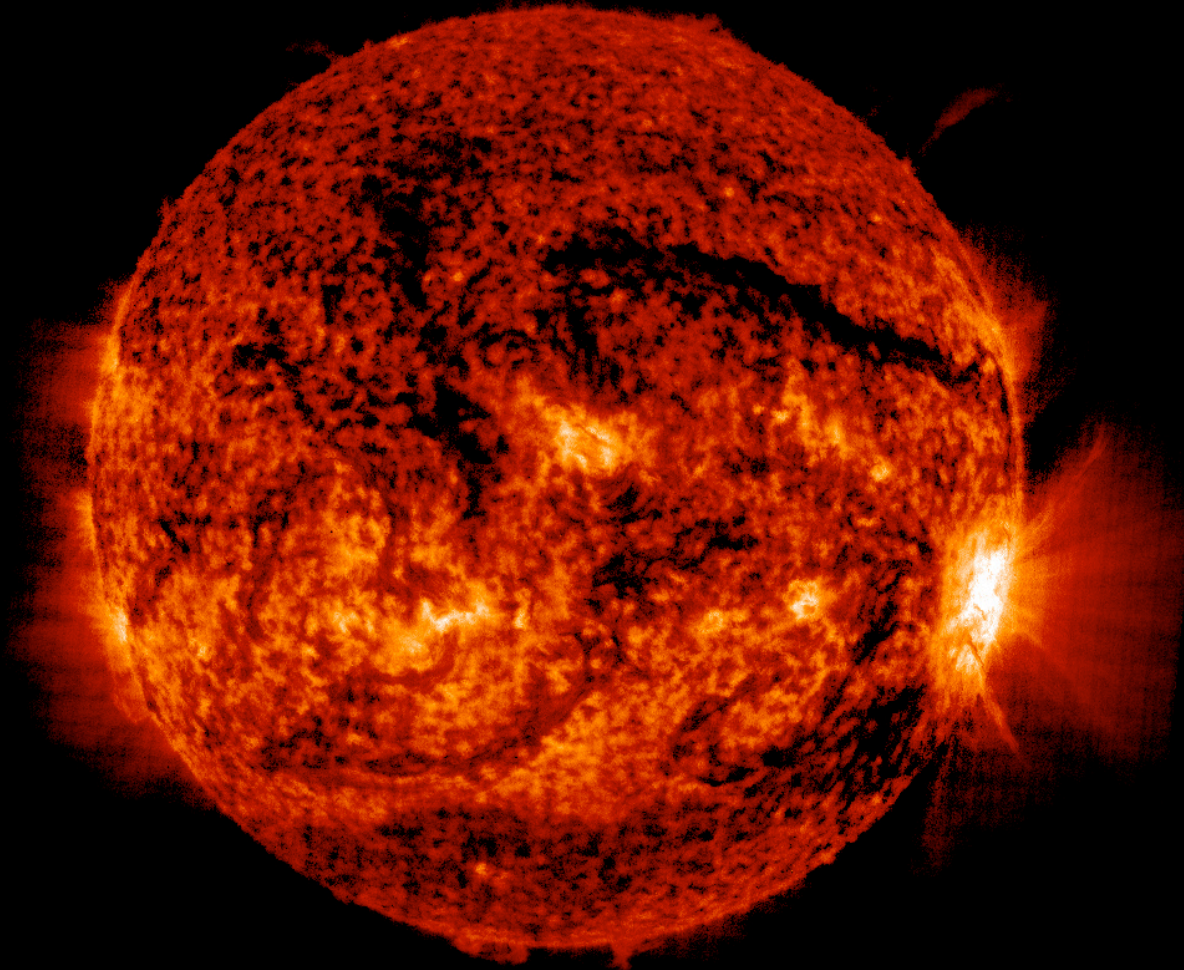




# Studying the Beginning of the Universe from the Bottom of the World

Clem Pryke – Headliners – May 2 2019

# Our Sun is a Star

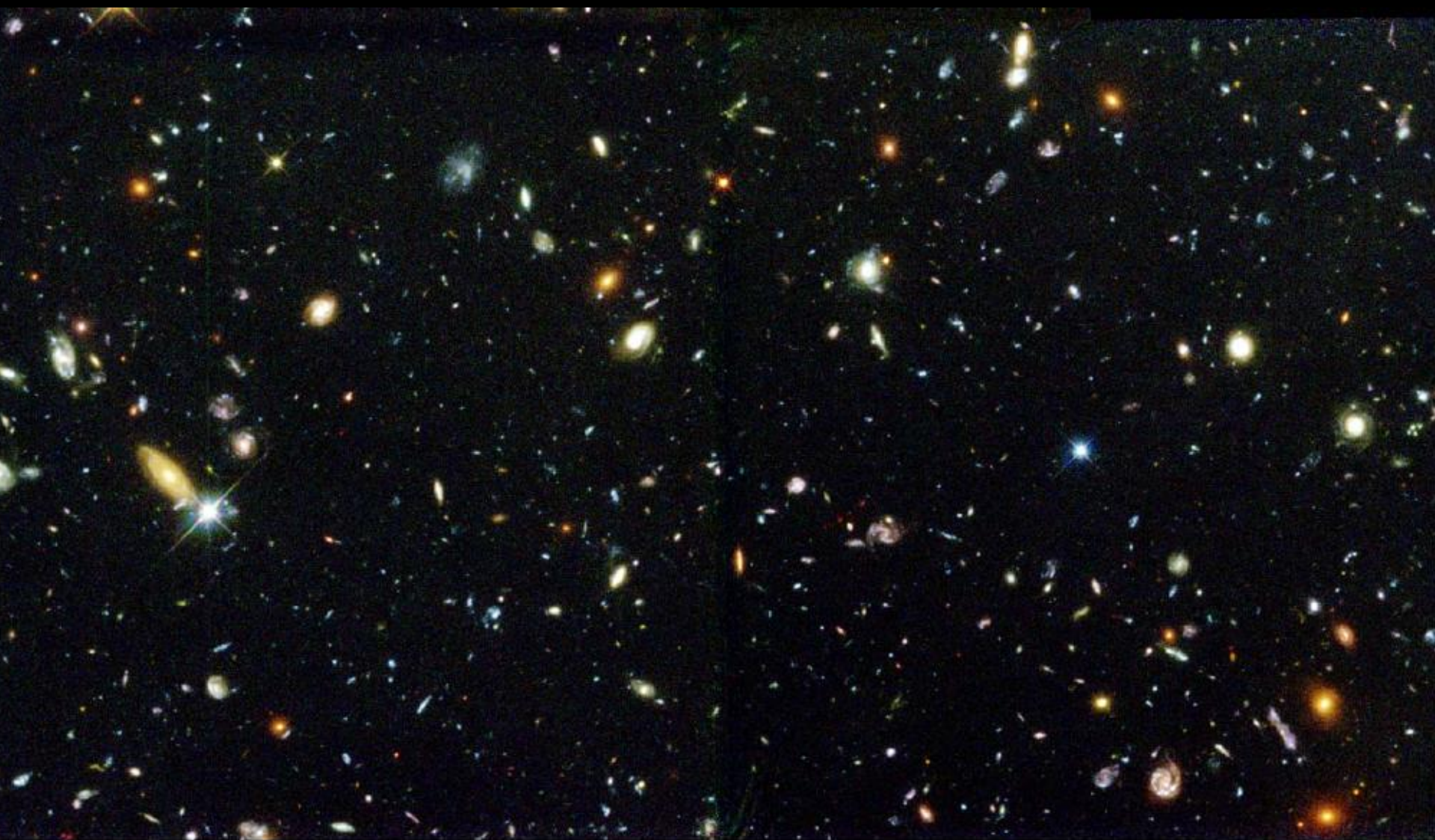


...Many stars make a galaxy...



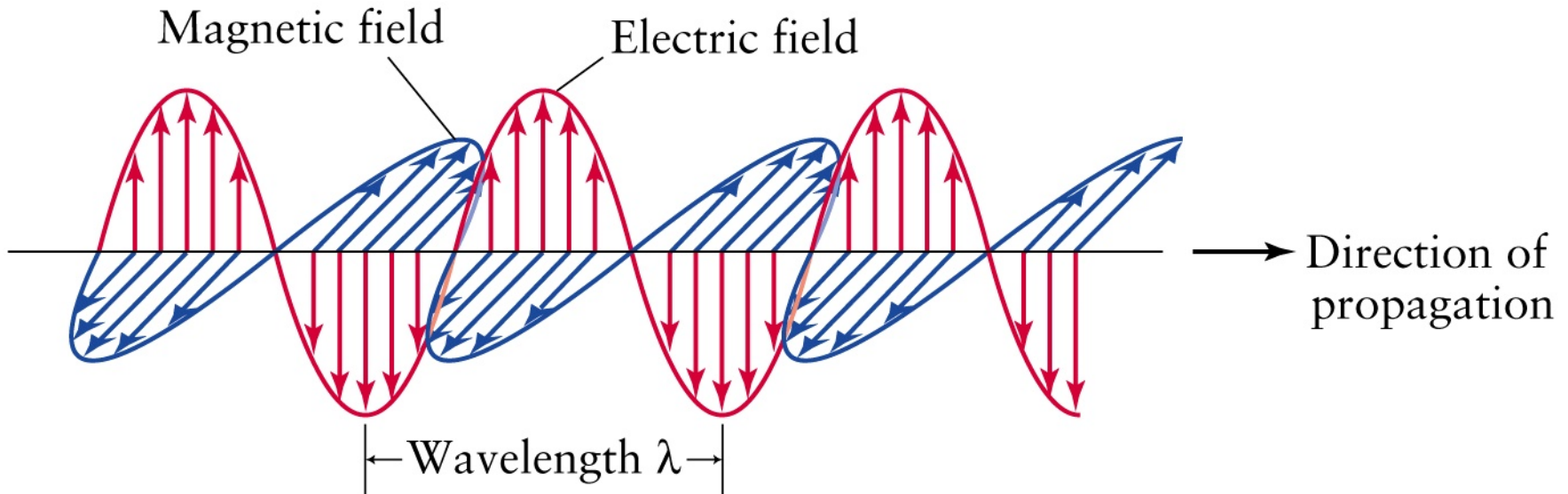
(A nearby galaxy similar to ours)

...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



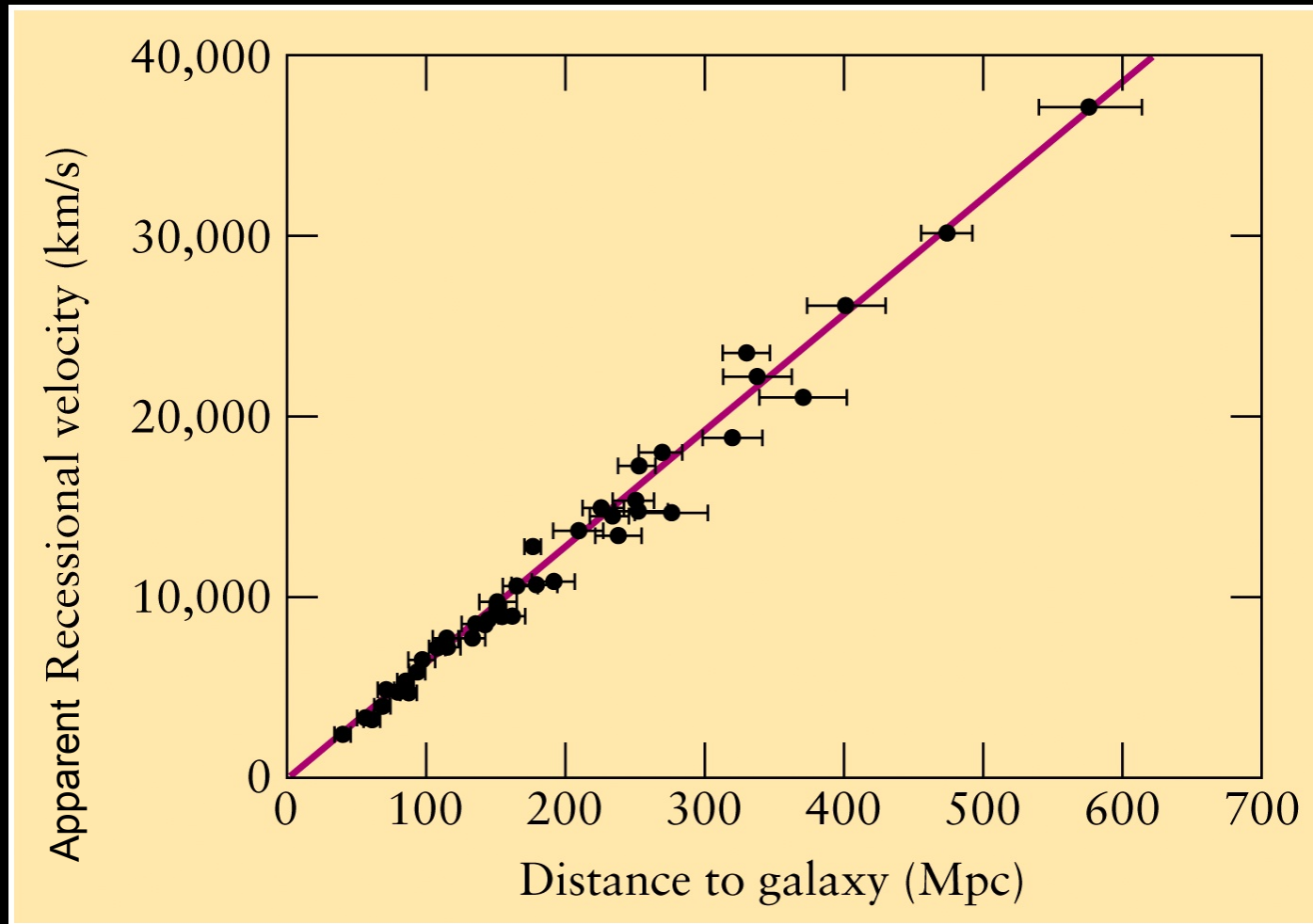
- Imagine 3 stars emitting rays of light of the same “natural” wavelength (color)
- But light moves through space always at the same speed...
- Moving towards us = compressed = bluer
- Moving away from us = stretched = redder

# Edwin Hubble “Observing” Distant Galaxies



Mount Wilson Observatory  
(LA) 1920's

# Hubble Diagram

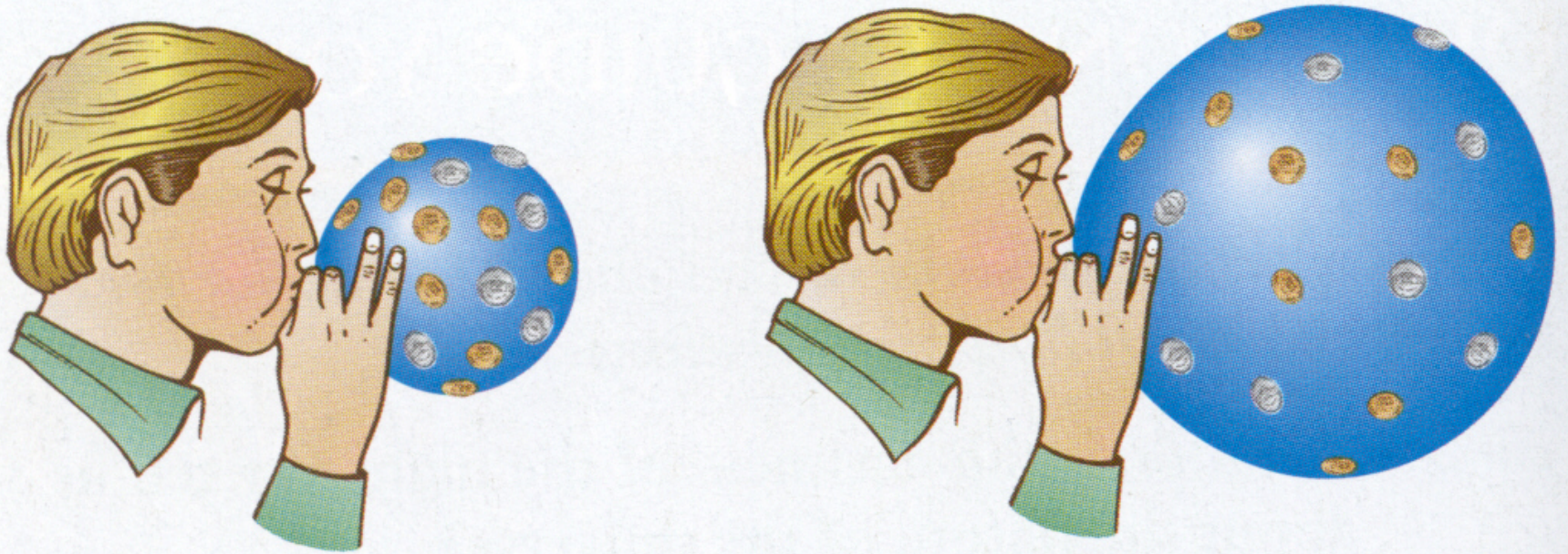


The farther away a galaxy is the faster it *appears* to be moving away from us...

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

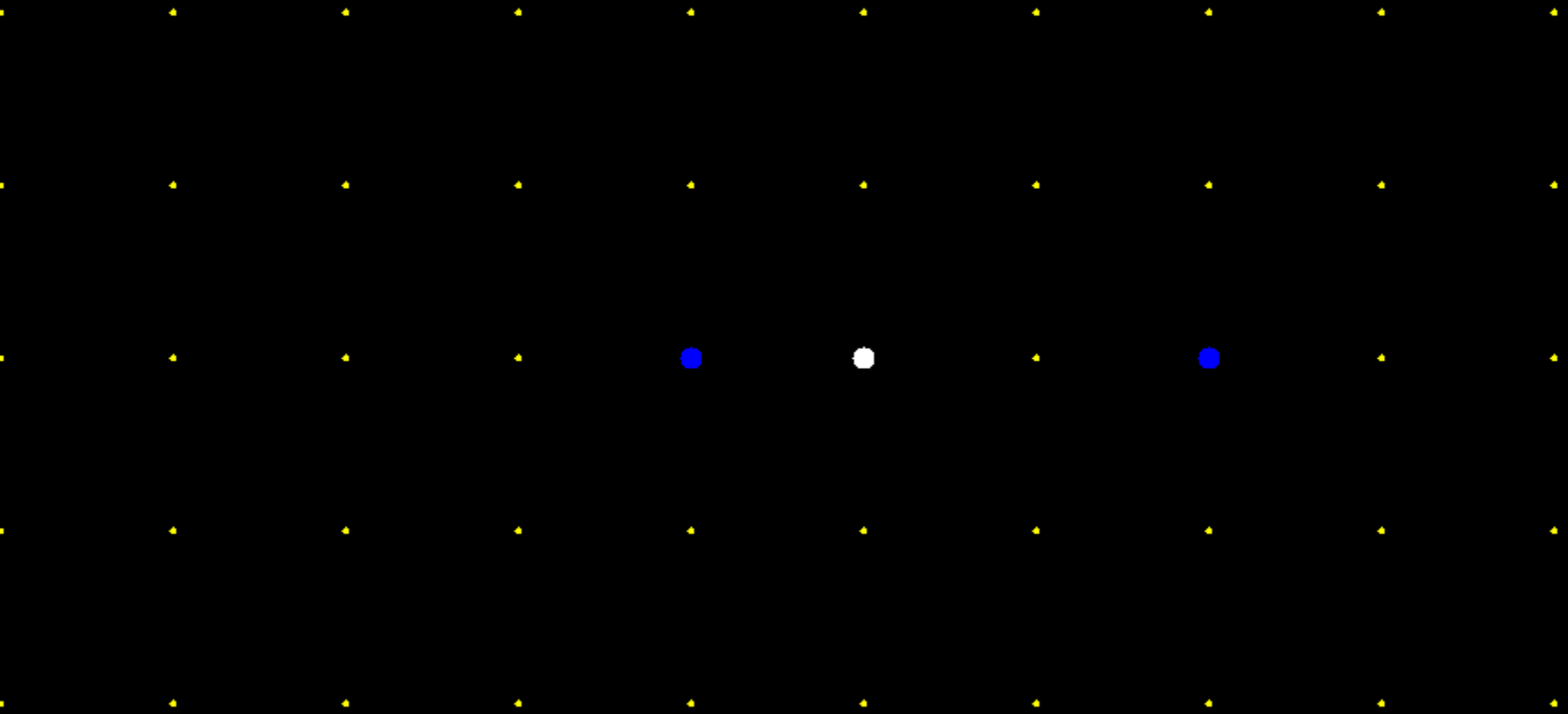


# Expanding Universe?



- 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

# 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)

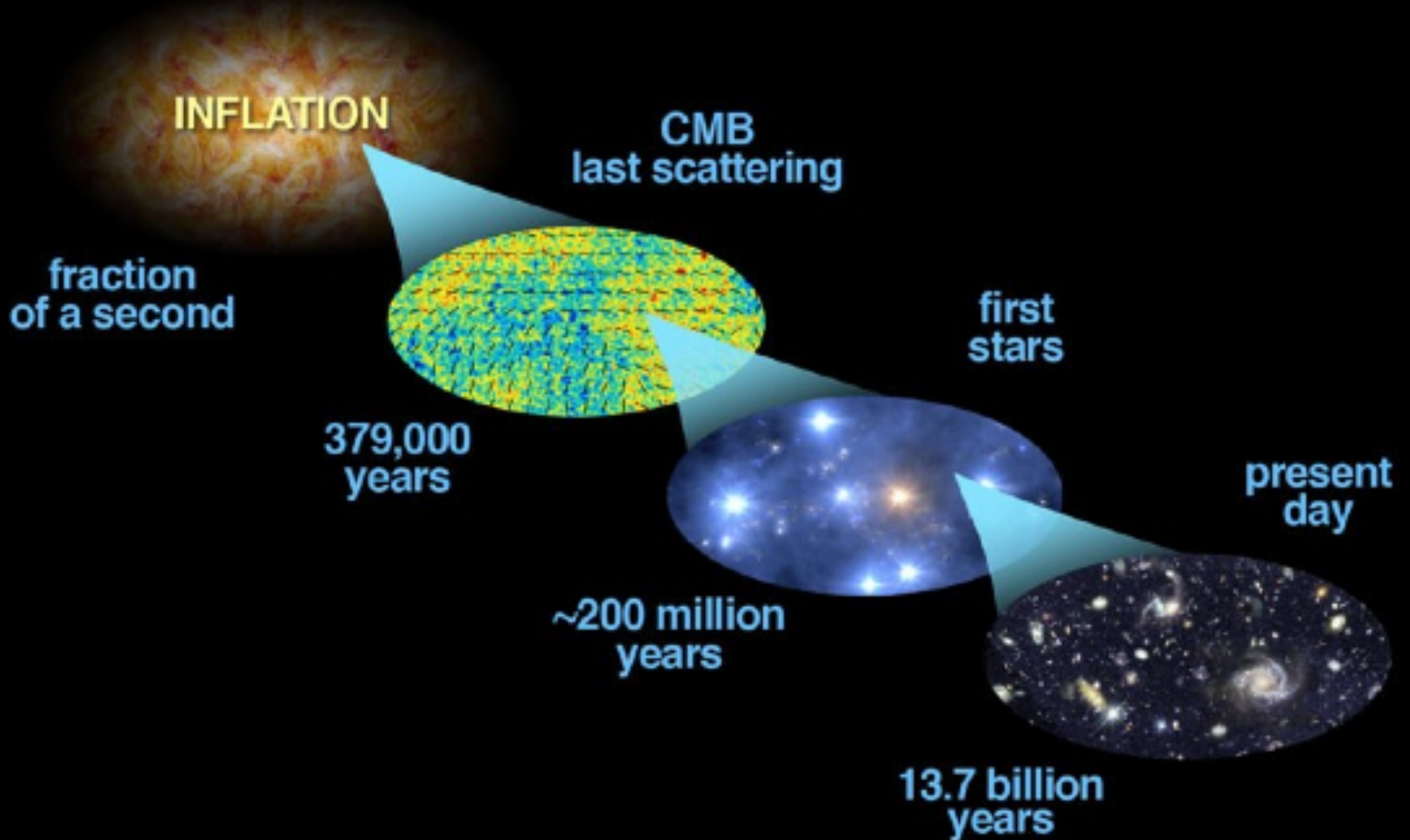
3) We can see the glow from that time!  
*The Cosmic Microwave Background*  
(Penzias & Wilson, 1964)



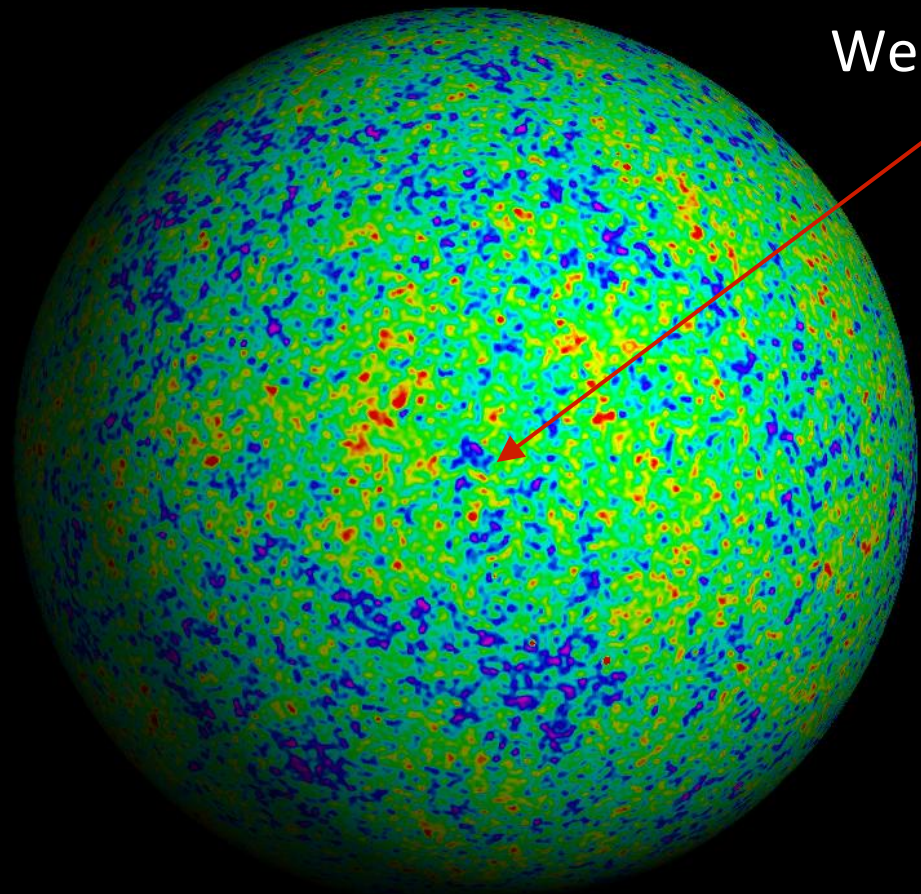
Bob Wilson & Arno Penzias  
1978 Nobel Prize

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

# Telescopes are time machines!



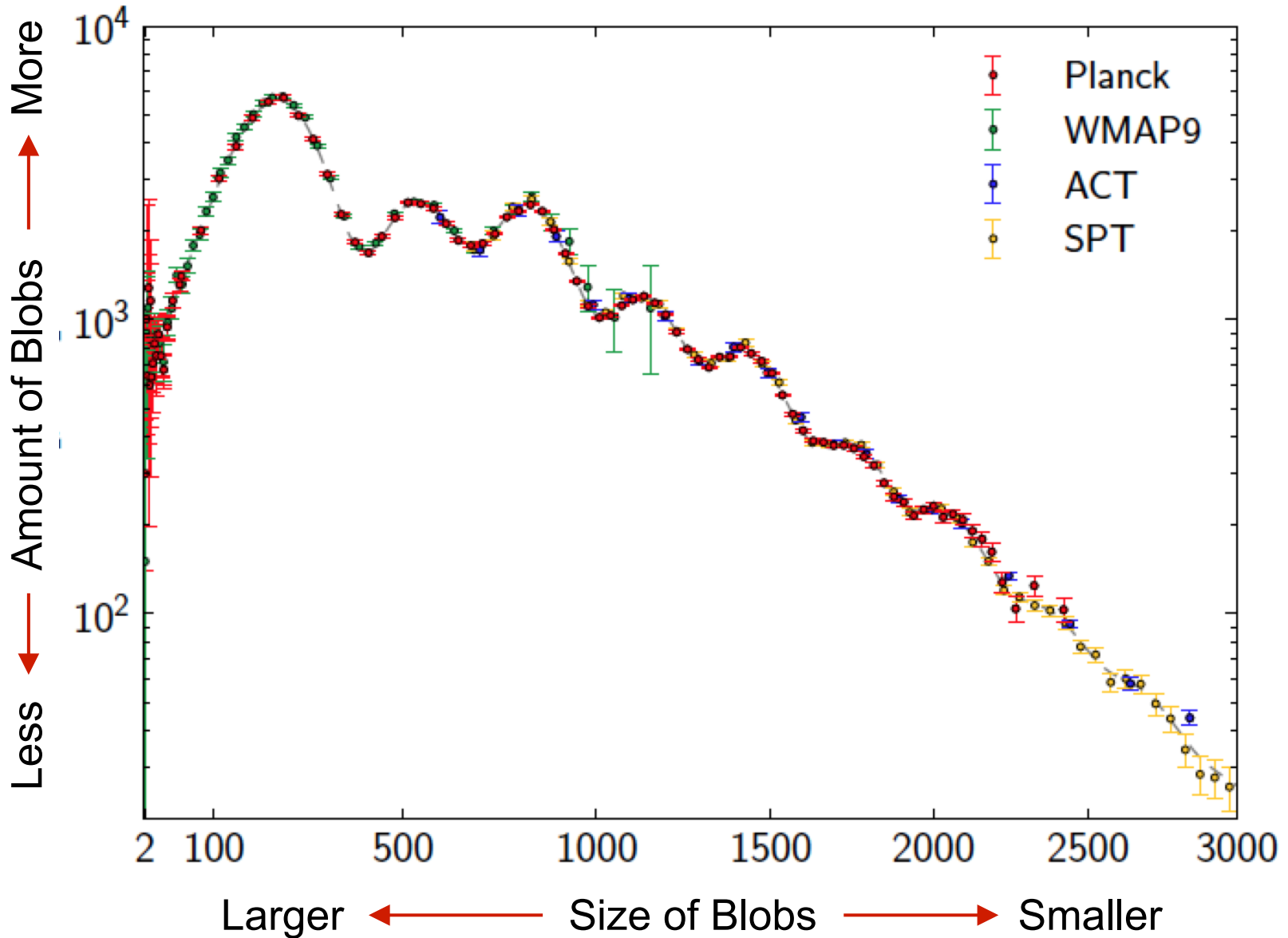
# All Sky Map of the Cosmic Microwave Background



We are at the center

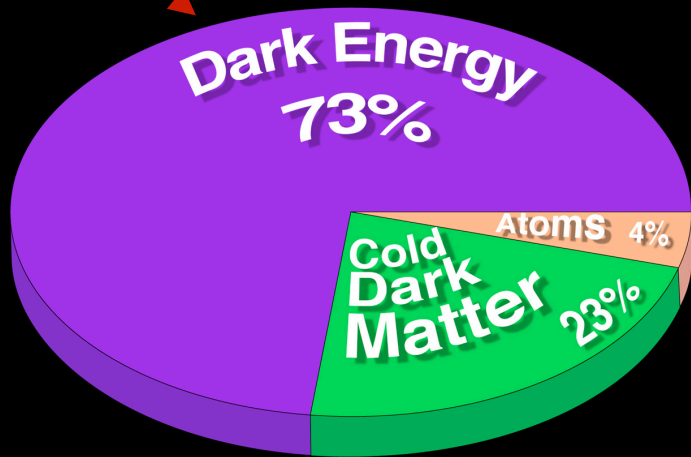
CMB is a sample of the density structure on a shell cut through the 380,000 year old Universe – at that time it was simple and nearly uniform

# “Lump Sorter” Plot

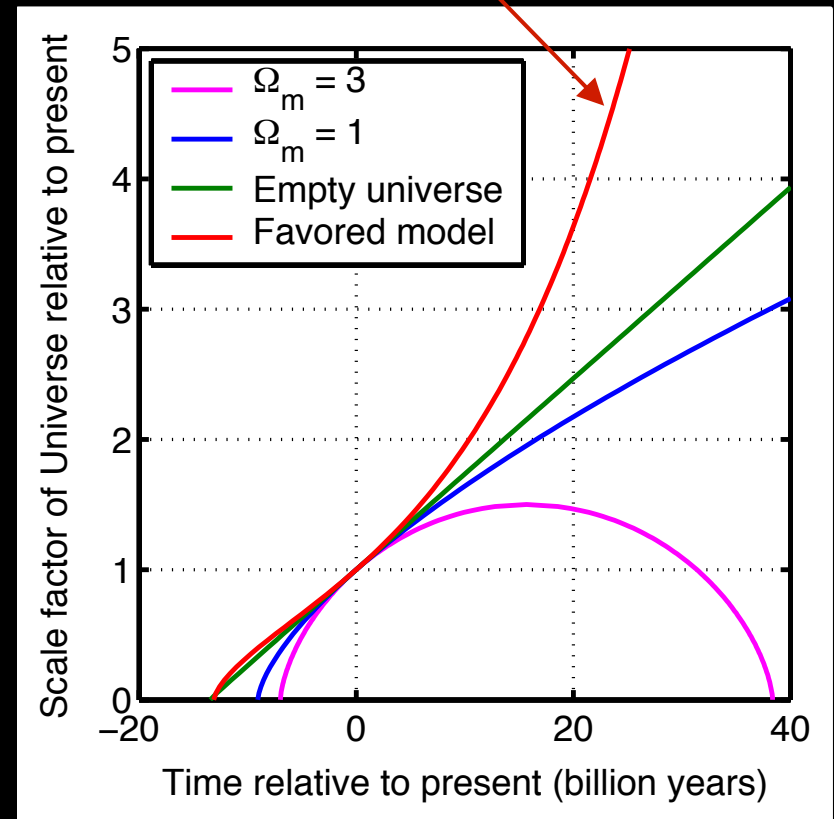


# Triumphant/Embarrassing Cosmology

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

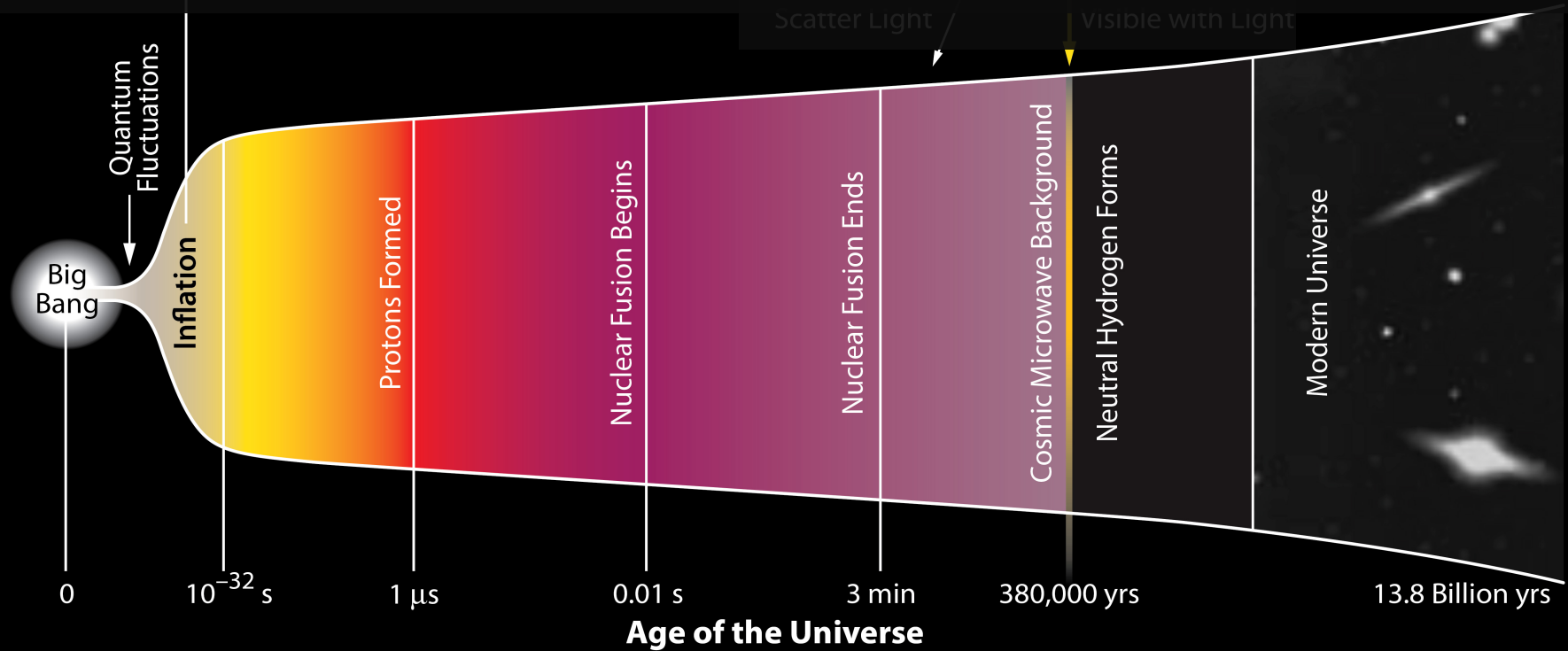


Alan Guth



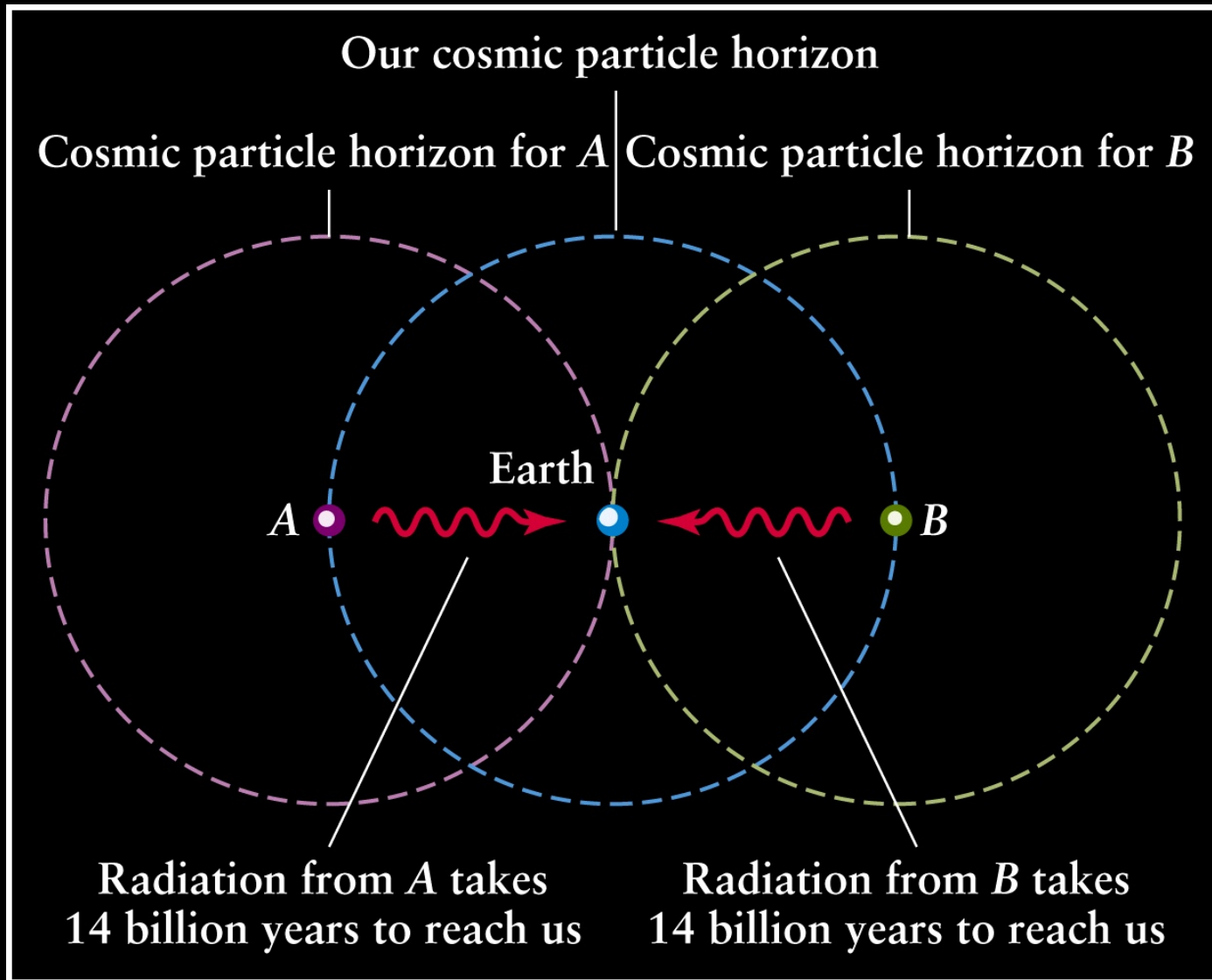
Andrei Linde

Radius of the Visible Universe



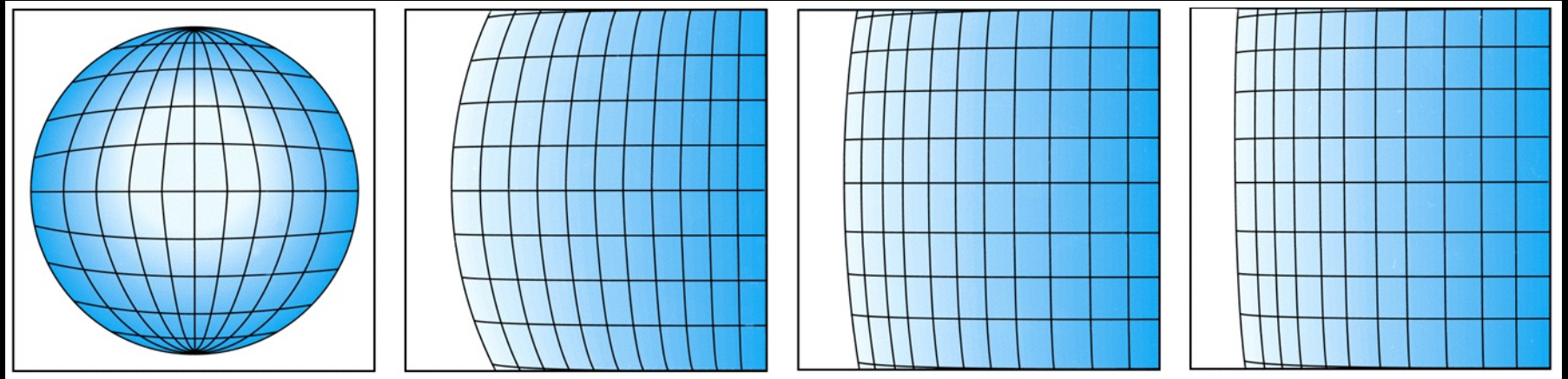


# Inflation solves the “Horizon Problem”



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

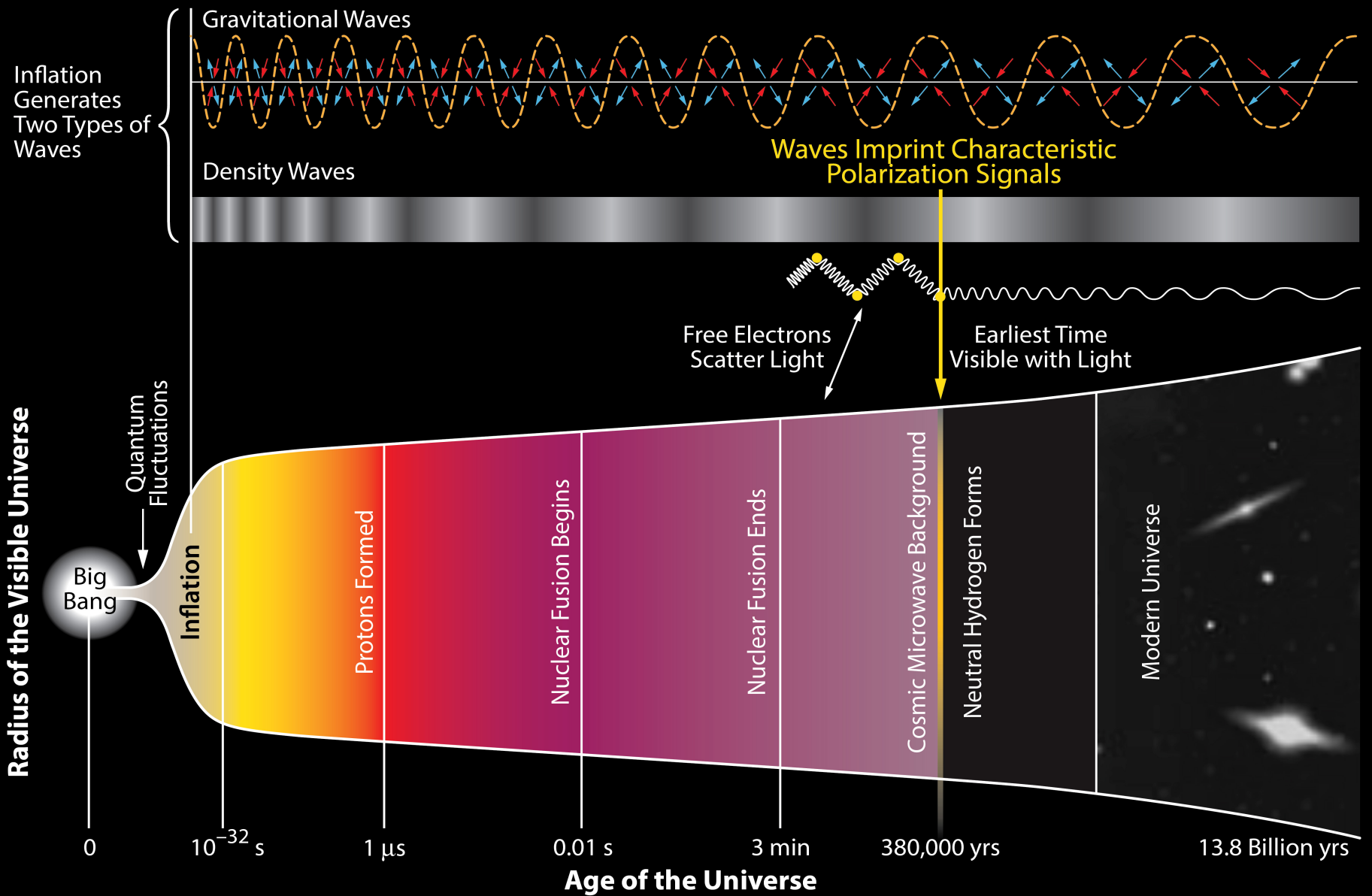
# Inflation solves the “Flatness Problem”



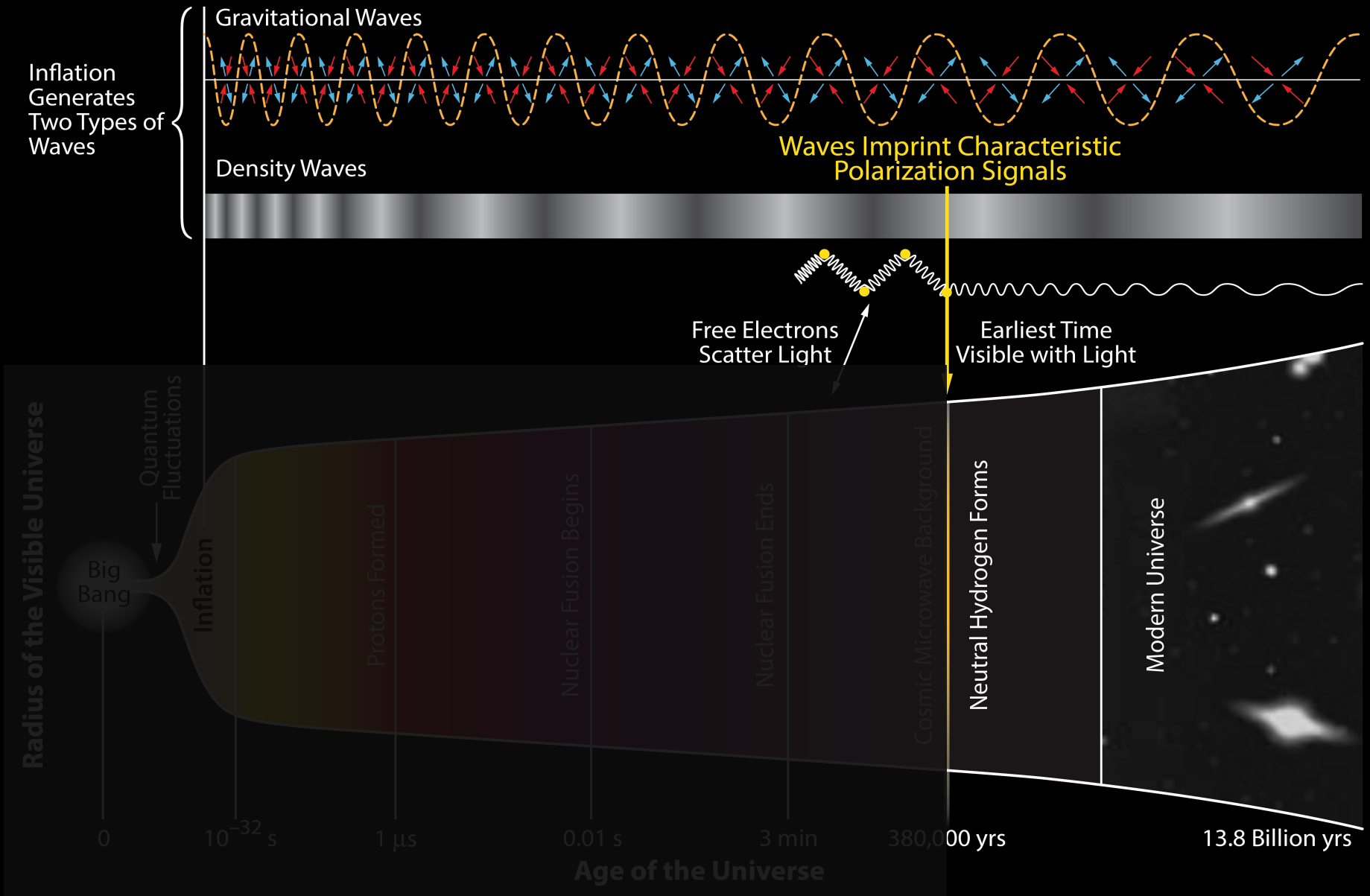
→ Inflation... →

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!

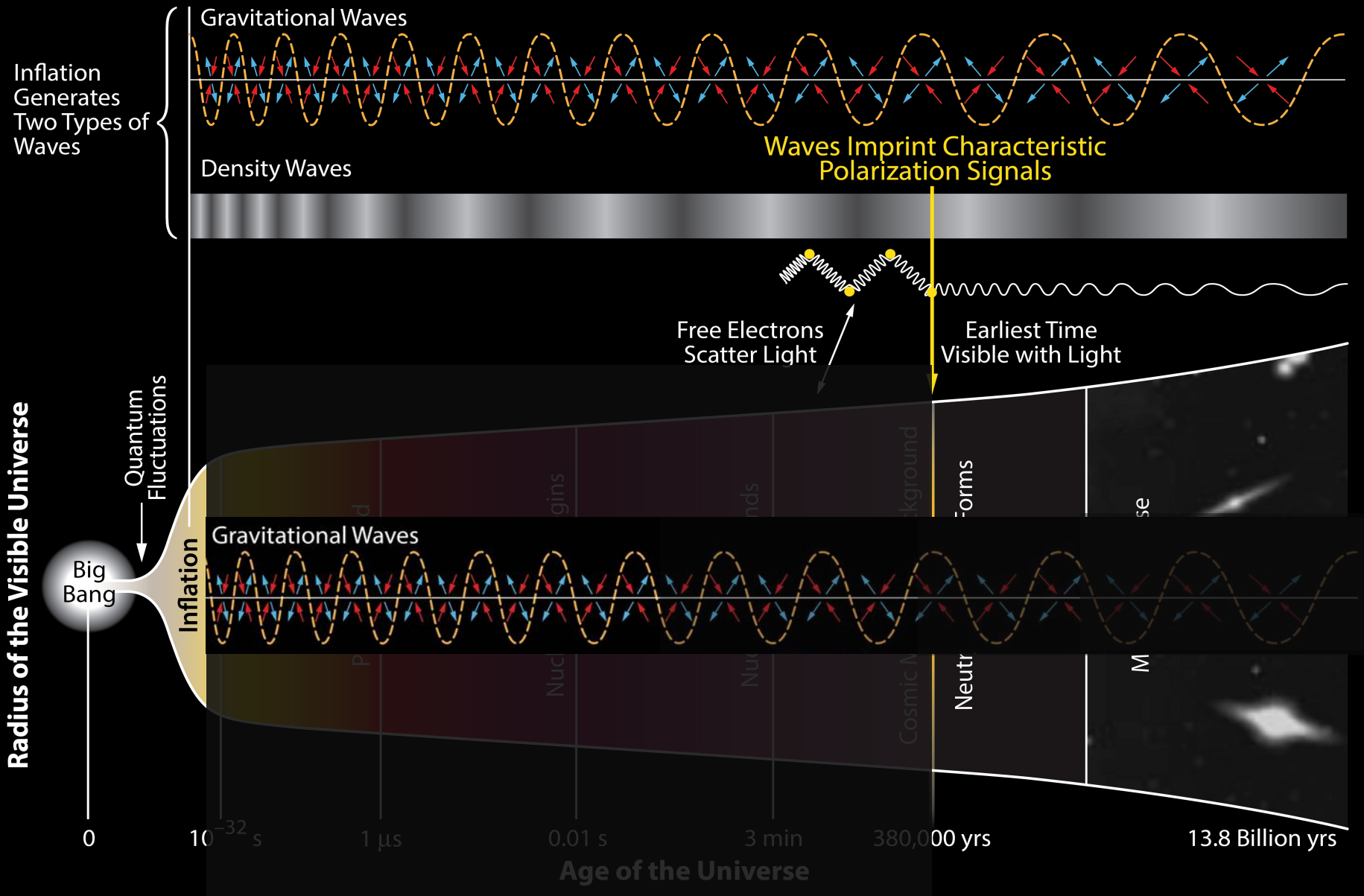
# History of the Universe



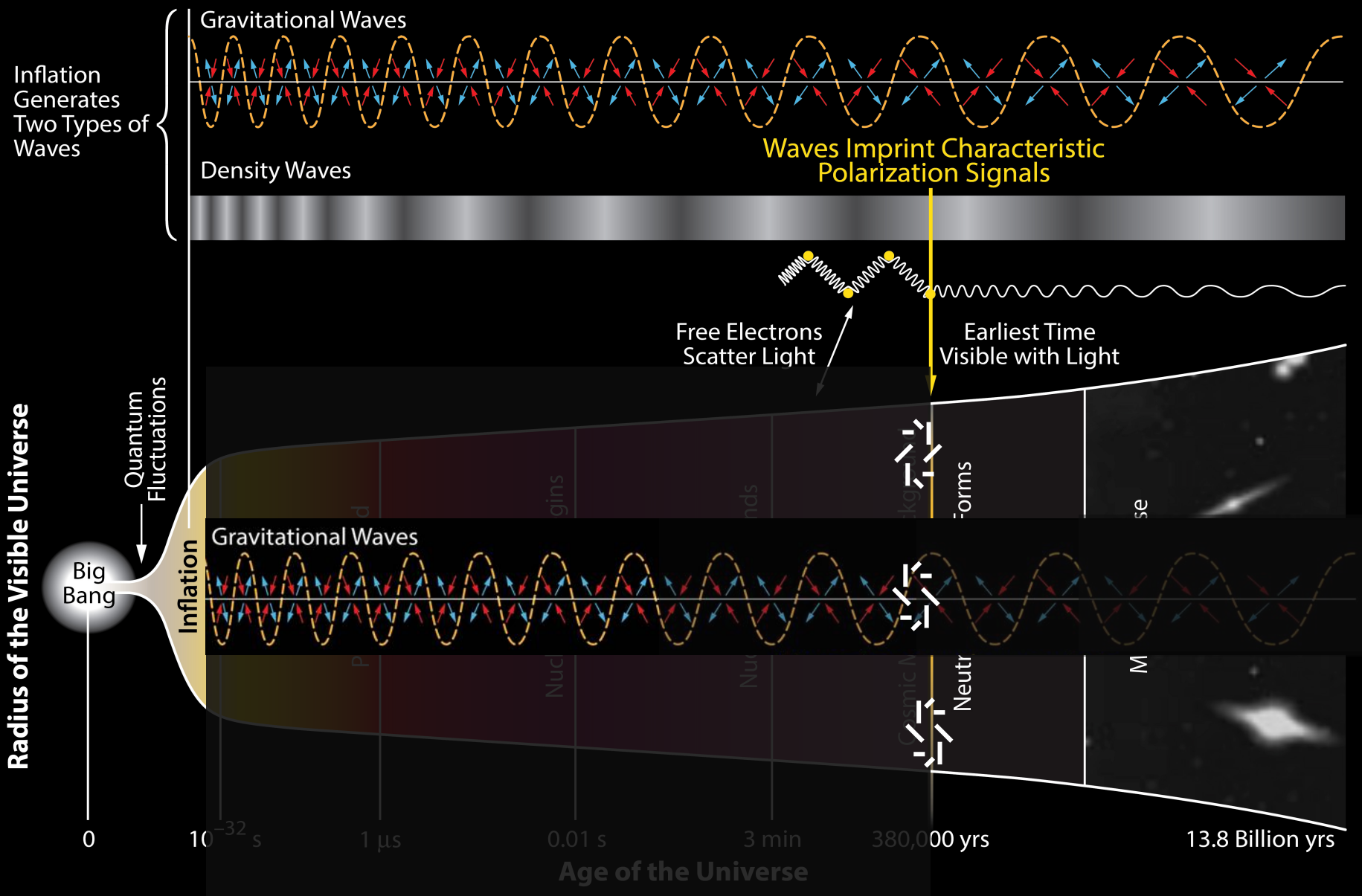
# History of the Universe



# History of the Universe



# History of the Universe



# 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*

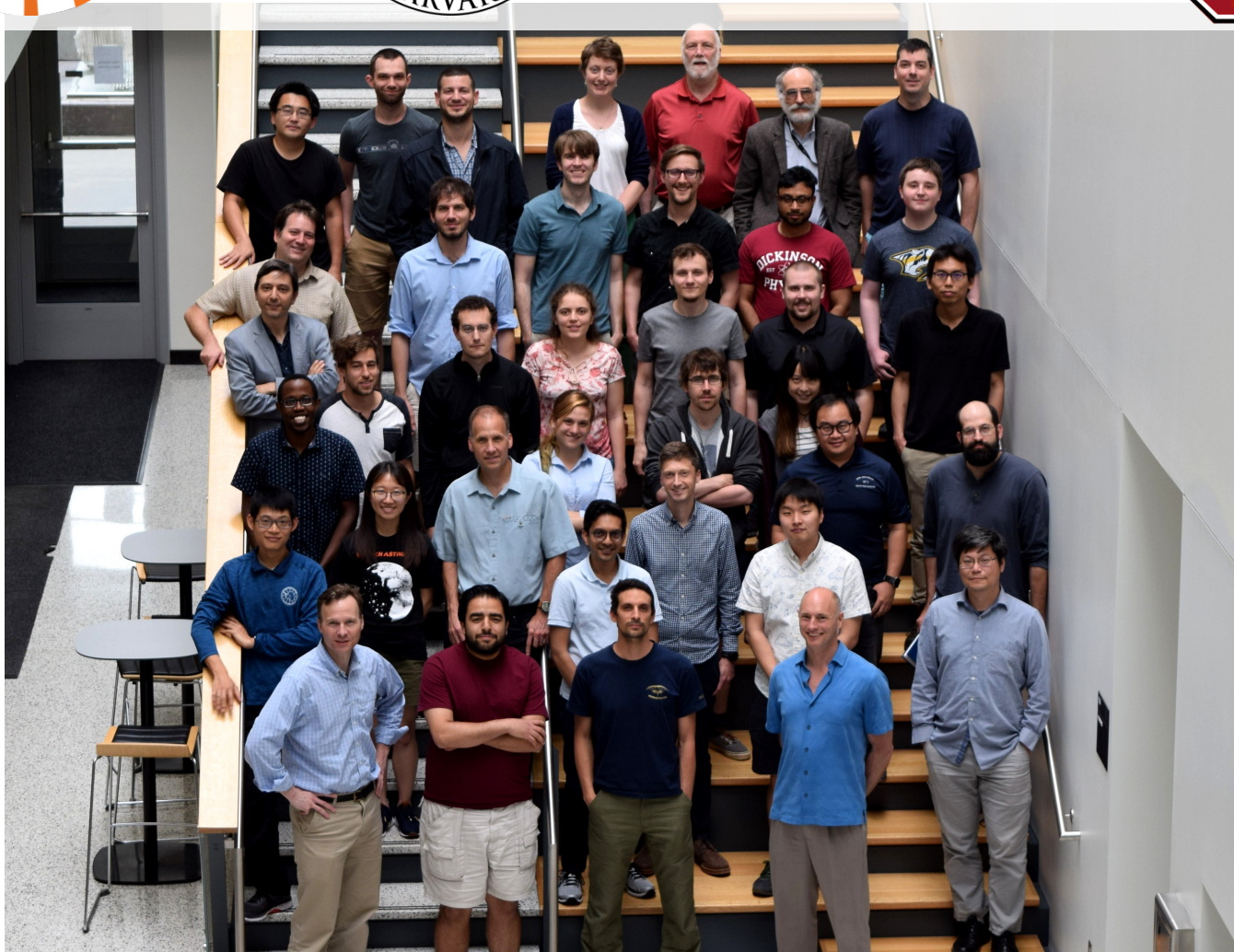
<sup>2</sup>*Rutgers University, New Brunswick, NJ 08901, USA*

<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)



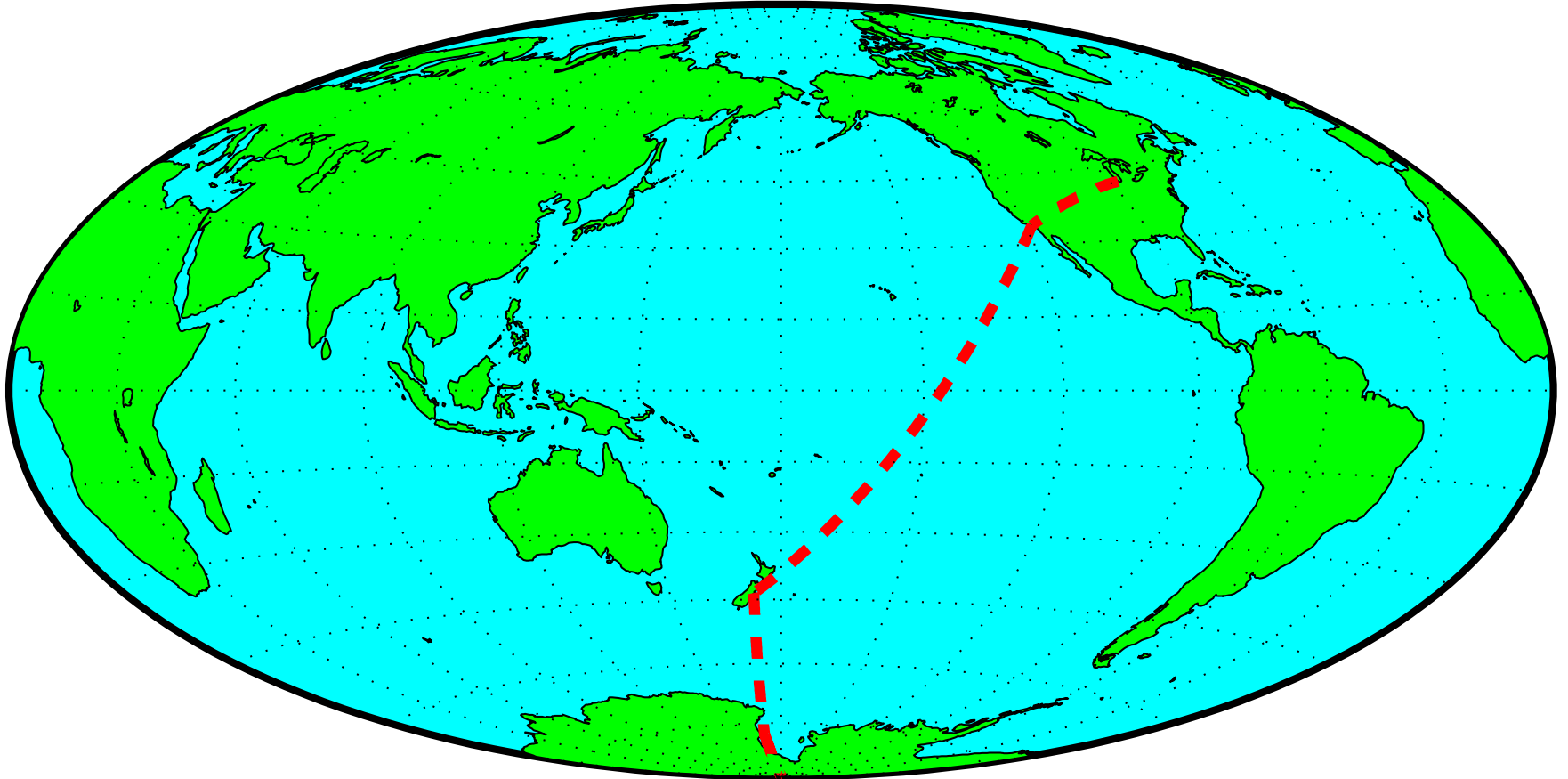


UNIVERSITY OF  
TORONTO



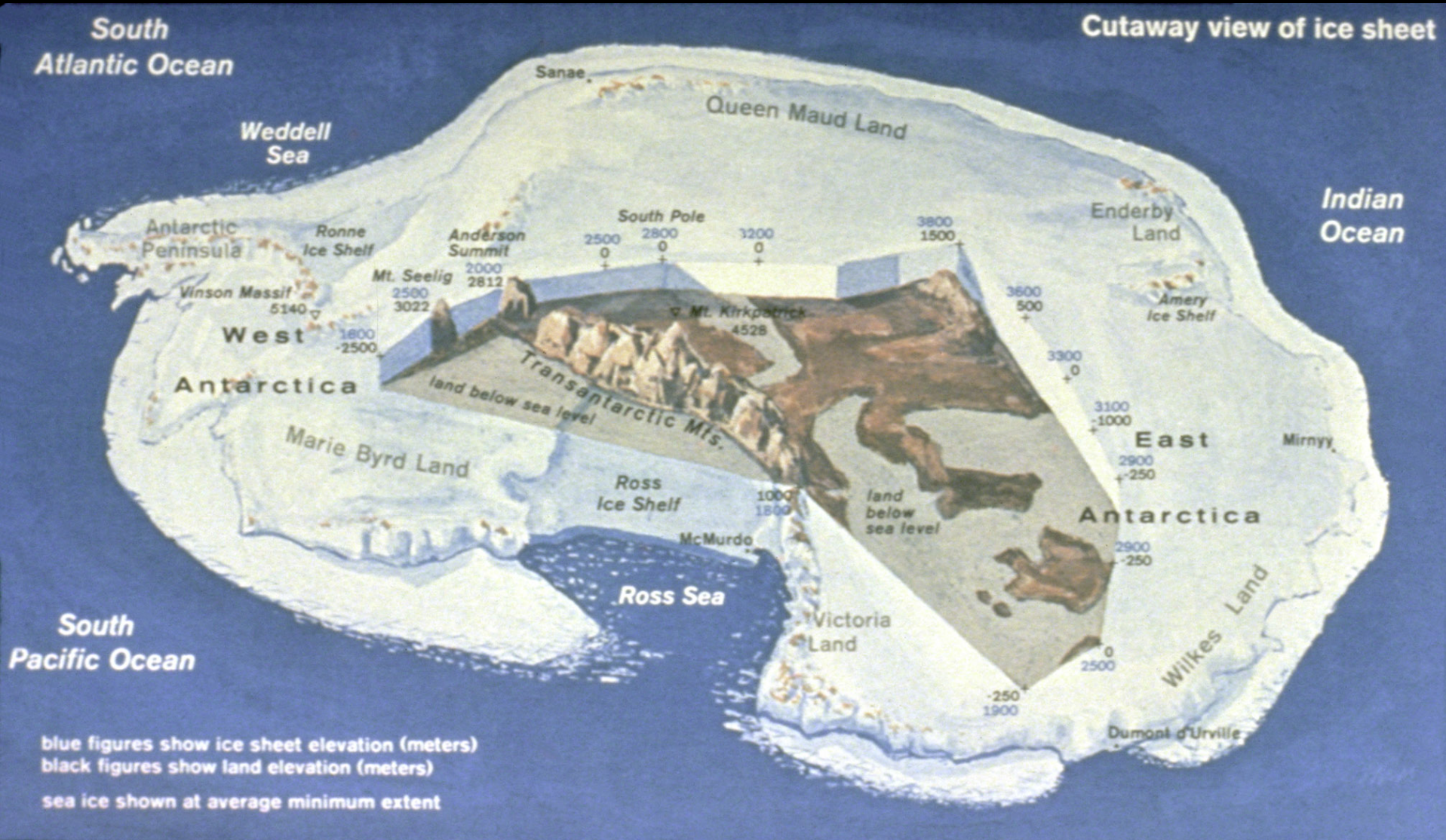


# Journey to the South Pole



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

# Antarctic Continent



Larger than the US – Ice sheet two miles thick!



# Christchurch New Zealand – Clothing Warehouse



**PARKA. RED**

**CARRHART. PARKA**

**CARRHART. JACKET**

**JACKET POLAR-FLEECE**

**PARKA. WITH WOOL**

**PARKA. EXPERT**

**CAP YAK**

**PARKA. POLAR-FLEECE**

**ATTENTION**  
WHEN RETURNING OR EXCHANGING  
CLOTHING YOU MUST BRING YOUR  
CLOTHING ISSUE FORM WITH YOU

# 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



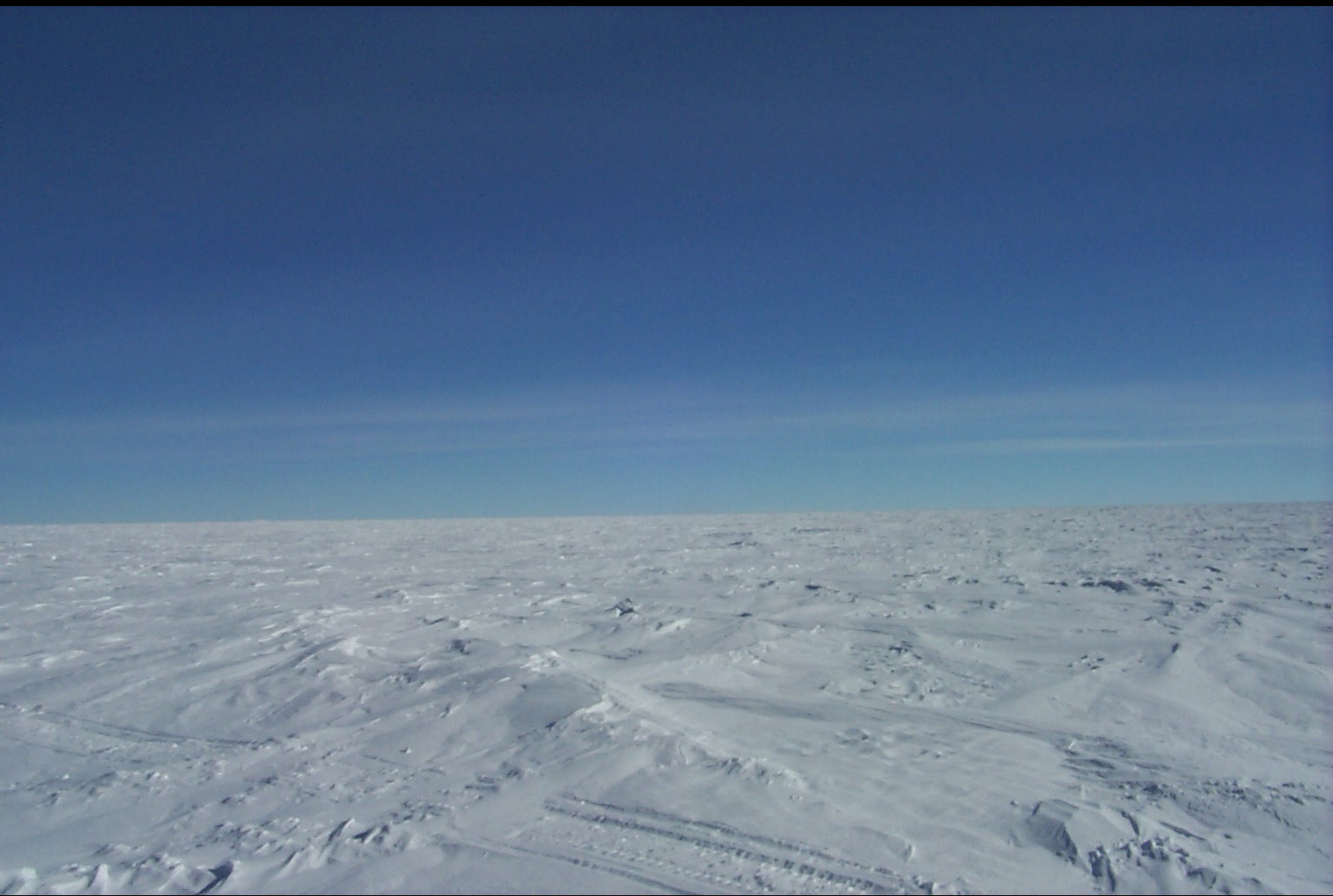
GEOGRAPHIC  
SOUTH POLE

ROBERT E. ADAMS  
DECEMBER 14, 1911

"So we arrived and were able to plant our flag at the geographical South Pole."

ELEVATION 9,301 FT.

**Nothing Out There!**



# Why do this at the Pole?

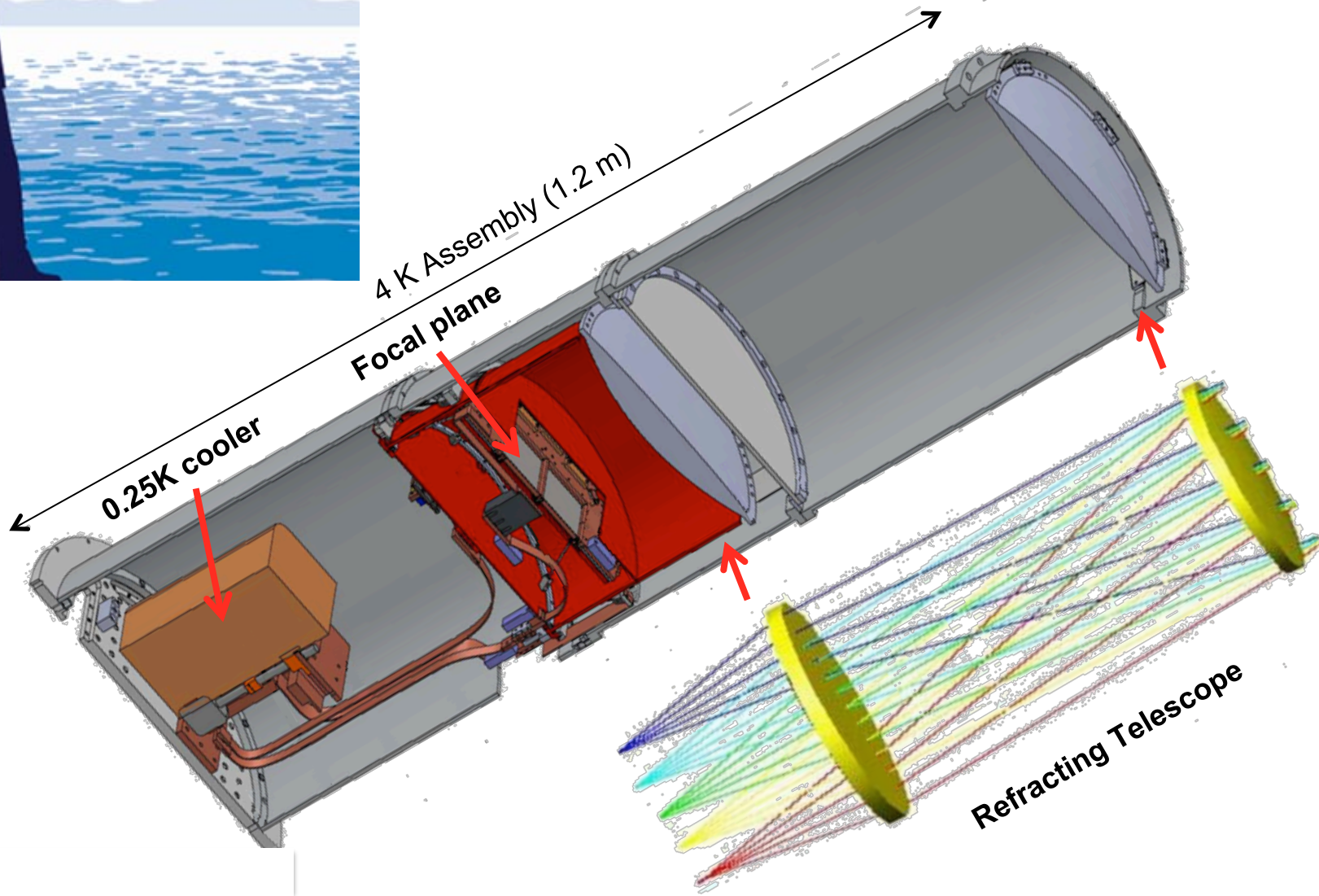
## South Pole CMB telescopes



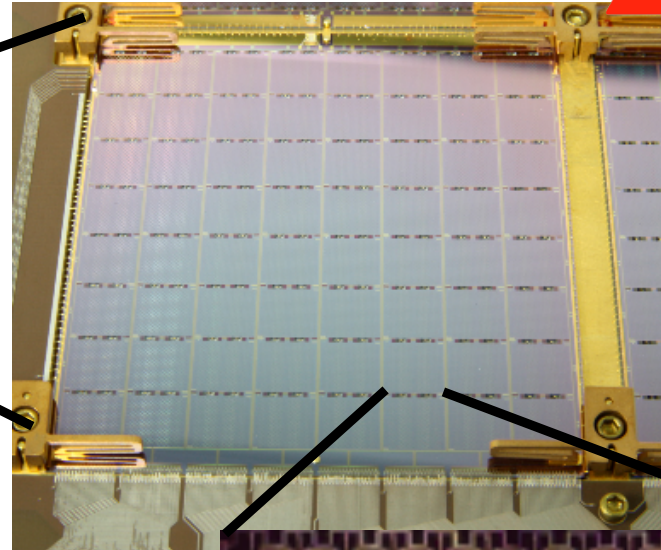
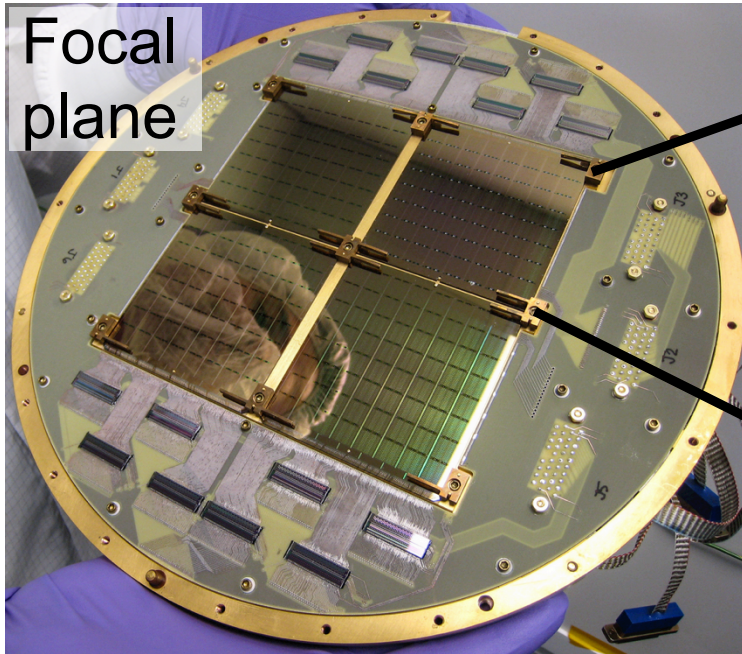
- High and *dry* – see out into space
- On Earth's rotational axis - One day/night cycle per year
  - Long night makes for great quality data
- Good support infrastructure – power, cargo, data comm
- Food and accommodation provided
- Even Tuesday night bingo...

# Basic Experiment Design

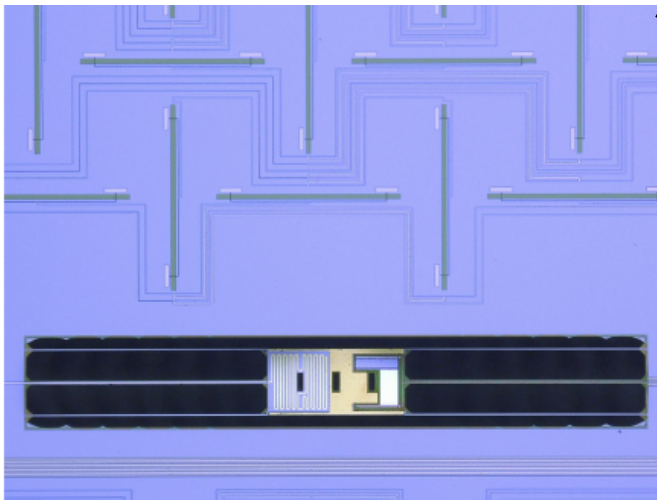
- Small aperture
- Wide field of view
- Cold refractor



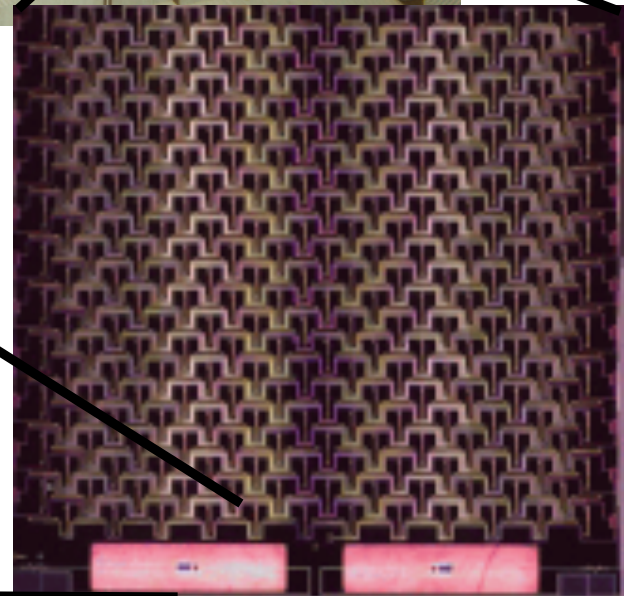
# Mass-produced Superconducting Detectors



Planar antenna array

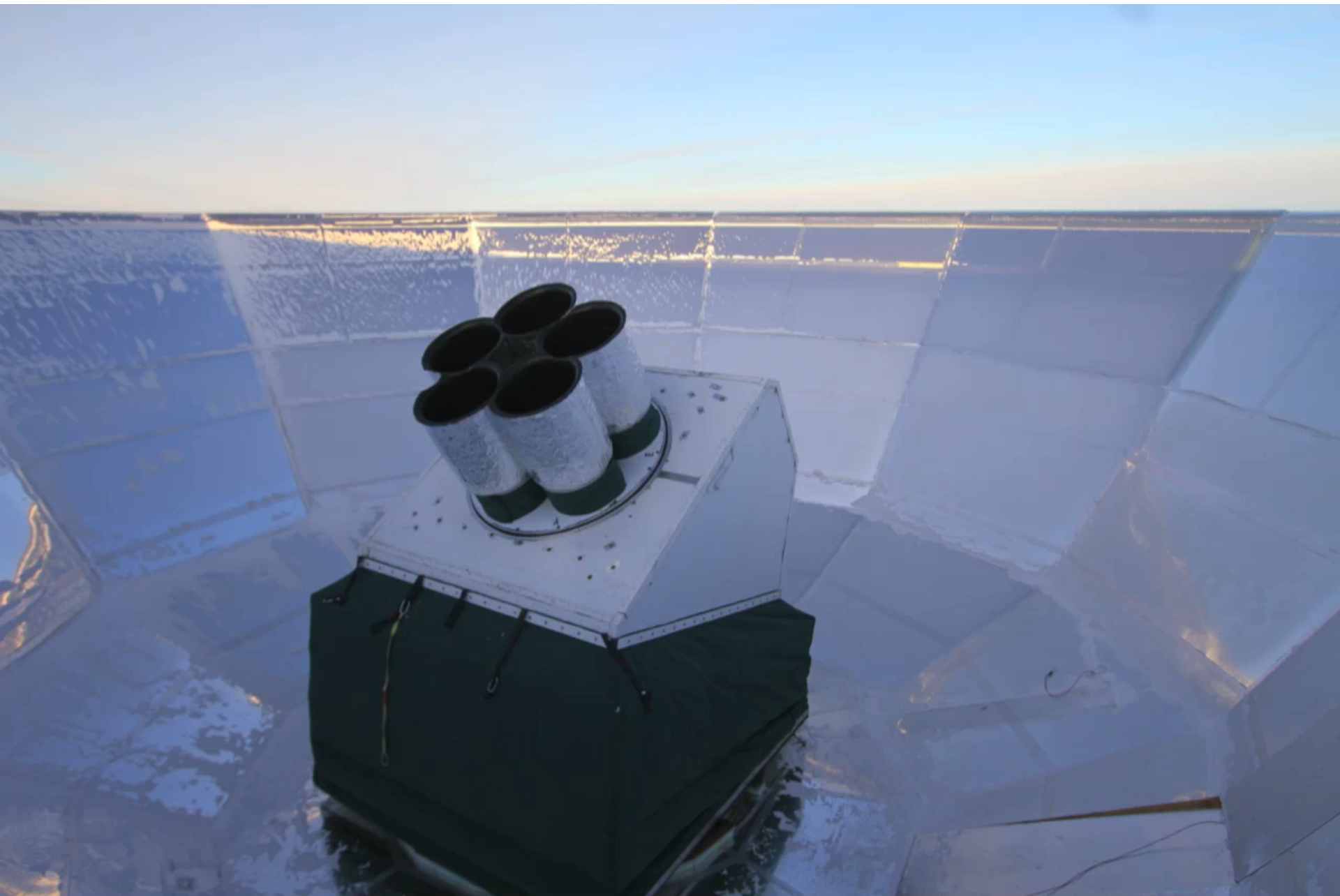


Slot antennas



Microstrip filters

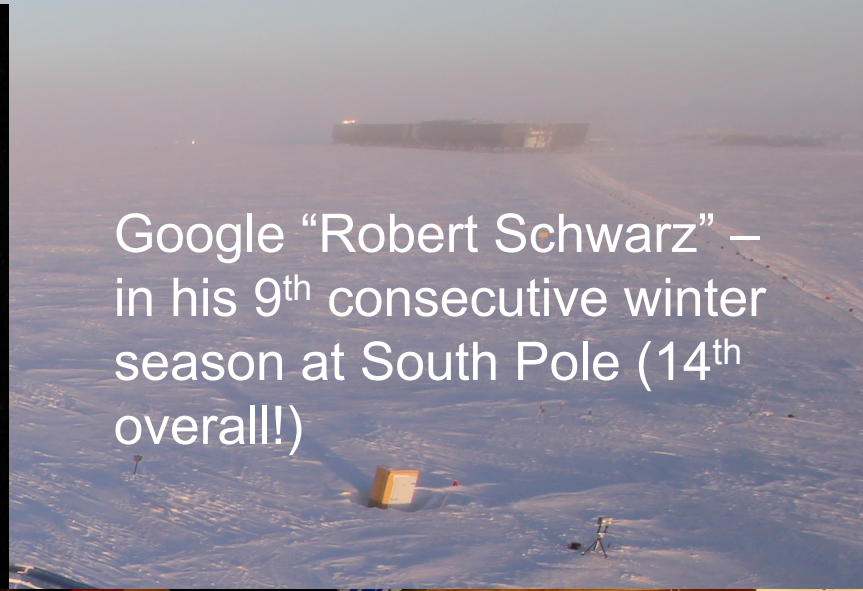
Transition edge sensor



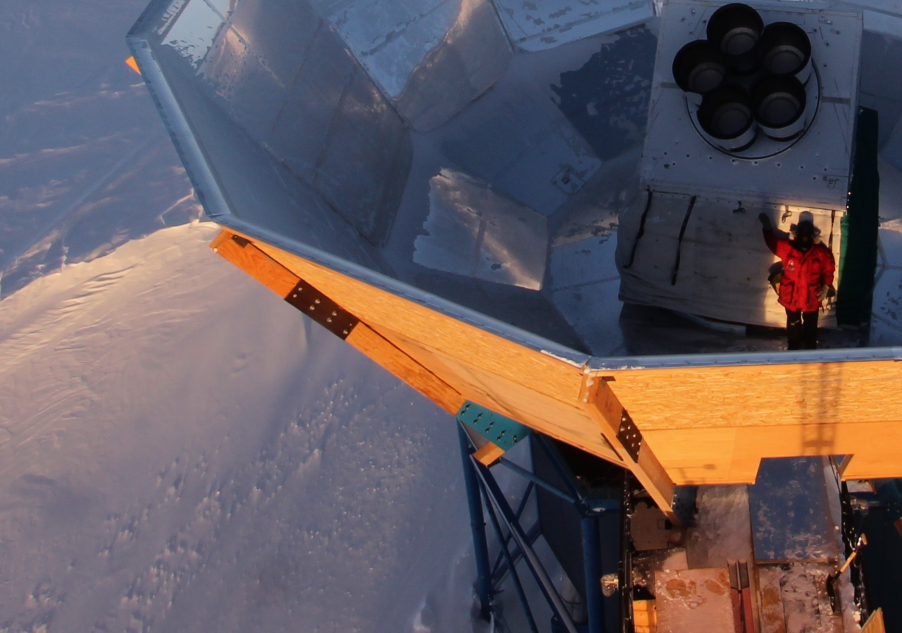
Clem Pryke for The Bicep2 Collaboration







Google “Robert Schwarz” –  
in his 9<sup>th</sup> consecutive winter  
season at South Pole (14<sup>th</sup>  
overall!)



## Stage 2

## Stage 3

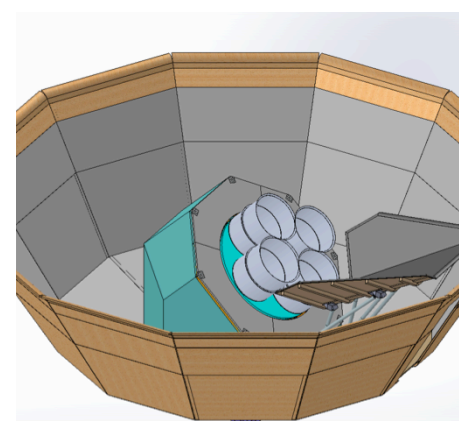
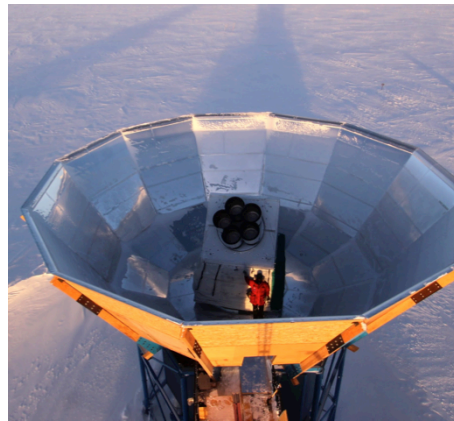
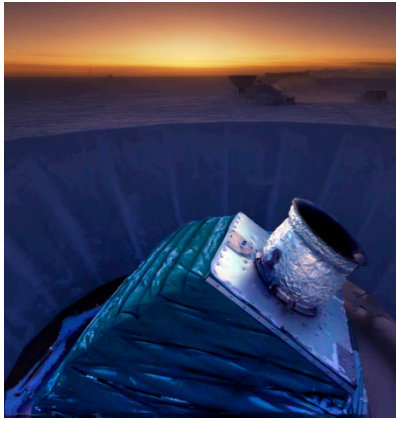
**BICEP2**  
(2010-2012)

**Keck Array**  
(2012-2019)

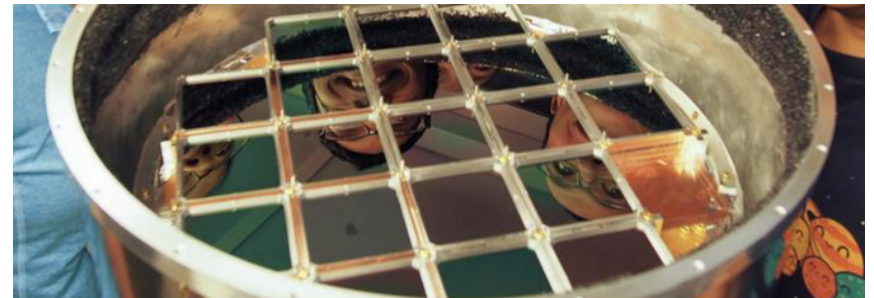
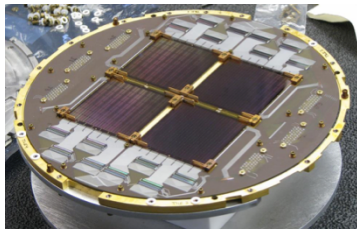
**BICEP3**  
(2015-)

**BICEP Array**  
(2020-)

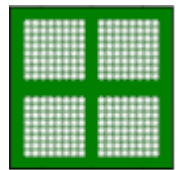
Telescope and Mount



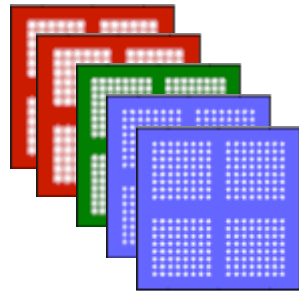
Focal Plane



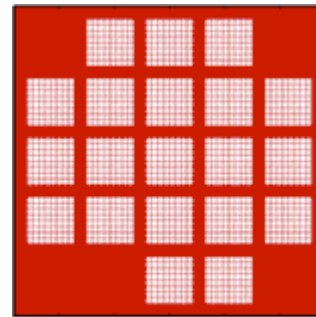
Beams on Sky



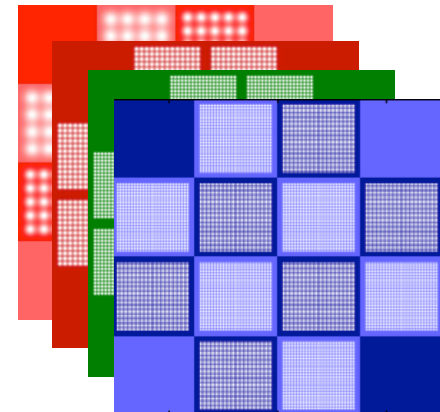
-5 0 5  
Degrees on sky



-5 0 5  
Degrees on sky

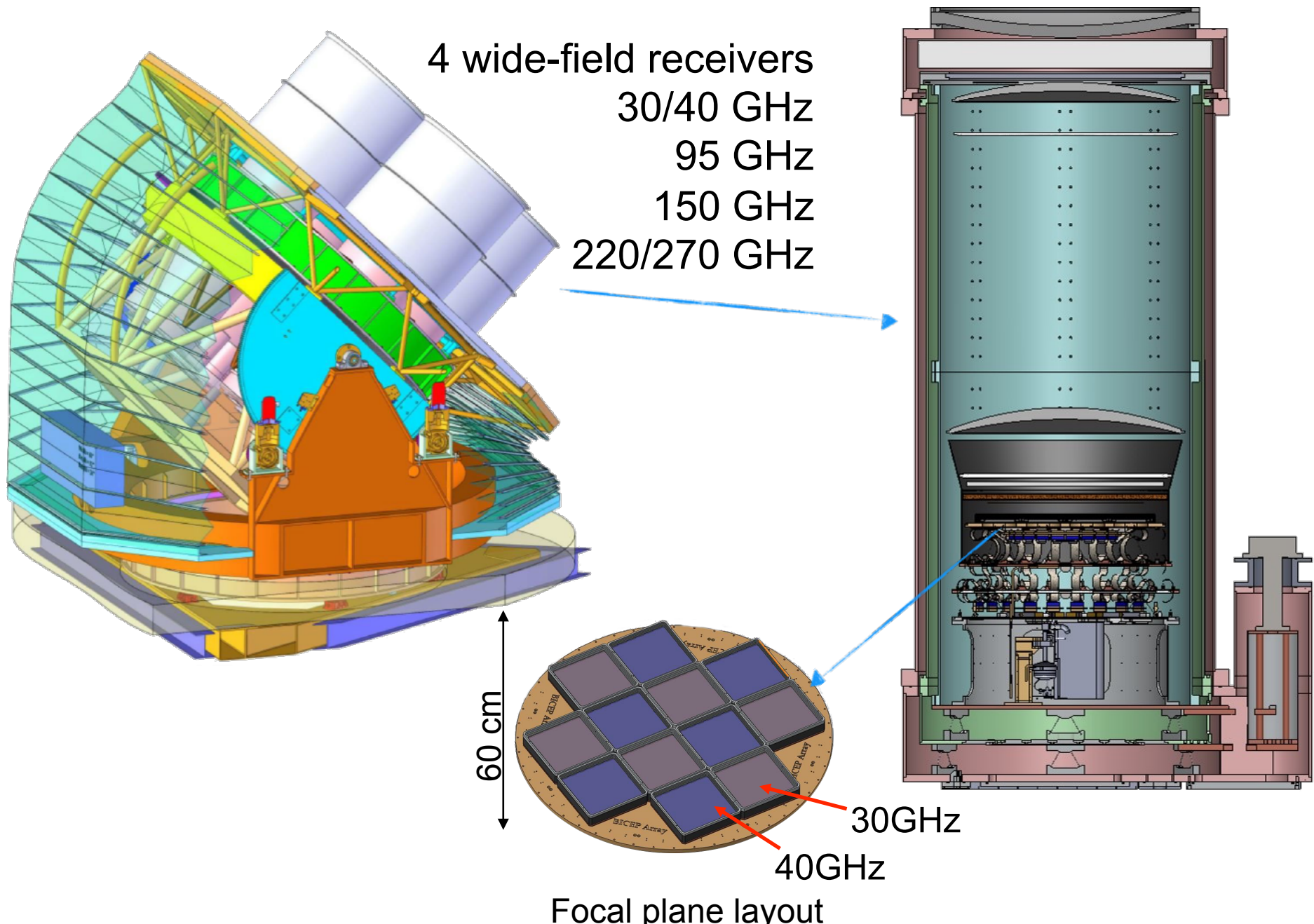


-10 -5 0 5 10  
Degrees on sky



-10 -5 0 5 10  
Degrees on sky

# Next Gen Experiment "BICEP Array" Under Construction



# Right Now Assembling New Telescope at UMN



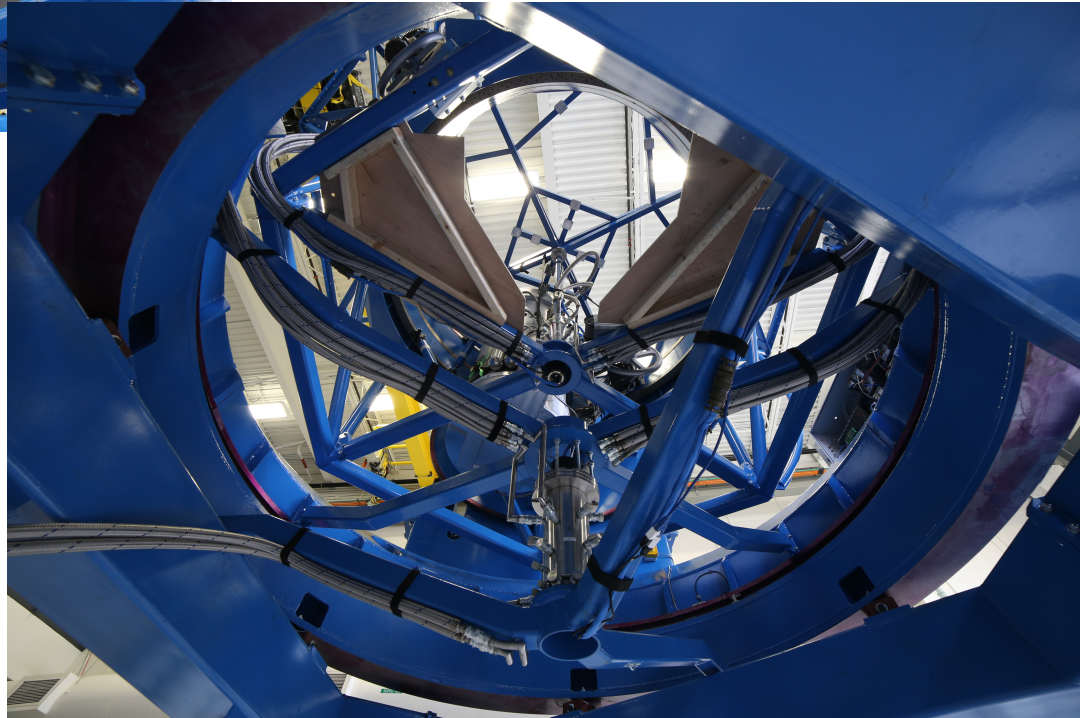
# New Telescope Moving Earlier Today



# 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...

# New Telescope at University of Minnesota





The BICEP/Keck Collaborati







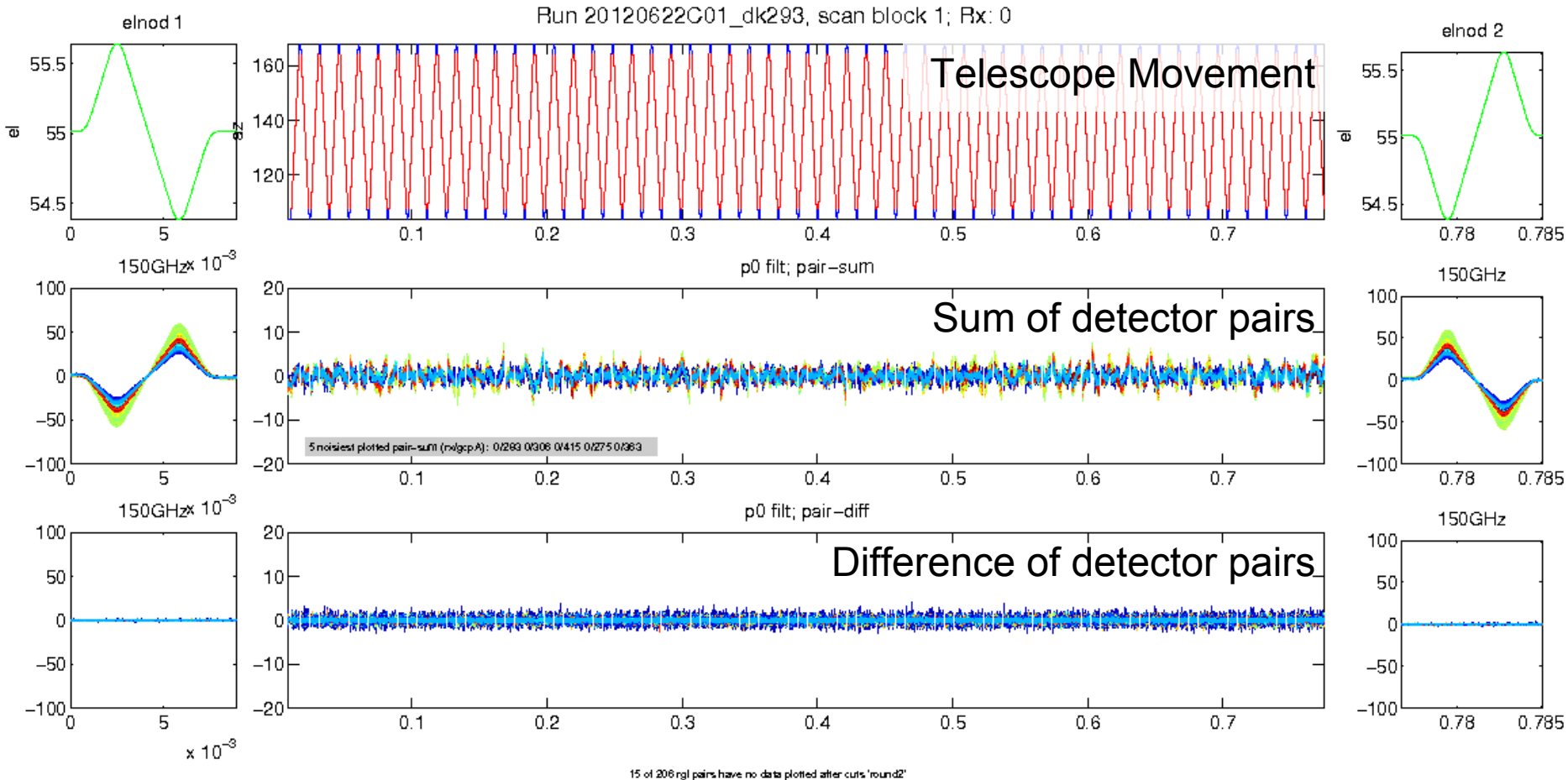


BA 3

hiep array

# Raw Data - Perfect Weather

Time 50 mins

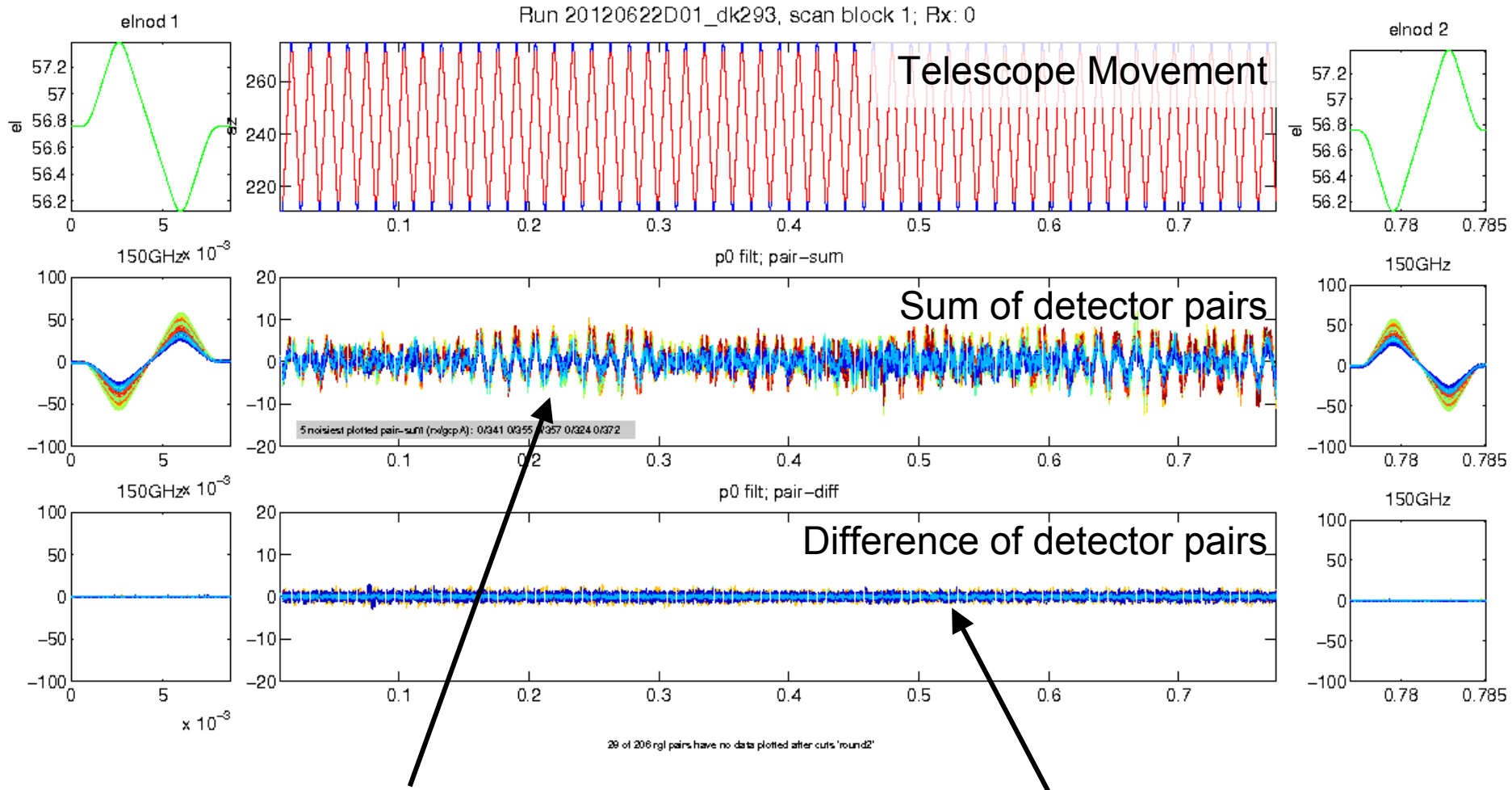


➤ Cover the whole field in 60 such scansets then start over at new boresight rotation

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

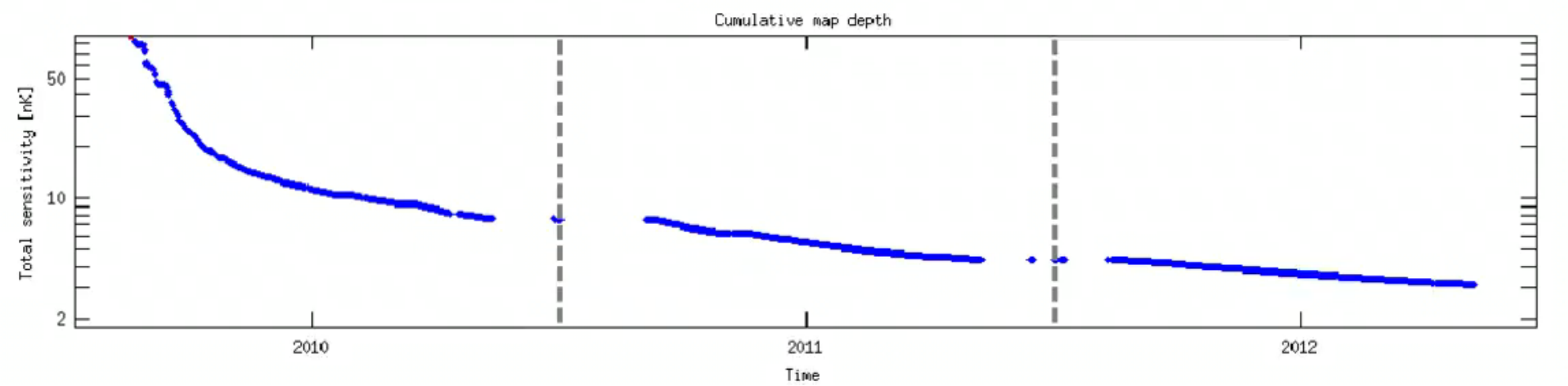
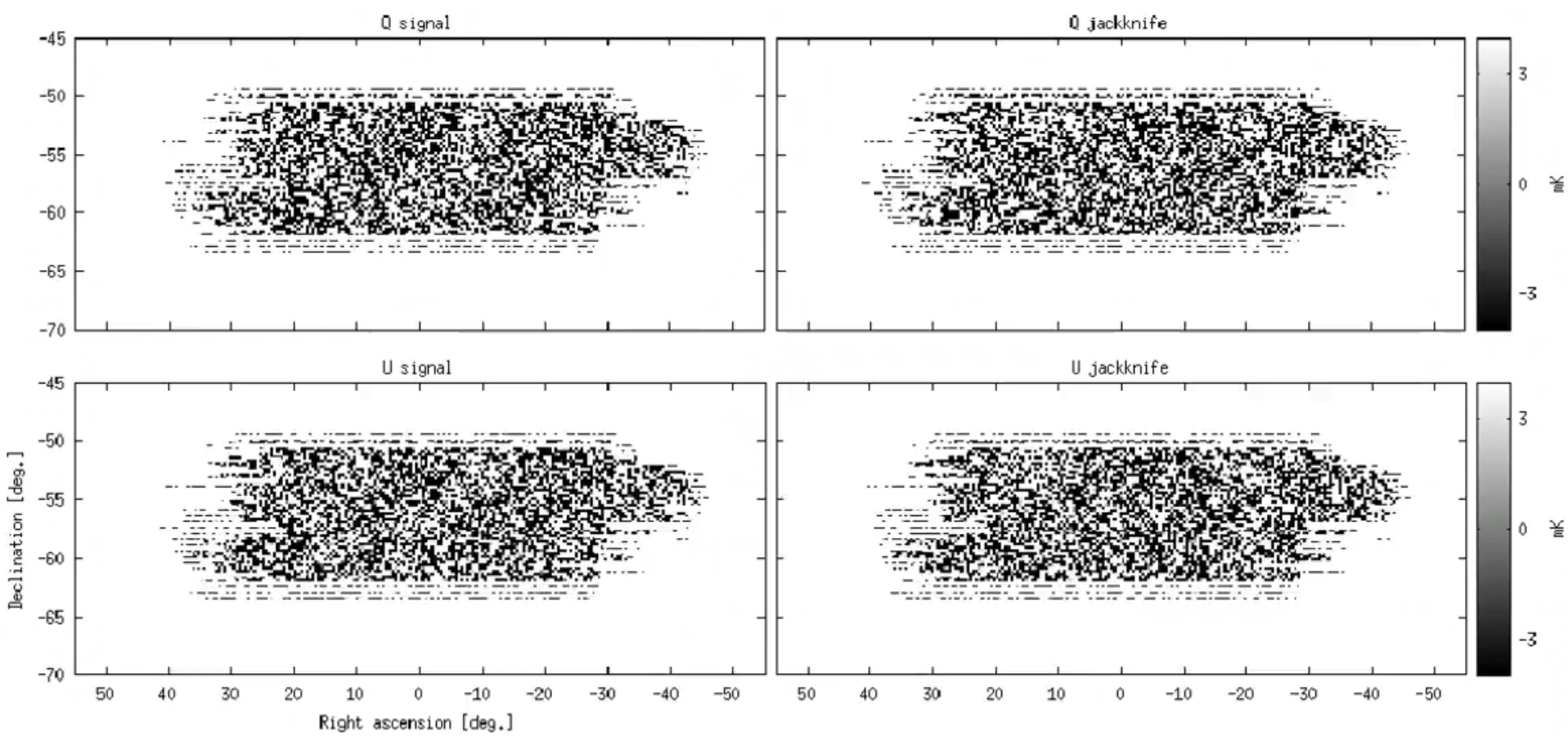
# Raw Data - Worse Weather

Time 50 mins



➤ Scanning over lumpy atmosphere  
→ “clouds”

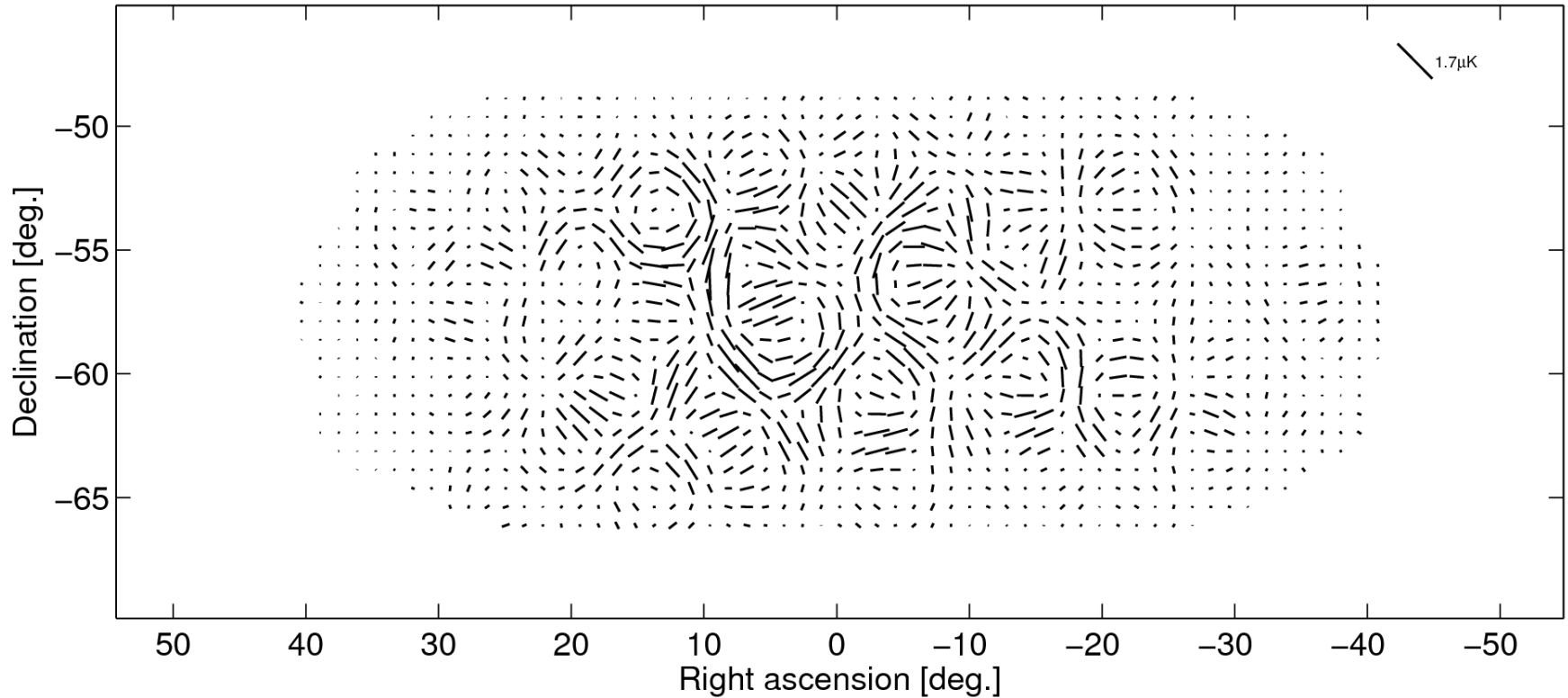
➤ Pair difference still clean  
→ atmosphere is unpolarized



# Total Polarization

BICEP2 total polarization signal

Scale:  $1.7 \mu K$

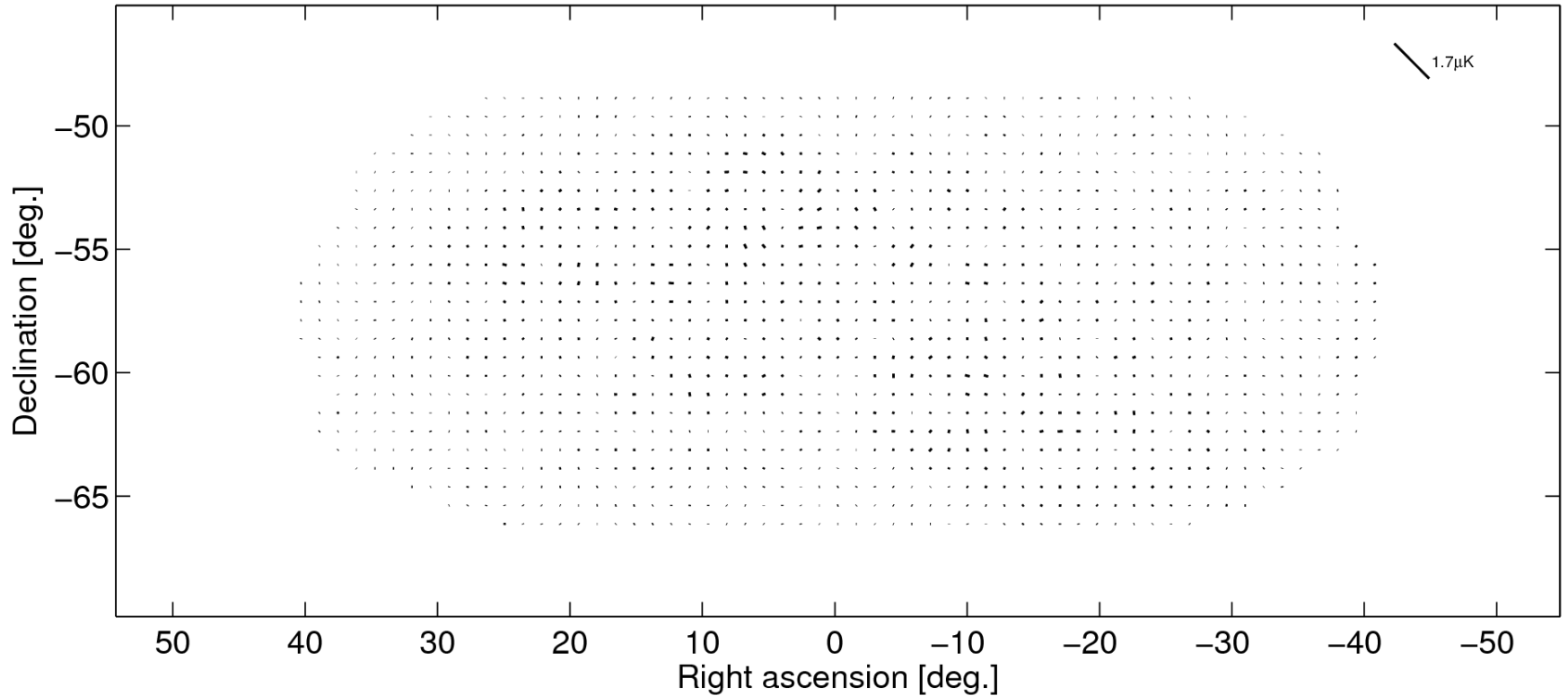


E-mode dominated pattern – no obvious curl component

# B-mode Contribution

BICEP2 B-mode signal

Scale:  $1.7 \mu K$



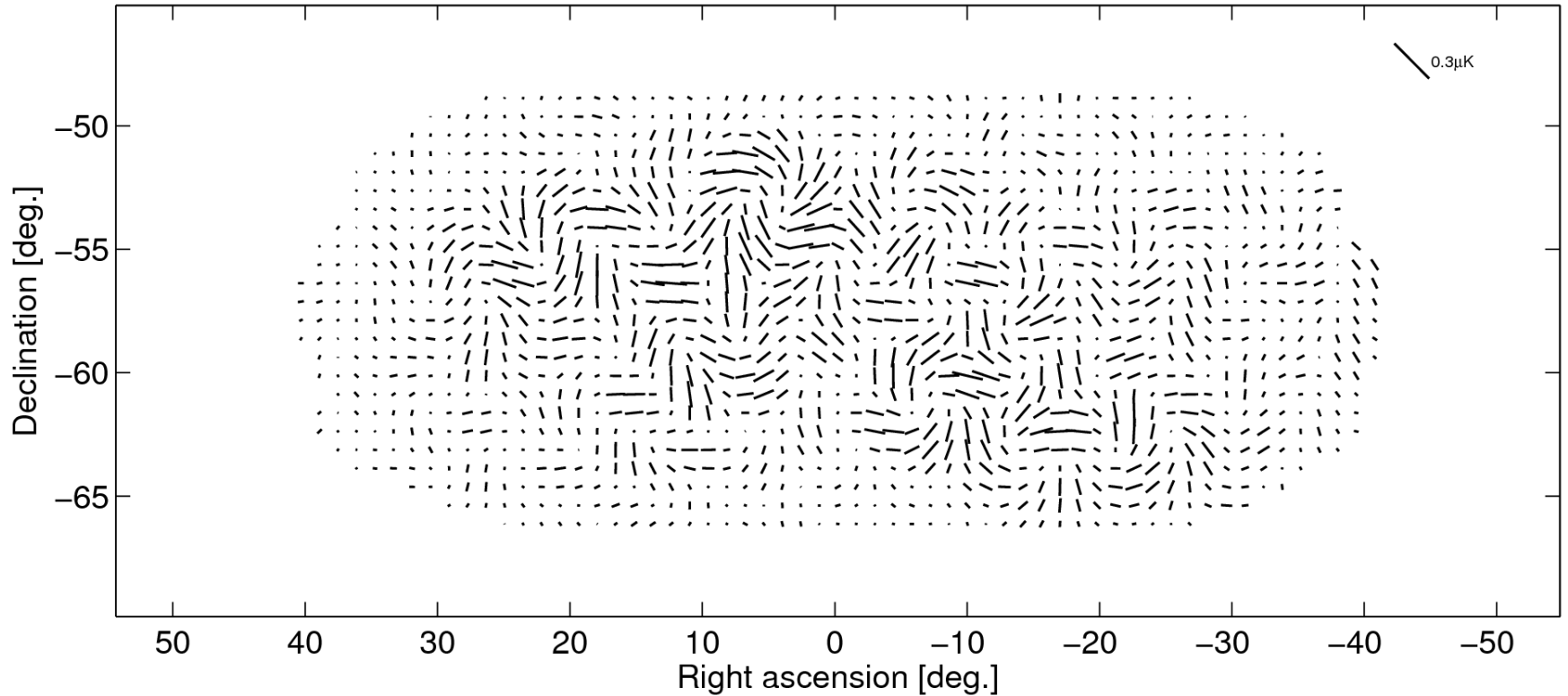
Apply purification operation which leaves only pure B-modes



# B-mode Contribution

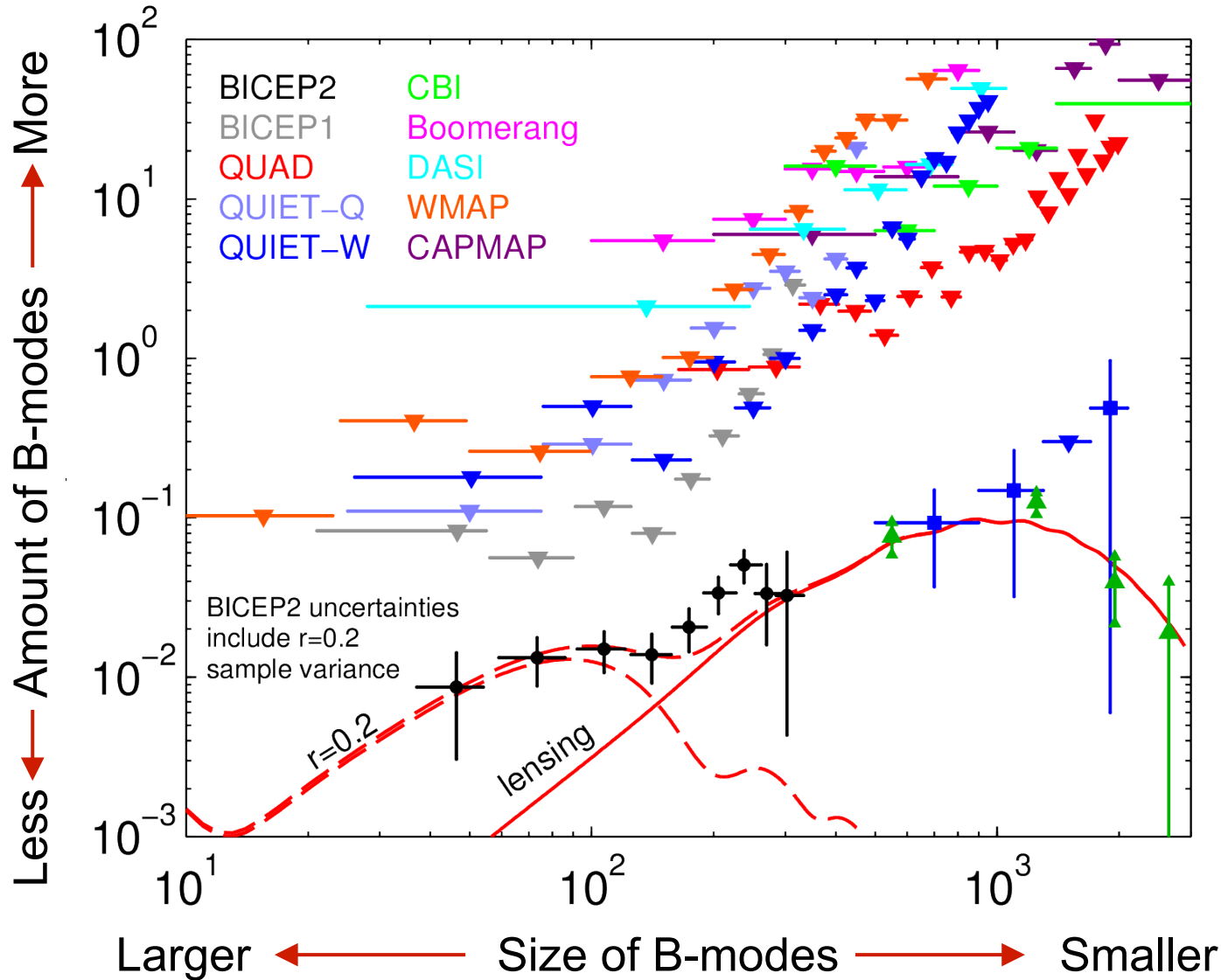
BICEP2 B-mode signal

Scale:  $0.3 \mu K$



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

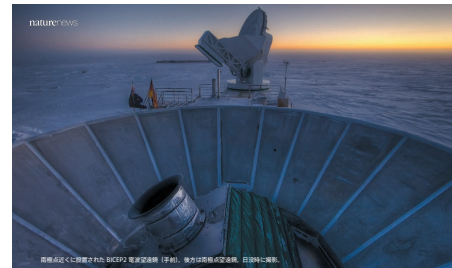
# In 2014 we thought we had found what we were looking for!



( $r$  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



9:30 THE NORTHERN NEWS

**USA TODAY**  
A GANNETT COMPANY

**03.18.14**

**UConn tops women's tourney**  
Analysis, Bracket 4C

**WHO HAS BEST 'DANCE CARDS'**  
A look at musical, dance and theatrical acts to watch, 5C

**UConn tops women's tourney**  
Analysis, Bracket 4C

## Putin, U.S. up ante after vote

### 'Always hope' missing jet's passengers alive

New recruits, Malaysia officials 'won't talk out of pocket'...  
 GM issues three new recalls  
 Homework load unchanged...  
 How Angela earned her big, bad wings

### WAVES COULD BE BIG BANG'S SMOKING GUN

Scientists of the South Pole-based gravitational waves...  
 The detection comes as European scientists were already...  
 The detection comes as European scientists were already...  
 The detection comes as European scientists were already...

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

**GRAVITATIONAL WAVES**  
**A THEORY**  
**SOUTH POLE VIEW**

### States engage in shadowy deals as death penalty drugs dwindle

Prisons here drug...  
 Prisons here drug...  
 Prisons here drug...

## The New York Times



### Putin Recognizes Crimea Secession, Defying the West

Decree Increases Fears of Annexation by Russia, Despite More Sanctions

**BY STEPHEN LEE MYRICK AND PETER HADFIELD**

Mr. Putin of Russia signed a decree on Monday recognizing Crimea as an independent state...  
 The decree is a clear step toward annexation...  
 The decree is a clear step toward annexation...  
 The decree is a clear step toward annexation...

### Lost Jet's Path Seen as Altered

**VIA COMPUTER**

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

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

Scientists say the discovery of gravitational waves...  
 The detection of gravitational waves...  
 The detection of gravitational waves...

### States engage in shadowy deals as death penalty drugs dwindle

Prisons here drug...  
 Prisons here drug...  
 Prisons here drug...

## 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

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

## Sanctions hit Russian top brass

### By Chris Chabris in London

Mr. Putin's decree...  
 The West has responded...  
 The West has responded...

### By Chris Chabris in London

Mr. Putin's decree...  
 The West has responded...  
 The West has responded...

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

By Eddie Teague in London...  
 The price of breakfast...  
 The price of breakfast...

### 宇宙急速膨張の証拠、検出される

Telescope captures view of gravitational waves

宇宙が急速に膨張していることを示す証拠が、重力波の検出によって明らかになった。この発見は、宇宙の膨張が加速していることを示唆している。重力波は、宇宙の大規模な構造が崩壊する際に発生する。この発見は、宇宙の膨張が加速していることを示唆している。

## PHYSICAL REVIEW LETTERS

Articles published week ending 20 JUNE 2014

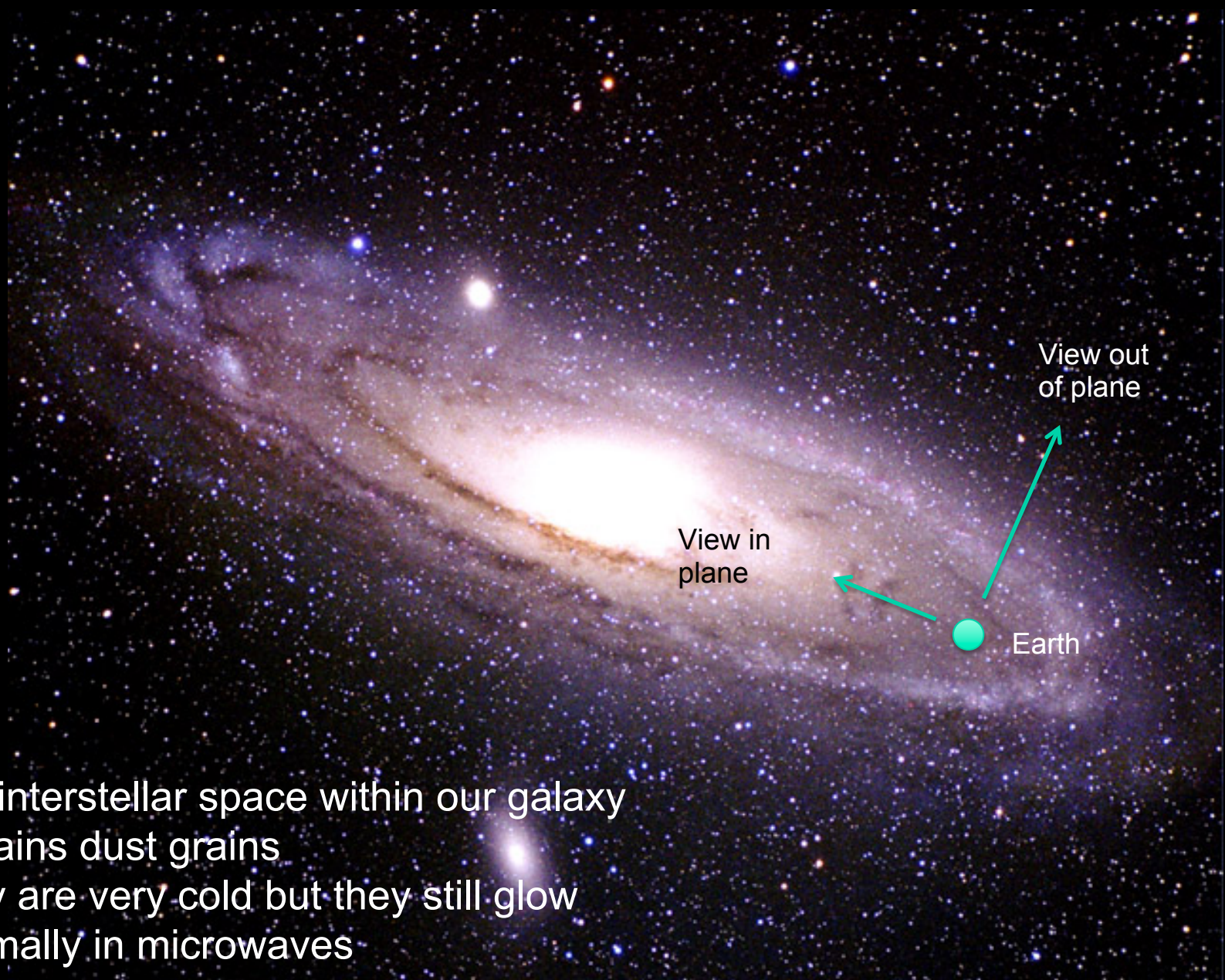
Number Subscription Dept.  
Library or other institutions (no individual sales)

Published by American Physical Society

Volume 112, Number 24

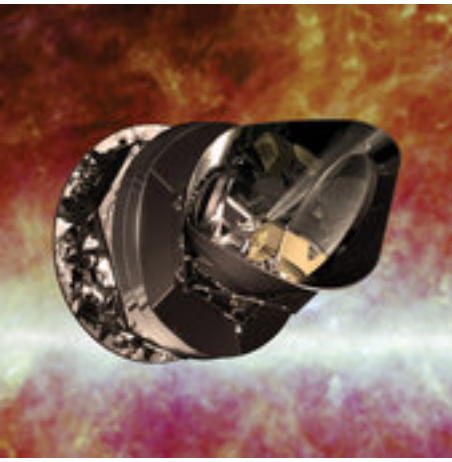
Actually not a lot of fun...

# Unfortunately we are in a galaxy!

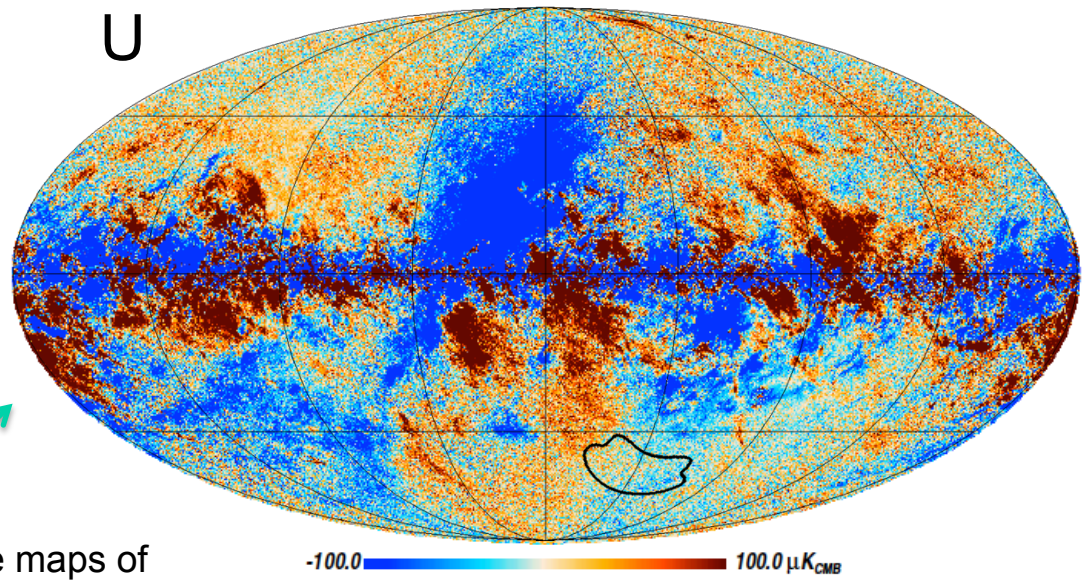
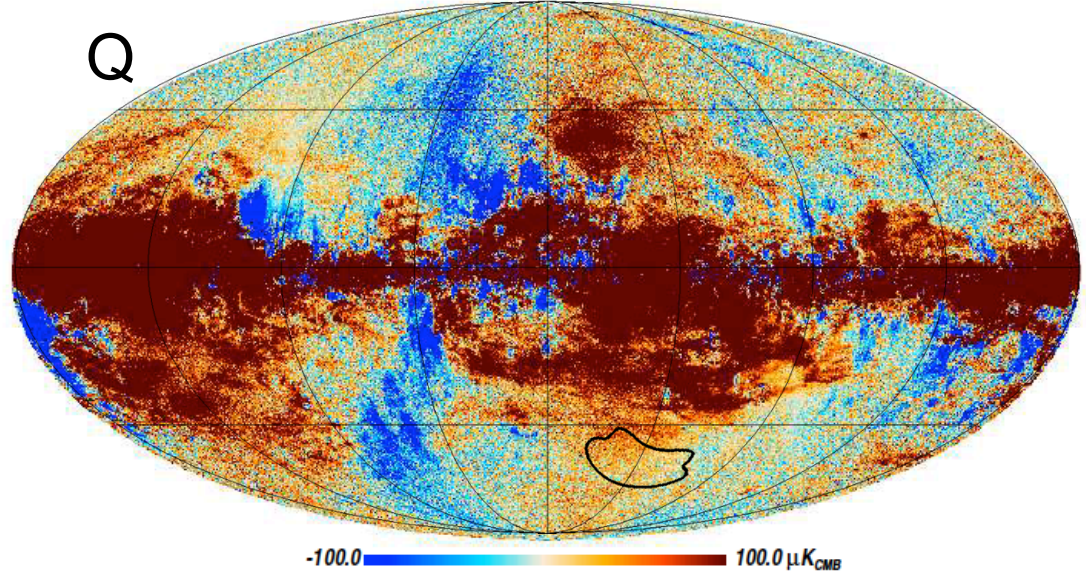


The interstellar space within our galaxy contains dust grains  
They are very cold but they still glow thermally in microwaves

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



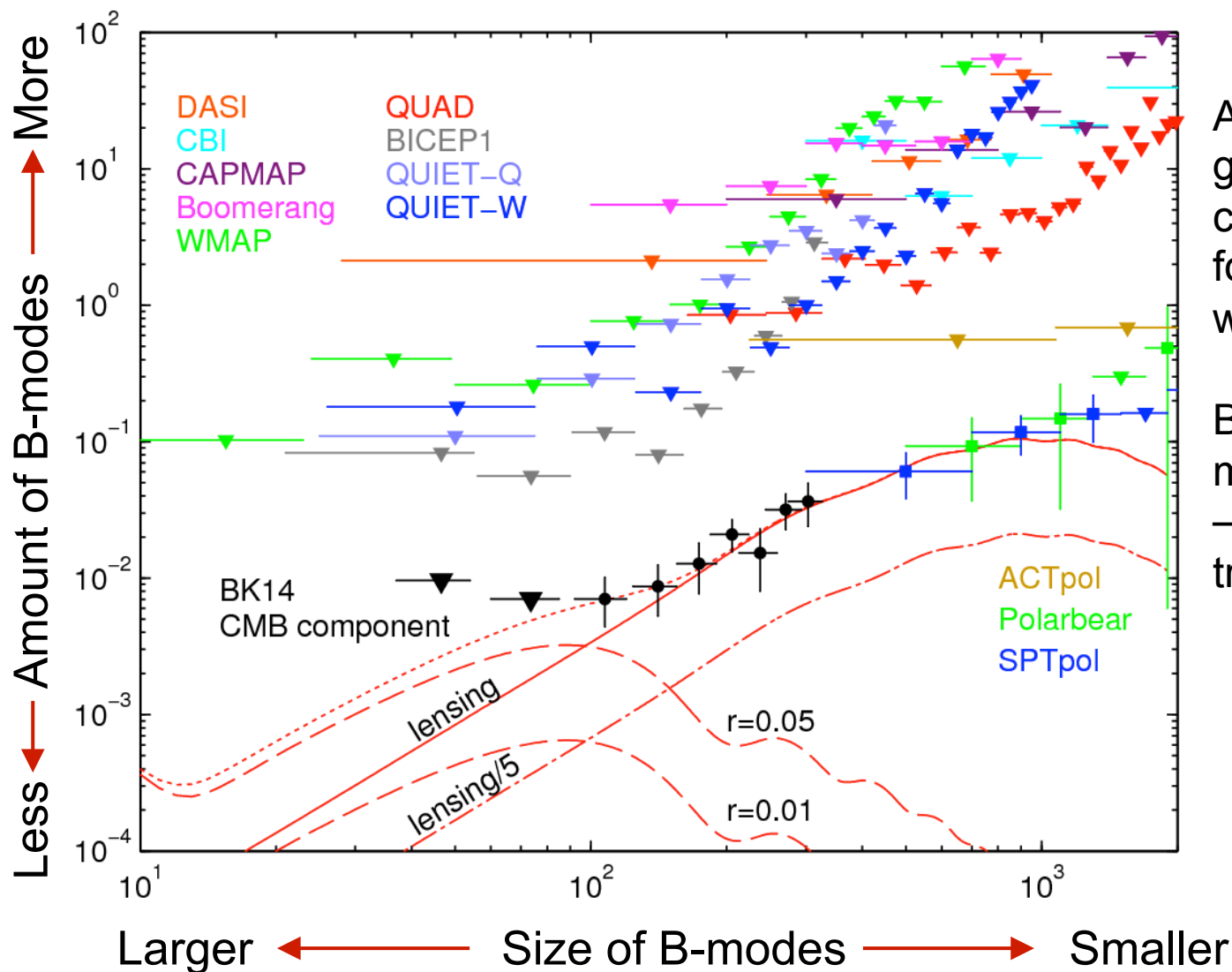
Planck was a billion dollar Euro/NASA space mission



All sky maps like maps of the Earth



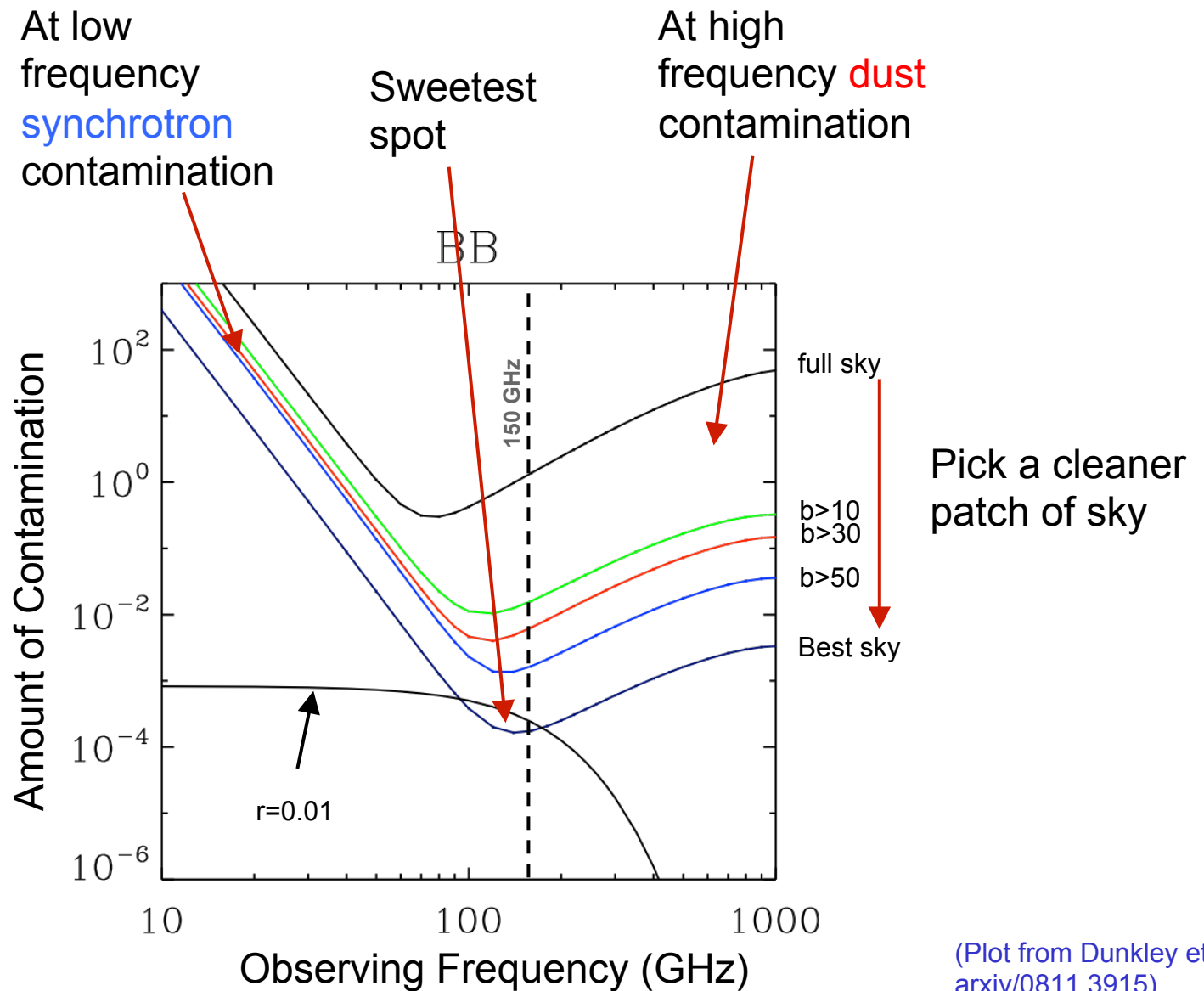
# So the Search Goes On...



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!

# Polarized Foreground Contamination from Our Galaxy

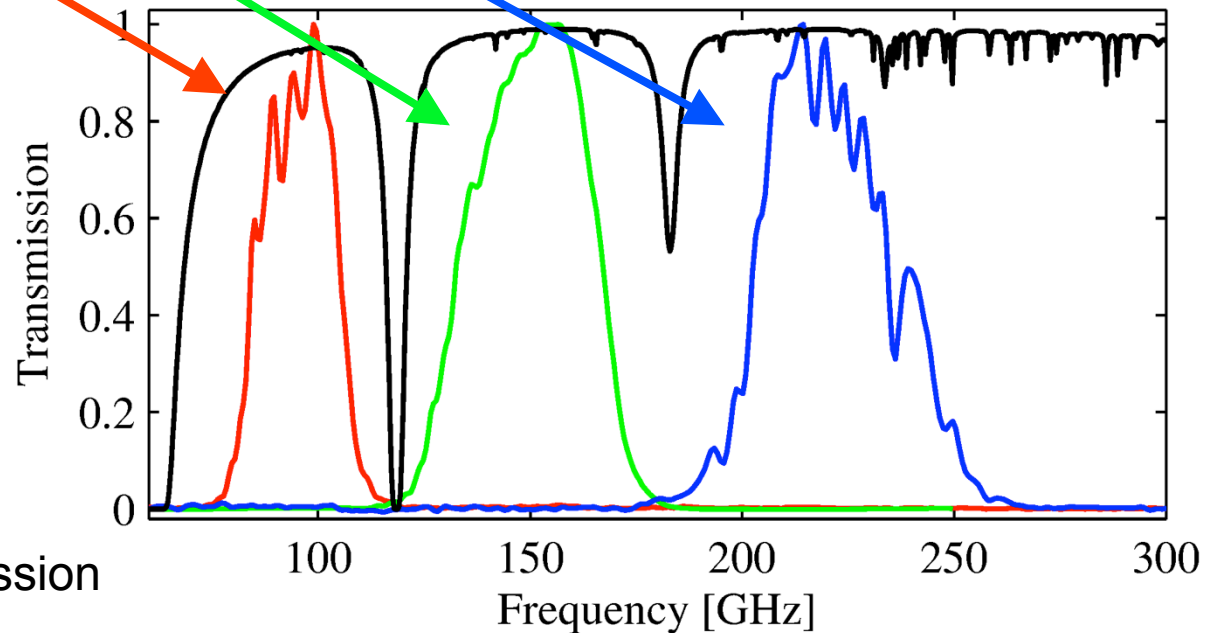
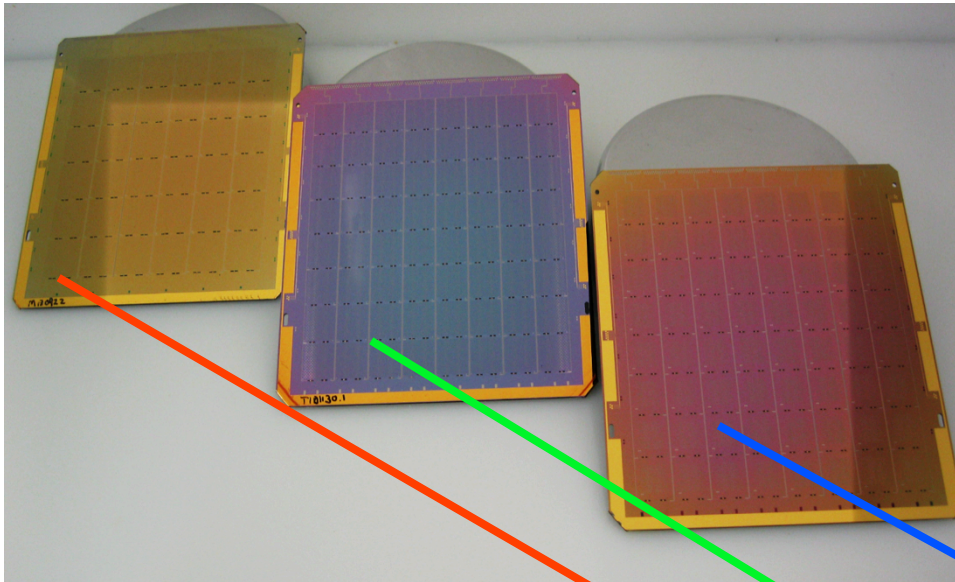


(Plot from Dunkley et al  
arxiv/0811.3915)

# Planar superconducting detector arrays

...designed to scale  
in frequency

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

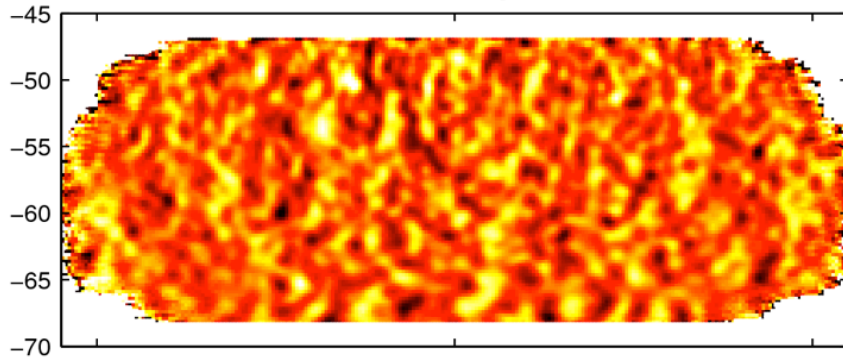


Typical South Pole  
atmospheric transmission

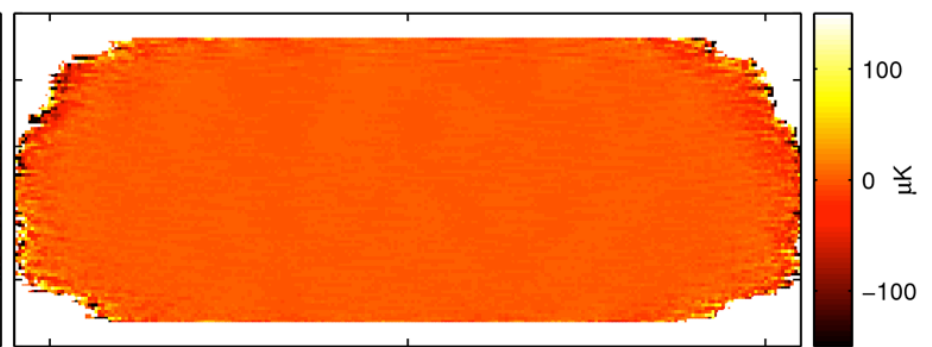


# BK15 95GHz Maps

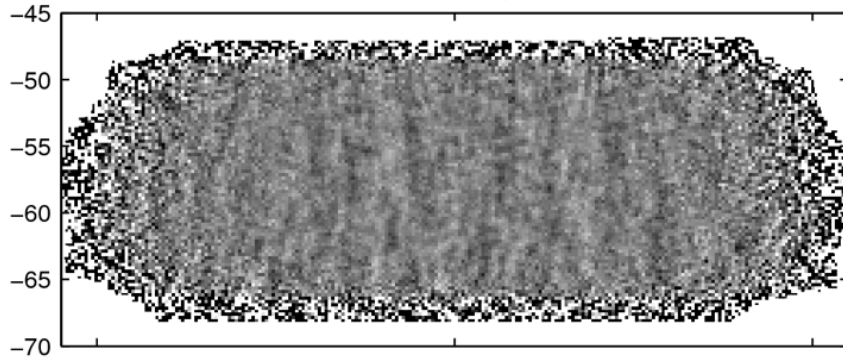
95 GHz T signal



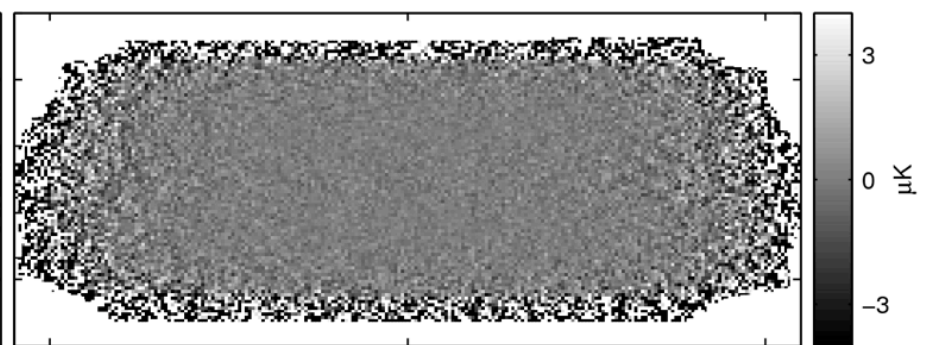
95 GHz T noise



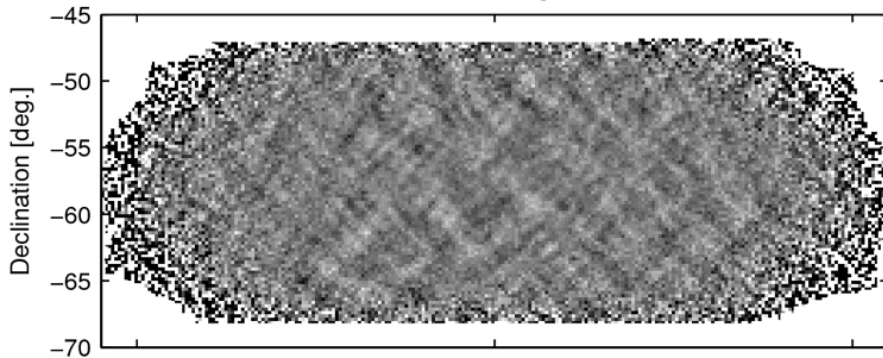
95 GHz Q signal



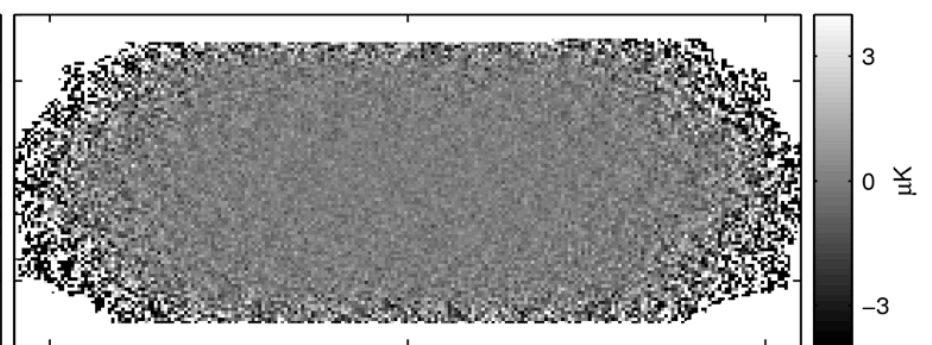
95 GHz Q noise



95 GHz U signal



95 GHz U noise

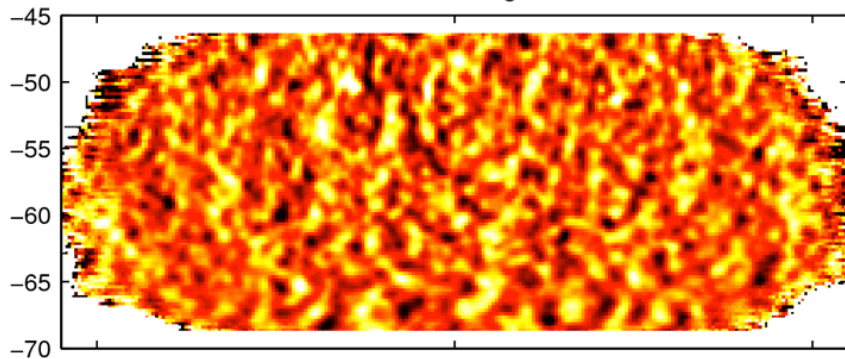


Right ascension [deg.]

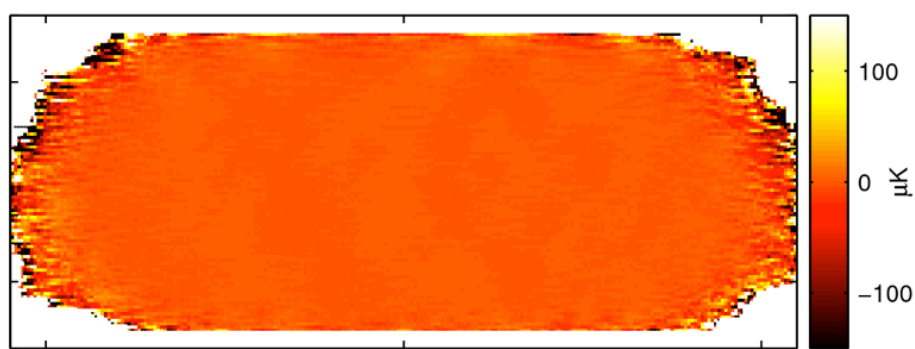
Declination [deg.]

# BK15 150GHz Maps

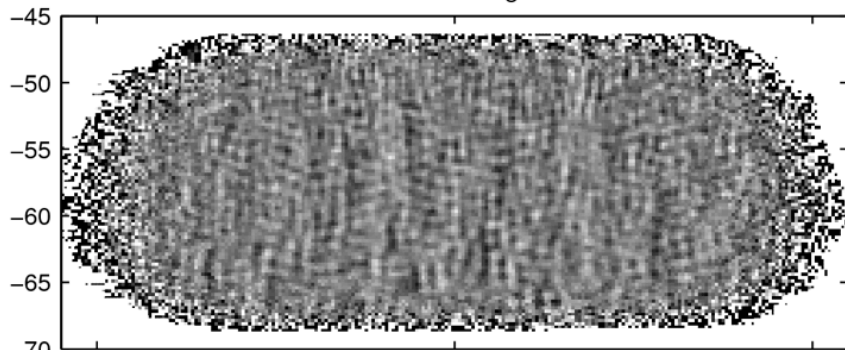
150 GHz T signal



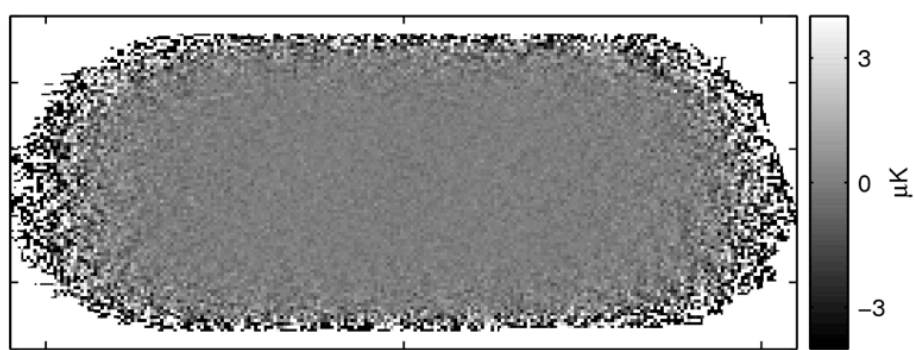
150 GHz T noise



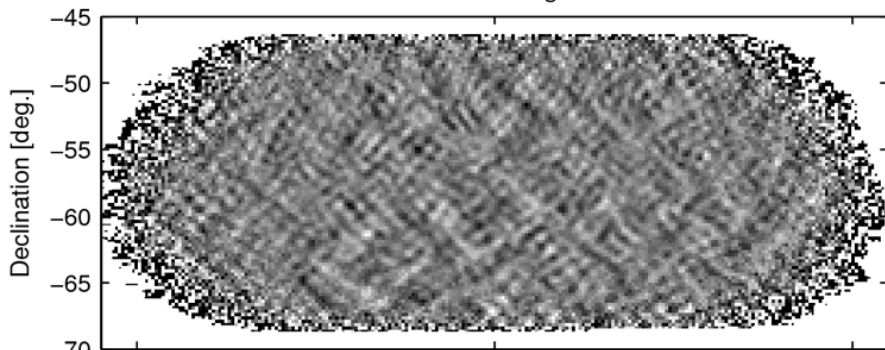
150 GHz Q signal



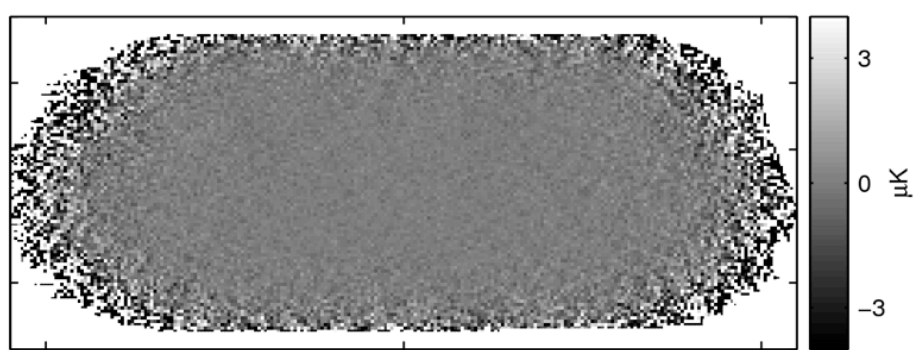
150 GHz Q noise



150 GHz U signal



150 GHz U noise



Declination [deg.]

50

0

-50

Right ascension [deg.]

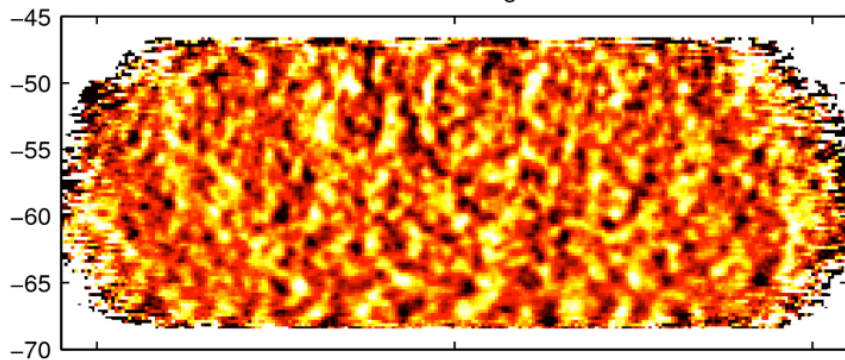
50

0

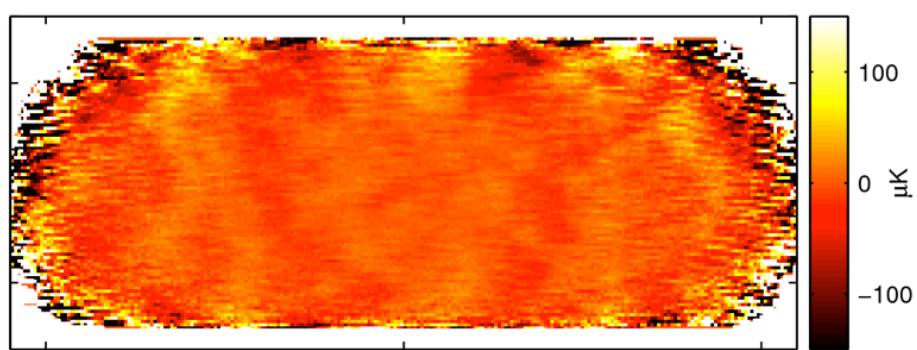
-50

# BK15 220GHz Maps

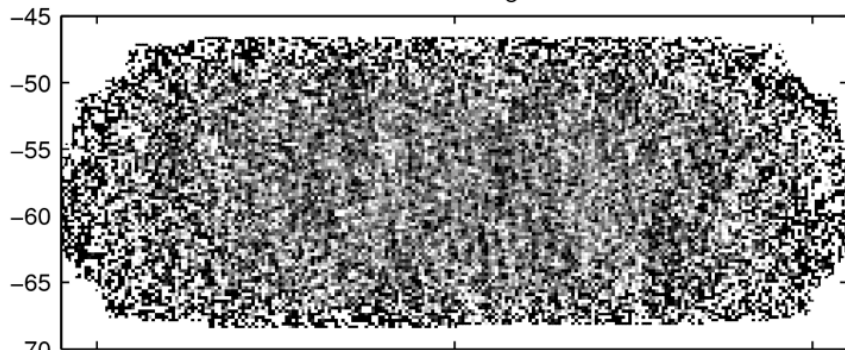
220 GHz T signal



220 GHz T noise



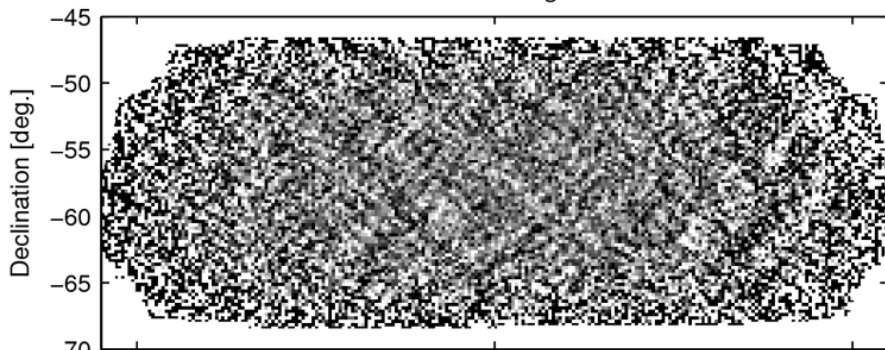
220 GHz Q signal



220 GHz Q noise



220 GHz U signal



220 GHz U noise



Right ascension [deg.]