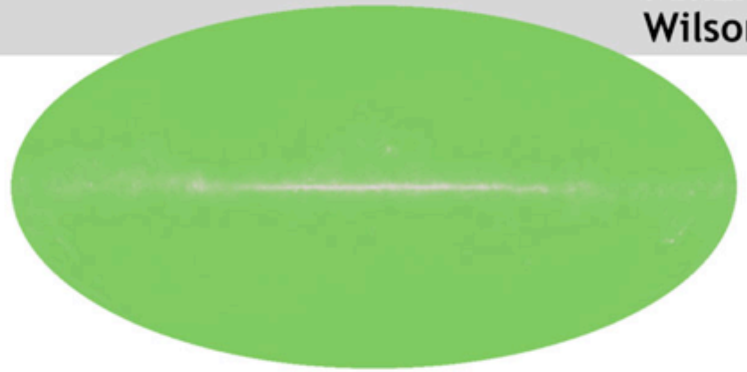
The cosmic microwave background is explained in the hot Big Bang model as the relic radiation from the hot, early universe.

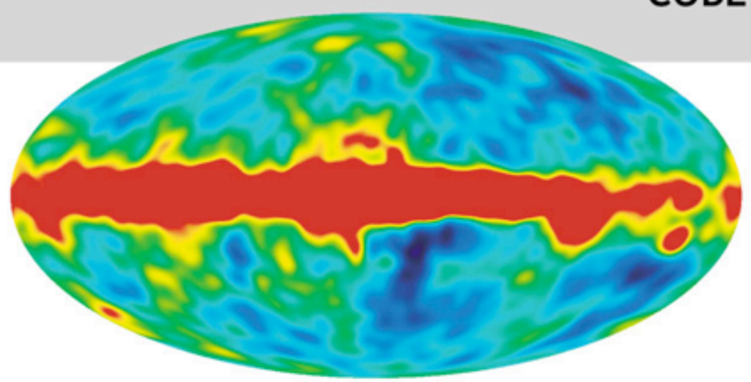
1965

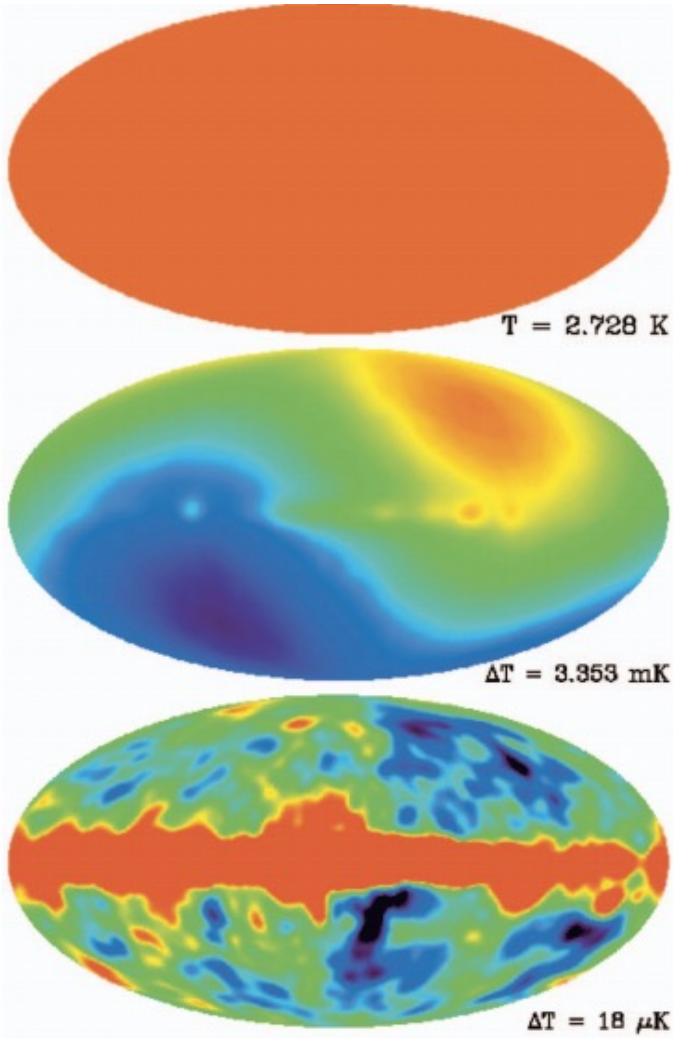
Penzias and Wilson

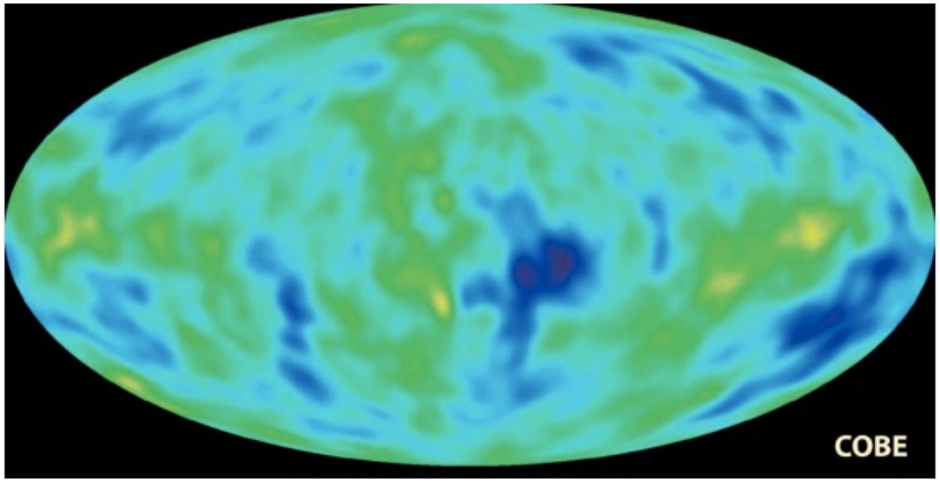


1992

COBE



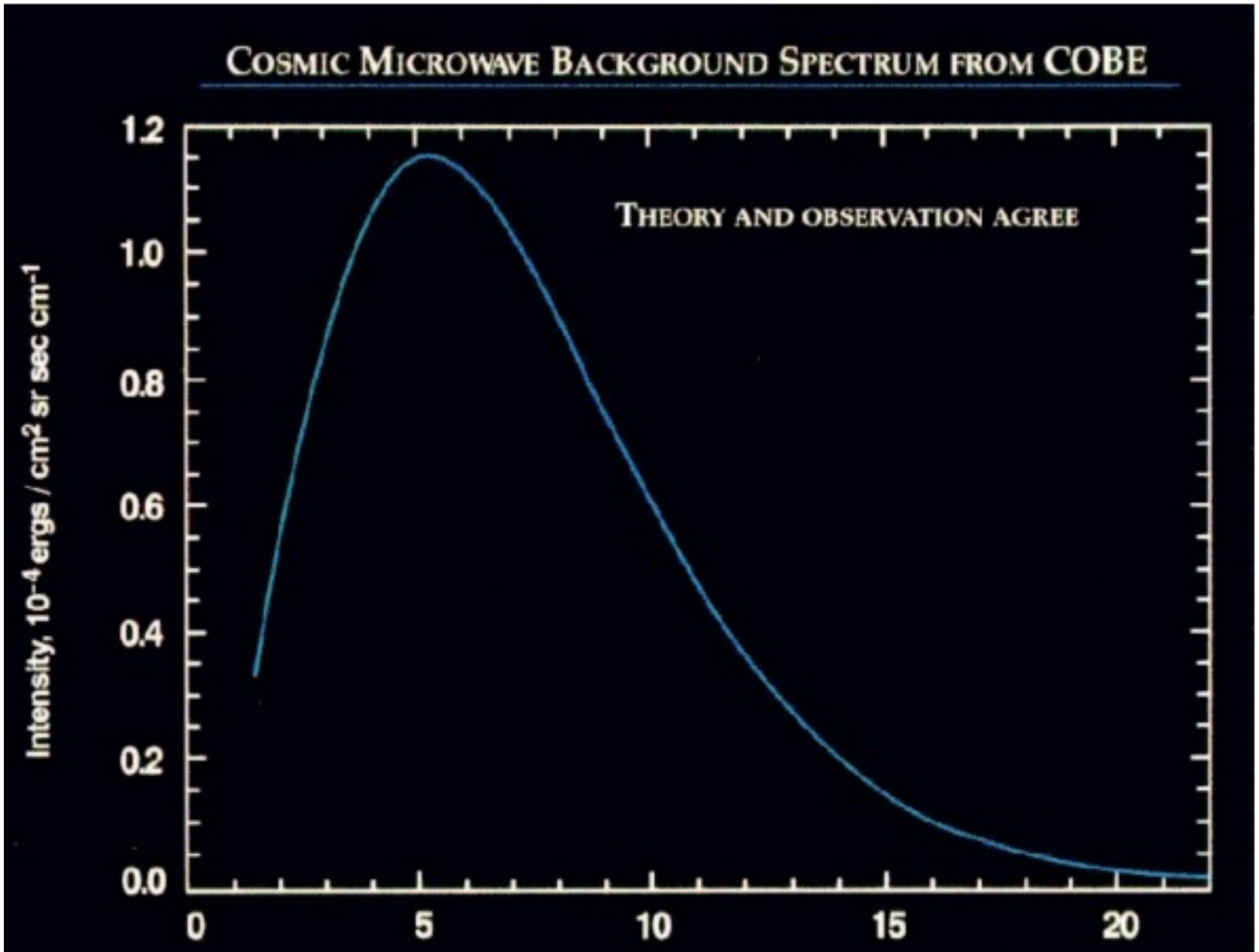




Temperature Fluctuations:
1 part in 100,000

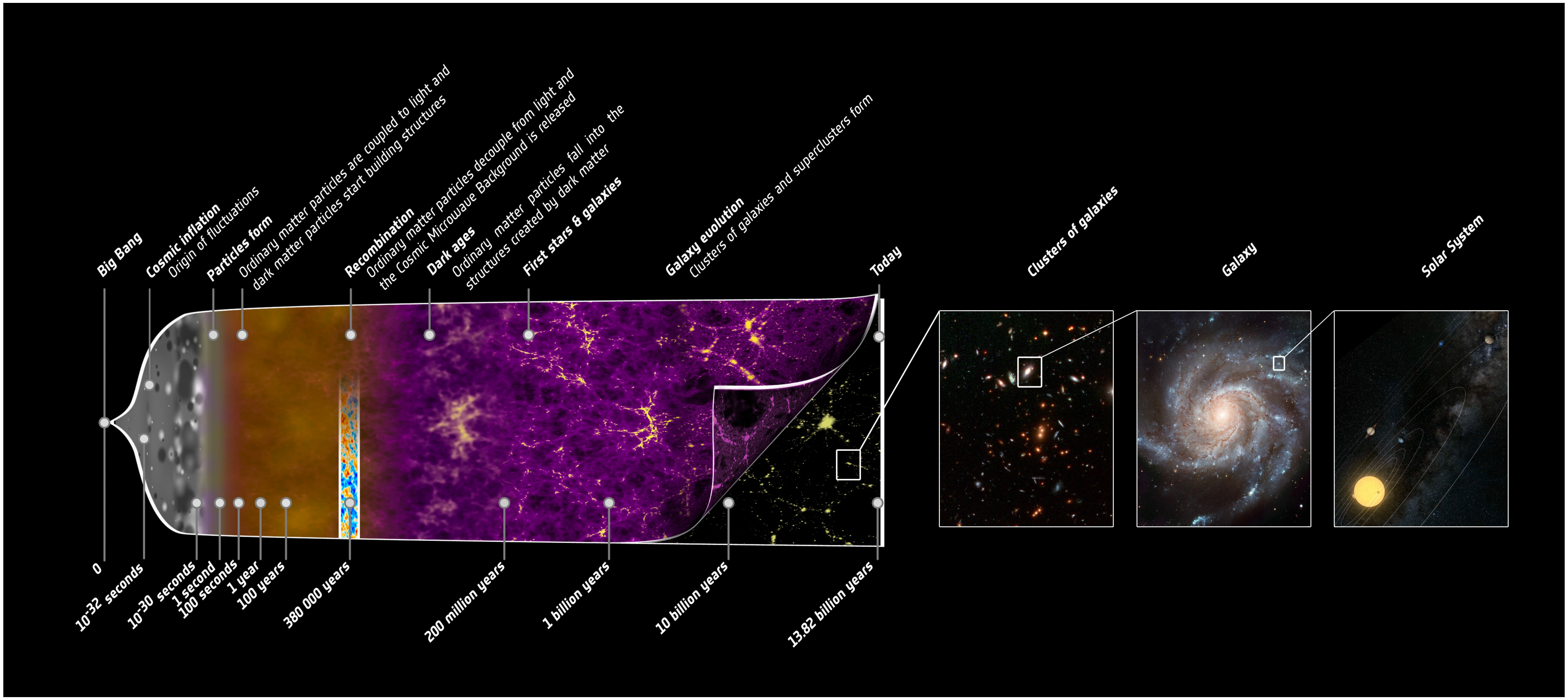
A perfect Black Body at :

T_o = 2.73 K



Mather 1994, Smoot 2007

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

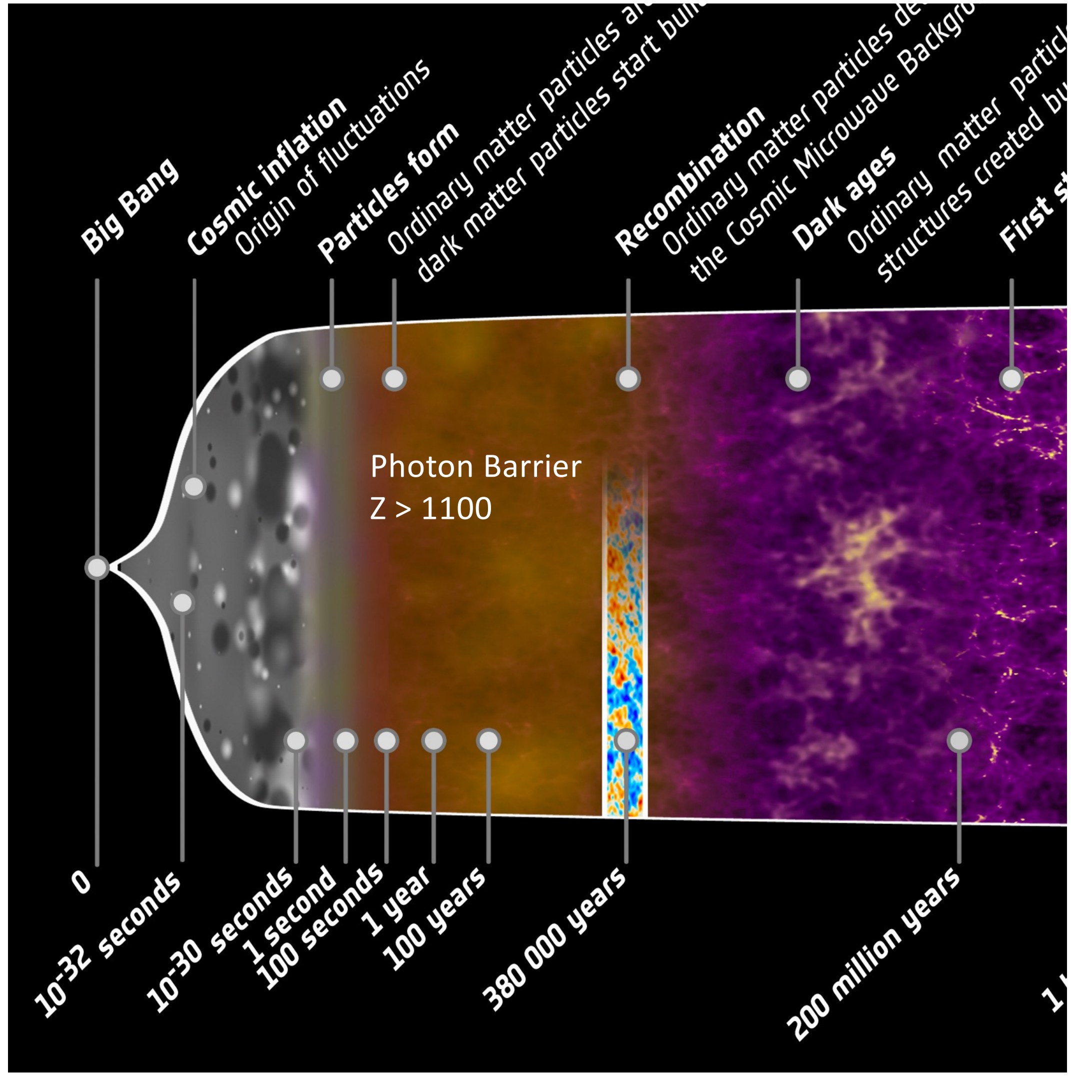
At z > 1100 photons are hot enough to ionize hydrogen – photons and electrons are coupled. Can't form atoms. **Photon Barrier.**

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.

<u>**Last Scattering: 380,000 years after BB**</u>
Time at which photons underwent final scattering from elections.

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



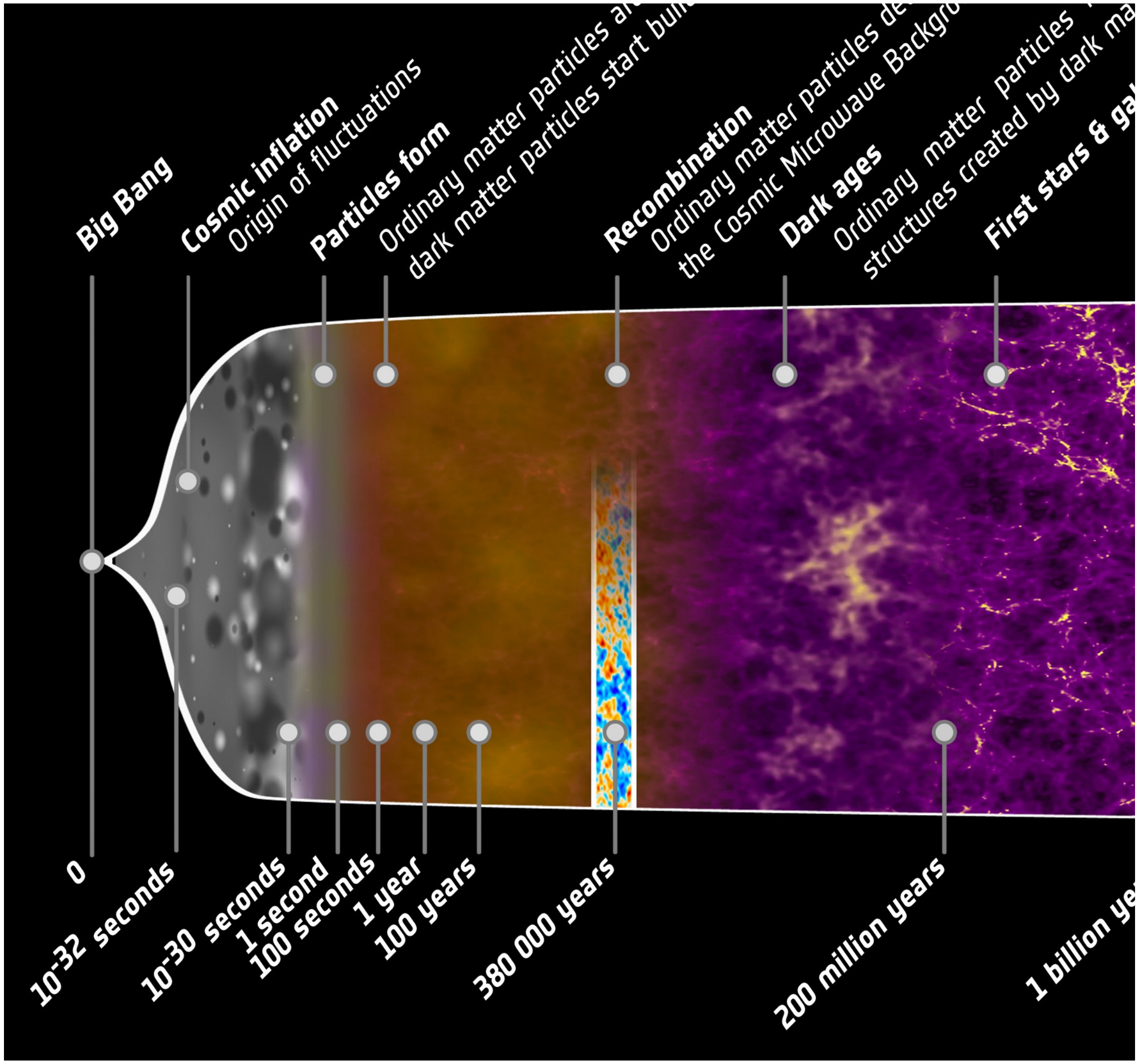
Era of Recombination

- **Photon Barrier:** Prior to z=1100, photons are scattered many times, losing al 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 elections. 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 appropriate to the mean temperature at that time**.

Assuming adiabatic expansion of the Universe, you should observe today a radiation field that retains the black body behavior, **but at a much lower temperature.**



Temperature Evolution of the Universe

$$\langle E \rangle = 3k_B T = \frac{hc}{\lambda} \qquad R(t) = \frac{1}{1+z} = \lambda_e/\lambda_{obs}$$

$$E(t)/E_o = T/To = \lambda_{obs}/\lambda_e = (1+z)$$

$$\boxed{T = T_0(R_0/R(t)) = T_0(1+z)}$$

Where $T_o = 2.73$ K

Last Scattering

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

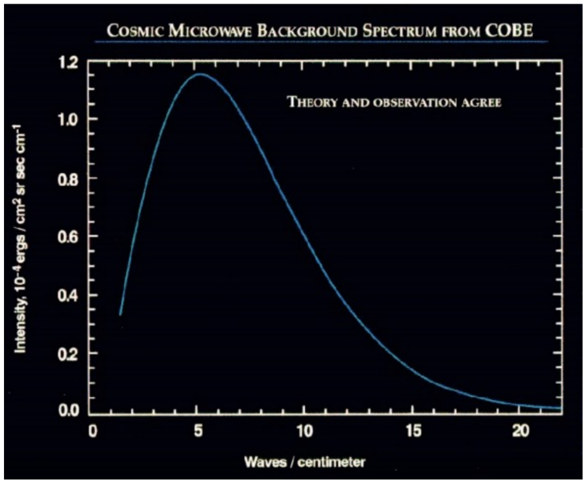
The reason is that the density of photons is much larger than that of baryons. There are roughly 1e9 photons per H atom.

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

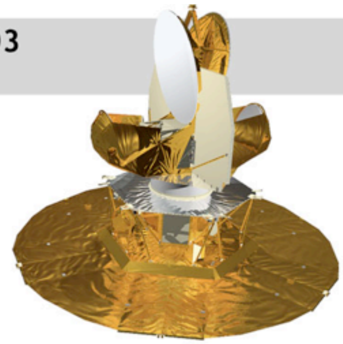
So even if the Planck spectrum peaks at a lower temperature, there is a high energy tail in that distribution (Wien, or exponential tail) and there are so many photons populating that tail that there are plenty around to cause the universe to be ionized – the gas will be ionized if there are as many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

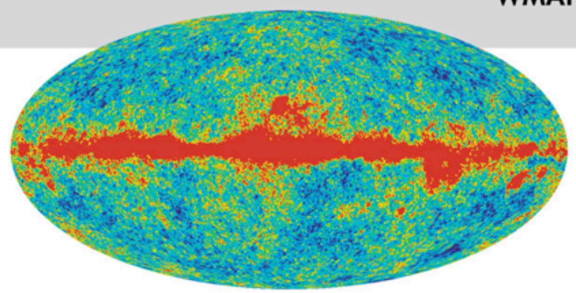
$$\mathrm{H} + \Gamma <\!\!-\!\!> \mathrm{p} + \mathrm{e}\text{-}$$

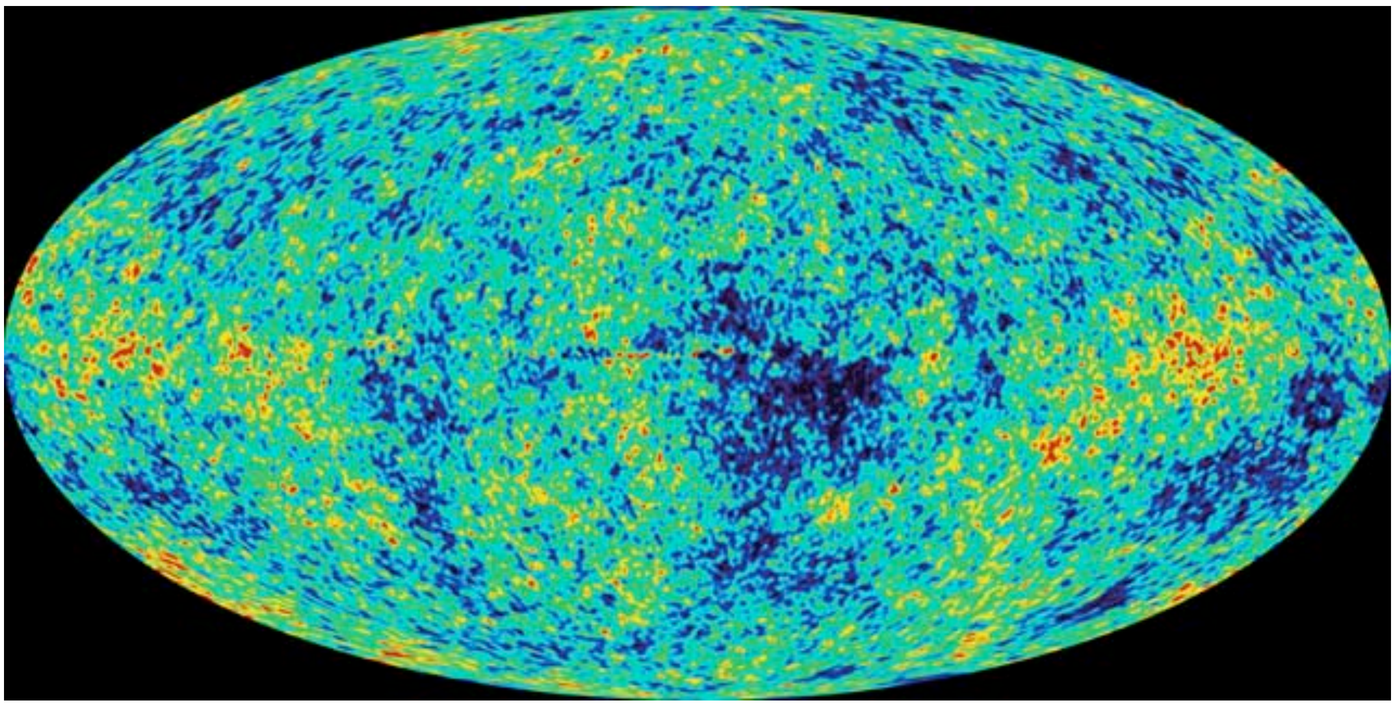
99% protons & e- "recombined" by z = 1100



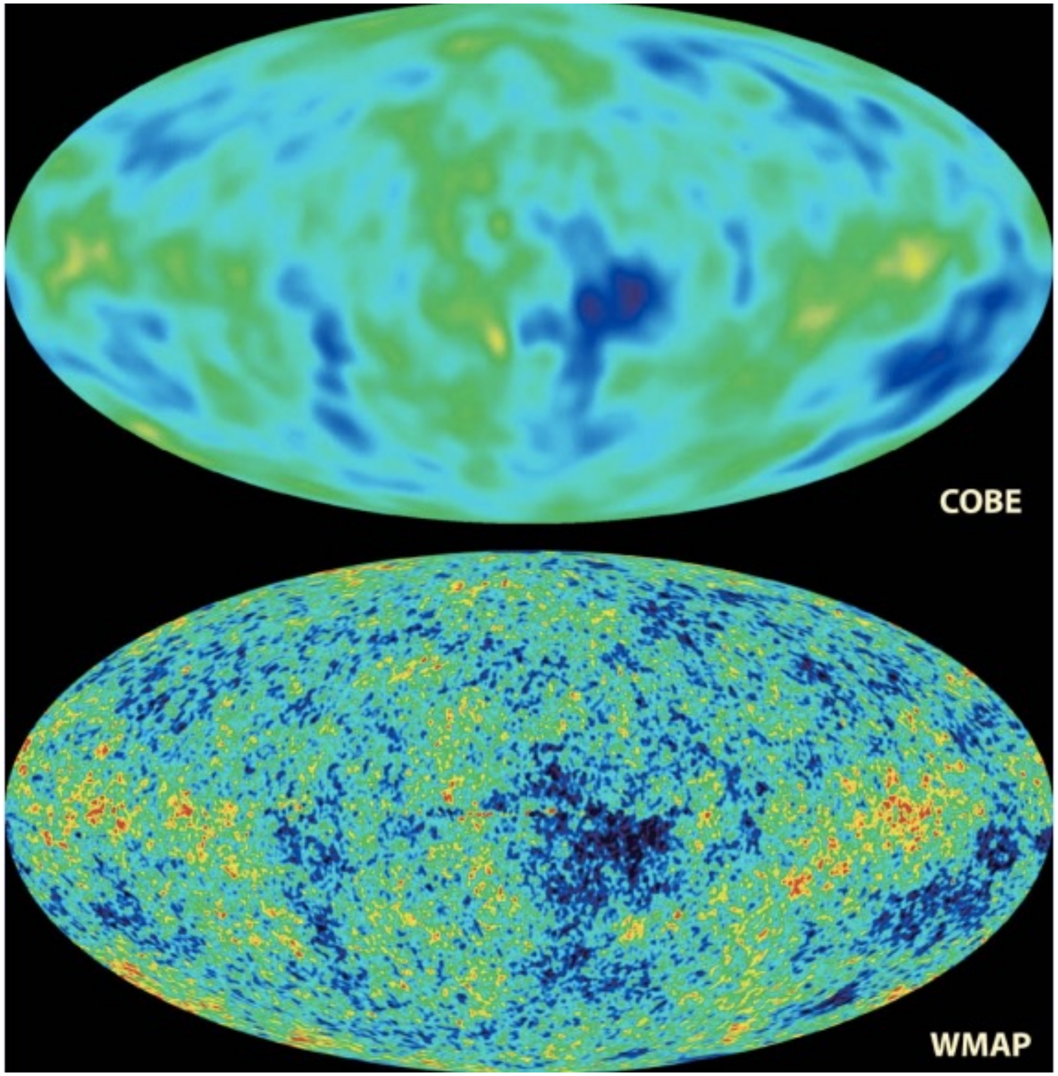
2003 WMAP



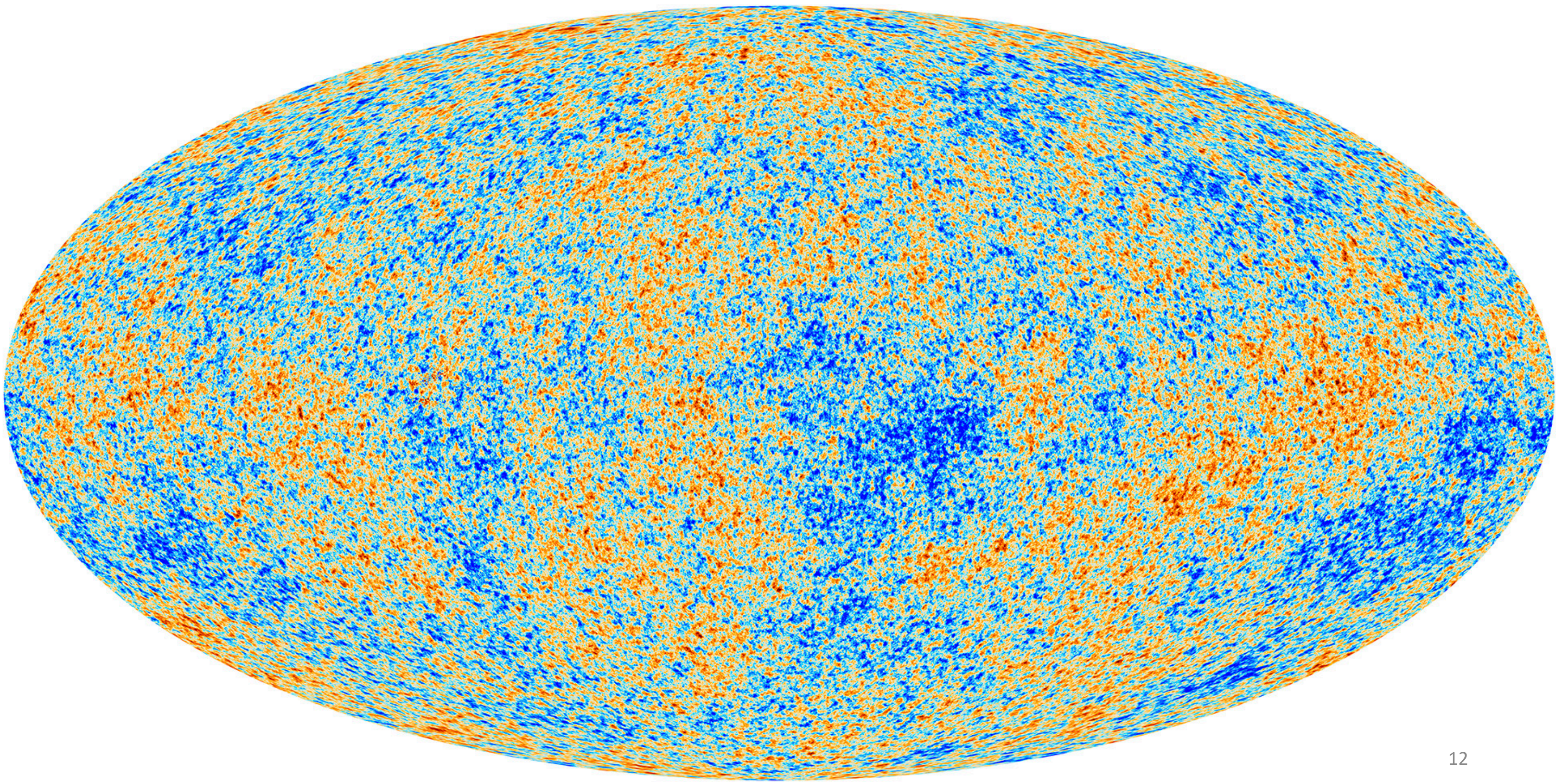




regions in red are 0.002 K hotter than regions in blue


COBE
WMAP

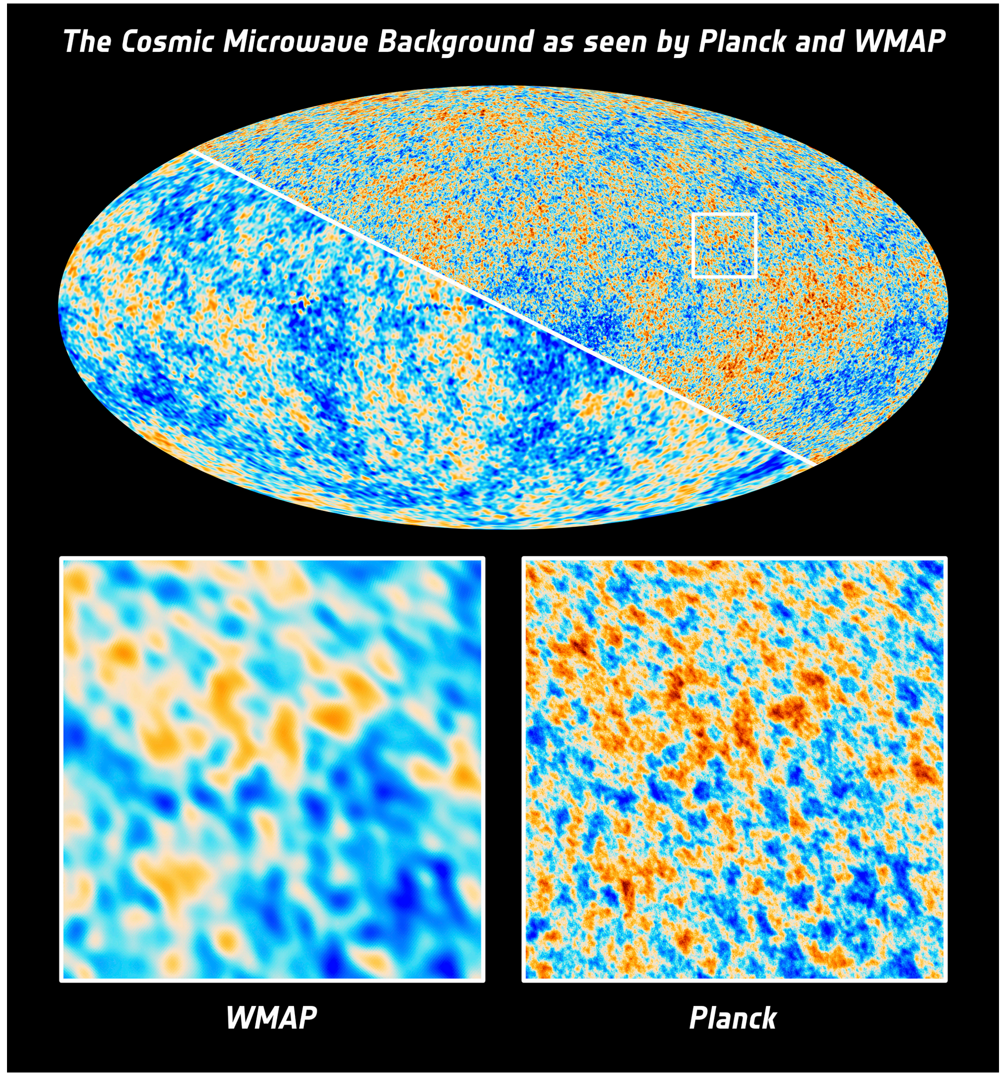
PLANCK 2015



1 part in 10^5 variation in temperature!!

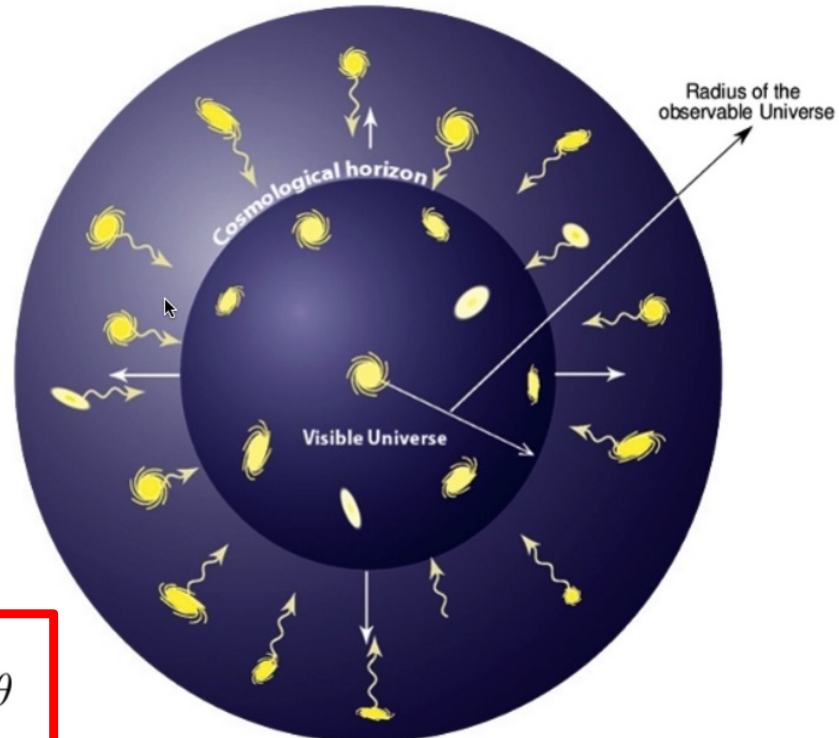
CMB is highly homogeneous!

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 recombination.**
- Regions further apart than the light-travel distance at the recombination epoch wouldn't know about each other (not causally connected).



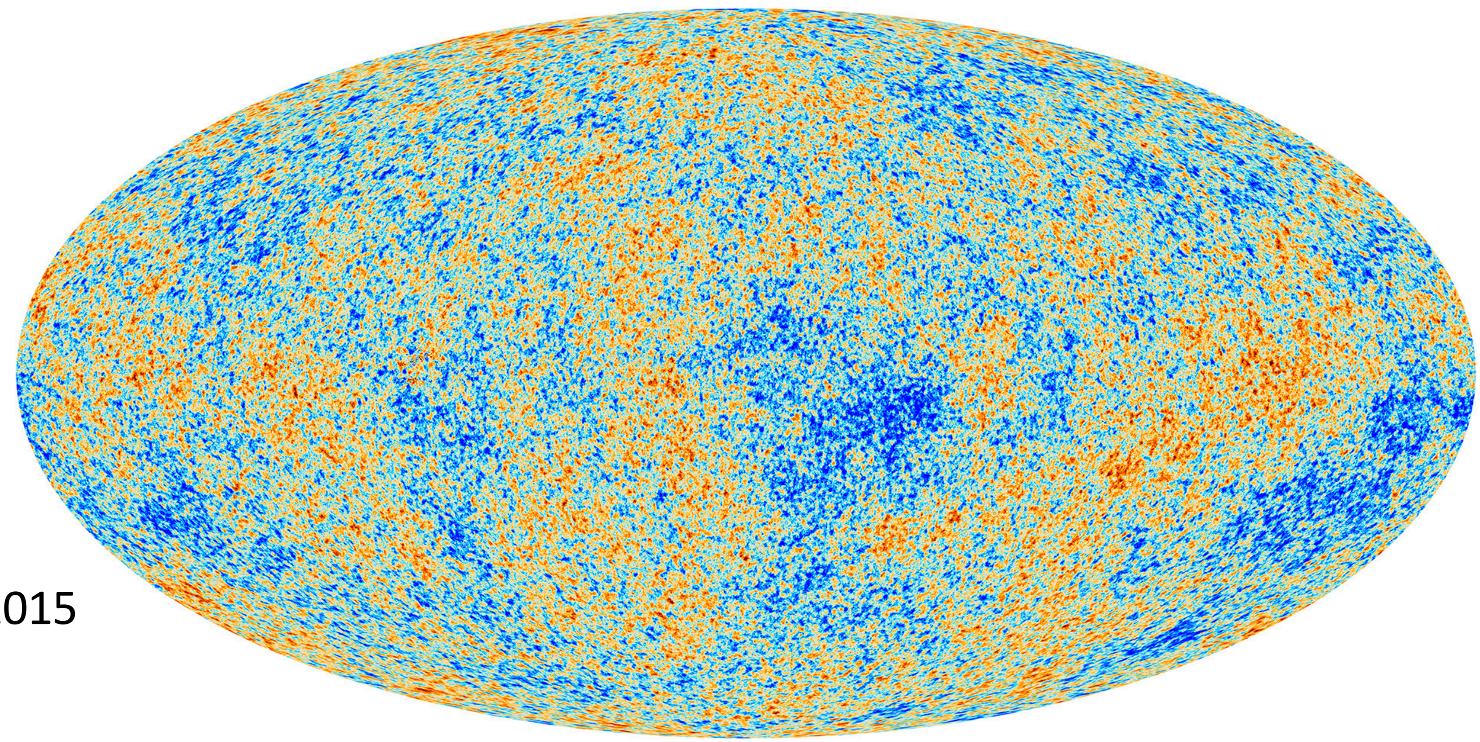
$$\boxed{S = \theta D_A = \frac{D_C}{1+z}\theta}$$

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

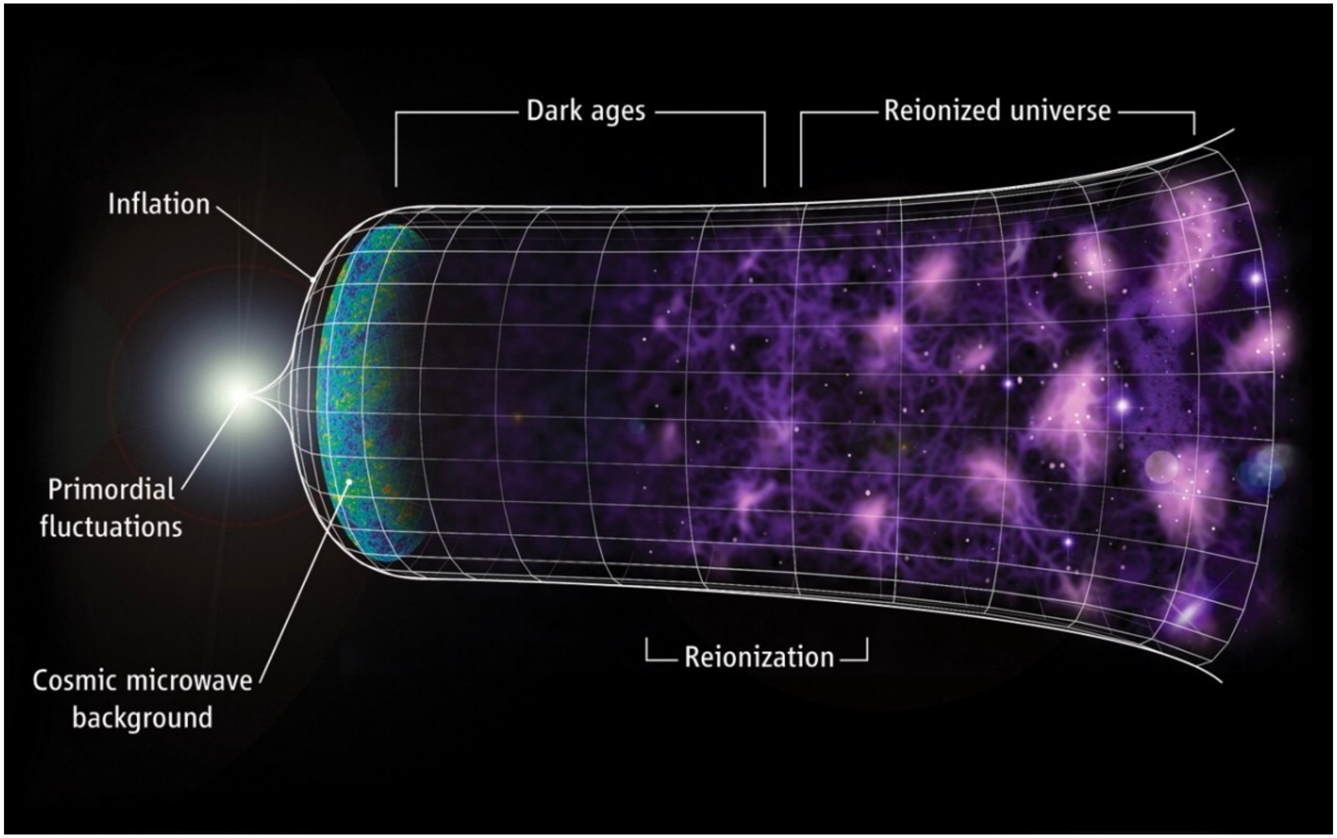
Causally connected region at recombination is only ~2 degrees on the sky!!!!!!!!!!
So why is the CMB so homogenous over larger angles?

The Horizon Problem: Assuming standard expansion, regions of space located on opposite sides of the sky could never have been in causal contact with each other.



PLANCK 2015

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



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 Ω_Λ = 1

$$\left(\frac{\dot{R}}{R}\right) = \mathrm{H}(\mathrm{t}_{\mathrm{inf}}) \quad R(t) \propto e^{\mathrm{H}(\mathrm{t}_{\mathrm{inf}})\,\mathrm{t}}$$

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

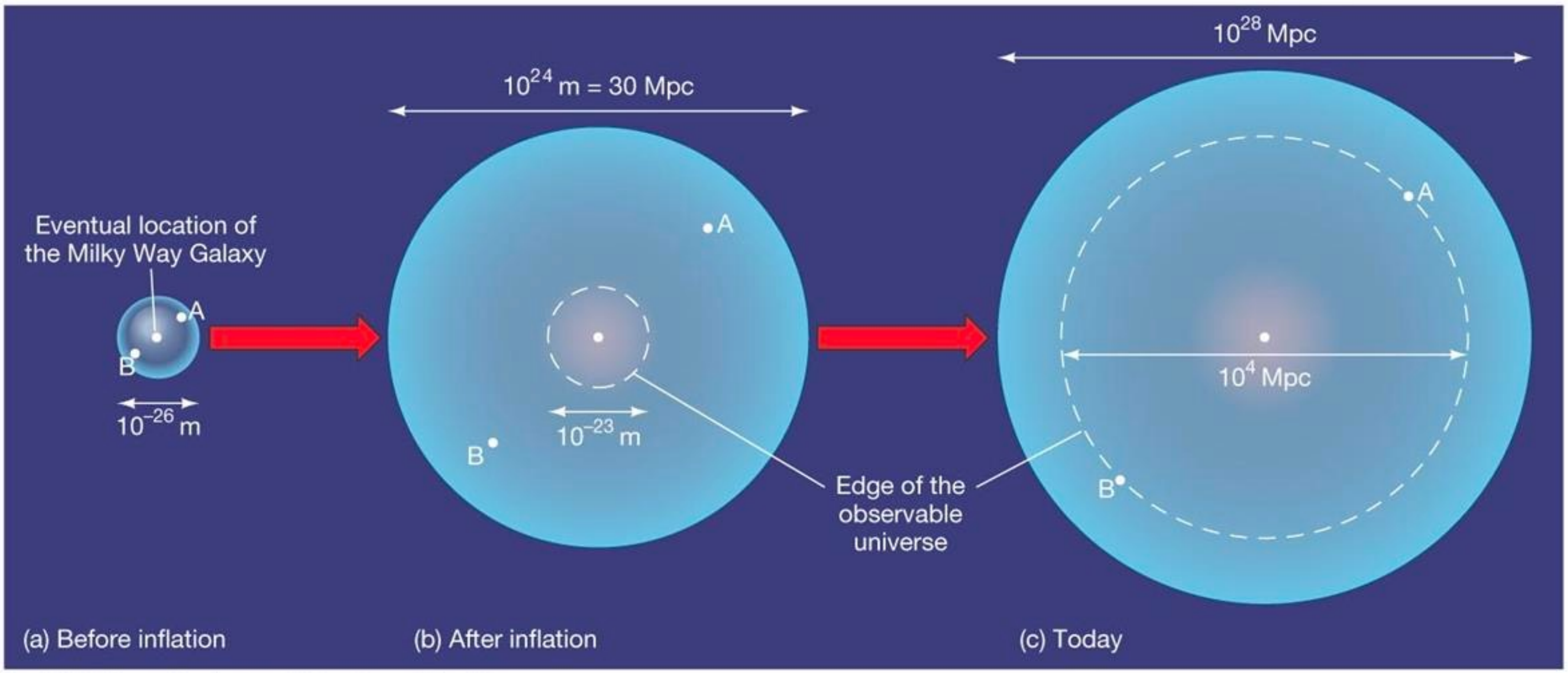
$$\mathrm{H}(\mathrm{t}_{\mathrm{inf}}) = \frac{1}{10^{-36}s} = 10^{36}$$

E-folding Time is REALLY REALLY FAST!!!!

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

Inflation

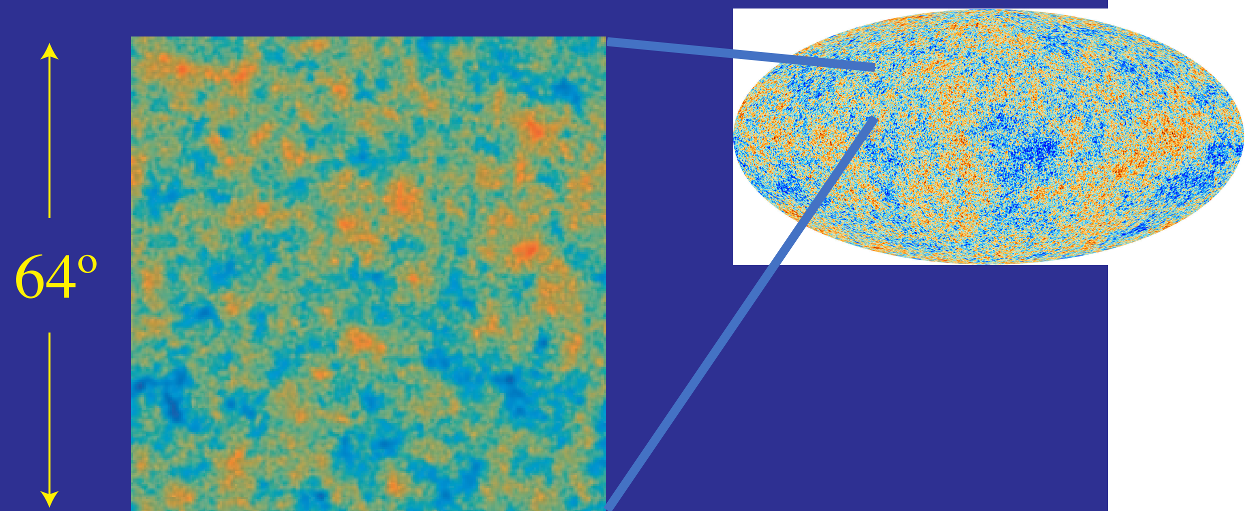
Solves the Horizon problem by allowing much larger scales to be in causal contact



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.

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

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



- 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.

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= infty until $z_e = z_{recombine}$

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

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

D_{sound} = Proper Distance / sqrt(3)

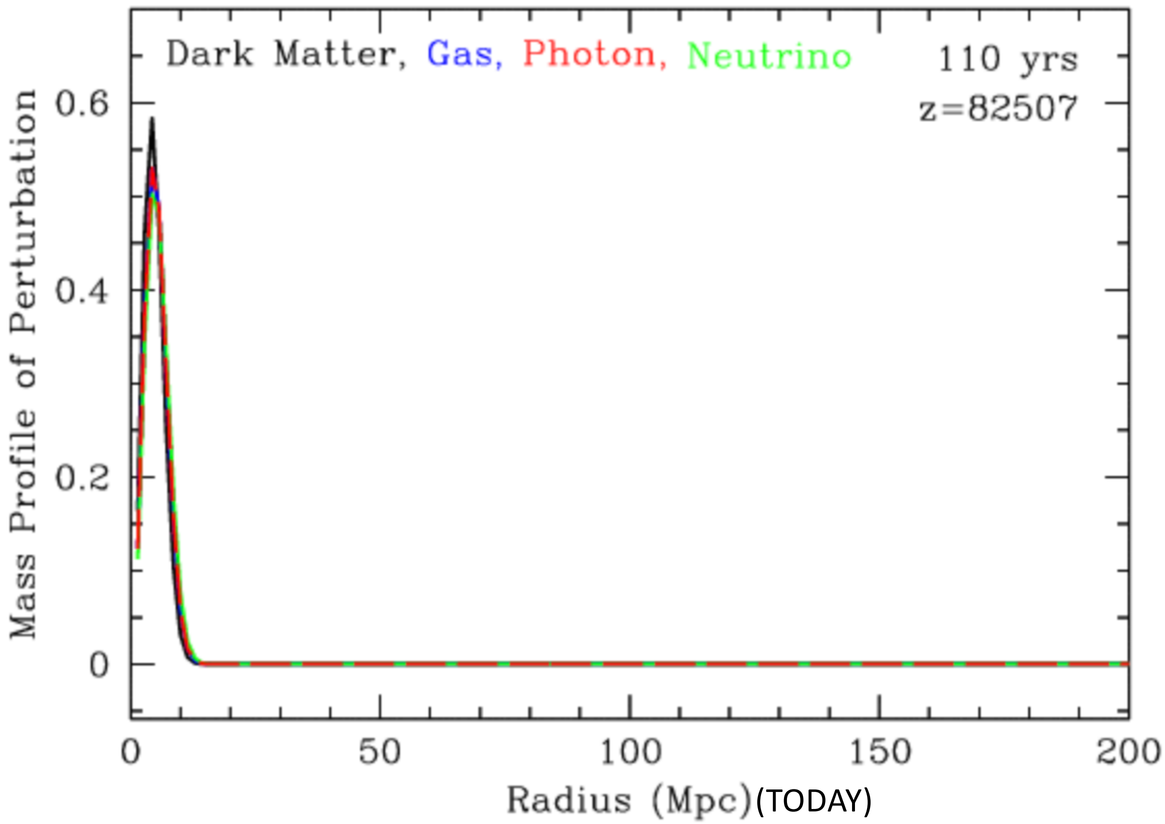
$c_s = \mathrm{c/sqrt}(3)$. Similar to pure photon gas.

sound speed in the baryon-photon fluid is about 170,000 km/sec

Scott Weissinger

Baryon Acoustic Oscillations

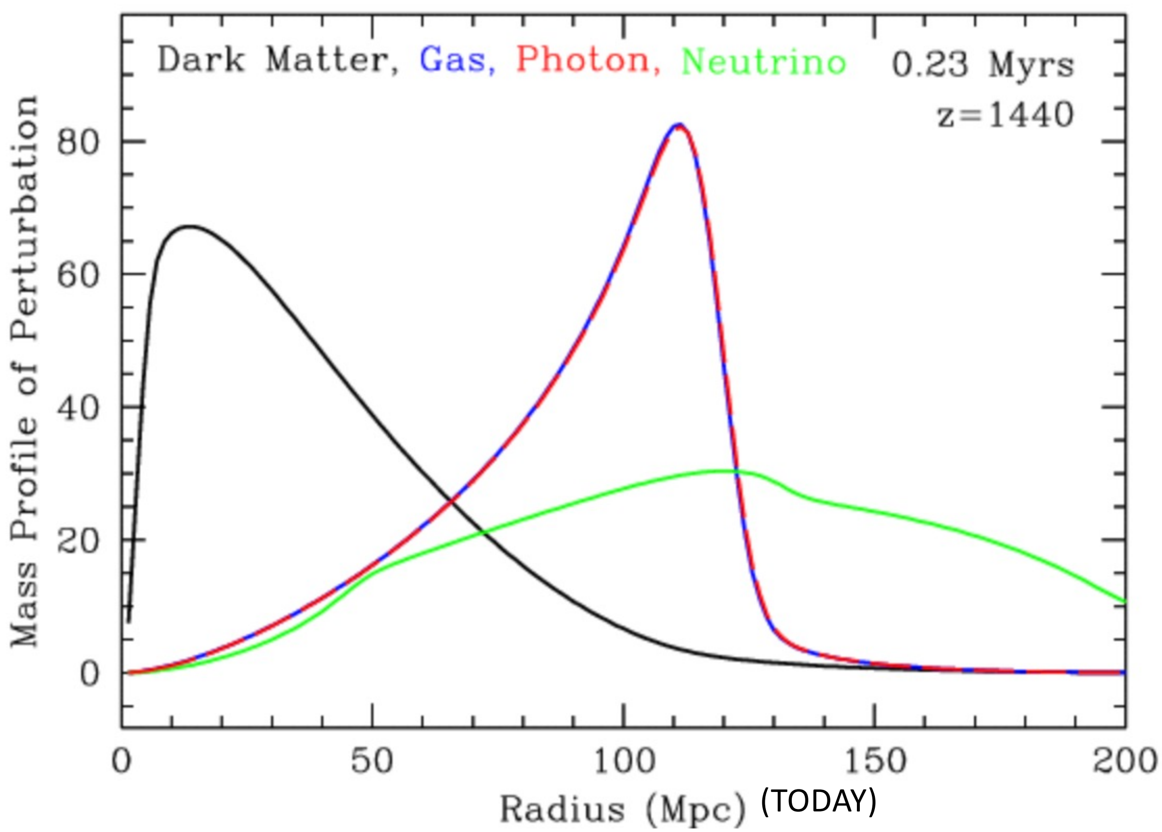
First Detected in Eisenstein+2005
Using SDSS data



- Consider a point-like initial, adiabatic perturbation
- All species impacted ~similarly

Courtesy: Daniel Eisenstein

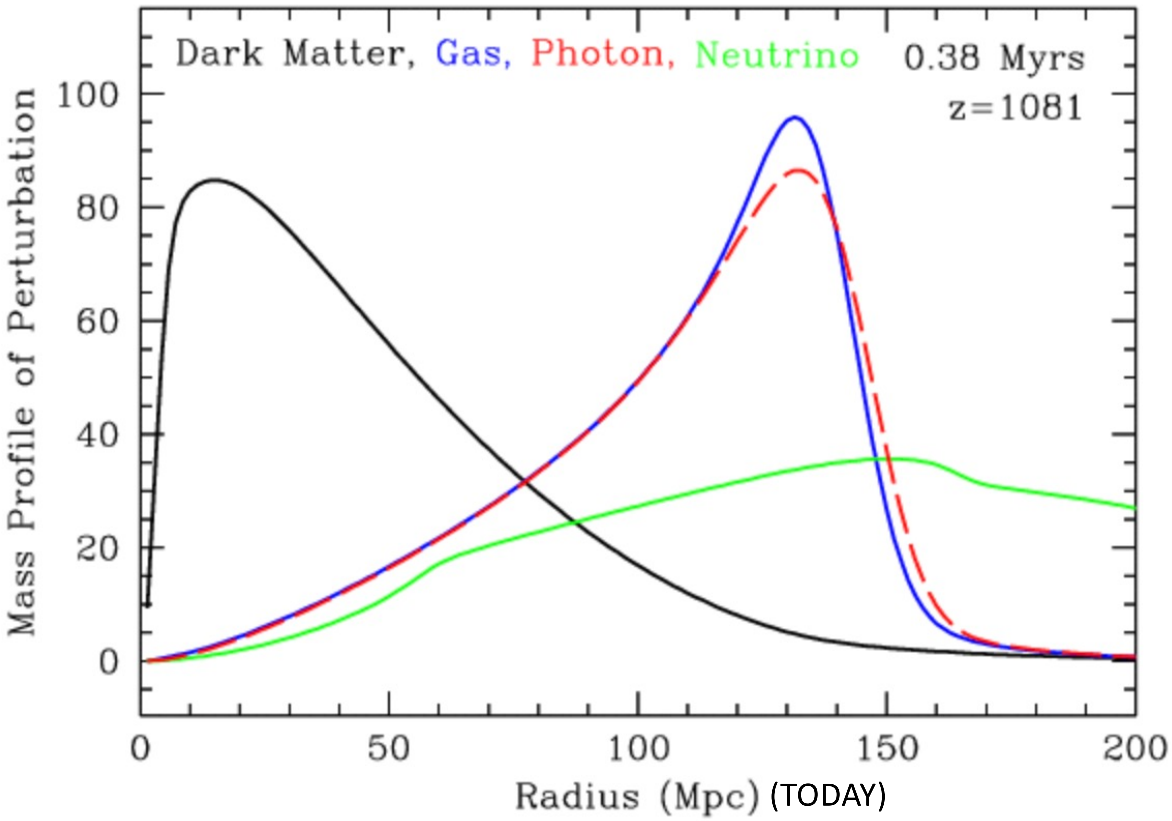
Baryon Acoustic Oscillations



- Neutrinos stream away
- Cold DM has no intrinsic motion – it sits still
- The perturbation is overdense so it pull mos DM -- causes the DM overdensity to grow in width
- Baryon-Photon fluid with enormous pressure relative to its density
- The pressure tries to equalize itself with the surroundings → expanding spherical sound wave
- Perturbation in baryon-photon fluid is carried outwards

Courtesy: Daniel Eisenstein

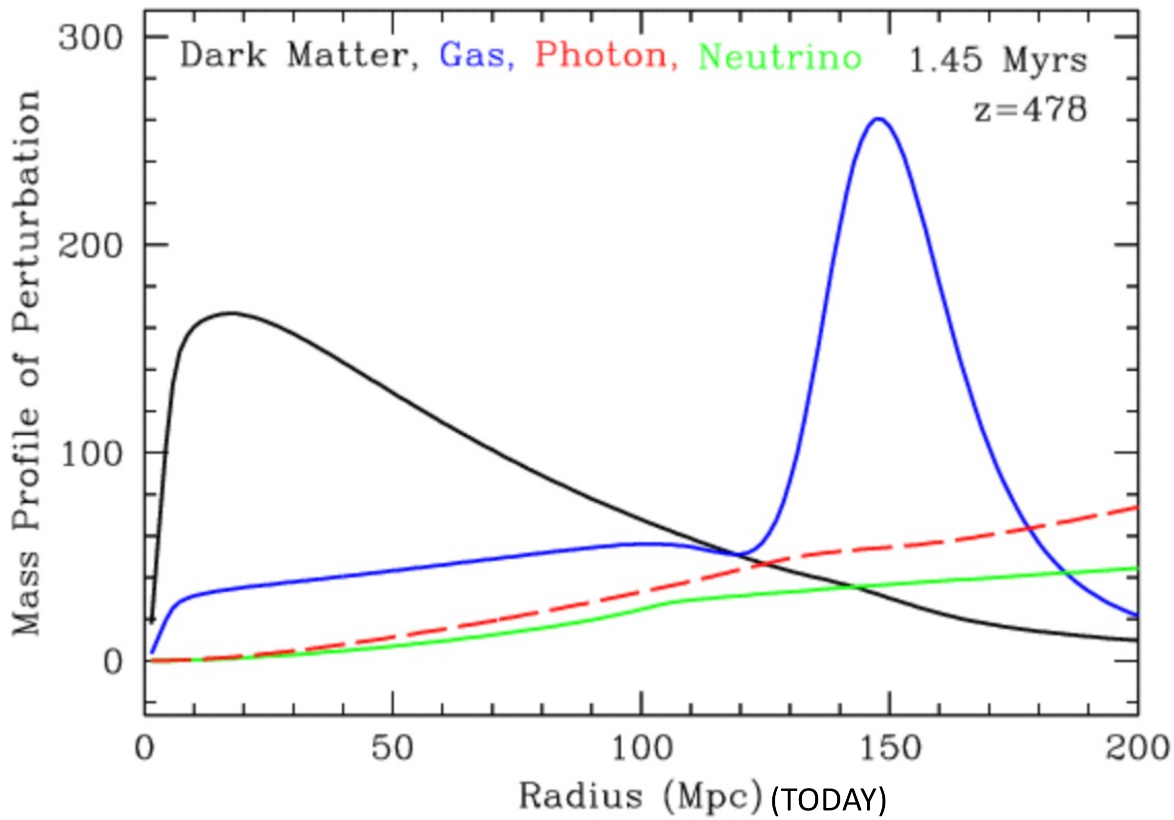
Baryon Acoustic Oscillations



- Recombination ~ 400K years after the Big Bang – atoms
- The sound speed begins to drop because of the reduced coupling between the photons and
- Hence, the pressure wave slows down (not accounted for in the Lab)

Courtesy: Daniel Eisenstein

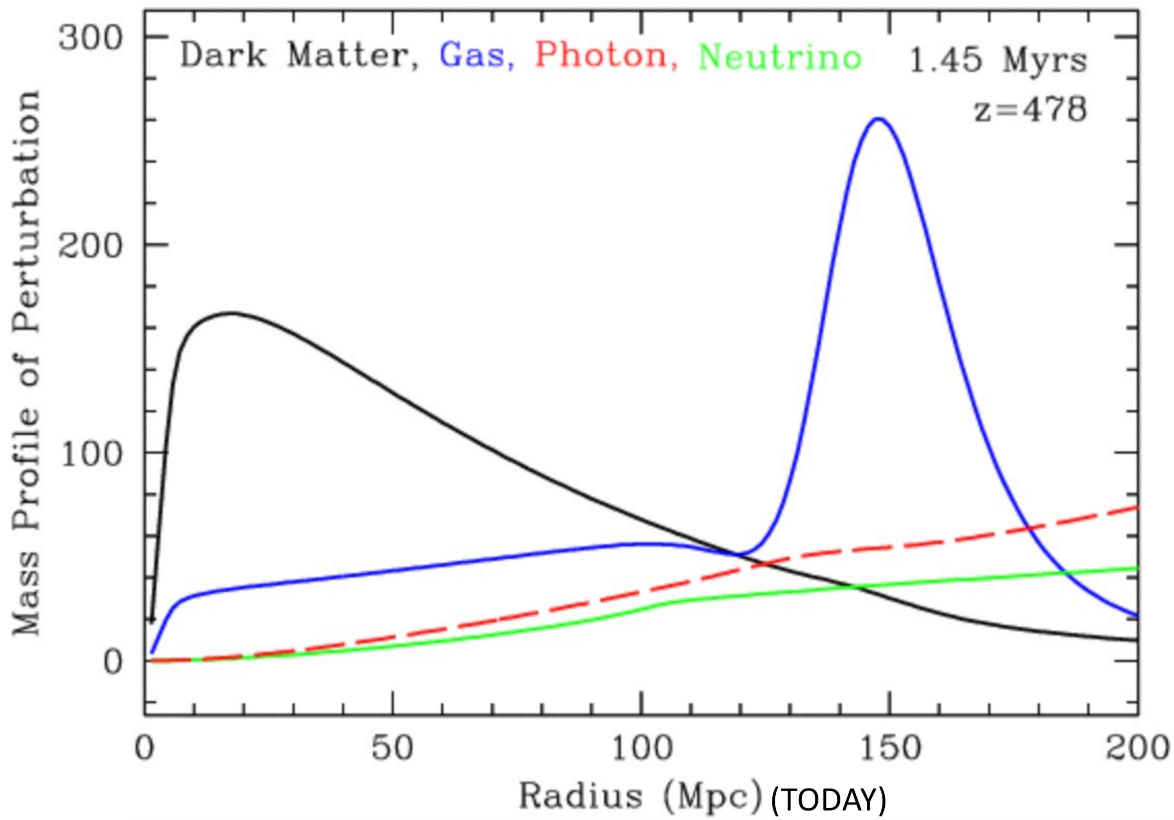
Baryon Acoustic Oscillations



- The photons travel (mostly) unimpeded until the present-day, where we can record them as the microwave background
- the sound speed in the gas has dropped to much less than the speed of light, so the pressure wave stalls.

Courtesy: Daniel Eisenstein

Baryon Acoustic Oscillations

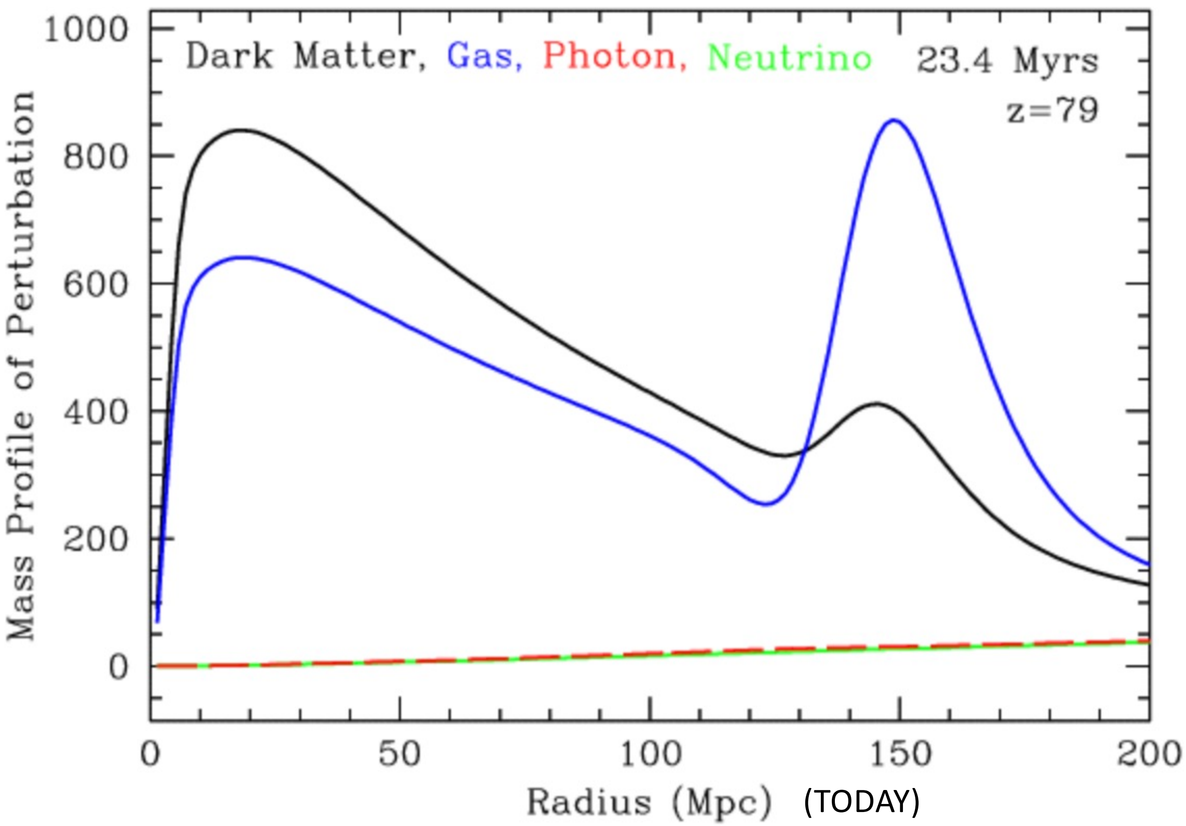


(TODAY)

- The photons travel (mostly) unimpeded until the present-day, where we can record them as the microwave background
- the sound speed in the gas has dropped to much less than the speed of light, so the pressure wave stalls.
- We are left with a dark matter perturbation around the original center and a gas perturbation in a shell about 150 Mpc (500 million light-years) in radius.

Courtesy: Daniel Eisenstein

Baryon Acoustic Oscillations

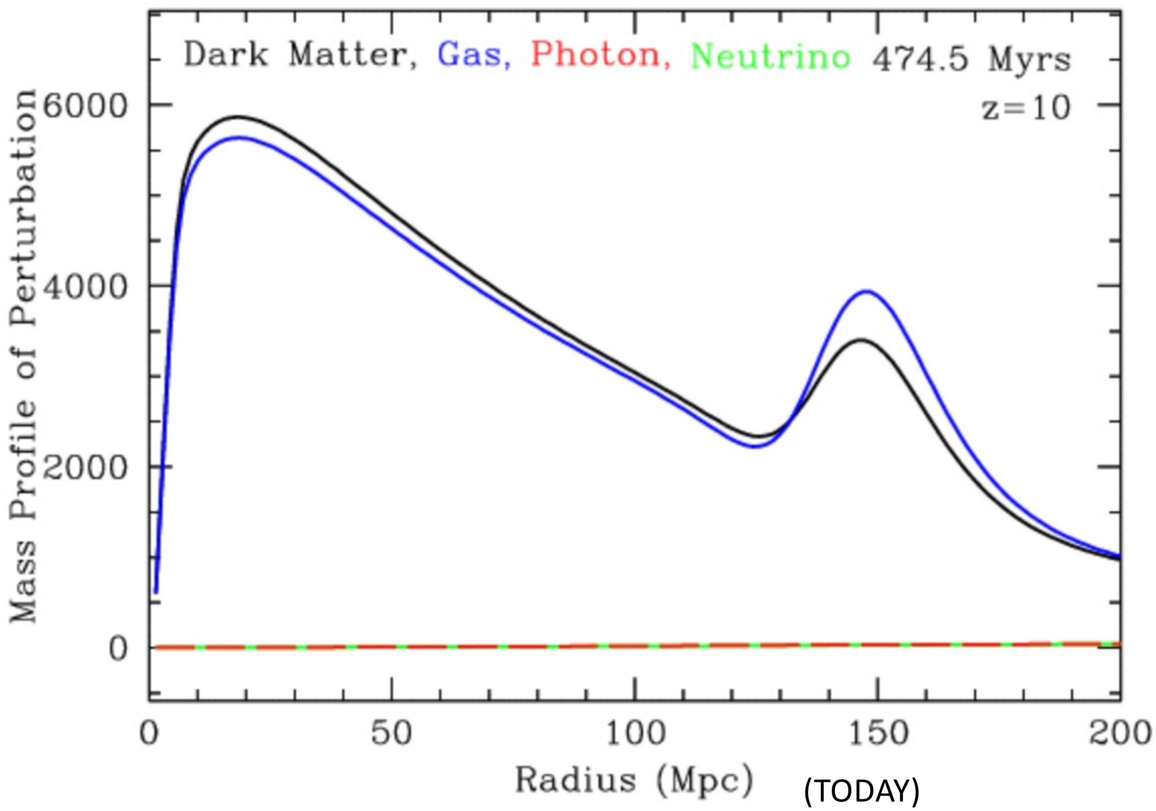


(TODAY)

- As time goes on these two species gravitationally attract each other.
- both perturbations are growing quickly in response to the combined gravitational forces of both the dark matter and the gas

Courtesy: Daniel Eisenstein

Baryon Acoustic Oscillations

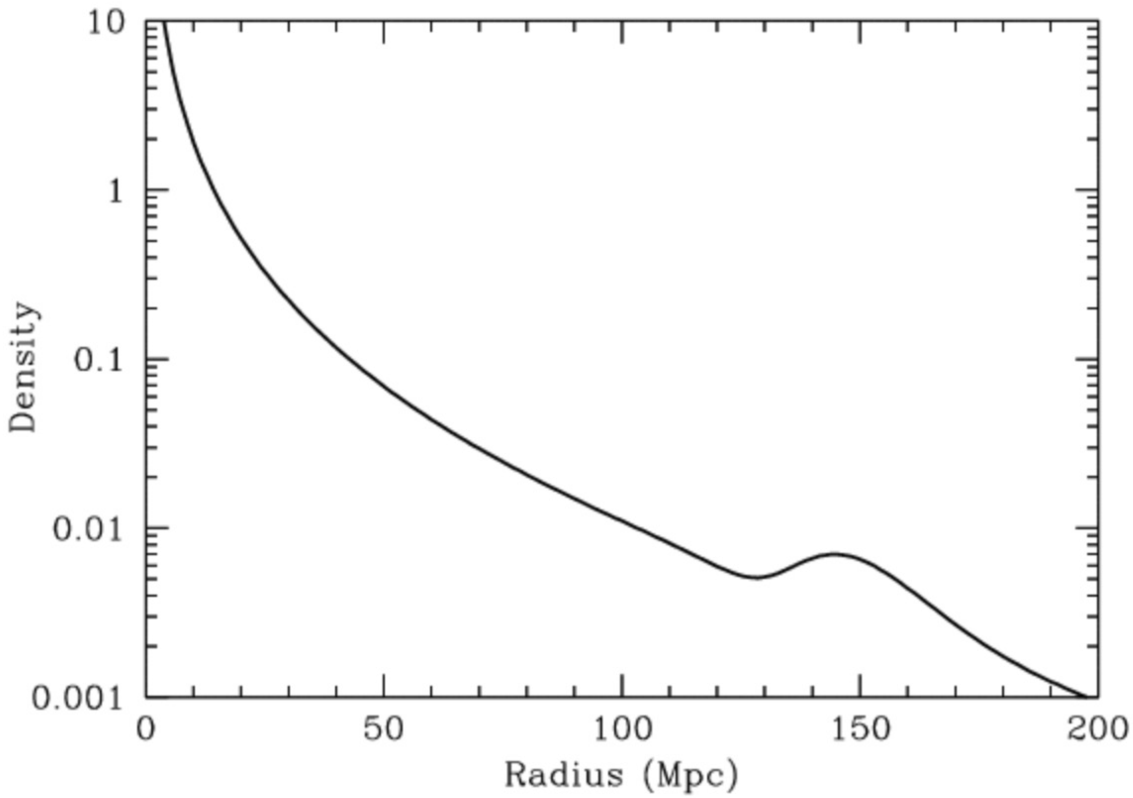


(TODAY)

- Eventually, the two look quite similar.
- The spherical shell of the gas perturbation has imprinted itself in the dark matter.
- This is known as the acoustic peak.

Courtesy: Daniel Eisenstein

Baryon Acoustic Oscillations



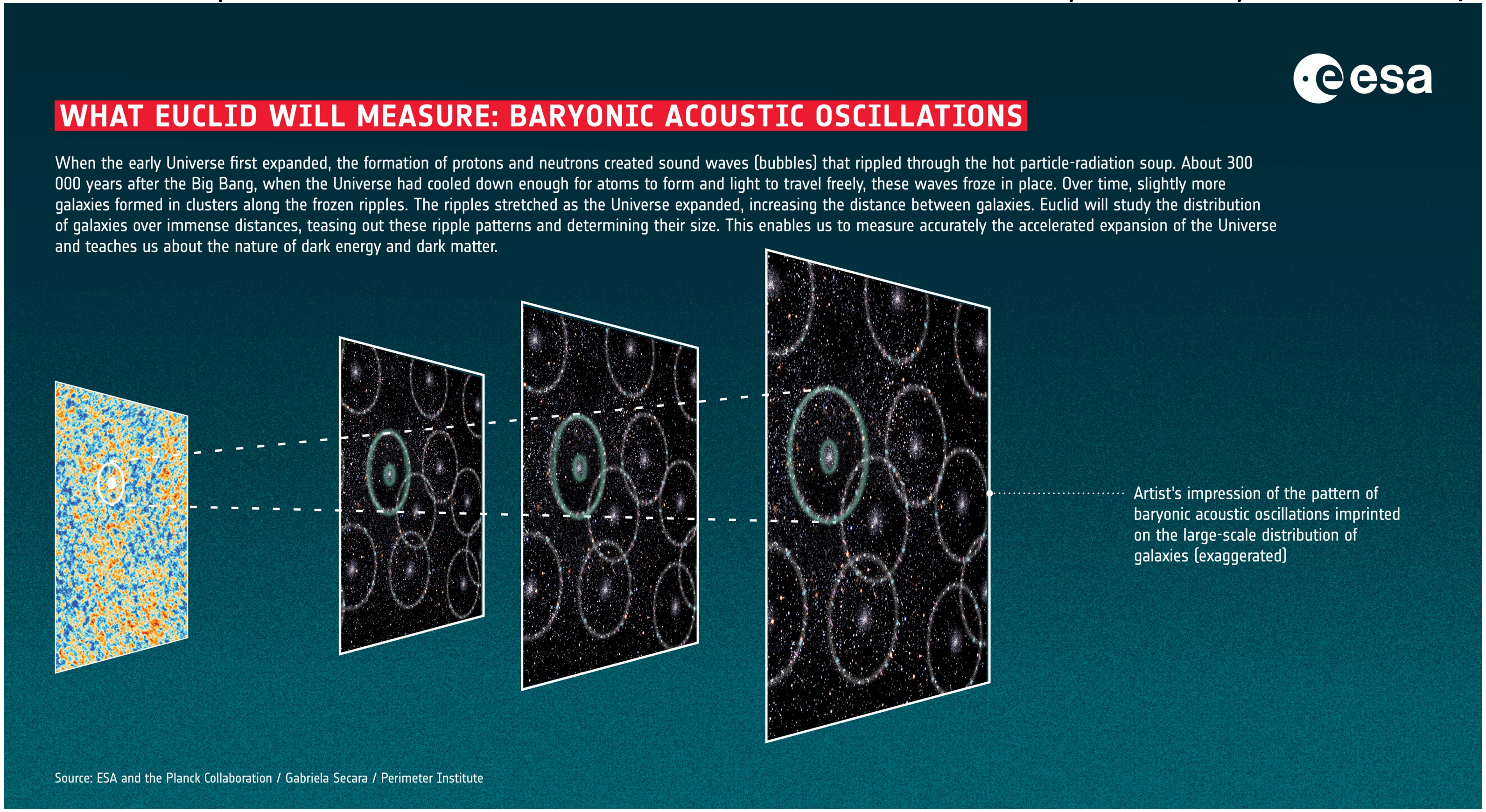
(TODAY)

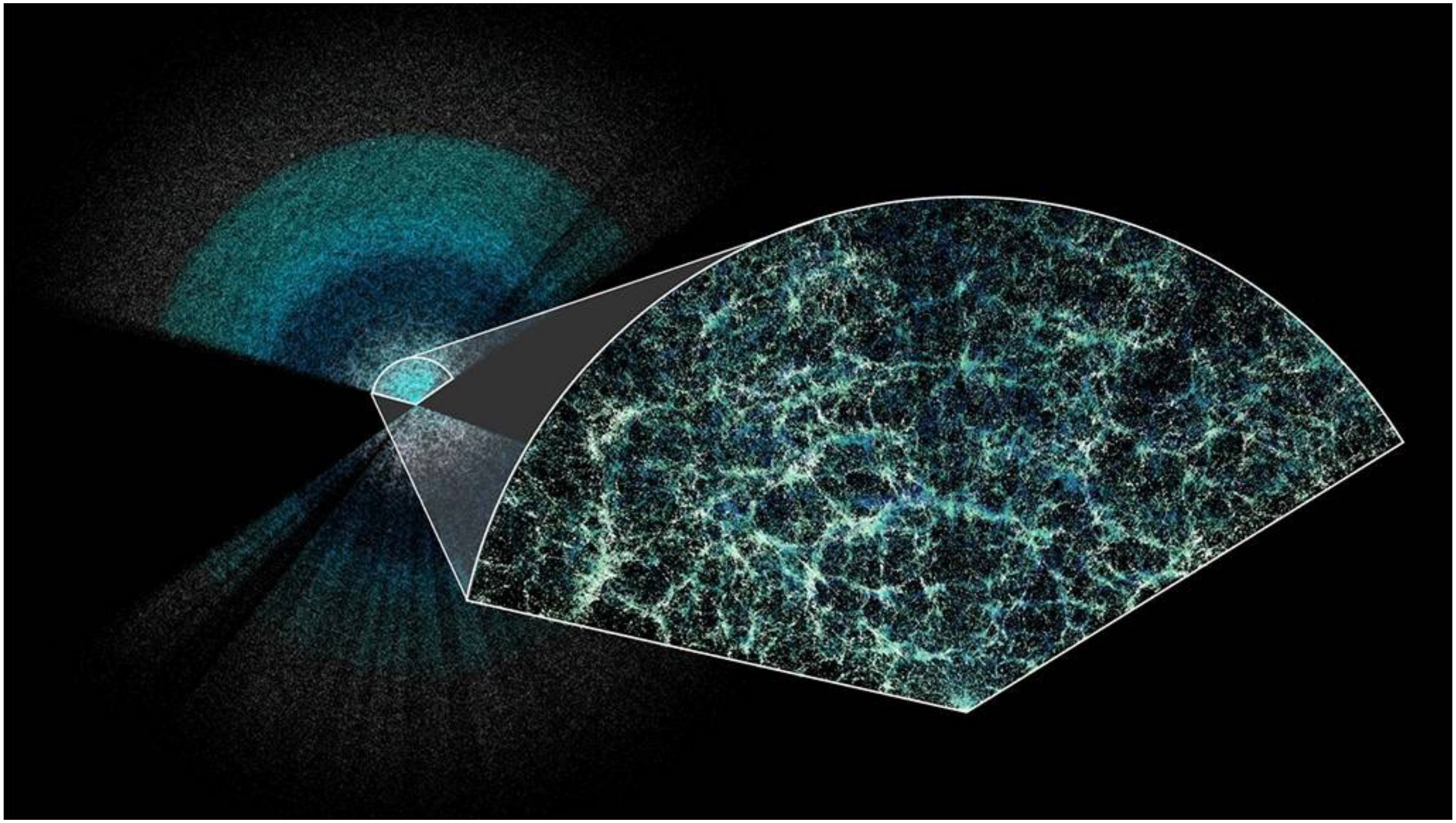
- We have been plotting the mass profile (density times radius squared). The density profile is much steeper, so that the peak at 150 Mpc is much less than 1% of the density near the center.
- At late times, galaxies form in the regions that are overdense in gas and dark matter.
- there should be a small excess of galaxies 150 Mpc away from other galaxies, as opposed to 120 or 180 Mpc

Courtesy: Daniel Eisenstein

BAO: Baryon Acoustic Oscillations

“Standard Ruler” = maximum distance the acoustic waves could travel in the primordial plasma before recombination ~ 150 Mpc today = 150*R(t)





Looking back in time: a slice in time of the universe showing bubbles of galaxies that are a result of baryon acoustic oscillations. (Courtesy: Claire Lamman/DESI collaboration/custom colormap package by cmastro)

Understanding Where the Benchmark Cosmology Comes From

$$\Omega_{m0} = 0.308 \pm 0.012 \qquad \Omega_{\Lambda 0} = 0.692 \pm 0.012$$

$$\Omega_{\text{rad}0} = 8.24 \times 10^{-5} \qquad H_o = 67.81 \pm 0.92$$