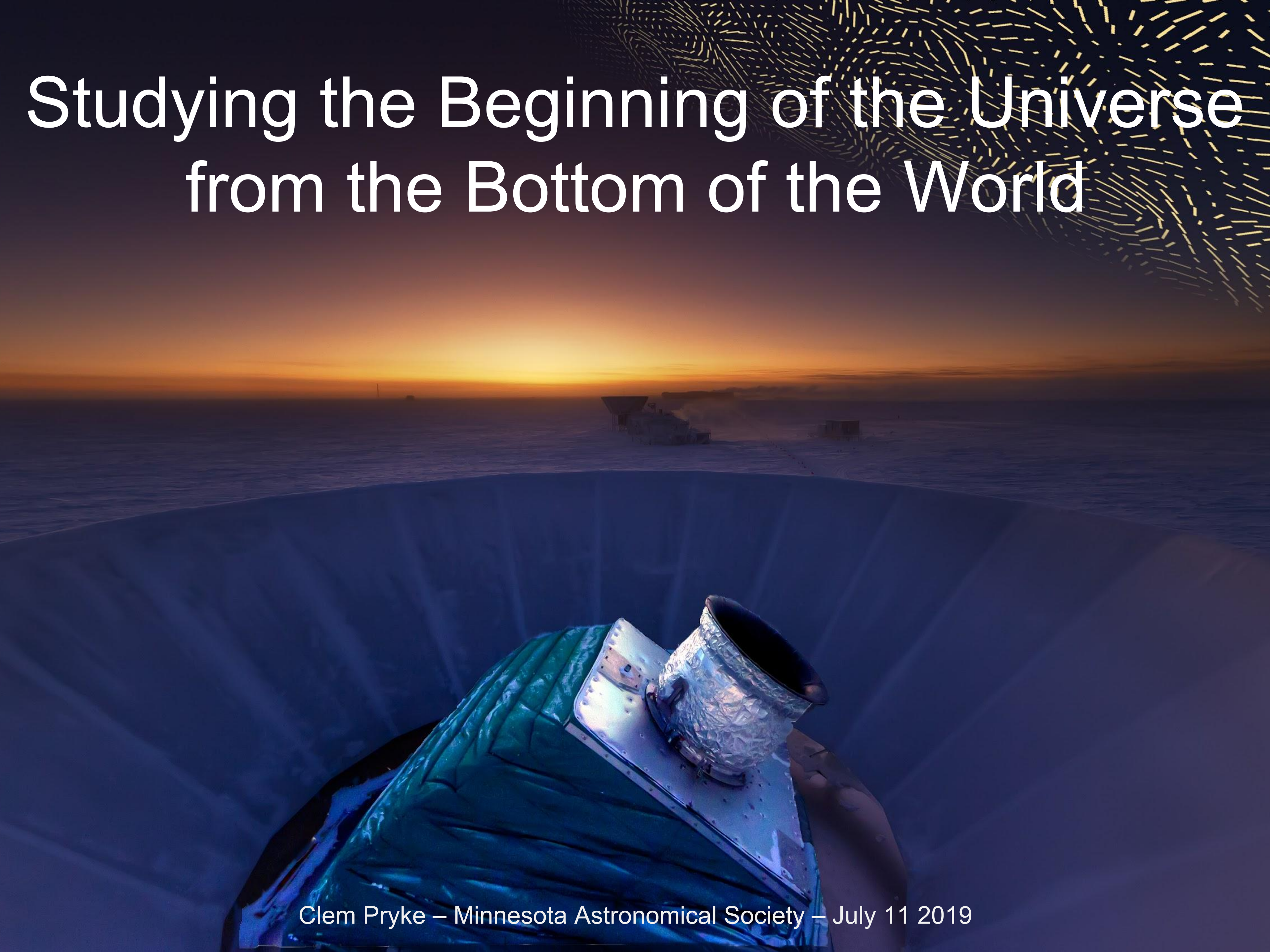
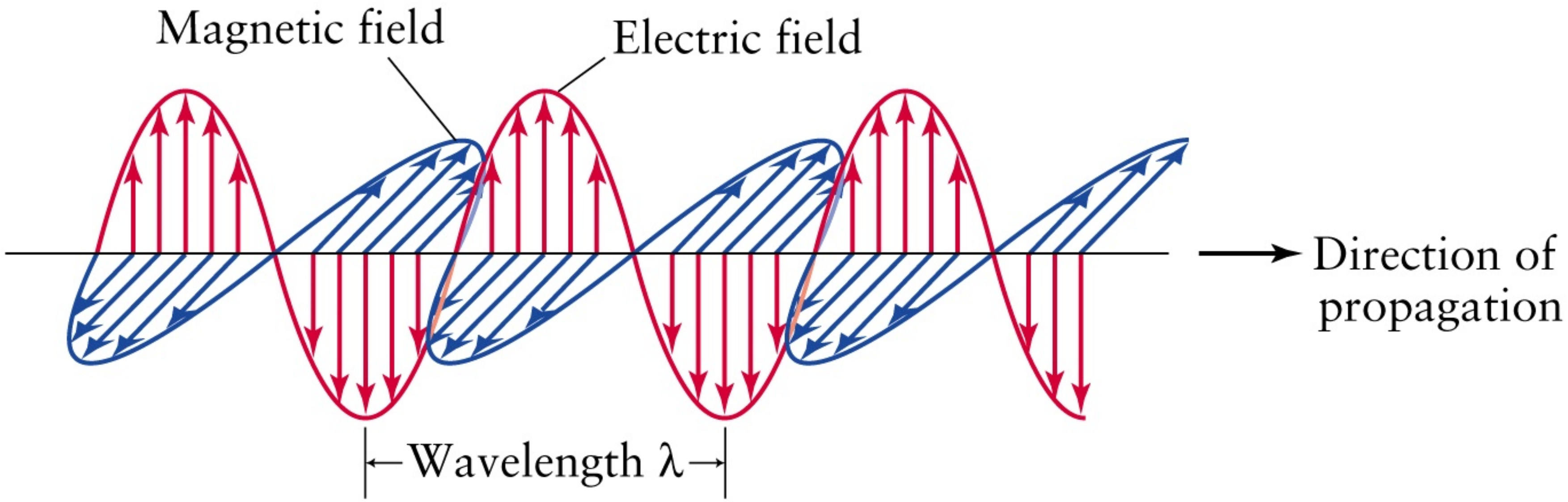
Studying the Beginning of the Universe from the Bottom of the World



Clem Pryke – Minnesota Astronomical Society – July 11 2019

What is Light?



- Think of each ray of light as a microscopic "wavepacket"
- Moves forward fast – 186,000 miles per second – but not infinite speed (8 minutes from Sun to Earth)
- The peak-to-peak distance (wavelength) determines the color
- Radio waves are just long wavelength light

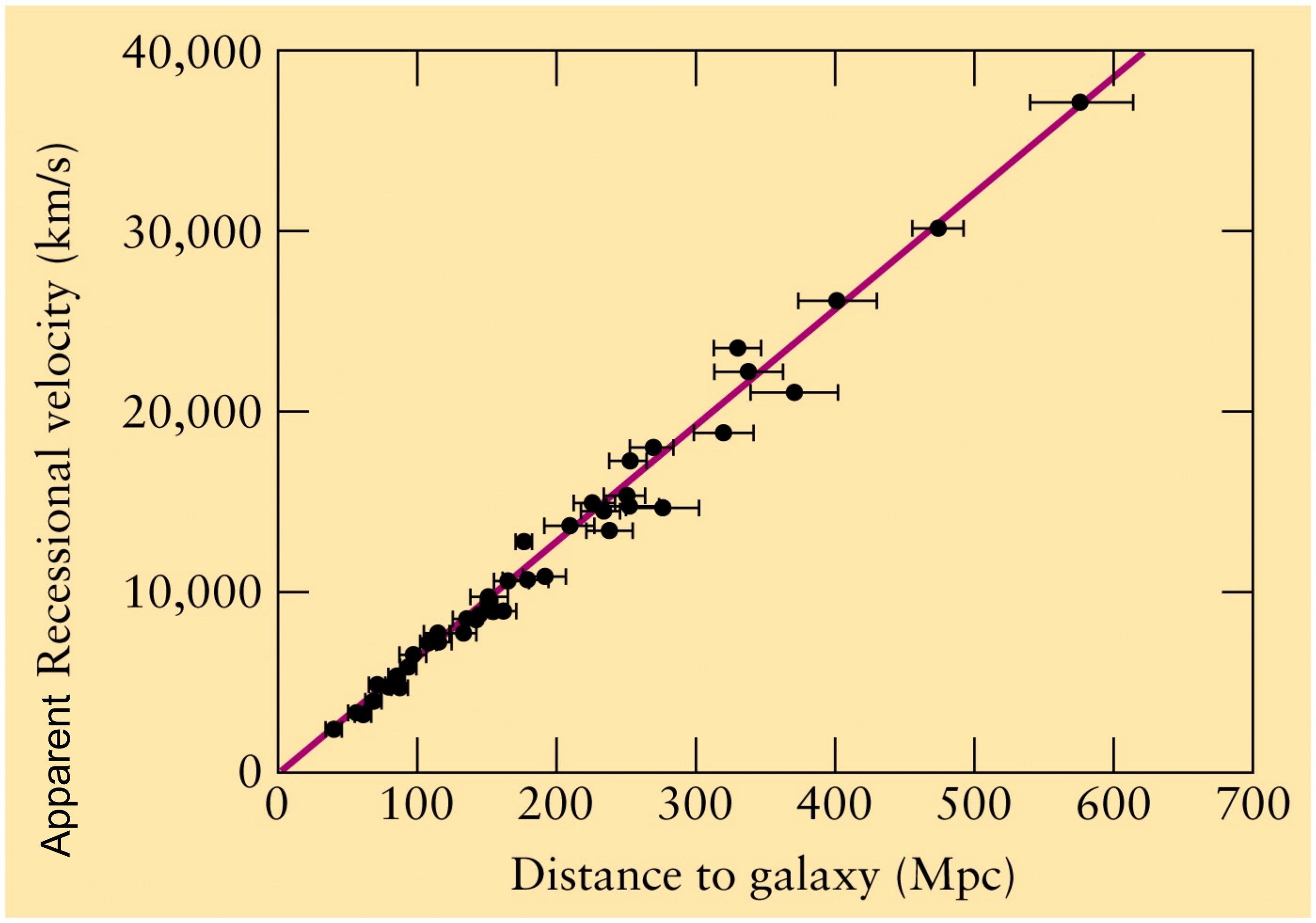
“Classic” Doppler Effect

- Imagine 3 stars emitting rays of light of the same “natural” wavelength (color)
- But light moves through space always at the same speed…
- Moving towards us = compressed = bluer
- Moving away from us = stretched = redder

Edwin Hubble “Observing” Distant Galaxies

Mount Wilson Observatory
(LA) 1920’s

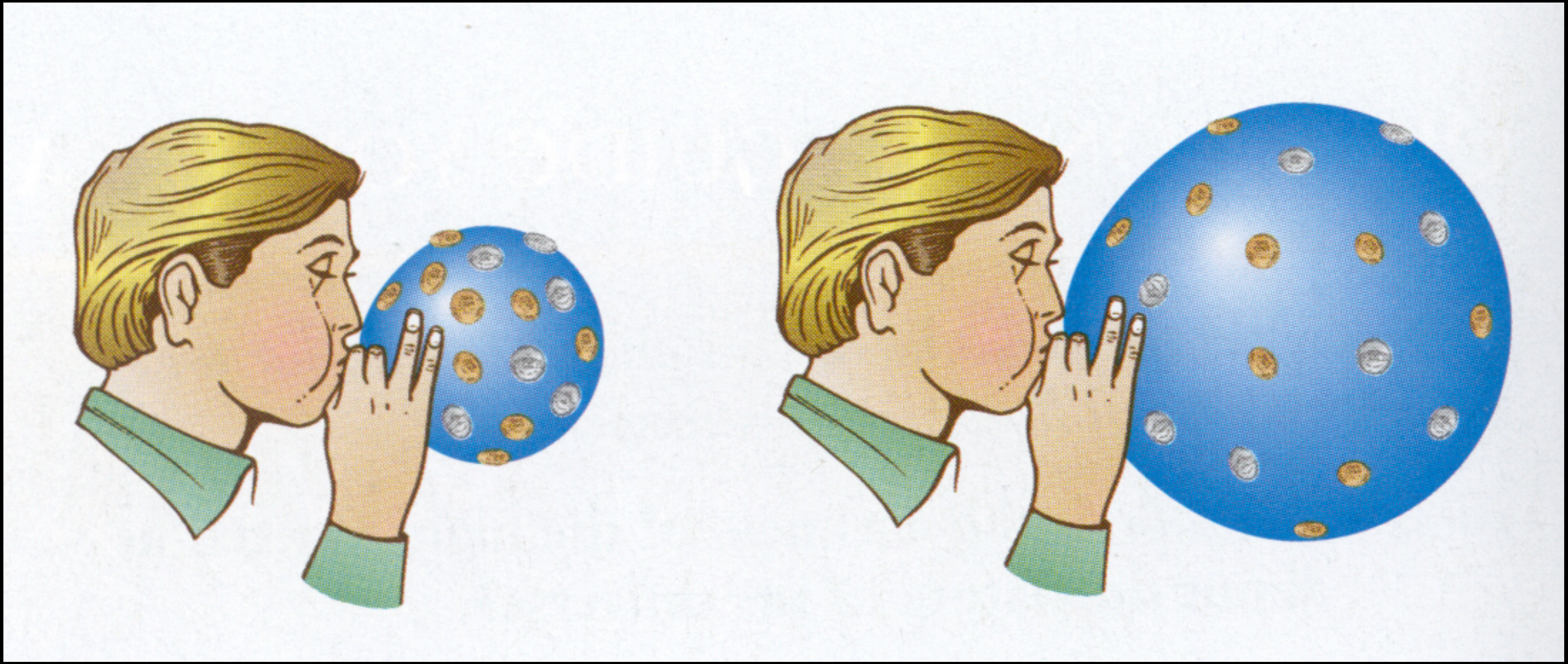
Hubble Diagram



The father away a galaxy is the faster it *appears* to be moving away from us…

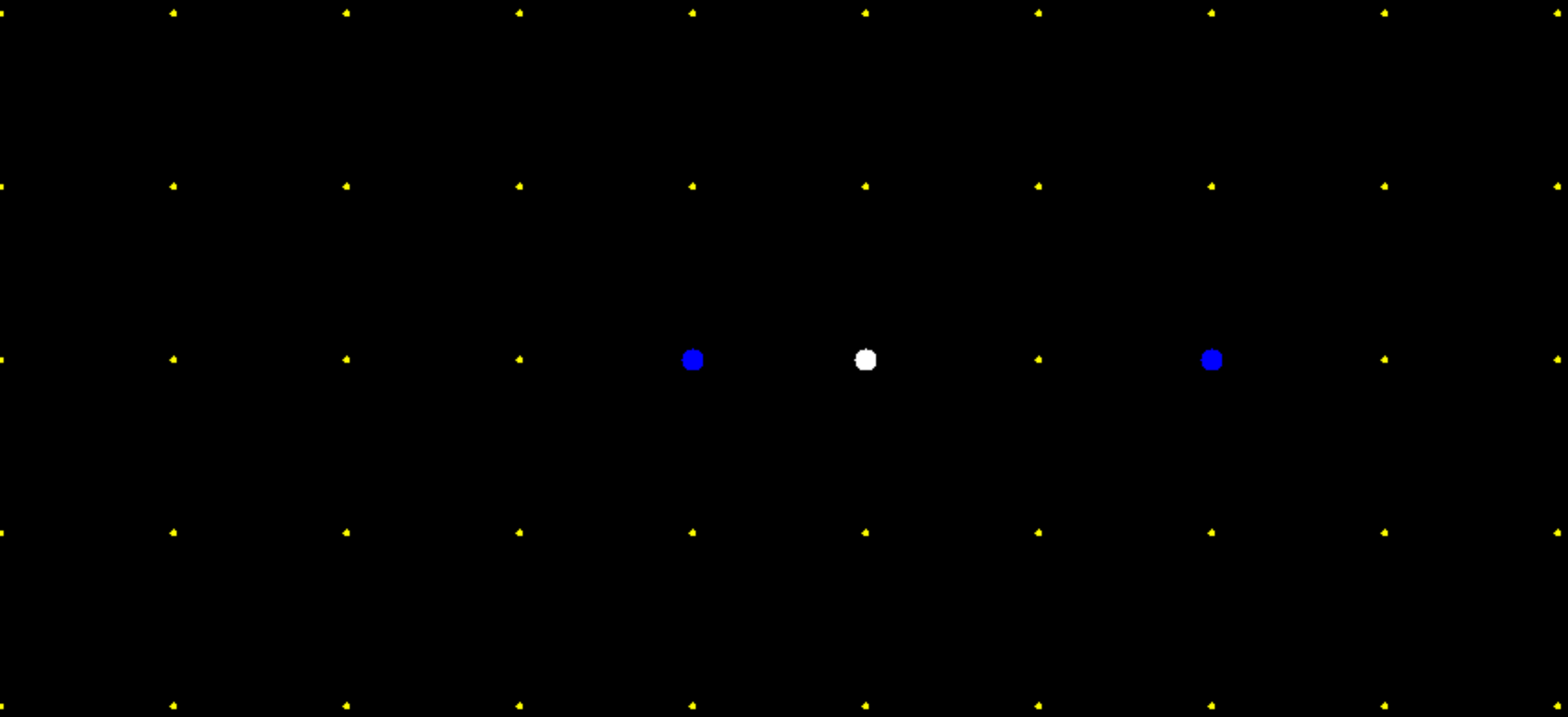
Are we the most unpopular place in the entire Universe?!

Expanding Universe?



- Simplest(!) explanation – the fabric of space itself is expanding
- From whereever you look more distant objects appear to be receding faster

Cosmological Doppler Effect



- Light rays stretch with the Universe – called "redshift"
- As we look *out* we look *back* in time

Modern cosmology in a nutshell:

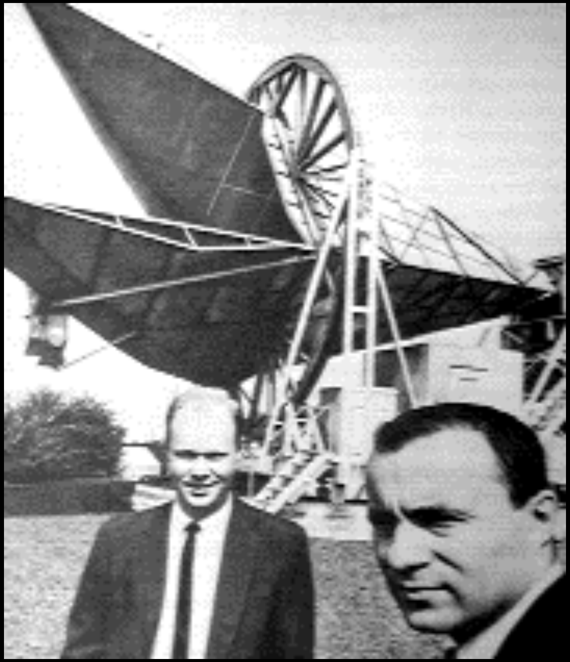
Edwin Hubble

1) The universe is expanding.

(Hubble, 1920s)

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

(Alpher, Gamow, Herman, 1940s)

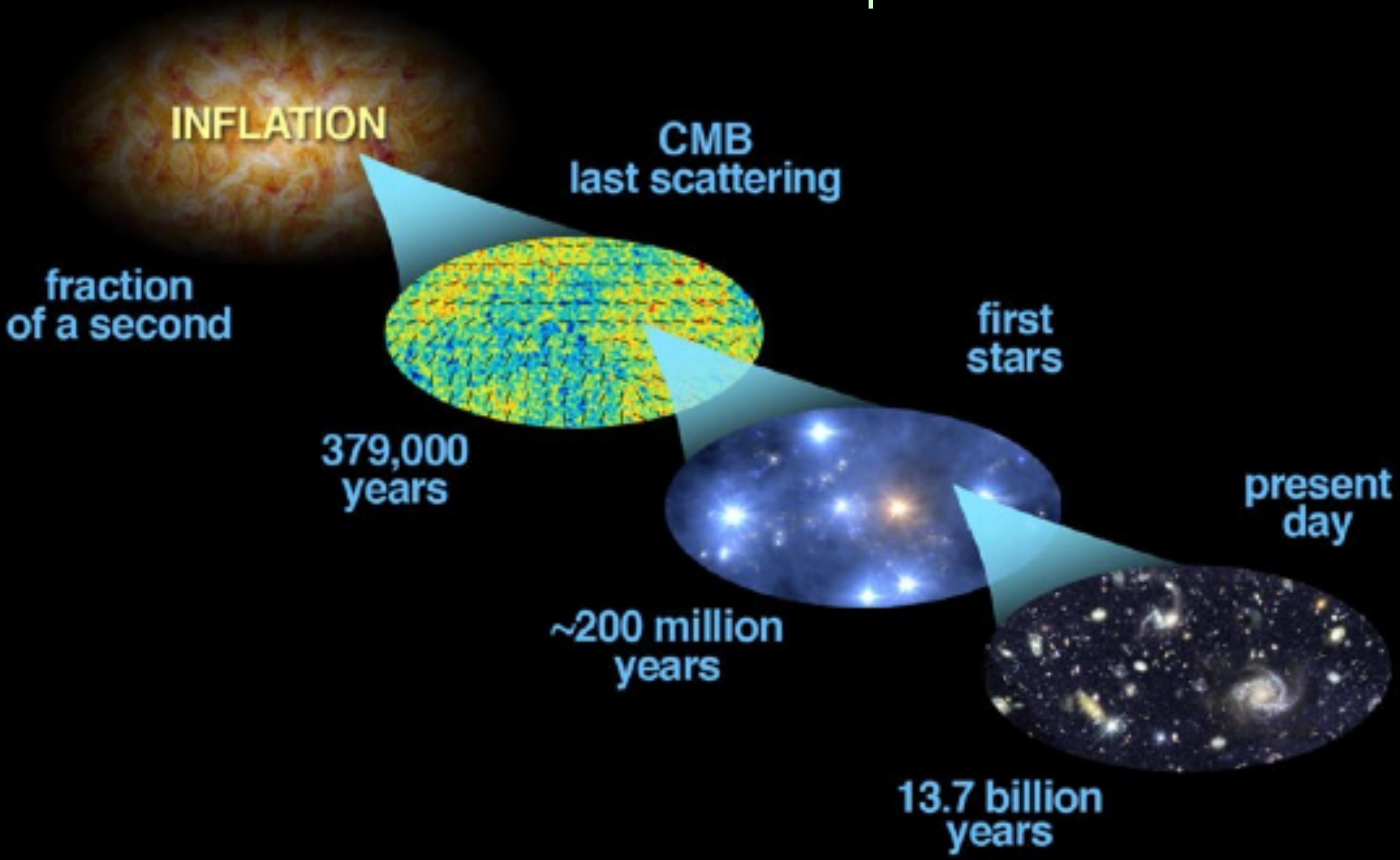


Bob Wilson & Arno Penzias
1978 Nobel Prize

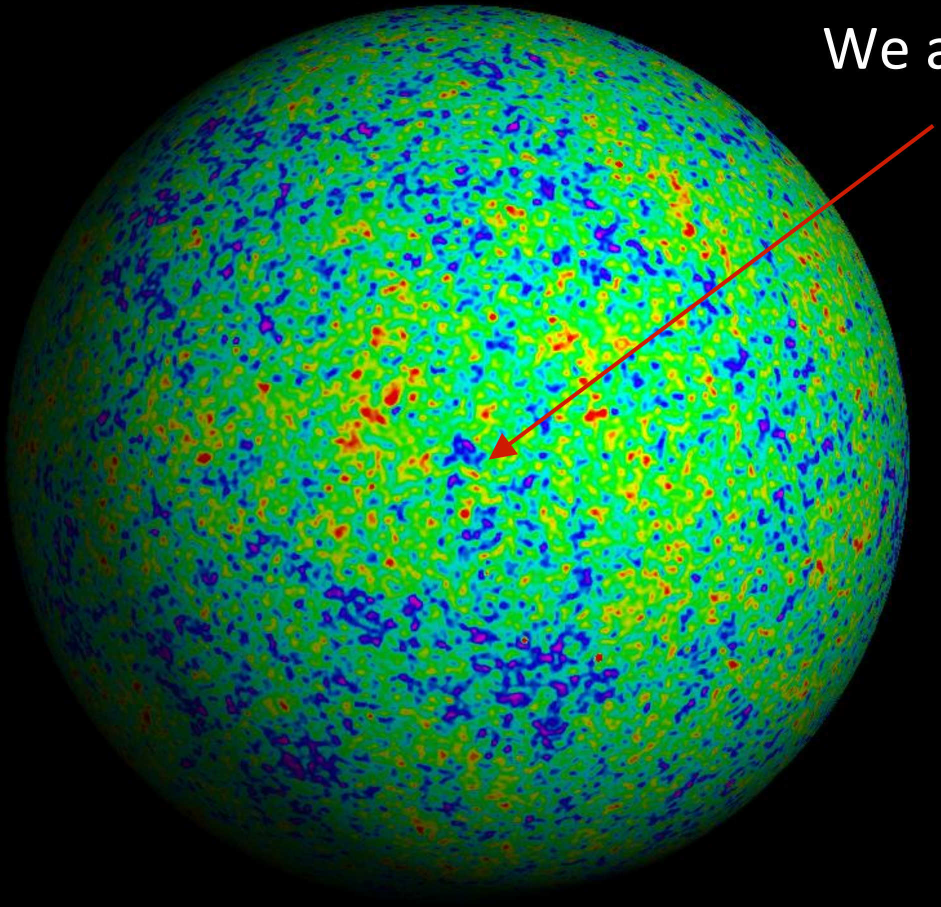
3) You can still see the (redshifted) glow!
The *Cosmic Microwave Background*
(Penzias & Wilson, 1964)

⇒ acceptance of the “HOT BIG BANG”

Telescopes are time machines!



Cosmic Microwave Background Surface of Last Scattering



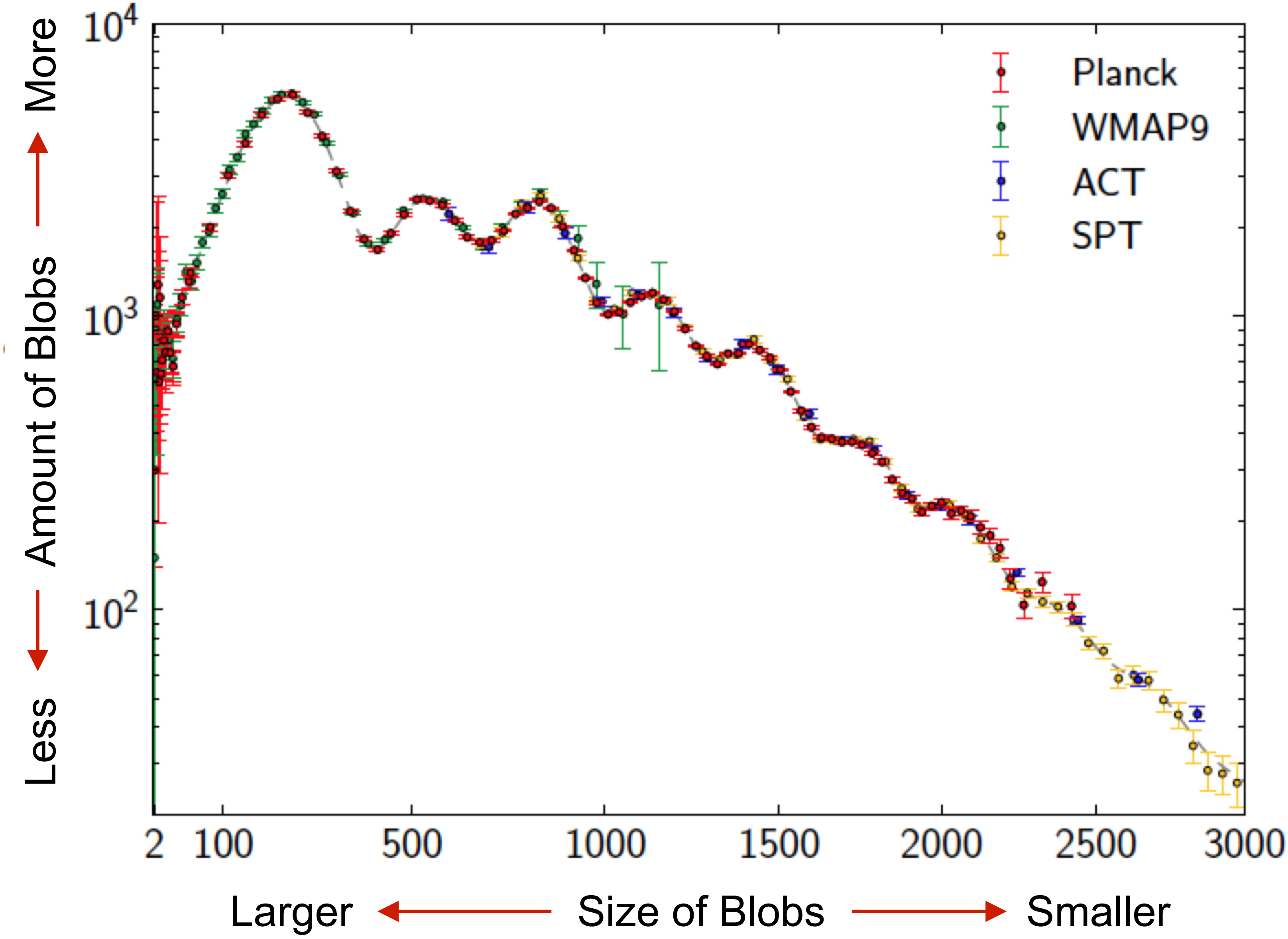
All sky temperature map
projected on a sphere

We are at the center

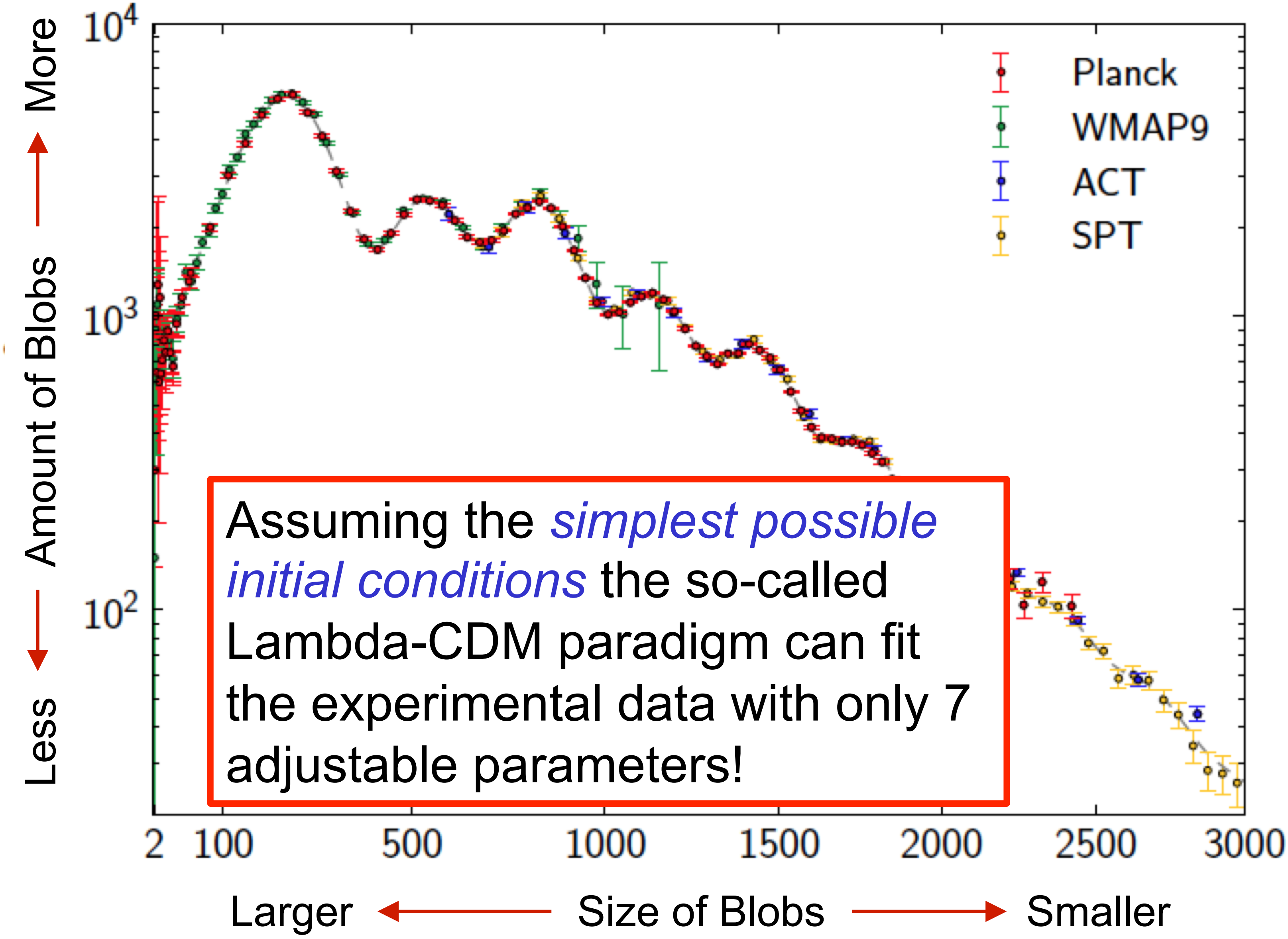
CMB temperature is a sample of the density structure on a shell cut through the 380,000 year old Universe

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

Power Spectrum (Blob size histogram)



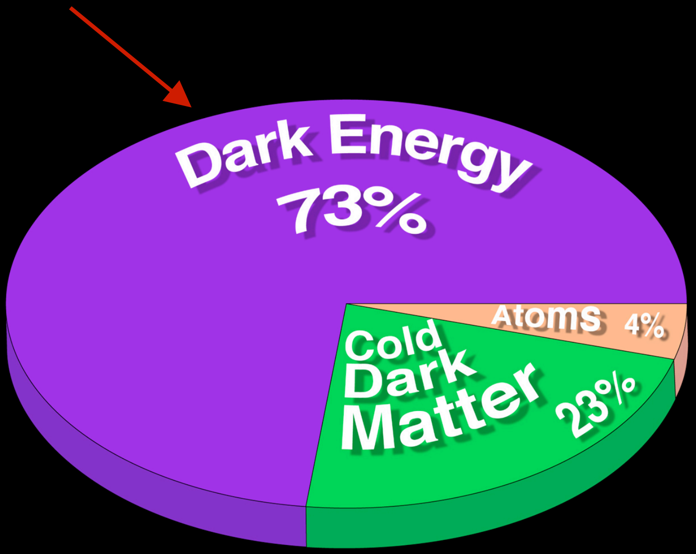
Power Spectrum (Blob size histogram)



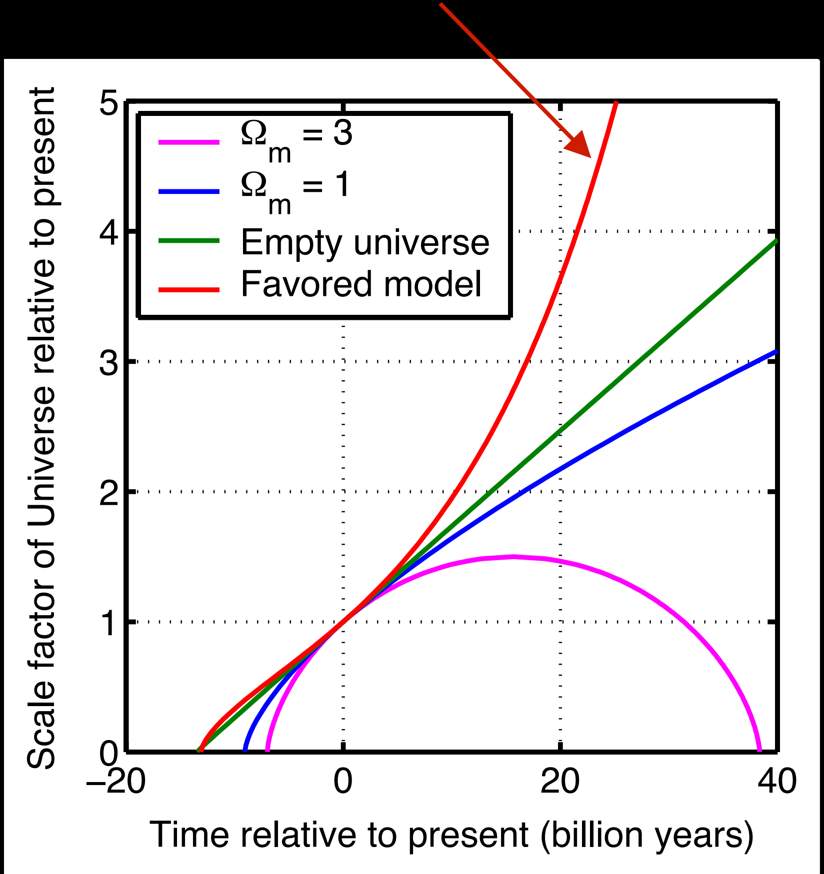
Assuming the *simplest possible initial conditions* the so-called Lambda-CDM paradigm can fit the experimental data with only 7 adjustable parameters!

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

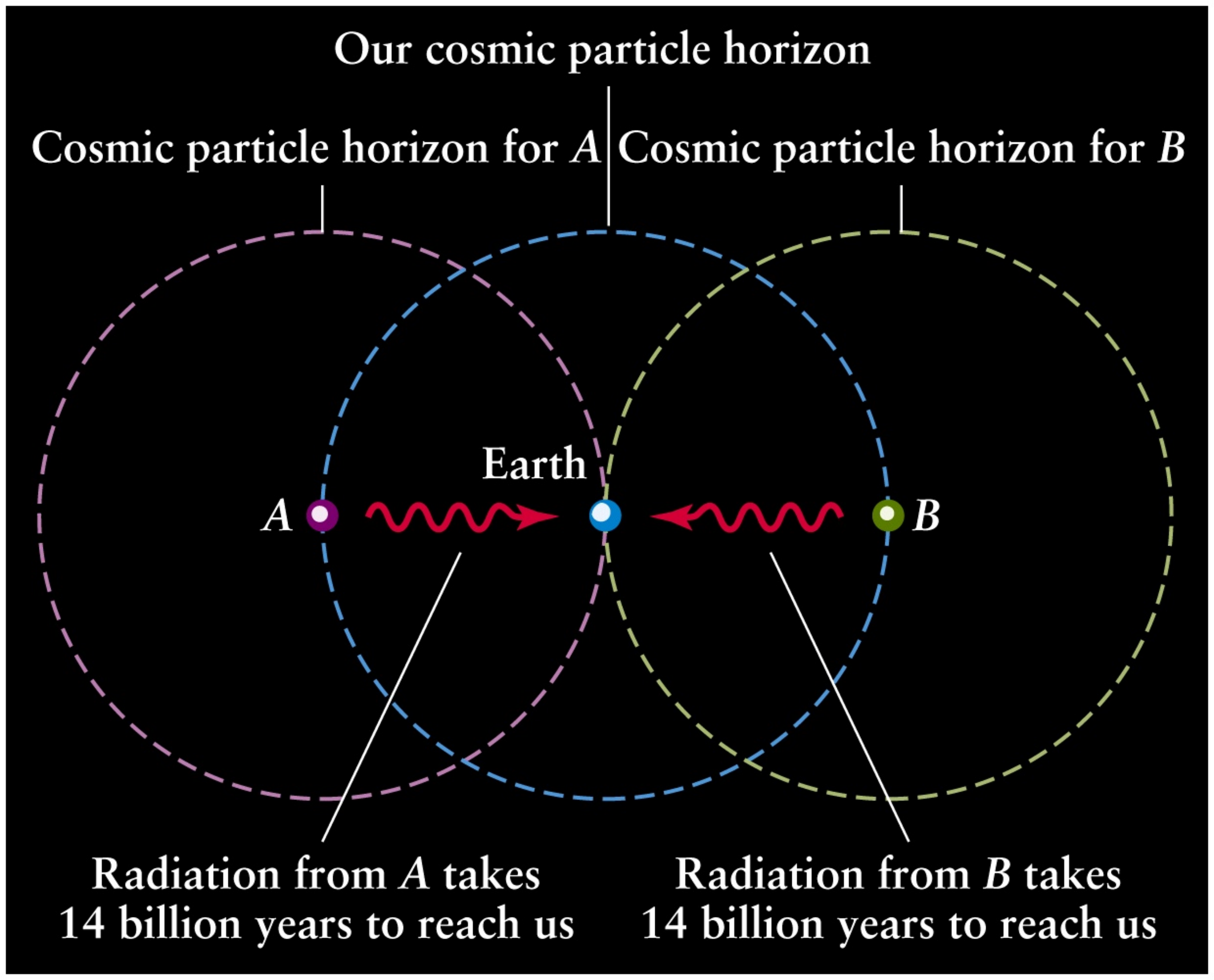


And it implies that the future is runaway expansion…



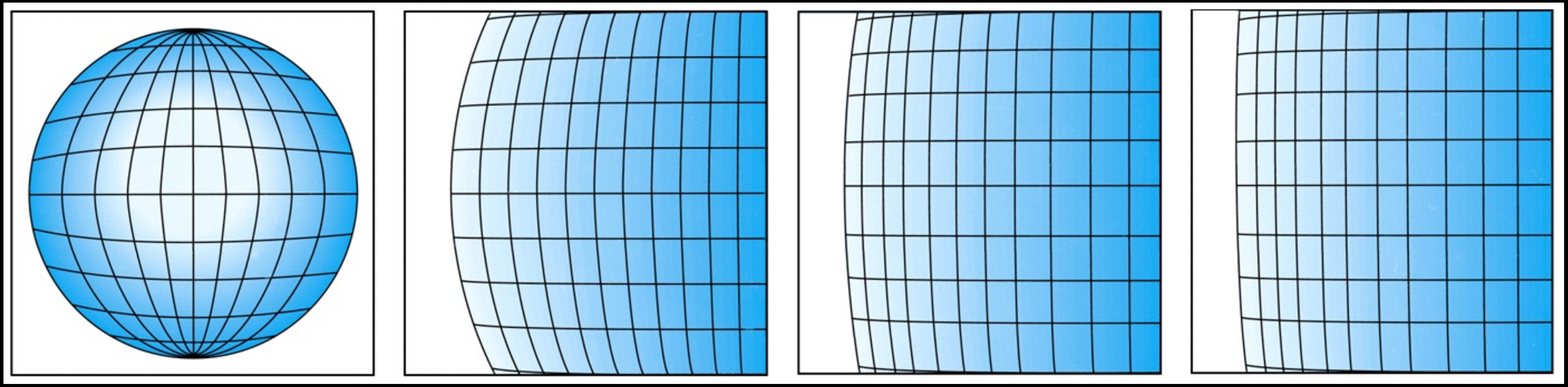
Also it doesn't explain horizon/flatness etc…

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…

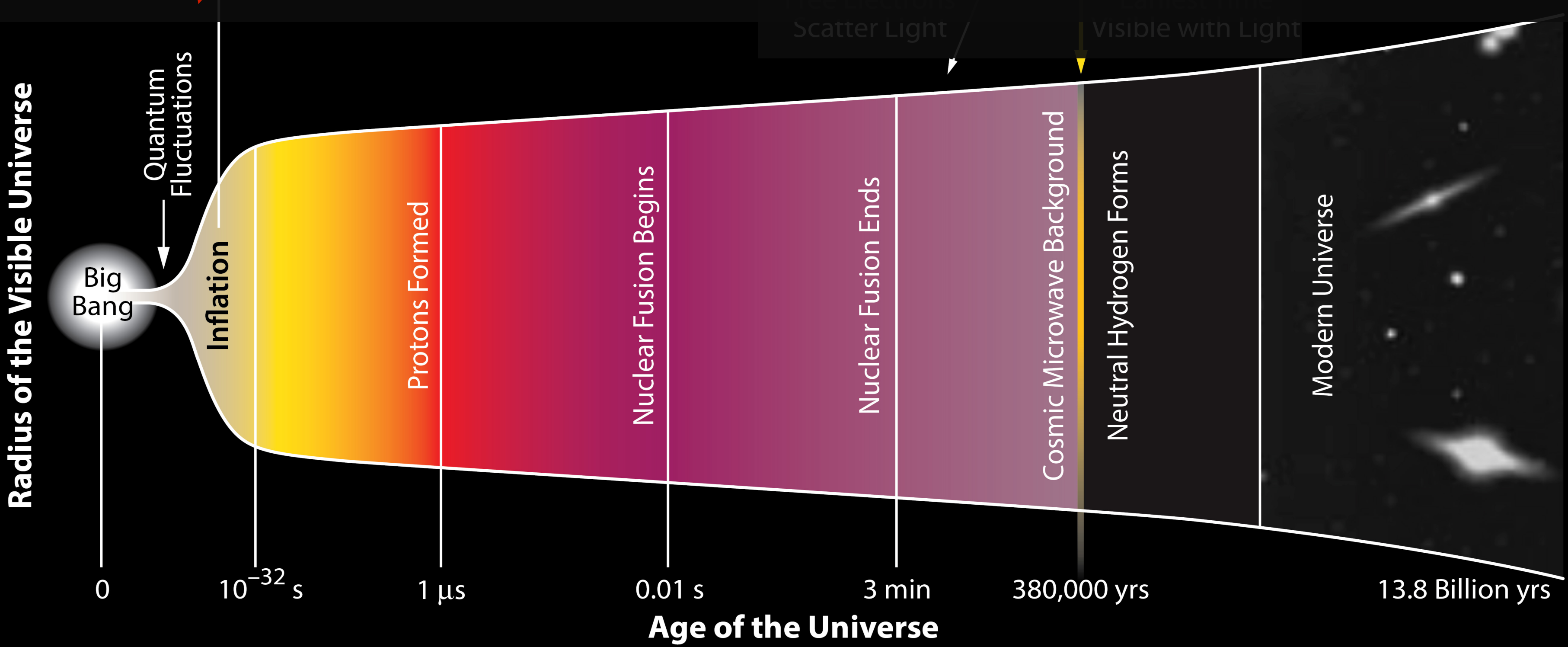
If you take some curved space and blow it up enough pretty soon it is no longer curved on a local scale – like our entire observable Universe!

History of the Universe

Inflation posits a pre-phase of exponential expansion

Alan Guth

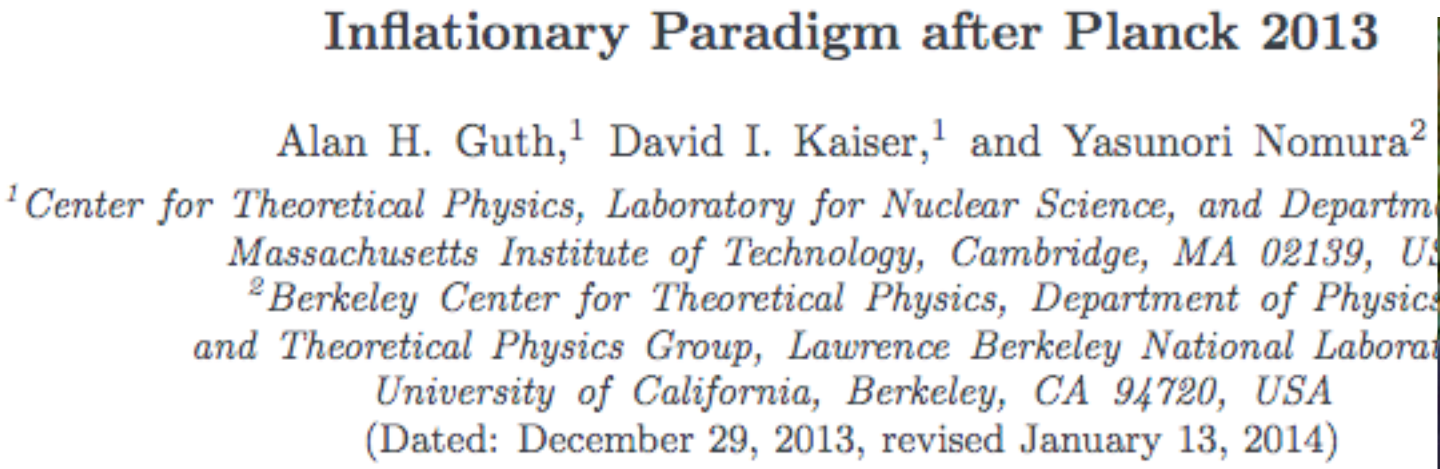
Andrei Linde



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

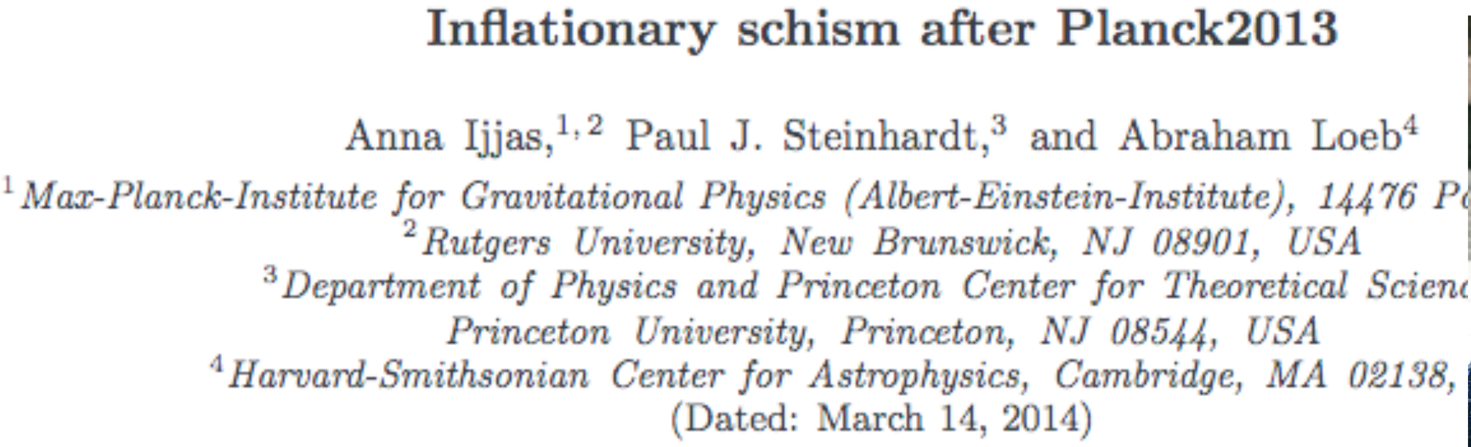


Inflationary Paradigm after Planck 2013

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



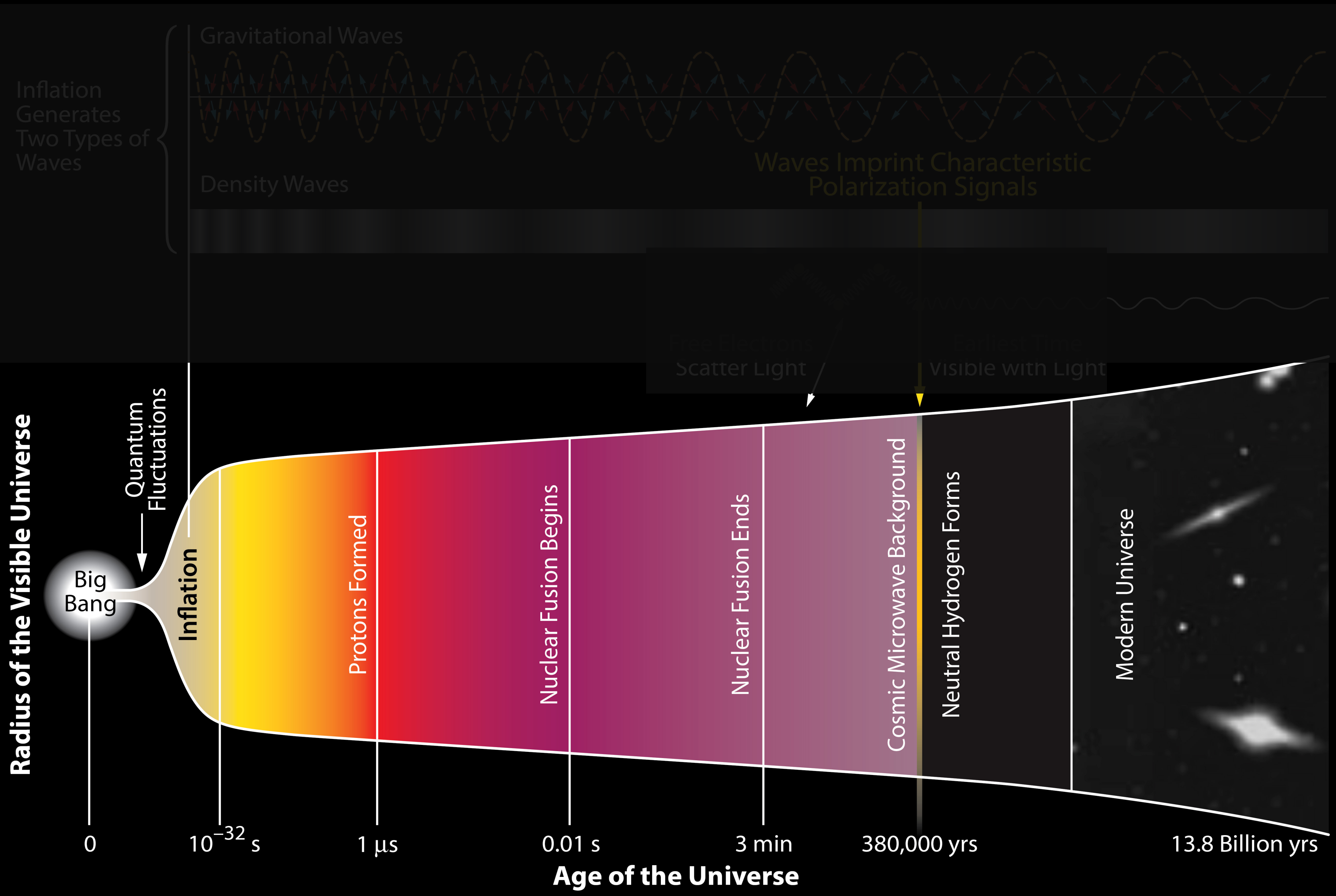
Inflationary schism after Planck2013

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,*

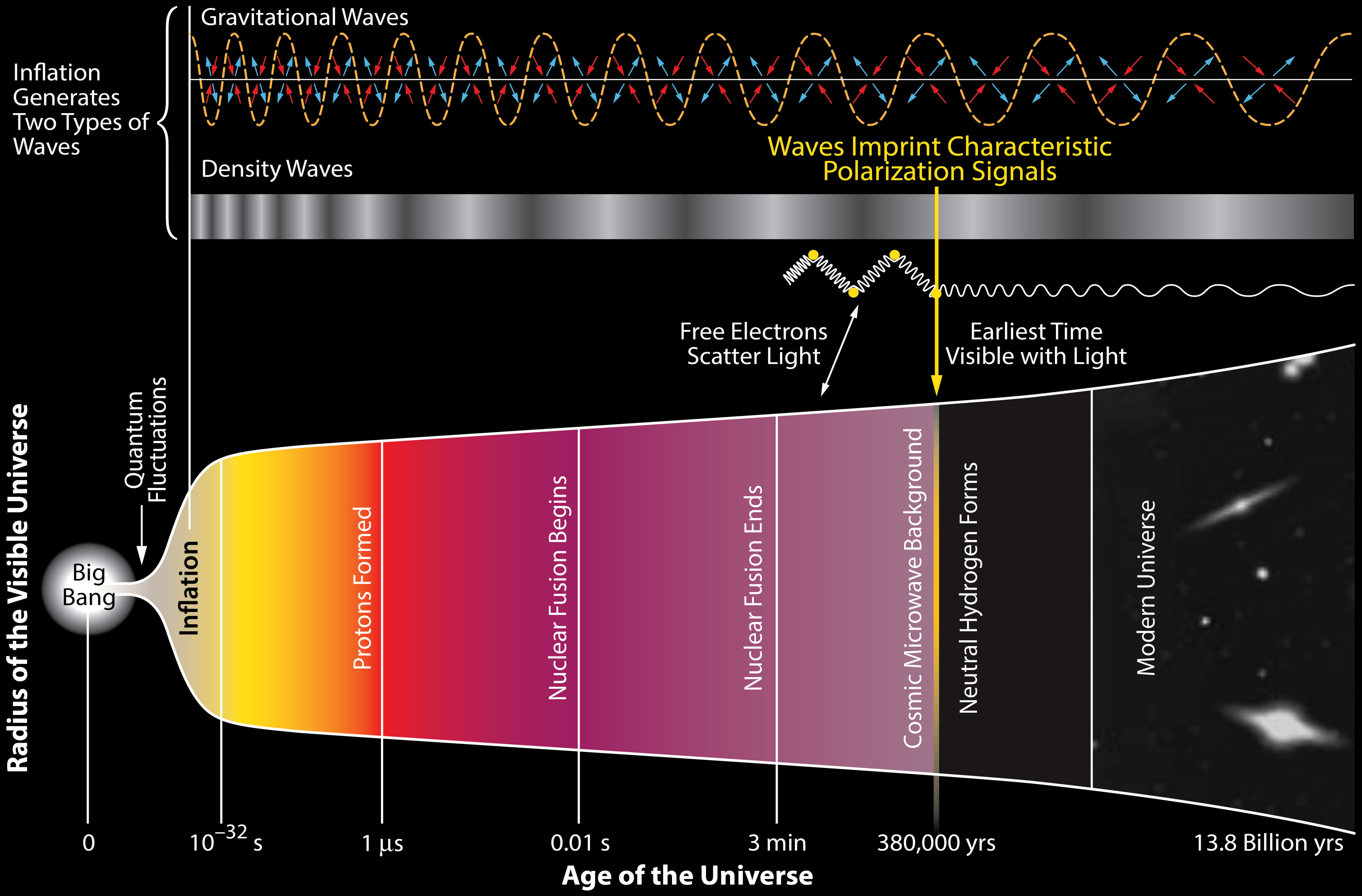
(Dated: March 14, 2014)

arxiv/1402.6980

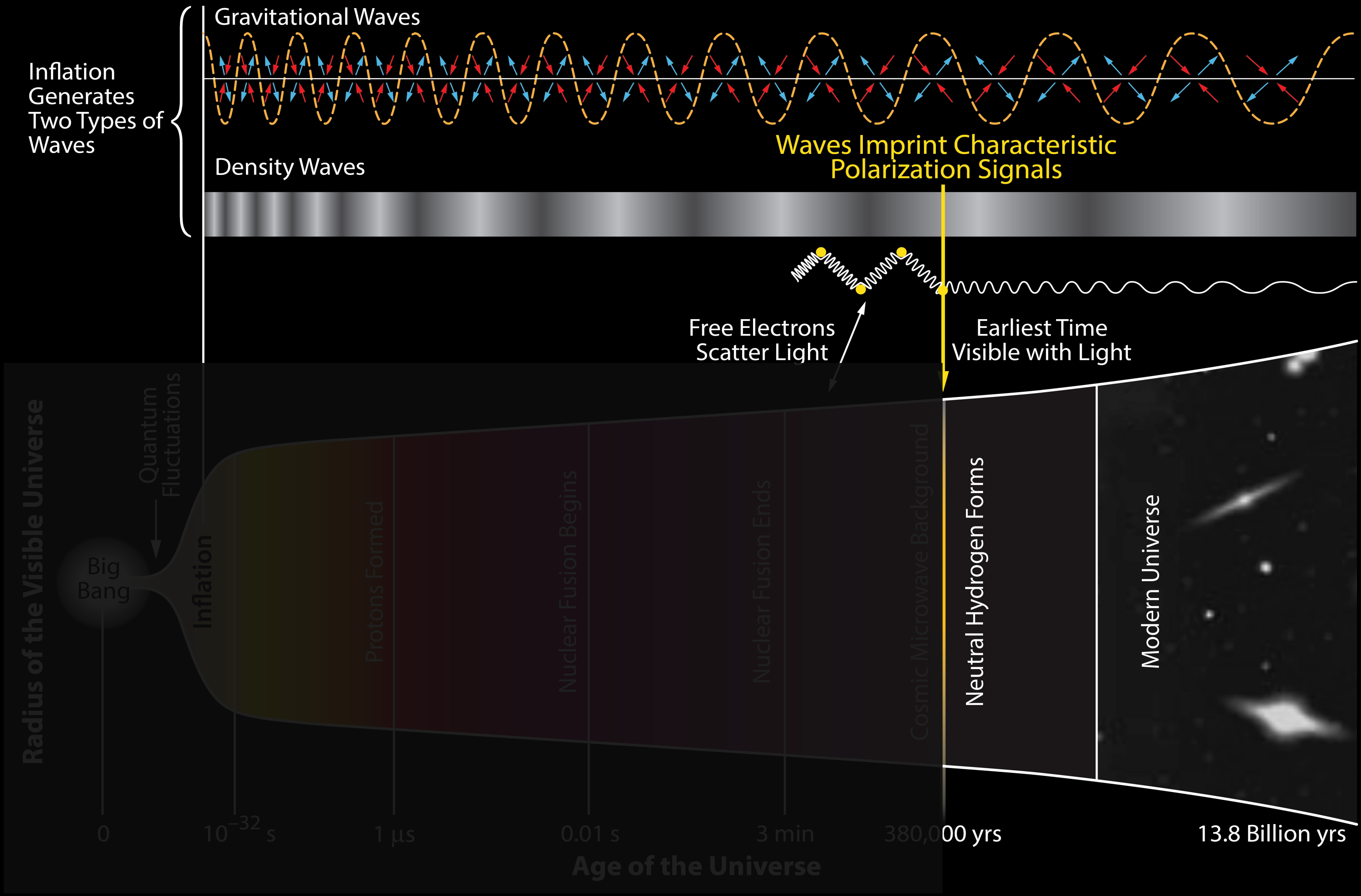
History of the Universe



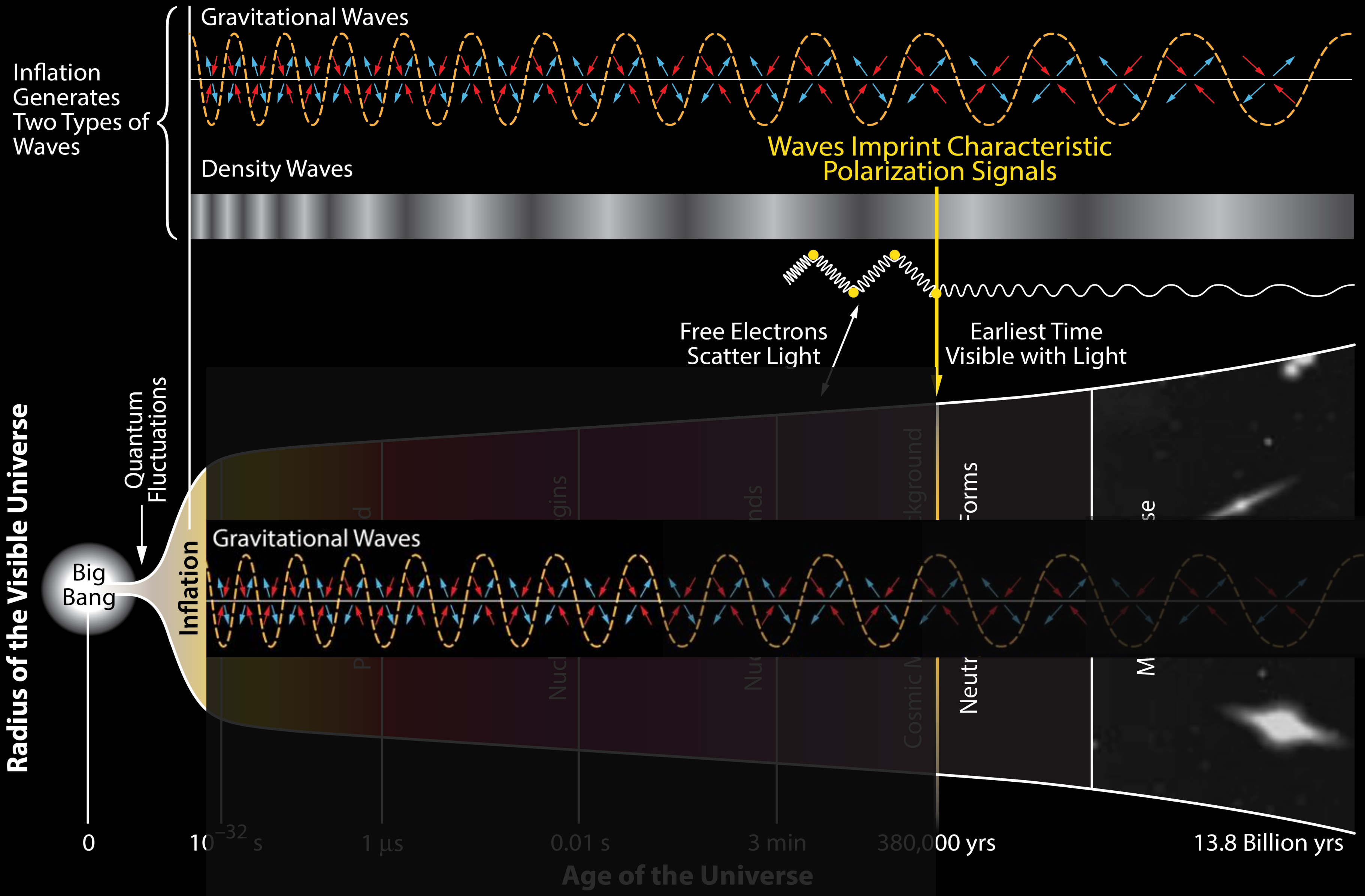
History of the Universe



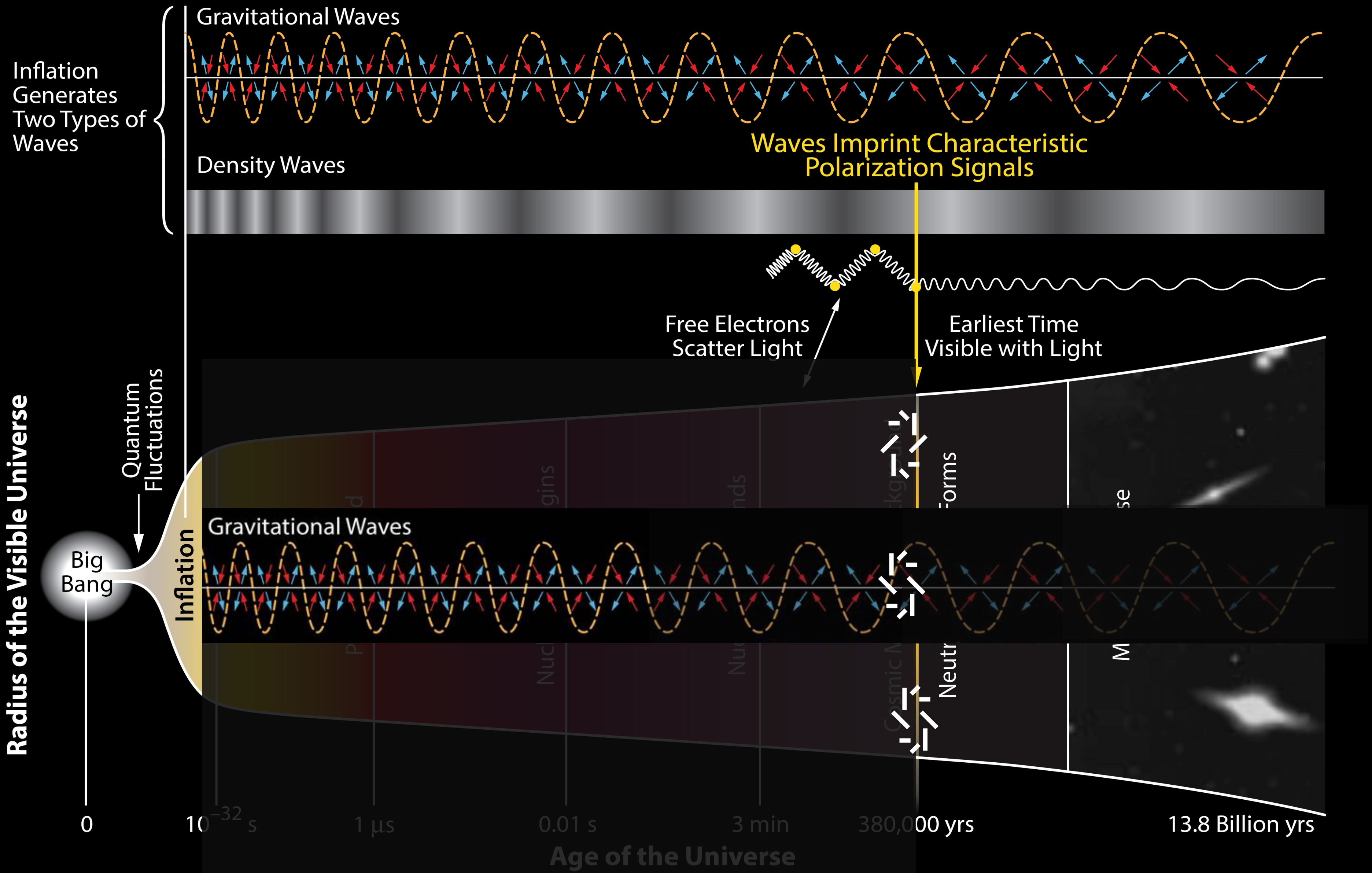
History of the Universe



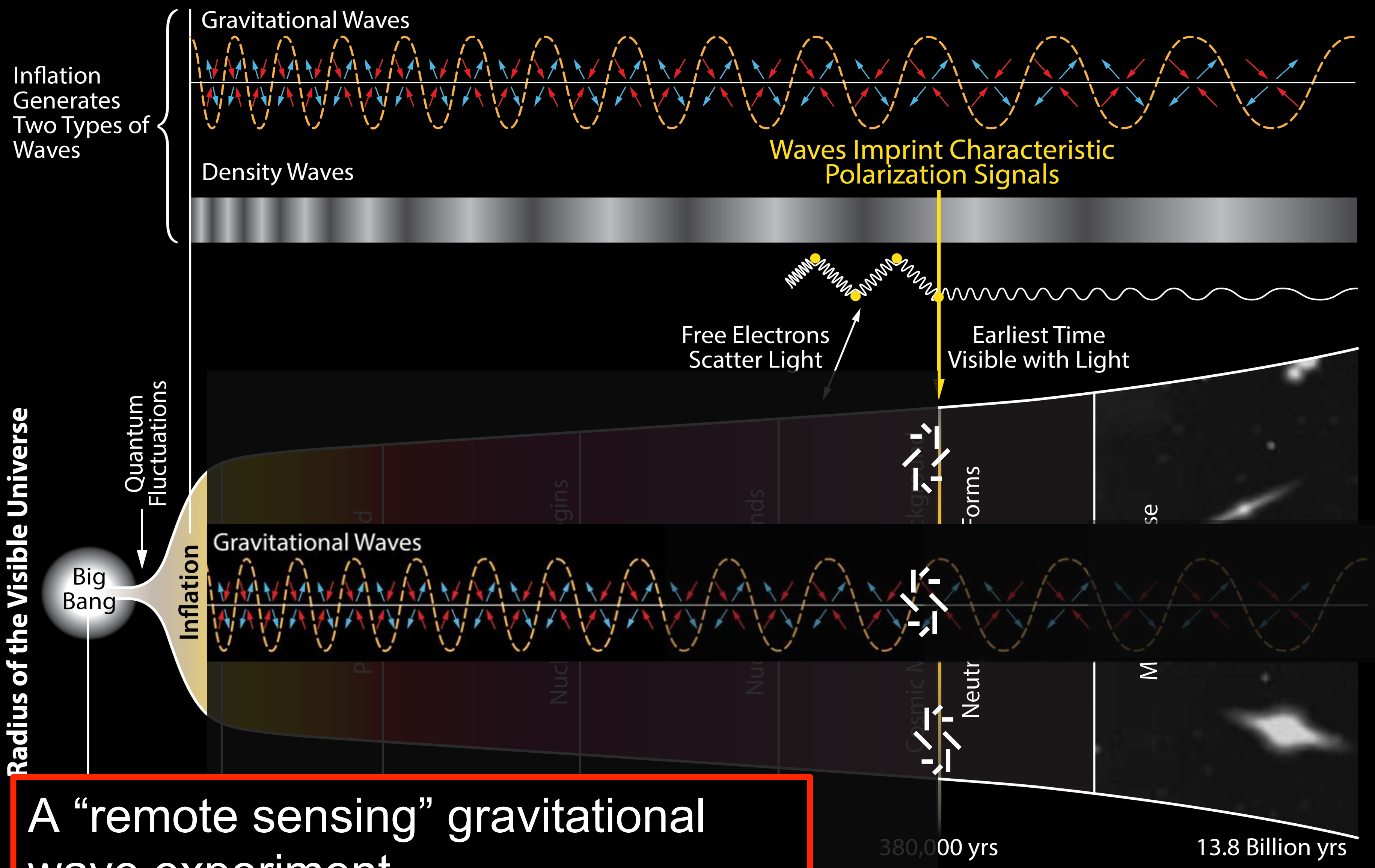
History of the Universe



History of the Universe



History of the Universe

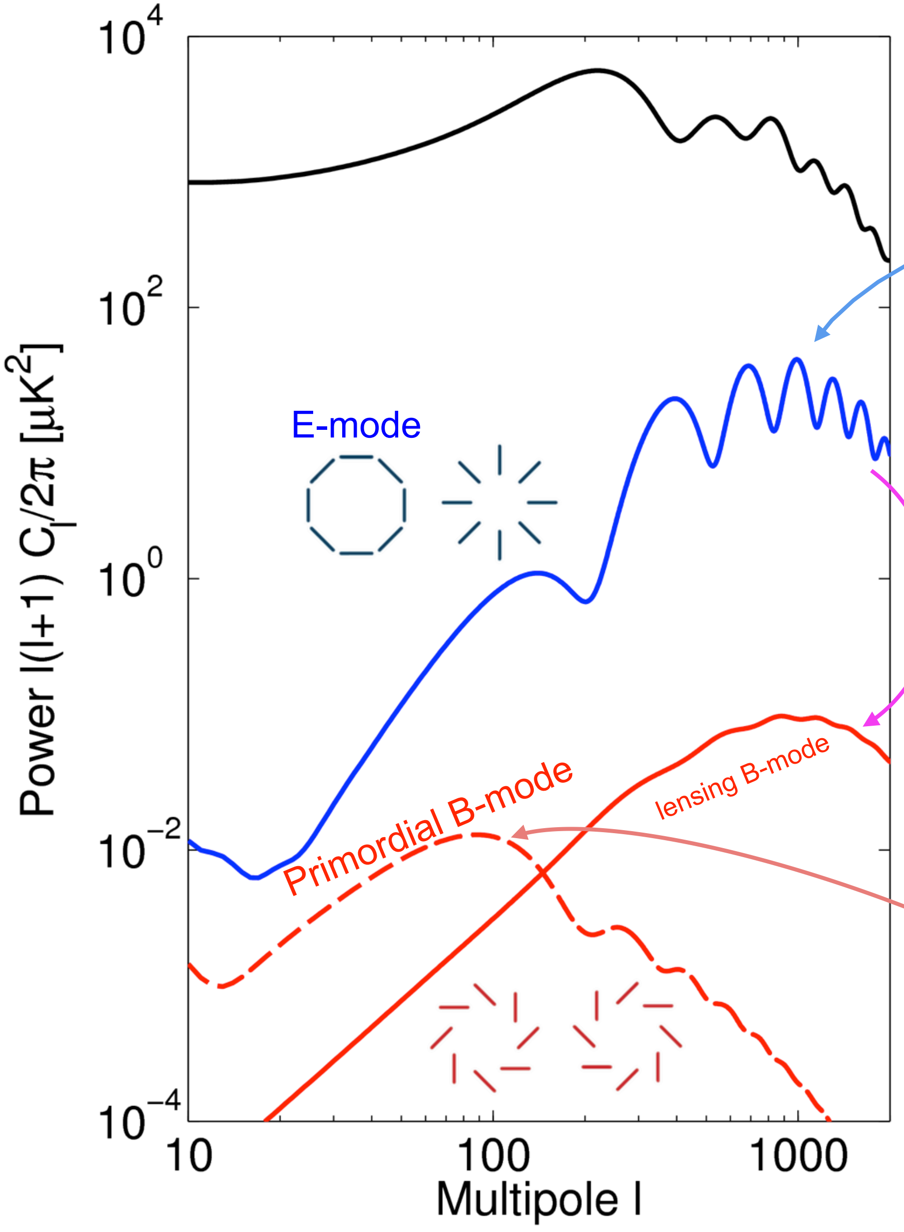


A “remote sensing” gravitational wave experiment

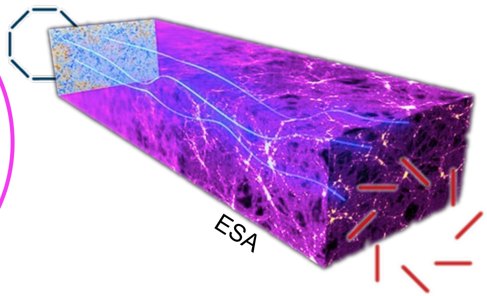
CMB Polarization, B-modes and *r*

- 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

CMB Polarization power spectra



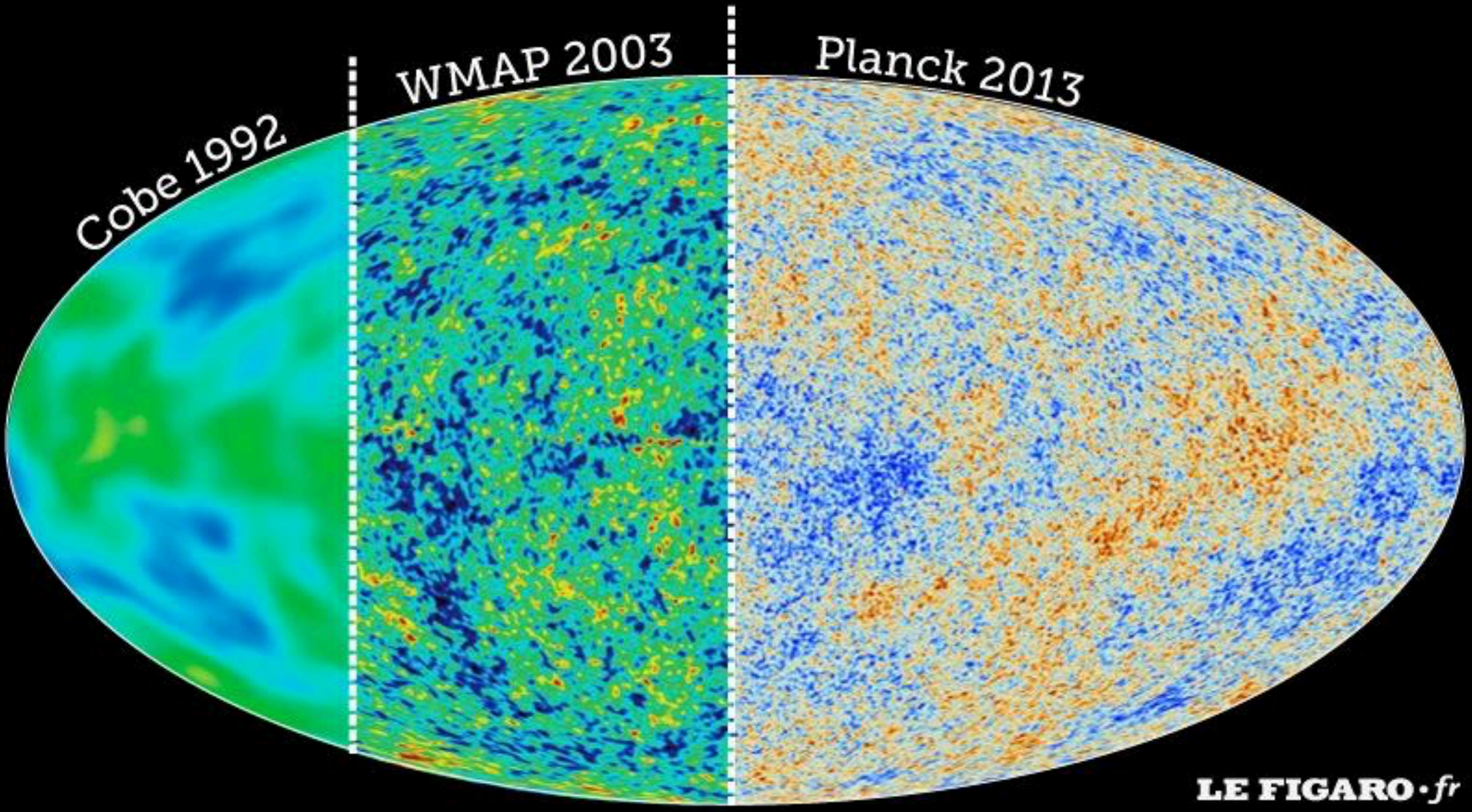
In standard ΛCDM only E-modes are present at last scattering



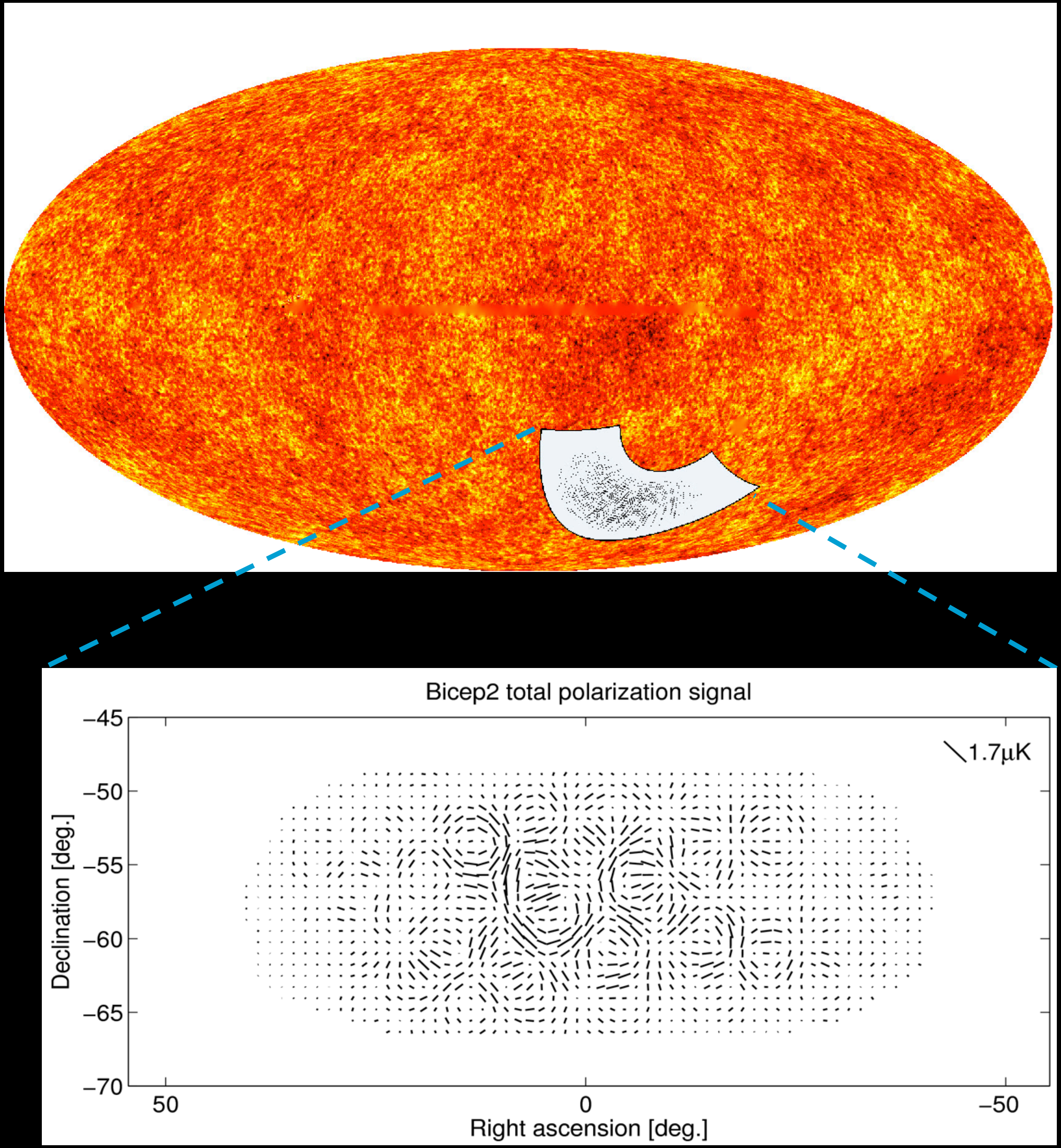
During propagation some of the E-modes are confused into B-modes by lensing

Inflationary gravitational waves are unique source of intrinsic B-modes
→ peaking at $l \approx 80$: few degree scales

CMB space missions map the full sky



Ground based telescopes map part of the sky more deeply



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cea

UCSD

JPL

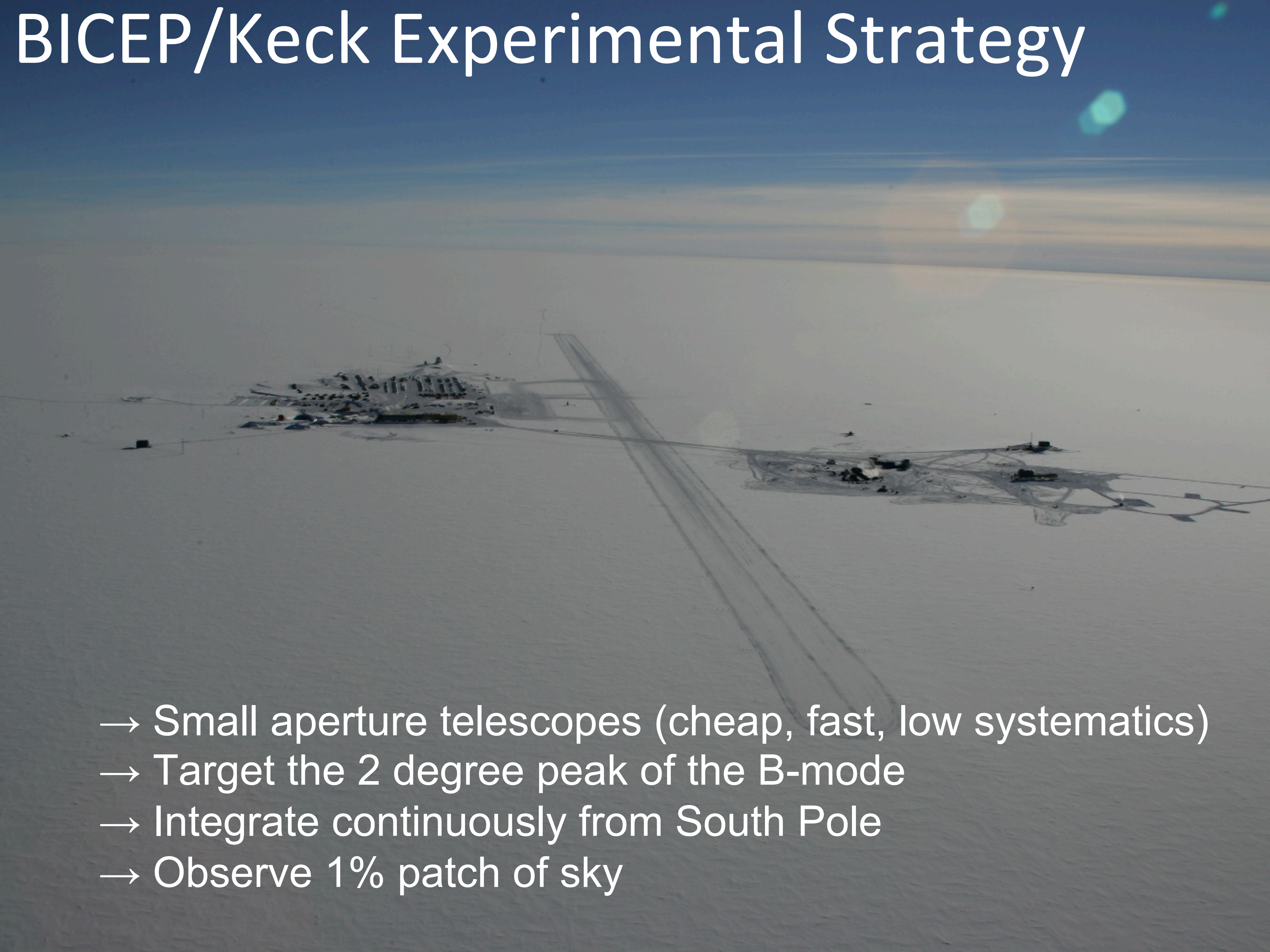
NIST

CARDIFF UNIVERSITY

UNIVERSITY OF TORONTO

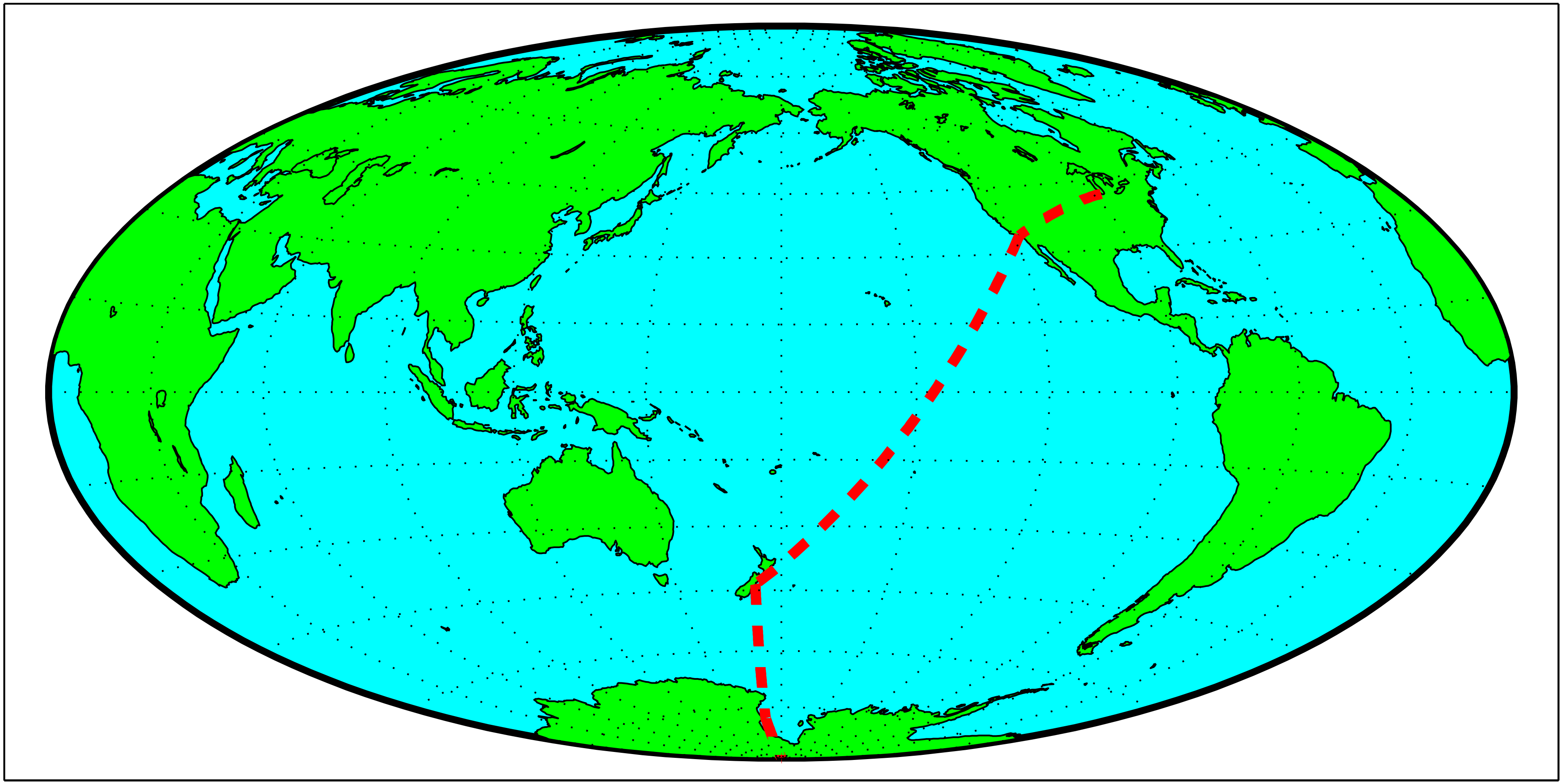
UBC

BICEP/Keck Experimental Strategy



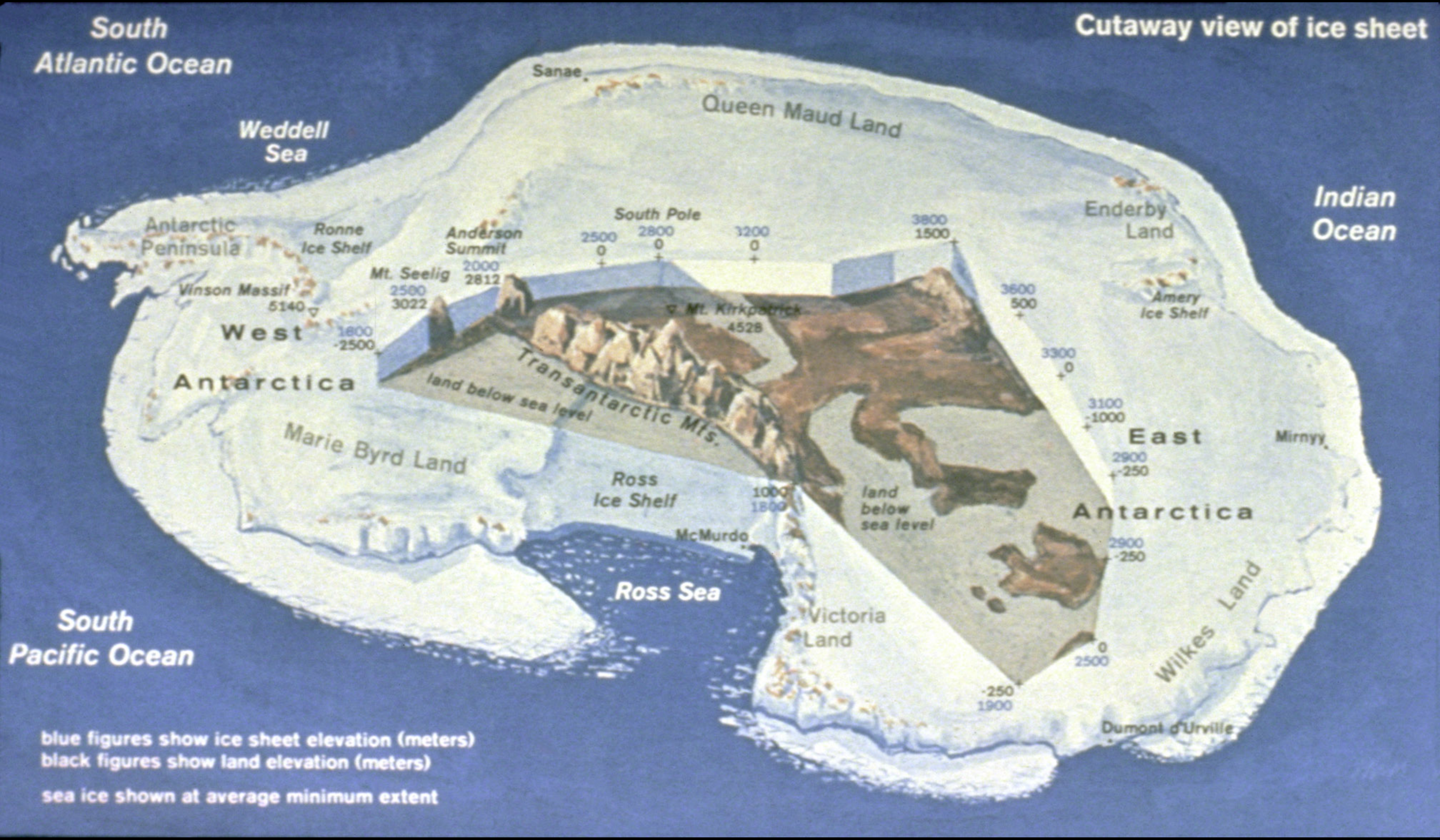
→ Small aperture telescopes (cheap, fast, low systematics)
→ Target the 2 degree peak of the B-mode
→ Integrate continuously from South Pole
→ Observe 1% patch of sky

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

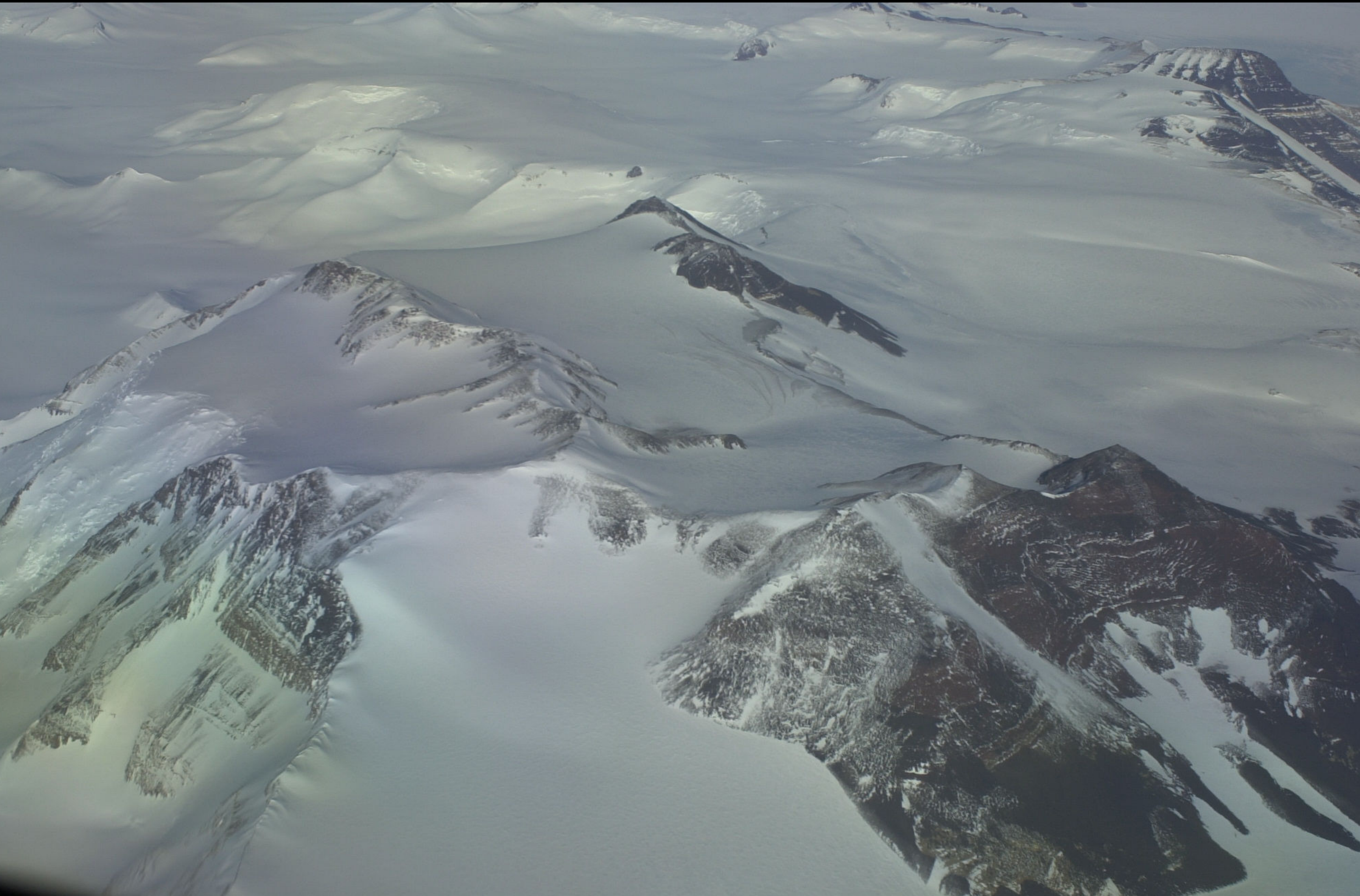
Christchurch New Zealand – Clothing Warehouse

Big Program!

Arrival in Antarctica

McMurdo – base on the coast

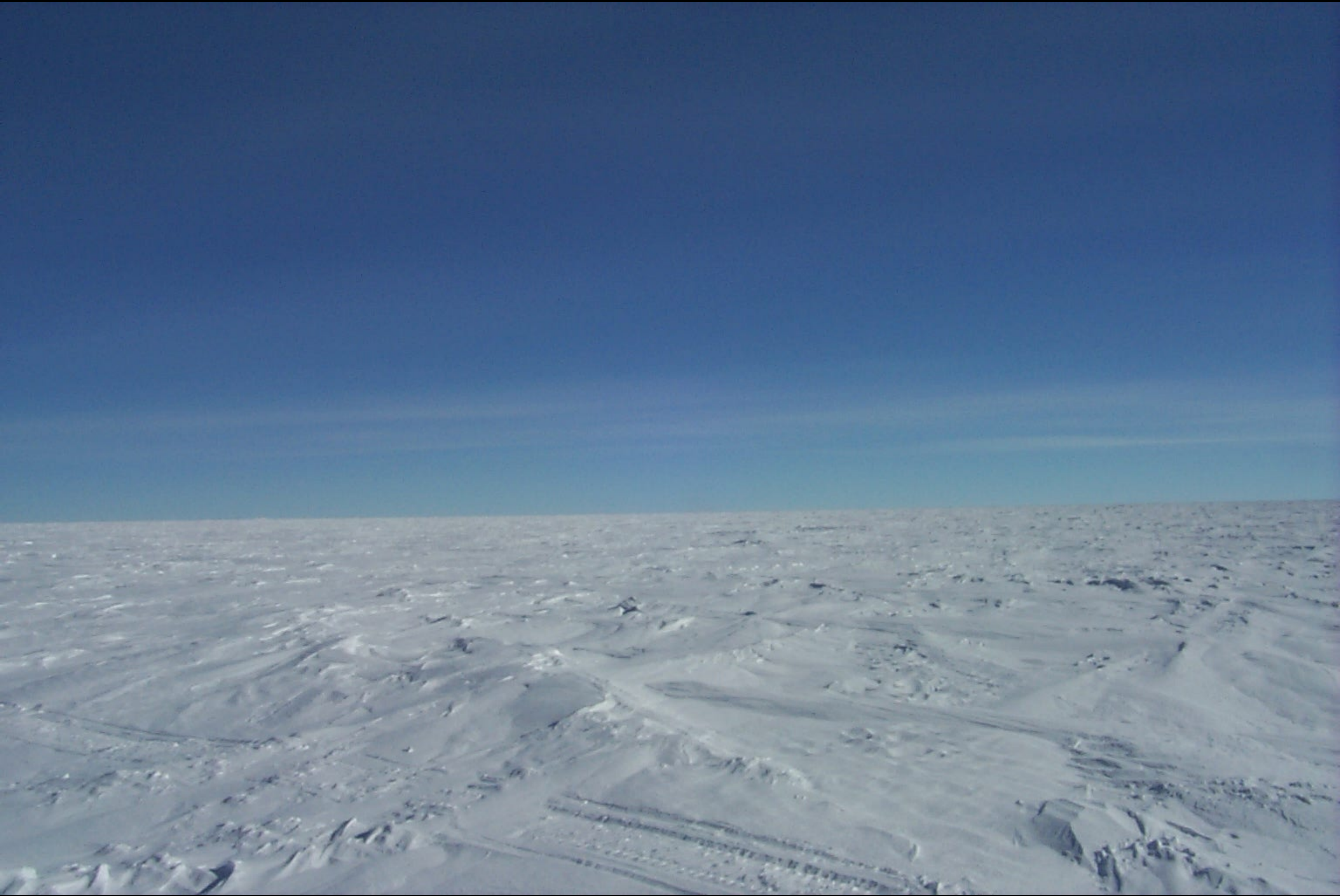
On to the Pole – over the Transantarctic Mountains



Unloading at Pole

The Actual South Pole

Nothing Out There!

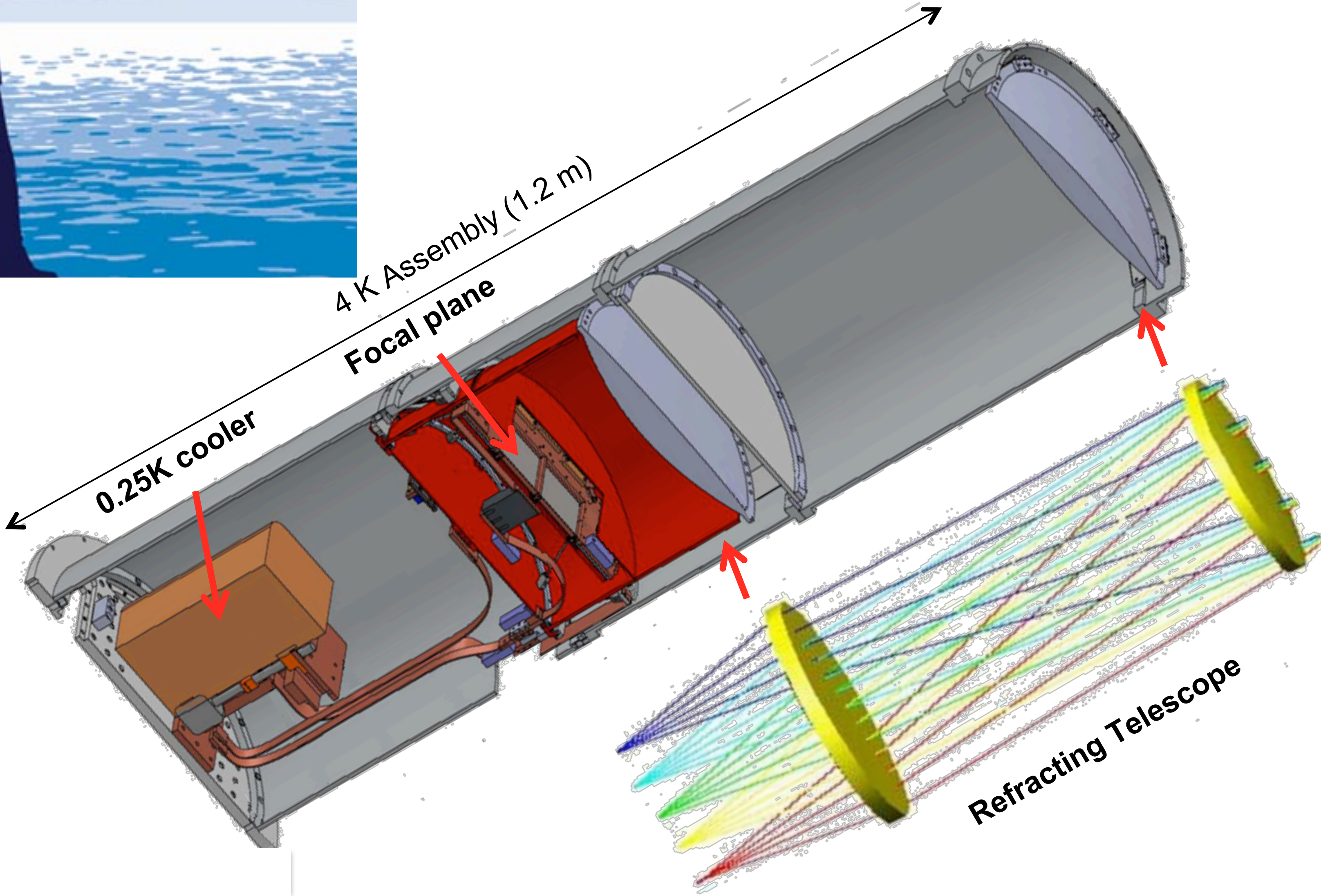


Why do this at the Pole?

- 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…

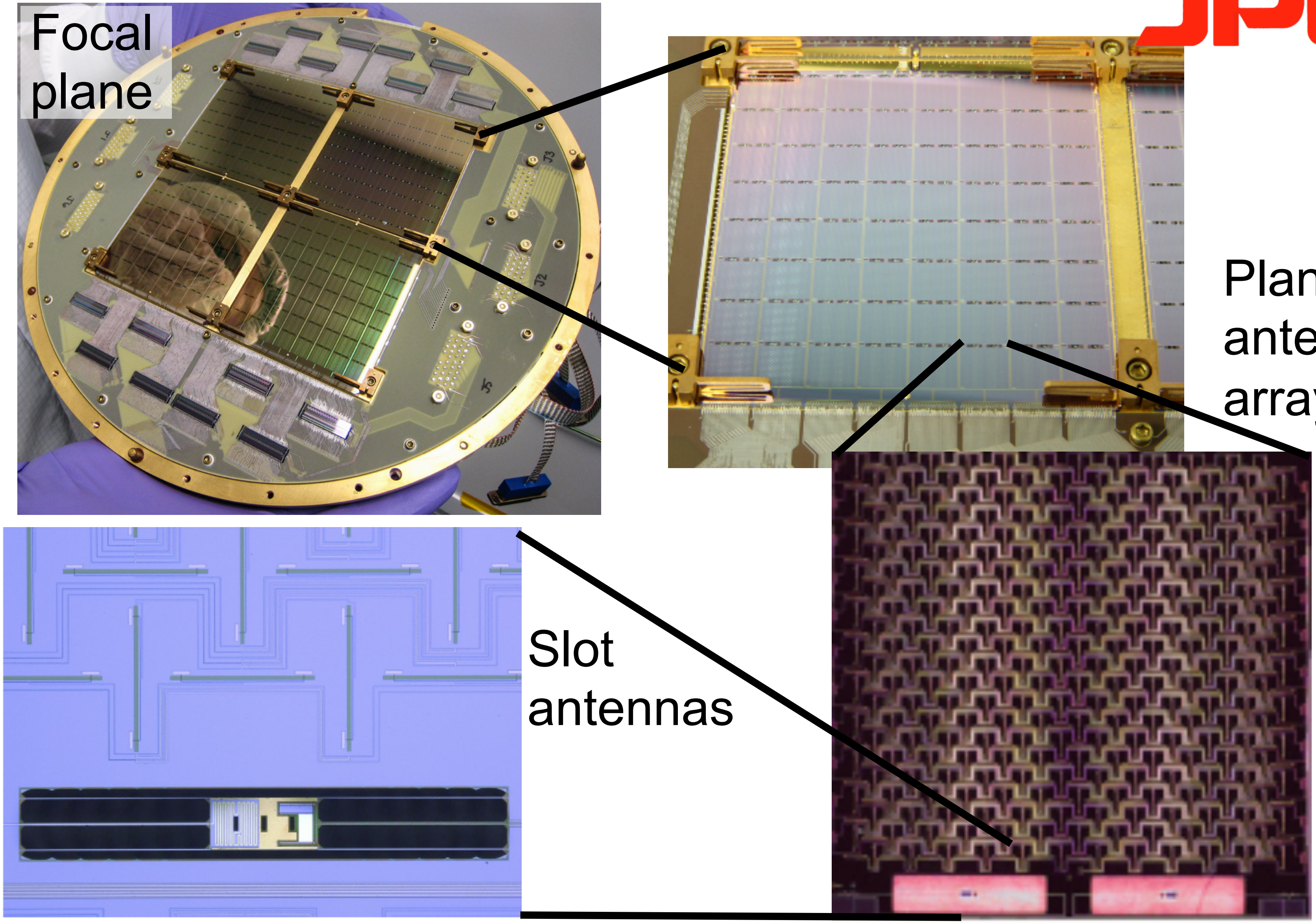
BICEP/Keck Experimental Concept

- Small aperture
- Wide field of view
- Cold refractor



Mass-produced Superconducting Detectors

JPL



Focal plane

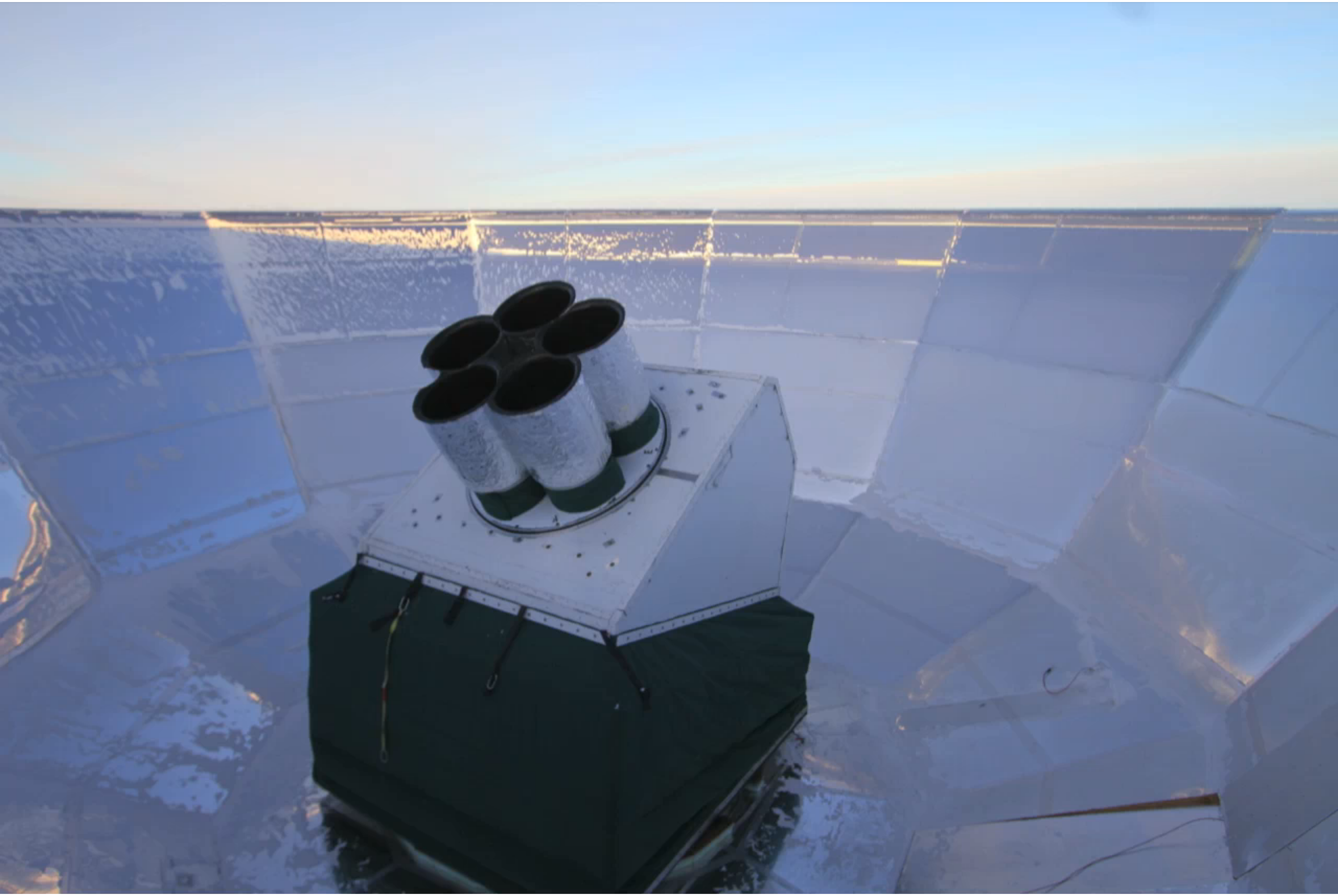
Planar antenna array

Slot antennas

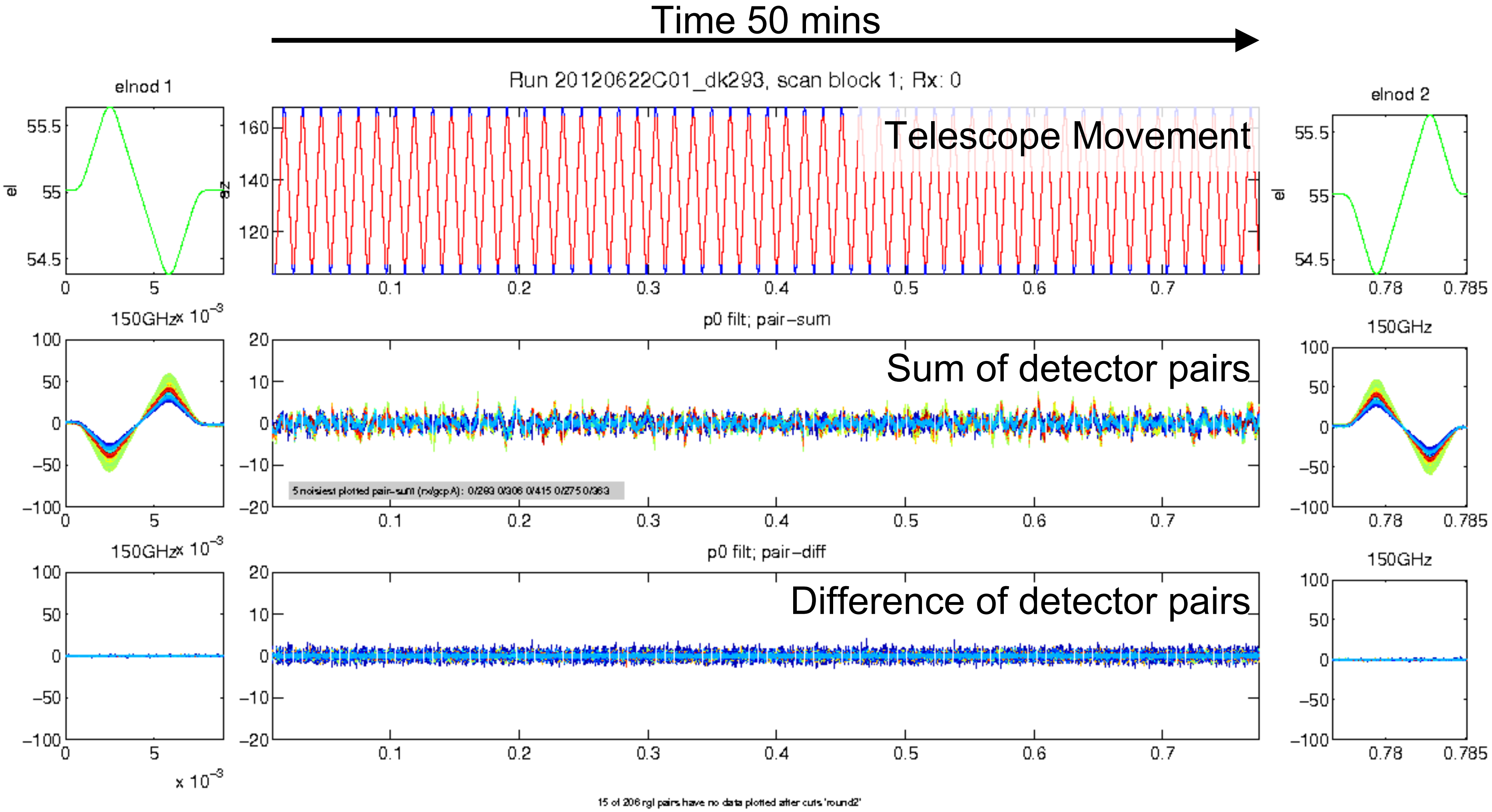
Transition edge sensor

Microstrip filters

Google “Robert Schwarz” – in his 9th consecutive winter season at South Pole (15th overall!)

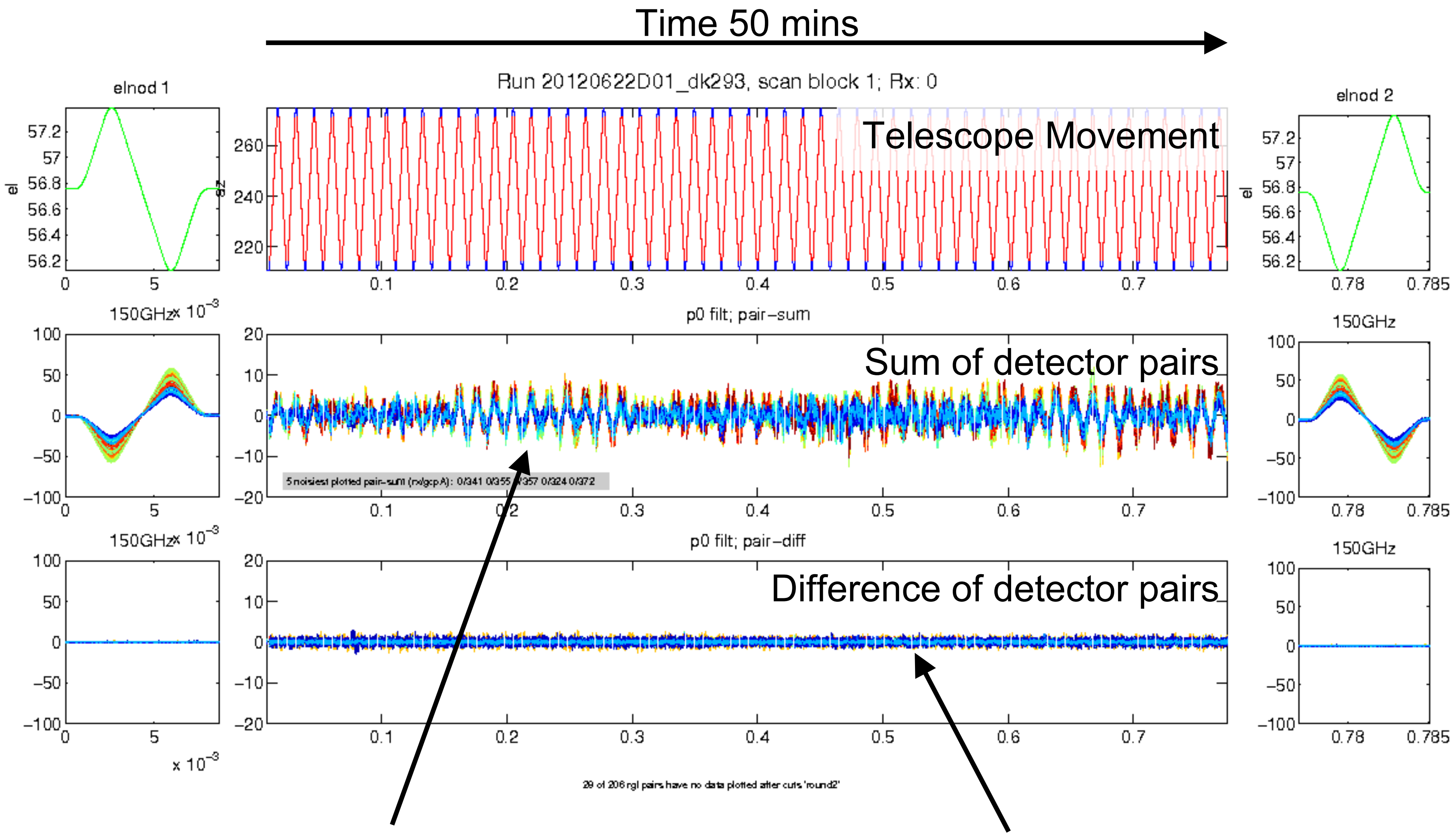


Raw Data - Perfect Weather



- 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



Time 50 mins

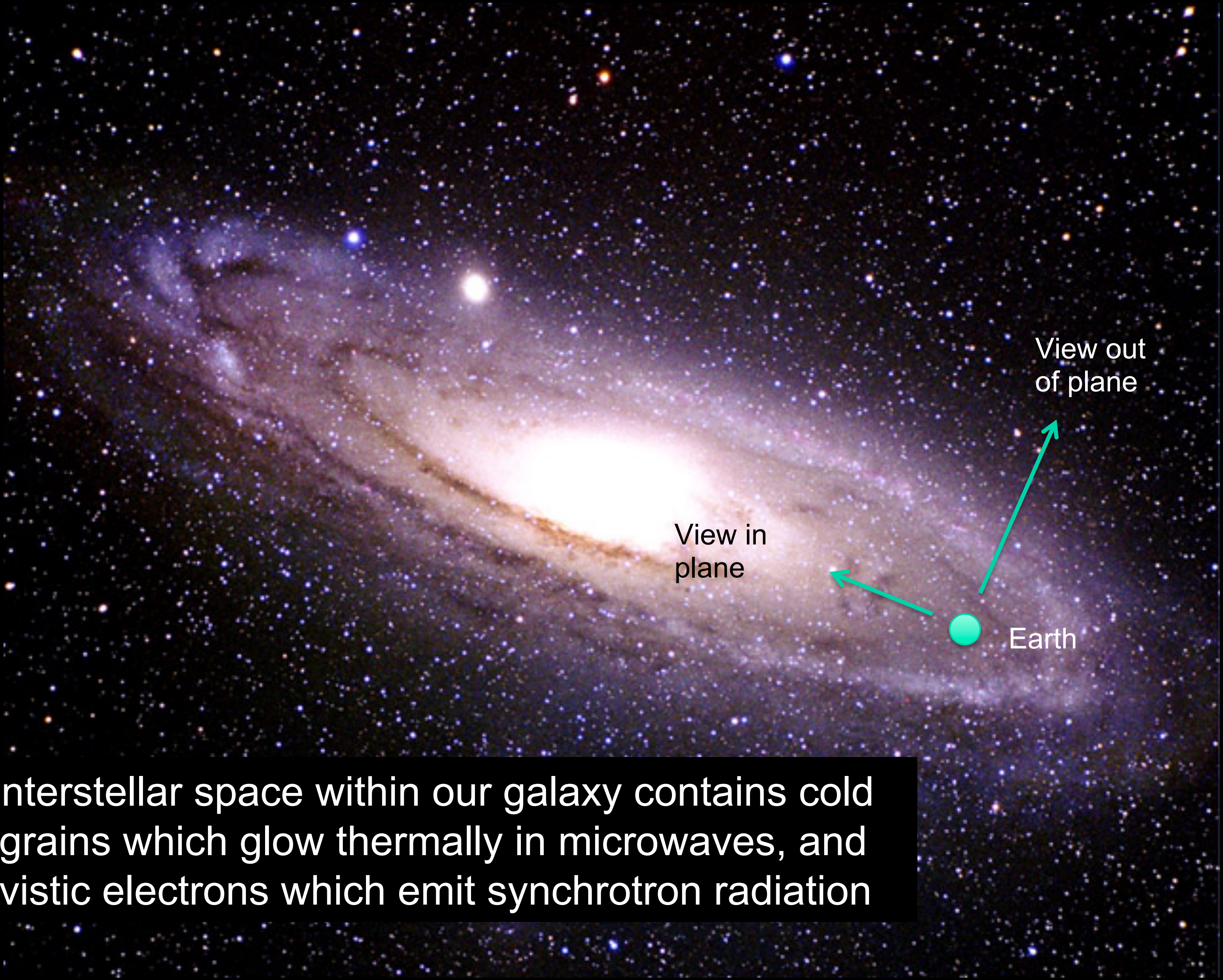
Telescope Movement

Sum of detector pairs

Difference of detector pairs

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

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

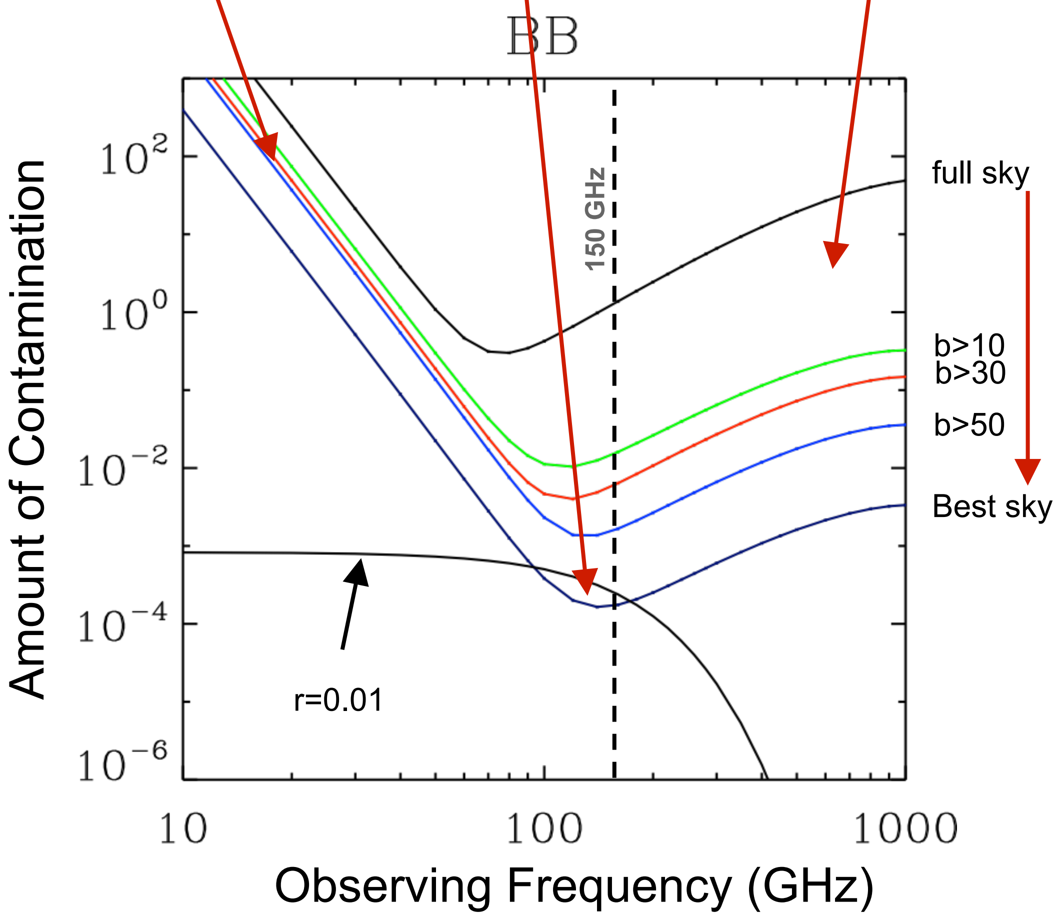
When CMB people talk about “foregrounds” it is analogous to what HEP people call “backgrounds” – something which gets in the way of the thing one is trying to measure.

Polarized Foreground Contamination from Our Galaxy

At low frequency synchrotron contamination

Sweetest spot

At high frequency dust contamination



Pick a cleaner patch of sky

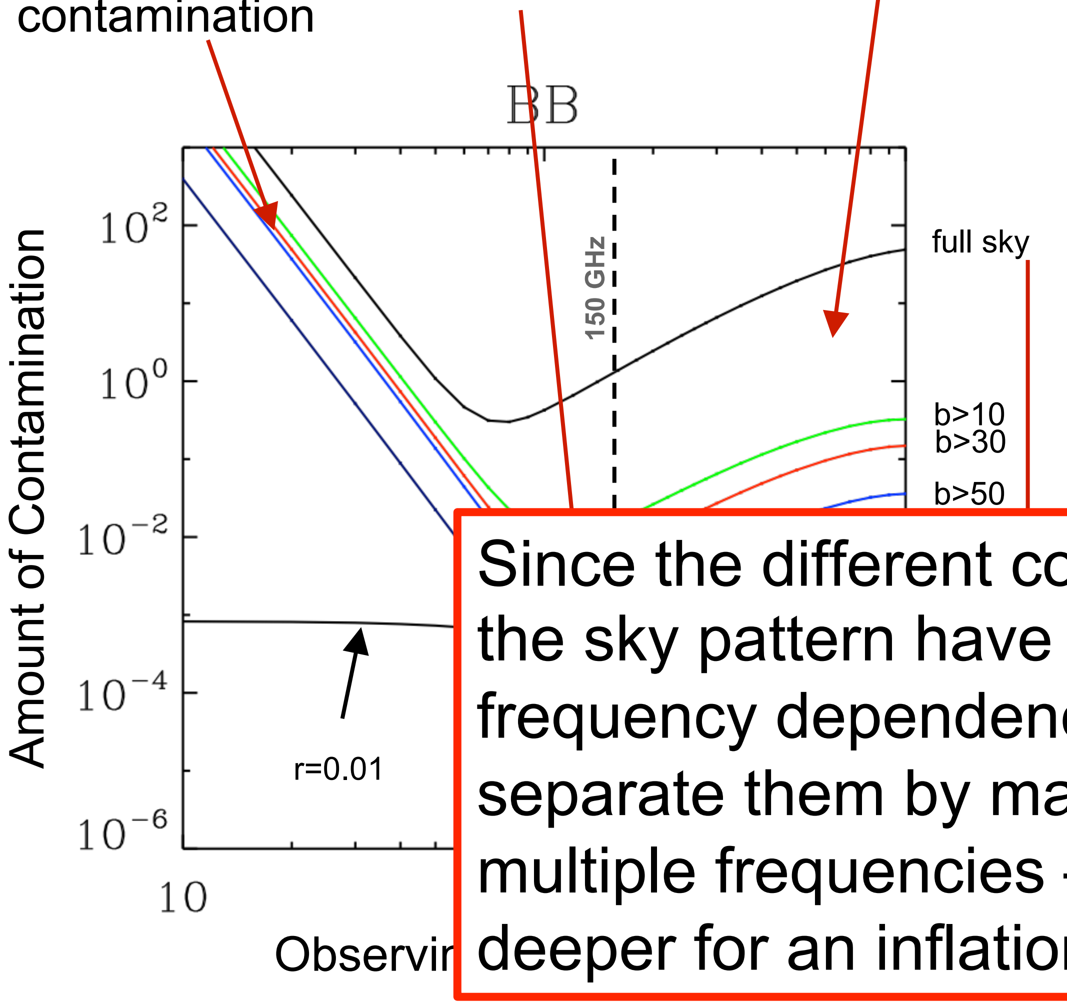
(Plot from Dunkley et al arxiv/0811.3915)

Polarized Foreground Contamination from Our Galaxy

At low frequency synchrotron contamination

Sweetest spot

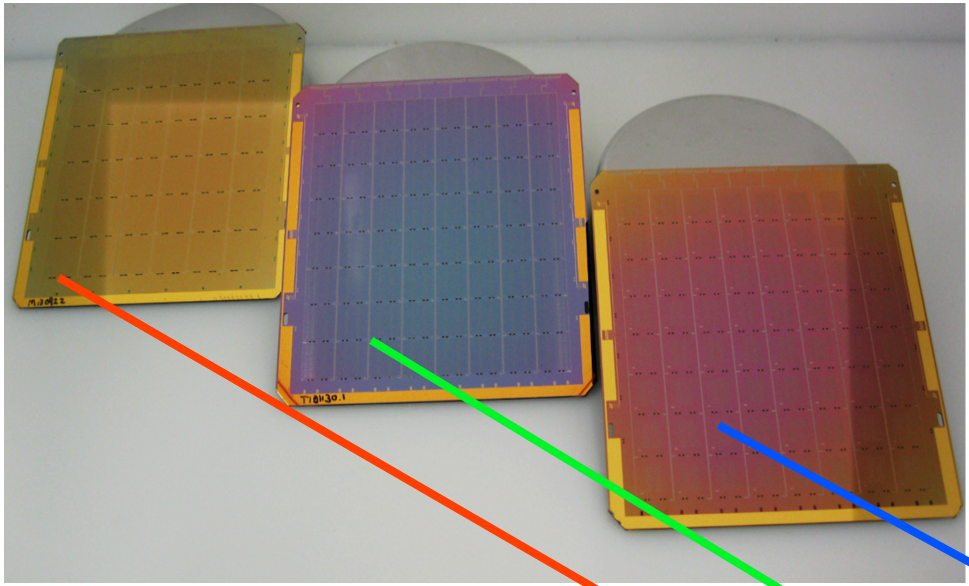
At high frequency dust contamination



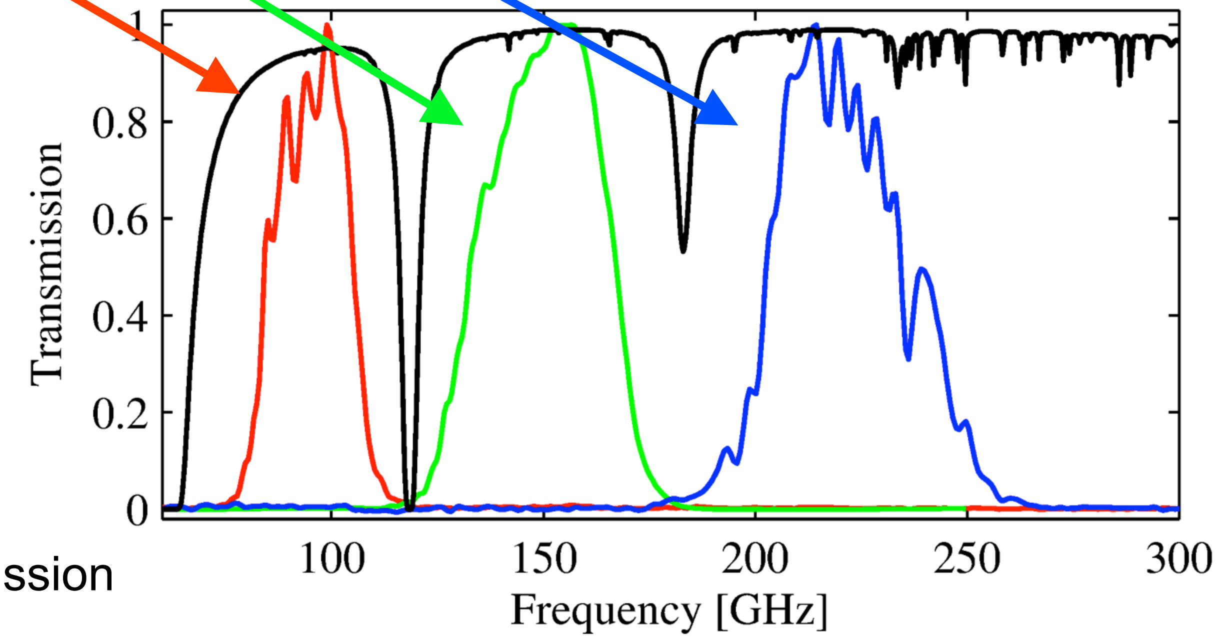
Pick a cleaner patch of sky

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

Can Make Detectors Tuned to Different Frequency Bands

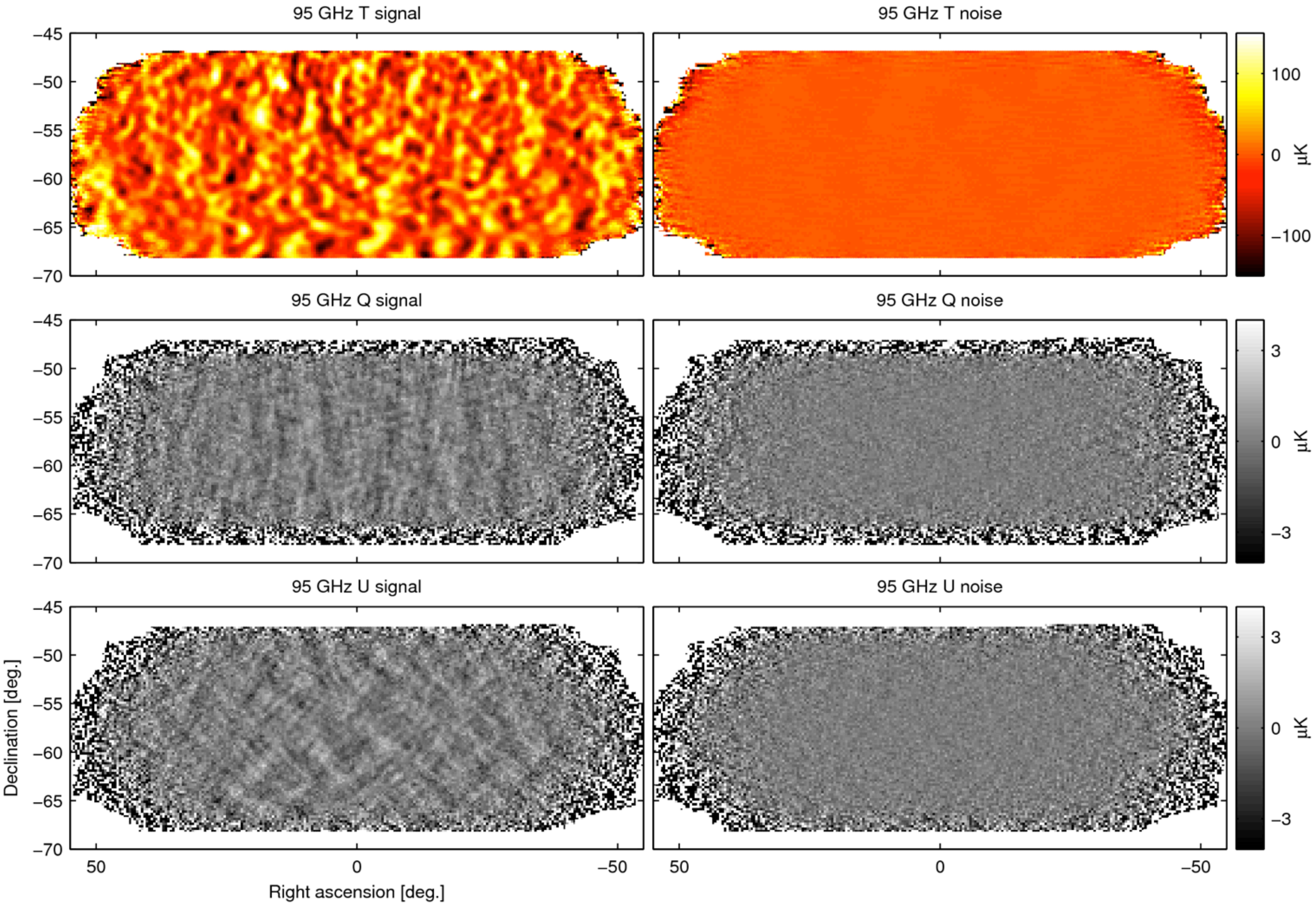


Up to 2013 – all 150GHz
2014 – 2x95 3x150GHz
2015 – 2x95 1x150 2x220GHz
2016 – B3 1x150 4x220GHz
2017 – B3 4x220 1x270GHz
2018 – B3 4x220 1x270GHz



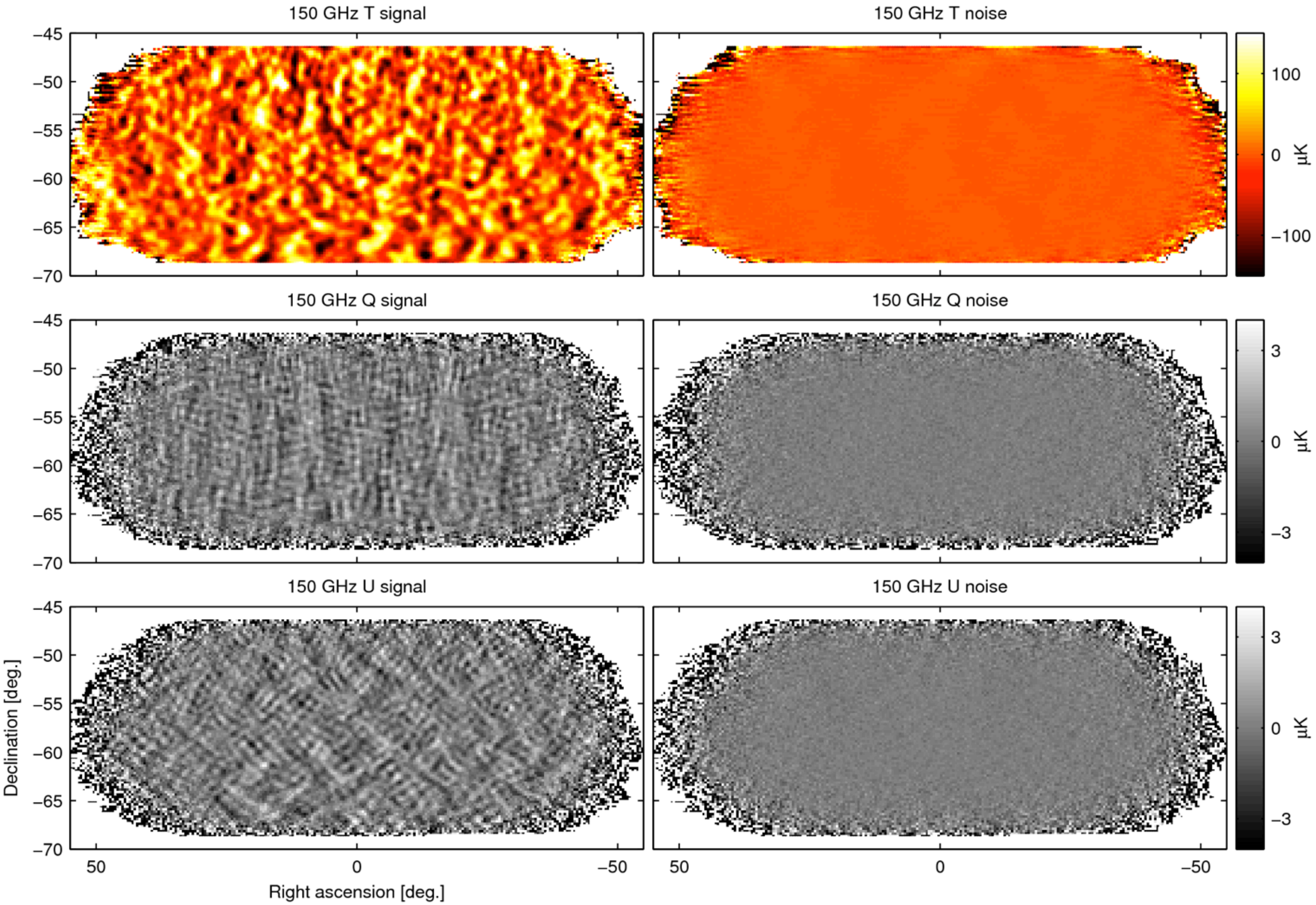
Typical South Pole atmospheric transmission

BK15 95GHz Maps



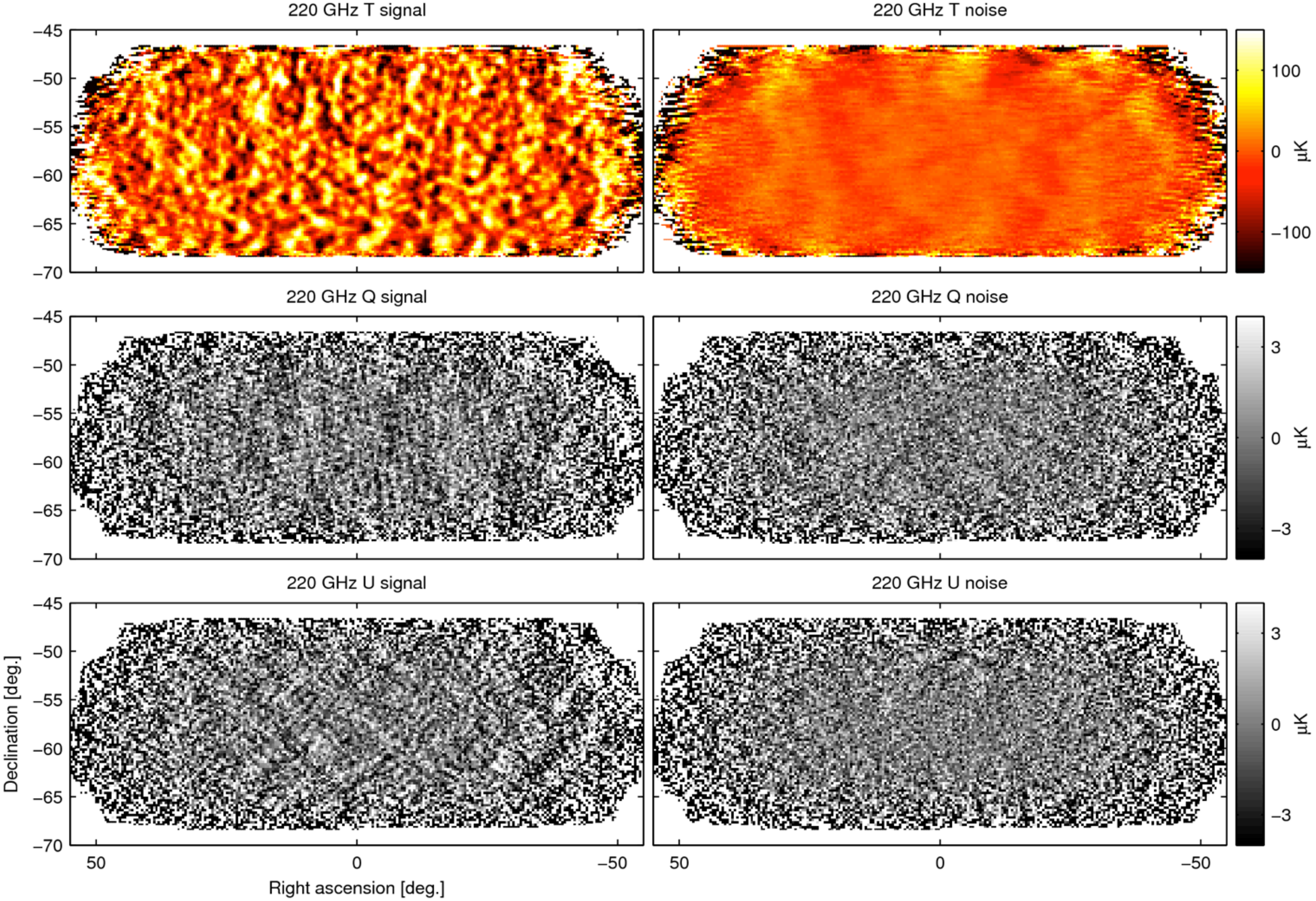
BK15 95GHz – 5 μK arcmin

BK15 150GHz Maps



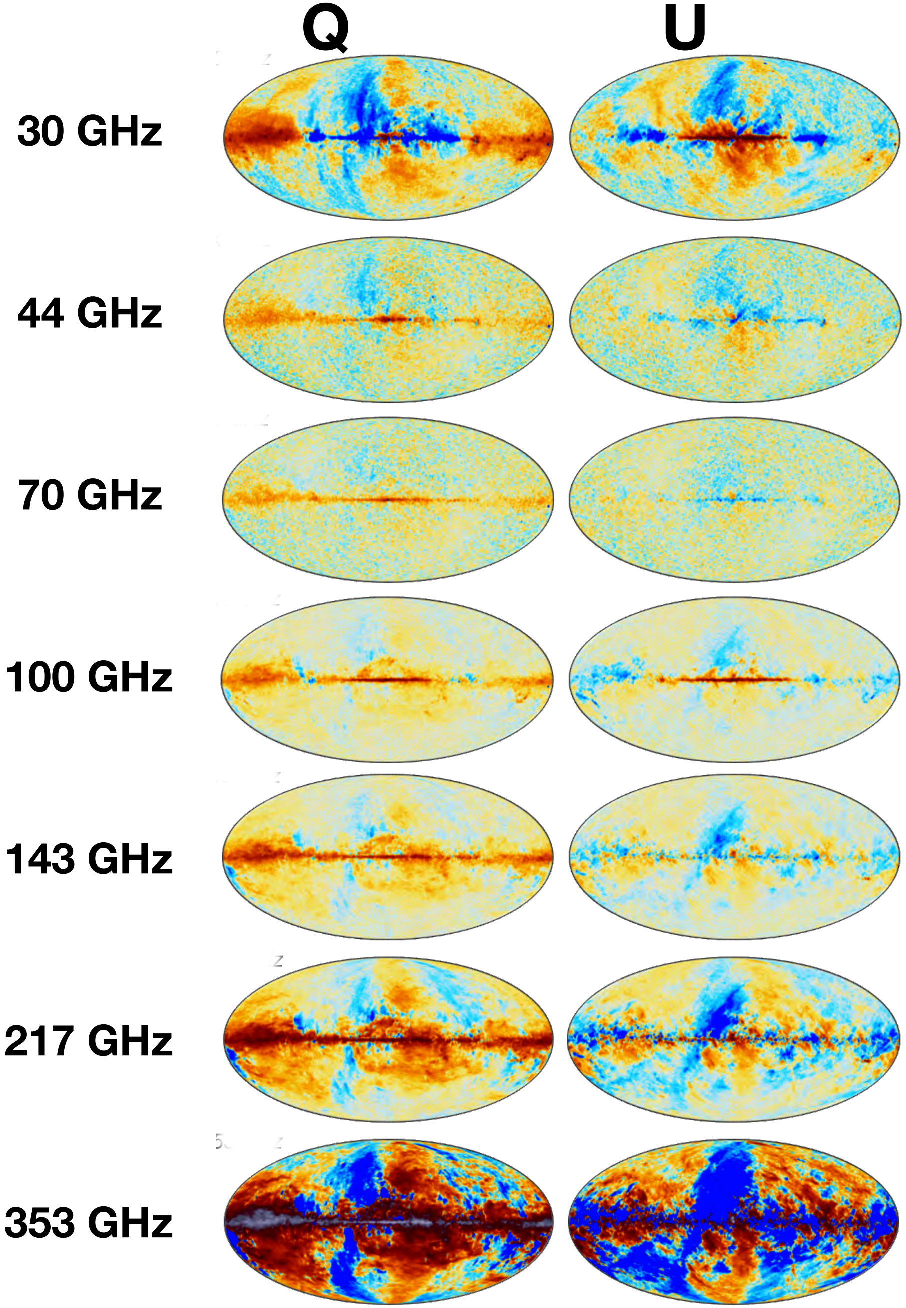
BK15 150GHz – 2.8 μK arcmin

BK15 220GHz Maps



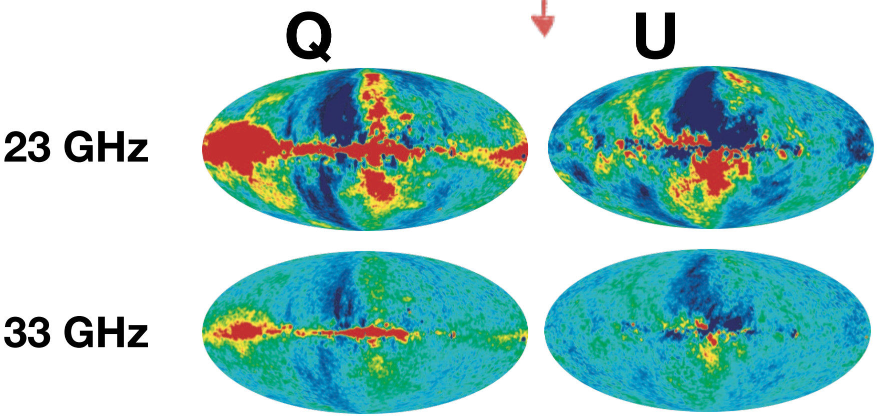
BK15 220GHz – 25 μK arcmin

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



From arxiv 1502.01582

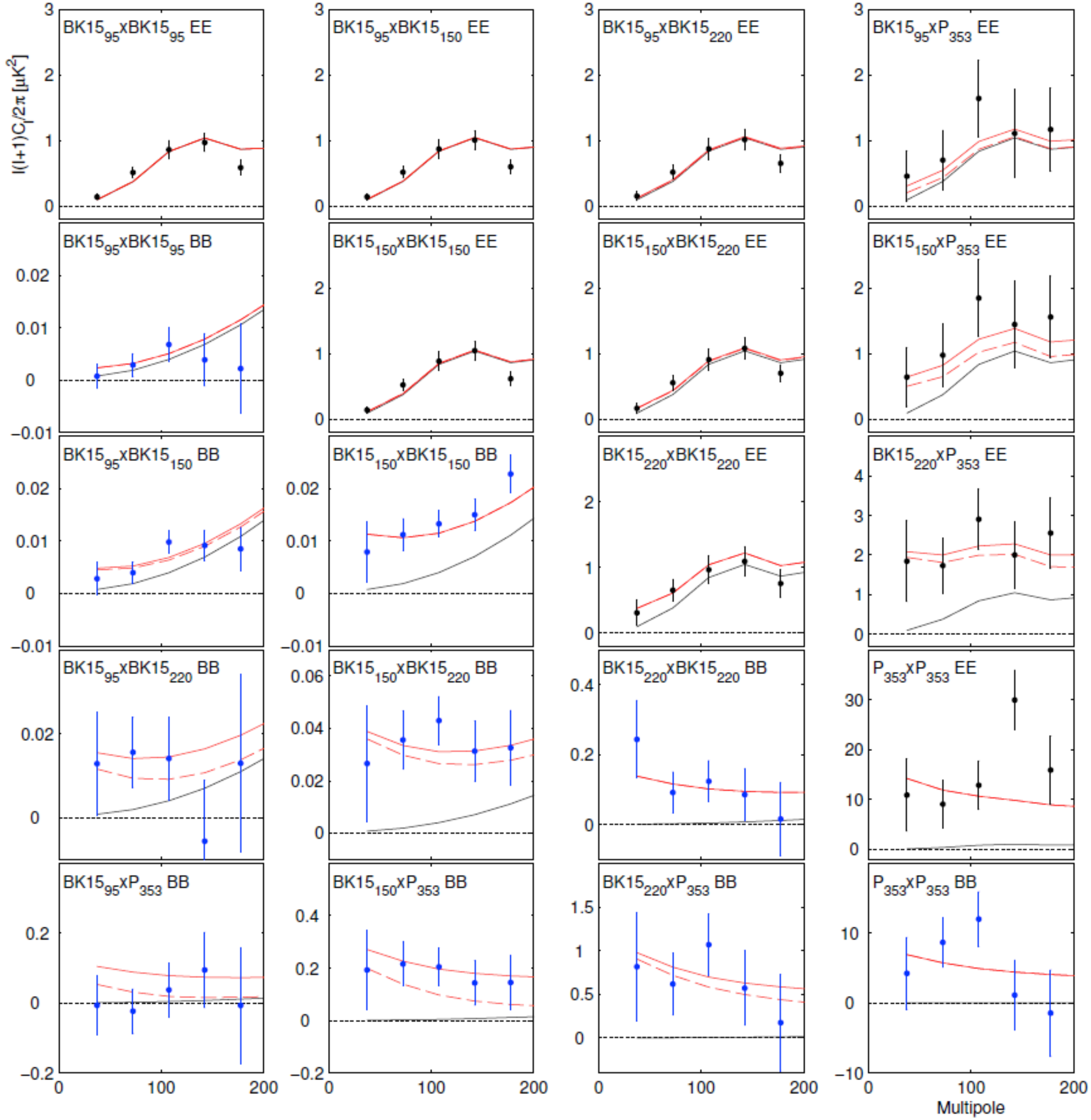
Polarized galactic **synchrotron** dominates at low frequencies



From arxiv 1212.5225

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

BK15+P353 Spectra



Upper/right plots are EE (black points)

Lower/left plots are BB (blue points)

220GHz auto/ cross spectra are all new

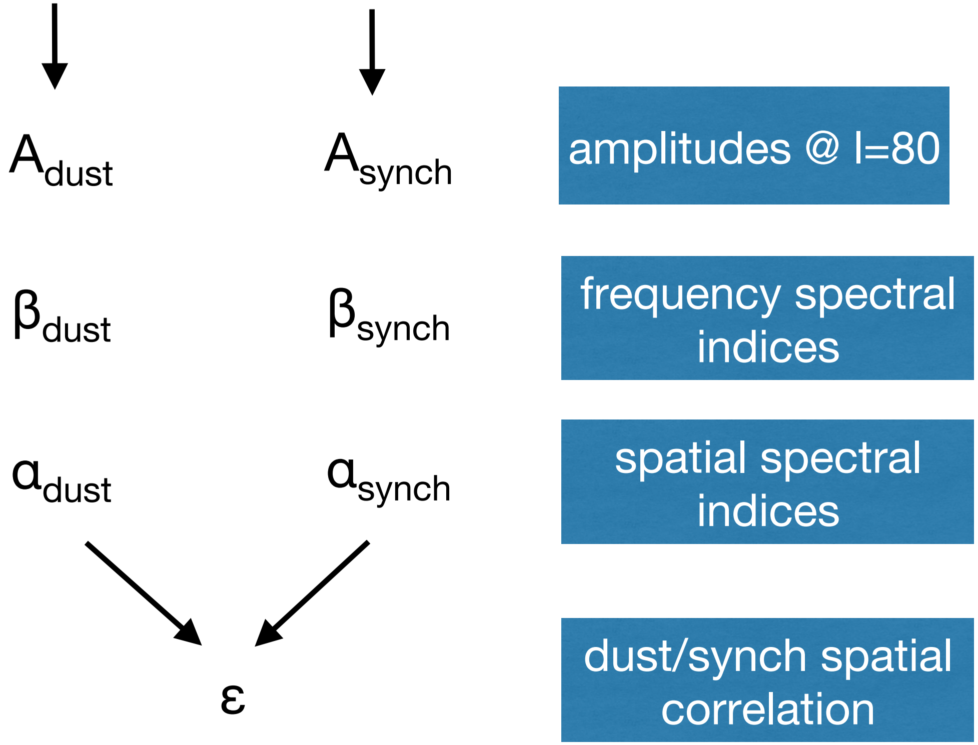
Red solid line is best fit multicomponent model from previous (BK14) analysis - It fits all the spectra

Chi-squared is OK – no evidence yet for non-Gaussianity of the dust pattern

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

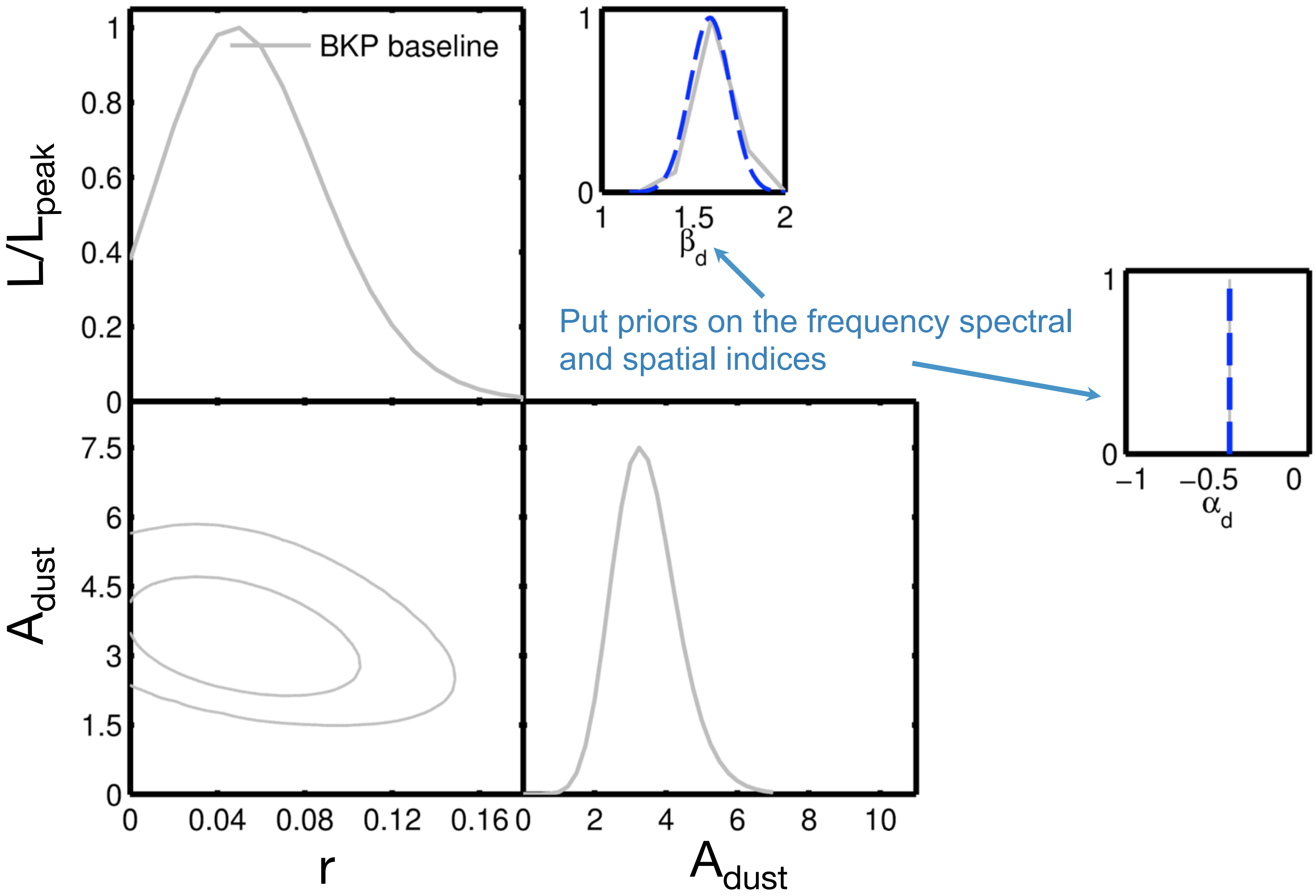


A_{dust} A_{synch} amplitudes @ l=80

β_{dust} β_{synch} frequency spectral indices

α_{dust} α_{synch} spatial spectral indices

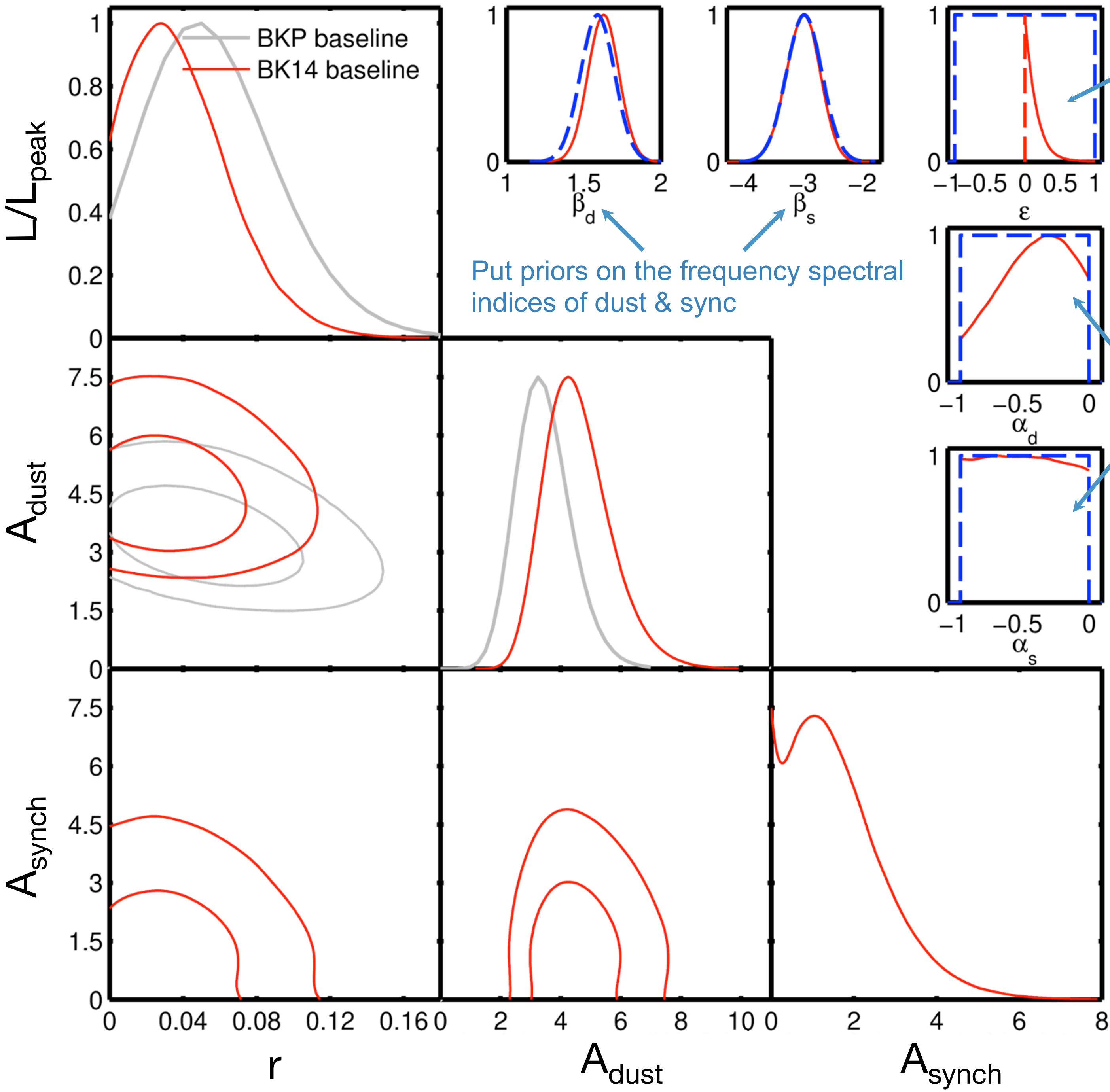
ε dust/synch spatial correlation



Put priors on the frequency spectral and spatial indices

BKP

arxiv/1502.00612



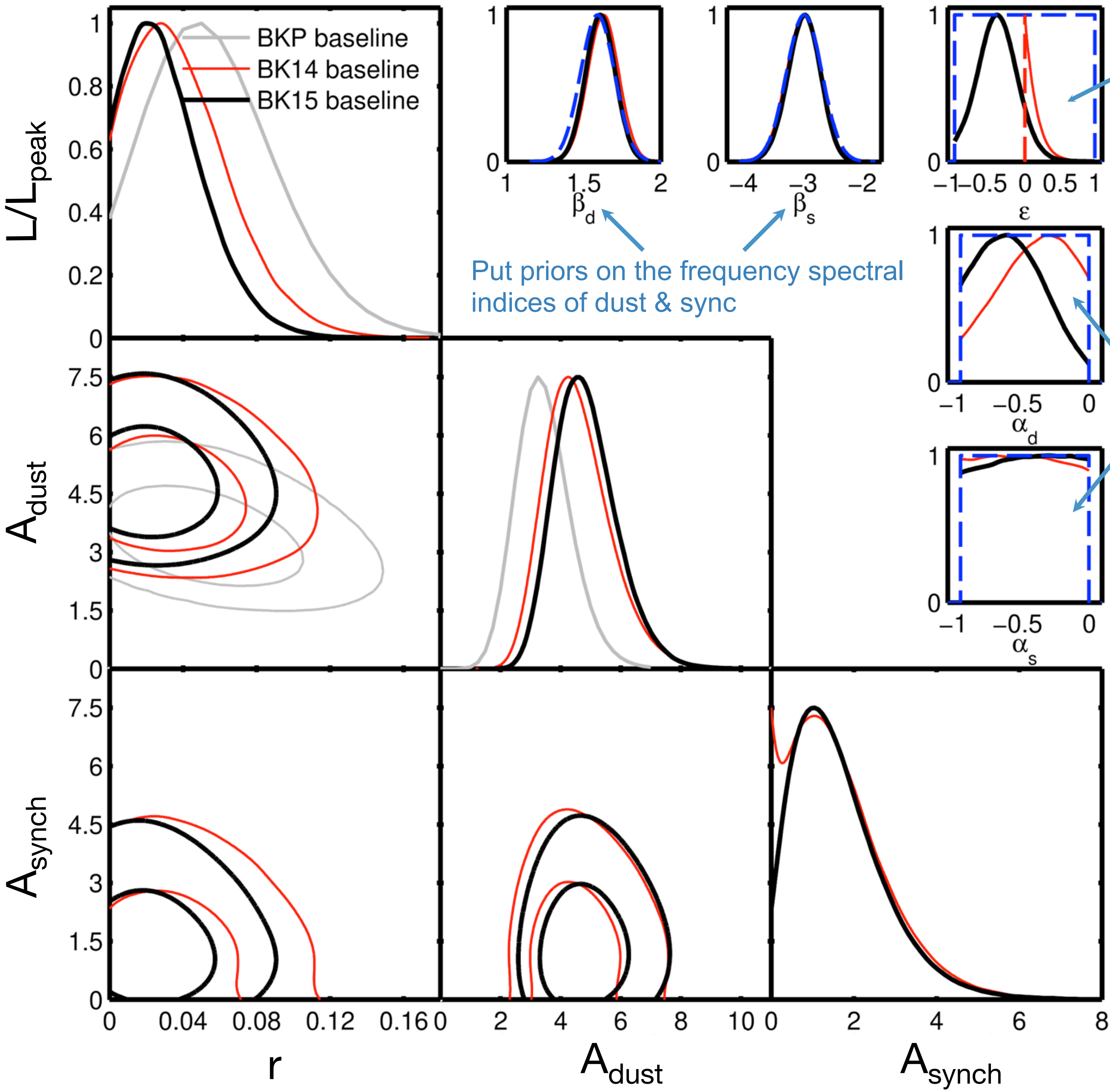
Put priors on the frequency spectral indices of dust & sync

Allow dust/sync correlation

Marginalize over generous ranges in spatial spectral indices

BK14

arxiv/1510.09217



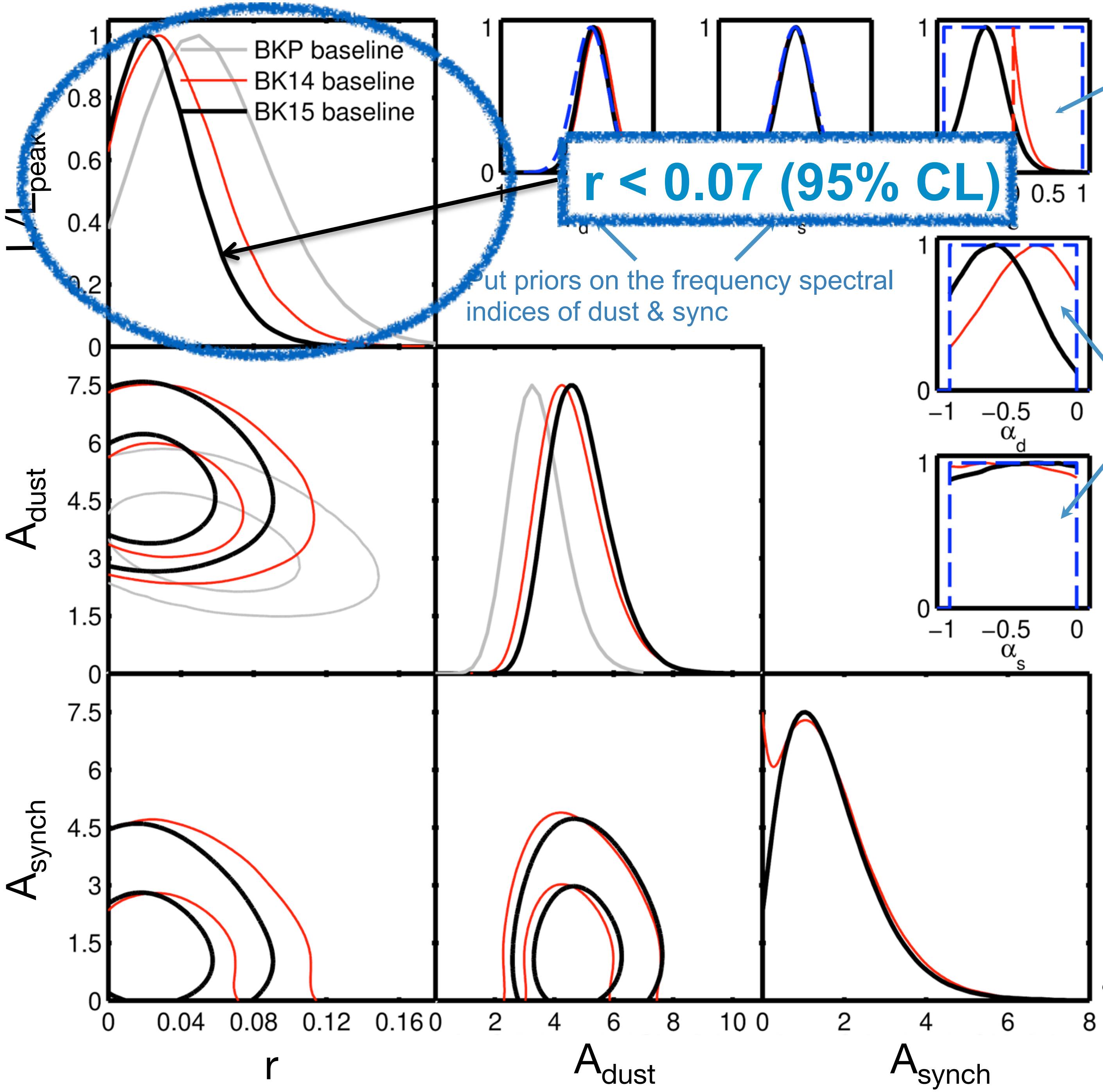
Allow dust/sync correlation

Put priors on the frequency spectral indices of dust & sync

Marginalize over generous ranges in spatial spectral indices

BK15

arxiv/1810.05216



r < 0.07 (95% CL)

Put priors on the frequency spectral indices of dust & sync

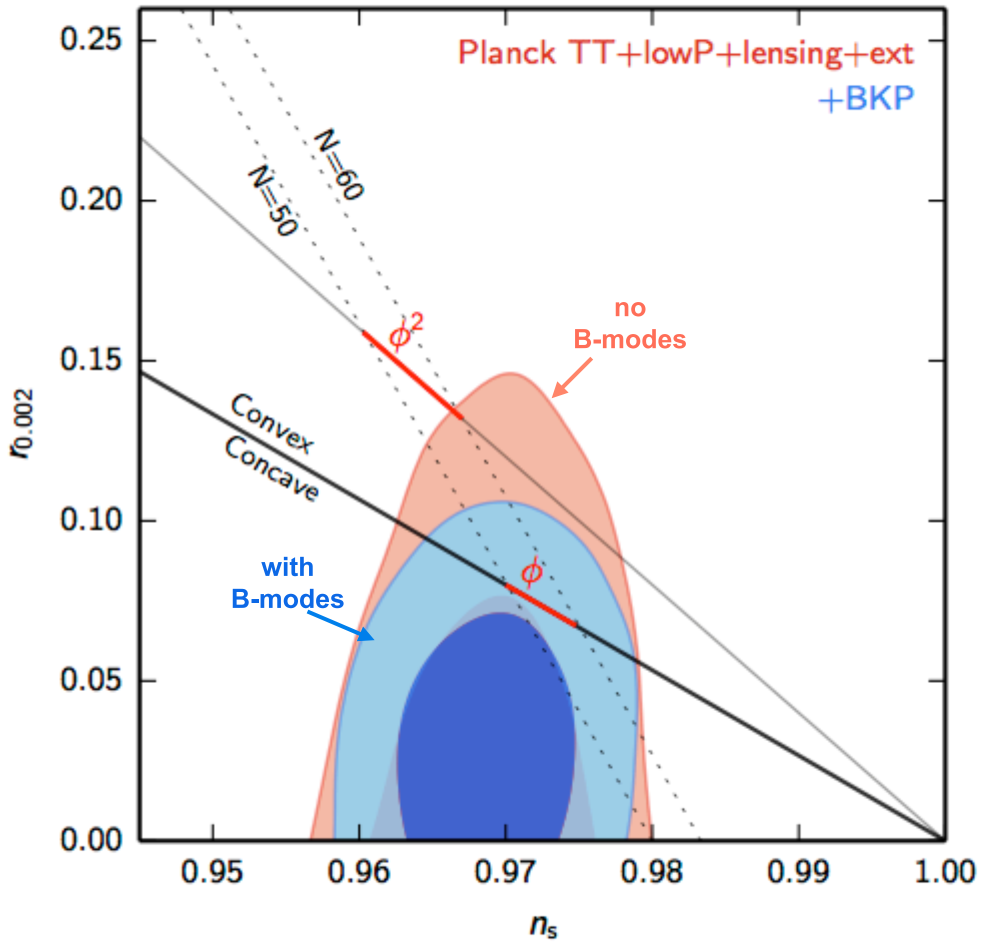
Allow dust/sync correlation

Marginalize over generous ranges in spatial spectral indices

BK15

arxiv/1810.05216

Adding in temperature

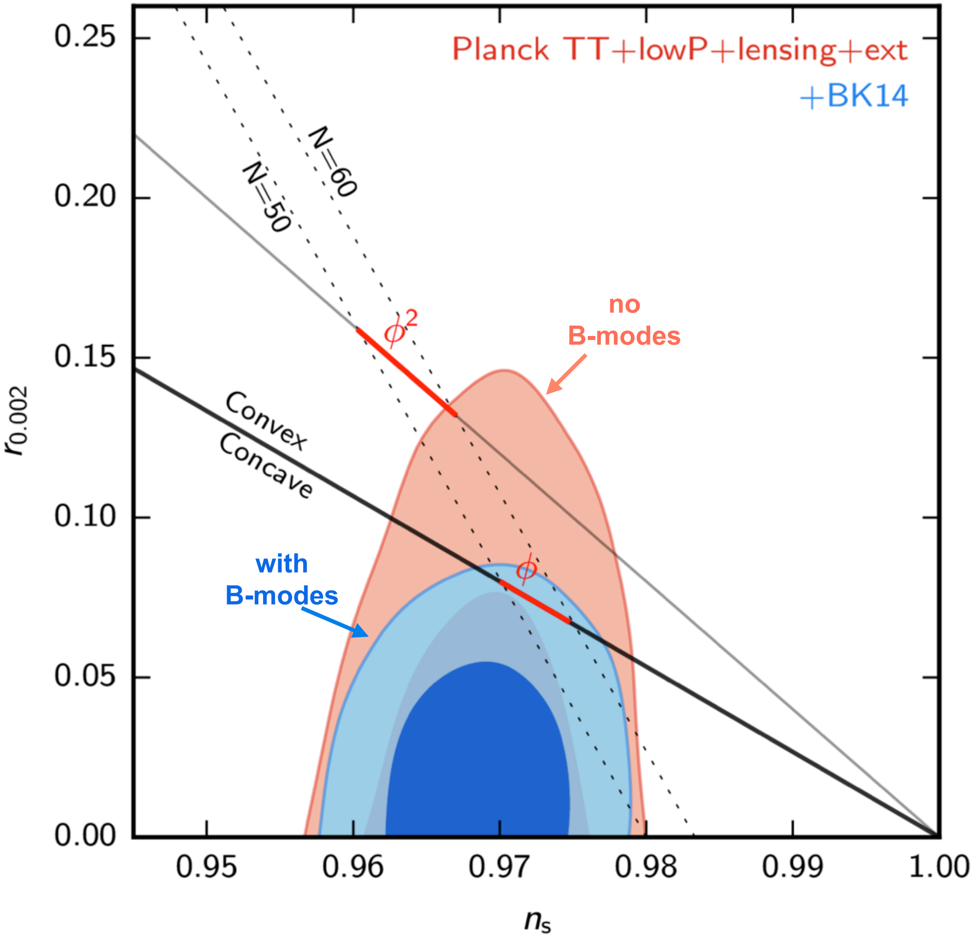


$r < 0.09$

BKP

arxiv/1502.00612

Adding in temperature

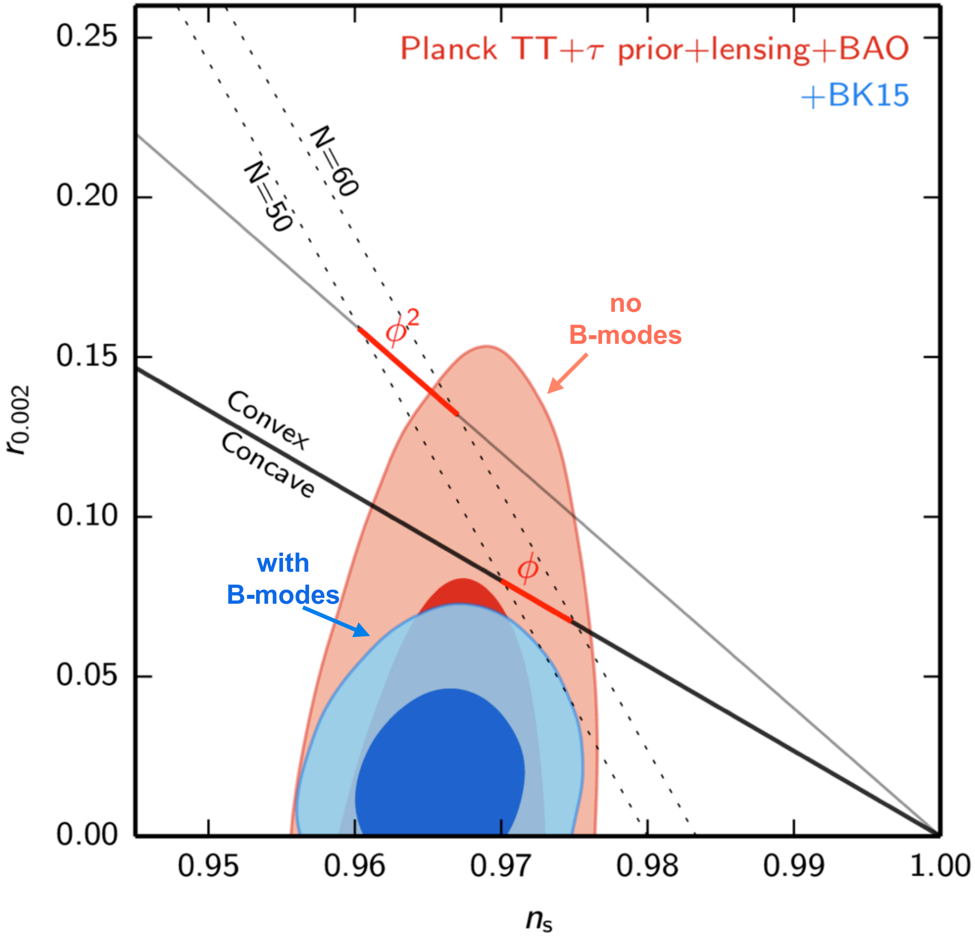


$r_{.05} < 0.07$

BK14

arxiv/1510.09217

Adding in temperature



$r_{.05} < 0.06$

BK15

arxiv/1810.05216

PRL Accepted

2016 onwards:
BICEP3 “Super receiver”

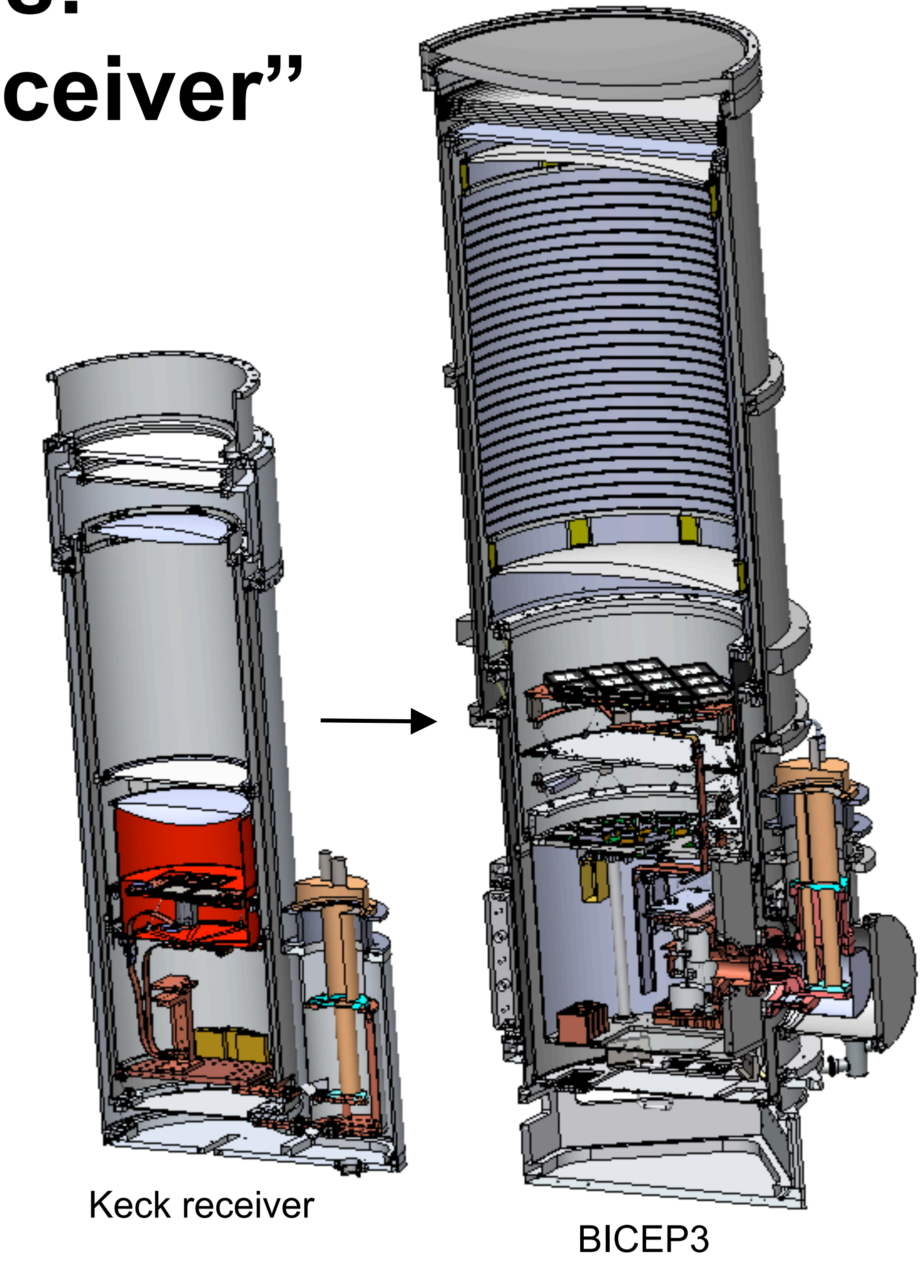
All 95 GHz

2560 detectors in modular focal plane

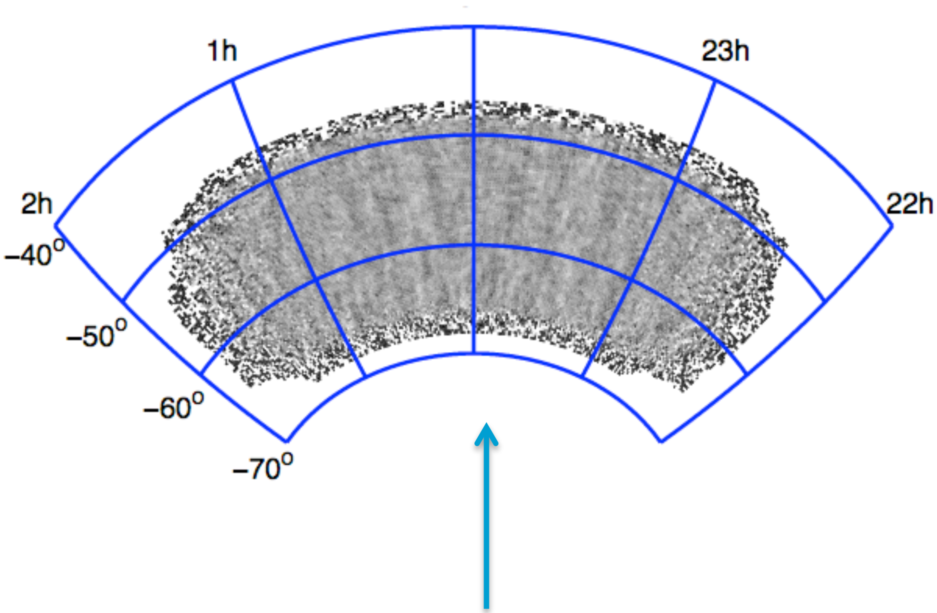
Larger-aperture optics

> 10x optical throughput of single BICEP2/Keck receiver

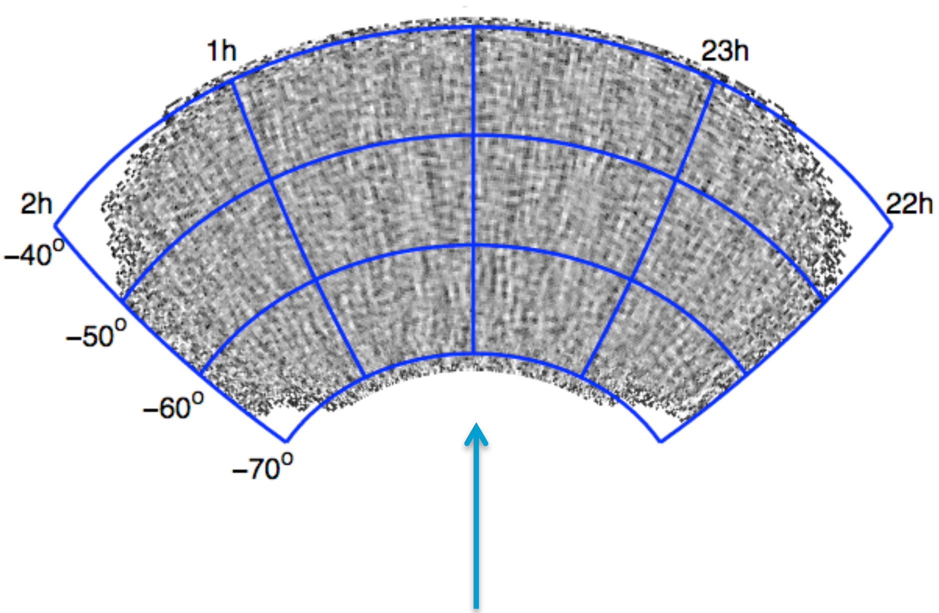
Means larger field of view and lower noise faster



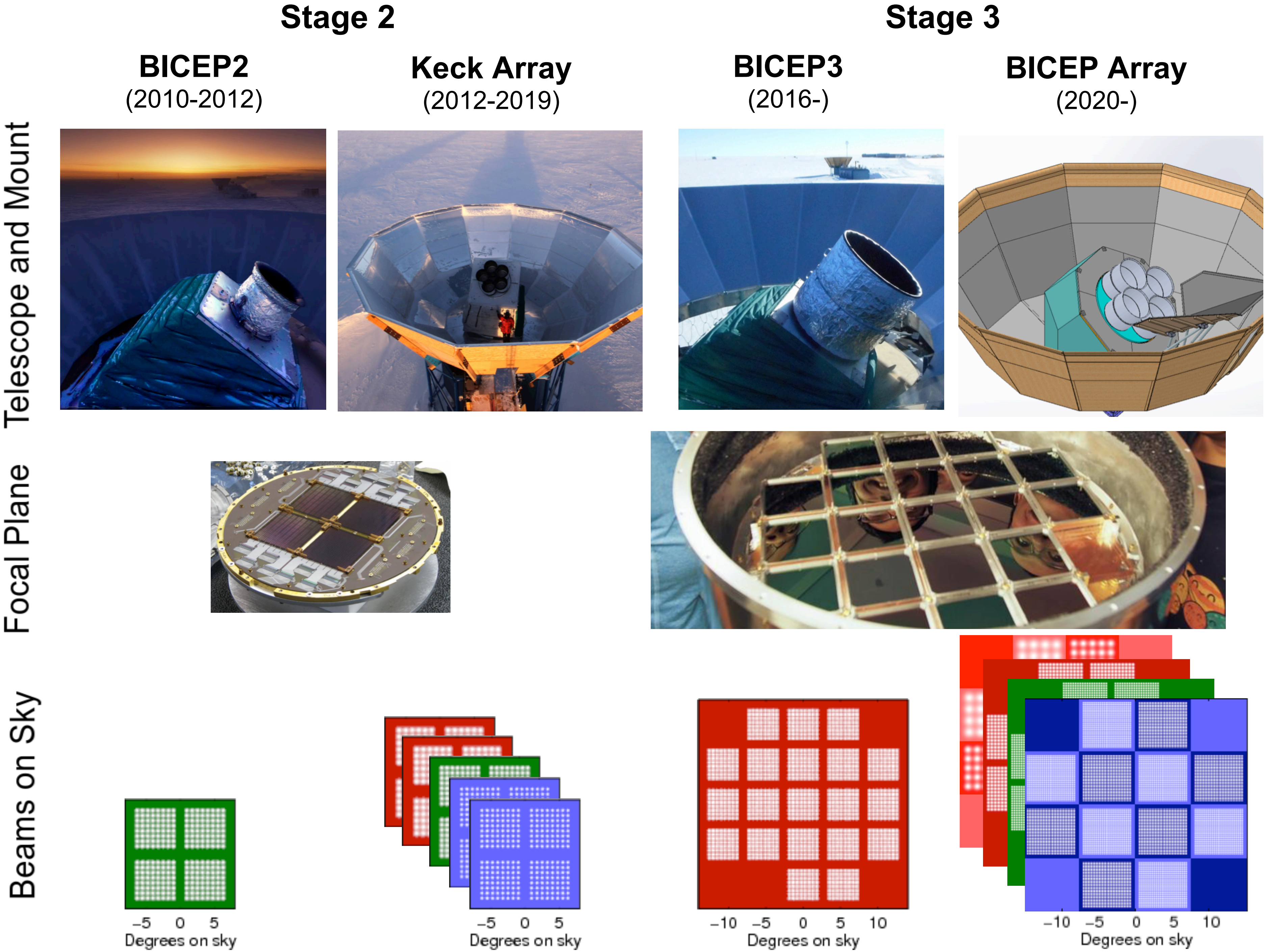
Larger receiver = more sky area



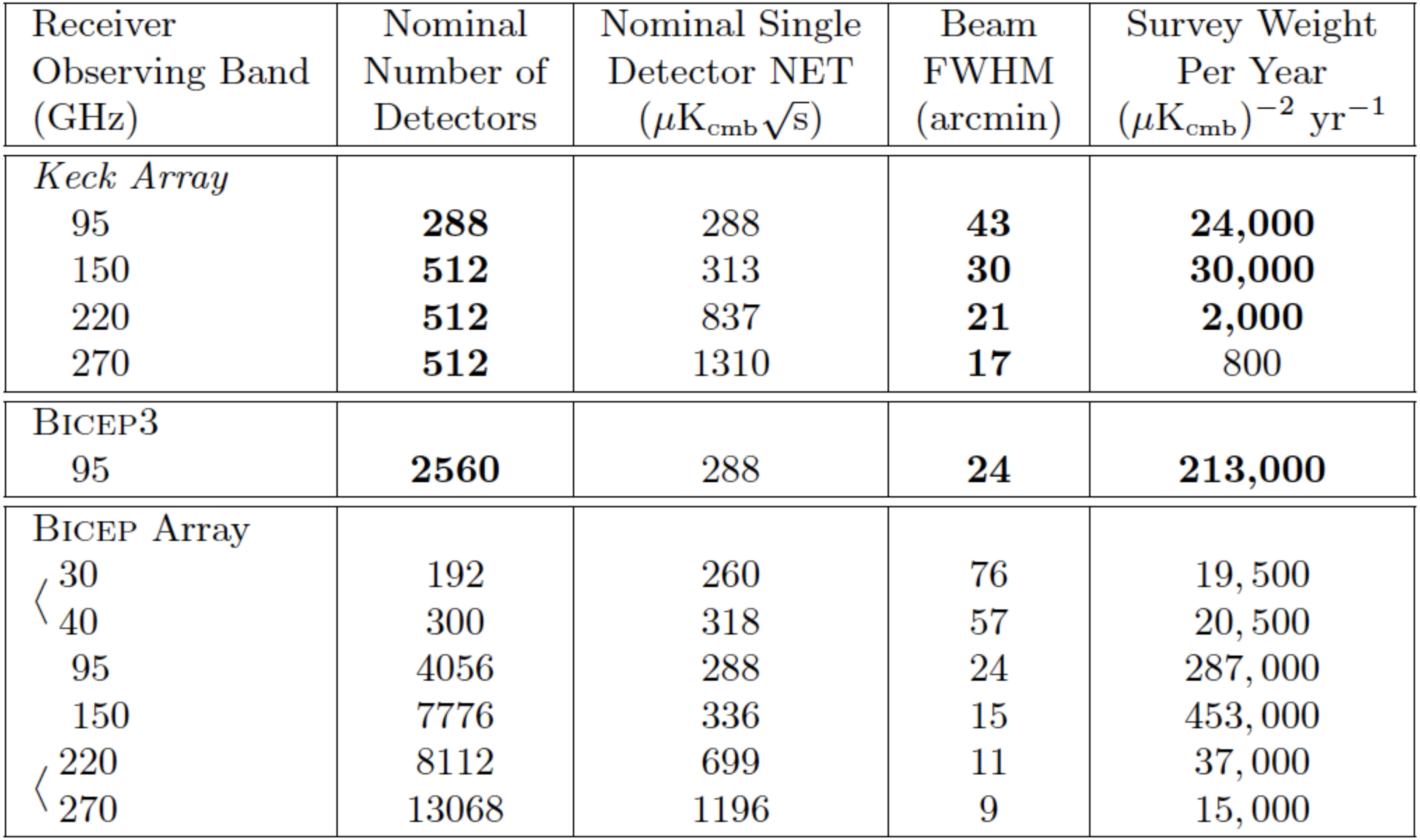
Keck 95 GHz *Q* map after 4 receiver years



BICEP3 95 GHz *Q* map after 1 receiver year (2017) (Increased area, angular-resolution and sensitivity)

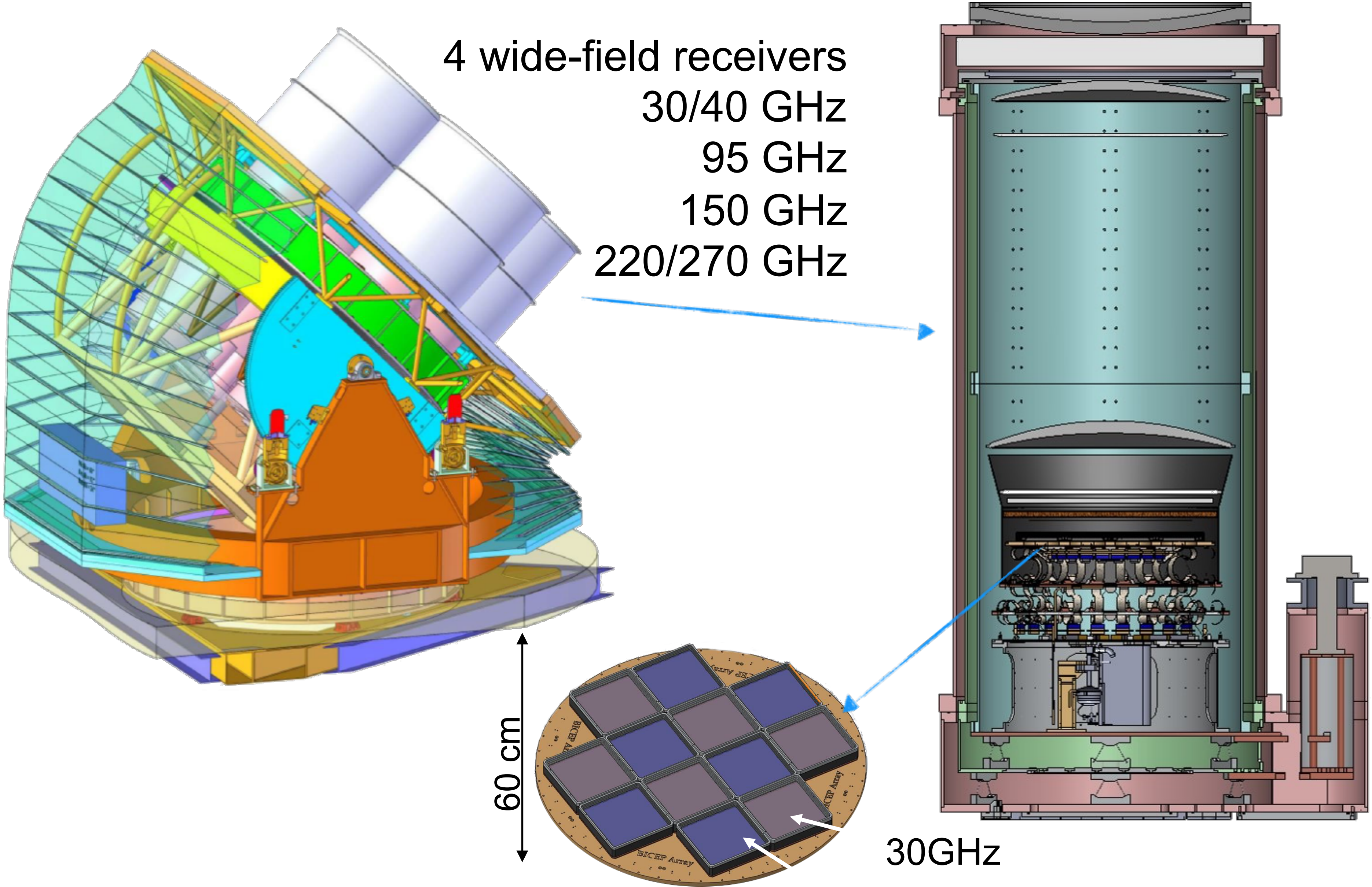

Stage 2
Stage 3
BICEP2
(2010-2012)
Keck Array
(2012-2019)
BICEP3
(2016-)
BICEP Array
(2020-)
Telescope and Mount
Focal Plane
Beams on Sky
−5 0 5
Degrees on sky
−5 0 5
Degrees on sky
−10 −5 0 5 10
Degrees on sky
−10 −5 0 5 10
Degrees on sky

Detector numbers



Receiver Observing Band (GHz)	Nominal Number of Detectors	Nominal Single Detector NET $(\mu\mathrm{K_{cmb}}\sqrt{\mathrm{s}})$	Beam FWHM (arcmin)	Survey Weight Per Year $(\mu\mathrm{K_{cmb}})^{-2}\ \mathrm{yr}^{-1}$
Keck Array				
95	**288**	288	**43**	**24,000**
150	**512**	313	**30**	**30,000**
220	**512**	837	**21**	**2,000**
270	**512**	1310	**17**	800
BICEP3				
95	**2560**	288	**24**	**213,000**
BICEP Array				
⟨ 30	192	260	76	19,500
40	300	318	57	20,500
95	4056	288	24	287,000
150	7776	336	15	453,000
⟨ 220	8112	699	11	37,000
270	13068	1196	9	15,000

Next Gen Experiment BICEP Array Under Construction

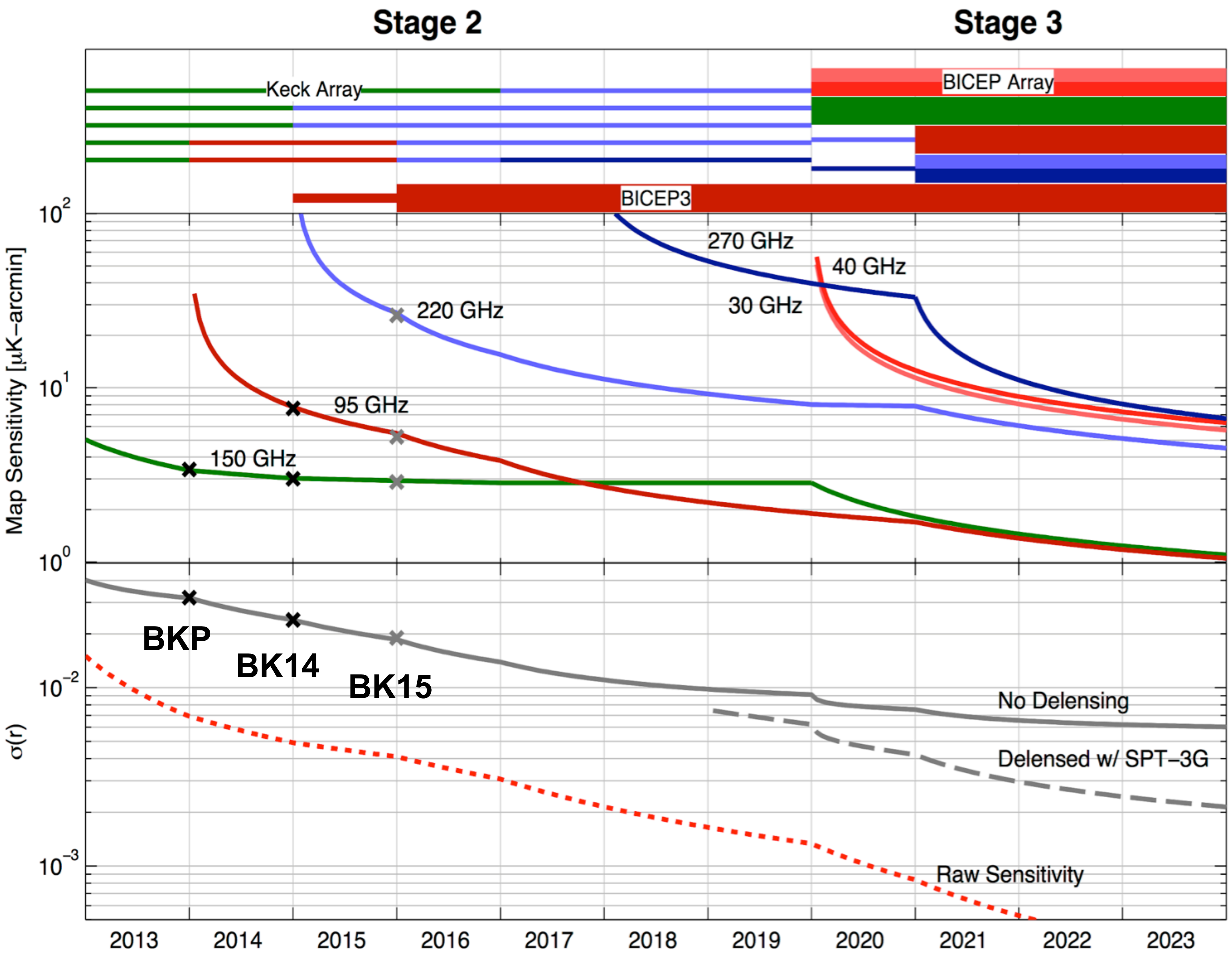


4 wide-field receivers
30/40 GHz
95 GHz
150 GHz
220/270 GHz

Focal plane layout

Right Now Assembling New Telescope at UMN

New Telescope Moving


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

Summary

- The Universe is expanding – it was once a hot dense “fireball”.
- We understand its development all the way back to very close to the beginning. (For instance we know it is 14 billion years old.)
- 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 as B-modes in the polarization pattern of the Cosmic Microwave Background
      - So we have built a series of ever more sensitive radio telescopes to search for this signal.
        - We didn’t find it yet but the search goes on with bigger and better experiments…