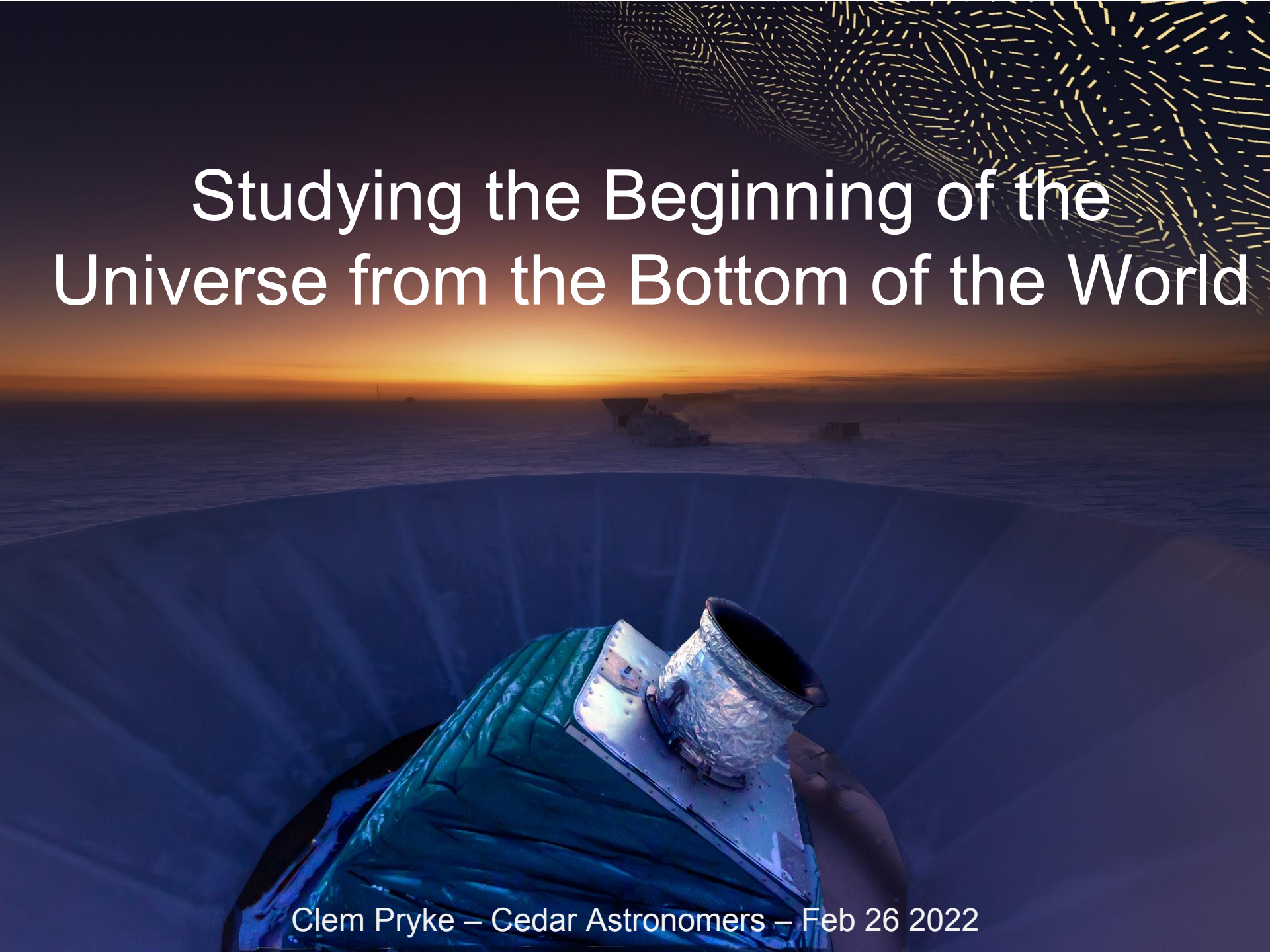
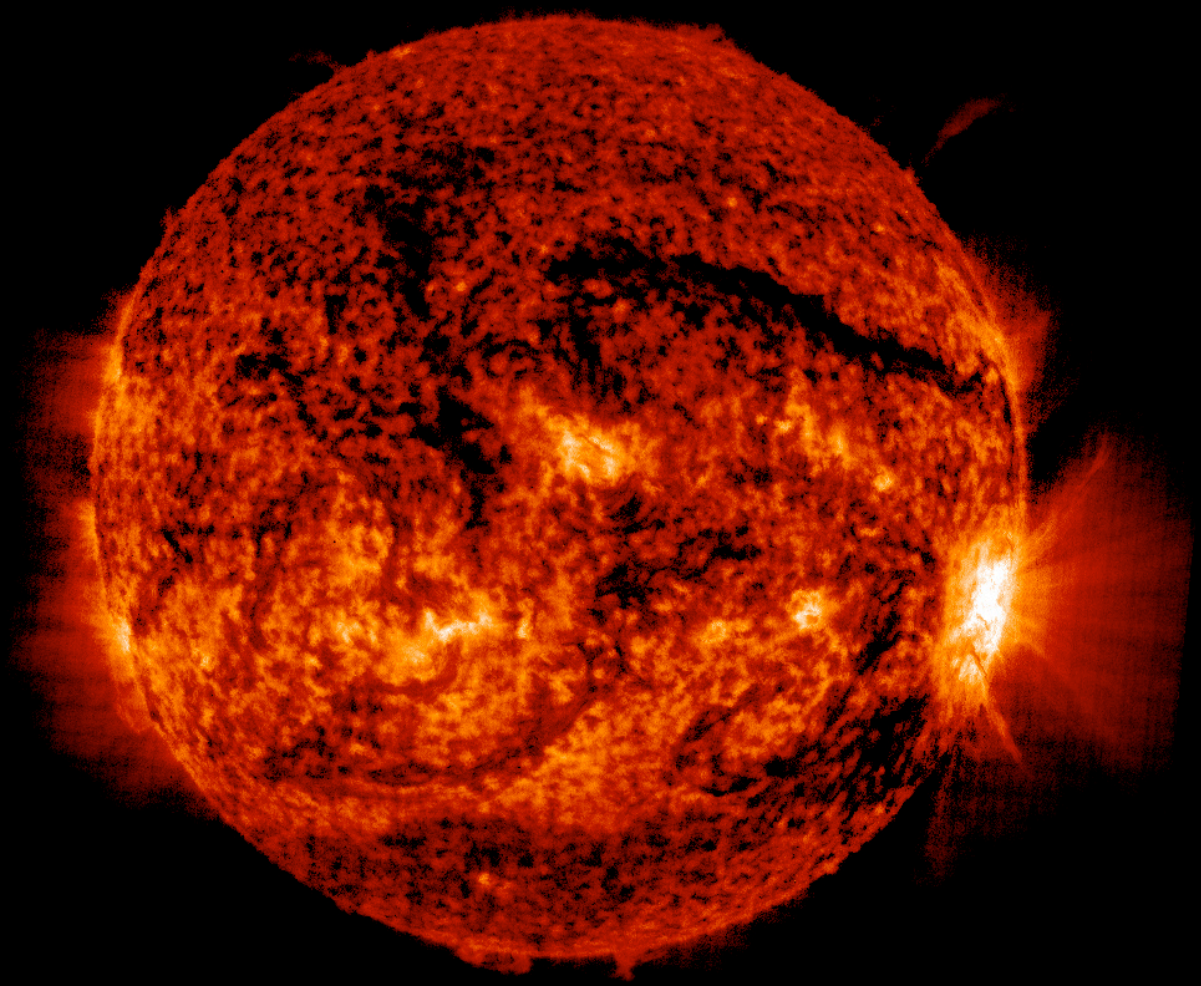
Studying the Beginning of the Universe from the Bottom of the World



Clem Pryke – Cedar Astronomers – Feb 26 2022

Our Sun is a Star

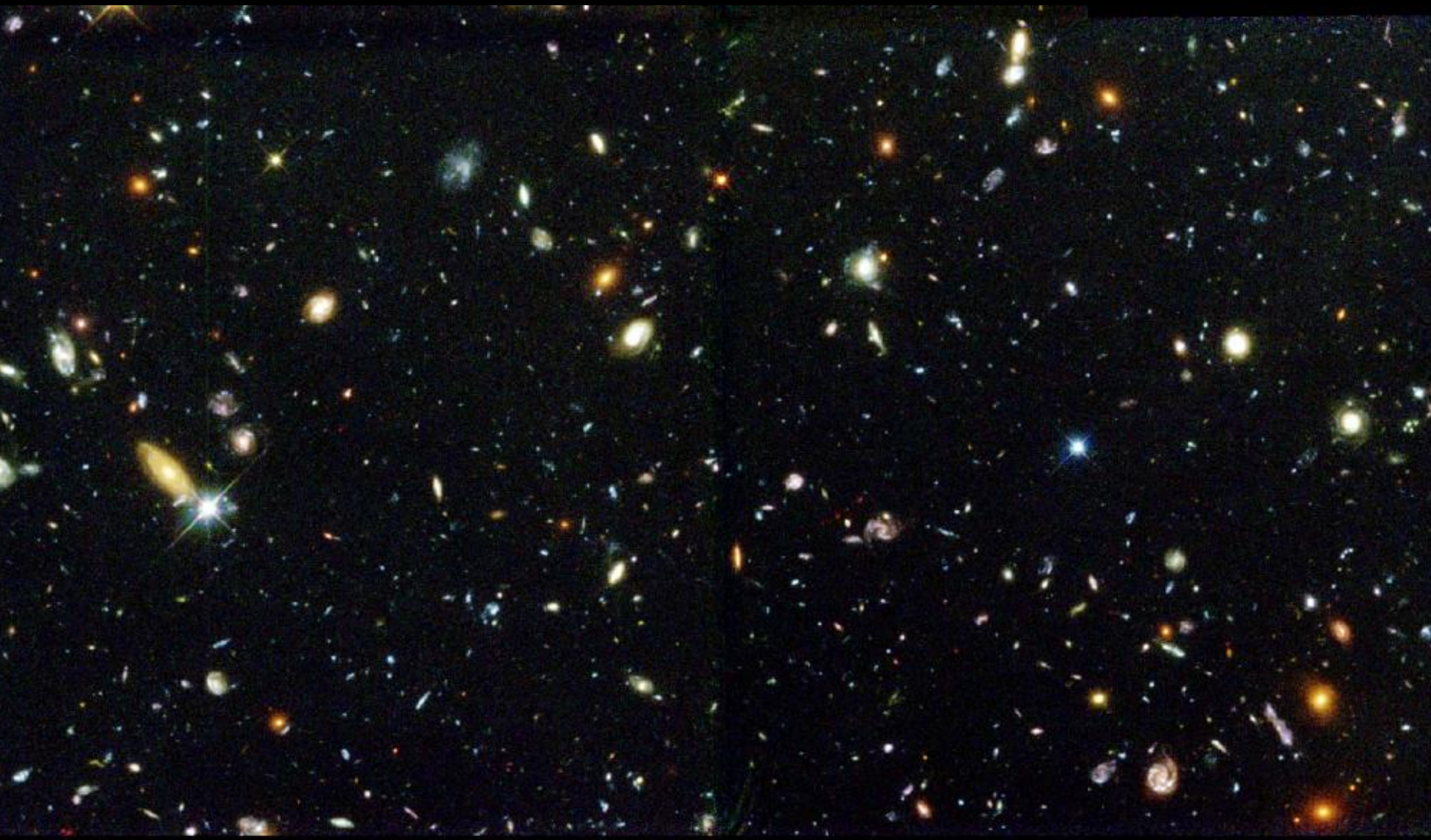


(Just an ordinary star)

…Many stars make a galaxy…

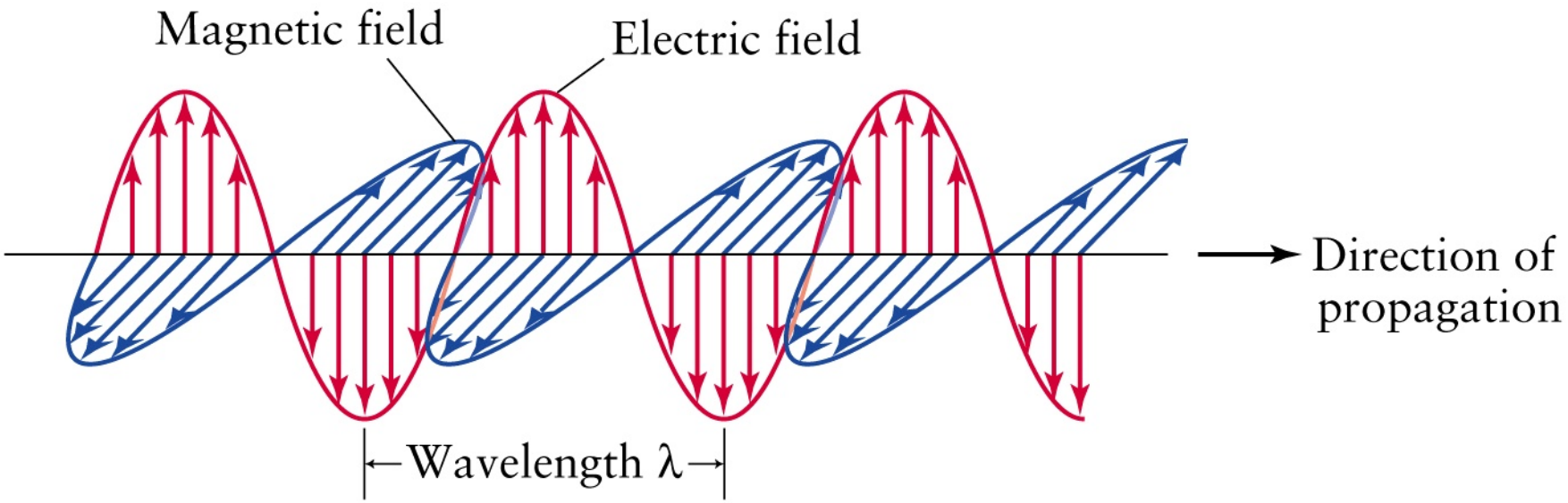
(A nearby galaxy similar to ours)

…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

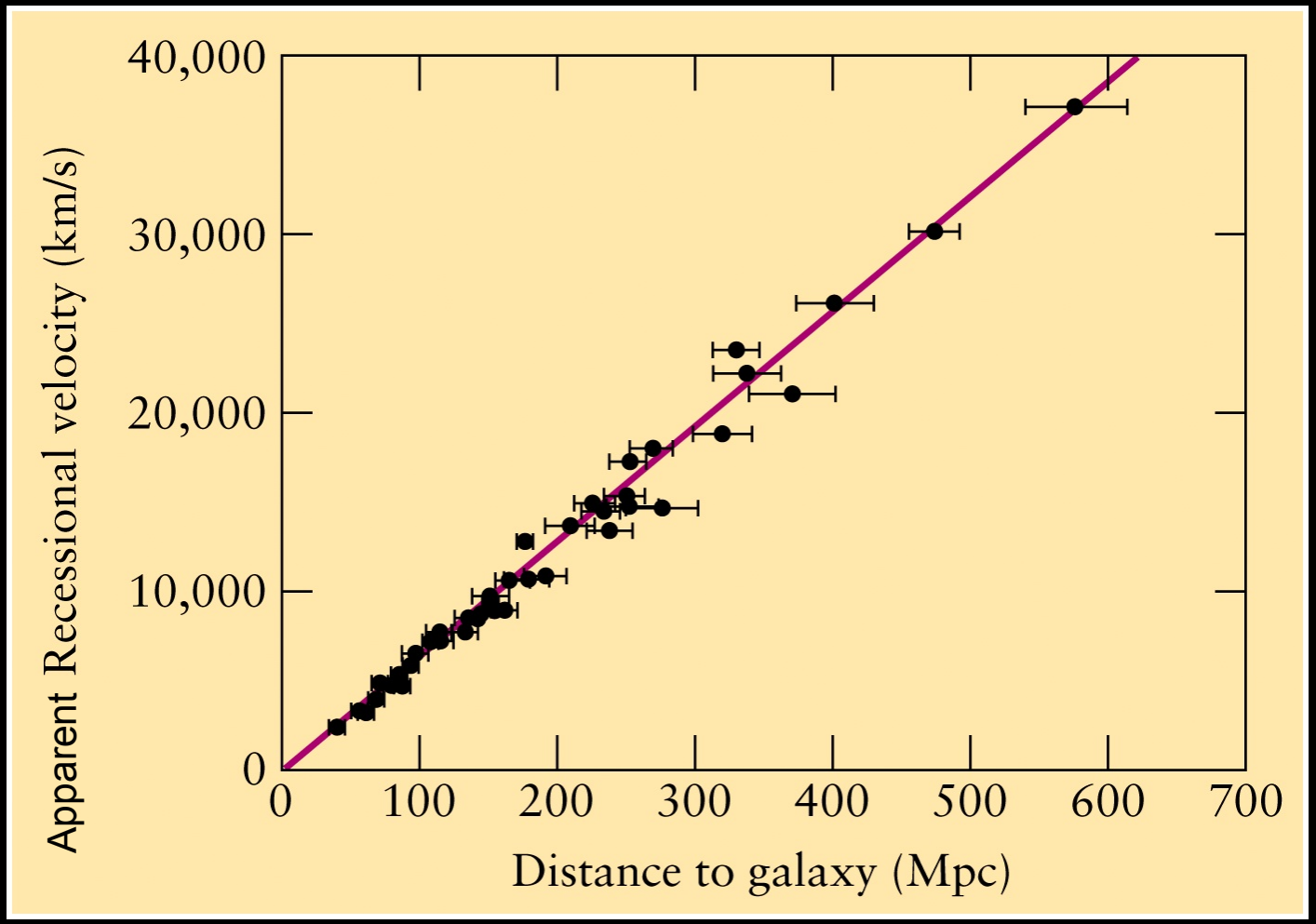
“Classic” Doppler Effect

- 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

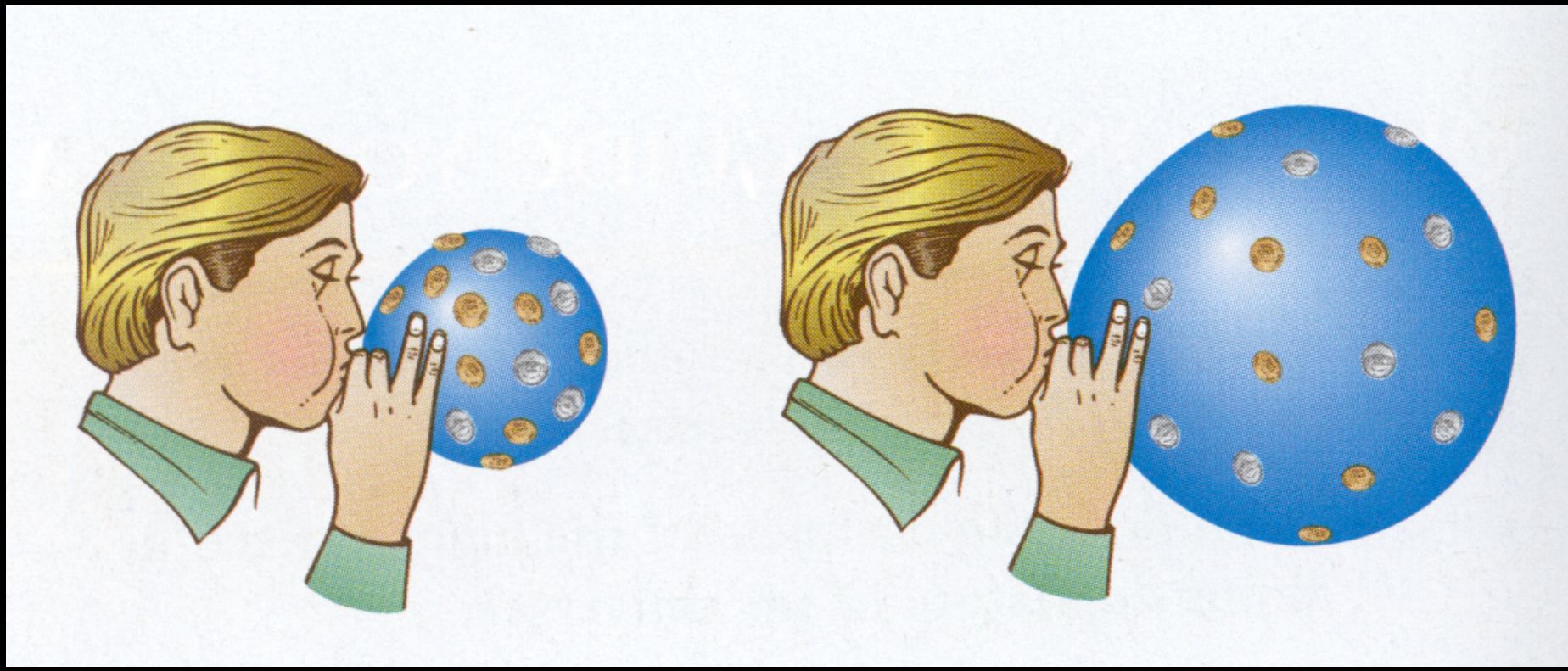
Hubble Diagram



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

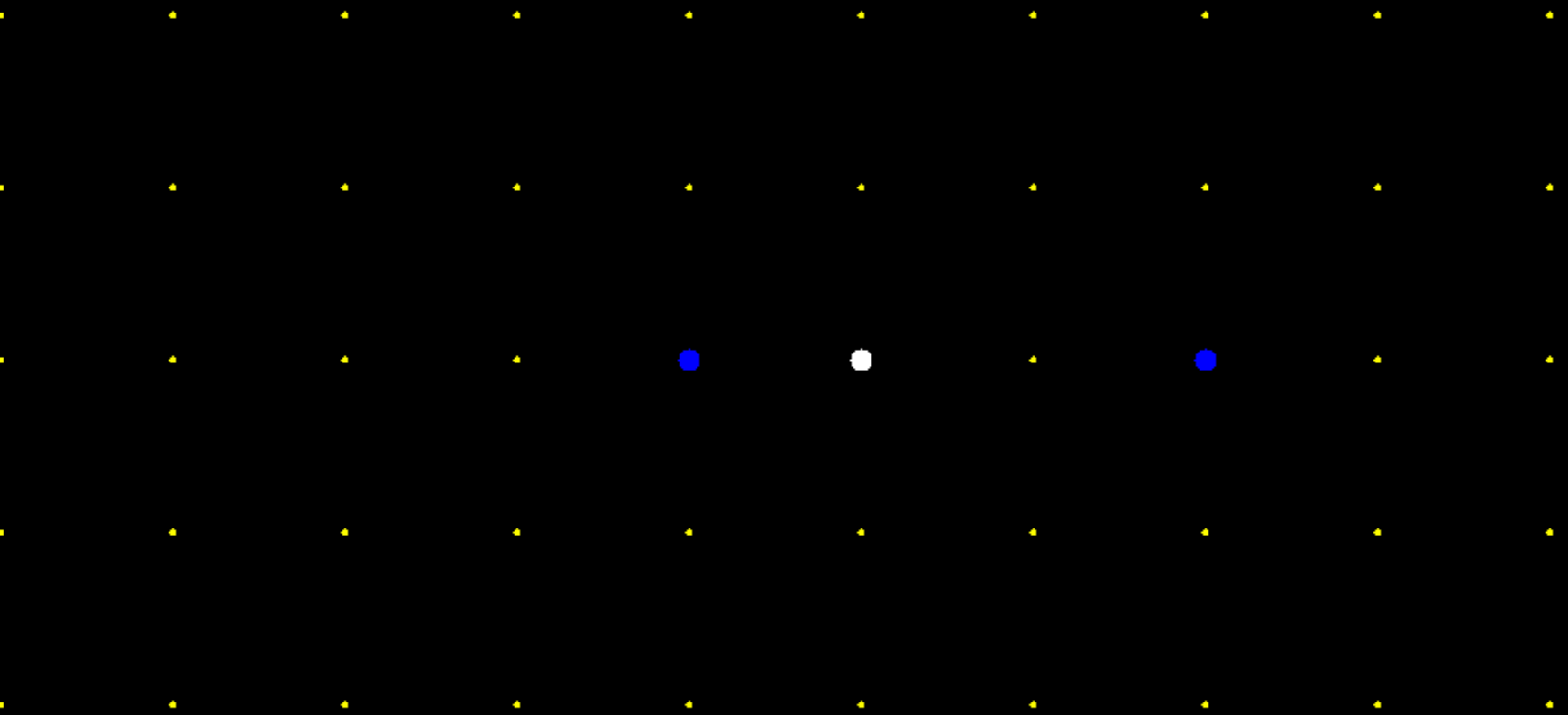
Are we the most unpopular place in the entire Universe?!

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

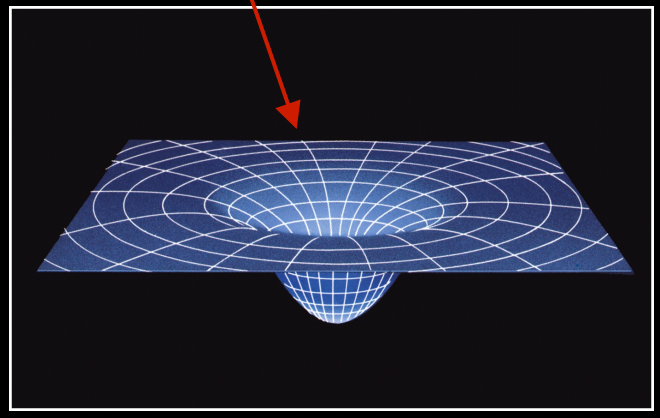


- Light rays stretch with the Universe – called “redshift”
- We see the more distant Universe as it was long ago – and redder

Einstein and General Relativity

In 1915 Albert Einstein devised the General Theory of Relativity

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



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

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

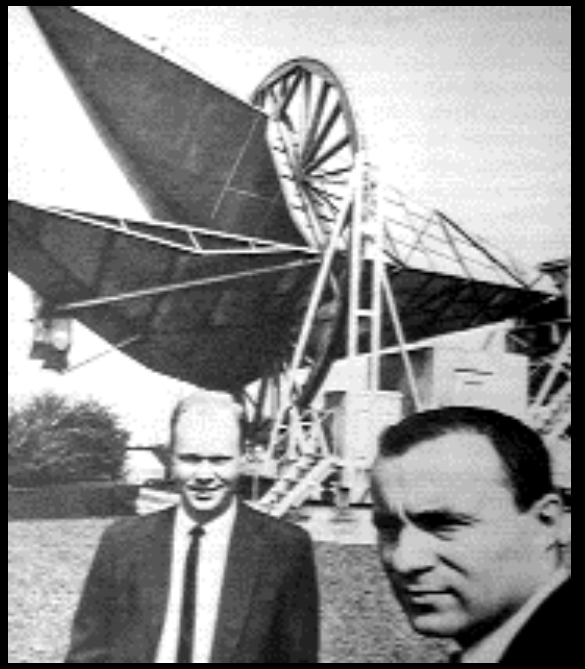
Modern cosmology in a nutshell:

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)

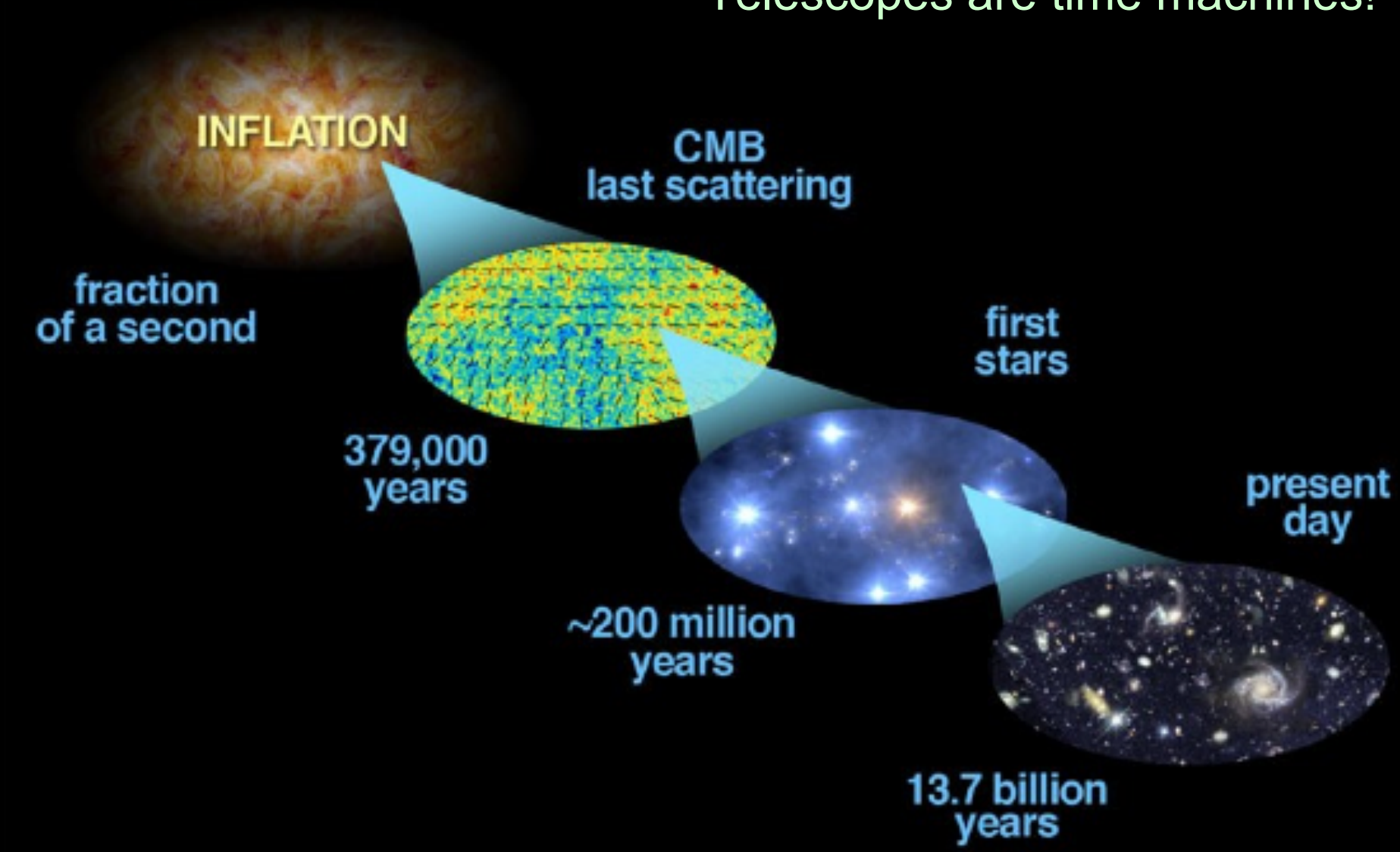


Bob Wilson & Arno Penzias
1978 Nobel Prize

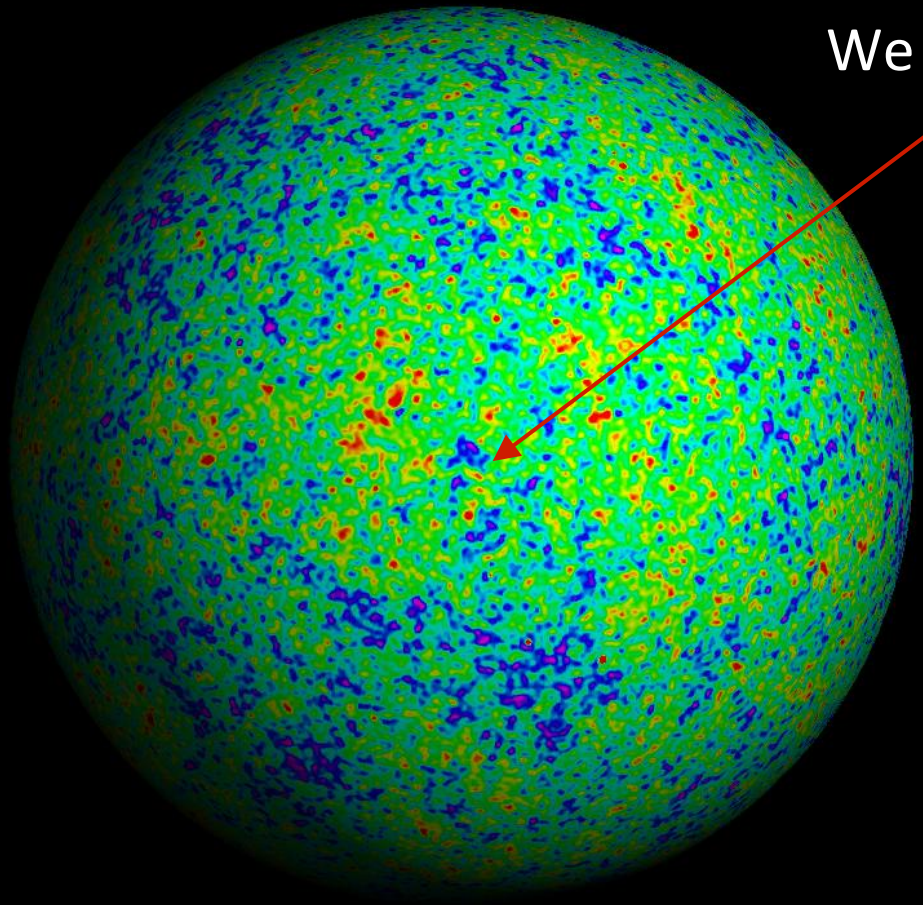
3) We can see the glow from that time!
The *Cosmic Microwave Background*
(Penzias & Wilson, 1964)

⇒ discovery lead to acceptance of the "HOT BIG BANG"

Telescopes are time machines!

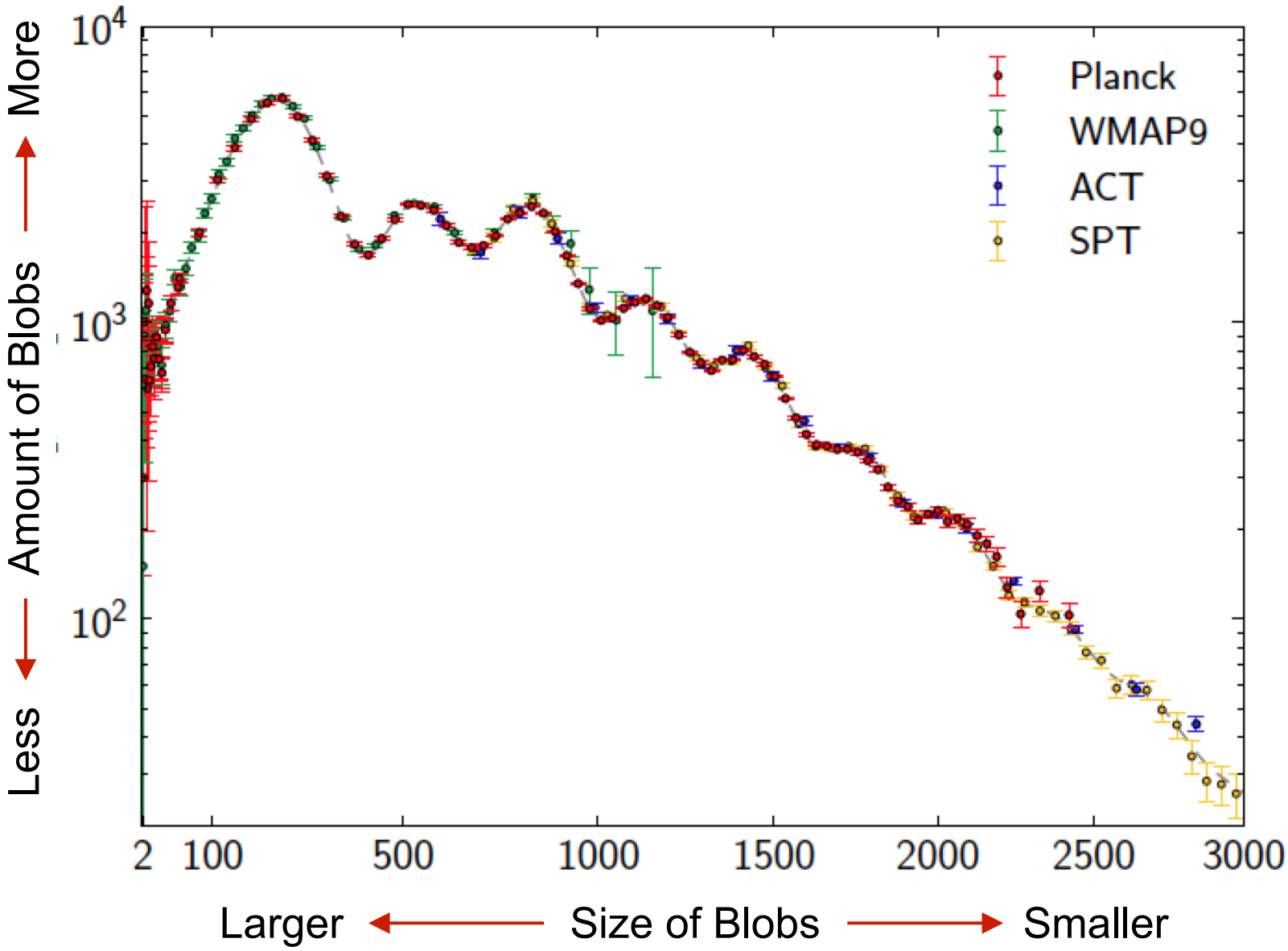


All Sky Map of the Cosmic Microwave Background



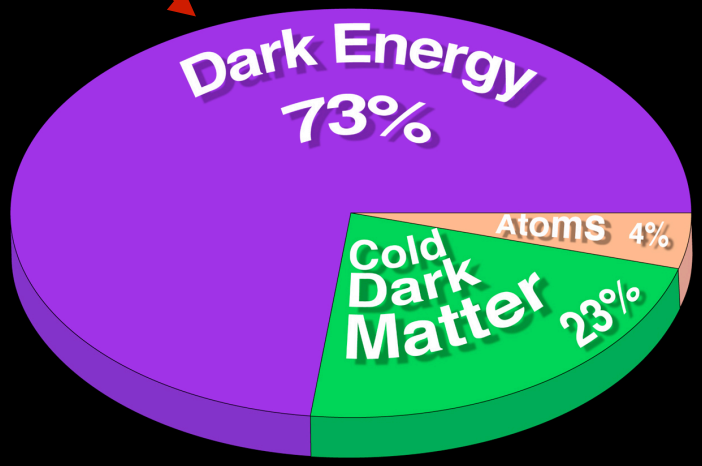
CMB is a sample of the density structure on a shell cut through the 380,000 year old Universe – at that time it was simple and nearly uniform

“Lump Sorter” Plot

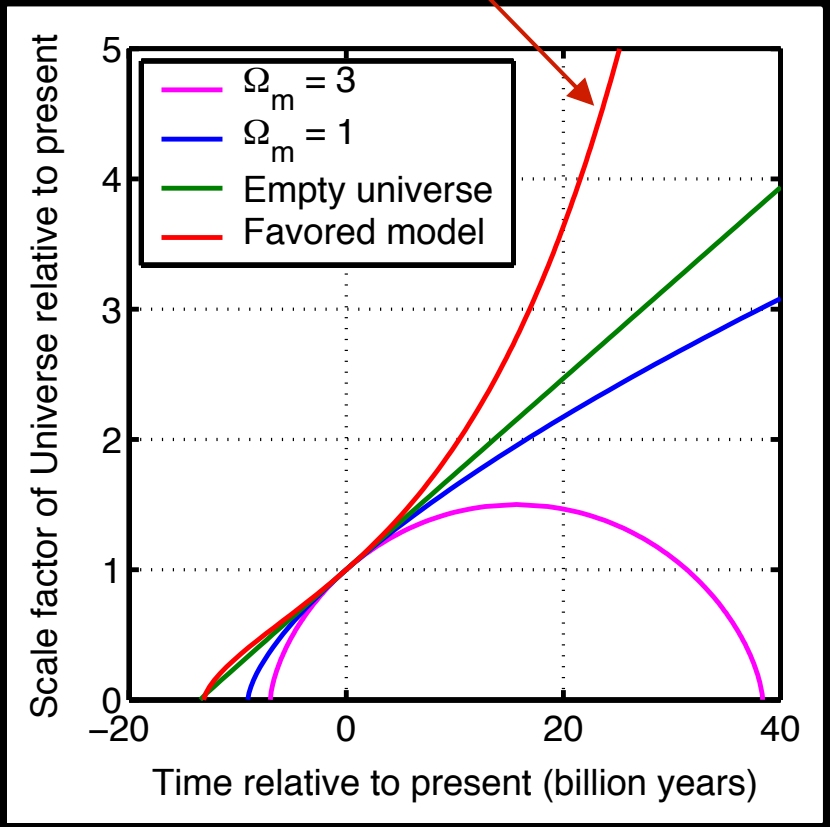


Triumphant/Embarrassing Cosmology

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…



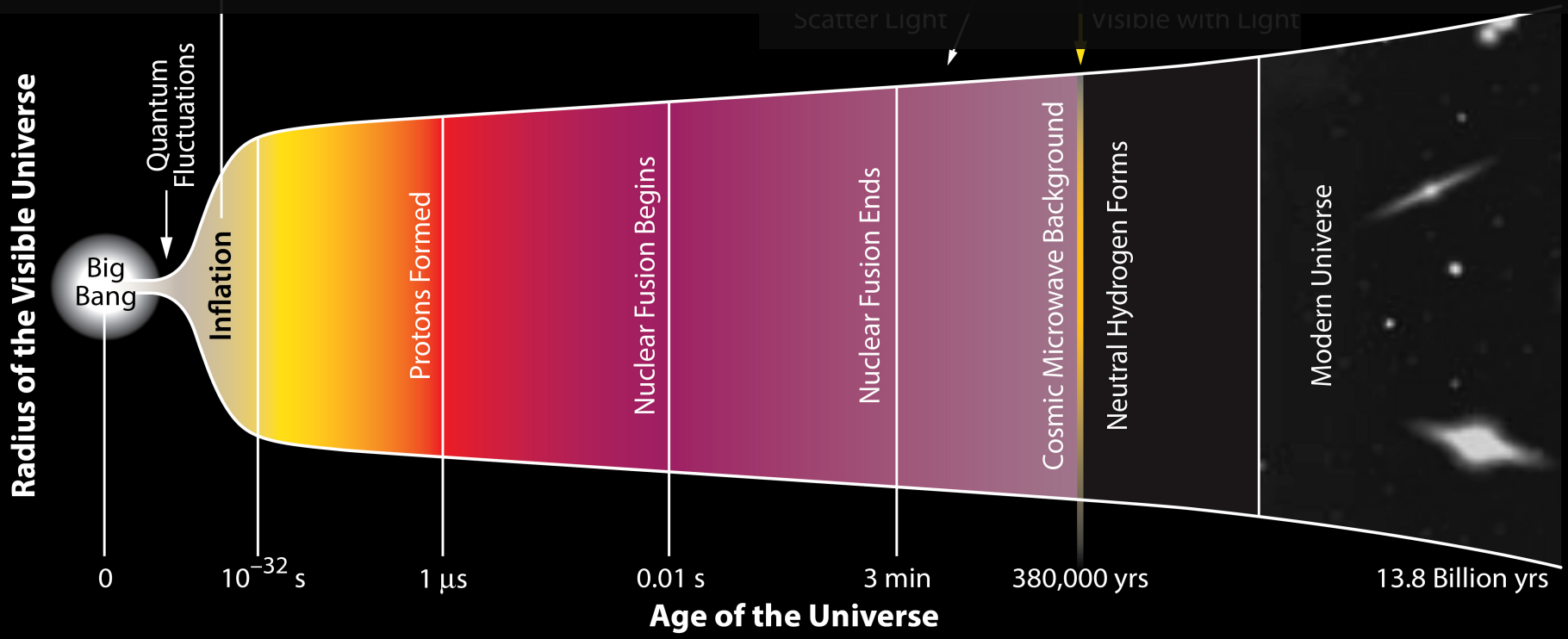
Also it doesn't explain the initial conditions…

History of the Universe

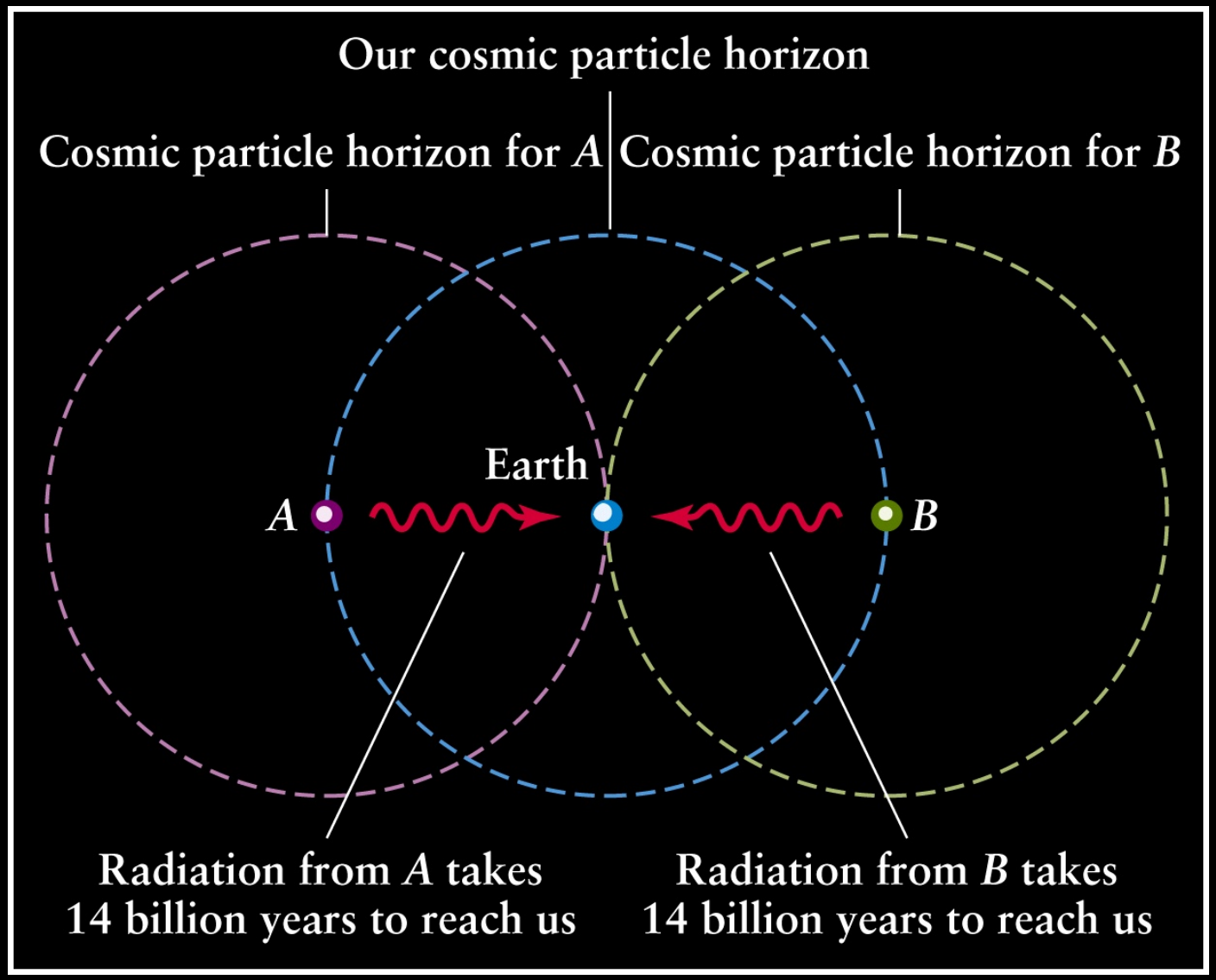
Inflation proposed to explain
Horizon and Flatness problems

Alan Guth

Andrei Linde

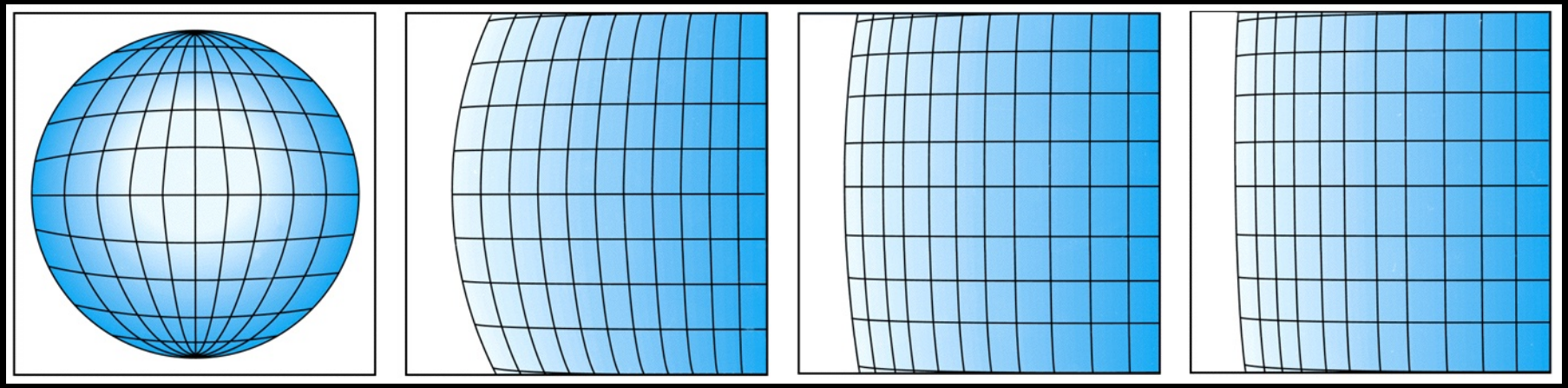


Inflation solves the "Horizon Problem"



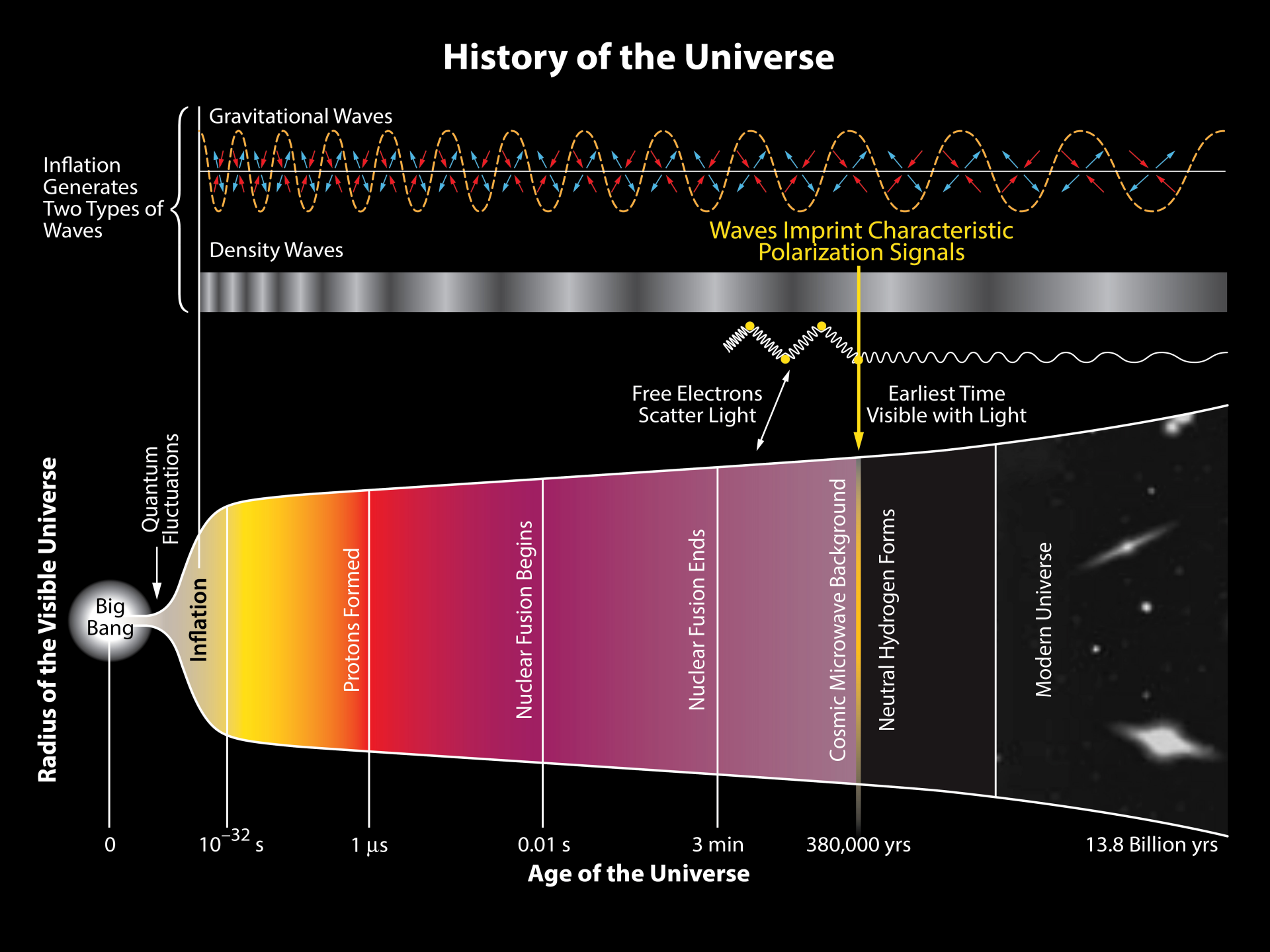
How did points A and B "know" to be at the same temperature at 380,000 years?

Inflation solves the “Flatness Problem”

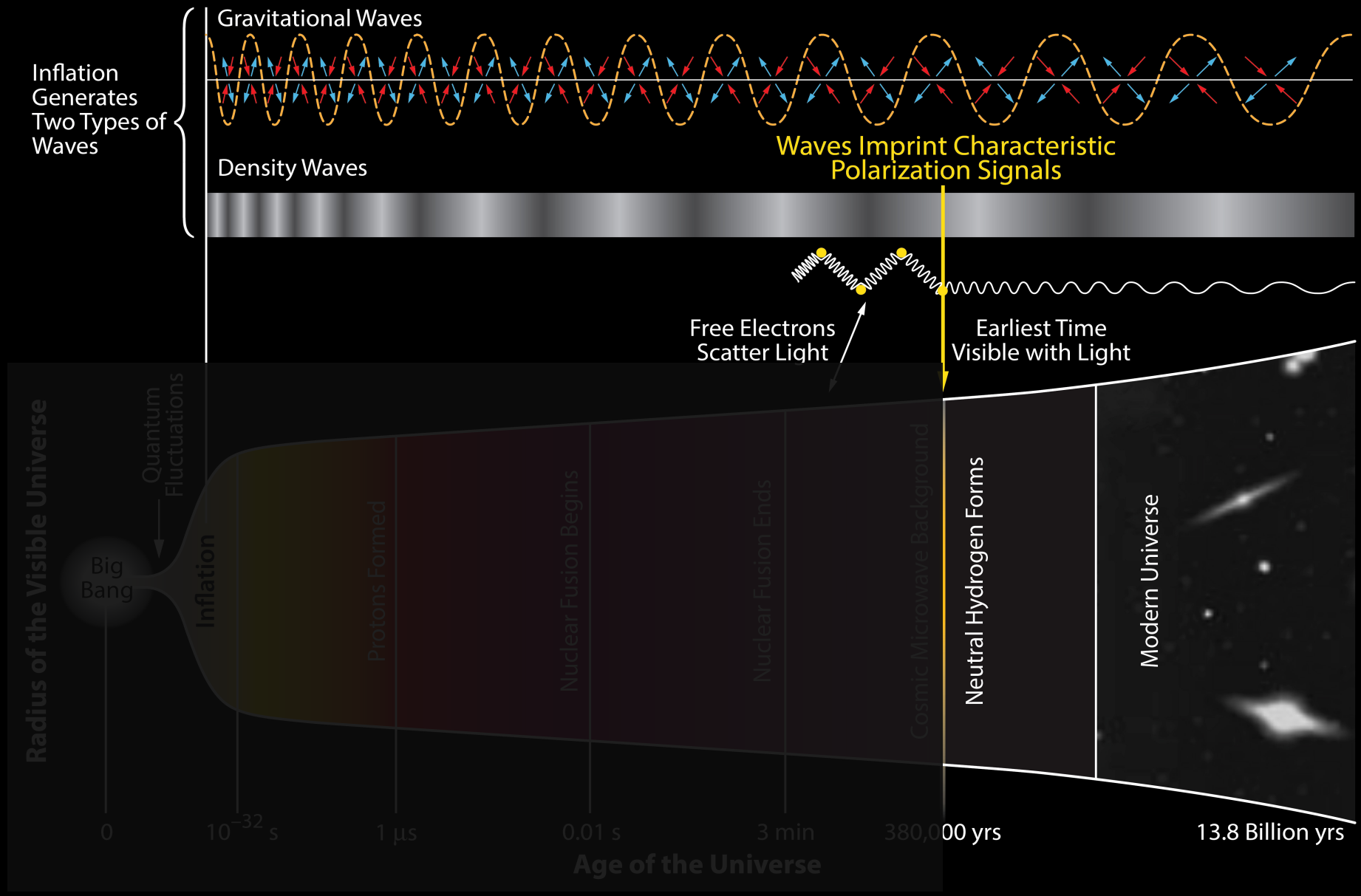


Inflation…

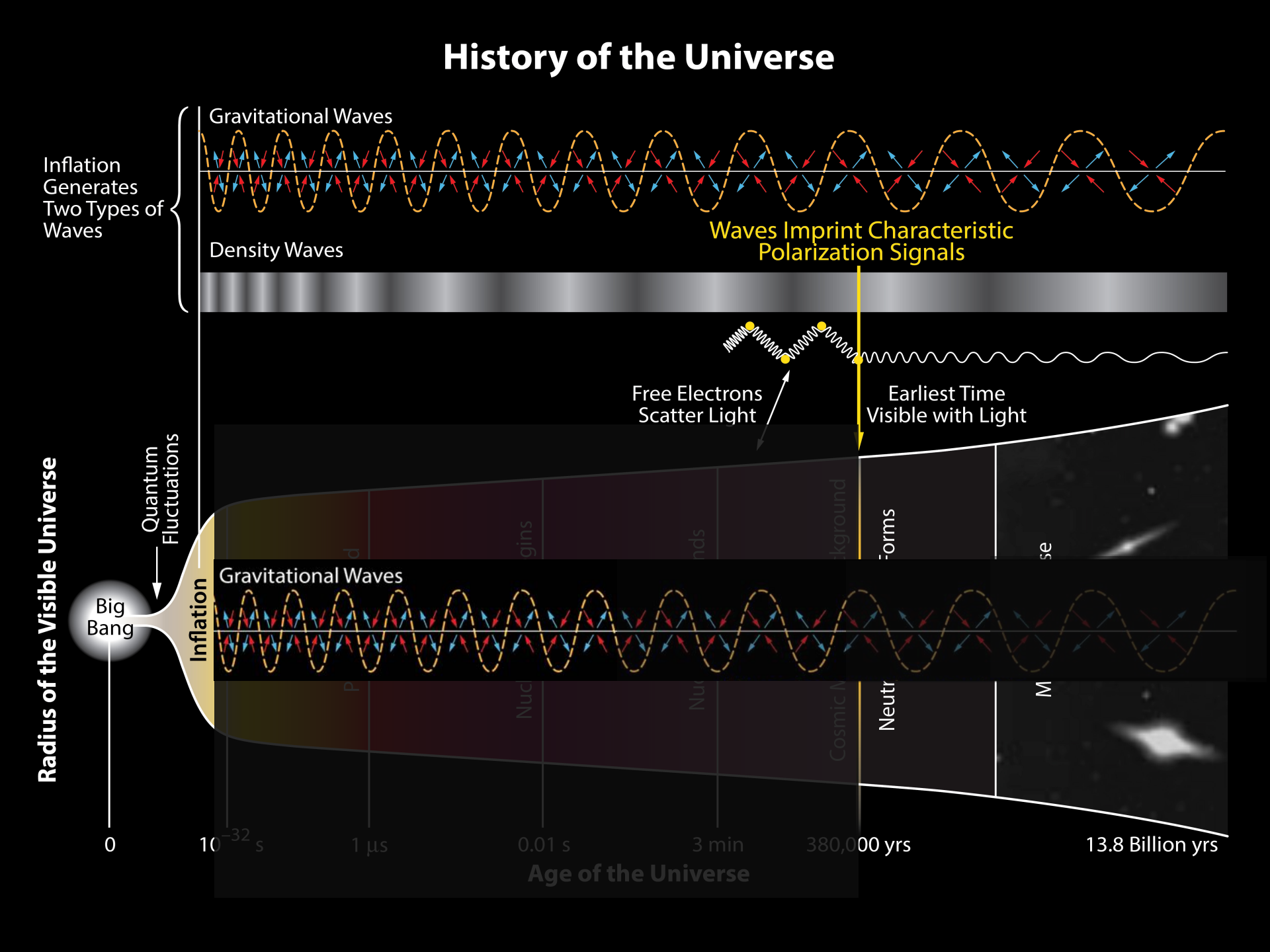
If you take some curved space and blow it up enough pretty soon it is no longer curved on a local scale – like our entire observable Universe!


History of the Universe
Inflation Generates Two Types of Waves
Gravitational Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Radius of the Visible Universe
Quantum Fluctuations
Big Bang
Inflation
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Neutral Hydrogen Forms
Modern Universe
0
10−32 s
1 μs
0.01 s
3 min
380,000 yrs
13.8 Billion yrs
Age of the Universe

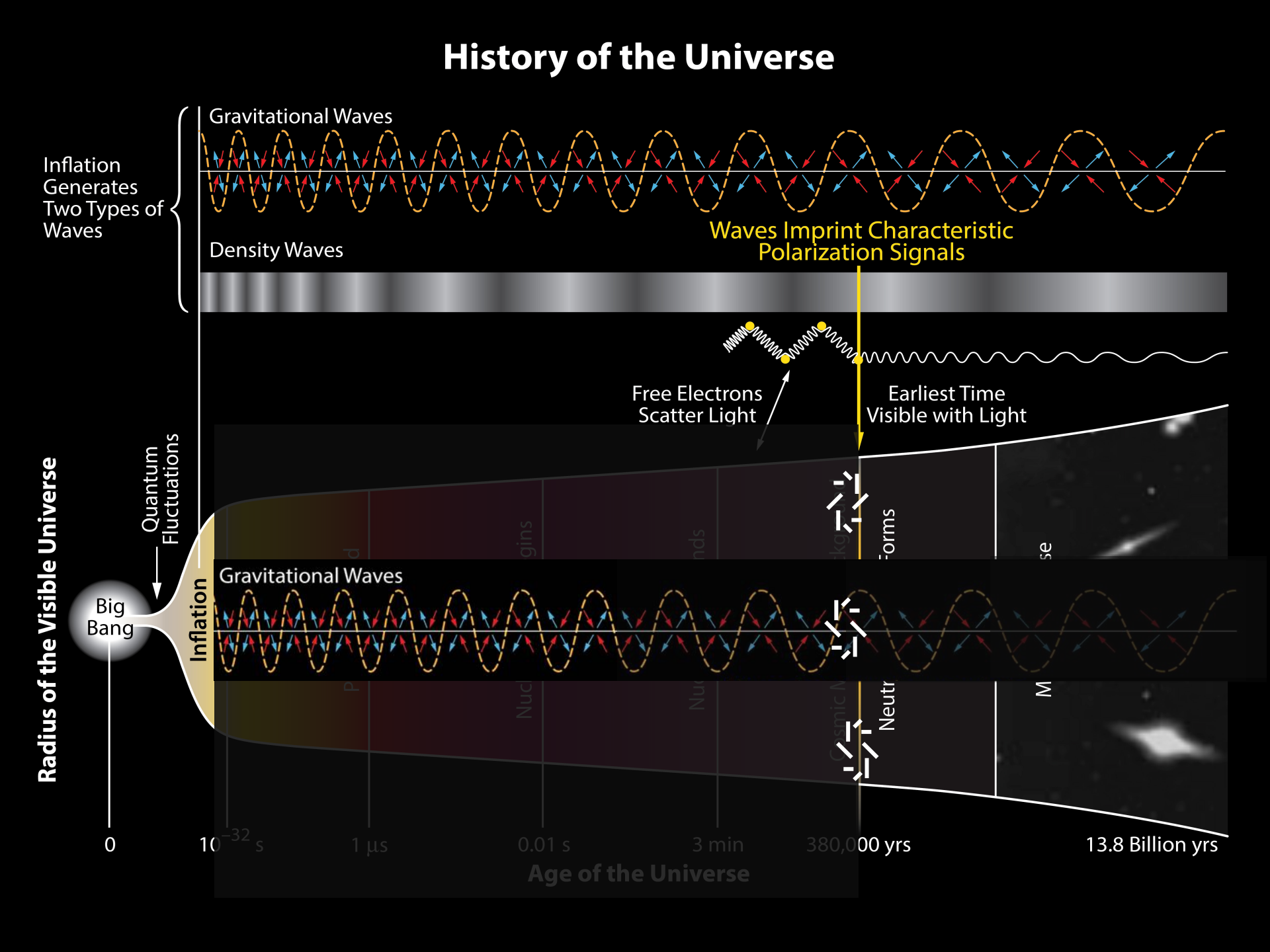
History of the Universe



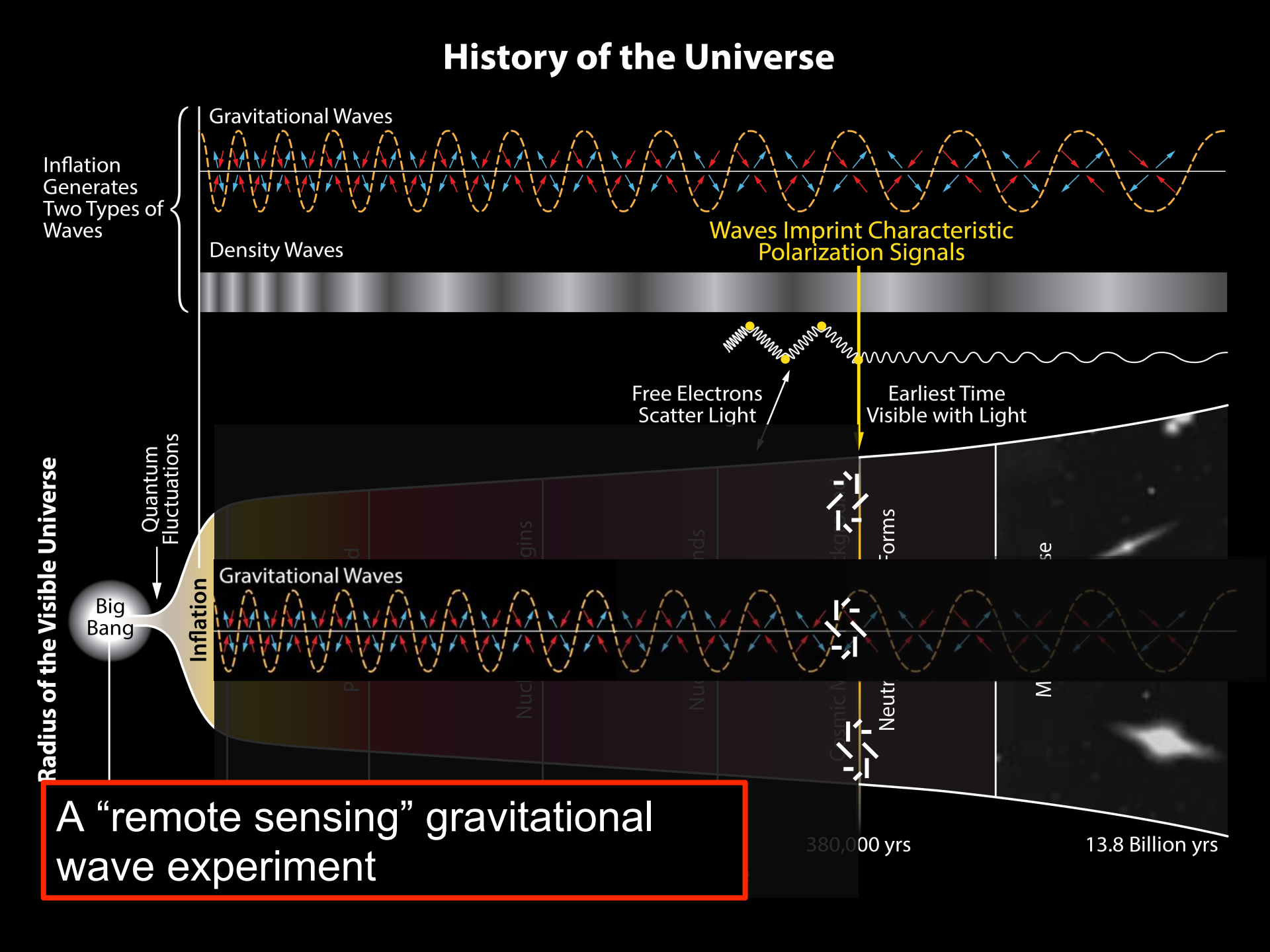
History of the Universe



History of the Universe

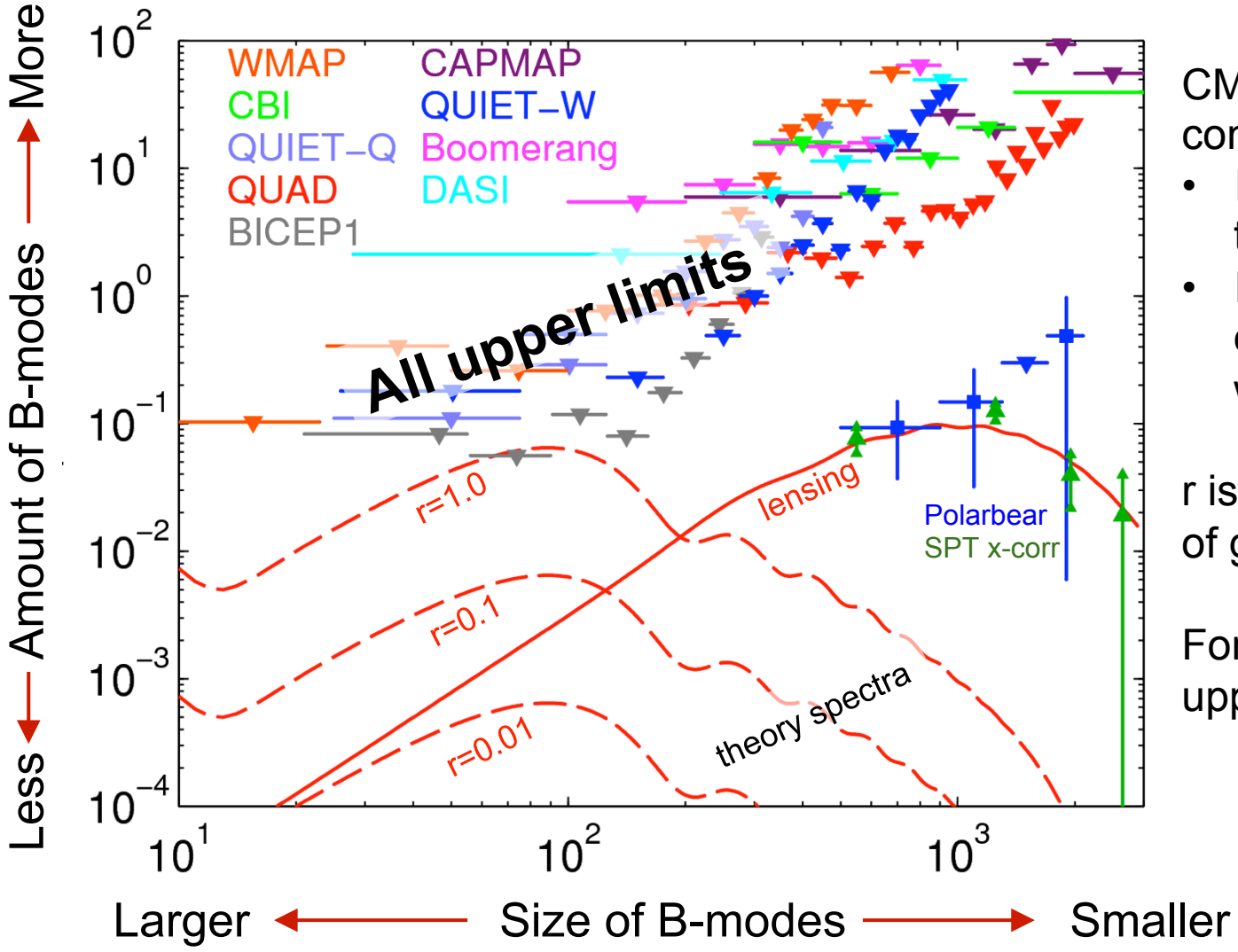


History of the Universe



A “remote sensing” gravitational wave experiment

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…

Clem Pryke for The Bicep2 Collaboration

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

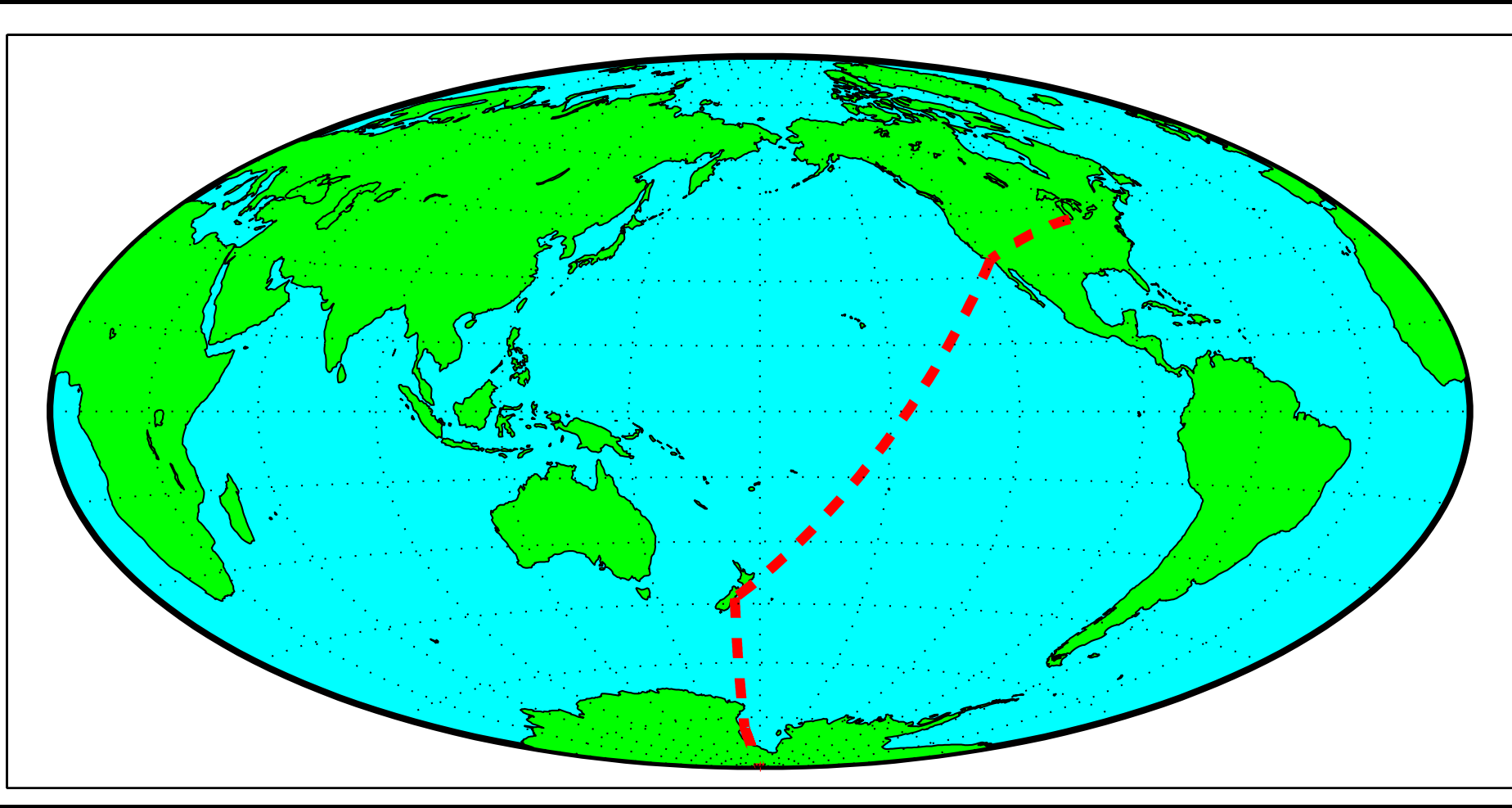
Anna Ijjas,[1,2] Paul J. Steinhardt,[3] and Abraham Loeb[4]

[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

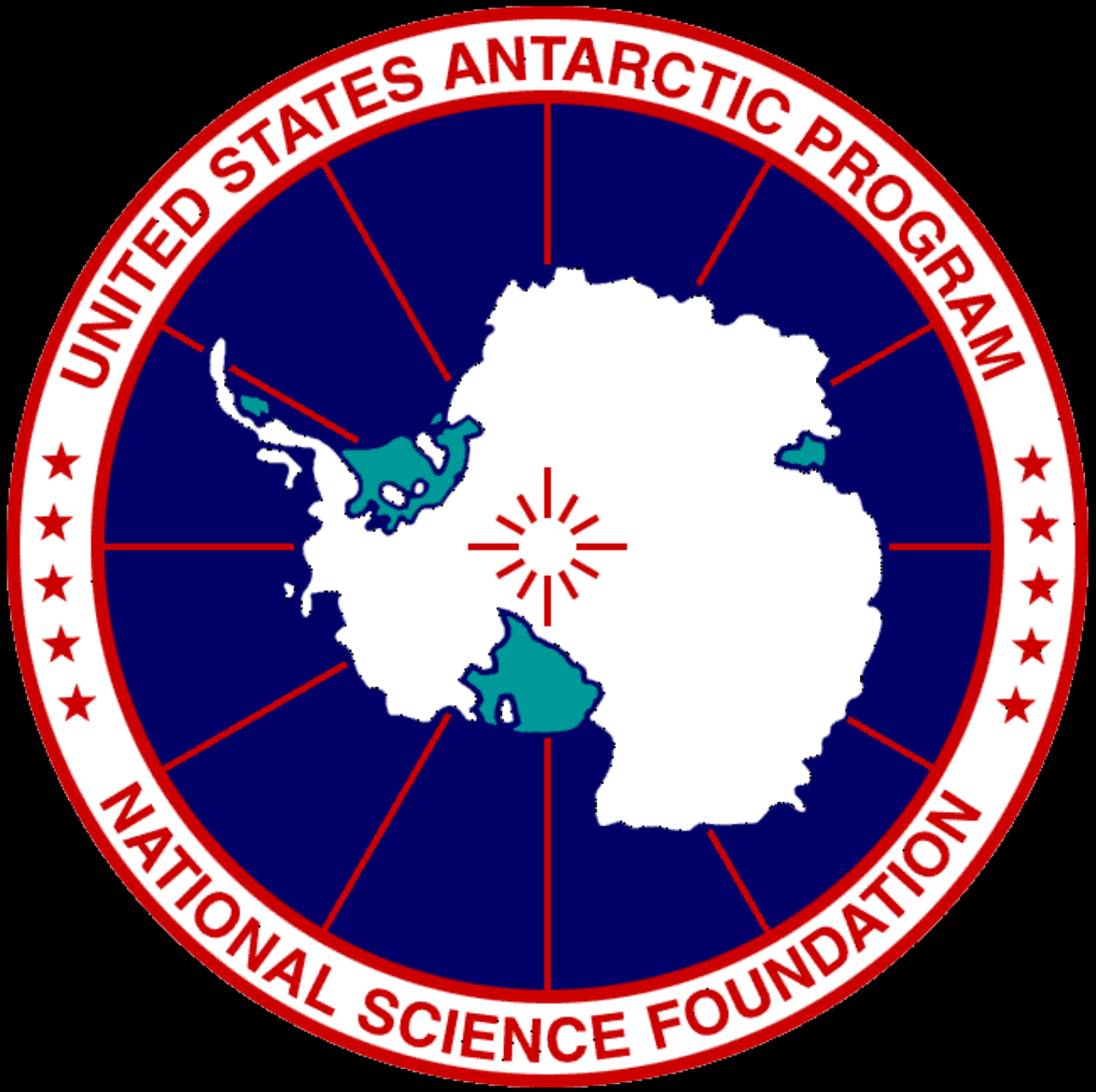
Journey to the South Pole



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

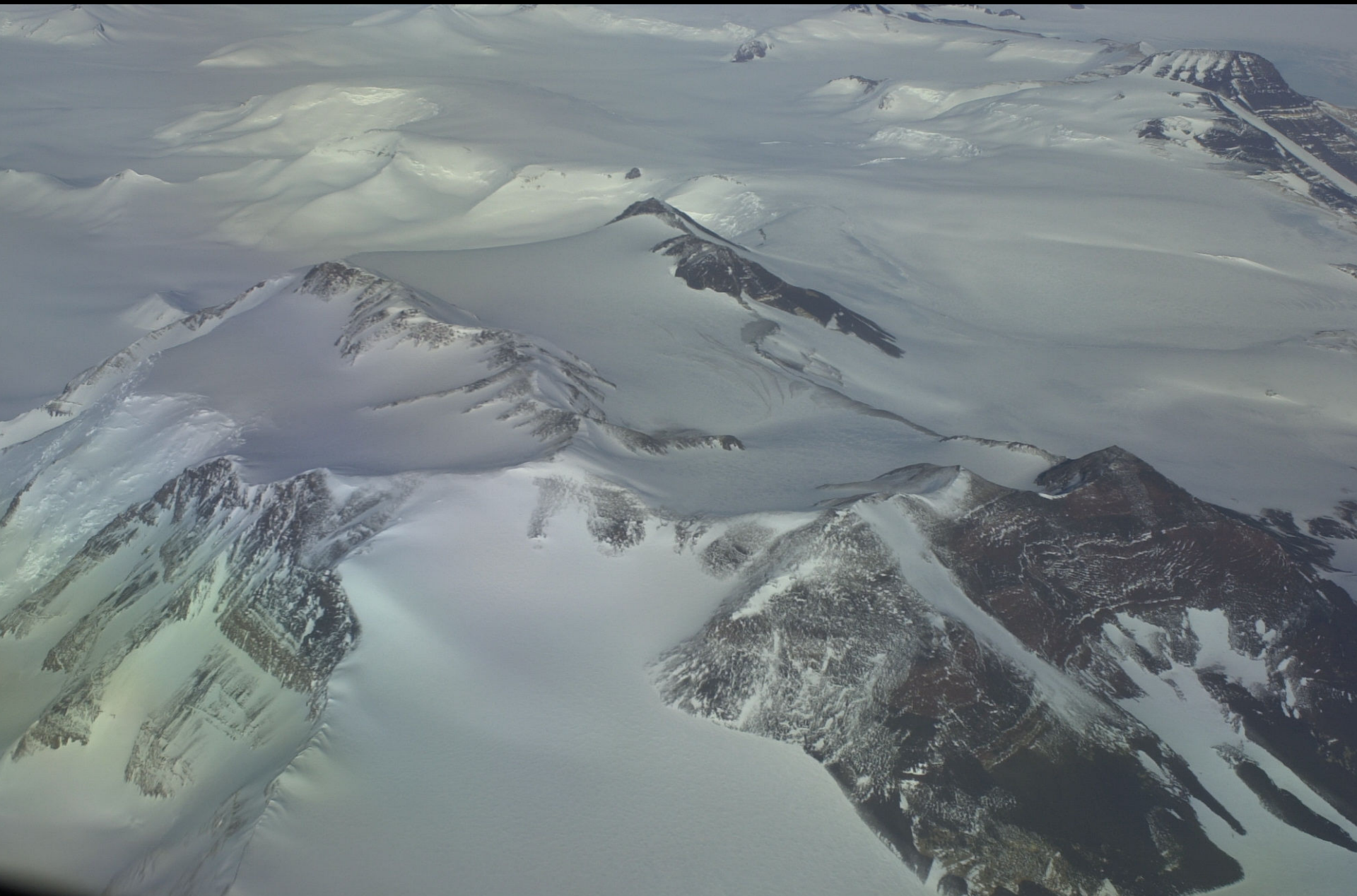
Christchurch New Zealand – Clothing Warehouse

Big Program!

Arrival in Antarctica

McMurdo – base on the coast

On to the Pole – over the Transantarctic Mountains

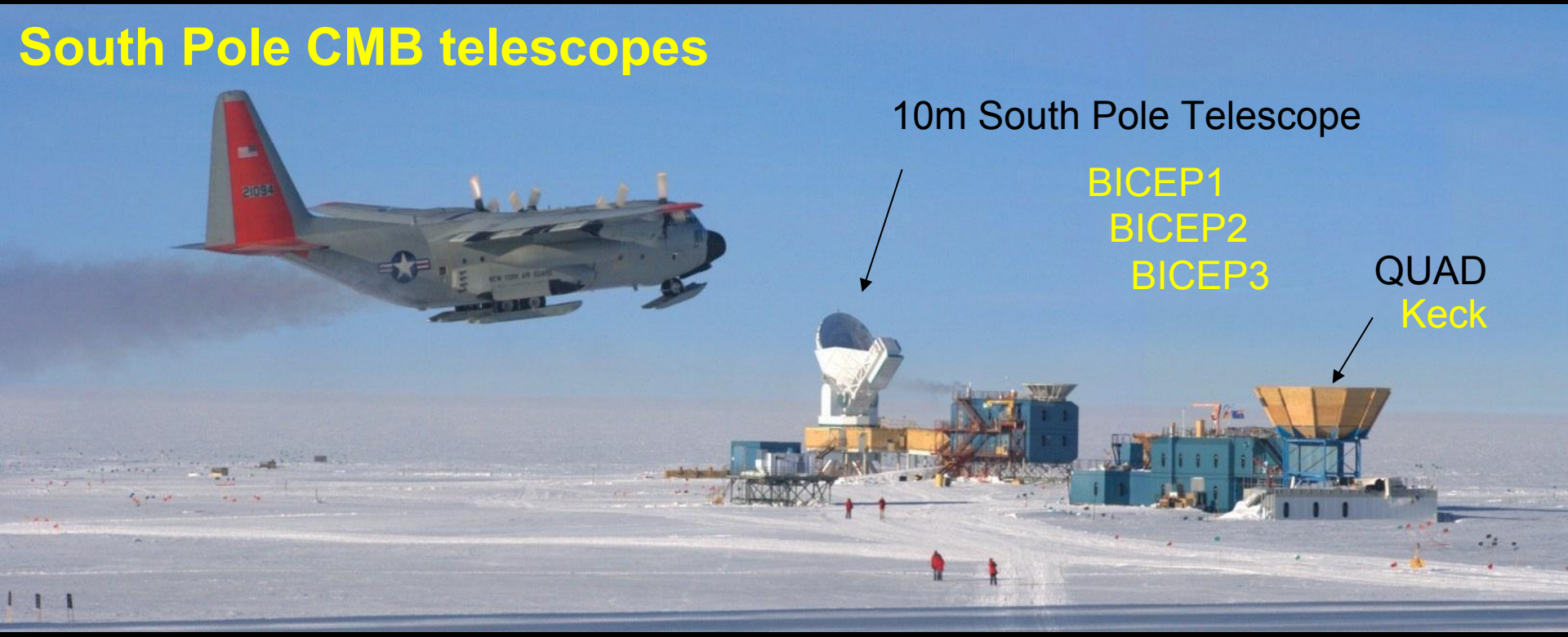


Unloading at Pole

The Actual South Pole

Nothing Out There!

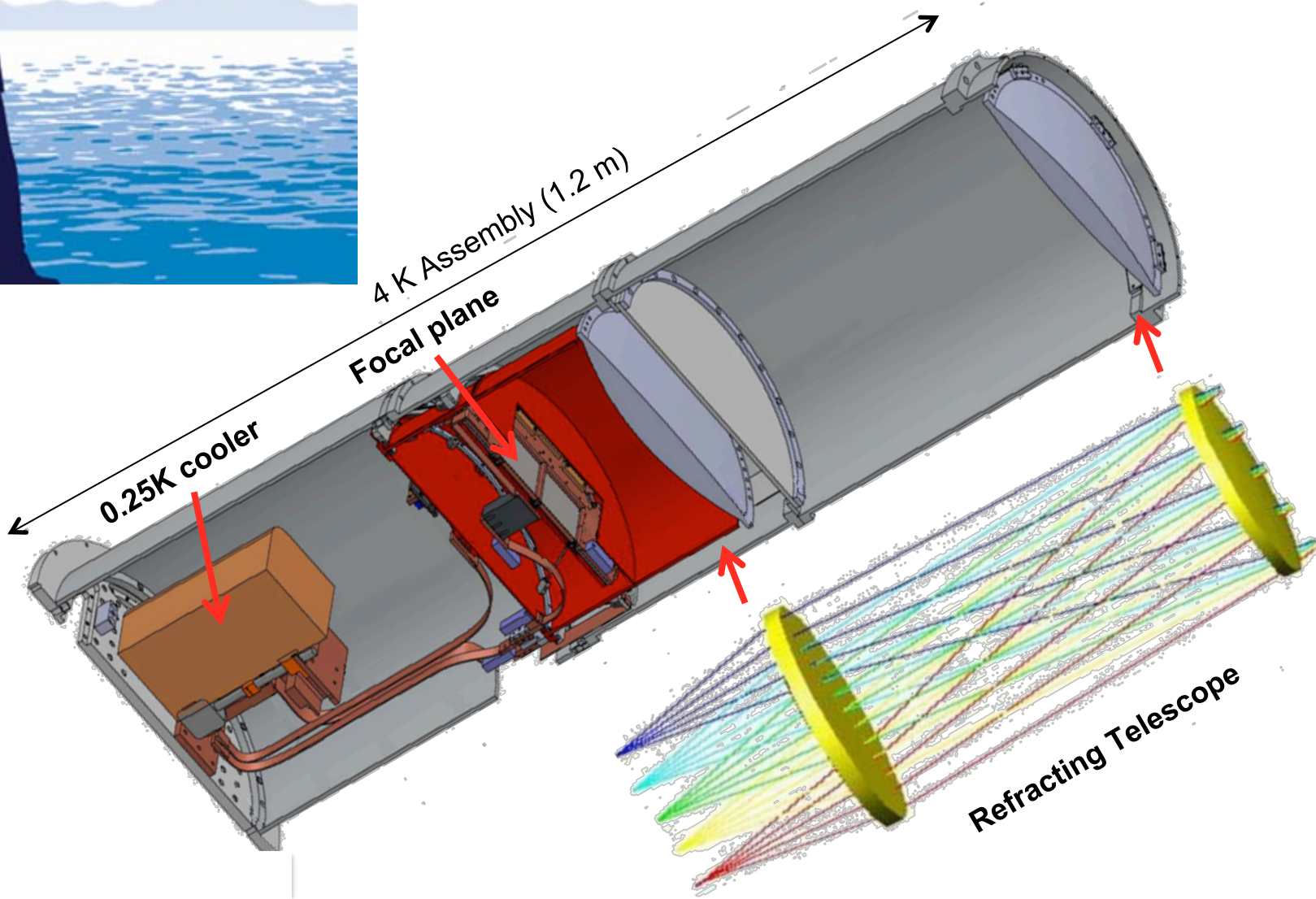
Why do this at the Pole?



- 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…

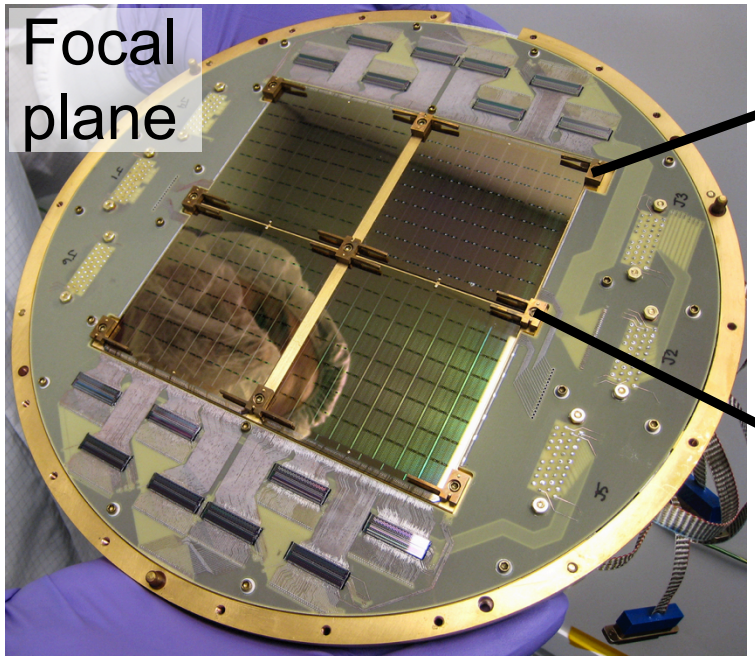
Basic Experiment Design

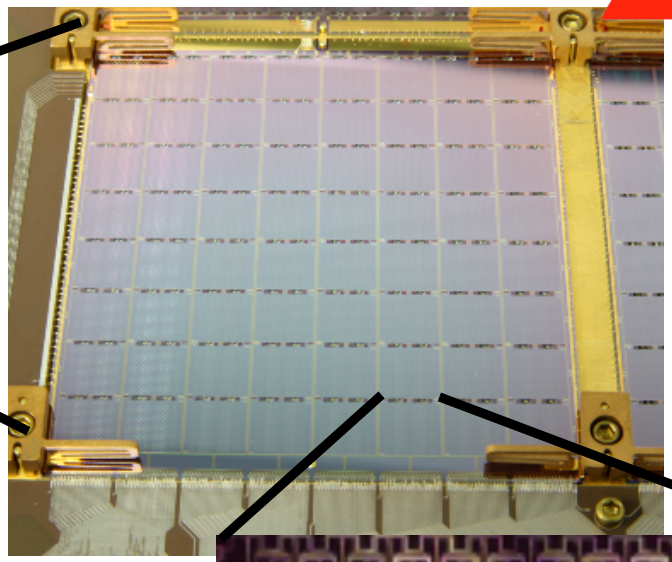
- Small aperture
- Wide field of view
- Cold refractor



Mass-produced Superconducting Detectors

JPL





Planar
antenna
array

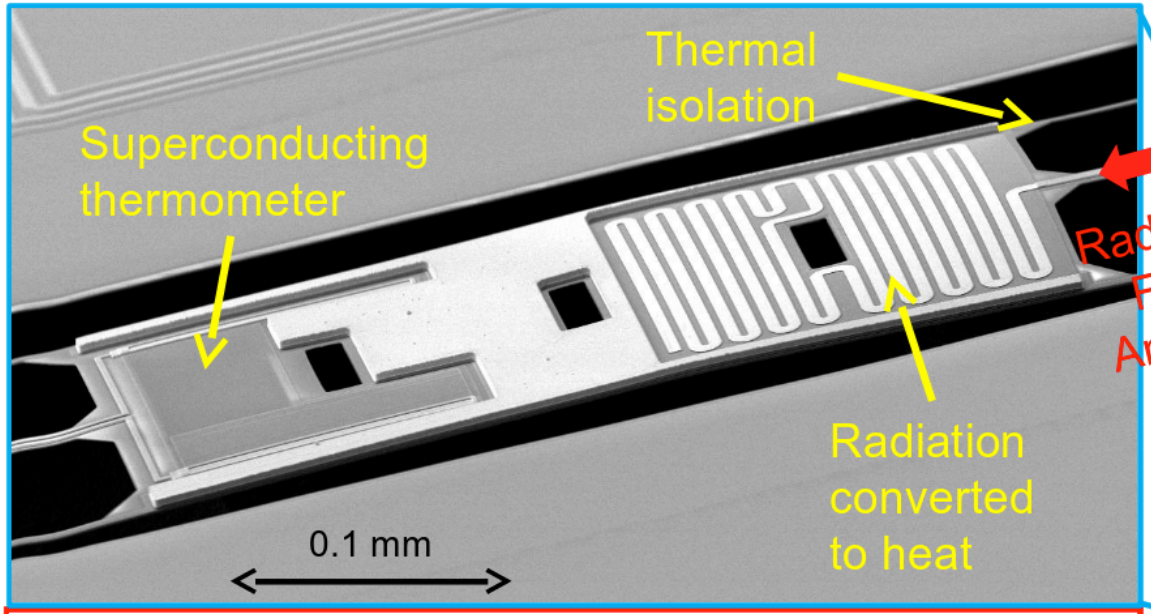
Slot
antennas

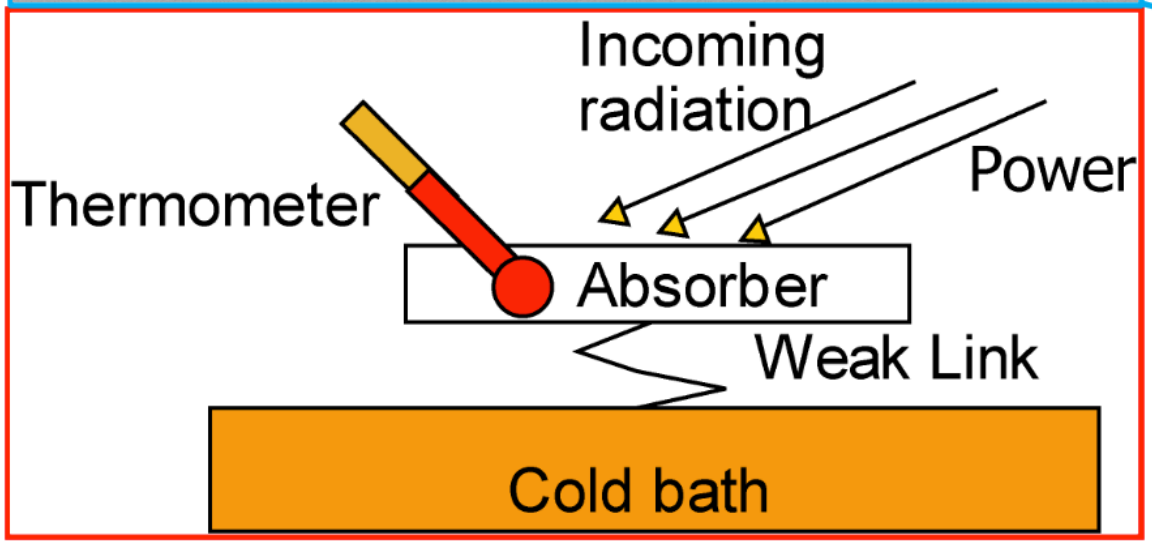
Transition edge sensor

Microstrip filters

Detecting CMB Radiation

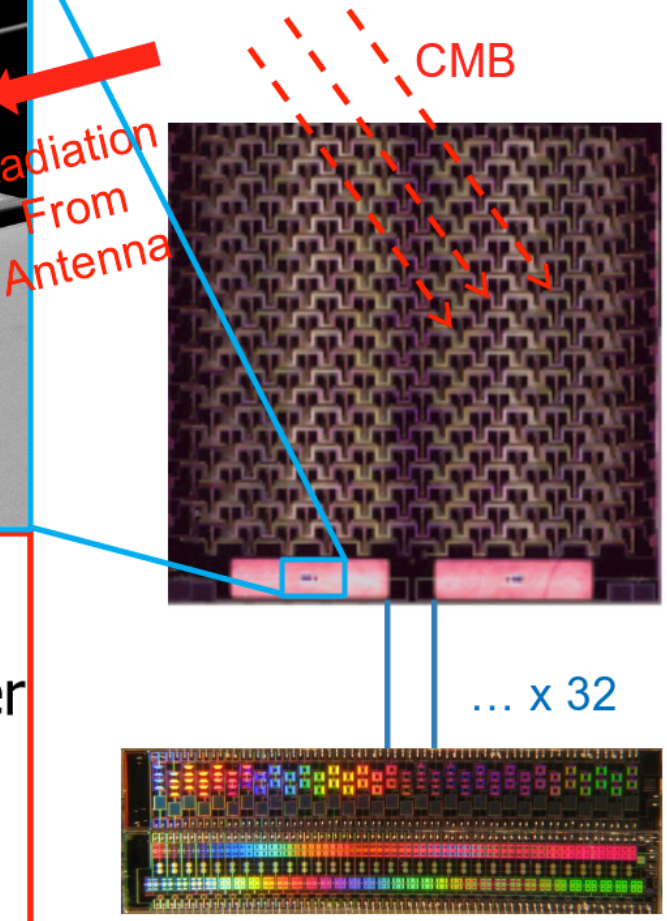
BICEP2 Detector: Transition-Edge Superconductor





Sensors cooled to 0.25 K to reduce thermal noise

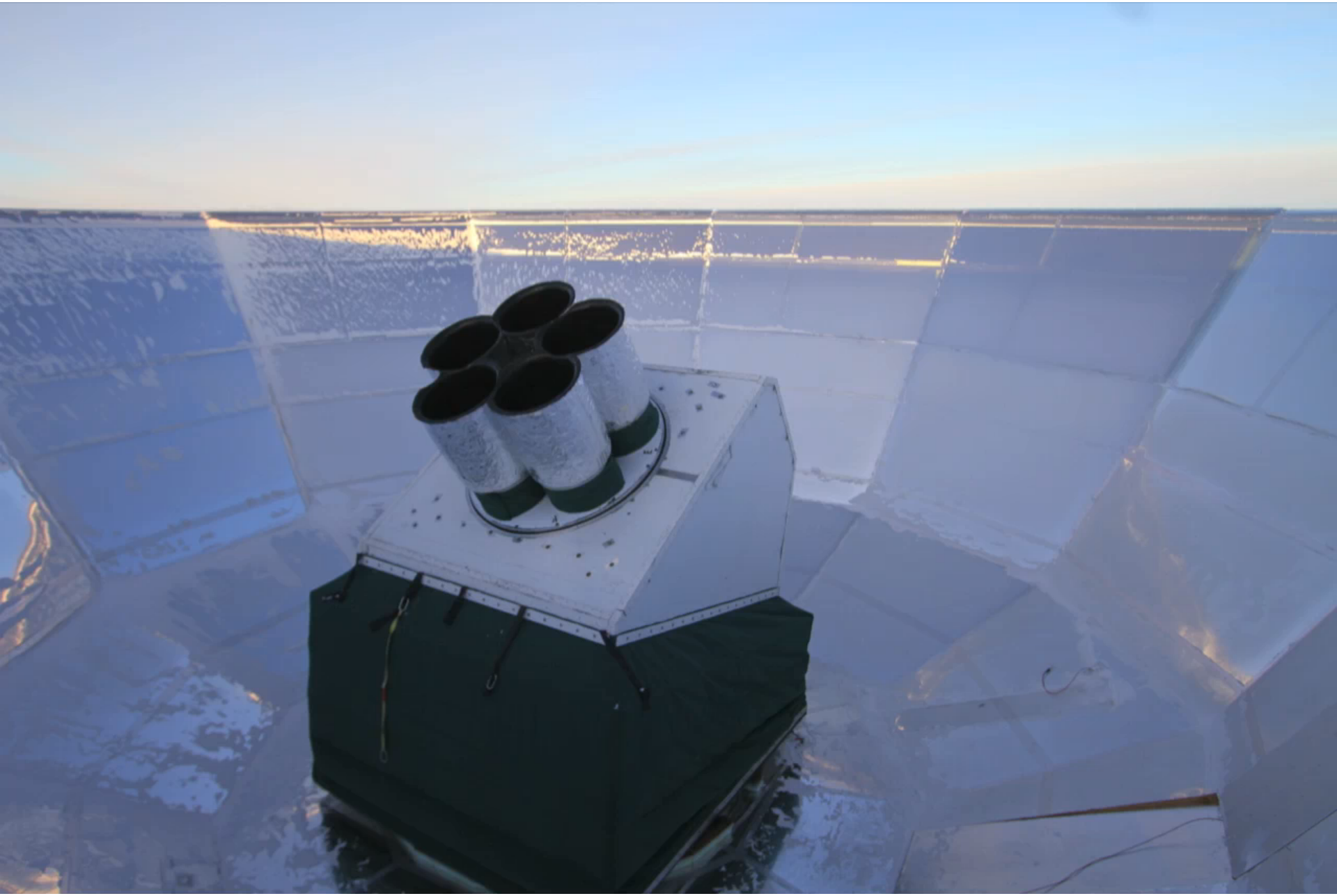
Printed Antenna Gathers CMB Light



SQUIDs Amplify and Multiplex Signals

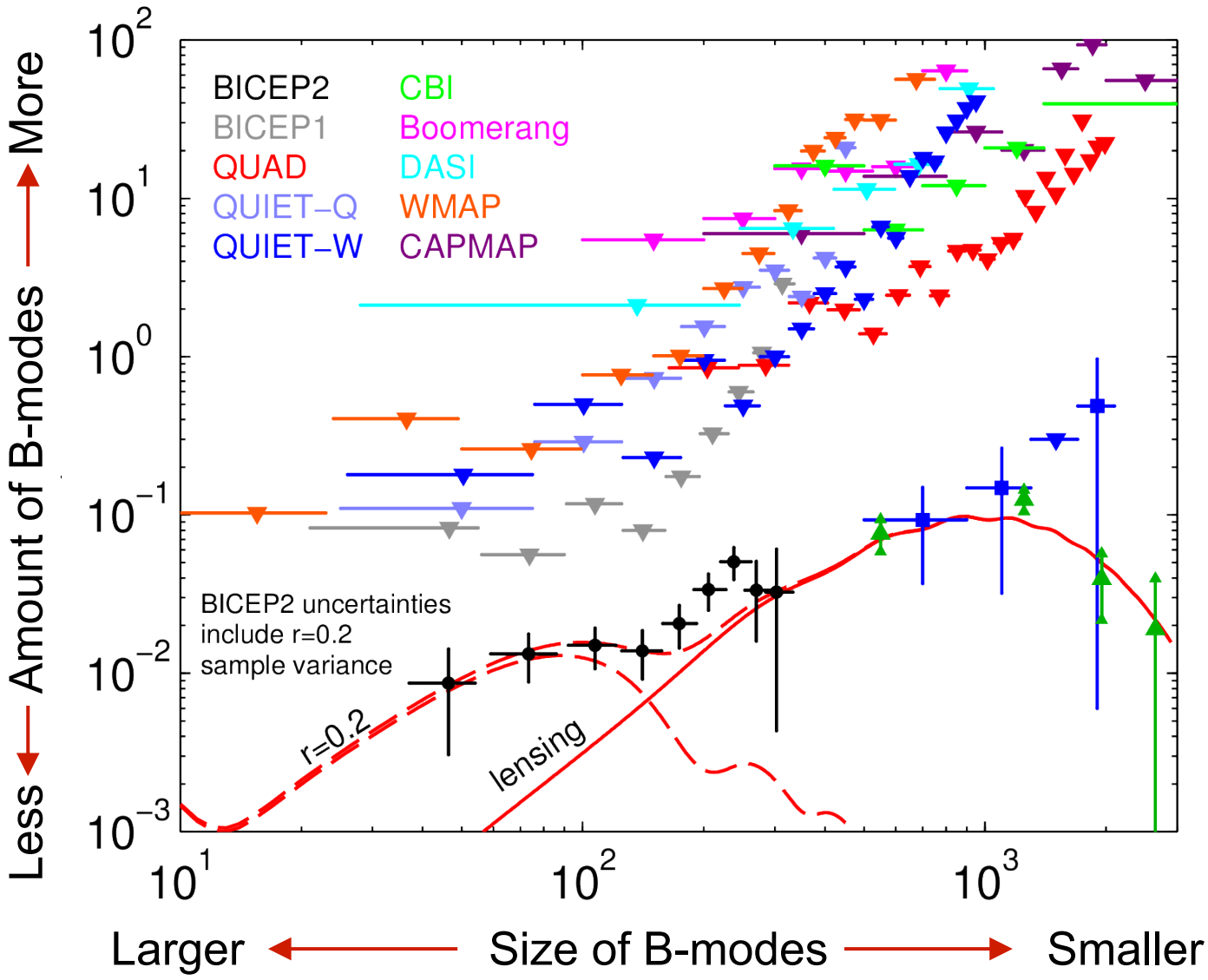
SQUIDs developed at NIST

Clem Pryke for The Bicep2 Collaboration



Clem Pryke for The Bicep2 Collaboration

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

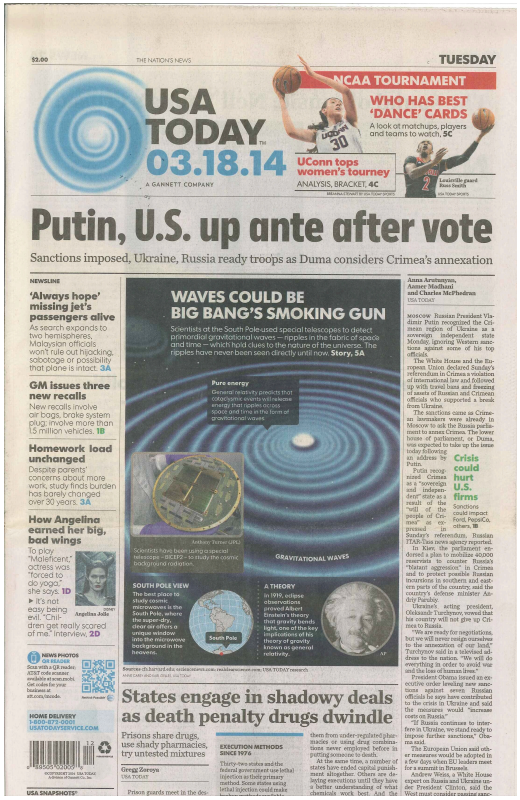


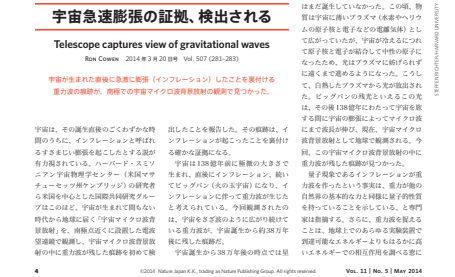
(r is a measure of amount of gravitational waves)

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

Clem Pryke for The Bicep2 Collaboration

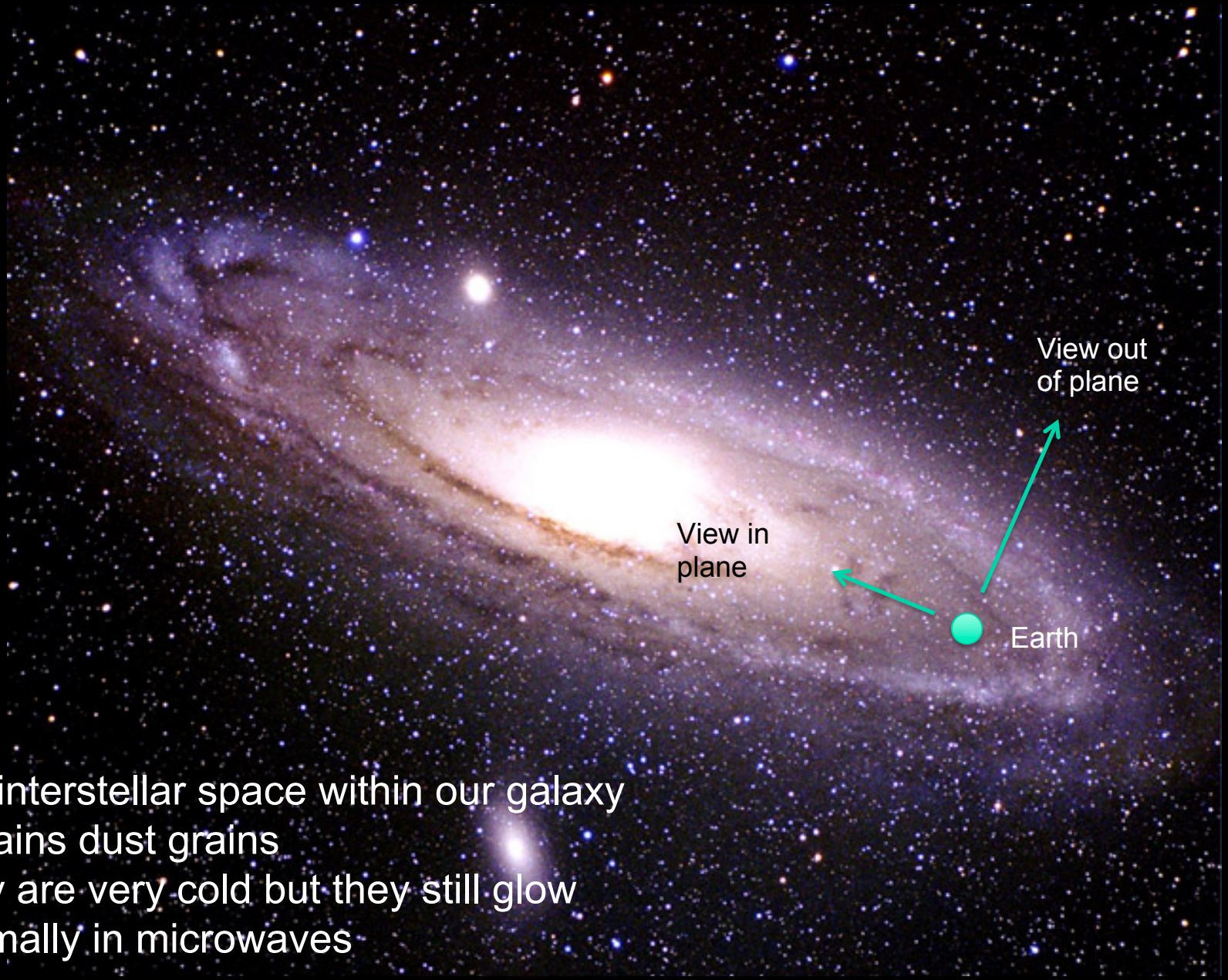
2014 Storm of Media Attention





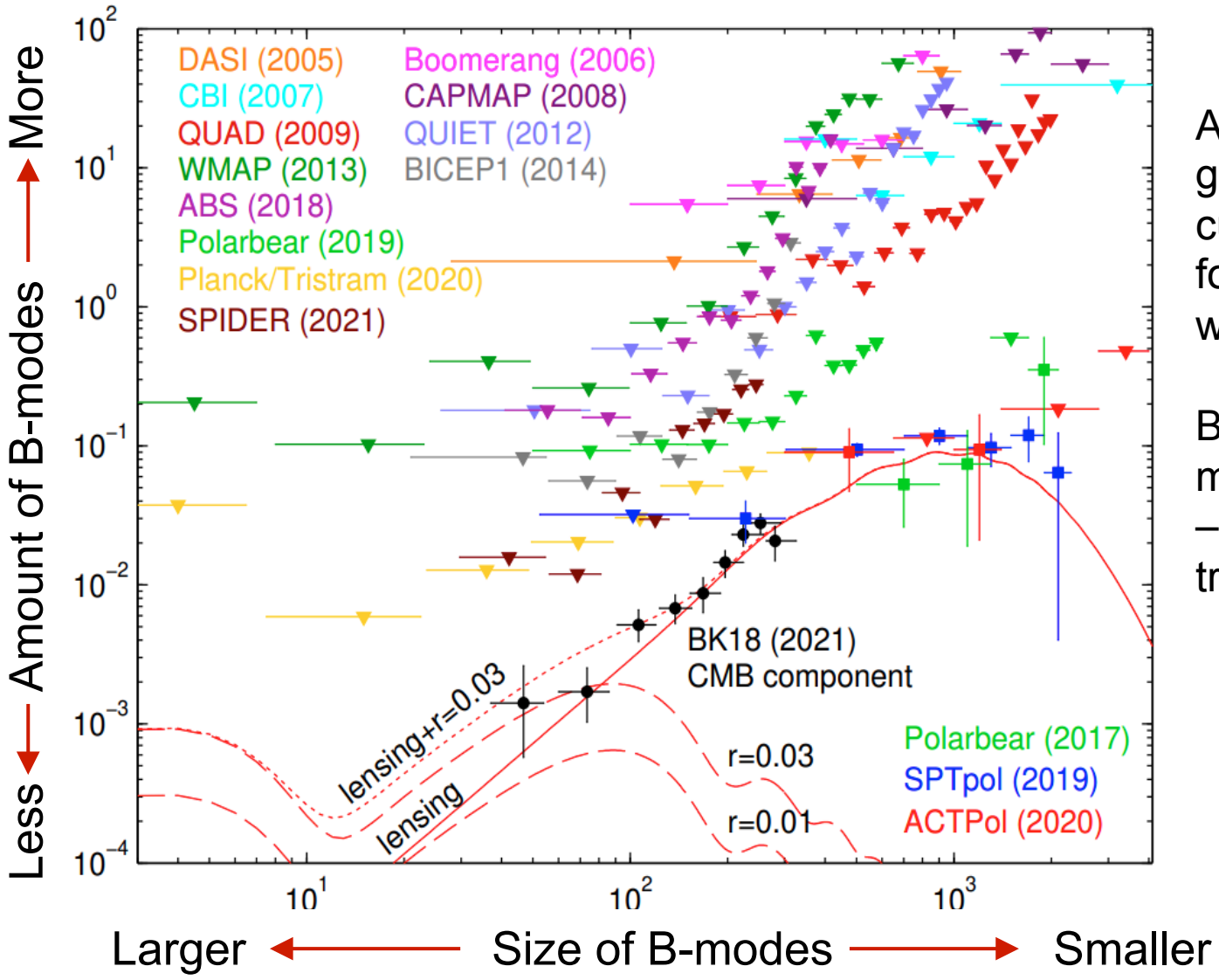
Actually not a lot of fun…

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…

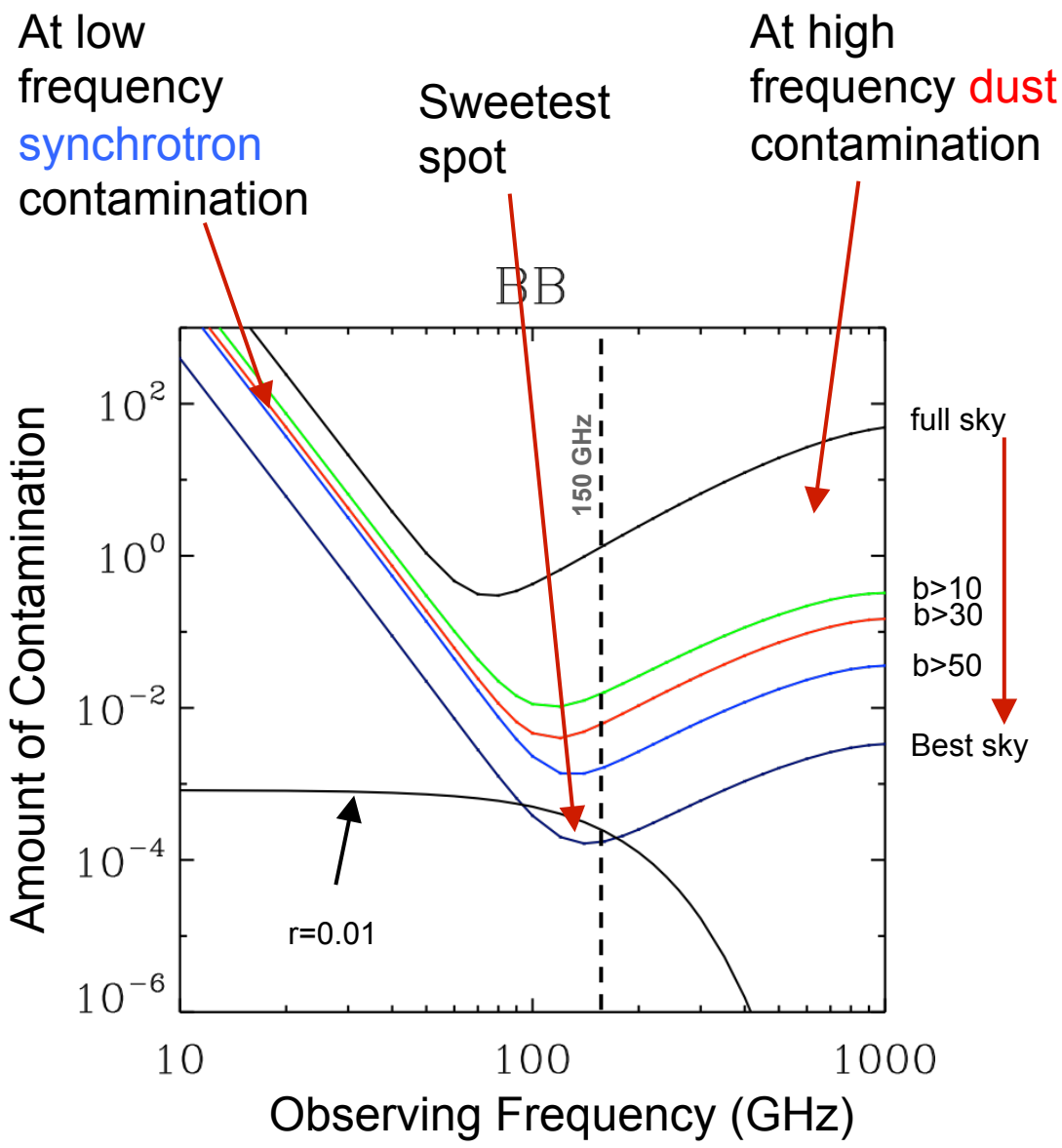


After accounting for galactic dust there is currently no evidence for gravitational waves

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

Clem Pryke for The Bicep2 Collaboration

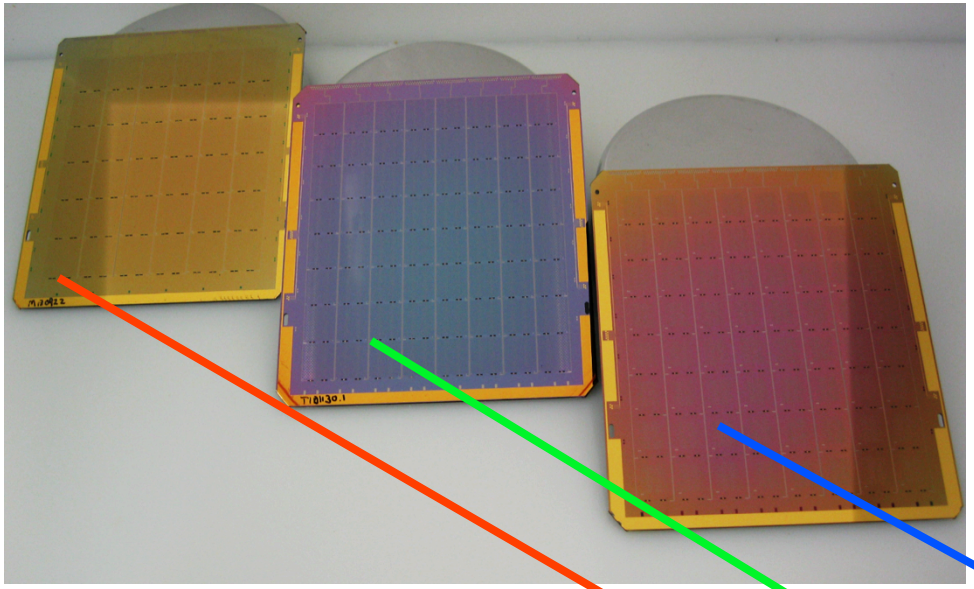
Polarized Foreground Contamination from Our Galaxy



Pick a cleaner patch of sky

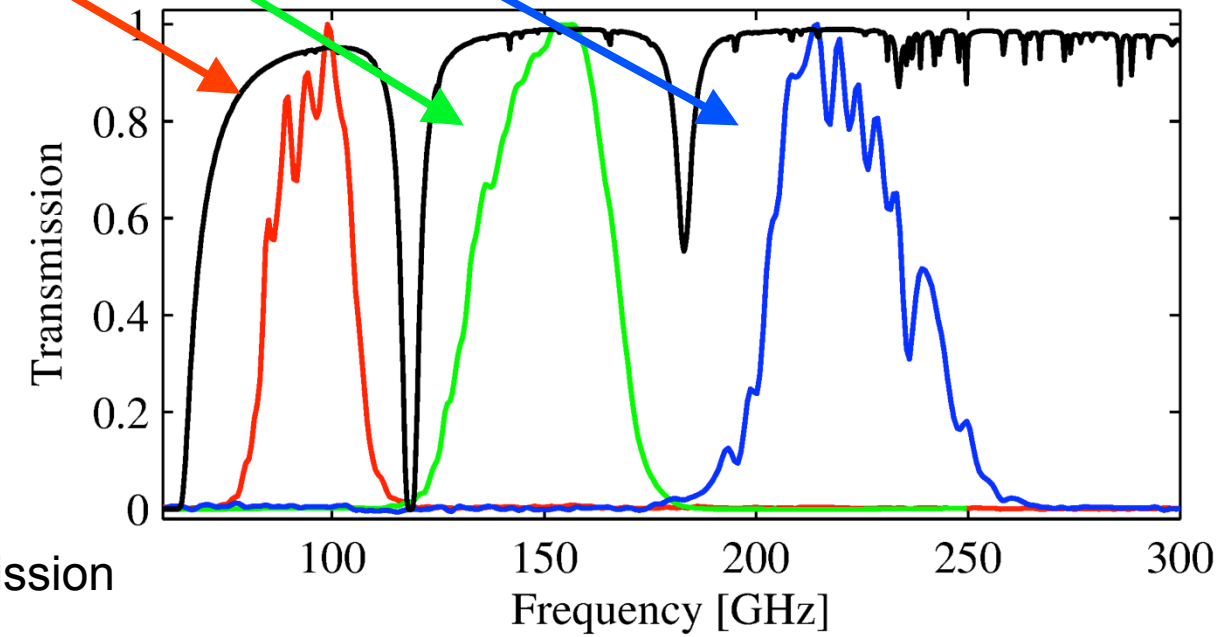
(Plot from Dunkley et al arxiv/0811.3915)

Planar superconducting detector arrays



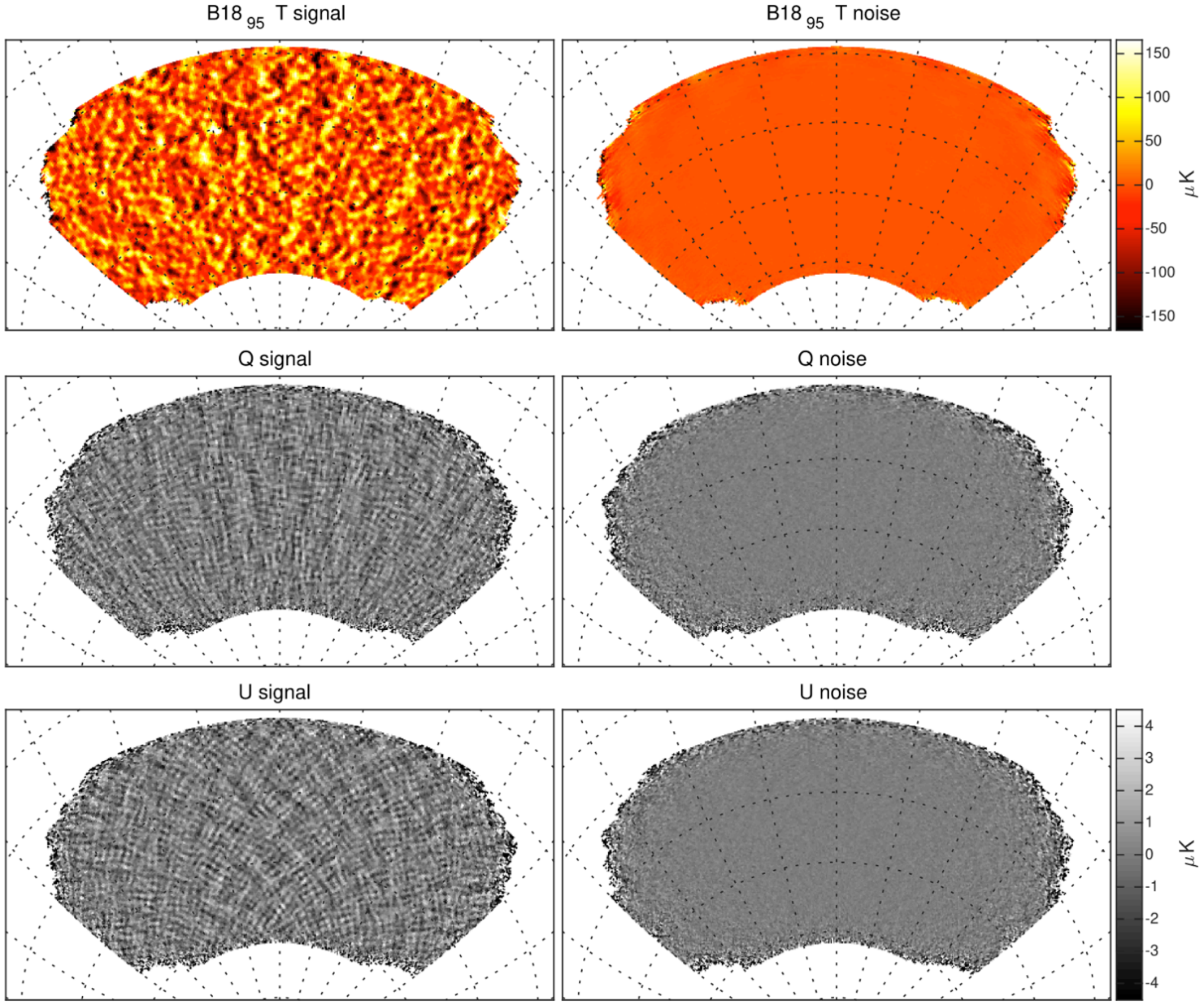
…designed to scale
in frequency

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

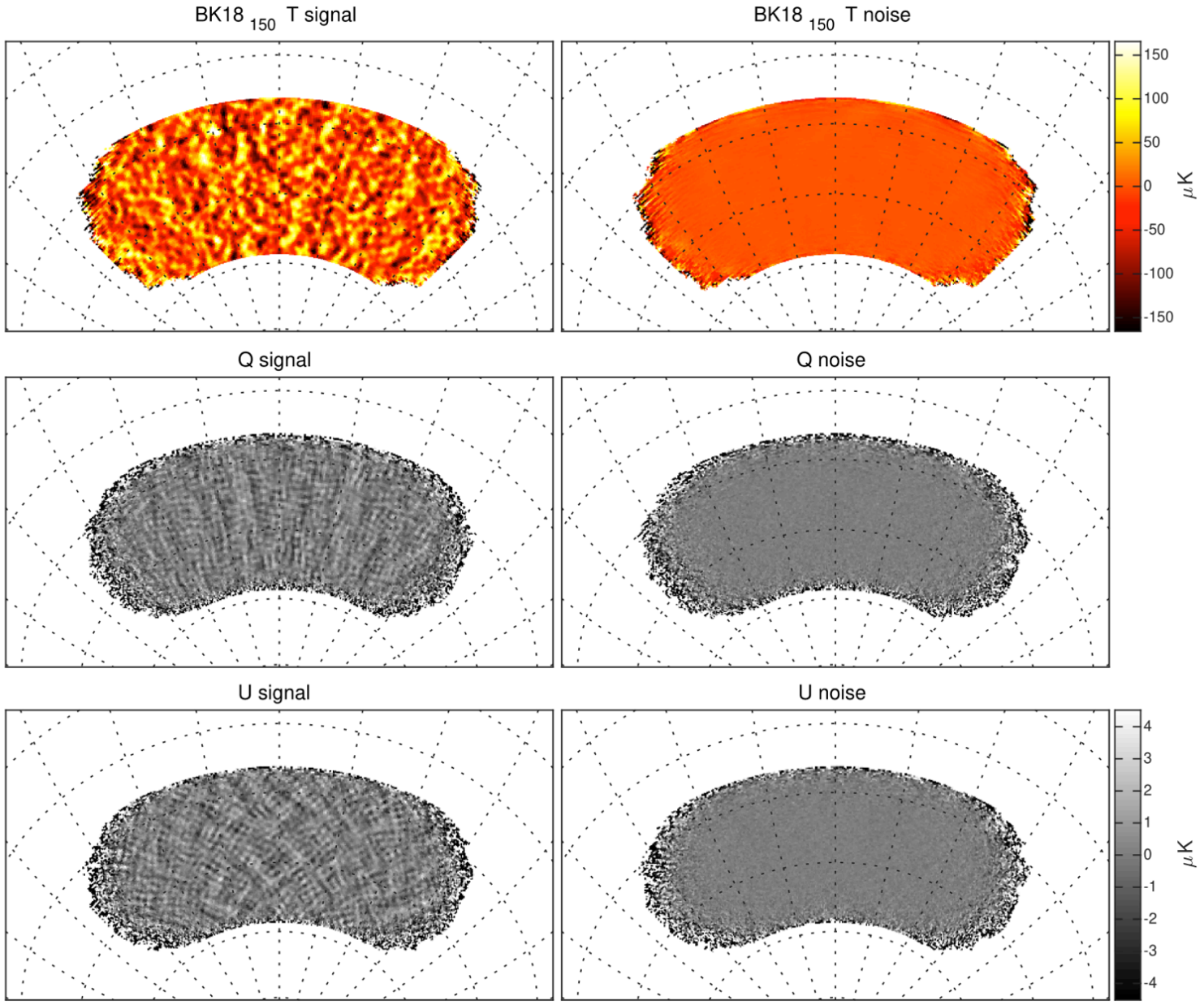


Typical South Pole
atmospheric transmission

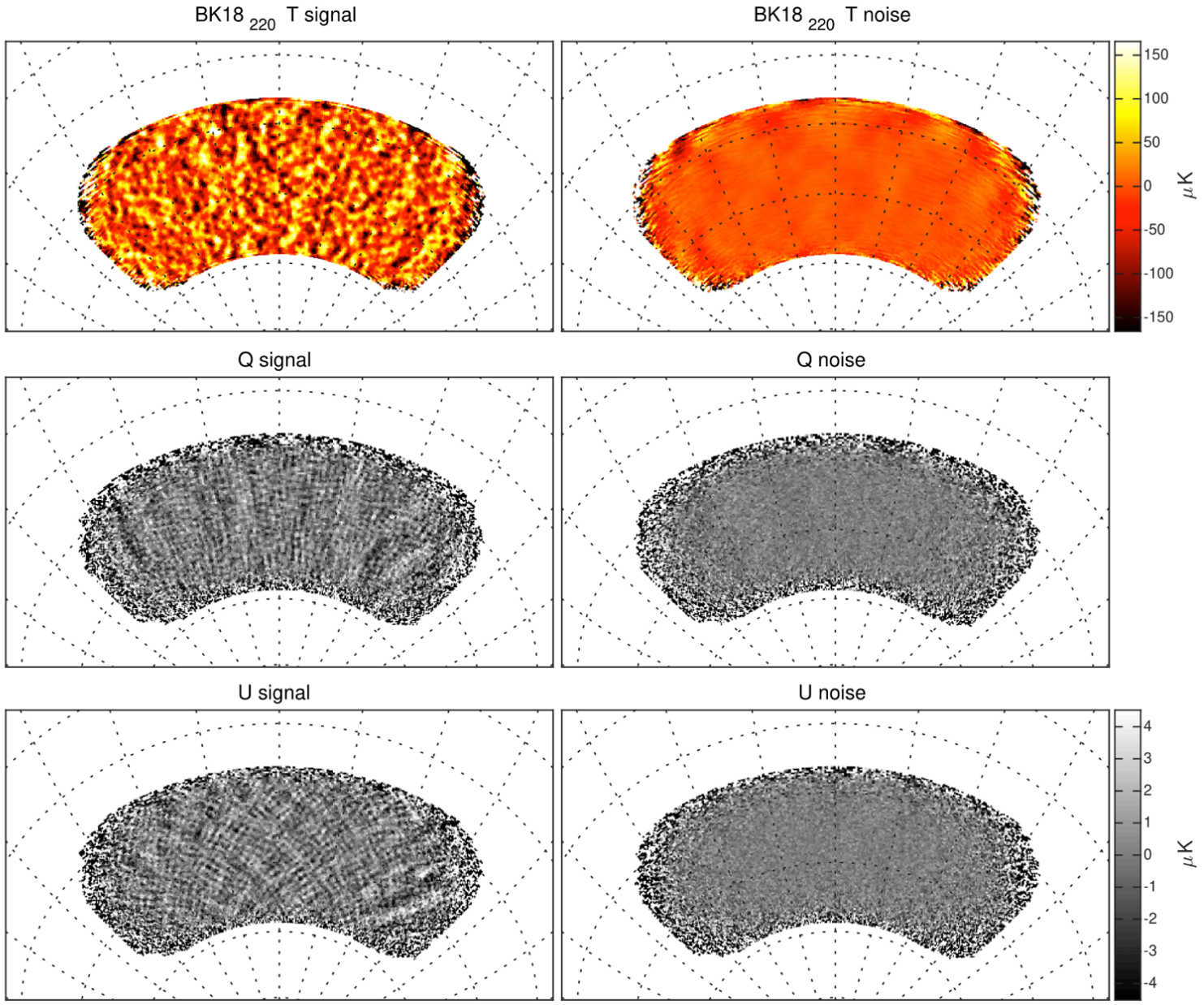
BK18 95GHz Map (BICEP3)



BK18 150GHz Map (BICEP2+*Keck*)



BK18 220GHz Map (*Keck*)



Stage 2

Stage 3

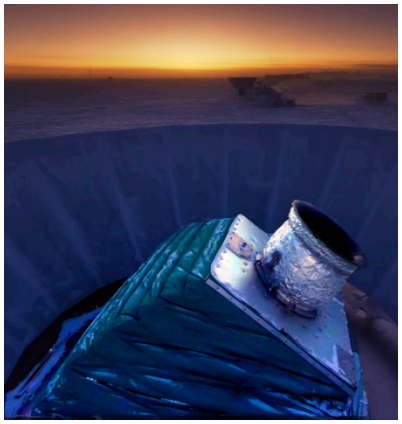
BICEP2
(2010-2012)

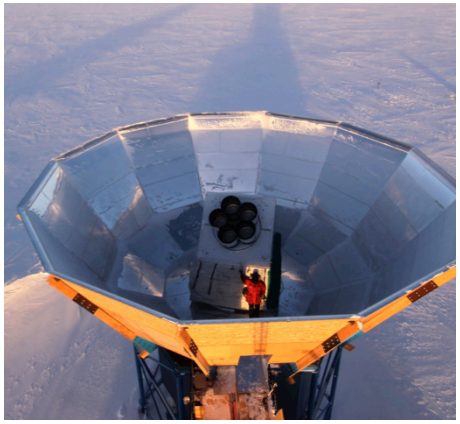
Keck Array
(2012-2019)

BICEP3
(2016-present)

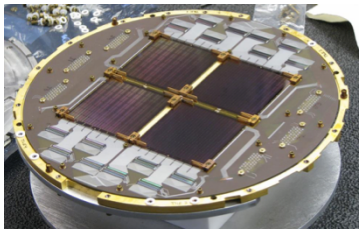
BICEP Array
(2020-present)

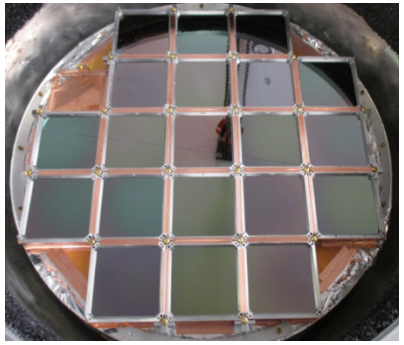
Telescope and Mount

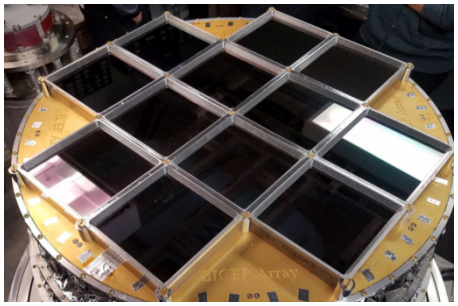




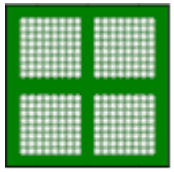
Focal Plane

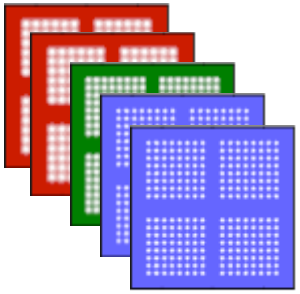


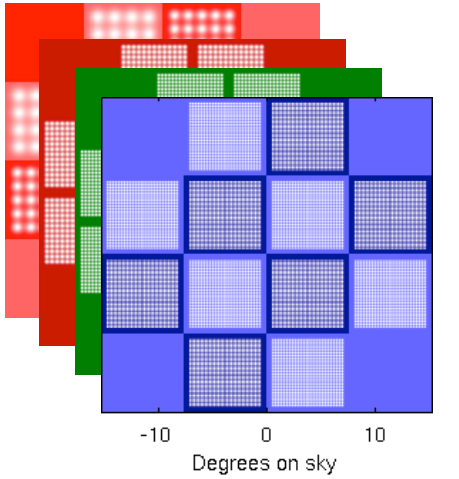


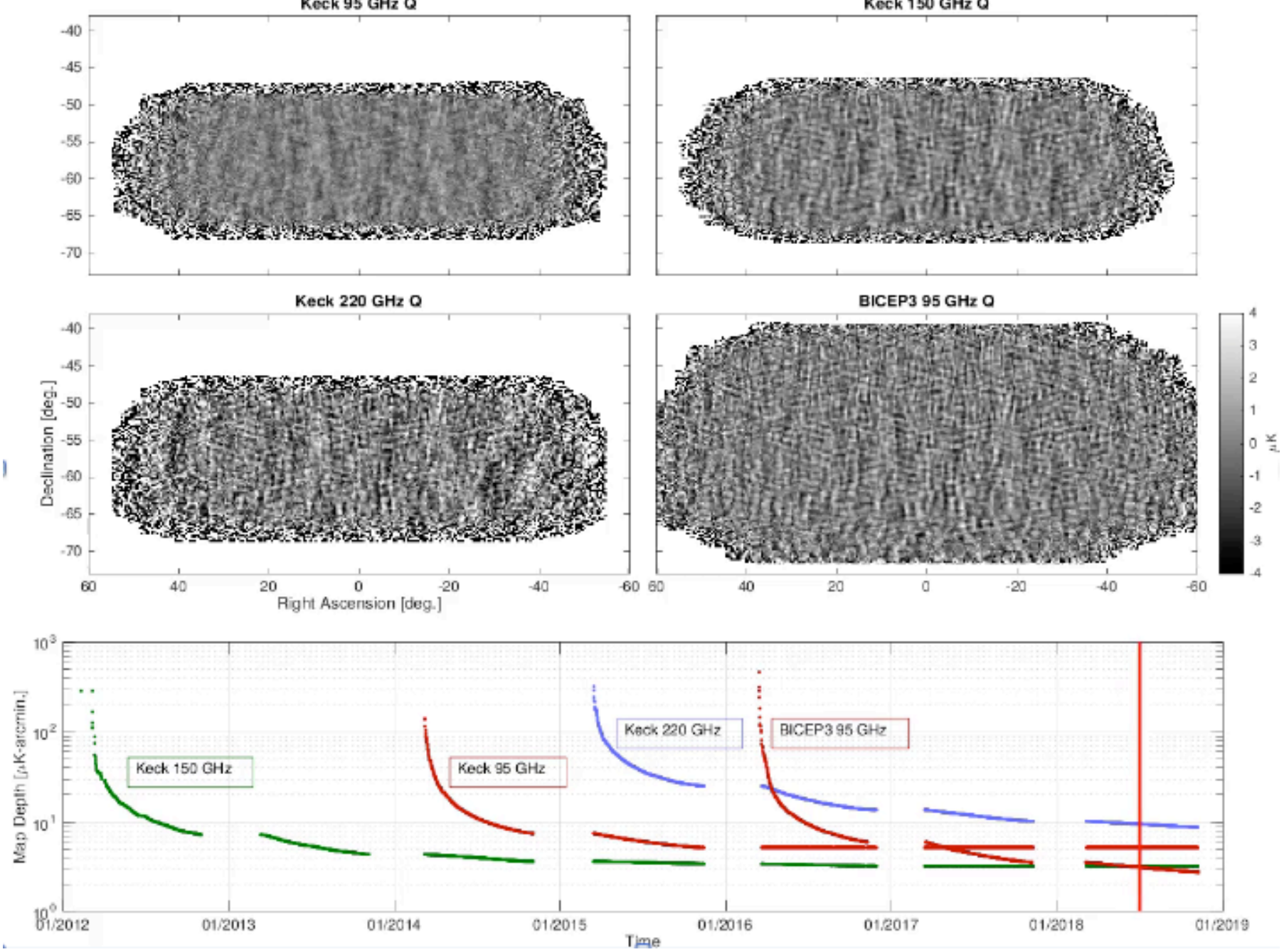


Beams on Sky



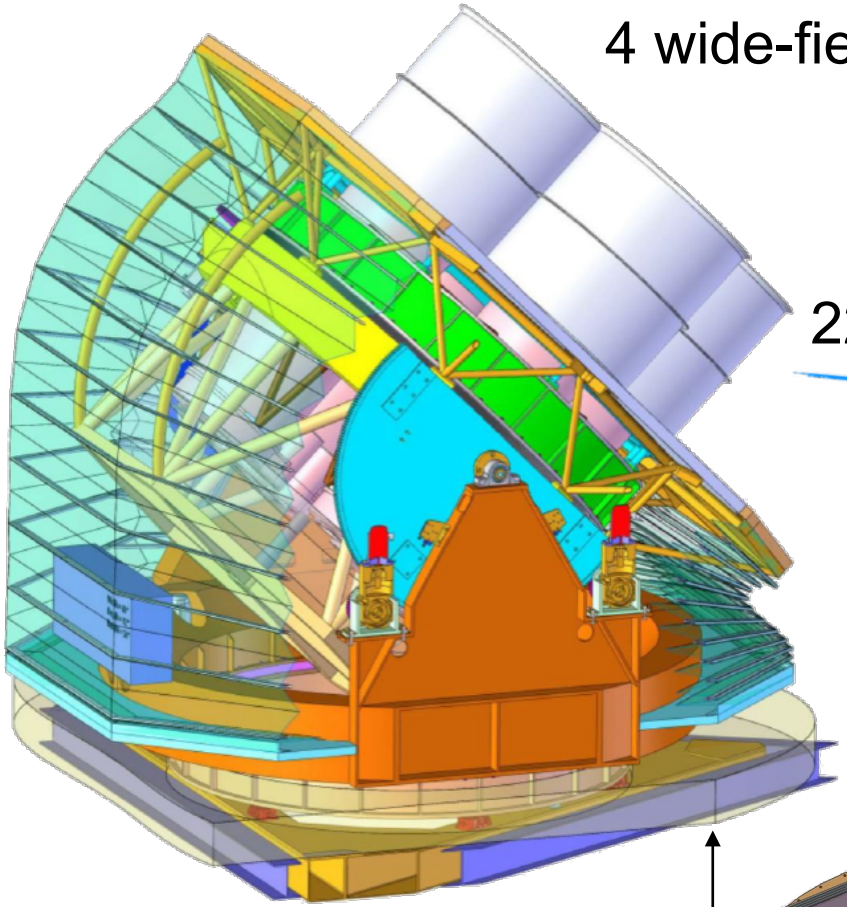




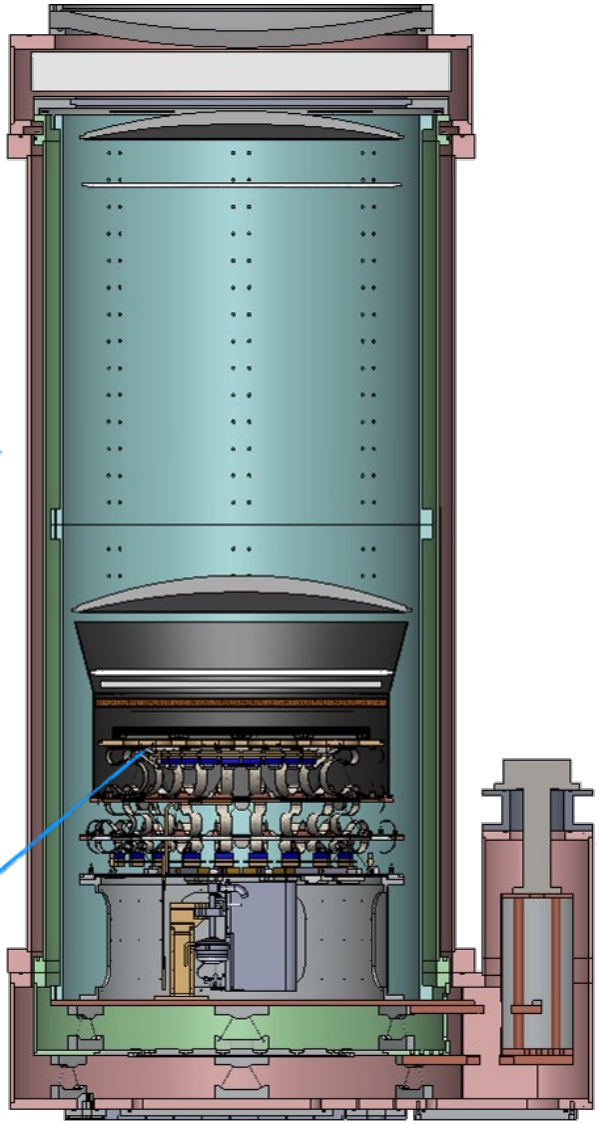

Keck 95 GHz Q
Keck 150 GHz Q
Keck 220 GHz Q
BICEP3 95 GHz Q
Declination [deg.]
Right Ascension [deg.]
μK
Map Depth [μK-arcmin.]
Keck 150 GHz
Keck 95 GHz
Keck 220 GHz
BICEP3 95 GHz
01/2012
01/2013
01/2014
01/2015
01/2016
01/2017
01/2018
01/2019
Time

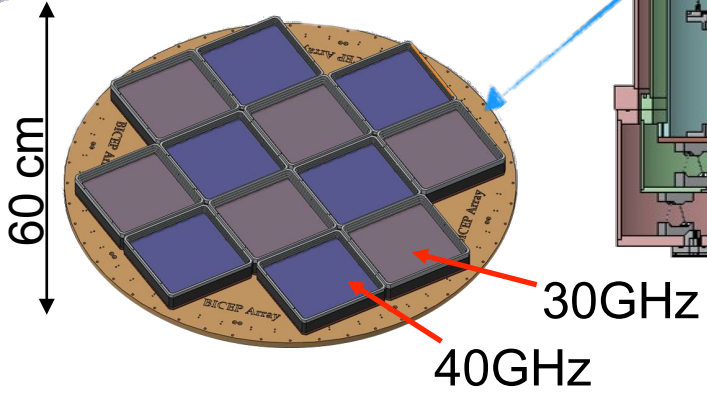
Google “Robert Schwarz” – did 9 consecutive winter seasons at South Pole (14 overall!)

Latest Generation Experiment “BICEP Array"



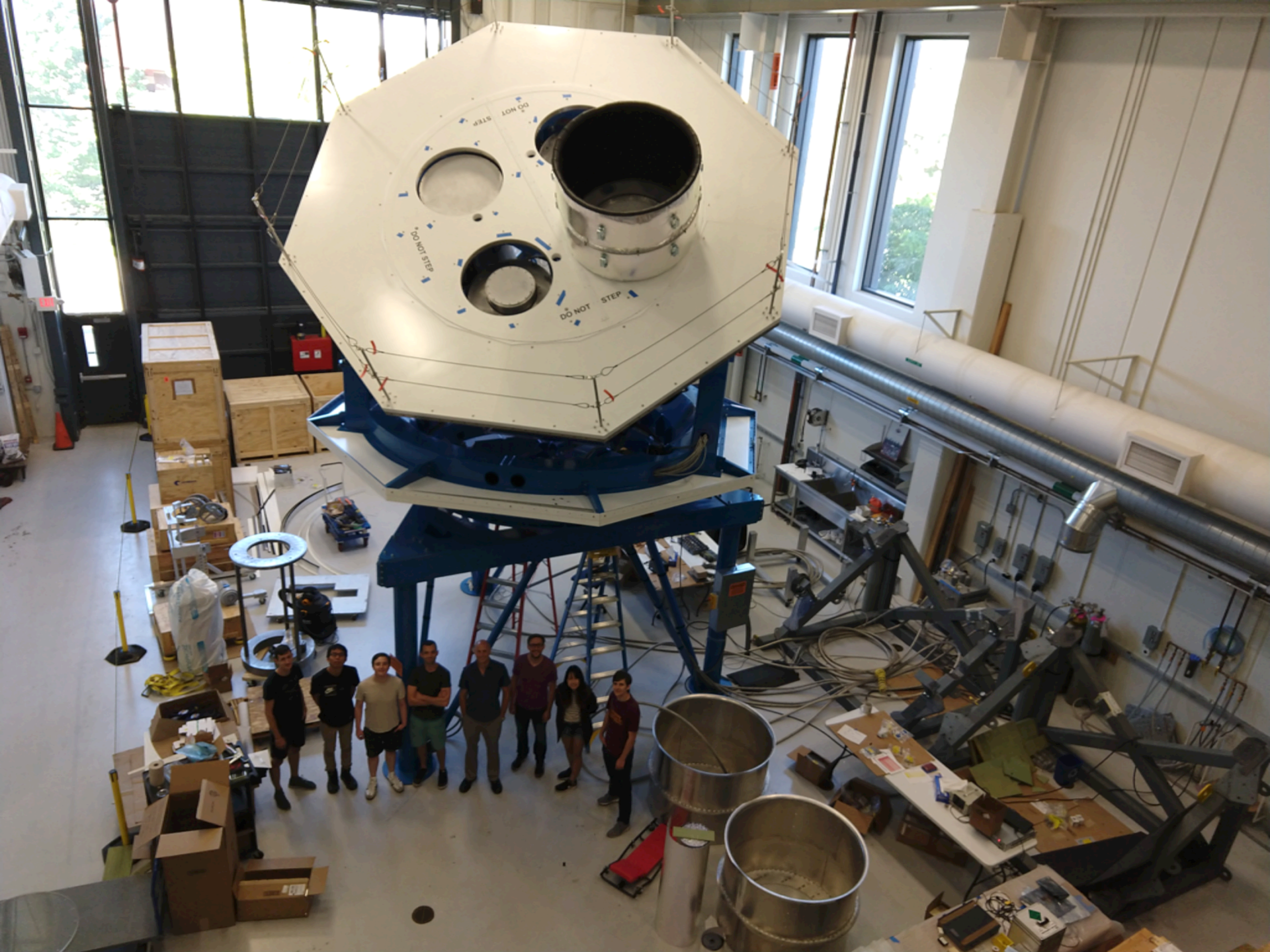
4 wide-field receivers
30/40 GHz
95 GHz
150 GHz
220/270 GHz

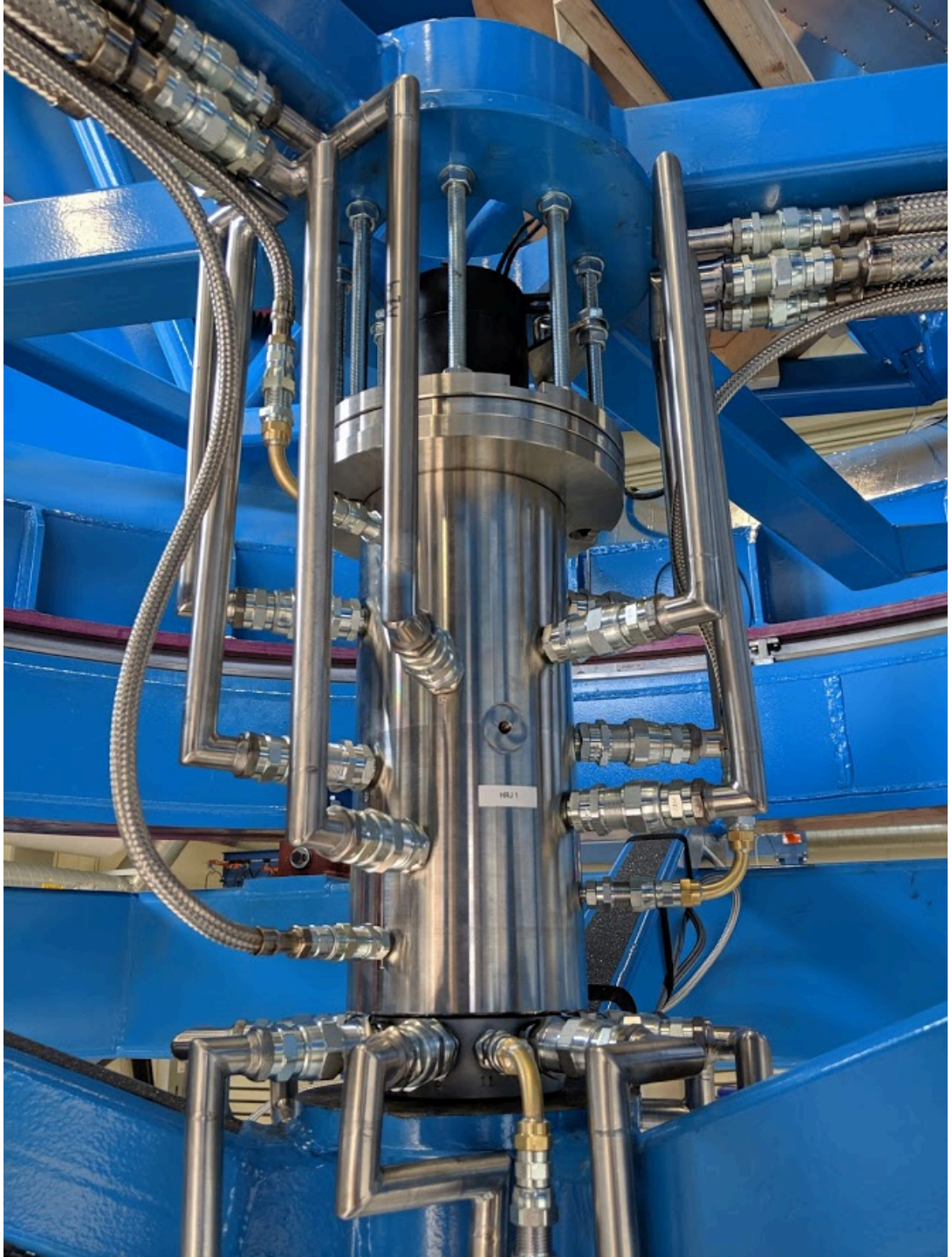




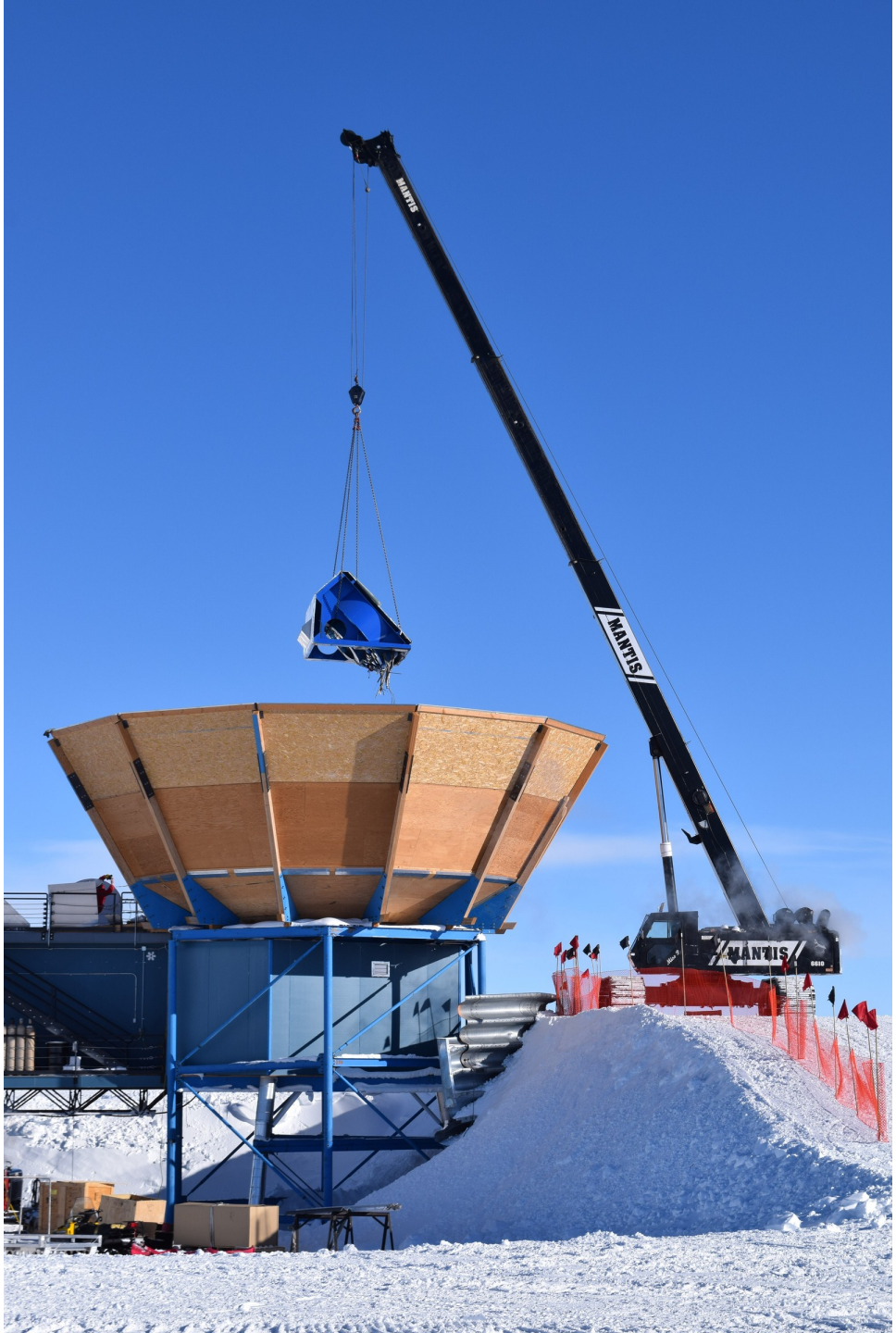
Focal plane layout

2018-19: Built New Telescope at UMN

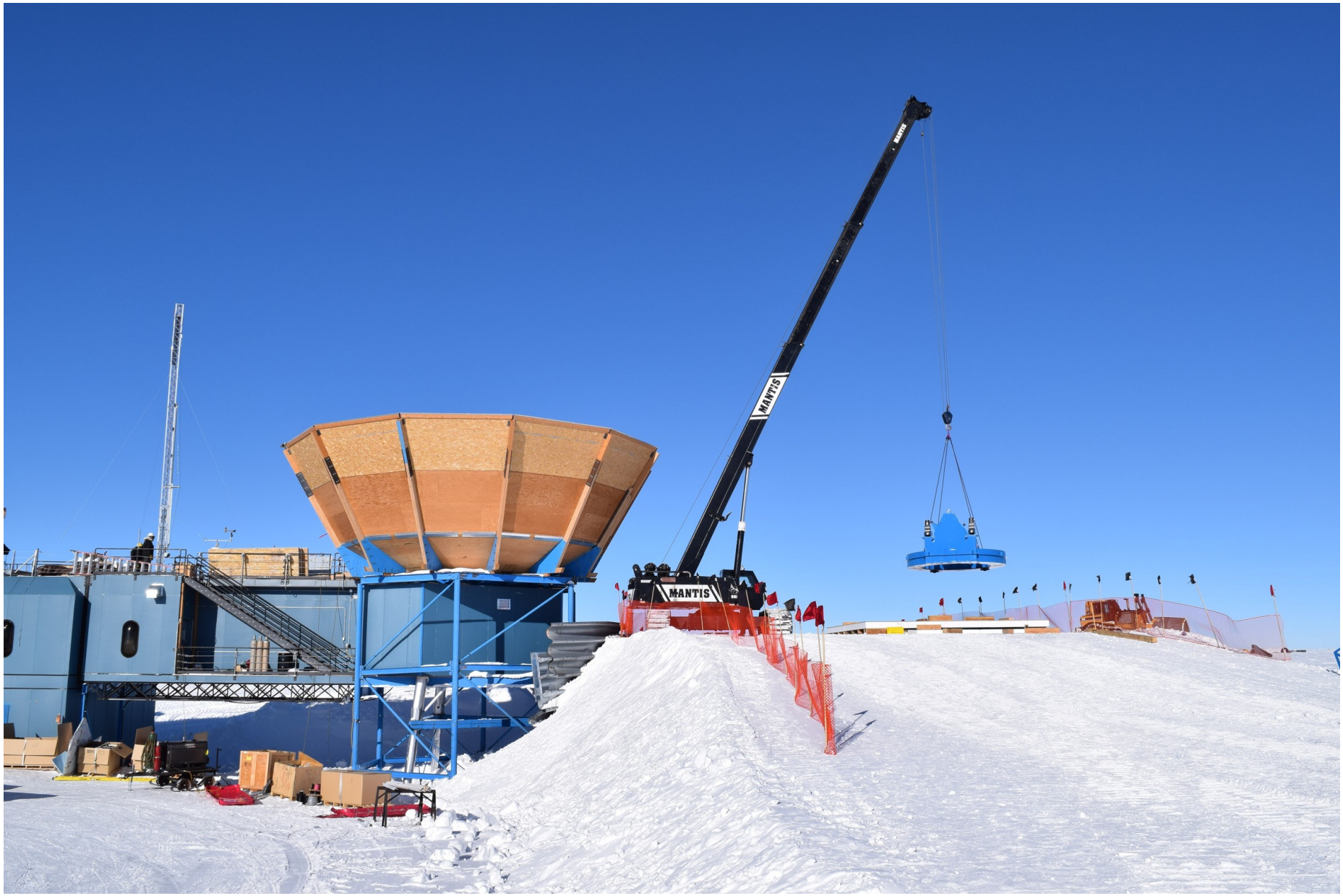

DO NOT STEP
DO NOT STEP
DO NOT STEP



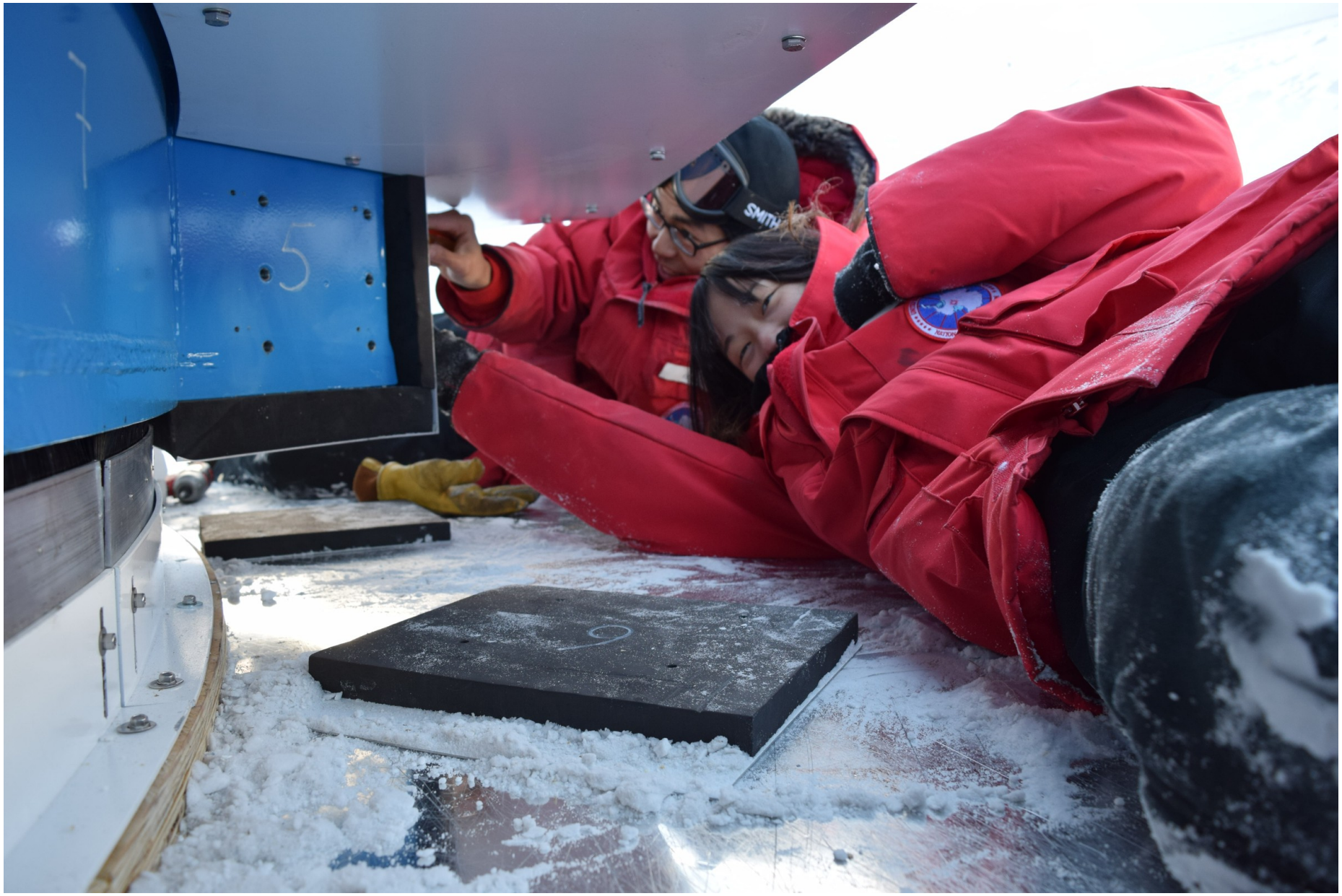

CLEM PRYKE

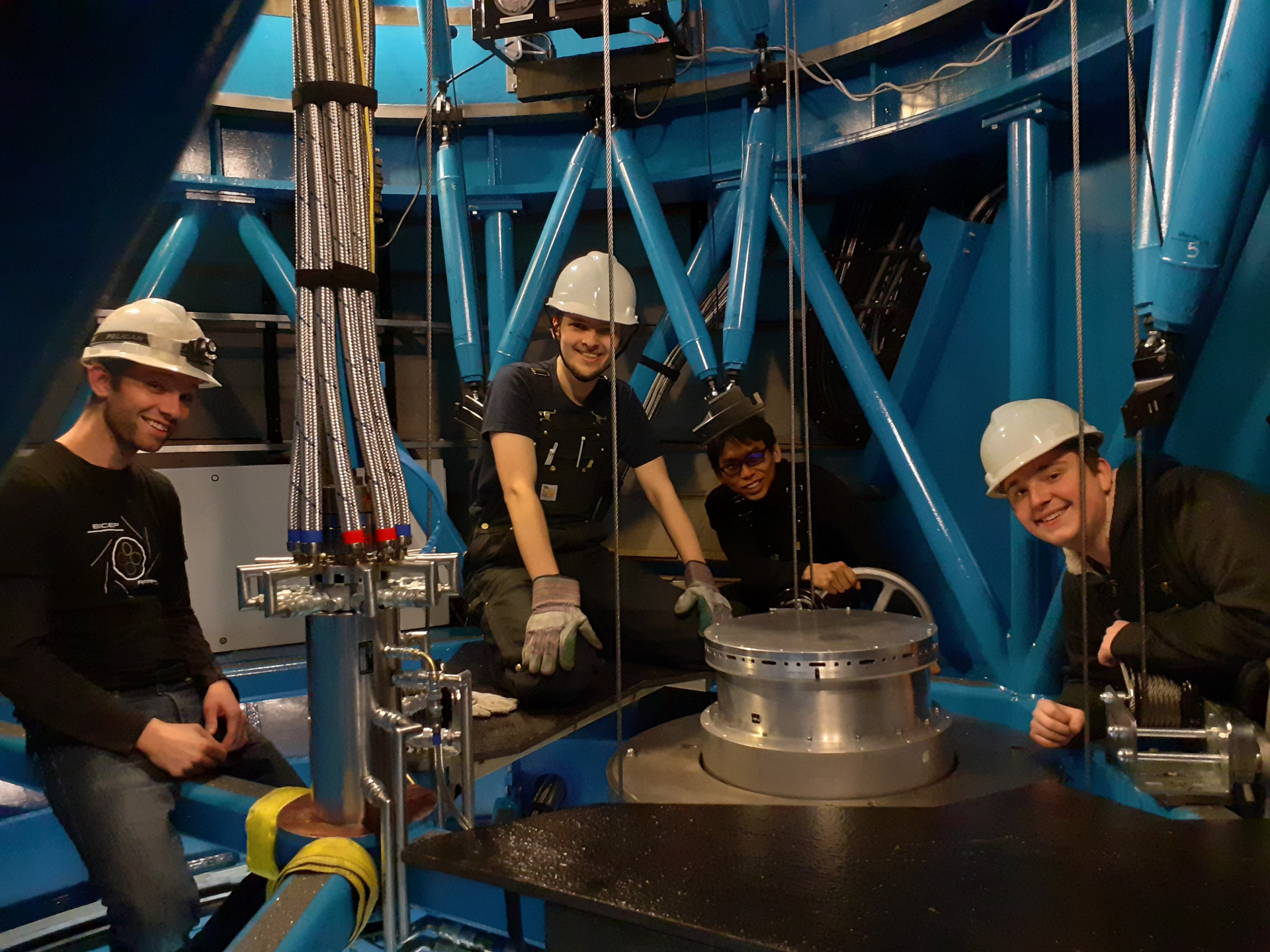

MANTIS
MANTIS
MANTIS

Lifting on part of new telescope



Working in the snow




BICEP

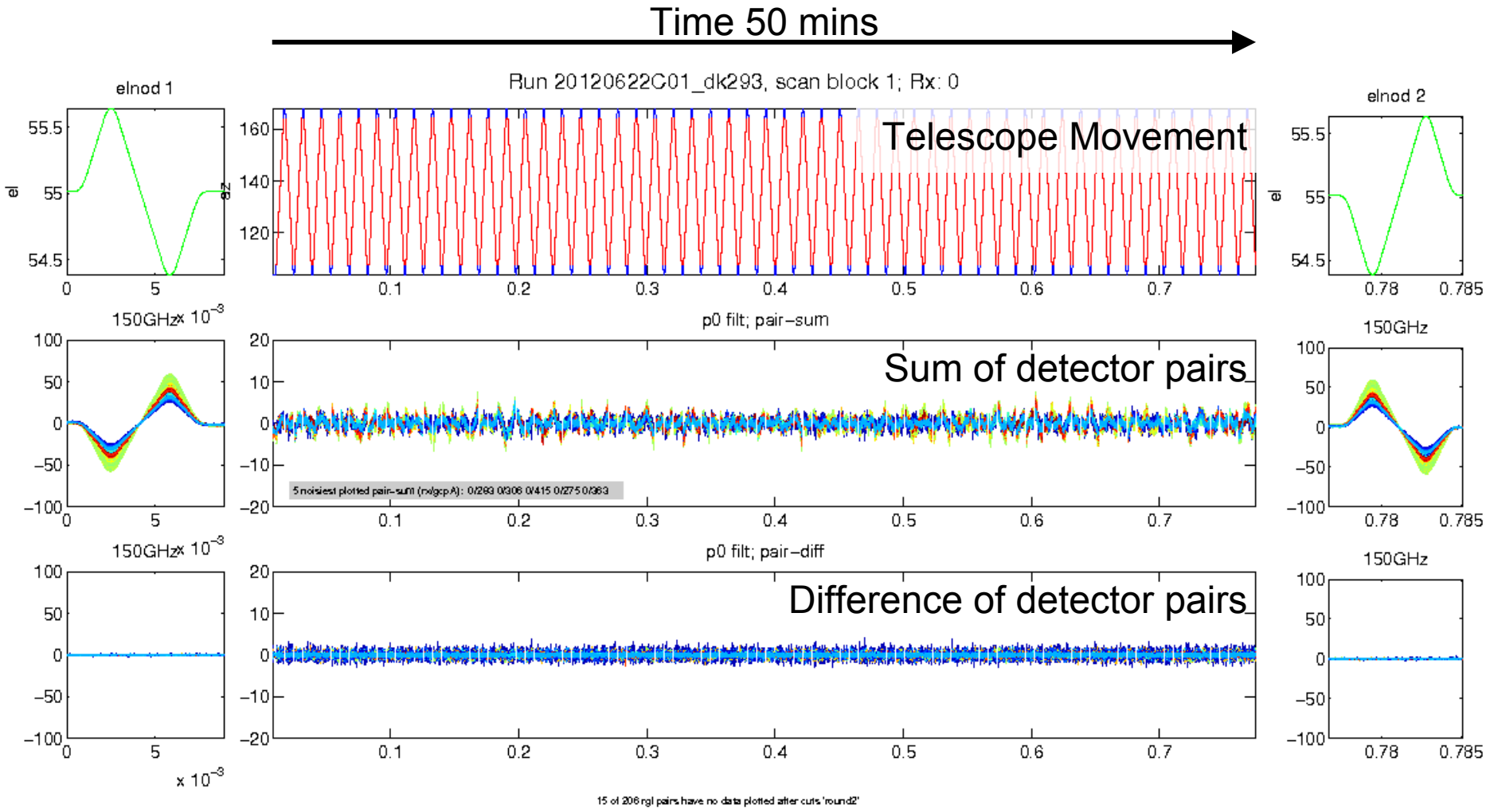
Feb 2020 – the finished product

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…

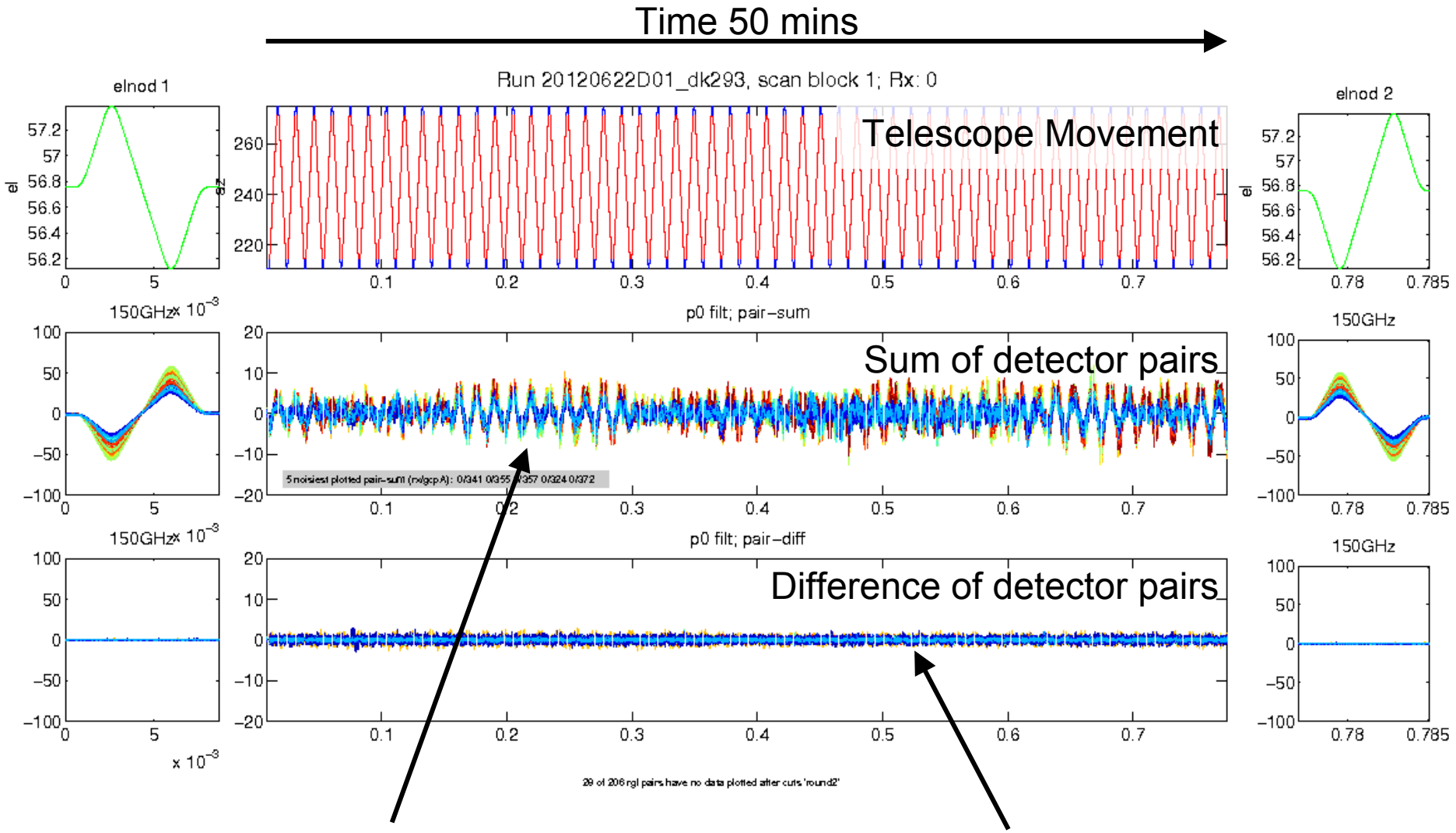

BA 3
UNSA
bicep array

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

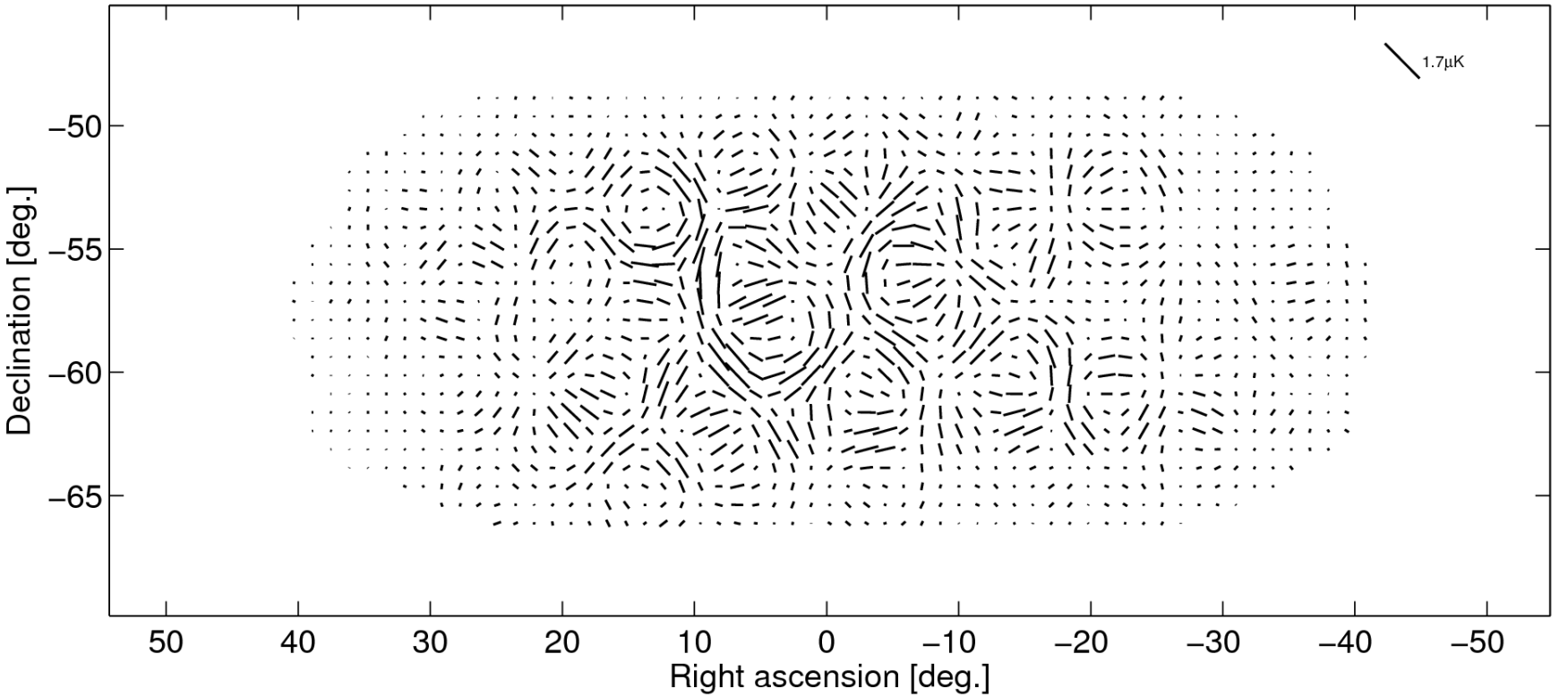


- Scanning over lumpy atmosphere
  → “clouds”
- Pair difference still clean
  → atmosphere is unpolarized

Clem Pryke for The Bicep2 Collaboration

Total Polarization

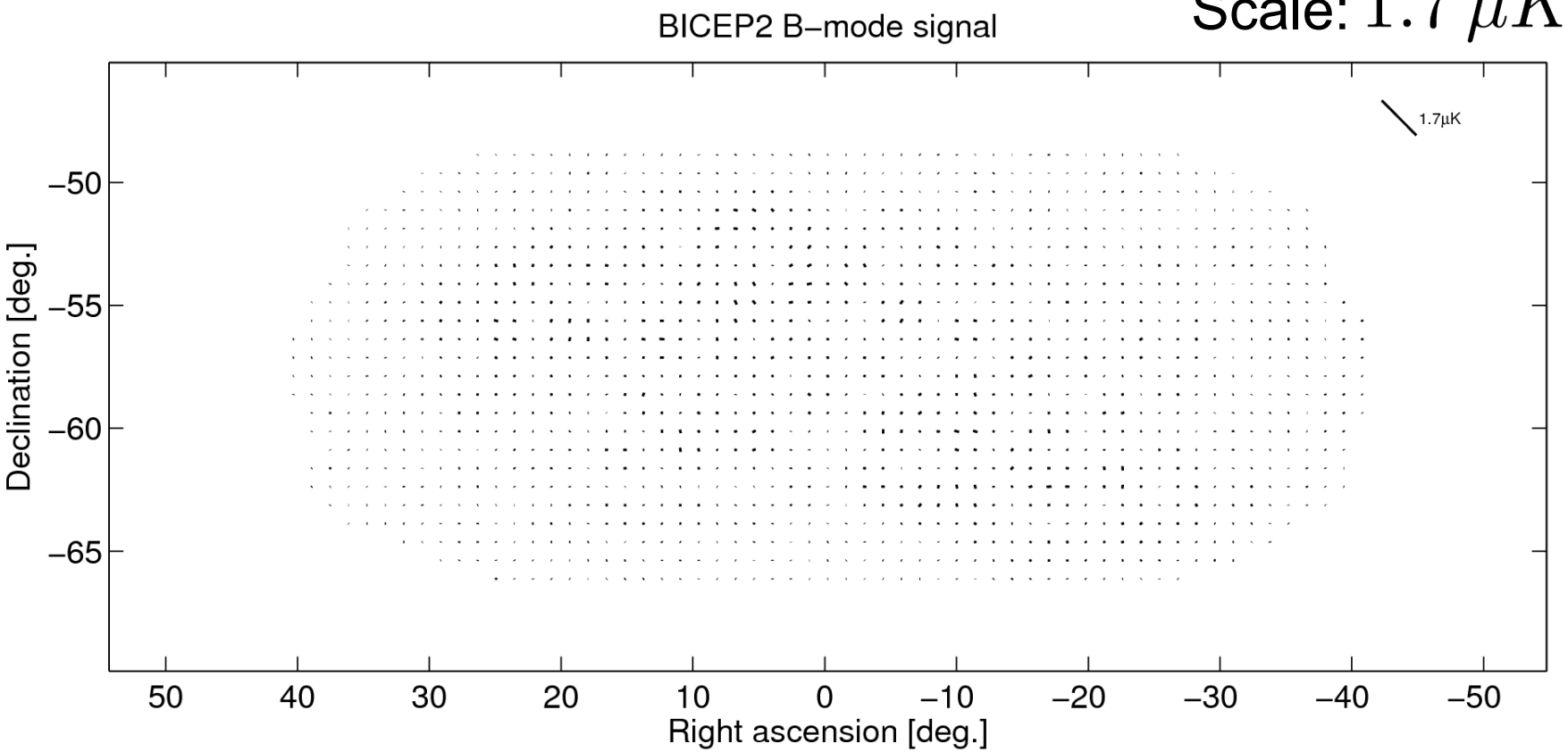
Scale: $1.7\ \mu K$



E-mode dominated pattern – no obvious curl component

B-mode Contribution

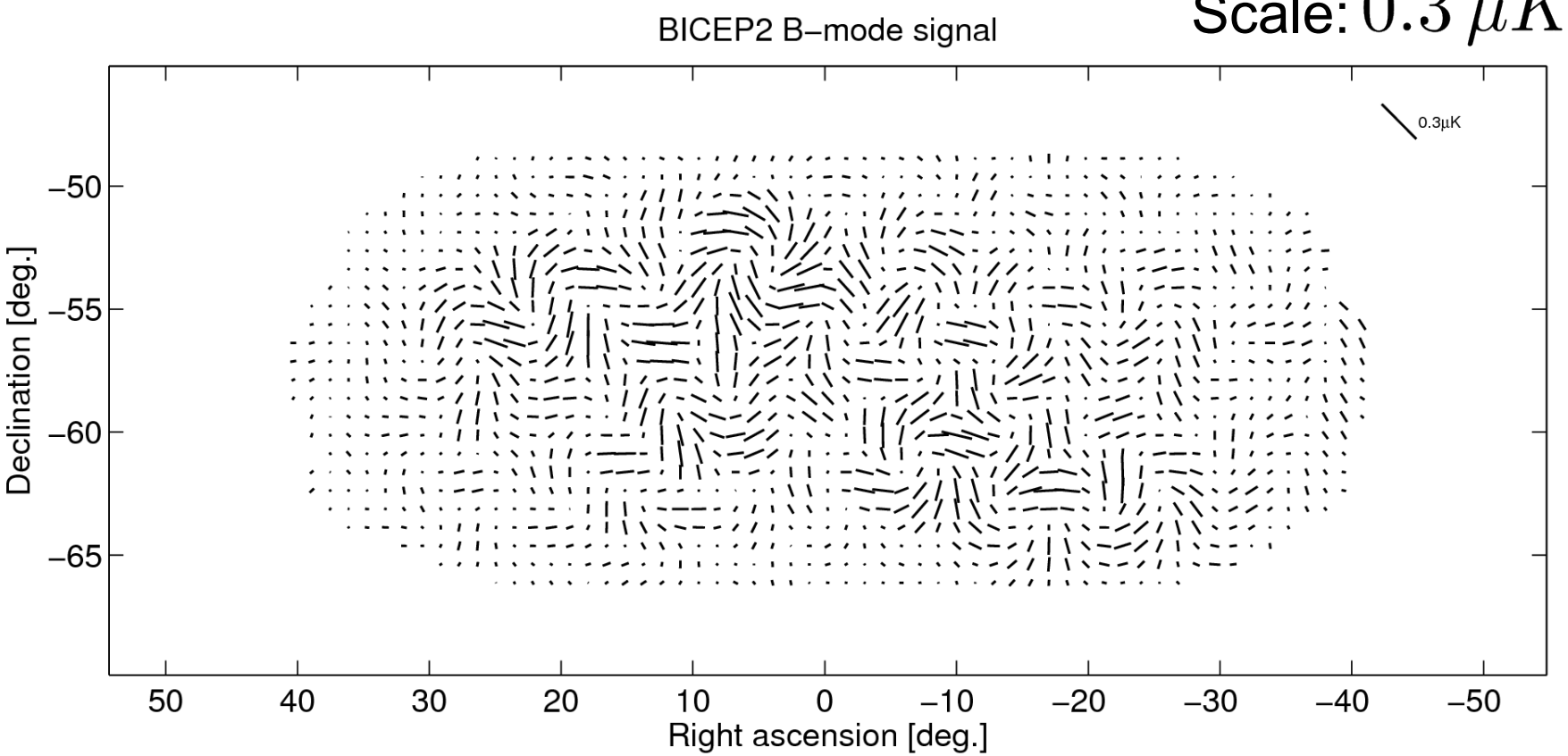
Scale: $1.7\ \mu K$



Apply purification operation which leaves only pure B-modes

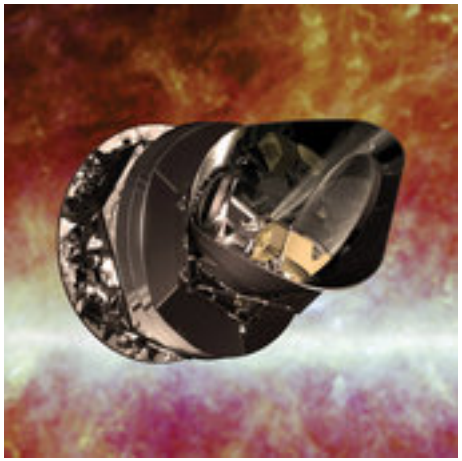
B-mode Contribution

Scale: $0.3\,\mu K$

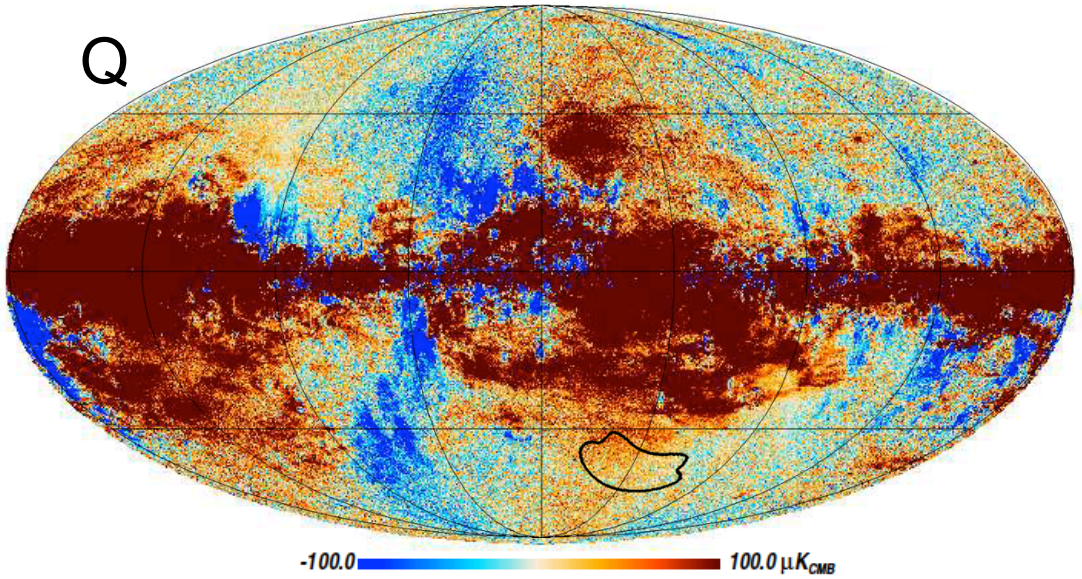


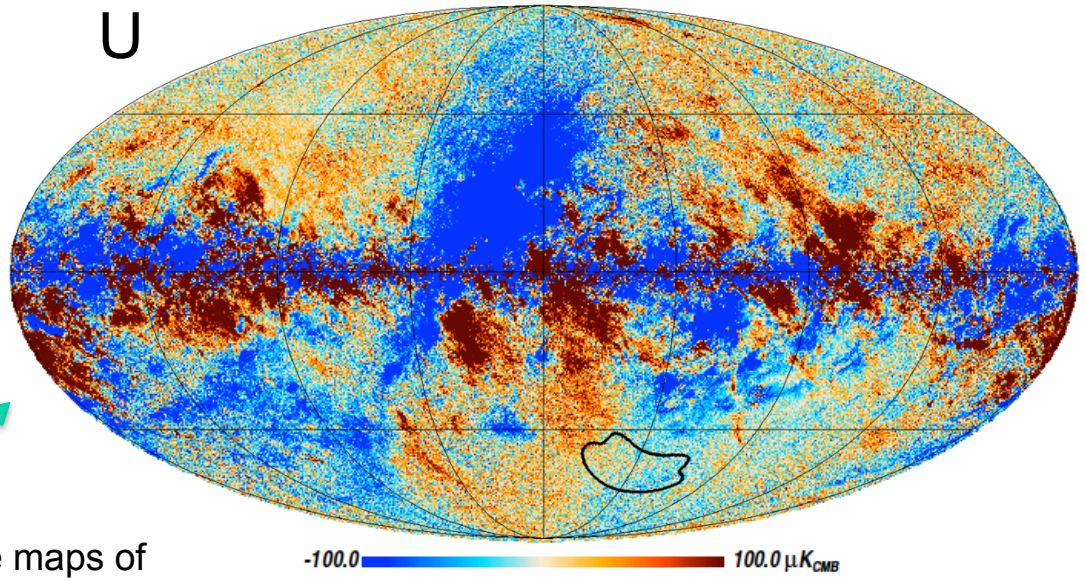
Zoom in by factor 6 – see “swirly” B-mode

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