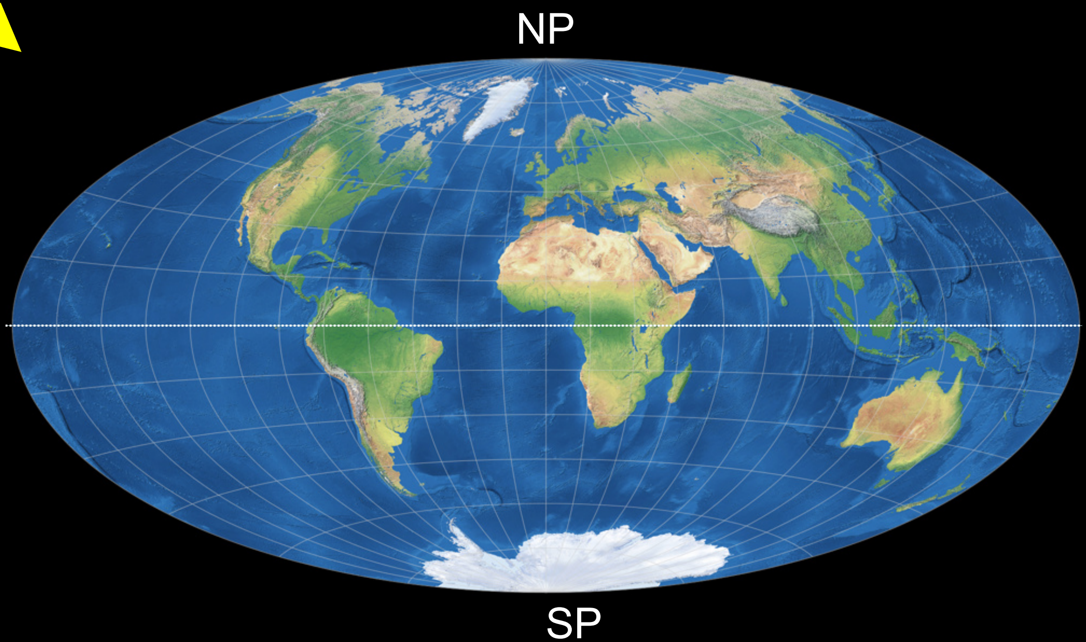
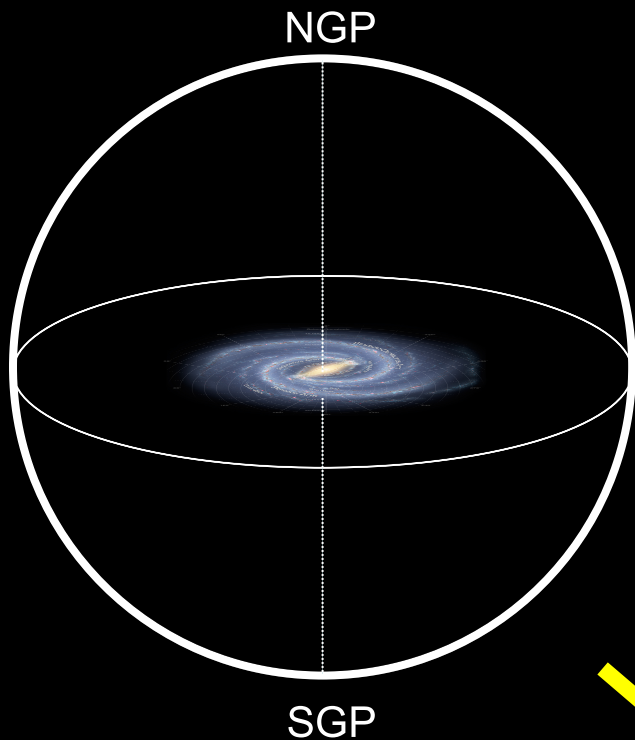
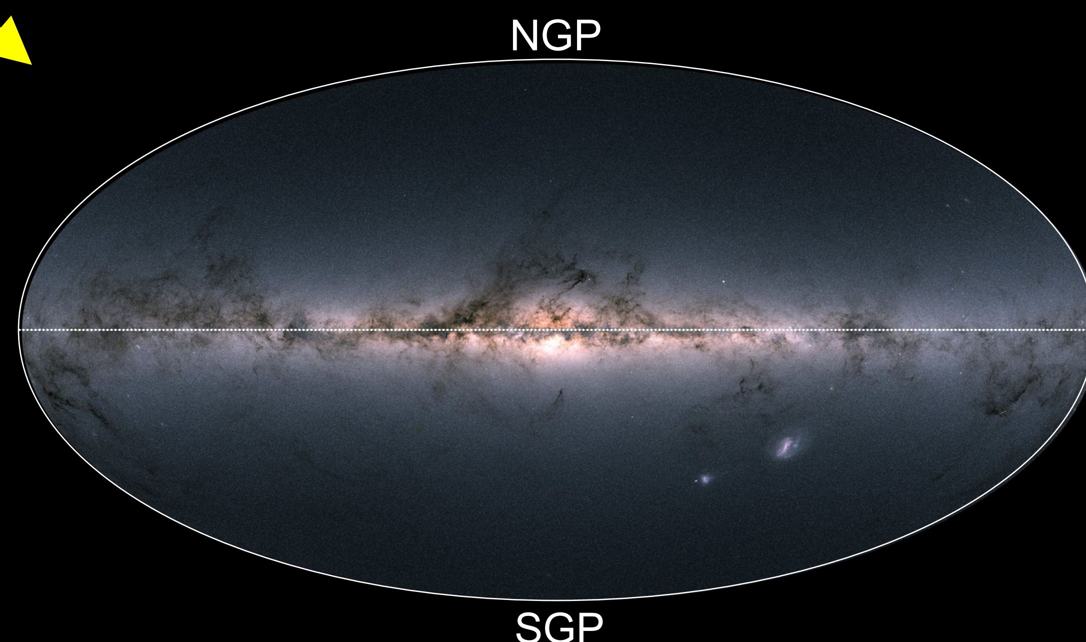
Projection of 3D map to 2D



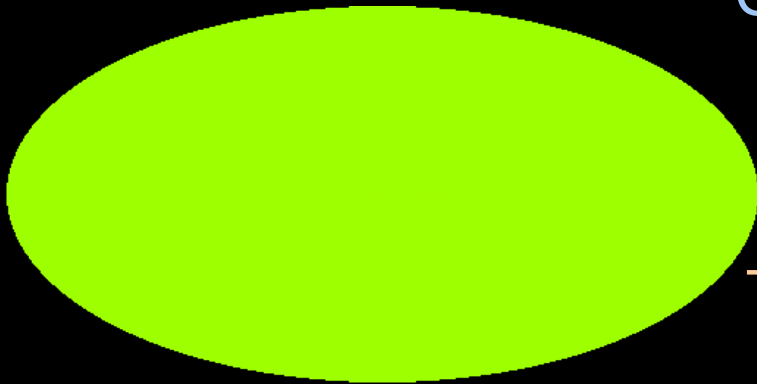
Projection of 3D map to 2D

Galactic coordinates

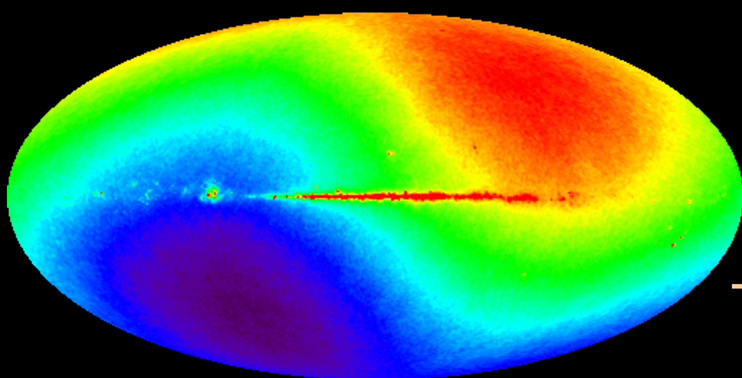




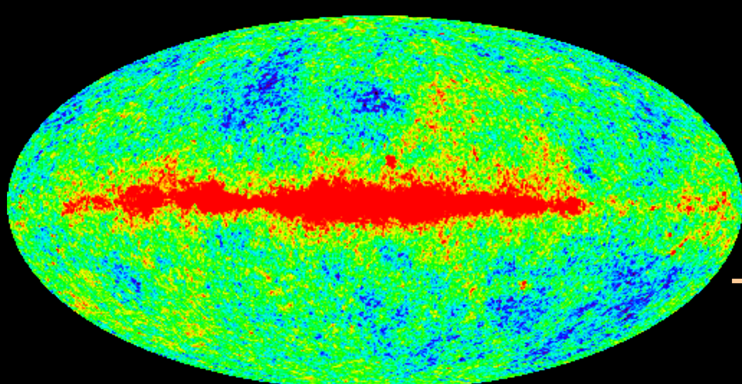
Cosmic Microwave Background (WMAP experiment)



Temperature = 2.72 Kelvin



Temperature = 2.721 – 2.729 Kelvin



Temperature = 2.7249 – 2.7251 Kelvin

But the universe today (13.7 billion years old) doesn't look like that at all!

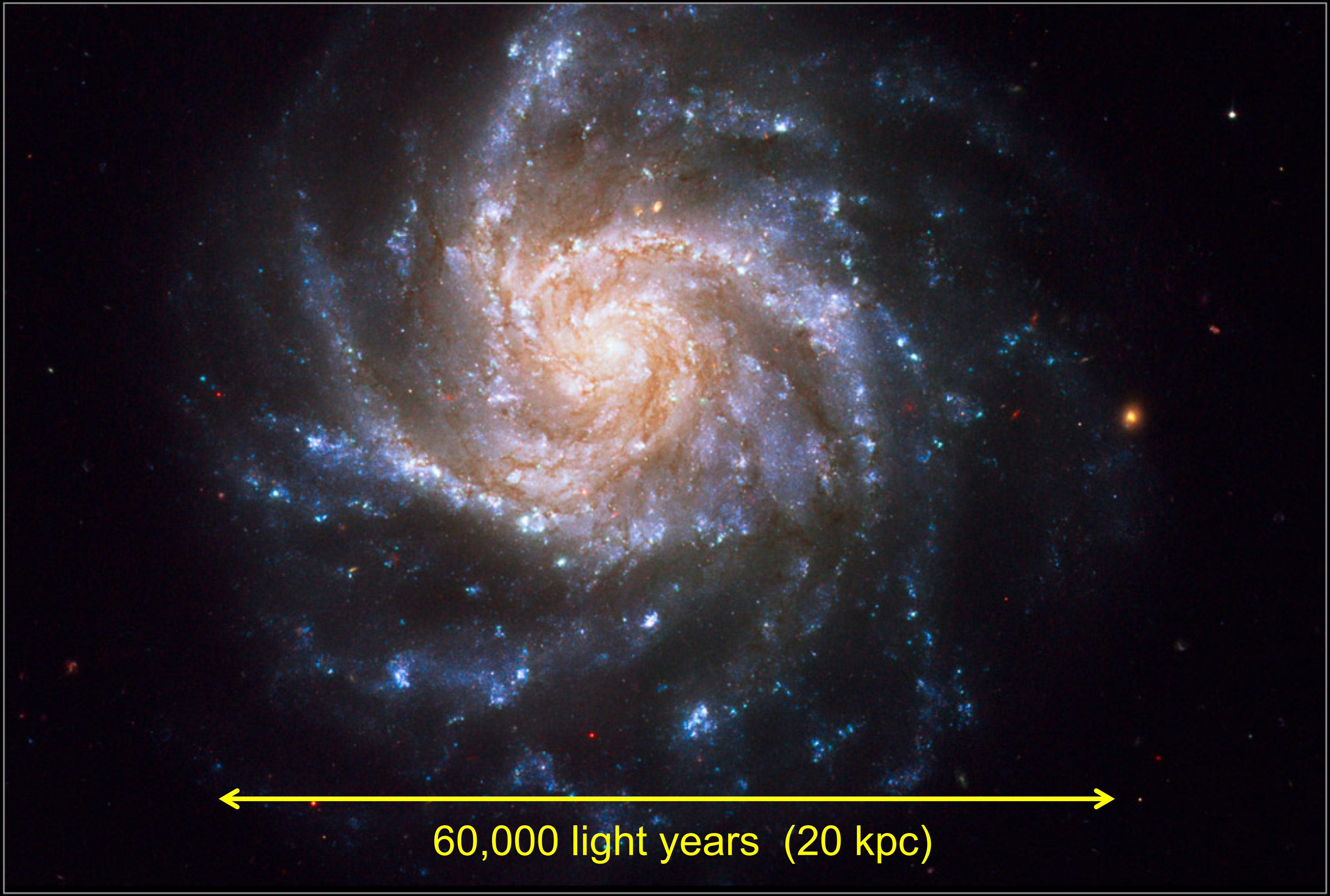
It contains structure on all scales.

- Small scales: planets, stars, solar systems…
  (less than one light year)

- Intermediate scales: galaxies
  (1 – million light years)

- Large scales: clusters of galaxies, super-clusters…
  (million – billion light years)

Spiral Galaxy NGC 1376

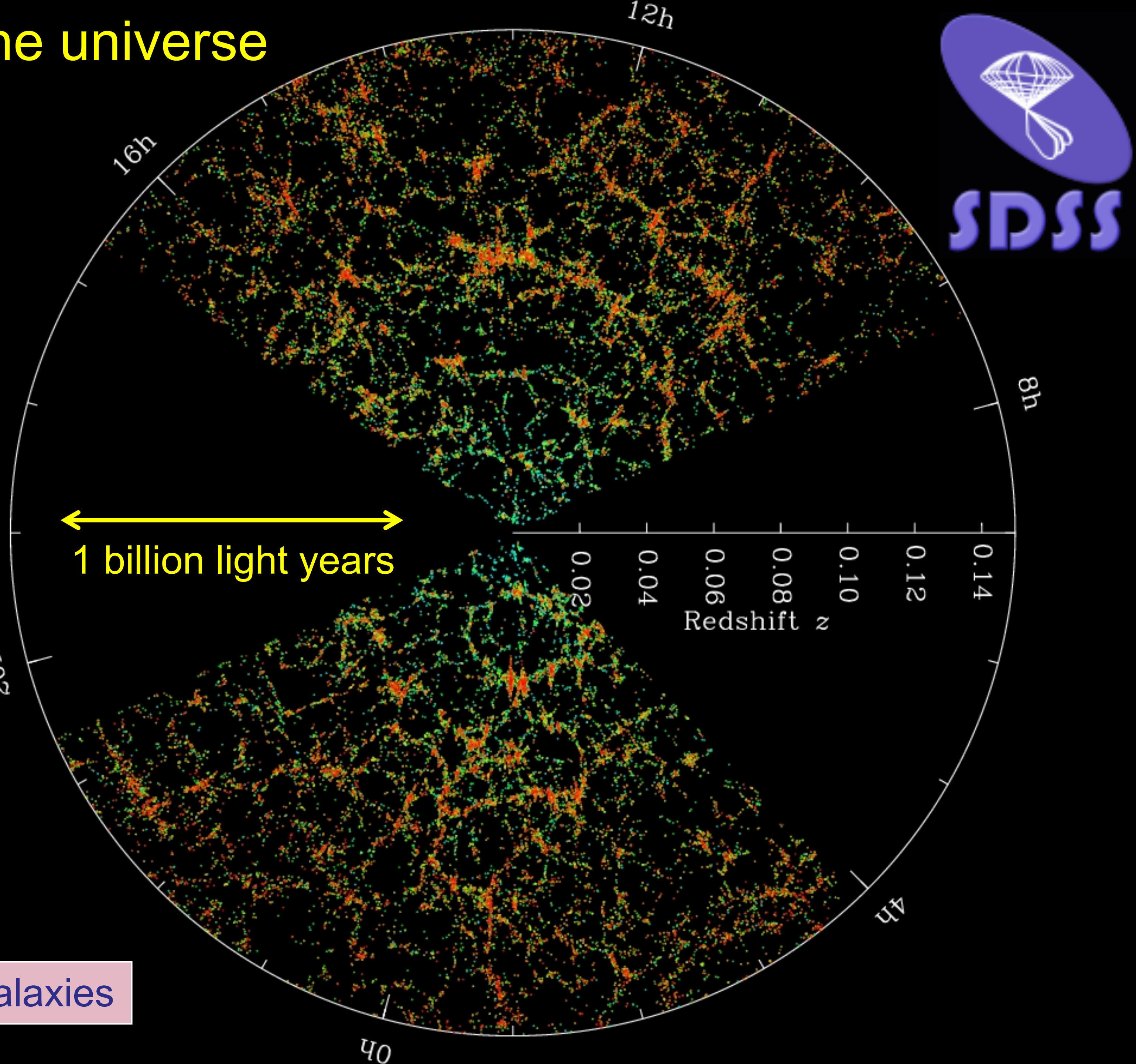


Hubble Heritage

NASA, ESA, and the Hubble Heritage Team (STScI/AURA) • *Hubble Space Telescope* ACS

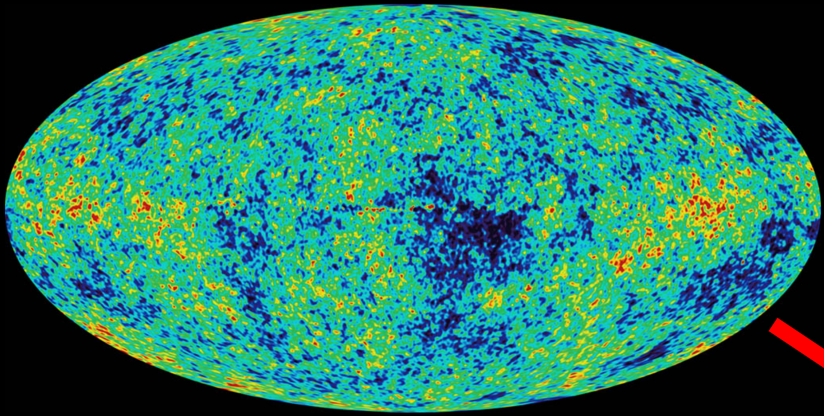

3 million light years (1 Mpc)

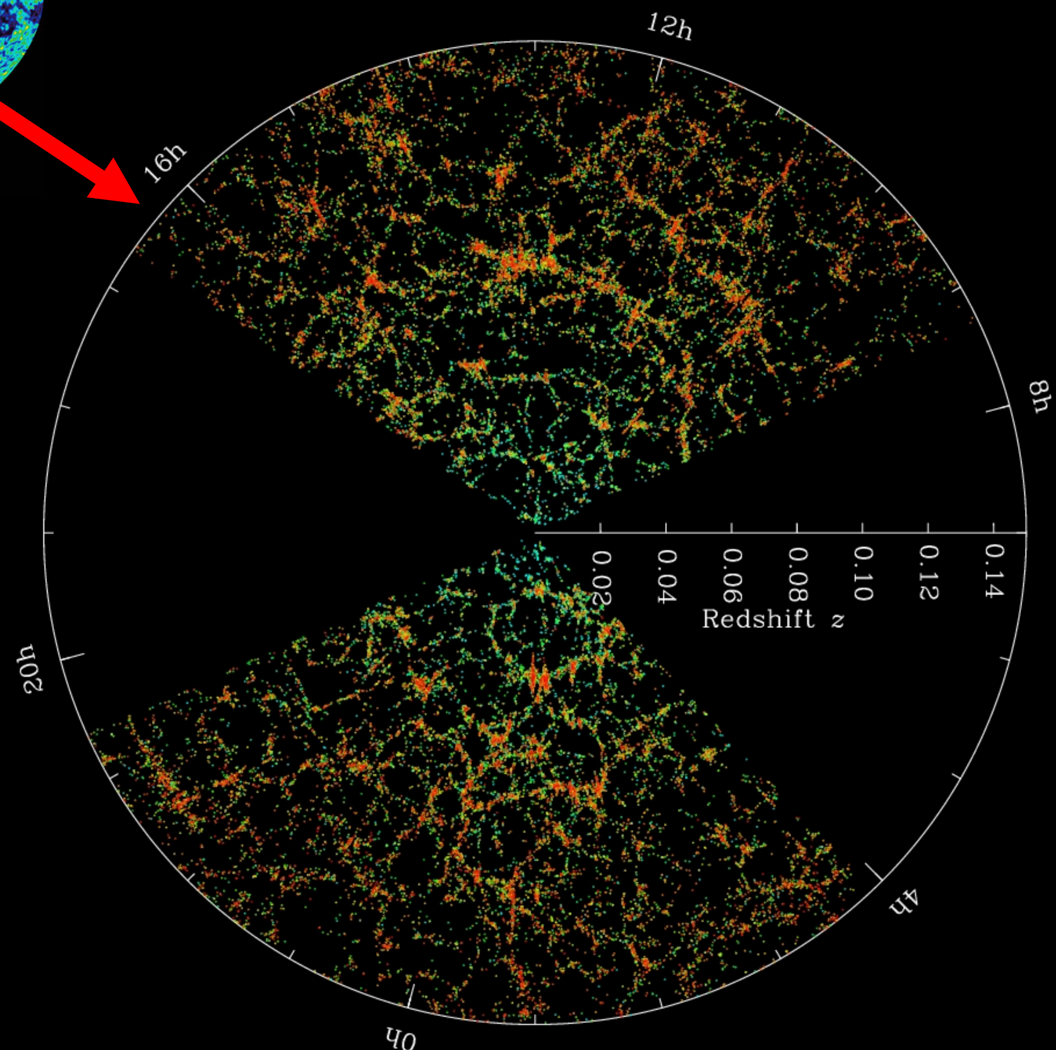
A map of the universe

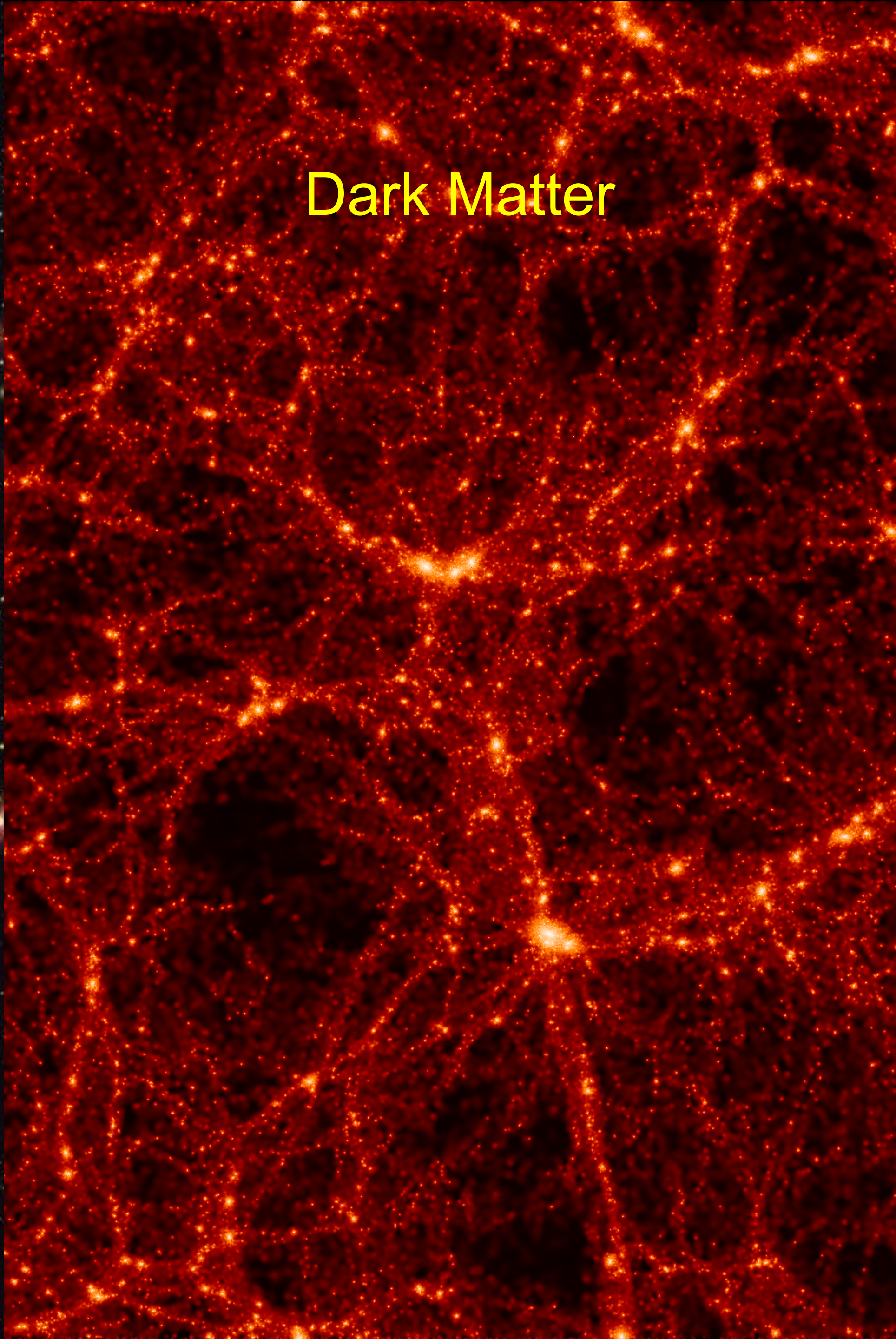


~1 million galaxies

How did structure in the universe grow?





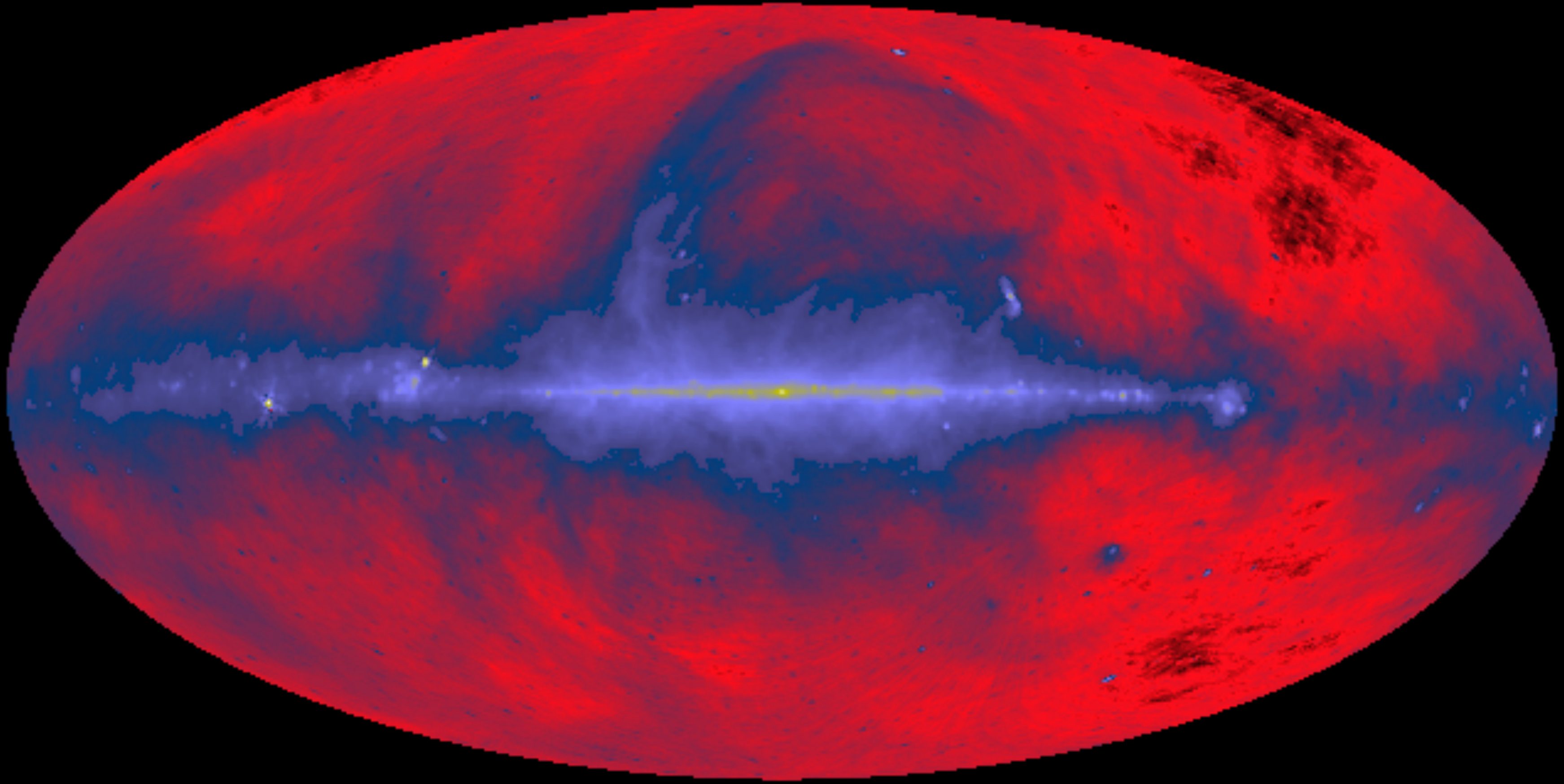

Galaxies

Dark Matter

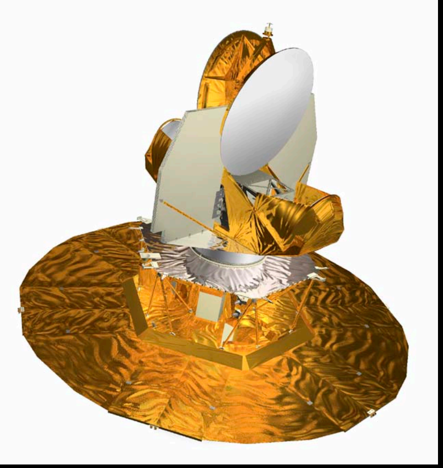
Aims of the course

- How do we measure galaxy properties?
- Galaxy surveys
- What statistics are used to quantify structure and how are they measured?
- Brief review of homogeneous universe
- How did the universe form structure on all scales?
- What models are used to connect observations to theory?
- What observational probes are used to constrain cosmology?
- How do galaxies form?

Radio Sky

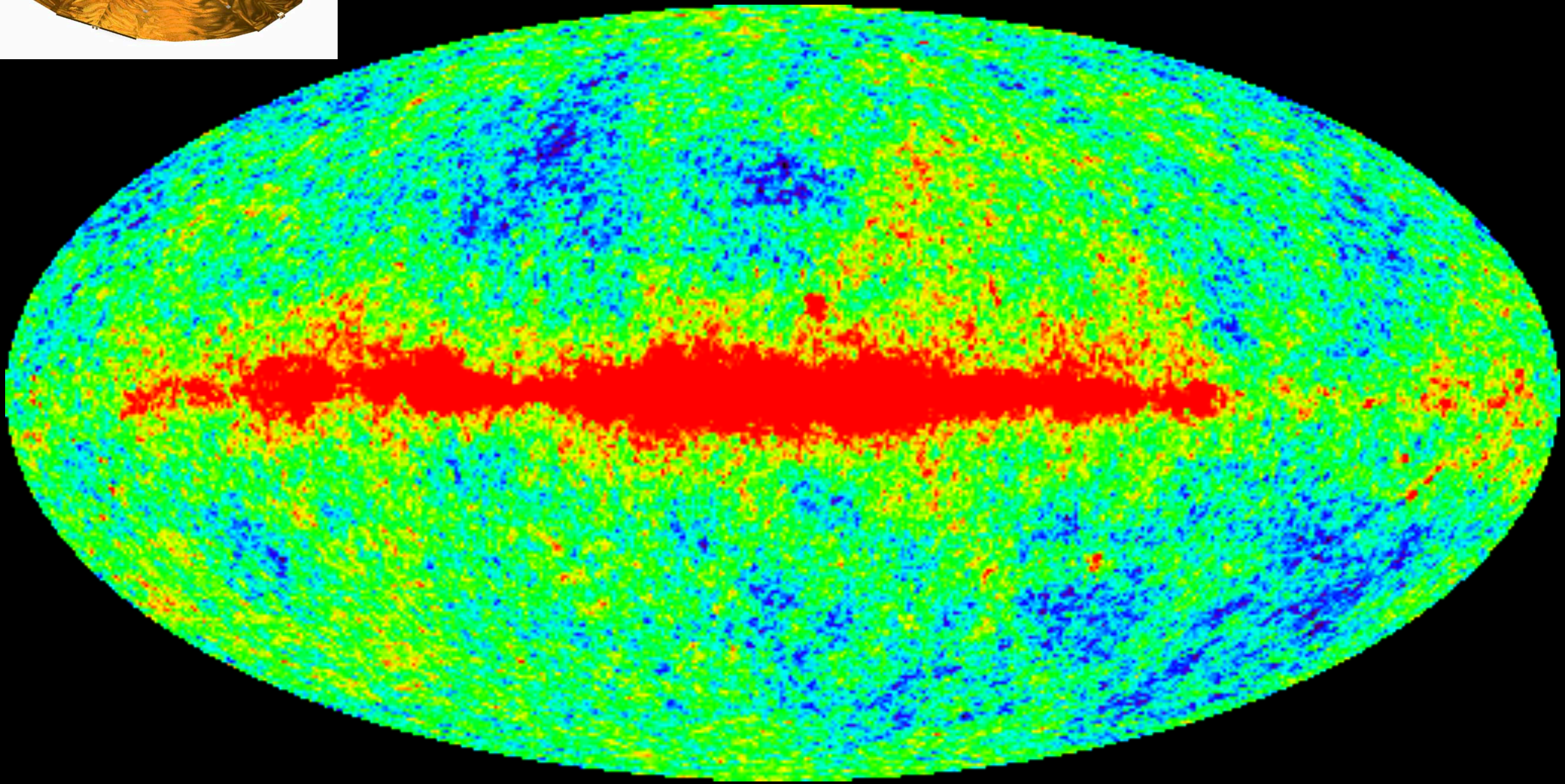
- Atomic gas
- Molecular gas
- Radio galaxies
- SN remnants
- Pulsars



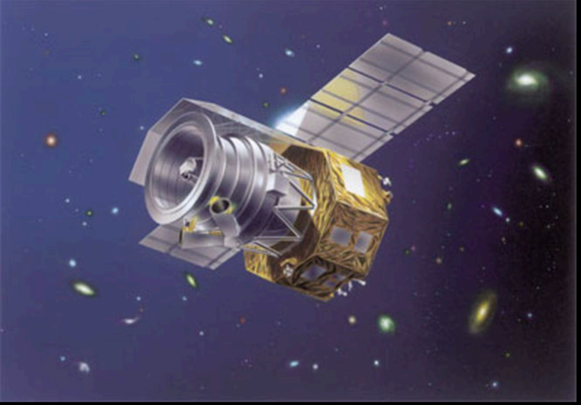


Microwave Sky

- CMB
- Dust

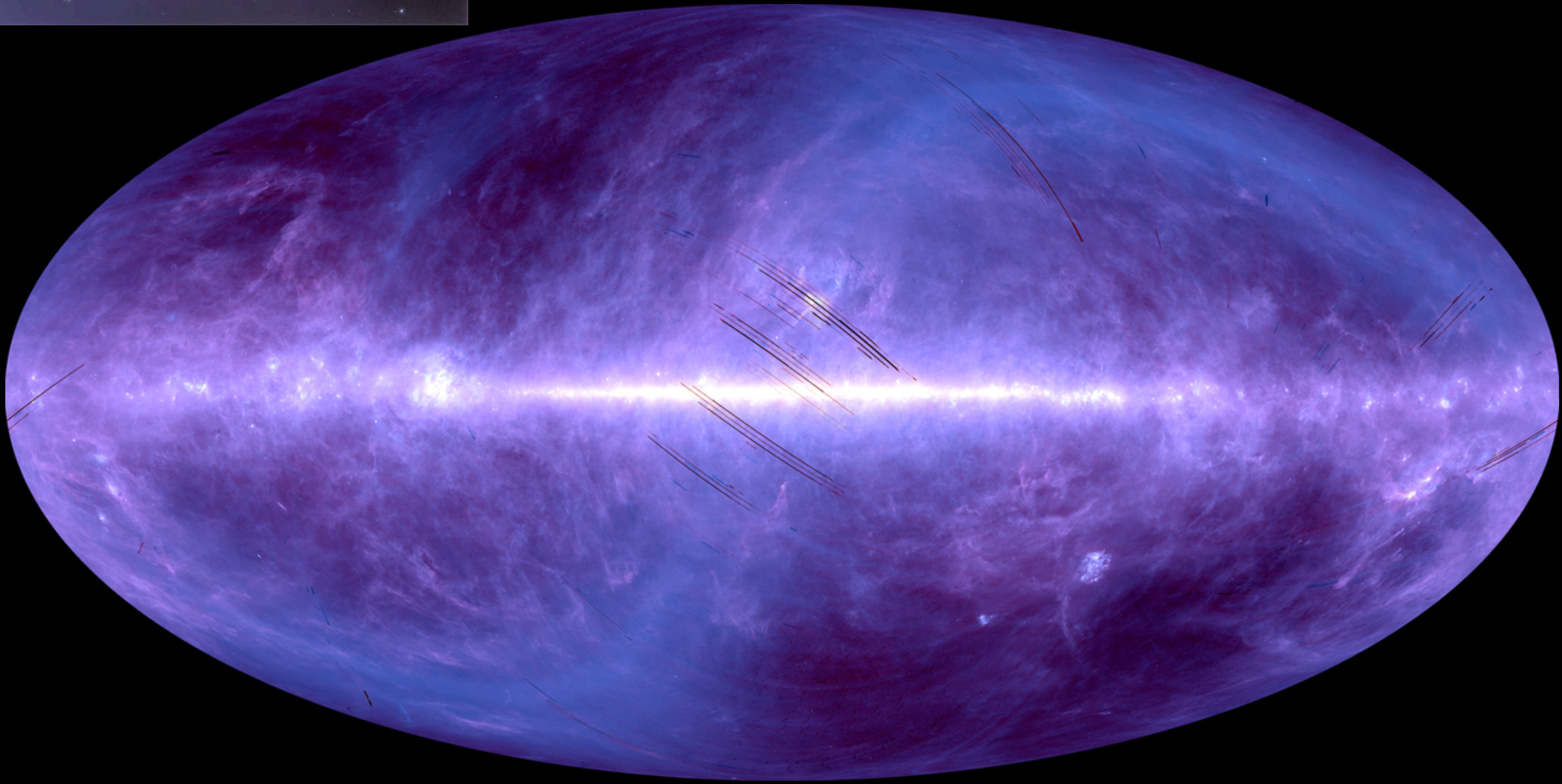


WMAP

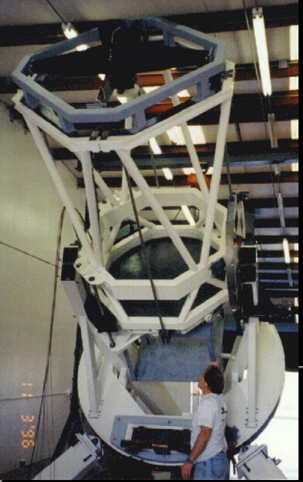


Far Infrared Sky

- Dust

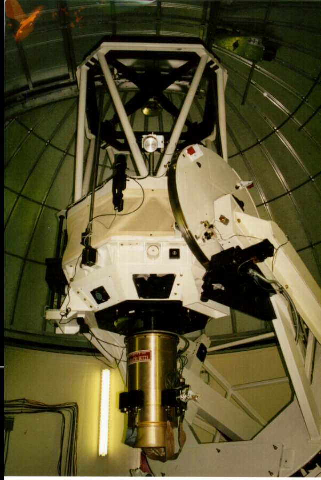


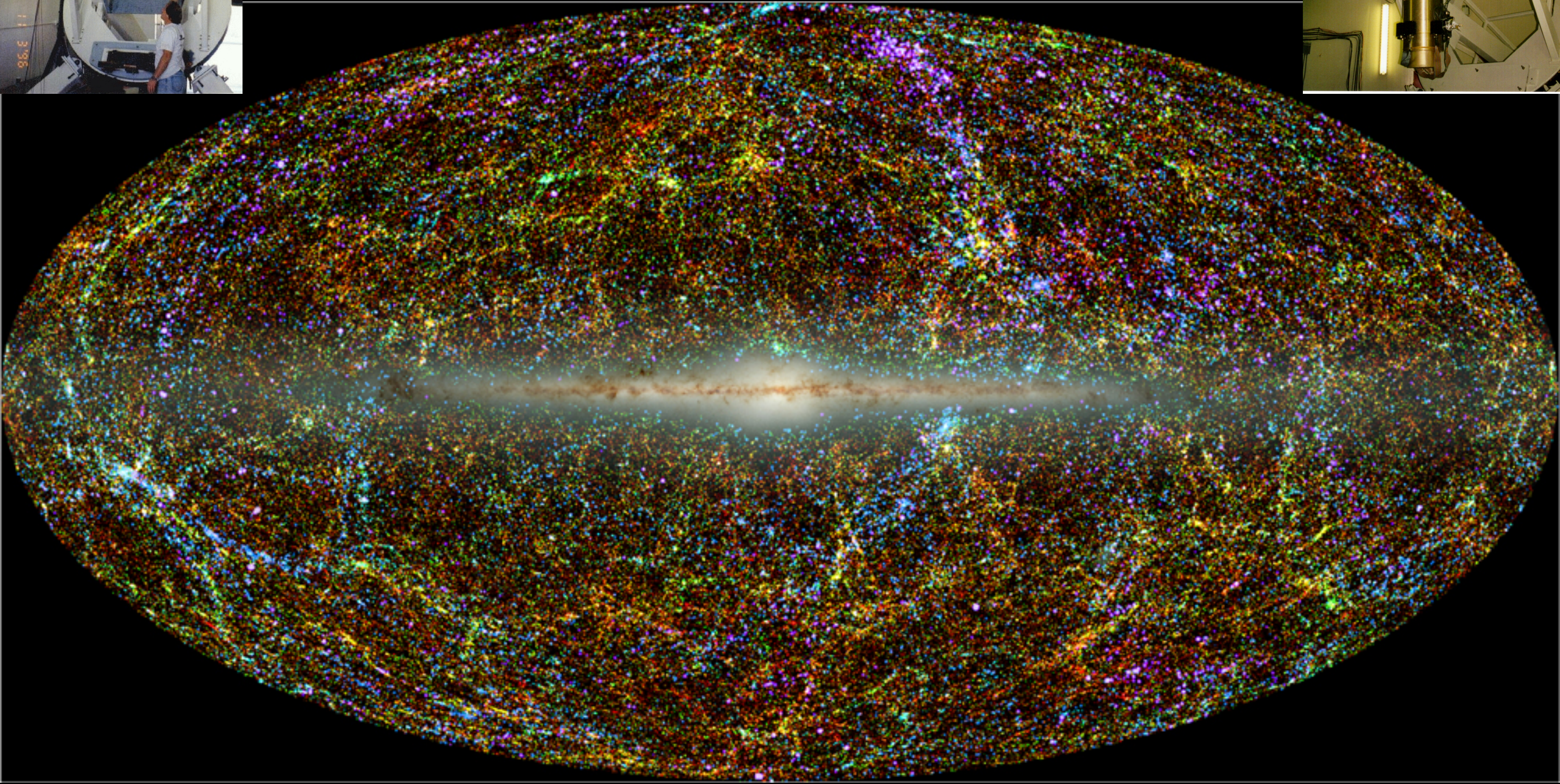
AKARI



Near Infrared Sky

- Stars
- Planets

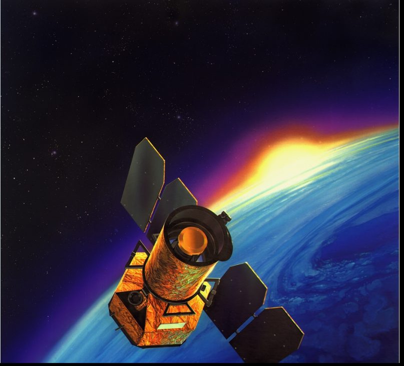




2MASS

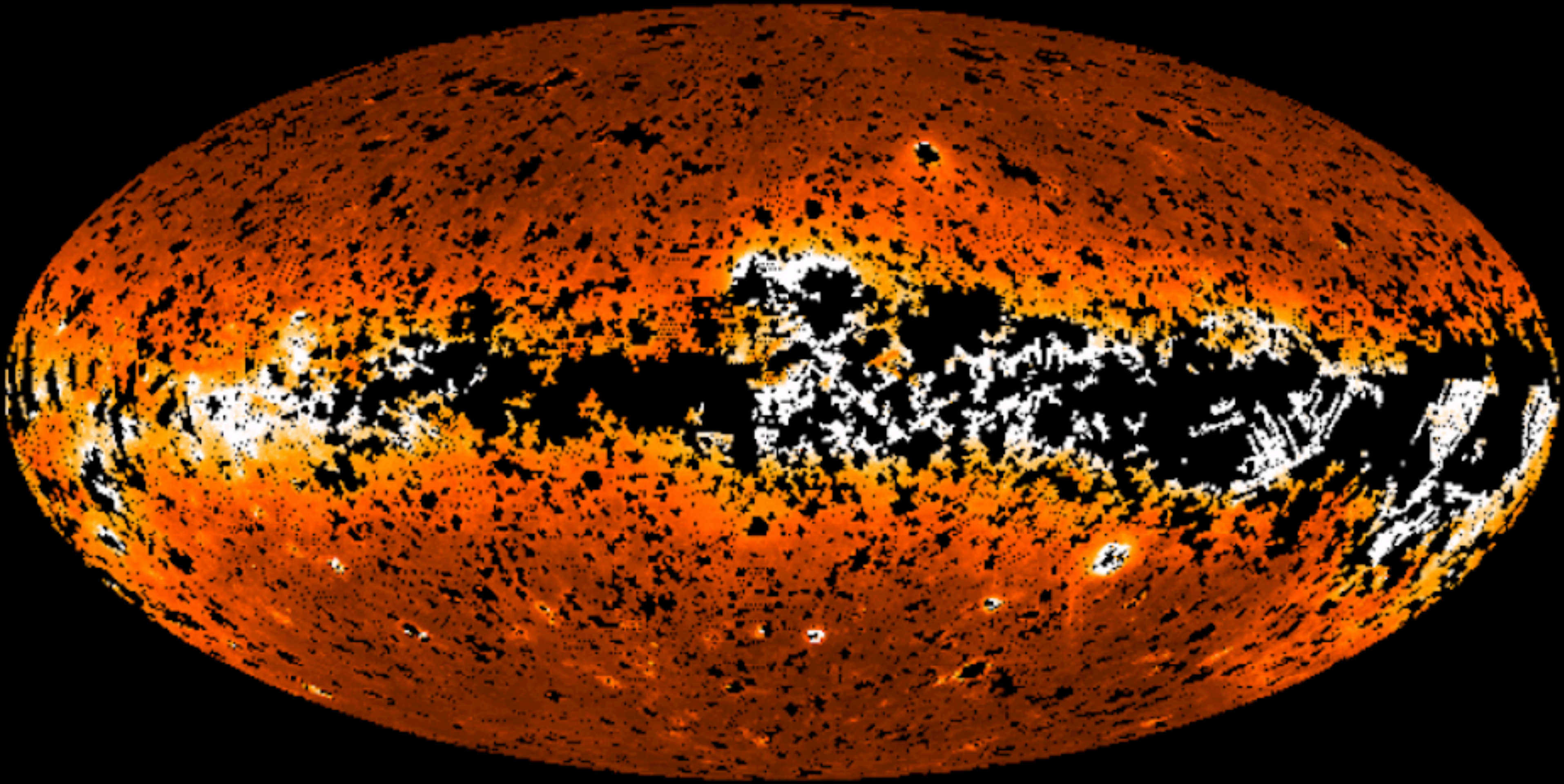
Optical Sky

- Stars

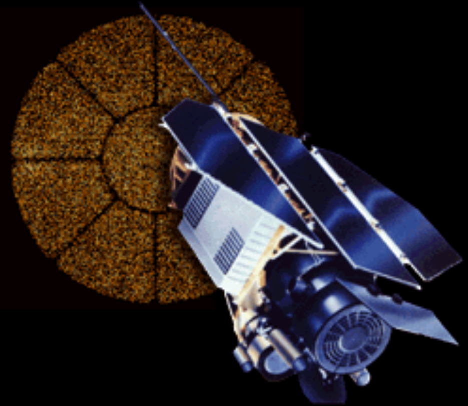


Ultraviolet Sky

- Massive stars
- Ionized gas

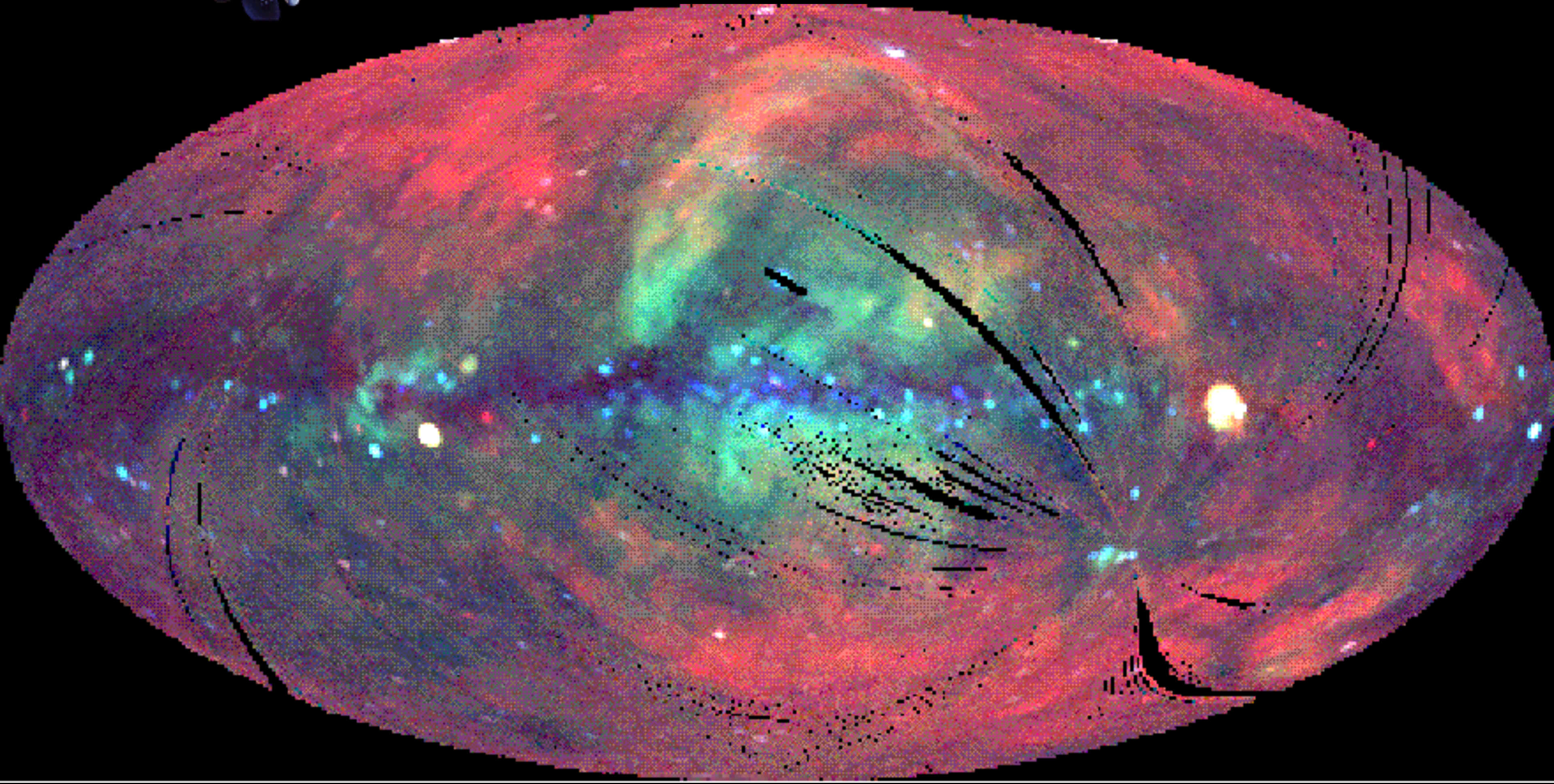


GALEX



X-ray Sky

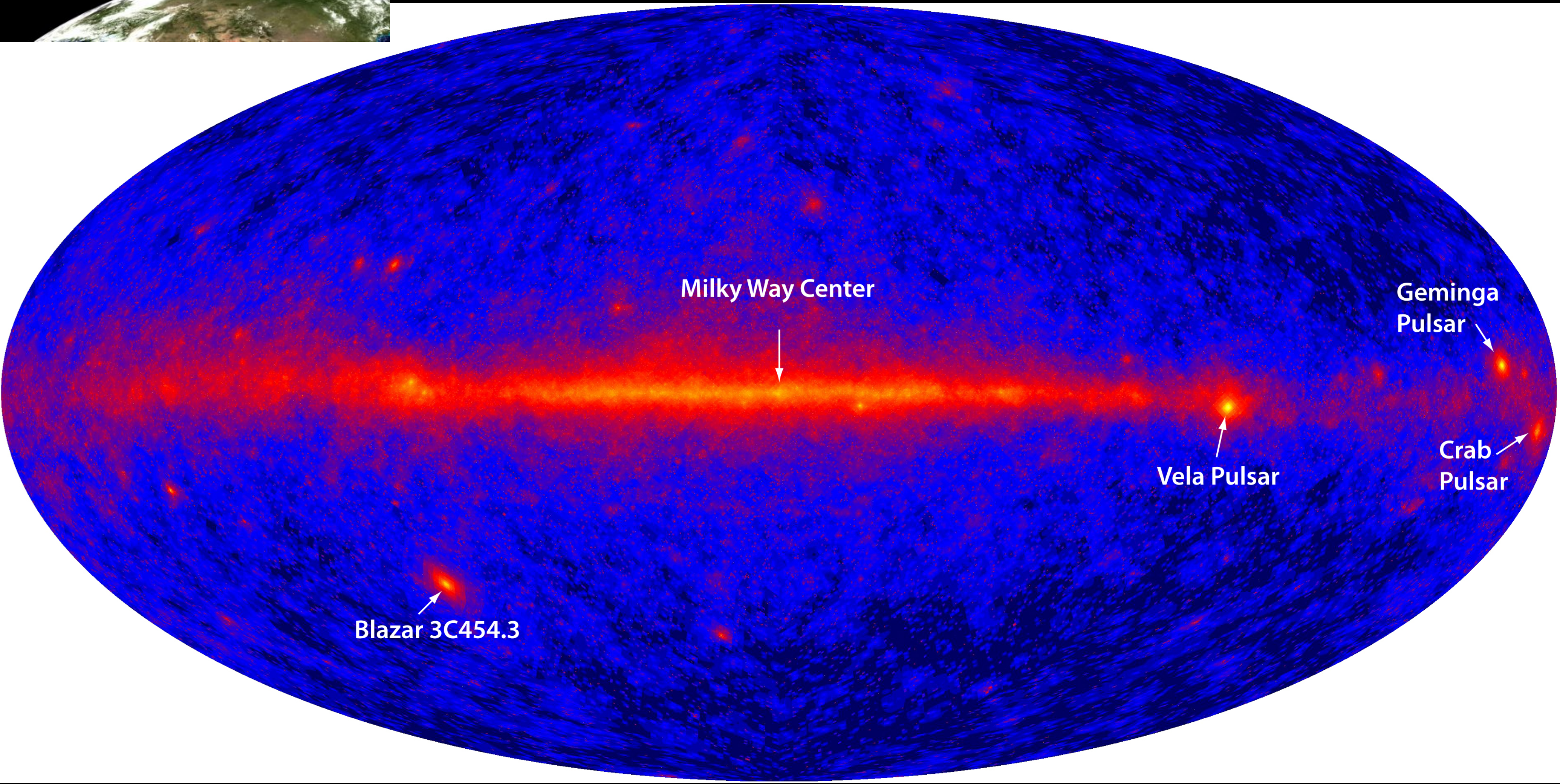
- Hot gas
- AGN
- Pulsars



ROSAT

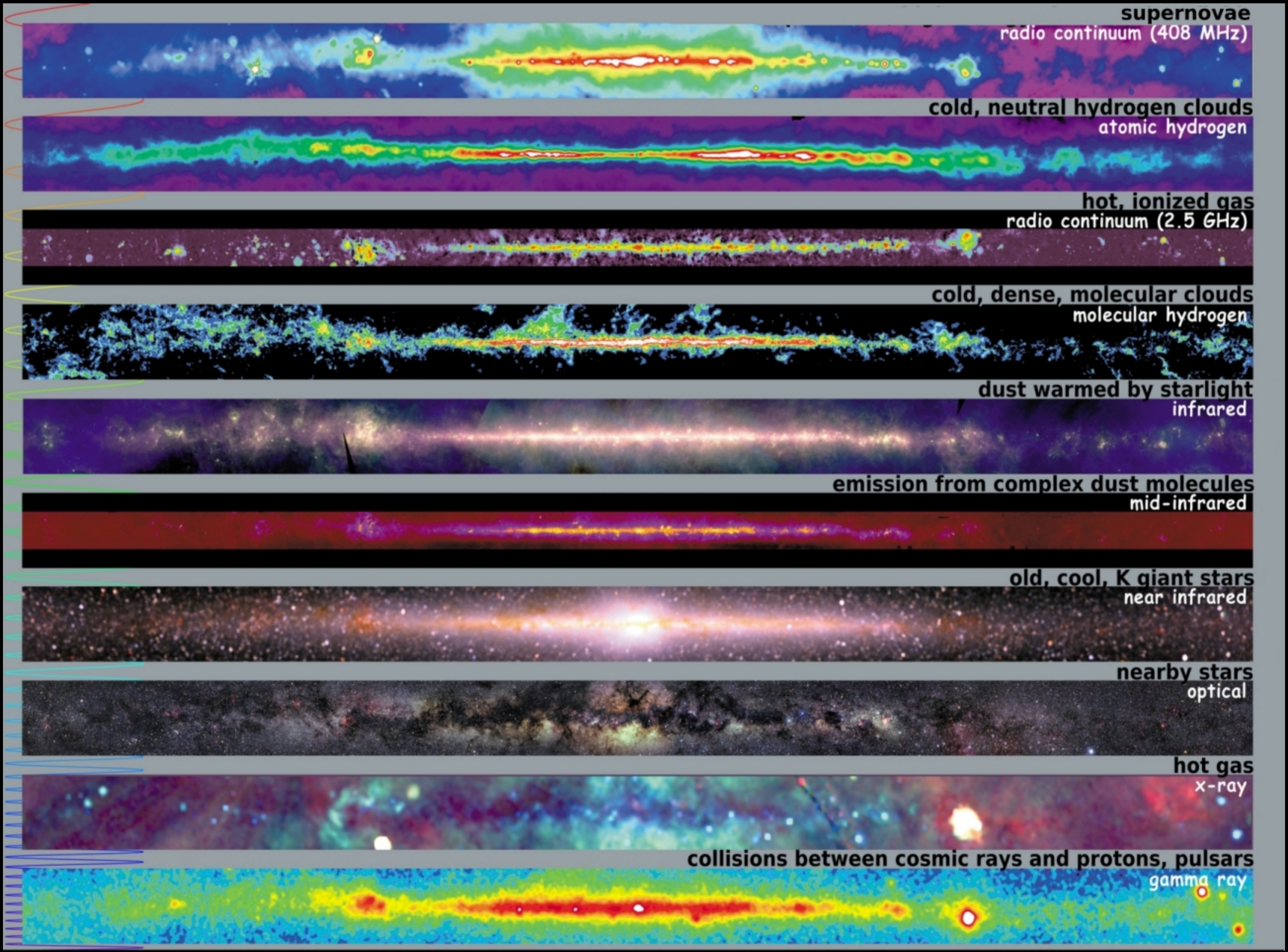
γ-ray Sky

- AGN
- Gamma ray bursts
- Pulsars
- Cosmic rays

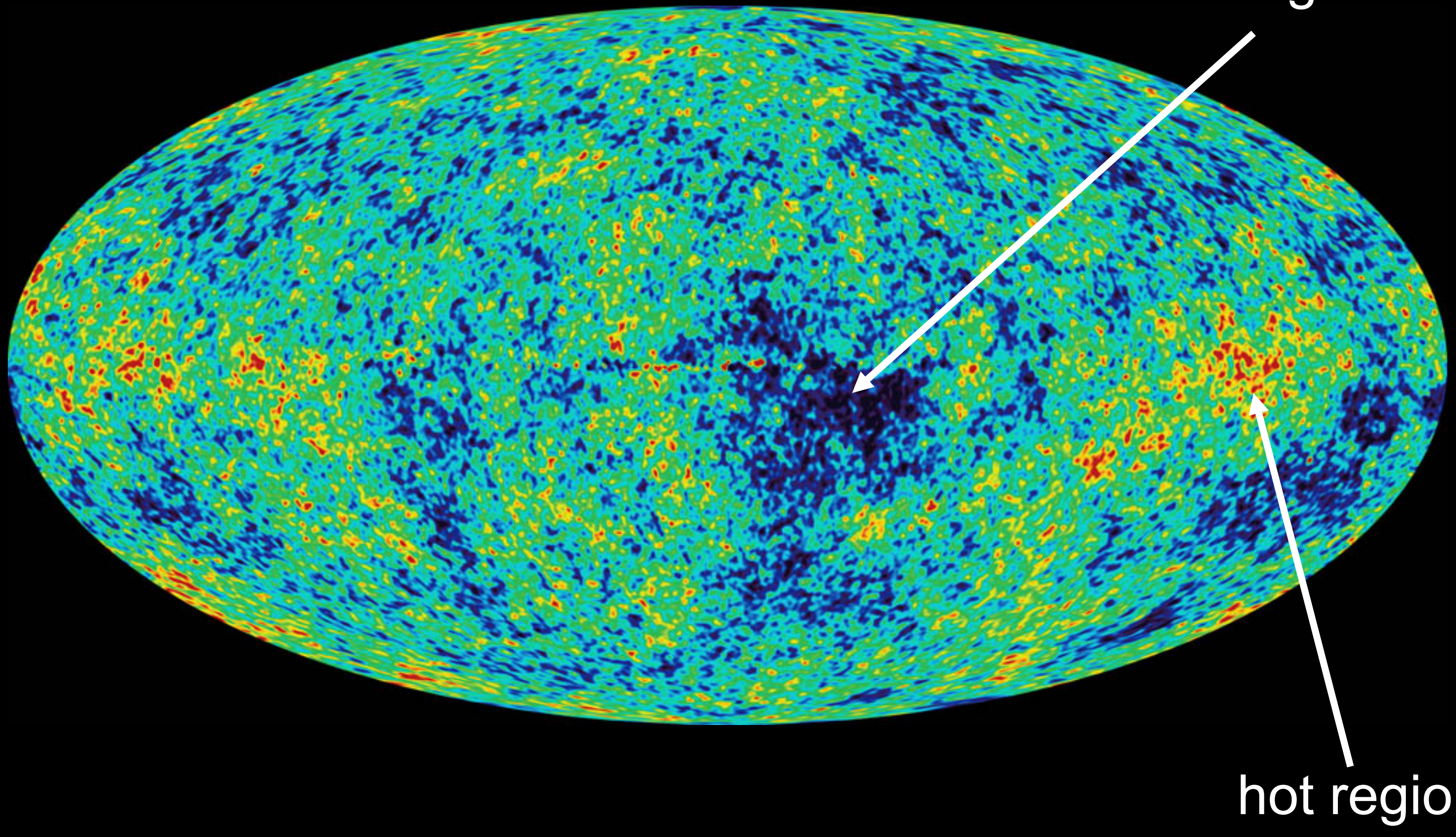


Fermi

Milky Way


supernovae
radio continuum (408 MHz)
cold, neutral hydrogen clouds
atomic hydrogen
hot, ionized gas
radio continuum (2.5 GHz)
cold, dense, molecular clouds
molecular hydrogen
dust warmed by starlight
infrared
emission from complex dust molecules
mid-infrared
old, cool, K giant stars
near infrared
nearby stars
optical
hot gas
x-ray
collisions between cosmic rays and protons, pulsars
gamma ray

The Cosmic Microwave Background



The Cosmic Microwave Background

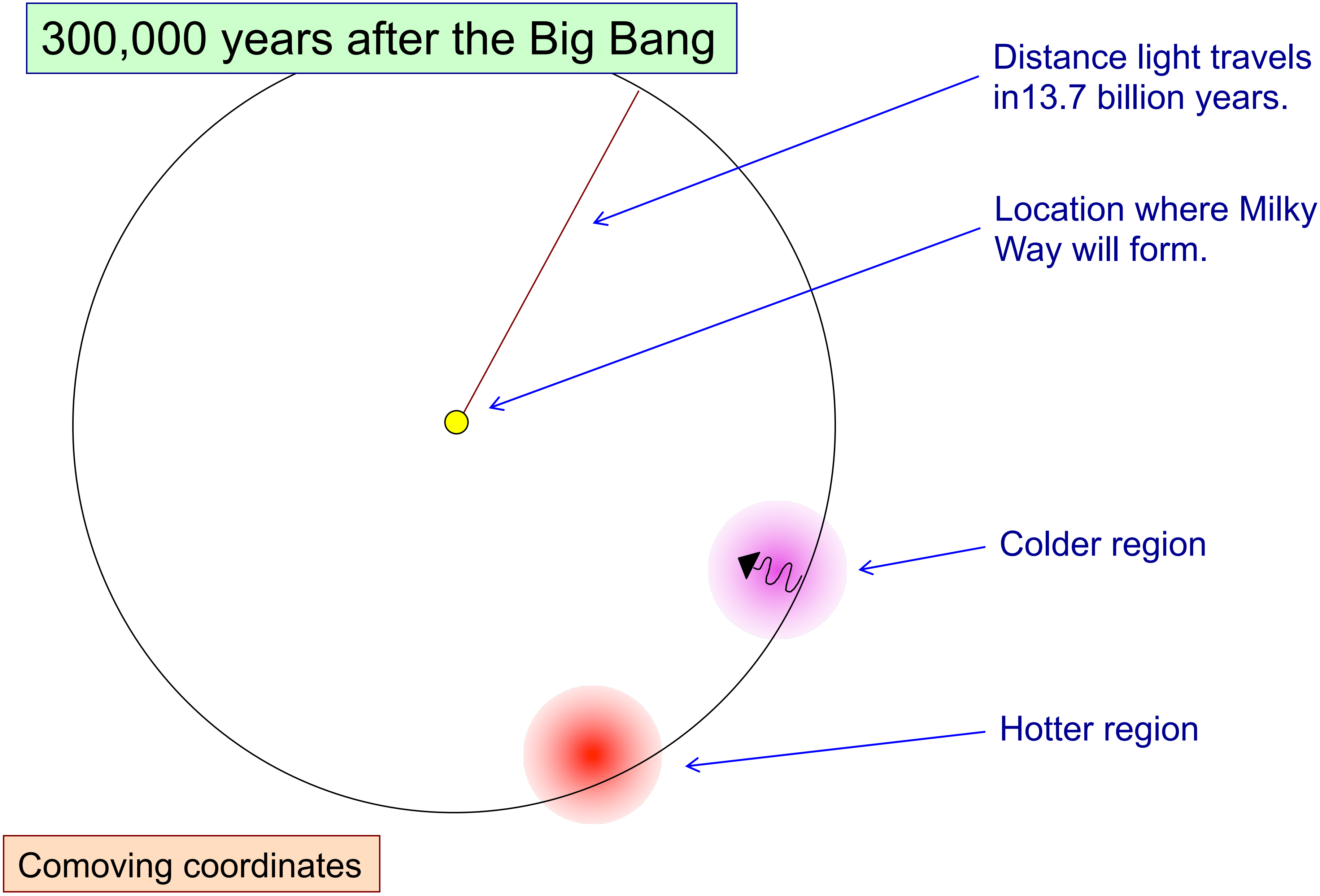
The CMB temperature map corresponds to a density map at the epoch of recombination: 300,000 years after the Big Bang

But the exact physics is complicated!

Basic picture:

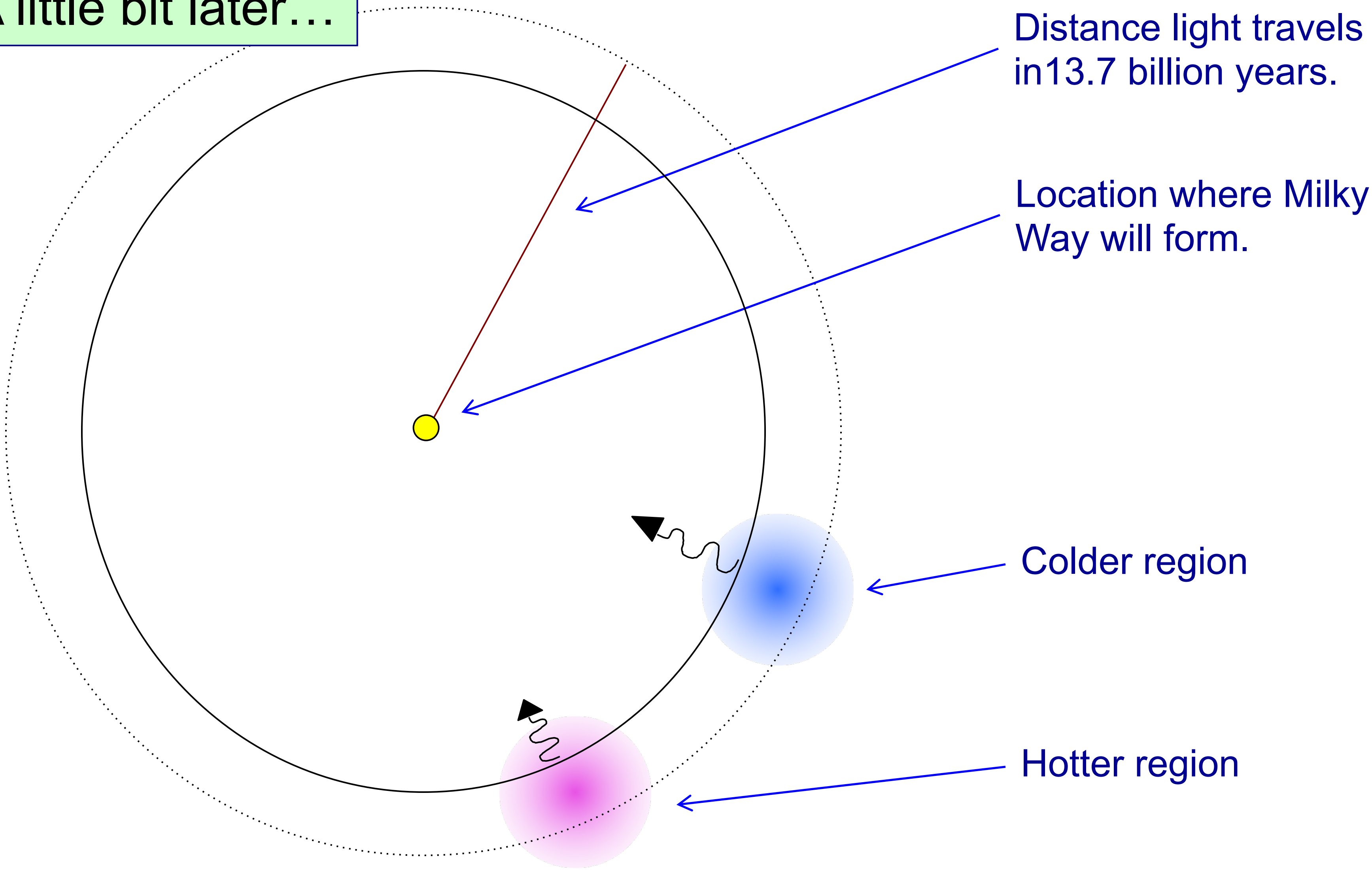
- As the universe expands, the photon-baryon plasma in it cools.
- When the temperature drops below about 3000^{o}K, electrons recombine with protons and photons can move freely.
- In some regions of the universe, the photon-baryon plasma is compressed and slightly hotter than average.

The Cosmic Microwave Background



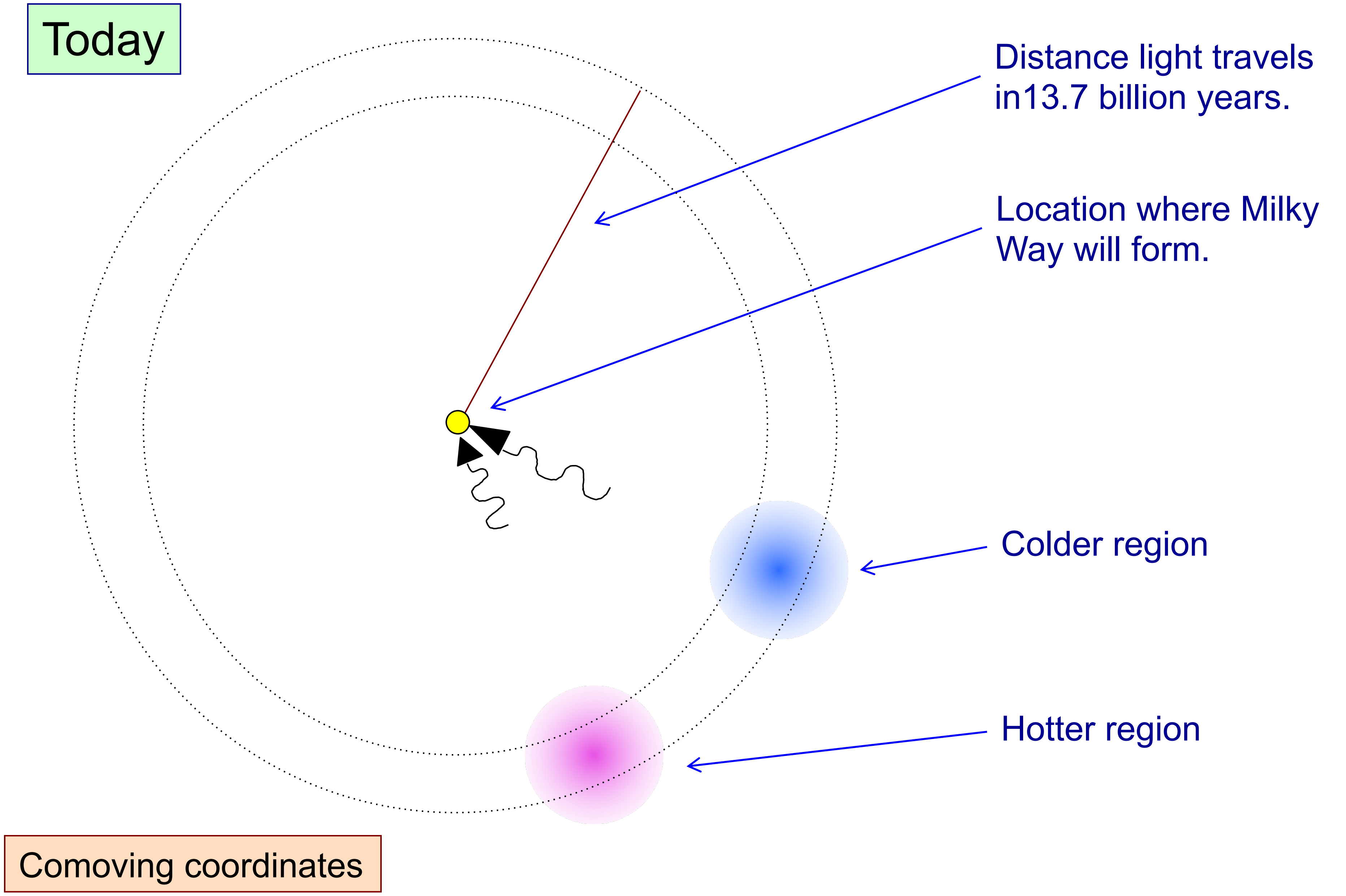
The Cosmic Microwave Background

A little bit later…



Comoving coordinates

The Cosmic Microwave Background



The Cosmic Microwave Background

The region of space we see with the CMB is like the surface of an orange.

The Cosmic Microwave Background

Primary fluctuations (at origin):

- Standard fluctuations: high density regions appear hot

- Acoustic oscillations of baryon-photon plasma

- Gravitational redshift: high density regions appear cold
  (Sachs-Wolfe)

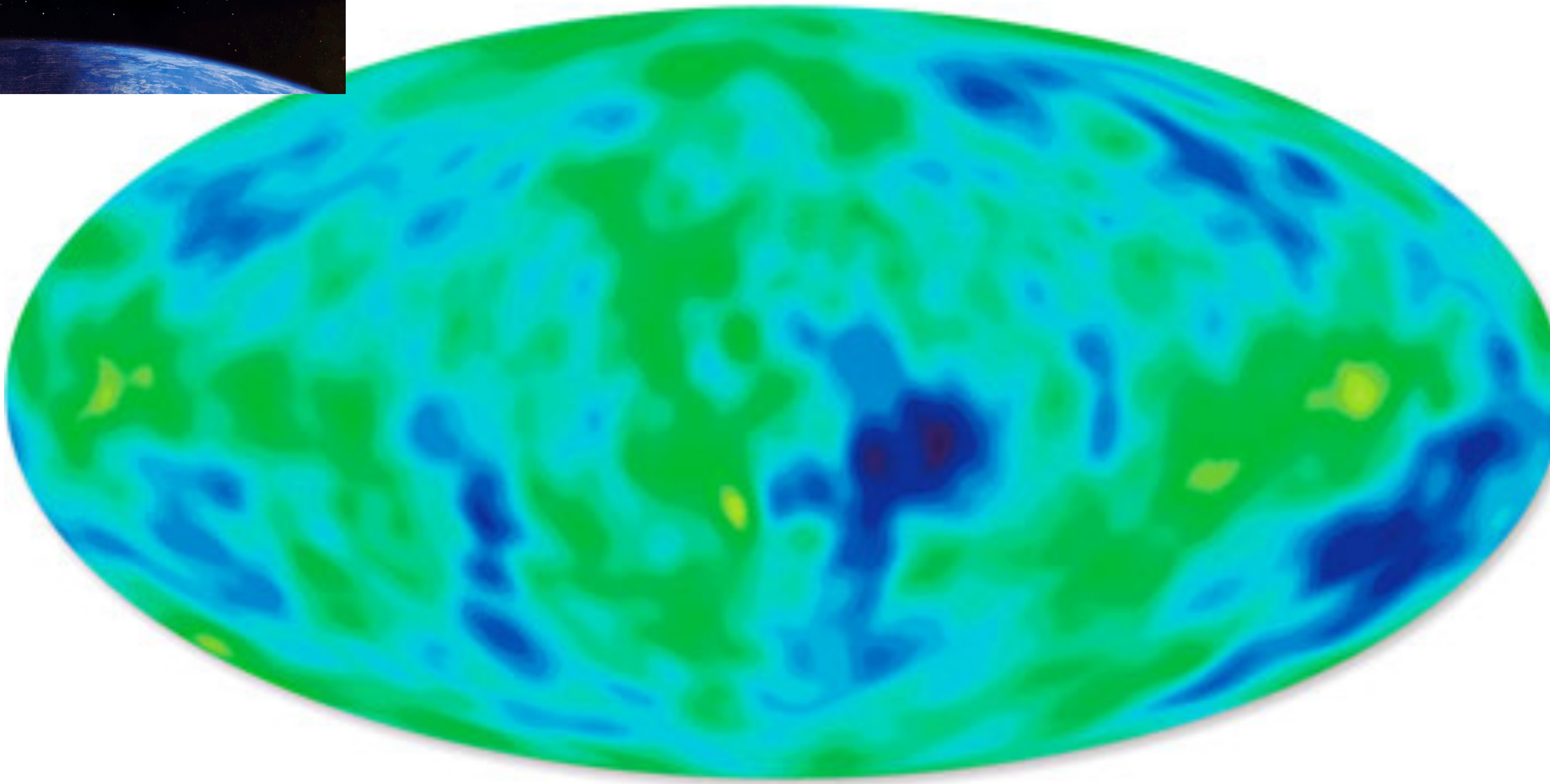
- Doppler effect: photons scattered by moving plasma

The Cosmic Microwave Background

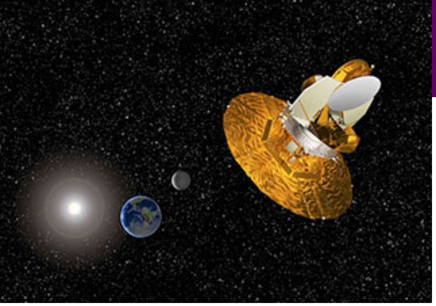
Secondary fluctuations (along path to us):

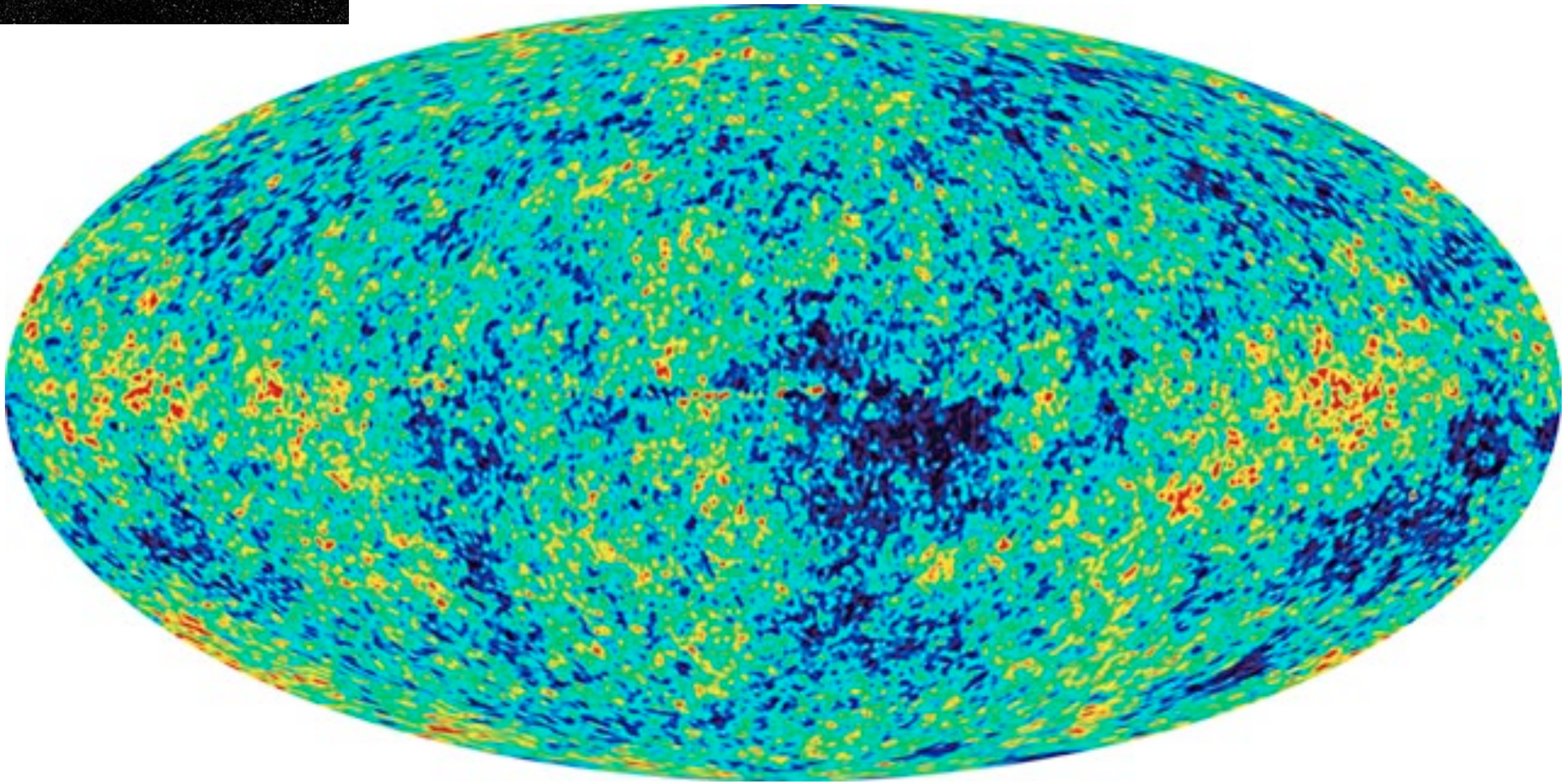
- CMB photons traverse changing gravitational field
  (Reese-Sciama, Integrated Sachs-Wolfe)
- CMB photons scatter off hot plasma in clusters
  (Sunyaev-Zel'dovich)
- CMB photons are gravitationally lensed
- + many more effects

The CMB: COBE (1989-1993)

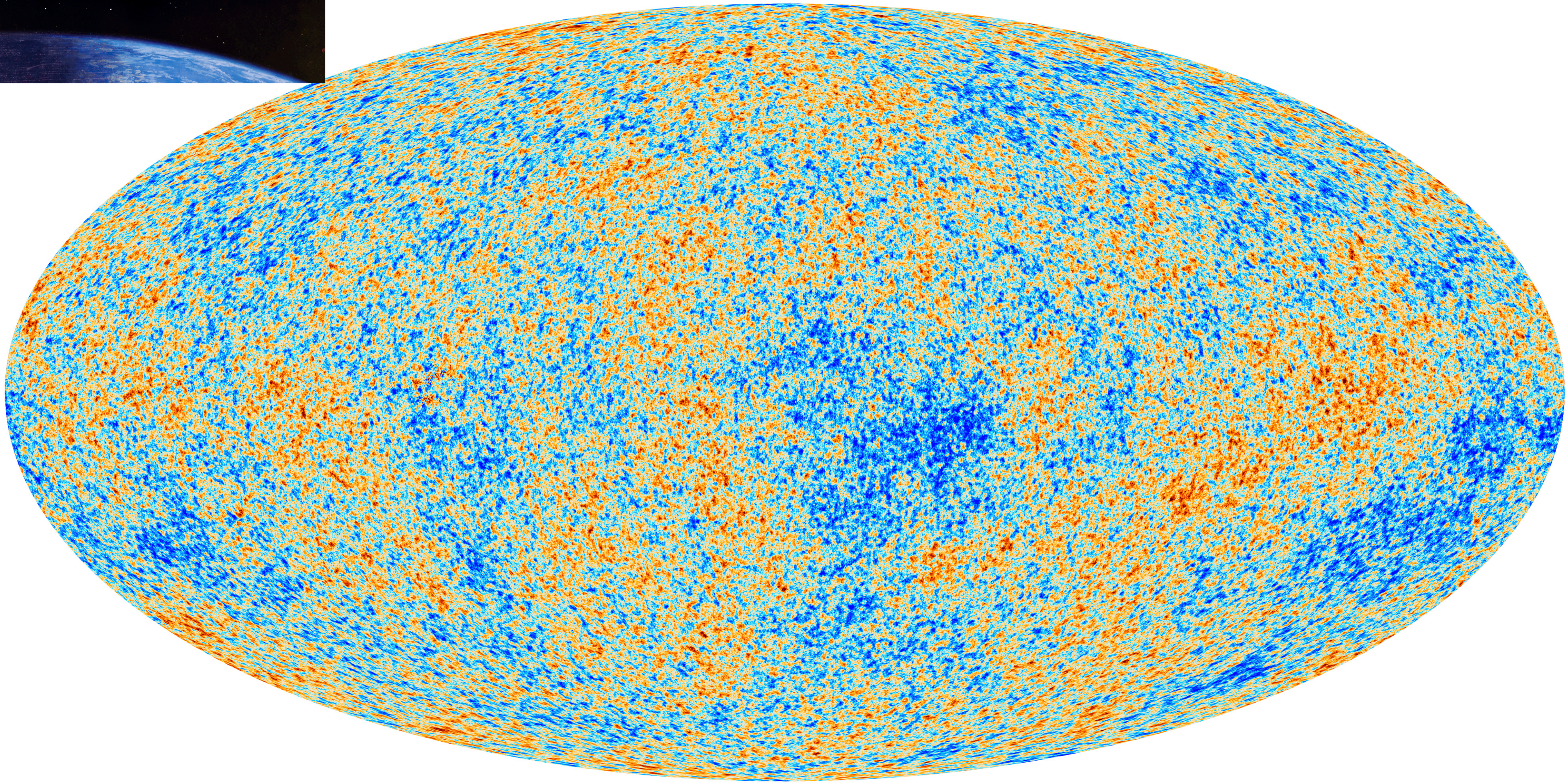


The CMB: WMAP (2001-2010)

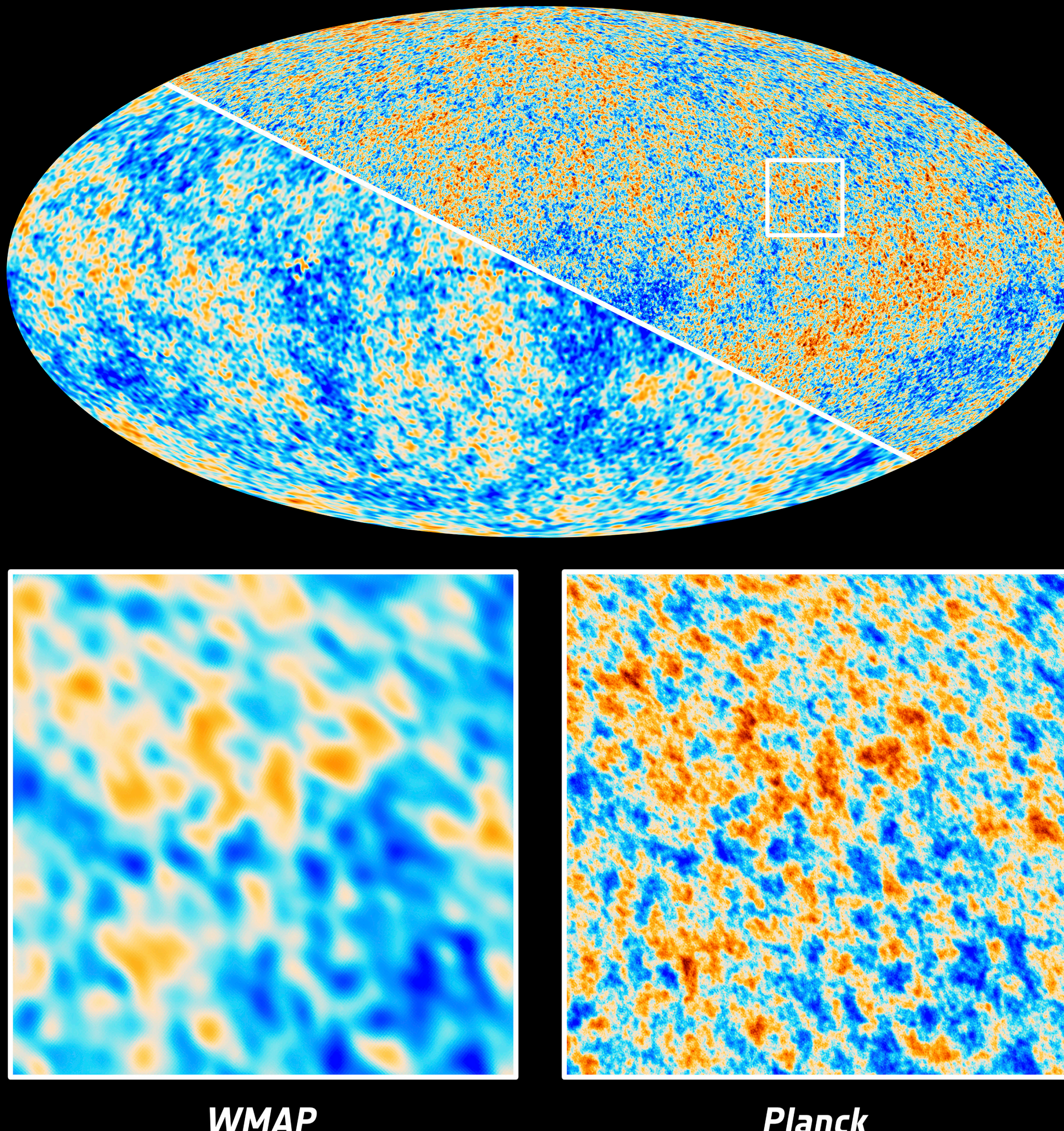




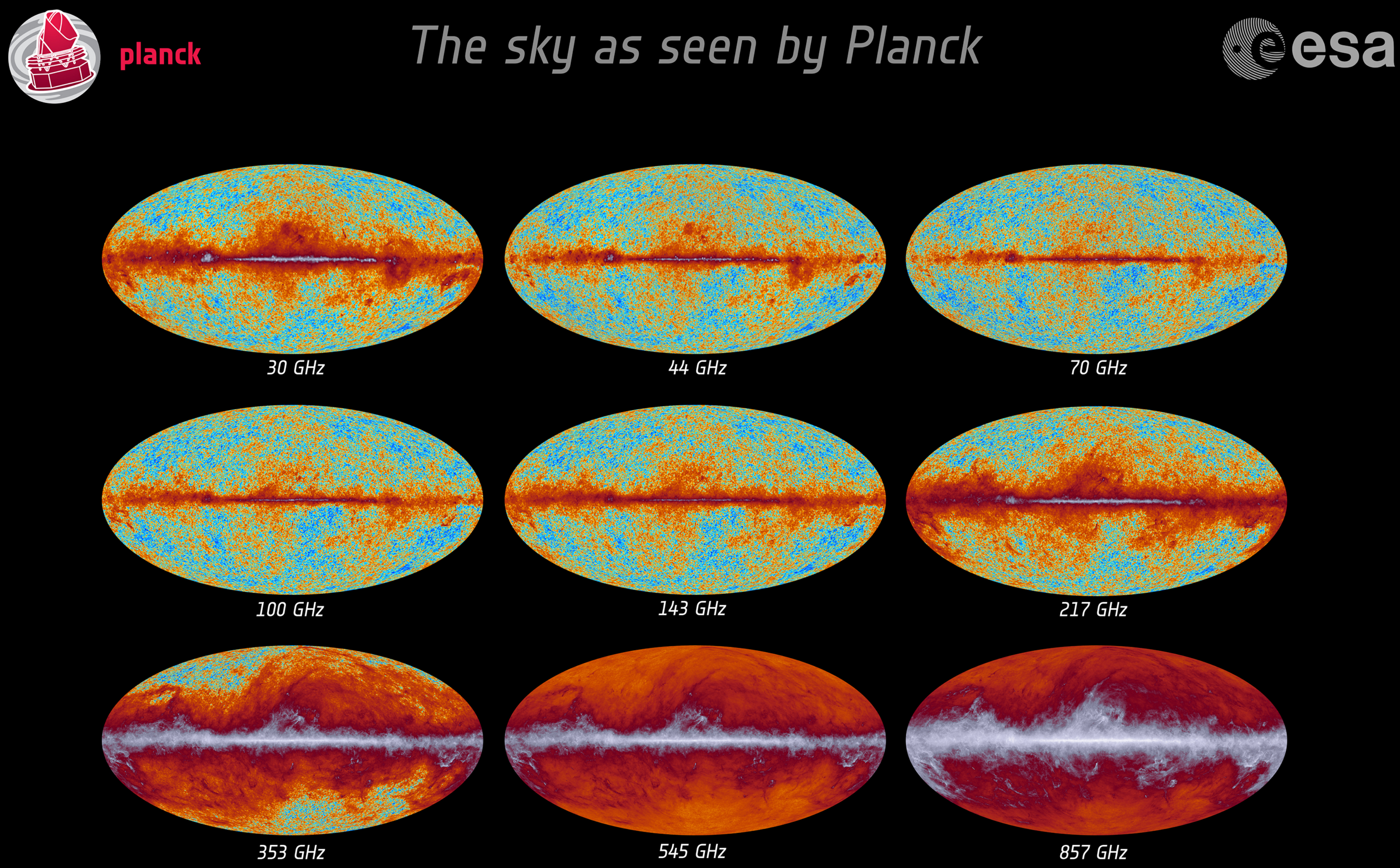
The CMB: Planck (2009-2013)



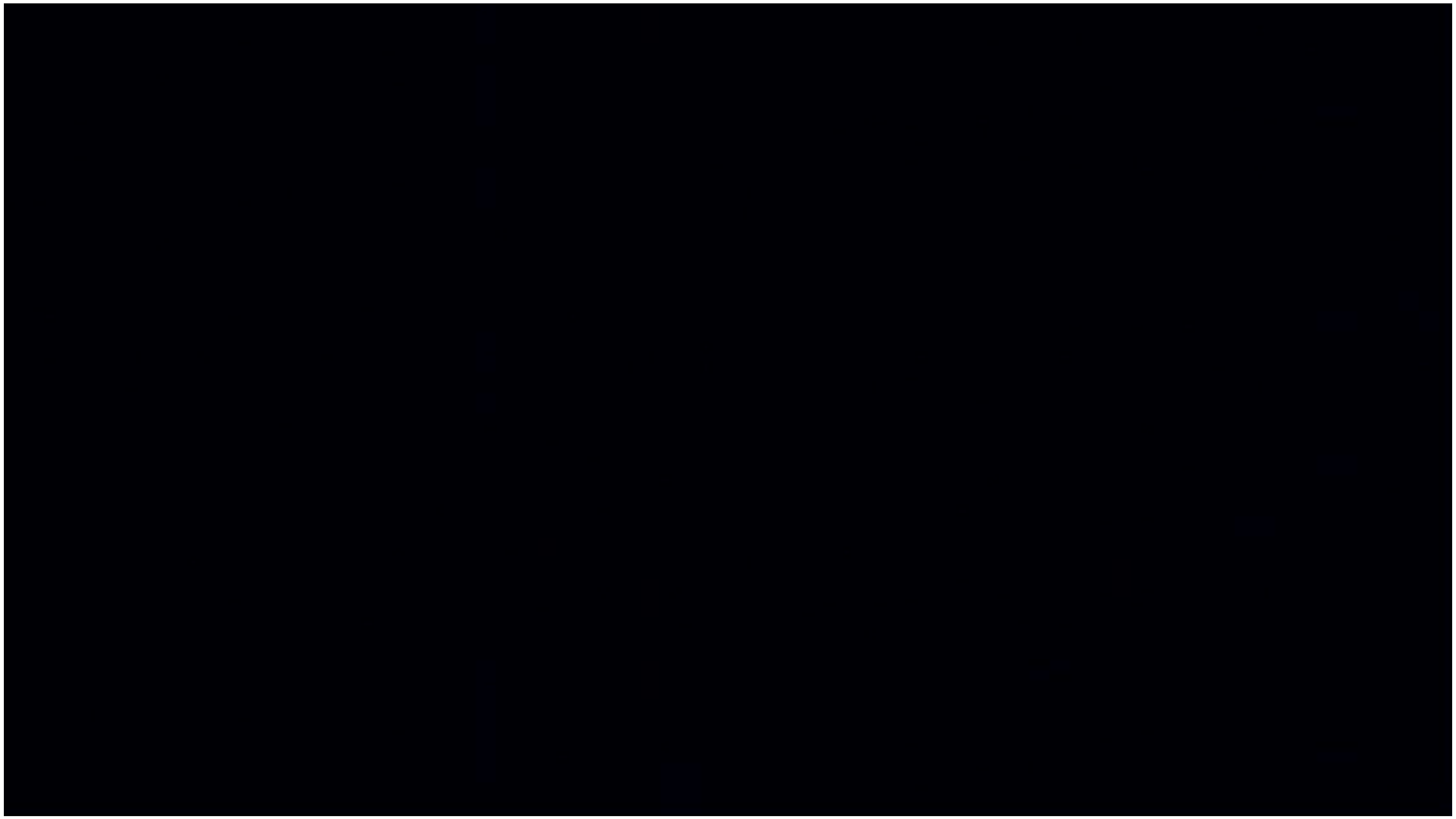
The Cosmic Microwave Background



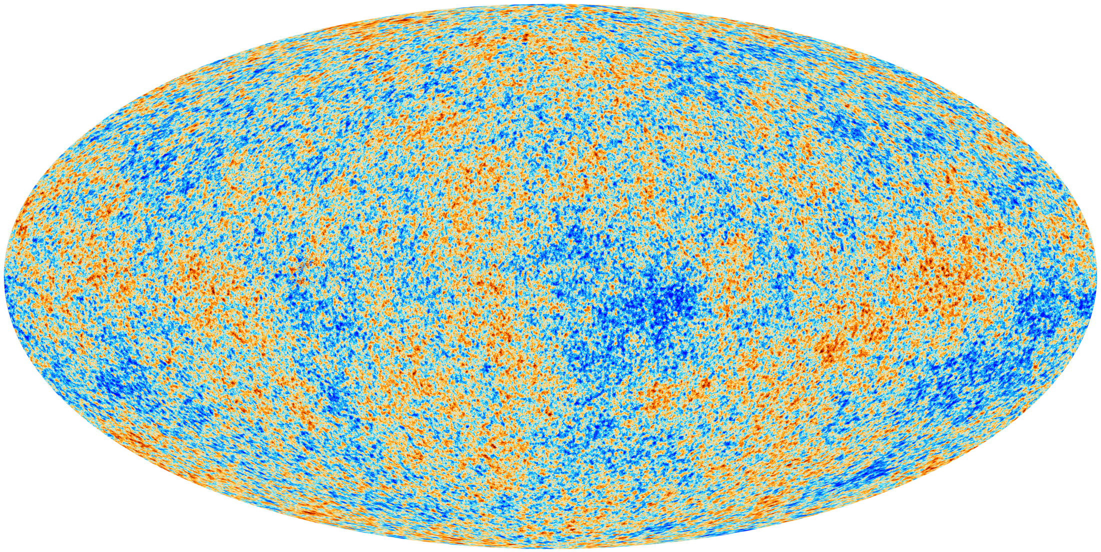
The Cosmic Microwave Background

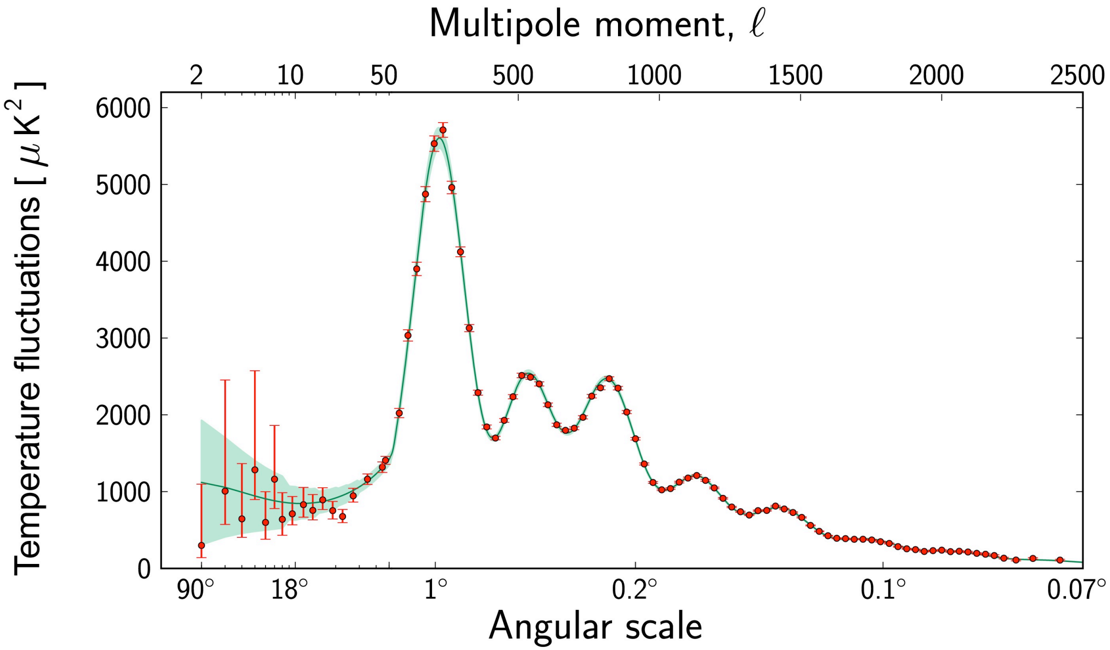


The CMB: How the Planck map is made

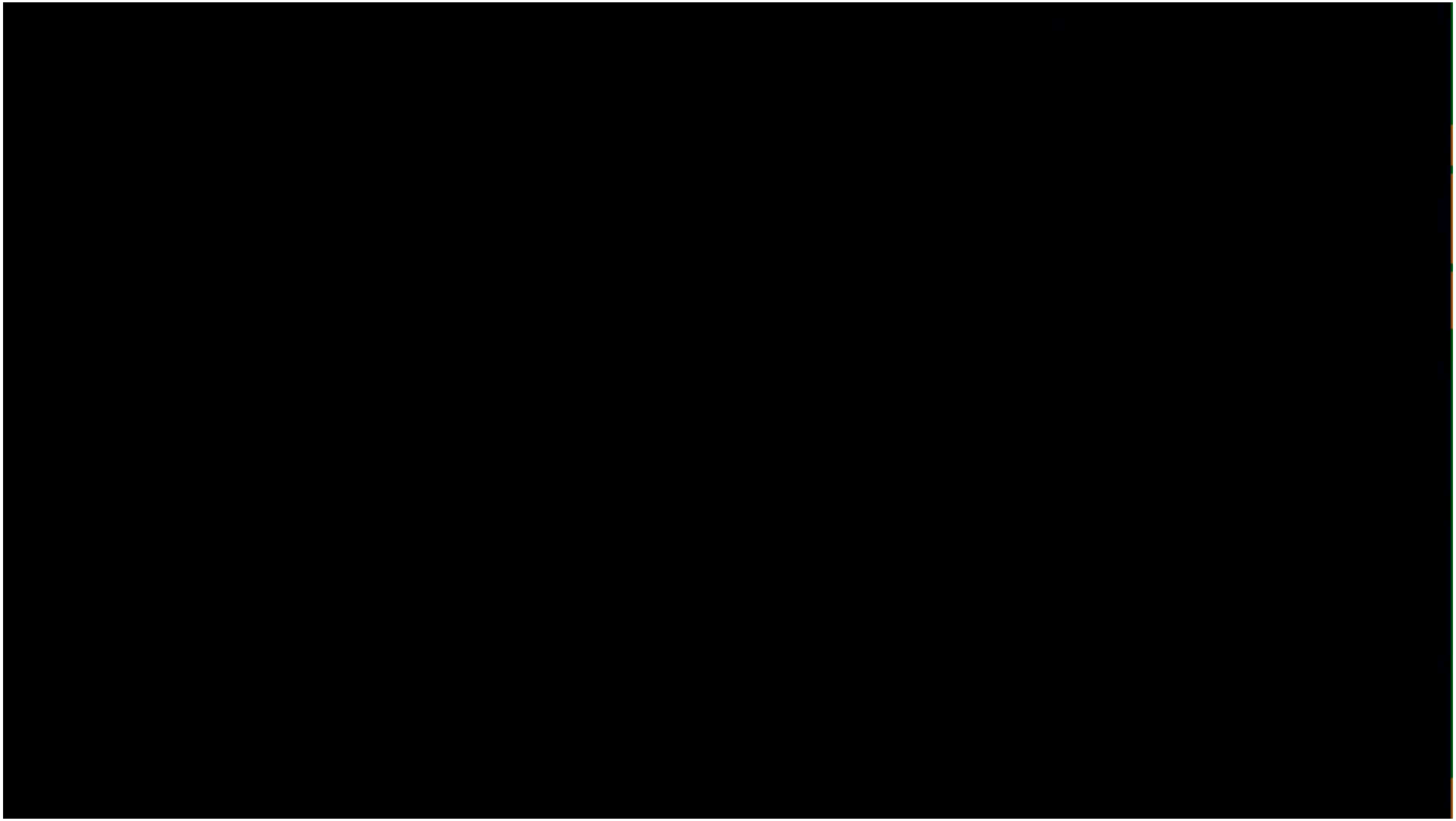


The CMB: The Planck power spectrum



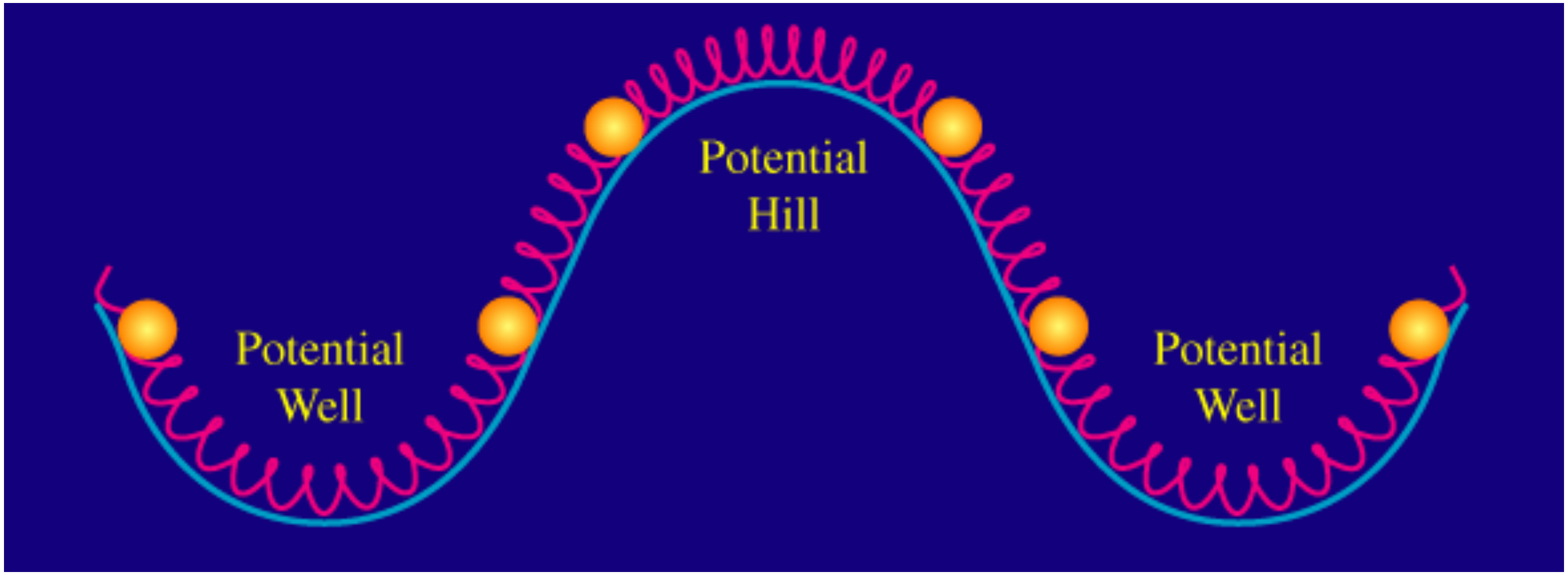


The CMB: How the Planck power spectrum is made

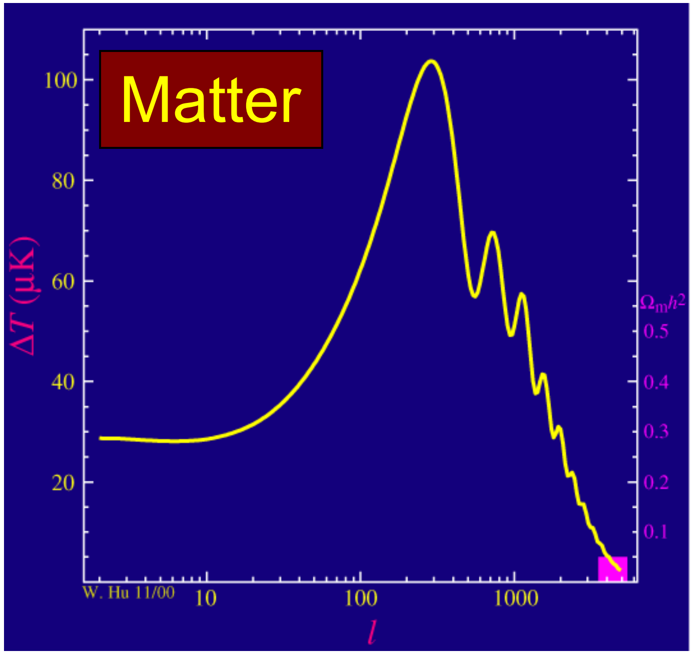


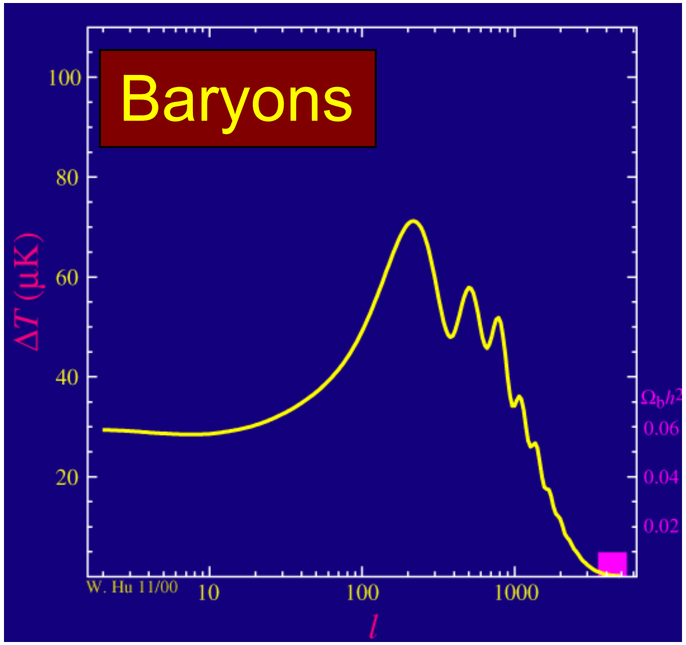
The CMB: Why are there wiggles in the power spectrum?

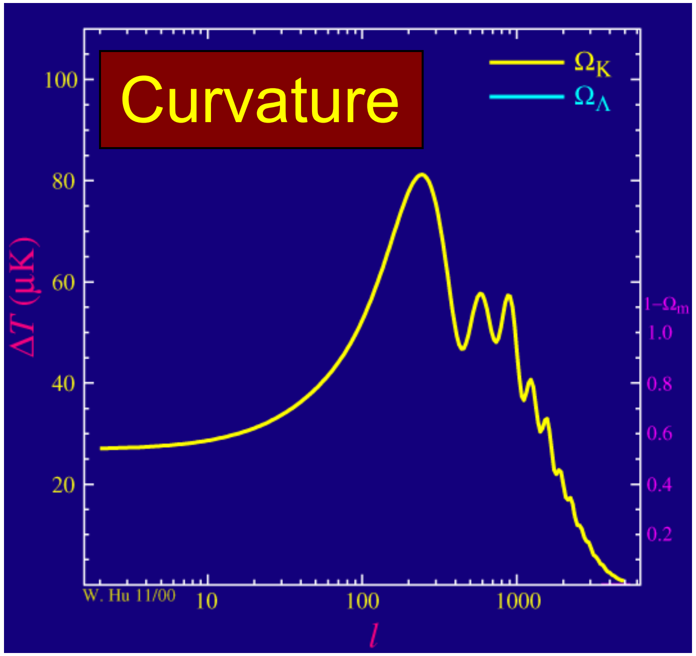
- Before recombination, photons and baryons were tightly coupled.
- Gravity and pressure competed to cause oscillating density waves.
- At maximum compression or rarefaction, density fluctuations are strongest.
- The frequency of oscillation depends on the fluctuation size.
- Specific fluctuation sizes reach maximum compression at recombination.



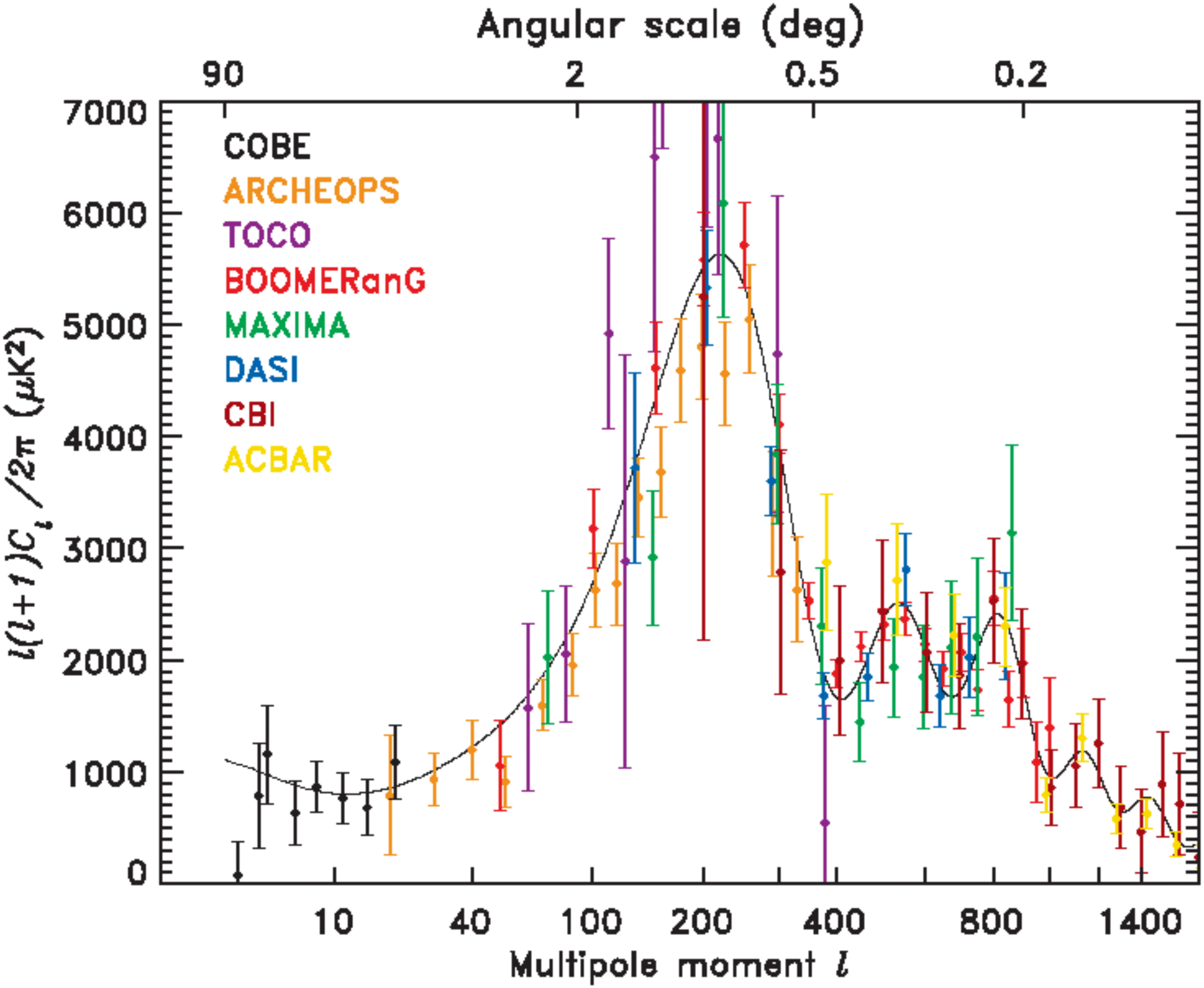
The CMB tells us what the universe is made of



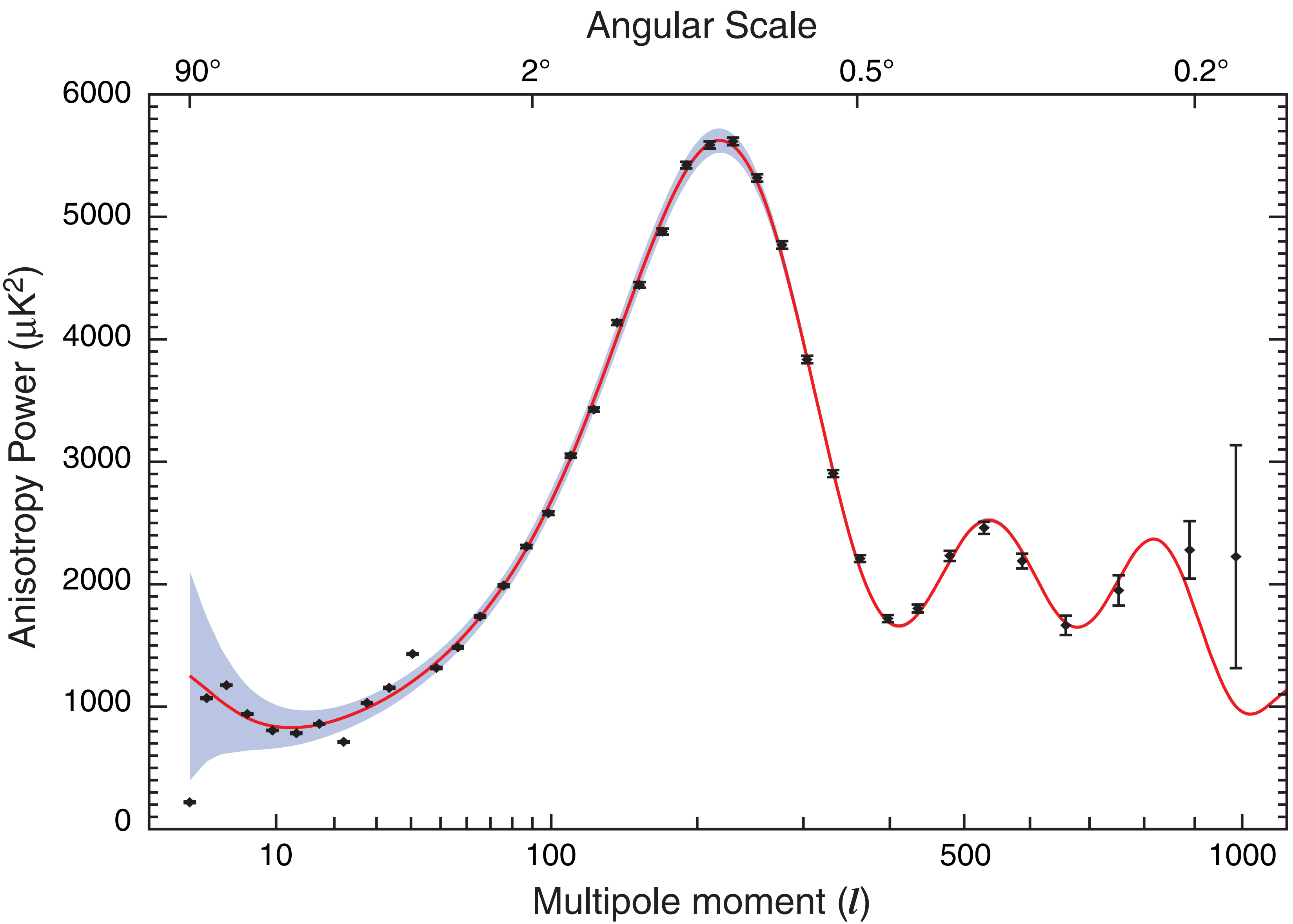




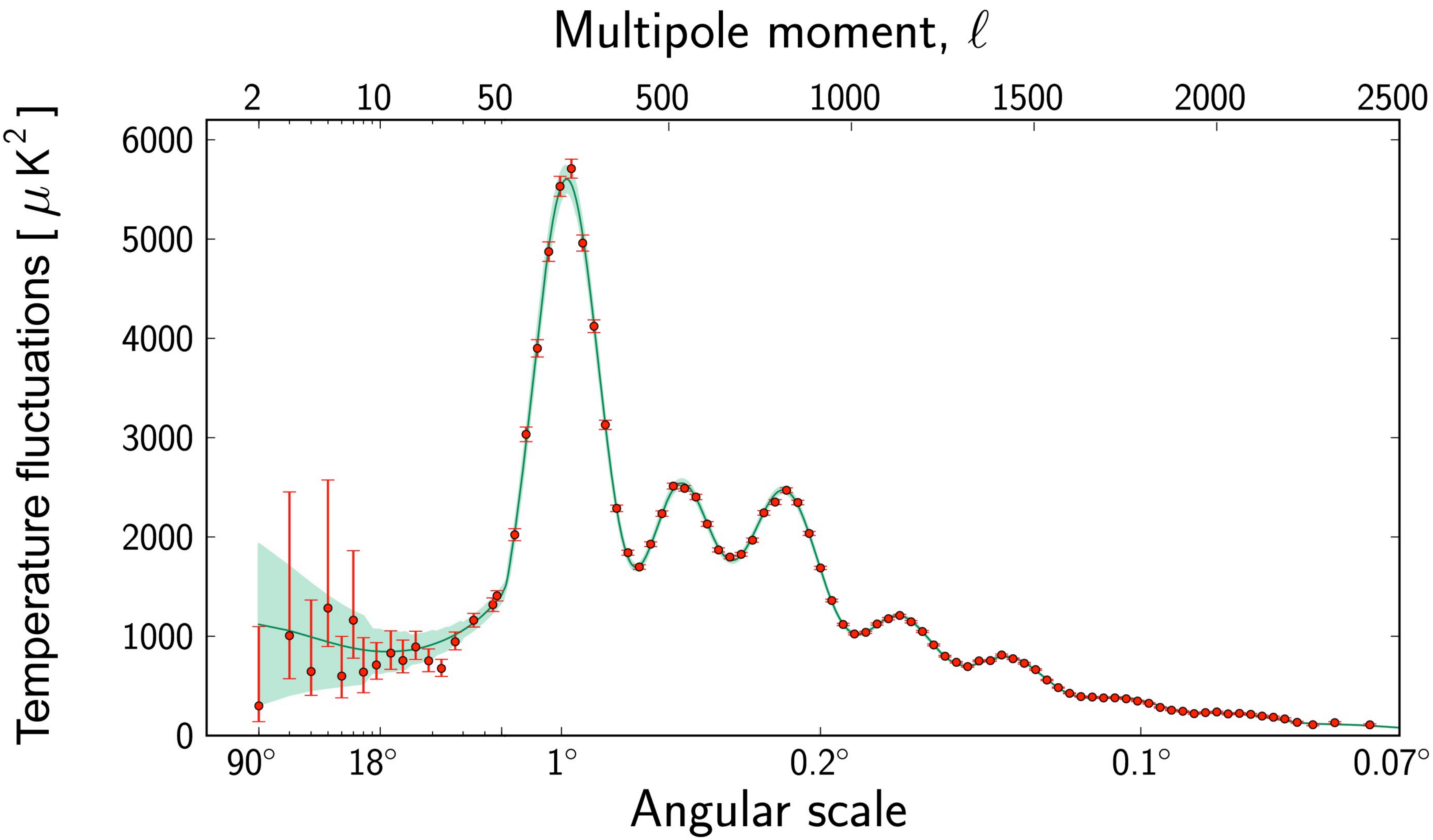
The CMB power spectrum: before WMAP (2003)



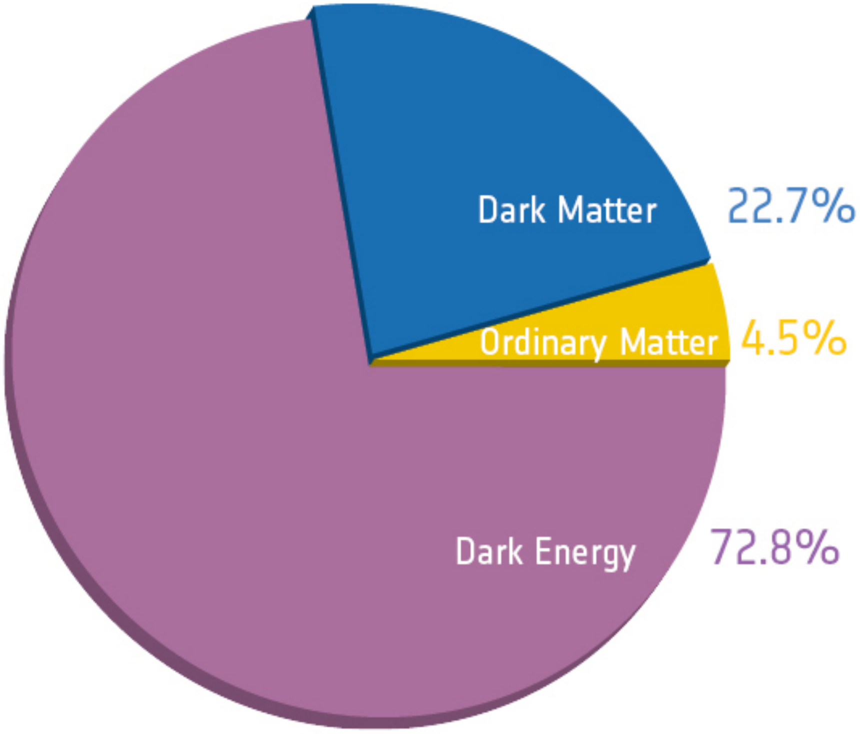
The CMB power spectrum: WMAP (2007)



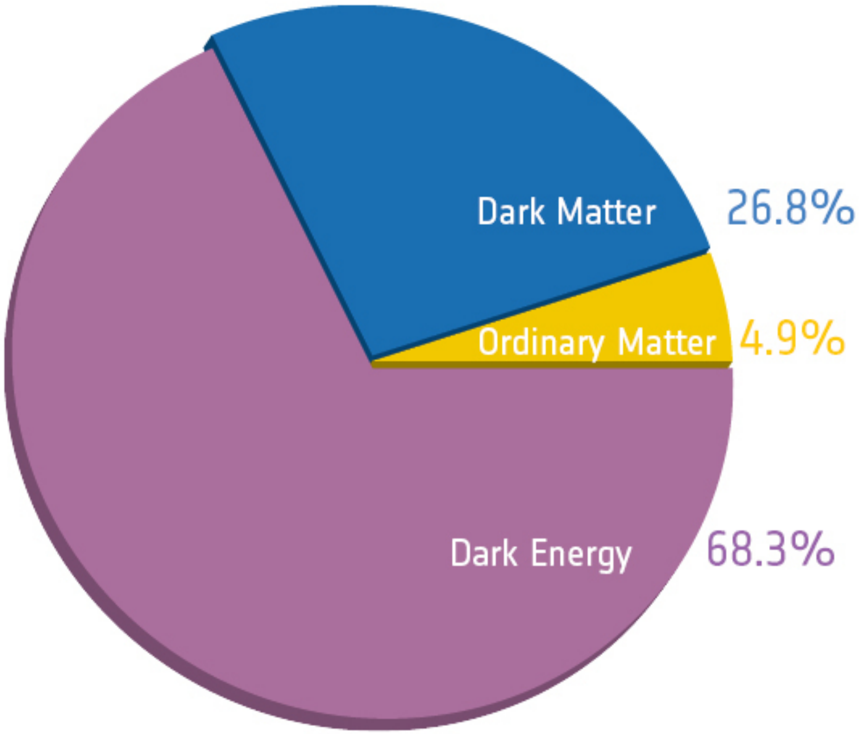
The CMB power spectrum: Planck (2013)



The CMB tells us what the universe is made of



Before Planck



After Planck