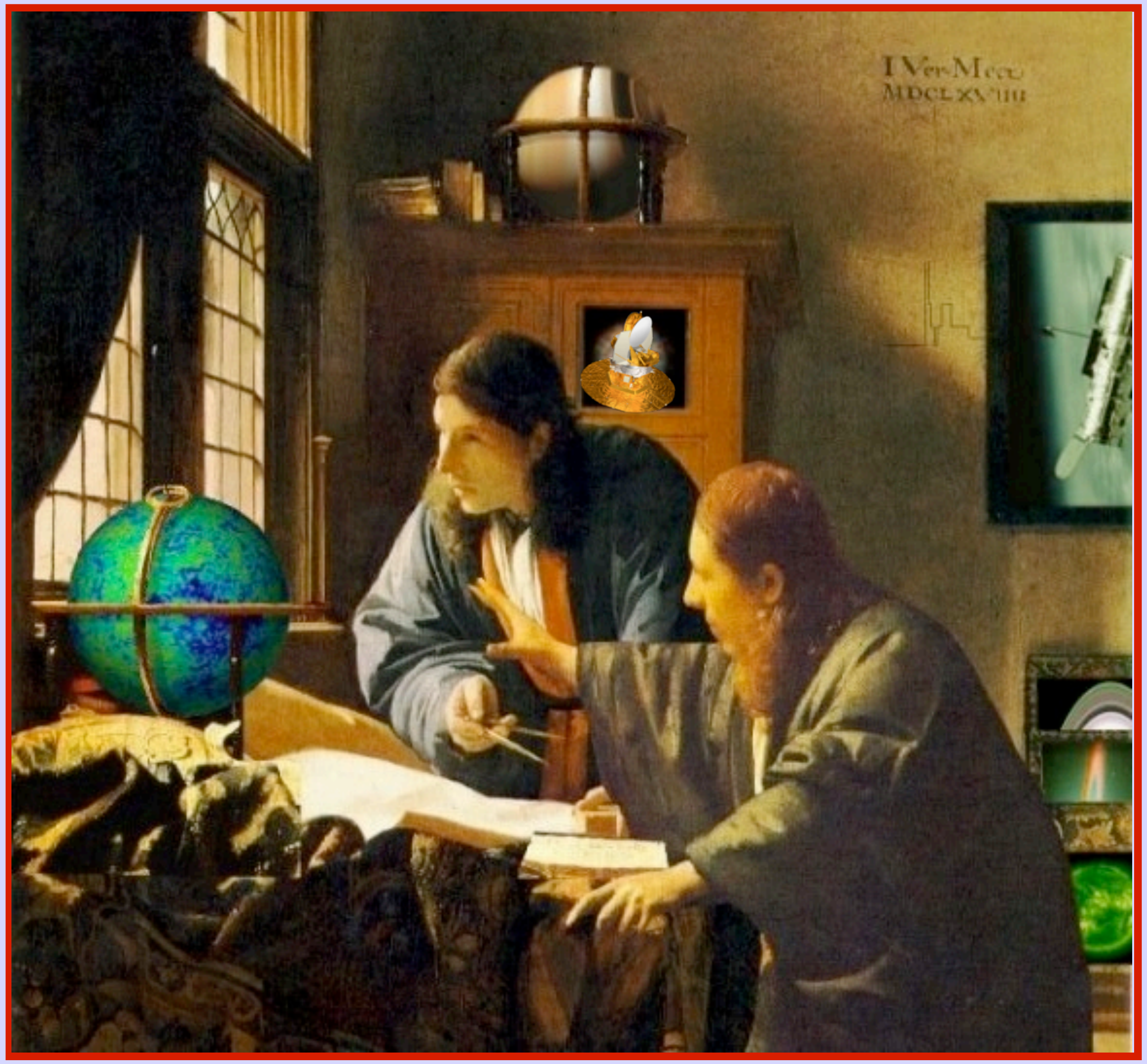
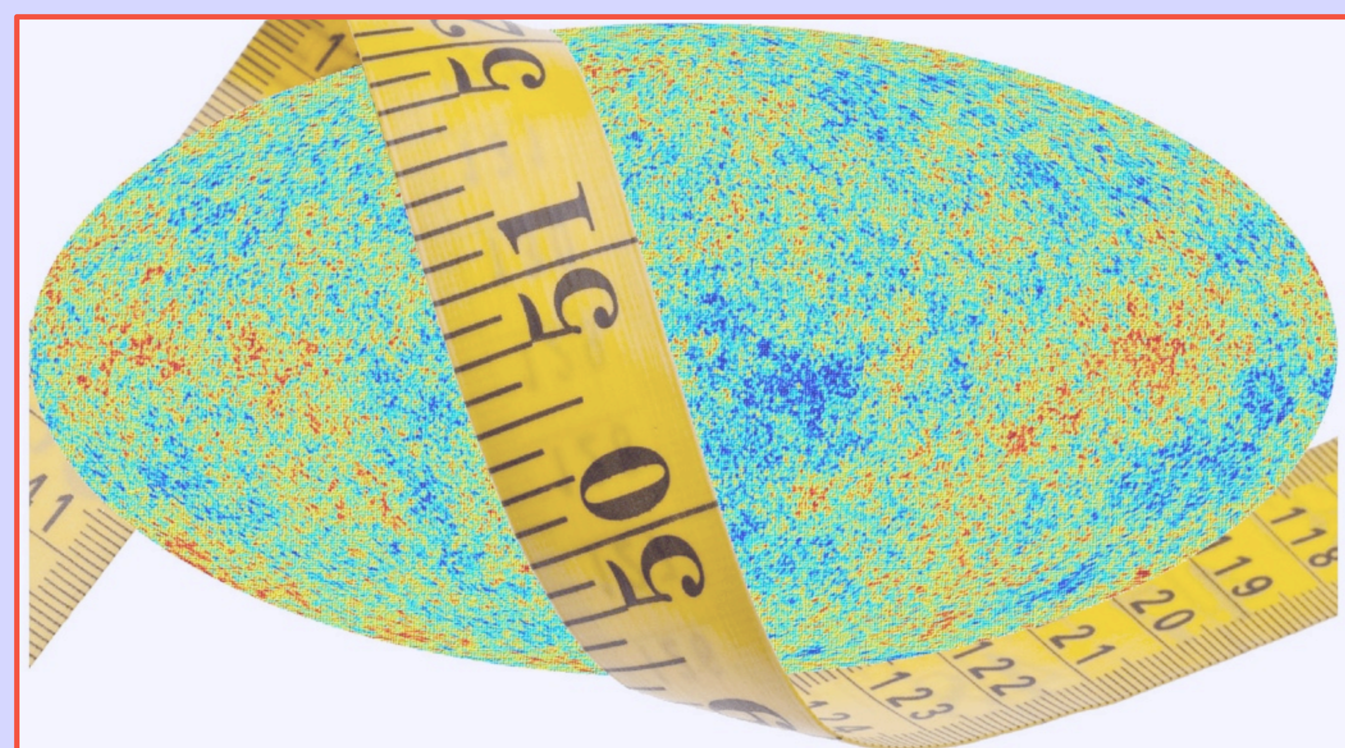
Taking the Measure of the Universe





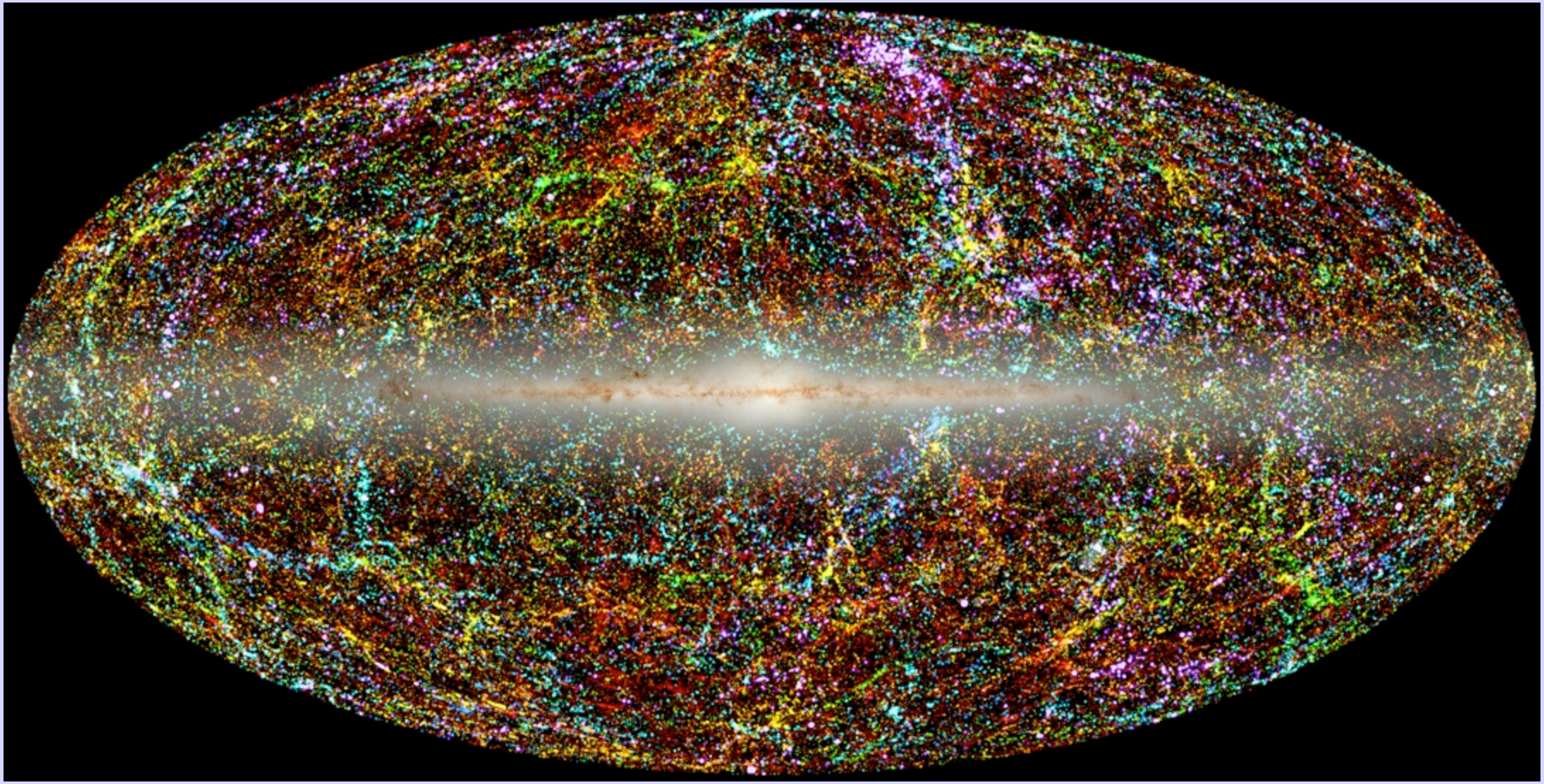
Gary Hinshaw

University of British Columbia

PITP Lectures @ St Johns College

7 December, 2011

Uniformity of Galaxy Distribution



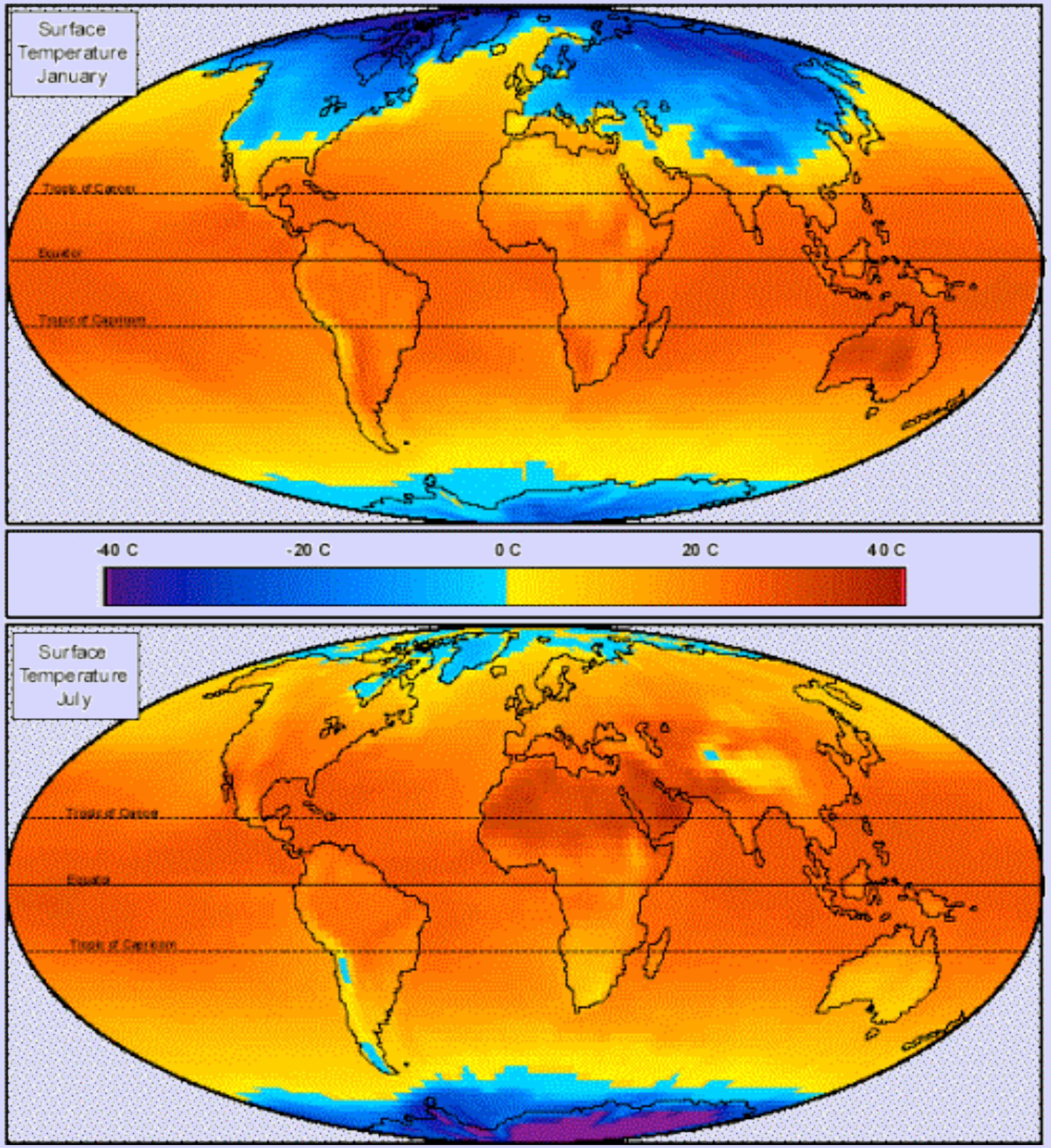
Smooth light in center of map is from stars in our Milky Way galaxy.

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.

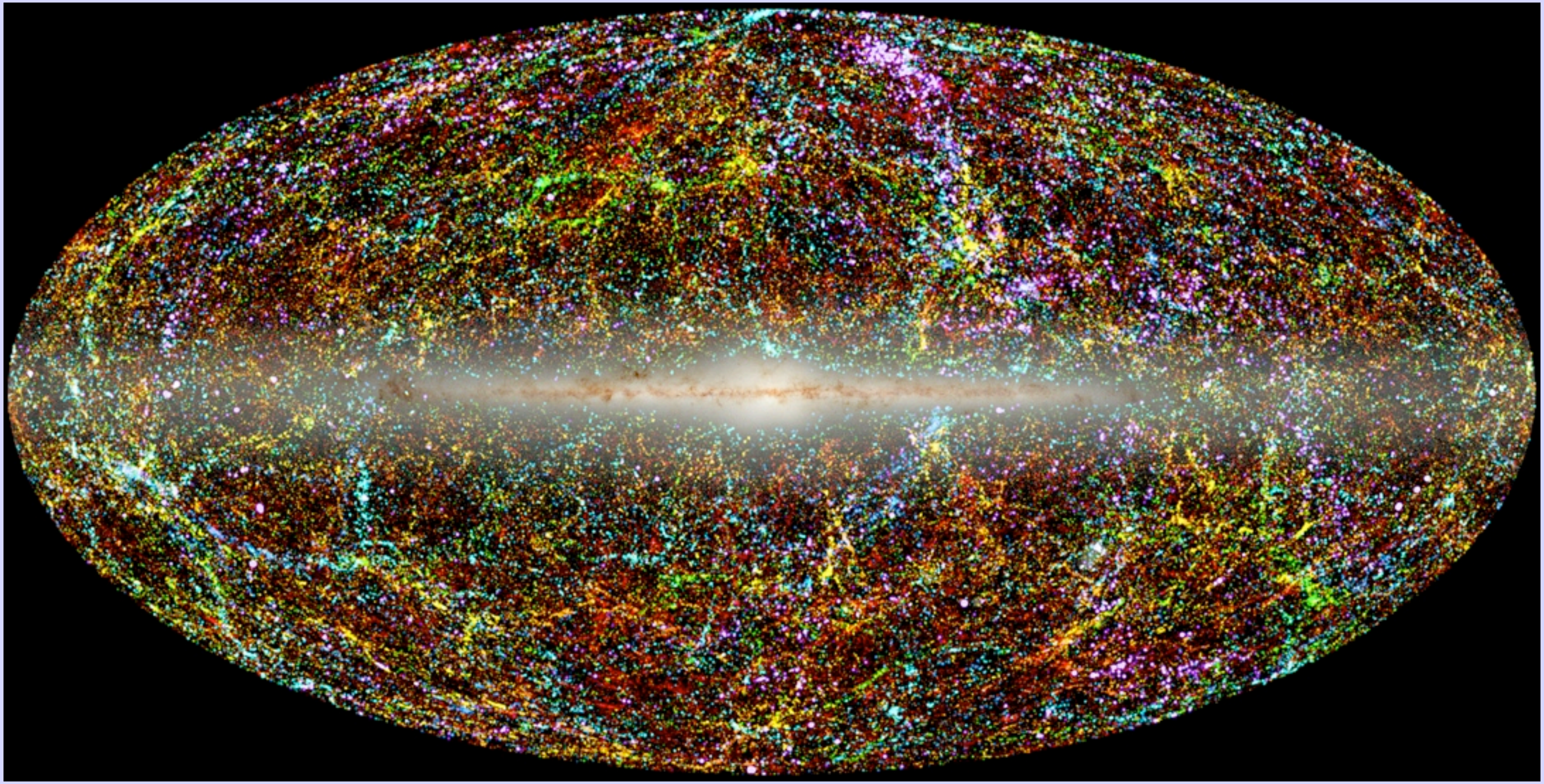
The nearby universe looks pretty similar in all directions.

Representing Data on a Sphere



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

Uniformity of Galaxy Distribution



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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

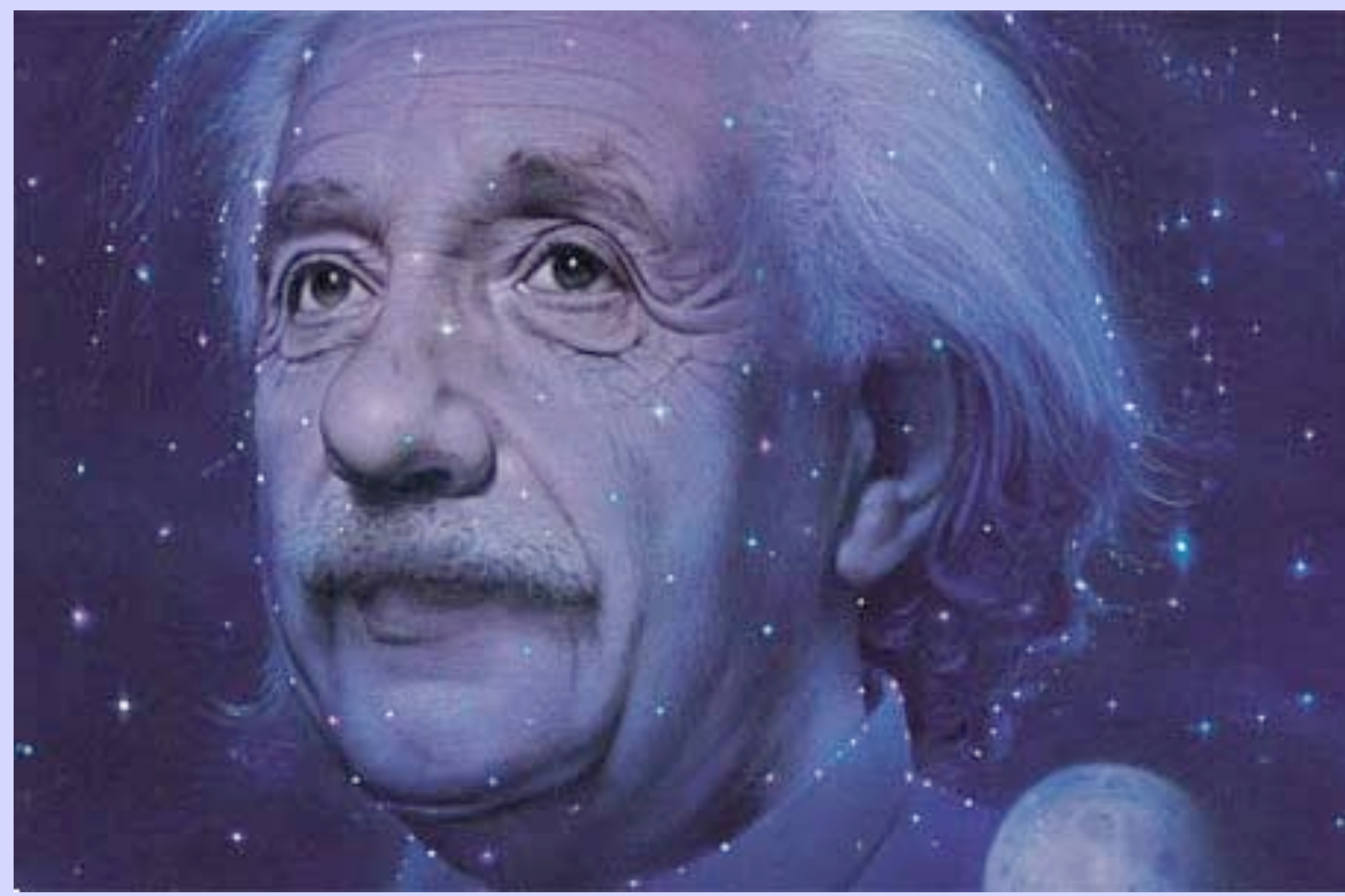
TIME MAGAZINE
"PERSON OF THE CENTURY"

"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:

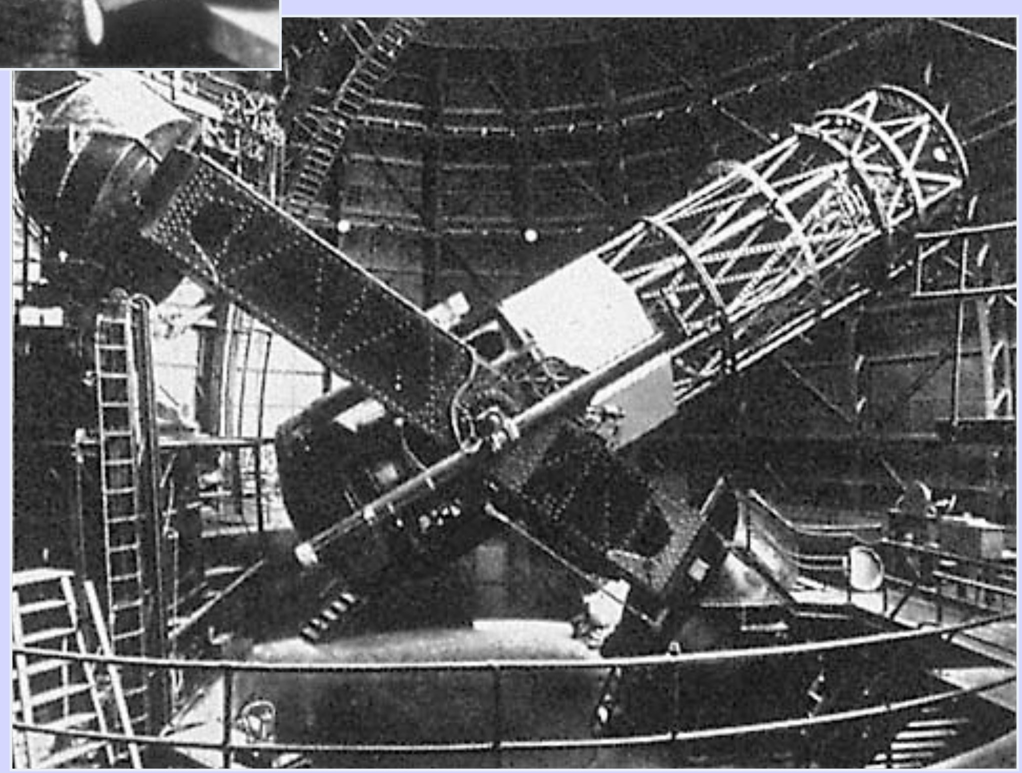
- **Dynamic universe that expands and possibly contracts.**
- **Seemingly in conflict with belief that the universe was static.**



1929: Hubble Discovers Expanding Universe

Edwin Hubble

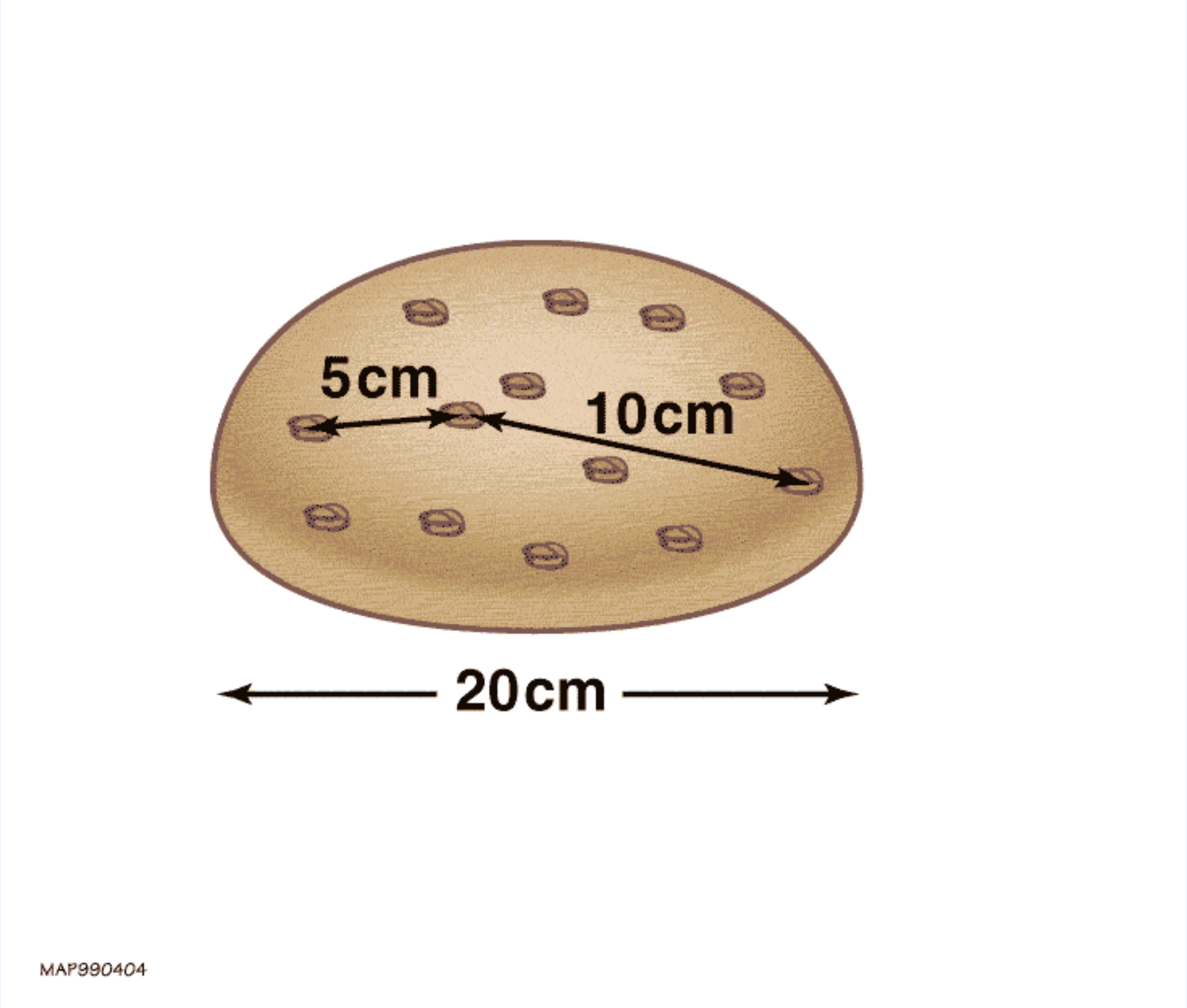
“…we know that we are reaching into space, farther and farther, until, with the faintest nebulae that can be detected with the greatest telescopes, we arrive at the frontier of the known universe.”



Mt. Wilson 100 Inch Telescope

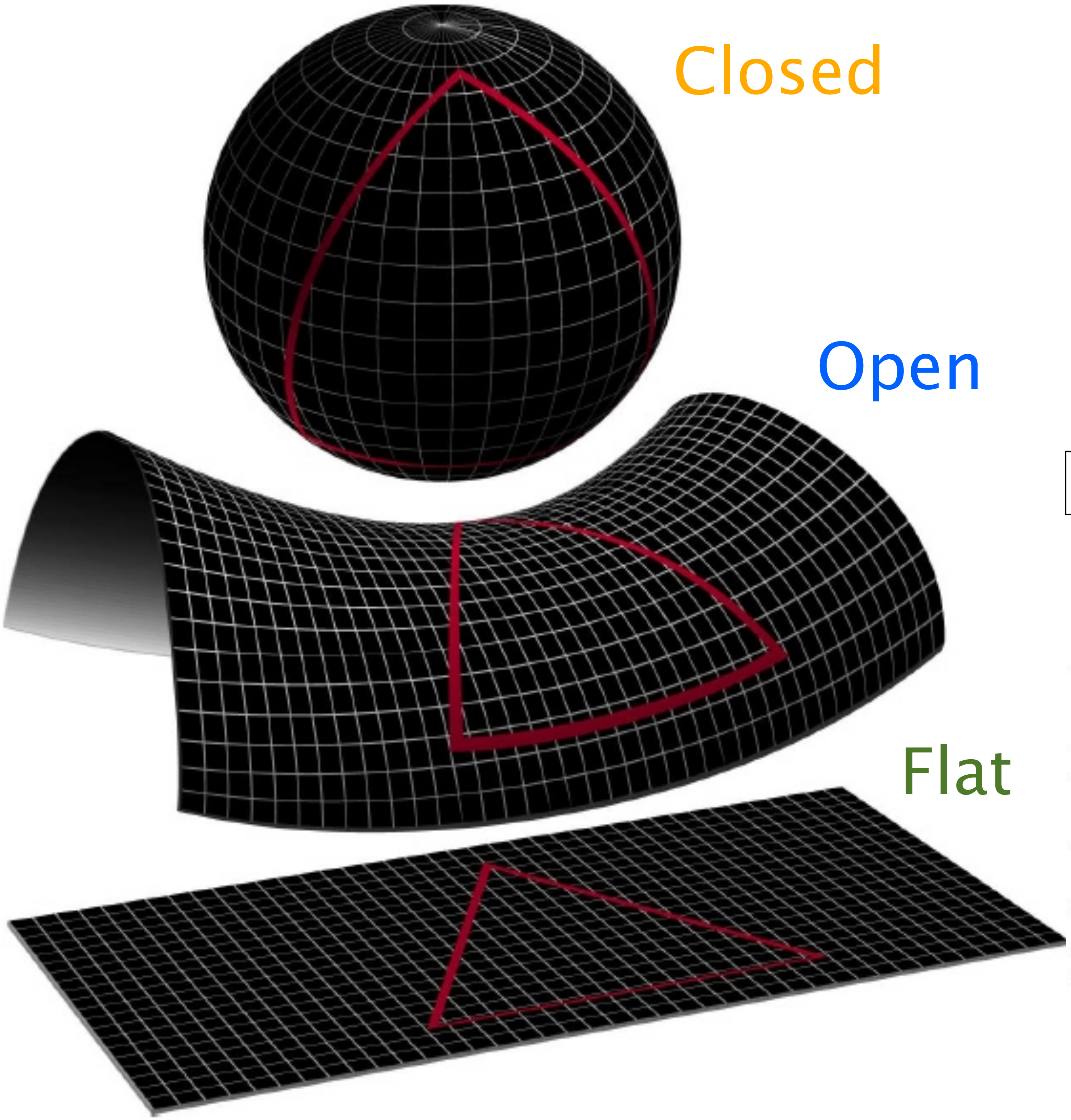
“..one of the most flabbergasting discoveries science has ever made.” TIME noted, Hubble had evolved his theory “**by looking at the universe itself**.”

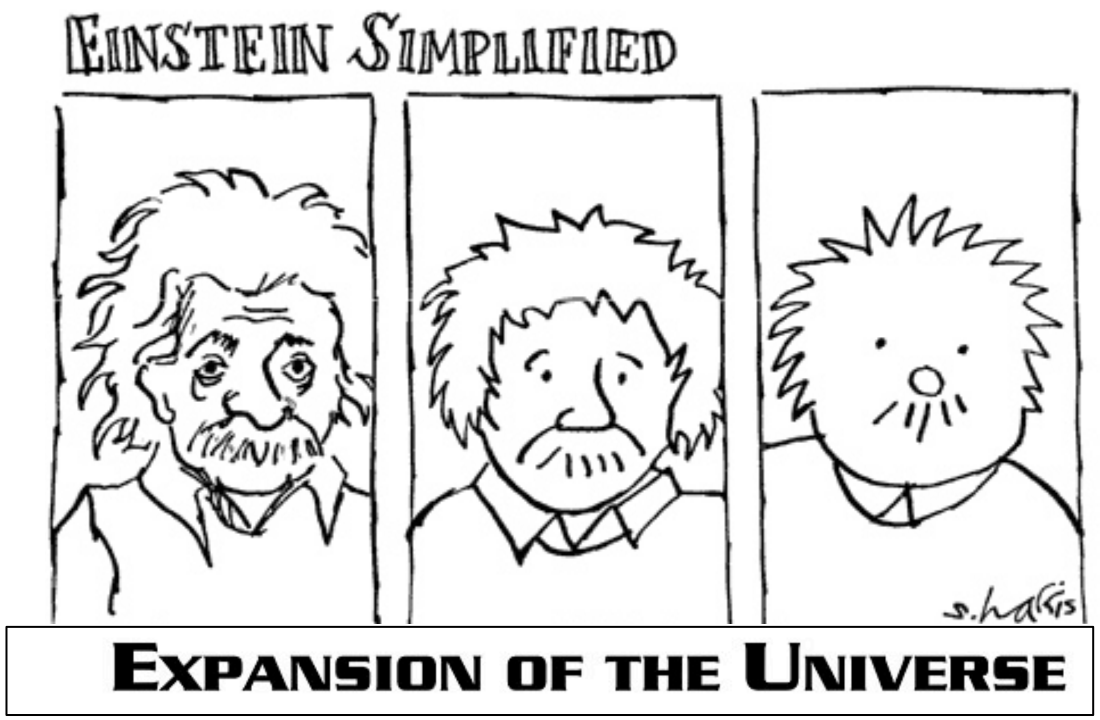
Homogeneous Expansion: v=H·d

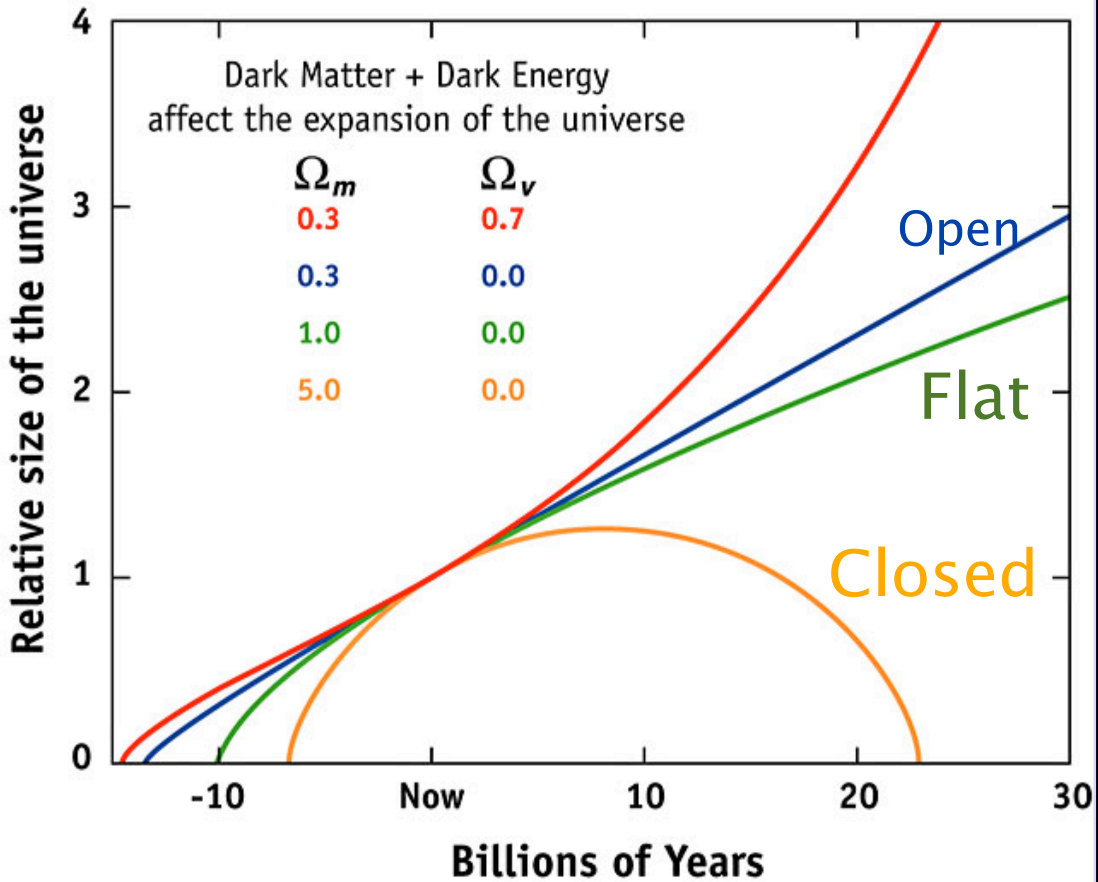


An “observer” on any raisin would measure the same expansion law

Cosmological Dynamics







1940's: Big Bang Physics

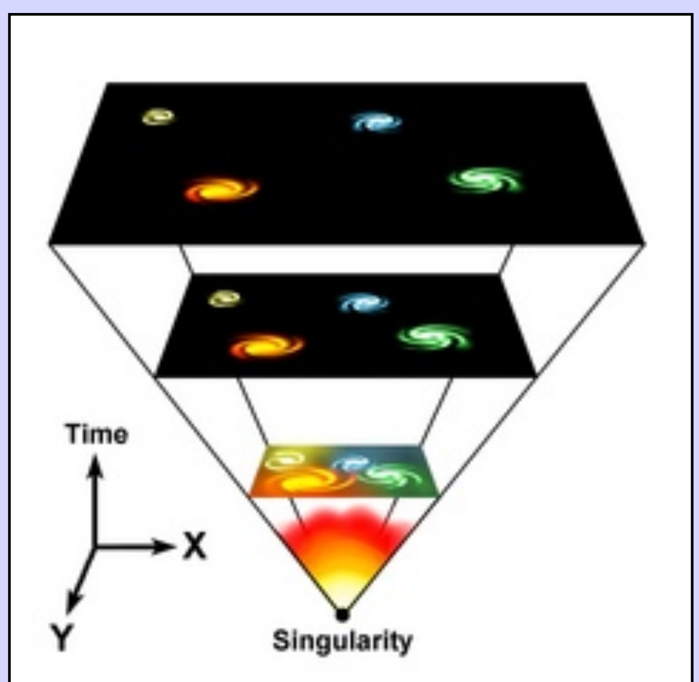
• Gamow (1946): Chemical elements might have been made in a hot early universe, stopping when expansion cools universe.

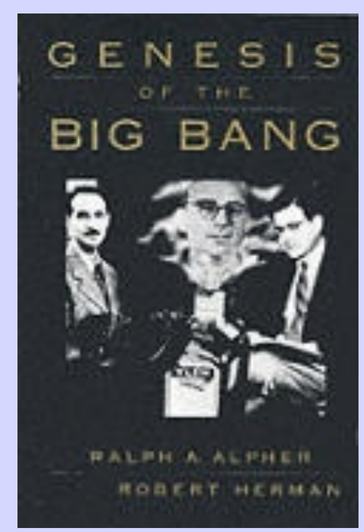
• Ralph Alpher (1946): Worked out the physics & found only the lightest chemical elements could have been made: D, He, Li, Be, B.

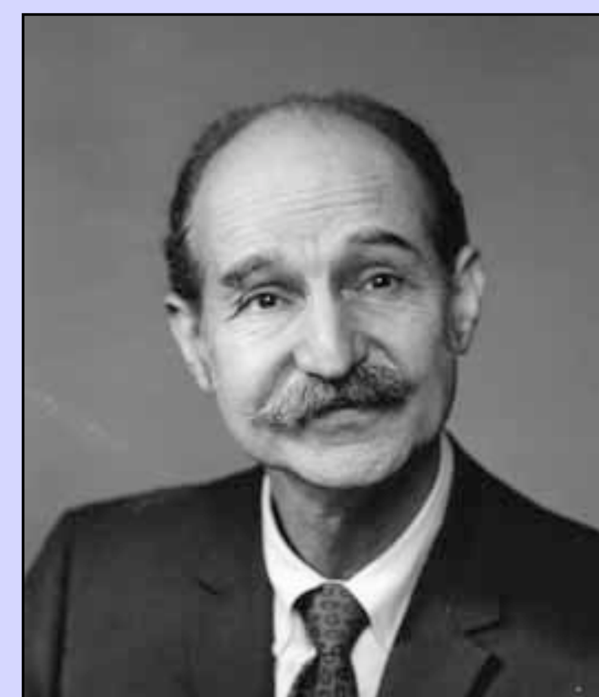
• Alpher, Bethe, Gamow (1948): Derives relative proportions of chemical elements in a hot expanding universe. [Bethe made no contribution whatsoever.]

• 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.

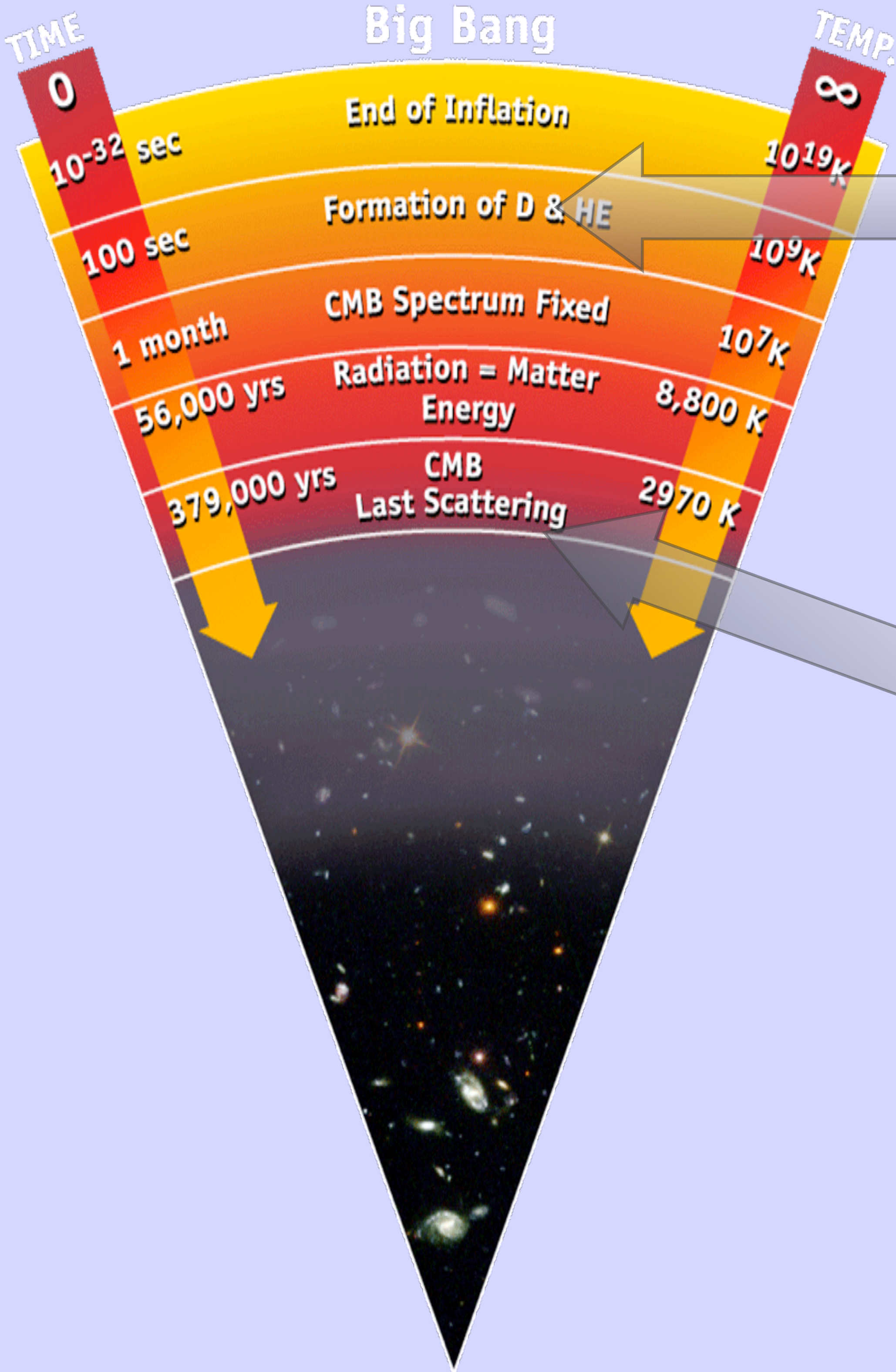

Ralph Alpher

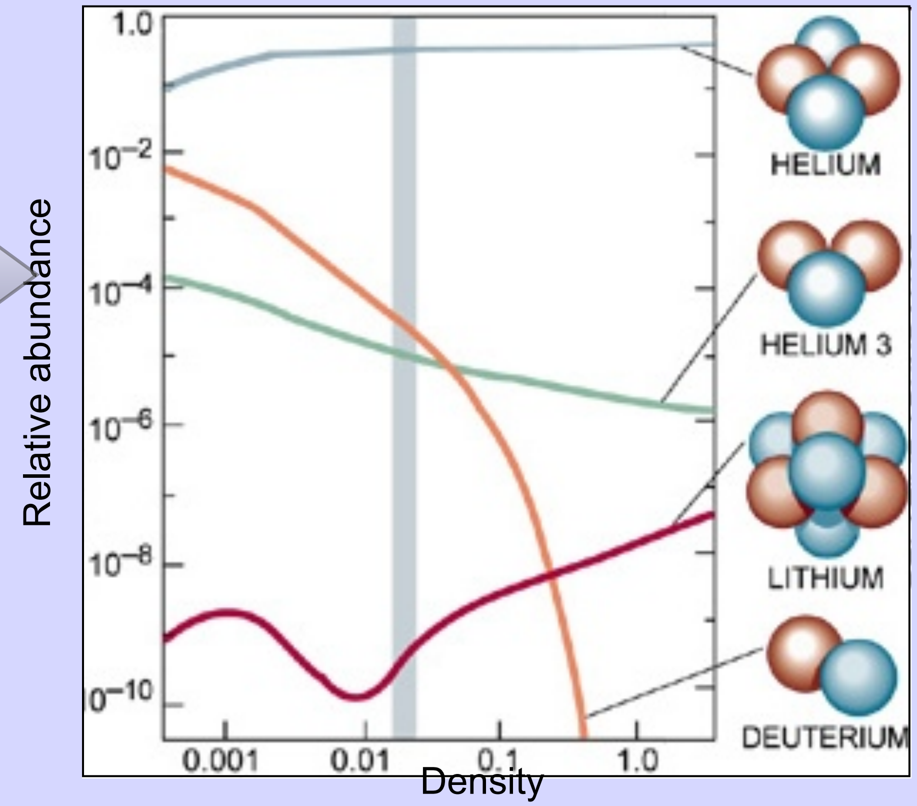




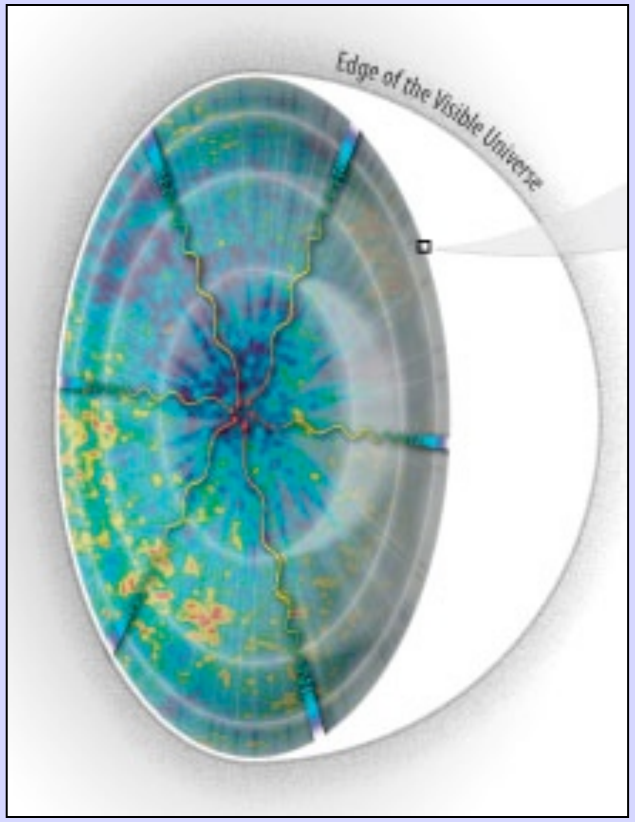

Robert Herman

Fossils from Cosmic History





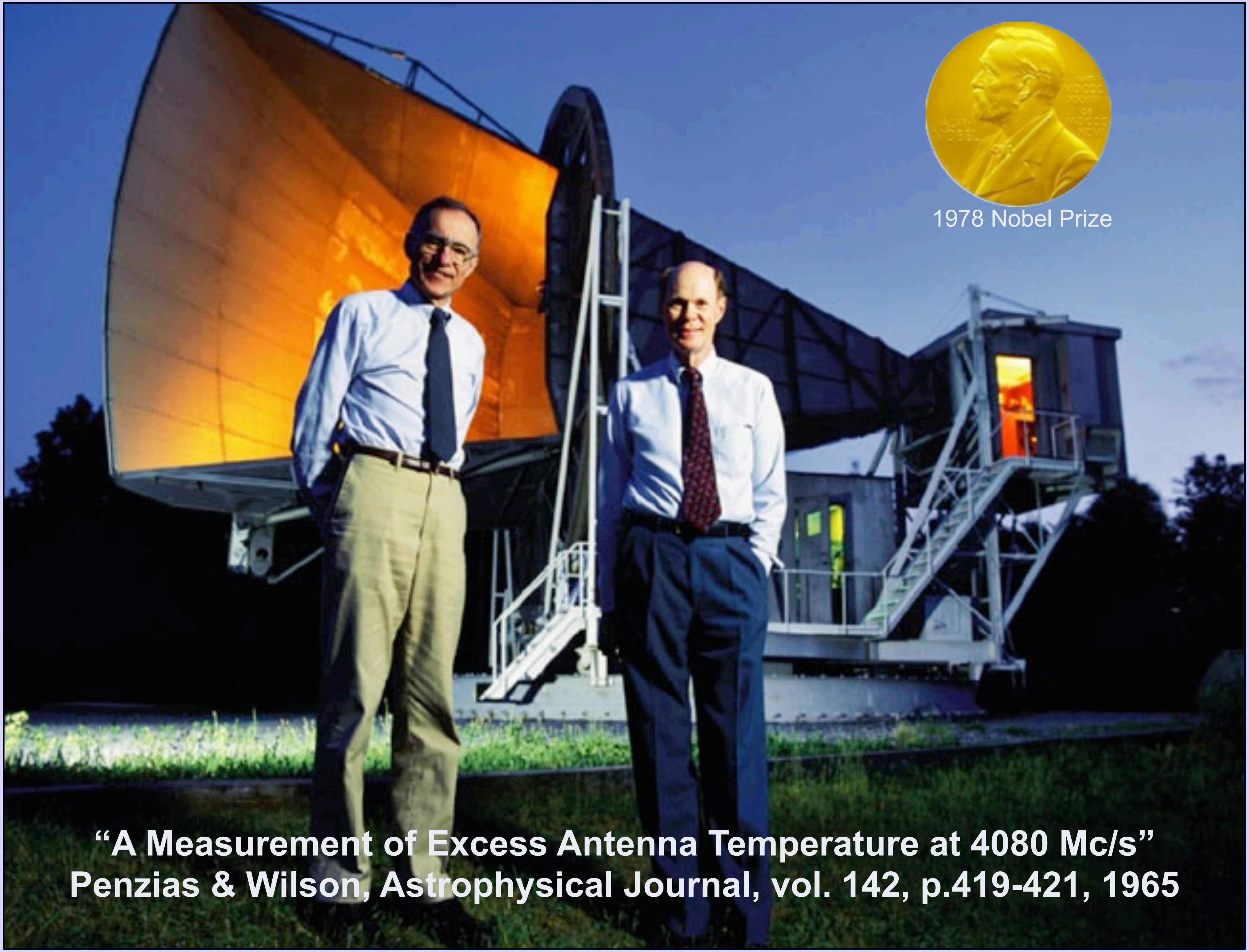
Big bang nucelo-synthesis



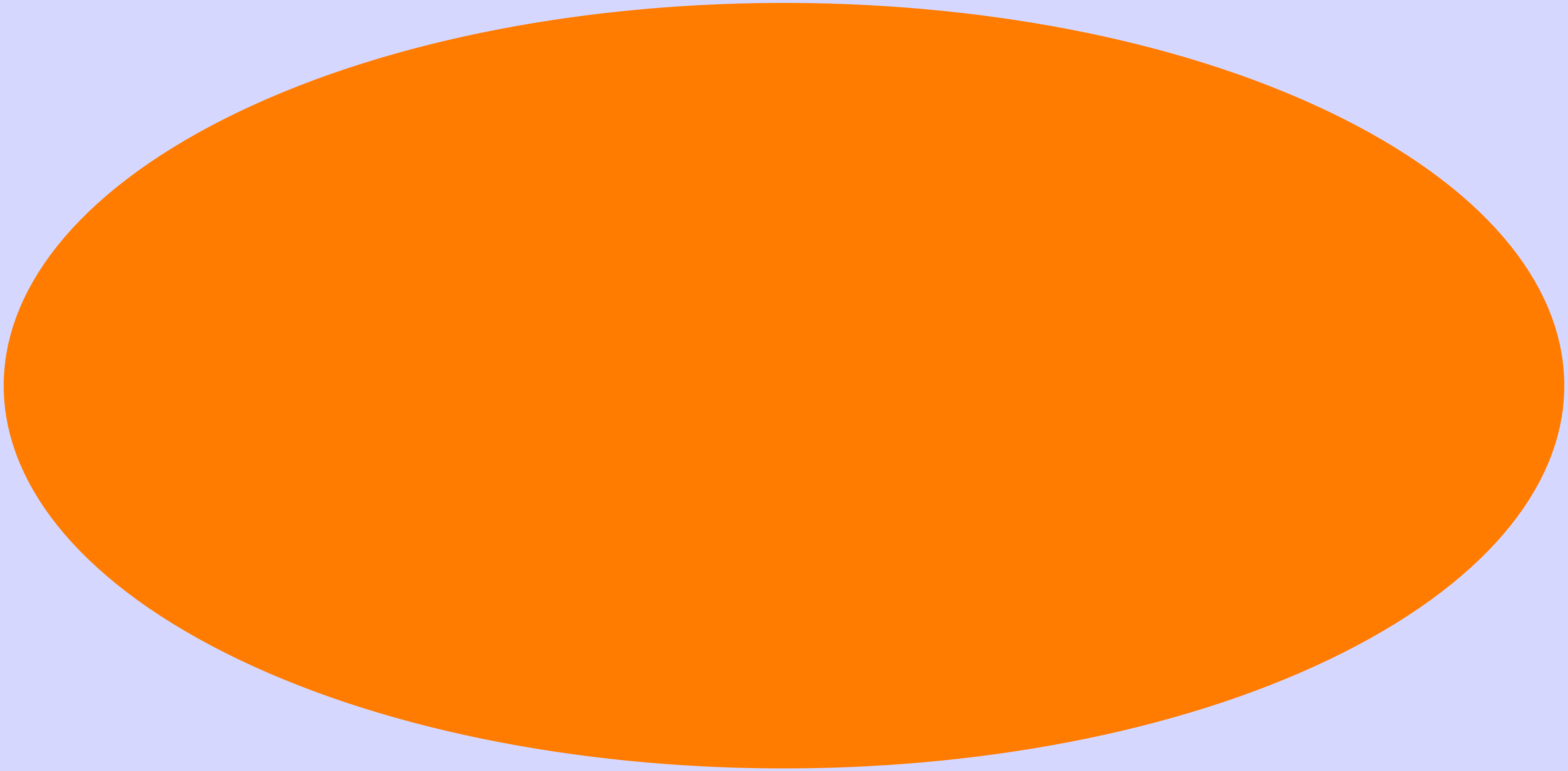
Cosmic microwave background radiation

AP990011

1960's: Discovery of the CMB



c.1990: Map of CMB Brightness



Brightness is isotropic – same in all directions!

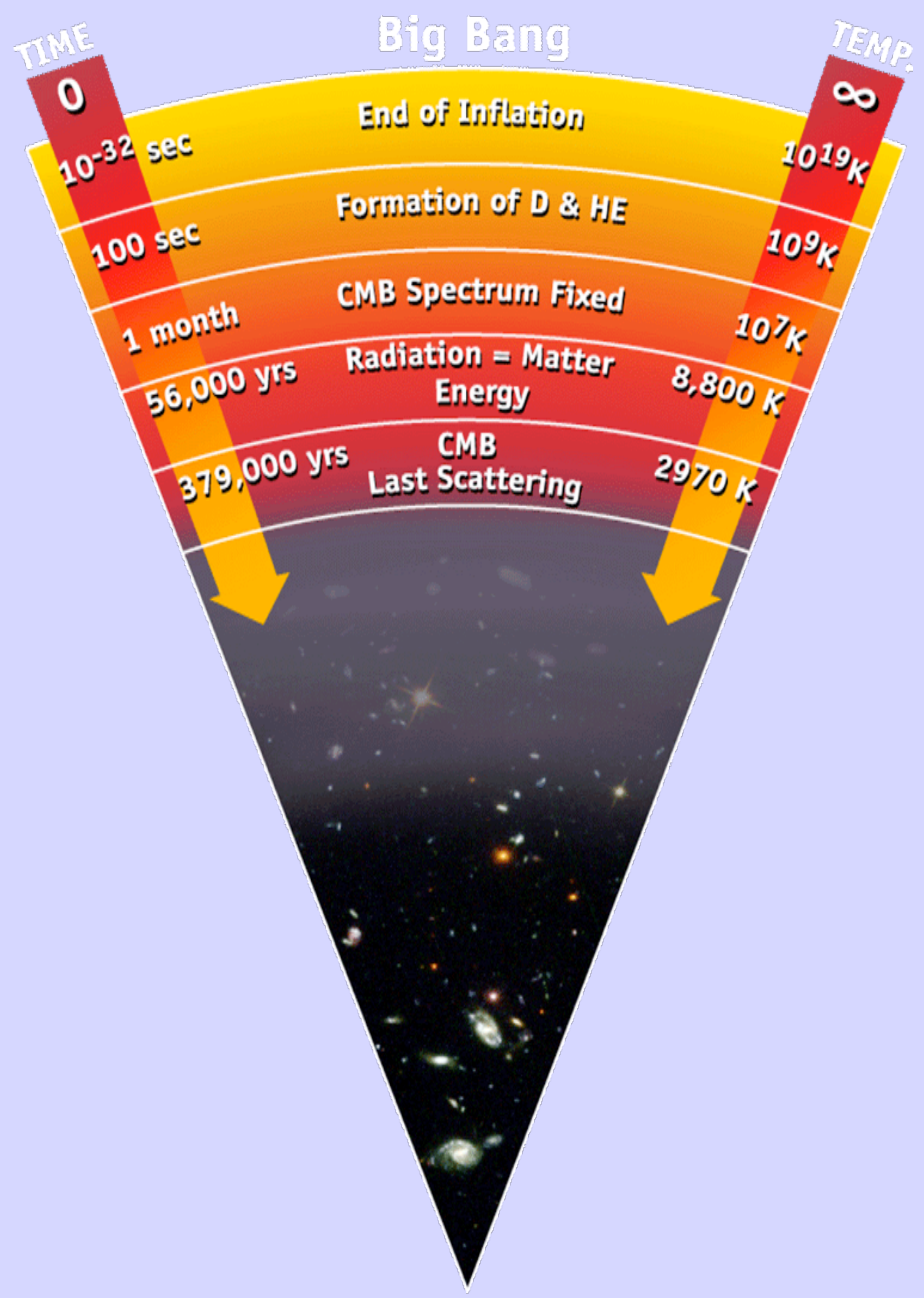
(COBE-DMR "early result" temperature anisotropy map – isotropic to ~100 ppm of mean brightness)

Review: Three Pillars of the Big Bang

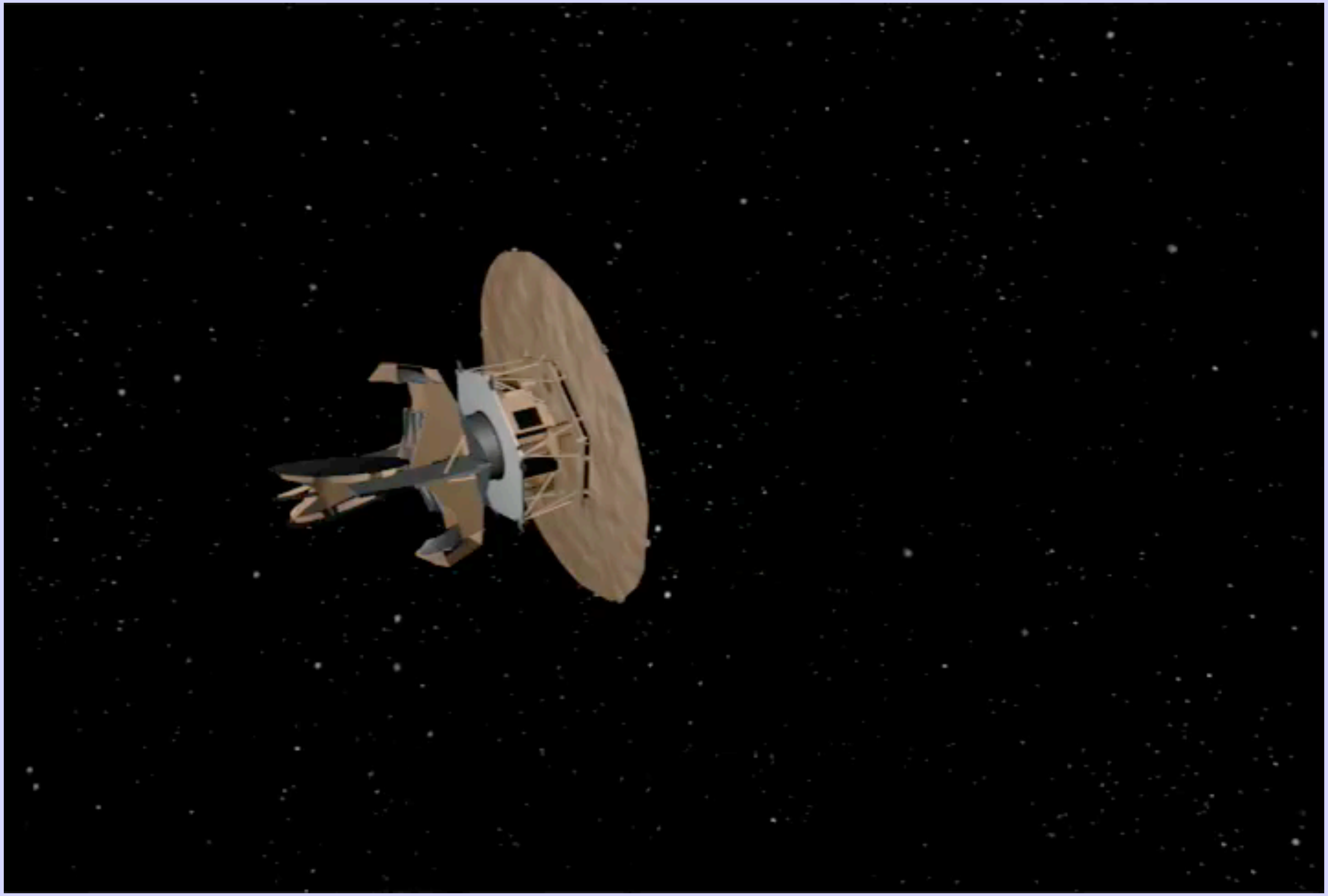
- **General Relativity and expansion** –
  Einstein, Hubble,…
- **Abundance of light elements: D, He,** …–
  Alpher, Herman, Gamow, …
- **Cosmic microwave background radiation –**
  Alpher, Herman, Penzias, Wilson,…

Remainder of talk will mostly focus on what we have learned from studying the cosmic microwave background (CMB) radiation.

Time travel: out in space = back in time



A Journey: Out in Space, Back in Time



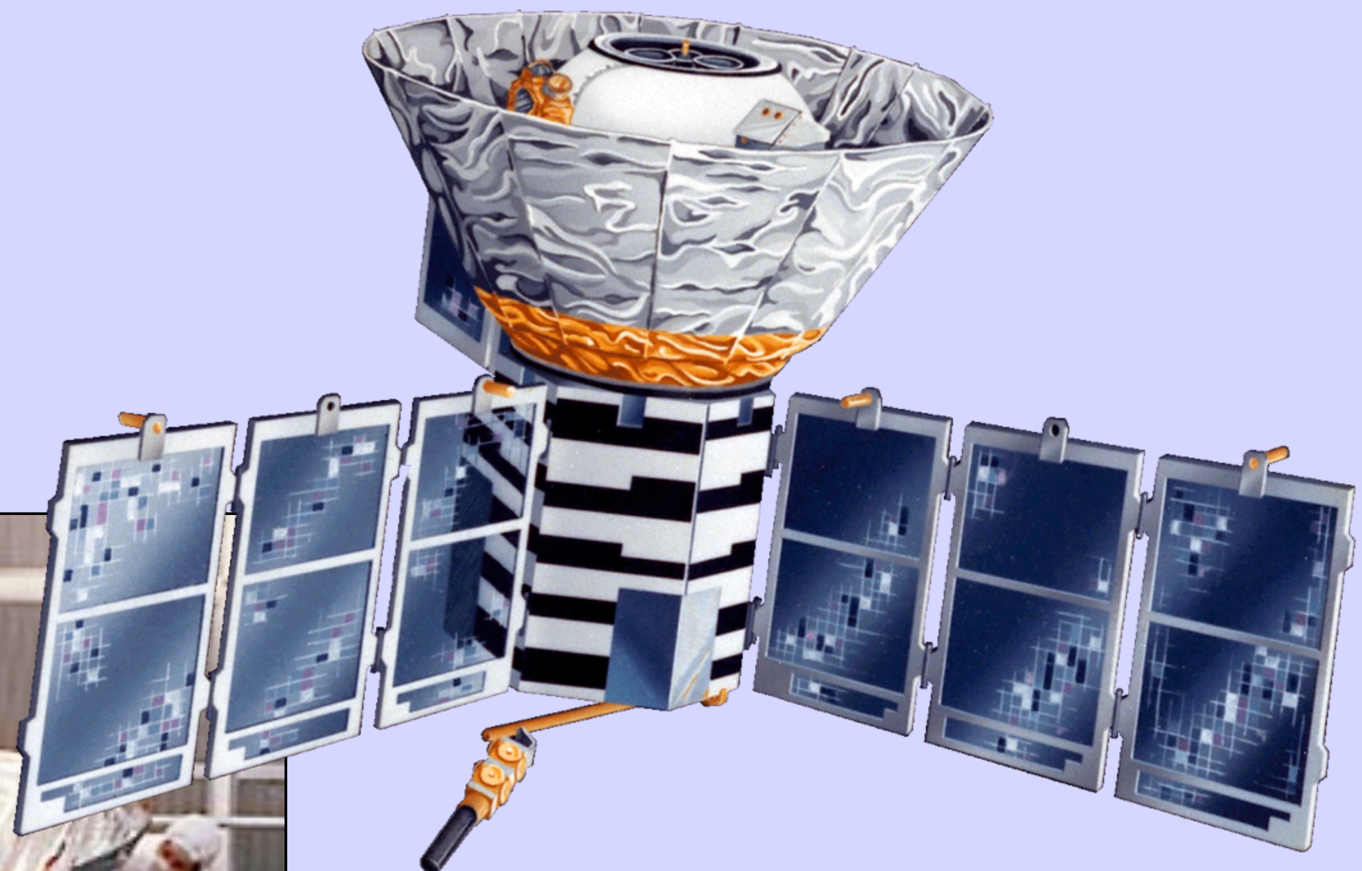
COSMIC BACKGROUND EXPLORER (COBE)

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 $\Delta T/T \sim 10^{-5}$



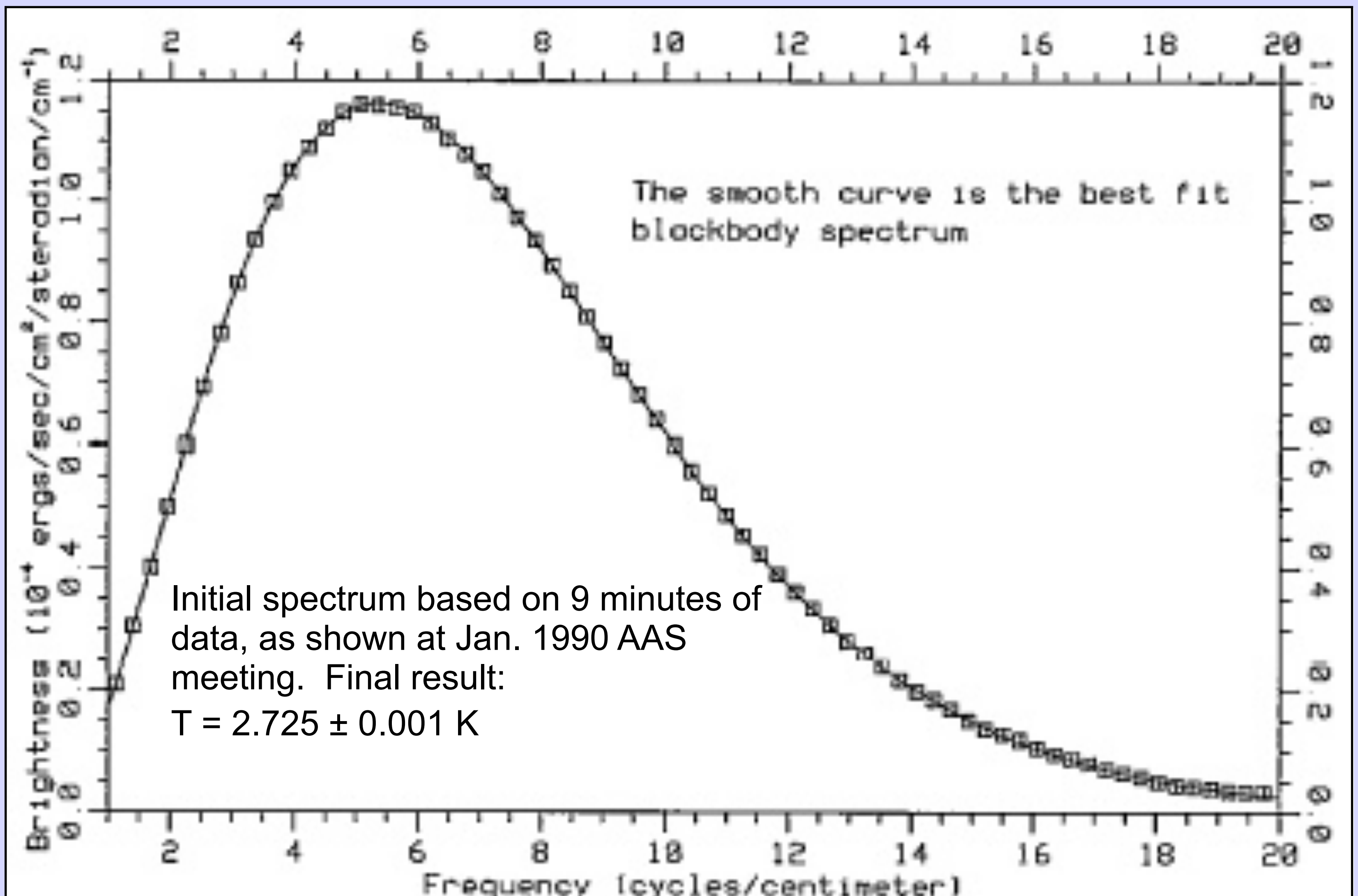
1990: Blackbody Spectrum of the CMB

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

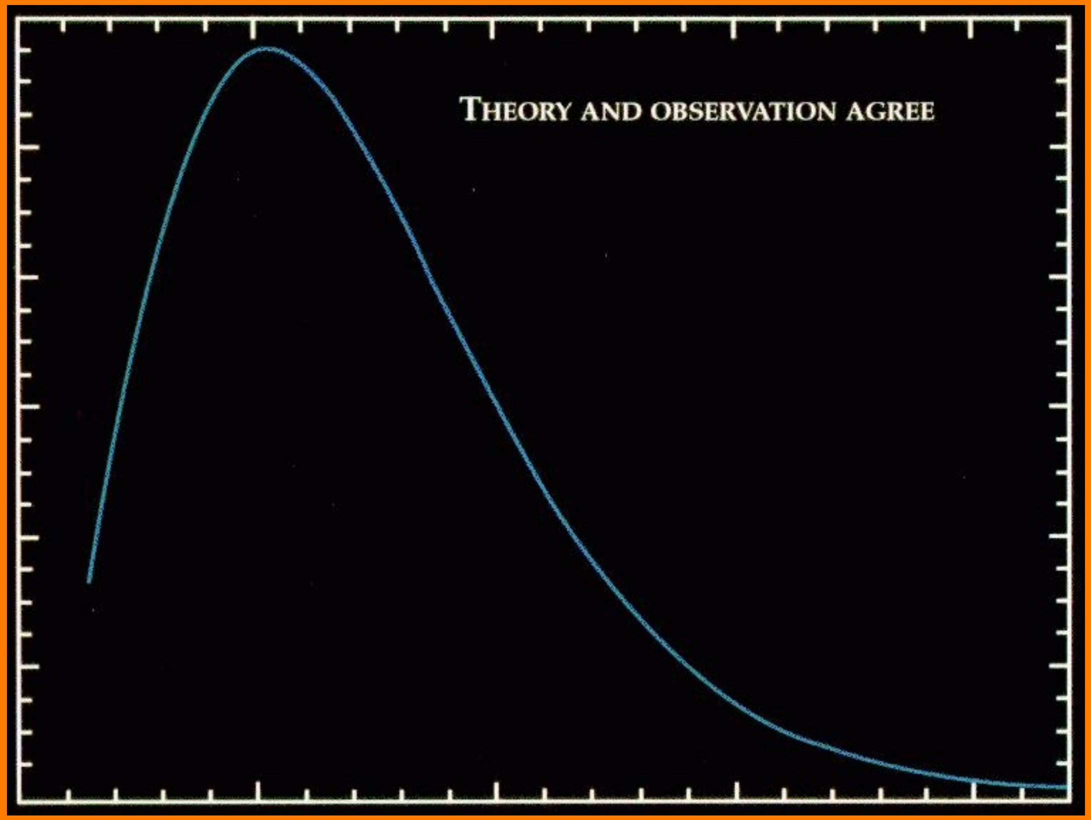
J. C. MATHER,[2] E. S. CHENG,[2] R. E. EPLEE, JR.,[3] R. B. ISAACMAN,[3] S. S. MEYER,[4] R. A. SHAFER,[2] R. WEISS,[4] E. L. WRIGHT,[5] C. L. BENNETT, N. W. BOGGESS,[2] E. DWEK,[2] S. GULKIS,[6] M. G. HAUSER,[2] M. JANSSEN,[6] T. KELSALL,[2] P. M. LUBIN,[7] S. H. MOSELEY, JR.,[2] T. L. MURDOCK,[8] R. F. SILVERBERG,[2] G. F. SMOOT,[9] AND D. T. WILKINSON[10]

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

2006

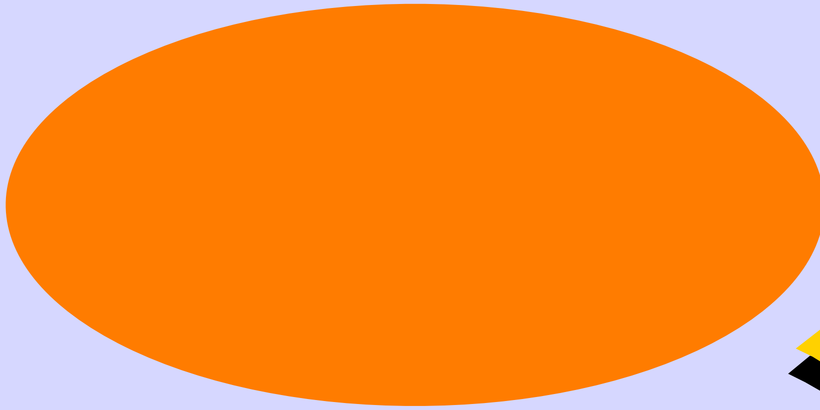


The Simplicity of the Early Universe



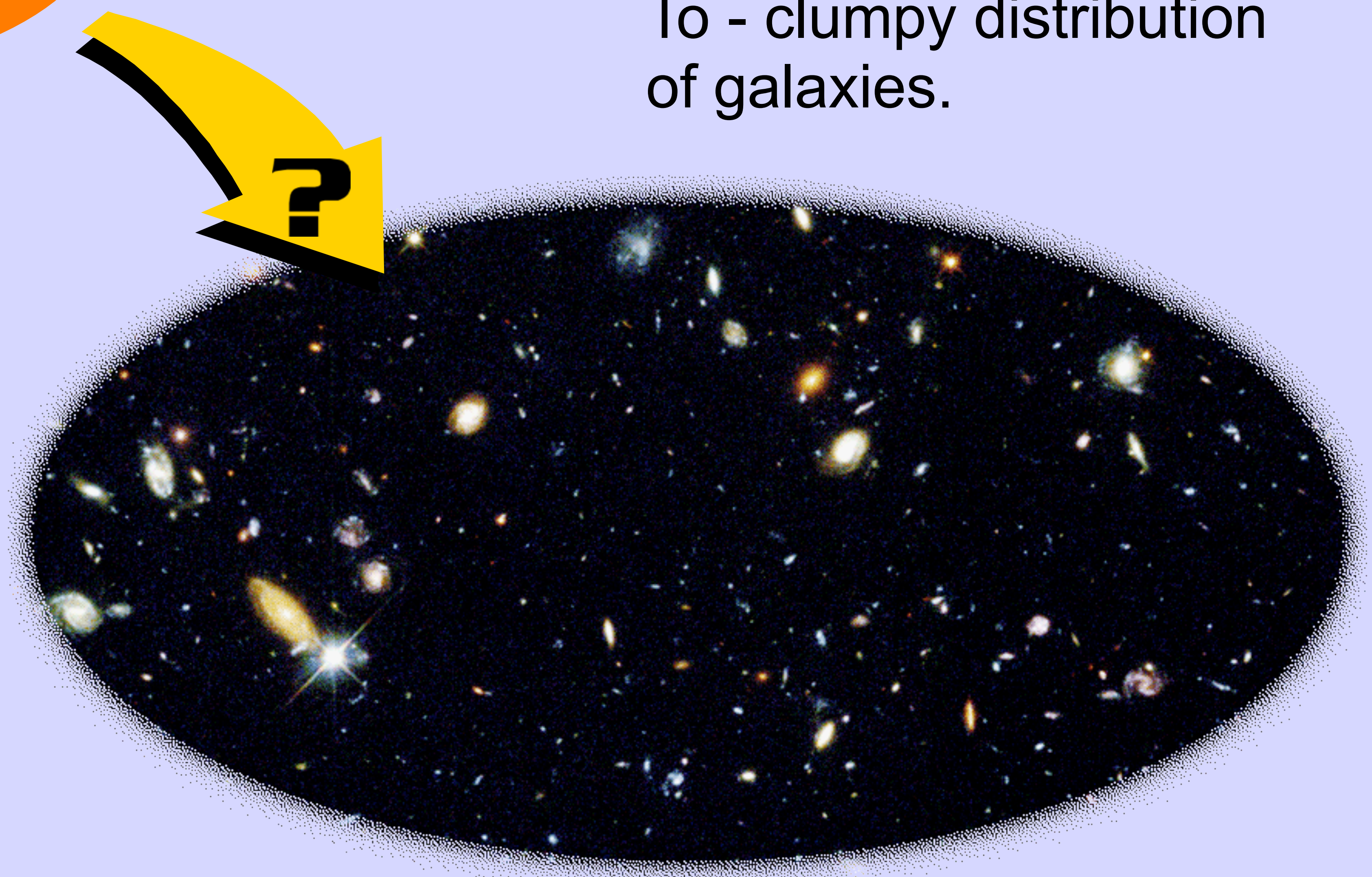
Important test! It is very difficult to produce such uniform blackbody radiation by any other means than with Big Bang evolution.

The Structure Problem



From - smooth
cosmic microwave
background radiation

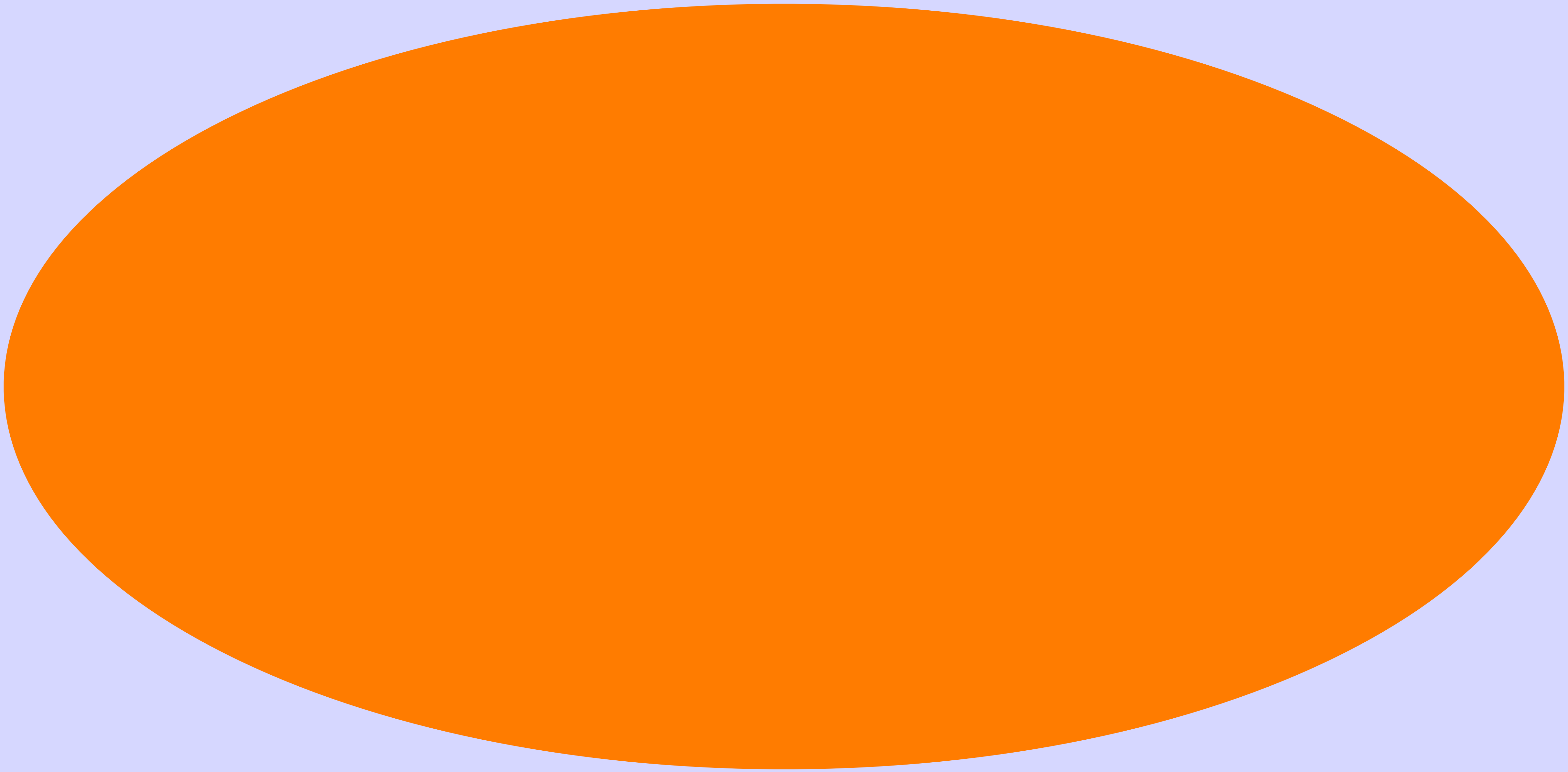
To - clumpy distribution
of galaxies.



How did this happen?

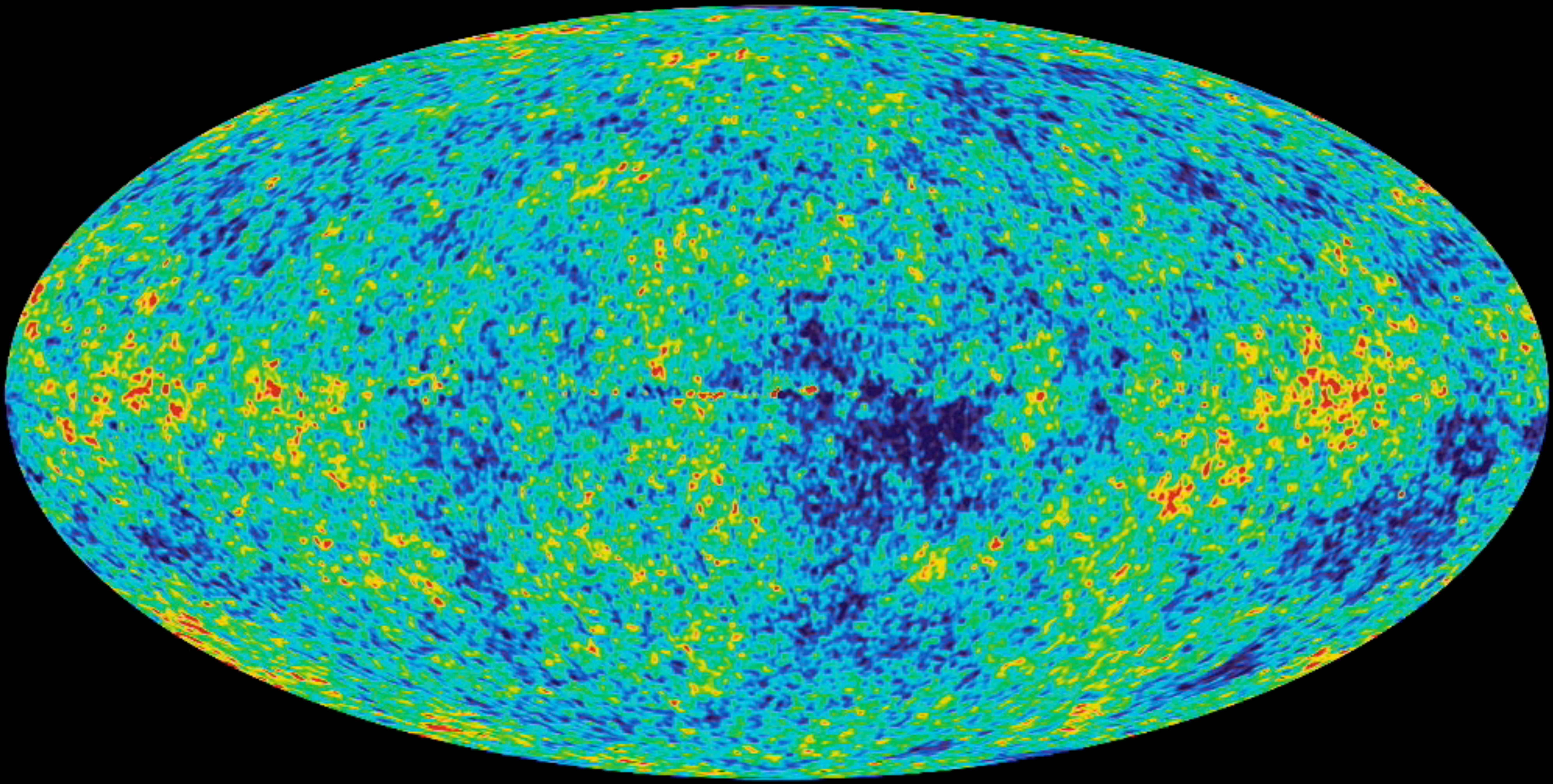
MAP990012

Where is the Anisotropy (Structure)?

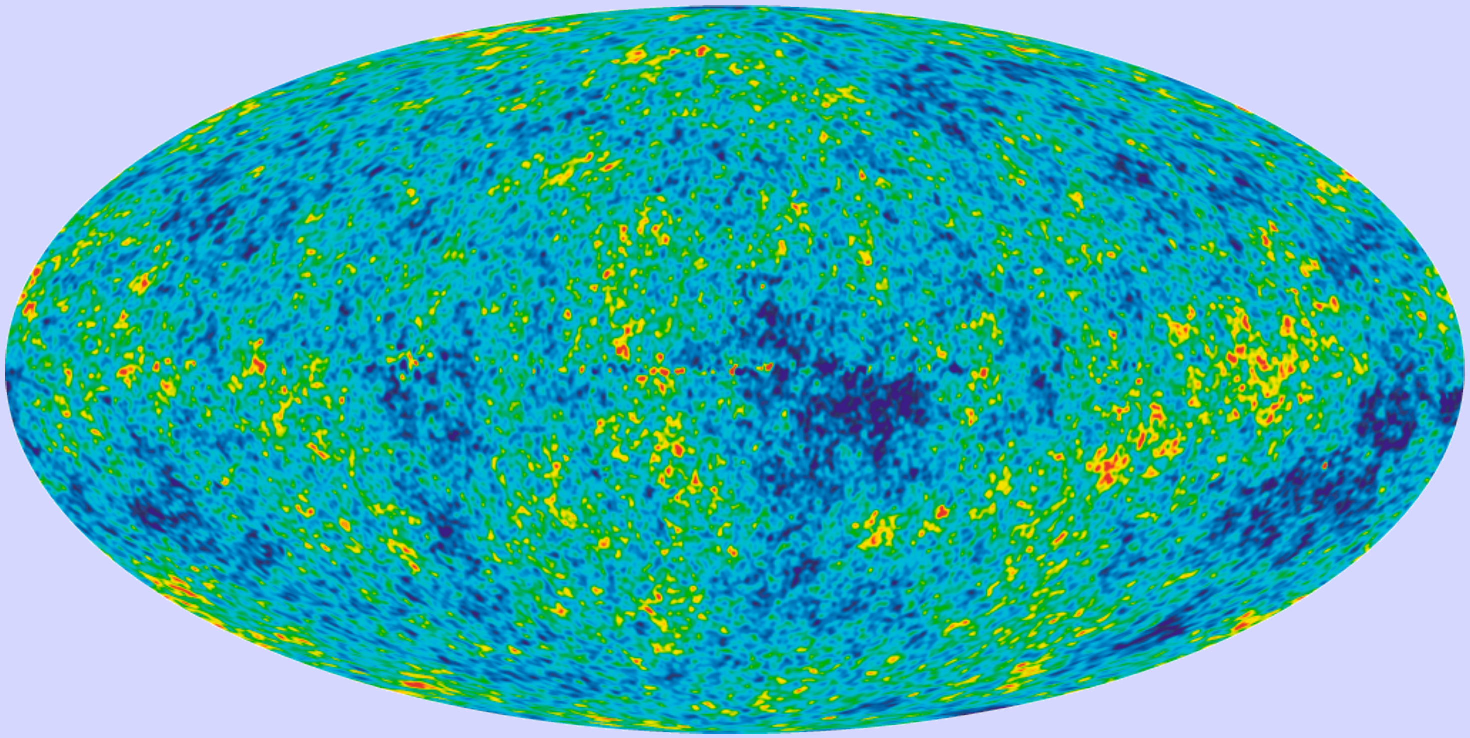


If ideas about growth of structure are correct, there should be variations in the CMB brightness ("temperature") across the sky that track density variations in the hydrogen gas that emitted the light.

Gravitational Growth of Structure

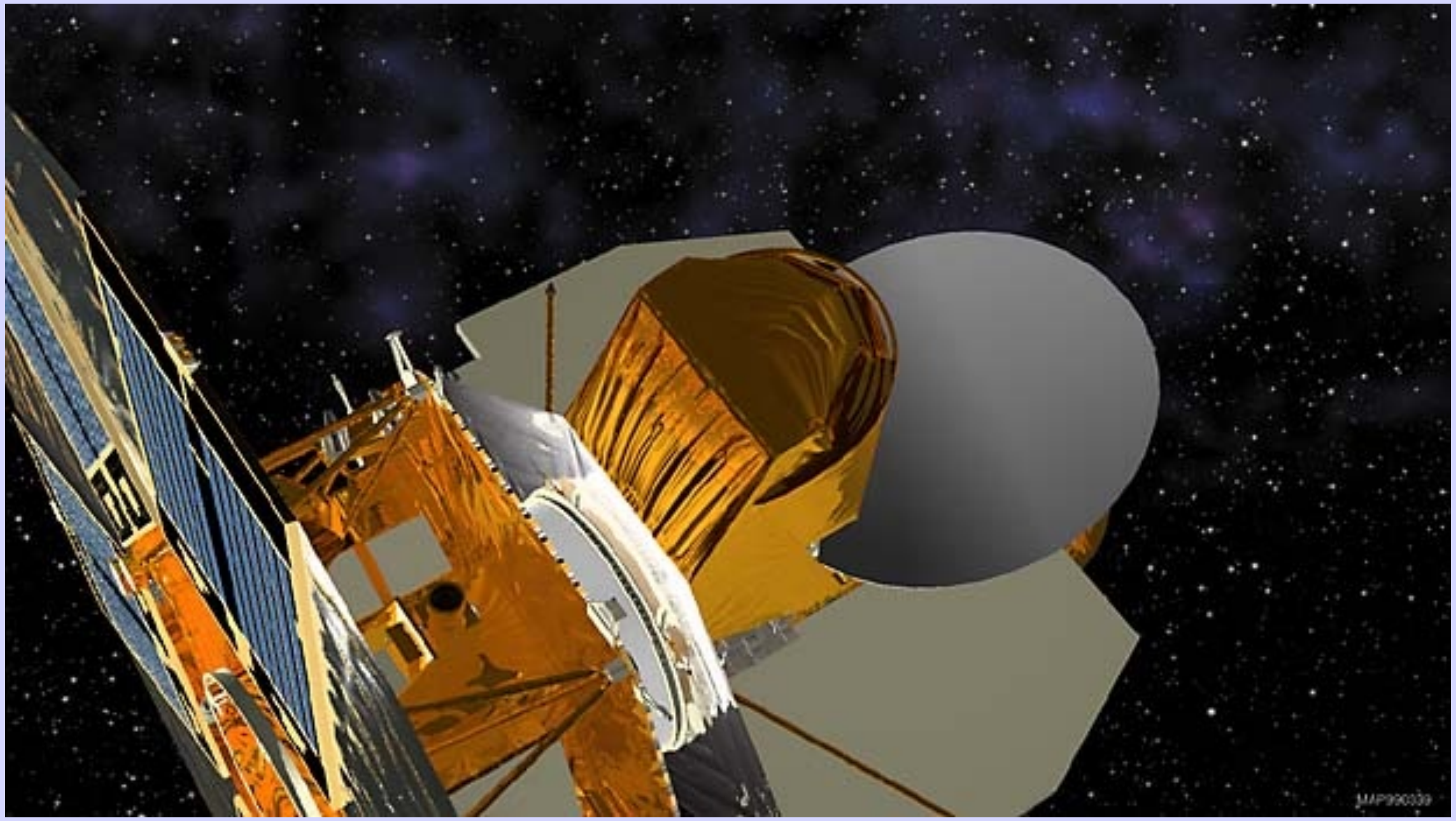


Wilkinson Microwave Anisotropy Probe (WMAP)

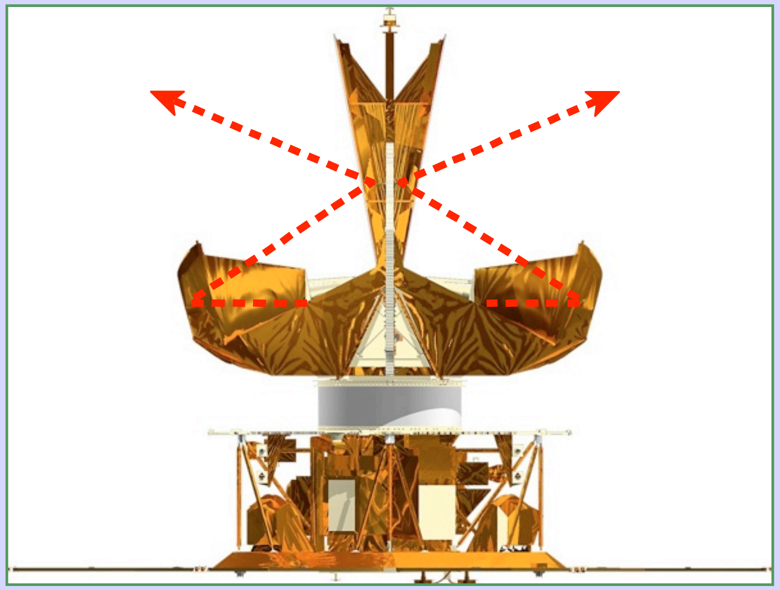


WMAP'S PURPOSE –

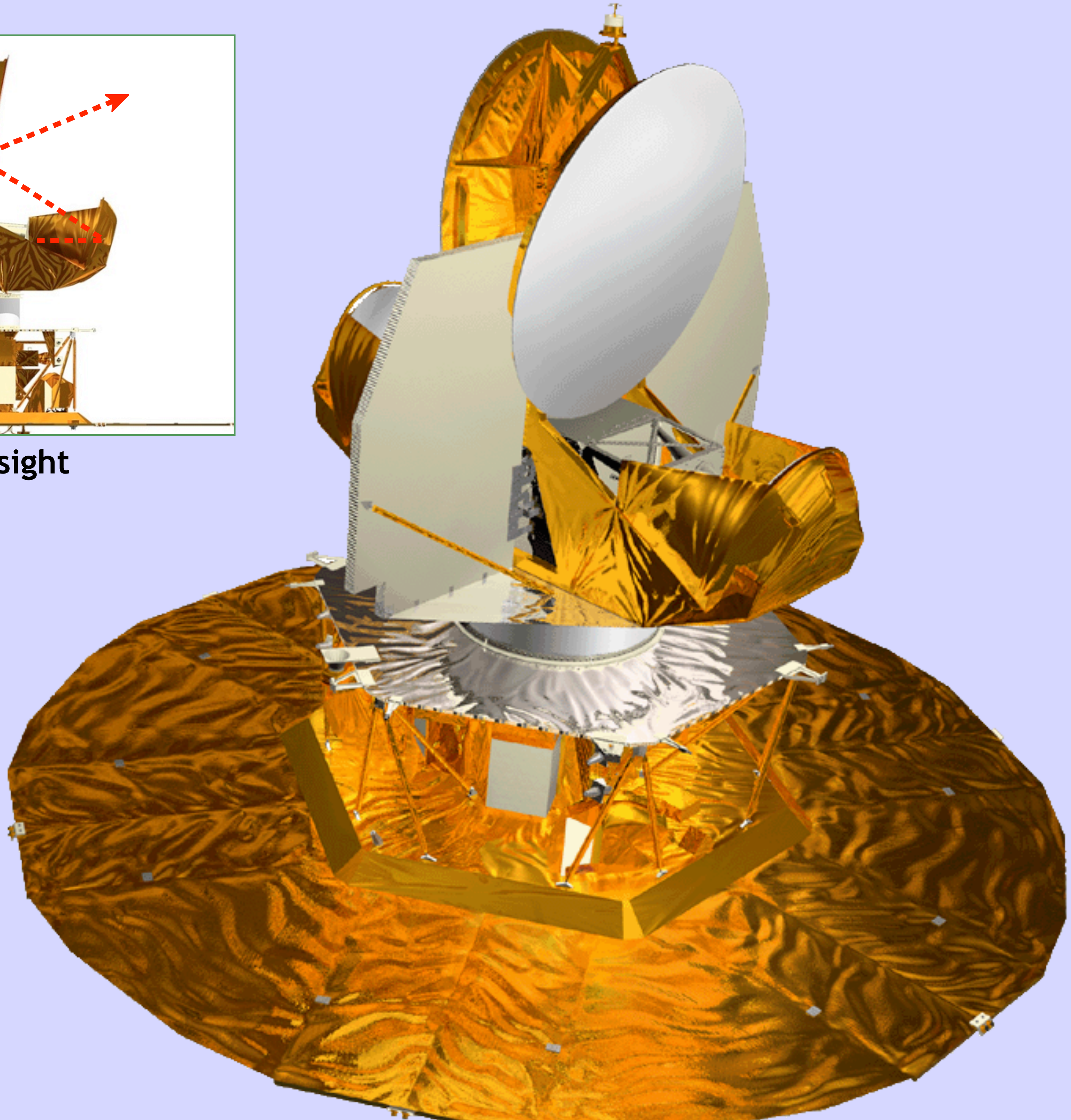
To make a detailed full-sky map of the CMB radiation anisotropy (temperature and polarization) to constrain the cosmology of our universe.



WMAP's Differential Design



lines of sight

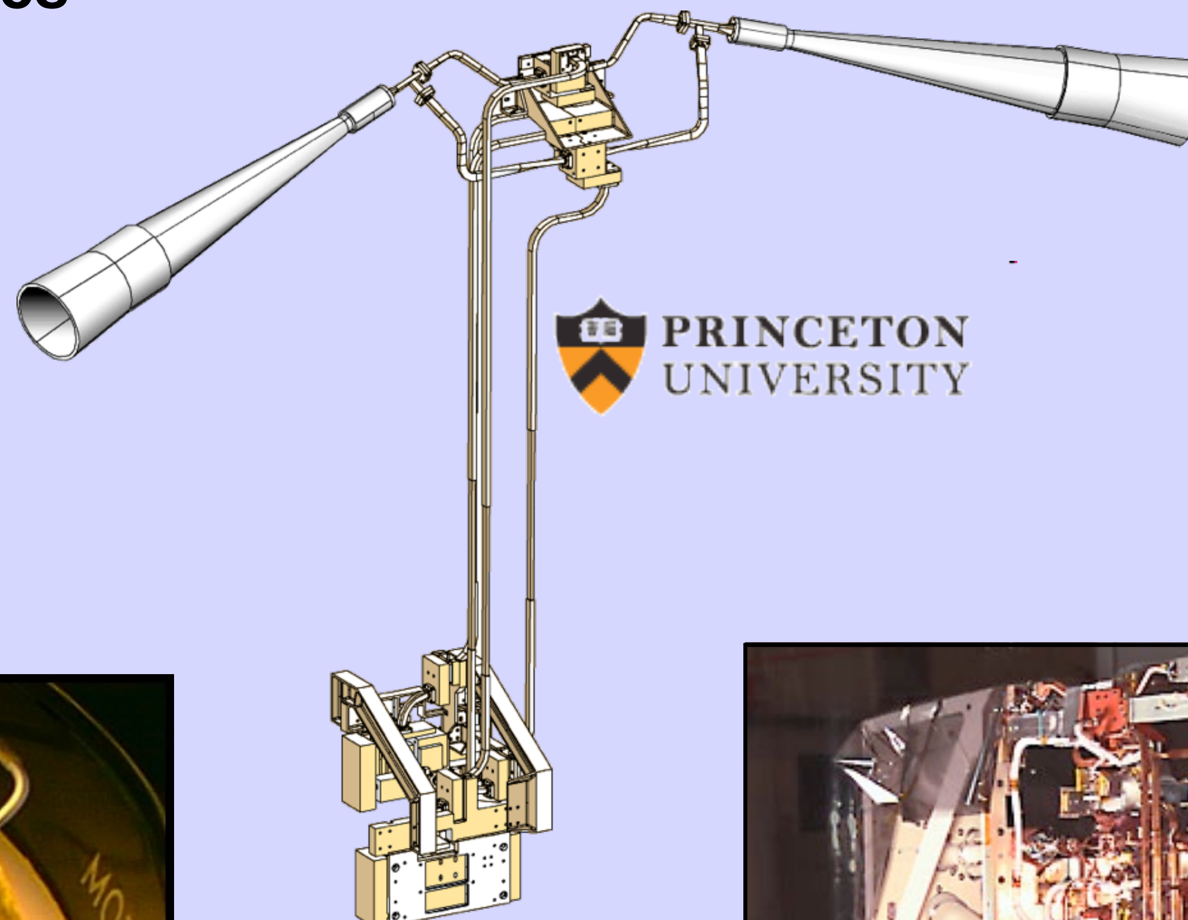


Accurately Measuring a Part-in-a-Million

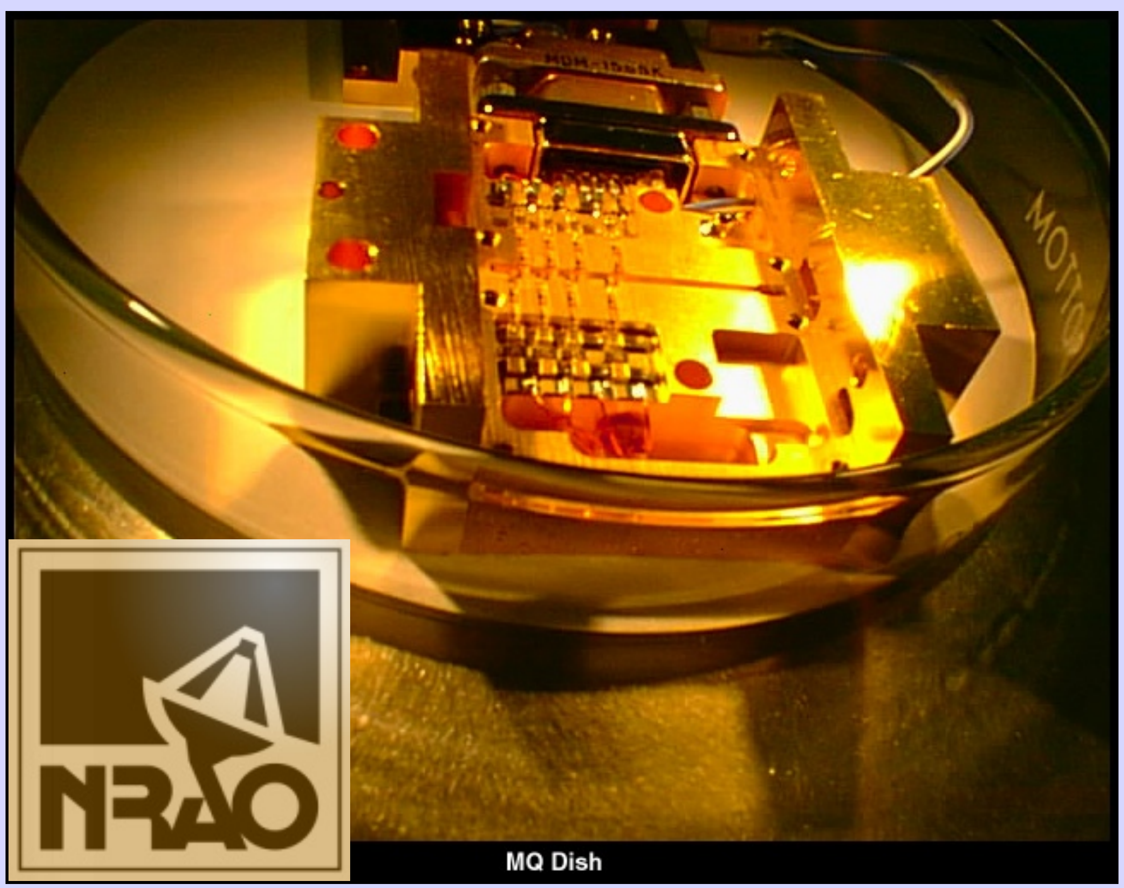
HEMT-Based Differential Receivers*

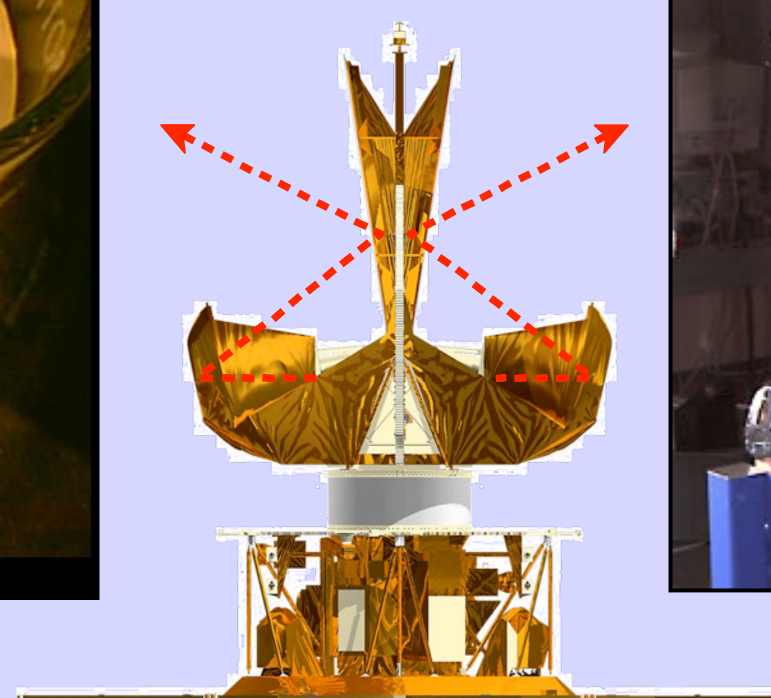
10 "Differencing Assemblies"

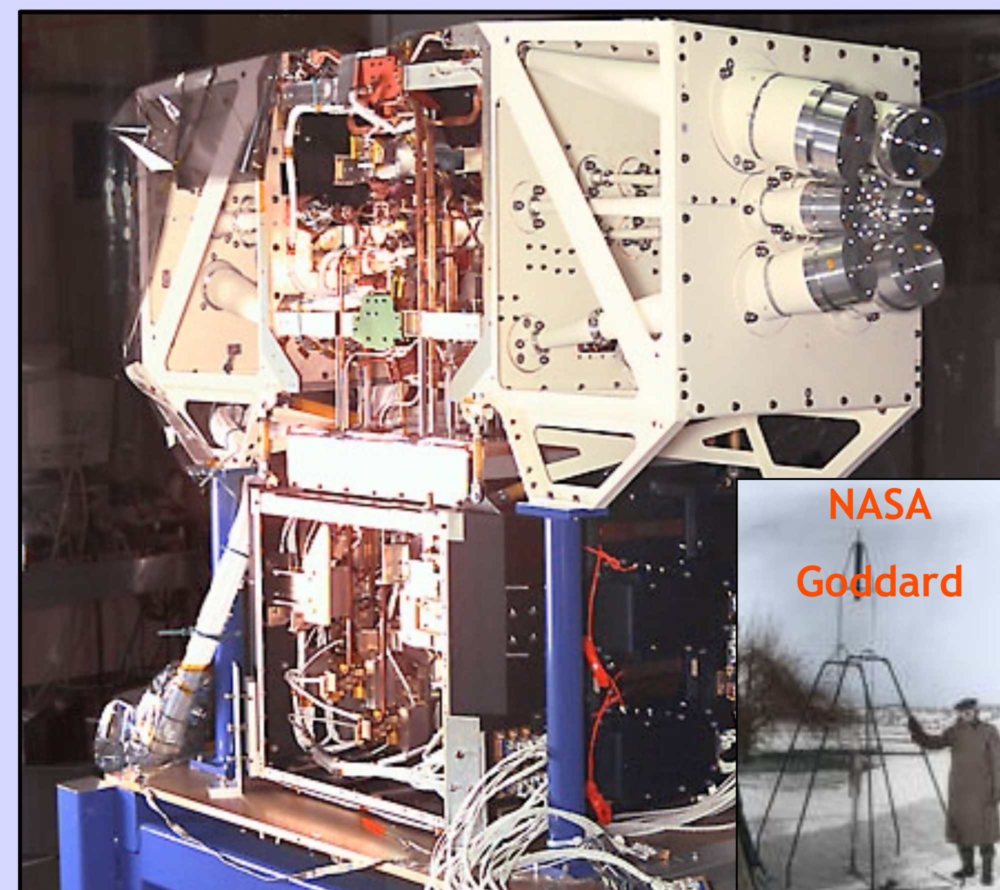
4 @ 94 GHz W-band
2 @ 61 GHz V-band
2 @ 41 GHz Q-band
1 @ 33 GHz Ka-band
1 @ 23 GHz K-band



PRINCETON UNIVERSITY

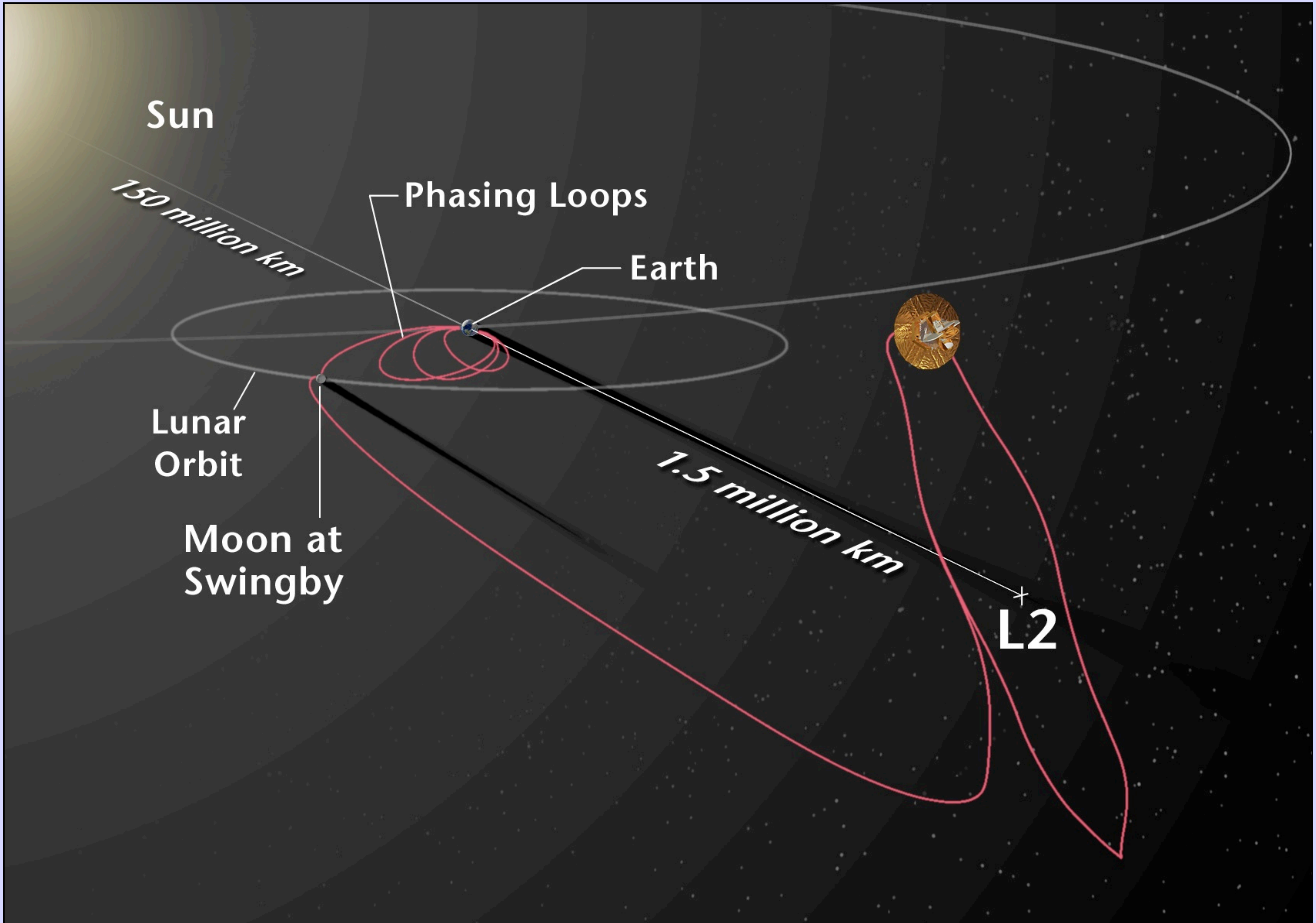






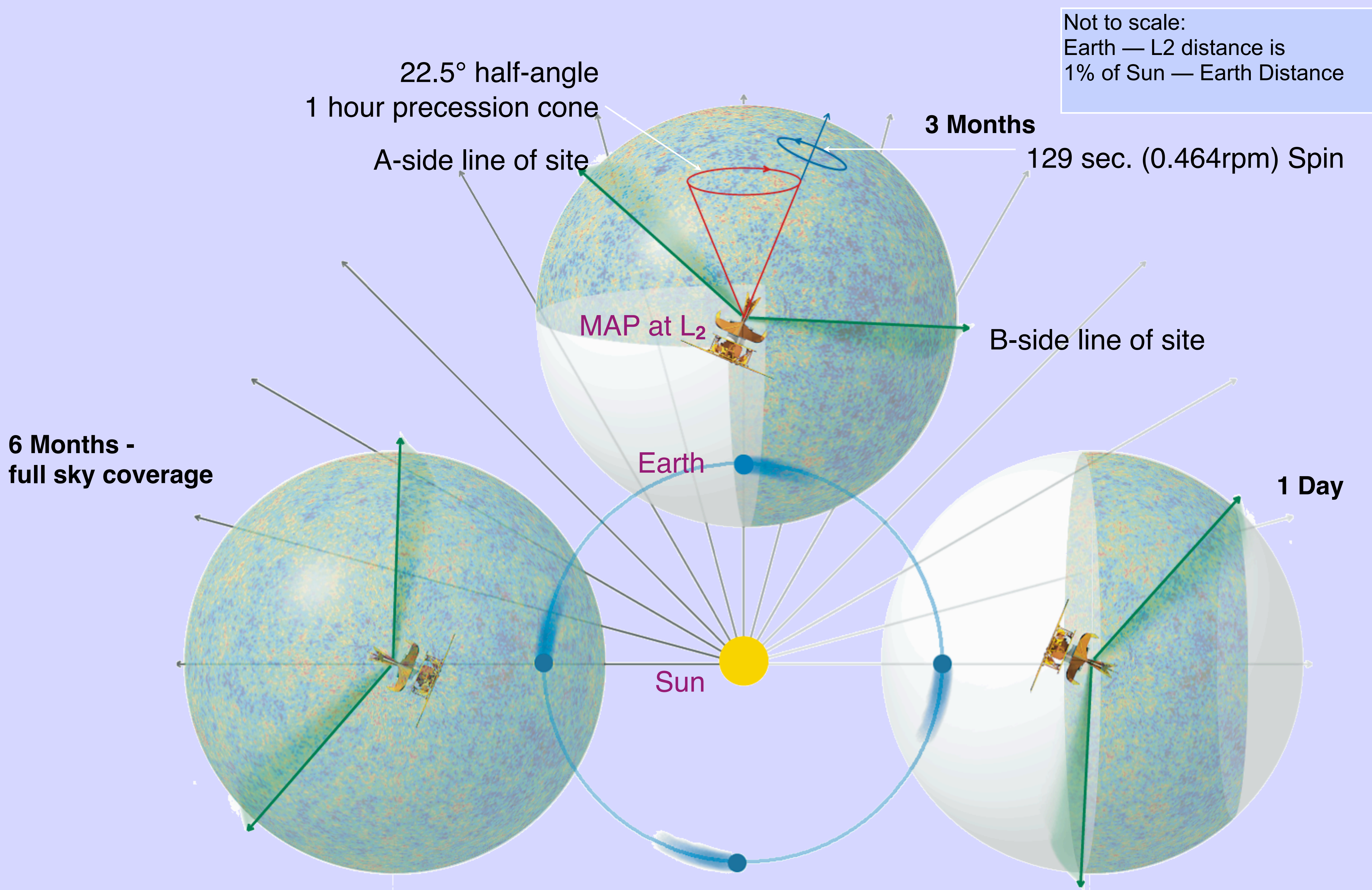
*based on design of M. Pospieszalski

WMAP at L2



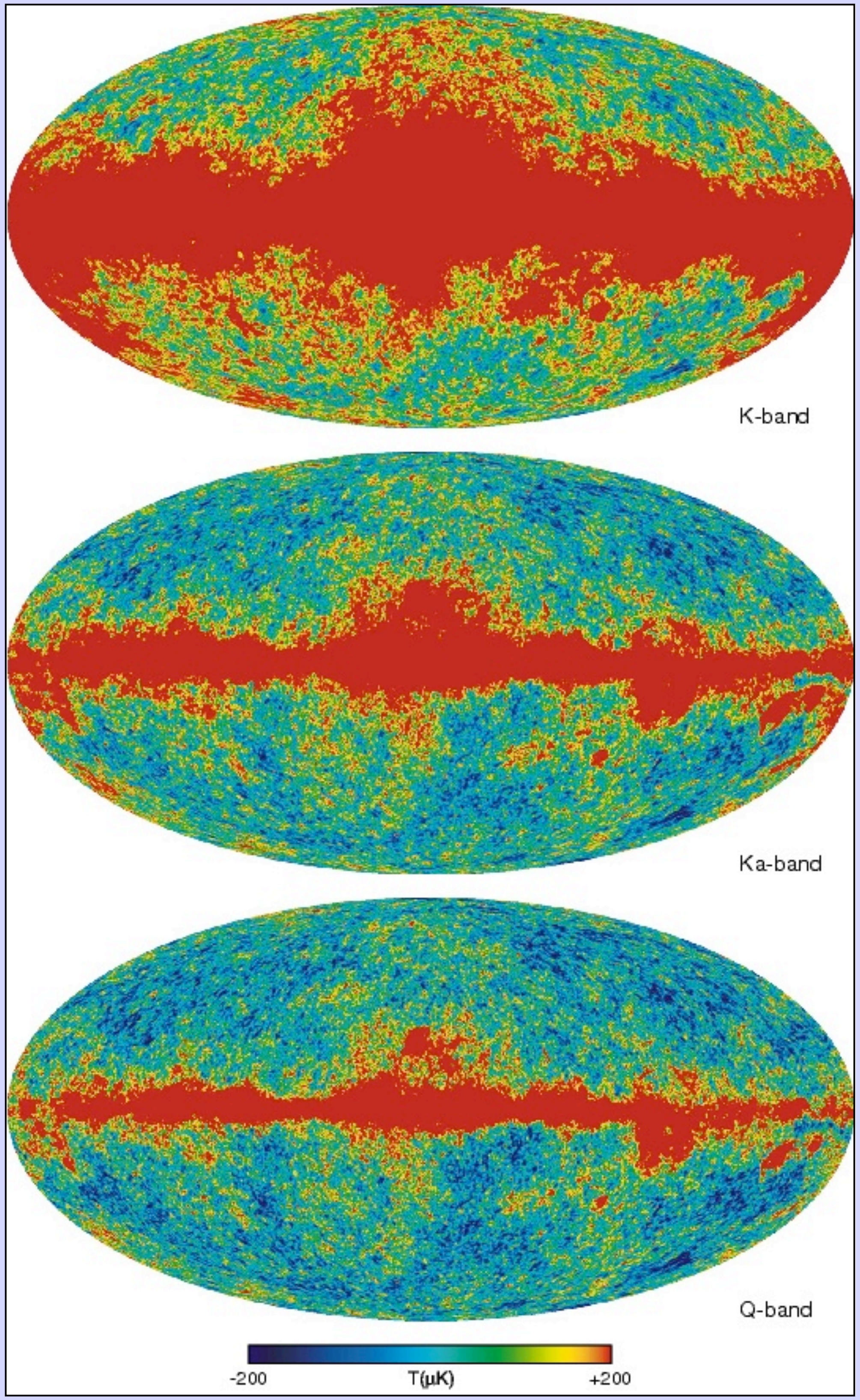
Sun
150 million km
Phasing Loops
Earth
Lunar Orbit
Moon at Swingby
1.5 million km
L2

WMAP Sky Coverage



Sky Maps

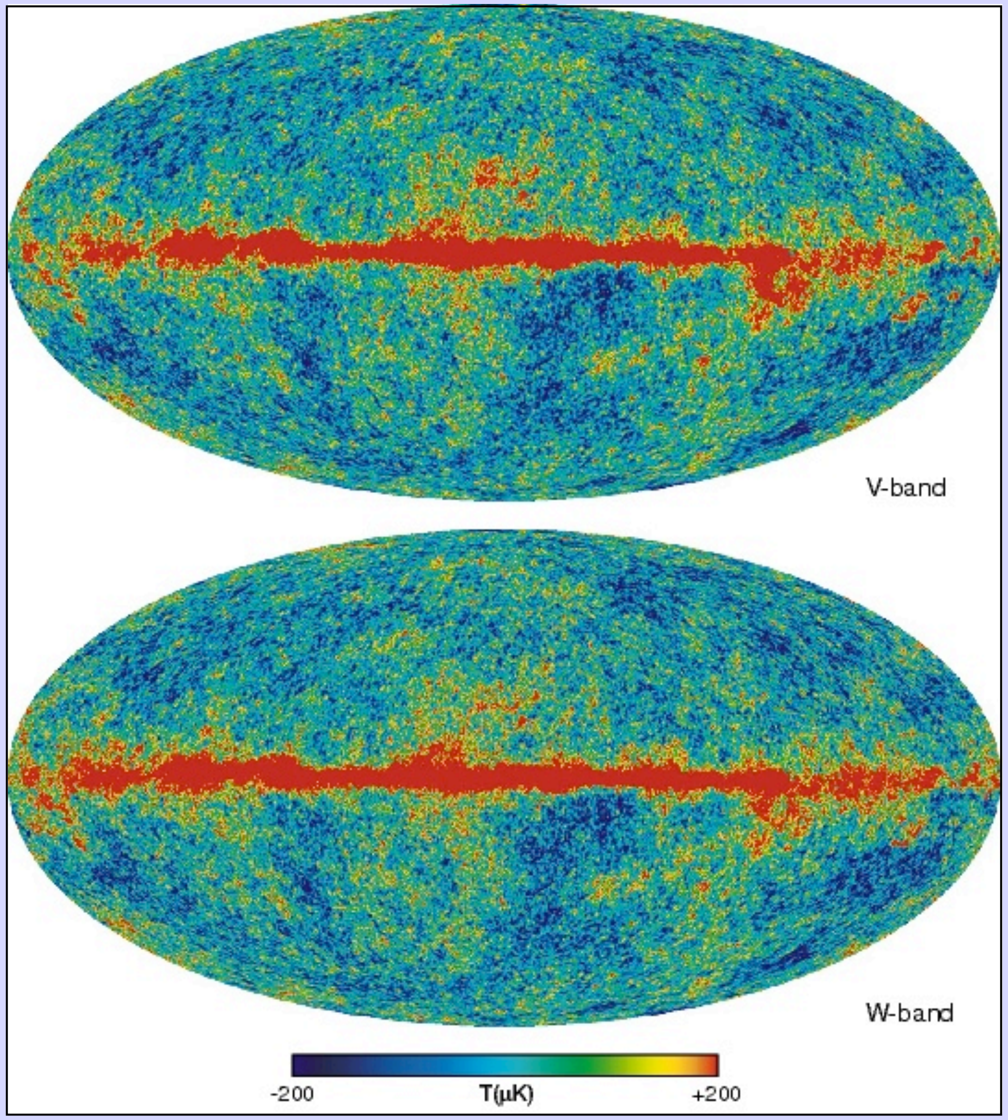
WMAP Full Sky Temperature Maps



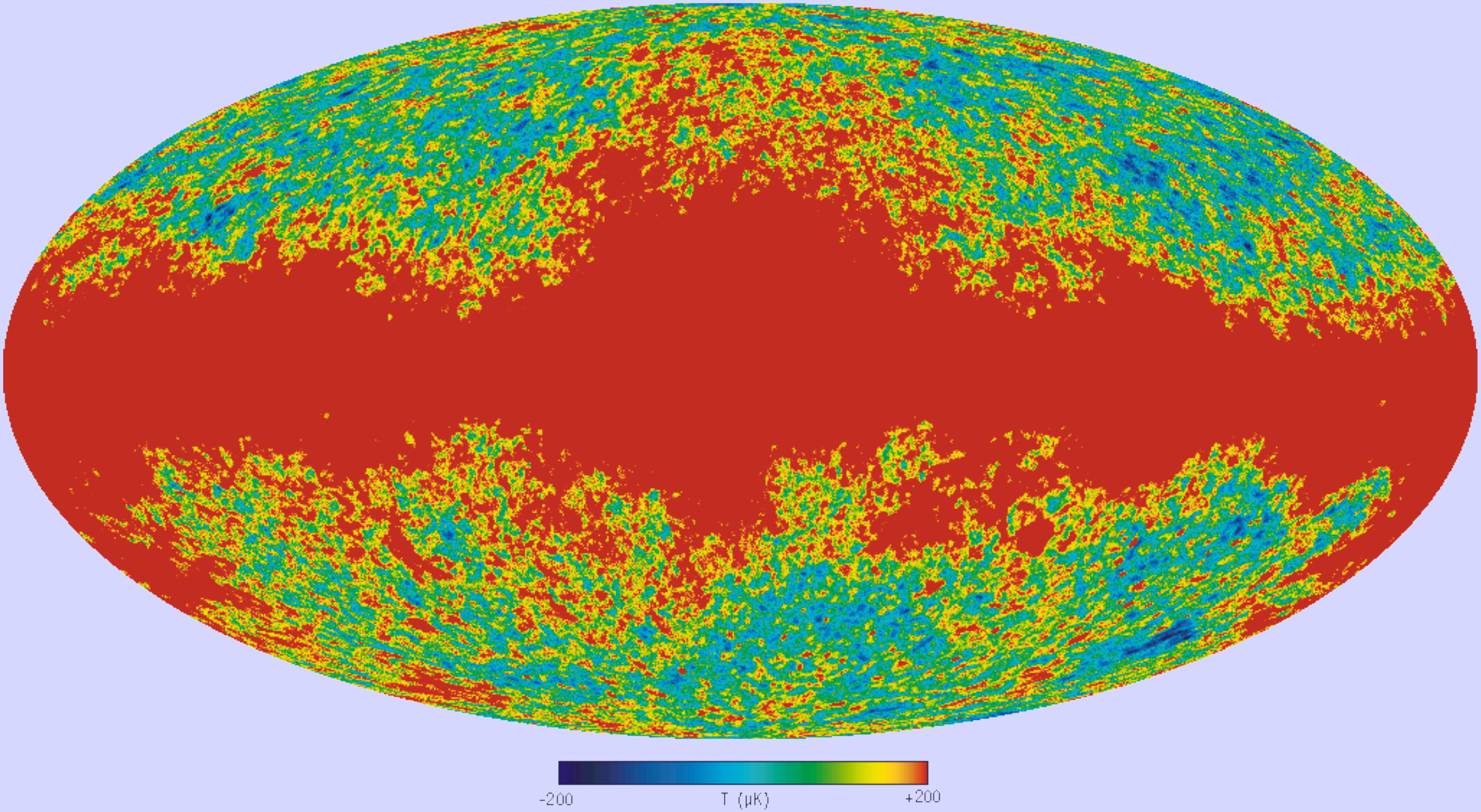
23 GHz
33 GHz
41 GHz

61 GHz
94 GHz

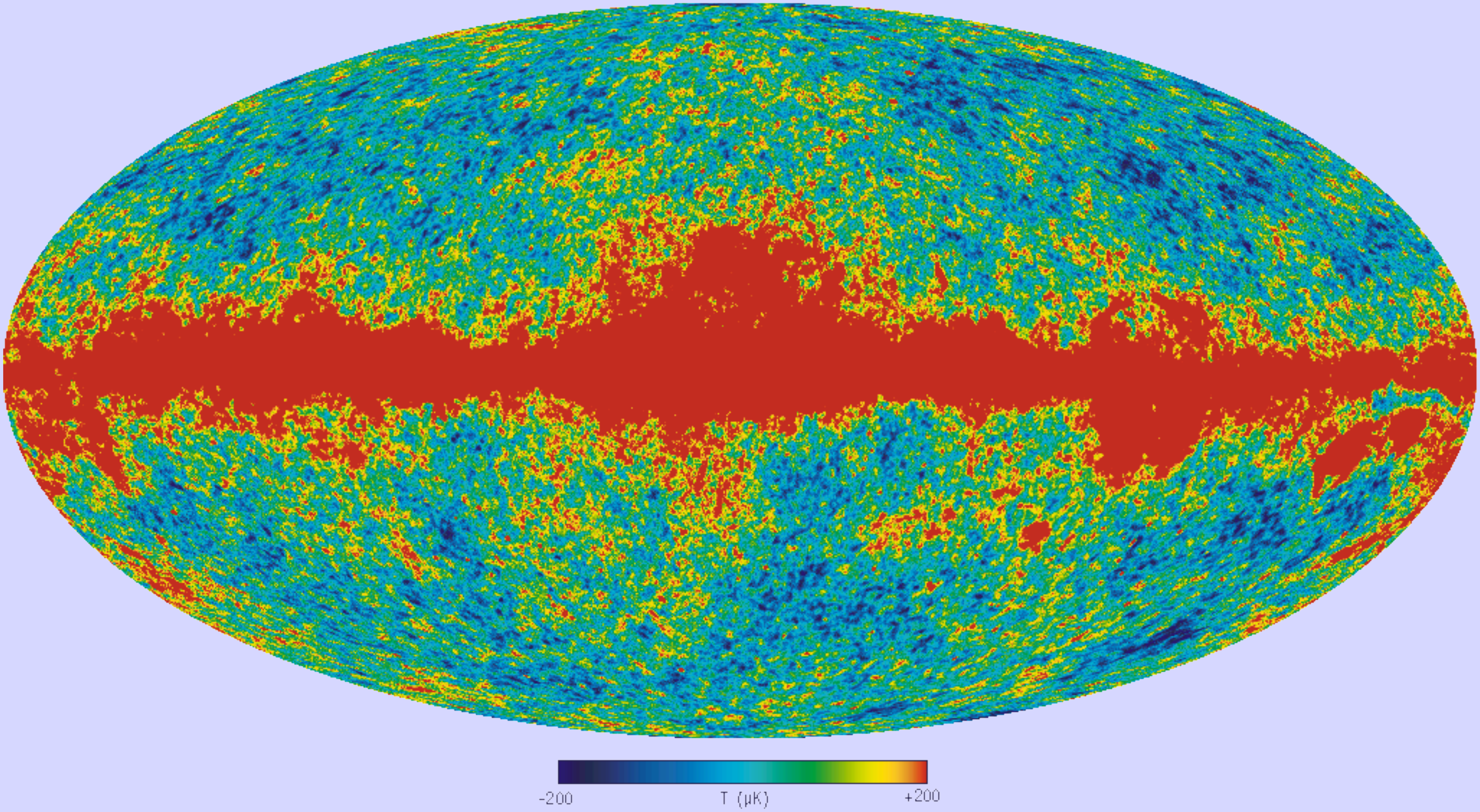
Color scale: ±200 μK
Smoothing: 0.2° FWHM



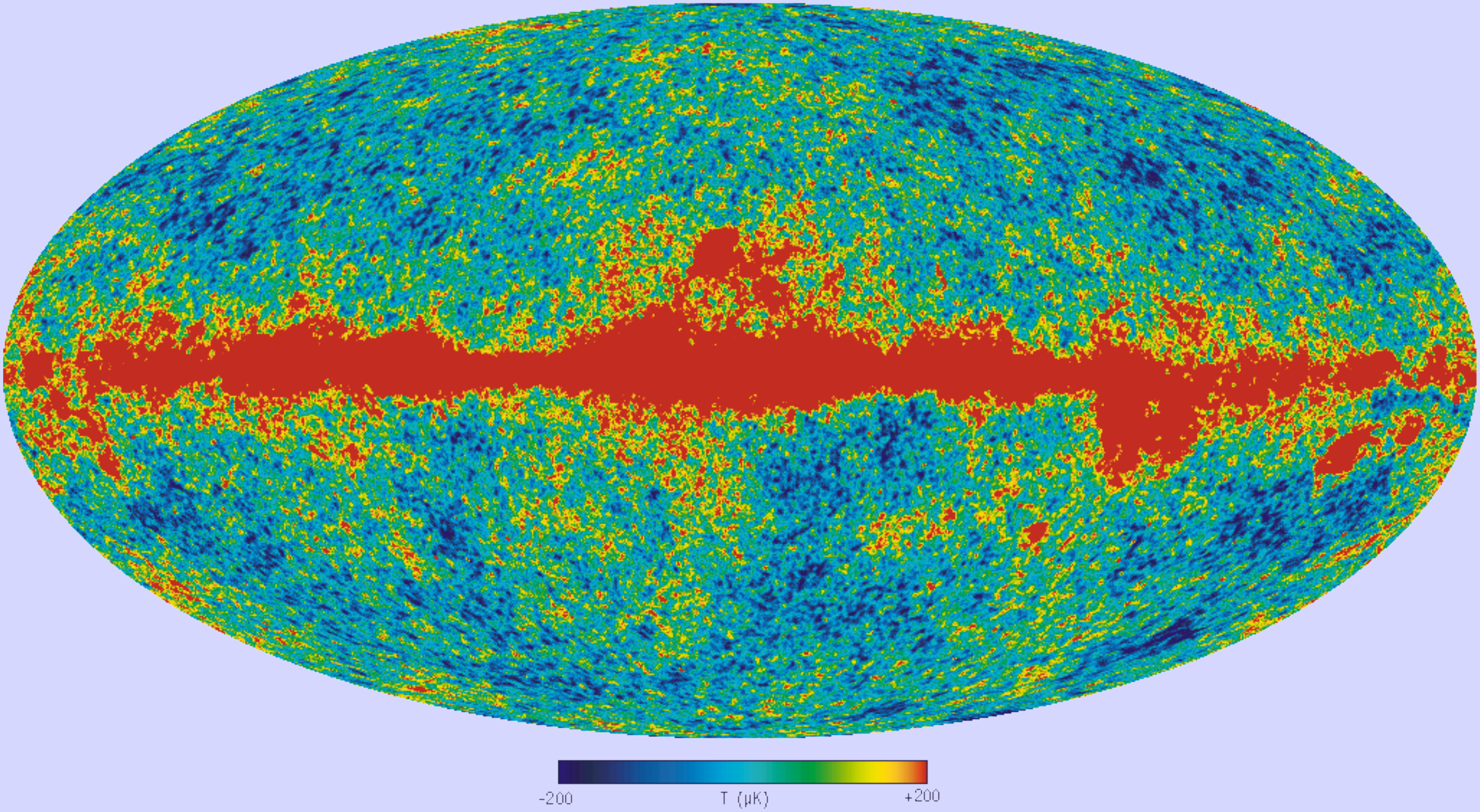
K Band Temperature, 23 GHz



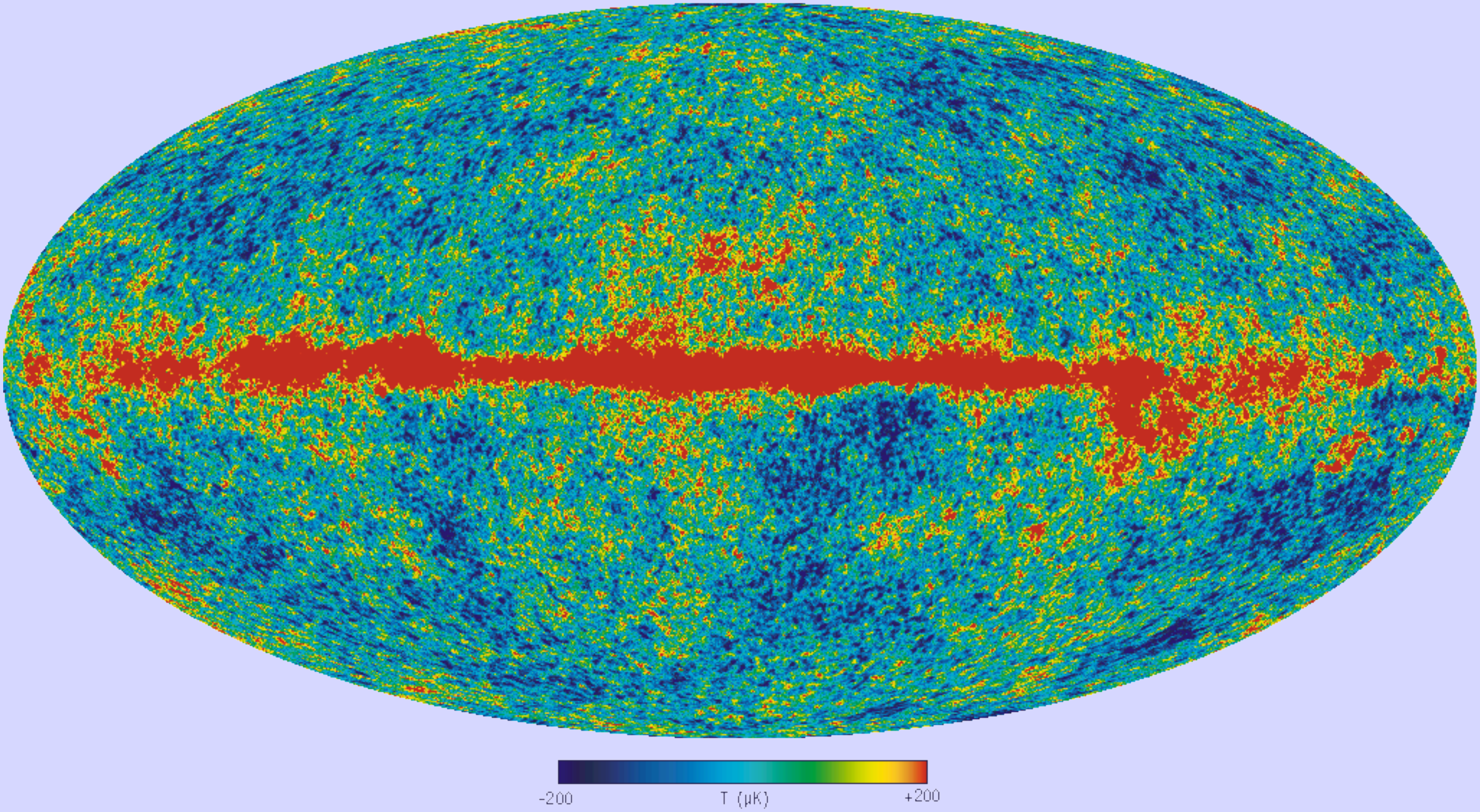
Ka Band Temperature, 33 GHz



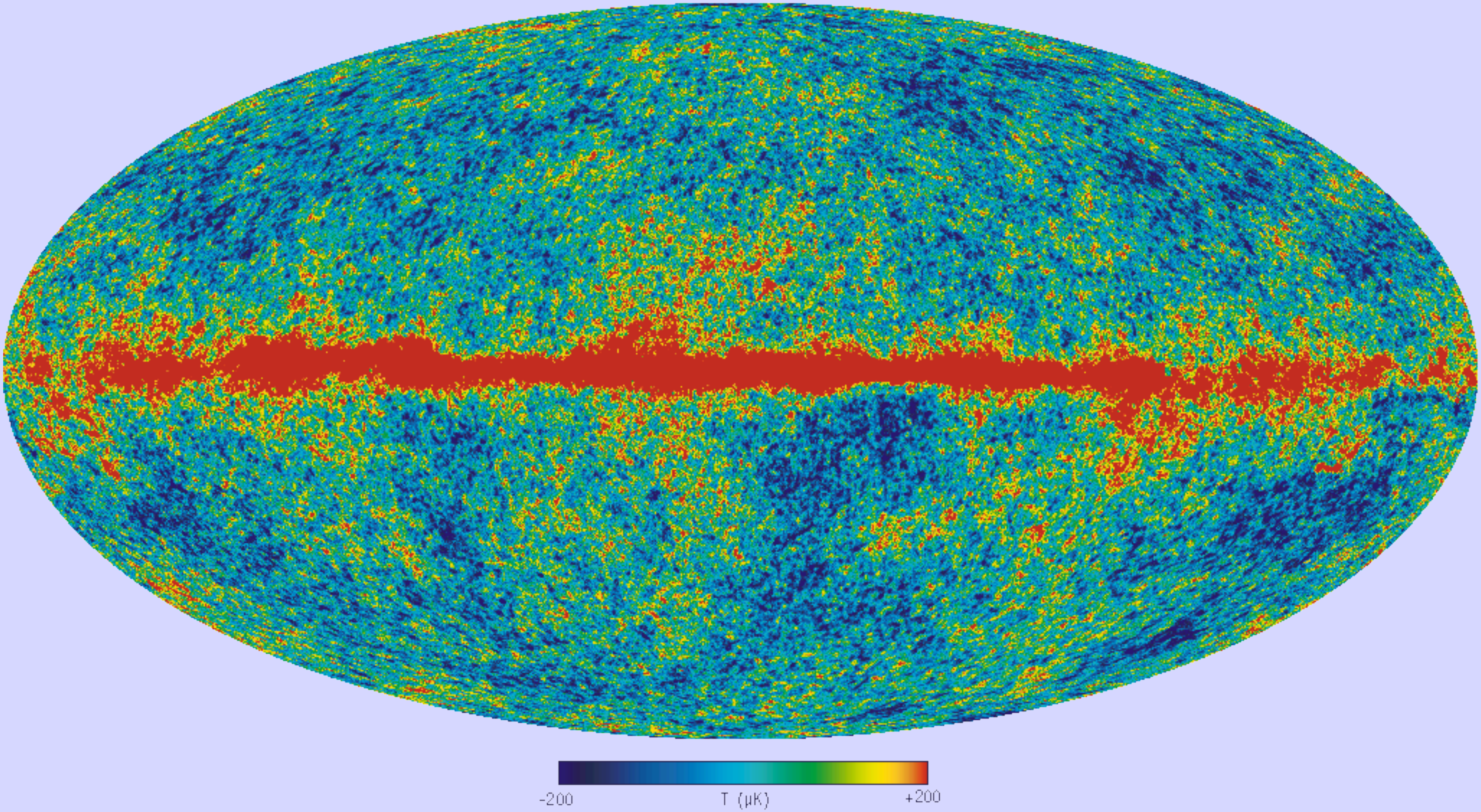
Q Band Temperature, 41 GHz



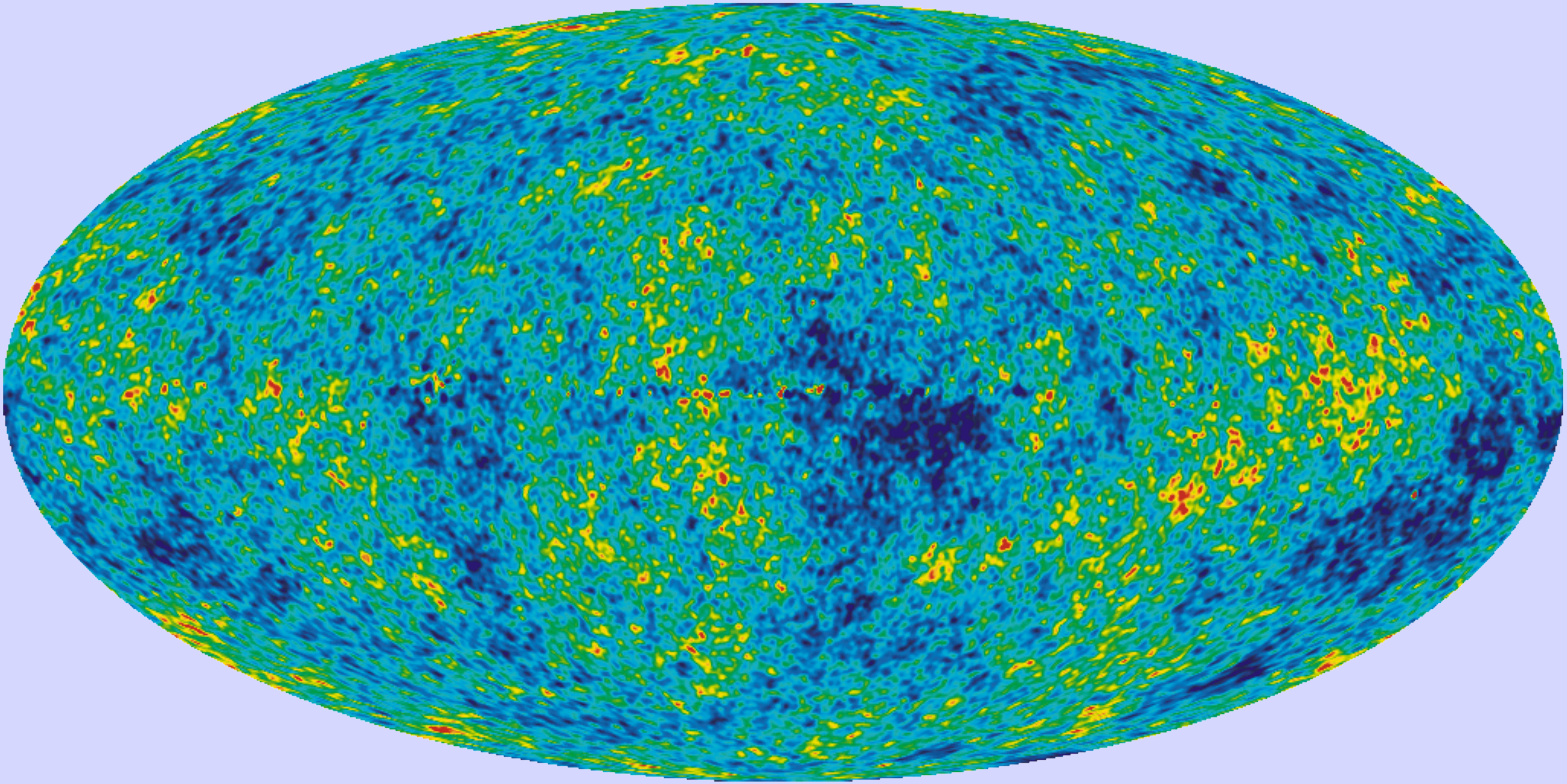
V Band Temperature, 61 GHz



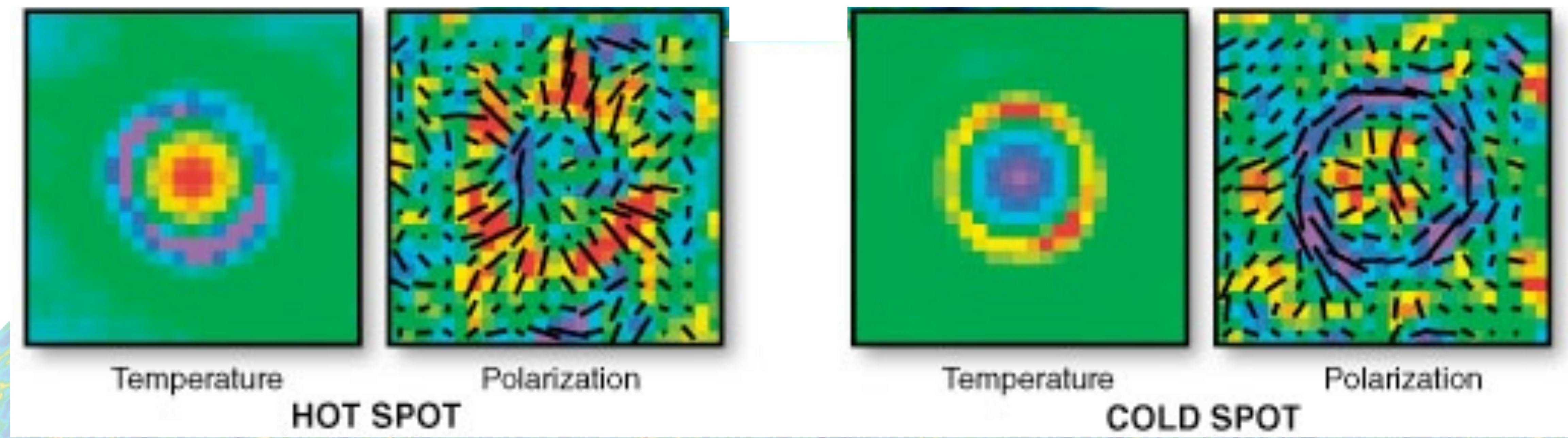
W Band Temperature, 94 GHz



5 Frequency Linear Combination (“ILC”)



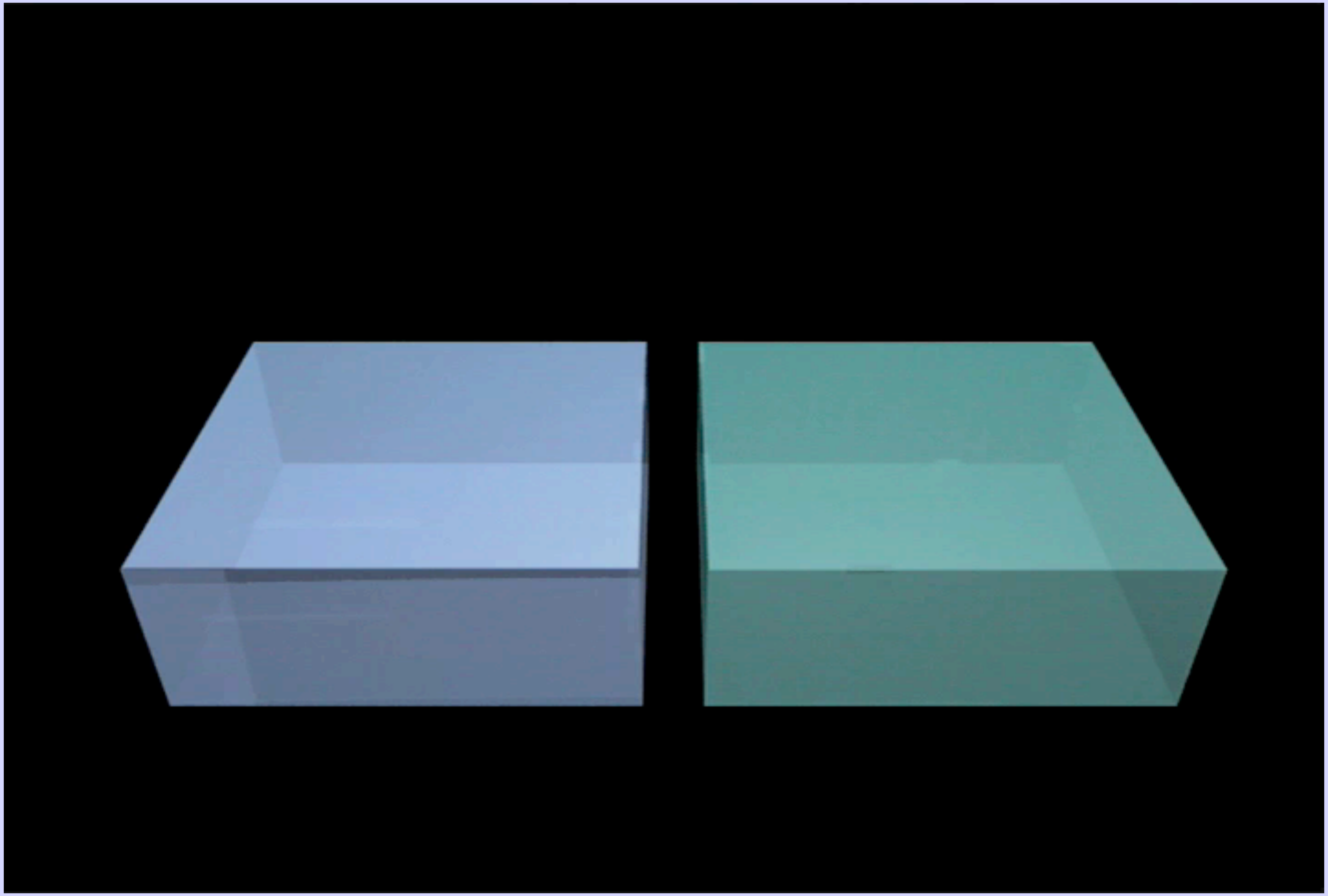
Acoustic Oscillations in the Spots



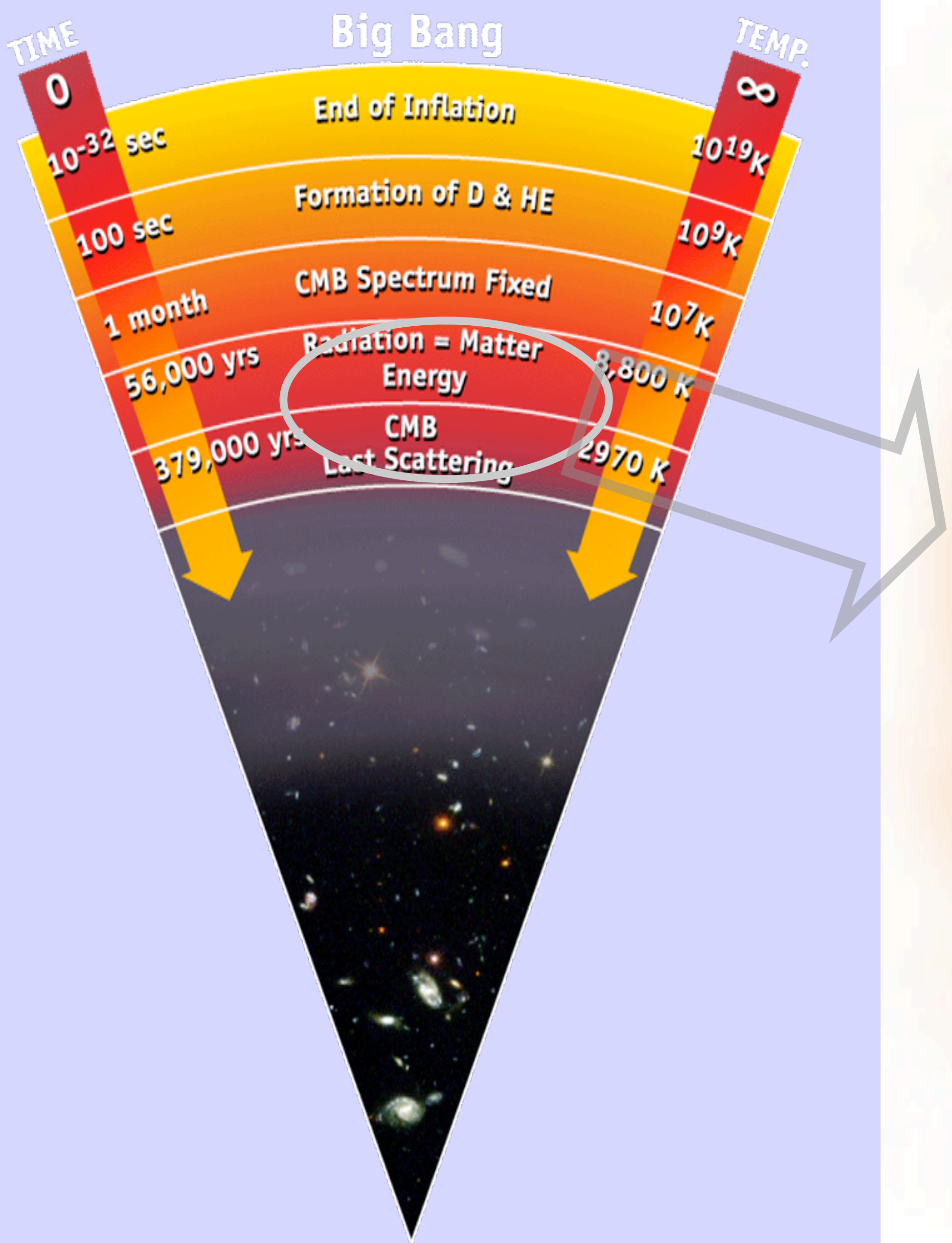
The imprint of sound waves is visible in the co-added degree-scale hot (left) & cold (right) spots. The expected radial/tangential polarization pattern around these extrema is now clearly seen in the 7-year WMAP data.

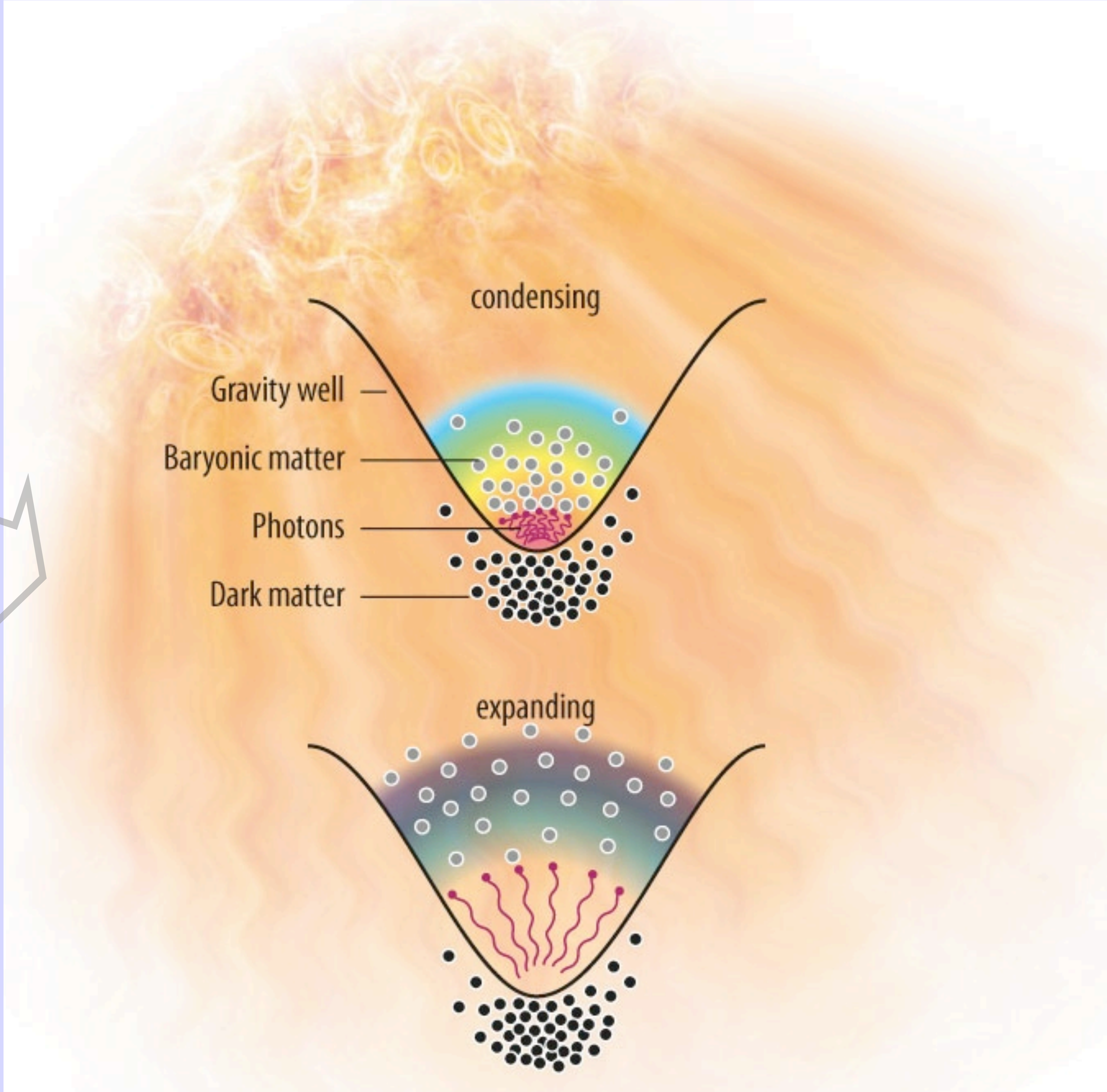
This pattern is also imprinted on the baryon gas (baryon acoustic oscillations or BAO) that evolves to form large scale structure.

Fingerprint of the Universe

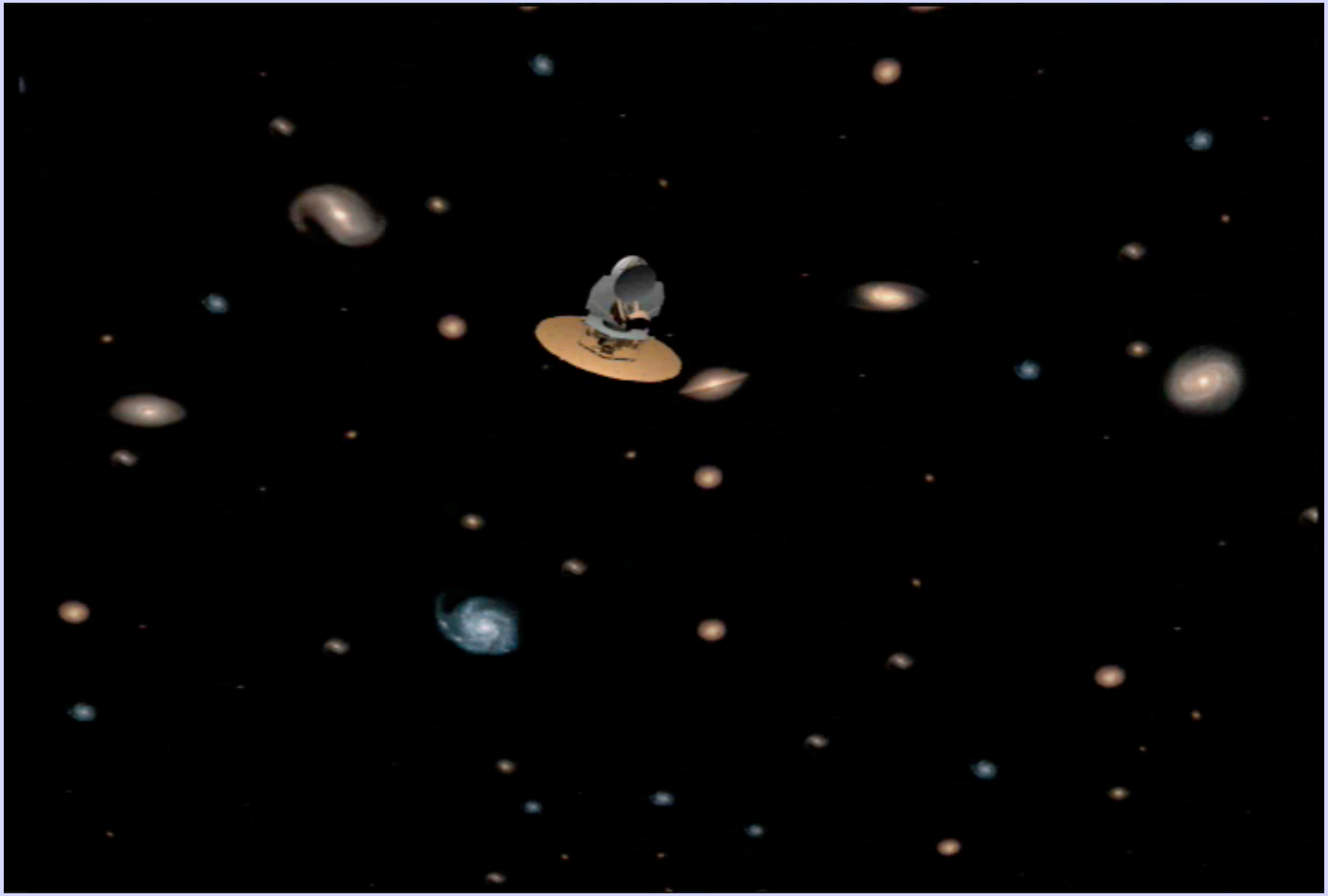


Sound Waves in the Early Universe

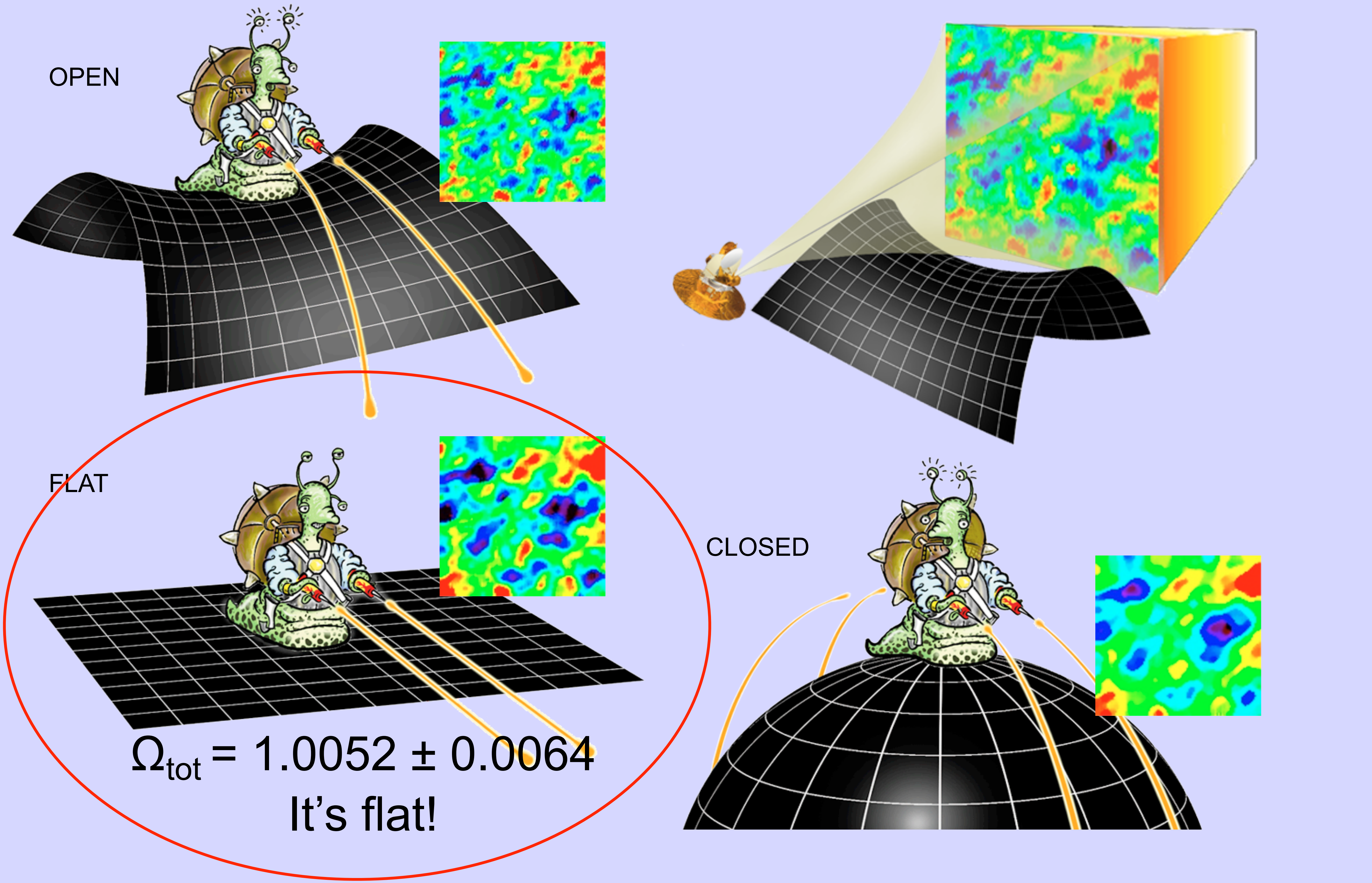




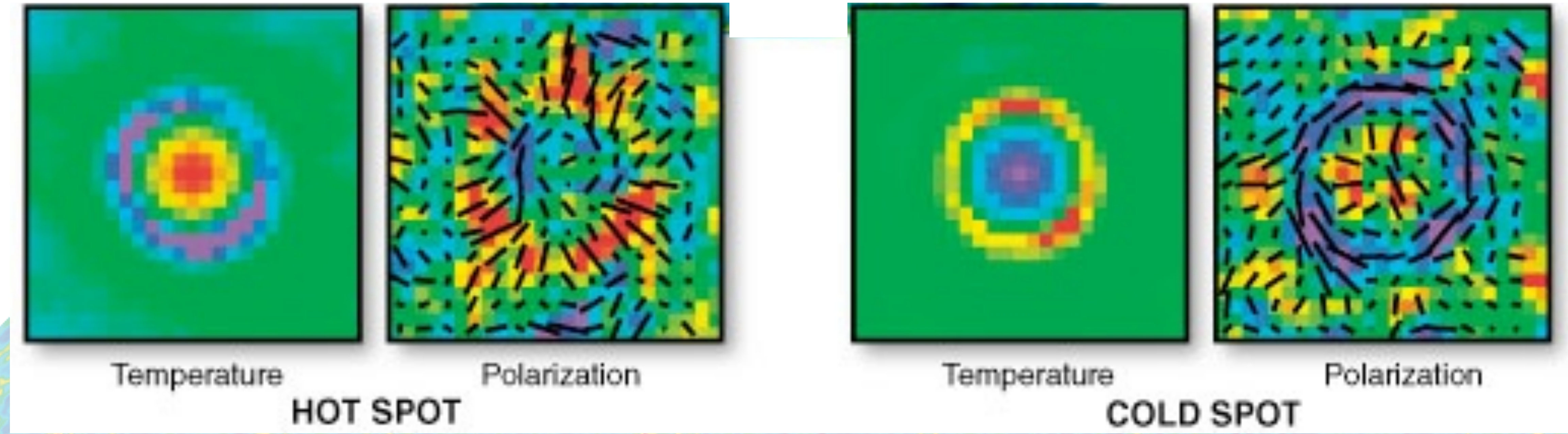
Geometry of the Universe



WMAP Measures the Shape of the Universe



Acoustic Oscillations in the Spots



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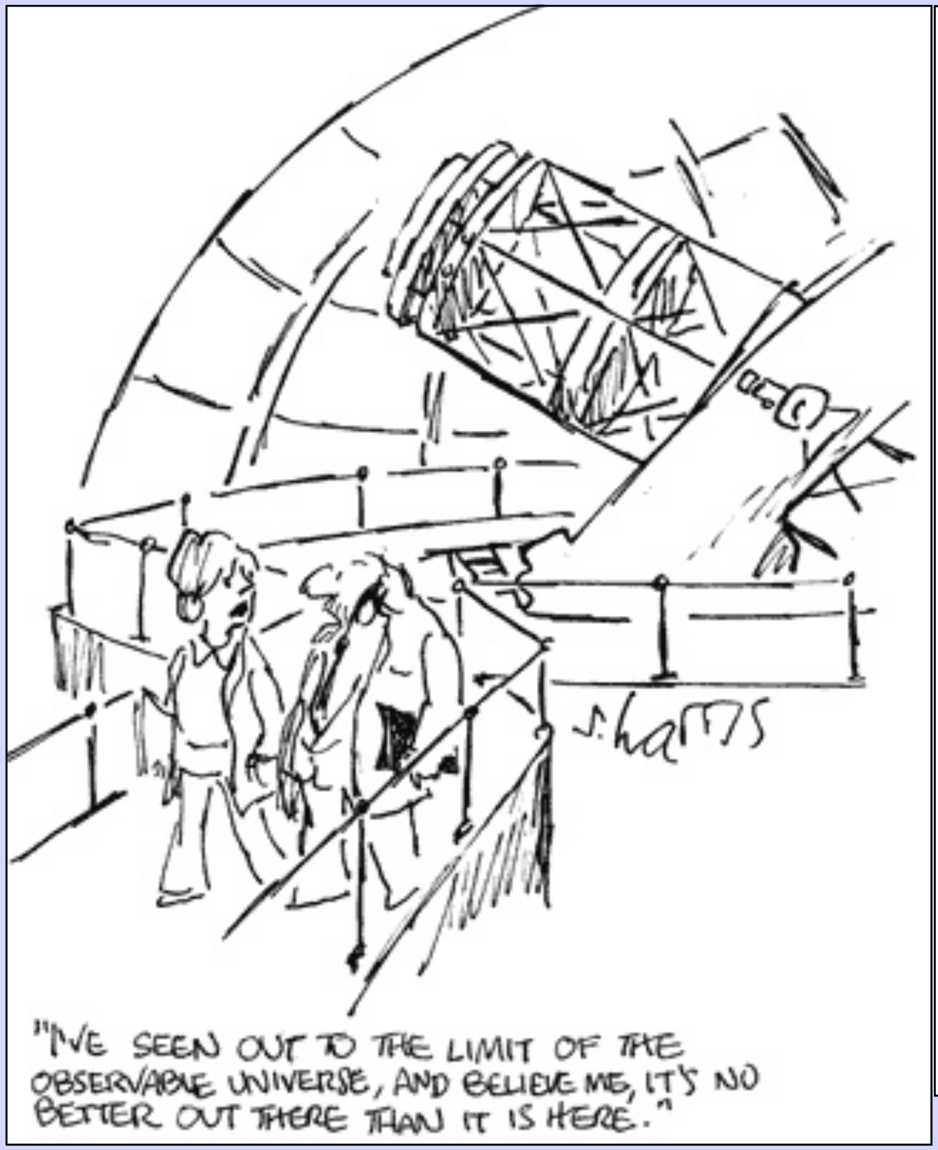
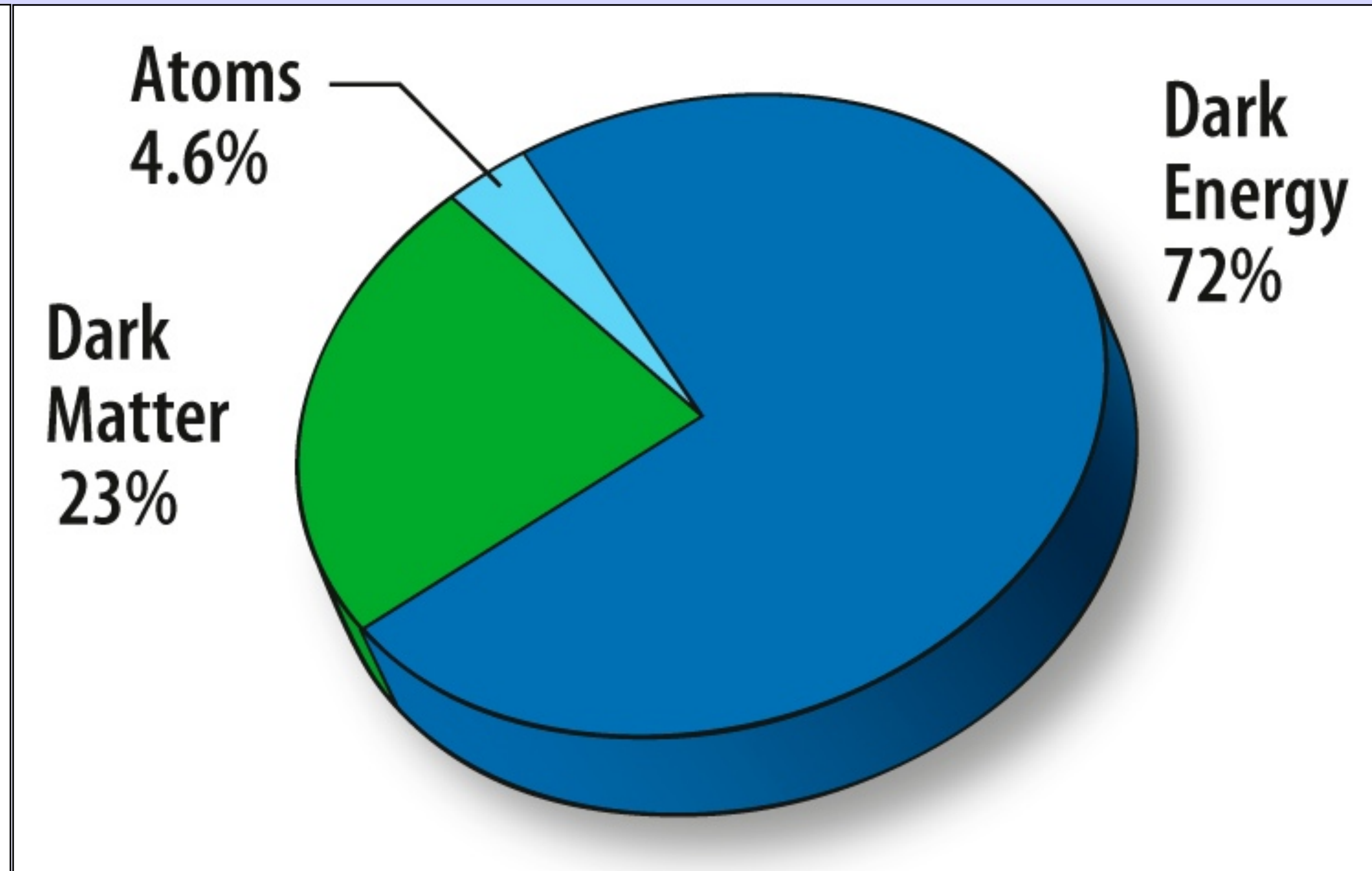
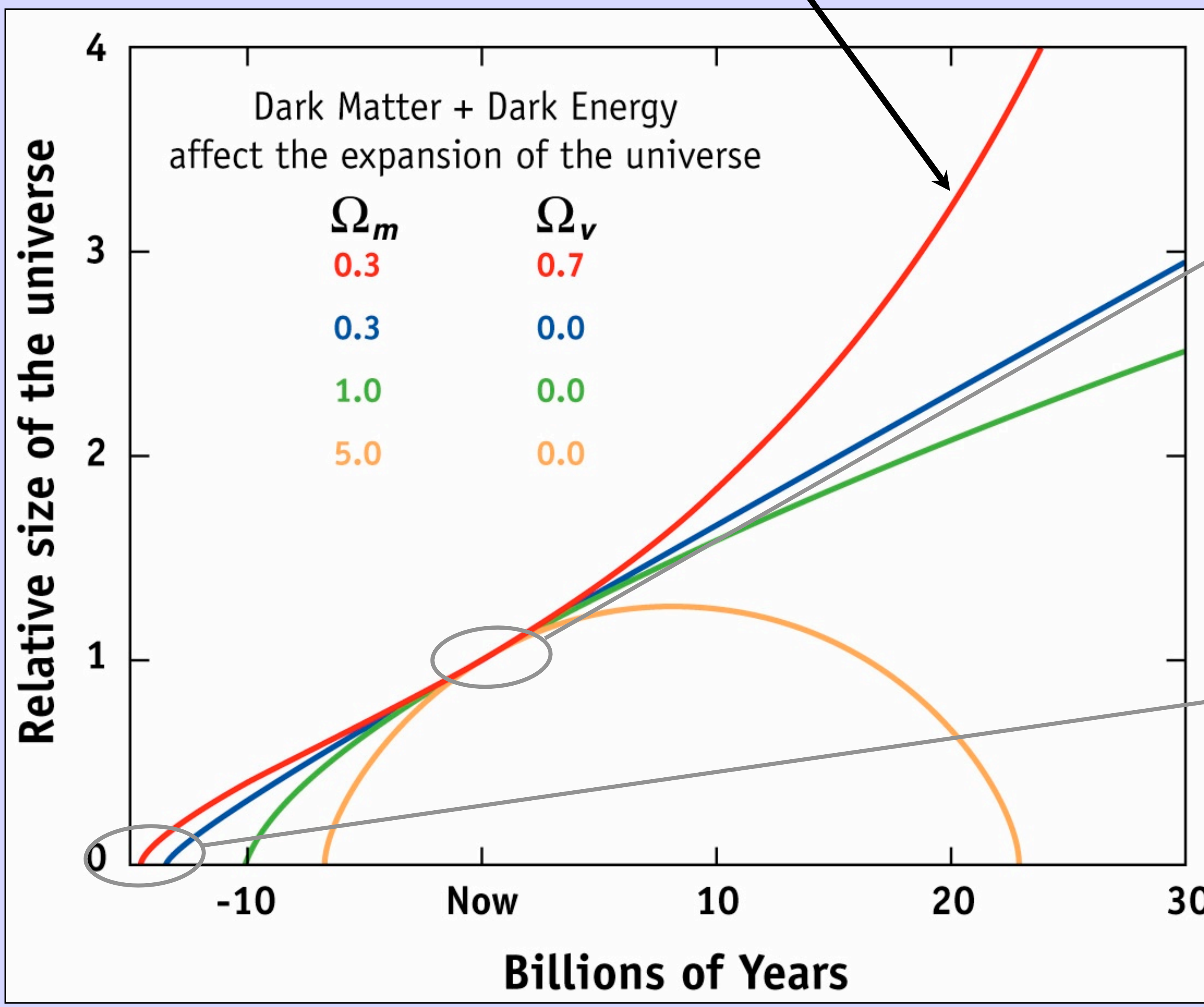
The Dark Side





Another Look at Expansion

Our universe



- Expansion rate (Hubble constant):

  70.4 ± 1.4 km/s/Mpc

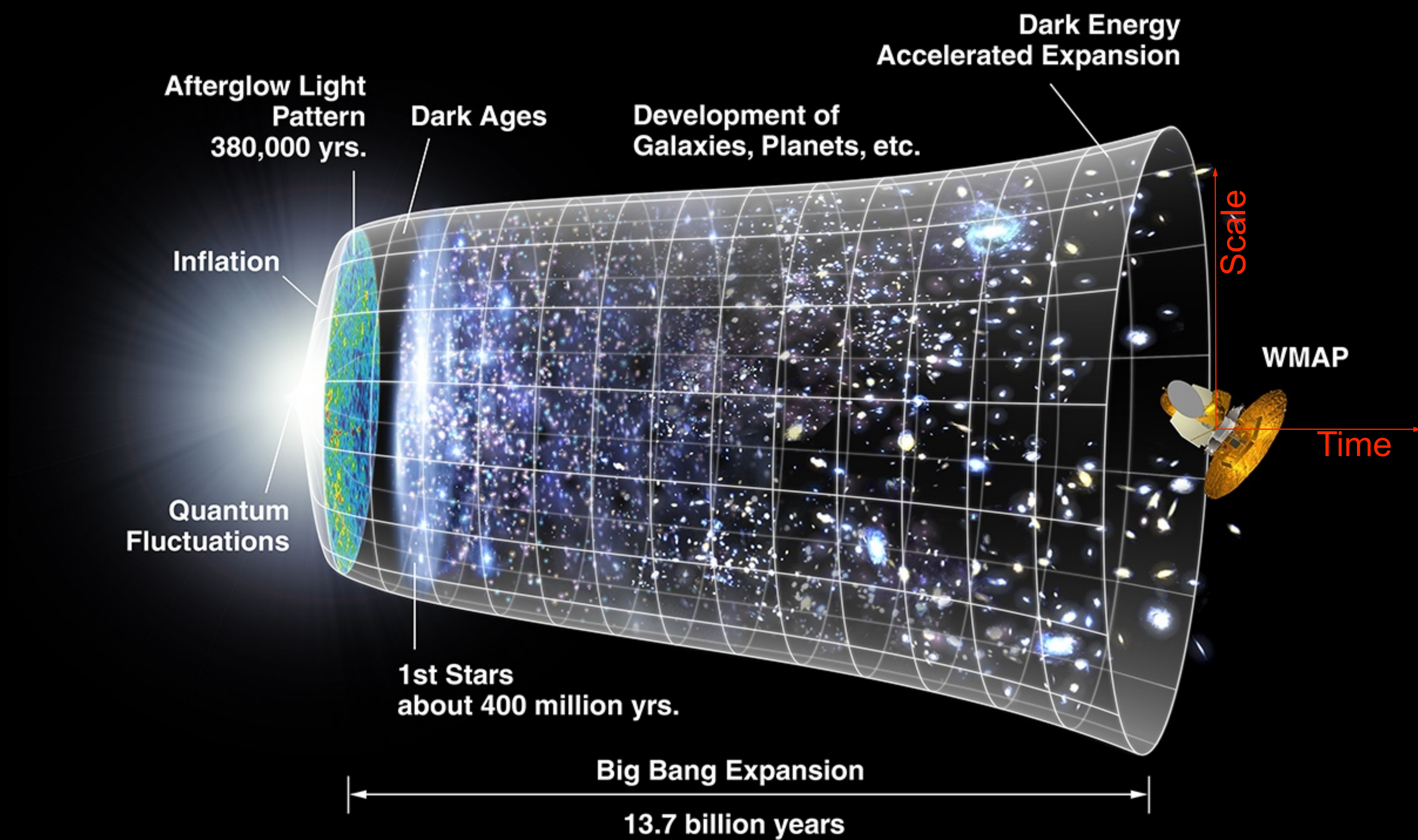
Compare to 72±3±7 km/s/Mpc from Hubble Key Project, Freedman et al. (2001)

- Age of the universe:

  13.75 ± 0.11 billion years

Compare to 12-20 billion years prior to WMAP

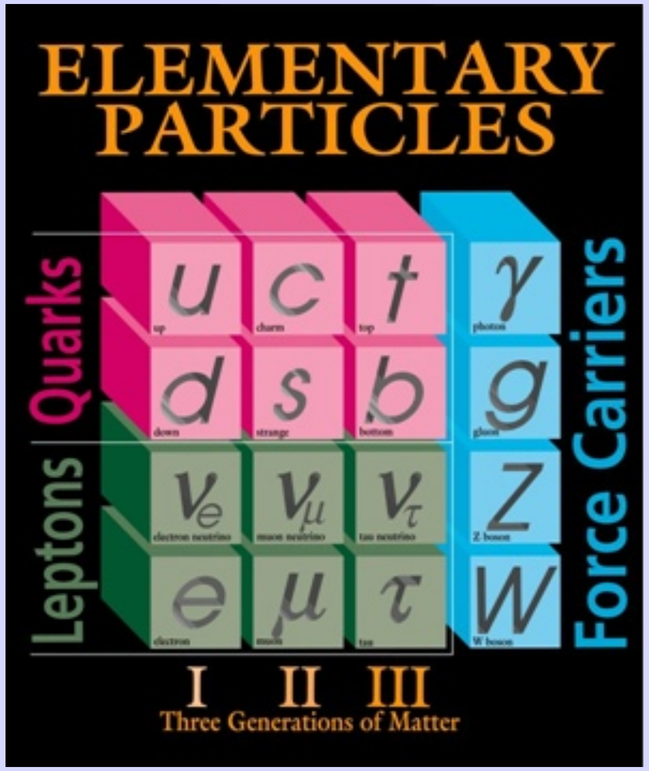
Cosmology, c. 2011

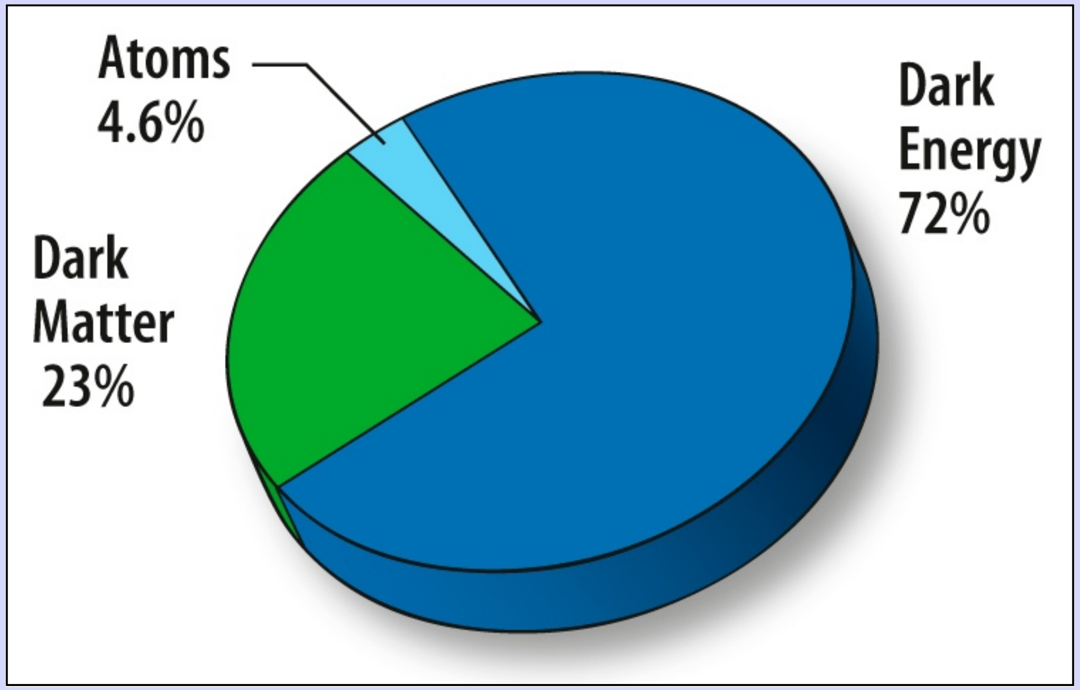


Progress in Cosmology

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.

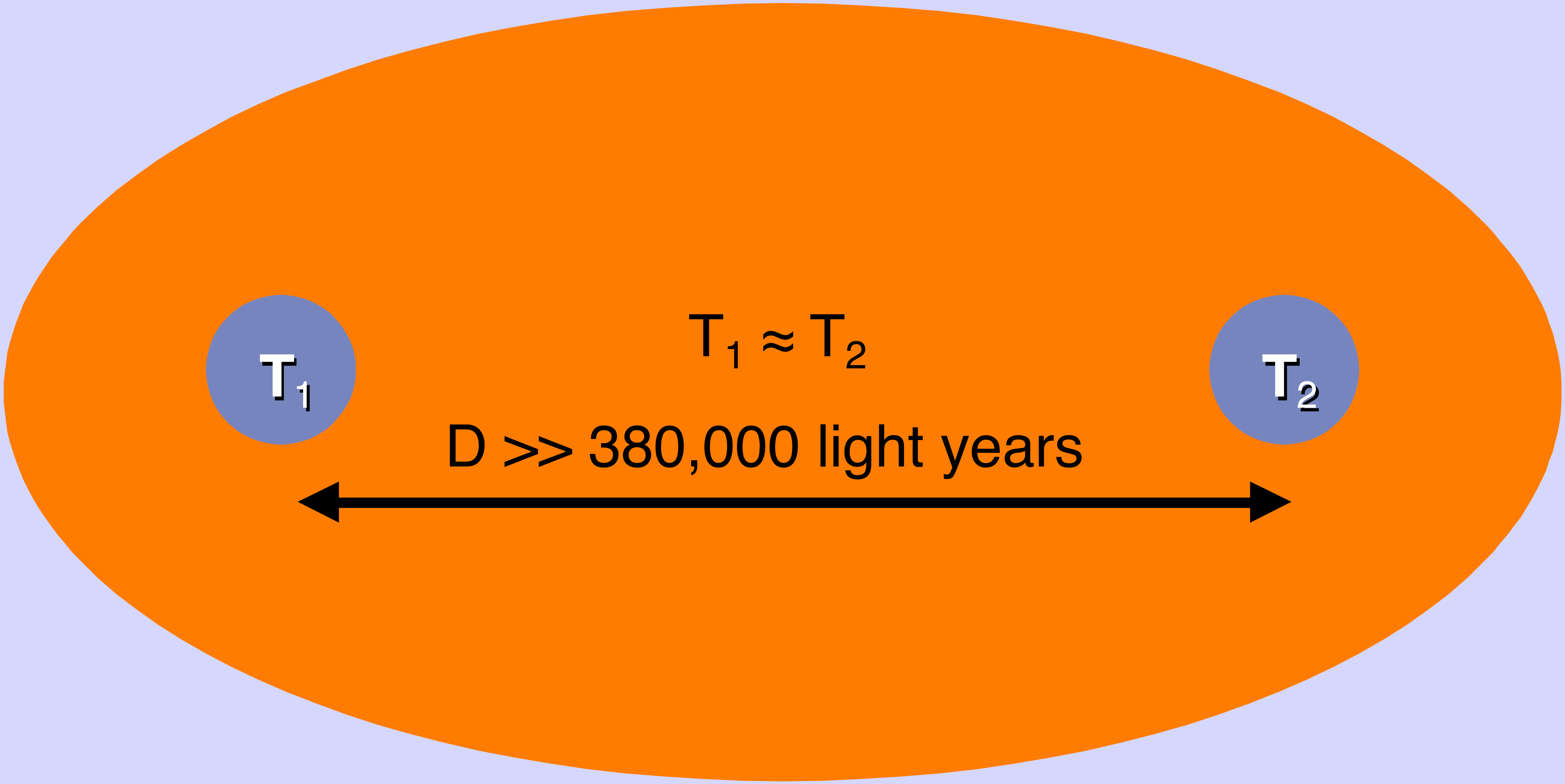
96% of the energy density in this model is in the form of dark matter and dark energy. Fundamental insight to the nature of these constituents may well be very difficult to come by, just as in the standard model of particle physics.





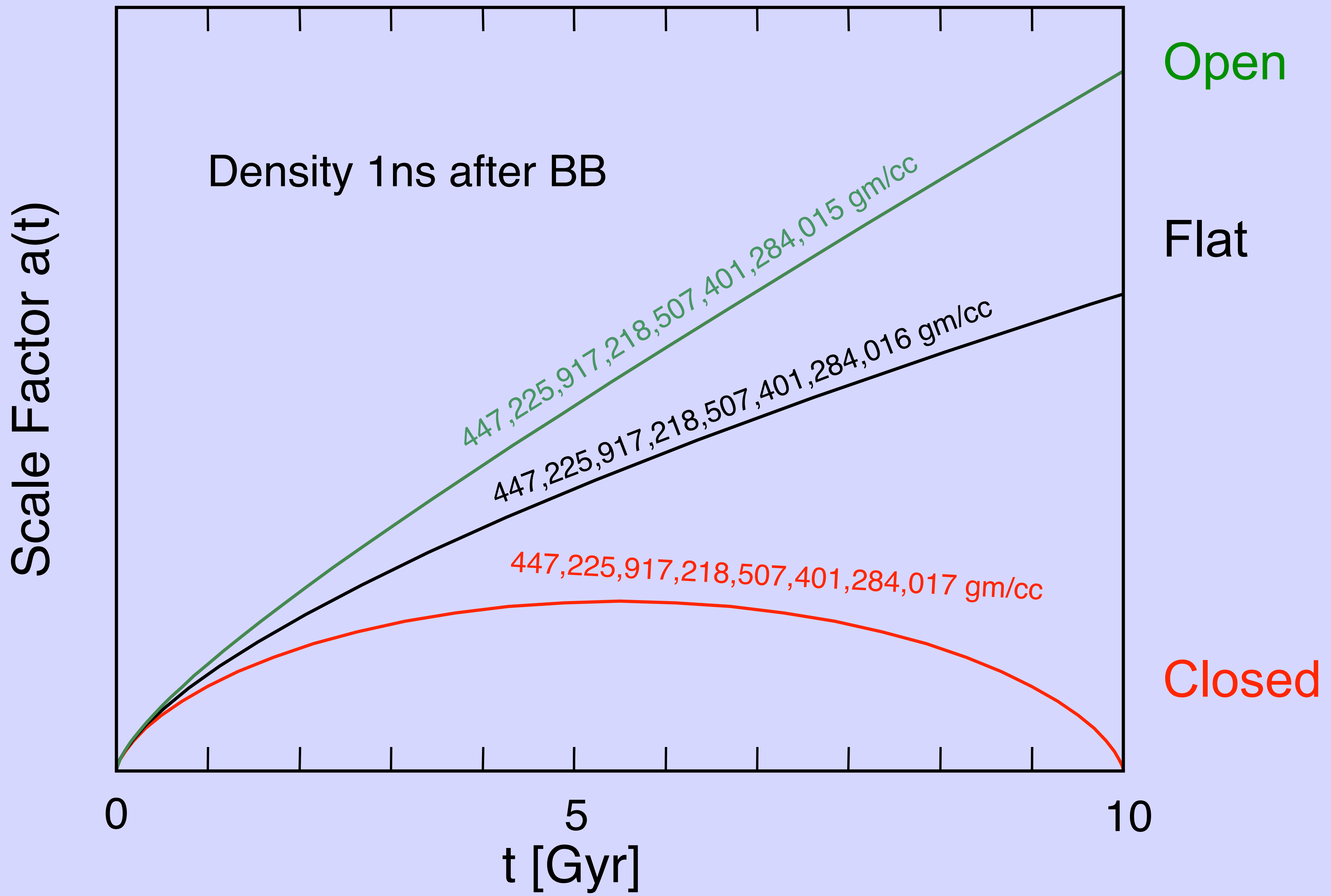
The Horizon Problem

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



The Flatness Problem

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



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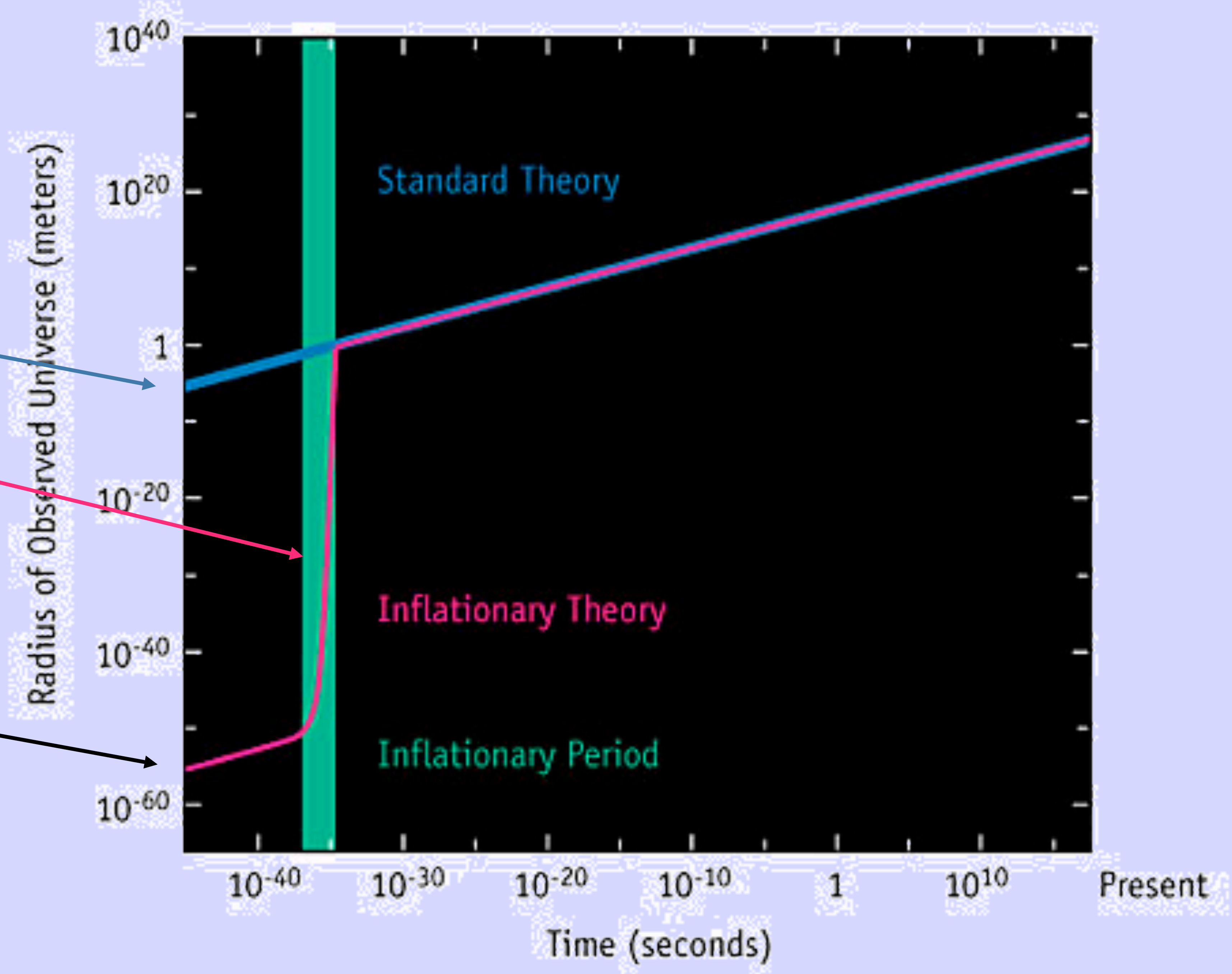
Inflation!

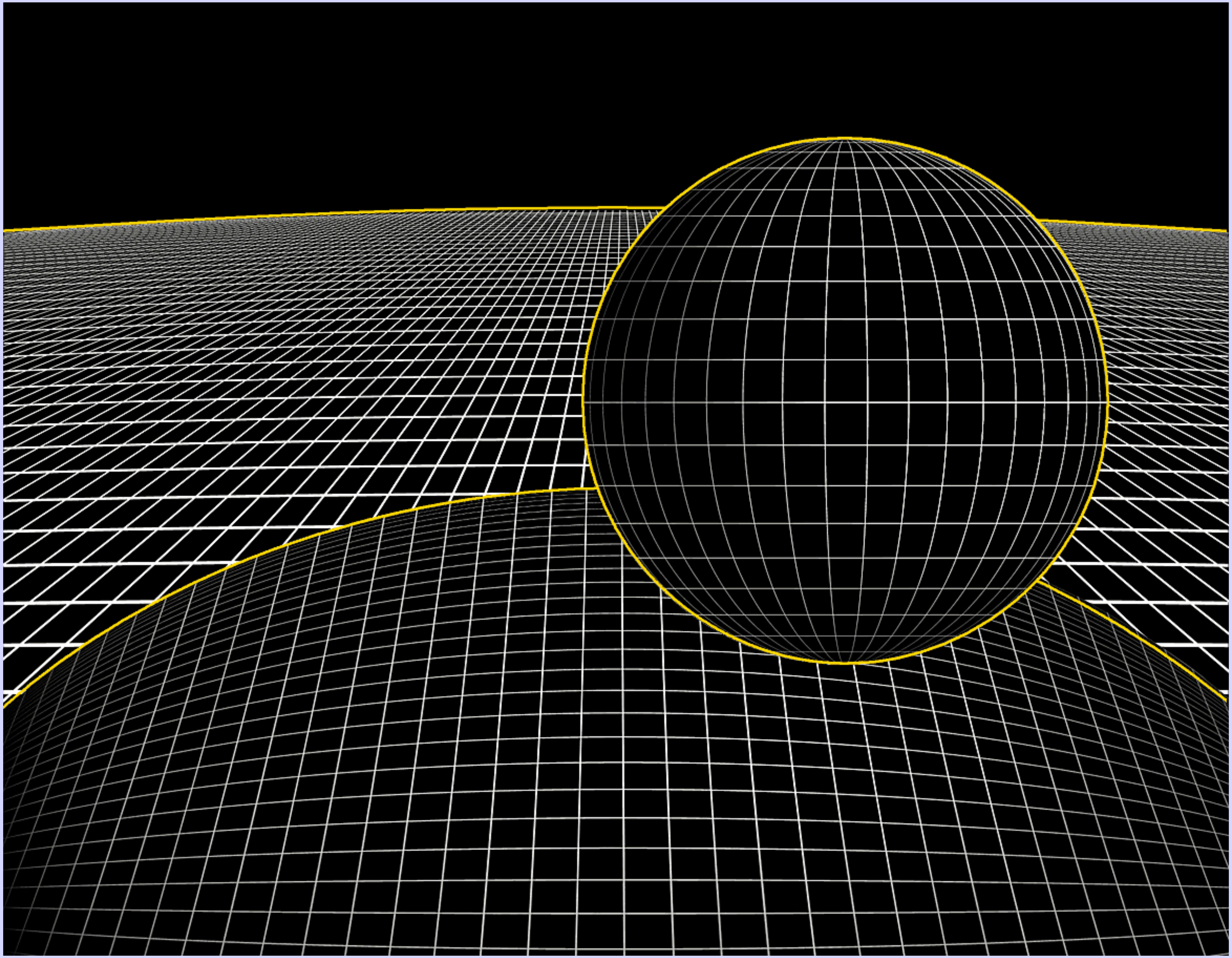
“Standard” expansion

“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



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From Quarks to the Cosmos!