

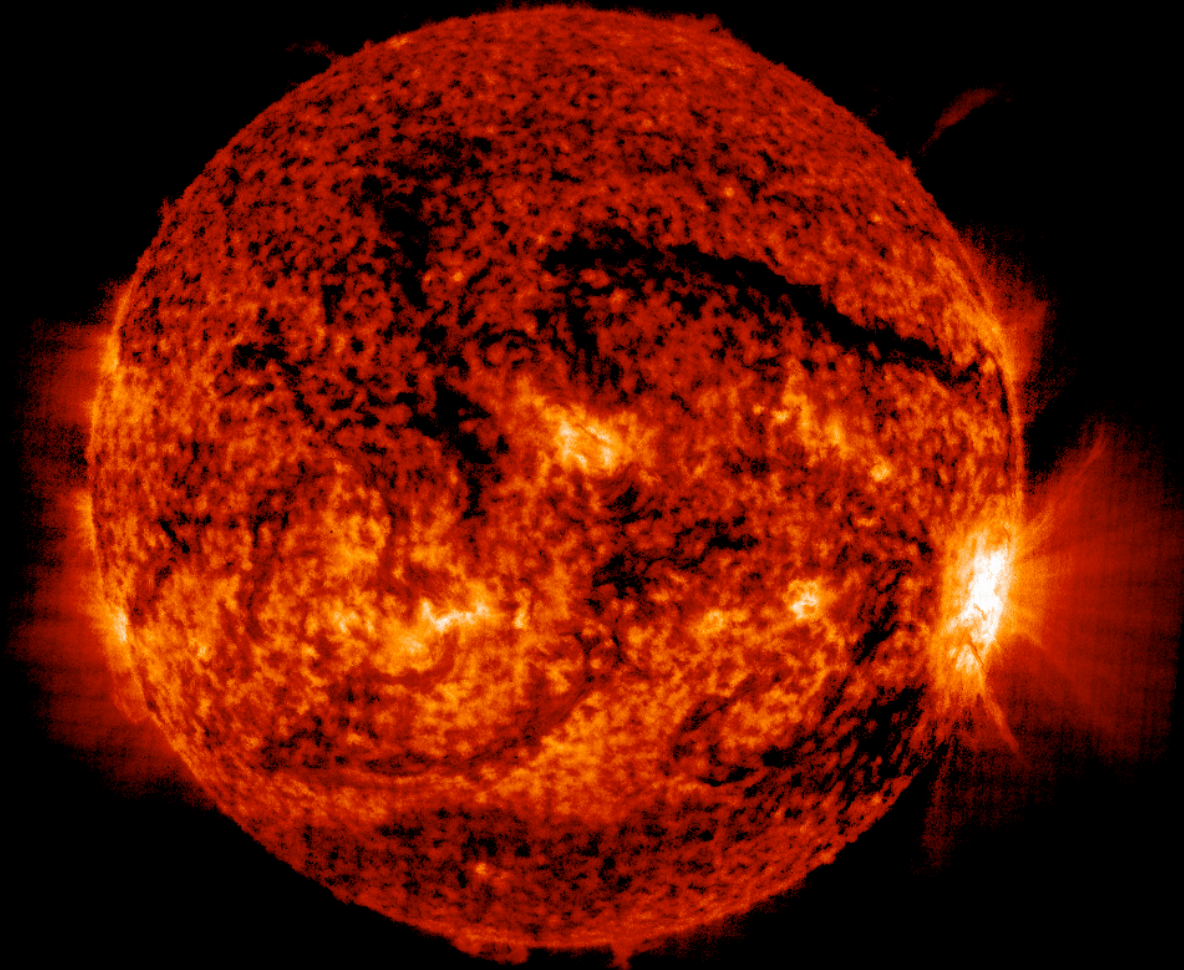
# Viewing the Beginning of the Universe from the Bottom of the World







# Our Sun is a Star



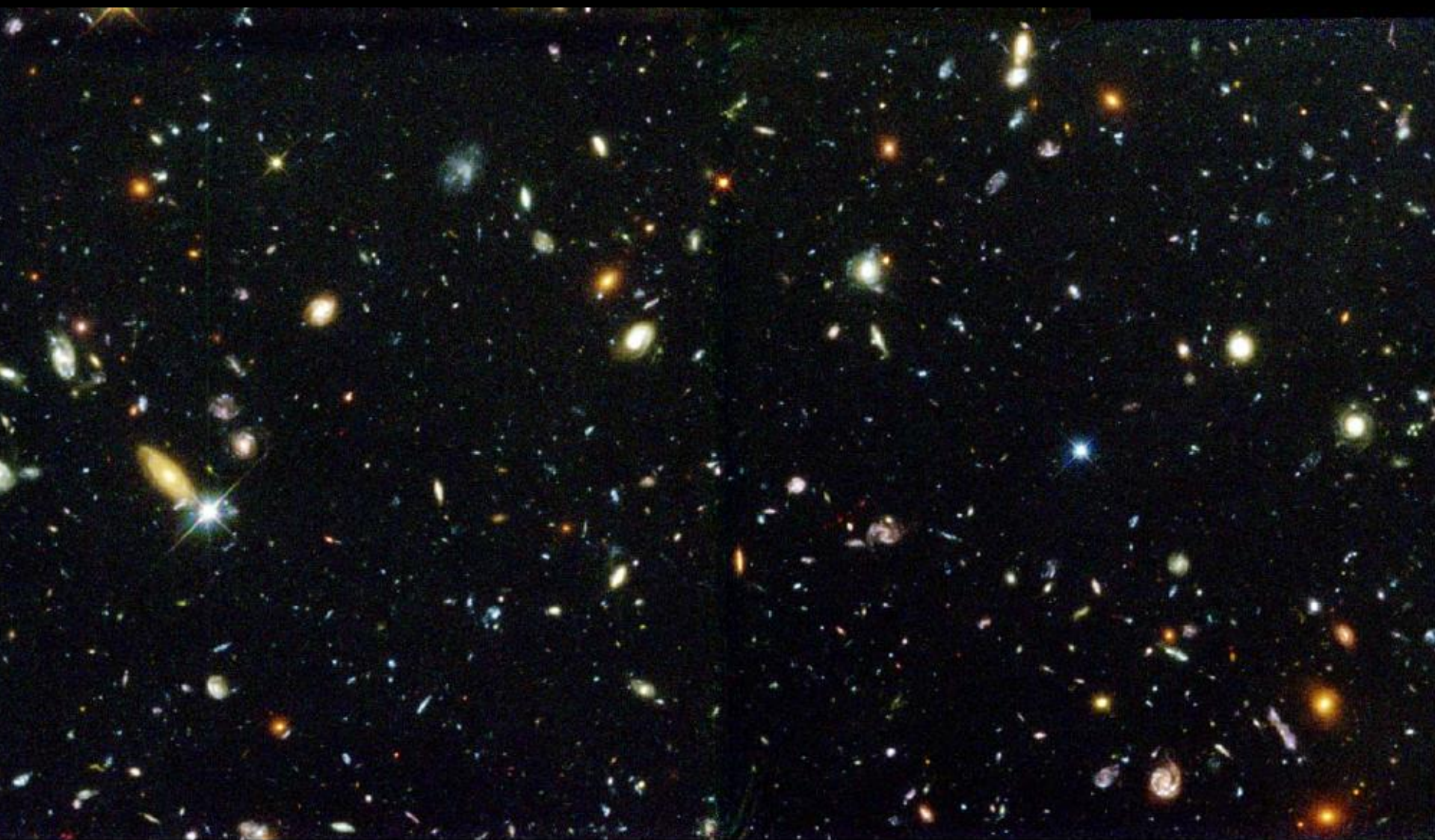
...Many stars make a galaxy...



(A nearby galaxy similar to ours)

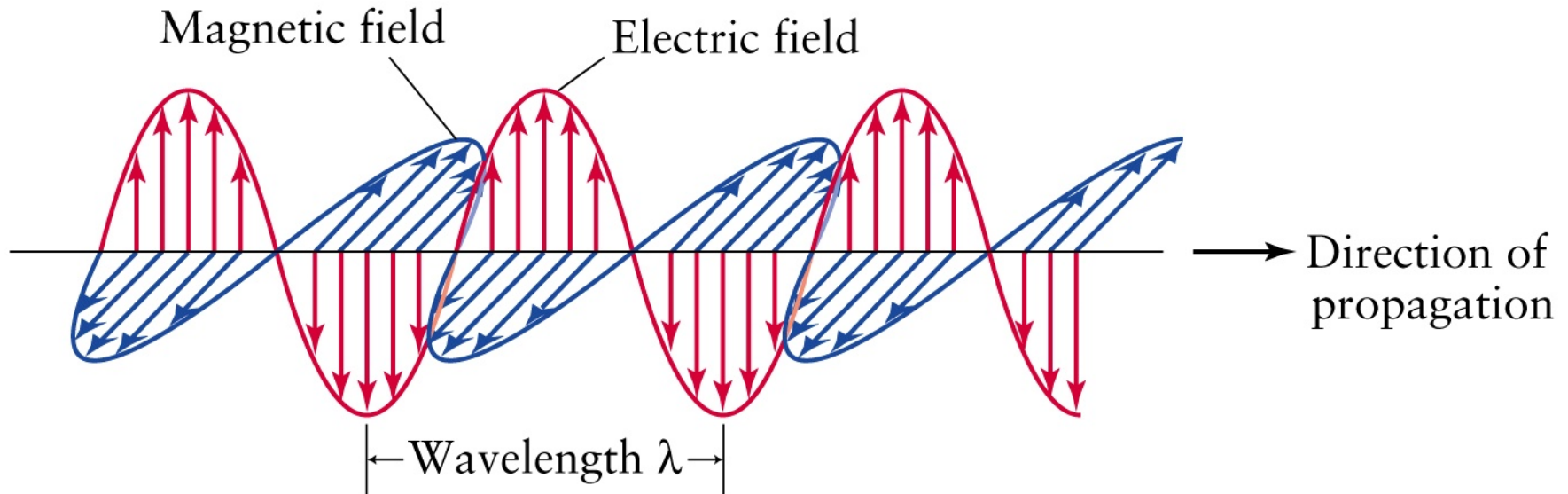


...There are many galaxies



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
- Radio waves are just long wavelength light



# “Classic” Doppler Effect



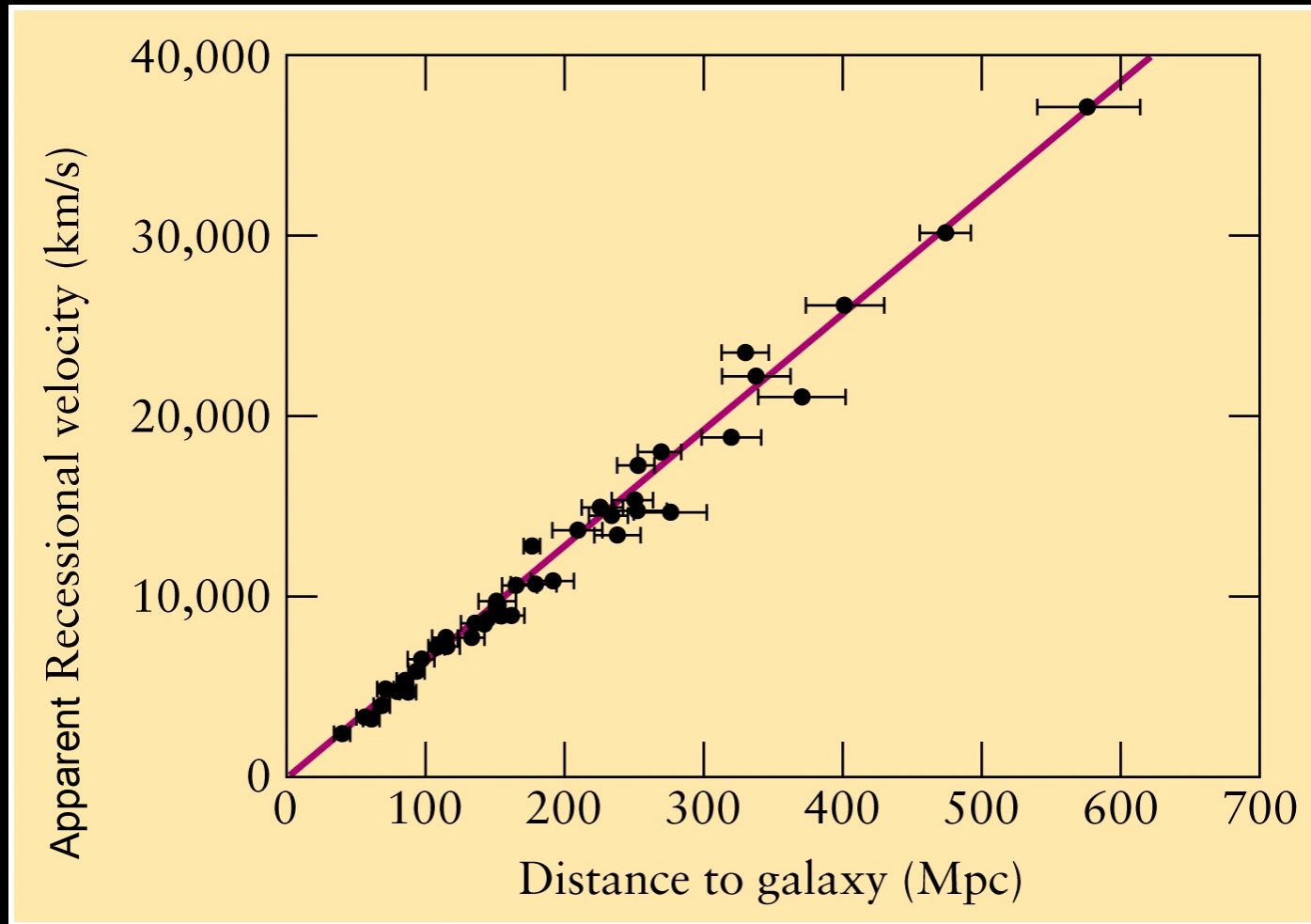
- Imagine 3 stars emitting rays of light of the same “natural” wavelength (color)
- But light moves through space always at the same speed...
- Moving towards us = compressed = bluer
- Moving away from us = stretched = redder

# Edwin Hubble “Observing” Distant Galaxies



Mount Wilson Observatory  
(LA) 1920's

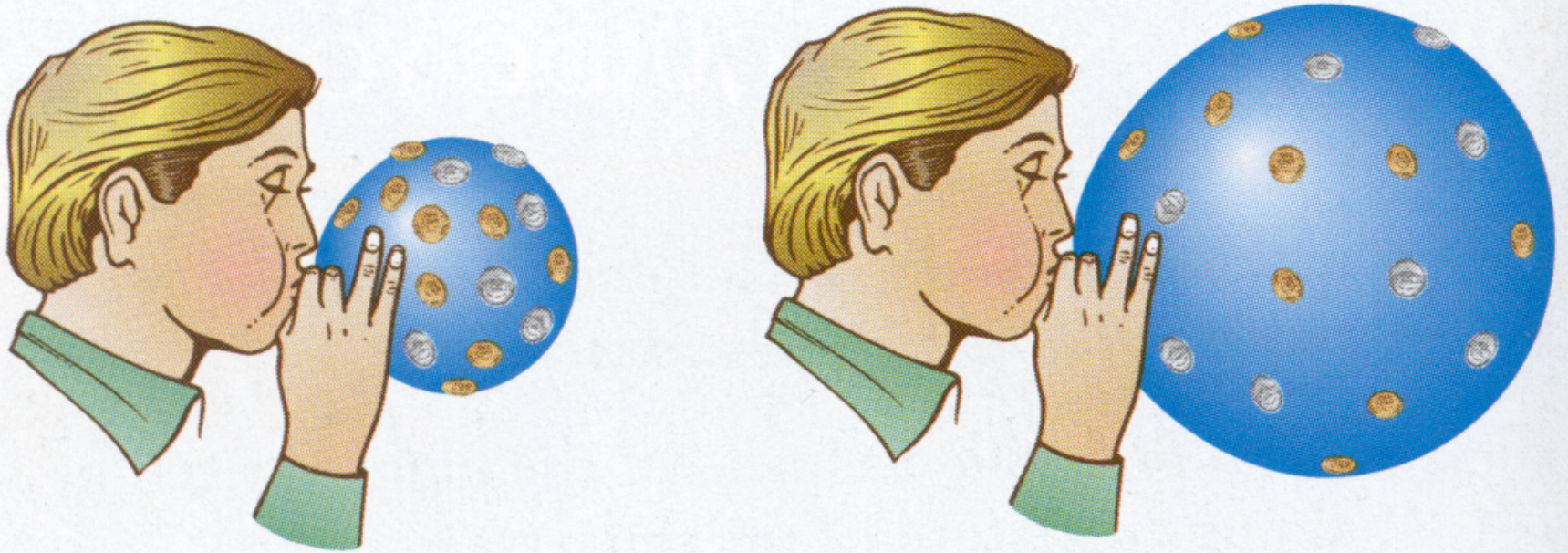
# Hubble Diagram



The 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?!

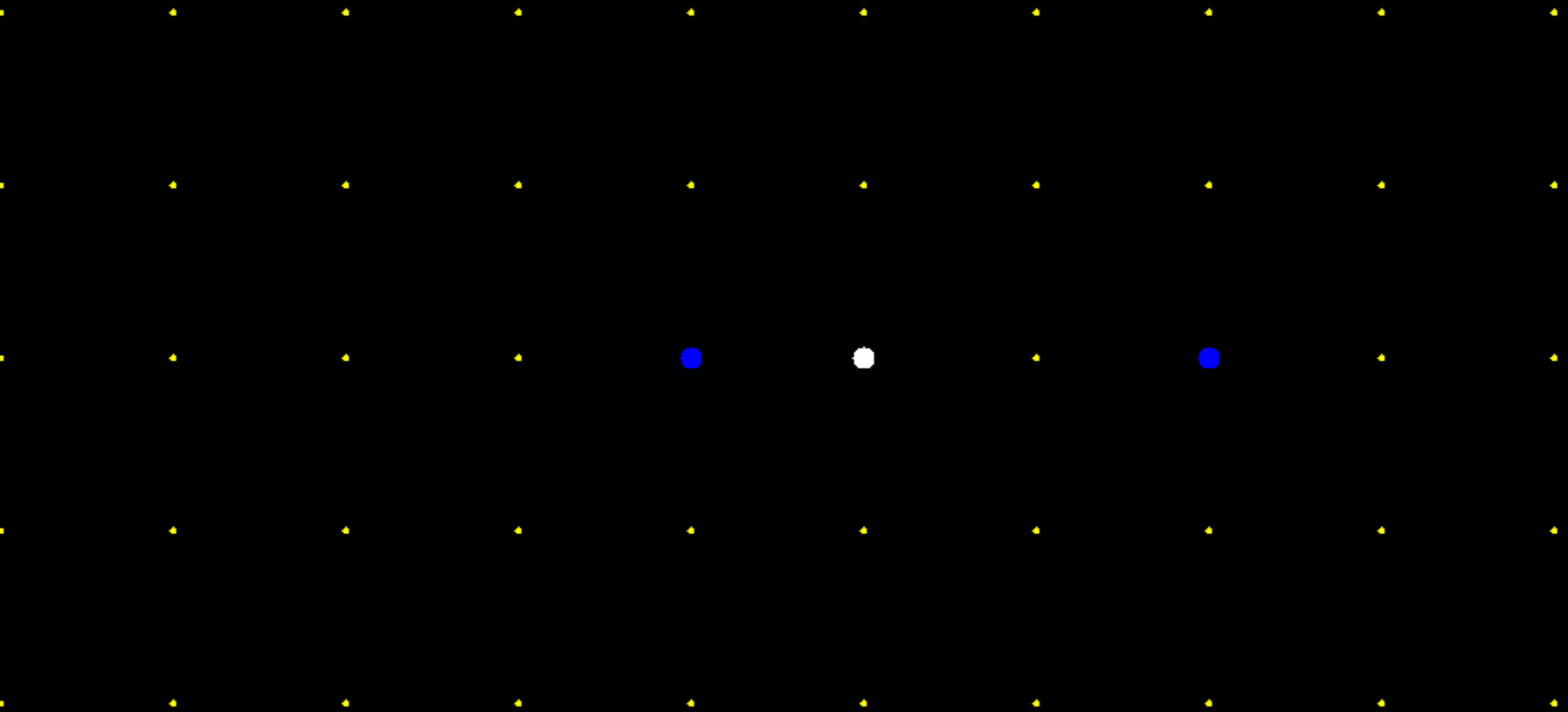
# Expanding Universe?



- 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”
- As we look *out* we look *back* in time

# Modern cosmology in a nutshell:



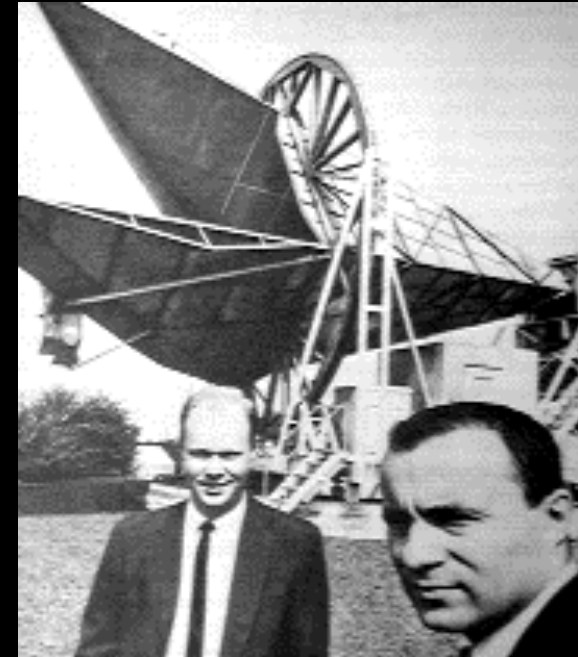
Edwin Hubble

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

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

(Alpher, Gamow, Herman, 1940s)

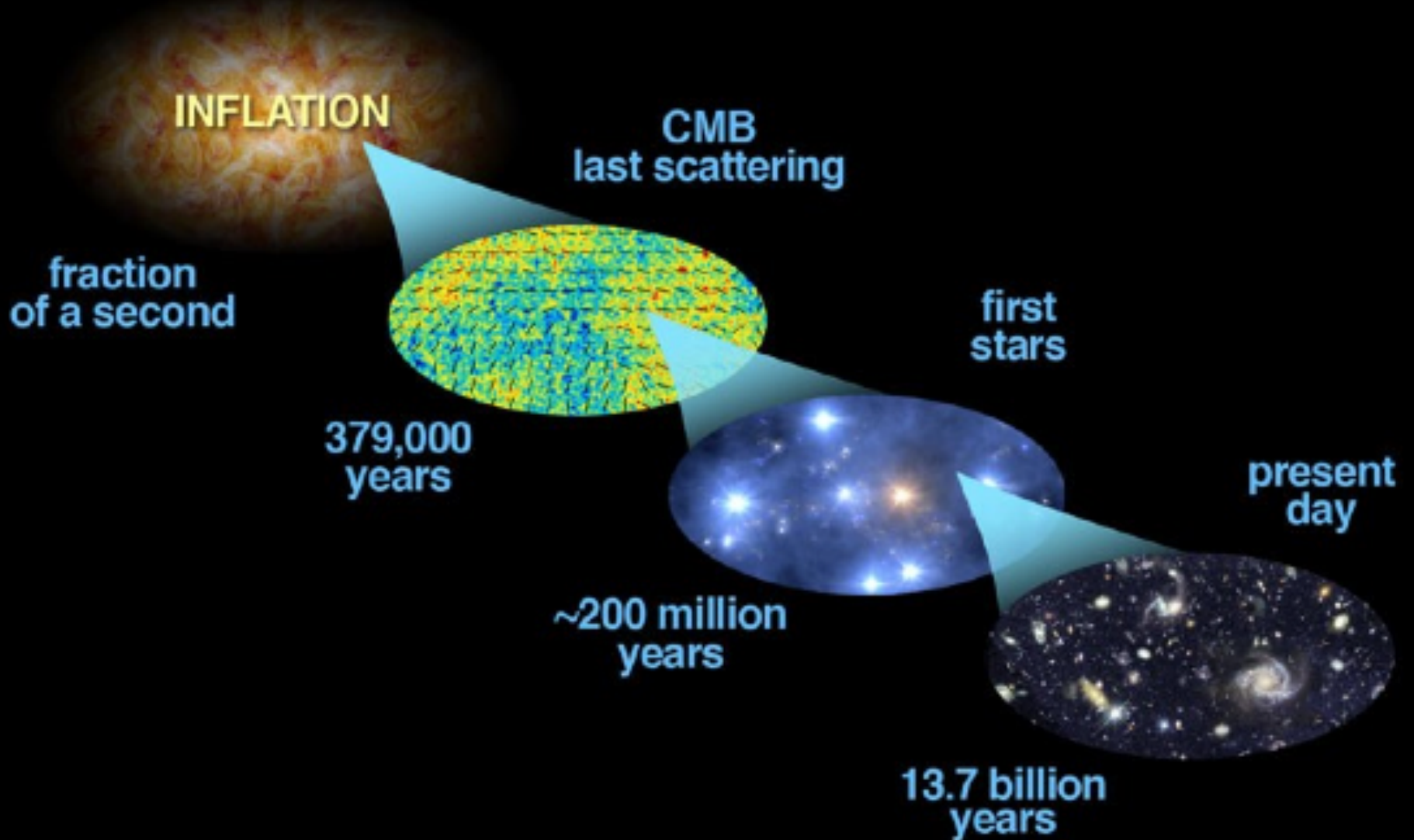
3) You can still see the glow!  
*The Cosmic Microwave Background*  
(Penzias & Wilson, 1964)



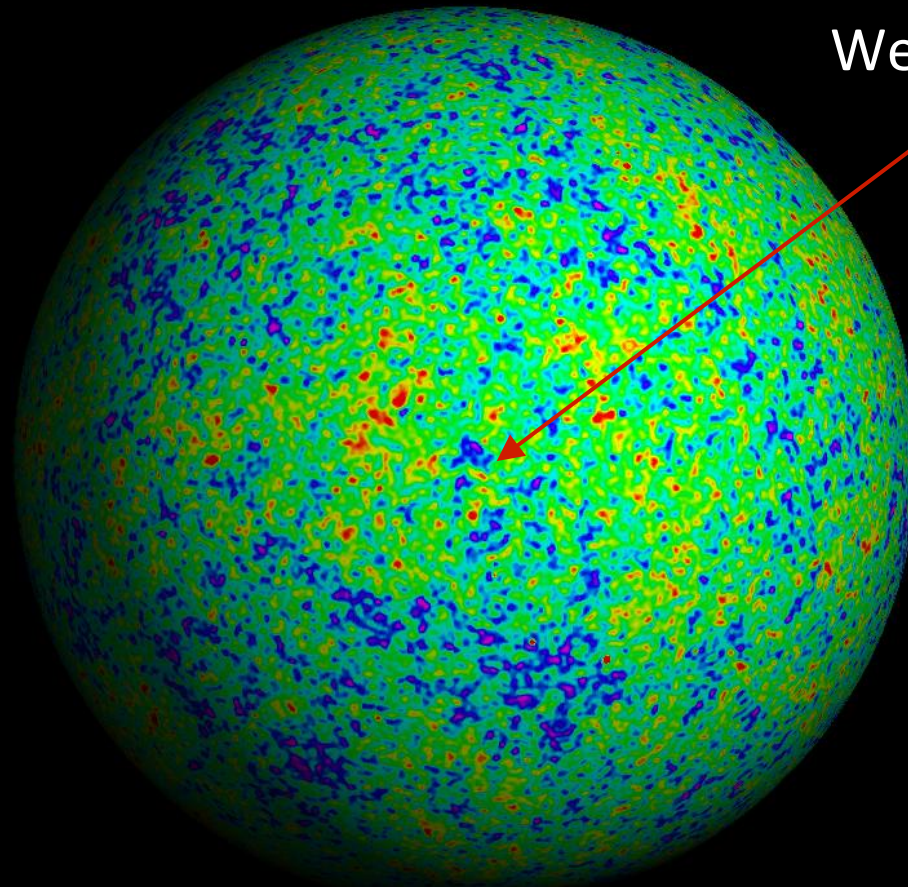
Bob Wilson & Arno Penzias  
1978 Nobel Prize

⇒ acceptance of the “HOT BIG BANG”

# Telescopes are time machines!



# All Sky MAP of the Cosmic Microwave Background

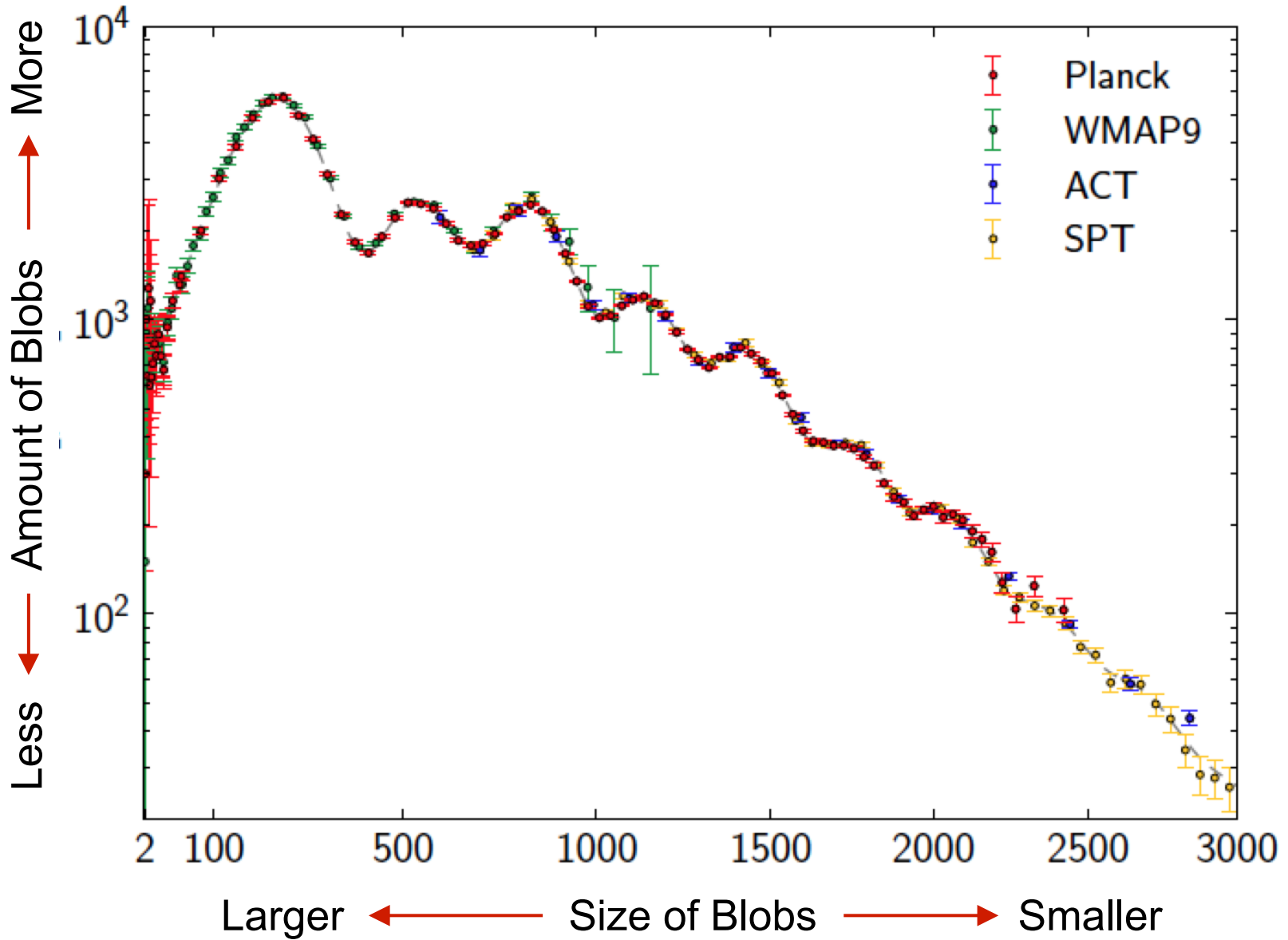


We are at the center

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

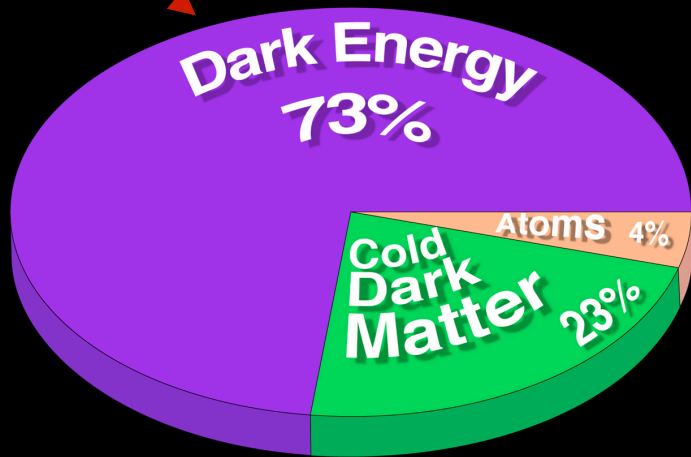


# “Lump Sorter” Plot

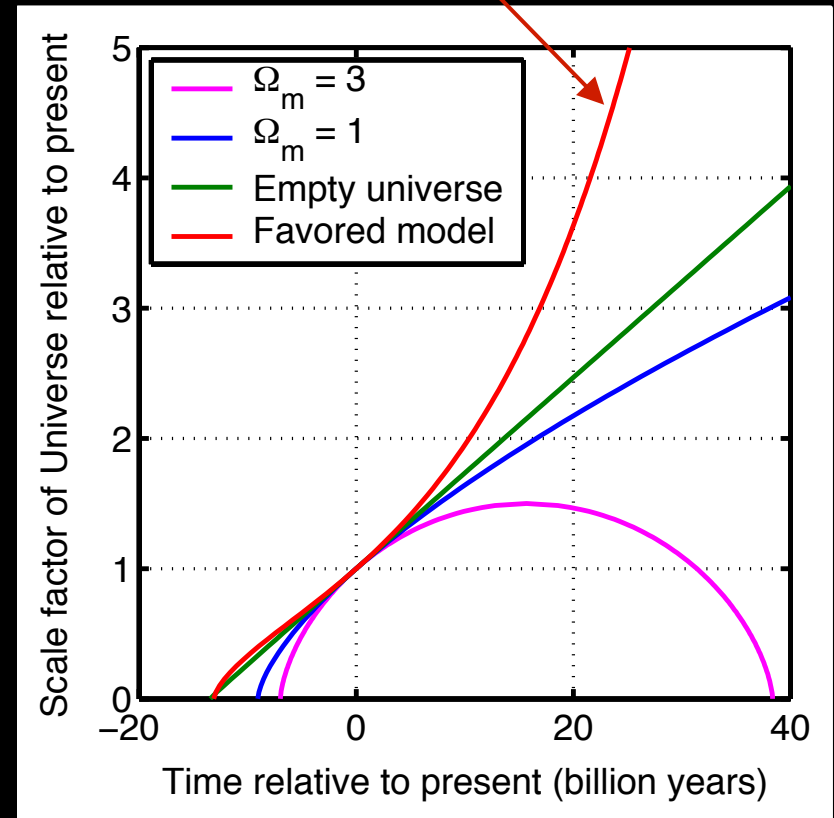


# Triumphant/Embarrassing Cosmology

CMB and other data fits GR based model *beautifully* – but it demands that 96% of the Universe is invisible to us



And it implies that the future is runaway expansion...



Also it doesn't explain the initial conditions...

# History of the Universe

Inflation proposed to explain  
Horizon and Flatness problems

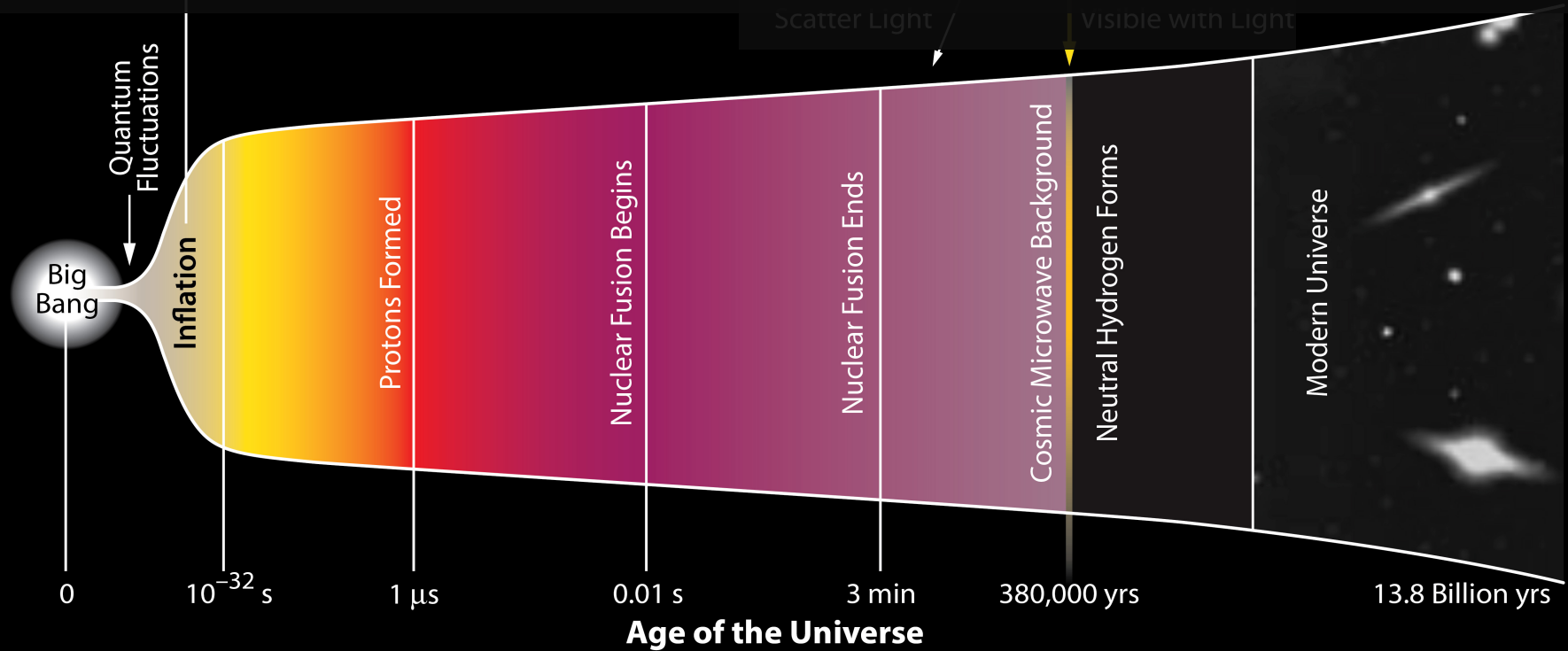


Alan Guth

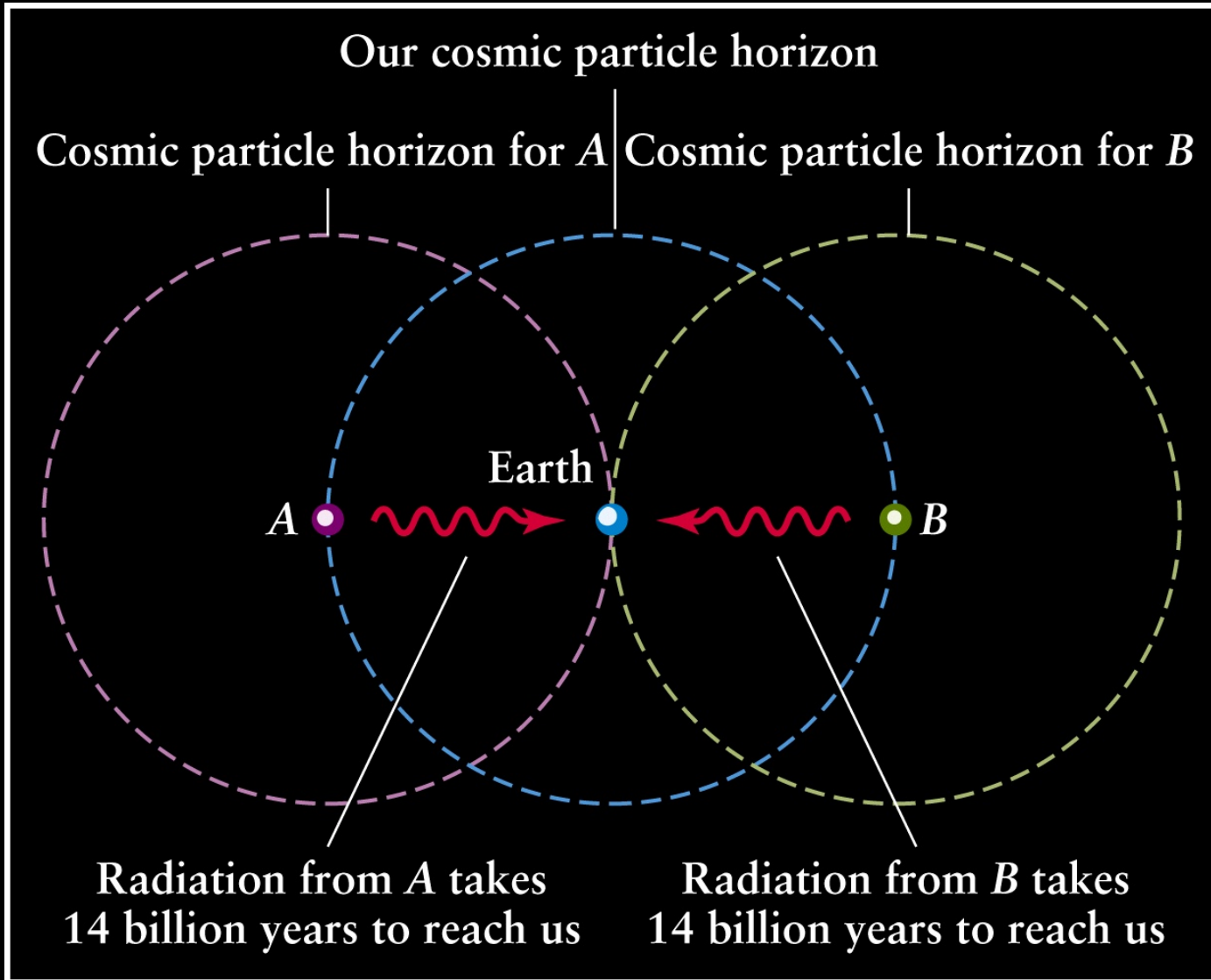


Andrei Linde

Radius of the Visible Universe



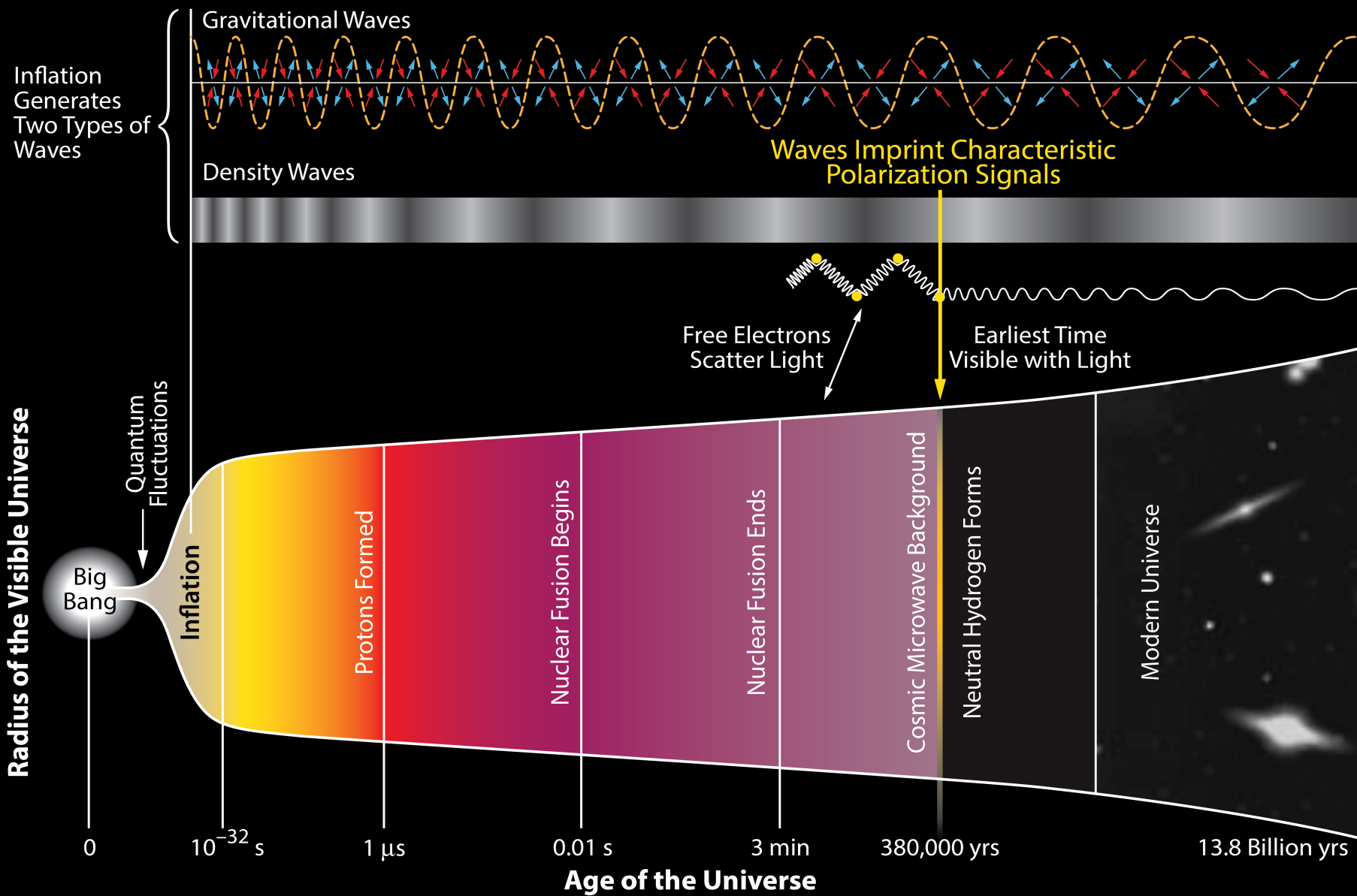
# The Horizon Problem



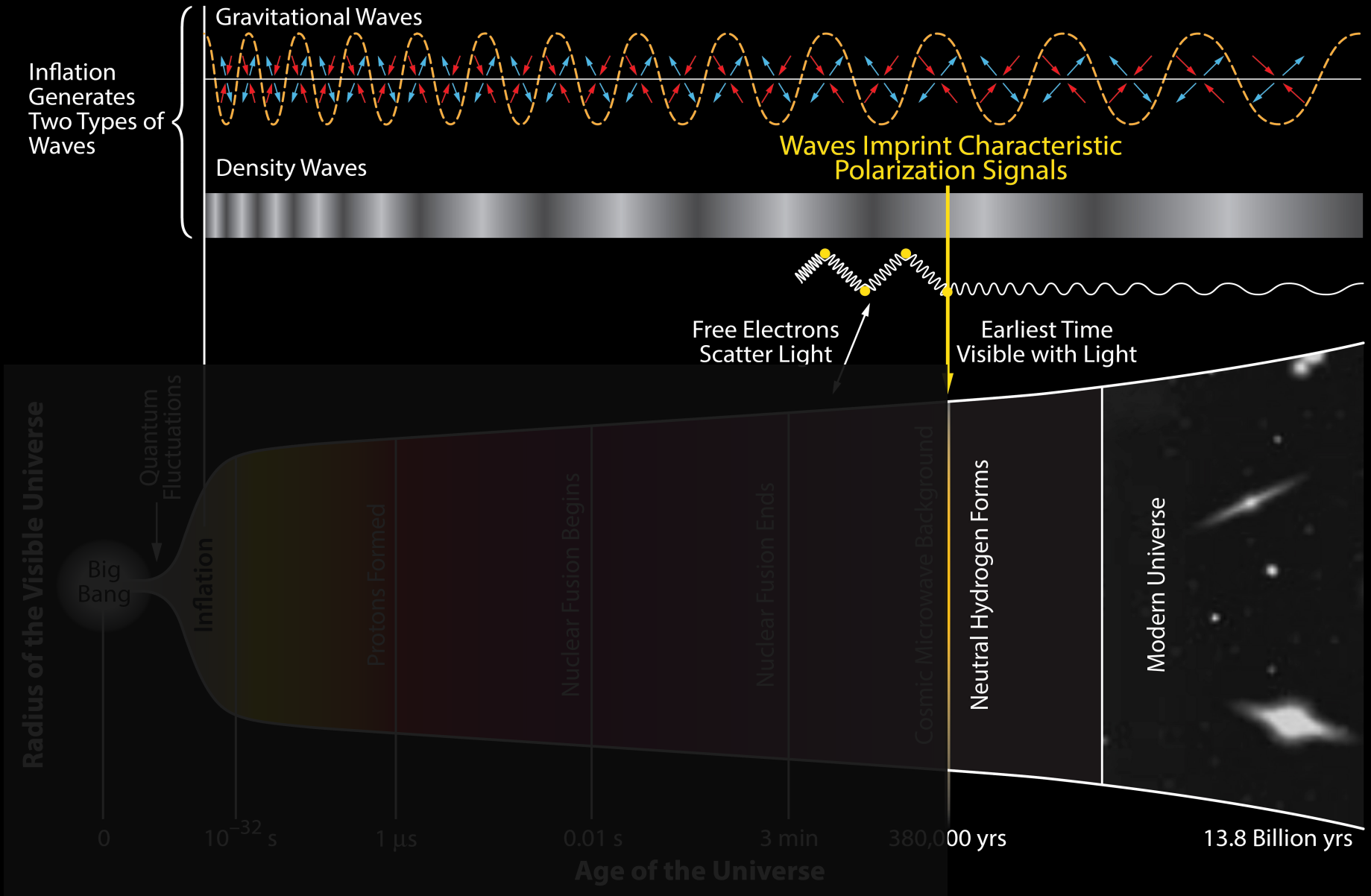
How did points A and B “know” to be at the same temperature at 380,000 years?



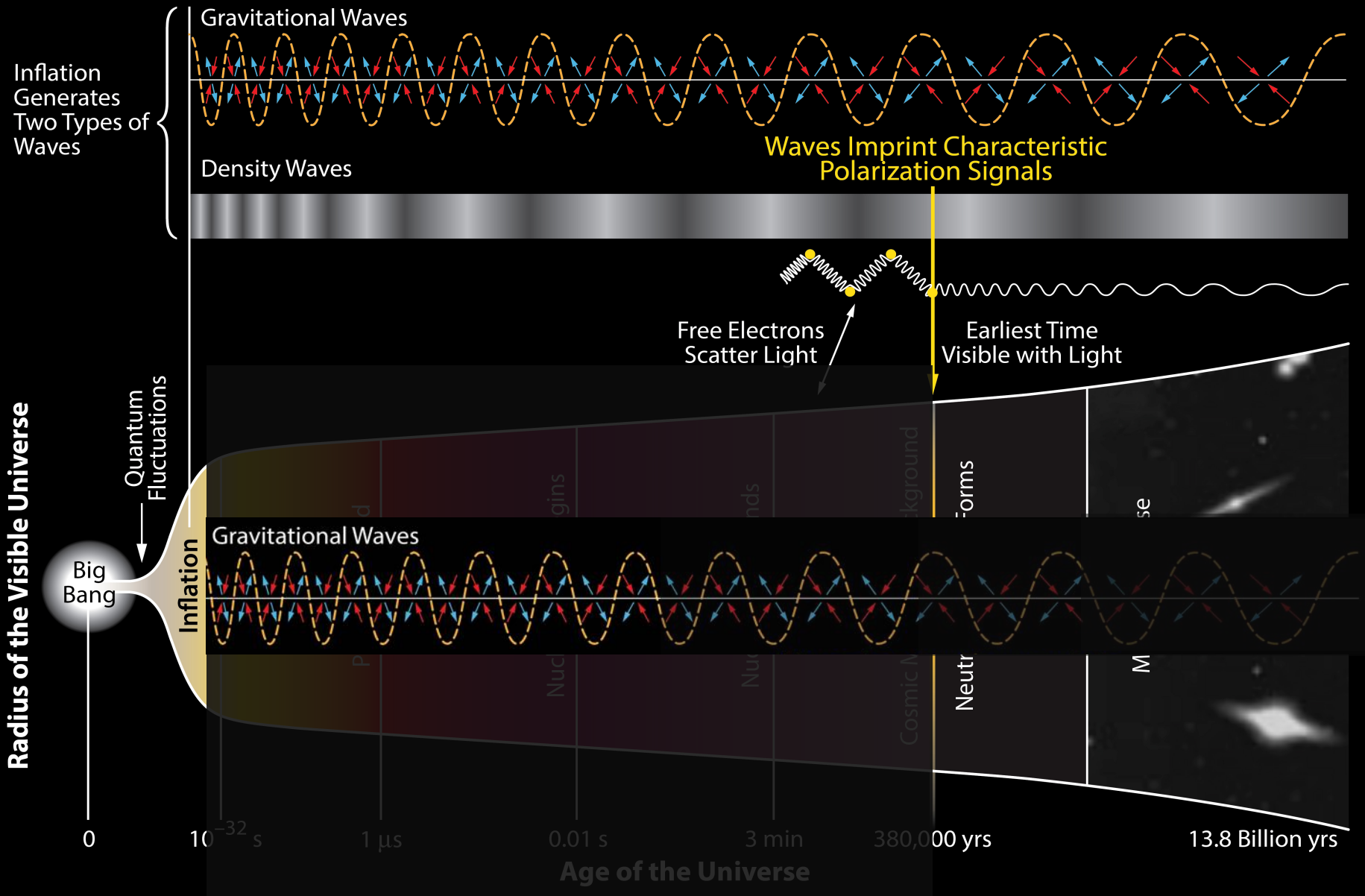
# History of the Universe



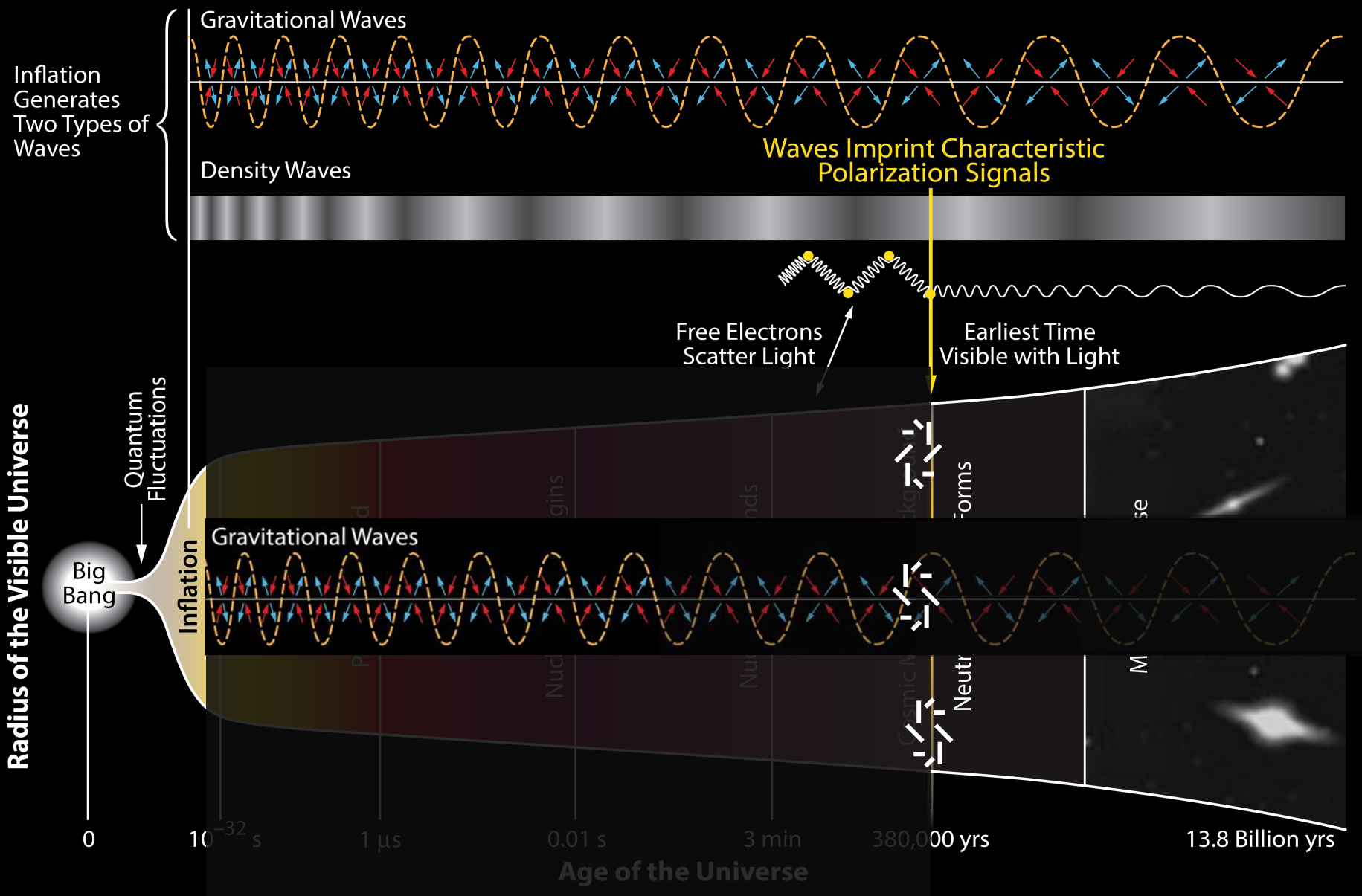
# History of the Universe



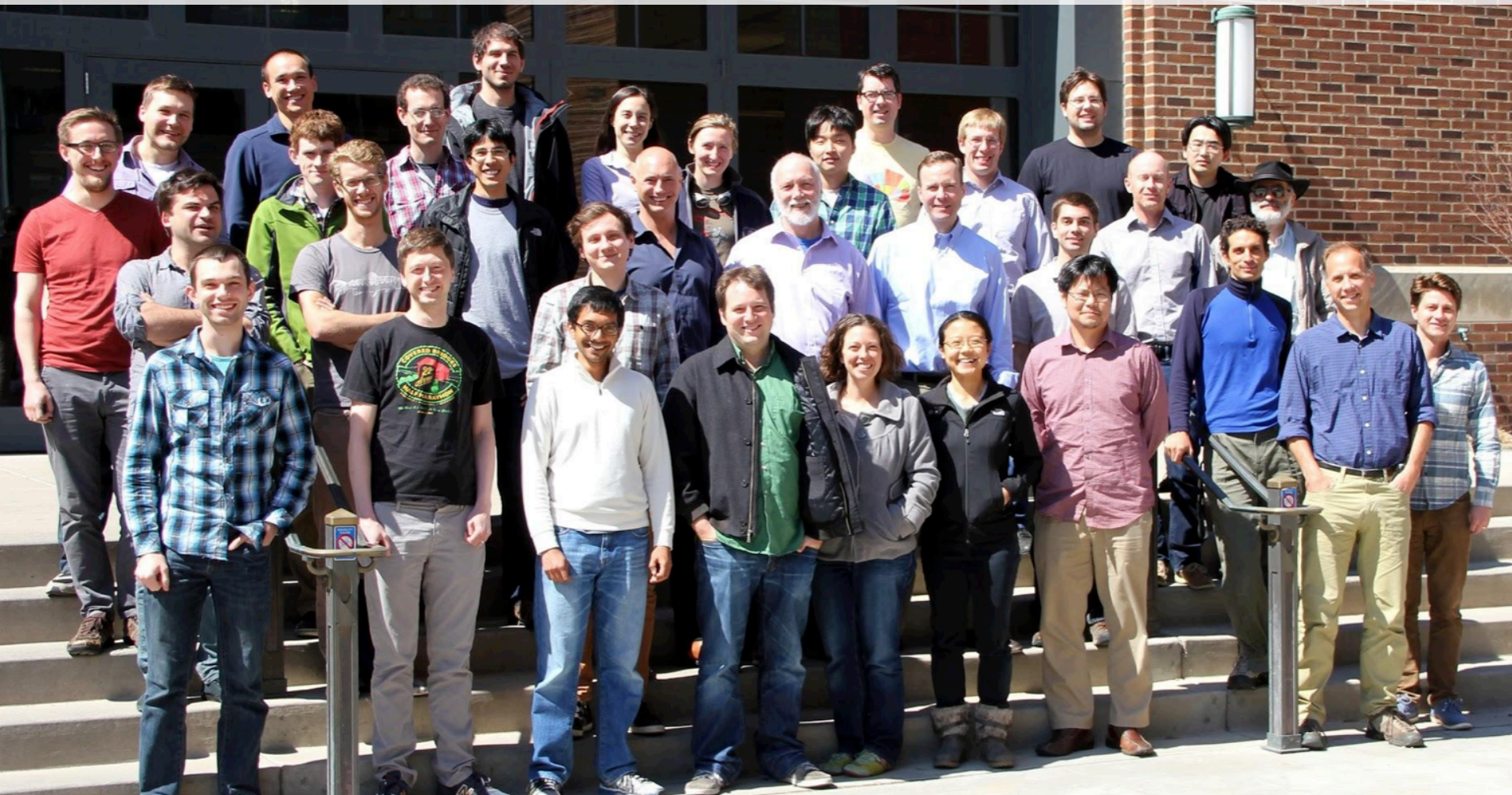
# History of the Universe



# History of the Universe



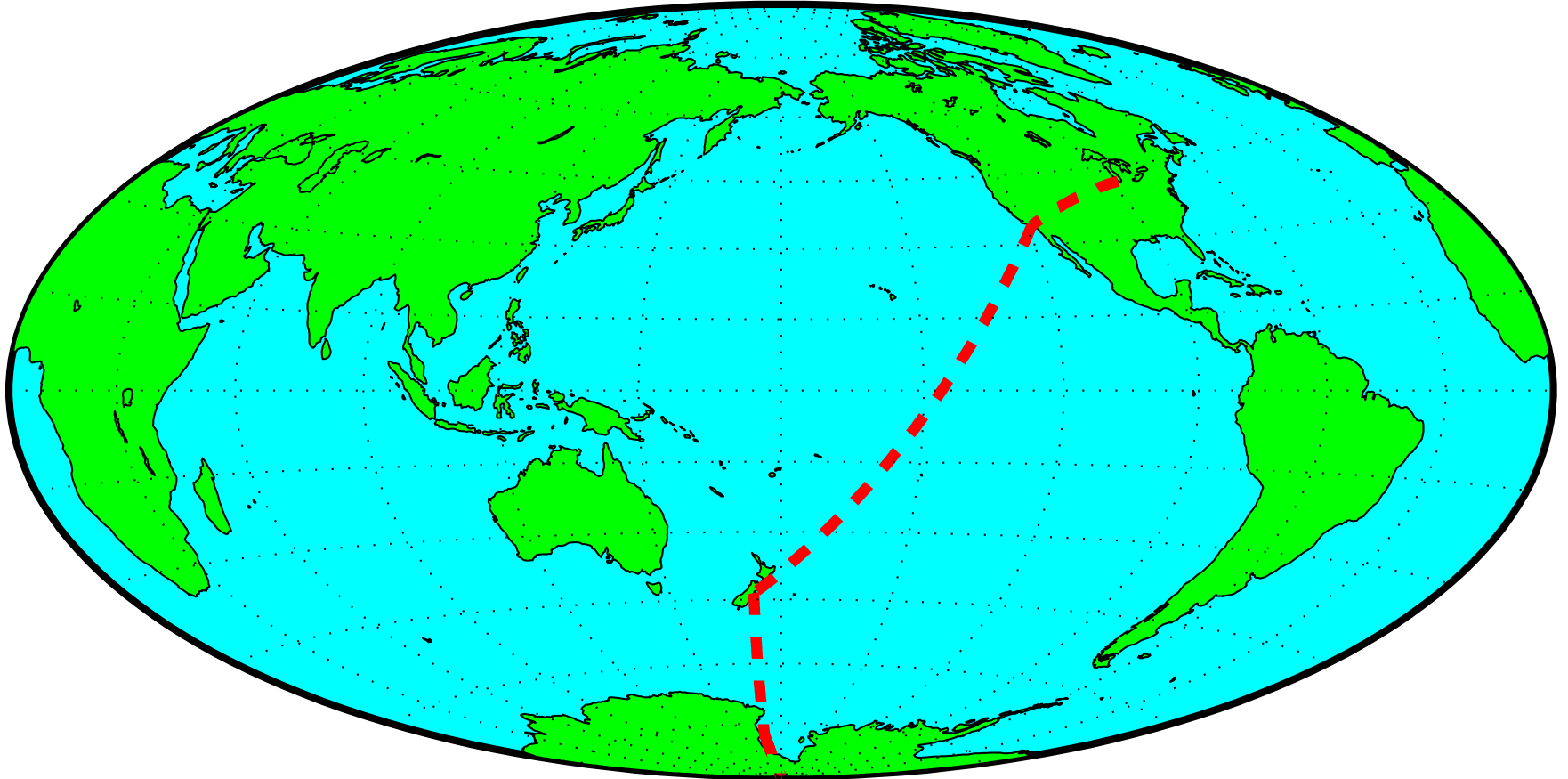




This is our collaboration – about half these people are graduate students, and undergrads also work with us.

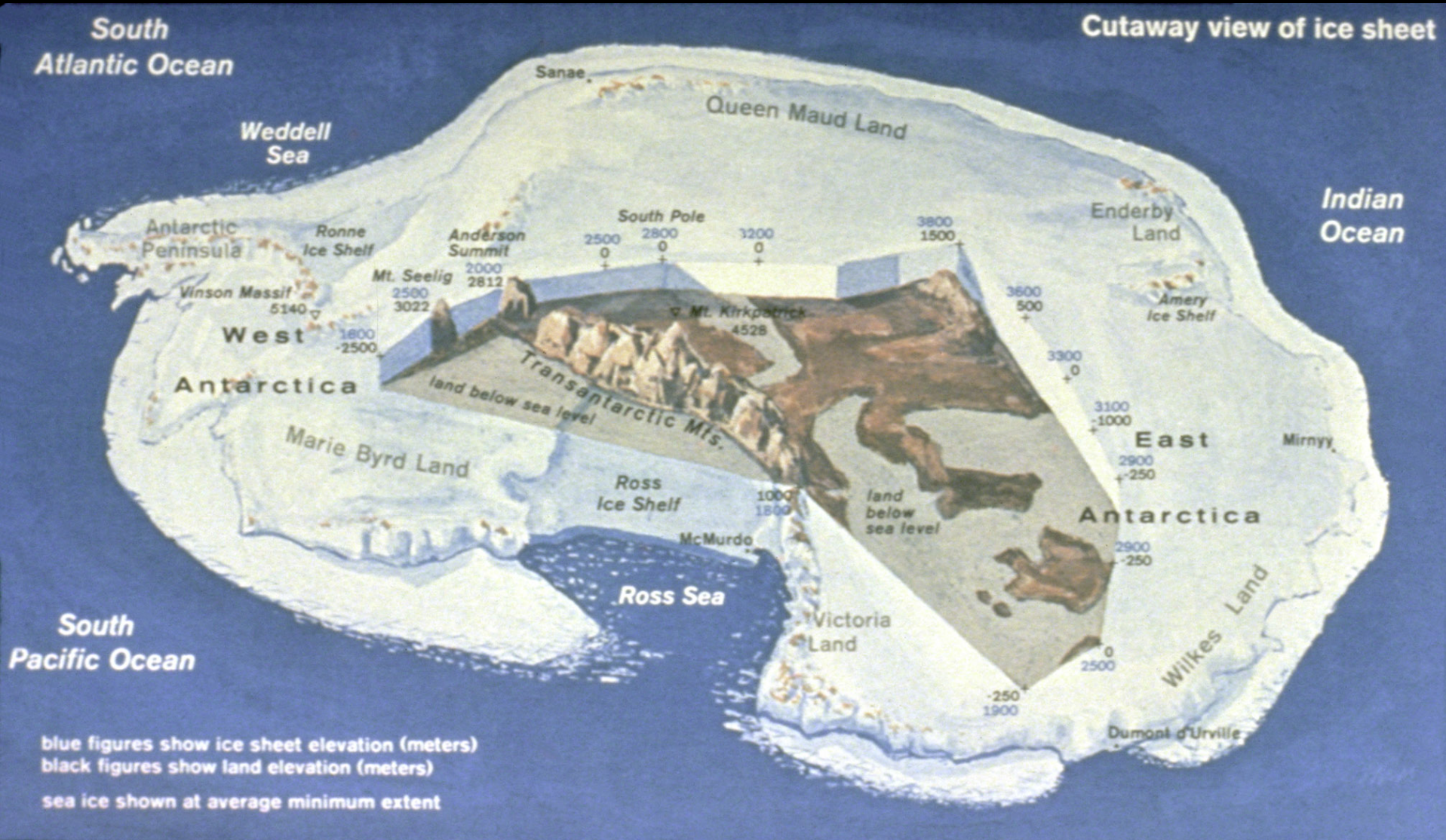


# Journey to the South Pole



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

# Antarctic Continent



Larger than the US – Ice sheet two miles thick!









# Big Program!





# Arrival in Antarctica





# McMurdo – base on the coast





# On to the Pole – over the Transantarctic Mountains





# Unloading at Pole





# The Actual South Pole



GEOGRAPHIC  
SOUTH POLE

ROALD AMUNDSEN      ROBERT E. PEARY

DECEMBER 14, 1911      JANUARY 17, 1909

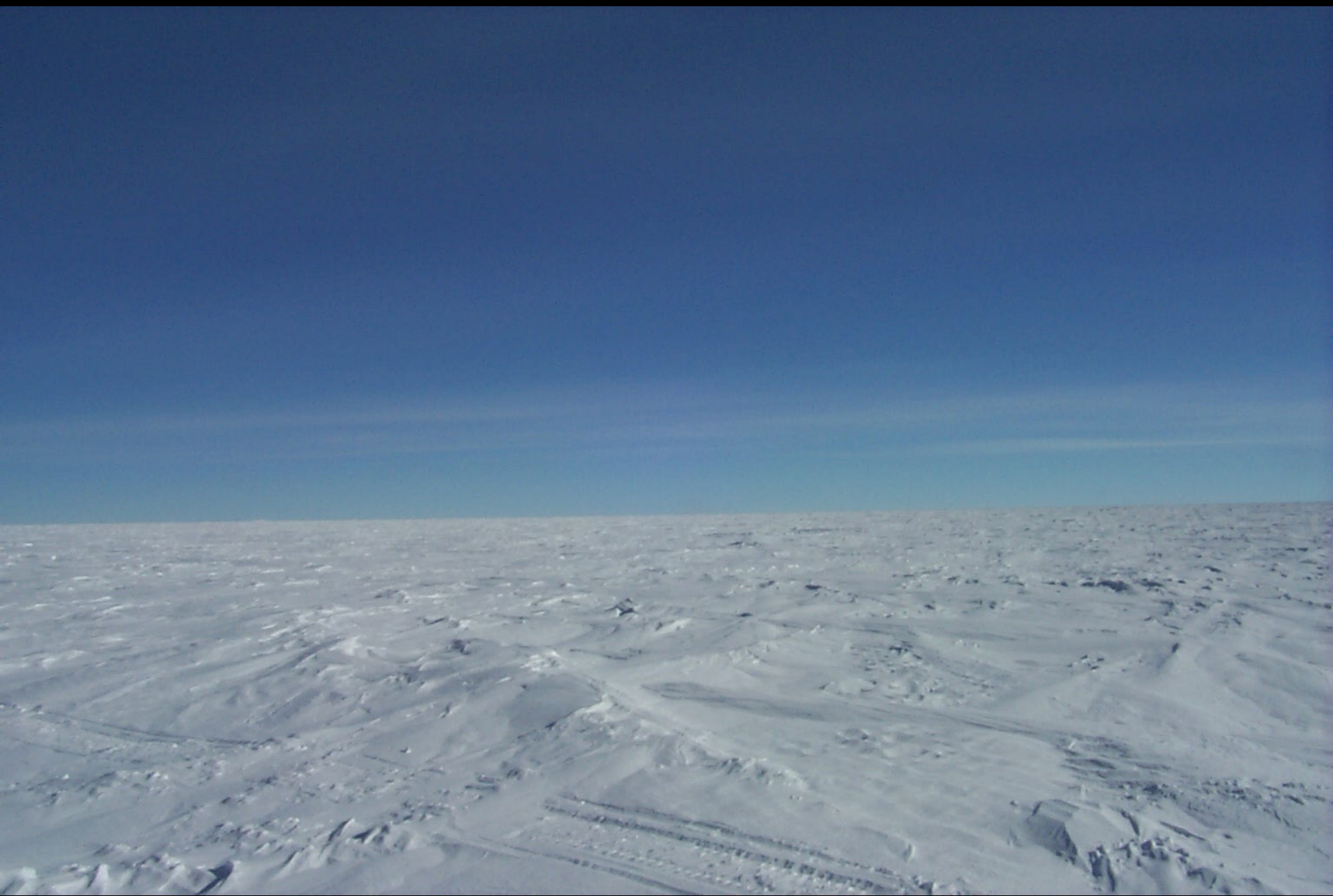
"So we arrived and were able to plant our flag at the geographical South Pole."

"The first man to reach the South Pole under the Arctic circle."

ELEVATION 9,301 FT.



**Nothing Out There!**



# Why do this at the Pole?

## South Pole CMB telescopes

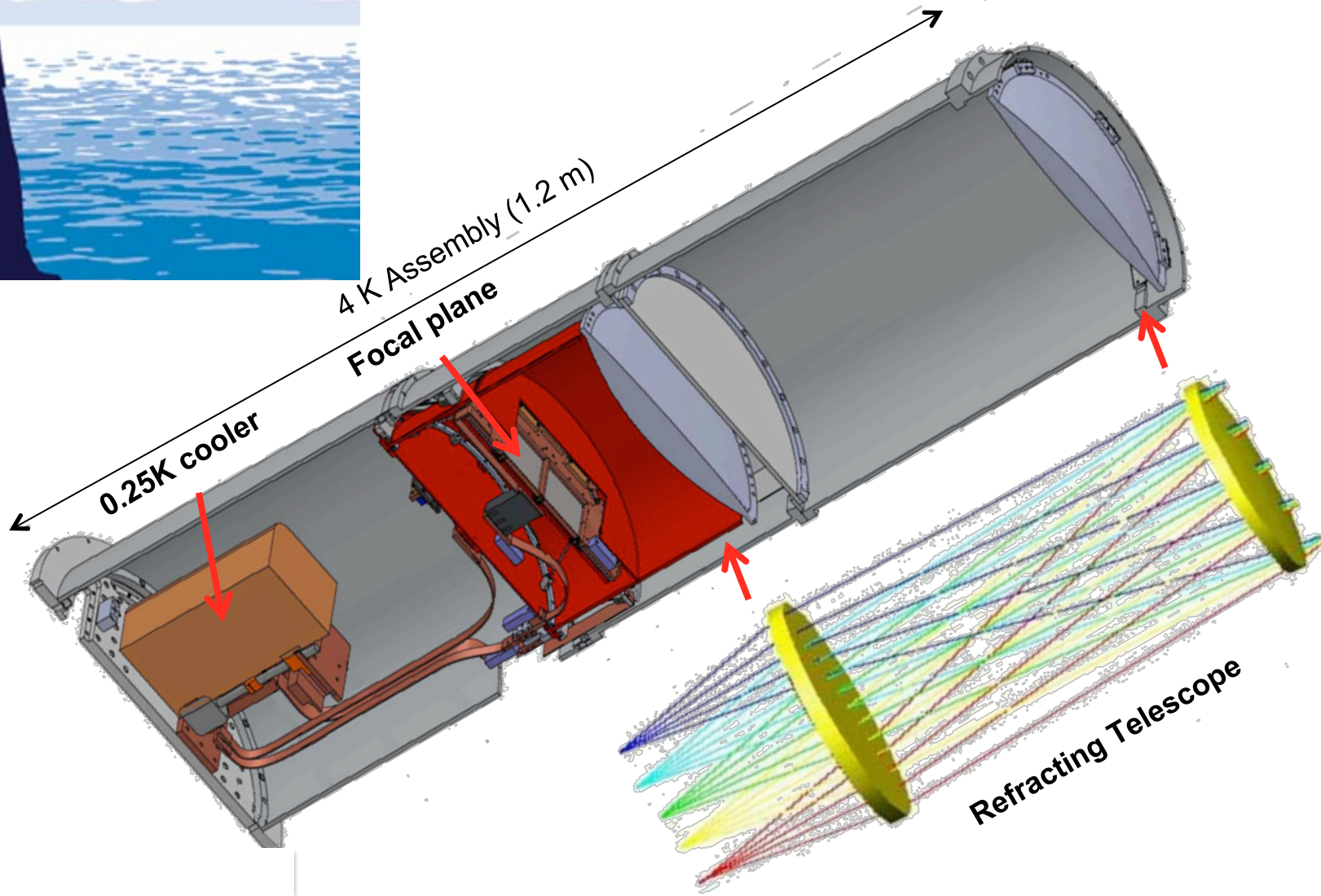


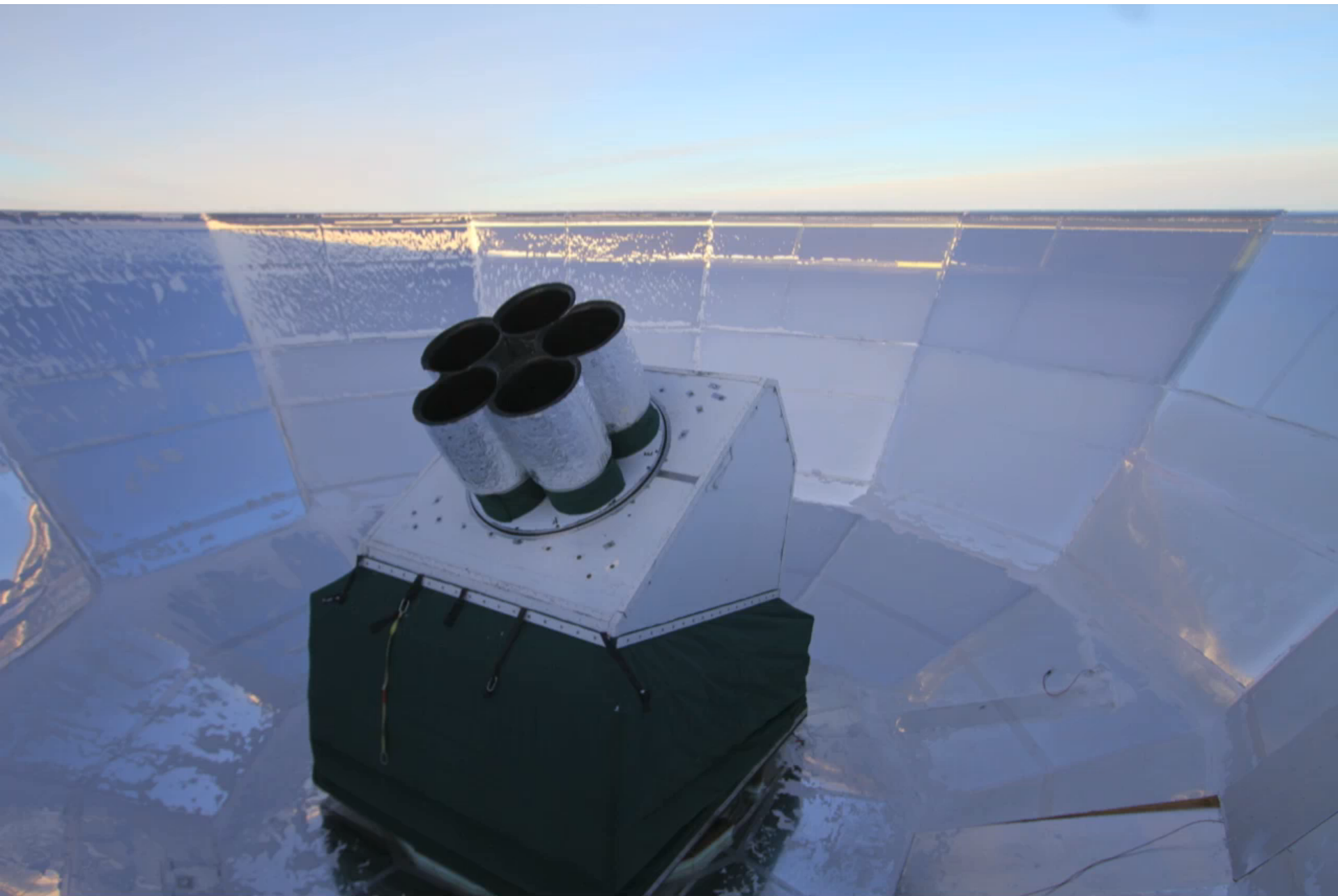
- High and *dry* – see out into space
- On Earth's rotational axis - One day/night cycle per year
  - Long night makes for great quality data
- Good support infrastructure – power, cargo, data comm
- Food and accommodation provided
- Even Tuesday night bingo...



# Basic Experiment Design

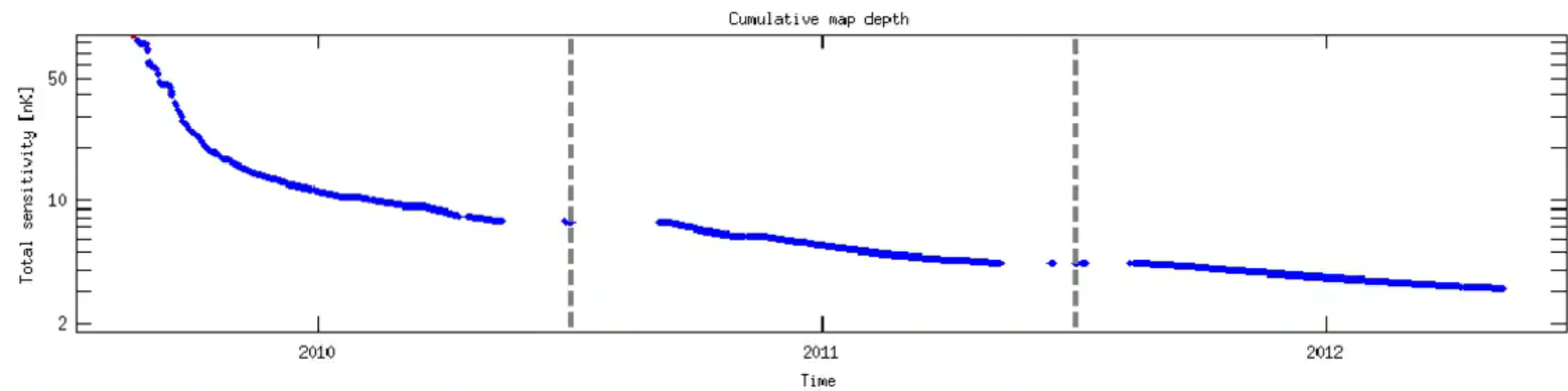
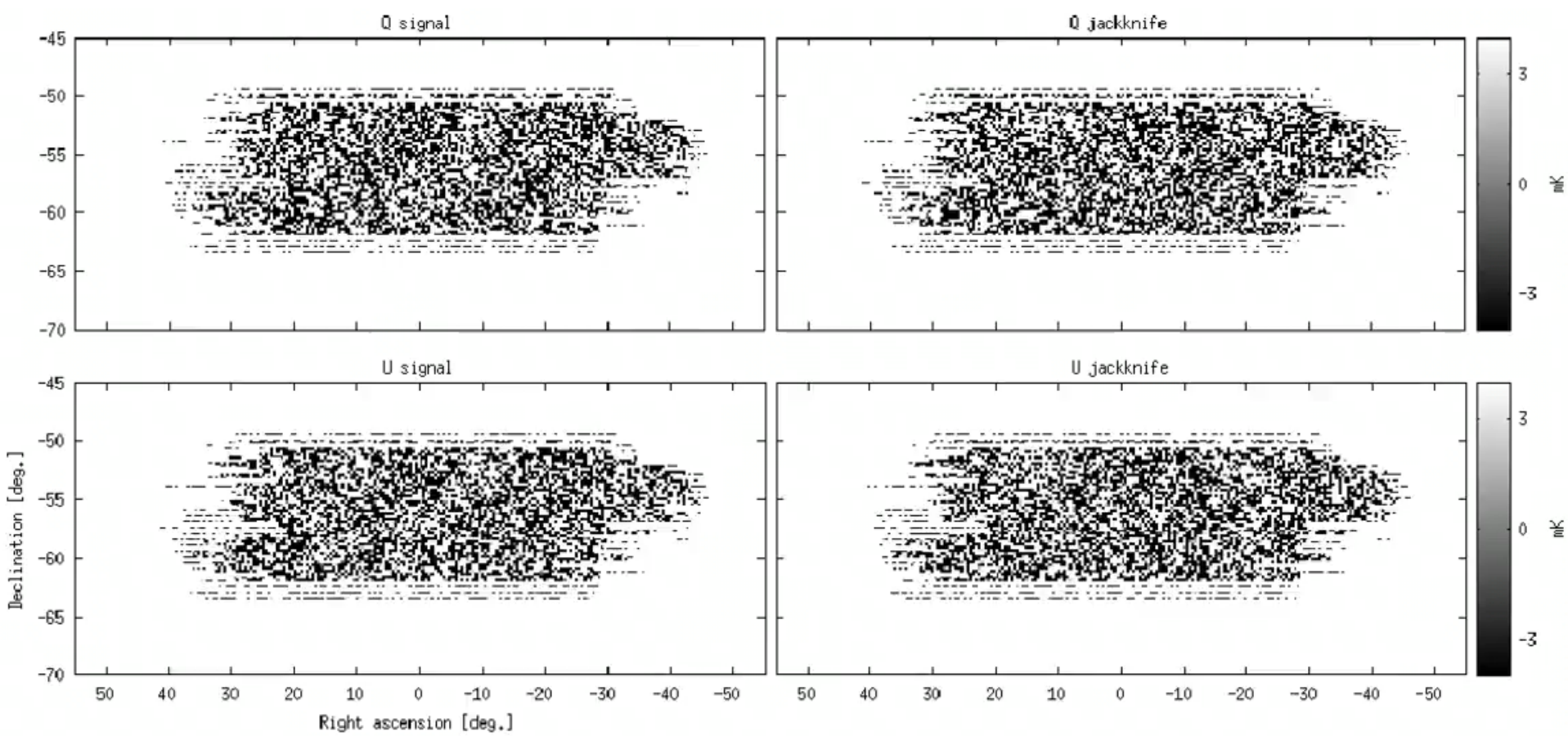
- Small aperture
- Wide field of view
- Cold refractor





Clem Pryke for The Bicep2 Collaboration

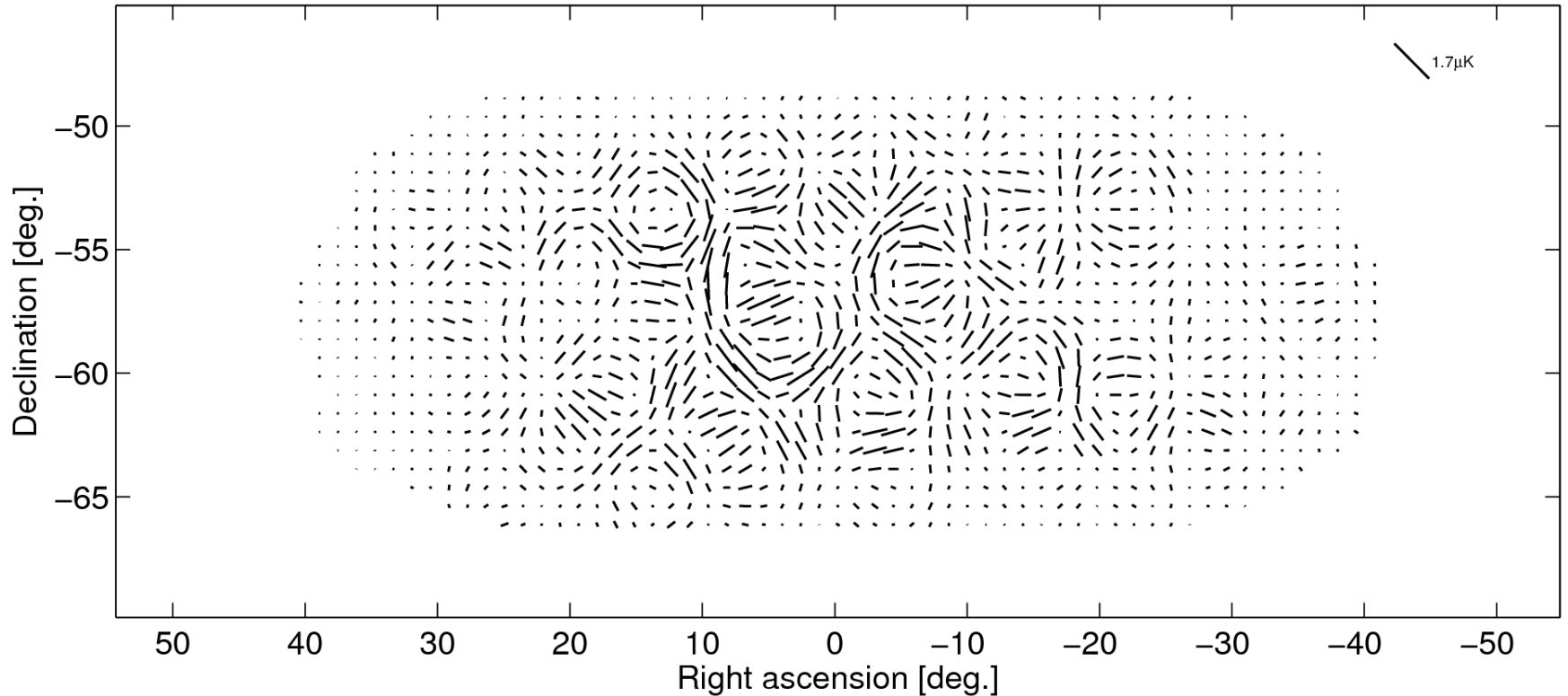




# Total Polarization

BICEP2 total polarization signal

Scale:  $1.7 \mu K$

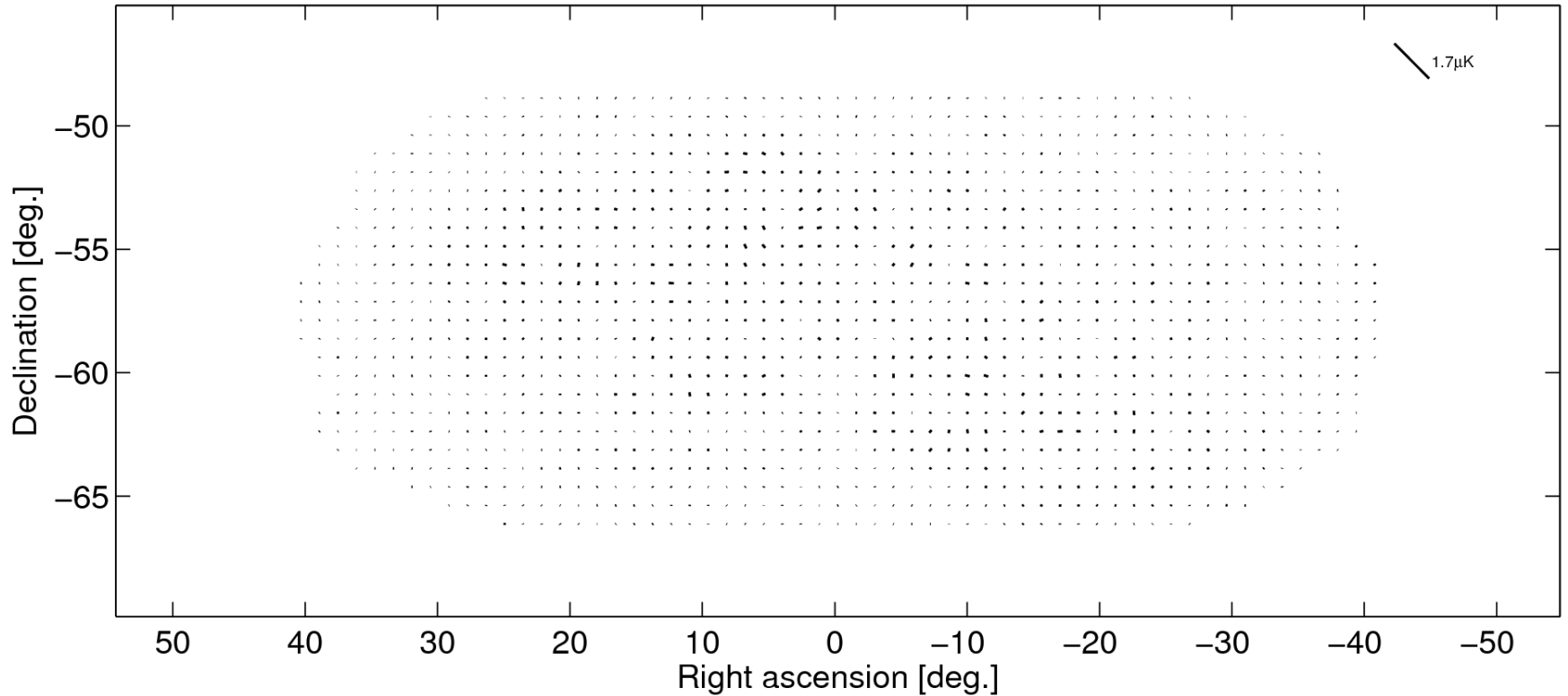


E-mode dominated pattern – no obvious curl component

# B-mode Contribution

BICEP2 B-mode signal

Scale:  $1.7 \mu K$



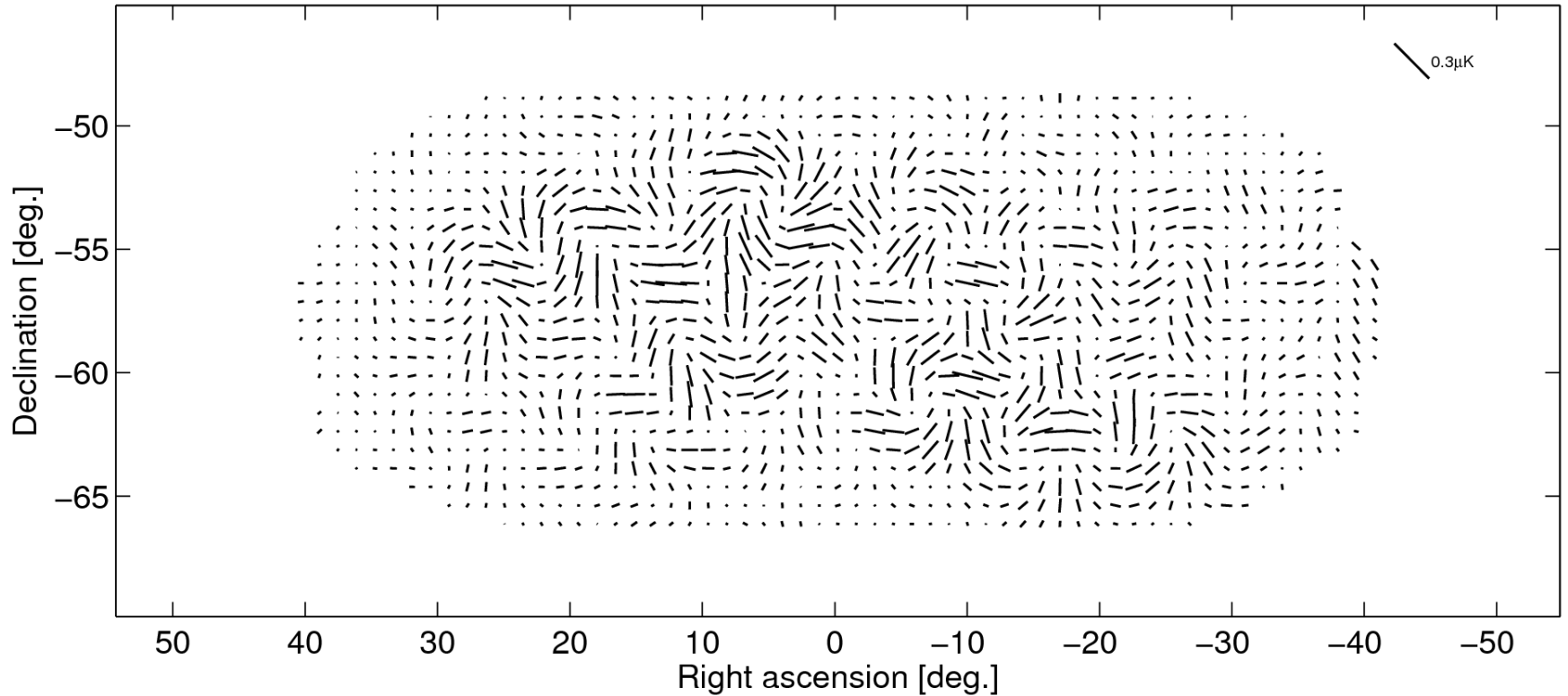
Apply purification operation which leaves only pure B-modes



# B-mode Contribution

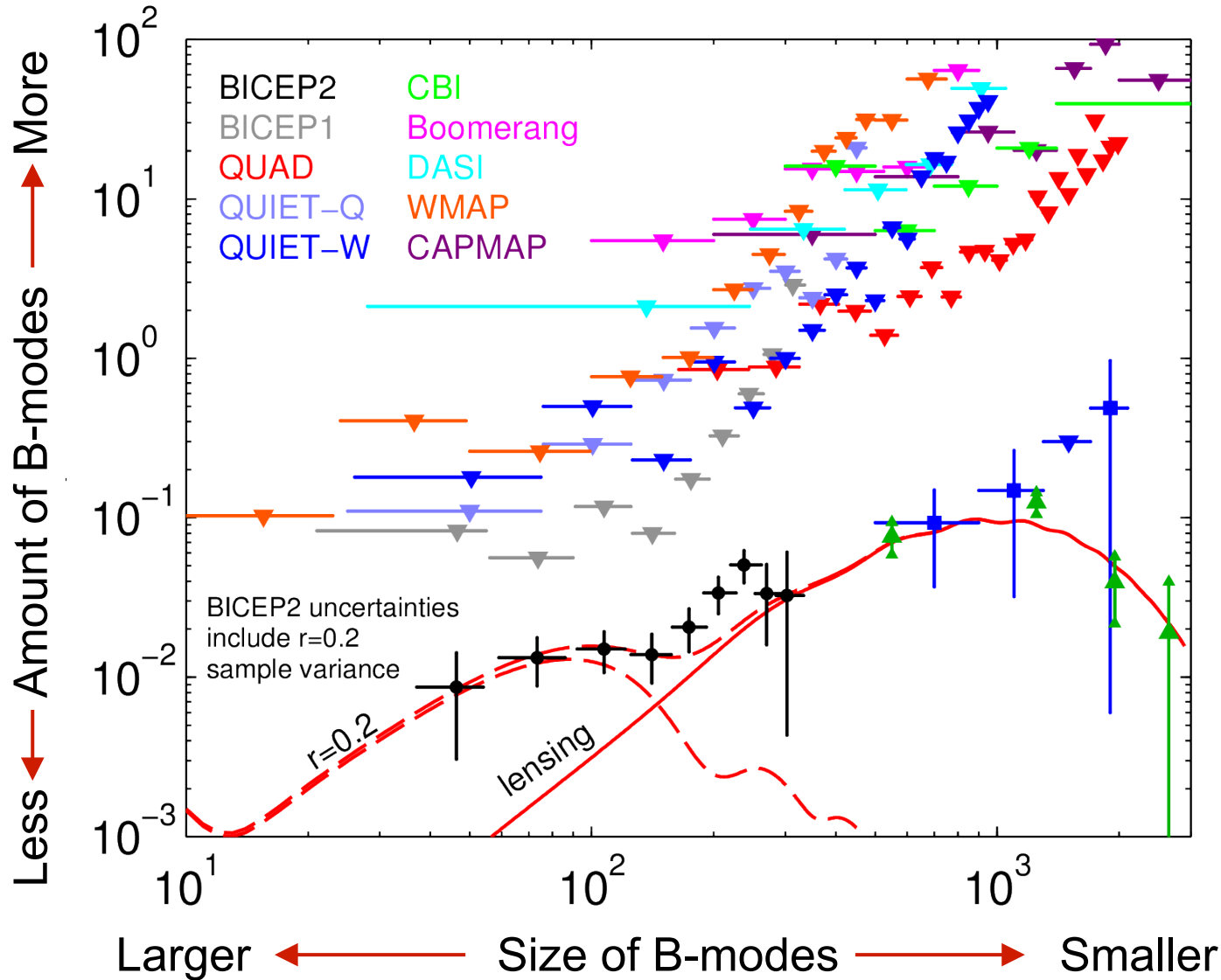
BICEP2 B-mode signal

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

9.90 THE NETHERLANDS

**TUESDAY**

**USA TODAY**  
A GANNETT COMPANY

**03.18.14**

**NCAA TOURNAMENT**  
UConn tops women's tourney  
ANALYSIS, BRACKET 4C

**WHO HAS BEST 'DANCE CARDS'**  
A look at matchups, from the underdogs to the favorites to watch, 5C

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

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

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

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

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

**How legals earned her big, bad wings**  
Scribble has been going strong for 30 years, but the owner's hobby is far from ordinary 2B

**SOUTH POLE VIEW**  
The best place to view comets, the South Pole offers an unparalleled view of the night sky 2B

**THEORY**  
A theory in 19th-century physics suggests that the universe is made of tiny particles 2B

**WAVES COULD BE BIG BANG'S SMOKING GUN**  
Scientists of the South Pole-based special telescope to detect primordial gravitational waves — ripples in the fabric of space and time — which hold clues to the nature of the universe. The ripples have never been seen directly until now. Story 5A

**Space Ripples Reveal Big Bang's Smoking Gun**  
BY HEINER GEBRUE  
CLASSICAL PHYSICS — The light left in 1915 by an expansion of space, predicted by Albert Einstein, could have been the first sign of the universe's expansion, according to a new study. The study says that the expansion of space could have been the first sign of the universe's expansion, according to a new study. The study says that the expansion of space could have been the first sign of the universe's expansion, according to a new study.

**Lost Jet's Path Seen as Altered**  
BY PATRICK J. WALSH  
AN AIRLINE'S SEARCH FOR MISSING MALAYSIAN AIRWAYS flight MH370 has been altered, according to a new study. The study says that the expansion of space could have been the first sign of the universe's expansion, according to a new study.

**Crisis could hurt U.S. firms**  
BY JEFFREY M. HESTER  
The U.S. economy could be hurt by a crisis in Ukraine, according to a new study. The study says that the expansion of space could have been the first sign of the universe's expansion, according to a new study.

**GRAVITATIONAL WAVES**  
BY JEFFREY M. HESTER  
The discovery of gravitational waves could be the smoking gun for the Big Bang, according to a new study. The study says that the expansion of space could have been the first sign of the universe's expansion, according to a new study.

**A THEORY**  
BY JEFFREY M. HESTER  
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# The New York Times

Vol. CLXXIII — No. 56,444 — TUESDAY, MARCH 18, 2014



SECOND CHINESE LEADERS (left) and Russian officials (right) at a meeting in Beijing. Page A8.

**Putin, U.S. up ante after vote**  
Sanctions imposed, Ukraine, Russia ready troops as Duma considers Crimea's annexation

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**FINANCIAL TIMES**

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

**The trouble with tinkering with textbooks**  
Gideon Rachman, Page 7

USA Tuesday March 18 2014

USA \$220 Canada \$300

## Sanctions hit Russian top brass

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

By Chris Cocks in Brussels  
EUROPEAN LEADERS have agreed to impose sanctions on Russian officials and military leaders in response to the annexation of Crimea. The EU has also agreed to freeze the assets of Russian officials and military leaders.

By Chris Cocks in London  
THE BRITISH GOVERNMENT has announced that it will impose sanctions on Russian officials and military leaders in response to the annexation of Crimea.

By Chris Cocks in Moscow  
VICTOR PUTIN has laid out his demands for the return of Crimea to Russia, including the withdrawal of Ukrainian troops and the restoration of the 2010 constitution.

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

By Chris Cocks in London

BY THE TIME YOU READ THIS, the first ripples of gravitational waves from the Big Bang will have been detected. The discovery is a major milestone in the study of the universe's expansion.

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

Prisons raise drug use, study pharmacists, try untested mixtures

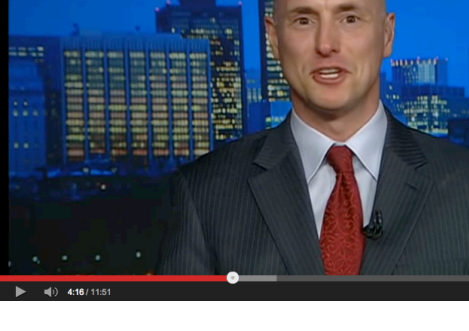
BY CHRIS COCKS IN WASHINGTON  
DEATH PENALTY DRUGS are being used in ever-increasing numbers as states engage in shadowy deals with pharmaceutical companies to secure supplies.

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Barack Obama, president of the United States.



Image courtesy of NASA. Credit: NASA/JPL-Caltech.

## 宇宙急速膨張の証拠、検出される

Telescope captures view of gravitational waves

By Chris Cocks in London

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**Actually not a lot of fun...**

Published by American Physical Society.

Volume 112, Number 24

Articles published week ending 20 JUNE 2014

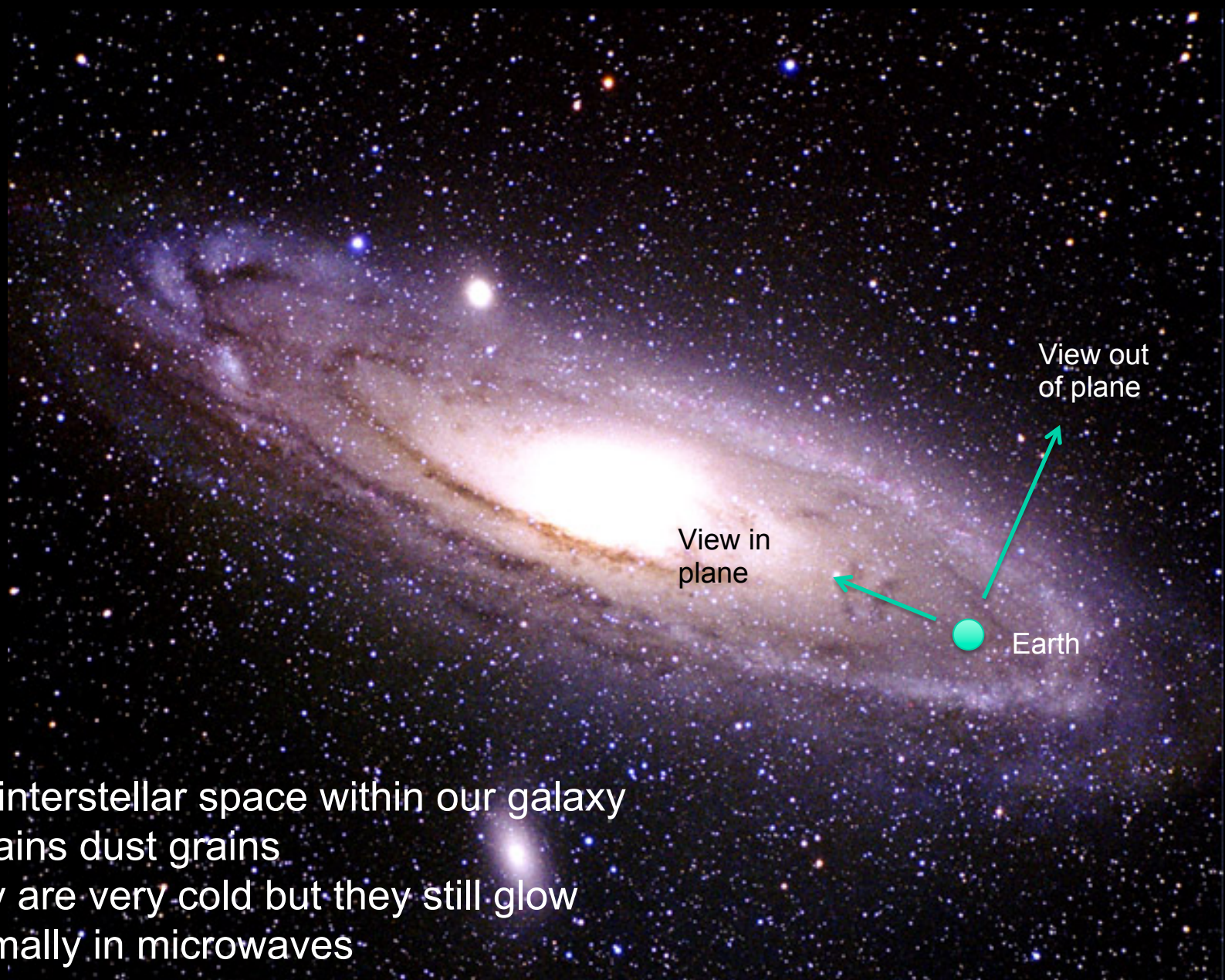
Number Subscription Dept.  
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Articles published week ending 20 JUNE 2014

24



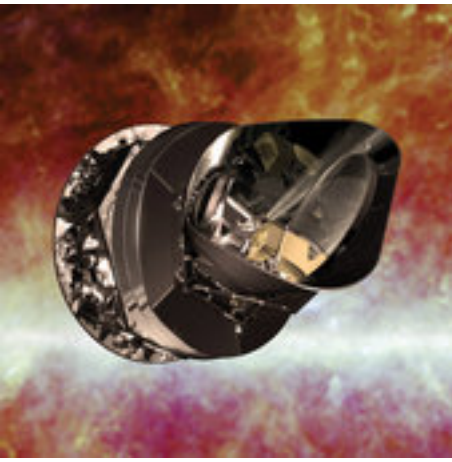
# Unfortunately we are in a galaxy!



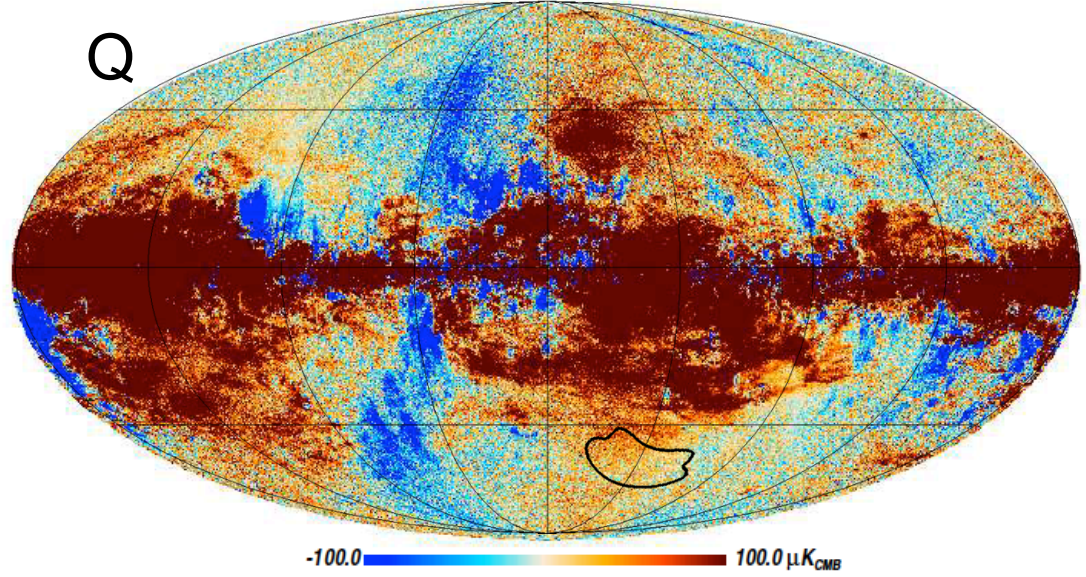
The interstellar space within our galaxy contains dust grains  
They are very cold but they still glow thermally in microwaves



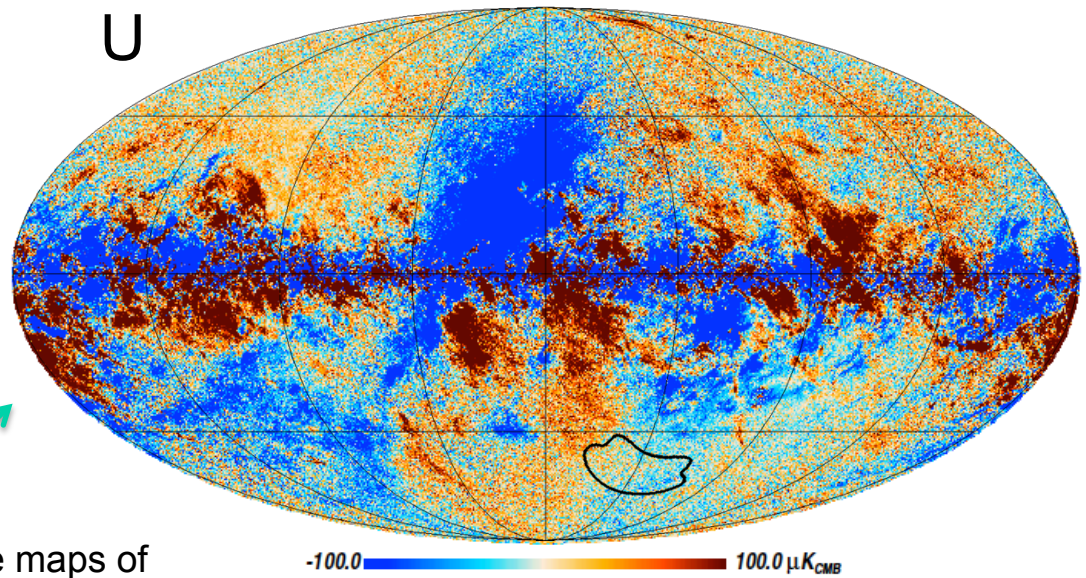
# Dust emission from our galaxy turns out to be brighter than expected...



Q



U

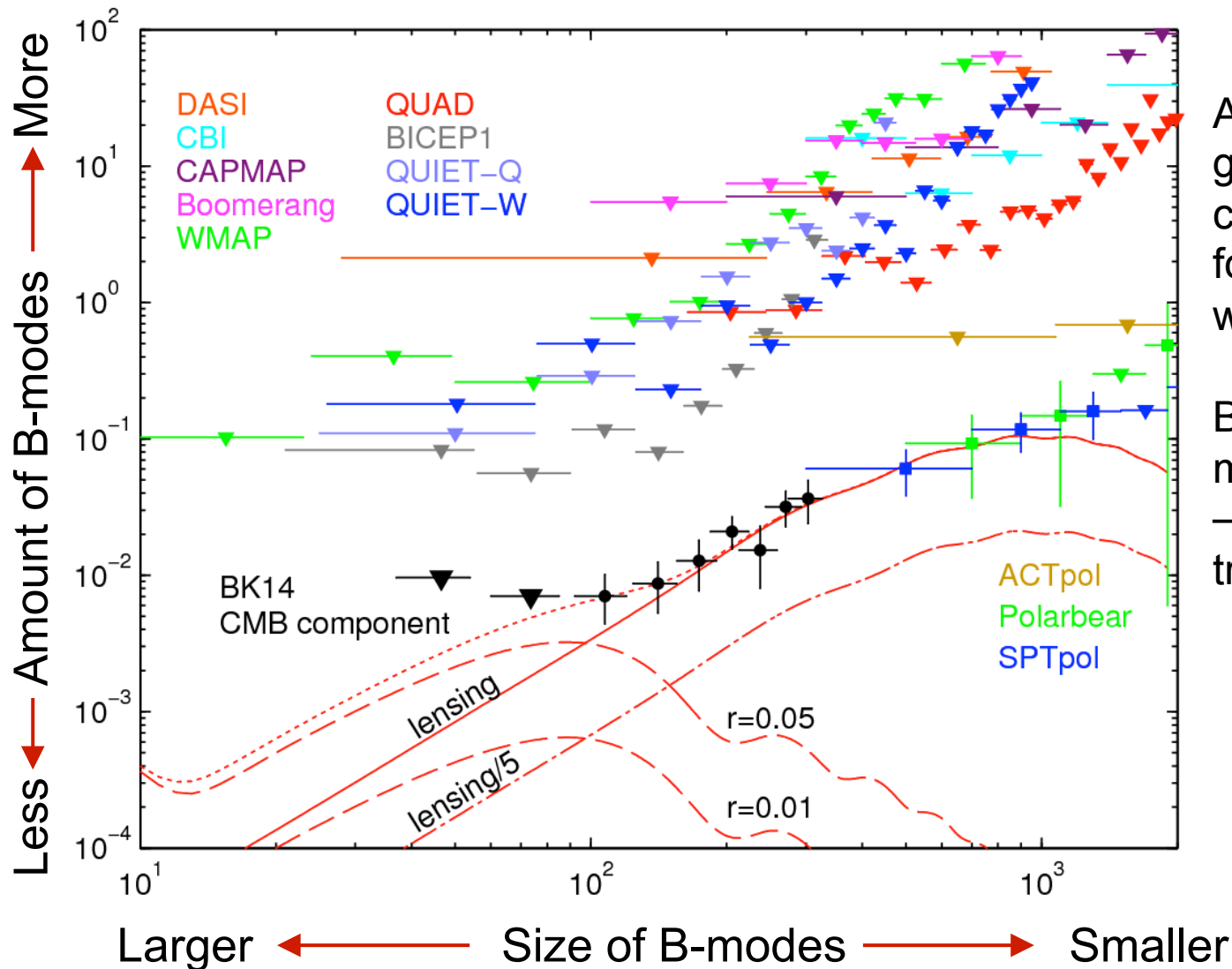


Planck was a billion dollar Euro/NASA space mission

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!

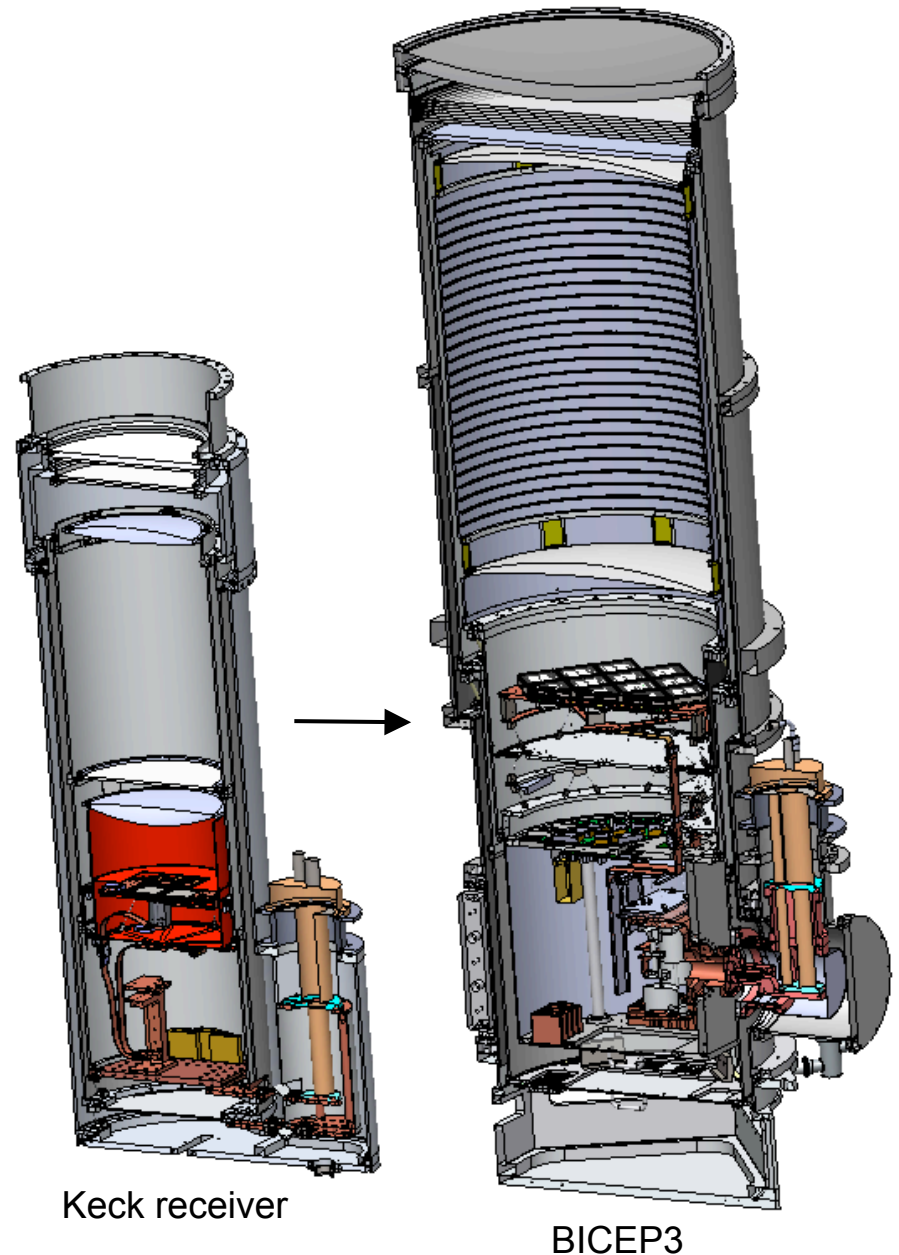


# BICEP3: Next Gen. Super receiver

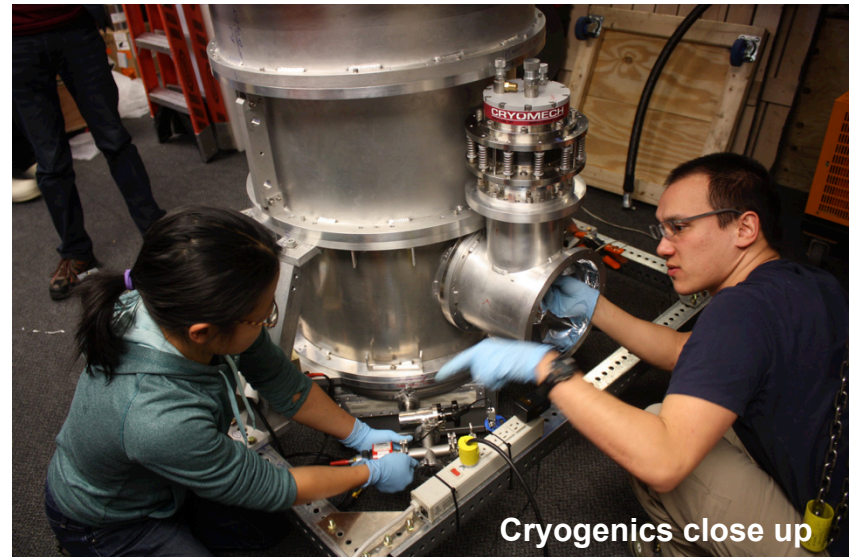
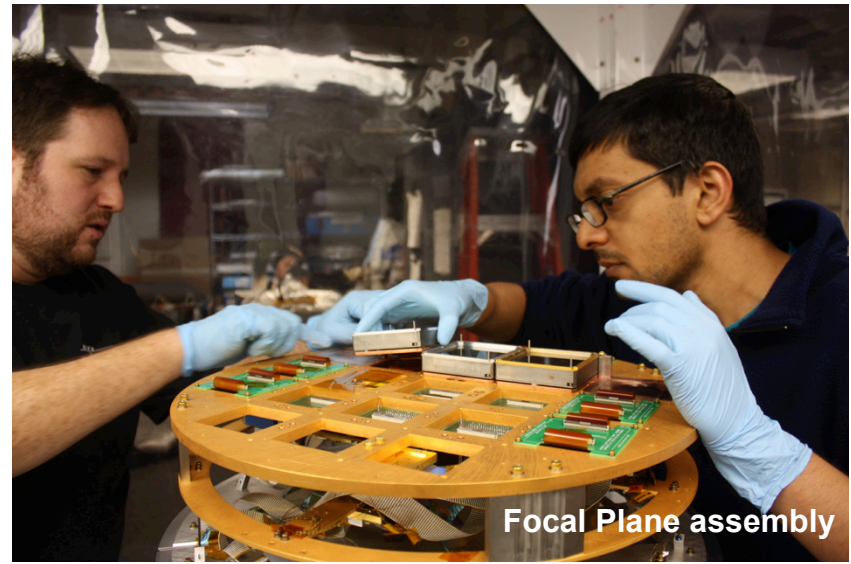
2560 detectors in modular focal plane

Large-aperture optics and infrared filtering

**> 10x optical throughput of single BICEP2/Keck receiver**



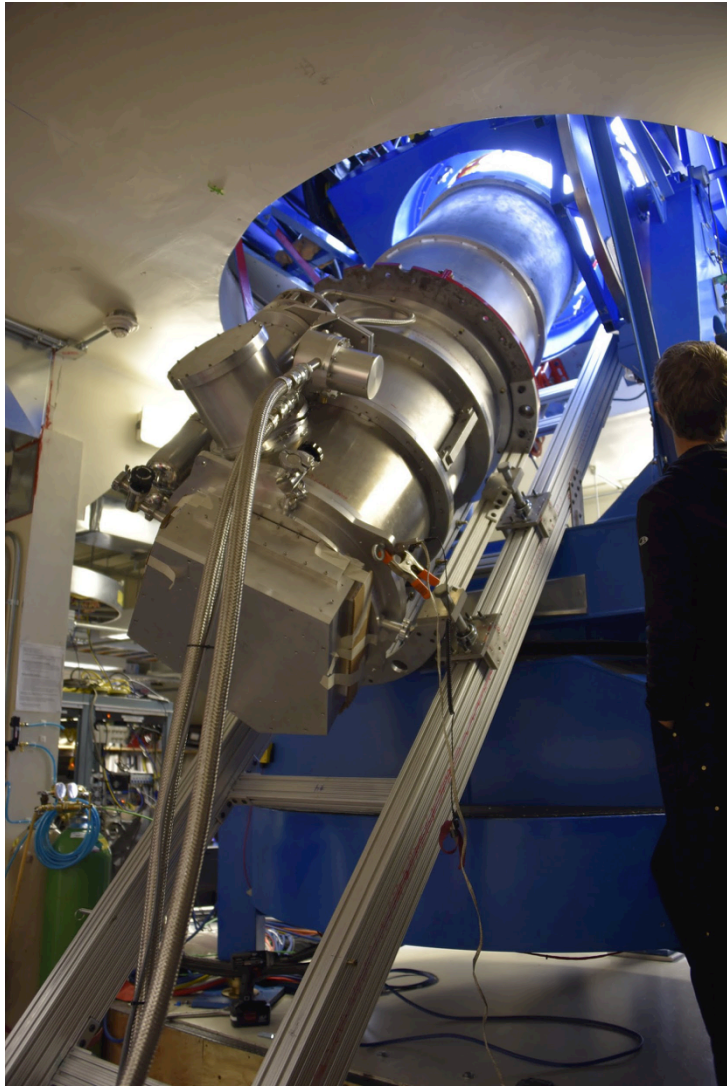
# December 2015: BICEP3 assembly at South Pole



Physics grad. Students designed and built this thing!



# January 2016: BICEP3 installed in the telescope



Physics grad. Students at the South Pole in Antarctica!



## Stage 2

## Stage 3

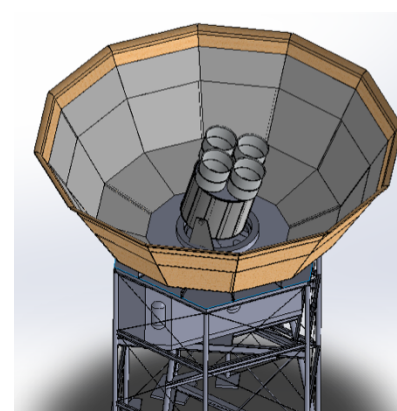
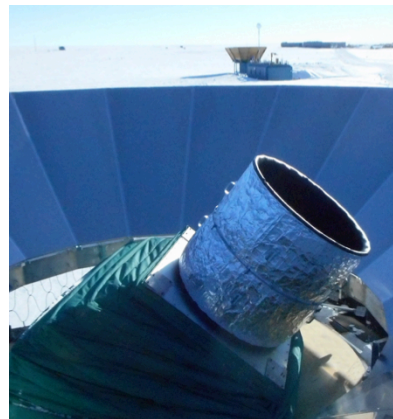
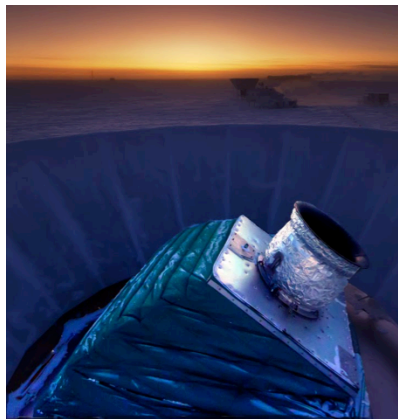
**BICEP2**  
(2010-2012)

**Keck Array**  
(2012-2017)

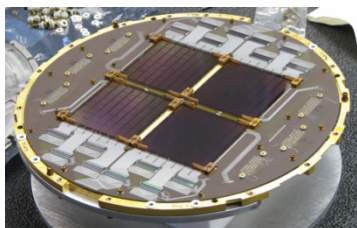
**BICEP3**  
(2015-)

**BICEP Array**  
(2018-)

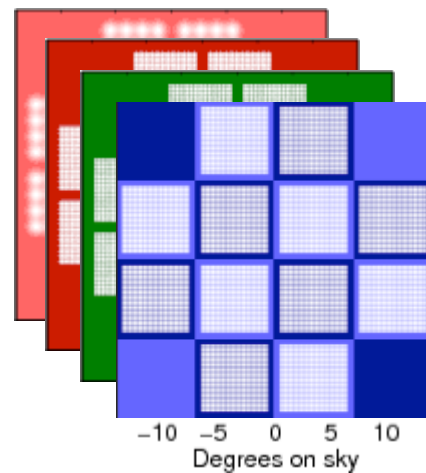
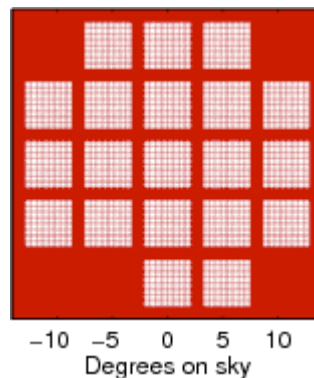
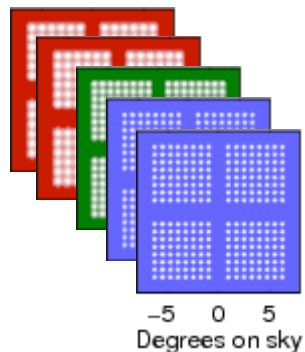
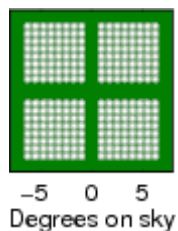
Telescope and Mount



Focal Plane



Beams on Sky



# Summary

- The Universe is expanding – it was once a hot dense “fireball”.
- We understand its development all the way back to very close to the beginning. (For instance we know it is 14 billion years old.)
- The theory of Inflation says that our entire observable Universe today all came from a single sub-atomic spec in a hyper expansion lasting a tiny fraction of a second
  - If this Inflation really happened it will have made a background of gravitational waves
    - We may be able to detect the imprint of these as B-modes in the polarization pattern of the Cosmic Microwave Background
      - A few years ago we thought we had actually done this but unfortunately we were fooled by galactic dust emission.
        - However the search goes on with bigger and better experiments...
- Physics under grad. students work in our research labs!