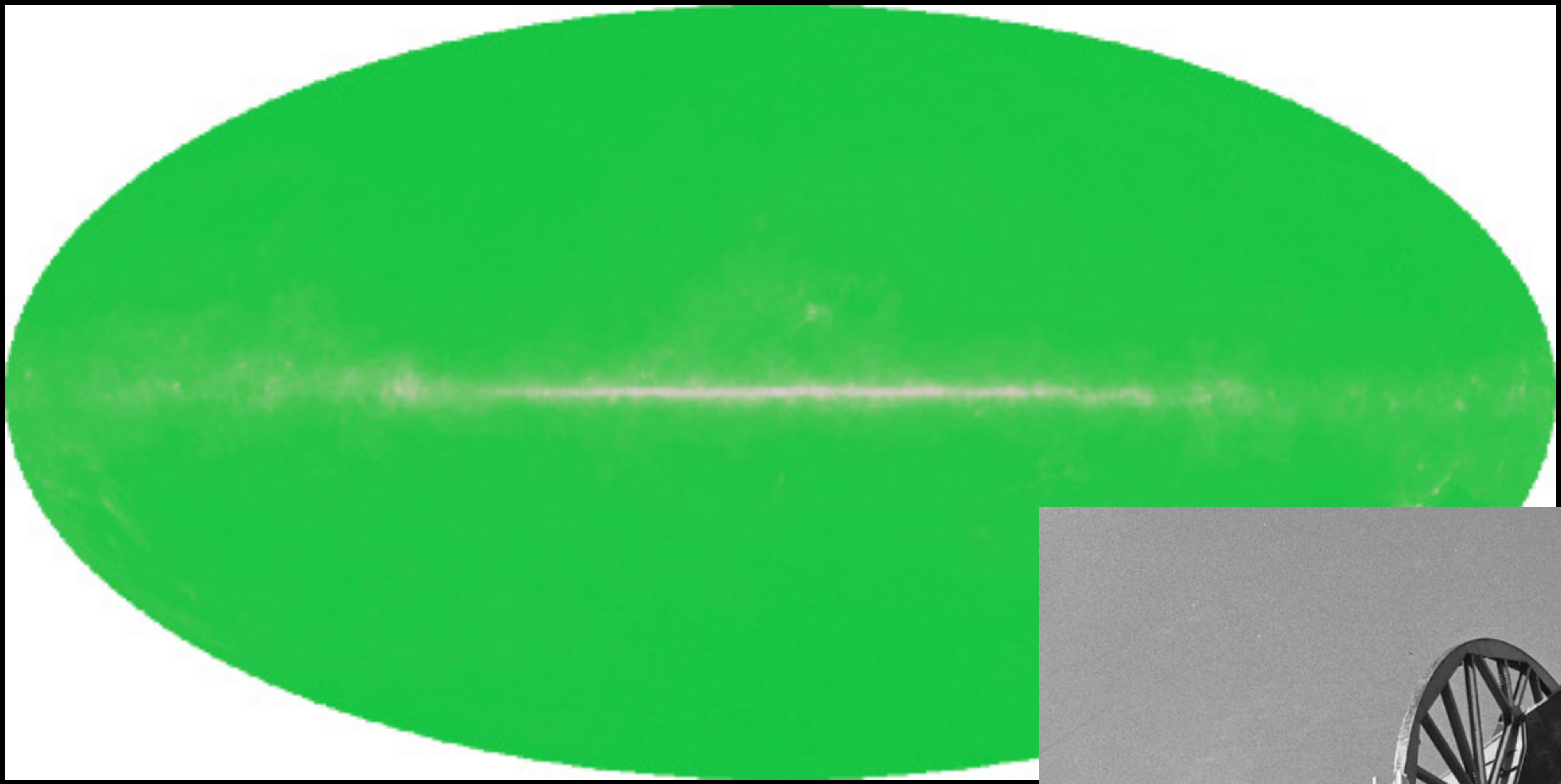
Cosmology I

Third part: early universe

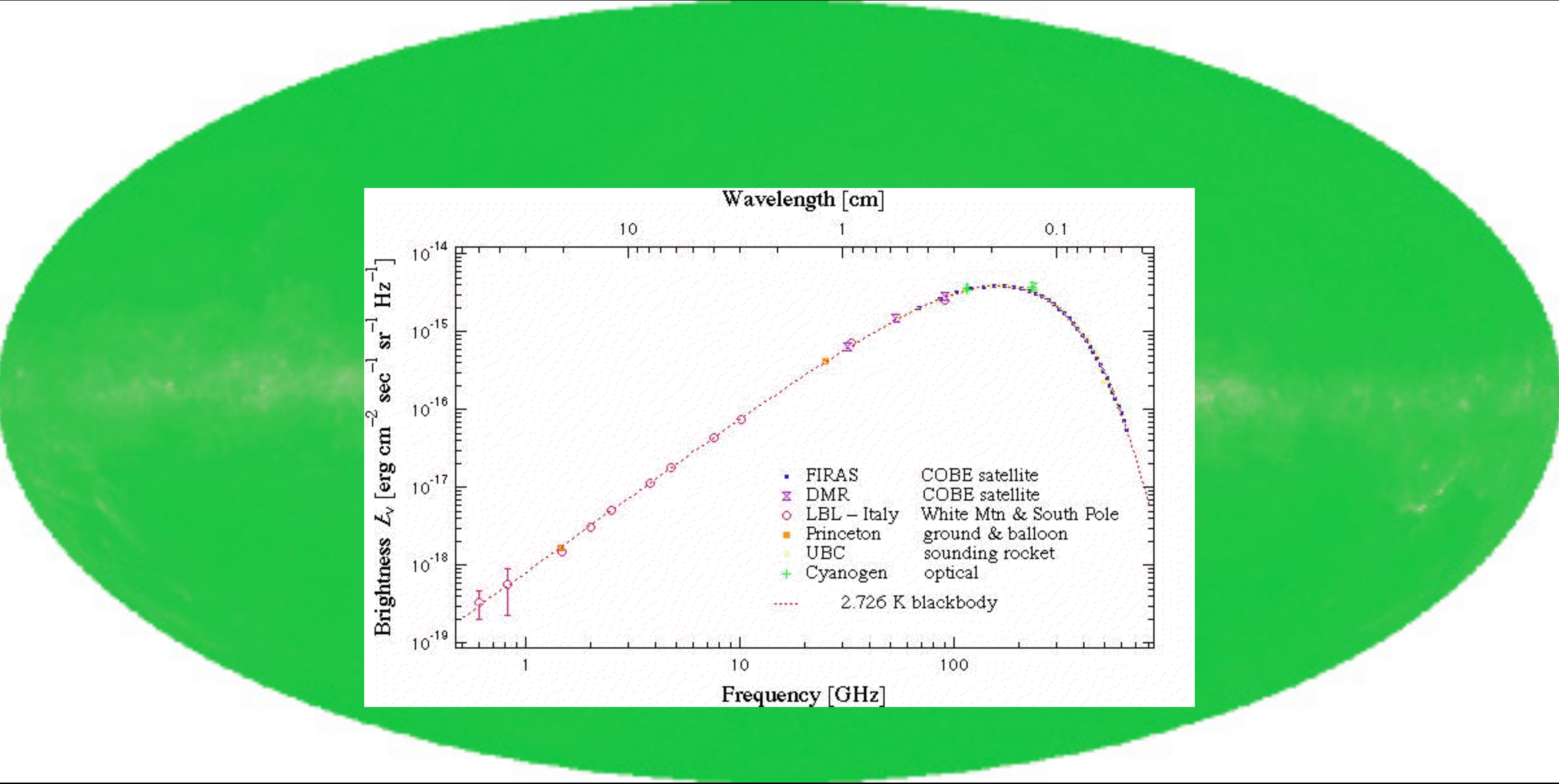
Pierluigi Monaco - Università di Trieste e INAF-Osservatorio Astronomico TS

Cosmic microwave background



1965, Penzias & Wilson

recent measurement:
$T_{\gamma 0} = 2.72548 \pm 0.00057$ K



The CMB is an almost perfect black body with T ≃ 2.73 K.
Its isotropy is a very strong basis for the cosmological principle.
It gives a very strong clue that the Universe was thermalized at early times.

$$\rho_\gamma(a) = \rho_{\gamma 0} a^{-4} = \rho_{\gamma 0}(1+z)^4$$

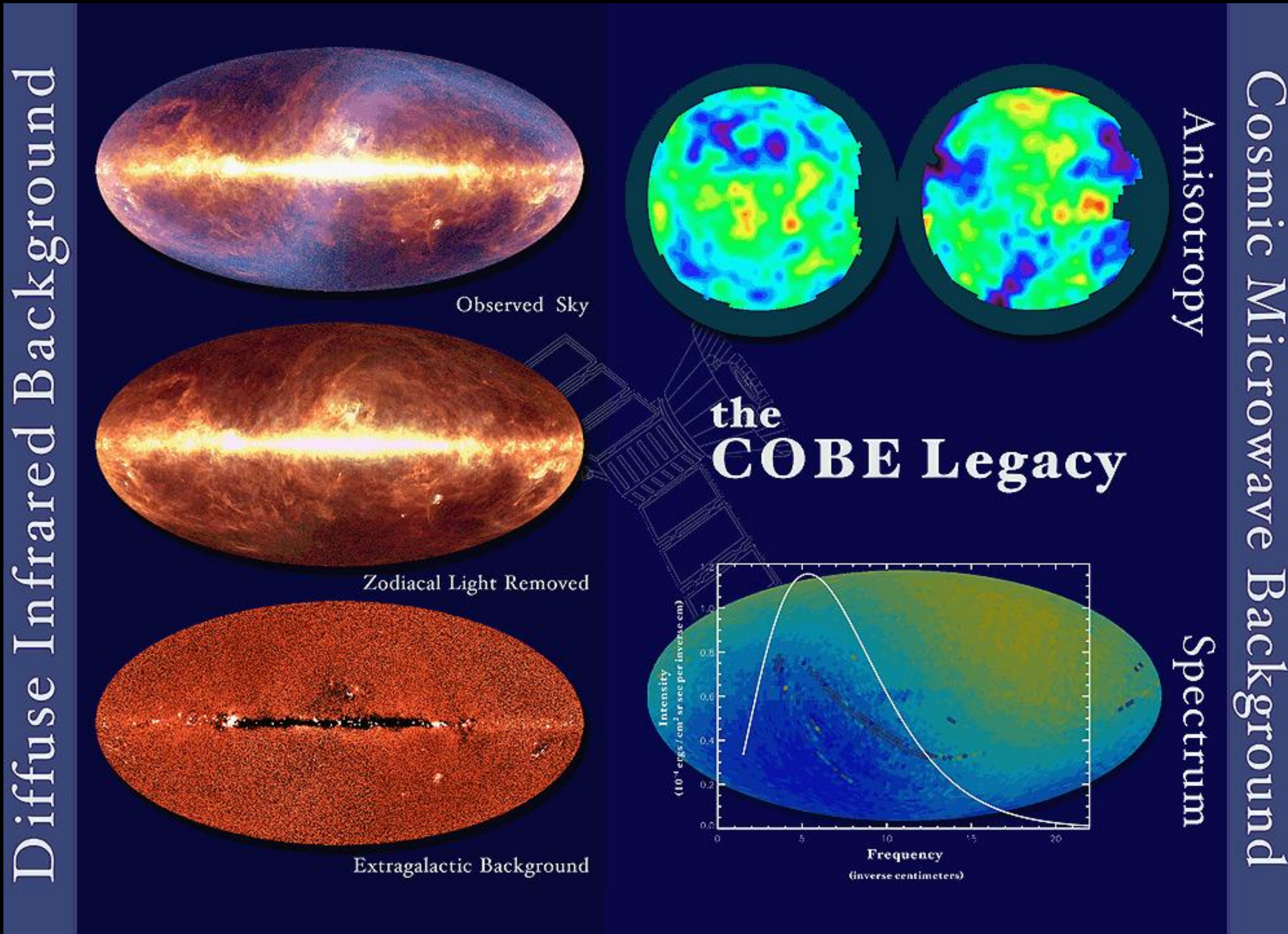
$$\rho_\gamma c^2 = \text{const}\ T_\gamma^4$$

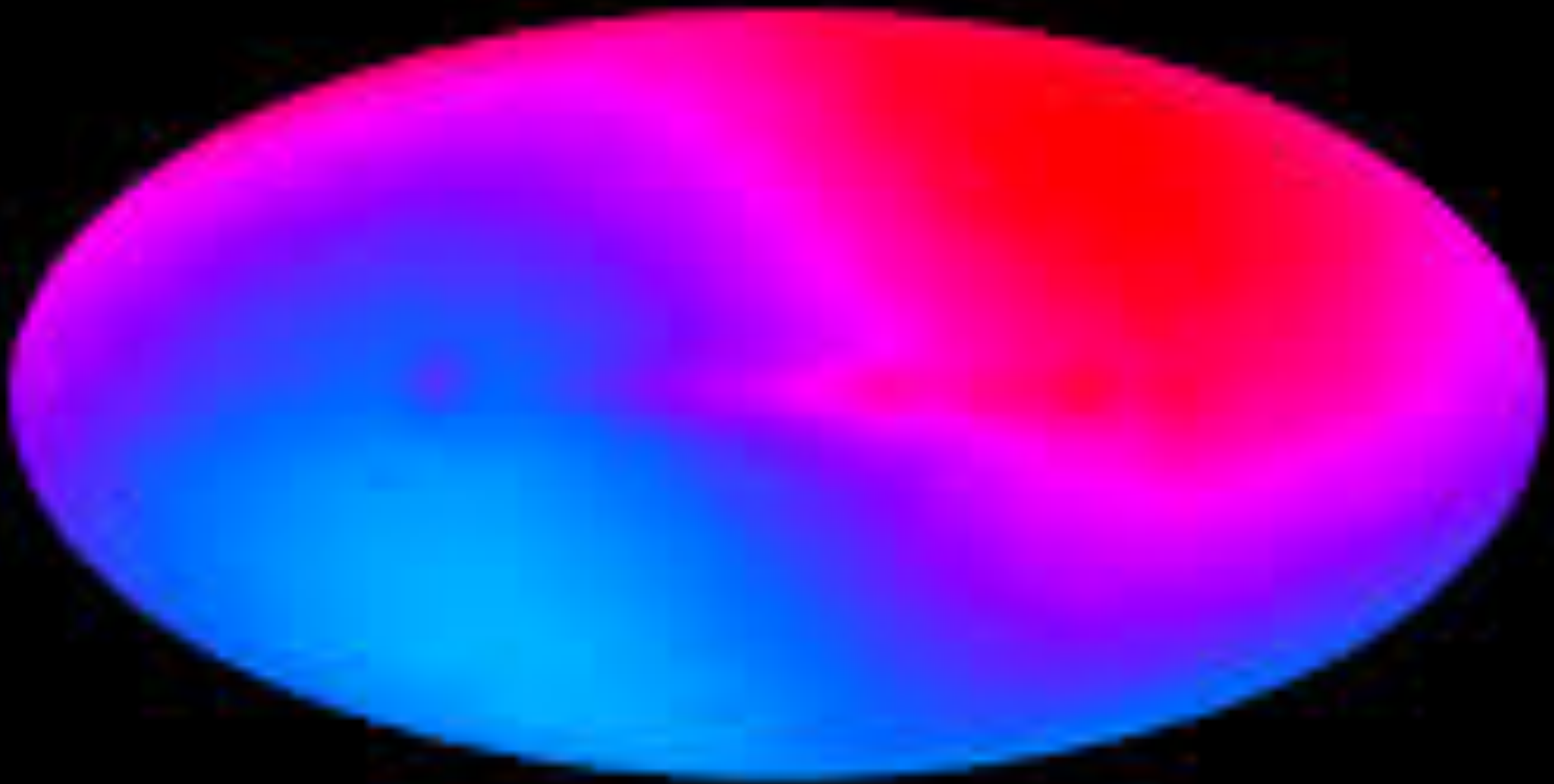
$$T_\gamma = T_{\gamma 0}(1+z)$$

$$\text{Recombination}: \quad T_\gamma \sim 3000K, z \sim 1100$$

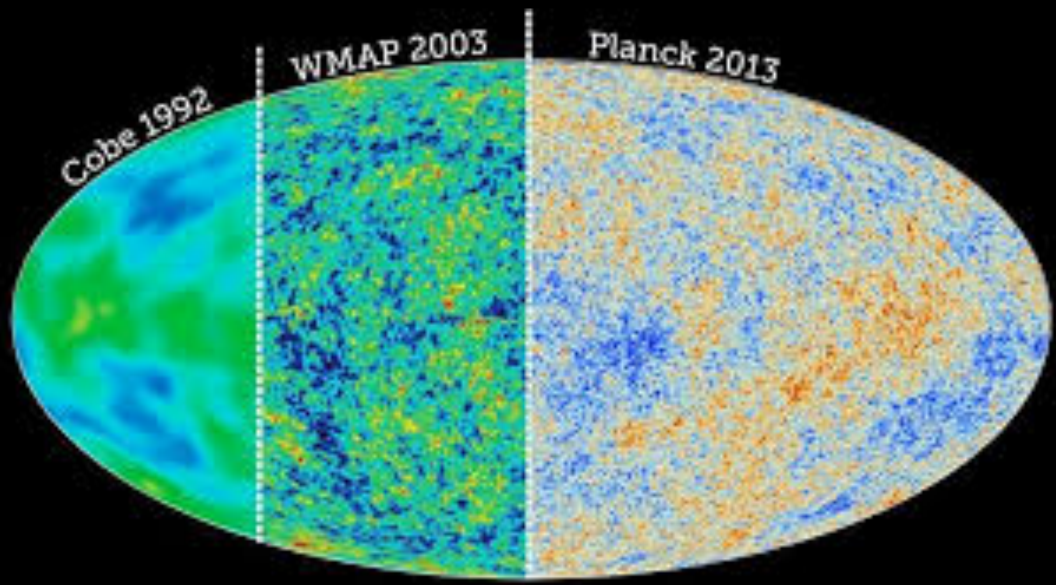
This is the redshift at which hydrogen combines into atoms, so the cross-section of photons and matter, dominated by Thomson scattering, drops and the Universe becomes transparent for the first time.
We see the CMB at the "last scattering surface".

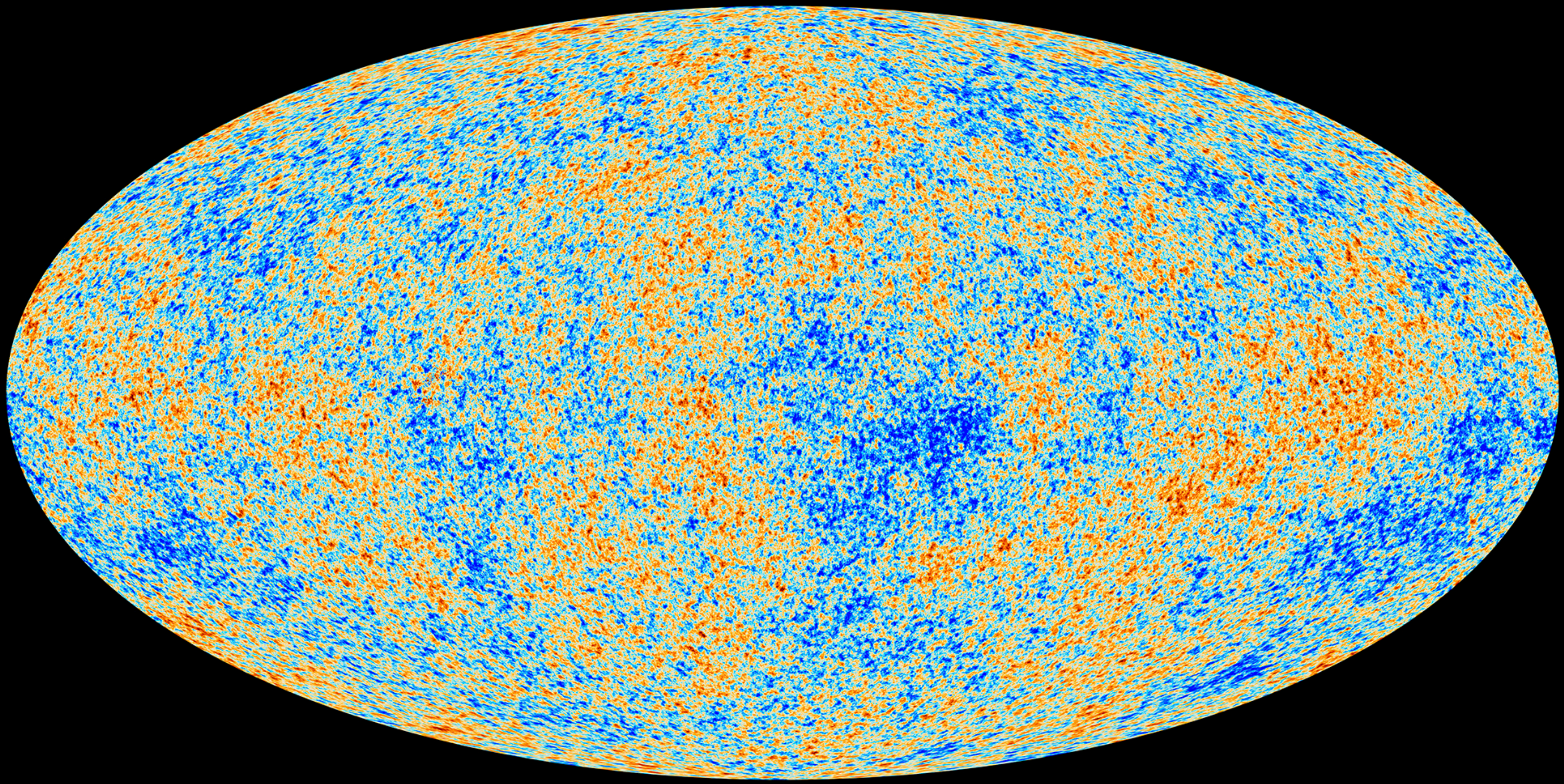
At higher redshift the Universe is opaque to radiation.


Diffuse Infrared Background
Observed Sky
Zodiacal Light Removed
Extragalactic Background
the
COBE Legacy
Anisotropy
Spectrum
Cosmic Microwave Background
Intensity
(10⁻⁴ ergs / cm² sr sec per inverse cm)
Frequency
(inverse centimeters)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
5
10
15
20



The CMB dipole, with $\delta T/T \sim 10^{-3}$, measures our velocity with respect to the radiation component

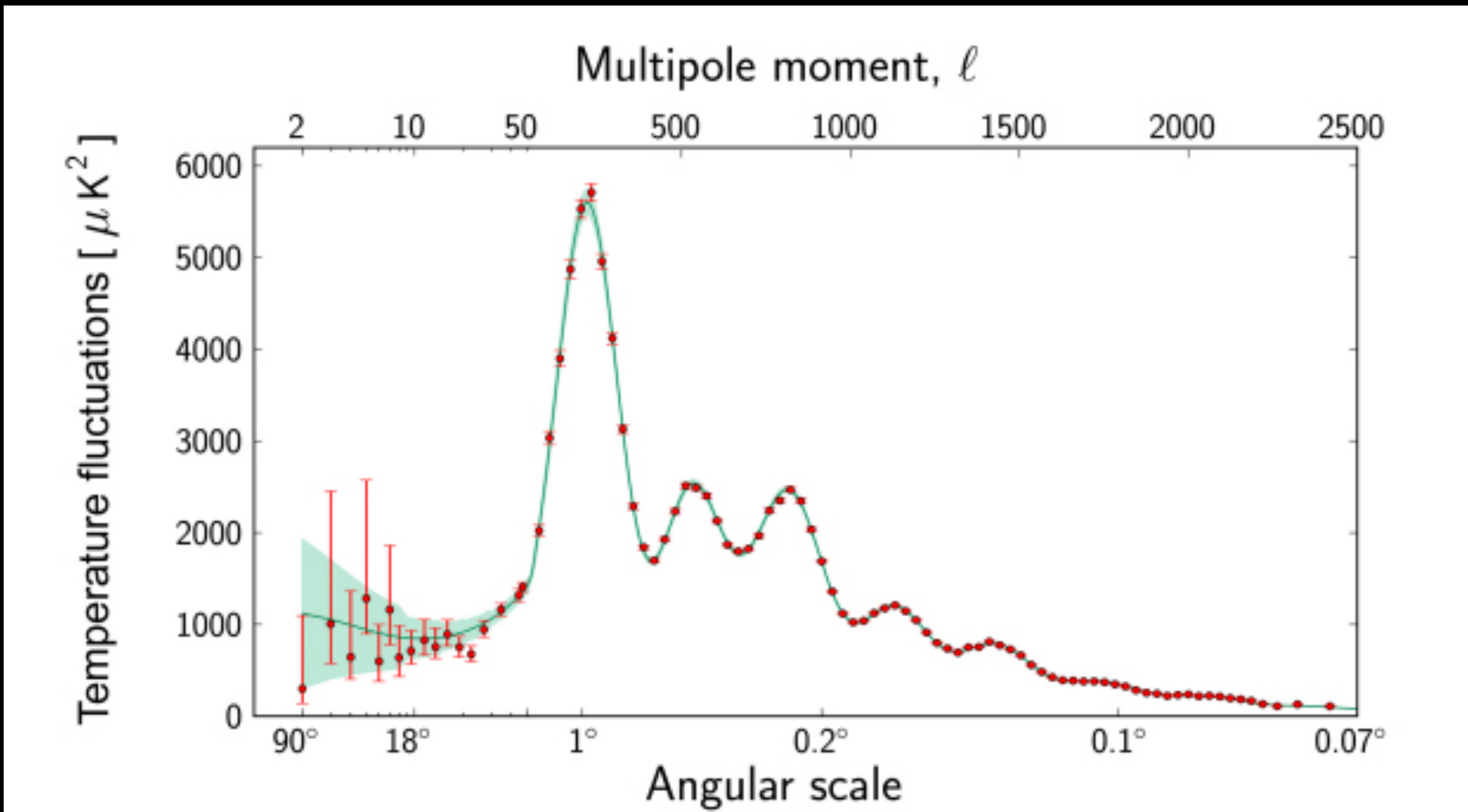




Temperature fluctuations measure the fluctuations of the potential at recombination.

The temperature map is expanded in spherical harmonics on the celestial sphere

$$\frac{\delta T}{T}(\theta, \phi) = \sum_{\ell} \sum_{m} a_{\ell m} Y_{\ell}^{m}(\theta, \phi) \qquad C_l = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$



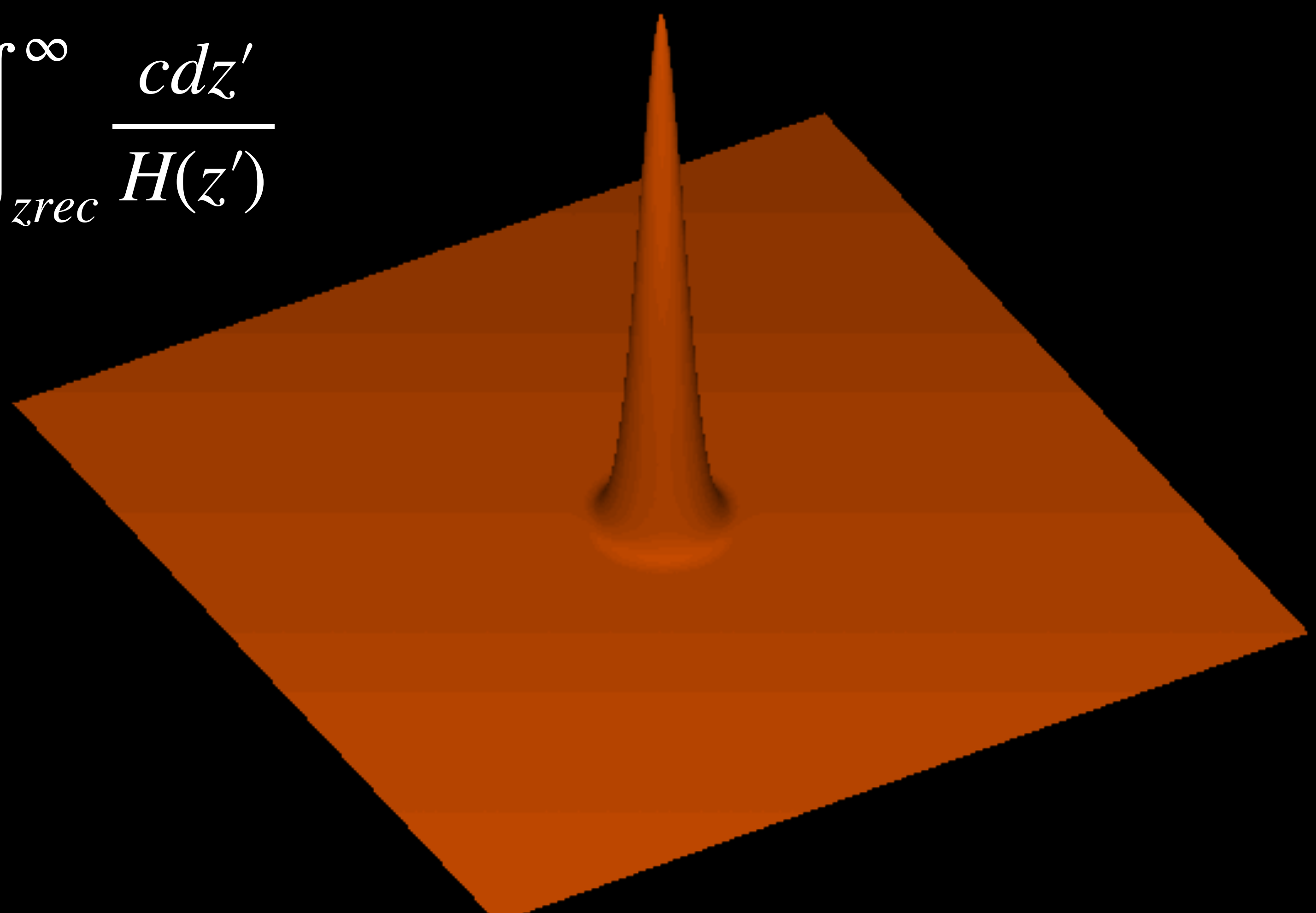
Sound waves propagate in the coupled baryon/photon plasma from very early times to recombination, at a speed determined by the dominant radiation pressure:

$$c_s = \sqrt{\frac{\partial p}{\partial \rho}} \simeq \frac{c}{\sqrt{3}}$$

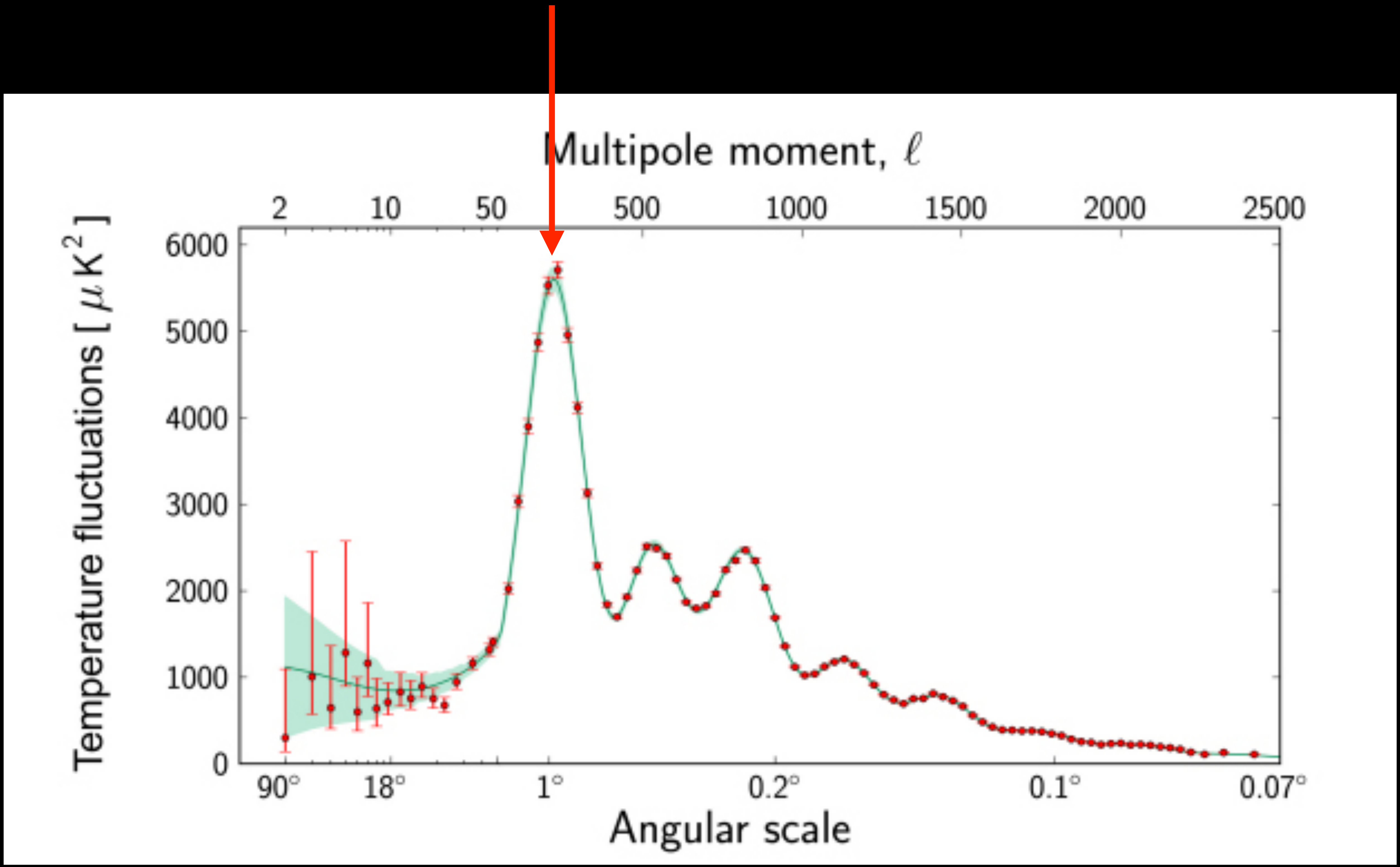
One can then define a "sound horizon", the distance traveled by a sound wave from t=0 to recombination:

$$d_{sh} \simeq \frac{1}{\sqrt{3}} \int_0^{t_{rec}} \frac{cdt'}{a(t')} = \frac{1}{\sqrt{3}} \int_{zrec}^{\infty} \frac{cdz'}{H(z')}$$

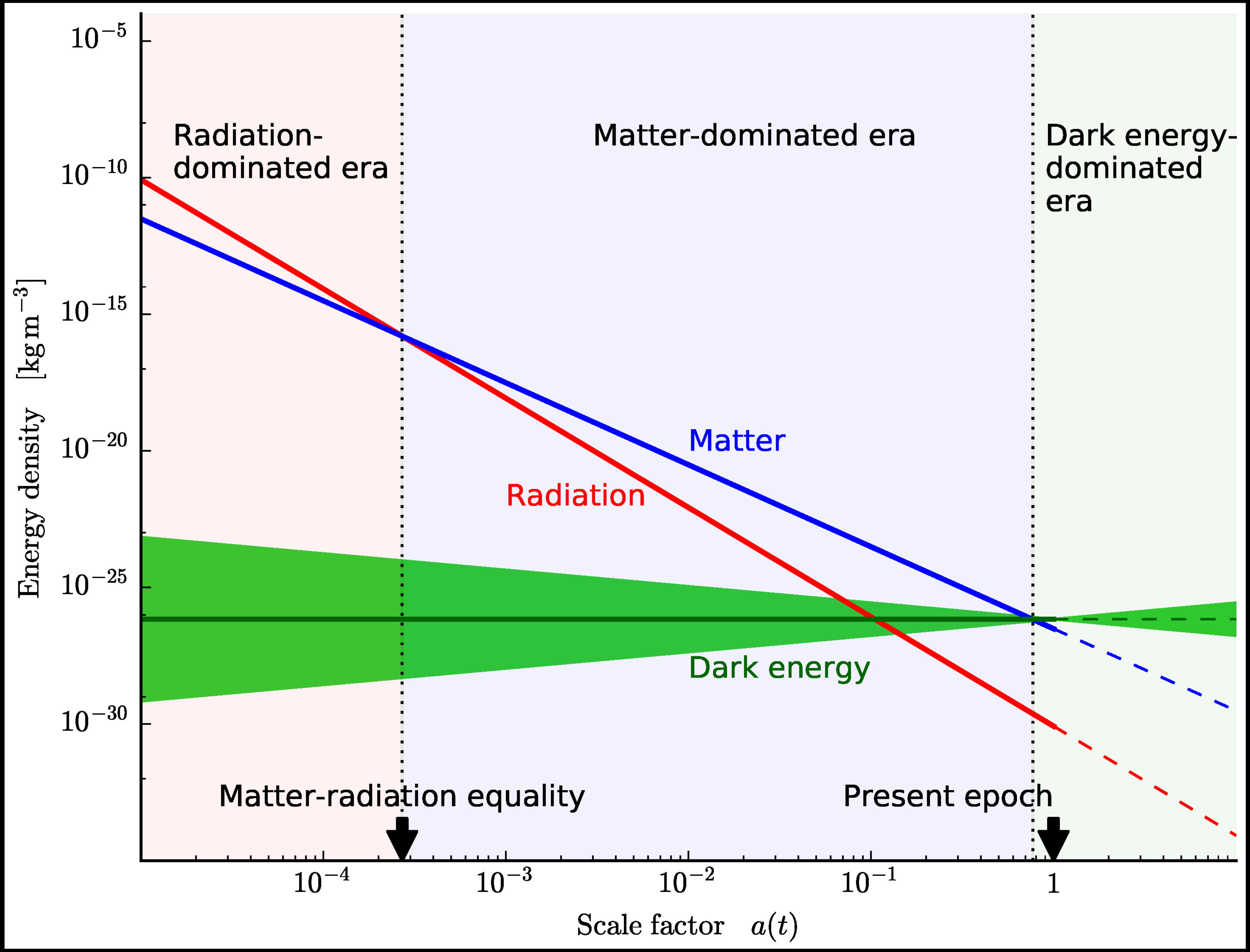
Fluctuations at wavelengths similar to the sound horizon are then amplified in the CMB temperature power spectrum



The first "acoustic peak" tracks the angular size subtended by the sound horizon at recombination, that is a standard ruler



CMB measurements lead to a precise history of the Universe

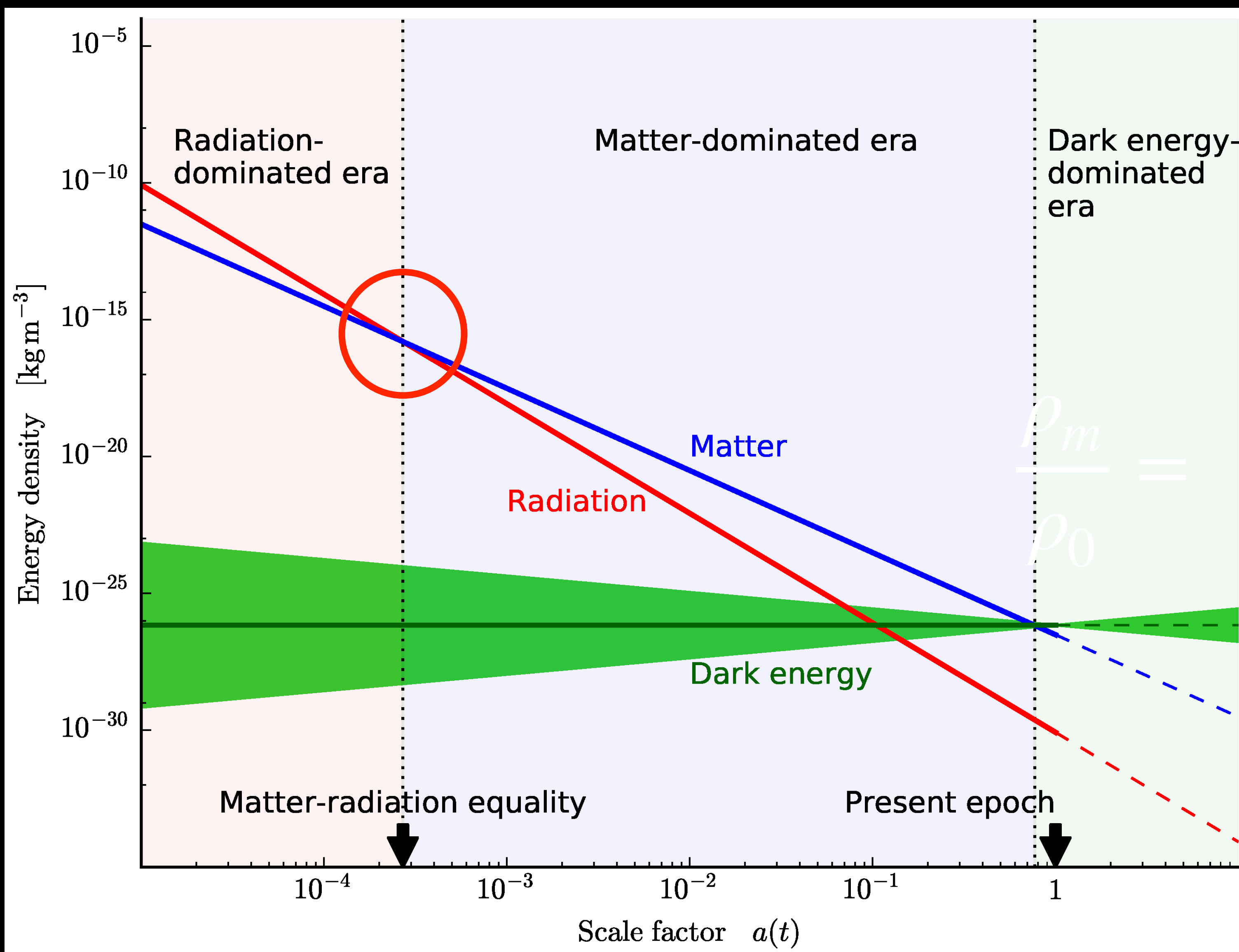


$$H^2 = H_0^2 \left[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda + \Omega_k a^{-2} \right]$$

Components in the Universe after Planck

Hubble constant	$h = 0.6736 \pm 0.0054$	$H_0 = 67.36 \pm 0.54$ km s^{-1} Mpc^{-1}
Matter, total	$\Omega_{m0} = 0.3153 \pm 0.0073$	$\rho_{m0} = 2.66\ 10^{-30}$ g cm^{-3}
Baryons	$\Omega_{b0} = 0.04930 \pm 0.00051$	$\rho_{b0} = 4.18\ 10^{-31}$ g cm^{-3}
Dark matter	$\Omega_{dm0} = 0.2660 \pm 0.0073$	$\rho_{dm0} = 2.24\ 10^{-30}$ g cm^{-3}
Dark energy	$\Omega_{\Lambda 0} = 0.6847 \pm 0.0073$	$\rho_{\Lambda 0} = 5.98\ 10^{-30}$ g cm^{-3}
Radiation, total	$\Omega_{r0} = 9.03\ 10^{-5}$	$\rho_{r0} = 7.85\ 10^{-34}$ g cm^{-3}
Photons	$\Omega_{\gamma 0} = 5.37\ 10^{-5}$	$\rho_{\gamma 0} = 4.67\ 10^{-34}$ g cm^{-3}
Neutrinos	$\Omega_{\nu 0} = 3.66\ 10^{-5}$	$\rho_{\nu 0} = 3.18\ 10^{-34}$ g cm^{-3}
Curvature	$\Omega_{k0} = -0.011 \pm 0.013$	

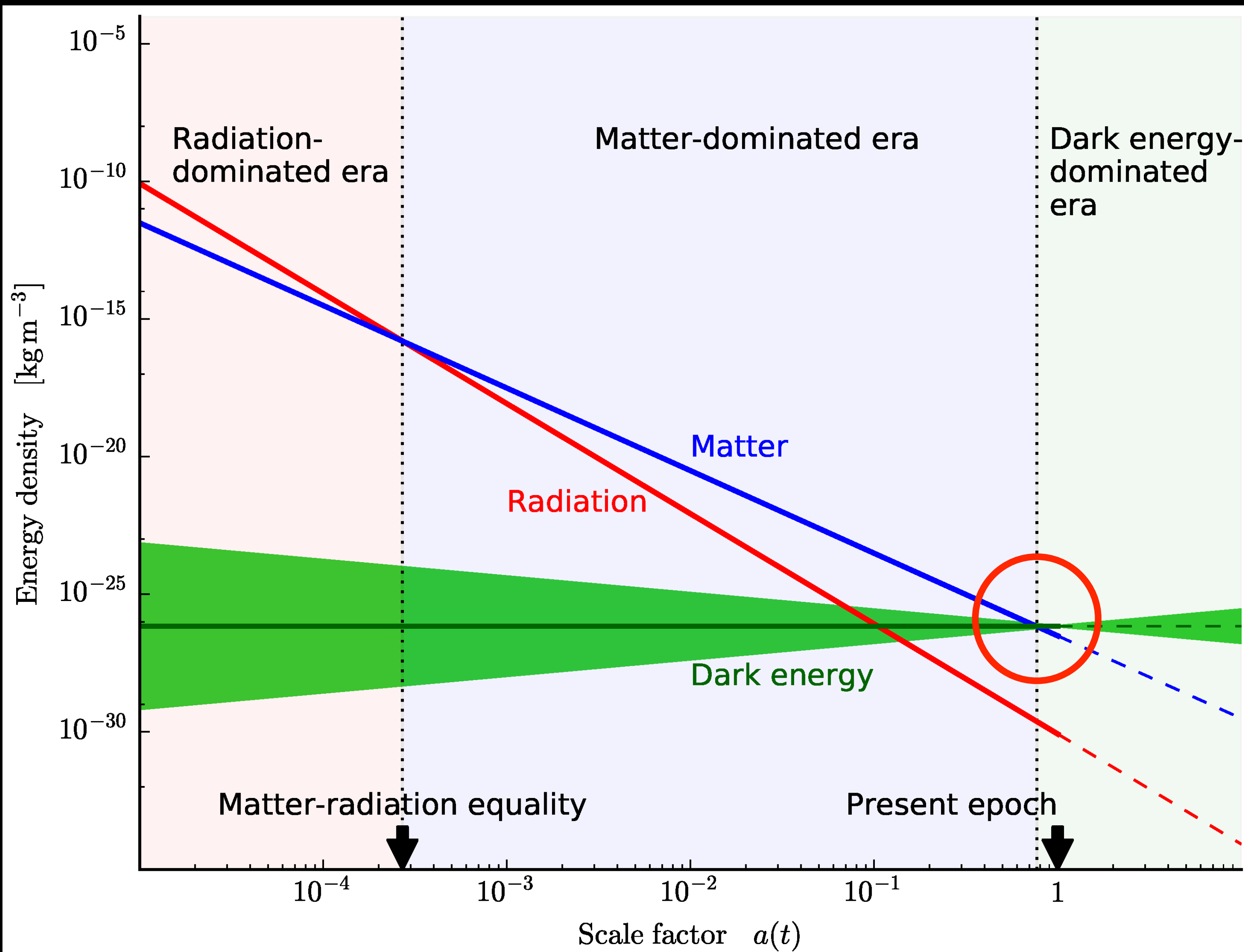
Equality



$$\frac{\rho_{\gamma 0}}{\rho_{m0}} \simeq 2.48 \times 10^{-5} \, (\Omega_m h^2)^{-1}$$

$$\frac{\rho_\gamma}{\rho_m} \propto 1 + z \implies z_{\rm eq} \simeq 5570$$

$$\text{with neutrinos} : z_{\rm eq} = 3402 \pm 26$$



Dominance of dark energy:

$$\frac{\rho_\Lambda}{\rho_m} = \frac{\rho_{\Lambda 0}}{\rho_{m0}} a^3 = \frac{\Omega_\Lambda}{\Omega_m} a^3$$

$$1 + z_{\text{de eq}} = \left(\frac{\Omega_\Lambda}{\Omega_m} \right)^{1/3} \simeq 1.31$$

$$z_{\text{de eq}} \simeq 0.31$$

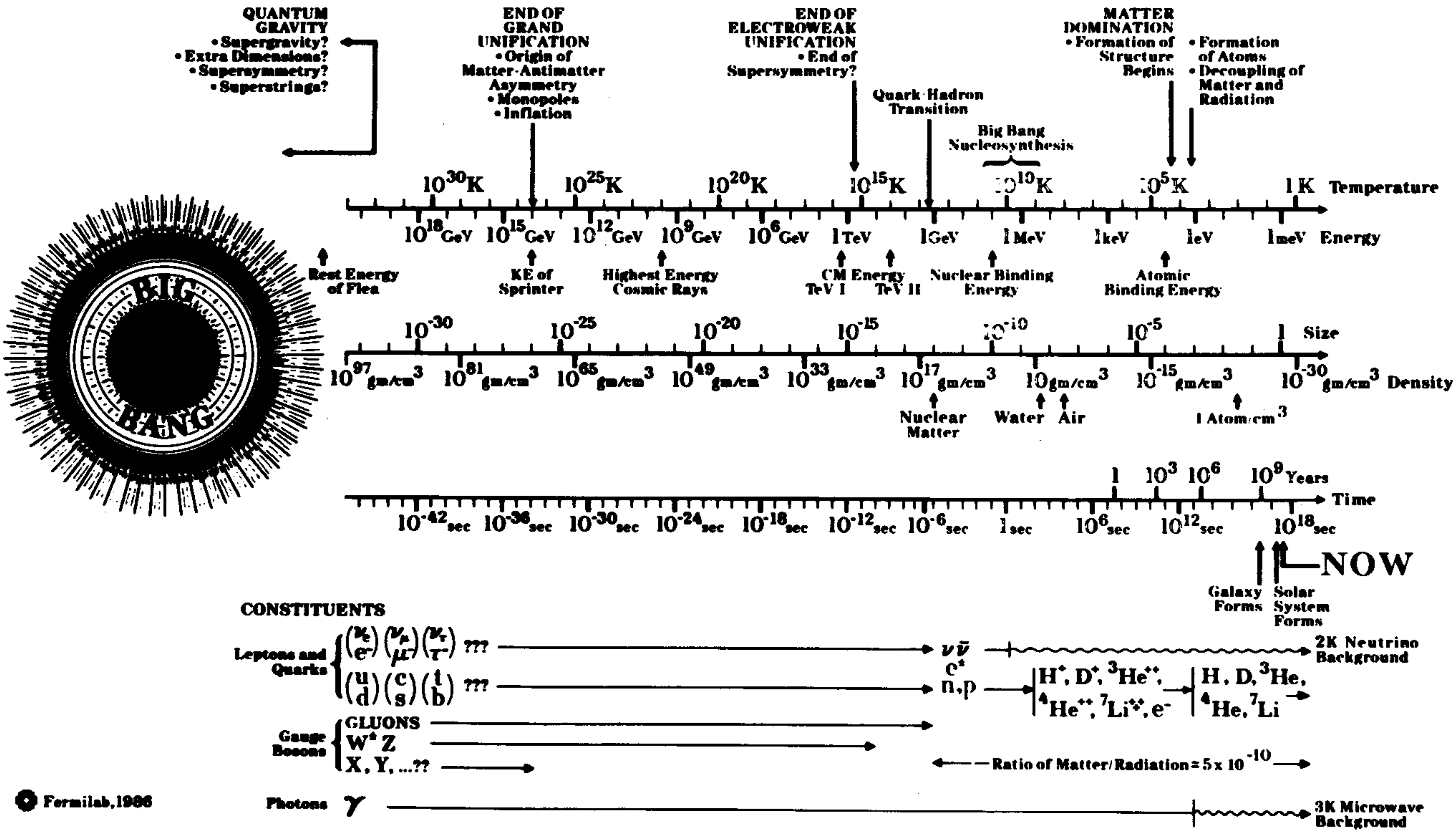
Start of acceleration:

$$\frac{\ddot{a}}{a} = -\frac{1}{2} H_0^2 \Omega_m (1+z)^3 + H_0^2 \Omega_\Lambda = 0$$

$$1 + z_{\text{acc}} = \left(2 \frac{\Omega_\Lambda}{\Omega_m} \right)^{1/3} \simeq 1.65$$

$$z_{\text{acc}} \simeq 0.65$$

Thermal history of the Universe

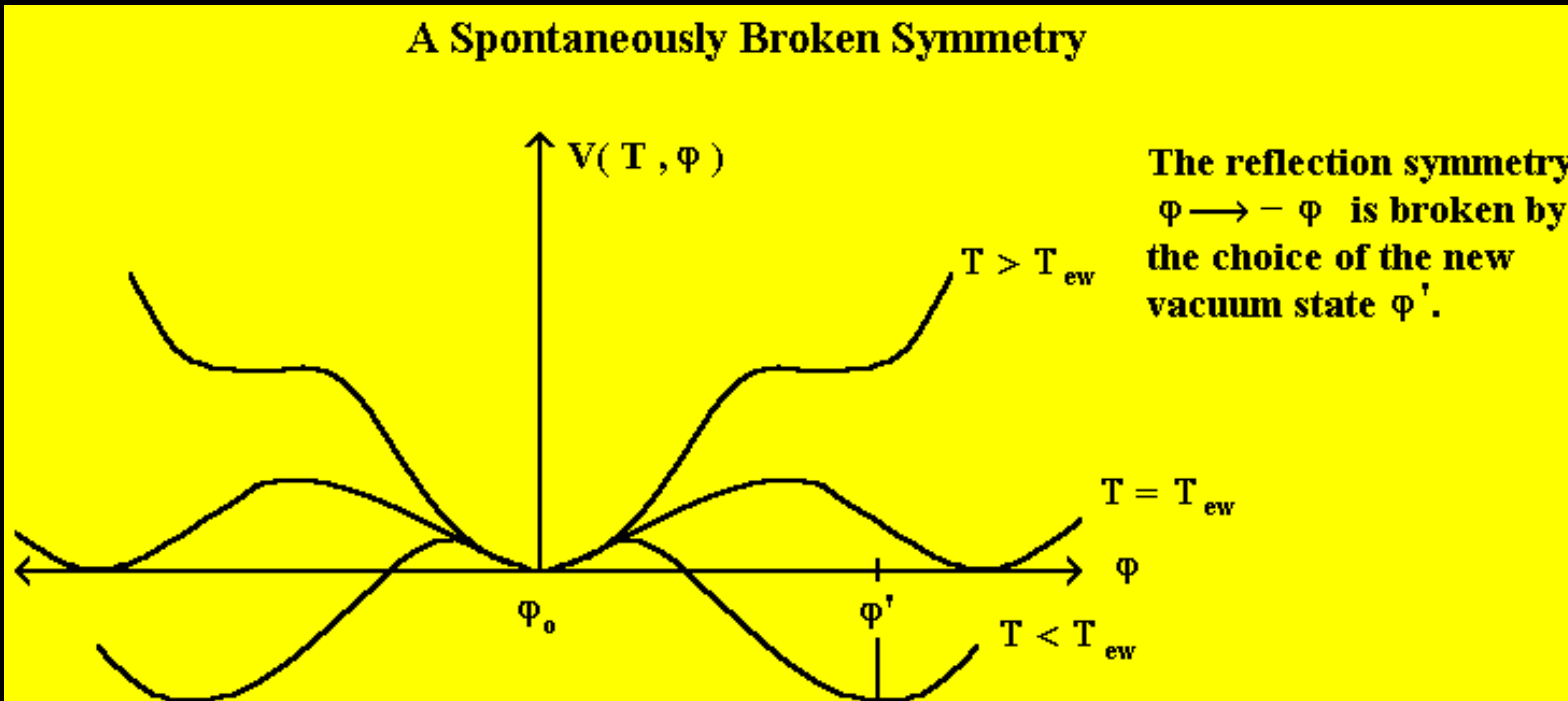


Thermal history of the Universe

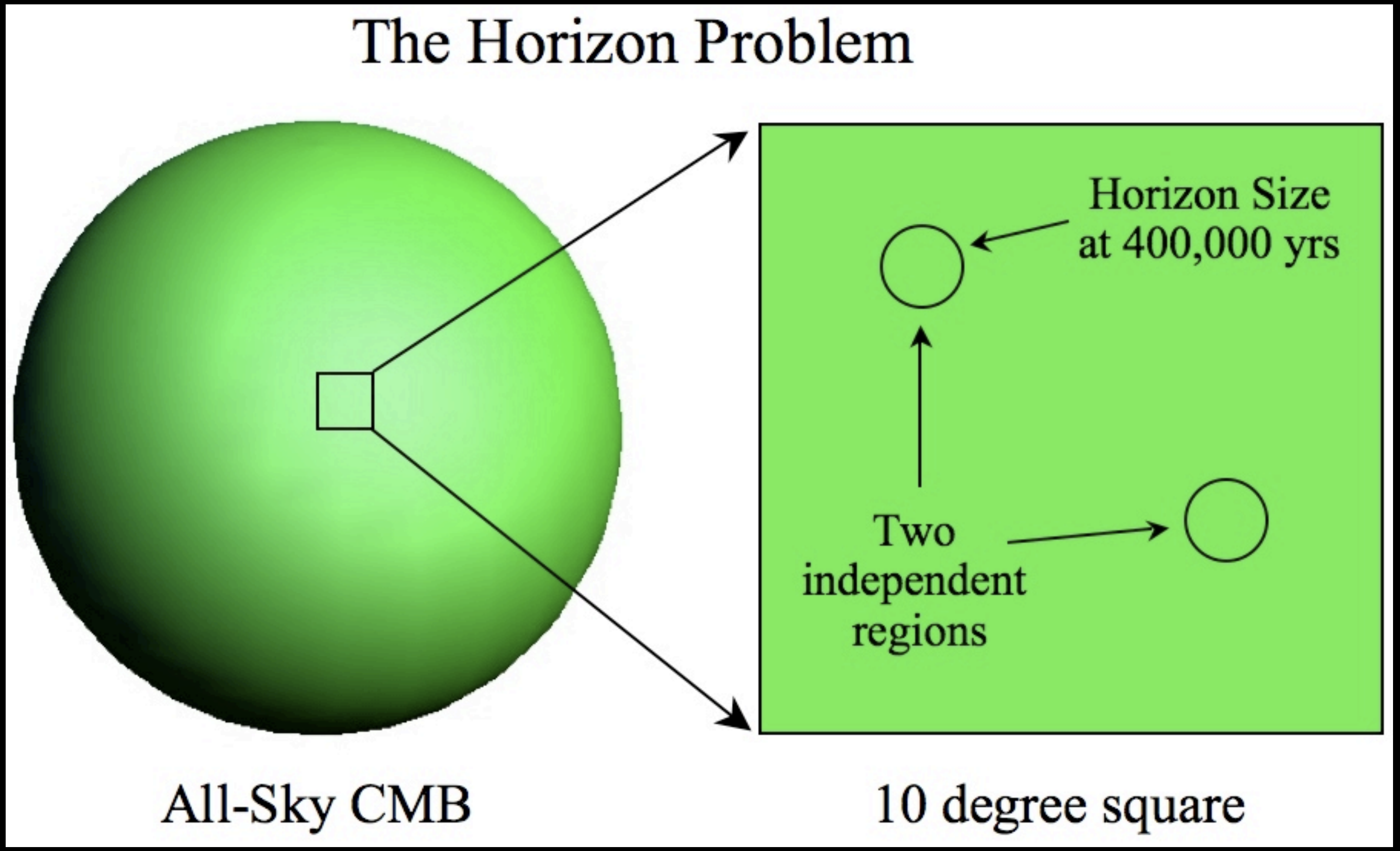
Epoca	t (s)	E (GeV)	T (K)	Eventi	Particelle presenti
Gravità quantistica	$5.4 \cdot 10^{-44}$	$1.2 \cdot 10^{19}$	10^{32}	fine della G.Q.	???
Transizioni di fase	10^{-38}	10^{16}	10^{29}	rotture di simm., inflazione?	part. supersimm.?
	10^{-36}	10^{15}	10^{28}	bariogenesi?	
	10^{-35}	10^{14}	10^{27}	fine GUT	q^+q^-, l^+l^-, g, bosoni e.d., H, DM
	10^{-10}	100	10^{15}	rottura E.D.	q^+q^-, e^+e^-, g, γ, ν, DM
	10^{-4}	300 MeV	$3 \cdot 10^{12}$	transizione Q.A.	$\pi^+\pi^-$, e^+e^-, γ, ν, DM
Adronica	$5 \cdot 10^{-3}$	130 MeV	$1.5 \cdot 10^{12}$	annichilazione $\pi^+\pi^-$	p^+, n, e^+e^-, γ, ν, DM
Leptonica	0.7	1 MeV	10^{10}	disaccoppiamento ν	
	5	0.5 MeV	$5 \cdot 10^{9}$	annichilazione e^+e^-	p^+, n, e^-, γ, ν, DM
Radiazione	2-3 min	0.1 MeV	10^{9}	nucleosintesi prim.	p^+, D, ^3He, ^4He, ^7Li,
	$4 \cdot 10^4$ yr	2-3 eV	10^4	equivalenza	e^-, γ, ν, DM
Materia	$3.8 \cdot 10^5$ yr	0.7 eV	3000	ricombinazione	
	10 Gyr	10^{-3} eV	3.6	dominio di Λ	
Λ	13-15 Gyr	$7 \cdot 10^{-4}$ eV	2.73	oggi	

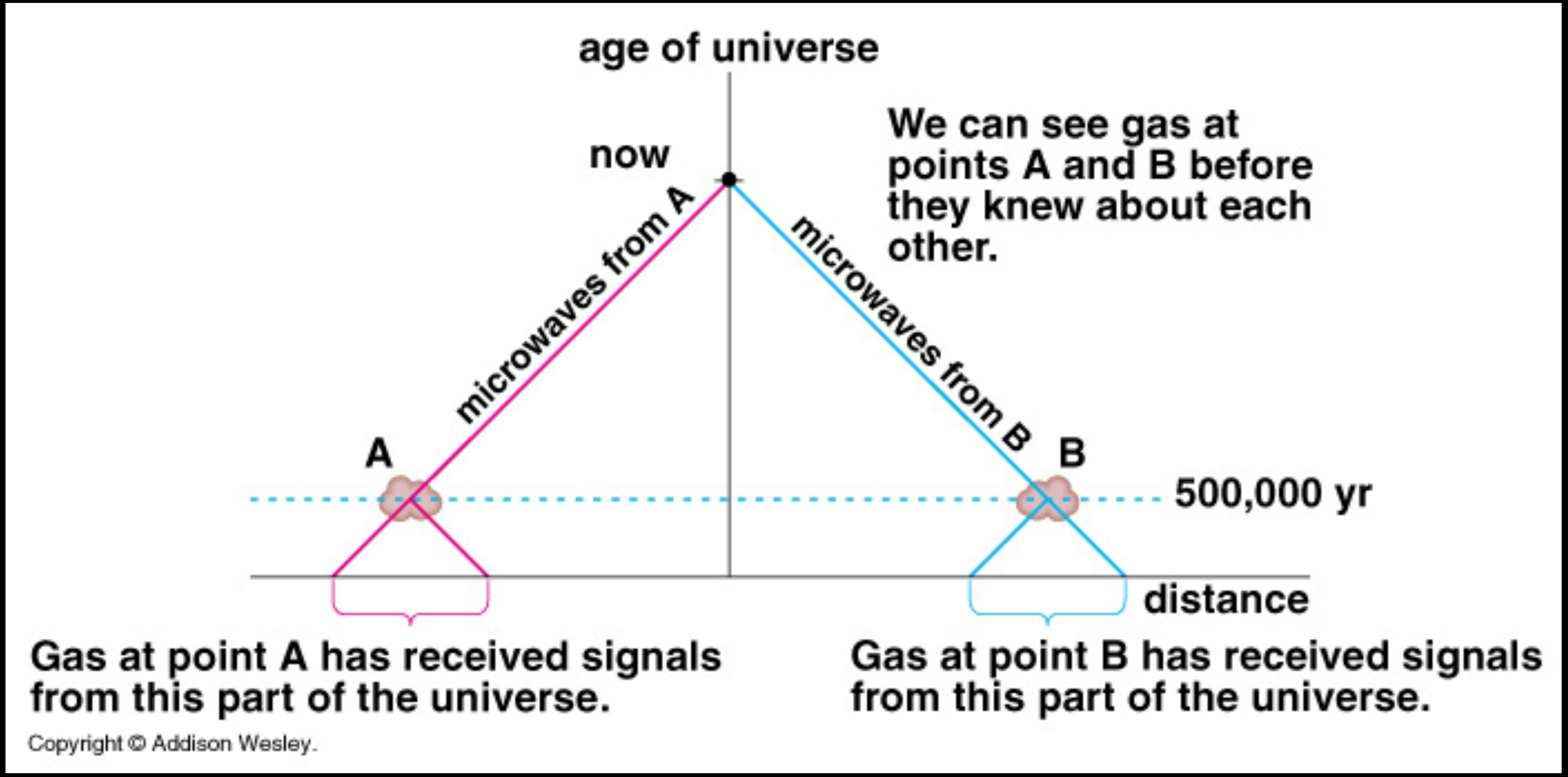
Legenda per le particelle: q^+q^-: coppie quark-antiquark; l^+l^-: coppie leptone-antileptone (prima della rottura elettro-debole); g: gluoni; H: bosone di Higgs; DM: materia oscura

Spontaneous symmetry breaking



Why is the Universe thermalized?





Big bang nucleosynthesis

$$n_{\gamma 0} = 412 \text{ cm}^{-3}$$

$$n_{b0} = \frac{\rho_{b0}}{m_p} = \frac{\Omega_b \rho_{c0}}{m_p}$$

$$= 1.10 \times 10^{-5} \text{ cm}^{-3} (\Omega_b h^2)$$

$$\eta = \frac{n_b}{n_\gamma} = 2.68 \times 10^{-8} (\Omega_b h^2)$$

$$= 6.00 \times 10^{-10}$$

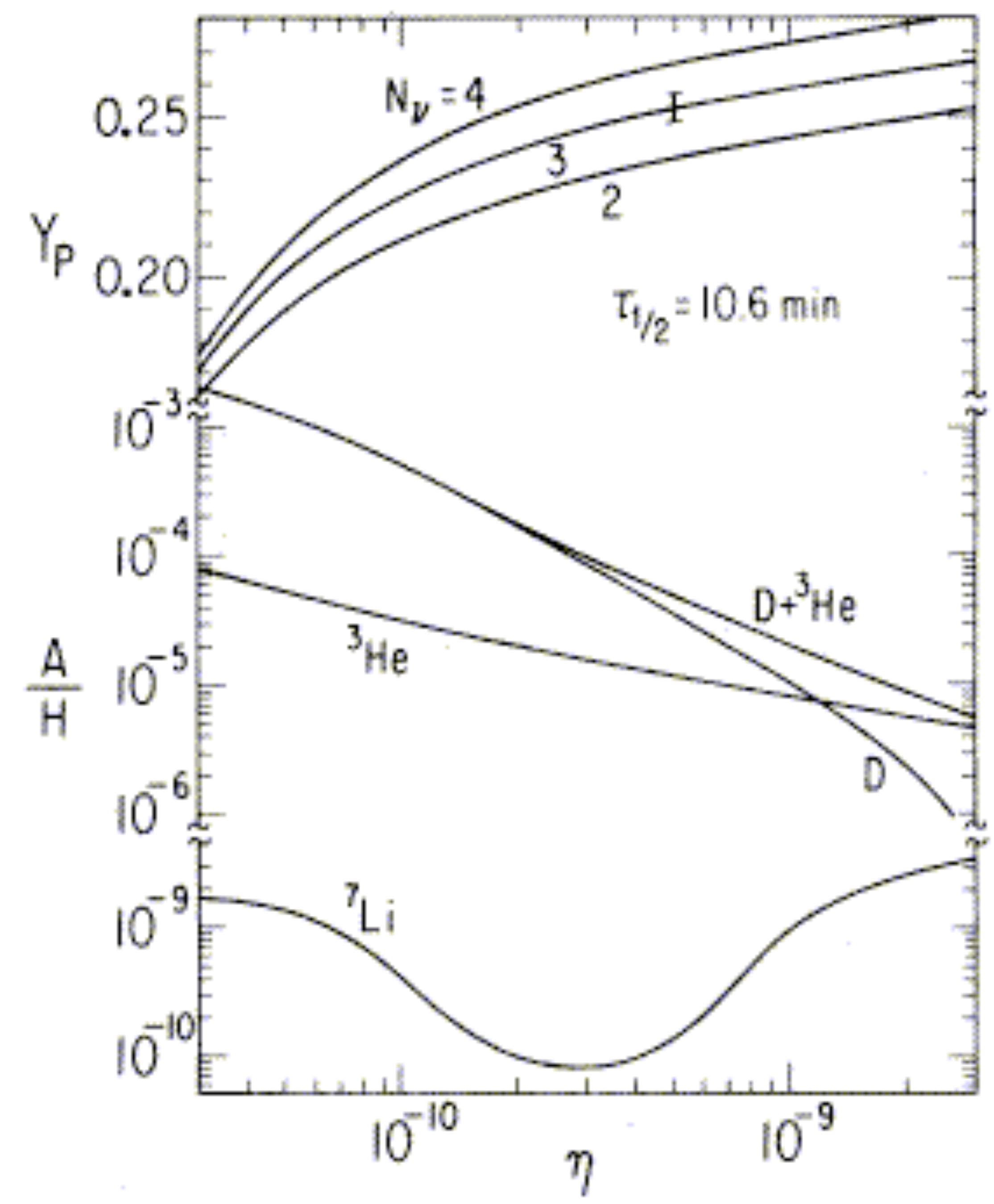


FIG. 5.—The predicted primordial abundances of ^{4}He (by mass), D, ^{3}He, and ^{7}Li (by number relative to H) as a function of η for $\tau_{1/2} = 10.6$ minutes; for ^{4}He the predictions for $N_\nu = 2, 3, 4$ are shown, and the size of the "error" bar shows the range in Y_p which corresponds to $10.4 < \tau_{1/2} < 10.8$ minutes. Note the changes in the abundance scales.

Evolution of perturbations

density contrast

$$\delta(\overrightarrow{x}, t) = \frac{\rho(\overrightarrow{x}, t) - \bar{\rho}(t)}{\bar{\rho}(t)}$$

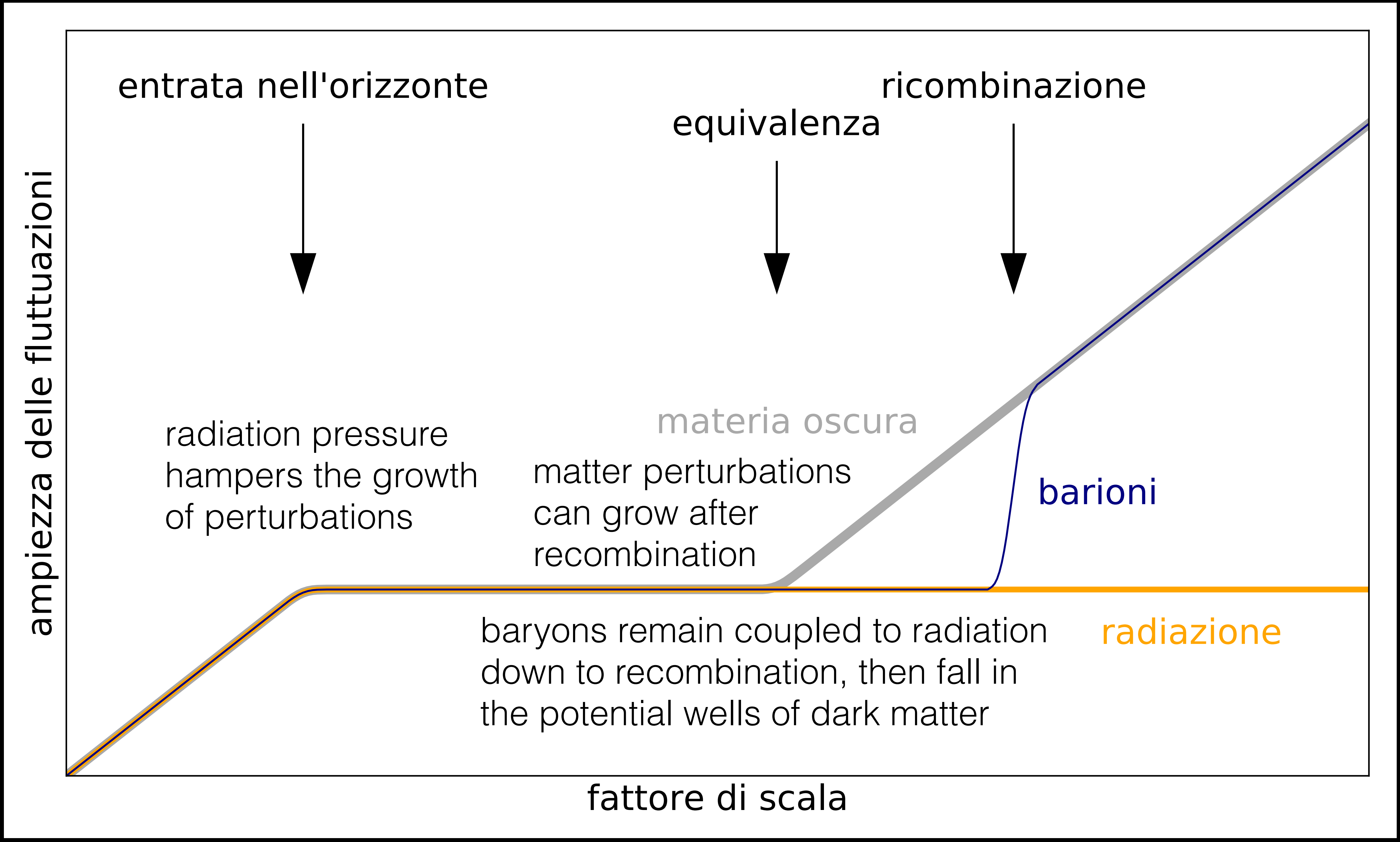
Fourier transform

$$\tilde{\delta}_{\overrightarrow{k}} = \frac{1}{(2\pi)^3} \int_V d^3\overrightarrow{x}\,\delta(\overrightarrow{x})\, e^{-i\overrightarrow{k}\cdot\overrightarrow{x}}$$

power spectrum

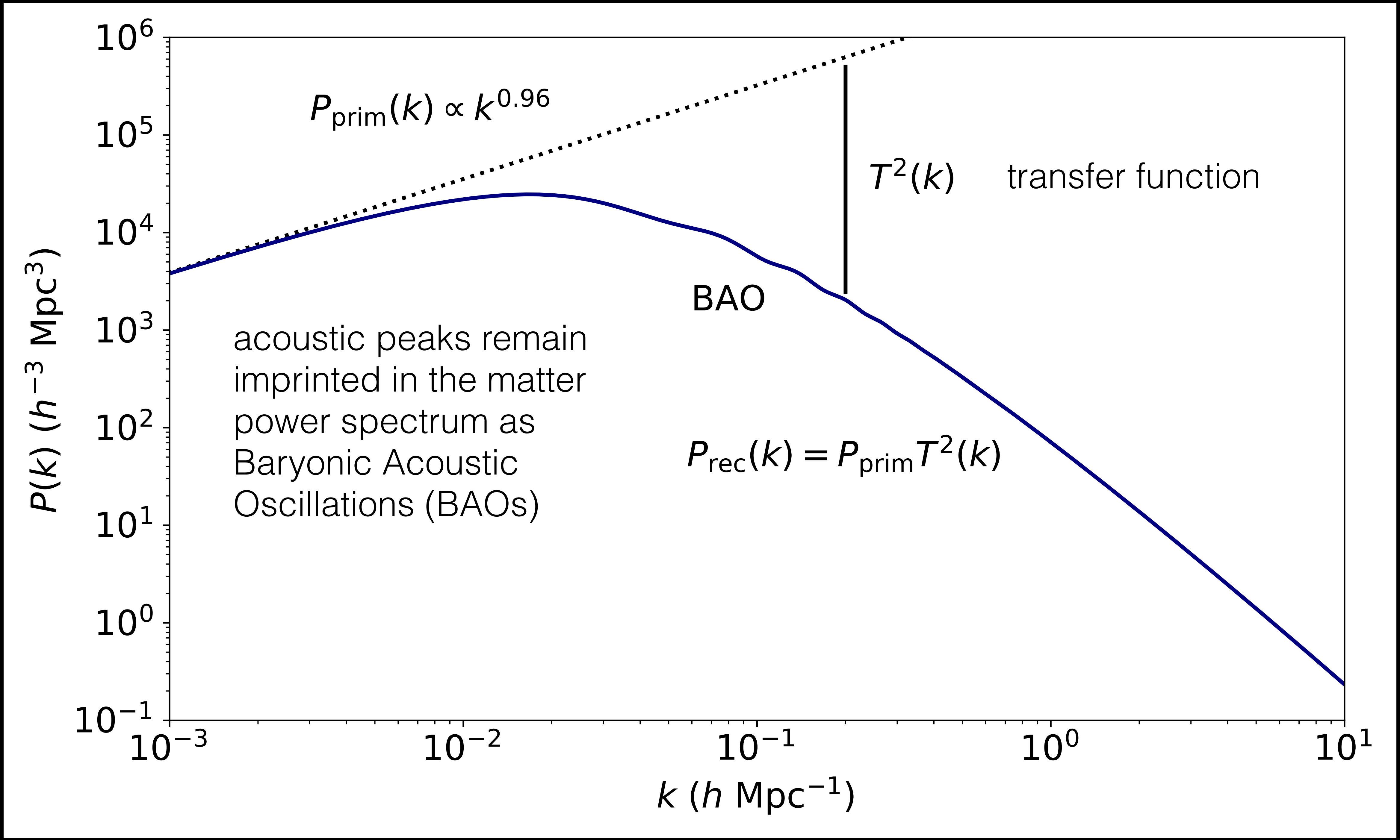
$$P(k) = \langle\, |\tilde{\delta}_{\overrightarrow{k}}|^2 \rangle$$

Evolution of perturbations

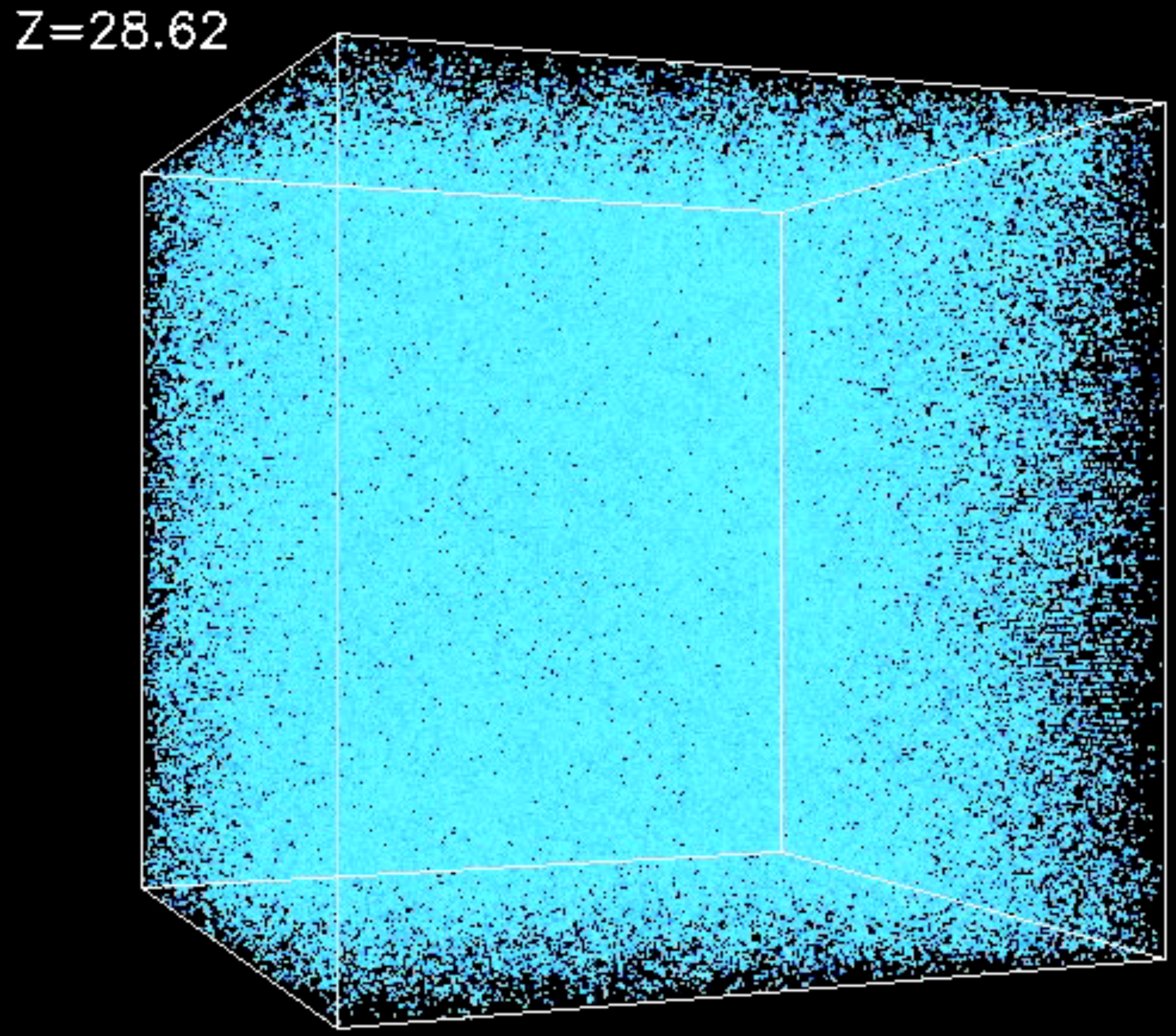


Evolution of perturbations

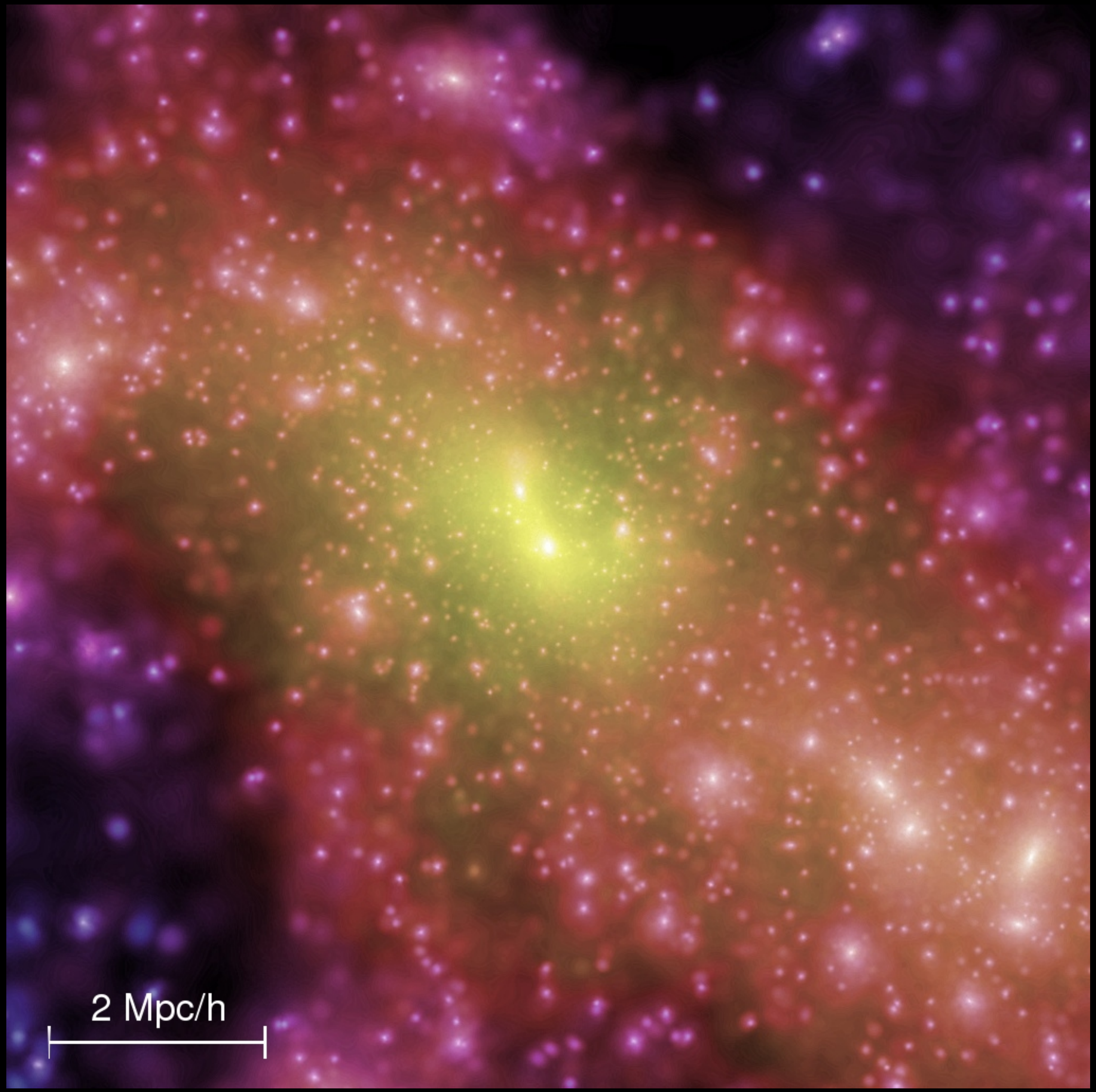
an unspecified process imprints
primordial fluctuations



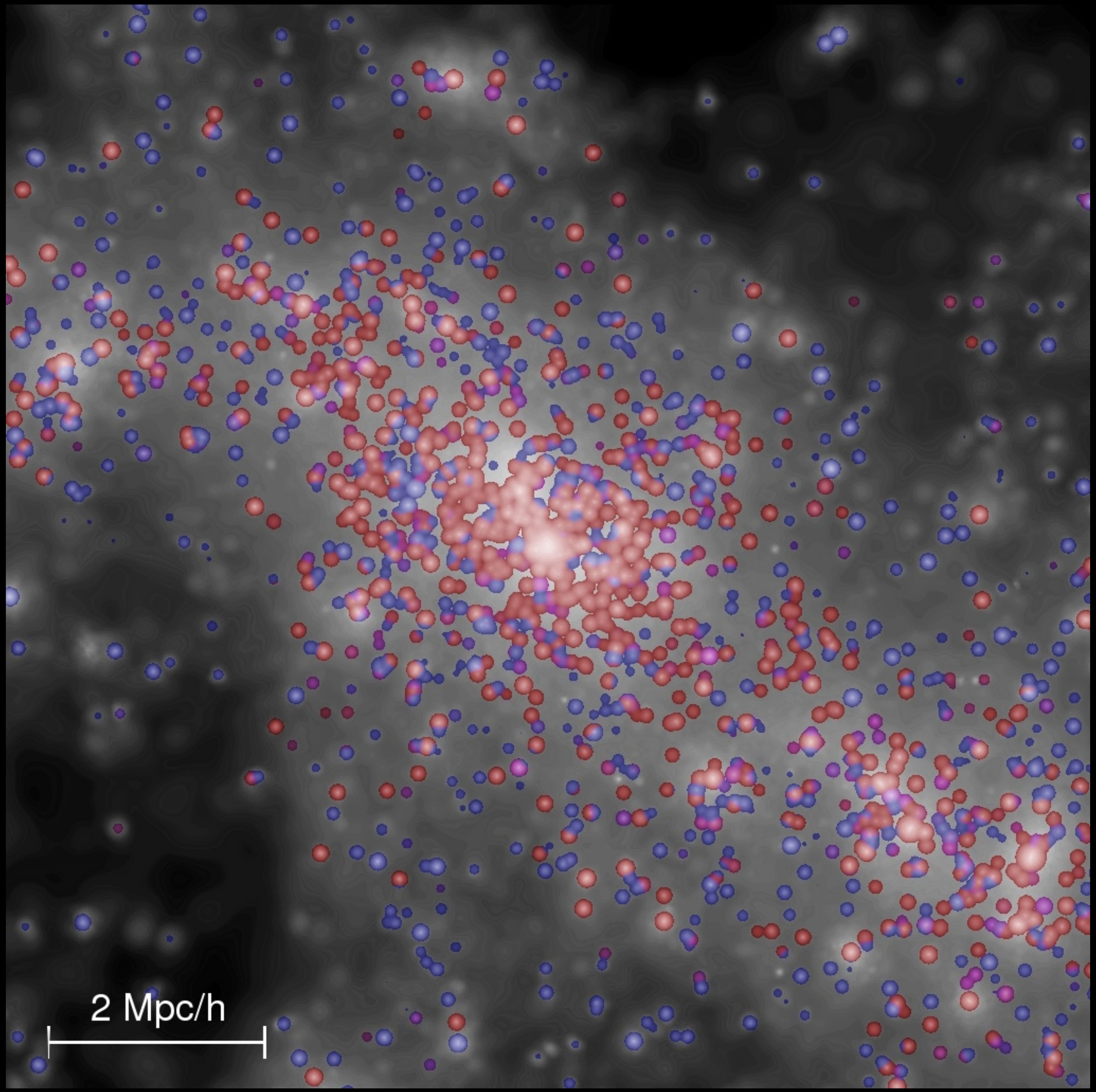
Matter perturbations evolve under their own gravity



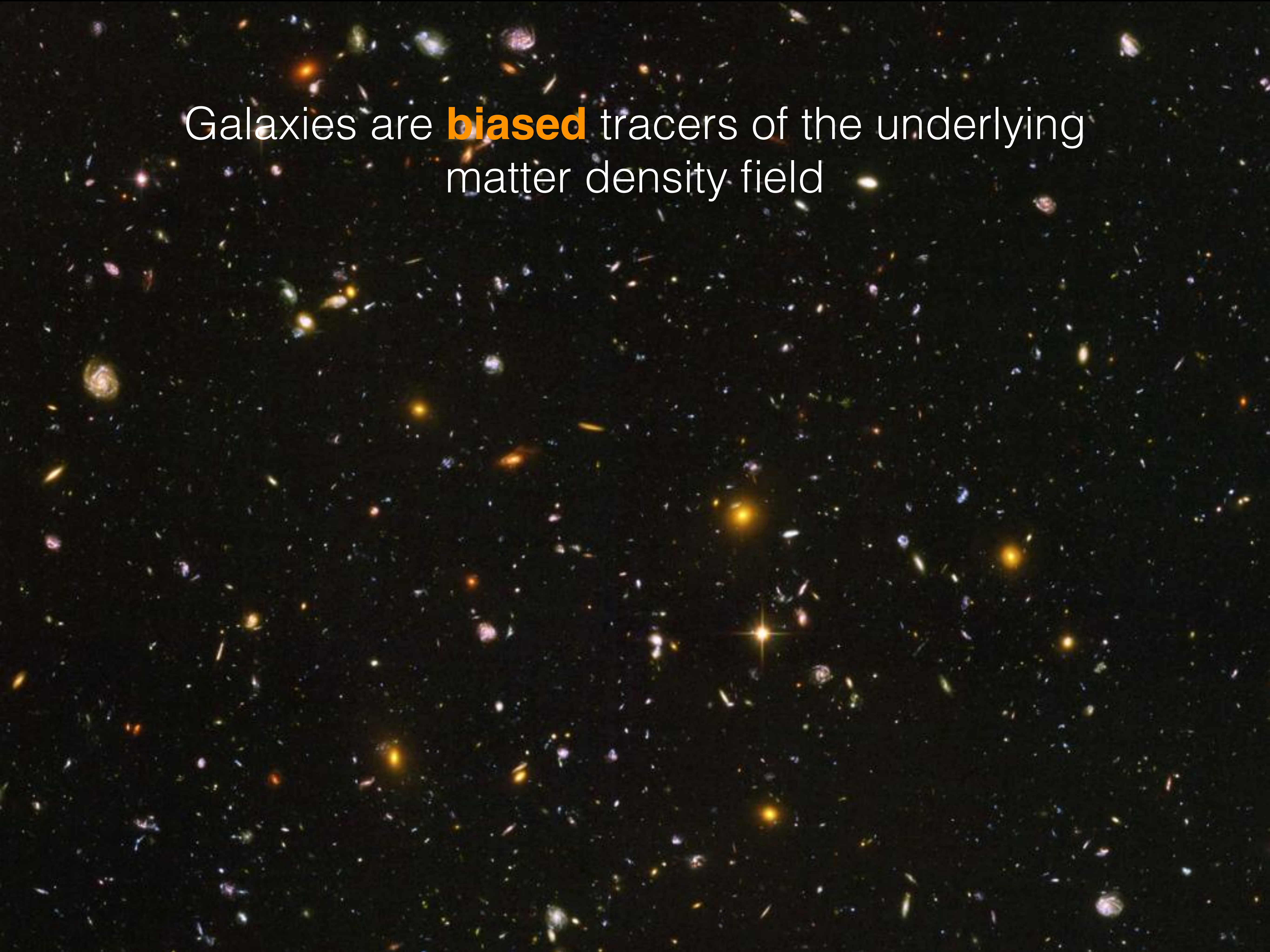
...then collapses into dark matter halos, where star formation can start and galaxies form

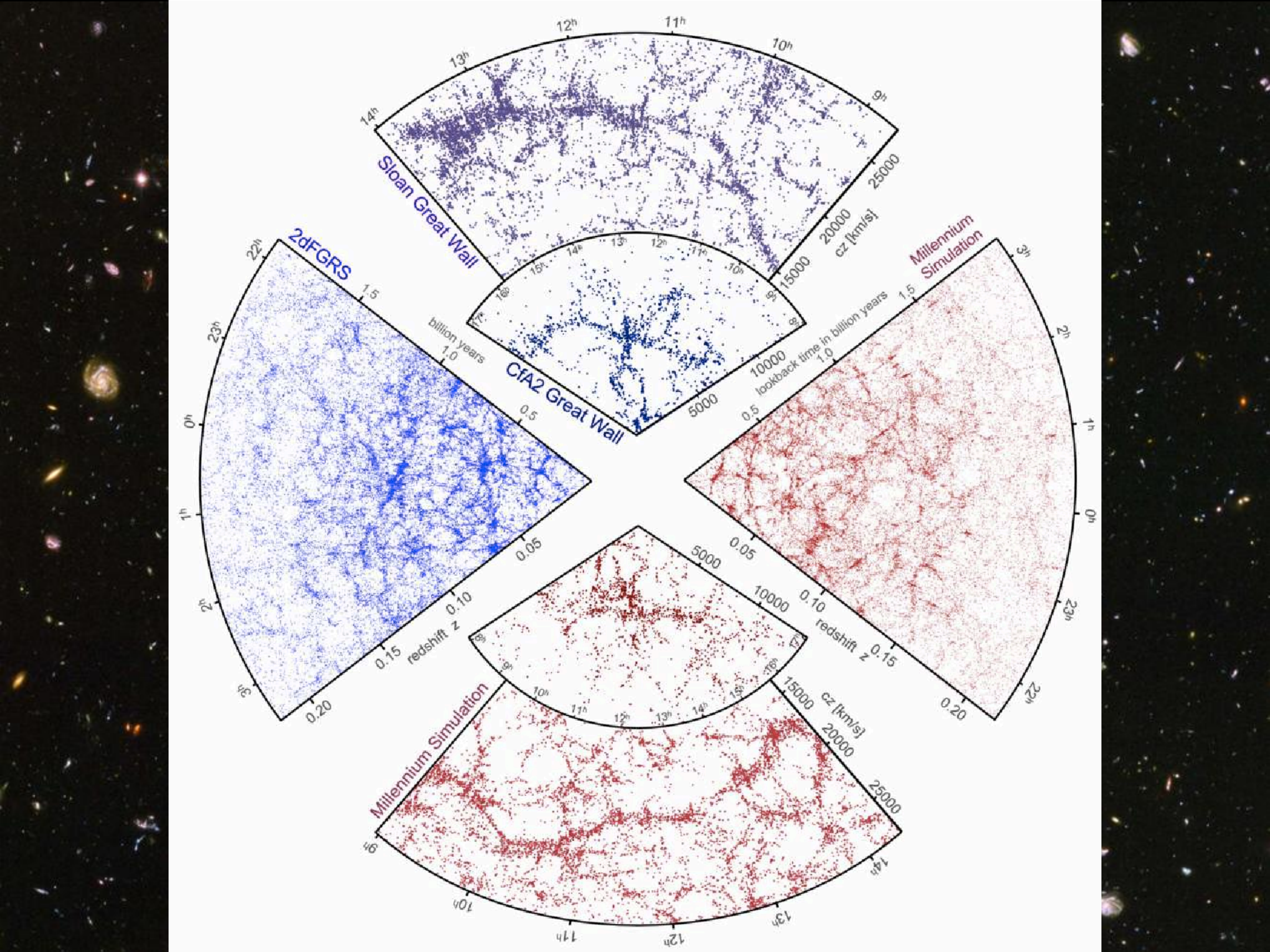


dark matter



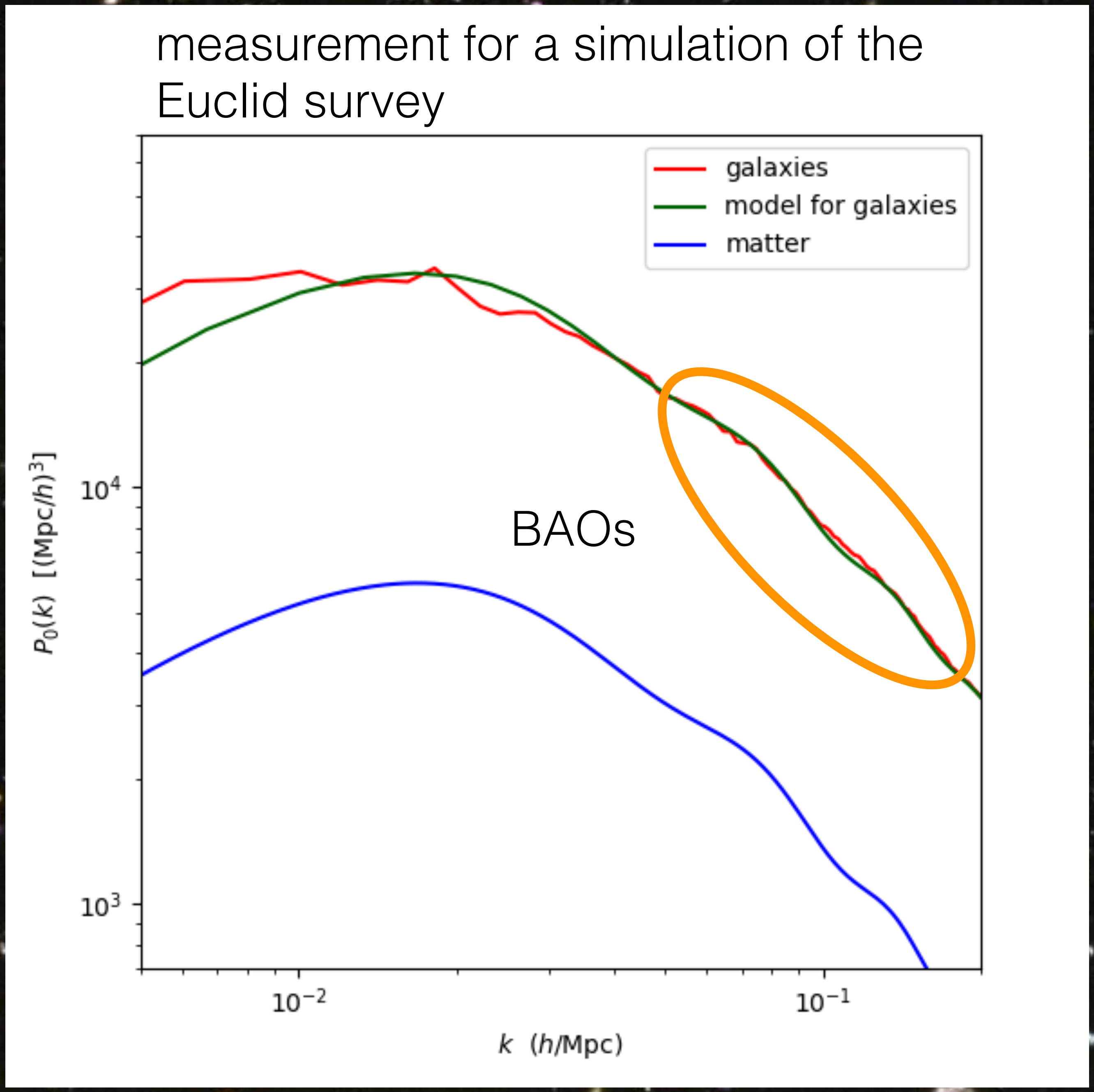
galaxies


Galaxies are **biased** tracers of the underlying matter density field



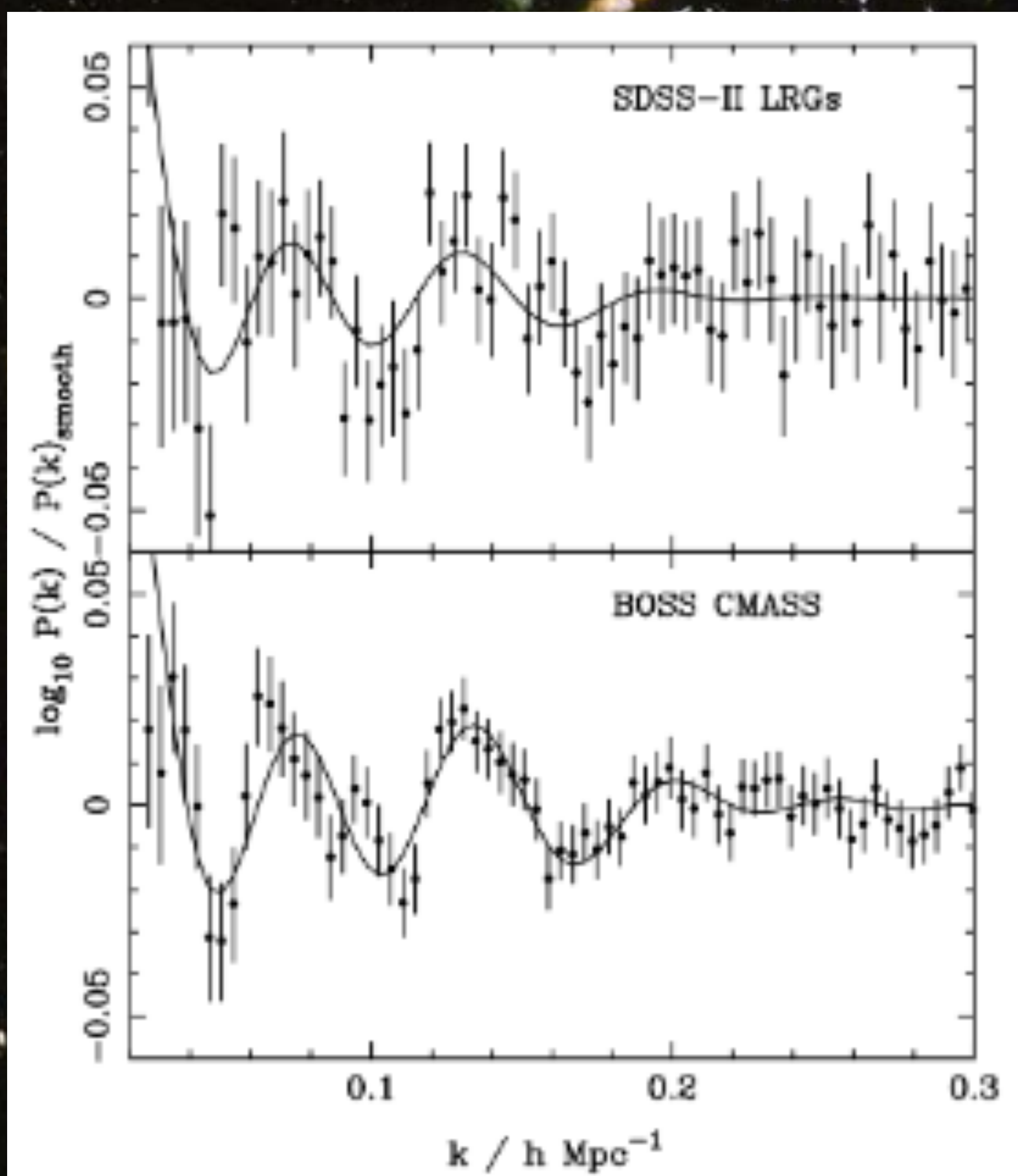
Sloan Great Wall
2dFGRS
CfA2 Great Wall
Millennium Simulation
Millennium Simulation
cz [km/s]
redshift z
lookback time in billion years
billion years

Galaxies are **biased** tracers of the underlying matter density field

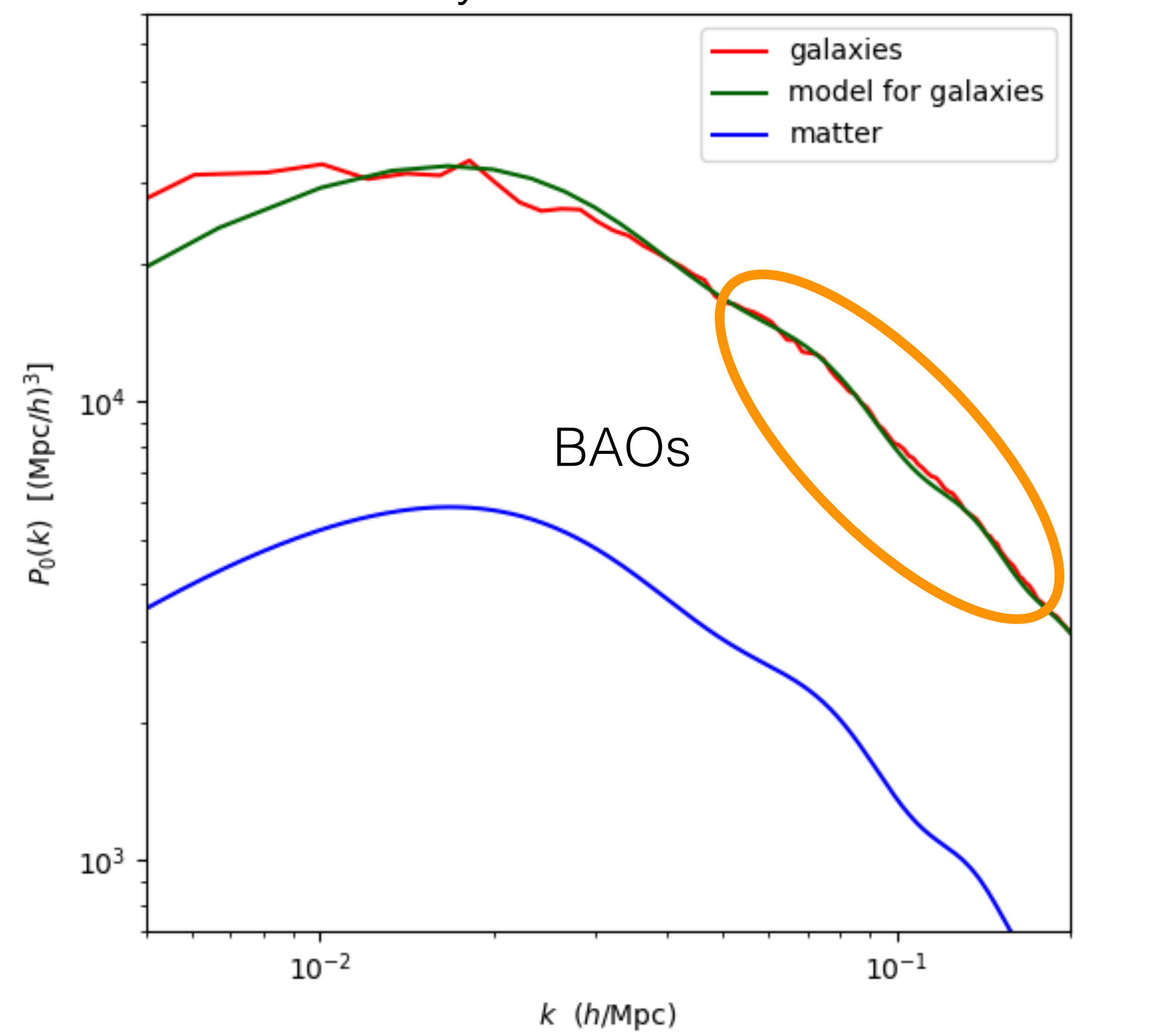


Galaxies are **biased** tracers of the underlying matter density field

measurement for the Baryonic Oscillations Spectroscopic Survey

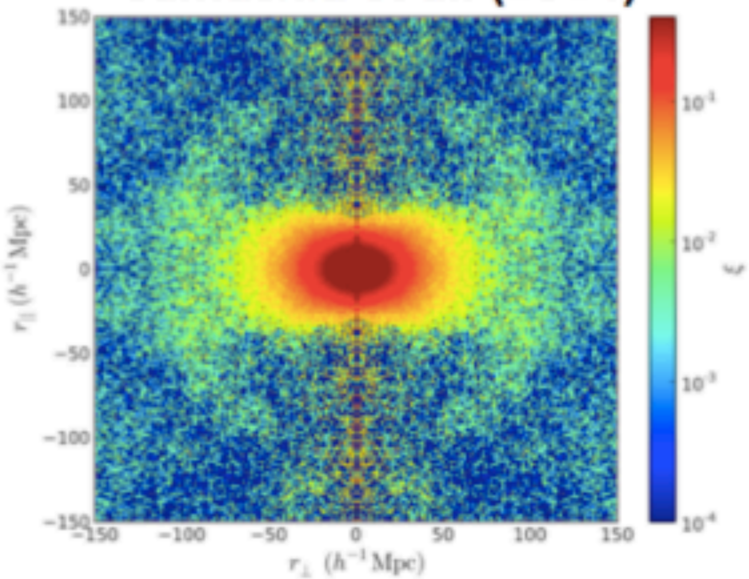


measurement for a simulation of the Euclid survey

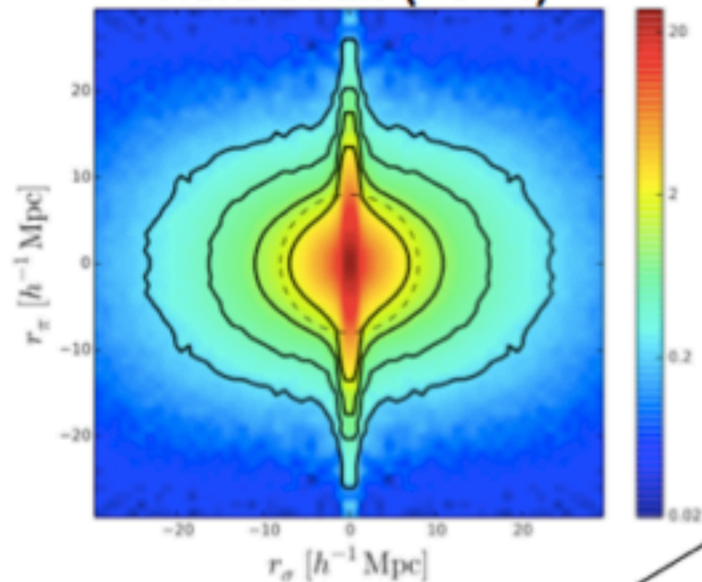


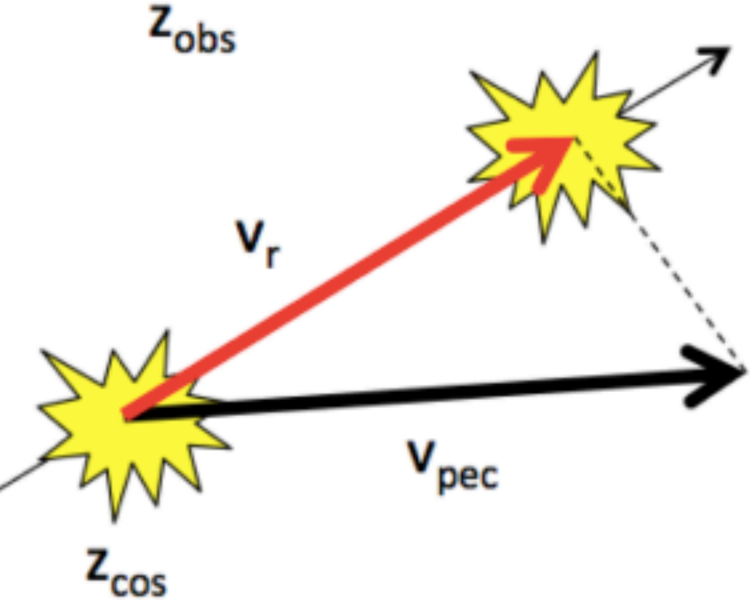
Redshift-space distortions

Samushia et al. (2014)



Reid et al. (2014)





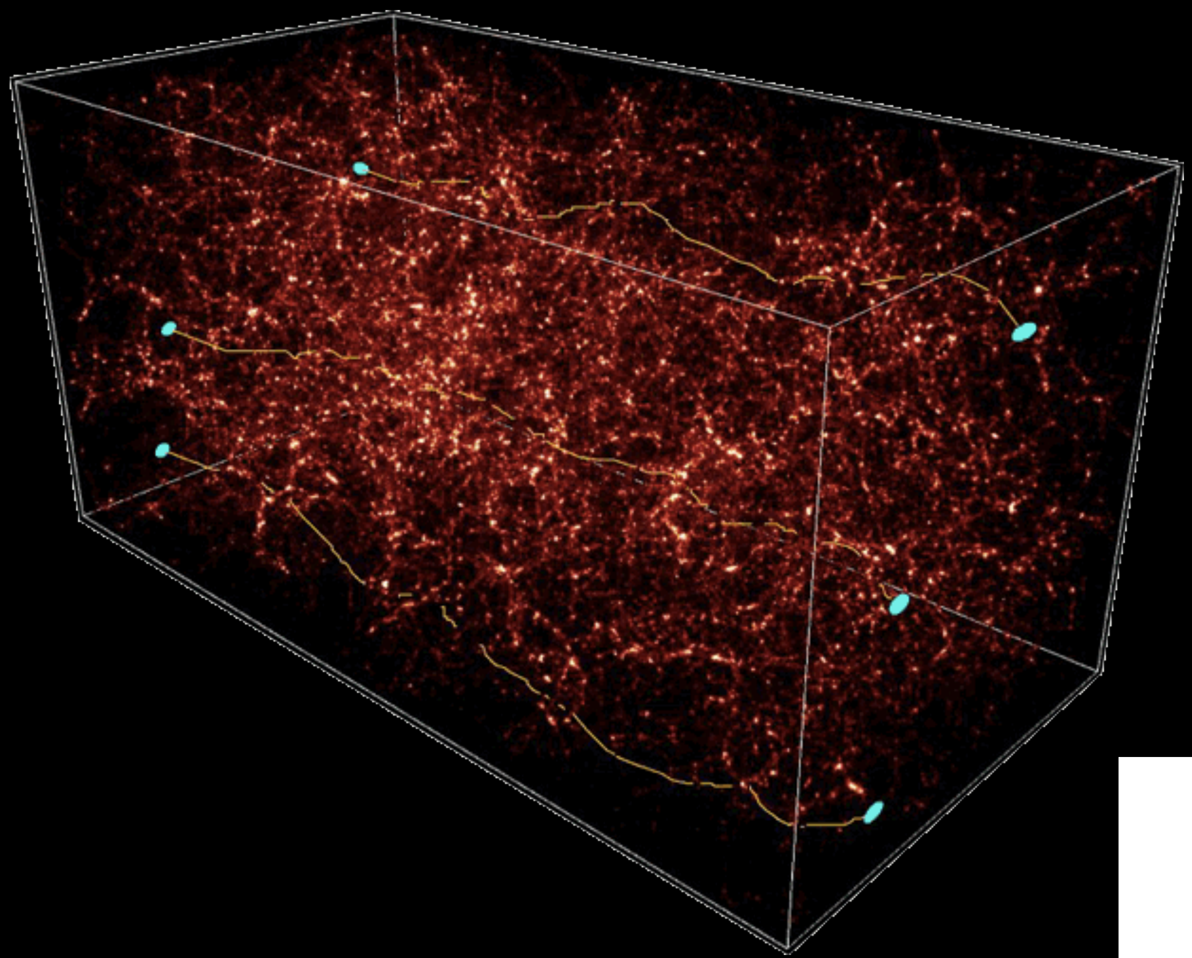
anisotropic power spectrum

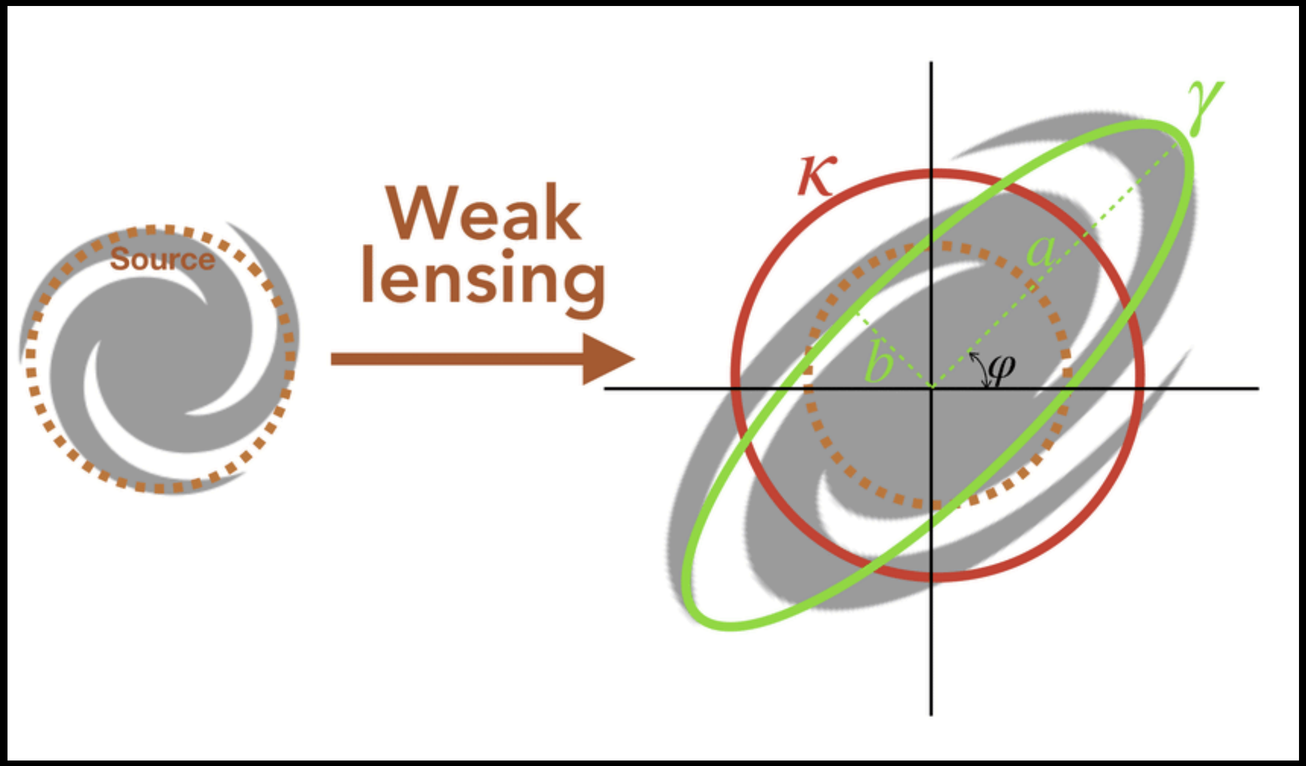
$$1 + z_{obs} = (1 + z_{\cos})(1 + \frac{v_r}{c})$$

Over-dense regions (eg galaxy clusters) and under-dense regions (eg voids) induce additional peculiar velocities relative to the Hubble flow.

Credit: Cristiano Porciani

Galaxy images are subject to weak lensing





Programme

+ Thermodynamics of the early Universe

+ Quantum fields in a FRW universe

+ From the Planck era to inflation

+ Big bang nucleosynthesis

+ Recombination and matter-dominated era