

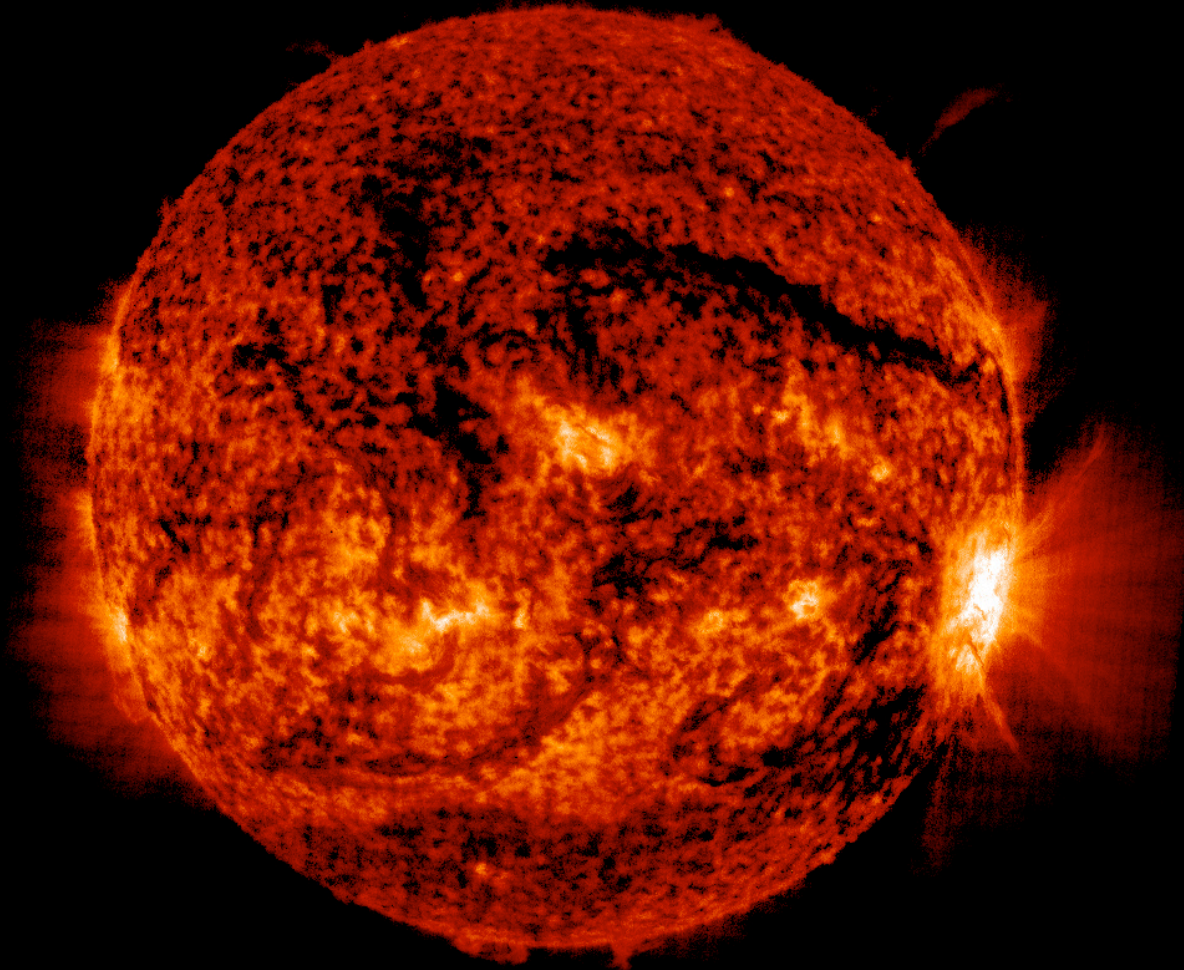




Studying the Beginning of the Universe from the Bottom of the World

Clem Pryke – Senior College – Mar 25 2021

Our Sun is a Star

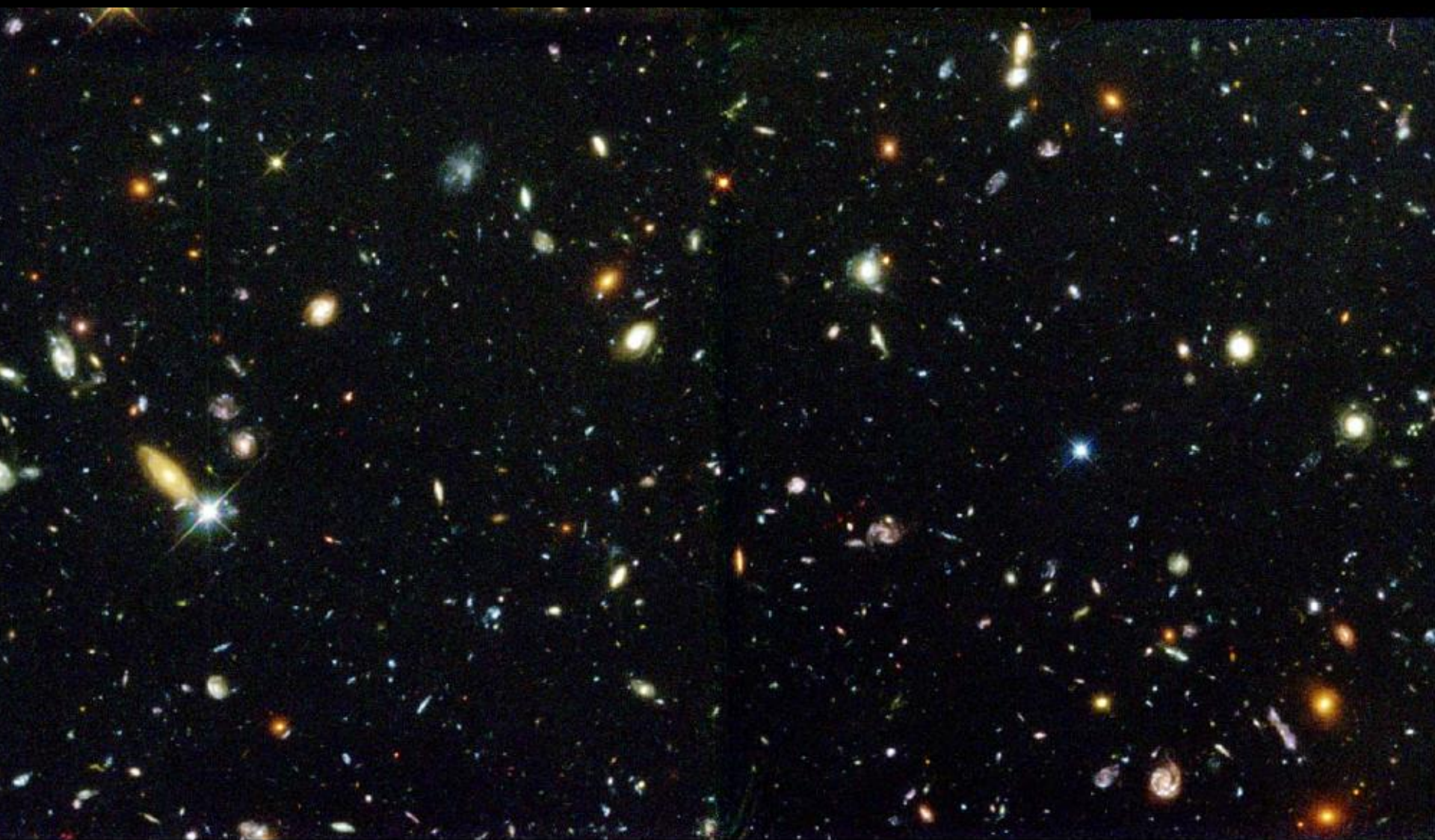


...Many stars make a galaxy...



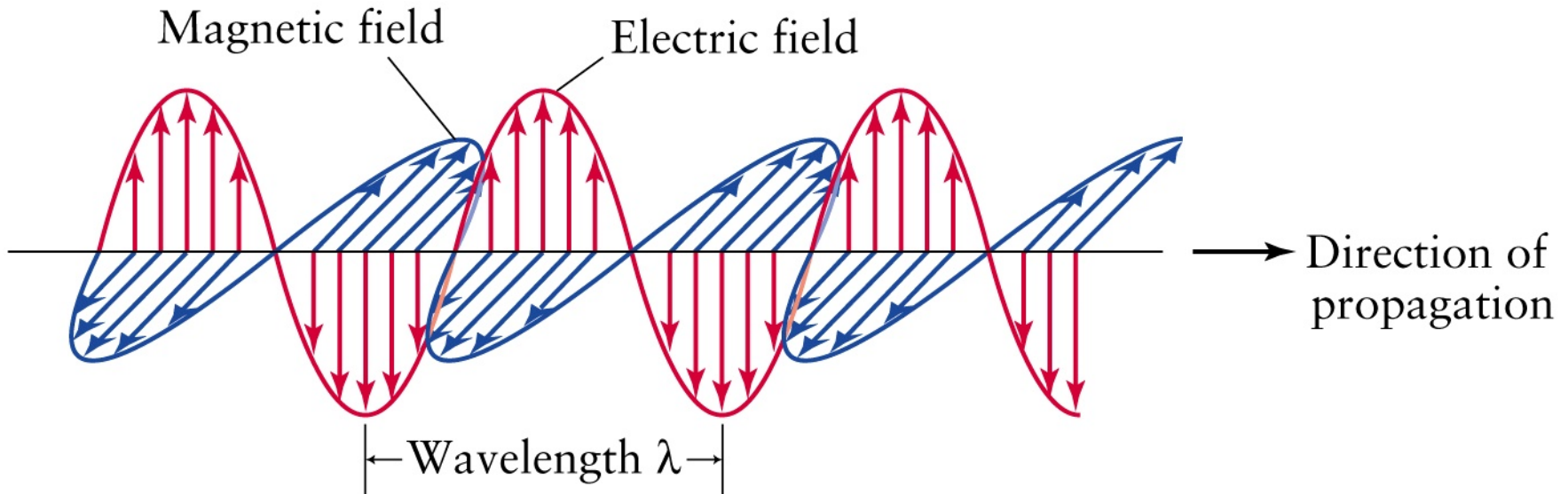
(A nearby galaxy similar to ours)

...There are many galaxies



The Universe is absolutely vast and we don't appear to be in the least bit special

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
- Microwaves and radio waves are just longer wavelengths of light

“Classic” Doppler Effect



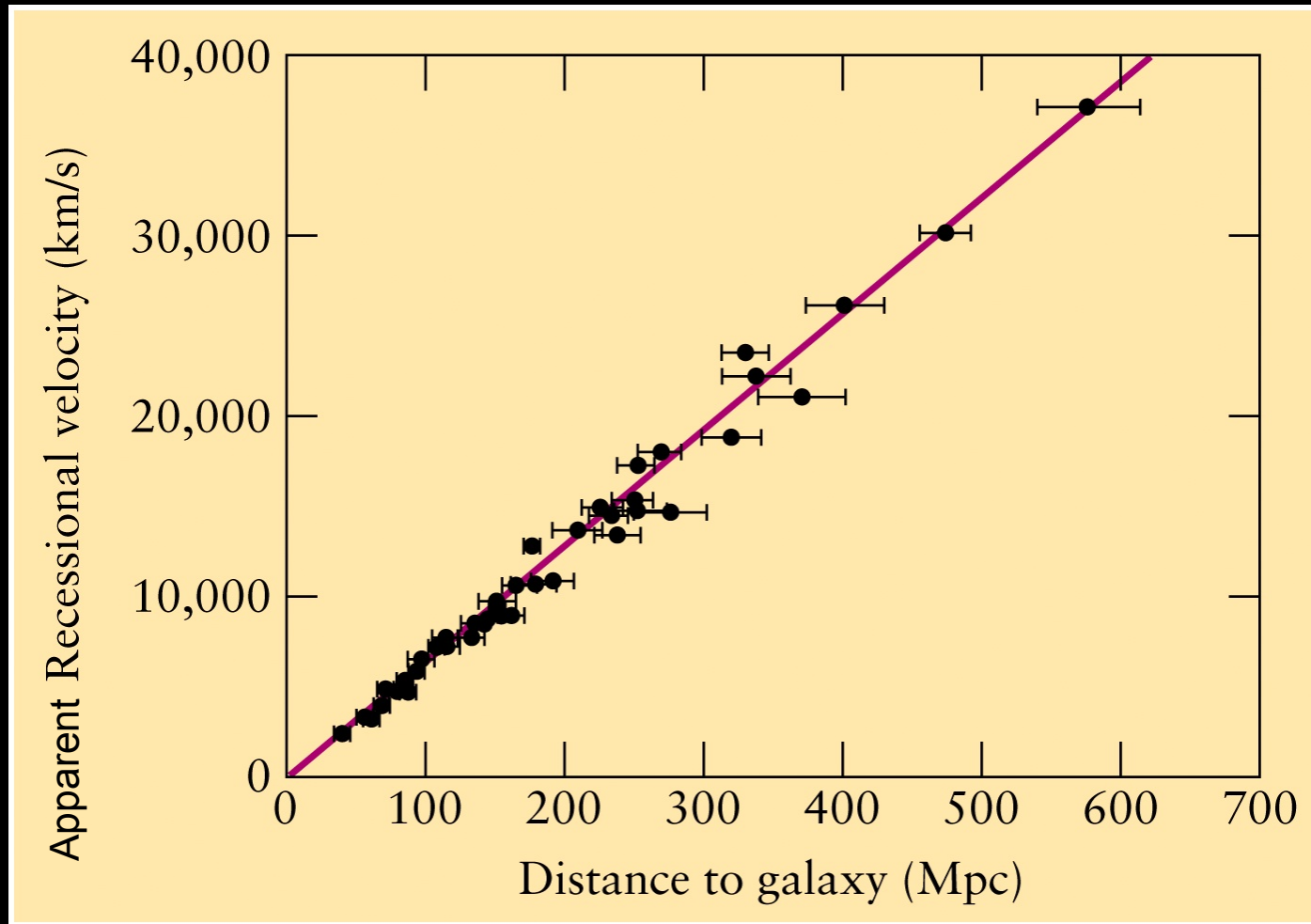
- Imagine 3 stars emitting rays of light of the same “natural” wavelength (color)
- But light moves through space always at the same speed...
- Moving towards us = compressed = bluer
- Moving away from us = stretched = redder

Edwin Hubble “Observing” Distant Galaxies



Mount Wilson Observatory
(LA) 1920's

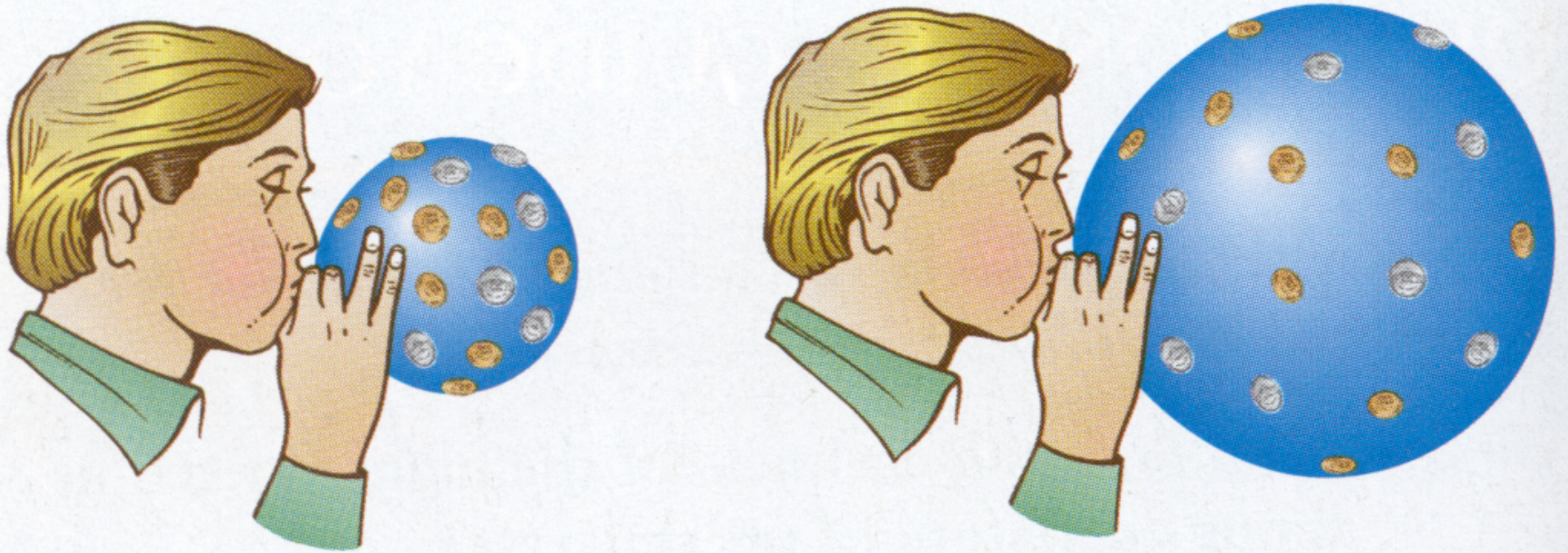
Hubble Diagram



The farther away a galaxy is the faster it *appears* to be moving away from us...

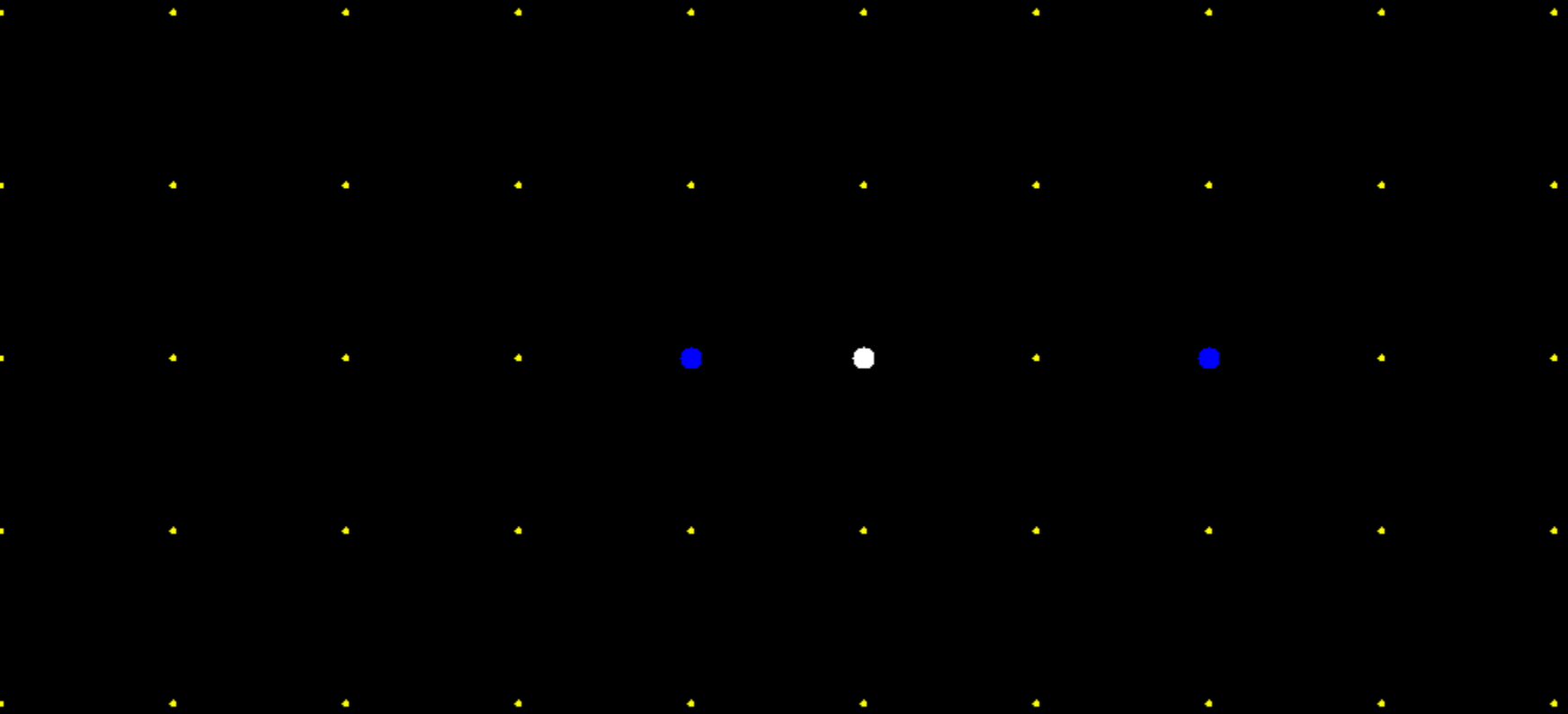
Are we the most unpopular place in the entire Universe?!

Expanding Universe?



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

Cosmological Doppler Effect



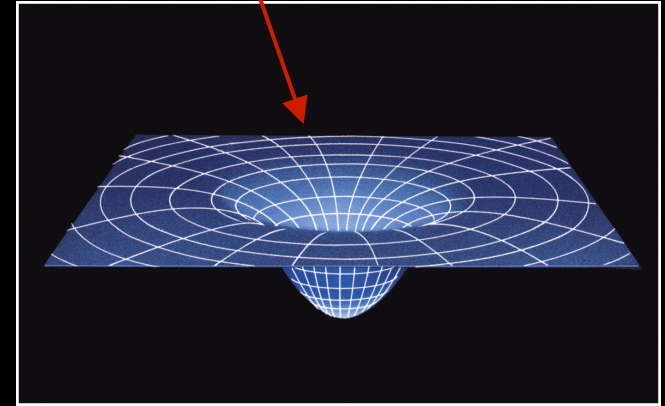
- Light rays stretch with the Universe – called “redshift”
- We see the more distant Universe as it was long ago – and redder

Einstein and General Relativity



↑
In 1915 Albert Einstein
devised the General
Theory of Relativity

In GR space can be curved
– and can expand/contract



$$R_{ij} - \frac{1}{2}g_{ij}R - \Lambda g_{ij} = 8\pi GT_{ij}$$

↑
He fudged his equation to force
a static Universe – later called
this his “biggest blunder”

Modern cosmology in a nutshell:



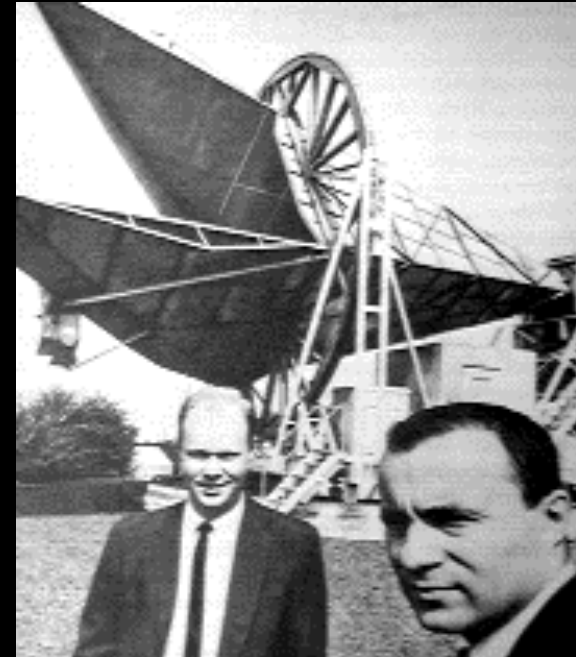
Edwin Hubble

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

2) It must have once been
hot and dense, like the
inside of the Sun.

(Alpher, Gamow, Herman, 1940s)

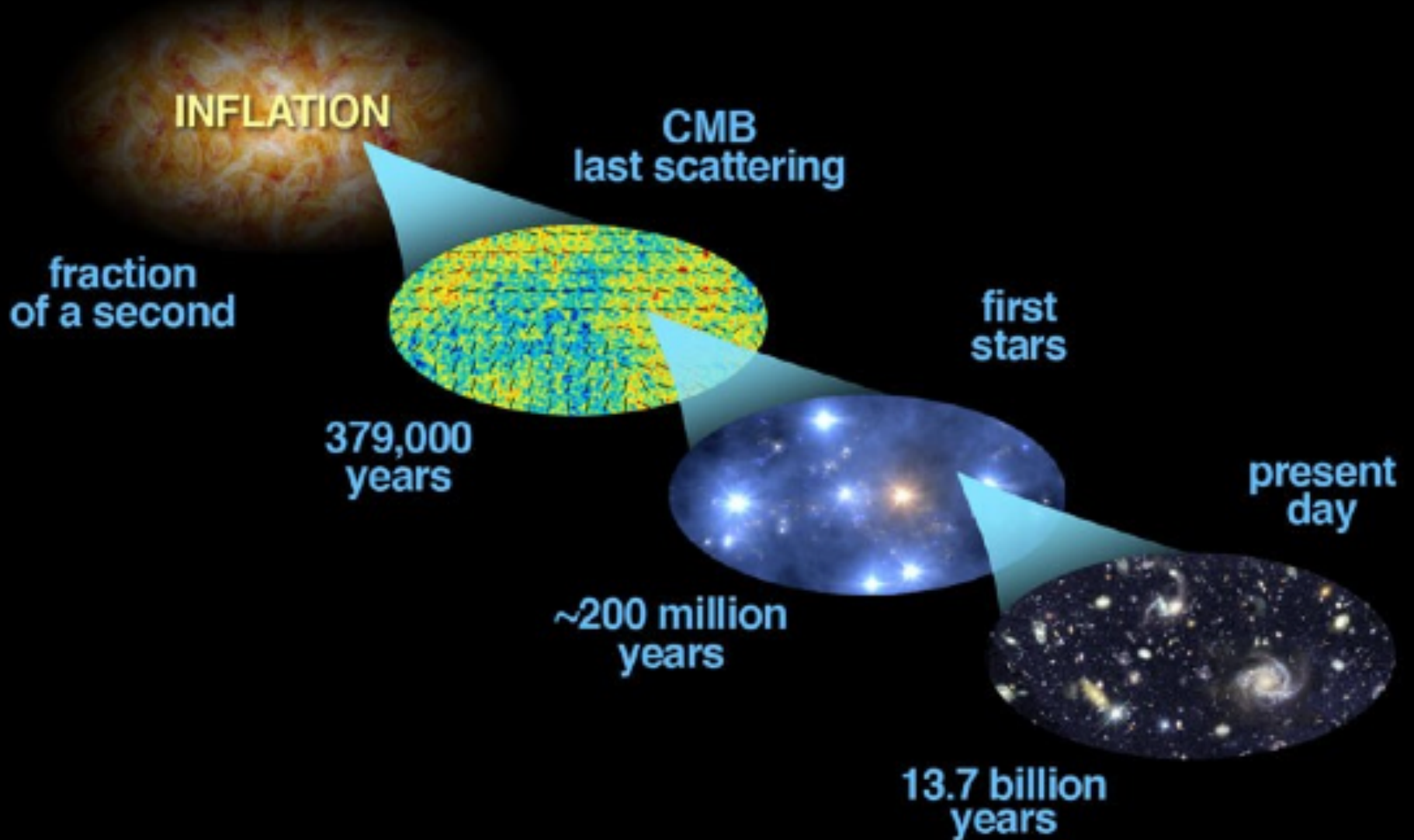
3) We can see the glow from that time!
The Cosmic Microwave Background
(Penzias & Wilson, 1964)



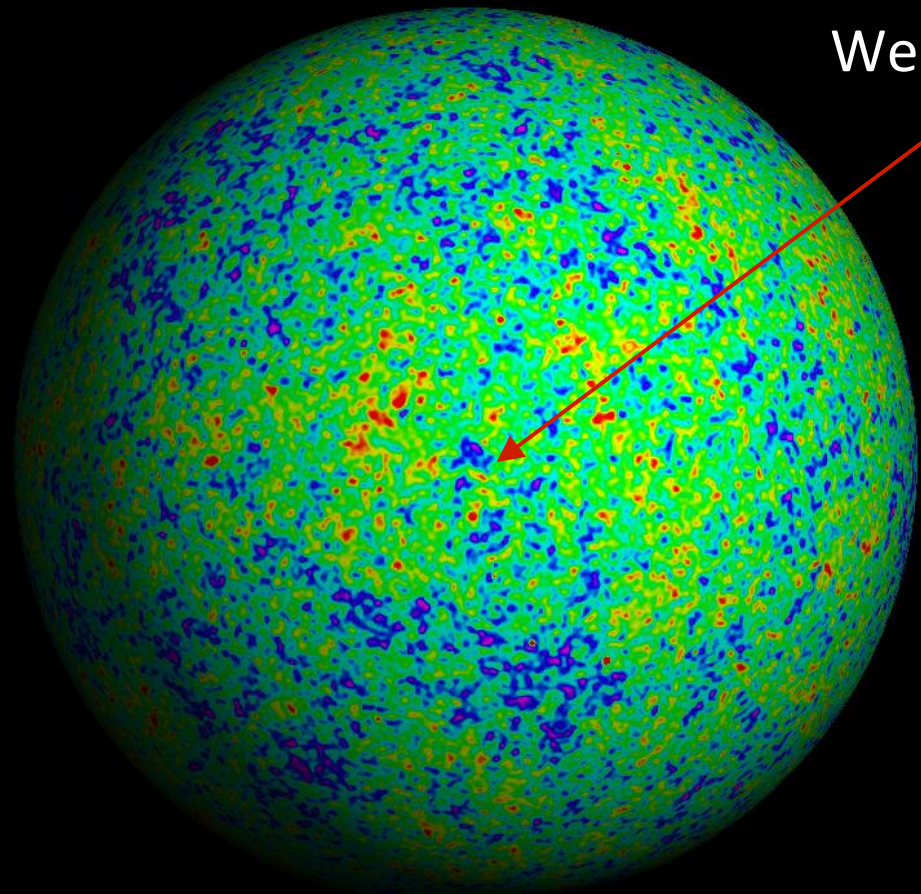
Bob Wilson & Arno Penzias
1978 Nobel Prize

⇒ **discovery lead to acceptance of the
“HOT BIG BANG”**

Telescopes are time machines!



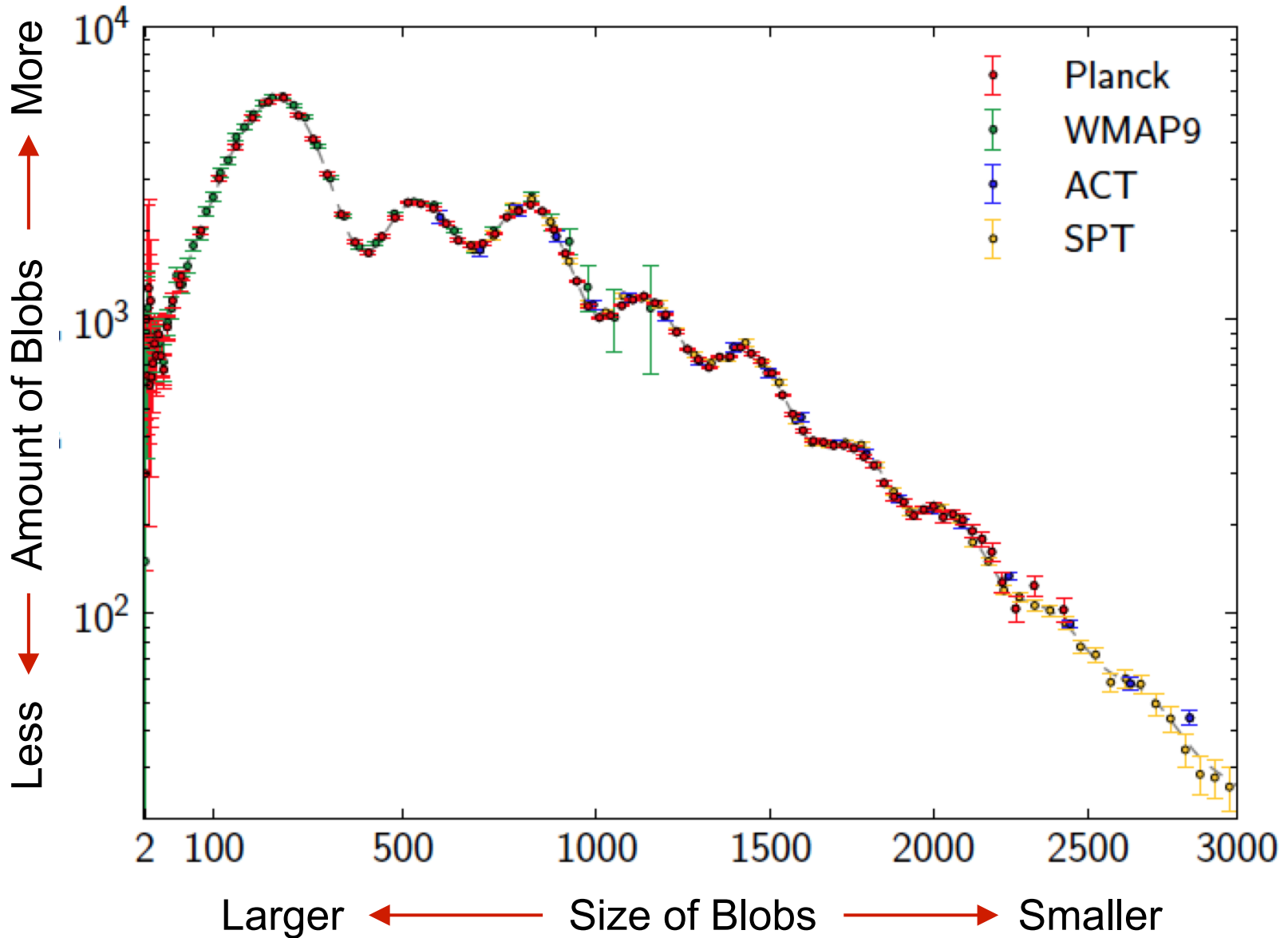
All Sky Map of the Cosmic Microwave Background



We are at the center

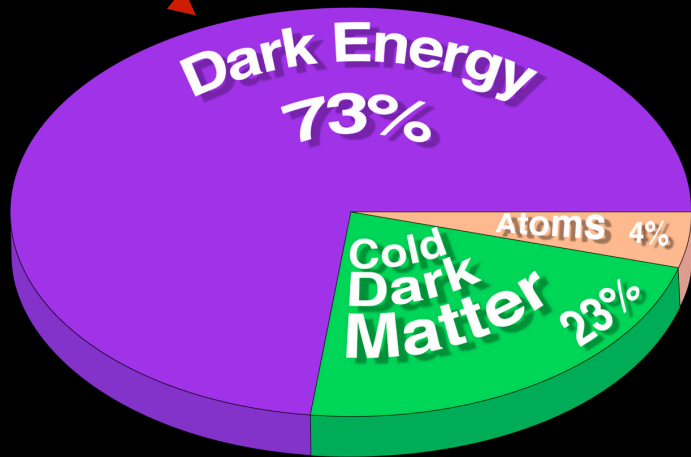
CMB is a sample of the density structure on a shell cut through the 380,000 year old Universe – at that time it was simple and nearly uniform

“Lump Sorter” Plot

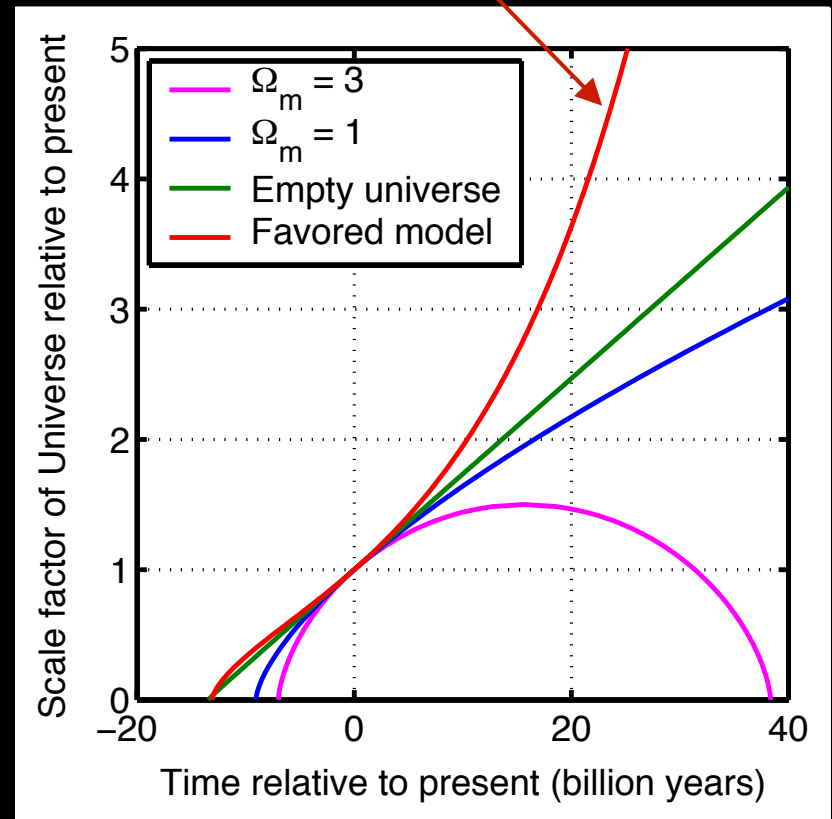


Triumphant/Embarrassing Cosmology

CMB and other data fits based model based on General Relativity *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 the initial conditions...

History of the Universe

Inflation proposed to explain
Horizon and Flatness problems

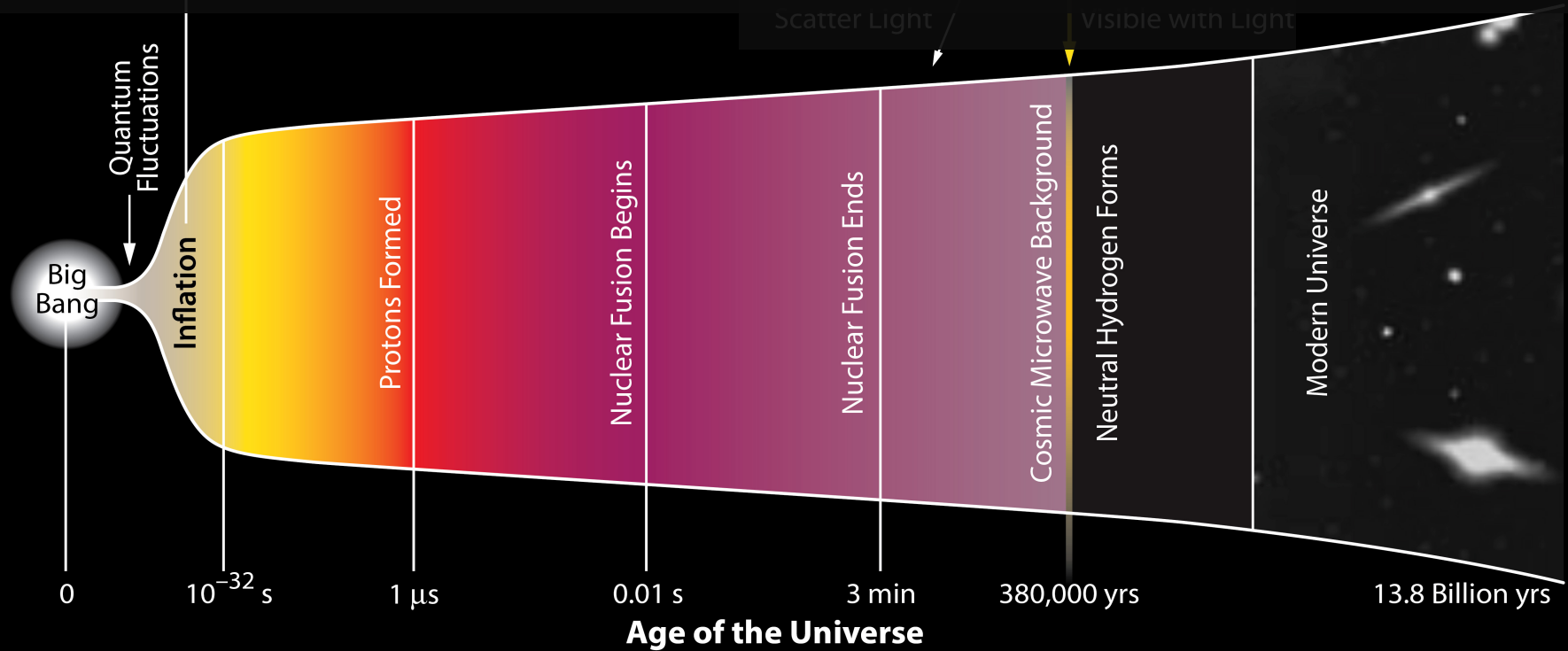


Alan Guth

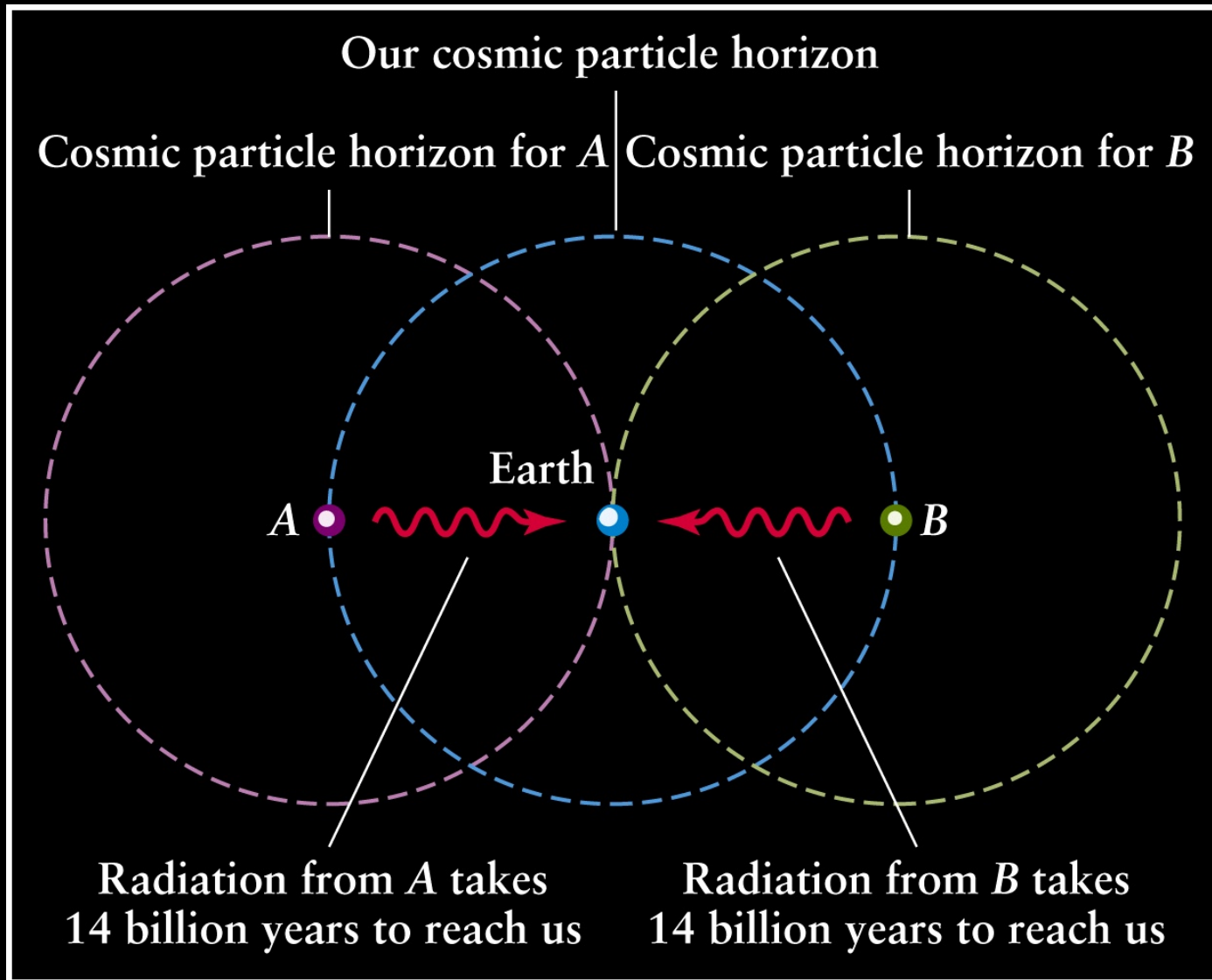


Andrei Linde

Radius of the Visible Universe

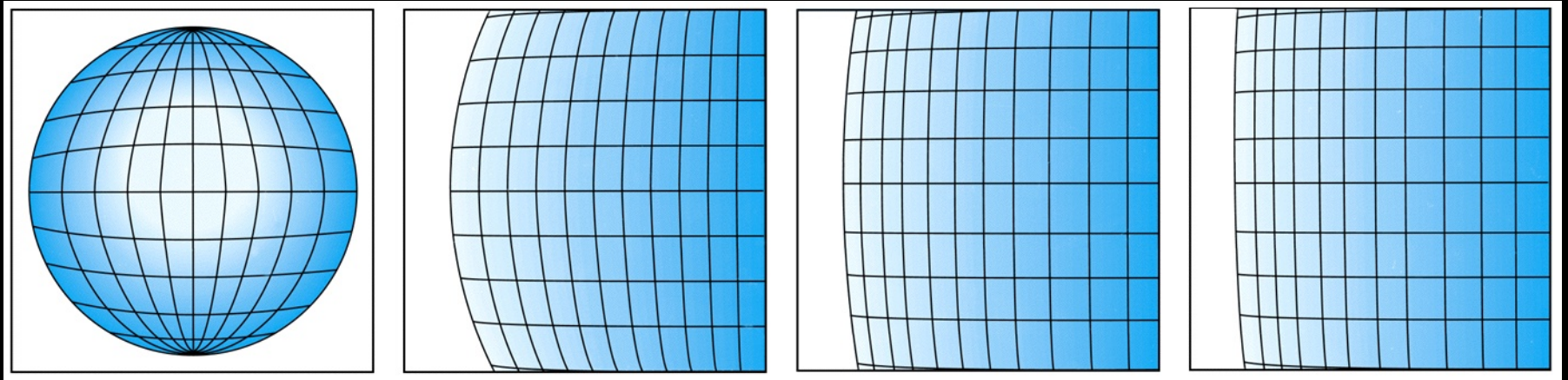


Inflation solves the “Horizon Problem”



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

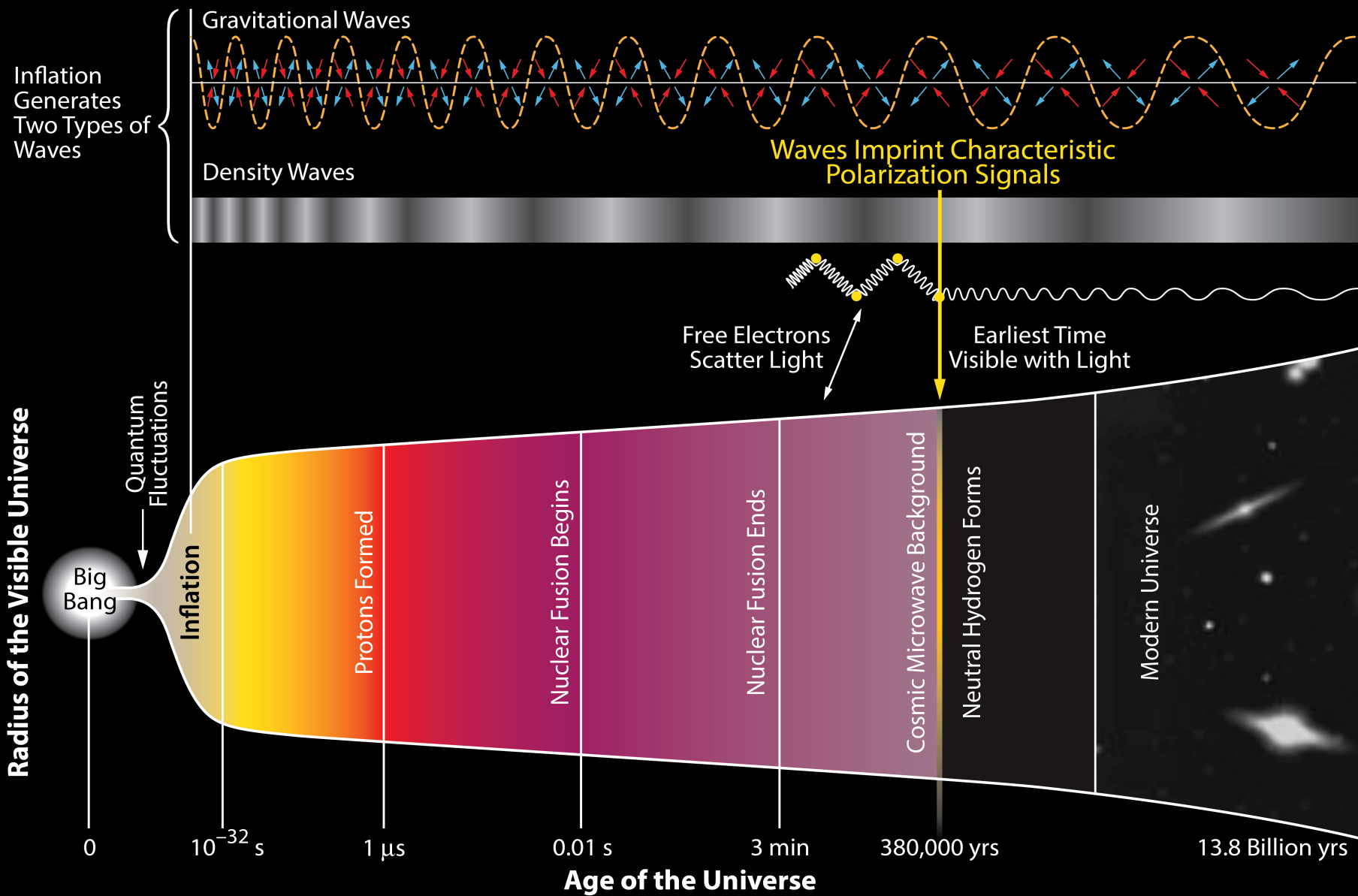
Inflation solves the “Flatness Problem”



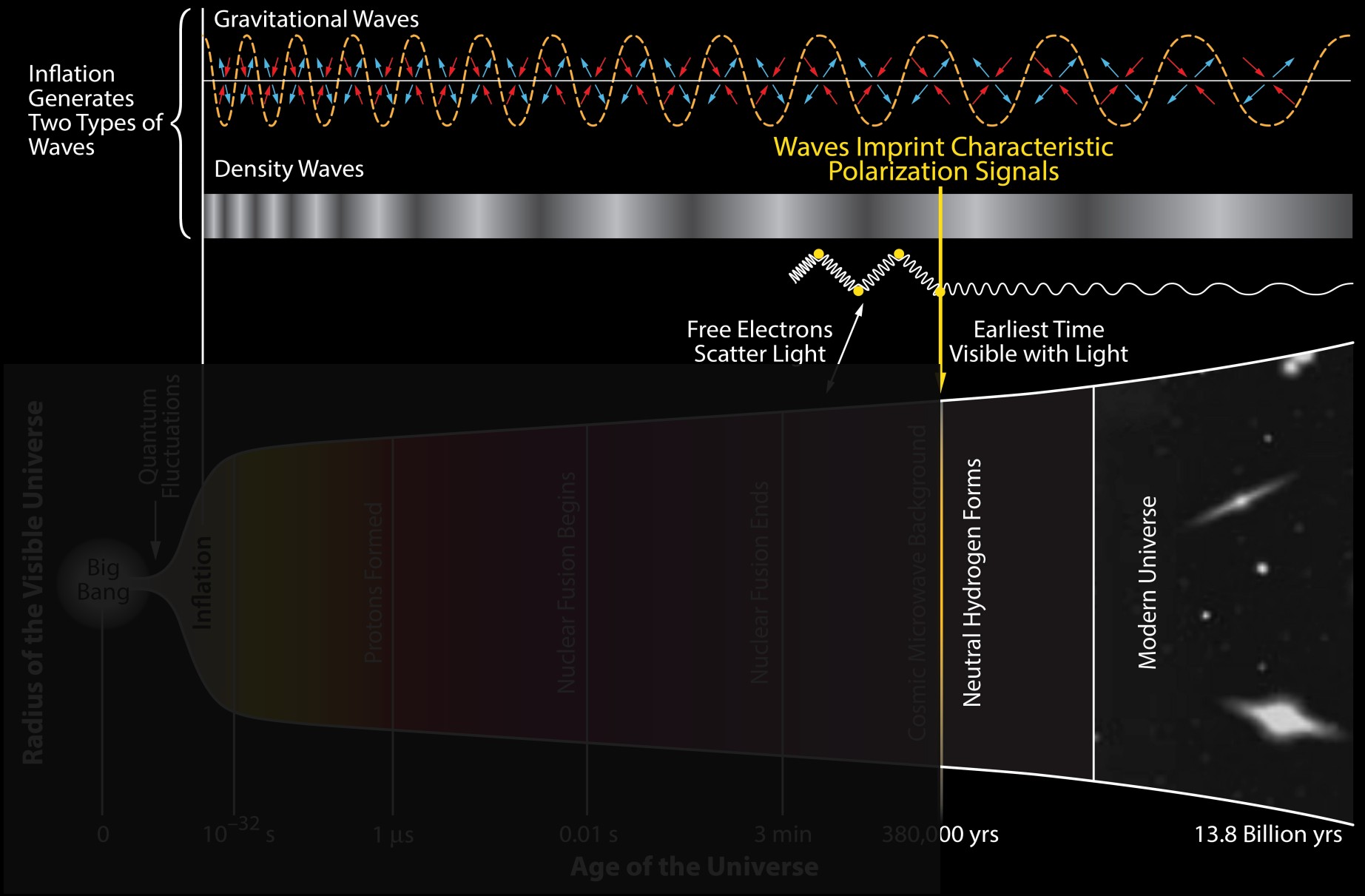
→ Inflation... →

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!

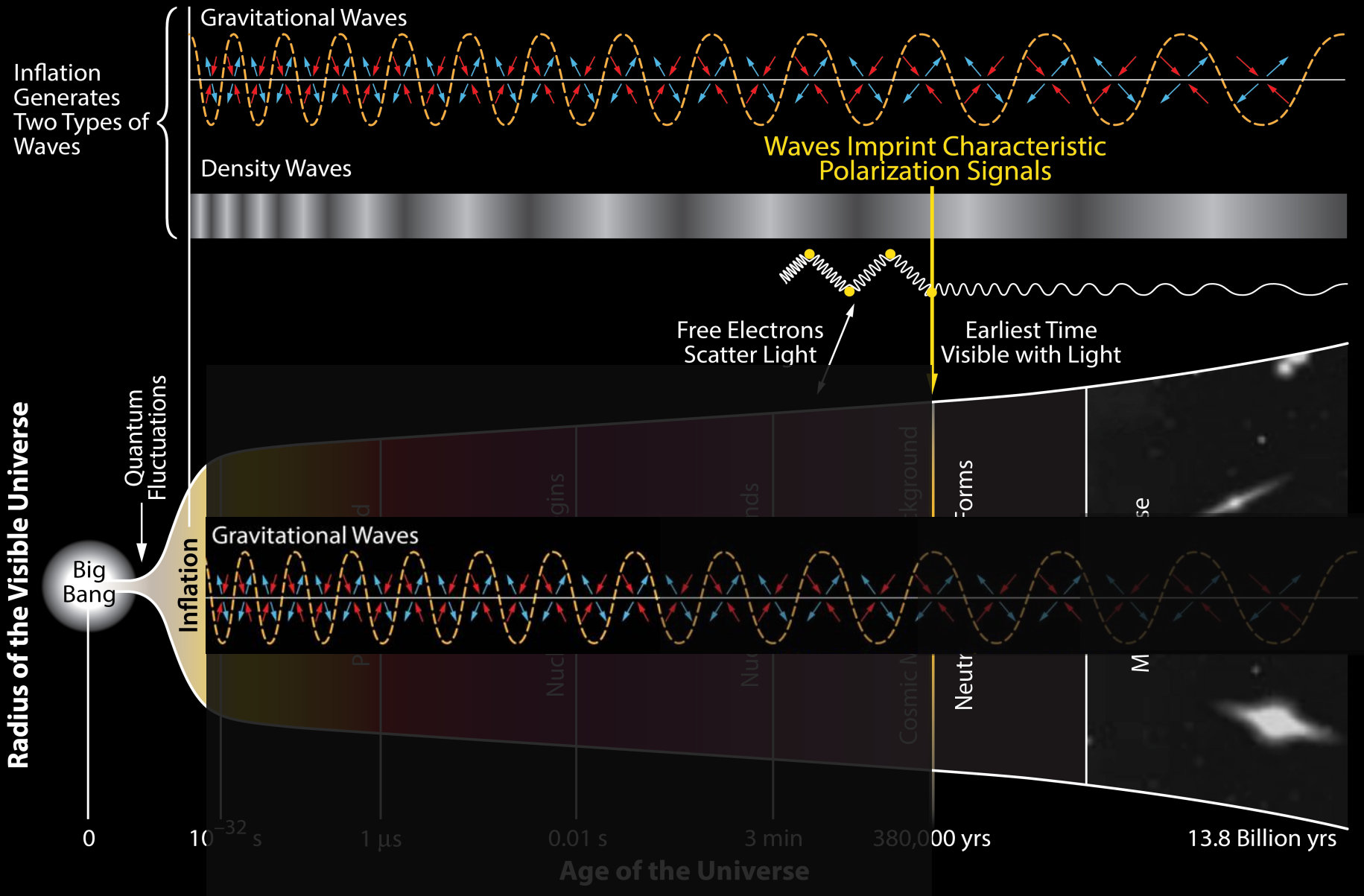
History of the Universe



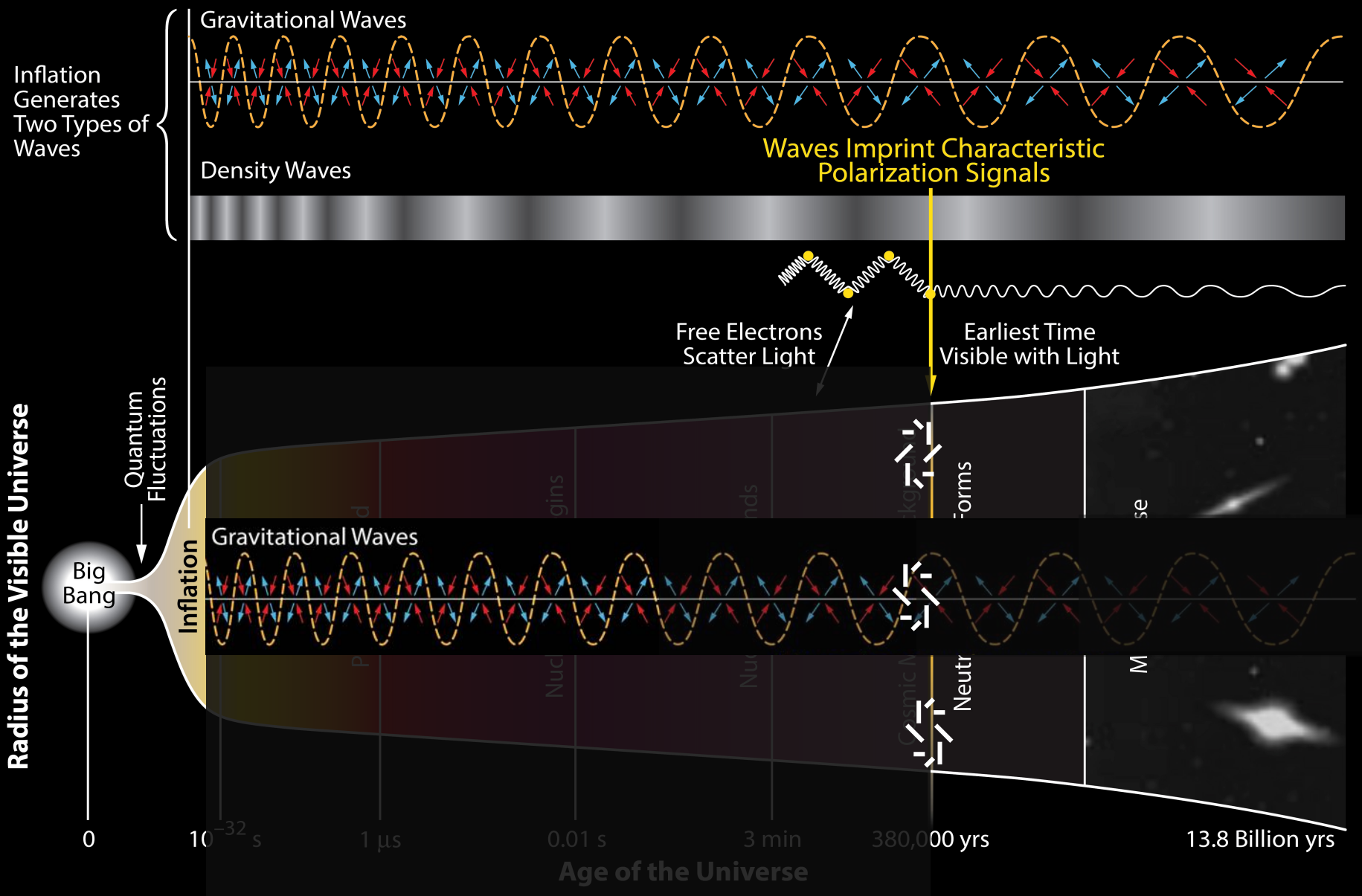
History of the Universe



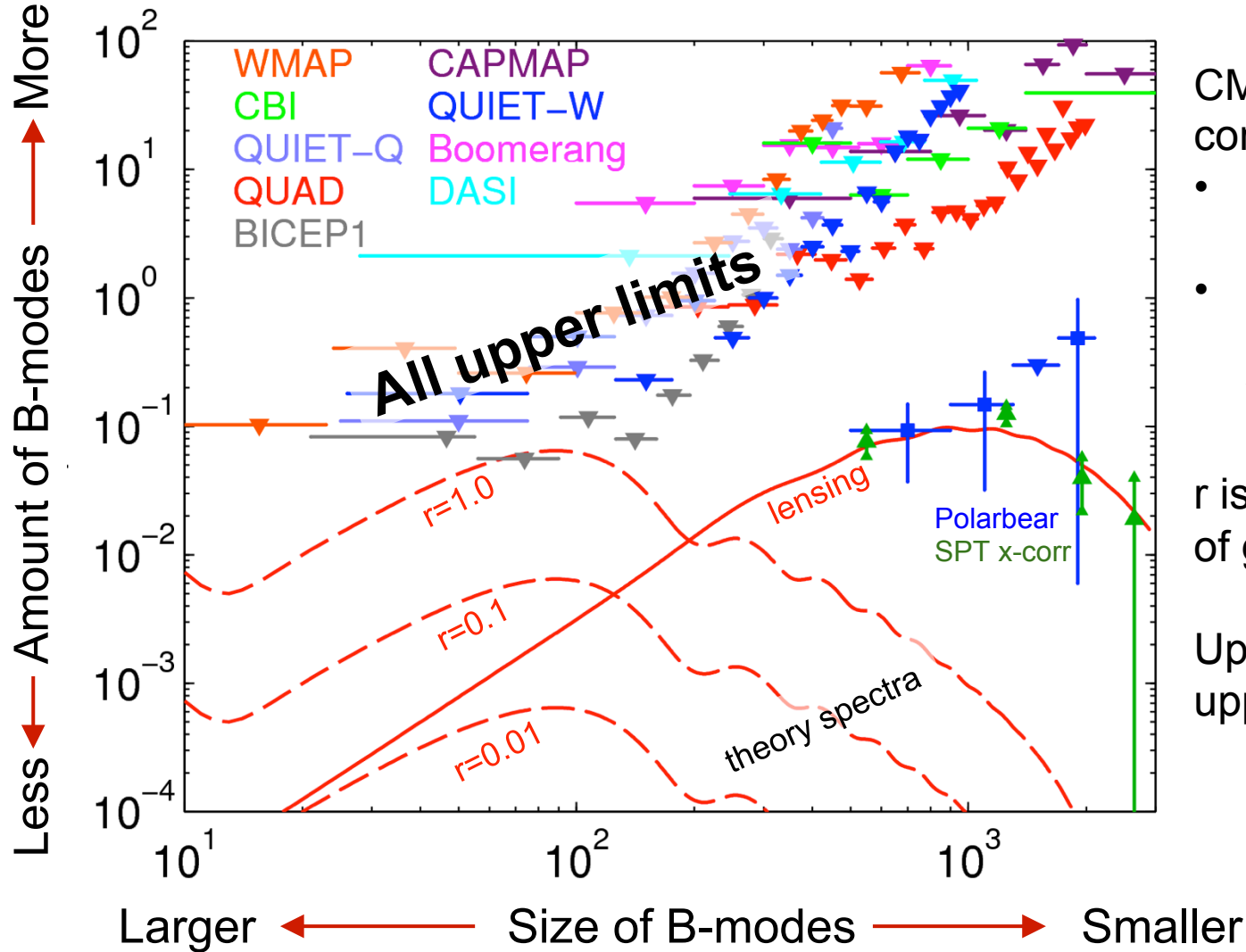
History of the Universe



History of the Universe



The Long Search for Inflationary B-modes



CMB polarization comes in two kinds

- E-modes – vanilla type
- B-modes – (mostly) only from gravity waves from Inflation

r is measure of amount of gravity waves

Up until recently only upper limits...

Inflation is controversial

Inflationary Paradigm after Planck 2013

Alan H. Guth,¹ David I. Kaiser,¹ and Yasunori Nomura²

¹*Center for Theoretical Physics, Laboratory for Nuclear Science, and Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

²*Berkeley Center for Theoretical Physics, Department of Physics and Theoretical Physics Group, Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720, USA*

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

[arxiv/1312.7619](https://arxiv.org/abs/1312.7619)



Inflationary schism after Planck2013

Anna Ijjas,^{1,2} Paul J. Steinhardt,³ and Abraham Loeb⁴

¹*Max-Planck-Institute for Gravitational Physics (Albert-Einstein-Institute), 14476 Potsdam, Germany*

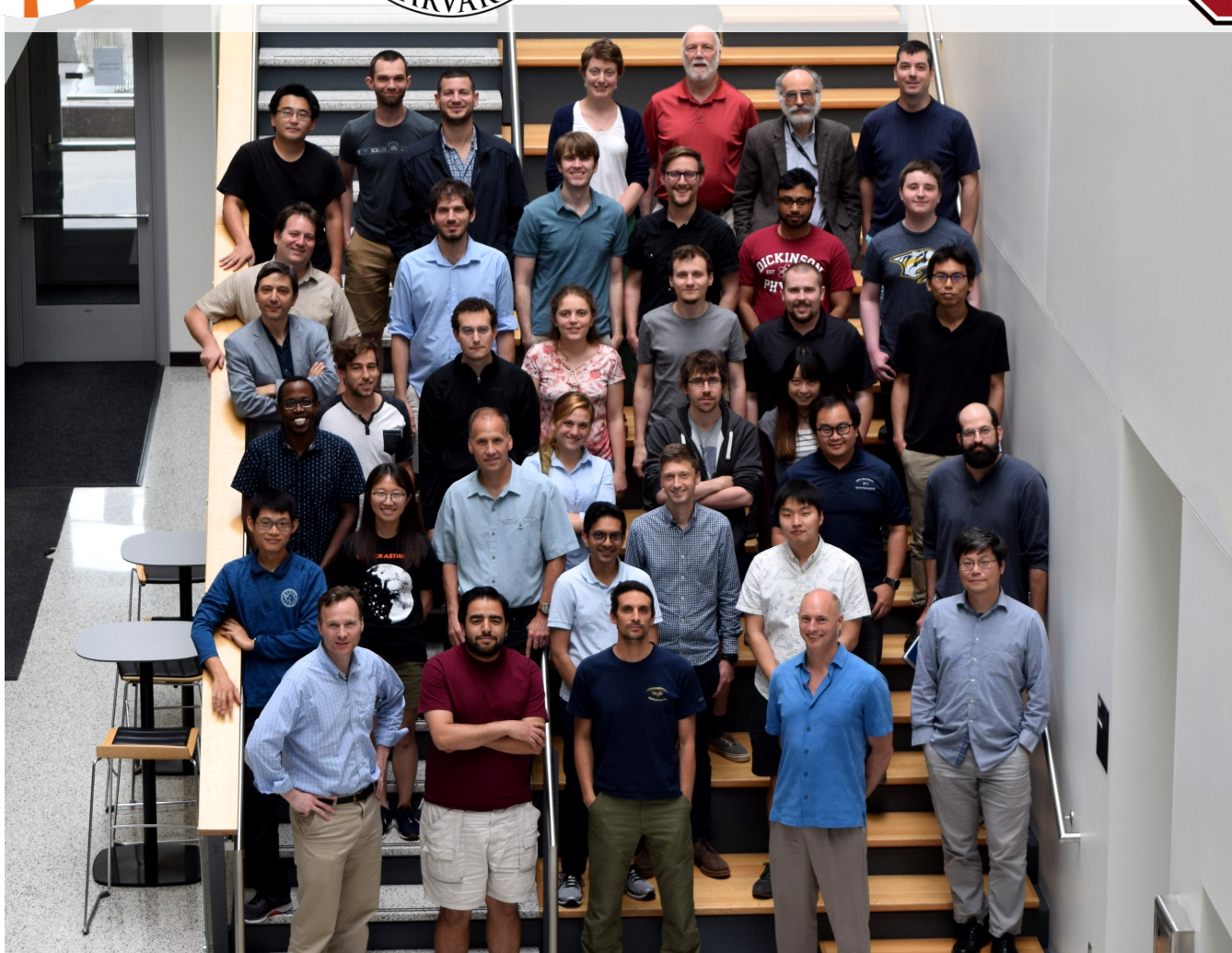
²*Rutgers University, New Brunswick, NJ 08901, USA*

³*Department of Physics and Princeton Center for Theoretical Science, Princeton University, Princeton, NJ 08544, USA*

⁴*Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA*
(Dated: March 14, 2014)

[arxiv/1402.6980](https://arxiv.org/abs/1402.6980)

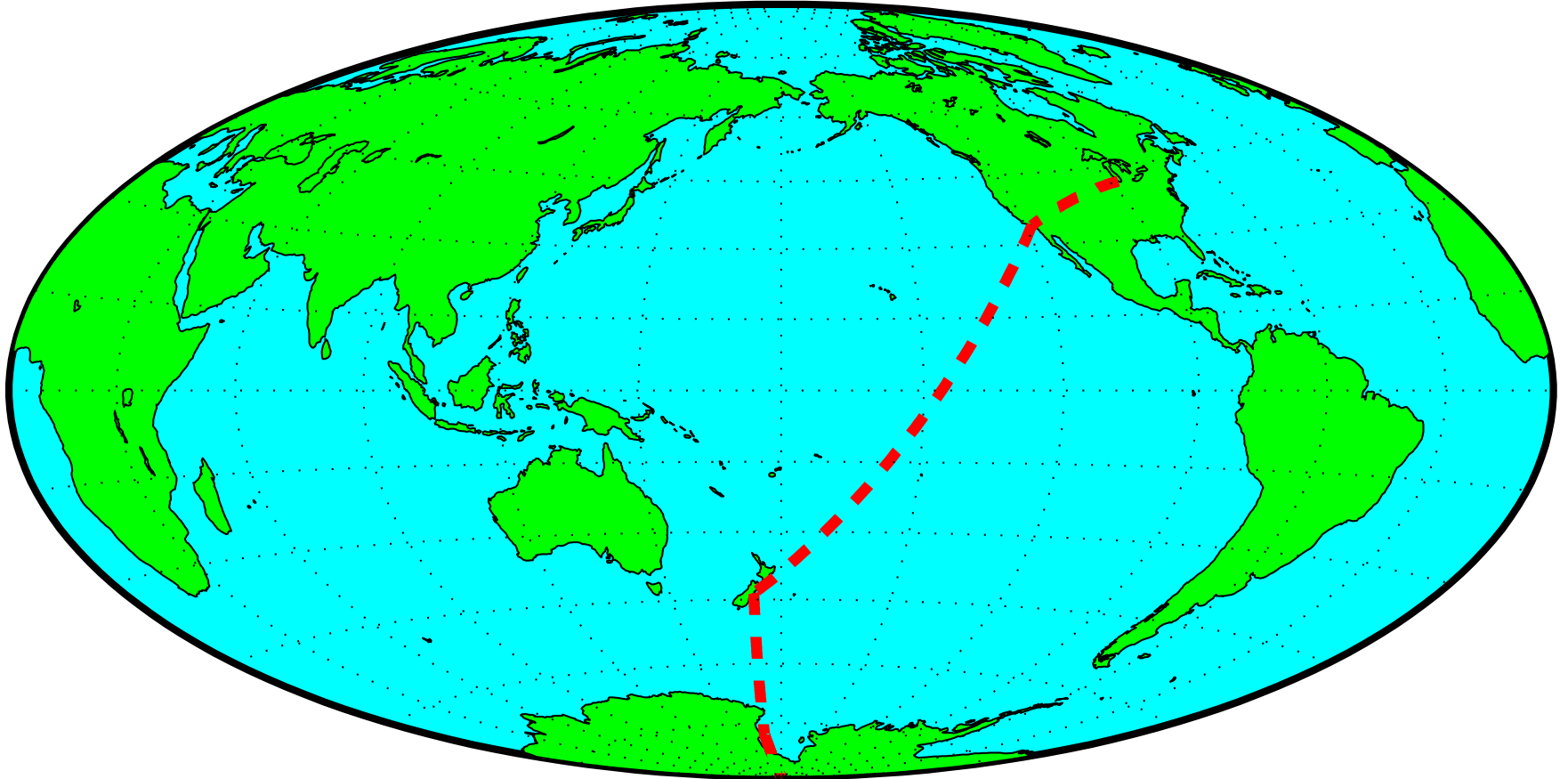




UNIVERSITY OF TORONTO

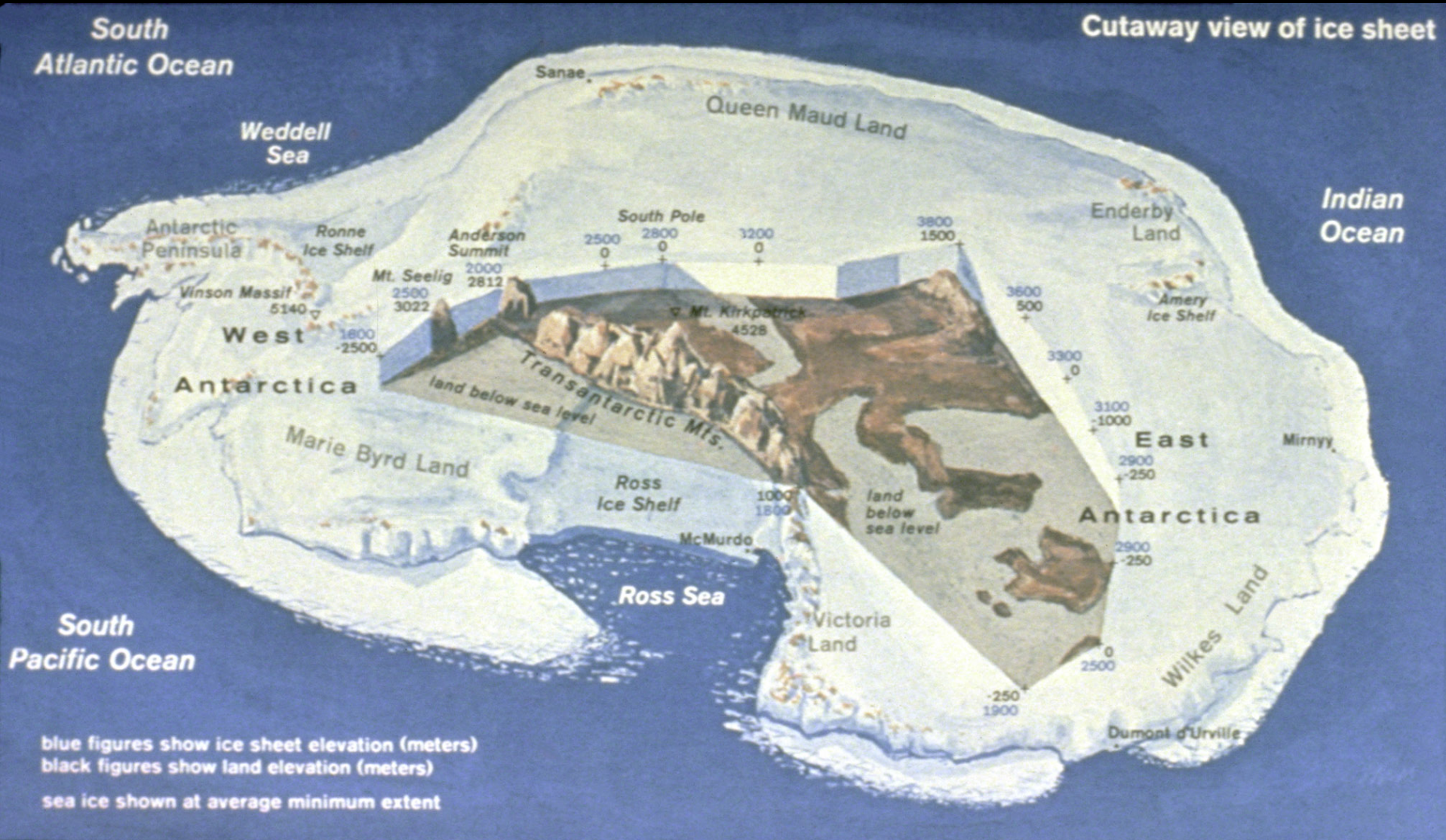


Journey to the South Pole



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

Antarctic Continent



Larger than the US – Ice sheet two miles thick!



Big Program!



Arrival in Antarctica



McMurdo – base on the coast



On to the Pole – over the Transantarctic Mountains



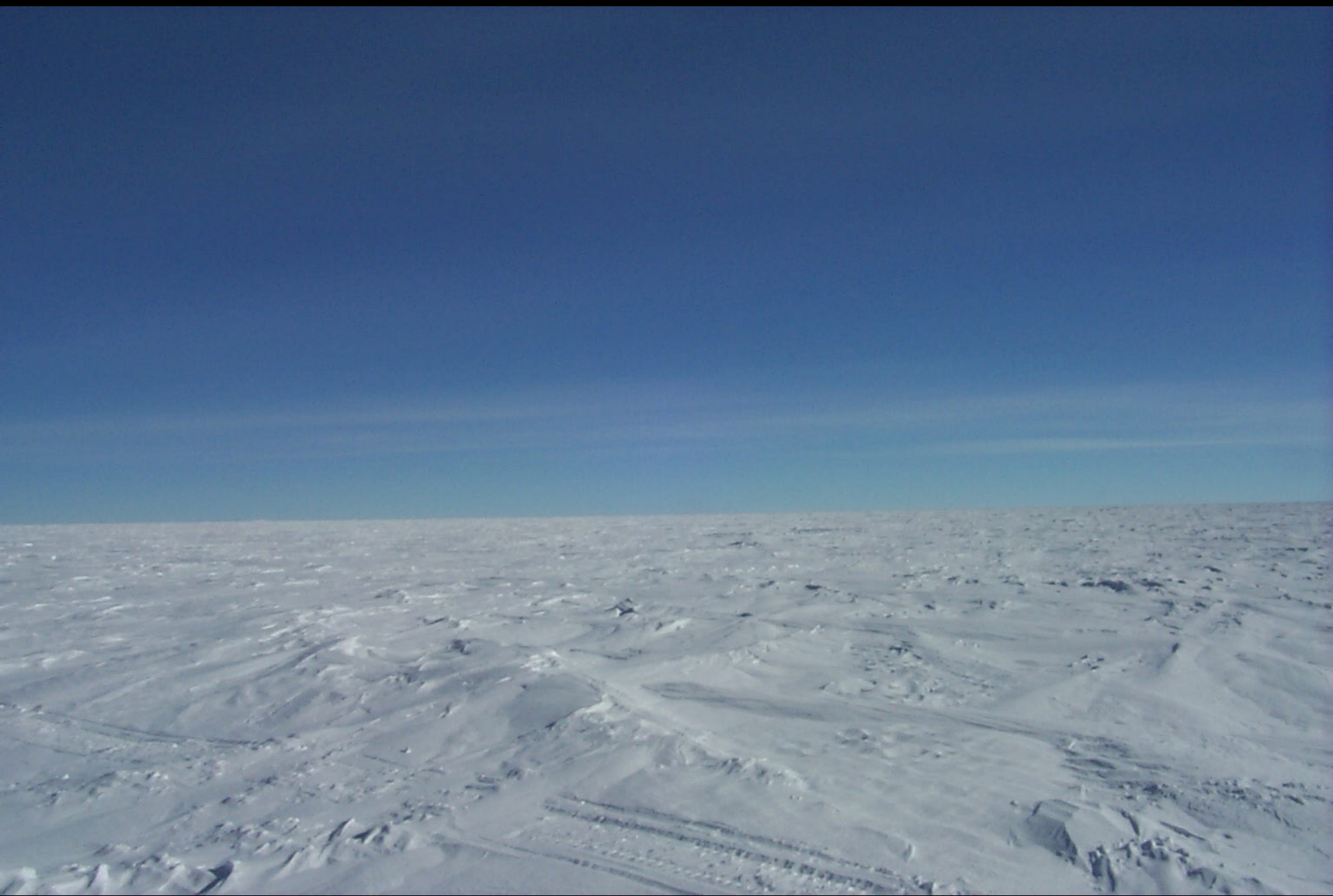
Unloading at Pole



The Actual South Pole



Nothing Out There!



Why do this at the Pole?

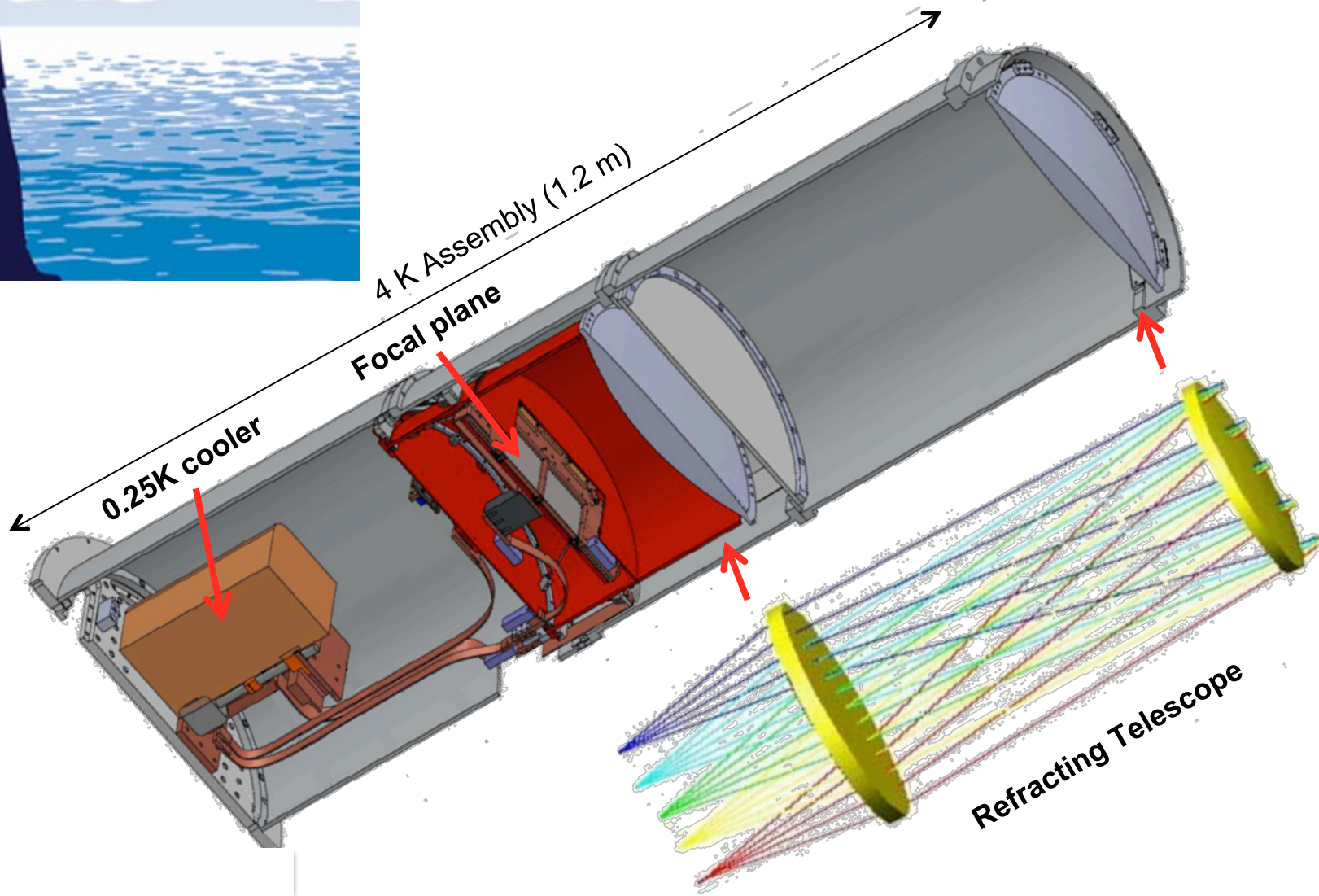
South Pole CMB telescopes



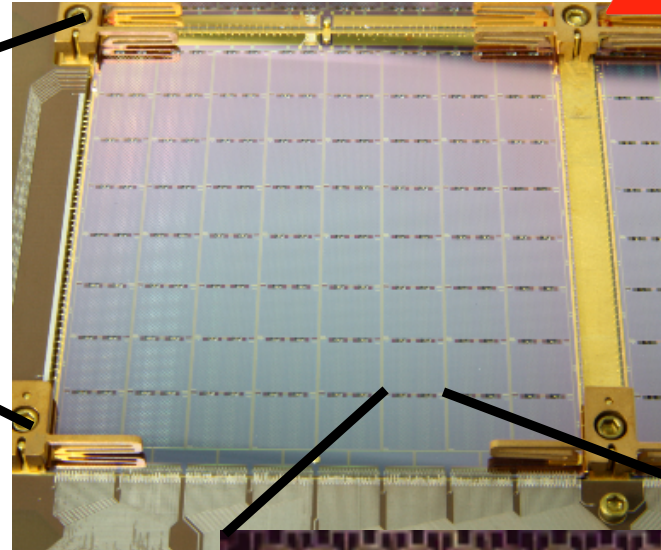
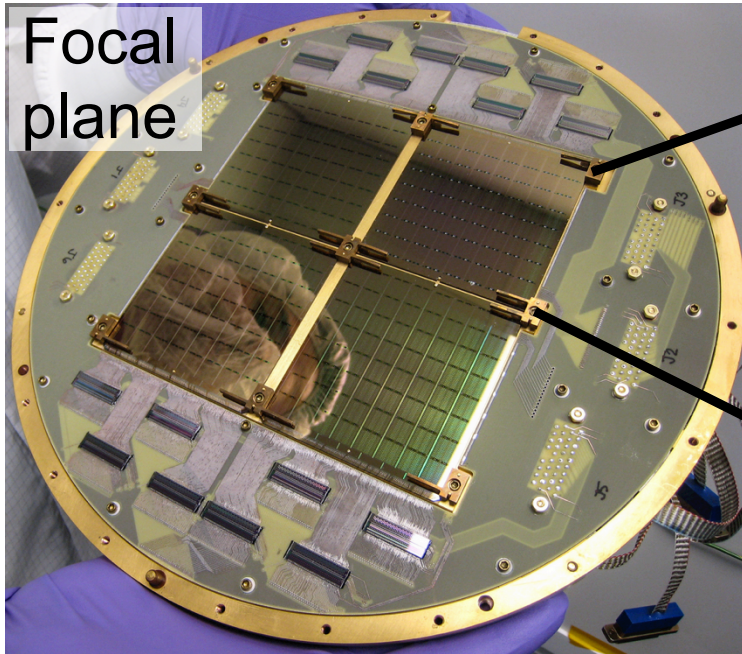
- High and *dry* – see out into space
- On Earth's rotational axis - One day/night cycle per year
 - Long night makes for great quality data
- Good support infrastructure – power, cargo, data comm
- Food and accommodation provided
- Even Tuesday night bingo...

Basic Experiment Design

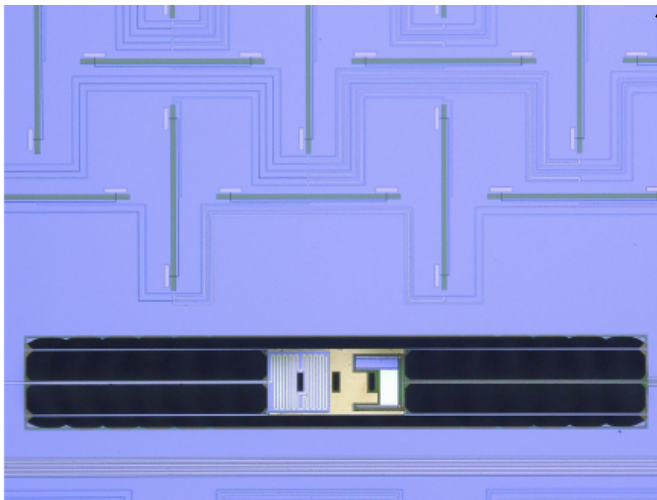
- Small aperture
- Wide field of view
- Cold refractor



Mass-produced Superconducting Detectors

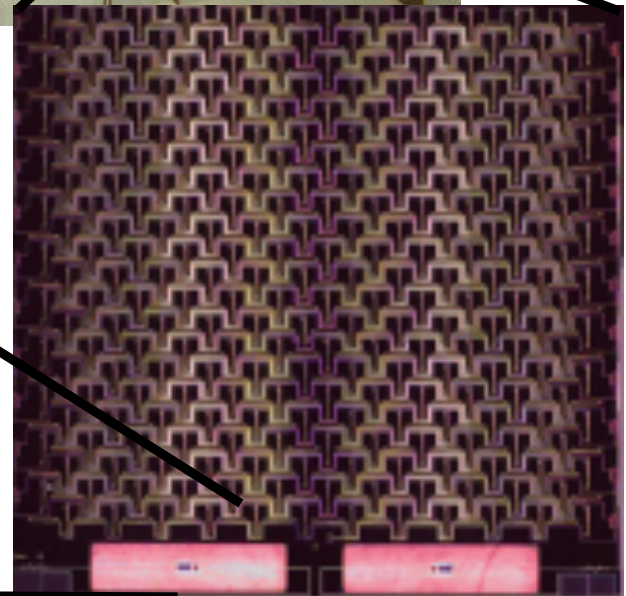


Planar antenna array



Slot antennas

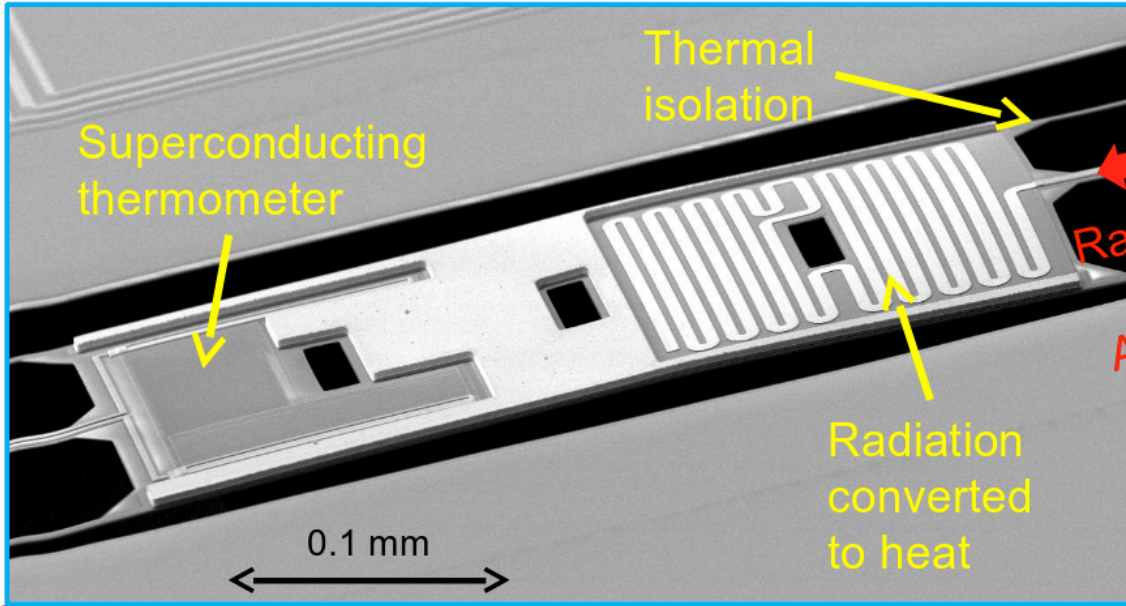
Transition edge sensor



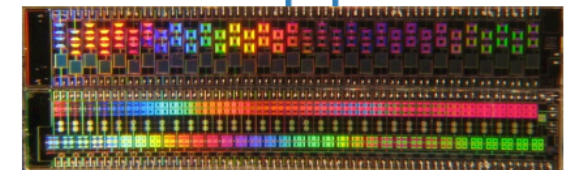
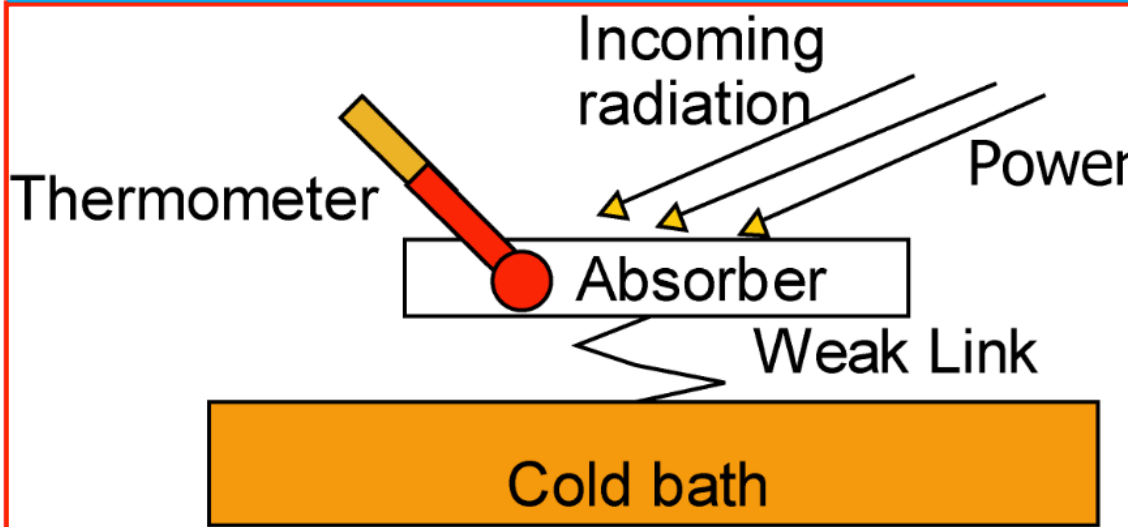
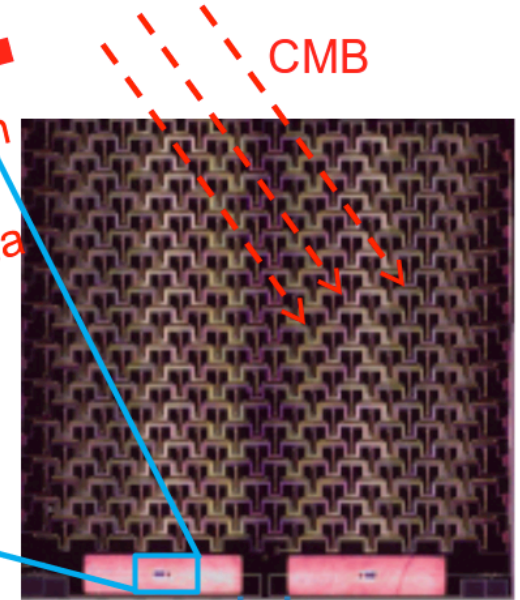
Microstrip filters

Detecting CMB Radiation

BICEP2 Detector: Transition-Edge Superconductor

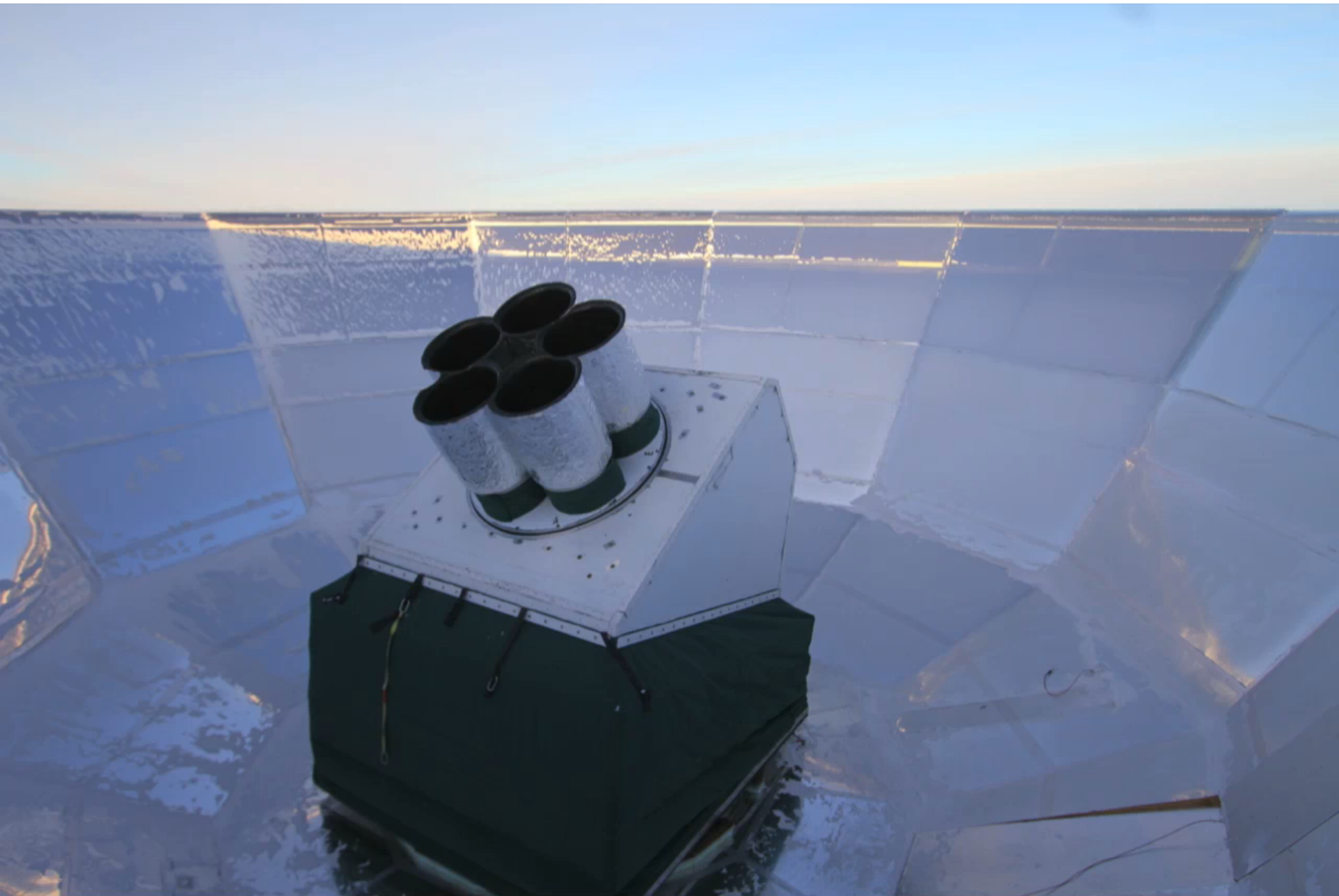


Printed Antenna
Gathers CMB Light



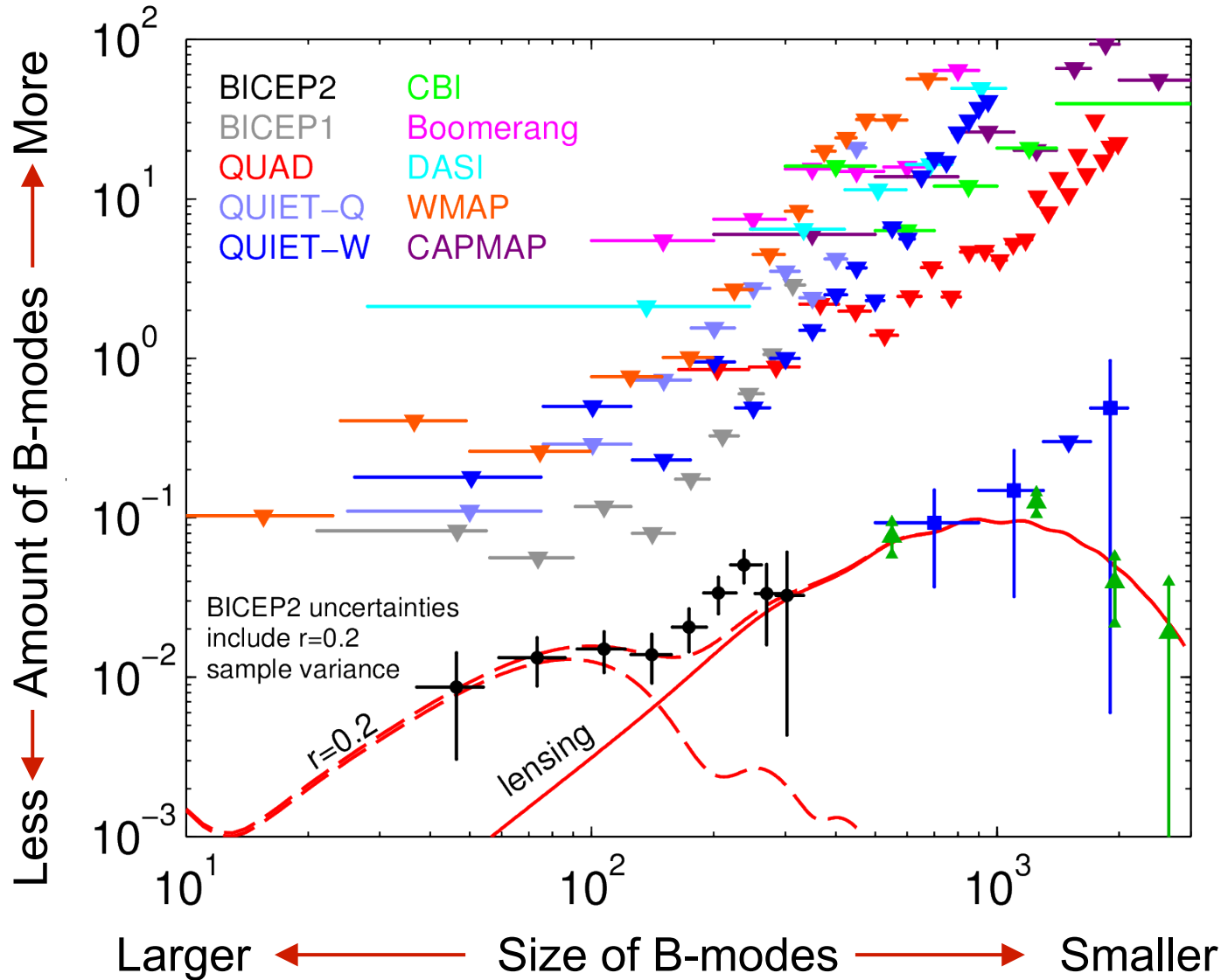
Sensors cooled to 0.25 K to reduce thermal noise

SQUIDs developed at NIST



Clem Pryke for The Bicep2 Collaboration

In 2014 we thought we had found what we were looking for!



(r is a measure of amount of gravitational waves)

In 2014 we thought we had found the signature of inflationary gravitational waves but...

2014 Storm of Media Attention

9.90 THE NETHERLANDS

TUESDAY

USA TODAY
03.18.14

NCAA TOURNAMENT
WHO HAS BEST 'DANCE CARDS'
A look at matchups, from the underdogs to the favorites to watch, SC

UConn tops women's tourney
ANALYSIS, BRACKET 4C

Putin, U.S. up ante after vote

Sanctions imposed, Ukraine, Russia ready troops as Duma considers Crimea's annexation

'Always hope' missing jet's passengers alive
As search expands to find Malaysia's MH370, Malaysia officials warn that plane is intact 3A

GM issues three new recalls
New recalls include oil logs, brake system plug, involve more than 15 million vehicles 1B

Homeport load unchanged
Despite concerns about more work, study finds Britain has barely changed over 30 years 3A

How earnings earned her big, bad wings
To play 'Mad Max: Fury Road' to go 'Mad Max' 2D

South Pole view
The best place to view comets, South Pole where the aurora, and other views from the continent 2D

Homebrew
Scientists have been brewing their own beer for decades 1B

GRAVITATIONAL WAVES

A THEORY
In 1915, Einstein's theory of gravity predicted gravitational waves. Now, scientists have detected the first one 2D

WAVES COULD BE BIG BANG'S SMOKING GUN

Scientists of the South Pole-based special telescope to detect predicted gravitational waves—ripples in the fabric of space and time—which hold clues to the nature of the universe. The ripples have never been seen directly until now. Story 5A

Space Ripples Reveal Big Bang's Smoking Gun

By HEINZ HEISE
CLASSICAL PHYSICS—The light left in 1915, an important piece of evidence that the universe is expanding, could be the smoking gun for the Big Bang. The new theory of gravity, which predicts the existence of gravitational waves, could be the smoking gun for the Big Bang. The new theory of gravity, which predicts the existence of gravitational waves, could be the smoking gun for the Big Bang.

Lost Jet's Path Seen as Altered

By PATRICK L. WALSH
AN INVESTIGATION—The flight path of the missing Malaysia Airlines plane has been altered, according to a new report. The flight path of the missing Malaysia Airlines plane has been altered, according to a new report.

Crisis could hurt U.S. firms

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The New York Times

Vol. CLXXIII, No. 56,644 TUESDAY, MARCH 18, 2014 \$2.50



SECOND-ROUND CHINESE relatives of those on the missing Malaysia plane watched news from Malaysia in Beijing. Page A8.

PUTIN RECOGNIZES CRIMEA SECESSION, DEFEYING THE WEST

Decree Increases Fears of Annexation by Russia, Despite More Sanctions

By STEVEN LEVITSKY and PETER HADFIELD
MOSCOW—President Vladimir Putin on Tuesday signed a decree on Monday that formally recognized the secession of Crimea from Ukraine and its incorporation into Russia. The move, which was widely expected, defied the West and raised the stakes of the conflict between the two nations.

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States engage in shadowy deals as death penalty drugs dwindle

By JEFFREY M. HESTER
LAW—States are engaging in shadowy deals to secure death penalty drugs as the supply dwindles.

Prisons raise drug use as study pharmacies, try untested medicines

By JEFFREY M. HESTER
HEALTH—Prisons are raising drug use as they study pharmacies and try untested medicines.

EU and US take action

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POLITICS—The EU and US have taken action against Russia over the Crimea crisis.

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SCIENCE—The discovery of gravitational waves adds muscle to the Big Bang theory.

New dawn for breakfast as disease and speculation push price rises

By JEFFREY M. HESTER
ECONOMICS—The price of breakfast cereals is rising due to disease and speculation.



THE BICEP2 COLLECTOR DISH ANTENNA (LEFT), BEING TRANSPORTED TO THE SOUTH POLE. PHOTO BY AP/WIDEWORLD.

宇宙急速膨張の証拠、検出される

Telescope captures view of gravitational waves

By JEFFREY M. HESTER
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宇宙急速膨張の証拠、検出される

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SCIENCE—Scientists have detected the first gravitational waves, providing evidence for the rapid expansion of the universe.

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FINANCIAL TIMES

The Apple alumni
Steve Jobs' acolytes are taking over the world, Page 8

The trouble with tinkering with textbooks
Gideon Rachman, Page 7

USA Tuesday March 18 2014

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PHYSICAL REVIEW LETTERS

Articles published week ending 20 JUNE 2014

Number Subscription Dept.
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20 June 2014

Actually not a lot of fun...

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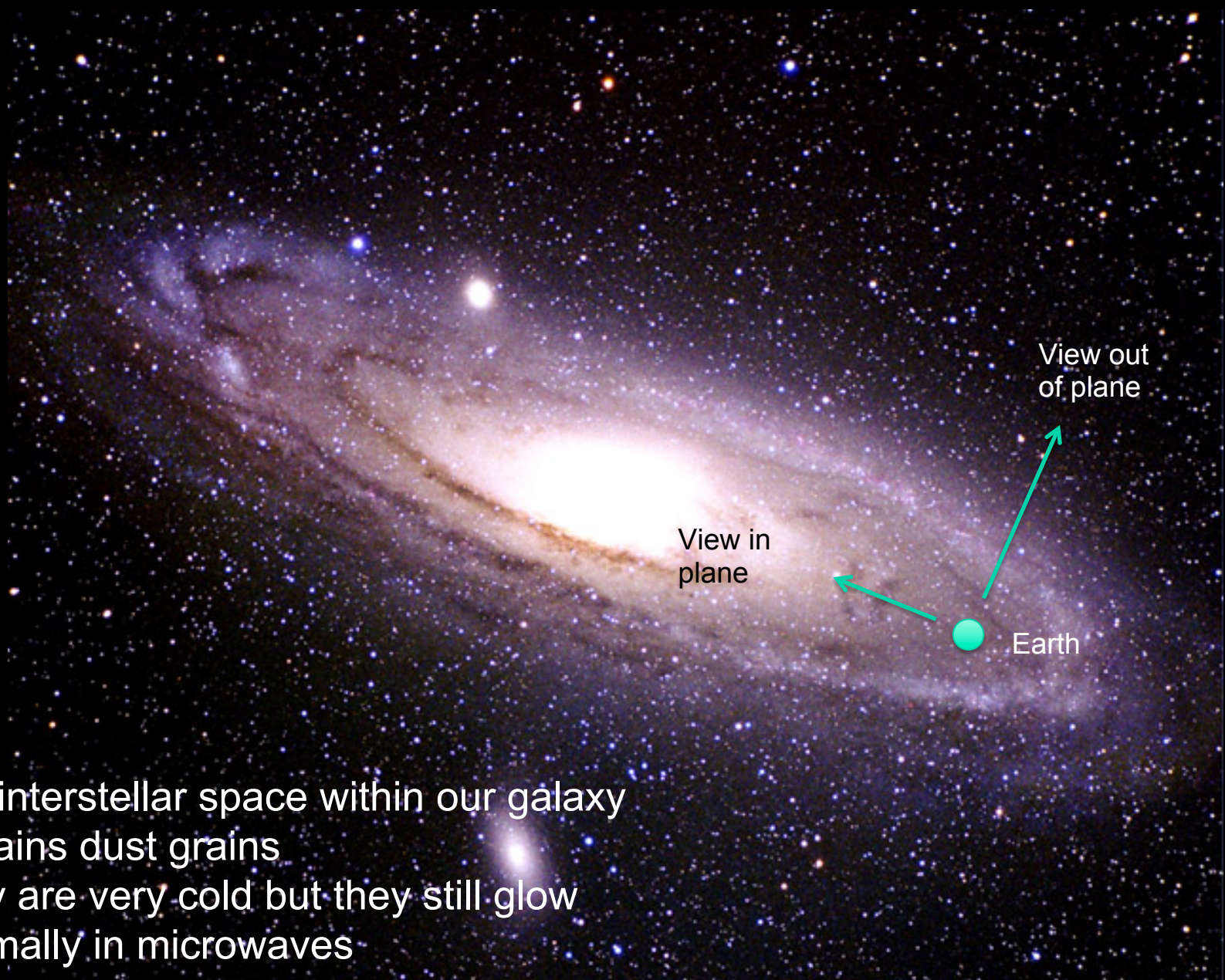
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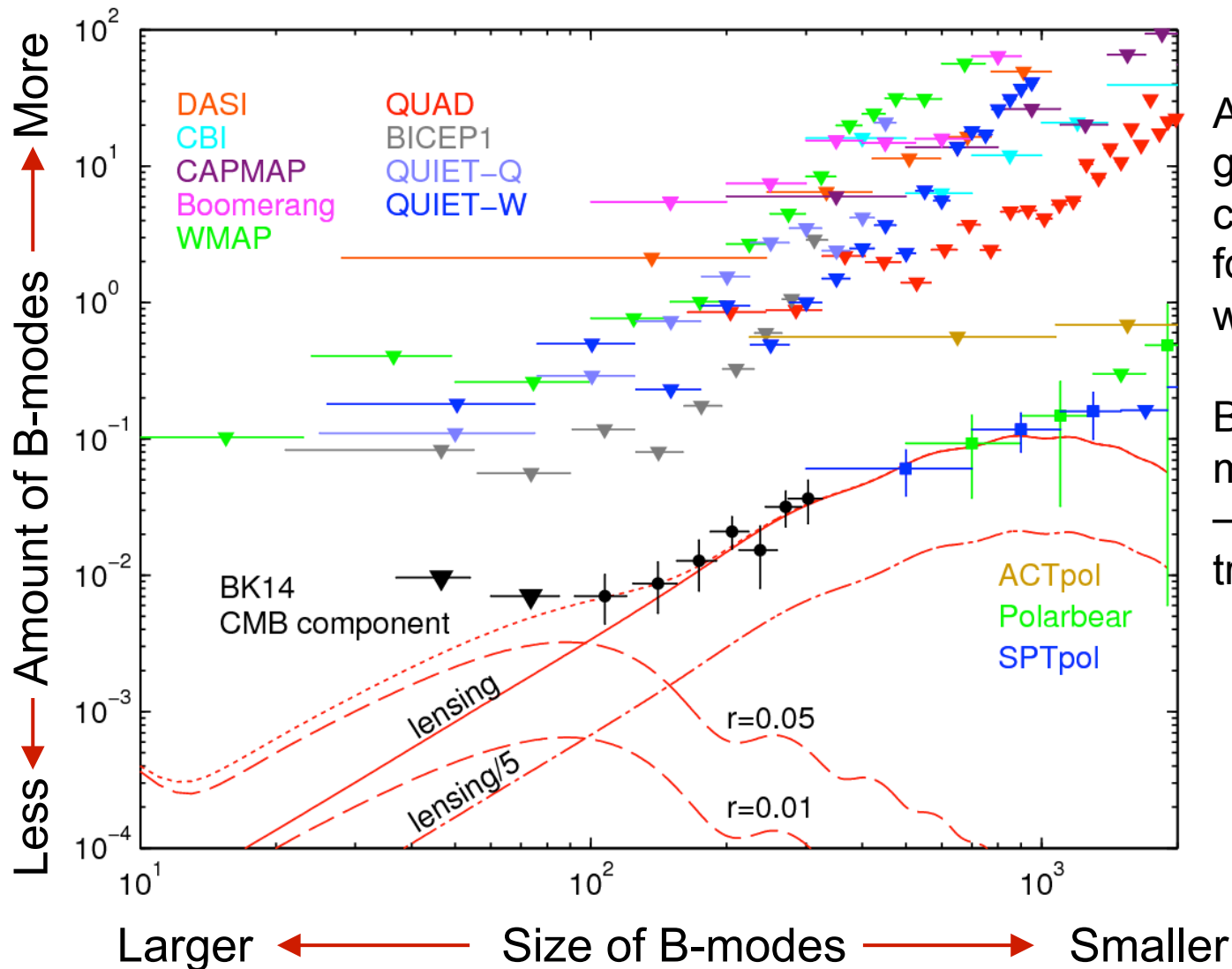
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Unfortunately we are in a galaxy!



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

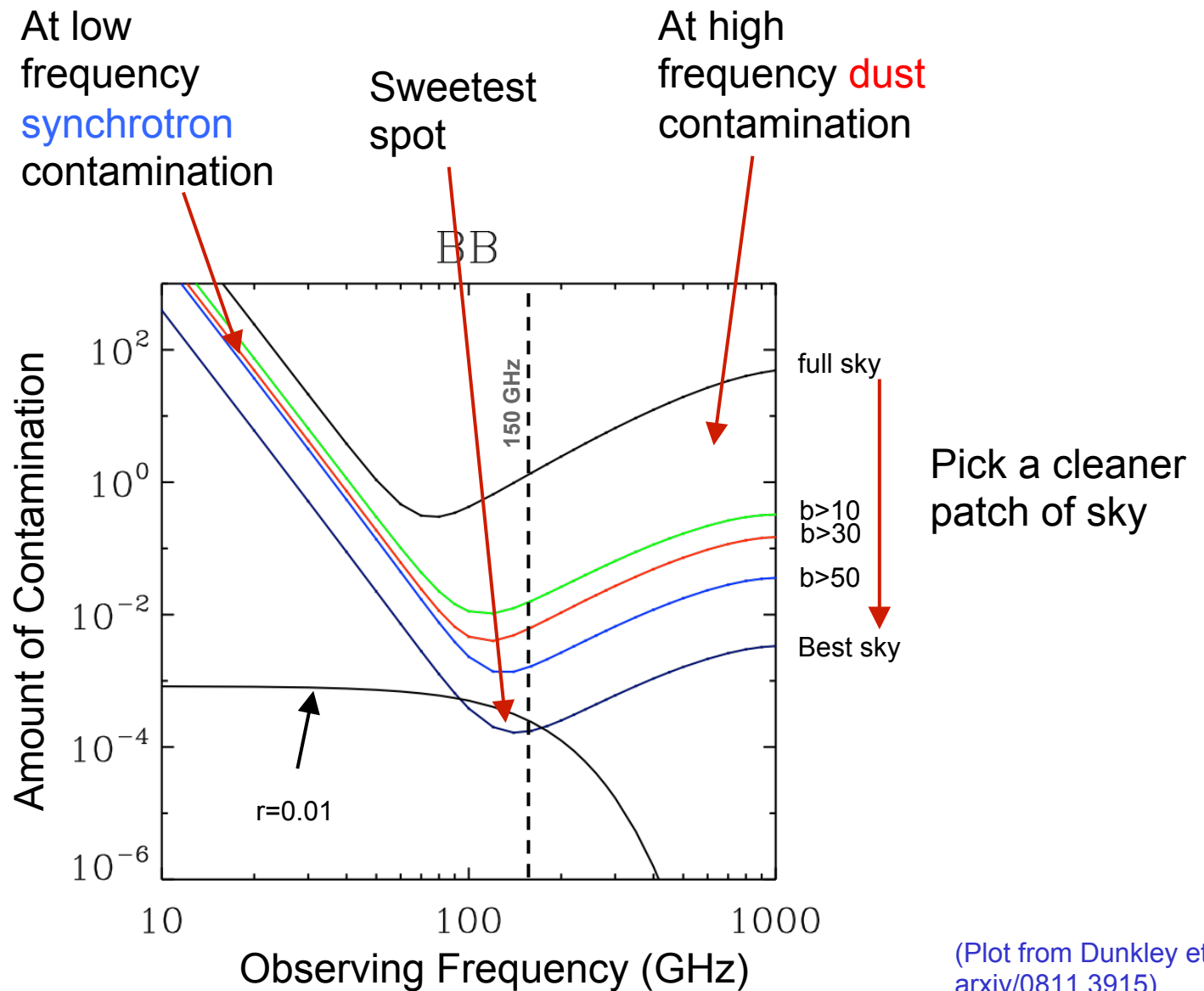
So the Search Goes On...



After accounting for galactic dust there is currently no evidence for gravitational waves

But that doesn't mean they don't exist – just that we need to try harder!

Polarized Foreground Contamination from Our Galaxy

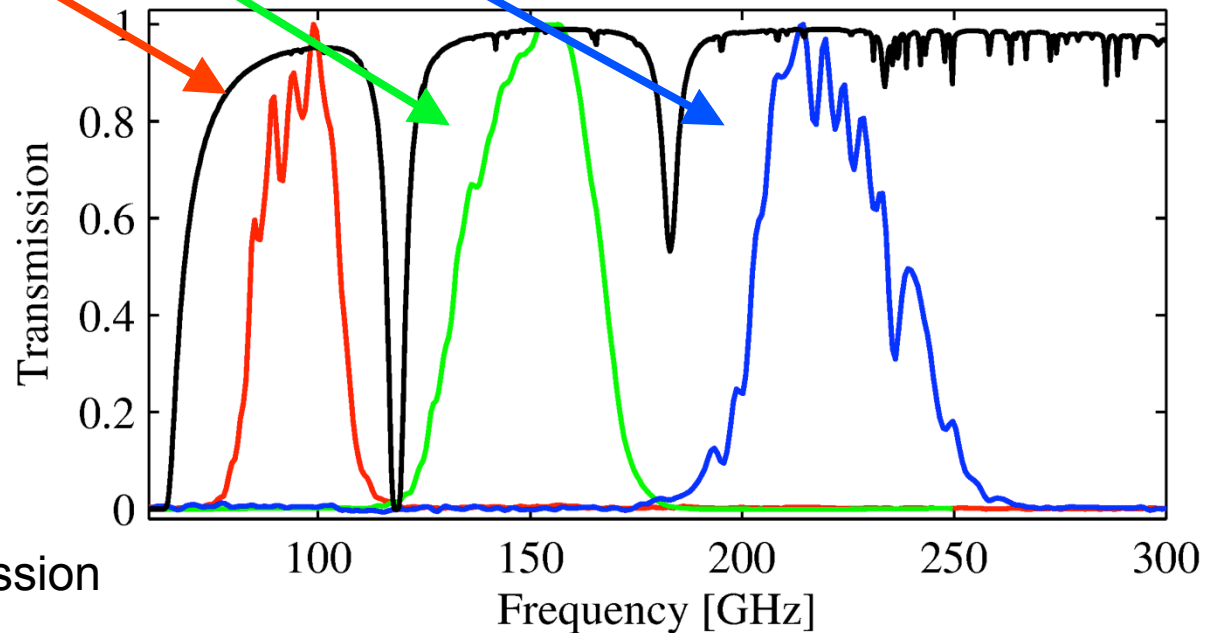
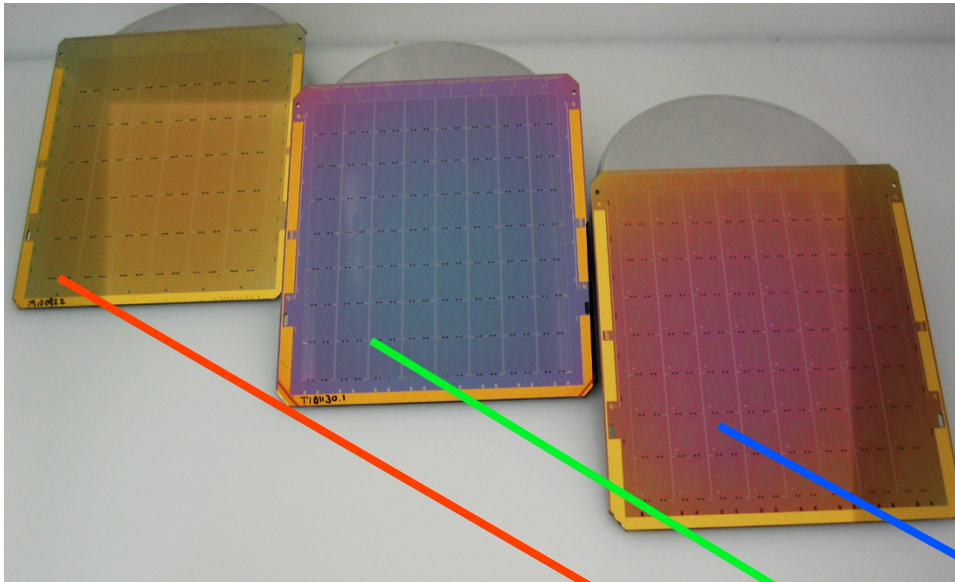


(Plot from Dunkley et al
arxiv/0811.3915)

Planar superconducting detector arrays

...designed to scale
in frequency

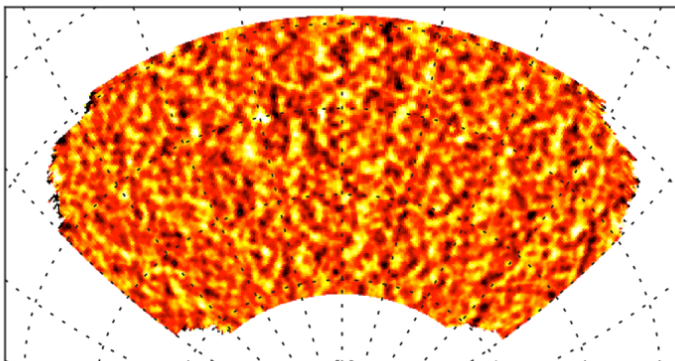
Up to 2013 – all 150GHz
2014 – 95/150GHz
2015 – 95/150/220GHz



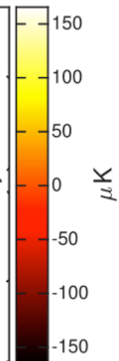
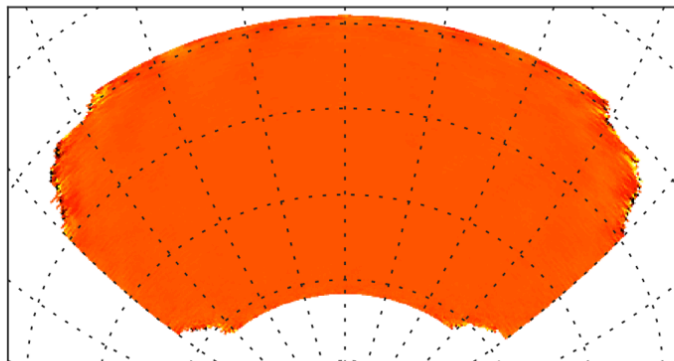
Typical South Pole
atmospheric transmission

BK18 95GHz Map (BICEP3)

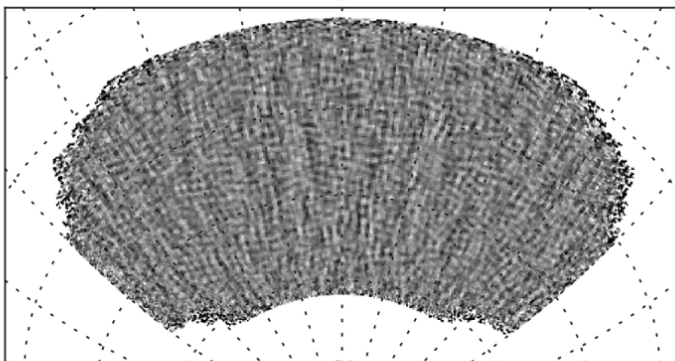
B18₉₅ T signal



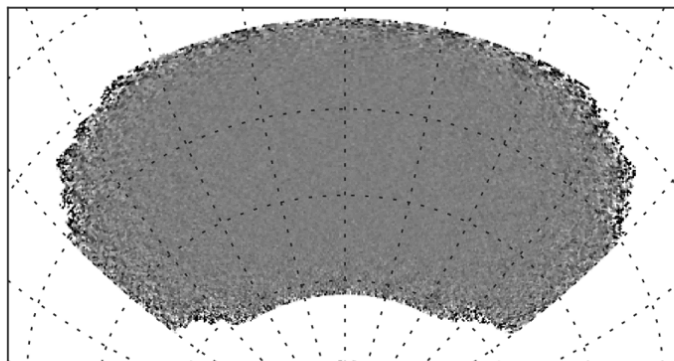
B18₉₅ T noise



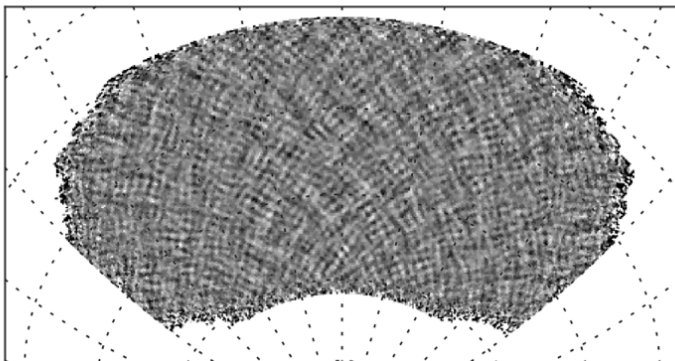
Q signal



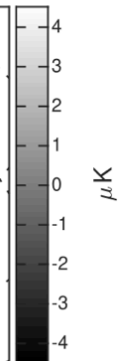
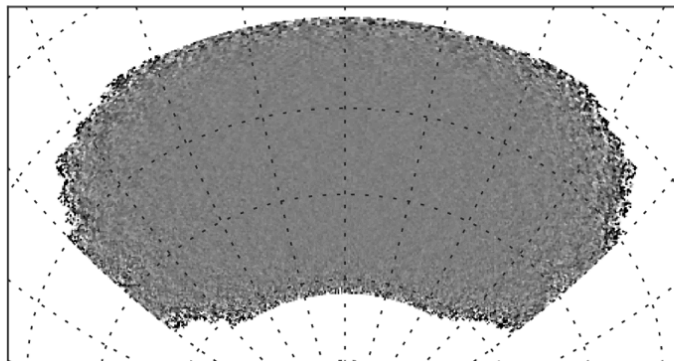
Q noise



U signal

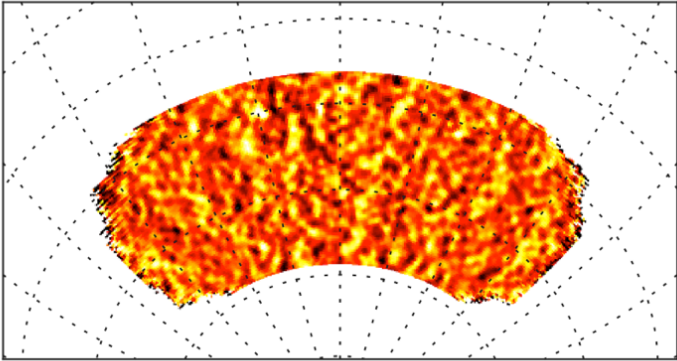


U noise

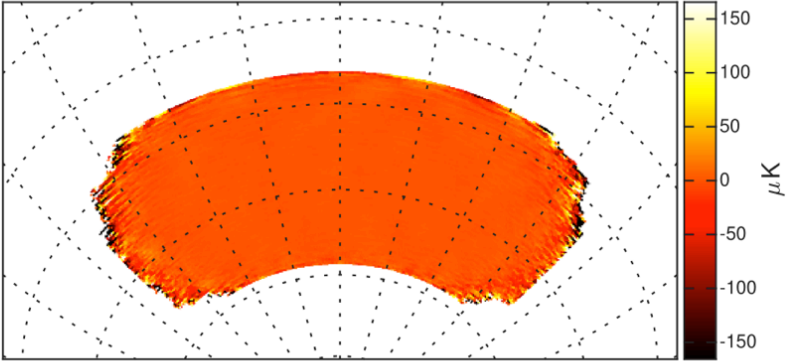


BK18 150GHz Map (BICEP2+Keck)

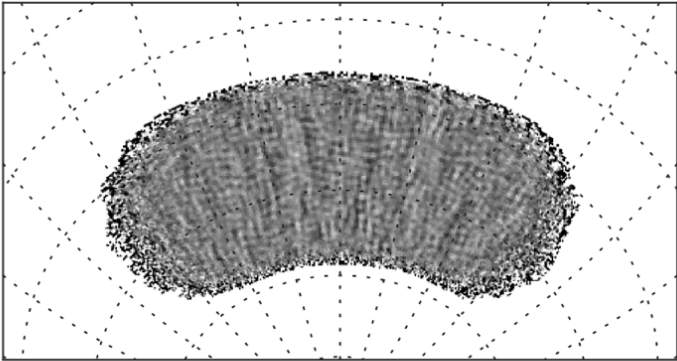
BK18₁₅₀ T signal



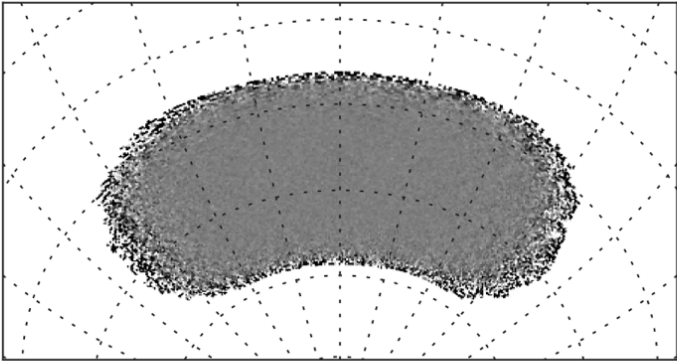
BK18₁₅₀ T noise



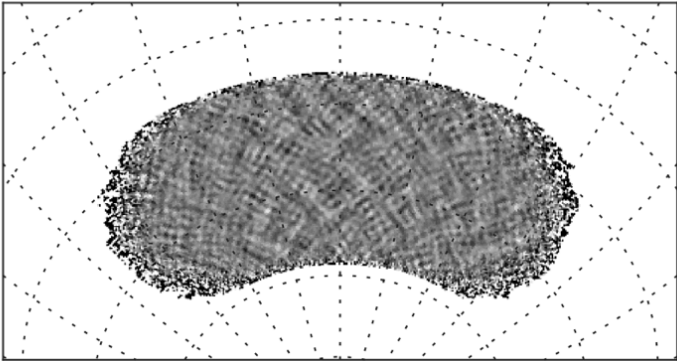
Q signal



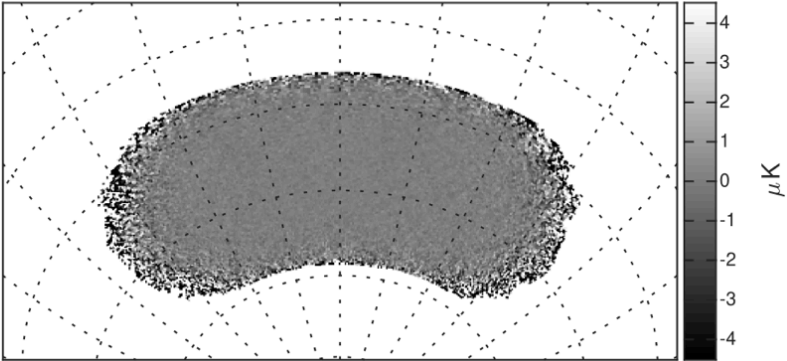
Q noise



U signal

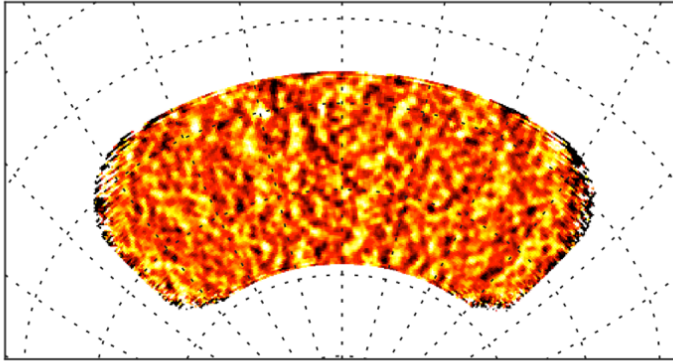


U noise

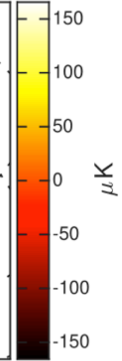
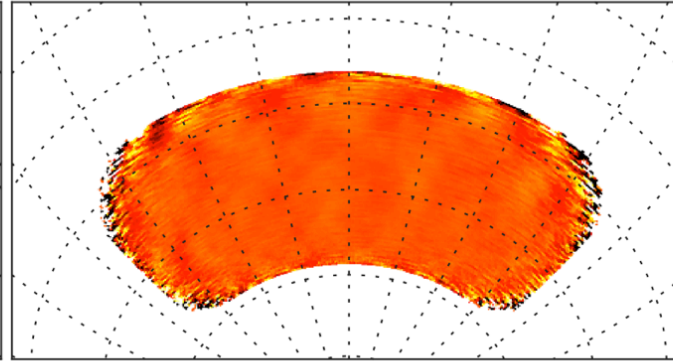


BK18 220GHz Map (*Keck*)

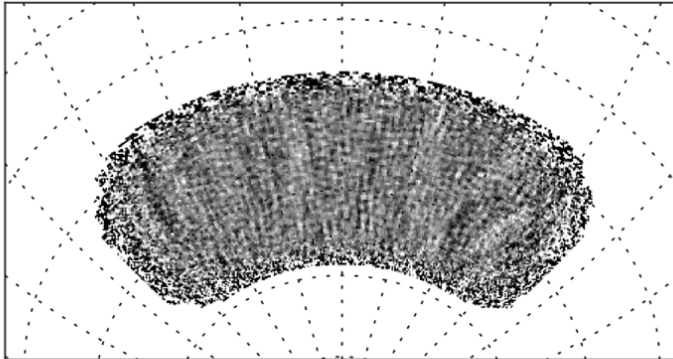
BK18₂₂₀ T signal



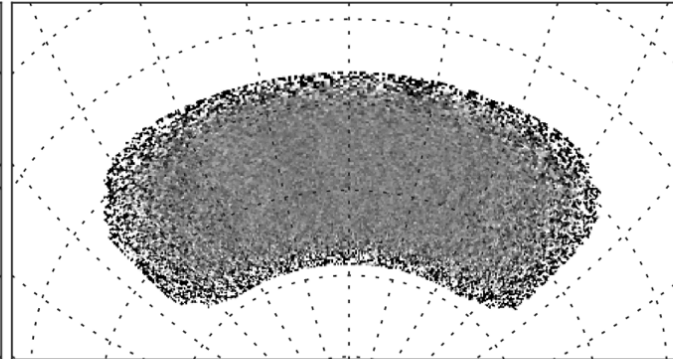
BK18₂₂₀ T noise



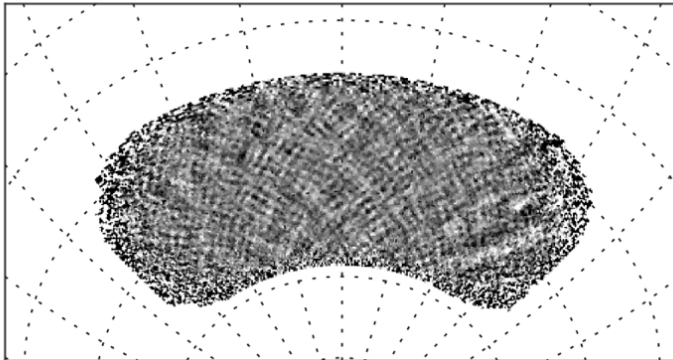
Q signal



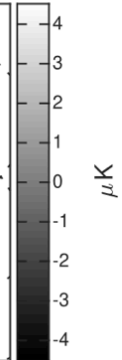
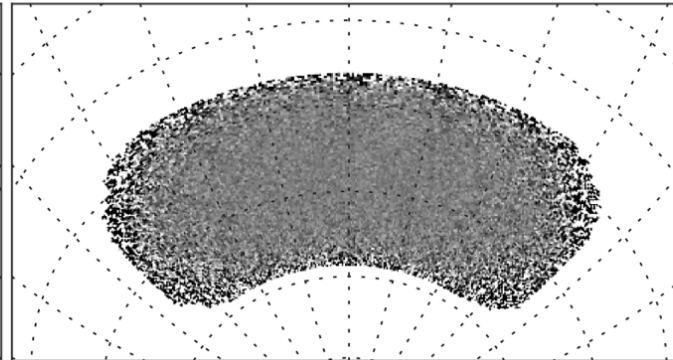
Q noise



U signal



U noise



Stage 2

Stage 3

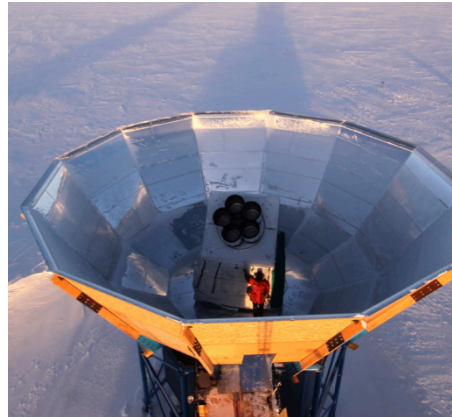
BICEP2
(2010-2012)

Keck Array
(2012-2019)

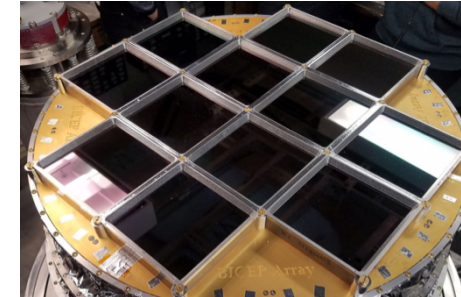
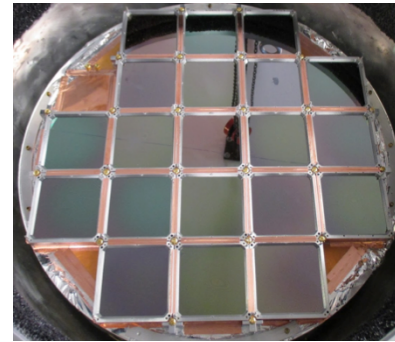
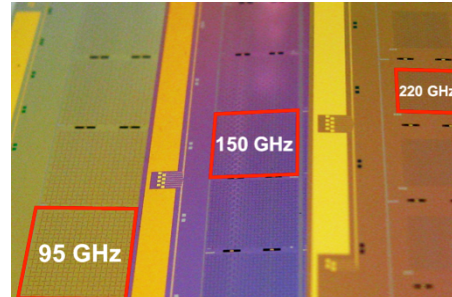
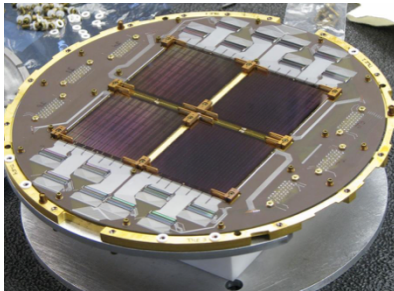
BICEP3
(2015-)

BICEP Array
(2020-)

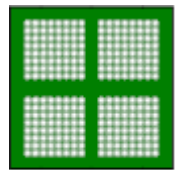
Telescope and Mount



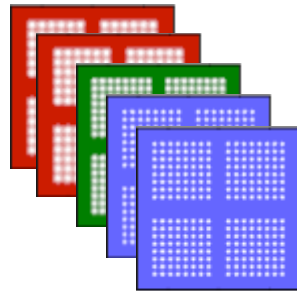
Focal Plane



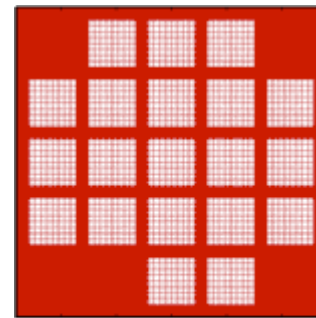
Beams on Sky



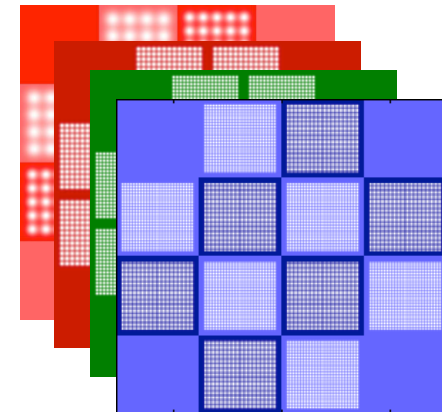
-5 0 5
Degrees on sky



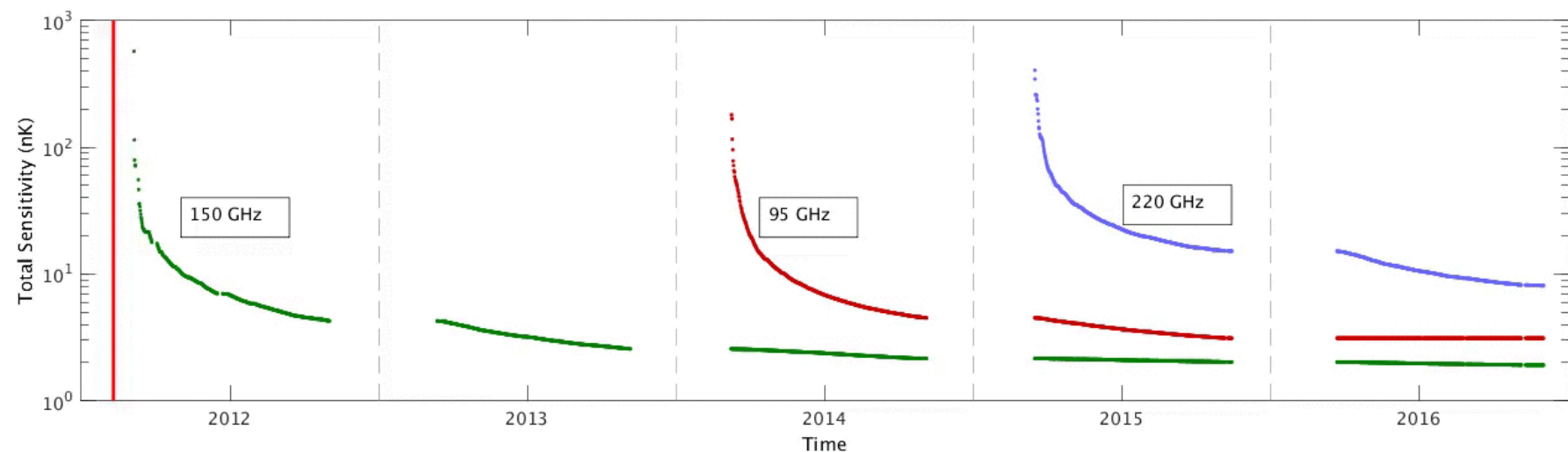
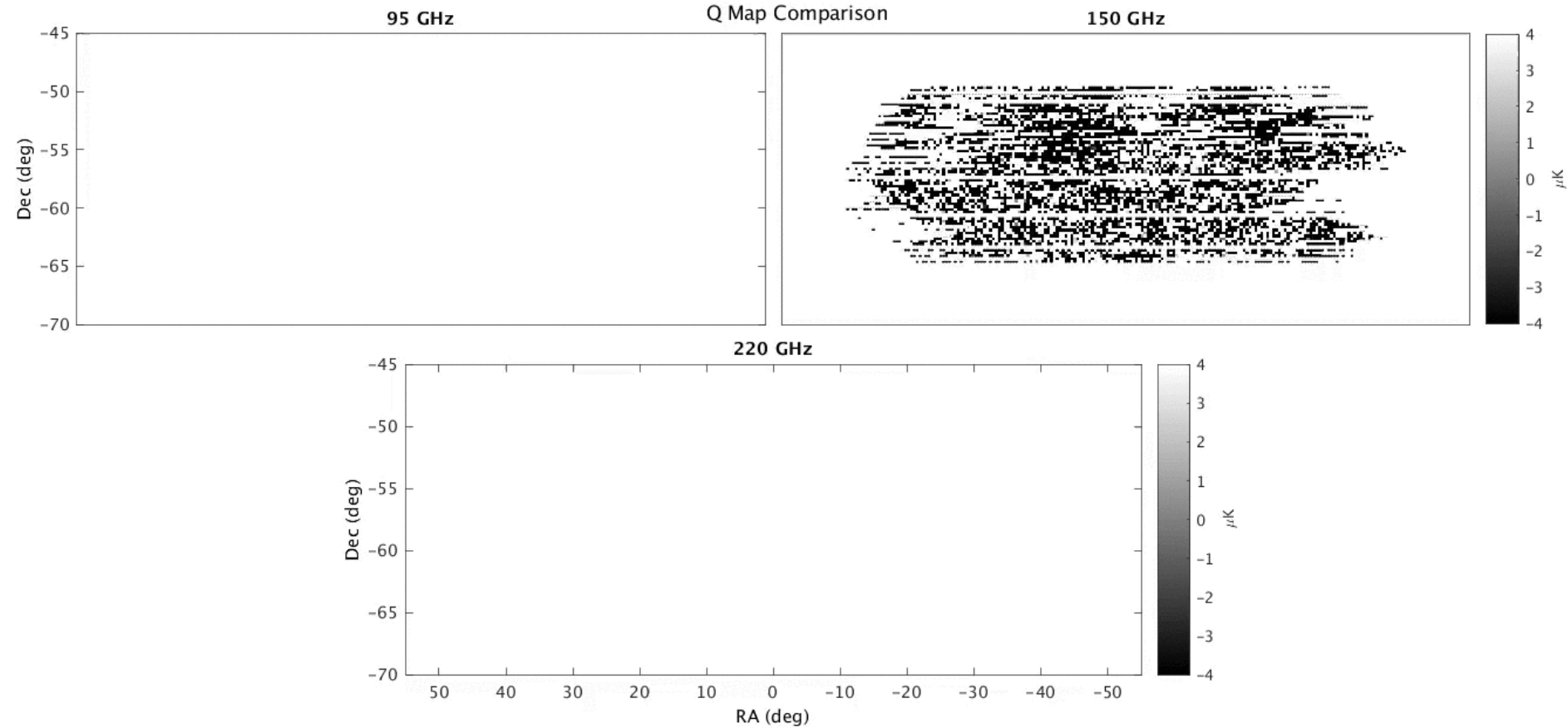
-5 0 5
Degrees on sky



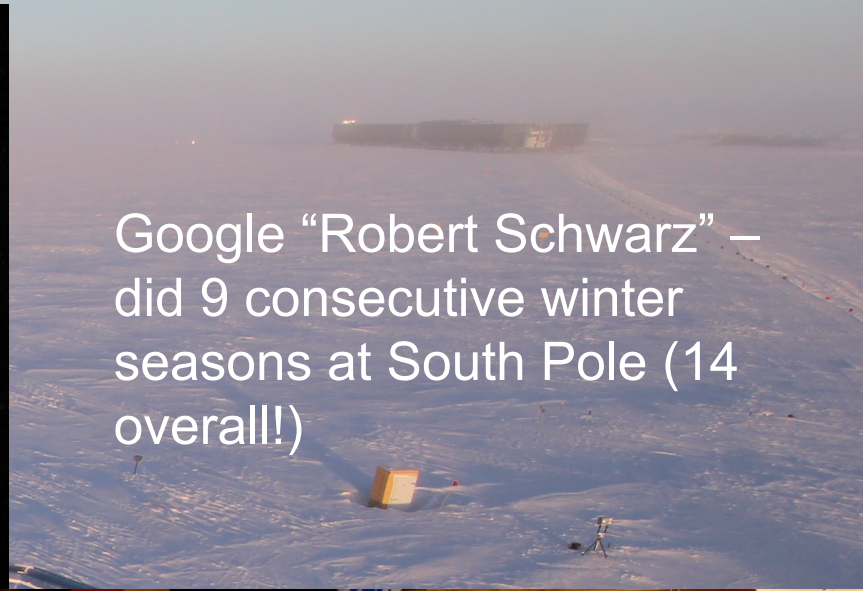
-10 -5 0 5 10
Degrees on sky



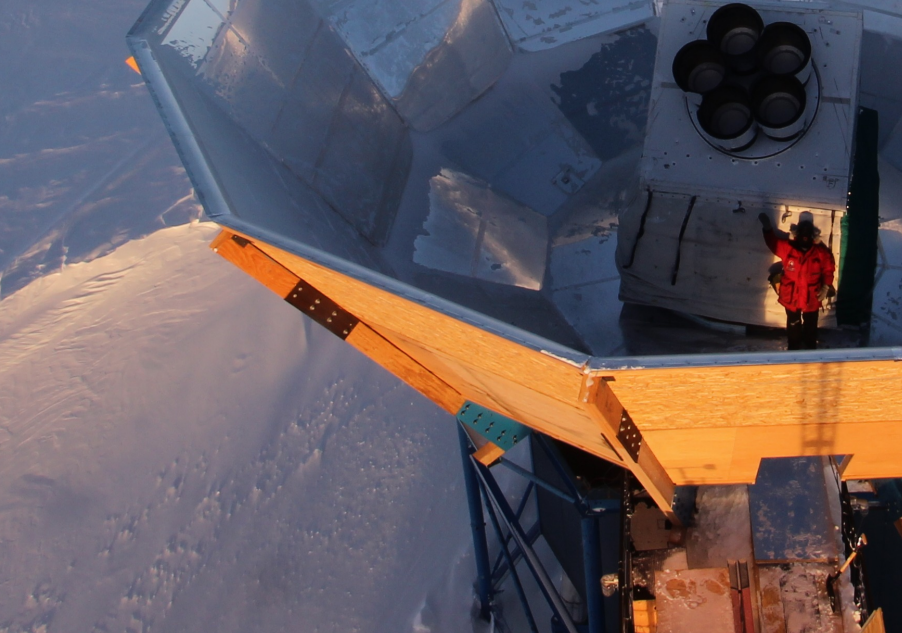
-10 0 10
Degrees on sky



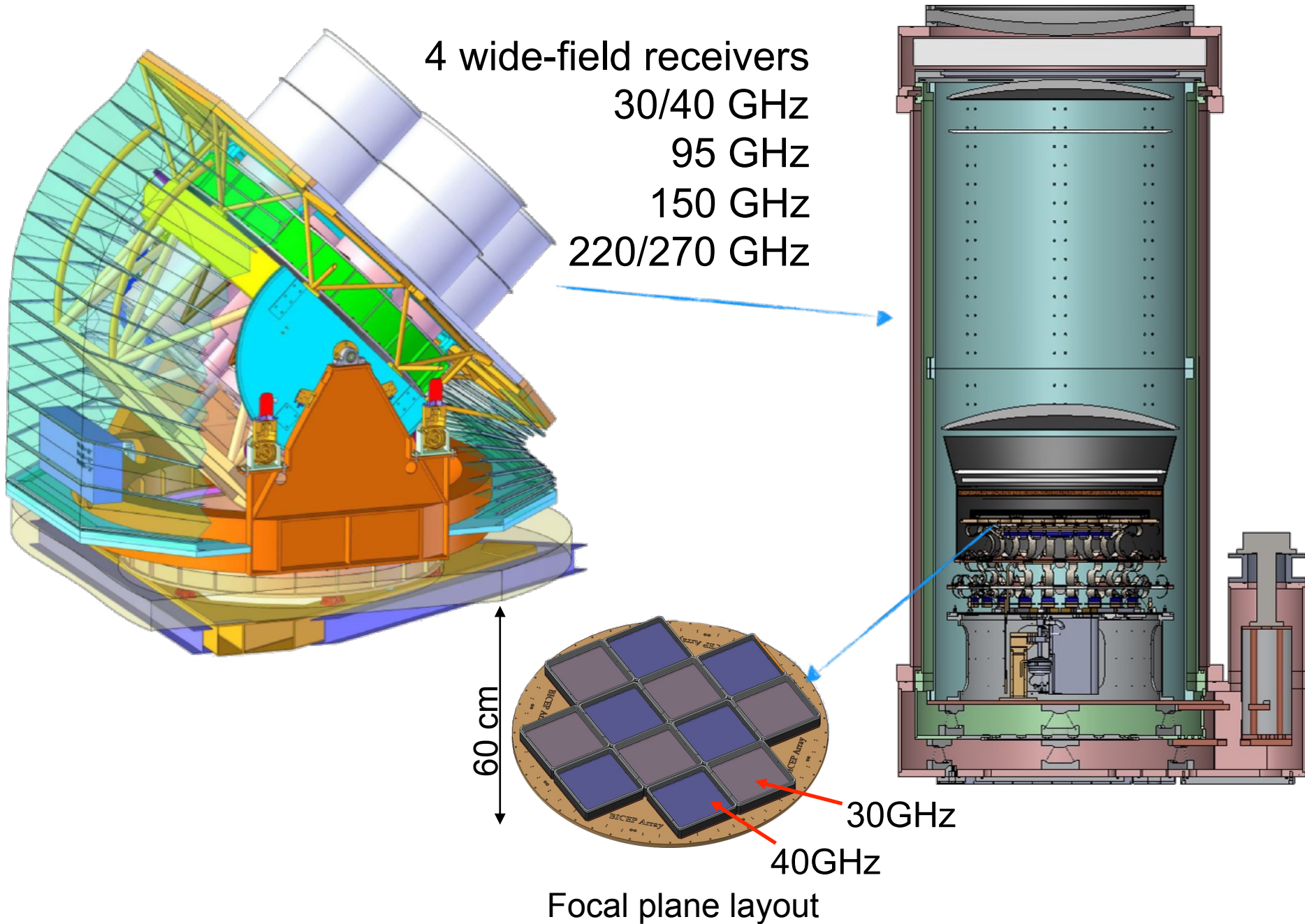




Google “Robert Schwarz” – did 9 consecutive winter seasons at South Pole (14 overall!)

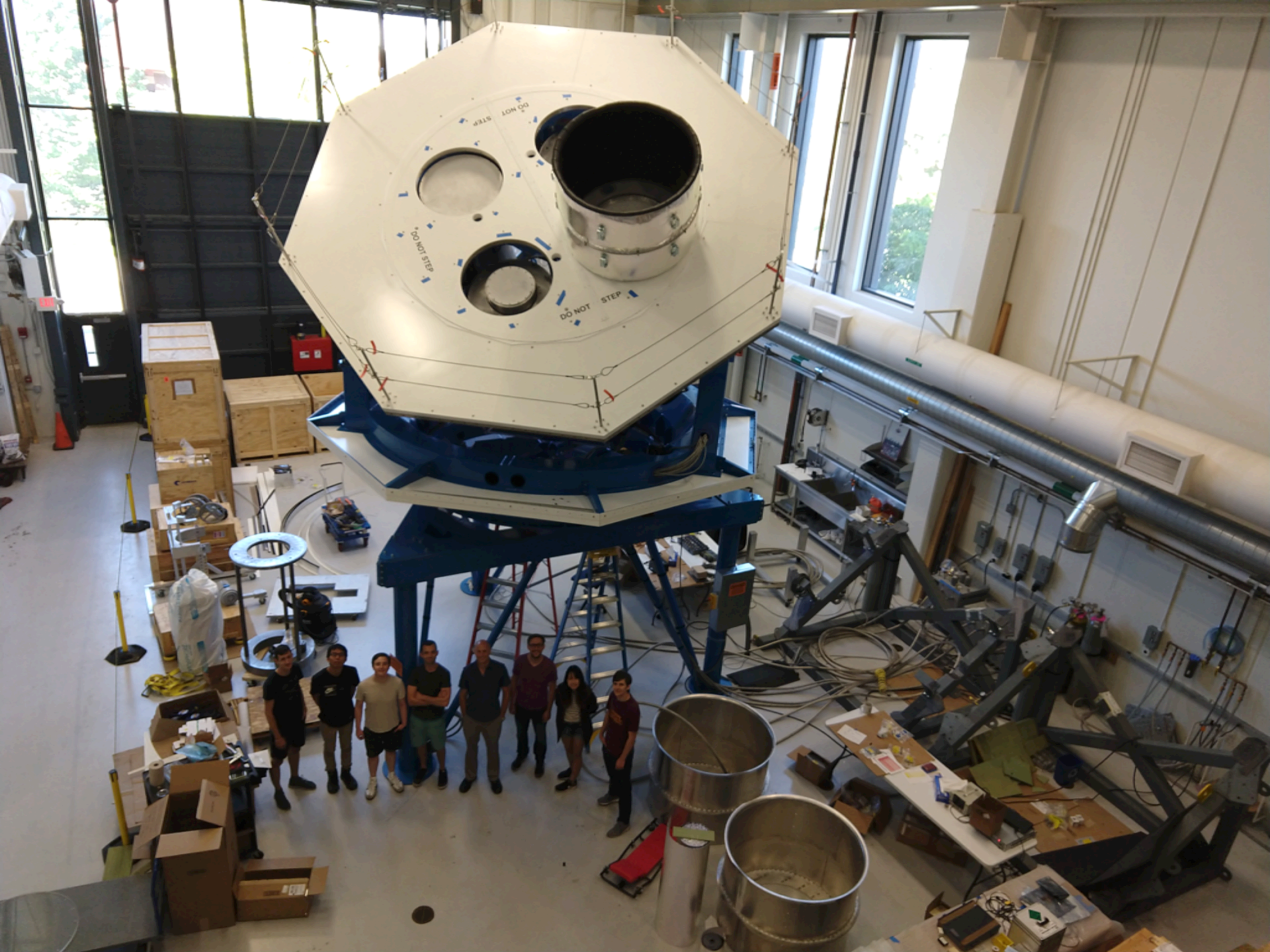


Latest Generation Experiment "BICEP Array"



2018-19: Built New Telescope at UMN



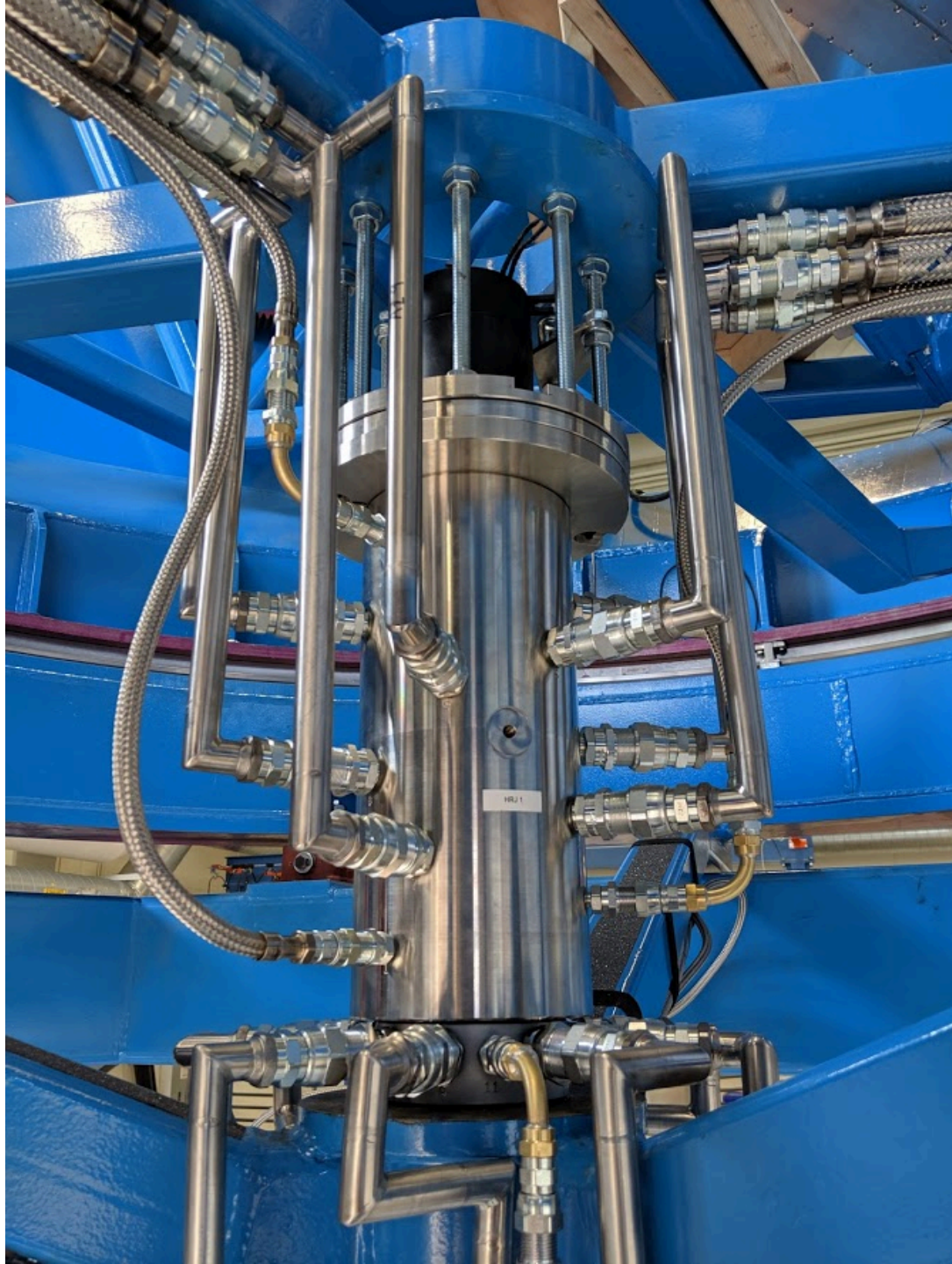


WALLS LONG DO

DO NOT STEP

DO NOT STEP









SCOTT

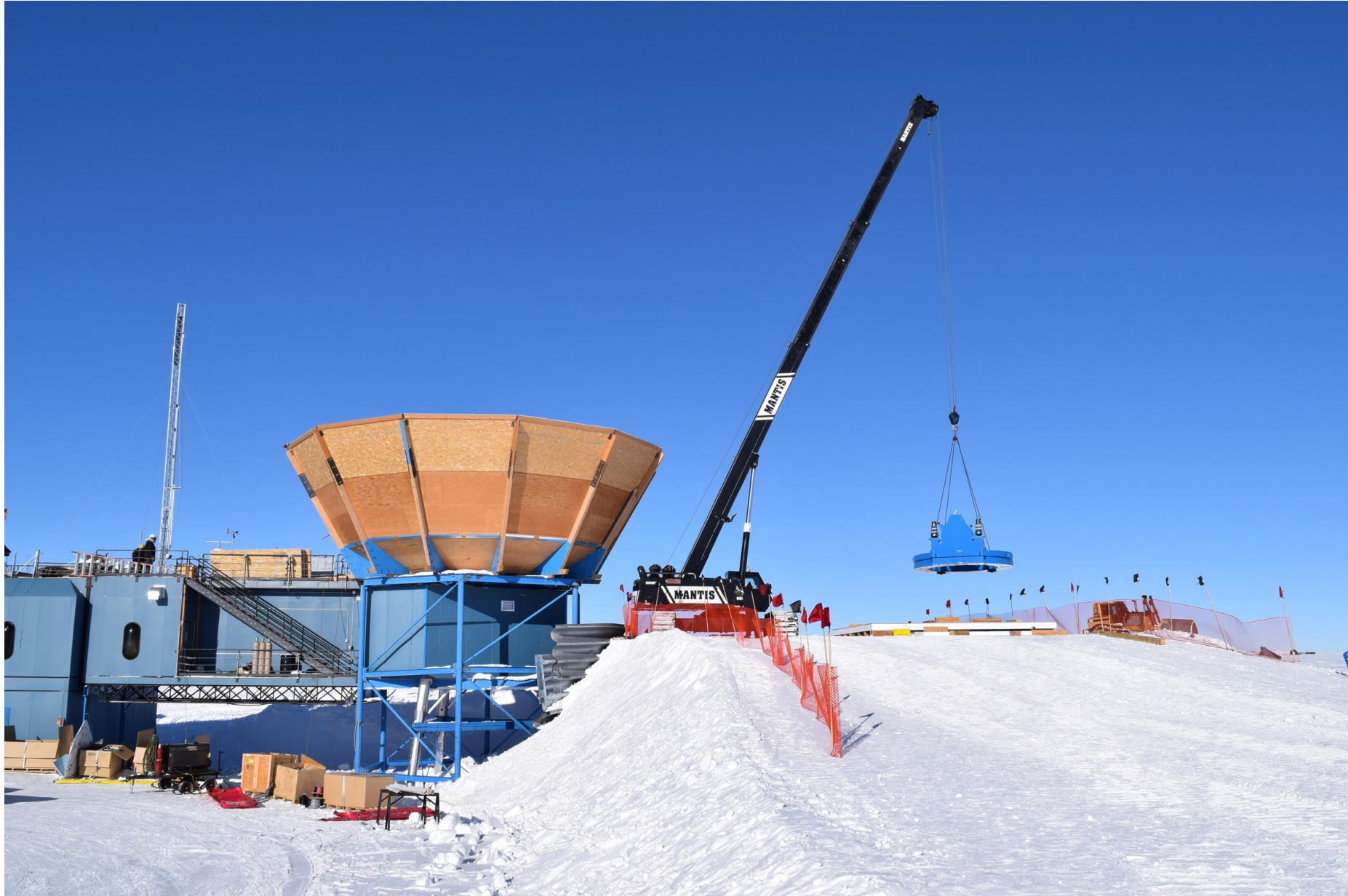
CLEM PRYKE



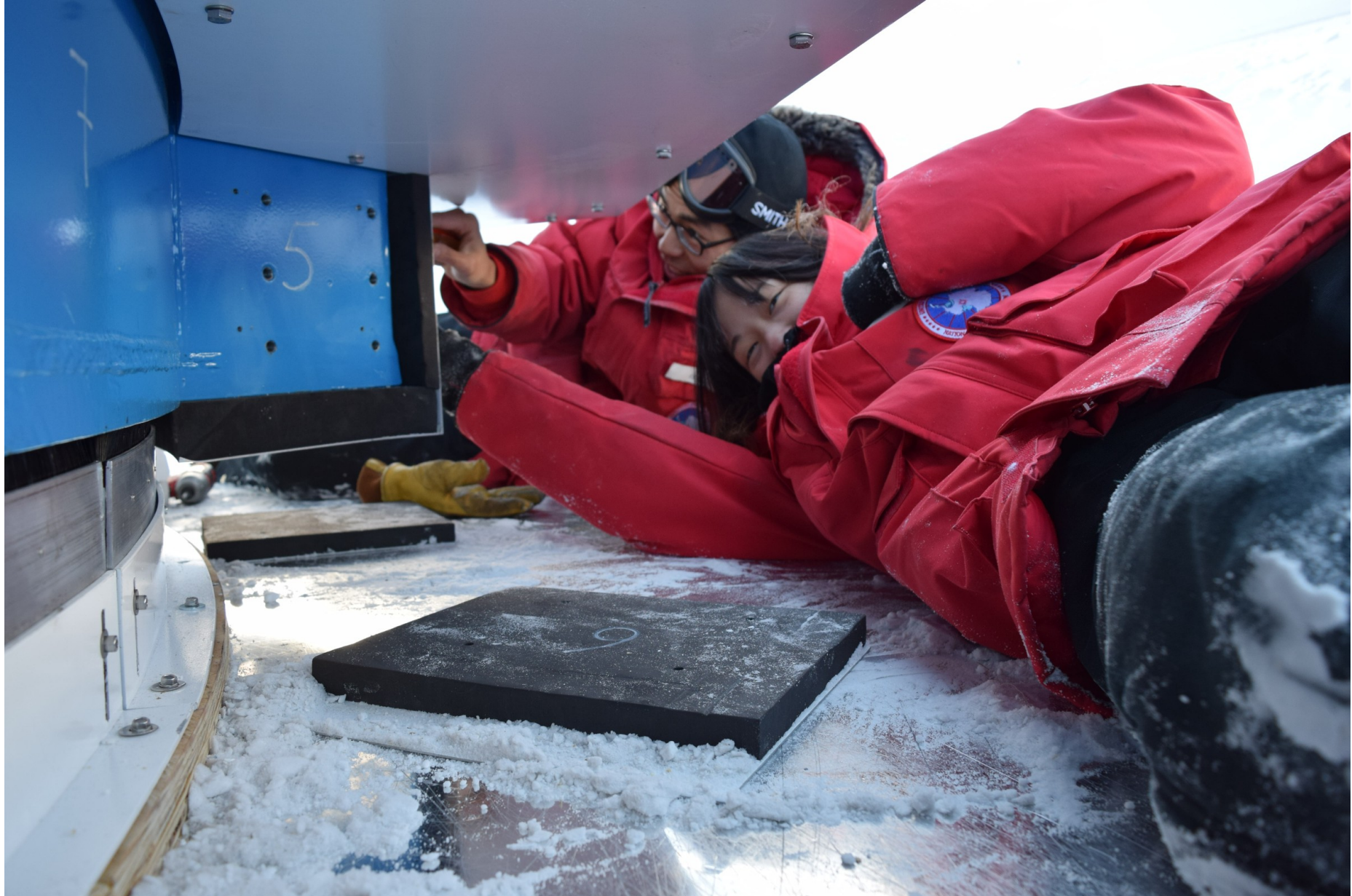
CR

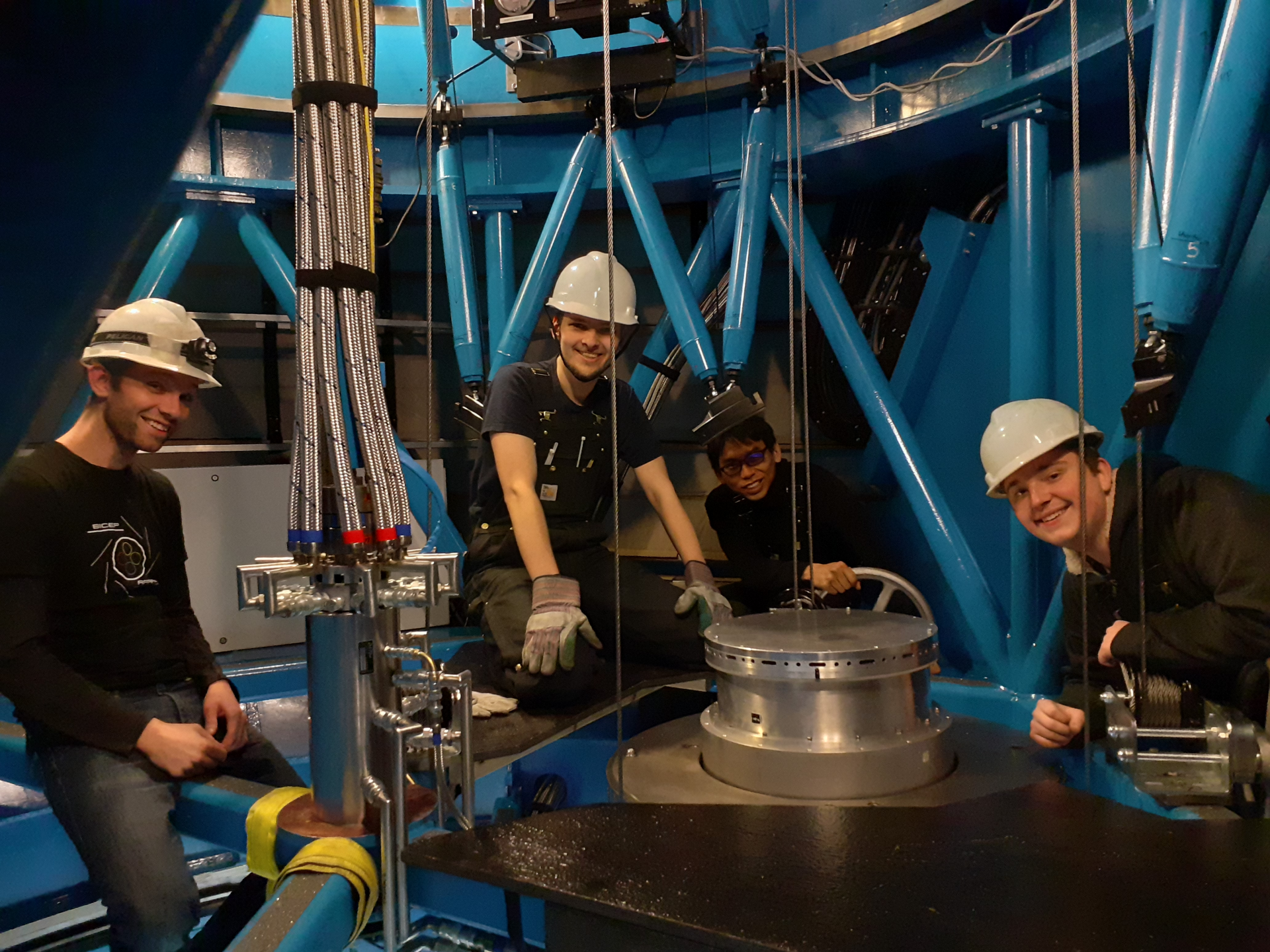


Lifting on part of new telescope



Working in the snow





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 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 by measuring the polarization pattern of the Cosmic Microwave Background – if we can built a sensitive enough telescope
 - A few years ago we thought we had actually done it but unfortunately we were fooled by dust emission from our own galaxy
 - However the search goes on with bigger and better experiments...





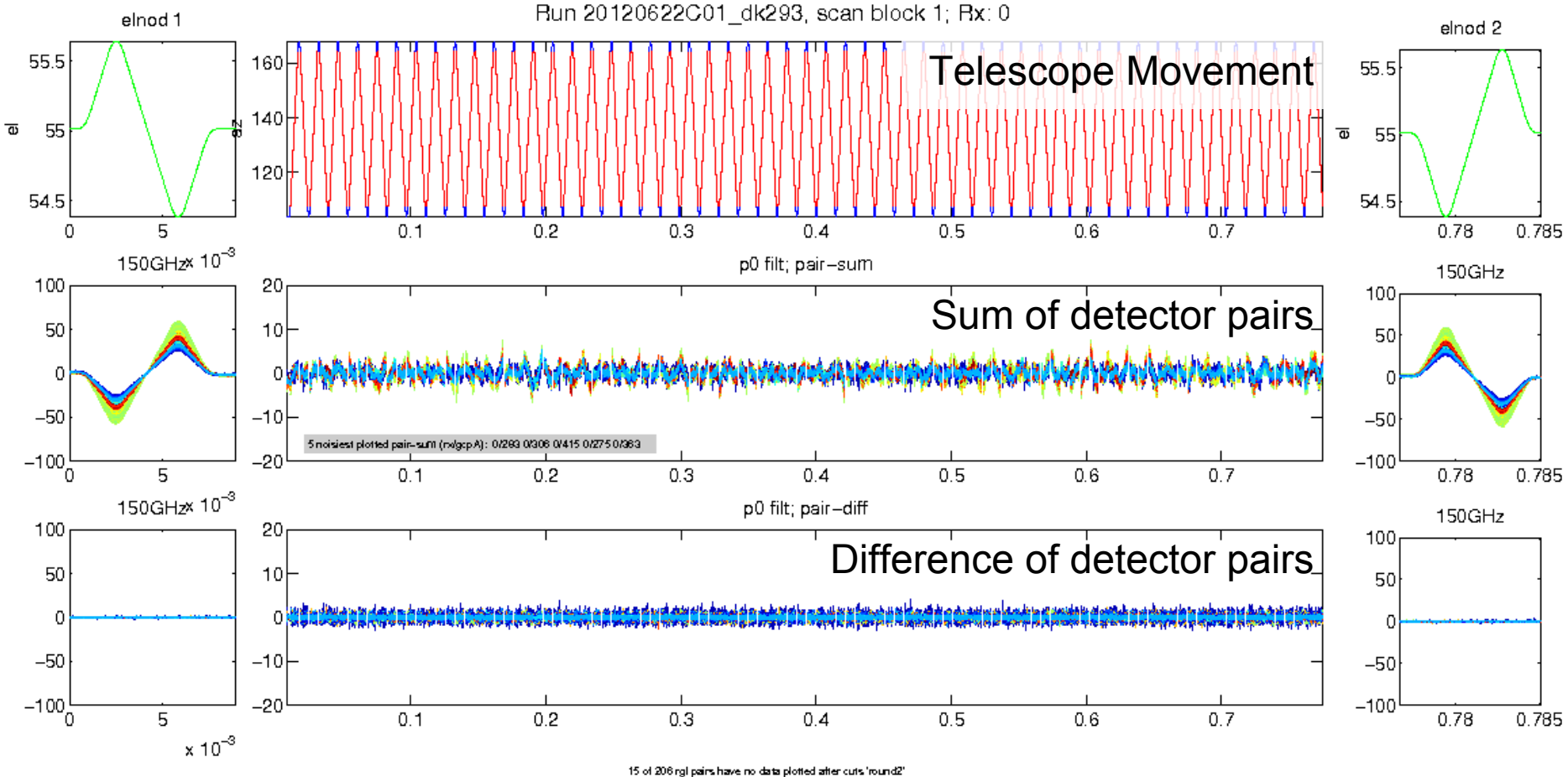


BA 3

hiep array

Raw Data - Perfect Weather

Time 50 mins

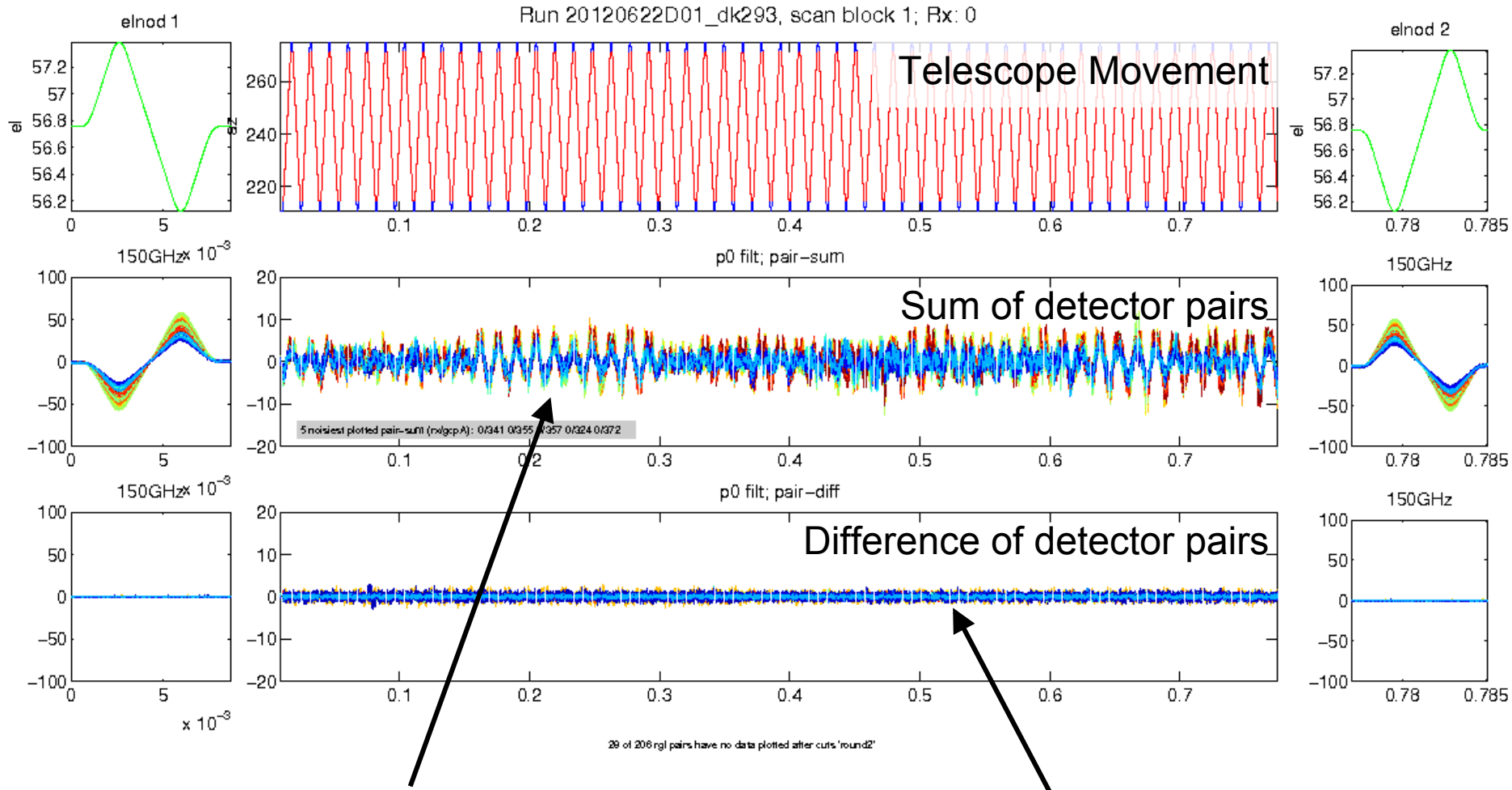


➤ Cover the whole field in 60 such scansets then start over at new boresight rotation

➤ Scanning modulates the CMB signal to freqs < 4 Hz

Raw Data - Worse Weather

Time 50 mins



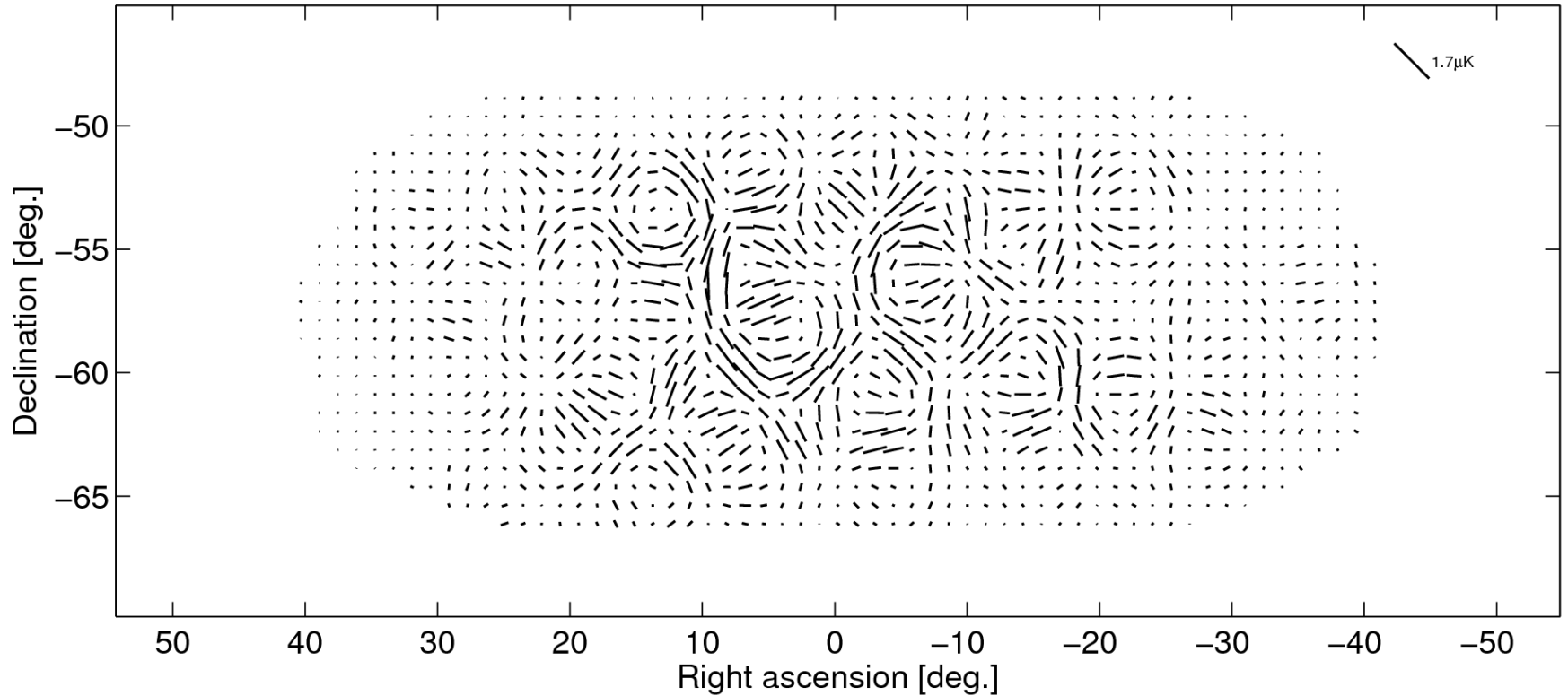
➤ Scanning over lumpy atmosphere
→ “clouds”

➤ Pair difference still clean
→ atmosphere is unpolarized

Total Polarization

BICEP2 total polarization signal

Scale: $1.7 \mu K$

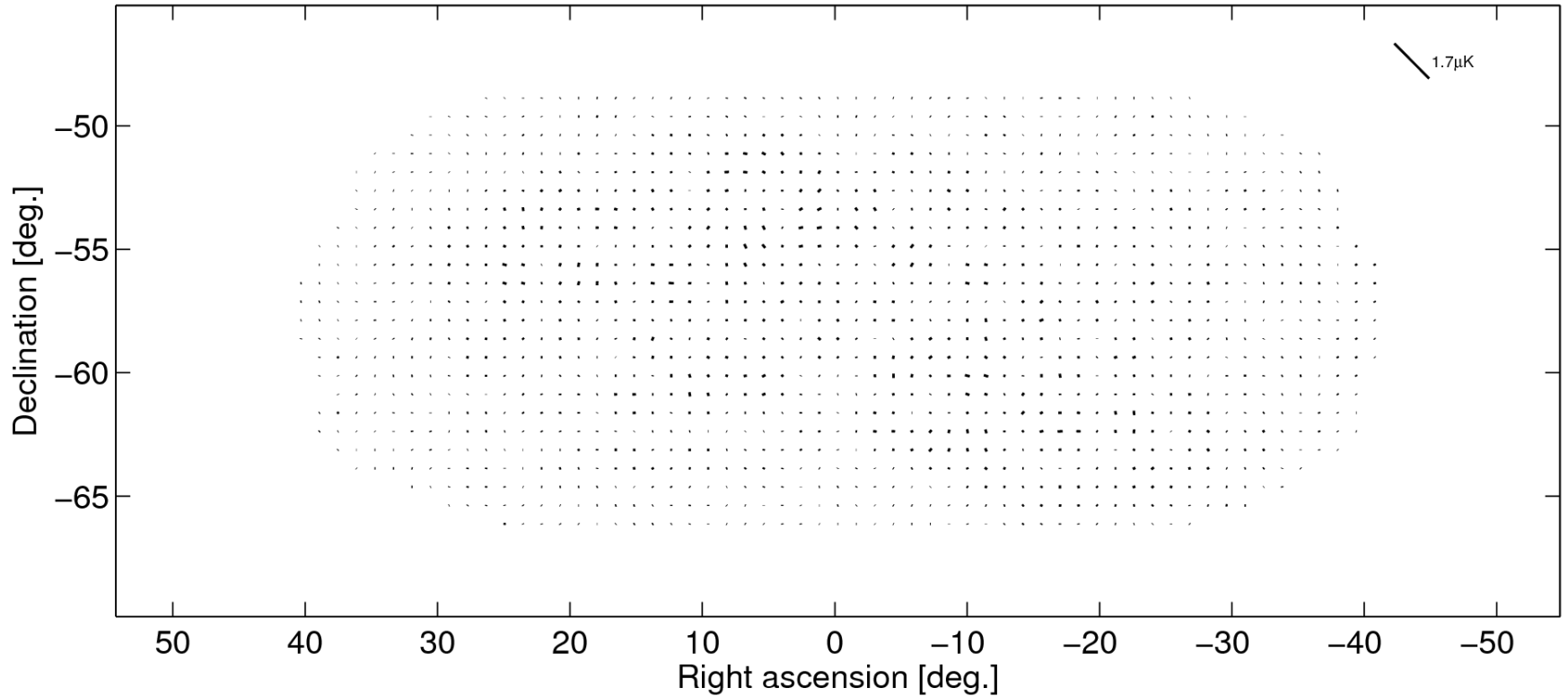


E-mode dominated pattern – no obvious curl component

B-mode Contribution

BICEP2 B-mode signal

Scale: $1.7 \mu K$

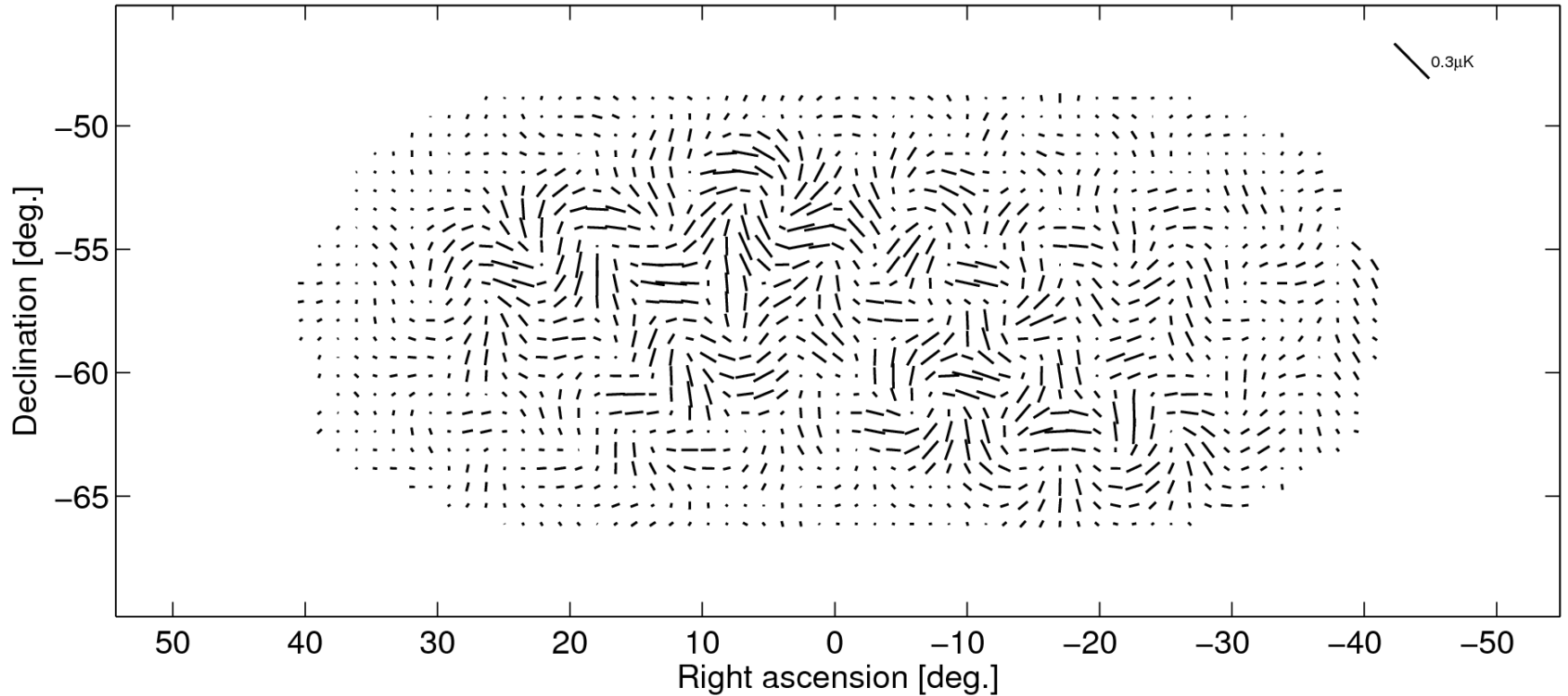


Apply purification operation which leaves only pure B-modes

B-mode Contribution

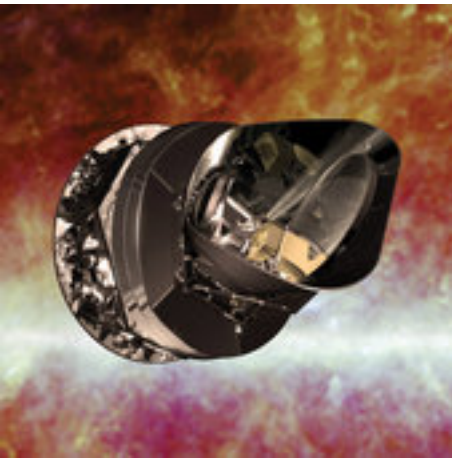
BICEP2 B-mode signal

Scale: $0.3 \mu K$

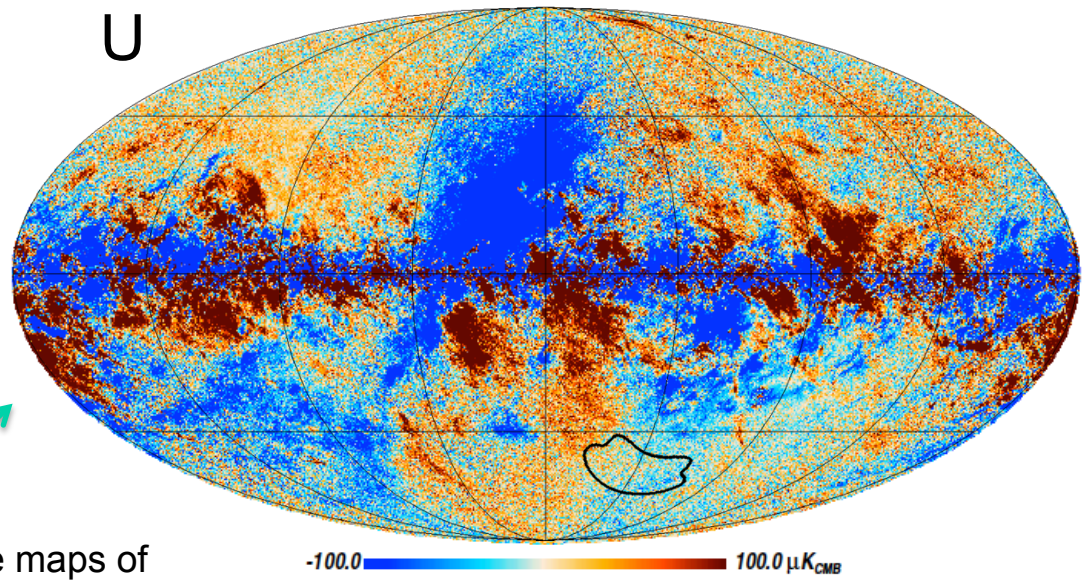
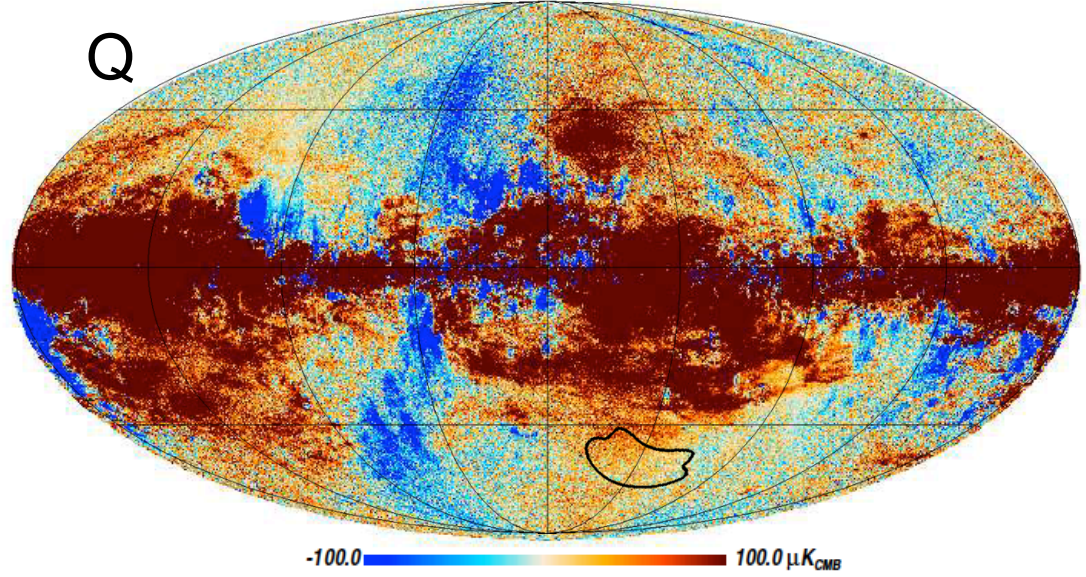


Zoom in by factor 6 – see “swirly” B-mode

Dust emission from our galaxy turns out to be brighter than expected...



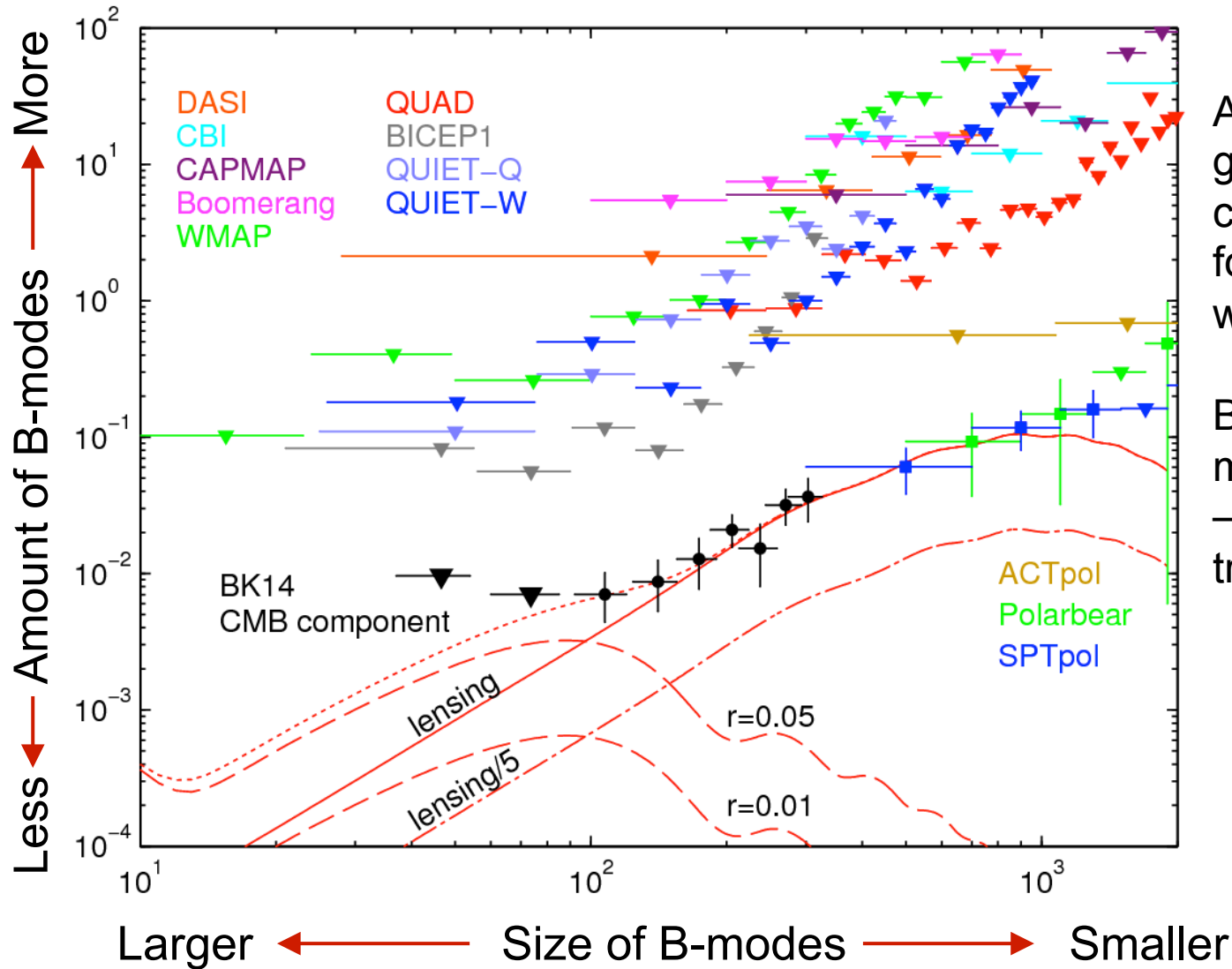
Planck was a billion dollar Euro/NASA space mission



All sky maps like maps of the Earth



So the Search Goes On...



After accounting for galactic dust there is currently no evidence for gravitational waves

But that doesn't mean they don't exist – just that we need to try harder!