

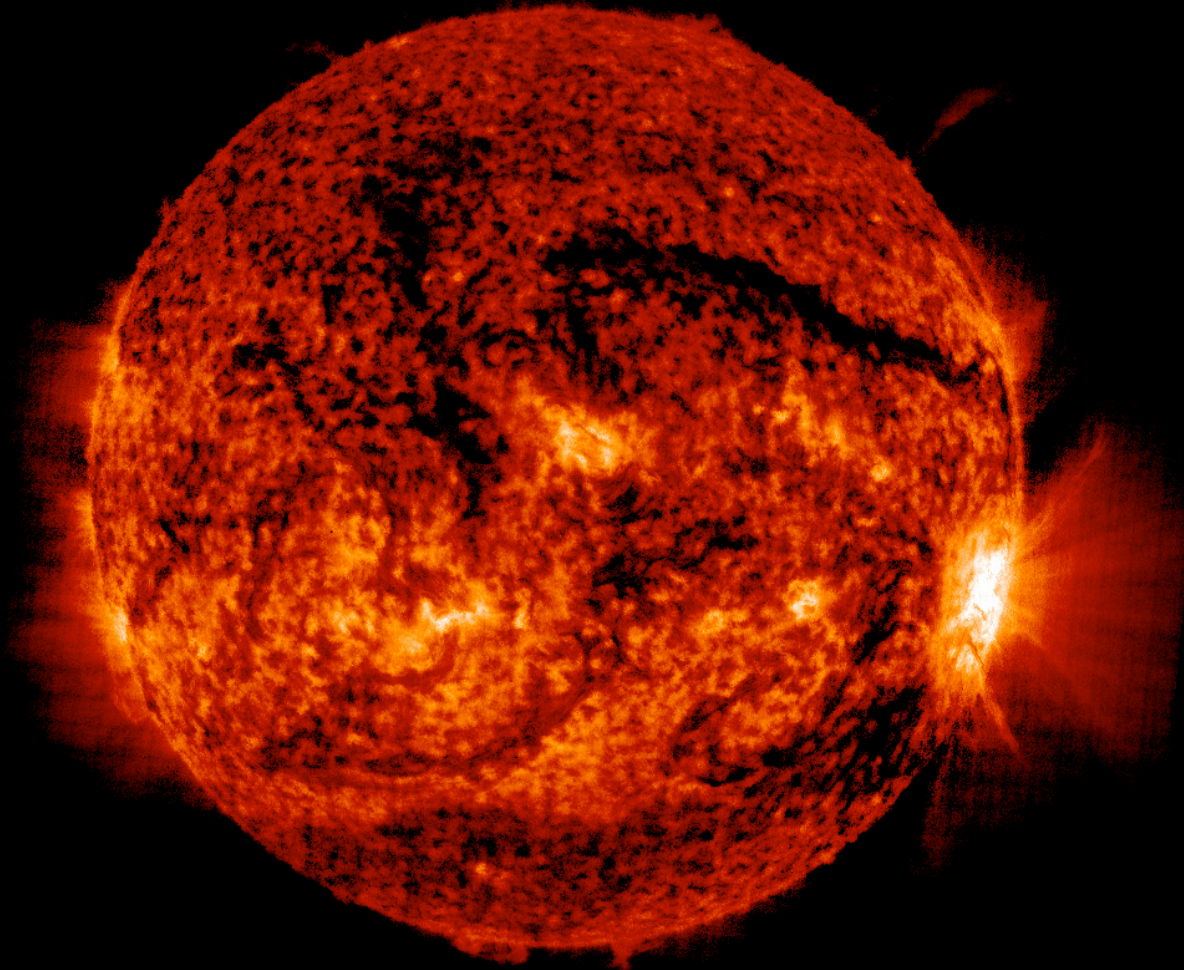


# Studying the Beginning of the Universe from the Bottom of the World



Clem Pryke – Cedar Astronomers – Feb 26 2022

# Our Sun is a Star

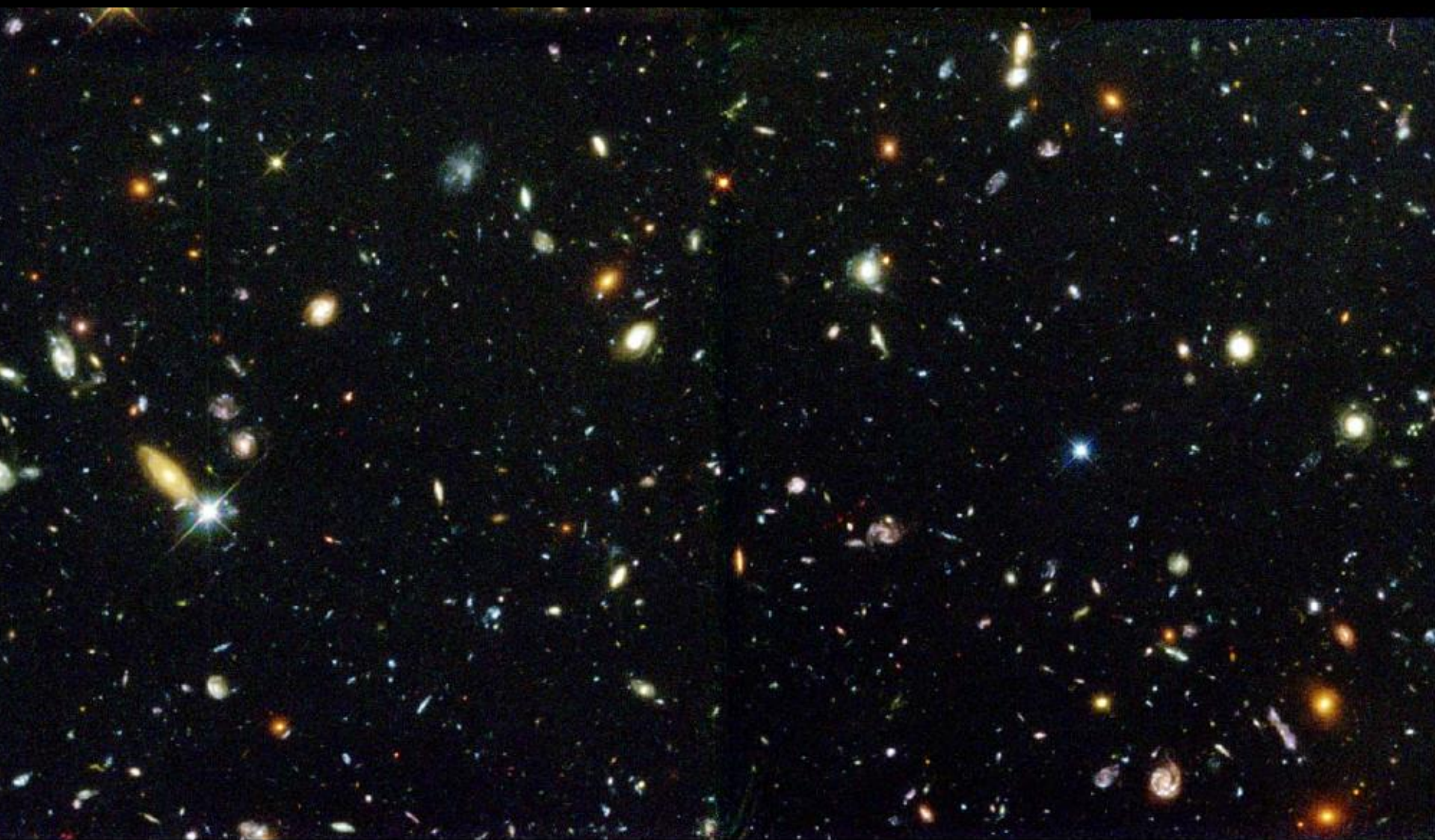


...Many stars make a galaxy...



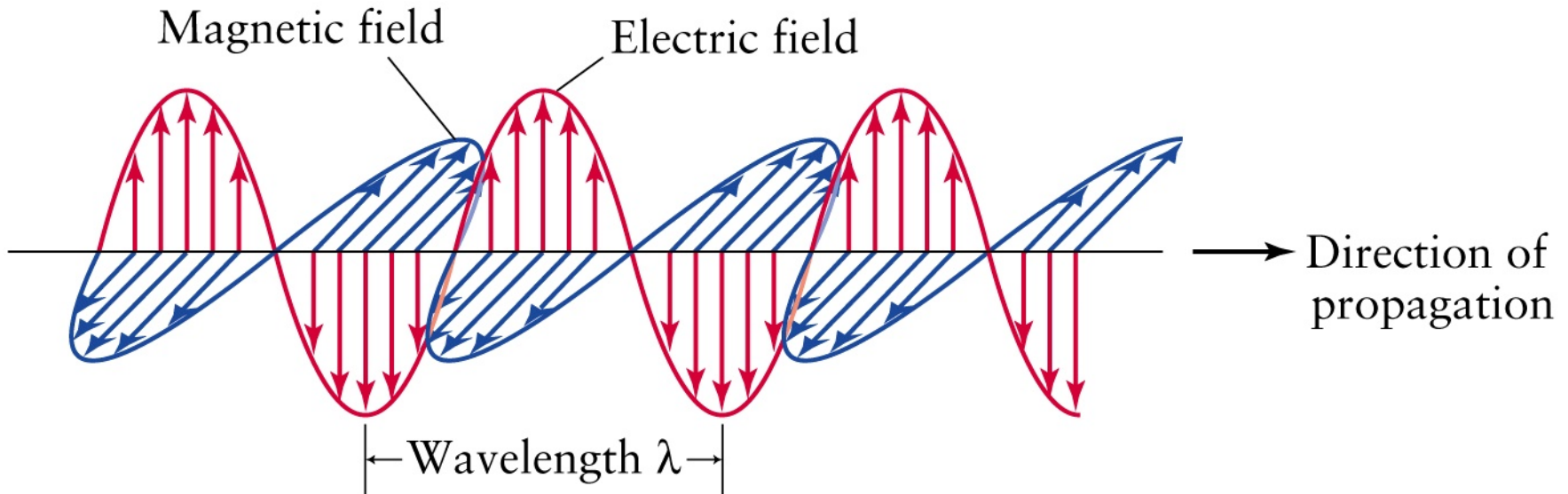
(A nearby galaxy similar to ours)

...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

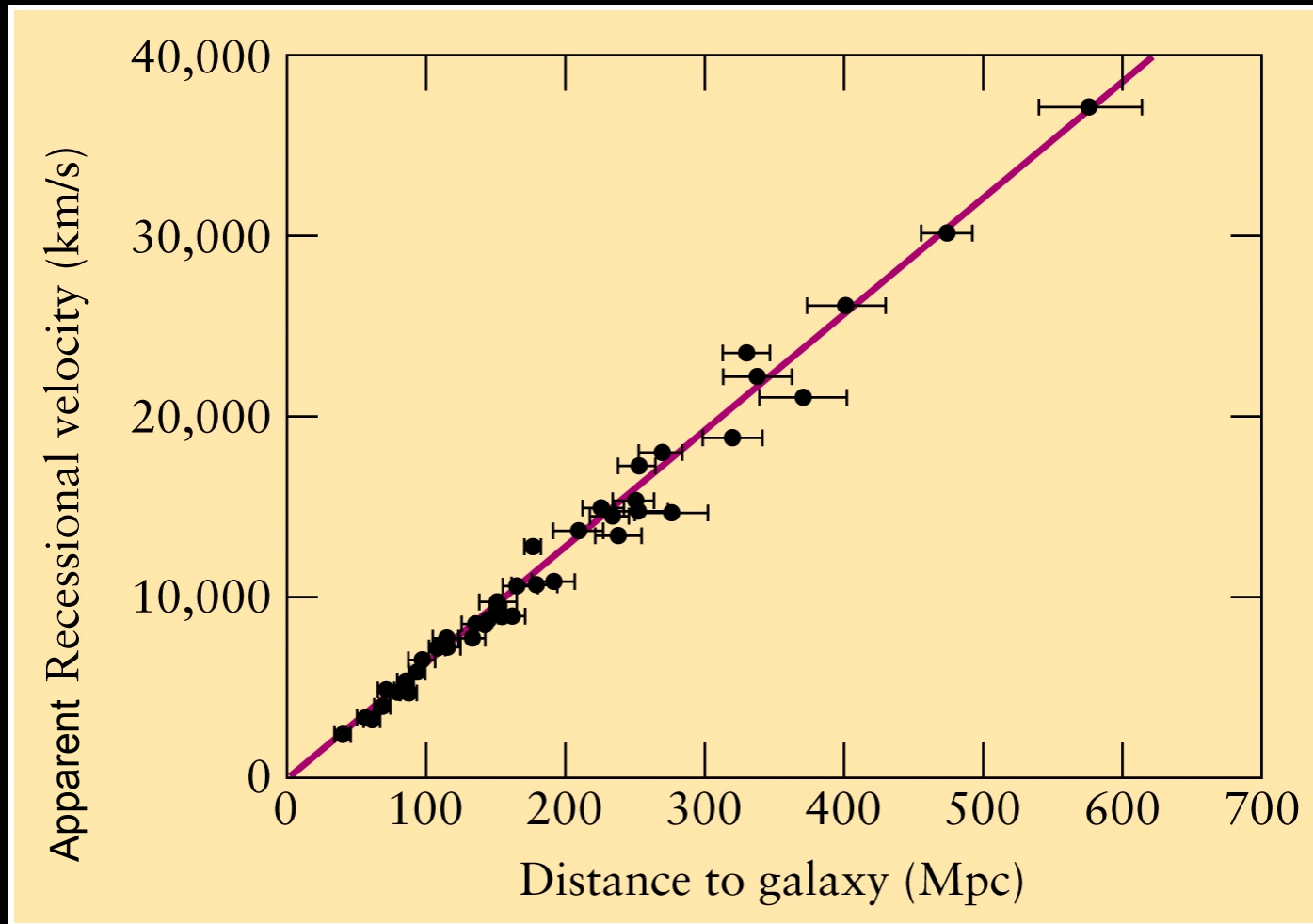
# Edwin Hubble “Observing” Distant Galaxies



Mount Wilson Observatory  
(LA) 1920's



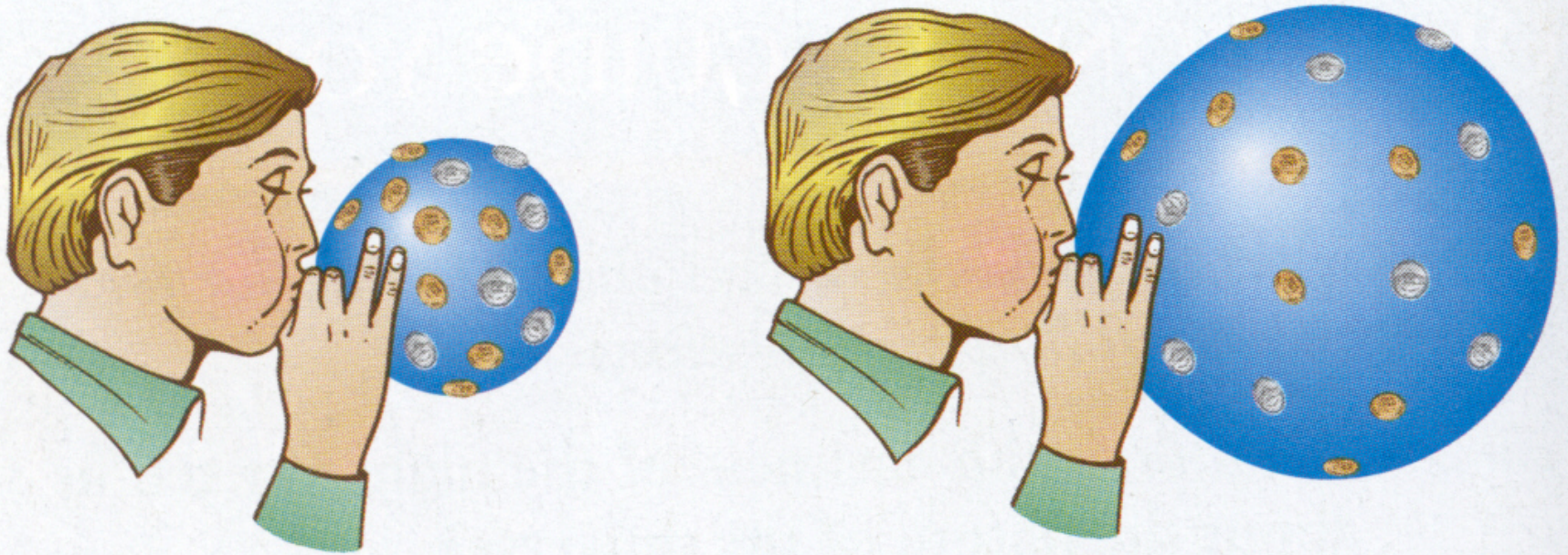
# Hubble Diagram



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

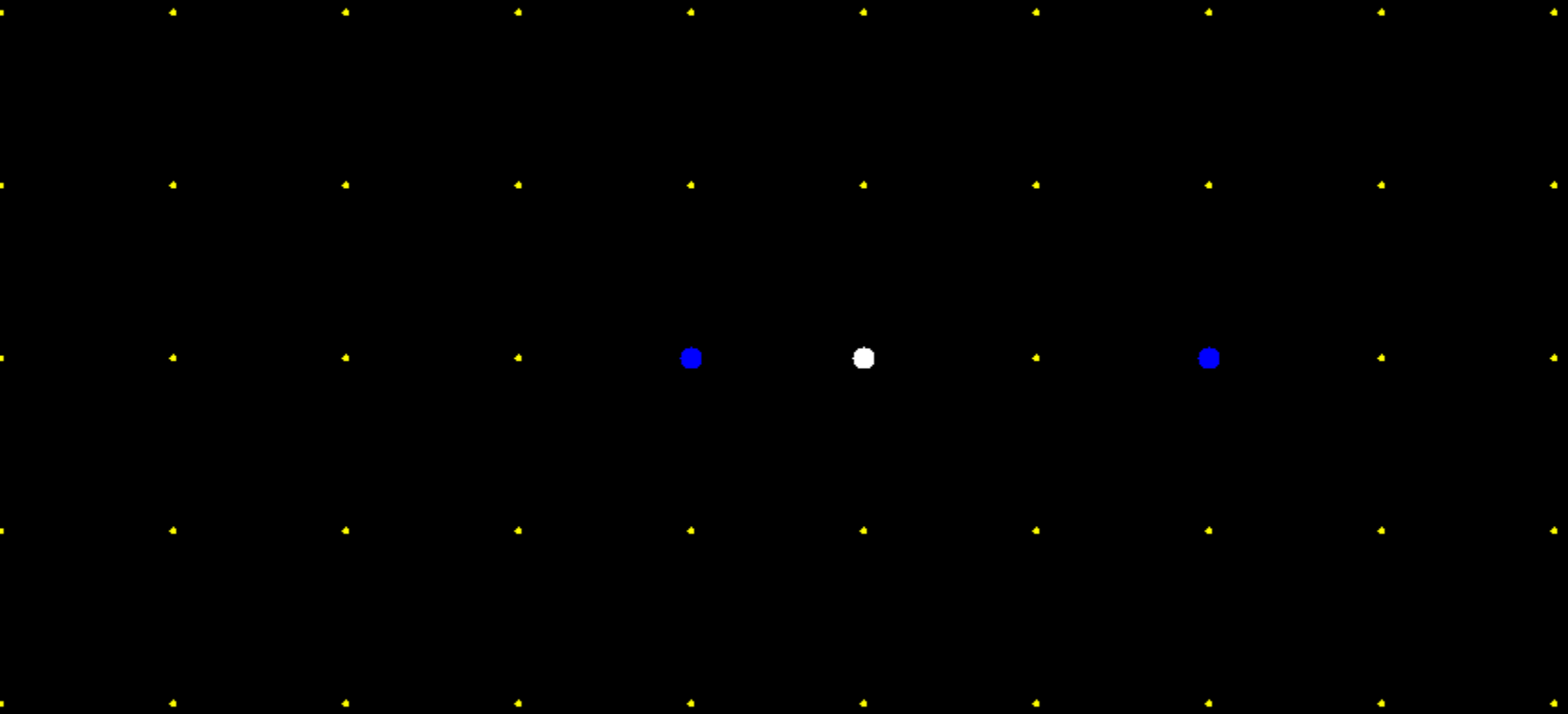
Are we the most unpopular place in the entire Universe?!

# 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



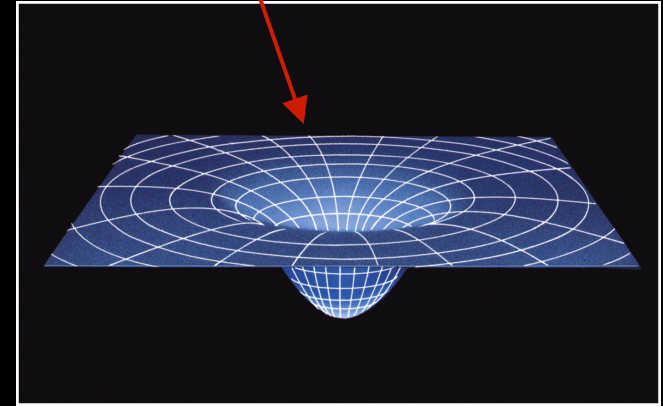
- Light rays stretch with the Universe – called “redshift”
- We see the more distant Universe as it was long ago – and redder

# 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)

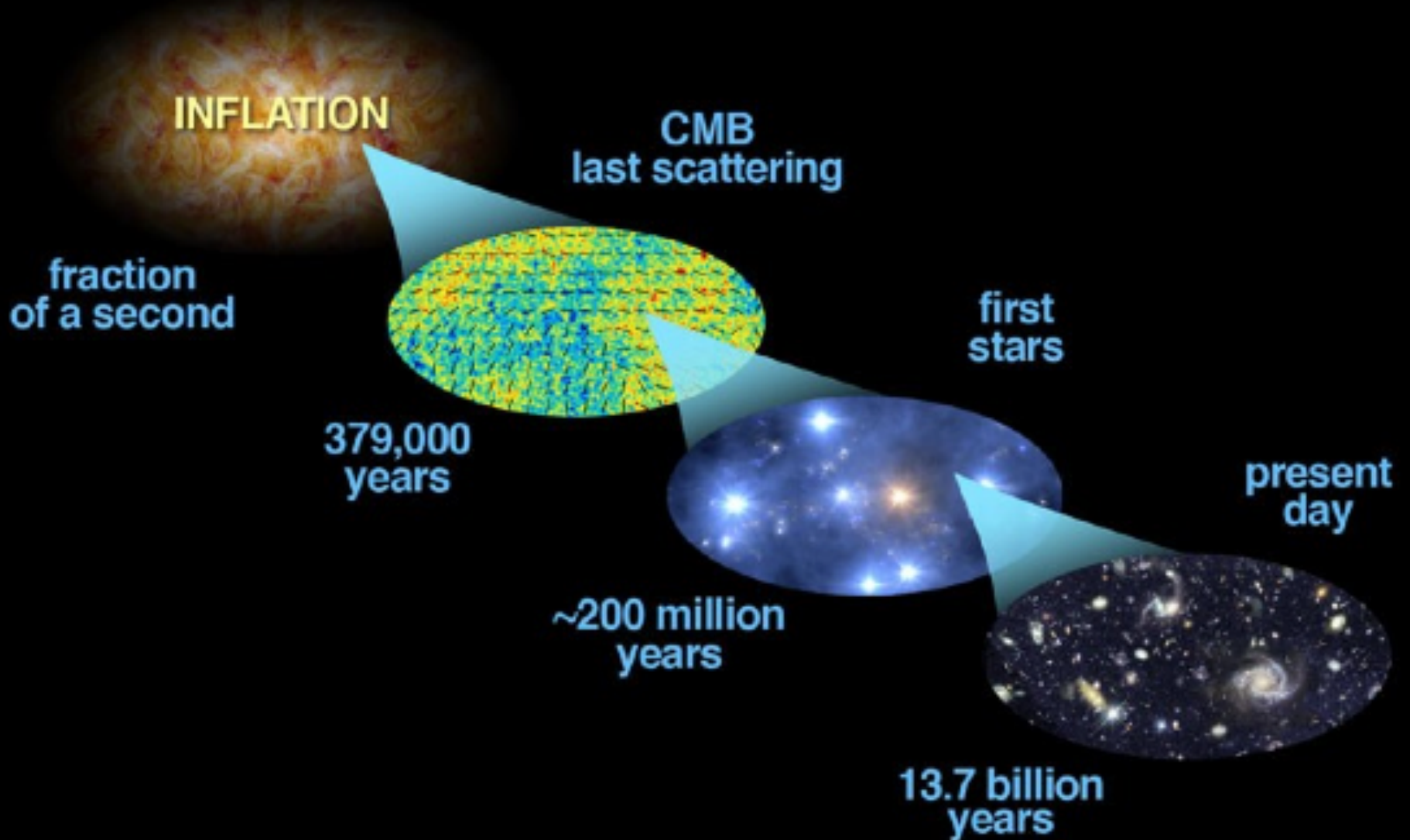
3) We can see the glow from that time!  
*The Cosmic Microwave Background*  
(Penzias & Wilson, 1964)



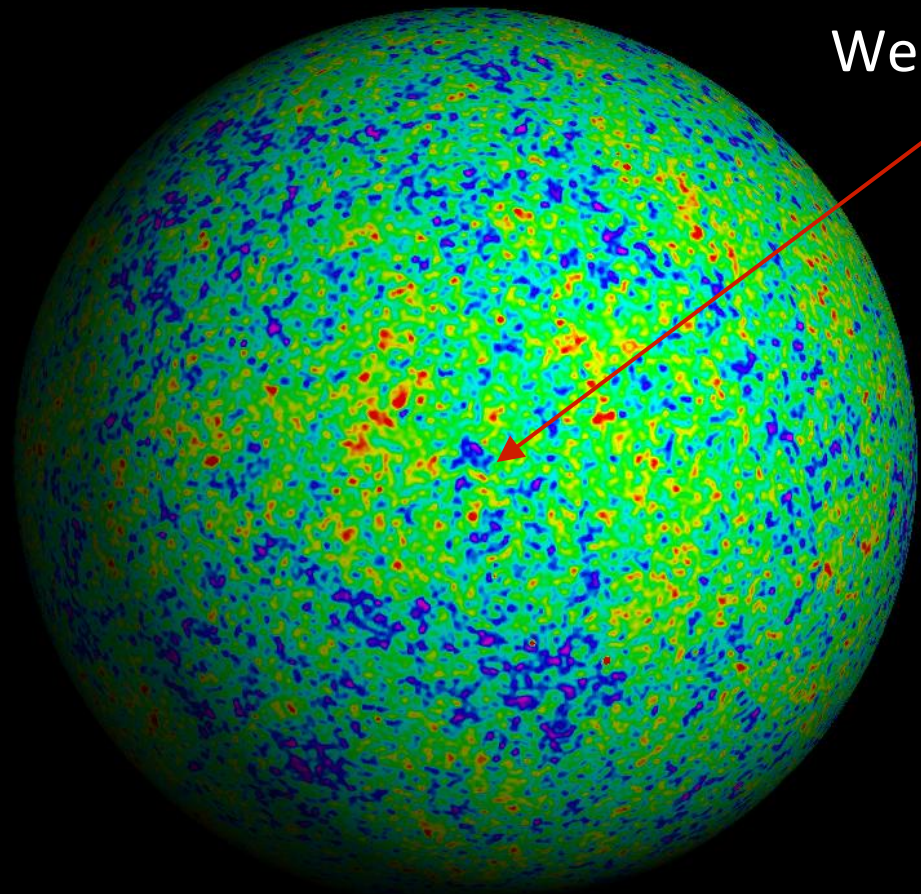
Bob Wilson & Arno Penzias  
1978 Nobel Prize

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

# Telescopes are time machines!



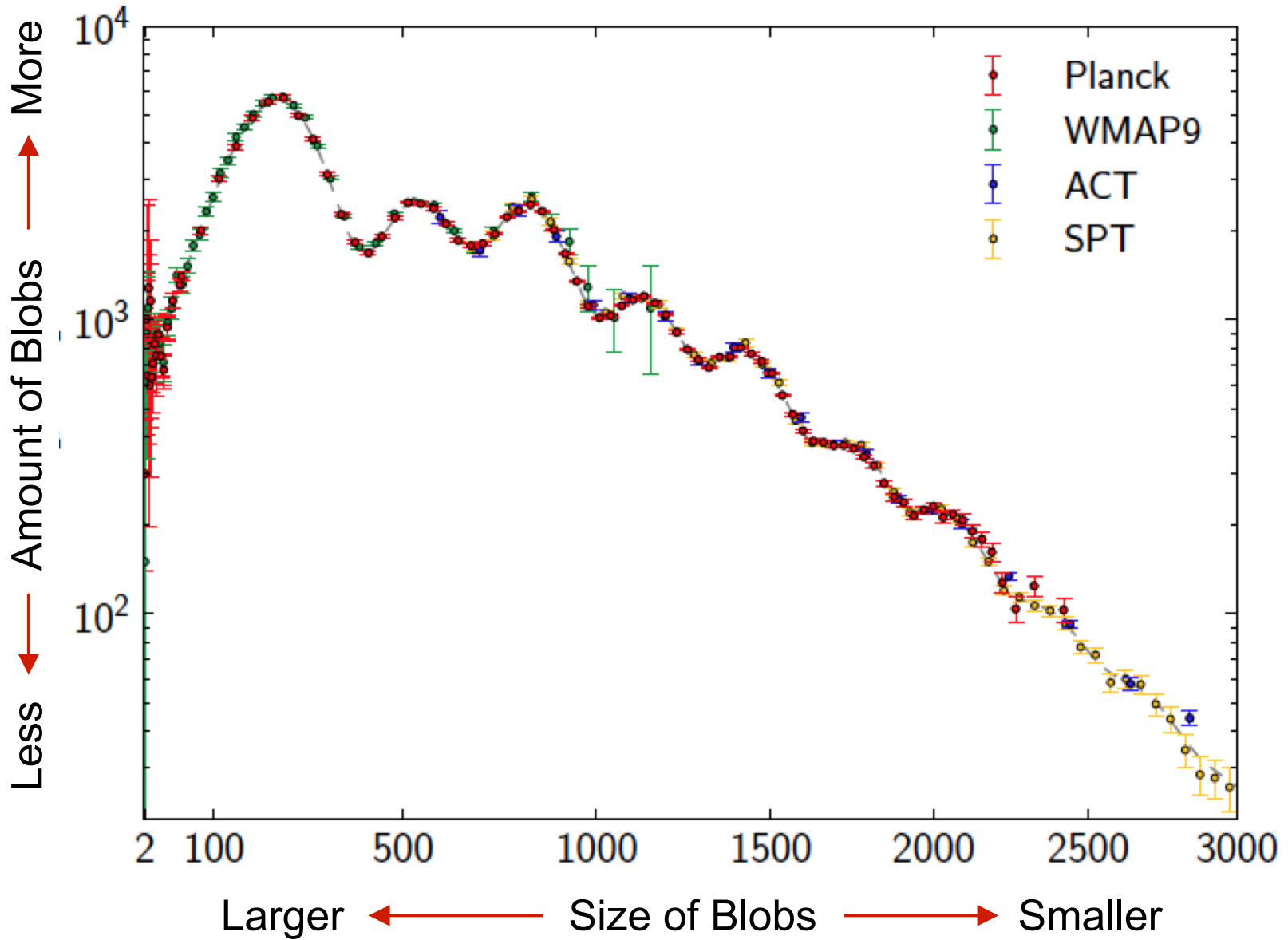
# All Sky Map of the Cosmic Microwave Background



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

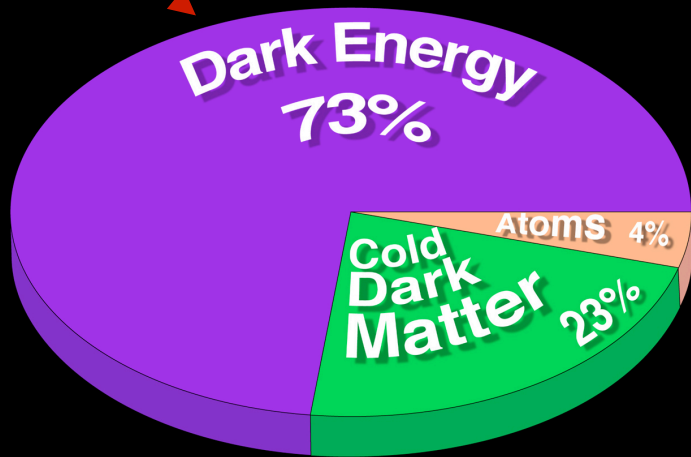
# “Lump Sorter” Plot



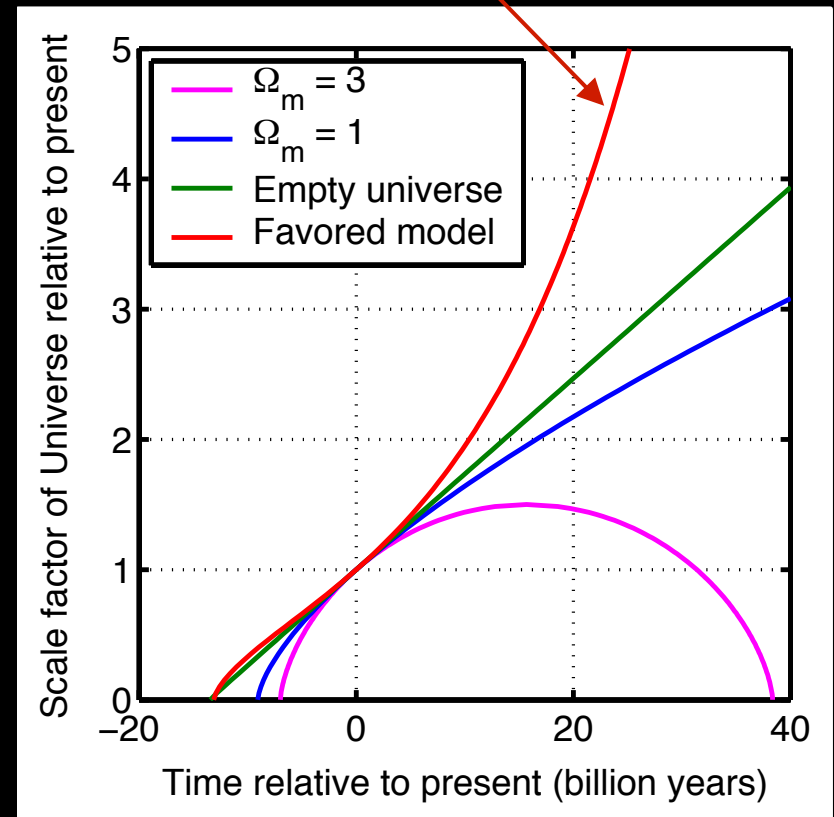


# Triumphant/Embarrassing Cosmology

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

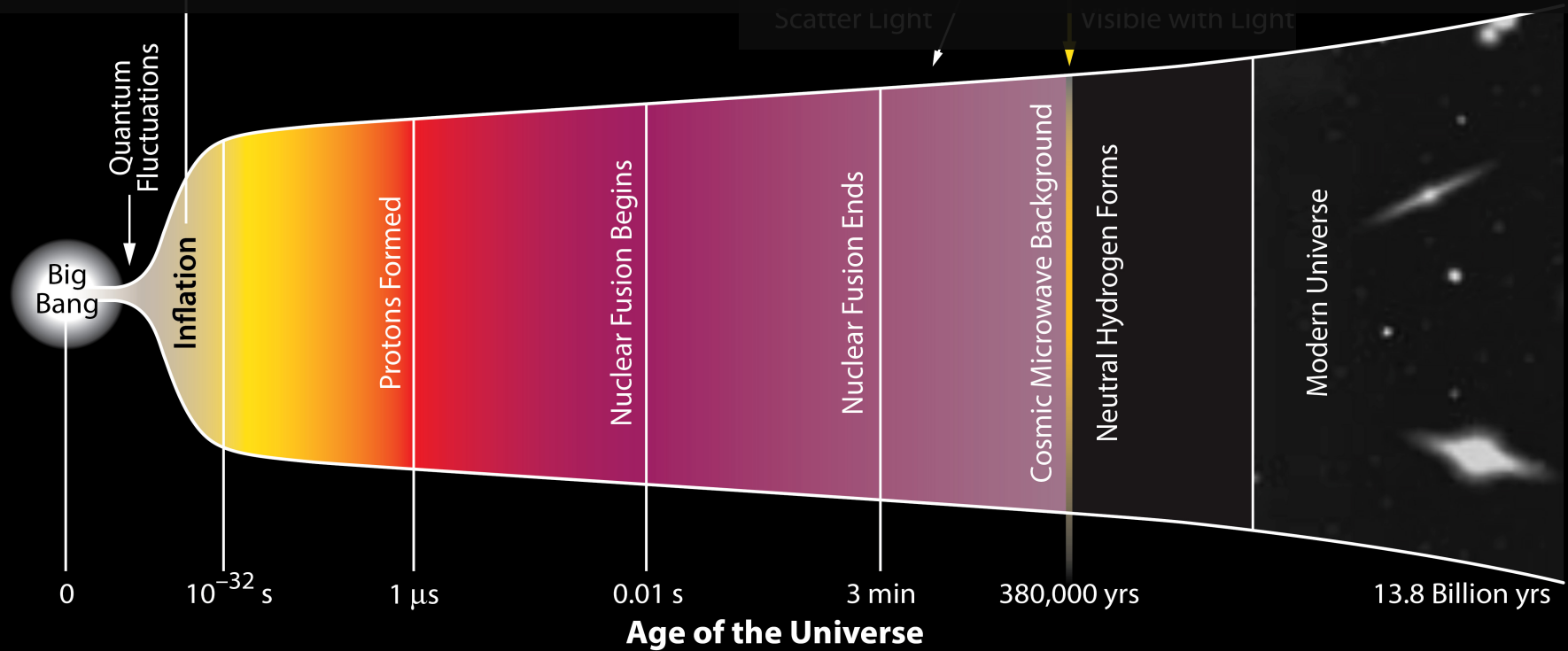


Alan Guth

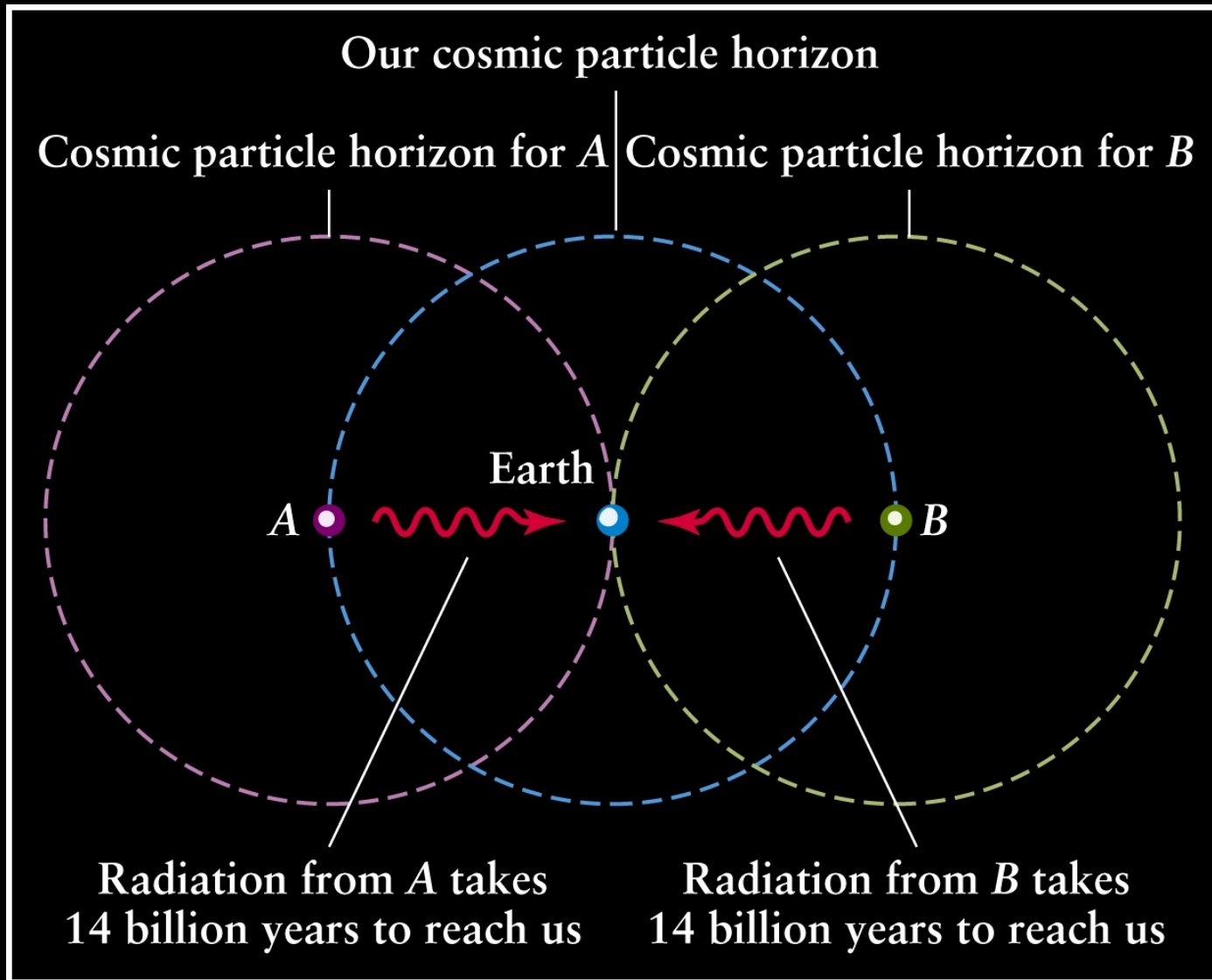


Andrei Linde

Radius of the Visible Universe

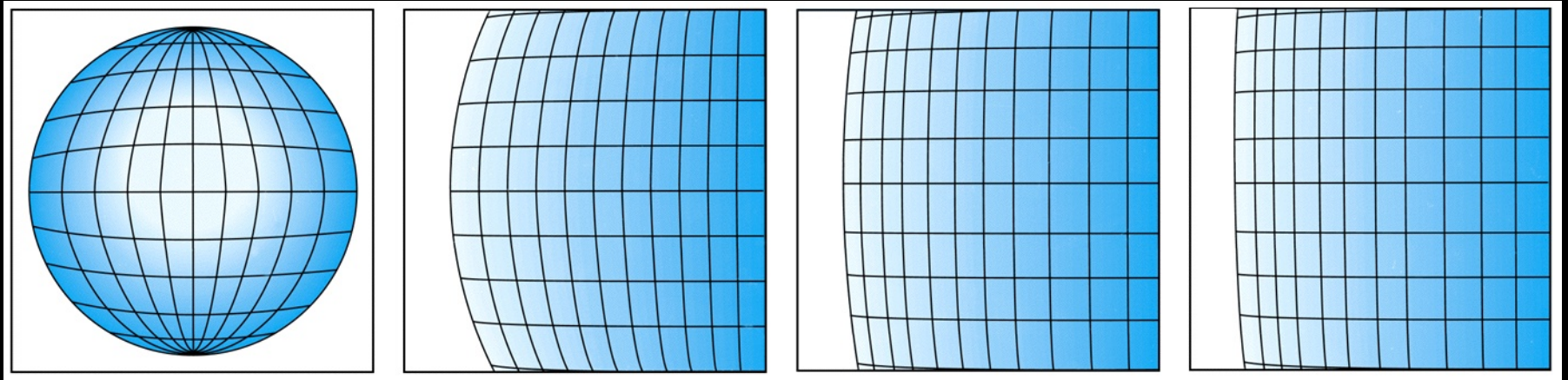


# Inflation solves the “Horizon Problem”



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

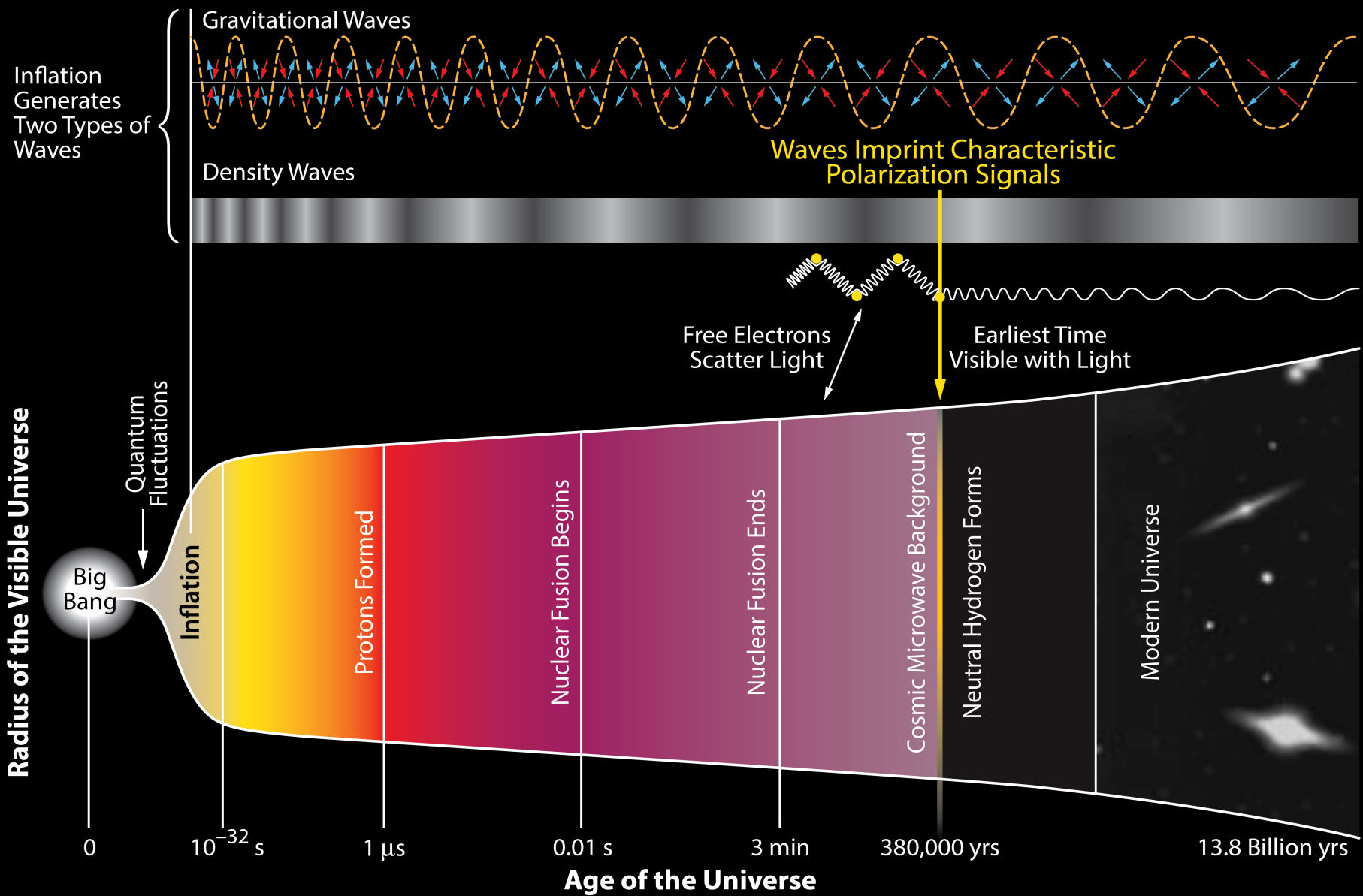
# Inflation solves the “Flatness Problem”



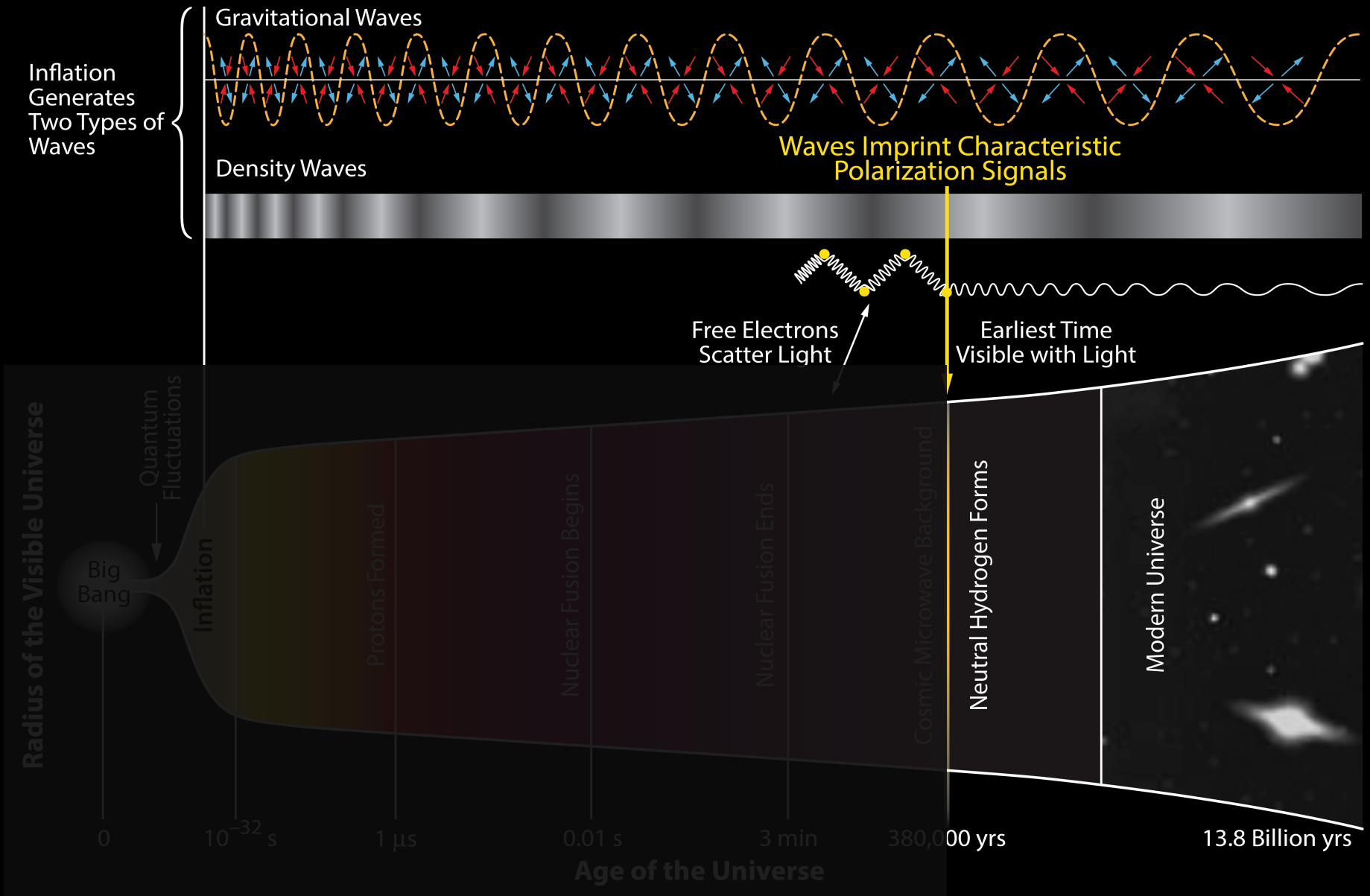
→ Inflation... →

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!

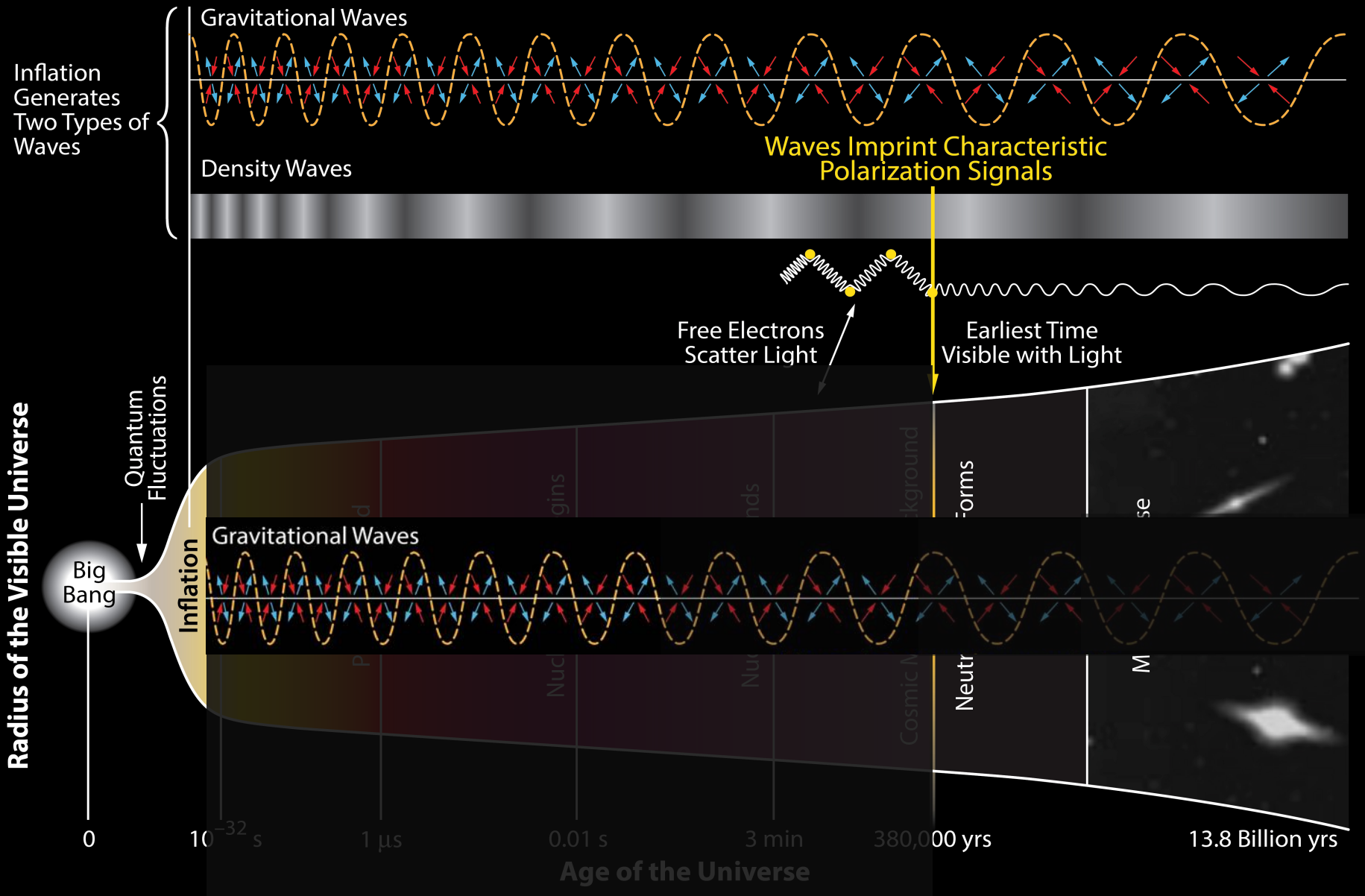
# History of the Universe



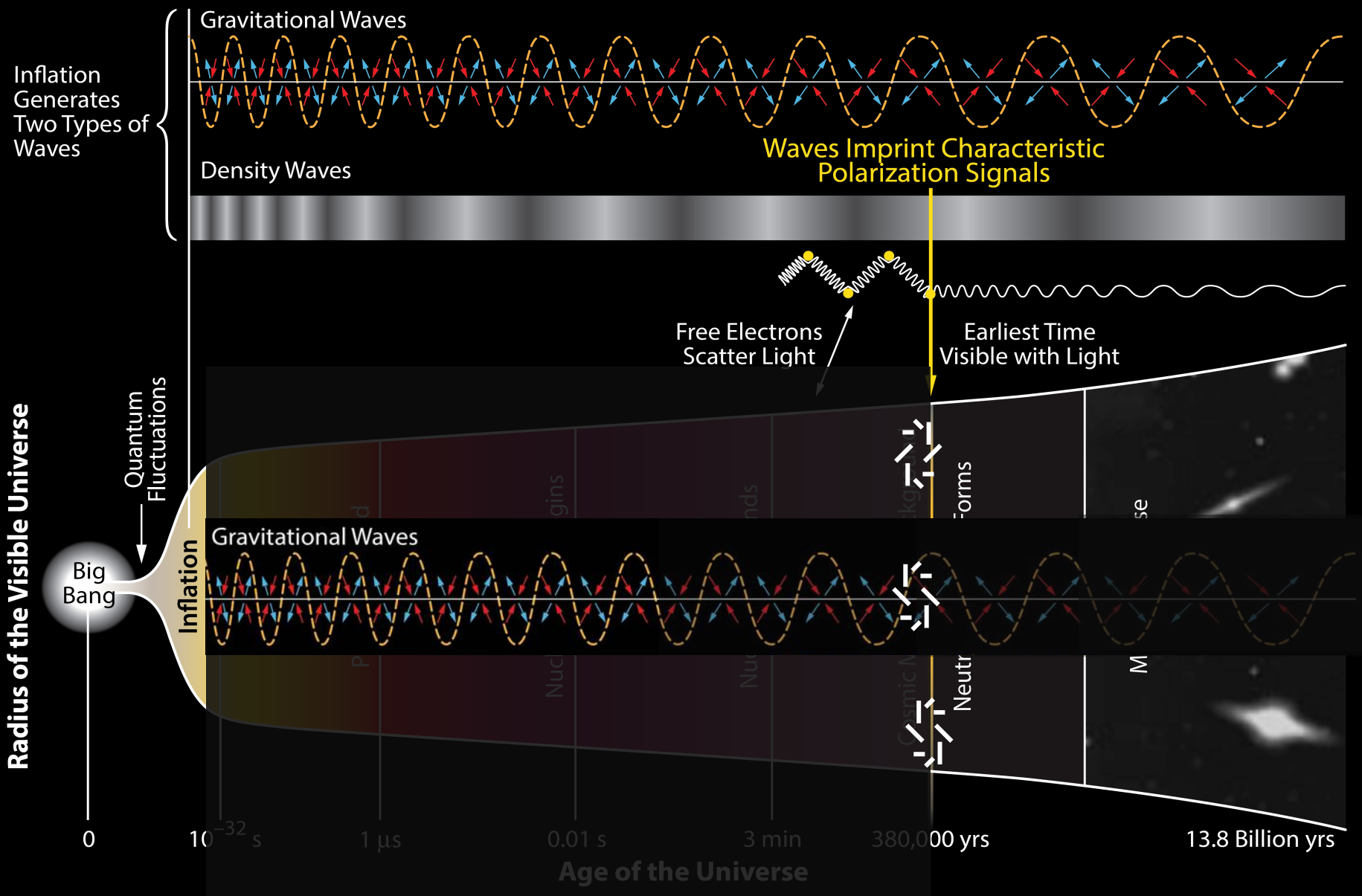
# History of the Universe



# History of the Universe

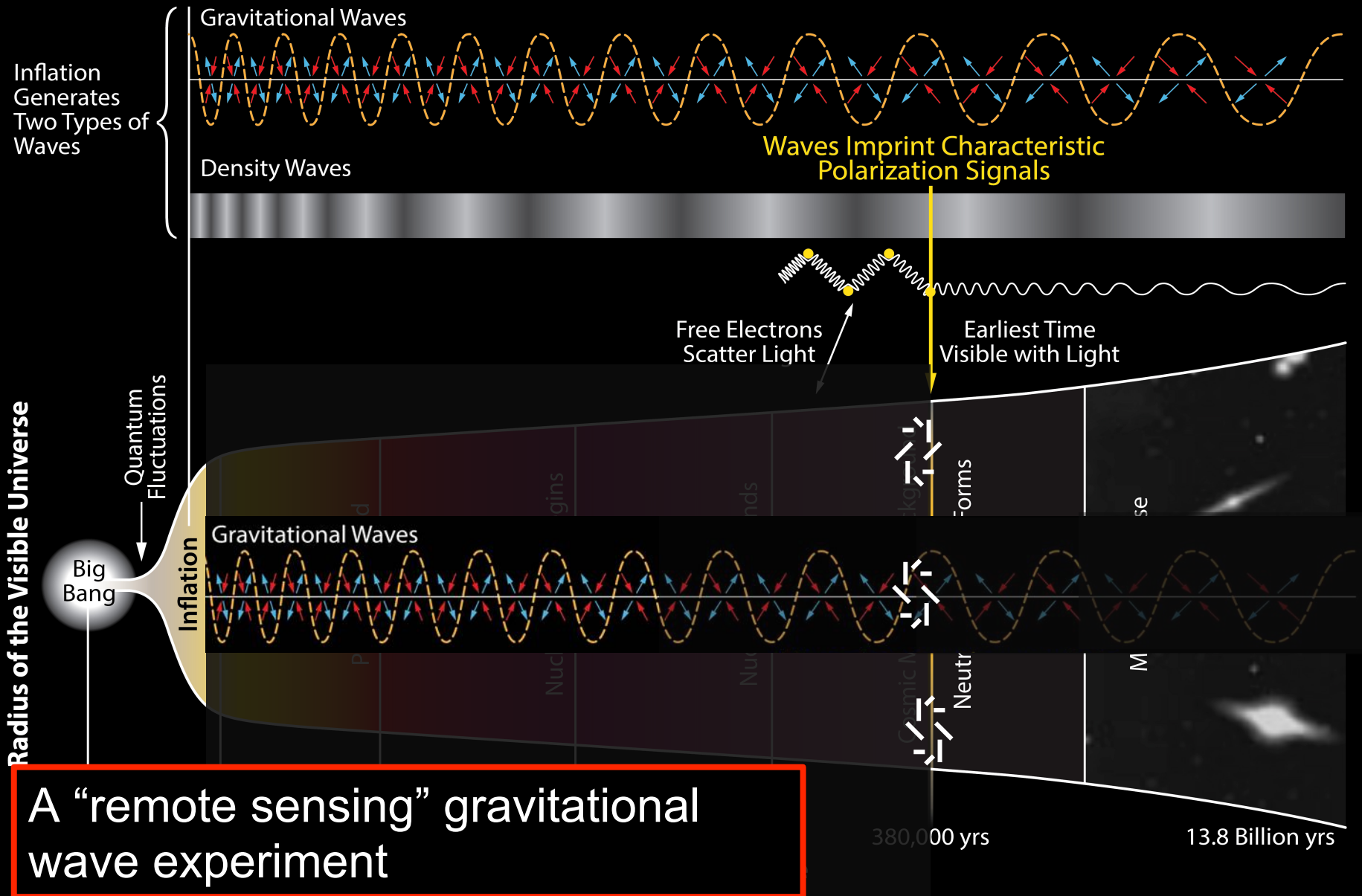


# History of the Universe

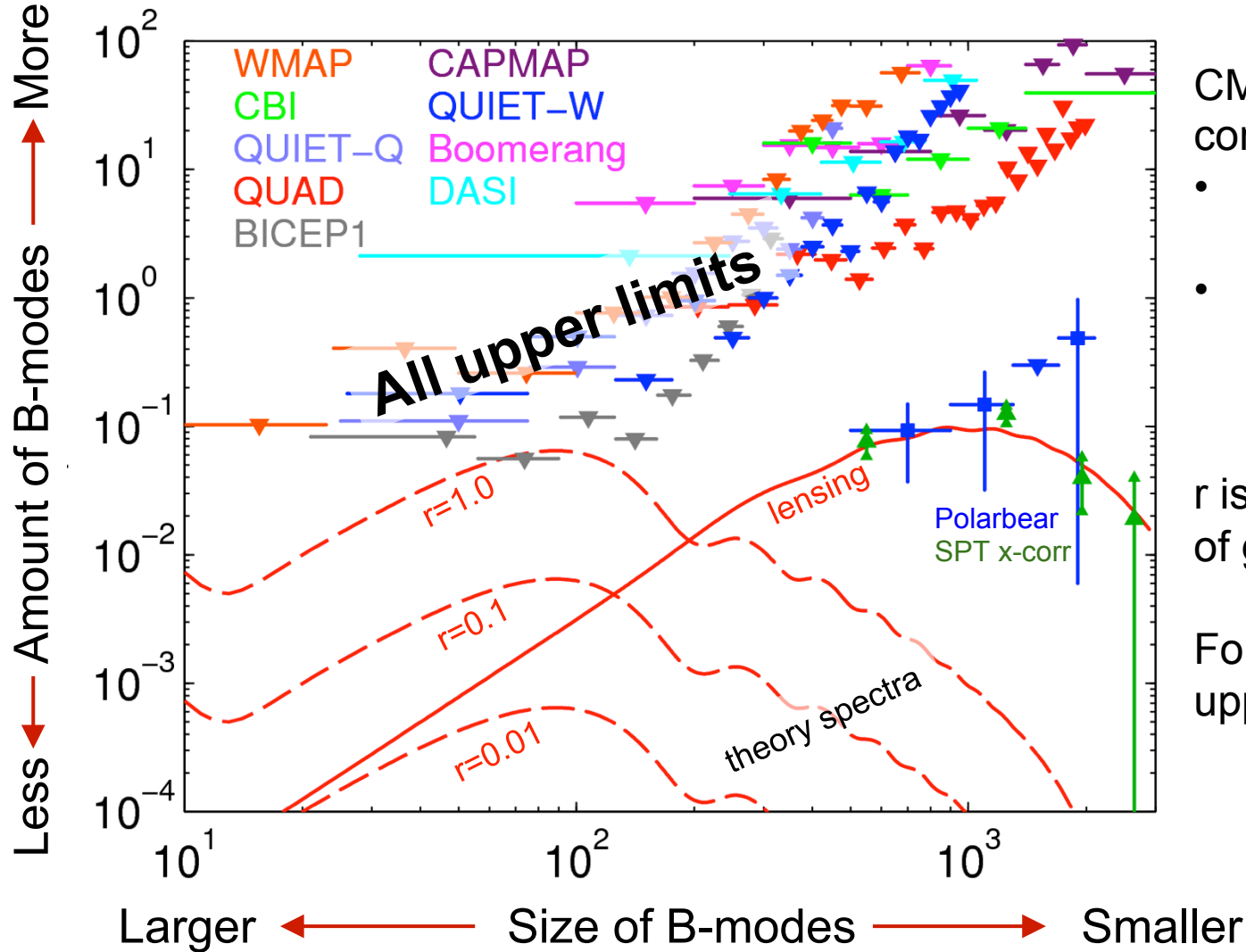




# History of the Universe



# 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

For a long time only upper limits...

# Inflation is controversial

## Inflationary Paradigm after Planck 2013

Alan H. Guth,<sup>1</sup> David I. Kaiser,<sup>1</sup> and Yasunori Nomura<sup>2</sup>

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

<sup>2</sup>*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,<sup>1,2</sup> Paul J. Steinhardt,<sup>3</sup> and Abraham Loeb<sup>4</sup>

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

<sup>2</sup>*Rutgers University, New Brunswick, NJ 08901, USA*

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

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

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

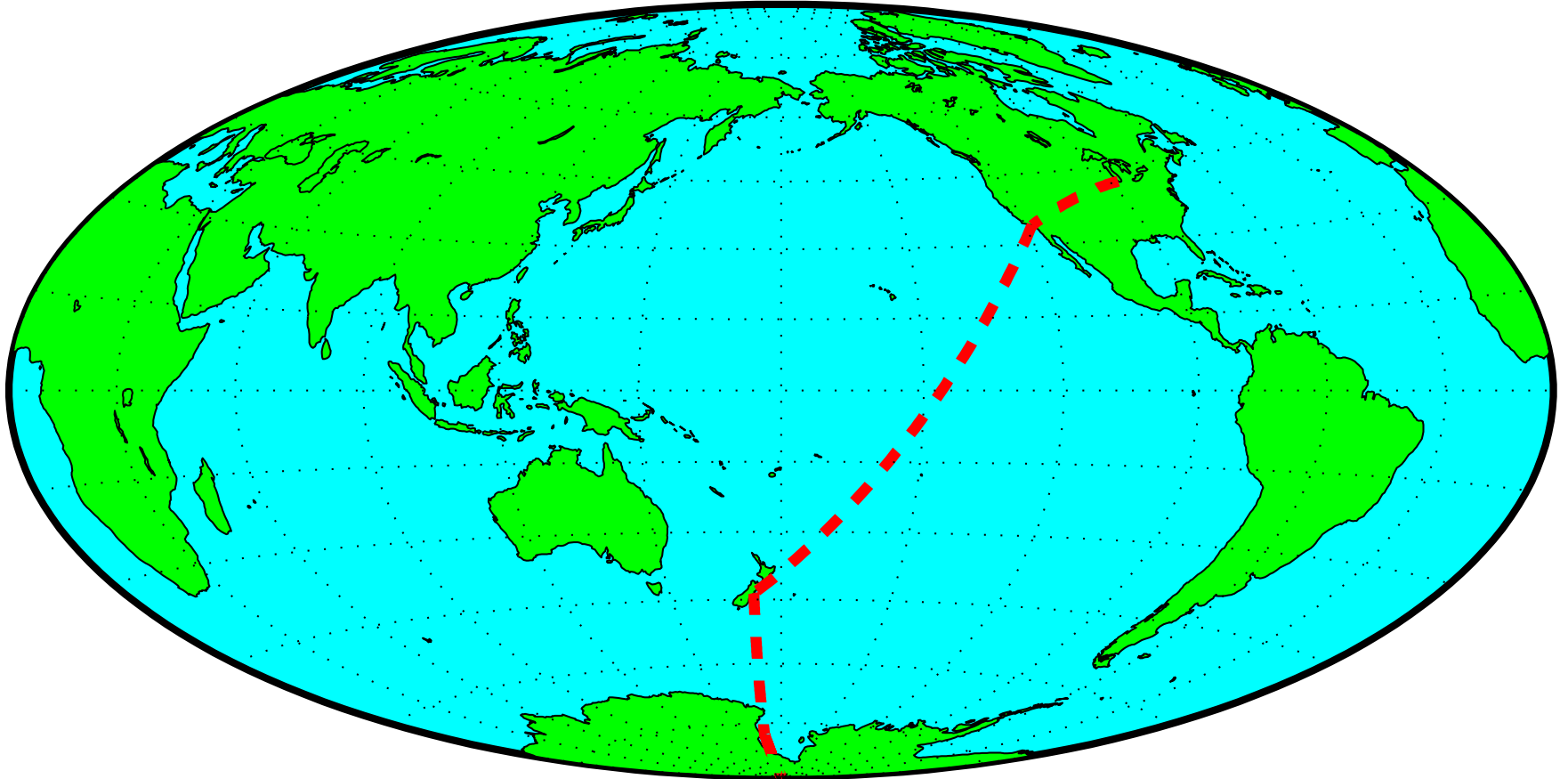




UNIVERSITY OF  
TORONTO

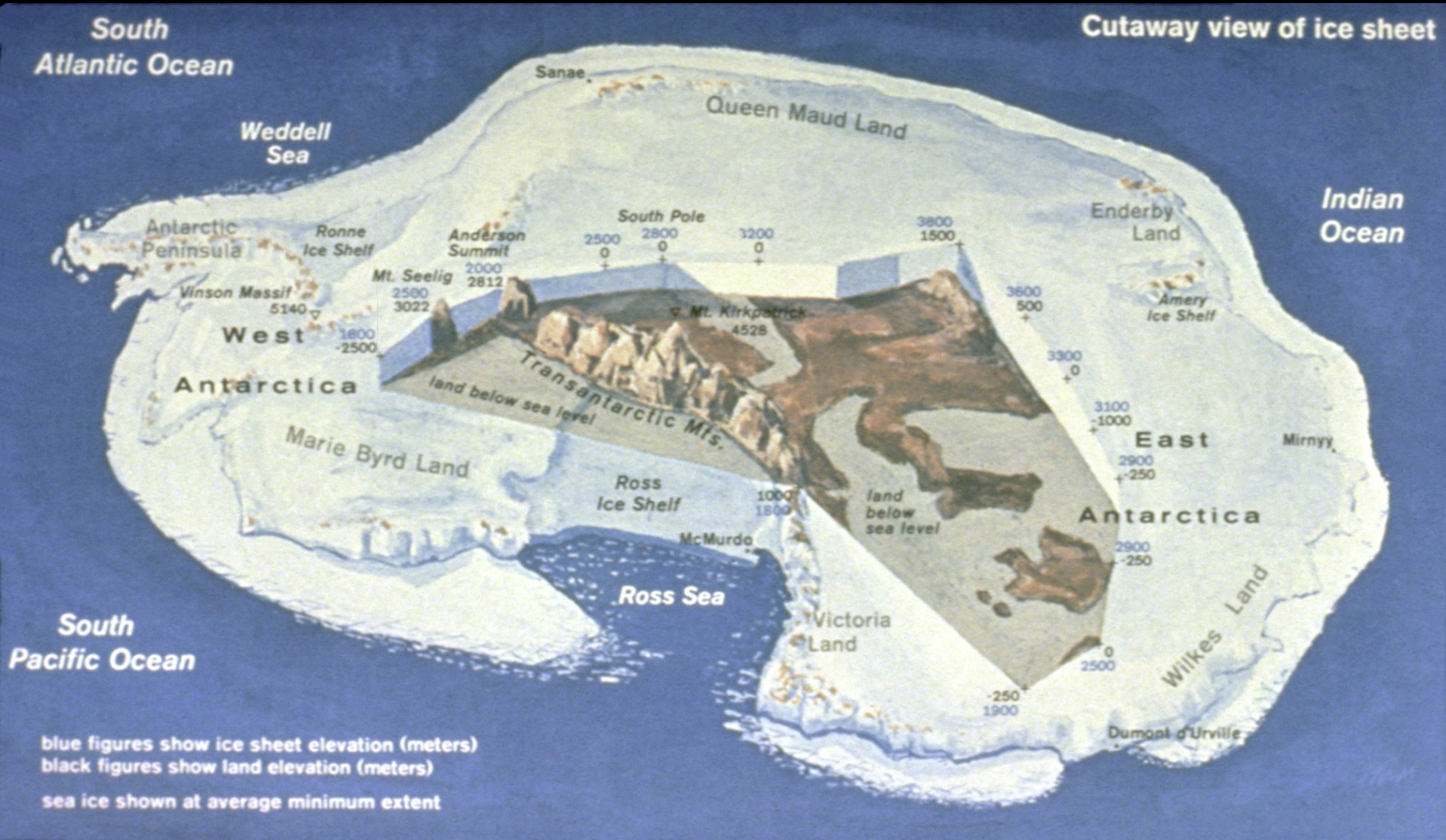


# Journey to the South Pole



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

# Antarctic Continent



Larger than the US – Ice sheet two miles thick!



# Christchurch New Zealand – Clothing Warehouse





# Big Program!



# Arrival in Antarctica



# McMurdo – base on the coast



# On to the Pole – over the Transantarctic Mountains



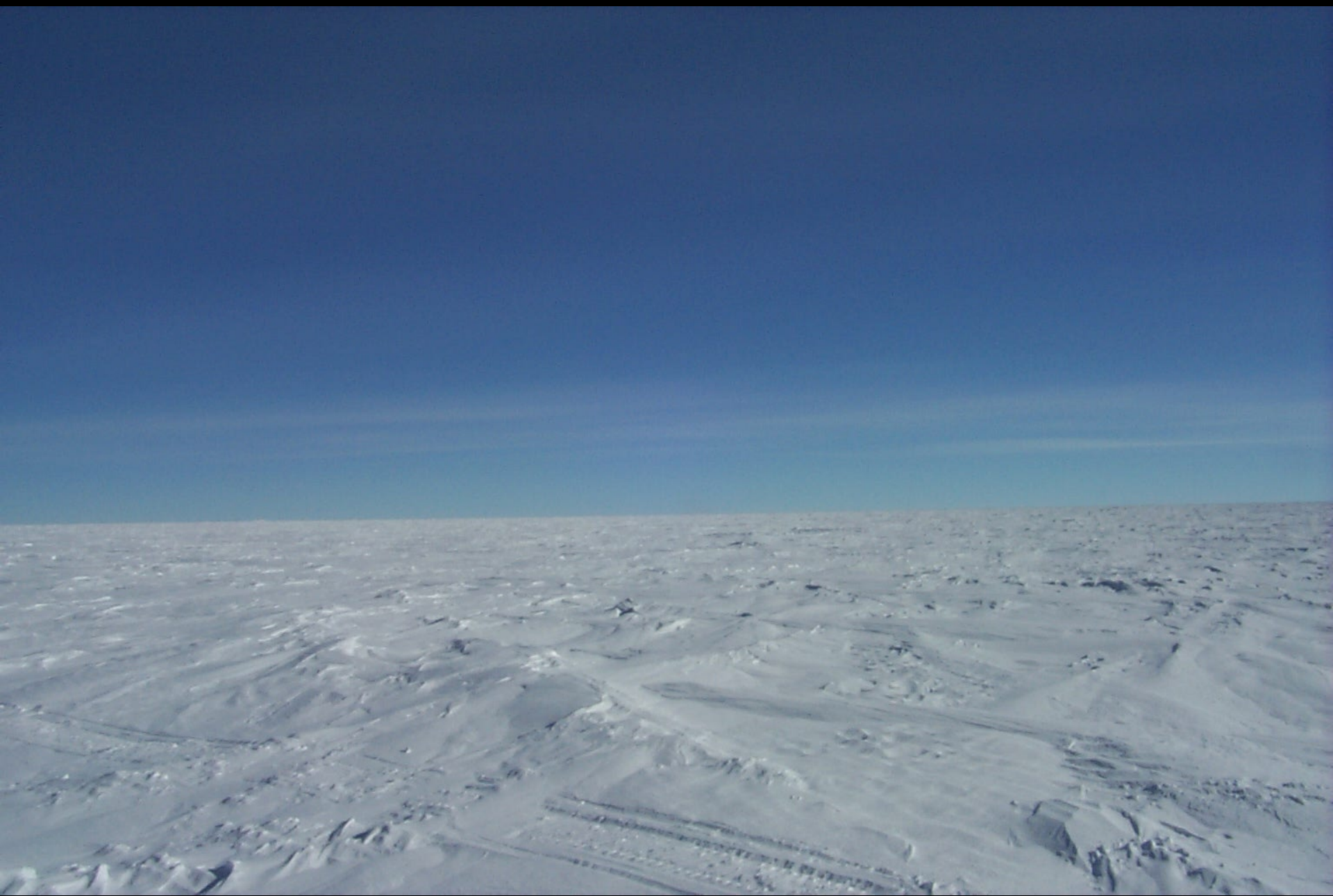
# Unloading at Pole



# The Actual South Pole



**Nothing Out There!**



# Why do this at the Pole?

## South Pole CMB telescopes

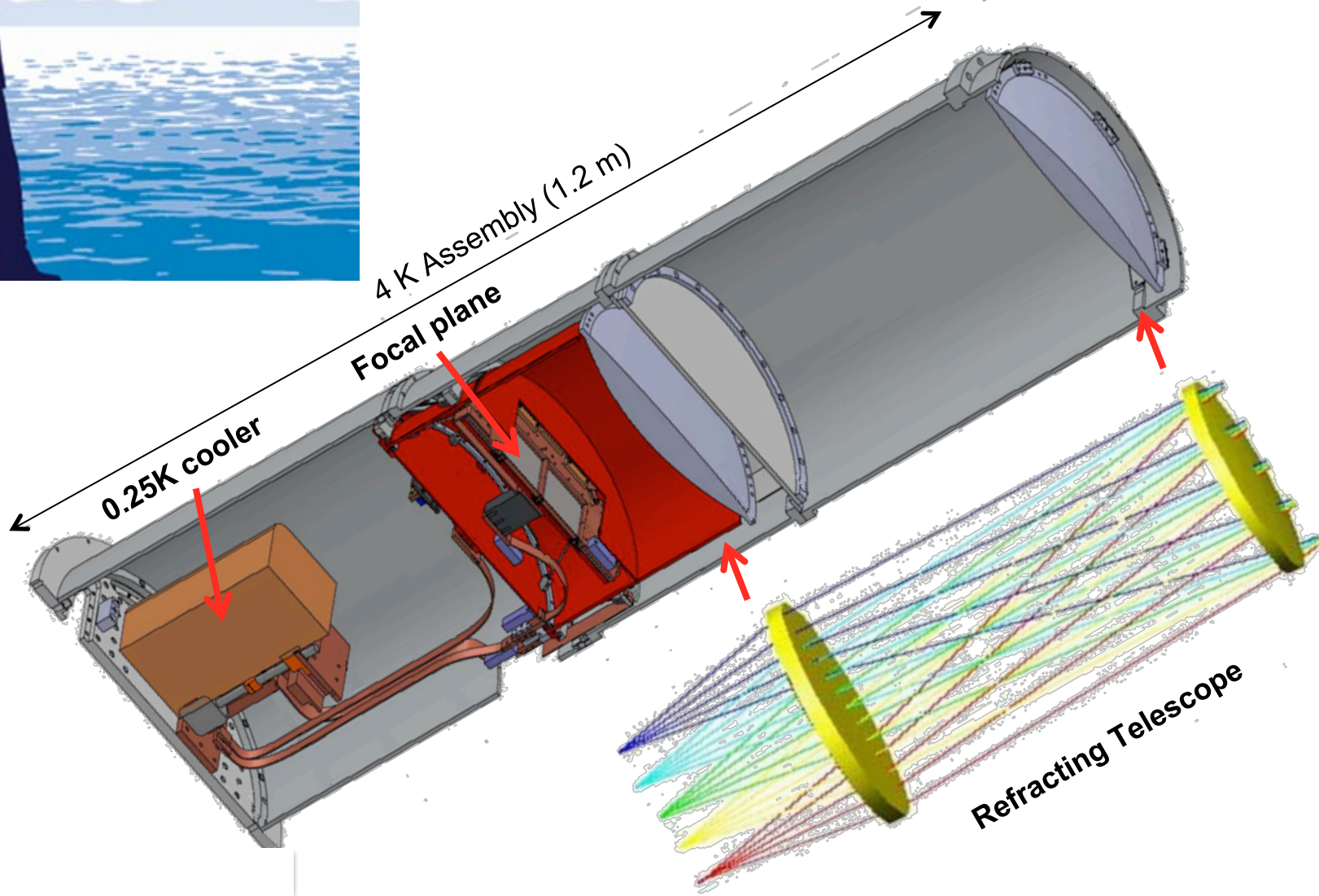


- High and *dry* – see out into space
- On Earth's rotational axis - One day/night cycle per year
  - Long night makes for great quality data
- Good support infrastructure – power, cargo, data comm
- Food and accommodation provided
- Even Tuesday night bingo...

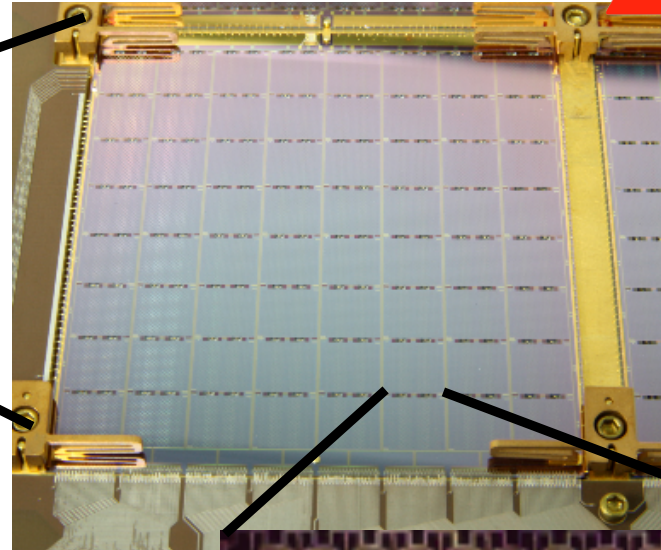
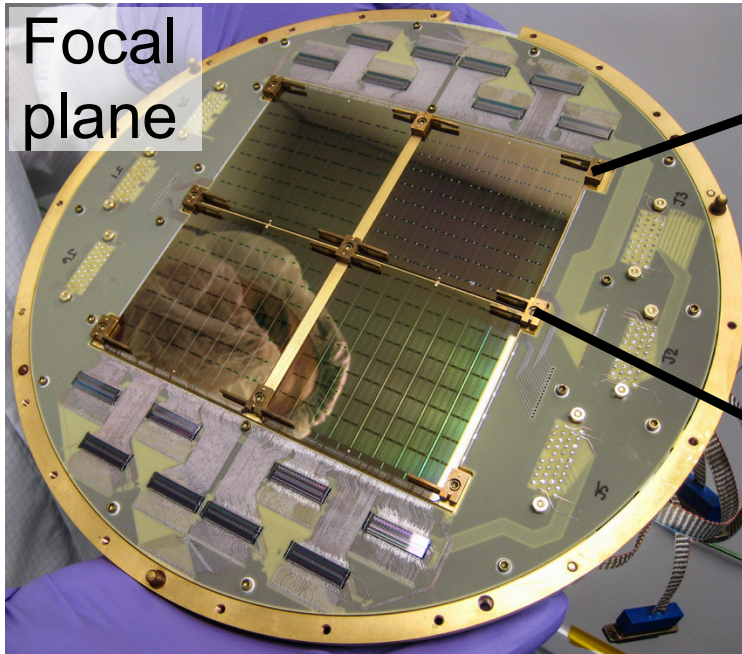


# Basic Experiment Design

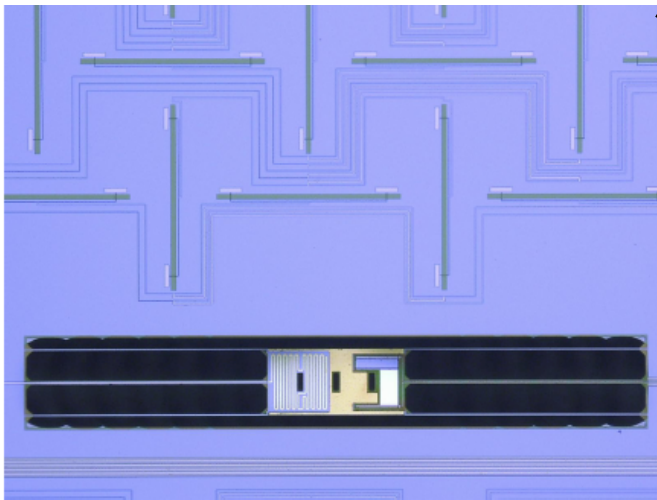
- Small aperture
- Wide field of view
- Cold refractor



# Mass-produced Superconducting Detectors

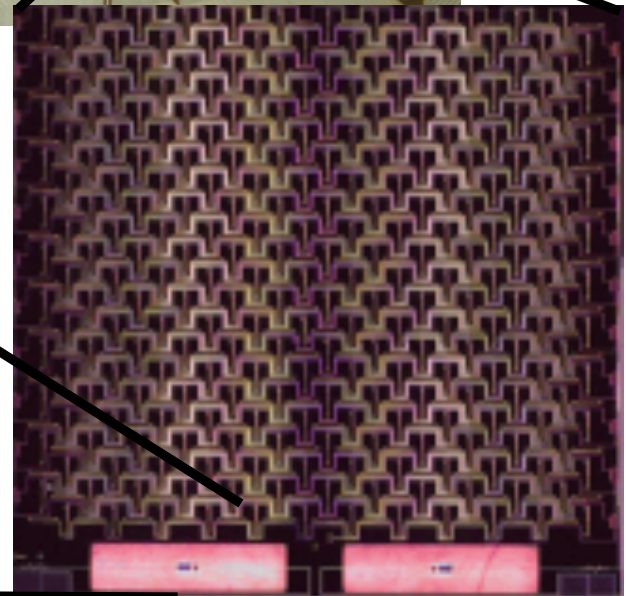


Planar antenna array



Slot antennas

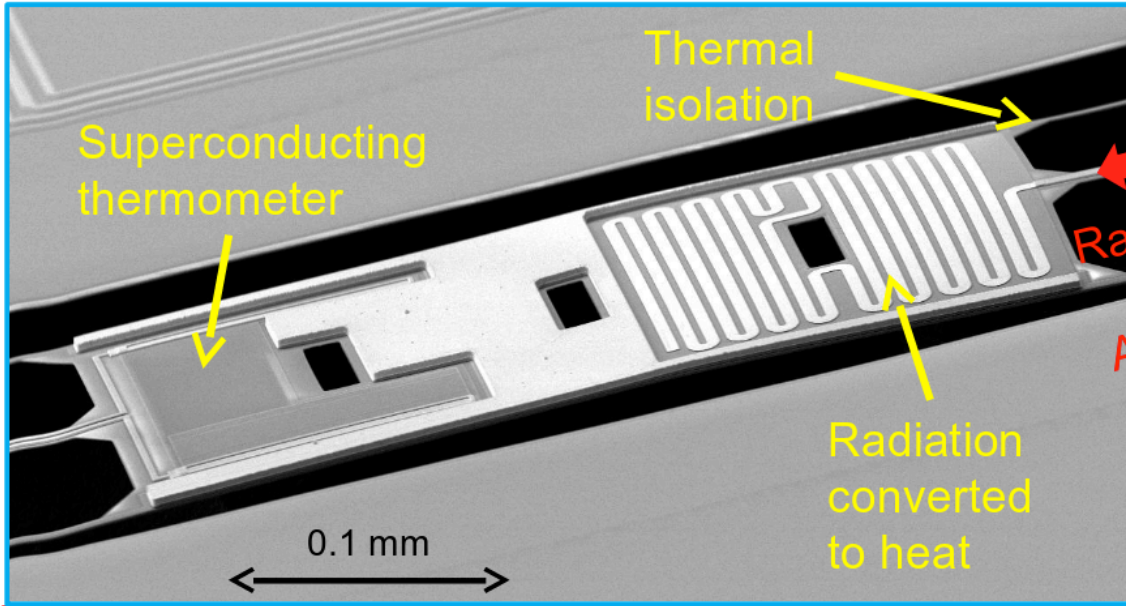
Transition edge sensor



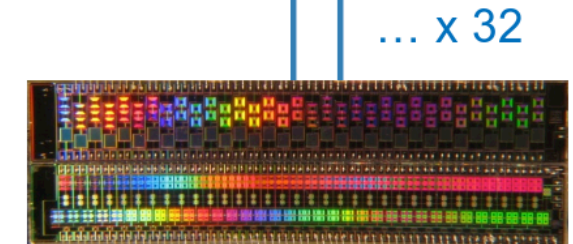
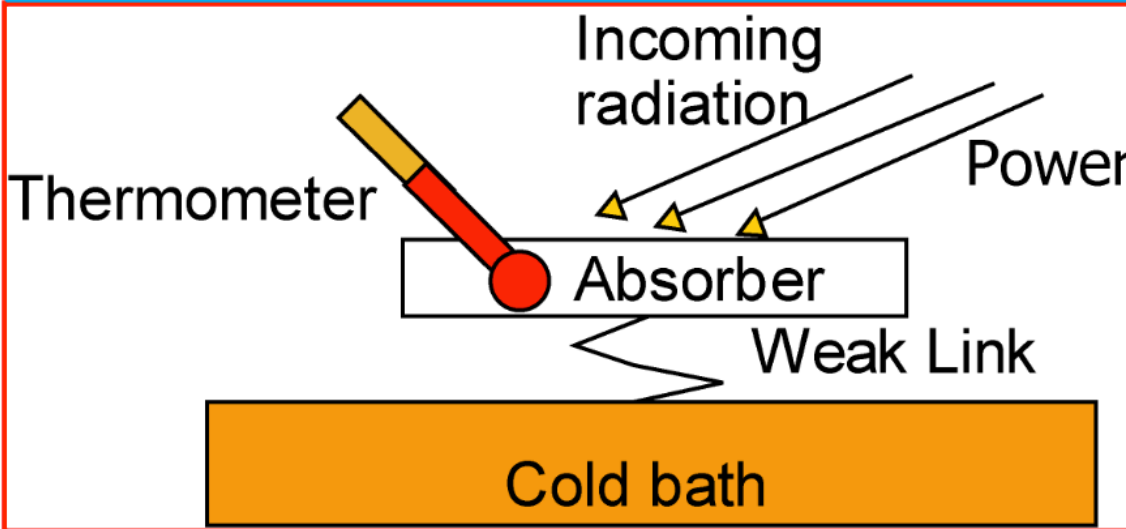
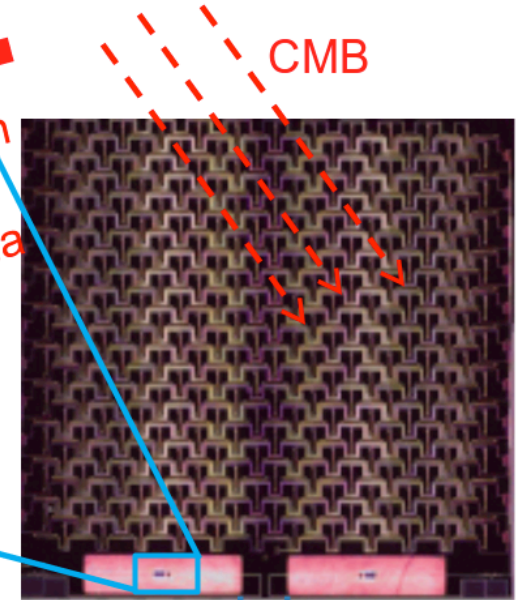
Microstrip filters

# Detecting CMB Radiation

BICEP2 Detector: Transition-Edge Superconductor

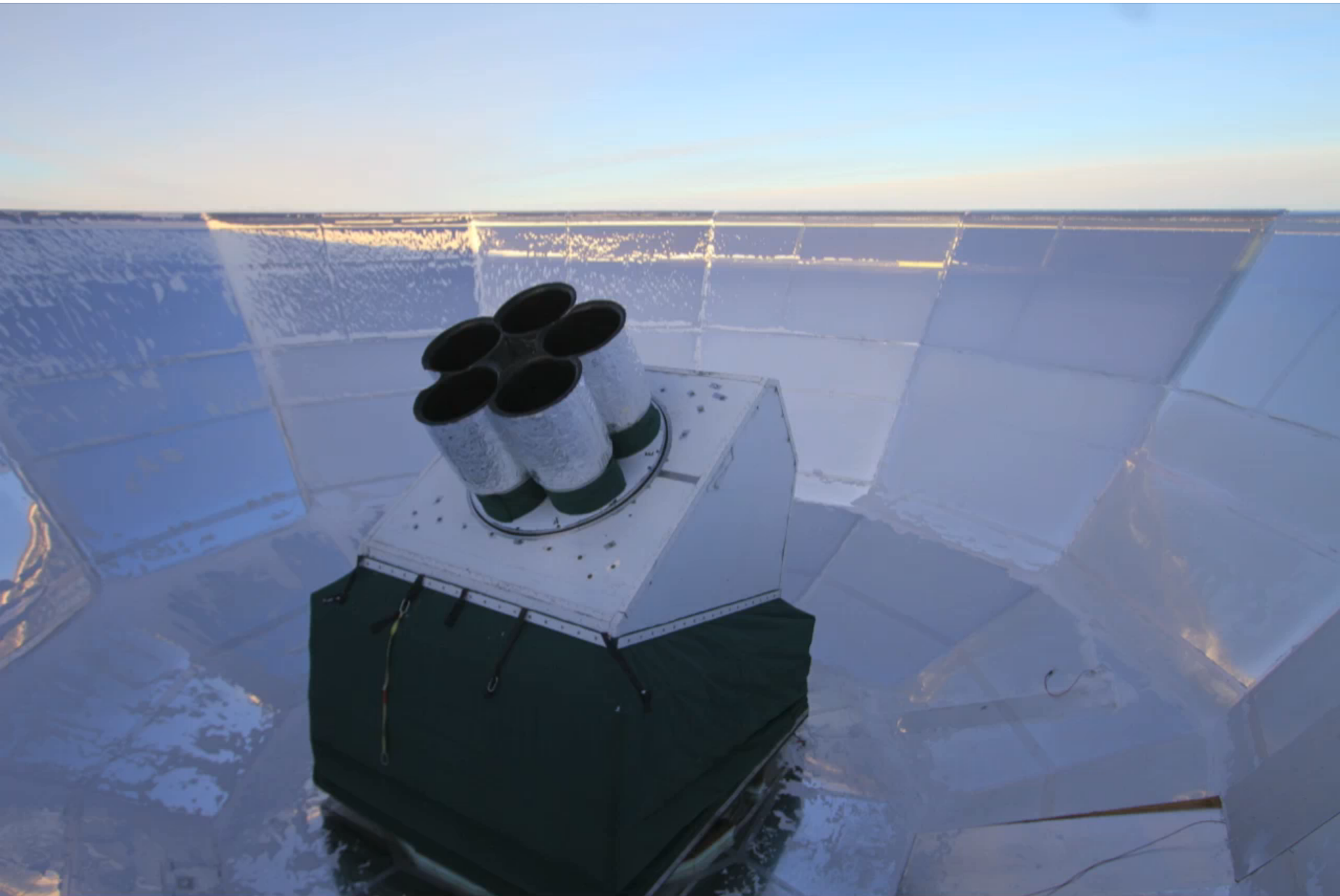


Printed Antenna  
Gathers CMB Light



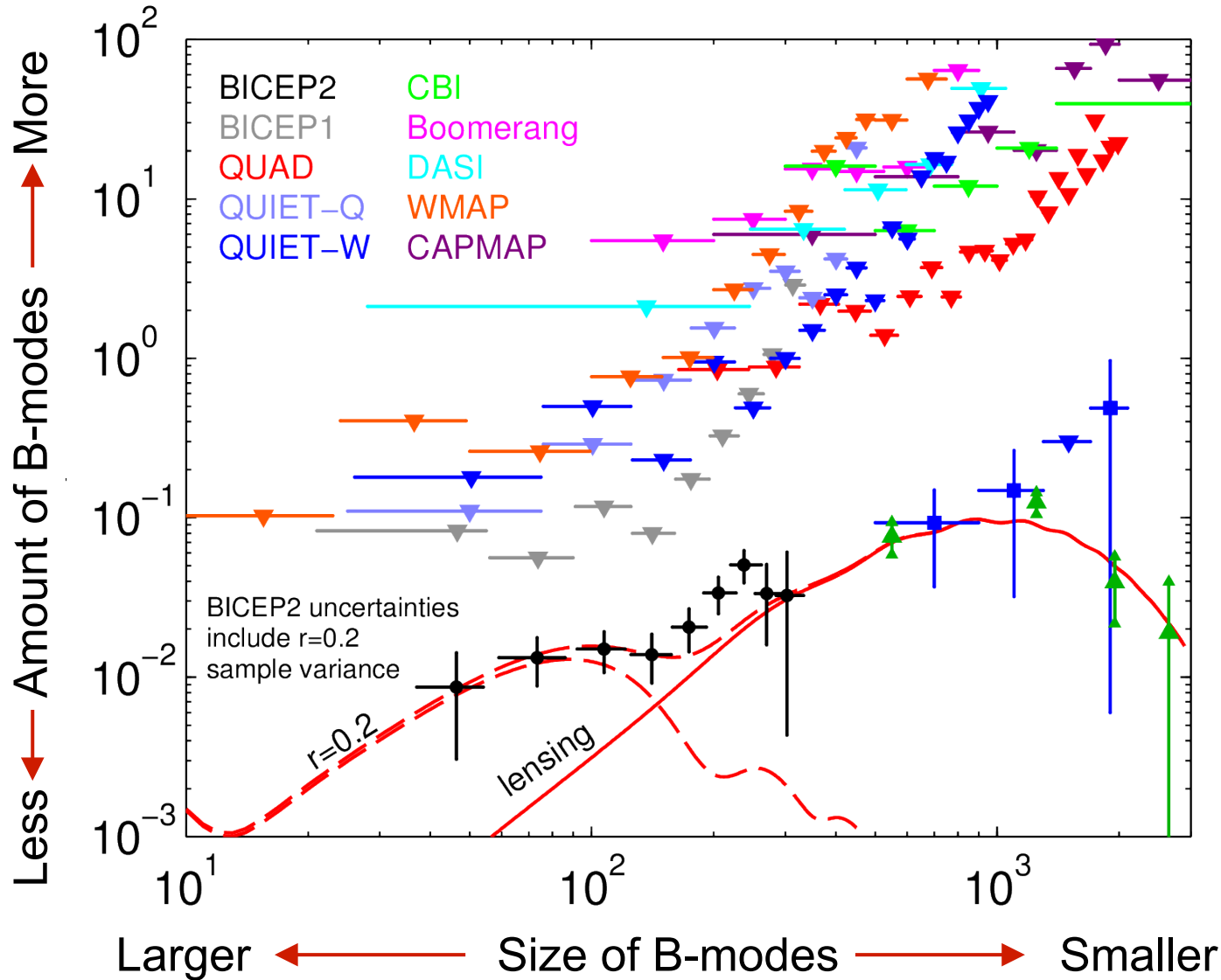
SQUIDs Amplify and  
Multiplex Signals  
SQUIDs developed at NIST

Sensors cooled to 0.25 K to reduce thermal noise



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 hope of finding plane is faint.

**GM issues three new recalls**  
New recalls include all Buicks, GM's largest pickup truck, and more than 15 million vehicles.

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

**How Angela earned her big, bad wings**  
To play the role of Victoria Beckham, the actress had to lose 20 pounds.

**SOUTH POLE VIEW**  
The best place to view the South Pole is not the South Pole.

**GRAVITATIONAL WAVES**  
Scientists have been searching for gravitational waves.

**A THEORY**  
A theory of gravity is being tested.

**States engage in shadowy deals as death penalty drugs dwindle**  
States have been using shadowy deals to secure drugs for the death penalty.

**Prisons raise drug use**  
Prisons are raising drug use among inmates.

**USASNSPUSHES**  
USASNSPUSHES

"All the News That Fits to You"

# The New York Times

Vol. CLXXIII, No. 56,444 TUESDAY, MARCH 18, 2014 \$2.50



Chinese Premier Wen Jiabao (left) and Malaysian Prime Minister Najib Razak (right) are seen in a meeting with other officials in Beijing.

### Space Ripples Reveal Big Bang's Smoking Gun

By HEINER HEISE  
Cosmologists have long sought the smoking gun of the Big Bang. It is now in the hands of space ripples.

### Lost Jet's Path Seen as Altered

By PATRICK M. WALSH  
The flight path of the missing Malaysia Airlines plane may have been altered.

### 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

## Sanctions hit Russian top brass

EU and US take action • More severe measures prepared • Putin lays out Crimea demands

By Chris Cilliers in Brussels  
The European Union and the United States have imposed sanctions on top Russian officials.

By Chris Cilliers in London  
The British government has announced that it will impose sanctions on Russian officials.

### Bicep 2's ripples add muscle to Big Bang

By Chris Cilliers in London  
The discovery of gravitational waves adds further evidence to the Big Bang theory.

4:16 / 11:51

### New dawn for breakfast as disease and speculation push price rises

By Chris Cilliers in London  
The price of breakfast cereals has risen due to disease and speculation.



A large satellite dish antenna is shown in a dark environment, possibly a space station or a deep-sea facility.

## 宇宙急速膨張の証拠、検出される

### Telescope captures view of gravitational waves

By Chris Cilliers in London

宇宙が急速に膨張しているという証拠が、重力波の検出によって明らかになった。重力波は、宇宙の膨張によって生じた波であり、重力波の検出は、宇宙の膨張の証拠となる。

重力波は、宇宙の膨張によって生じた波であり、重力波の検出は、宇宙の膨張の証拠となる。重力波は、宇宙の膨張によって生じた波であり、重力波の検出は、宇宙の膨張の証拠となる。

重力波の検出は、宇宙の膨張の証拠となる。重力波は、宇宙の膨張によって生じた波であり、重力波の検出は、宇宙の膨張の証拠となる。

© 2014 Nature News & Media, a division of Nature Publishing Group. All rights reserved. Vol. 121 No. 5180 18 March 2014

# PHYSICAL REVIEW LETTERS

Articles published week ending 20 JUNE 2014

Number Subscription Dept  
Library or Other Institution (no Postpaid) Last 2017

340000  
340001  
340002  
340003  
340004  
340005  
340006  
340007  
340008  
340009  
340010  
340011  
340012  
340013  
340014  
340015  
340016  
340017  
340018  
340019  
340020

PHYSICAL REVIEW LETTERS (248 total pages)

24

Published by American Physical Society, APS physics

Volume 112, Number 24

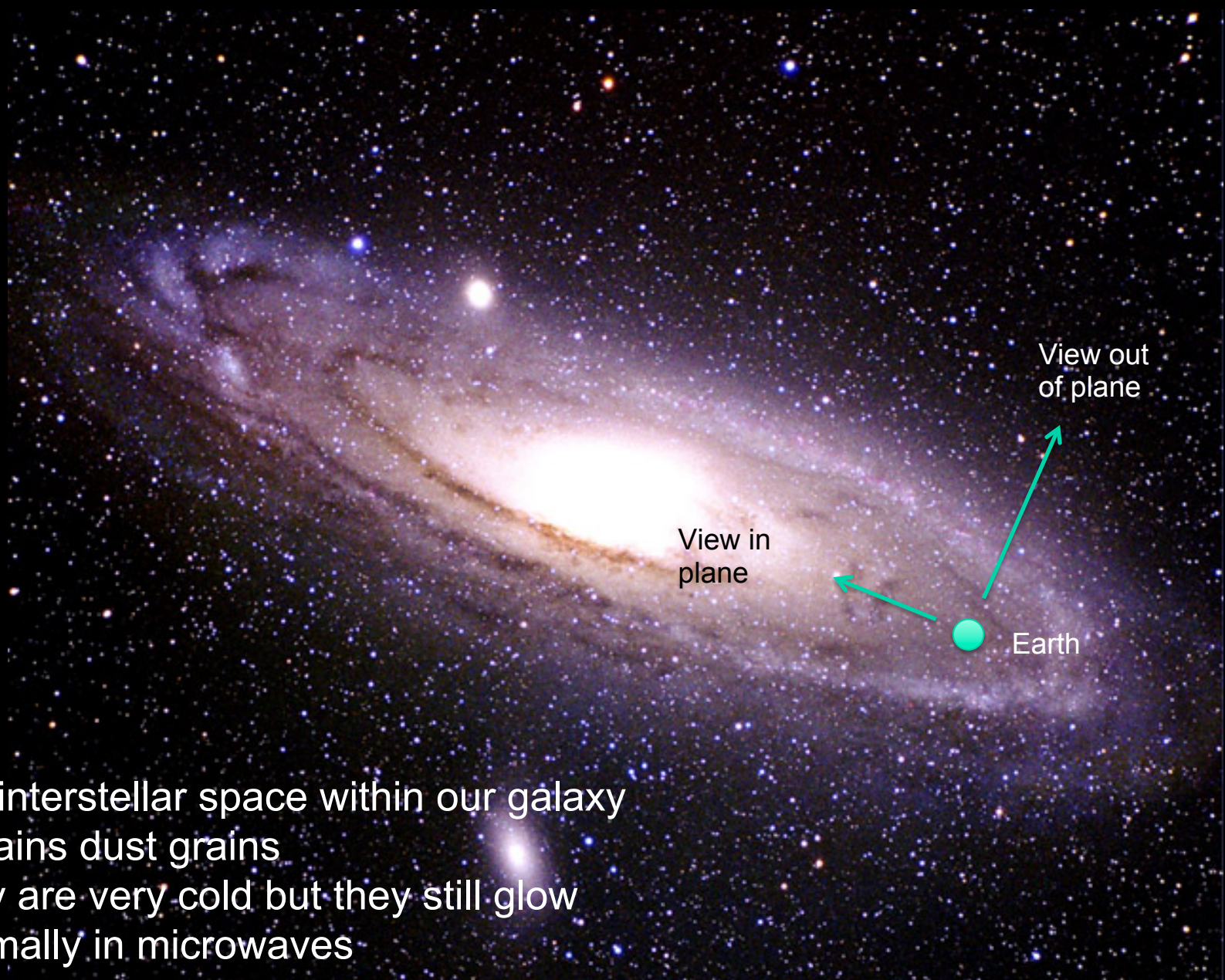
## Actually not a lot of fun...

© 2013 Interactive Brokers Inc. All rights reserved.

\$1 Billion in our customer's margin accounts at an average rate of 1.1%.

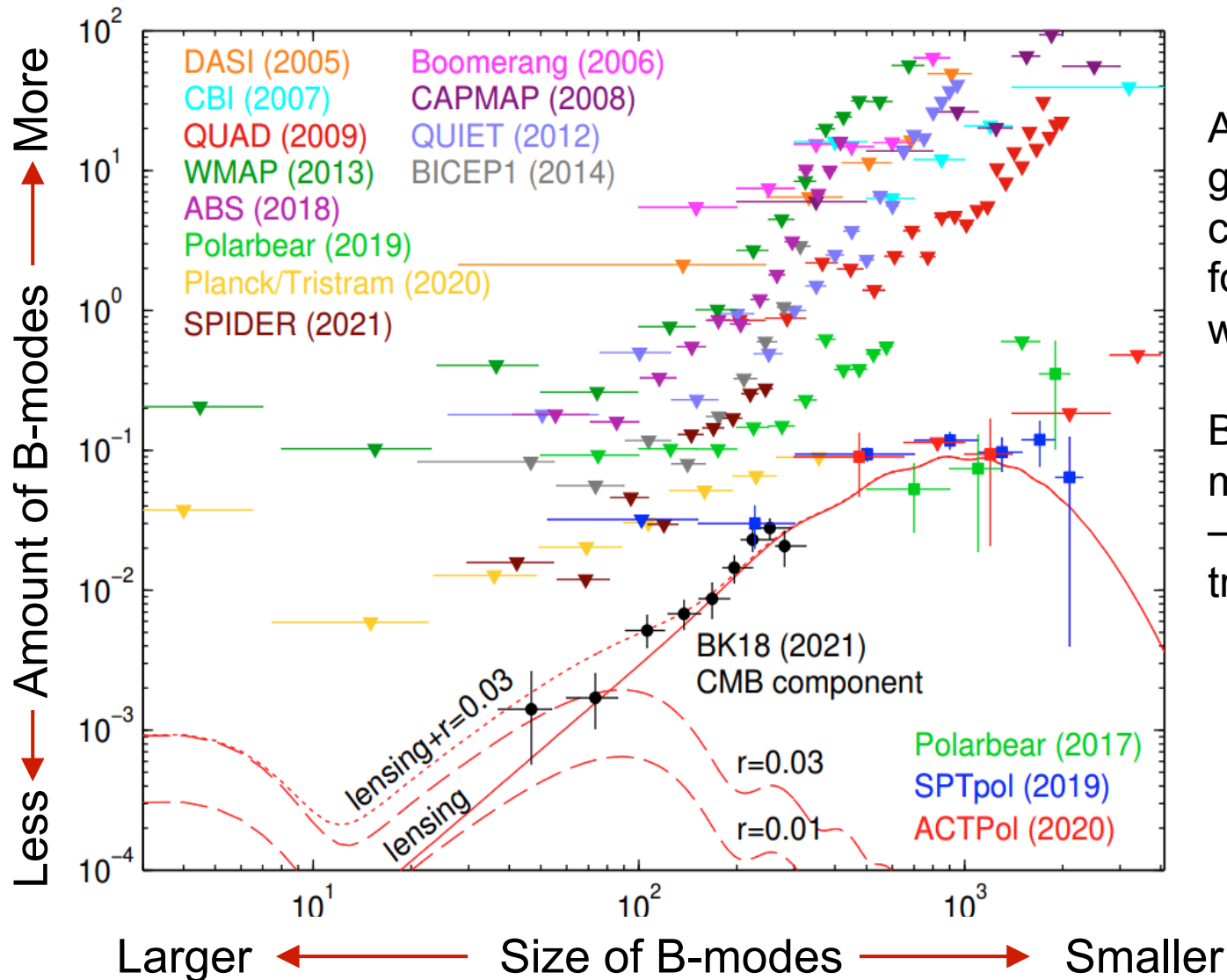
On the average day, our customers:

# 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...

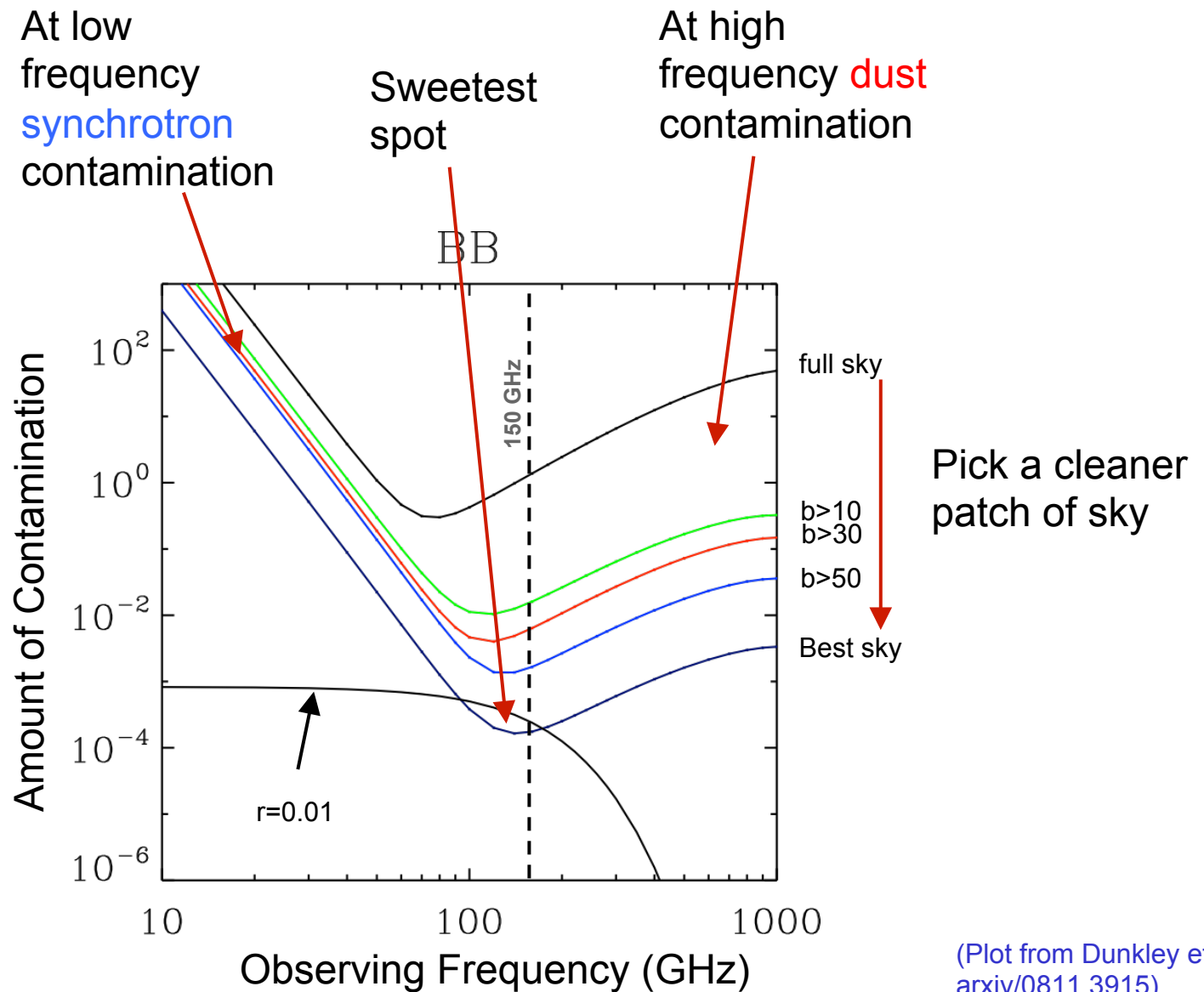


After accounting for galactic dust there is currently no evidence for gravitational waves

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



# Polarized Foreground Contamination from Our Galaxy

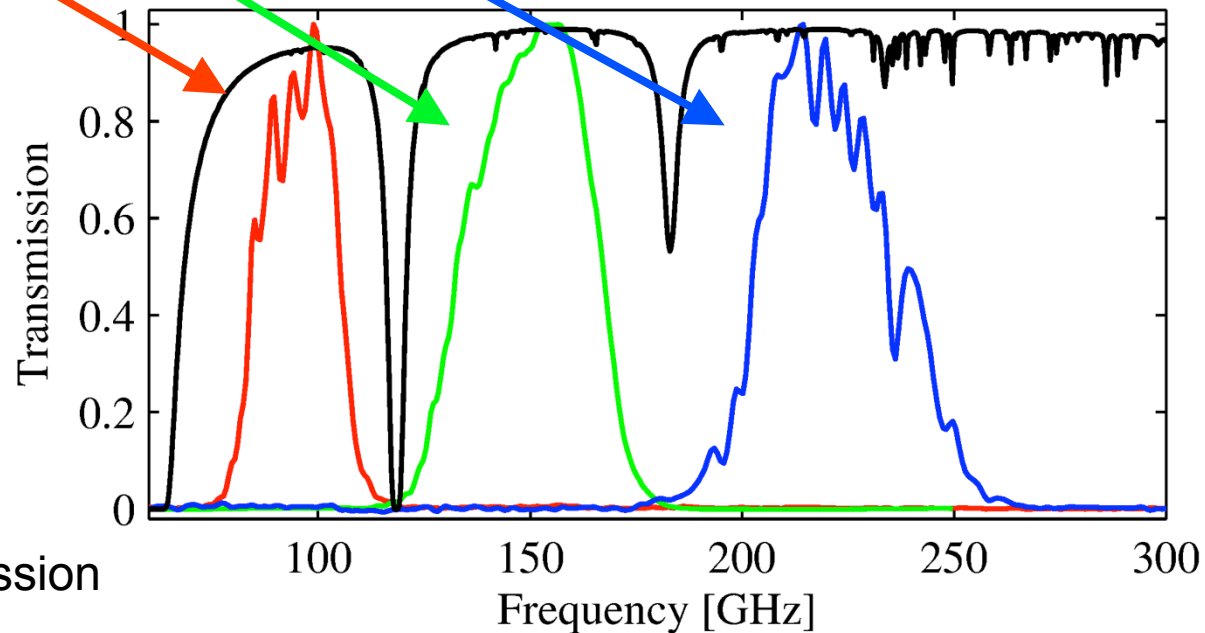
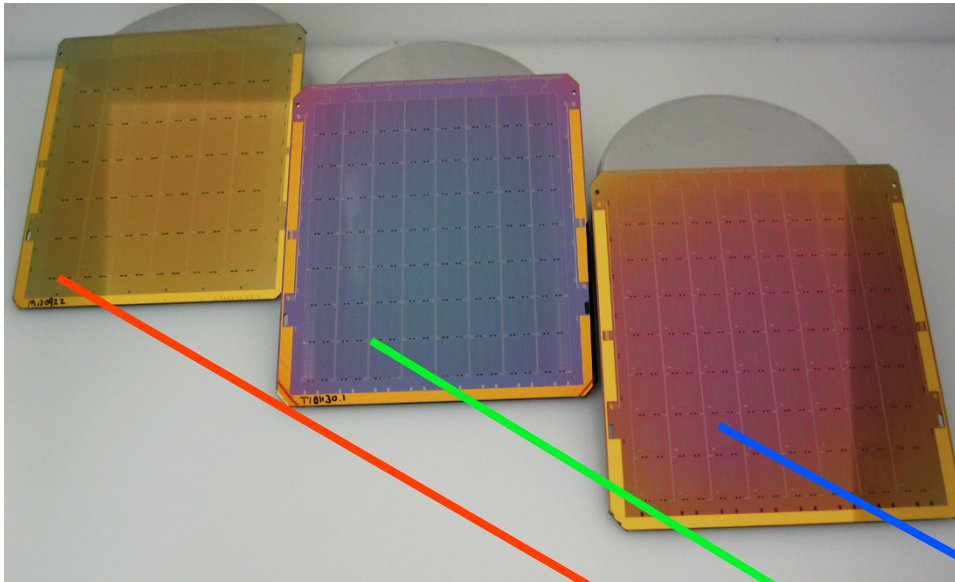


(Plot from Dunkley et al  
arxiv/0811.3915)

# Planar superconducting detector arrays

...designed to scale  
in frequency

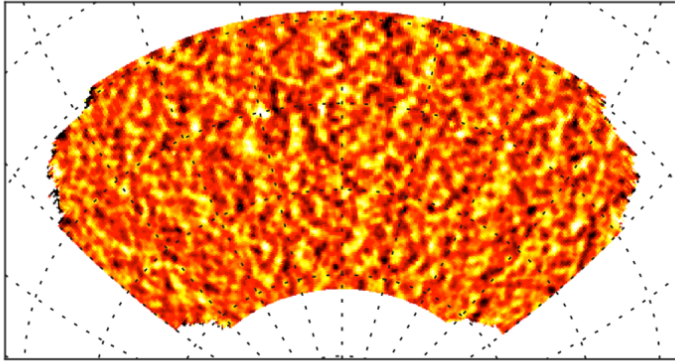
Up to 2013 – all 150GHz  
2014 – 95/150GHz  
2015 – 95/150/220GHz



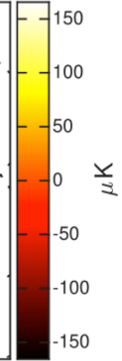
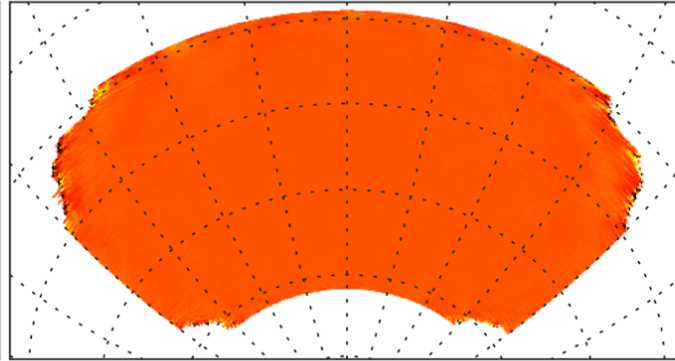
Typical South Pole  
atmospheric transmission

# BK18 95GHz Map (BICEP3)

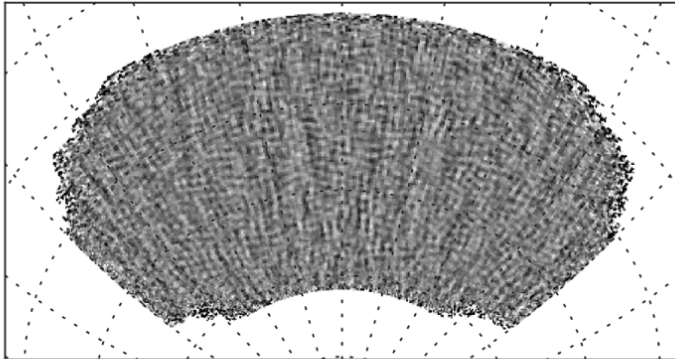
B18<sub>95</sub> T signal



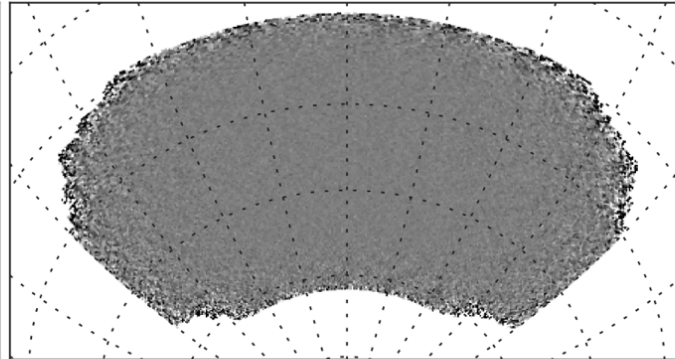
B18<sub>95</sub> T noise



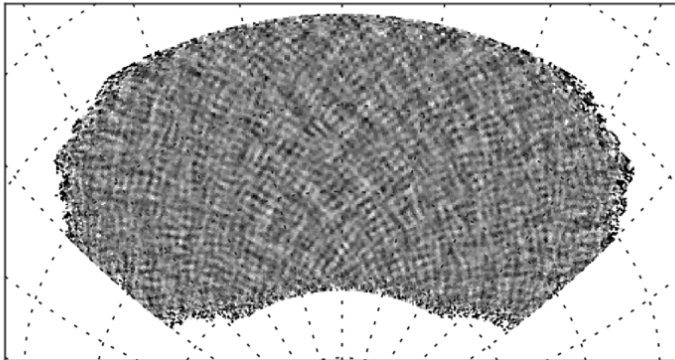
Q signal



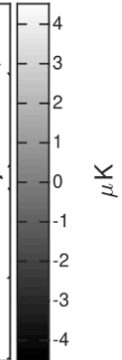
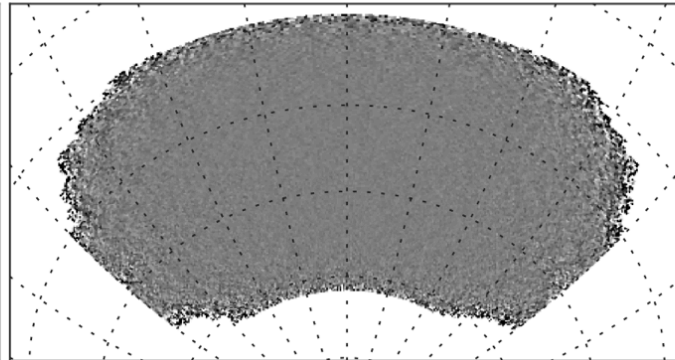
Q noise



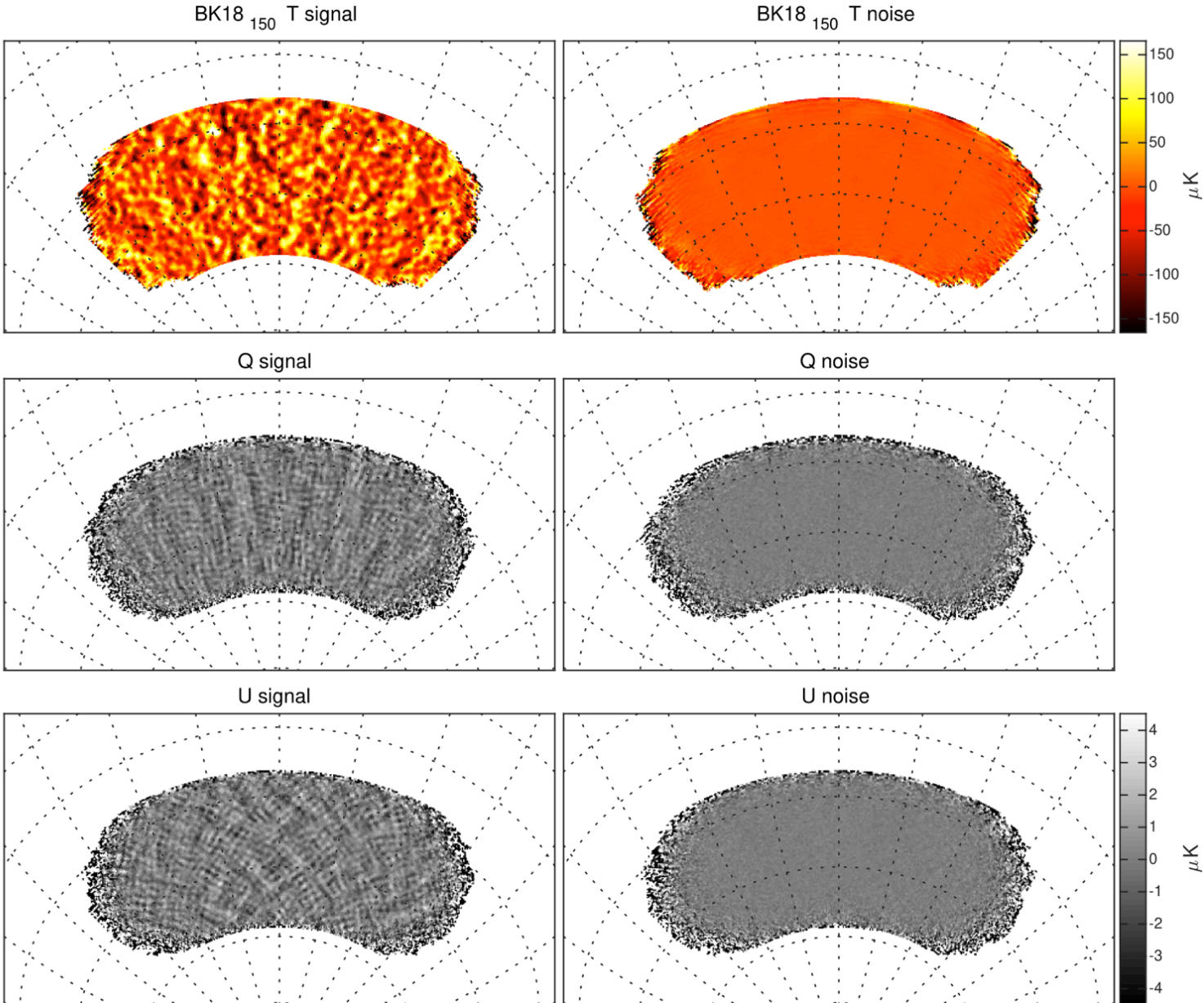
U signal



U noise

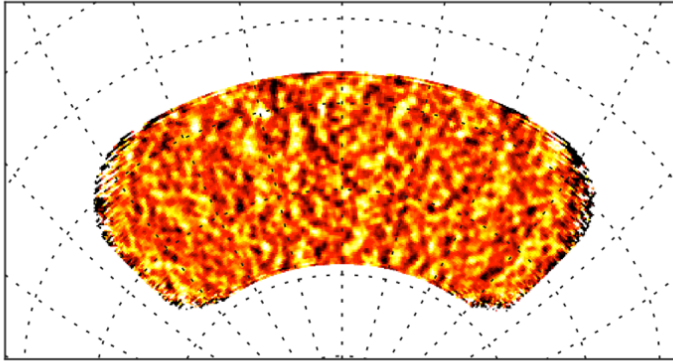


# BK18 150GHz Map (BICEP2+Keck)

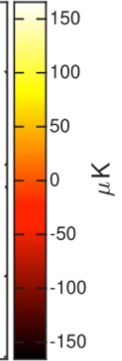
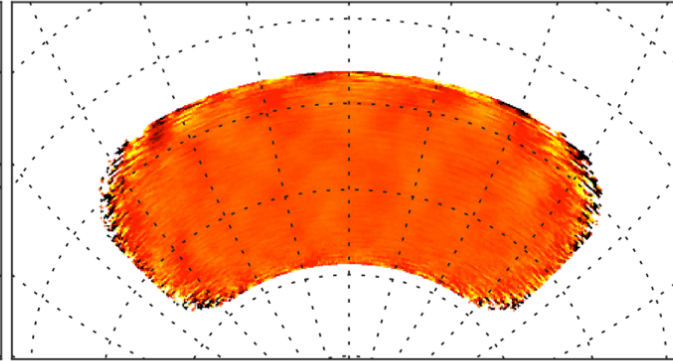


# BK18 220GHz Map (*Keck*)

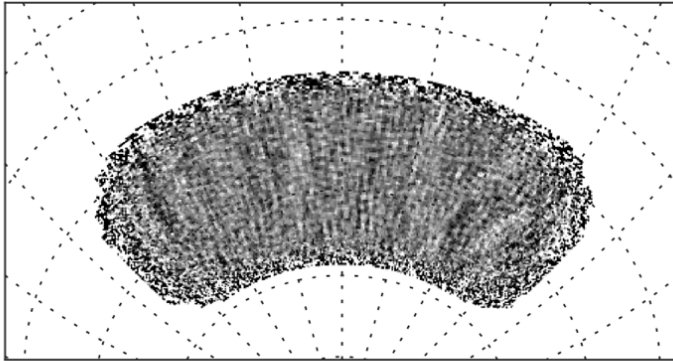
BK18<sub>220</sub> T signal



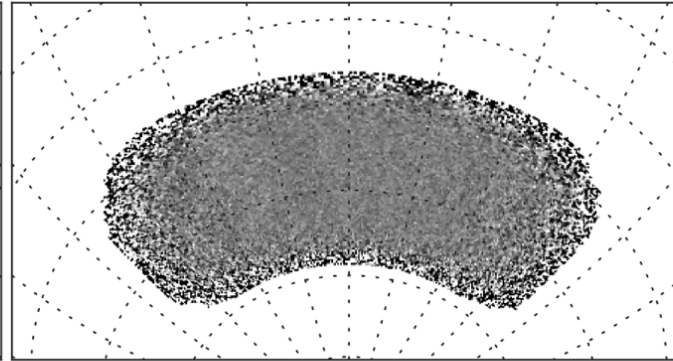
BK18<sub>220</sub> T noise



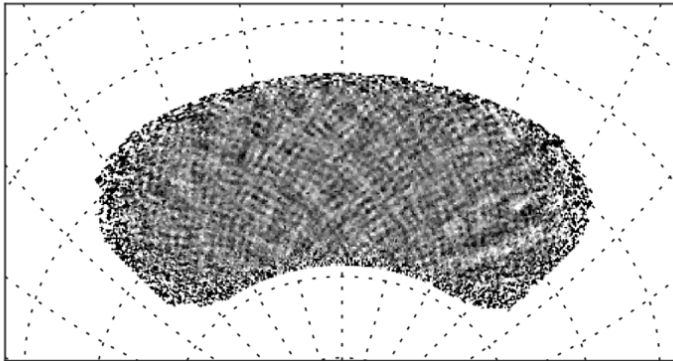
Q signal



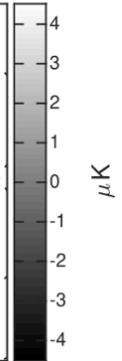
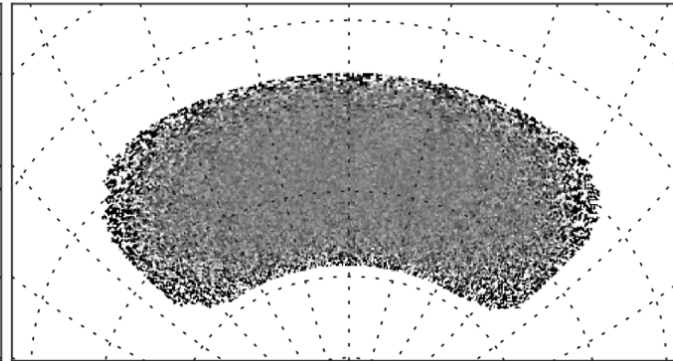
Q noise



U signal



U noise



## Stage 2

## Stage 3

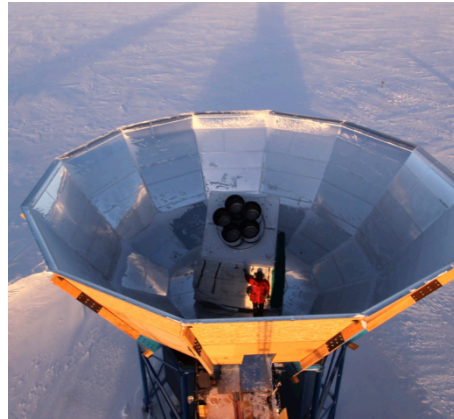
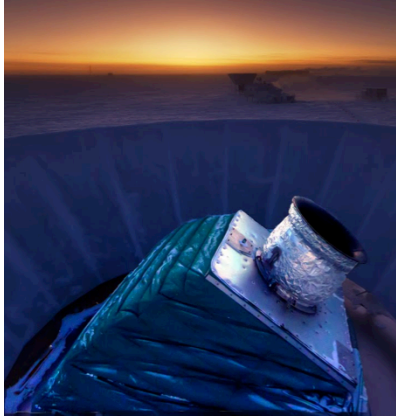
**BICEP2**  
(2010-2012)

**Keck Array**  
(2012-2019)

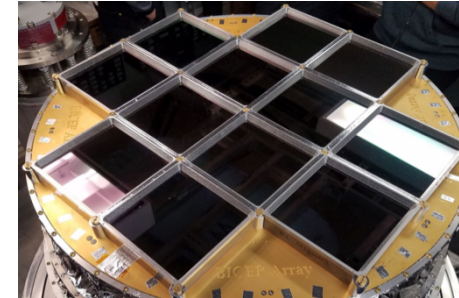
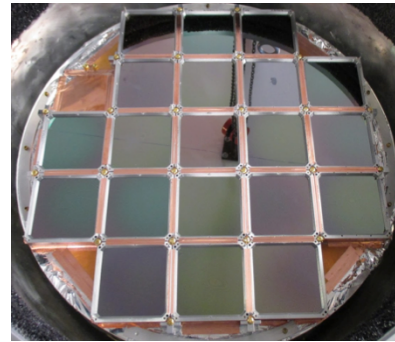
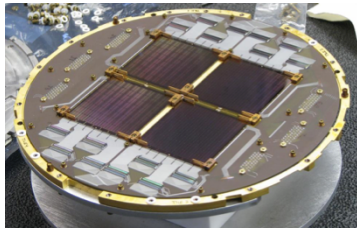
**BICEP3**  
(2016-present)

**BICEP Array**  
(2020-present)

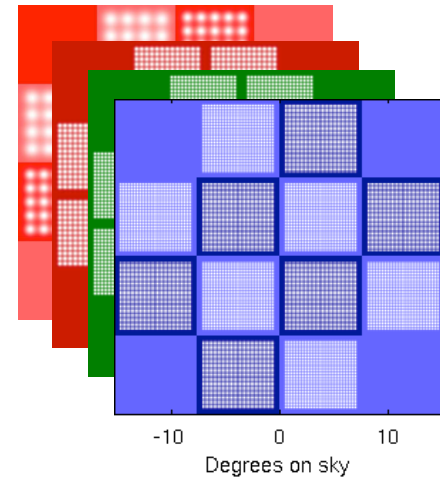
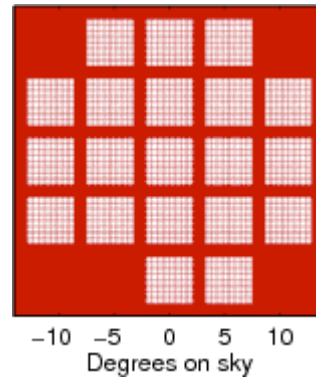
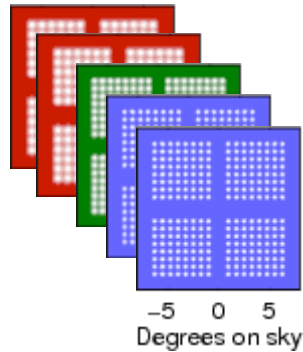
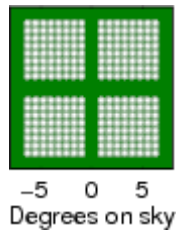
Telescope and Mount

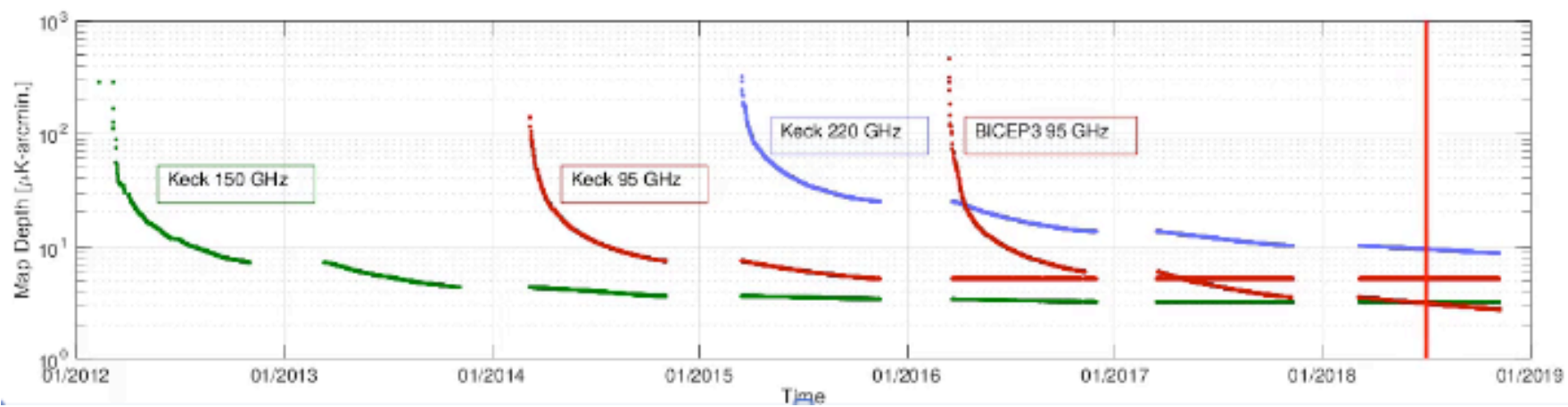
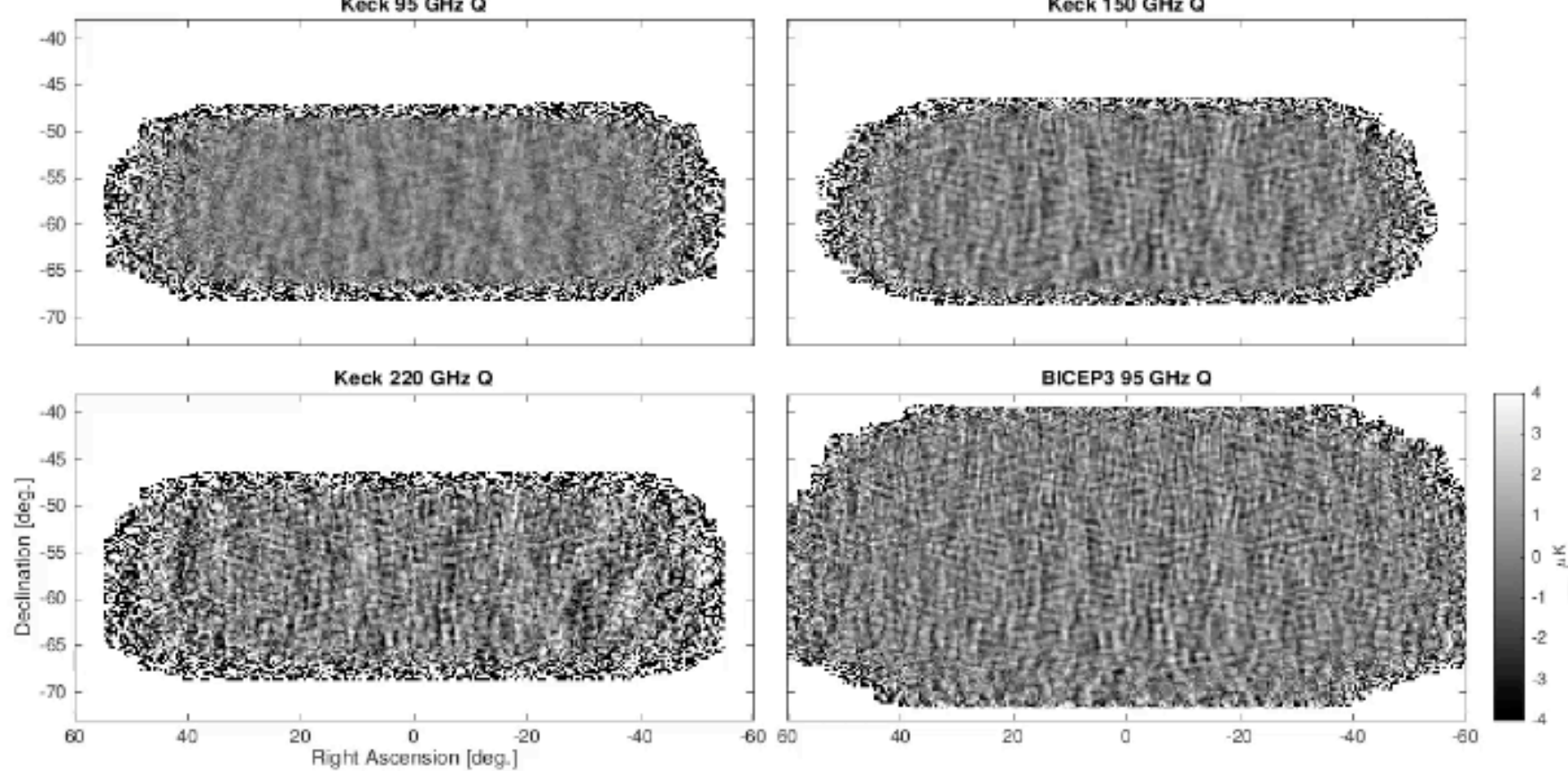


Focal Plane



Beams on Sky







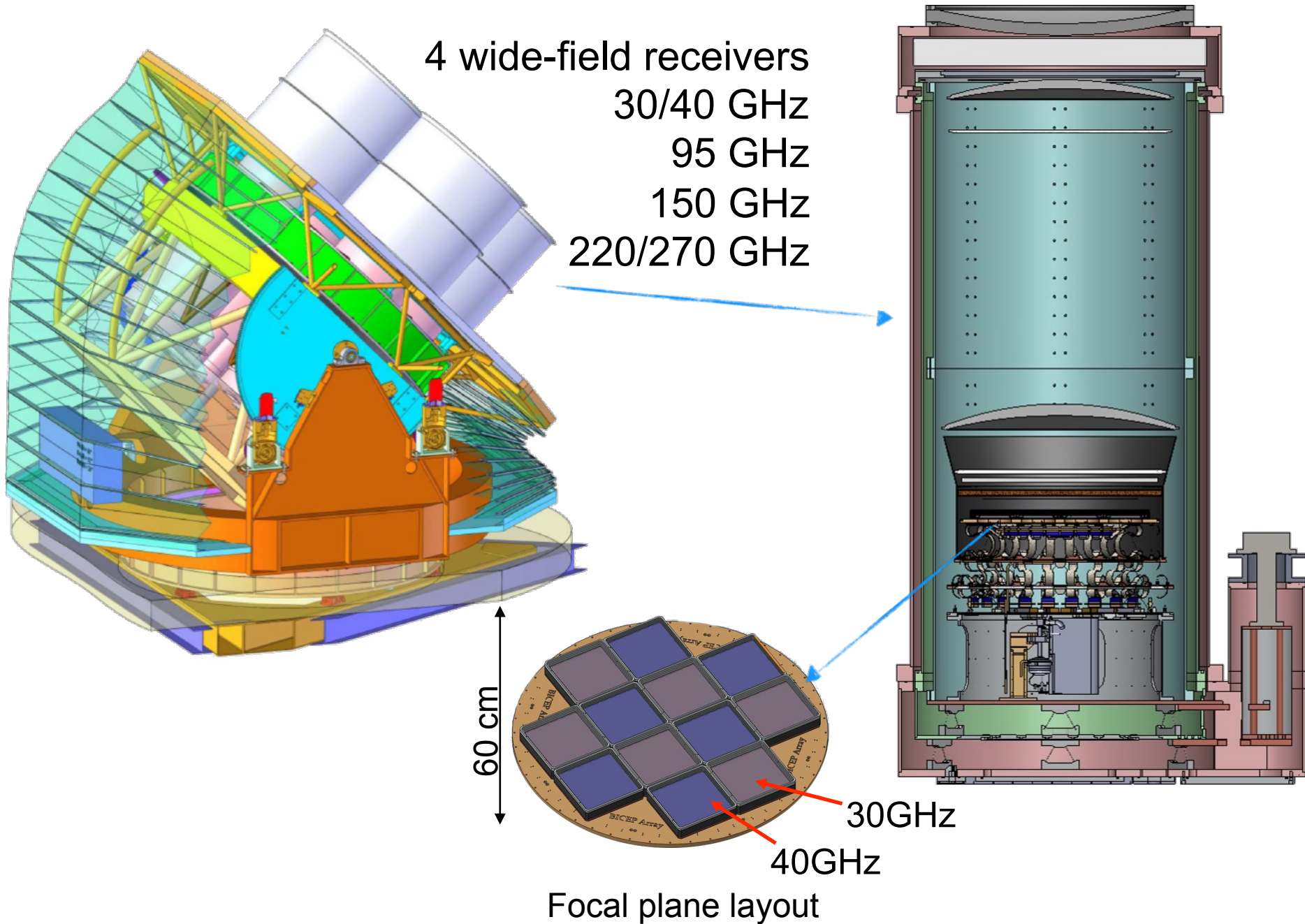




Google “Robert Schwarz” – did 9 consecutive winter seasons at South Pole (14 overall!)

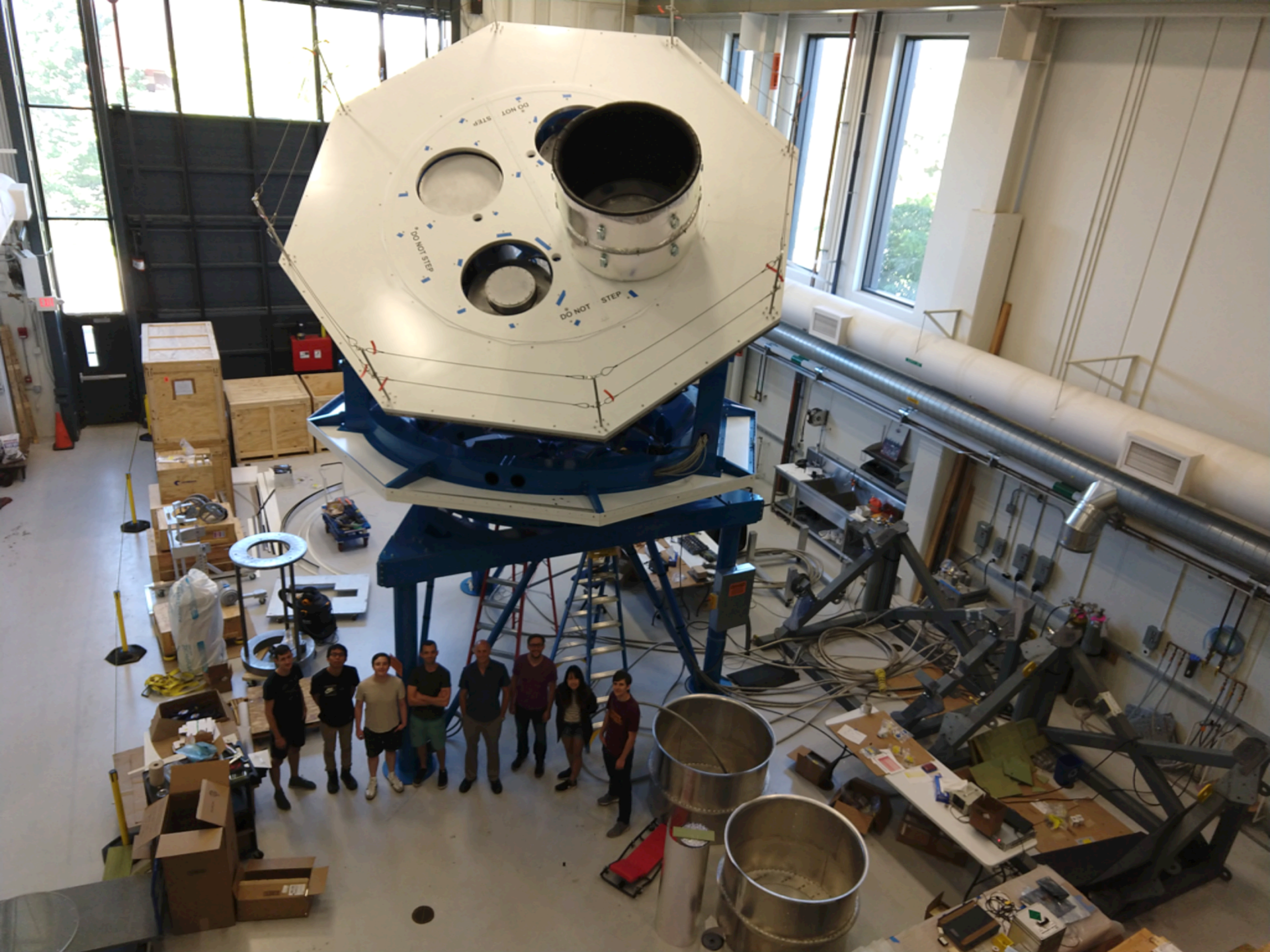


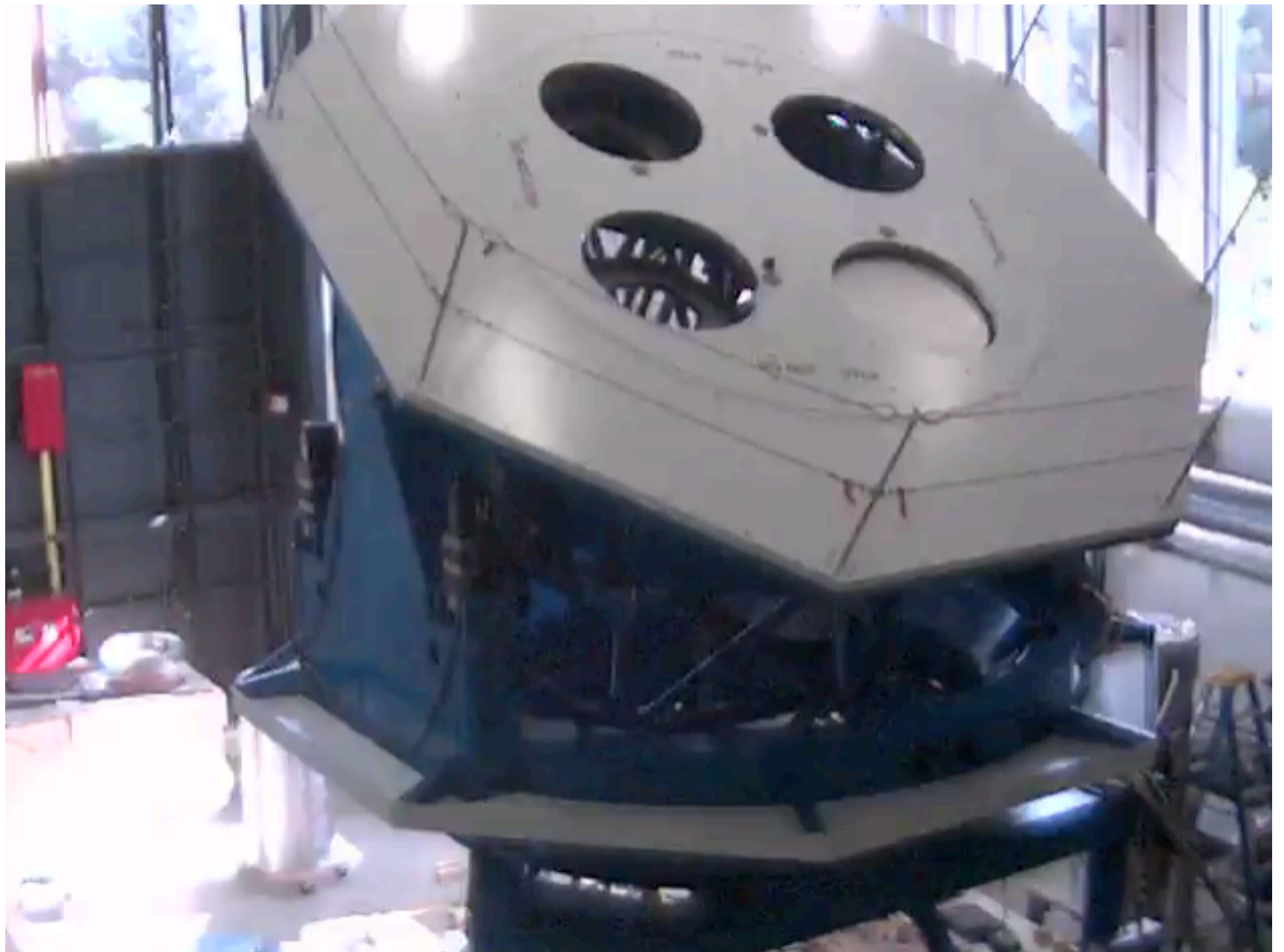
# Latest Generation Experiment "BICEP Array"



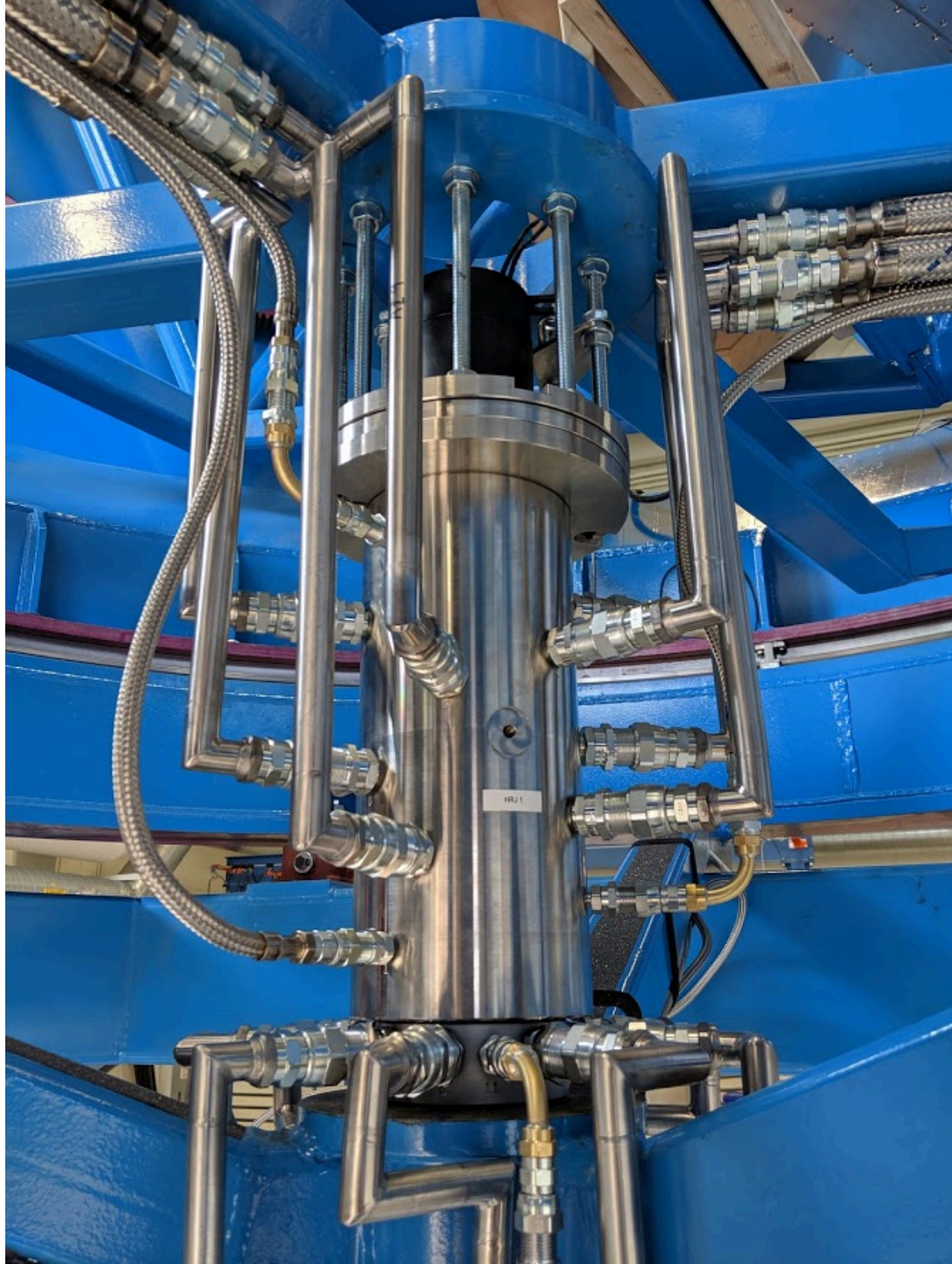
# 2018-19: Built New Telescope at UMN

















CR

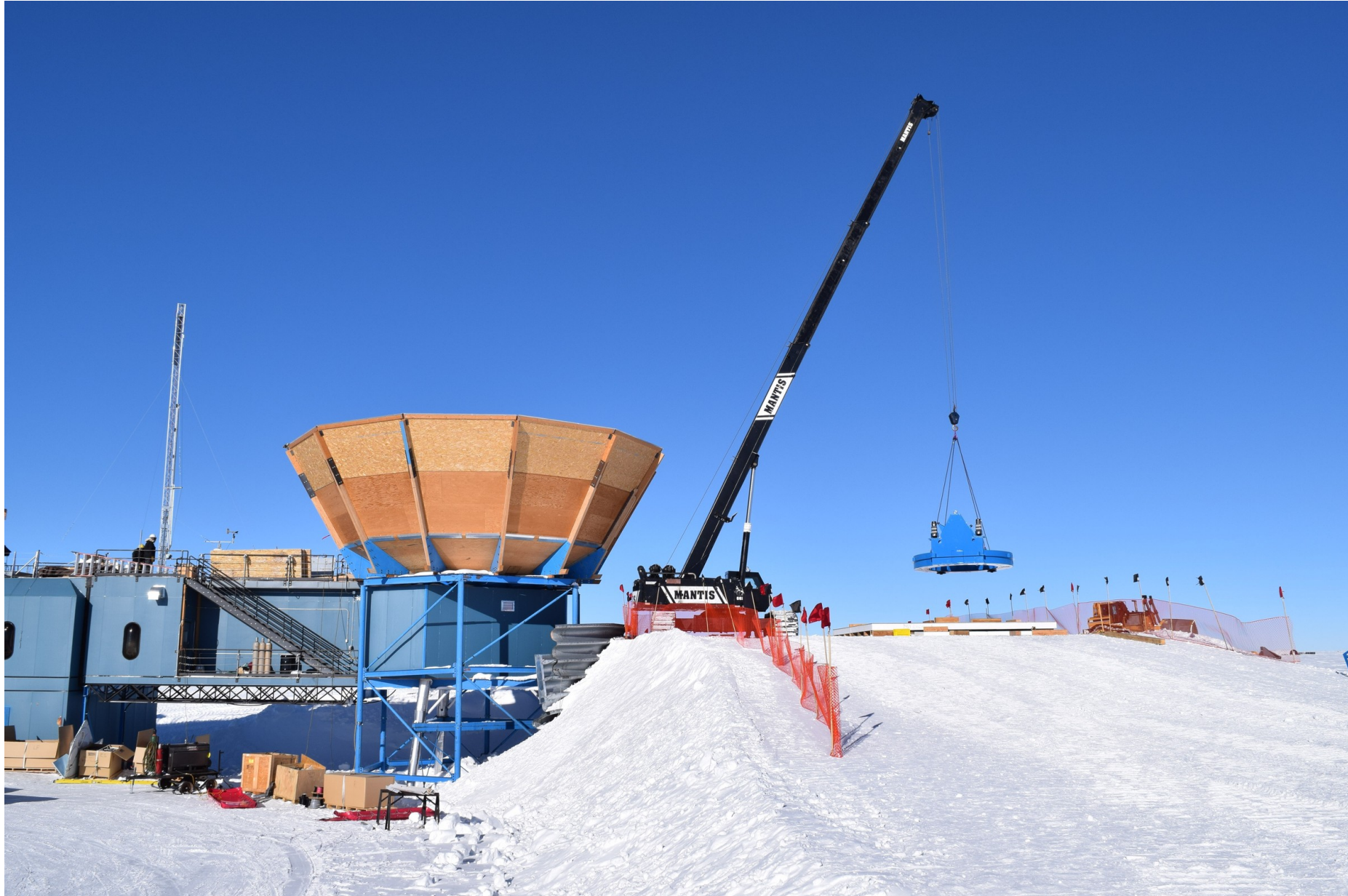
SCOTT

CLEM PRYKE

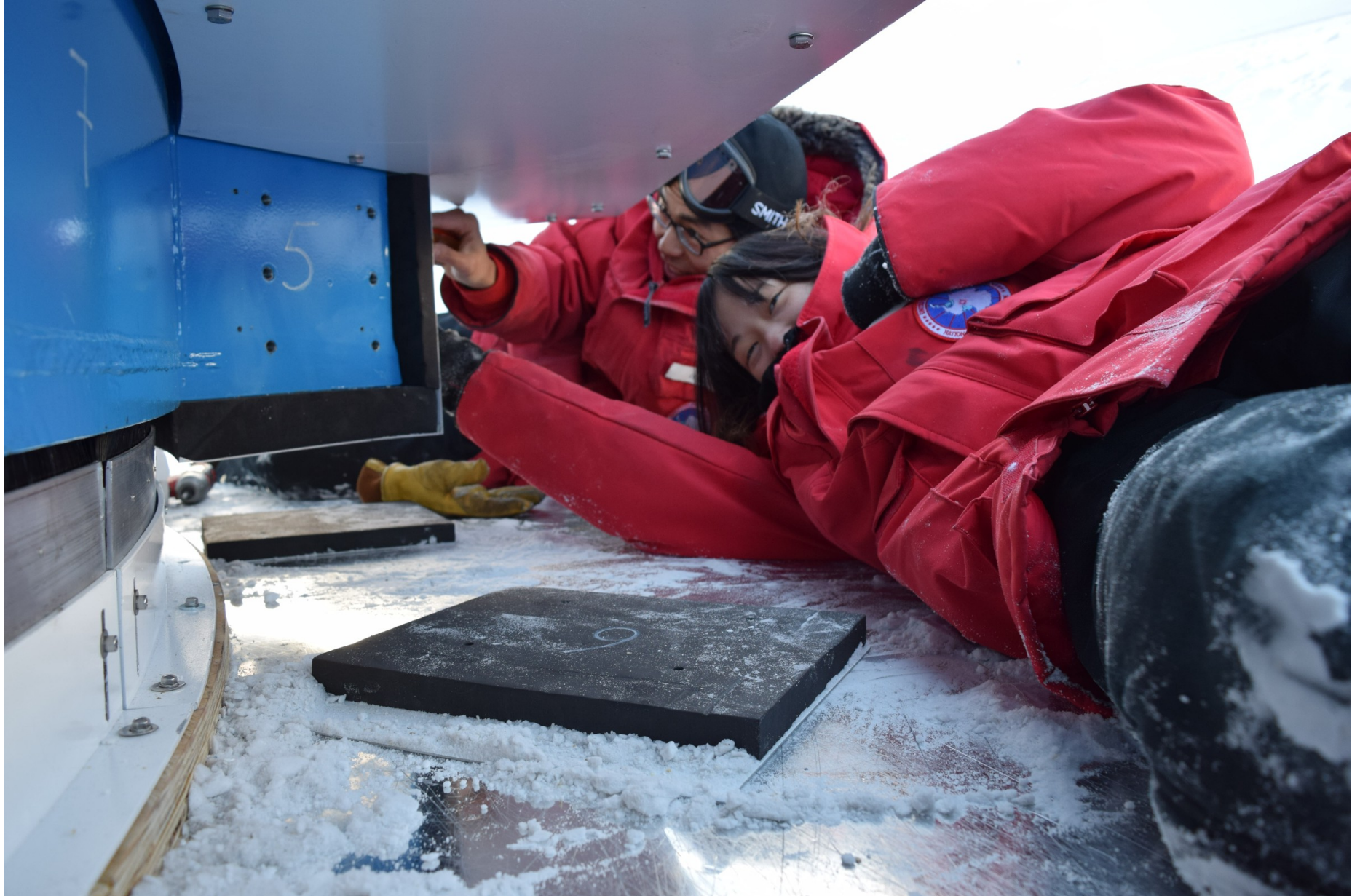


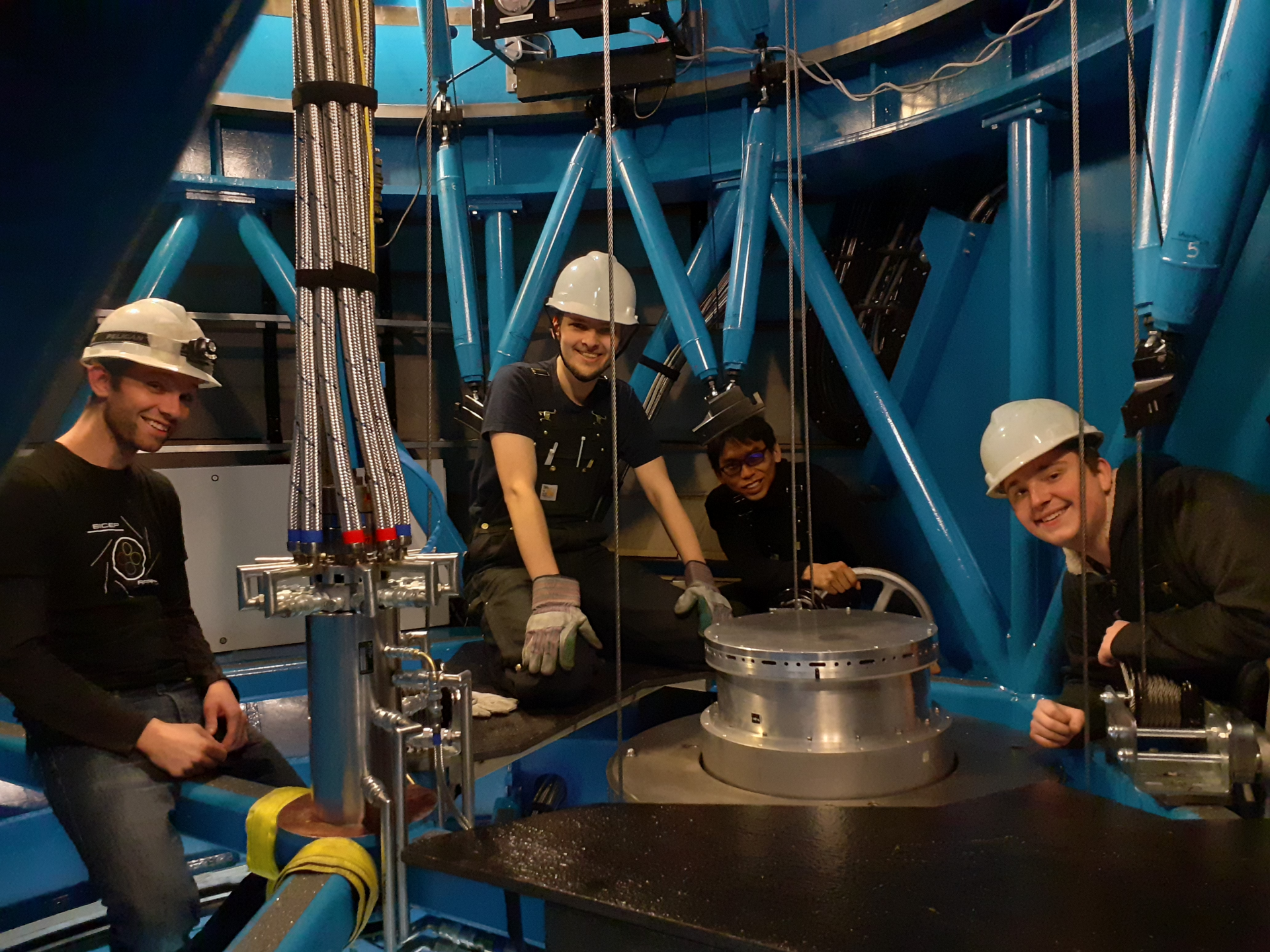


# Lifting on part of new telescope



# 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

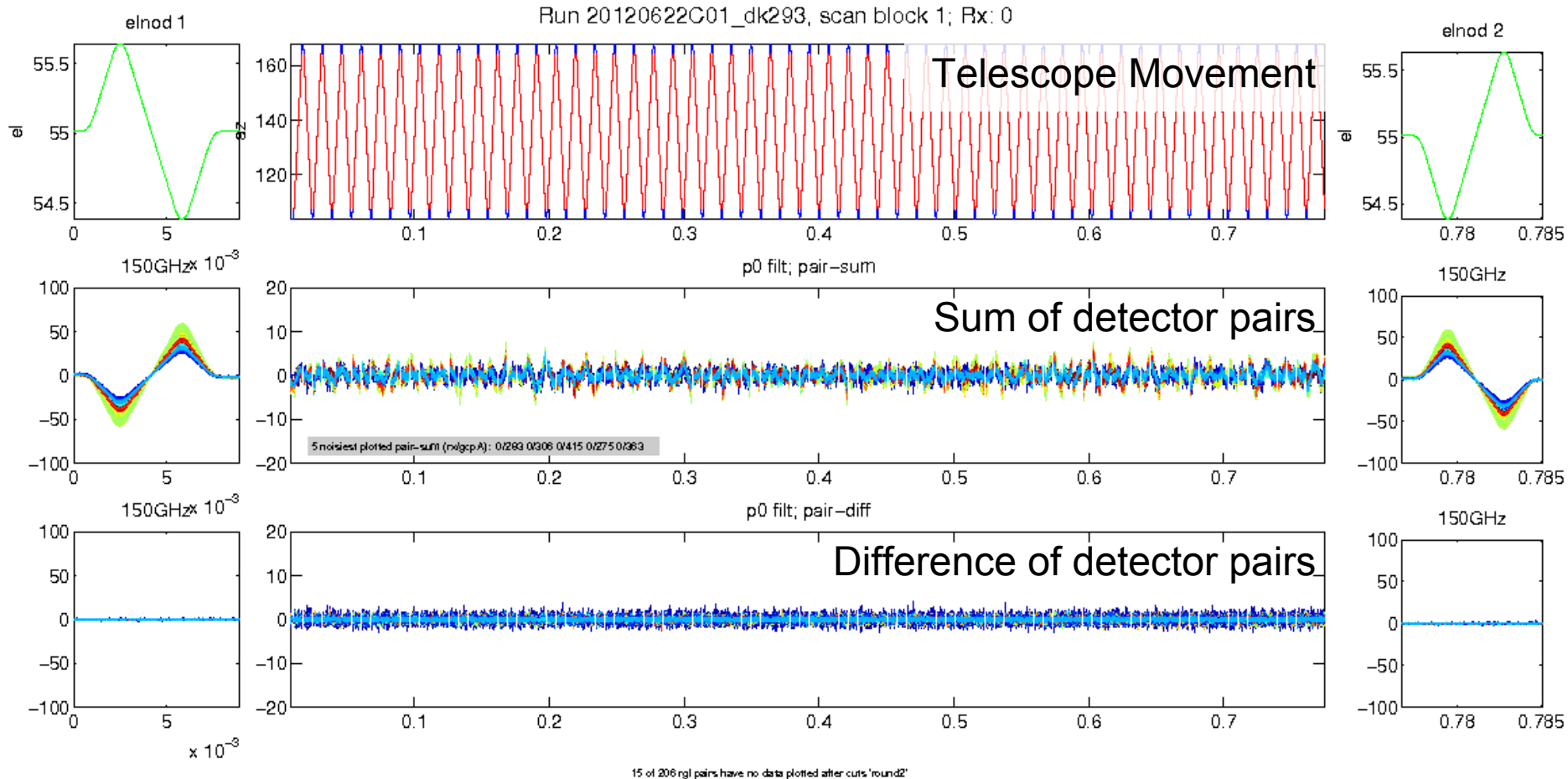
hiep array

USA

12

# Raw Data - Perfect Weather

Time 50 mins

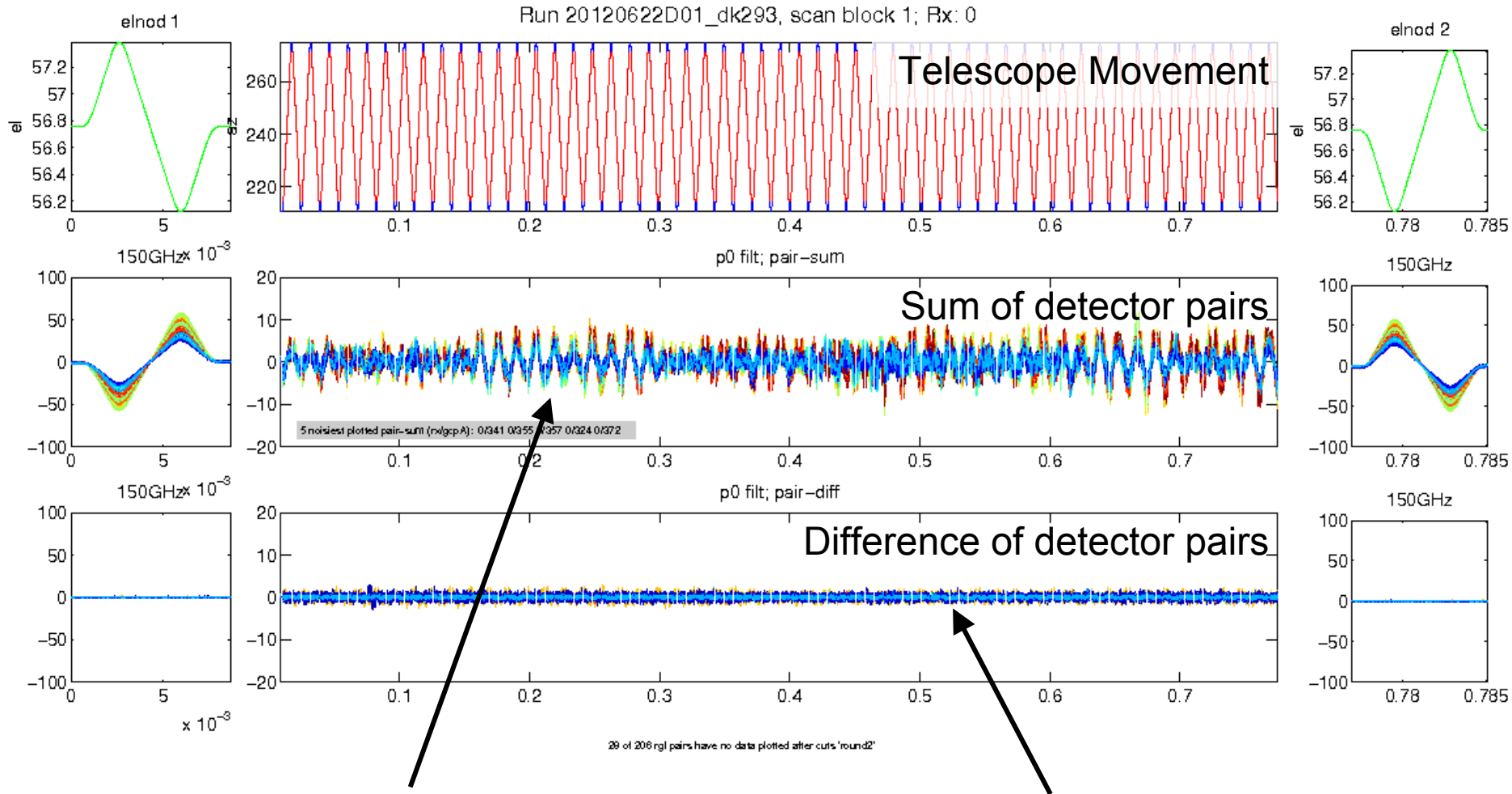


➤ Cover the whole field in 60 such scansets then start over at new boresight rotation

➤ Scanning modulates the CMB signal to freqs  $< 4$  Hz

# Raw Data - Worse Weather

Time 50 mins



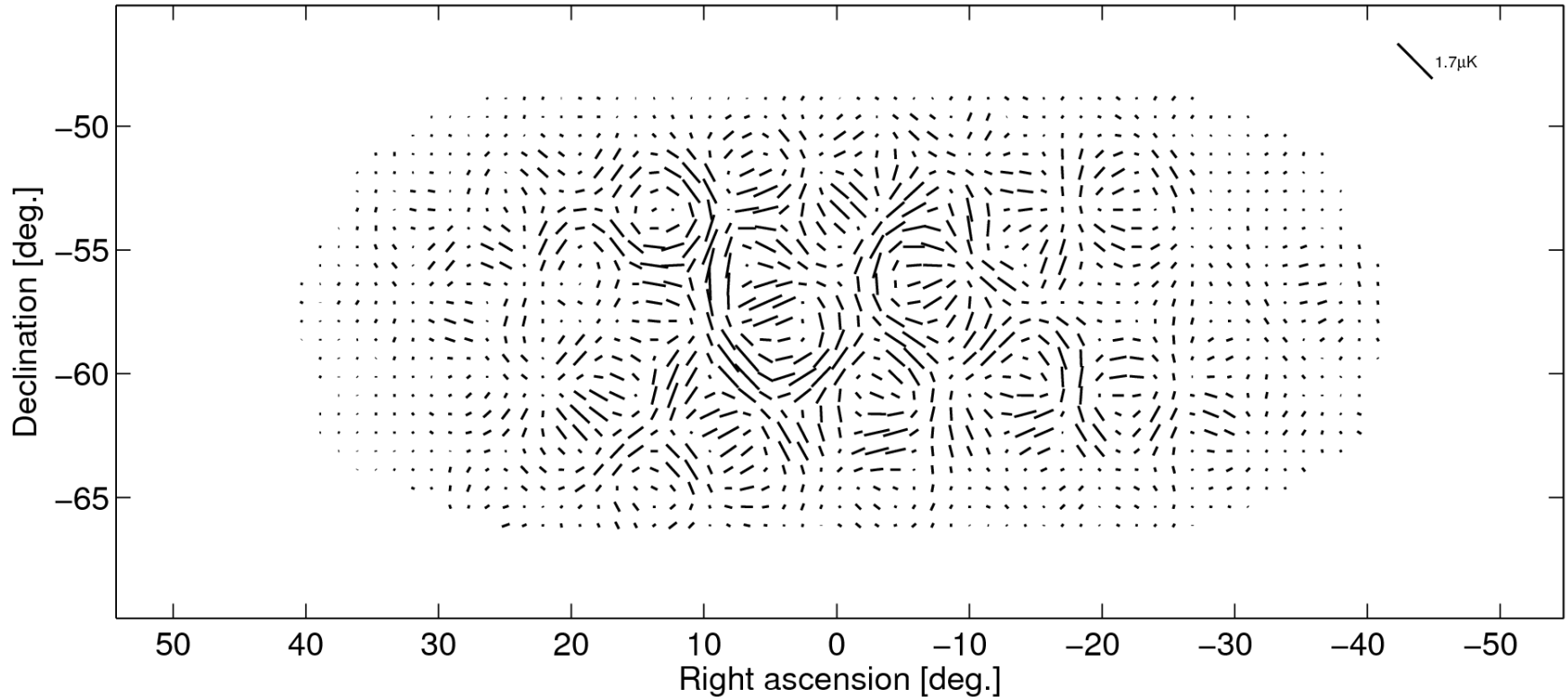
➤ Scanning over lumpy atmosphere  
→ “clouds”

➤ Pair difference still clean  
→ atmosphere is unpolarized

# Total Polarization

BICEP2 total polarization signal

Scale:  $1.7 \mu K$

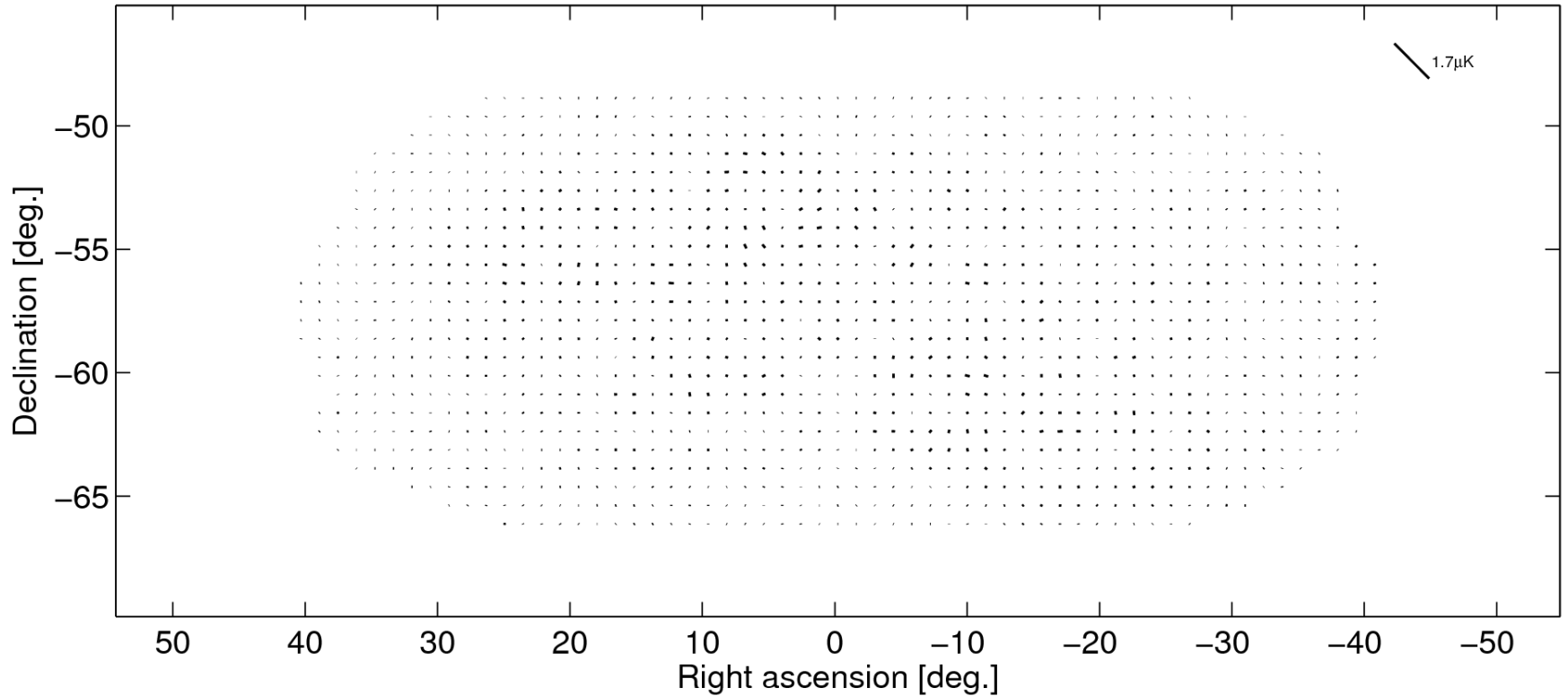


E-mode dominated pattern – no obvious curl component

# B-mode Contribution

BICEP2 B-mode signal

Scale:  $1.7 \mu K$

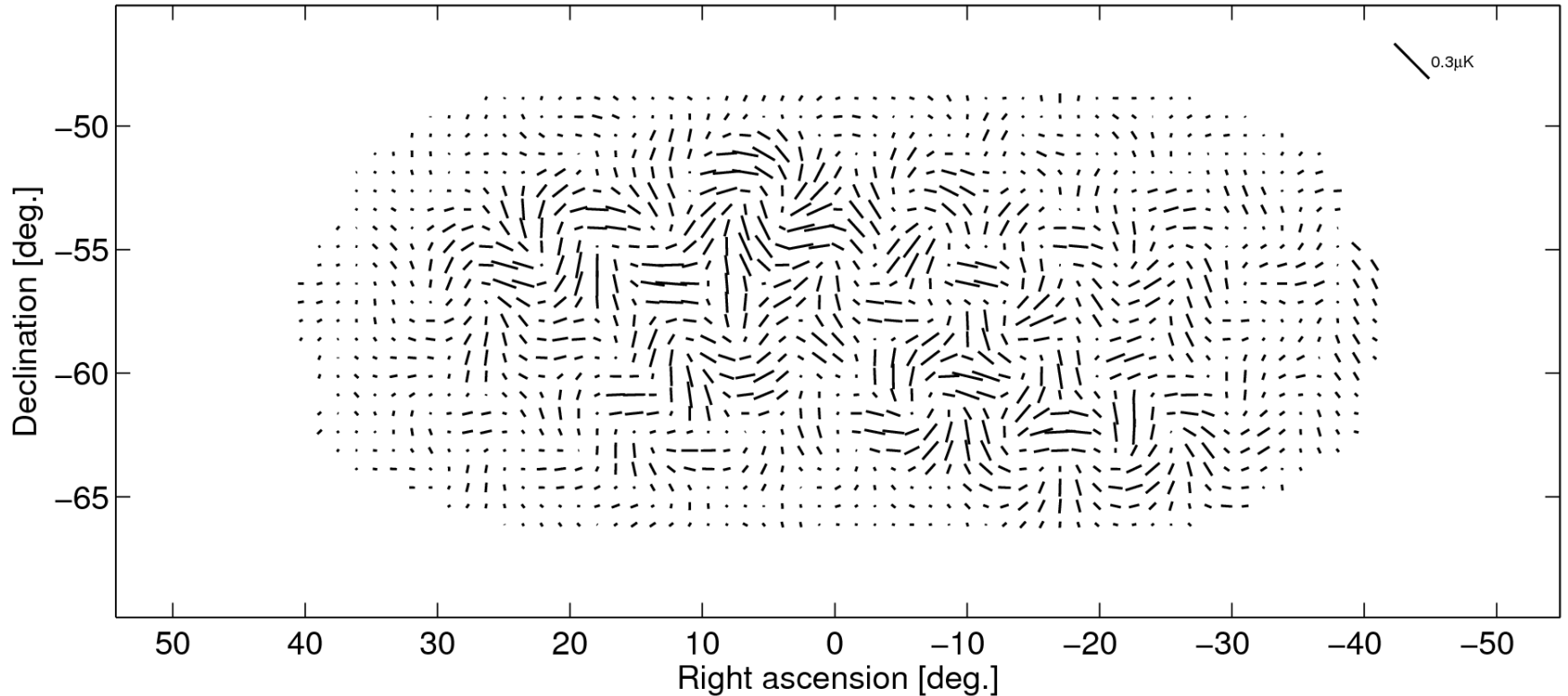


Apply purification operation which leaves only pure B-modes

# B-mode Contribution

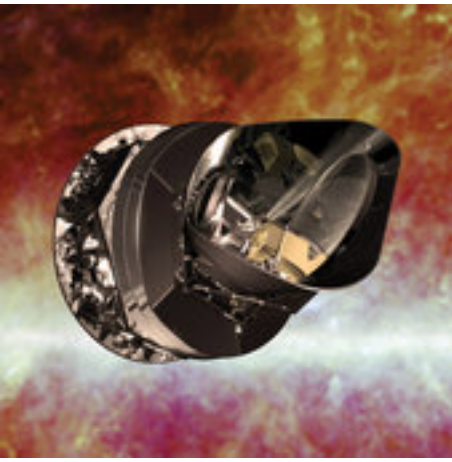
BICEP2 B-mode signal

Scale:  $0.3 \mu K$

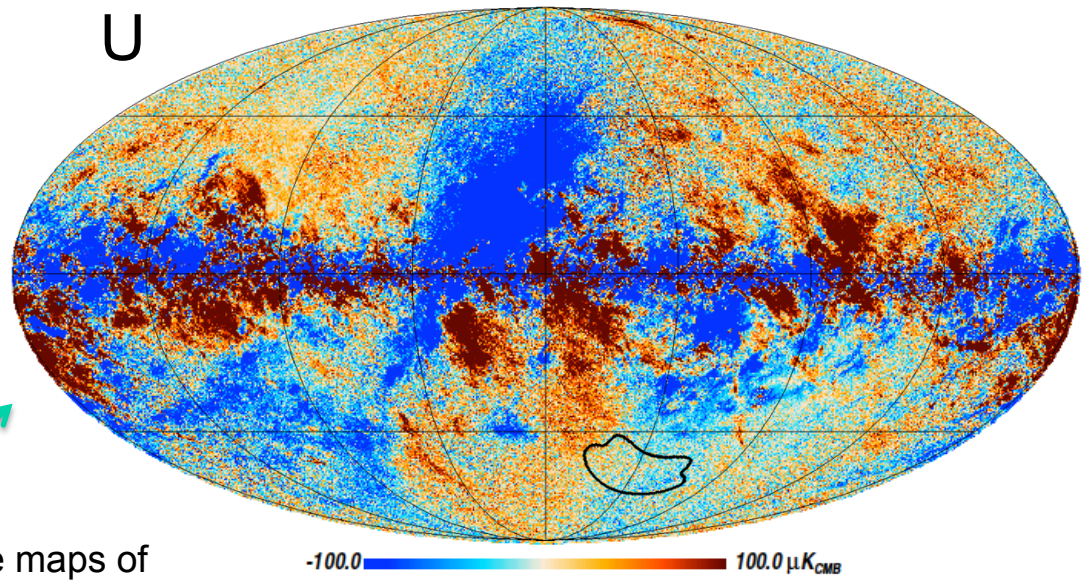
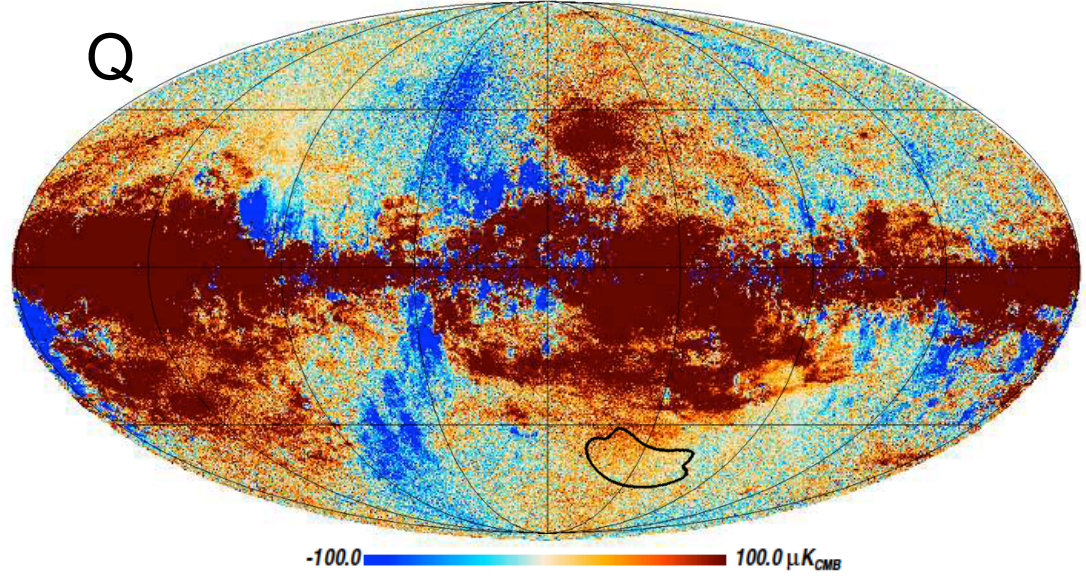


Zoom in by factor 6 – see “swirly” B-mode

# 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

