Introduction to astroparticle physics

Part 1: Andrii Neronov

Cosmic ray physics

... direct continuation of research started by V.Hess

Gamma-ray astronomy

.... application of particle physics methods in astronomy

Gravitational waves

Neutrino physics

* neutrino oscillations
* high-energy neutrino astronomy

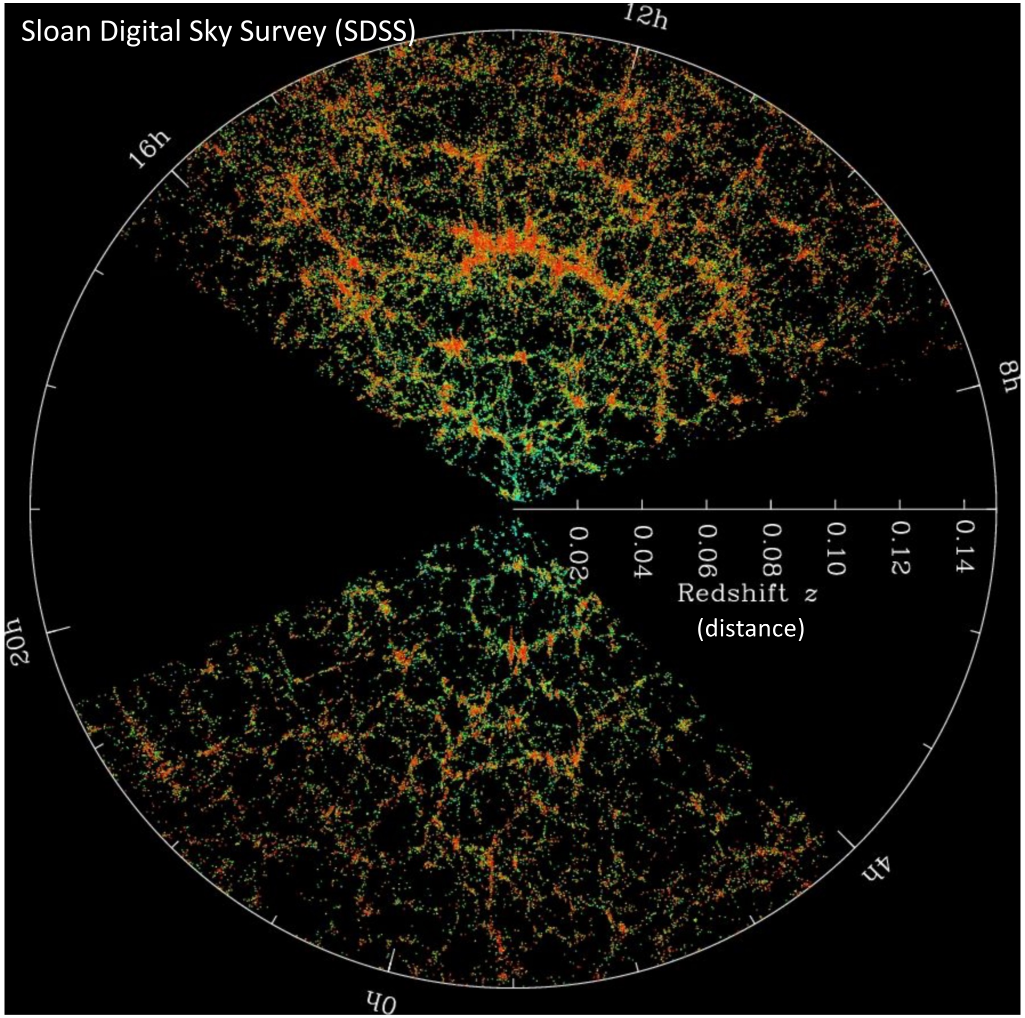
Dark matter physics

... direct continuation of research started by F.Zwicky

Particle physics in the Early Universe

... direct continuation of research started by Gamow

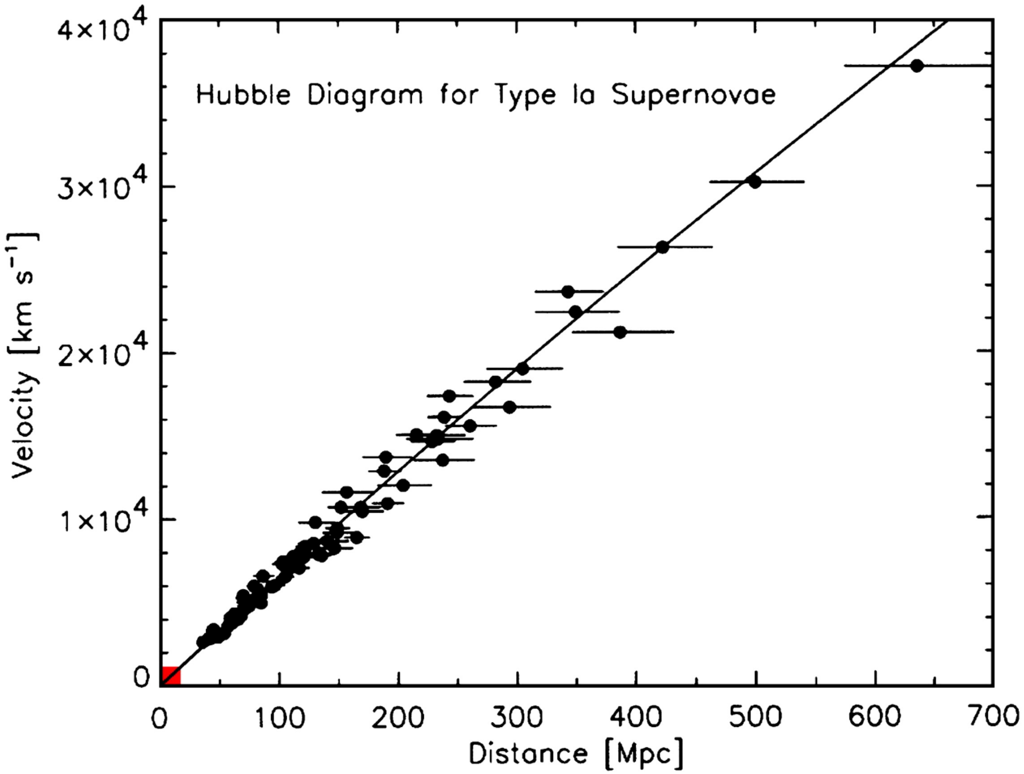
Matter distribution in the Universe



Astronomical data indicate that galaxies are distributed homogeneously and isotropically throughout the Universe.

Toy model: a gas of galaxies with average density ρ.

Expansion of the Universe



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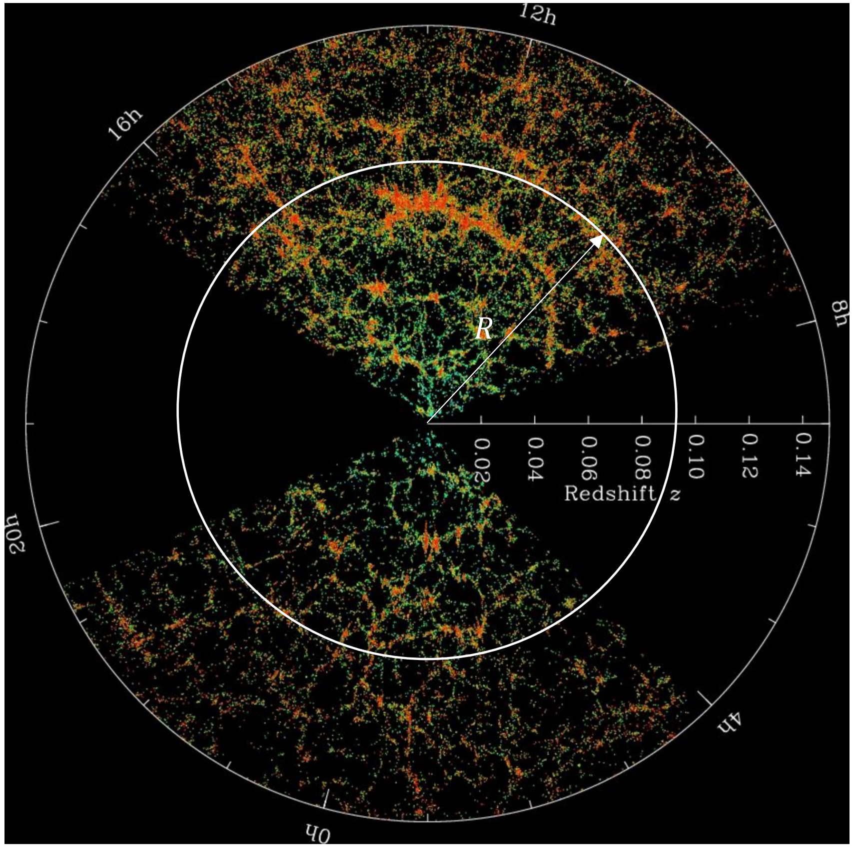
The galaxy distribution is not static. The velocity pattern follows the Hubble law: the velocity is predominantly radial, scaling proportionally to the distance

$$v = H_0 d$$

$$H_0 \simeq 70 \frac{\text{km/s}}{\text{Mpc}}$$

Such a velocity pattern corresponds to homogeneous expansion of the ”gas of galaxies”. The density of the galaxy gas decreases with time $\rho = \rho(t)$.

Expansion of the Universe



Toy dynamical model of expanding Universe in Newtonian gravity. Consider a galaxy of mass m at the distance R from an (arbitrary) origin of coordinate system.

The mass inside the shell is $M = \frac{4\pi}{3} R^3 \rho$.

The galaxy moves radially, its velocity is $V = \dot{R}$.

The mechanical energy of the thin shell is conserved:

$$\frac{mV^2}{2} - \frac{GMm}{R} = E_{tot} = cons$$

$$\frac{\dot{R}^2}{2} - \frac{GM}{R} = \frac{E_{tot}}{m}$$

$$\frac{\dot{R}^2}{2} - \frac{4\pi G \rho R^3}{3R} = \frac{E_{tot}}{m}$$

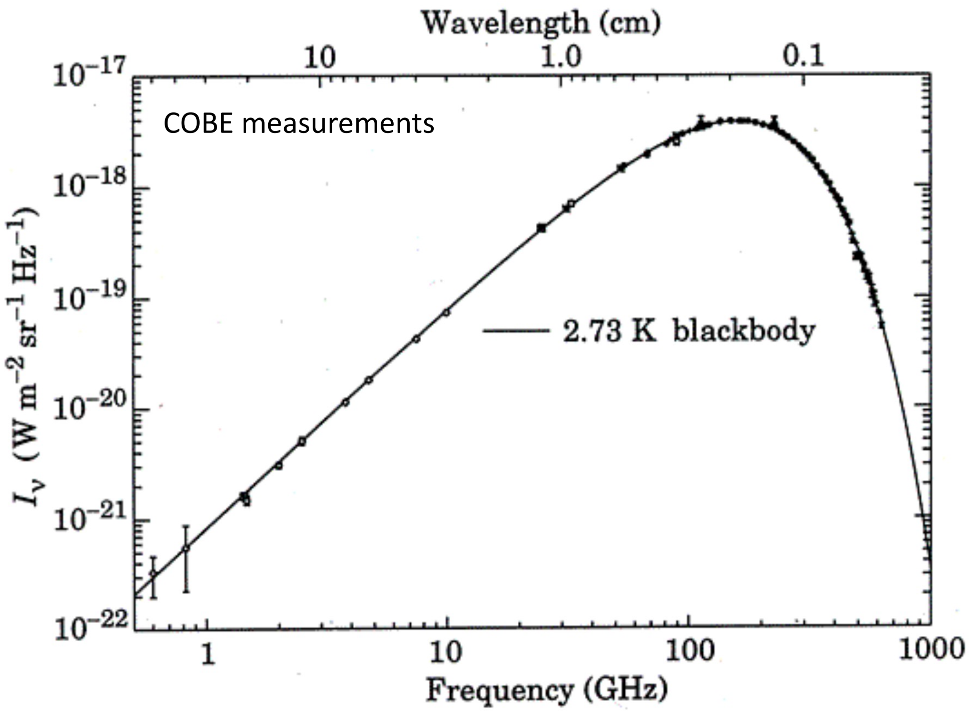
$$H^2 = \frac{\dot{R}^2}{R^2} = \frac{8\pi G}{3}\rho + \frac{E_{tot}/m}{R^2}$$

Here H is the "expansion rate" (measured in $1/s$, i.e. in the same units as H_0). Identifying H with H_0 we obtain an estimate of the density scale of matter in the Universe:

$$\rho_0 = \frac{3H_0^2}{8\pi G} \simeq 10^{-29} \frac{\mathrm{g}}{\mathrm{cm}^3}$$

This density scale is two orders of magnitude larger than an estimate that can be obtained via account of all matter visible in telescopes ("luminous matter"): stars and gas in galaxies. This is the first indication of the presence of "dark" matter.

Cosmic Microwave Background Radiaiton



Observations show that the Universe is filled with thermal radiation with temperature $T \simeq 2.73$ K (Cosmic Microwave Background, CMB).The density of the CMB is

$$n \simeq 4\times10^2 \frac{\mathrm{ph}}{\mathrm{cm}^3} \propto T^3$$

Expansion of the Universe dilutes this density:

$$n \propto R^{-3}$$

This dilution is accompanied by the decrease of temperature:

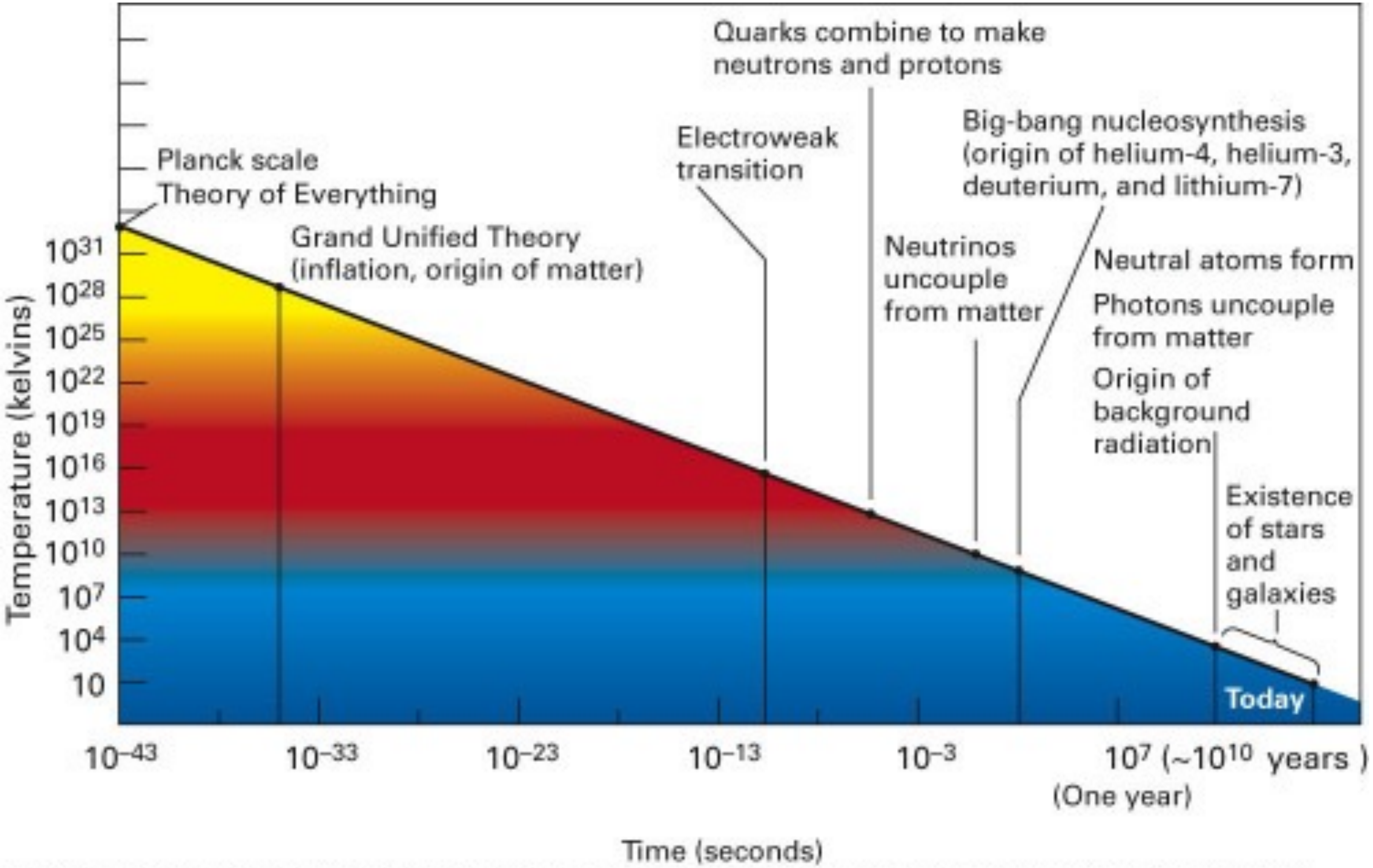
$$n \propto R^{-3} \propto T^3$$

$$T \propto \frac{1}{R} \propto t^{-2/3}$$

in the the present-day Universe.

The temperature was higher in the past. The density was higher in the past. Overall, the Universe was (arbitrarily) hot and dense in the past: for any temperature scale T_*, it is possible to find a moment when the temperature of radiation was $T \sim T_*$.

Thermal history of the Universe



Exercise 1

Calculate energy density of CMB in the present-day Universe (in eV/cm^3). Compare to the critical density of the Universe (also expressed in eV/cm^3).

Exercise 2

Consider the Universe at the moment when it was 10^9 times smaller than today ($R = 10^{-9}$, if we normalize $R = 1$ today). Find the average energy, energy density and number density of the photon gas that was filling the Universe at that moment of time. Compare with the number and energy density of "matter", assuming that it consists of matter similar to hydrogen gas (particles with masses $m = m_p$, that today have density $\rho \simeq \rho_{cr}$).