Searching for Gravitational Waves from Inflation with BICEP/Keck

Clem Pryke – UC Irvine – May 18 2017

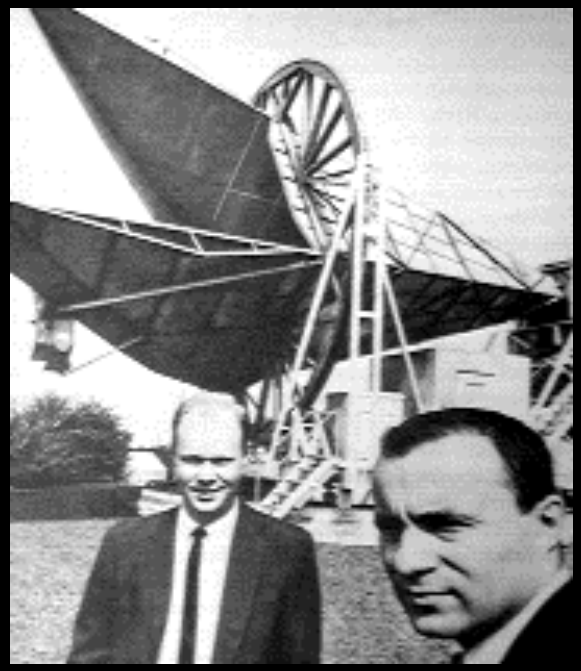
Modern cosmology in a nutshell:

Edwin Hubble

1) The universe is expanding.
(Hubble, 1920s)

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

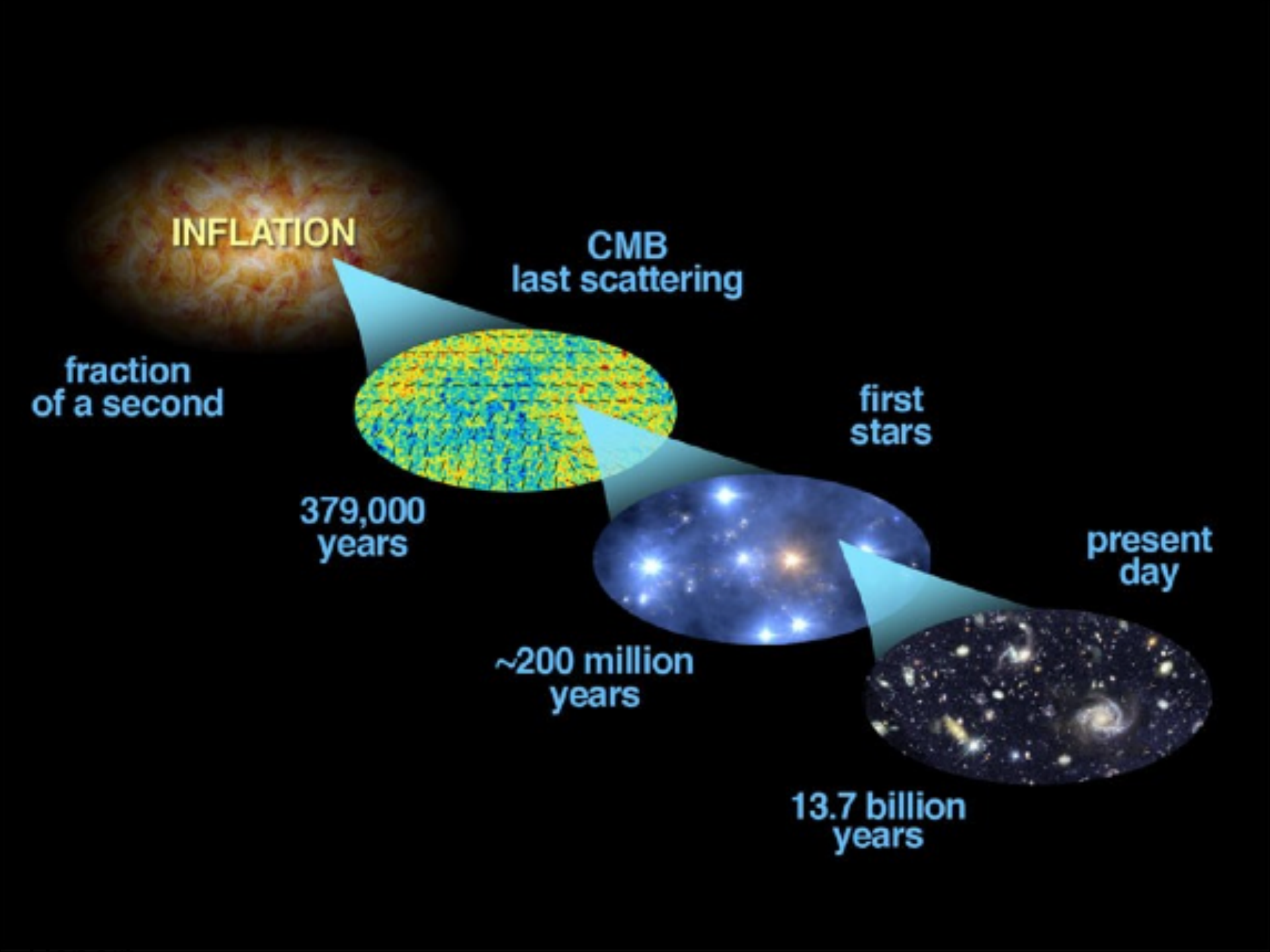
(Alpher, Gamow, Herman, 1940s)



Bob Wilson & Arno Penzias
1978 Nobel Prize

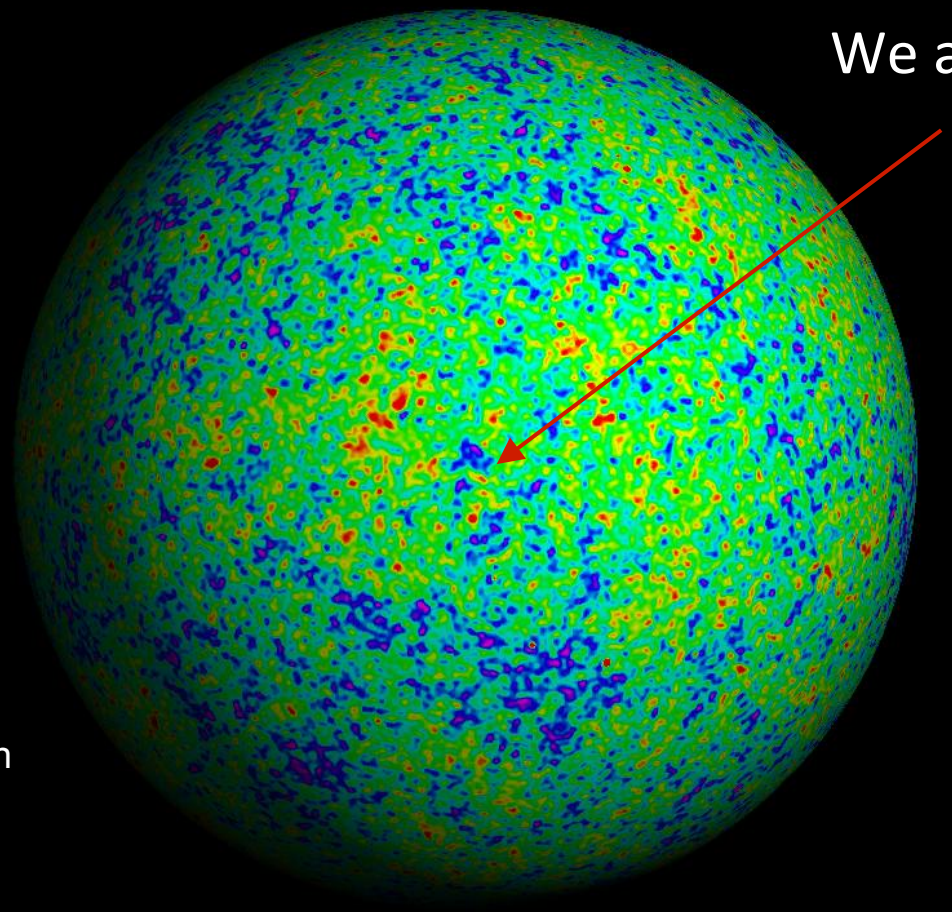
3) You can still see the glow!
The *Cosmic Microwave Background*
(Penzias & Wilson, 1964)

⇒ acceptance of the "HOT BIG BANG"


INFLATION
fraction
of a second
CMB
last scattering
379,000
years
first
stars
~200 million
years
present
day
13.7 billion
years

CMB Surface of Last Scattering

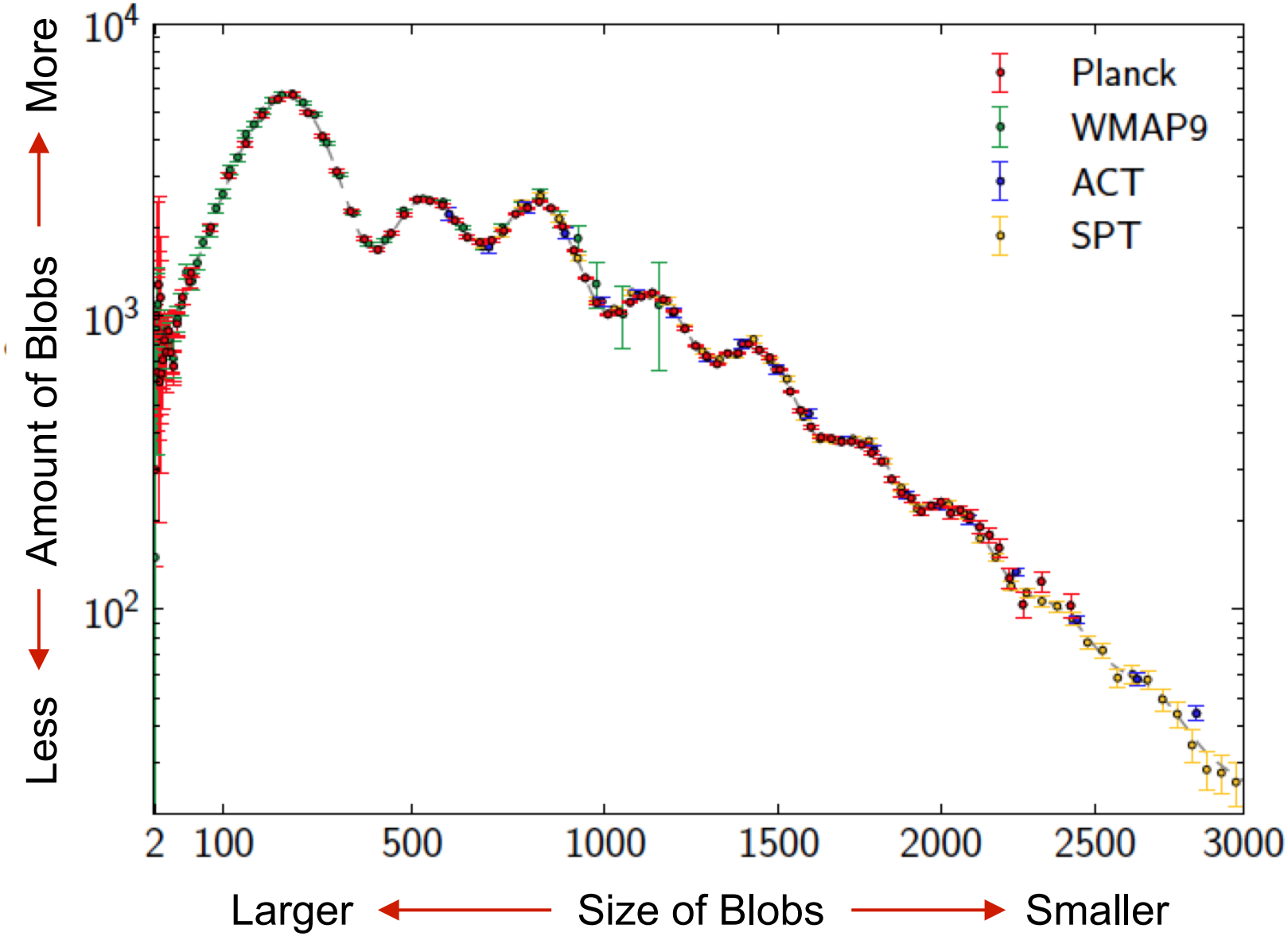
We are at the center



All sky map projected on
a sphere

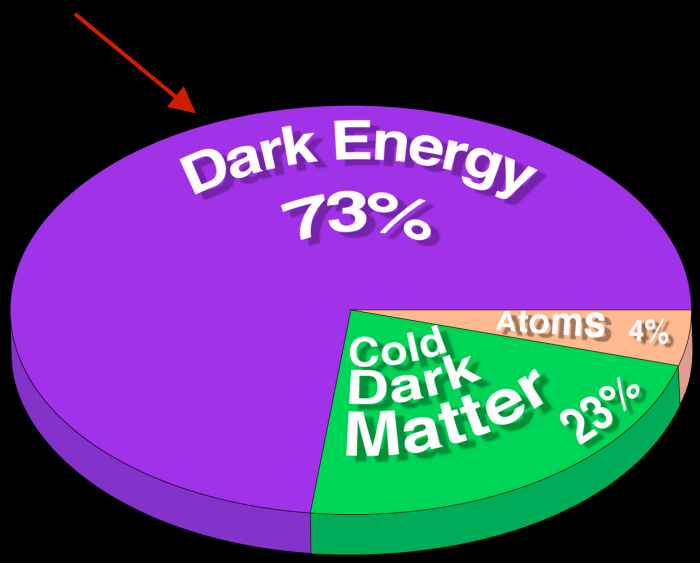
CMB is a sample of the density structure on a shell cut through the 380,000 year old Universe

Power Spectrum (Blob size histogram)

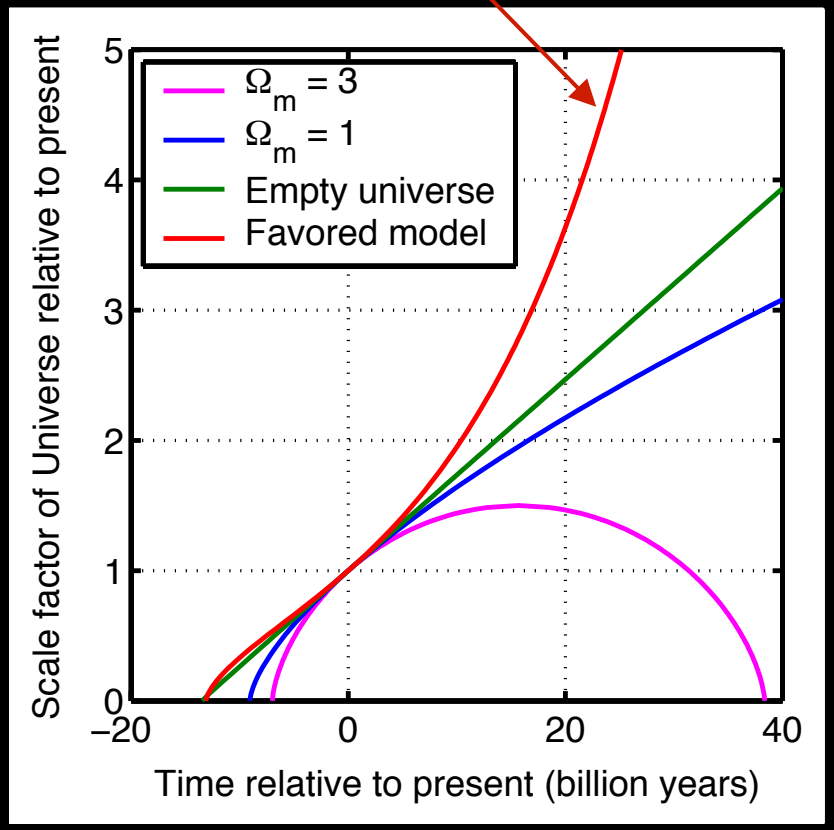


Triumphant/Embarrassing Contemporary Cosmology

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

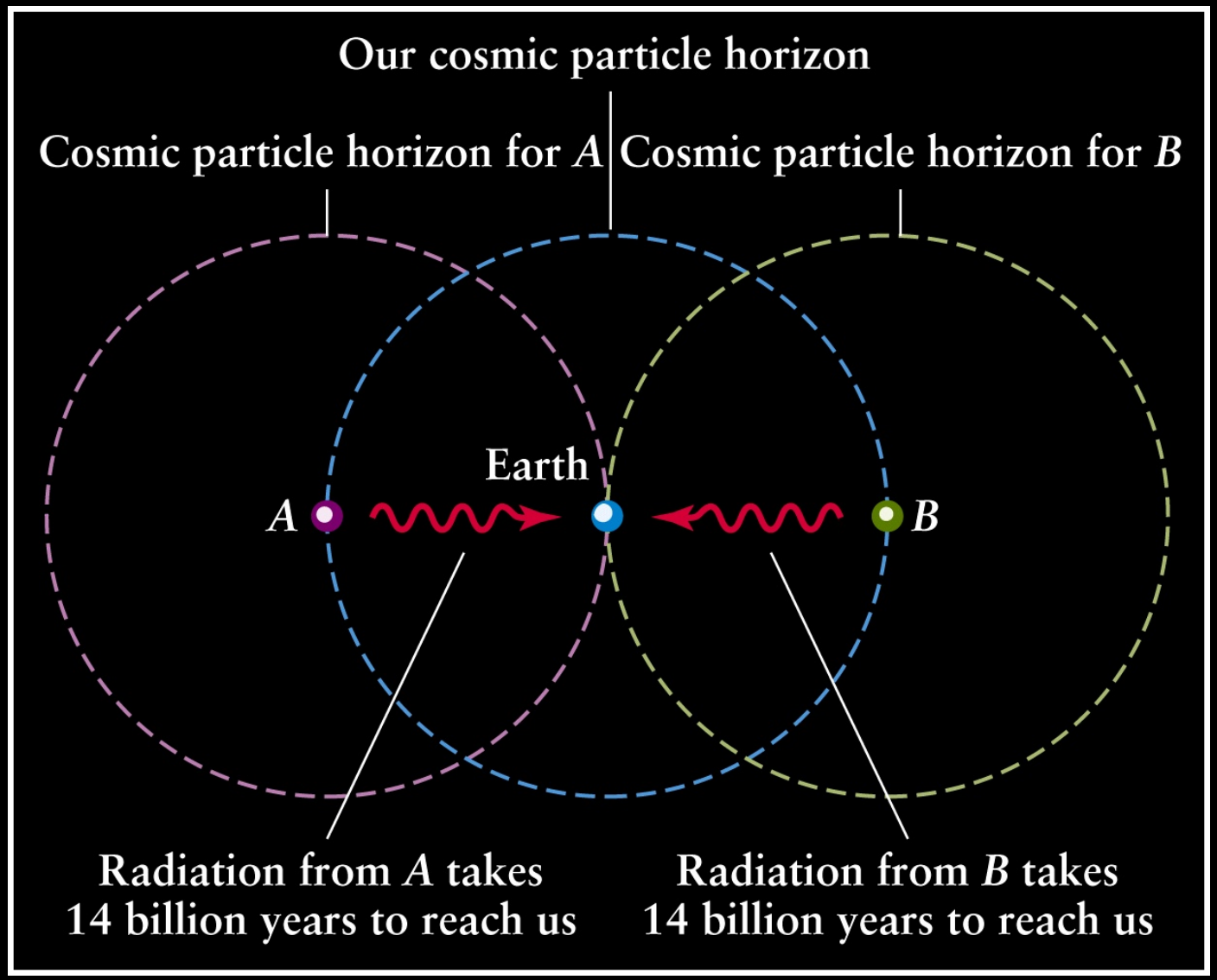


And it implies that the future is runaway expansion…



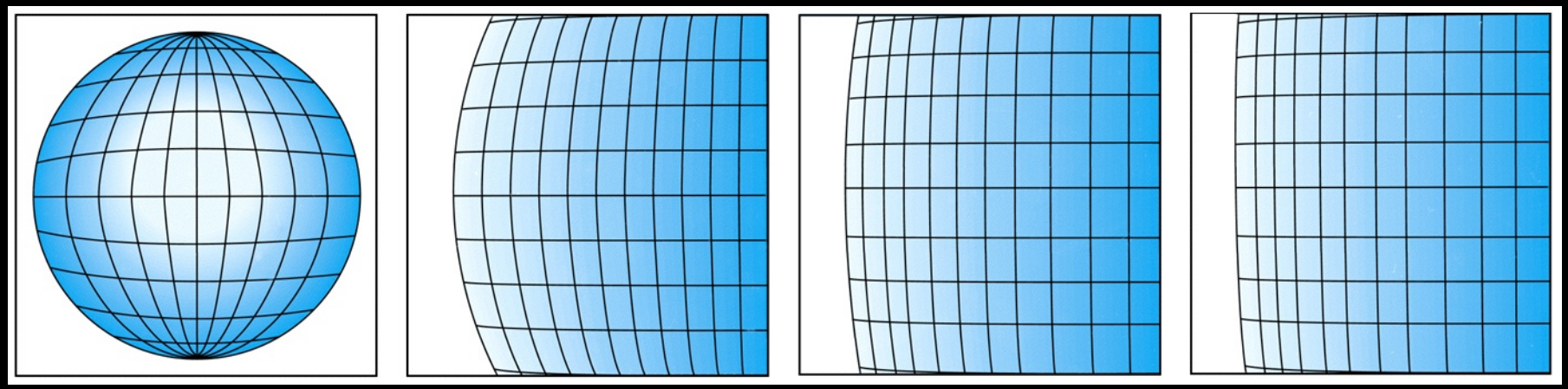
Also it doesn't explain horizon/flatness etc…

The Horizon Problem



How did points A and B “know” to be at the same temperature at 380,000 years?

Inflation solves the Flatness Problem



Inflation…

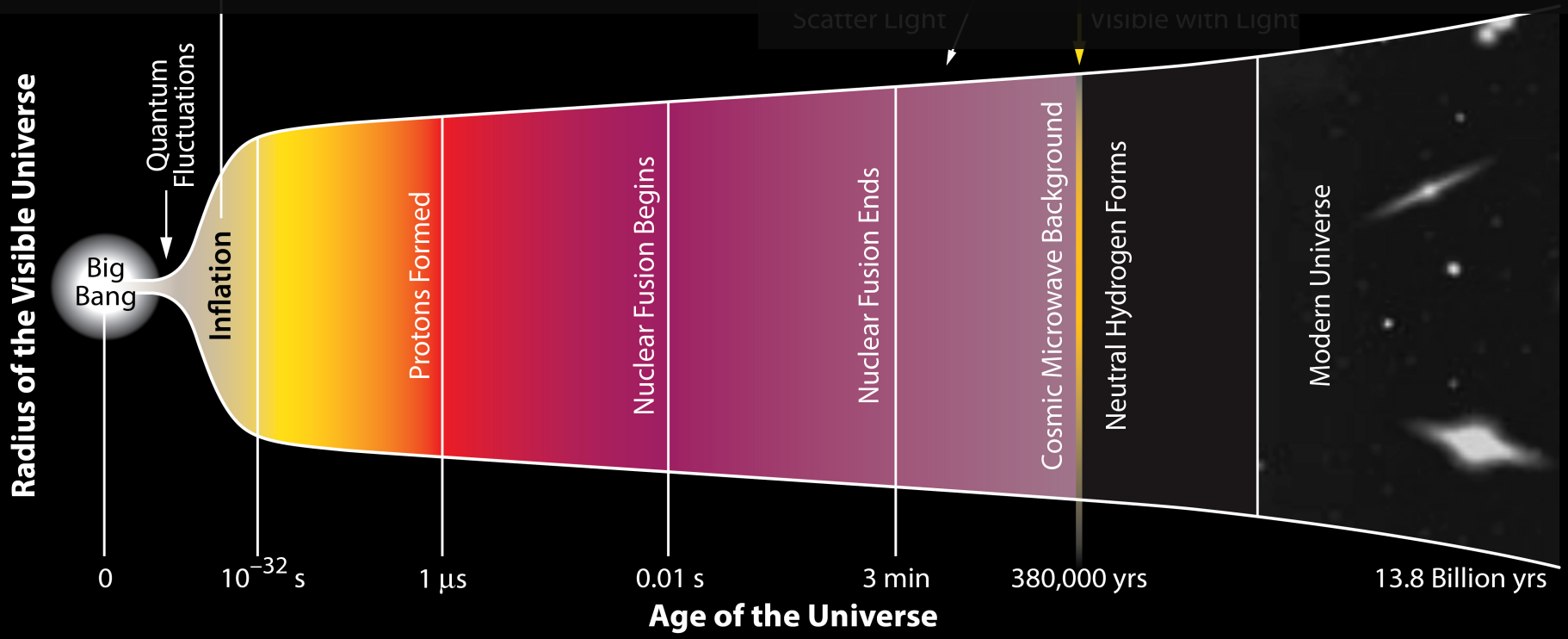
If you take some curved space and blow it up enough pretty soon it is no longer curved on a local scale – like our entire observable Universe!

History of the Universe

Inflation posits a pre-phase of exponential expansion

Alan Guth

Andrei Linde



Why Inflation?

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 spec.

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

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

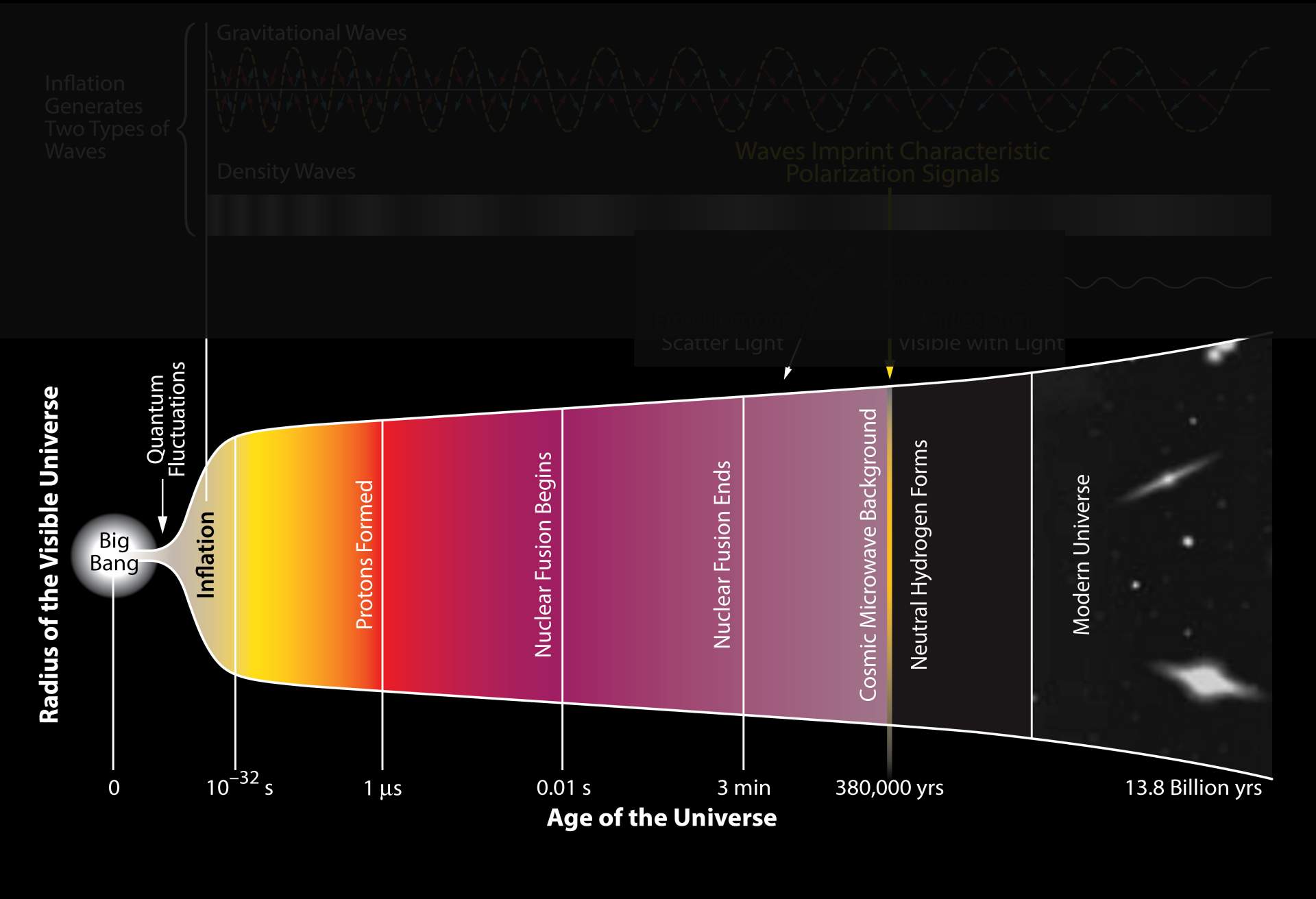
Explains the initial perturbation spectrum: Why was it close to flat power law?

→ Equal amount of perturbations are injected at each step in the exponential expansion.

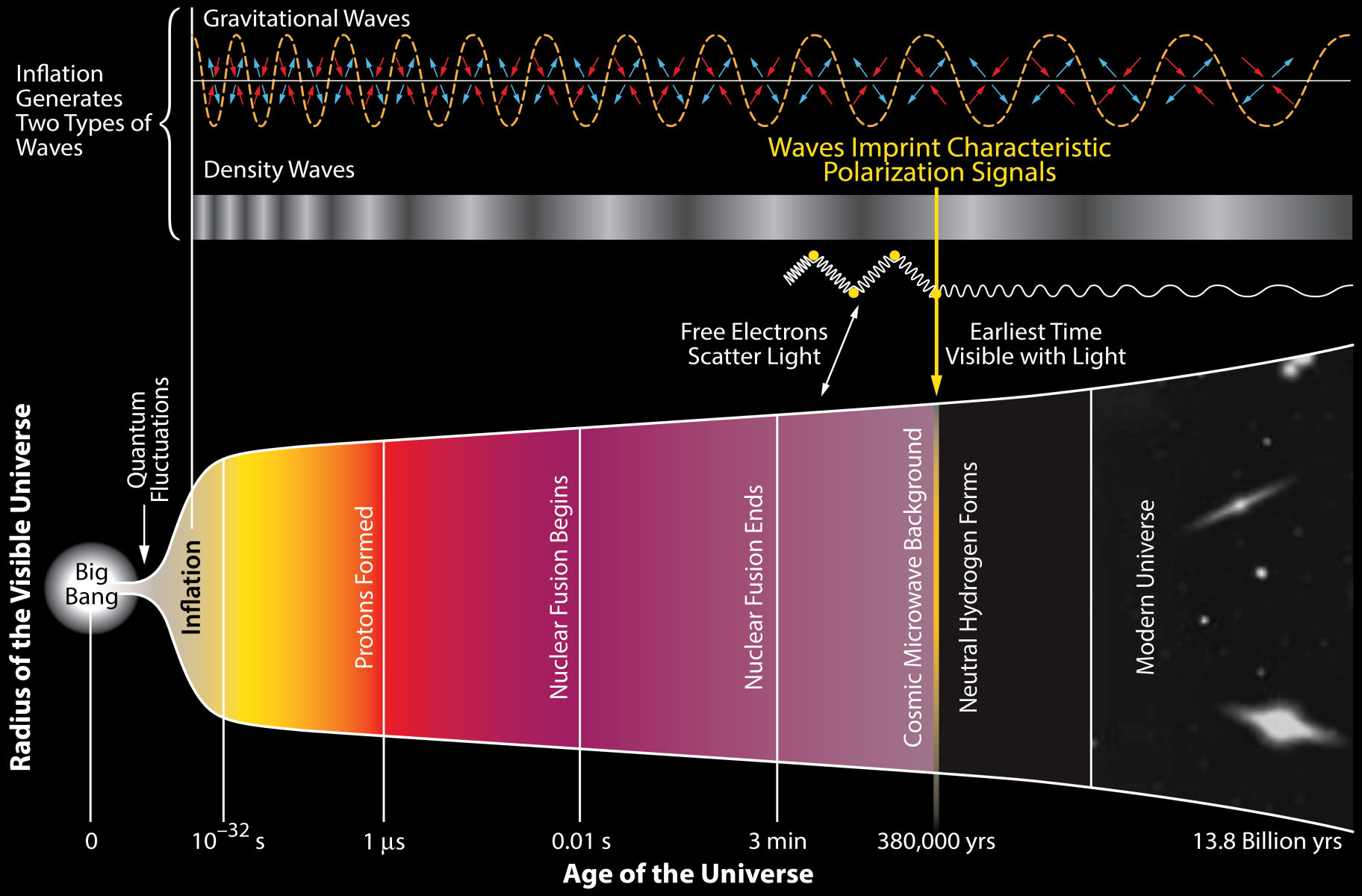
Solves the monopole problem:
Why do we not observe magnetic monopoles in the Universe today?

→ Monopoles are diluted away to undetectability.

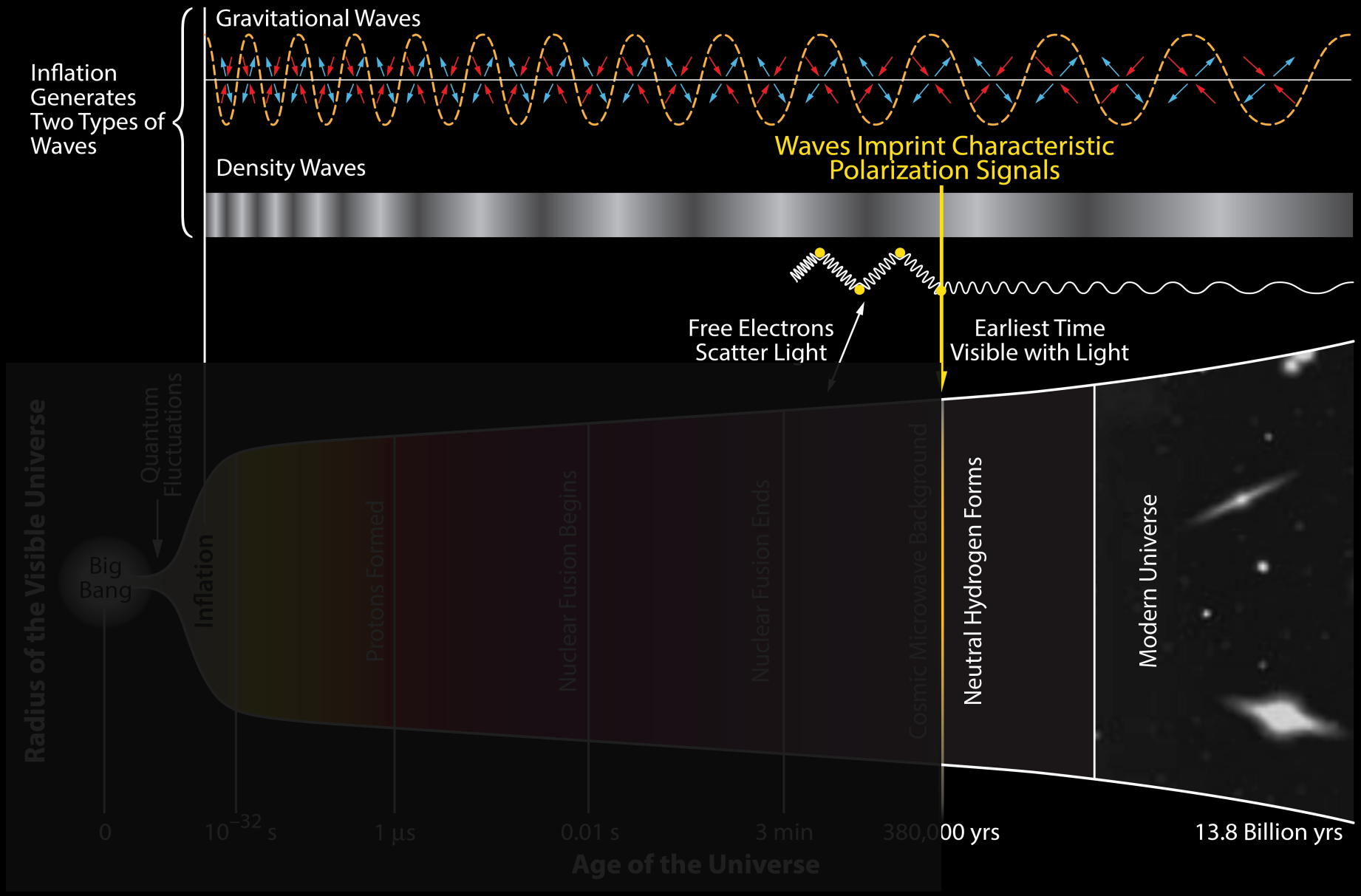
History of the Universe



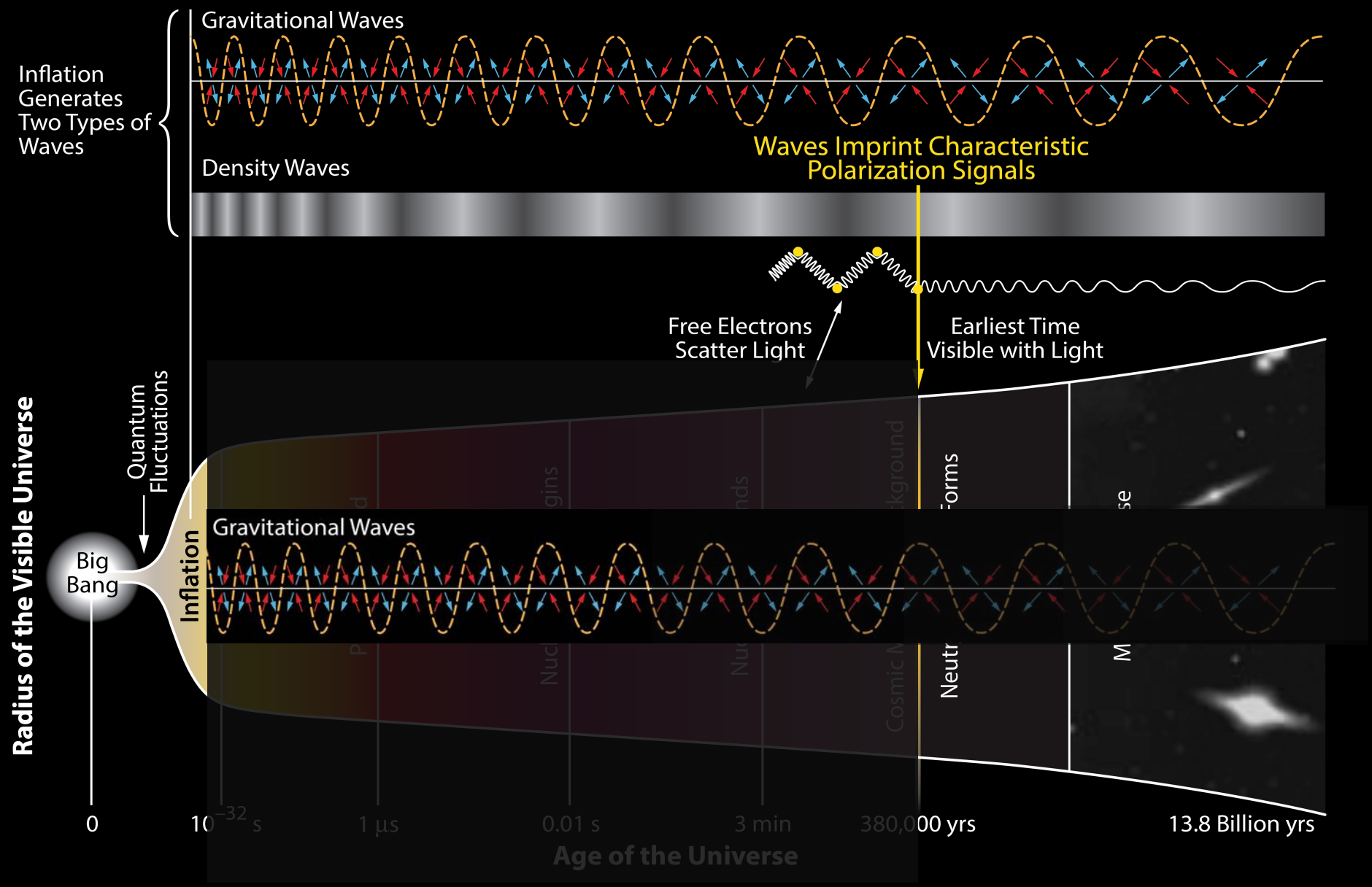
History of the Universe



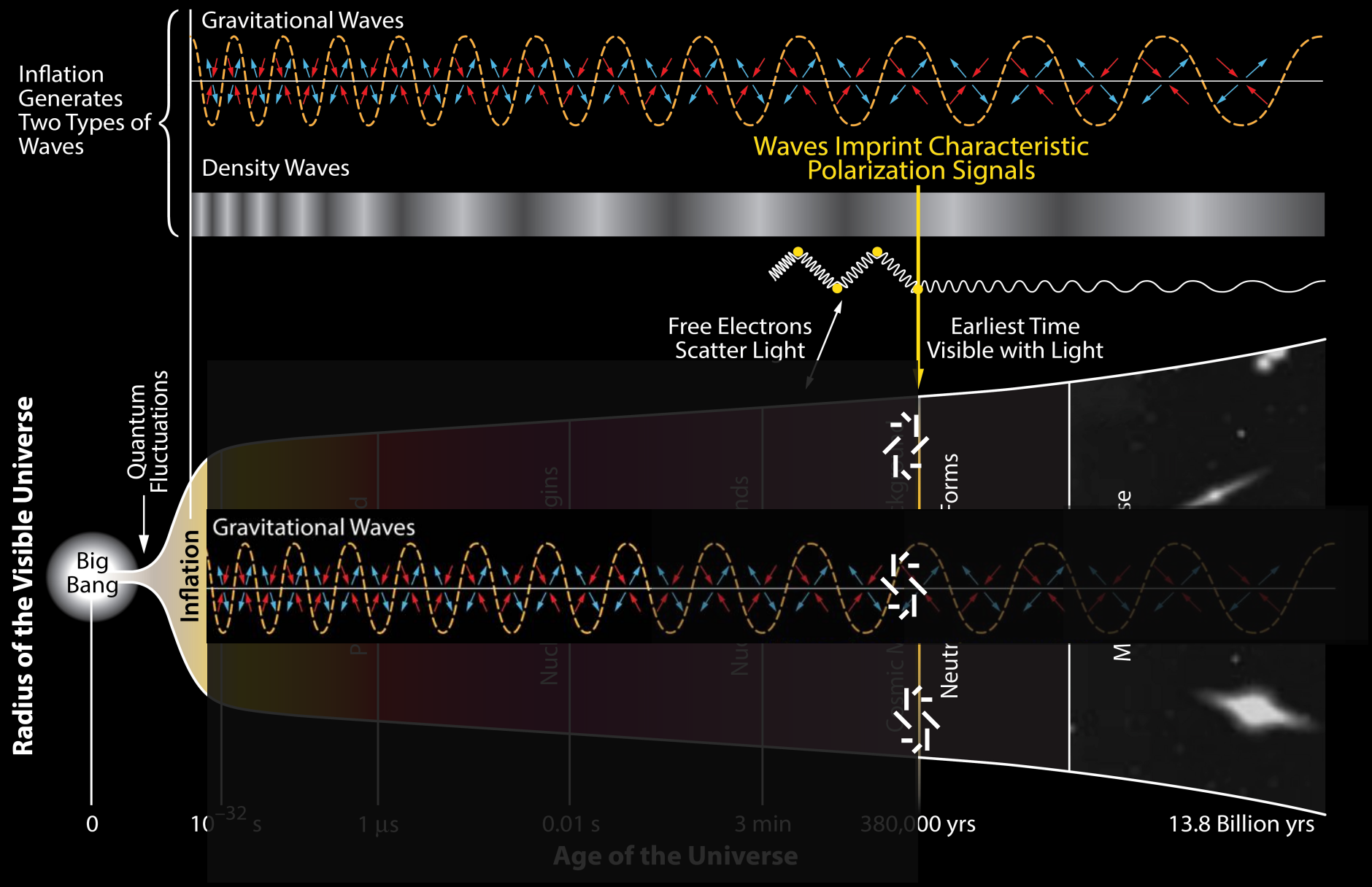
History of the Universe



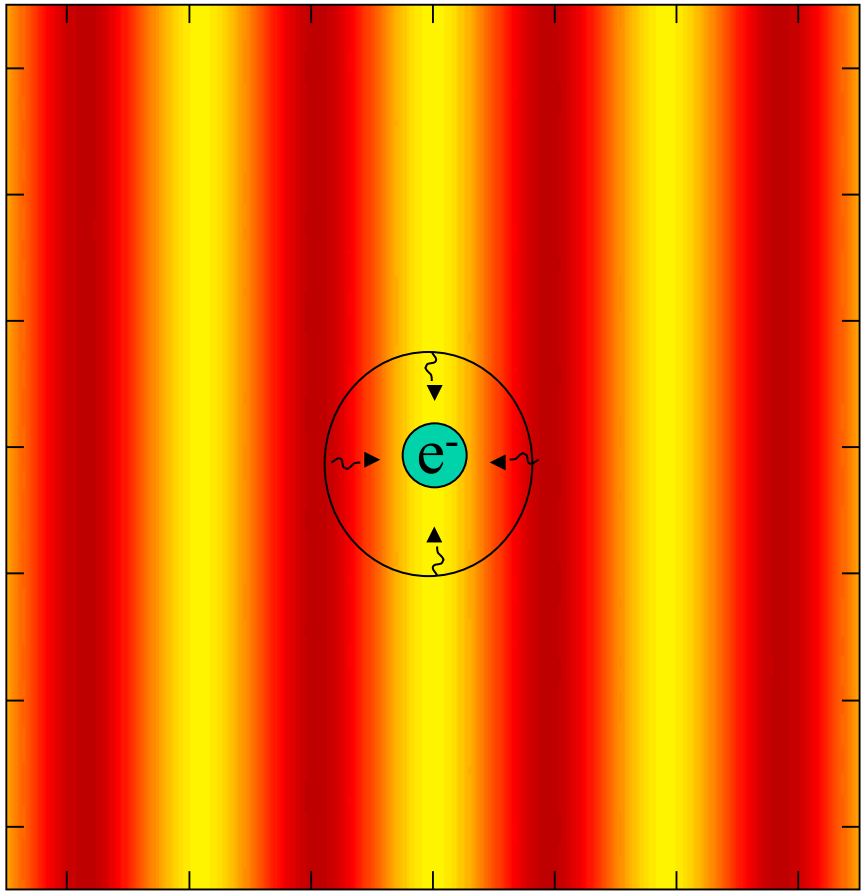
History of the Universe



History of the Universe

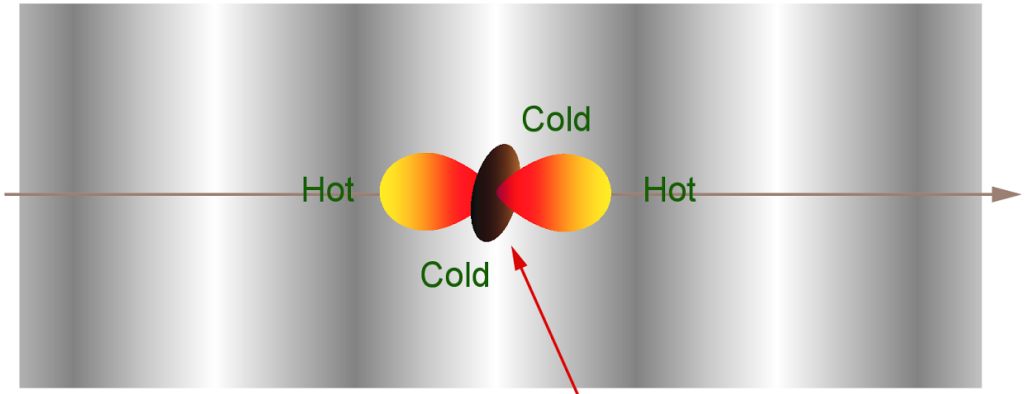


CMB polarization: arises at last scattering from local radiation quadrupole

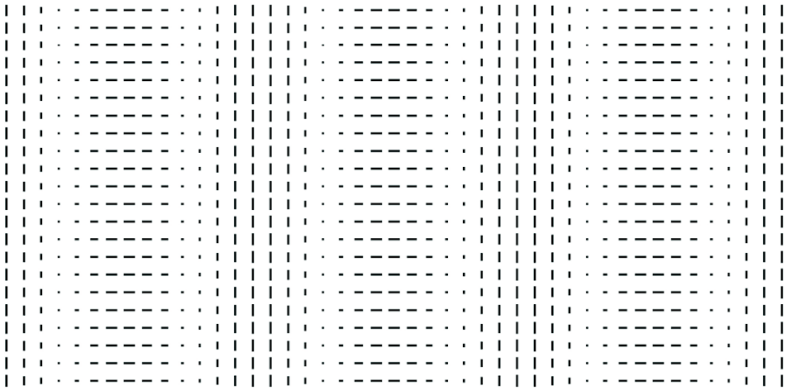


CMB polarization

Density Wave

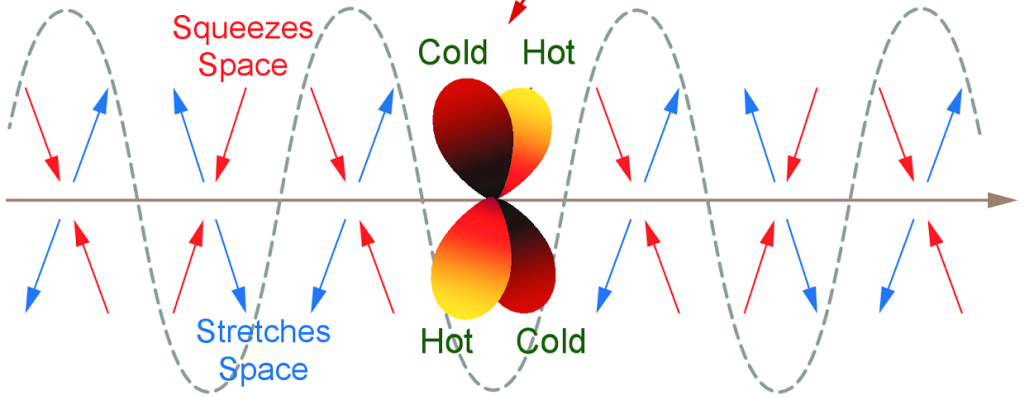


E-Mode Polarization Pattern

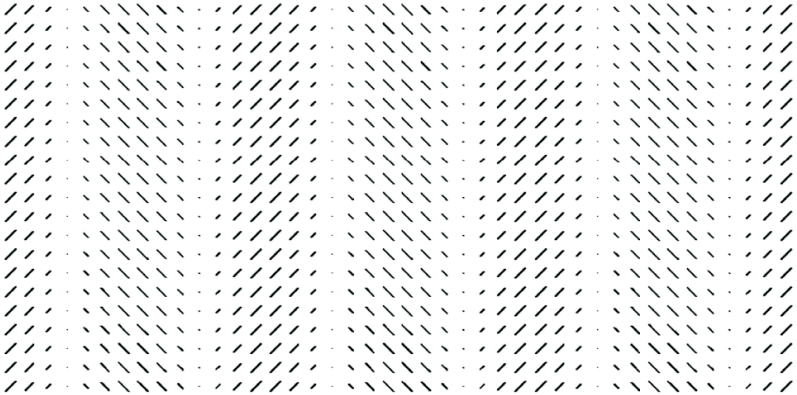


Temperature Pattern Seen by Electrons

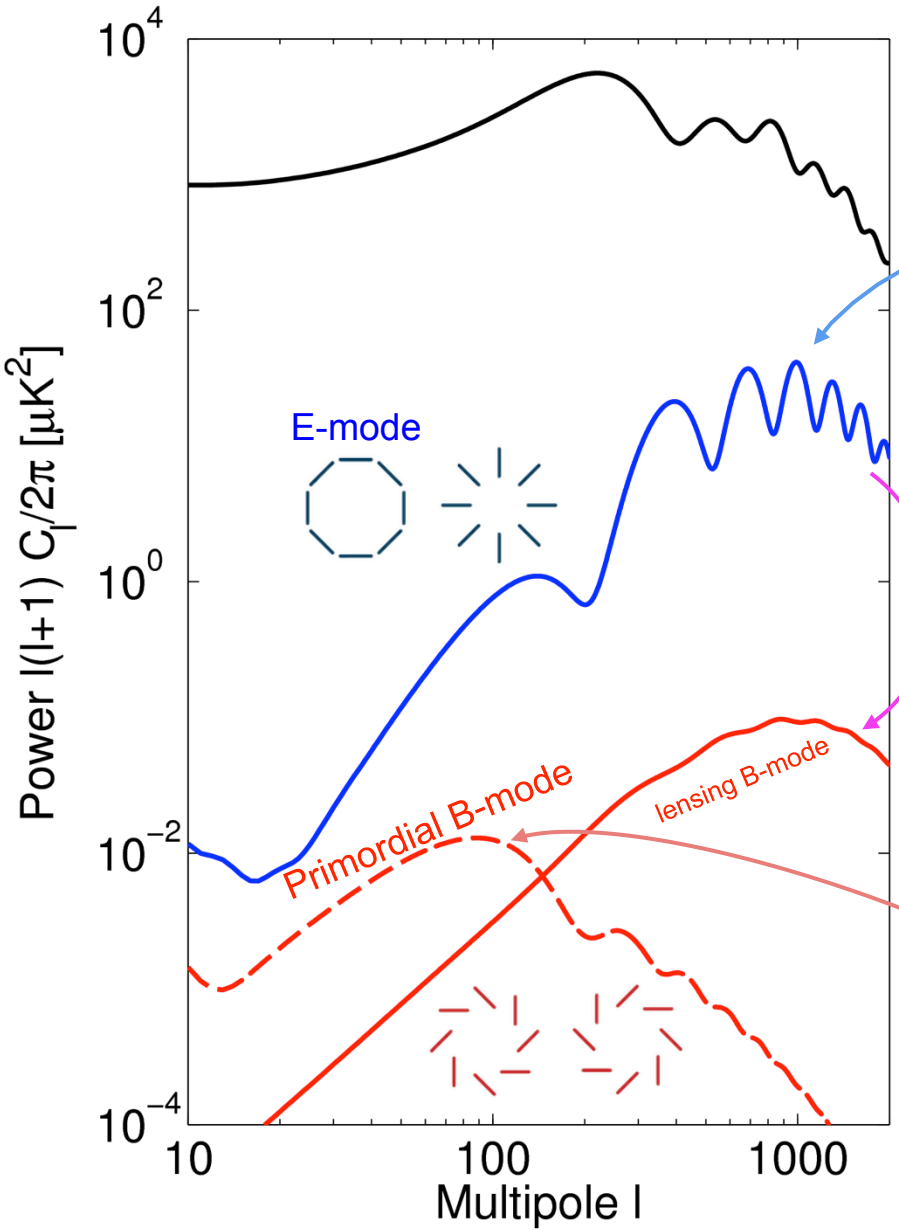
Gravitational Wave



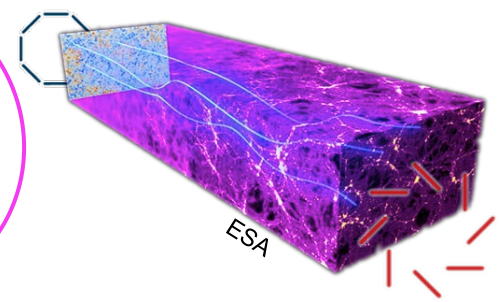
B-Mode Polarization Pattern



CMB Polarization power spectra



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

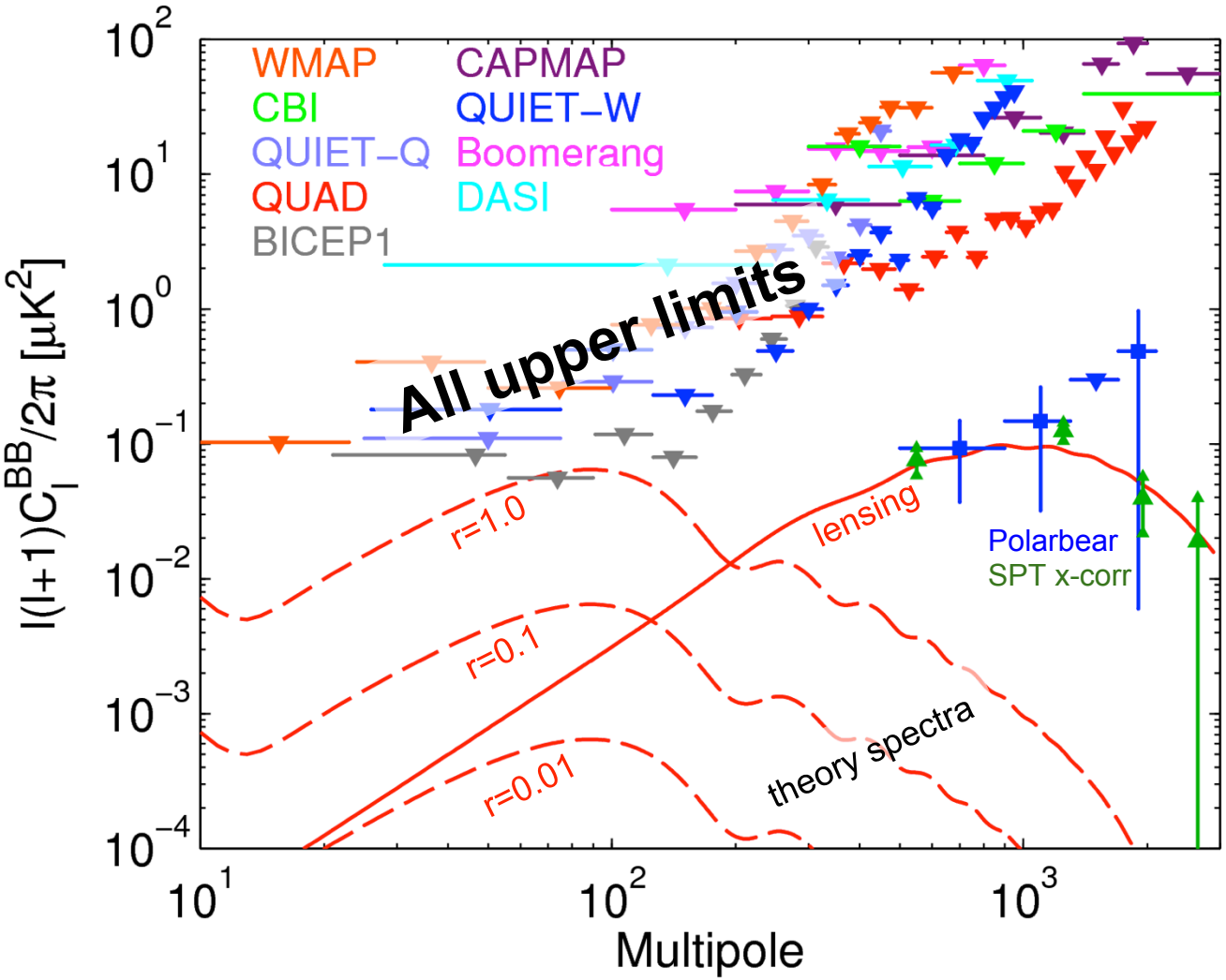


During propagation some of the E-modes are confused into B-modes by lensing

Inflationary gravitational waves are unique source of intrinsic B-modes
→ peaking at l≈100 : degree scales

The BICEP/Keck Collaboration

The State of B-mode Measurements in early 2014



In simple inflationary gravitational wave models the

tensor-to-scalar ratio r

is the only parameter to the B-mode spectrum.

Before BICEP2: only upper limits from searches for Inflationary B-modes

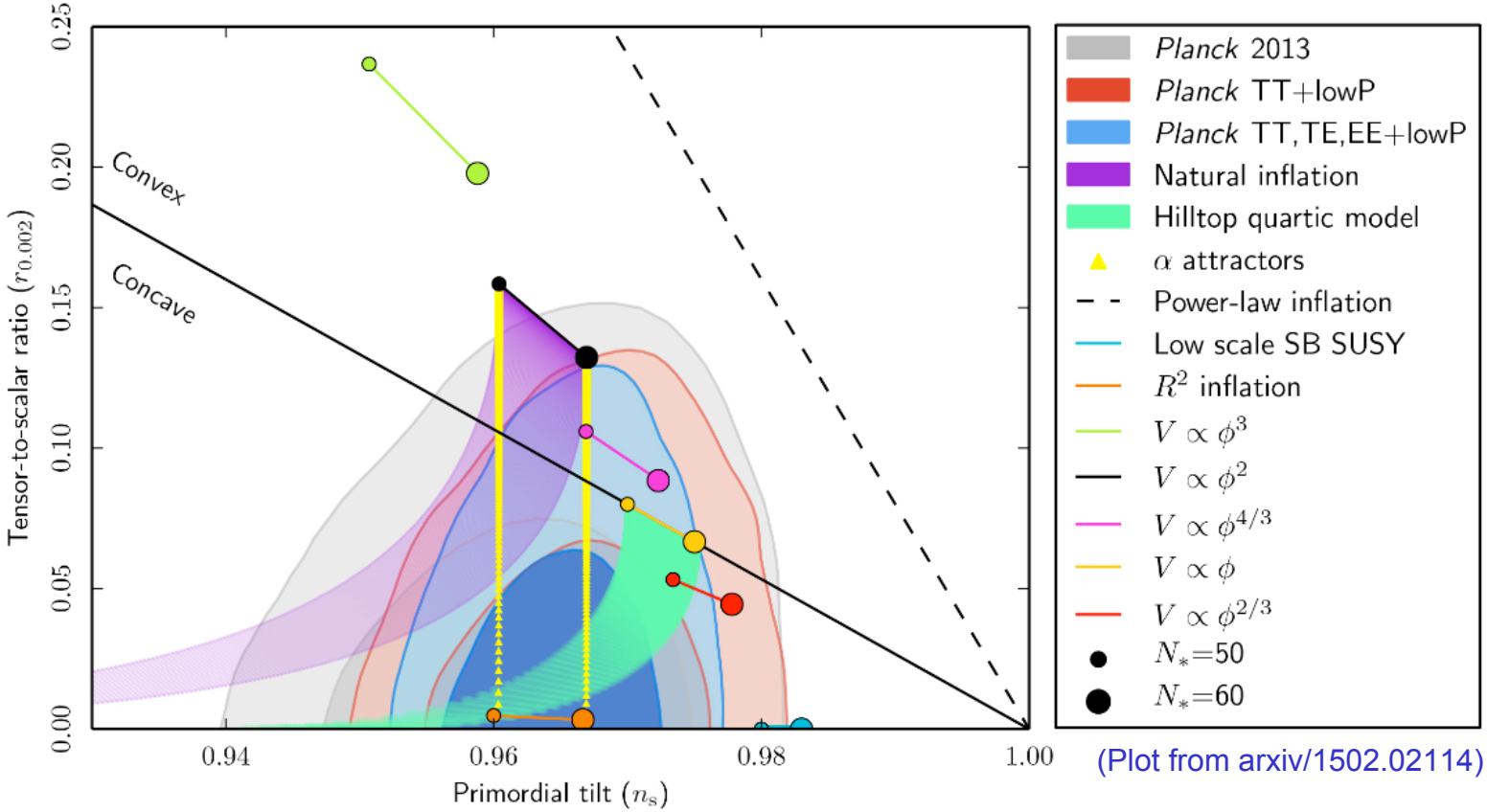
BICEP1 limits translated to:

r < 0.7 (95% CL)

SPT x-corr: lower limits on lensing B-mode from cross correlation using the CIB

Clem Pryke for The Bicep2 Collaboration

Planck Inflationary model constraints



(Plot from arxiv/1502.02114)

- Limits on inflationary model parameters can be set using non B-mode data – Planck has maxed these out at *r*<0.12 (95%) – the only way forward is B-mode polarization measurements
- Inflation is more of an idea than a "theory" – there is a huge array of specific models. Some of these produce *r* values which are very small and perhaps undetectable…

Inflation is controversial

Inflationary Paradigm after Planck 2013

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Massachusetts Institute of Technology, Cambridge, MA 02139, U
[2] *Berkeley Center for Theoretical Physics, Department of Physic*
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]

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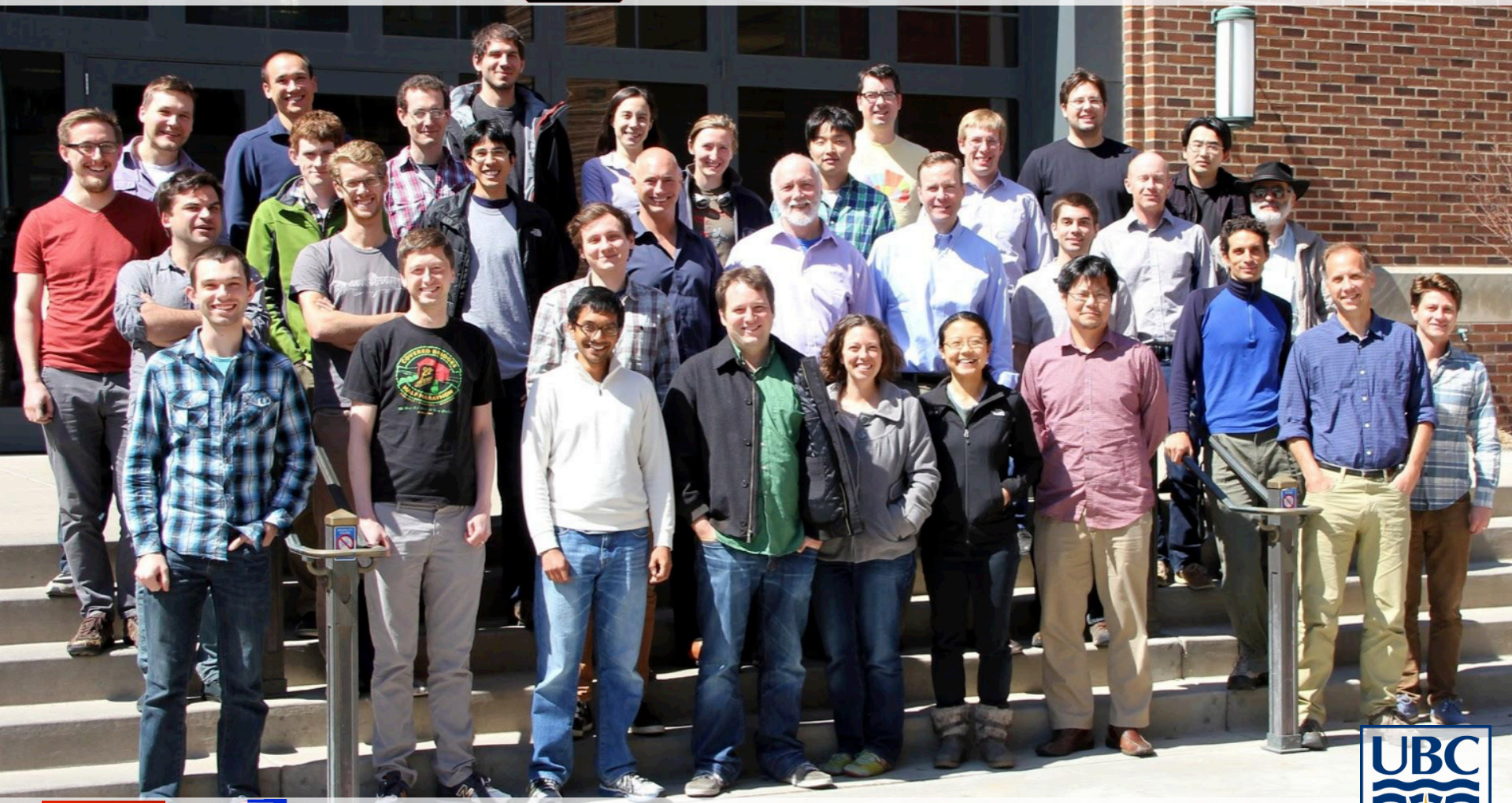
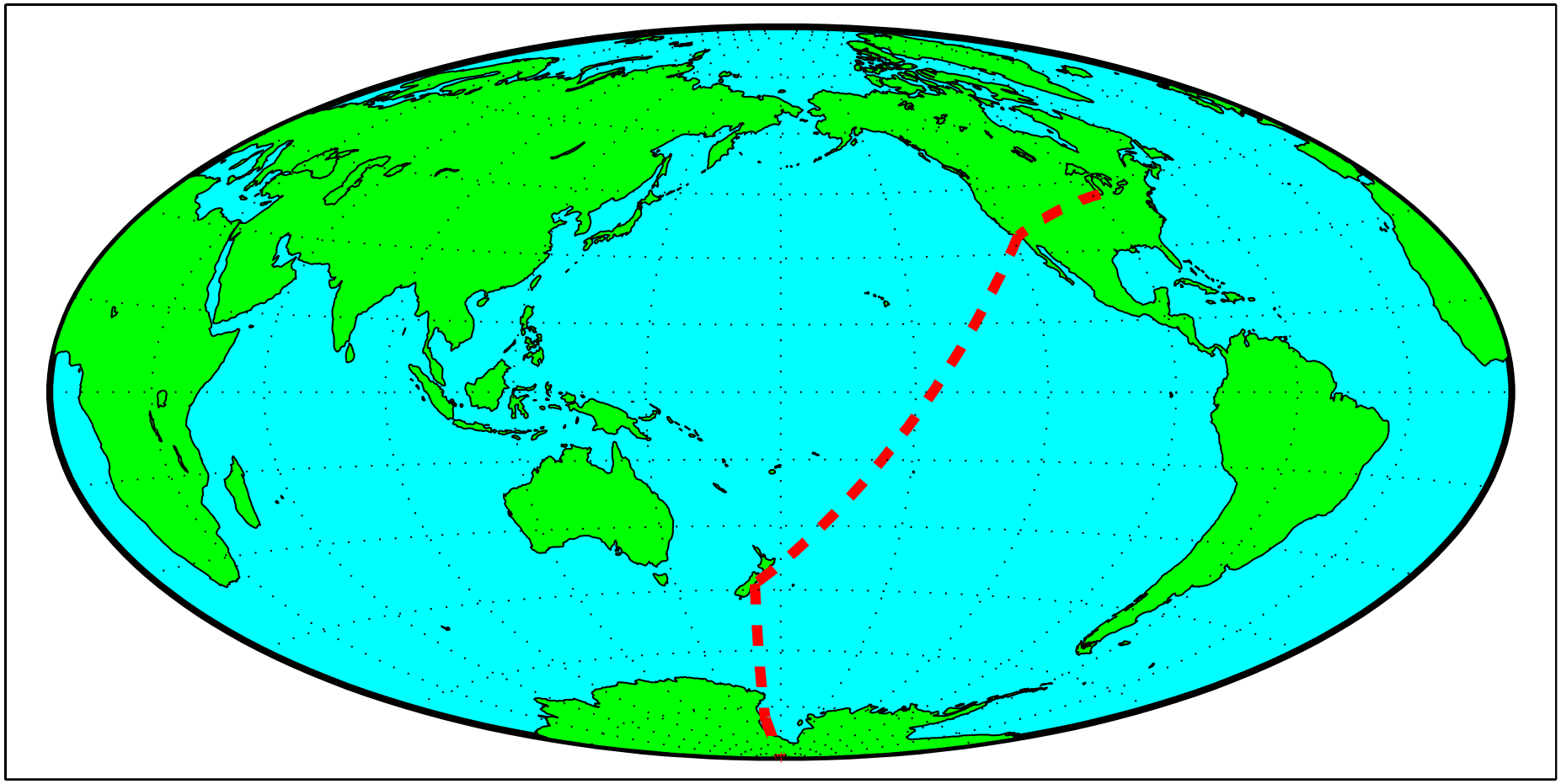
Princeton University, Princeton, NJ 08544, USA
[4] *Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138,*

(Dated: March 14, 2014)

arxiv/1402.6980

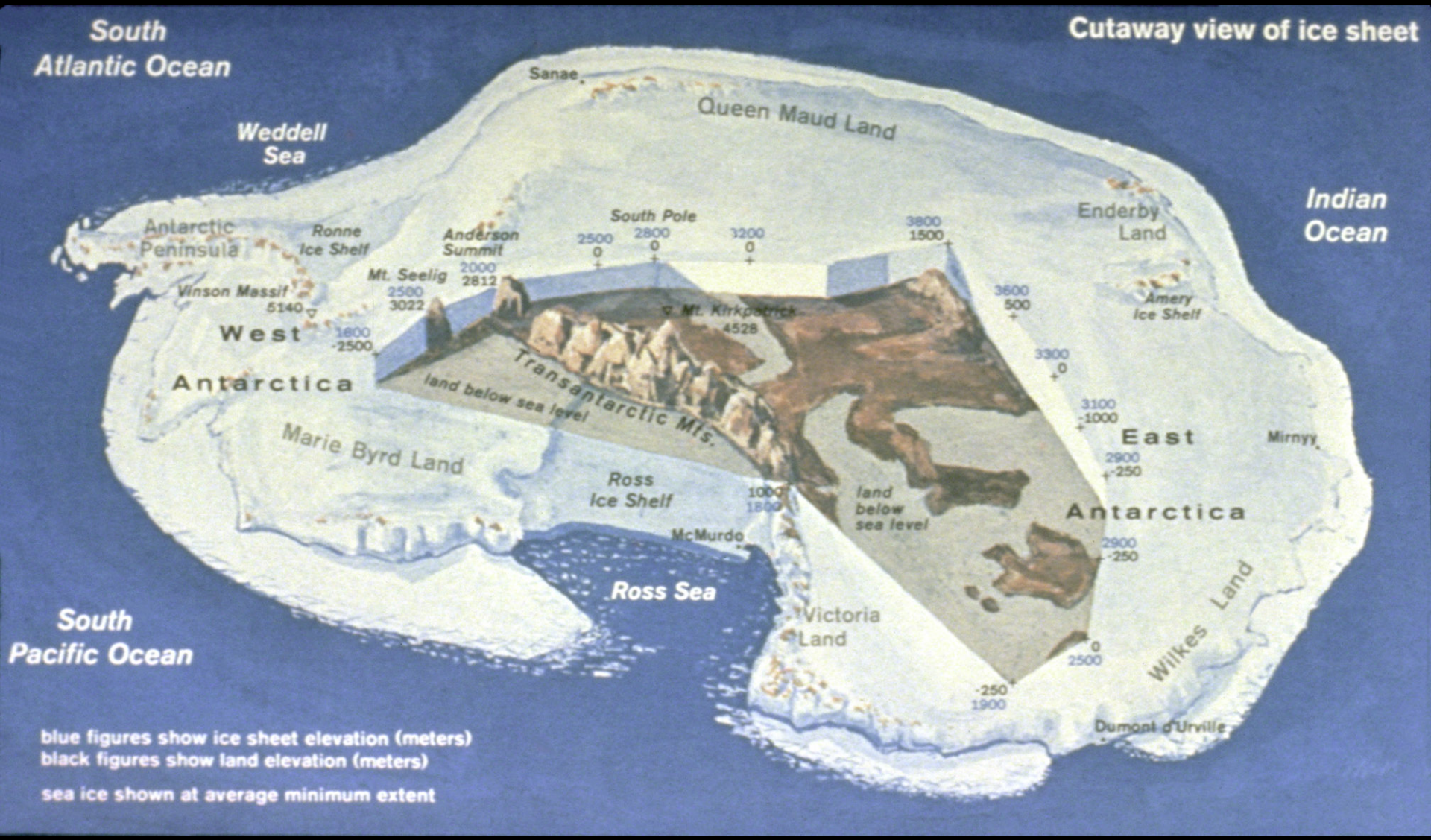

VE RI TAS
HARVARD
CALIFORNIA INSTITUTE OF TECHNOLOGY
1891
cea
UCSD
JPL
NIST
CARDIFF UNIVERSITY
UNIVERSITY OF TORONTO
UBC

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

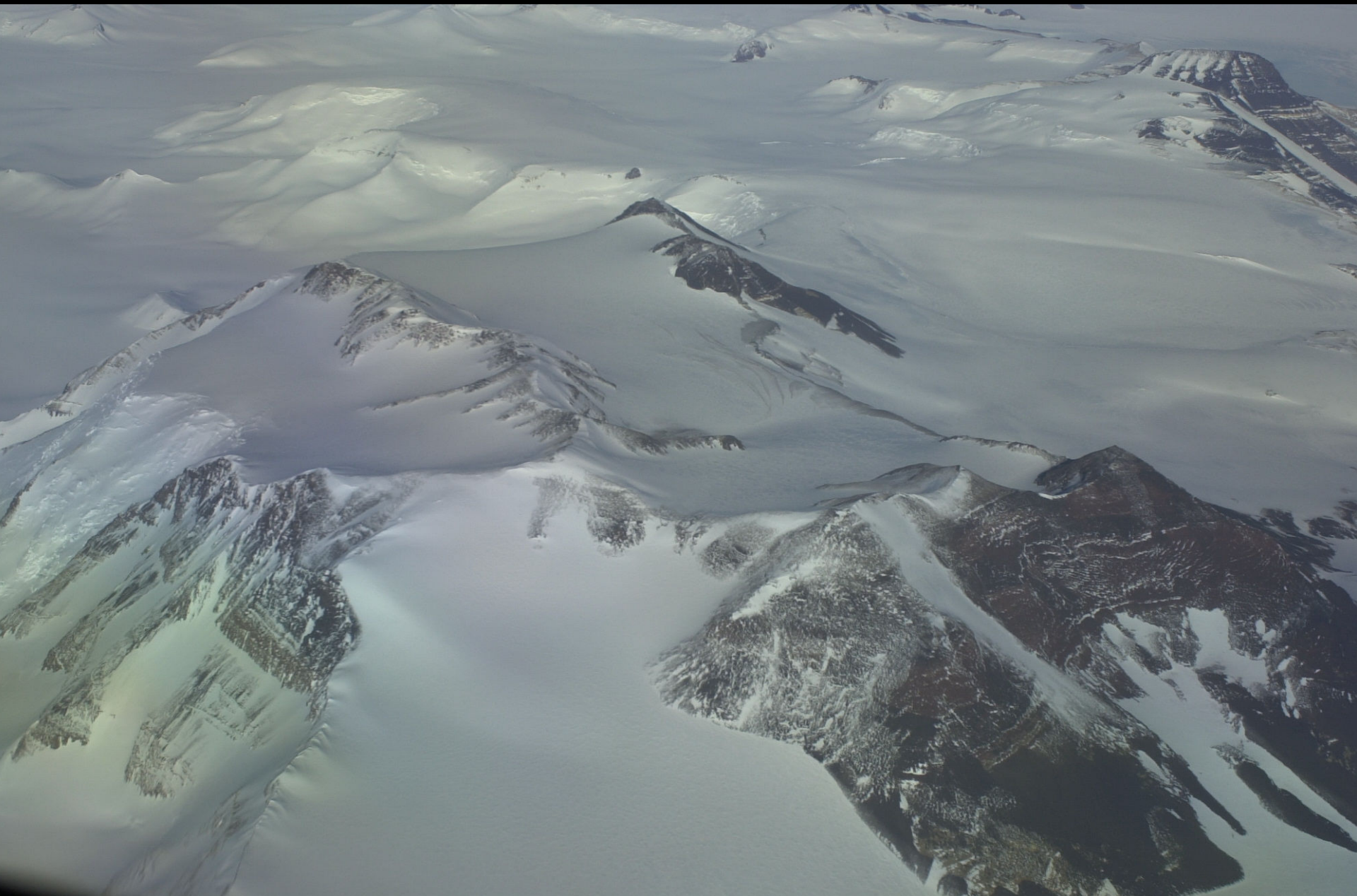
Christchurch New Zealand – Clothing Warehouse

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?

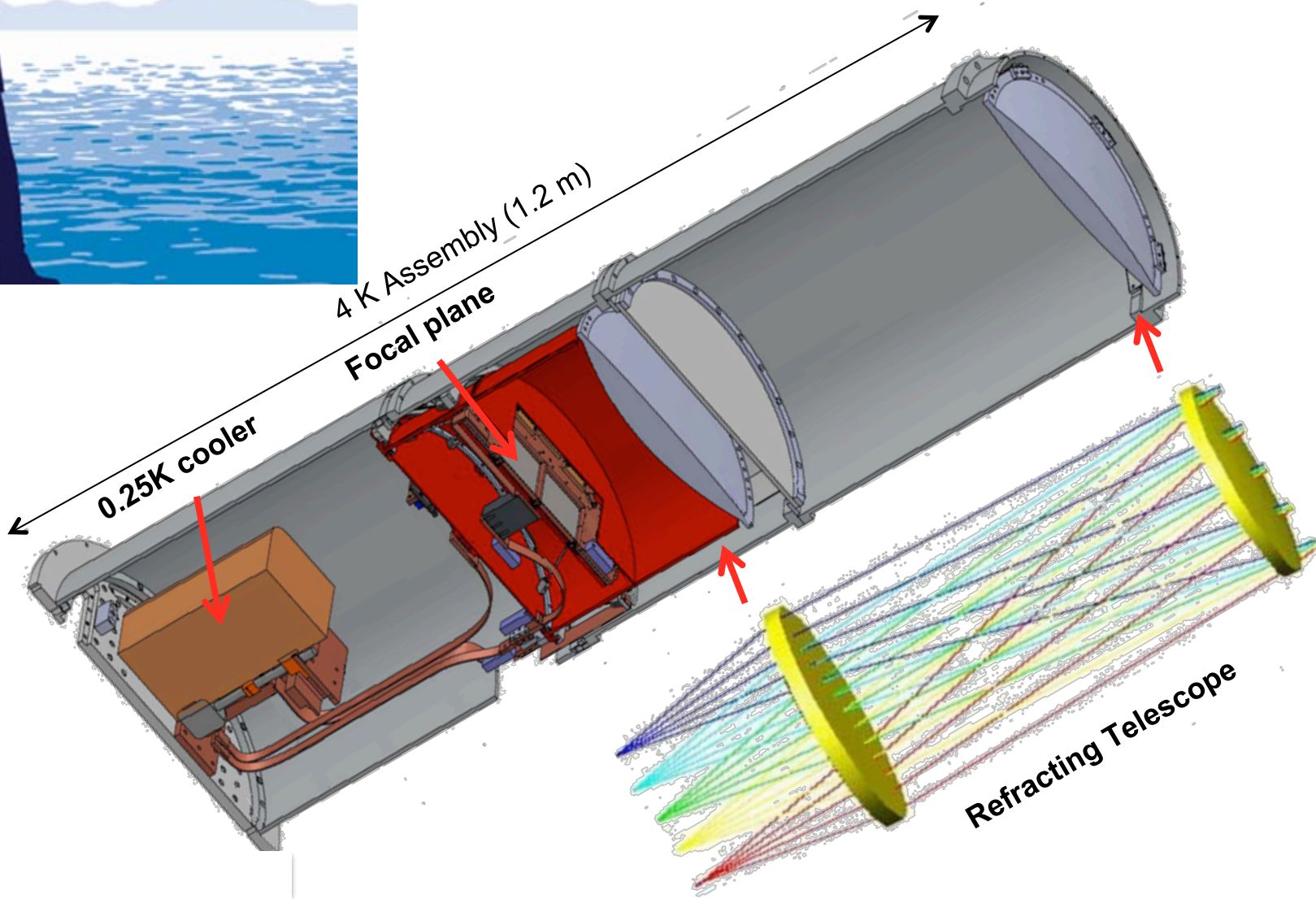
- High and *dry* – see out into space
- On Earth's rotational axis - One day/night cycle per year
  - Long night makes for great quality data
- Good support infrastructure – power, cargo, data comm
- Food and accommodation provided
- Even Tuesday night bingo…

Experimental Strategy

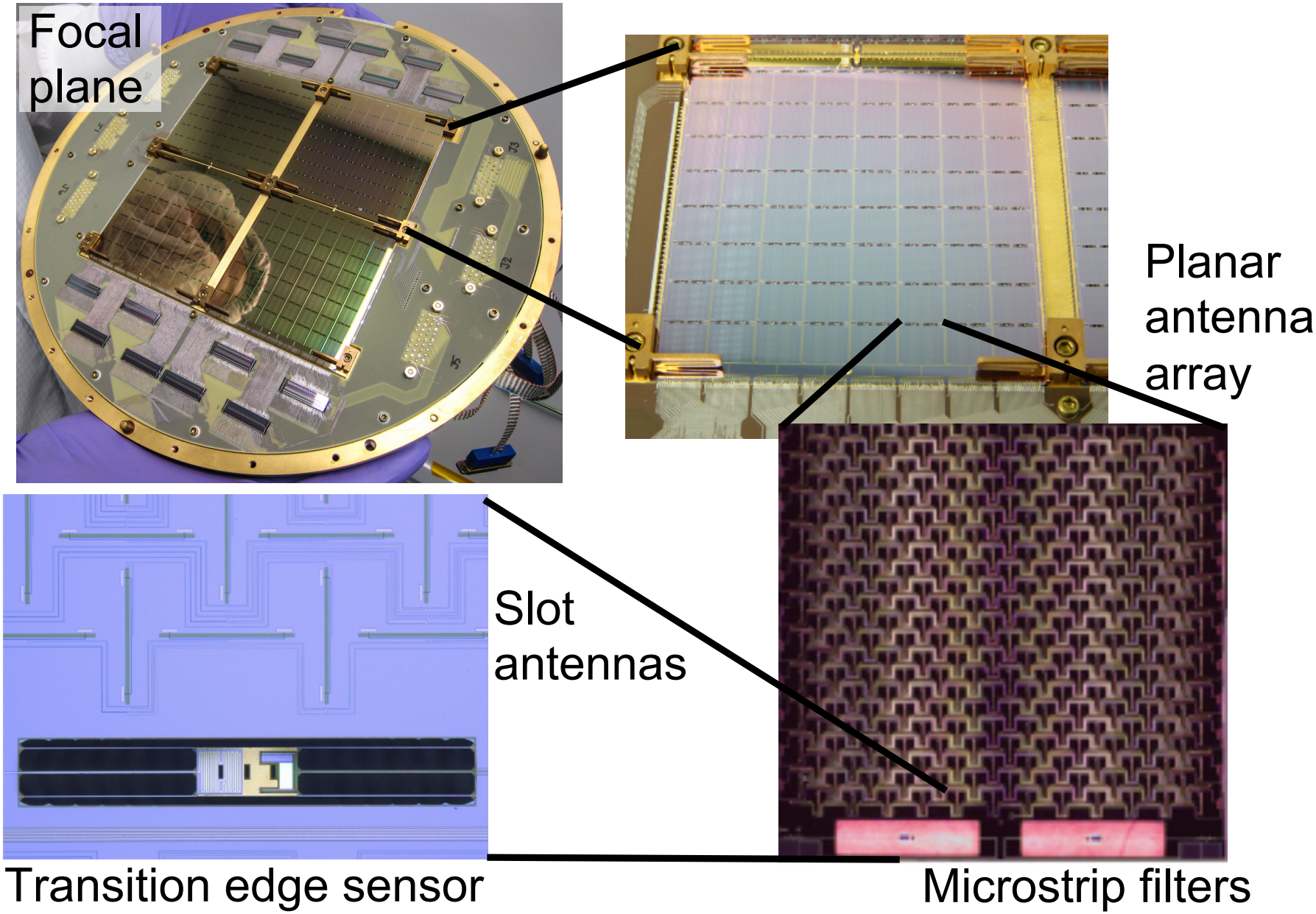
→ Small aperture telescopes (cheap, fast, low systematics)
→ Target the 2 degree peak of the B-mode
→ Integrate continuously from South Pole
→ Observe 1% patch of sky

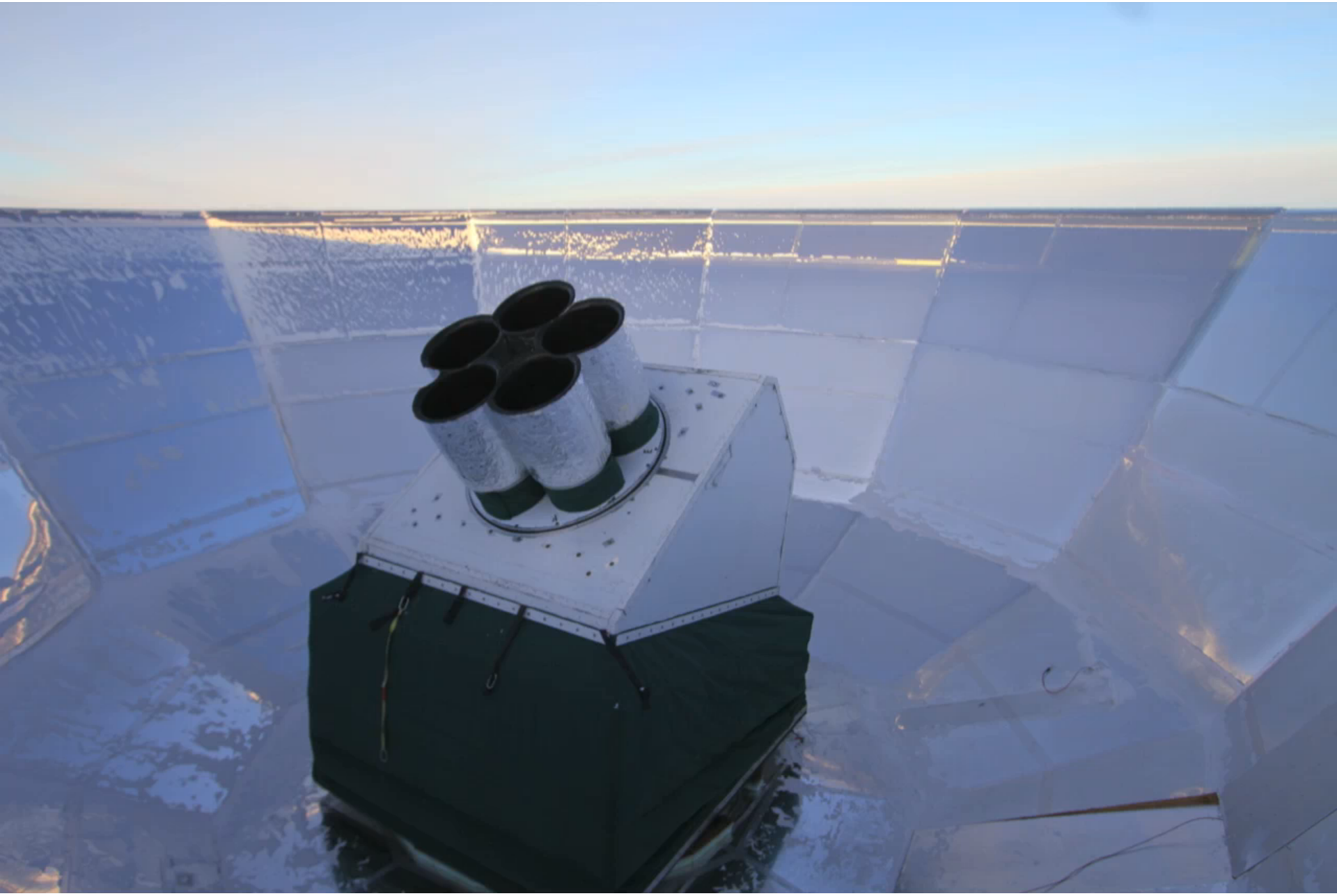
BICEP2/Keck Experimental Concept

- Small aperture
- Wide field of view
- Cold refractor



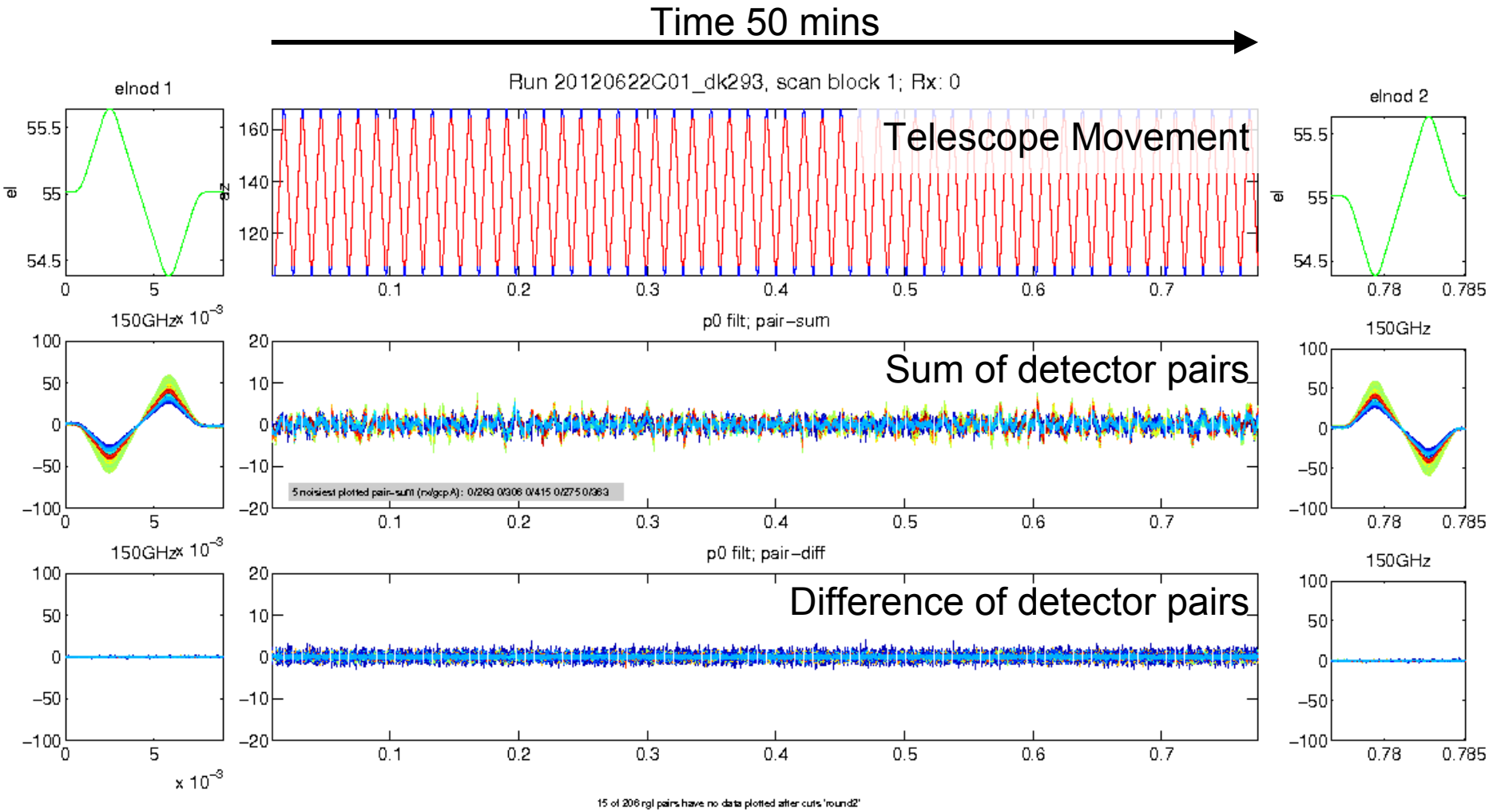
Mass-produced superconducting detectors





Clem Pryke for The Bicep2 Collaboration

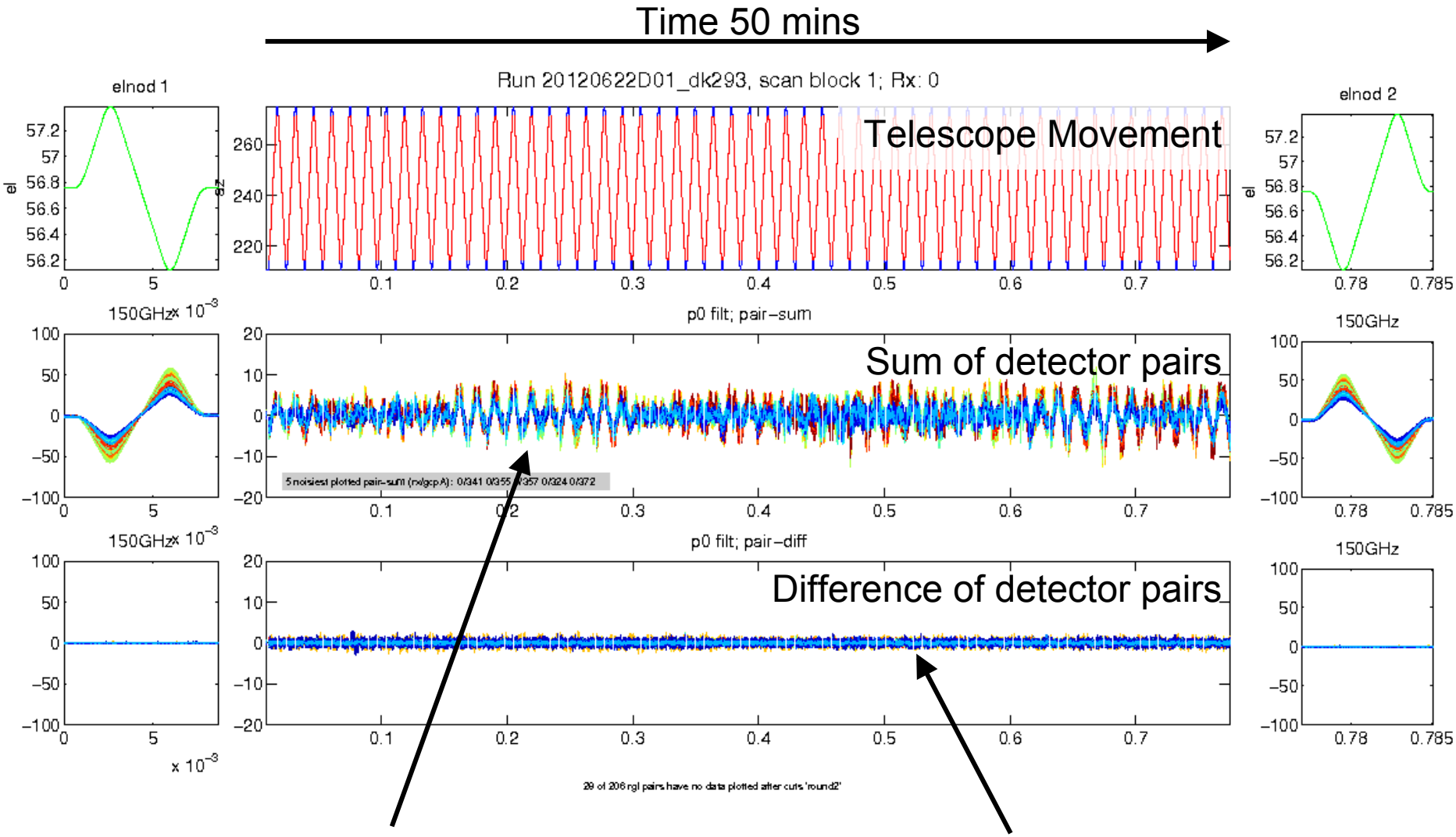
Raw Data - Perfect Weather



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

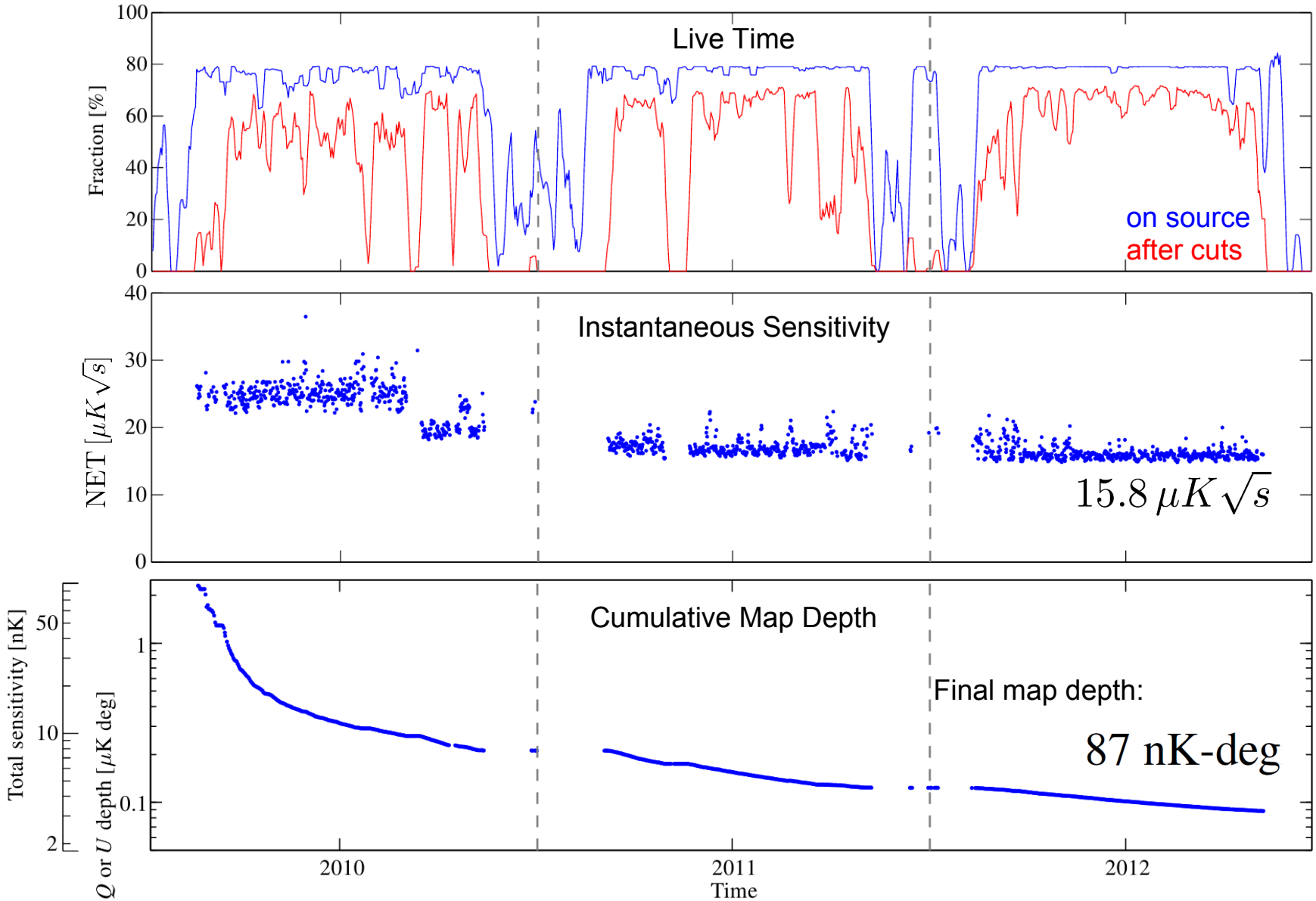
Clem Pryke for The Bicep2 Collaboration

Raw Data - Worse Weather

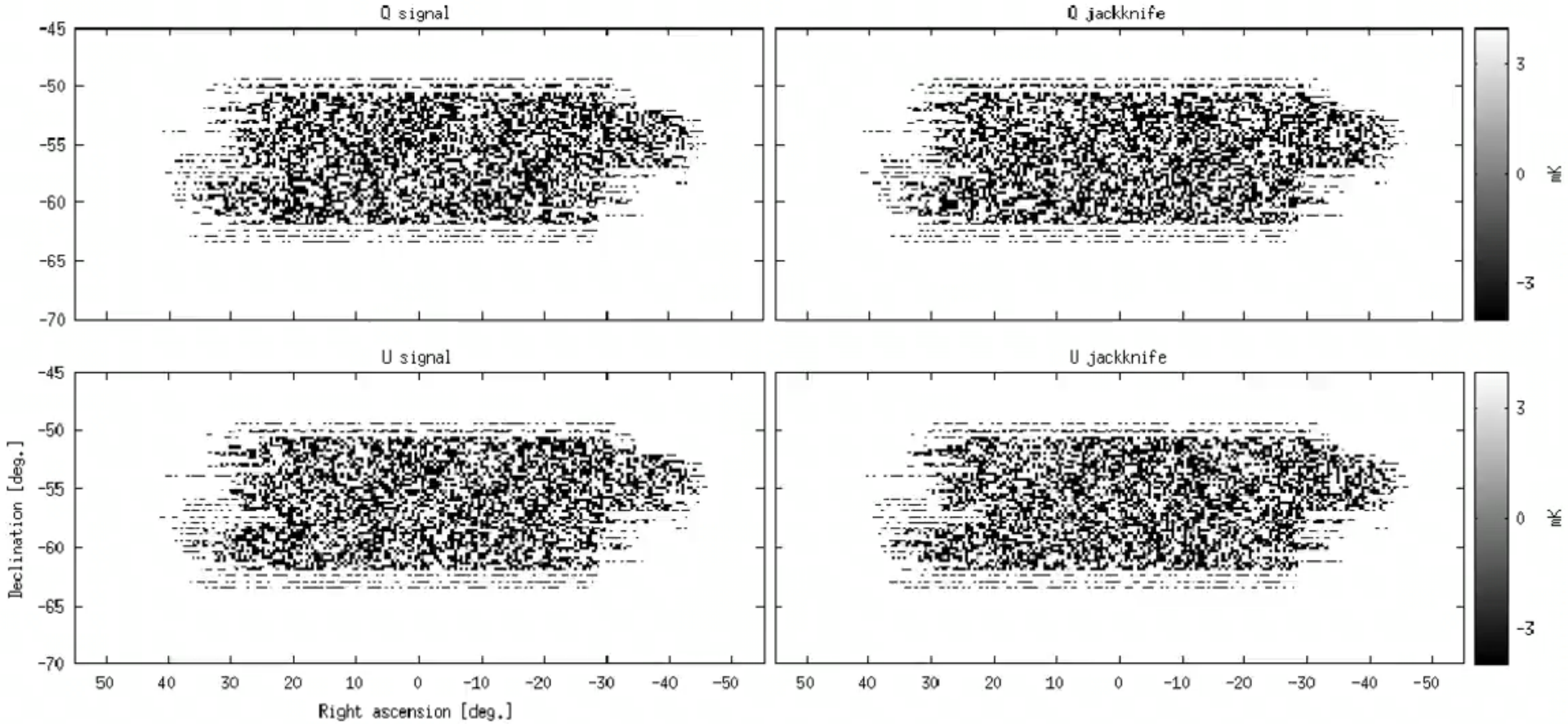


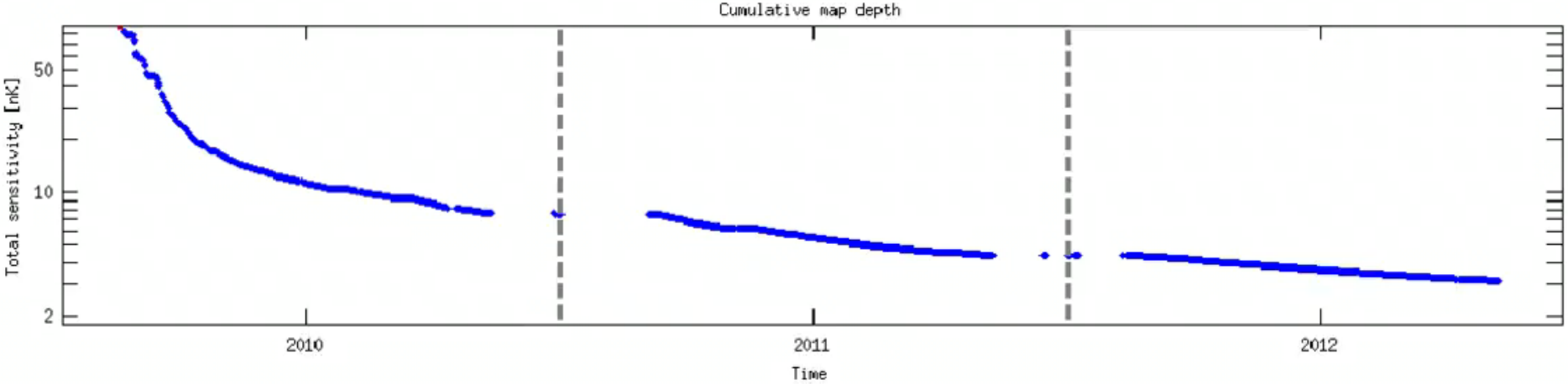
- Scanning over lumpy atmosphere → "clouds"
- Pair difference still clean → atmosphere is unpolarized

BICEP2 3-year Data Set



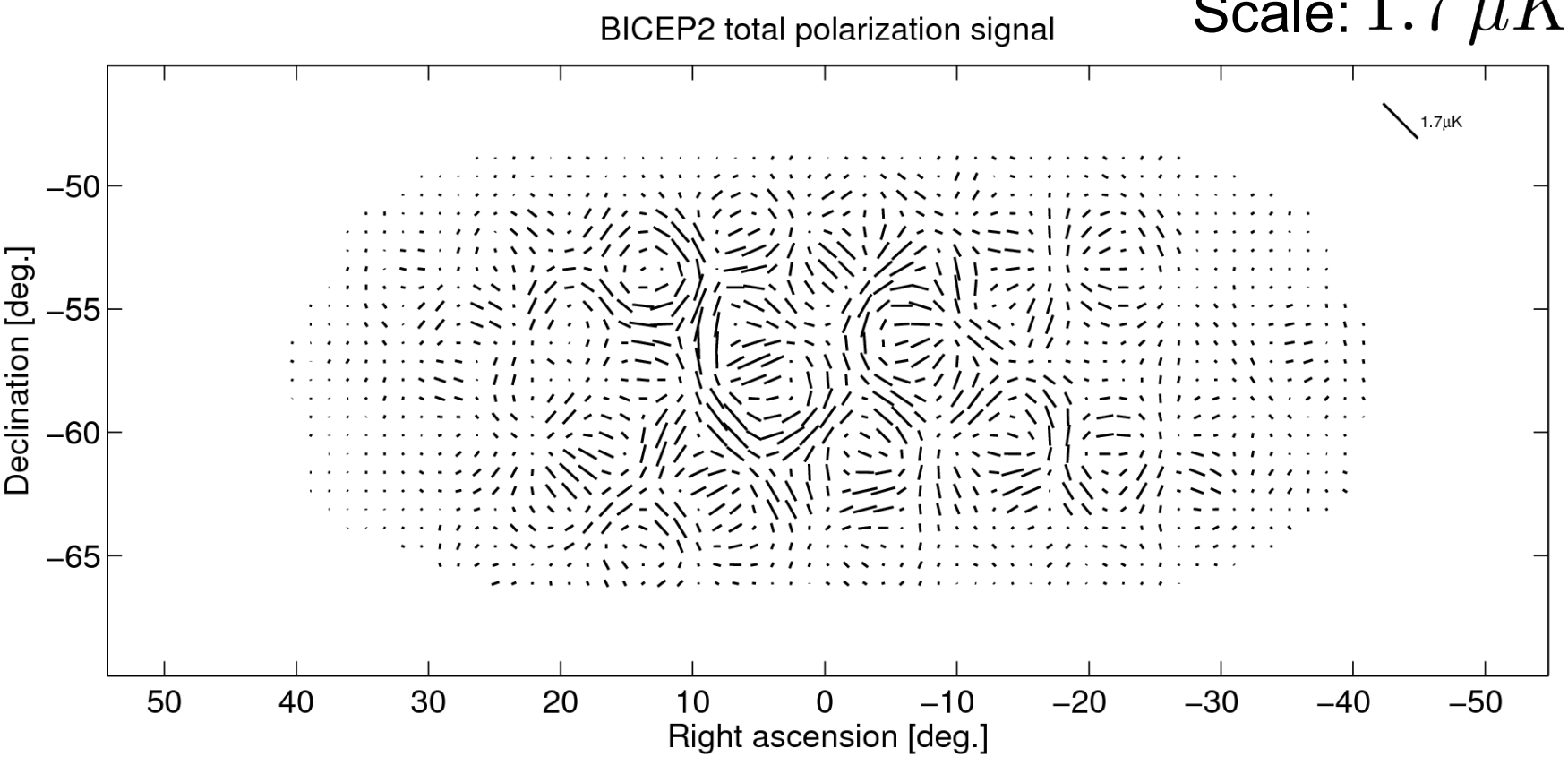
Clem Pryke for The Bicep2 Collaboration


Q signal
Q jackknife
U signal
U jackknife
Declination [deg.]
Right ascension [deg.]
mK
3
0
-3
-45
-50
-55
-60
-65
-70
50
40
30
20
10
0
-10
-20
-30
-40
-50


Cumulative map depth
Total sensitivity [nK]
50
10
2
2010
2011
2012
Time

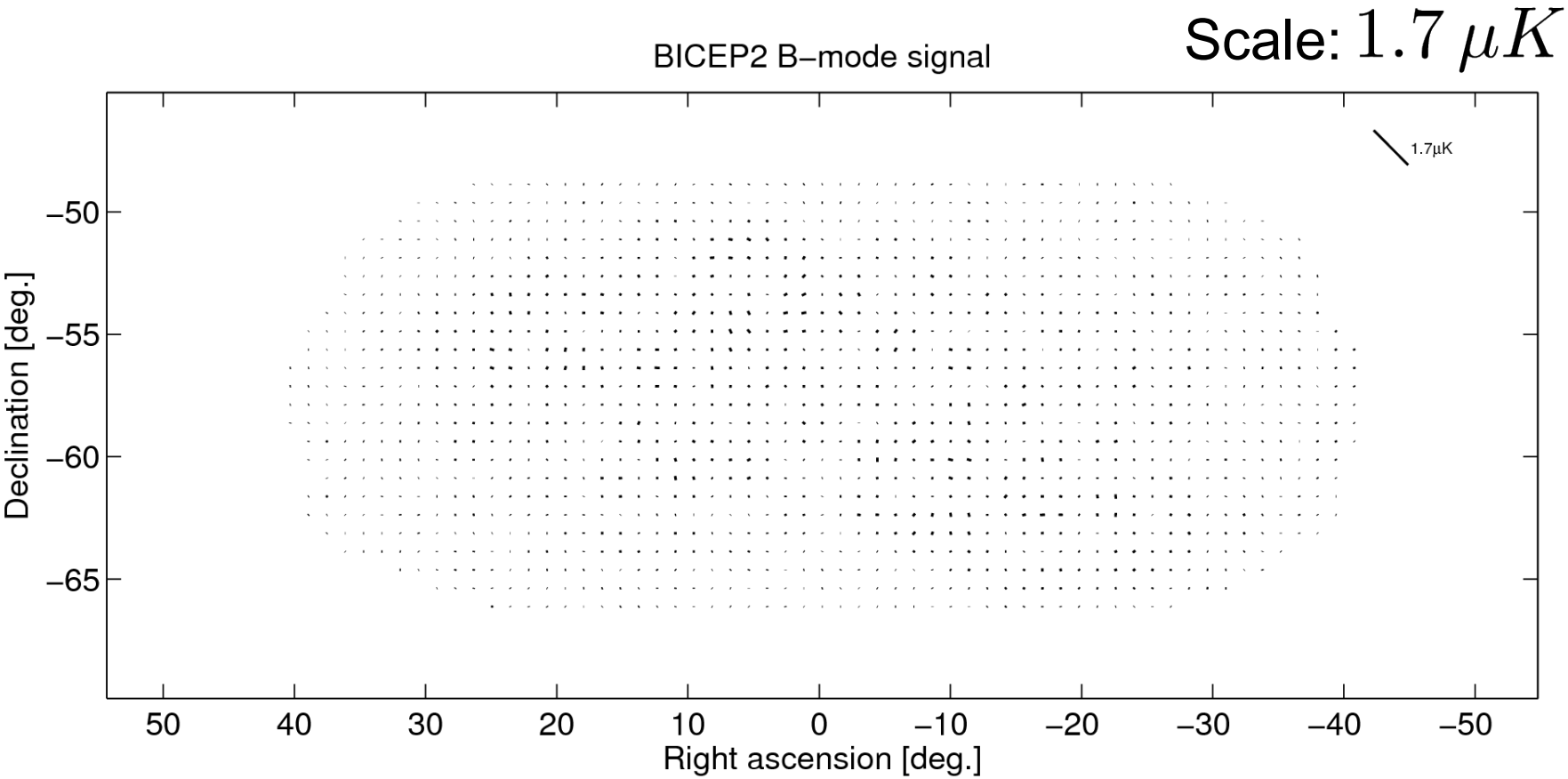
Total Polarization

Scale: $1.7\ \mu K$



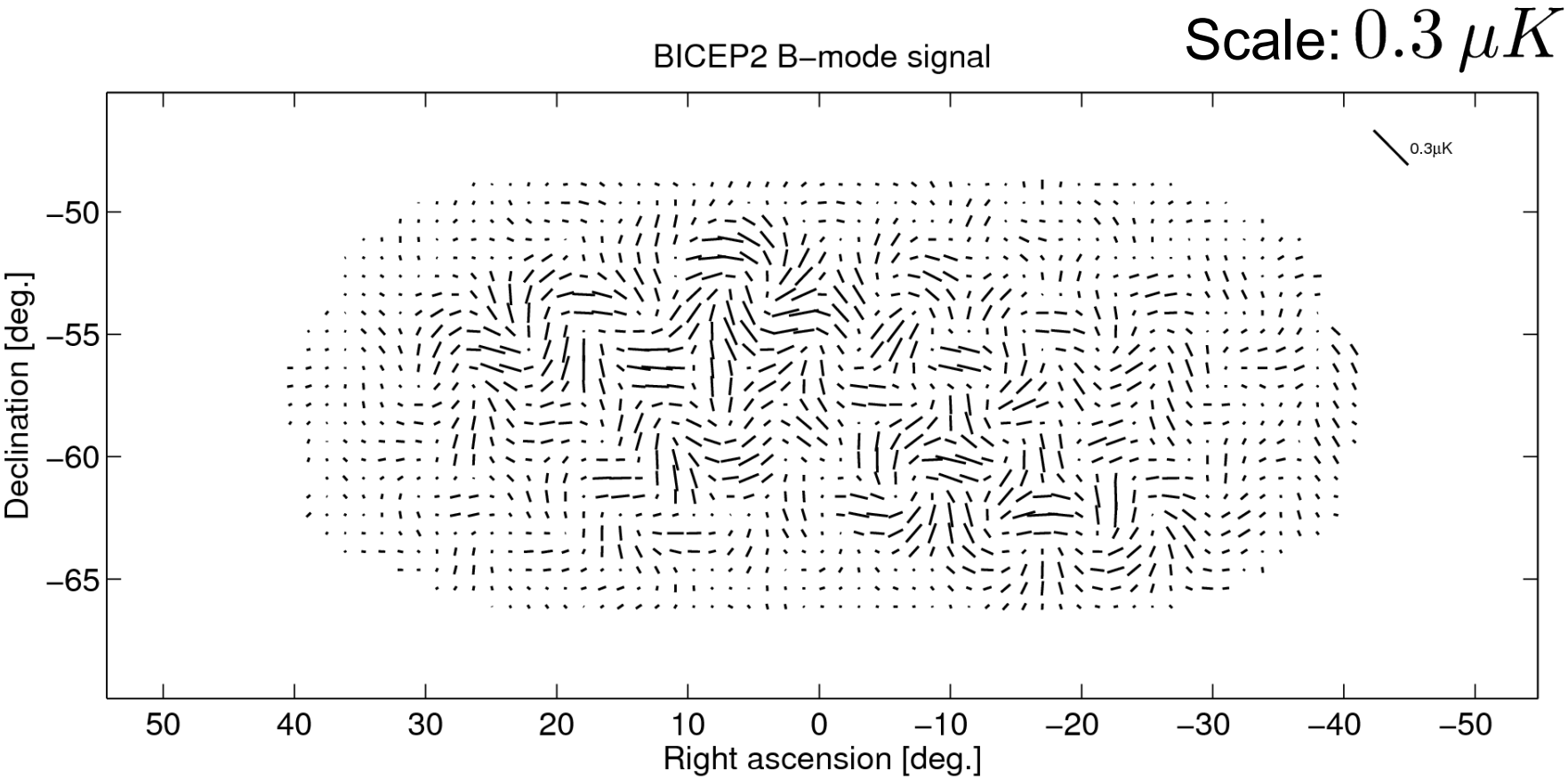
E-mode dominated pattern – no obvious curl component

B-mode Contribution



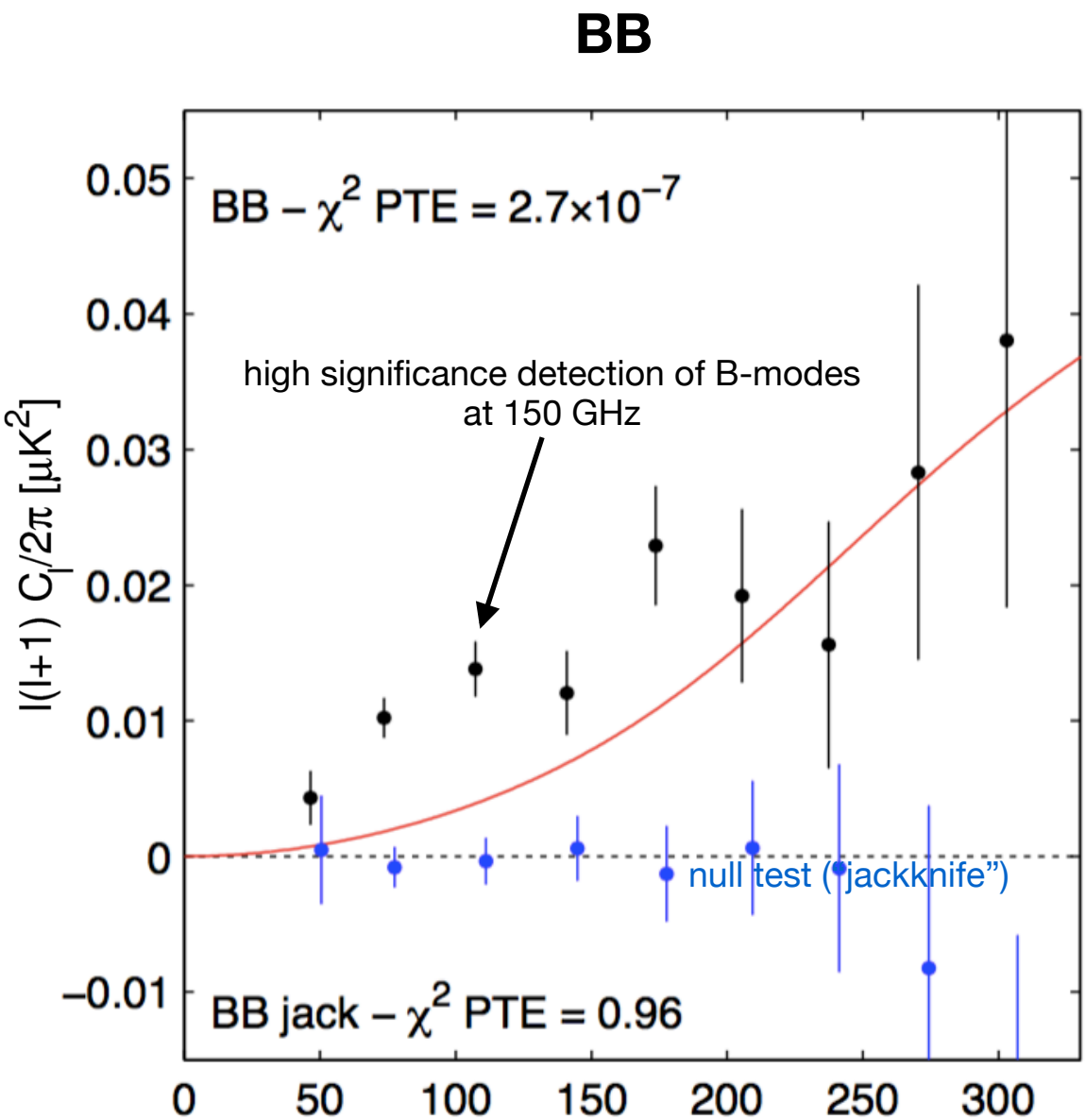
Apply purification operation to Q/U maps which leaves only B-modes (given all timestream filterings etc.)

B-mode Contribution



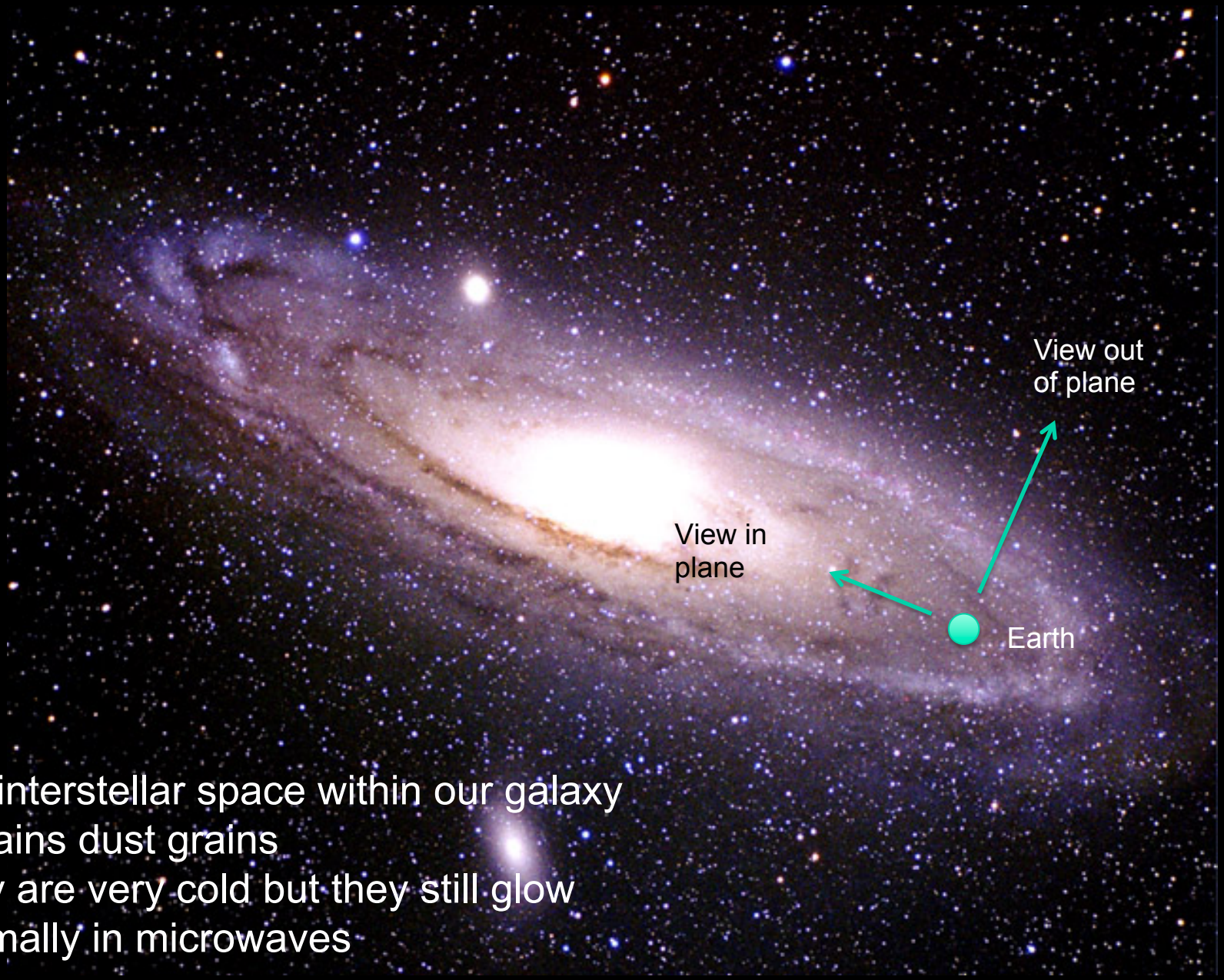
Stretch scale by factor 6 – see “swirly” B-mode

First detection of B-modes at degree scales and 150GHz



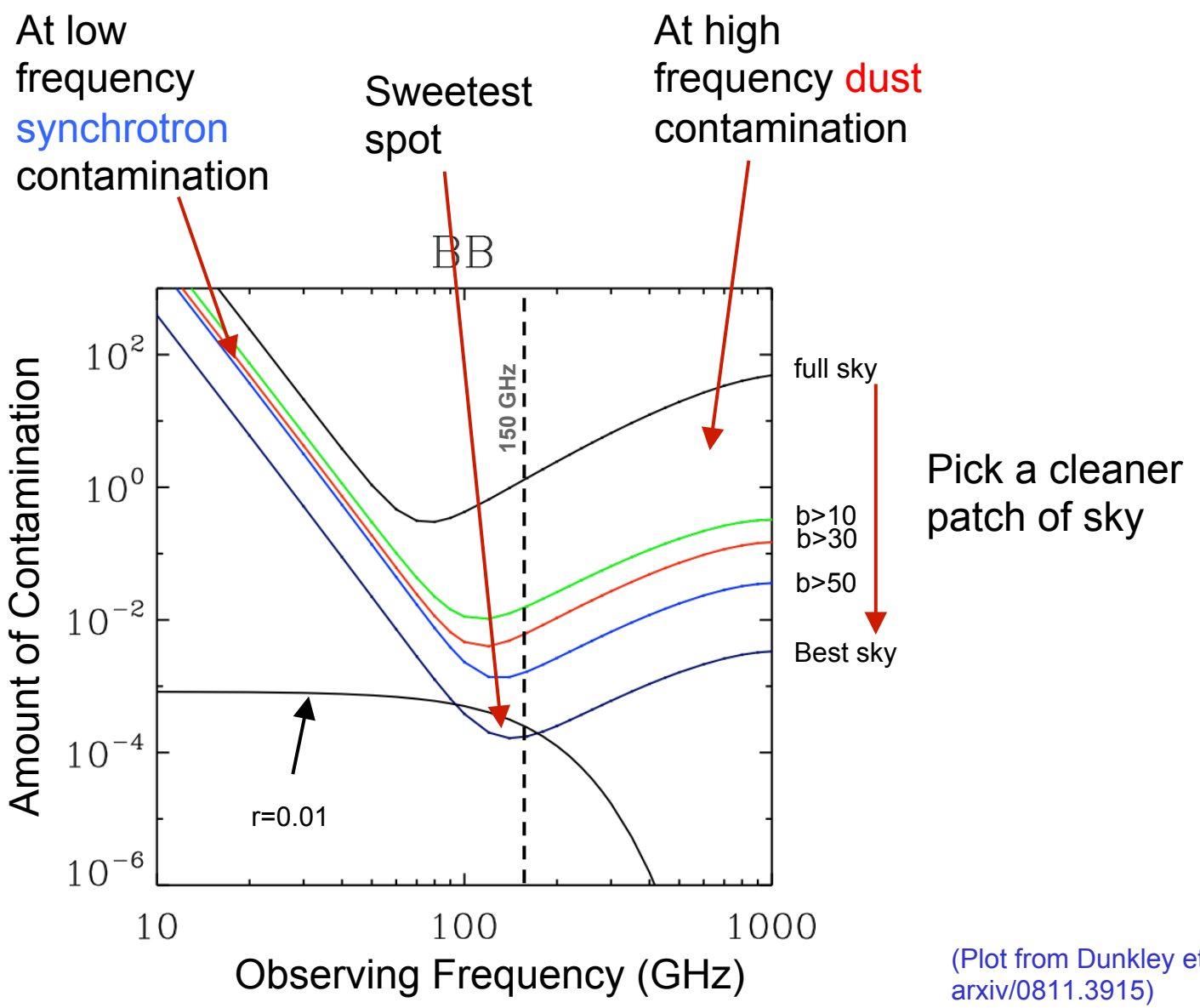
(This plot uses all data taken through 2013)

Unfortunately we are in a galaxy!



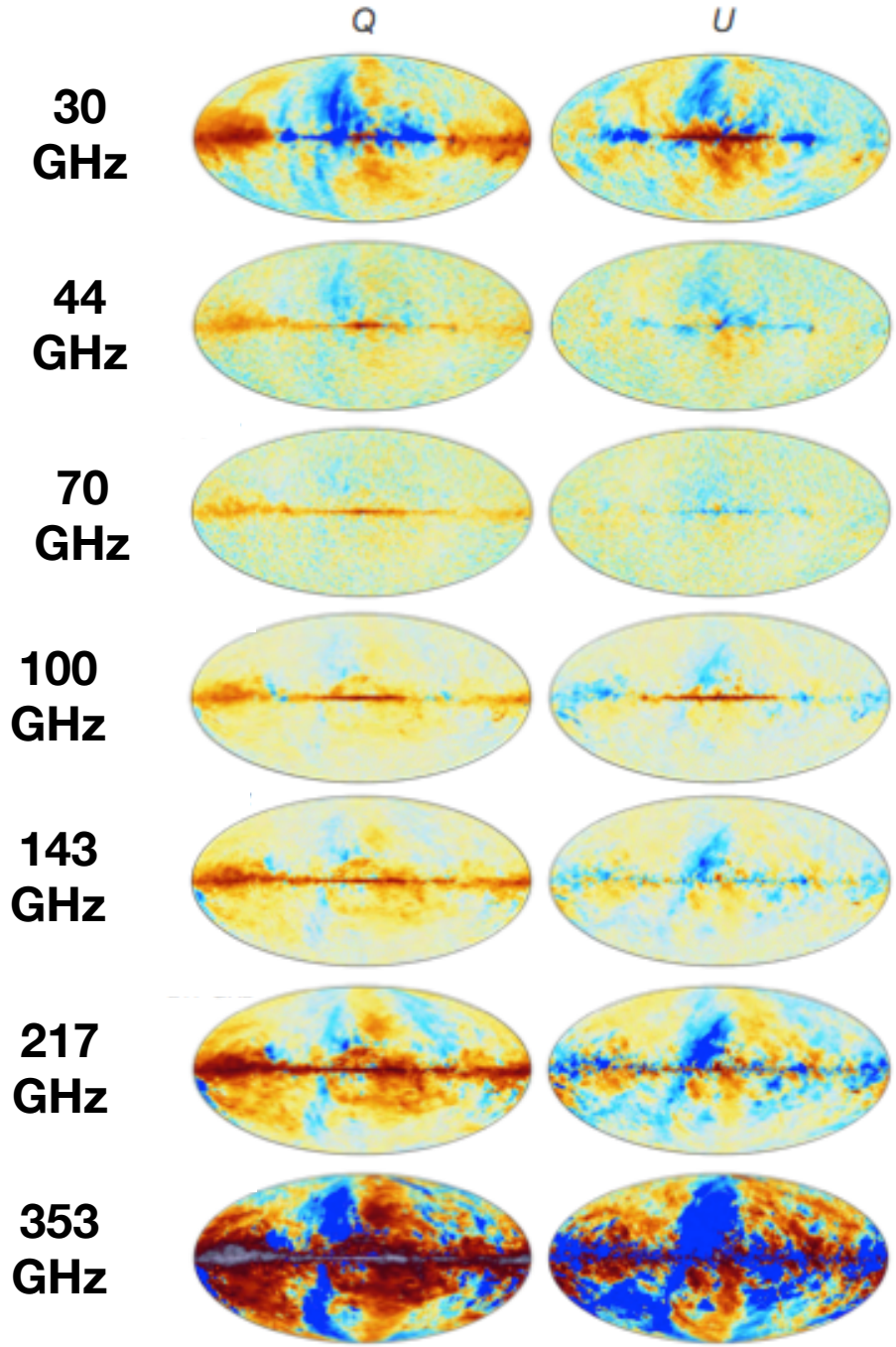
The interstellar space within our galaxy contains dust grains
They are very cold but they still glow thermally in microwaves

Polarized Foreground Contamination from Our Galaxy



(Plot from Dunkley et al arxiv/0811.3915)

Slightly after BICEP2 results came Planck polarized maps at 7 frequencies
(two more from WMAP at low frequencies already existed)

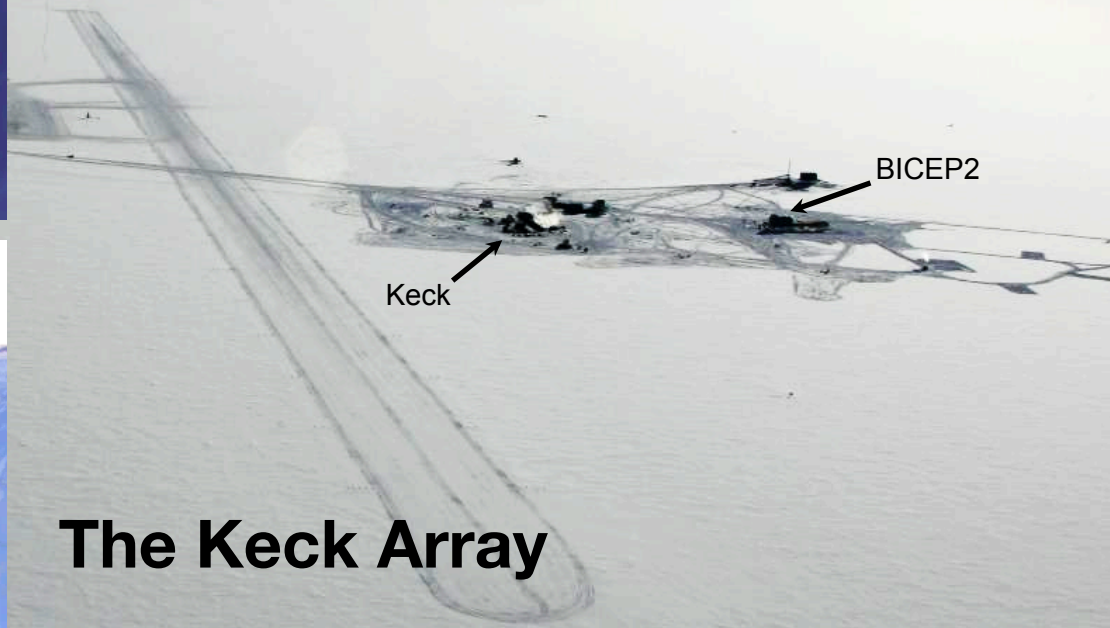


The highest frequency have decent signal-to-noise for dust signal in the BICEP/Keck field

BICEP2 and Keck Array

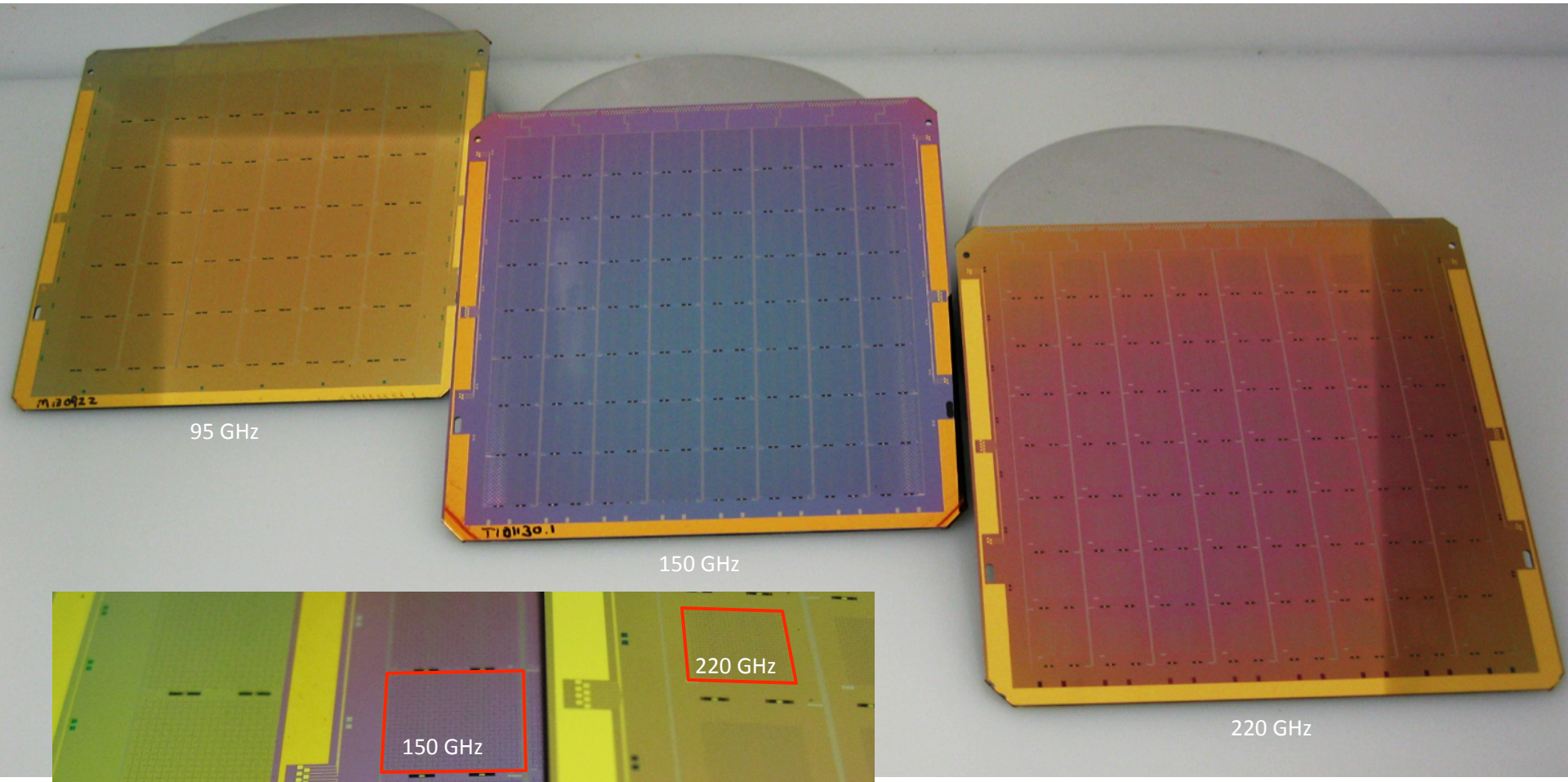
Keck Array 2011-present

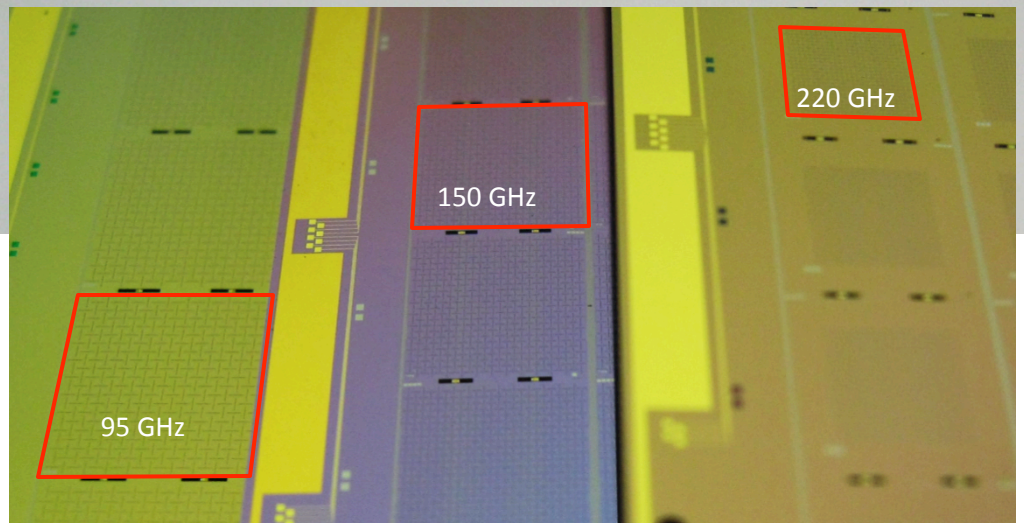
BICEP2 x 5 =



The Keck Array

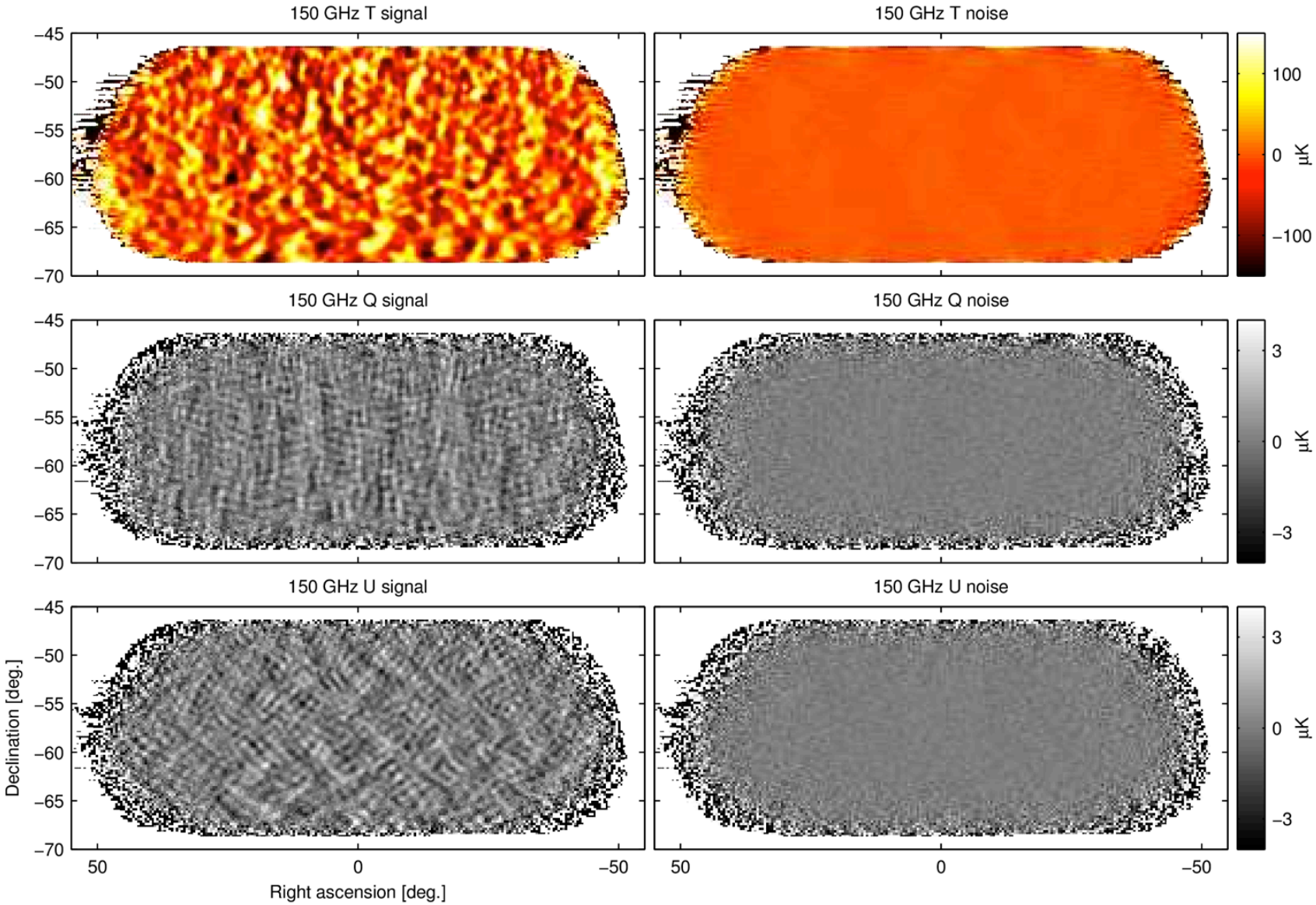
Detectors Designed to Scale in Frequency (JPL)





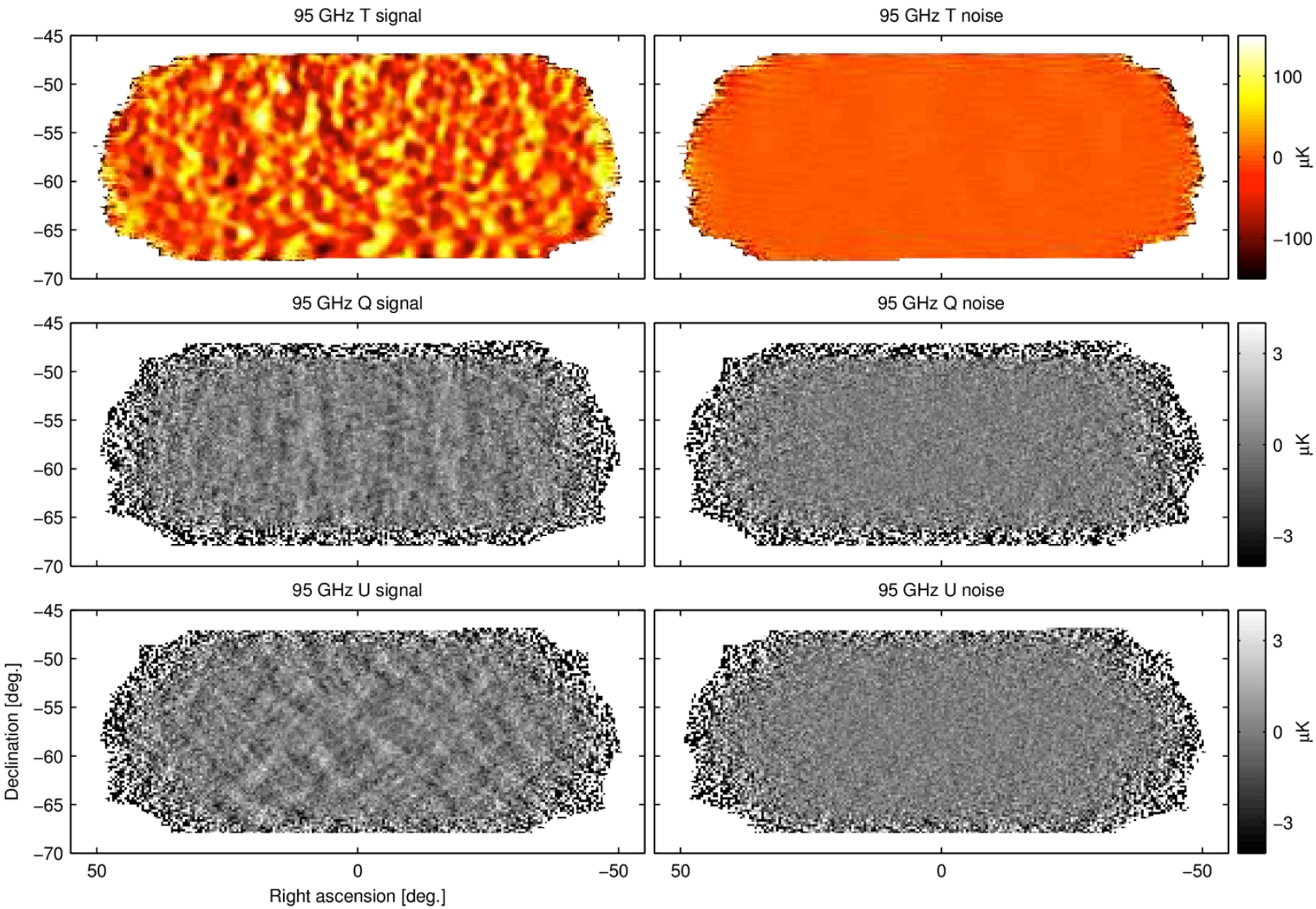
Up to 2013 – all 150GHz
2014 – 95/150GHz
2015 – 95/150/220GHz

150 GHz maps



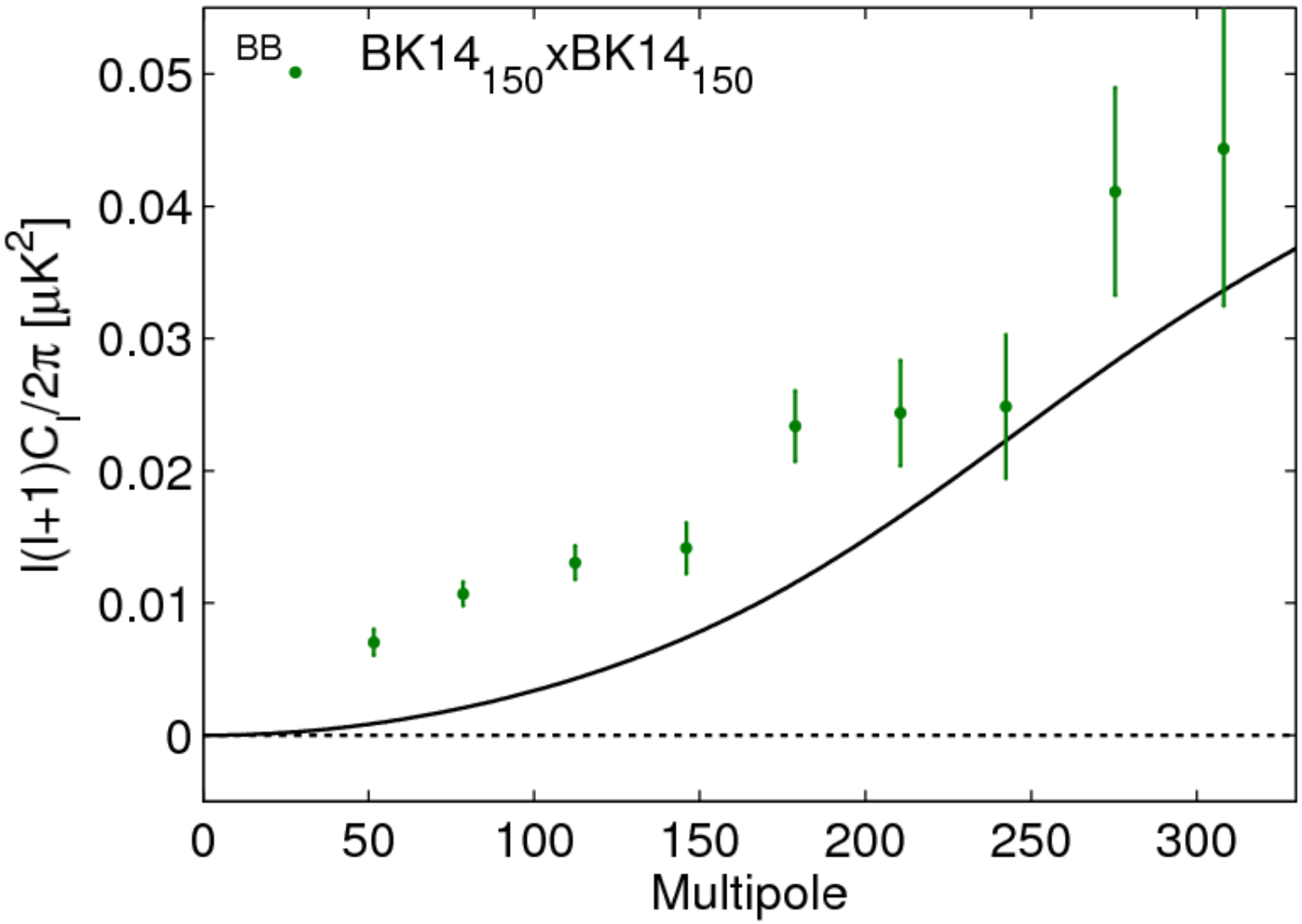
BK14 150GHz – 50 nK deg (3.0μK arcmin)

95 GHz maps

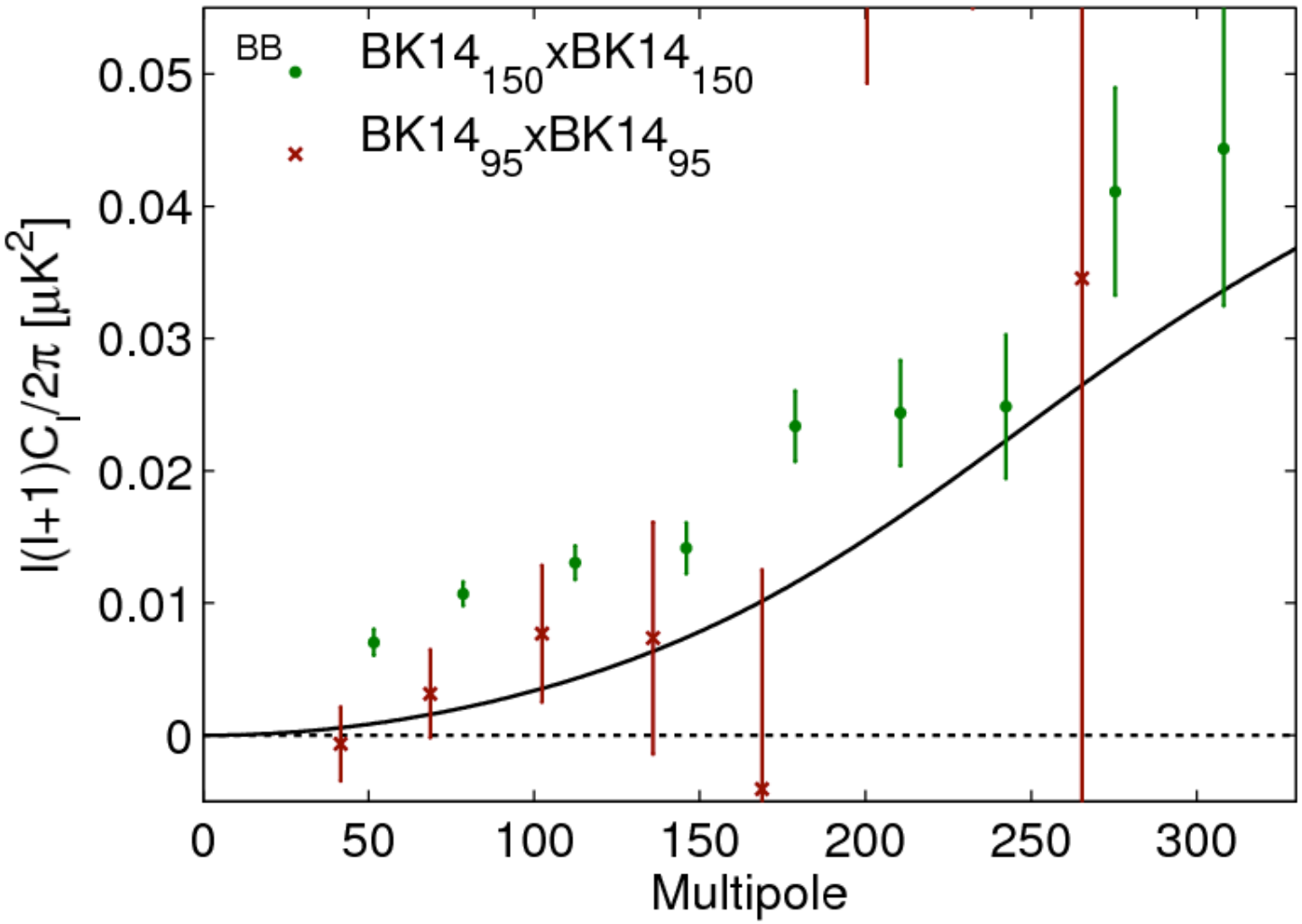


BK14 95GHz – 127 nK deg (7.6μK arcmin)

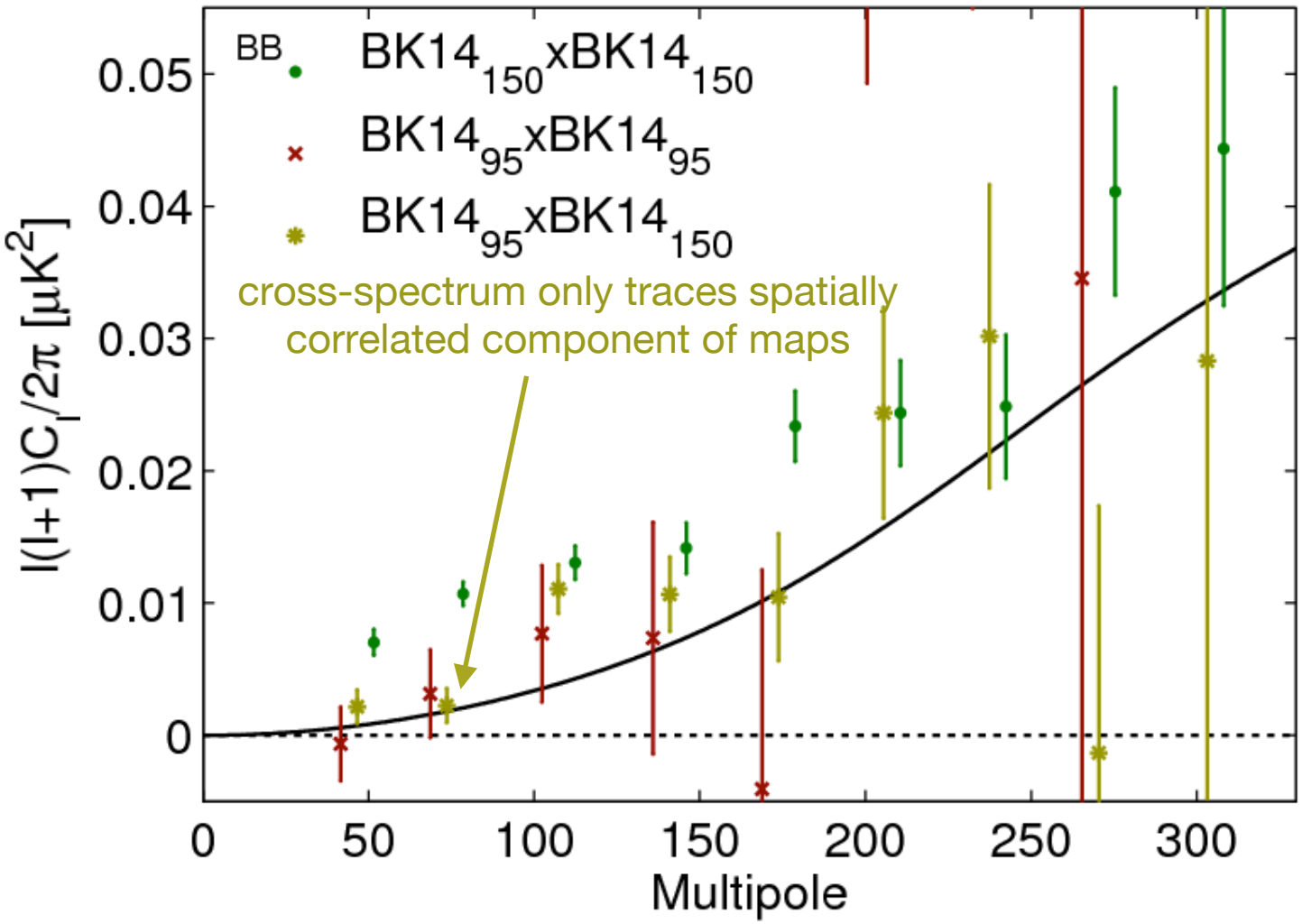
auto and cross-spectra



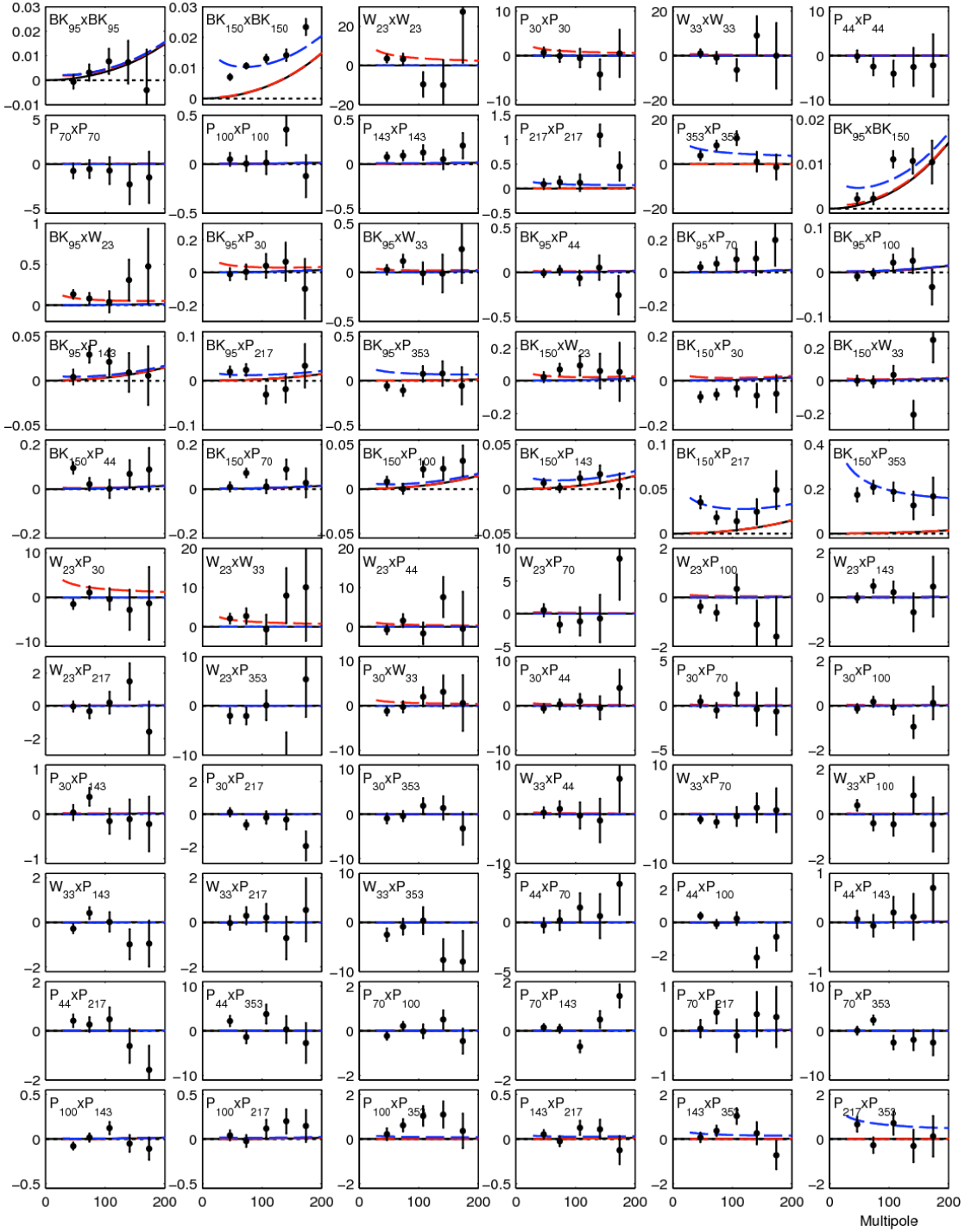
auto and cross-spectra



auto and cross-spectra



Take all possible auto- and cross spectra between BICEP/Keck, WMAP, and Planck bands (66 of them)



Multicomponent 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

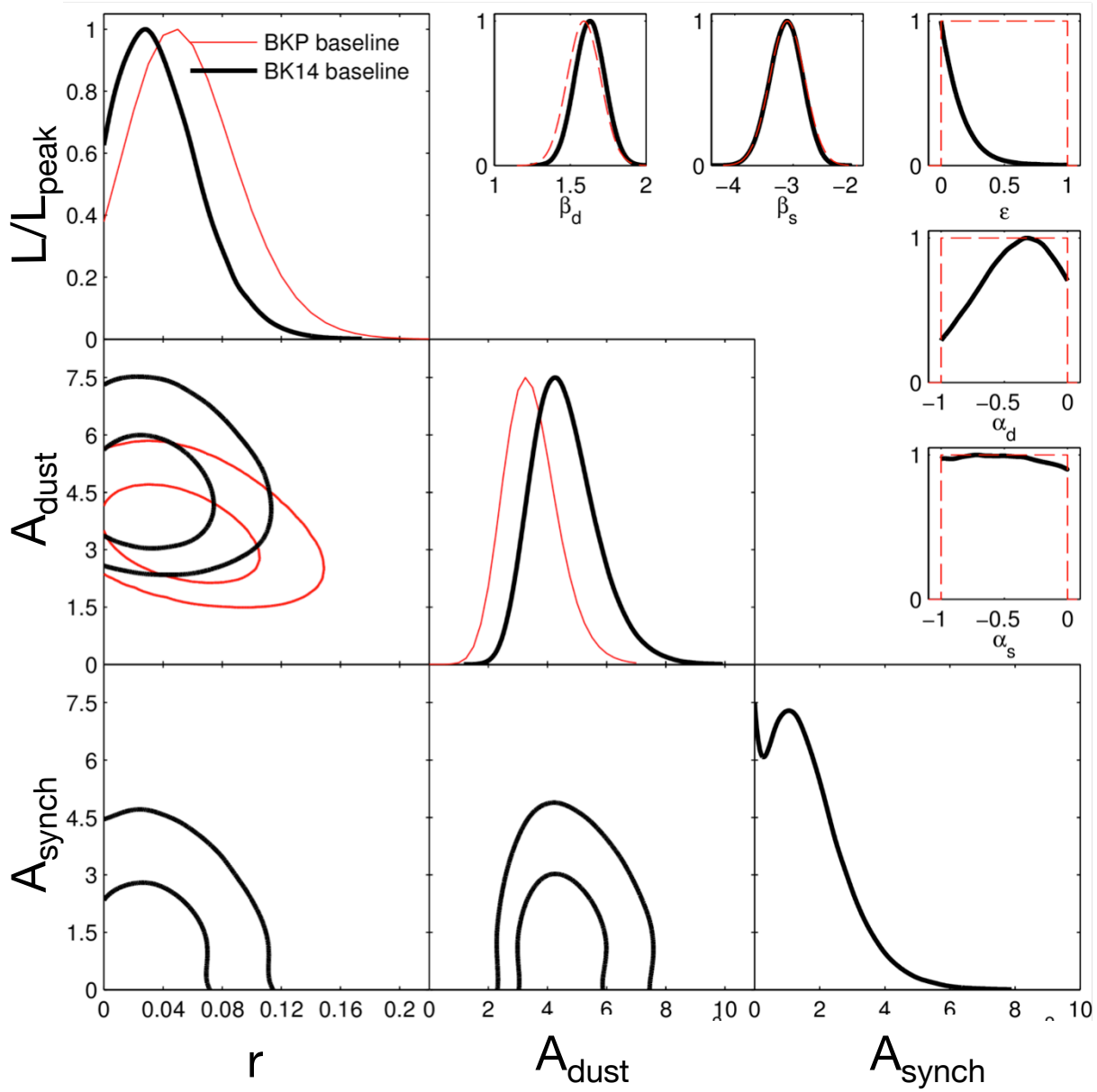
α_{dust} α_{synch} — spatial spectral indices

ε — dust/synch spatial correlation

Put priors on the frequency spectral indices of dust & sync

Allow dust/sync correlation

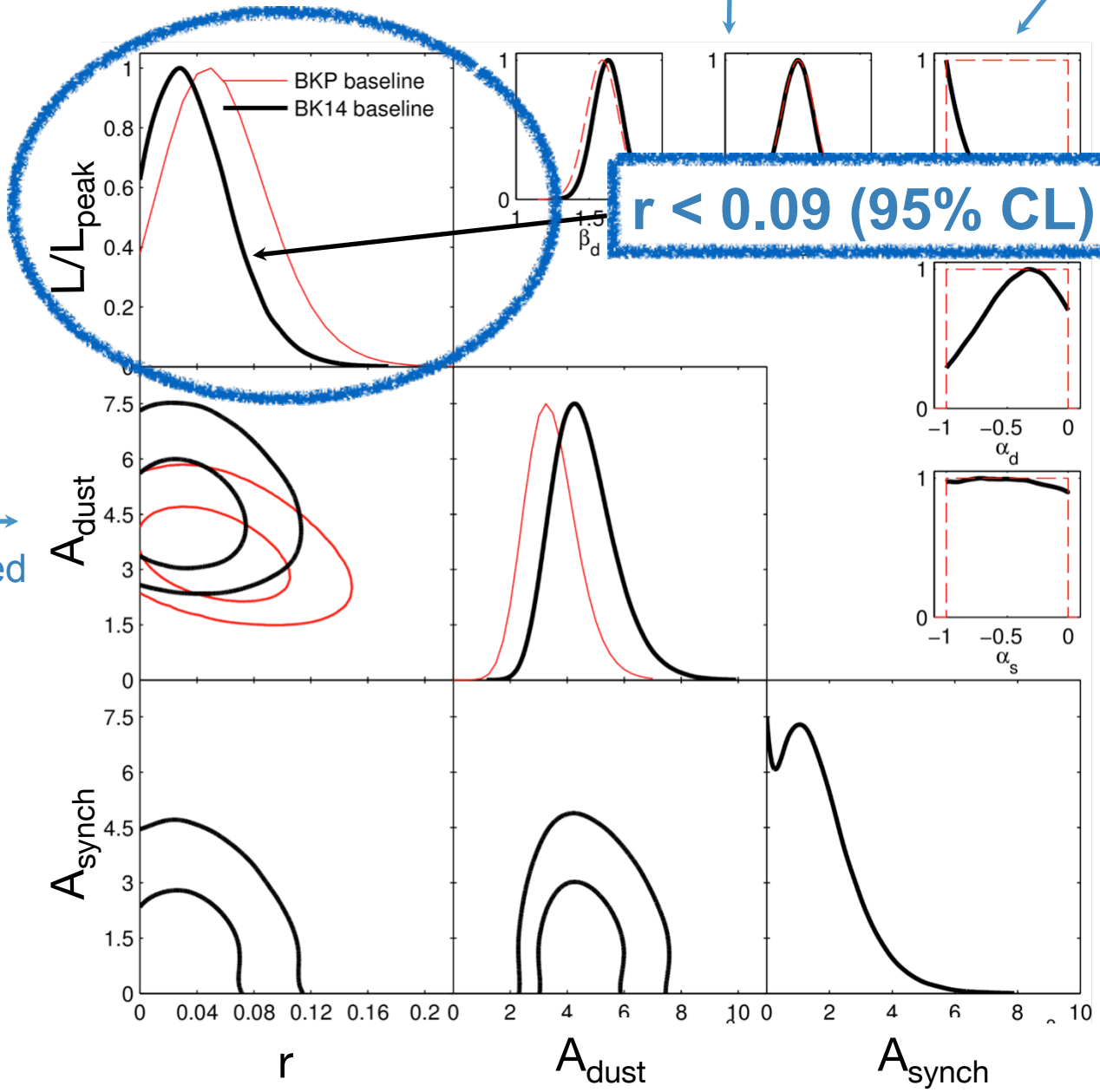
dust vs. r degeneracy lifted



Marginalize over generous ranges in spatial spectral indices

Put priors on the frequency spectral indices of dust & sync

Allow dust/sync correlation



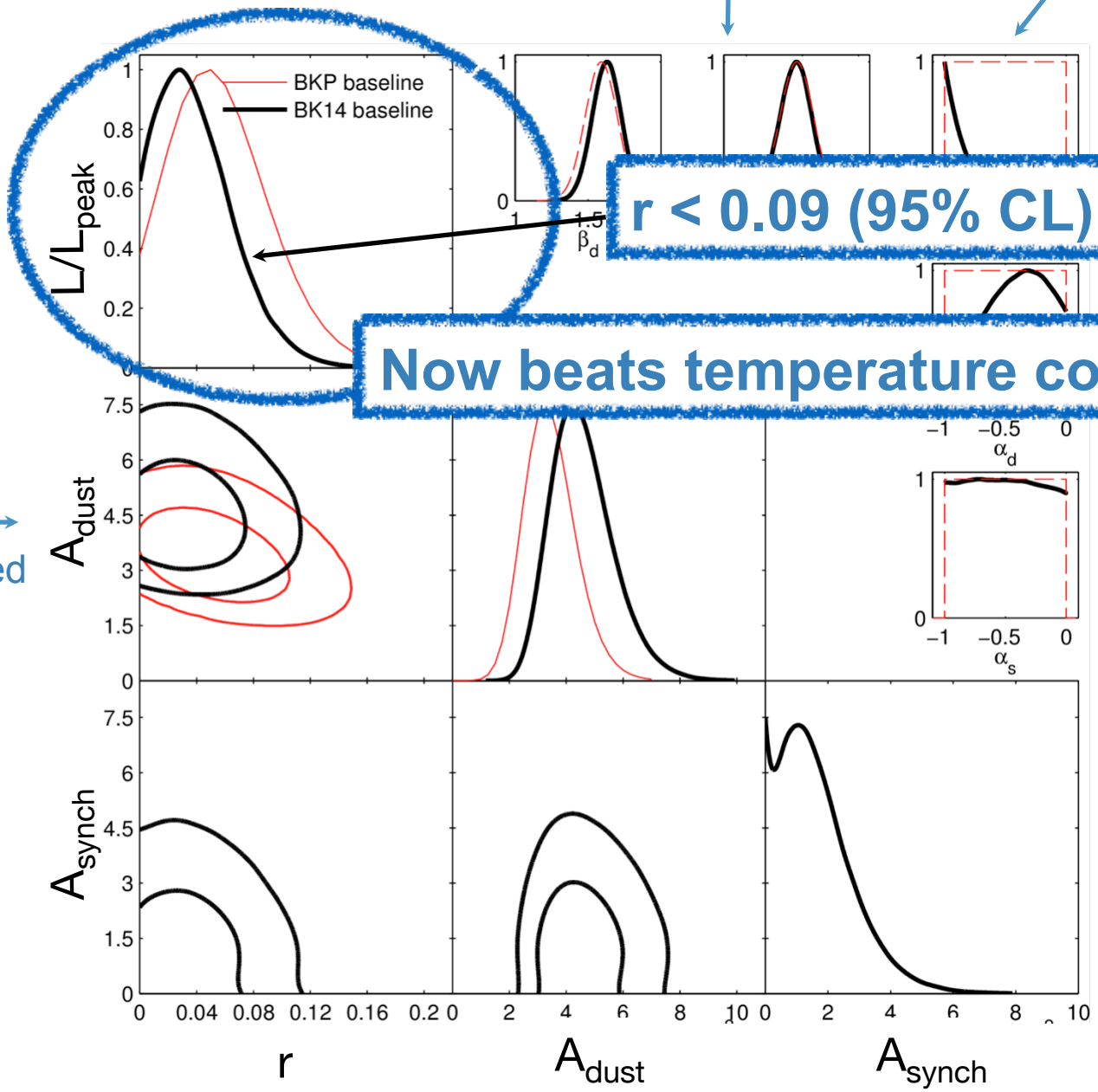
r < 0.09 (95% CL)

dust vs. r degeneracy lifted

Marginalize over generous ranges in spatial spectral indices

Put priors on the frequency spectral indices of dust & sync

Allow dust/sync correlation



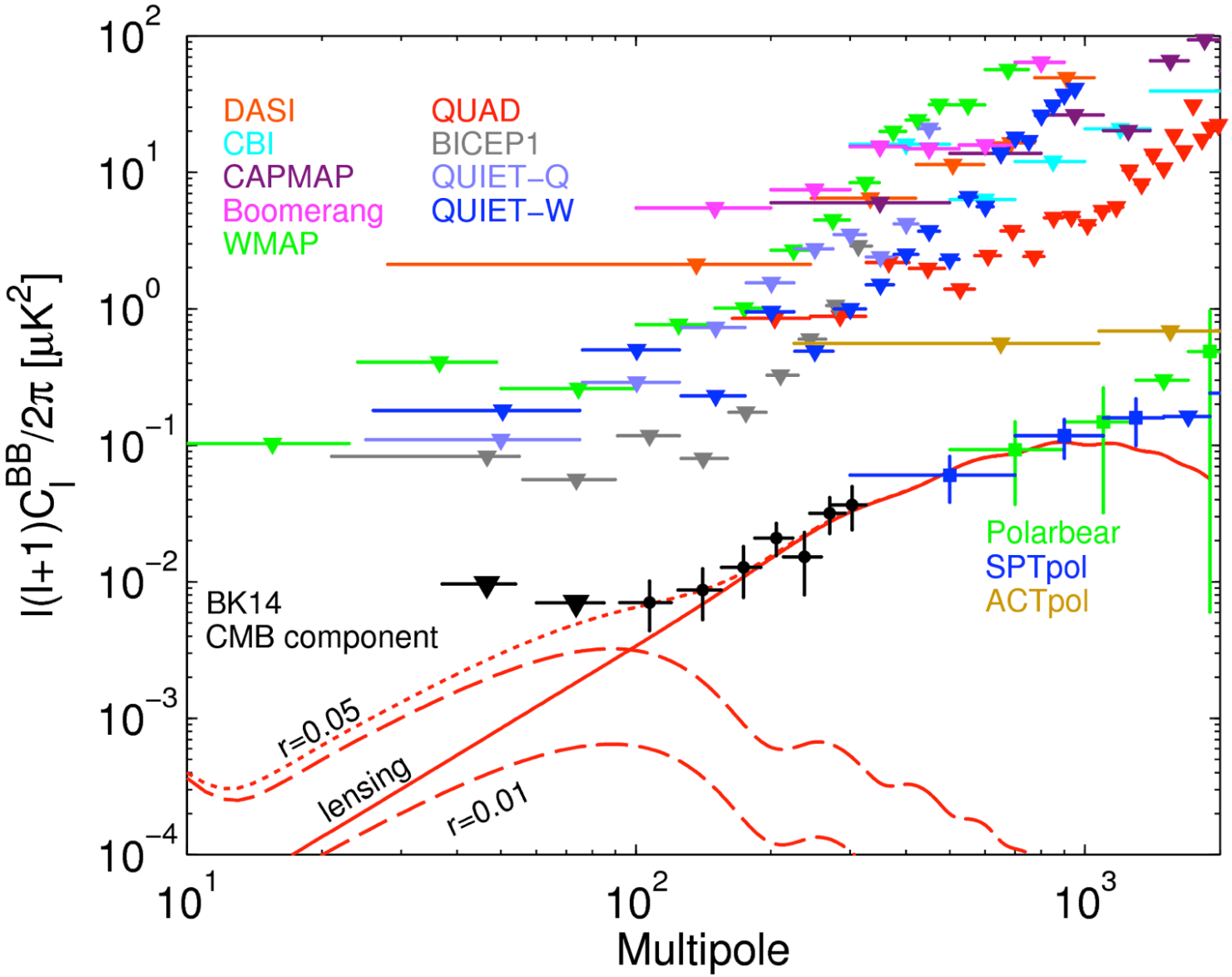
r < 0.09 (95% CL)

Now beats temperature constraints

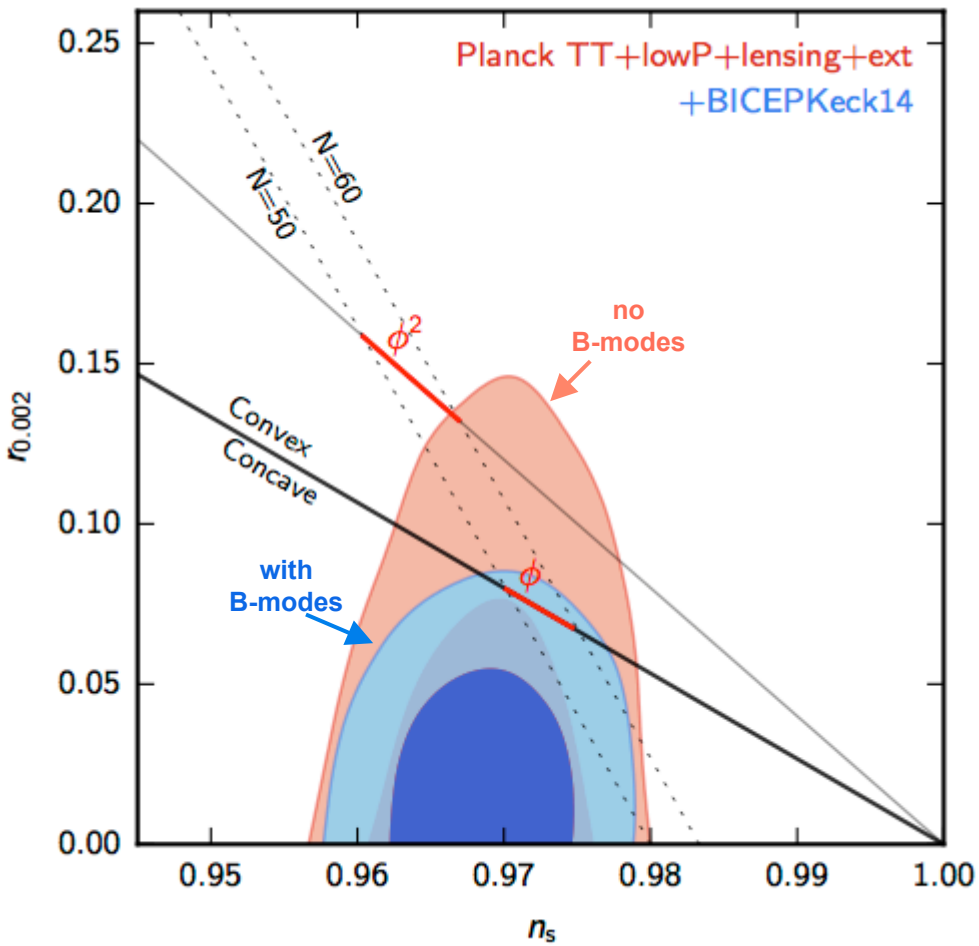
dust vs. r degeneracy lifted

Marginalize over generous ranges in spatial spectral indices

Component separated power spectrum (BK14)

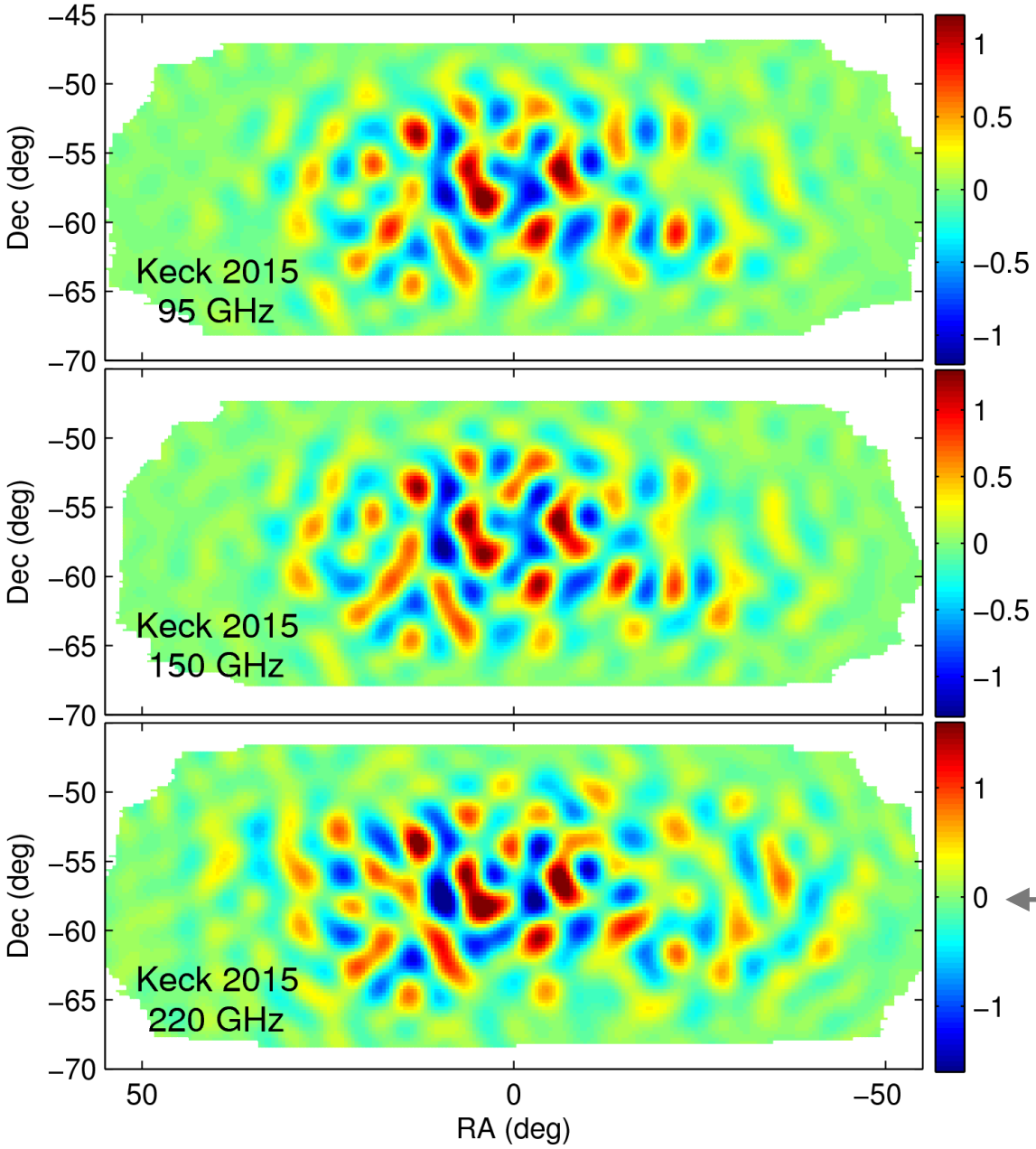


Adding in temperature: constraints on Inflation



Steadily tightening the constraints on inflationary models

Teaser for the future: Keck 2015 E-mode maps



LCDM E-modes with high s/n at three frequencies in a single year!

Already deeper than Planck 217 GHz

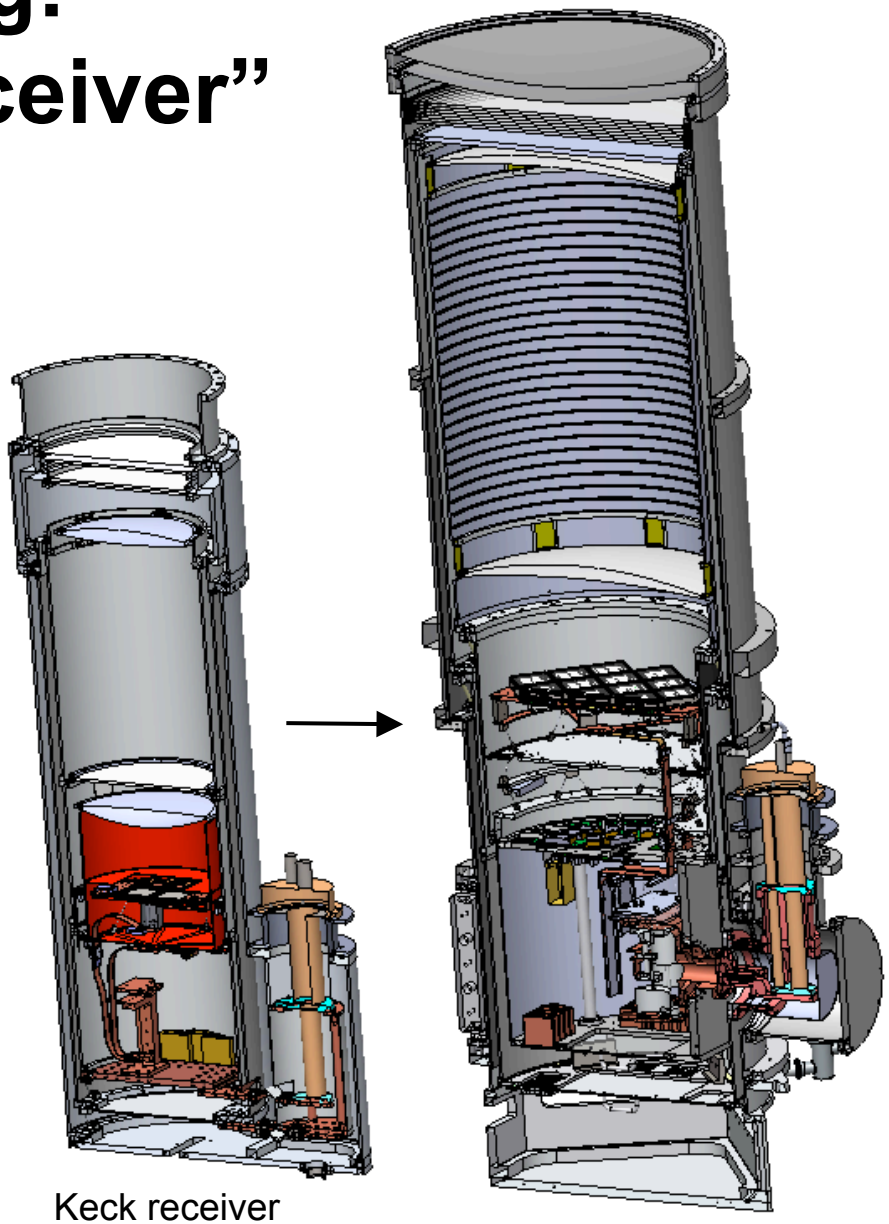
Now operating: BICEP3 "Super receiver"

All 95 GHz

2560 detectors in modular focal plane

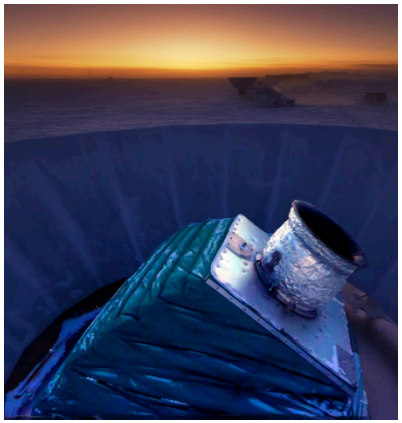
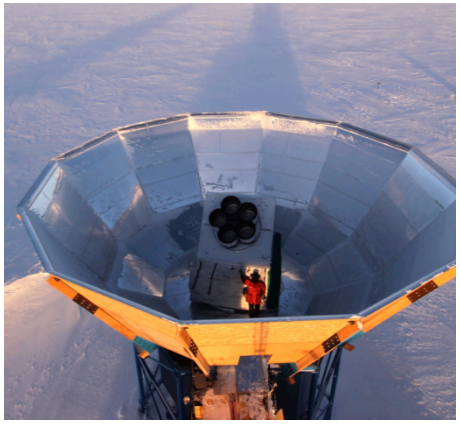
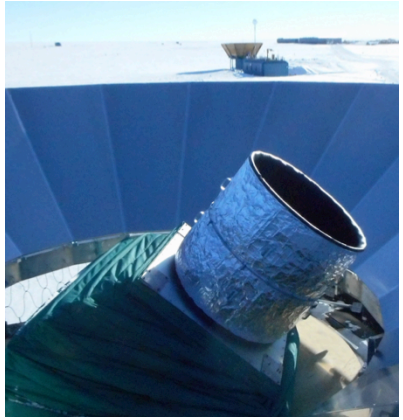
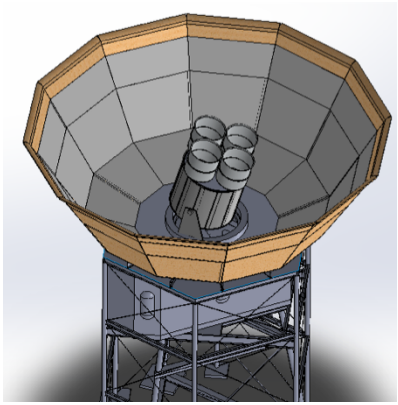
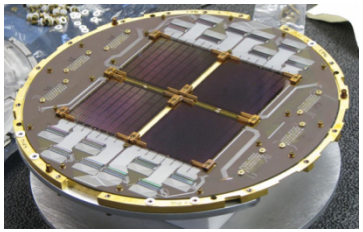
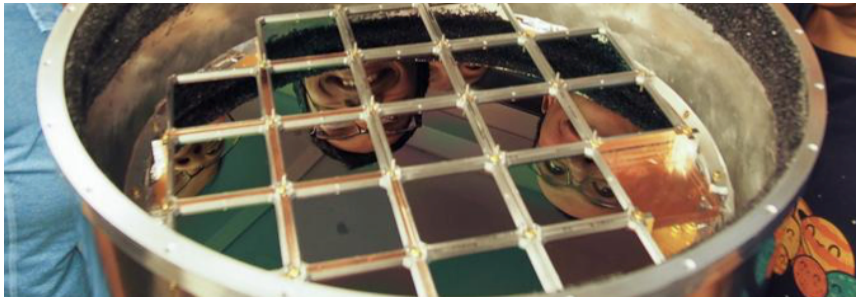
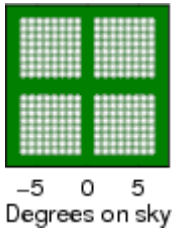
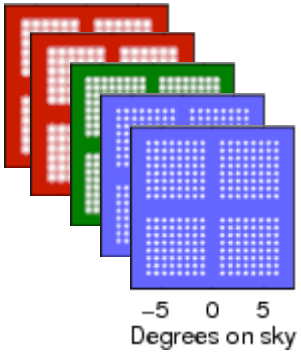
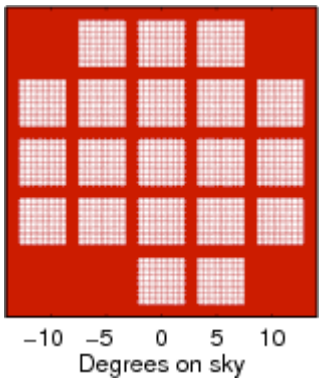
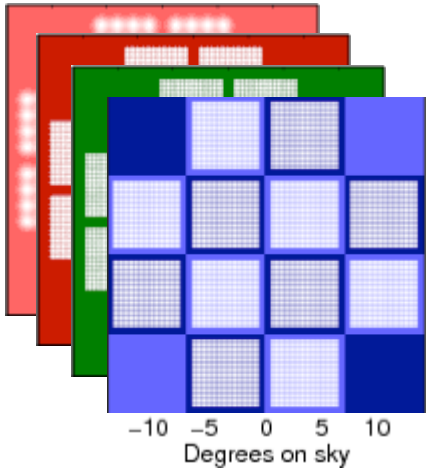
Large-aperture optics and infrared filtering

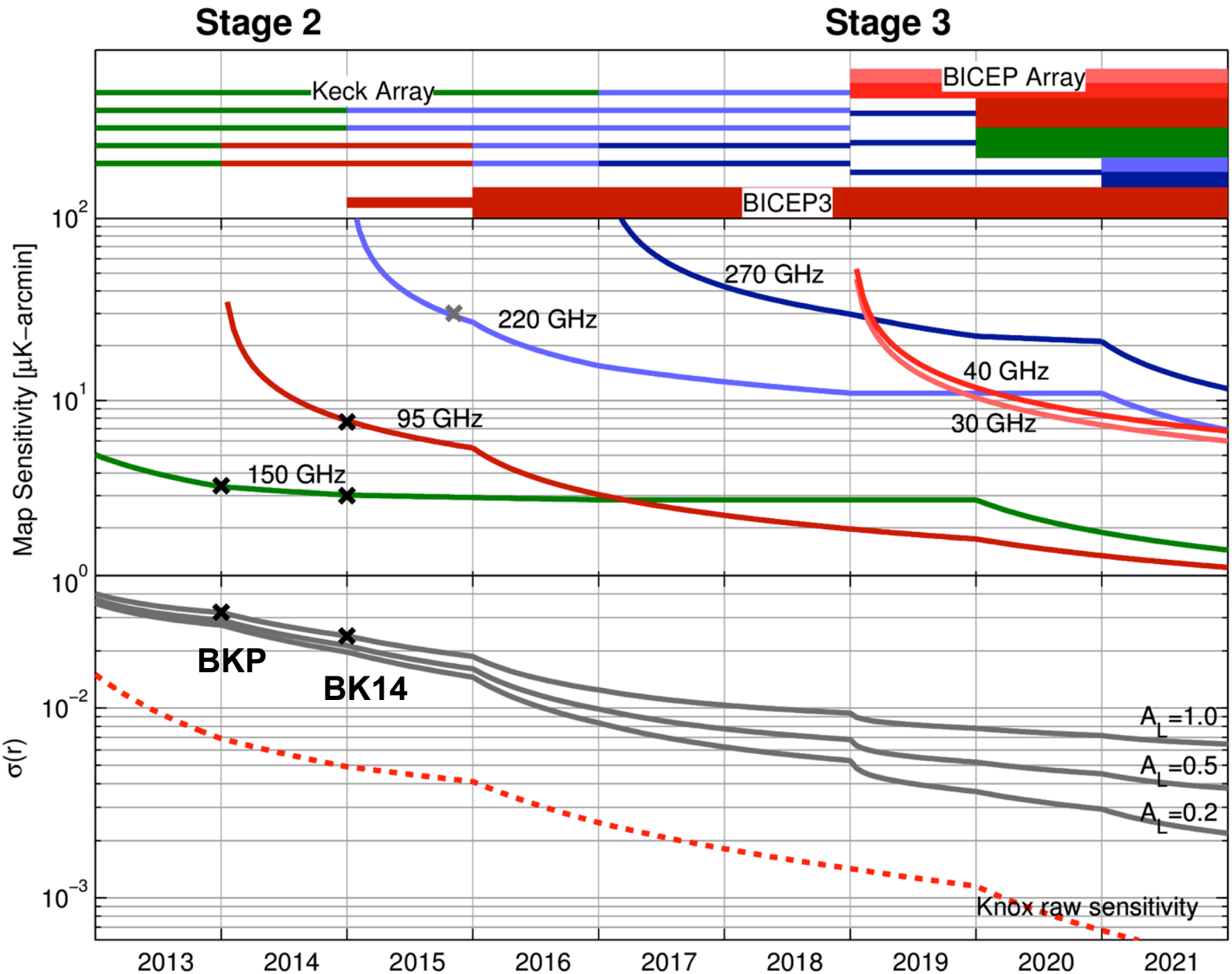
> 10x optical throughput of single BICEP2/Keck receiver



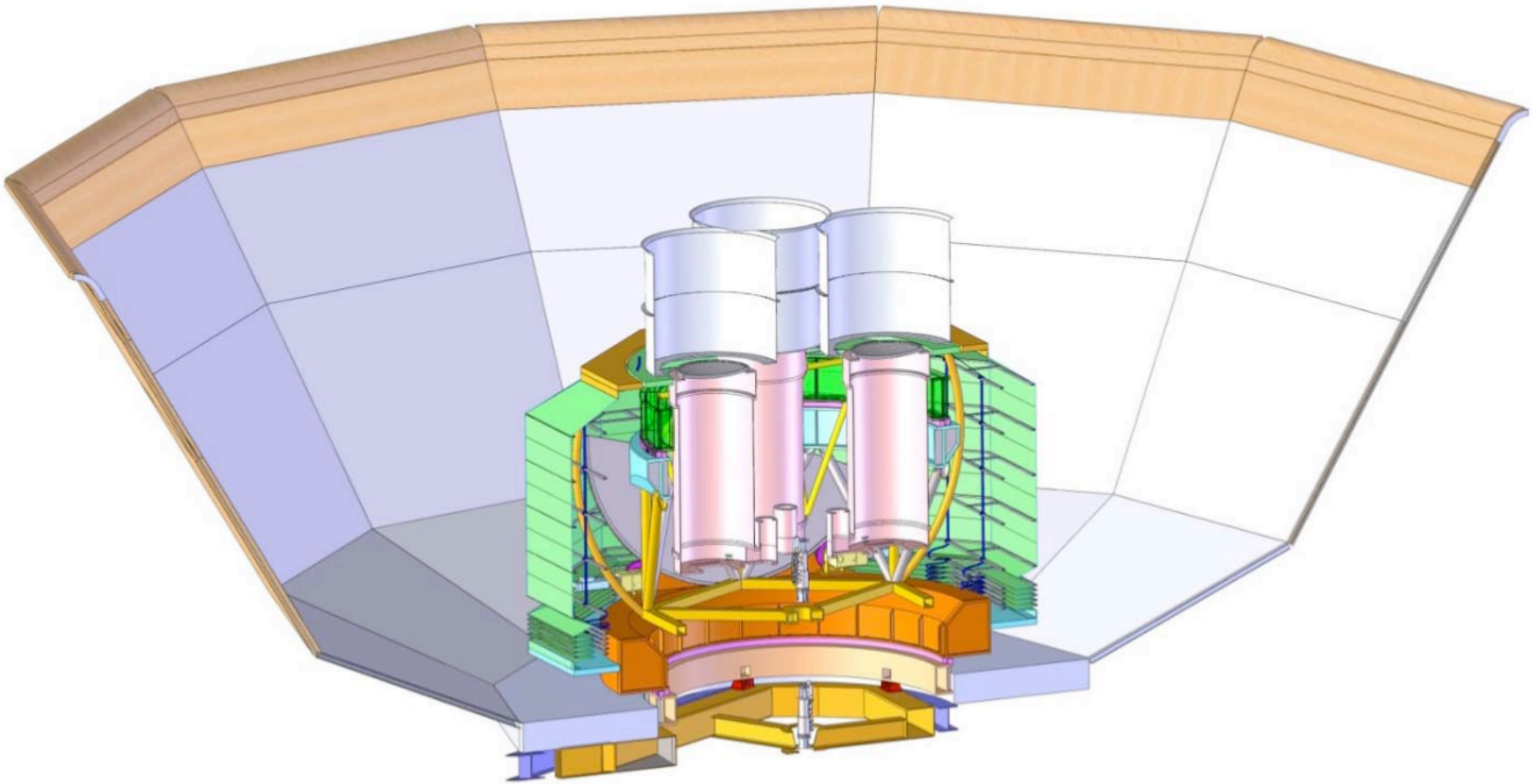
Stage 2

Stage 3

	BICEP2 (2010-2012)	Keck Array (2012-2017)	BICEP3 (2015-)	BICEP Array (2018-)
Telescope and Mount				
Focal Plane				
Beams on Sky				

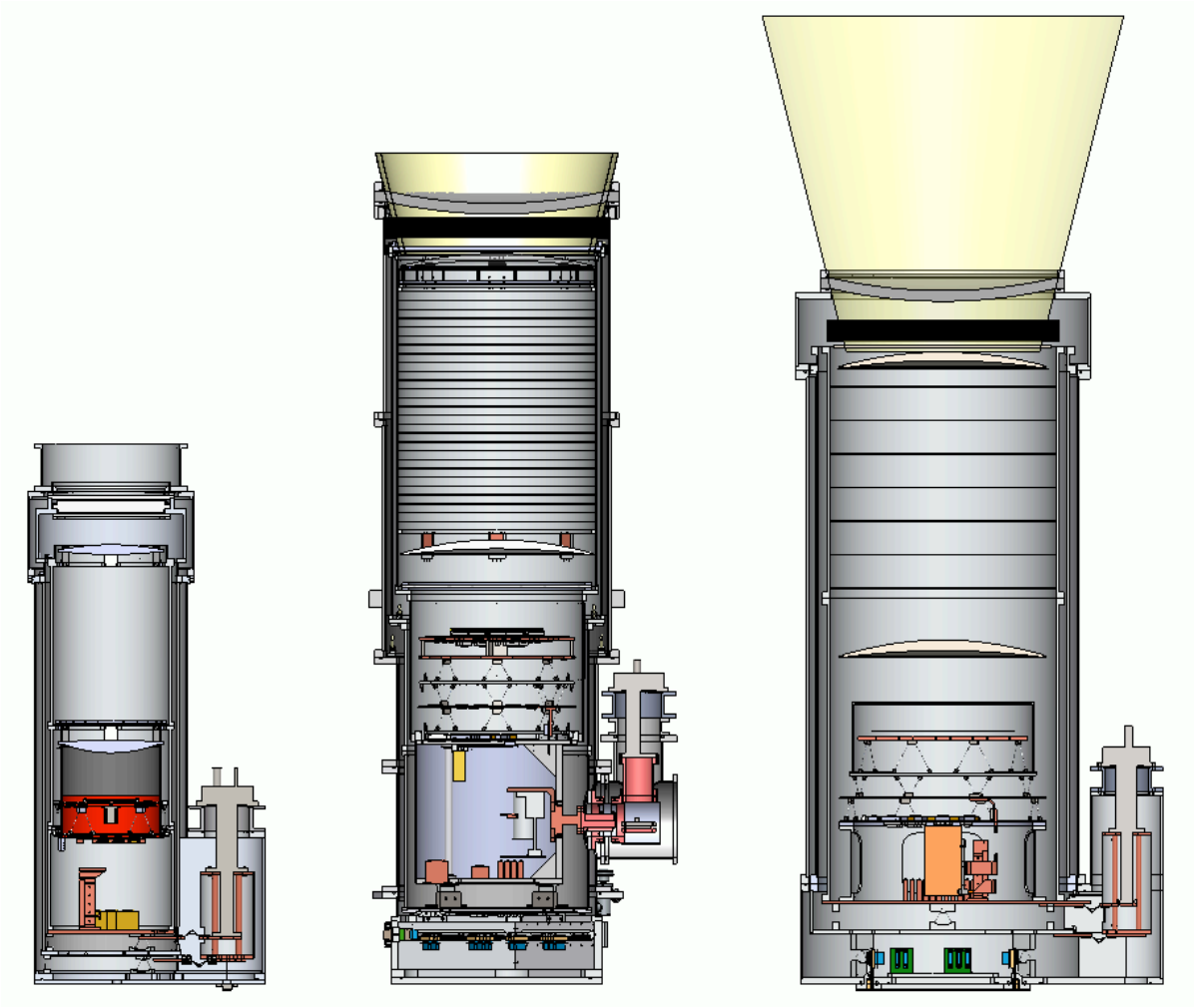

Stage 2
Stage 3
Keck Array
BICEP Array
BICEP3
270 GHz
220 GHz
40 GHz
30 GHz
95 GHz
150 GHz
Map Sensitivity [μK−arcmin]
10^2
10^1
10^0
BKP
BK14
A_L=1.0
A_L=0.5
A_L=0.2
Knox raw sensitivity
σ(r)
10^{-2}
10^{-3}
2013
2014
2015
2016
2017
2018
2019
2020
2021

Designing BICEP Array Telescope Mount



This time next year this machine will be in the PAN high-bay for outfitting – then it will be shipped to South Pole for installation

Designing BICEP Array Cryostat



Right now UMN grad student Mike Crumrine is designing the BICEP Array cryostat (right)

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 2014 data including, for the first time 95GHz data:
- Results in modest improvement: $r_{0.05}<0.12$ goes to $r_{0.05}<0.09$
- However this is an important milestone: for the first time B-mode only constraint exceeds the sensitivity of (Planck) TT derived constraint ($r_{0.05}<0.12$)

- And we can go much further:
- 2015 data also includes 220GHz - $\sigma(r)=0.018$
- And BICEP3 is now online at 95GHz
- …and we have BIG plans for the BICEP3G-Array – $\sigma(r)=0.005$

- And beyond that is mega experiment CMB-S4…

Backup Slides