICEP1 to BICEP2 & KECK

July 2009 KICP CMPpol workshop

BICEP1 initial results

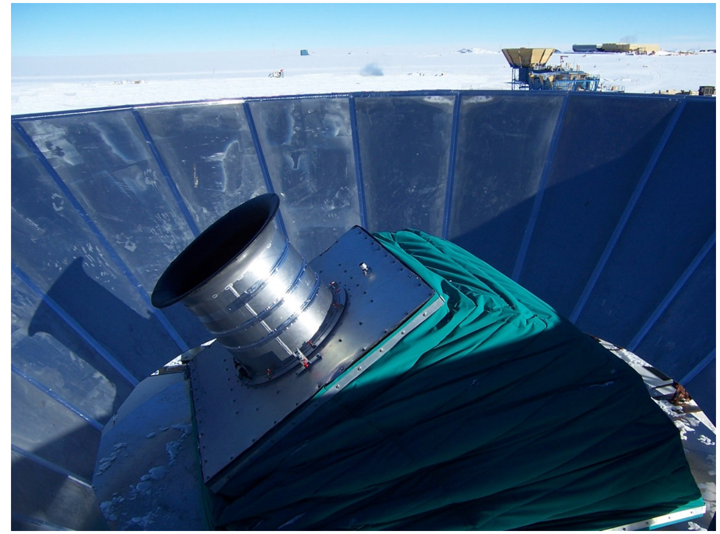
CMB result: **Chiang et al. 0906.1181**
Characterization: **Takahashi et al. 0906.4069**

- **This is doable.**
  - Instrument worked as designed
  - No exotic polarization modulators – just careful optical design and azimuth scanning.
  - Systematics controllable down to at least r = 0.01
  - First high S/N measurement of CMB (E) polarization at l = 100

- **This is hard.**
  - Initial result from first 2 seasons after massive analysis effort:
    r = 0.03, +0.31, -0.27, or upper limit r < 0.73 at 95% confidence

July 2009 KICP CMPpol workshop

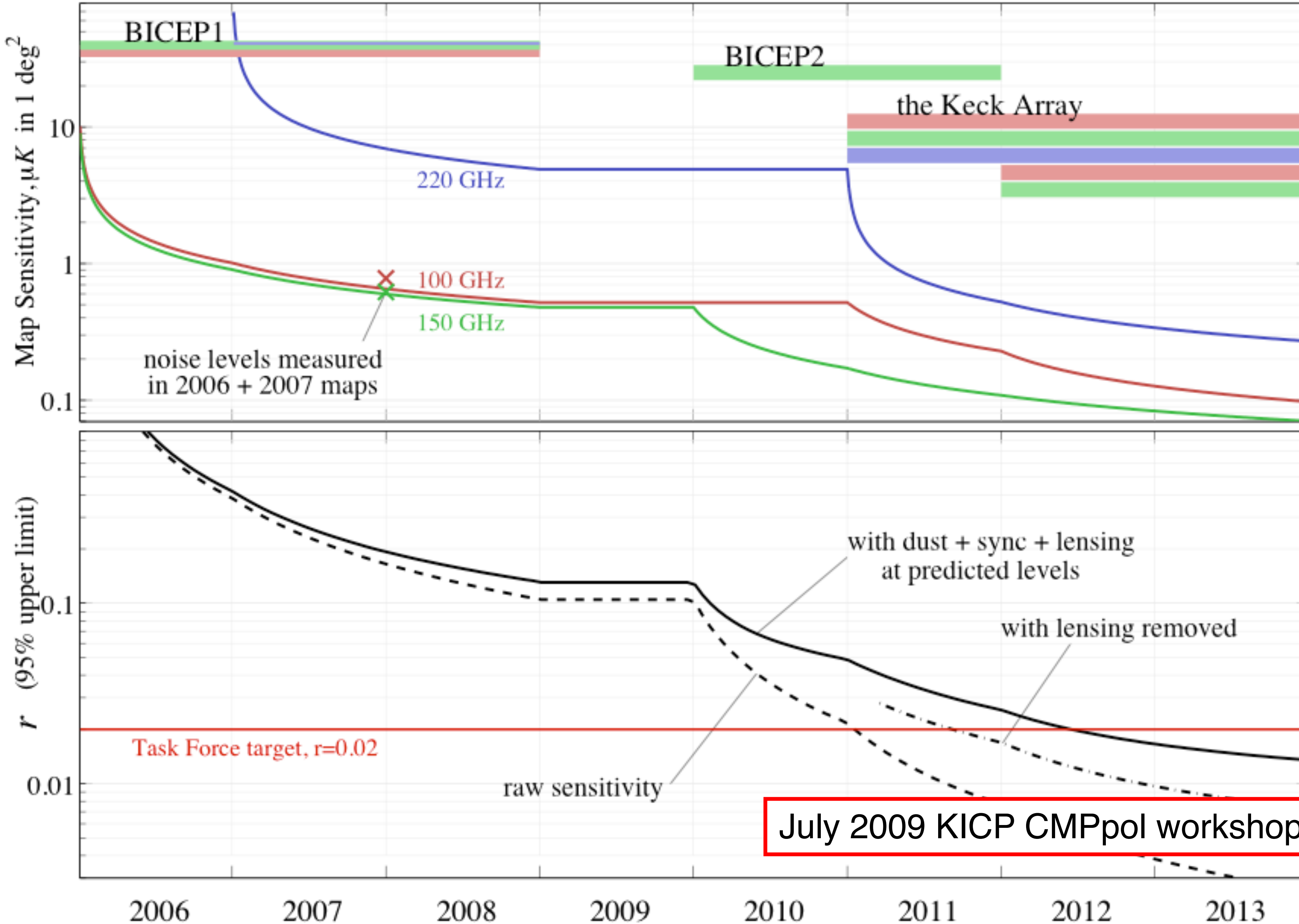
Why a small aperture?



- Efficient ($) to integrate / test / deploy
- Stability of (4K) telescope & beams
- Aperture filling calibrators
- Aperture filling waveplate (BICEP2)
- Superior sidelobe suppression

July 2009 KICP CMPpol workshop

BICEP / Keck : map depth & sensitivity to *r*



July 2009 KICP CMPpol workshop

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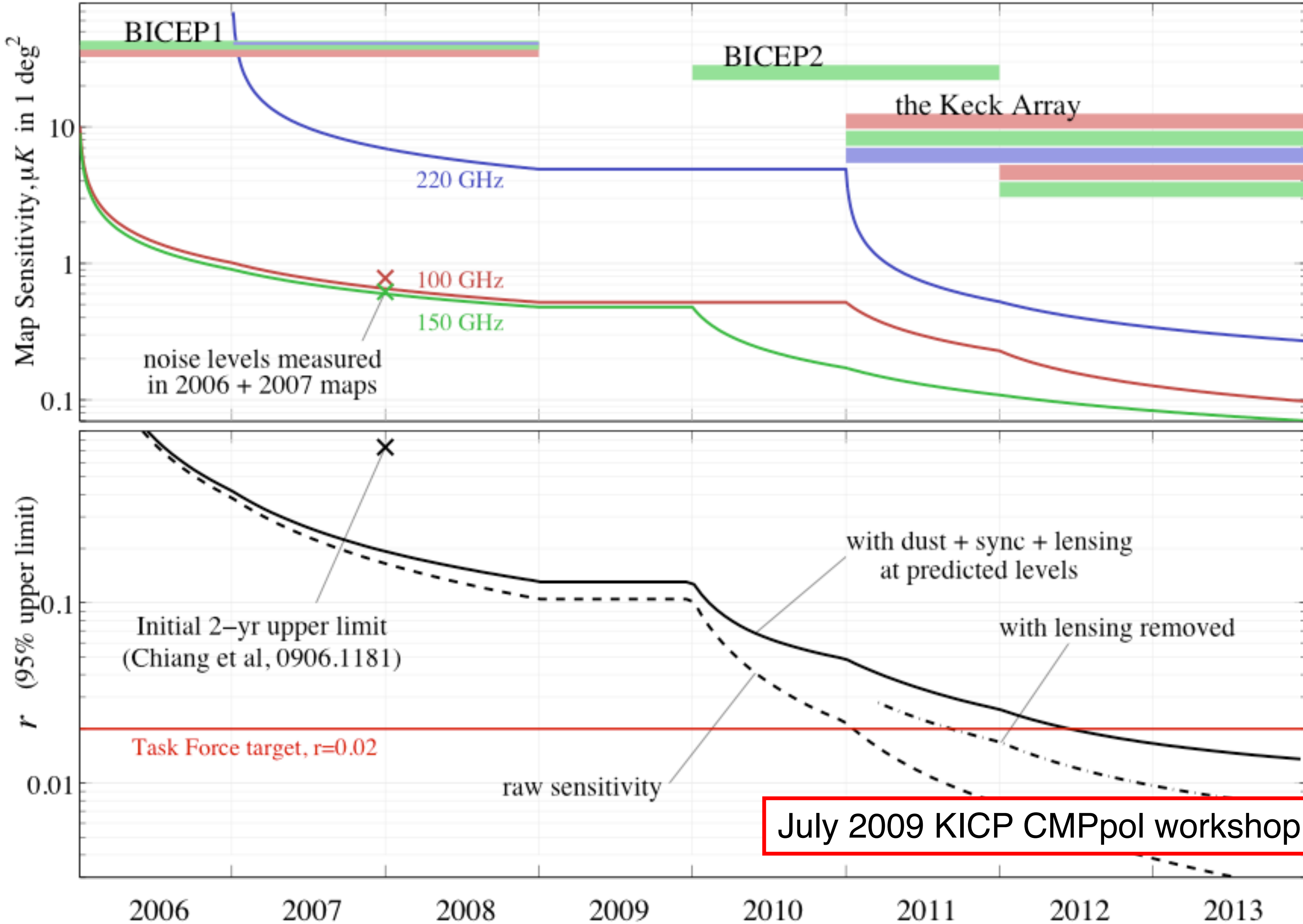

July 2009 KICP CMPpol workshop

WTF?

(where’s the four?)

Where did the factor of 4 go?

- **NOT:**
  - Time on target. > 3000 hours / season on Southern Hole, better than projected
  - Foreground removal
  - 1/f noise. Very small in pair difference across science band
  - E/B separation
  - Chance fluctuation… sims show 95% limit could have been $r < 0.5$ or $r < 1.3$

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  - Chance fluctuation

- **Small factors:**

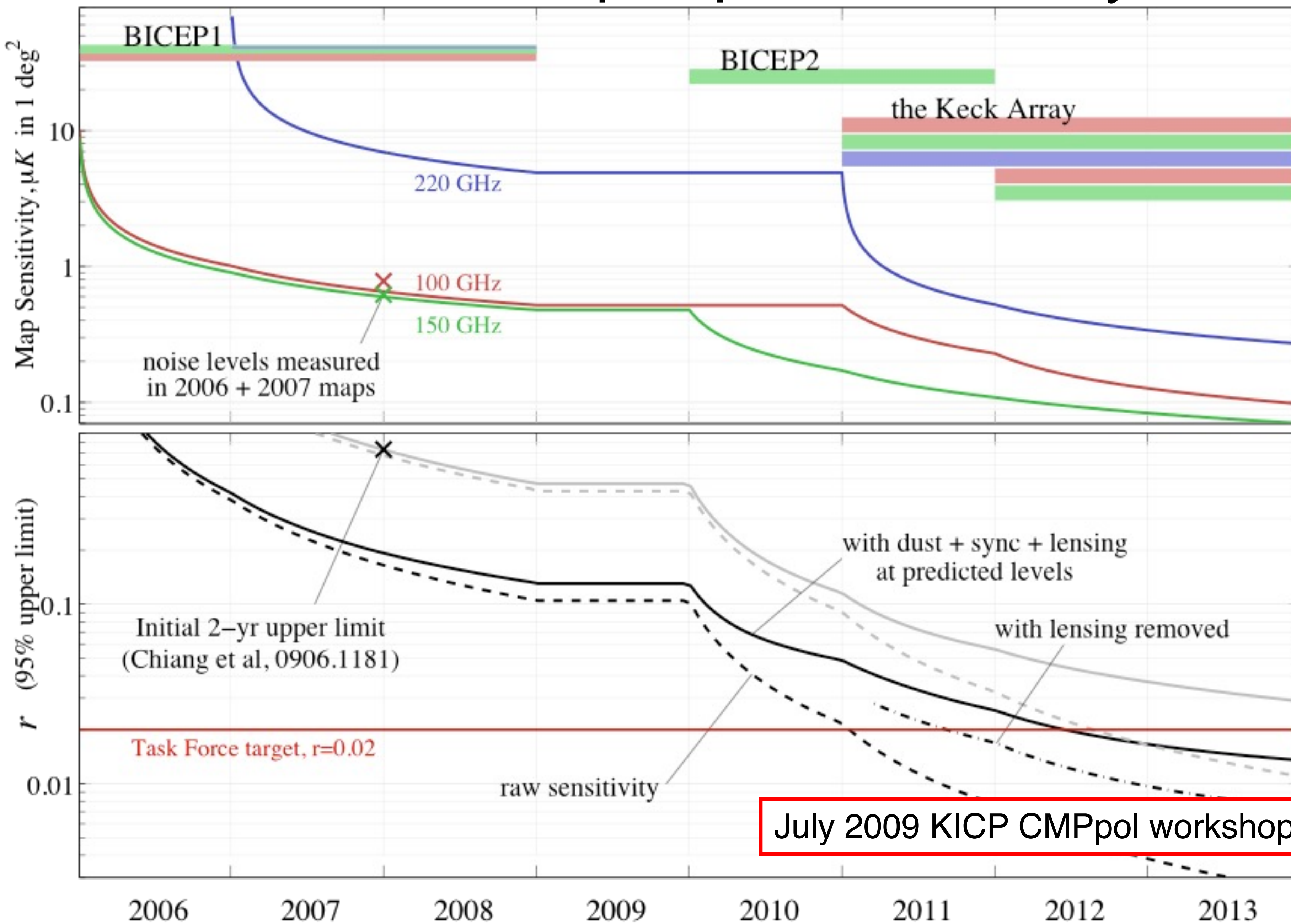
– Final array-averaged NEQs in science band: 19%, 14% high	1.3
– Channels cut for unusual transfer functions	1.2
– Channels lost for other reasons	1.2
– Fraction of scanning time used: 60%	1.6
– Exclusion of partial scans	1.05
– Mode-loss due to aggressive filtering scheme	1.3 ?
– Sub-optimal B spectrum estimation?	1.2 ?
	total: 4.9

So what factor can realistically be gained back with more work?

Guess: 1.5 - 3

July 2009 KICP CMPpol workshop

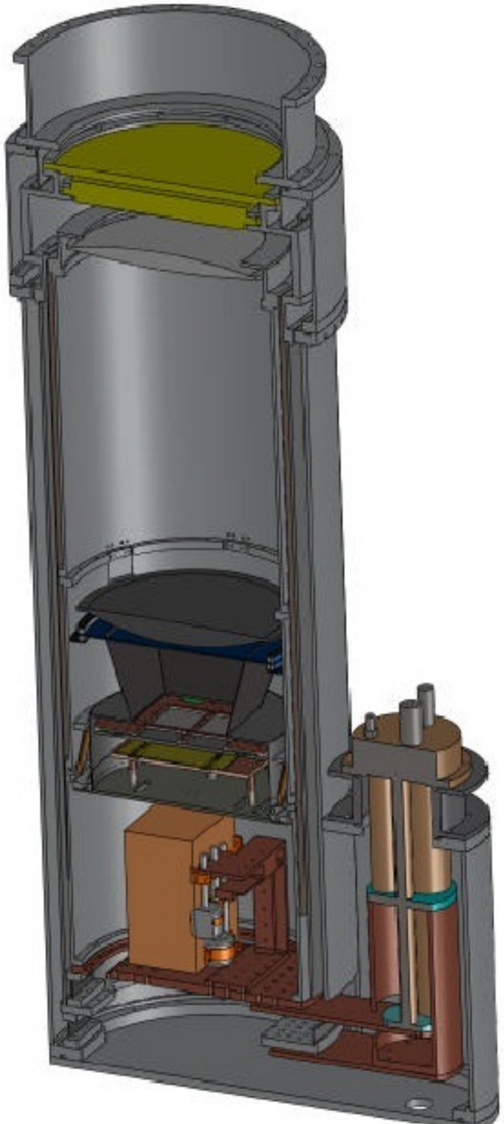
BICEP / Keck : map depth & sensitivity to *r*



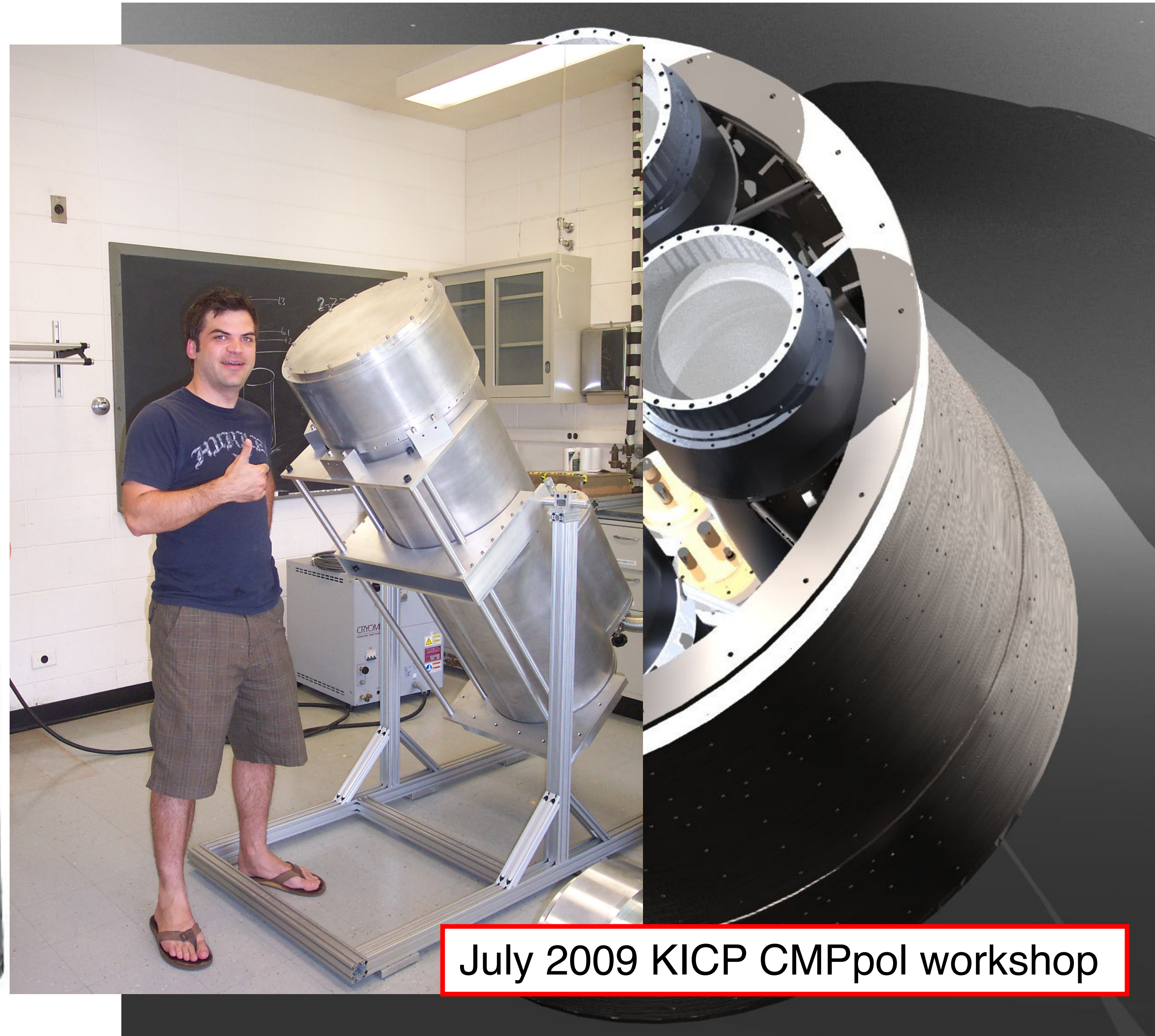
July 2009 KICP CMPpol workshop

Keck Array status:

- Cryostat and insert integration underway this summer

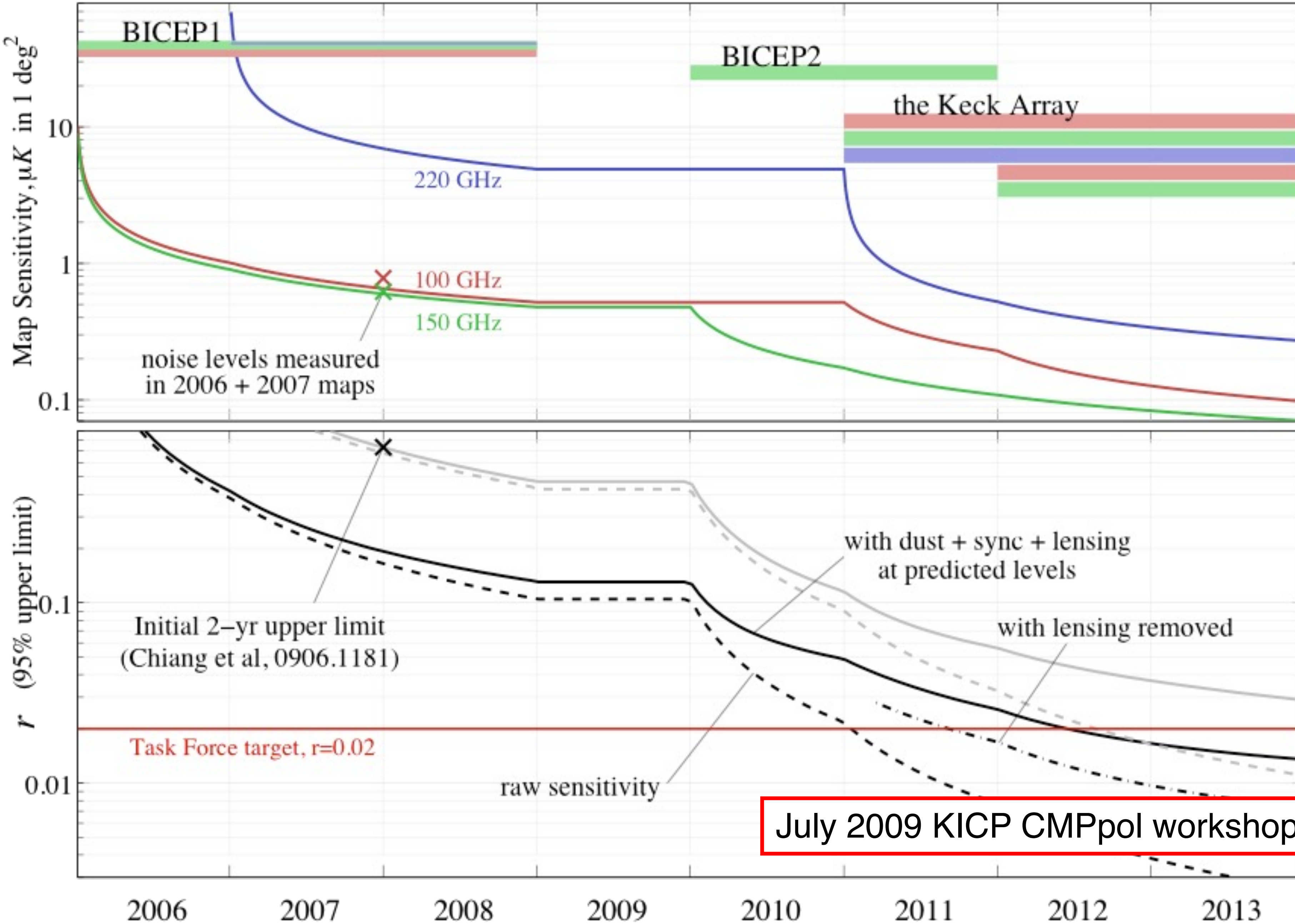


Design: Chris Sheehy

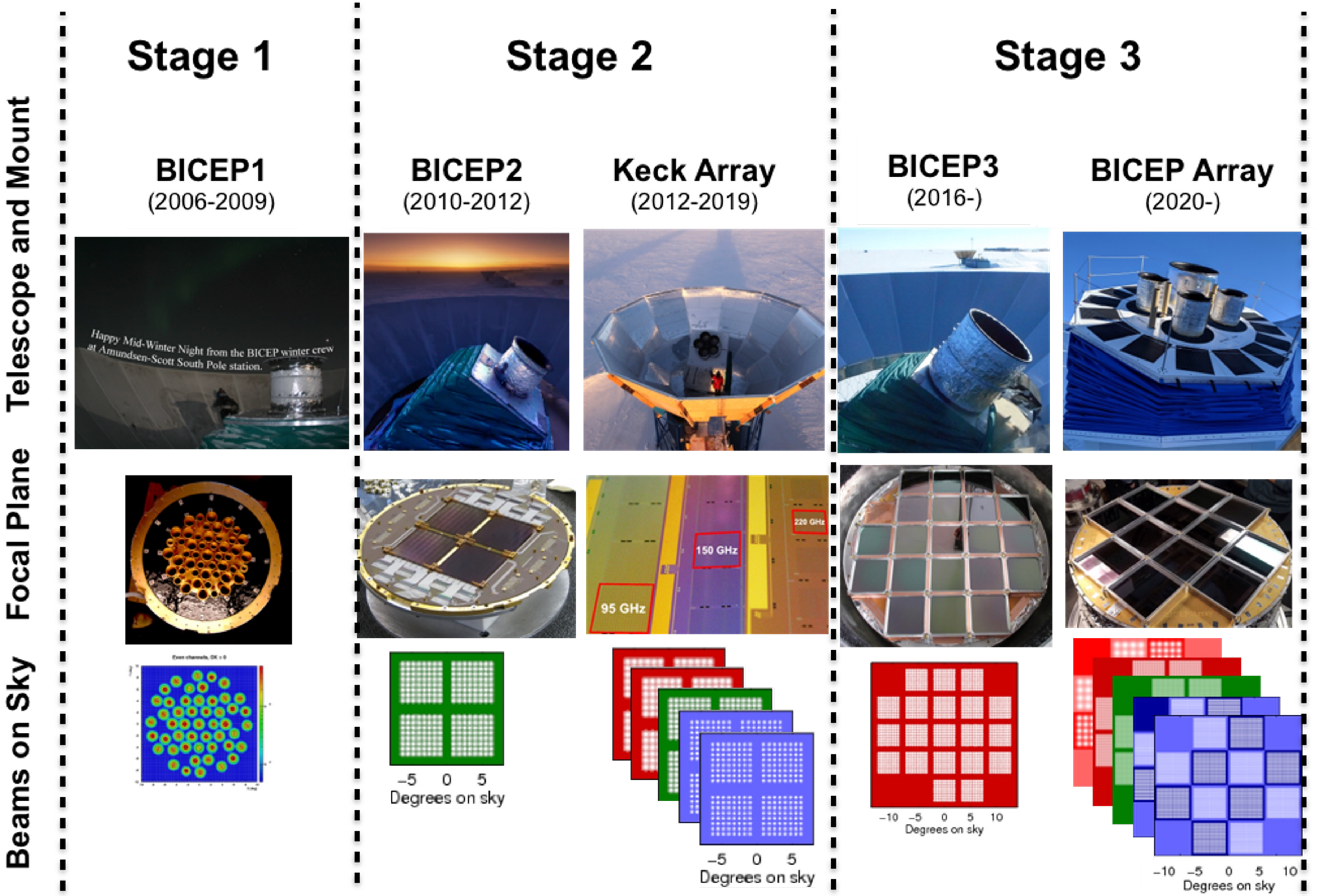


July 2009 KICP CMPpol workshop

BICEP / Keck : map depth & sensitivity to *r*

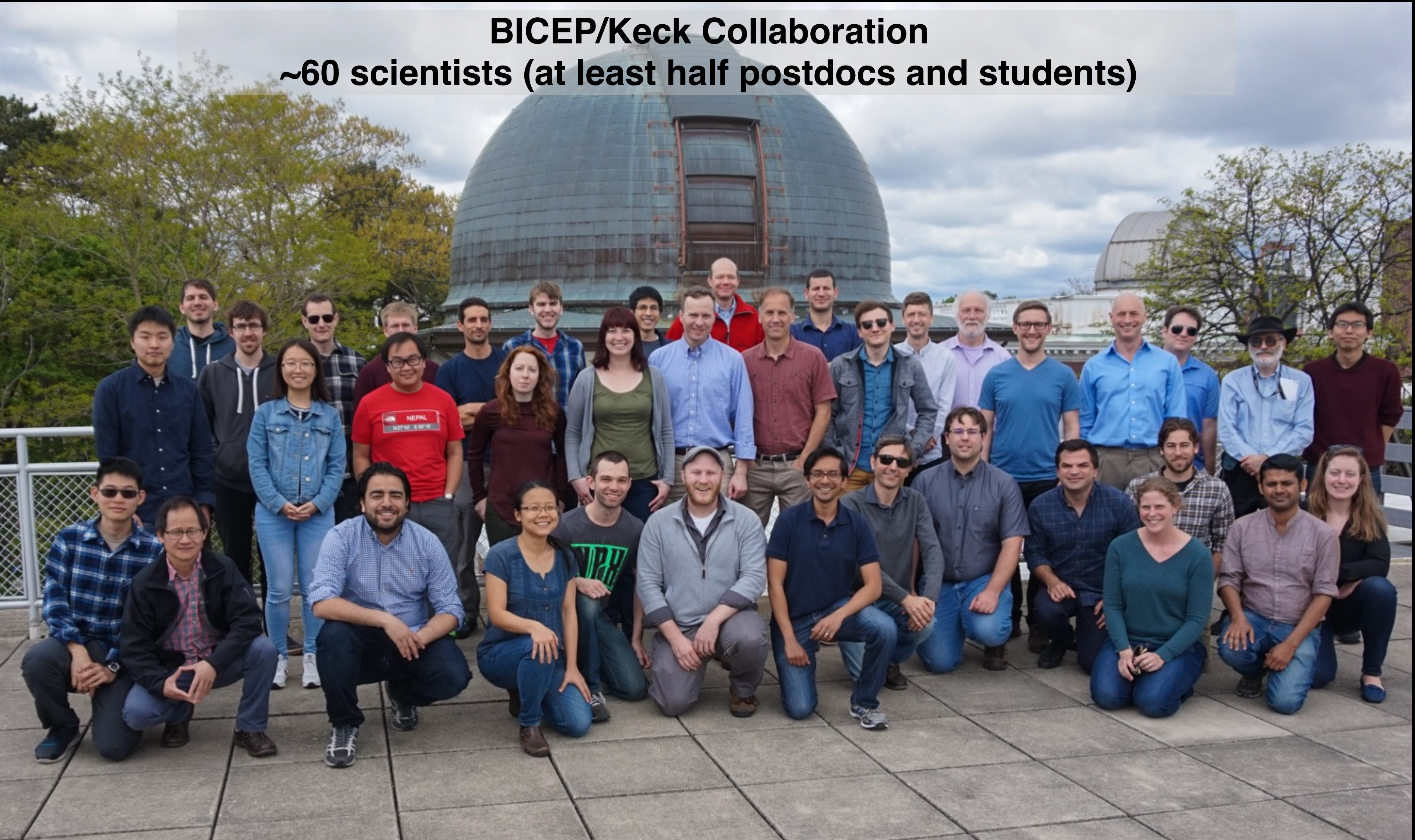


July 2009 KICP CMPpol workshop

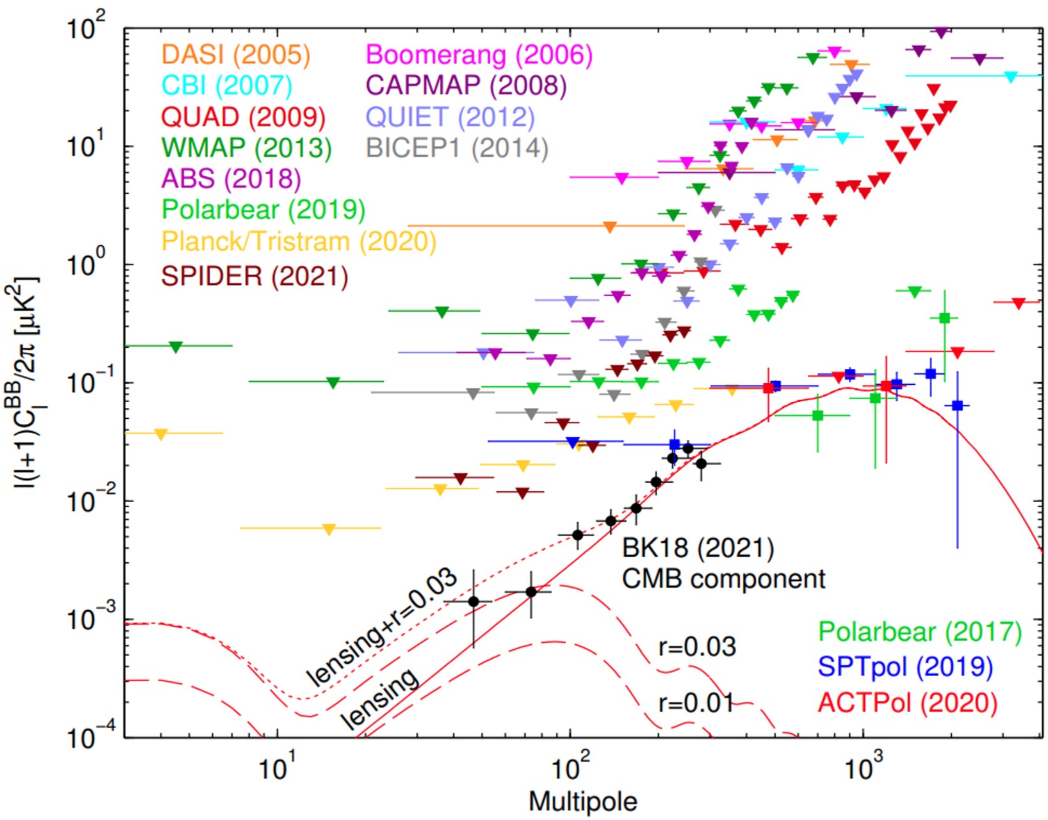


Stage 1
Stage 2
Stage 3
Telescope and Mount
Focal Plane
Beams on Sky
BICEP1
(2006-2009)
BICEP2
(2010-2012)
Keck Array
(2012-2019)
BICEP3
(2016-)
BICEP Array
(2020-)
Happy Mid-Winter Night from the BICEP winter crew at Amundsen-Scott South Pole station.
95 GHz
150 GHz
220 GHz
Degrees on sky

BICEP/Keck Collaboration
~60 scientists (at least half postdocs and students)



Constraints on Inflation from B-modes to Date



Published B-Mode Sensitivity to r

Experiment	arxiv post	Bands [GHz]	σ(r)
DASI	0409357	26…36	7.5
BICEP1 2yr	0906.1181	100, 150	0.28
WMAP 7yr	1001.4538	30…60	1.1
QUIET-Q	1012.3191	43	0.97
QUIET-W	1207.5034	95	0.85
BICEP1 3yr	1310.1422	100, 150	0.25
BICEP2	1403.3985	150	0.10
BK13 + Planck	1502.00612	150 + Planck	0.034
BK14 + WP	1510.09217	95, 150 + WP	0.024
ABS	1801.01218	150	0.7
Planck	1807.06209	30...353	~0.2
BK15 + WP	1810.05216	95,150,220+WP	0.020
Polarbear	1910.02608	150 + P	0.3
SPTpol	1910.05748	95 + 150	0.22
Planck/Tristram	2010.01139	30...353	0.07
SPIDER	2103.13334	95 + 150	0.13
BK18 + WP	2110.00483	95,150,220+WP	0.009
Polarbear	2203.02495	150 + P	~0.16

Challenges

- Astrophysical Foregrounds
  - Polarized thermal dust emission!
    - fairly well-characterized by now
  - As maps get deeper: galactic synchrotron, extragalactic sources will become more relevant

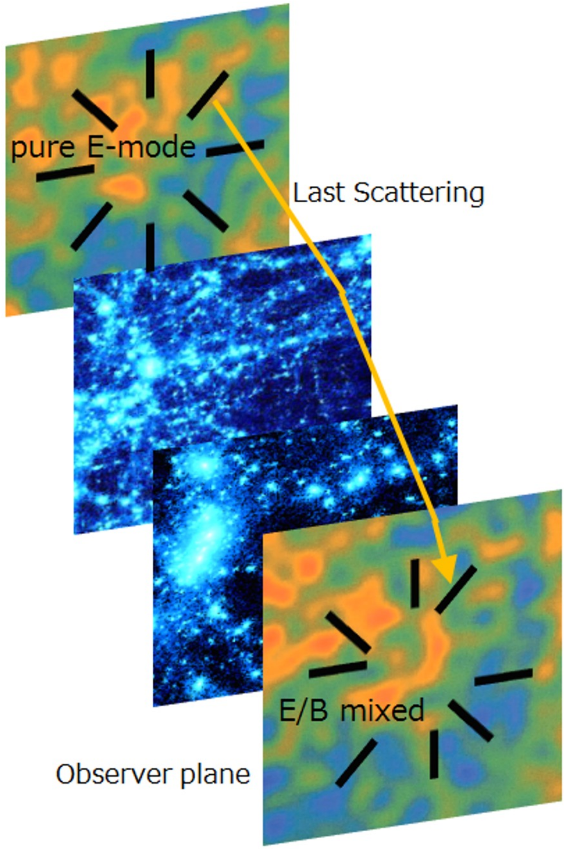
- Gravitational Lensing
  - Lensing of ΛCDM E-modes by large-scale structure mixes E/B
  - Currently the dominant contribution to BK18's σ(**r**)
  - Require high-resolution data to understand integrated lensing potential

    →synergy with SPT-3G (BK+SPT="SPO")

- Instrumental Systematics
  - Residual beam mismatch, crosstalk, etc.

- Terrestrial contamination, stability

- The Earth's atmosphere, both unpolarized AND polarized

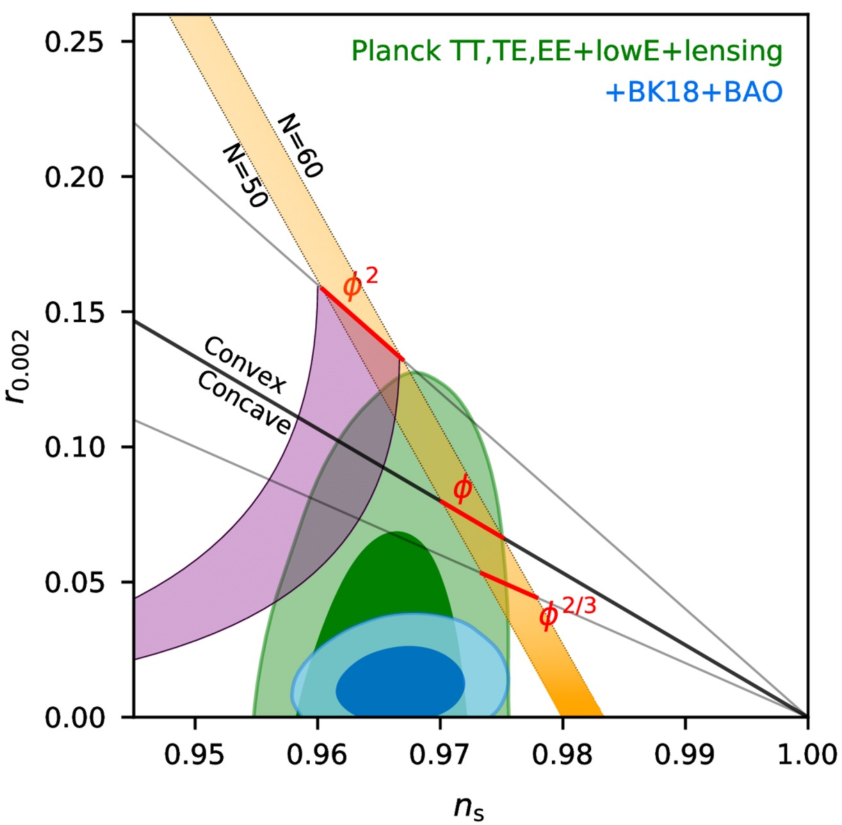


Latest r Constraint: "BK18"

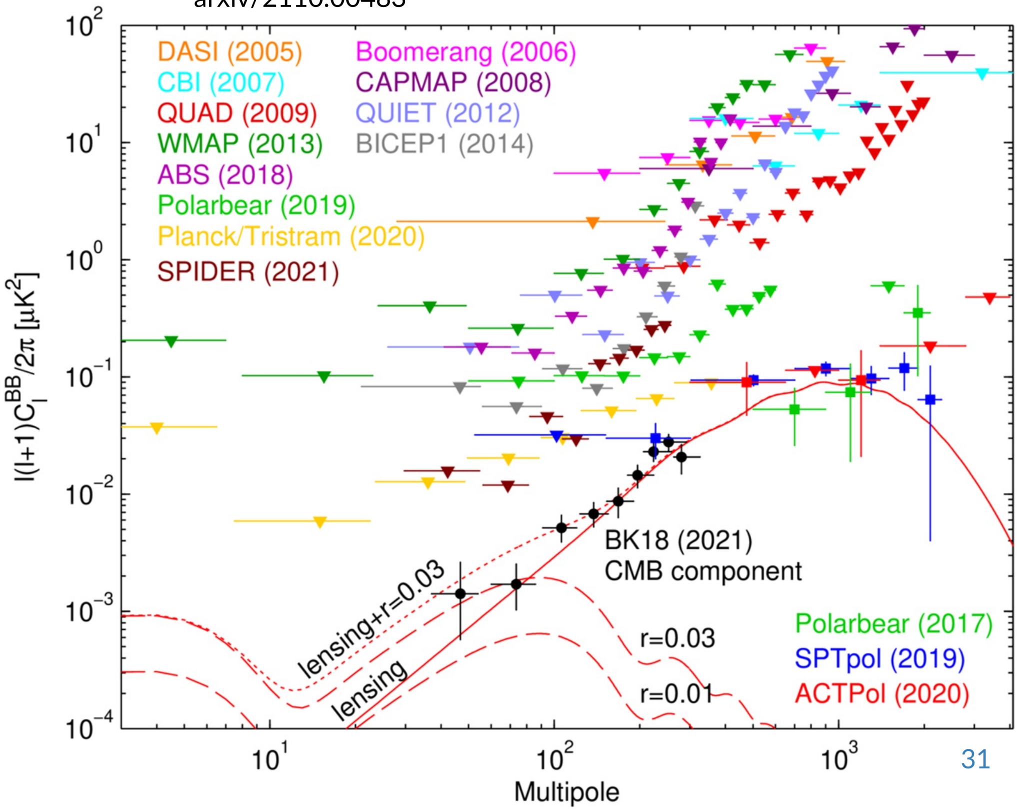
(uses data up to 2018 season, released 10/2021)

r < 0.036 (95% C.L.), σ(**r**) = 0.009

→ The most sensitive primordial B-mode constraints to-date
→ Sensitivity dominated by only 3 years of BICEP3 data (5 more in the can!)
→ Lensing sample variance is now the dominant source of uncertainty



The BICEP/Keck Collaboration, Phys. Rev. Lett. **127**, 151301, 2021
arxiv/2110.00483



Multicomponent Likelihood Analysis

Take joint likelihood of all BK and external (WMAP+*Planck*) BB auto- and cross-spectra against lensed-ΛCDM+foregrounds+***r*** model

Foreground model = dust + synchrotron

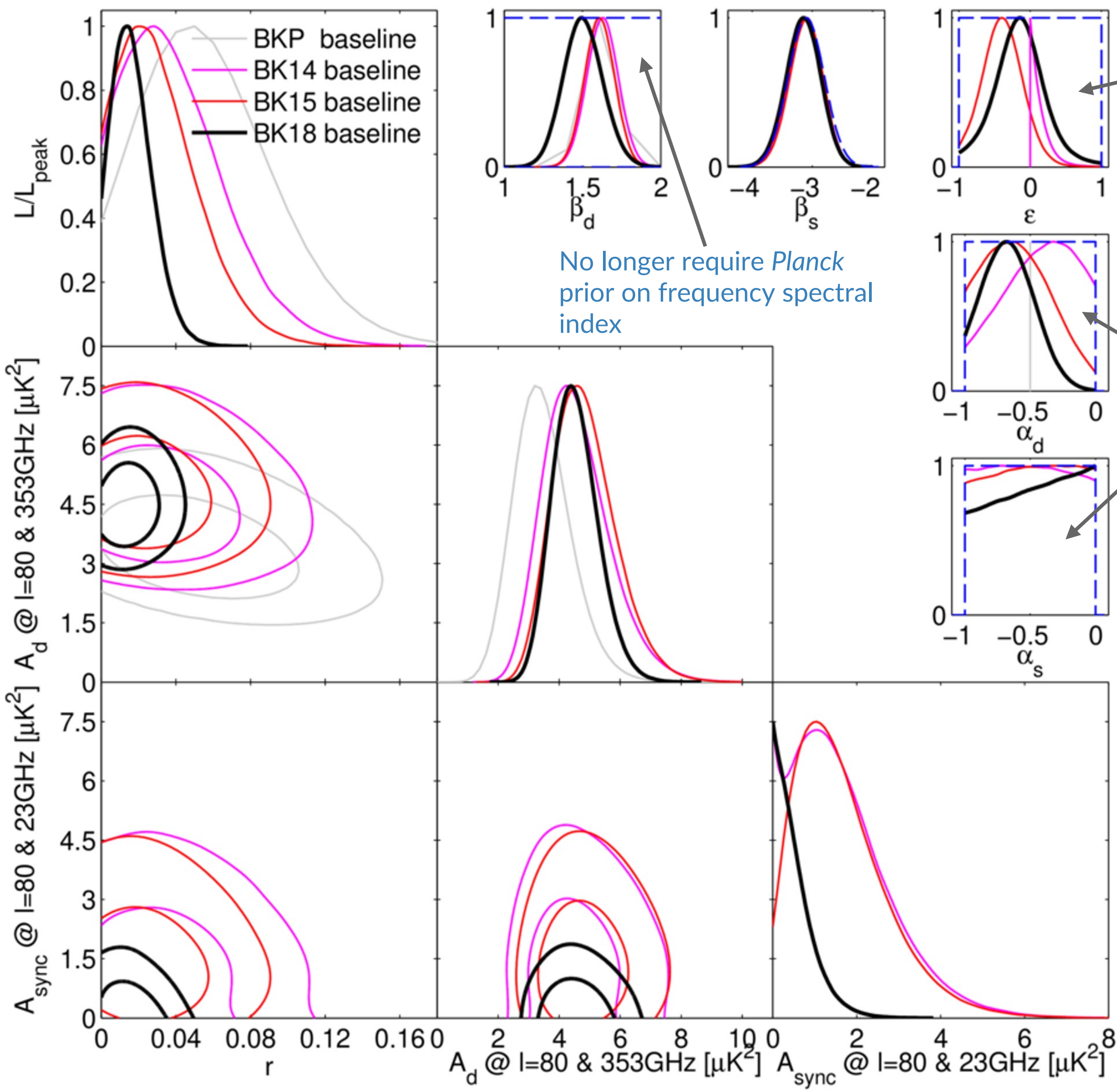
A_{dust} A_{synch} — amplitudes @ l=80

β_{dust} β_{synch} — frequency spectral indices

α_{dust} α_{synch} — spatial spectral indices

ε — dust/synch spatial correlation

Latest r Constraint: "BK18" (2021)



Allow dust/synch correlation in [-1,1]

No longer require *Planck* prior on frequency spectral index

Marginalize over generous ranges in spatial spectral indices

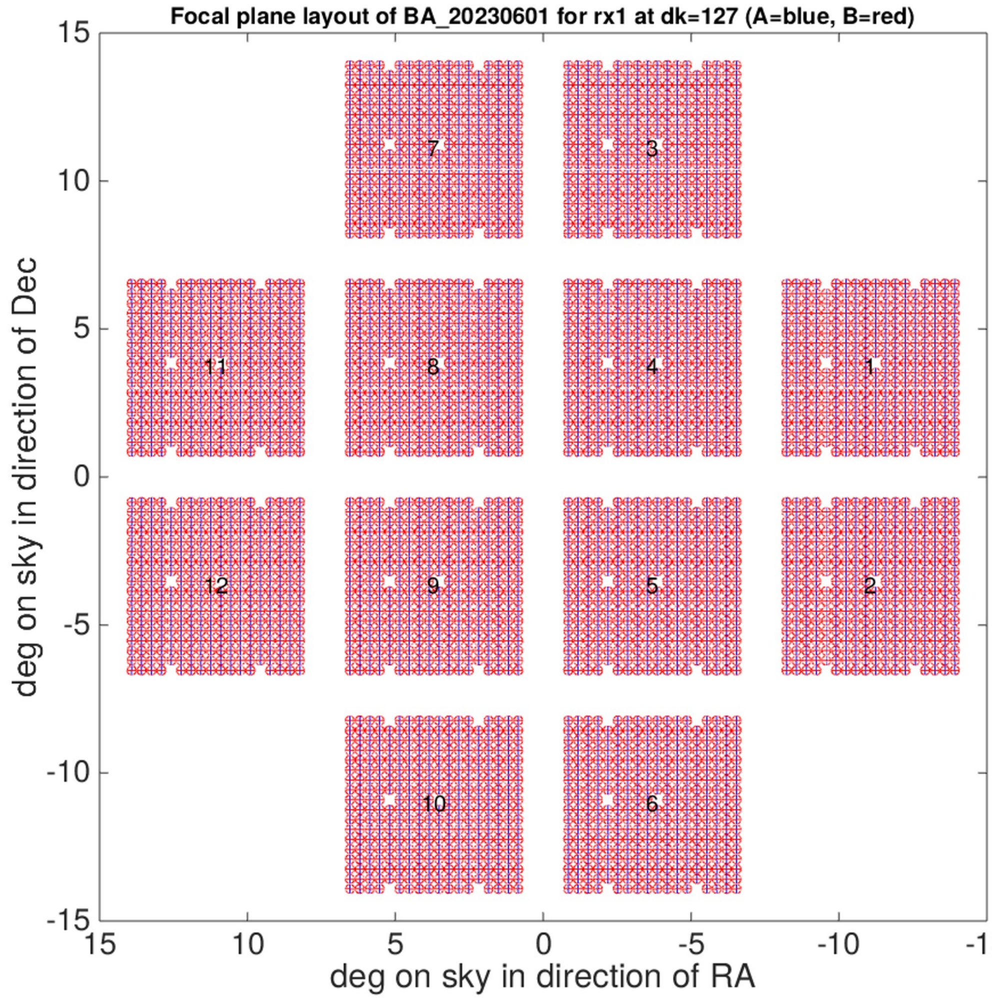
Since BK18…

- +5 seasons of BICEP3 95 GHz data (**+167%** vs. BK18)
- +10 *Keck* receiver-years of 220 GHz data (**+56%** vs. BK18)
- First BK observations at 30/40 (BA1) and 270 GHz (**+∞%** vs. BK18)
- New 150 GHz observations with BA2
  - + ~50% vs. BK18 – from just one season with partial (5/12) focal plane!
- 220/270 GHz “BA4” receiver coming together at Stanford, to deploy this coming Austral summer season (~Nov. 2024)

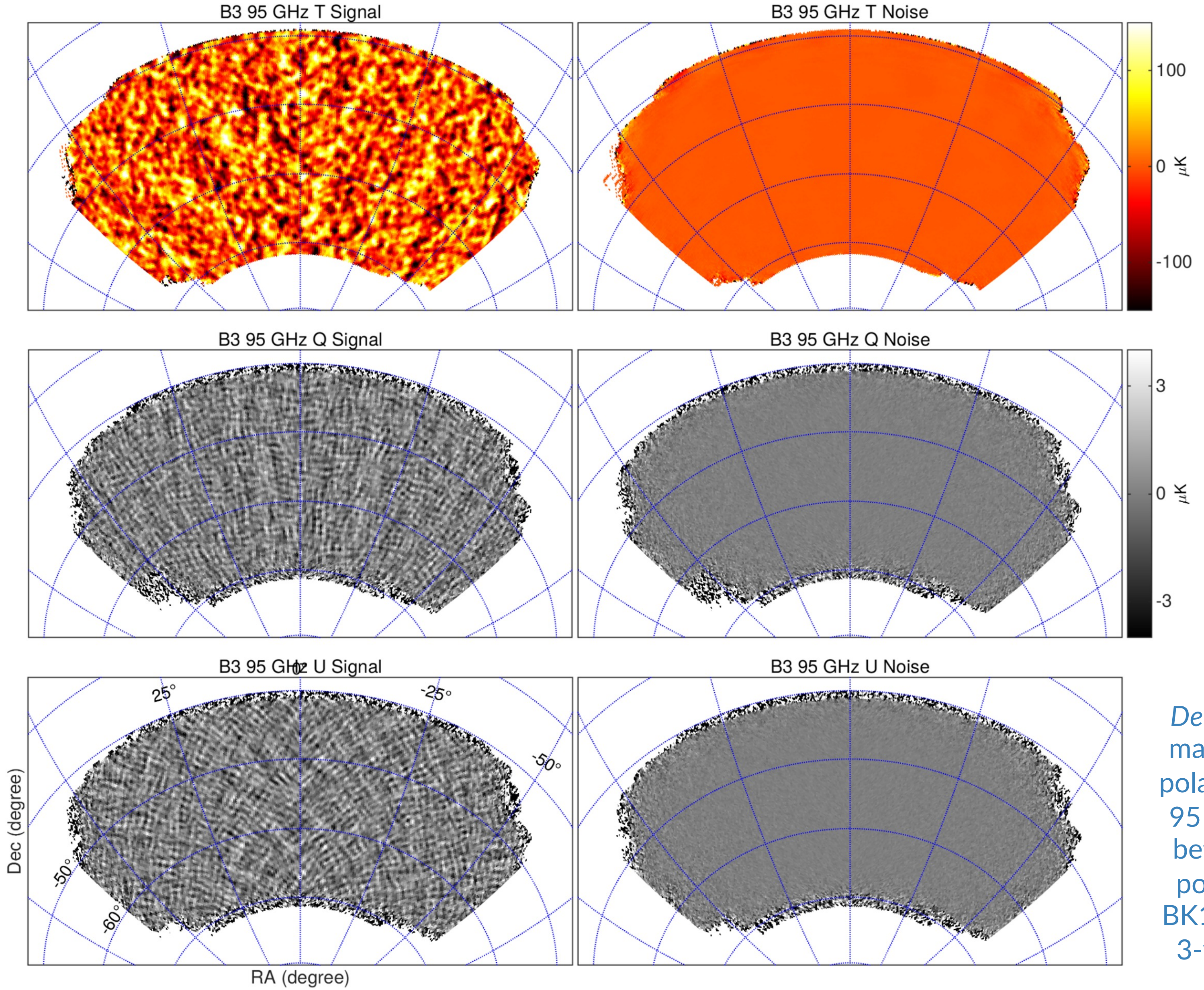
BICEP Array

- New mount installed 2019-2020
- 2020: First BK observations at 30/40 GHz
- 2023: BA2 began observations at 150 GHz
- BA2 currently observing with ~5500 live detectors (2.75x BICEP3!) after 2023-2024 upgrade

BA2 (150 GHz) Deployment and Upgrade (2022-2024)

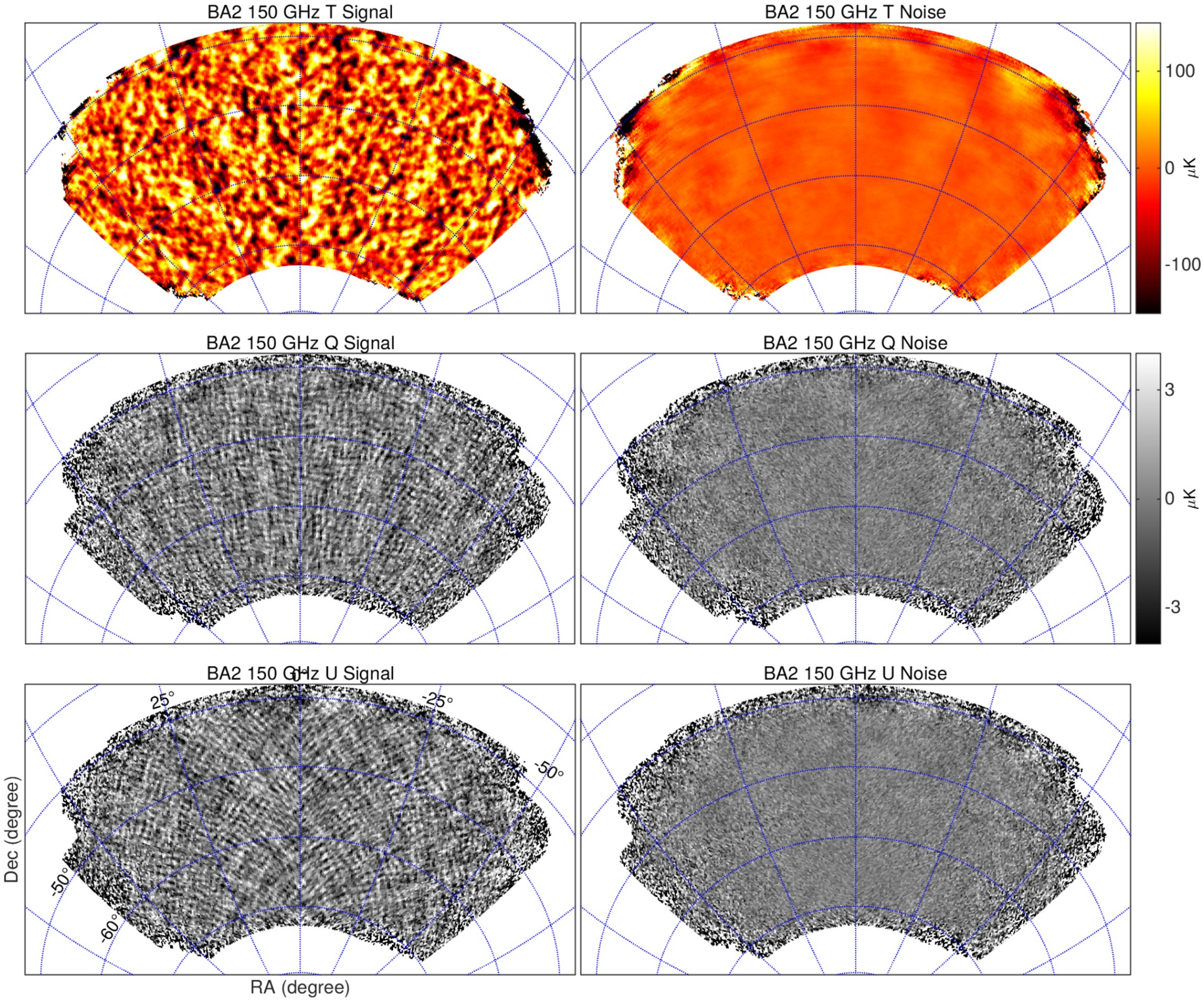


BICEP3 95 GHz 8-year map (up to 2023)

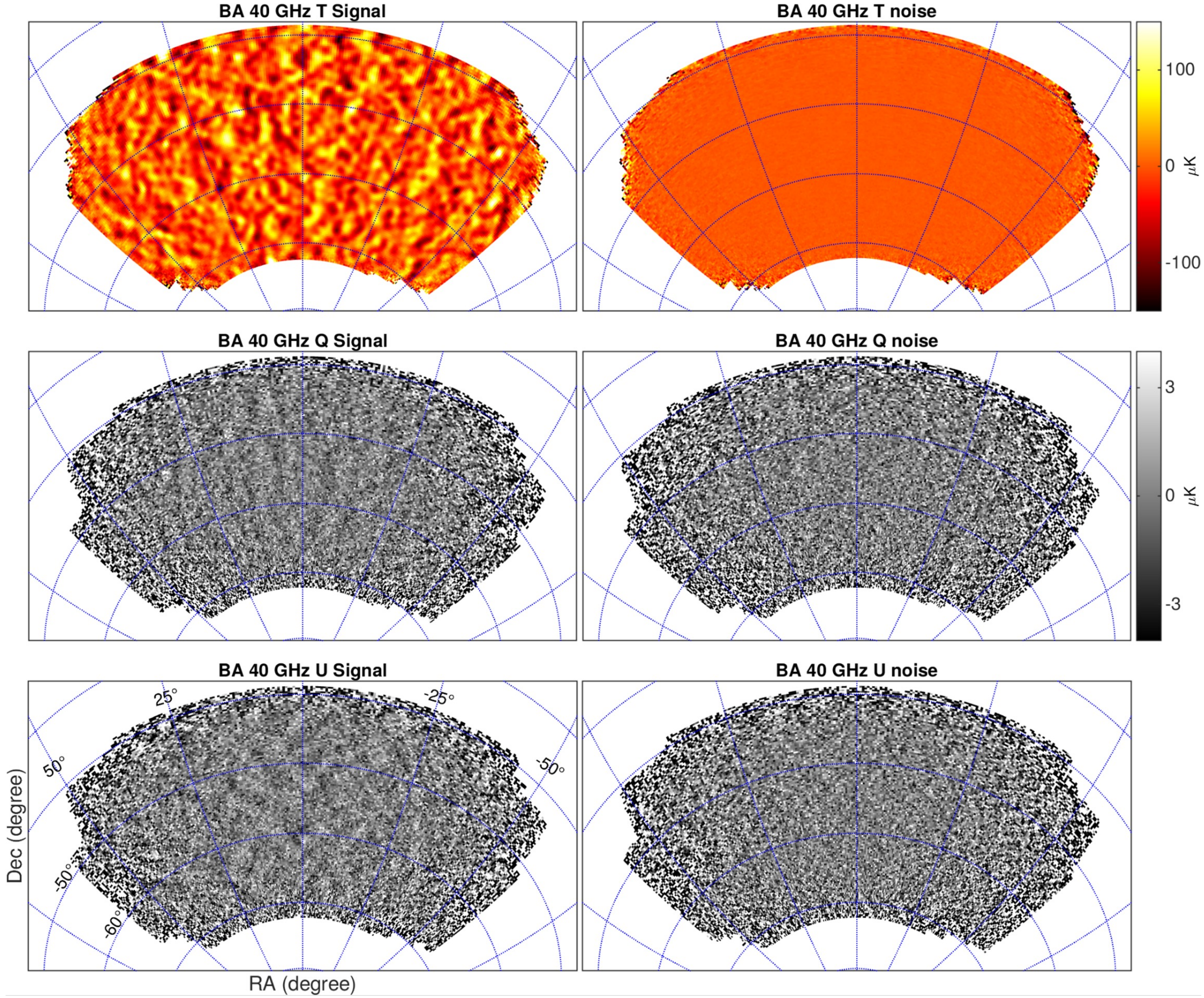


Deepest ever map of CMB polarization at 95 GHz! ~3x better noise power than BK18 BICEP3 3-year map

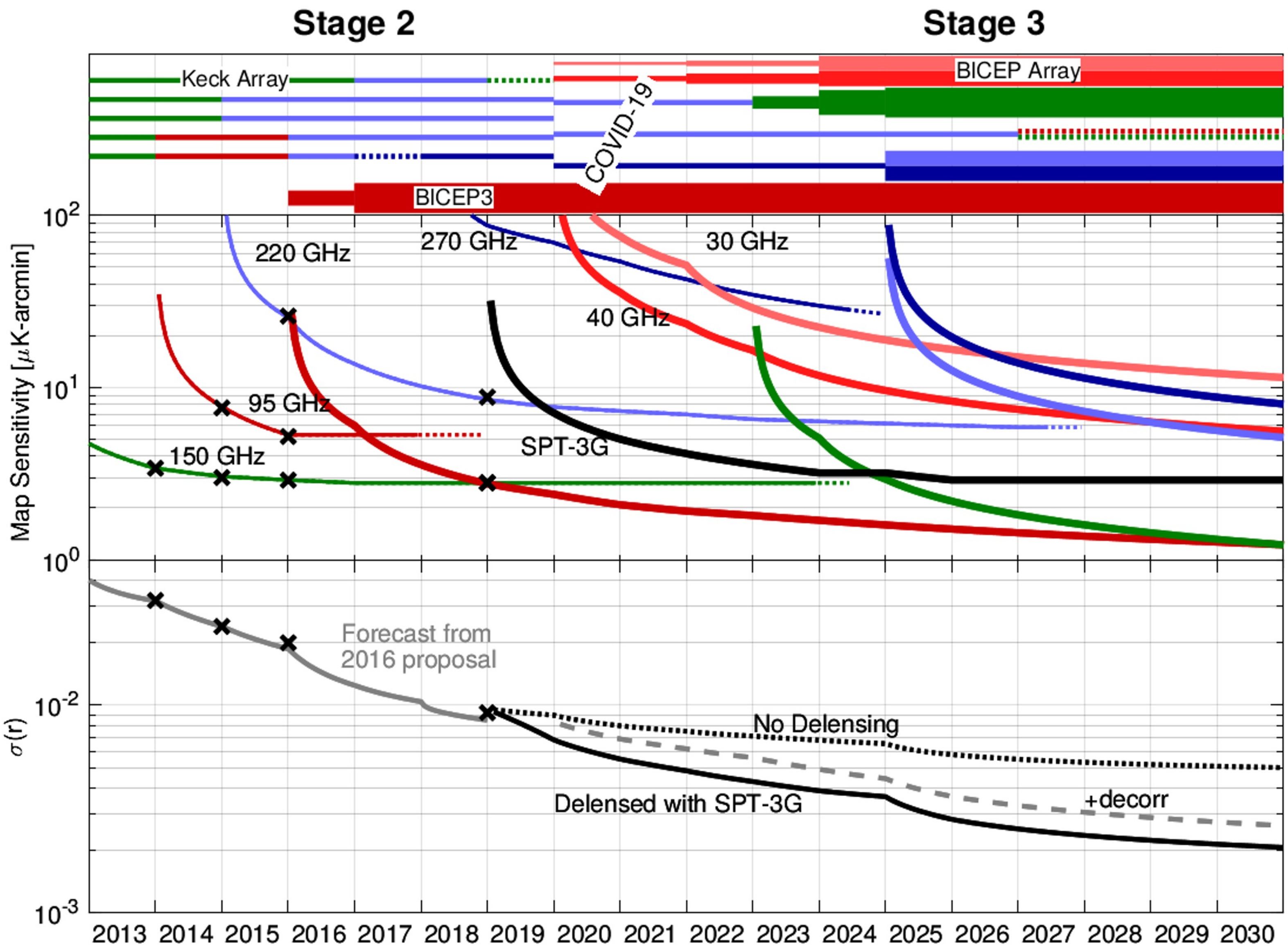
BA2 150 GHz 1-year map (with only 40% of a focal plane!)



BA1 40 GHz 3-year map



Advancing Polarization: BK and SPT σ(r) through 2030



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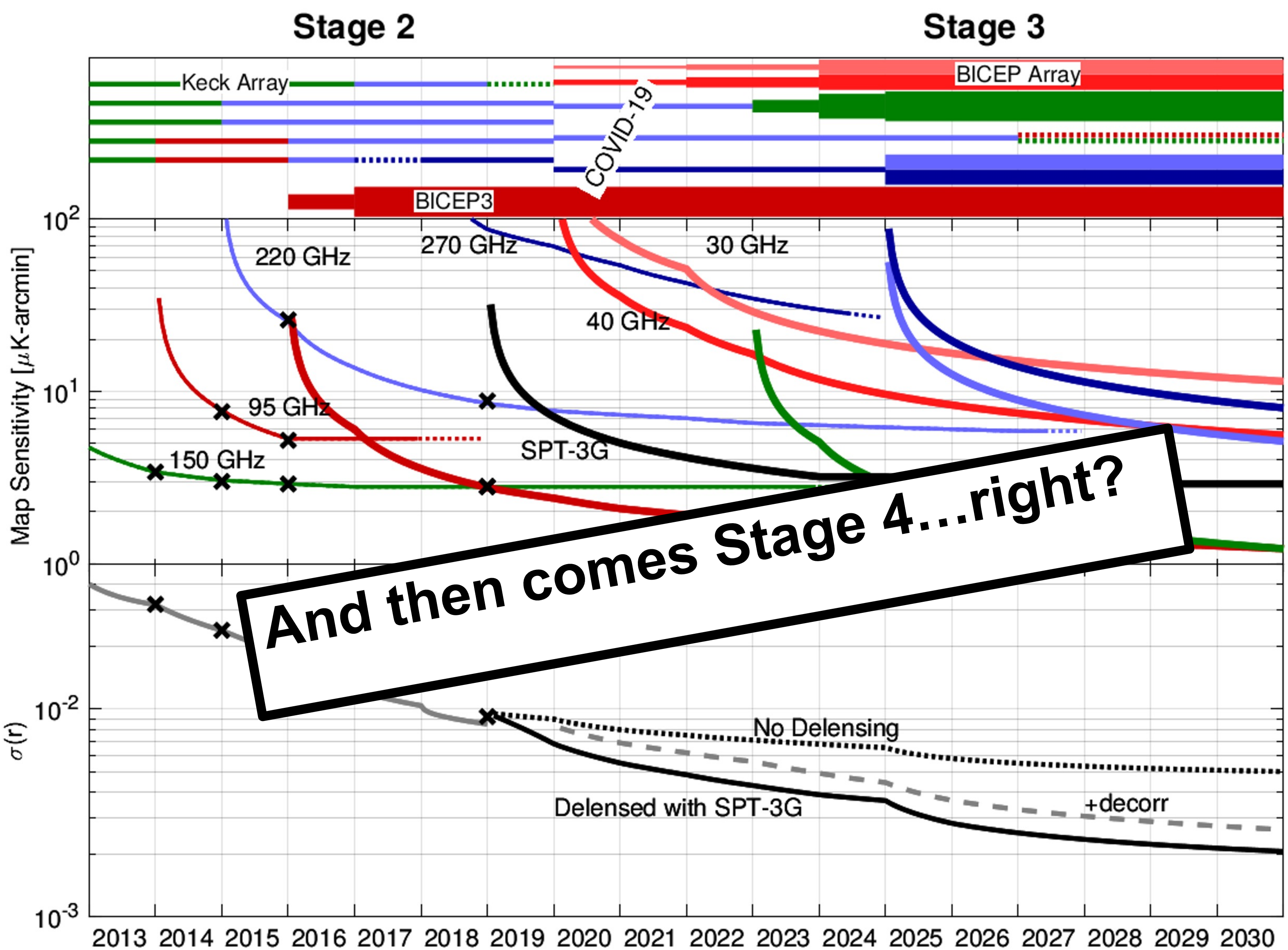
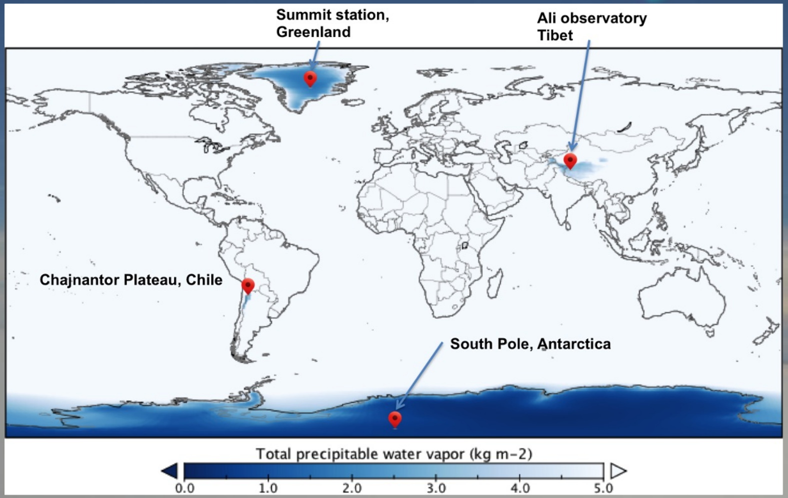


The South Pole is a unique Window to the CMB… like being in space!



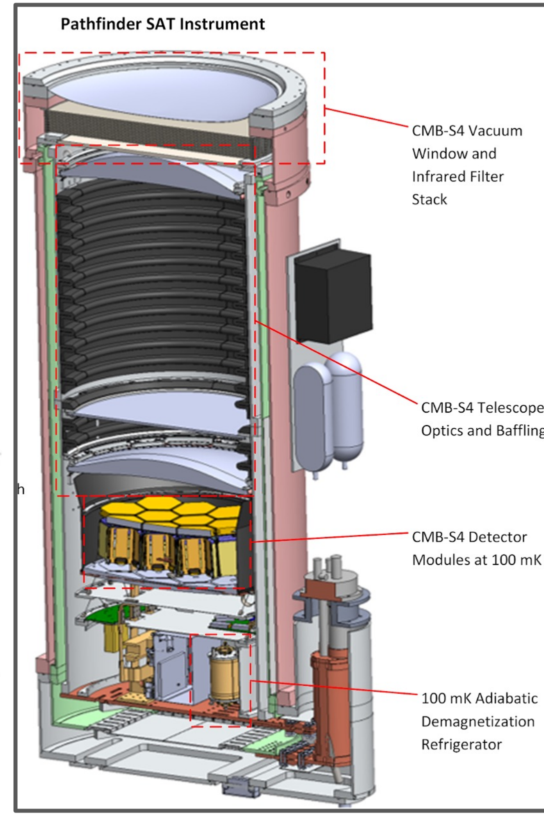
South Pole Environment

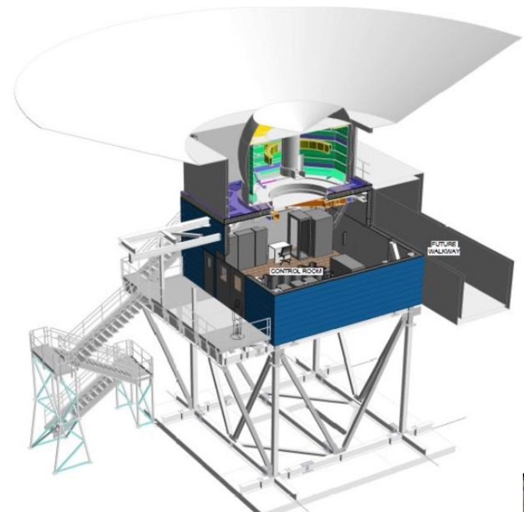
- **High Altitude (~10,000 ft) PLUS unique Polar Vortex**
- **Driest desert on Earth with most stable atmosphere**
  - At Pole, the water vapor is 4x lower with a ~30-100x more stable atmosphere than the Chilean Atacama desert.
- **Featureless, thermally-stable terrain**
- **Relentless Observing**
  - 24/7 year-round access to Southern Sky, including the Black Hole at the Milky Way's center for Event Horizon Telescope
- **Annual Access for rapid technology deployment**

Next-step pathfinders

The CfA CMB group and SAO Receiver Lab, along with the wider BICEP/Keck collaboration, are developing instruments that will serve as prototypes of several elements of the CMB-S4 SATs:

- **preSAT** - a hybrid BICEP Array/CMB-S4 SAT receiver, incorporating CMB-S4 optics and dual band detector modules with field proven BA cryogenic hardware
  - Providing essential testing for CMB-S4 SATs this year
- **BA Replacement Tower (BART)** - replacement tower and control room for BA, and prototype for CMB-S4 SAT towers, incorporating solar arrays to reduce fuel usage in summer (SAO and Harvard).
  - NSF has just asked (Feb 2024) us to lead construction of this facility at Pole, funded under a novel MREFC execution model
- **BICEP Array Mount** - replacement telescope mount for BA, prototype for CMB-S4 SAT mount (UMN lead for BICEP/Keck; SAO, Harvard and NSF funding)
  - Delivered to North America last Nov (UMN), incorporated into this year's CMB-S4 test plan





Concluding thoughts…

- South Pole measurements have been uniquely successful in this wild goose chase for r.
  - Current instruments: $\sigma(r) \sim 0.005$ today, 0.002 by late decade
- **Very** hard news from NSF last month!
- Personally, I remain hopeful that NSF will clarify that there IS a future for US polarization at South Pole, e.g. by committing to:
  - Sustain progress within current footprint of telescopes there, while infrastructure work proceeds
  - Open a possibility to plan for new telescopes in 6-8 years
  - Allow CMB-S4 to proceed. A mostly-Chile posture for now is fine as long as we have a door open at Pole, and can react to the evidence.
- Chile is vital to future of CMB. So is Pole.
  - They are very, very different environments. We are really looking forward to deep comparisons of SO and Pole data to understand how these differences play out in fundamental degree-scale limitations.

- This is doable. This is hard.

Thank you KICP, and HAPPY BIRTHDAY!