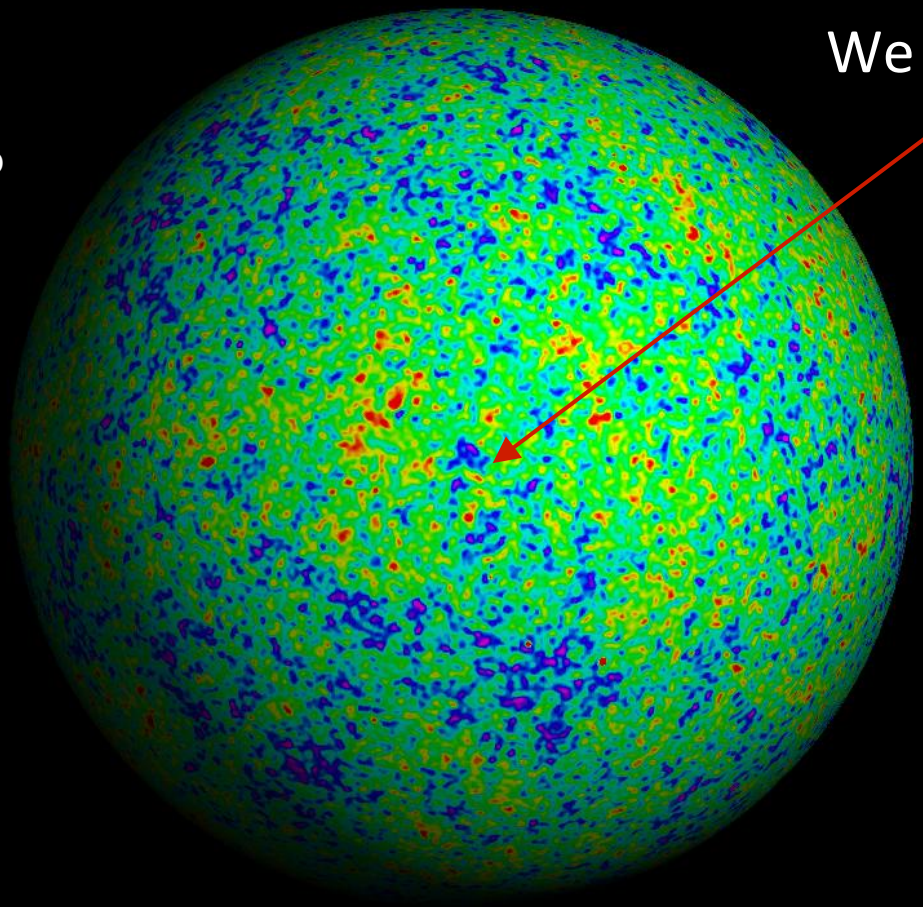
Pursuing the Shadows of Gravitational Waves from the Beginning of Time with BICEP/Keck and Future Experiments

Clem Pryke for the BICEP/Keck Collaboration – Rencontres du Vietnam – Aug 8 2018

Cosmic Microwave Background Surface of Last Scattering

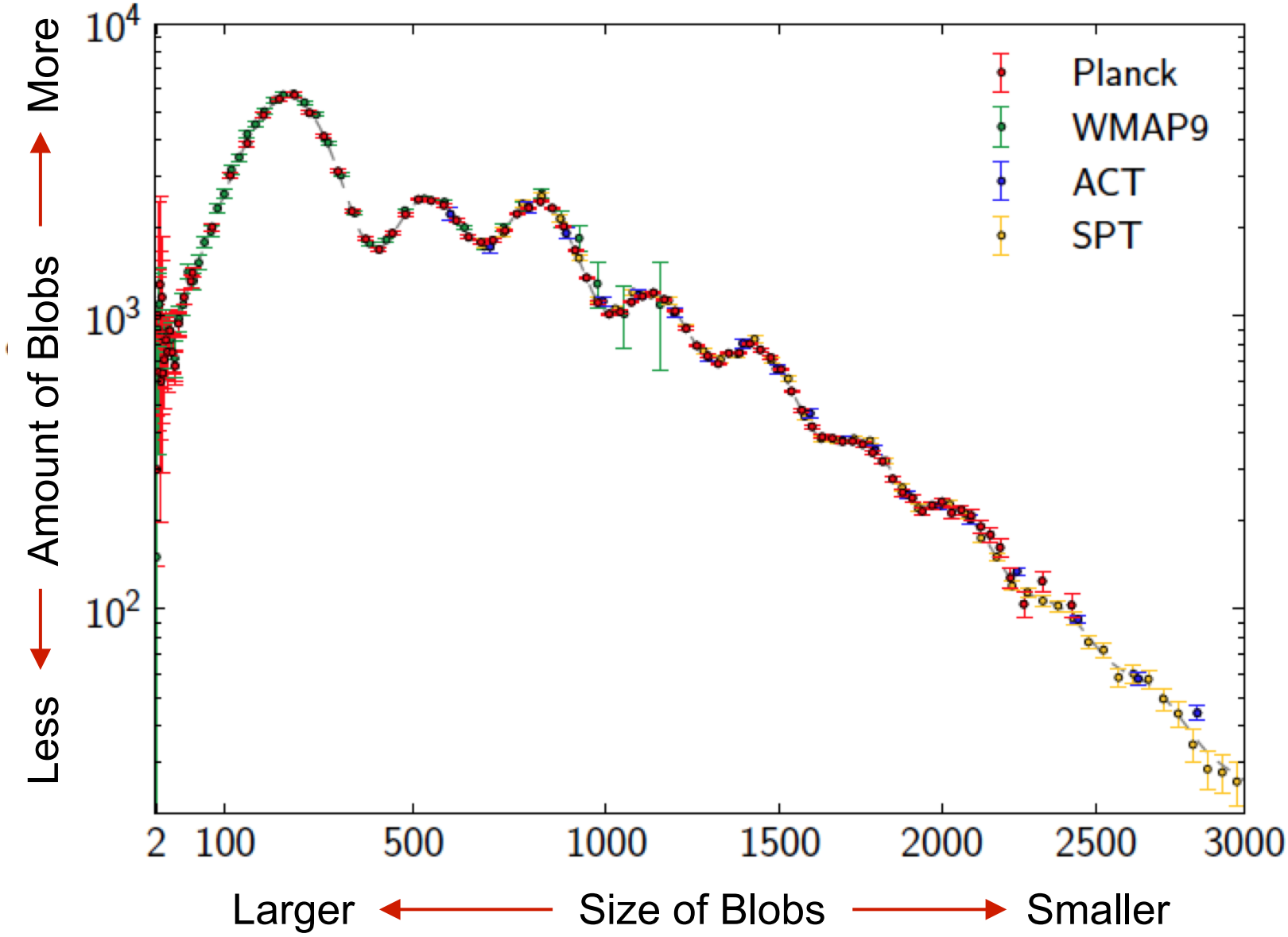
All sky temperature map
projected on a sphere



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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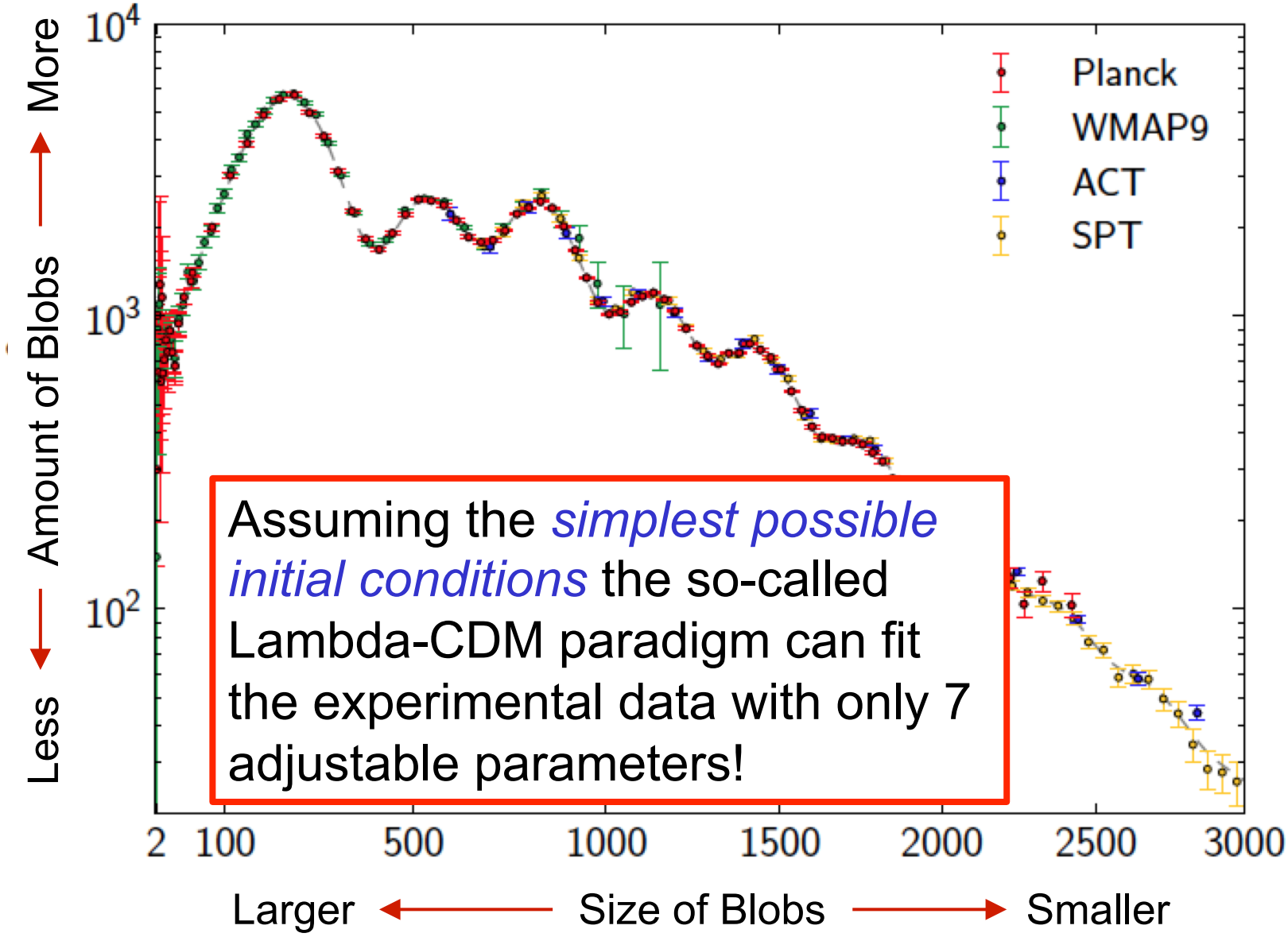
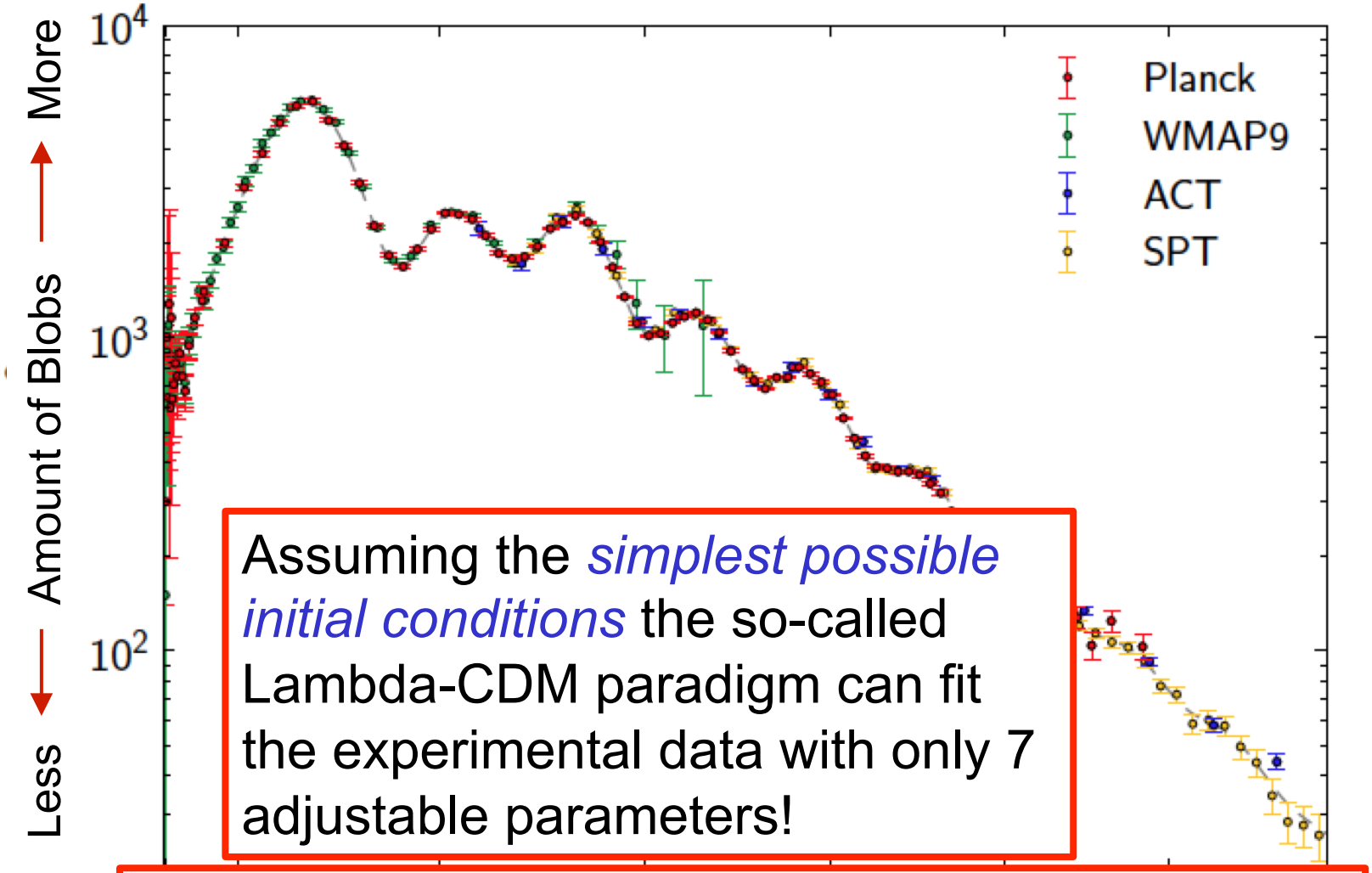


Power Spectrum (Blob size histogram)

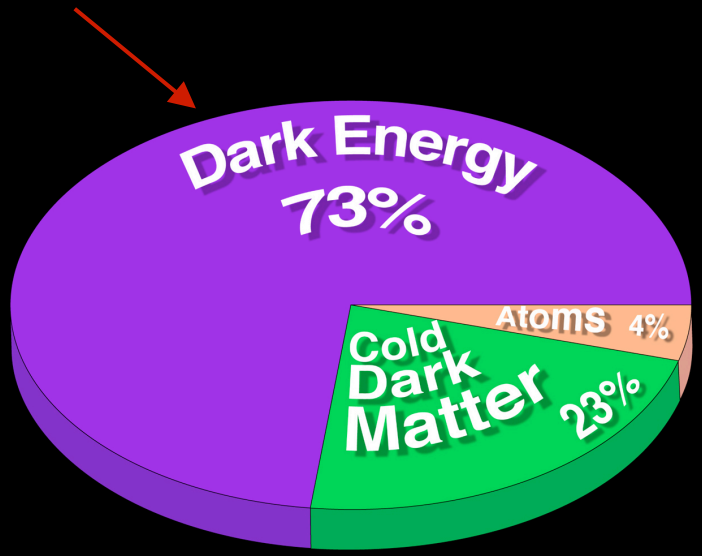


Assuming the *simplest possible initial conditions* the so-called Lambda-CDM paradigm can fit the experimental data with only 7 adjustable parameters!

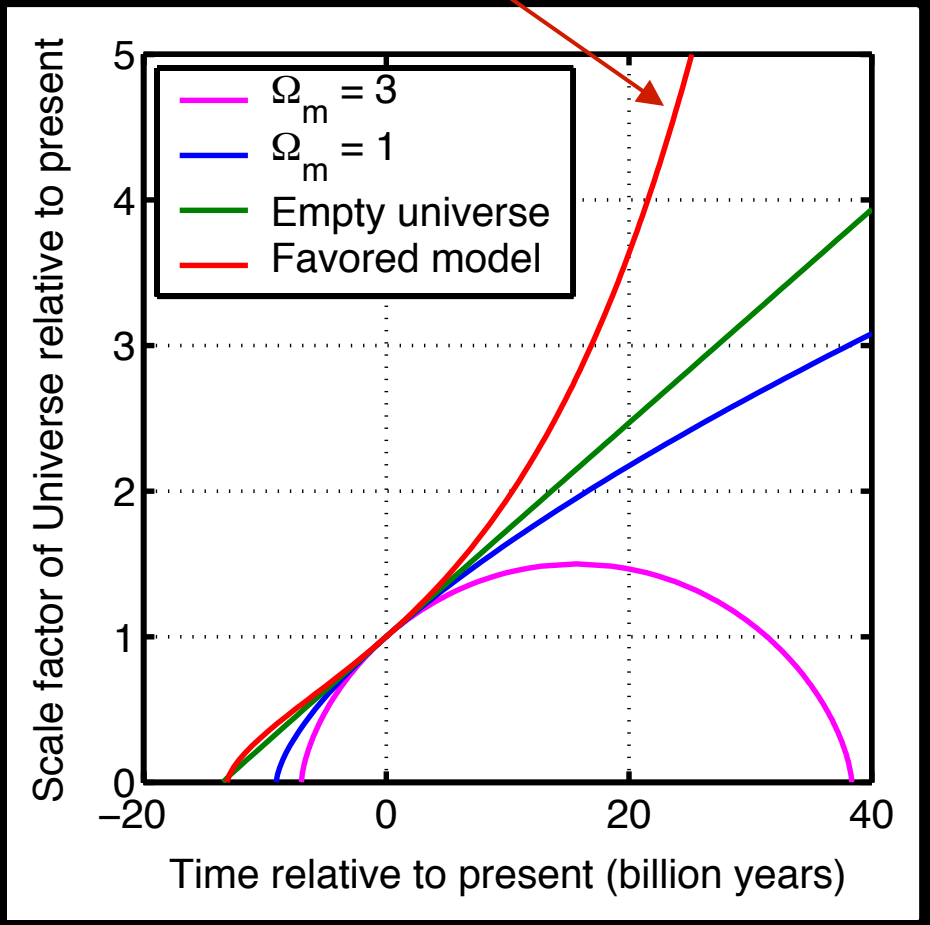
Compare that to the 26 parameters of the (extended) standard model of particle physics ;-)

Triumphant/Embarrassing LCDM

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…



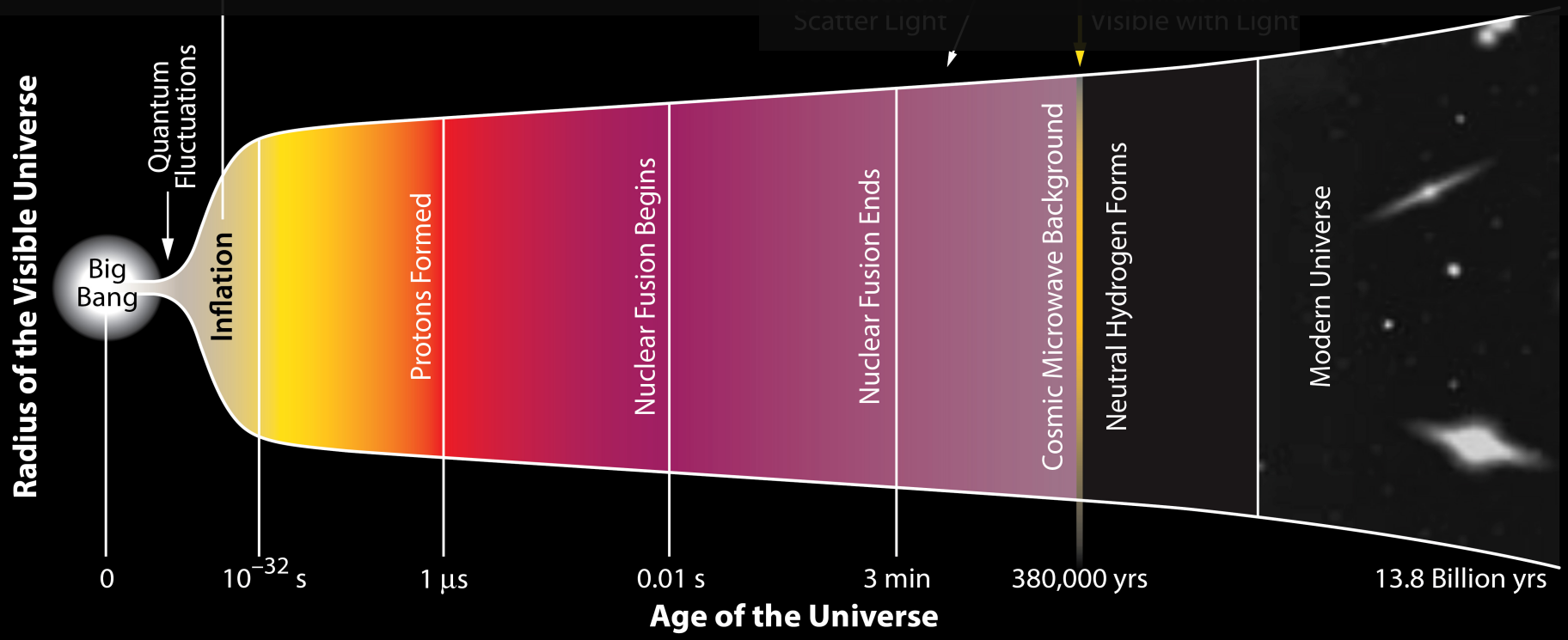
Also it doesn't explain horizon/flatness etc…

History of the Universe

Inflation posits a pre-phase of exponential expansion before LCDM

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 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 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

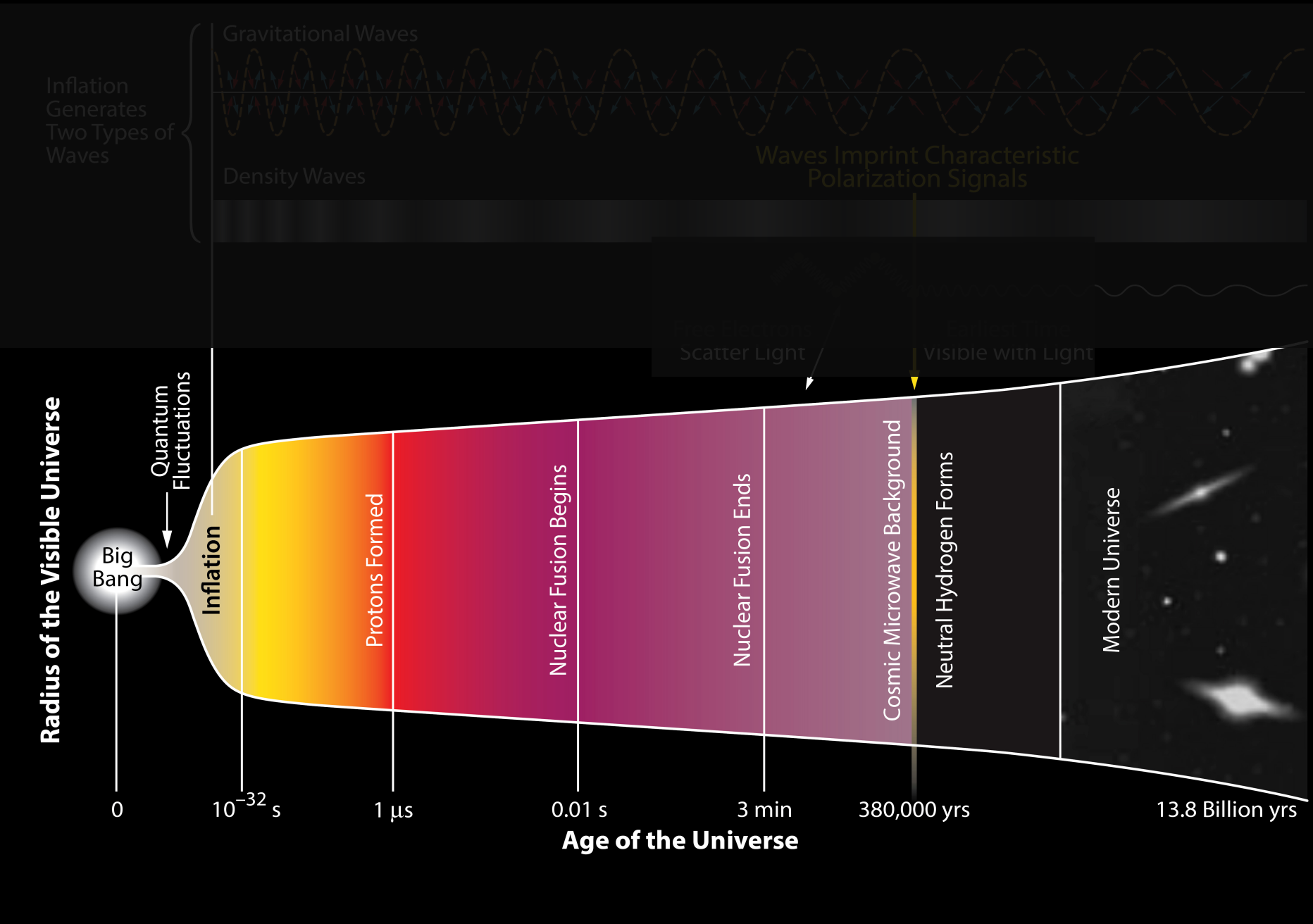
Anna Ijjas,[1,2] Paul J. Steinhardt,[3] and Abraham Loeb[4]

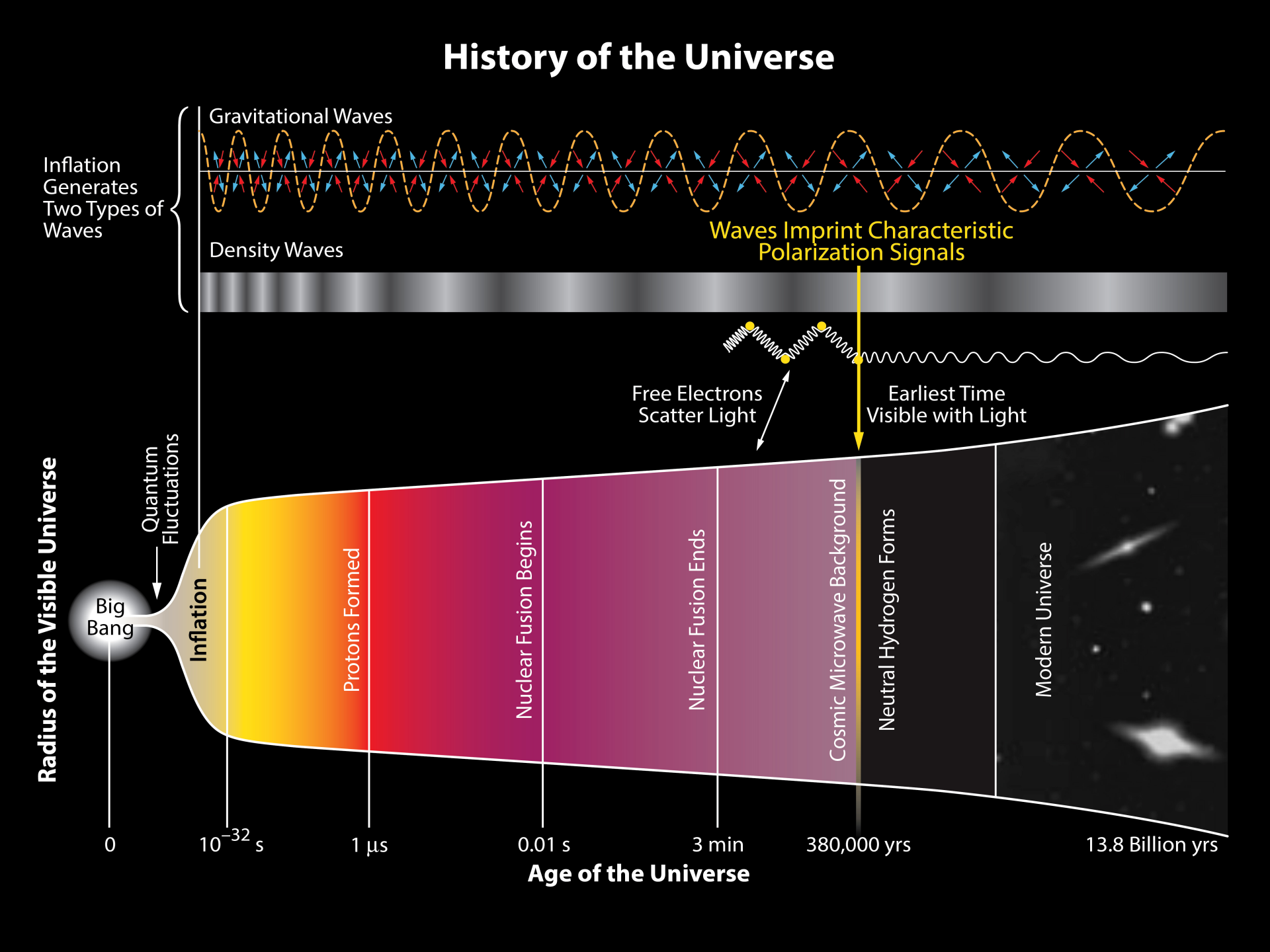
[1] *Max-Planck-Institute for Gravitational Physics (Albert-Einstein-Institute), 14476 P*
[2] *Rutgers University, New Brunswick, NJ 08901, USA*
[3] *Department of Physics and Princeton Center for Theoretical Scien*
Princeton University, Princeton, NJ 08544, USA
[4] *Harvard-Smithsonian Center for Astrophysics,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

(Dated: March 14, 2014)

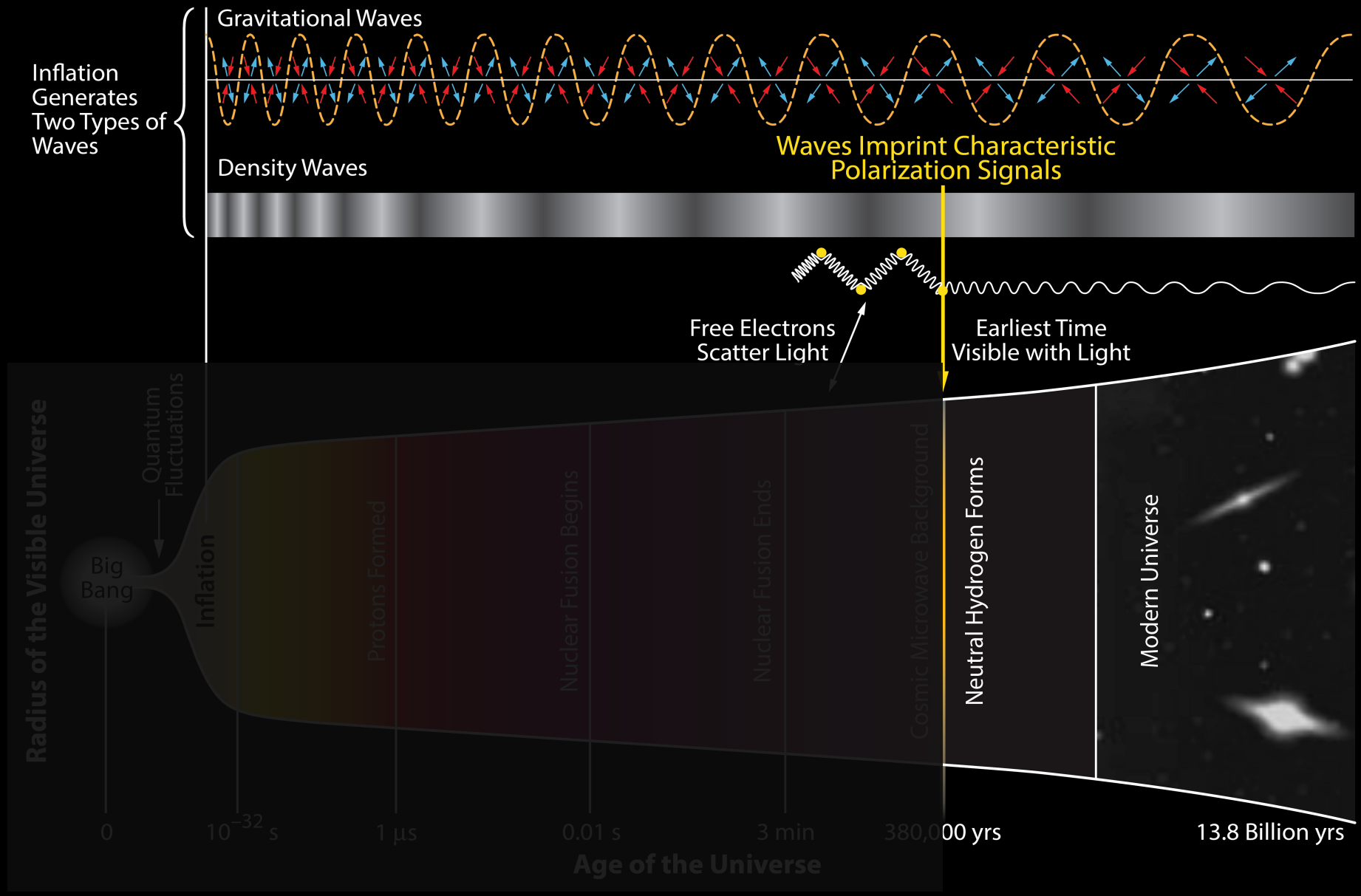
arxiv/1402.6980

History of the Universe

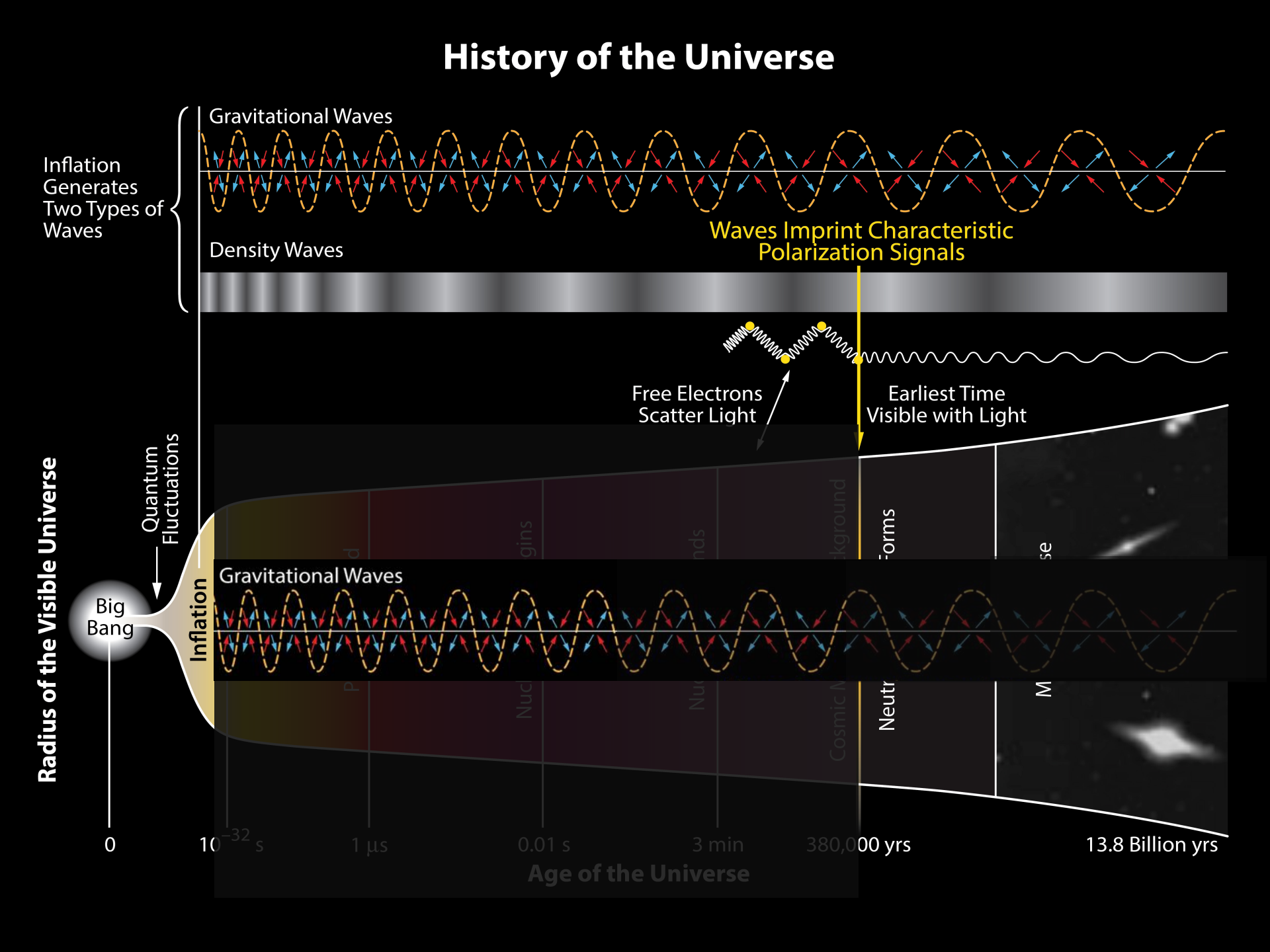



History of the Universe
Inflation Generates Two Types of Waves
Gravitational Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Radius of the Visible Universe
Quantum Fluctuations
Big Bang
Inflation
Protons Formed
Nuclear 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

History of the Universe



History of the Universe



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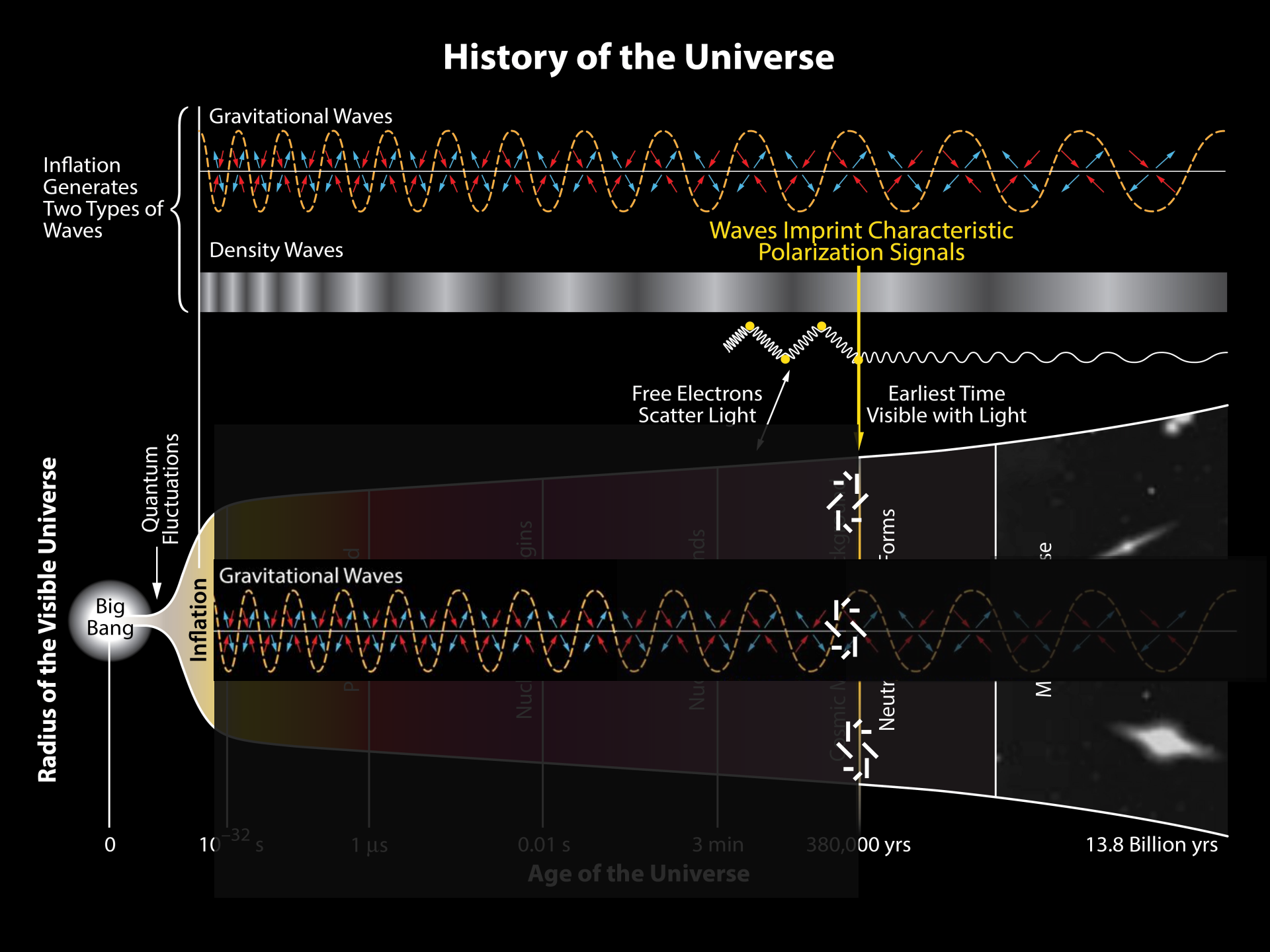

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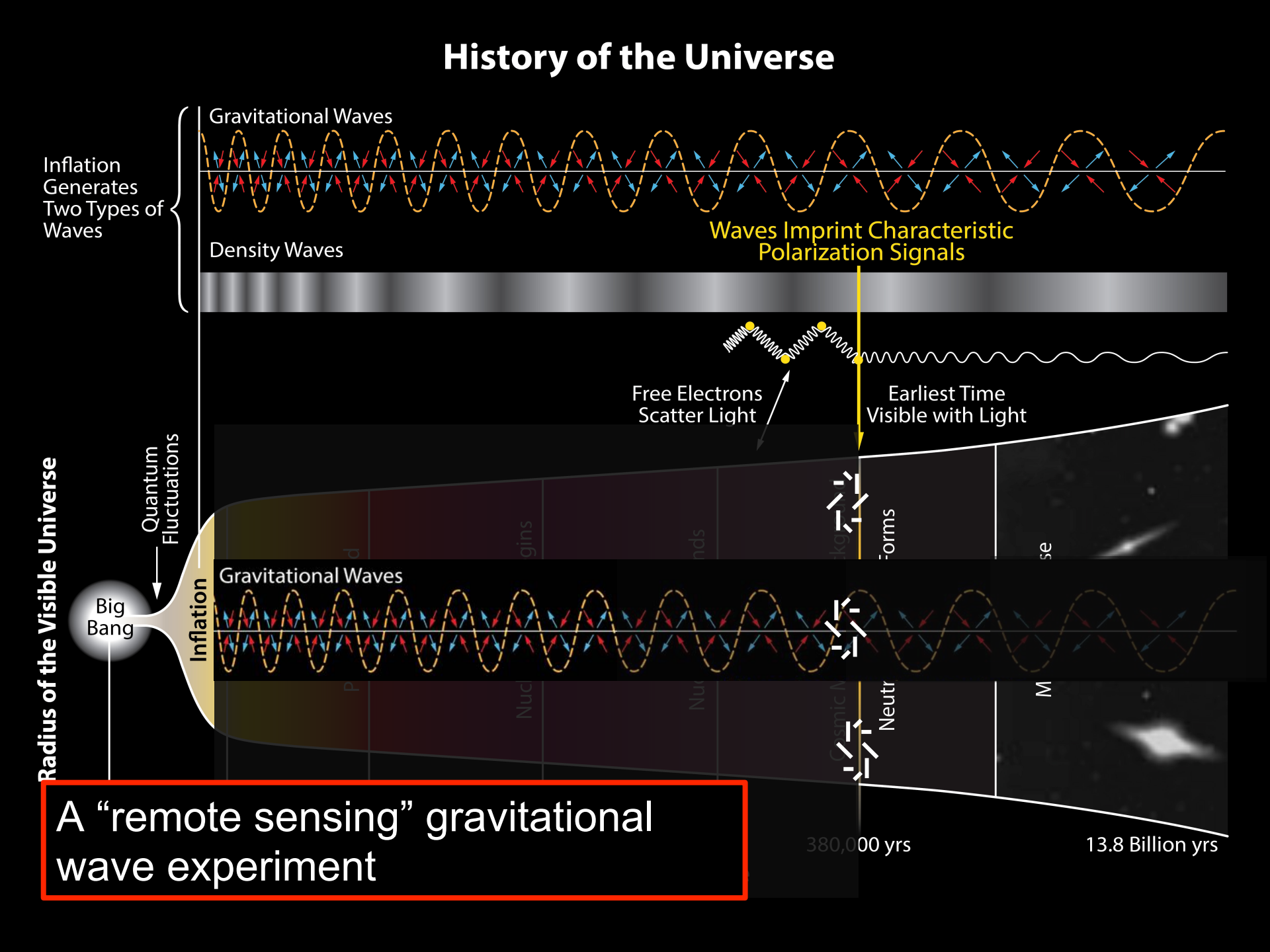

A “remote sensing” gravitational wave experiment

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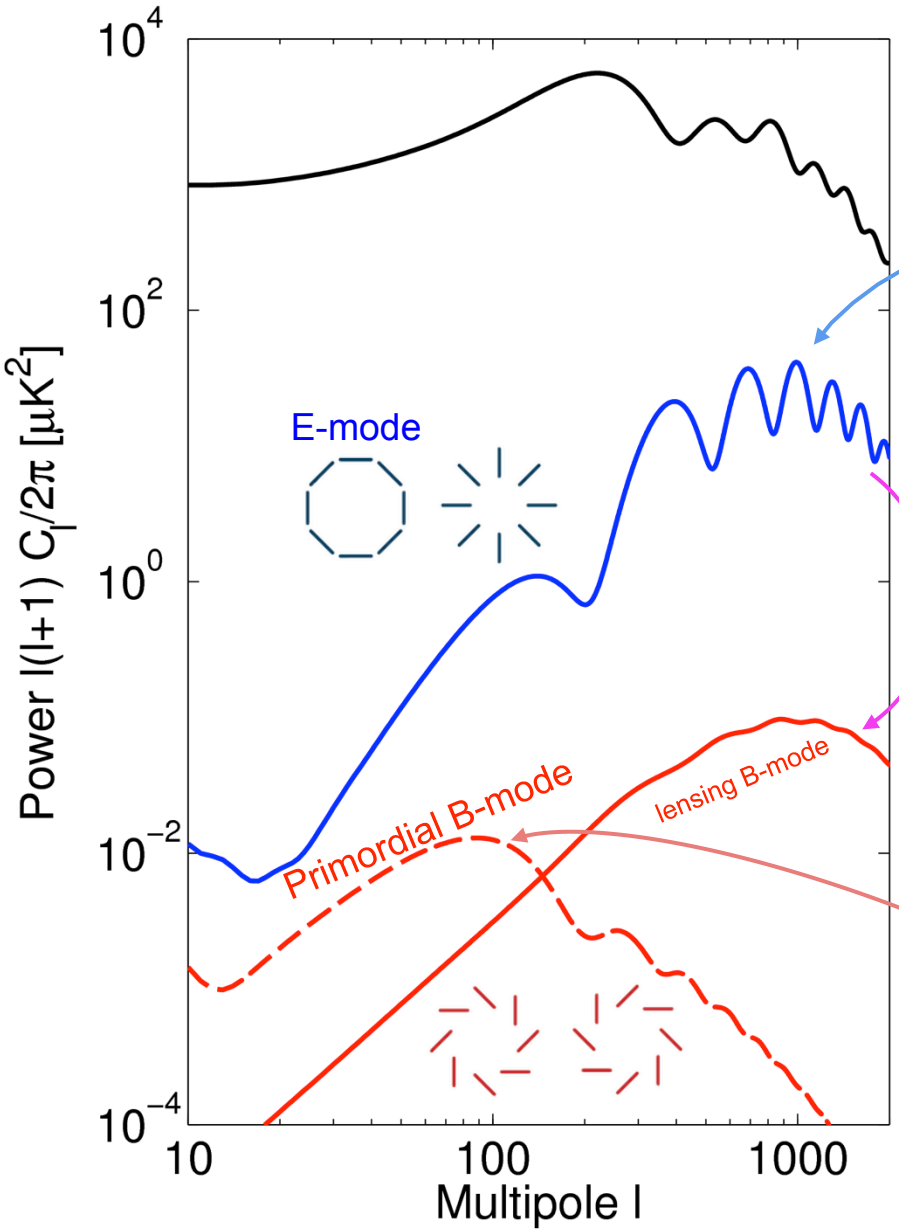
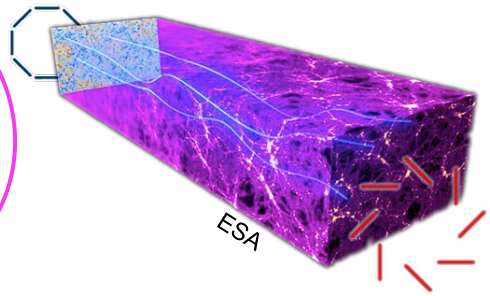
Warning: It's a bit like the search for proton decay – a well motivated physics target to look for, but theories can be adjusted to make the amplitude arbitrarily small…

CMB Polarization power spectra



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

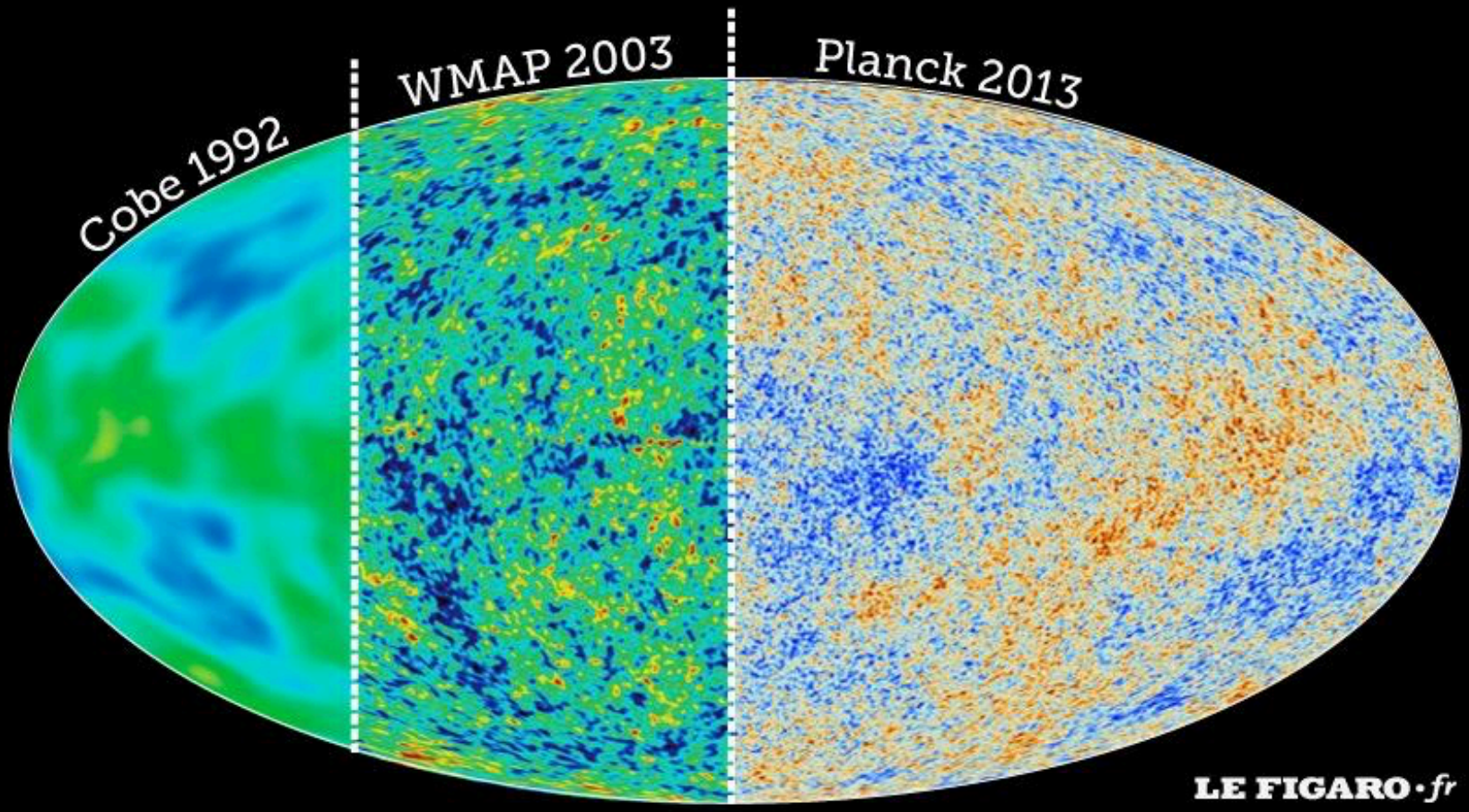


During propagation some of the E-modes are confused into B-modes by lensing

Inflationary gravitational waves are unique source of intrinsic B-modes
→ peaking at l≈80 : degree scales

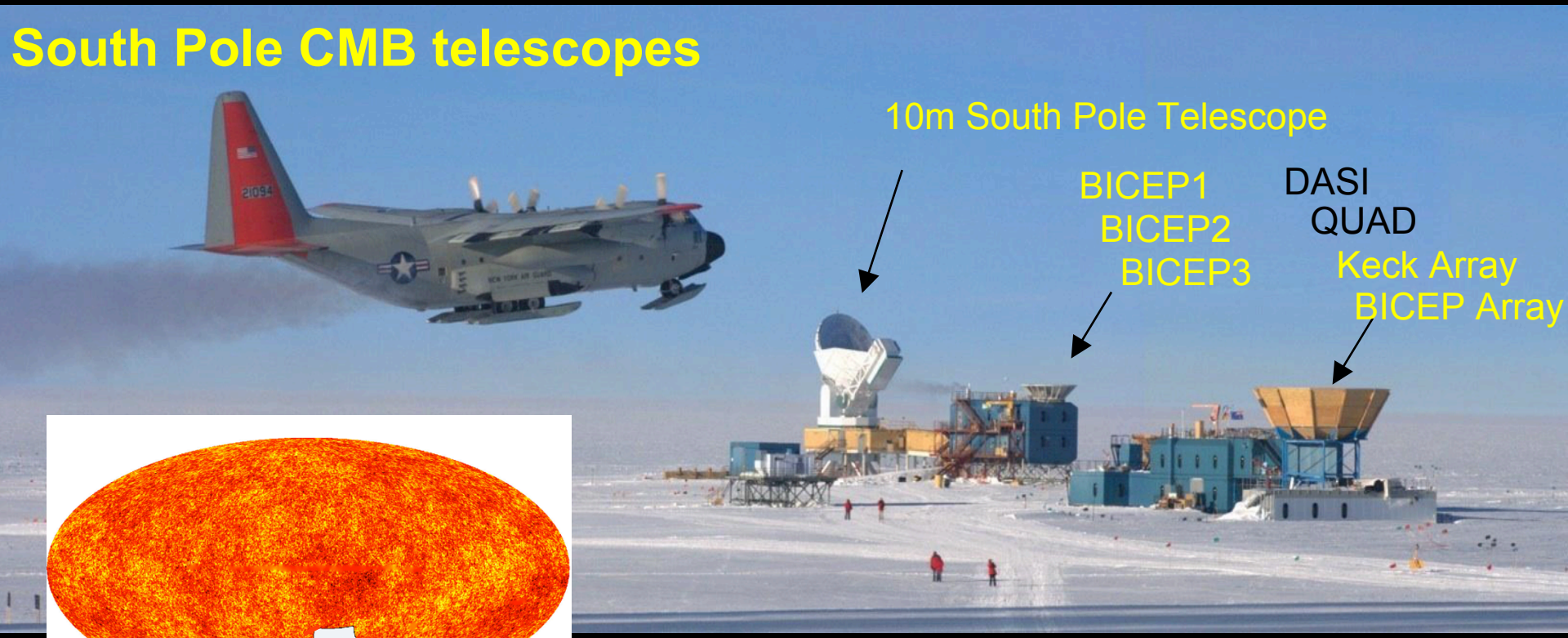
The BICEP/Keck Collaboration

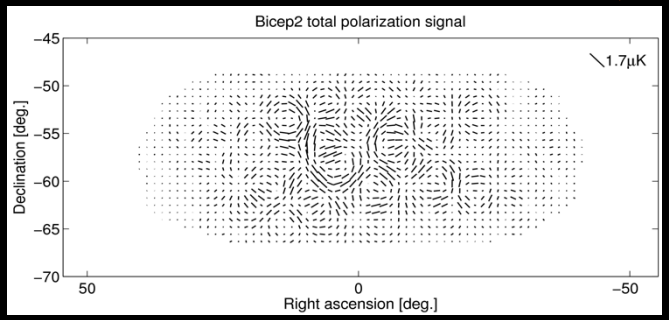
CMB space missions map the full sky



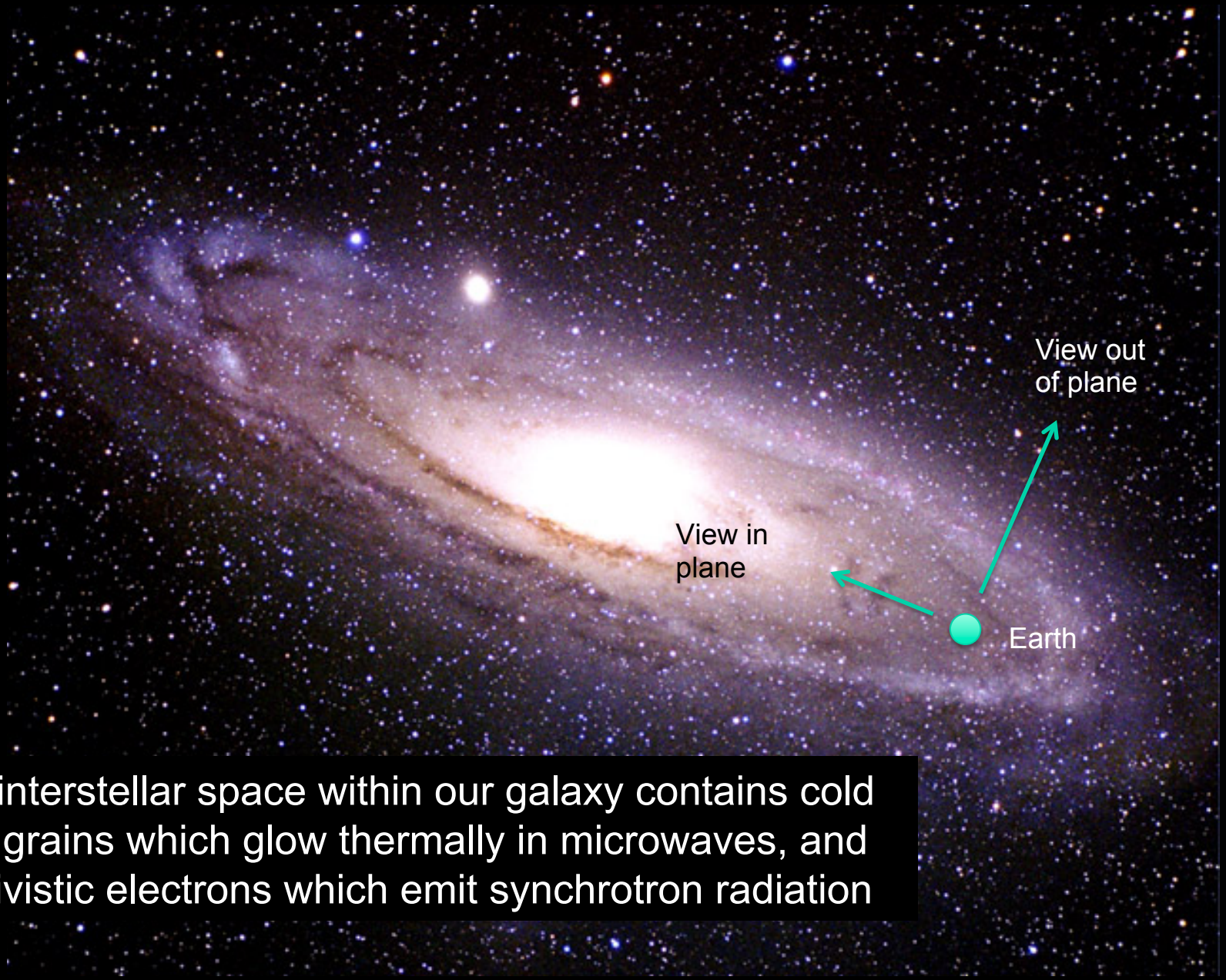
Ground based telescopes map part of the sky more deeply

South Pole CMB telescopes





Foreground emission from our galaxy

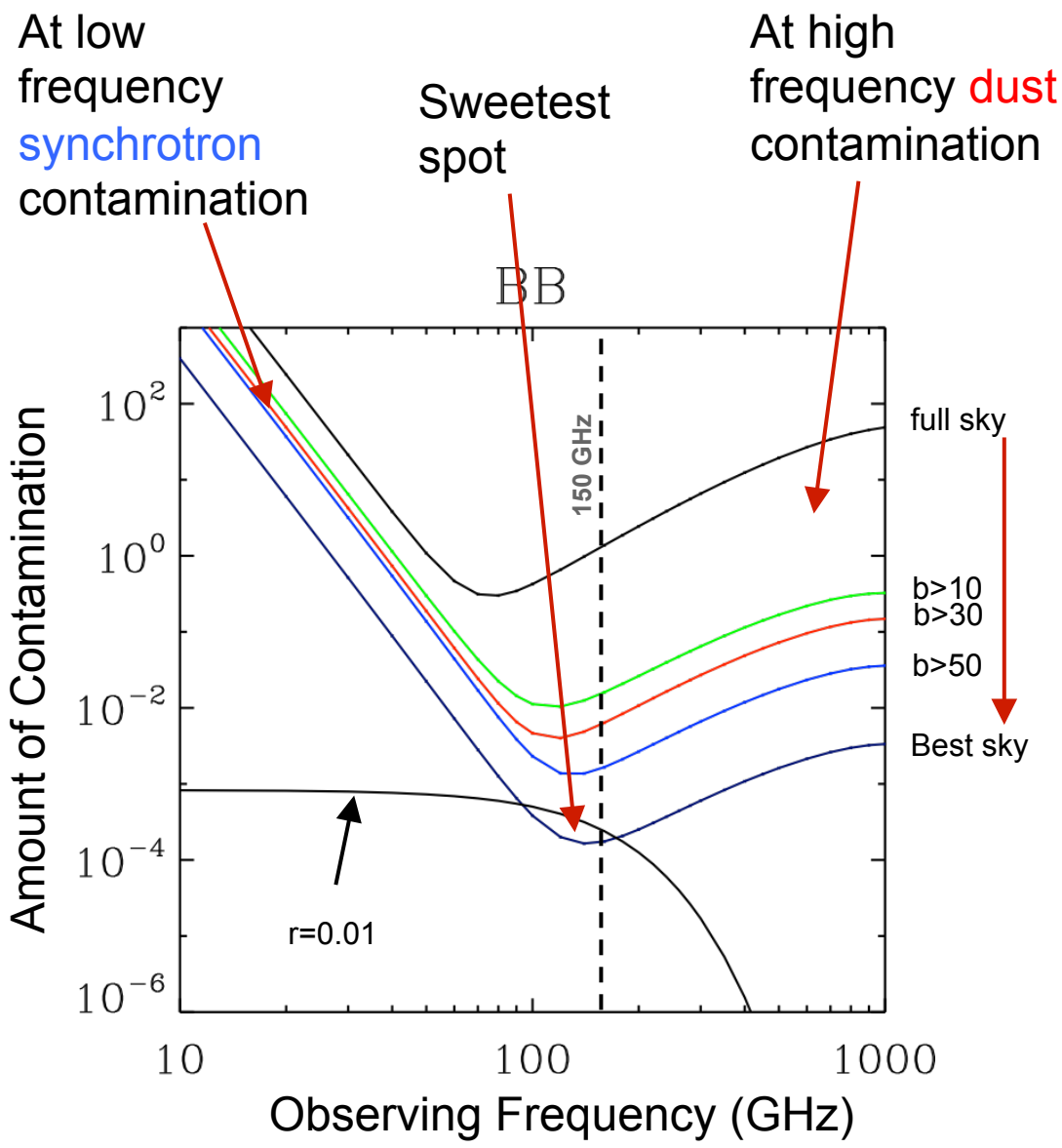


The interstellar space within our galaxy contains cold dust grains which glow thermally in microwaves, and relativistic electrons which emit synchrotron radiation

Foreground emission from our 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.

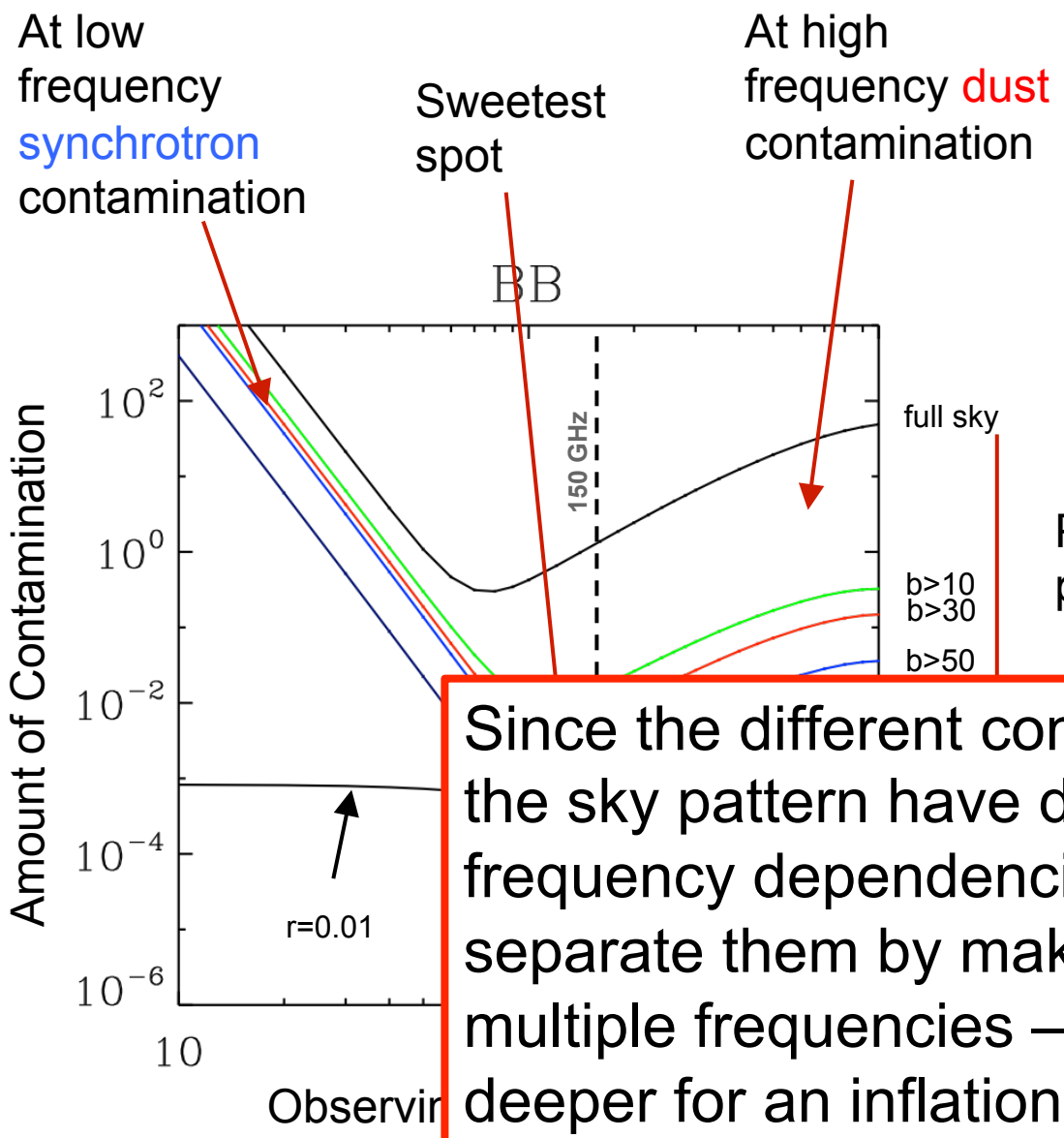
Polarized Foreground Contamination from Our Galaxy



Pick a cleaner patch of sky

(Plot from Dunkley et al arxiv/0811.3915)

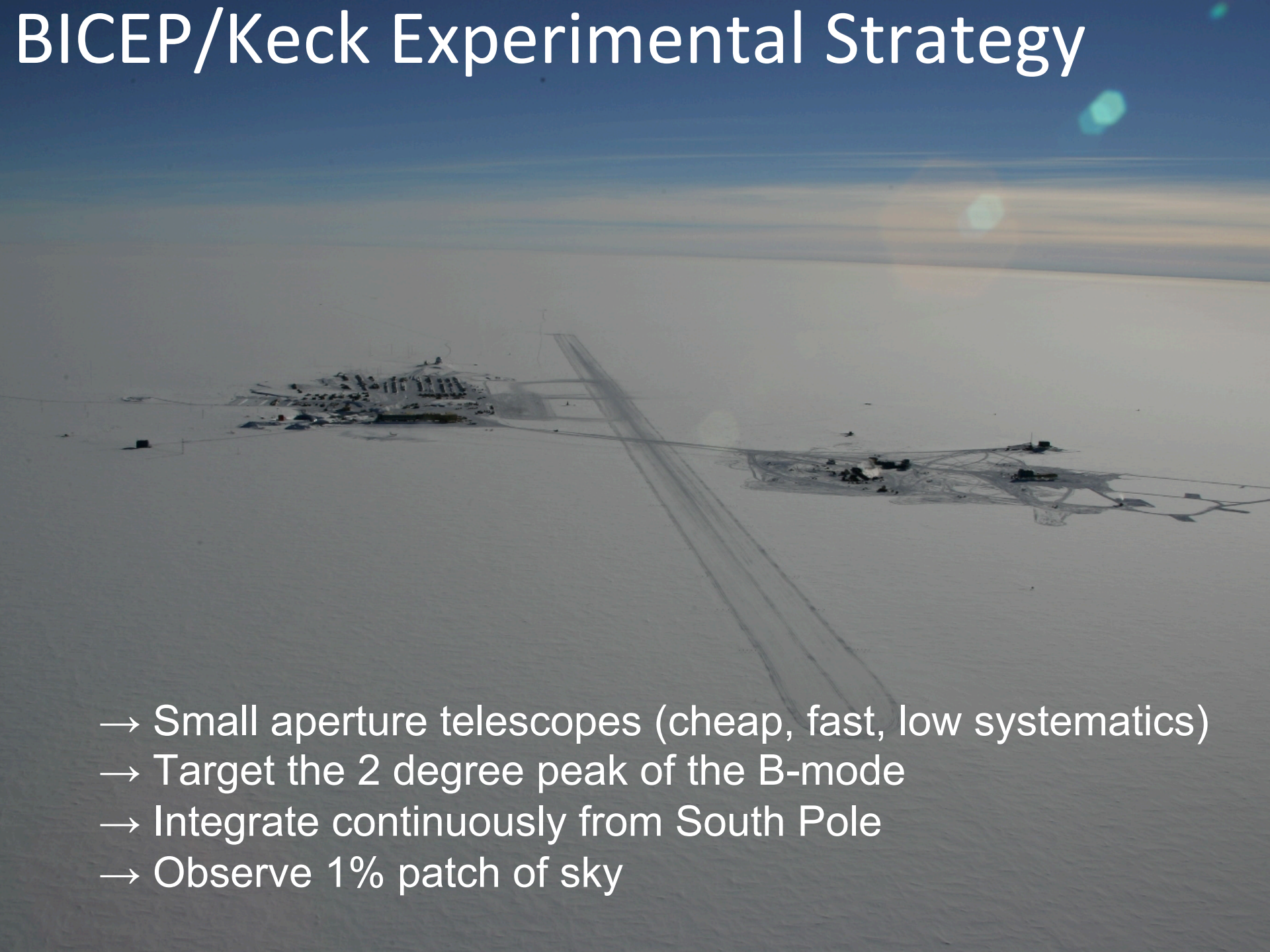
Polarized Foreground Contamination from Our Galaxy



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

BICEP/Keck 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

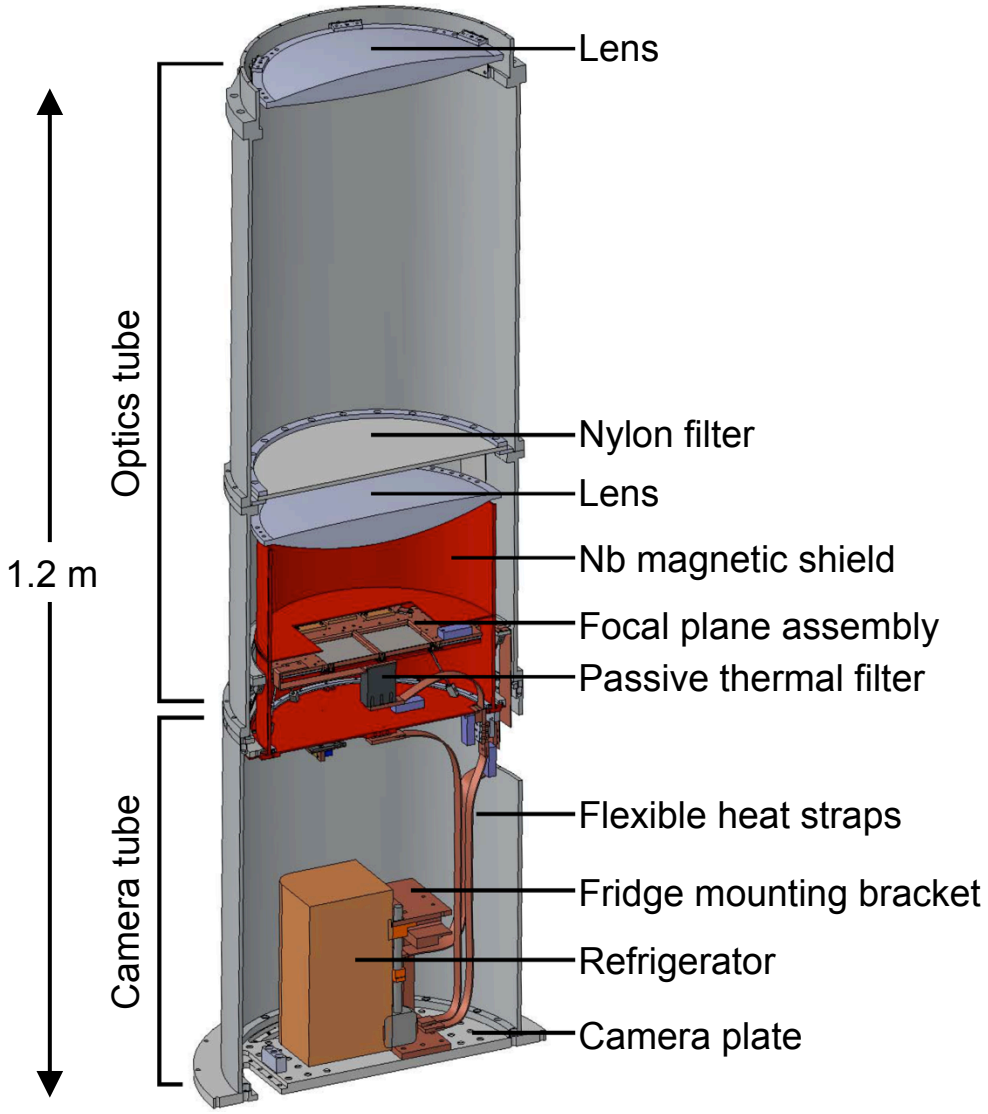
The BICEP/Keck Telescopes

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

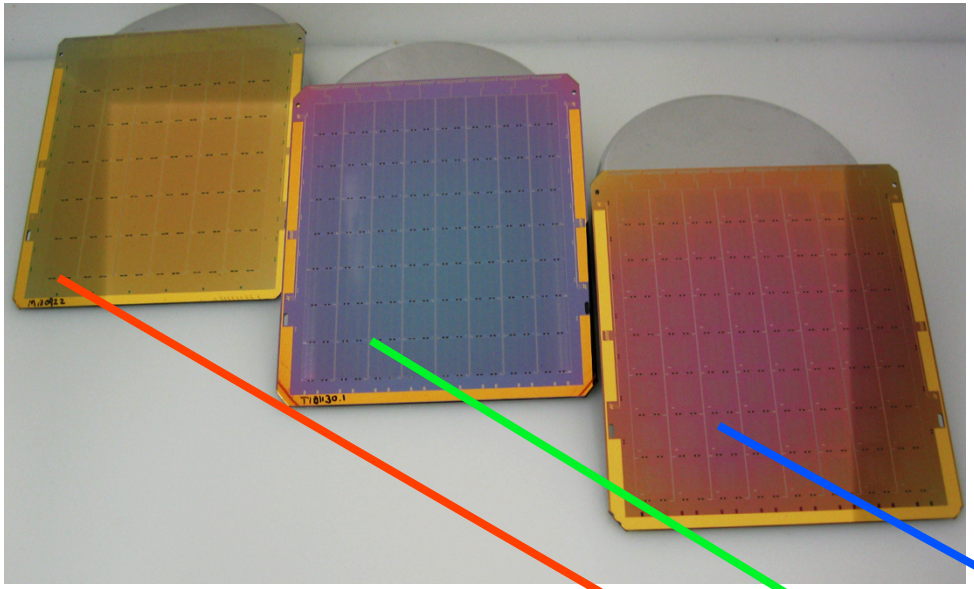
On-axis, refractive optics allow the entire telescope to rotate around boresight for polarization modulation

Liquid helium/pulse tube cools the optical elements to 4 K

3-stage helium sorption refrigerator further cools the detectors to 0.27 K

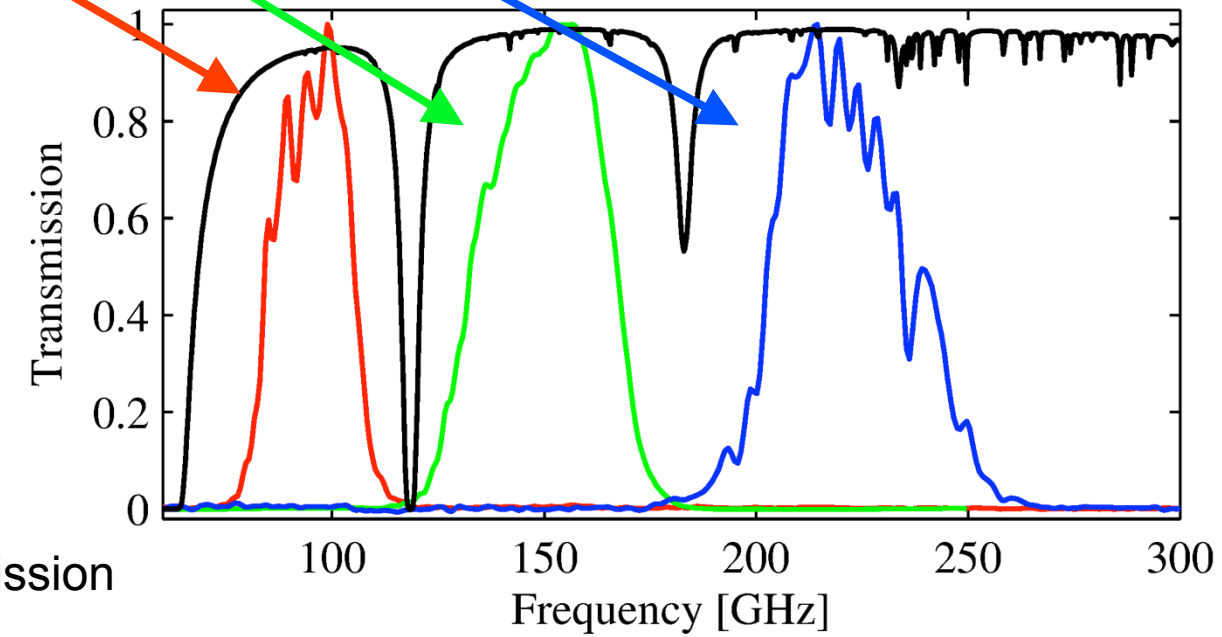


Planar superconducting detector arrays



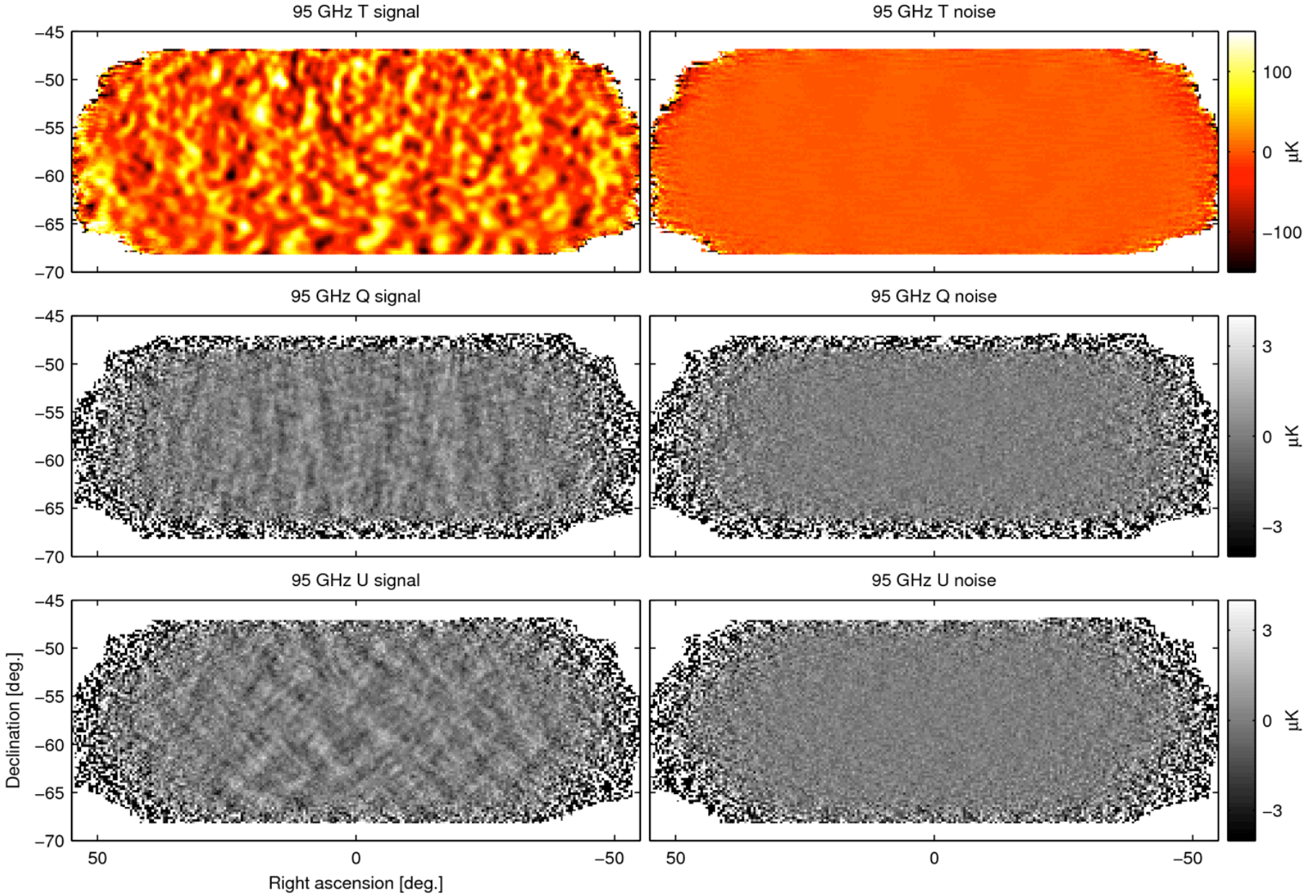
…designed to scale
in frequency

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



Typical South Pole
atmospheric transmission

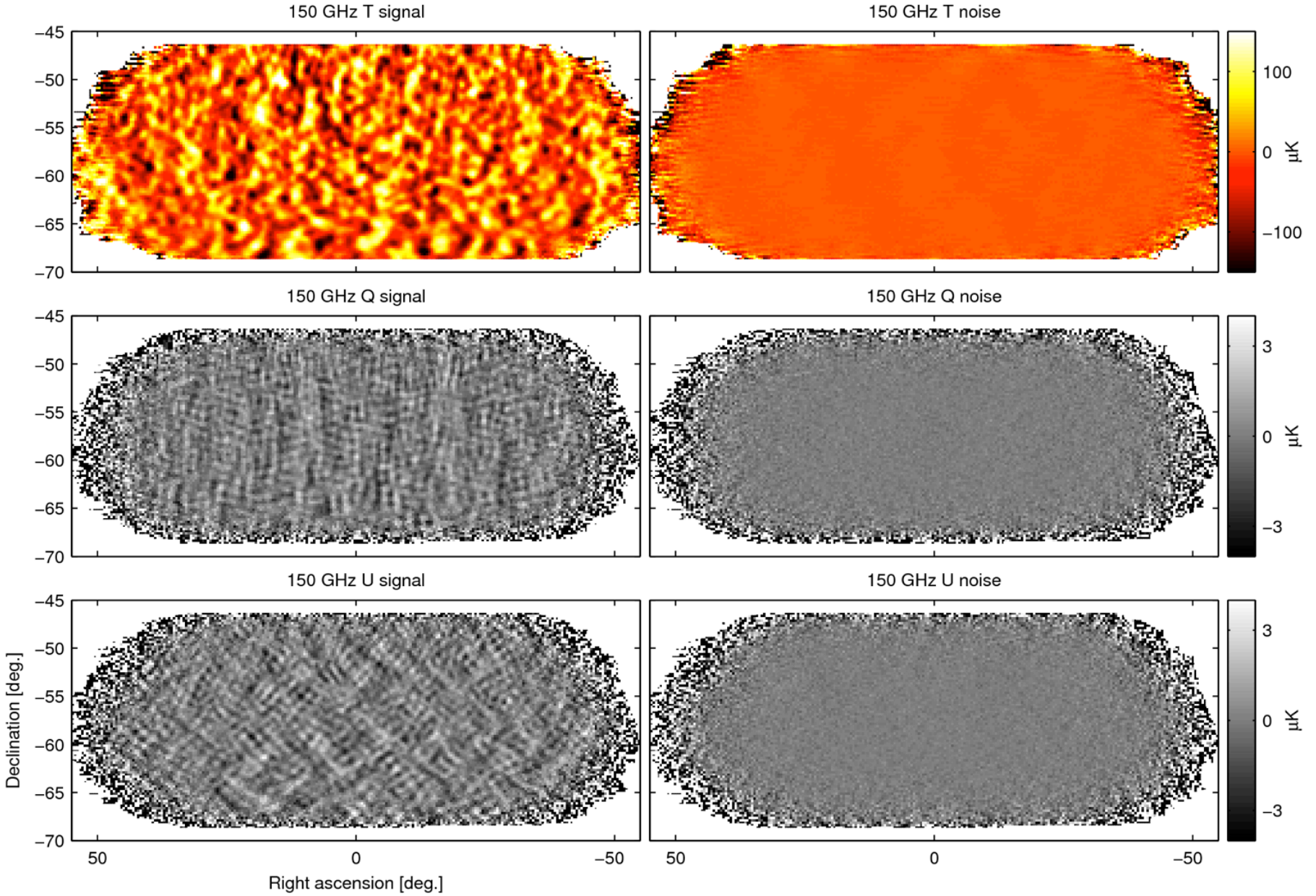
BK15 95GHz Maps



The BICEP/Keck Collaboration

BK15 95GHz – 5 μK arcmin

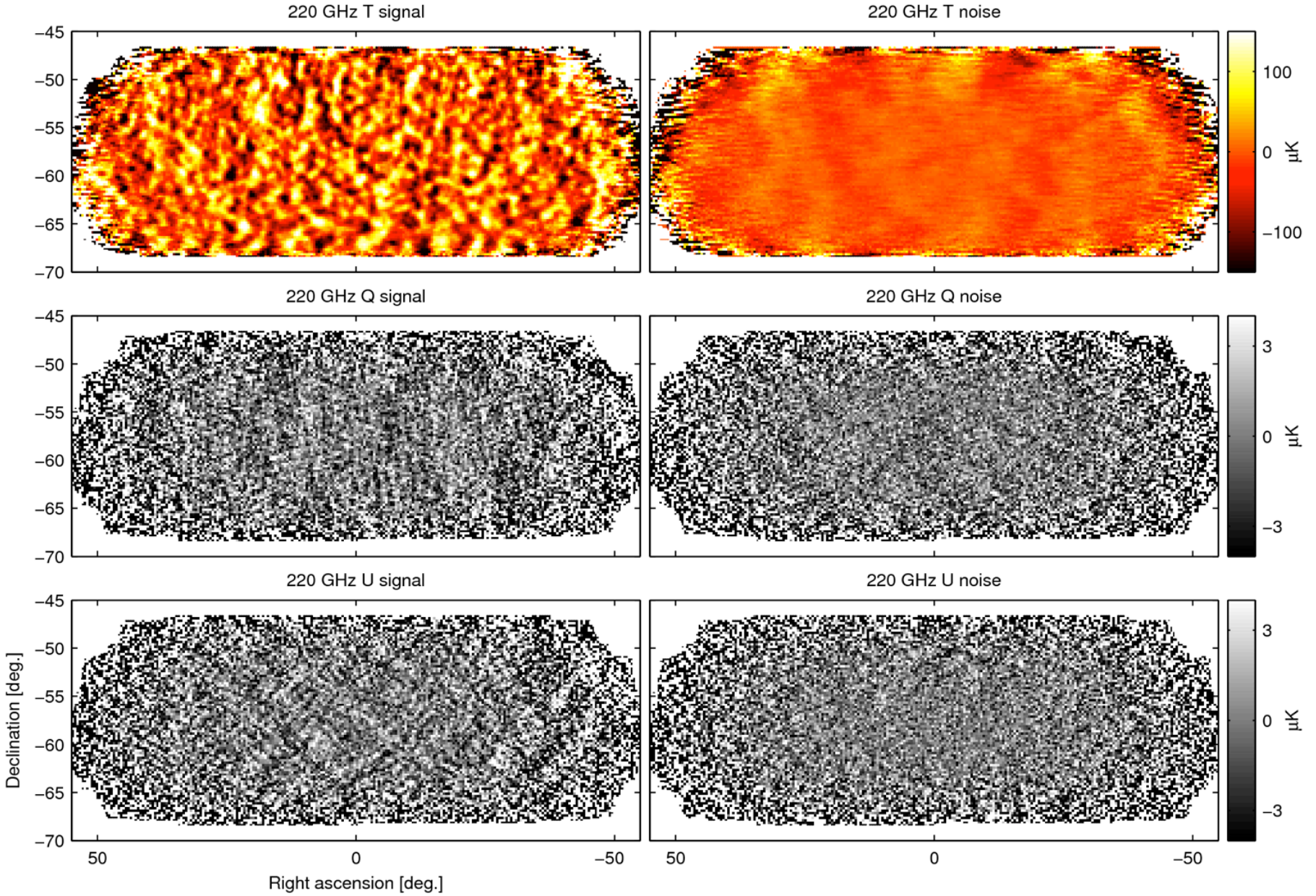
BK15 150GHz Maps



The BICEP/Keck Collaboration

BK15 150GHz – 2.8 μK arcmin

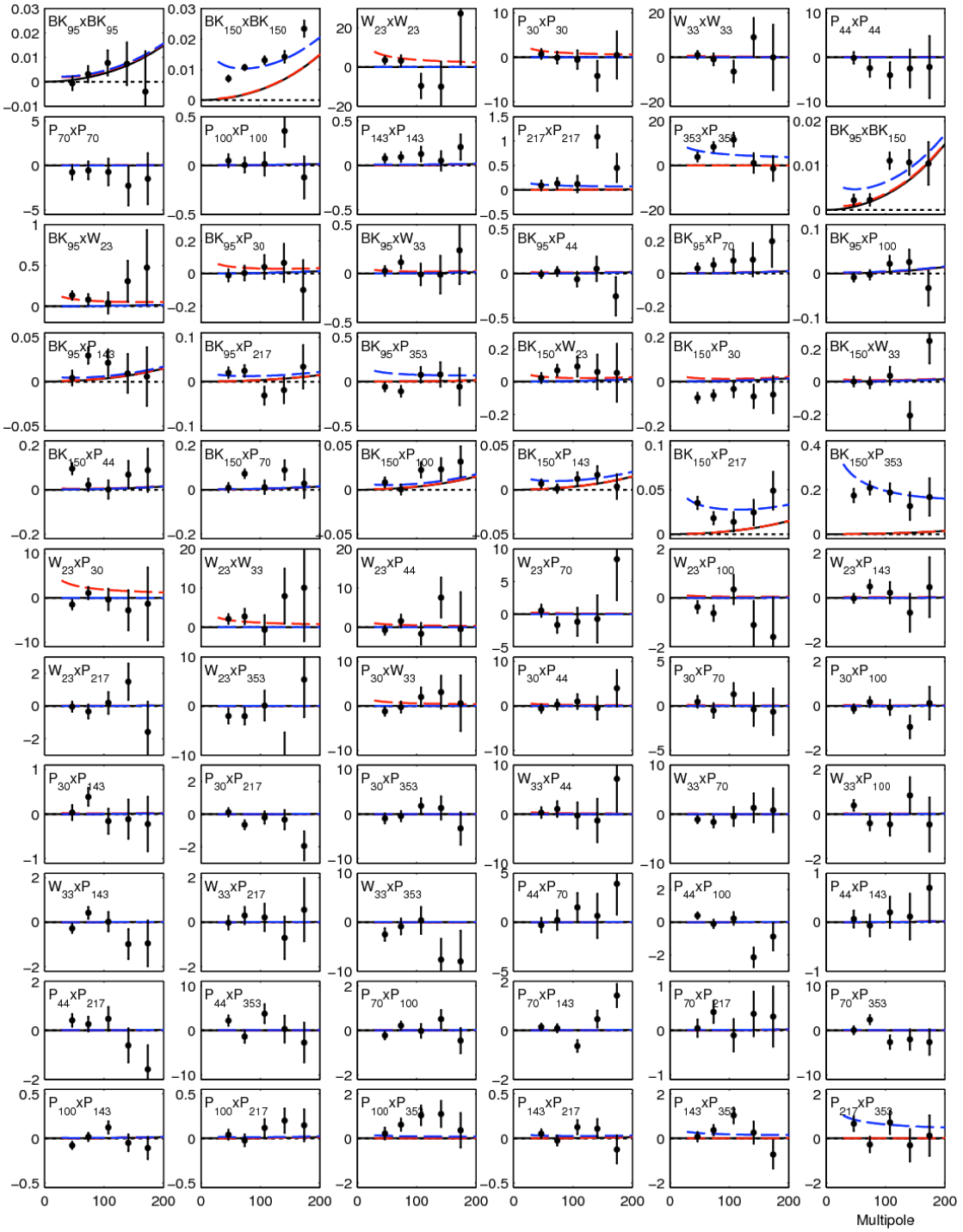
BK15 220GHz Maps



The BICEP/Keck Collaboration

BK15 220GHz – 25 μK arcmin

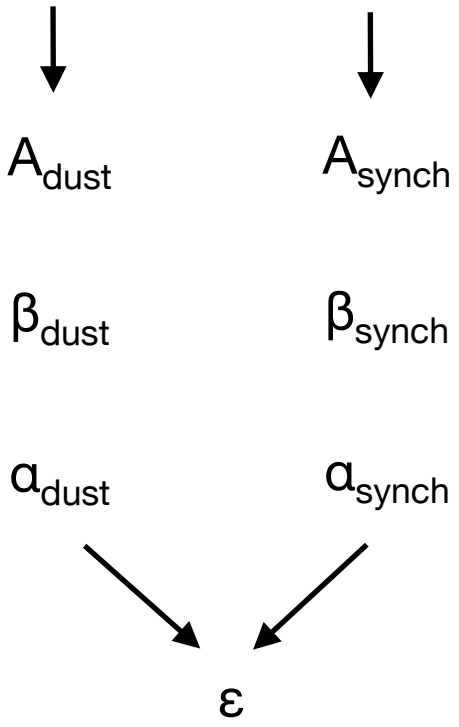
Take all possible auto- and cross spectra between BICEP/Keck, WMAP, and Planck bands (66 of them)



Multicomponent parametric likelihood analysis

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

foreground model = dust + synchrotron



amplitudes @ l=80

frequency spectral indices

spatial spectral indices

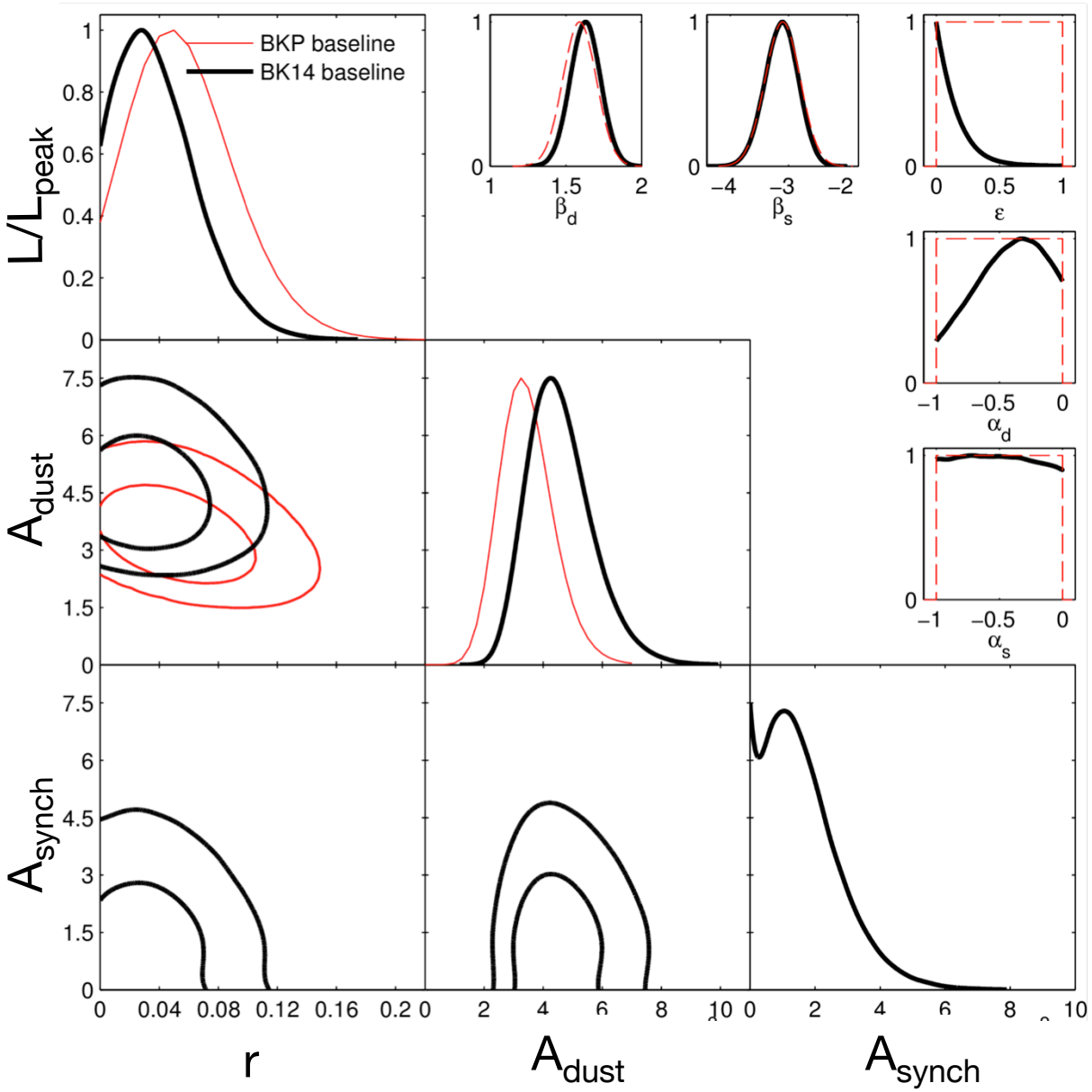
dust/synch spatial correlation

BK14 Results:

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

BK14 Results:

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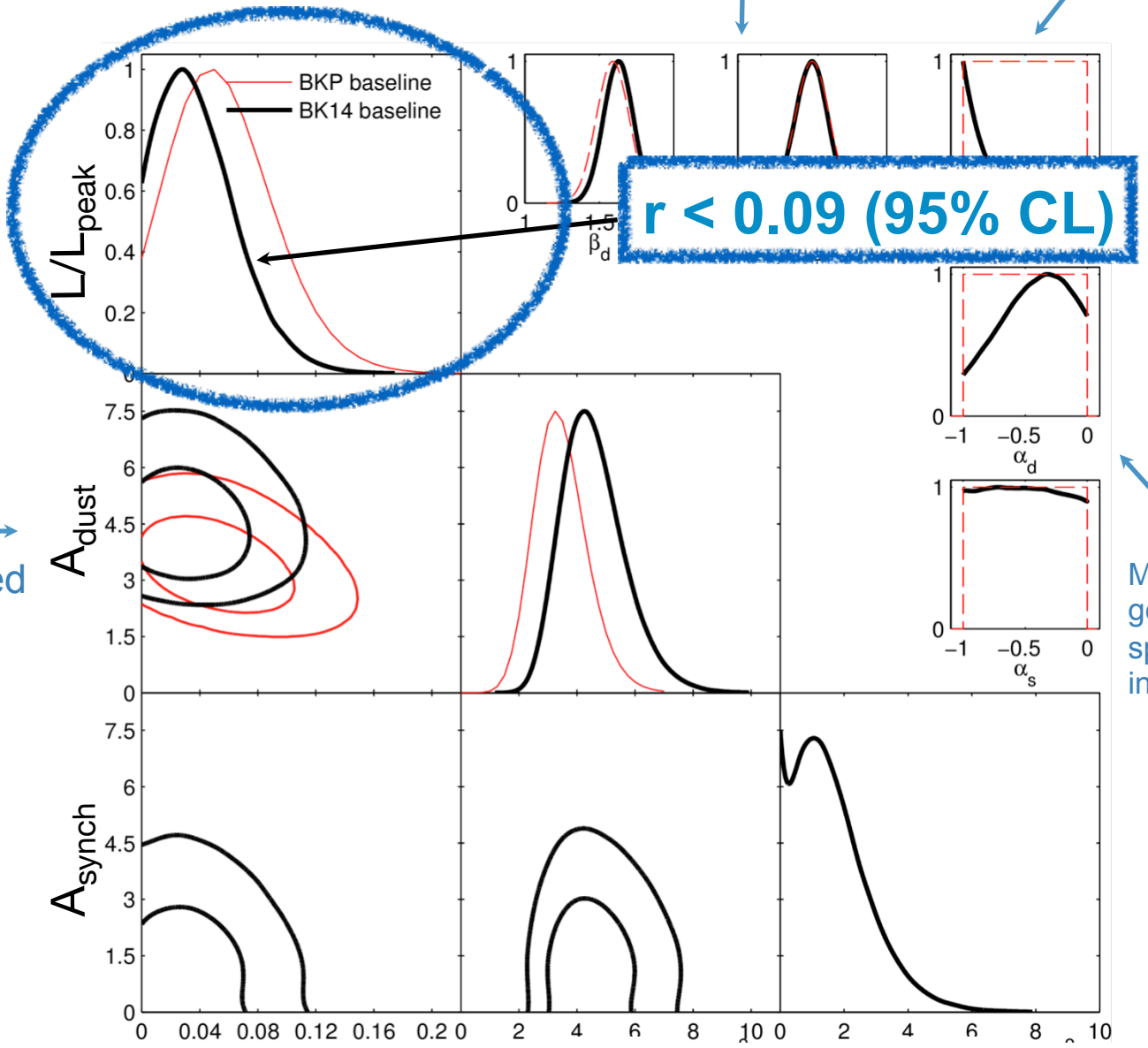

dust vs. r degeneracy lifted

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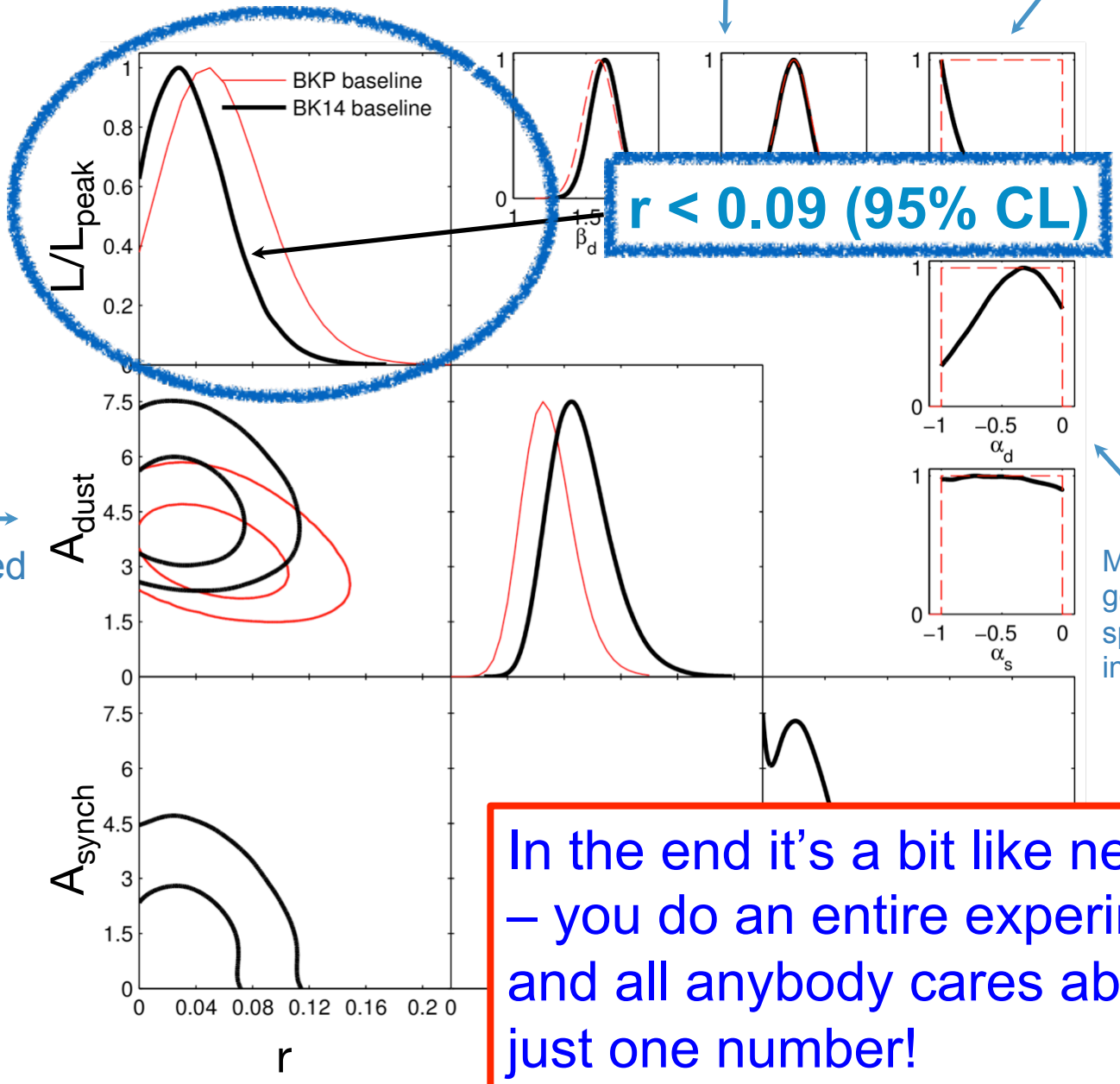
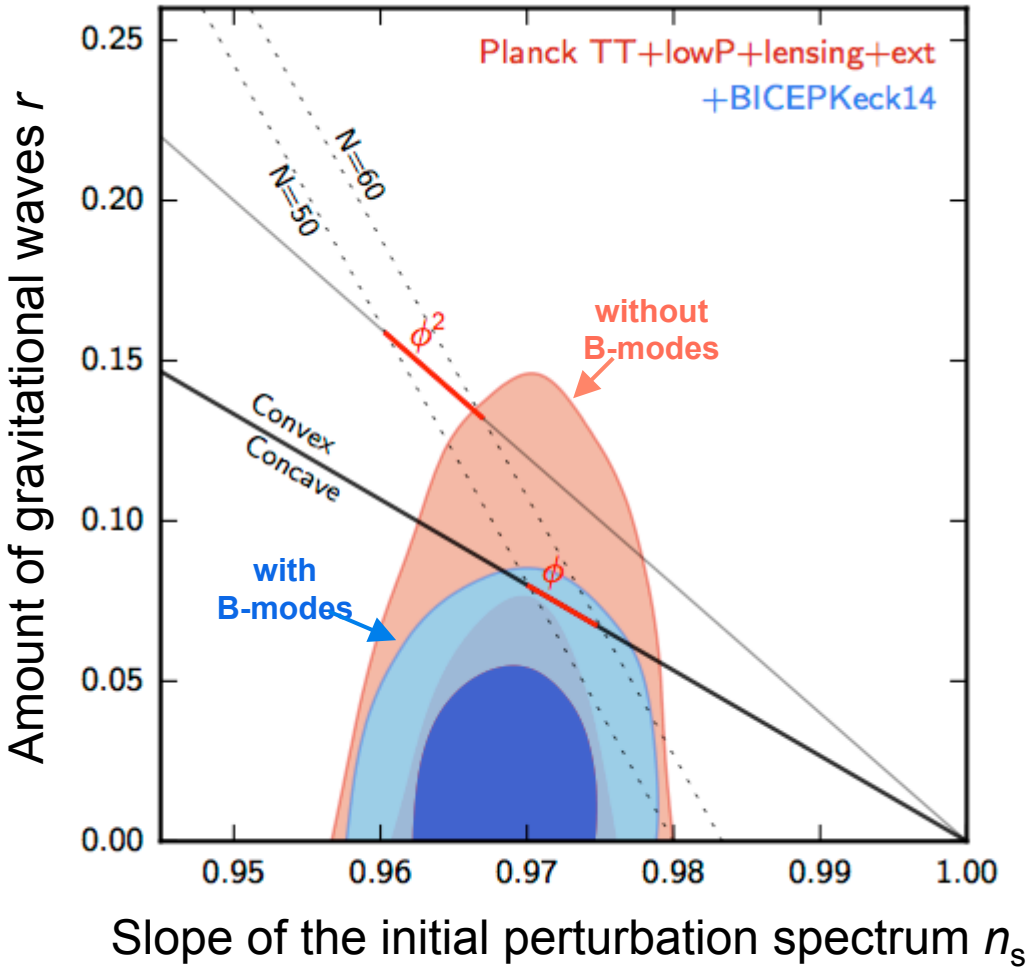


dust vs. r degeneracy lifted

Marginalize over generous ranges in spatial spectral indices

In the end it's a bit like neutrinos – you do an entire experiment and all anybody cares about is just one number!

Adding in Planck temperature measurements



Steadily tightening the constraints on inflationary models…

Stage 2

Stage 3

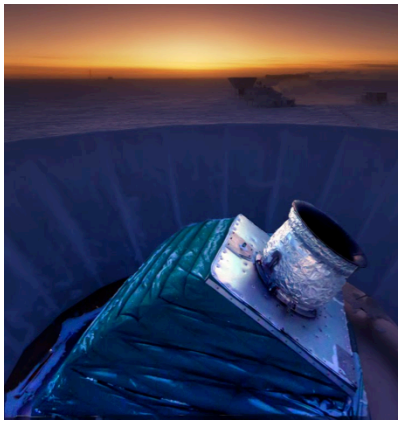
BICEP2
(2010-2012)

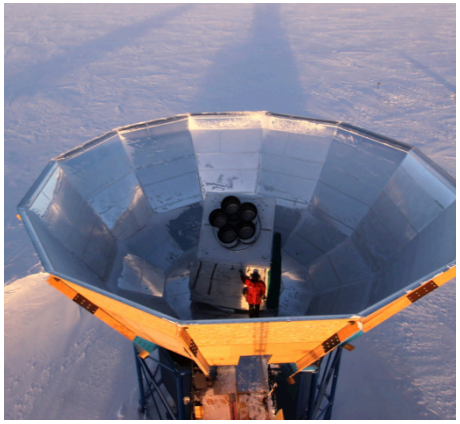
Keck Array
(2012-2019)

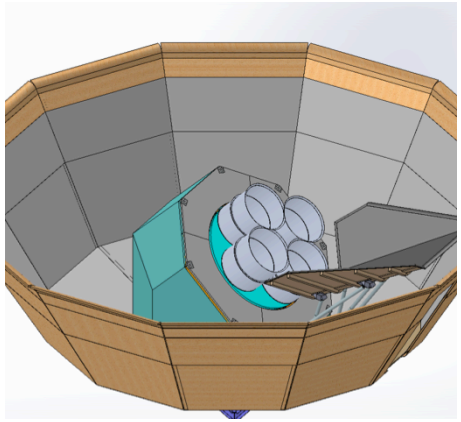
BICEP3
(2015-)

BICEP Array
(2020-)

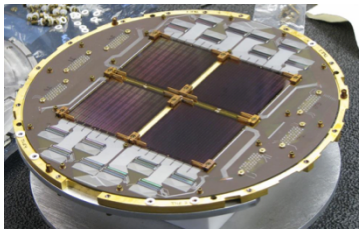
Telescope and Mount

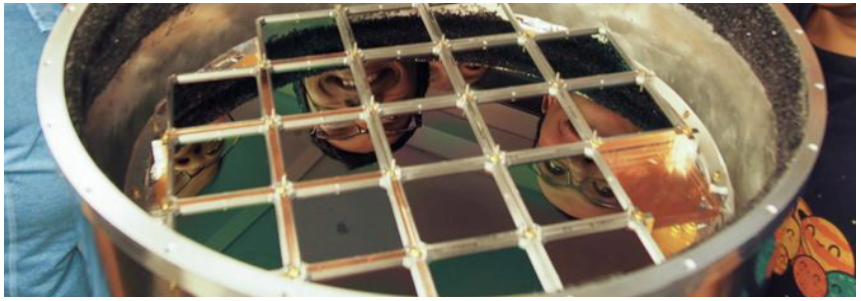




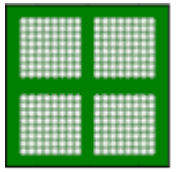


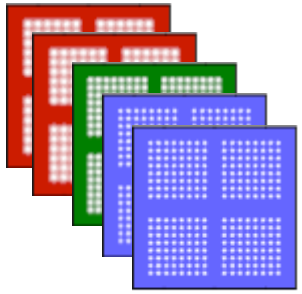
Focal Plane

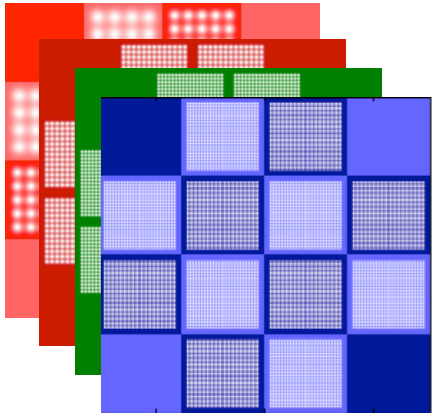




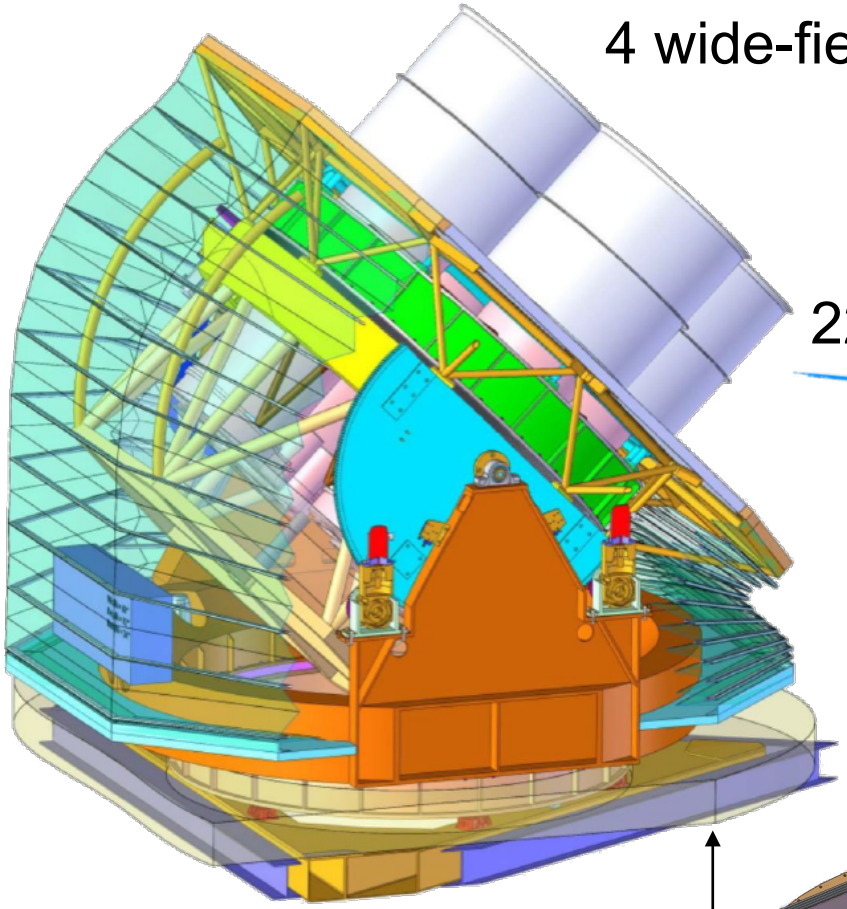
Beams on Sky



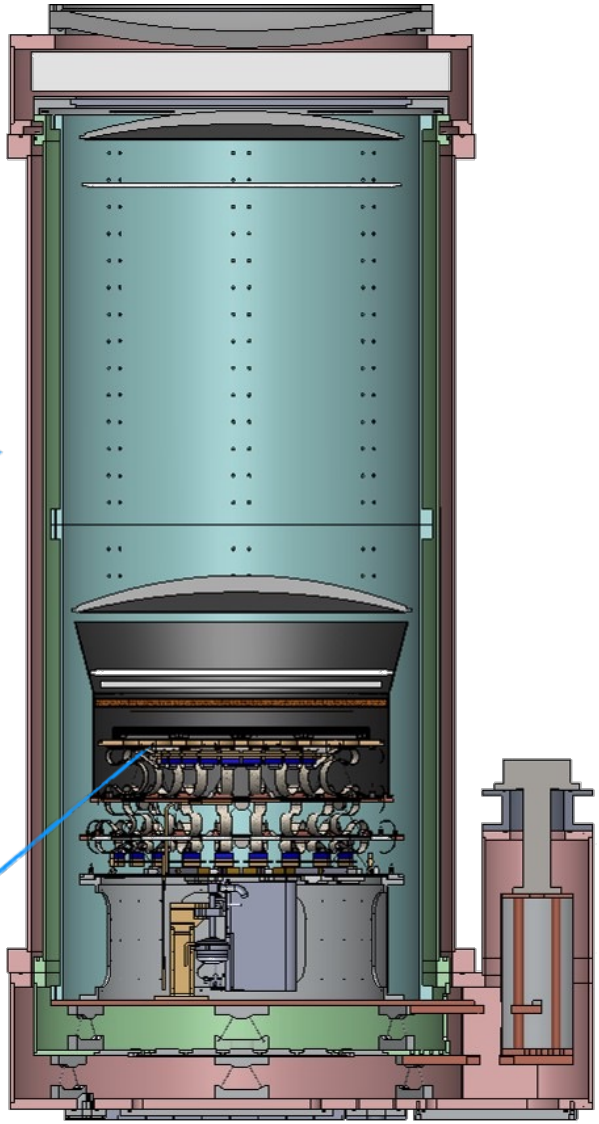


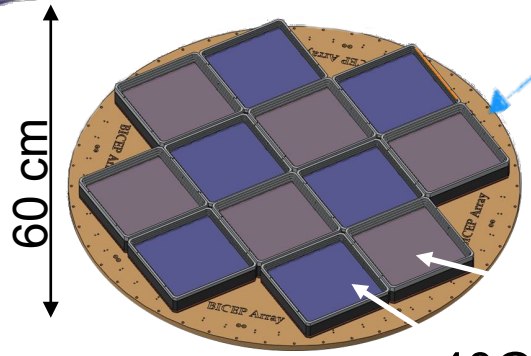


Next Gen Experiment BICEP Array Under Construction



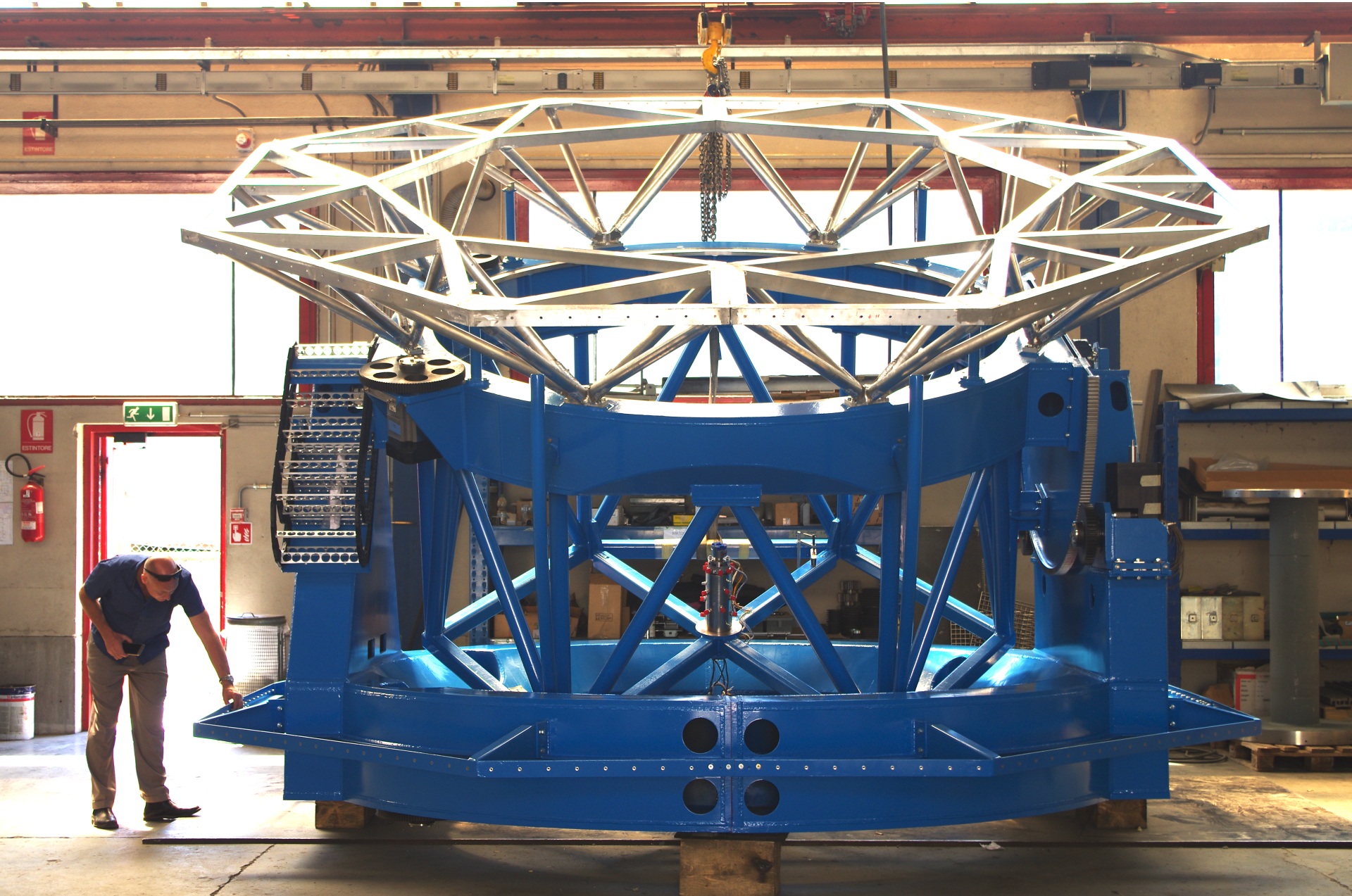
4 wide-field receivers
30/40 GHz
95 GHz
150 GHz
220/270 GHz



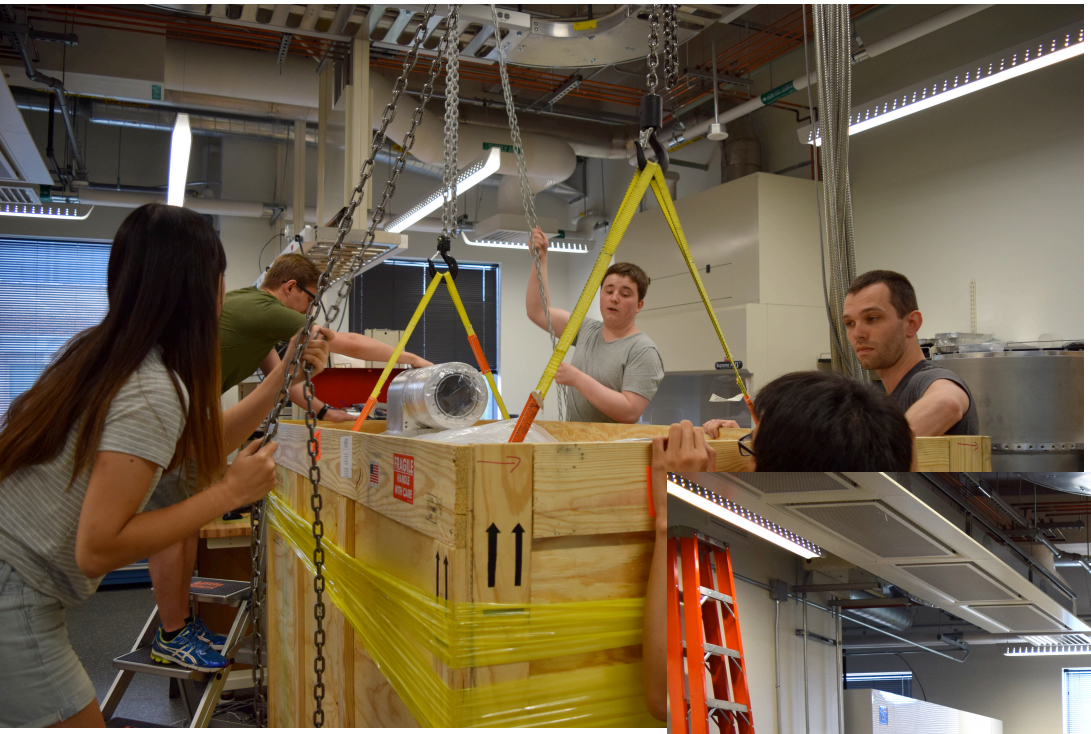


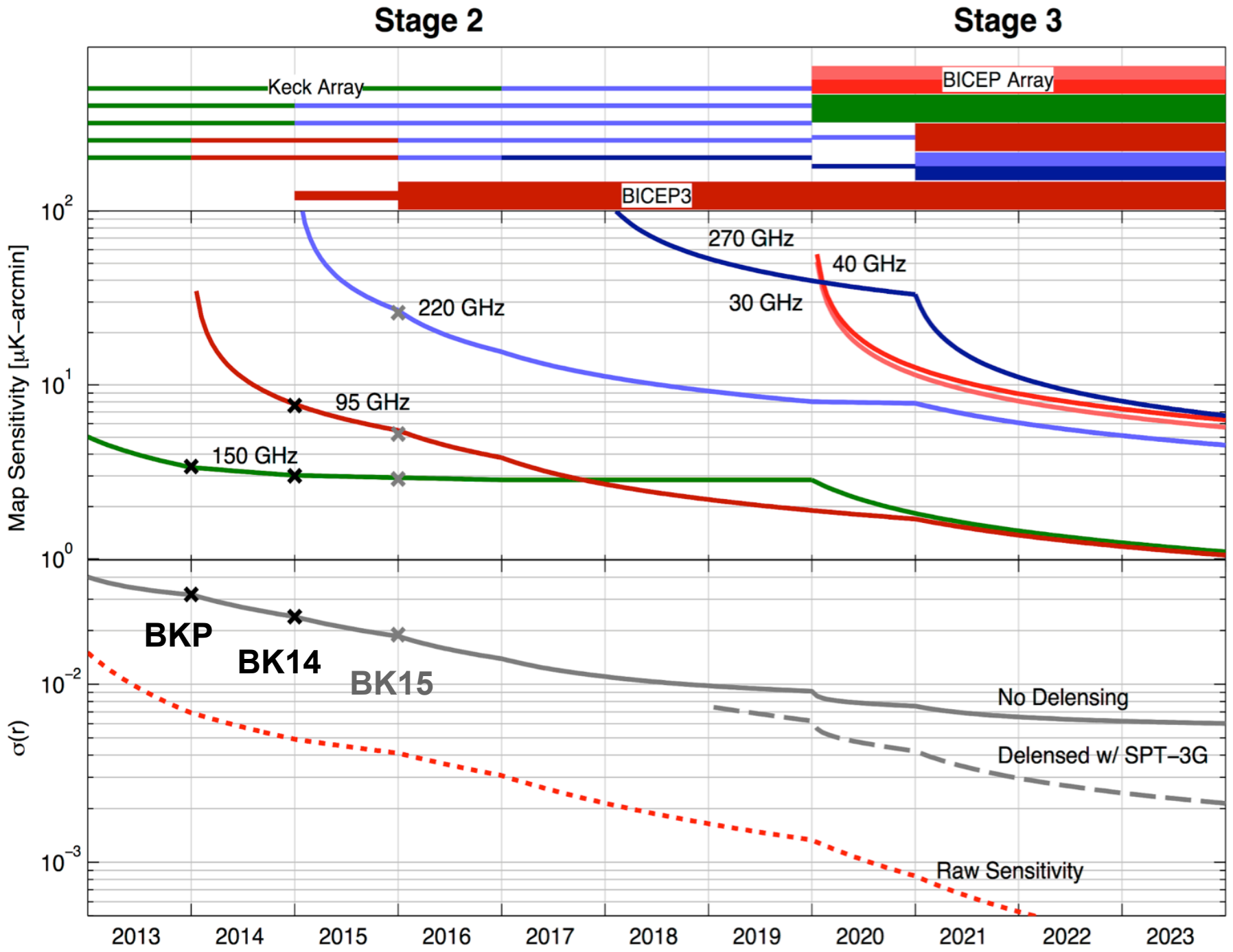
Focal plane layout

BICEP Array Mount Completed



Cryostat Arrival at University of Minnesota




Stage 2
Stage 3
Keck Array
BICEP Array
BICEP3
270 GHz
40 GHz
30 GHz
220 GHz
95 GHz
150 GHz
Map Sensitivity [μK–arcmin]
10^2
10^1
10^0
BKP
BK14
BK15
No Delensing
Delensed w/ SPT–3G
Raw Sensitivity
σ(r)
10^{-2}
10^{-3}
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023

Conclusions

- By measuring CMB polarization we can look for primordial gravitational waves and either measure the energy scale of inflation, or rule out additional inflationary models

- BICEP/Keck leads the field in this endeavor:
- Published BK14 result sets $r_{0.05}<0.09$ and $\sigma(r)=0.024$
- (BK15 will shortly appear with $\sigma(r)=0.020$)

- Galactic Foregrounds are a major issue but in principle can be overcome by multi-frequency measurements – we will only find out how well by trying

- BICEP Array is under construction and will go much further with next generation receivers in five bands
- Delensing in conjunction with SPT3G is under development
- BK23 result $\sigma(r)<0.003$ by 2024

- We have competition from Simons Observatory who are building a BICEP Array like machine – and beyond that is merged mega experiment CMB-S4…