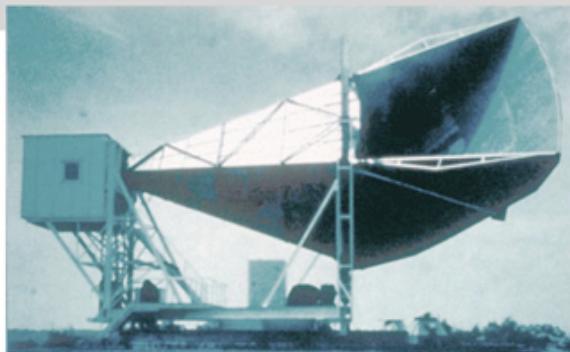
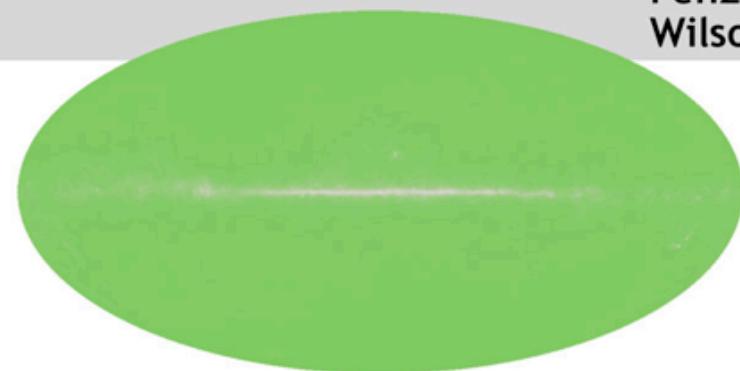


The cosmic microwave background is explained in the hot Big Bang model as the relic radiation from the hot, early universe.

1965



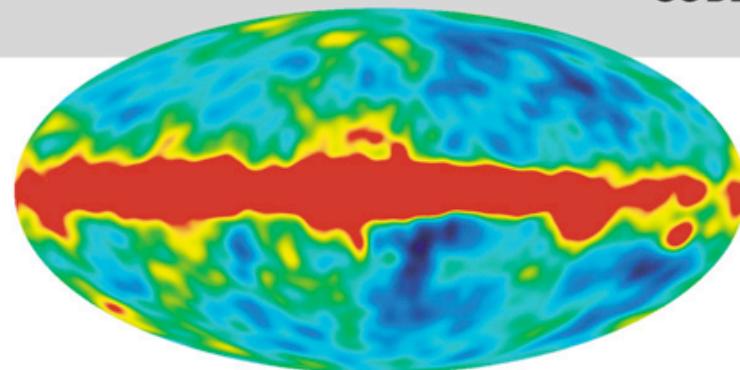
Penzias and
Wilson



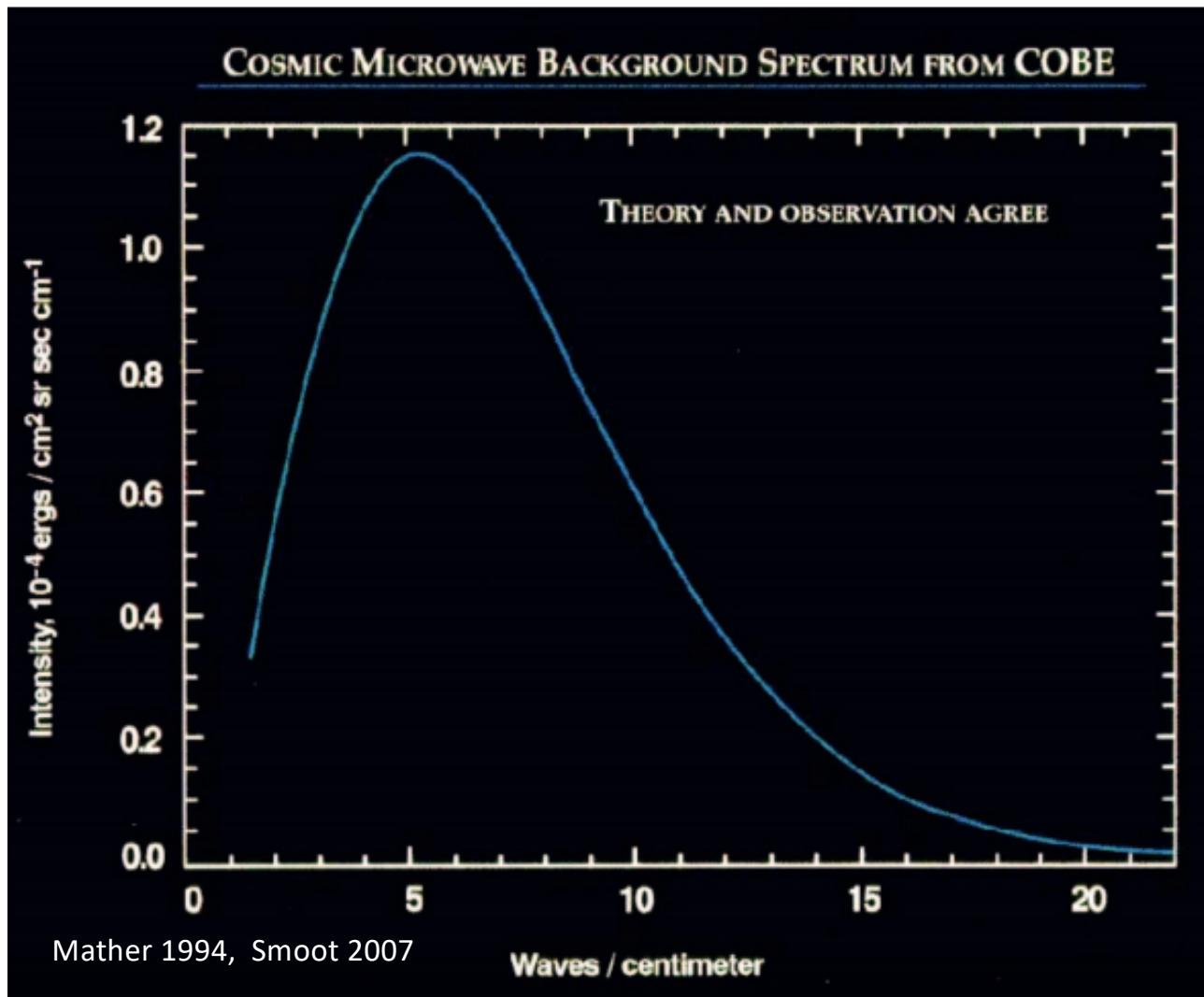
1992

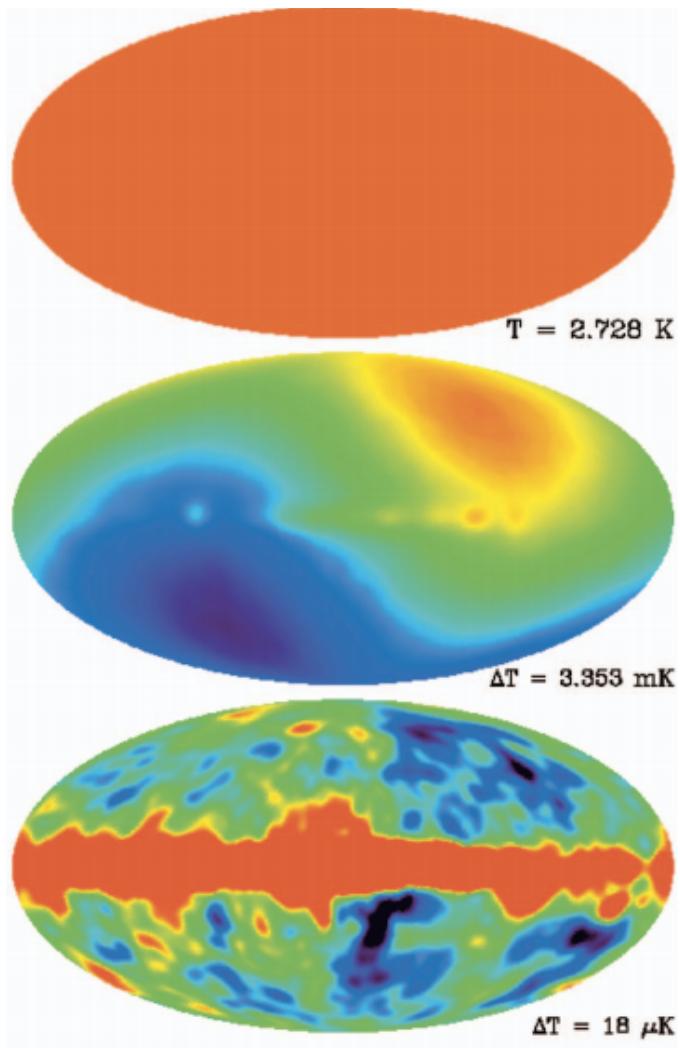


COBE



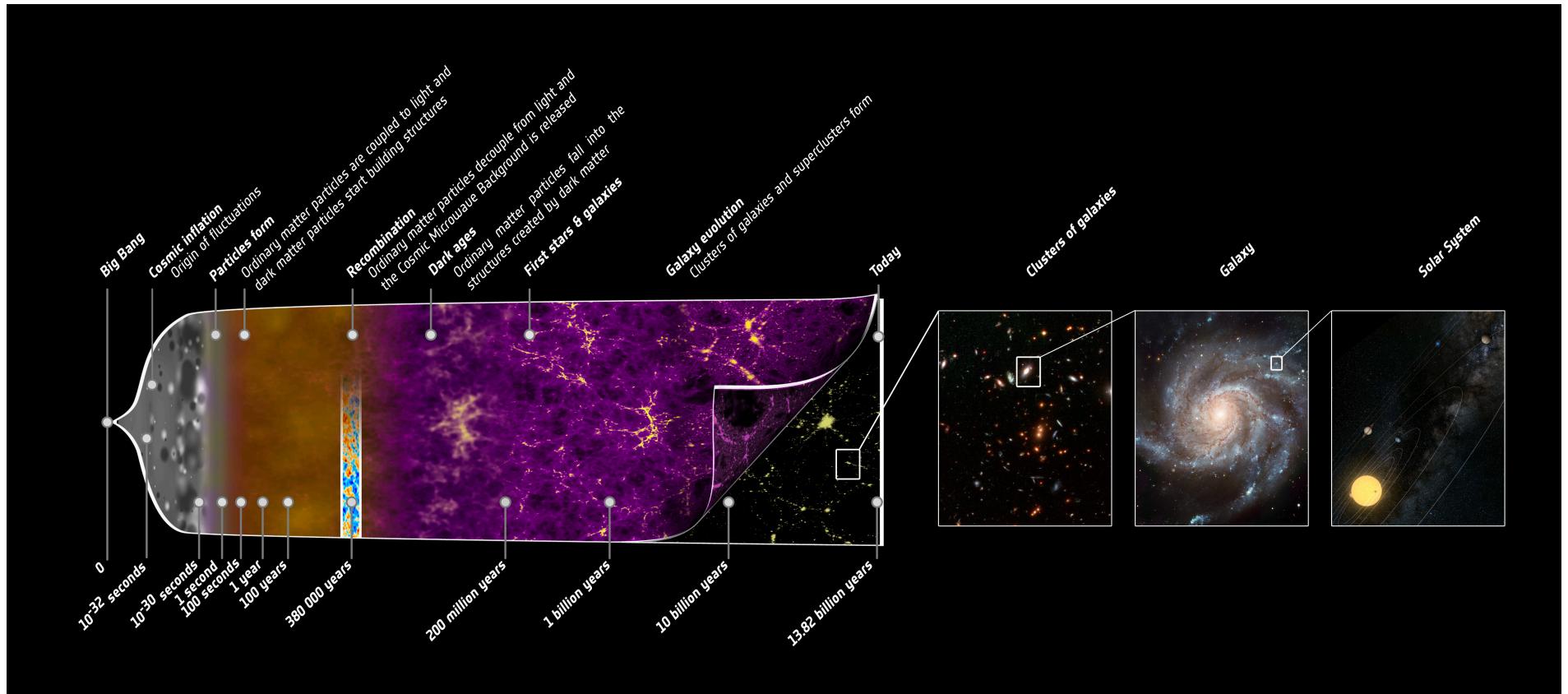
A perfect
Black Body at
2.73 K





Temperature Fluctuations:
1 part in 100,000

- 1) The universe expands today – it must have been smaller and denser in the past (big bang)
- 2) When a gas is compressed, it gets hot – the early universe must have been very hot.



Era of Recombination

At $z > 1000$ photons are hot enough to ionize hydrogen – photons and electrons are coupled. Can't form atoms.

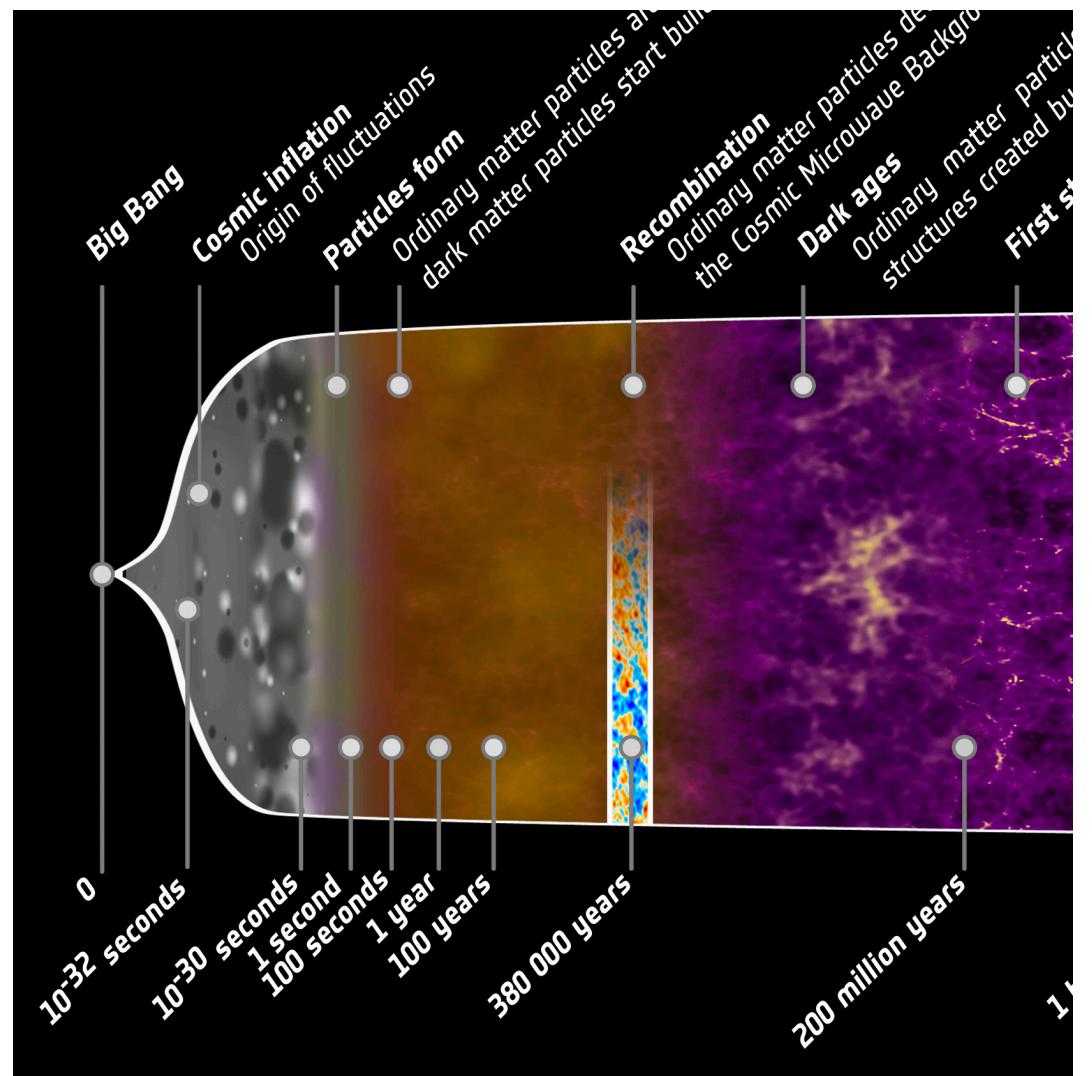
This creates a high-optical depth plasma that can thermalize the spectrum (photons are continuously captured by H atoms, making their mean free path extremely long).

As the universe expands, it also cools – photons and electrons eventually decouple.

Last Scattering: 380,000 years after BB

Time at which photons underwent final scattering from electrons.

This defines the last scattering surface - **this is what we see as the CMB**. This epoch defines the beginning of the observable universe.



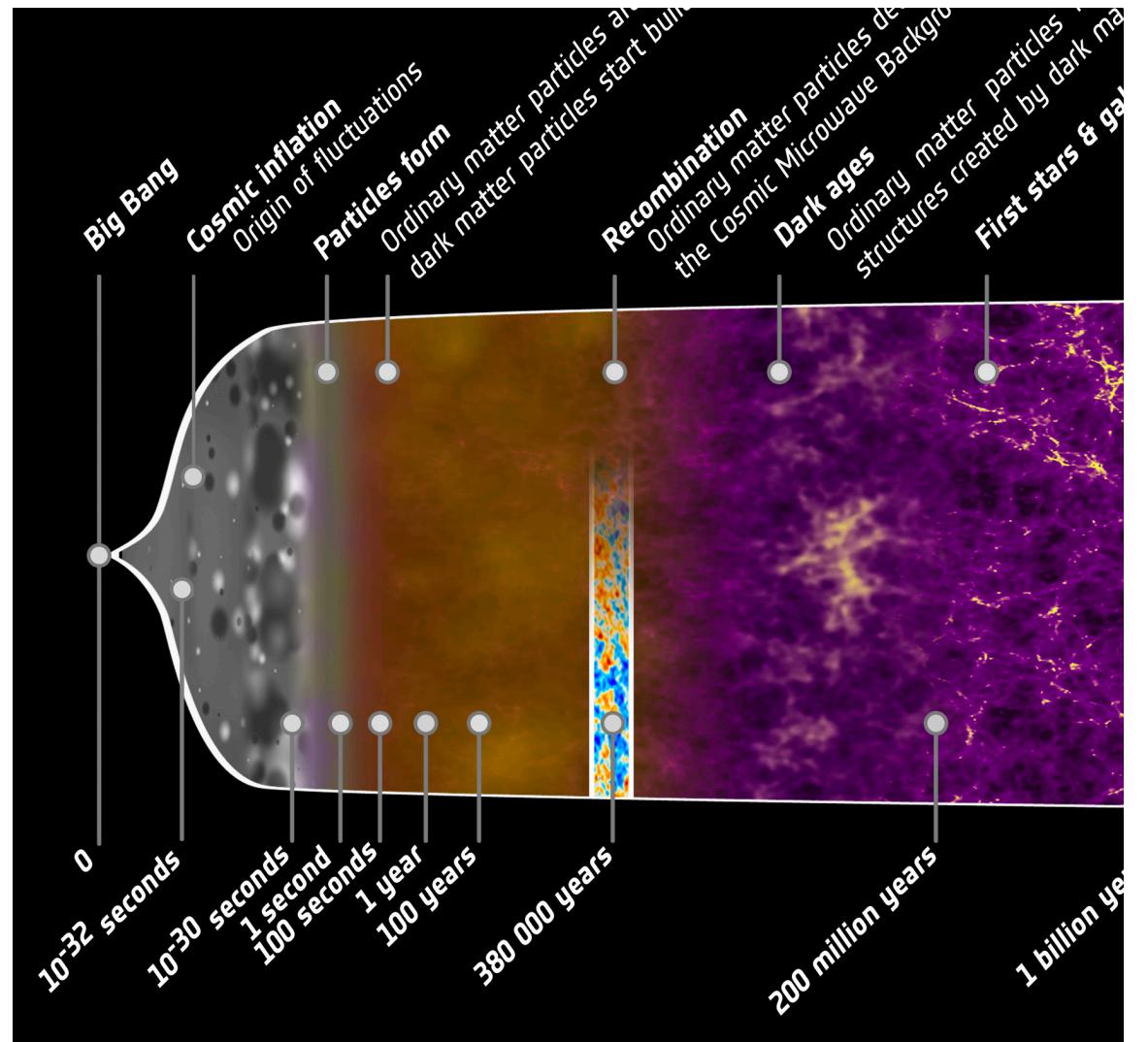
Era of Recombination

- **Photon Barrier:** Prior to $z=1100$, photons are scattered many times, losing all information about their origin.
- **Recombination** $z = 1100$, Baryons transition from ionized to neutral. $n_{ion} = n_{neutral}$ electron density plummets, leading to :
- **Photon Decoupling** Rate at which photons scatter through collision with $e^- <$ Hubble expansion rate (photons can travel Hubble distance without e^- scattering).
- **Last Scattering** Time at which photons underwent final scattering from electrons. This defines the last scattering surface - this is what we see as the CMB. This epoch defines the beginning of the observable universe.

Era of Recombination

Thompson scattering and Bremsstrahlung processes thermalize the radiation field efficiently - get **black body radiation**.

Assuming adiabatic expansion of the Universe, you should observe today a radiation field that would have retained the black body temperature of this era, **but at a much lower temperature**.



Temperature Evolution of the Universe

$$\langle E \rangle = 3k_B T = \frac{hc}{\lambda} \propto 1/R = 1 + z$$

$T = T_0(R_0/R(t)) = T_0(1 + z)$, where $T_0 = 2.7$ K

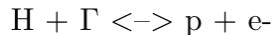
Last Scattering “Surface”

Decoupling doesn't occur instantaneously. Lasts over a period of $\sim 70,000$ years

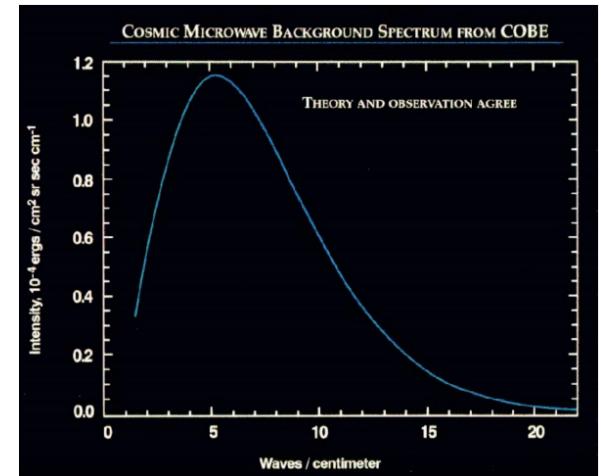
The reason is that the density of photons is much larger than that of baryons. There are roughly $1e9$ photons per H atom.

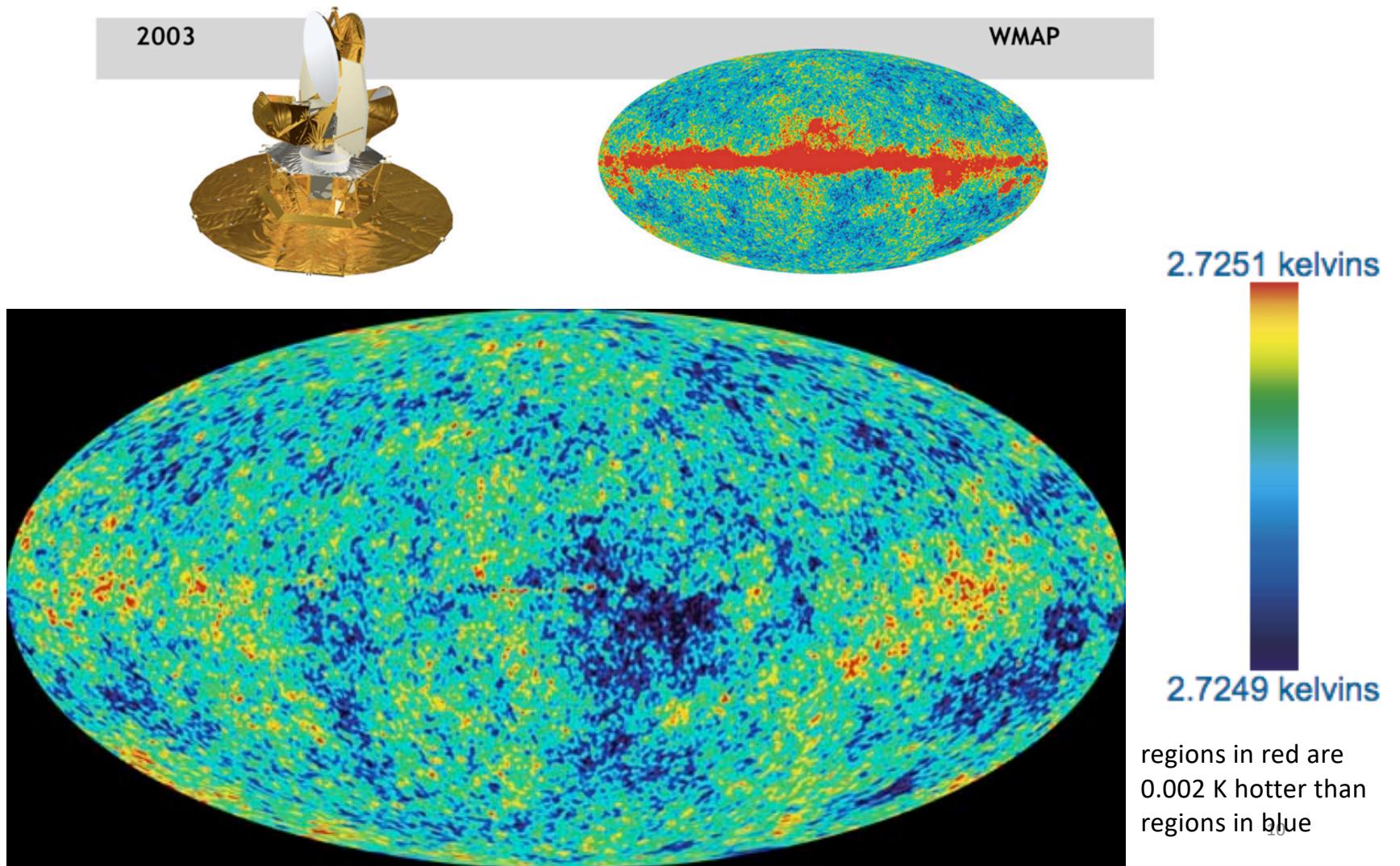
$$N_\Gamma/N_H \sim 10^9 \quad (3)$$

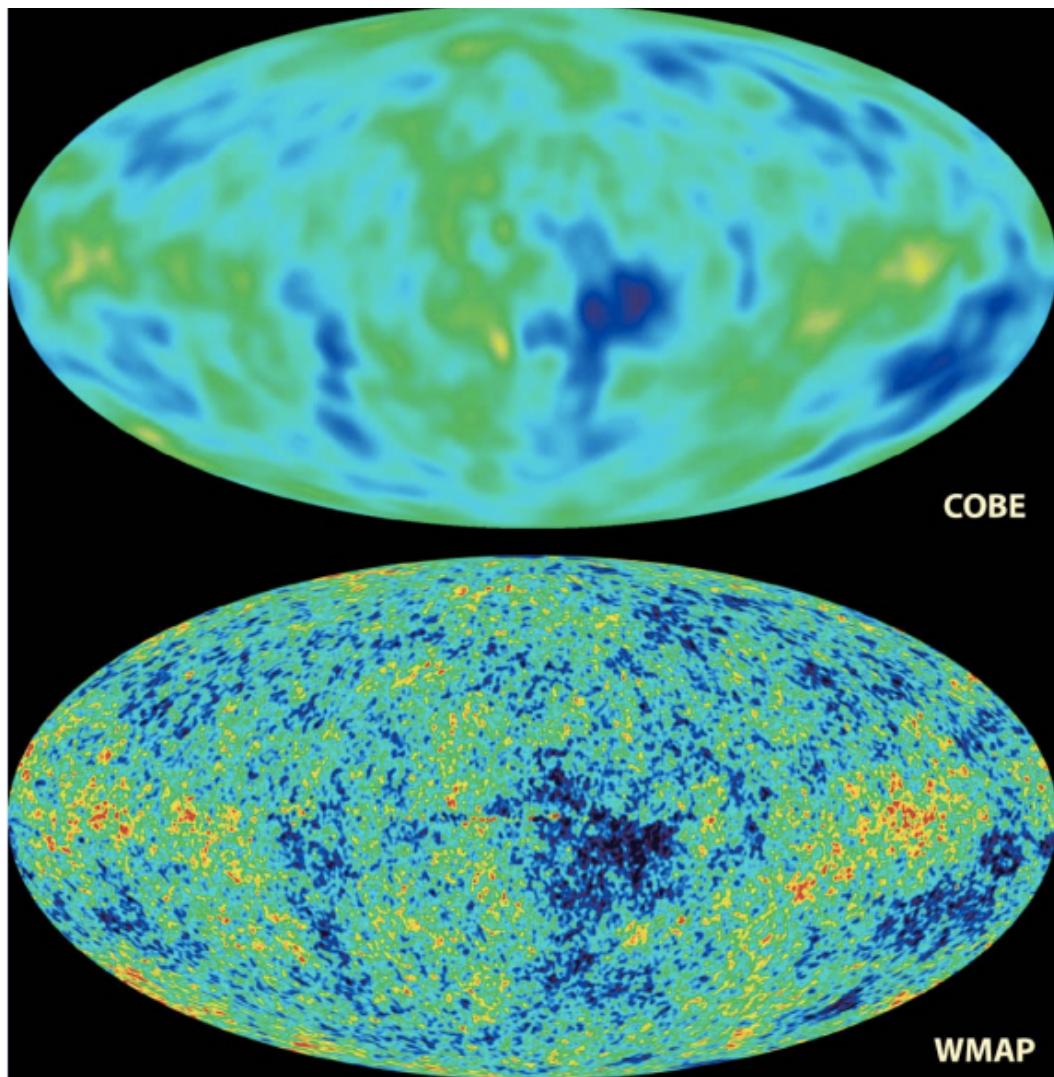
So even if the Planck spectrum peaks at a lower temperature, there is a high energy tail in that distribution (Wien, or exponential tail) and there are so many photons populating that tail that there are plenty around to cause the universe to be ionized – the gas will be ionized if there are as many photons with $h\nu > 13.6\text{eV}$ as there are H atoms.



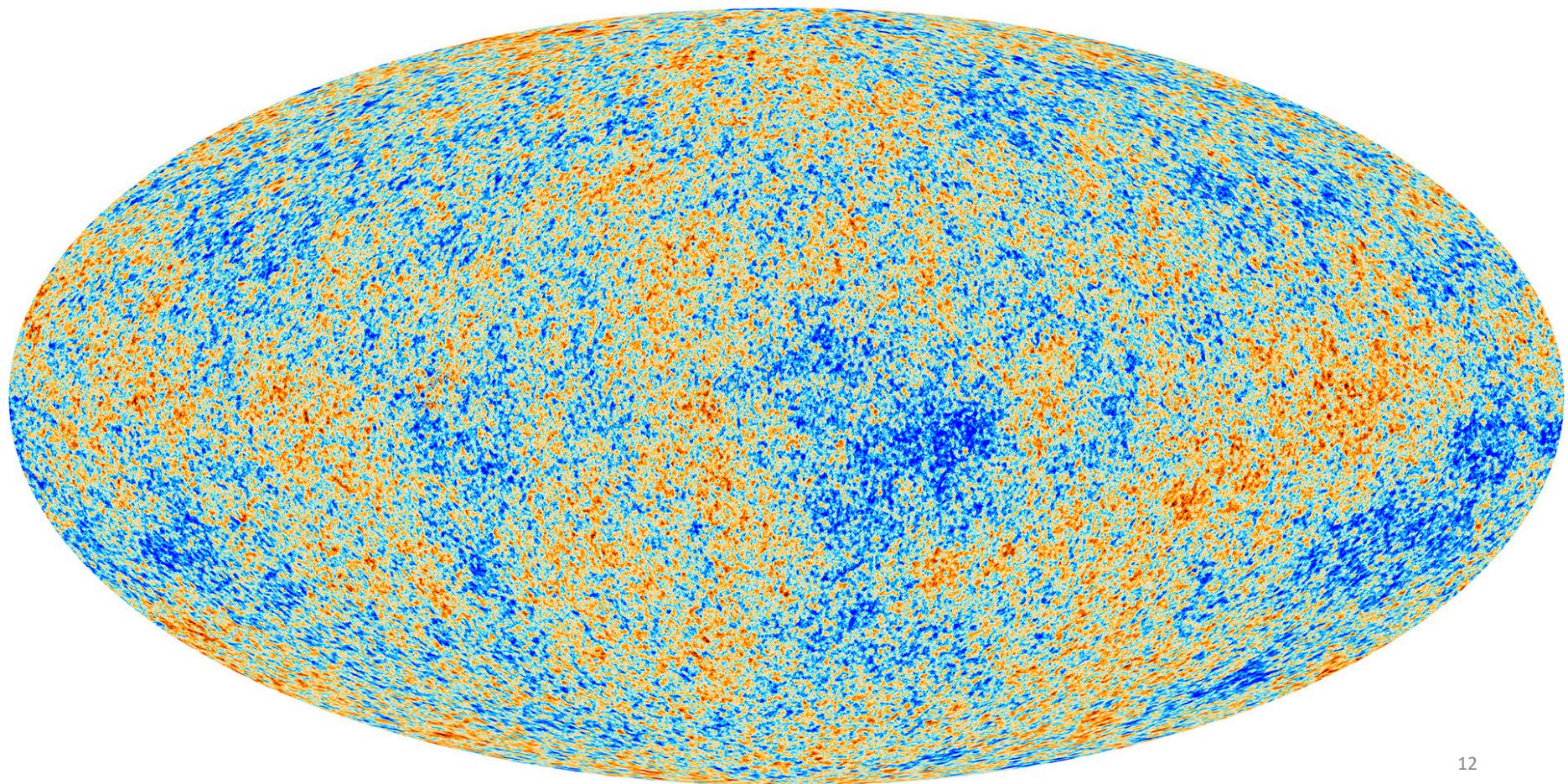
99% protons & e- “recombined” by $z = 1100$







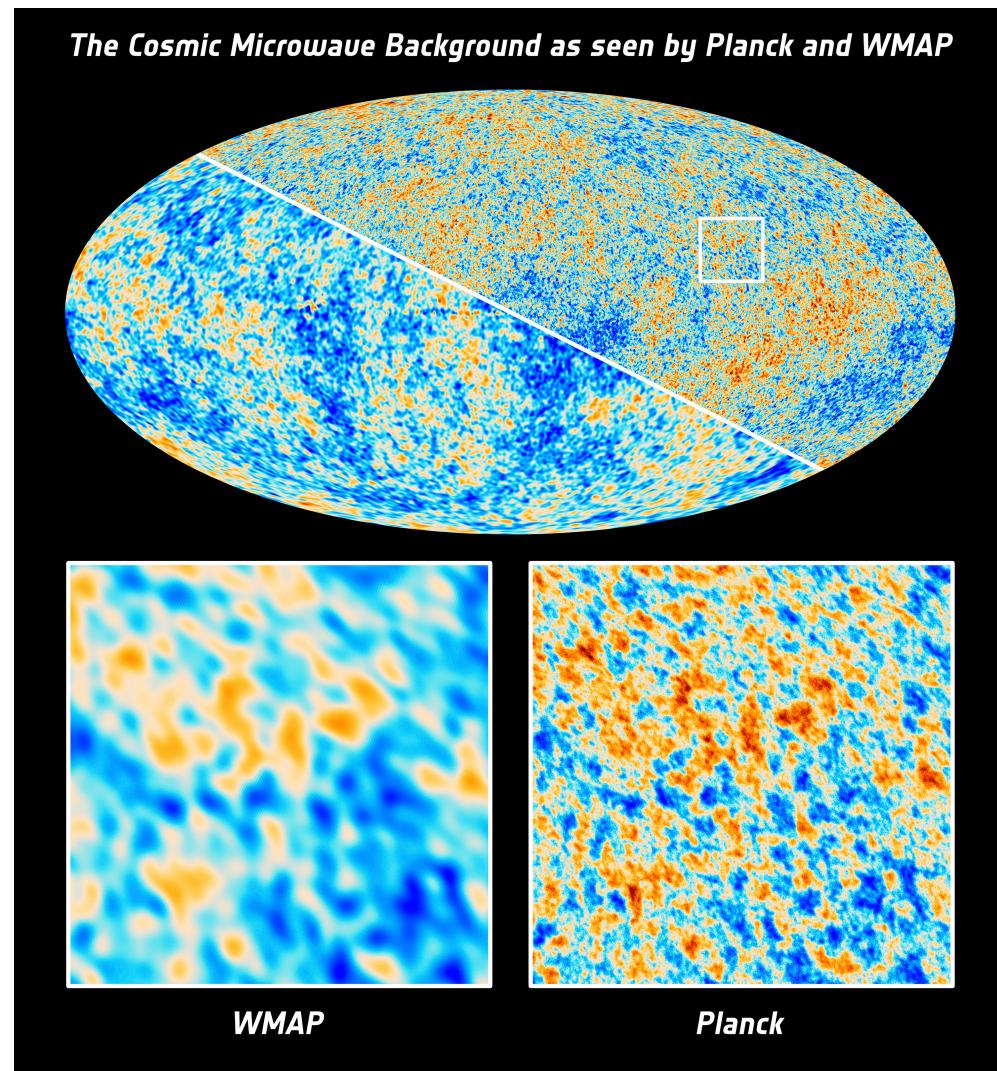
PLANCK 2015



1 part in 10^5 variation in temperature!!

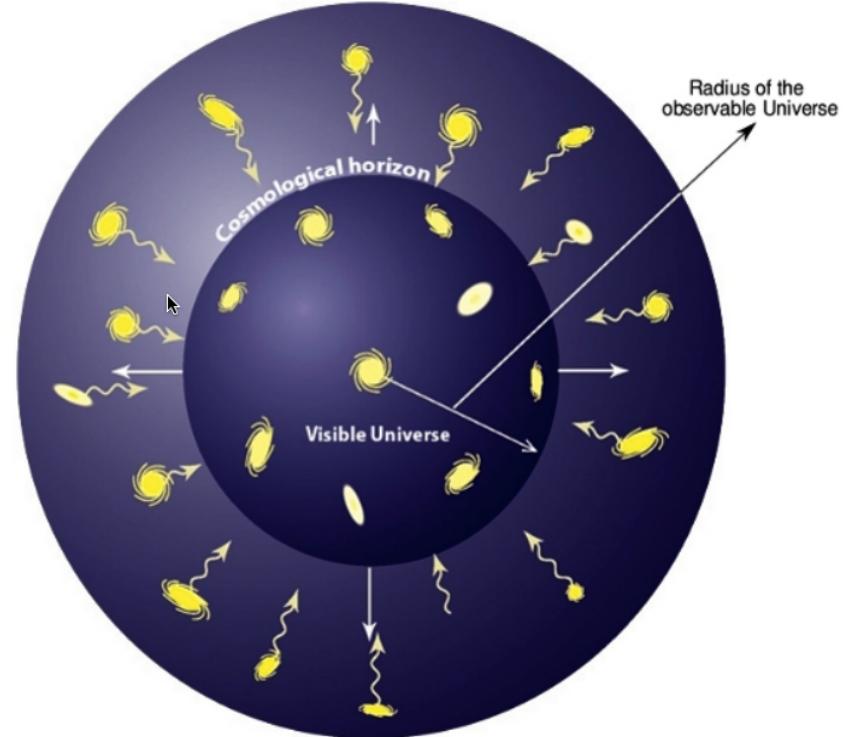
CMB is highly homogeneous!

Isotropy: Everywhere in the universe you would see this CMB.



Horizon Problem

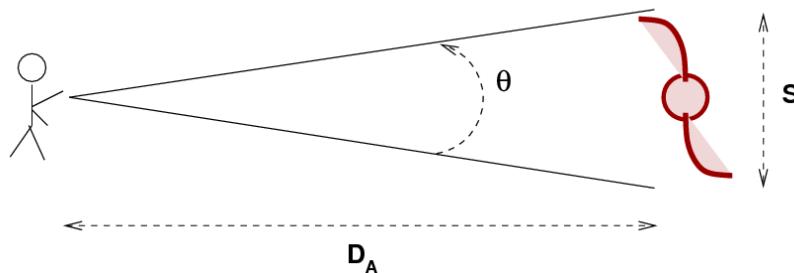
- CMB is homogeneous
- Expect the size of a region over which isotropy holds **to be the horizon distance at the time of photon decoupling.**
- Regions further apart than the light-travel distance at the photon decoupling epoch wouldn't know about each other (not causally connected).



What angle does the causally connected region of the universe at $z=1100$ subtend on the sky today?

Horizon Distance ($z=1100$) = Proper Distance to the edge of the visible universe at $z=1100$

Angular Diameter Distance



D_A is the distance to the source, such that it subtends the same angle it would have in Euclidean Space

$$D_A \equiv \frac{S}{\theta}$$

If $K = 0$, flat universe

$$\theta \text{ [rad]} = \frac{S}{R(t_e)u_e} \equiv \frac{S}{D_A}$$

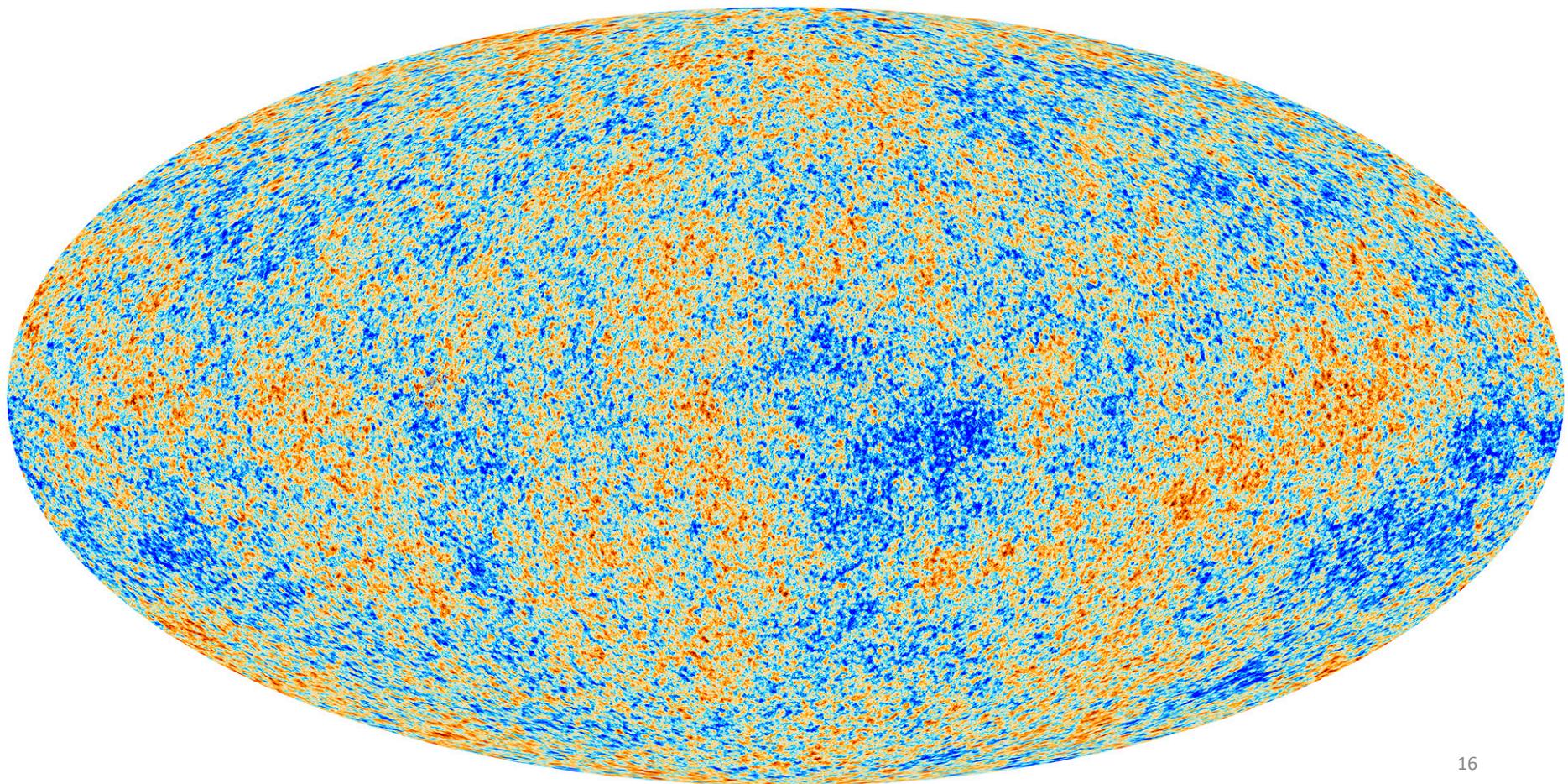
This is the Proper Distance at the time of emission – so that you see the correct angle

$$D_A = R(t_e)u_e = \frac{R(t_0)u_e}{1+z} = \frac{D_C}{(1+z)} = \frac{D_L}{(1+z)^2} = \frac{S}{\theta}$$

PLANCK 2015

The Horizon Problem:

Causally connected region is only 2 degrees on the sky!!!!!!!!!



Inflation: A period of very early rapid expansion where the scale factor increased exponentially

First Friedmann Equation

$$\left(\frac{\dot{R}}{R}\right)^2 = H(t)^2 = H_o^2 \left[\Omega_{m,o}(1+z)^3 + \Omega_{rad,o}(1+z)^4 + \Omega_{\Lambda,o} + (1-\Omega_o)(1+z)^2 \right]$$

Consider a universe where $K = 0$ and Dark Energy Dominates (DeSitter Universe), $\Omega_{\Lambda} = 1$

$$\left(\frac{\dot{R}}{R}\right) = H_o \quad R(t) \propto e^{H_0 t}$$

(We are actually heading towards this era)

E-folding Time is REALLY REALLY FAST

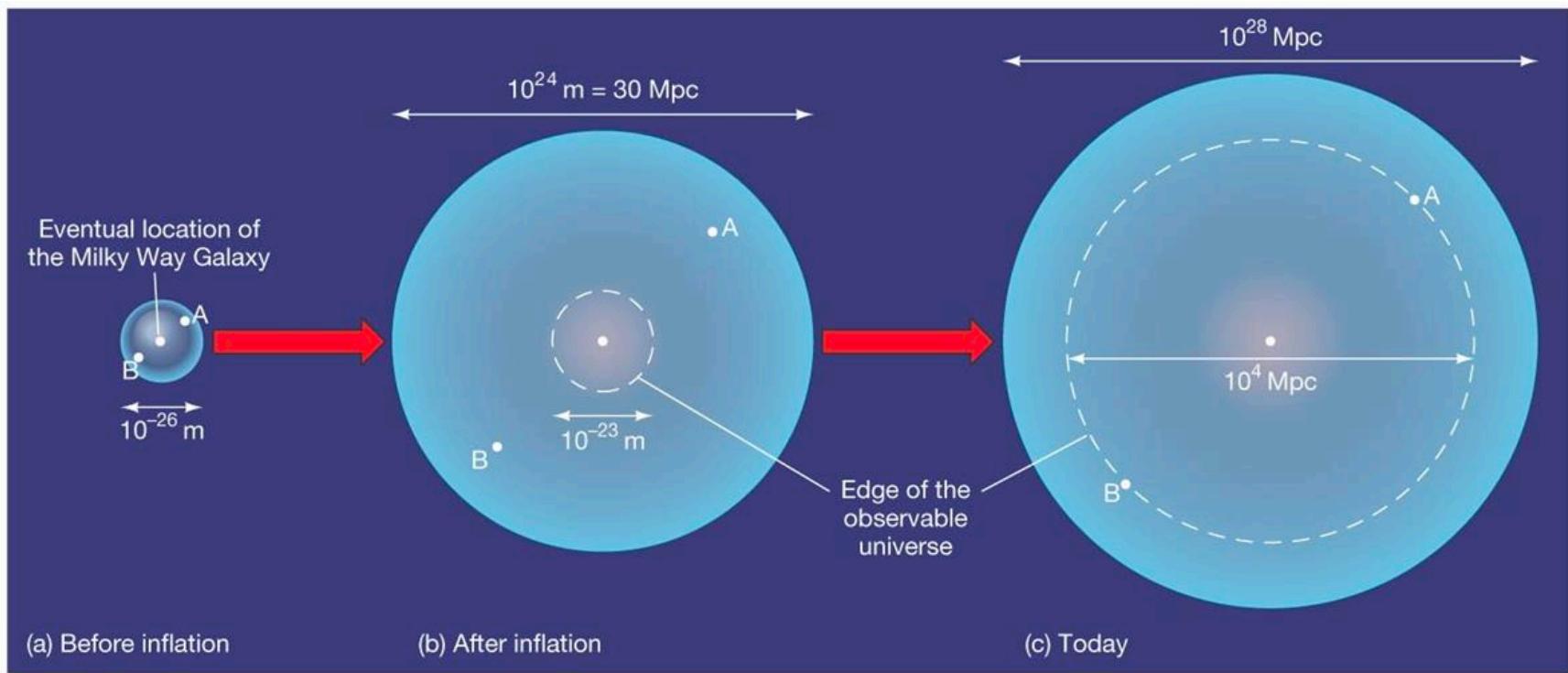
Inflation occurred at $t \sim 10^{-36}$ s,
hubble parameter at that time is
roughly inverse age

$$H_o = \frac{1}{10^{-36} s} = 10^{36}$$

In just a few e-folding times, the
Universe is already huge!

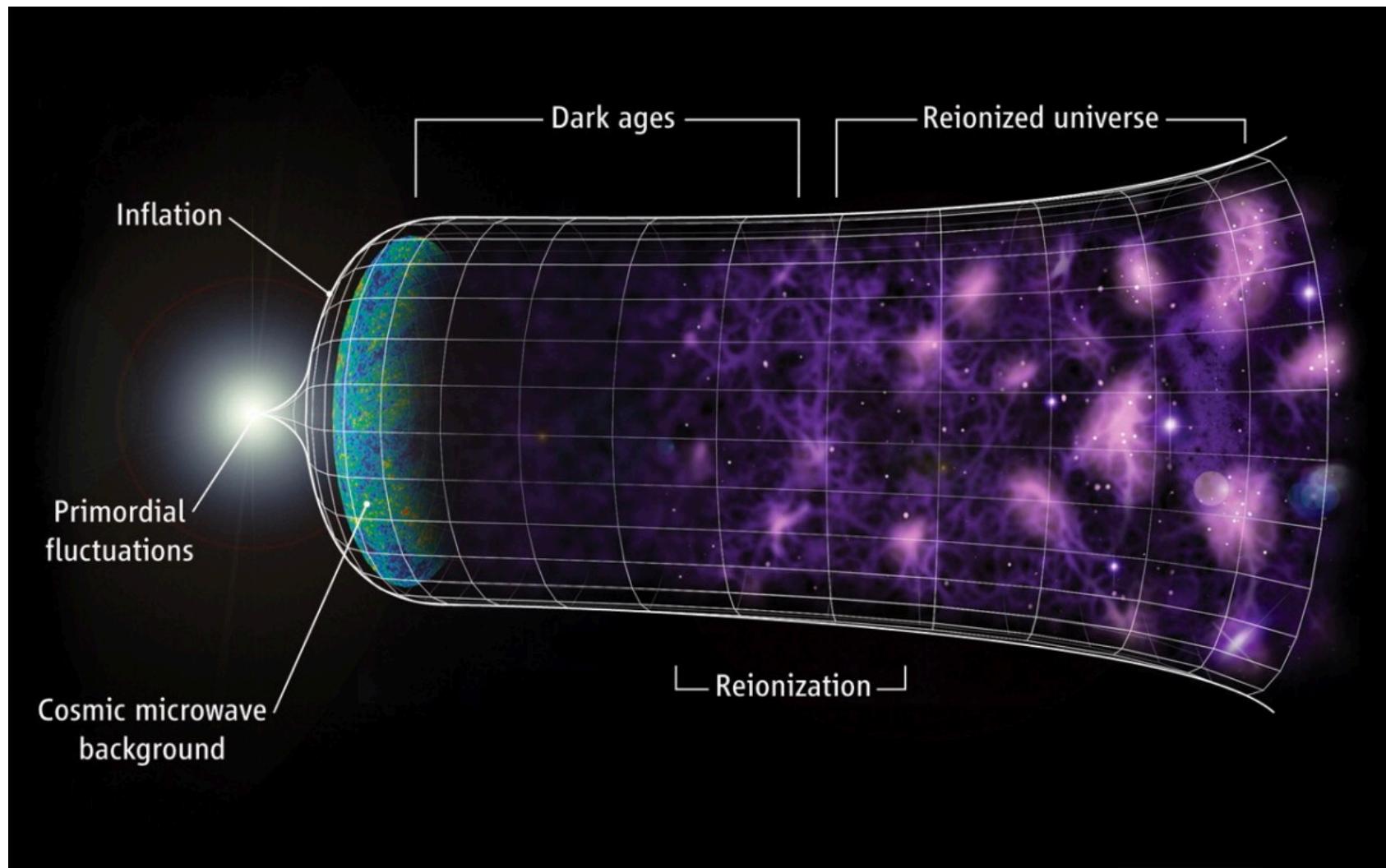
Inflation

Solves the Horizon problem by allowing much larger scales to be in causal contact



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The exponential expansion of the scale factor means that the physical distance between any two observers will eventually be growing faster than the speed of light.



Sound Horizon Sets the Scale of the Fluctuations

- Pre-Recombination, colliding electrons, protons and photons form a high pressure plasma - tightly coupled through thompson scattering.
- Thus the normal matter (“baryons”) and the CMB photons are tied together to make a “baryon-photon” fluid.
- Sound horizon distance is the maximum proper distance travelled by a sound wave between $z = \text{infty}$ and $z = z_{\text{decoupling}}$

$$D_{\text{sound}} = \frac{c_s}{1 + z_{\text{dec}}} \int_{z_{\text{dec}}}^{\infty} \frac{dz'}{H(z)}$$

Same as proper distance calculation,
Except we have speed of sound, not light

$c_s = c/\sqrt{3}$. Similar to pure photon gas. (baryon-photon fluid)

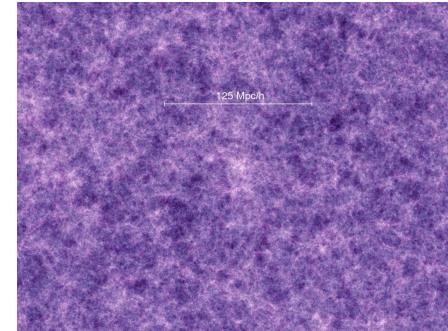
Acoustic Oscillations

Baryon-photon fluid falls into overdensities, heating up.

This increases radiation pressure, causing fluid to expand (rarefaction wave).

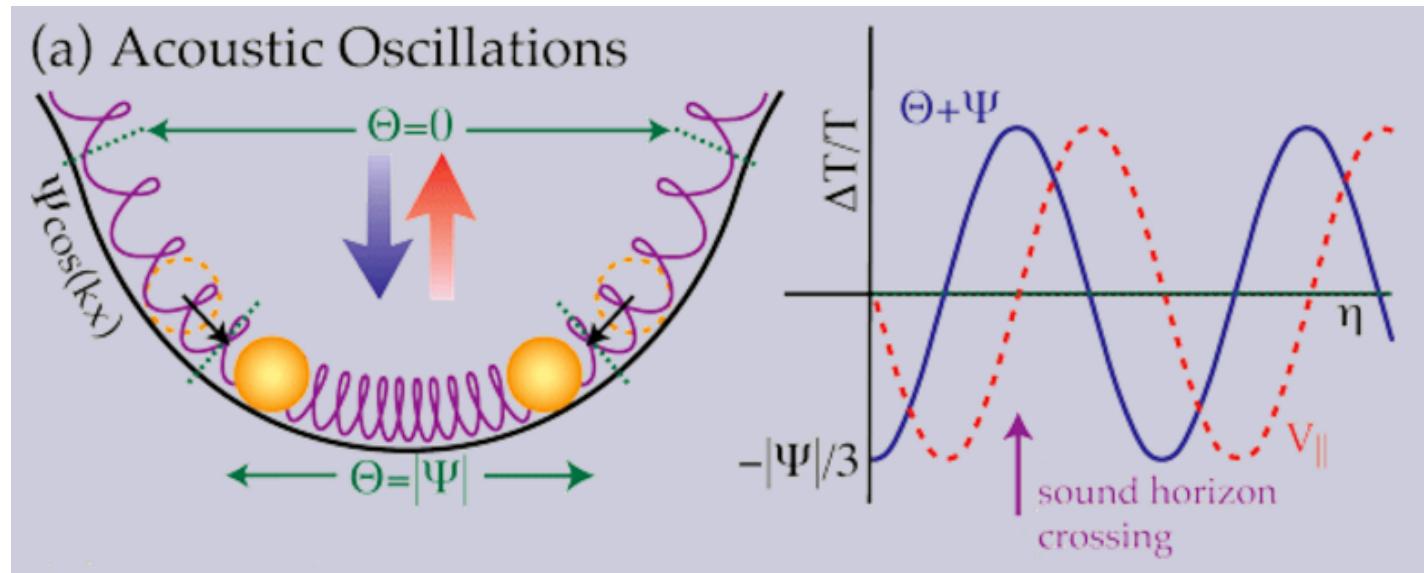
The fluid then cools and gravity wins again.

The fluid falls back into an overdensity and heat up.



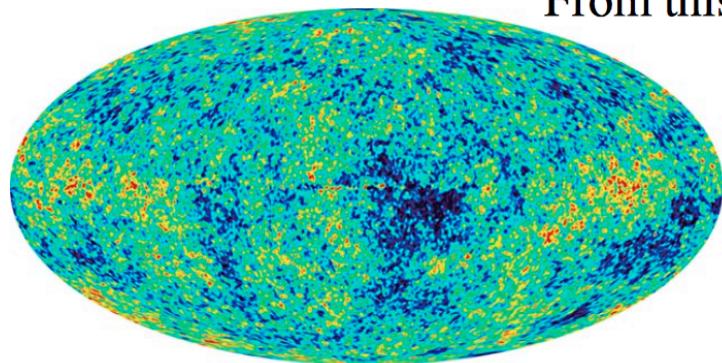
Called “acoustic oscillations”. The typical scale of these oscillations is the sound horizon distance.

At recombination, these oscillations “freeze” - if caught in a compressed state, it will give rise to a hot spot. else, cold spot.

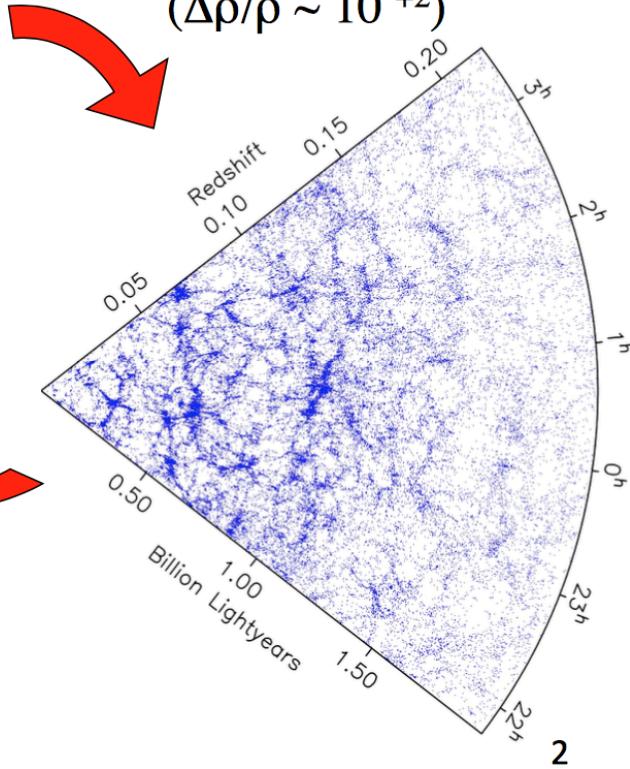


Structure Formation and Evolution

From this ($\Delta\rho/\rho \sim 10^{-6}$)



to this
($\Delta\rho/\rho \sim 10^{+2}$)



Cold = rarefaction of photon-baryon fluid
Hot = Compression of photon-baryon fluid

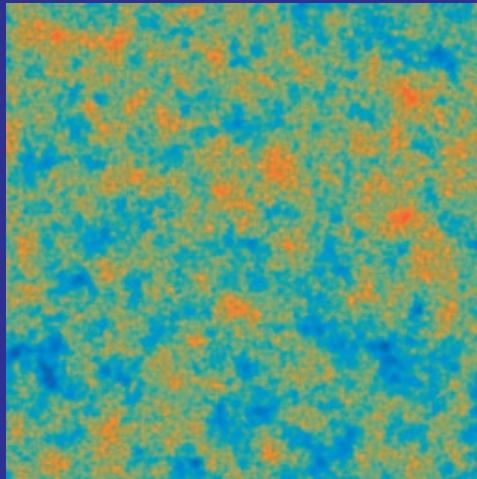


to this
($\Delta\rho/\rho \sim 10^{+6}$)

- 1 part in 100000 variations in temperature
- Spot sizes ranging from a fraction of a degree to 180 degrees

So these variations in temperature in the CMB provide a snapshot of the distribution of dark matter at this epoch.

64°



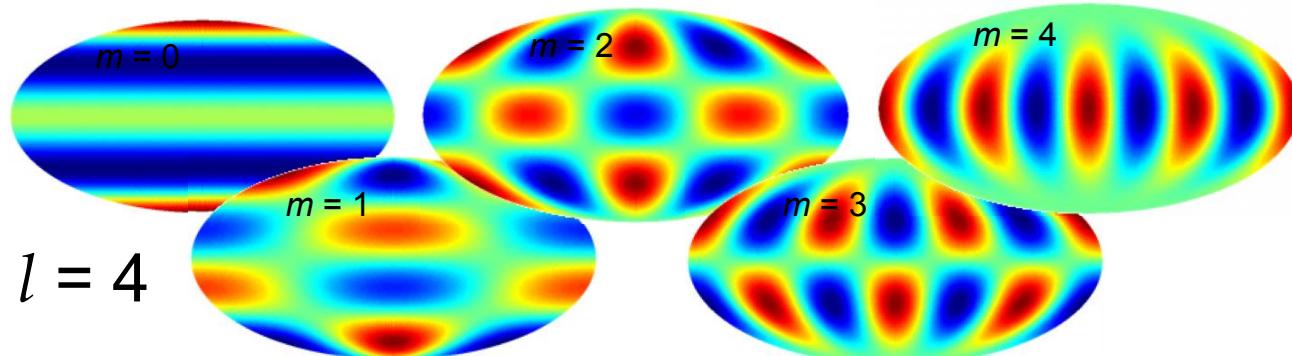
- Selecting only spots of a given range of sizes gives a power spectrum or frequency spectrum of the variations much like a graphic equalizer for sound.

Spherical harmonics

- The spherical harmonics are wave functions on the sphere
 - Completely analogous to the complex exponential in flat space

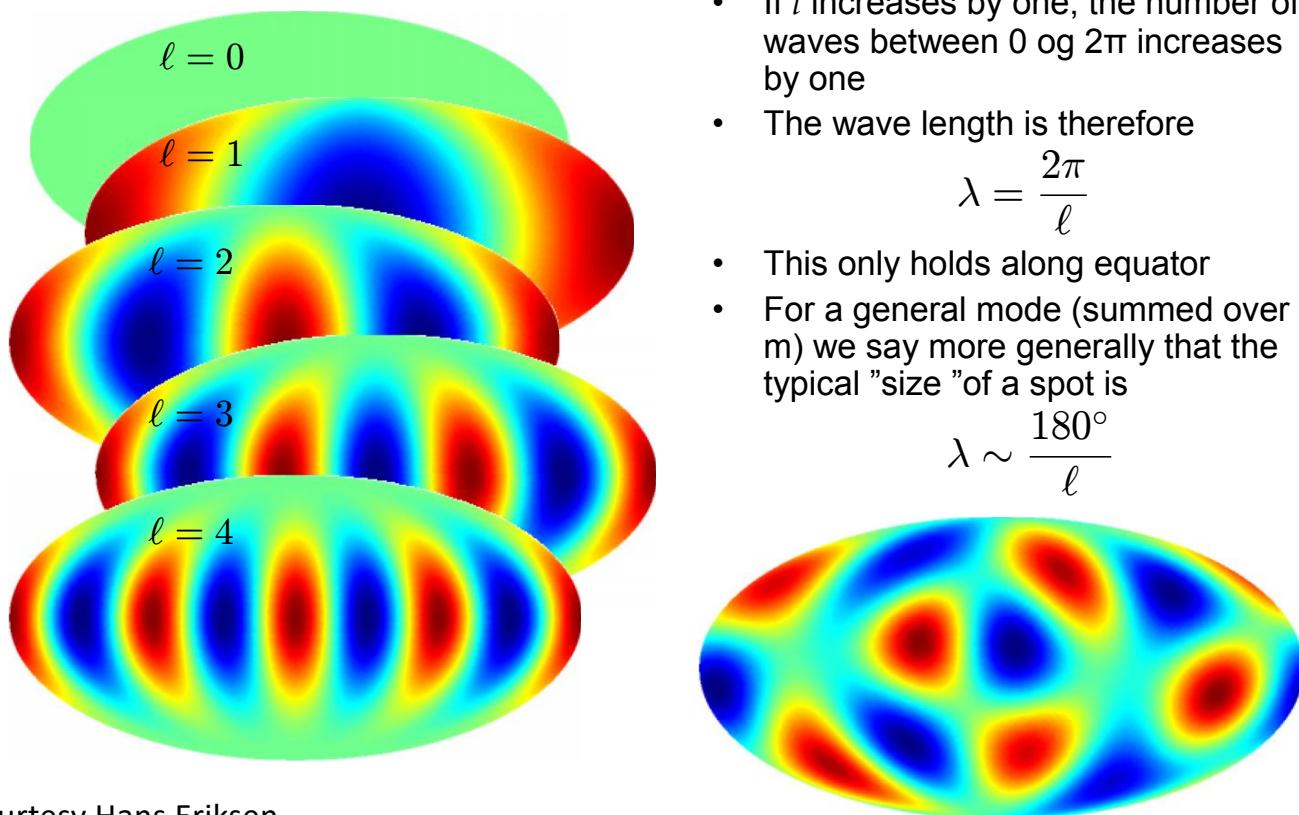
$$e^{ikx} \leftrightarrow Y_{\ell m}(\theta, \phi)$$

- Instead of wave number k , these are described by ℓ and m
 - ℓ determines "the wave length" of the mode
 - ℓ is the number of waves along a meridian
 - m determines the "shape" of the mode
 - m is the number of modes along equator

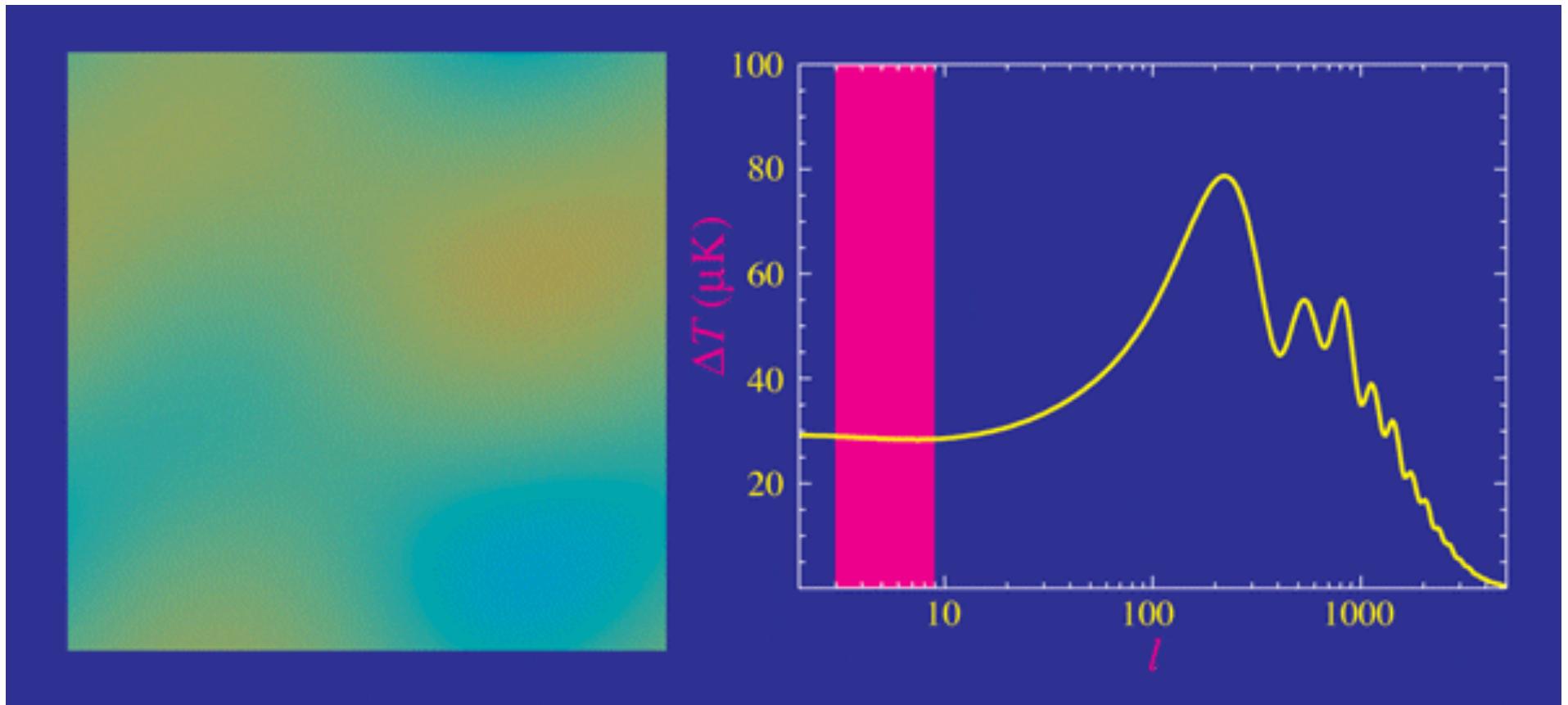


Courtesy Hans Eriksen

Relationship between ℓ and scale



Courtesy Hans Eriksen



Wayne Hu's Cosmology Tutorial
<http://background.uchicago.edu/~whu/metaanim.html>

Power Spectrum

