

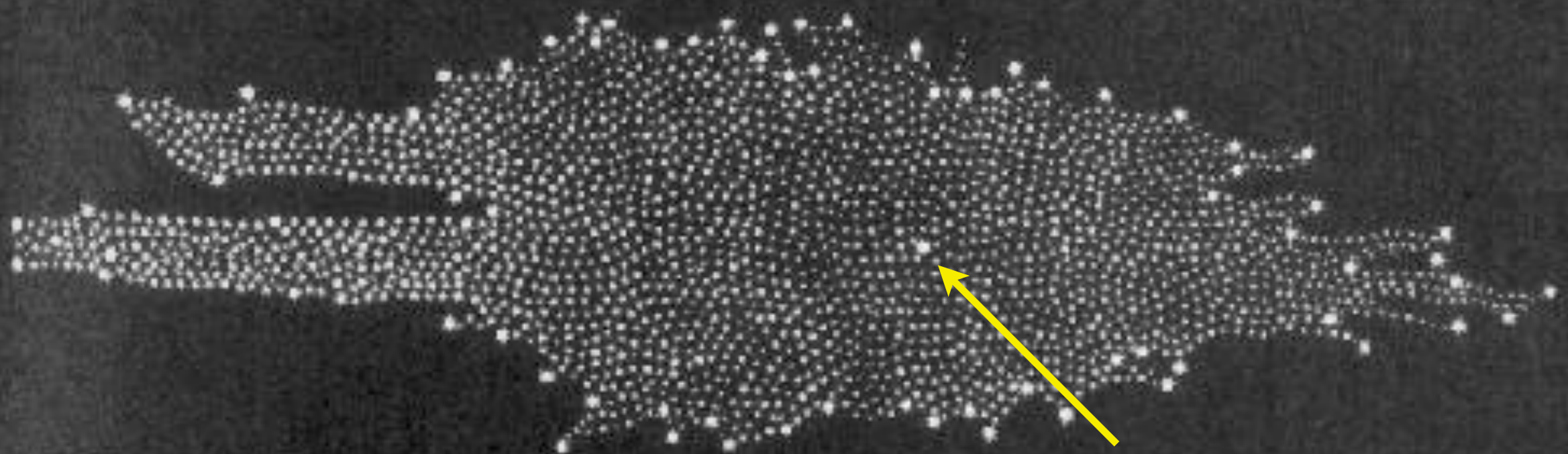
Detecting Gravitational Radiation from the Beginning of the Universe

Prof. Kevork N. Abazajian

Department of Physics & Astronomy

UCI University of
California, Irvine

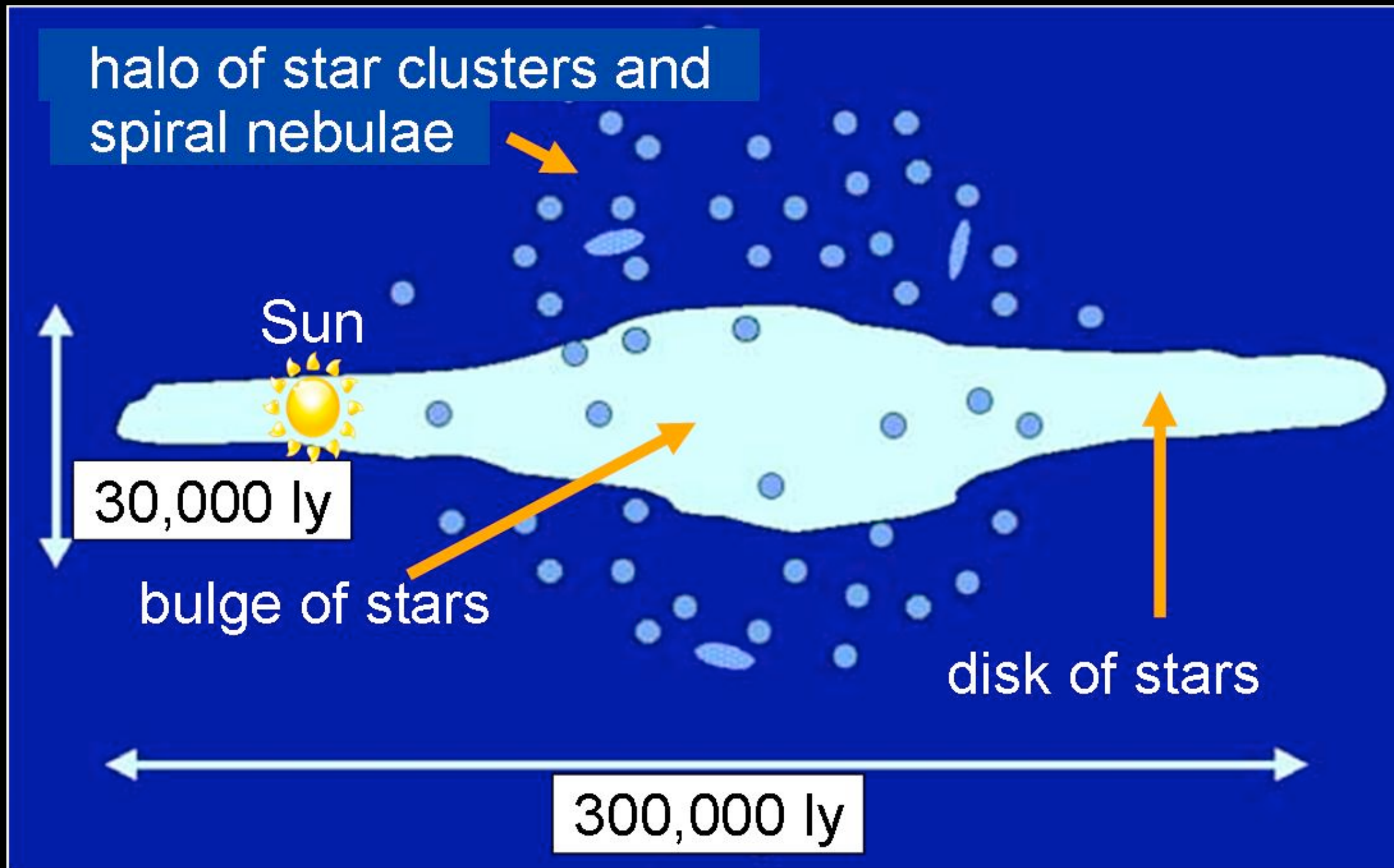
The Universe in 1785: Herschel's Map



The Sun

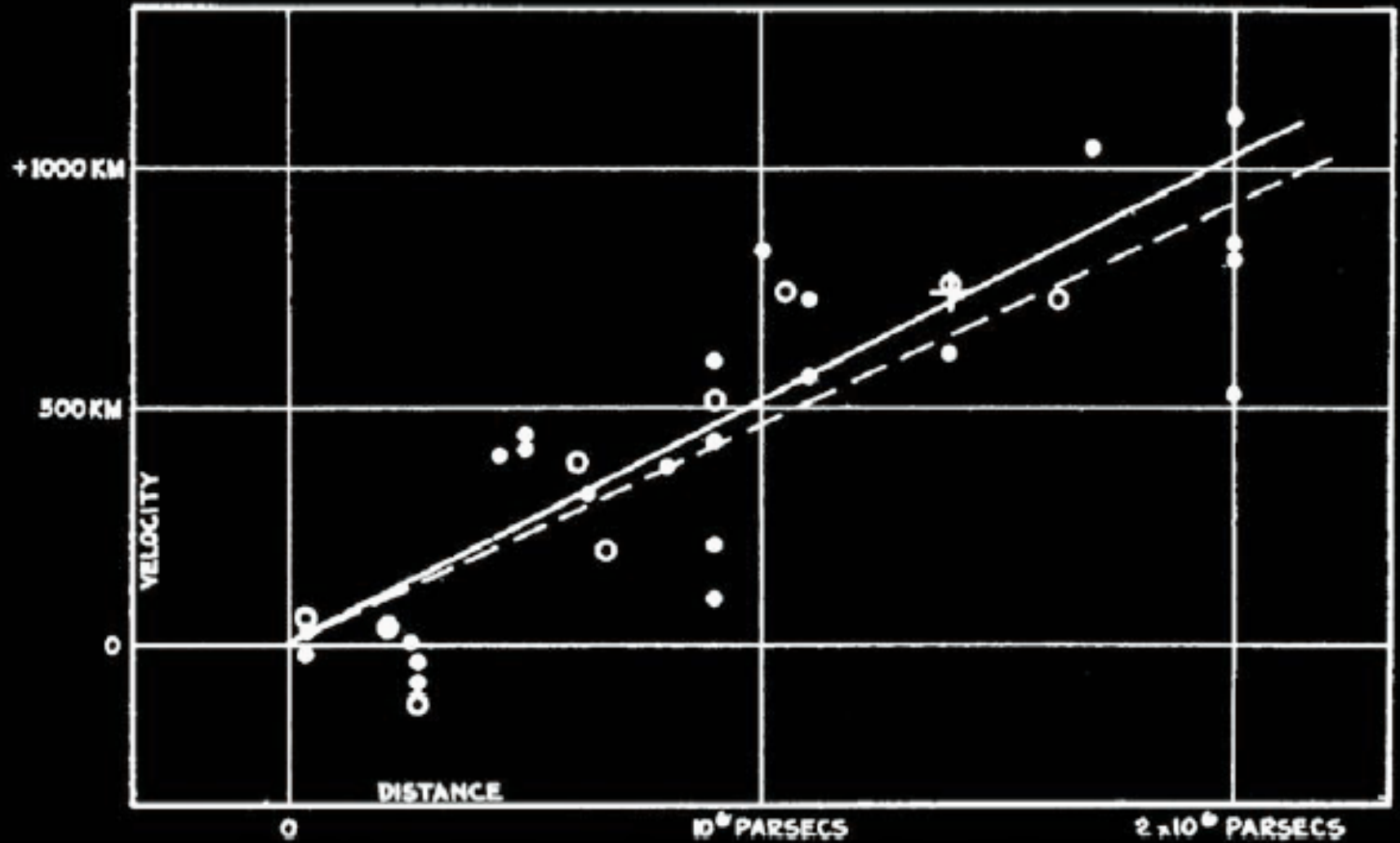
Star map assuming
constant luminosity and
density

The Universe in 1921: The Shapley Model



Hubble's new distance determinations (1929)

velocity, v (km/s)

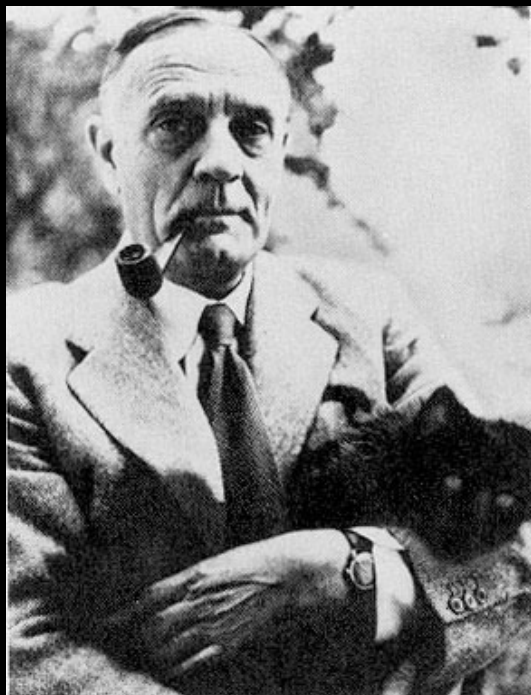


distance, d

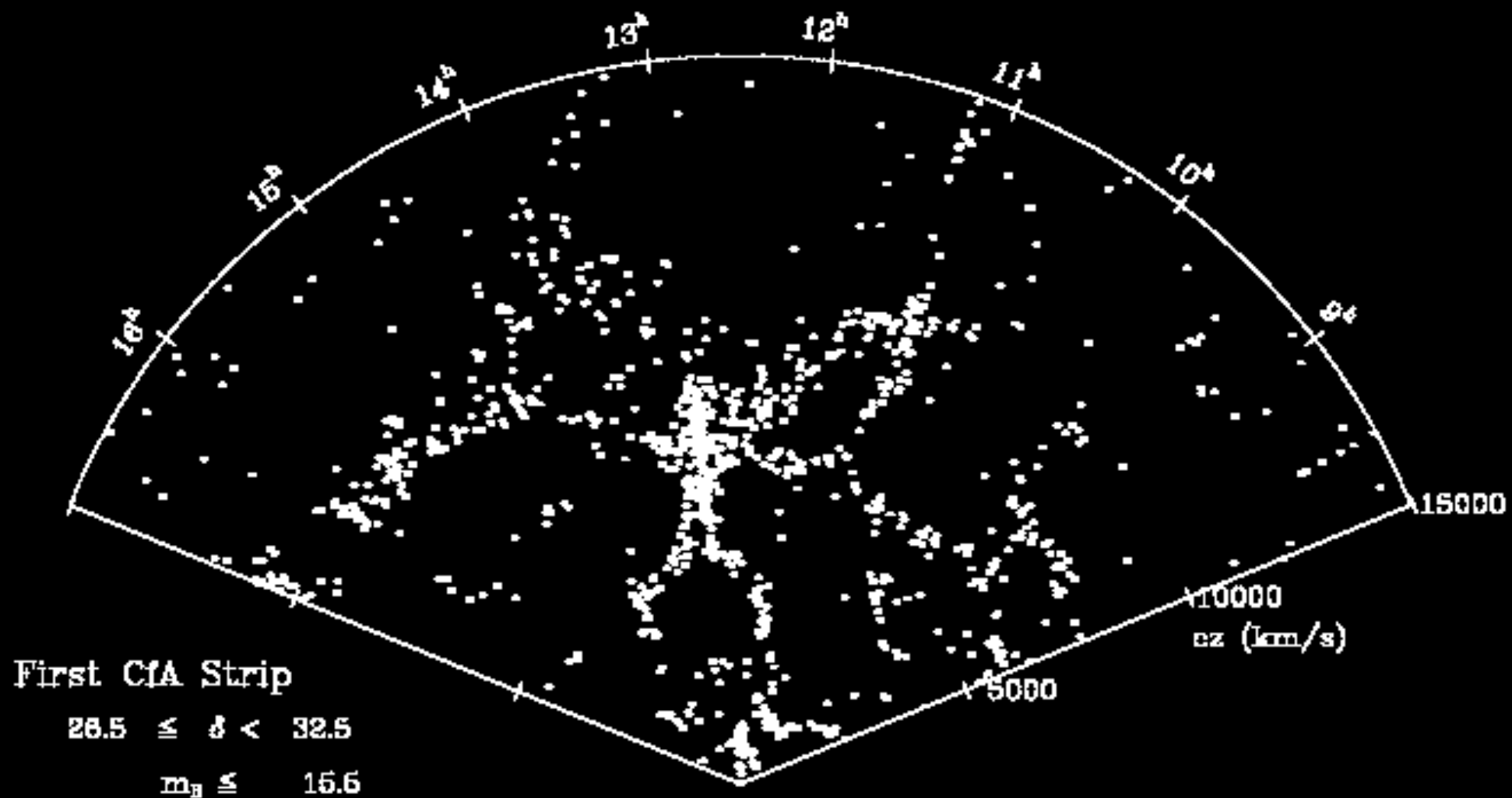


6 Million Light Years

$$v \propto H_0 d$$

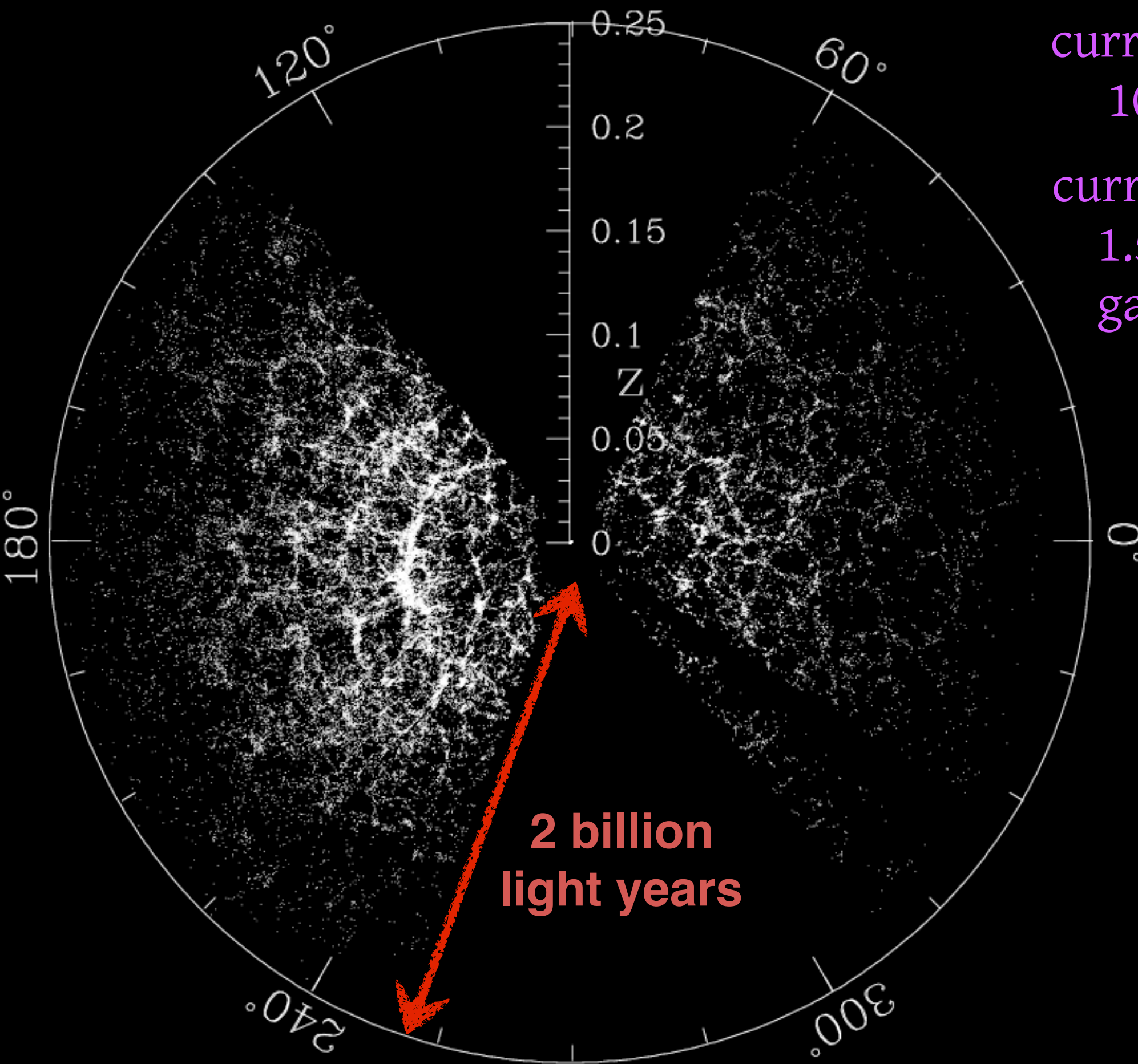


Galaxy Surveys in 1985



CfA: 1100 galaxies in $6^\circ \times 130^\circ$, in this slice

Galaxy Surveys Today: the Sloan Digital Sky Survey

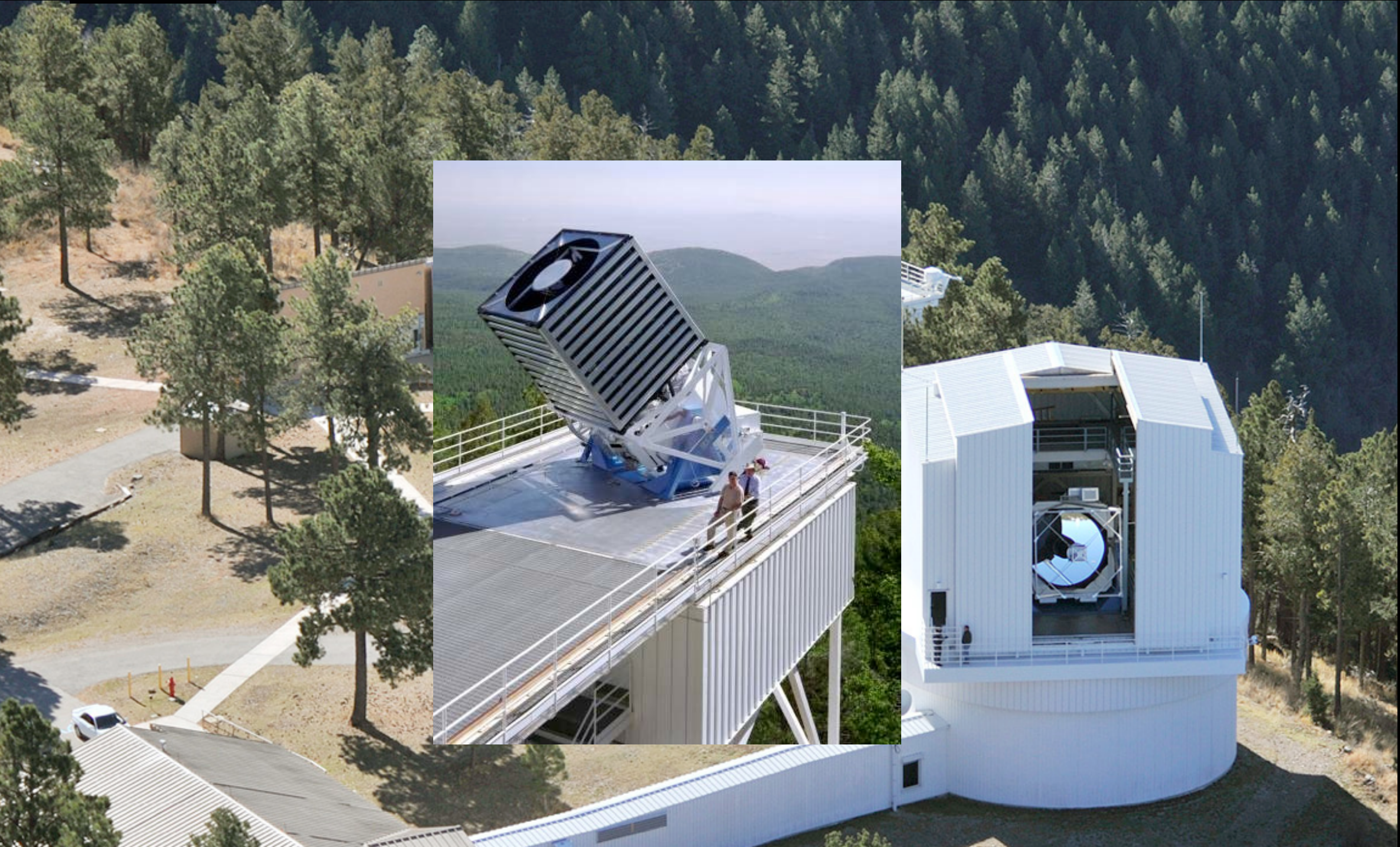


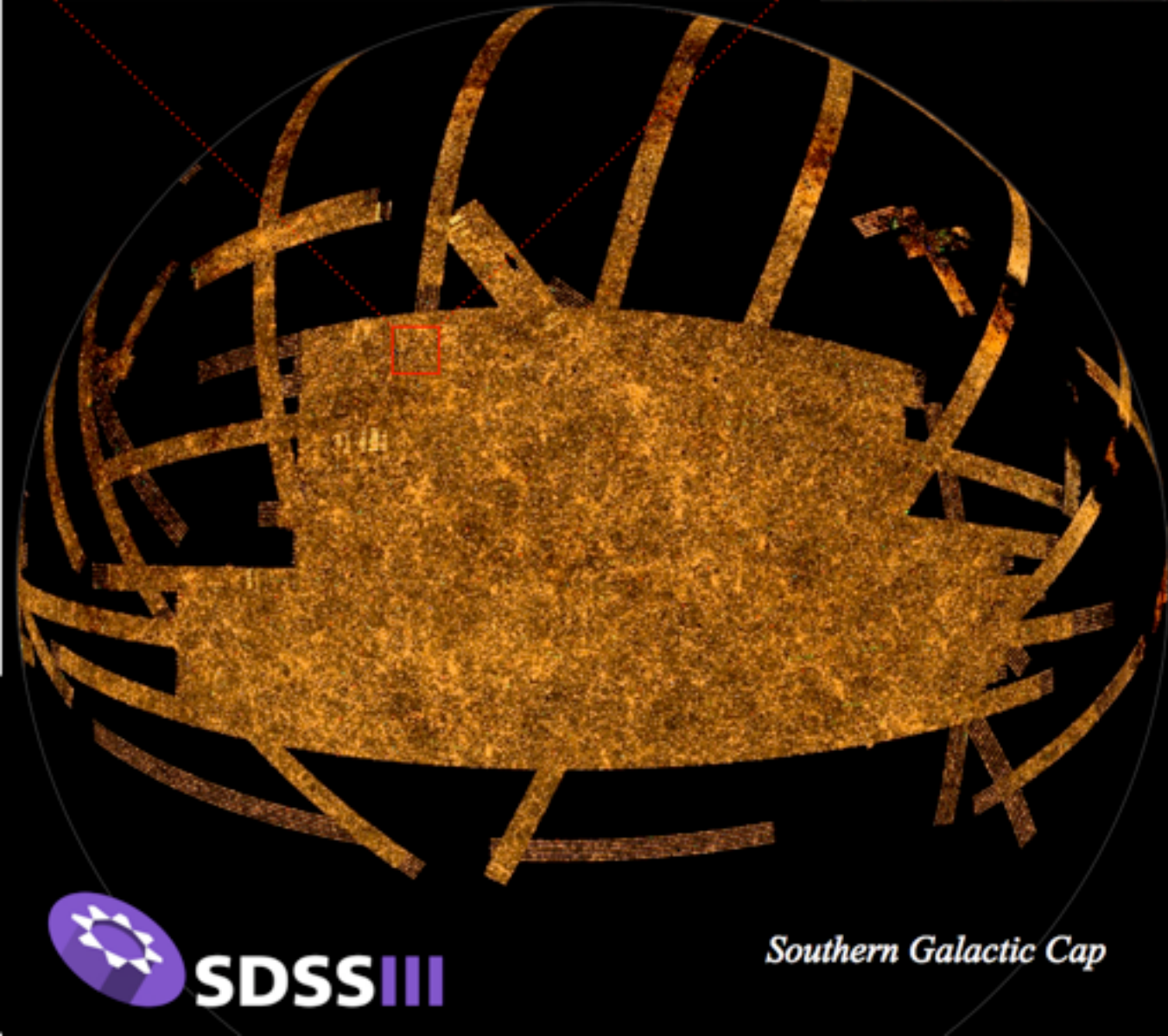
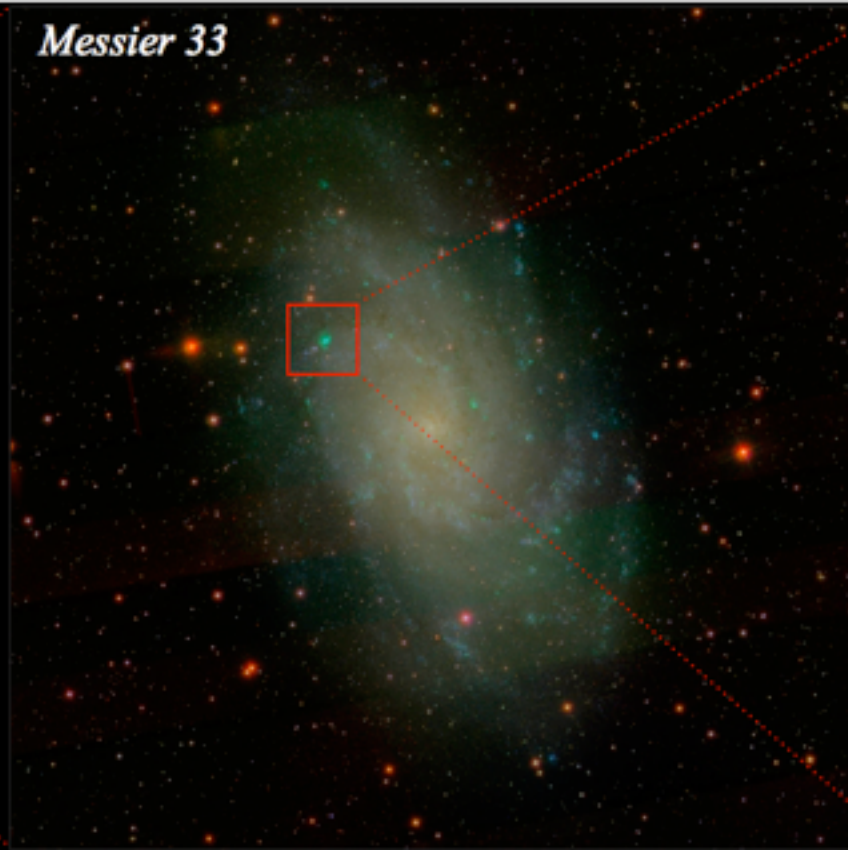
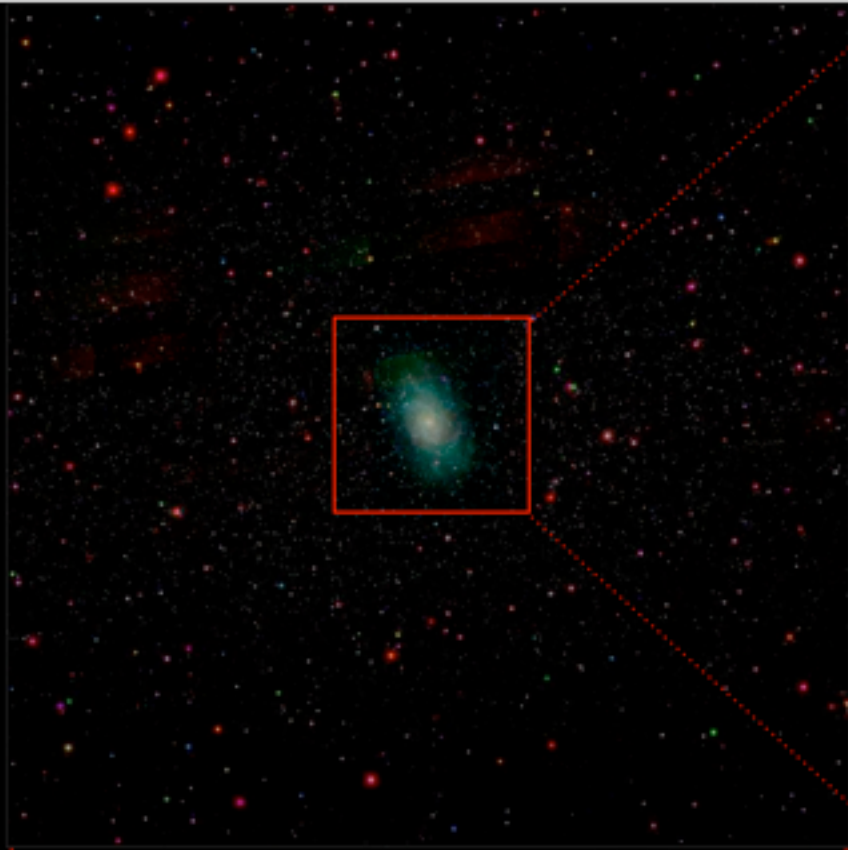
currently:
 10^6 main galaxies

current & upcoming:
 1.5×10^6 luminous red
galaxies to 2.5×10^9 pc



Sloan Digital Sky Survey: Galaxies from Large to Small Scales





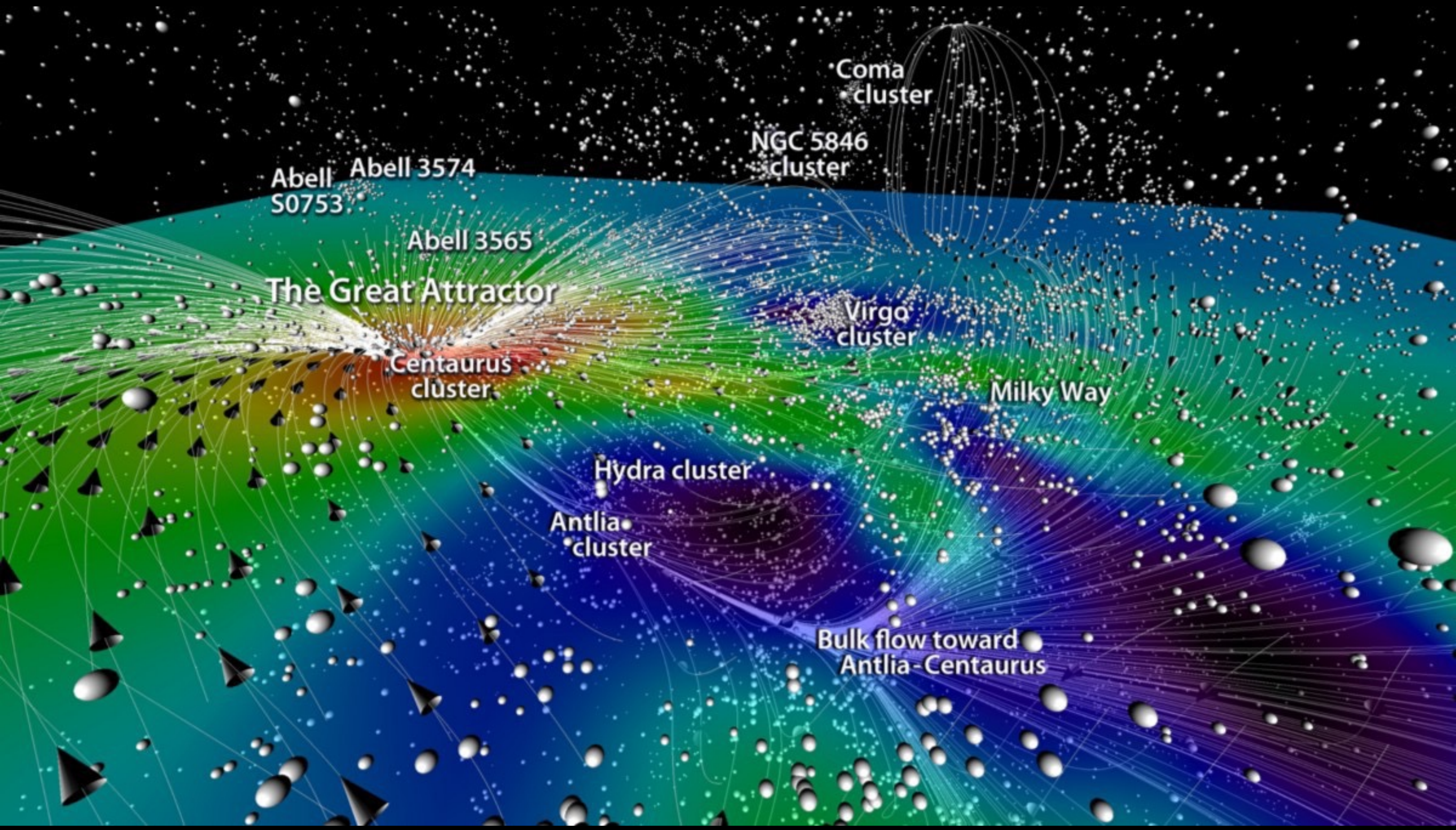
Southern Galactic Cap



**THE LARGEST COLOR
IMAGE OF THE SKY EVER
MADE:
1.6 GIGAPIXELS!**

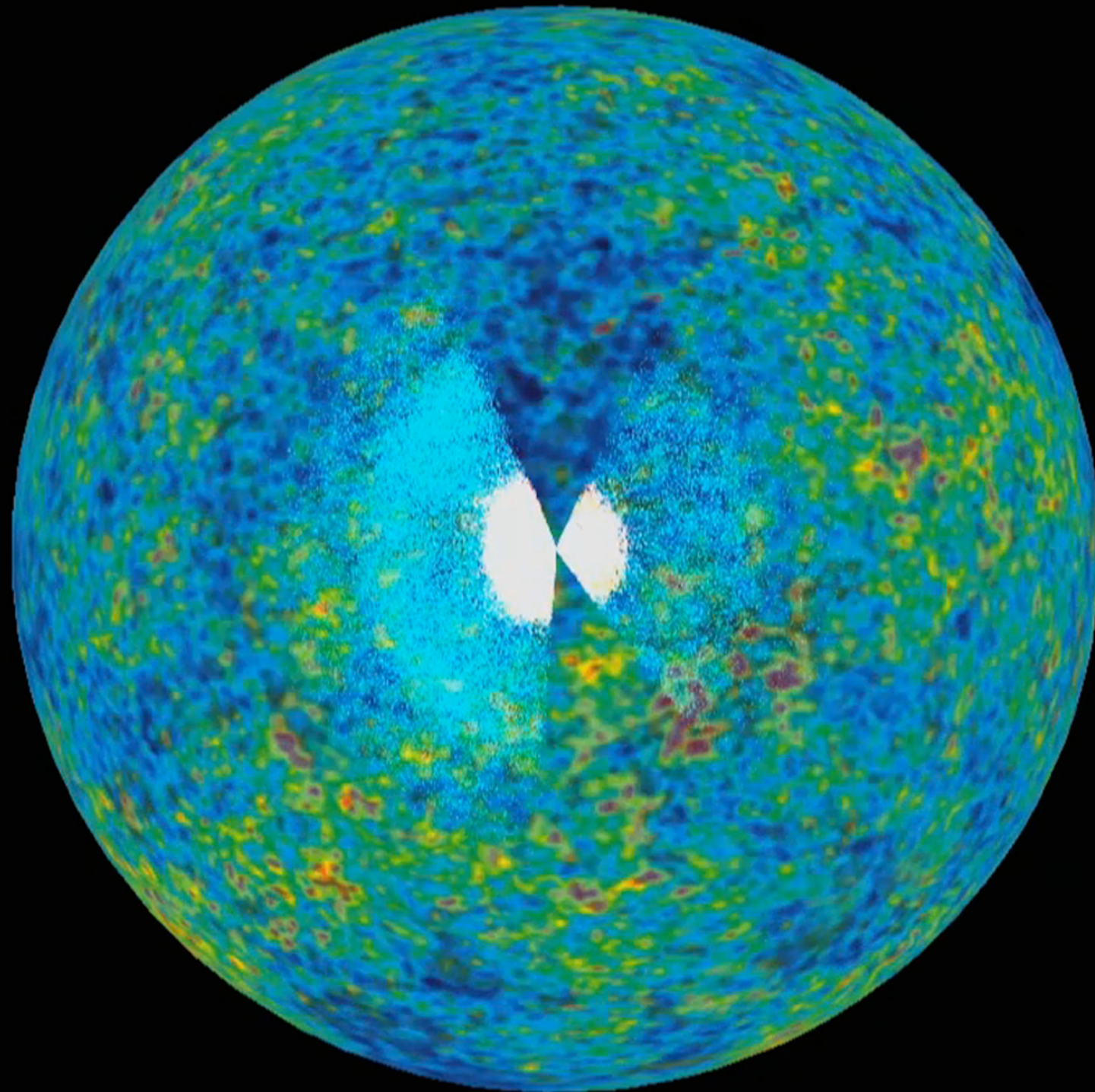
Northern Galactic Cap

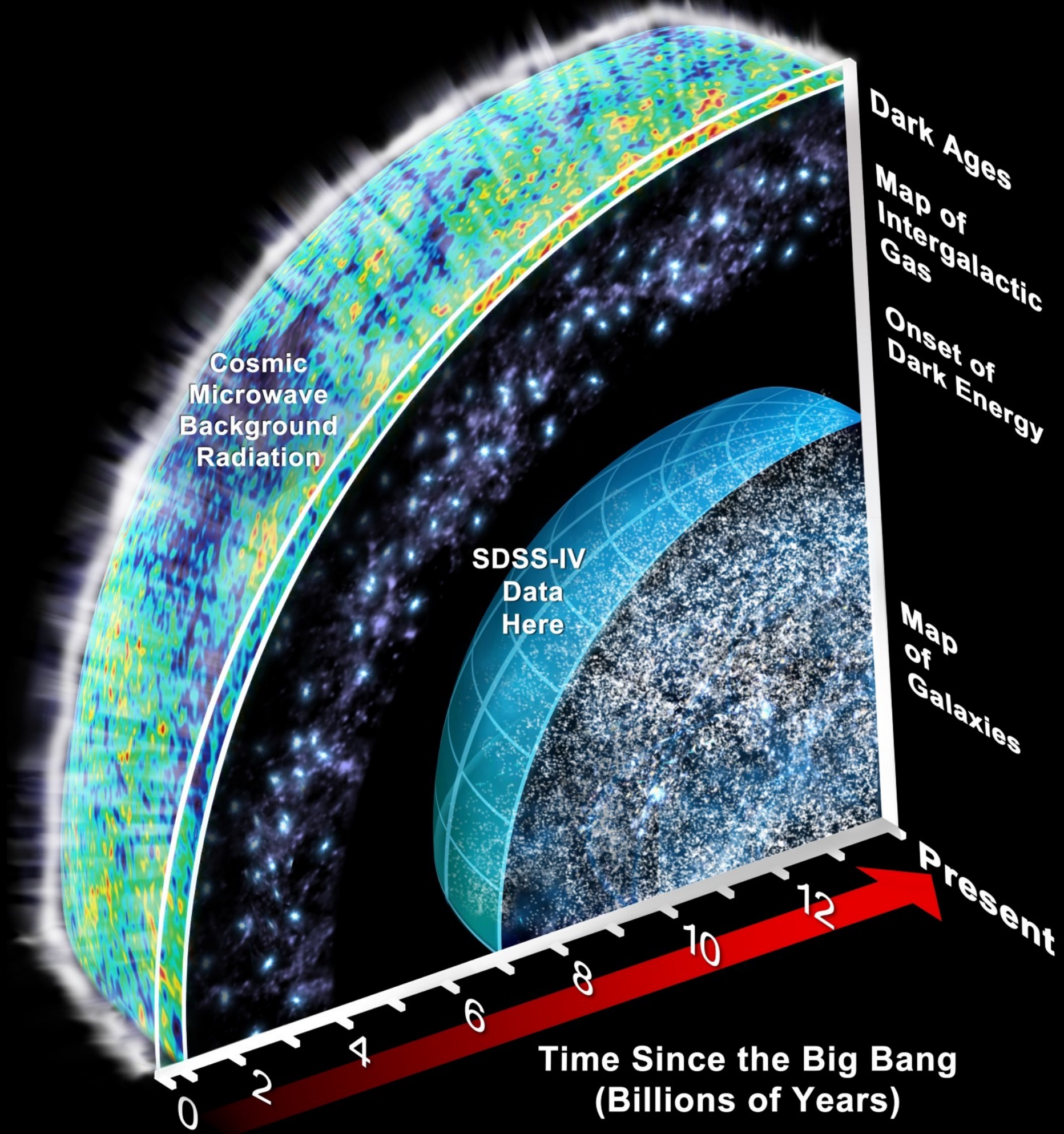
Our local universe: the Laniakea Supercluster of Galaxies (Tully et al 2014)



The Known Universe: American Museum of Natural History

Our Cosmic Microwave
Background Horizon:
The Earliest Light We Can See





Cosmic
Microwave
Background
Radiation

SDSS-IV
Data
Here

Dark Ages

Map of
Intergalactic
Gas

Onset of
Dark Energy

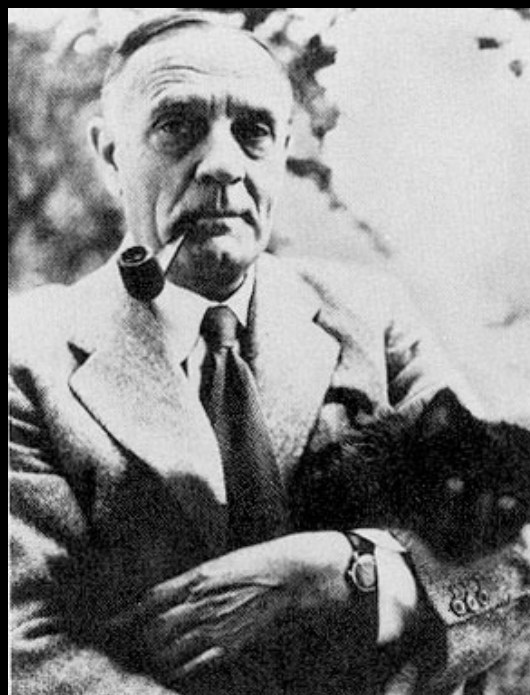
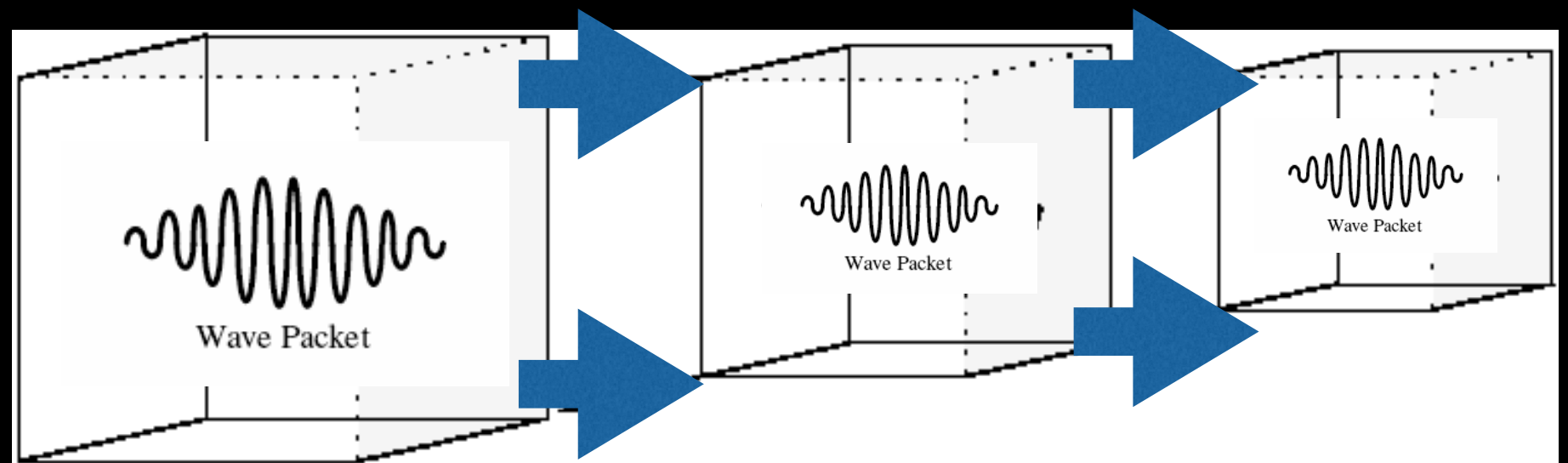
Map
of
Galaxies

Present

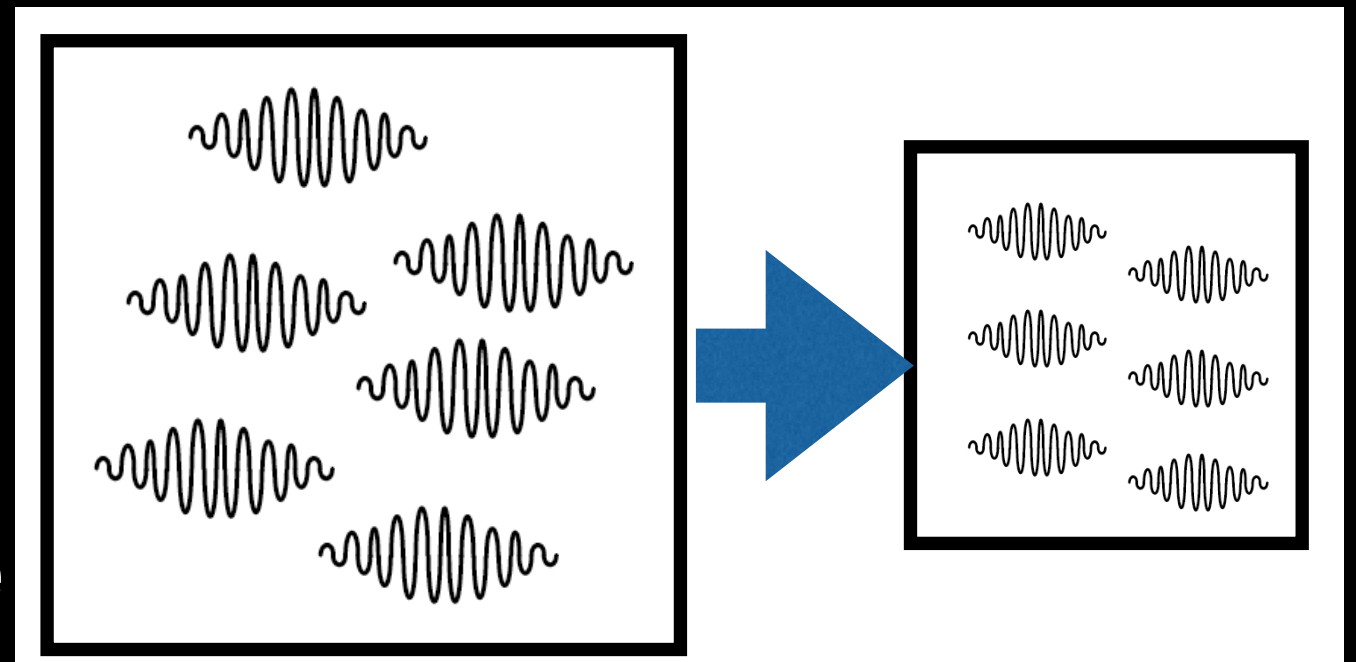
Time Since the Big Bang
(Billions of Years)

Hubble's Expansion Means the Universe was *Hotter & Denser* Early On

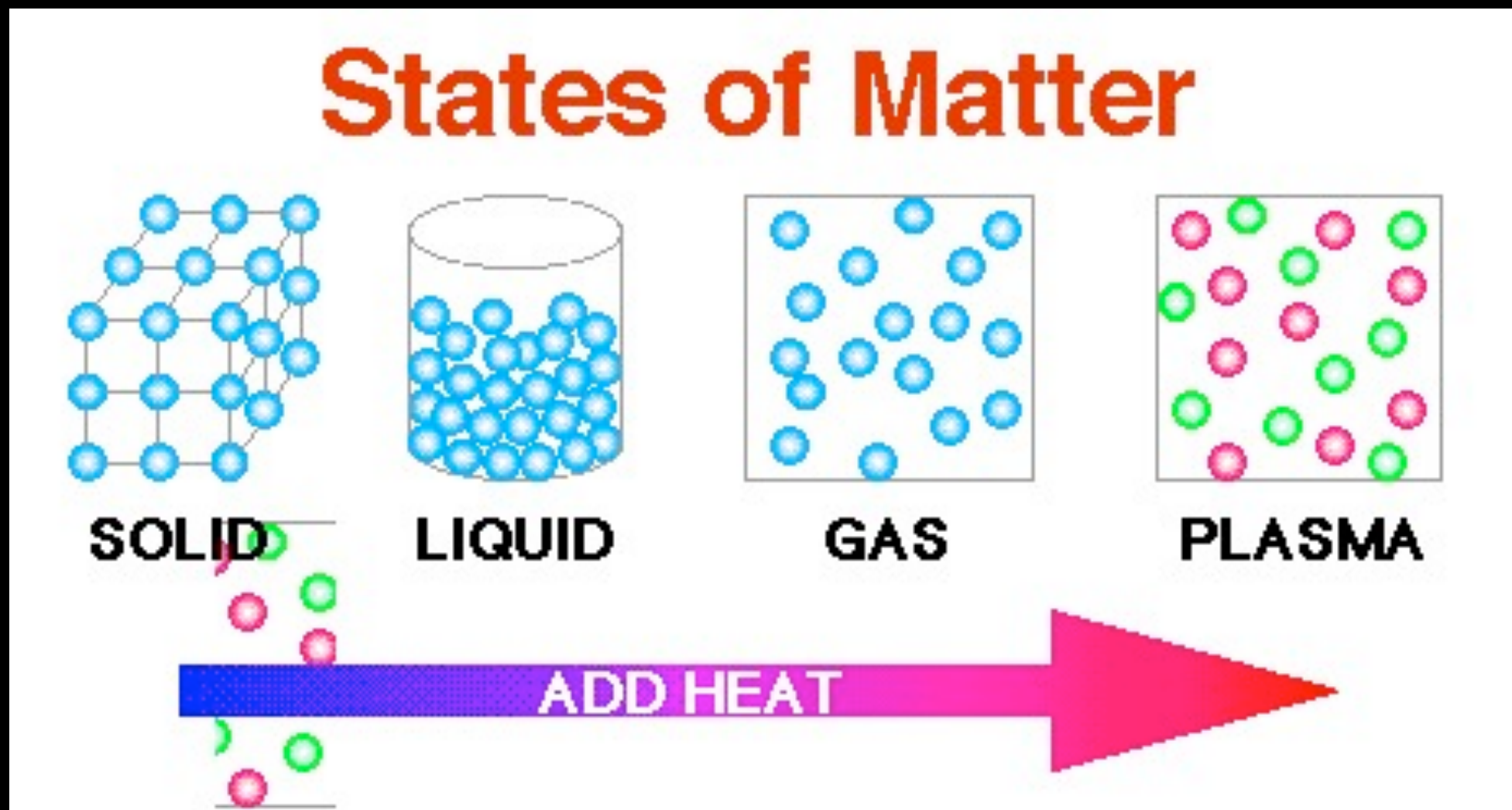
Light Wavelength: shorter, more energetic back in time



Light density: increases back in time

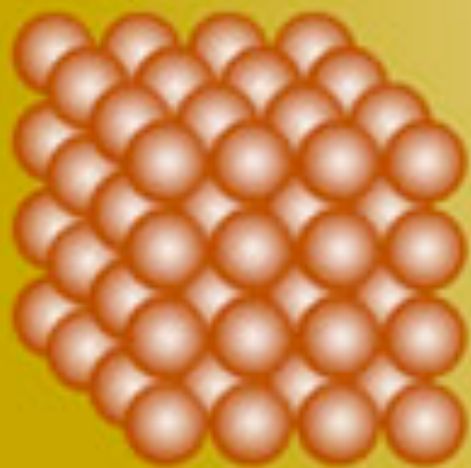
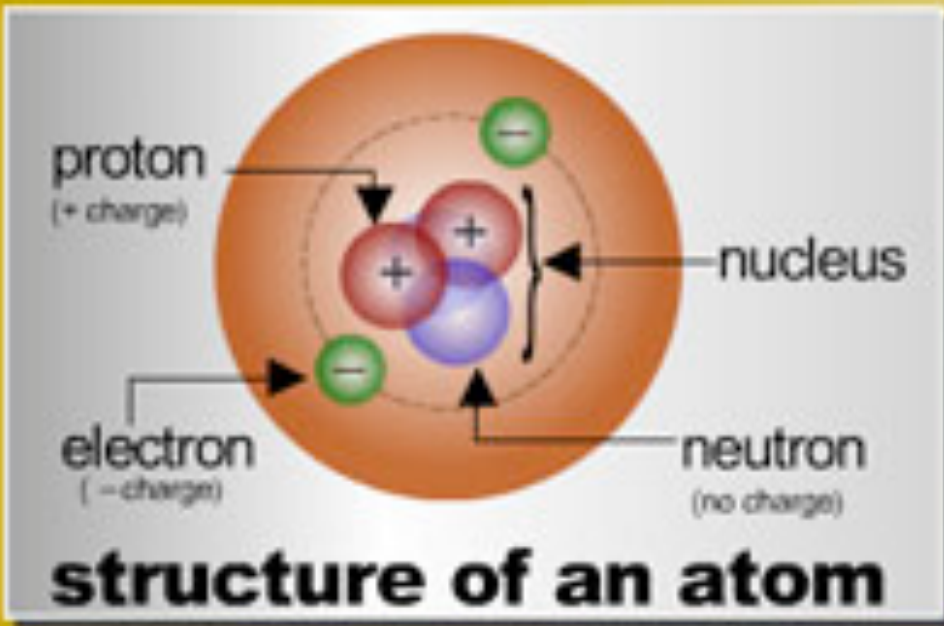


The Hot, Dense Early Universe is a *Plasma*

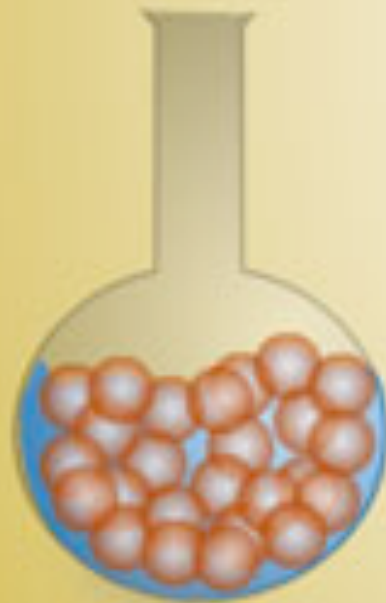


What is a *Plasma*?

PHASES OF MATTER



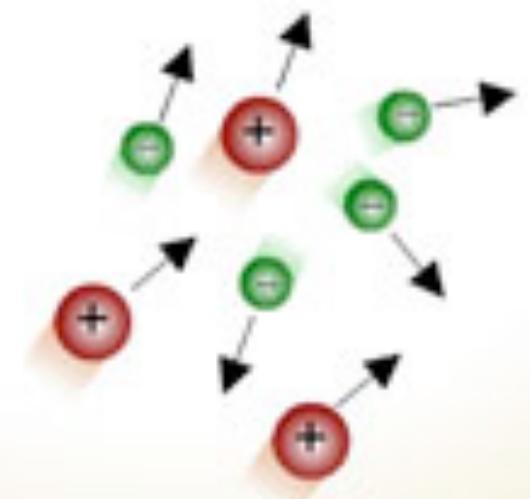
Solid



Liquid



Gas



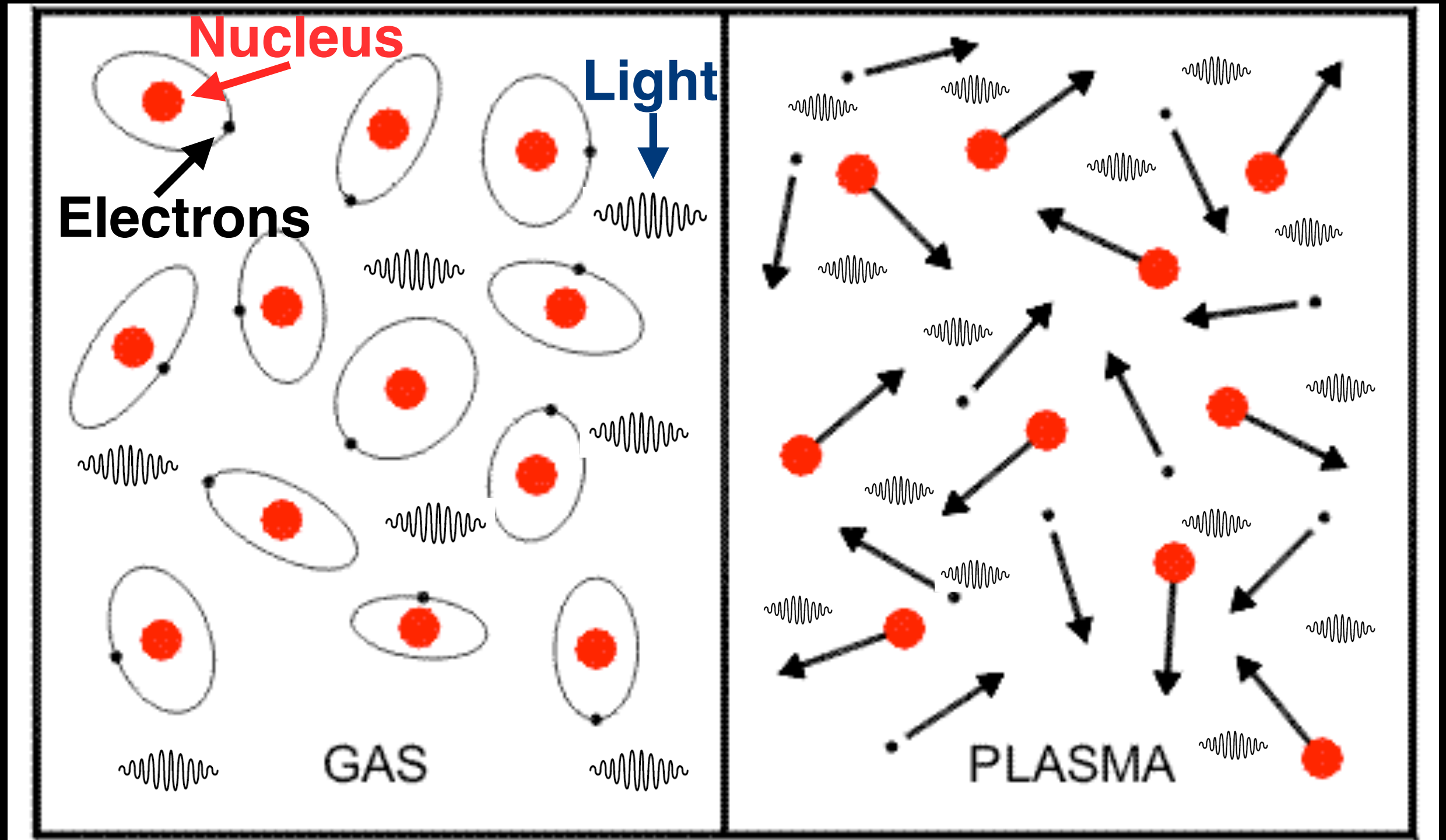
Plasma

LOW

HIGH

Temperature or Energy

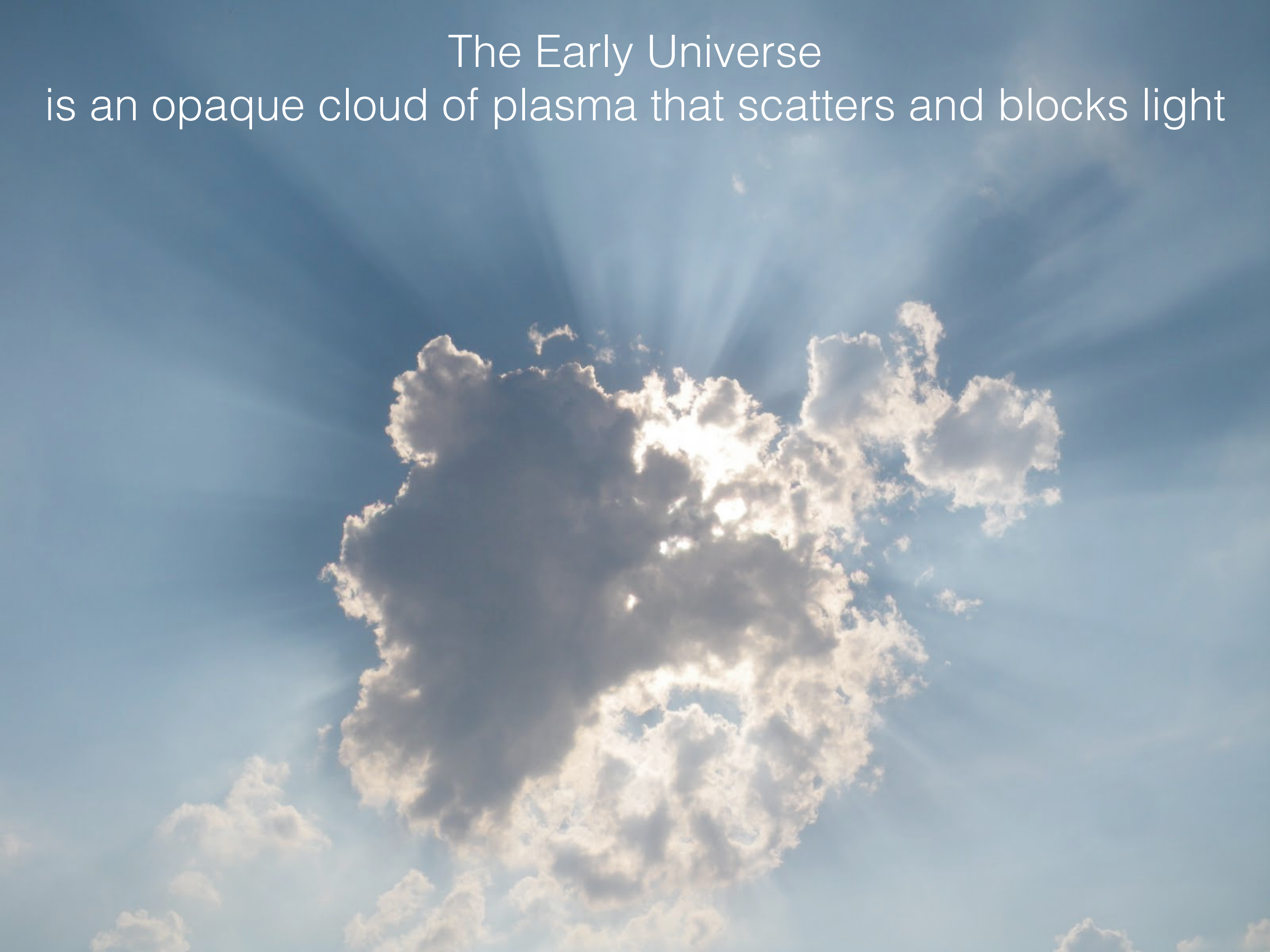
The Early Universe is a *Plasma* and is opaque to light



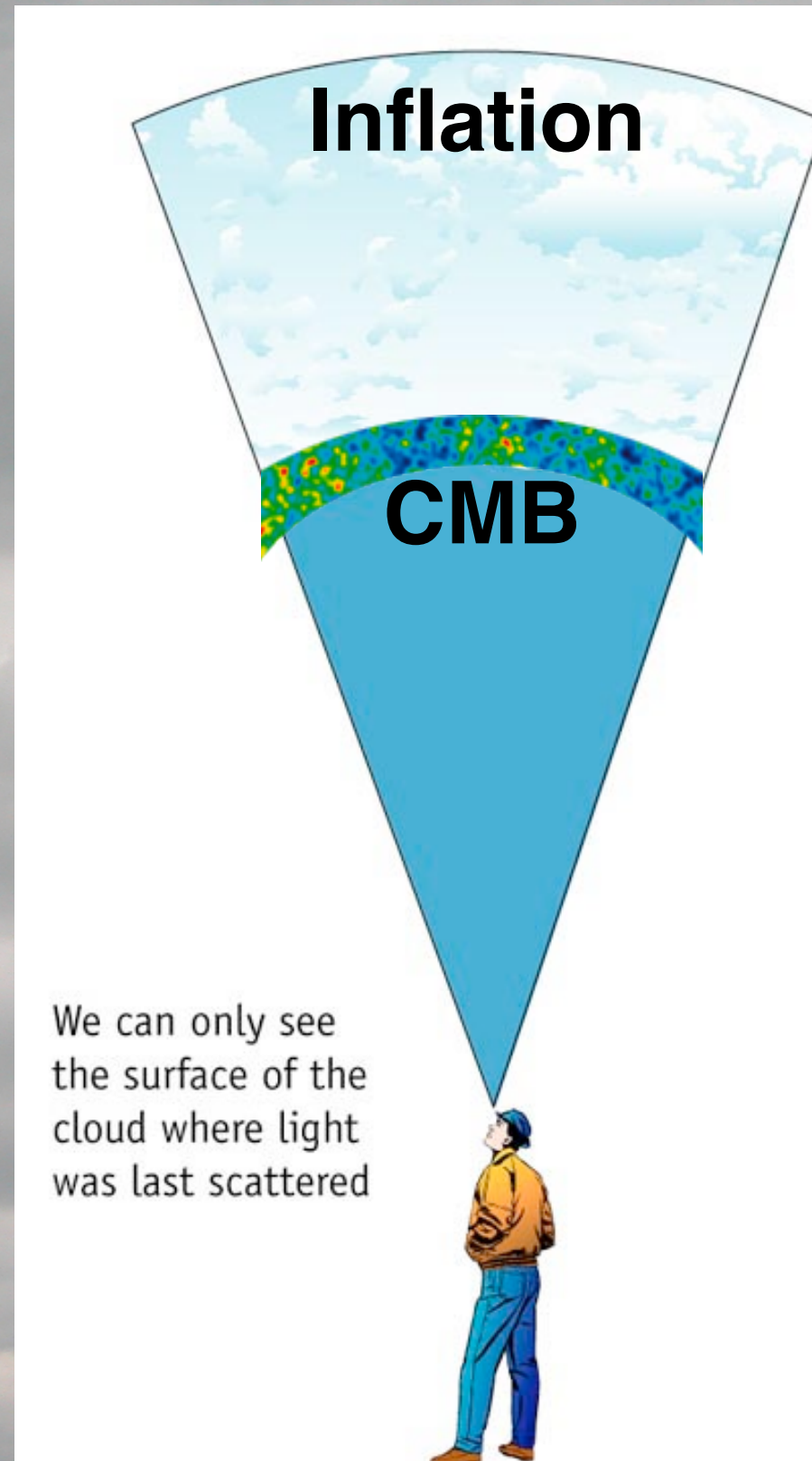
What can we see (almost) every day
and is a plasma opaque to light?



The Early Universe
is an opaque cloud of plasma that scatters and blocks light

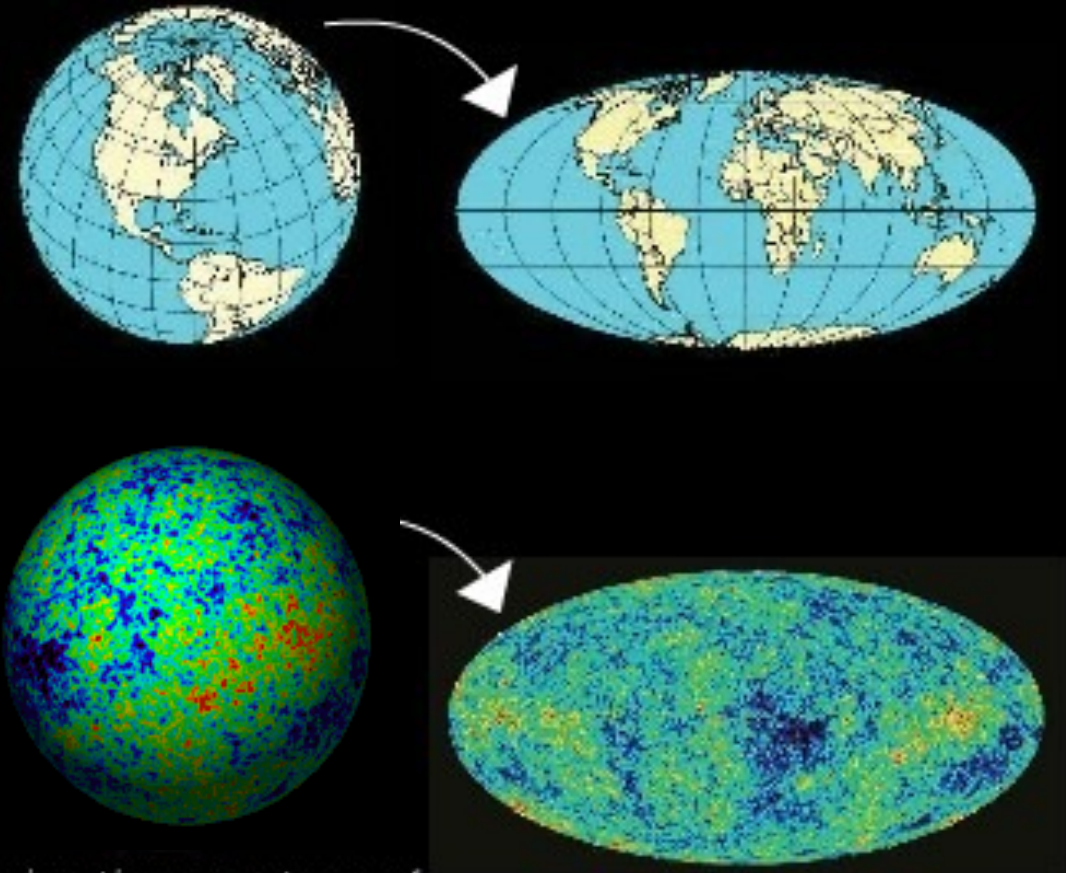
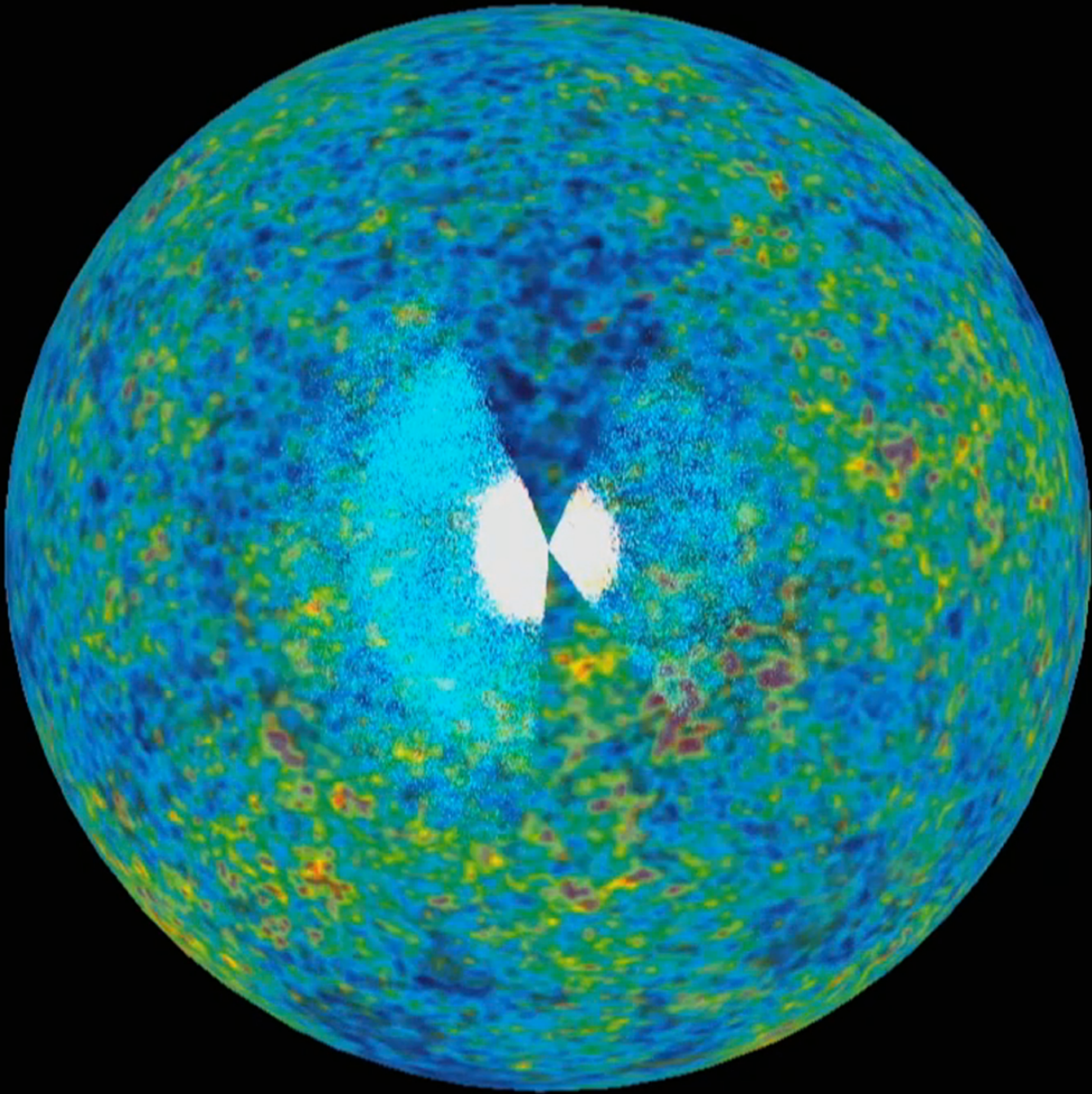


The Early Universe
is an opaque cloud of plasma that scatters and blocks light



The Cosmic Microwave Background Can Be Mapped

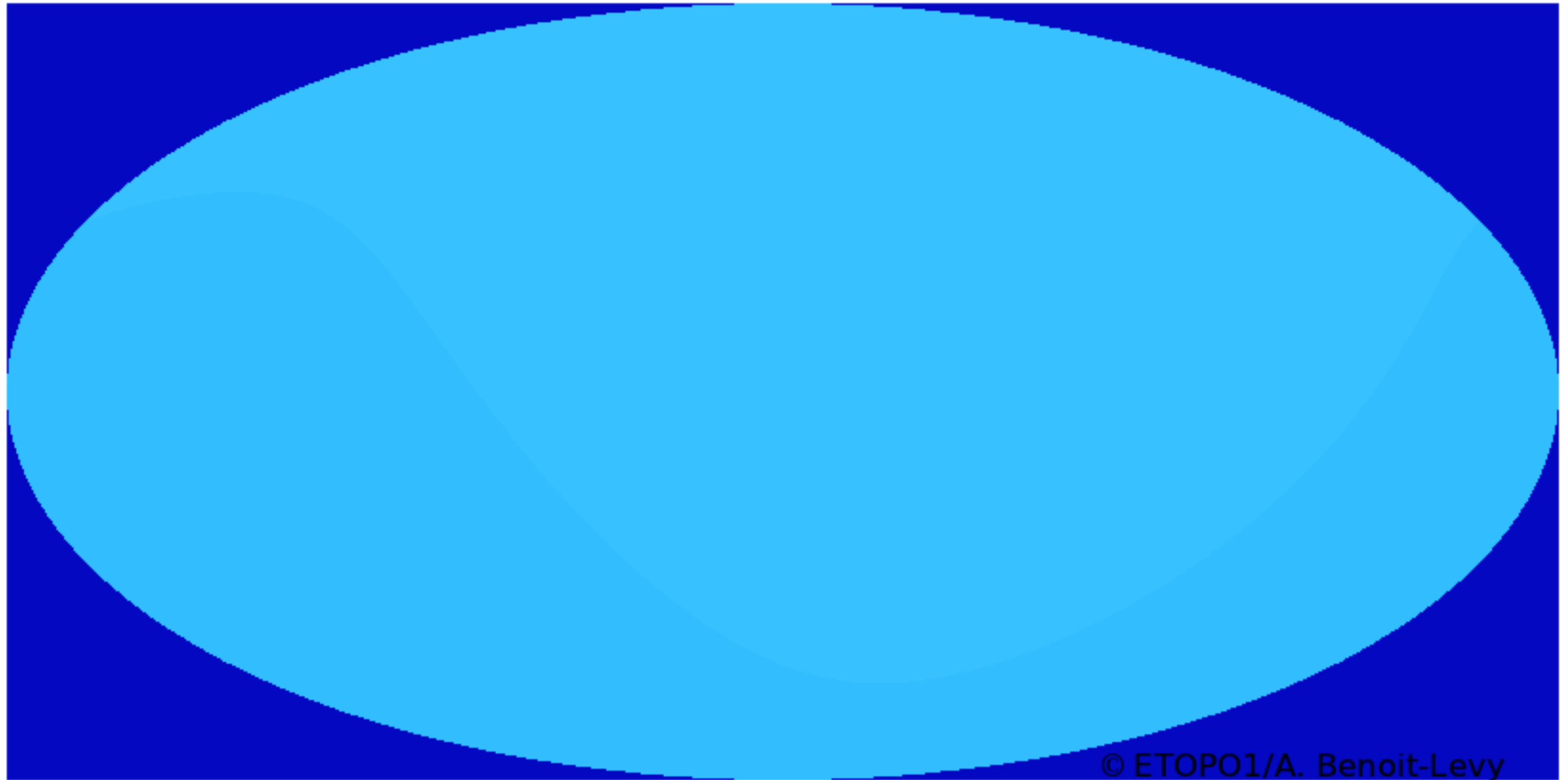
Just like the Earth...



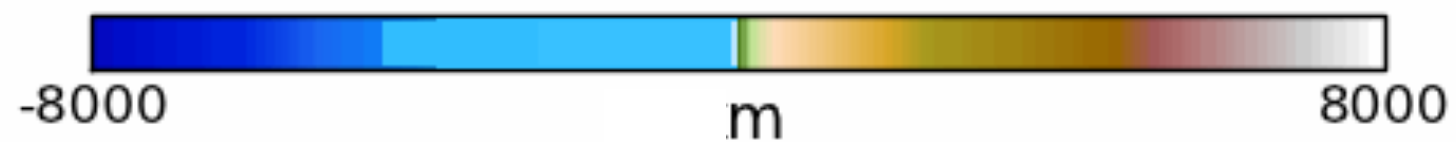
*Animation courtesy of
NASA and WMAP*

The More Detailed The Map, The Better...

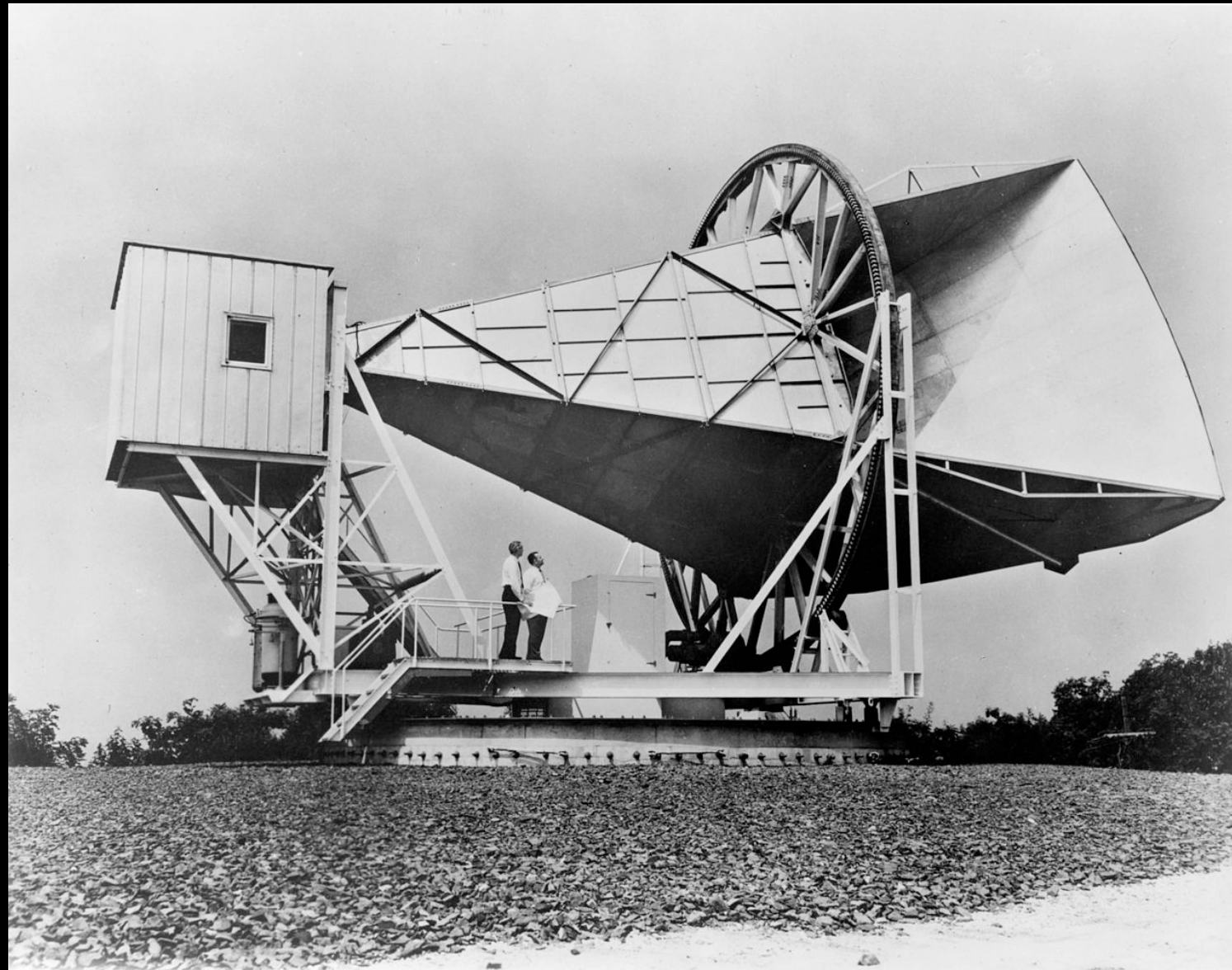
Resolution = 180.00 degrees



© ETOPO1/A. Benoit-Levy



Penzias & Wilson Discovered the CMB
in 1964 at Bell Labs in New Jersey
in Horn Antennas for Radio Transmission

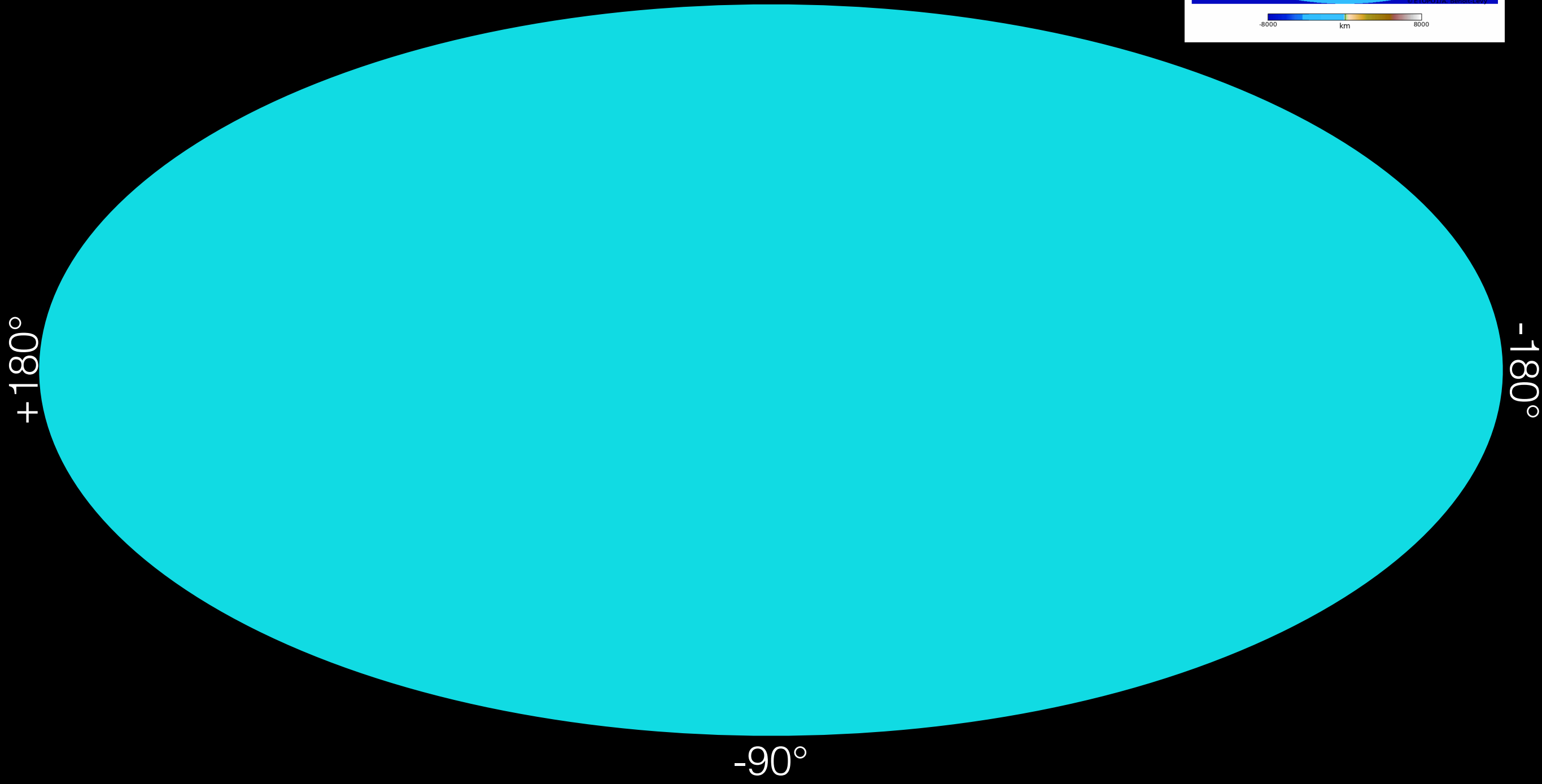
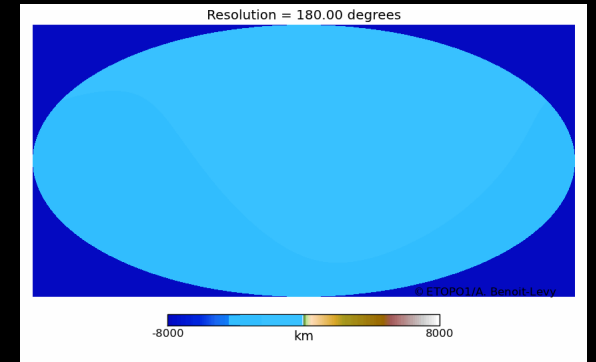


1978 Nobel Prize in Physics

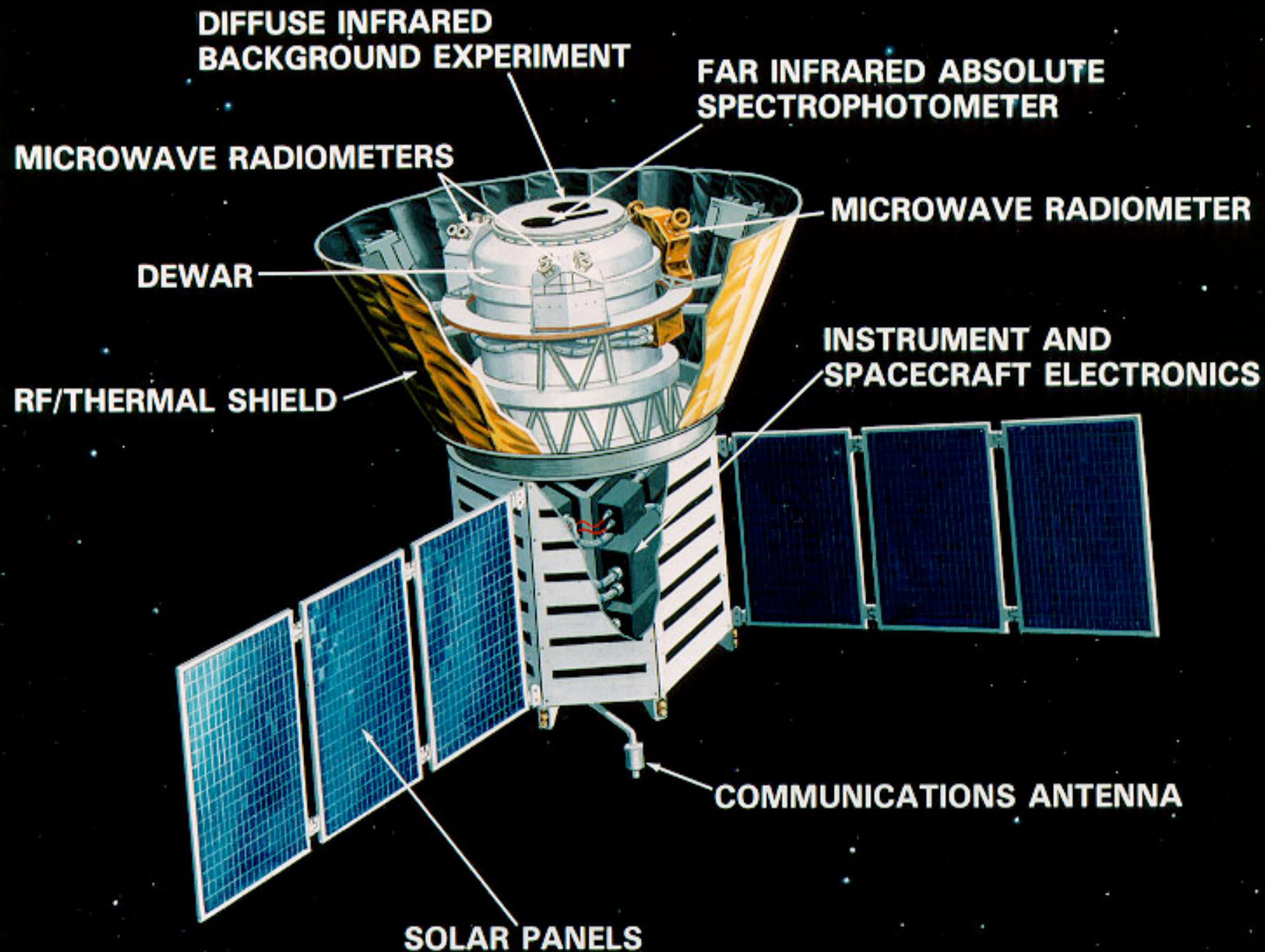
Penzias & Wilson saw near perfect isotropy in CMB emission

Measured its temperature to be 3 K

+90°



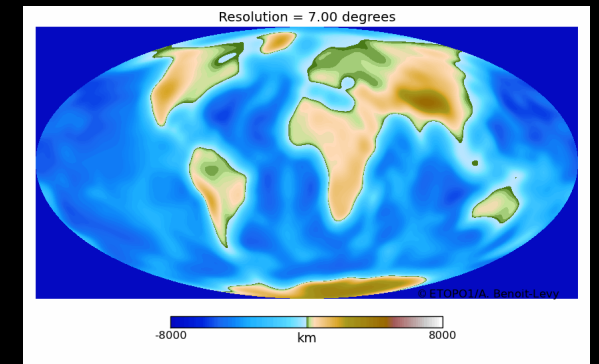
COBE Mission: US-NASA Project



The Cosmic Microwave Background from the **COBE** Satellite, 1992

7° angular resolution

+90°



Anisotropy measured at the level of 1 in 100,000

**Like measuring fluctuations on a billiard ball of
1/2 micron (1/2 millionth of a meter)**

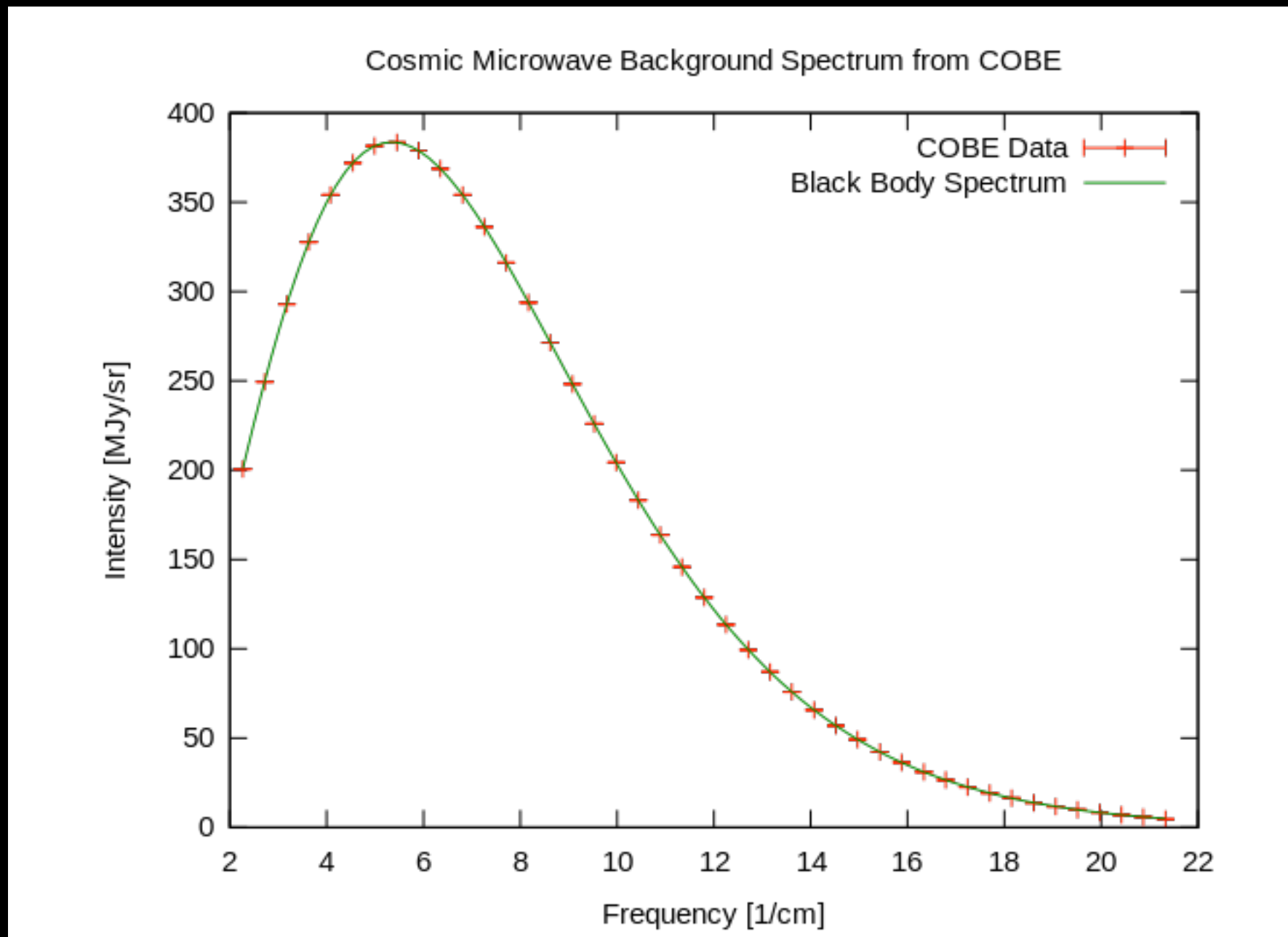
2006 Nobel Prize in Physics

+180°

-180°

-90°

COBE Mission also gave most precise measurement of the Universe's temperature

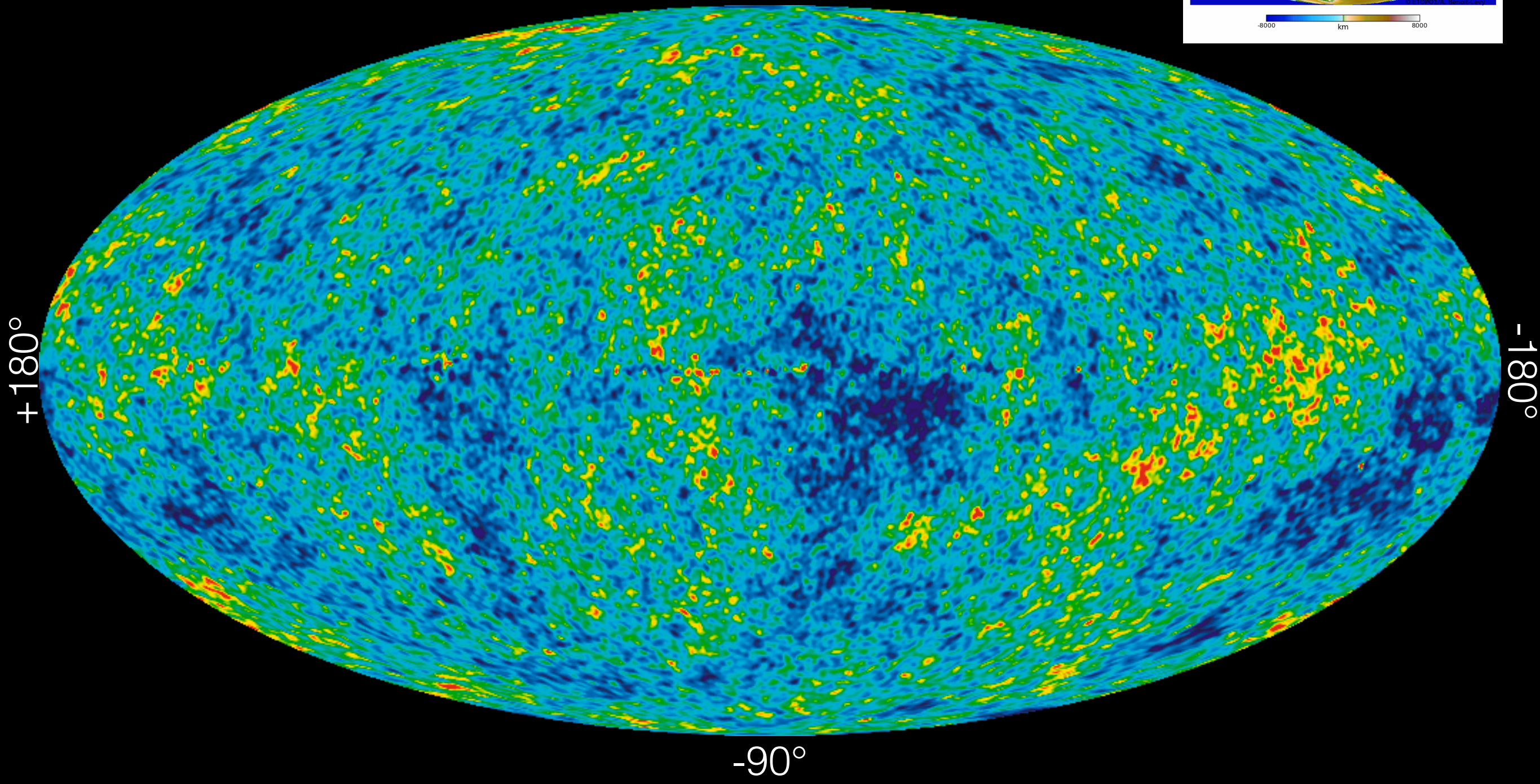
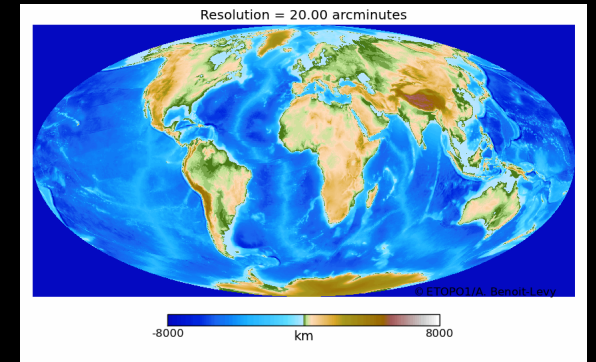


Data from COBE showed a perfect fit between the black body curve predicted by big bang theory and that observed in the microwave background: $T = 2.725 \text{ K} = -454.8 \text{ }^\circ\text{F}$

NASA's Wilkinson Microwave Anisotropy Probe: A Detailed Image of the CMB, 2003-13

0.3° angular resolution

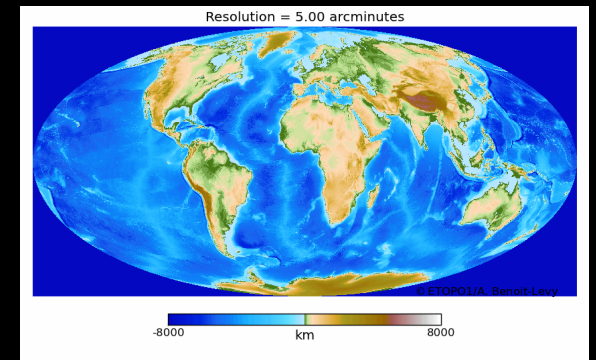
+90°



European Space Agency's *Planck Probe*: The Best Image Yet of the CMB, 2013-15

0.08° angular resolution

+90°



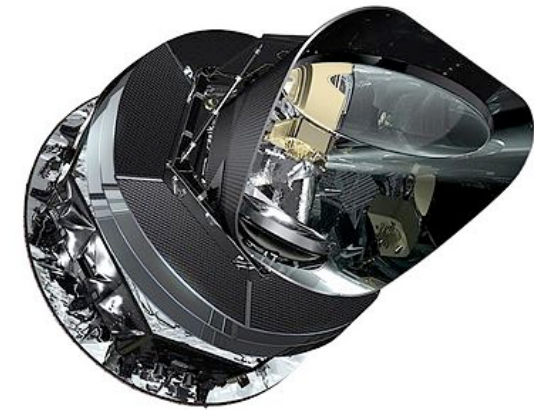
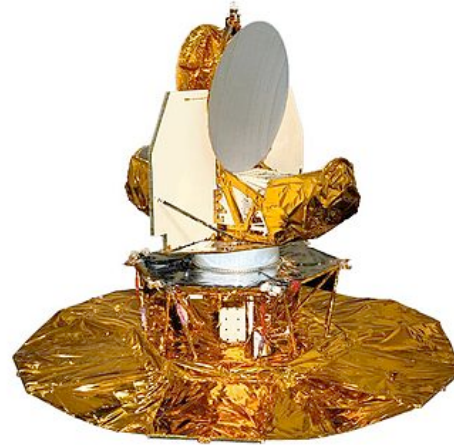
A detailed map of the initial conditions
of cosmological perturbations

+180°

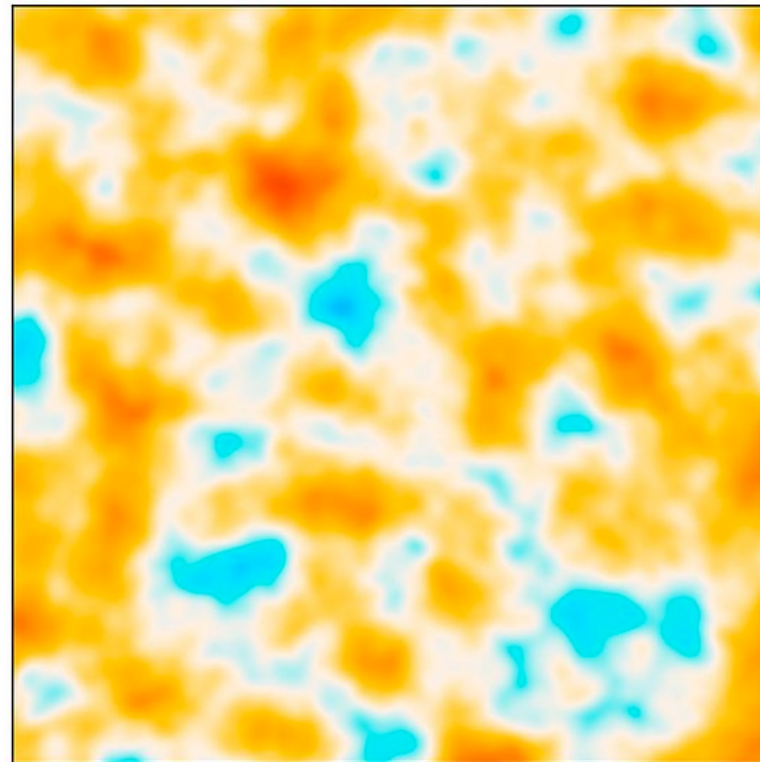
-180°

-90°

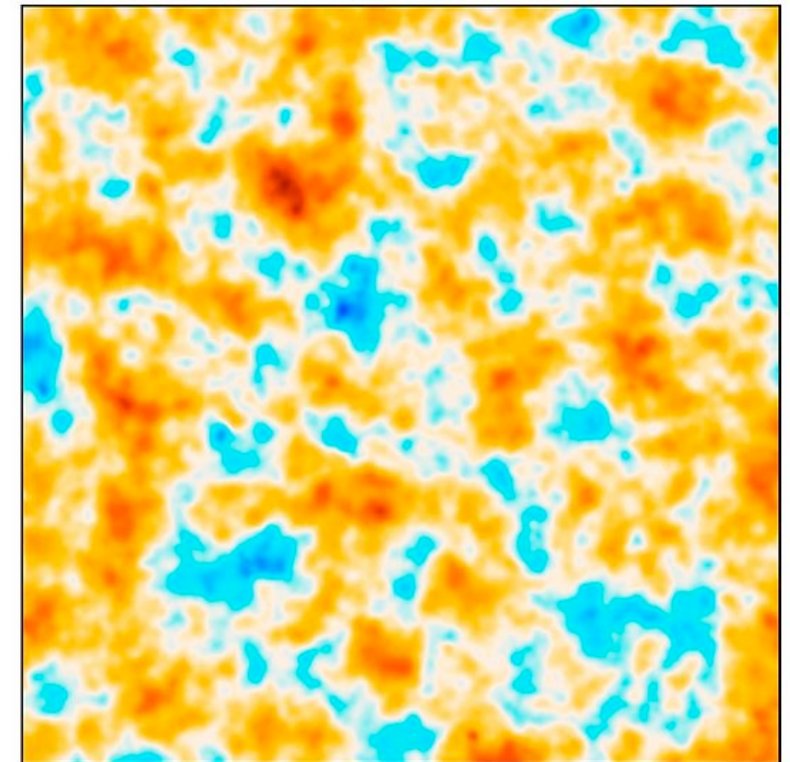
Comparison of COBE, WMAP, Planck Measurements



COBE



WMAP

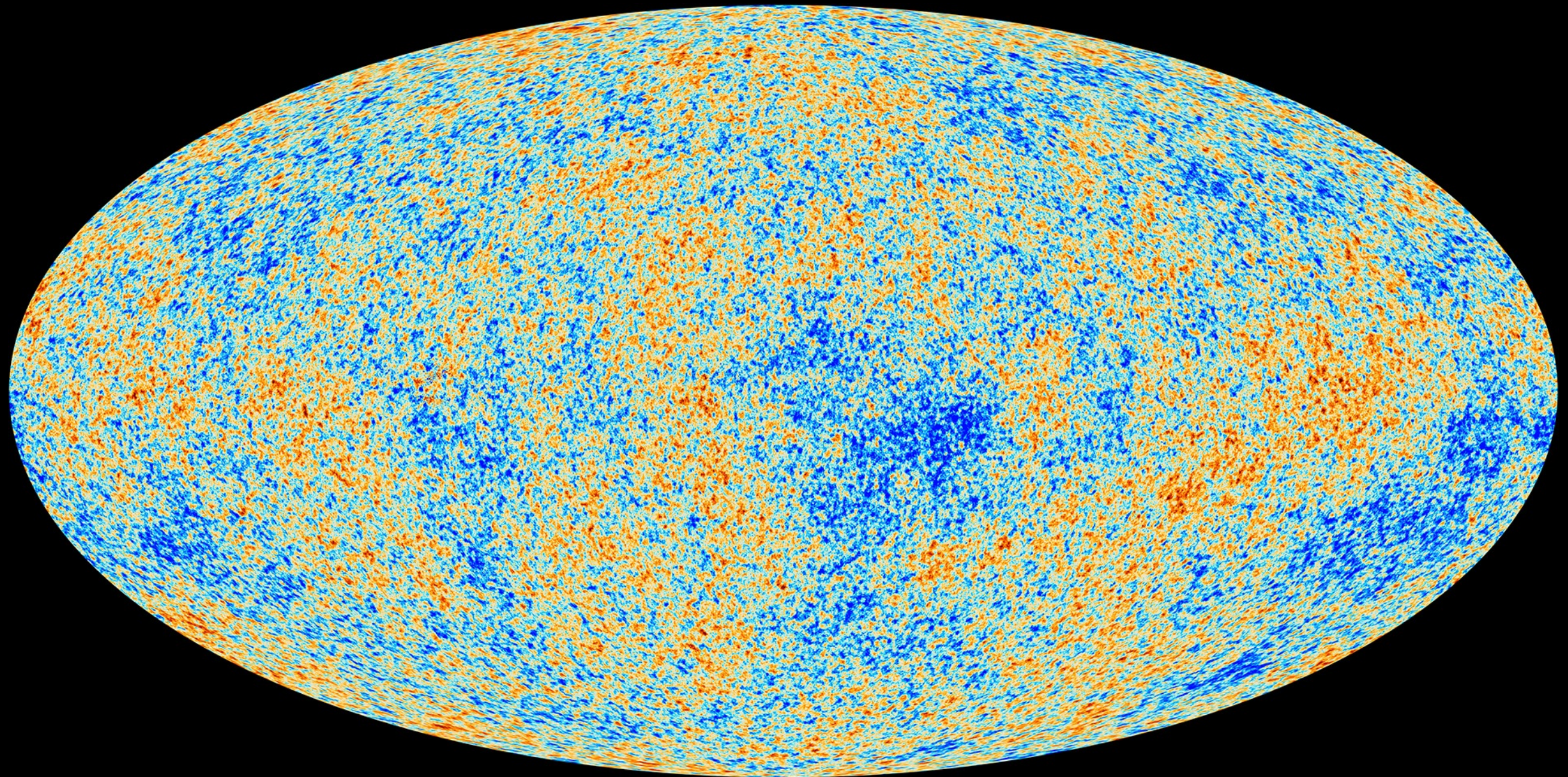


Planck

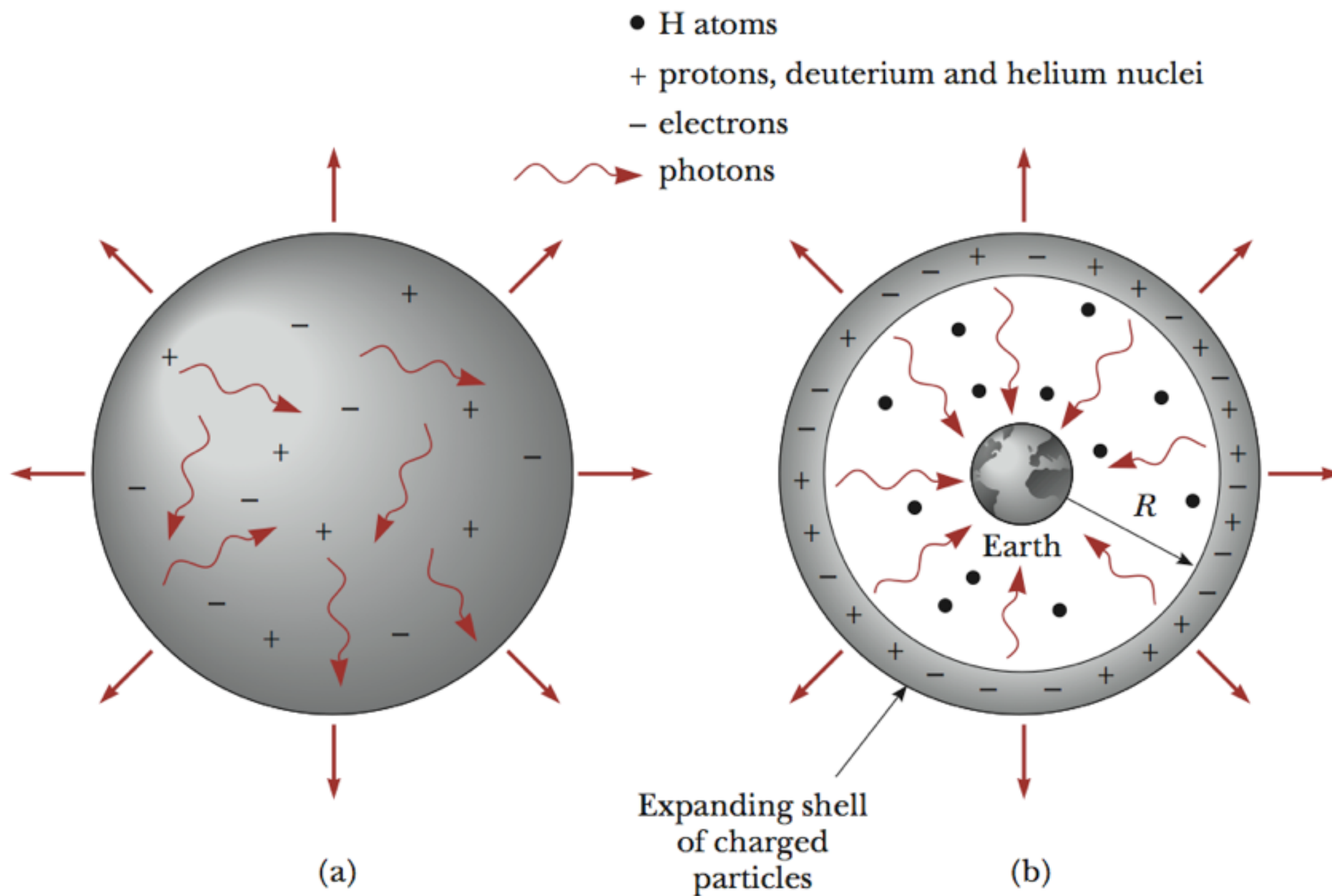
What gave rise to this uniformity
across scales that are disconnected from each other?

What gave rise to the small perturbations?

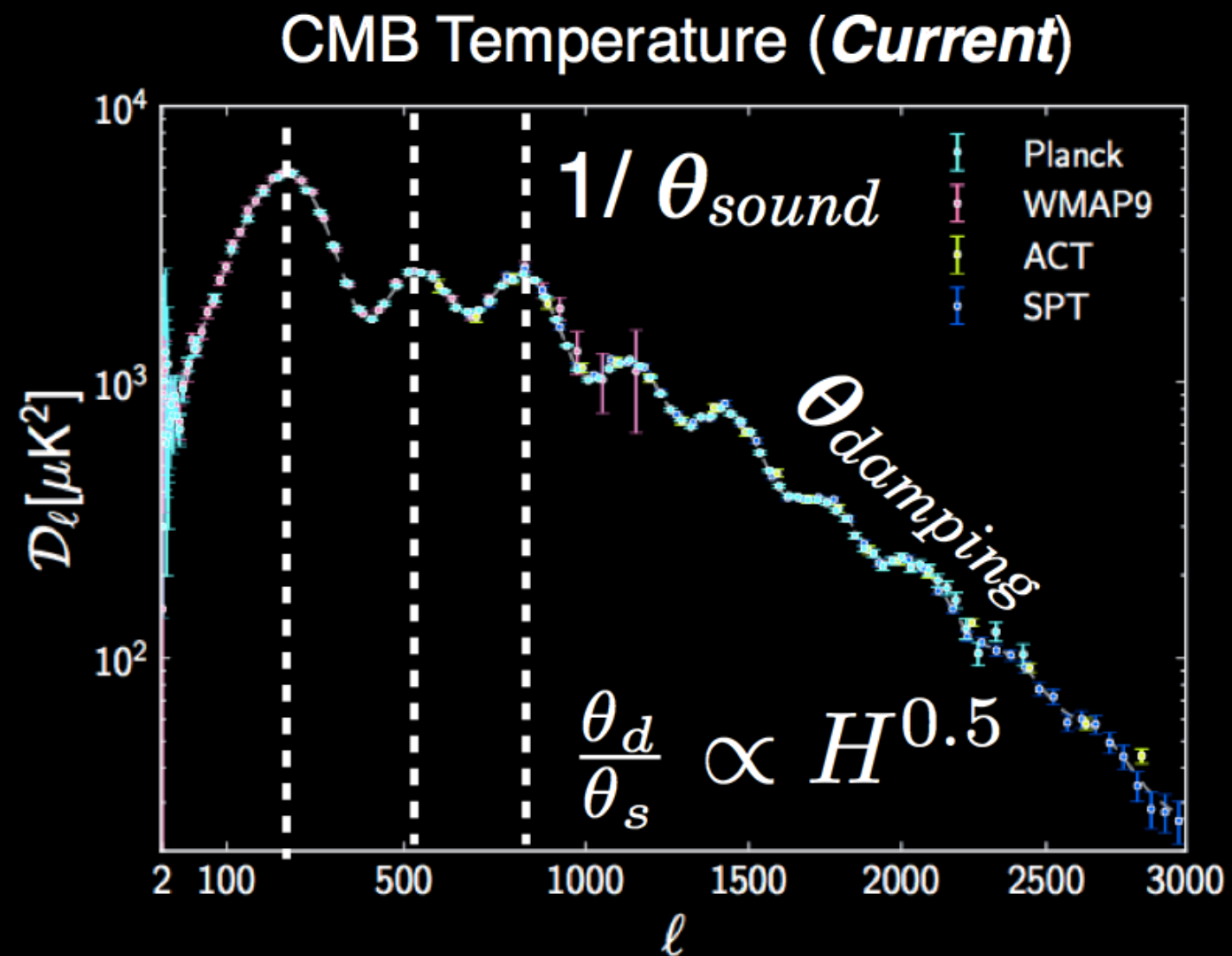
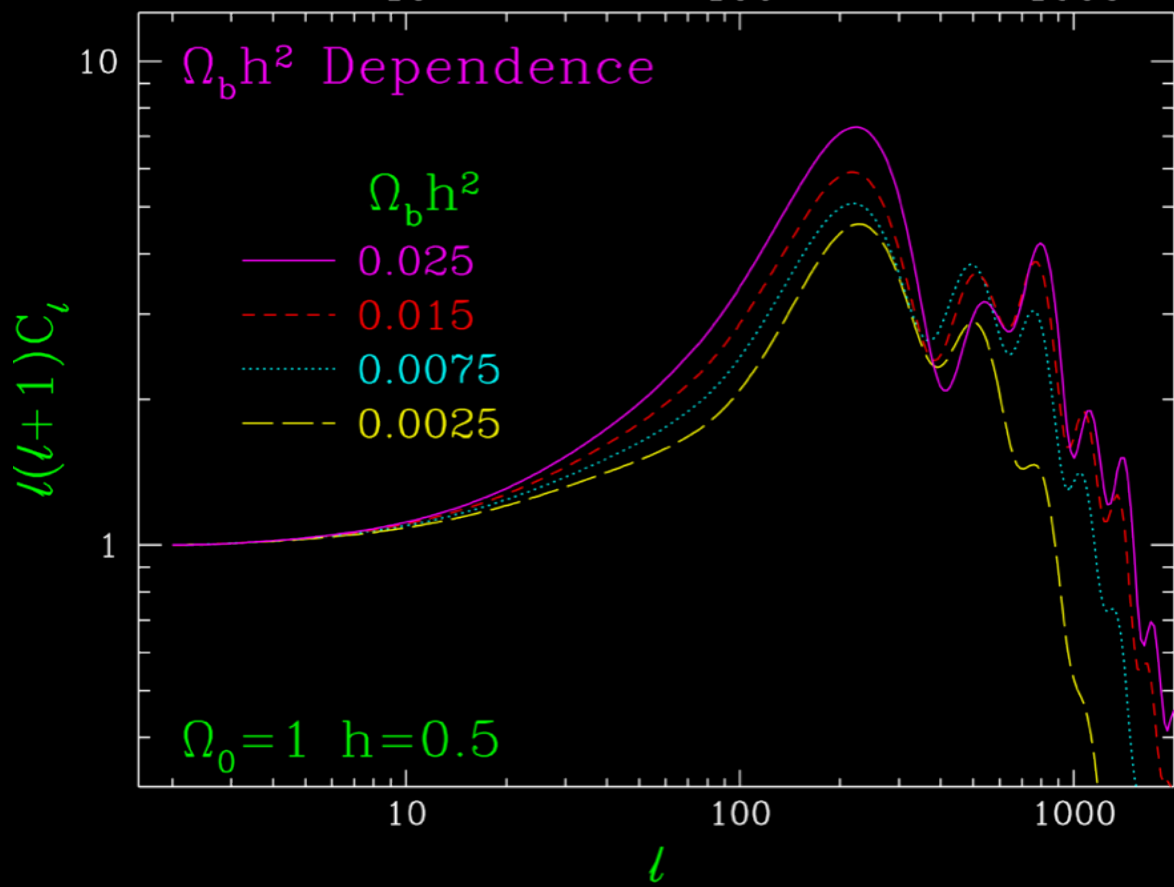
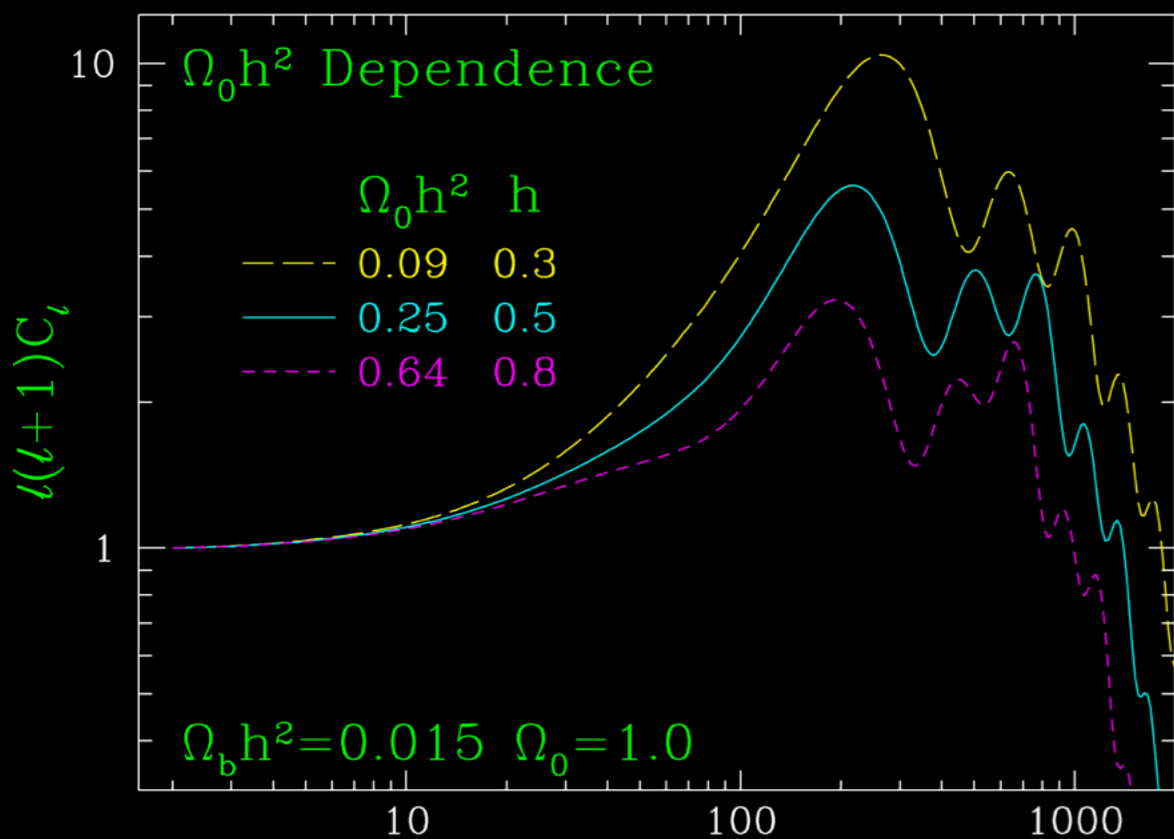
The leading theory: ***inflation***



Another View of the Cosmic Microwave Background (CMB)



Cosmic Microwave Background (CMB): Precision Cosmological Measure of Dark Matter



$$\Omega_{DM} = 0.220 \pm 0.011$$

CMB alone

The image shows a dense, interconnected network of thin, yellowish-orange lines against a dark purple background. This network represents the cosmic web of dark matter filaments and nodes. The lines are most prominent in the upper half of the image and become sparser towards the bottom. A horizontal white line with vertical end caps is positioned at the top, indicating a scale of 1 Gpc/h.

1 Gpc/h

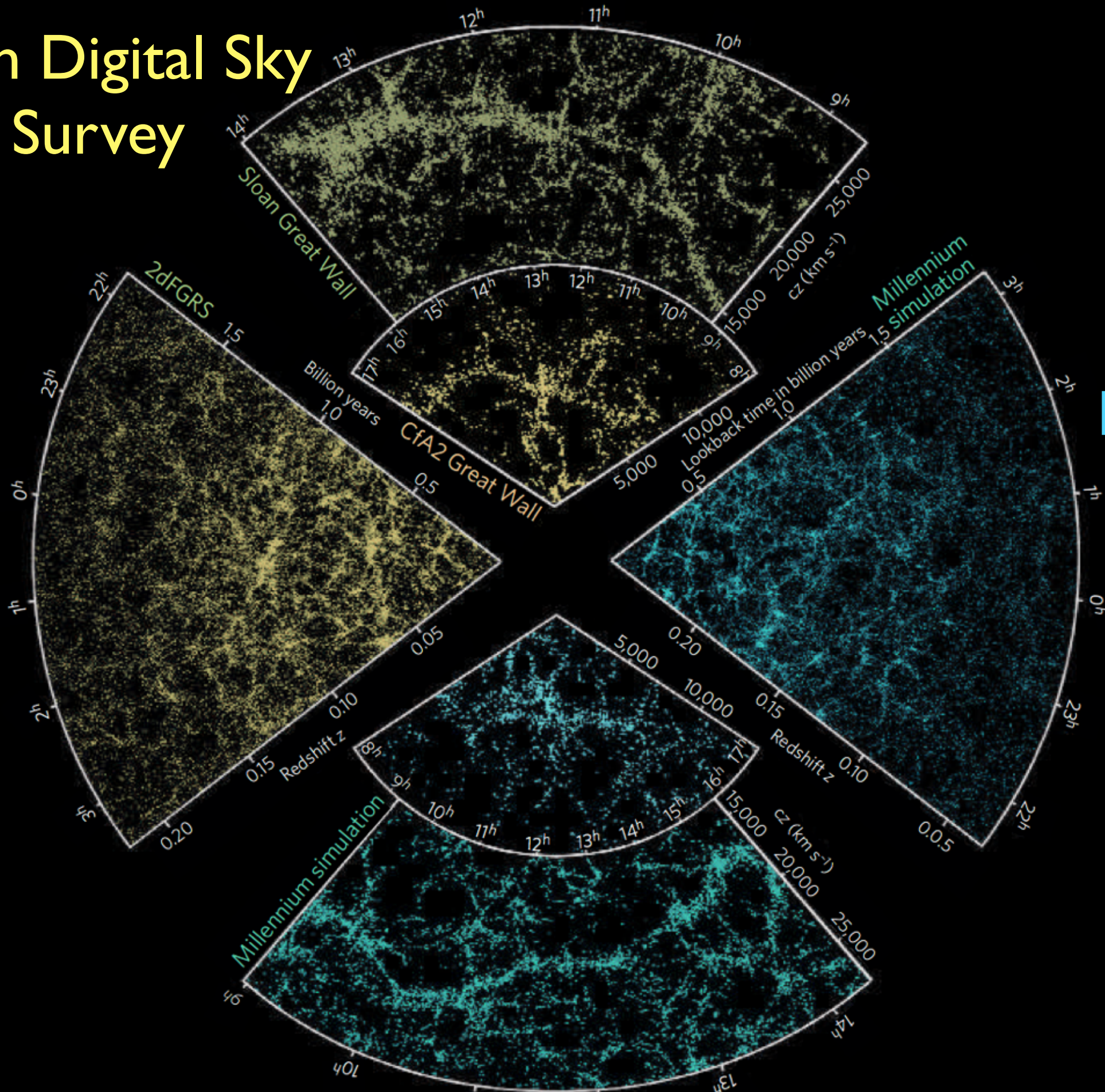
Millennium Simulation

10,077,696,000 particles

($z = 0$)

Sloan Digital Sky Survey

2dF Galaxy Survey

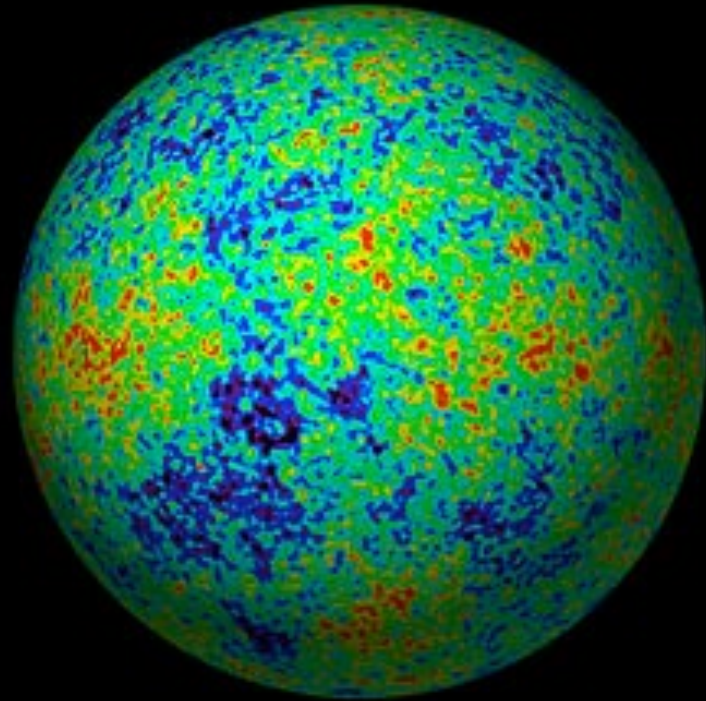


Model

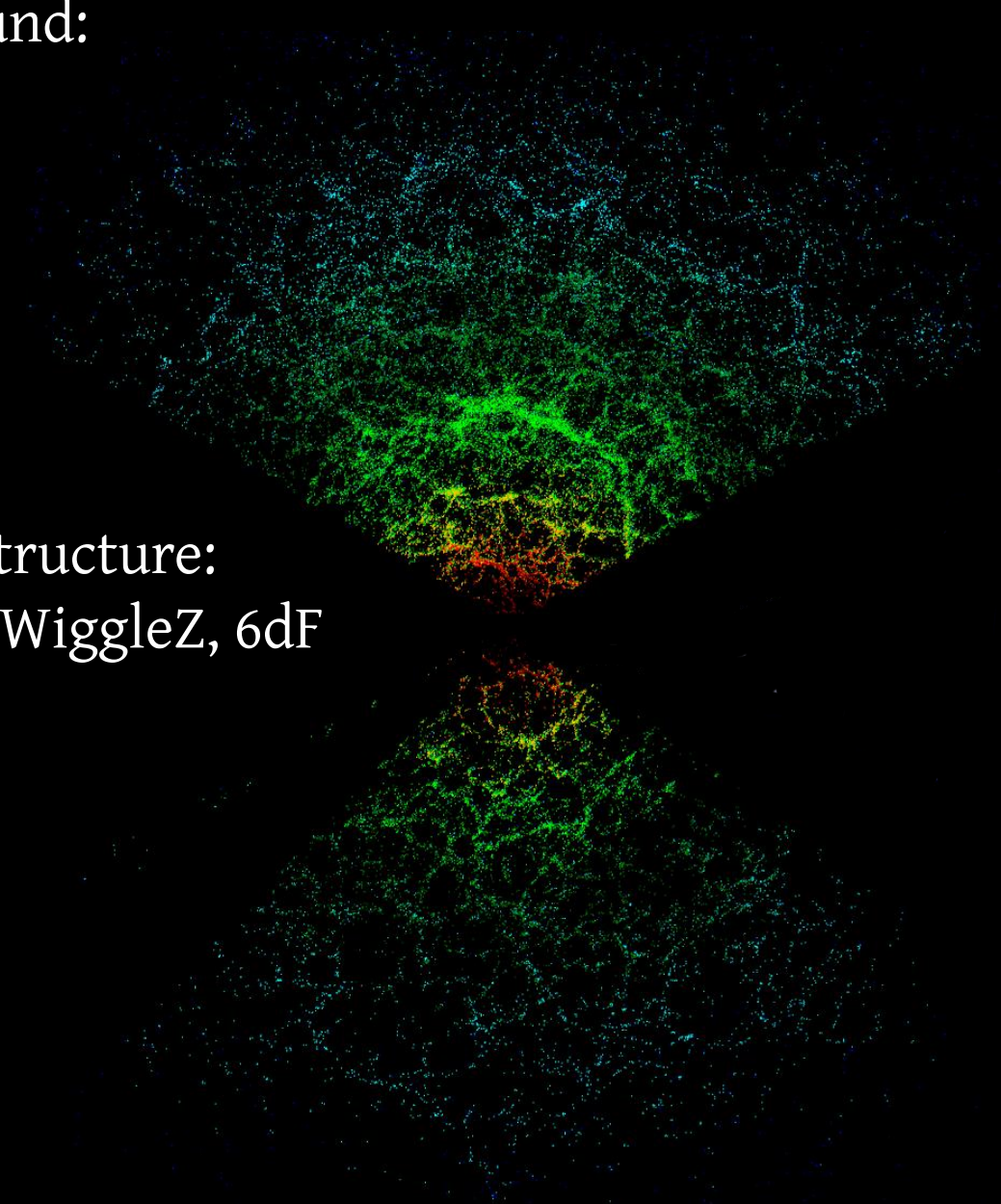
Model

Springel, Frenk & White , 2006

Dark Matter Today: from large scale cosmology



Cosmic Microwave Background:
Planck, SPT, ACT, PolarBEAR



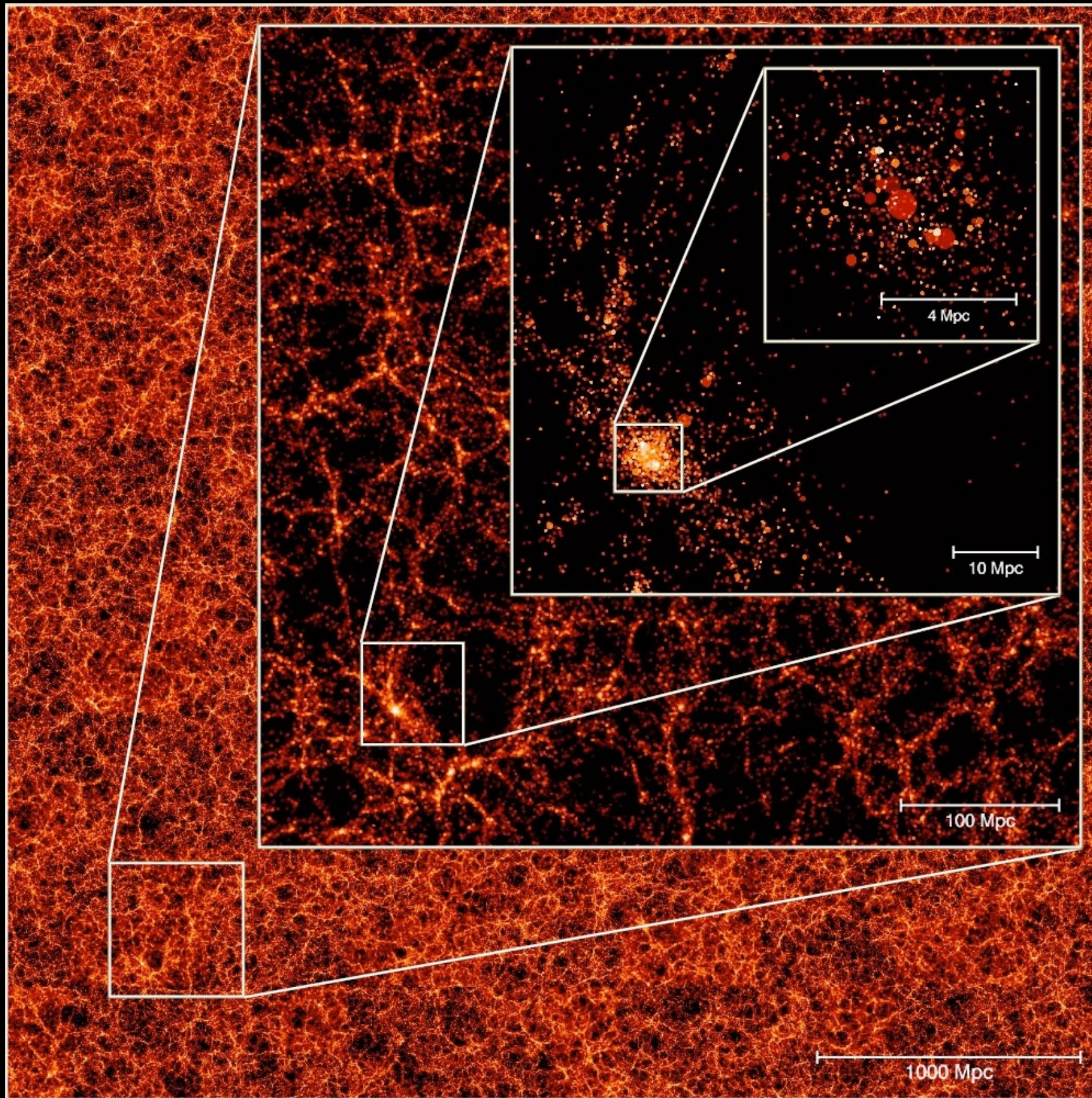
Large Scale Structure:
SDSS (BOSS), WiggleZ, 6dF

$$\Omega_{\text{DM}} \equiv \frac{\rho_{\text{DM}}}{\rho_{\text{crit}}} = 0.259 \pm 0.002$$

Planck 2015 + BAO + SNe + H_0
(Planck Collab. 2015)

Millennium Simulation XXL (2011)

Dark
Matter
Galaxies

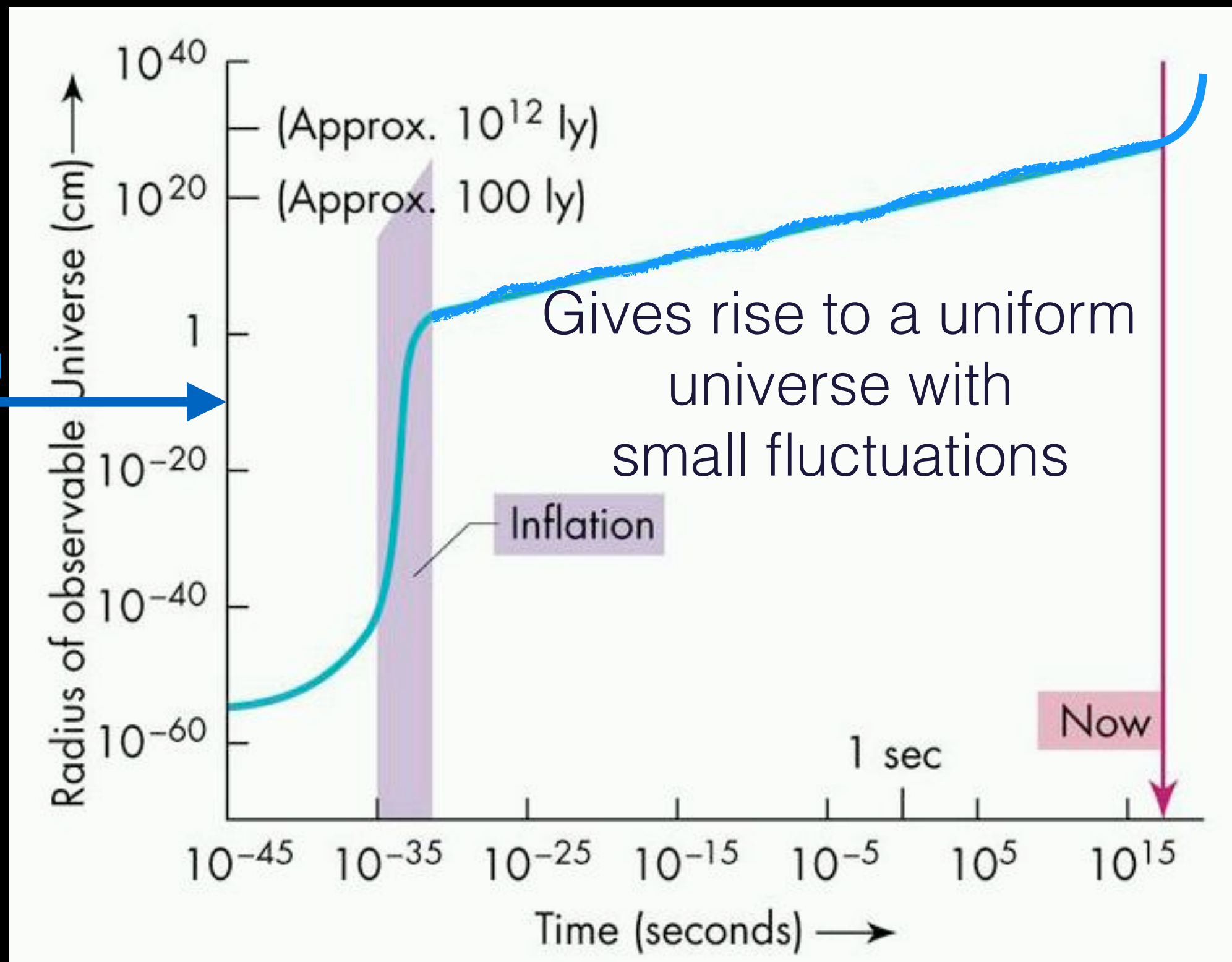


Structure of dark matter on the Milky Way Galaxy scale

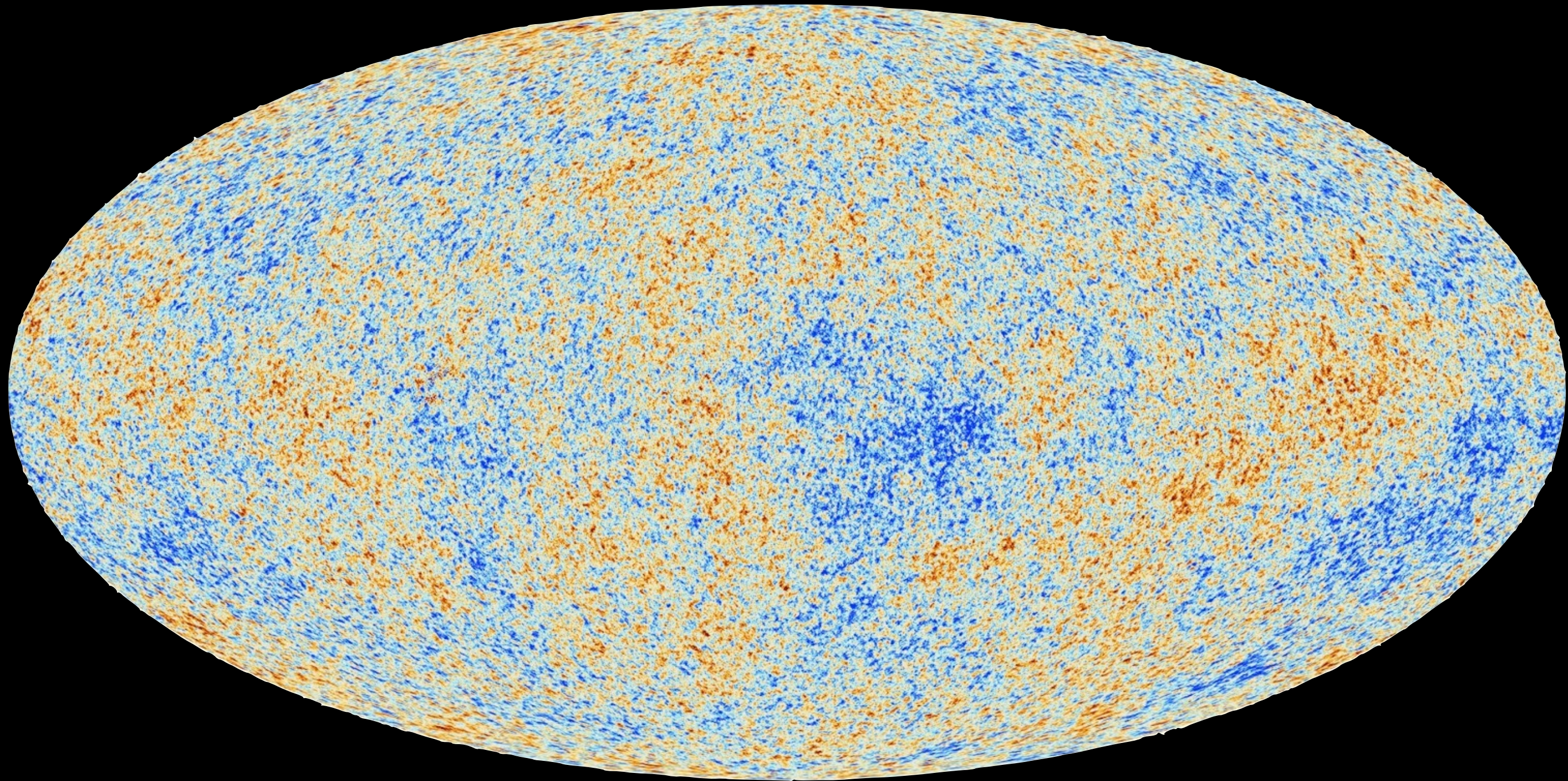
The background of the slide is a dense field of stars, likely representing the Milky Way galaxy. The stars are concentrated in a central region, creating a bright, glowing core that fades out towards the edges. The colors of the stars vary, with many appearing as bright white or yellow points, and some showing hints of blue or red. The overall effect is a rich, multi-colored star field against a dark, almost black background.

Inflationary Universe Expansion

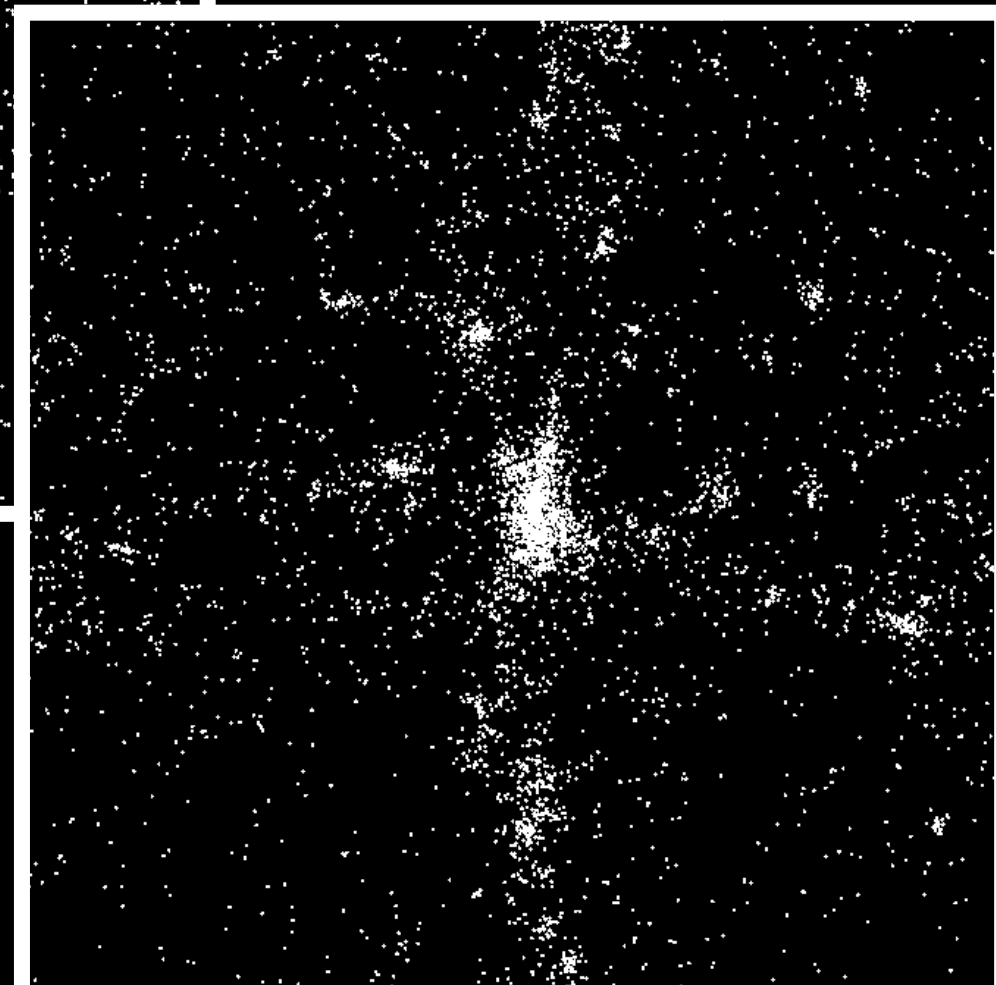
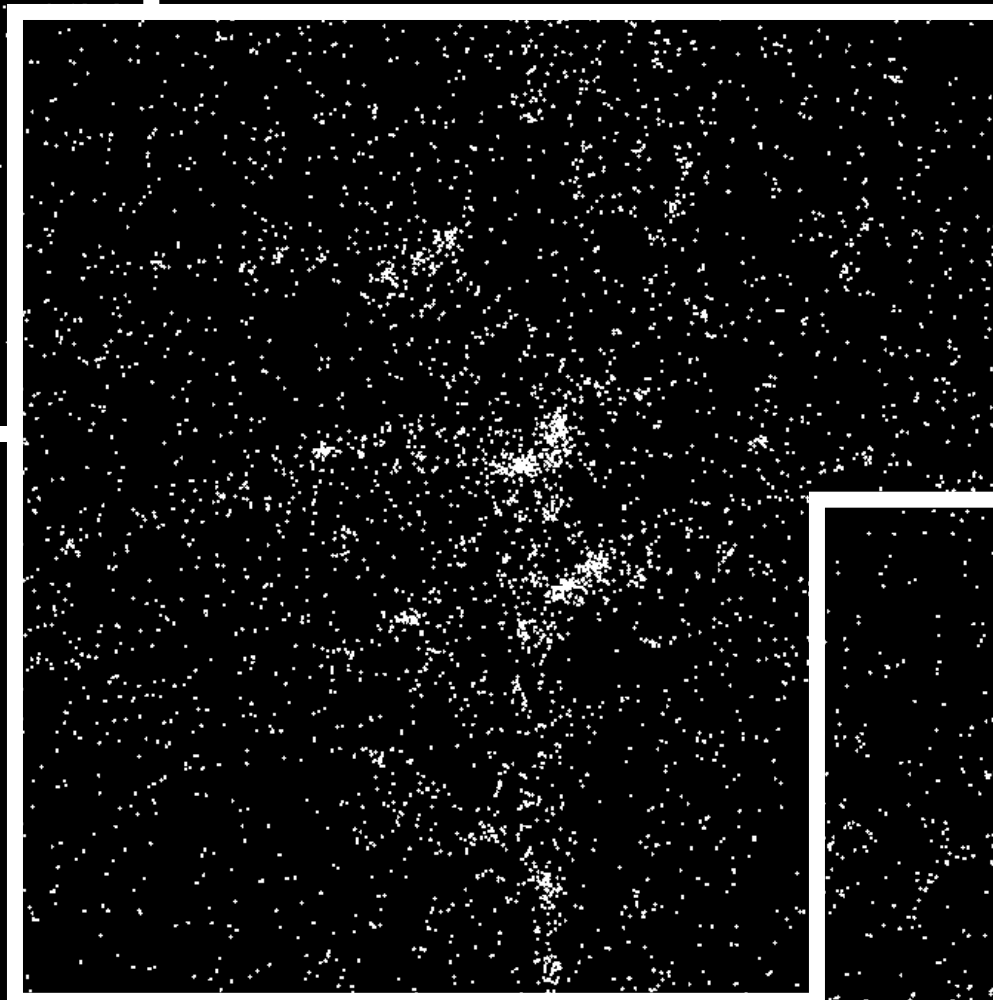
➔ Small fluctuations are caused by quantum randomness in the energy of inflation



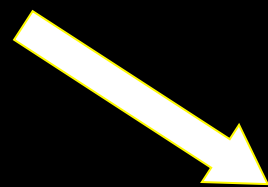
The Initial Conditions of Cosmic Structure:
The Cosmic Microwave Background
from the Planck Satellite, 2013-15



**These quantum
fluctuations
were the seeds
of structure**



time



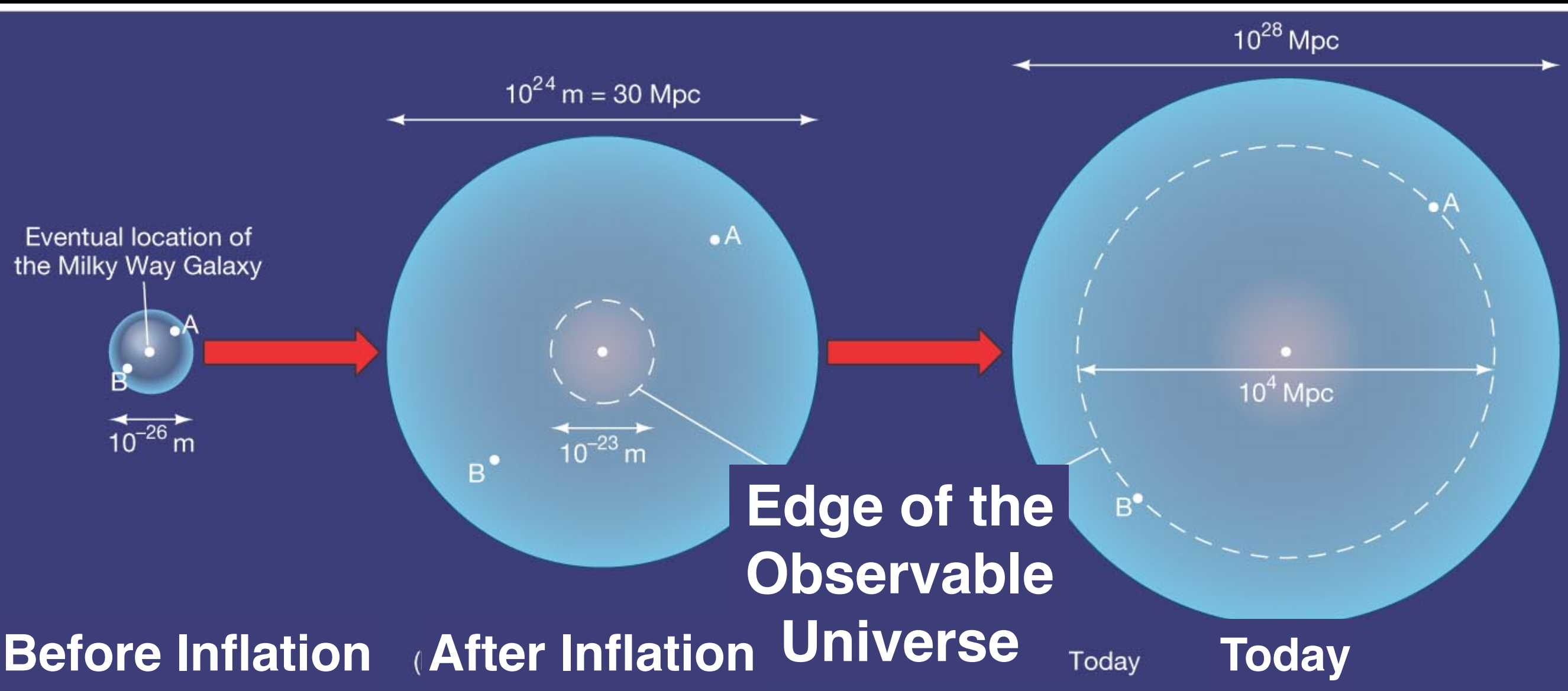
Dark matter in Galaxies

$t = 18.815$ Myr, $z = 93.125$

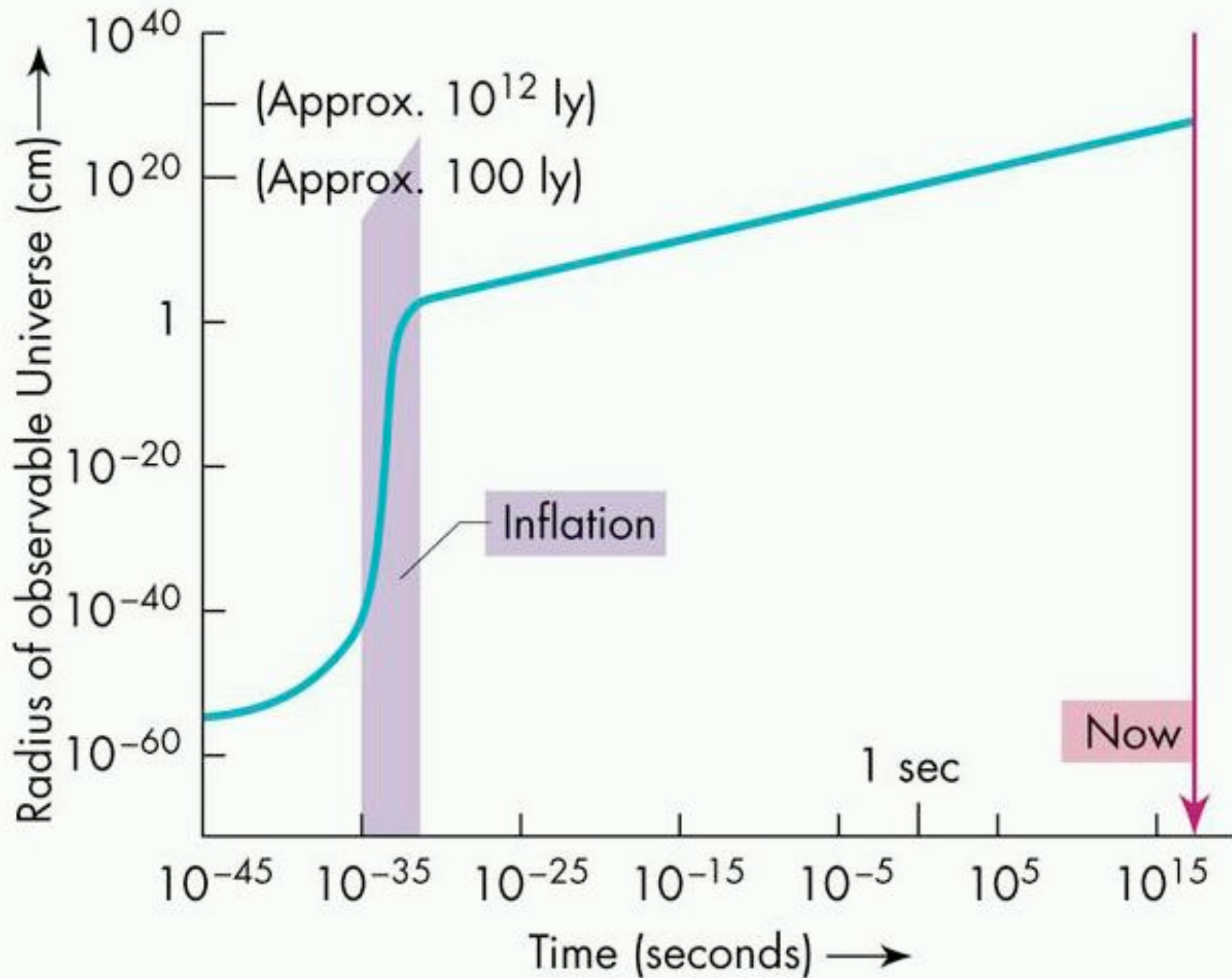
1 Mpc

UC Irvine: Garrison-Kimmel + 2013

Inflation: what makes the Universe smooth, flat and mostly empty

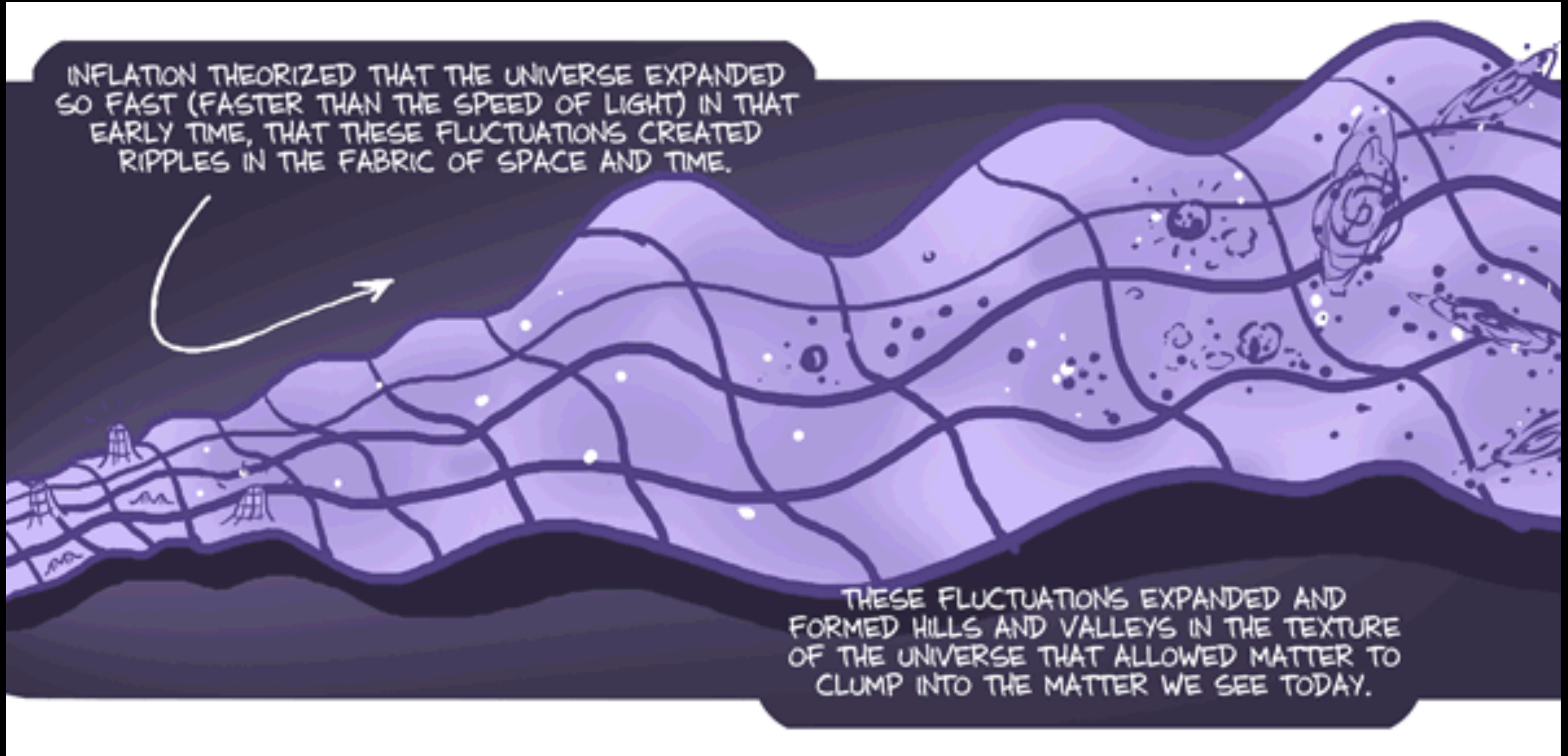


The Inflationary Universe



The Amplification of Quantum Fluctuations

INFLATION THEORIZED THAT THE UNIVERSE EXPANDED SO FAST (FASTER THAN THE SPEED OF LIGHT) IN THAT EARLY TIME, THAT THESE FLUCTUATIONS CREATED RIPPLES IN THE FABRIC OF SPACE AND TIME.



THESE FLUCTUATIONS EXPANDED AND FORMED HILLS AND VALLEYS IN THE TEXTURE OF THE UNIVERSE THAT ALLOWED MATTER TO CLUMP INTO THE MATTER WE SEE TODAY.

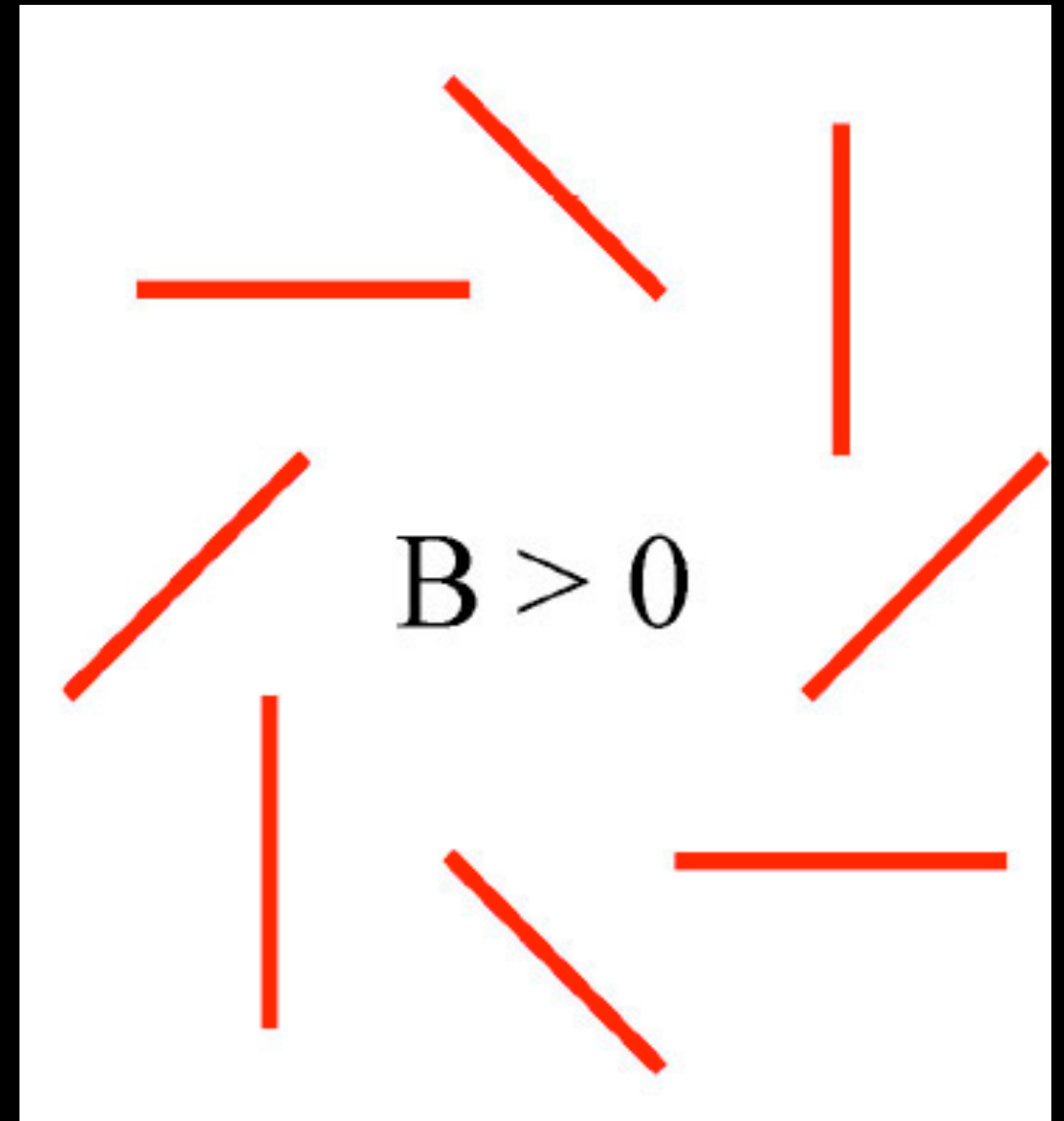
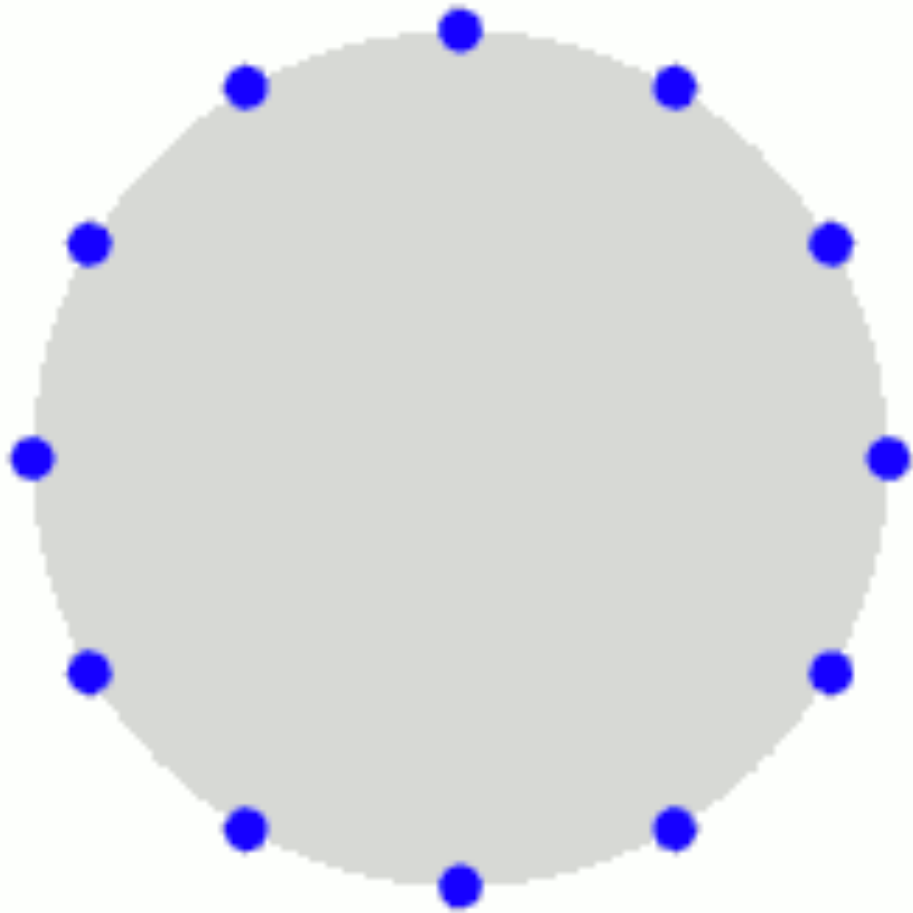
How can we get more information from the Cosmic Microwave Background?

Polarization!

Light has color and “direction”



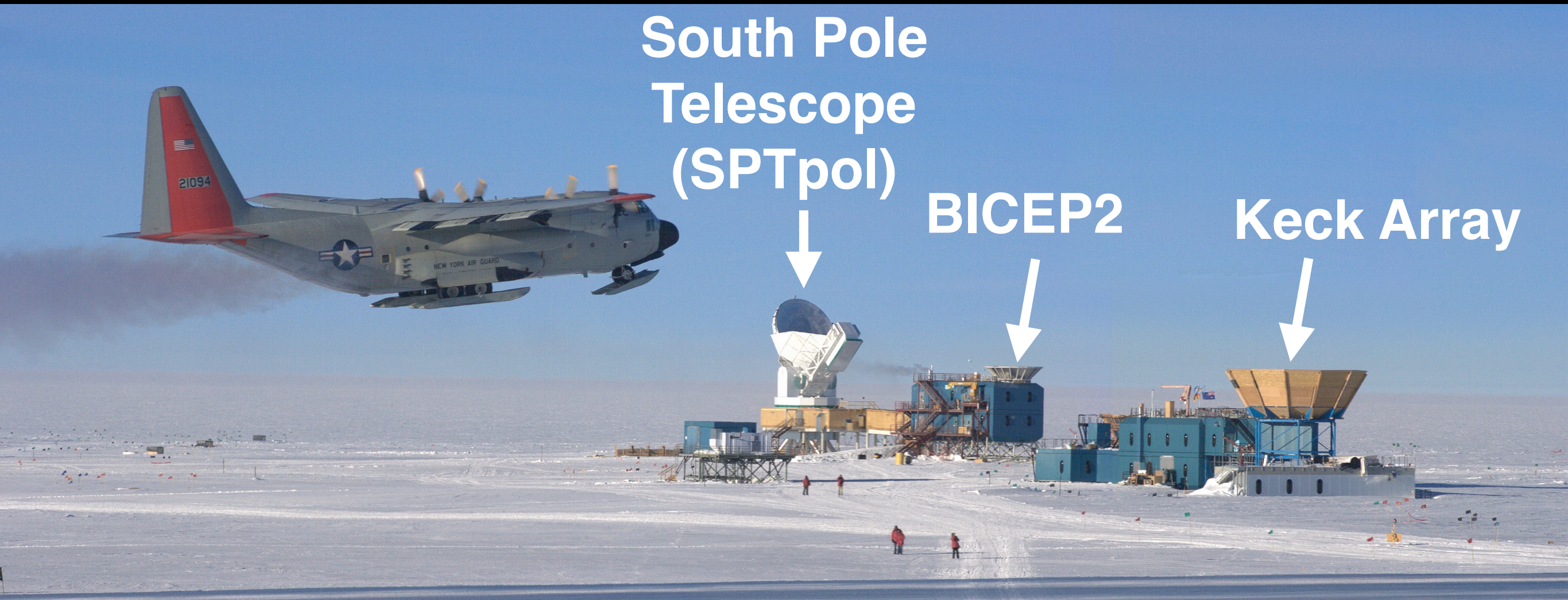
Polarization Can Reveal New Perturbations: Gravitational Waves from Inflation



“B-Modes”

At best, 1% of the
anisotropy in temperature

Experiments going for detecting the *B*-modes from Inflation: Science at the South Pole



South Pole
Telescope
(SPTpol)

BICEP2

Keck Array

The BICEP2 Experiment at the South Pole

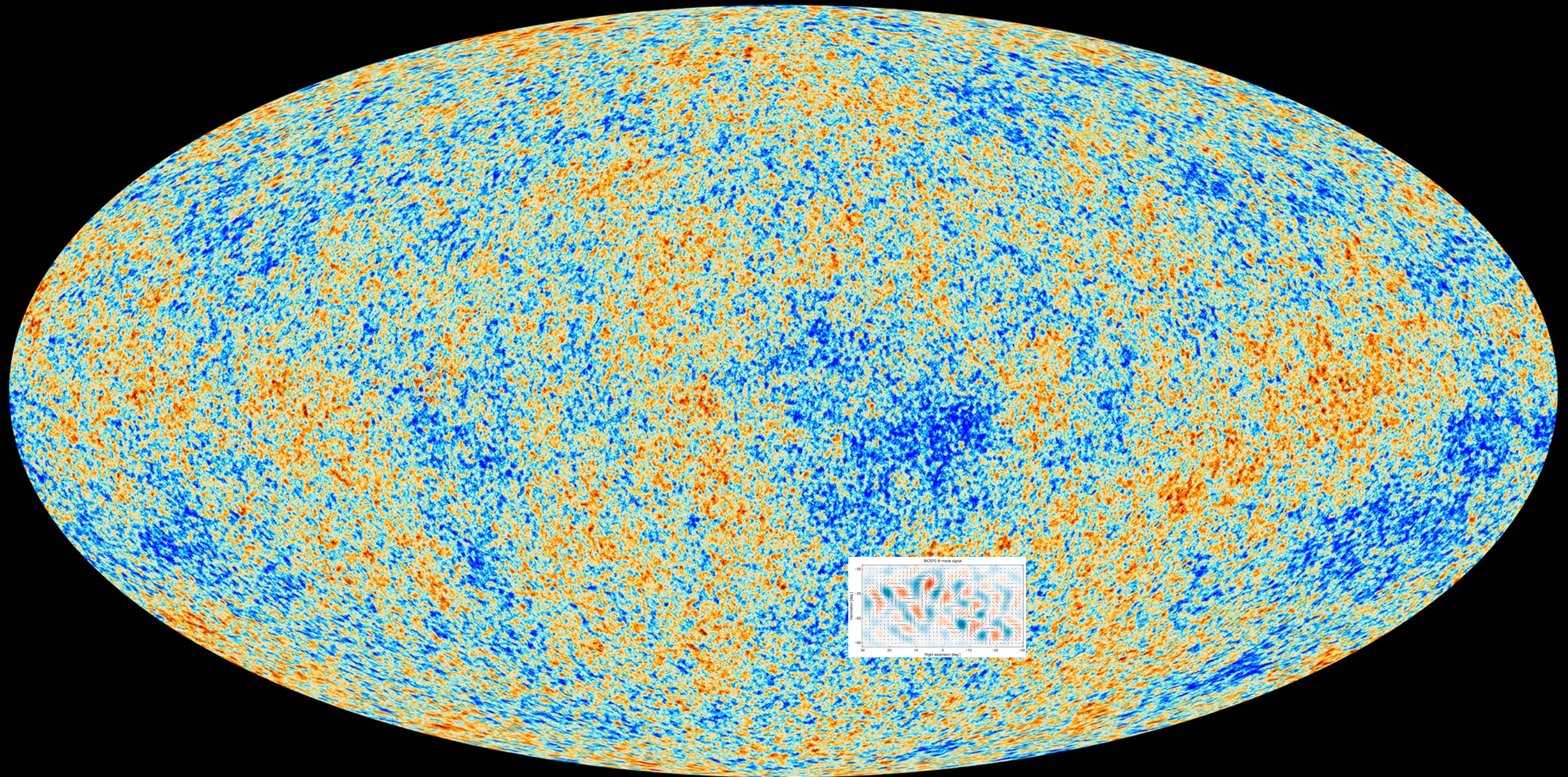
Observed a tiny part of the sky non-stop
for 2 years to hope to find the minuscule
B-mode signature

ICECUBE Neutrino Experiment



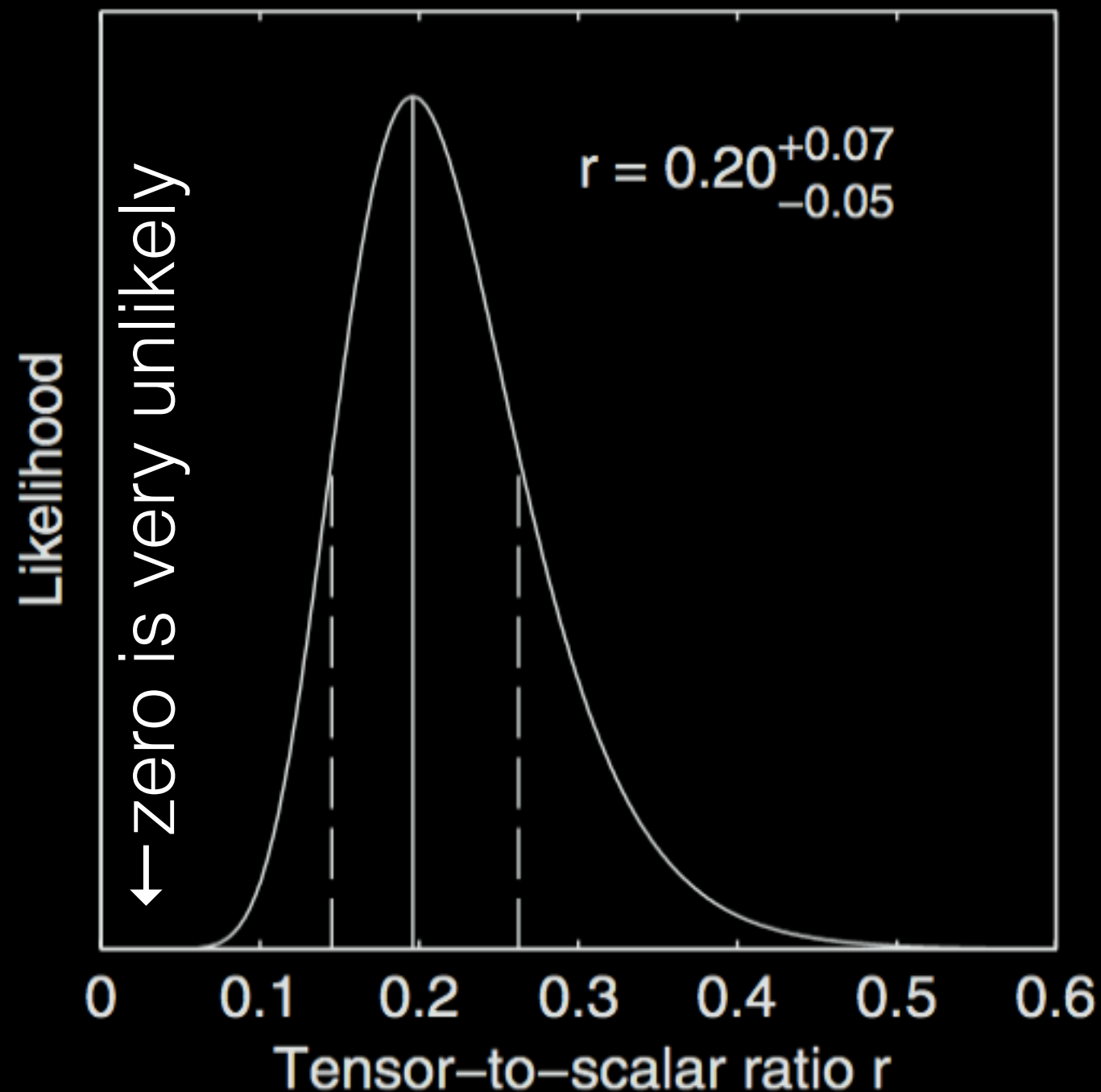
Polarization Signal In the CMB Found by the BICEP2 Collaboration in March 2014


The level of the signal, *if primordial*, reveals the energy scale of inflation...



Polarization Signal In the CMB Found by the BICEP2 Collaboration in March 2014

Claimed 7σ detection of B-modes (gravitational waves) in the CMB: 3 in 10 trillion chance to get these results if $r = 0$





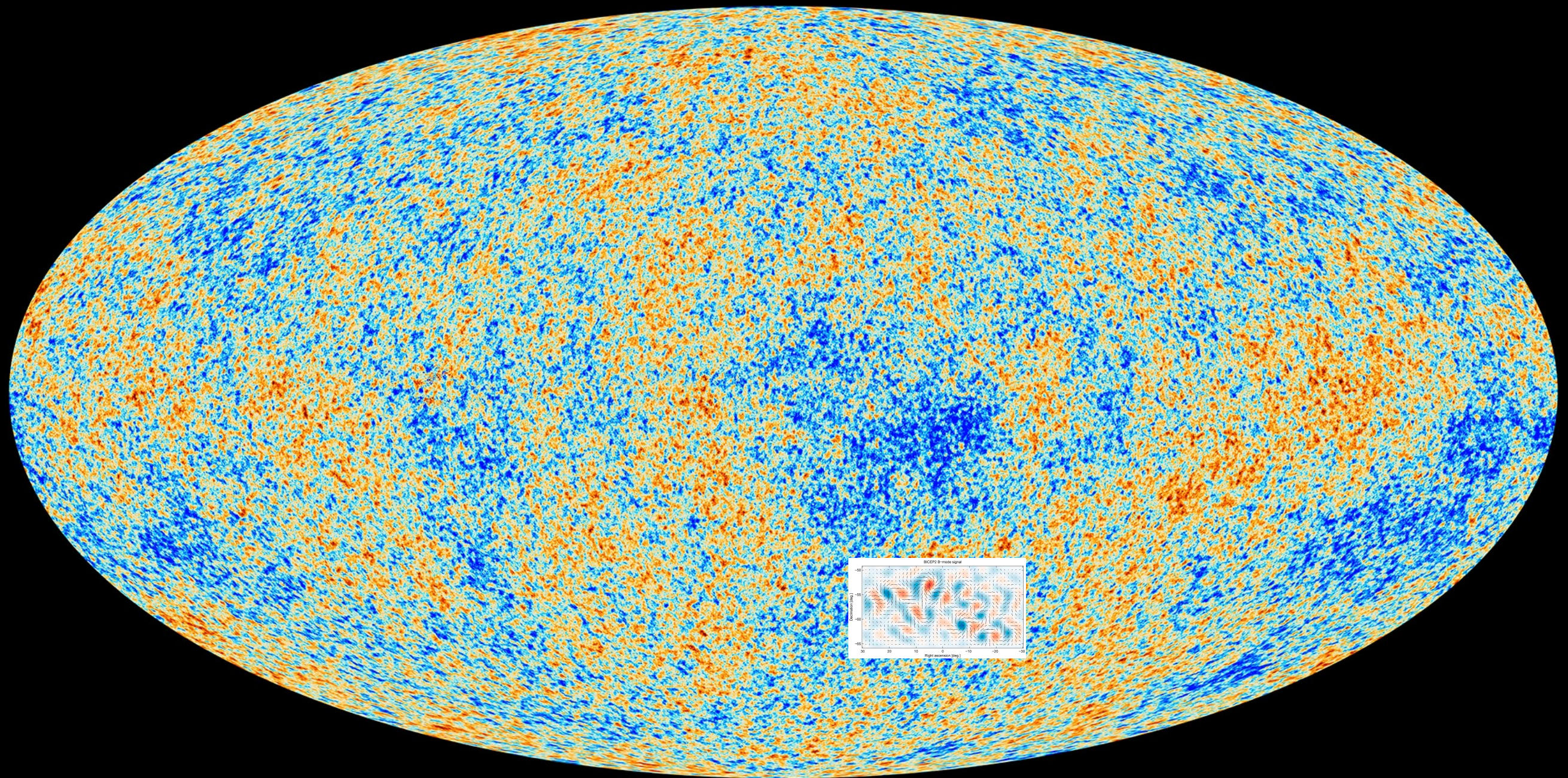
Dust!

Gave rise
to the B-mode
signal seen in
BICEP2

Dust is being subtracted in more detailed observations...
Providing a Measure of the Inflationary Universe

Is it primordial or dust?

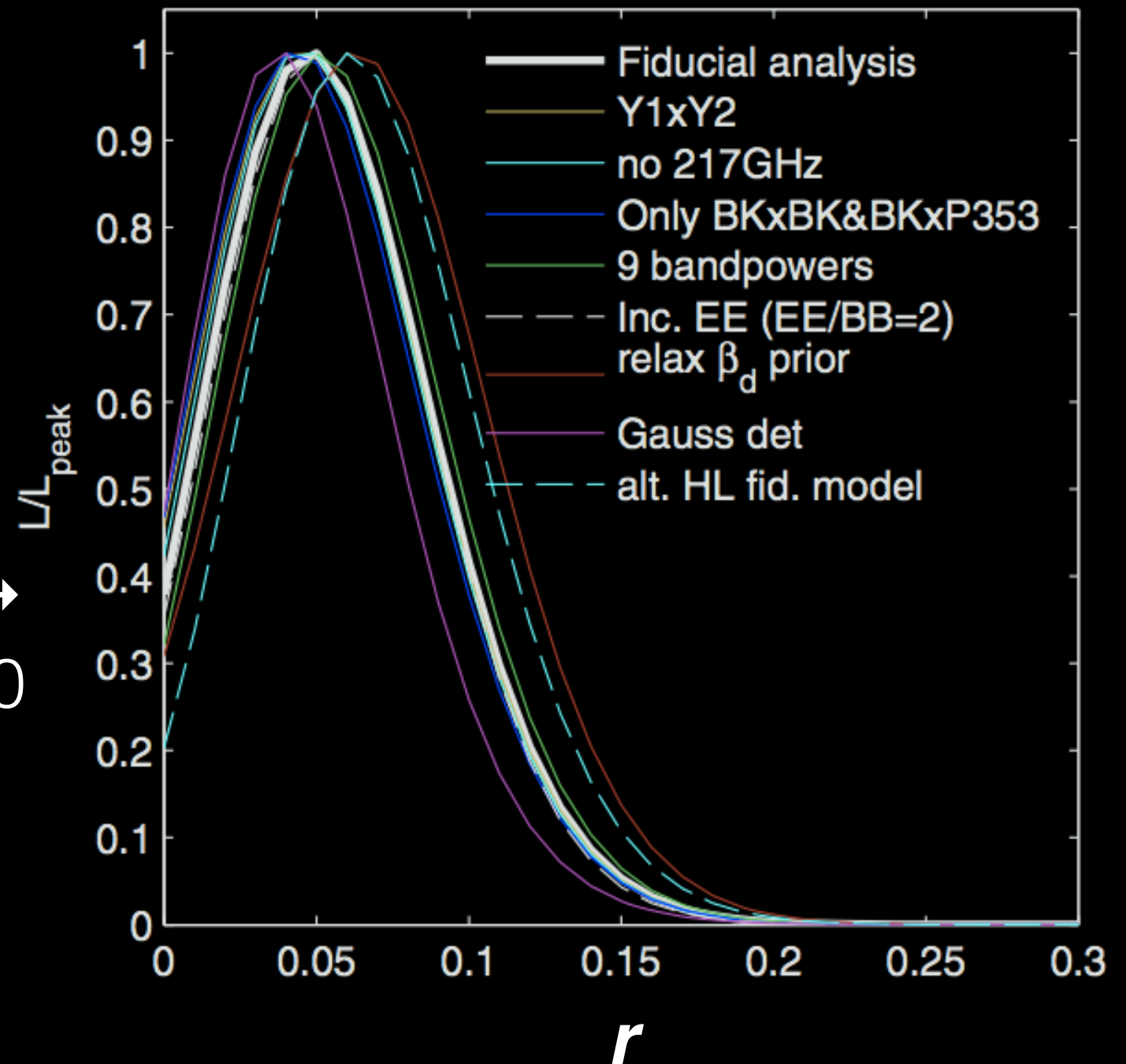
Cross-Analysis of Planck Mission and
BICEP2: Released January 21, 2015



BICEP2 Combined with Planck (January 21, 2015):
Dust was found to significantly contribute
to signal, and was removed

No longer a detection, but still found < 8% chance that $r = 0$

zero is more likely →
but < 8% chance that $r = 0$



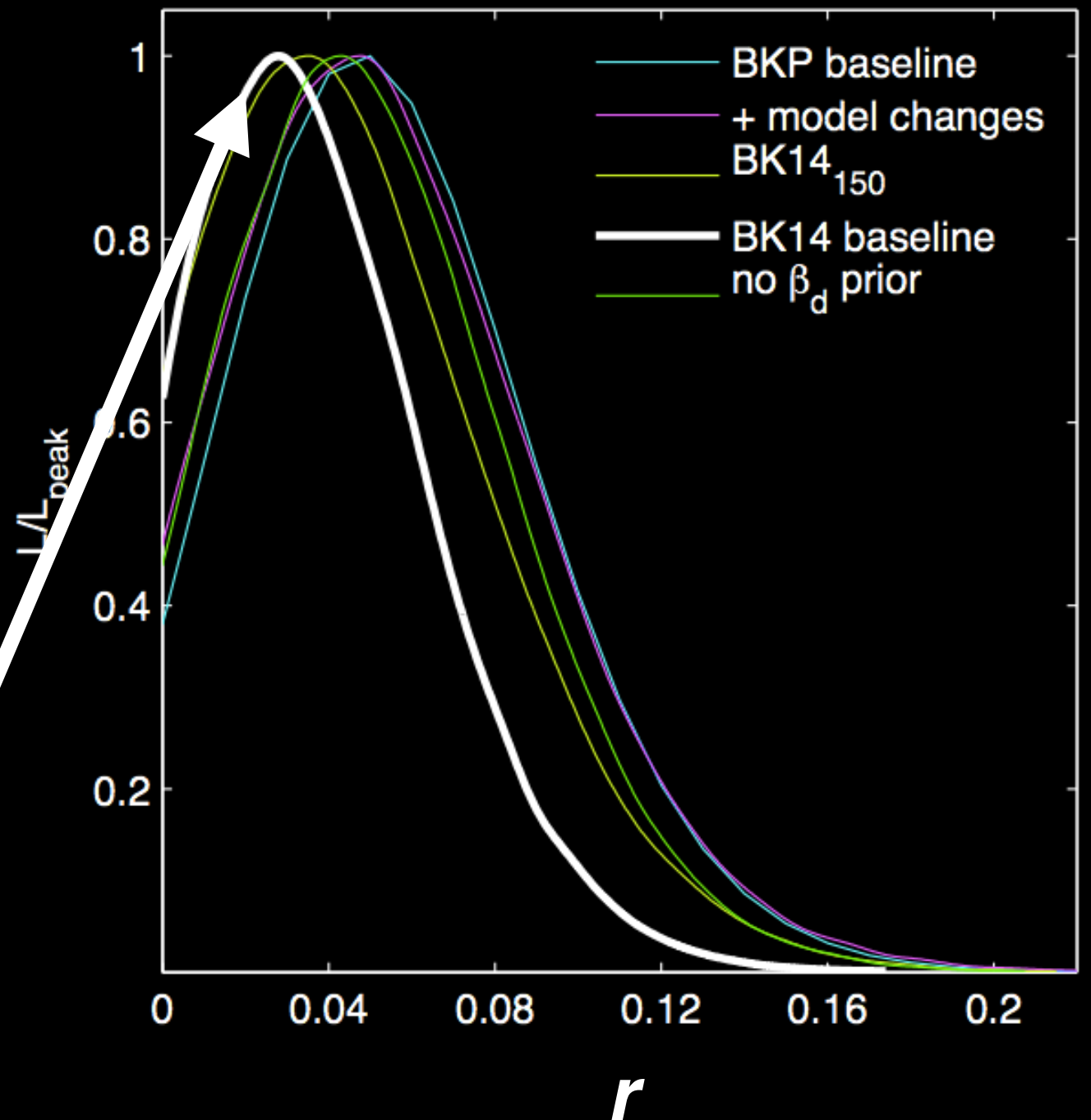
BICEP2 + Keck + Planck (**October 30, 2015**):

Even stronger constraints on dust and
primordial gravitational waves r

now < 18% chance that $r = 0$

zero is even more likely →
but **< 18% chance** that $r = 0$

but peak likelihood still
nonzero!



More results coming!

The SPIDER Telescope

Data in
January,
results
in progress



Upcoming Experiments on *B*-modes from Inflation



***Interested in helping unlock the
mysteries of the Universe?***

Center for Cosmology at UC Irvine:

<http://is.gd/UCICosmo>