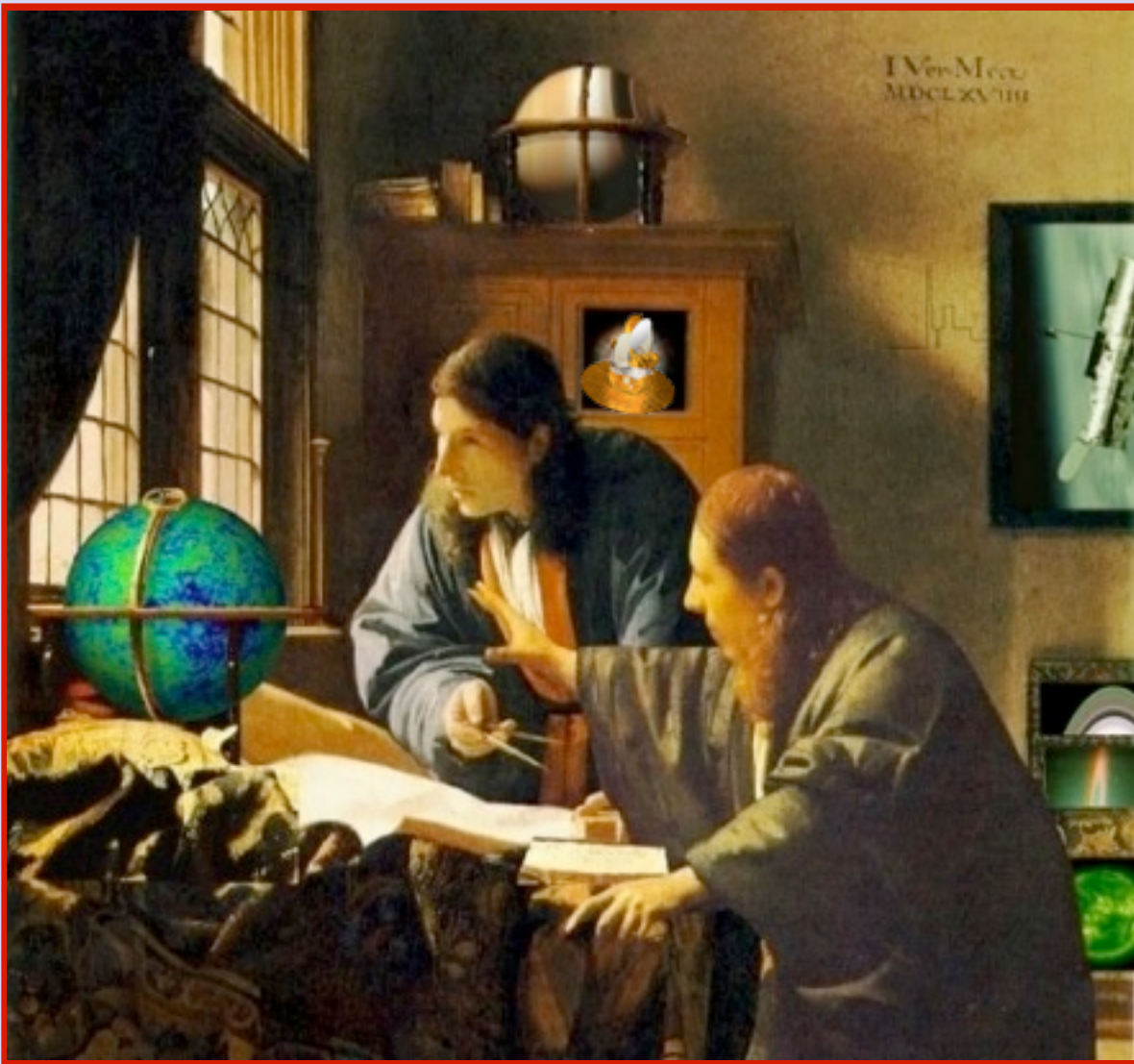


Taking the Measure of the Universe

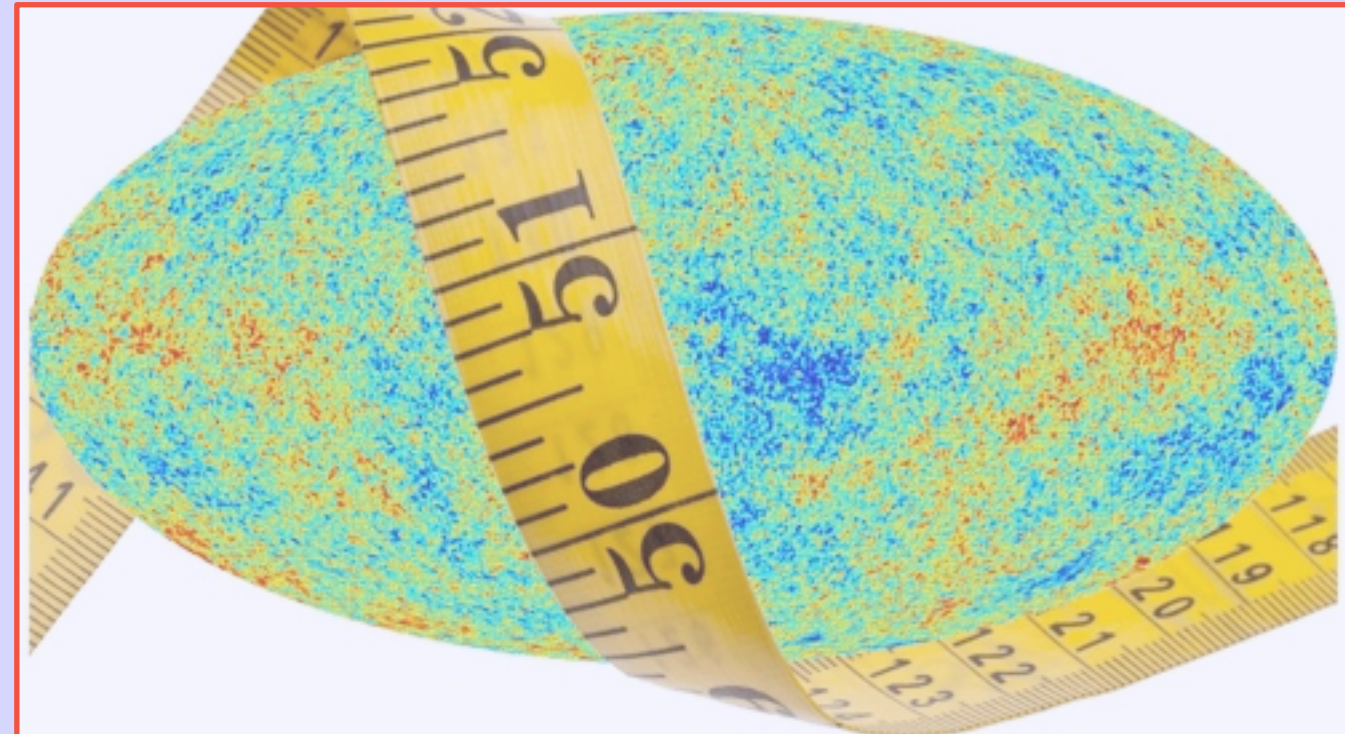


Gary Hinshaw

University of British Columbia

TRIUMF Saturday Series

24 November 2012



The Big Bang Theory



What is wrong with this picture?

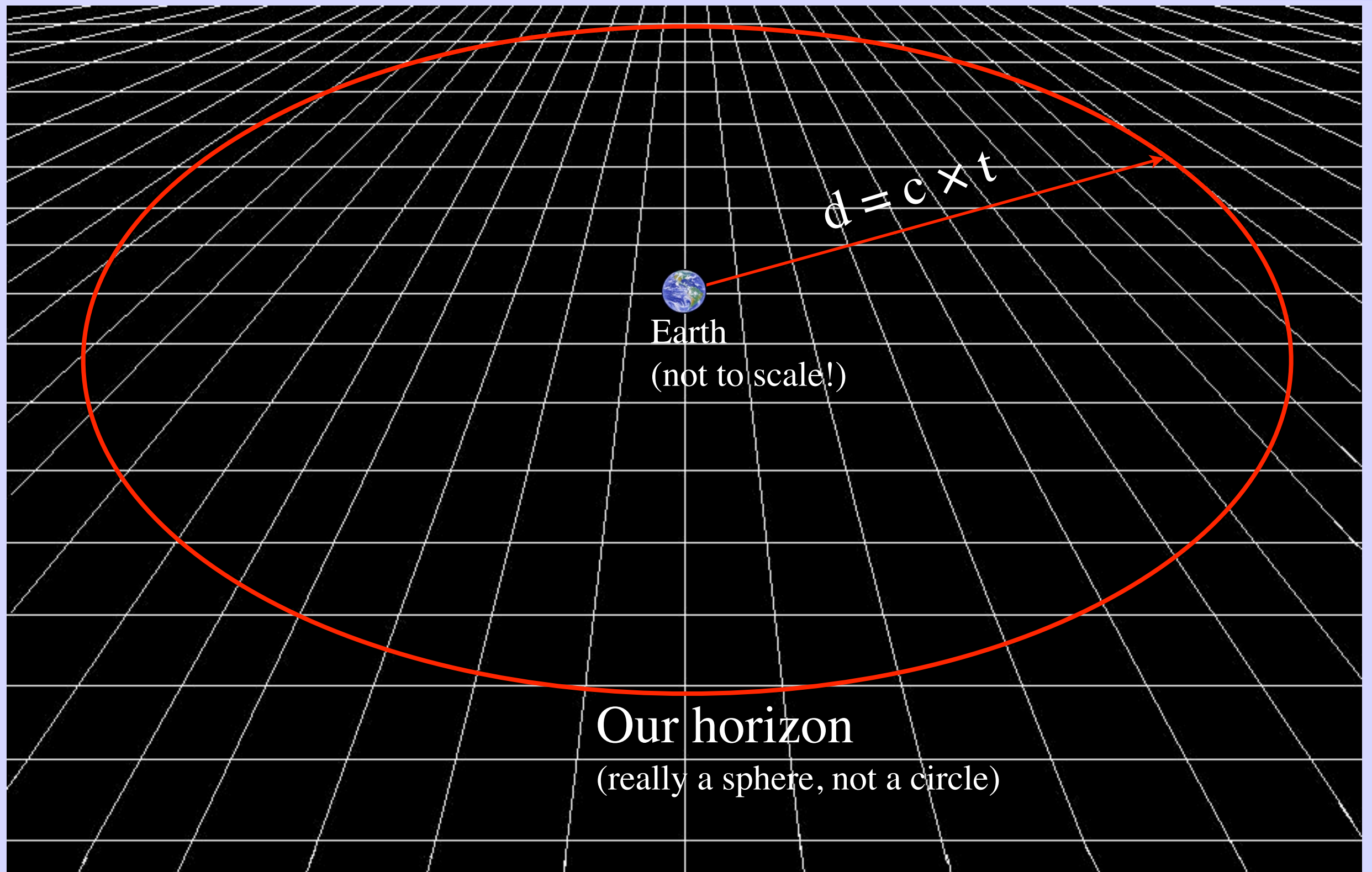
The Big Bang Theory



The Big bang is not an “explosion” that we can view from the outside!

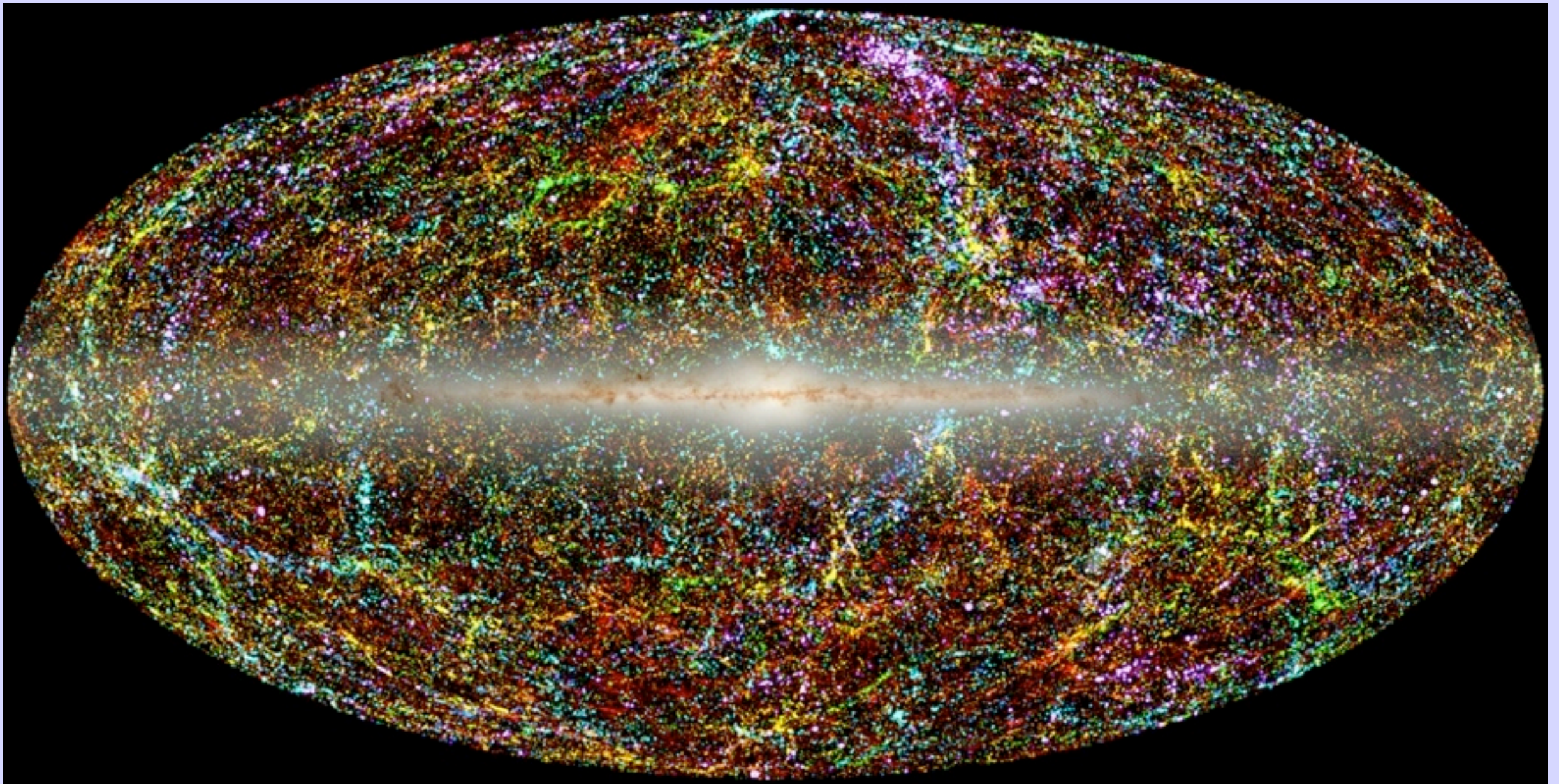
We are immersed in the expanding universe.

Horizon and Look Back Time



When we look out in space, we look back in time.
The limit is the speed of light (c) times the age of the universe (t).

Uniformity of Galaxy Distribution



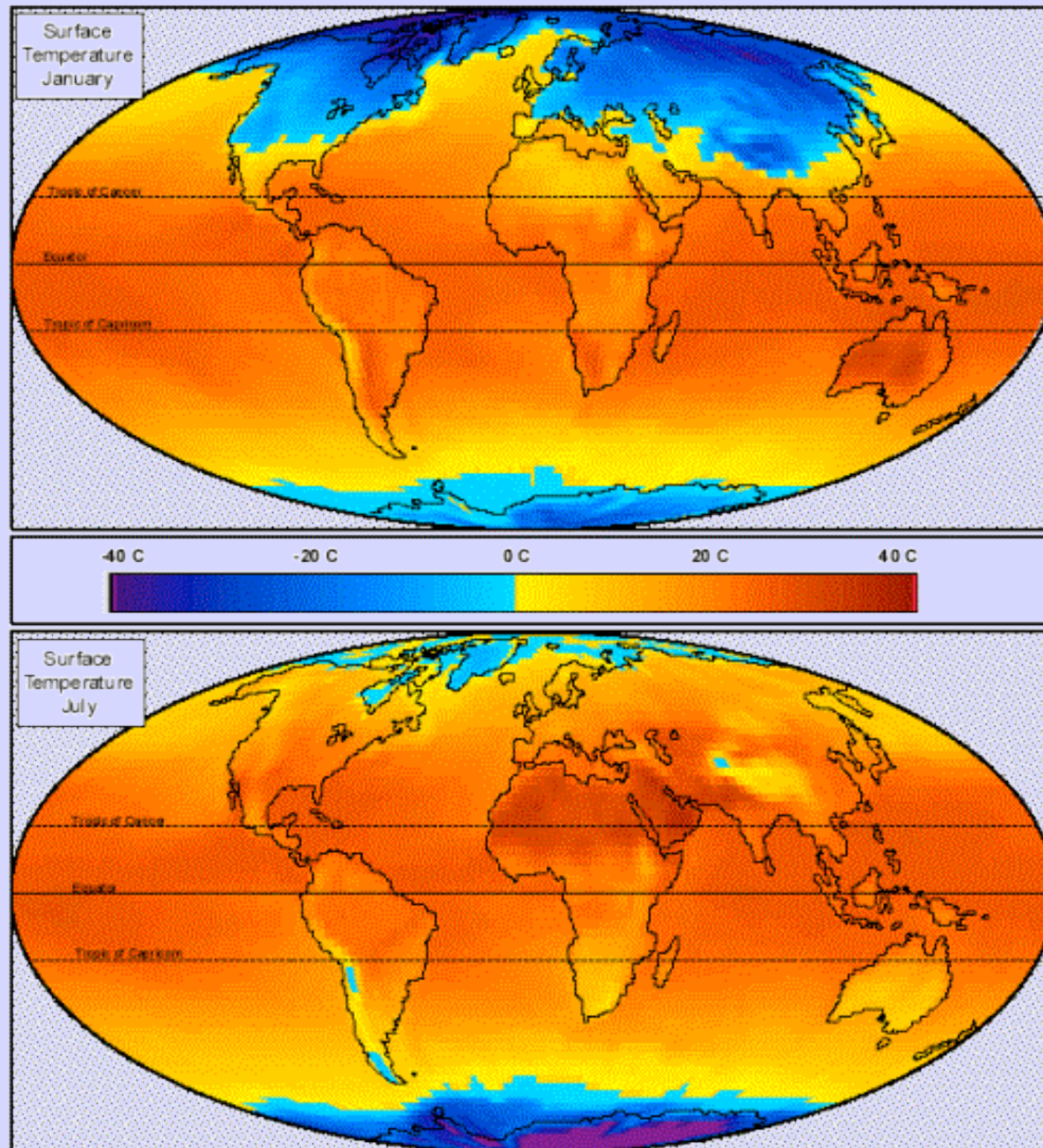
Smooth light in center of map is from stars in our Milky Way galaxy.

Other points are “nearby” galaxies, color-coded by distance: near-to-far=blue-to-red.

2MASS survey data compiled by T. Jarret, IPAC/CalTech, 2004.

The nearby universe looks pretty similar in all directions.

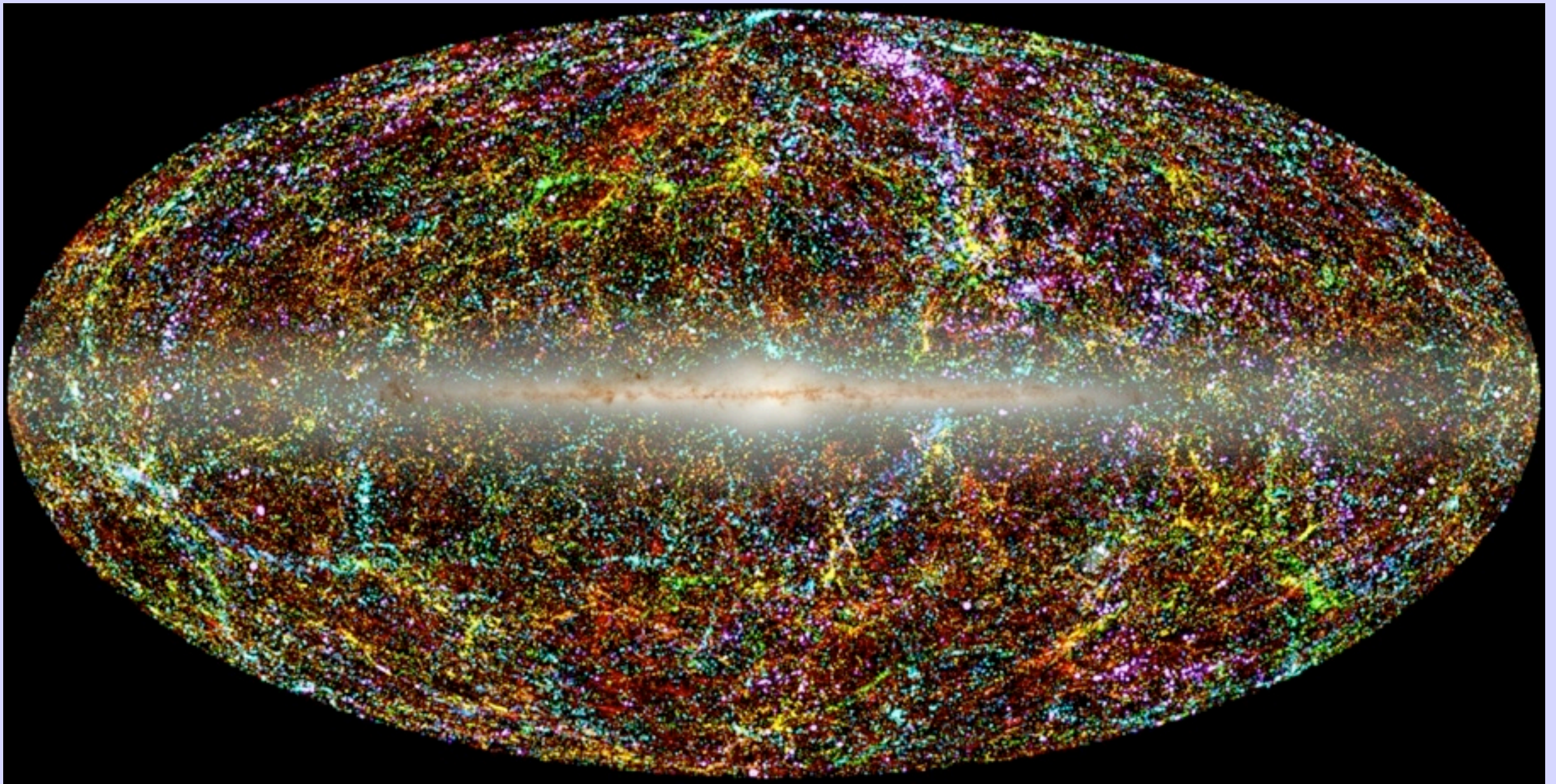
Representing Data on a Sphere



False color representation of surface temperature in Mollweide projection of the spherical Earth.



Uniformity of Galaxy Distribution



Smooth light in center of map is from stars in our Milky Way galaxy.

Other points are “nearby” galaxies, color-coded by distance: near-to-far=blue-to-red.

2MASS survey data compiled by T. Jarret, IPAC/CalTech, 2004.

The nearby universe looks pretty similar in all directions.

The Cosmological Principle (c. 1910's)

The universe is homogenous and isotropic

- **Homogenous** – it has the same average properties (e.g., temperature, density) everywhere in space.
- **Isotropic** – it has the same average properties in every direction.

If true, the Earth does not occupy a special place in the universe.

1916: Einstein Shows How Gravity Works



ALBERT EINSTEIN

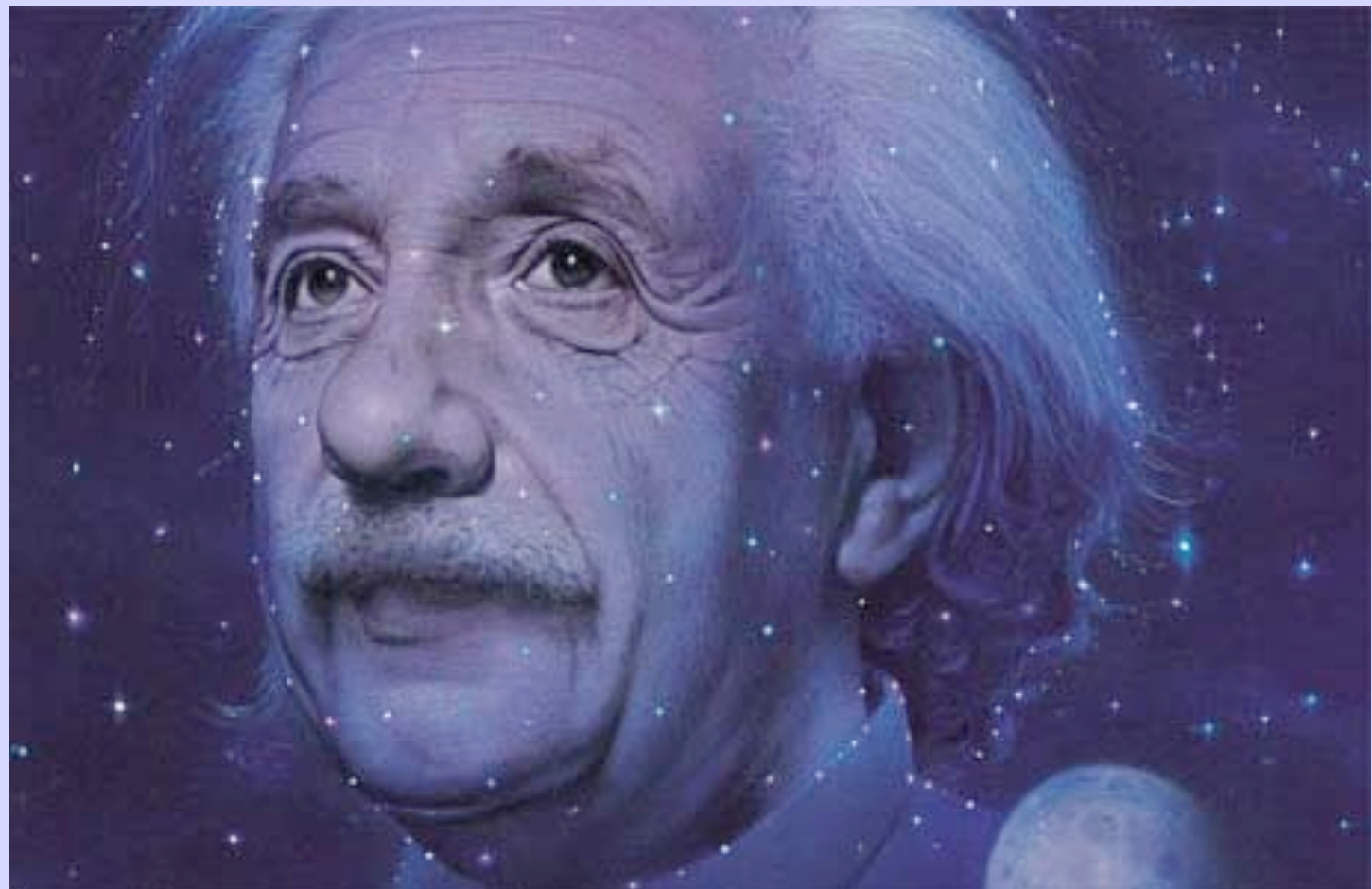
TIME MAGAZINE
"PERSON OF THE
CENTURY"

"Einstein's equations didn't have a solution that described a universe that was unchanging in time. ... he fudged the equations by adding a term called the cosmological constant... The repulsive effect of the cosmological constant would balance the attractive effect of matter and allow for a universe that lasts for all time."

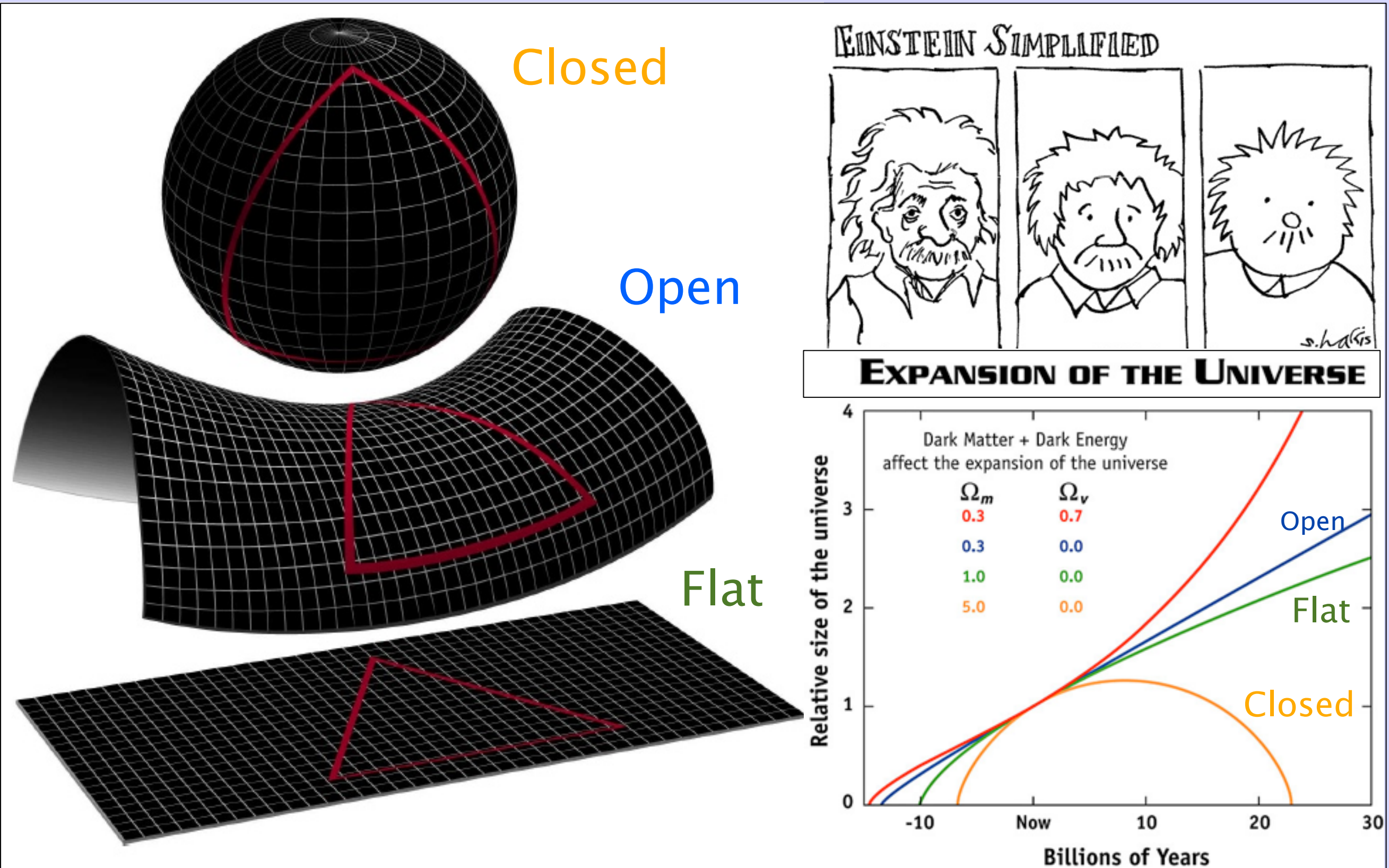
---Stephen Hawking

Einstein applied the General Theory of Relativity to the Universe as a whole:

- **Dynamic universe that expands and possibly contracts.**
- **Seemingly in conflict with belief that the universe was static.**



Cosmological Dynamics

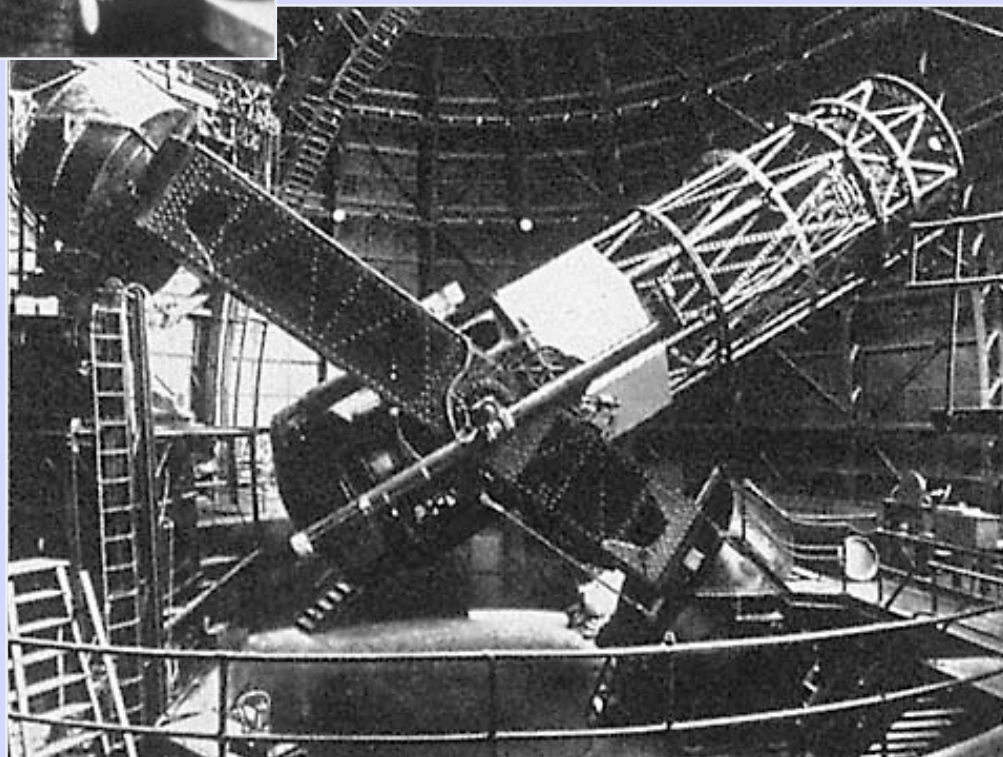


1929: Hubble Discovers Expanding Universe



Edwin Hubble

“...we know that we are reaching into space, farther and farther, until, with the faintest nebulae that can be detected with the greatest telescopes, we arrive at the frontier of the known universe.”

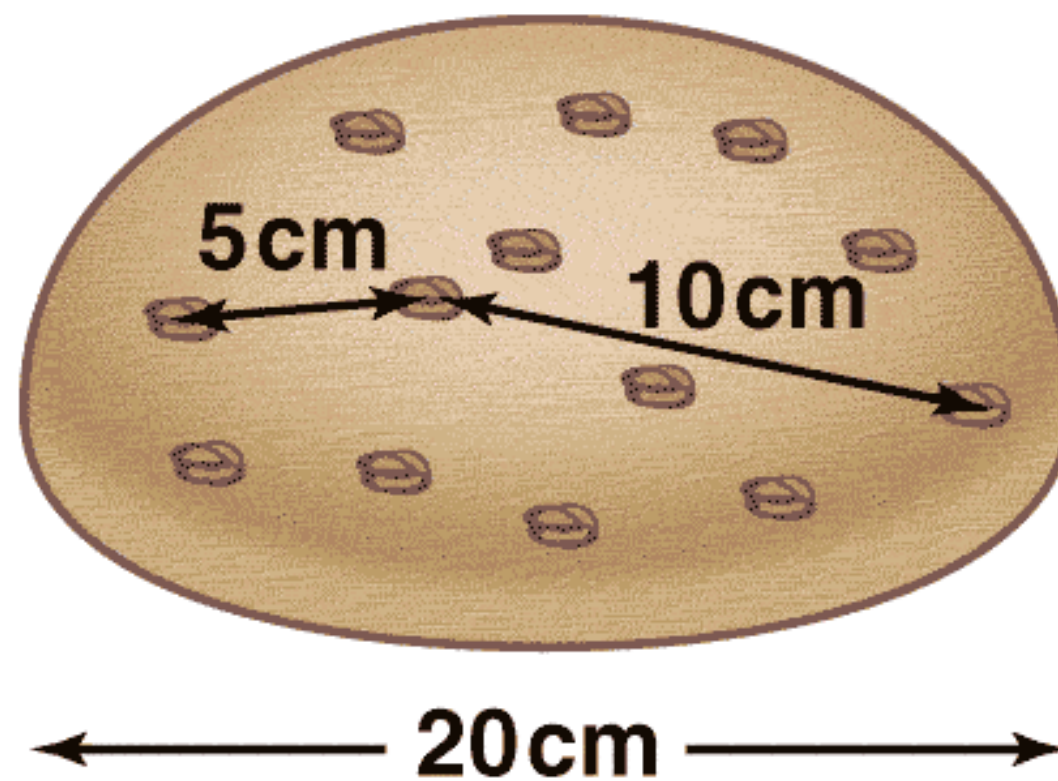


Mt. Wilson 100 Inch Telescope



“..one of the most flabbergasting discoveries science has ever made.” TIME noted, Hubble had evolved his theory “**by looking at the universe itself.**”

Homogeneous Expansion: $v=H \cdot d$



MAP990404

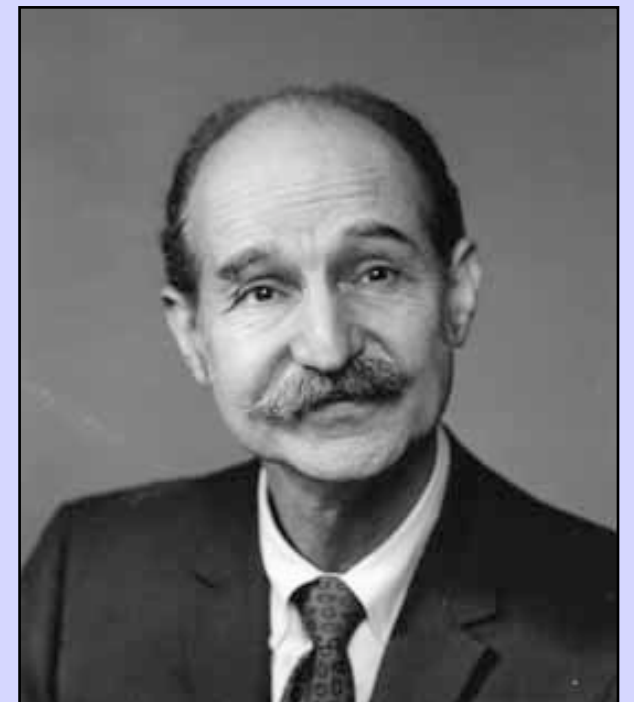
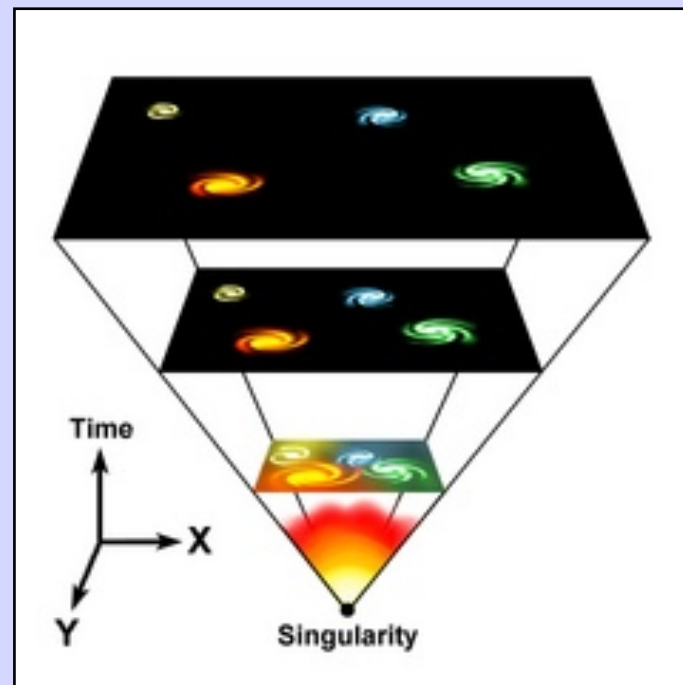
An “observer” on any raisin would measure the same expansion law

1940's: Big Bang Physics

- Gamow (1946): Chemical elements might have been made in a hot early universe, stopping when expansion cools universe.
- Ralph Alpher (1946): Worked out the physics & found only the lightest chemical elements could have been made: D, He, Li, Be, B.
- Alpher, Bethe, Gamow (1948): Derives relative proportions of chemical elements in a hot expanding universe. [Bethe made no contribution whatsoever.]
- Alpher & Herman (no input from Gamow): Calculated that the afterglow heat would make the temperature of the universe today about 5 Kelvin – a cosmic microwave background.

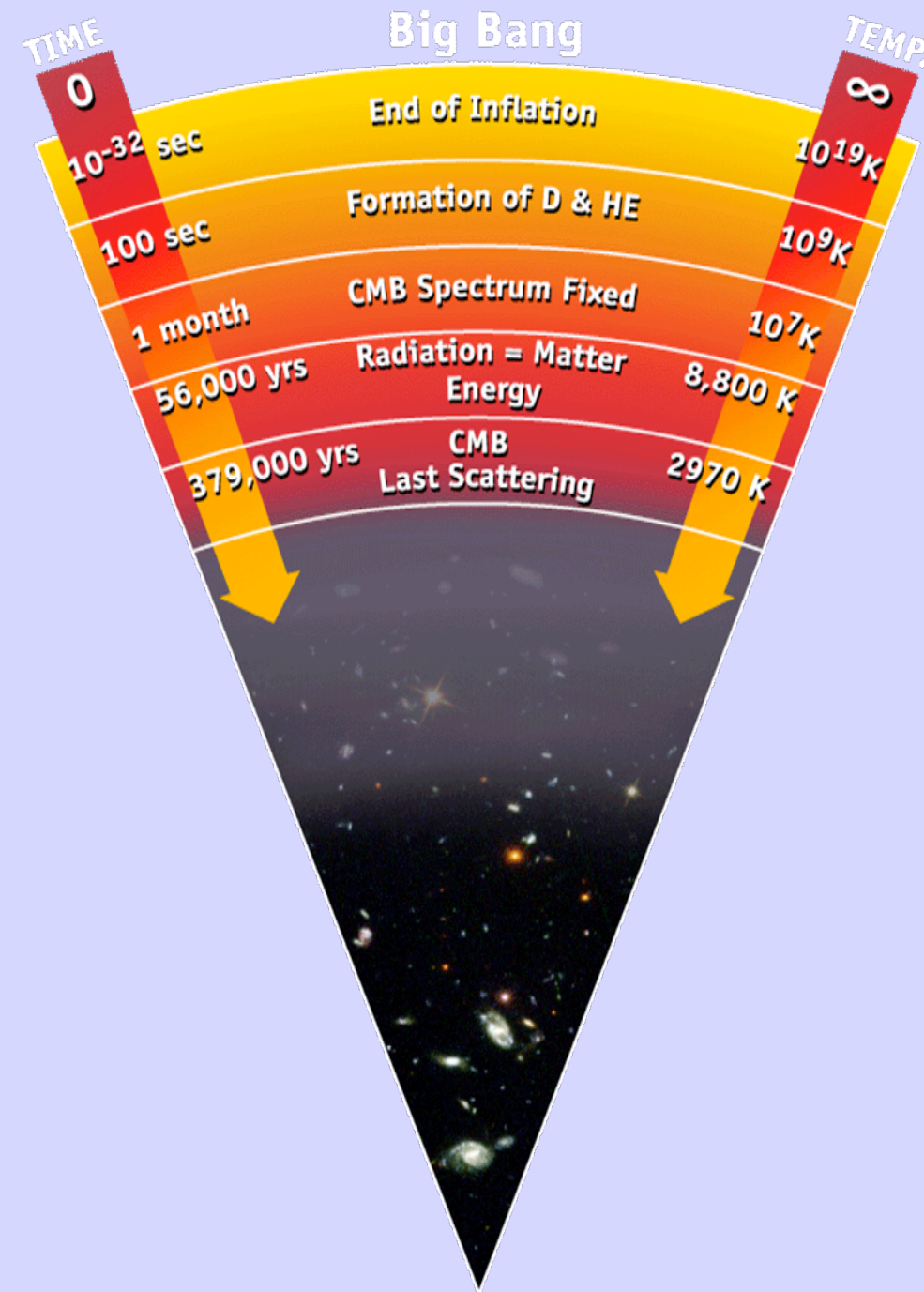


Ralph Alpher

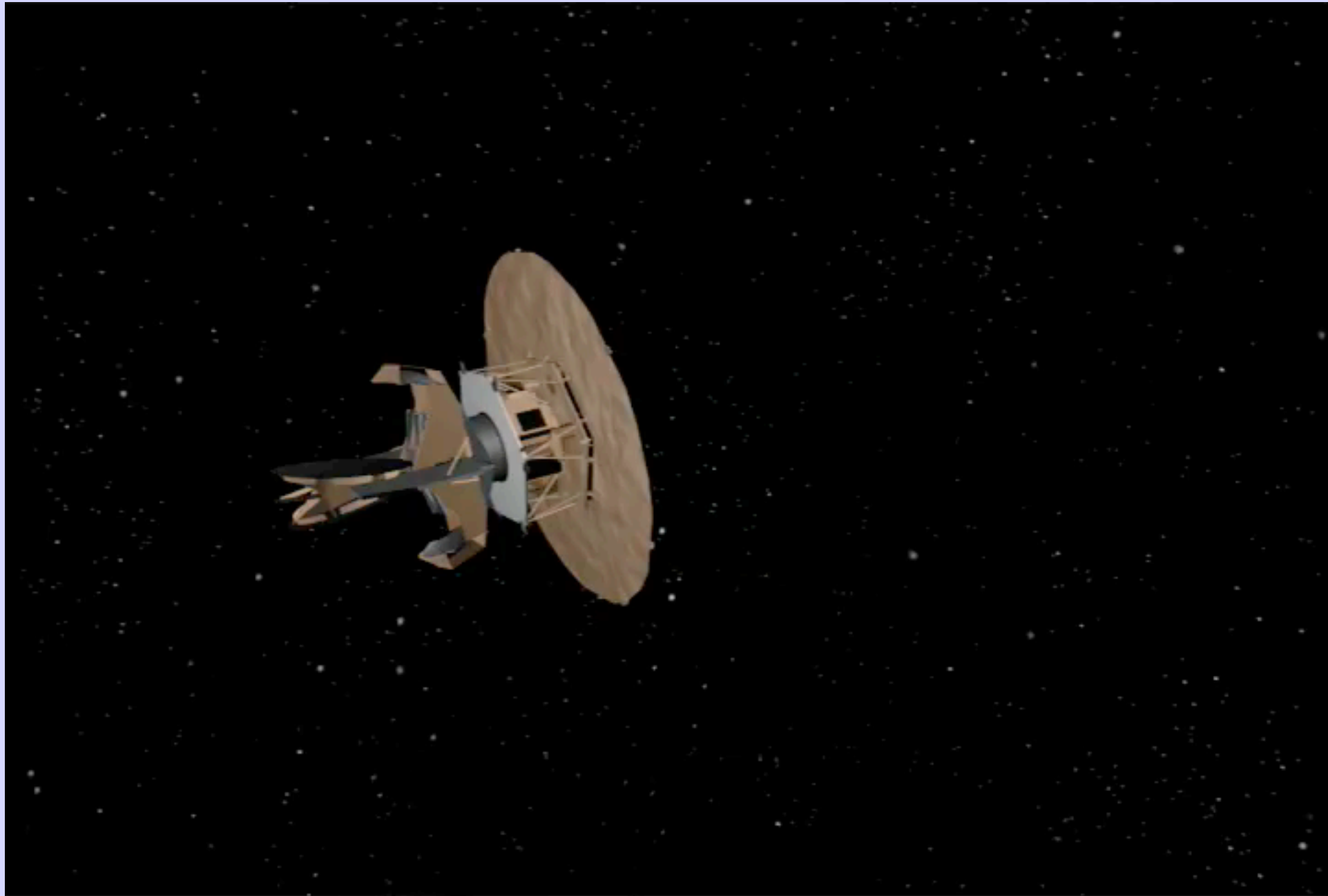


Robert Herman

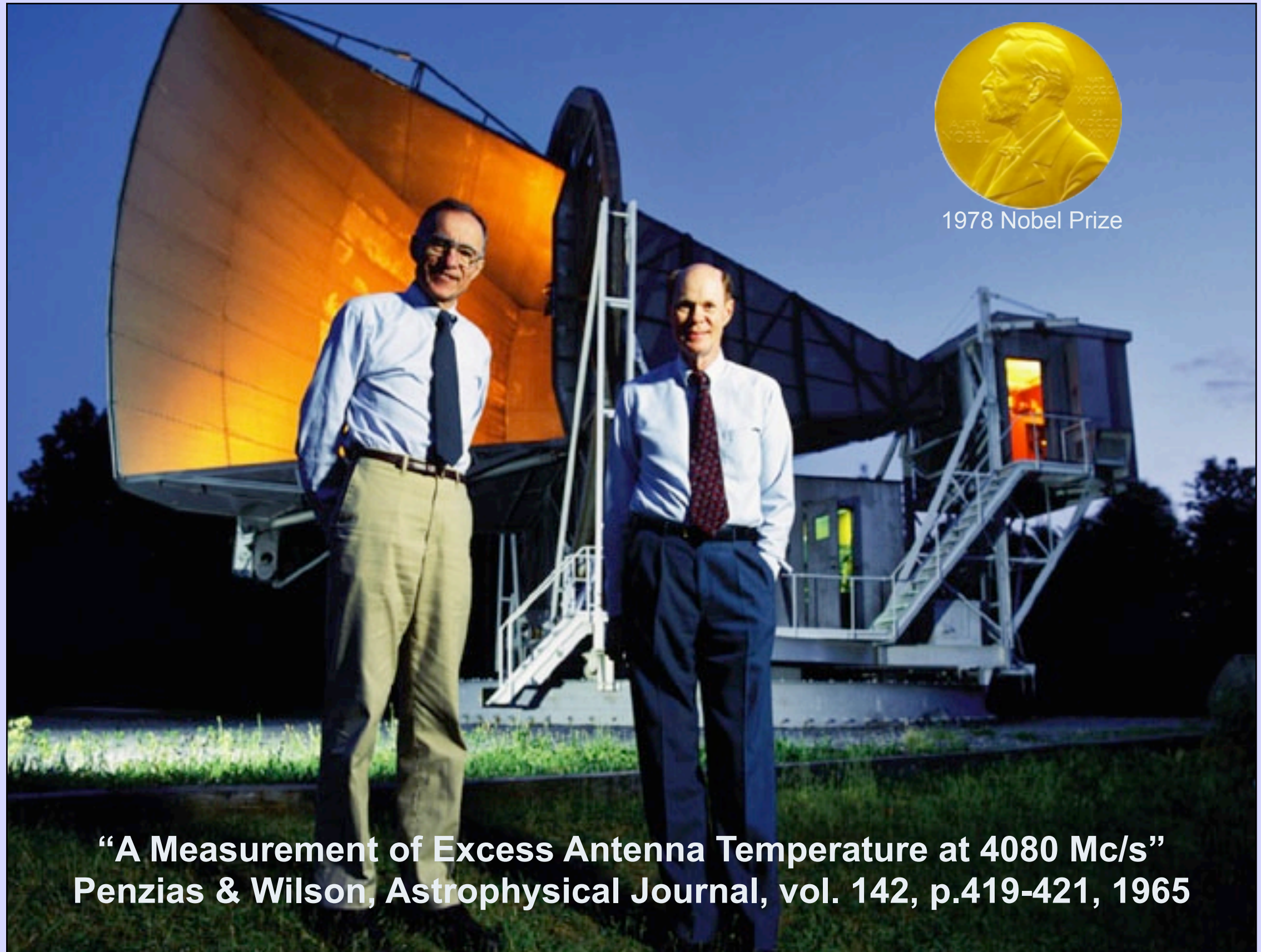
Time travel: out in space = back in time



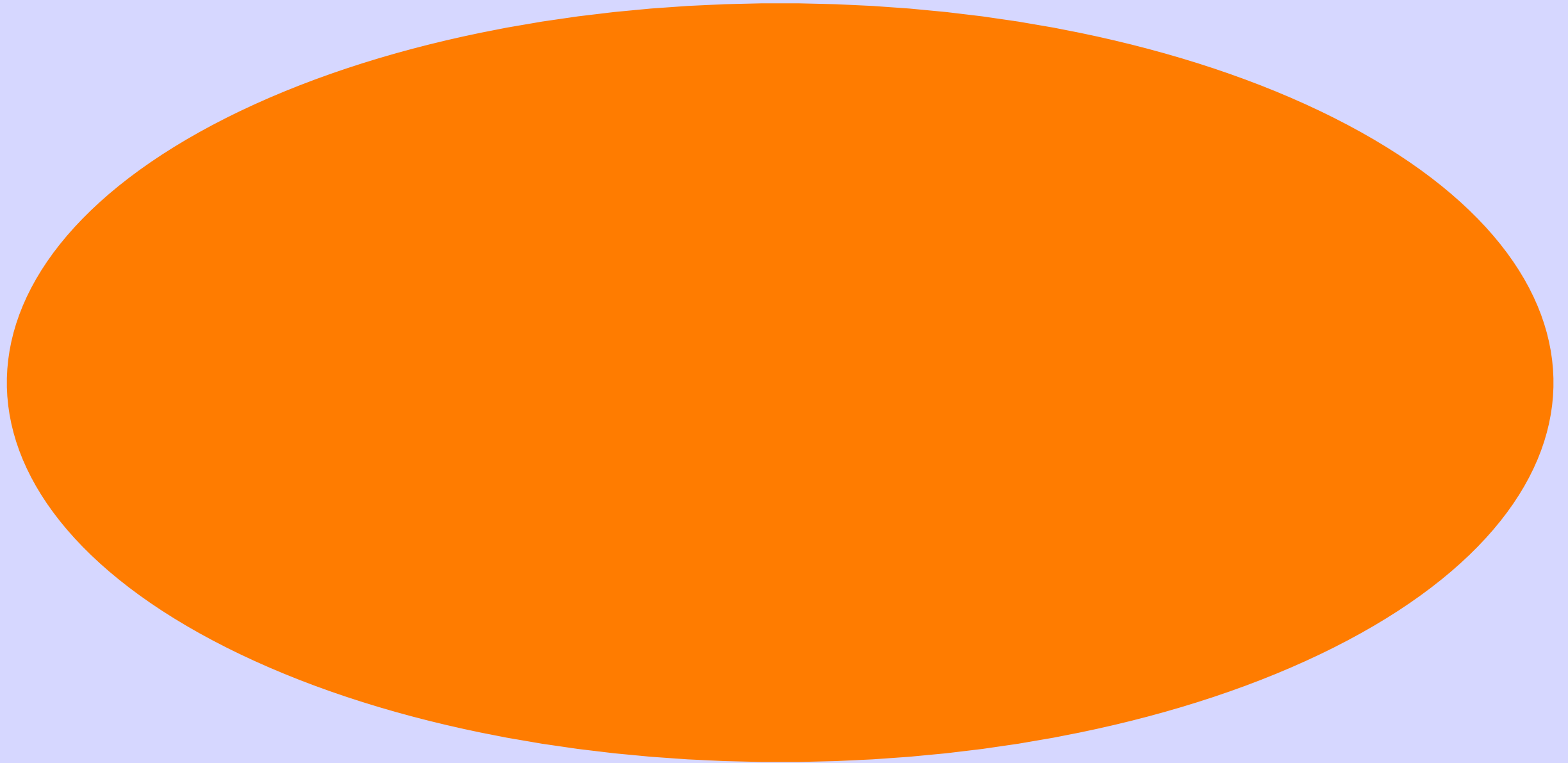
A Journey: Out in Space, Back in Time



1960's: Discovery of the CMB

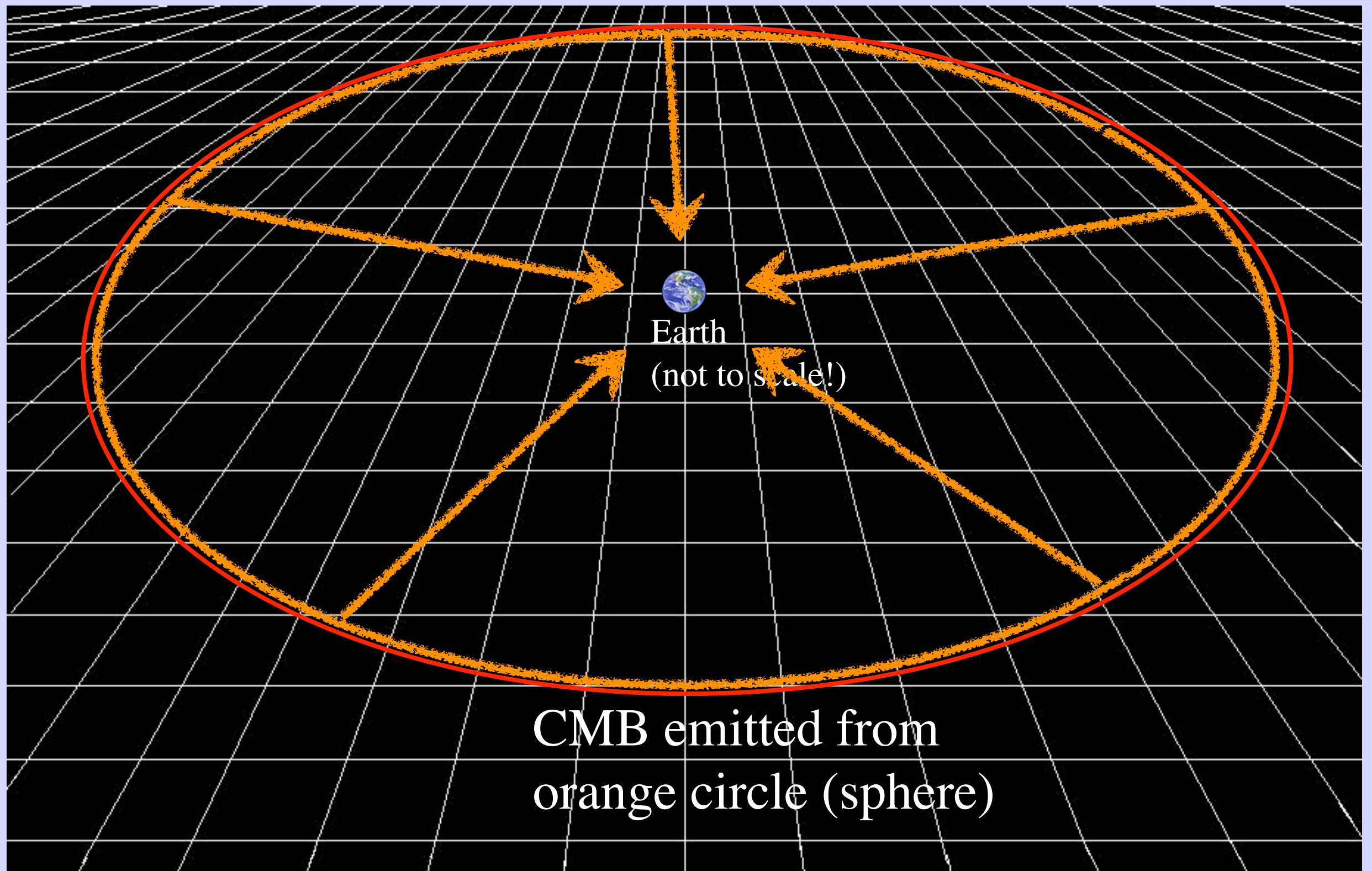


c.1990: Map of CMB Brightness



Brightness is “isotropic” – same in all directions!
We are immersed in a uniform glow.

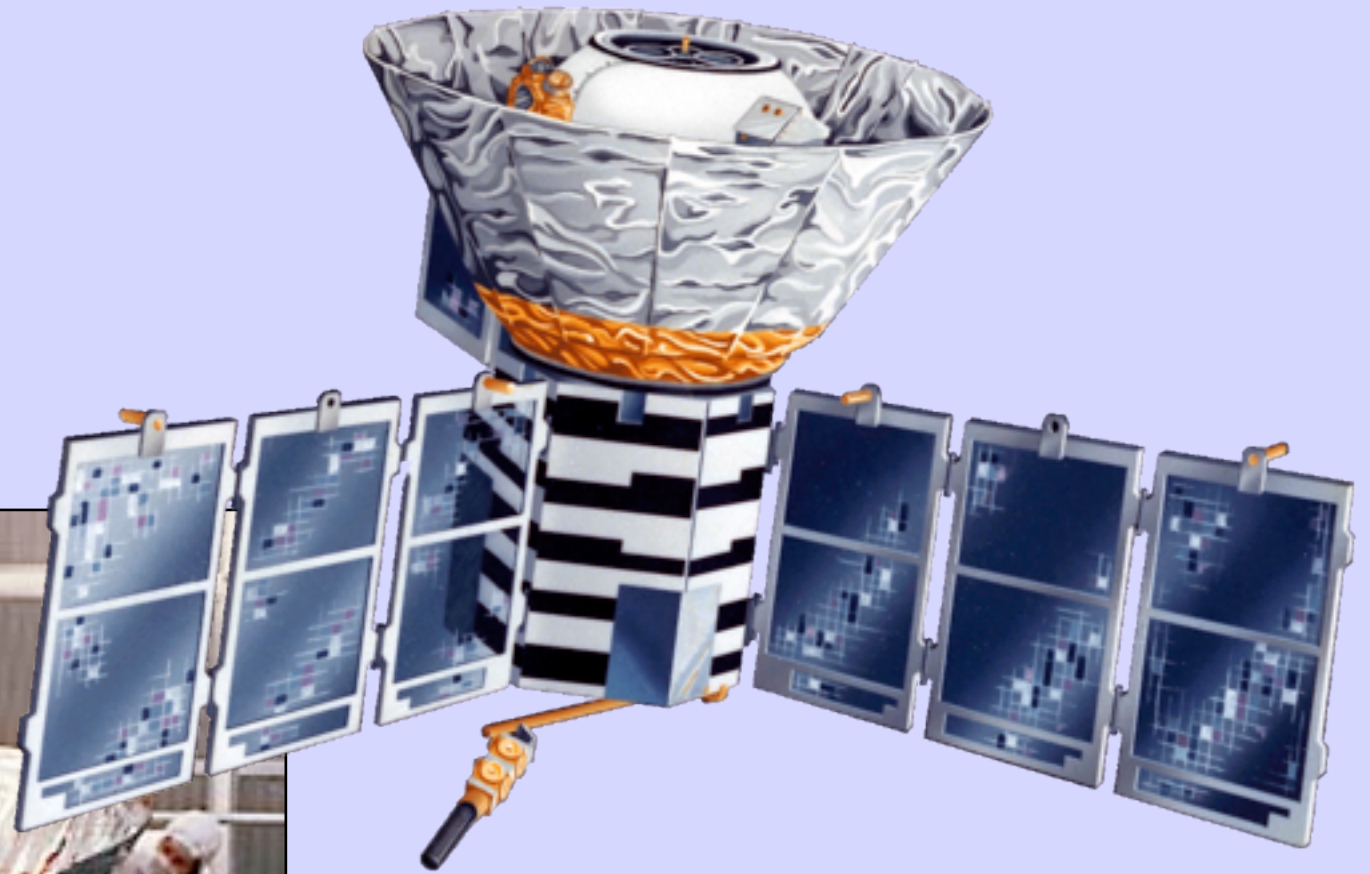
Epoch (=surface) of the CMB



When we look out in space, we look back in time.
The limit is the speed of light (c) times the age of the universe (t).

COSMIC BACKGROUND EXPLORER (COBE)

- 1974 COBE proposed
Spacecraft & all 3 instruments built at Goddard
- 1989 COBE Launched from Vandenberg AFB
- 1990 FIRAS - spectrum results favor blackbody
- 1992 DMR - anisotropy discovered at $\Delta T/T \sim 10^{-5}$



1990: Blackbody Spectrum of the CMB

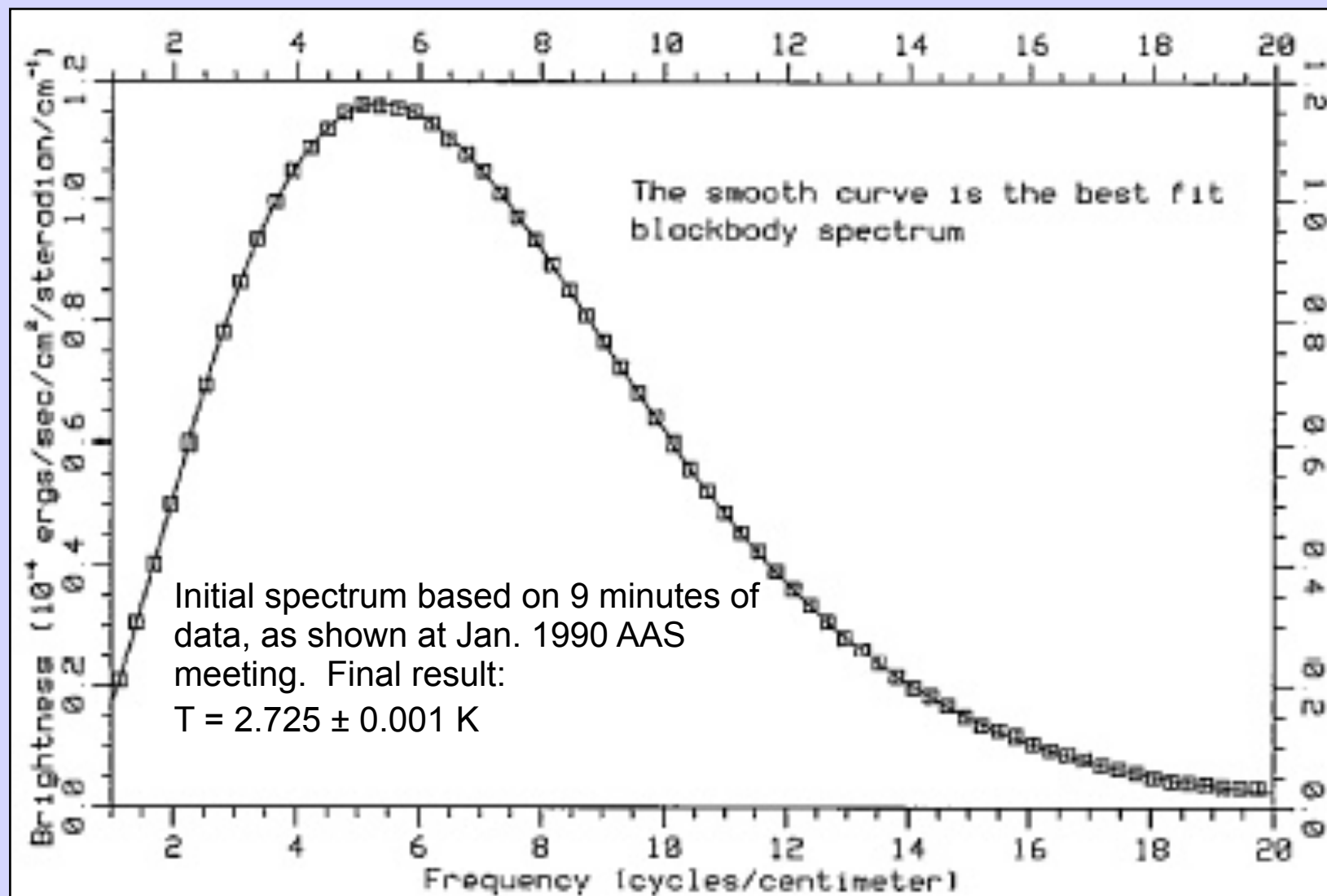
A PRELIMINARY MEASUREMENT OF THE COSMIC MICROWAVE BACKGROUND SPECTRUM BY THE *COSMIC BACKGROUND EXPLORER (COBE)*¹ SATELLITE

J. C. MATHER,² E. S. CHENG,² R. E. EPLEE, JR.,³ R. B. ISAACMAN,³ S. S. MEYER,⁴ R. A. SHAFER,² R. WEISS,⁴ E. L. WRIGHT,⁵ C. L. BENNETT, N. W. BOGGESE,² E. DWEK,² S. GULKIS,⁶ M. G. HAUSER,² M. JANSSEN,⁶ T. KELSALL,² P. M. LUBIN,⁷ S. H. MOSELEY, JR.,² T. L. MURDOCK,⁸ R. F. SILVERBERG,² G. F. SMOOT,⁹ AND D. T. WILKINSON¹⁰

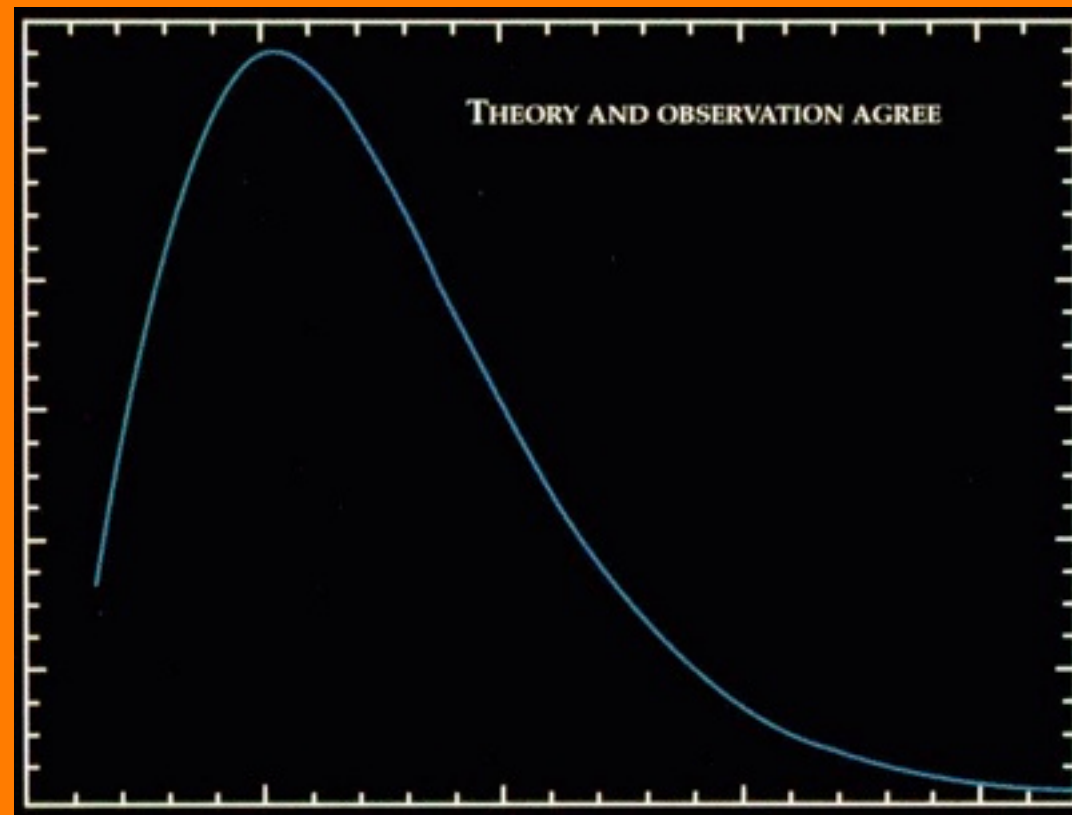
THE ASTROPHYSICAL JOURNAL, 354:L37-L40, 1990 May 10



2006

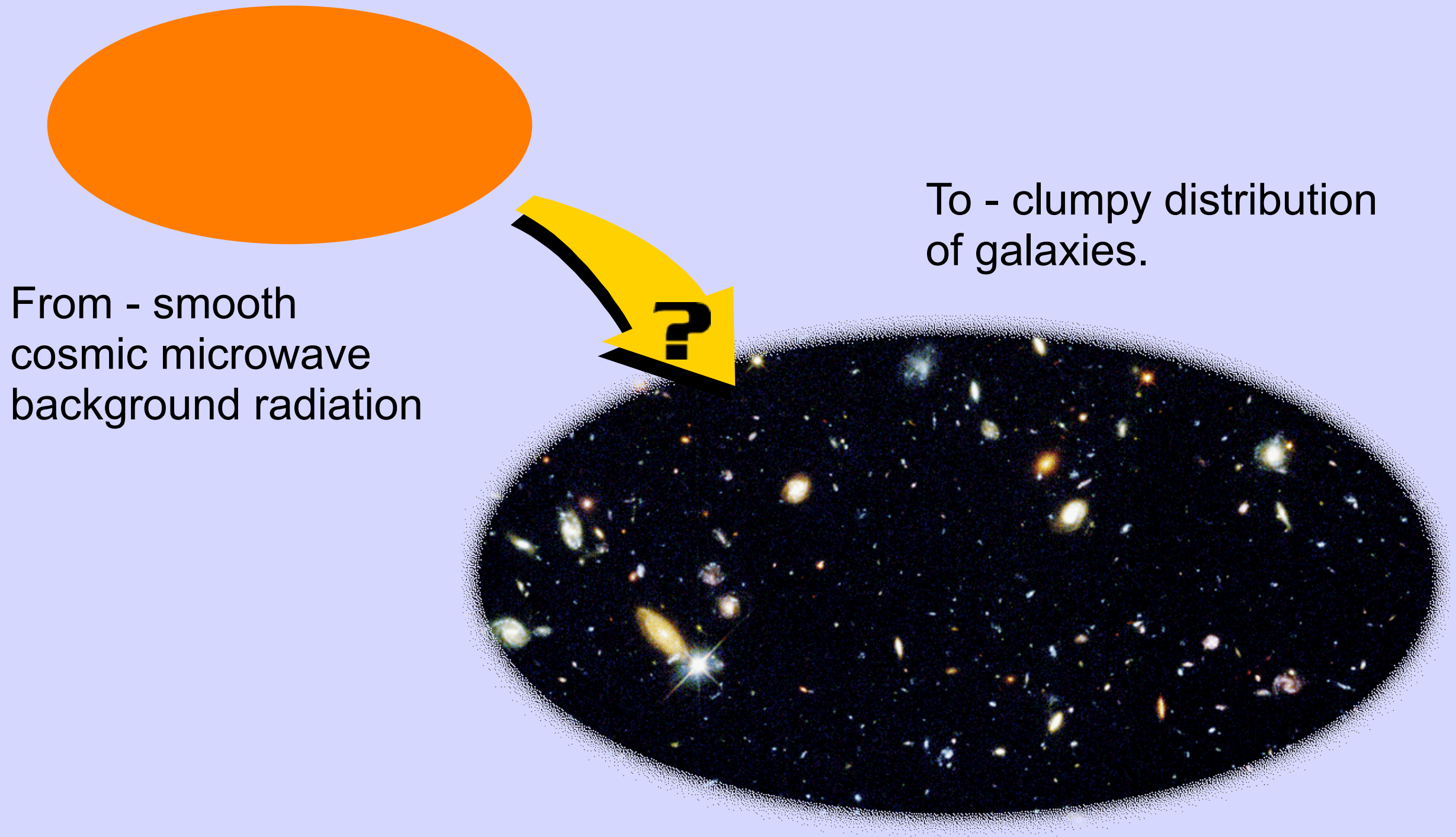


The Simplicity of the Early Universe



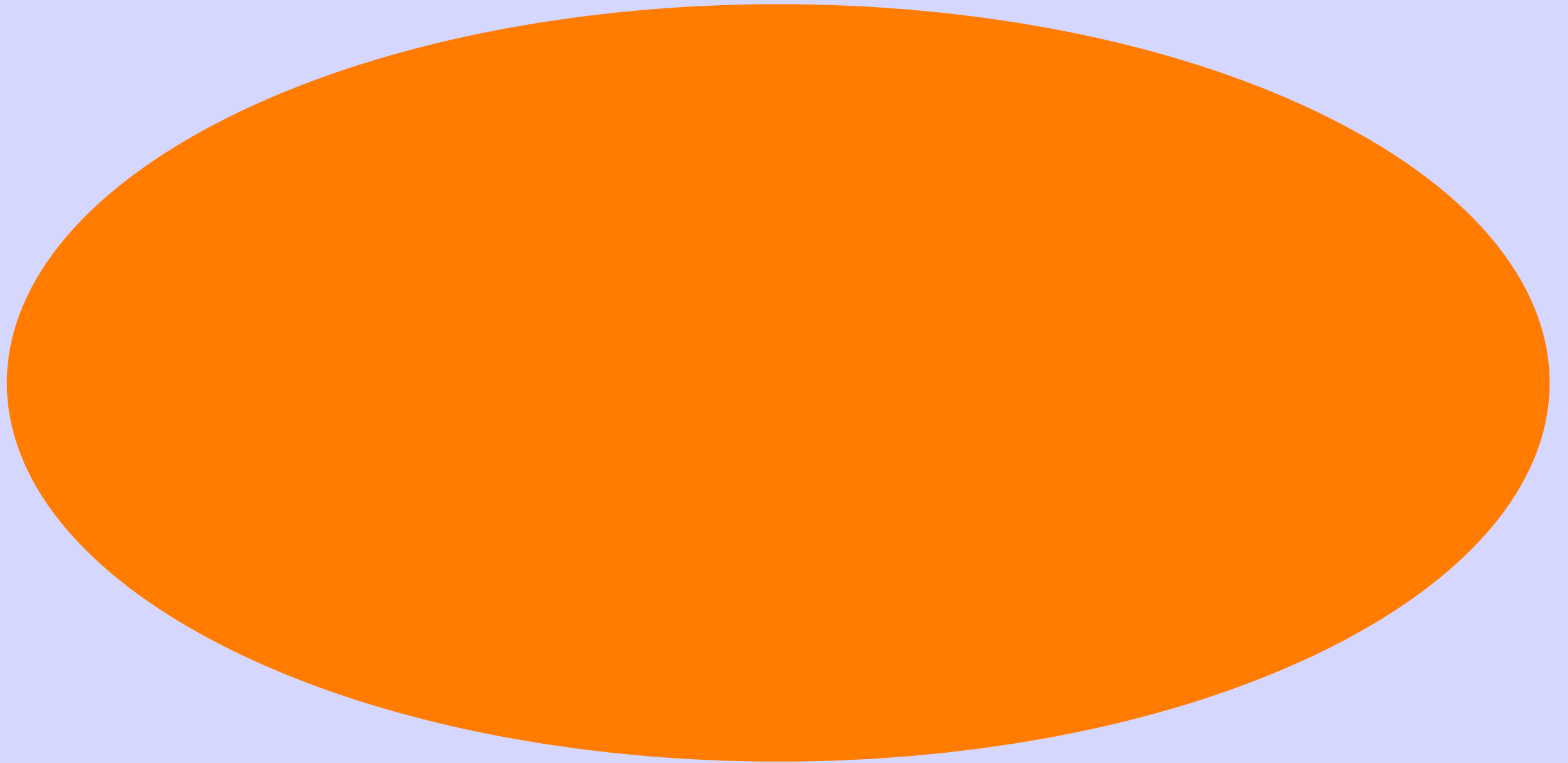
Important test! It is very difficult to produce such uniform blackbody radiation by any other means than with Big Bang evolution.

The Structure Problem



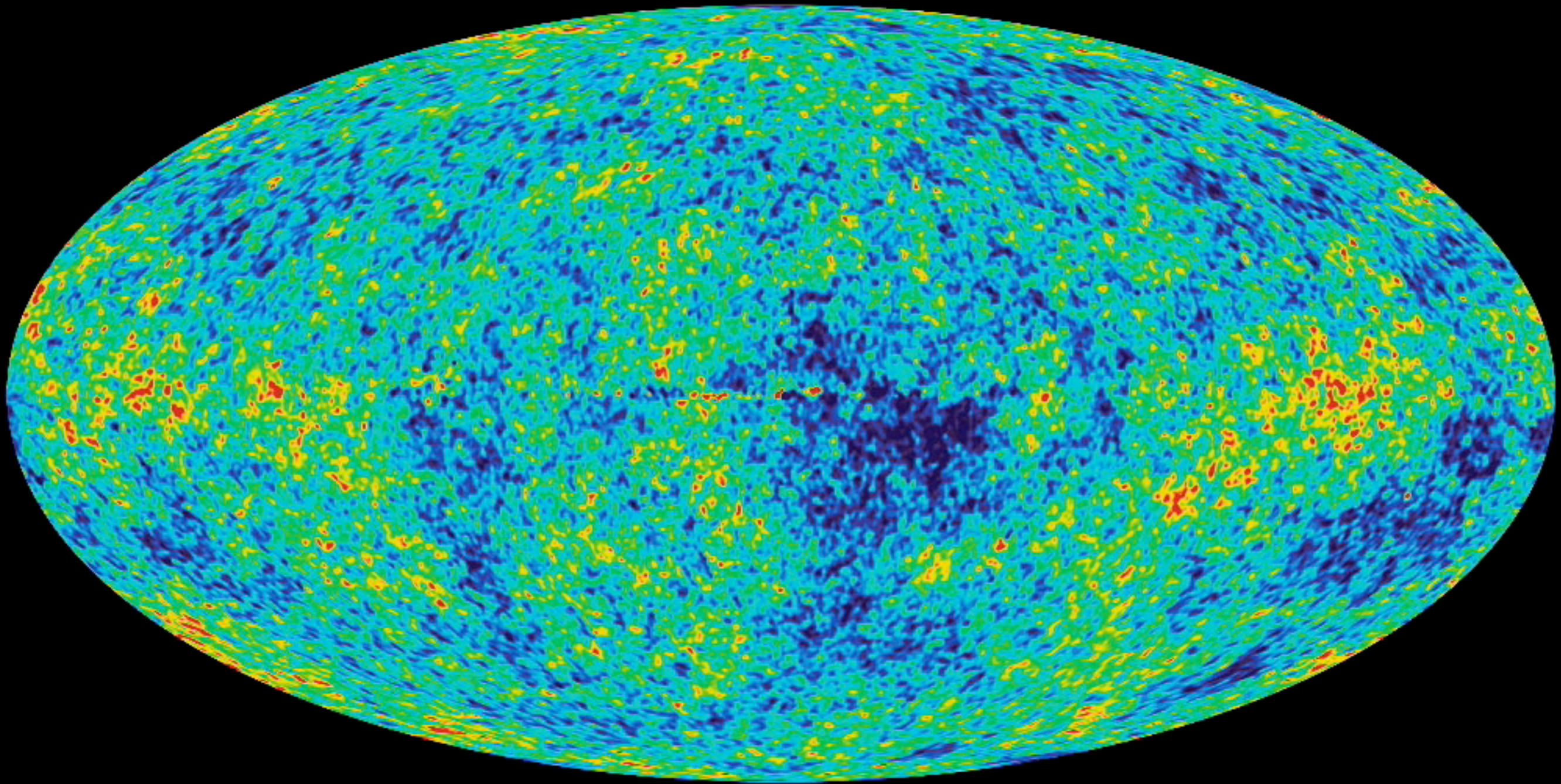
How did this happen?

Where is the Anisotropy (Structure)?

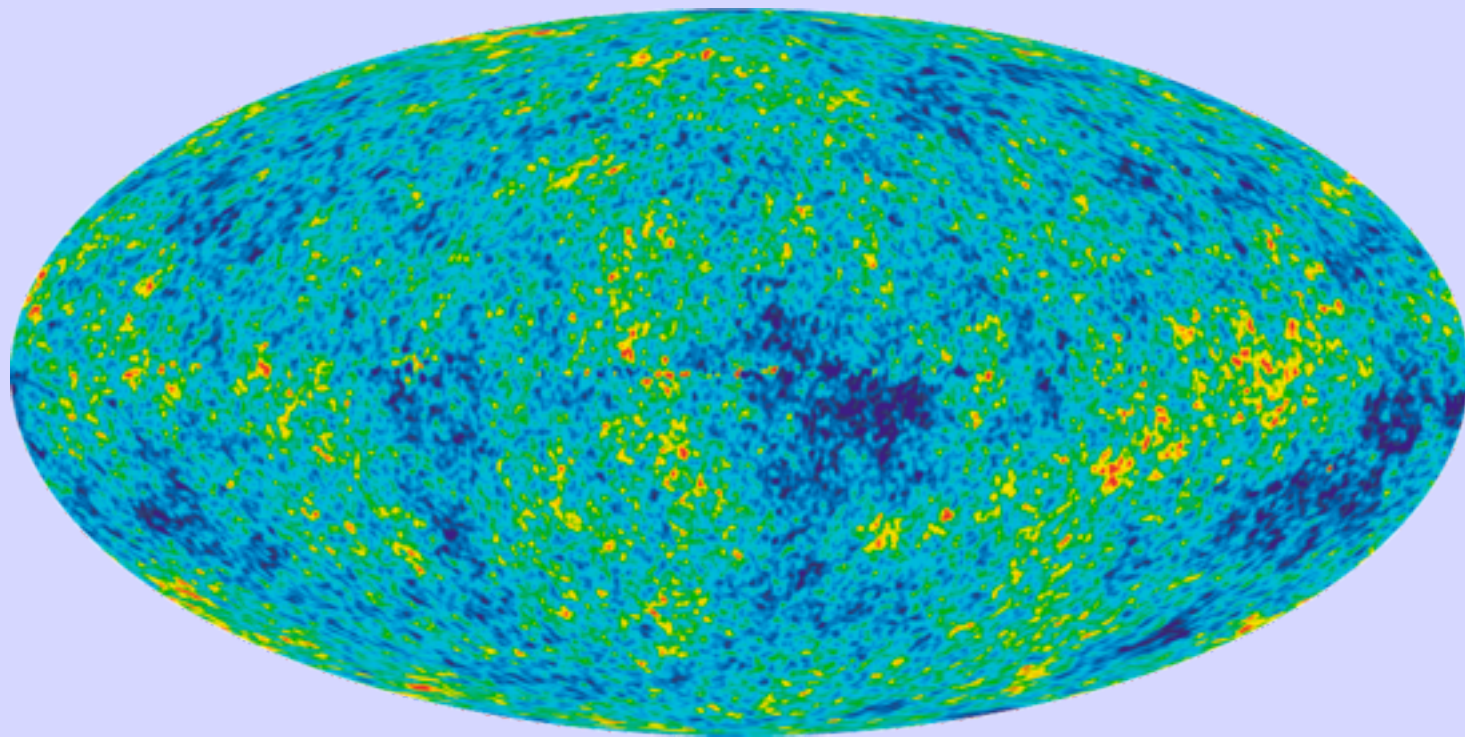


If ideas about growth of structure are correct, there should be variations in the CMB brightness (“temperature”) across the sky that track density variations in the hydrogen gas that emitted the light.

Gravitational Growth of Structure

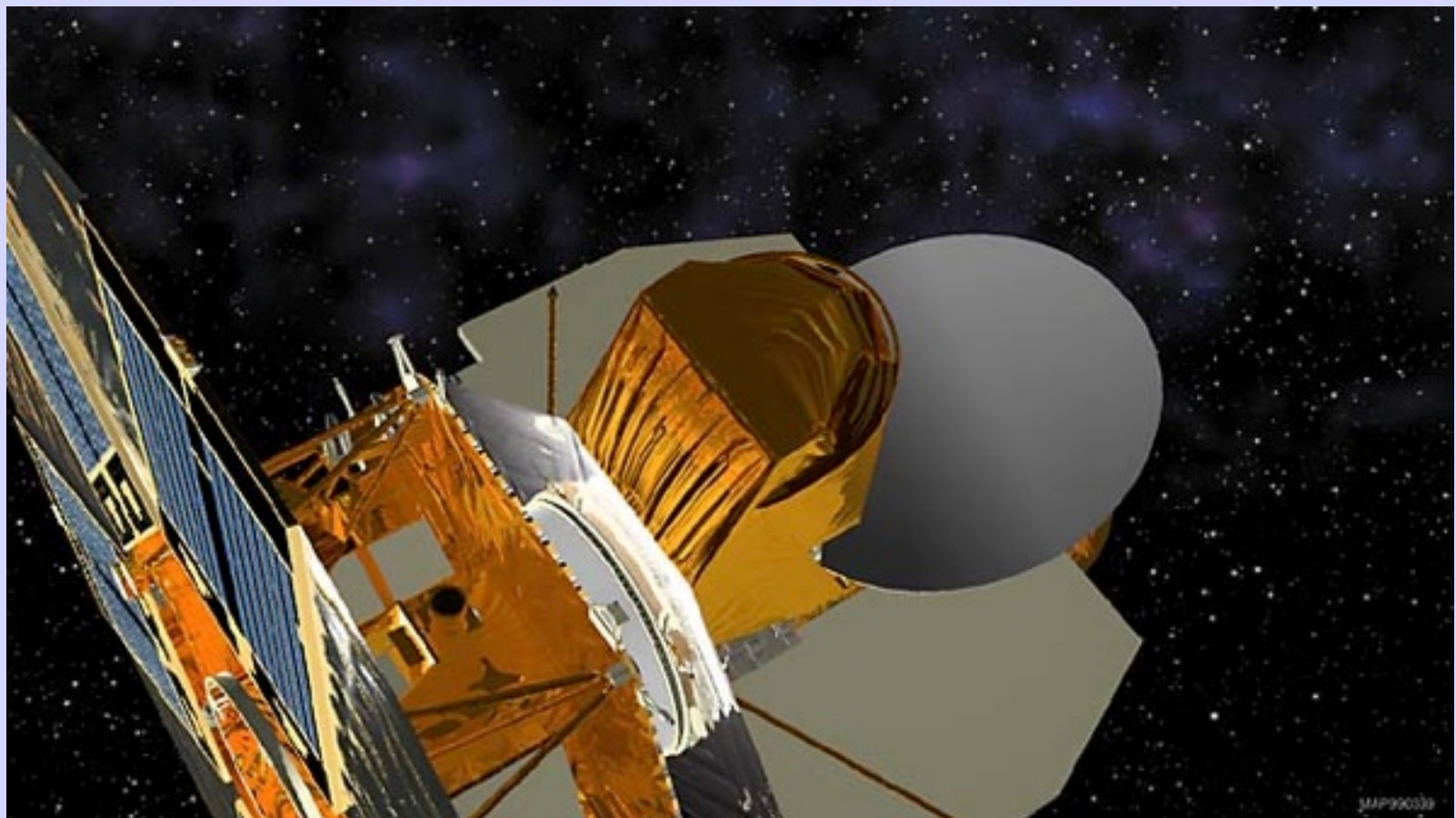


Wilkinson Microwave Anisotropy Probe (WMAP)

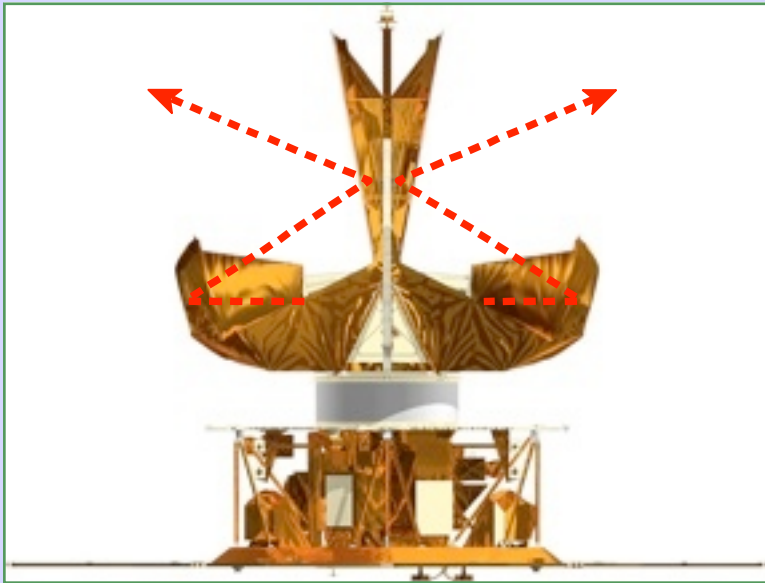


WMAP'S PURPOSE –

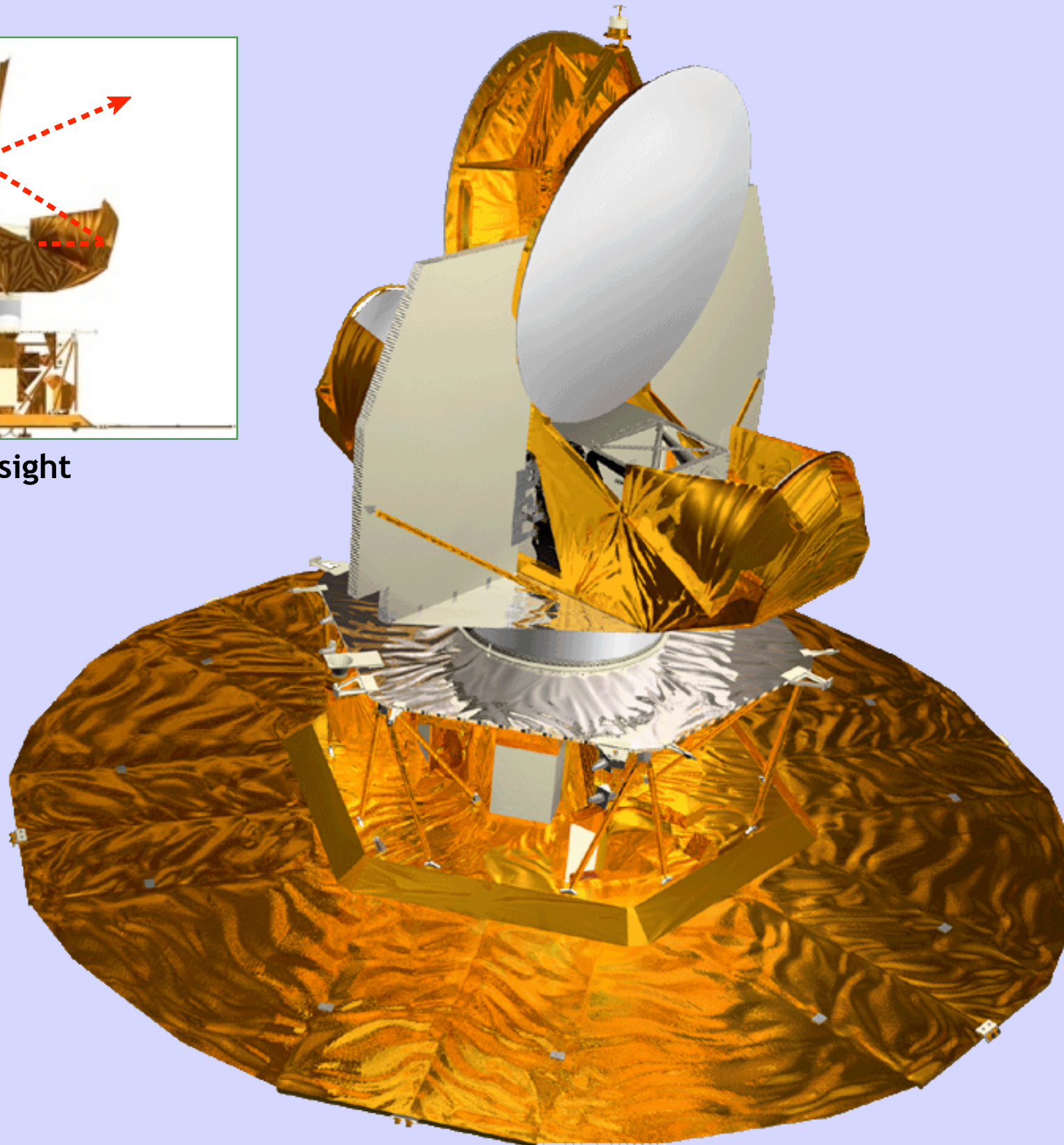
To make a detailed full-sky map of the CMB radiation anisotropy (temperature and polarization) to constrain the cosmology of our universe.



WMAP's Differential Design



lines of sight



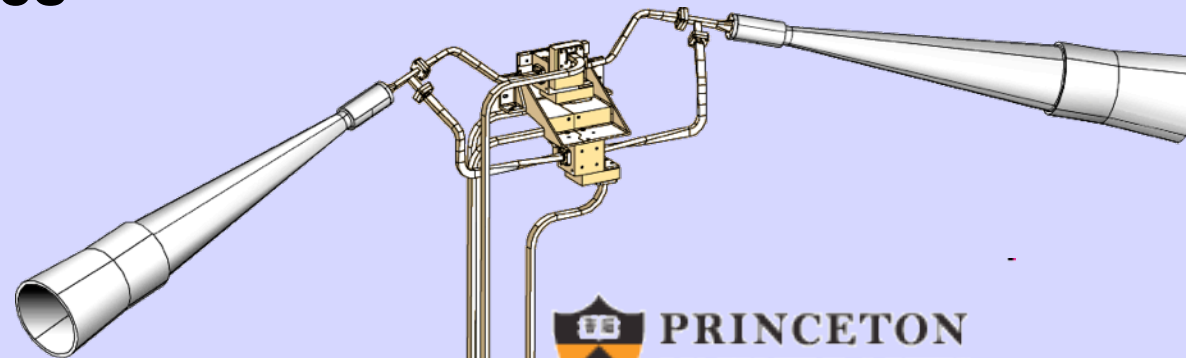
Accurately Measuring a Part-in-a-Million



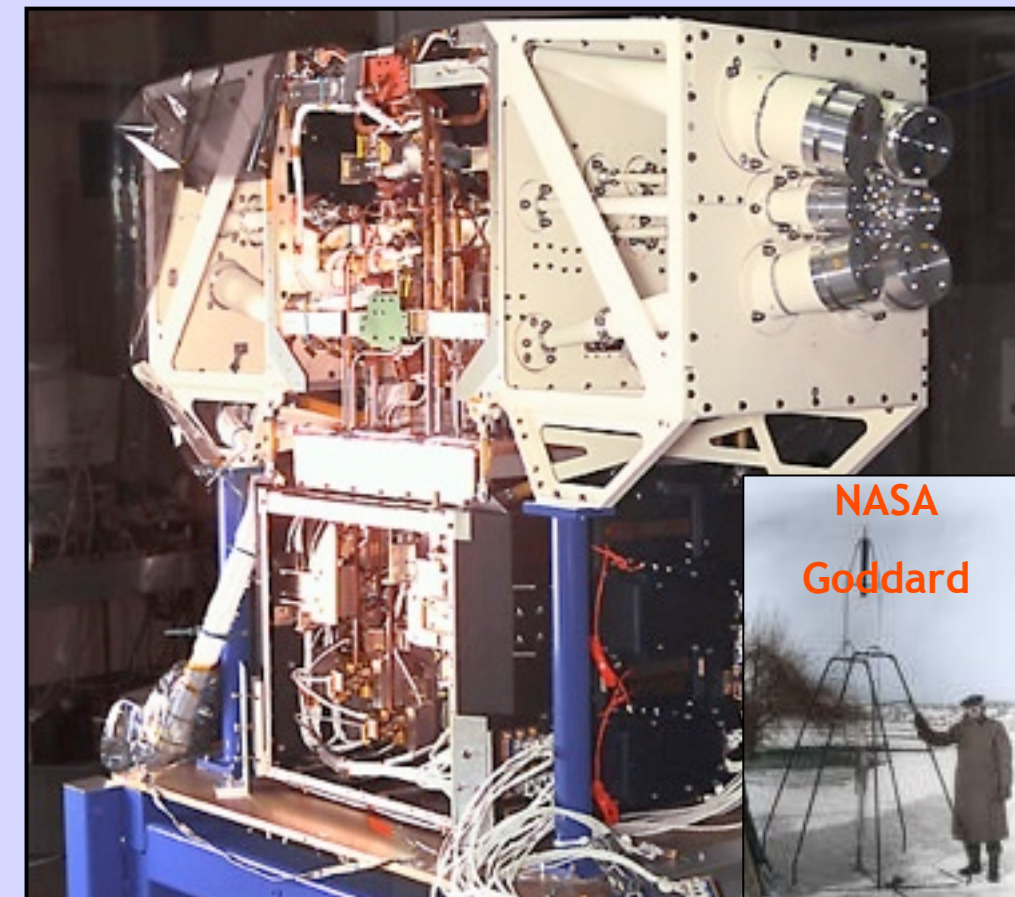
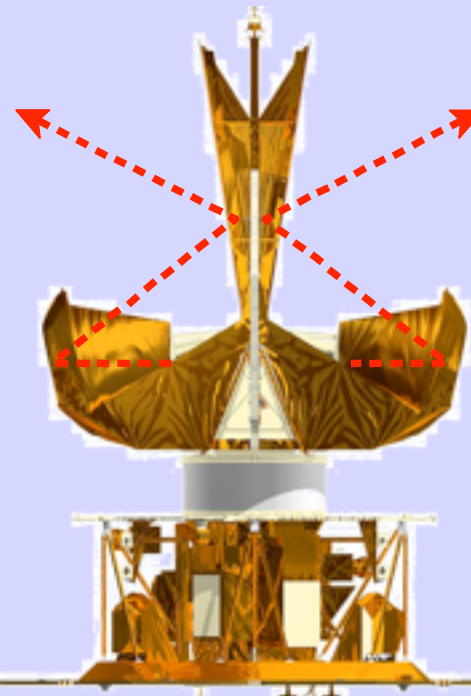
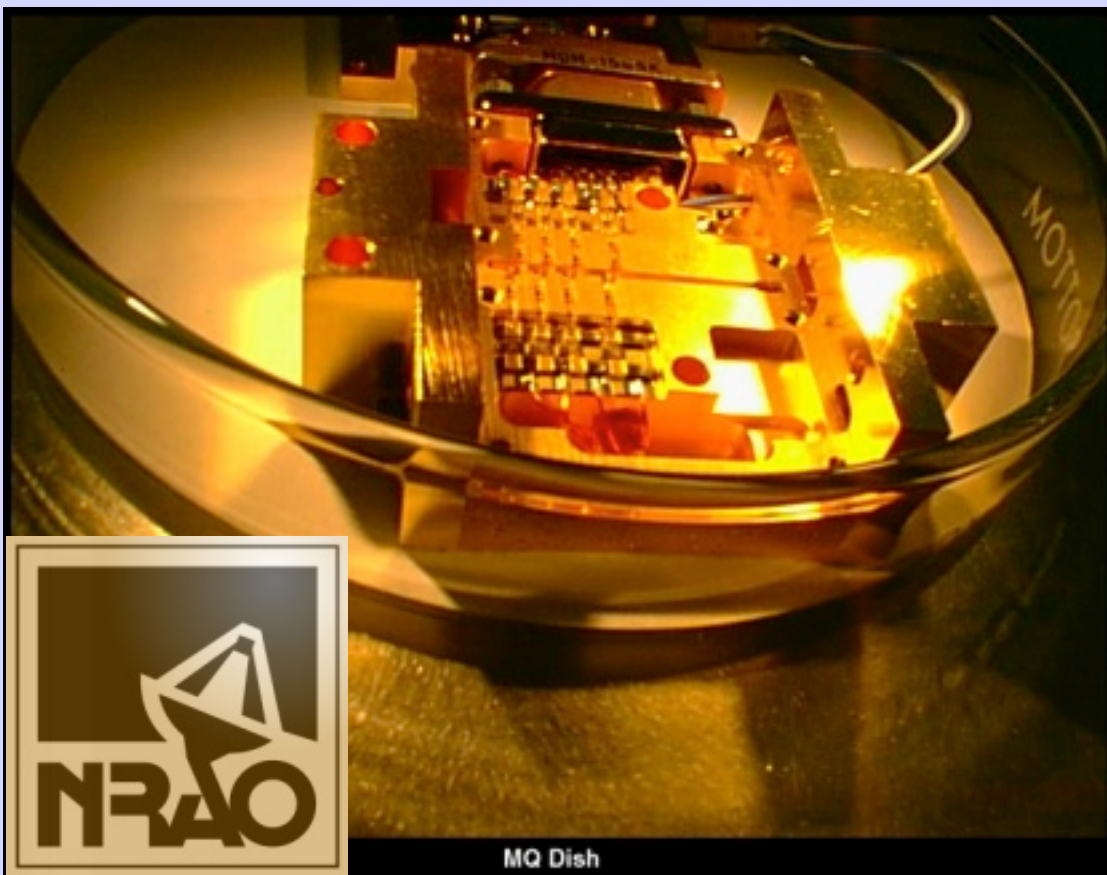
HEMT-Based Differential Receivers*

10 “Differencing Assemblies”

4 @ 94 GHz W-band
2 @ 61 GHz V-band
2 @ 41 GHz Q-band
1 @ 33 GHz Ka-band
1 @ 23 GHz K-band

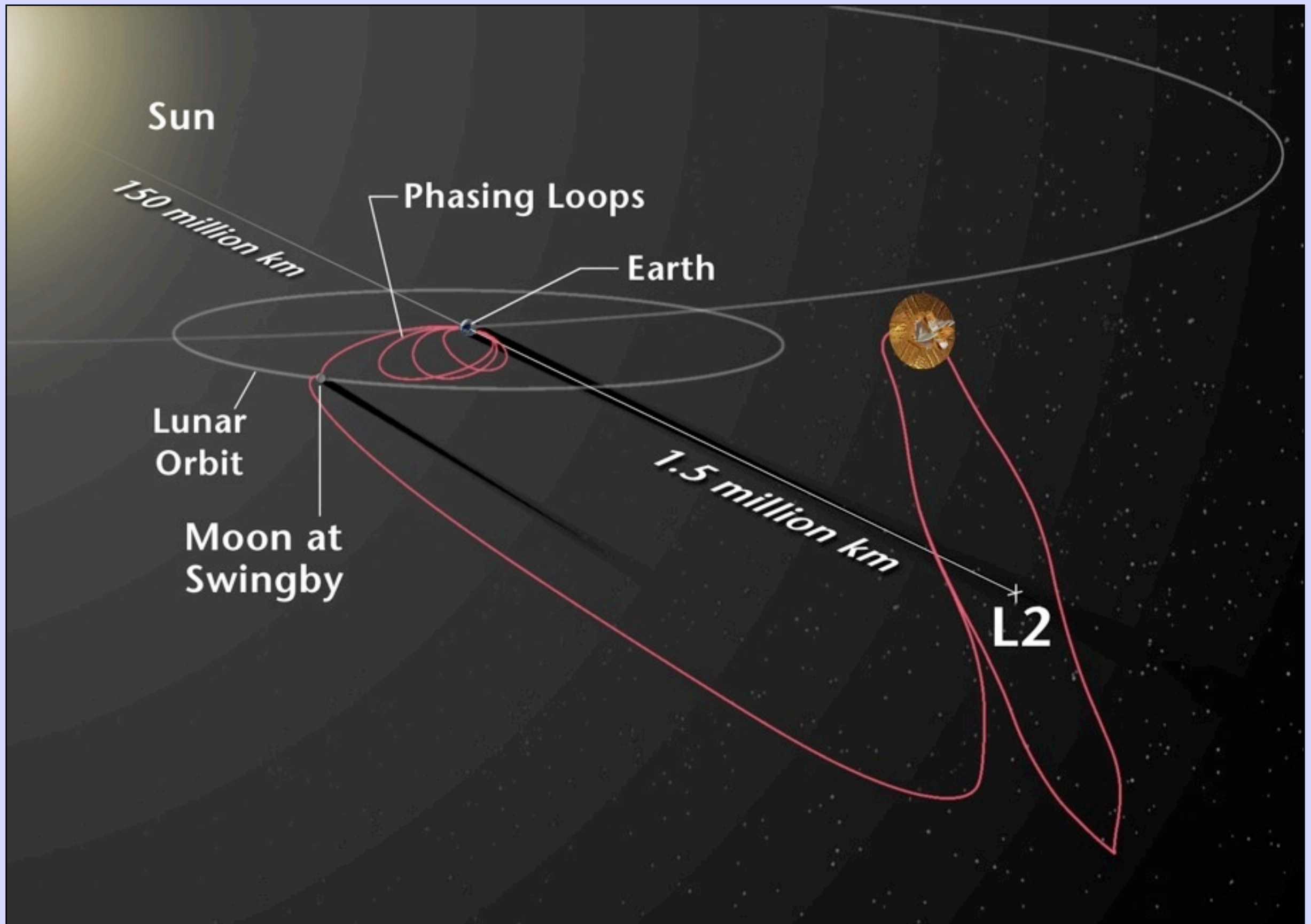


PRINCETON
UNIVERSITY

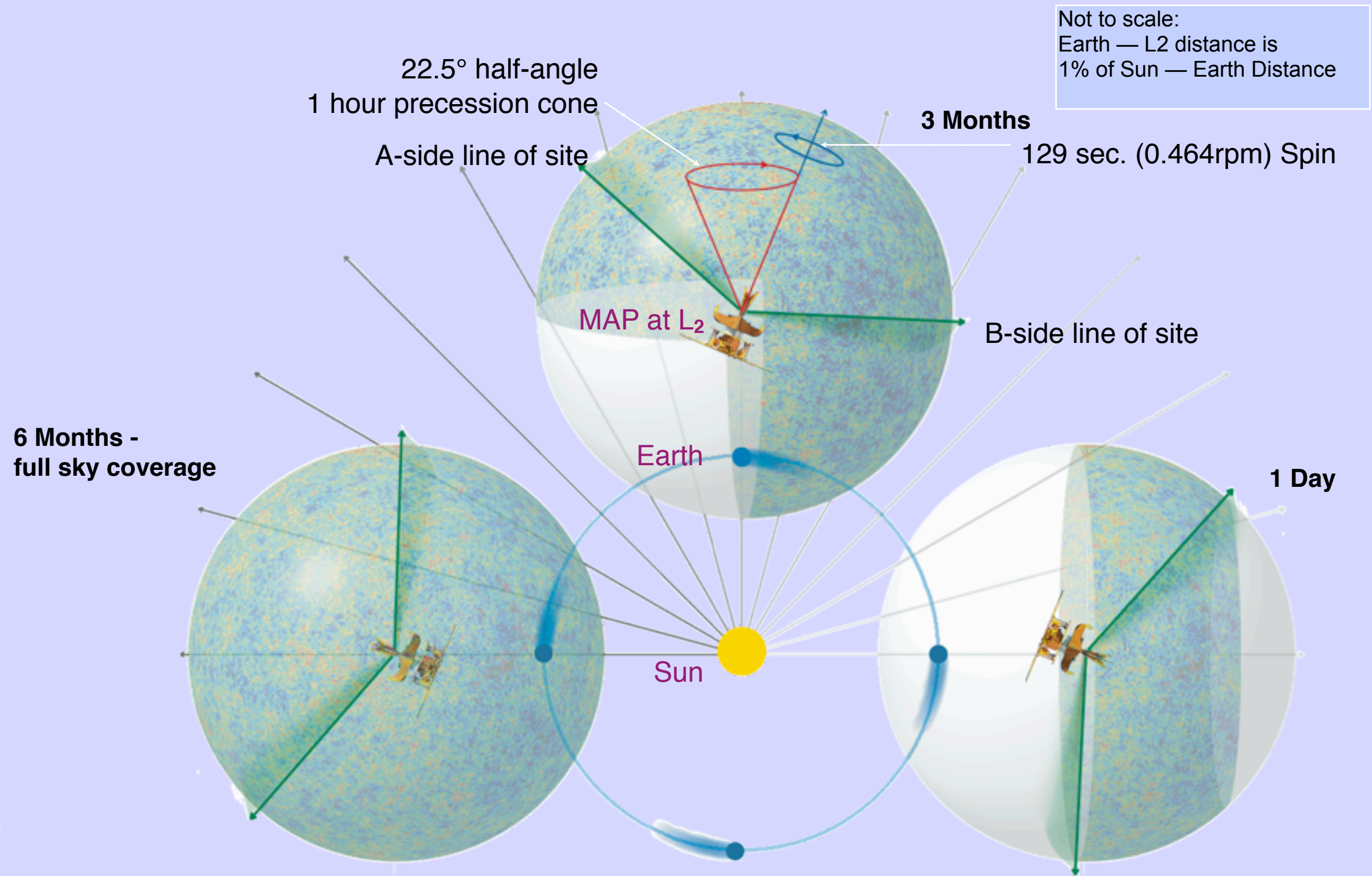


*based on design of M. Pospieszalski

WMAP at L2



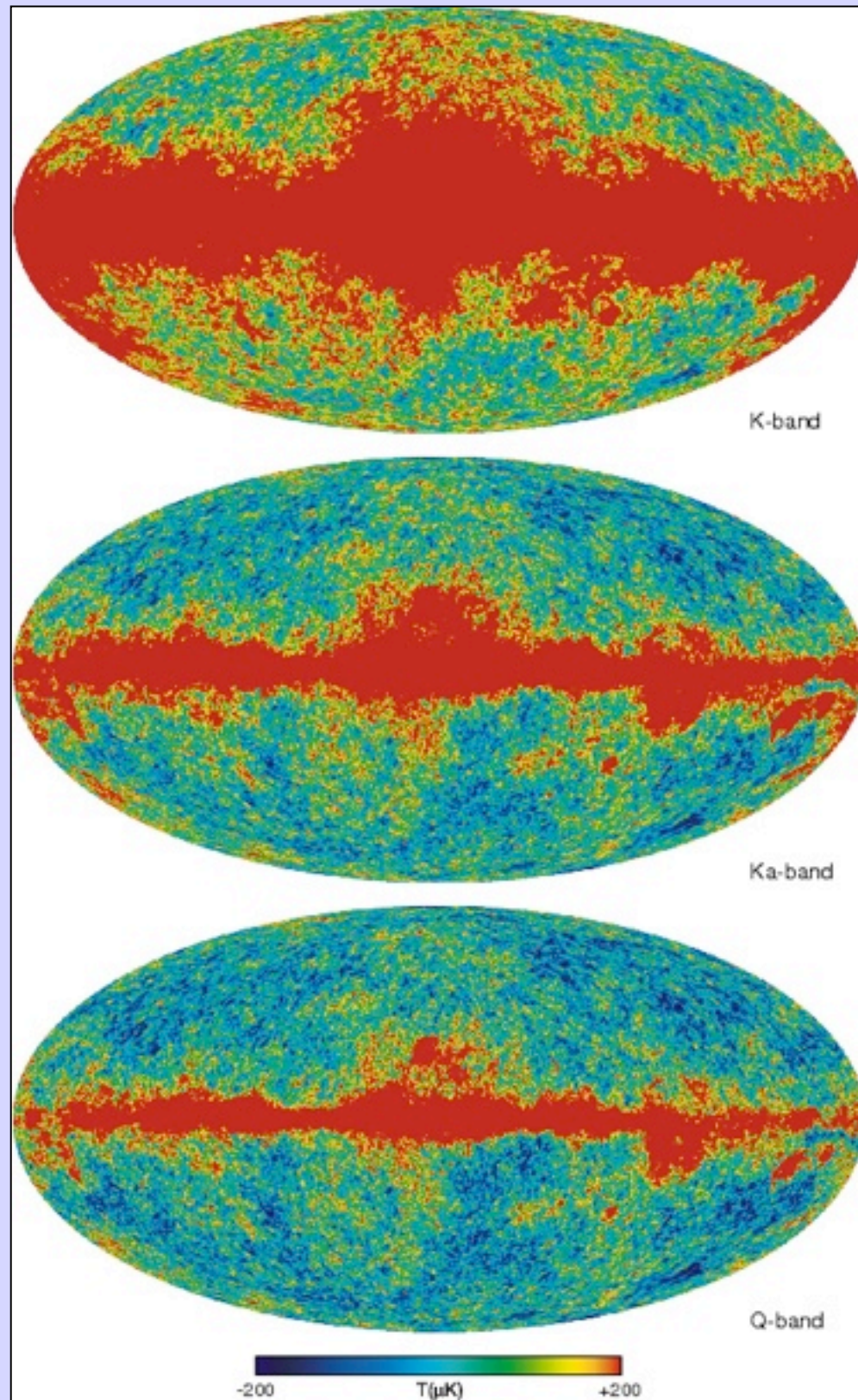
WMAP Sky Coverage



MAP990159

Sky Maps

WMAP Full Sky Temperature Maps



23 GHz

33 GHz

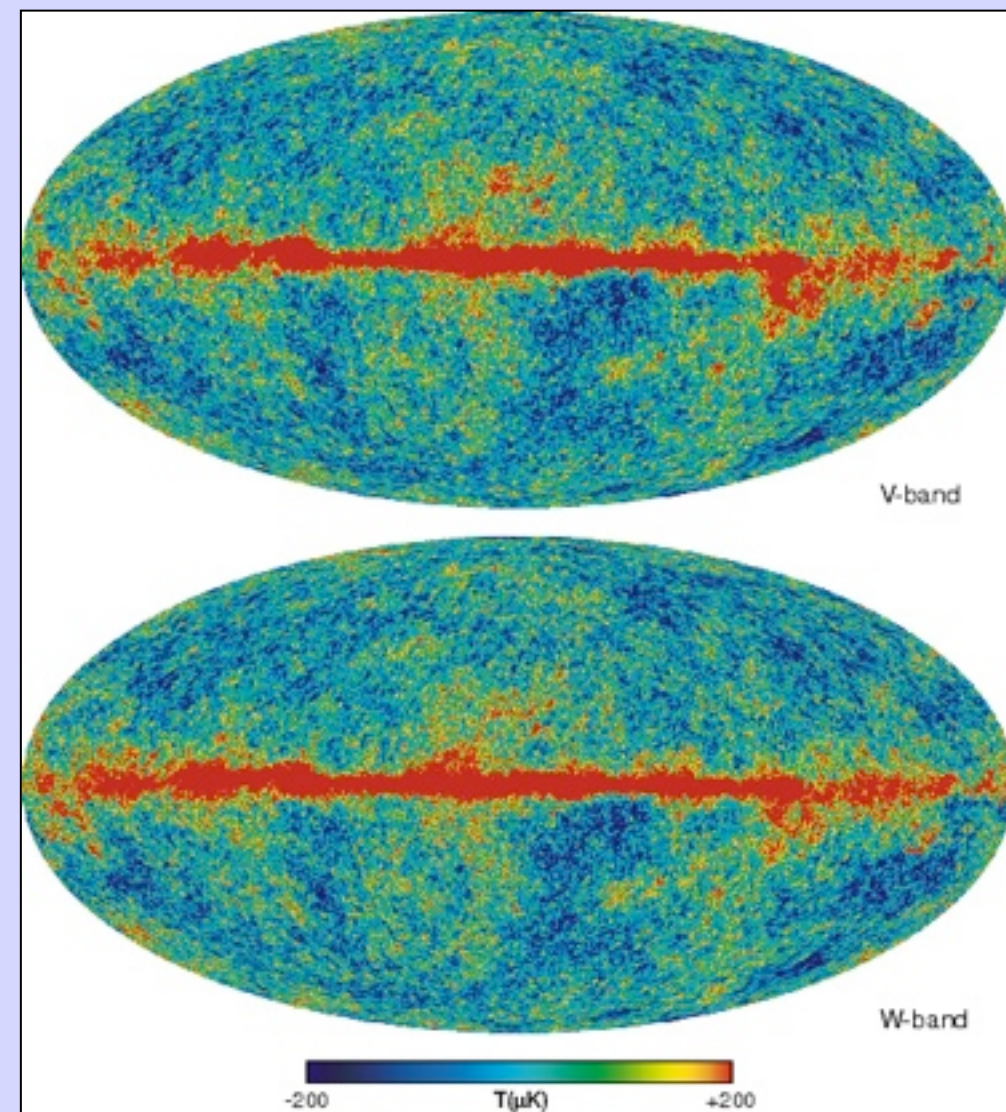
41 GHz

61 GHz

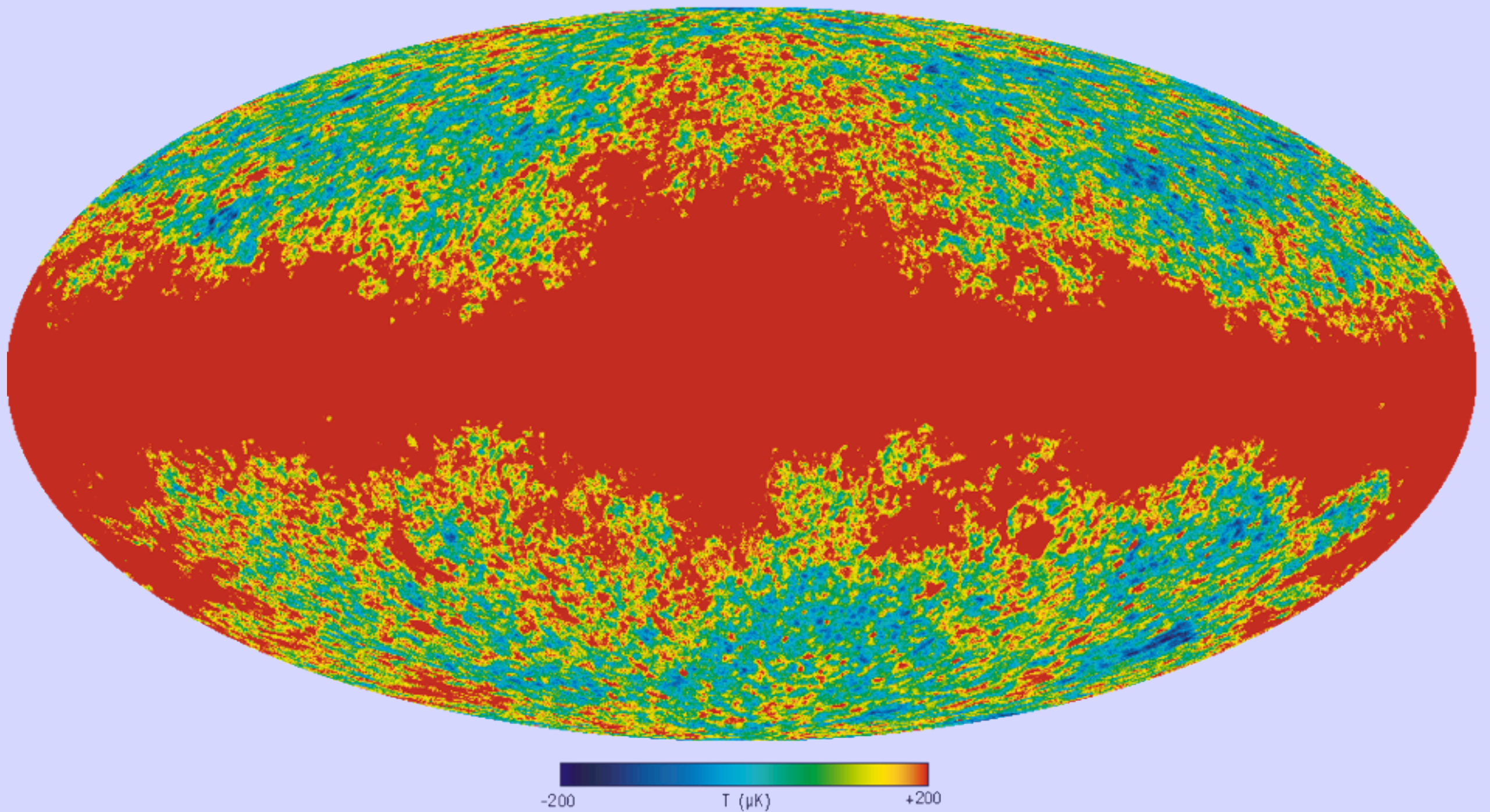
94 GHz

Color scale: $\pm 200 \mu\text{K}$

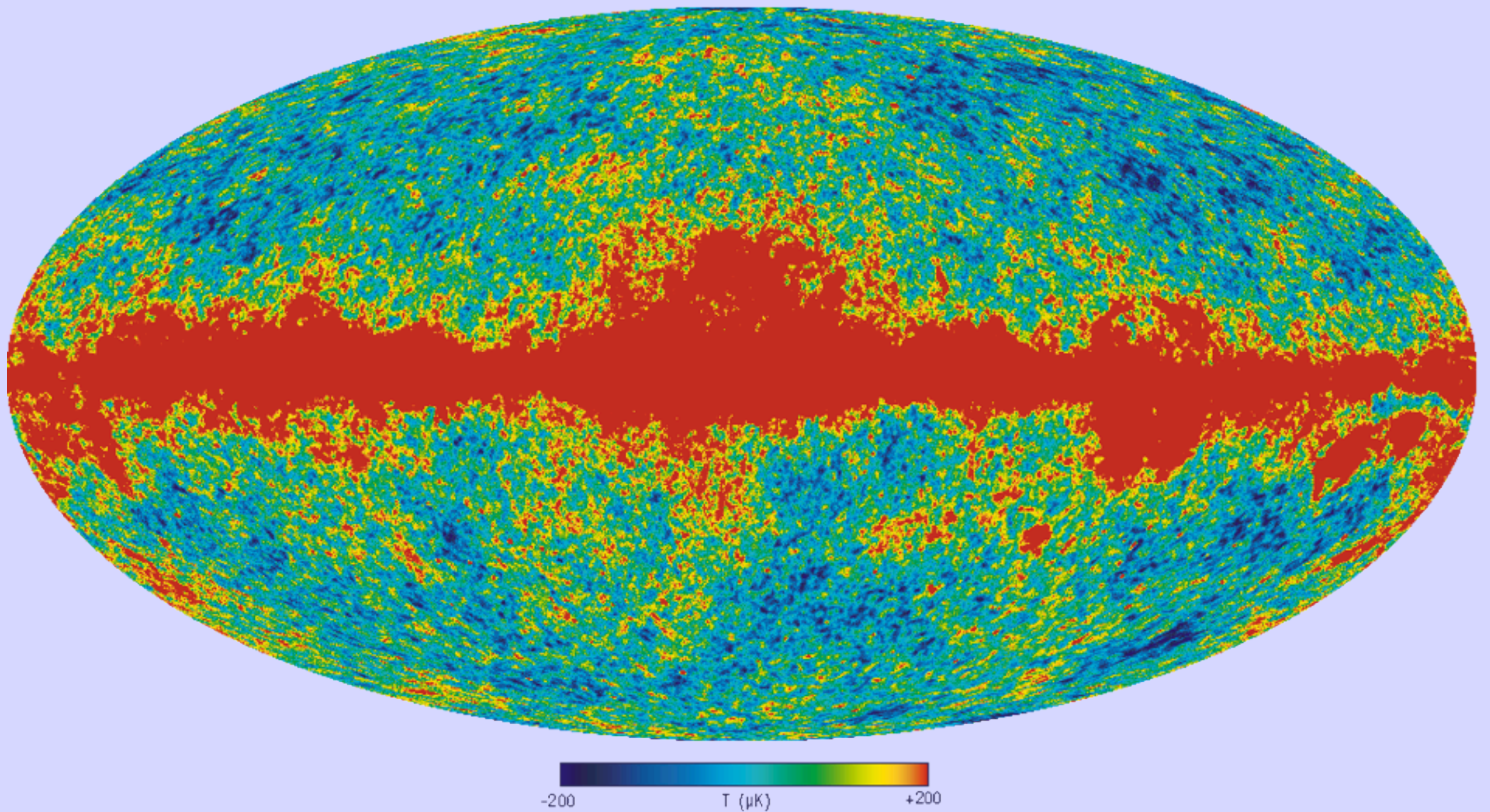
Smoothing: 0.2° FWHM



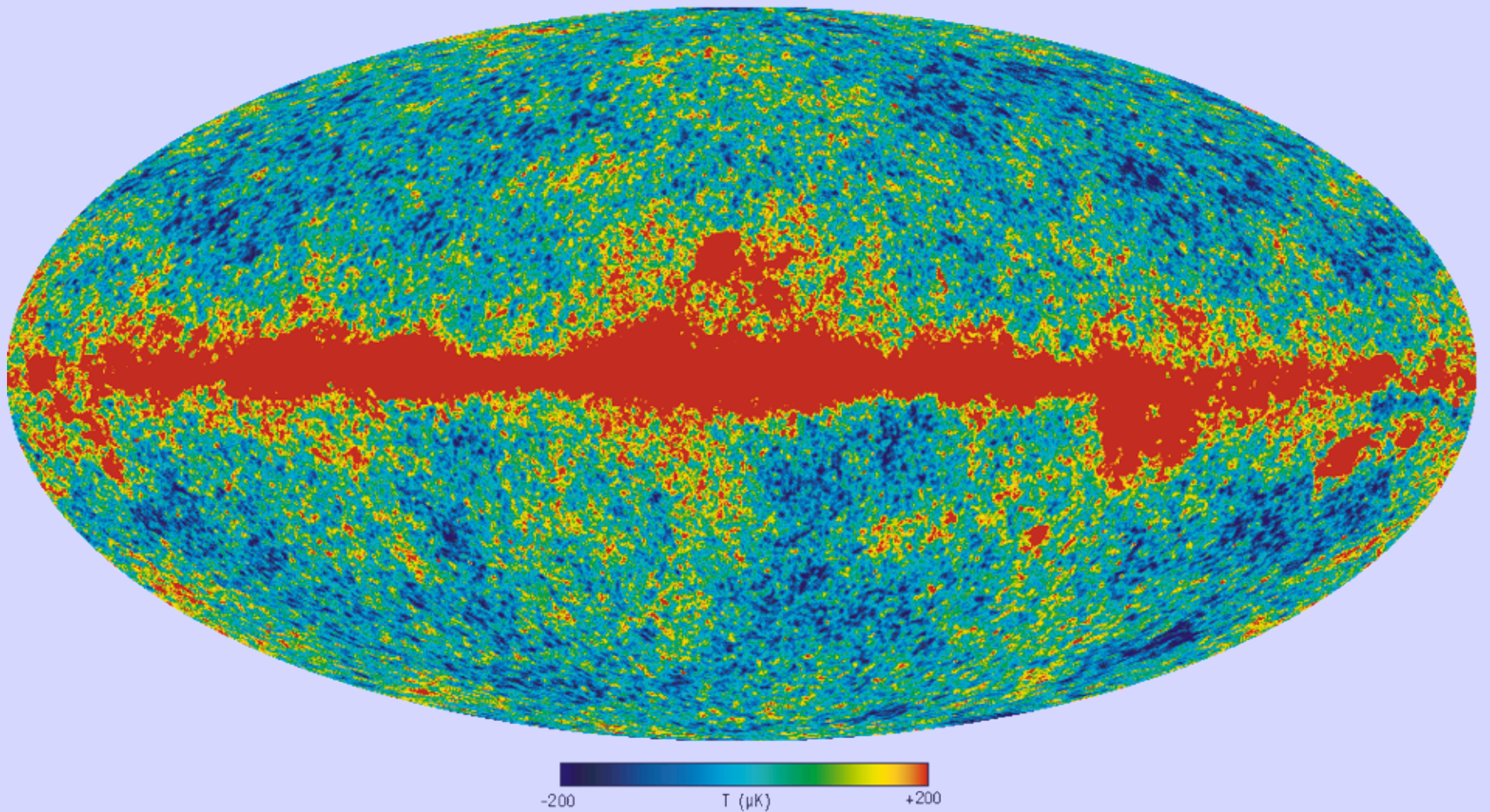
K Band Temperature, 23 GHz



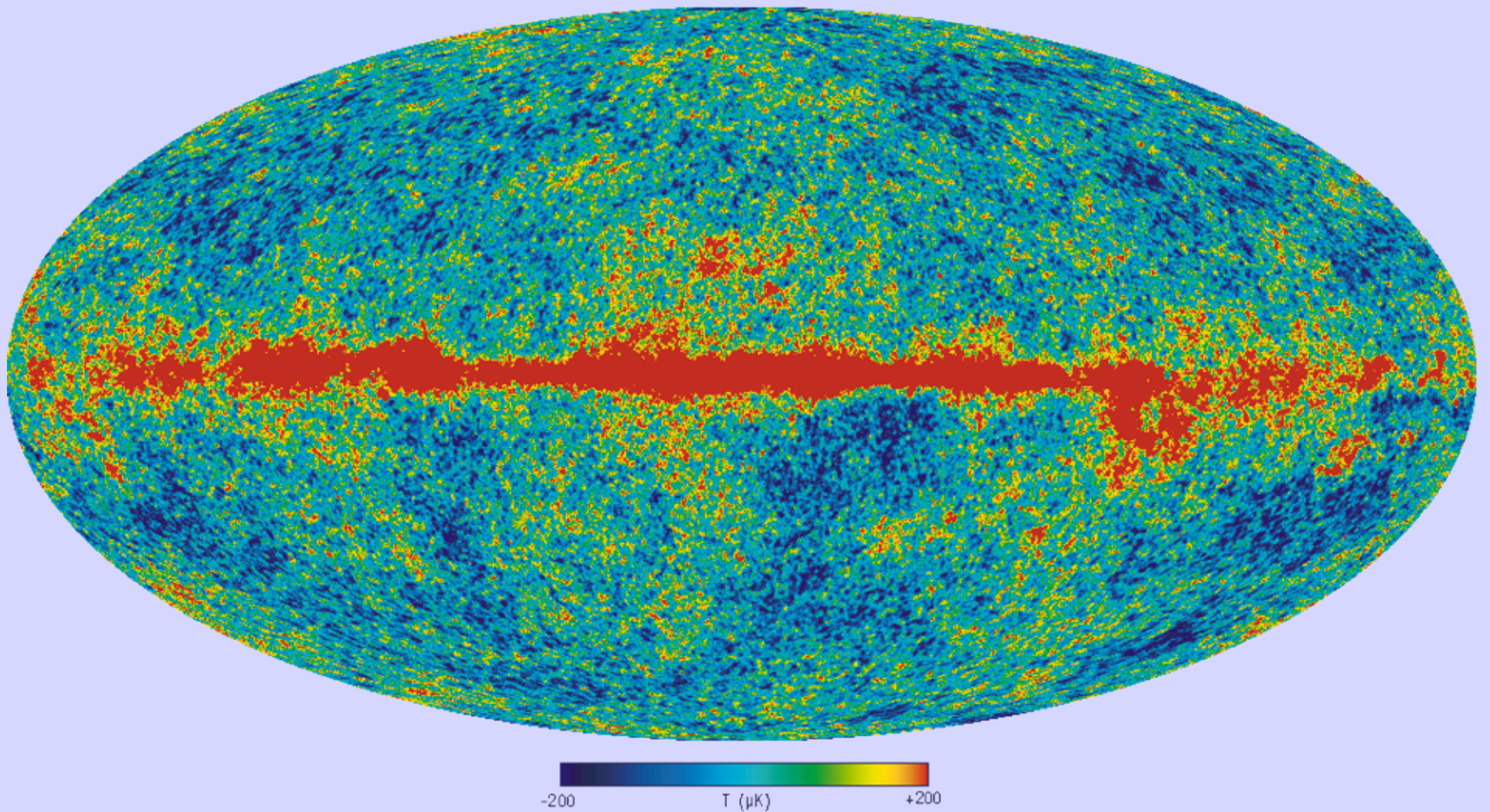
Ka Band Temperature, 33 GHz



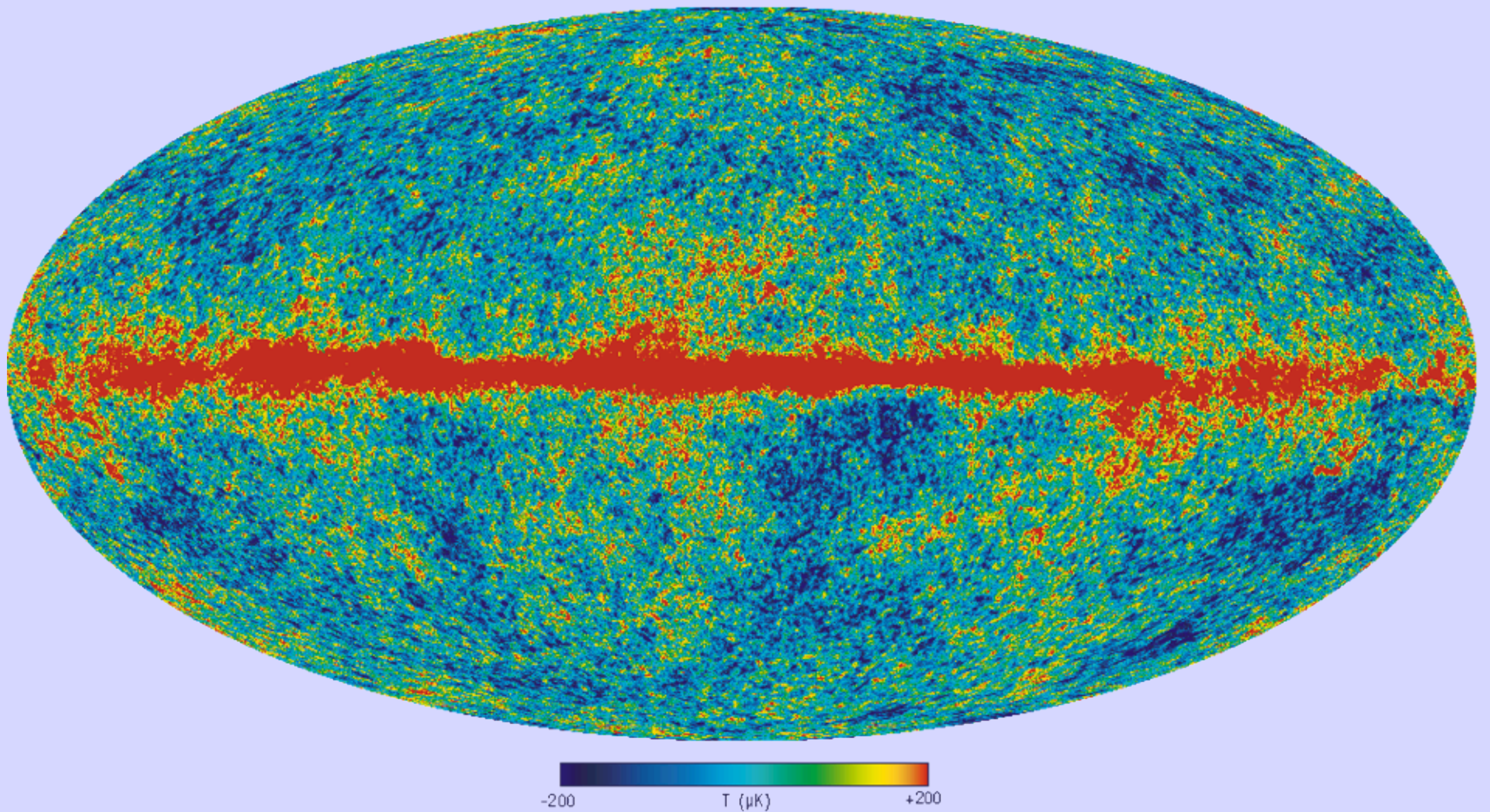
Q Band Temperature, 41 GHz



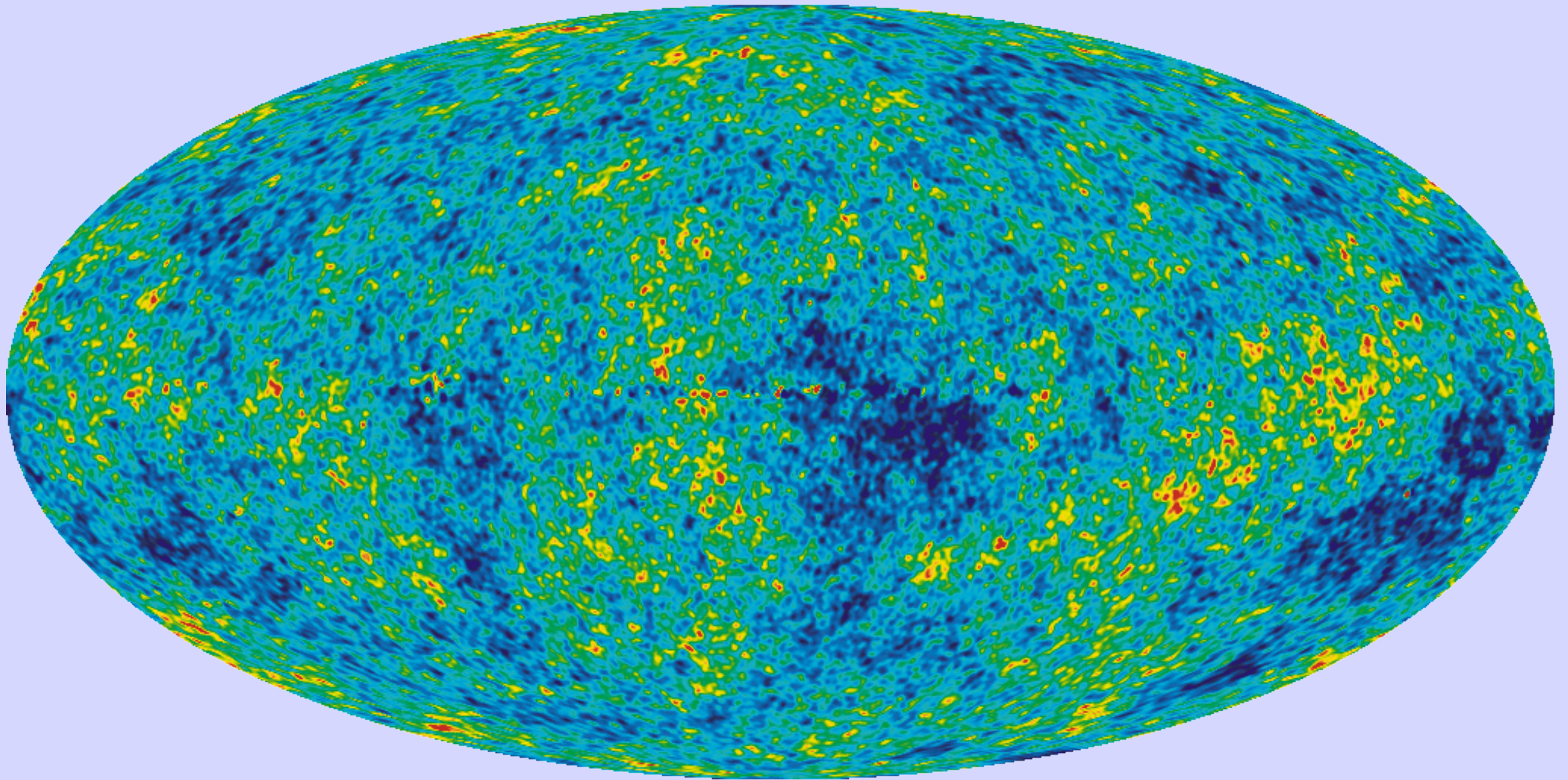
V Band Temperature, 61 GHz



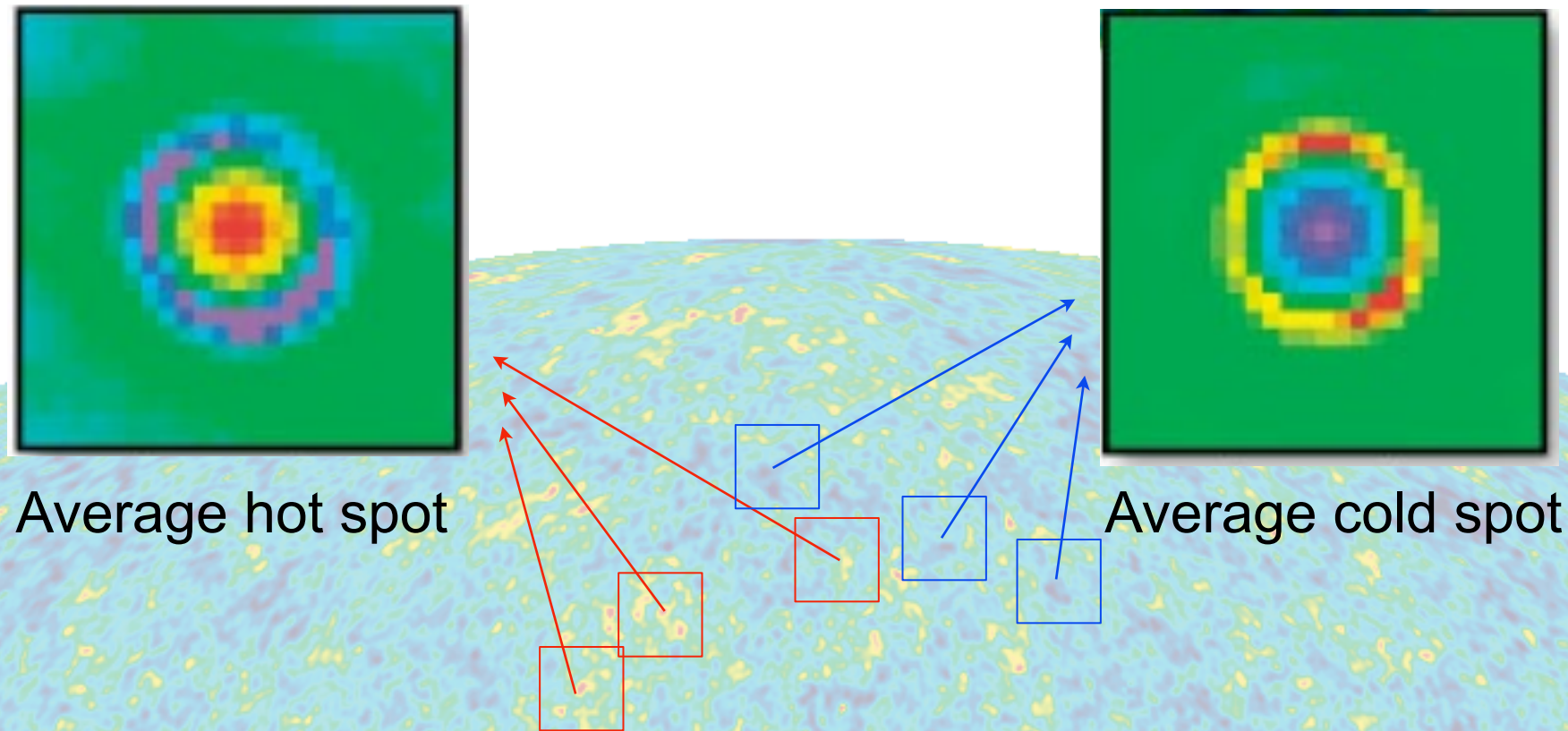
W Band Temperature, 94 GHz



5 Frequency Linear Combination (“ILC”)

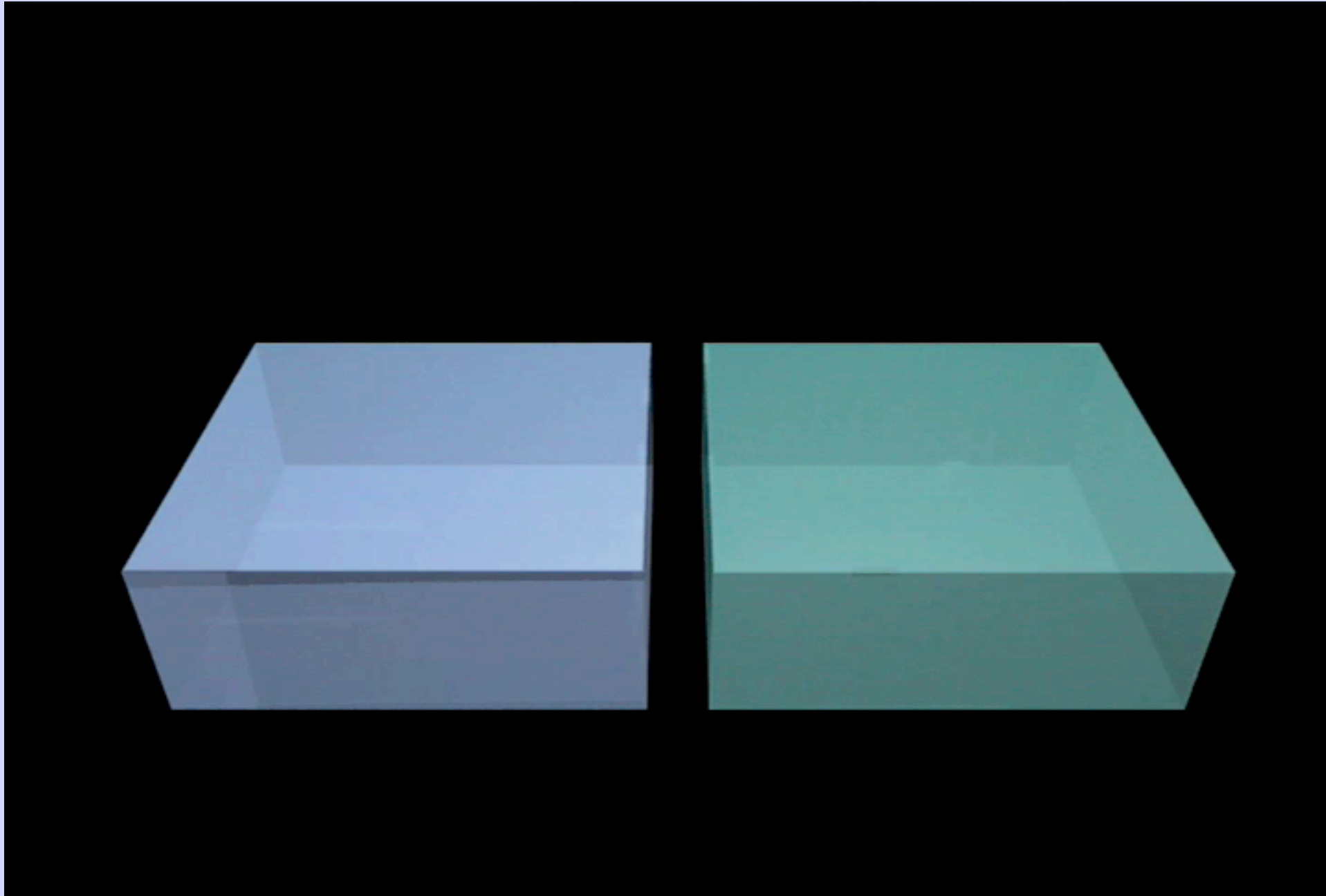


Sound Waves in the CMB

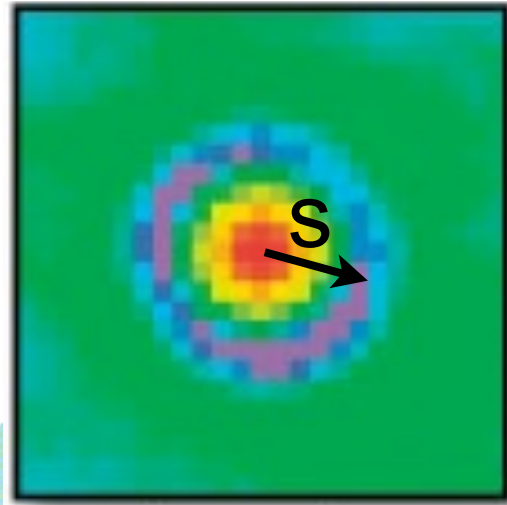


We can't make sense of the CMB map by just looking at it. If we analyze it by averaging all the hot & cold spots together we see a pattern: sound waves rumbling through the gas!

Fingerprint of the Universe



Sound Waves as a “Standard Ruler”



Average hot spot



Average cold spot

- We can calculate the speed of sound in the gas,
- We know how long the sound travelled,
- Therefore we can determine the physical size of the wave front:

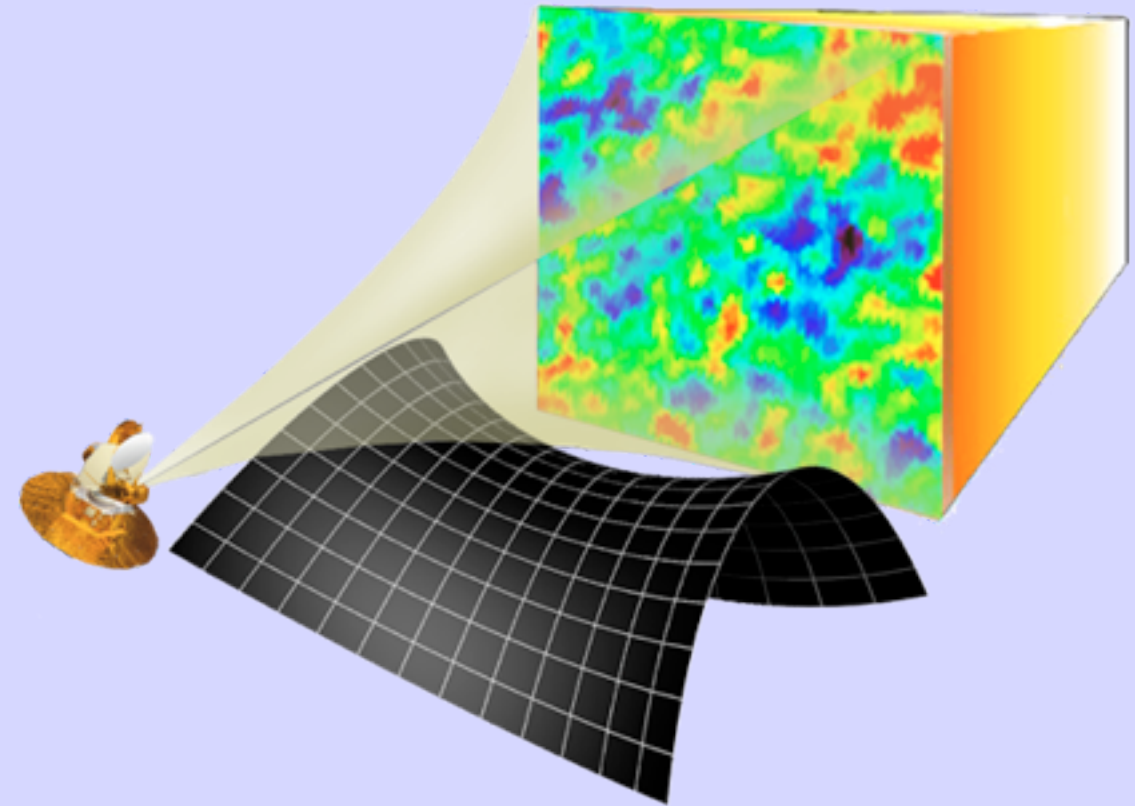
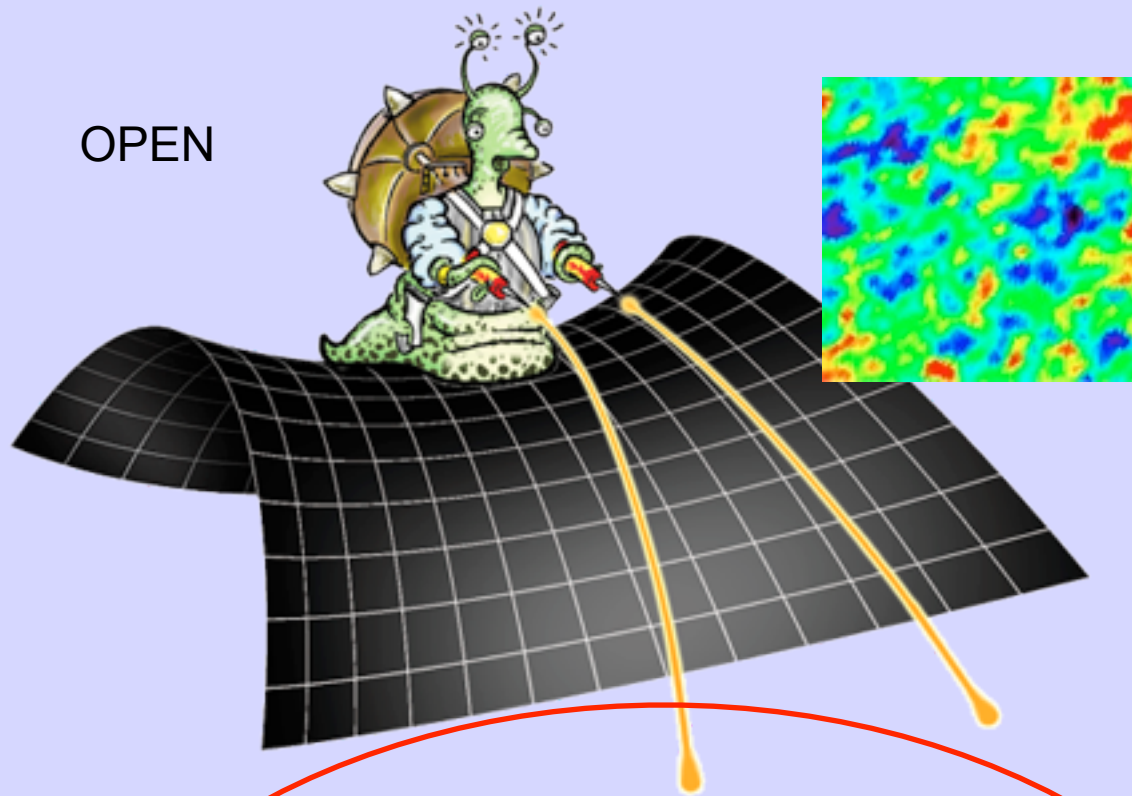
$$s = v \times t$$

Geometry of the Universe



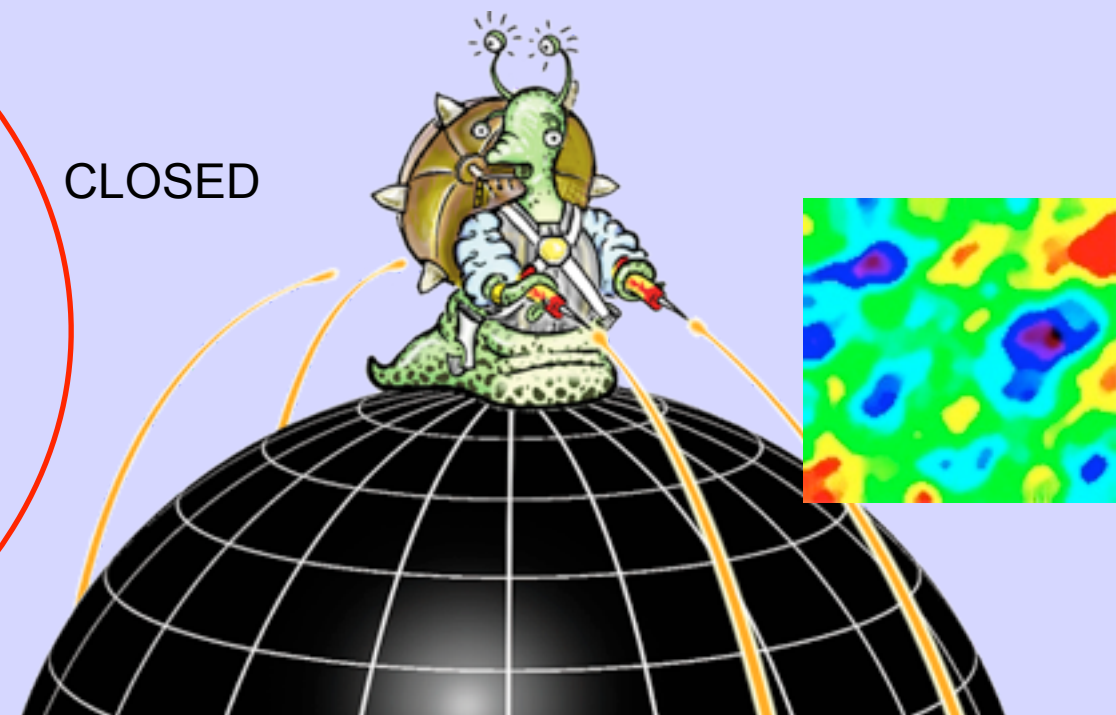
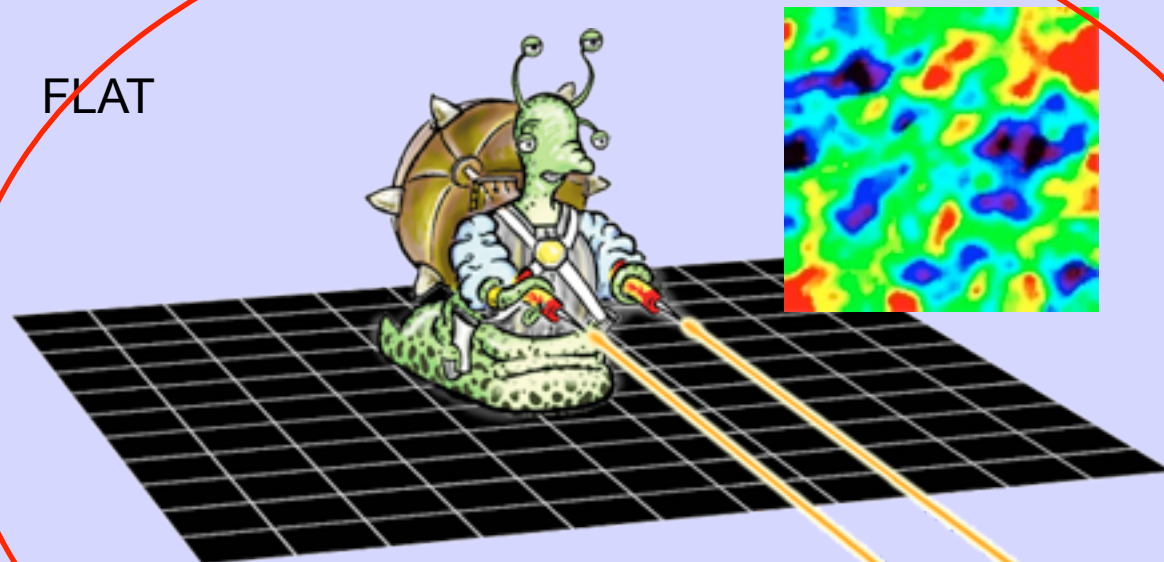
WMAP Measures the Shape of the Universe

OPEN



FLAT

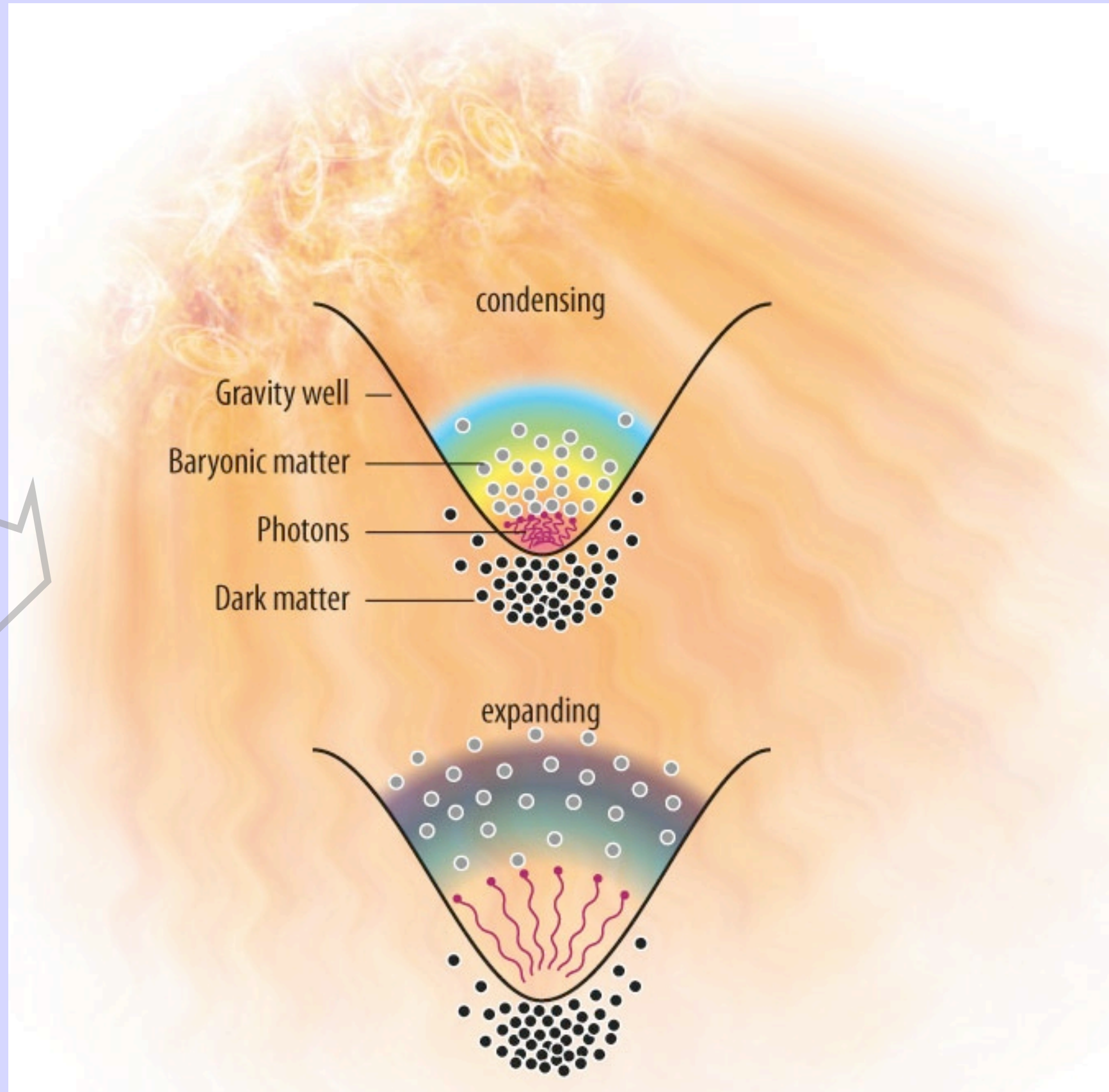
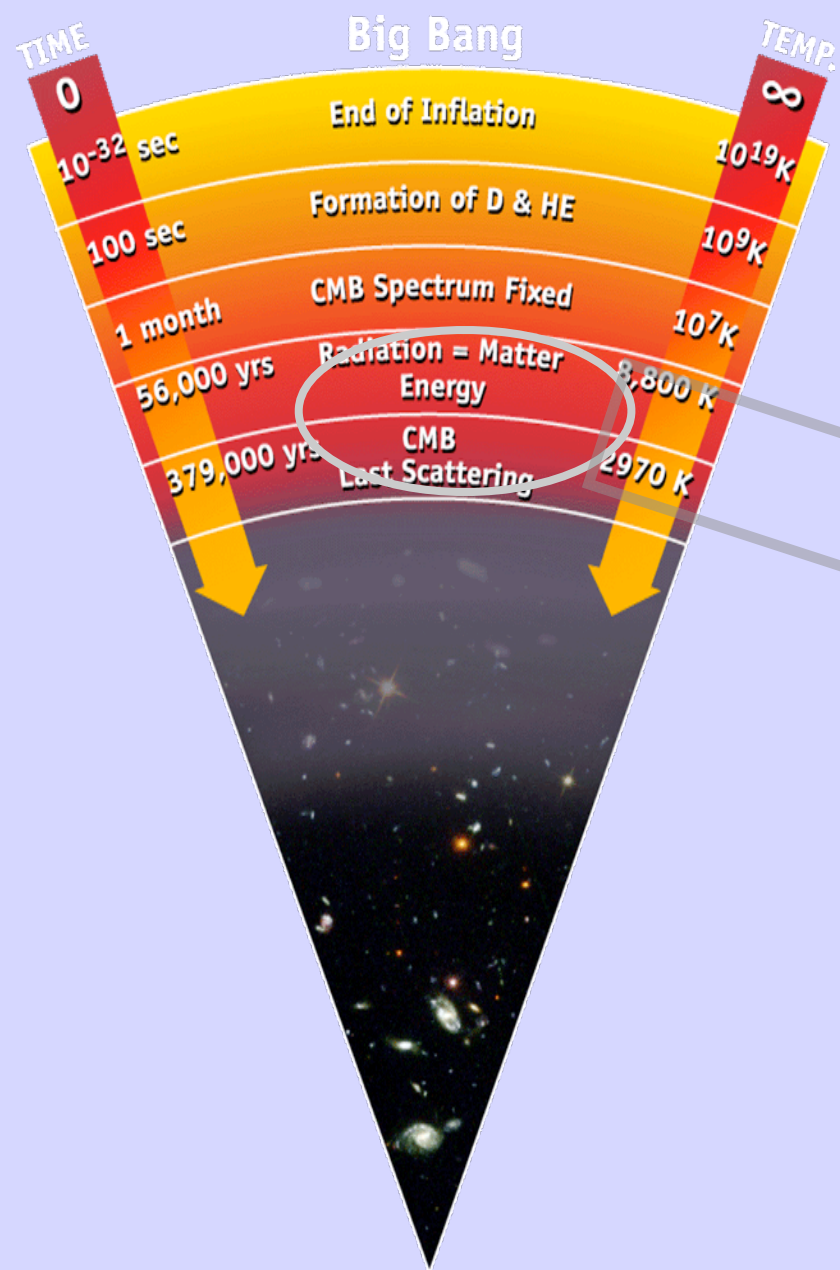
CLOSED



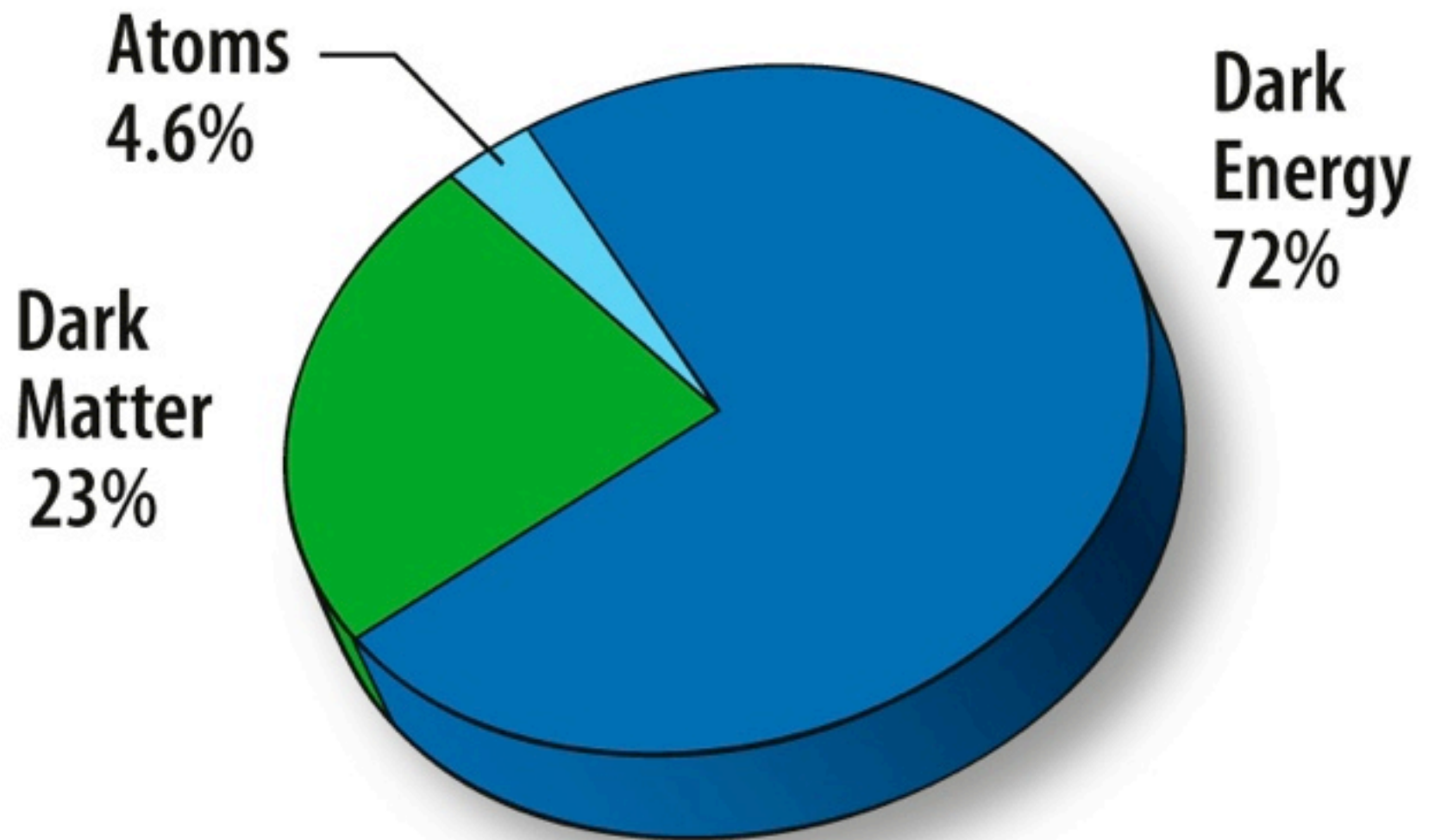
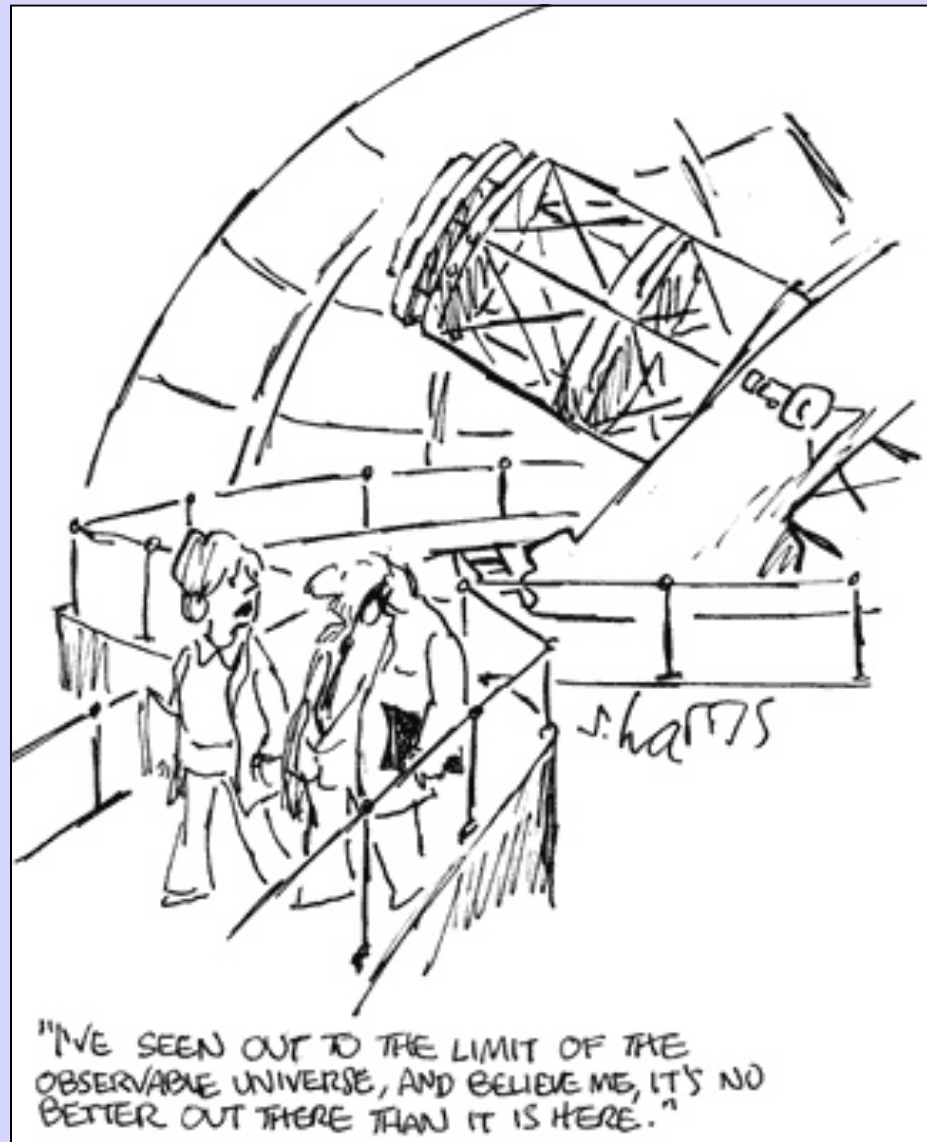
$$\Omega_{\text{tot}} = 1.0052 \pm 0.0064$$

It's flat!

Sound Waves in the Early Universe

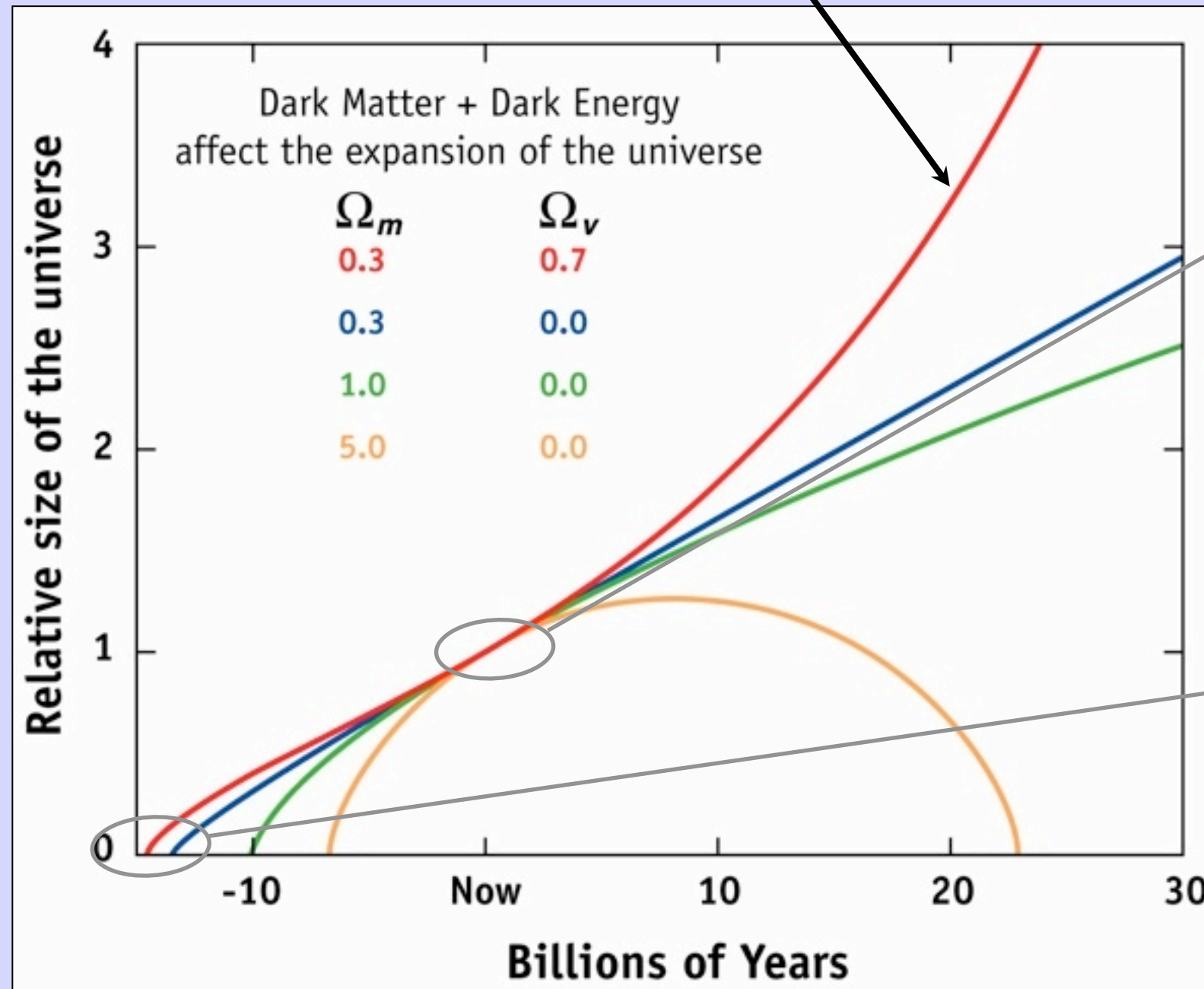


The Dark Side



Another Look at Expansion

Our universe



- Expansion rate (Hubble constant):

$$70.4 \pm 1.4 \text{ km/s/Mpc}$$

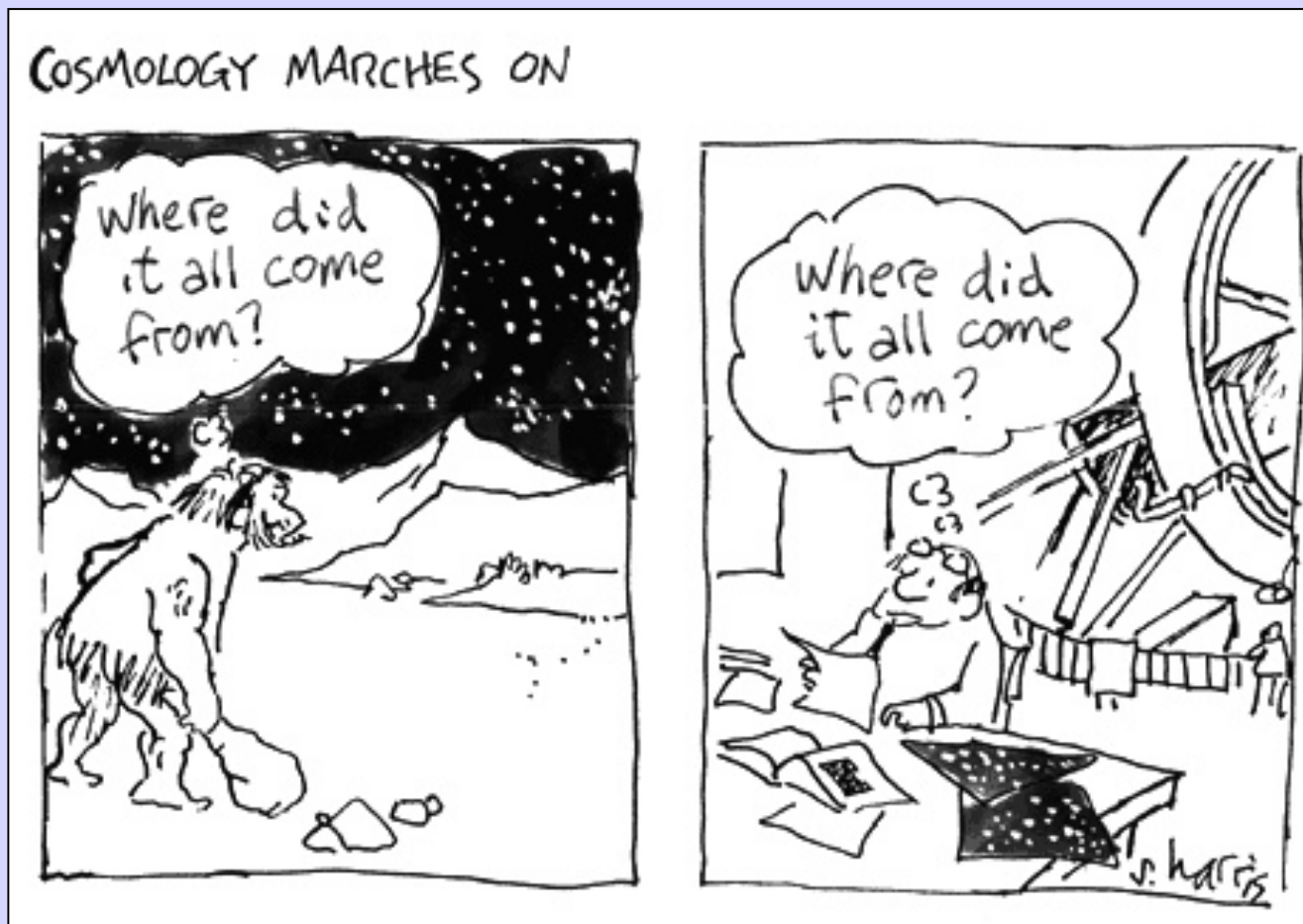
Compare to $72 \pm 3 \pm 7$ km/s/Mpc from Hubble Key Project, Freedman et al. (2001)

- Age of the universe:

$$13.75 \pm 0.11 \text{ billion years}$$

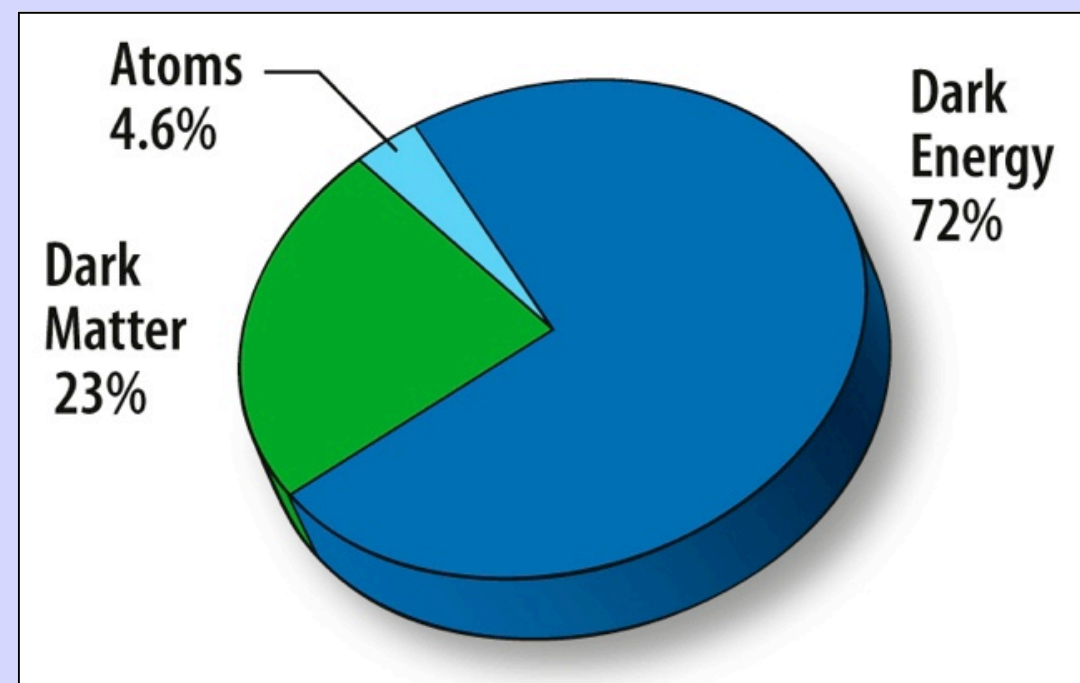
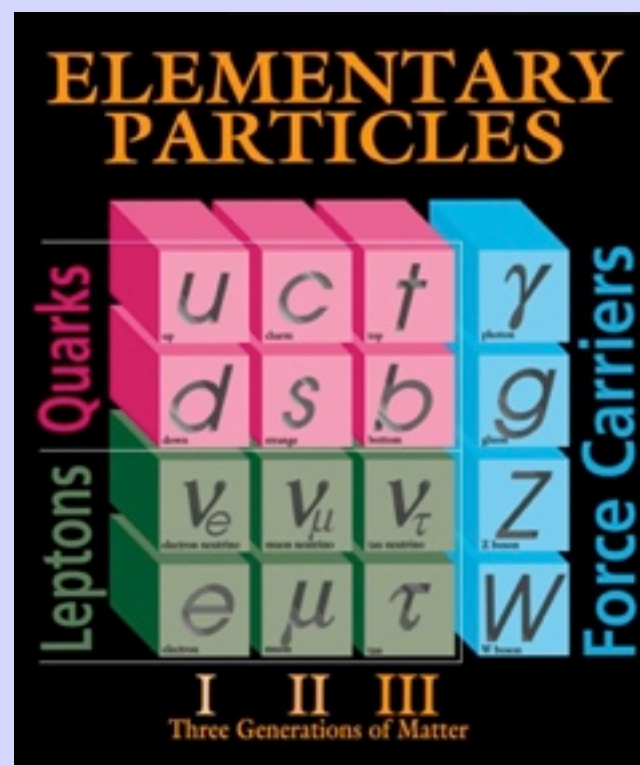
Compare to 12-20 billion years prior to WMAP

Progress in Cosmology

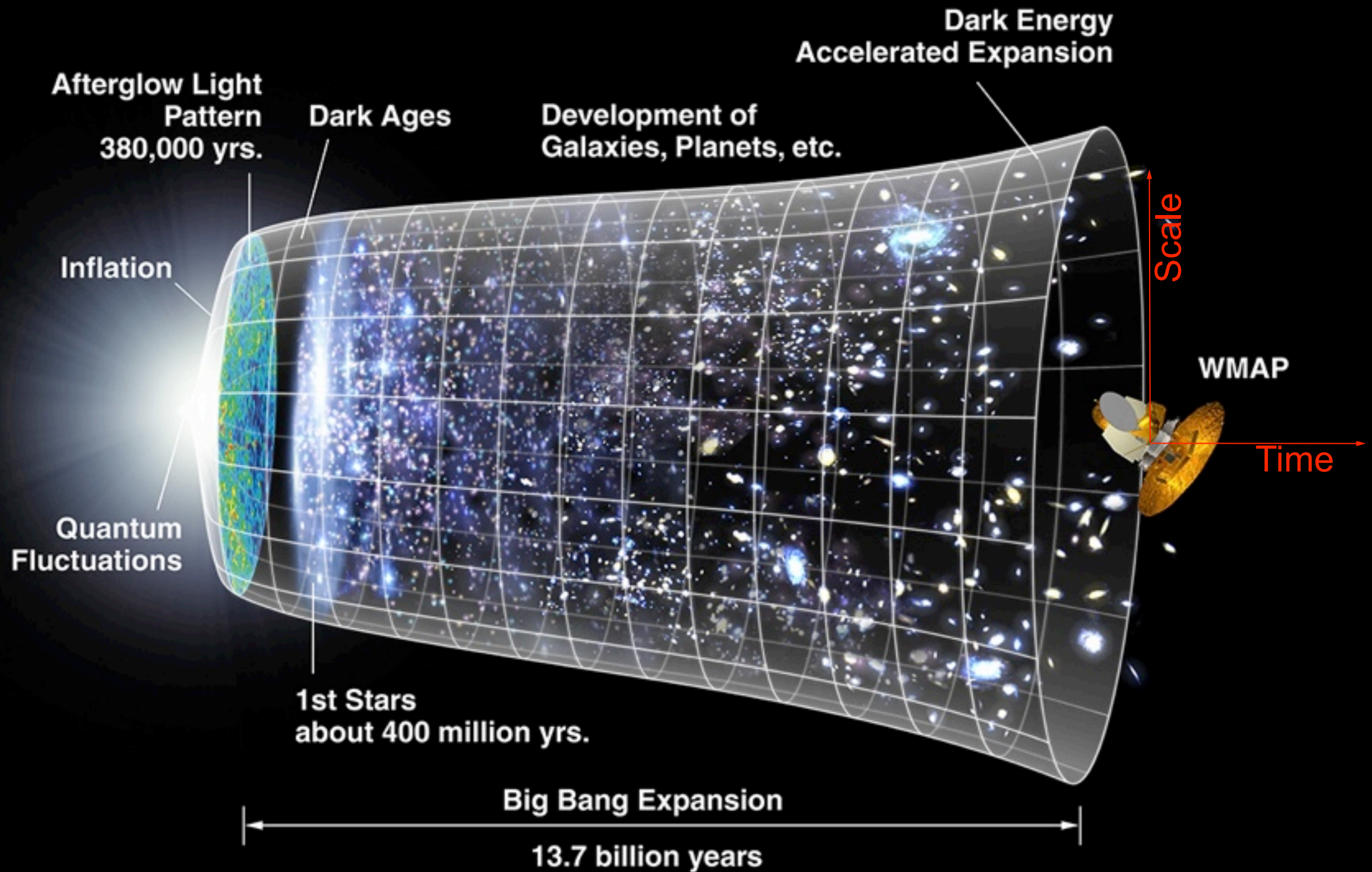


The culmination of this ~two decade old program to measure CMB anisotropy, large-scale structure, and other cosmological probes has produced a remarkable “concordance” model that fits *all* of the major data sets in cosmology.

96% of the energy density in this model is in the form of dark matter and dark energy. Fundamental insight to the nature of these constituents may well be very difficult to come by, just as in the standard model of particle physics.



Cosmology, c. 2011

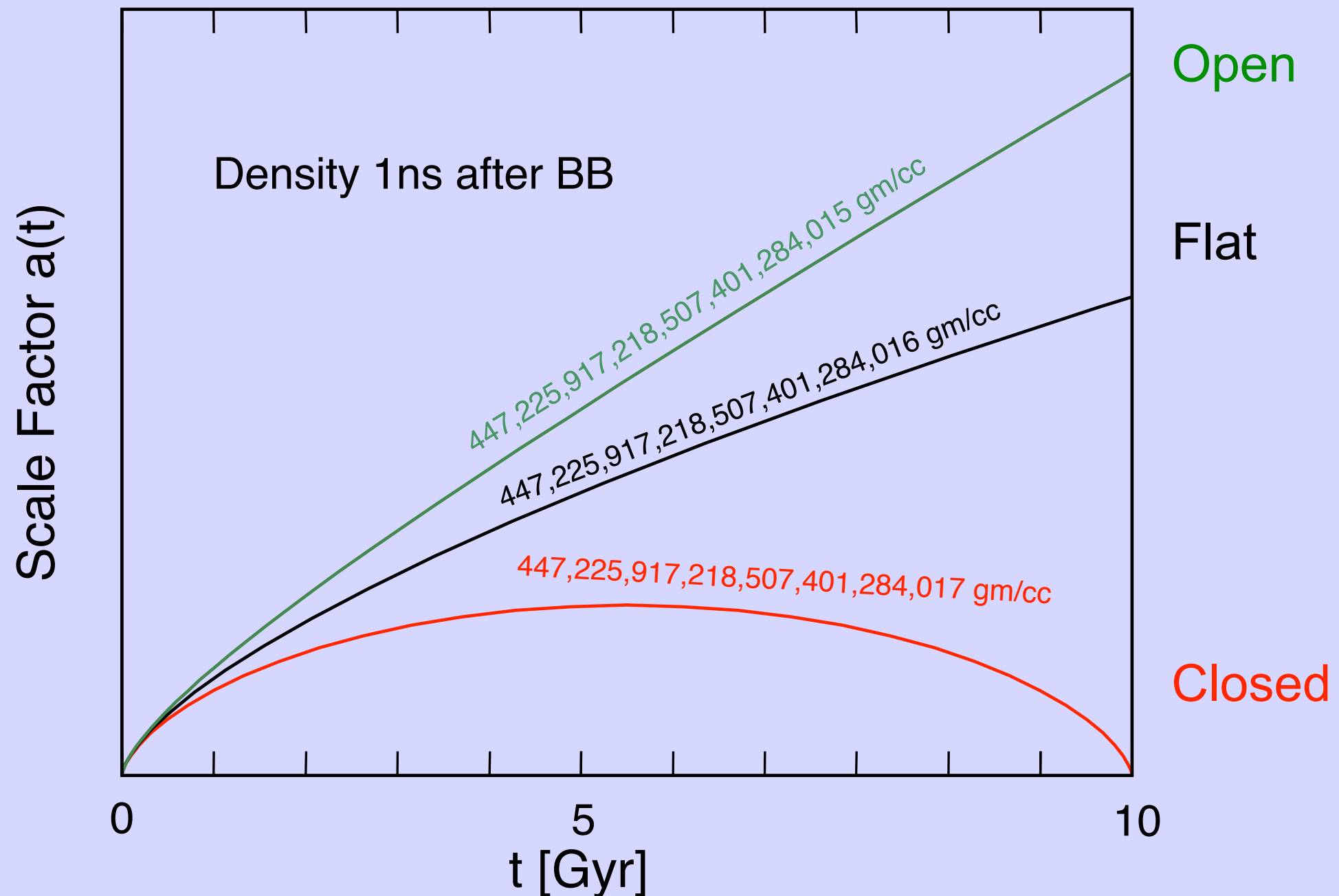


Thanks for listening



The Flatness Problem

Why is the universe anywhere close to “flat” now?
Flatness is an unstable state for the universe.

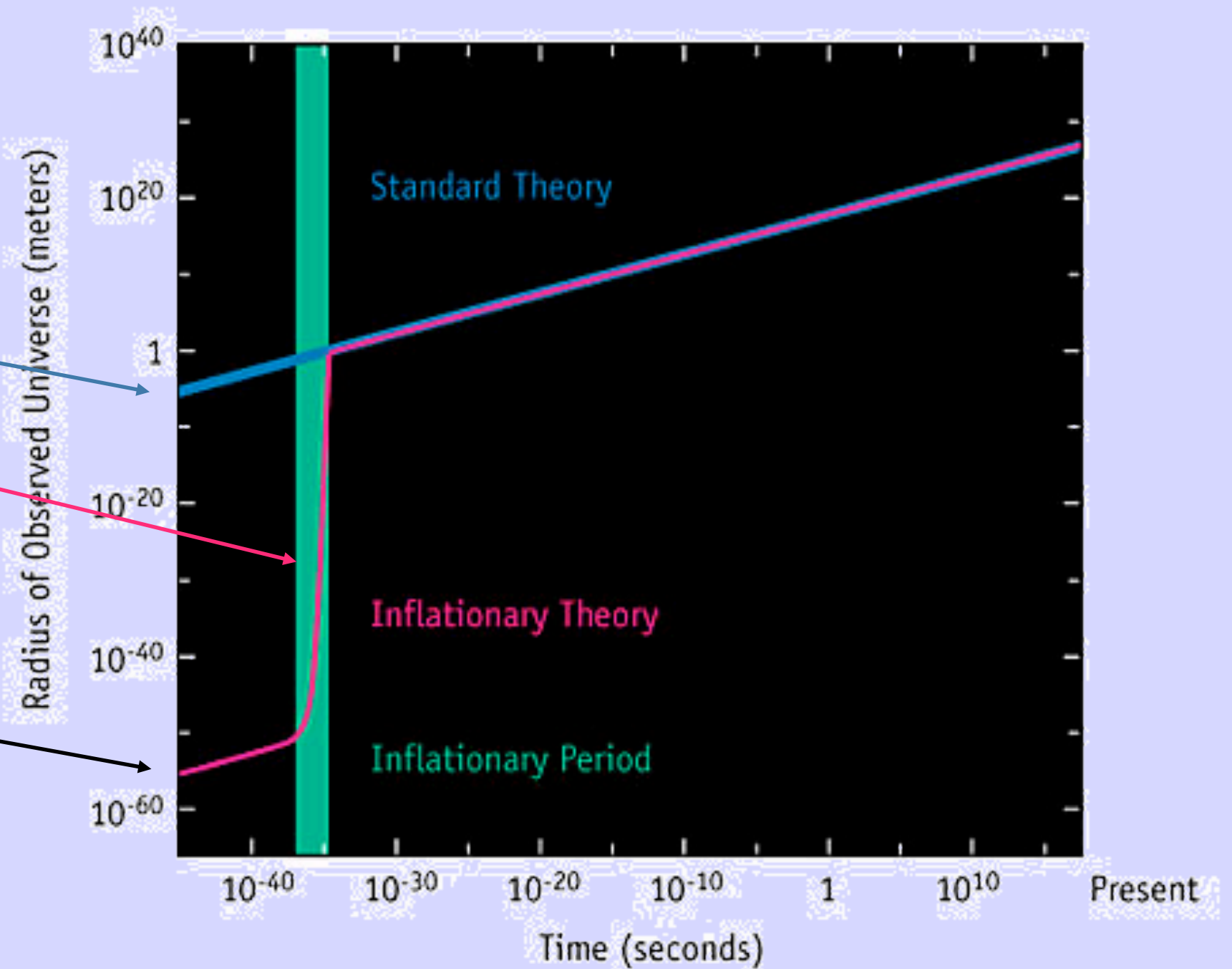


Inflation!

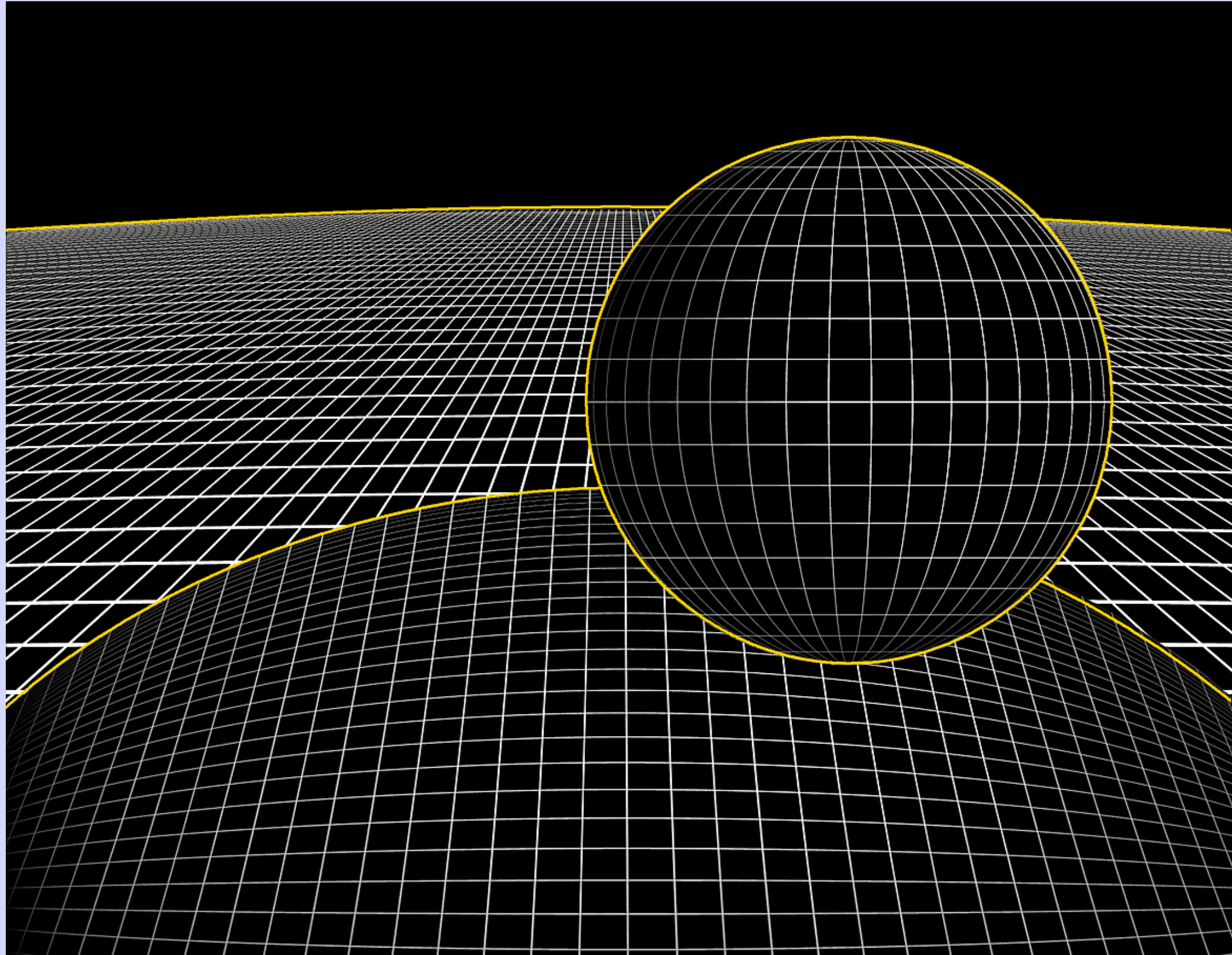
“Standard” expansion

“Inflationary” expansion

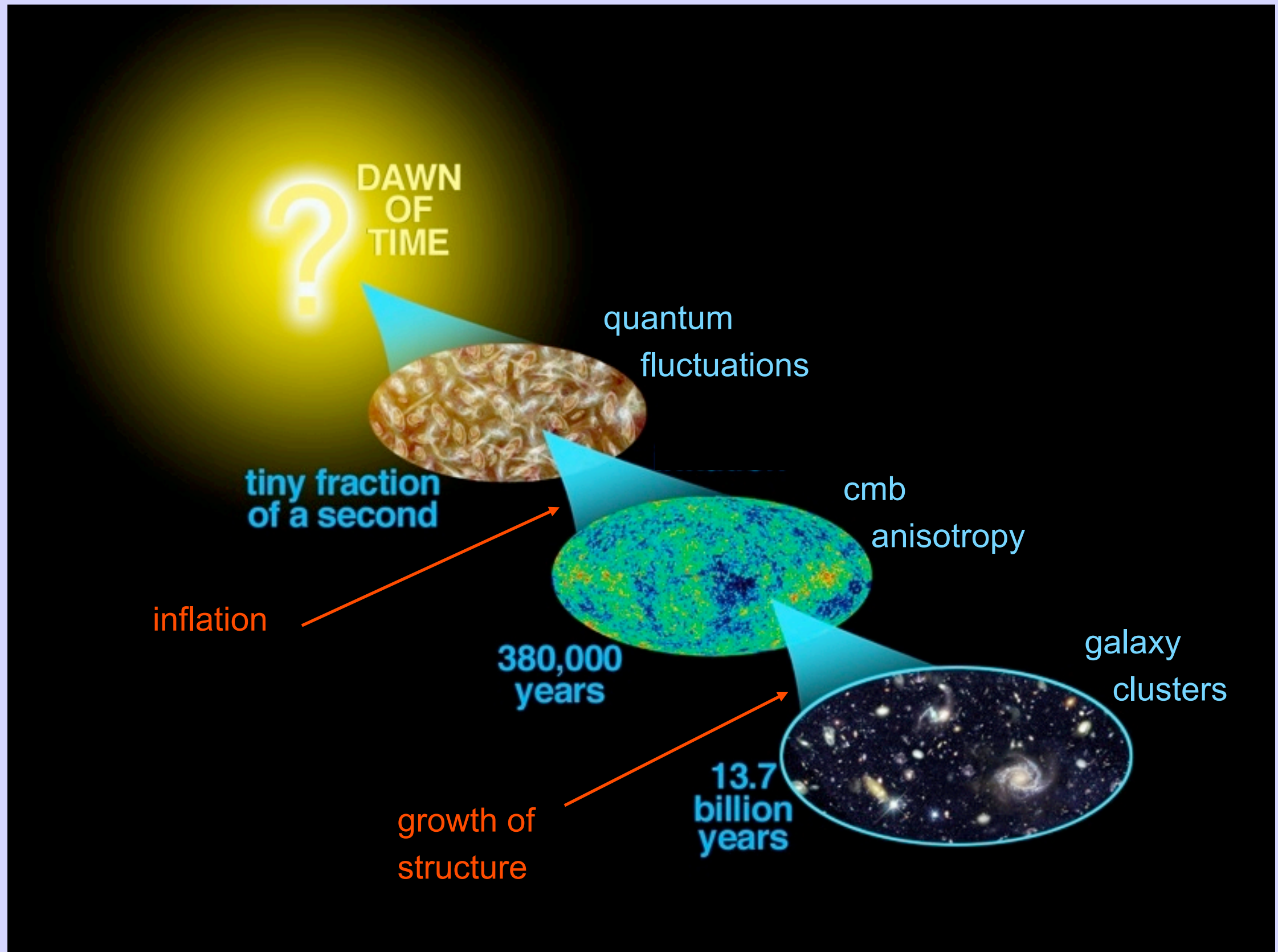
Prior to inflation, universe was much smaller than previously thought. It could have been in thermal contact at one temperature.



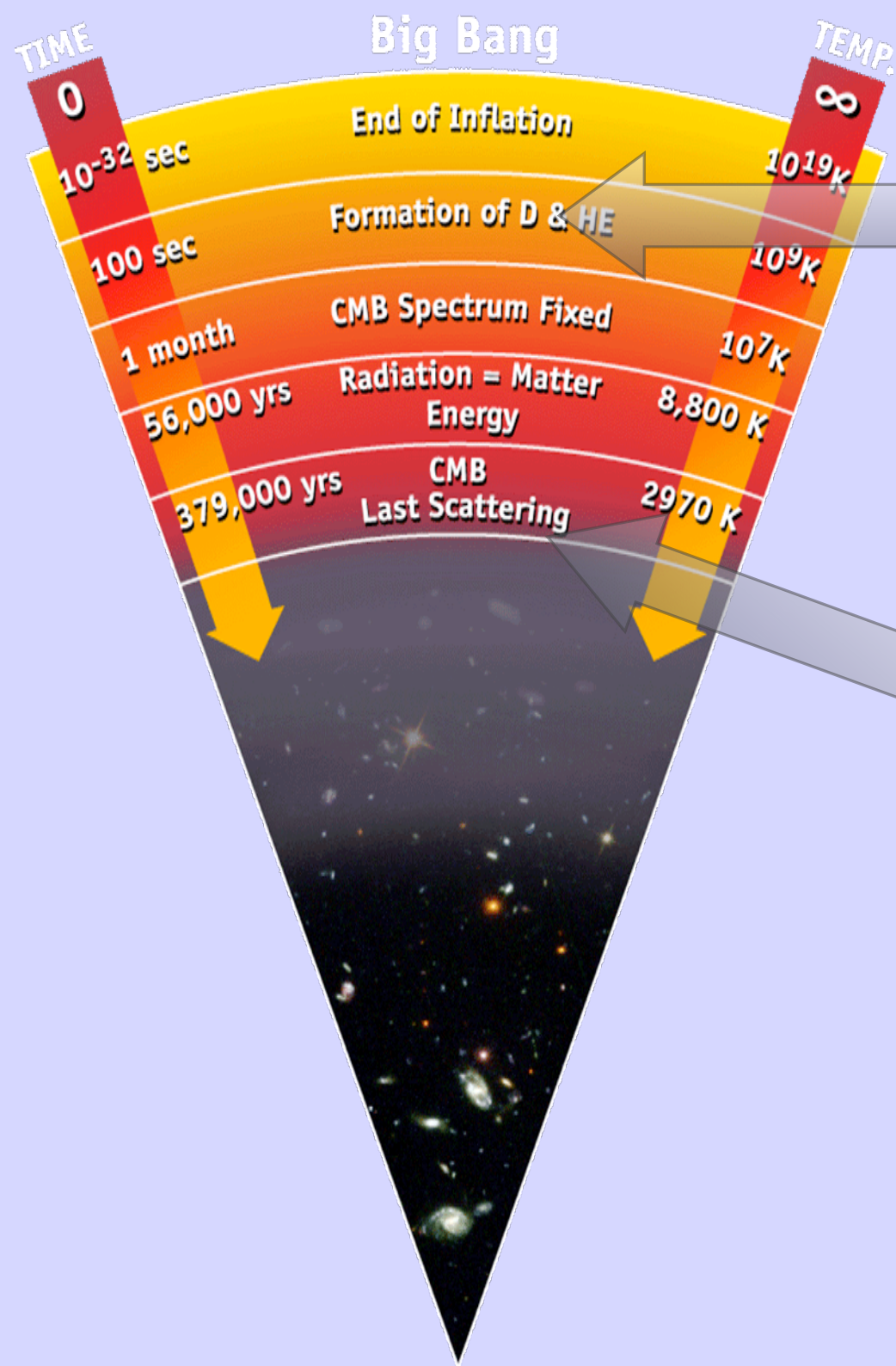
Inflated Space is Locally Flat



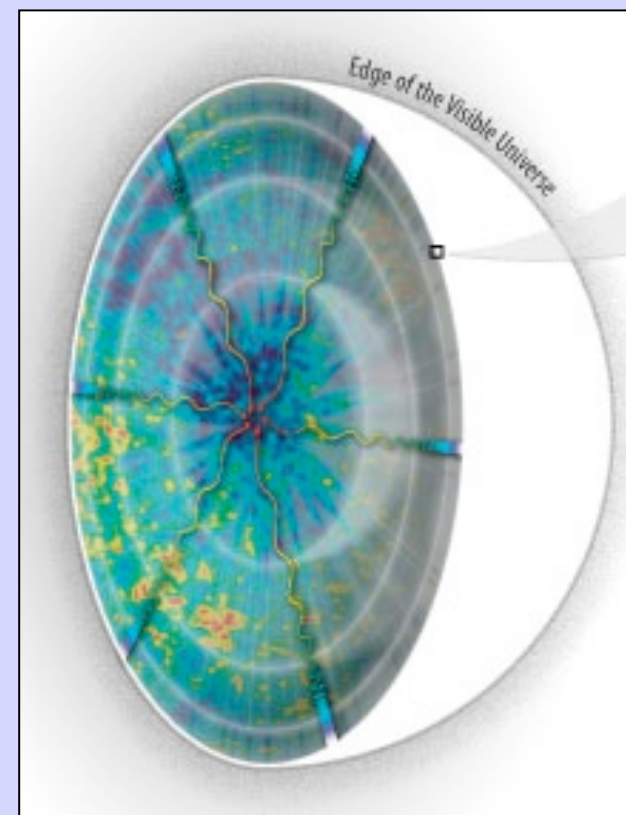
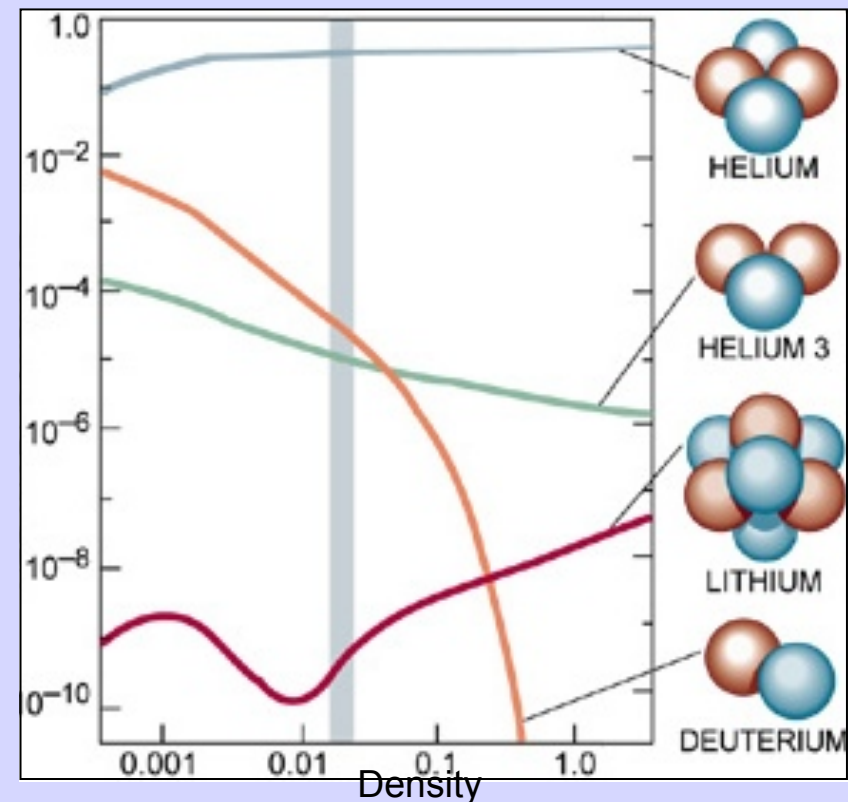
From Quarks to the Cosmos!



Fossils from Cosmic History



Relative abundance



The Horizon Problem

Why is the cosmic microwave background temperature so uniform on large scales?

