Astronomy at 100 below:
Going to the ends of the Earth to see the beginnings of time

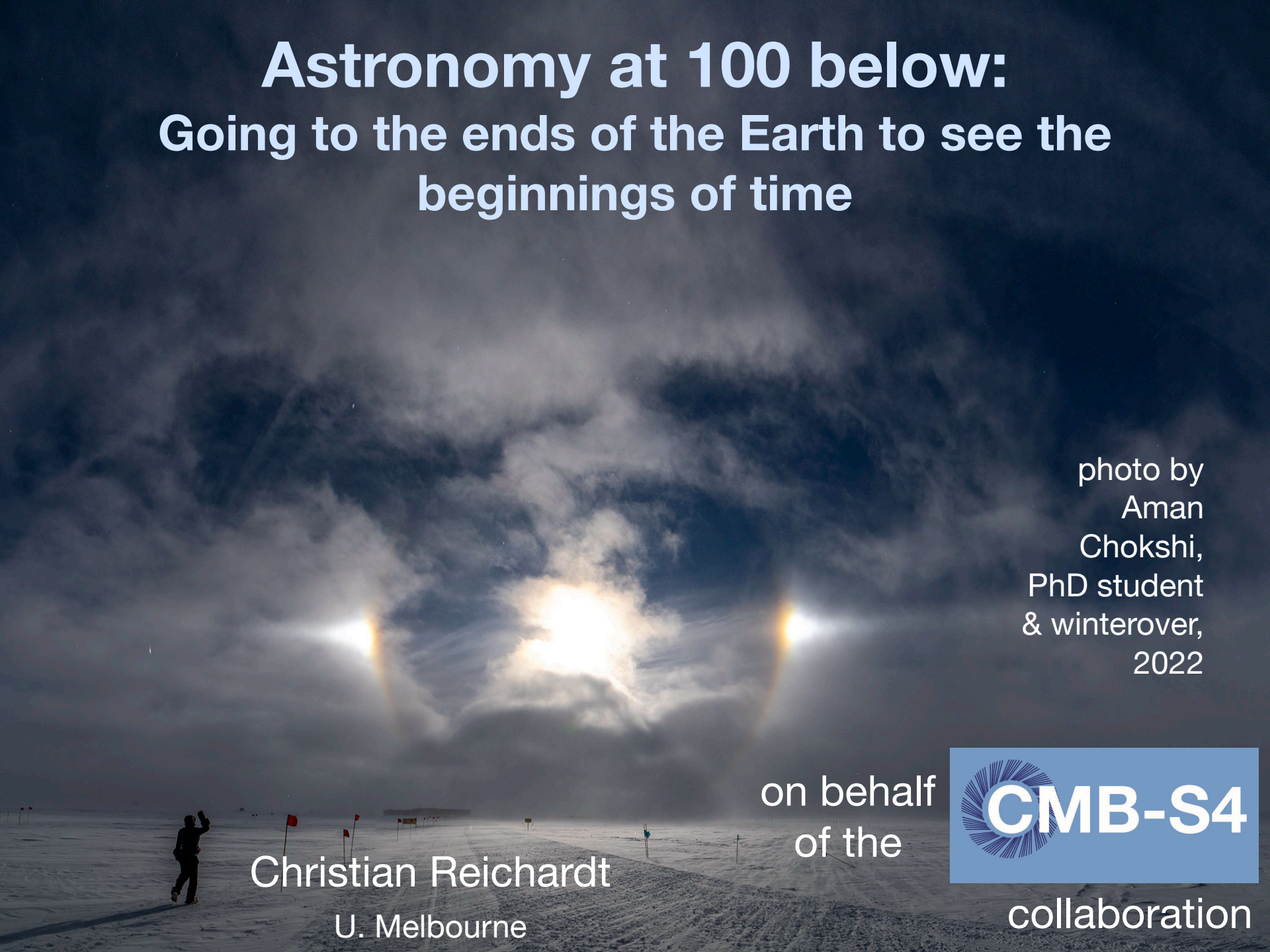


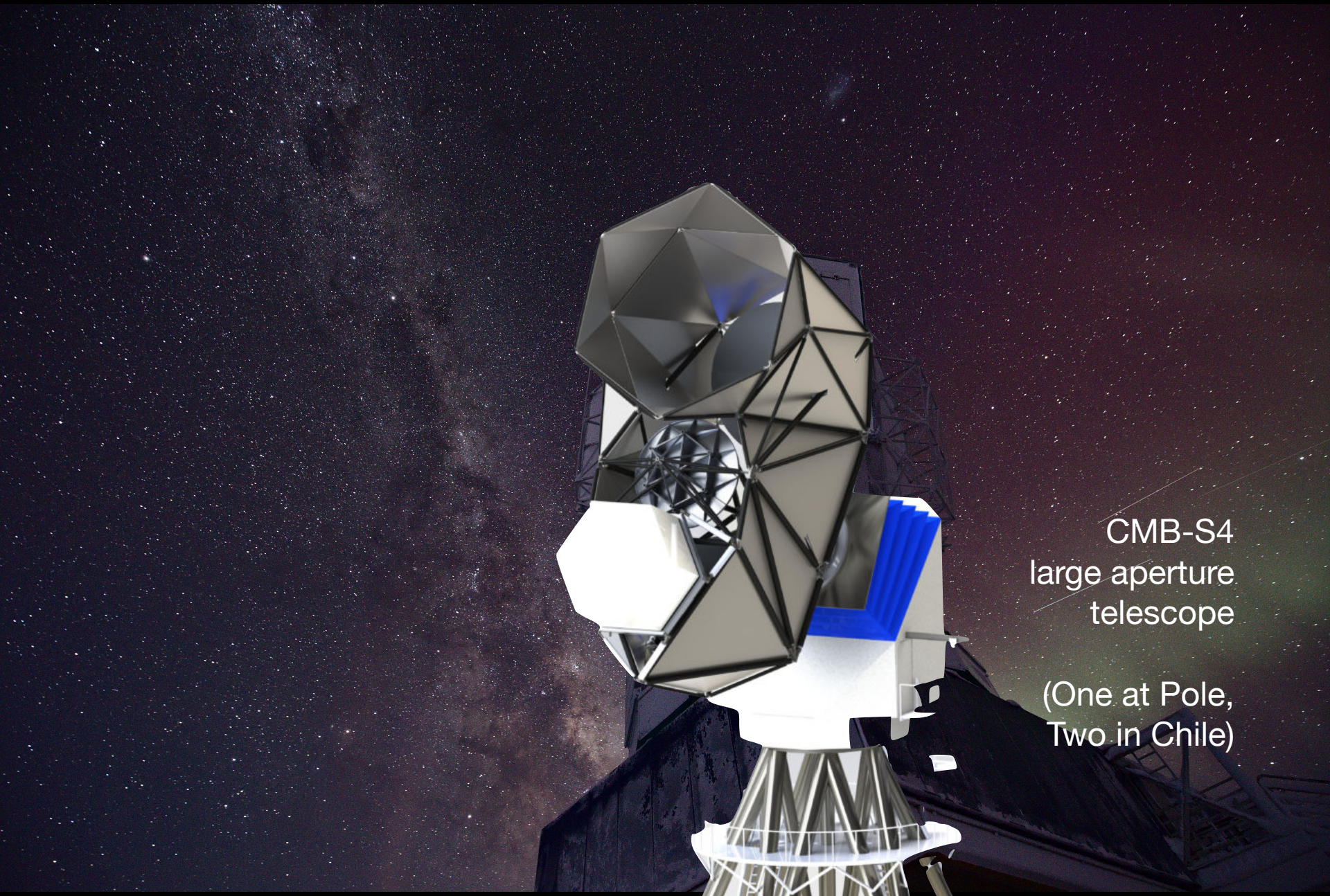
photo by Aman Chokshi, PhD student & winterover, 2022

Christian Reichardt

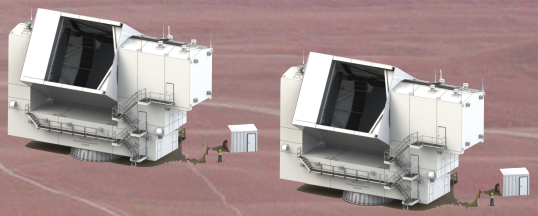
U. Melbourne

on behalf of the CMB-S4 collaboration

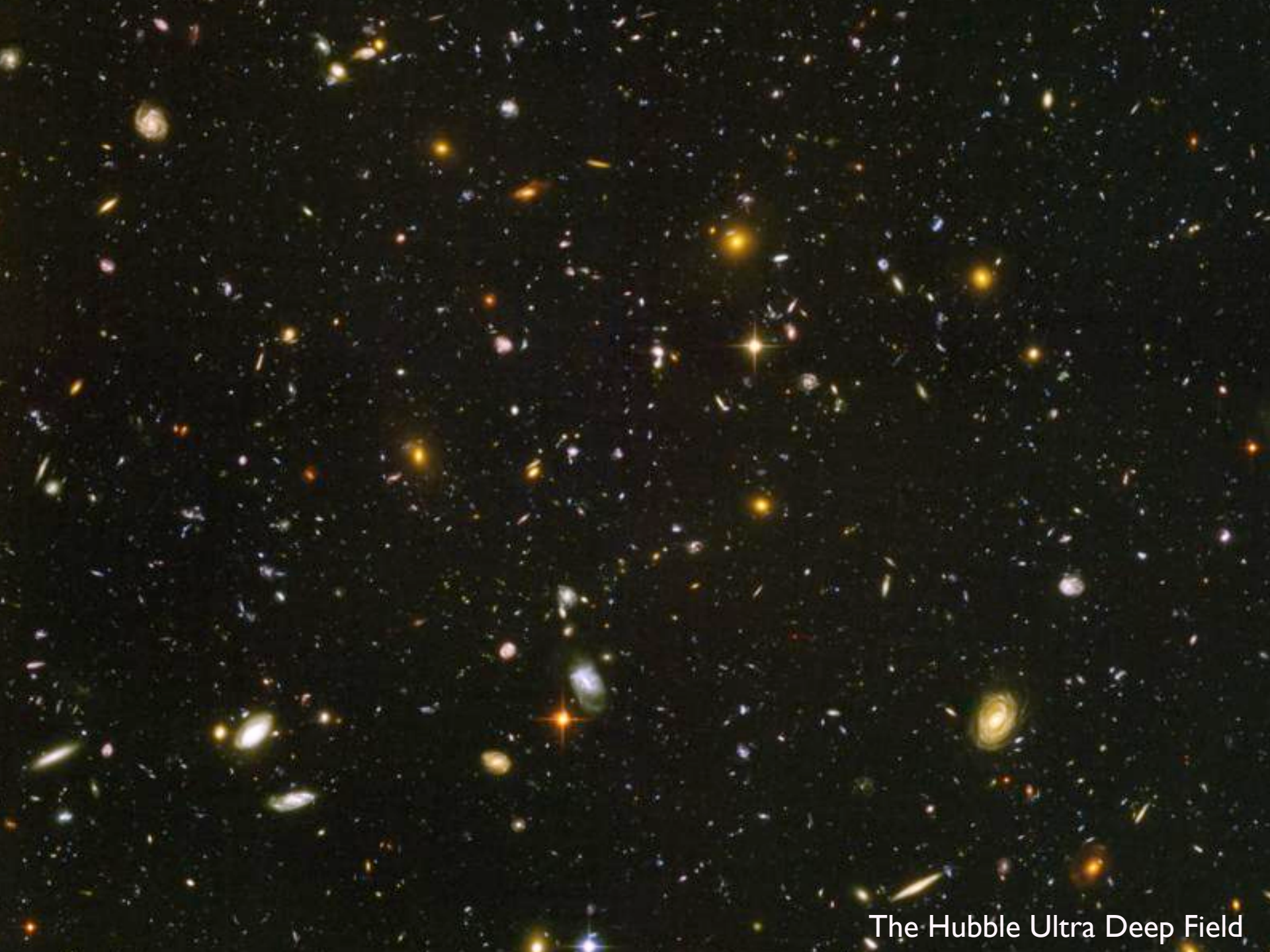
photo by Robert Schwartz, 2014


CMB-S4
large aperture
telescope
(One at Pole,
Two in Chile)
photo by Robert Schwartz, 2014

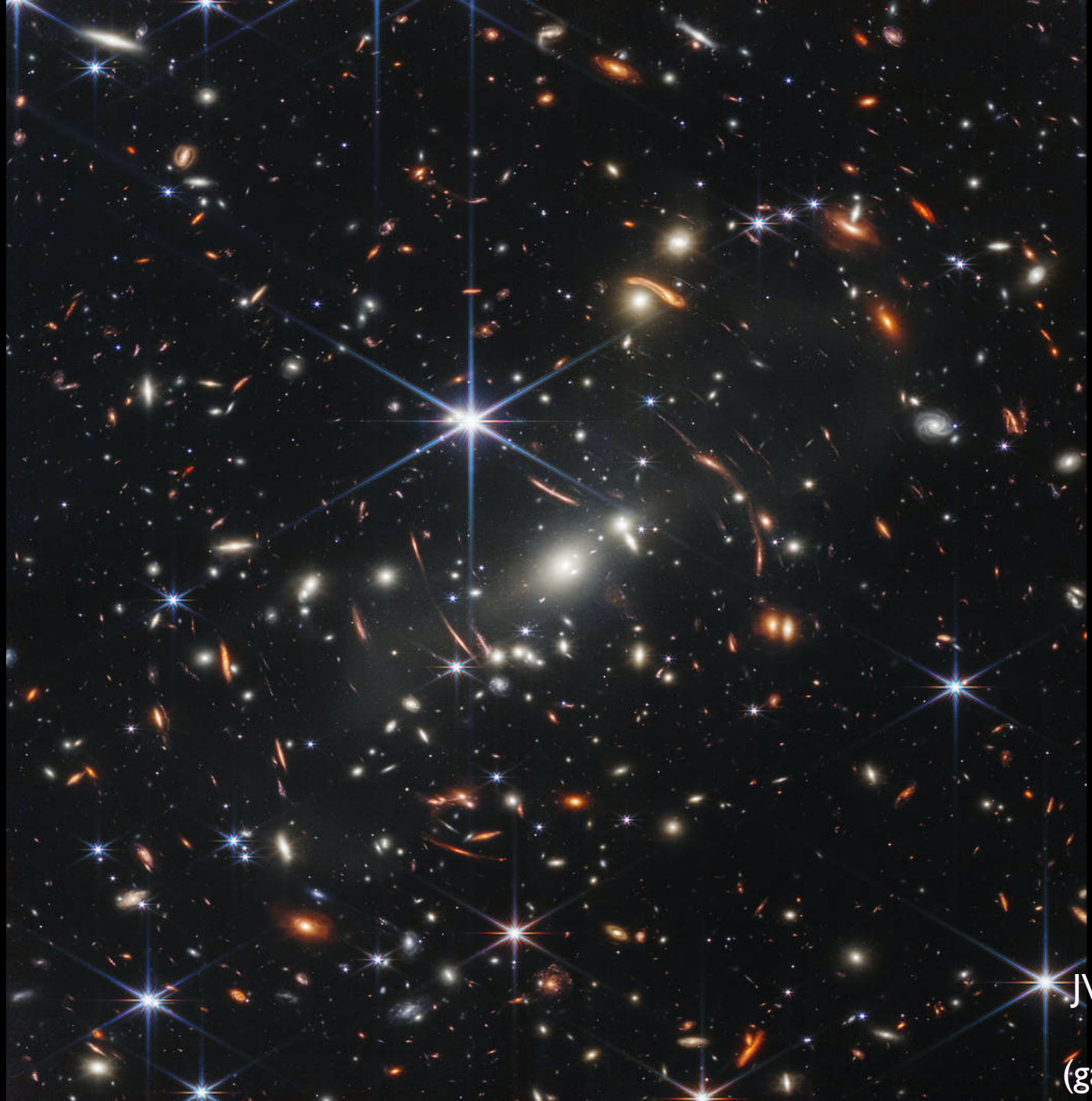
Credit: Ricardo Bustos



10secs of photoshop version
of CMB-S4



The Hubble Ultra Deep Field

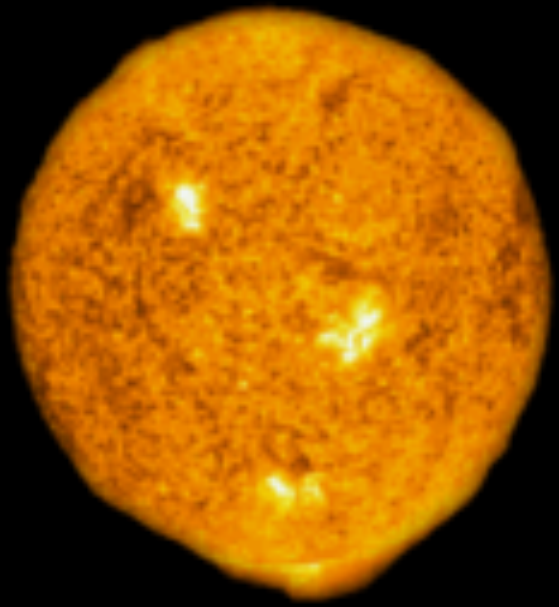


JWST - Webb
Deep Field
(galaxy cluster)

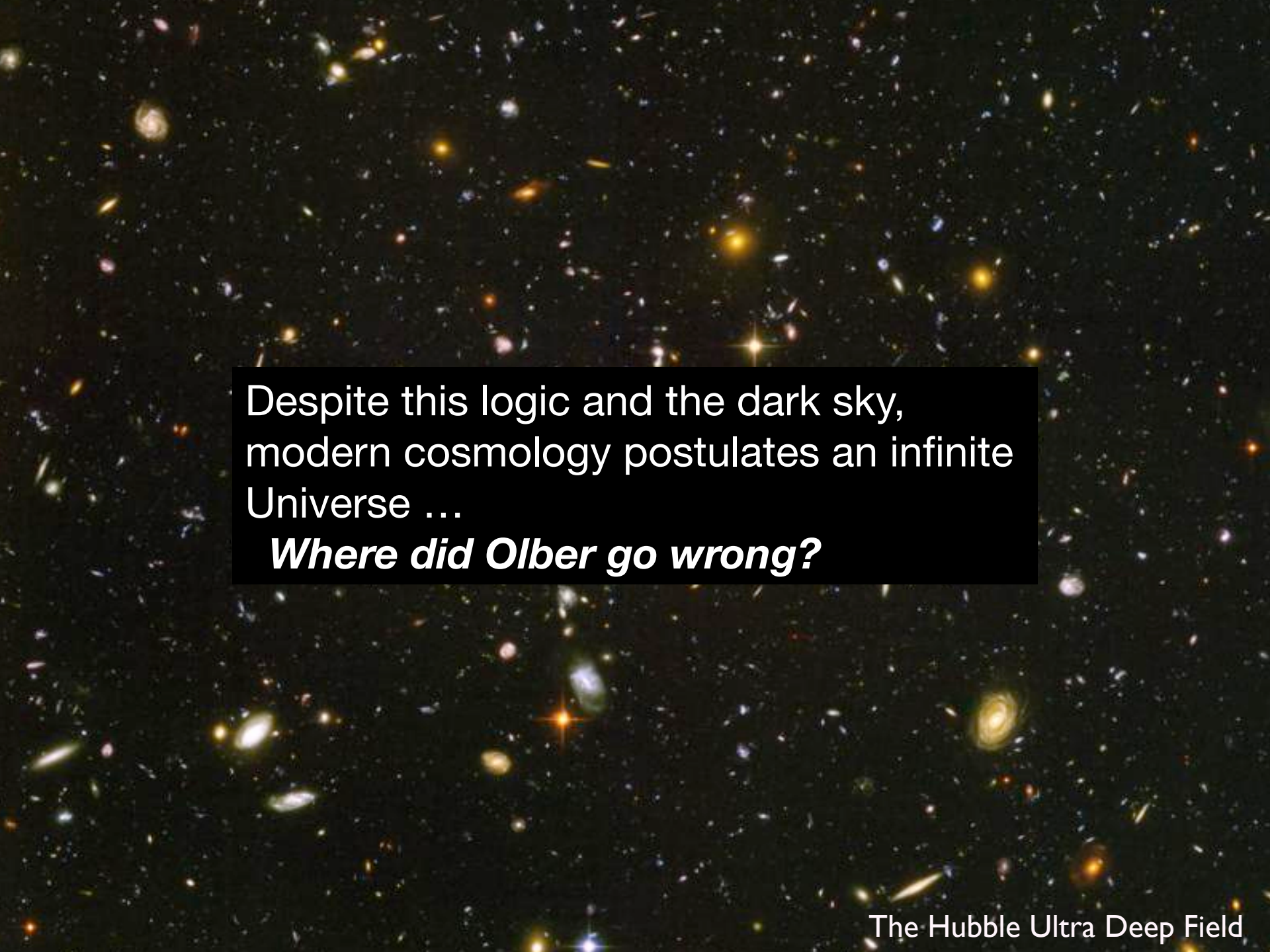
JWST - Webb Deep Field (galaxy cluster)

Olber's Paradox

In an infinite cloud of stars,
all rays hit a star



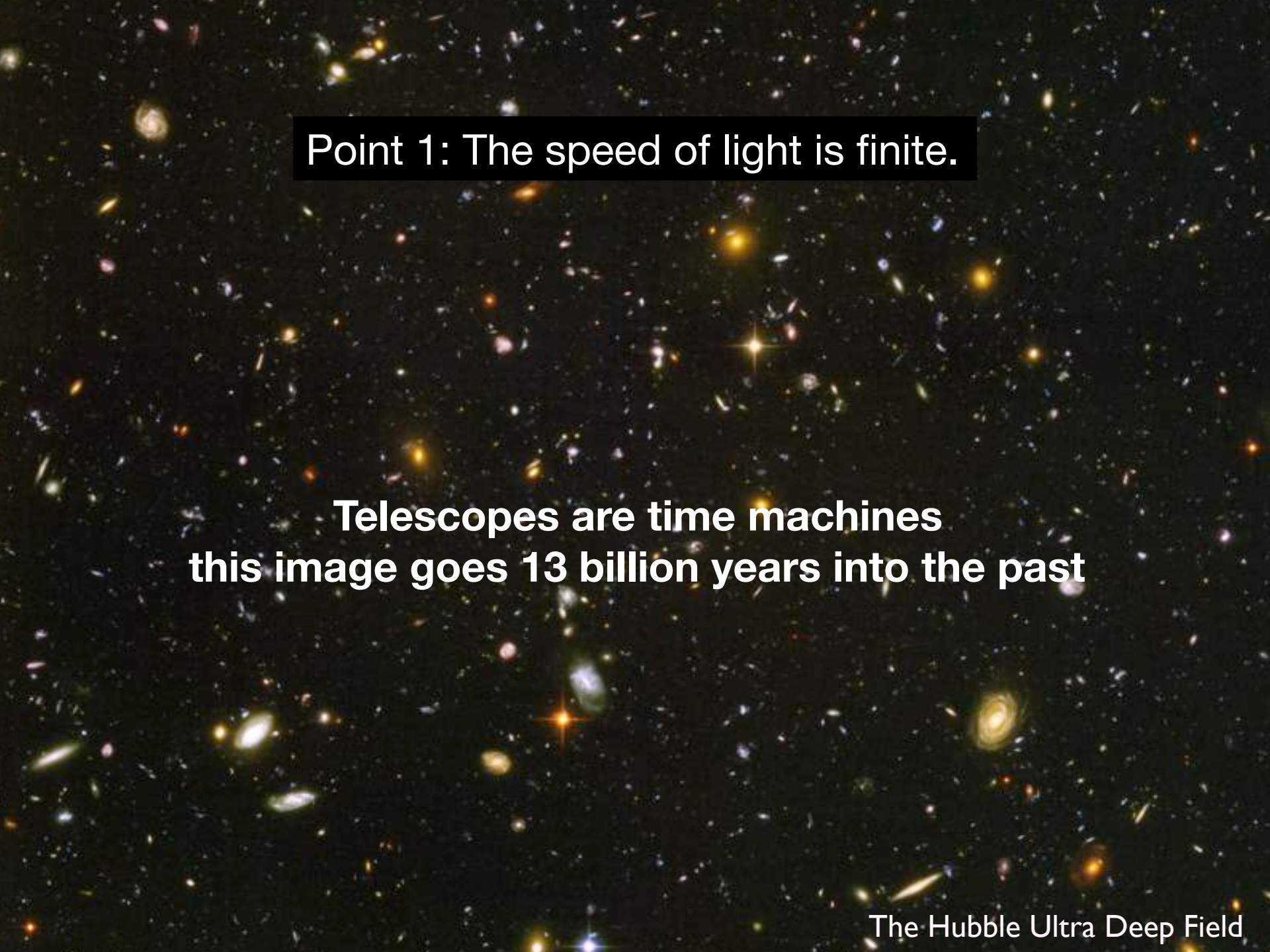
Deep Field

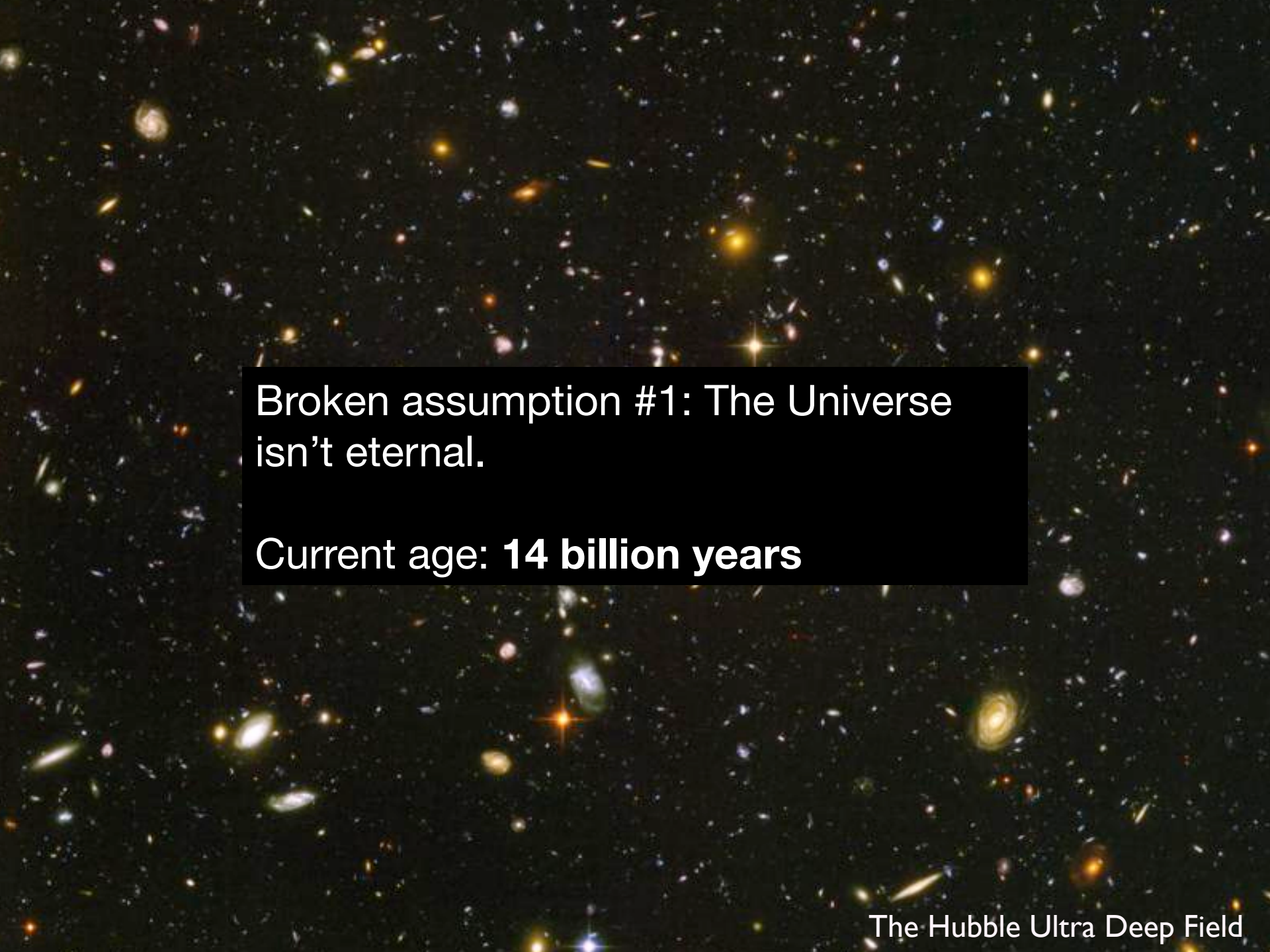


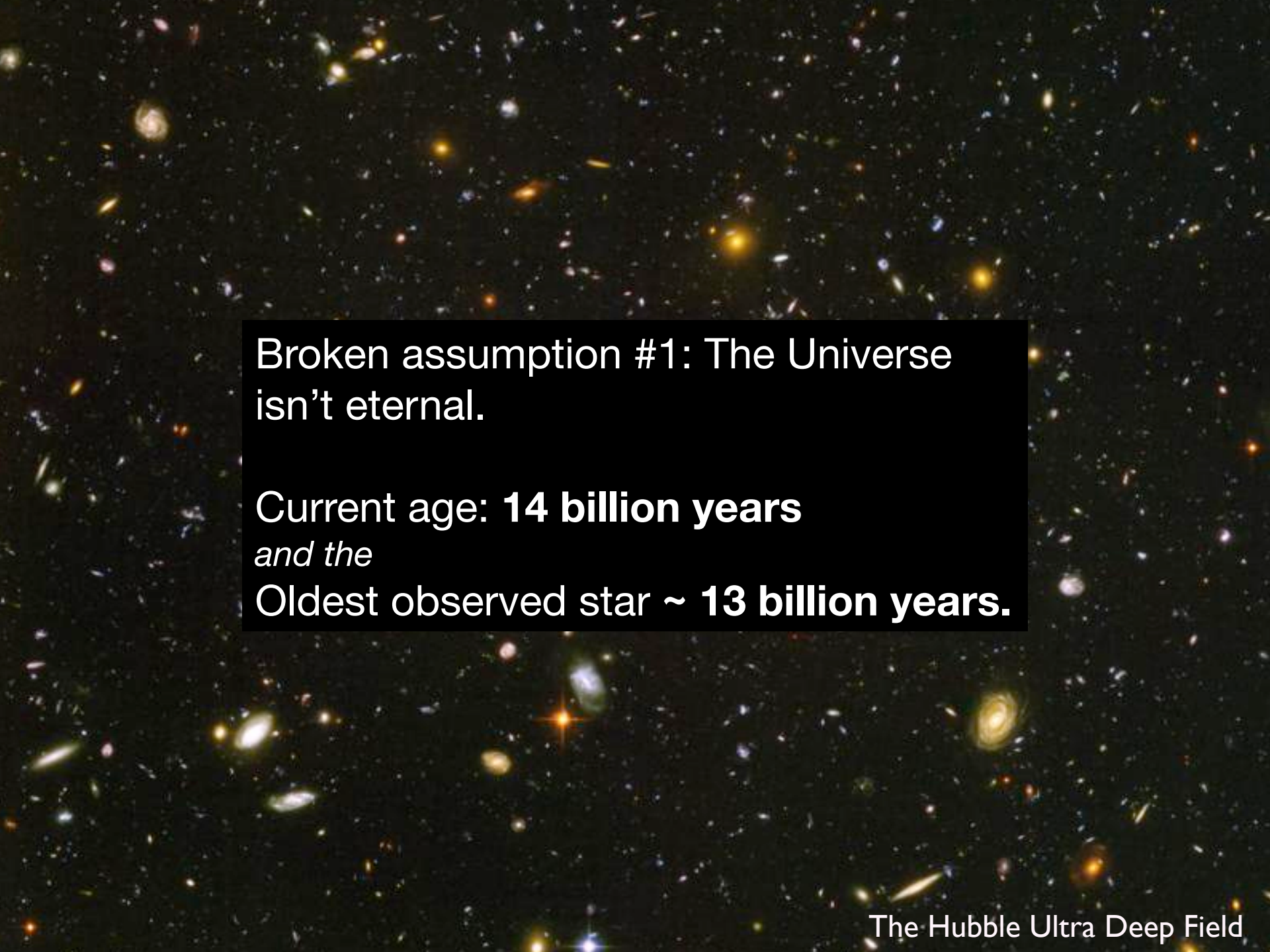
Despite this logic and the dark sky, modern cosmology postulates an infinite Universe …

Where did Olber go wrong?

The Hubble Ultra Deep Field

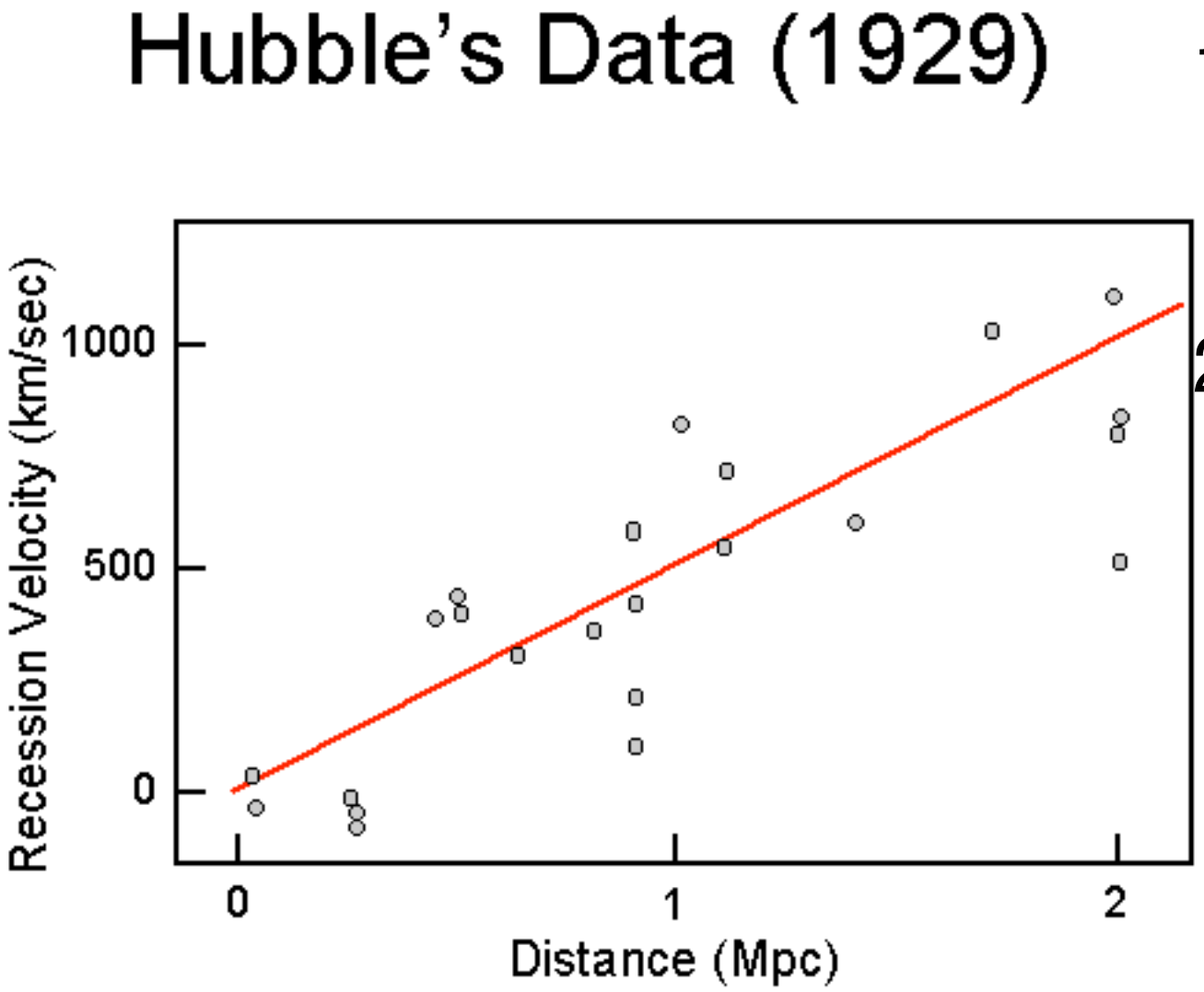

Point 1: The speed of light is finite.
Telescopes are time machines
this image goes 13 billion years into the past
The Hubble Ultra Deep Field


Broken assumption #1: The Universe isn’t eternal.
Current age: **14 billion years**
The Hubble Ultra Deep Field


Broken assumption #1: The Universe isn't eternal.
Current age: **14 billion years**
and the
Oldest observed star **~ 13 billion years.**
The Hubble Ultra Deep Field


Broken assumption #2: The Universe isn’t static.
It’s expanding.
The Hubble Ultra Deep Field

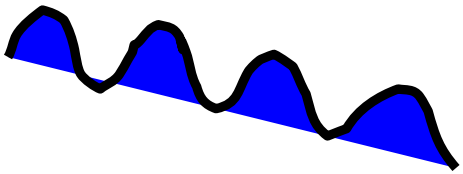
First noticed by Edwin Hubble



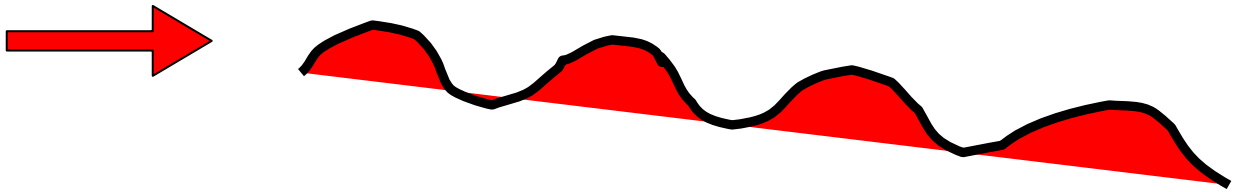
1. Everything is moving away from us…
2. Further away objects move faster

The Universe is expanding!

Cosmological redshift (z)

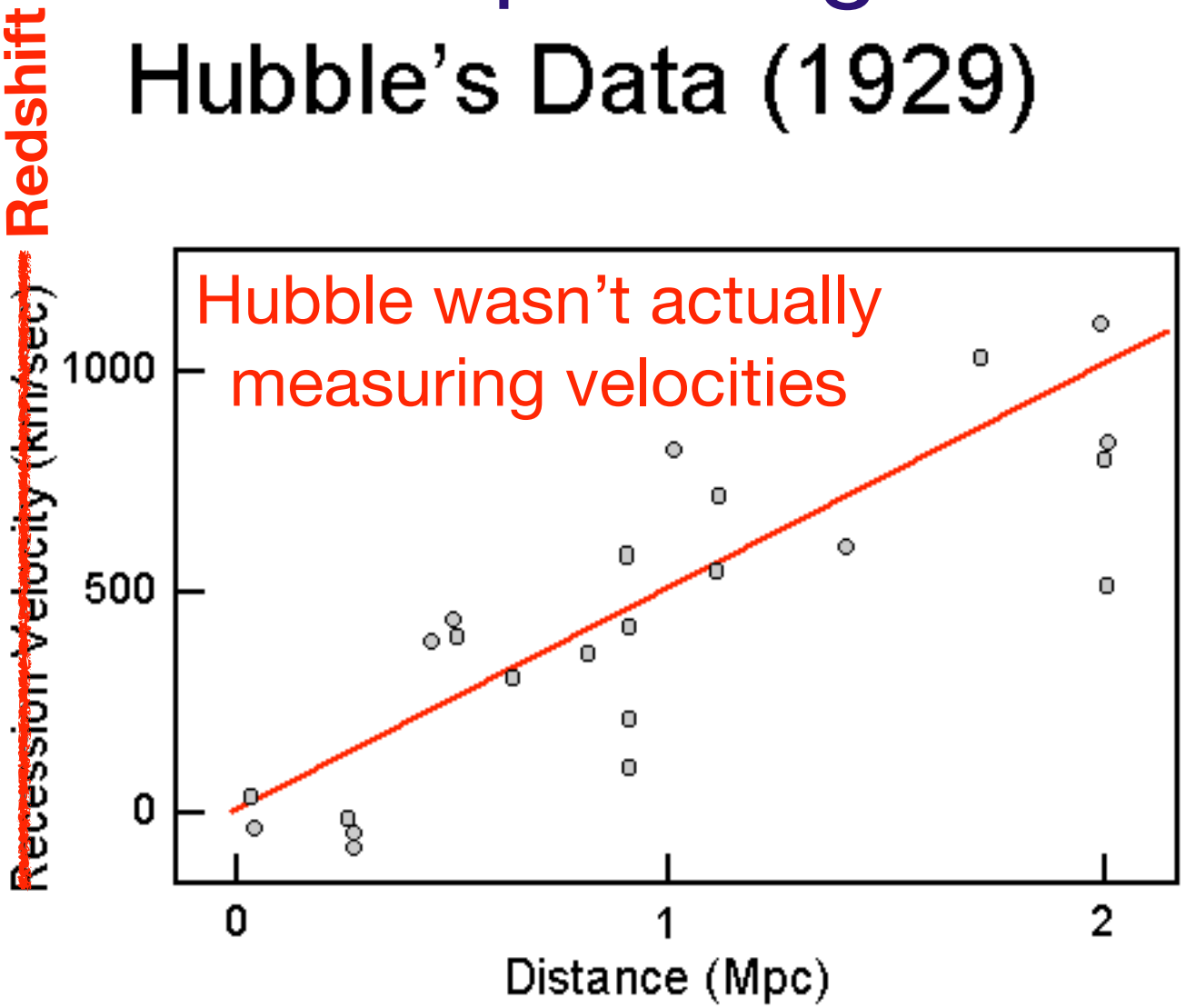


universe expands...



photon wavelength stretched *or* redshifted

Expanding Universe



1. A measure of how much larger the Universe is today than when the light started its journey to us

George Lemaitre first proposed this in 1931

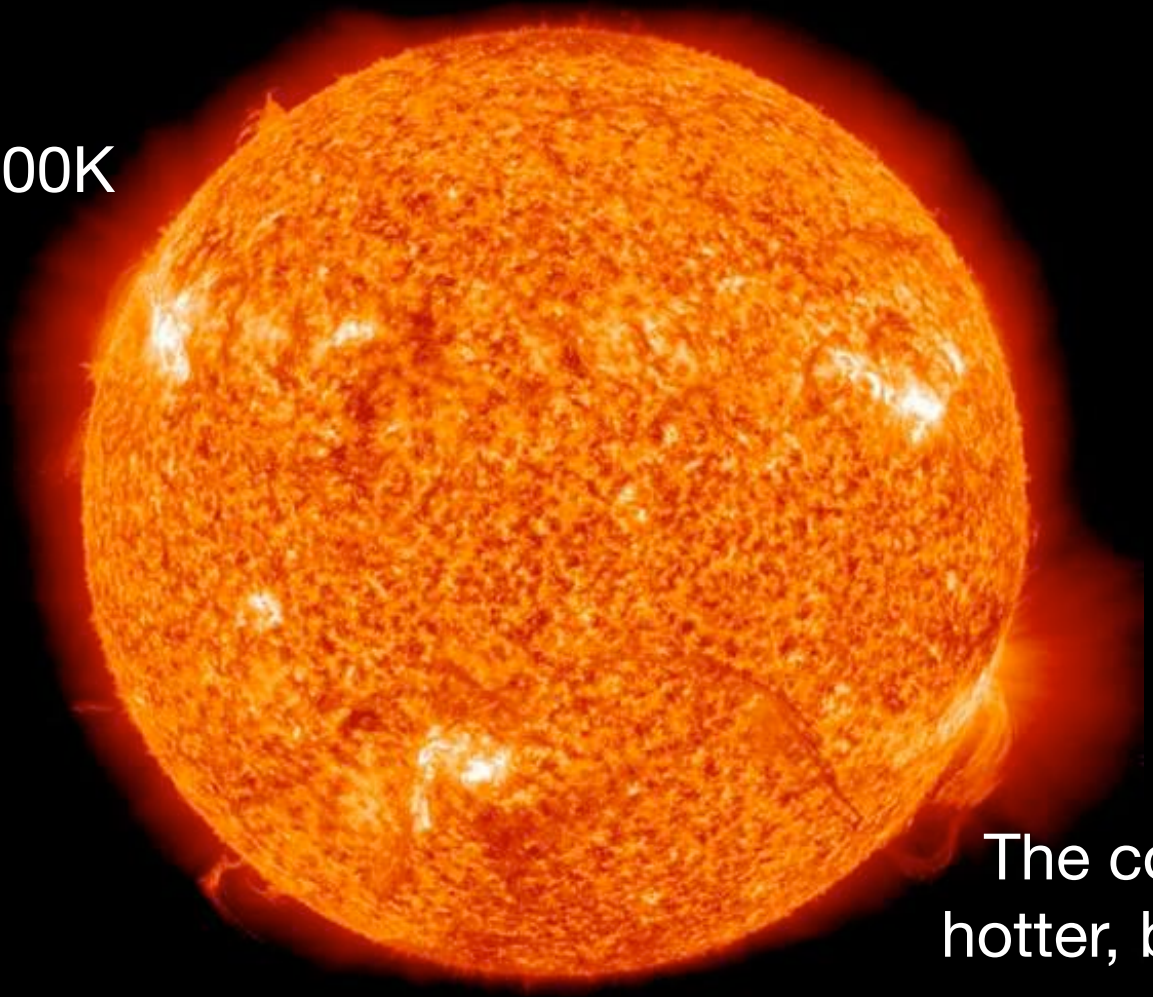
There is a beginning

- Run the clock backwards
  - Galaxies converge together
  - Universe gets smaller, denser, hotter
  - Till you hit the singularity

- The Universe has a finite age!

Can we see the beginning?

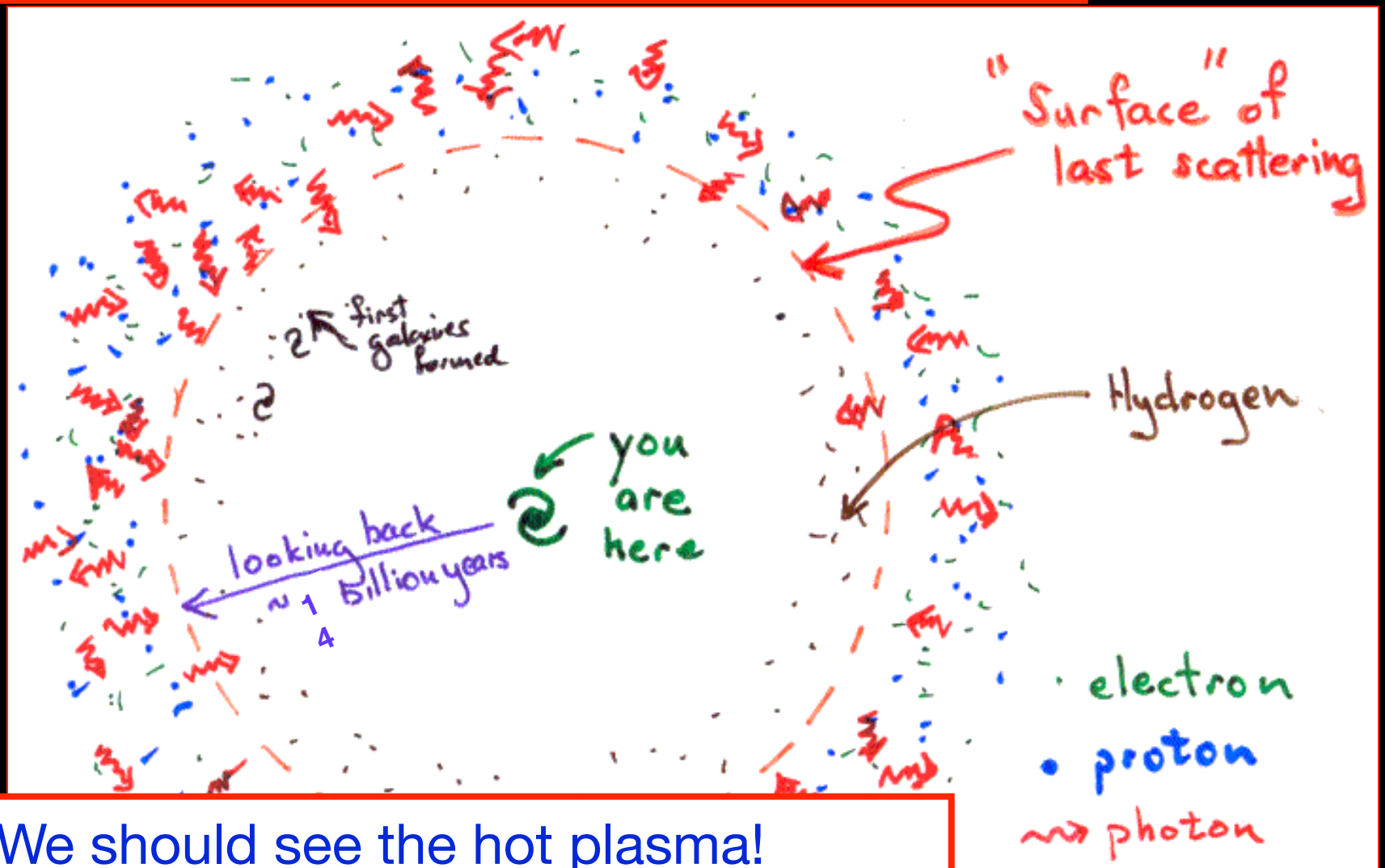
Our sun:
We see the
surface ~ 5500K



The core is 3000x
hotter, but shielded
from view

We are inside a glowing sphere

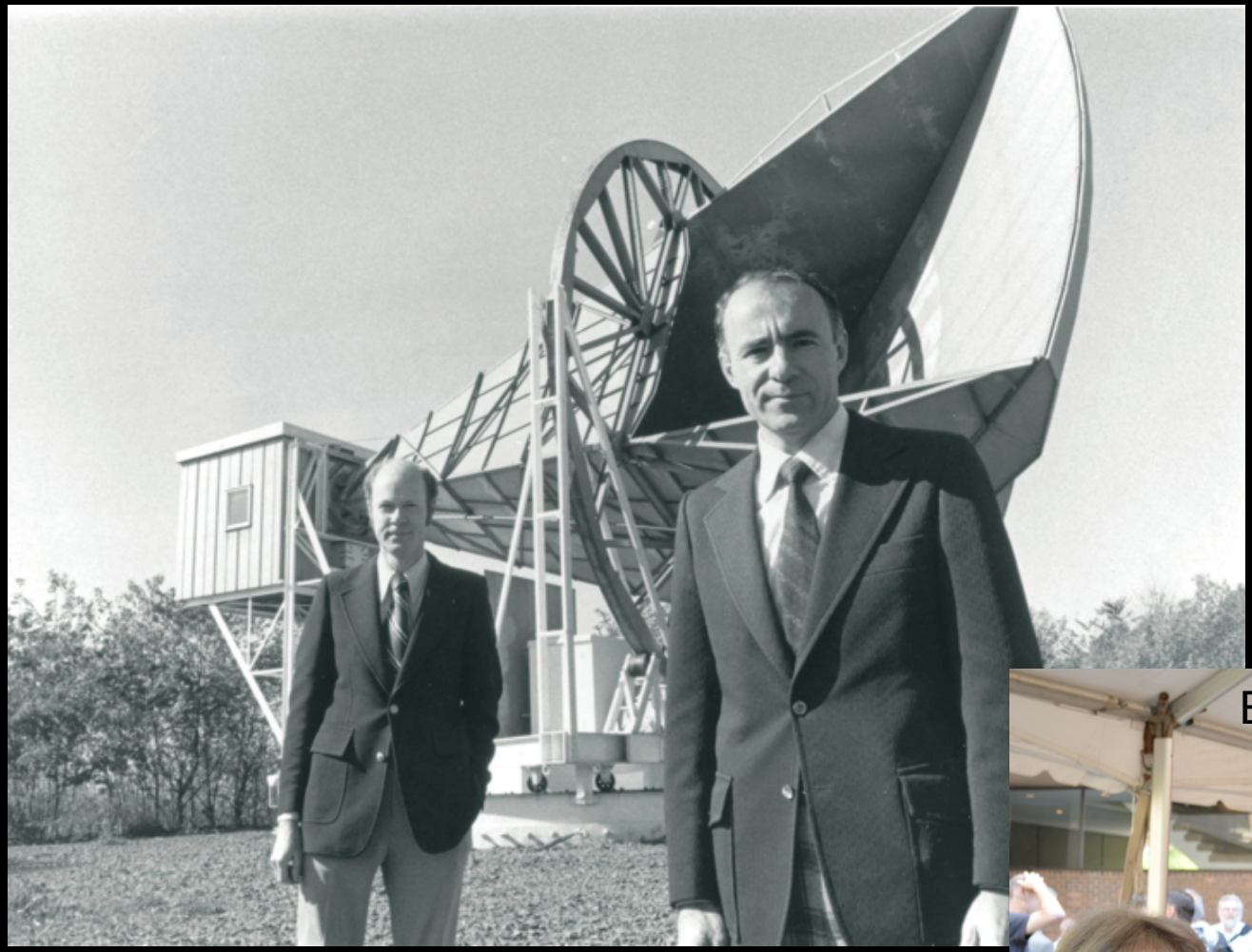
Image credit:
J. Carlstrom



We should see the hot plasma!
Expected temperature (back then): half the Sun's

First predicted in 1948

Discovery of the Cosmic Microwave Background



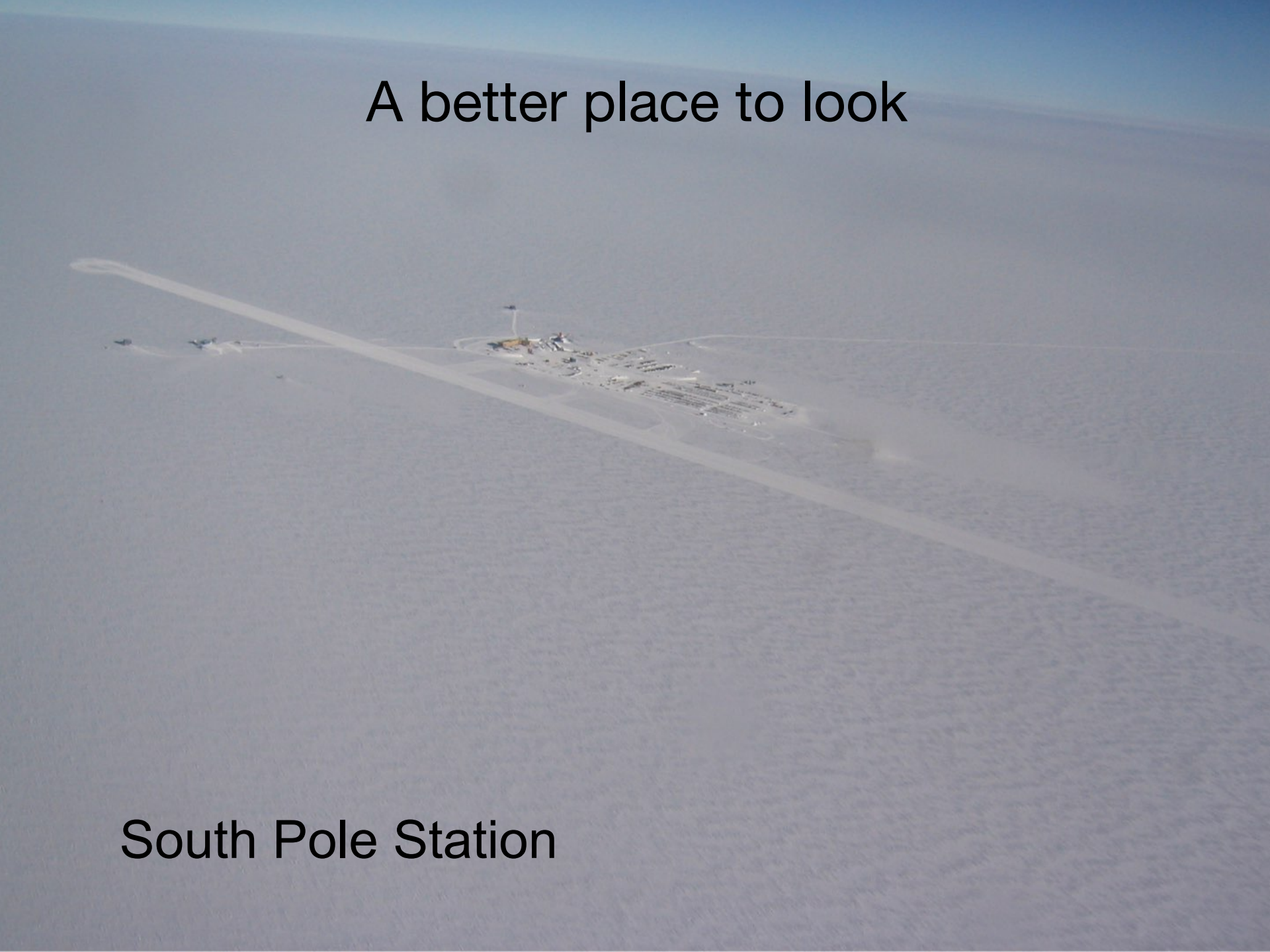
Arno Penzias & Robert Wilson in front of the 20ft Bell Labs antenna used to discover the microwave background in 1965

direct evidence for a Hot Big Bang

1978 Nobel prize

Bob Wilson @ anniversary 2015

A better place to look

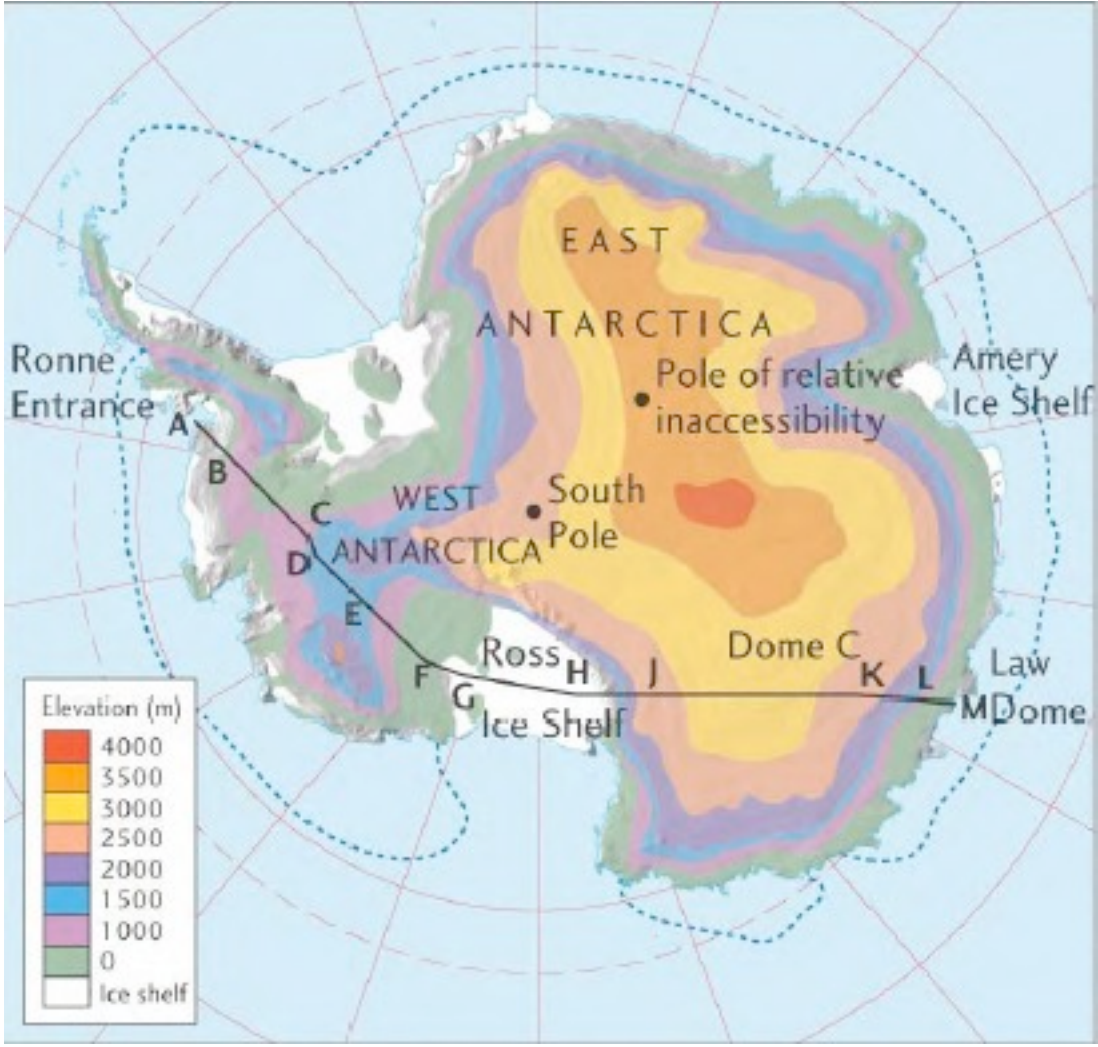


South Pole Station

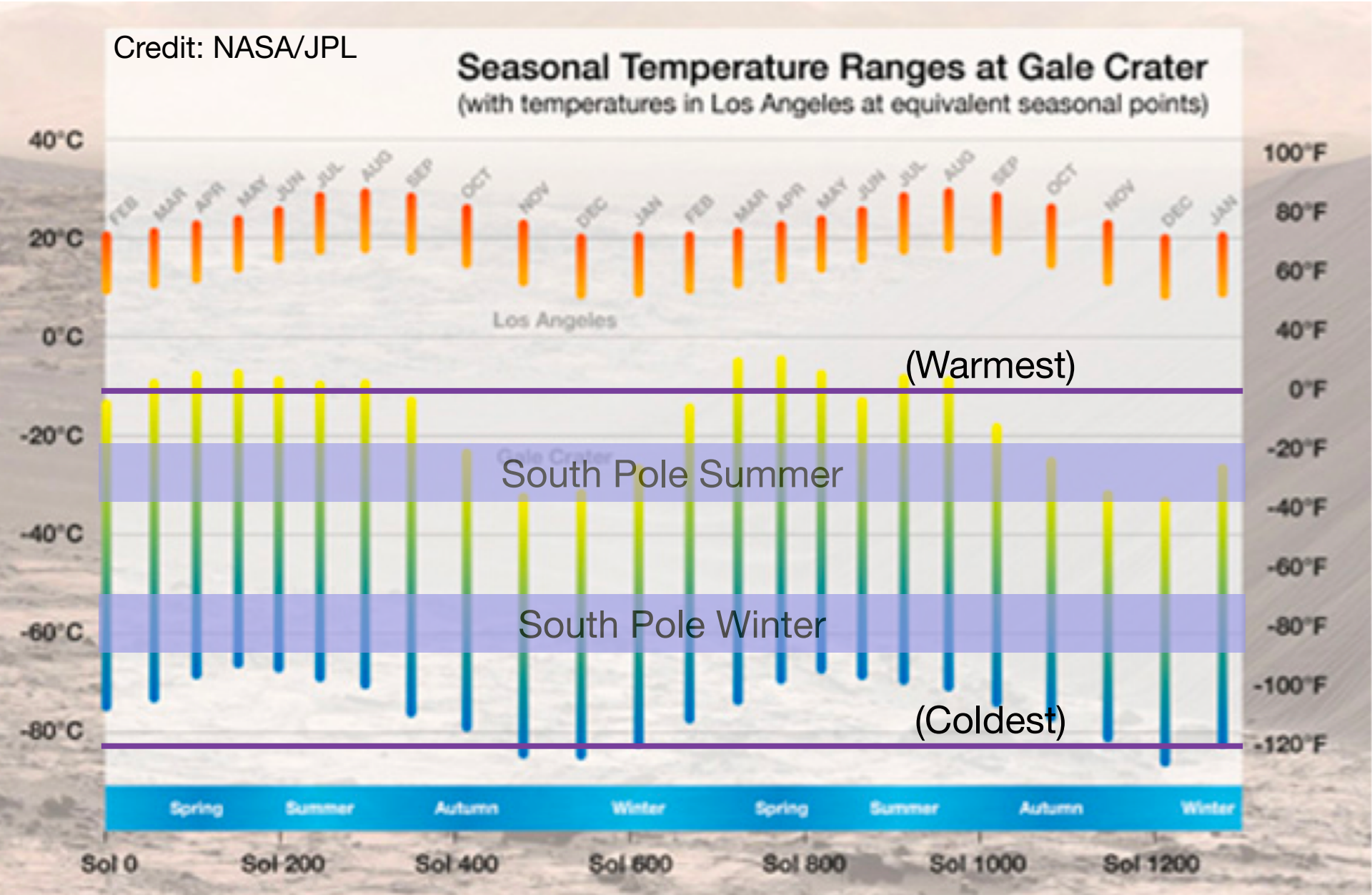
Why Antarctica?

1. Height

- Highest point:
  - 4.9 km
- Lowest:
  - -2.6 km (+4 km of ice)
- The ice is *really* thick. Plateau averages 3km (SLAC is 86m above sea level)



Reason 2: Martian Temperatures



the cold means its Very Dry!

Precipitation:

- Outback deserts: <15 cm/year
- Sahara: 10 cm/year
- **South Pole: 7cm/year**

Effectively a **desert** despite sitting on 2km of ice

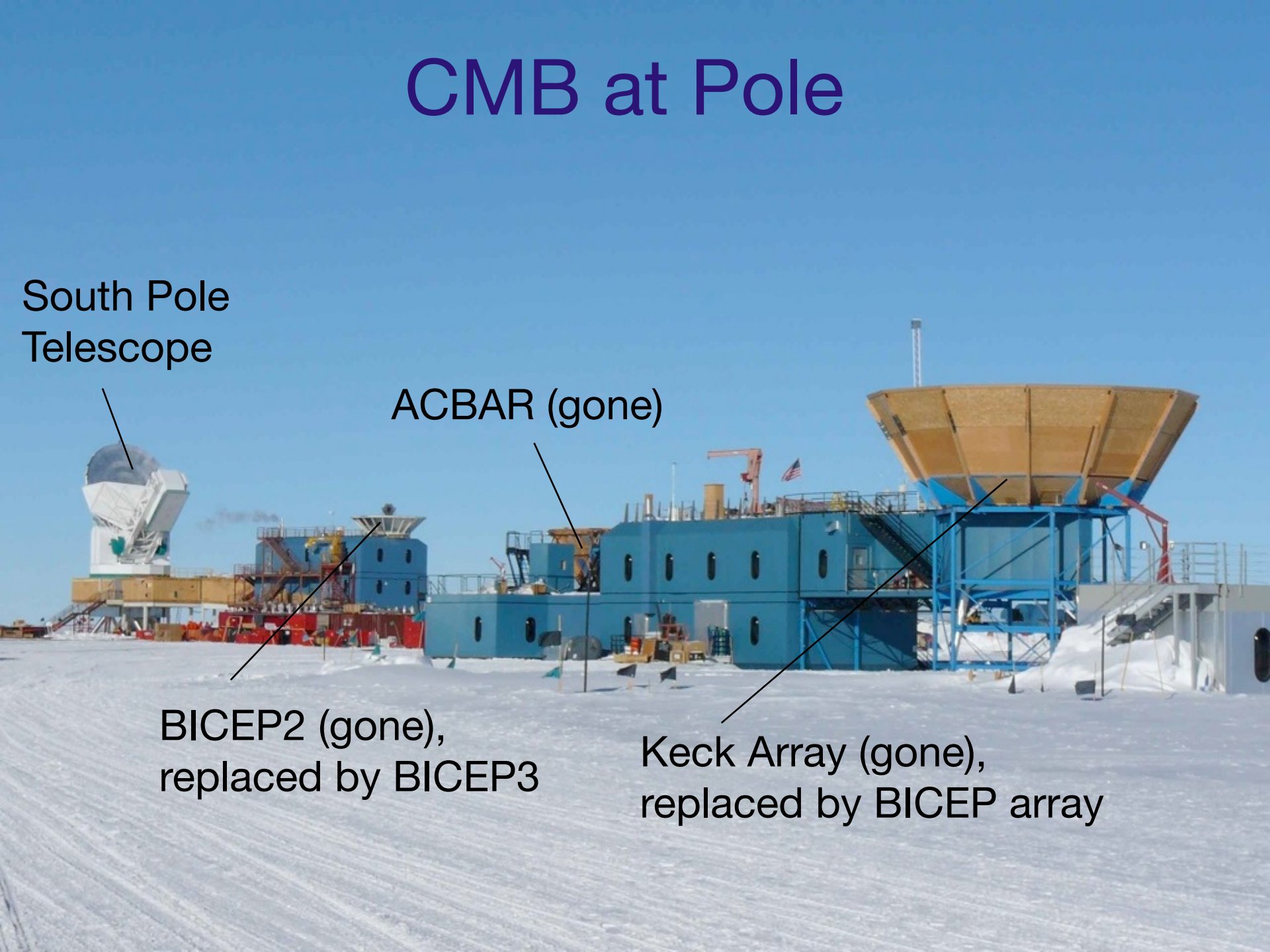
which matters because

Water is terrible for microwave astronomy

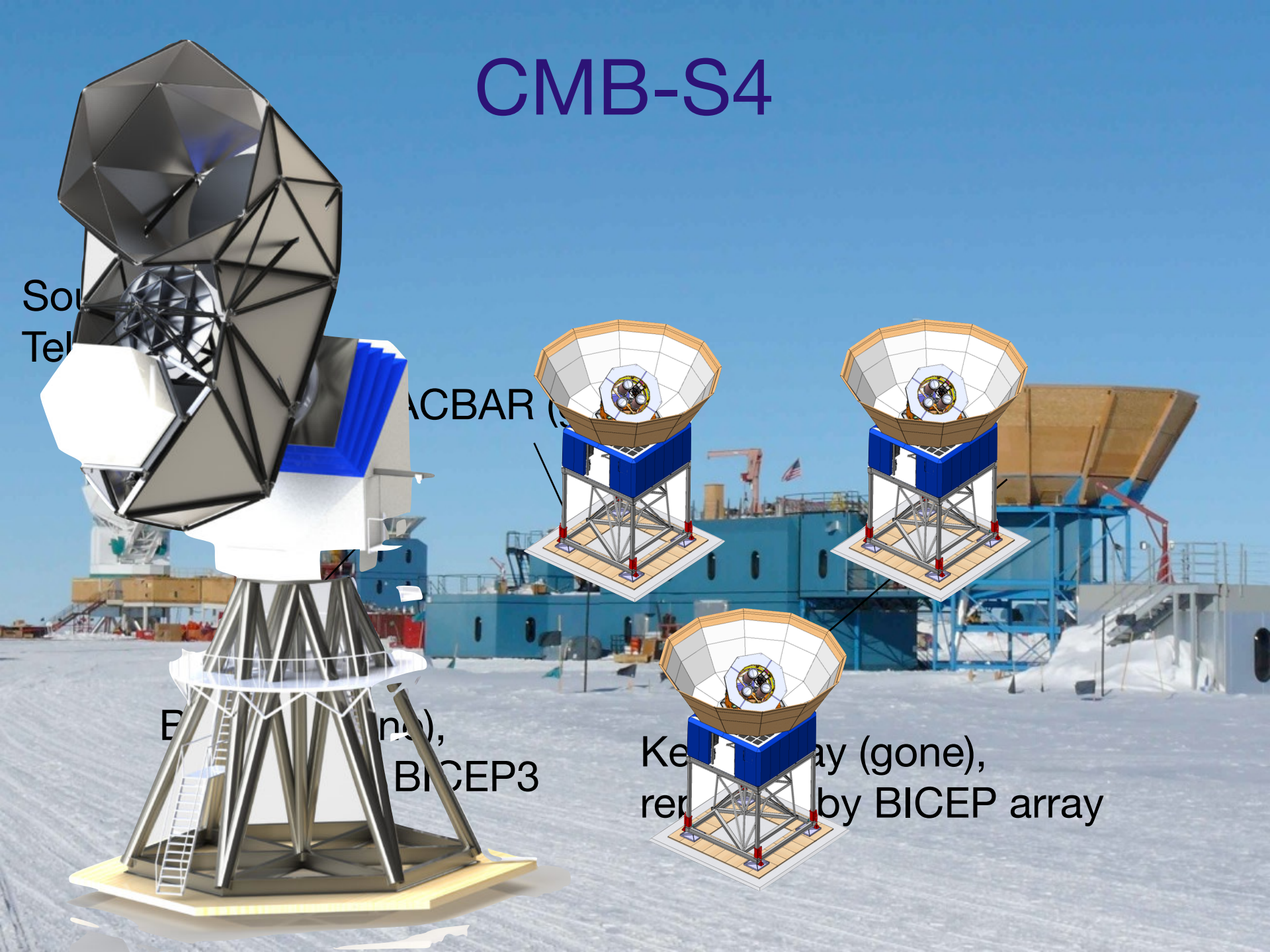
Why is water bad for microwave astronomy?

Remember how your microwave works…

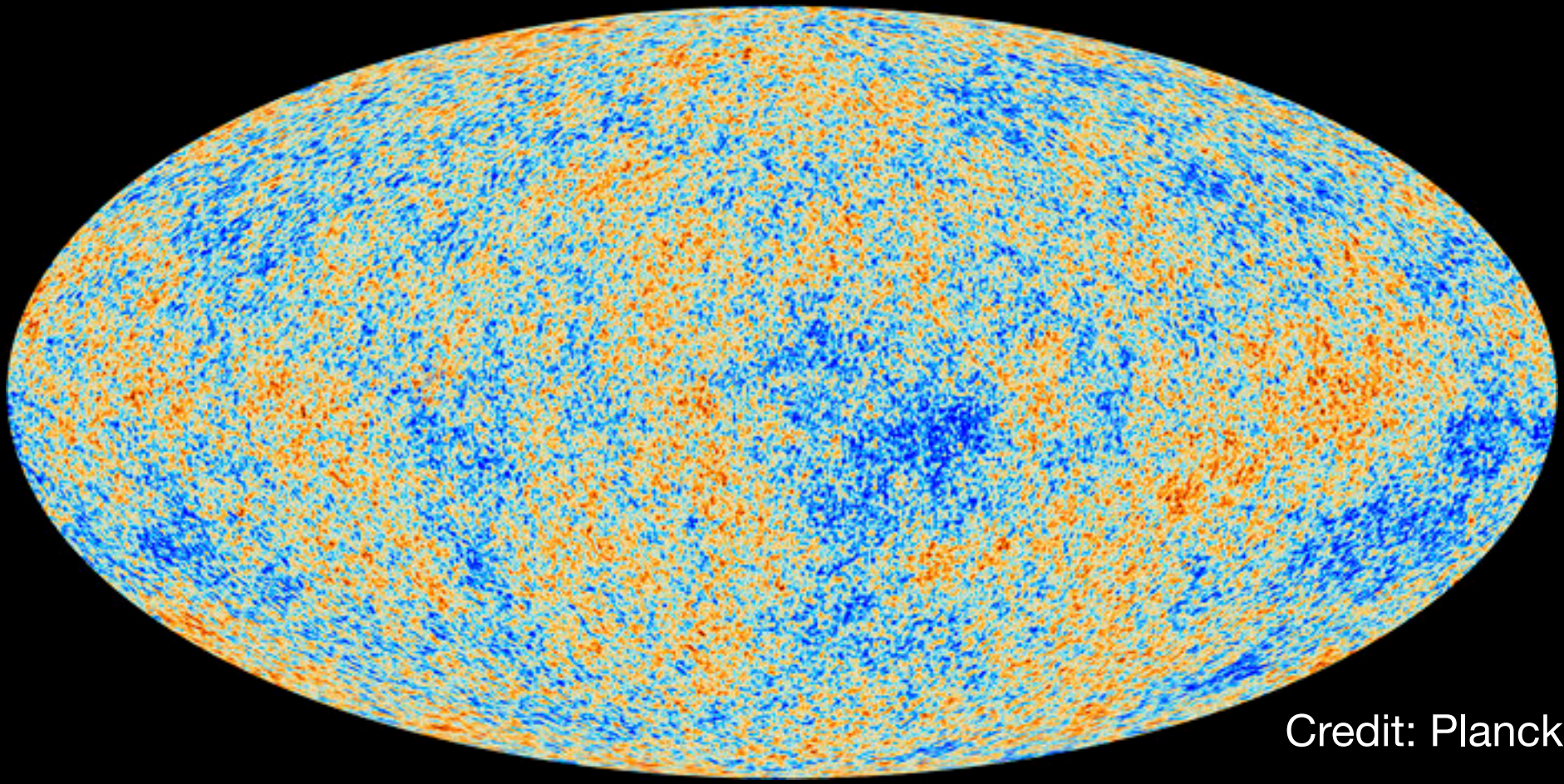
CMB at Pole


South Pole Telescope
ACBAR (gone)
BICEP2 (gone), replaced by BICEP3
Keck Array (gone), replaced by BICEP array

CMB-S4



The goal: exquisite maps of the Universe just after the Big Bang



Credit: Planck

What are we looking at?

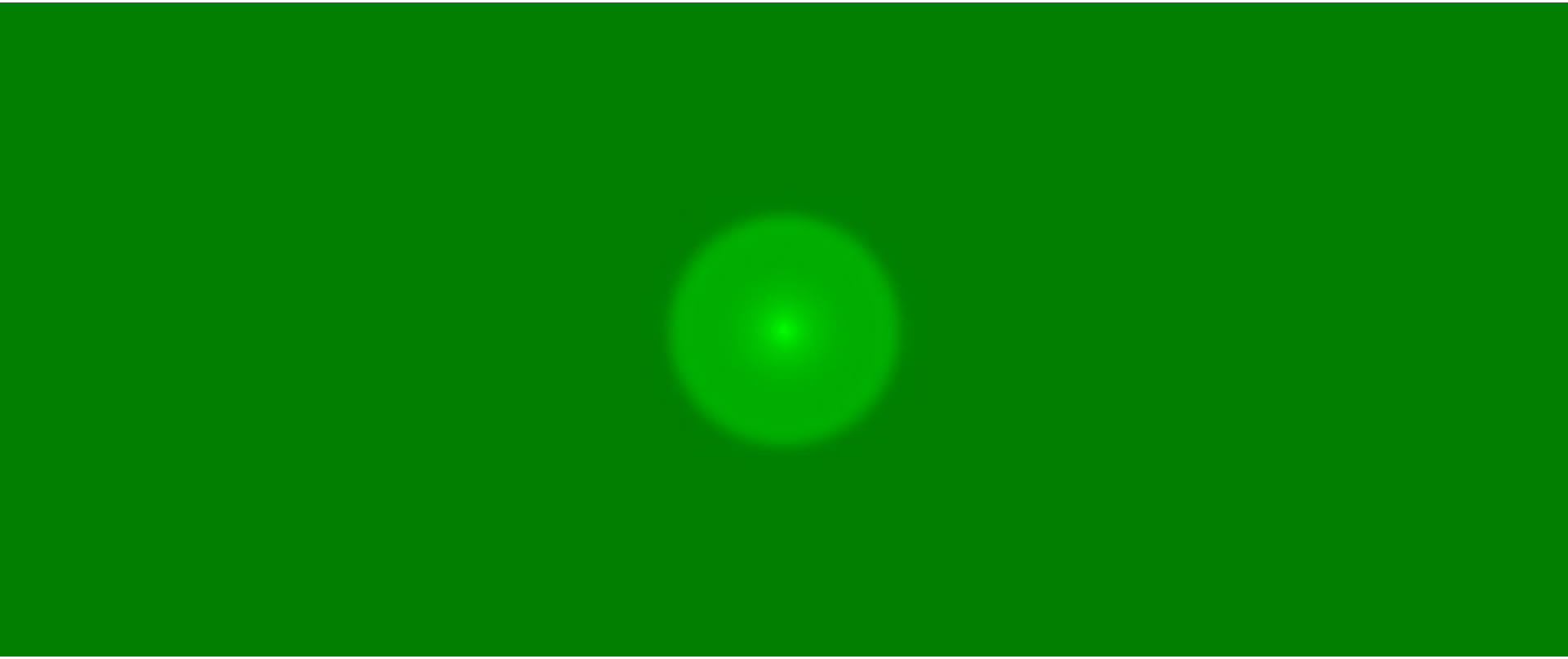
Lots of expanding spherical sound waves

Credit: Sergiu Bacioiu

Credit: Planck

Adding “pebbles”

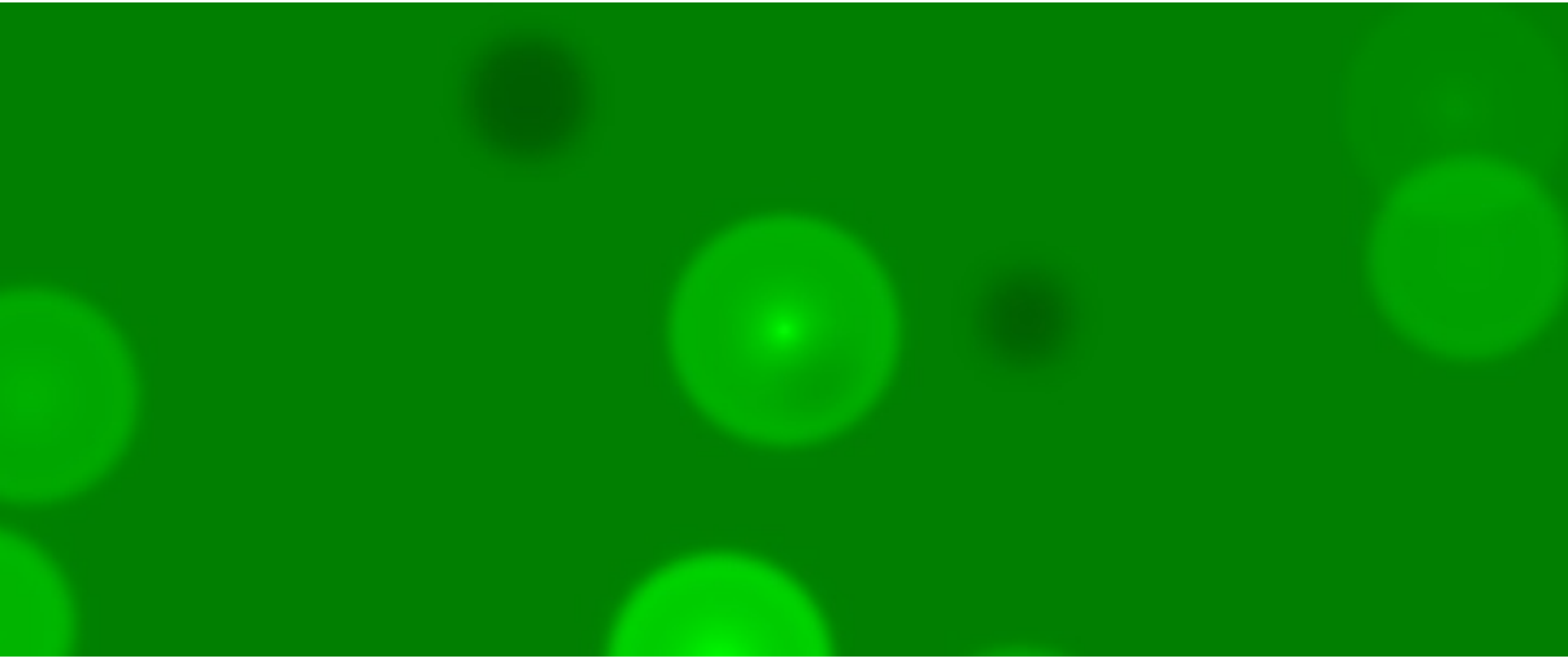
1



Credit: Adam Hincks

Adding “pebbles”

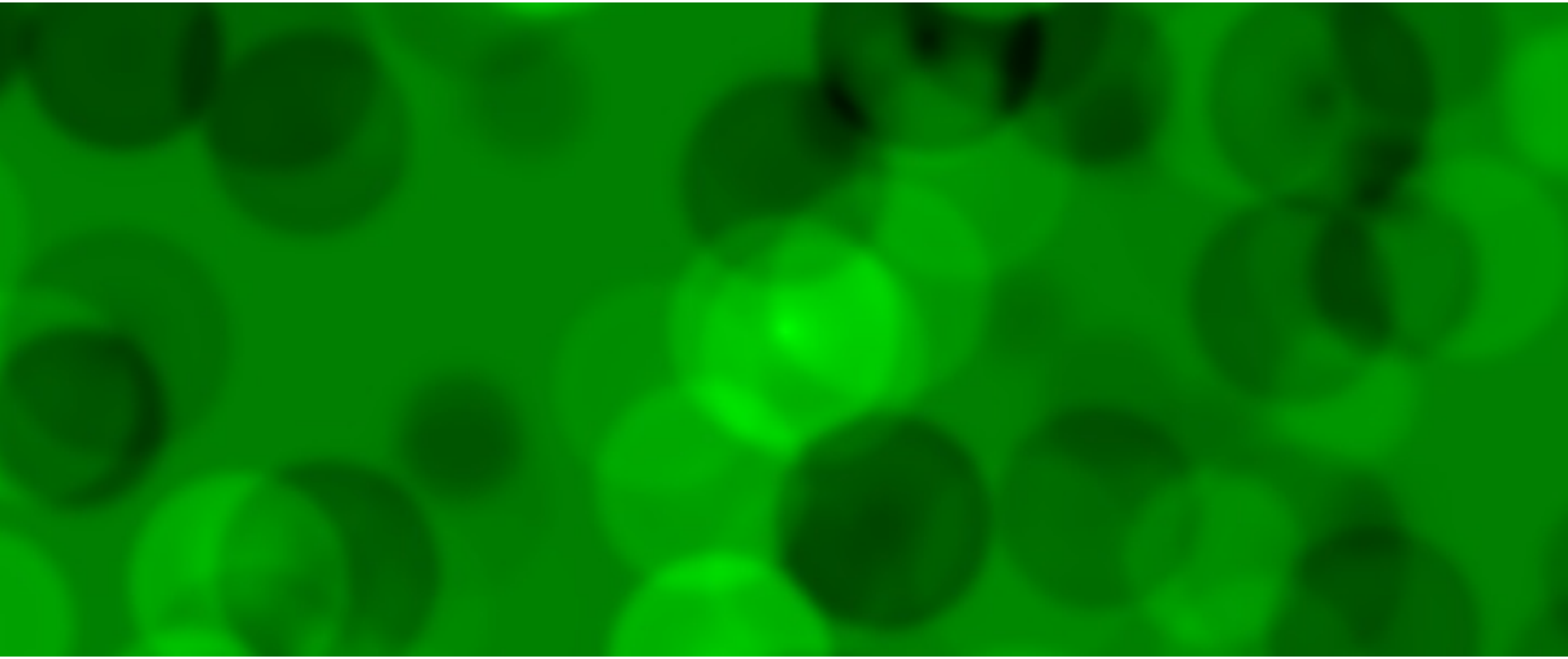
10



Credit: Adam Hincks

Adding “pebbles”

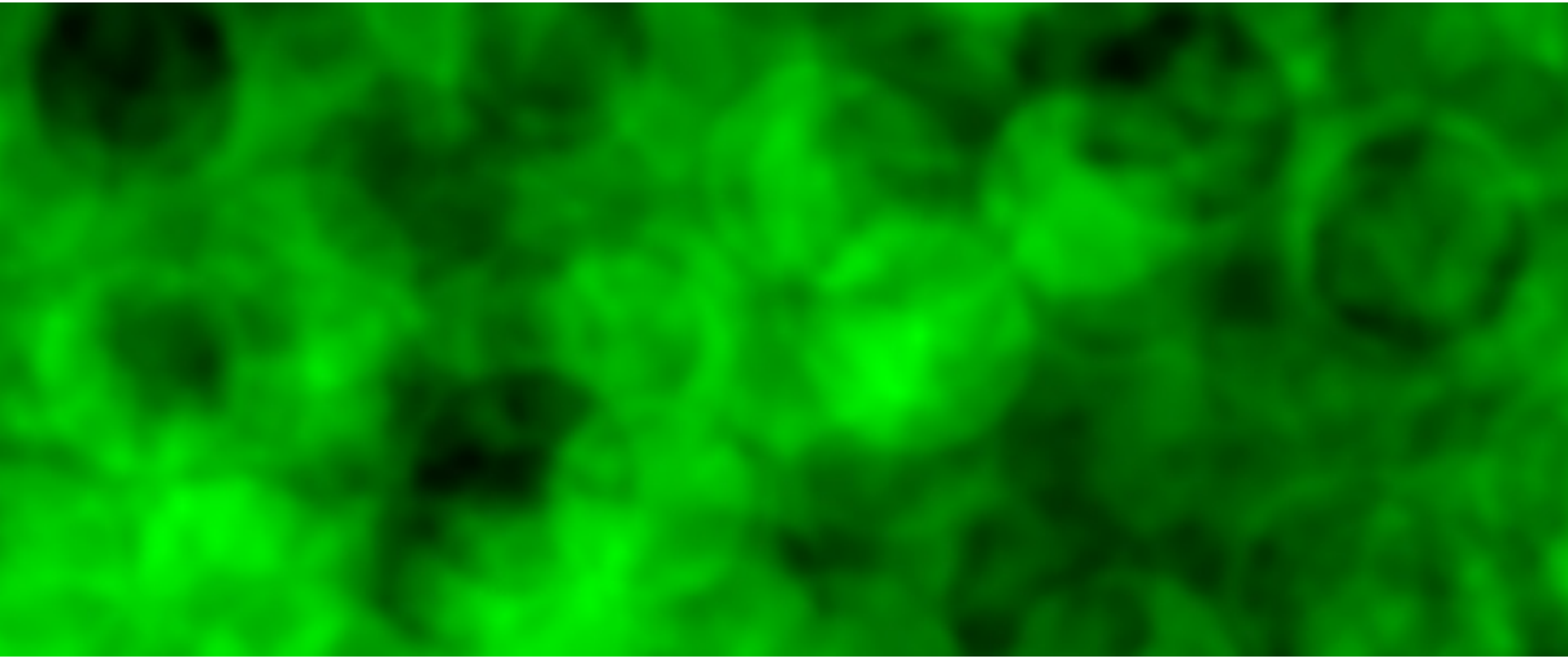
100



Credit: Adam Hincks

Adding “pebbles”

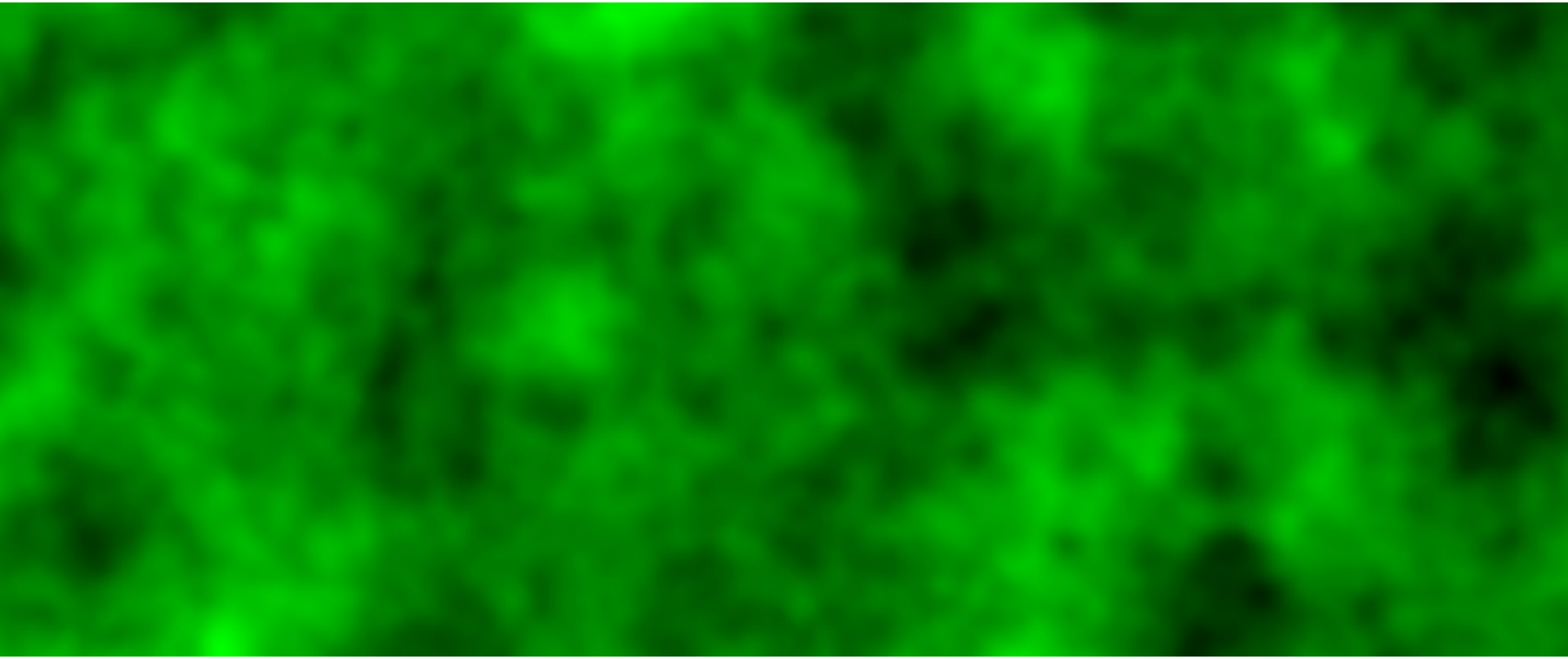
1000



Credit: Adam Hincks

Adding “pebbles”

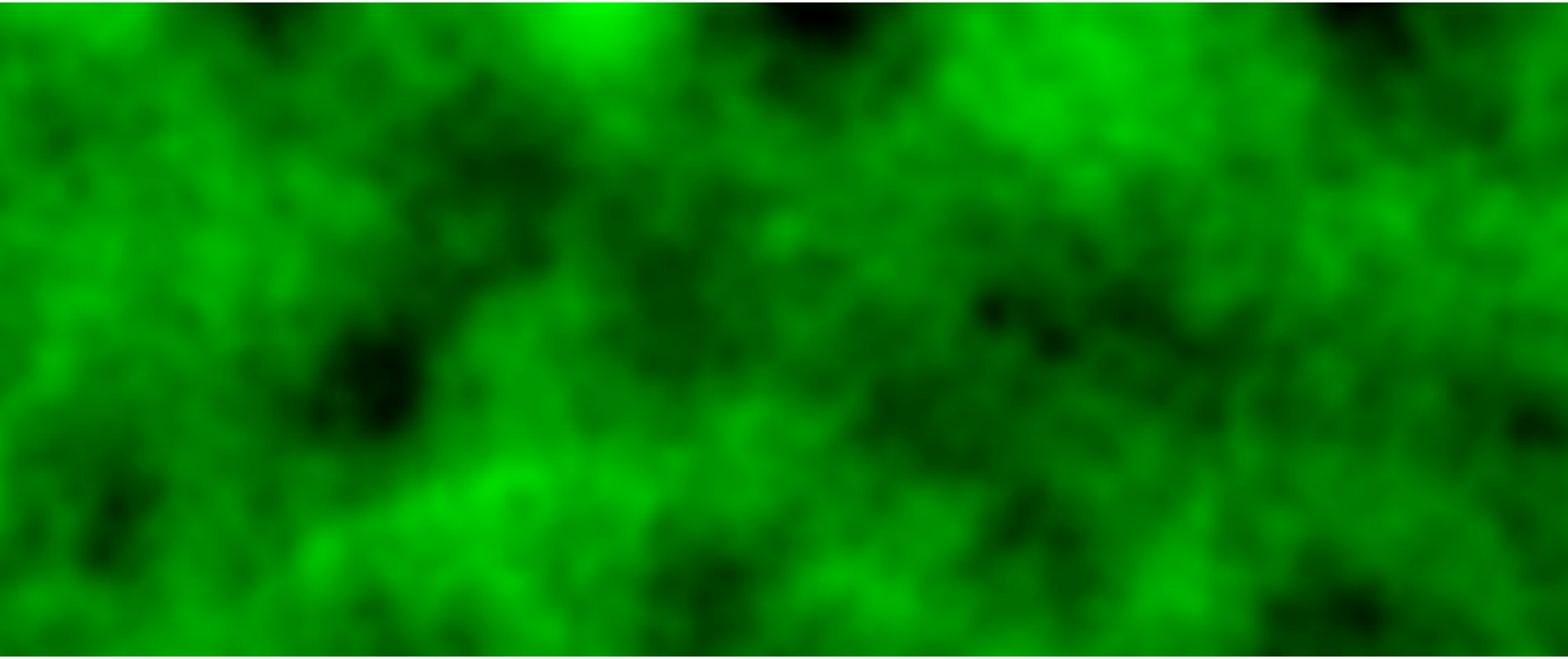
10,000



Credit: Adam Hincks

Adding “pebbles”

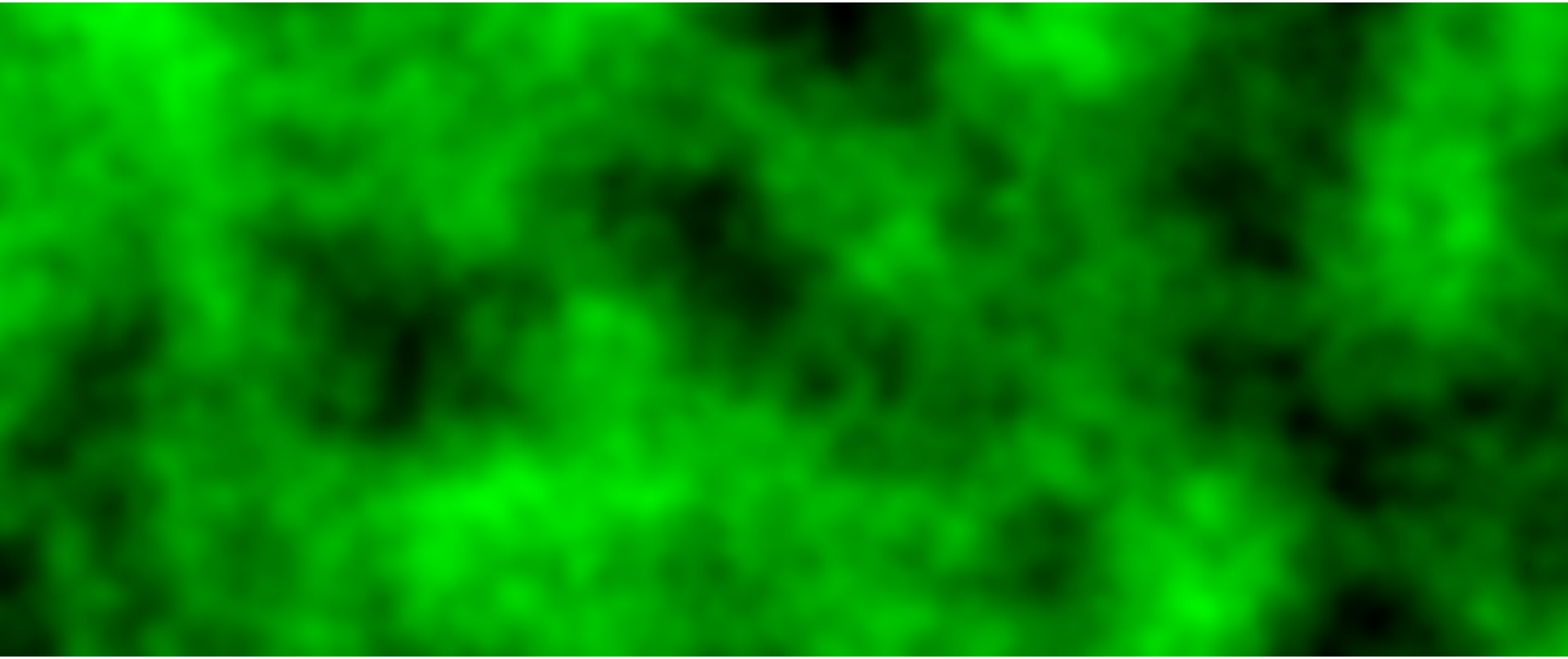
100,000



Credit: Adam Hincks

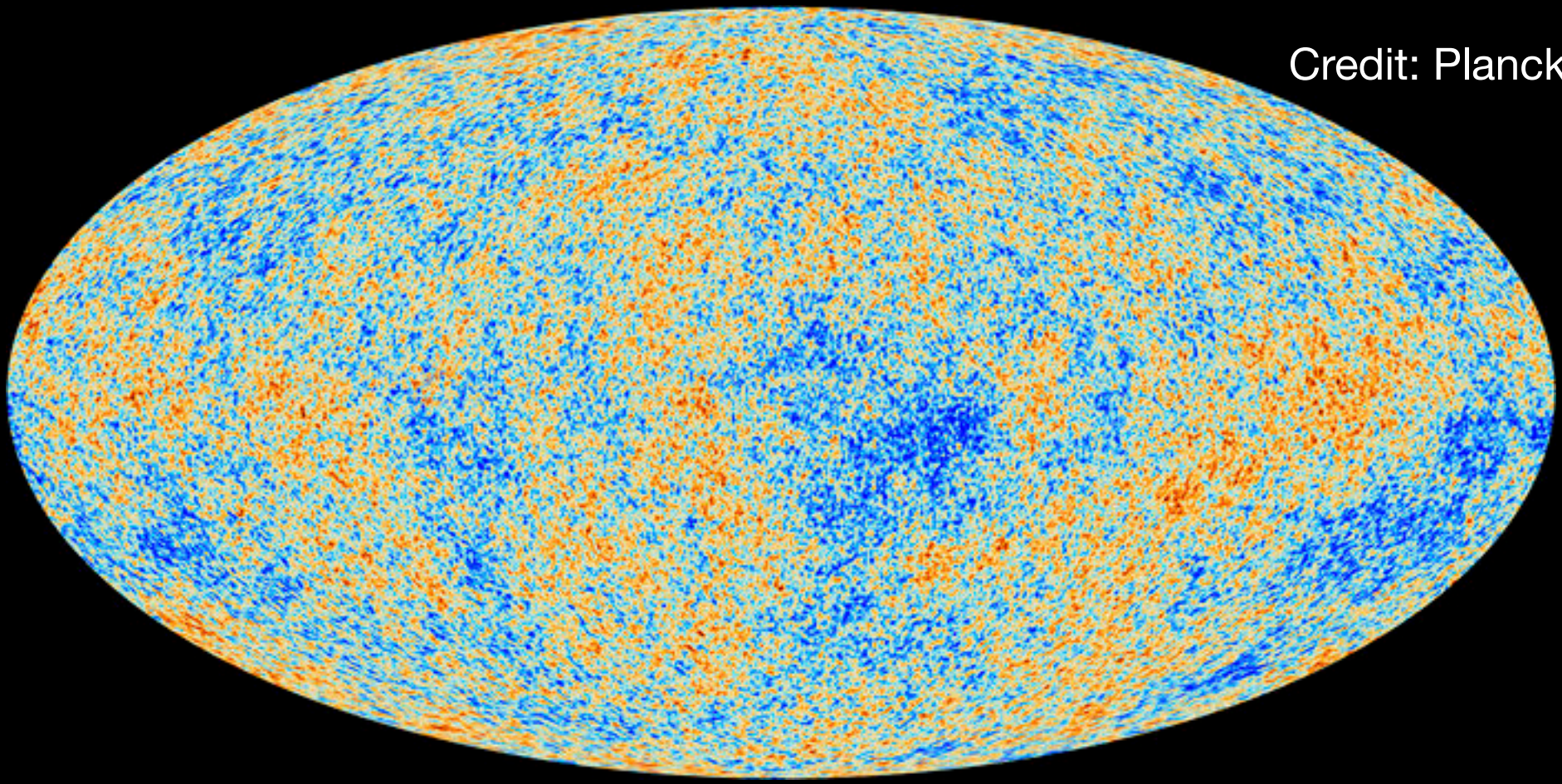
Adding “pebbles”

490,000



Credit: Adam Hincks

We know how sound works!



Credit: Planck

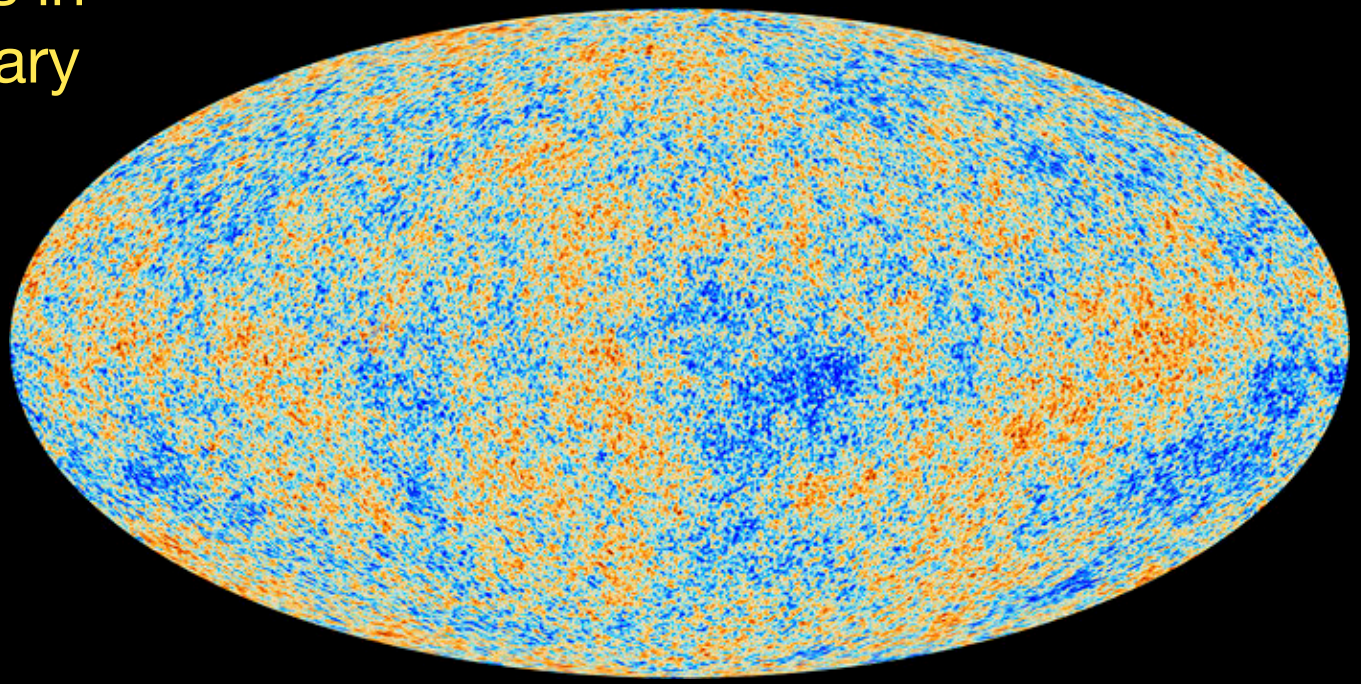
Thus, we can use the patterns to learn about:

what is the Universe made of?

what are the ‘pebbles’ - what caused the Big Bang? What is dark matter?

Follow up: The Smoothness problem

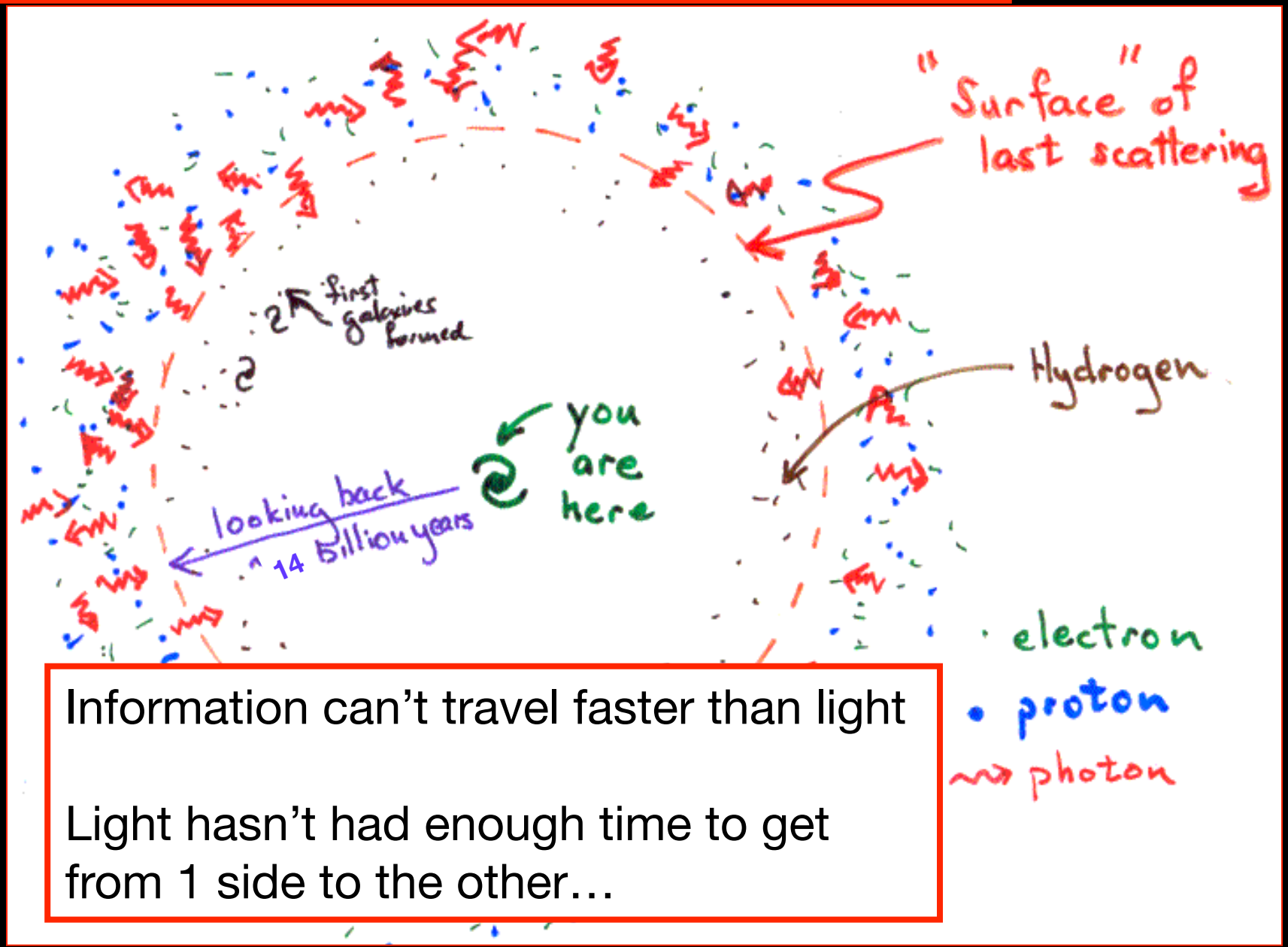
The temperatures in this room likely vary by 1° C
ie 1 part in a 300



How can you do better across the entire Universe?!?

Observed temperature variations in CMB:
1 part in 100,000

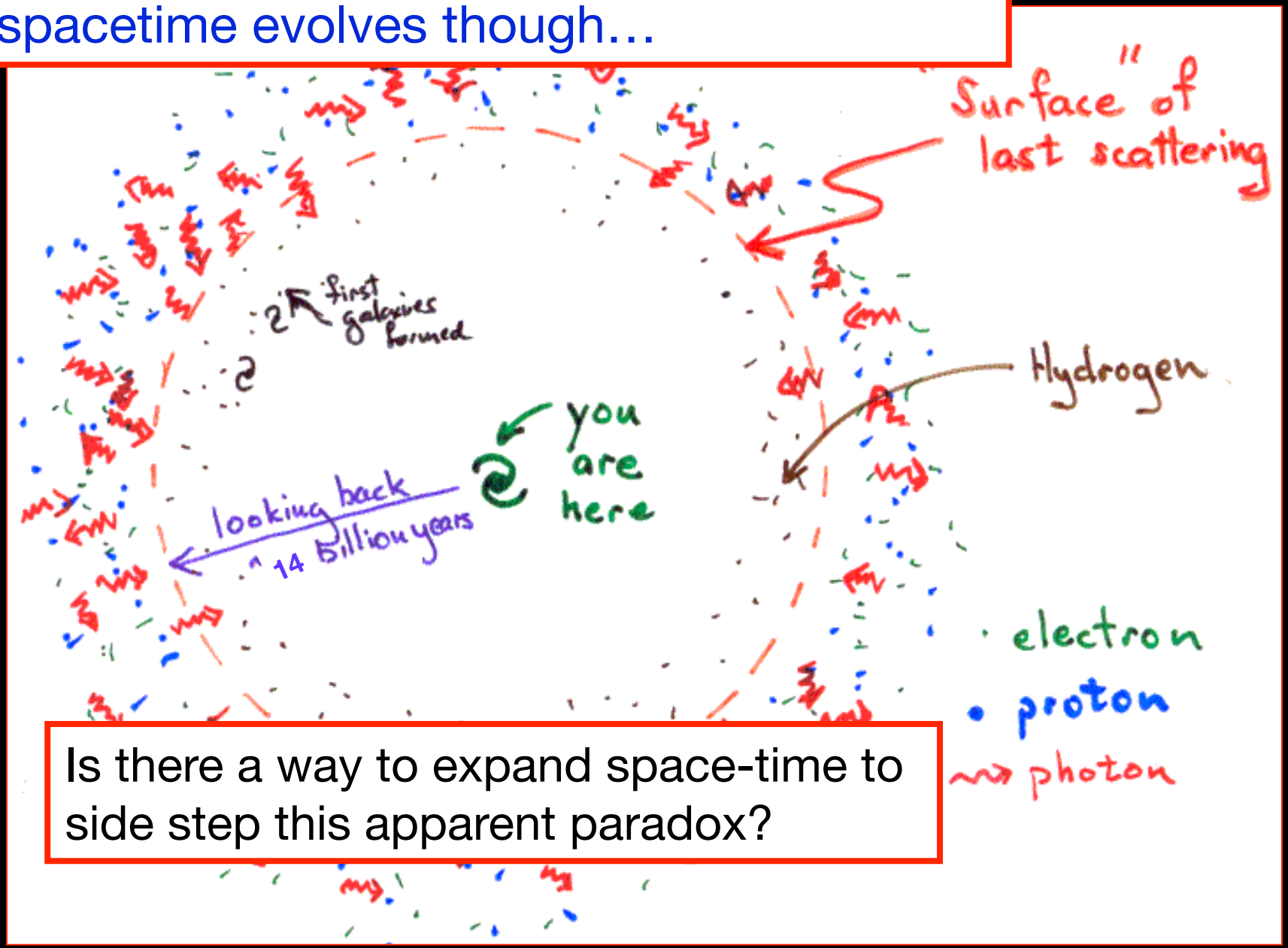
Is special relativity wrong???



Information can't travel faster than light

Light hasn't had enough time to get from 1 side to the other…

Special relativity says nothing about how spacetime evolves though…



Is there a way to expand space-time to side step this apparent paradox?

Solving the Smoothness Problem

It's easy, in

~0.00000000000000000000000000001 seconds

you simply stretch out space by at least

100,000,000,000,000,000,000,000,000,000 times

That's

INFLATION

Can we see Inflation?

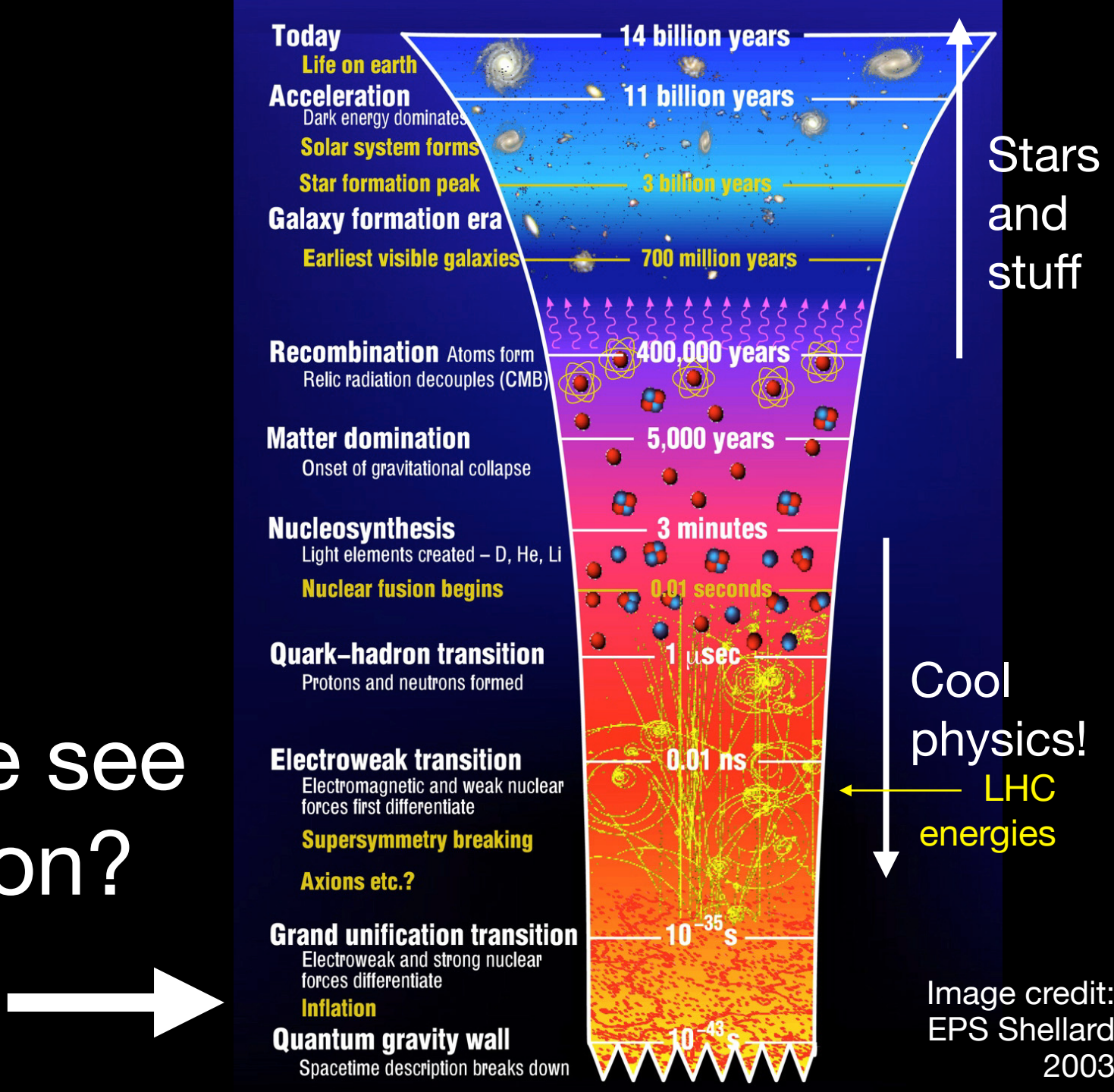


Image credit: EPS Shellard 2003

~400,000 years post Big Bang

Light

Early Universe is opaque to light

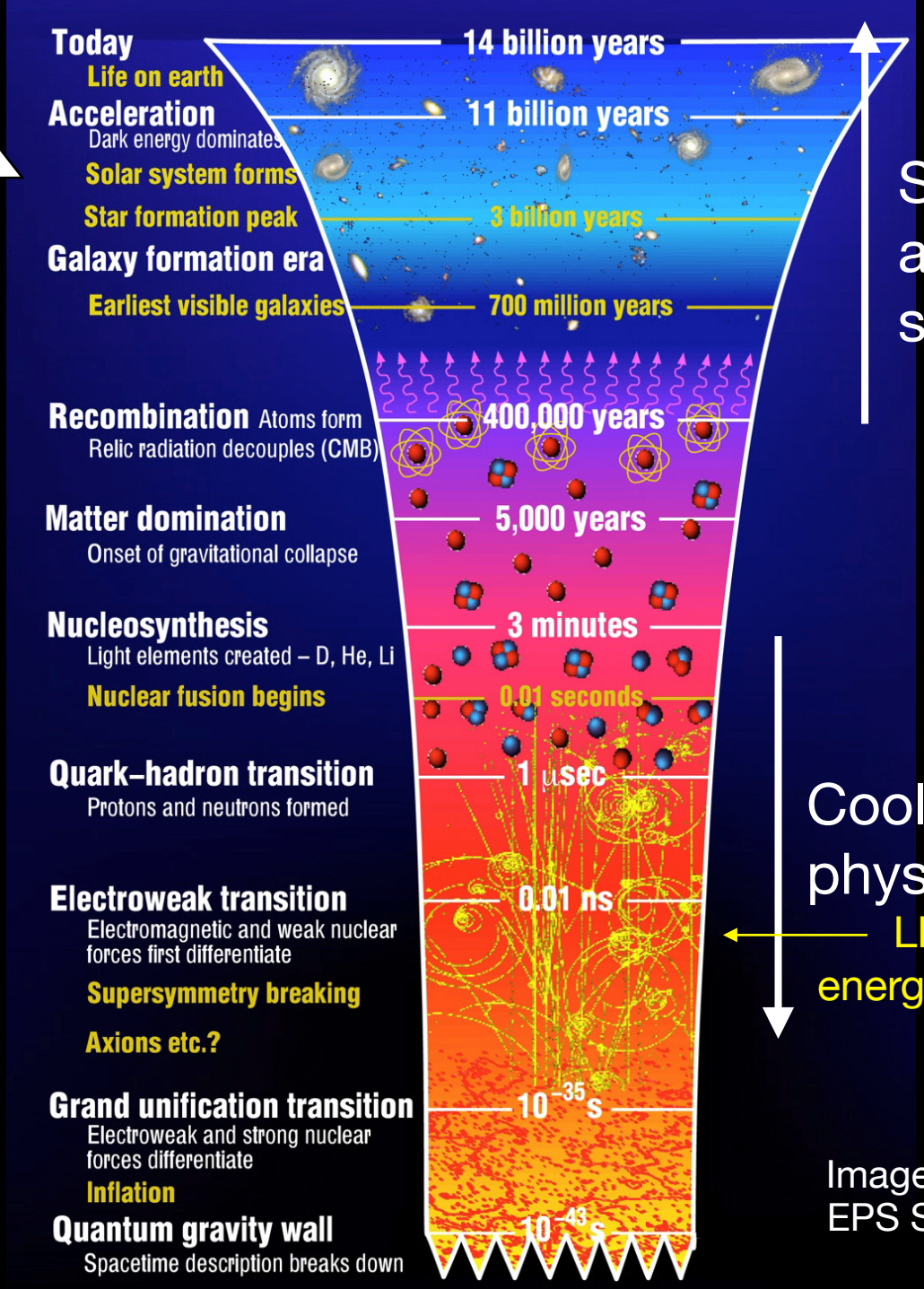


Image credit: EPS Shellard 2003

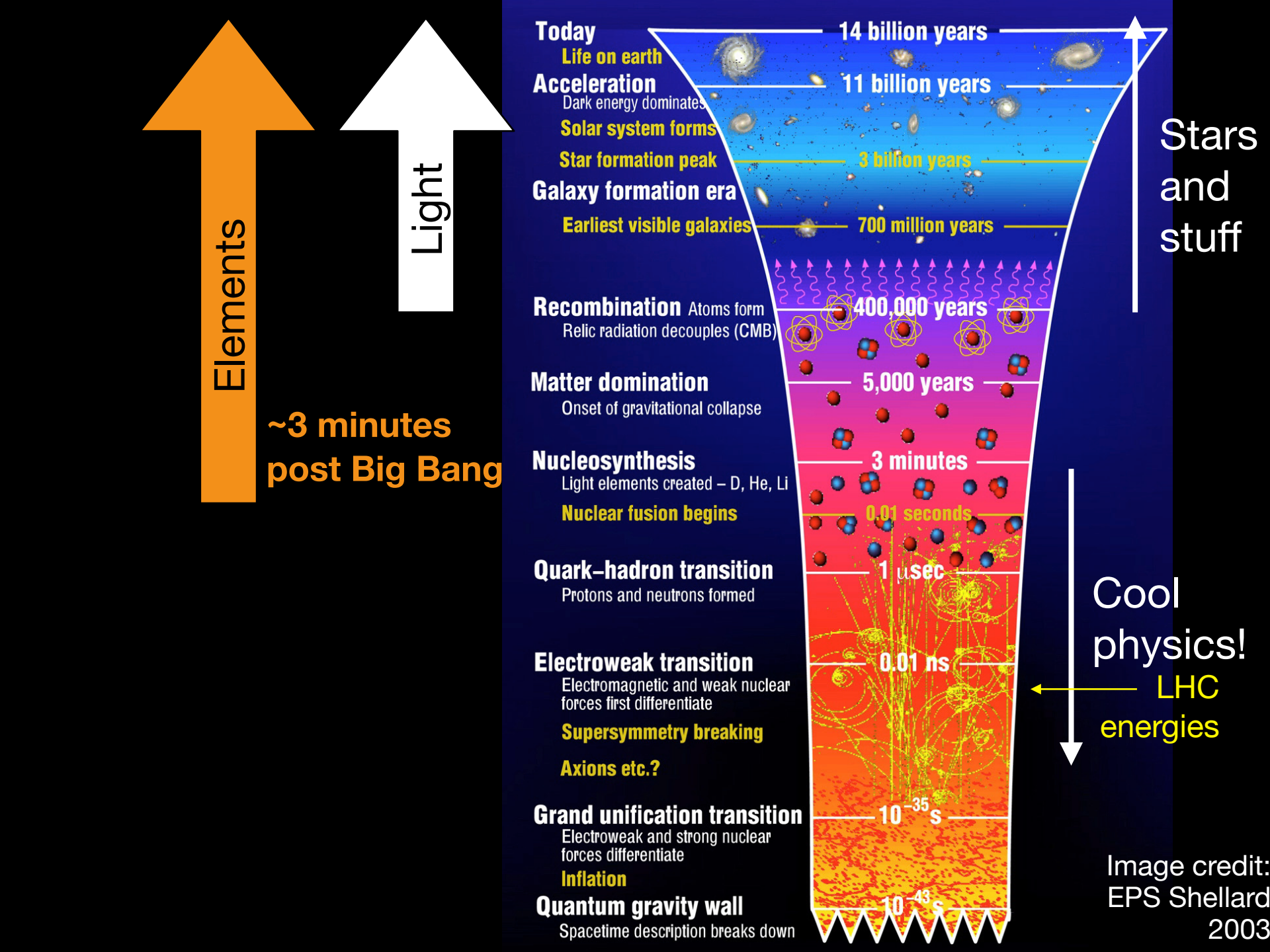


Image credit: EPS Shellard 2003

Gravitational Waves

Elements

Light

Early Universe is opaque to light

but not gravitational waves

so maybe

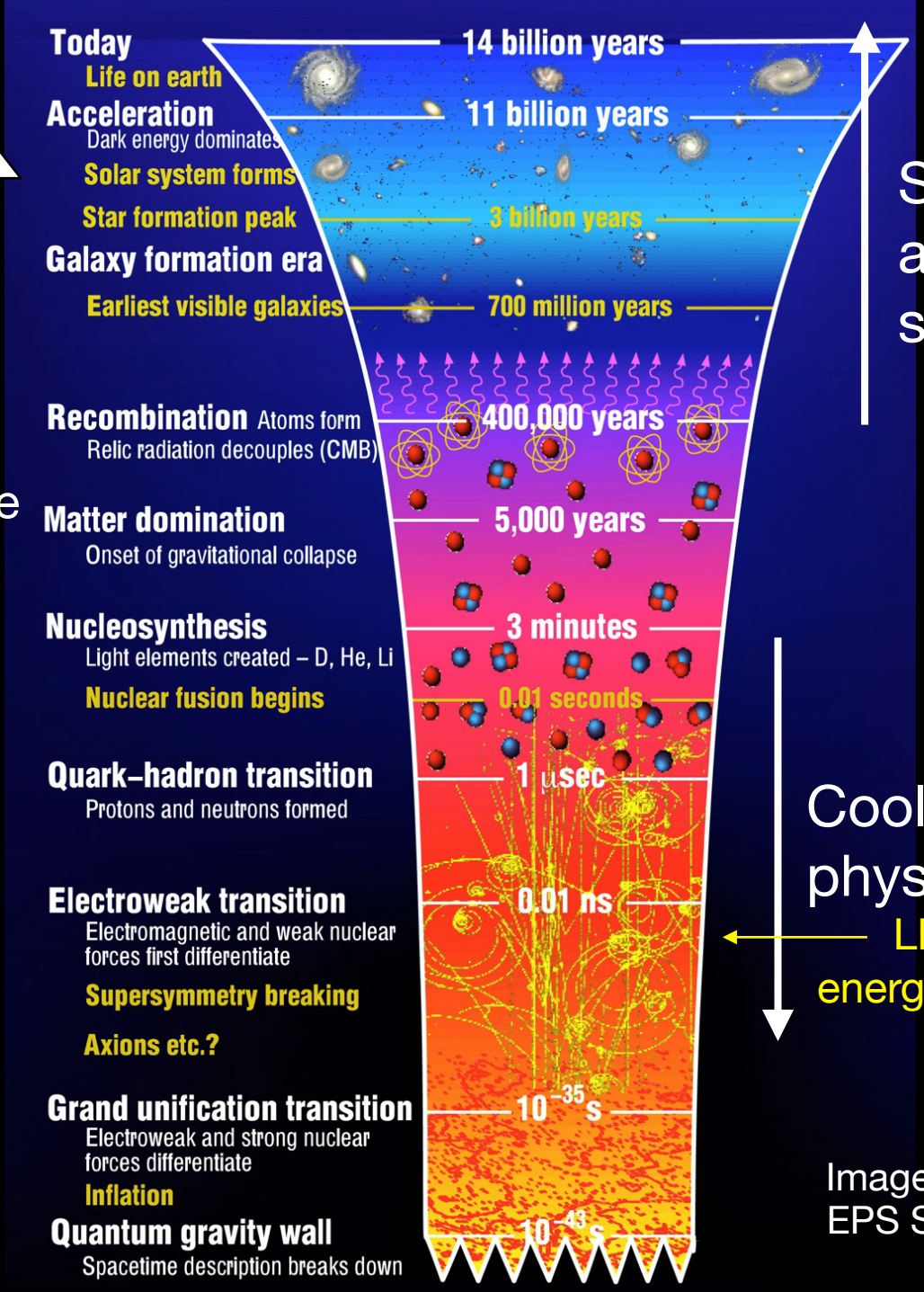
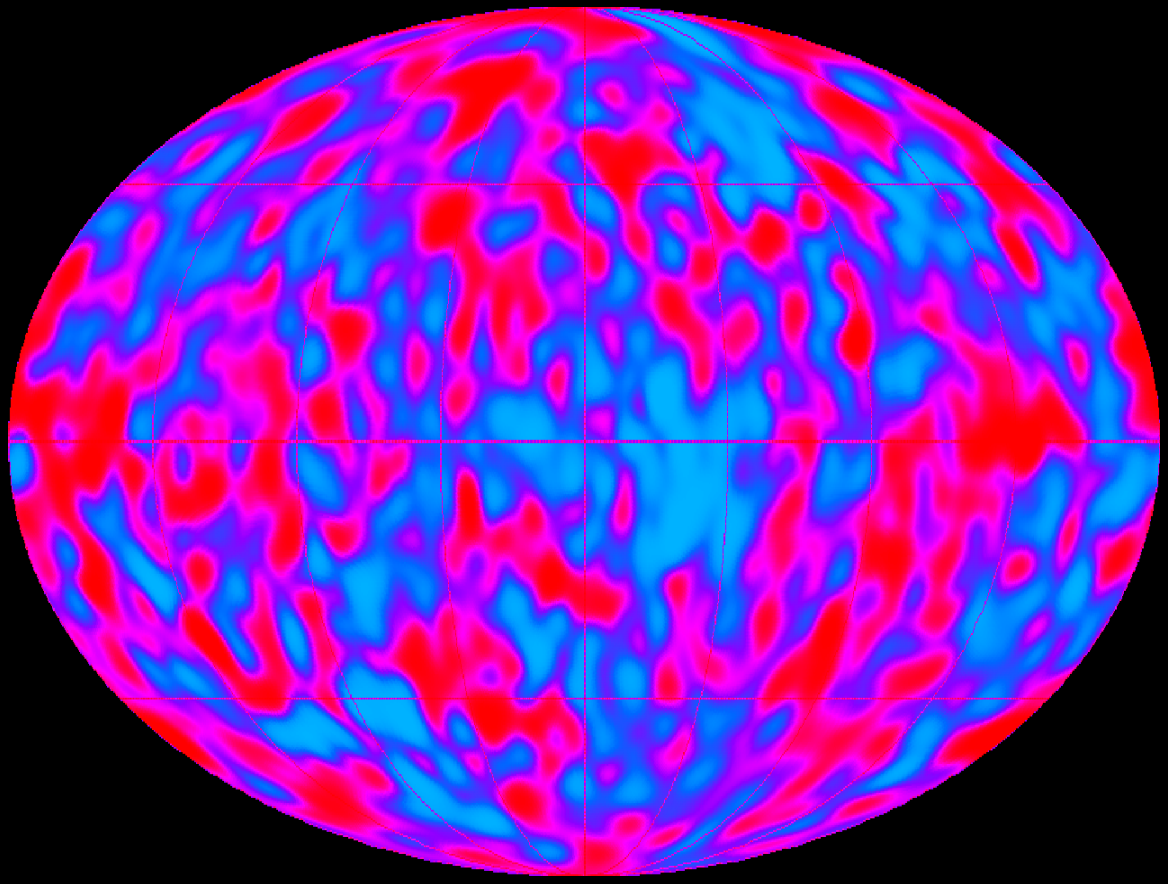


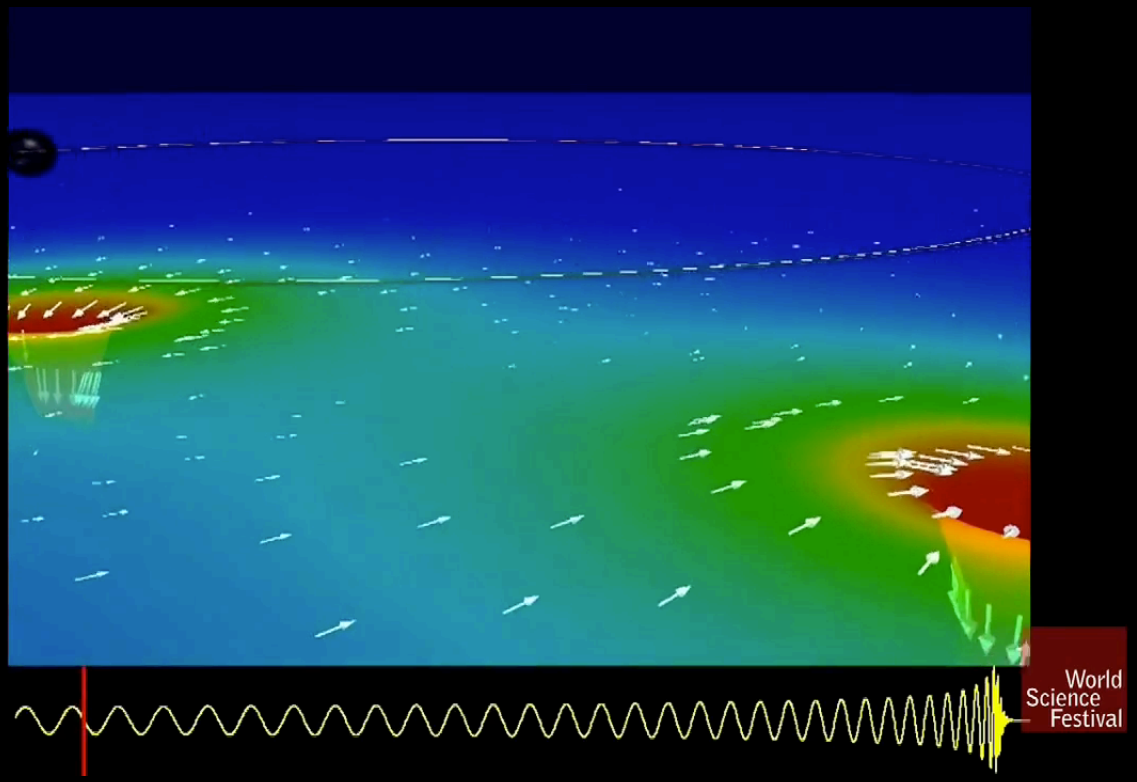
Image credit: EPS Shellard 2003

Will there be gravitational waves?



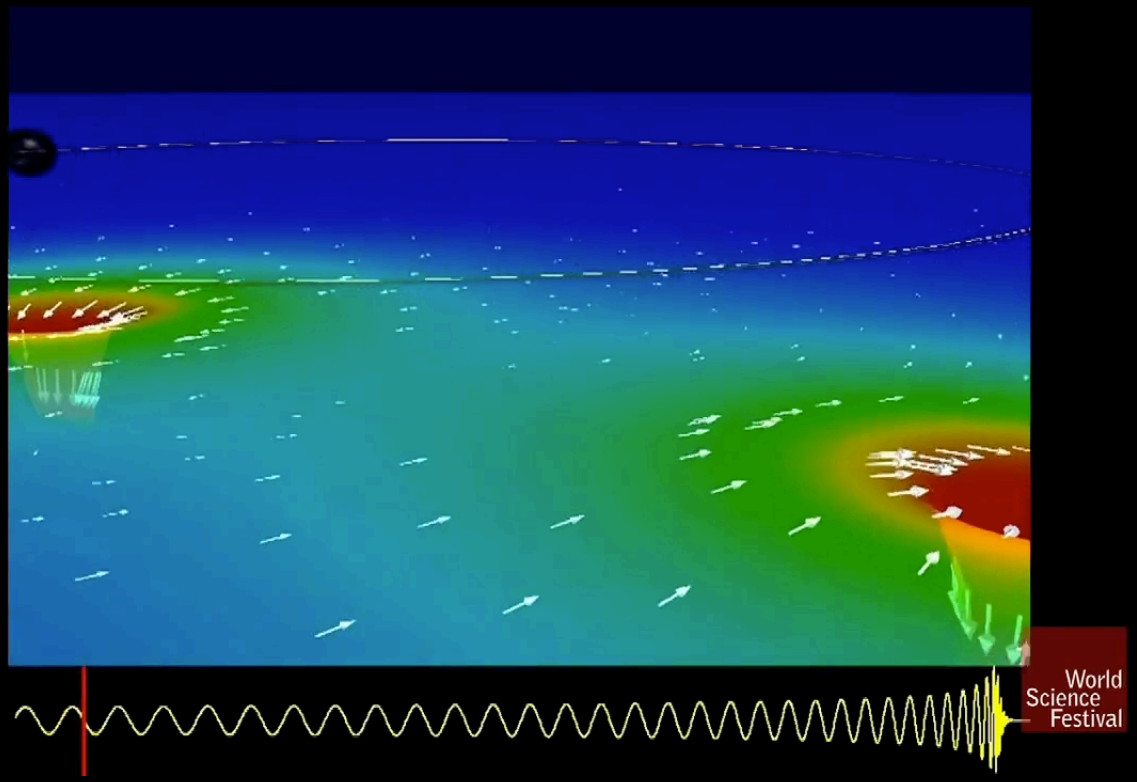
Will there be gravitational waves?

- G. Waves come from accelerating masses



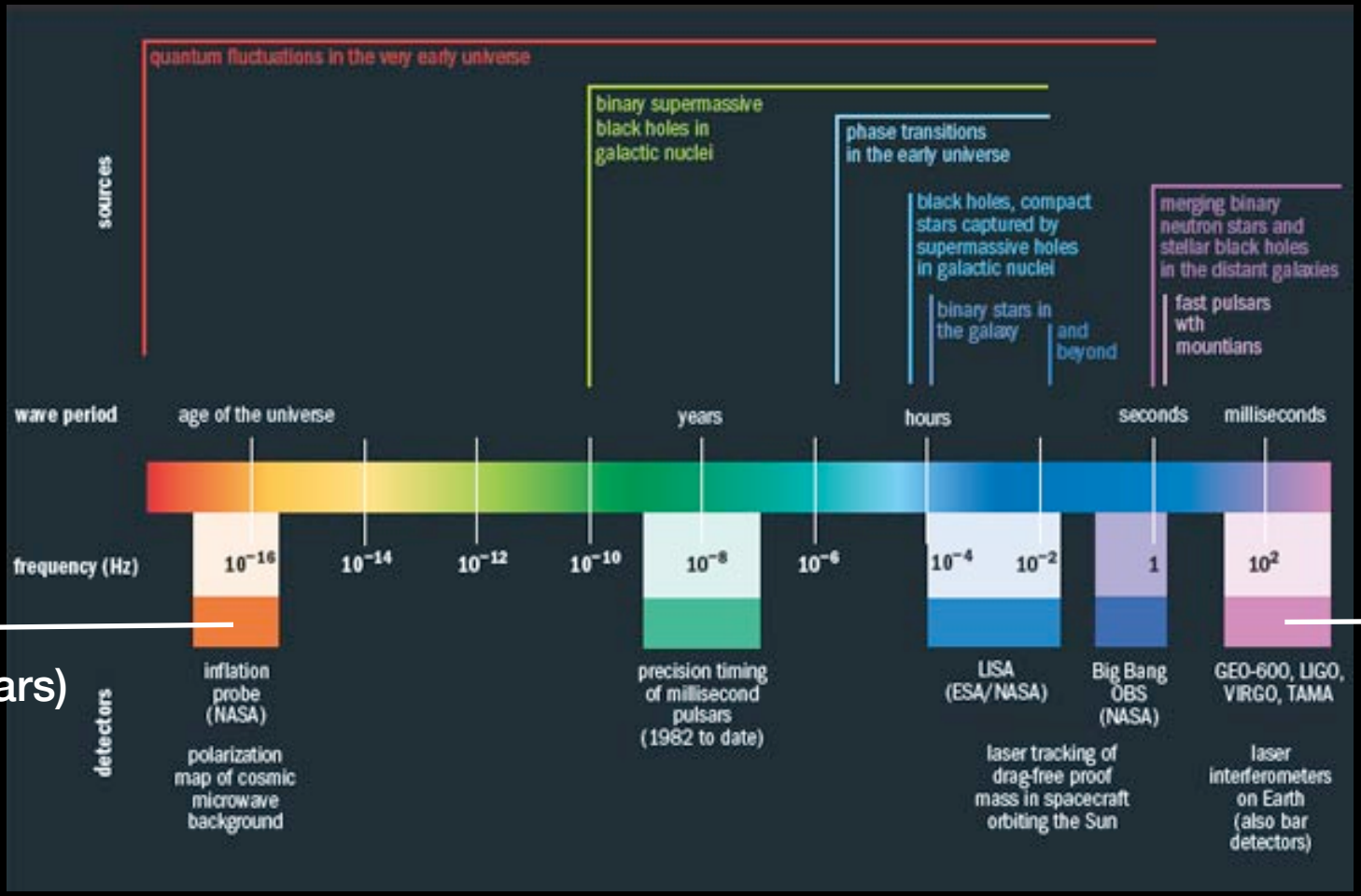
Will there be gravitational waves?

- G. Waves come from accelerating masses
- Plenty of acceleration…
- Almost perfectly homogenous …
  - But still quantum fluctuations



So yes

Wavelengths comparable to the size of the Universe



Inflation (CMB): $T=10^{16}$ s

(billion years)

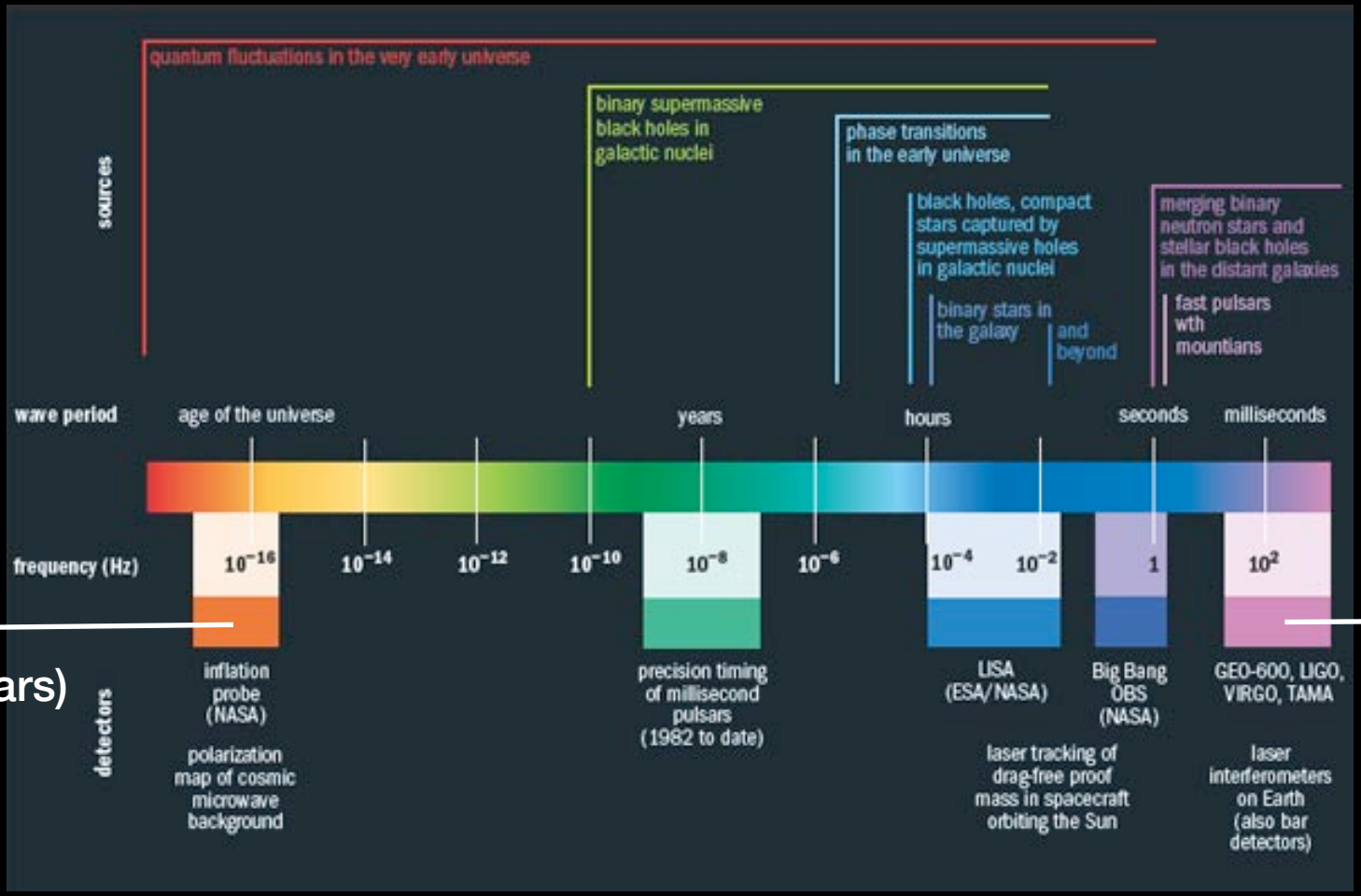
Neutron star mergers (LIGO): $T=10^{-2}$ s

(10 ms)

A million trillion times larger than LIGO

Inflation (CMB): $T=10^{16}$ s

(billion years)



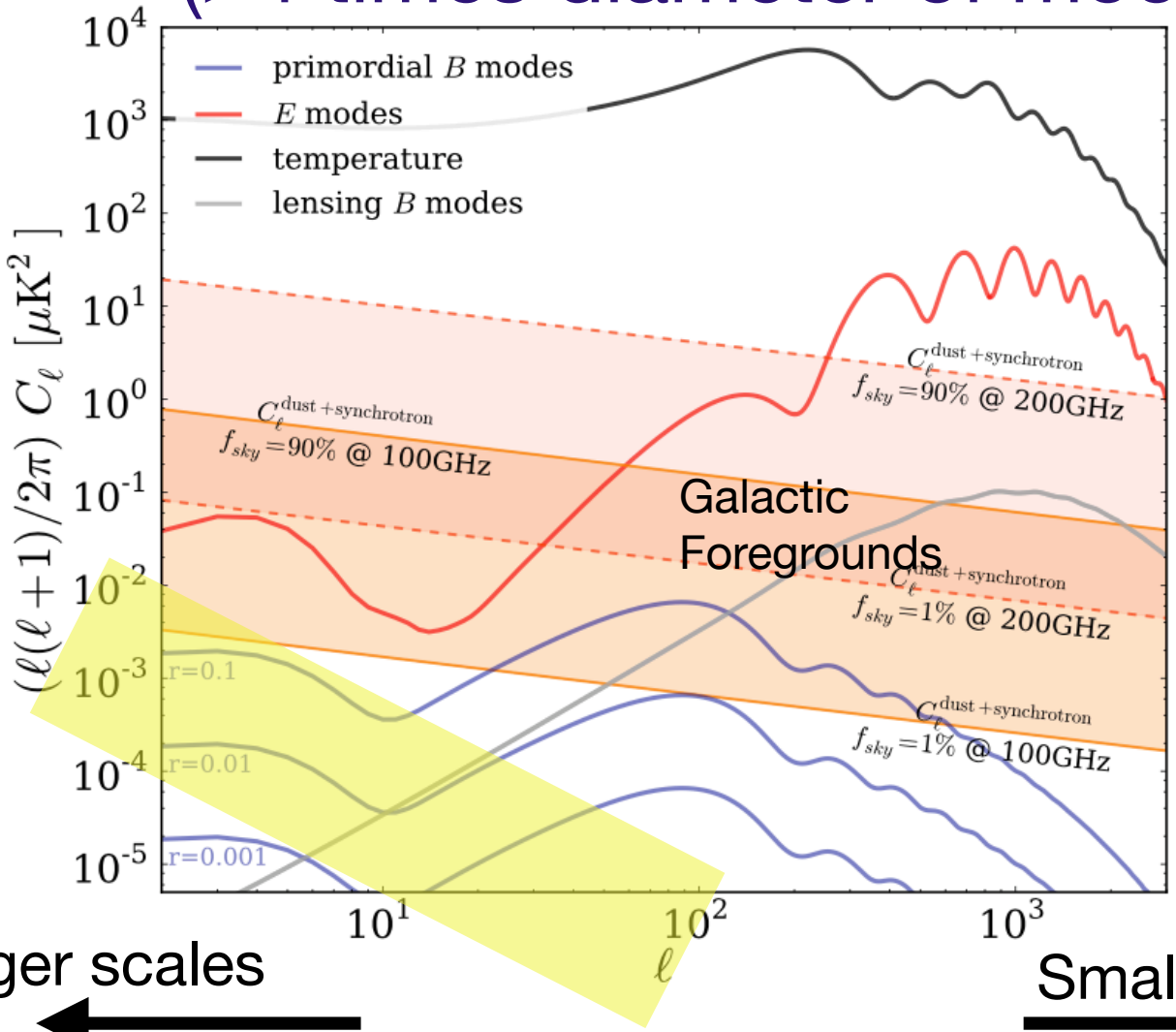
Neutron star mergers (LIGO): $T=10^{-2}$ s

(10 ms)

We can't build a big enough tunnel…

G. Waves show up as polarized power at large scales

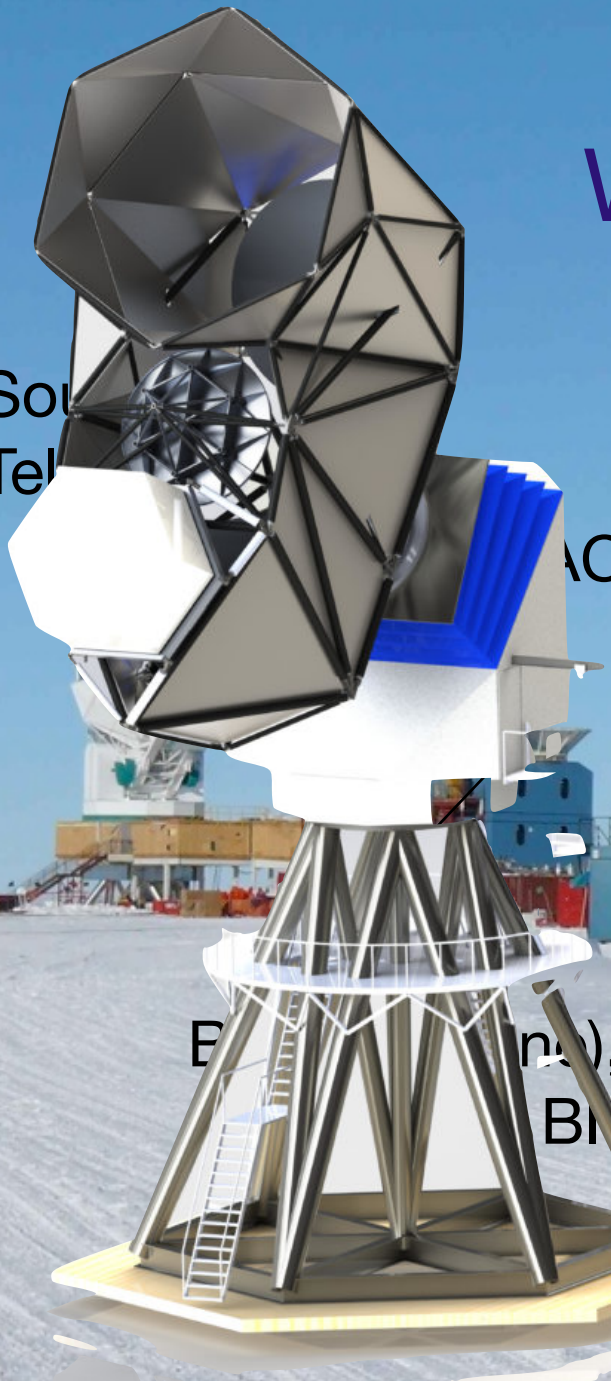
(>4 times diameter of moon)



from CMB-S4 Science Book

Larger scales ← → Smaller scales

CMB-S4 at Pole: Will we detect GWs from inflation?



Sou
Tel

ACBAR (

B ne),
BICEP3

Array (gone),
ed by BICEP array

Searches underway for gravitational waves from inflation

Movie Credit:
Robert
Schwartz

Questions?