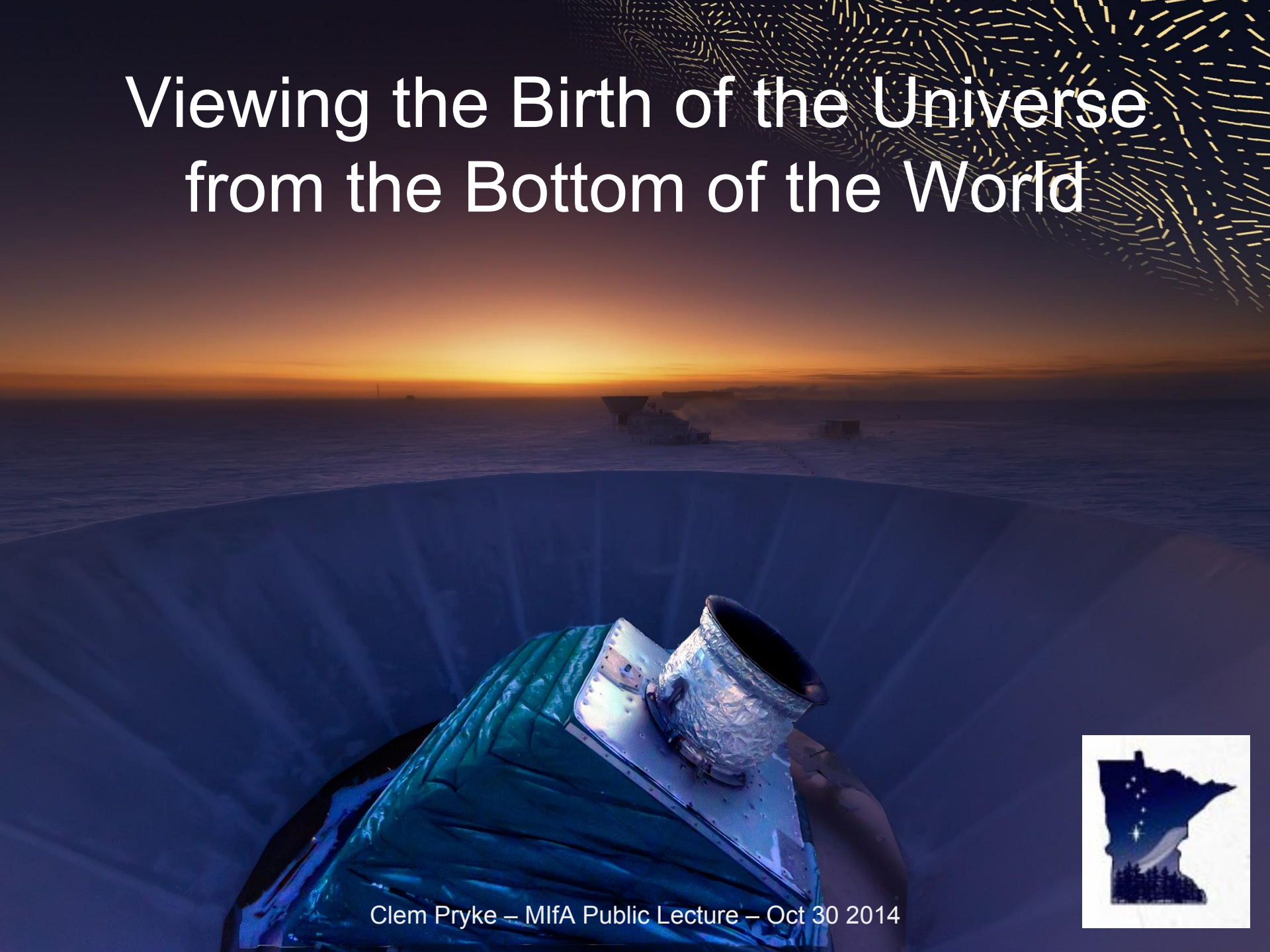


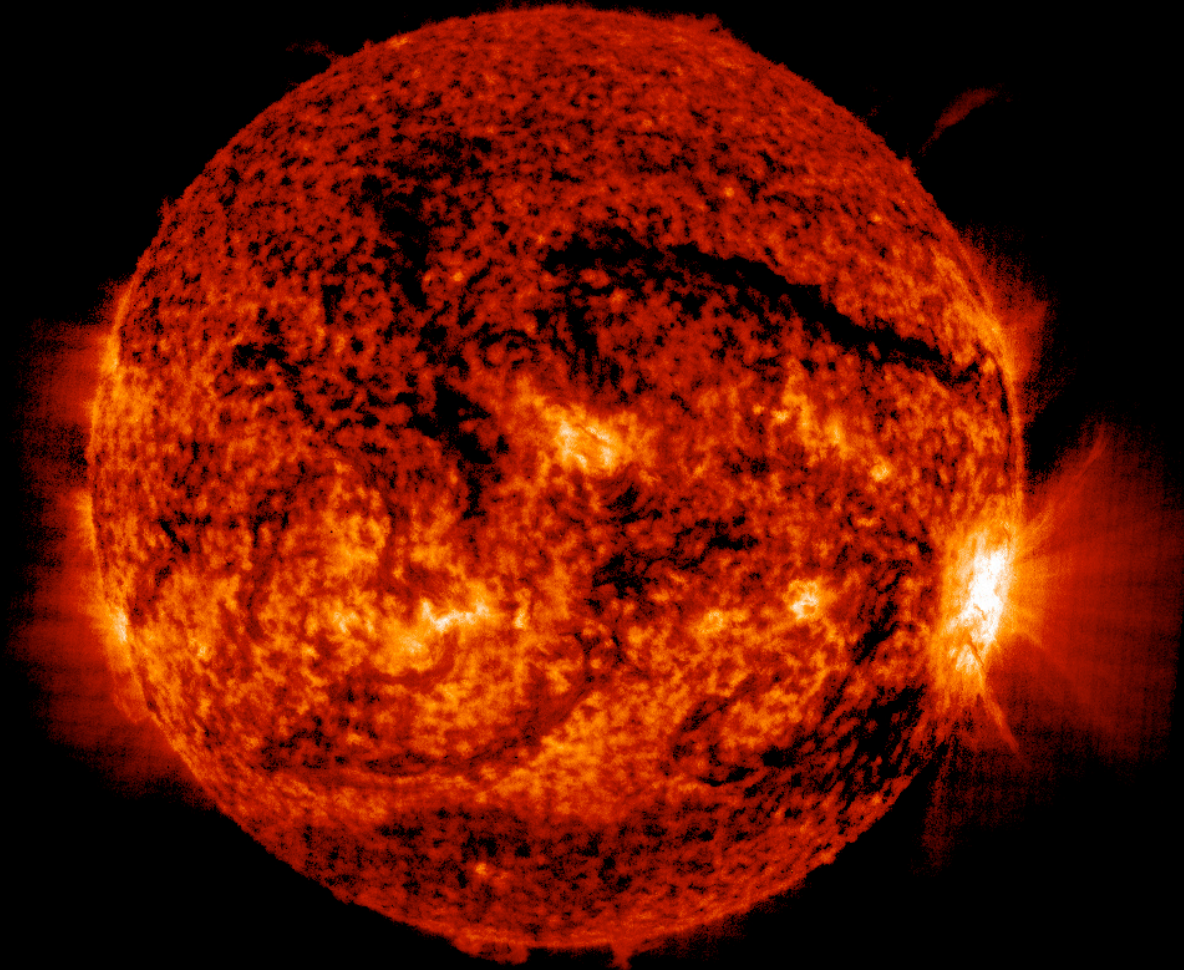
Viewing the Birth of the Universe from the Bottom of the World



Clem Pryke – MfA Public Lecture – Oct 30 2014



Our Sun is a Star

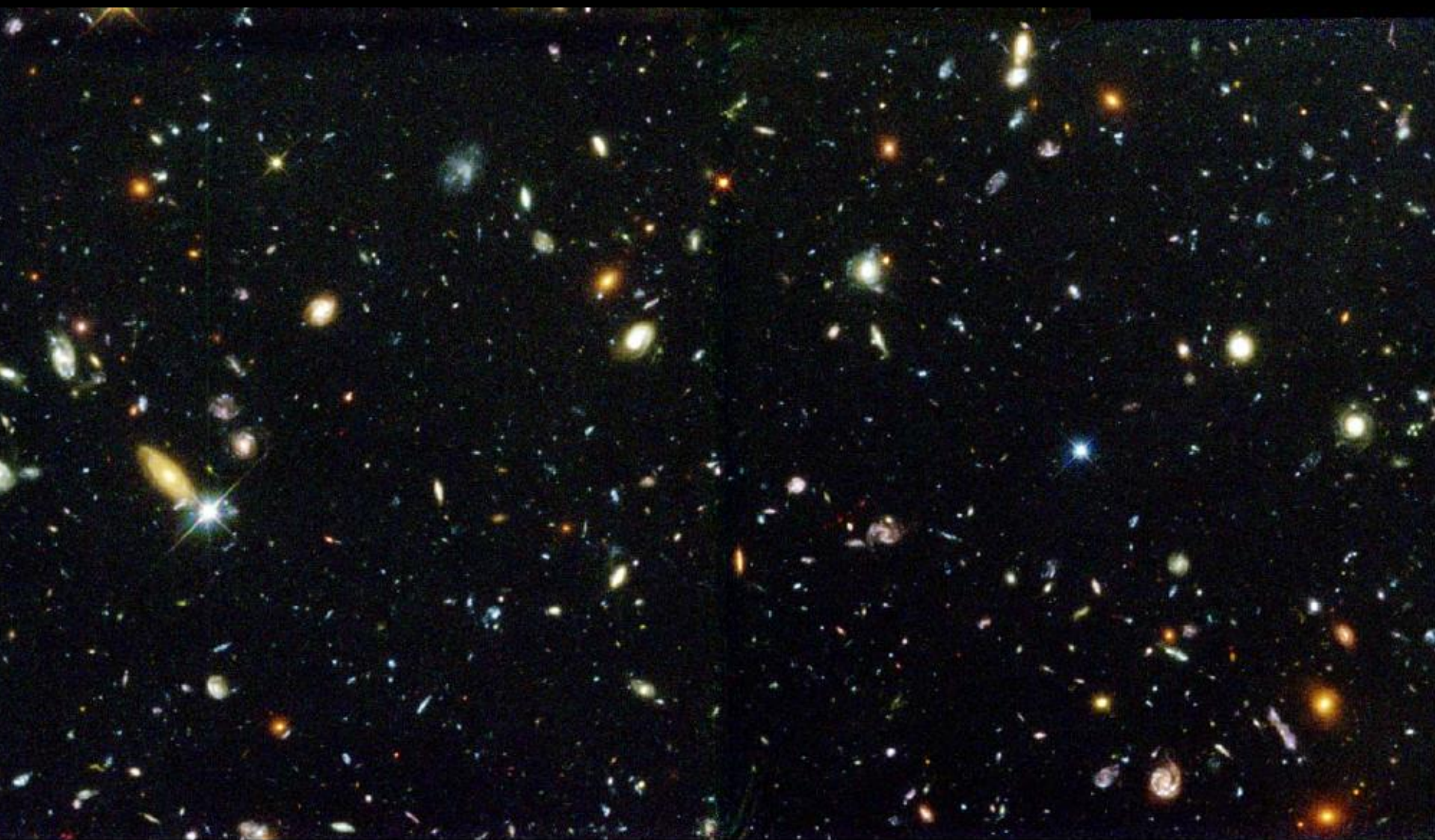


...Many stars make a galaxy...



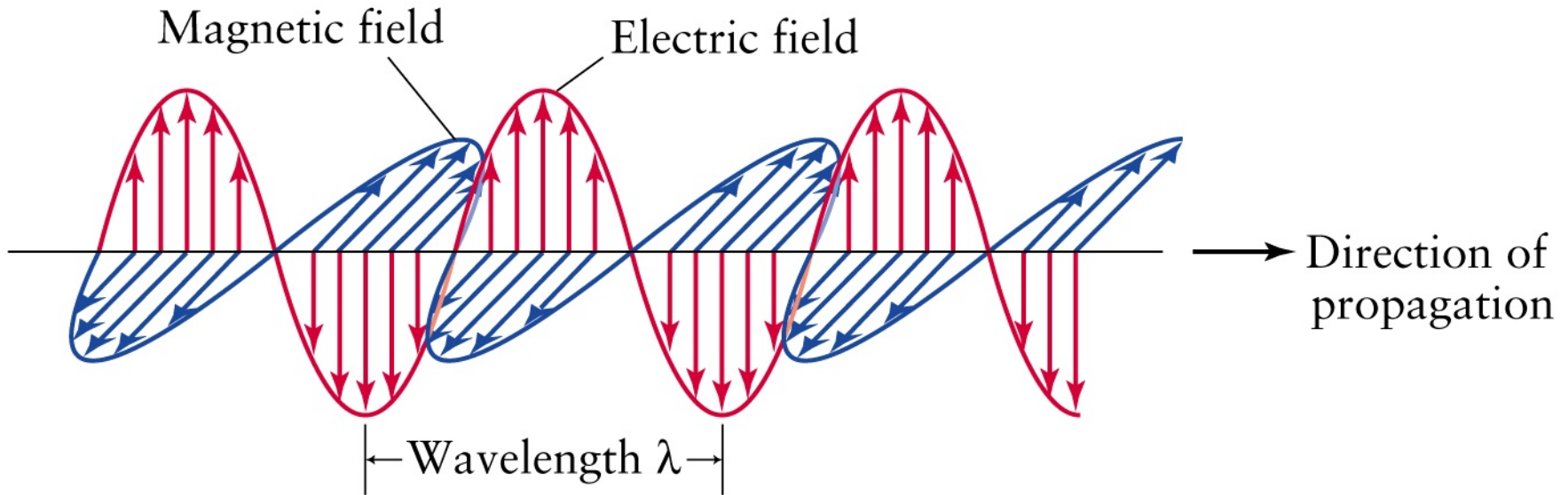
(A nearby galaxy similar to ours)

...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



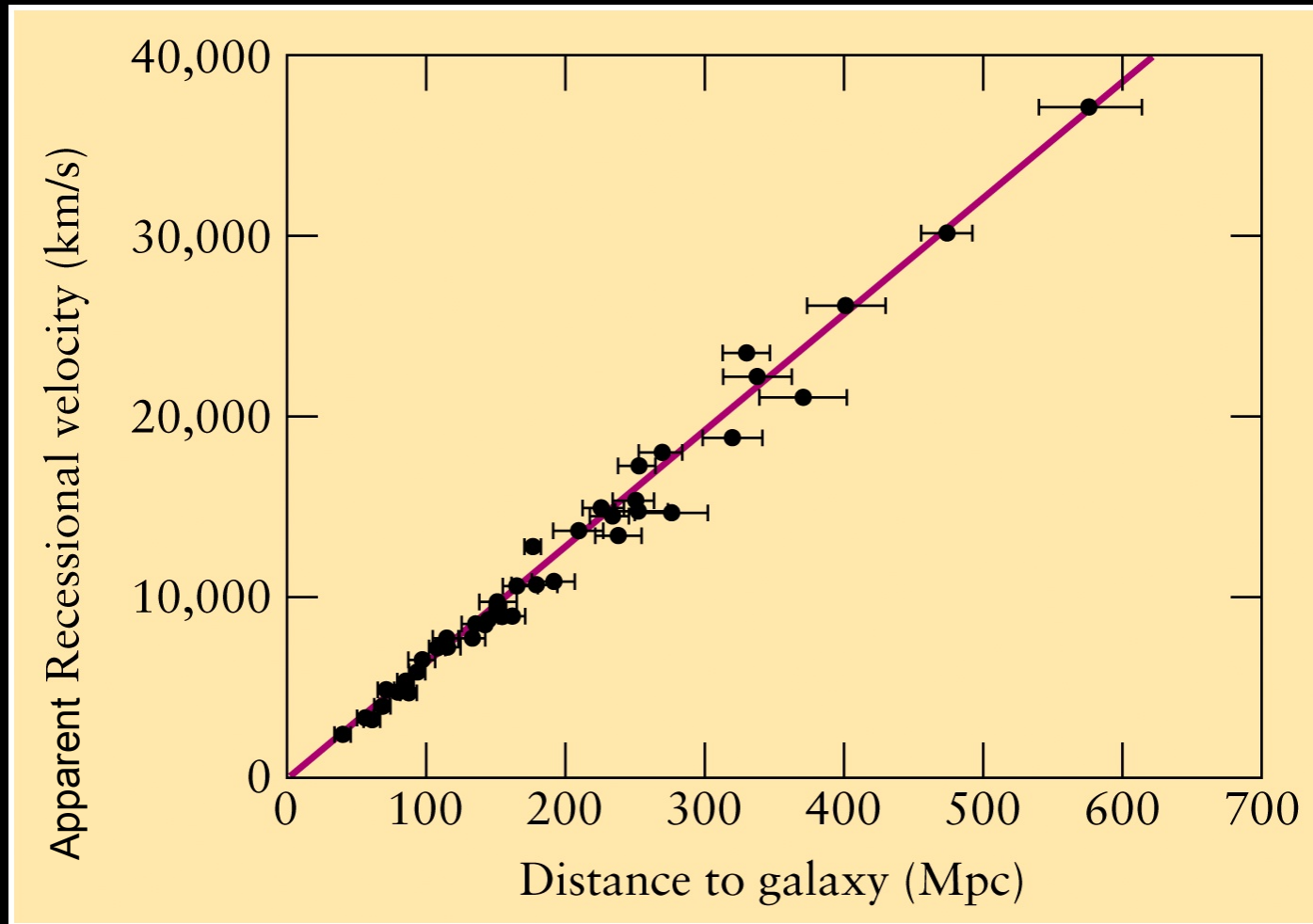
- Imagine 3 stars emitting rays of light of the same “natural” wavelength (color)
- But light moves through space always at the same speed...
- Moving towards us = compressed = bluer
- Moving away from us = stretched = redder

Edwin Hubble “Observing” Distant Galaxies



Mount Wilson Observatory
(LA) 1920's

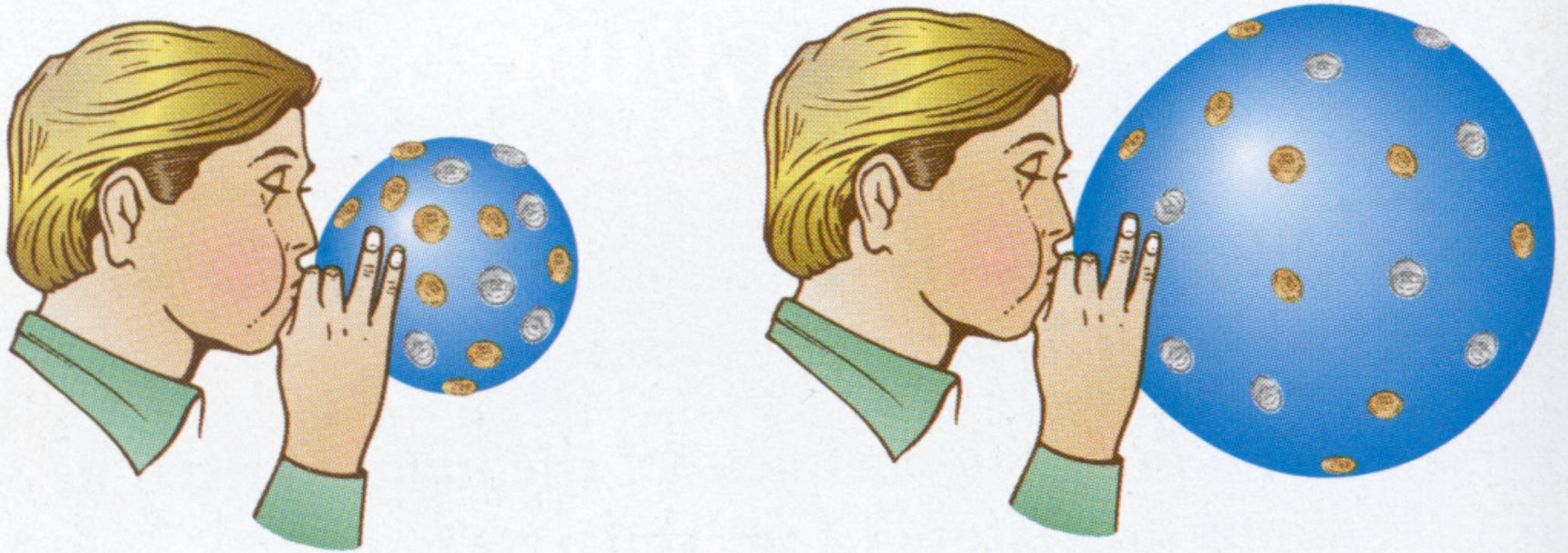
Hubble Diagram



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

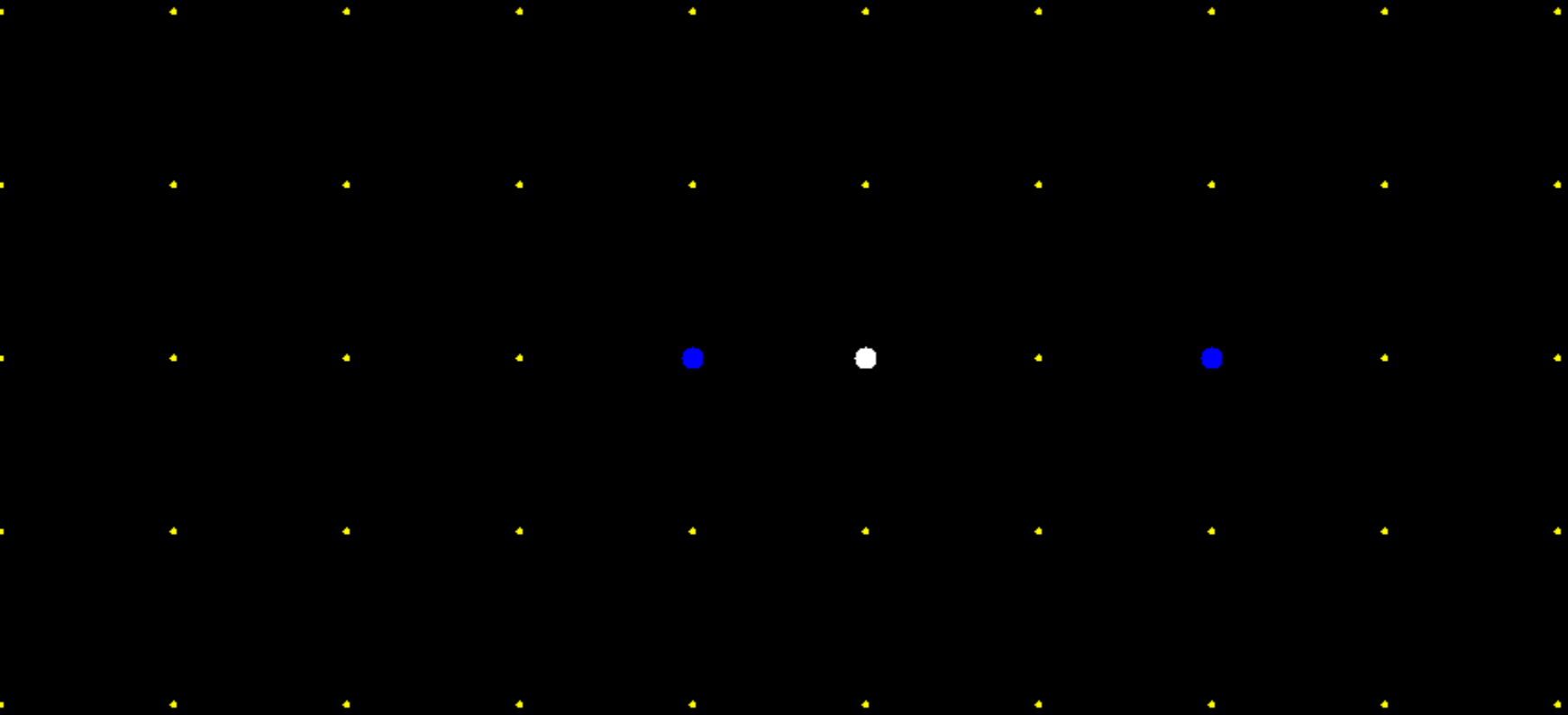
Are we the most unpopular place in the entire Universe?!

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



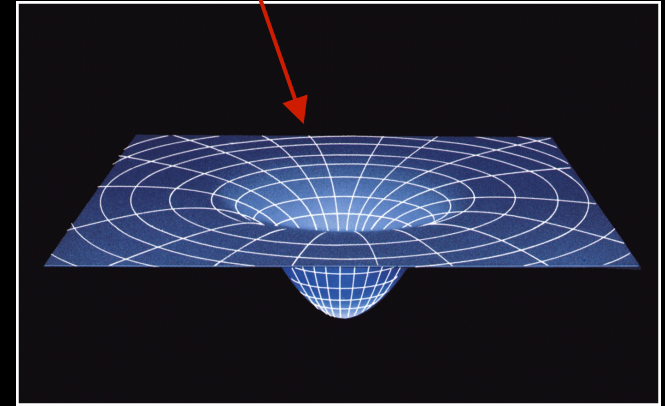
- Light rays stretch with the Universe – called “redshift”
- As we look *out* we look *back* in time

Einstein and General Relativity



↑
In 1915 Albert Einstein
devised the General
Theory of Relativity

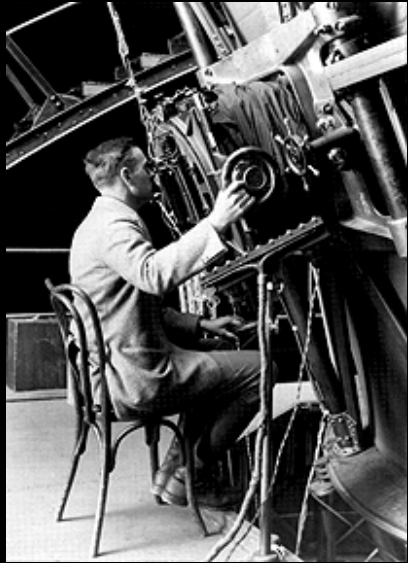
In GR space can be curved
– and can expand/contract



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

↑
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 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”

INFLATION

**CMB
last scattering**

**fraction
of a second**

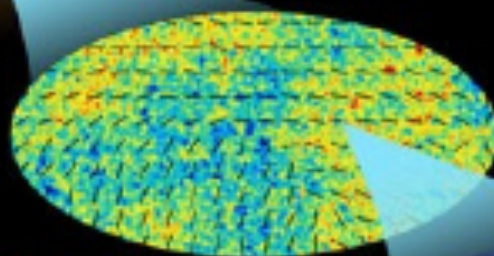
**379,000
years**

**first
stars**

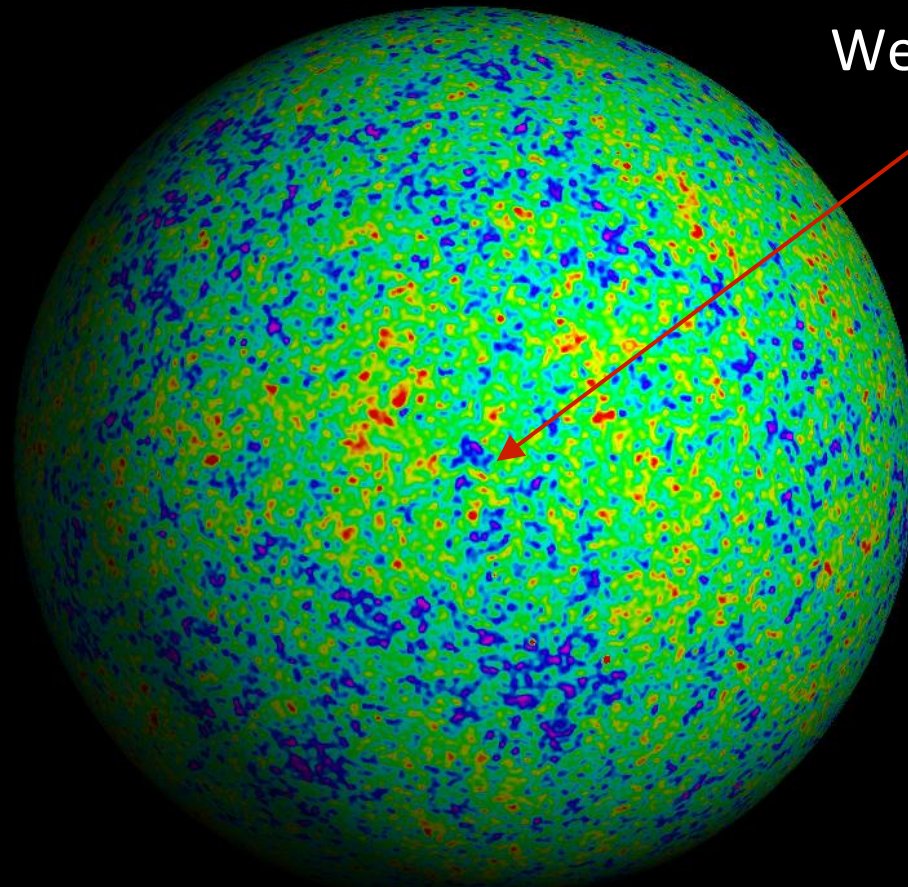
**~200 million
years**

**present
day**

**13.7 billion
years**



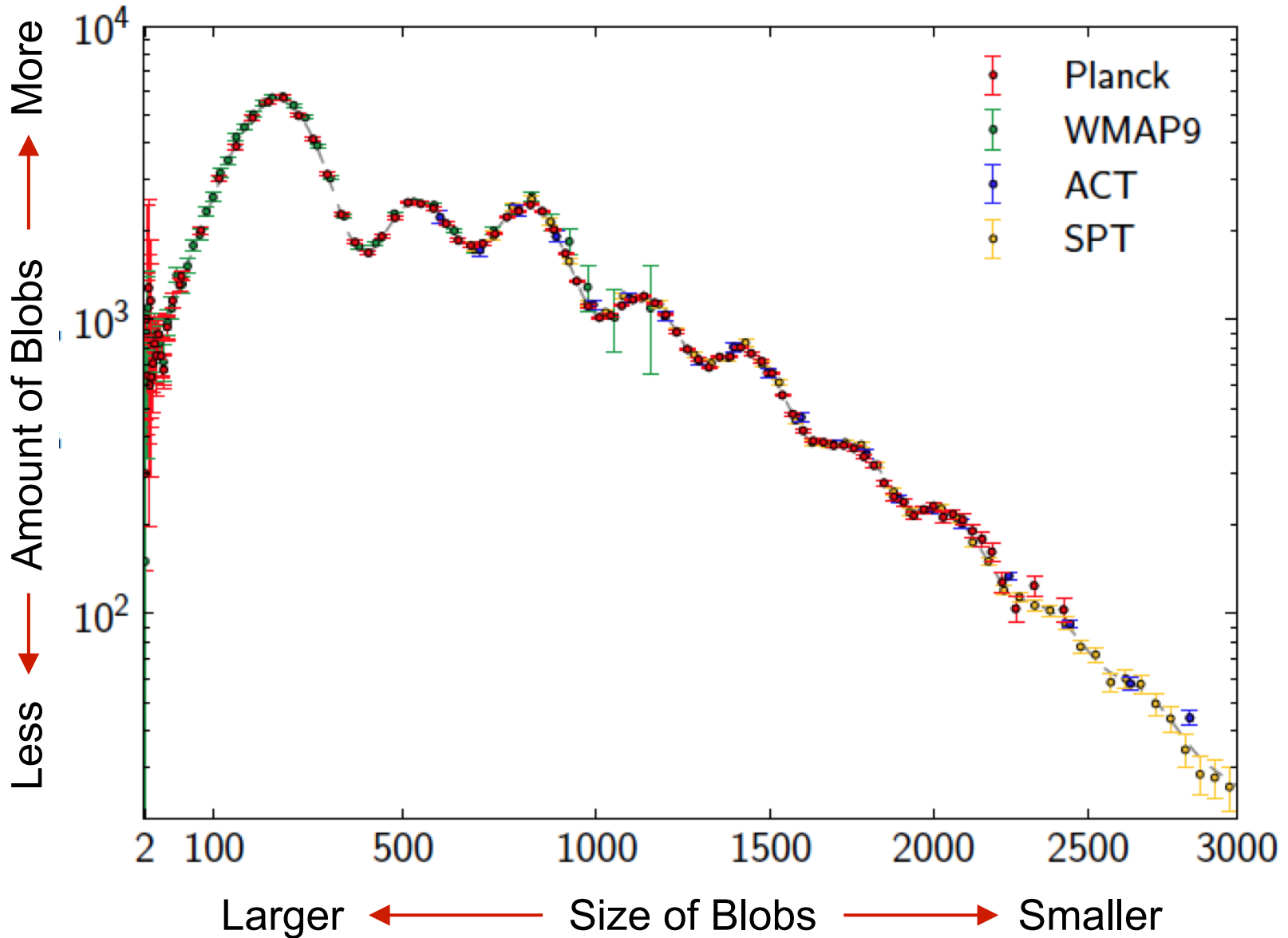
The Cosmic Microwave Background



We are at the center

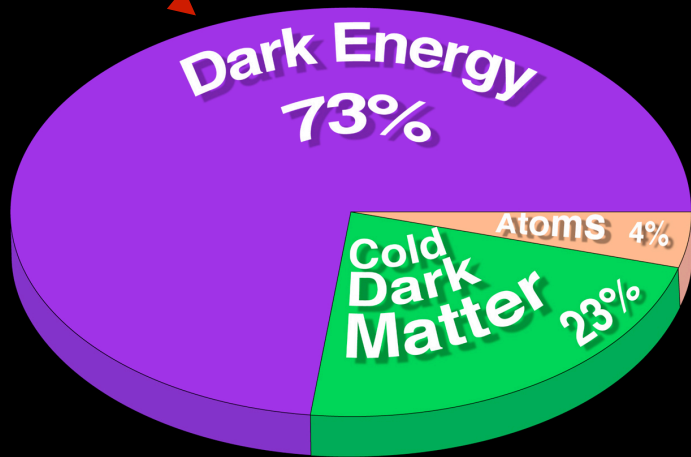
CMB is sample of the density structure on a shell cut through the 380,000 year old Universe

“Lump Sorter” Plot

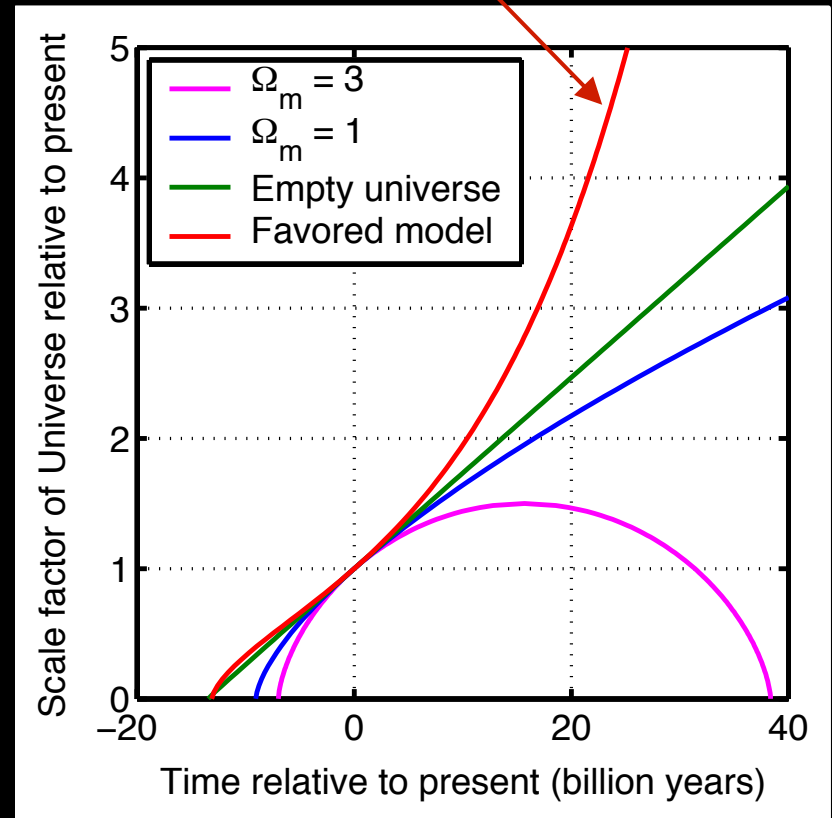


Triumphant/Embarrassing Cosmology

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

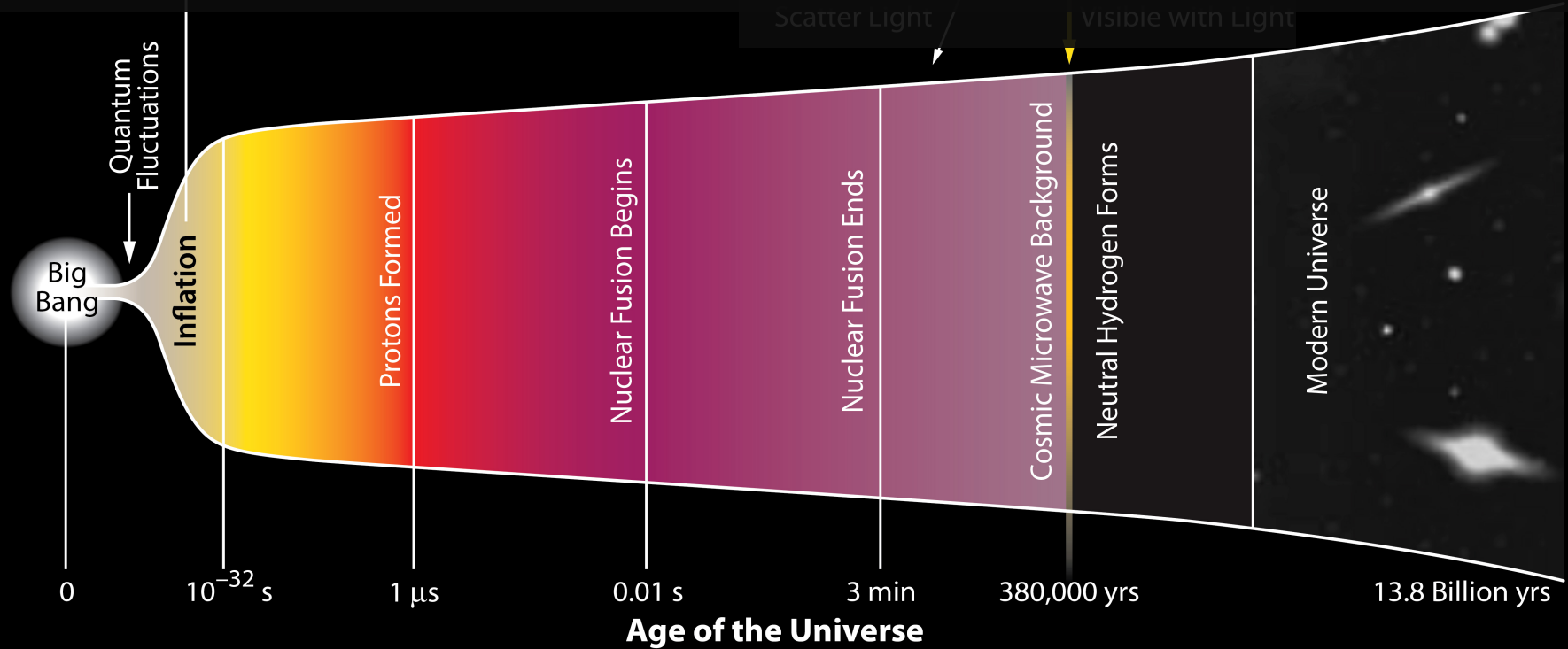


Alan Guth

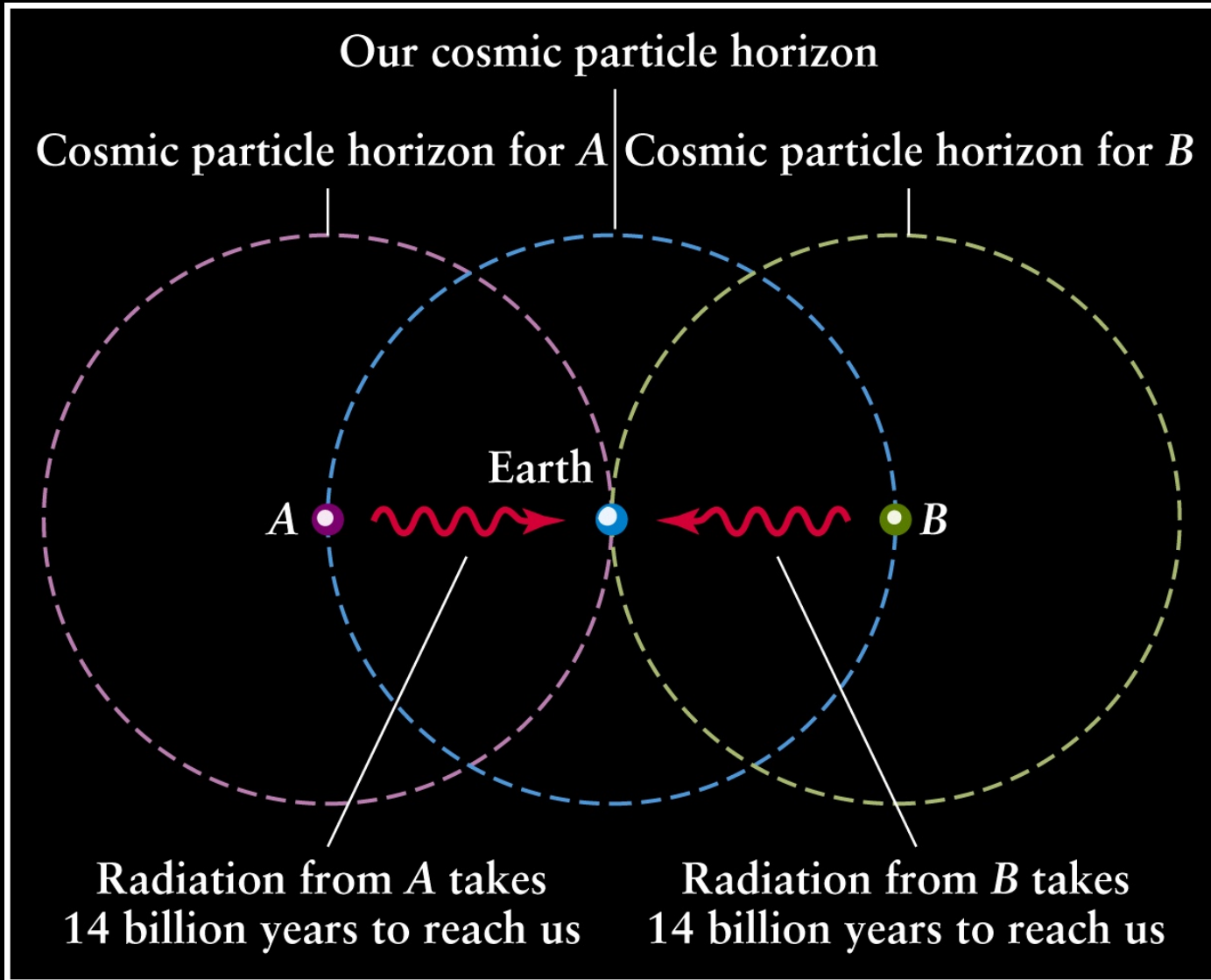


Andrei Linde

Radius of the Visible Universe

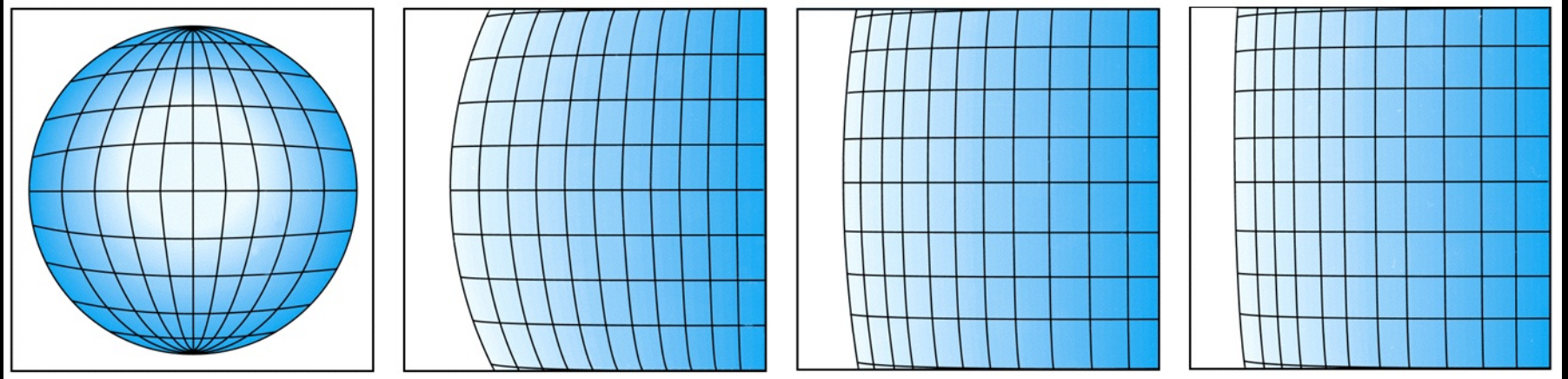


The Horizon Problem



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

Solving the Flatness Problem

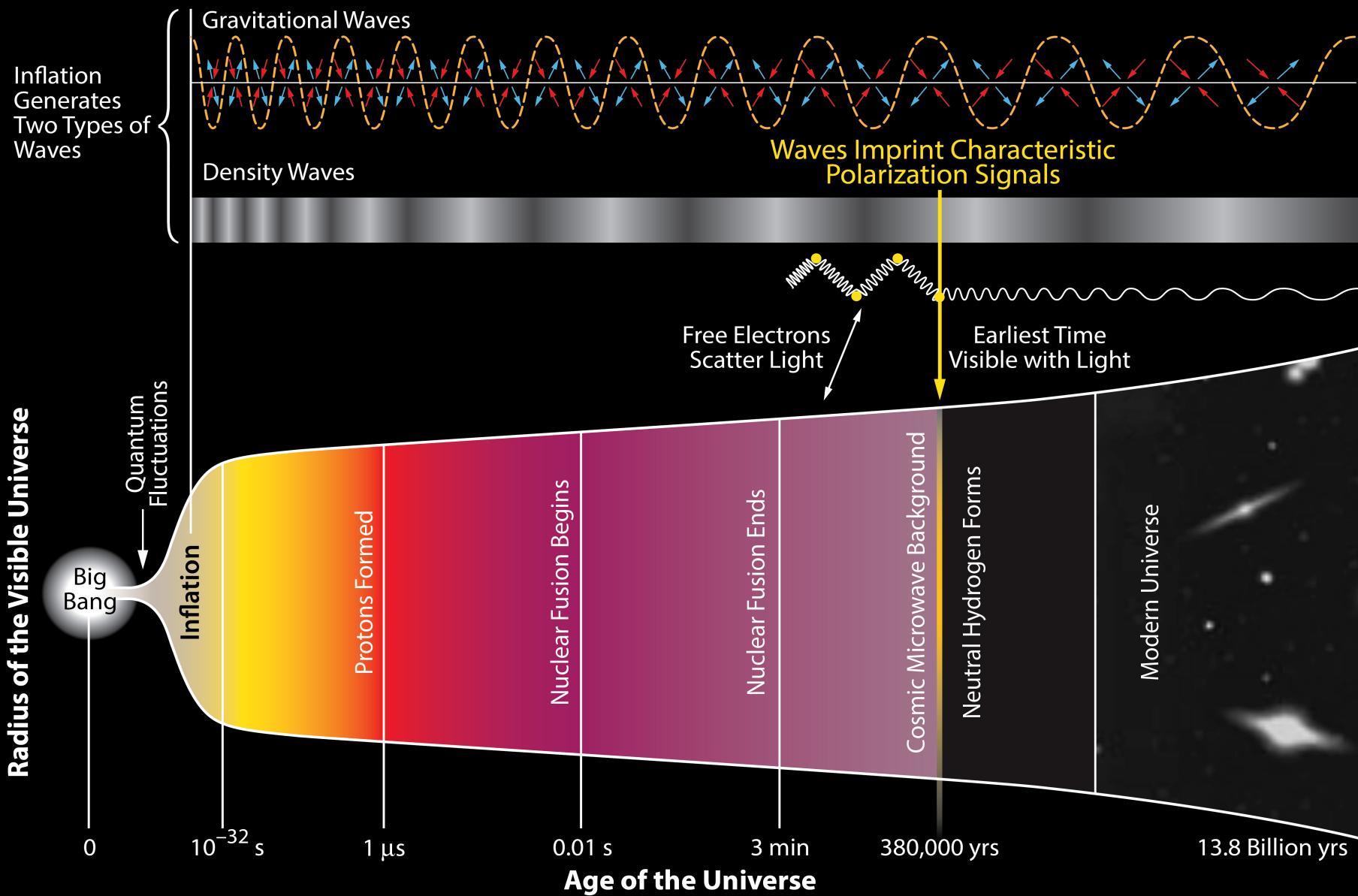


→ Inflation... →

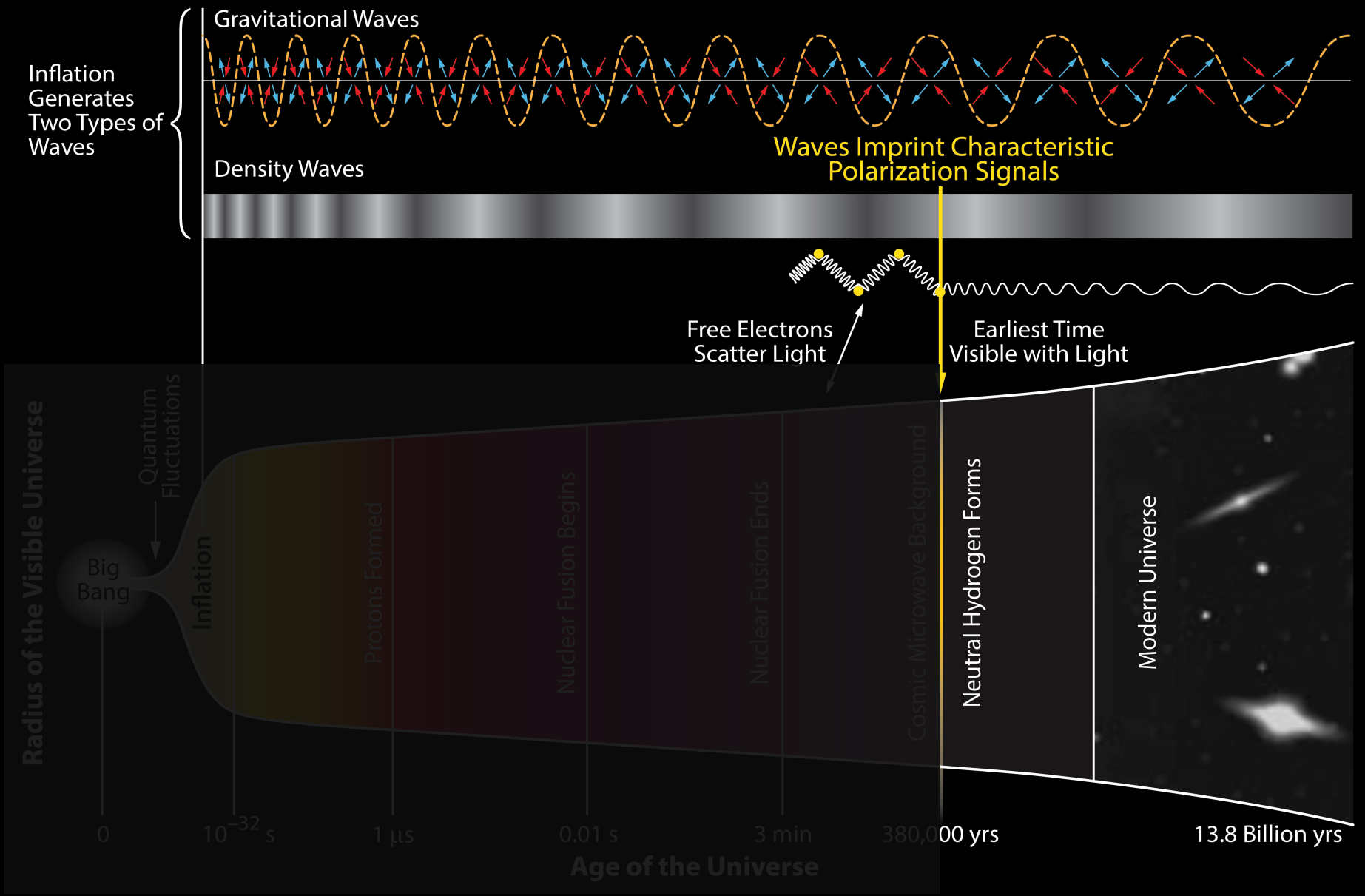
If you take some curved space and blow it up enough pretty soon it is no longer curved on a local scale – like our entire observable Universe!

So nice idea – but how can we get direct evidence if it happened?
Makes another prediction...

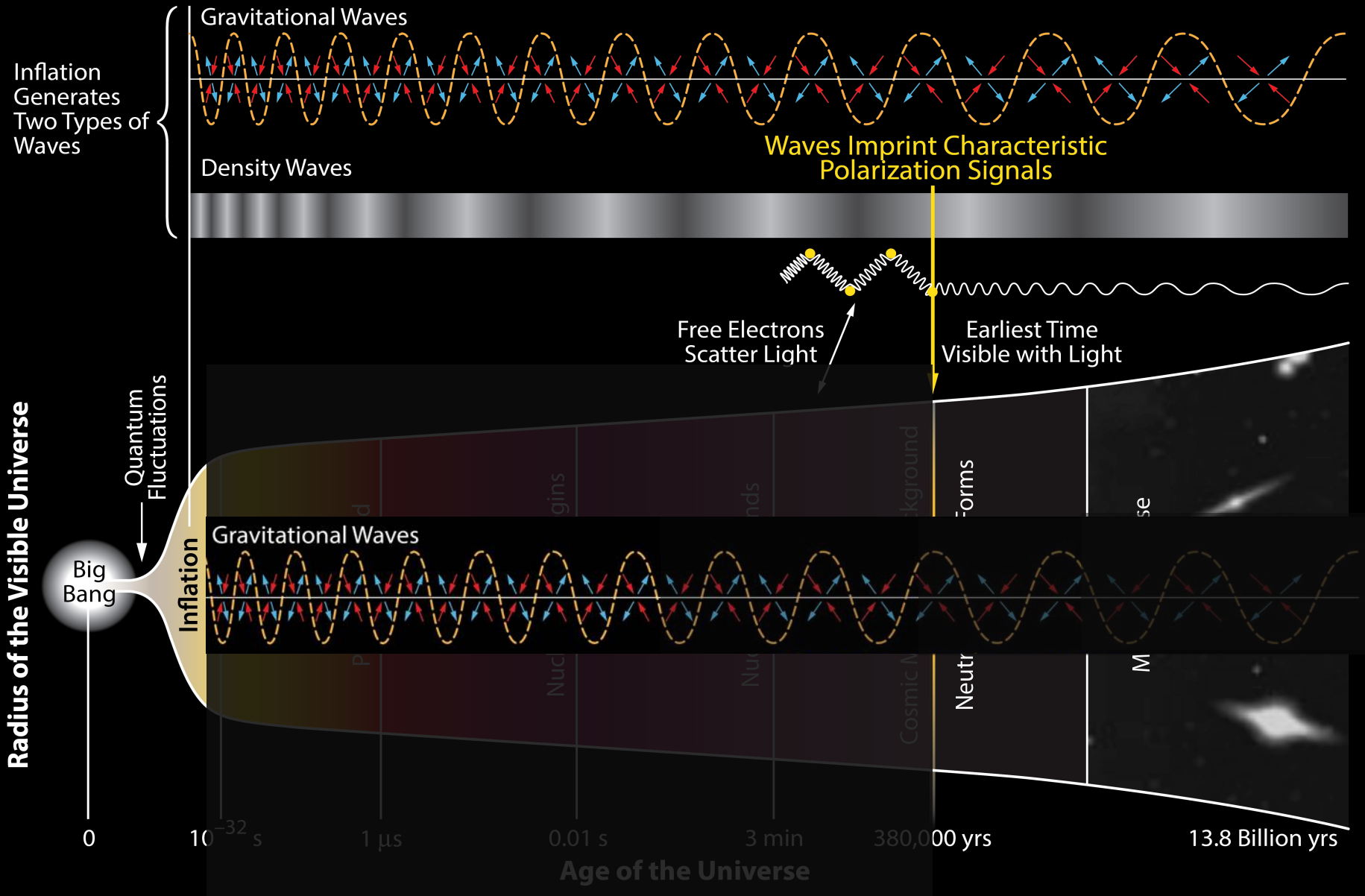
History of the Universe



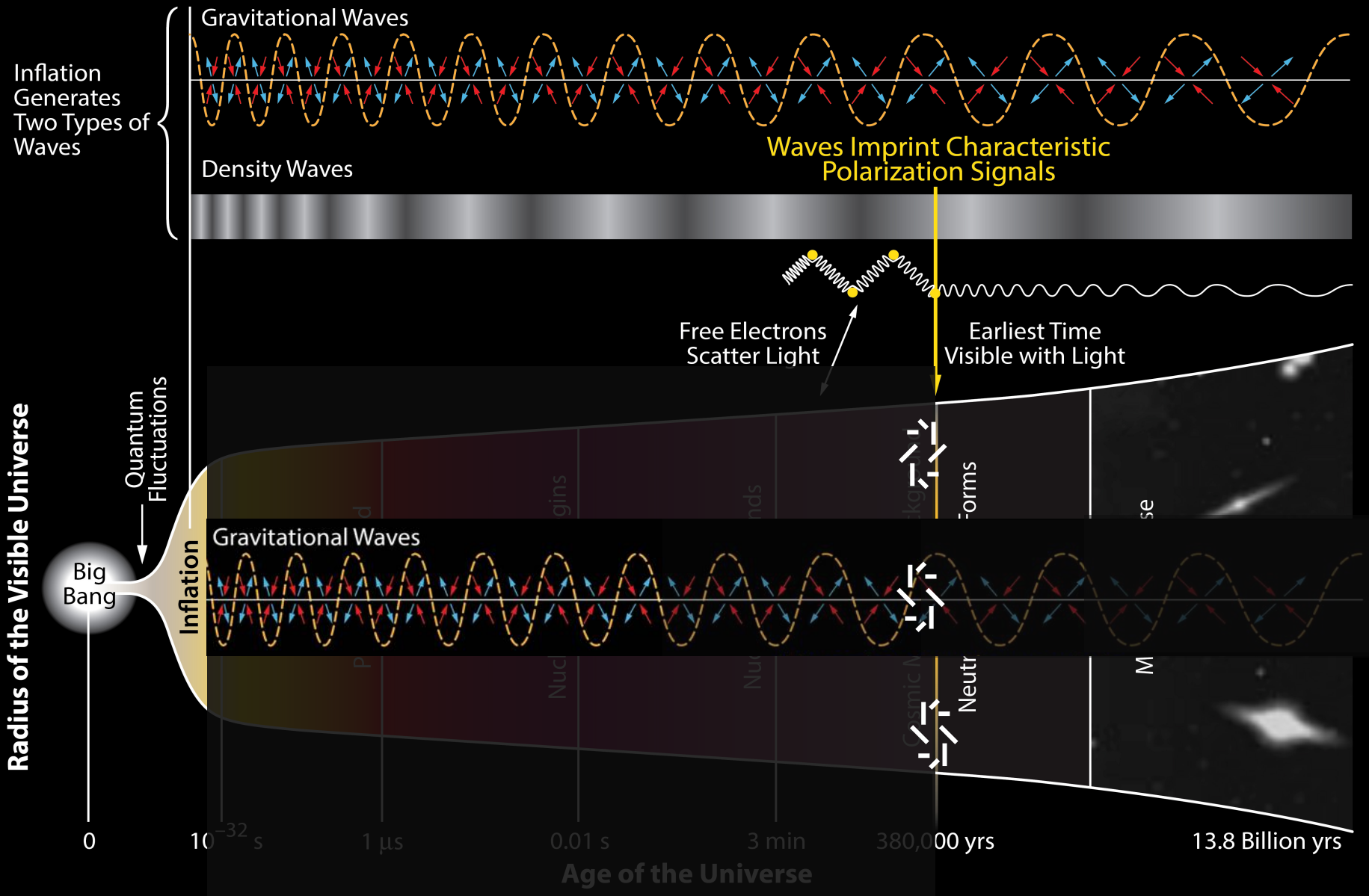
History of the Universe



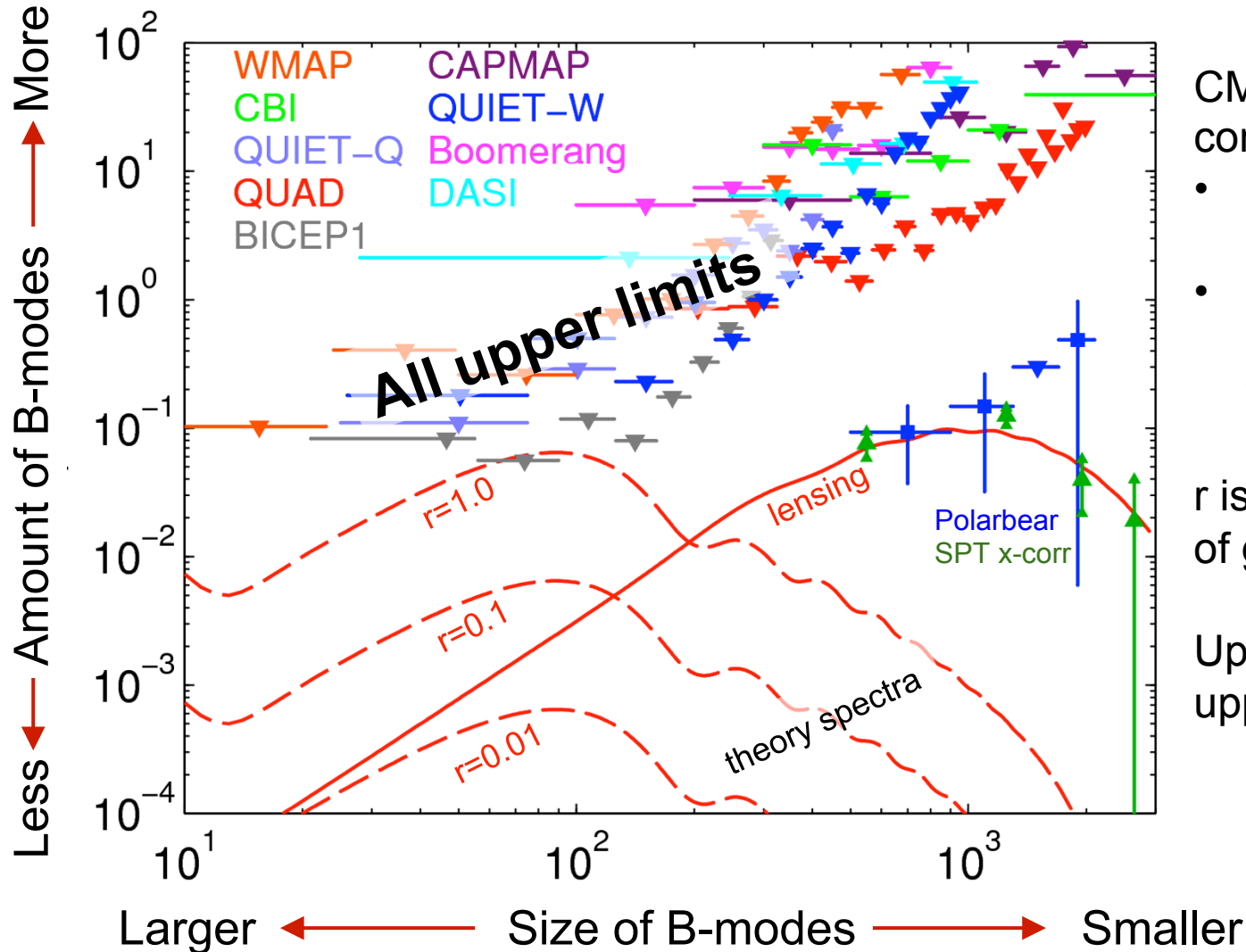
History of the Universe



History of the Universe



The Long Search for Inflationary B-modes

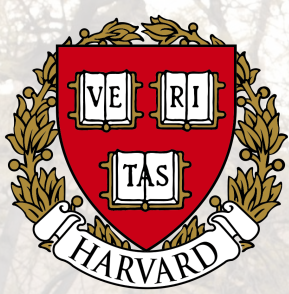


CMB polarization comes in two kinds

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

r is measure of amount of gravity waves

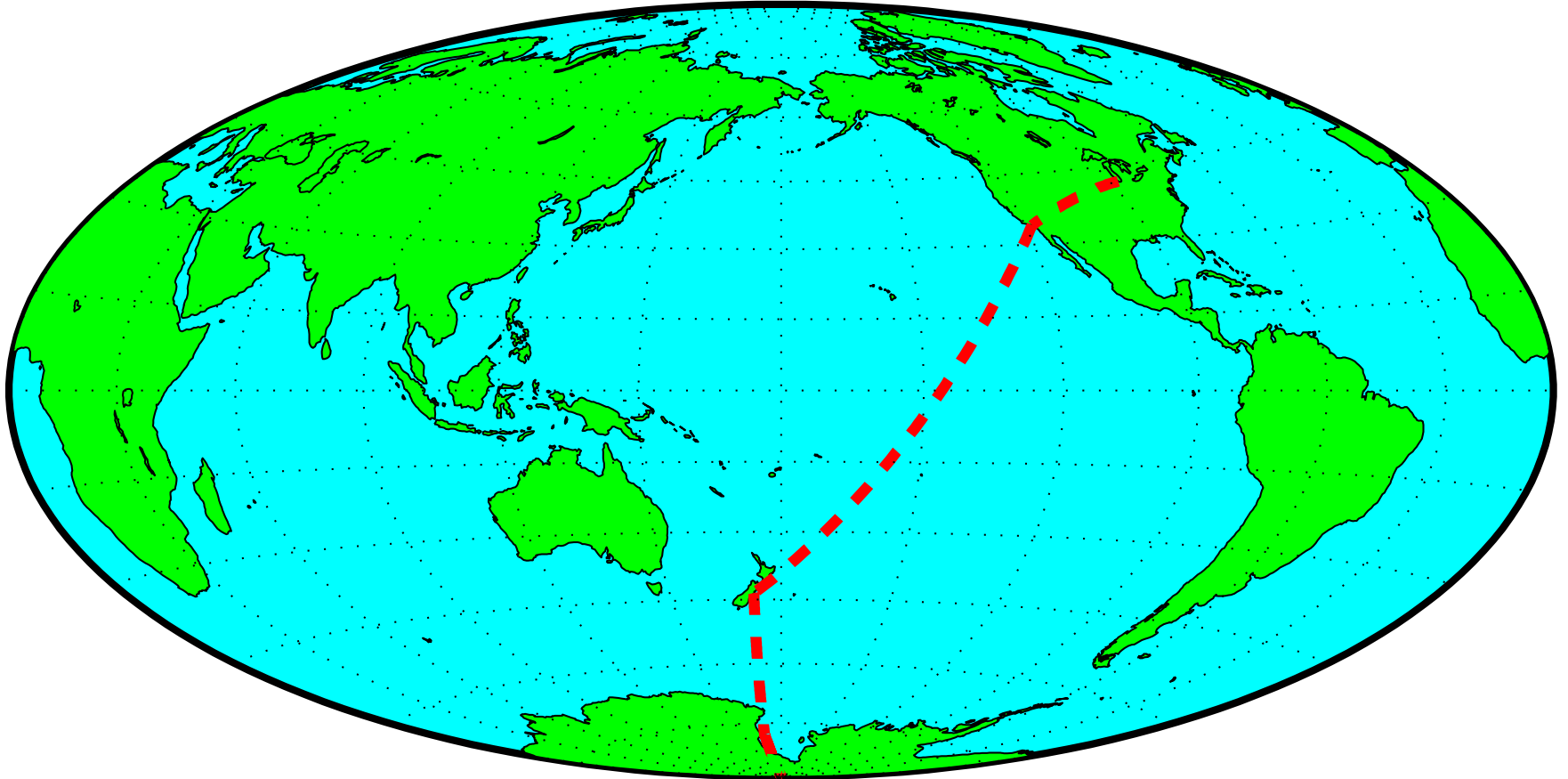
Up until recently only upper limits...



UNIVERSITY OF TORONTO

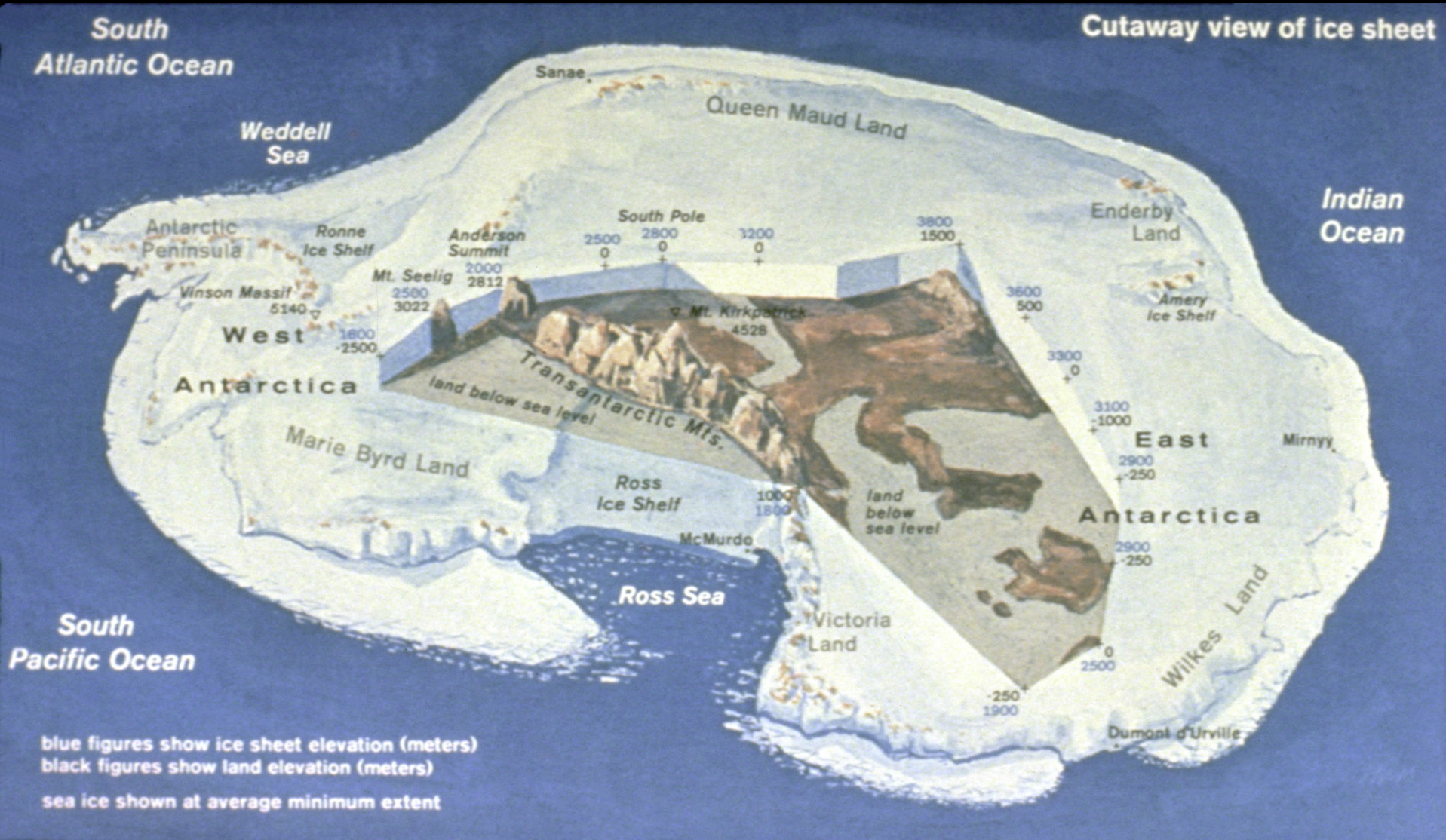


Journey to the South Pole



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



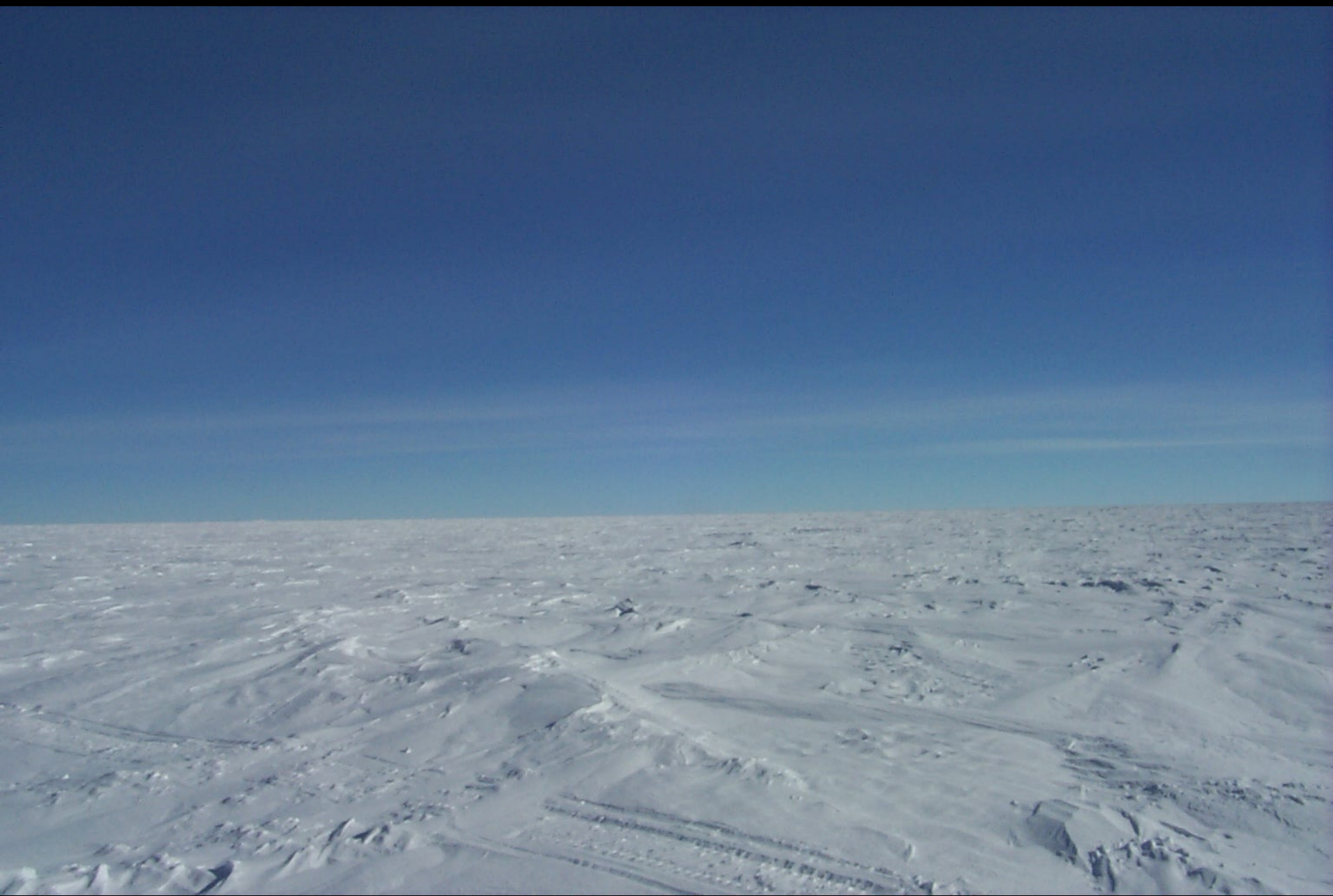
GEOGRAPHIC
SOUTH POLE

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...

The BICEP2 Postdocs



Colin Bischoff



Jeff Filippini



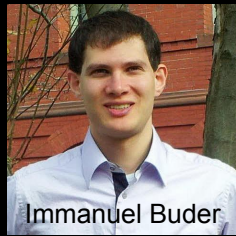
Martin Lueker



Walt Ogburn



Abigail Viereggen



Immanuel Buder



Stefan Fliescher



Roger O'Brient



Angiola Orlando



Zak Staniszewski

The BICEP2 Graduate Students



Randol Aikin



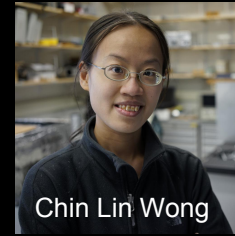
Justus Brevik



Chris Sheehy



Grant Teply



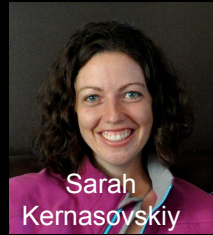
Chin Lin Wong



Kirit Karkare



Jon Kaufman



Sarah
Kernasovskiy



Jamie Tolan

BICEP2 Winterovers



Steffen Richter

2010



Steffen Richter

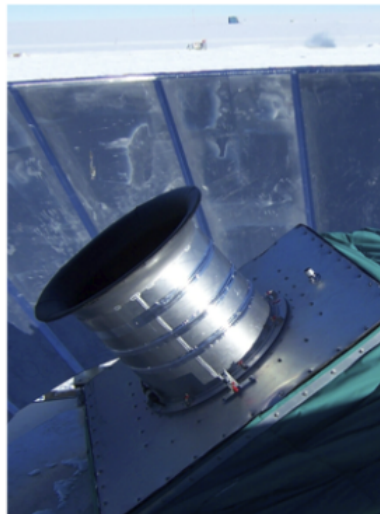
2011



Steffen Richter

2012

BICEP1
(2006 - 8)



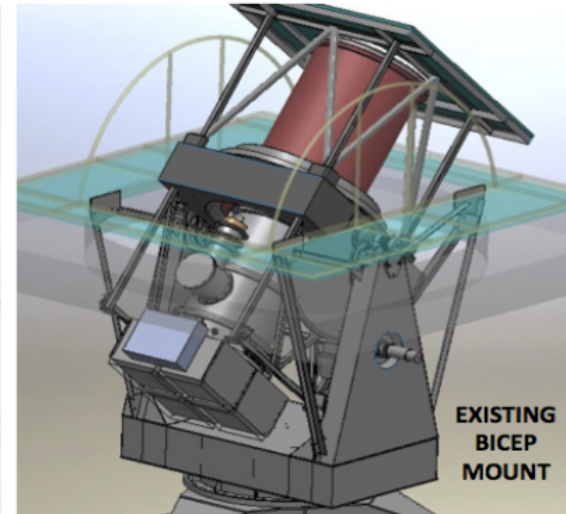
BICEP2
(2010 - 12)



Keck Array
(2011 -)

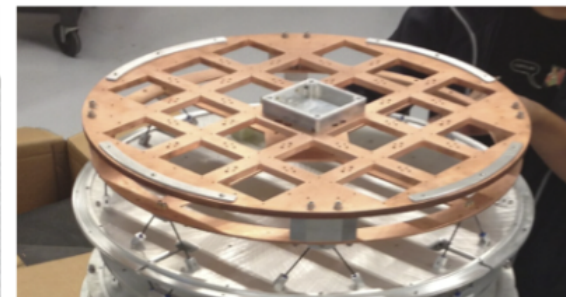
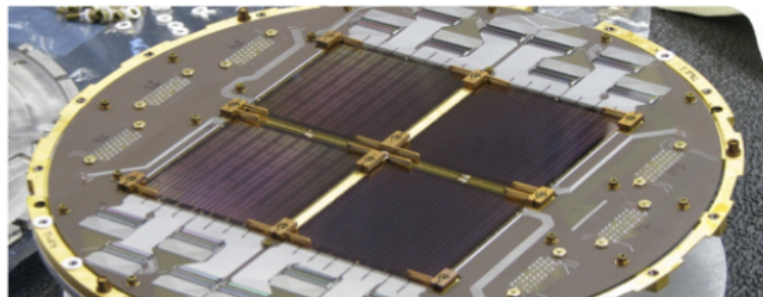
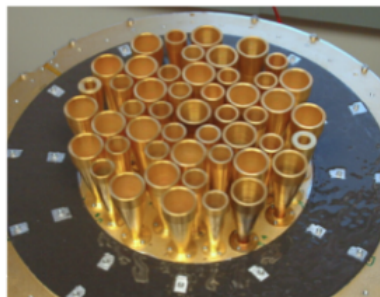


BICEP3
(2014 -)

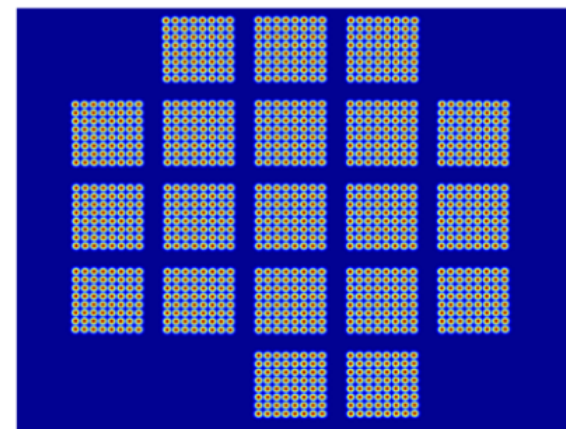
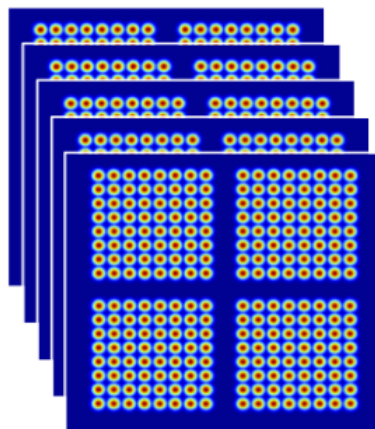
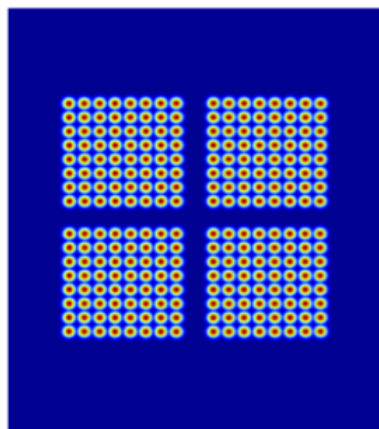
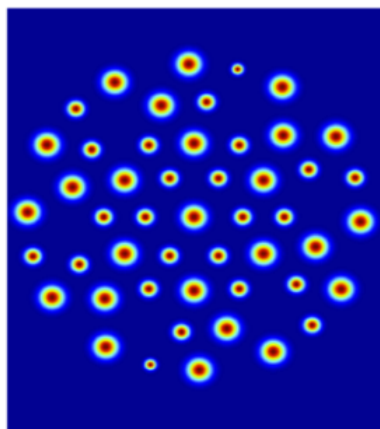


Telescope and Mount

Focal Plane



Beams on Sky



-5 0 5
Longitude (degrees)

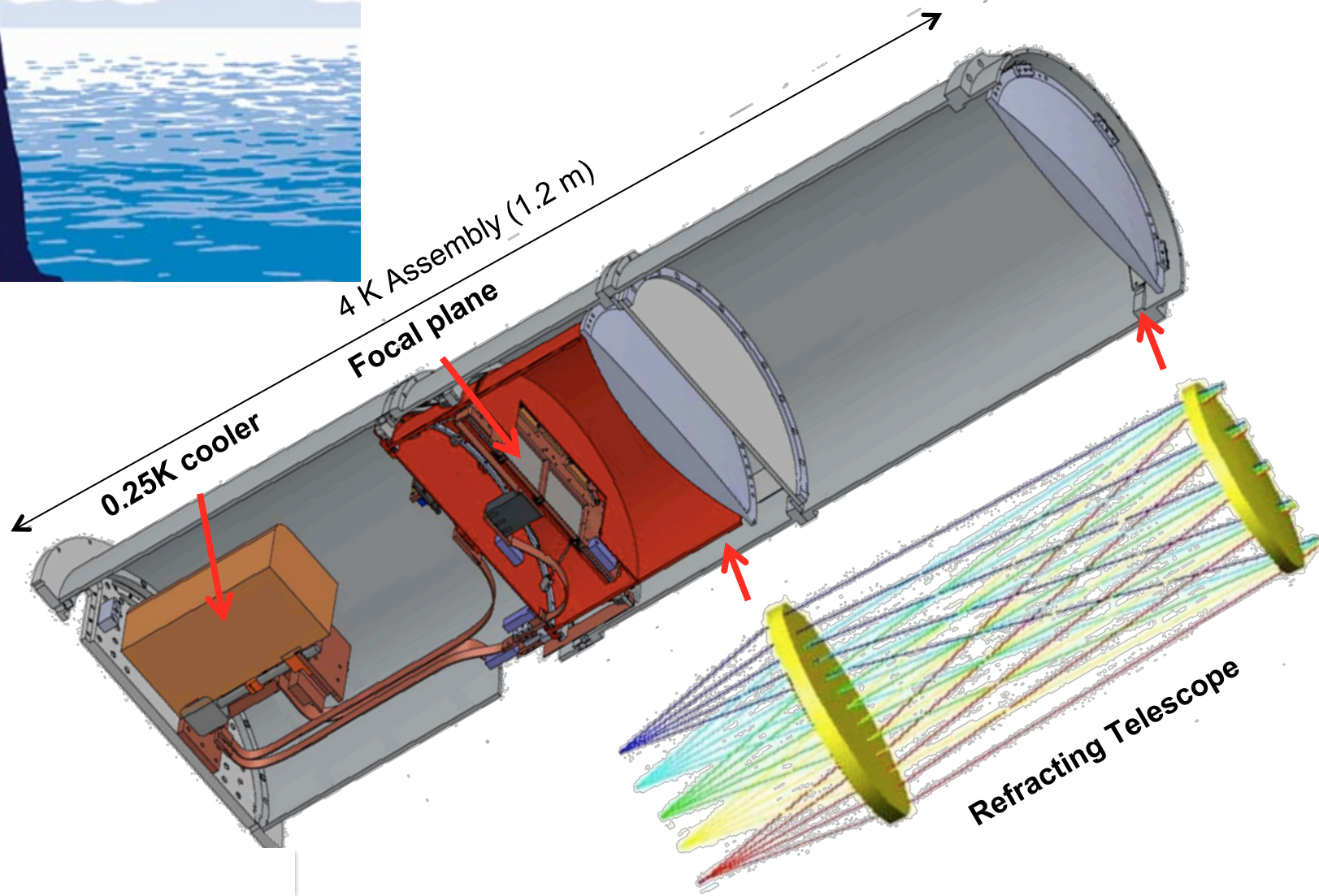
-5 0 5
Longitude (degrees)

-5 0 5
Longitude (degrees)

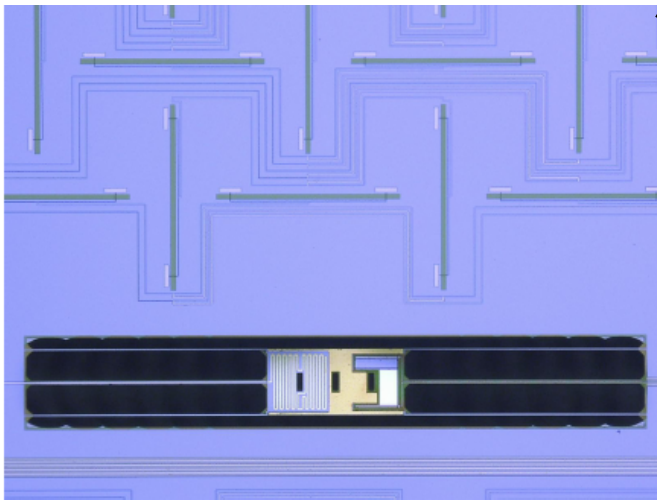
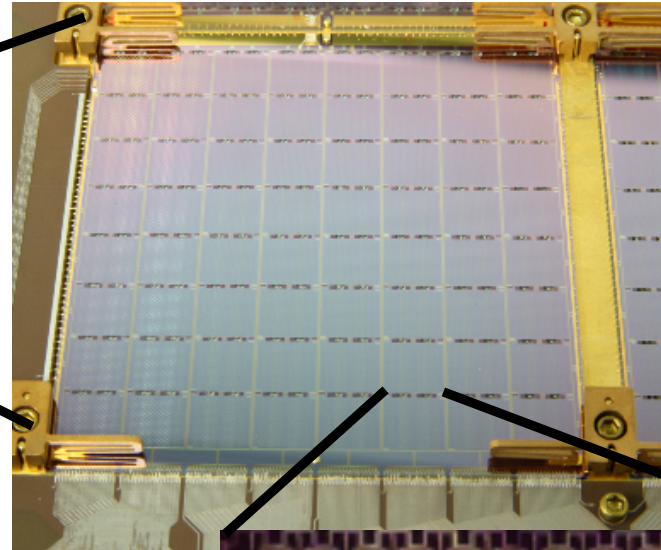
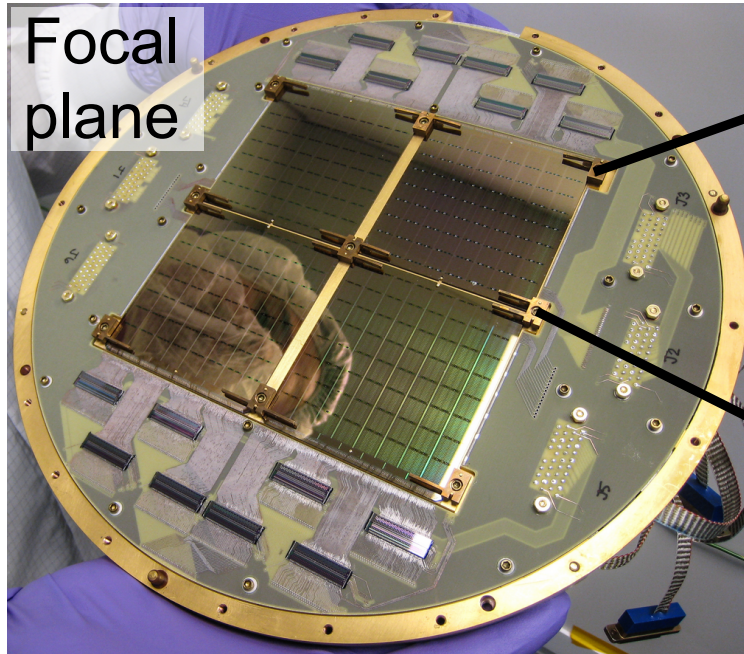
-10 -5 0 5 10
Longitude (degrees)

BICEP2 Experimental Concept

- Small aperture
- Wide field of view
- Cold refractor



Mass-produced superconducting detectors

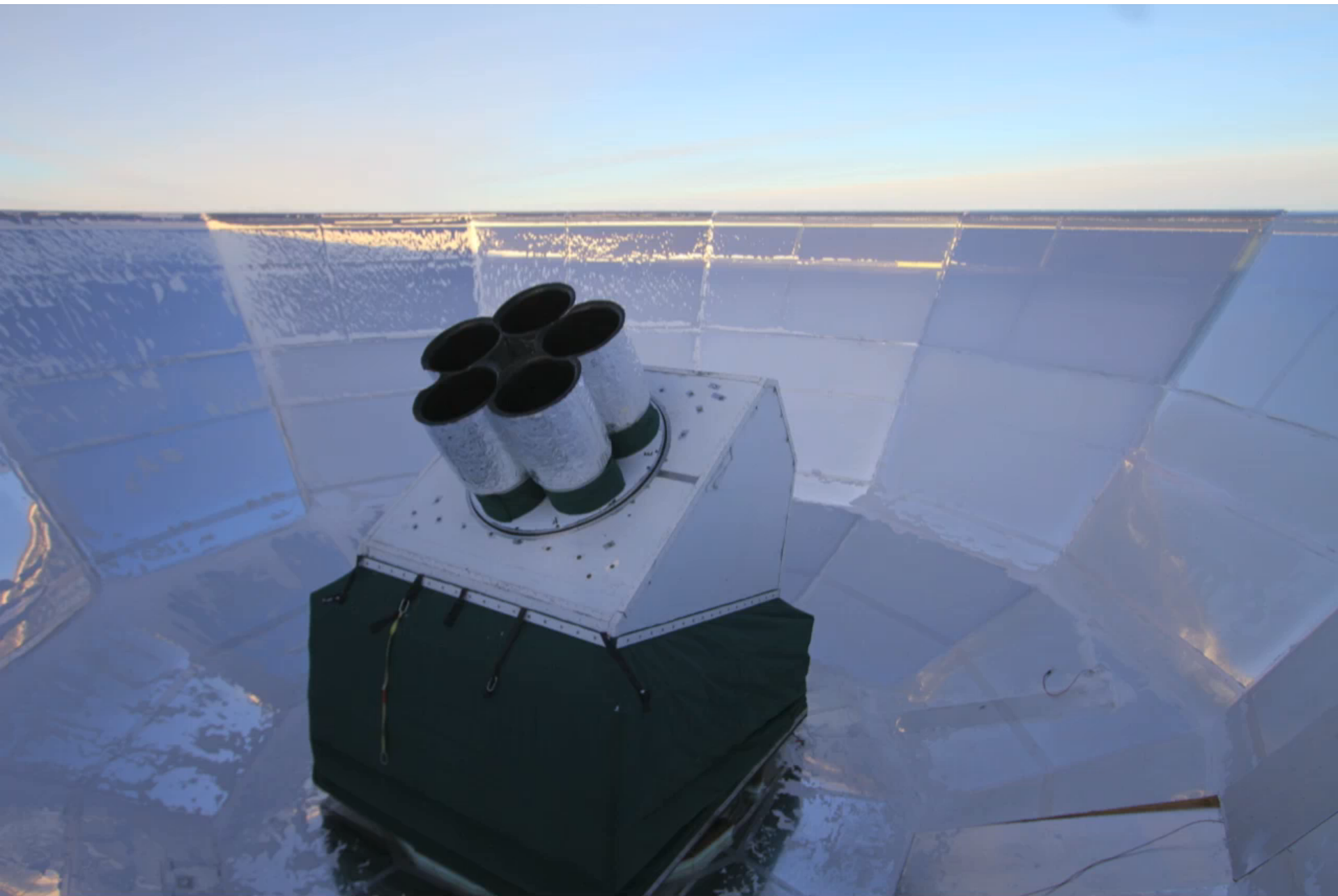


Slot antennas



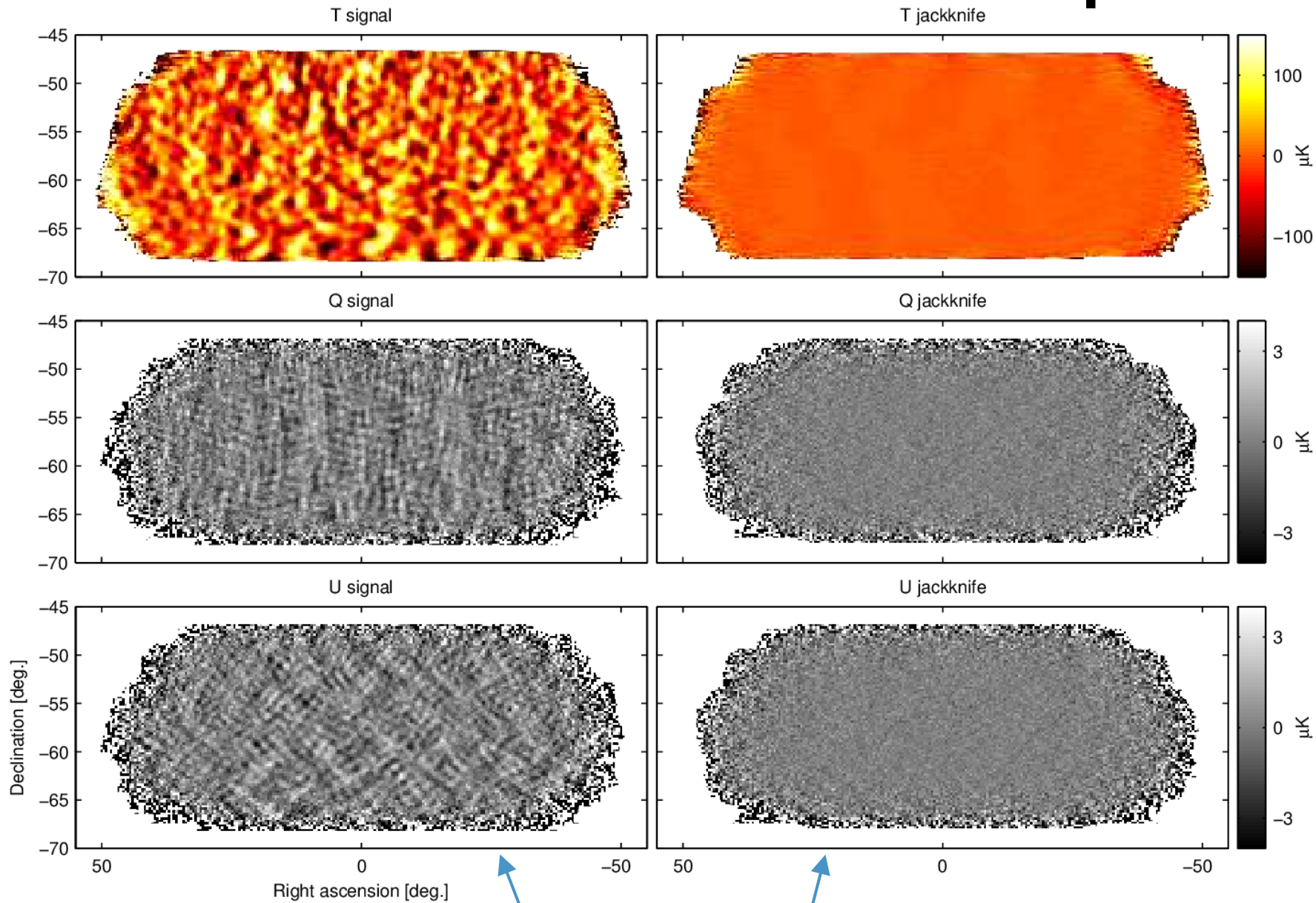
Transition edge sensor

Microstrip filters



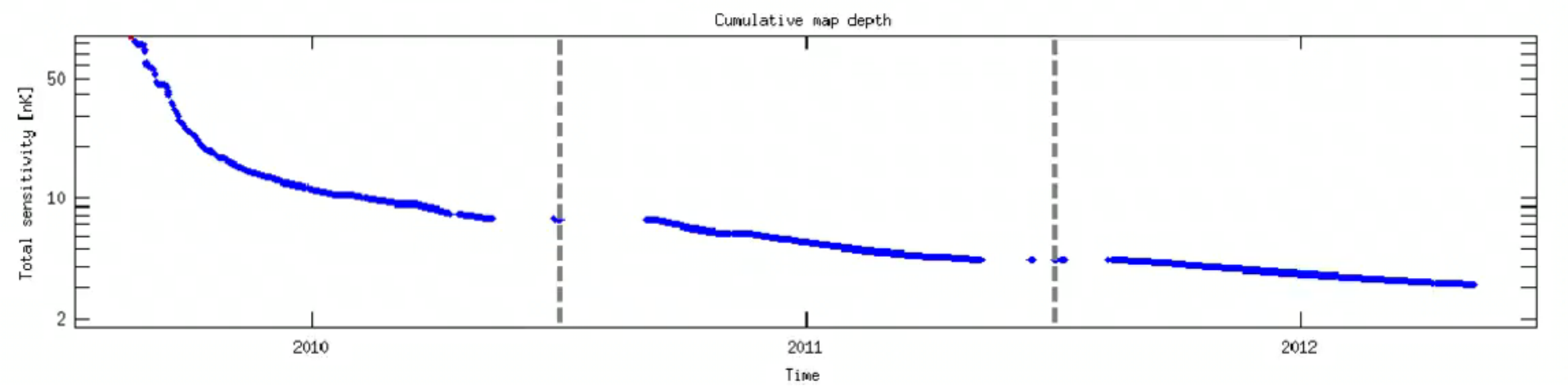
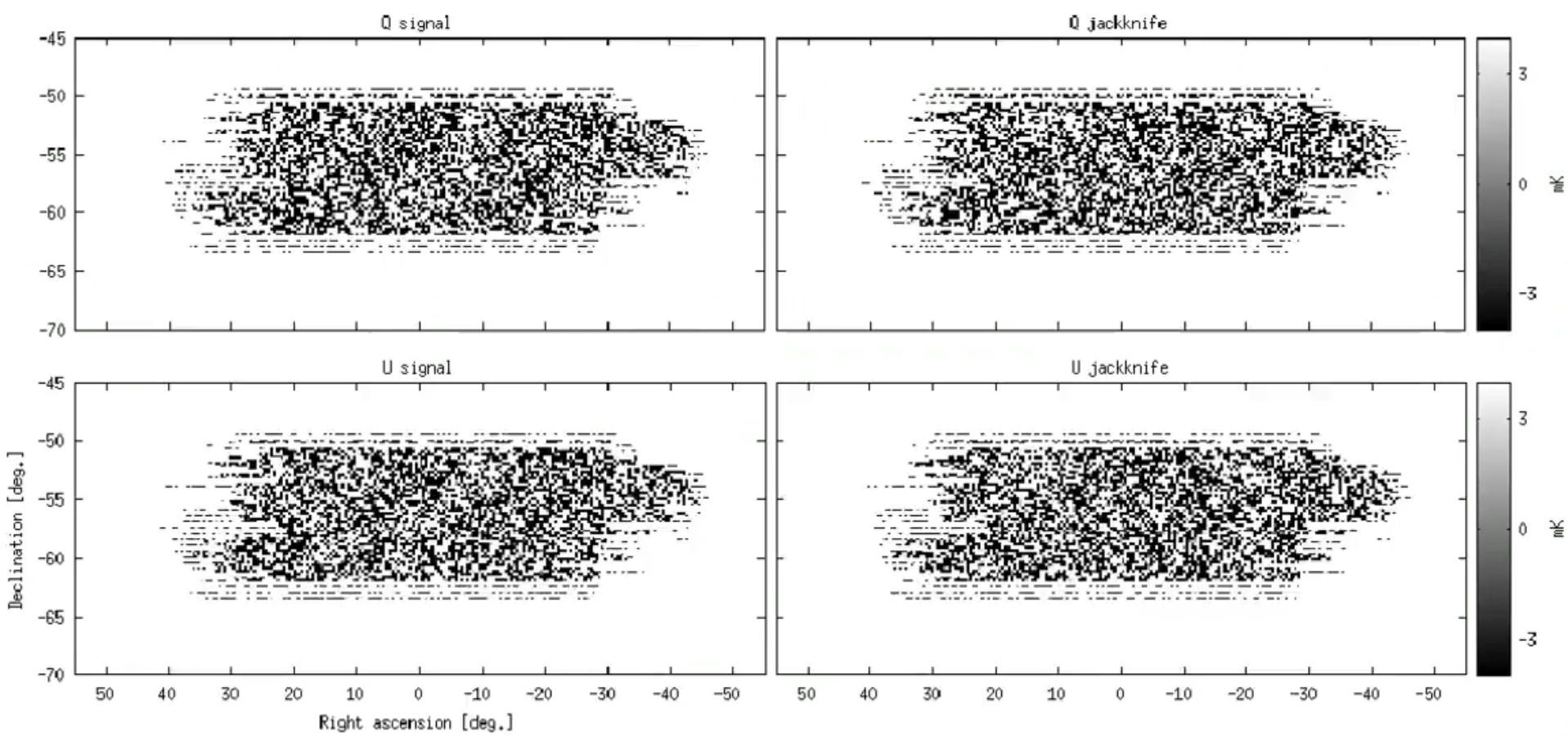
Clem Pryke for The Bicep2 Collaboration

BICEP2 T and Stokes Q/U Maps



Sum Maps

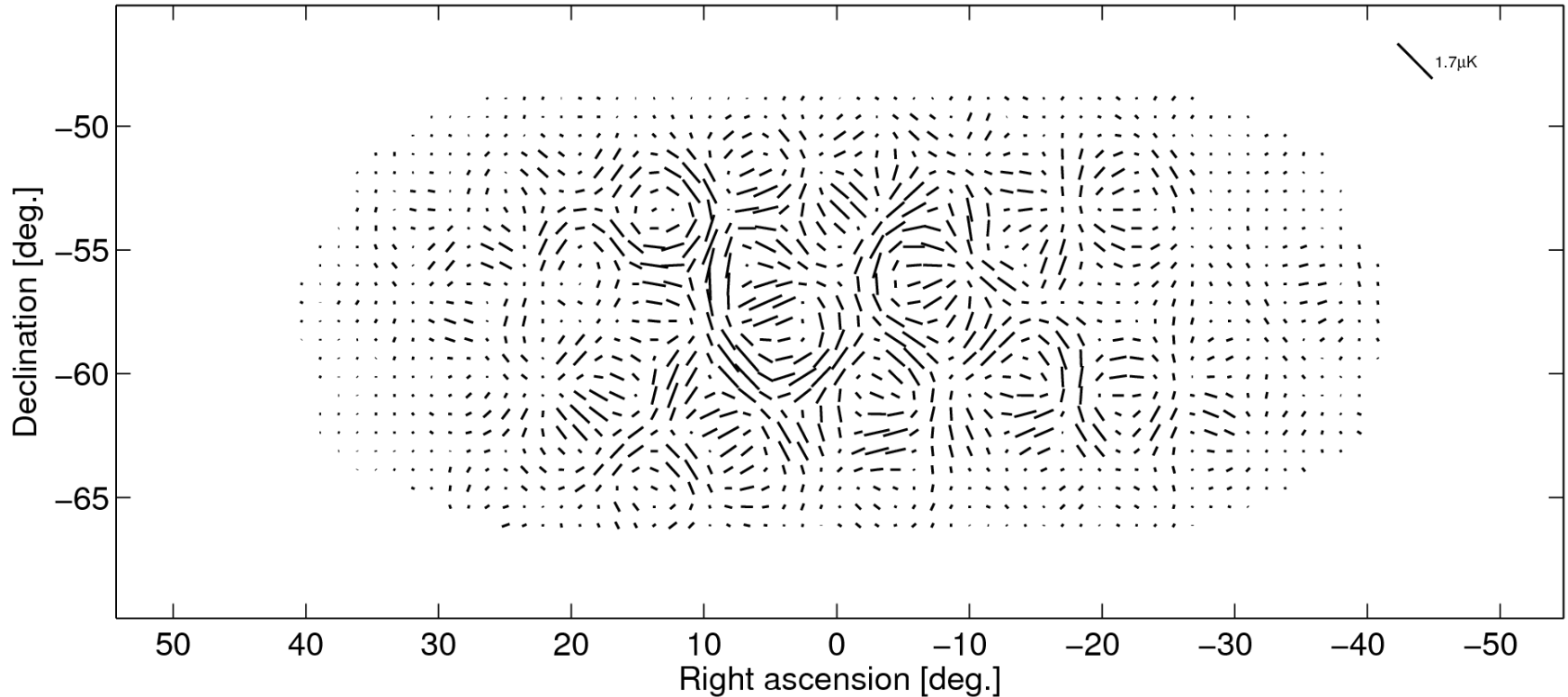
Difference Maps



Total Polarization

BICEP2 total polarization signal

Scale: $1.7 \mu K$

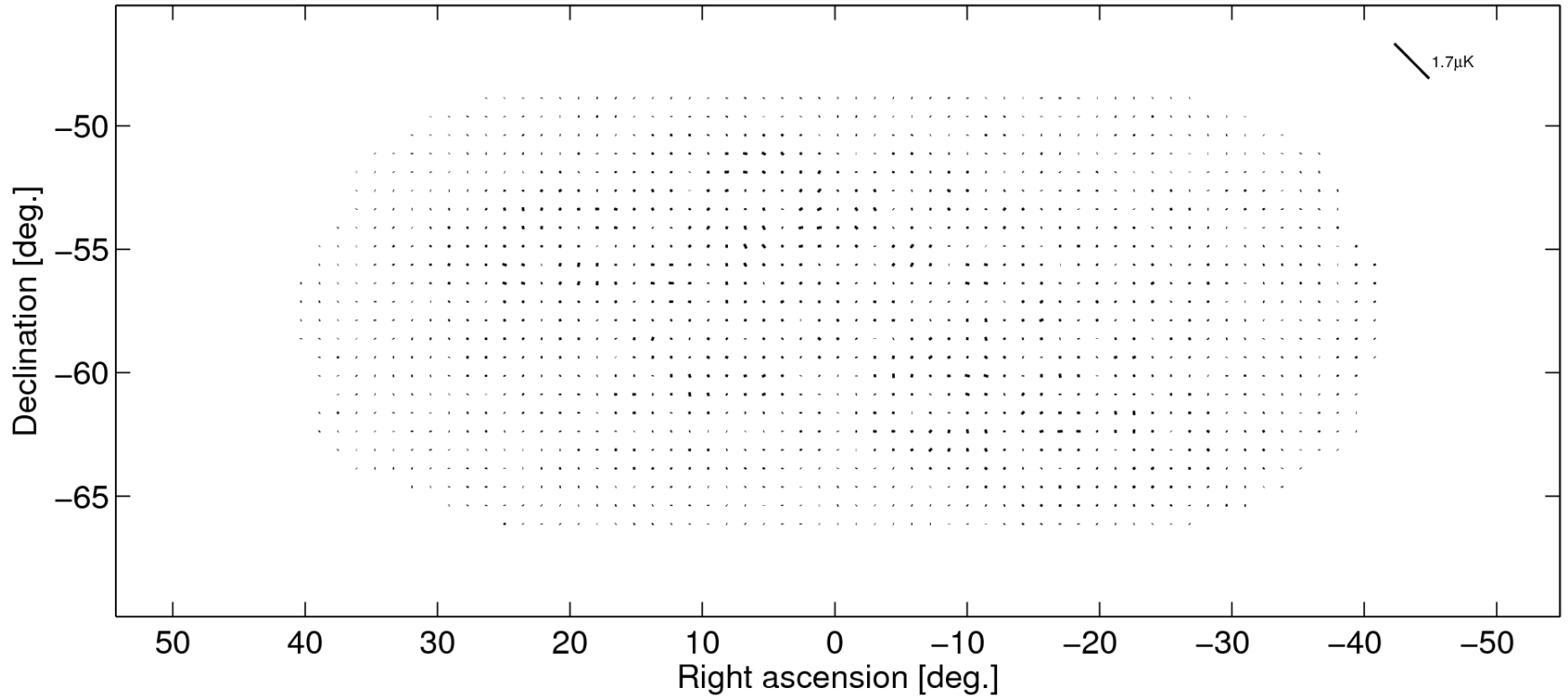


E-mode dominated pattern – no obvious curl component

B-mode Contribution

BICEP2 B-mode signal

Scale: $1.7 \mu K$

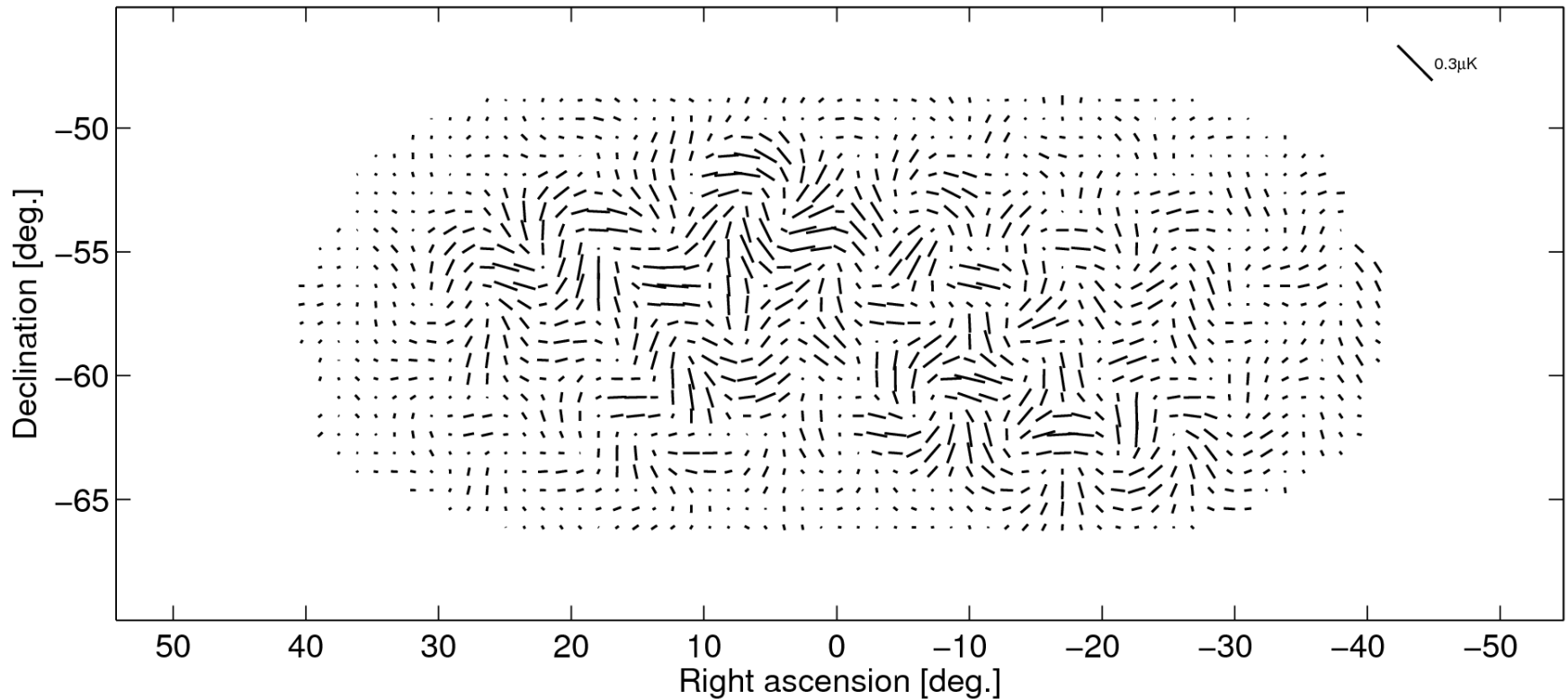


Apply purification operation which leaves only pure B-modes

B-mode Contribution

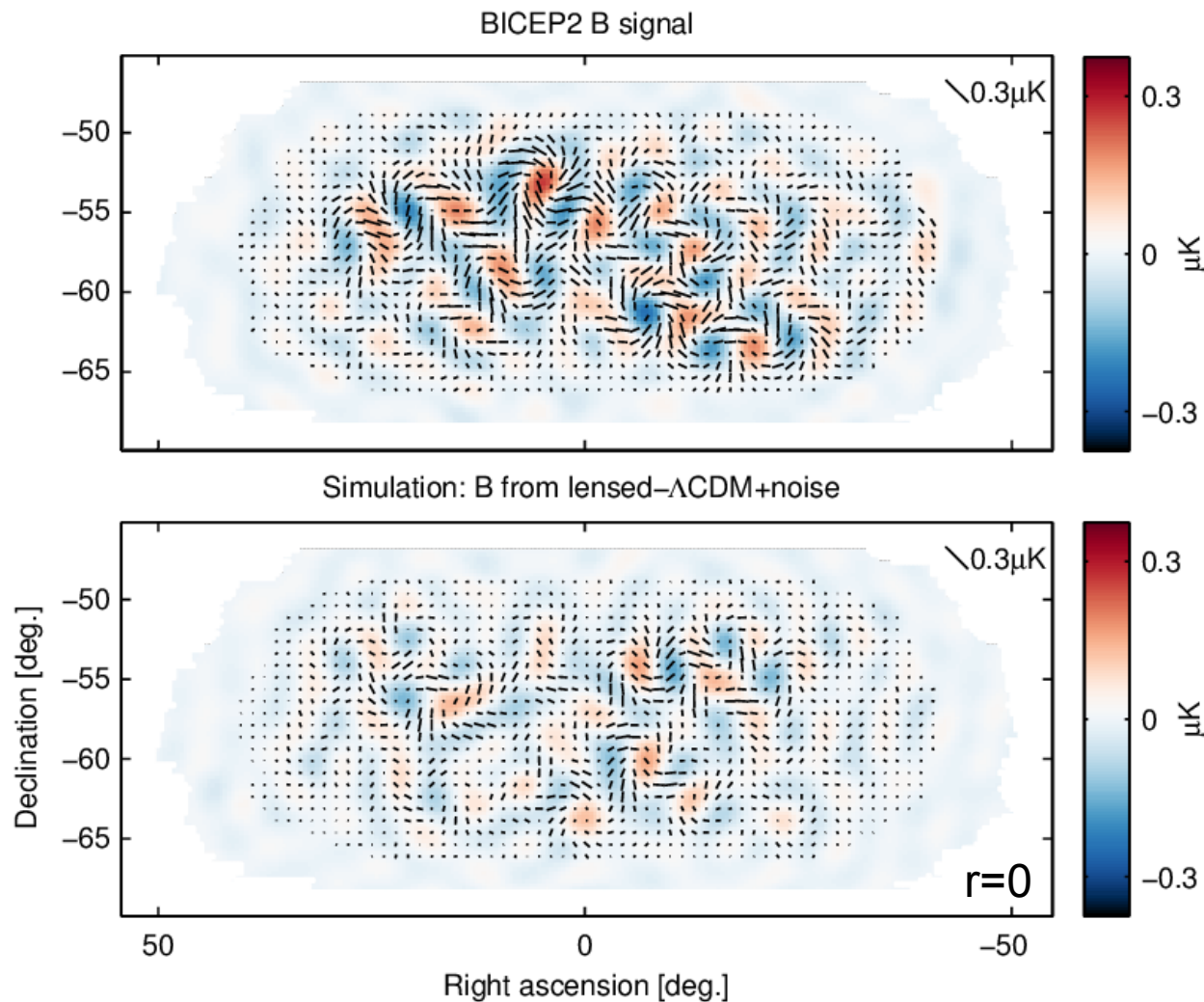
BICEP2 B-mode signal

Scale: $0.3 \mu K$



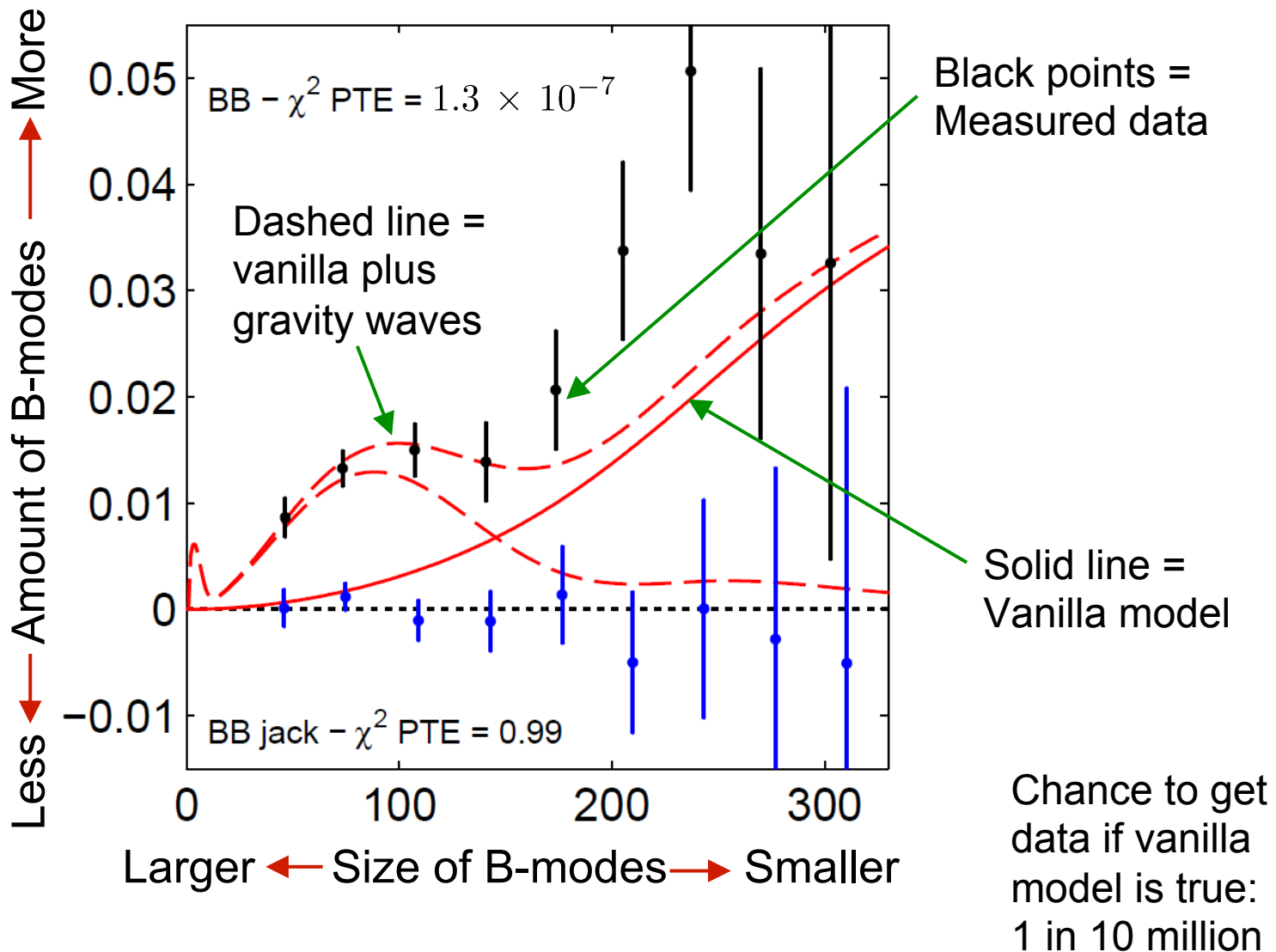
Zoom in by factor 6 – see “swirly” B-mode

Real B-mode Map vs. Simulation



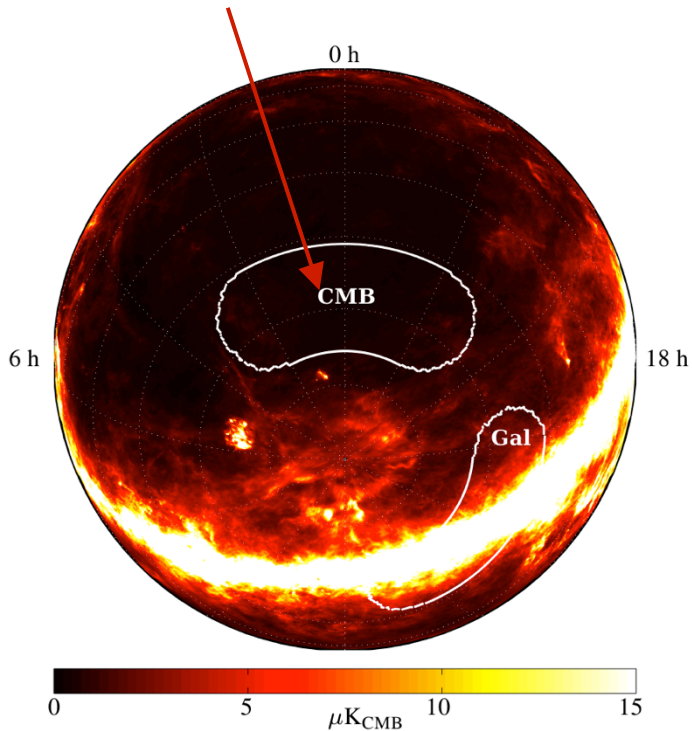
Way more B-modes in the real map (upper) than in simulations containing vanilla model plus experimental noise (lower)

BICEP2 B-mode Power Spectrum



Foreground Contamination from Our Galaxy

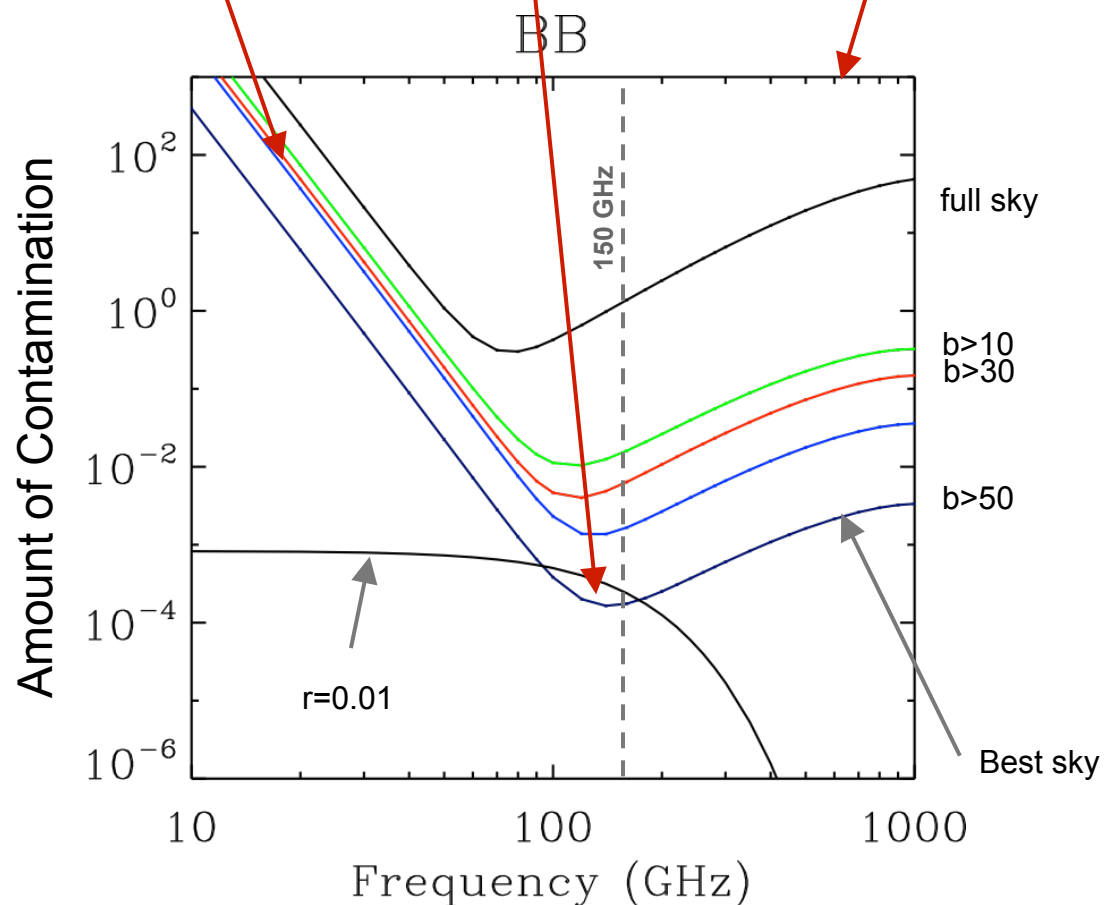
Pick a clean patch of sky



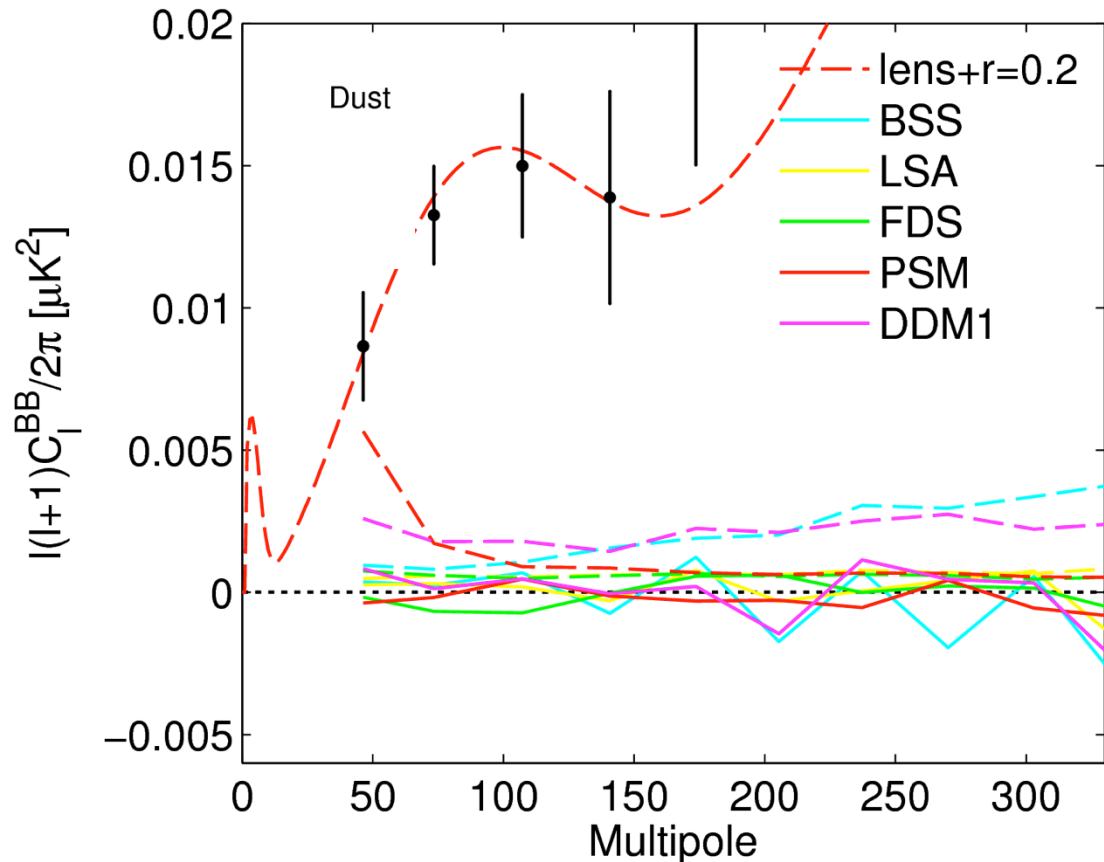
At low frequency
synchrotron
contamination

Sweetest spot

At high frequency dust
contamination



Pre-Planck Polarized Dust Foreground Projections



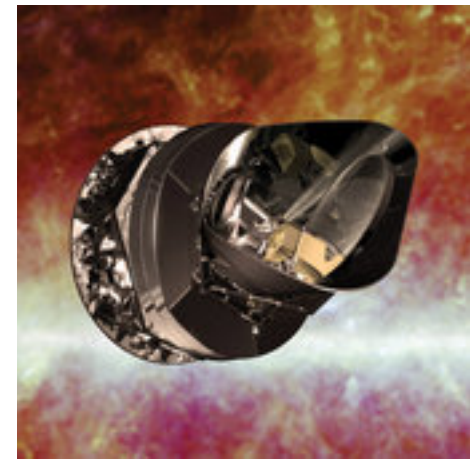
The BICEP2 observation region was chosen on the basis of extremely low unpolarized dust contamination

Used various models of polarized dust emission to estimate dust contamination

Result: All well below observed signal level

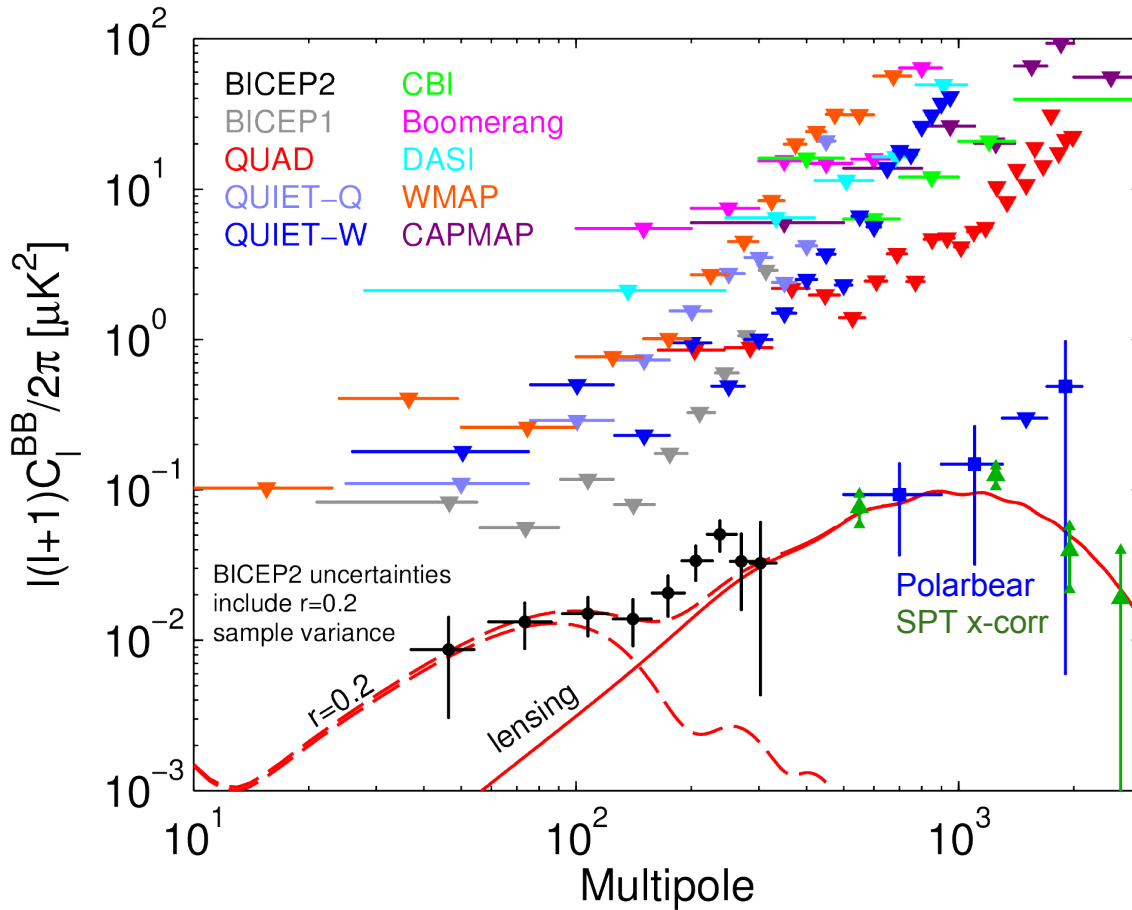
But considerable uncertainty in these models...

Nobody really knew the true level of polarized dust – except the Planck space mission which had taken data but not released it...



Conclusions circa March 17th

BICEP2 and upper limits from other experiments:



Really looked like we'd found gravitational waves from inflation

...but a lot of uncertainty about galactic dust polarization remained...

<http://bicepkeck.org>

Press Conference at Harvard/CfA March 17



Storm of Media Attention

9.90 THE NORTHERN NEWS

TUESDAY

USA TODAY™
03.18.14

NCAA TOURNAMENT
WHO HAS BEST "DANCE CARDS"
A look at matchups, players and teams to watch, 5C

UConn tops women's tourney
ANALYSIS, BRACKET, 4C

UConn's guard leads team to title

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 all plug, brake systems for 15 million vehicles. **B**

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

How Angela earned her big, bad wings
To play Victoria Beckham, actress goes to go-go's. **10**

South Pole view
It's not easy being a scientist at the South Pole, where the world's driest spot really is. **20**

Home delivery
1-800-877-3000
bestdeals.com

USA SNAPSHOTS
Pills show more to do.

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—watch hold clues to the nature of the universe. The ripples have never been seen directly until now. **5A**

Penalty
Overseas banks that provide that information to the IRS are subject to a new penalty. **10**

CRISIS COULD BRIST U.S.
The White House and the Pentagon are on edge as the crisis in Ukraine worsens. **10**

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The New York Times

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RUSSIAN PRESIDENT VLADIMIR PUTIN (left) and U.S. President Barack Obama (right) are seen with other leaders at a meeting in Beijing.

PUTIN RECOGNIZES CRIMEA SECESSION, DEFEYING THE WEST

Decree Increases Fears of Annexation by Russia, Despite More Sanctions

By STEVEN LEVITSKY and PETER HADJIKAKIS
WASHINGTON—Vladimir Putin's decree on Tuesday recognizing the secession of Crimea from Ukraine as a permanent and independent state, leaving the government of the peninsula in charge, was a major step toward annexation, the United States and Europe said. The move also defied the West's demand that Russia withdraw its troops from the Crimean Peninsula.

Mr. Putin said he signed the decree after a referendum in Crimea that he said was free and fair. He said the move would address both Russia's and Ukraine's interests.

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Physicists at the BICEP2 experiment in Antarctica are using a satellite dish to detect gravitational waves.

宇宙急速膨張の証拠、検出される

Telescope captures view of gravitational waves

By CONNOR SWAN 2014年3月18日 14時 50分 (JST+9)

宇宙が急速に膨張しているという証拠が、南極大陸にある望遠鏡によって検出された。重力波の観測は、宇宙の膨張速度を測定し、宇宙の膨張が加速していることを示唆する。これは、宇宙の膨張速度が時間とともに速くなるという予測と一致している。

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FINANCIAL TIMES

PAPER

USA Tuesday March 18 2014 USA \$2.00 Canada \$3.00

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 Chantler in Brussels and David S. Johnston in London
The European Union and the United States have imposed sanctions on top Russian officials, including members of the government and military, in response to the annexation of Crimea. The sanctions include asset freezes and travel bans.

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PHYSICAL REVIEW LETTERS

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PHYSICAL REVIEW LETTERS (248 total pages)

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Published by American Physical Society, APS physics

Volume 112, Number 24

New dawn for breakfast as disease and speculation push price rises

By Emily Toppin in London
The price of breakfast cereals has risen sharply in recent months, driven by a combination of factors including increased demand and speculation. The price of cereals is expected to continue to rise in the coming months.

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Actually not a lot of fun...

Developments Since...

- Intense media and science community interest...
- Many early instrumental queries – faded away – everybody now seems to trust the measurement.
- Concerns about synchrotron – also faded away.
- But persistent concerns about dust...
 - Mostly based on online pdf's of Planck talks
- As of 19 Sept we finally have some solid information from Planck about the actual level of polarized dust emission in the BICEP2 field. Looks to be much higher than any of the projections...

What's Next?

- We are actively working with the Planck collaboration on a joint analysis of the two data sets:
 - meeting at UMN next week to discuss
- We ran two of the Keck Array receivers this season at 100GHz:
 - Guys in the audience are gearing up to analyze as fast as possible when the data taking finishes a few days from now
- BICEP3 is right now on its way to Pole
- Stay tuned...
- The amount we have discovered about the Universe is really quite amazing – and we are not done yet!