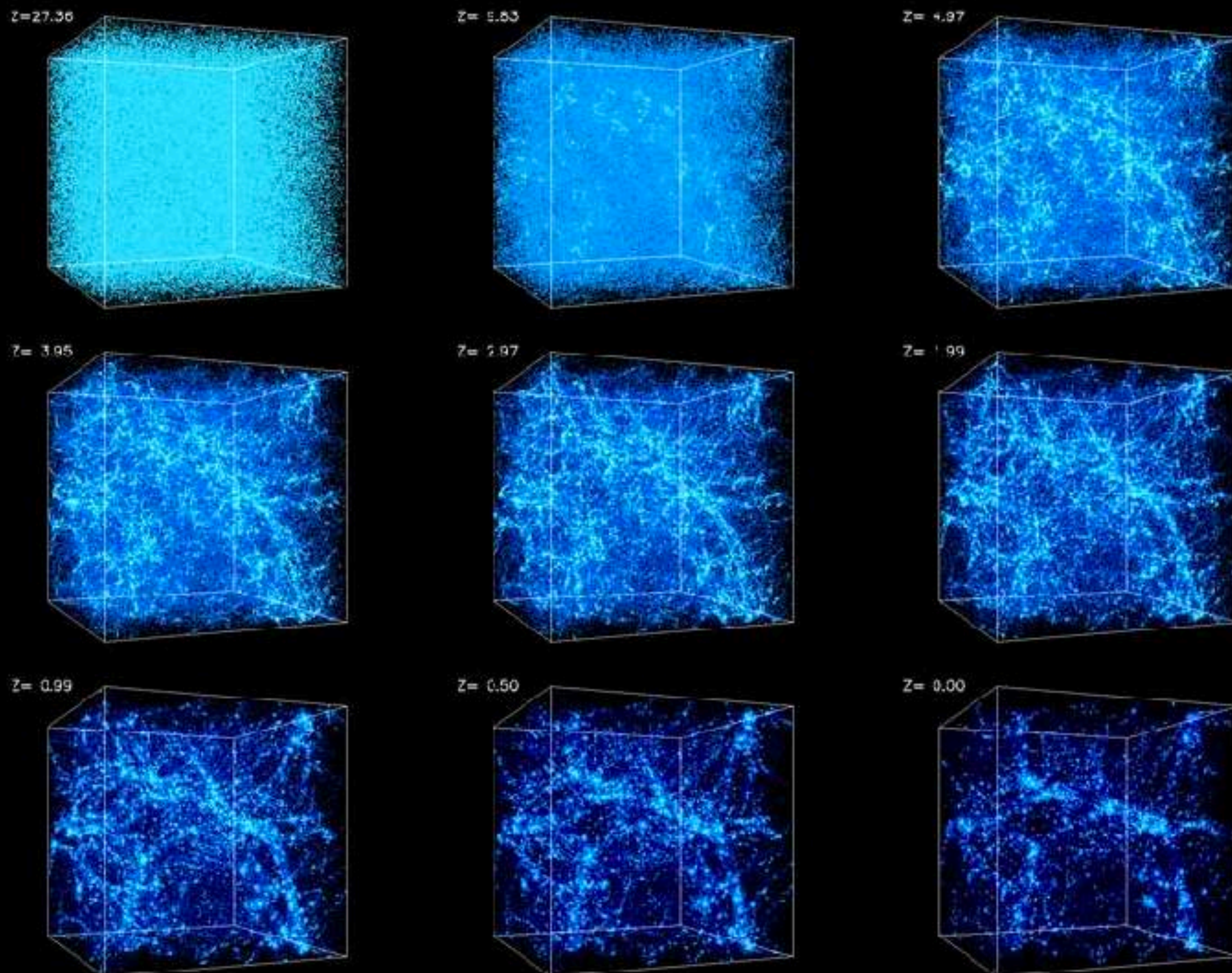
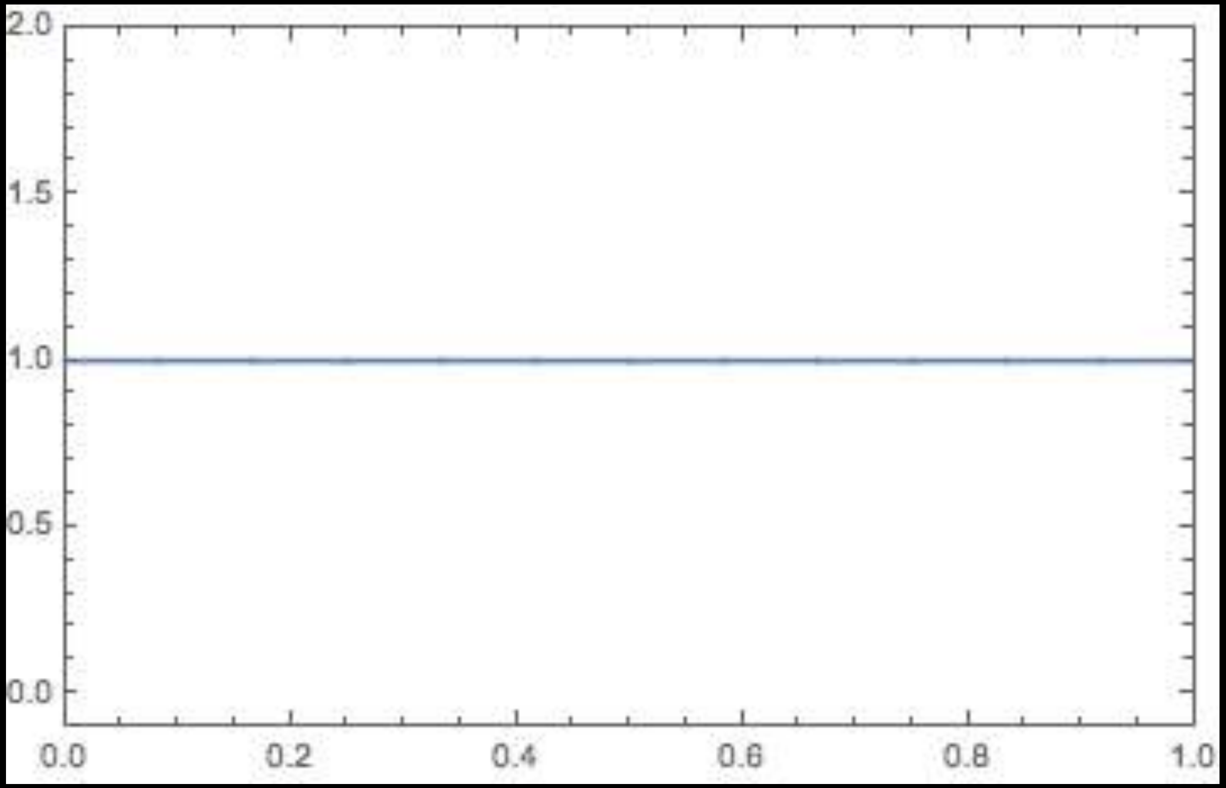
THE VISIBLE AND THE INVISIBLE WEBS

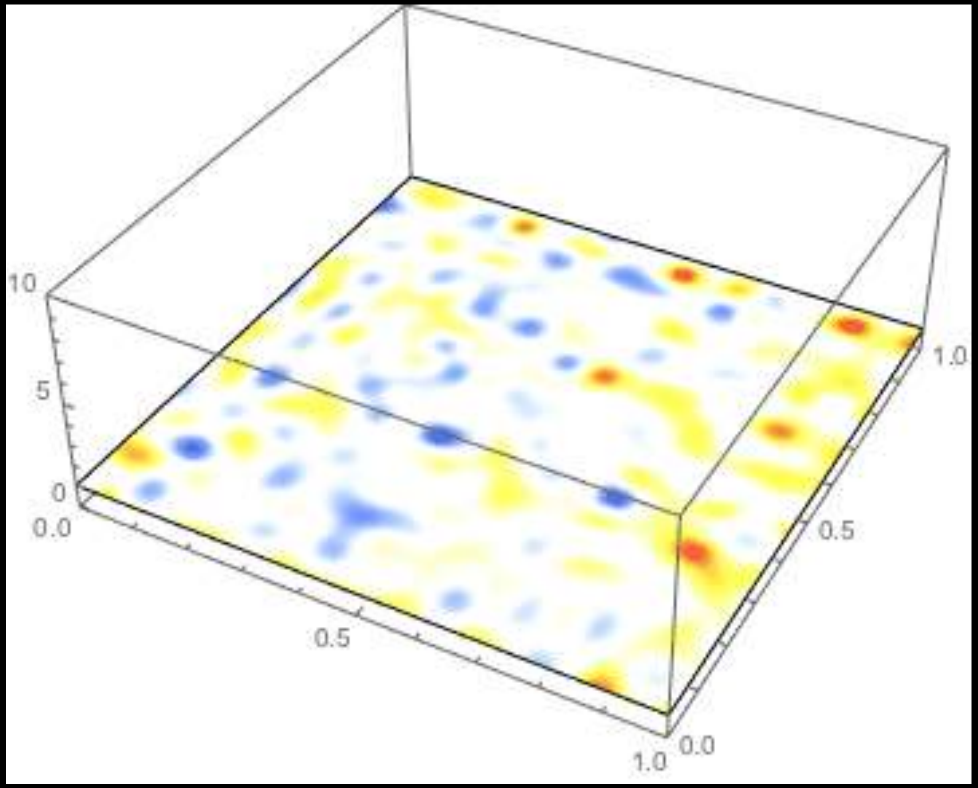


THE VISIBLE AND THE INVISIBLE WEBS

1D

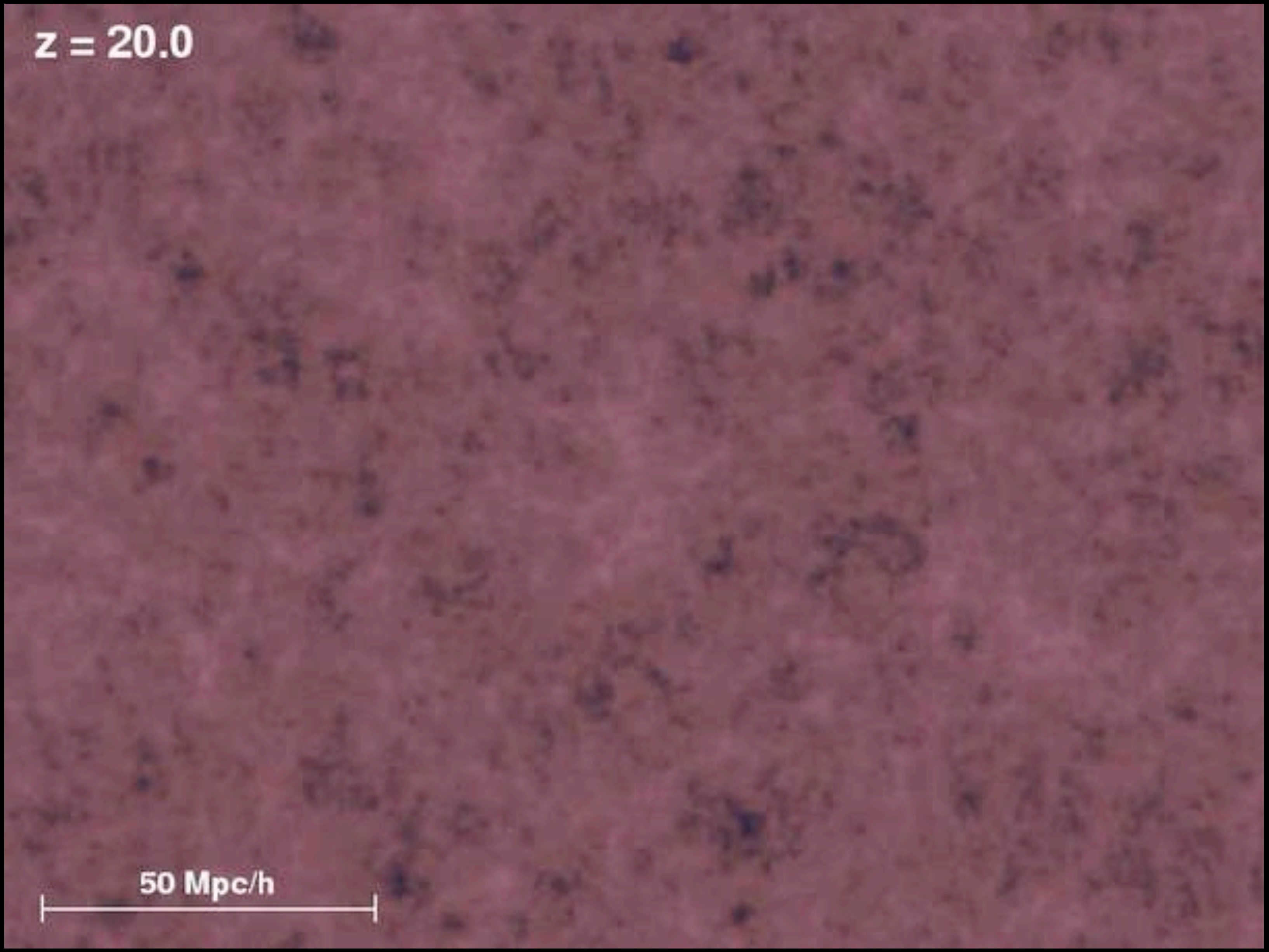


2D



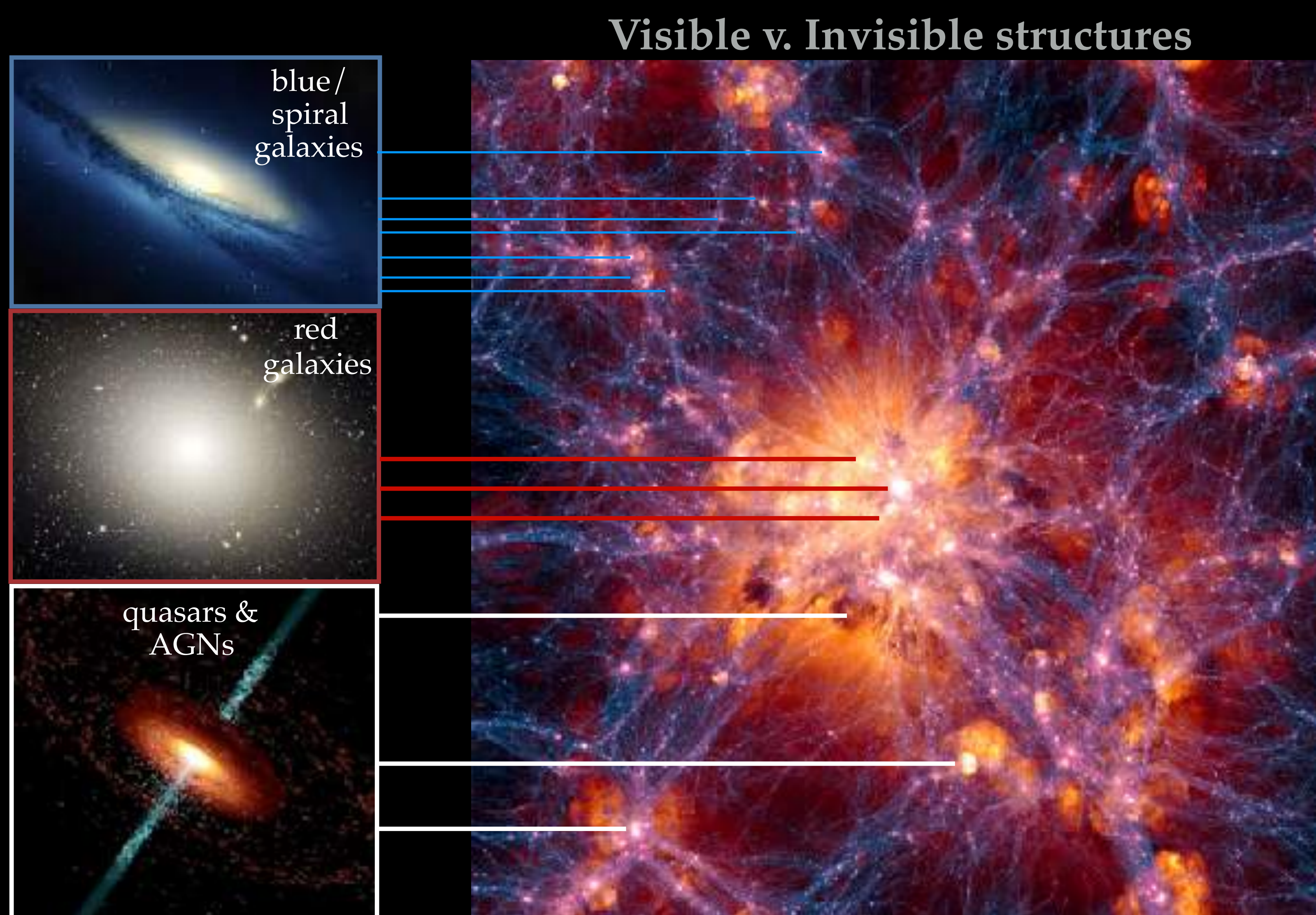
Initially, density fluctuations are very small ($\delta\rho/\rho \sim 10^{-4}$), and in this linear regime, structure formation proceeds at a moderate pace

THE VISIBLE AND THE INVISIBLE WEBS



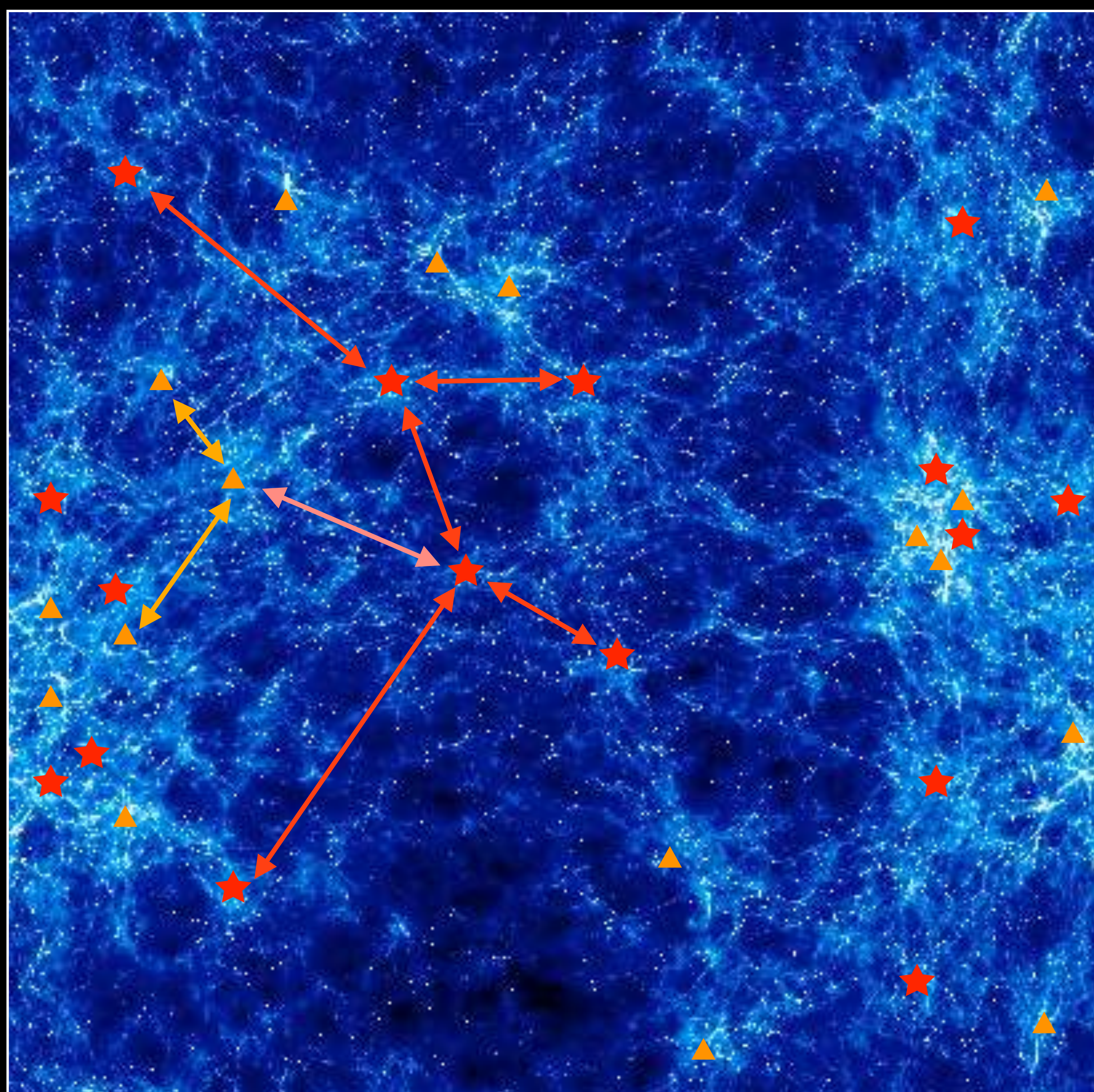
However, soon the linear regime fails to describe the growing concentration of matter in the initially overdense regions. Gravity is a relentless force ***driving inequality*** in the Universe.

THE VISIBLE AND THE INVISIBLE WEBS



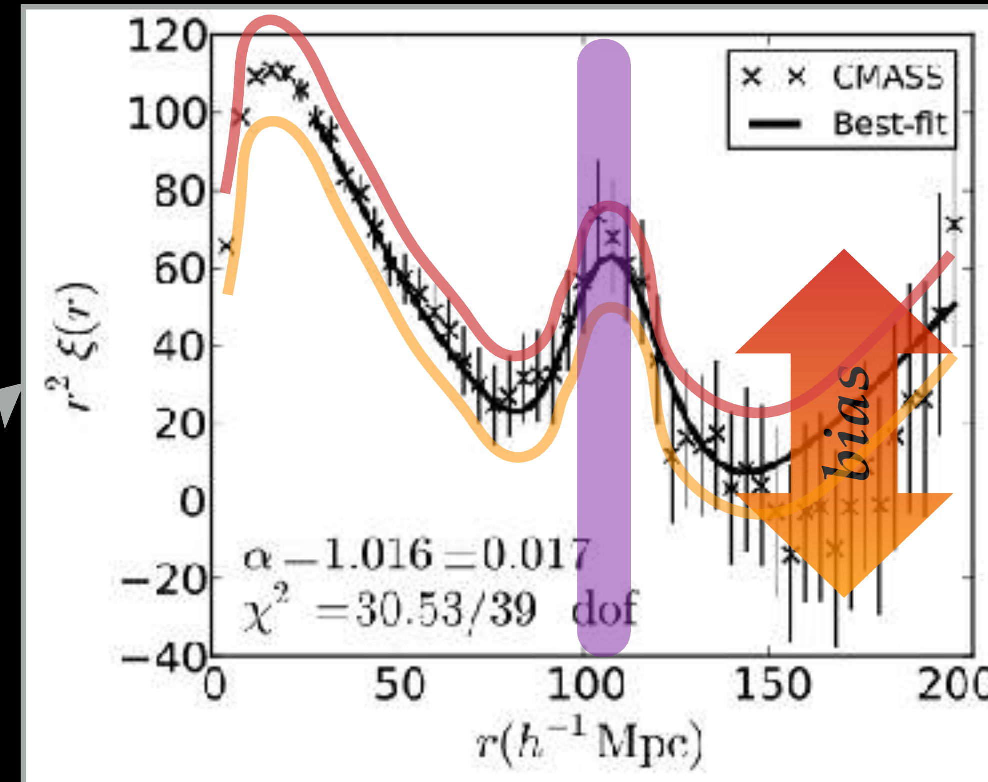
Dark matter is 5-6x more abundant than baryonic matter, therefore it often determines the gravitational wells where we also find luminous baryons– galaxies of all kinds, quasars, gas clouds, etc.

THE CLUSTERING OF MATTER

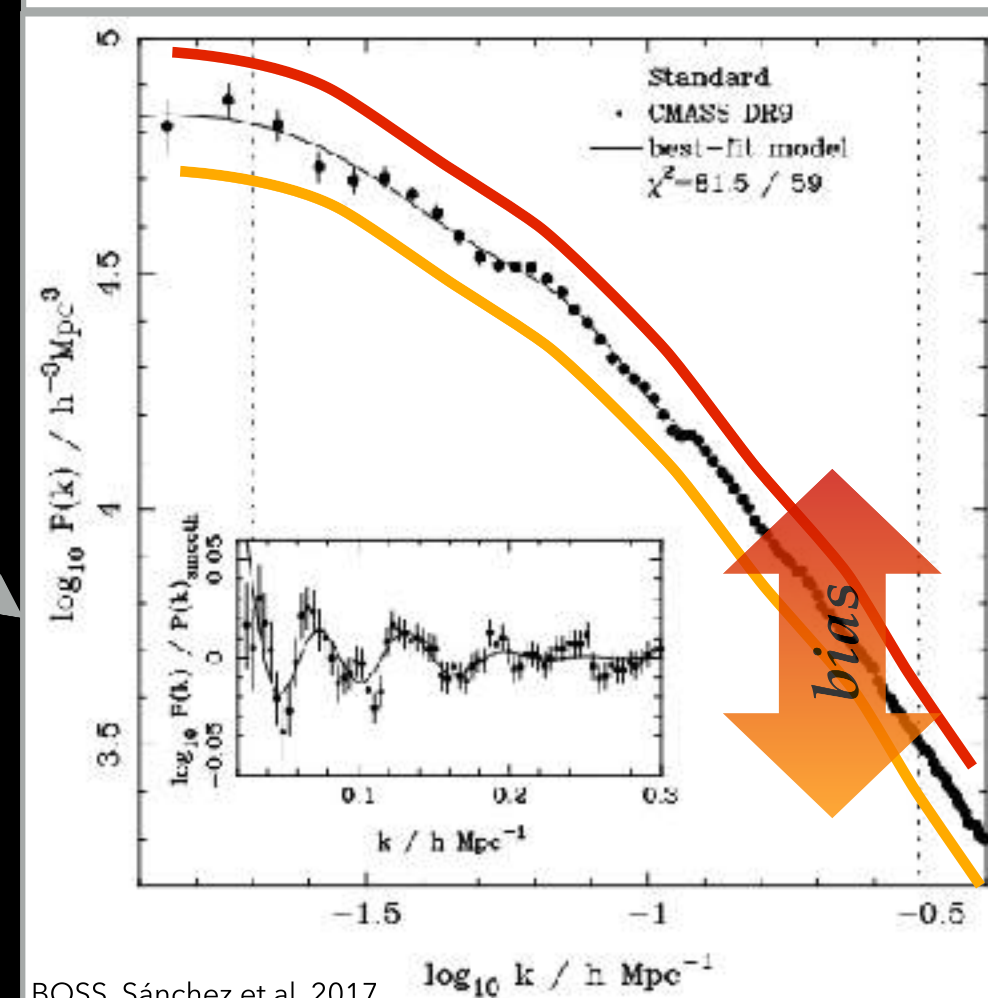


Galaxies serve as *tracers* of the dense regions of the Universe, where we find more matter. Although their *absolute* positions are irrelevant, their *relative positions* tells us about *clustering*

Clustering in position space



Clustering in Fourier space



BOSS, Sánchez et al. 2017

To the blackboard!

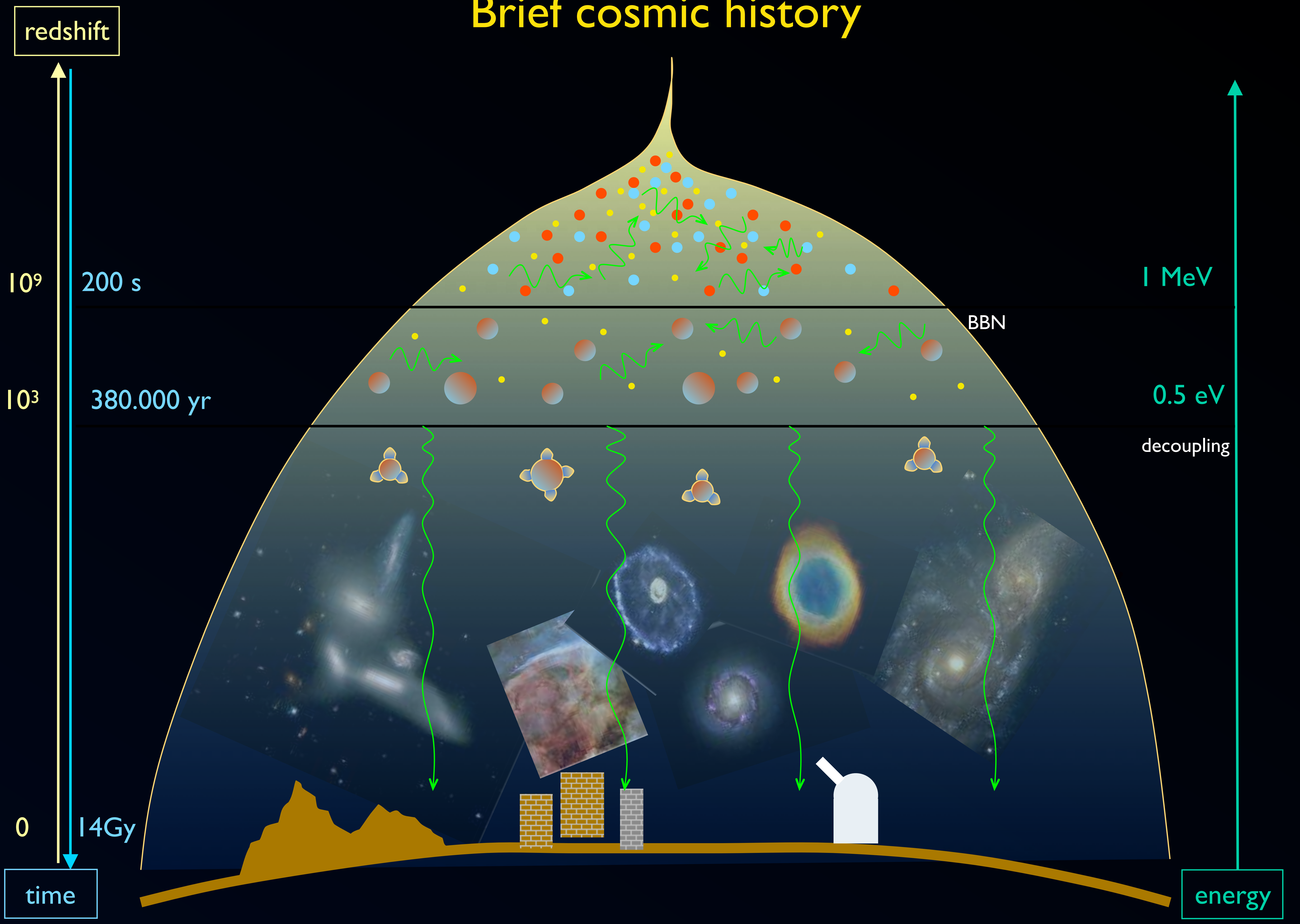
Brief review of

Cosmic Microwave Background Radiation

and

Baryon Acoustic Oscillations

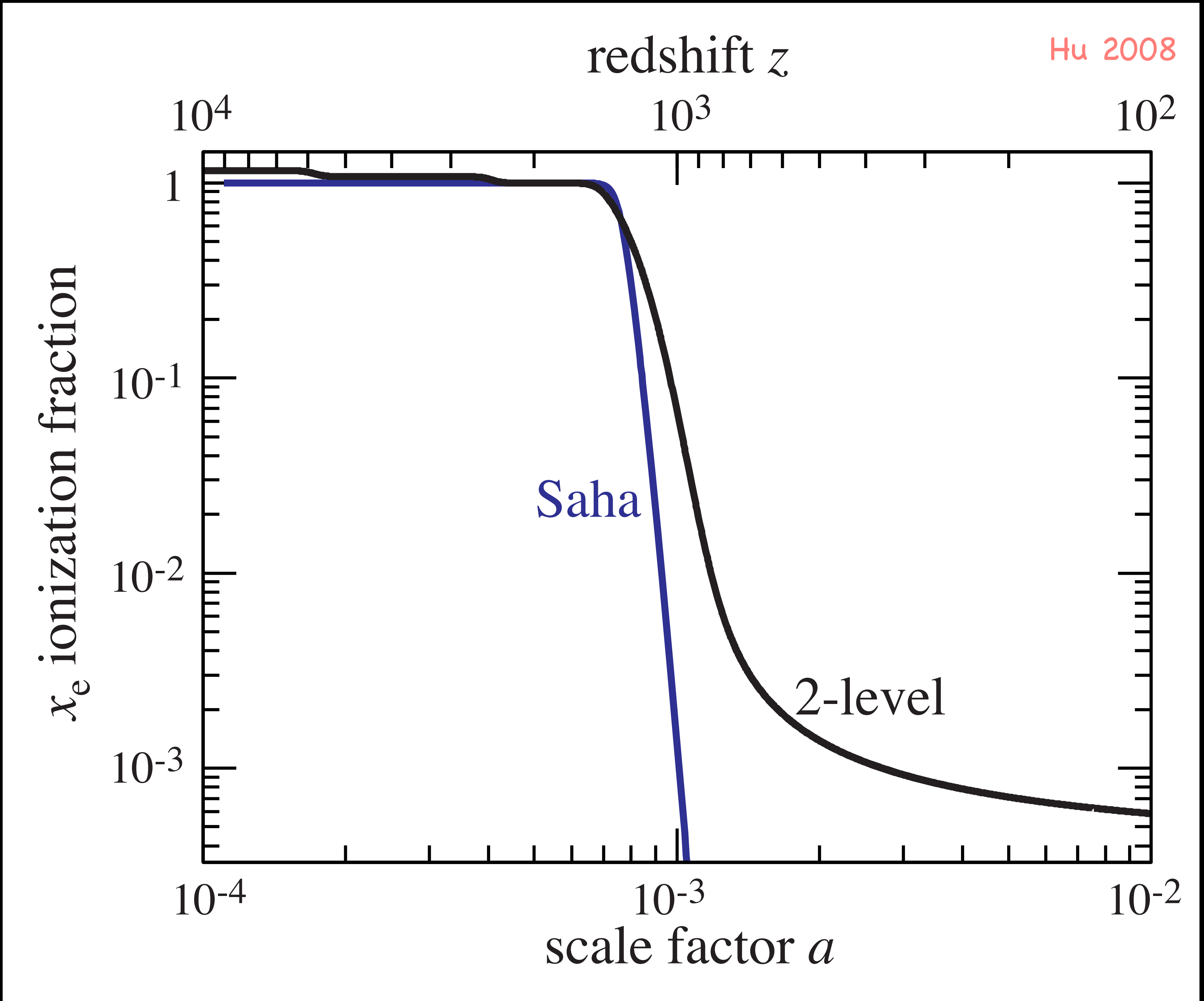
Brief cosmic history



Recombination: the Saha equation and full recombination

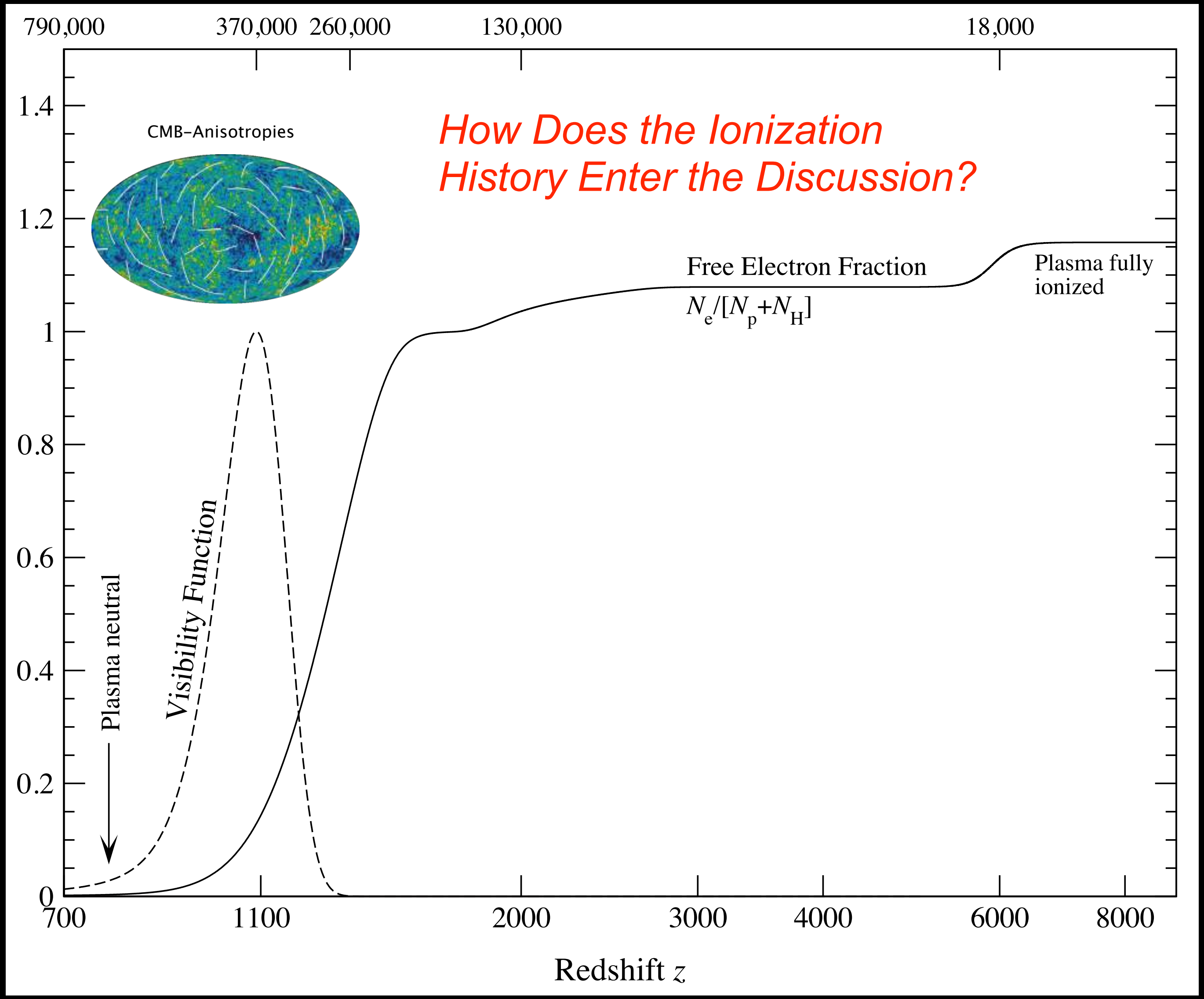
Number of free (ionized) electrons and ionized fraction::

$$n_e = (1-Y)X_e n_b = x_e \times 1.12 \times 10^{-5}\Omega_b h^2 (1+z)^3 \mathrm{cm}^{-3}$$



This **probability per unit length** that a photon **is scattered** by some time **t**, but not afterwards, is called the **visibility function:**

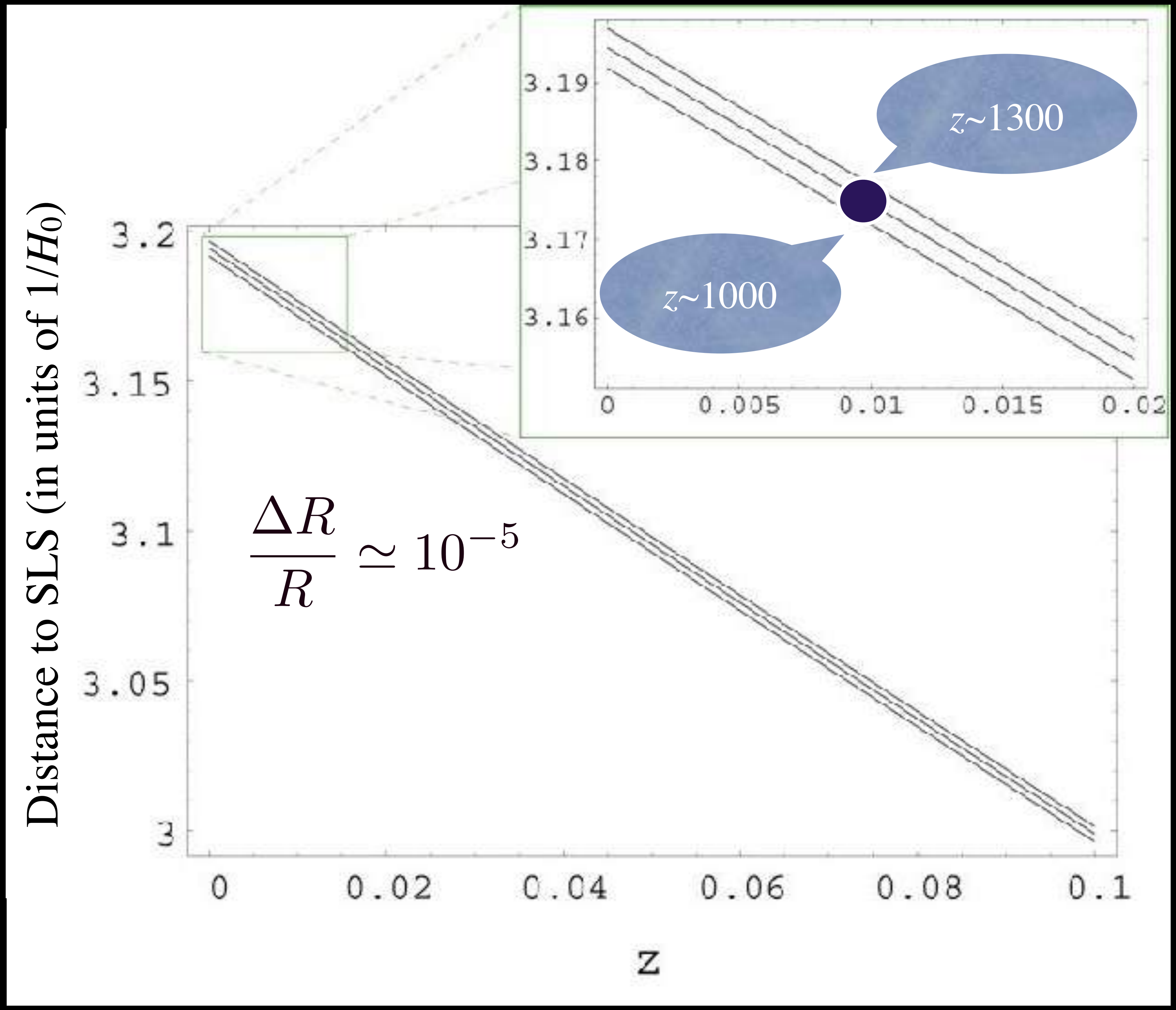
$$g(\eta) = \mu'(\eta) e^{-\mu(\eta)} \;=\; \sigma_T X_e(\eta) n_b(\eta) a(\eta) \times \exp\left[\int_0^\eta d\eta' \, \sigma_T X_e(\eta') n_b(\eta') a(\eta')\right]$$



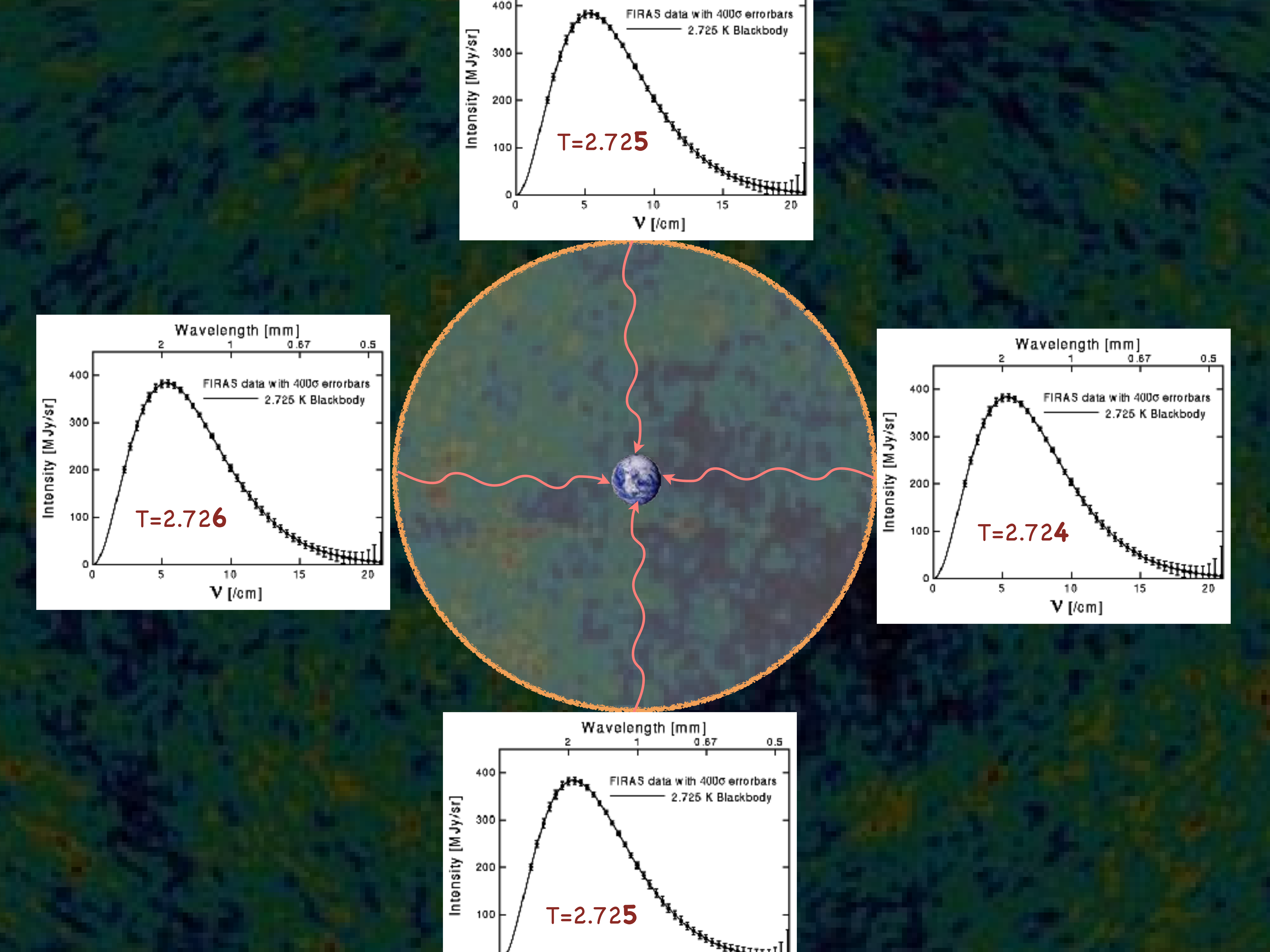
Peak probability: $$z_* \approx 1089 \left(\frac{\Omega_m h^2}{0.14}\right)^{0.0105} \left(\frac{\Omega_b h^2}{0.024}\right)^{-0.028}$$

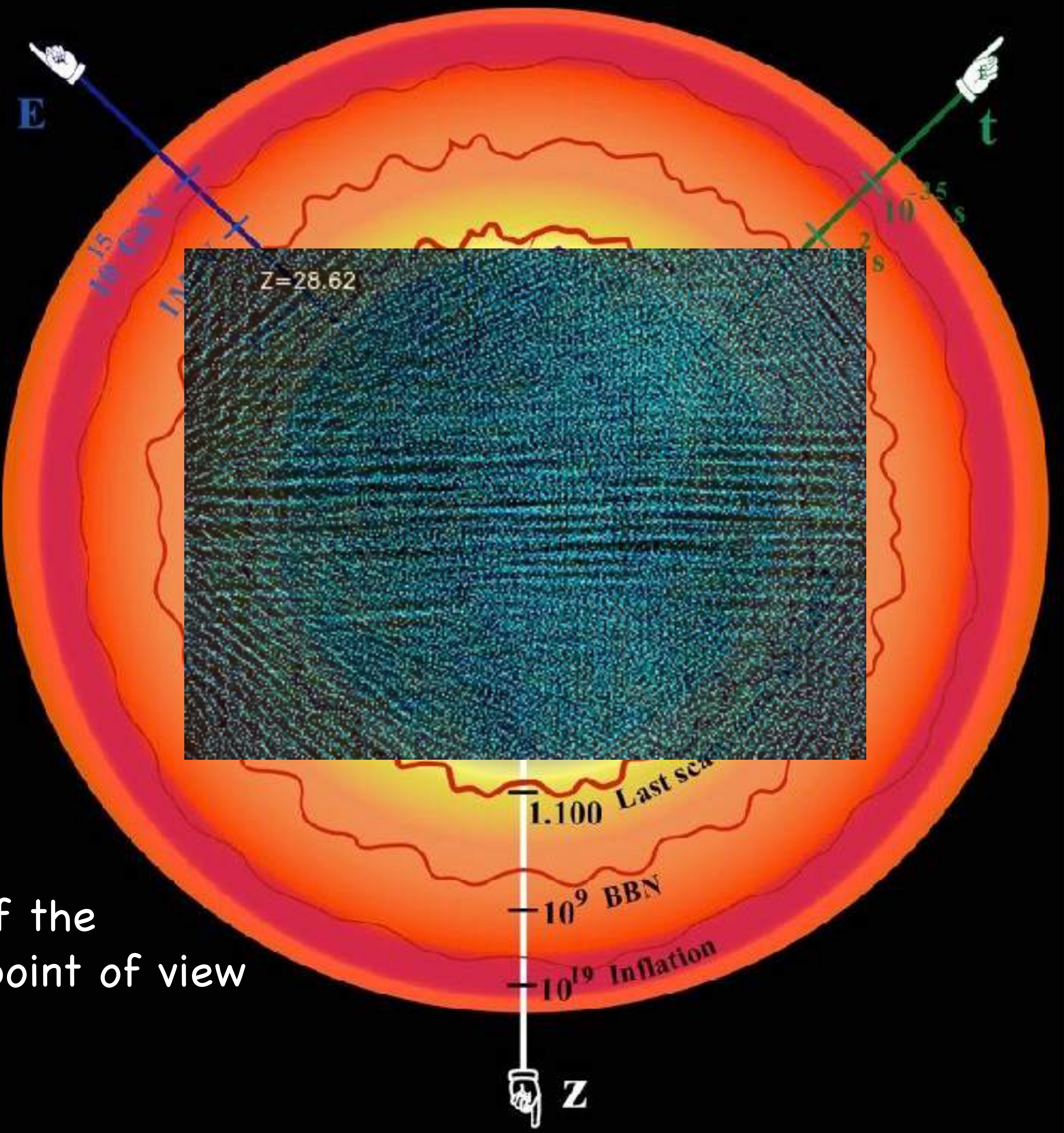
Hu 2005

Width of the Surface of Last Scattering, as observed today:



- The CMB is really a snapshot of an "instant": a picture of a spherical shell of radius R_{SLS}, when the Universe was 400,000 yrs old


Intensity [MJy/sr]
FIRAS data with 400σ errorbars
2.725 K Blackbody
T=2.725
ν [/cm]
Wavelength [mm]
Intensity [MJy/sr]
FIRAS data with 400σ errorbars
2.725 K Blackbody
T=2.726
ν [/cm]
Wavelength [mm]
Intensity [MJy/sr]
FIRAS data with 400σ errorbars
2.725 K Blackbody
T=2.724
ν [/cm]
Wavelength [mm]
Intensity [MJy/sr]
FIRAS data with 400σ errorbars
2.725 K Blackbody
T=2.725

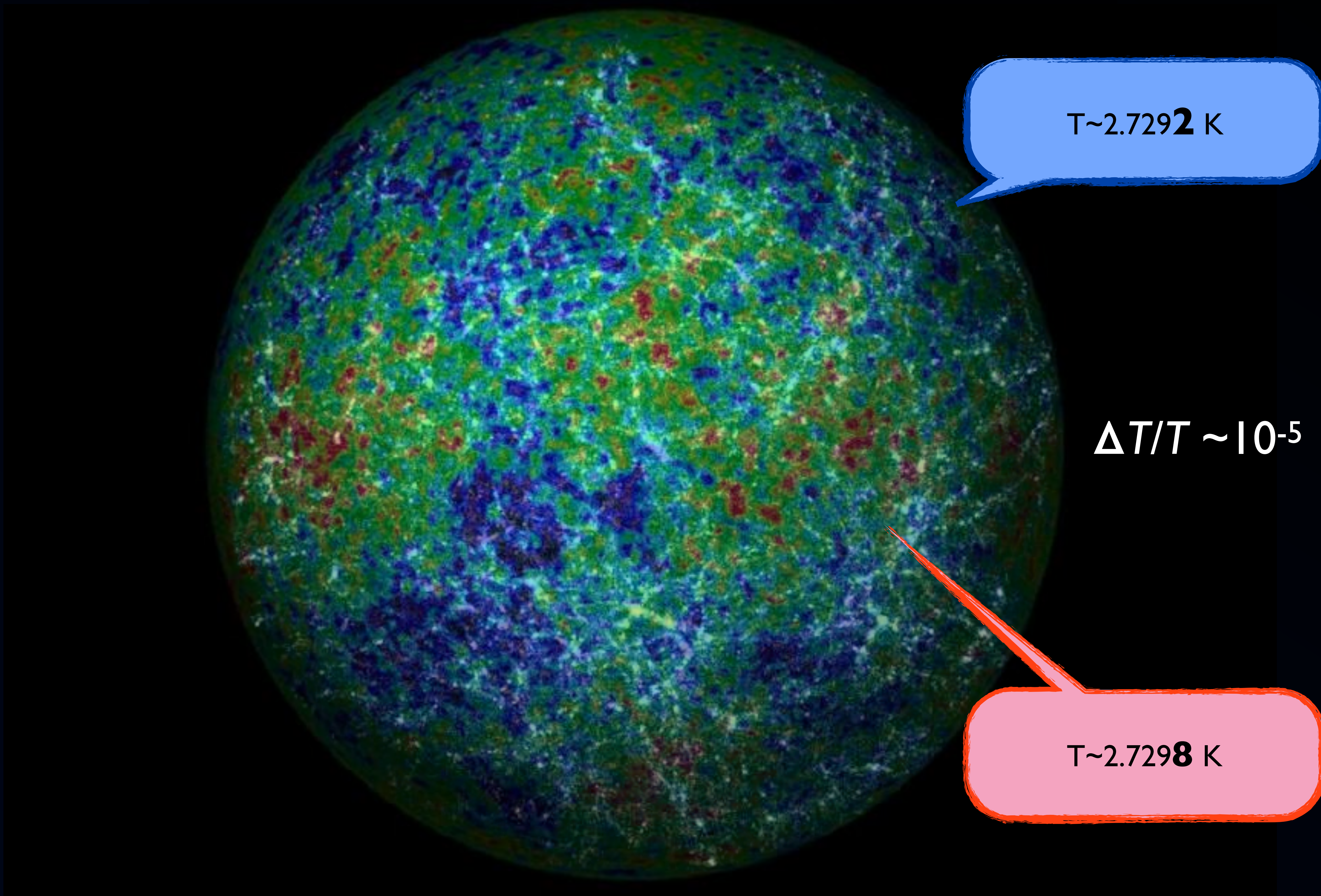


Causal description of the
Universe, from our point of view

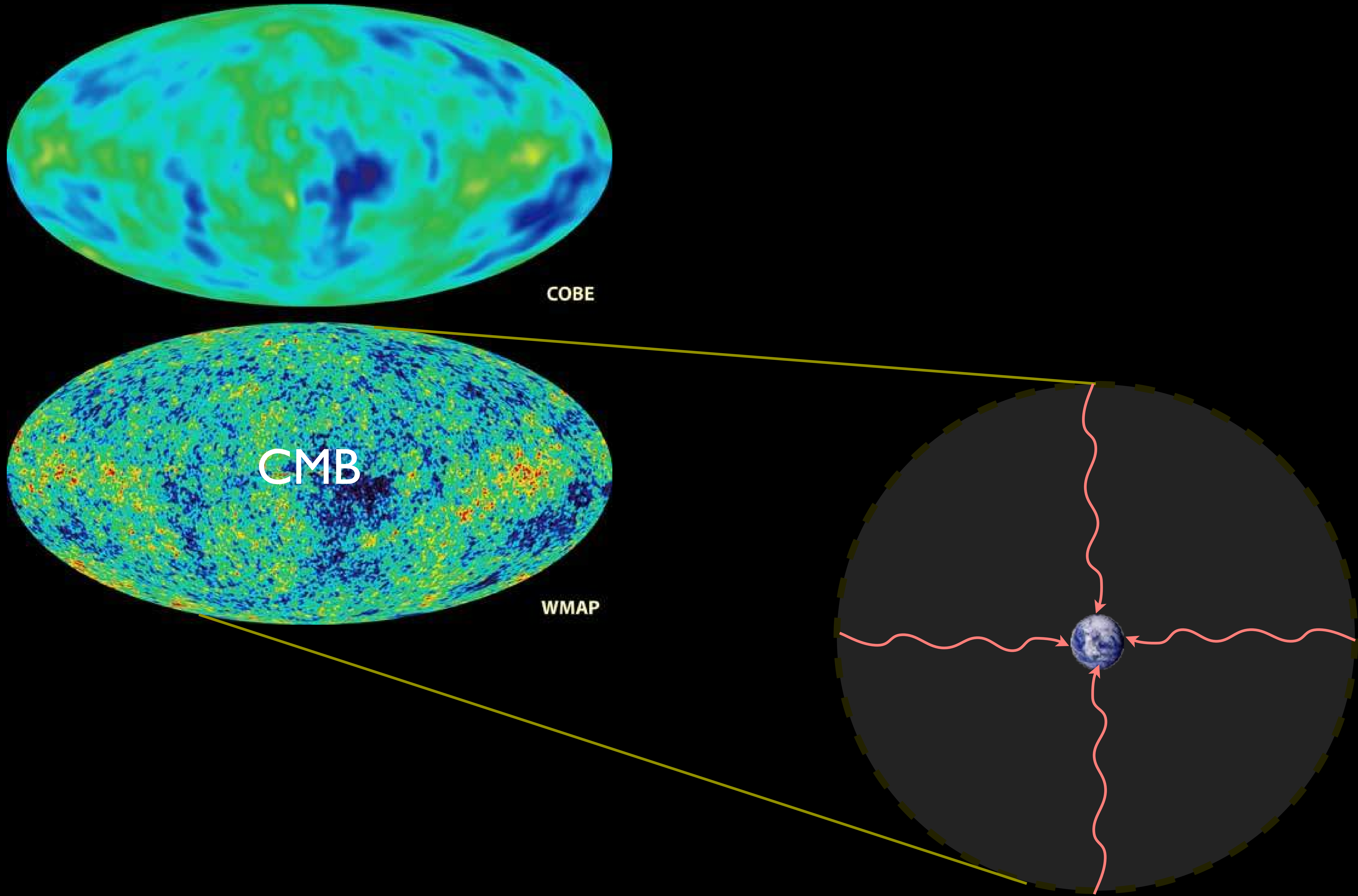
Illustris simulation

Cosmic Microwave Background:

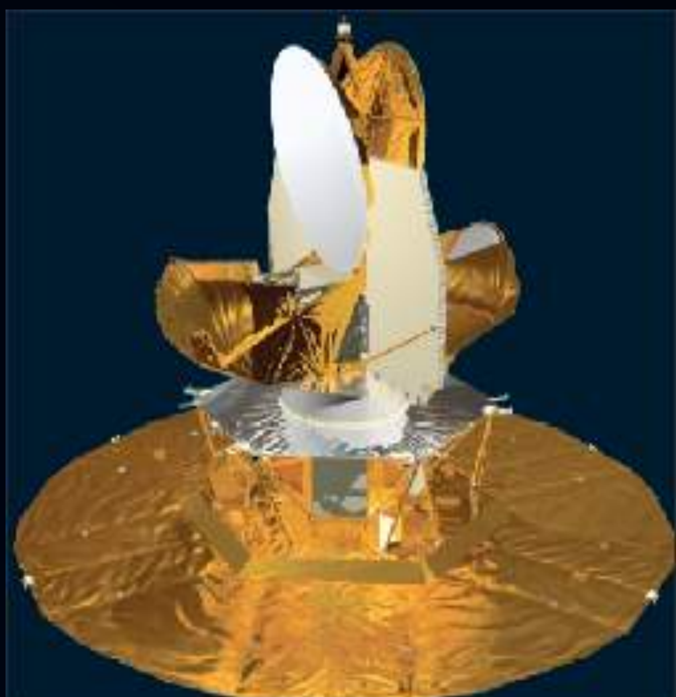
initial conditions to build the structures of the Universe

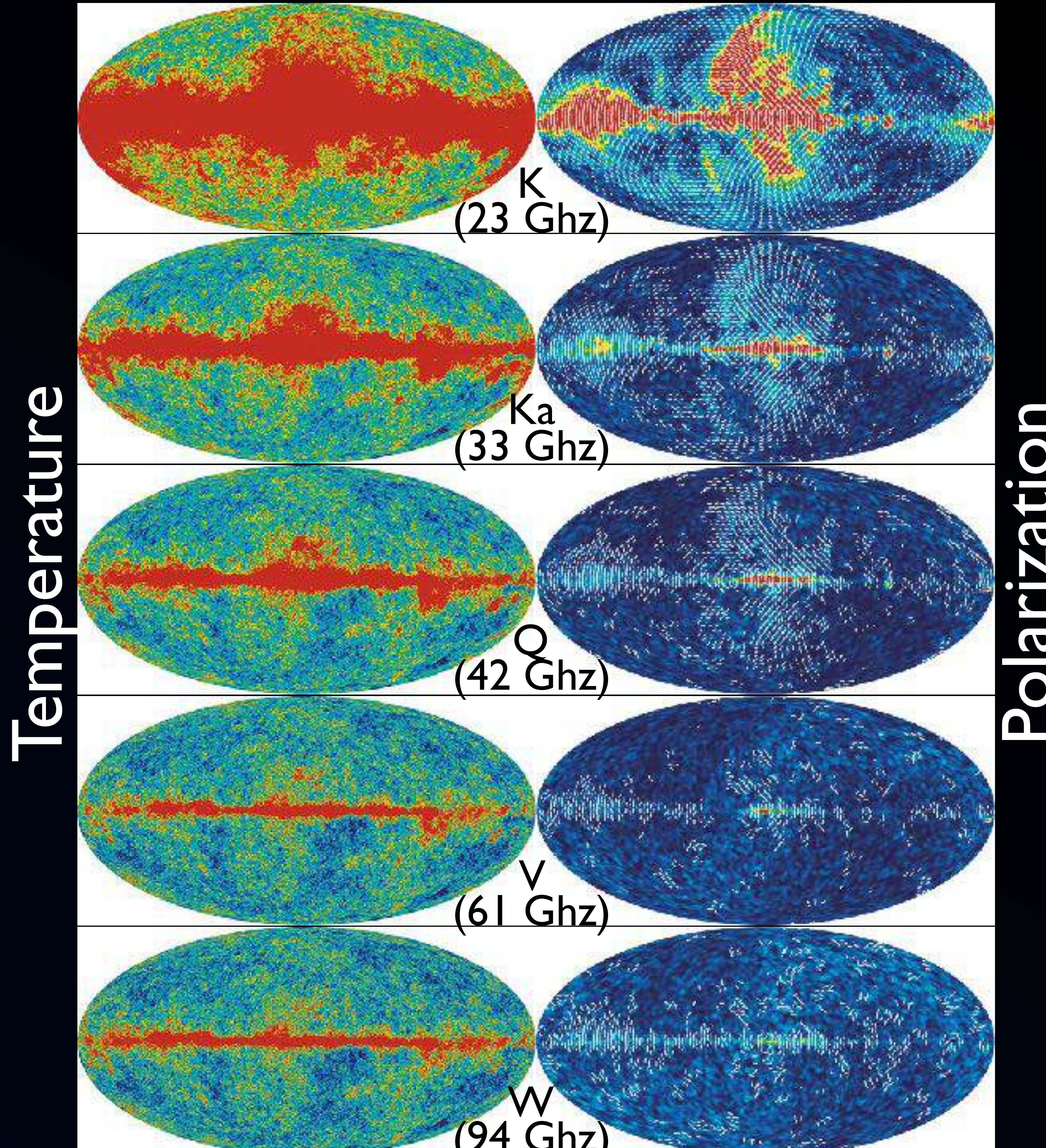


$\Delta T/T \sim 10^{-5}$

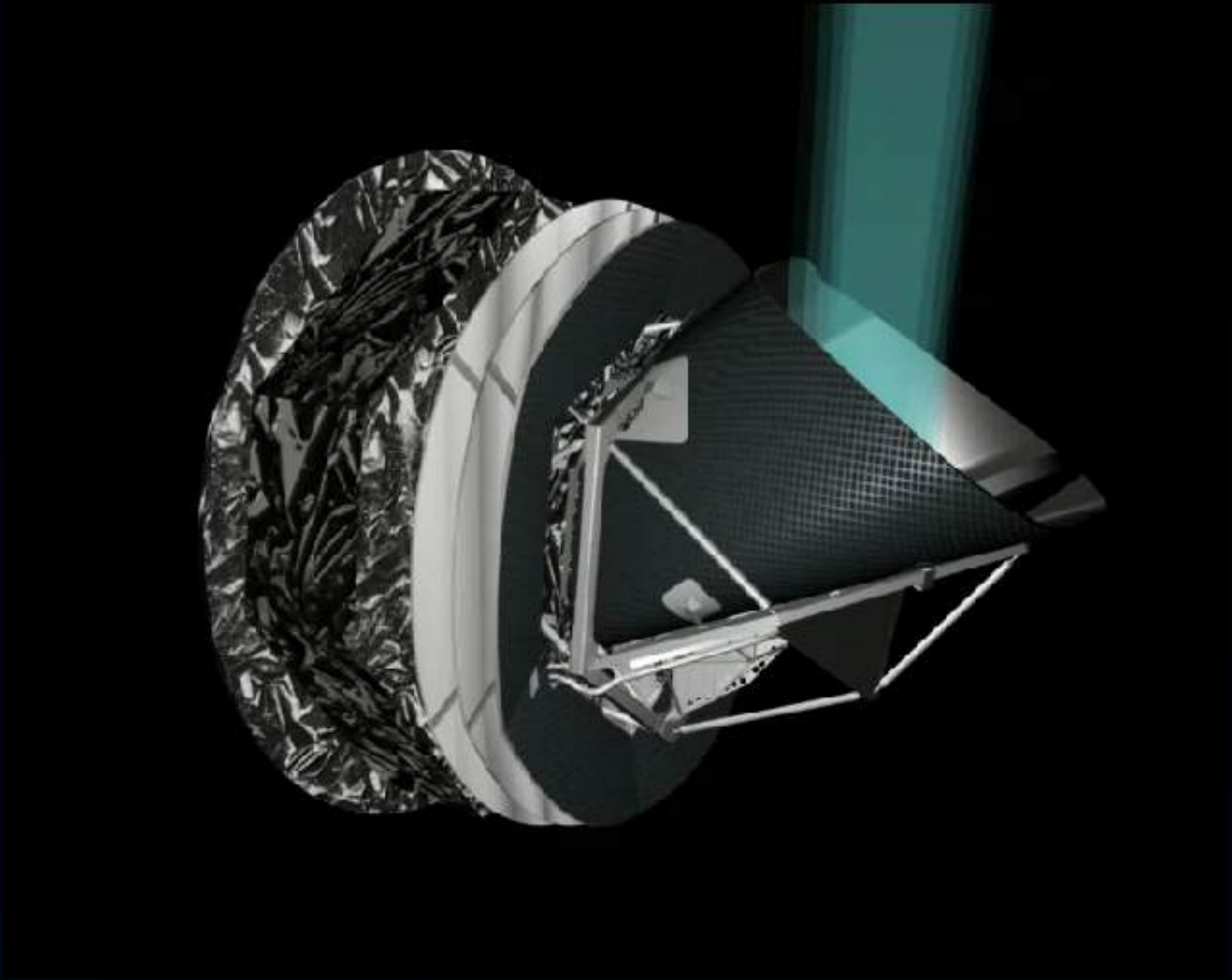

COBE
CMB
WMAP

WMAP: 2003-2012

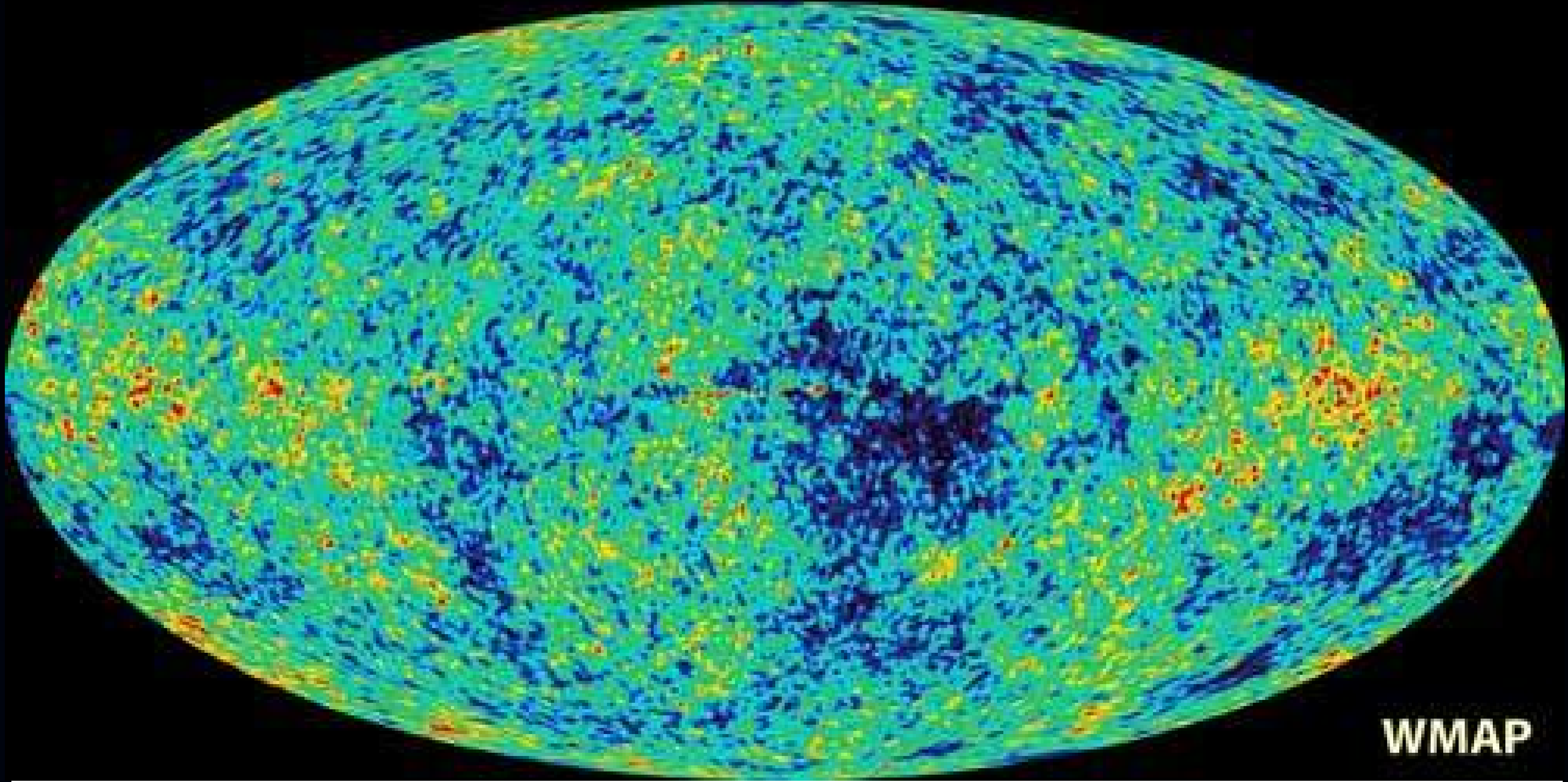


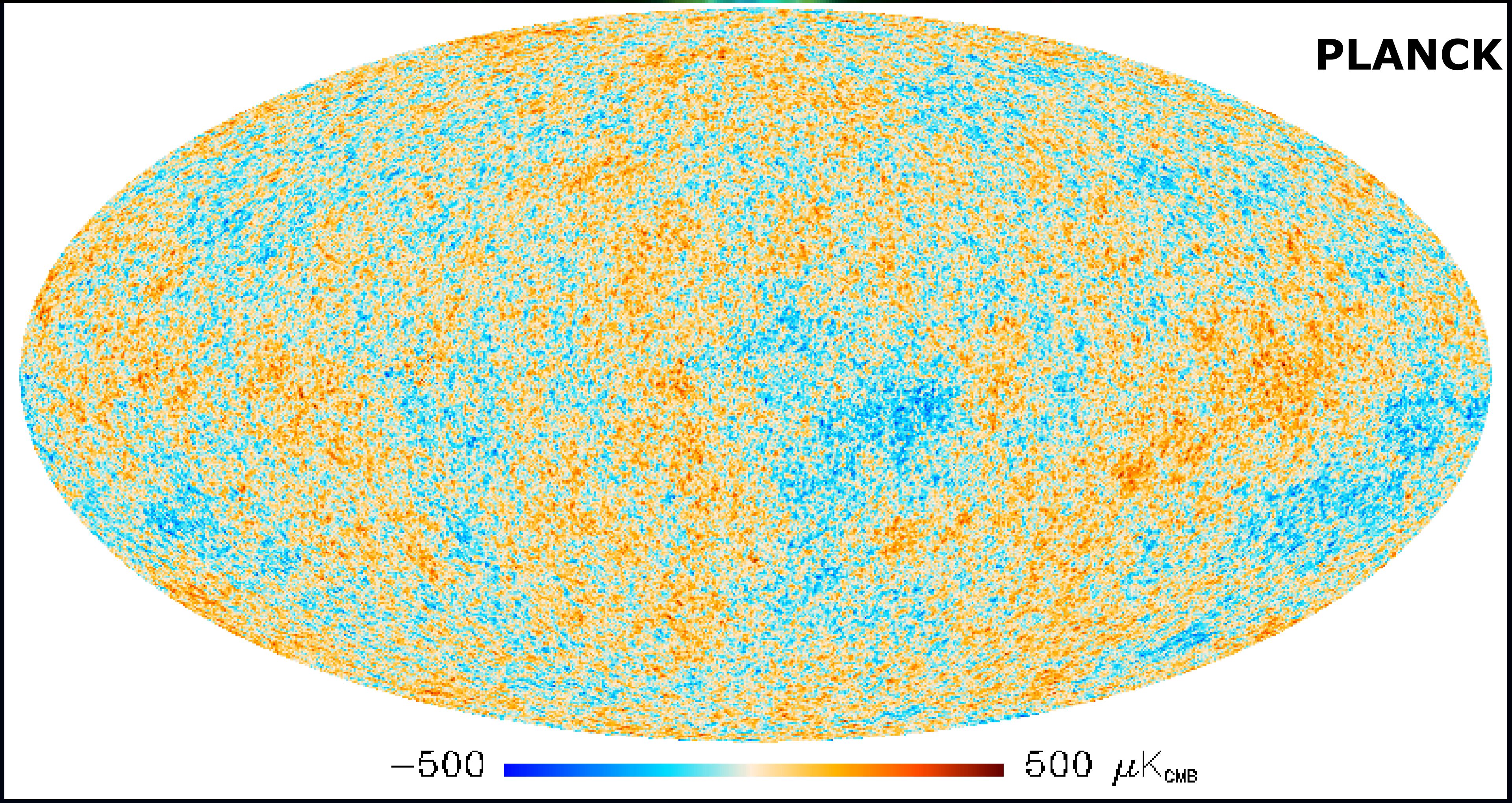


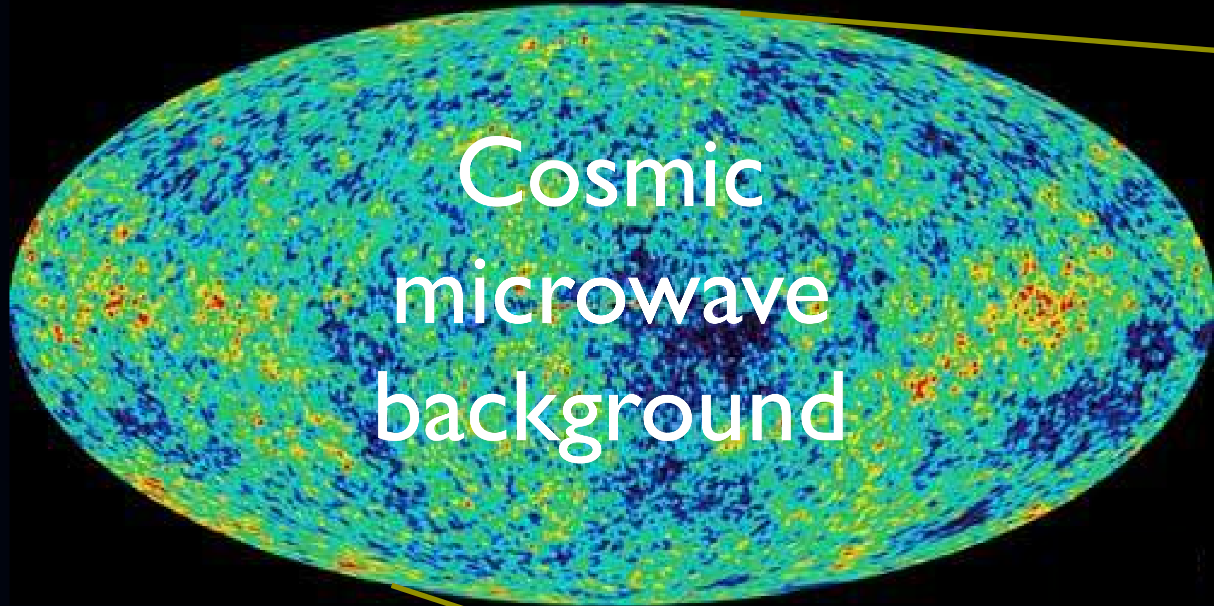
PLANCK

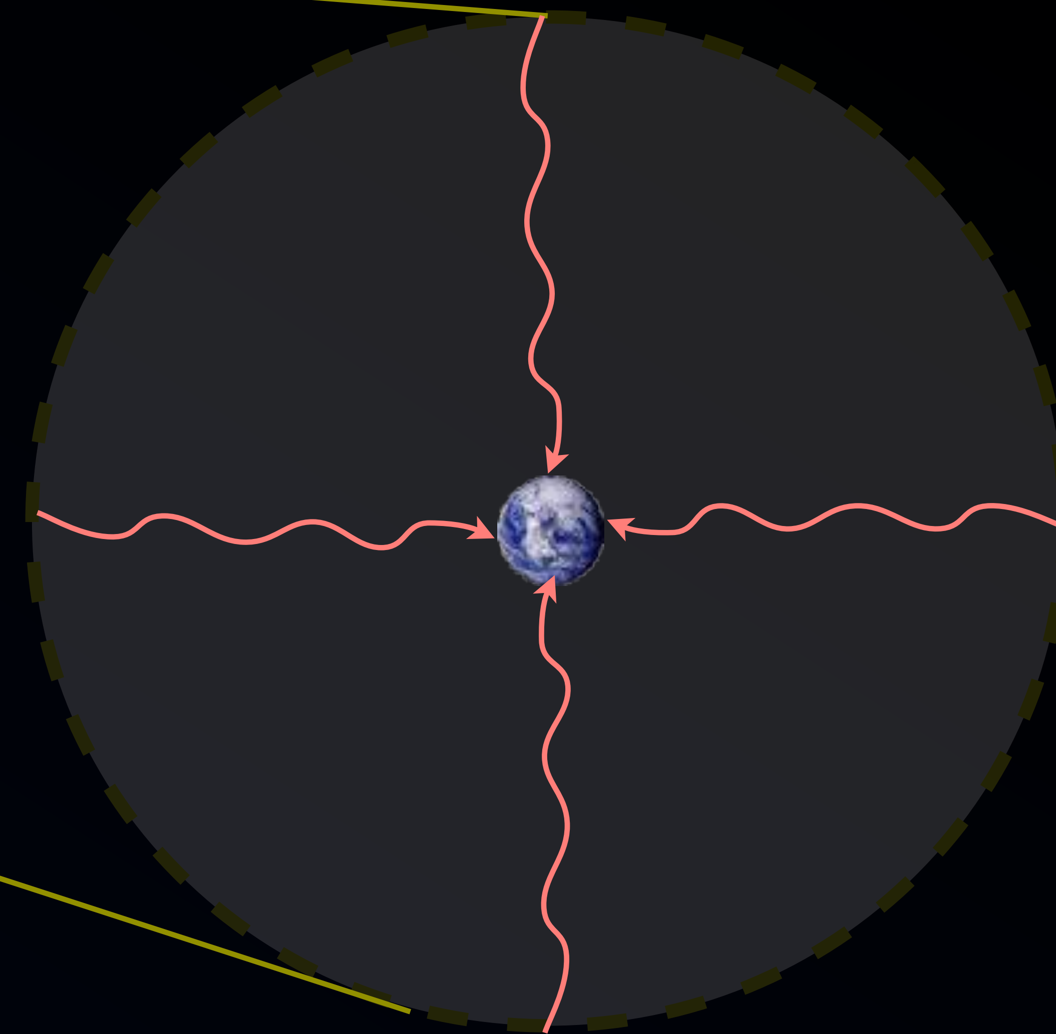


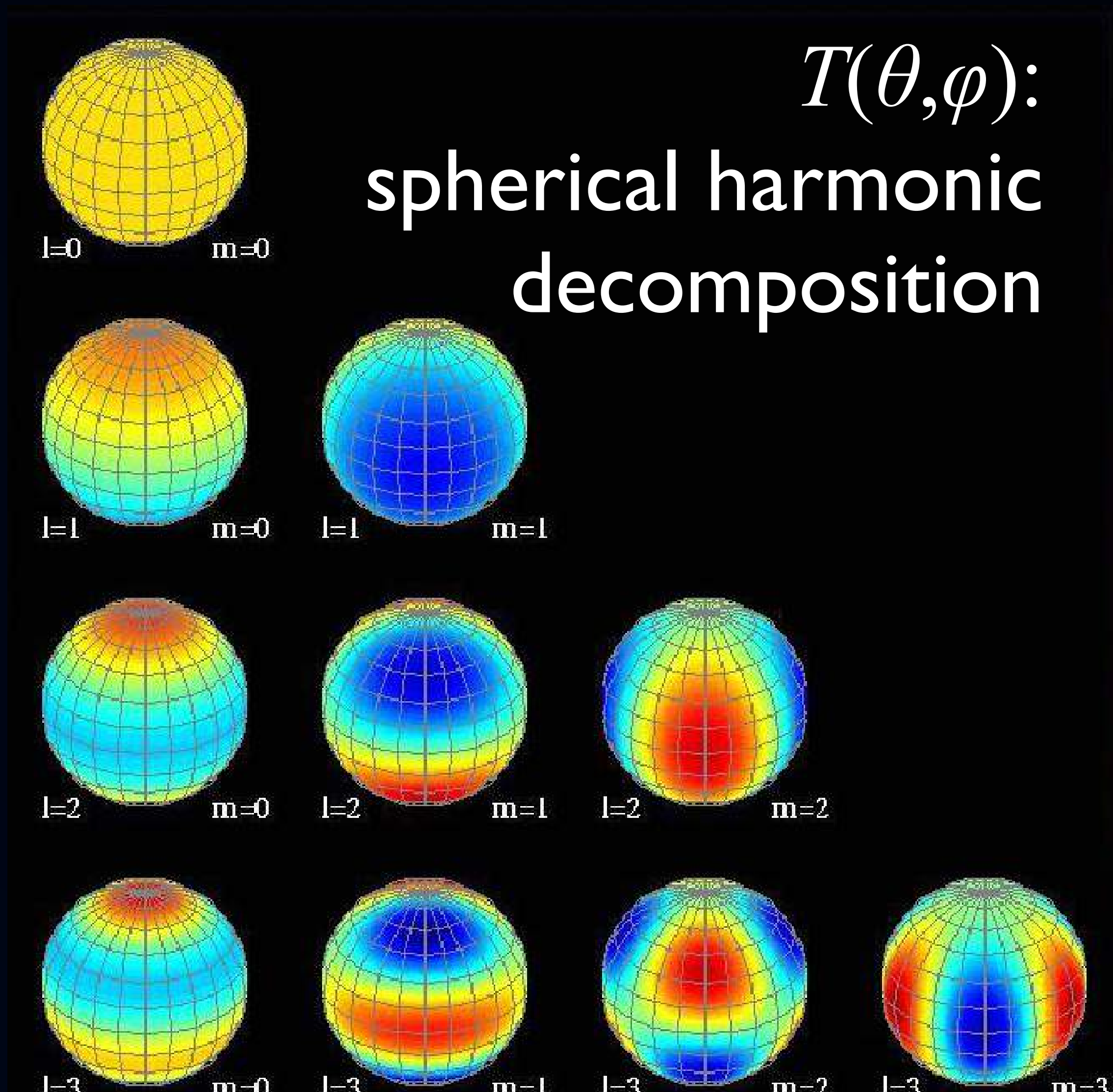
Hu & White


WMAP


PLANCK
−500
500 μK_CMB





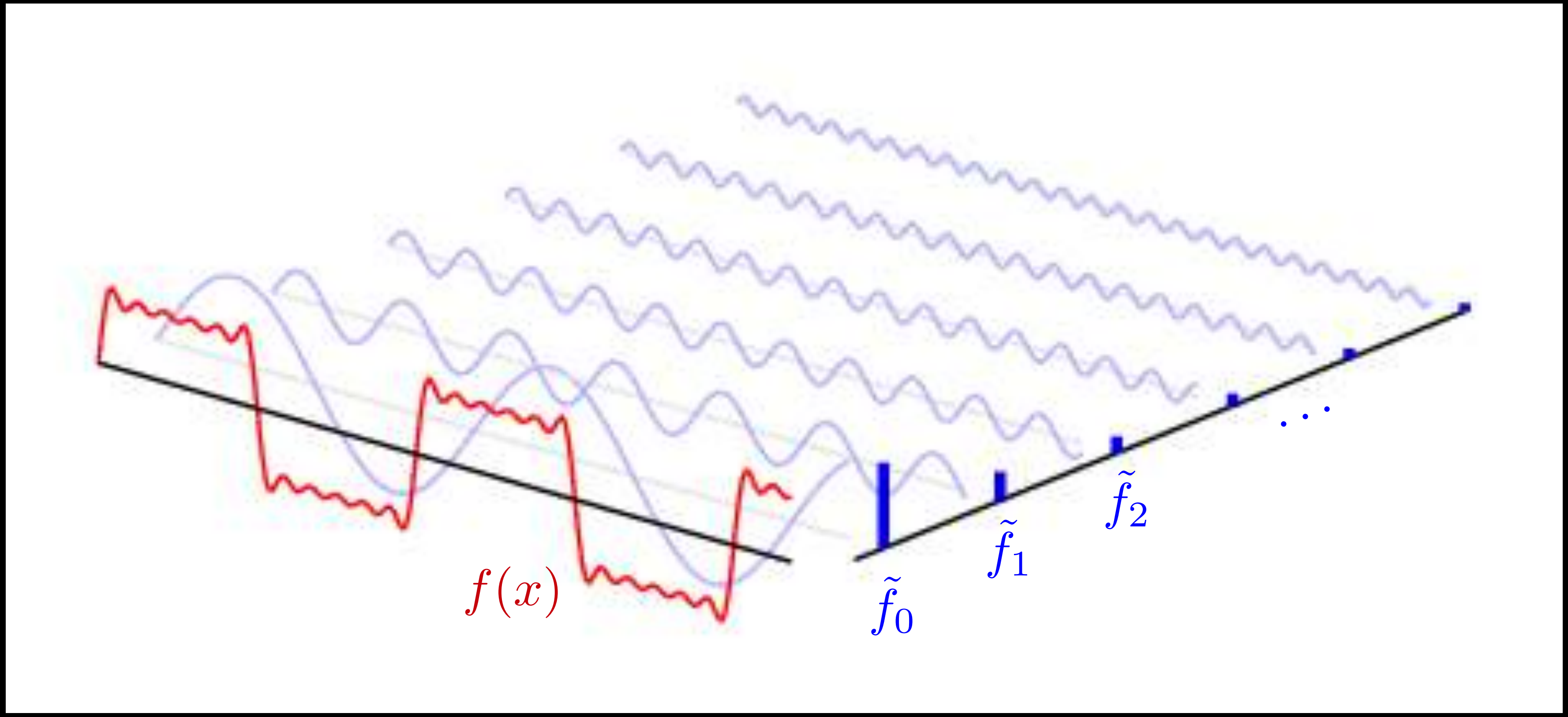


$$\delta T(\theta,\varphi) = \sum_{\ell,m} a_{\ell m} Y_\ell^m(\theta,\varphi)$$

$$C_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} \left| a_{\ell m} \right|^2$$

Spherical Harmonics and Fourier Transform

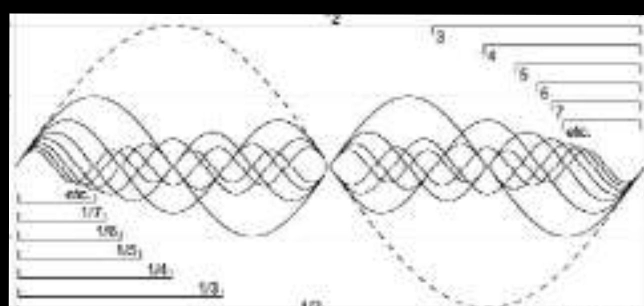
Decomposition into Fourier modes (*Fourier Transform*)



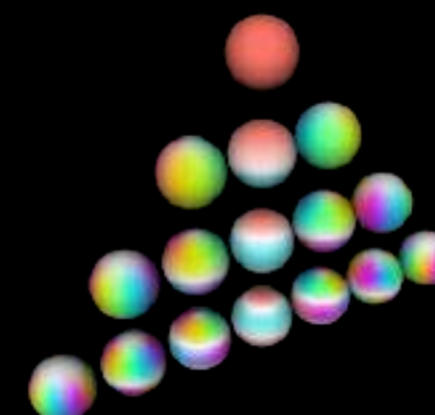
$$f(x) = \sum_k \tilde{f}_k \, e^{ikx}$$

Spherical Harmonics and Fourier Transform

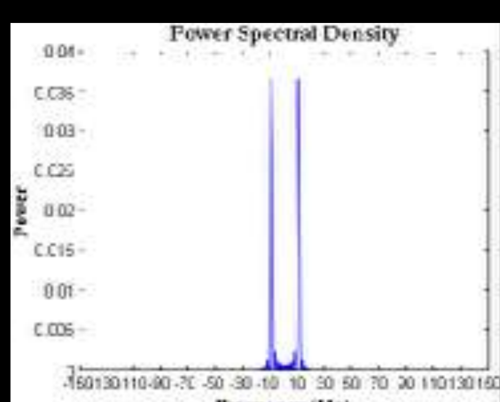
$$f(x,y) \quad \longleftrightarrow \quad f(\theta,\phi)$$



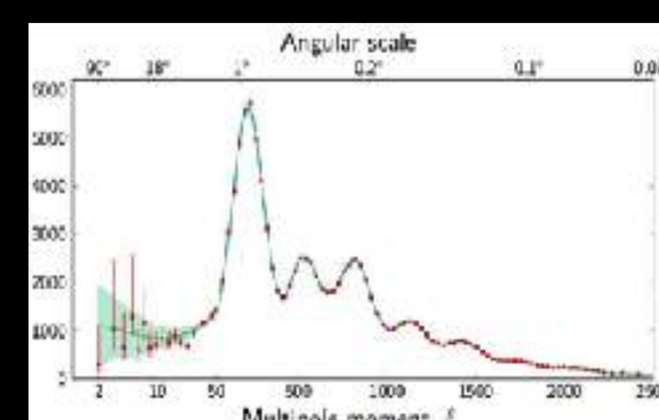
$$e^{i(k_x x + k_y y)} \quad \longleftrightarrow \quad Y_{\ell m}(\theta,\phi)$$



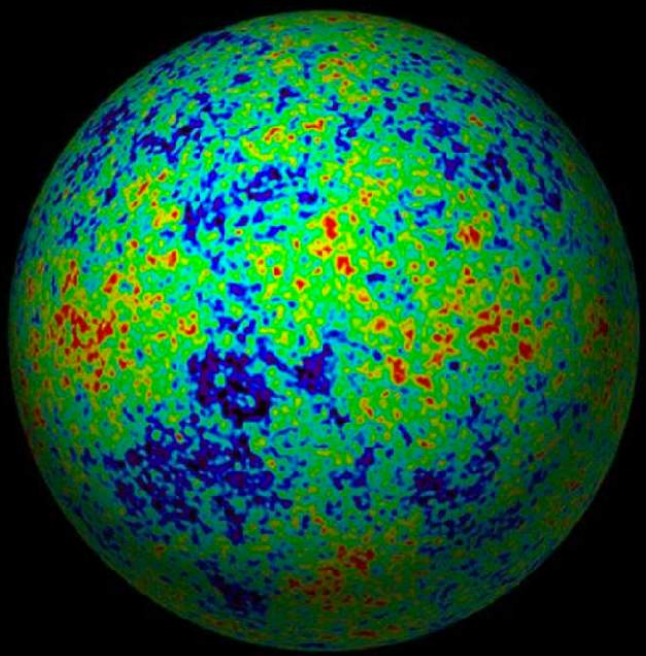
$$f(x,y) = \sum_{\vec{k}} \tilde{f}_{\vec{k}}\, e^{i(k_x x + k_y y)} \quad \longleftrightarrow \quad f(\theta,\phi) = \sum_{m=-\ell}^{\ell} \sum_{\ell=0}^{\infty} a_{\ell m} Y_{\ell m}(\theta,\phi)$$



$$P_k = \left|\tilde{f}_{\vec{k}}\right|^2 \quad \longleftrightarrow \quad C_\ell = \langle |a_{\ell m}|^2 \rangle$$



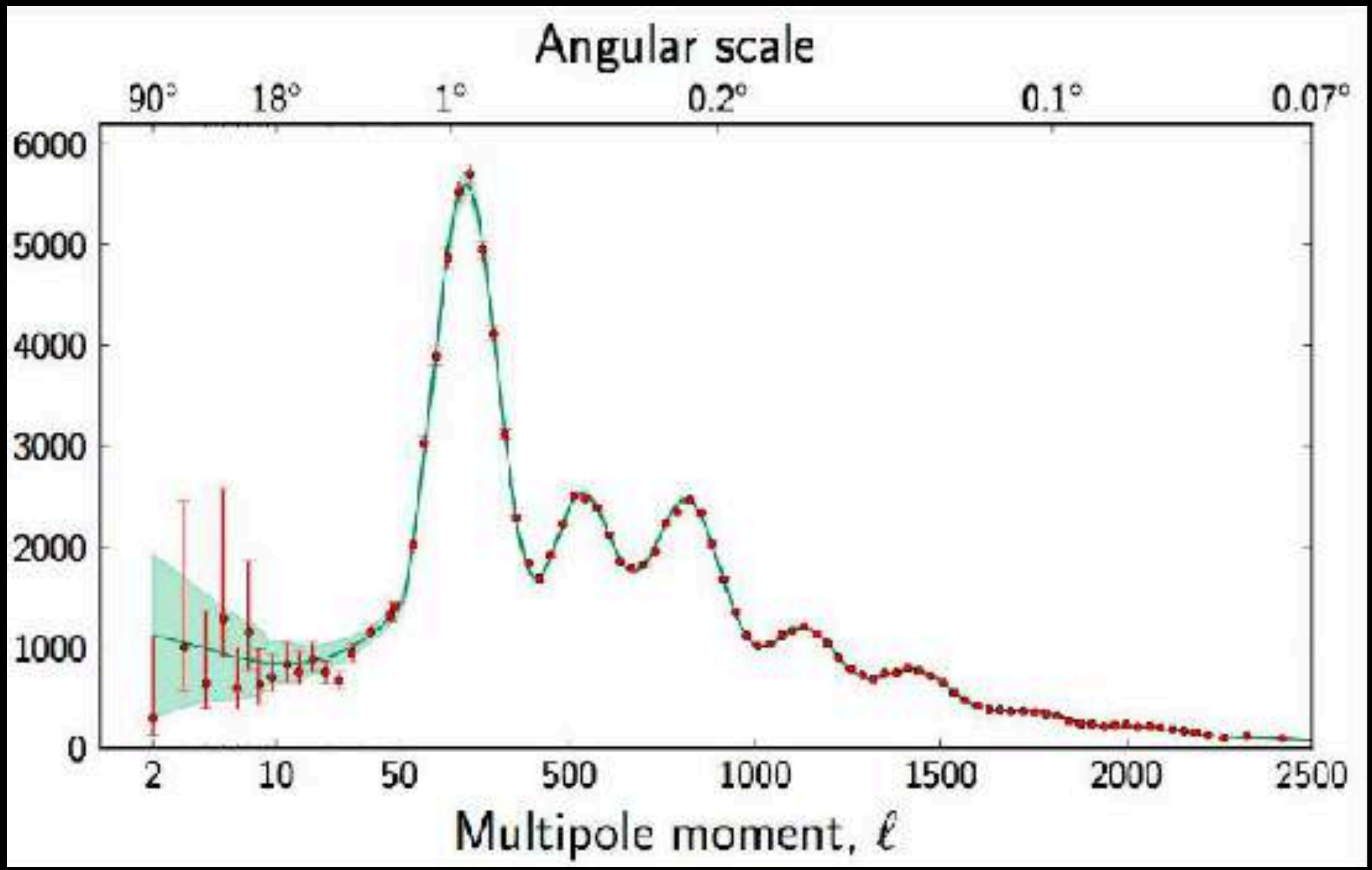
Angular power spectrum of the CMB



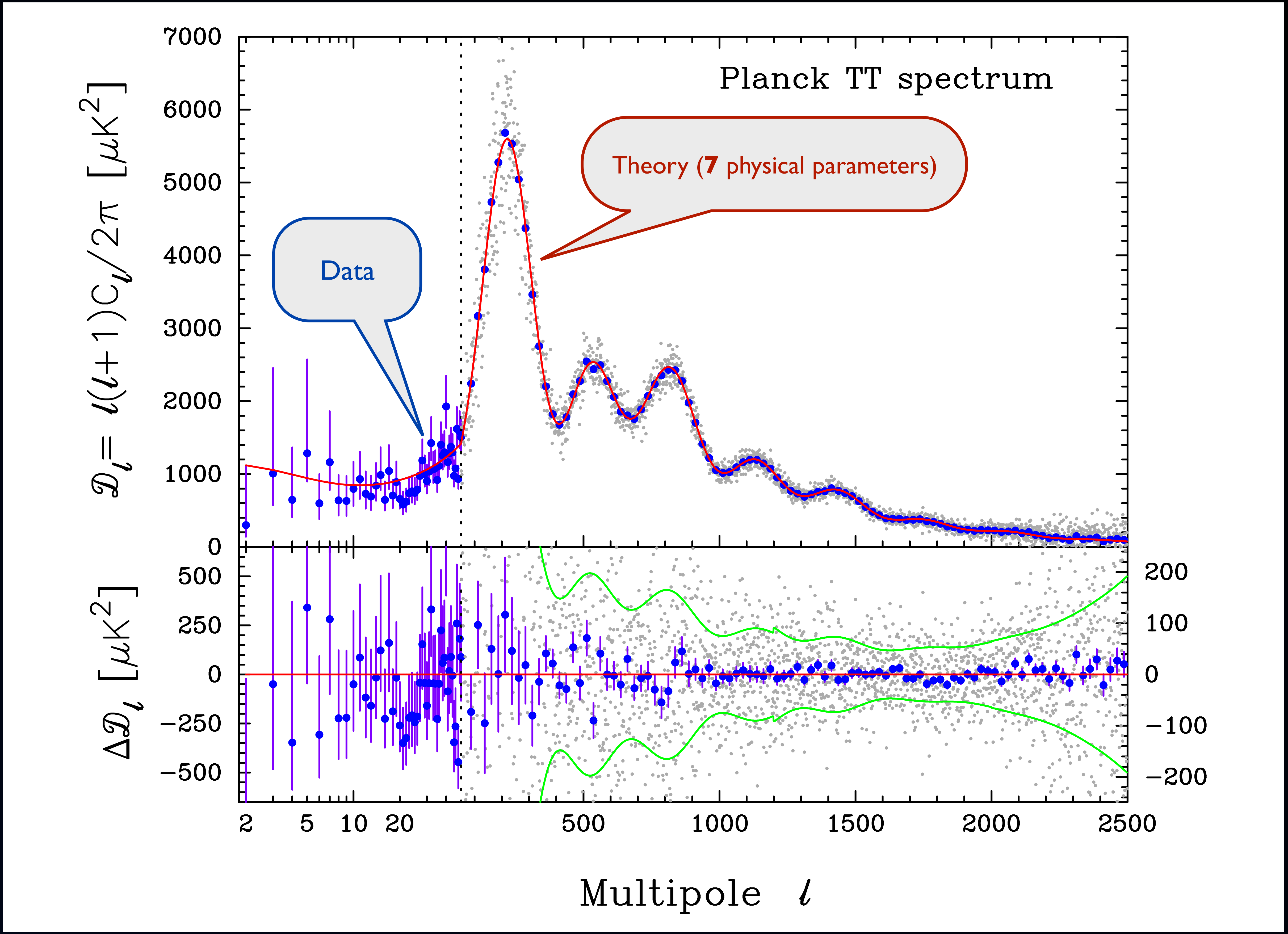
NASA, WMAP

$$f(\theta, \phi) = \sum_{m=-\ell}^{\ell} \sum_{\ell=0}^{\infty} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

$$C_\ell = \langle |a_{\ell m}|^2 \rangle$$



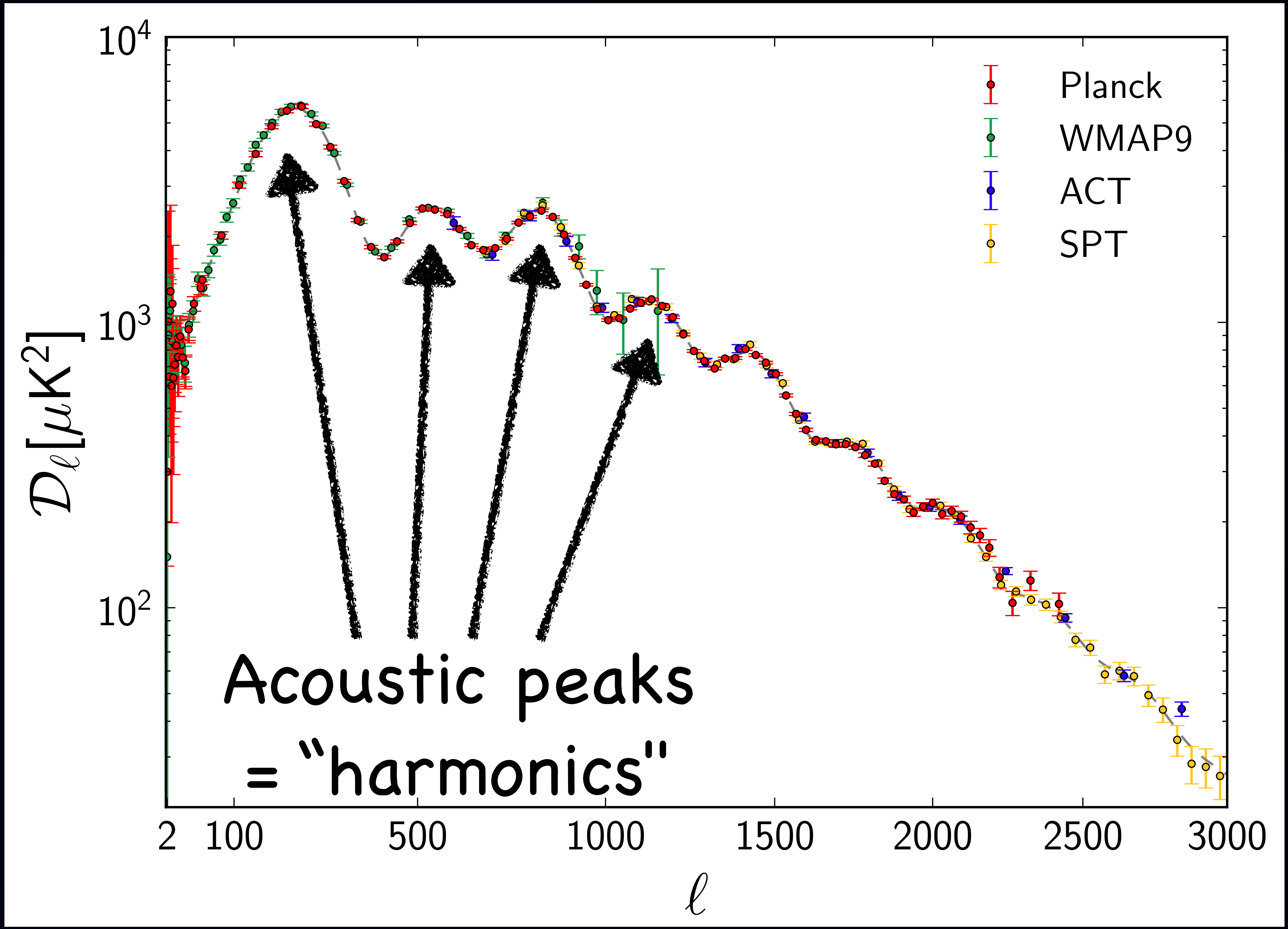
Teory *v.* data (temperature)



CMB:
“Precision cosmology”

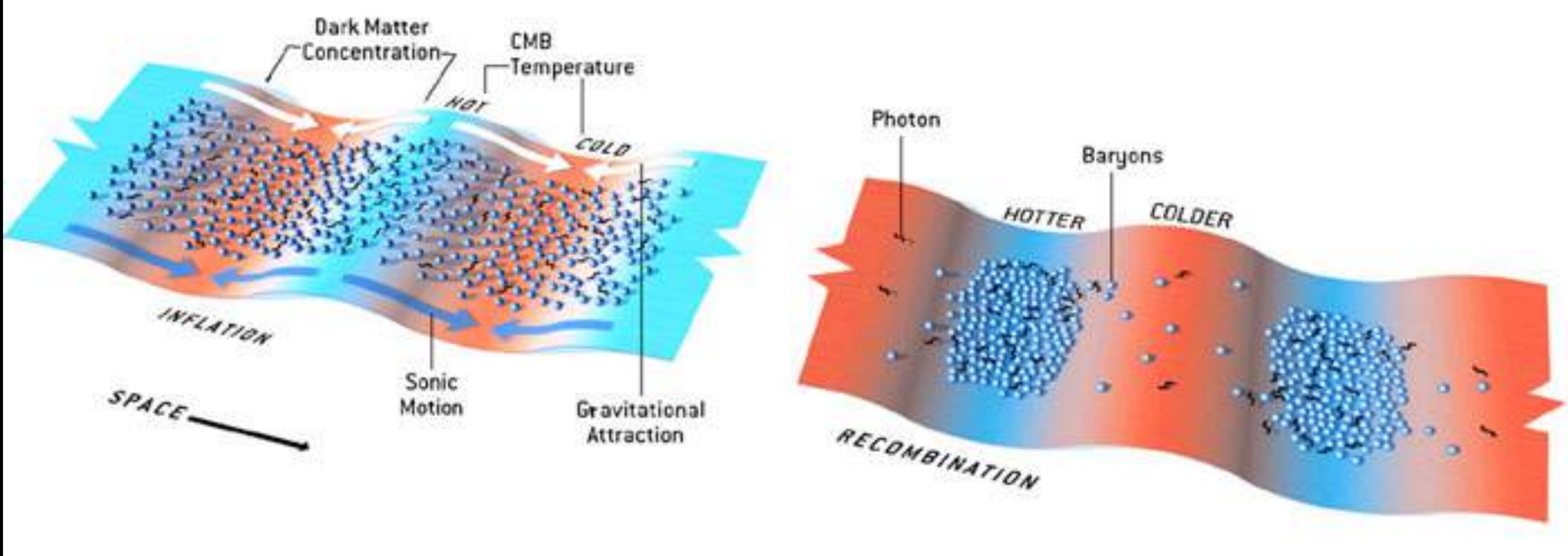
	Planck (CMB+lensing)		*Planck*+WP+highL+BAO	
Parameter	Best fit	68 % limits	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025
Ω_Λ	0.6964	0.693 ± 0.019	0.6914	0.692 ± 0.010
σ_8	0.8285	0.823 ± 0.018	0.8288	0.826 ± 0.012
z_{re}	11.45	$10.8^{+3.1}_{-2.5}$	11.52	11.3 ± 1.1
H_0	68.14	67.9 ± 1.5	67.77	67.80 ± 0.77
Age/Gyr	13.784	13.796 ± 0.058	13.7965	13.798 ± 0.037
$100\theta_*$	1.04164	1.04156 ± 0.00066	1.04163	1.04162 ± 0.00056
r_{drag}	147.74	147.70 ± 0.63	147.611	147.68 ± 0.45
$r_{drag}/D_V(0.57)$	0.07207	0.0719 ± 0.0011		

Acoustic waves of radiation, baryonic matter (and dark matter)



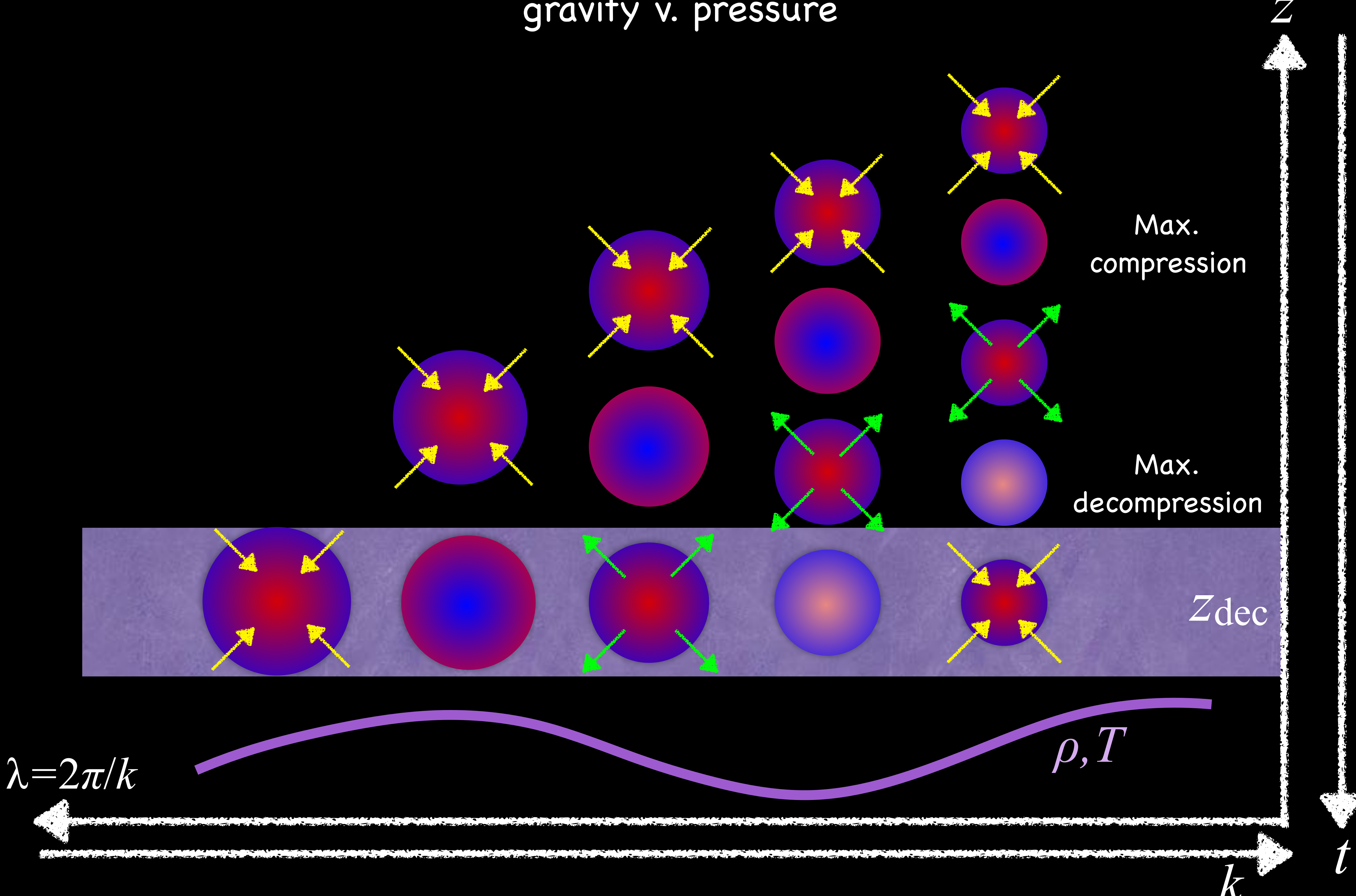
Physics of the CMB: pressure waves ("acoustic waves")

Physical processes around decoupling: pressure waves ("acoustic waves")



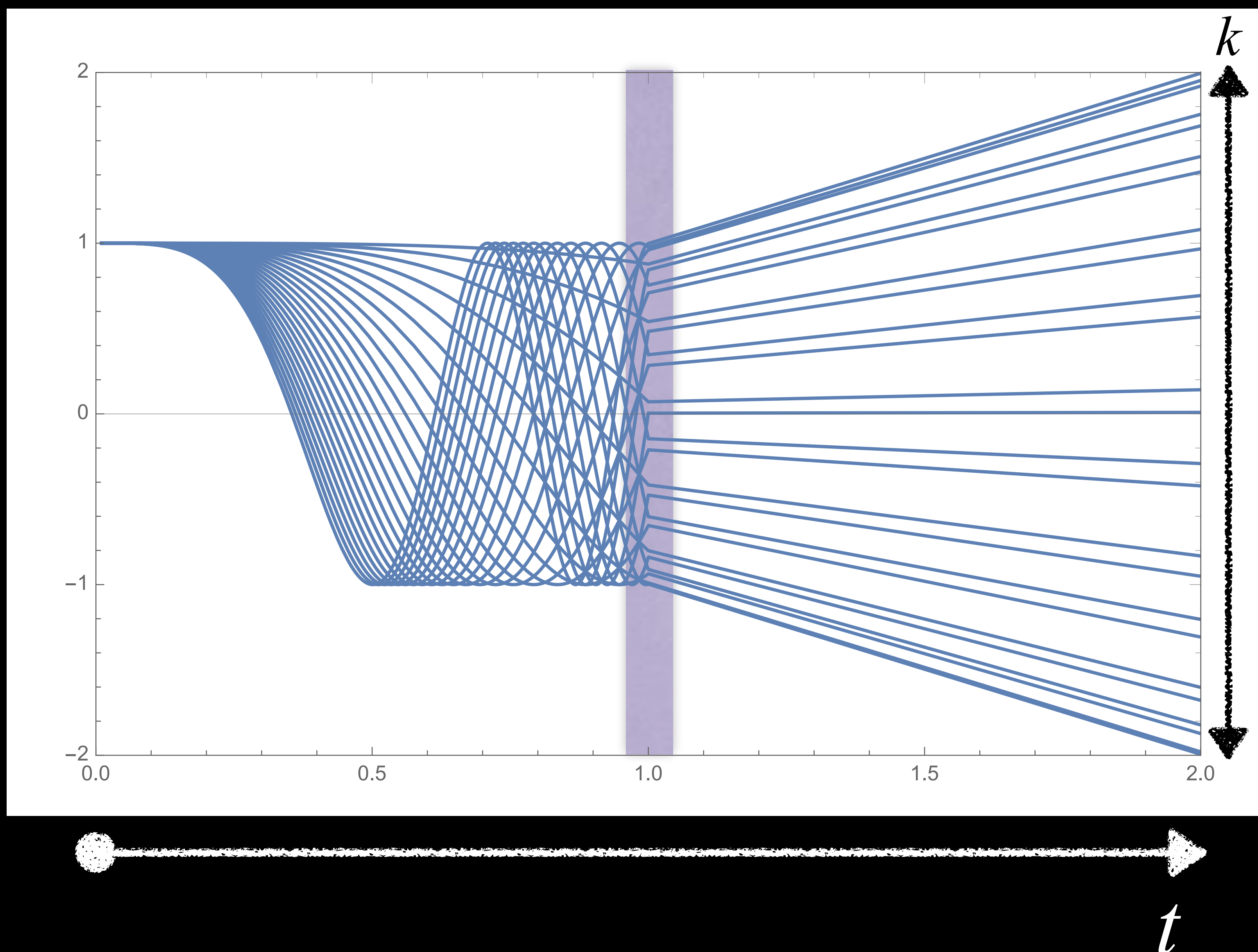
W. Hu - background.uchicago.edu

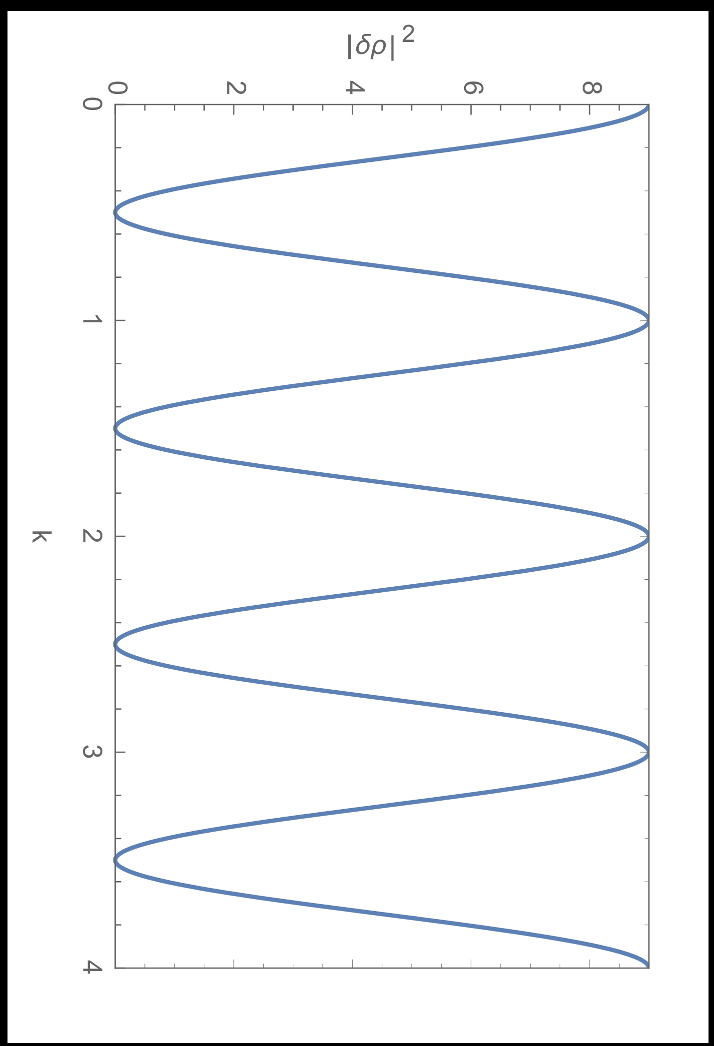
Acoustic waves of the photon+baryon+dark matter fluid: gravity v. pressure



When the photons decouple from matter, the density fluctuations (of baryons + DM, mostly) lose the pressure support and start evolving only according to gravity — growing with the scale factor:

$$\delta \sim a$$





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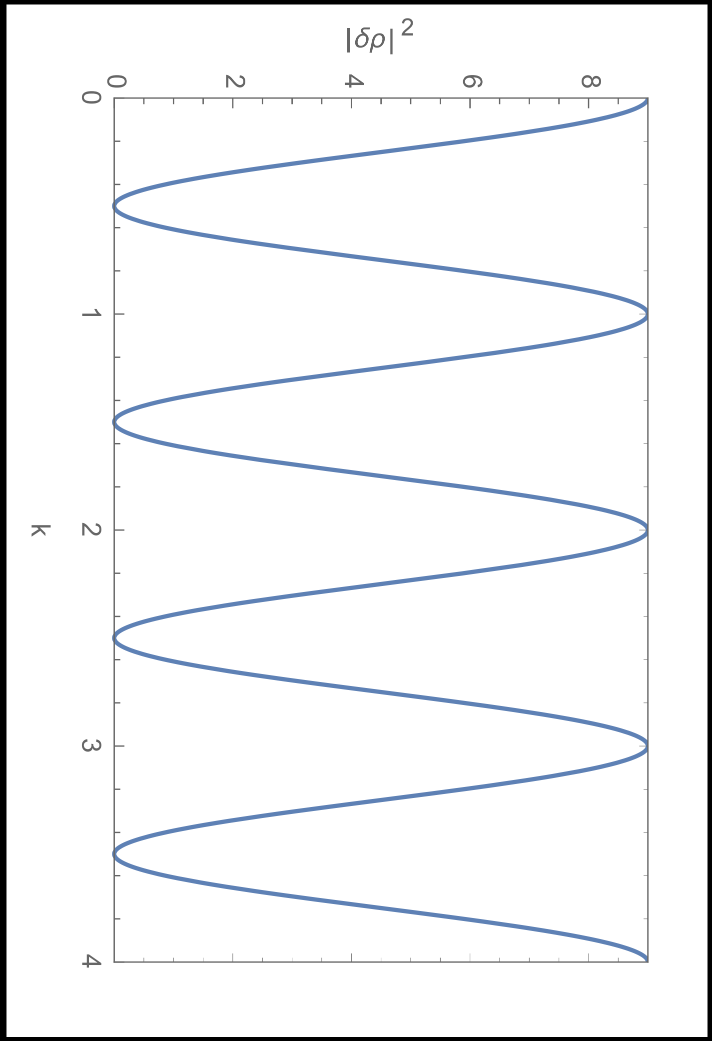
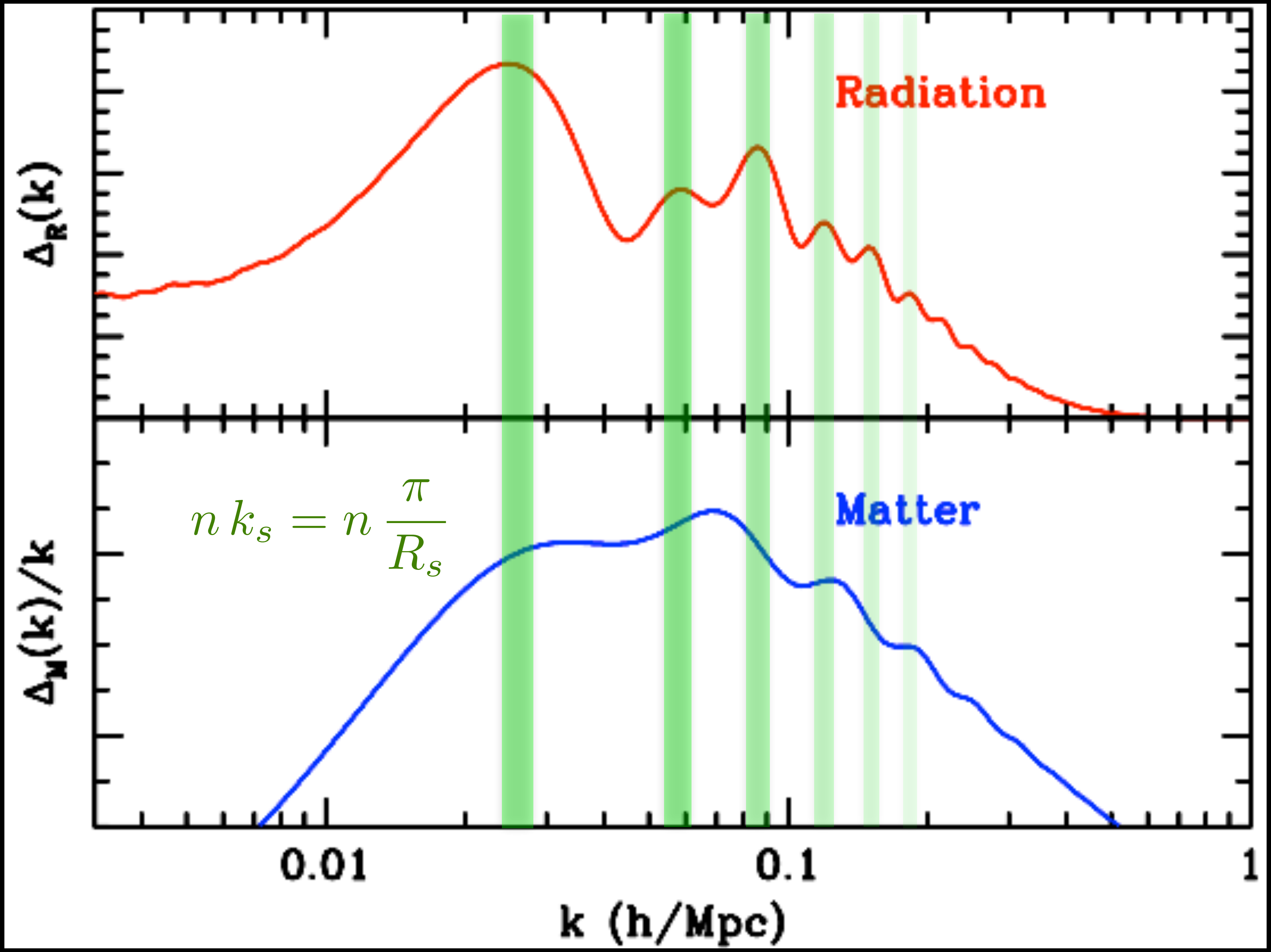
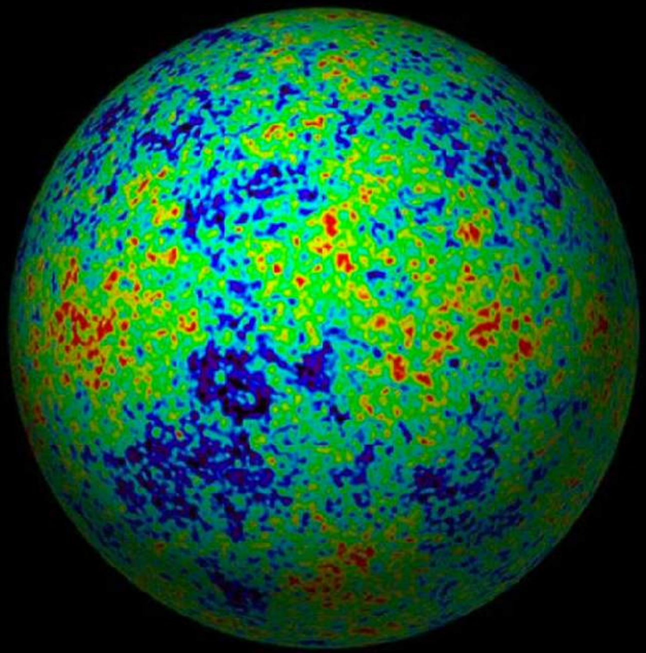


Acoustic waves of radiation, baryons and dark matter



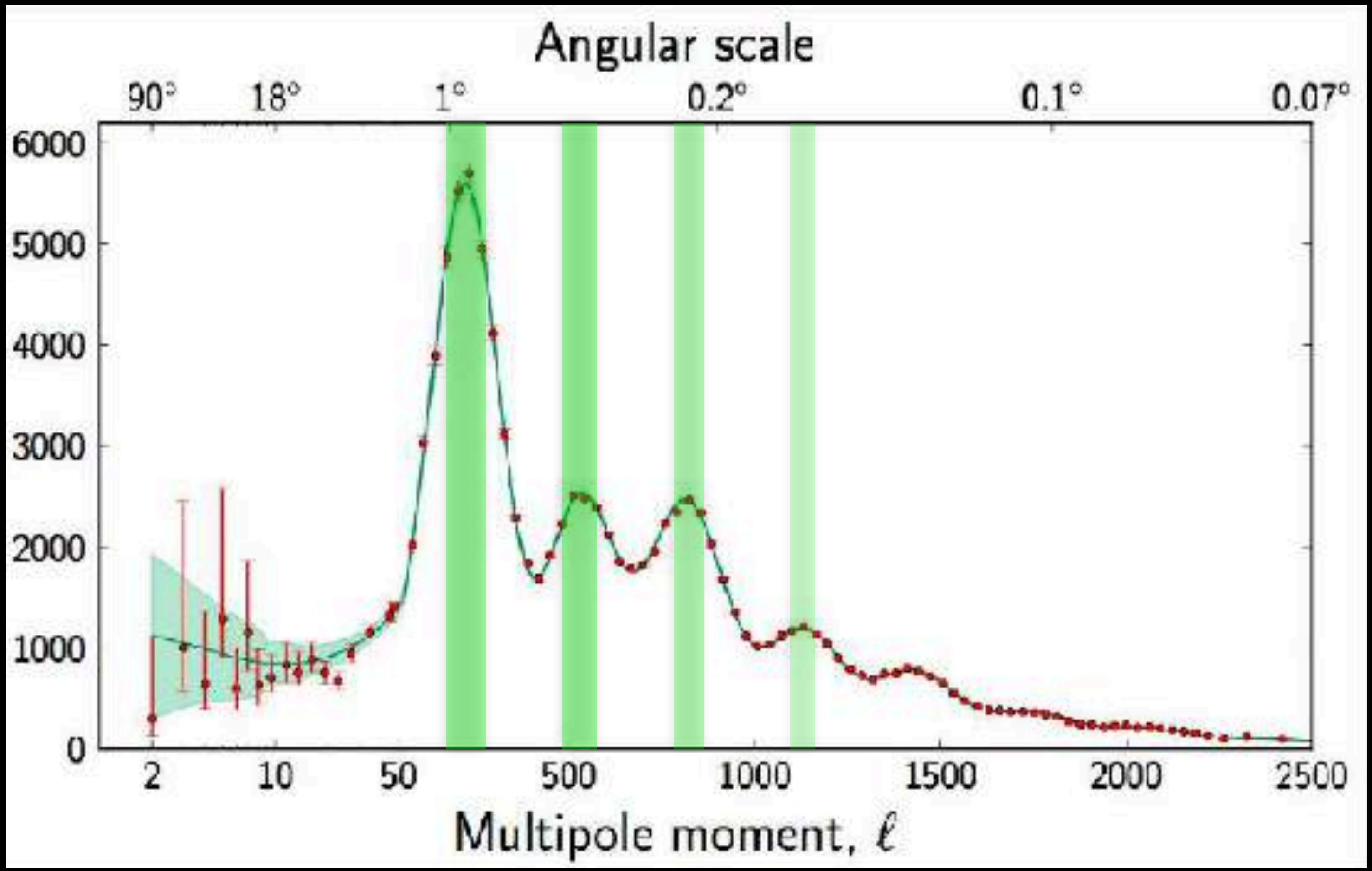
$$R_s = \int_0^{t_{dec}} dt\,\frac{c_s}{a(t)} = \int_0^{a_{dec}} da\,\frac{c_s}{H(a)\,a^2} = \int_{z_{dec}}^{\infty} dz\,\frac{c_s}{H(z)}$$

Angular power spectrum of the CMB

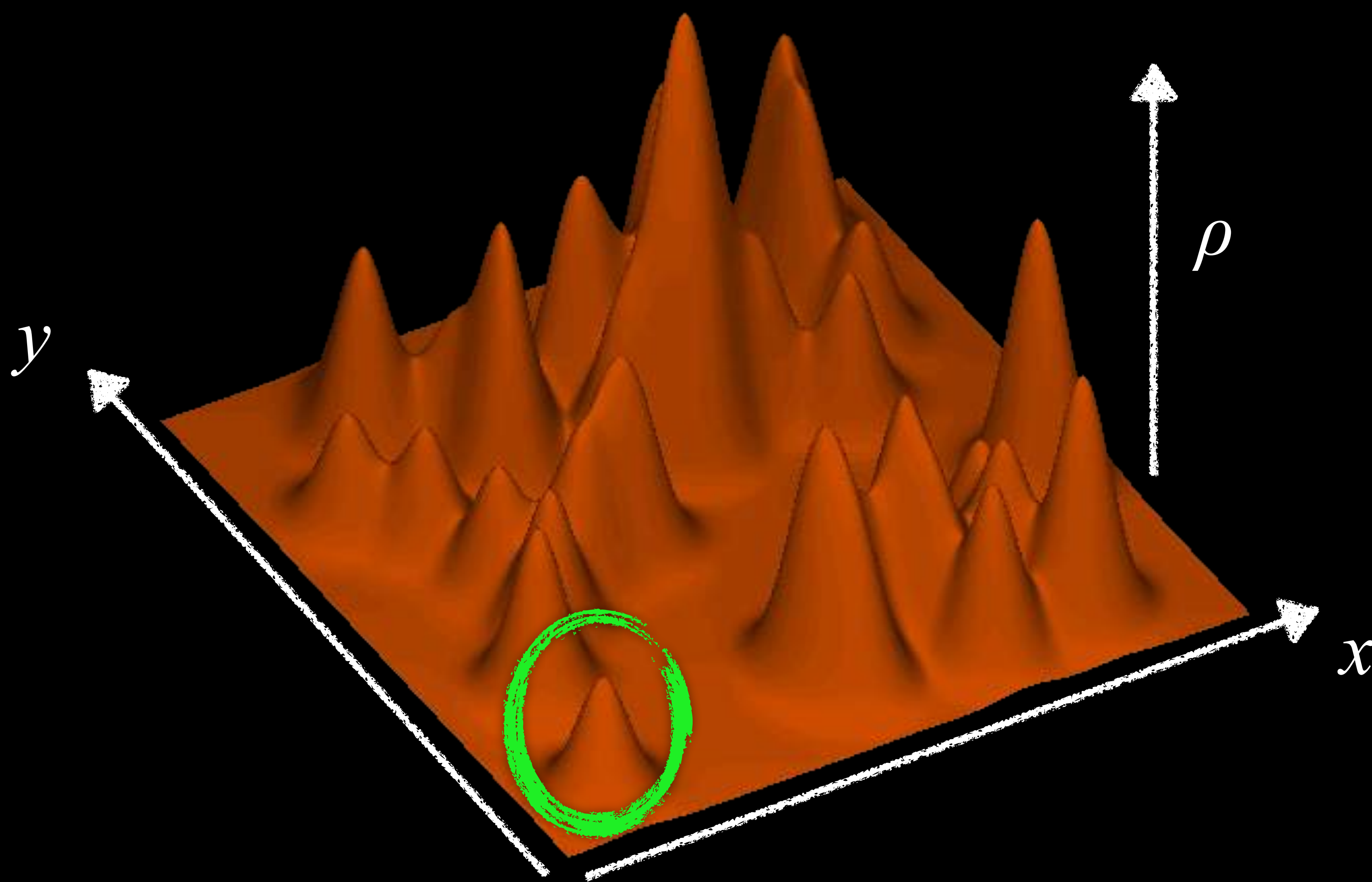


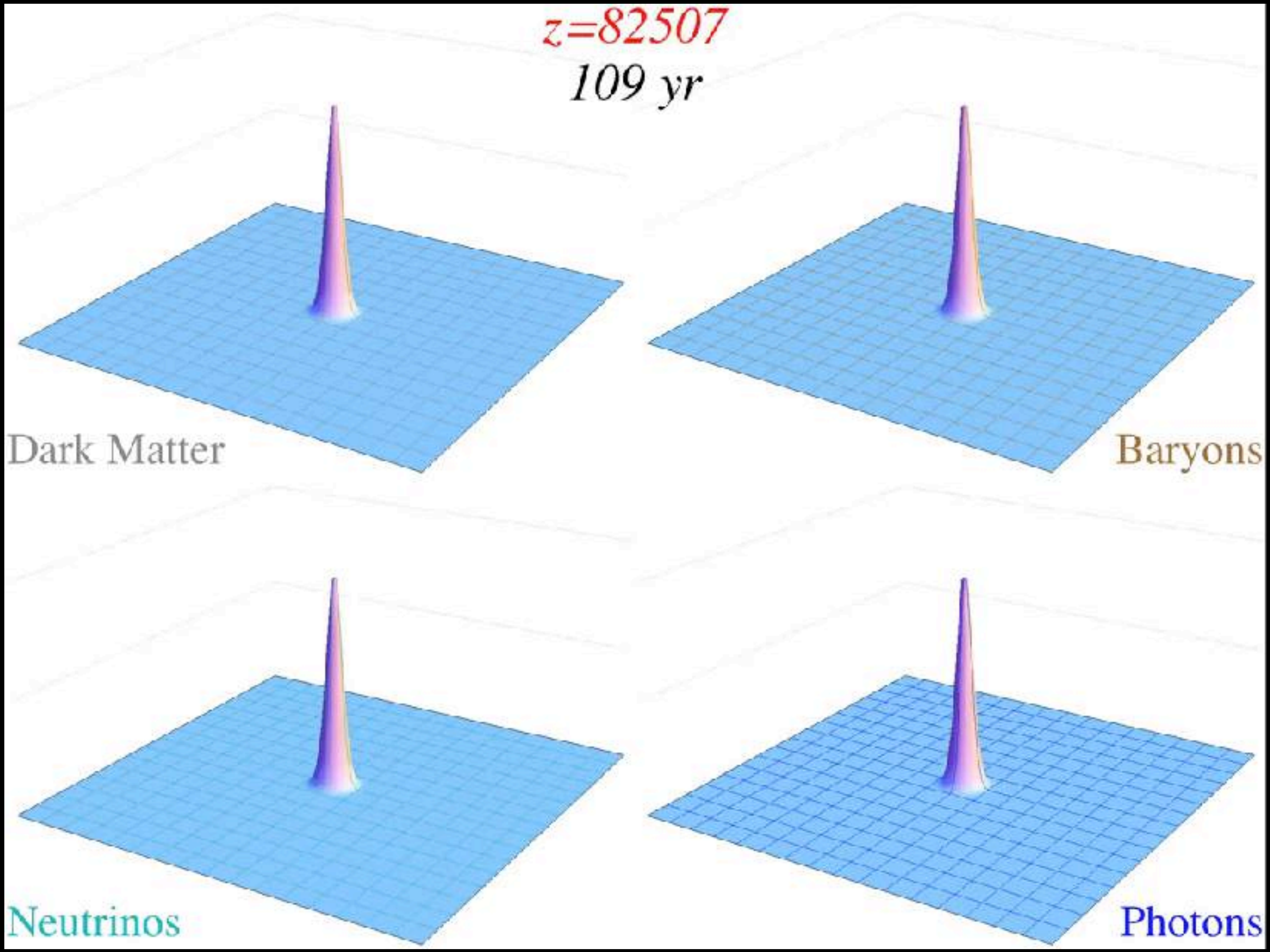
$$f(\theta, \phi) = \sum_{m=-\ell}^{\ell} \sum_{\ell=0}^{\infty} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

$$C_\ell = \langle |a_{\ell m}|^2 \rangle$$

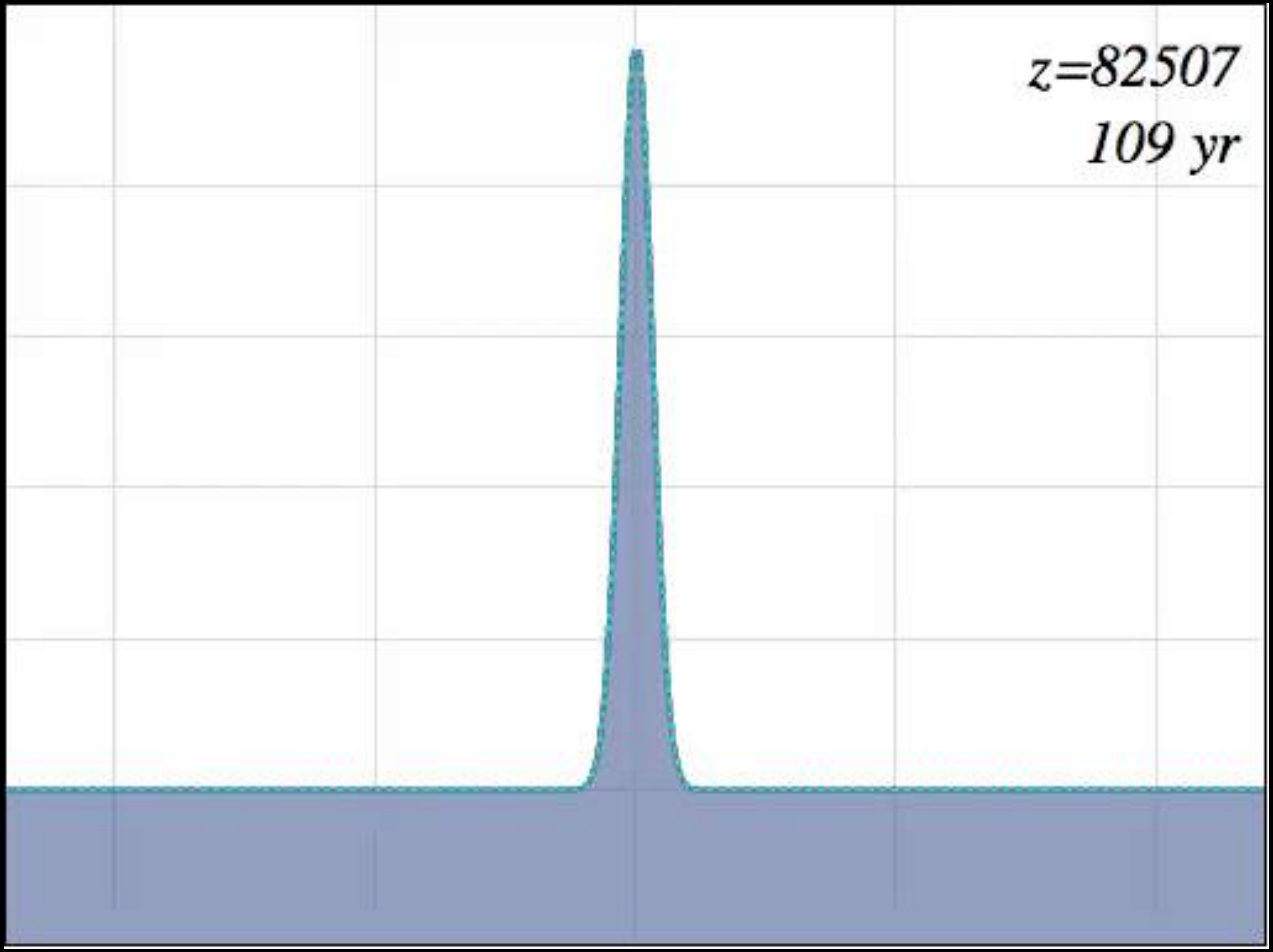


In matter the effect is subtle, when we observe a more realistic distribution of matter (below, a 2D section of a 3D distribution)



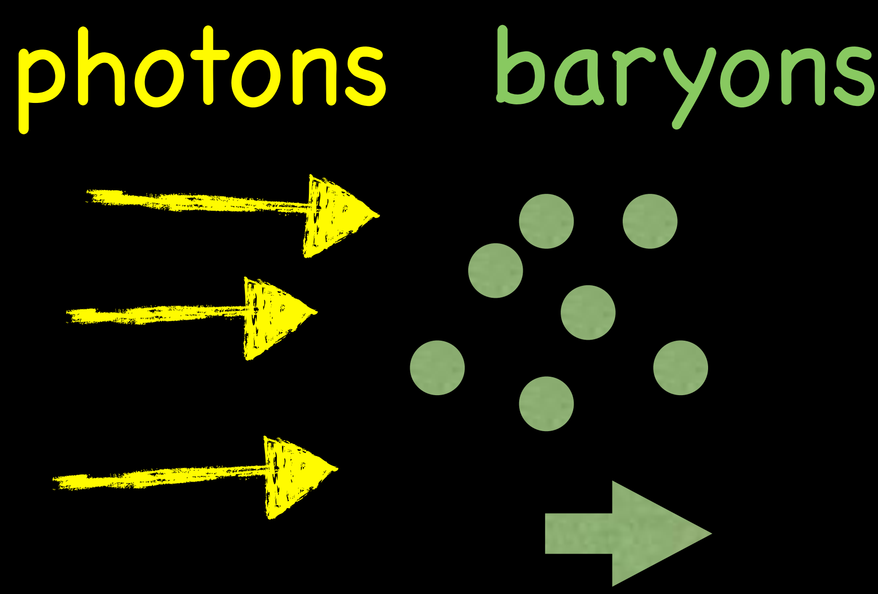


https://www.youtube.com/watch?v=GPiQVRS8kCg



https://www.youtube.com/watch?v=L7ws68XmgKo

Let's add some more substance, by taking into account the additional inertia that the baryons impose on photons due to scattering ("baryon drag")



This drag is proportional to the baryon/photon ratio

$$R_b \equiv \frac{(\rho_b + p_b)v_b}{(\rho_r + p_r)v_r} = \frac{\rho_b}{\rho_r + \frac{1}{3}\rho_r} = \frac{\rho_b}{\frac{4}{3}\rho_r} \simeq 31.5\,\Omega_b\,h^2\,\frac{10^3}{z}$$

The sound speed of this medium then becomes:

$$c_s^2(z) = \frac{1}{3}\frac{1}{1 + R_b(z)}$$

Acoustic horizon at decoupling:

Observations: WMAP, Planck

$$z_{dec} \simeq 1090.5 \pm 1 \quad \longleftrightarrow \quad R_s(z_{dec}) = (146.8 \pm 1.8)\ \mathrm{Mpc}$$

Acoustic horizon at "baryon drag"

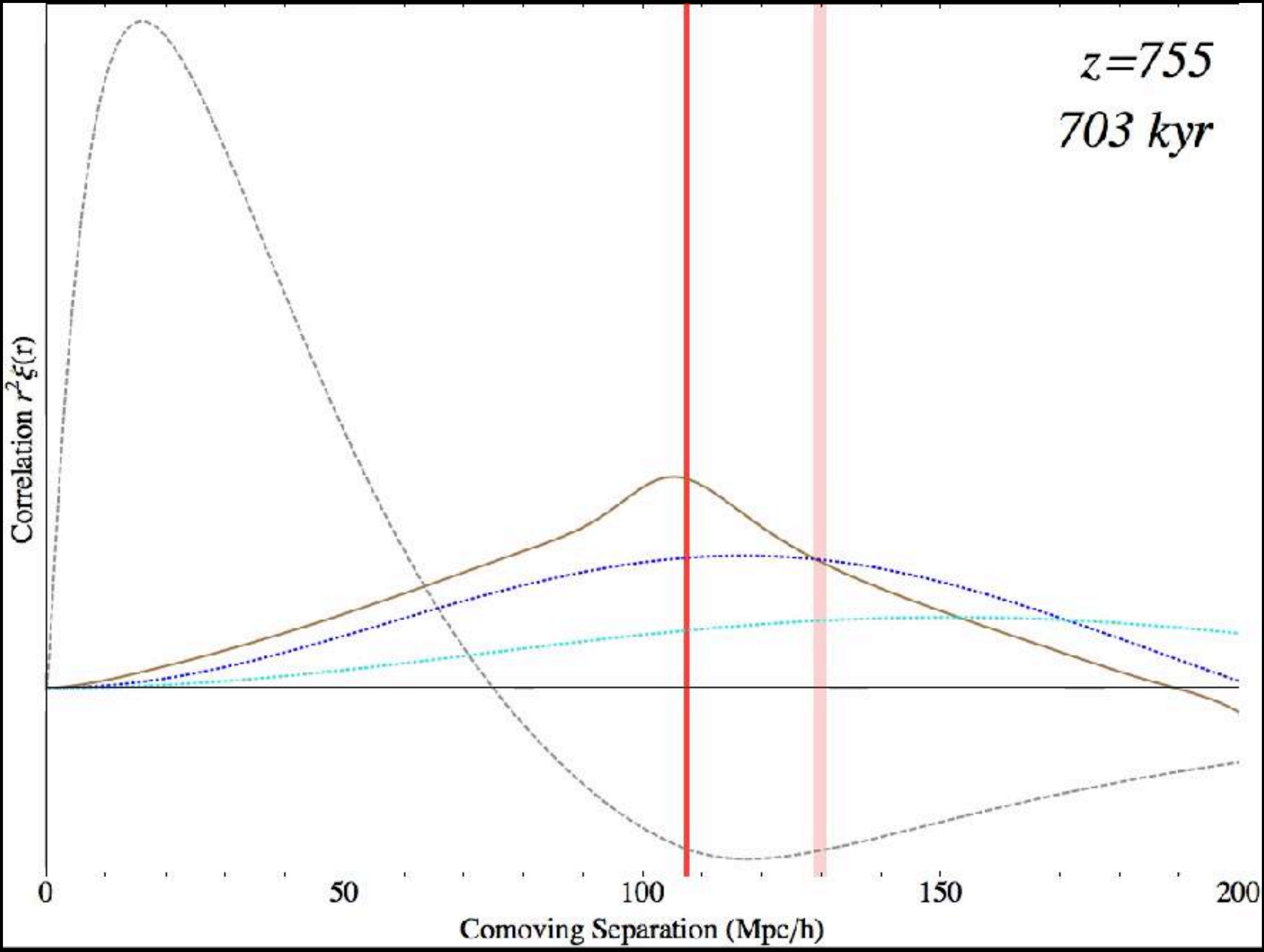
Since we have $\sim 10^9$ photons for each baryon (!!!), even after decoupling, even if the photons are not so affected by the baryons, the baryons do feel the drag of radiation, as it moves away from over-dense ("hot") regions and into under-dense ("cold") ones.

This drag ends shortly **after** decoupling:

Uncertainty in the **prediction** based on WMAP, Planck

$$z_{drag} \simeq 1020.5 \pm 1.6 \quad \longleftrightarrow \quad R_s(z_{drag}) = (153.3 \pm 2)\ \mathrm{Mpc}$$

This acoustic horizon, which can be predicted with **high accuracy** by observations of the CMB, shows up in the present **matter distribution**



z=755
703 kyr
Correlation $r^2\xi(r)$
0
50
100
150
200
Comoving Separation (Mpc/h)