Studying the Beginning of the Universe from the Bottom of the World

Clem Pryke – University of Washington Physics Colloquium – April 11 2022

Modern cosmology in a nutshell:

Edwin Hubble

1) The universe is expanding.

(Hubble, 1920s)

2) It was once hot and dense, like the inside of the Sun.

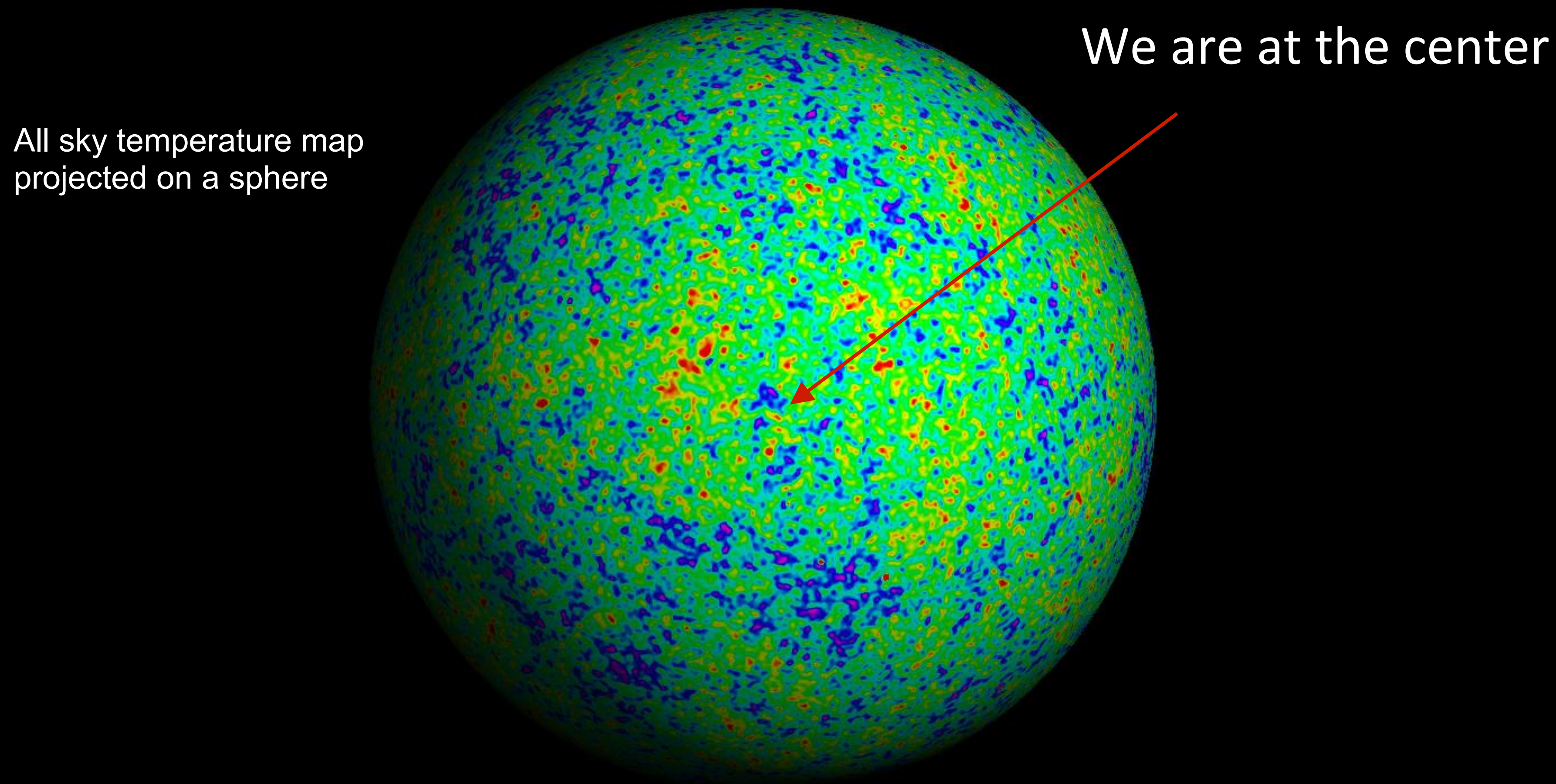
(Alpher, Gamow, Herman, 1940s)

Bob Wilson & Arno Penzias
1978 Nobel Prize

3) We can see the (redshifted) glow!
The *Cosmic Microwave Background*
(Penzias & Wilson, 1964)

⇒ acceptance of the "HOT BIG BANG"

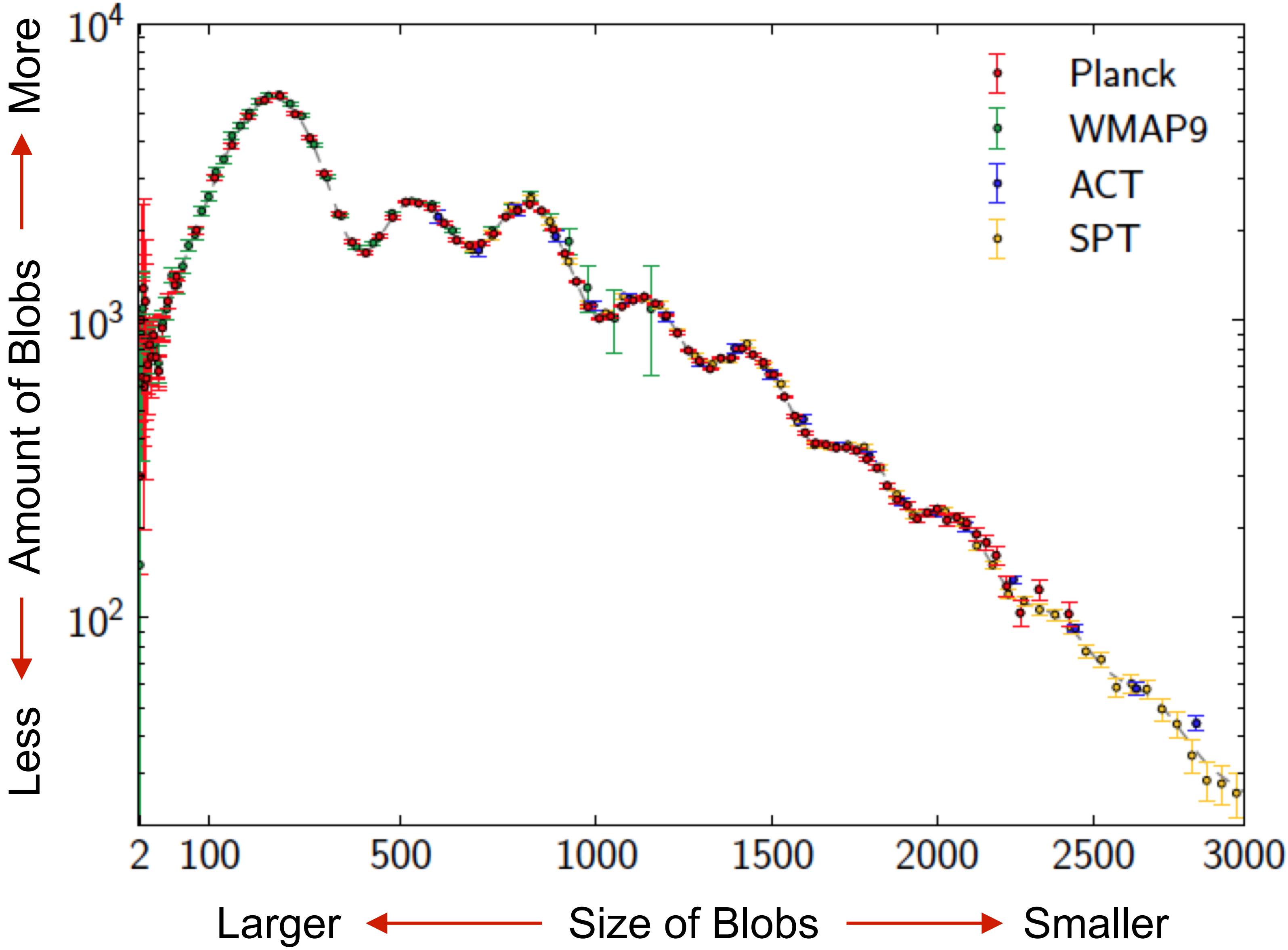
Cosmic Microwave Background Surface of Last Scattering



CMB temperature is a sample of the density structure on a shell cut through the 380,000 year old Universe

Perturbations are one part in 10,000 at that time – and Gaussian!

Power Spectrum (Blob size histogram)



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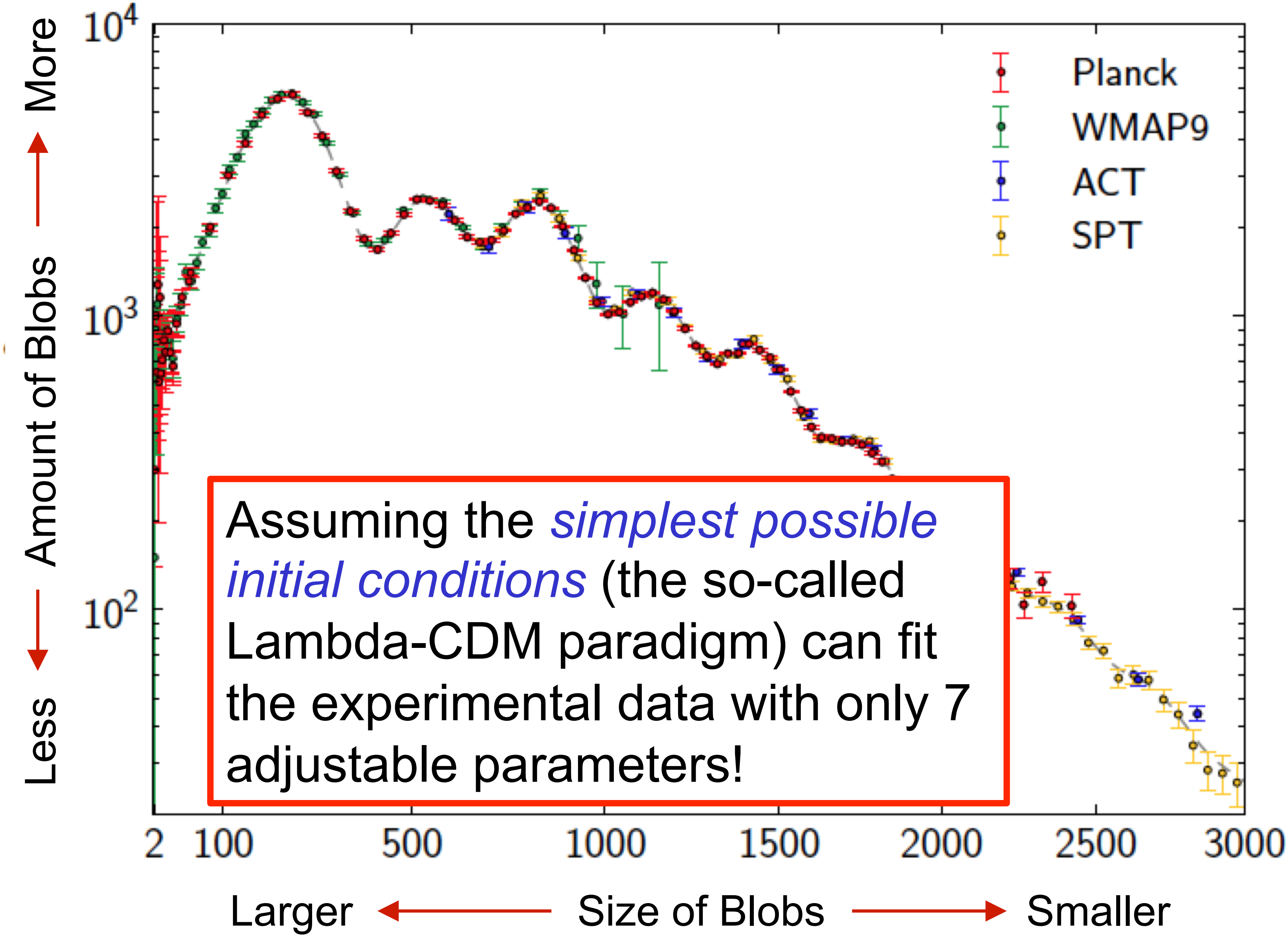
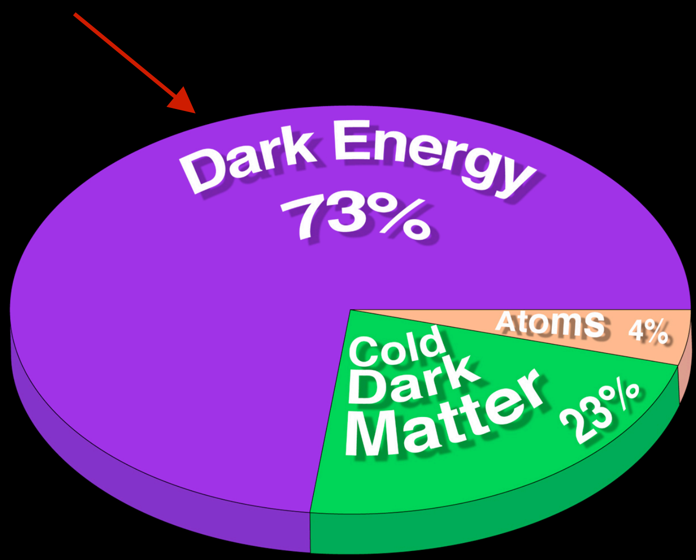
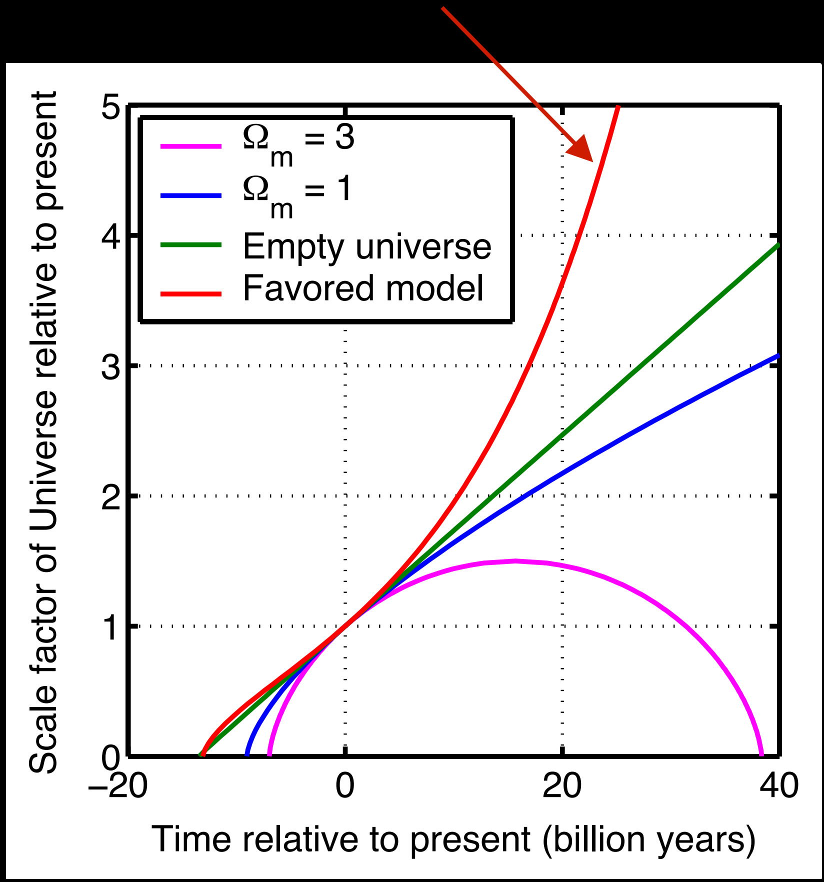


Triumphant/Embarrassing Contemporary Cosmology

CMB and other data fits GR based LCDM model *beautifully* – but it demands that 96% of the Universe is invisible to us

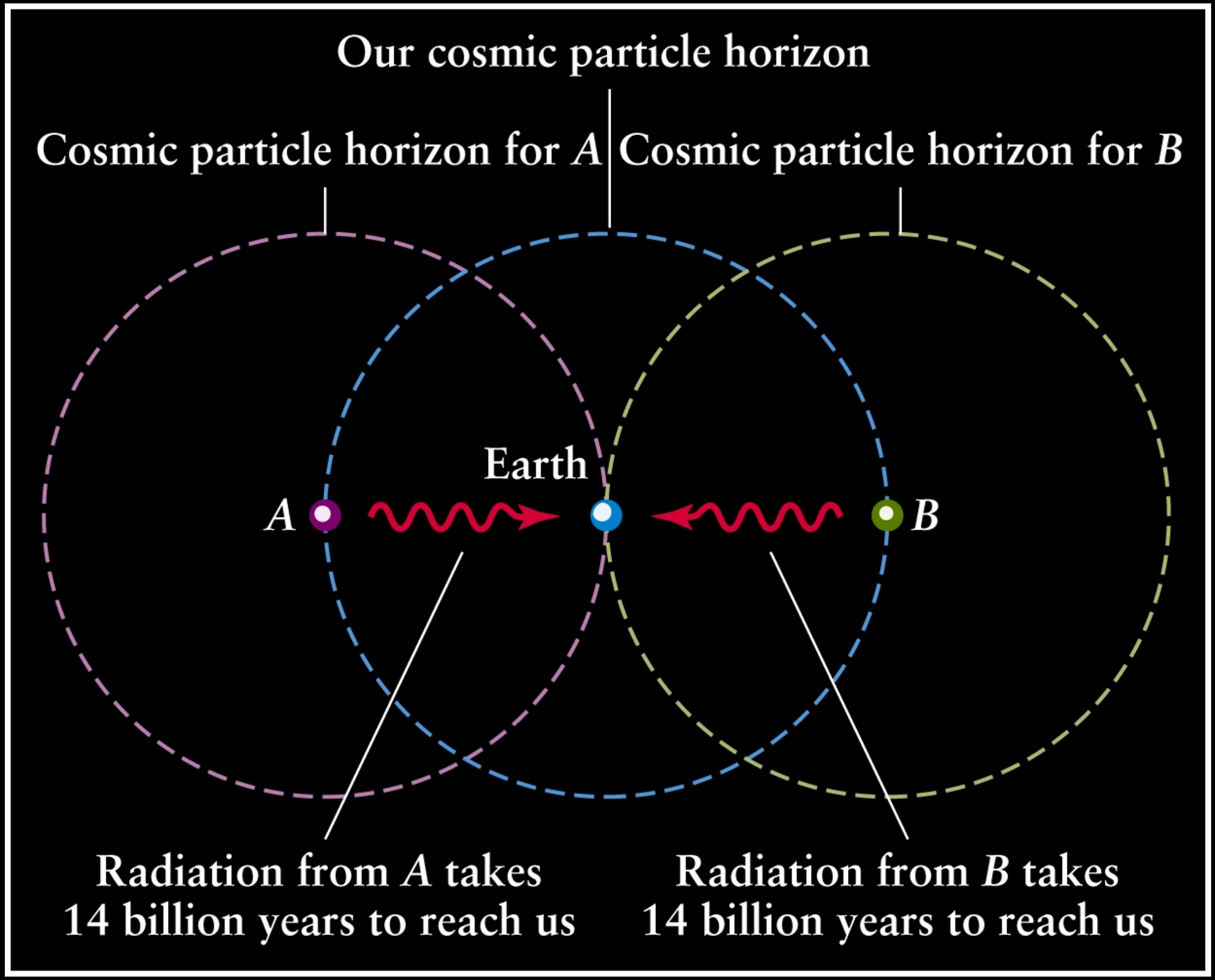


And it implies that the future is runaway expansion…



Also it doesn't explain horizon/flatness etc…

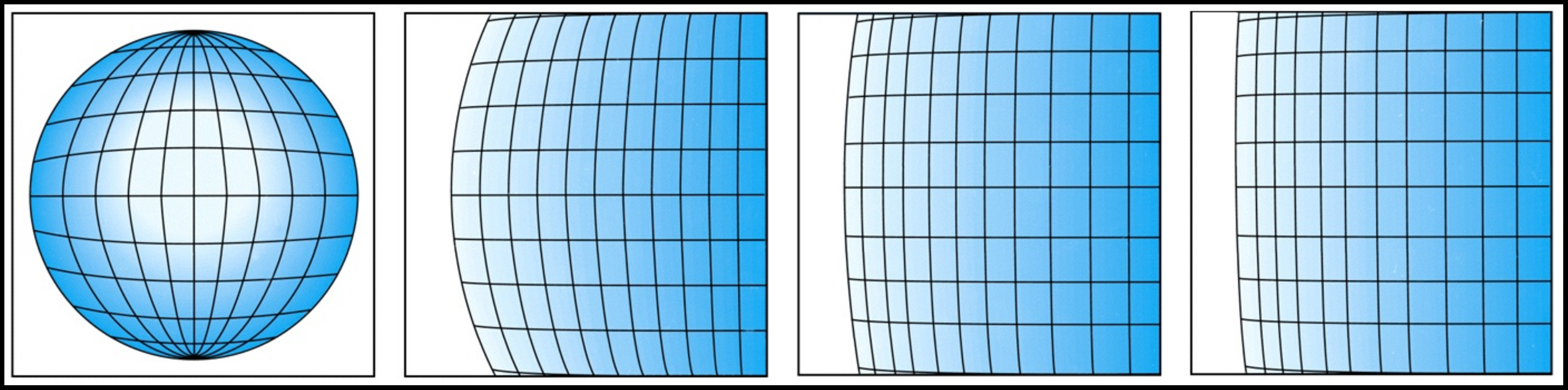
The Horizon Problem



How did points A and B “know” to be at the same temperature in the distant past when they had never been in causal contact?

(They still aren’t today!)

Inflation solves the Flatness Problem



Inflation...

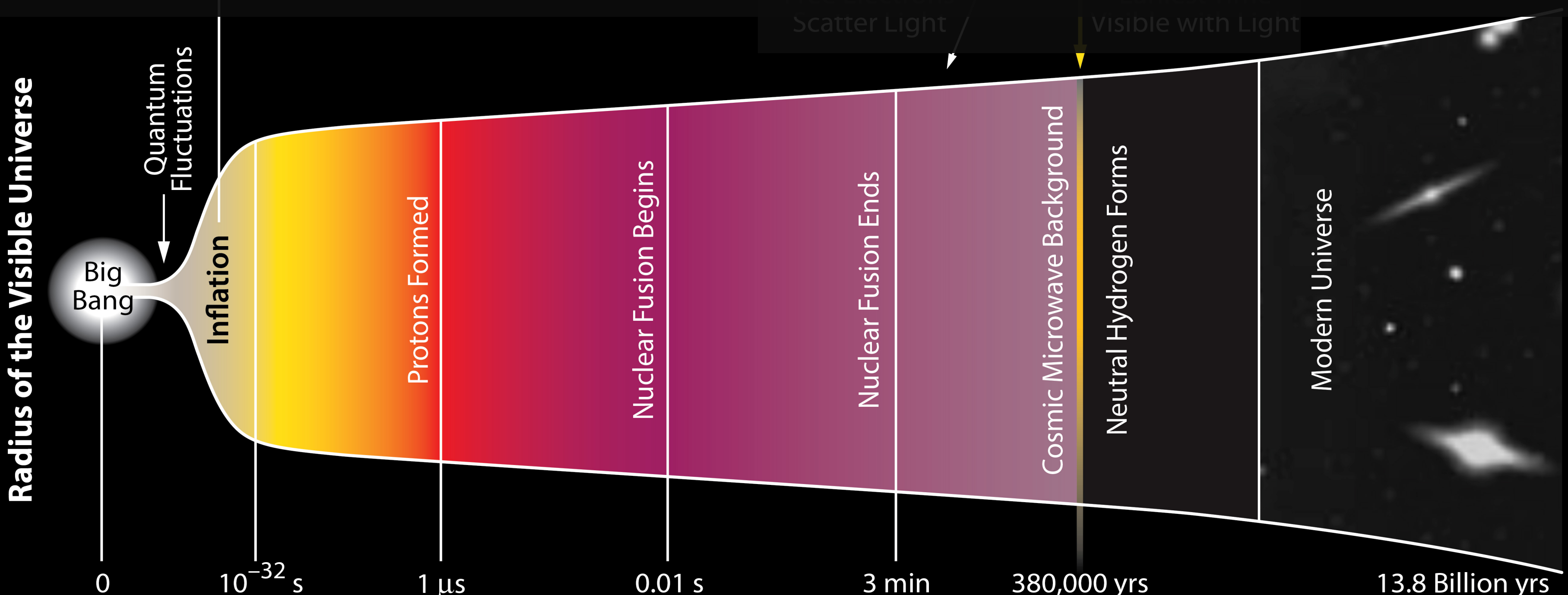
If you take some curved space and blow it up enough pretty soon it is no longer curved on a local scale – where "local scale" here means our entire observable Universe!

History of the Universe

Inflation posits a pre-phase of exponential expansion

Alan Guth

Andrei Linde



What Does Inflation Do For Us?

Solves the horizon problem: Why is the CMB nearly uniform? How do apparently causally disconnected regions of space get set to the same temperature?

→ A volume much larger than our entire observable universe today was once a caussally connected sub atomic speck.

Solves the flatness problem: Why is the net spatial curvature so close to zero?

→ Any initial spatial curvature is diluted away to undetectabilty by the hyper expansion.

Explains the initial perturbations: Why Gaussian with close to flat power law spectrum?

→ Equal amounts of perturbations are injected by quantum fluctuations at each step in the exponential expansion.

Solves the monopole problem: Why do we not observe magnetic monopoles in the Universe today?

→ Monopoles are diluted away to undetectability.

Inflation is controversial

Inflationary Paradigm after Planck 2013

Alan H. Guth,[1] David I. Kaiser,[1] and Yasunori Nomura[2]

[1]Center for Theoretical Physics, Laboratory for Nuclear Science, and Departm
Massachusetts Institute of Technology, Cambridge, MA 02139, U
[2]Berkeley Center for Theoretical Physics, Department of Physics
and Theoretical Physics Group, Lawrence Berkeley National Labora
University of California, Berkeley, CA 94720, USA

(Dated: December 29, 2013, revised January 13, 2014)

arxiv/1312.7619

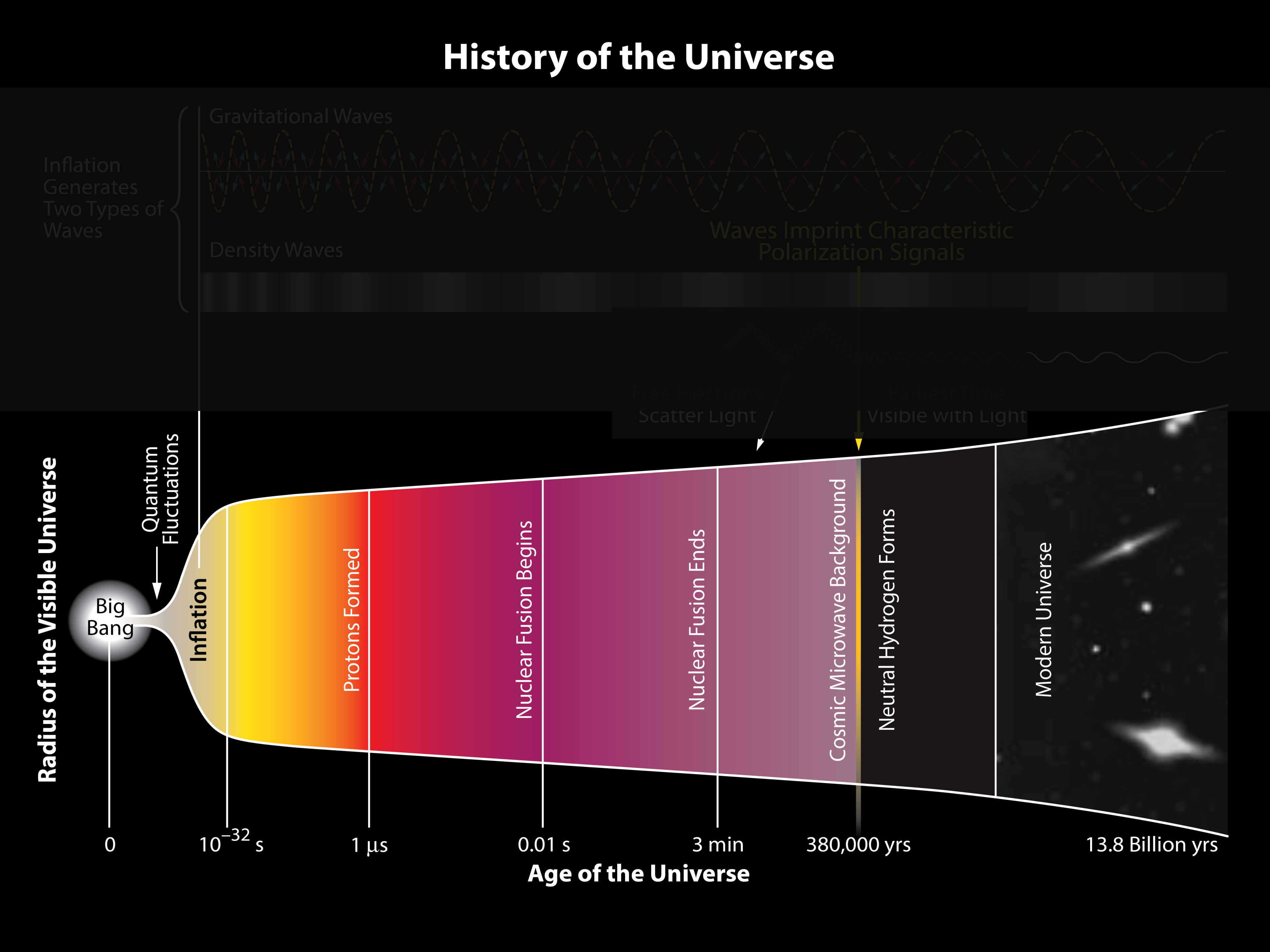
Inflationary schism after Planck2013

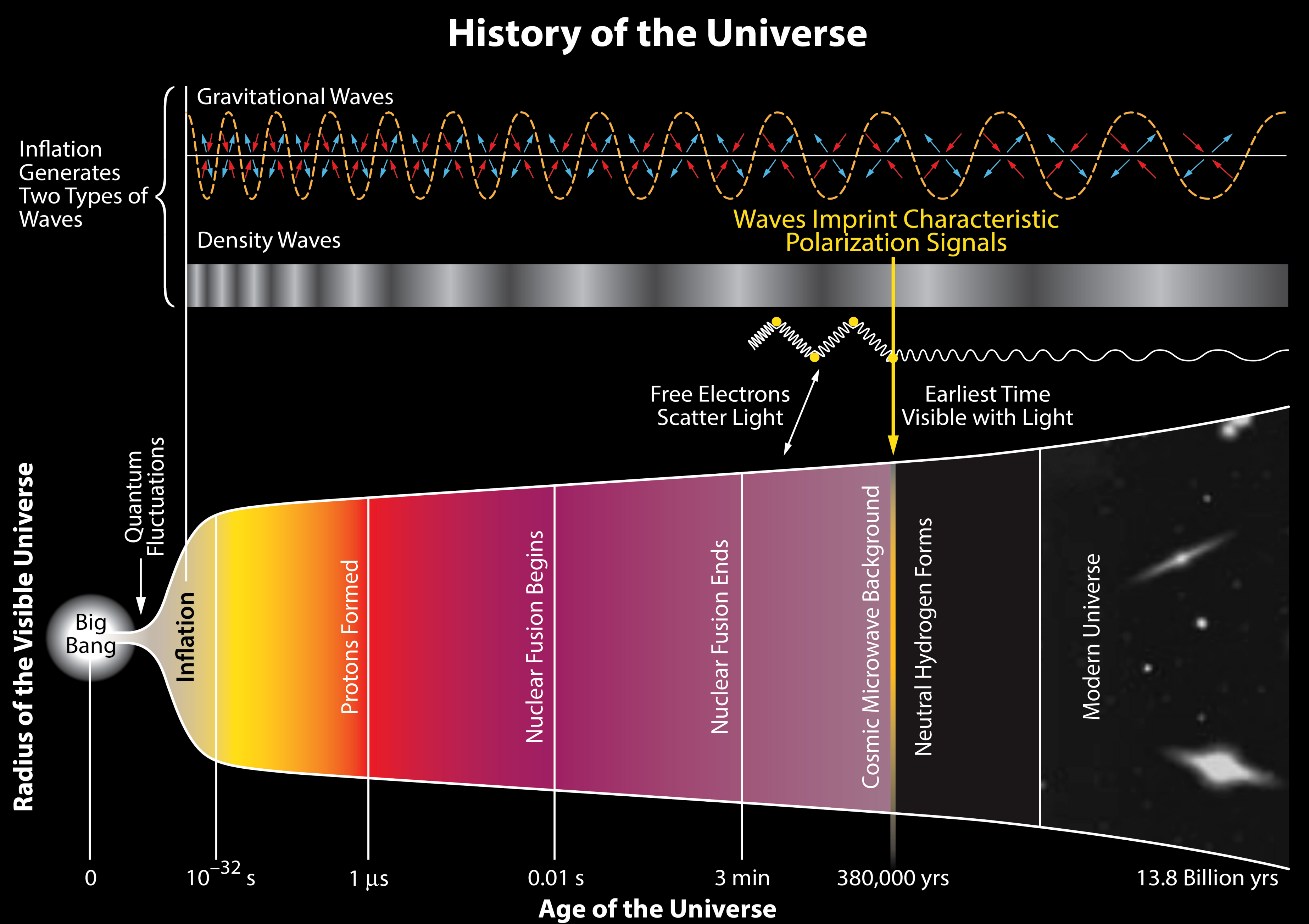
Anna Ijjas,[1,2] Paul J. Steinhardt,[3] and Abraham Loeb[4]

[1]Max-Planck-Institute for Gravitational Physics (Albert-Einstein-Institute), 14476 P
[2]Rutgers University, New Brunswick, NJ 08901, USA
[3]Department of Physics and Princeton Center for Theoretical Scien
Princeton University, Princeton, NJ 08544, USA
[4]Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138,

(Dated: March 14, 2014)

arxiv/1402.6980


History of the Universe
Gravitational Waves
Inflation Generates Two Types of Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Radius of the Visible Universe
Big Bang
Quantum Fluctuations
Inflation
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Neutral Hydrogen Forms
Modern Universe
0
10^{-32} s
1 μs
0.01 s
3 min
380,000 yrs
13.8 Billion yrs
Age of the Universe



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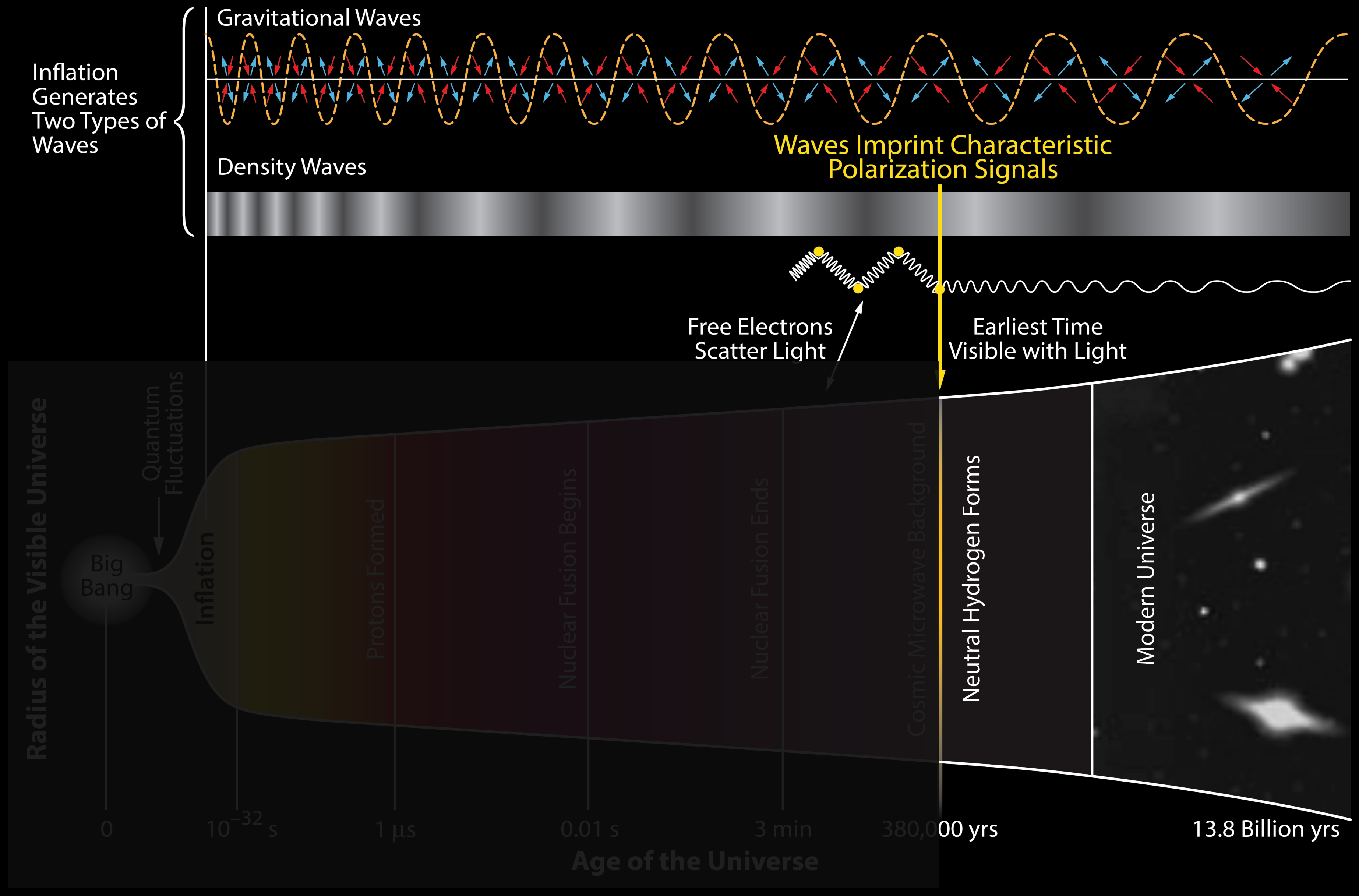

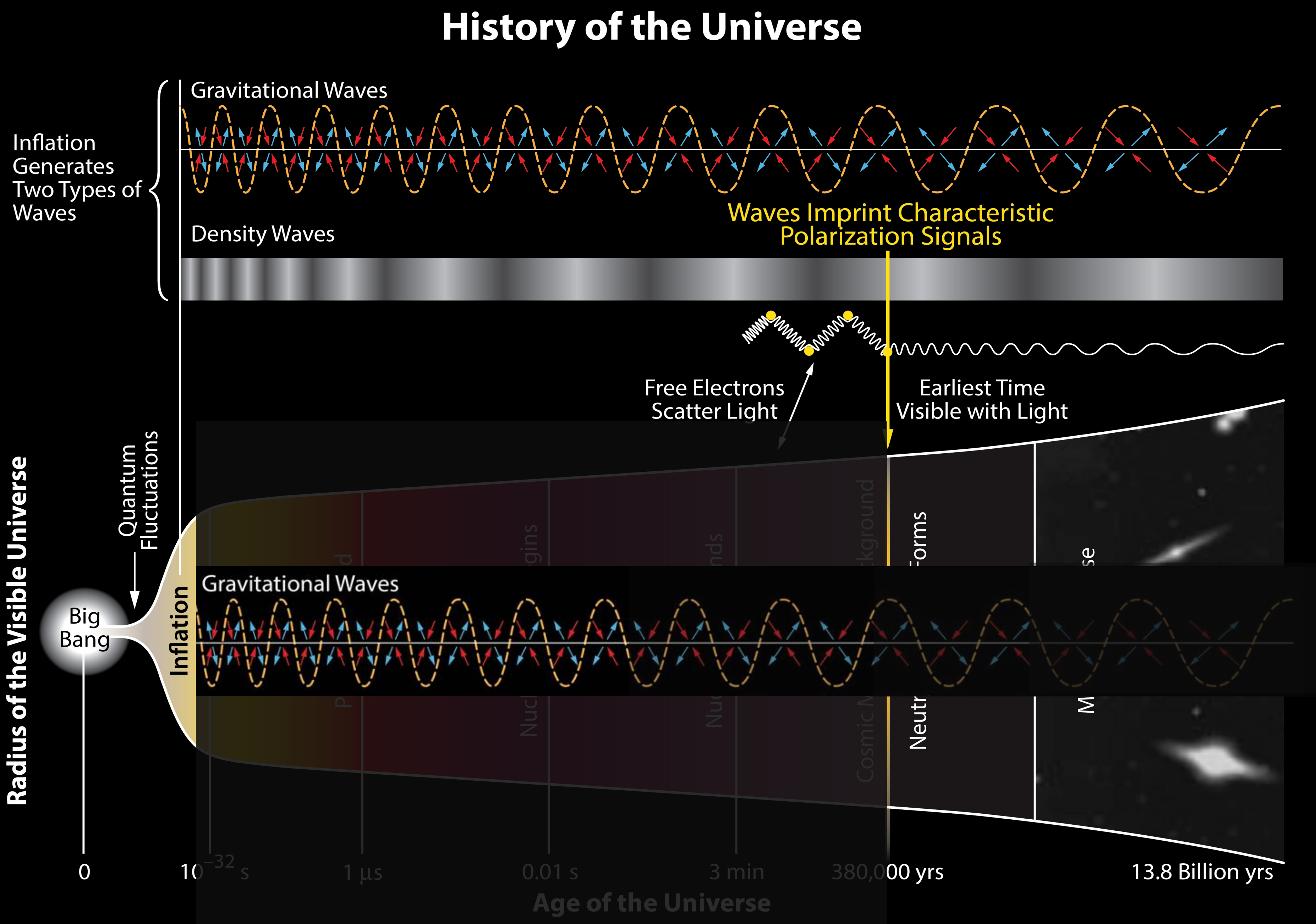
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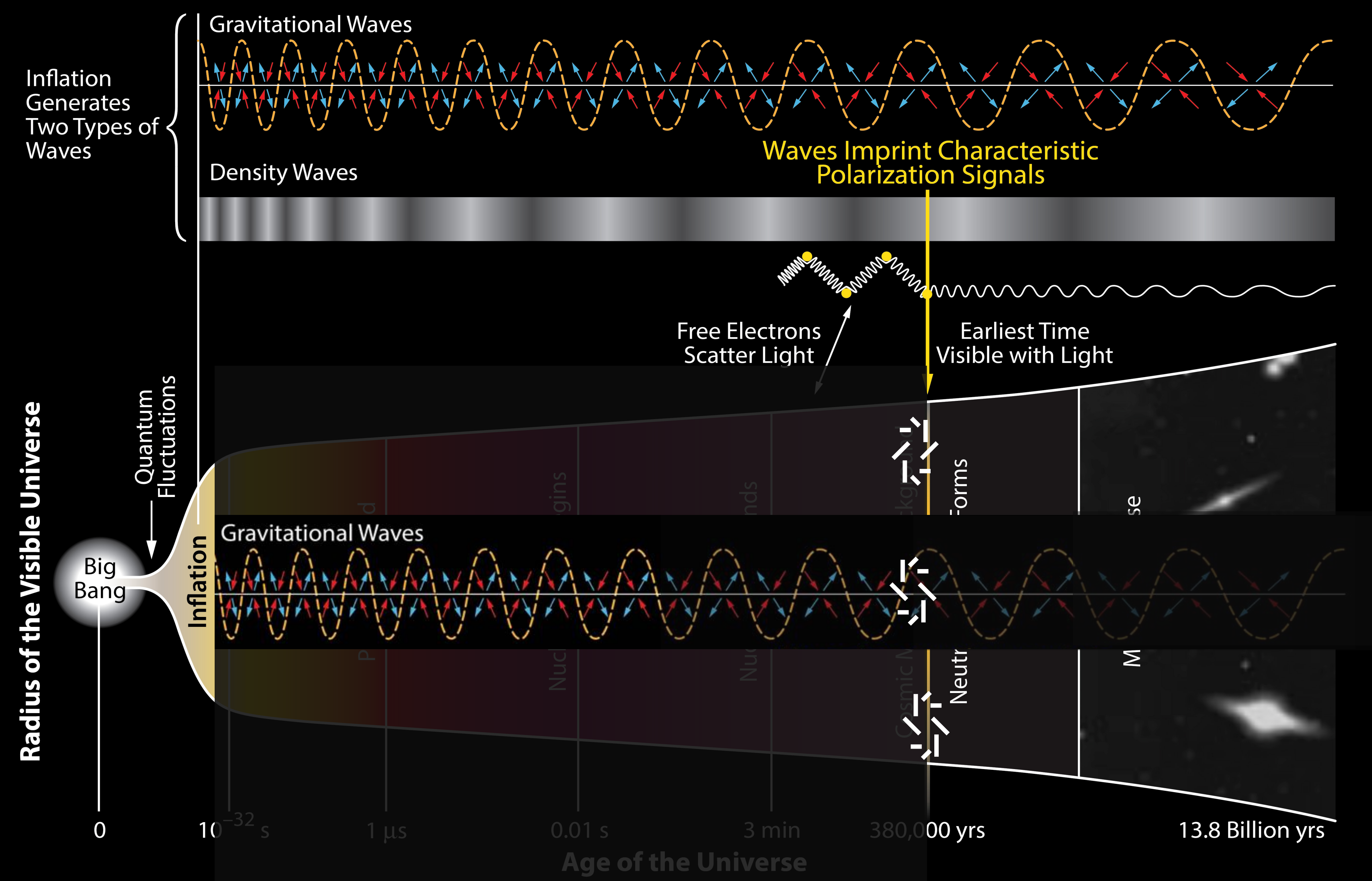
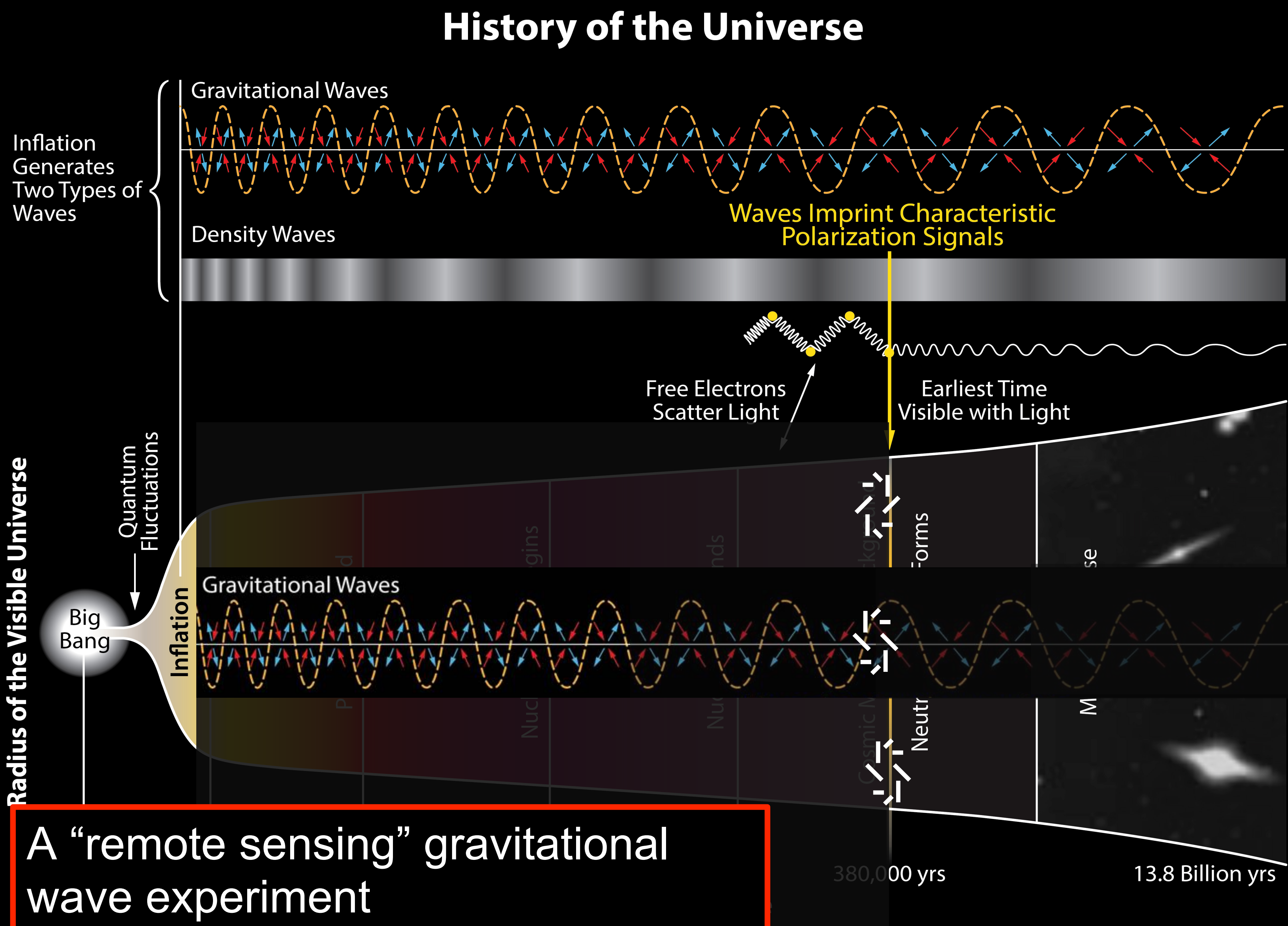
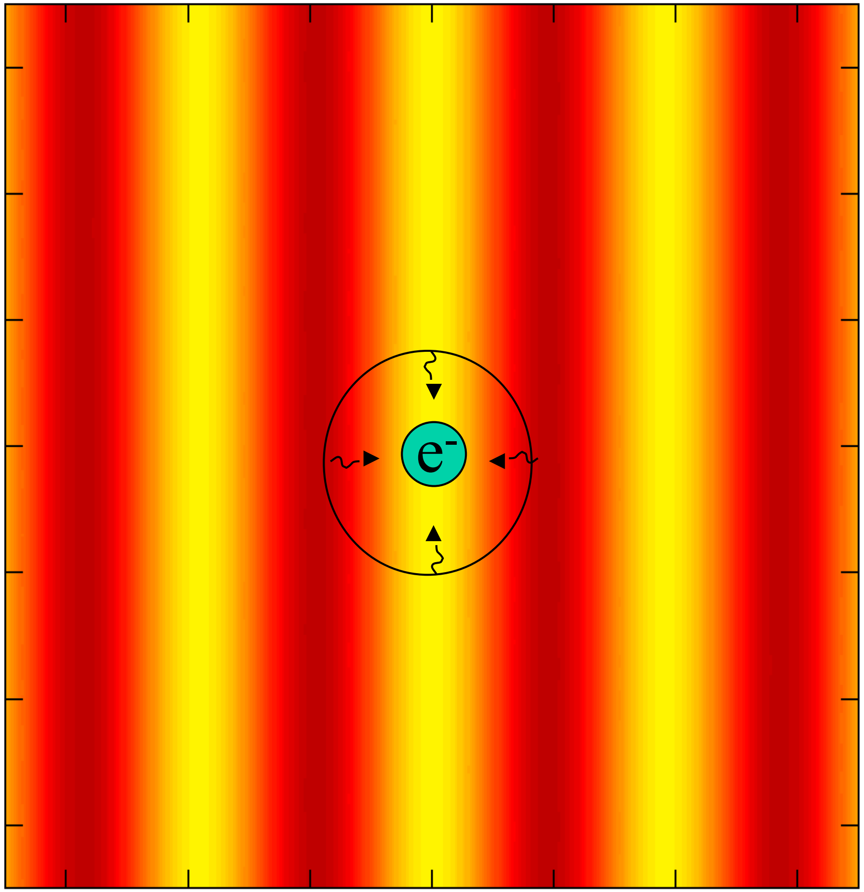




A “remote sensing” gravitational wave experiment

CMB polarization: arises at last scattering from local radiation quadrupole



CMB Polarization, B-modes and *r*

- The CMB is partially polarized (due to local radiation quadrupoles at last scattering)
- Any polarization pattern can be decomposed into E-modes (gradient modes) and B-modes (curl modes)
- Basic LCDM makes only E-modes at last scattering – although lensing deflections in flight produce a bit of a B-mode
- Primordial gravitational waves produce both E-modes and B-modes – but best to look for the B-modes since most distinct there
- Theory gives us a good template shape for the gravitational wave signal – but it does *not* tell us the amplitude
- The amplitude is parameterized by a single number *r*
- A wide range of inflation theories exist – the simplest are already ruled out – more complex ones can produce *r* which is undetectably small
- The experimental mission is to obtain the best possible sensitivity to *r*
- If we can detect *r* we determine the energy scale of inflation – if not we can rule out additional inflationary models

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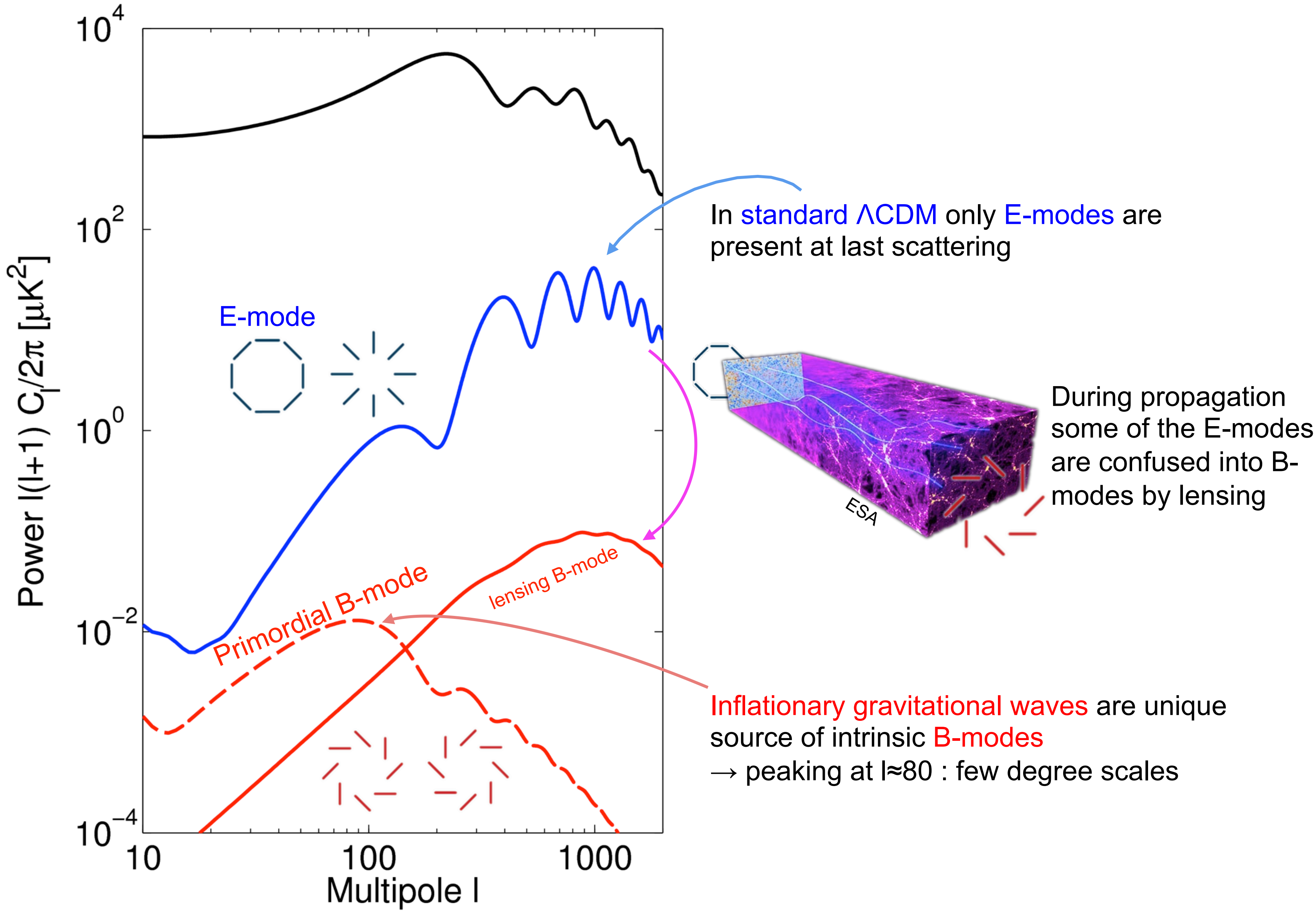
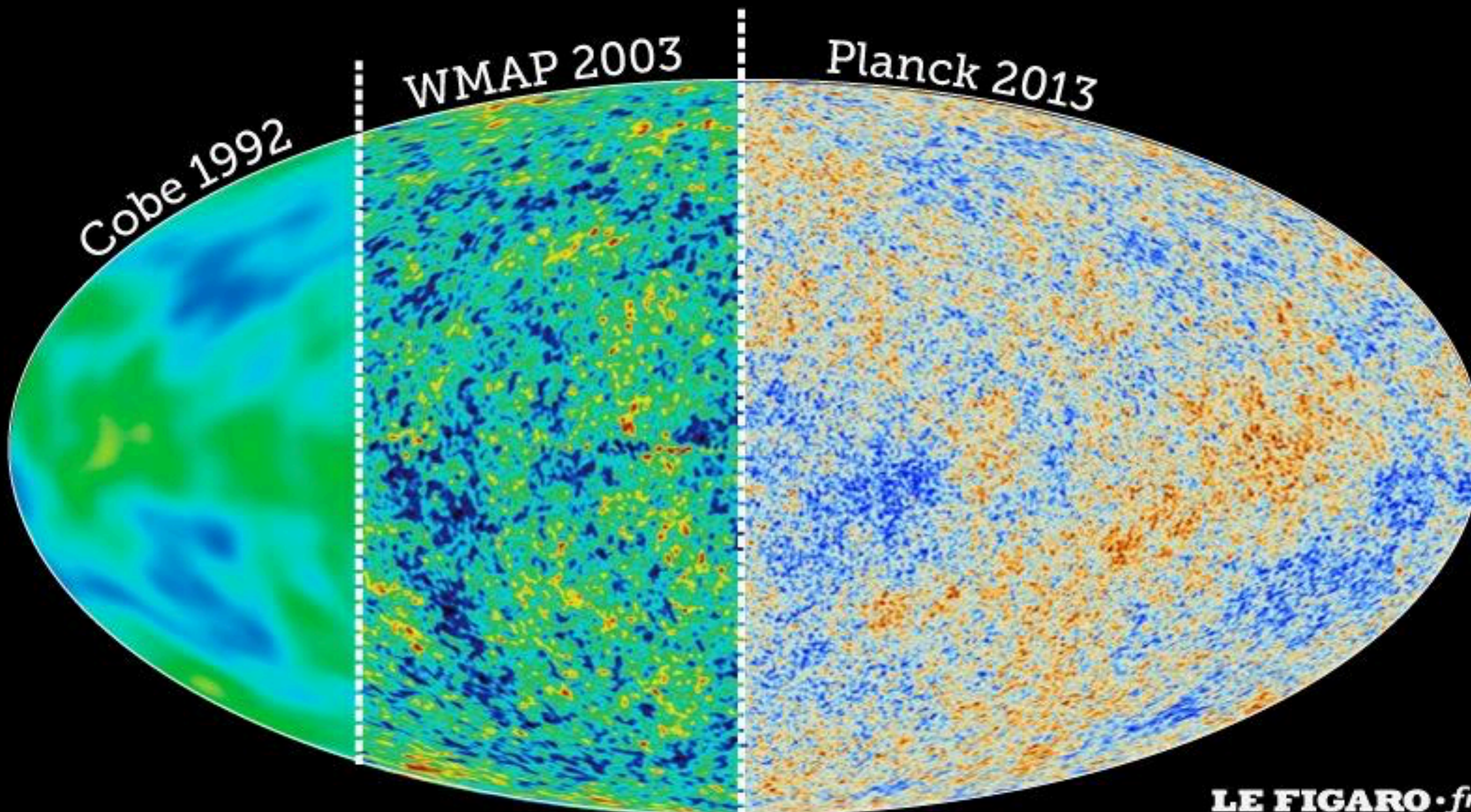
Warning: It's a bit like the search for proton decay – a well motivated physics target to look for, but theories can be adjusted to make the amplitude arbitrarily small…

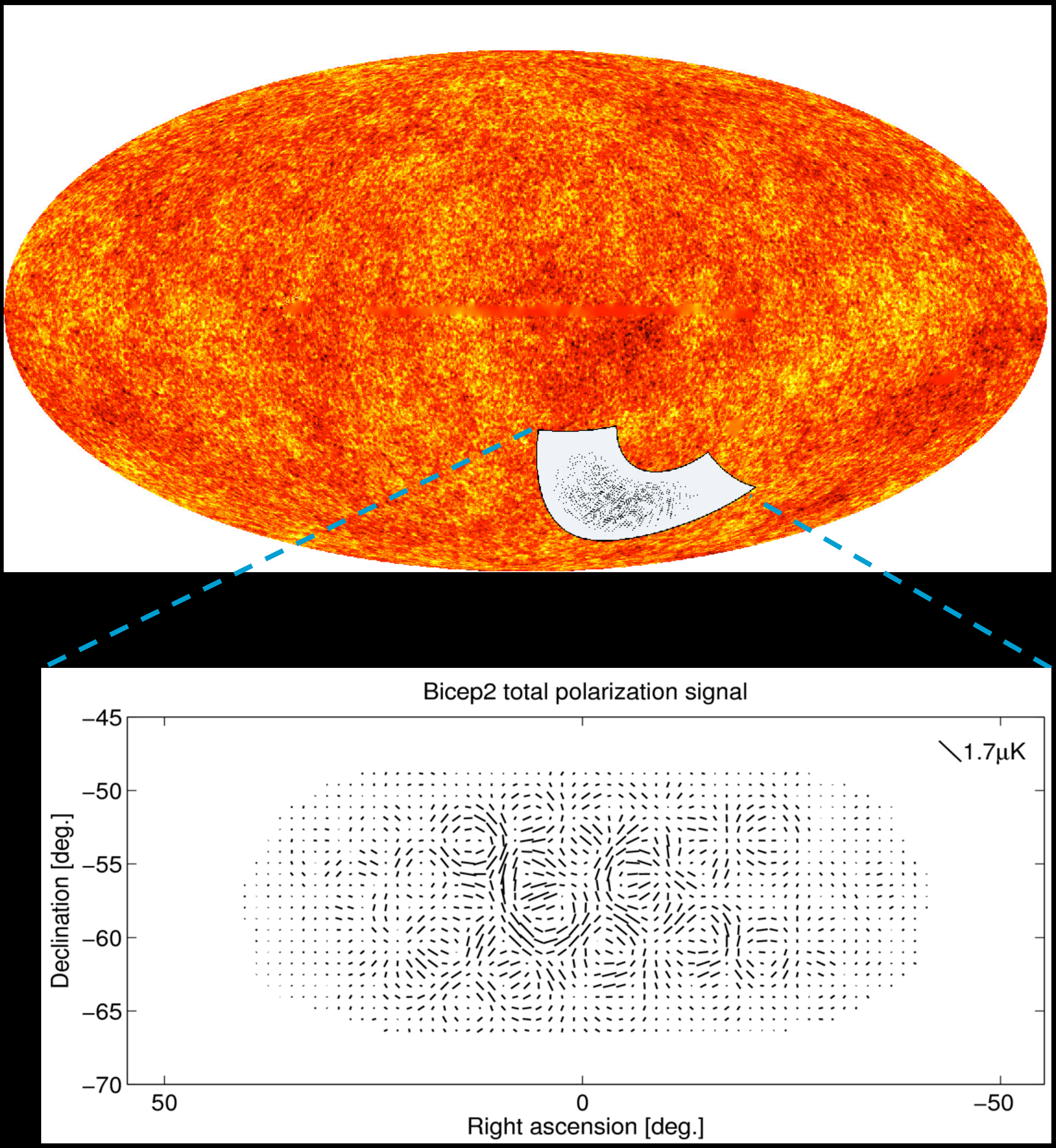
CMB Polarization power spectra



CMB space missions map the full sky



Ground based telescopes map part of the sky more deeply



CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

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cea

NIST

CARDIFF UNIVERSITY

UNIVERSITY OF Cincinnati

UBC

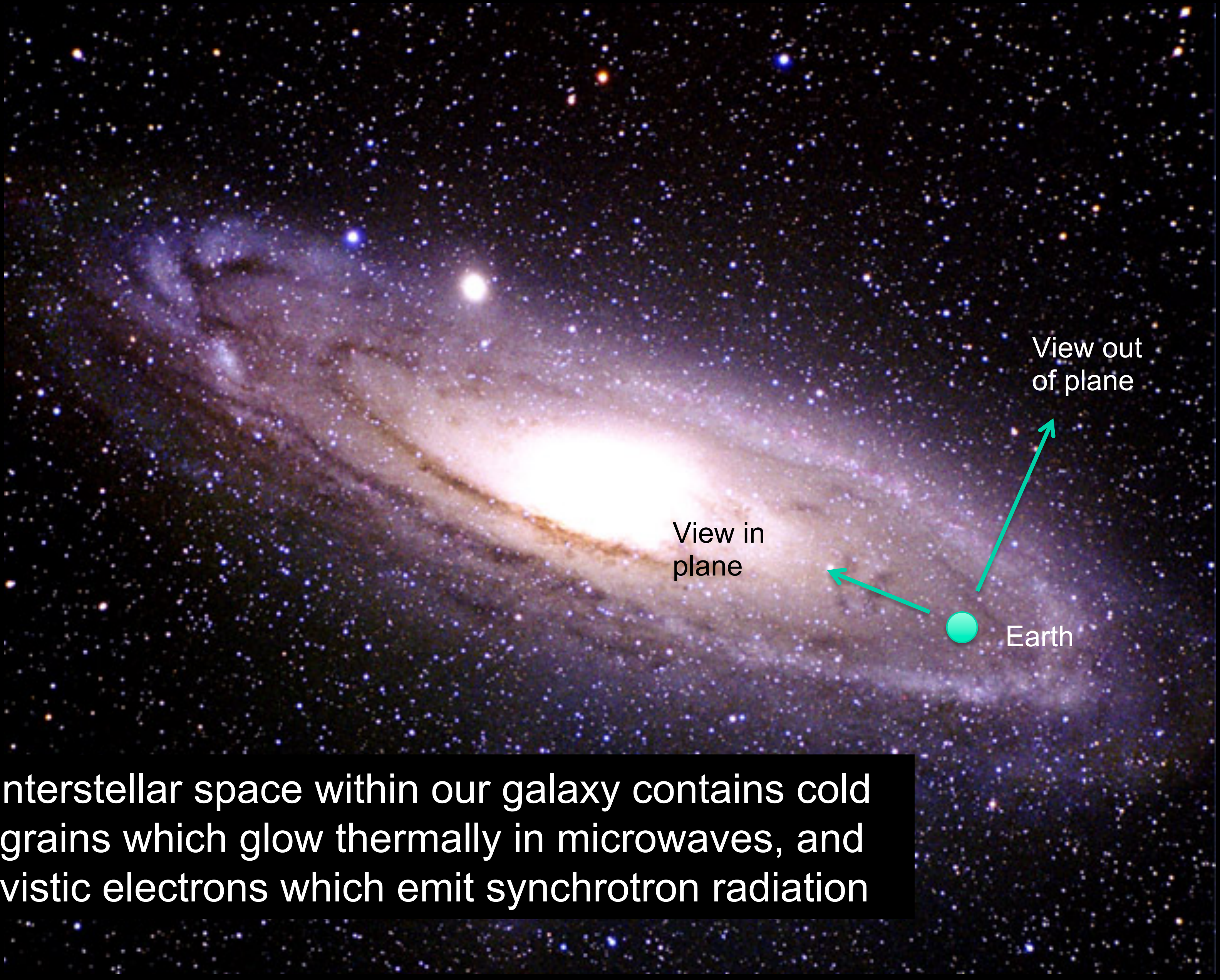
SLAC

JPL

BICEP/Keck Basic Experimental Strategy

→ Small aperture telescopes (cheap, fast, low systematics)
→ Target the 2 degree peak of the PGW B-mode
→ Integrate continuously from South Pole
→ Observe order 1% patch of sky (smaller is actually better!)
→ Scan and pair difference modulation

Unfortunately we are in a galaxy



The interstellar space within our galaxy contains cold dust grains which glow thermally in microwaves, and relativistic electrons which emit synchrotron radiation

Unfortunately we are in a galaxy

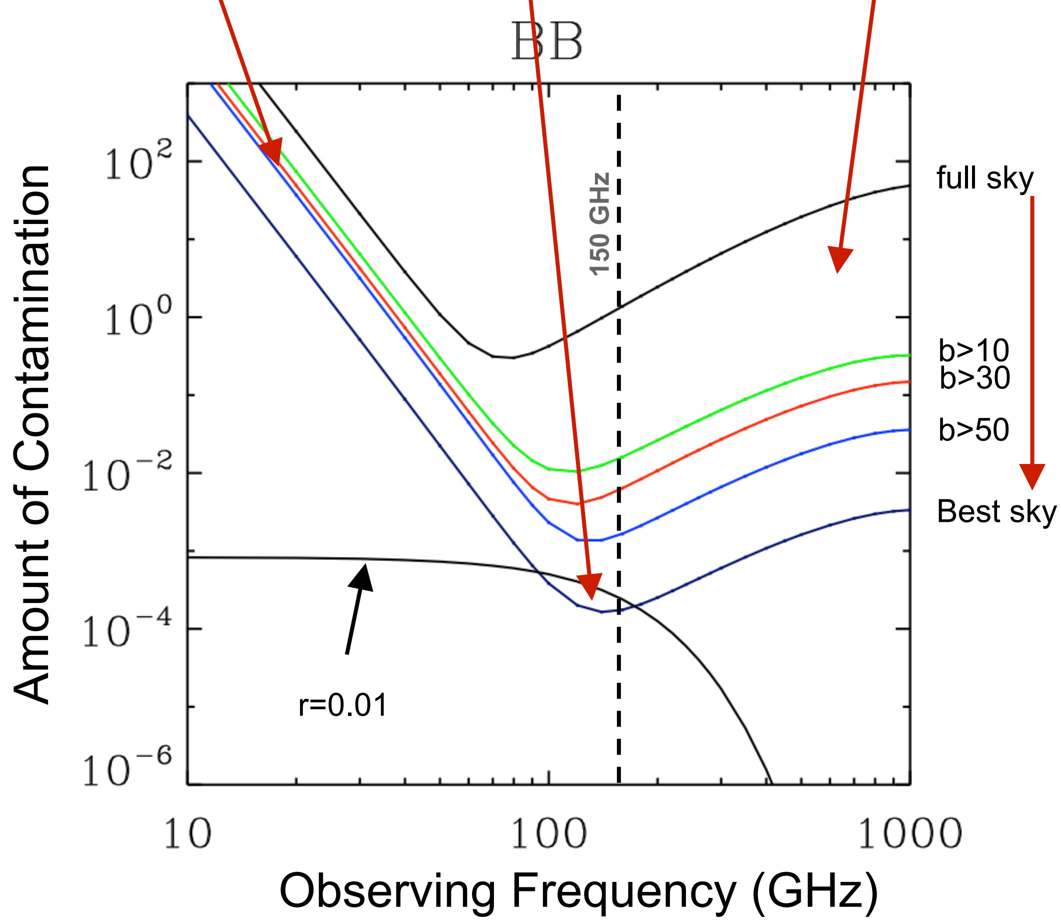
When CMB people talk about “foregrounds” it is analogous to what HEP people call “backgrounds” – something which gets in the way of the thing one is trying to measure.

Polarized Foreground Contamination from Our Galaxy

At low frequency synchrotron contamination

Sweetest spot

At high frequency dust contamination



Pick a cleaner patch of sky

(Plot from Dunkley et al arxiv/0811.3915)

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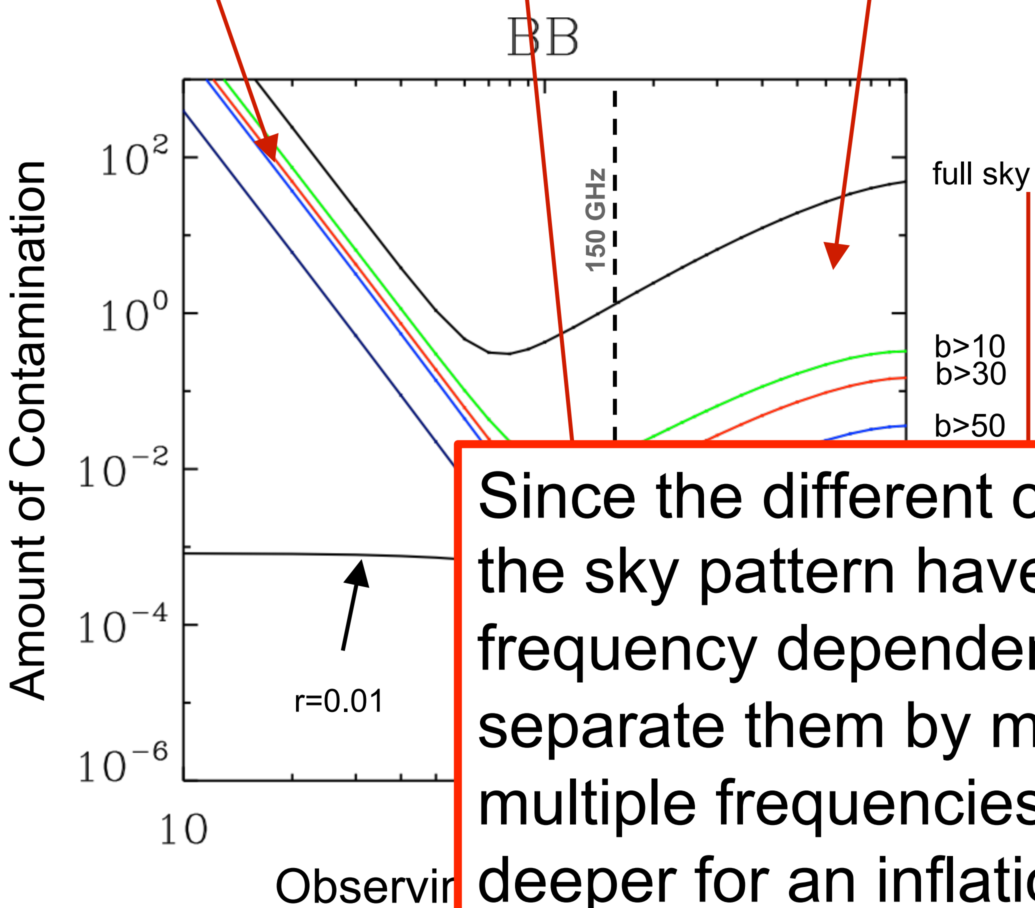


Pick a cleaner patch of sky

Since the different components of the sky pattern have different frequency dependencies one can separate them by making maps at multiple frequencies – and probe deeper for an inflation signal

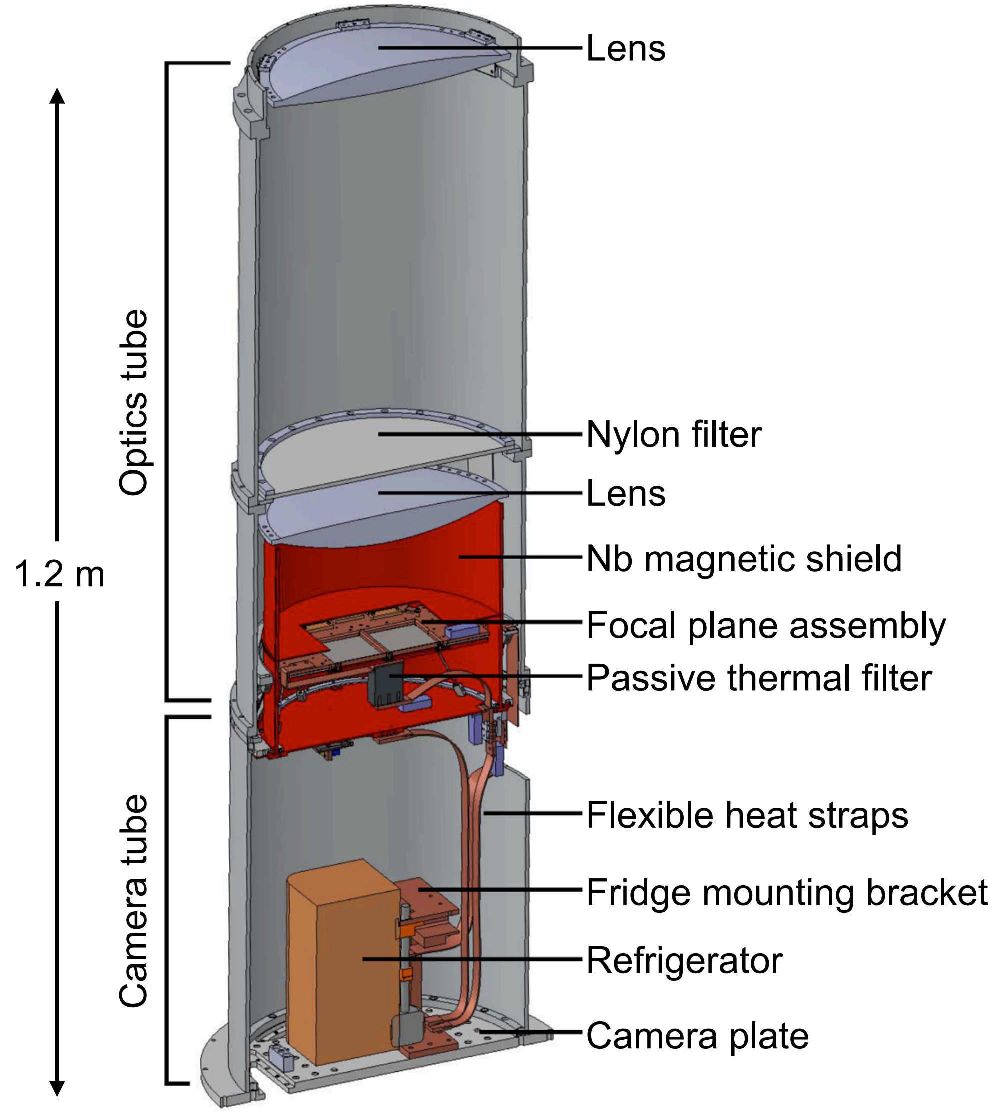
The BICEP/Keck Telescopes

Telescope as compact as possible while still having the angular resolution to observe degree-scale features.

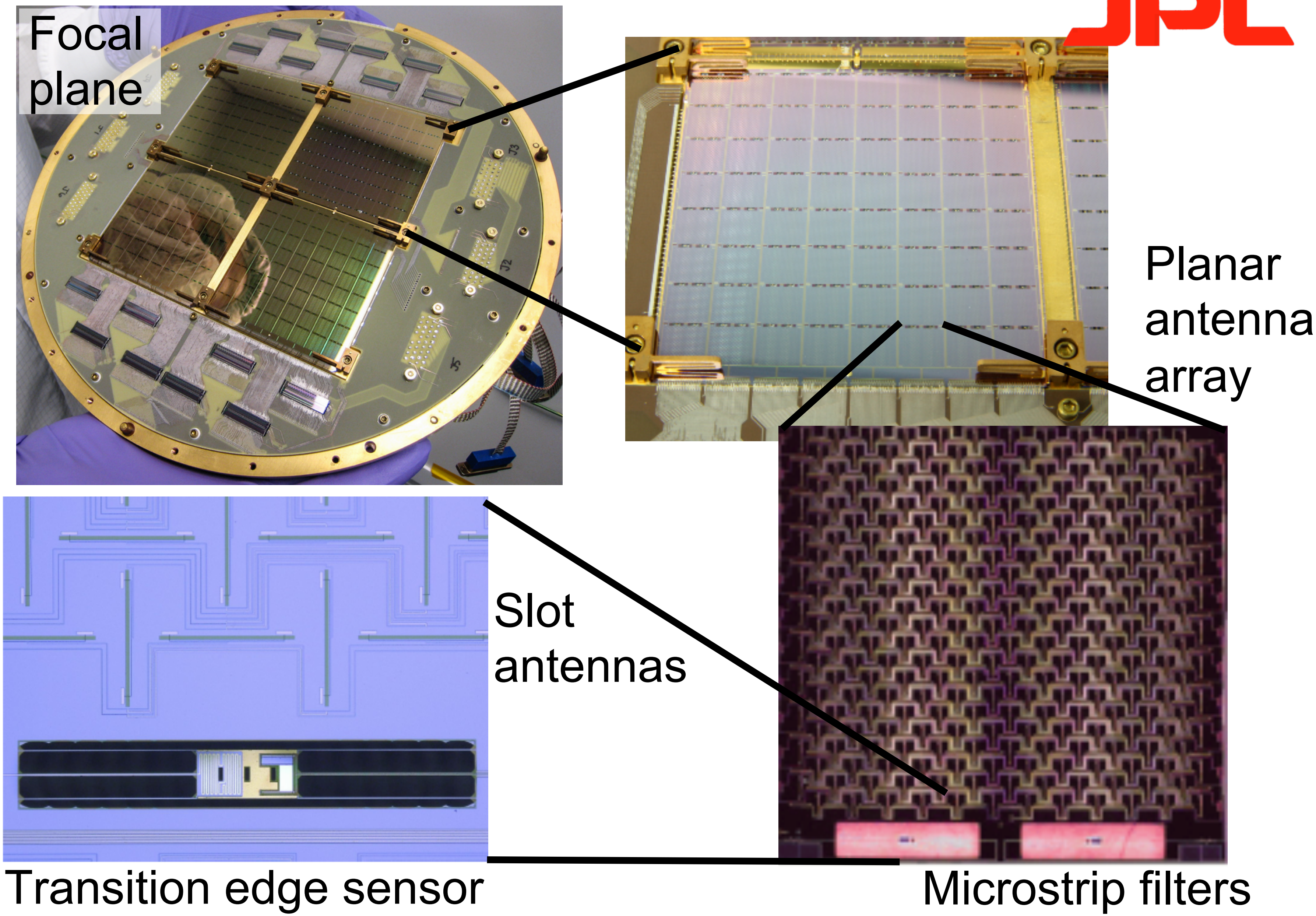
On-axis, refractive optics allow the entire telescope to rotate around boresight for polarization modulation.

Pulse tube cooler cools the optical elements to 4 K.

3-stage helium sorption refrigerator further cools the detectors to 0.3 K.



Mass-produced Superconducting Detectors



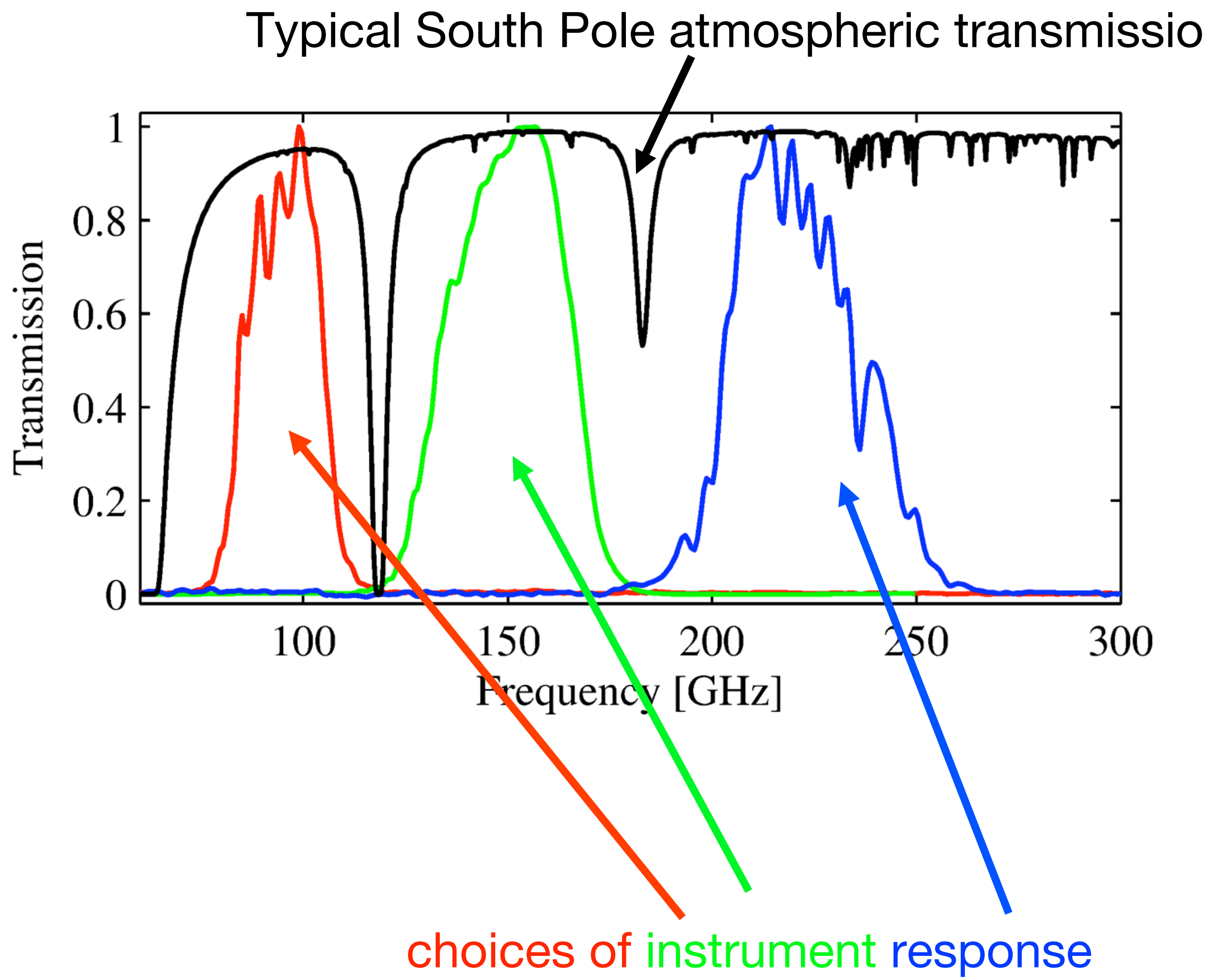
BICEP/Keck Band Passes

The dry South Pole atmosphere provides excellent observing conditions most of the year.

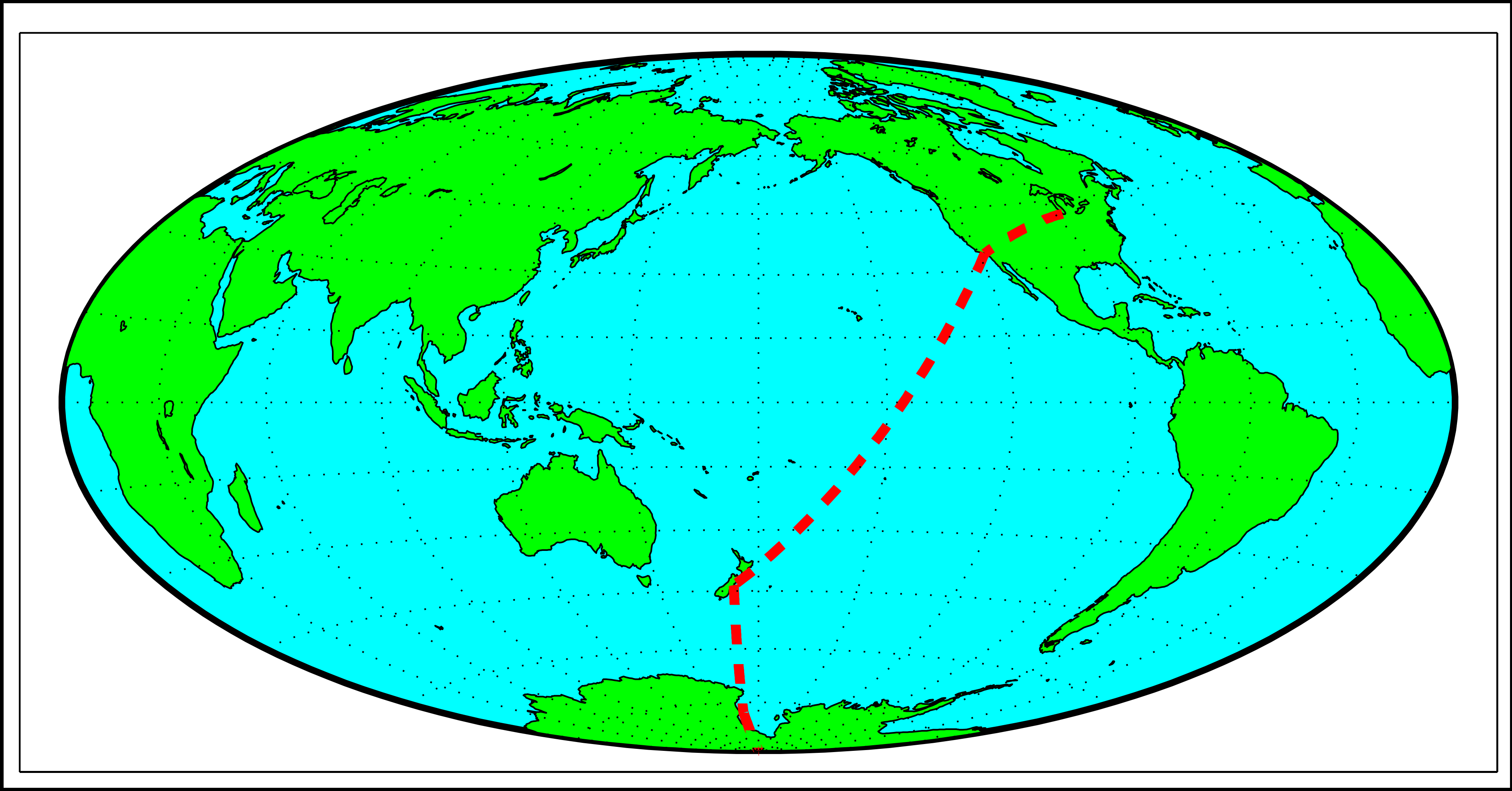
The approx. 30% fractional bandpasses fit within atmospheric transmission windows straddled by oxygen and water lines.

In these windows, the atmosphere is quite transparent to microwaves.

The detector passbands are defined by a filter printed directly onto the focal plane wafers.



Journey to the South Pole



Minneapolis ->California -> New Zealand -> McMurdo -> South Pole

Antarctic Continent

Larger then the US – Ice sheet two miles thick!

UNITED STATES ANTARCTIC PROGRAM

NATIONAL SCIENCE FOUNDATION

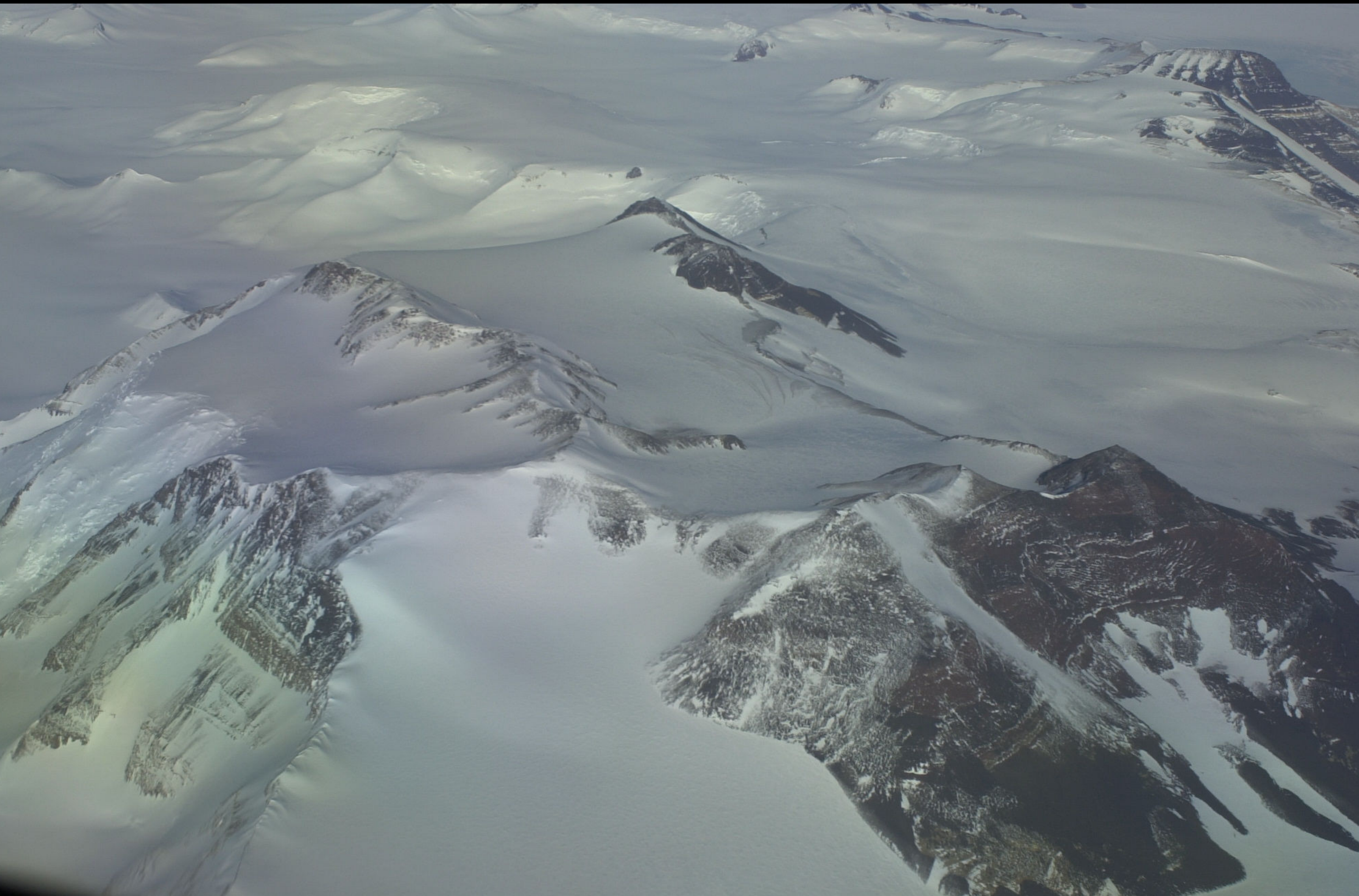
Christchurch New Zealand – Clothing Warehouse

Big Program!

Arrival in Antarctica

McMurdo – base on the coast

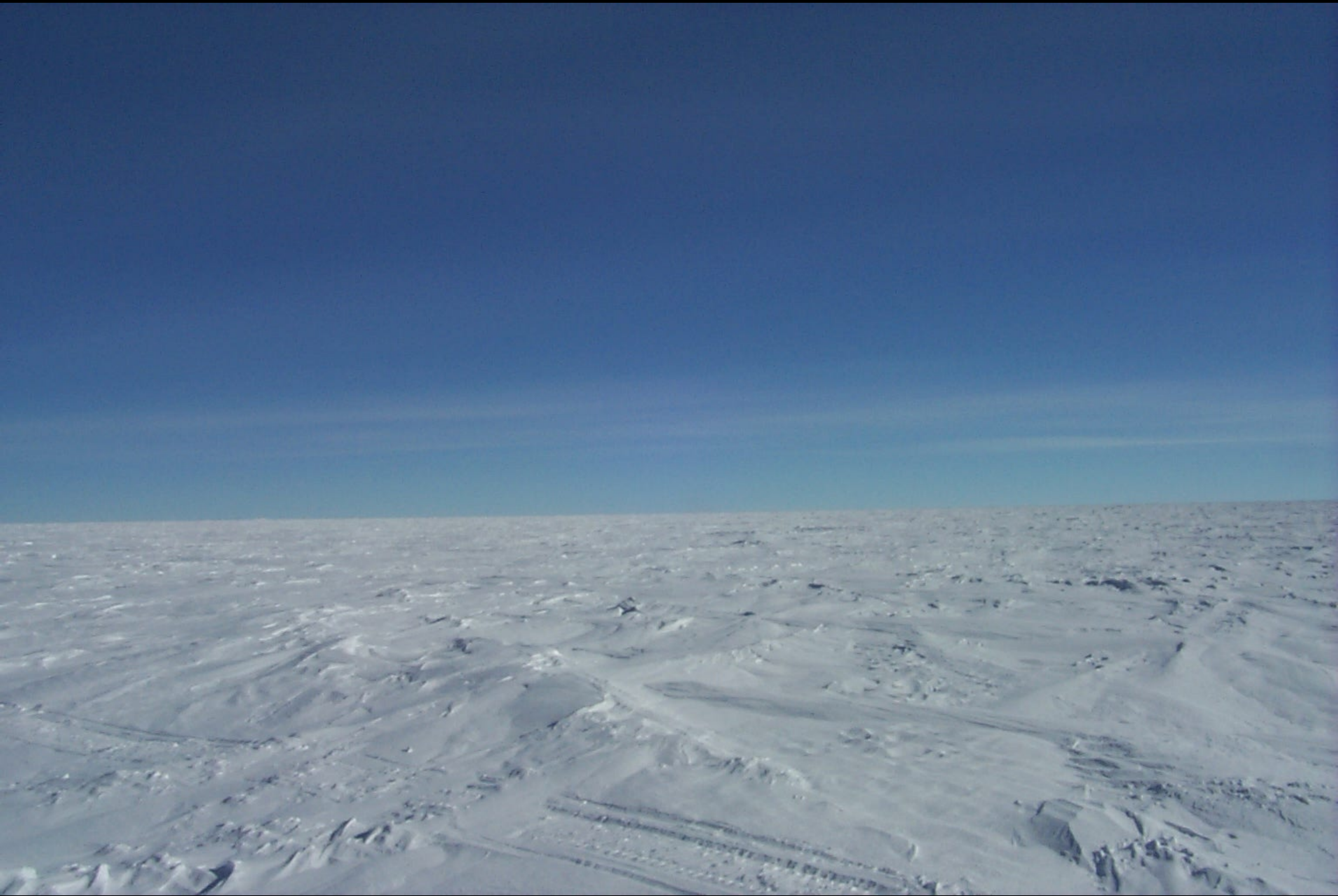
On to the Pole – over the Transantarctic Mountains



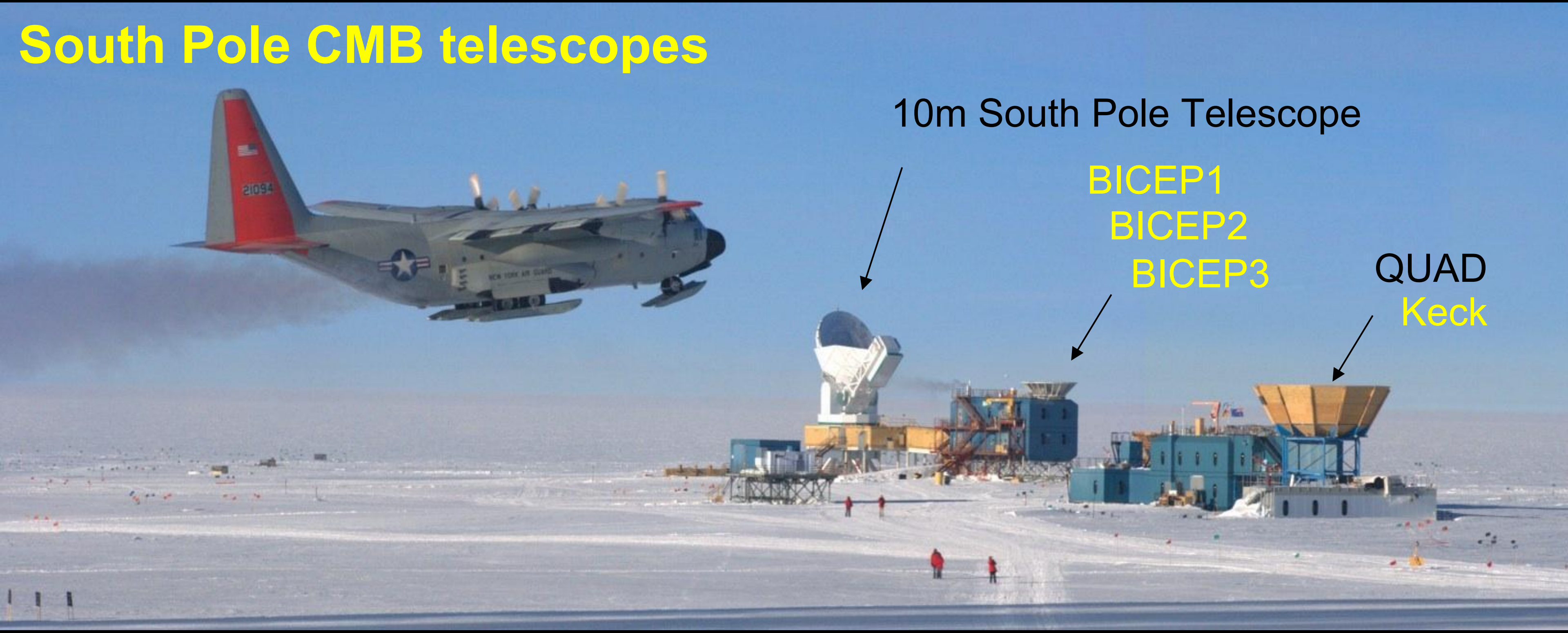
Unloading at Pole

The Actual South Pole

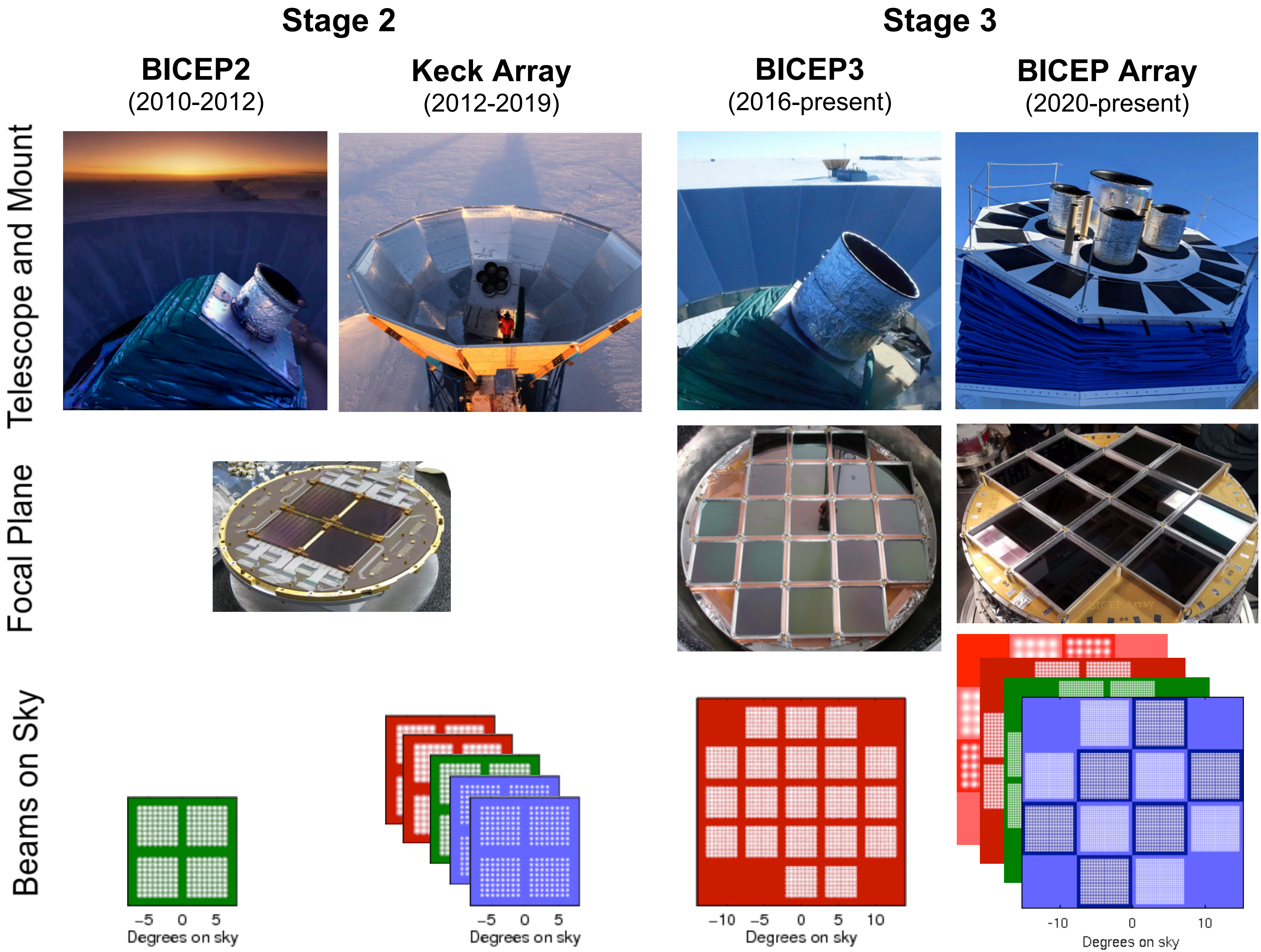
Nothing Out There!



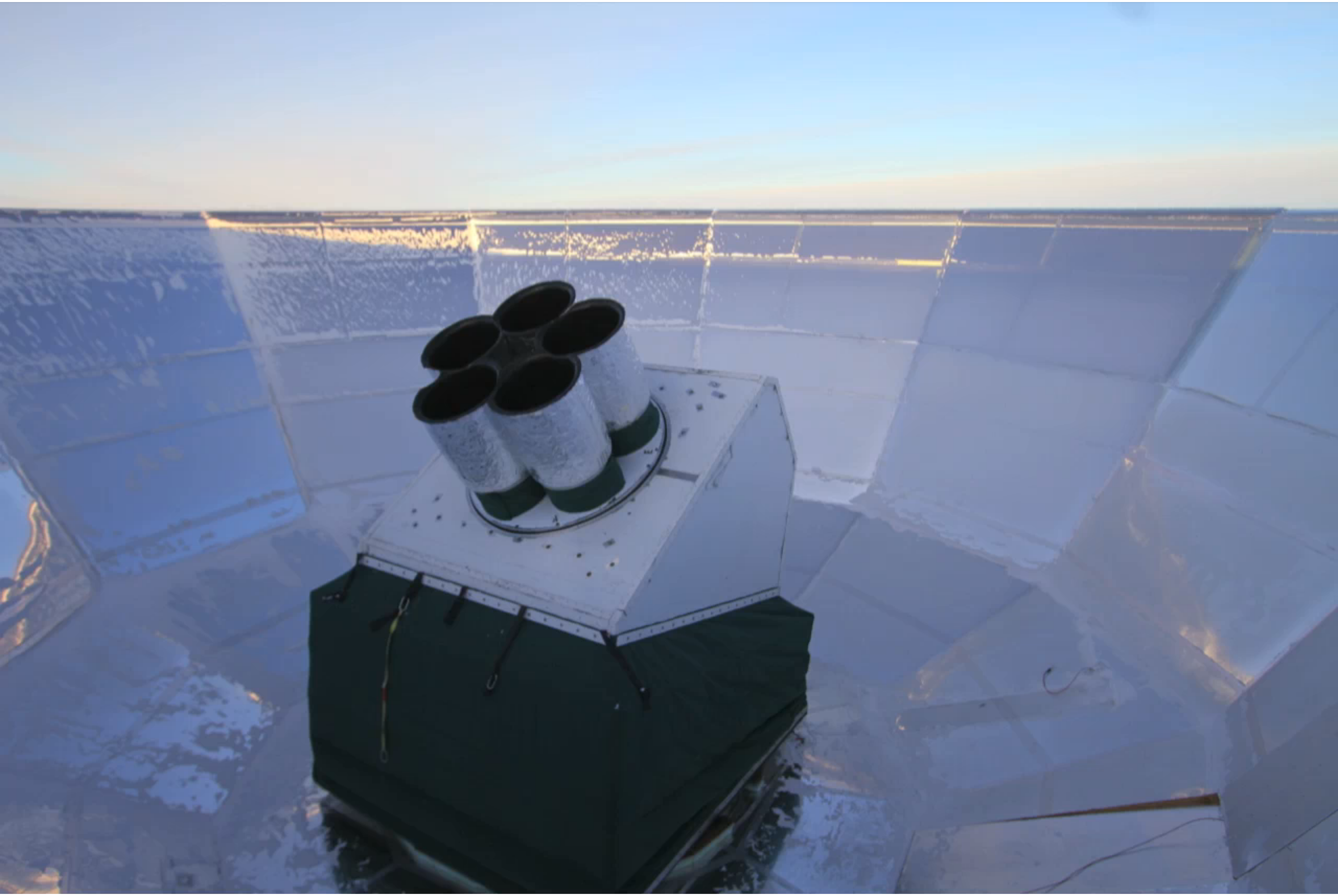
Why do this at the Pole?



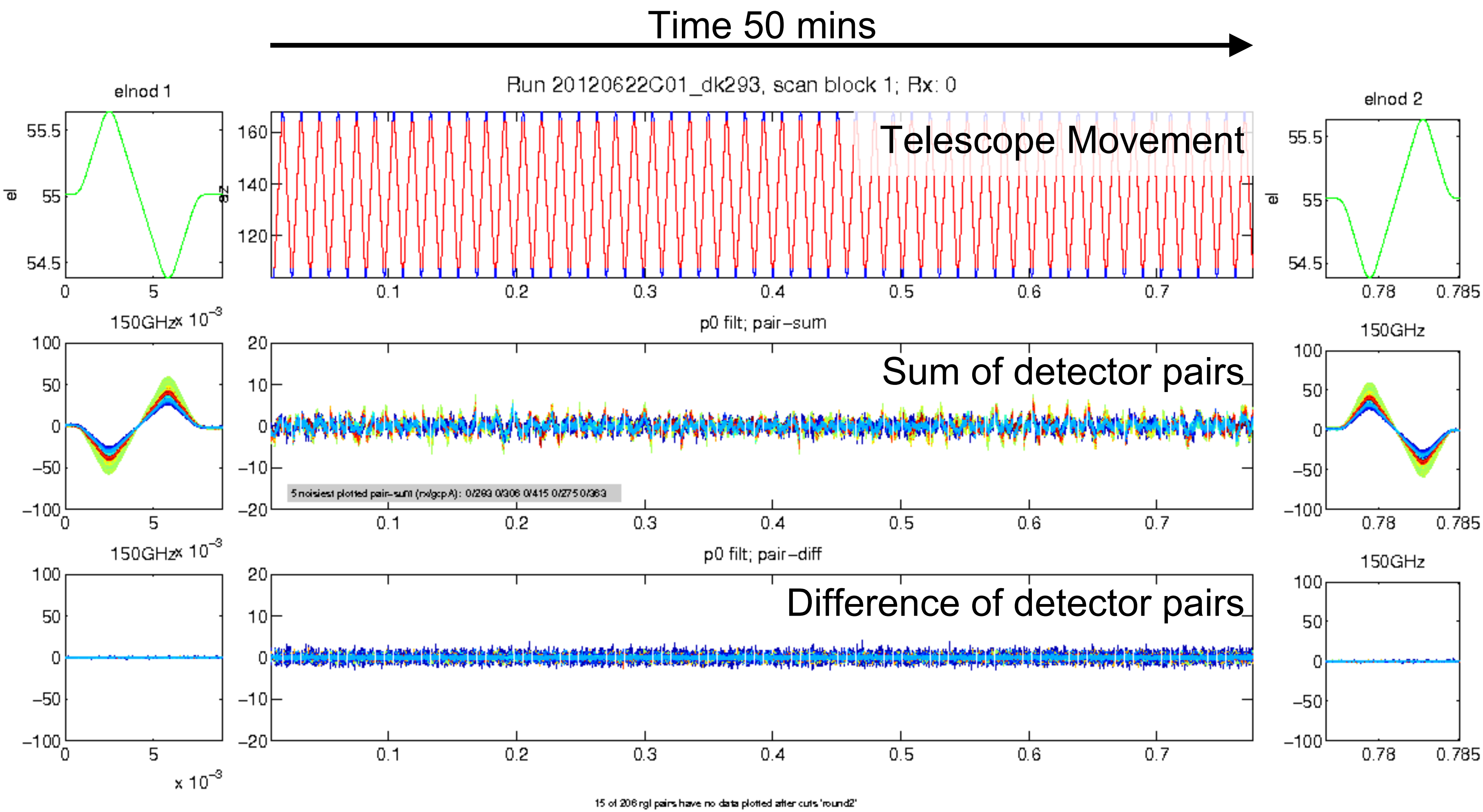
- High and *dry* – see out into space
- On Earth's rotational axis - One day/night cycle per year
  - Long night makes for great quality data
- Good support infrastructure – power, cargo, data comm
- Food and accommodation provided
- Even Tuesday night bingo…



Stage 2
Stage 3
BICEP2
(2010-2012)
Keck Array
(2012-2019)
BICEP3
(2016-present)
BICEP Array
(2020-present)
Telescope and Mount
Focal Plane
Beams on Sky
−5 0 5
Degrees on sky
−5 0 5
Degrees on sky
−10 −5 0 5 10
Degrees on sky
-10 0 10
Degrees on sky

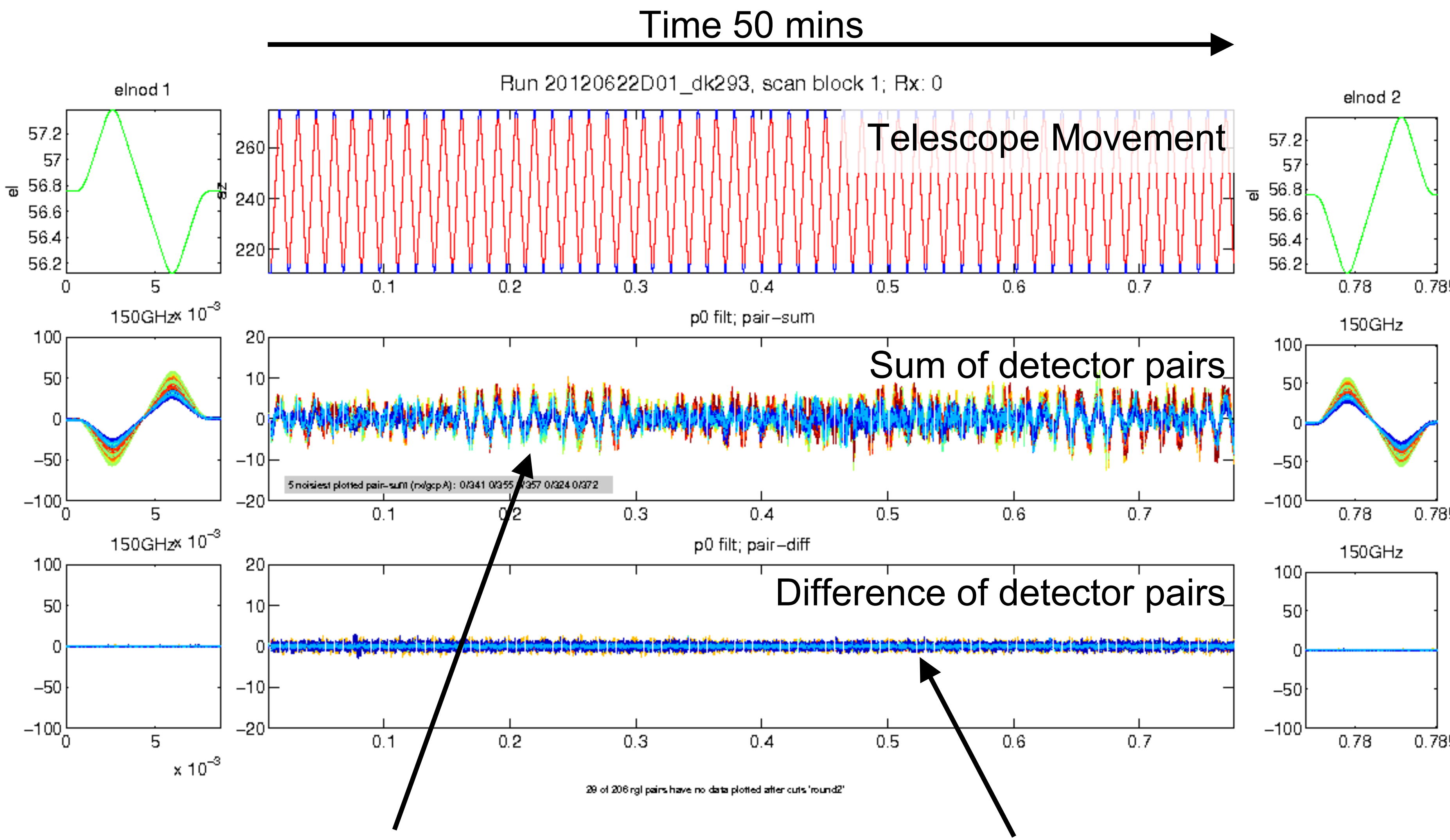


Raw Data - Perfect Weather

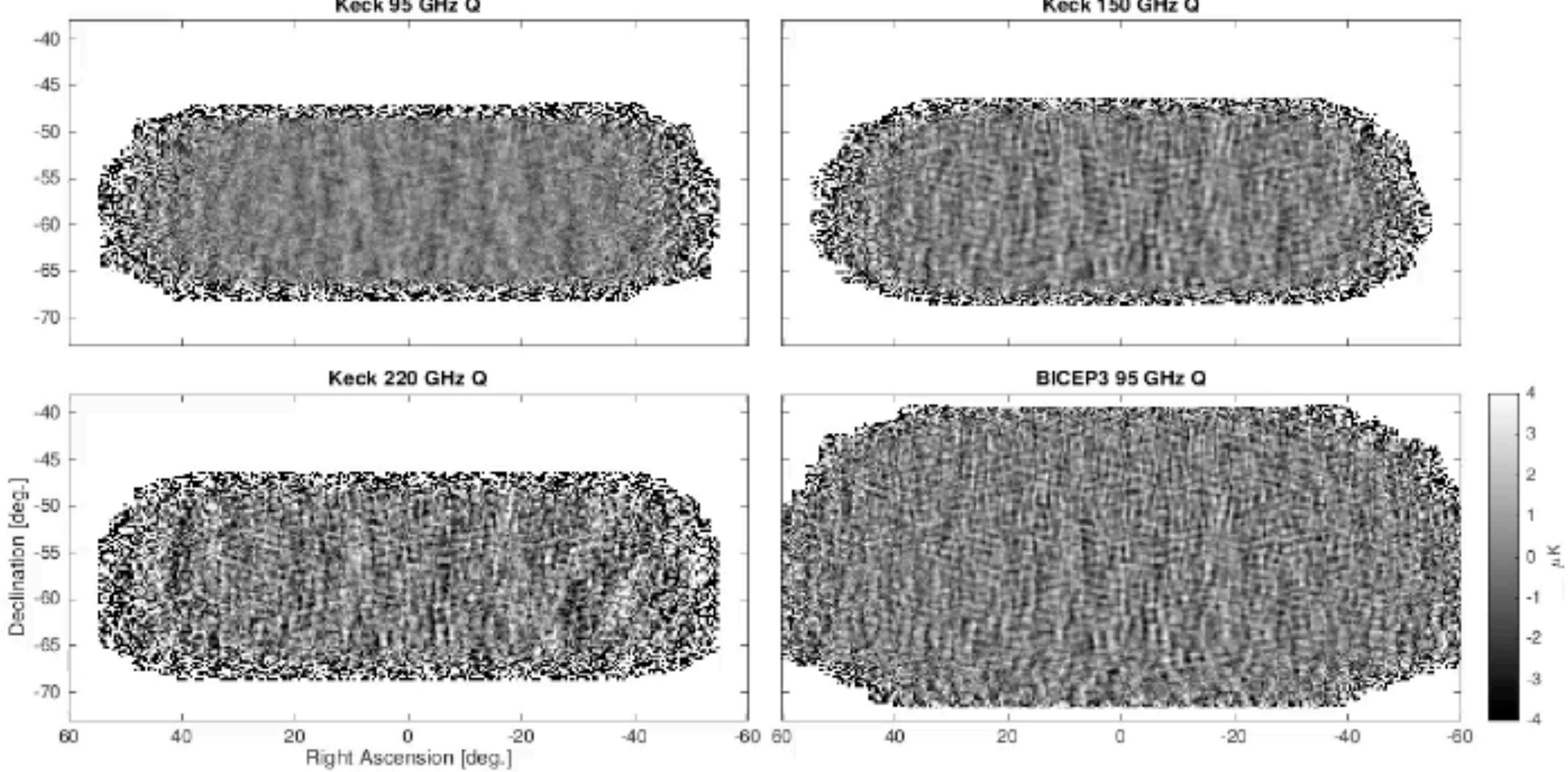


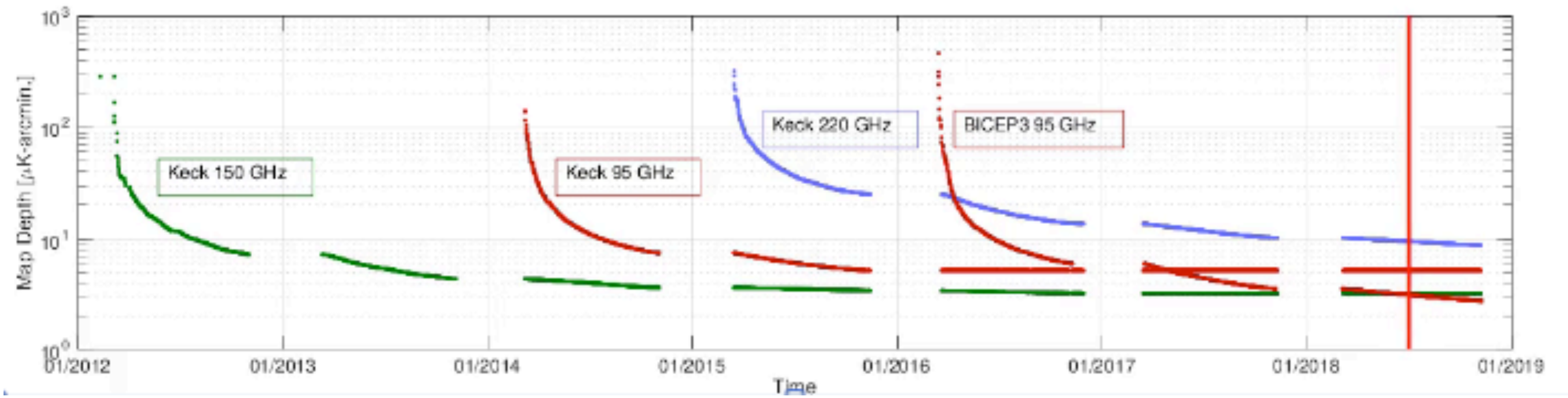
- ➢ Cover the whole field in 60 such scansets then start over at new boresight rotation
- ➢ Scanning modulates the CMB signal to freqs < 4 Hz

Raw Data - Worse Weather

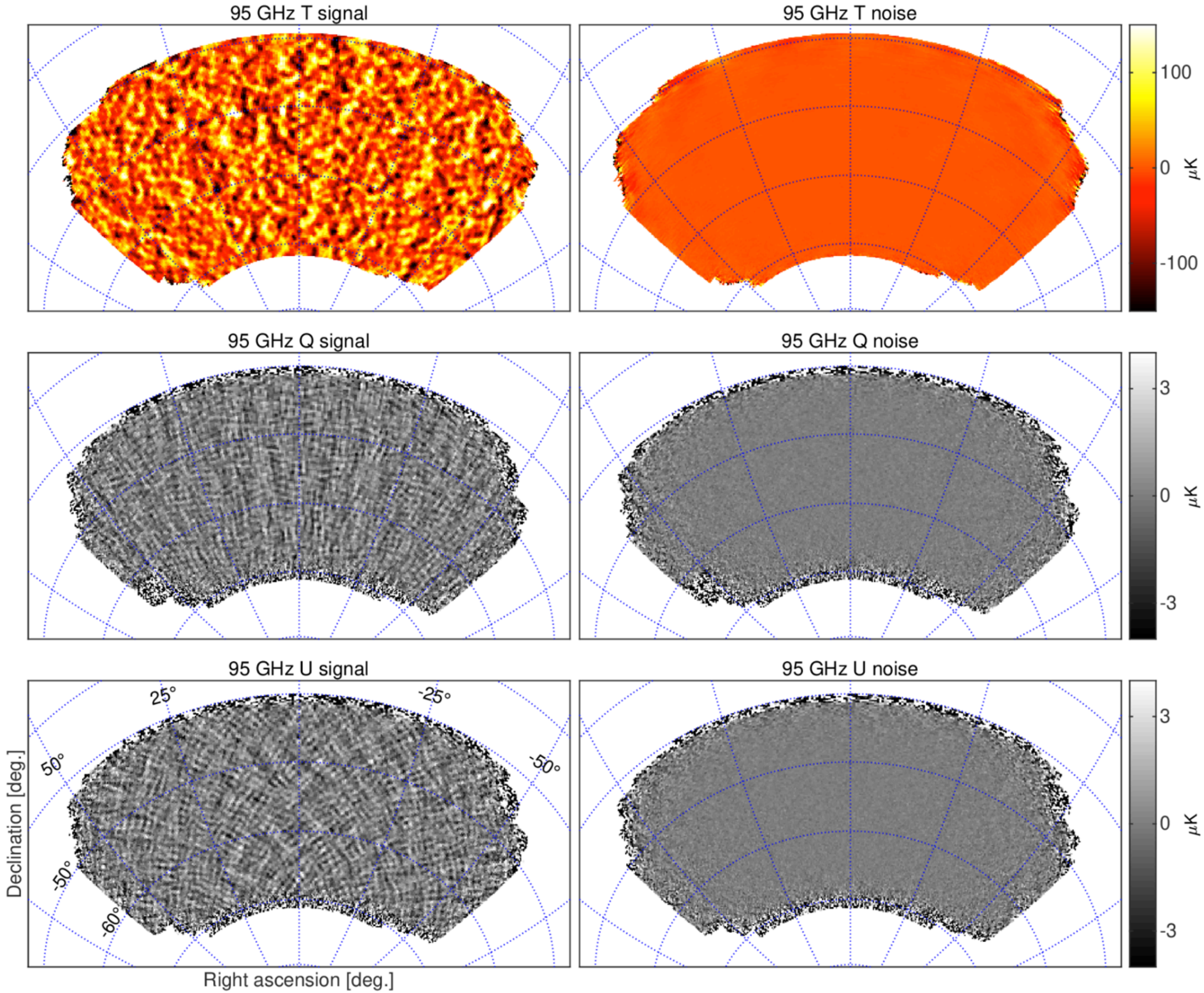


- ➢ Scanning over lumpy atmosphere → "clouds"
- ➢ Pair difference still clean → atmosphere is unpolarized

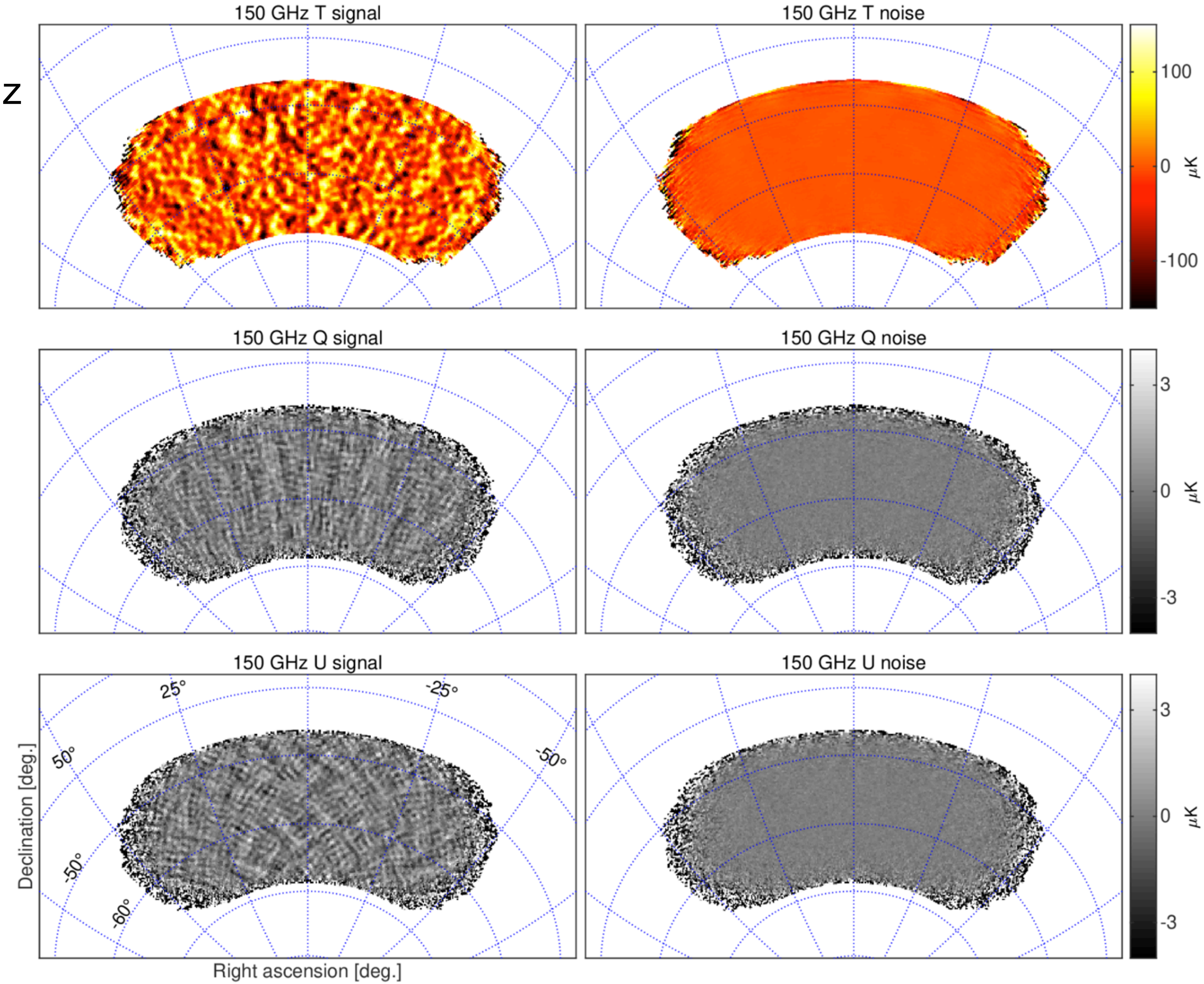

Keck 95 GHz Q
Keck 150 GHz Q
Keck 220 GHz Q
BICEP3 95 GHz Q
Declination [deg.]
Right Ascension [deg.]
μK


Keck 150 GHz
Keck 95 GHz
Keck 220 GHz
BICEP3 95 GHz
Map Depth [μK-arcmin.]
Time
01/2012
01/2013
01/2014
01/2015
01/2016
01/2017
01/2018
01/2019

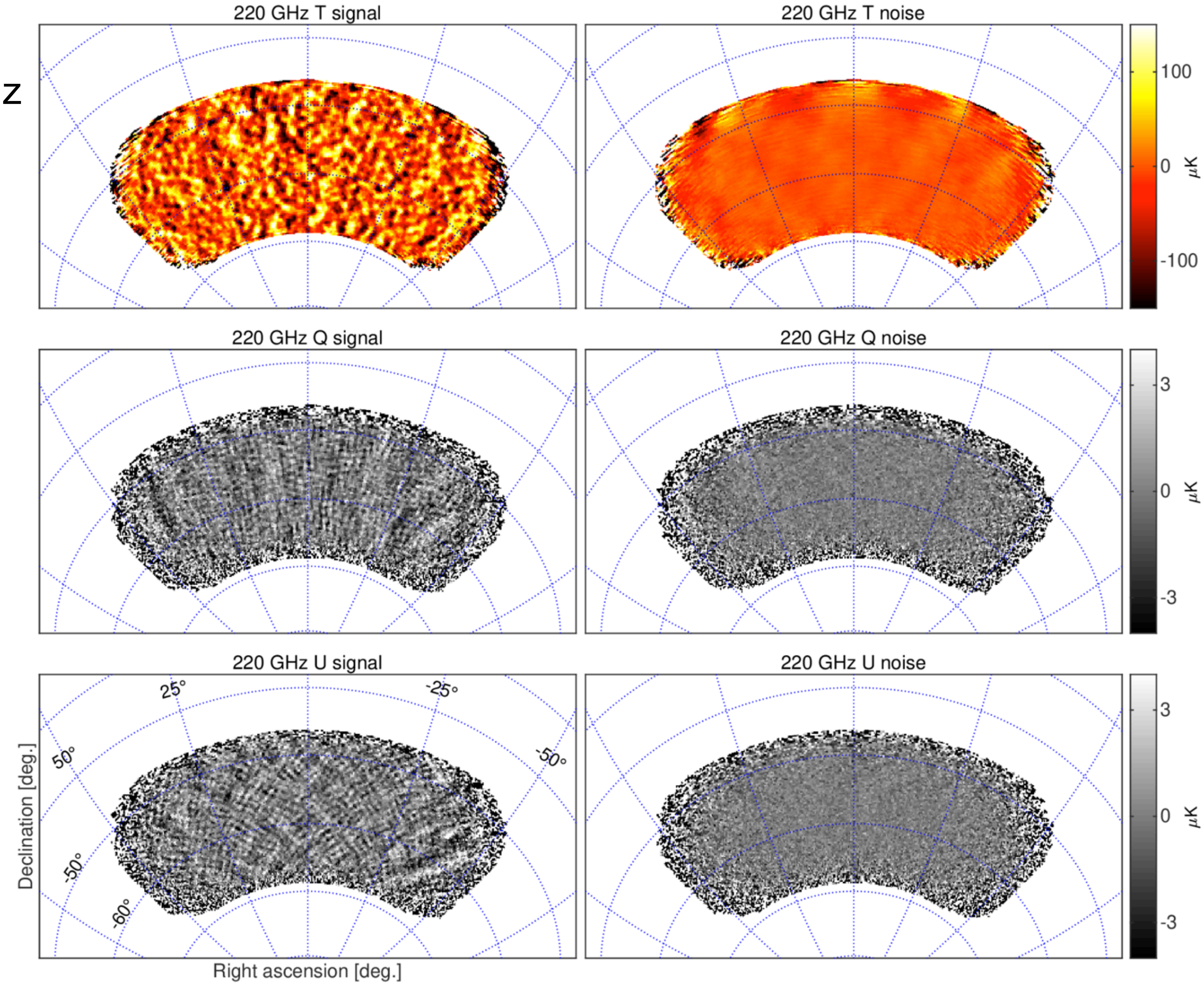
BK18
95GHz
Maps



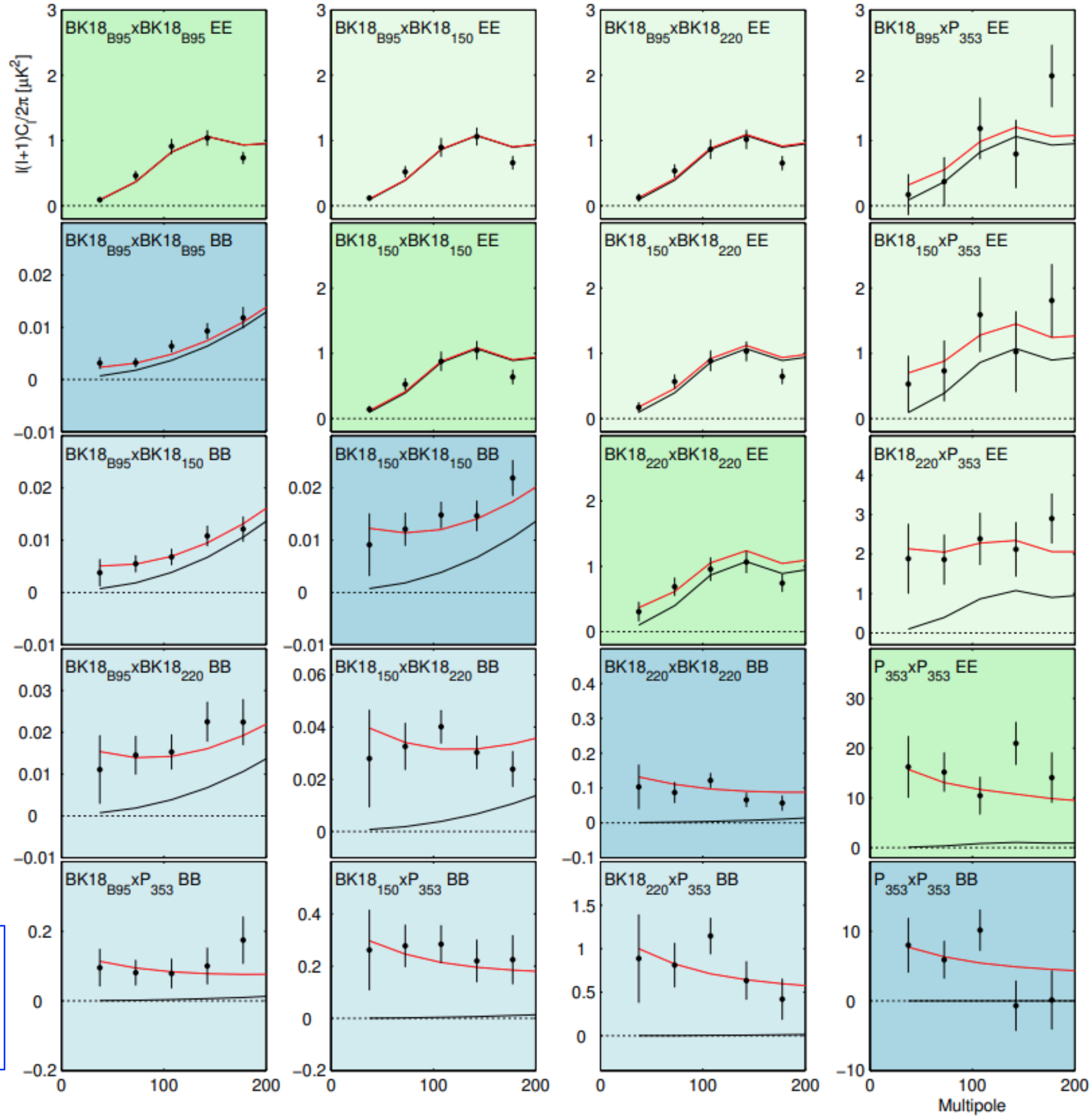
BK18
150GHz
Maps



BK18
220GHz
Maps



BK18 auto/cross spectra between: BICEP3 95GHz, BICEP2/Keck 150GHz, Keck 220GHz, and Planck 353GHz



Green panels are EE spectra

Black lines are LCDM

Red lines are LCDM+dust

Blue panels are BB spectra

Multicomponent parametric likelihood analysis

Take the joint likelihood of all the spectra simultaneously vs. model for BB that is the ΛCDM lensing expectation + 7 parameter foreground model + r

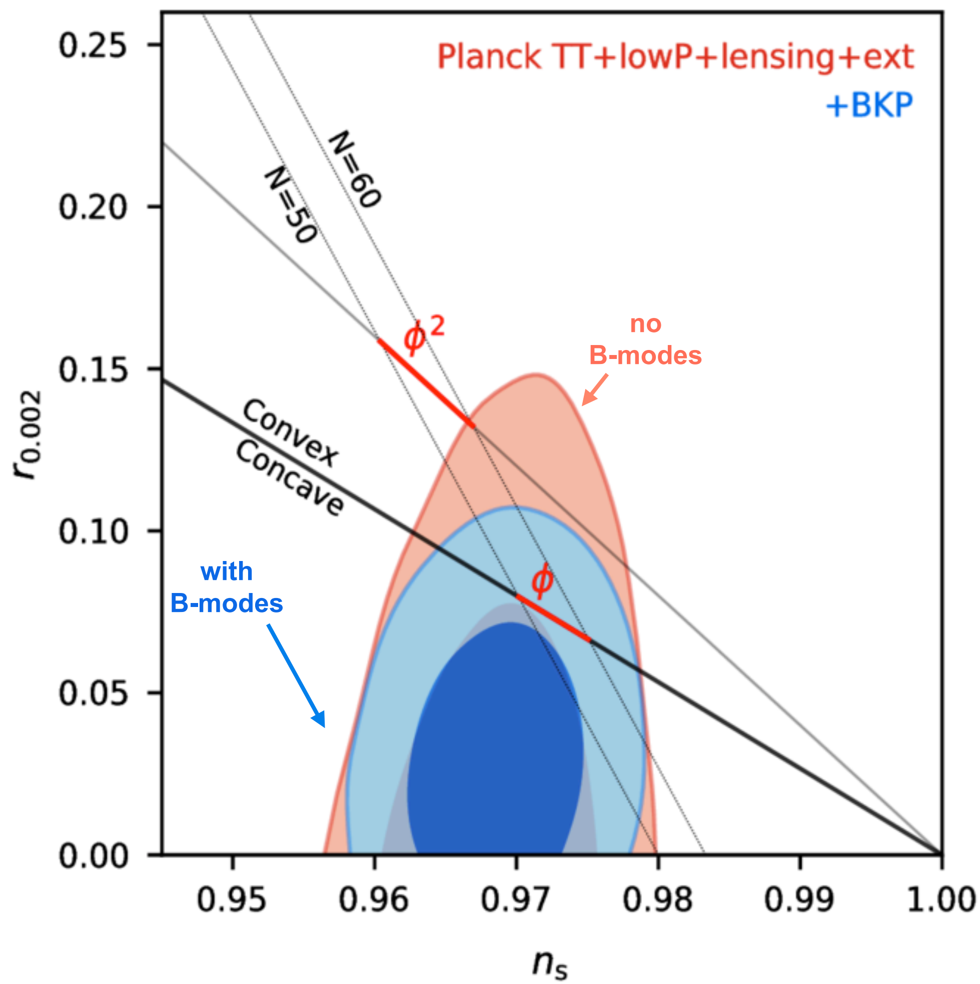
foreground model = dust + synchrotron

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

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

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

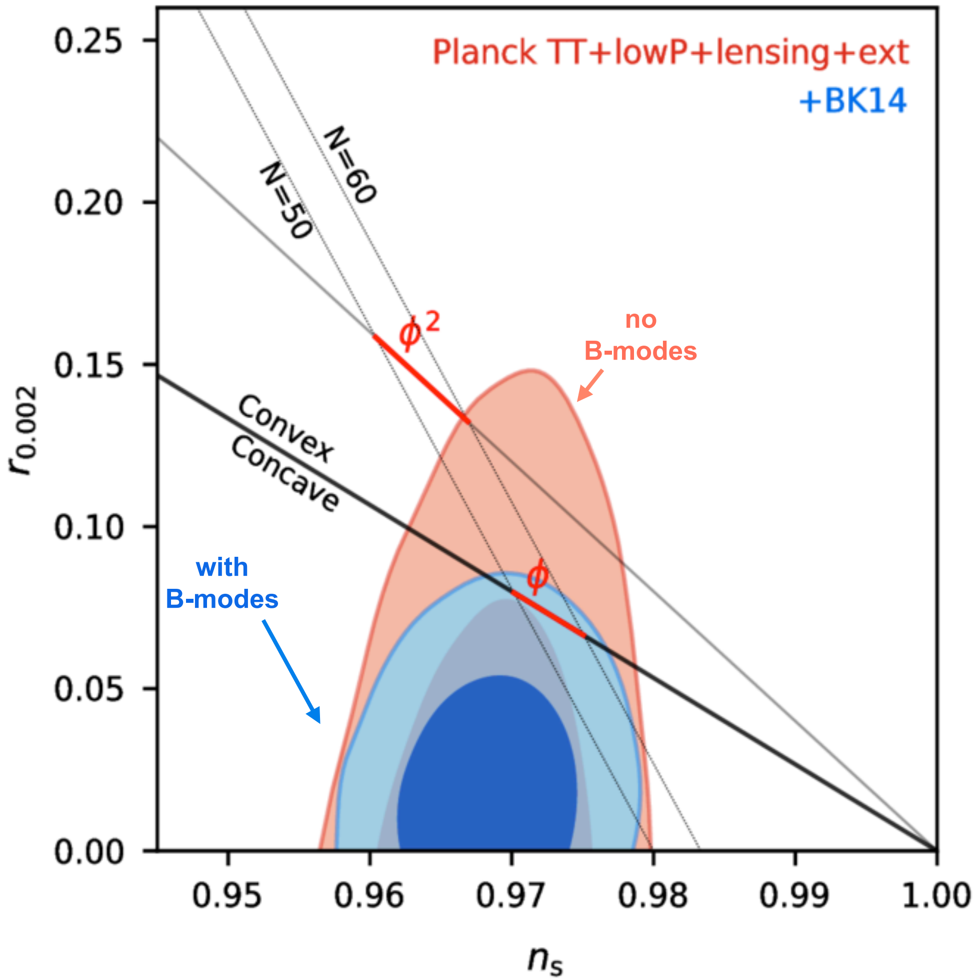
ε — dust/synch spatial correlation



$r_{.05}$ < 0.09

BKP

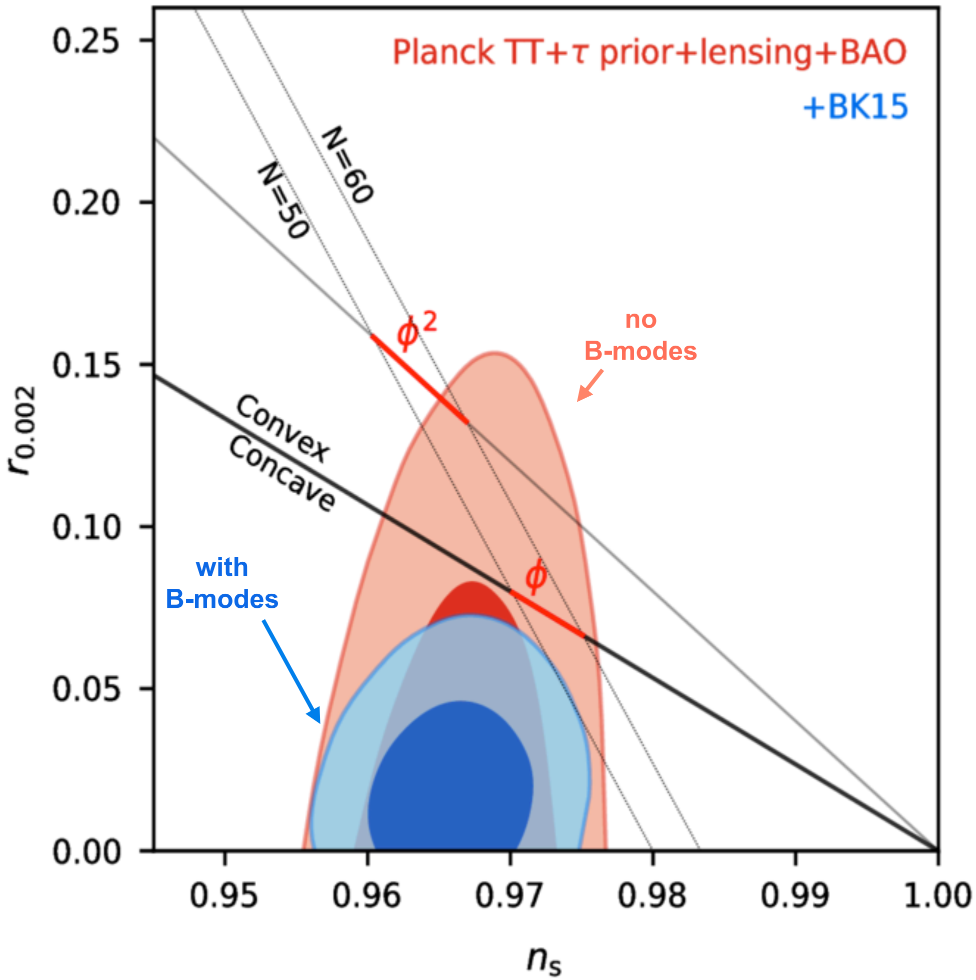
arxiv/1502.00612



$r_{.05} < 0.07$

BK14

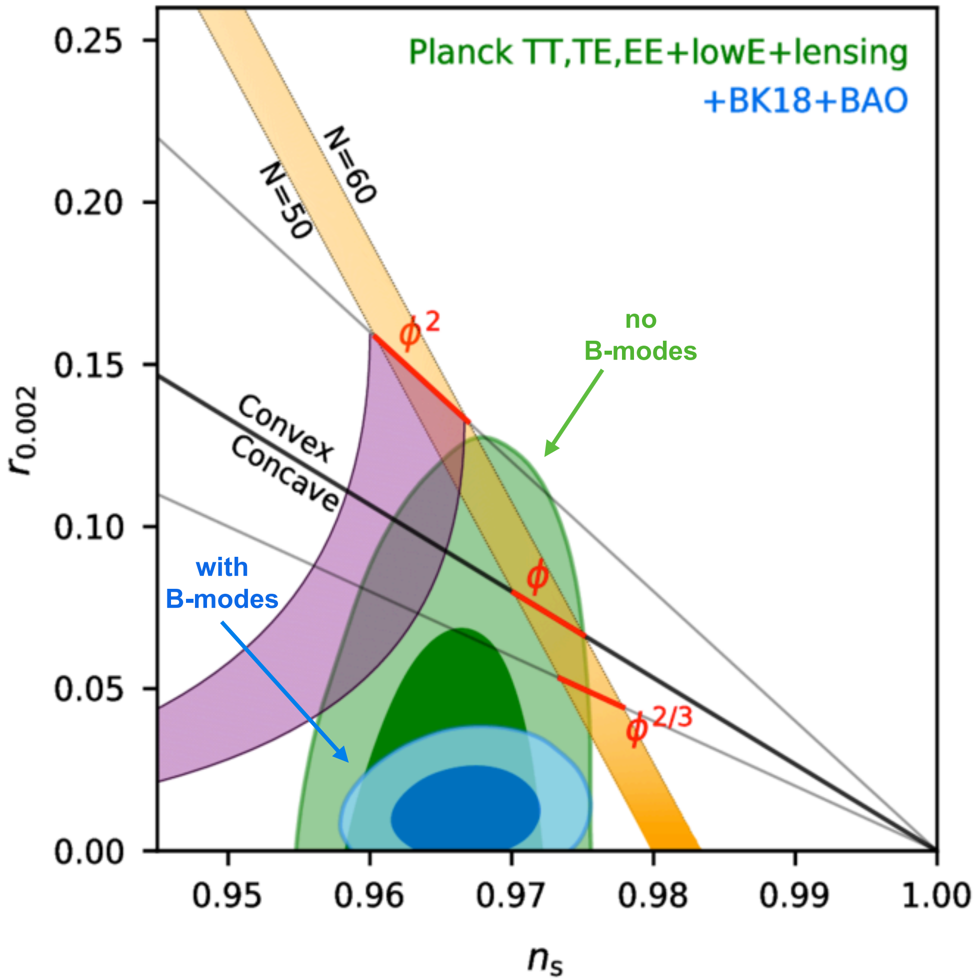
arxiv/1510.09217



$r_{.05} < 0.06$

BK15

arxiv/1810.05216

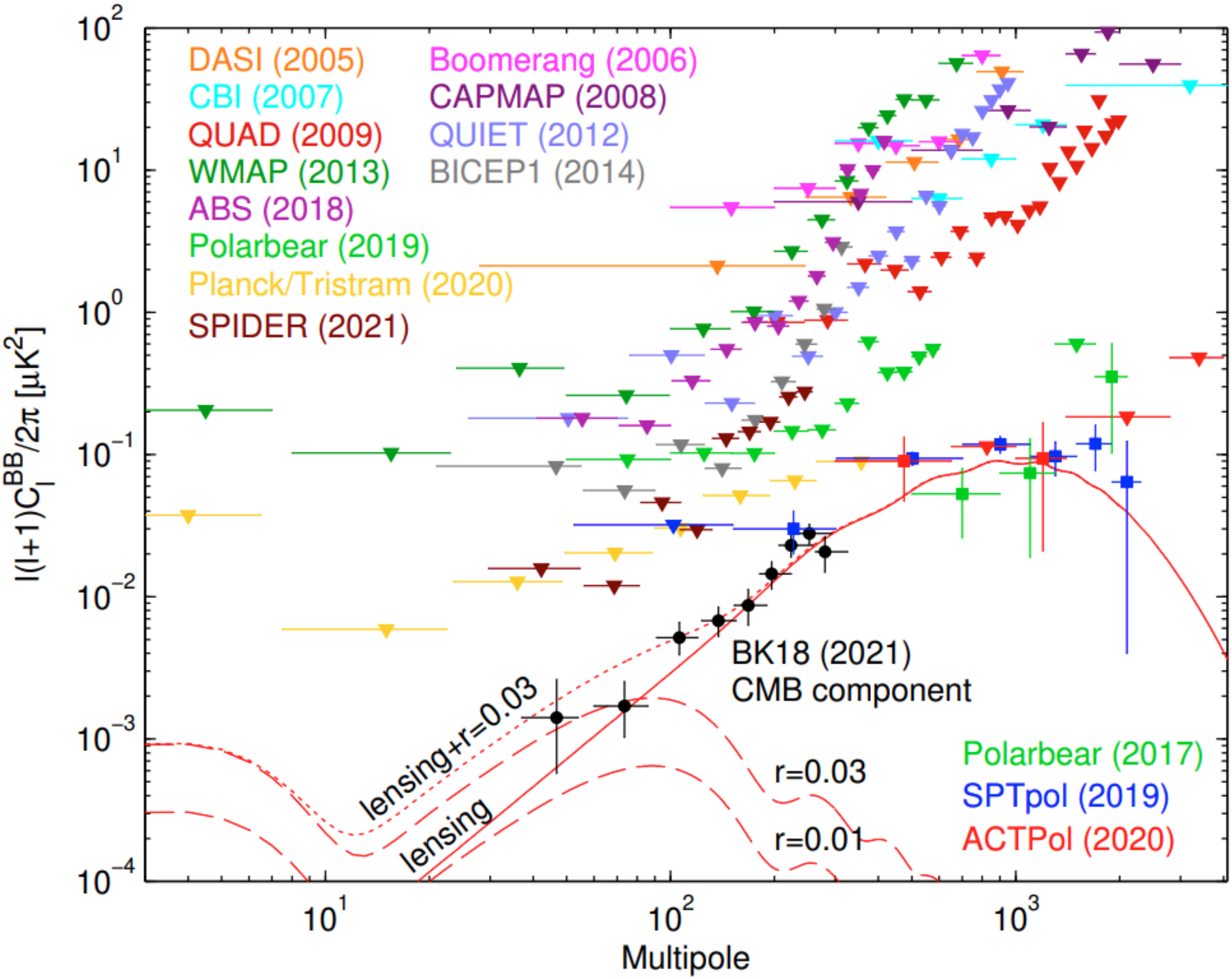


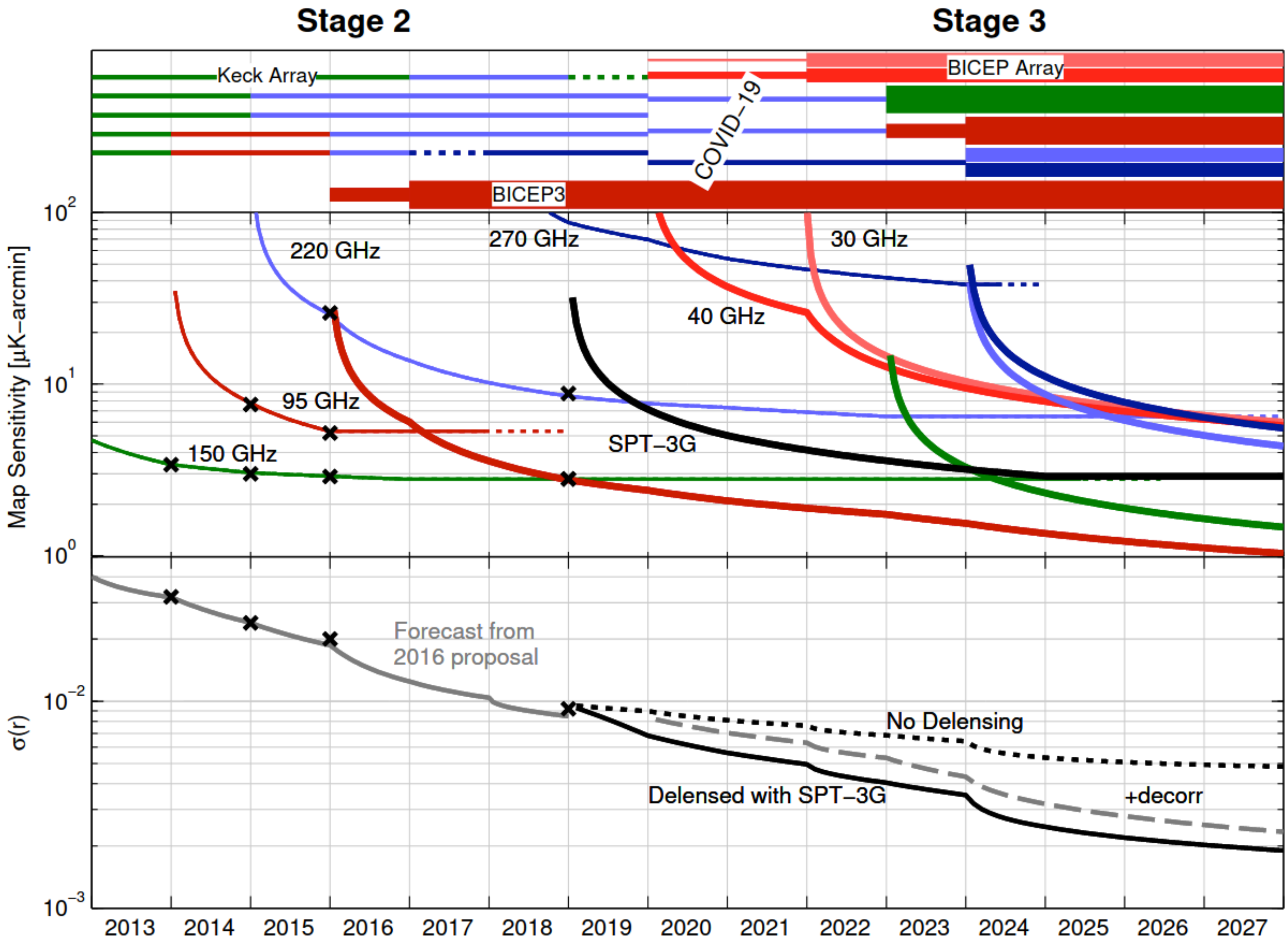
$r_{.05} < 0.035$

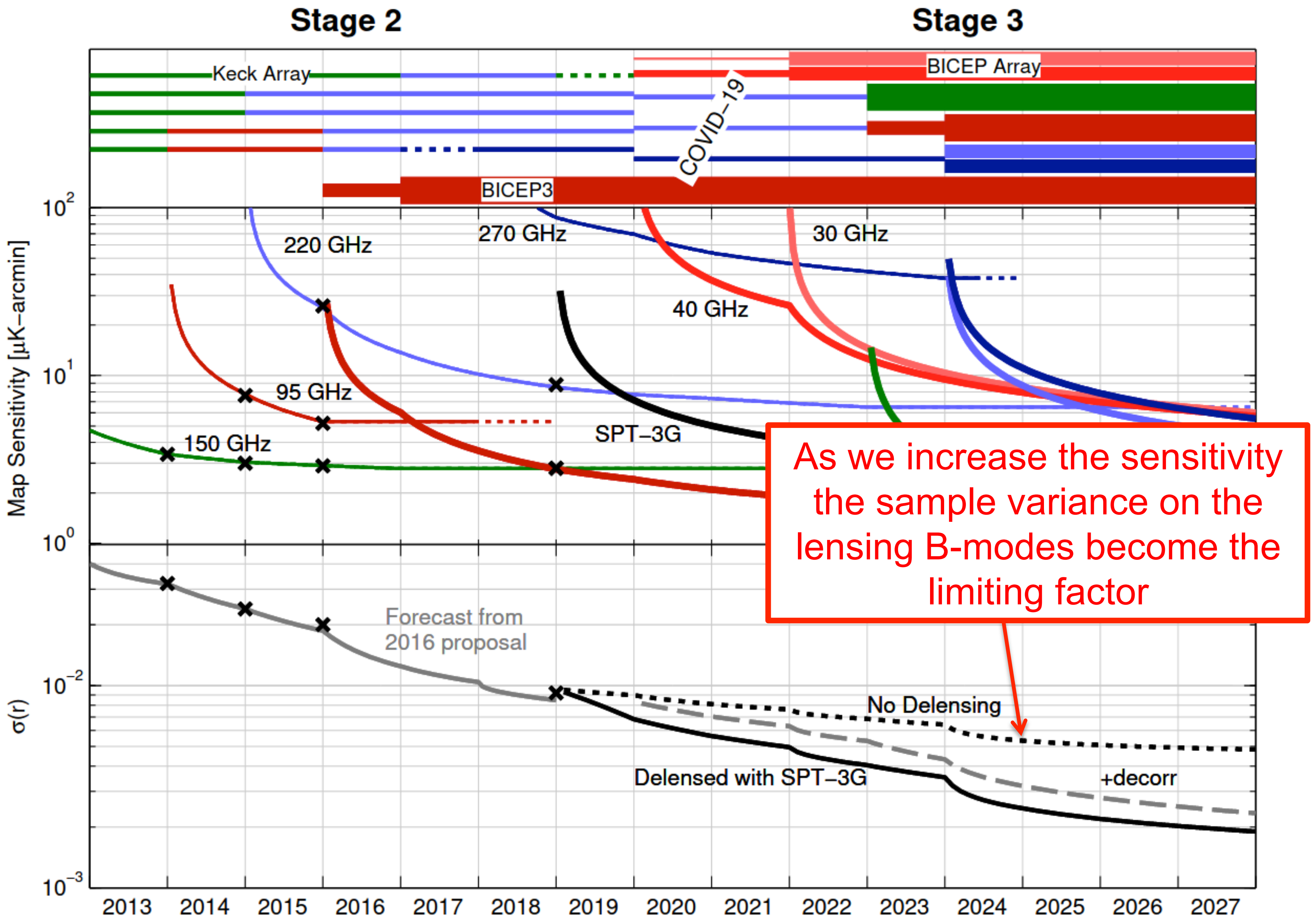
BK18

arxiv/2110.00483

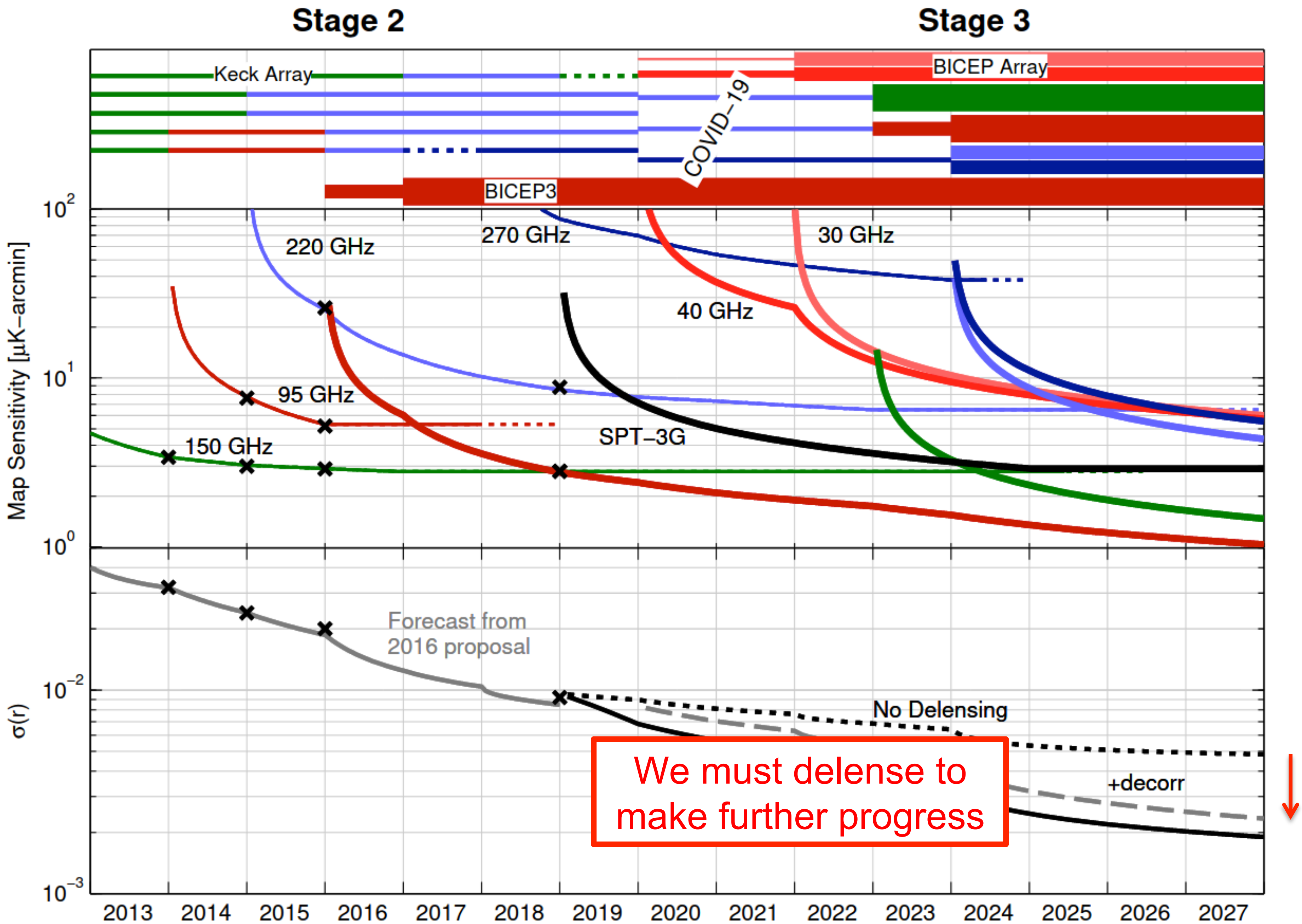
Per bandpower CMB component extraction



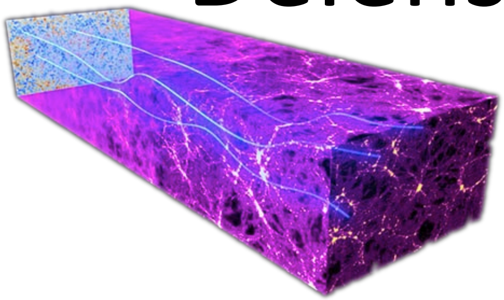

Stage 2
Stage 3
Keck Array
BICEP Array
COVID–19
BICEP3
220 GHz
270 GHz
30 GHz
40 GHz
95 GHz
150 GHz
SPT–3G
Map Sensitivity [μK–arcmin]
Forecast from
2016 proposal
No Delensing
Delensed with SPT–3G
+decorr
σ(r)
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027

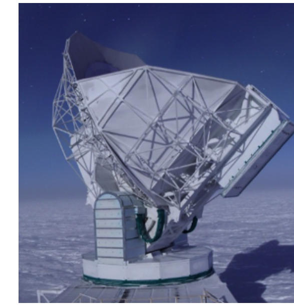


Stage 2
Stage 3
Keck Array
BICEP Array
COVID–19
BICEP3
220 GHz
270 GHz
30 GHz
40 GHz
95 GHz
150 GHz
SPT–3G
Map Sensitivity [μK–arcmin]
As we increase the sensitivity the sample variance on the lensing B-modes become the limiting factor
Forecast from 2016 proposal
No Delensing
Delensed with SPT–3G
+decorr
σ(r)
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027

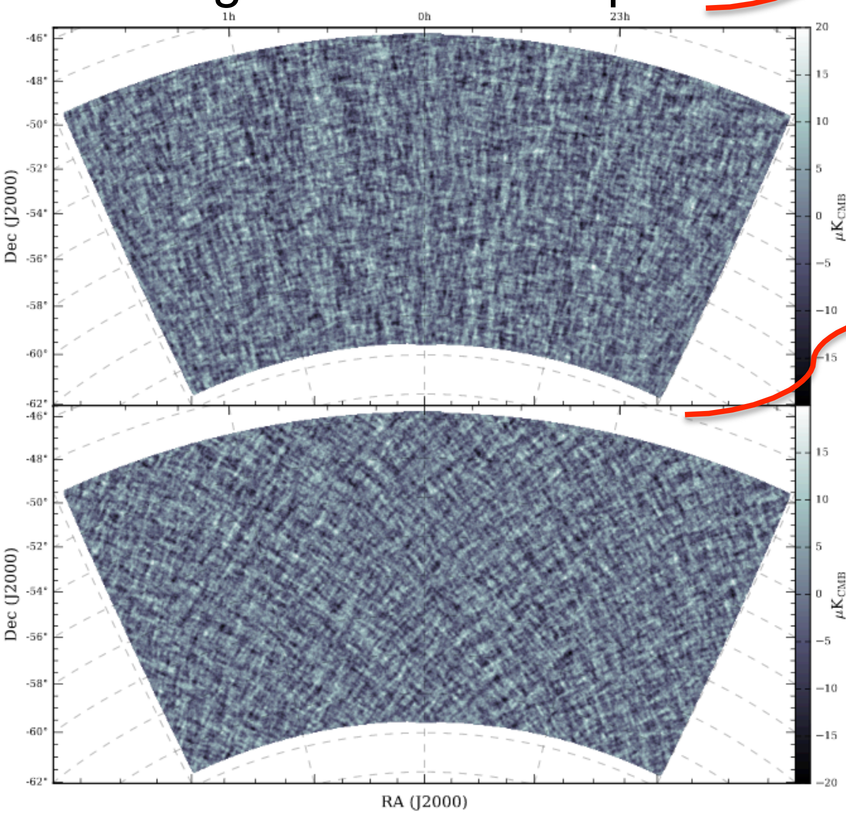

Stage 2
Stage 3
Keck Array
BICEP Array
COVID–19
BICEP3
220 GHz
270 GHz
30 GHz
40 GHz
95 GHz
150 GHz
SPT–3G
Map Sensitivity [μK–arcmin]
10^2
10^1
10^0
Forecast from
2016 proposal
No Delensing
+decorr
σ(r)
10^{-2}
10^{-3}
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
We must delense to
make further progress

Delensing with SPT-3G data

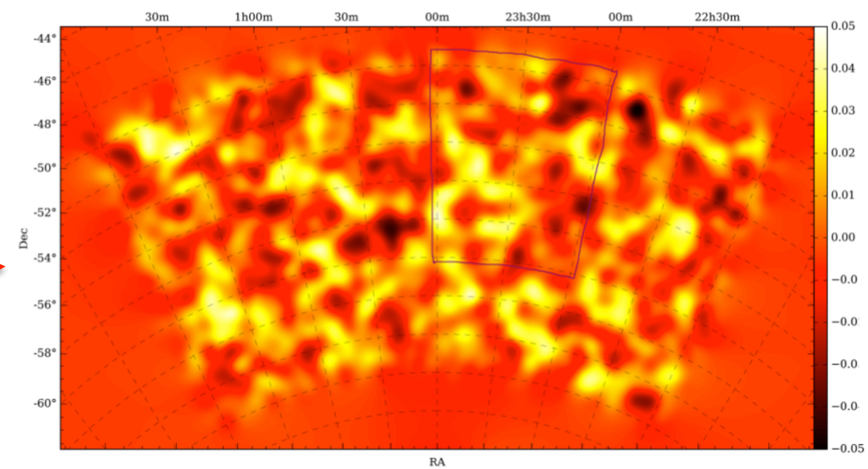




High resolution maps

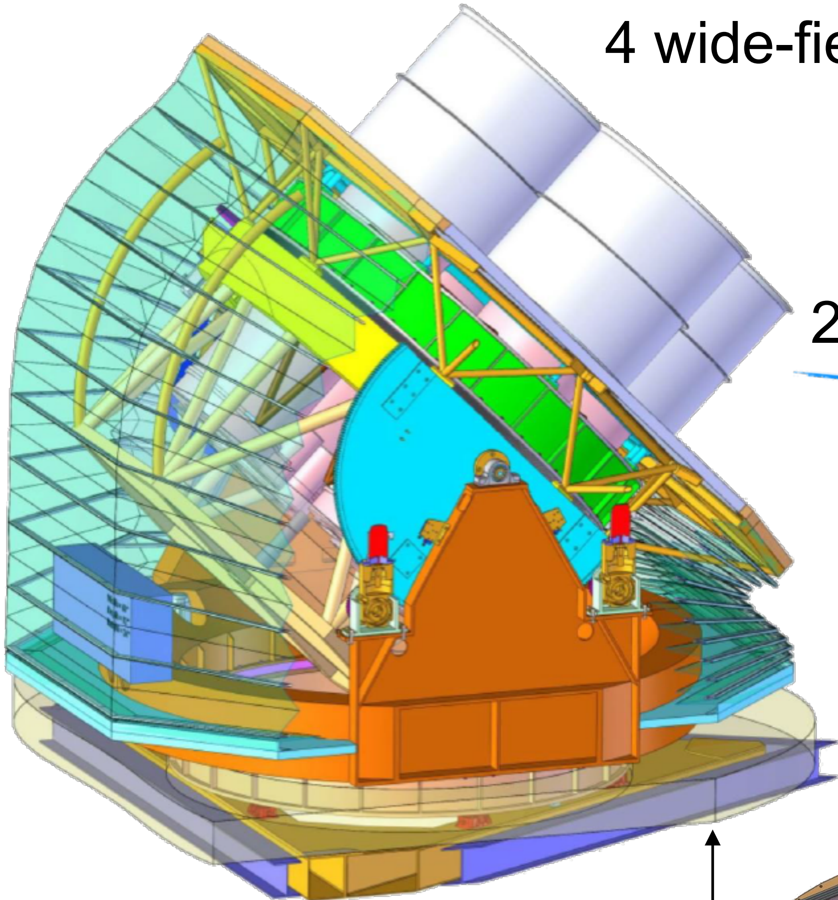


Can be used to reconstruct the lensing deflection map…

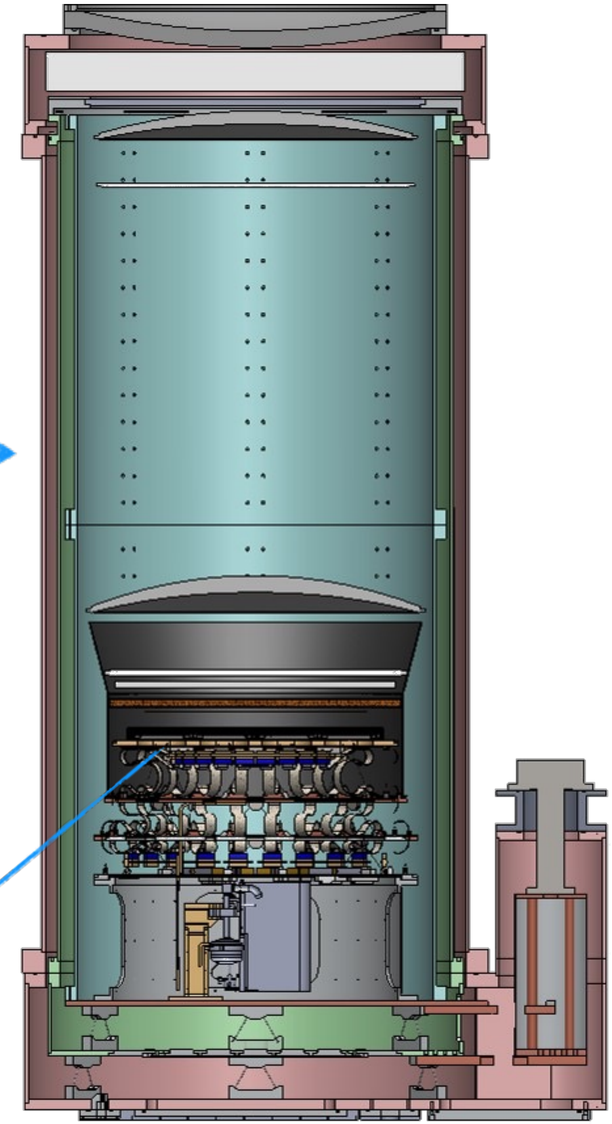


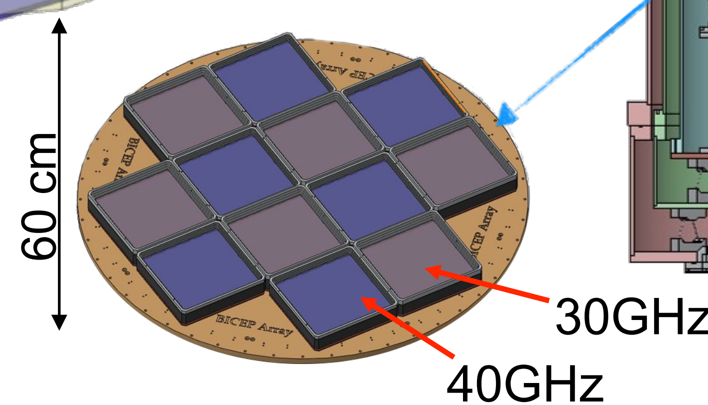
…which can then be used to calculate the lensing signal enabling a deeper search for inflationary gravitational waves

Latest Generation Experiment “BICEP Array"



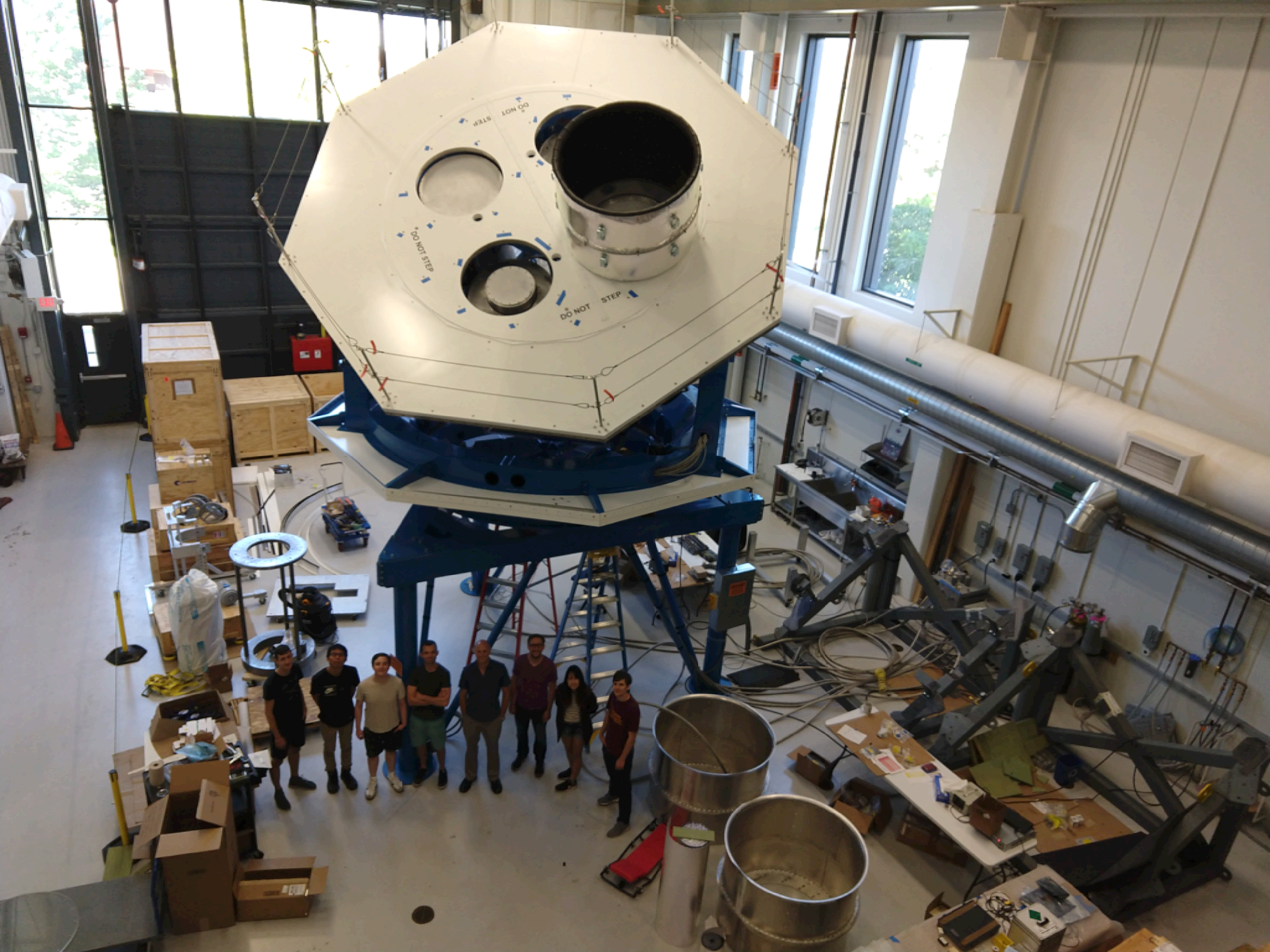
4 wide-field receivers
30/40 GHz
95 GHz
150 GHz
220/270 GHz



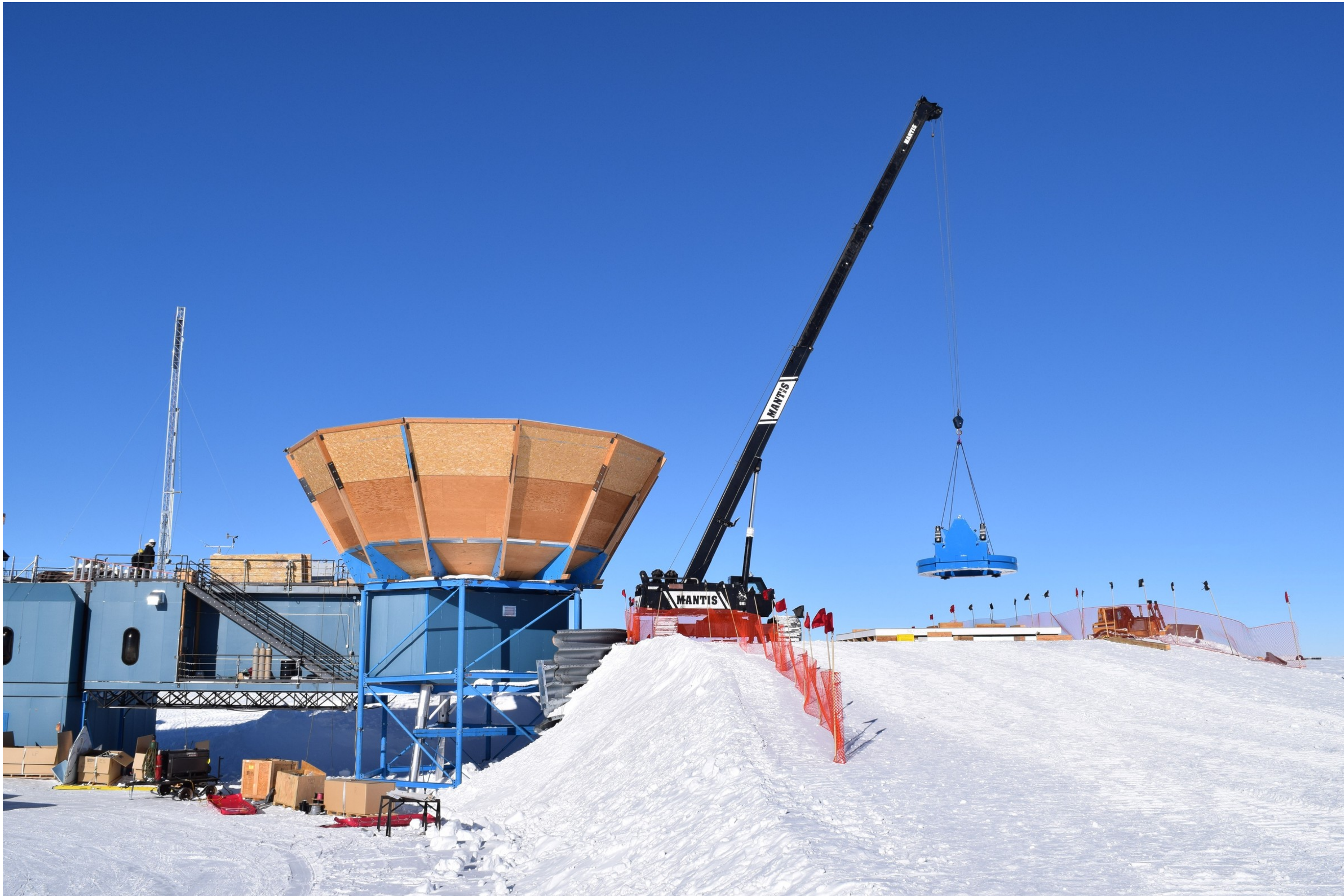


Focal plane layout

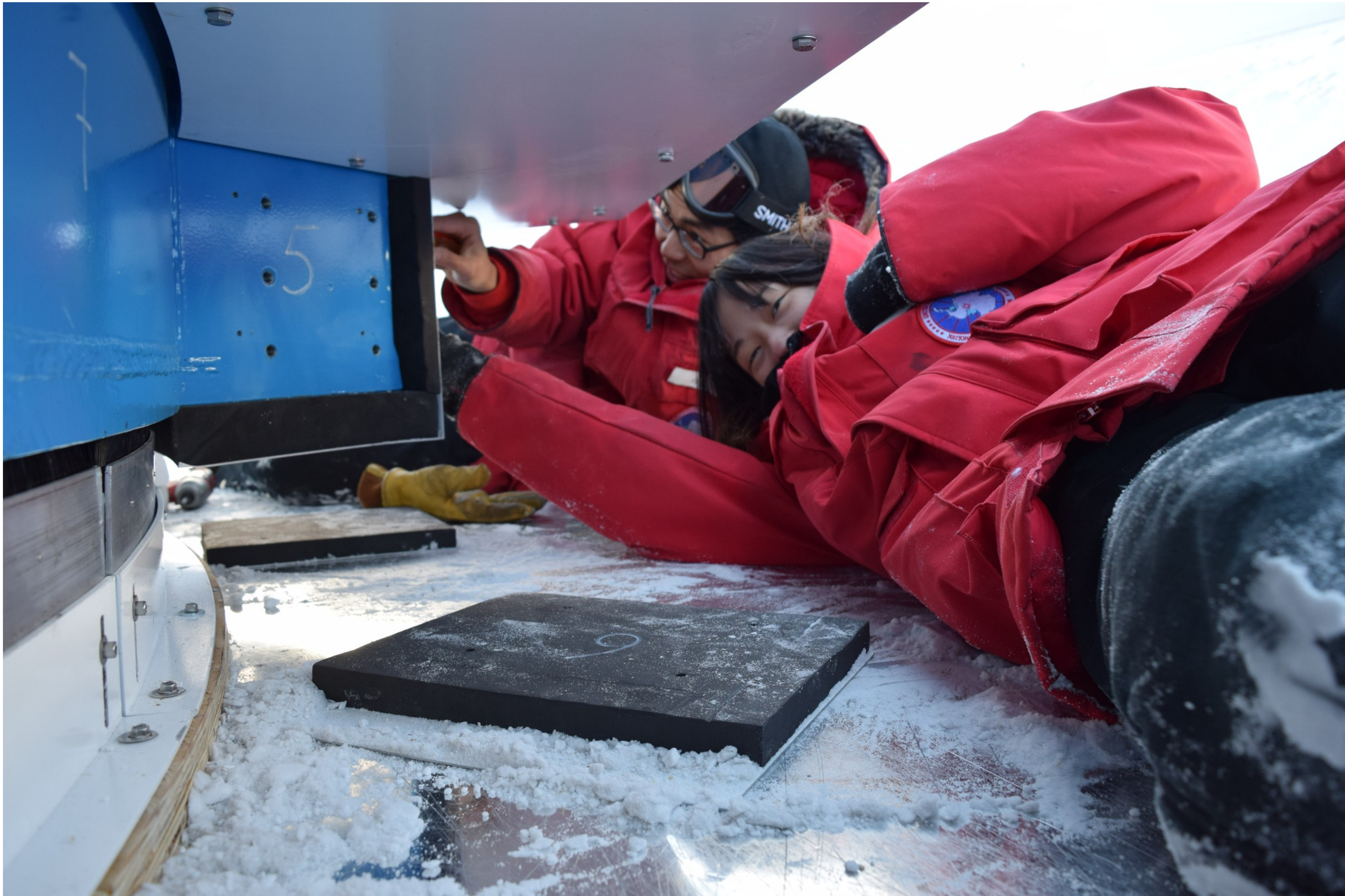
2018-19: Built New Telescope at UMN

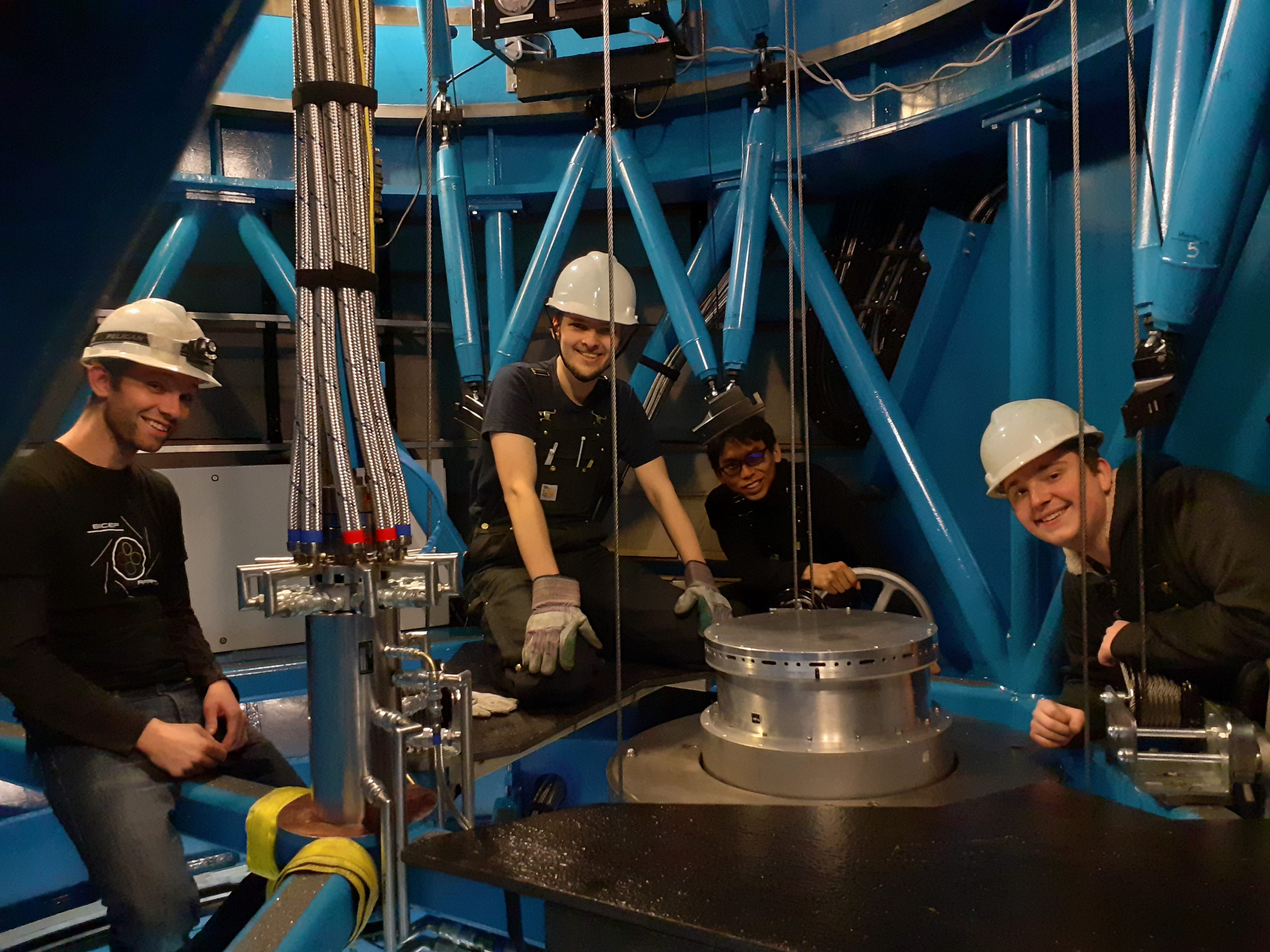

DO NOT STEP
DO NOT STEP
DO NOT
STEP

Lifting on part of new telescope



Working in the snow




BICEP

Feb 2020 – the finished product

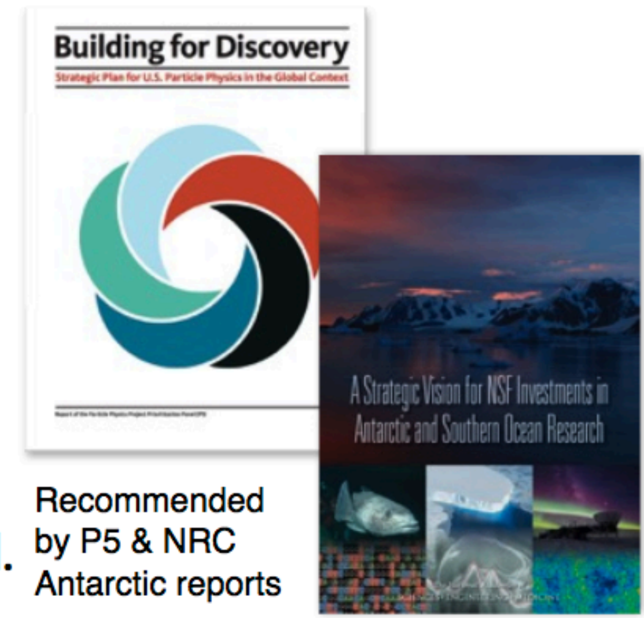
Summary

- The Universe is expanding – it was once a hot dense “fireball”.
- We understand its development all the way back to a very high energy state.
- The theory of “Inflation” says that our entire observable Universe today all came from a single sub-atomic spec in a hyper expansion lasting a tiny fraction of a second
  - If this “Inflation” really happened it will have made a background of gravitational waves
    - We may be able to detect the imprint of these by measuring the polarization pattern of the Cosmic Microwave Background – if we can build a sensitive enough telescope
      - BICEP/Keck set the world’s best upper limits to date ruling out multiple previously popular classes of inflationary models
        - And the search goes on with bigger and better experiments…

Stage IV CMB experiment: CMB-S4

CMB-S4
Next Generation CMB Experiment

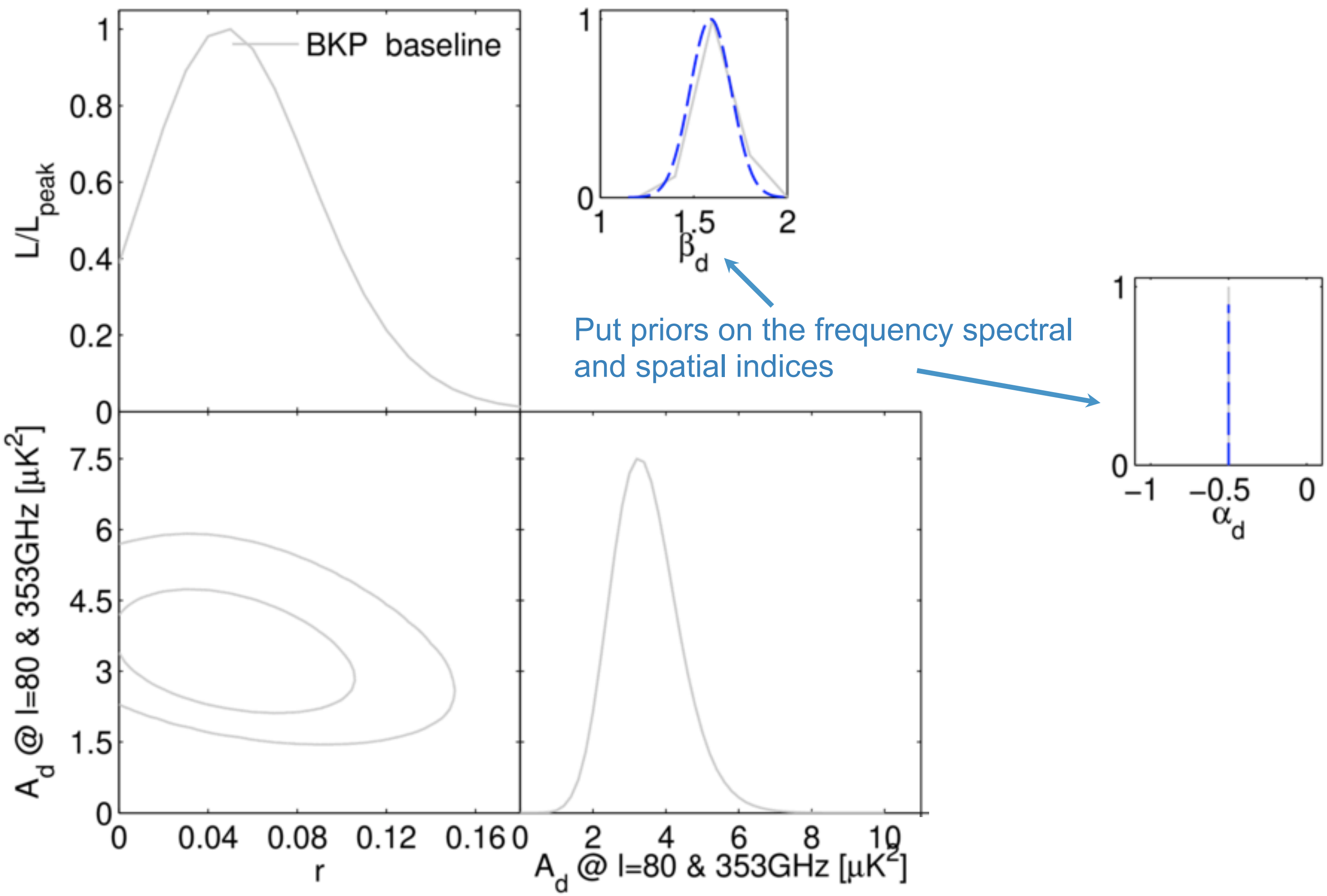
- CMB-S4: a next generation ground-based program building on CMB stage 2 & 3 projects to pursue inflation, neutrino properties, dark energy and new discoveries.
- **Targeting to deploy O(500,000) detectors spanning 30 - 300 GHz using multiple telescopes and sites to map most of the sky to provide sensitivity to cross critical science thresholds.**
- Multi-agency effort (DOE & NSF). Complementary with balloon and space-based instruments.
- Broad participation of the US CMB community, including the existing NSF CMB groups, DOE National Labs and the High Energy Physics community.
- U.S. led program; international partnerships expected.



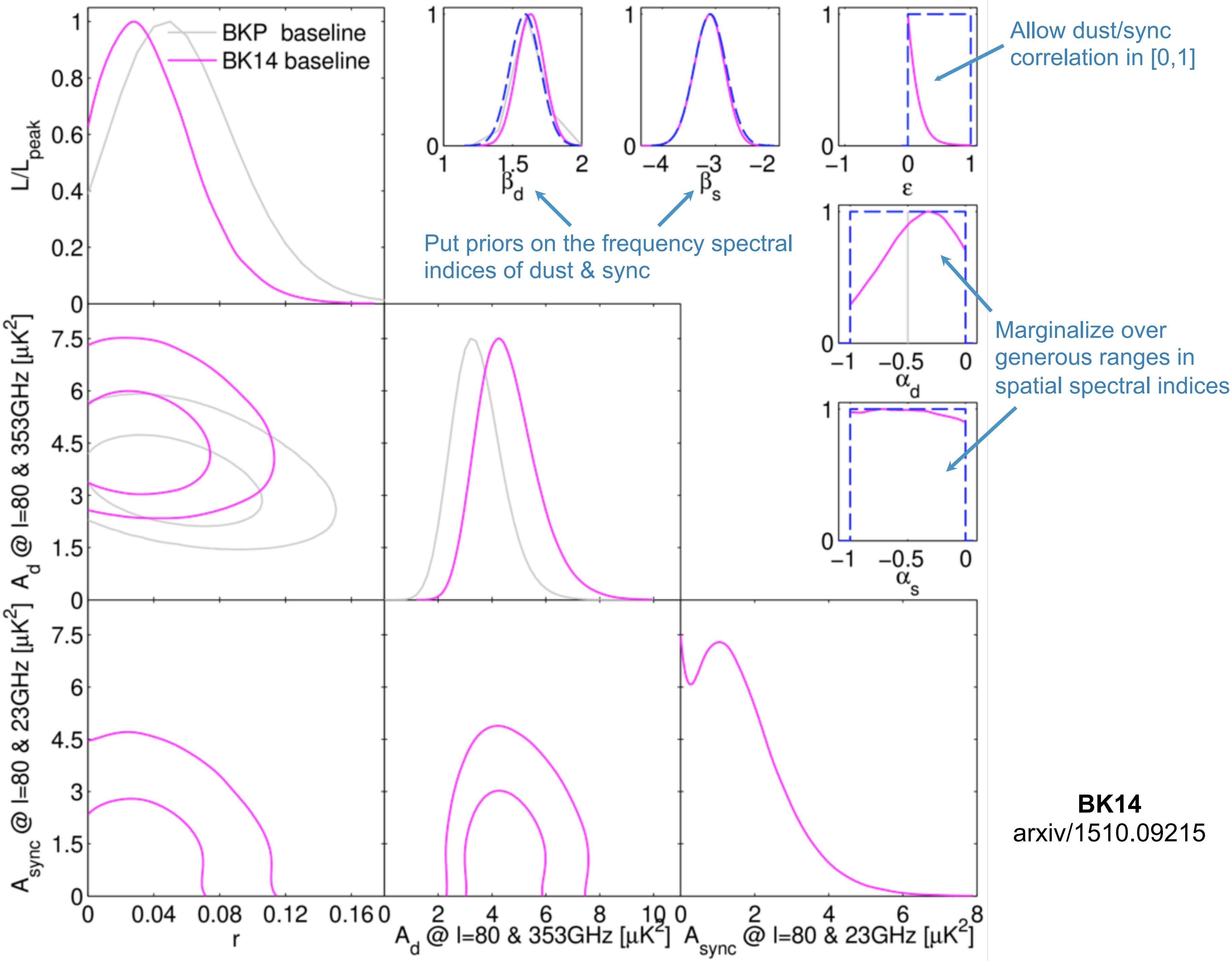
Recommended by P5 & NRC Antarctic reports

A science driven program combining the deep CMB experience of the university groups with the expertise and resources at the national labs.

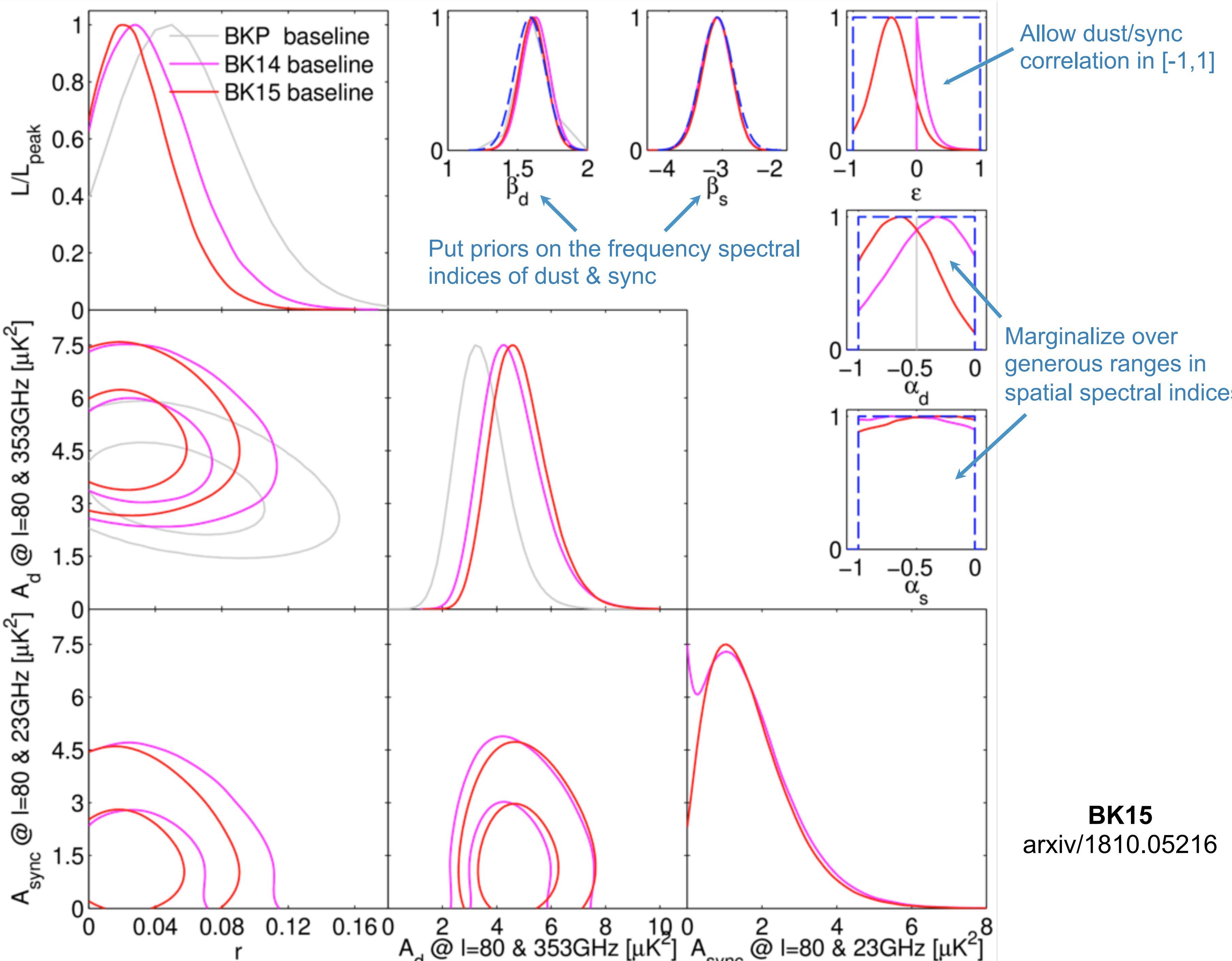
Backup Slides



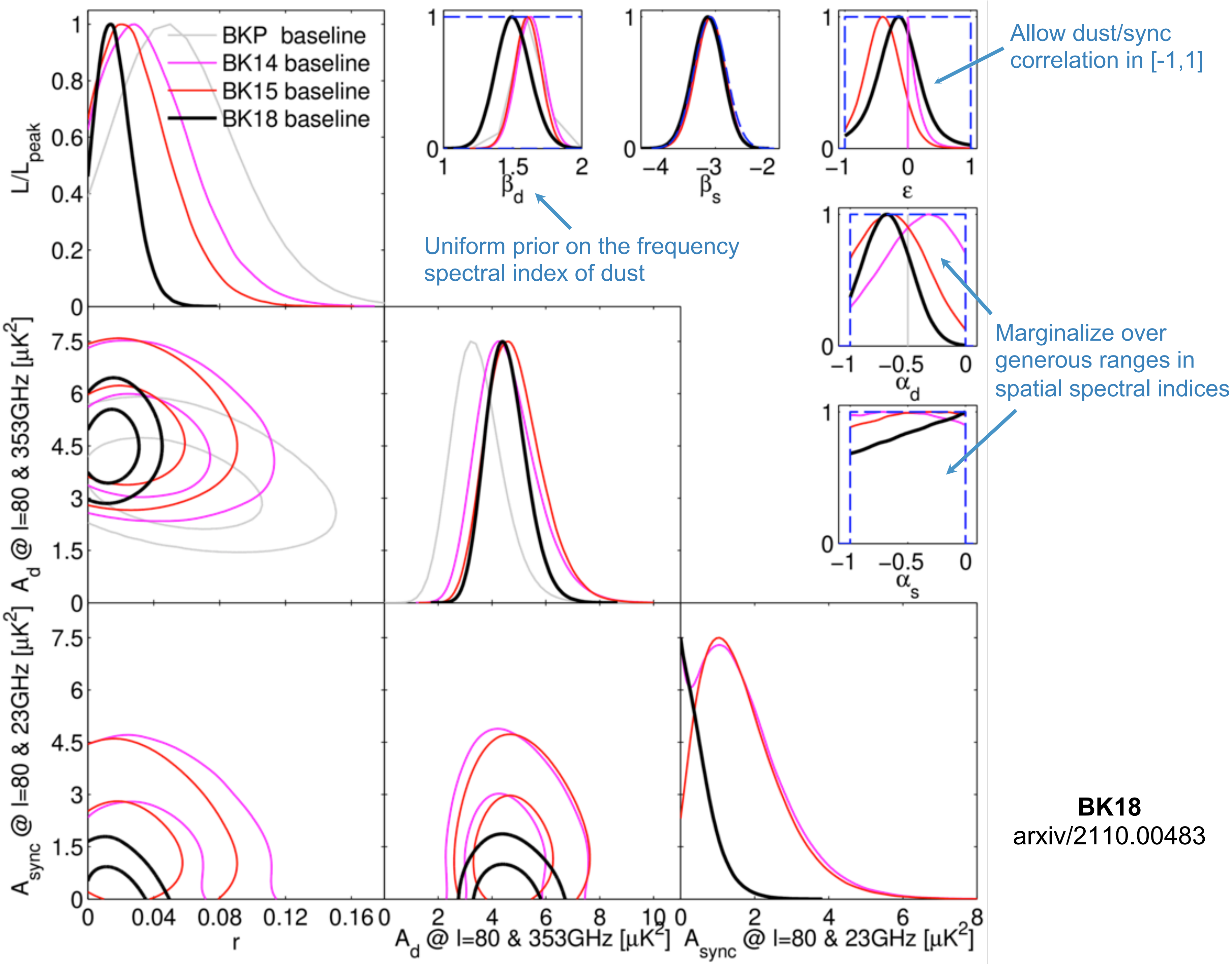
BKP
arxiv/1502.00612



BK14
arxiv/1510.09215

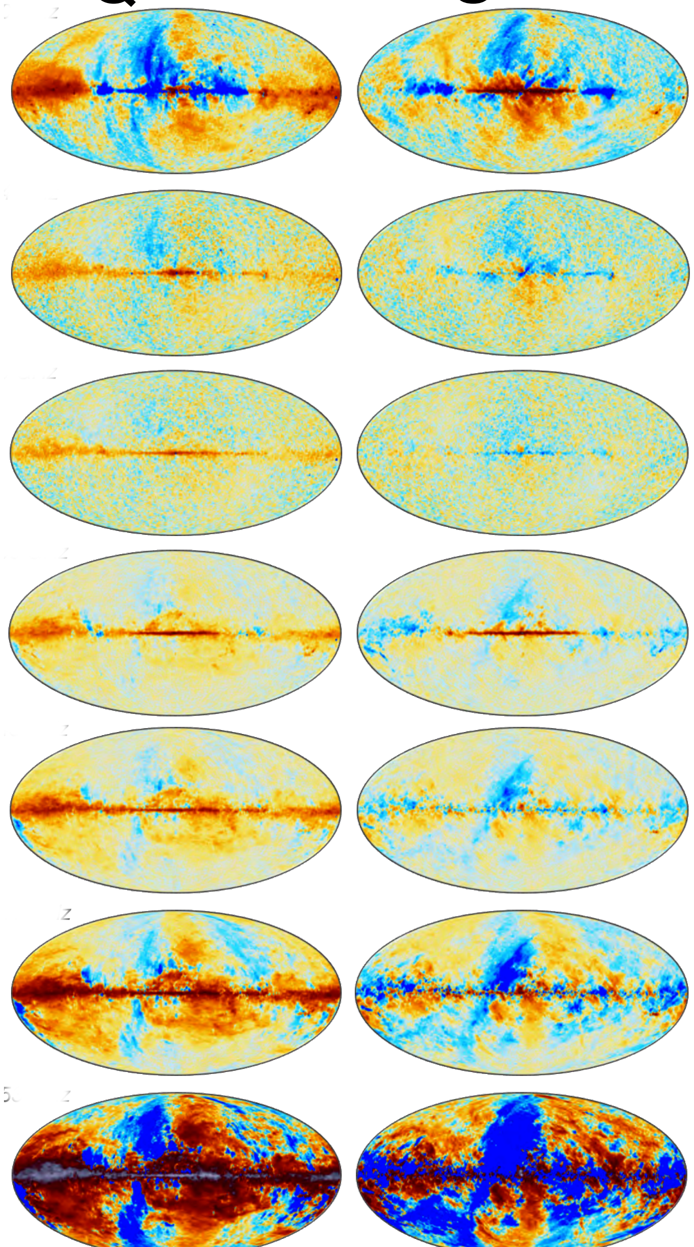


BK15
arxiv/1810.05216



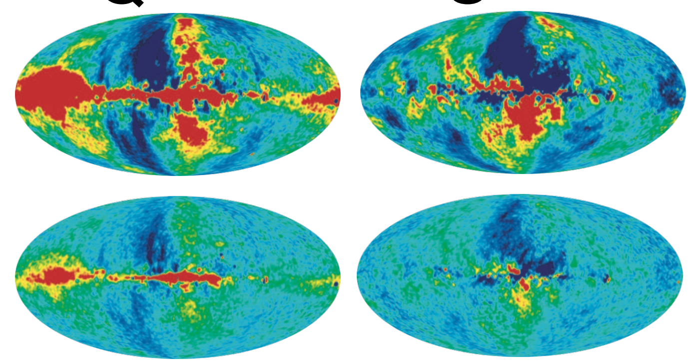
BK18
arxiv/2110.00483

Add to the mix: Planck at 7 frequencies and WMAP at 2 frequencies



From arxiv 1502.01582

Polarized galactic **synchrotron** dominates at low frequencies



From arxiv 1212.5225

Polarized thermal emission (~20K) from galactic **dust** aligned in magnetic fields dominates at high frequencies

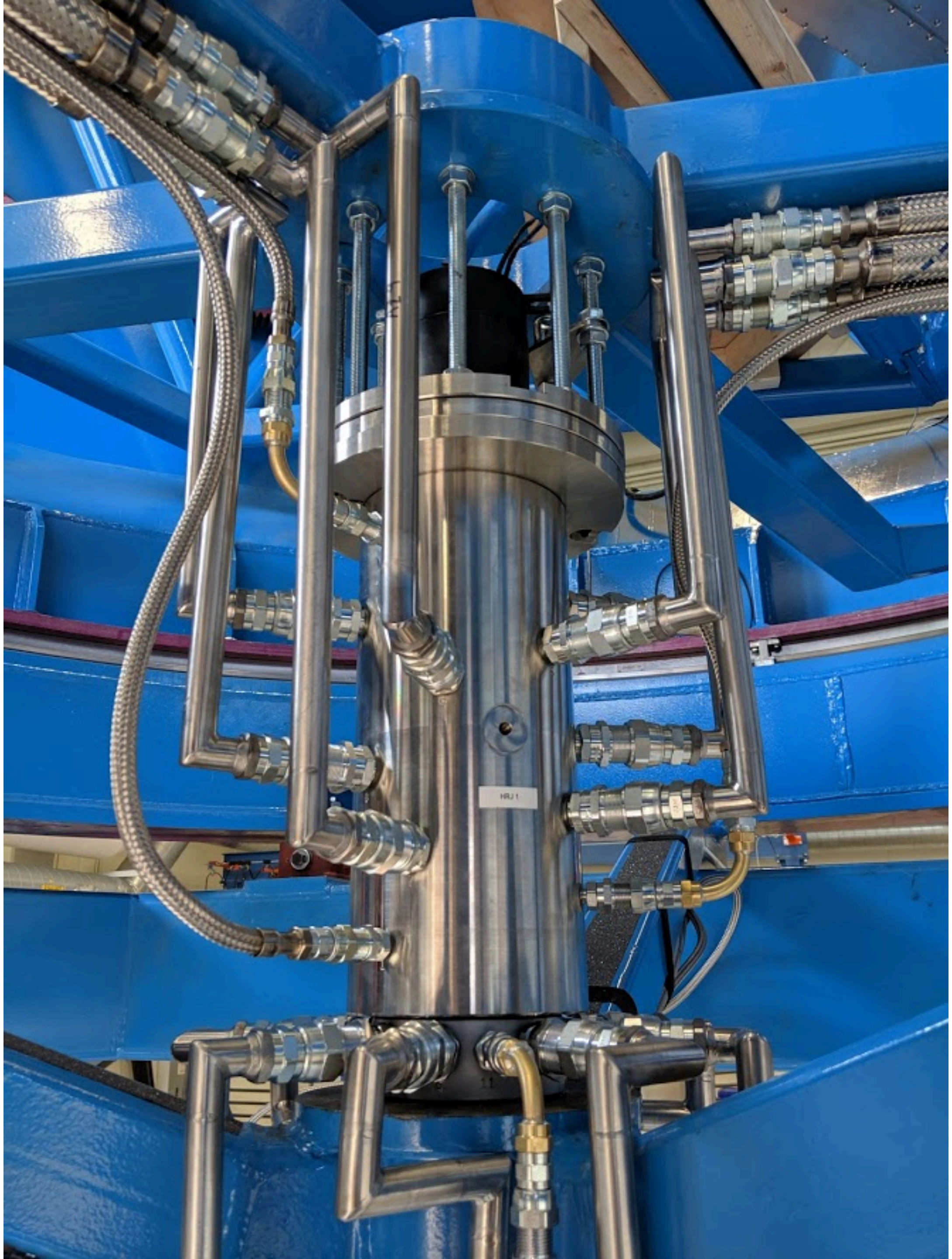
Conclusions

- BICEP/Keck lead the field in the quest to detect or set limits on inflationary gravitational waves:
- Best published sensitivity to date
- Best proven systematic control at degree angular scales

- Adding 2016-18 data (from BK15 to BK18):
- Goes from $r_{0.05}<0.07$ to $r_{0.05}<0.036$
- For the first time no priors from other regions of sky

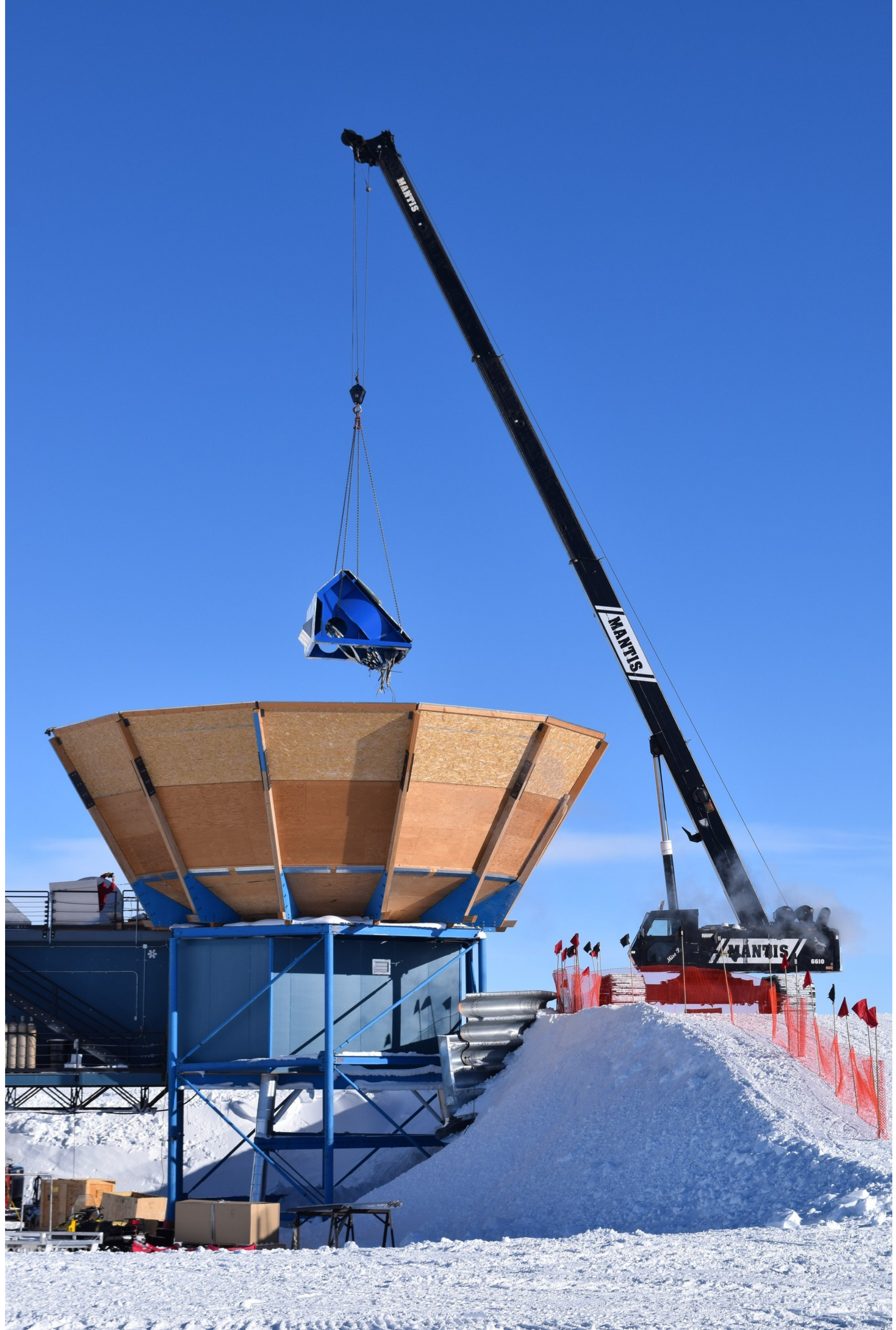
- And we can keep going:
- BICEP Array mount and first receiver running
- Delensing in conjunction with SPT3G

- Other things I can talk about:
- Delensing technique (lensing template)
- E/B separation (matrix purification)
- Beam systematics and deprojection thereof
- Detailed beam measurements to predict undeprojected residual


HRJ 1


WERNER


CLEM PRYKE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What limits BK18?

- BK18 mainline simulations with dust and lensing give σ(*r*)=0.009
- Running without foreground parameters on simulations where the dust amplitude is set to zero gives σ(*r*)=0.007

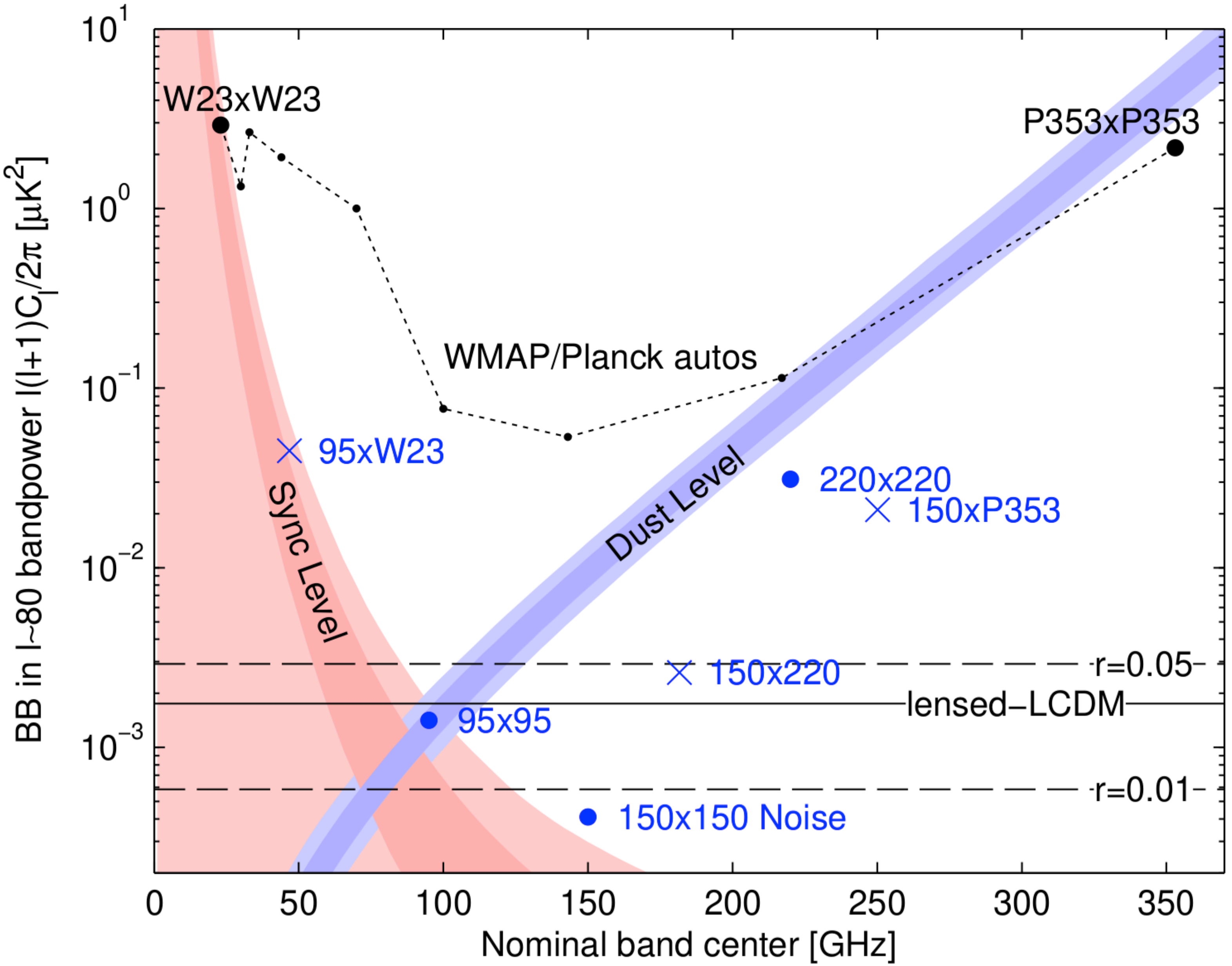
The above is as it should be - we have correctly tuned the relative sensitivity of the 95/150/220 bands such that we don’t suffer much penalty due to the presence of foregrounds.

- Running on simulations which contain no lensing gives σ(*r*)=0.004

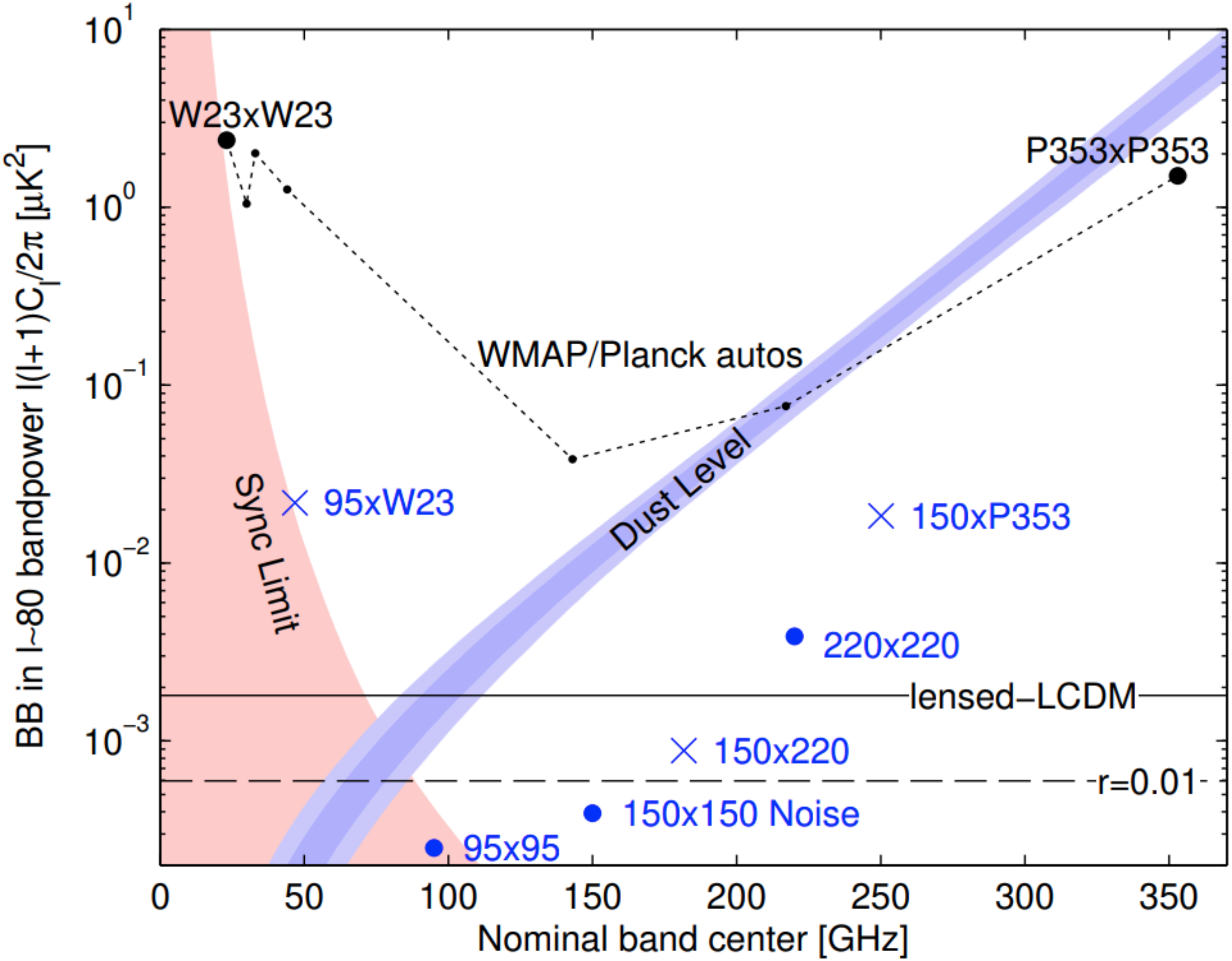
The sample variance of the achromatic lensing foreground is a major limiting factor - we need delensing via high resolution measurements.

- Running without foreground parameters on simulations which have neither dust or lensing gives σ(*r*)=0.002

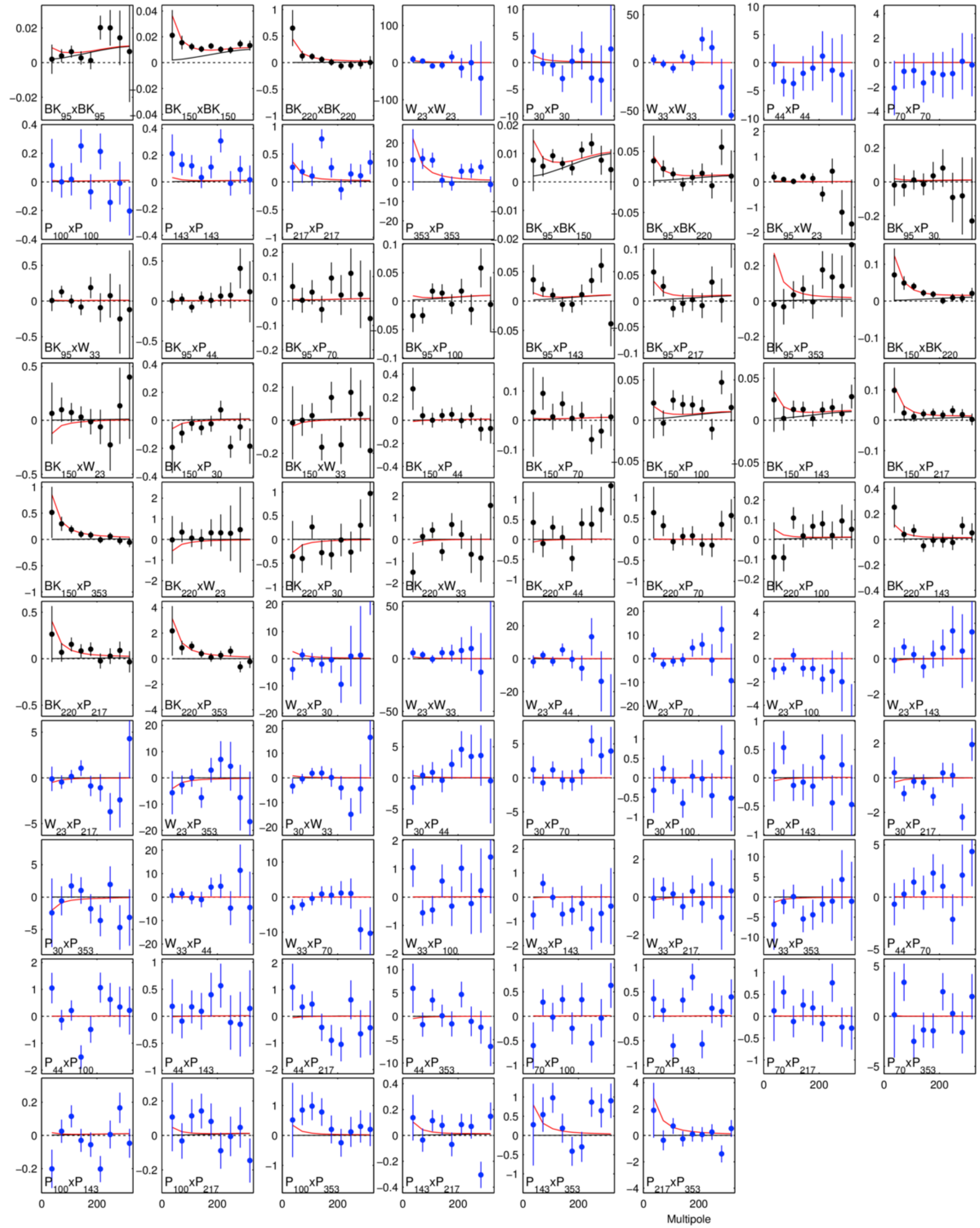
BK15 ell=80 bandpower noise/signal



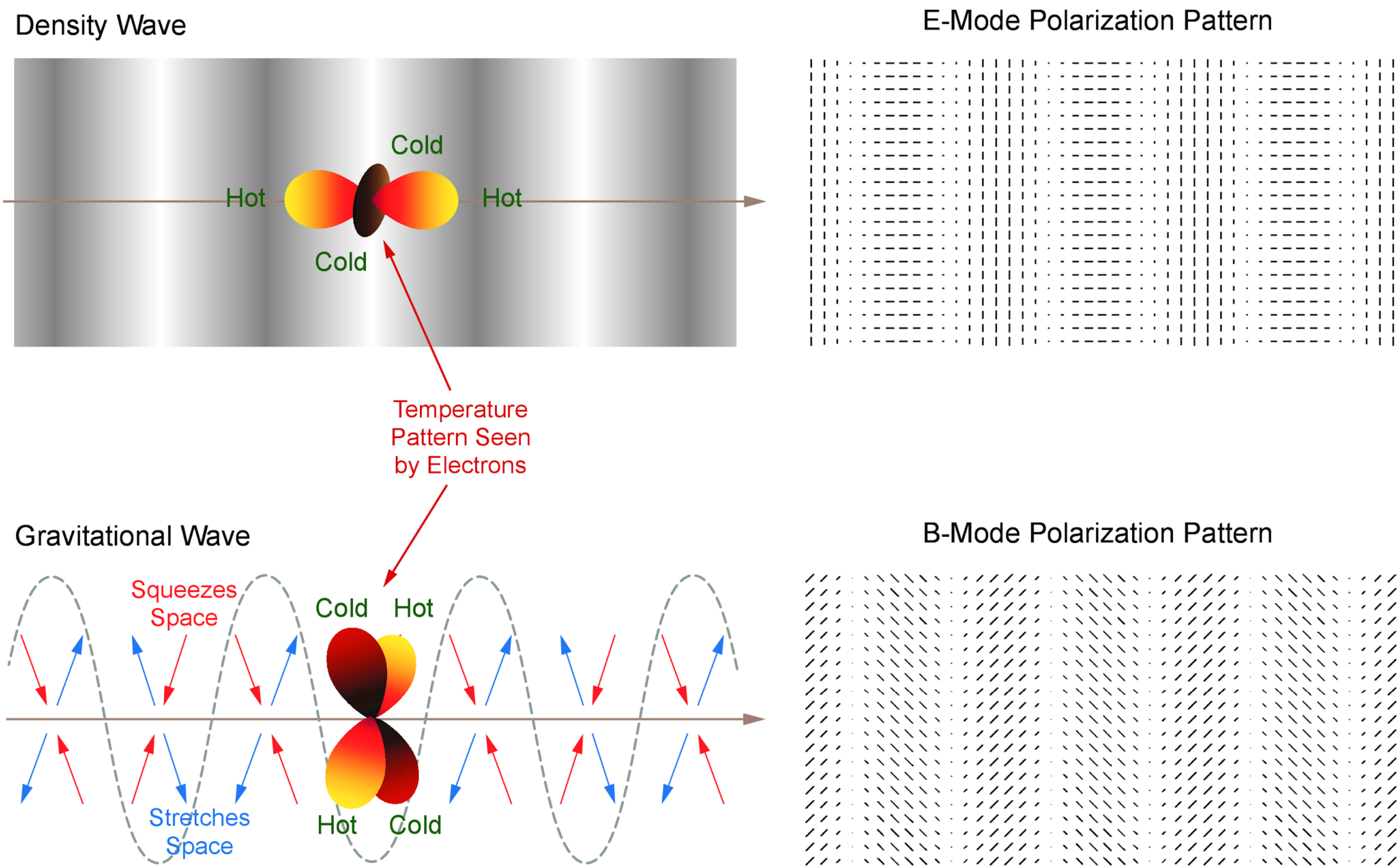
BK18 ell=80 bandpower noise/signal



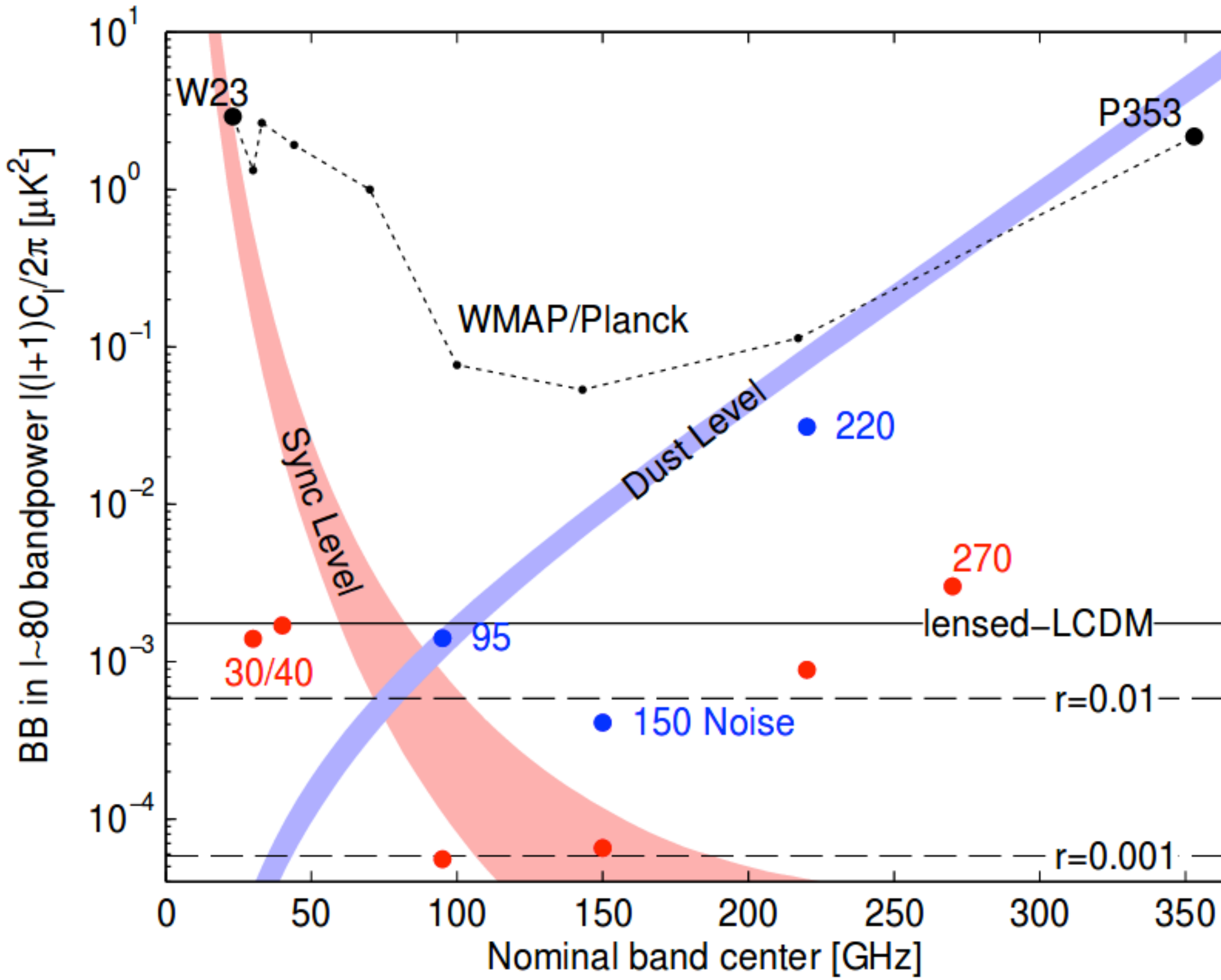
Take all possible auto- and cross spectra between the BICEP/Keck, WMAP, and Planck bands (78 of them)



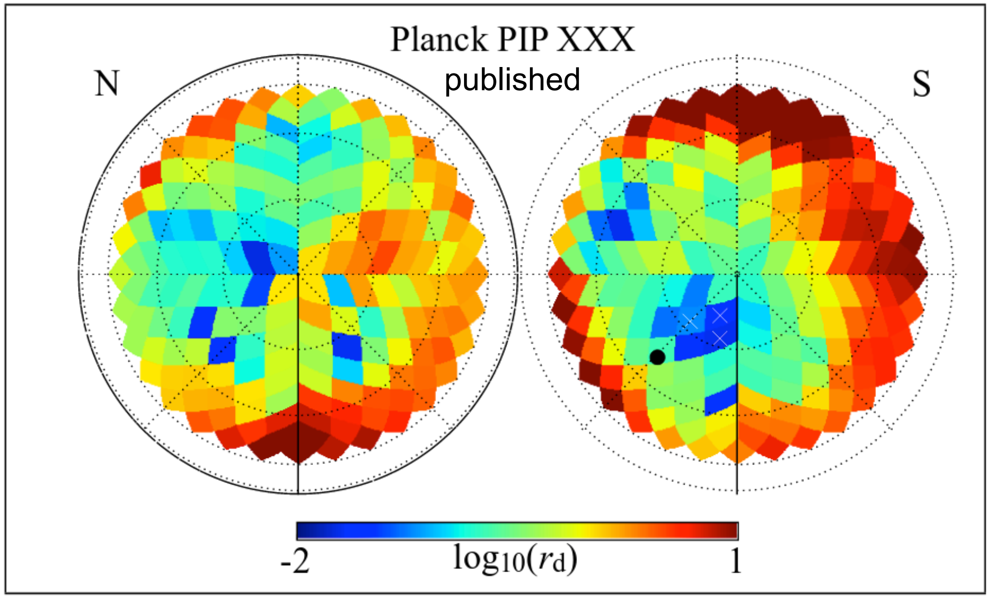
CMB polarization

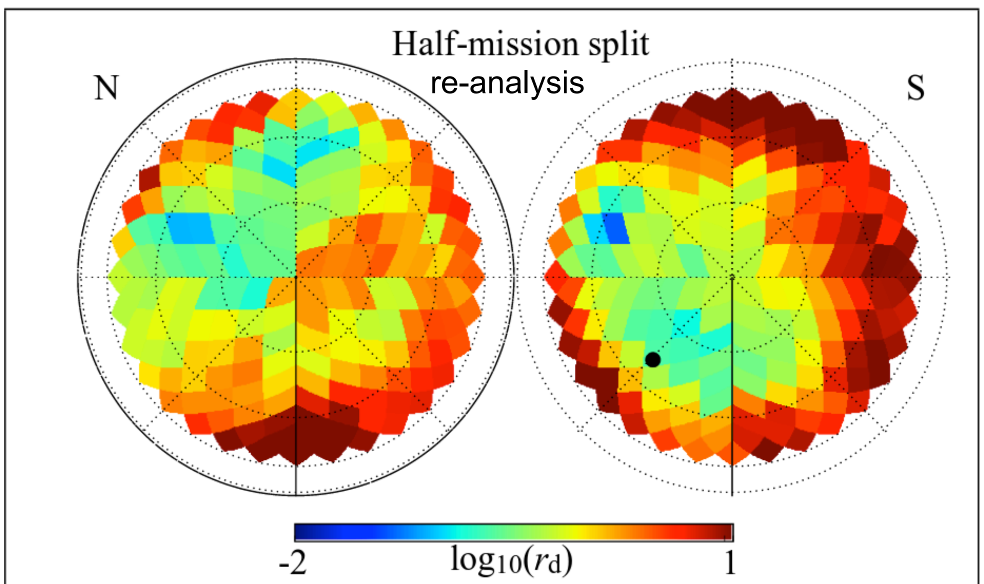


BK23 Noise levels



Is there a cleaner small field than the BICEP/Keck field?

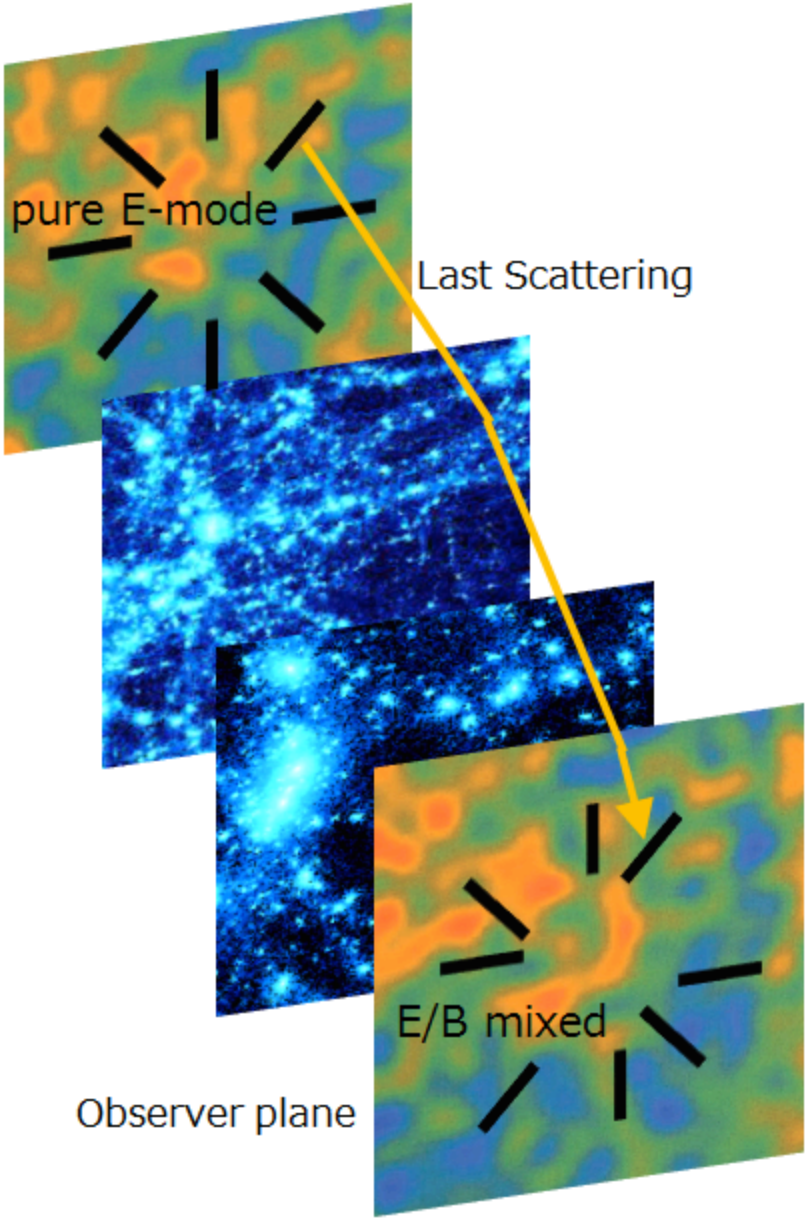




- The Planck 353GHz Q/U maps hit their noise floor in the cleanest regions
  - From this data it is not really possible to tell if there are cleaner small regions than the BICEP/Keck field
- When we attempt to reproduce the Planck PIPXXX analysis we find that the apparent cleaner regions shift around depending on the data split selected
- The BK patch is currently the only low dust field where we actually know the dust level!

Slides summarizing BK-VIII: Measurement of Gravitational Lensing from Large-scale B-mode Polarization

Measurement of Gravitational Lensing



- **Gravitational lensing converts some of the E mode into B mode**

Zaldarriaga & Seljak (1998)

$$B_{\vec{\ell}} = \int d\vec{L}\, w_{\vec{\ell},\vec{L}} E_{\vec{L}} \kappa_{\vec{\ell}-\vec{L}}$$

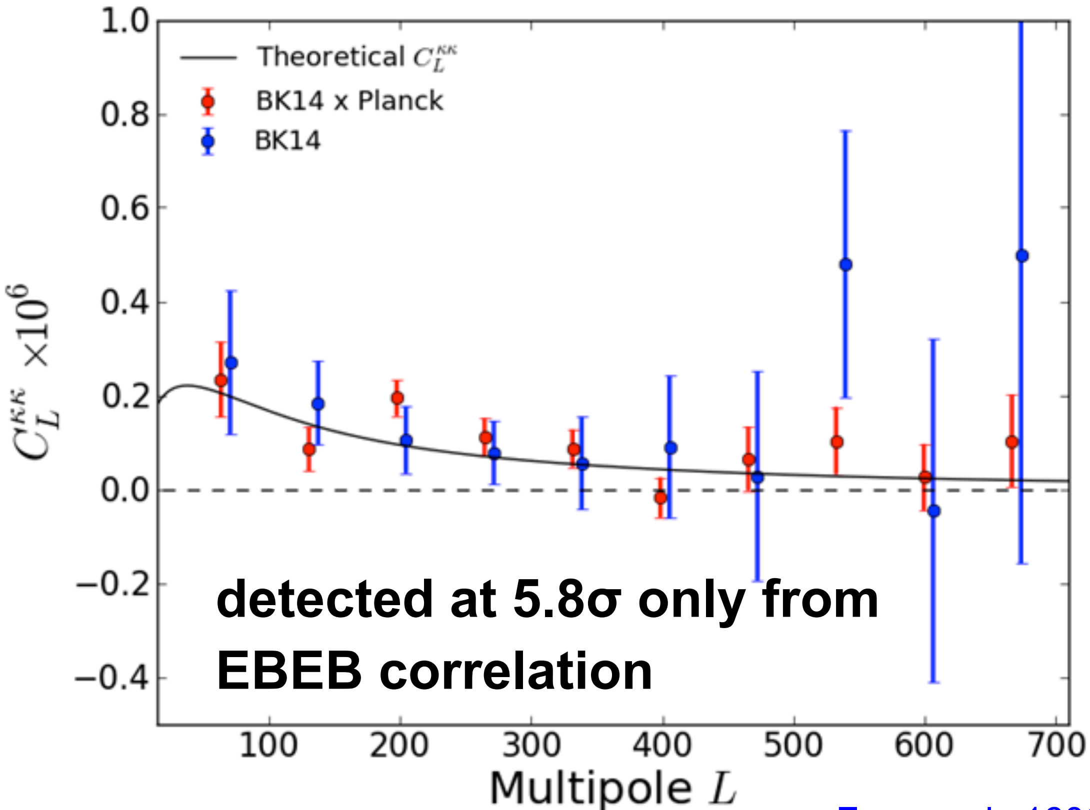
Lensing convergence

- **Lensing B mode behaves as 5uK' white noise at large angular scales**

(e.g. Lewis & Challinor 2006)

- **Despite our modest angular resolution (0.5deg), the excellent sensitivity (~3μK') of our maps makes it possible to directly reconstruct lensing signals using only information at larger angular scales (ℓ≤700).**

Measurement of Gravitational Lensing



From arxiv 1606.01968

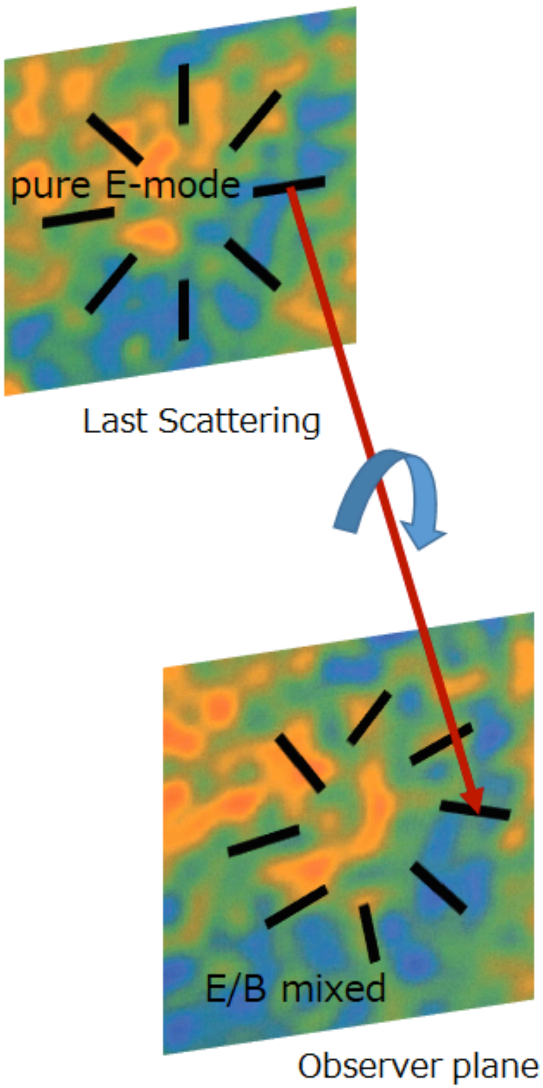
- **κ map is reconstructed from BK14 Q/U map at 150GHz**
- **κ map is used for computing auto spectrum and also correlated with that of Planck, finding that they are consistent**

Measured amplitude is in good agreement with the BB results, and we can start to constrain alternative B-mode sources!

(cosmic string, magnetic field, axion, modified gravity,…)

Slides summarizing BK-IX: New Bounds on Anisotropies of CMB Polarization Rotation and Implications for Axion-Like Particles and Primordial Magnetic Fields

Cosmological origins of anisotropies of polarization rotation



- **Axion-like particles**

String theory generally predicts presence of axion-like particles coupled with electromagnetic fields

(e.g. Pospelov+'09, Caldwell+'11)

$$\text{Lagrangian} \supset \frac{\phi}{2f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Coupling constant

This coupling leads to spatial variation of polarization angle rotation

rotation angle → $$\alpha(n) = \frac{\Delta\phi(n)}{f_a}$$ ← Changes in phi during photon propagation

- **Primordial magnetic fields**

Lead to the polarization rotation by the Faraday rotation

(e.g. Kosowsky&Loeb'96, Harari+'97)

Total rotation angle

$$\alpha(n) = \frac{3c^2}{16\pi e^2}\nu^{-2}\int \dot{\tau}\, \vec{B}\cdot d\vec{l}$$

Magnetic field

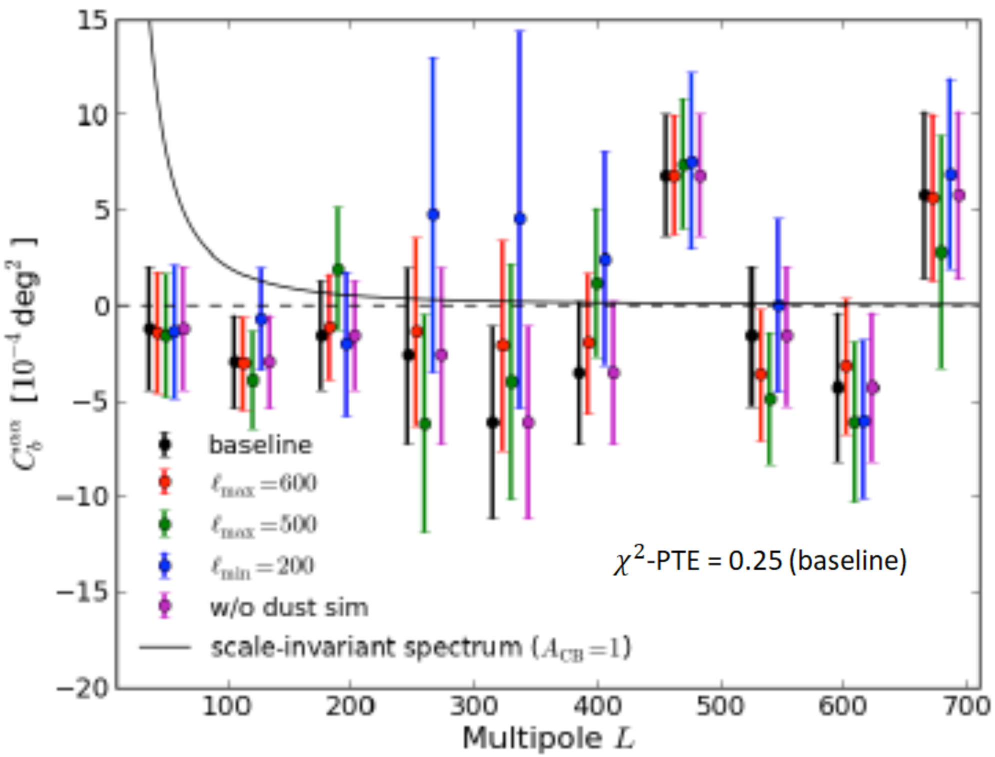
Measurement of the anisotropic polarization rotation is a unique probe of the early universe and provides important implications for high energy physics!

Measurement of the polarization rotation spectrum

- **Analysis Method**

Anisotropic pol. rotation leads to mode-coupling between E and B modes as similar to lensing. Thus we can apply the same analysis method as in the lensing case but using different weight function to optimally reconstruct rotation angle

- **Measured spectrum**



From arxiv 1705.02523

- The spectrum is consistent with null

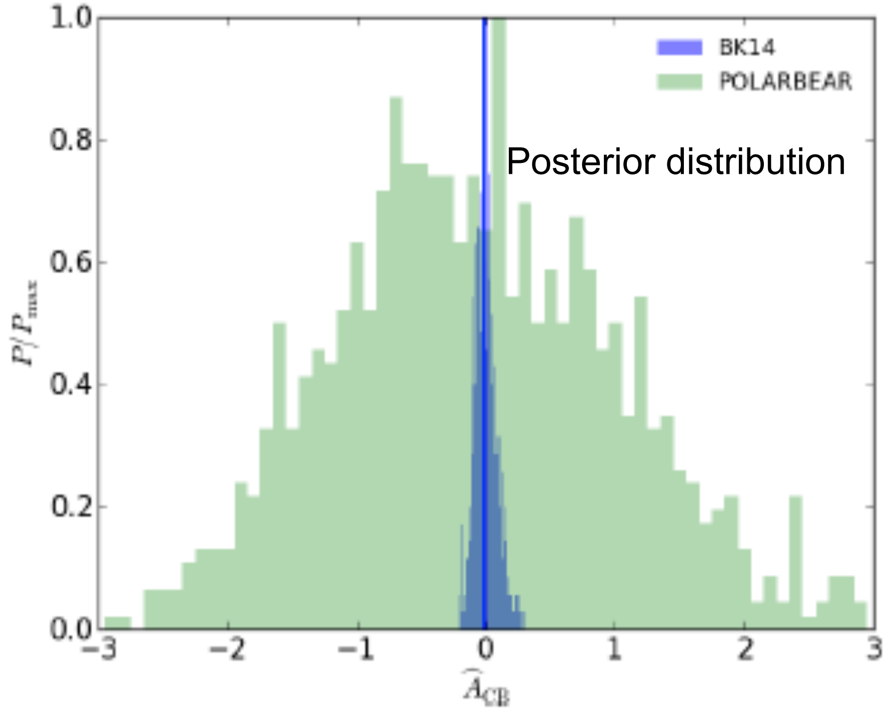
(even if we change the analysis choices)

- The reconstructed spectra measured from our 14 jackknife maps are also consistent with null

- Instrumental relative pol. rotation < 1% of the 1 sigma statistical error

Comparison w/ previous works & cosmological implications

- **Improved constraints on inflationary pol. rotation spectrum**



If sources of the pol. rotation are originated from inflation, the expected rotation spectrum has the following scale-invariant shape

$$\frac{L(L+1)}{2\pi} C_L^{\alpha\alpha} = A_{CB} \times 10^{-4}$$

Compared to previous attempts, we improve the constraints on this inflationary rotation spectrum by an order of magnitude.

$$A_{\rm CB} \leq 0.33 \text{ at } 95\%$$

From arxiv 1705.02523

- **Implications**

The above results lead to constraints on

1) Coupling constant of the Chern-Simons term $f_a \geq 1.7 \times 10^2 \frac{H_I}{2\pi}$

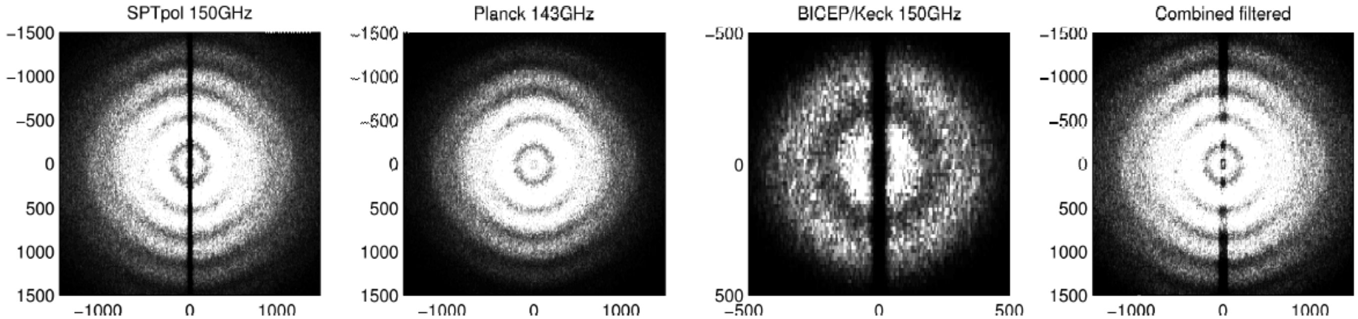
an order of magnitude better than Pospelov et al. (2009) PRL

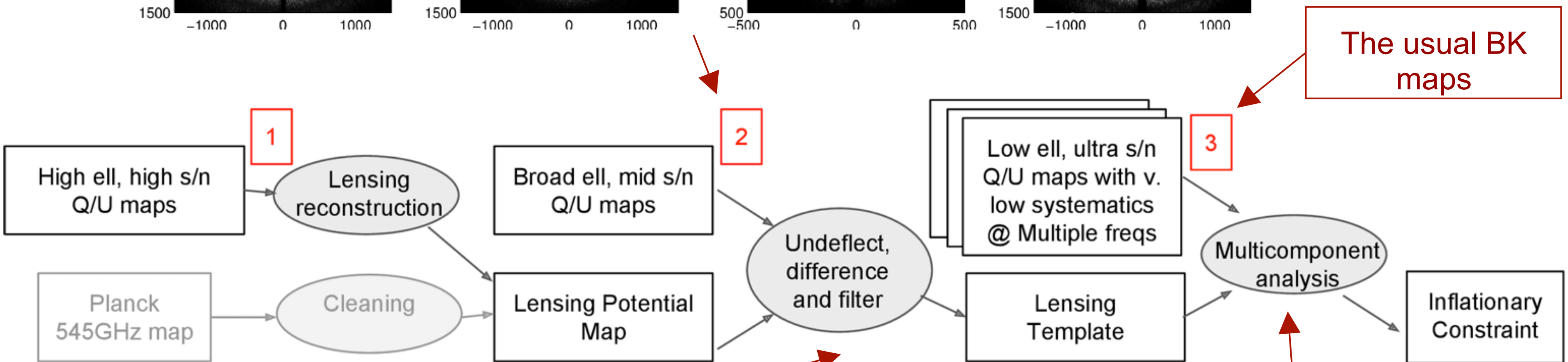
2) Strength of the scale-invariant PMF smoothed over 1Mpc $B_{1Mpc} \leq 30\text{nG}.$

Delensing slides

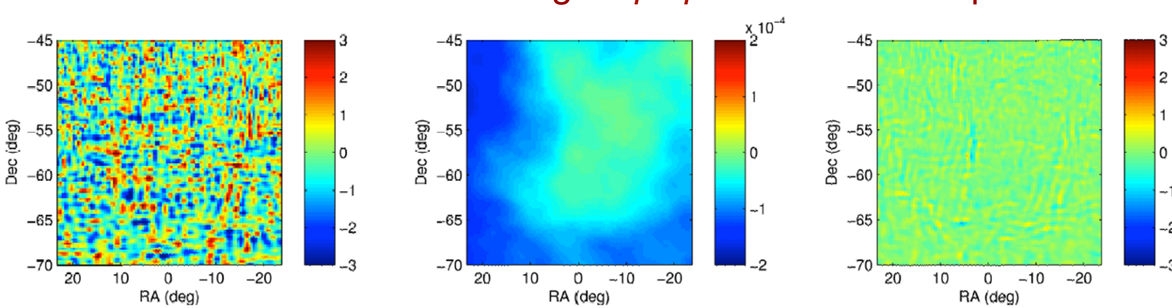
How to make the lensing template:

Combine SPT/Planck/BK Q/U maps



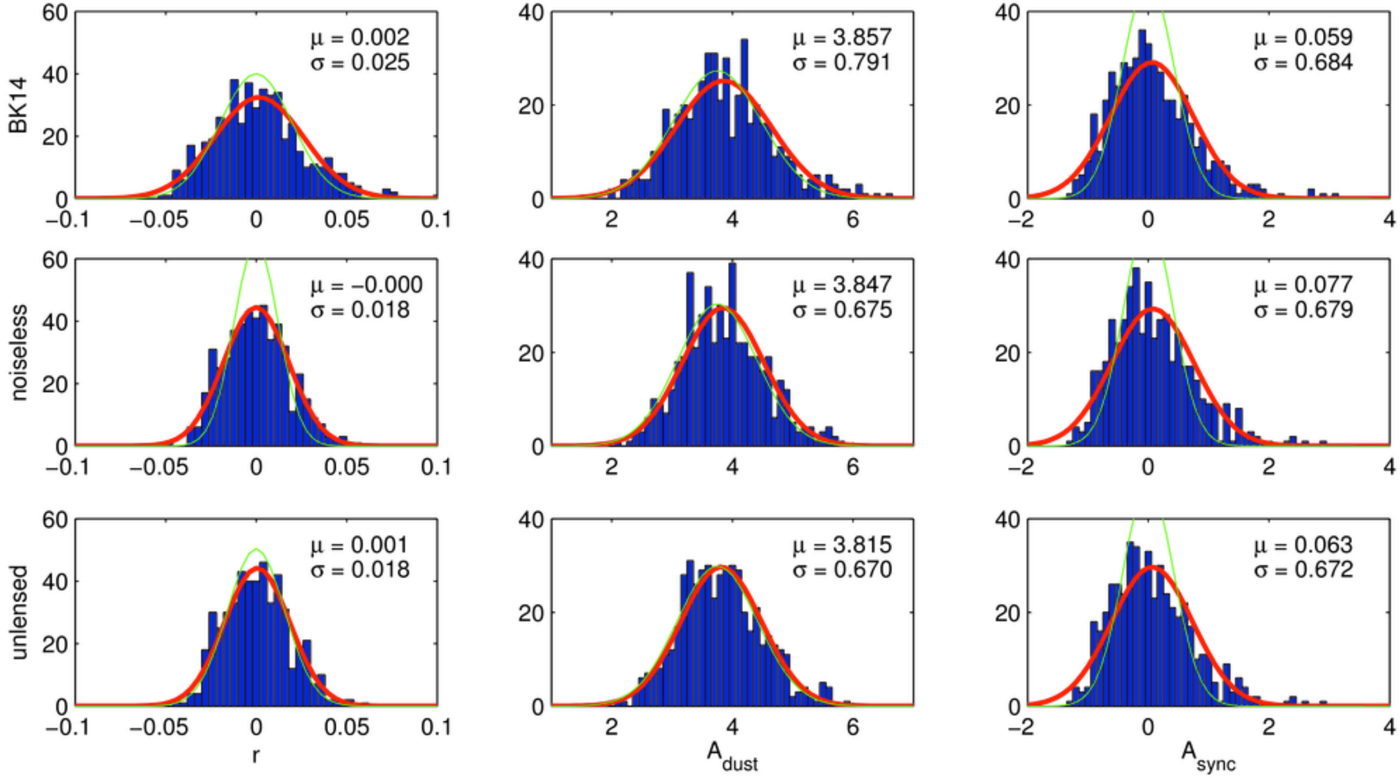


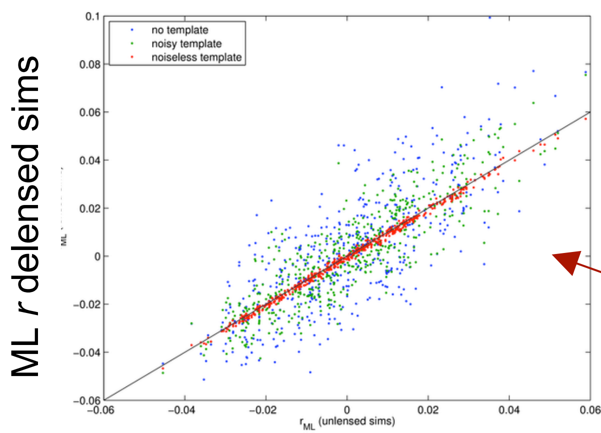
At the moment doing *map space* un-deflect operation



Natural extension: don't "delens" maps and take spectra - instead add a "lensing template" virtual band to the stack of multi-frequency input maps. So long as we can calculate expectation values for the auto and cross spectra it fits right in.

Perfect lensing template in multicomponent analysis matches performance from sims that do not include CMB lensing, σ(r) ~ 0.018 for BK14.





If we have a perfect lensing template then "delensing" works perfectly - the ML *r* values are identical between unlensed and delensed sims on a *realization-by-realization* basis. (red points)

Current delensing efforts

Analysis now includes simulations of more realistic lensing template, using Planck CIB map as Φ tracer and SPT+Planck+BK E modes.

- Similar to Manzotti et al SPT delensing paper, but using Planck CIB instead of Herschel for sky coverage.
- Expect ~10% improvement in σ(r)
- Limited by Φ map, not E modes

Future delensing with BICEP Array + SPT-3G will reconstruct Φ from high resolution CMB maps.

- ○ Need to characterize internal delensing biases
- ○ Expect to achieve > 60% reduction in lensing BB power