Detecting Gravitational Radiation from the Beginning of the Universe

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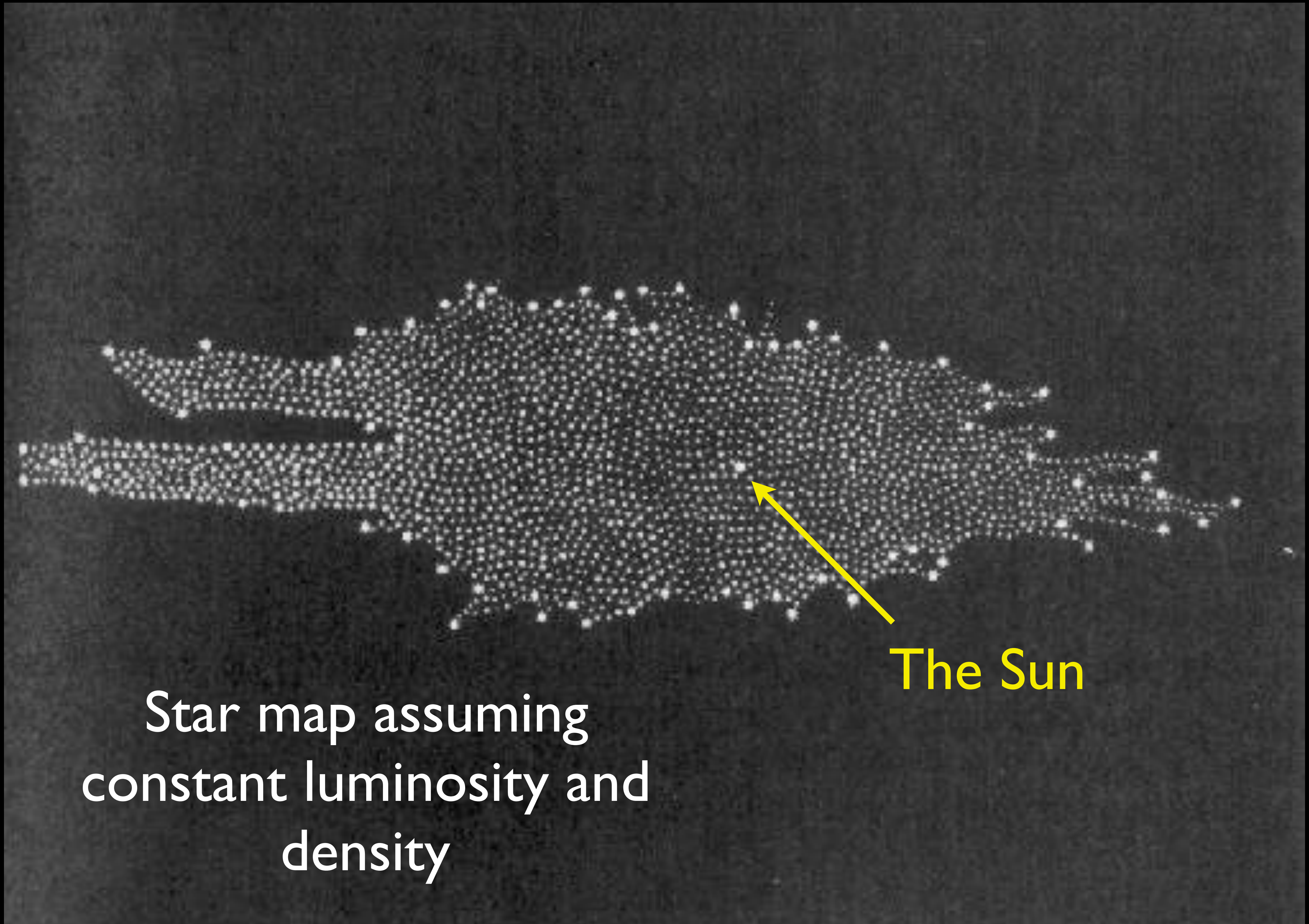
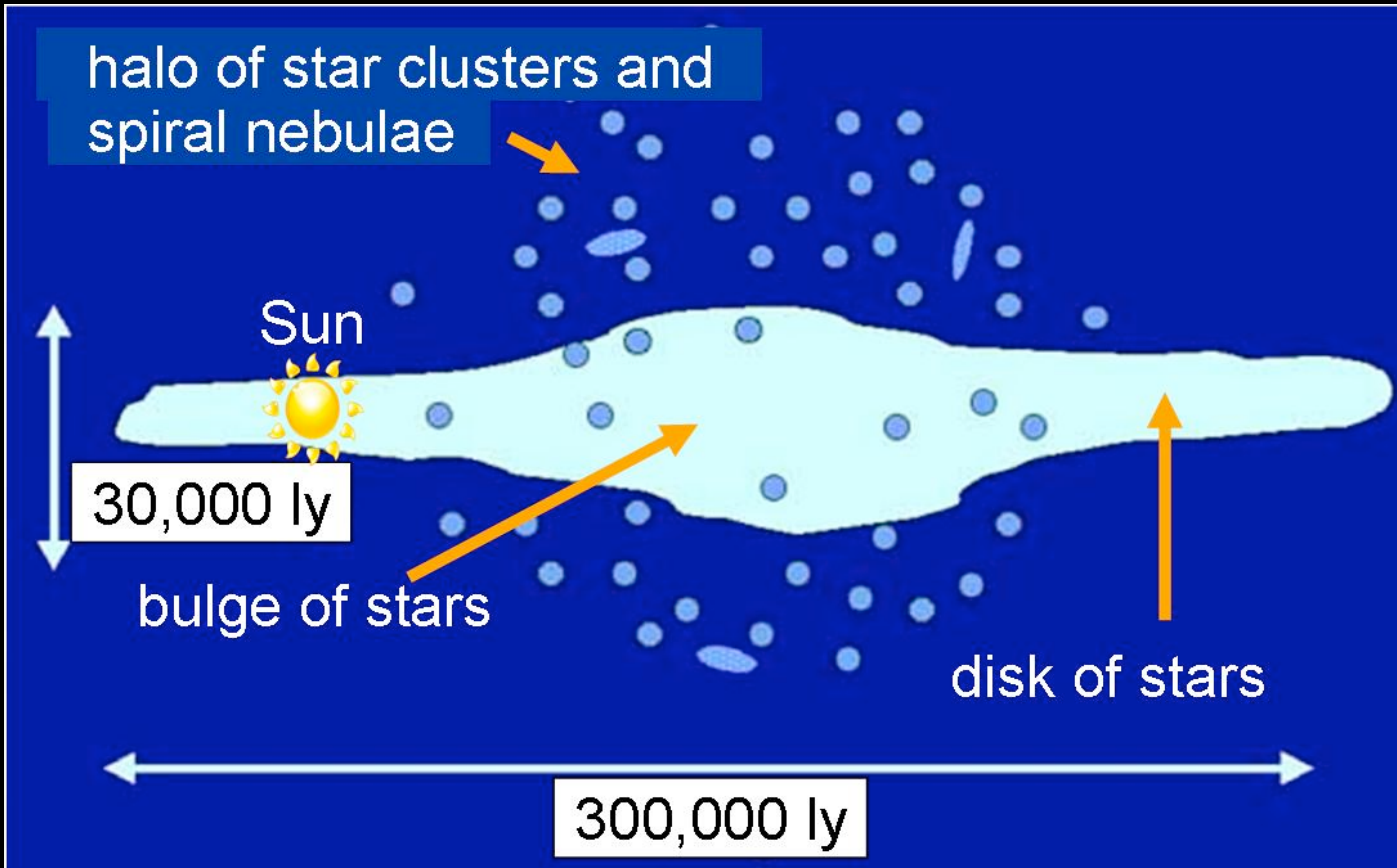
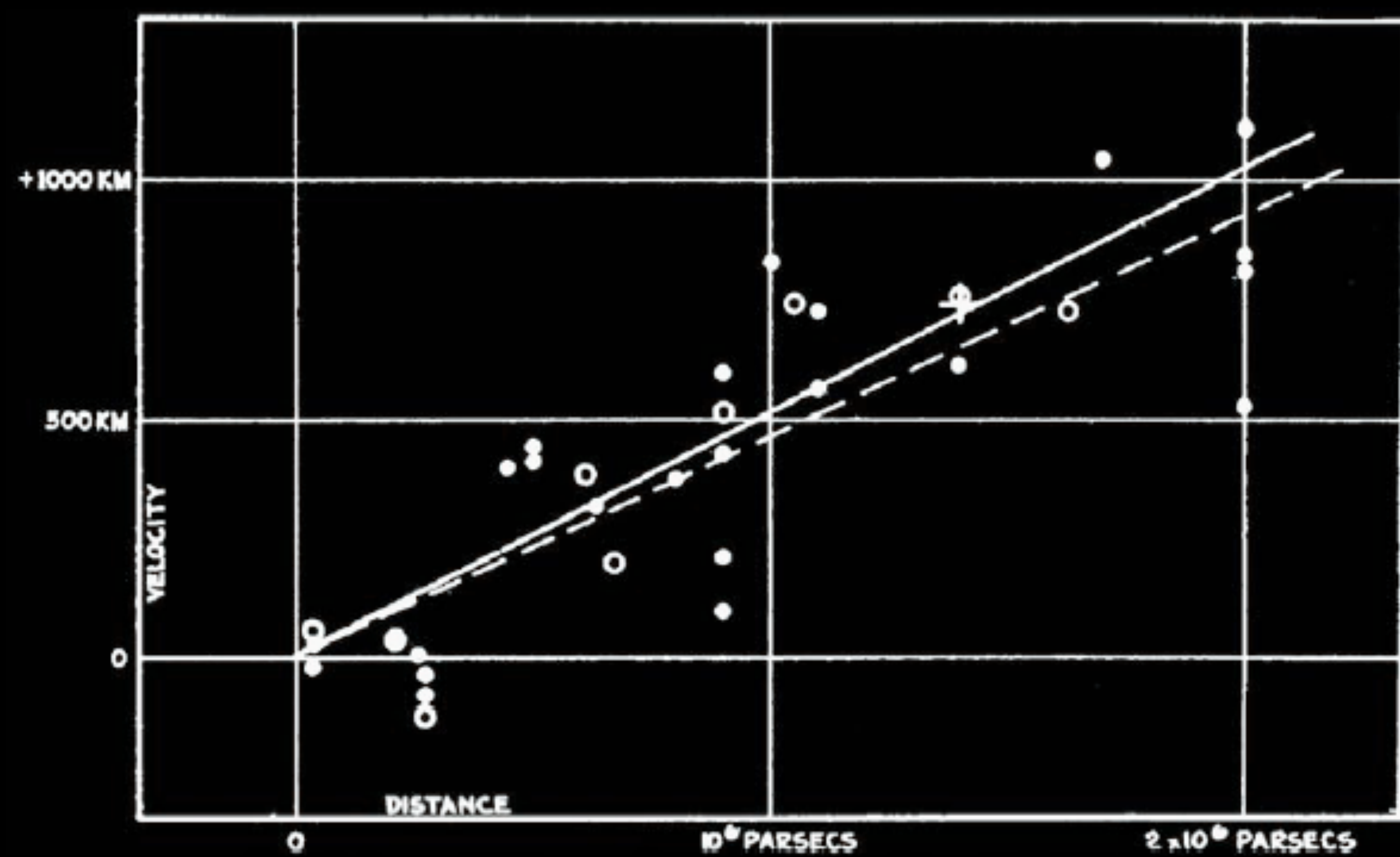
The Universe in 1785:
Herschel's Map



The Universe in 1921:
The Shapley Model



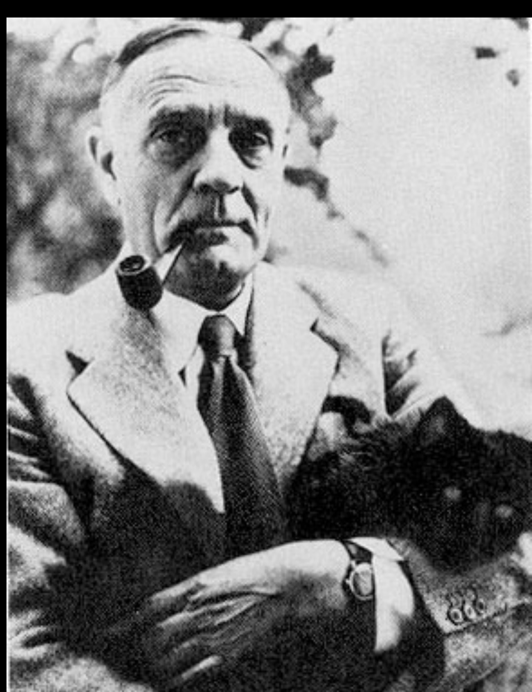
Hubble's new distance determinations (1929)



velocity, v (km/s)

distance, d

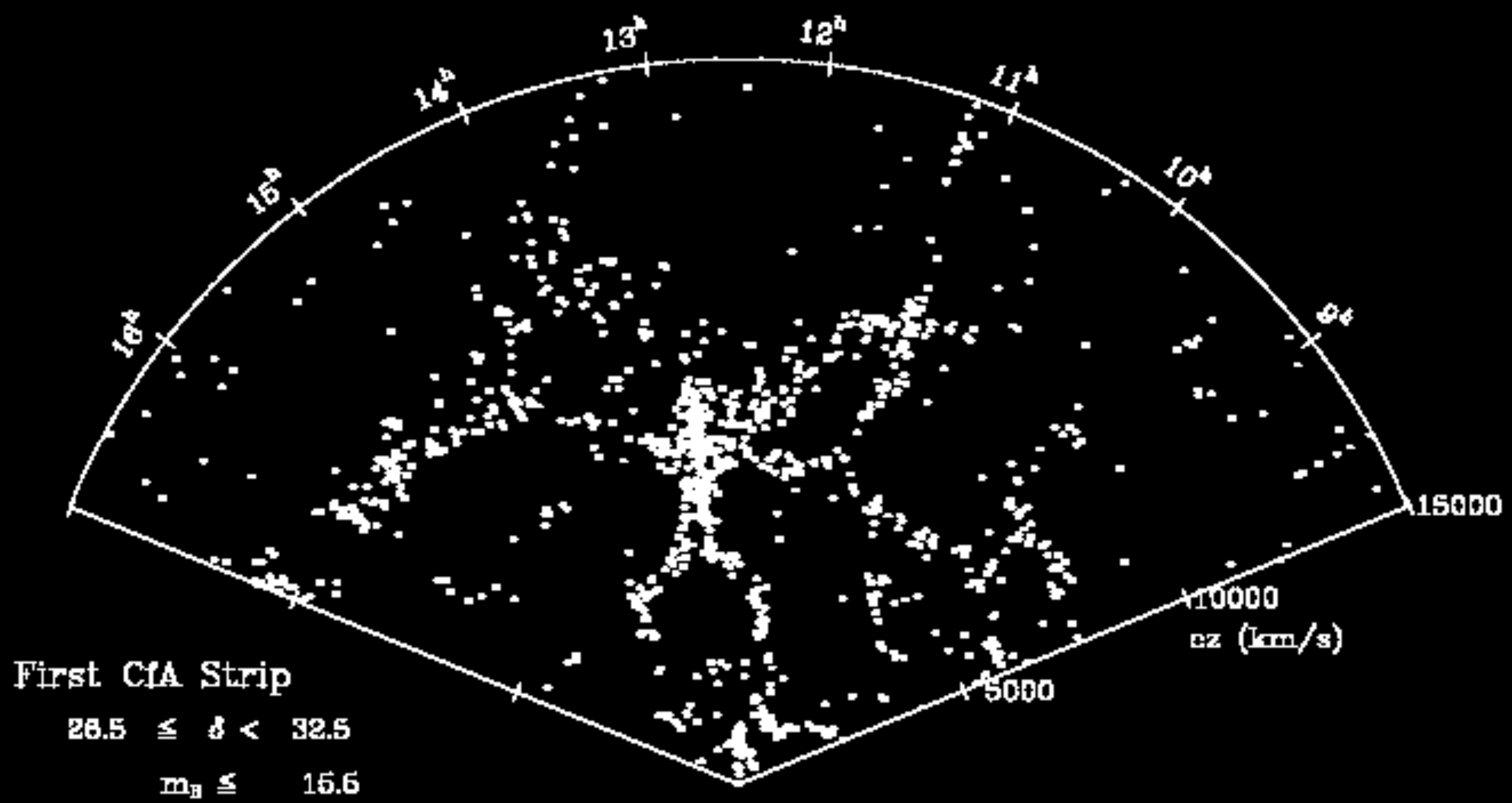
6 Million Light Years



$$v \propto d$$

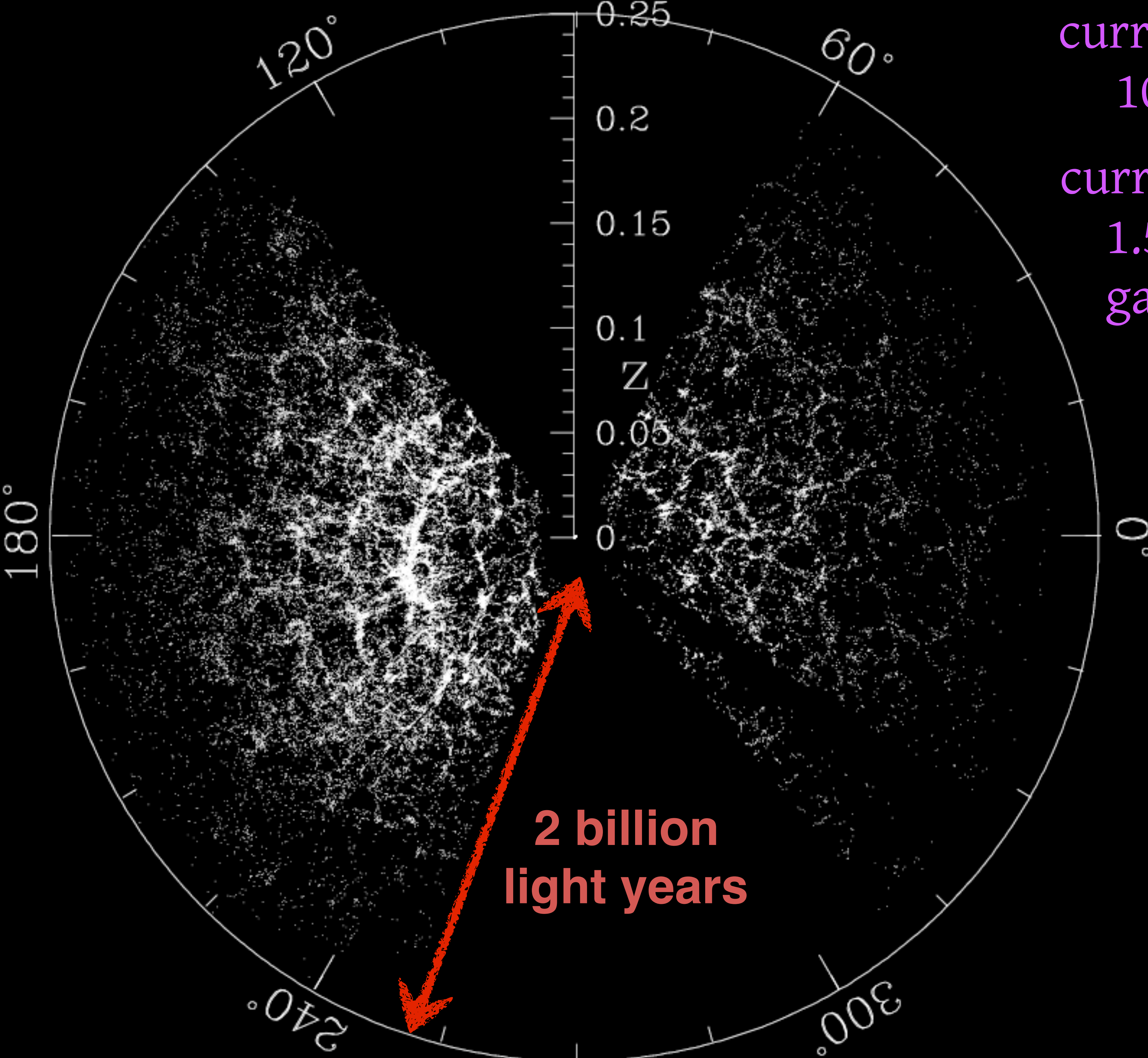
$$v = H_0 d$$

Galaxy Surveys in 1985



CfA: 1100 galaxies in 6° × 130°, in this slice

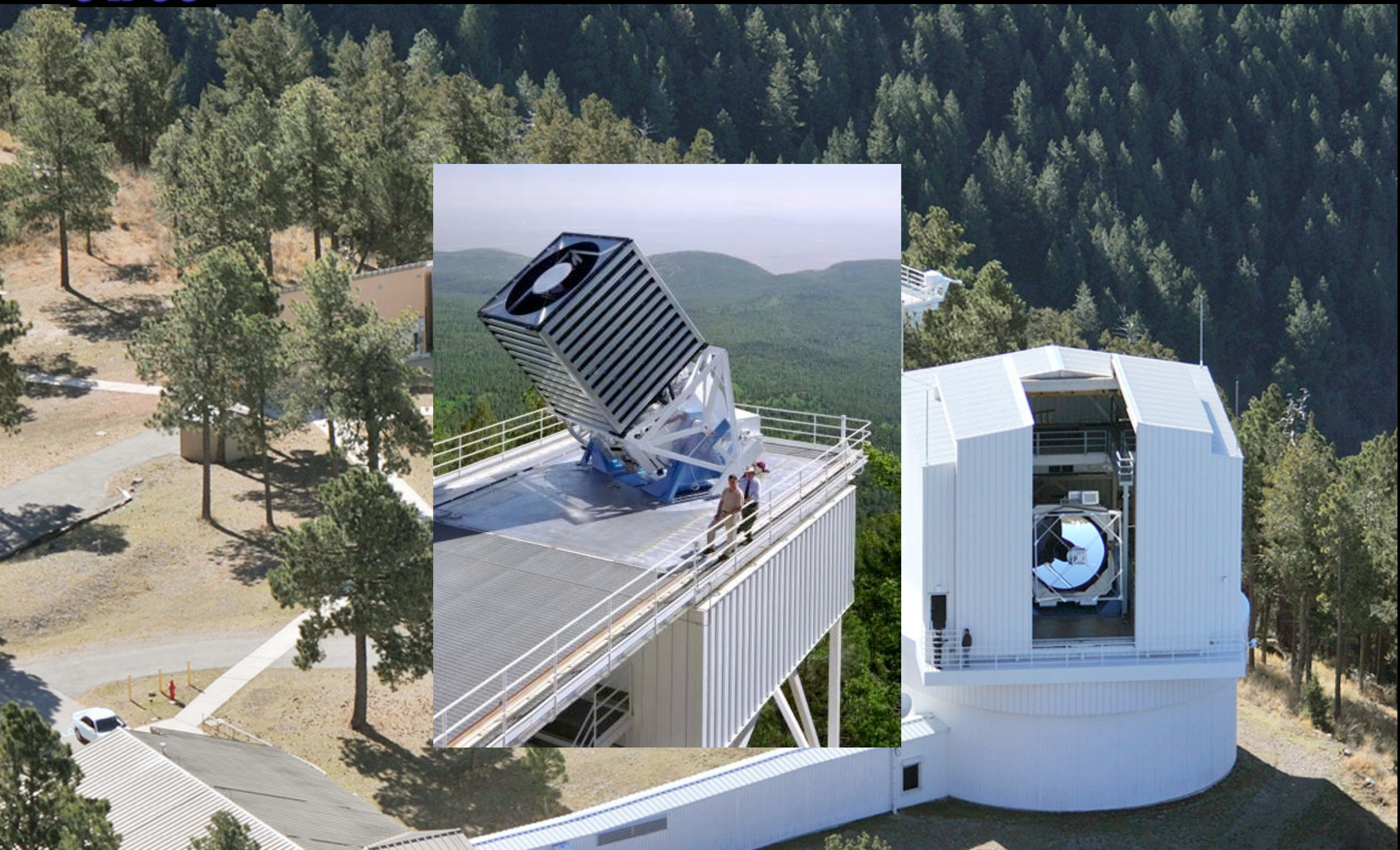
Galaxy Surveys Today: the Sloan Digital Sky Survey

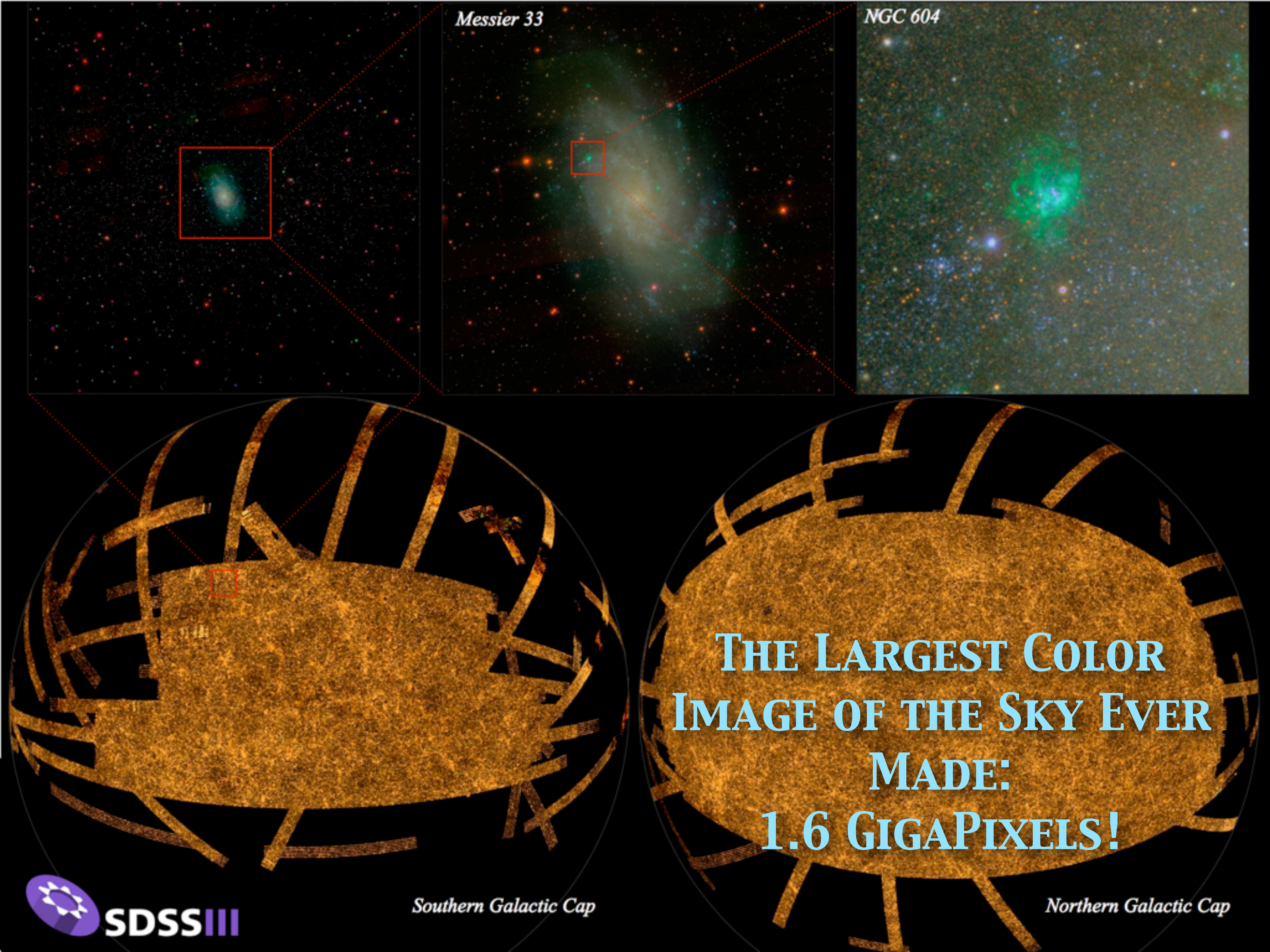


currently:
10^6 main galaxies

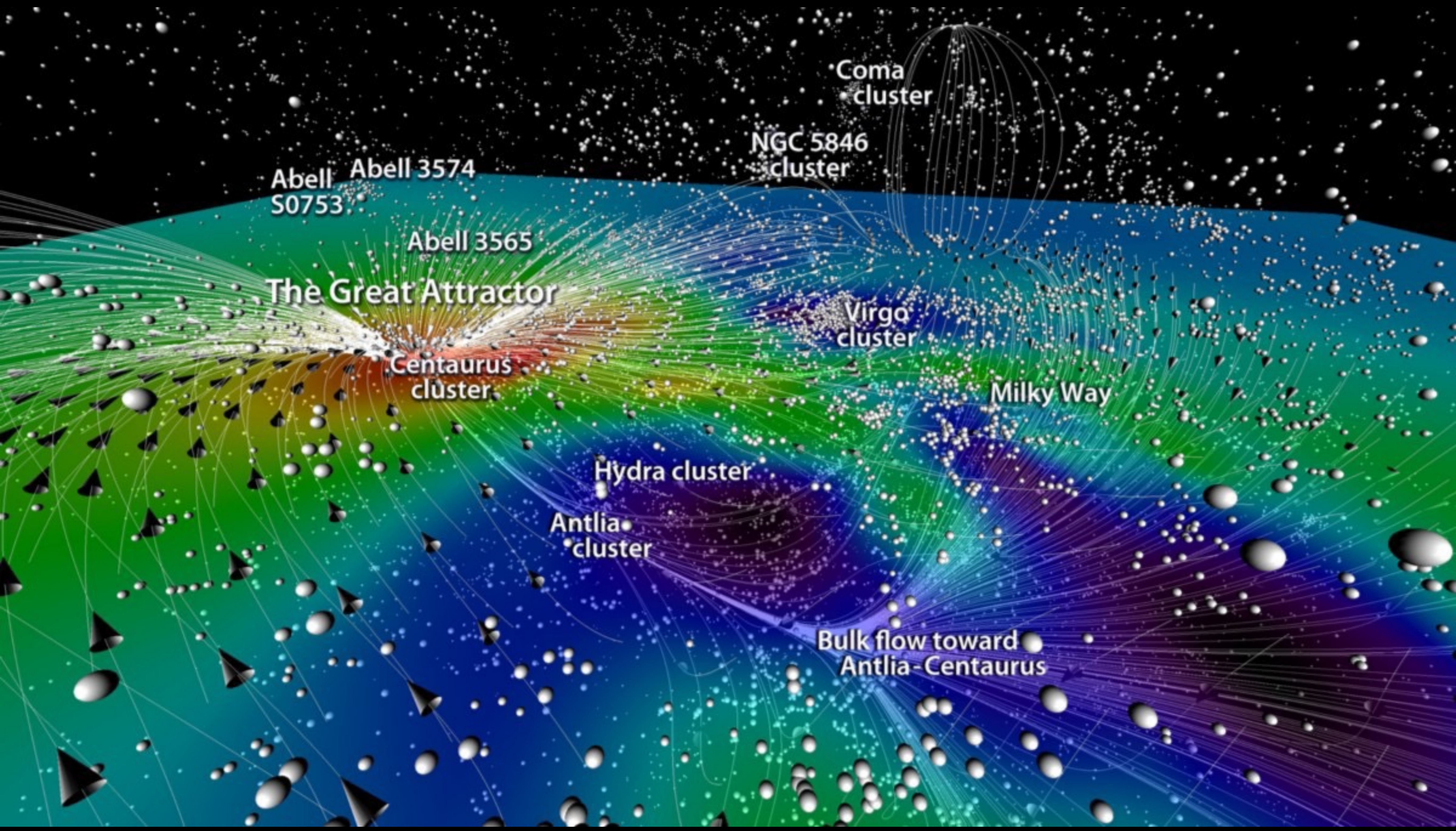
current & upcoming:
1.5×10^6 luminous red galaxies to 2.5×10^9 pc

Sloan Digital Sky Survey: Galaxies from Large to Small Scales



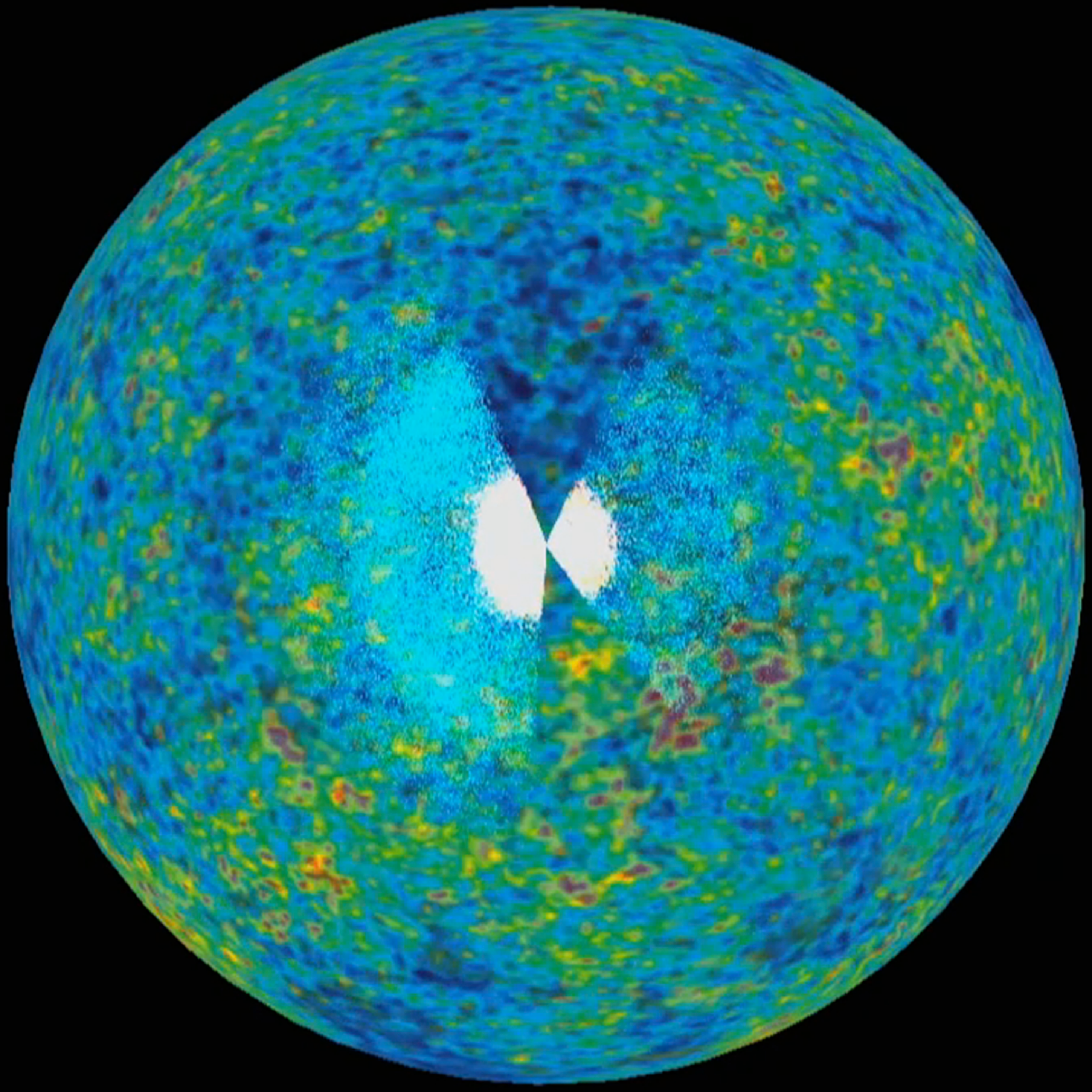

Messier 33
NGC 604
The Largest Color Image of the Sky Ever Made: 1.6 GigaPixels!
SDSS III
Southern Galactic Cap
Northern Galactic Cap

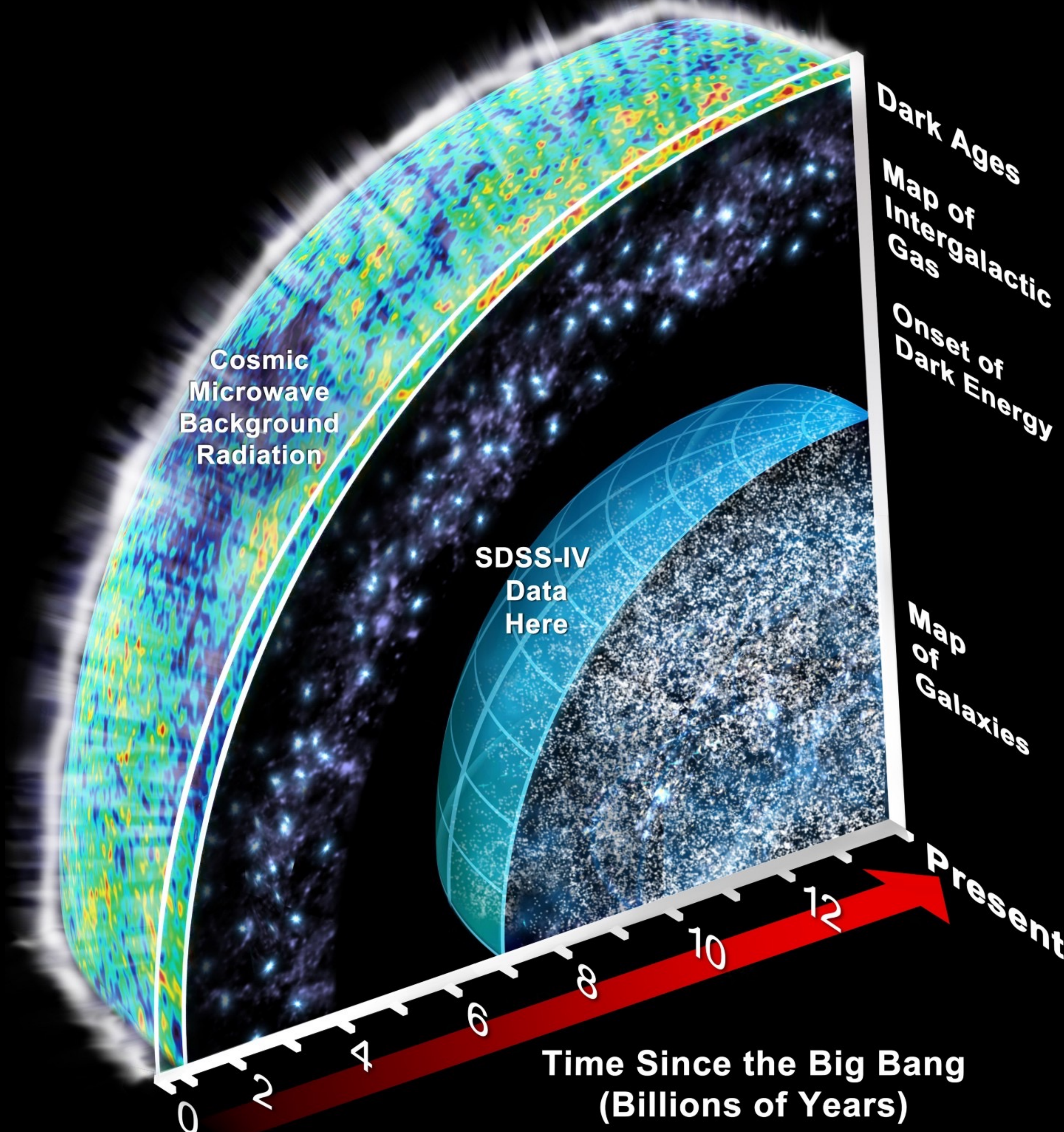
Our local universe: the Laniakea Supercluster of Galaxies (Tully et al 2014)



The Known Universe: American Museum of Natural History

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

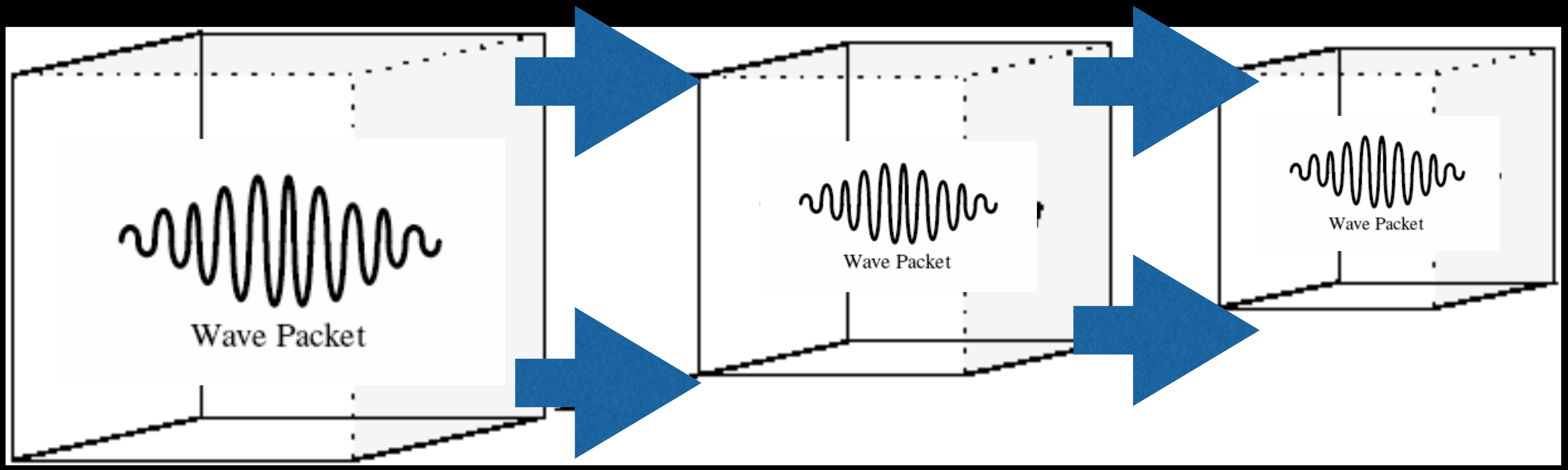


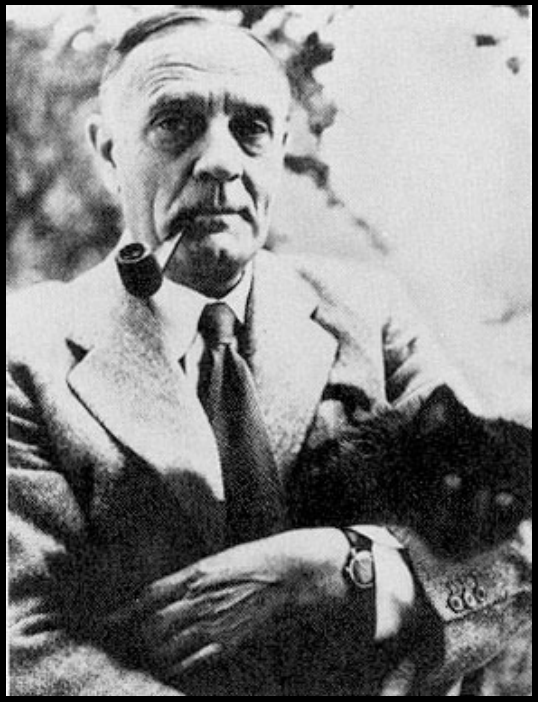


Dark Ages
Map of Intergalactic Gas
Onset of Dark Energy
Cosmic Microwave Background Radiation
SDSS-IV Data Here
Map of Galaxies
Present
0
2
4
6
8
10
12
Time Since the Big Bang (Billions of Years)

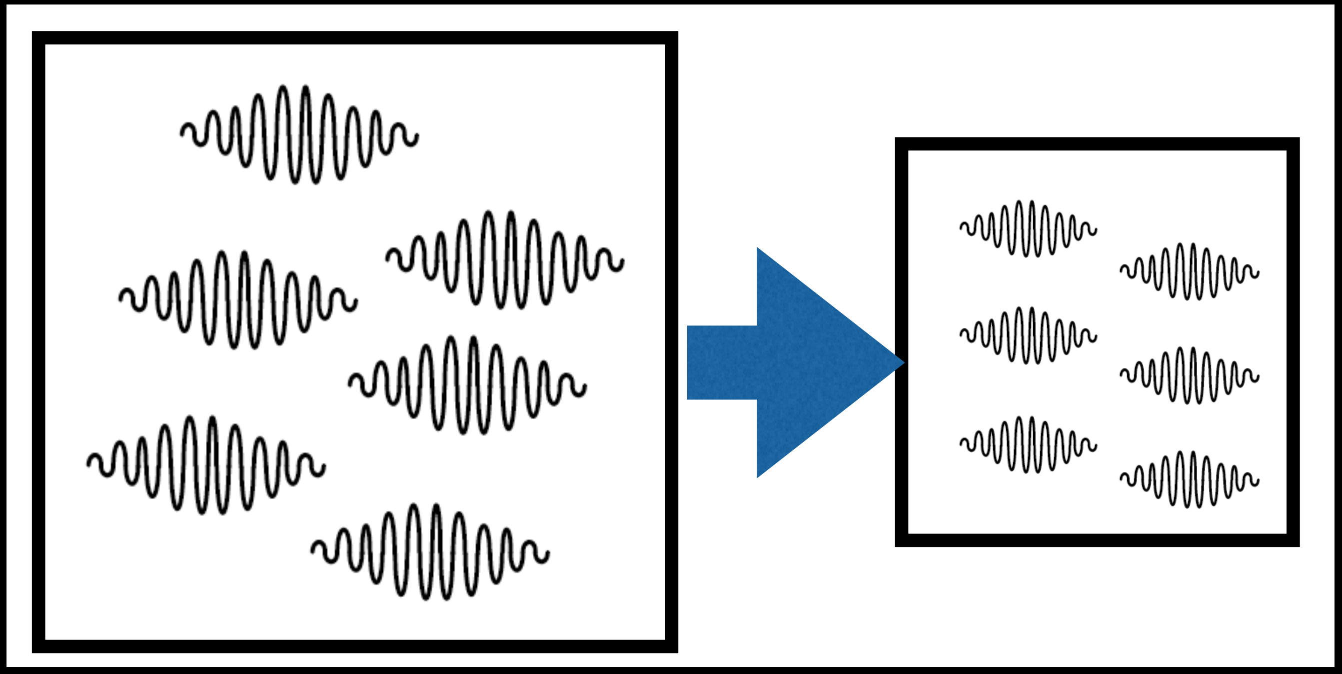
Hubble's Expansion Means the Universe was ***Hotter*** & ***Denser*** Early On

Light Wavelength:
shorter, more energetic back in time

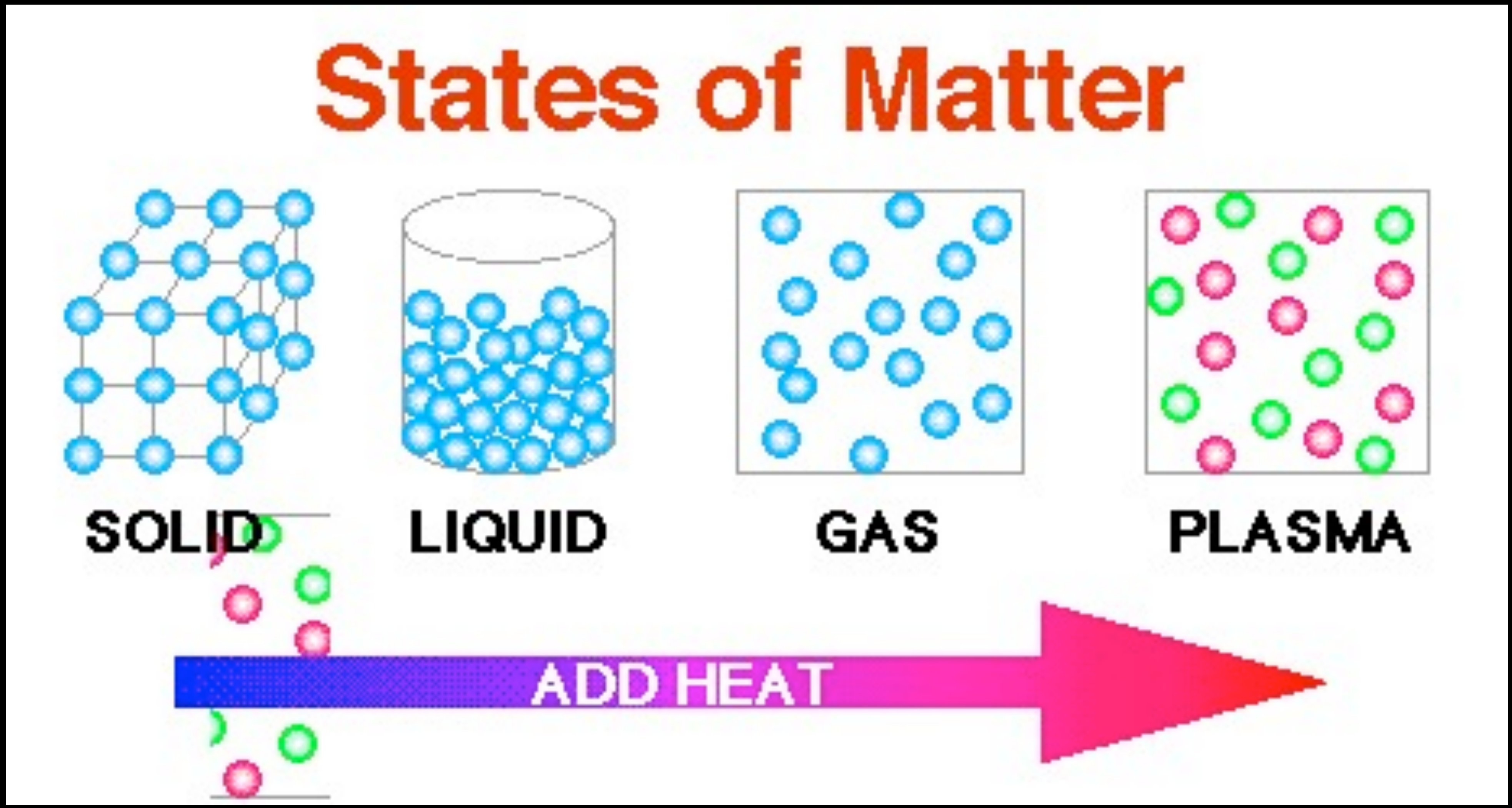




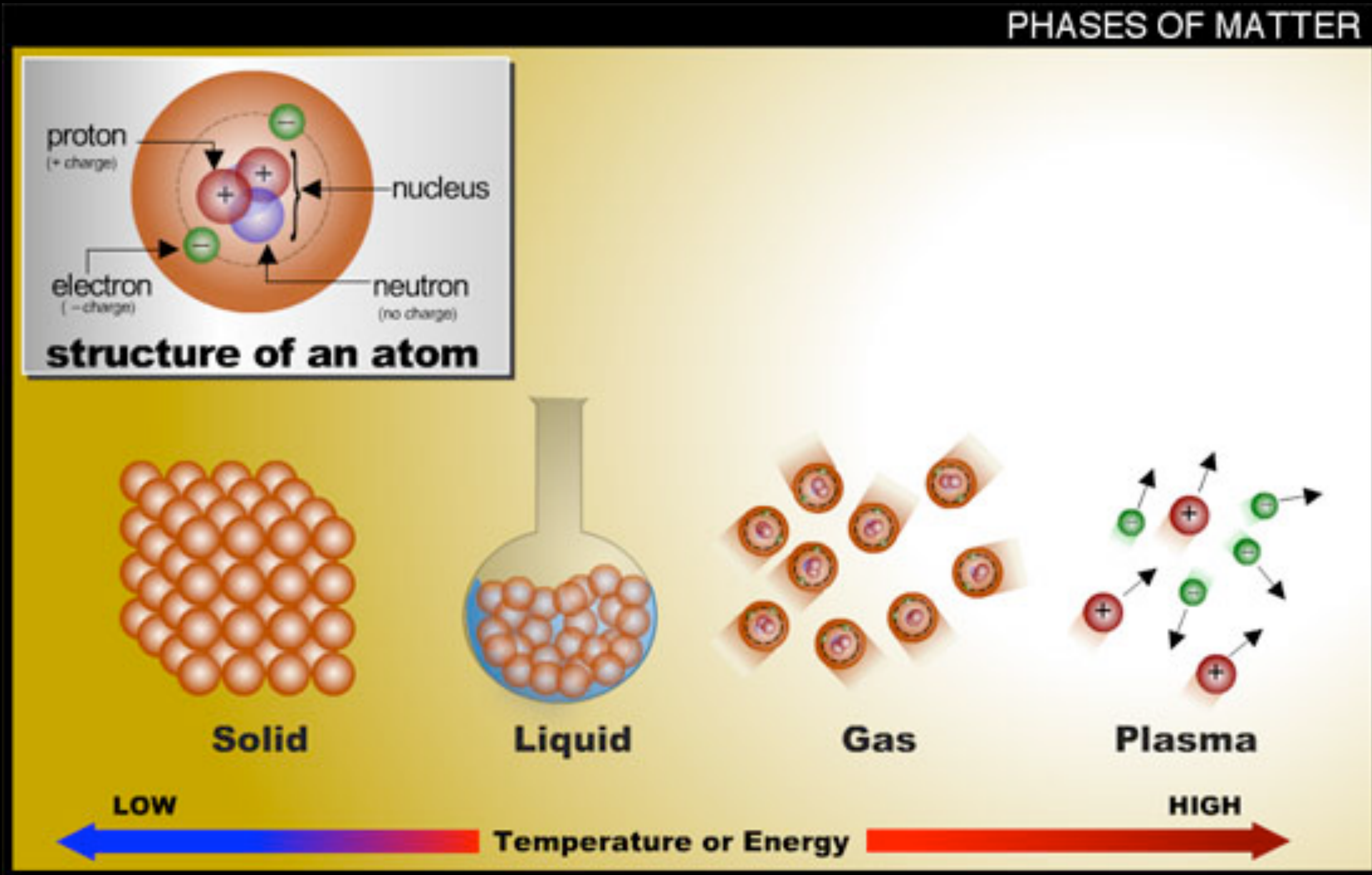
Light density:
increases back in time



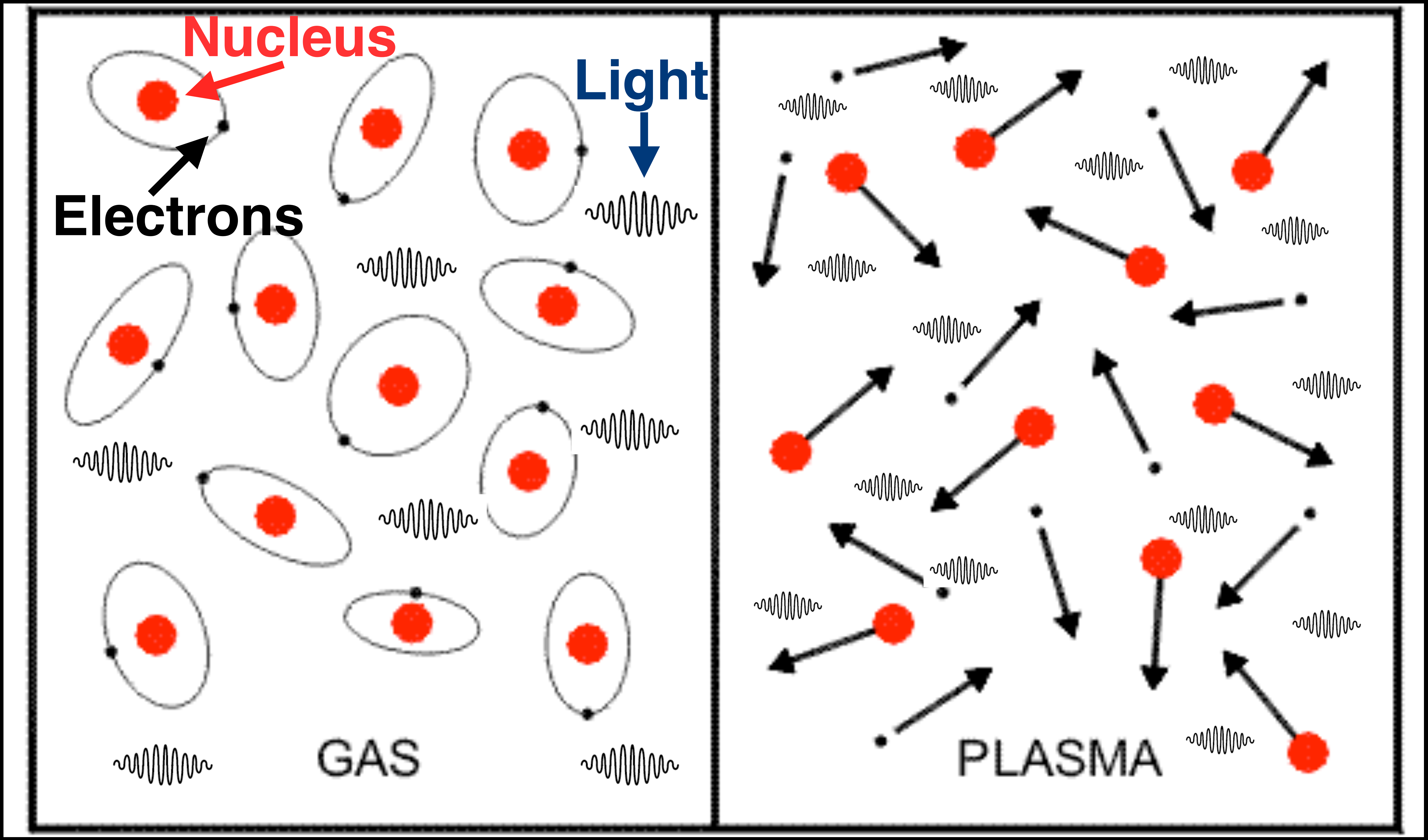
The Hot, Dense Early Universe is a ***Plasma***



What is a ***Plasma***?



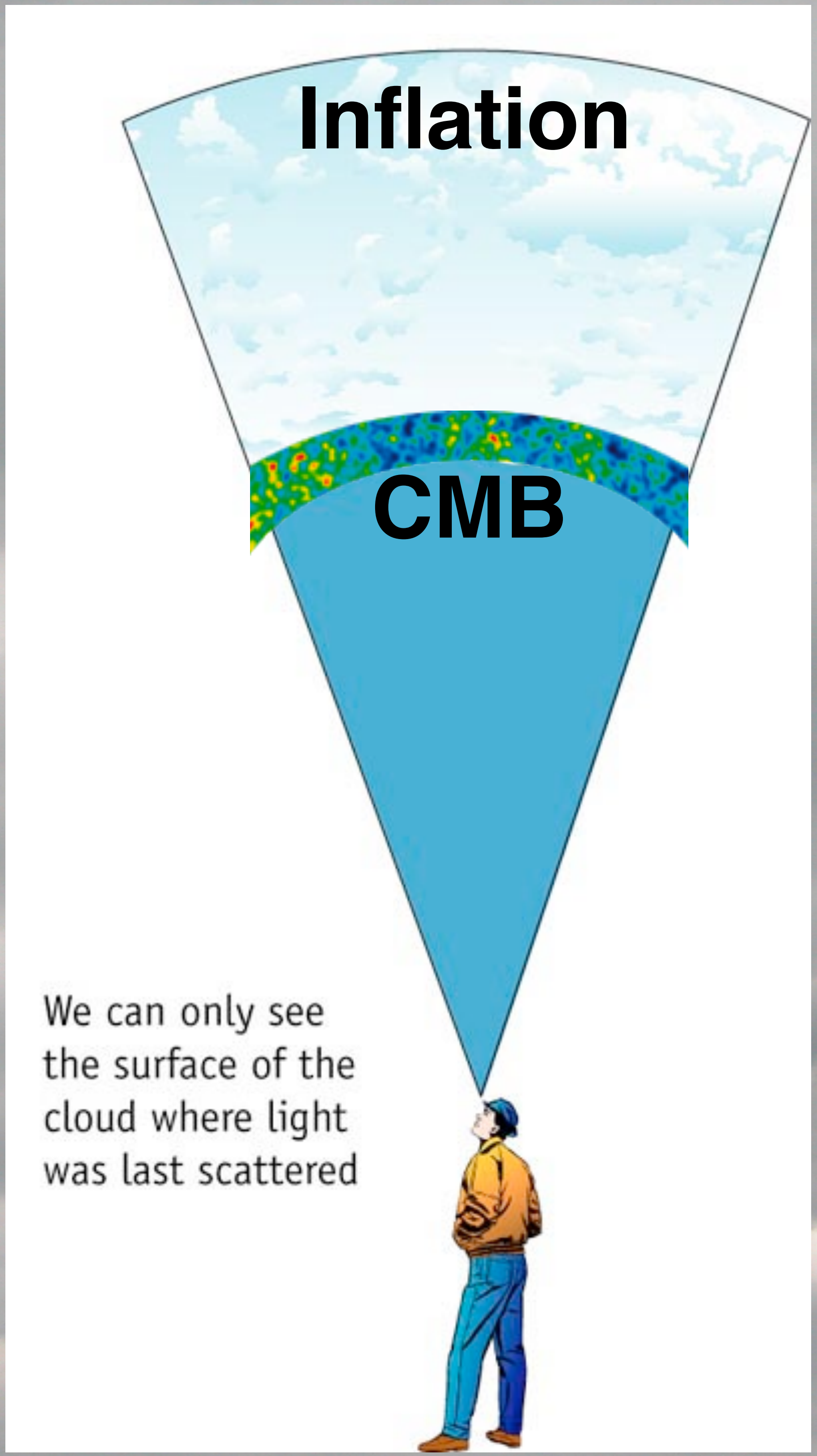
The Early Universe is a ***Plasma*** *and is opaque to light*



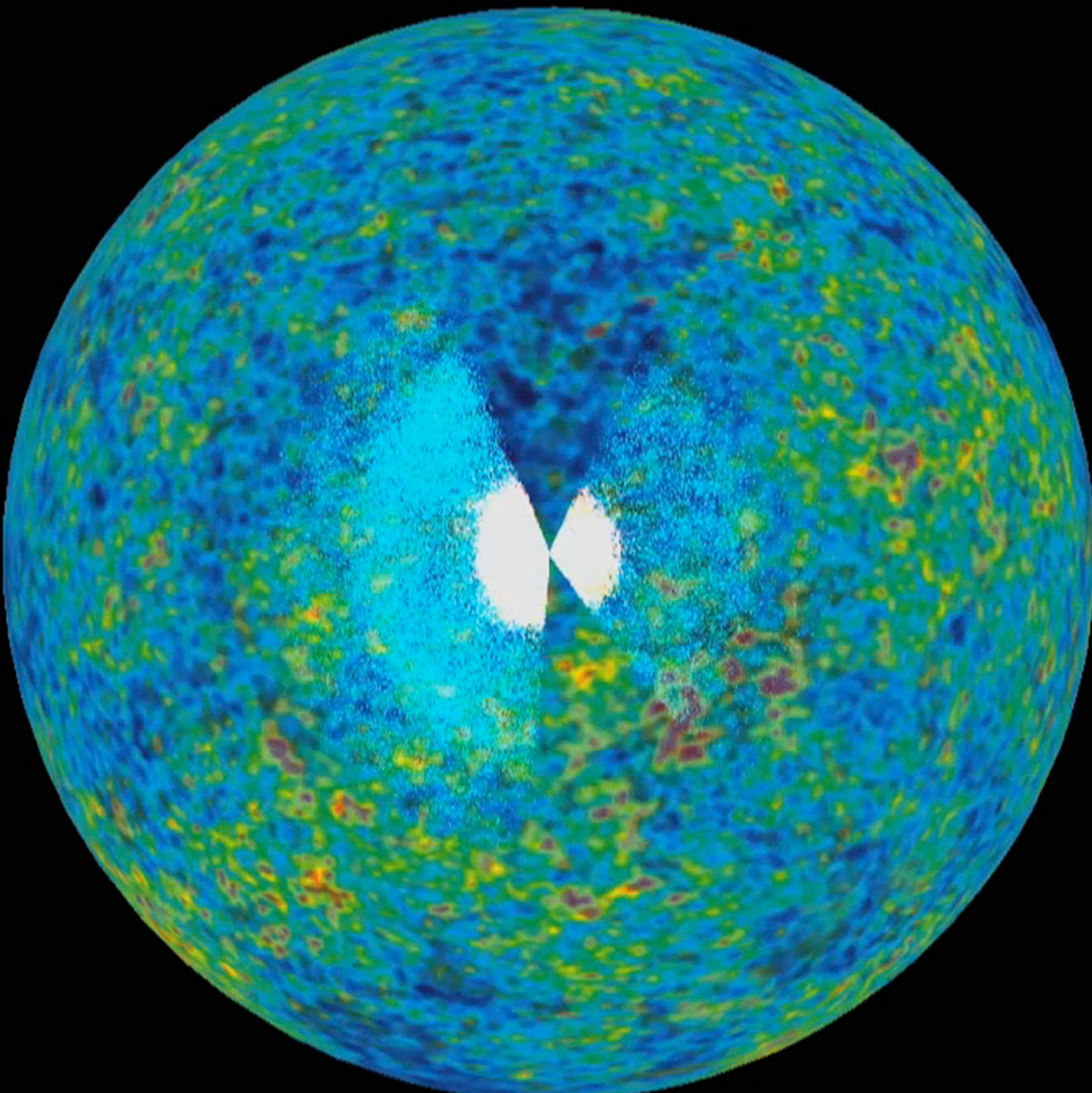
What can we see (almost) every day and is a plasma opaque to light?

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

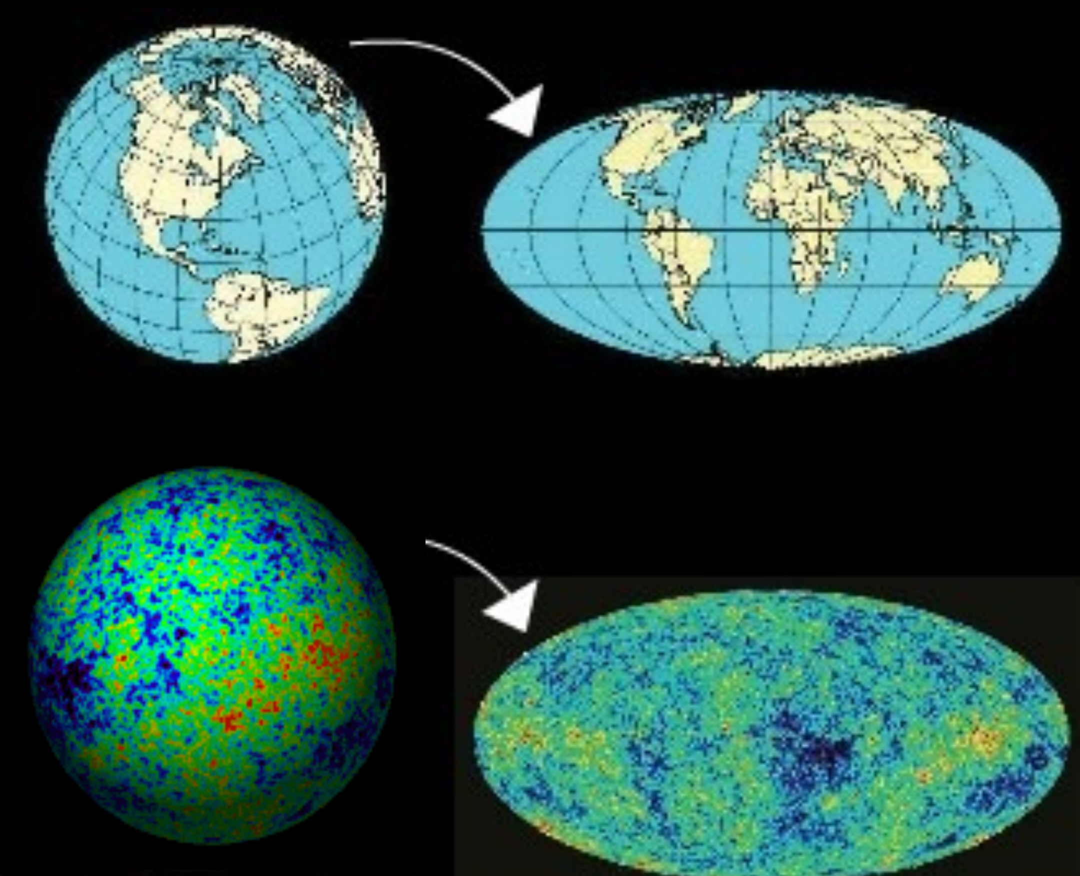
The Early Universe
is an opaque cloud of plasma that scatters and blocks light



The Cosmic Microwave Background Can Be Mapped

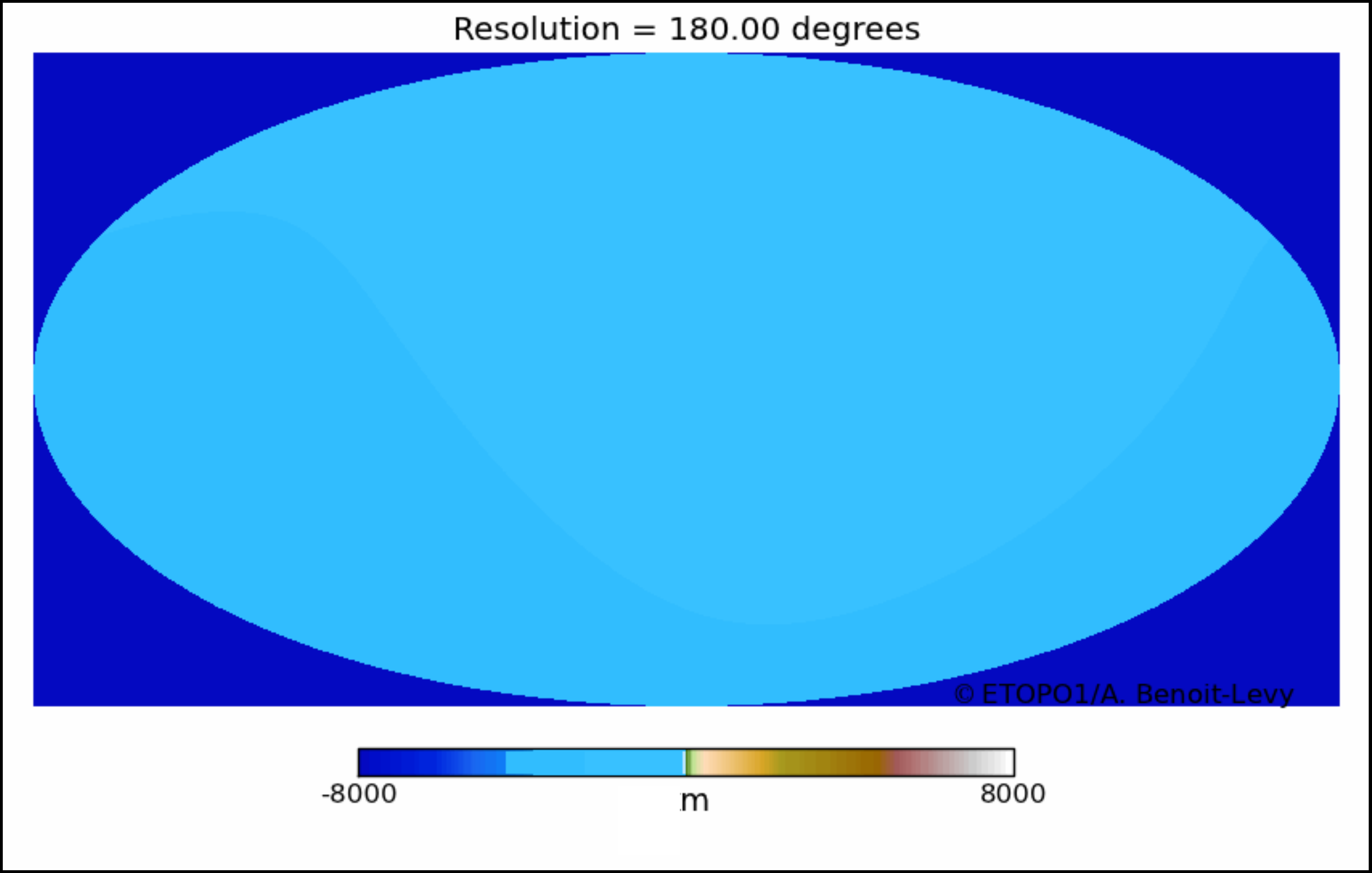


Just like the Earth…

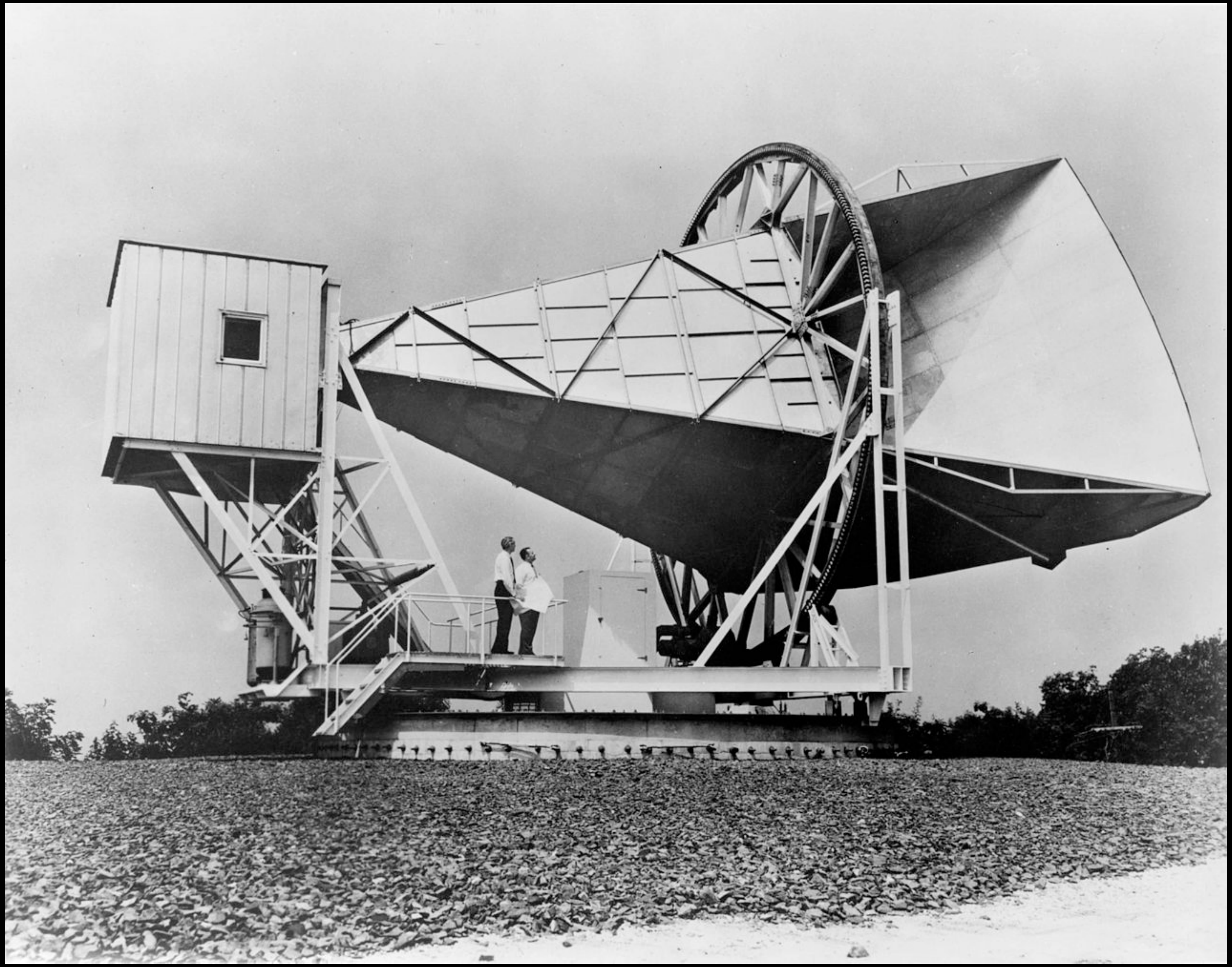


Animation courtesy of NASA and WMAP

The More Detailed The Map, The Better…



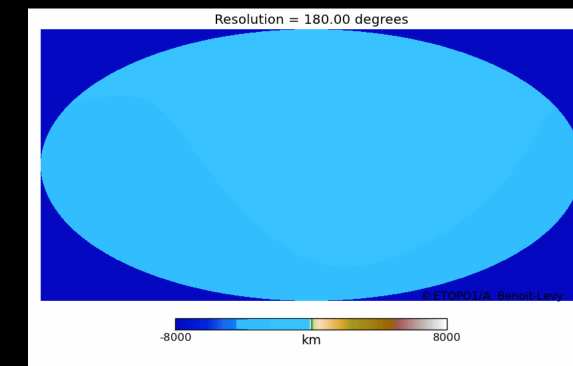
Penzias & Wilson Discovered the CMB in 1964 at Bell Labs in New Jersey in Horn Antennas for Radio Transmission

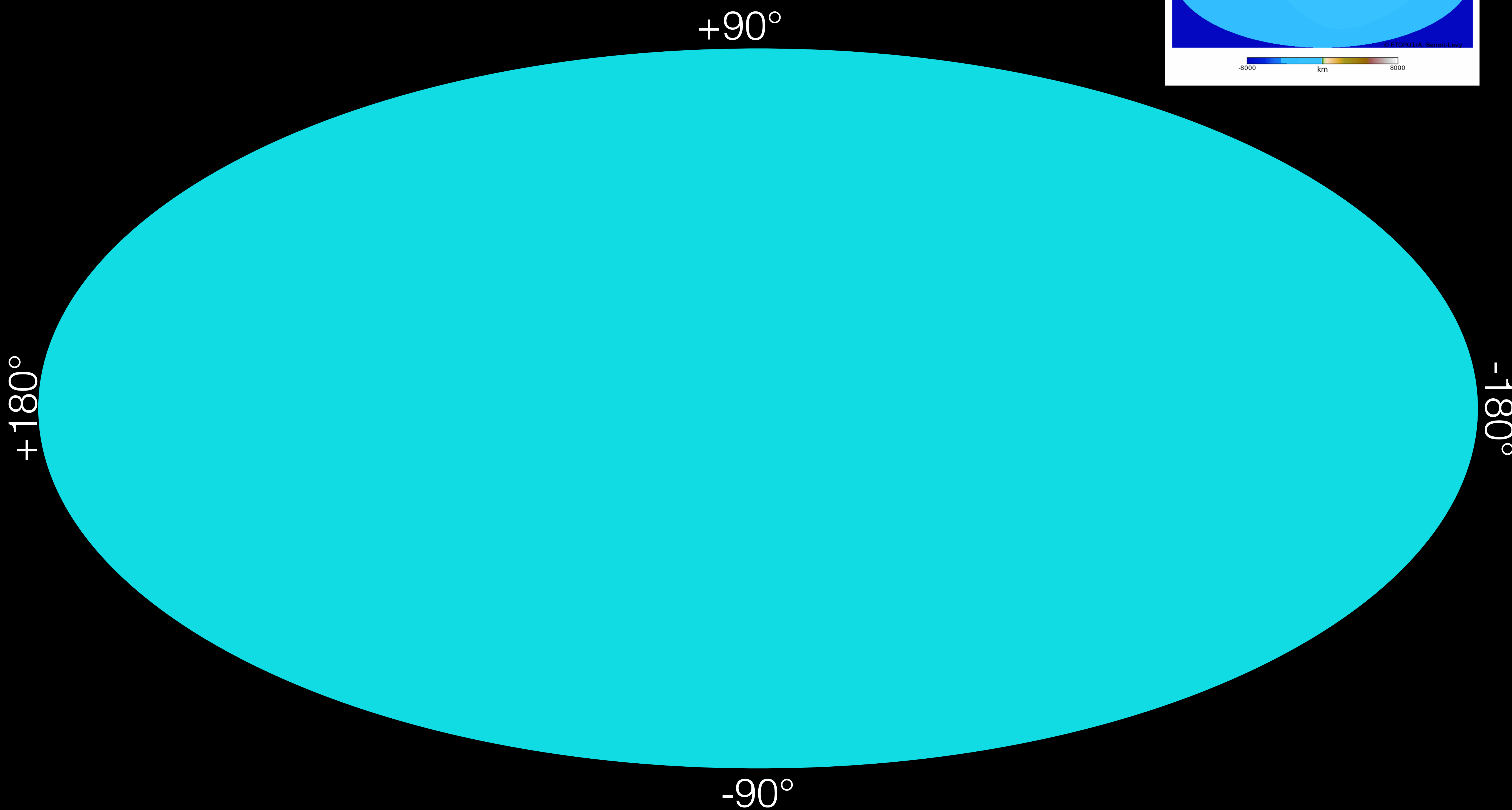


1978 Nobel Prize in Physics

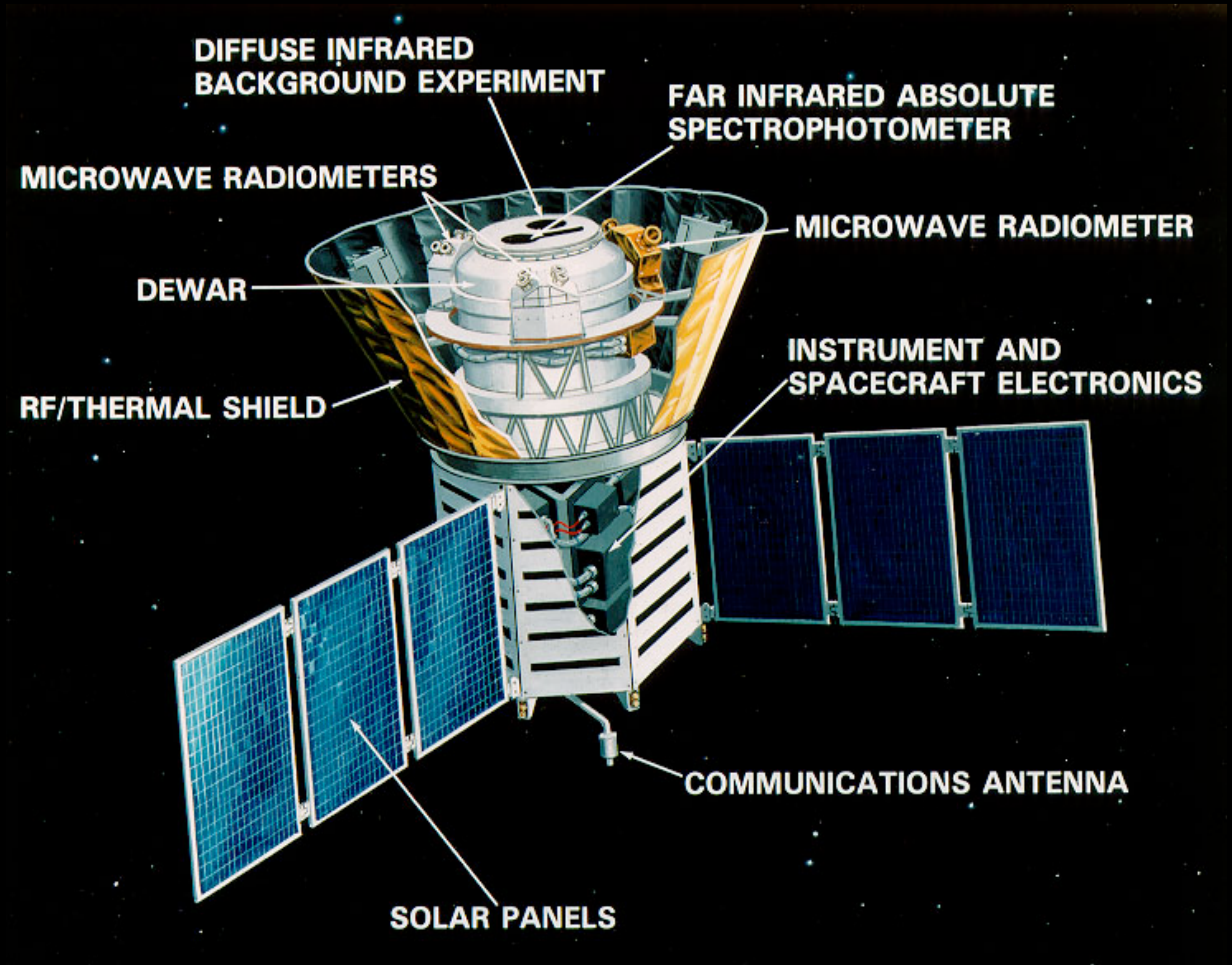
Penzias & Wilson saw near perfect isotropy in CMB emission

Measured its temperature to be 3 K



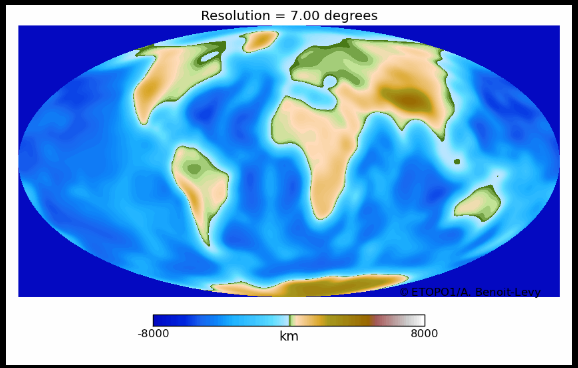


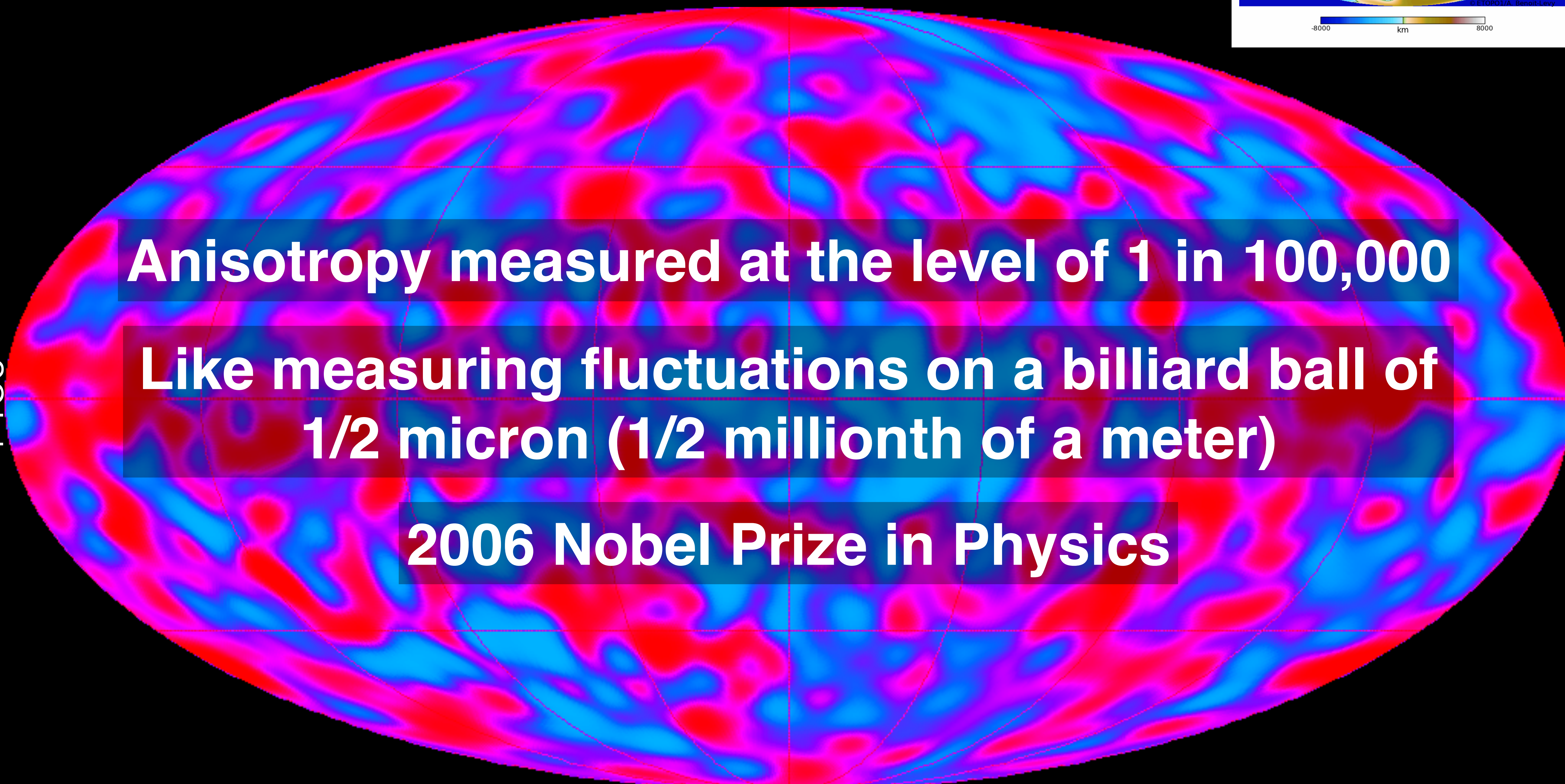
COBE Mission: US-NASA Project



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

7° angular resolution



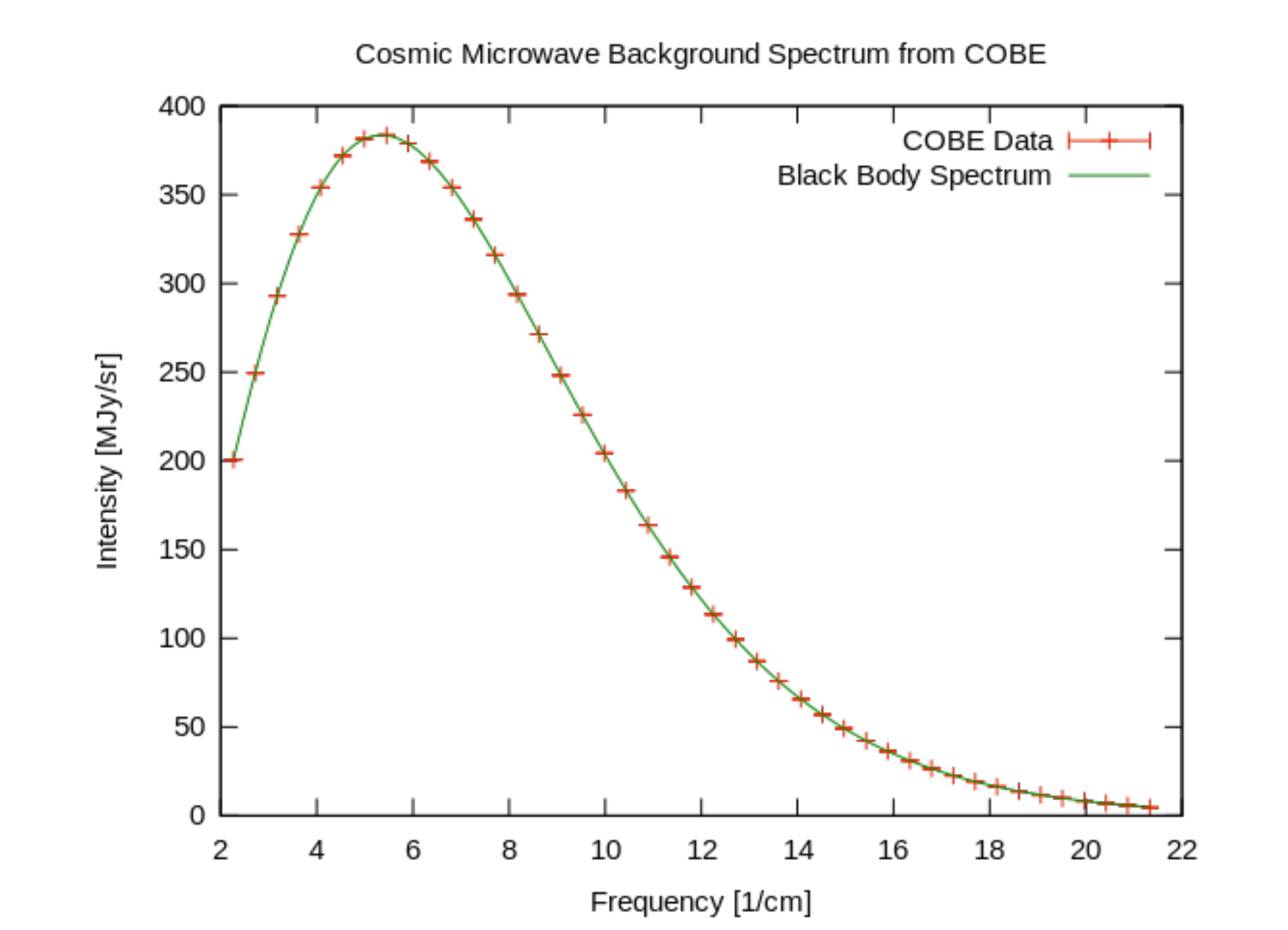


Anisotropy measured at the level of 1 in 100,000

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

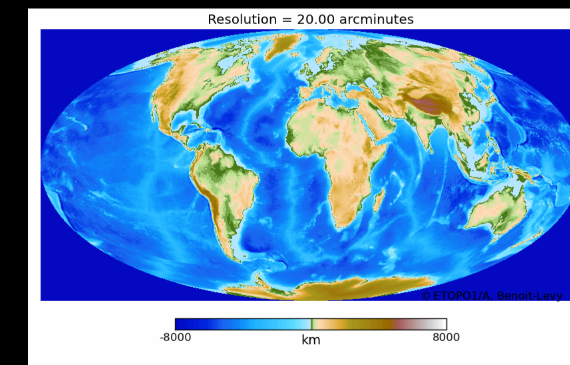
2006 Nobel Prize in Physics

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

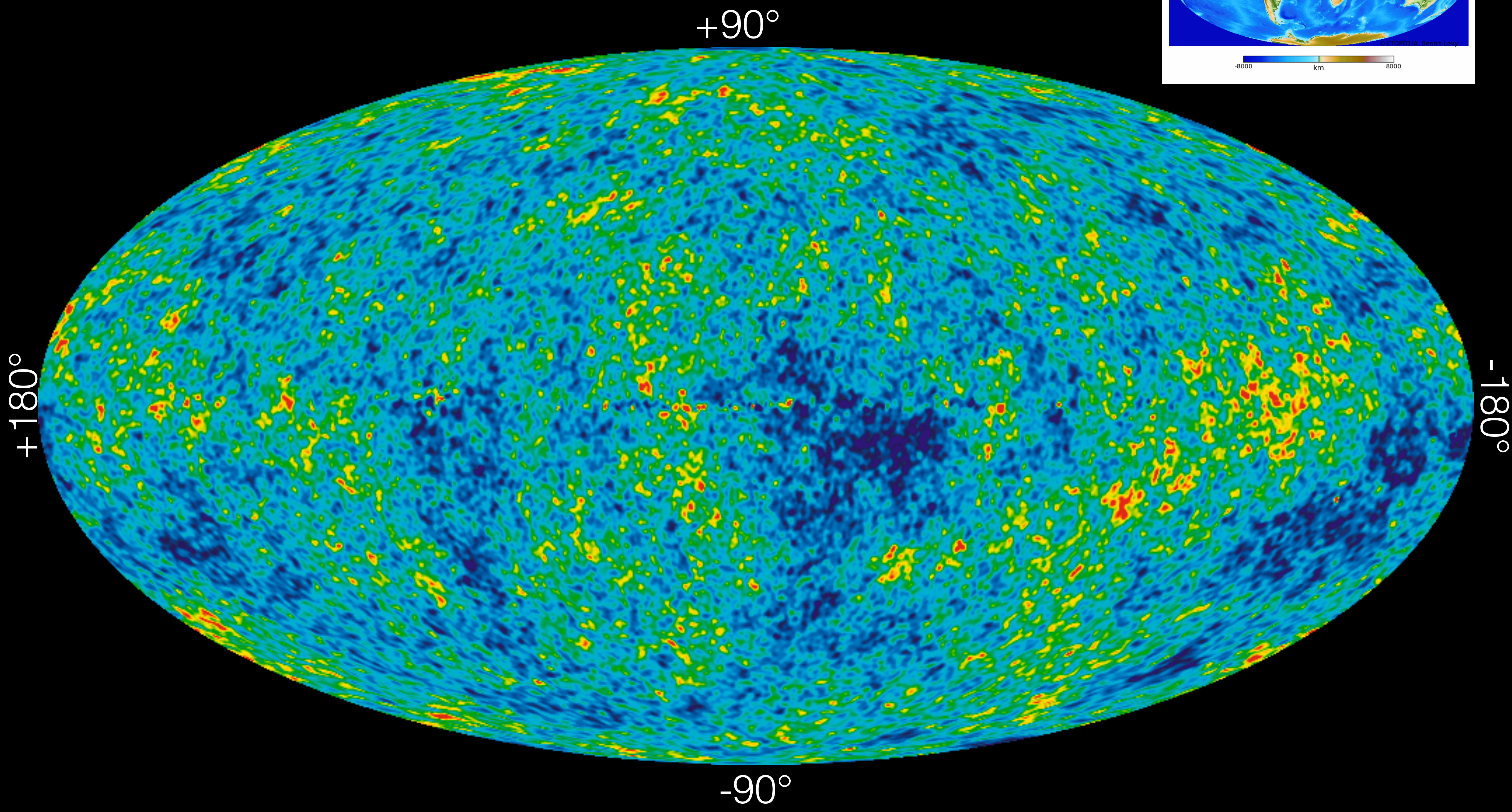


Data from COBE showed a perfect fit between the black body curve predicted by big bang theory and that observed in the microwave background: T = 2.725 K = -454.8 °F

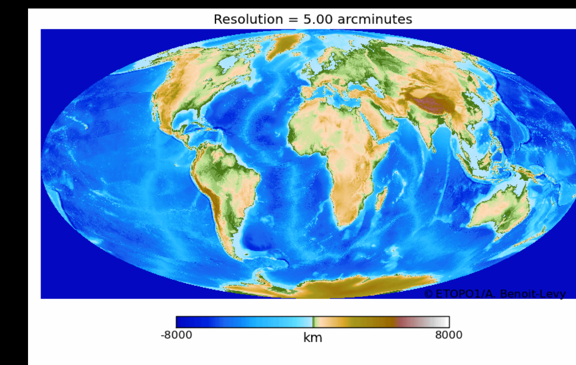
NASA's **Wilkinson Microwave Anisotropy Probe**: A Detailed Image of the CMB, 2003-13



0.3° angular resolution

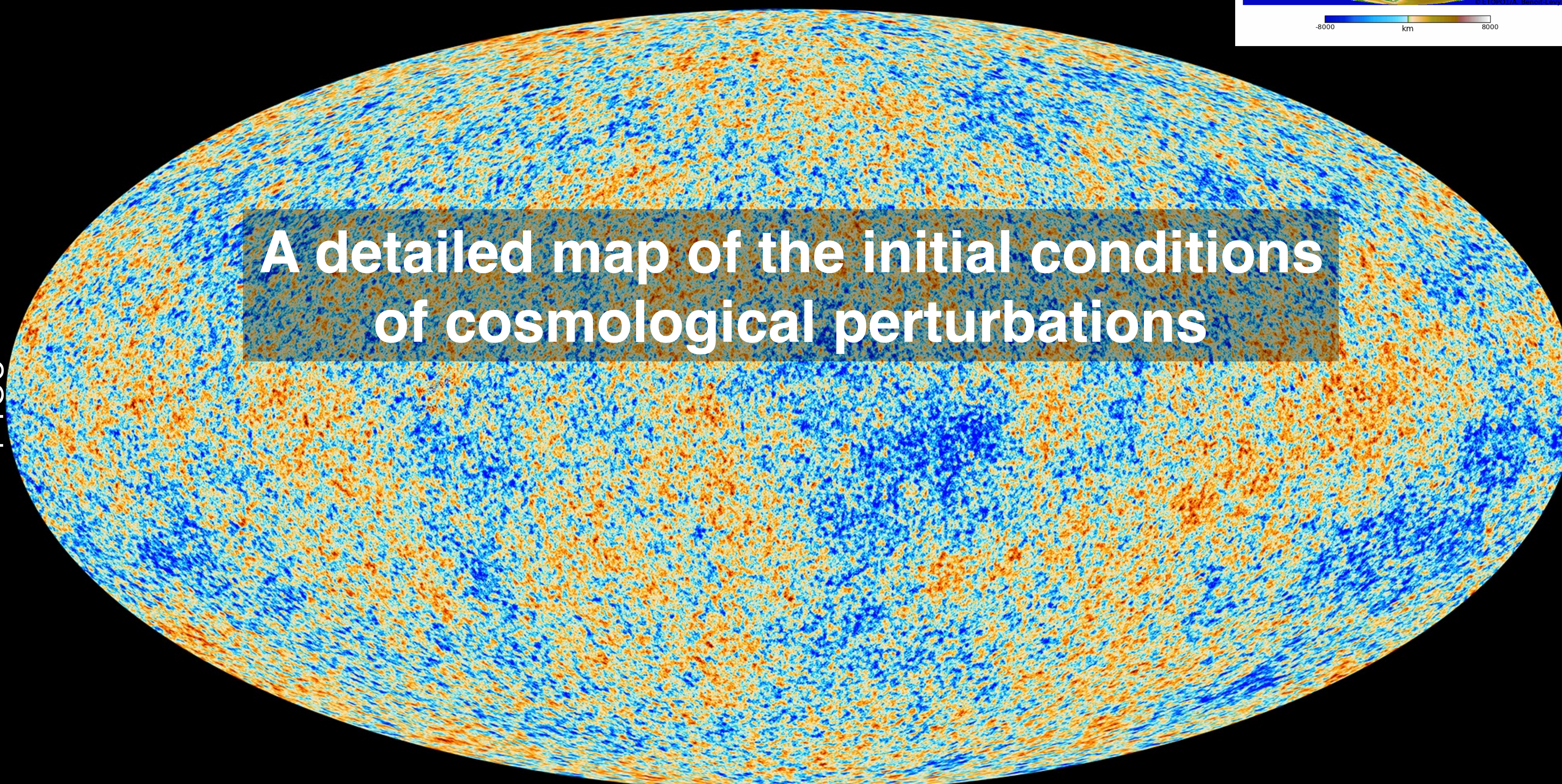


European Space Agency's ***Planck Probe***: The Best Image Yet of the CMB, **2013-15**



0.08° angular resolution

+90°

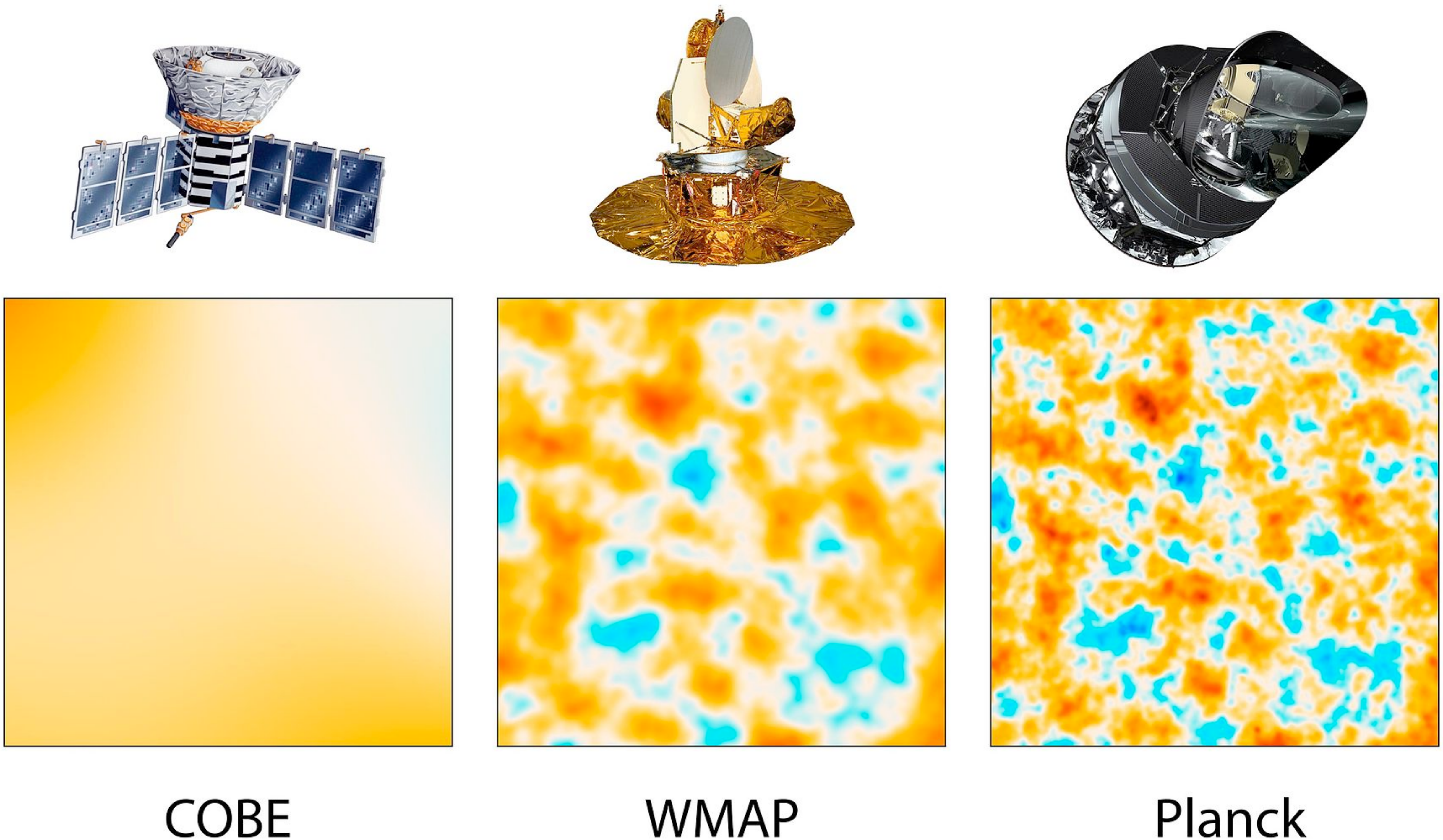


+180°

-180°

-90°

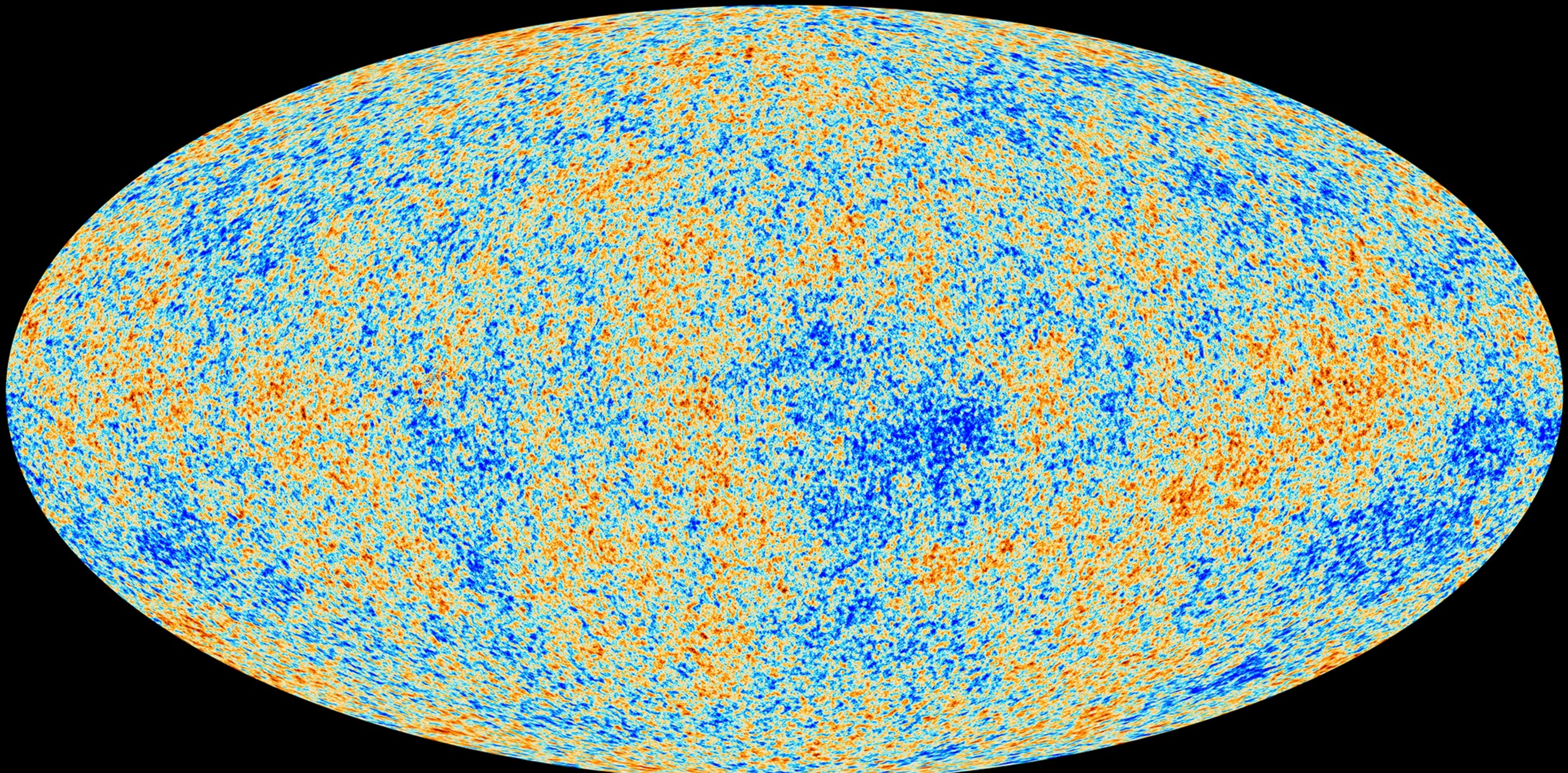
Comparison of COBE, WMAP, Planck Measurements



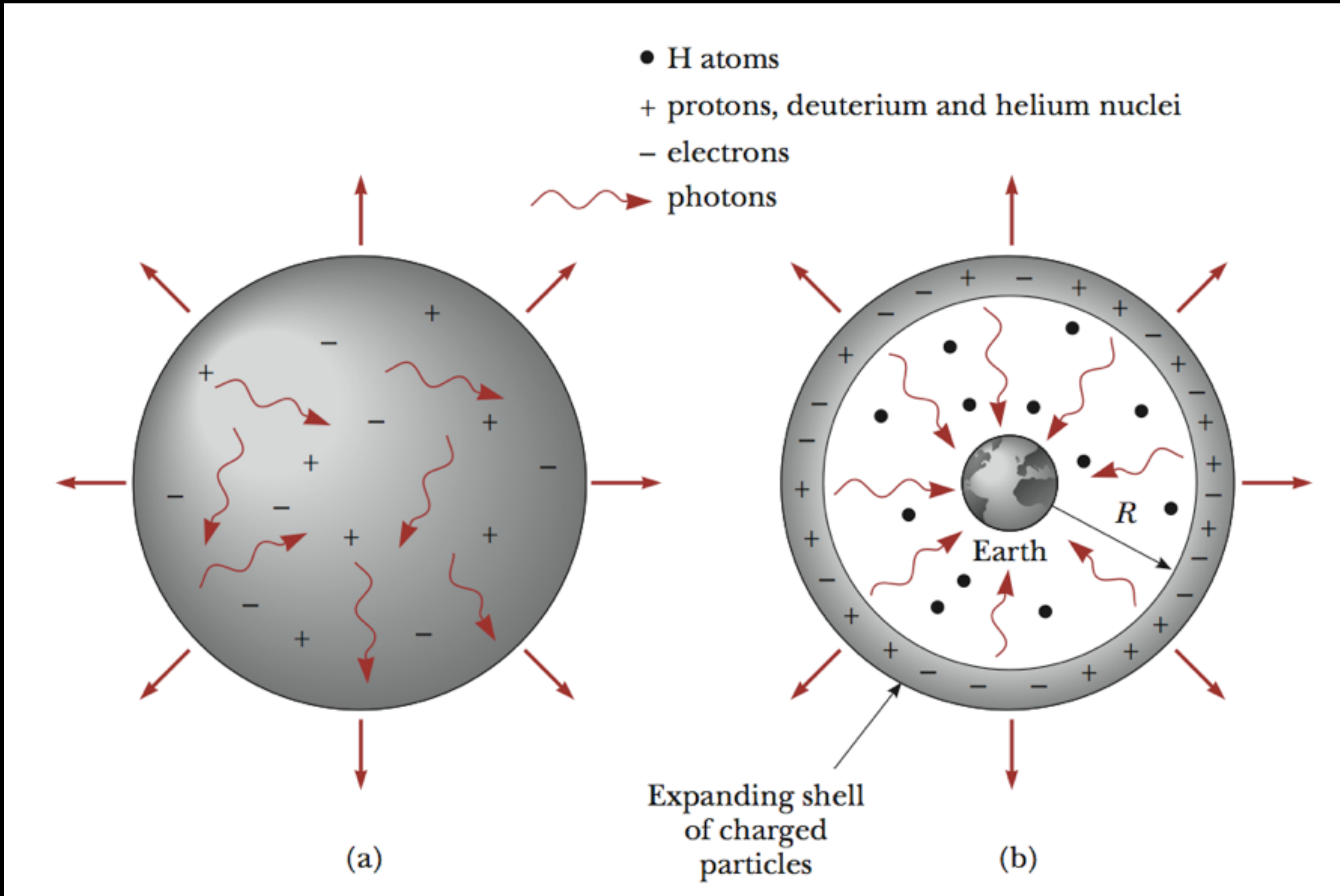
What gave rise to this uniformity across scales that are disconnected from each other?

What gave rise to the small perturbations?

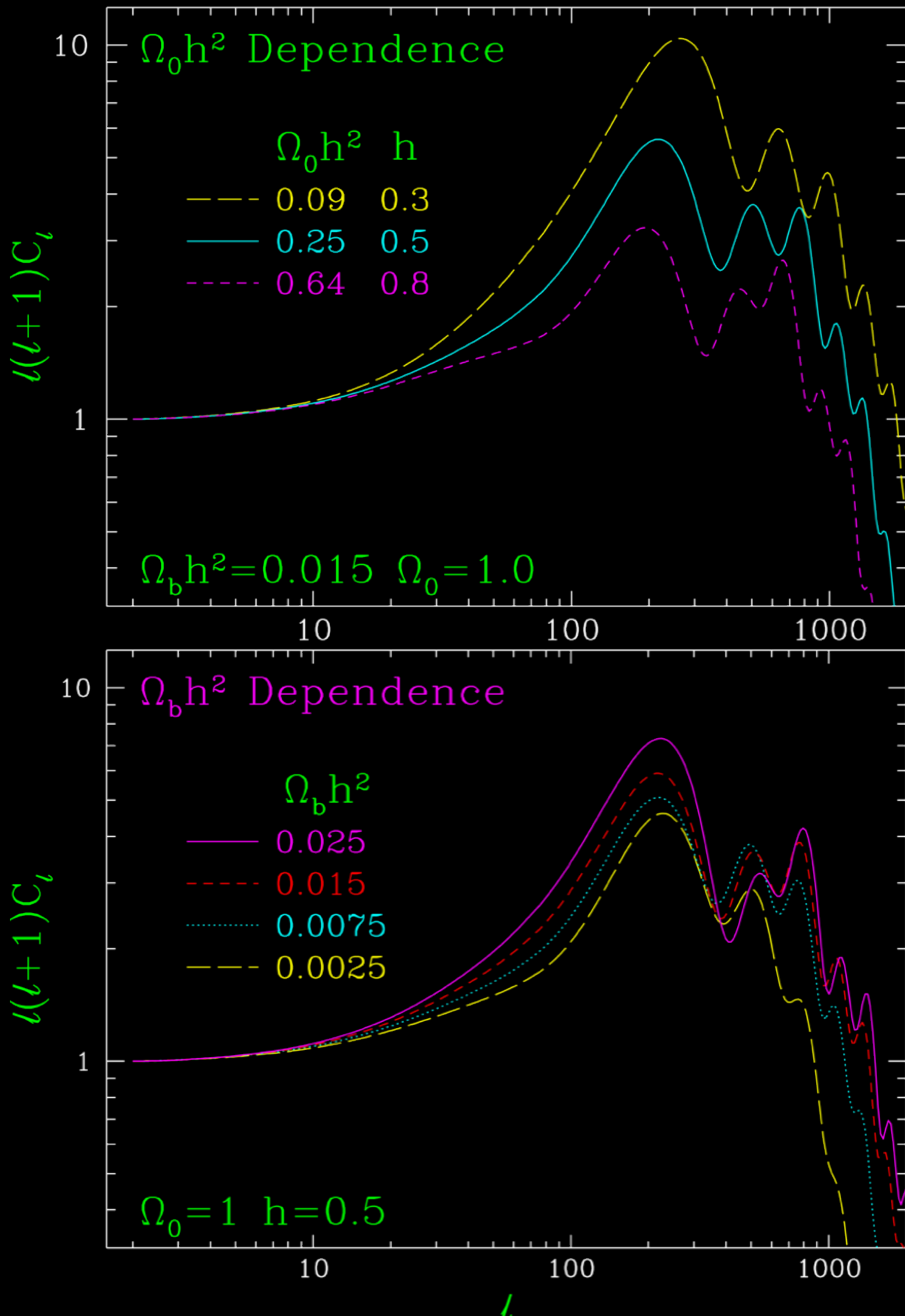
The leading theory: ***inflation***

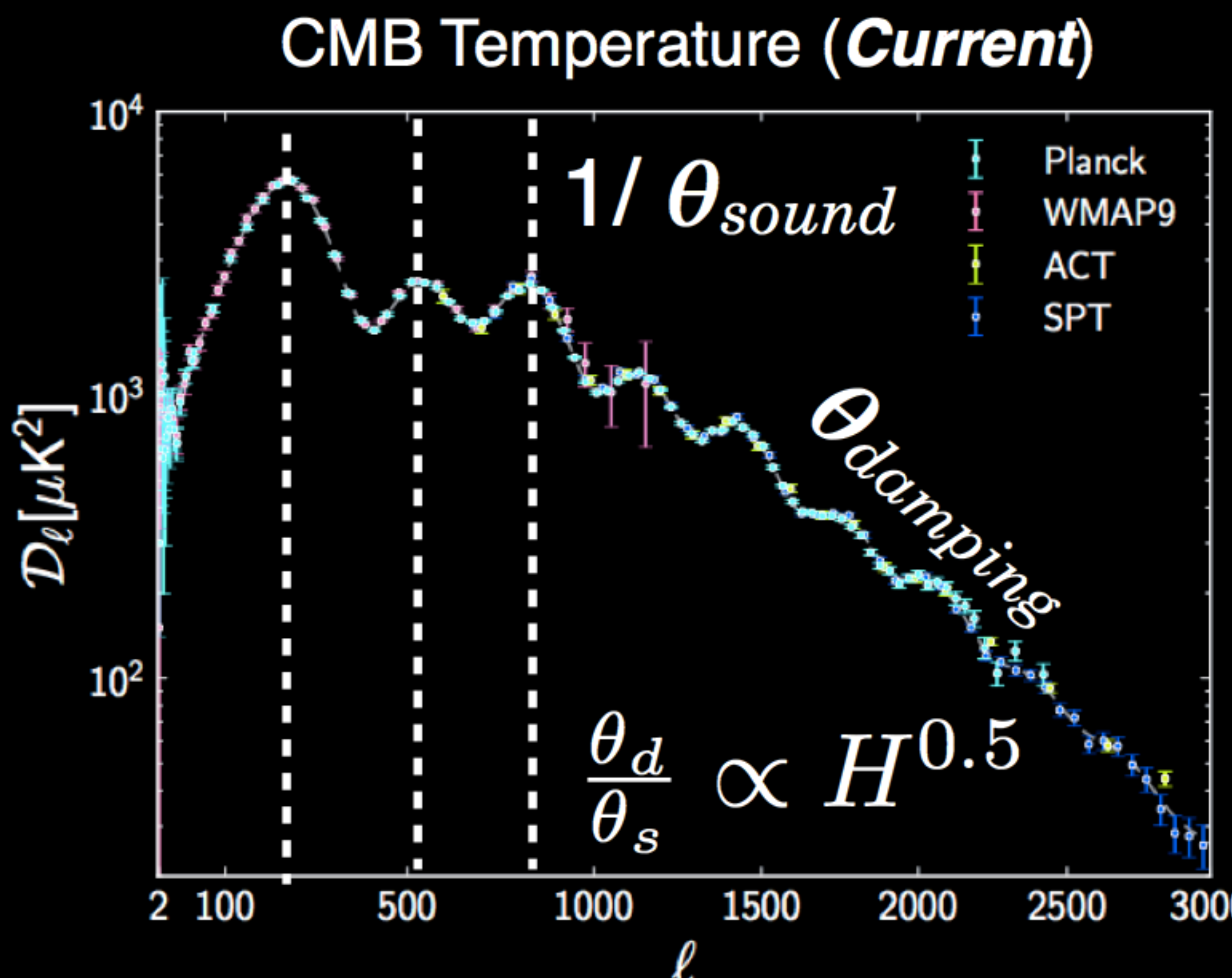


Another View of the Cosmic Microwave Background (CMB)



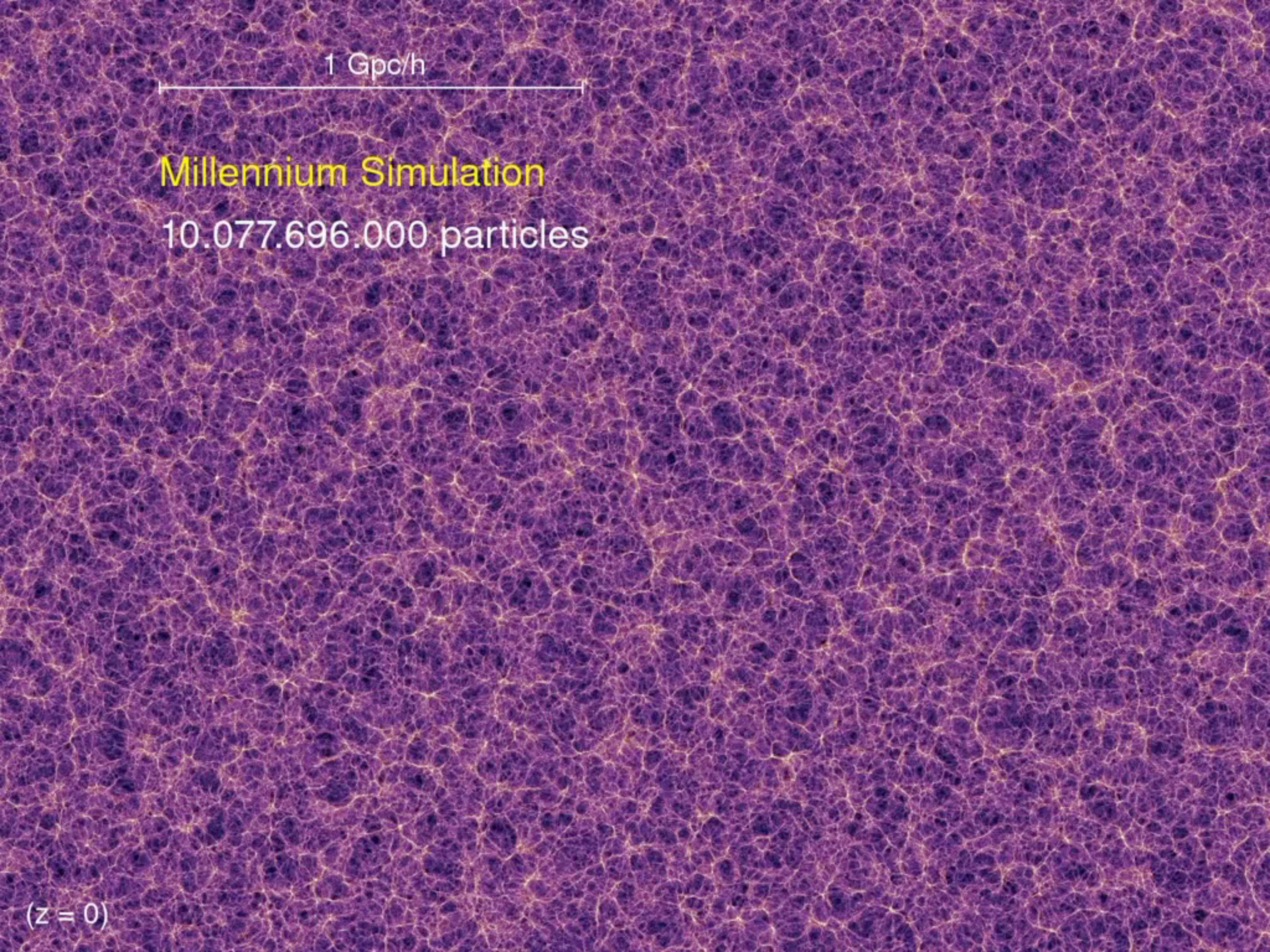
Cosmic Microwave Background (CMB): Precision Cosmological Measure of Dark Matter

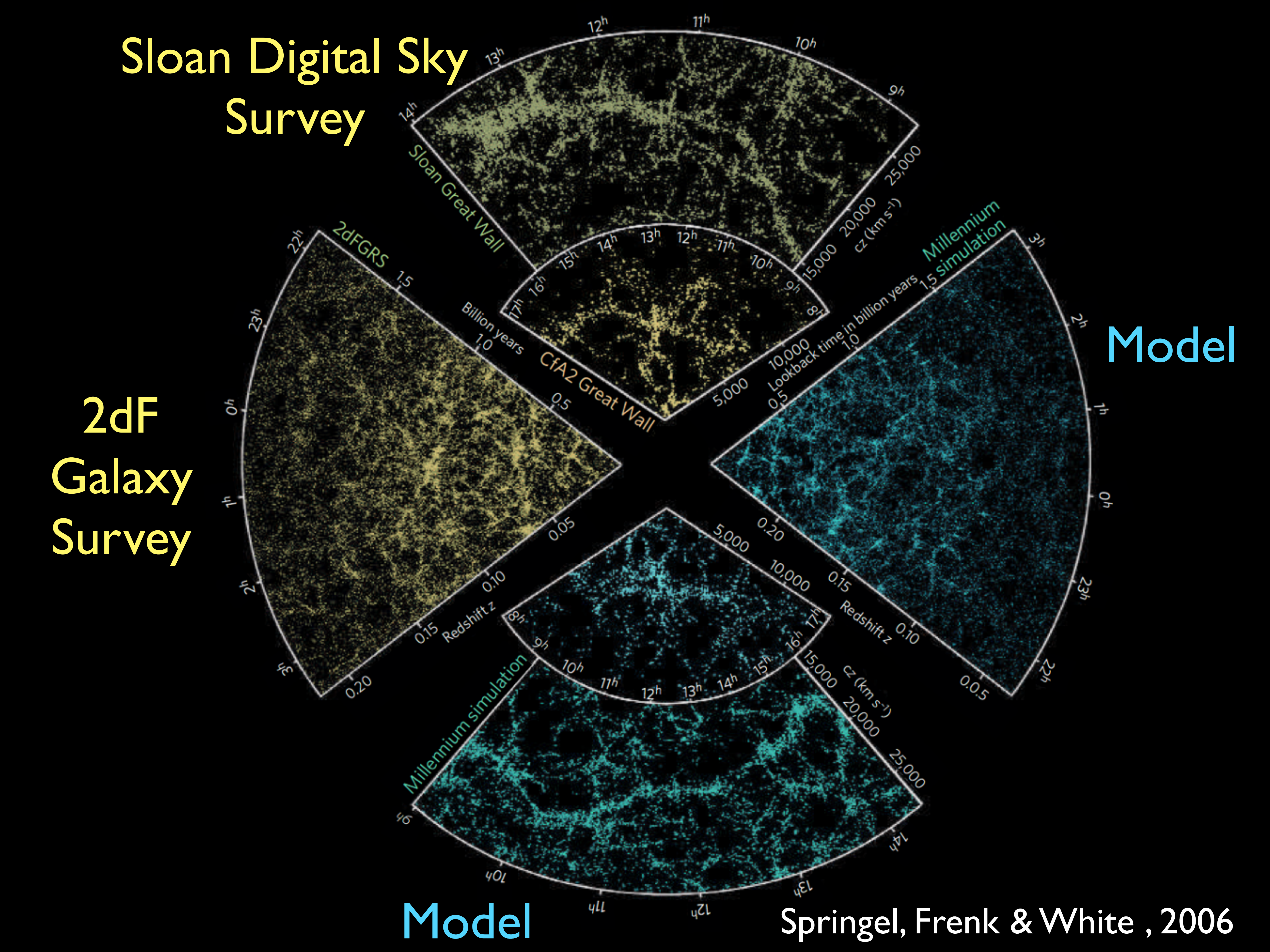




$$\Omega_{DM} = 0.220 \pm 0.011$$

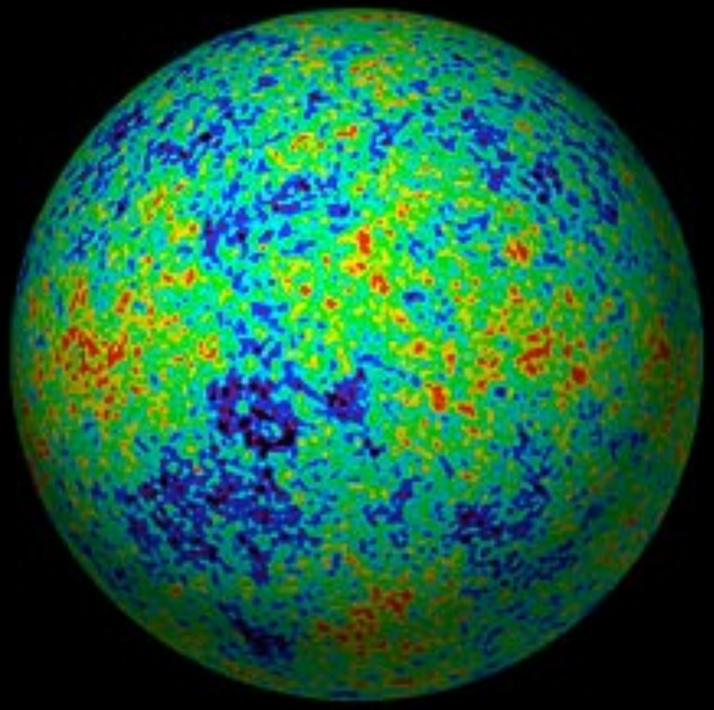
CMB alone


1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)

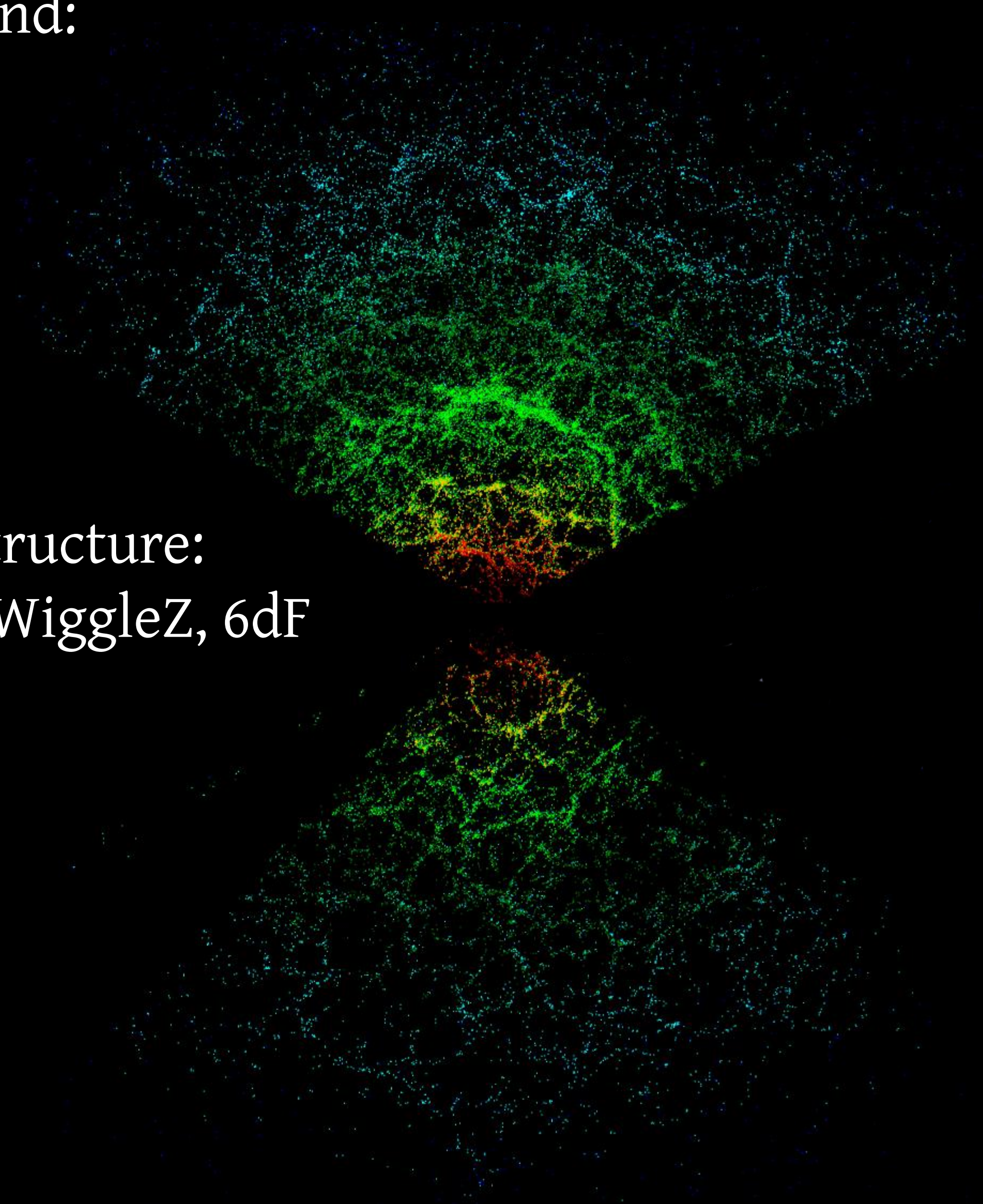


Springel, Frenk & White , 2006

Dark Matter Today: from large scale cosmology



Cosmic Microwave Background:
Planck, SPT, ACT, PolarBEAR



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

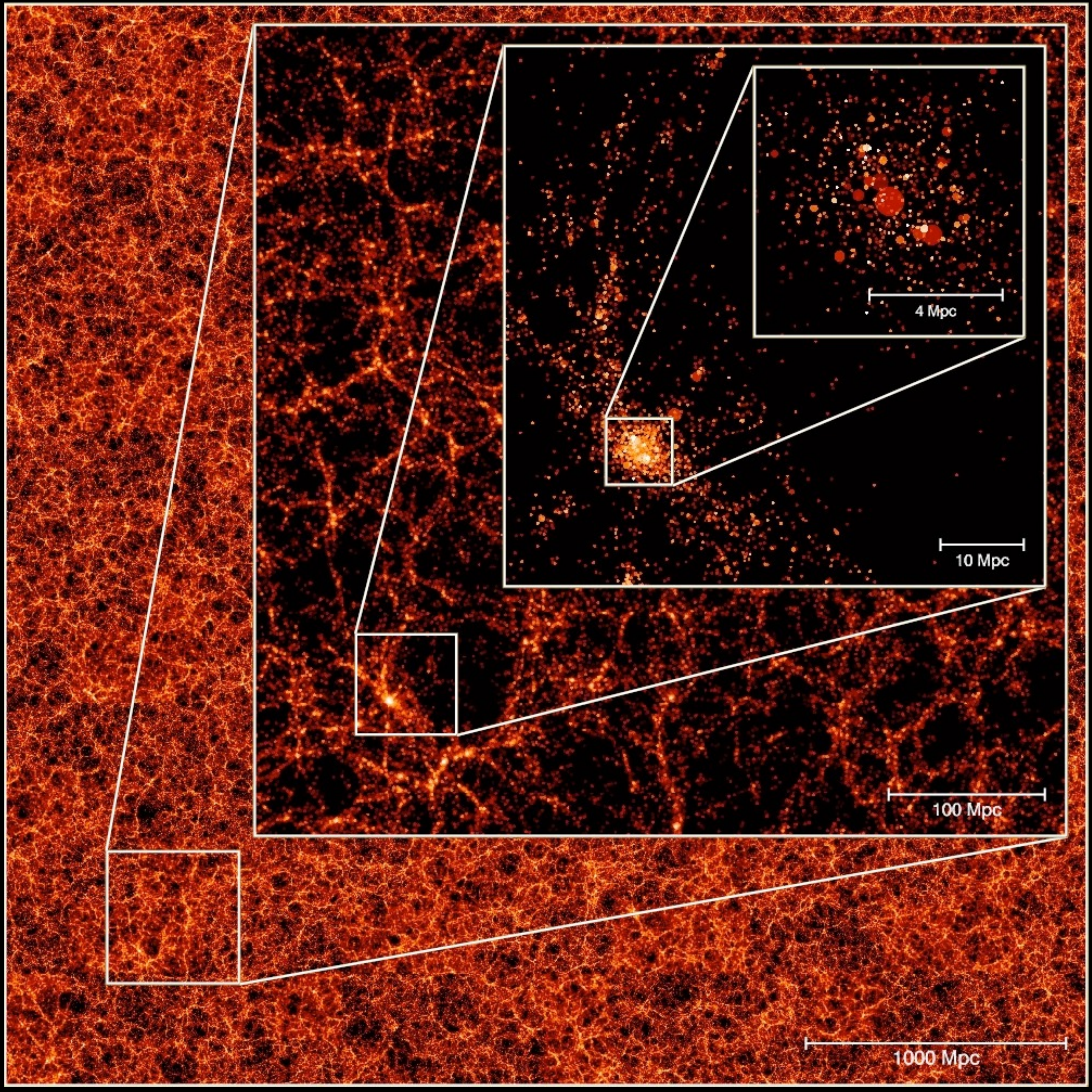
$$\Omega_{\rm DM} \equiv \frac{\rho_{\rm DM}}{\rho_{\rm crit}} = 0.259 \pm 0.002$$

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

Millennium Simulation XXL (2011)

Dark
Matter

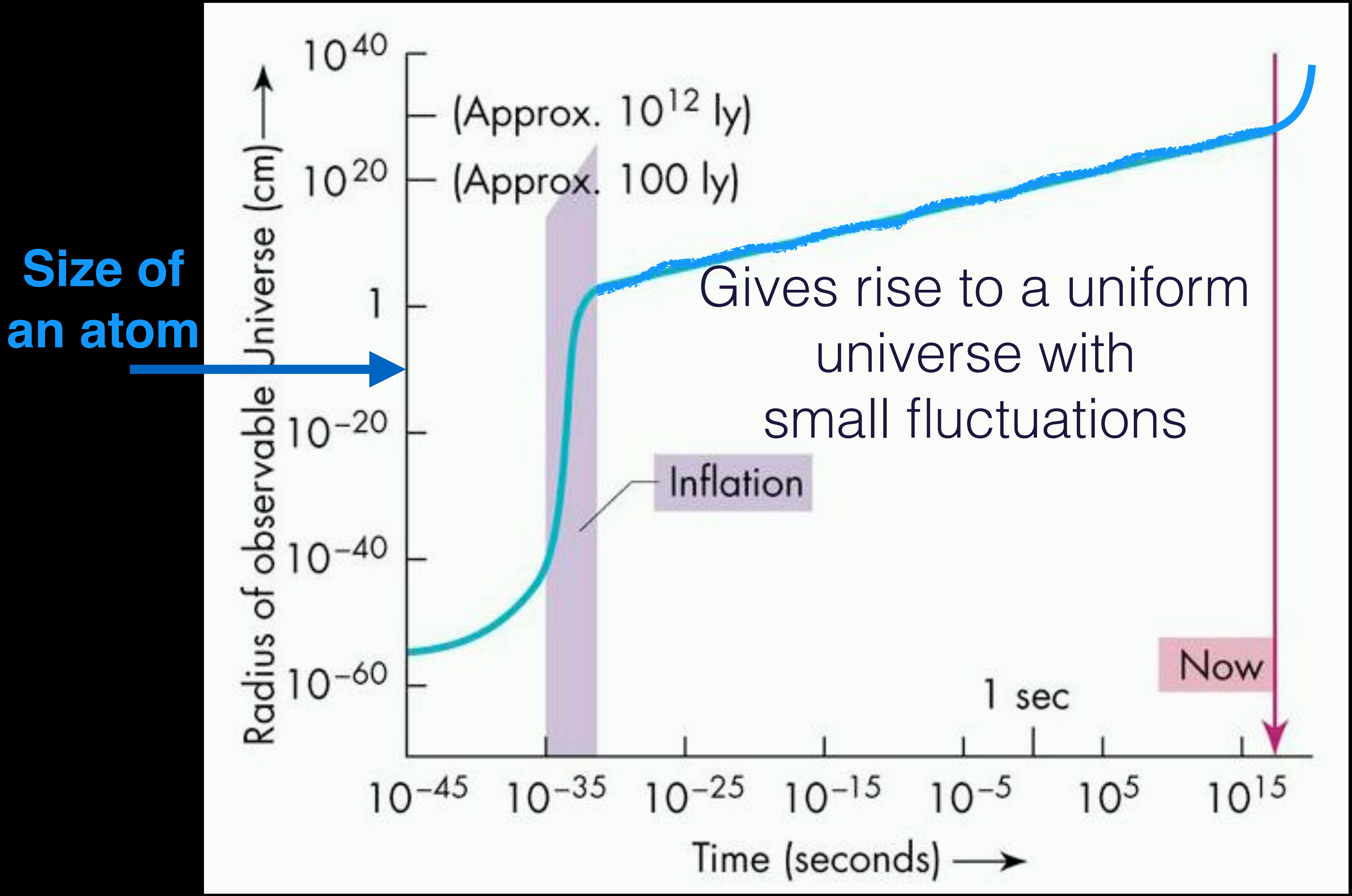
Galaxies



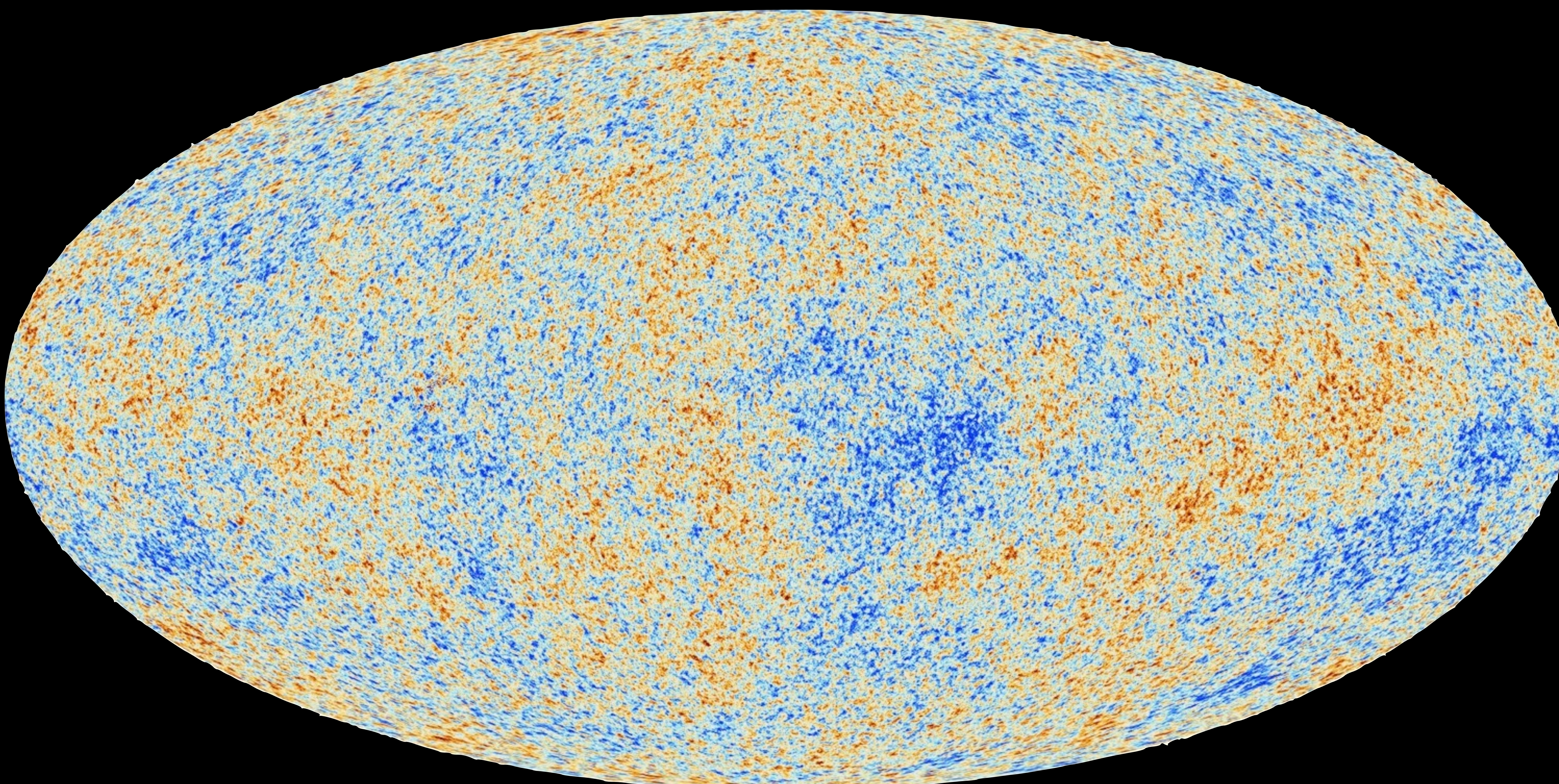
Structure of dark matter on the Milky Way Galaxy scale

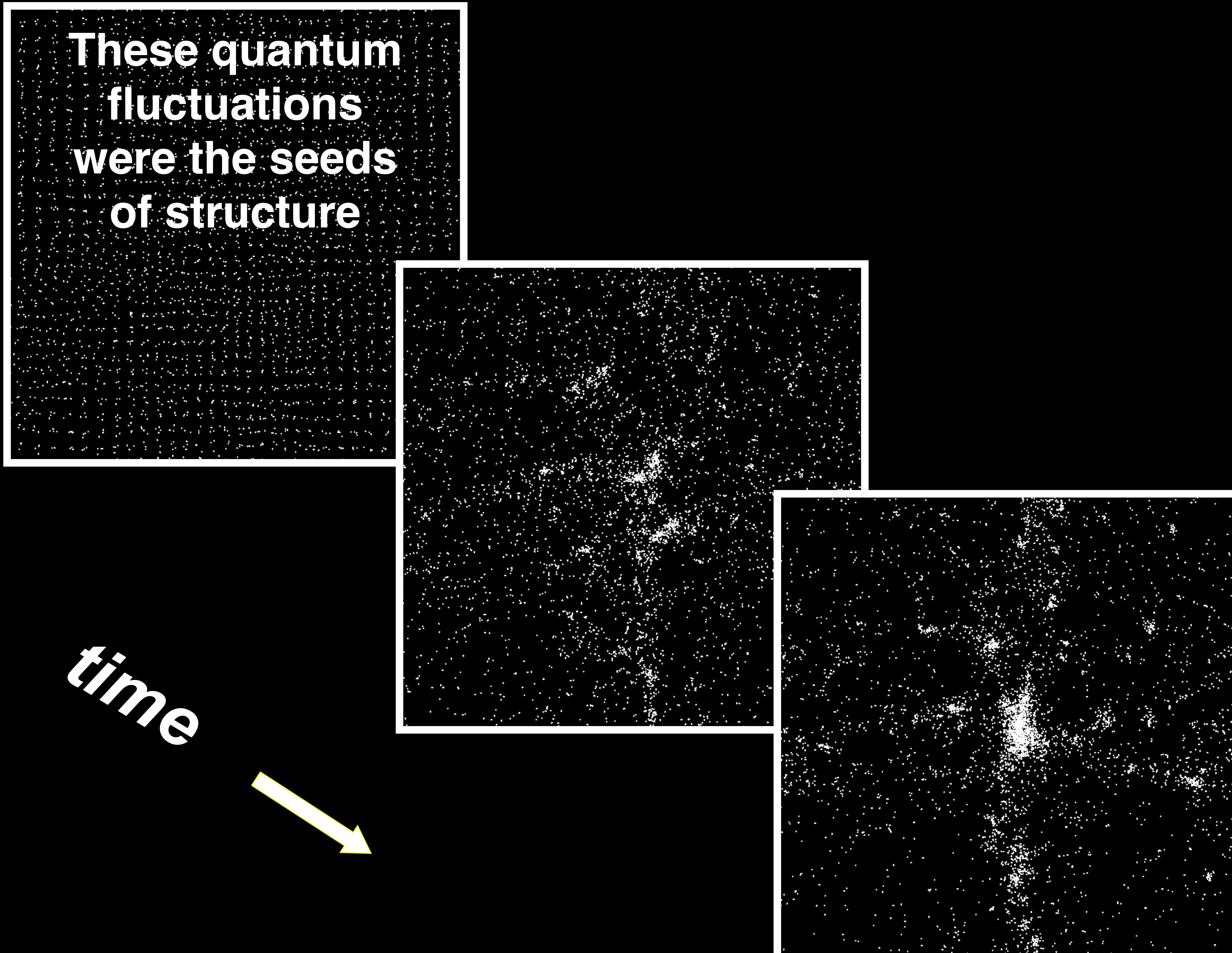
Inflationary Universe Expansion

➨ 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

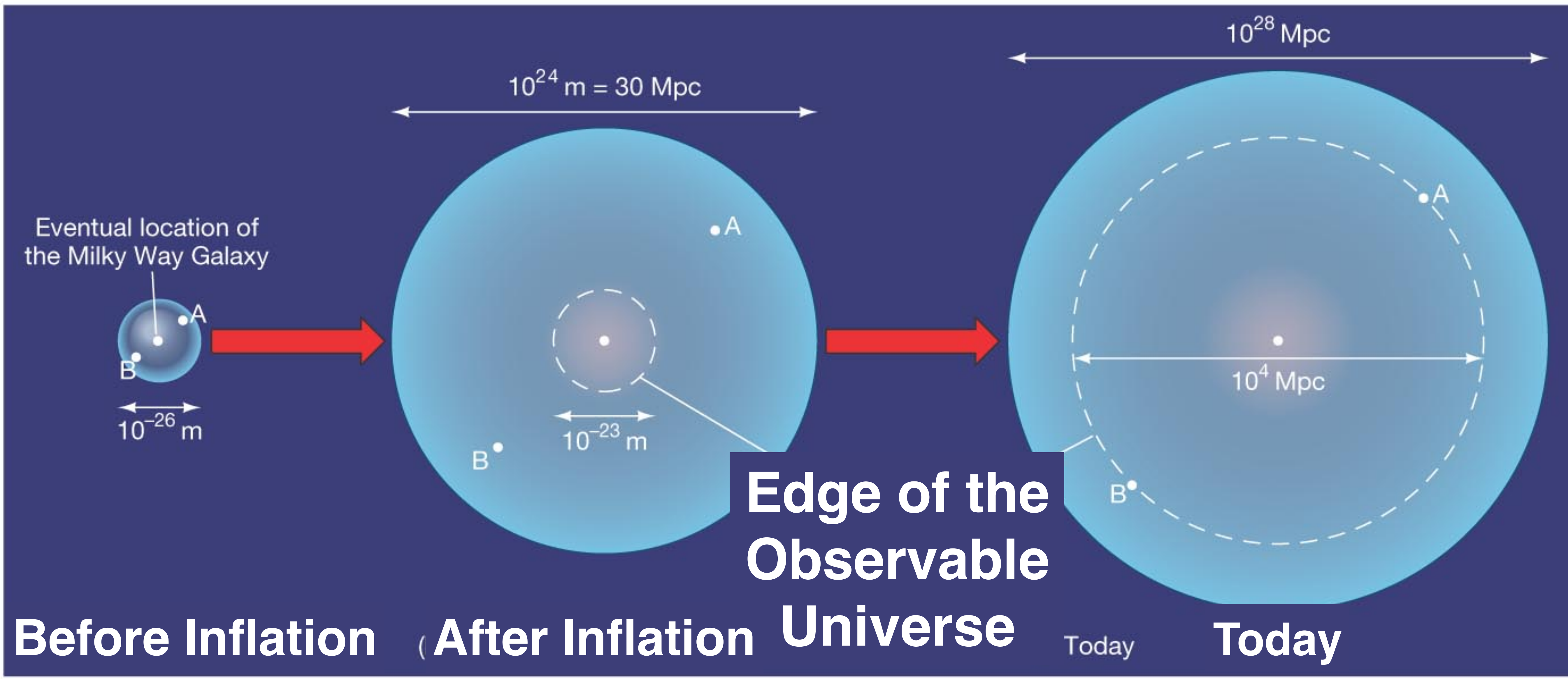



These quantum fluctuations were the seeds of structure
time

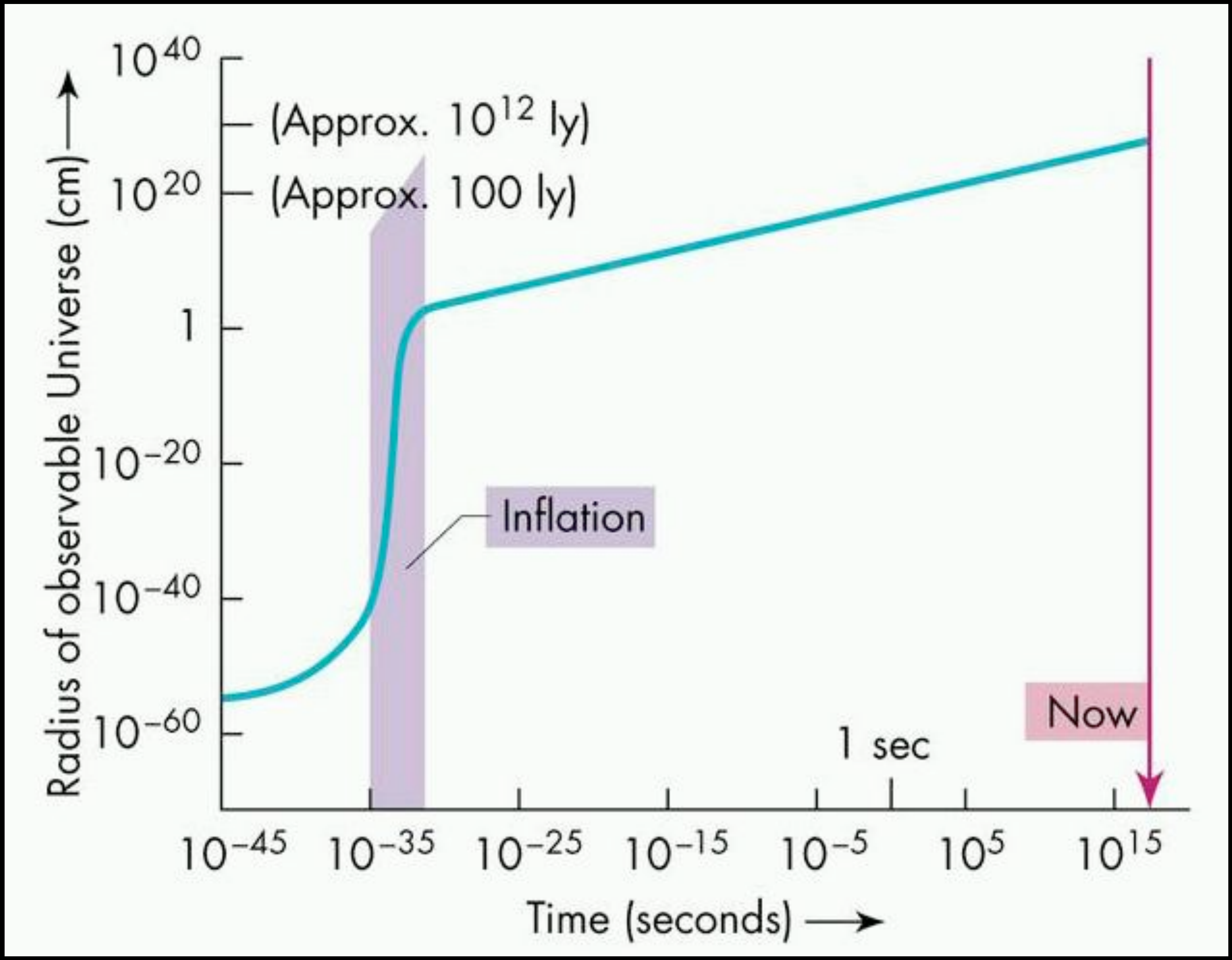
Dark matter in Galaxies

UC Irvine: Garrison-Kimmel + 2013

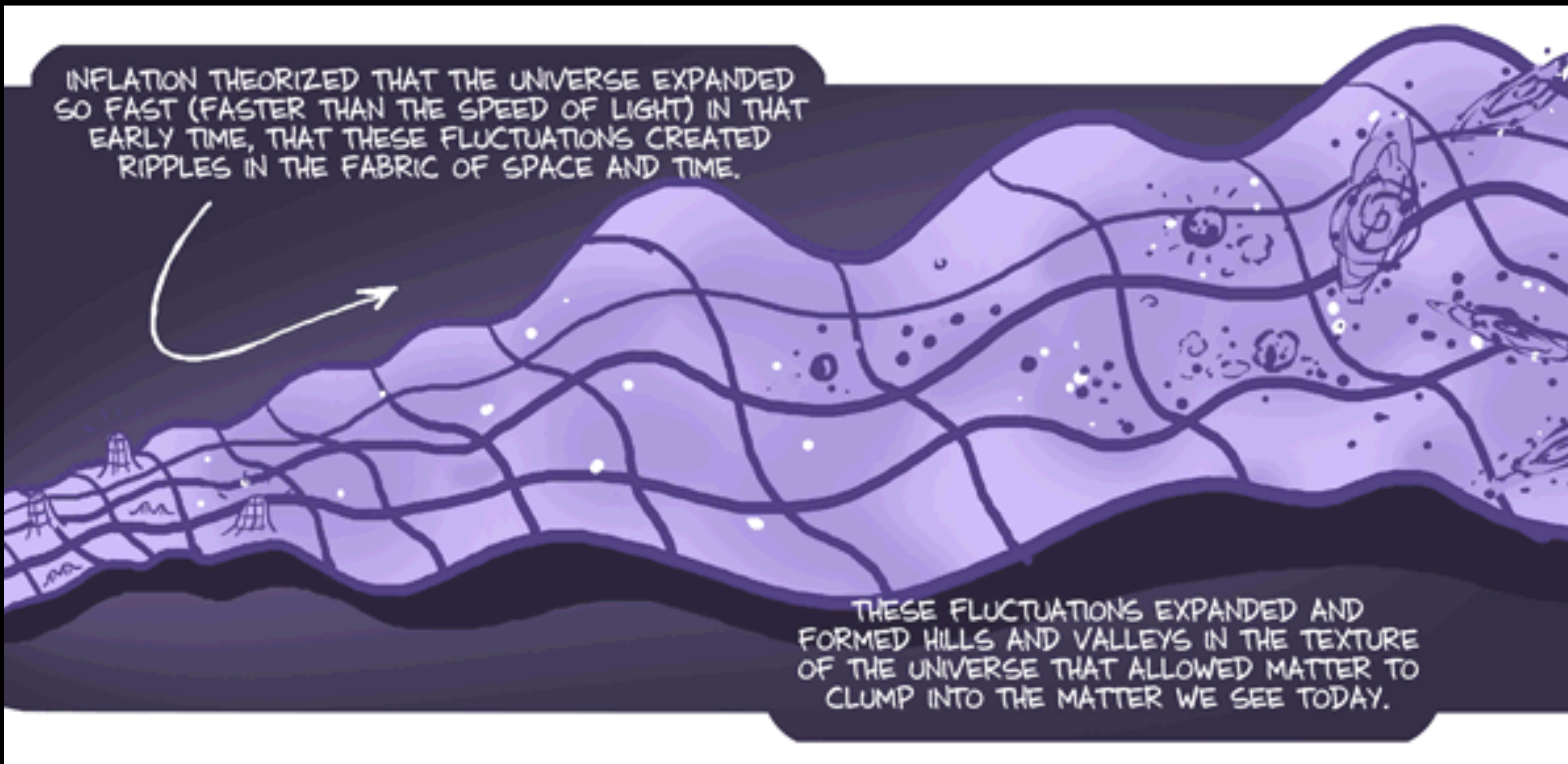
Inflation: what makes the Universe smooth, flat and mostly empty

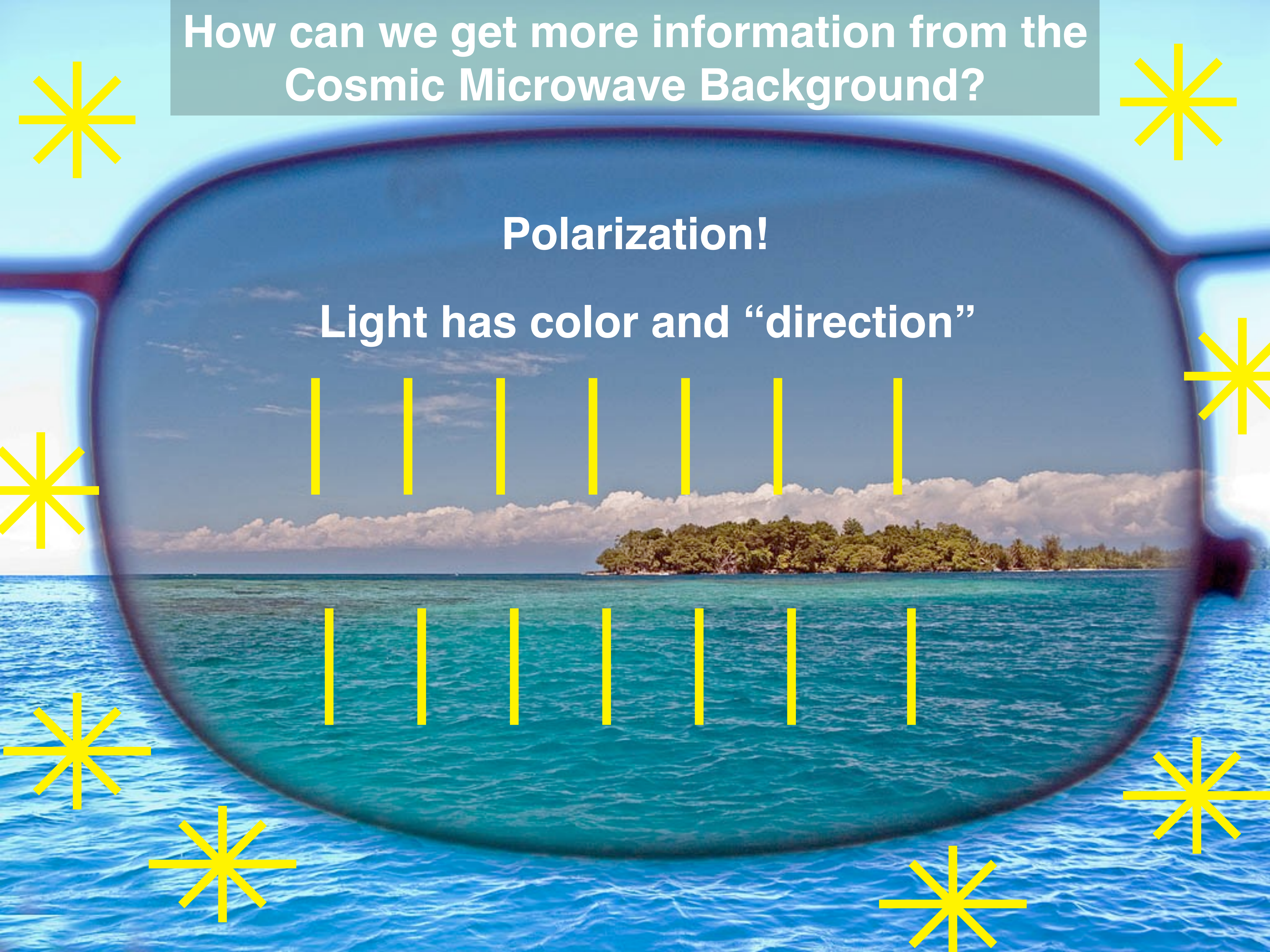


The Inflationary Universe

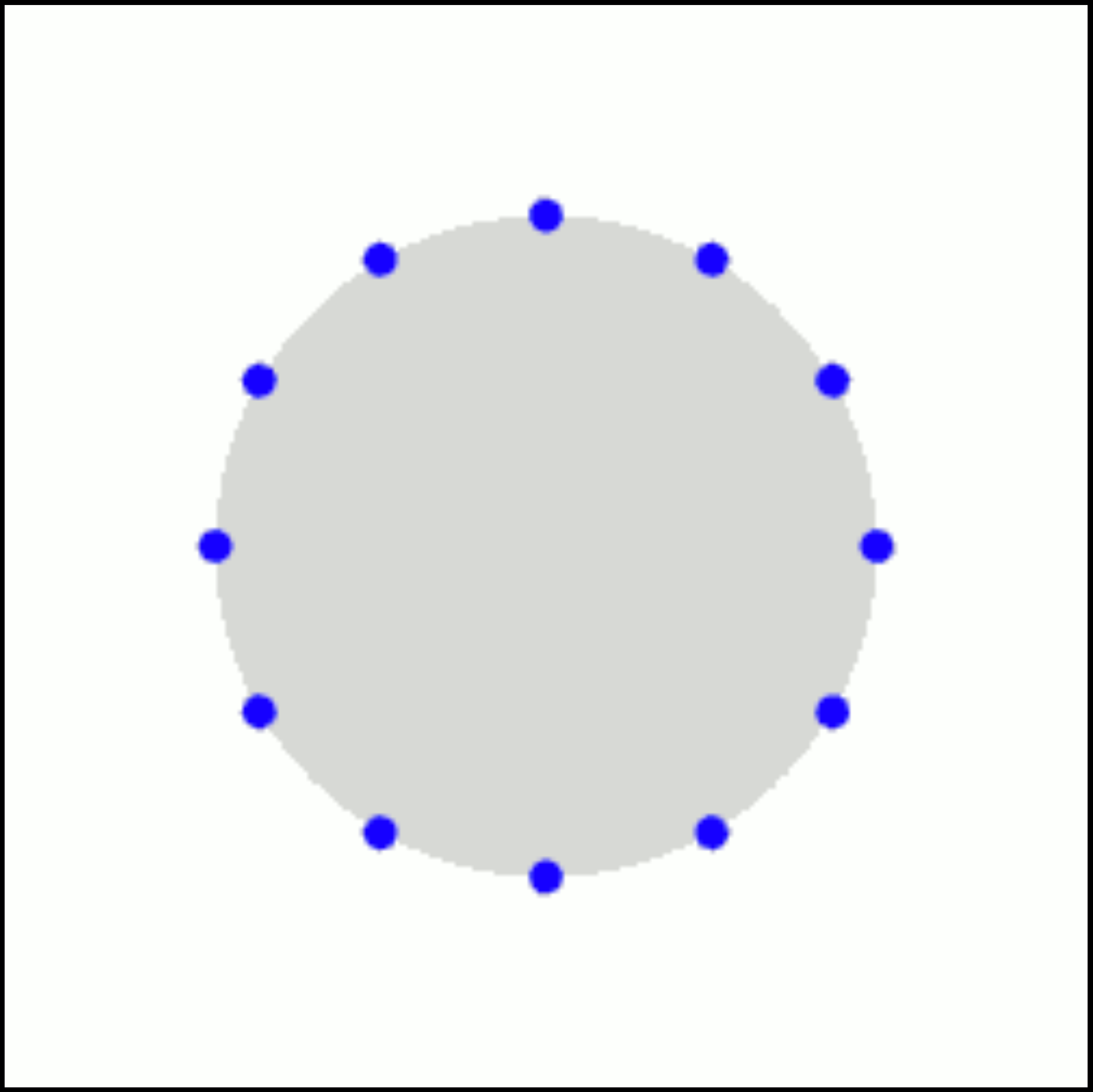


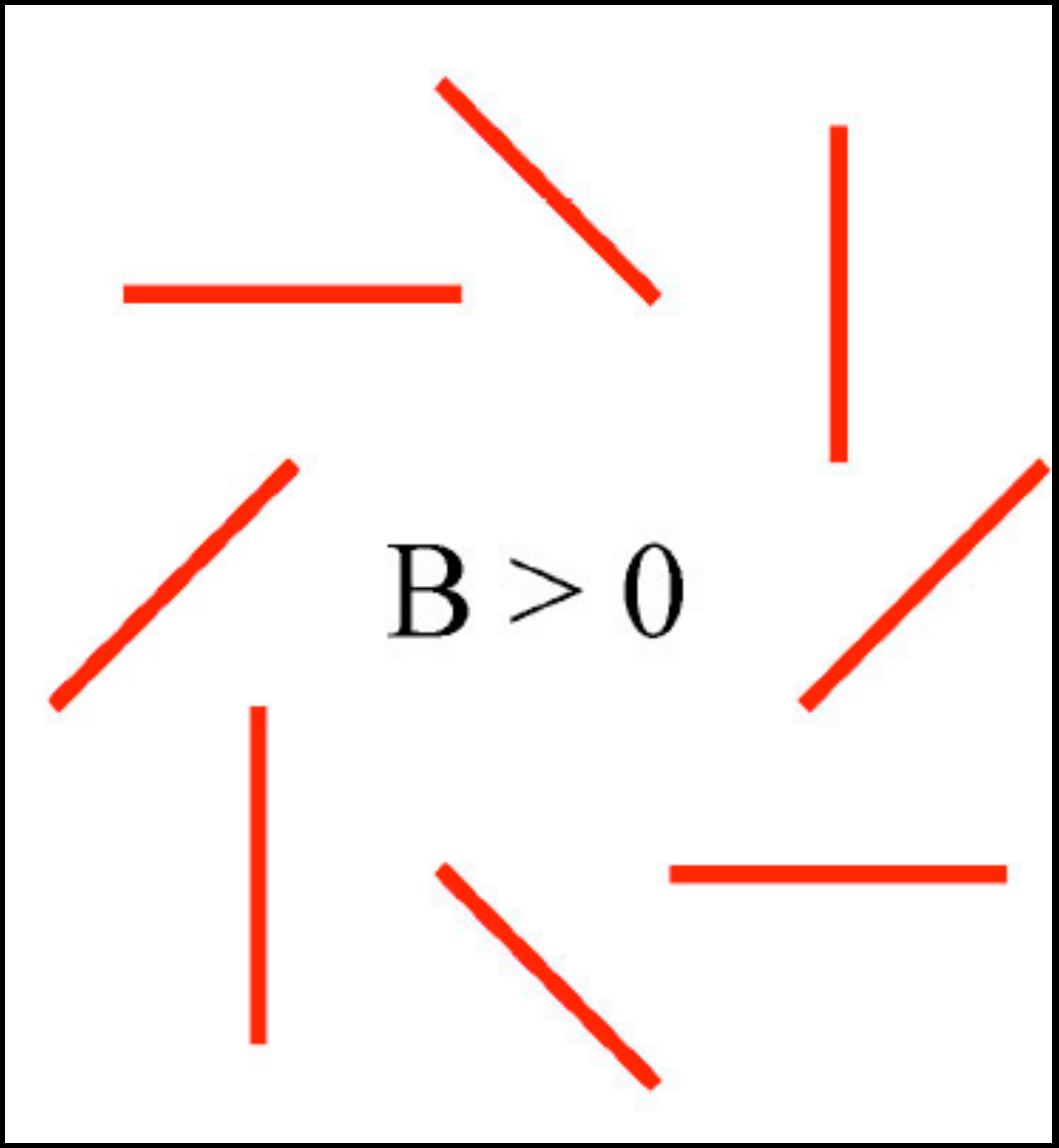
The Amplification of Quantum Fluctuations




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

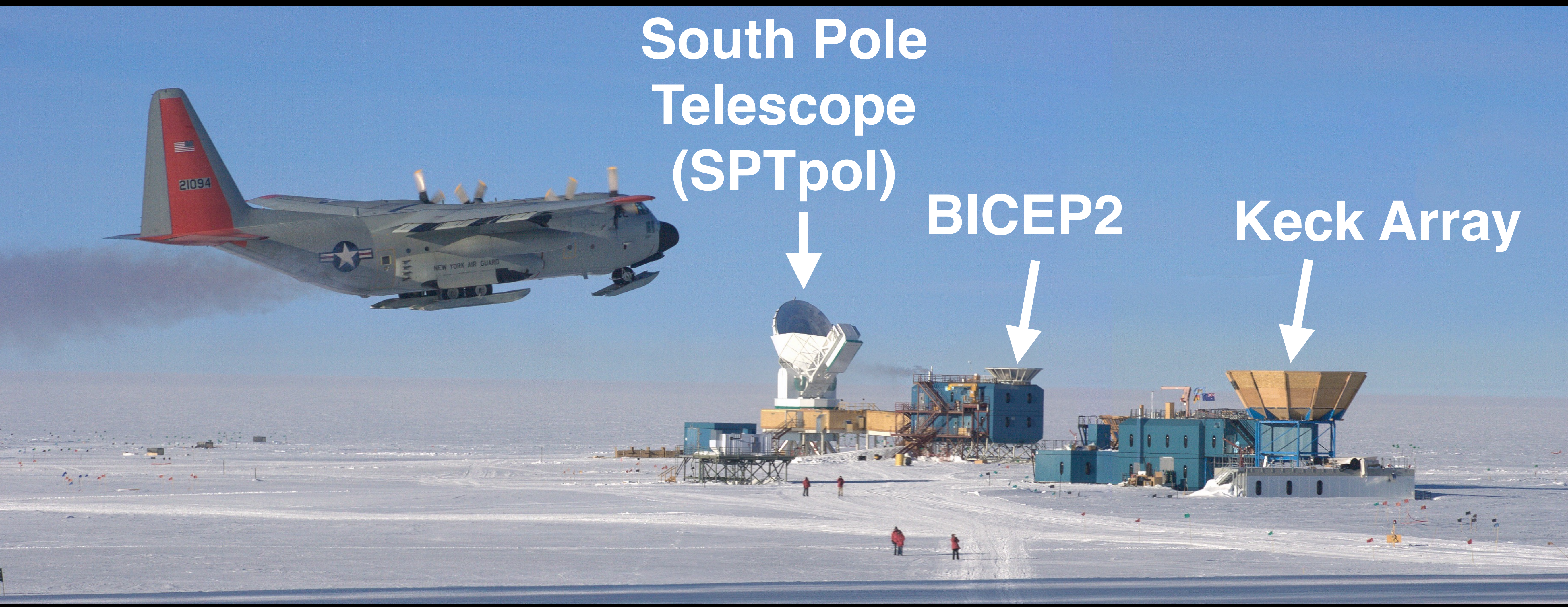




"B-Modes"

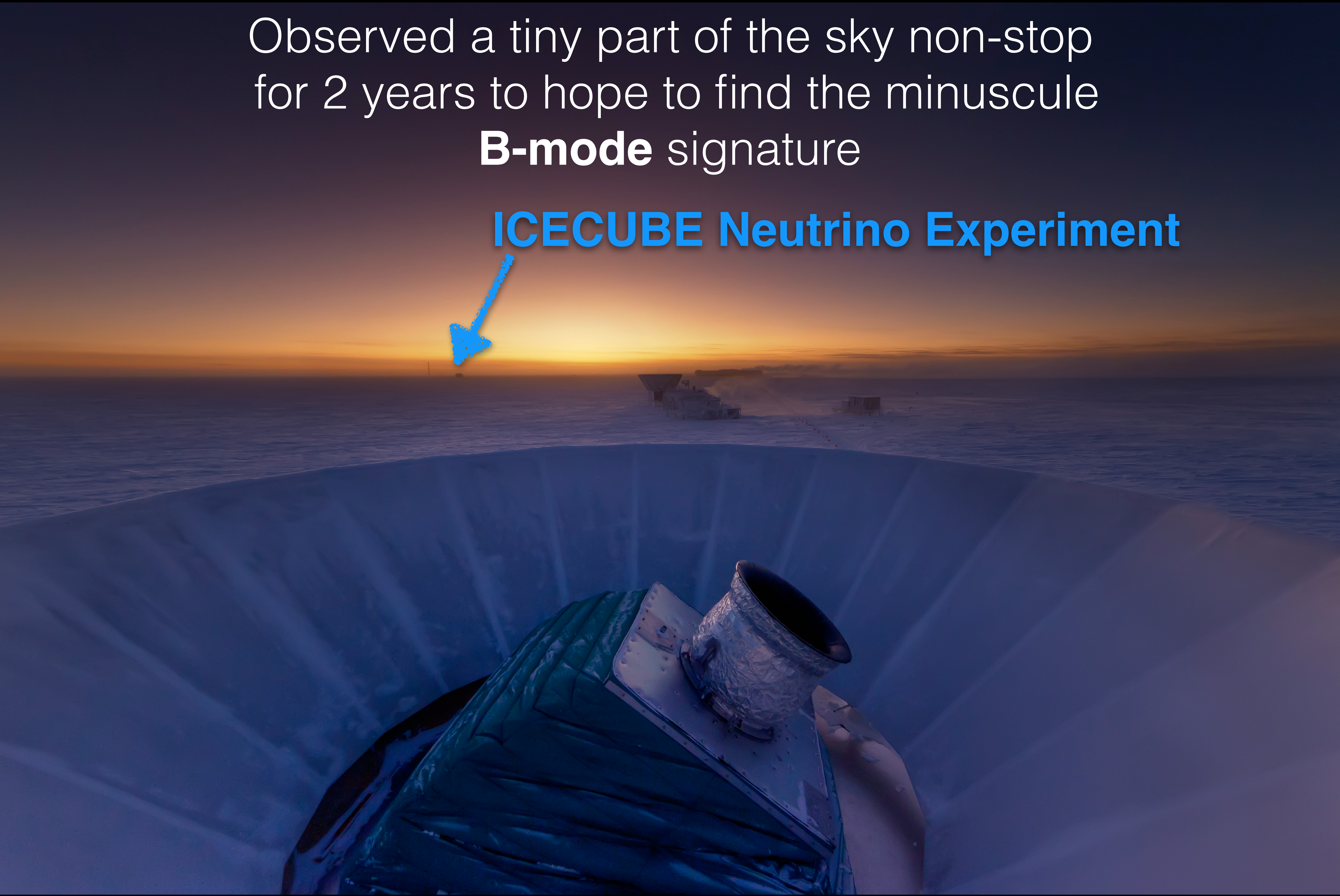
At best, 1% of the anisotropy in temperature

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



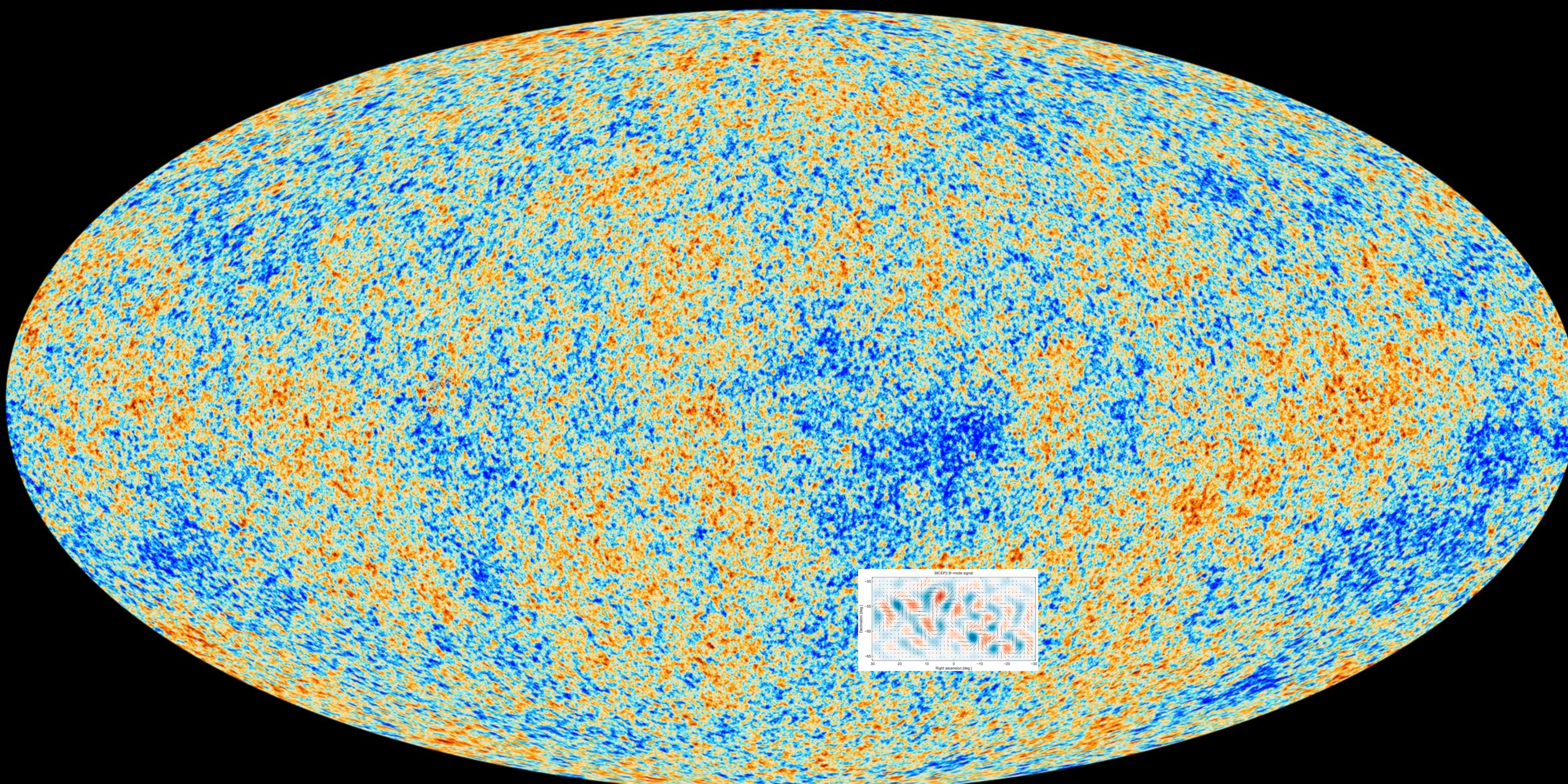
The BICEP2 Experiment at the South Pole

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



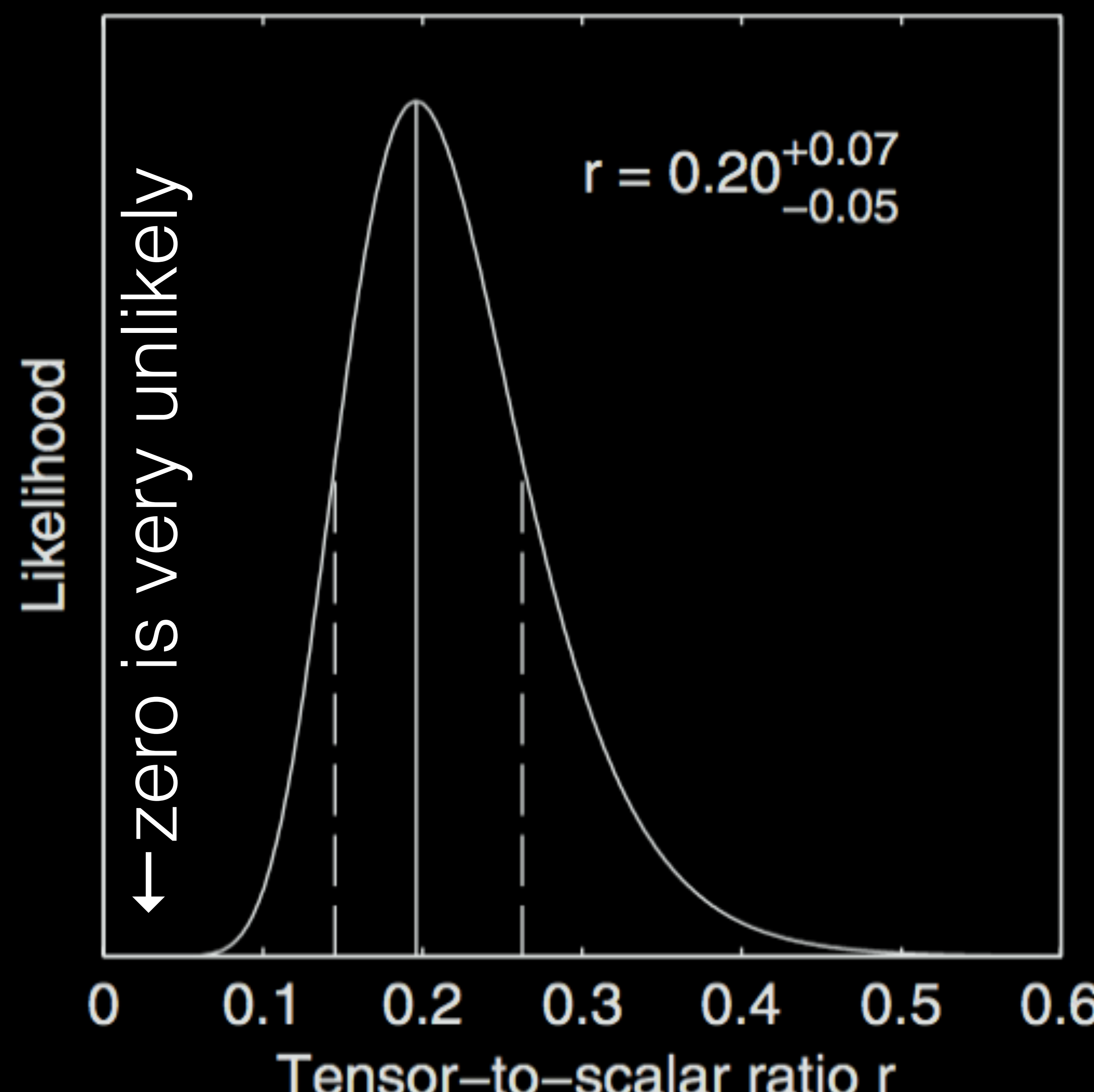
Polarization Signal In the CMB Found by the BICEP2 Collaboration in March 2014

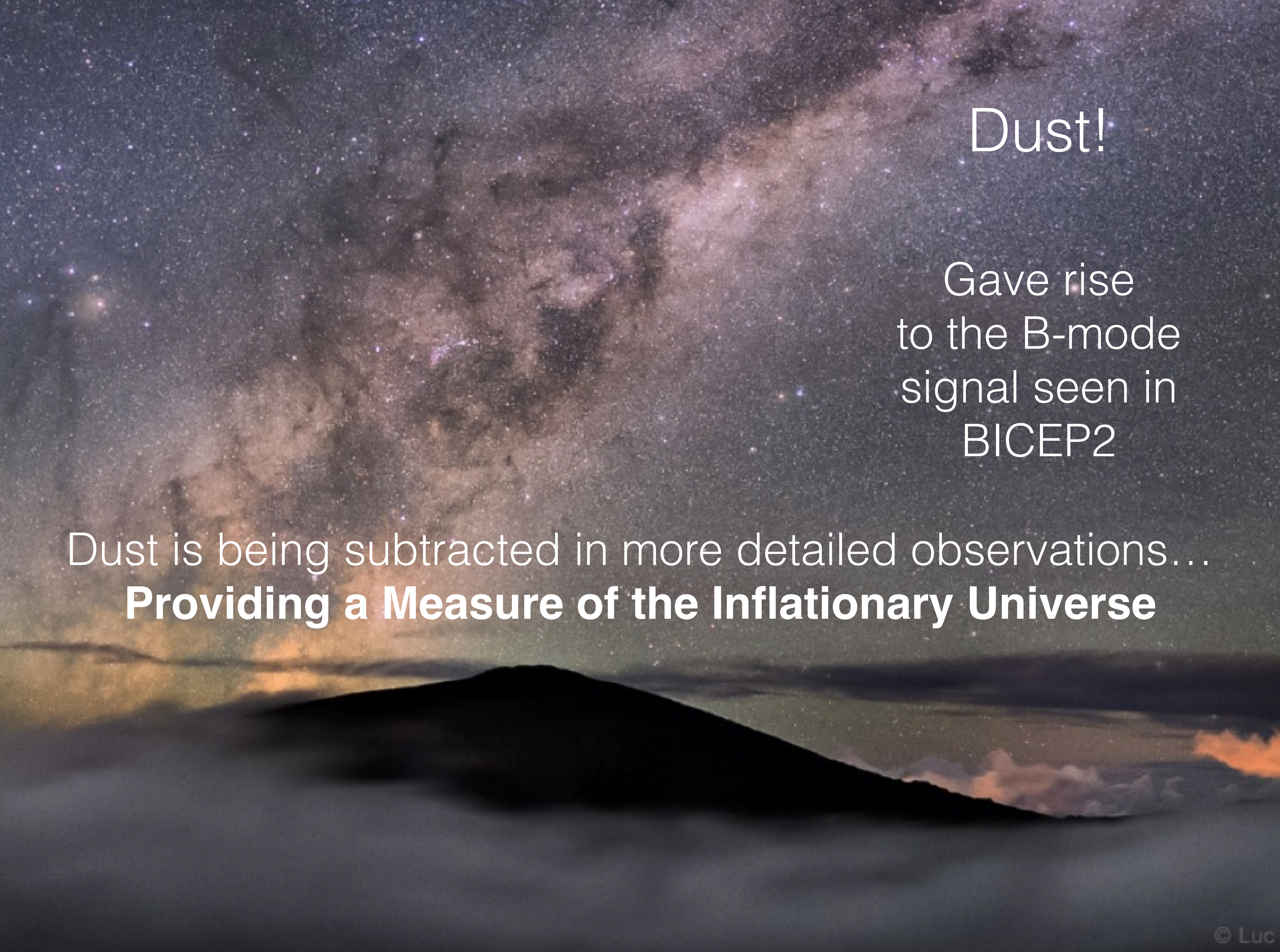
The level of the signal, *if primordial*,
reveals the energy scale of inflation…



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

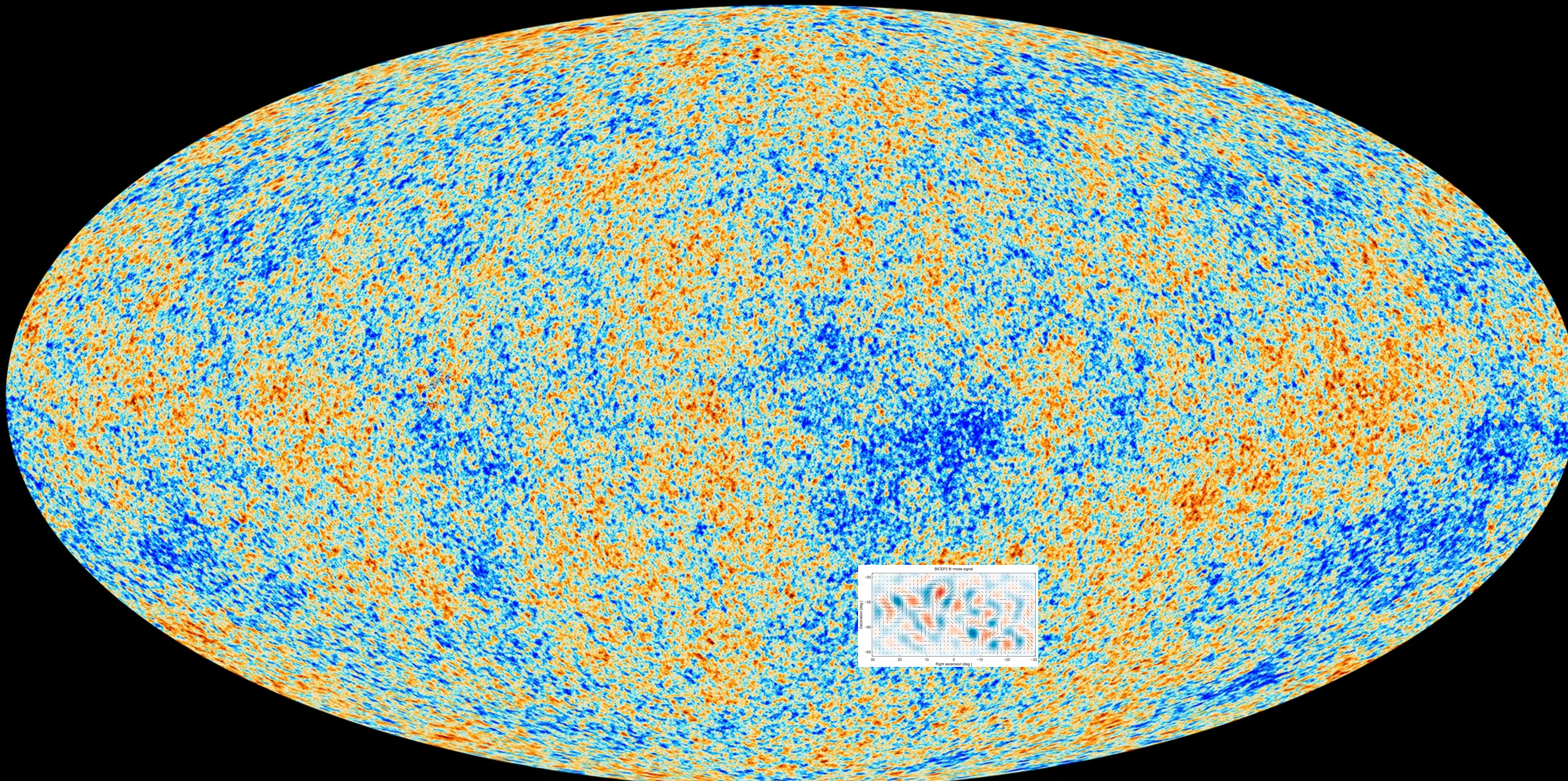
Claimed 7σ detection of B-modes (gravitational waves) in the CMB: 3 in 10 trillion chance to get these results if $r = 0$




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
© Luc

Is it primordial or dust?

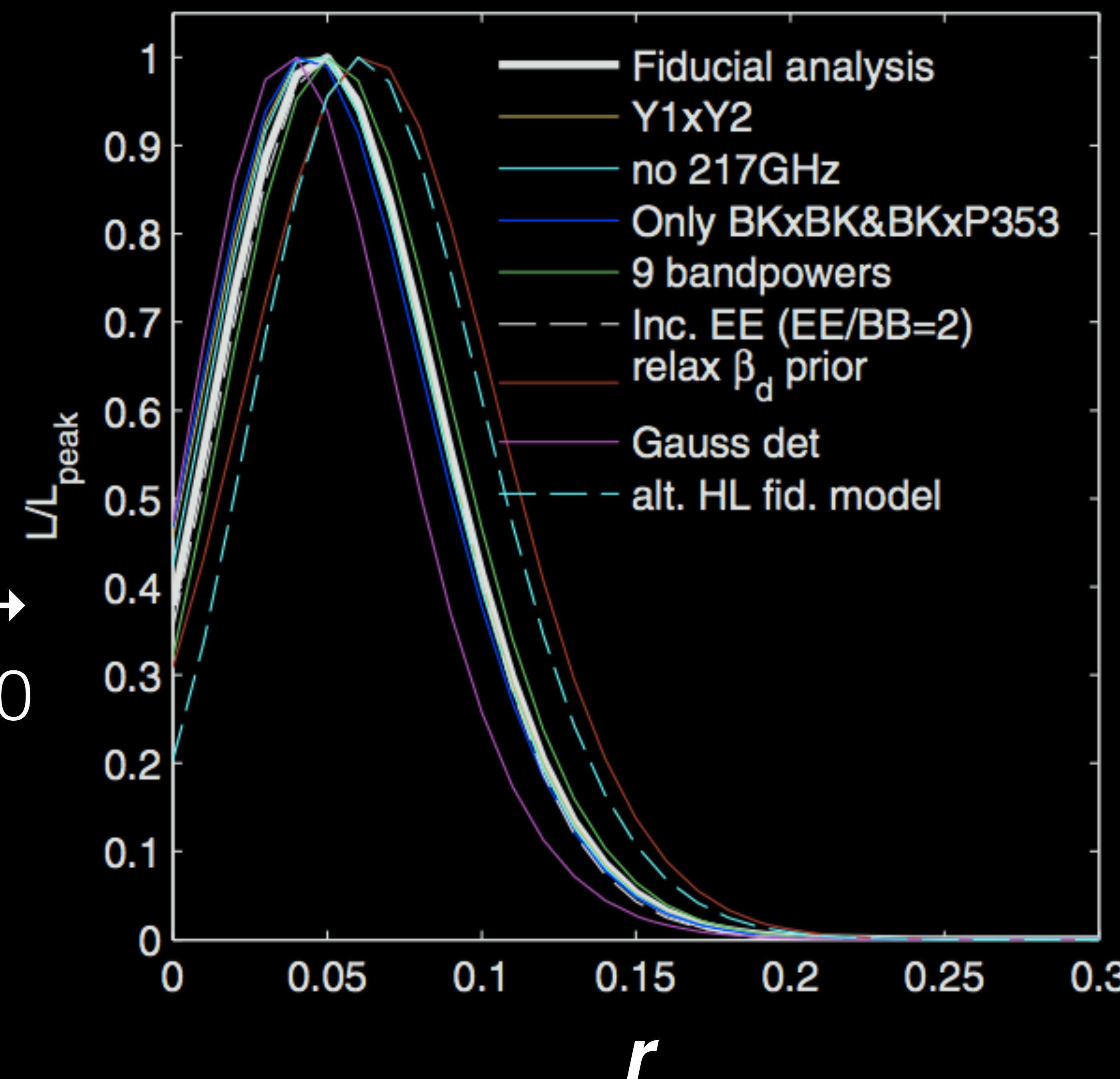
Cross-Analysis of Planck Mission and BICEP2: Released January 21, 2015



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 $r = 0$

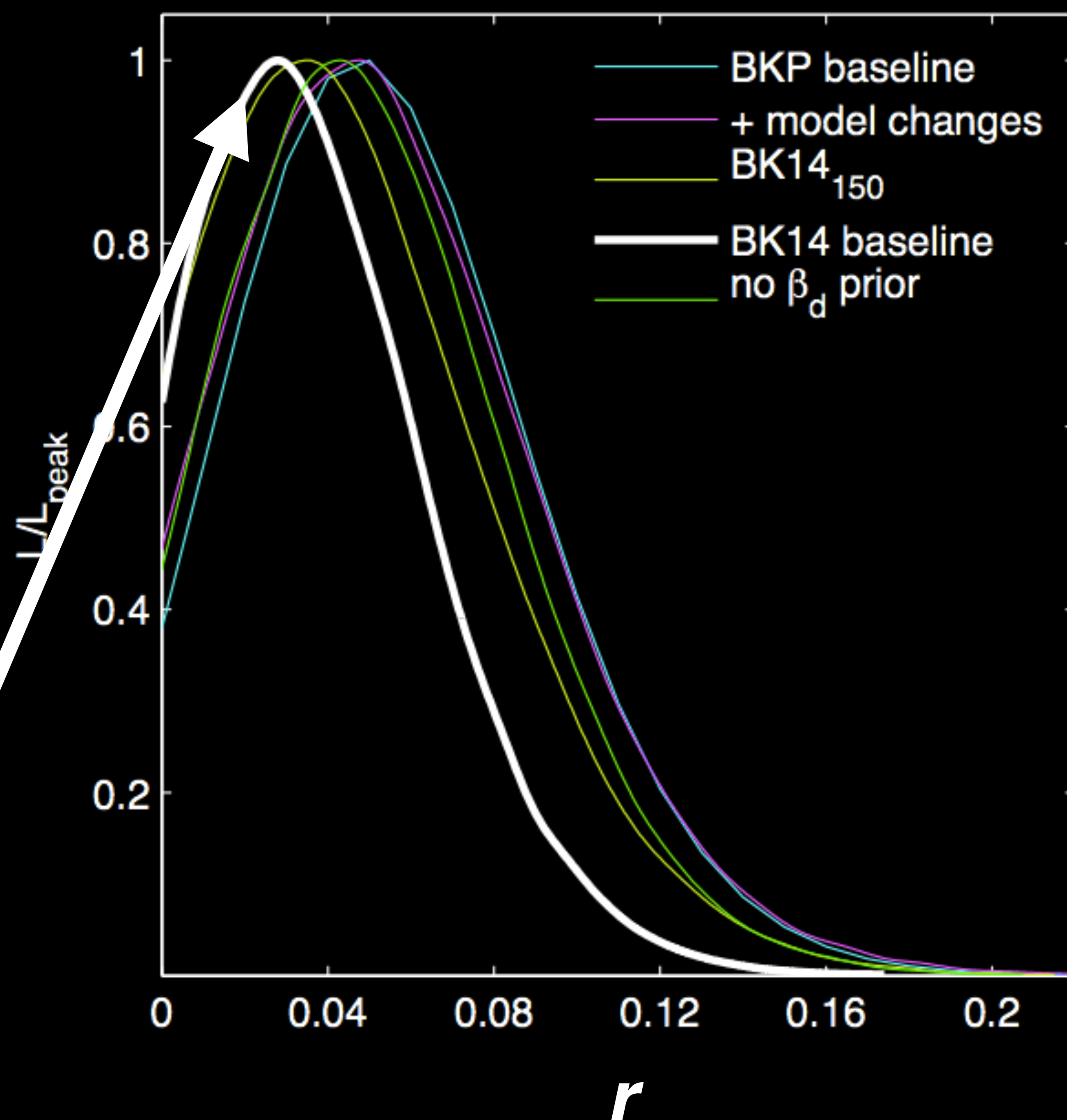


BICEP2 + Keck + Planck (**October 30, 2015**):
Even stronger constraints on dust and primordial gravitational waves ***r***

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