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

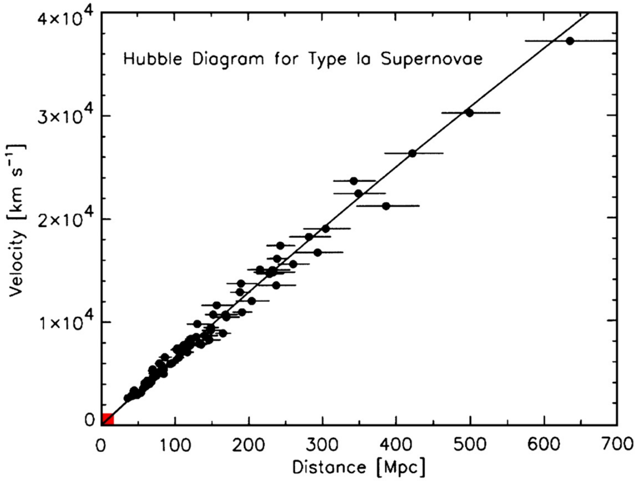
Dark matter physics

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

Particle physics in the Early Universe

... direct continuation of research started by Gamow

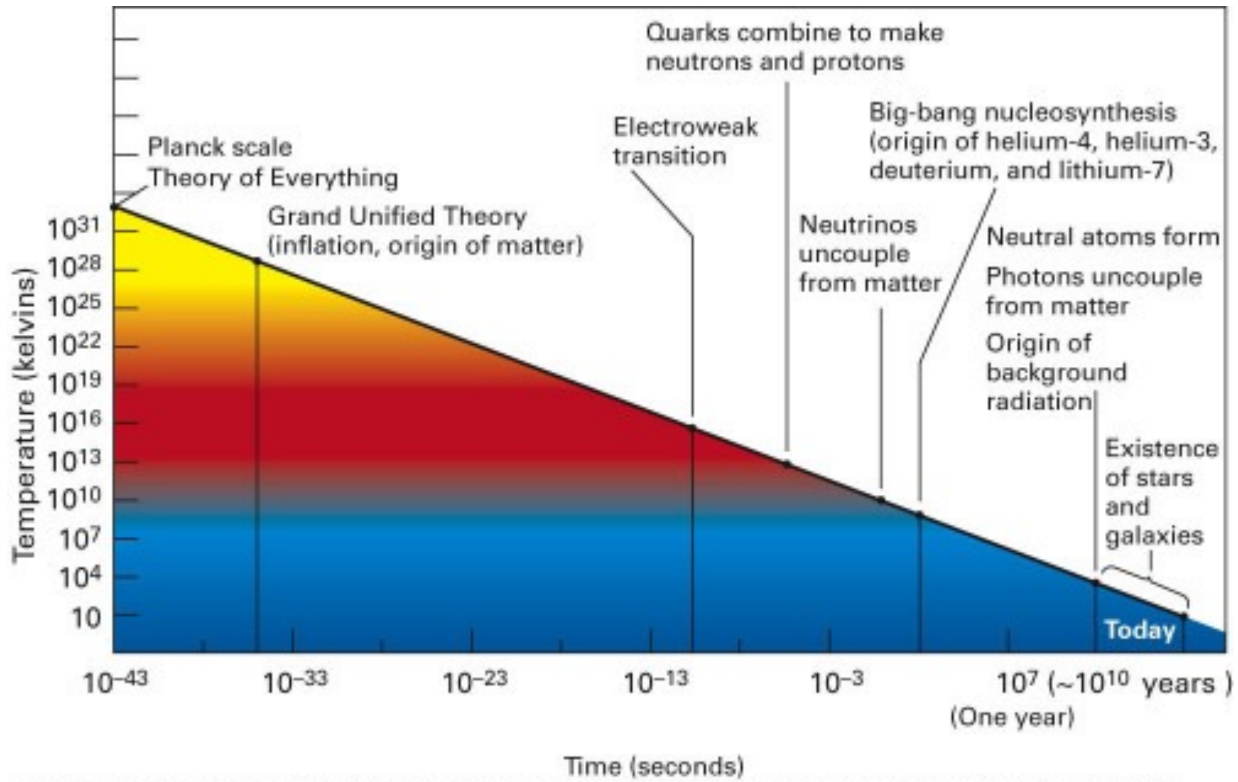
Reminder previous lecture



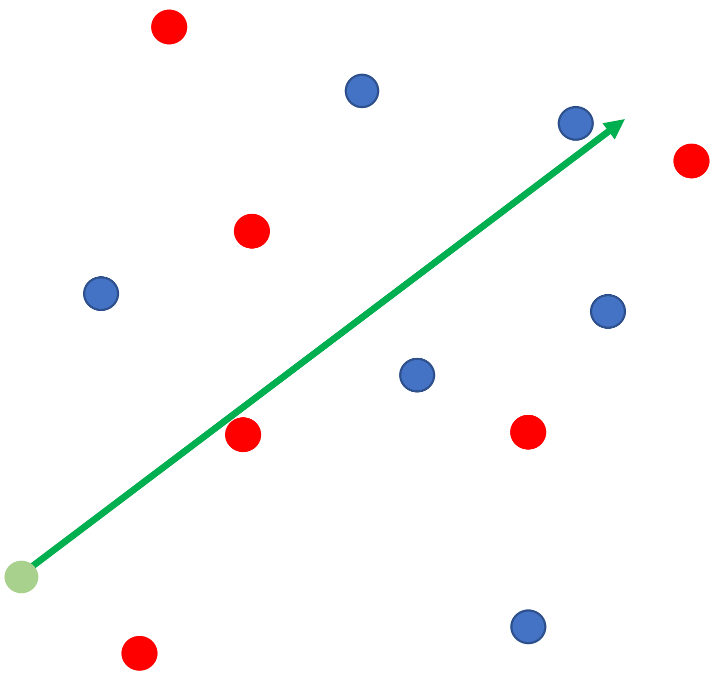
$$v = H_0 d$$

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

$$H^2 = \frac{\dot{R}^2}{R^2} = \frac{8\pi G}{3}\rho; \qquad \rho_0 = \frac{3H_0^2}{8\pi G} \simeq 10^{-29}\frac{\mathrm{g}}{\mathrm{cm}^3}$$



Neutrinos as dark matter?



Neutrinos interact with electrons / positrons / nucleons through weak interaction reactions:

$$n \leftrightarrow p + e^- + \overline{\nu}_e; p + e^- \leftrightarrow n + \nu_e; e^+ + e^- \leftrightarrow \overline{\nu}_e + \nu_e; \ldots$$

with cross-section

$$\sigma_w \sim G_F^2 \langle E \rangle^2$$

where $G_F \simeq 10^{-5}\mathrm{GeV}^{-2}$ is the Fermi constant and $\langle E \rangle$ is the "characteristic" energy scale.

Neutrino mean free path / interaction time scale:

$$t_{int} \sim \lambda = \frac{1}{\sigma_w n} \sim \frac{1}{G_F^2 T^2} \frac{1}{T^3} = \frac{1}{G_F^2 T^5}$$

This time scale can be shorter or longer than time elapsed from the Big Bang moment $R = 0$:

$$t_H = H^{-1} = \sqrt{\frac{3}{8\pi G_N \rho}} \sim \frac{1}{G_N^{1/2}\, T^2}$$

Neutrino interaction time scale is comparable to the Hubble time scale when

$$\frac{1}{G_F^2 T^5} \sim \frac{1}{G_N^{1/2} T^2}$$

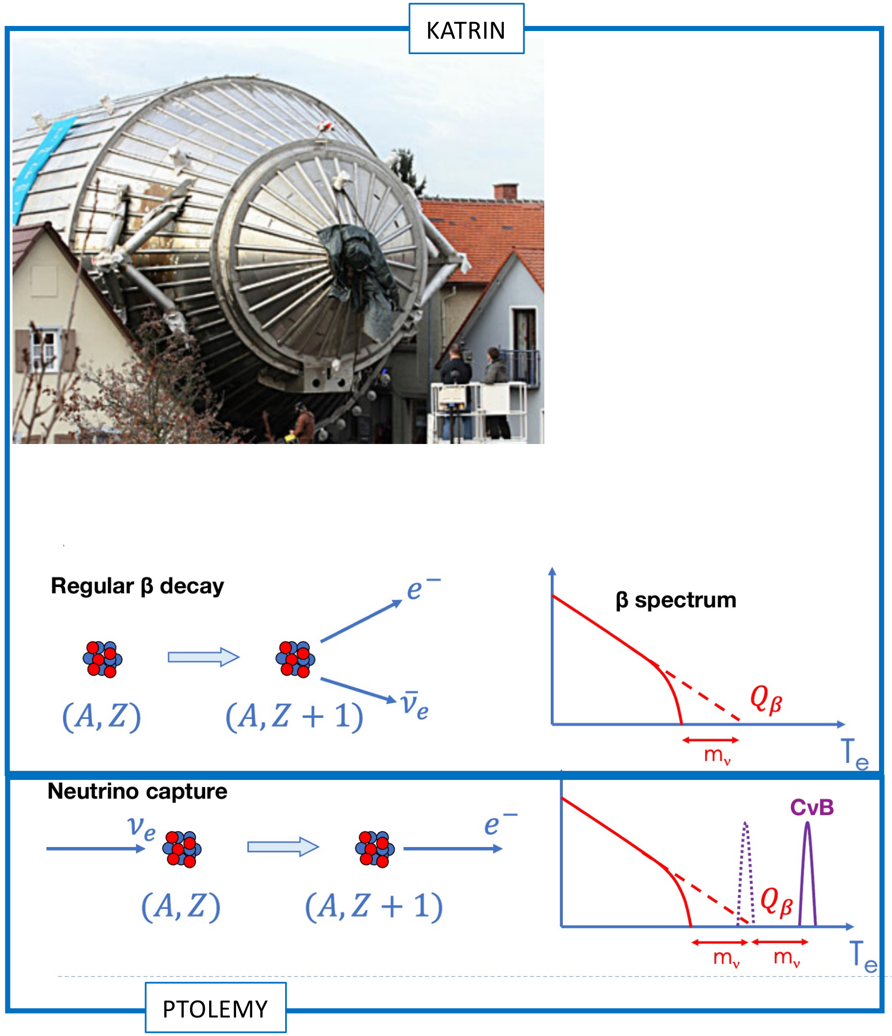
$$T_* \sim \frac{G_N^{1/6}}{G_F^{2/3}}$$

The moment when the temperature of the Universe drops down to $T_* \simeq 10^{10}$ K ($k_B T \sim 1$ MeV) defines the moment of "decoupling" of neutrino. Starting from this moment, neutrinos stop interacting. Their density keeps decreasing because of expansion of the Universe:

$$n_\nu \propto \frac{1}{R^3}$$

* Formulas in the lecture notes use Natural system of units: $\hbar = 1; c = 1; k_B = 1$

Cosmological neutrino background



$$n_\nu = n_* \frac{R_*^3}{R^3} \sim 10^2 \frac{1}{\mathrm{cm}^3}$$

(compare with density of photons of Cosmic Microwave Background: $n_\gamma \simeq 4{\times}10^2\ \mathrm{cm}^{-3}$).

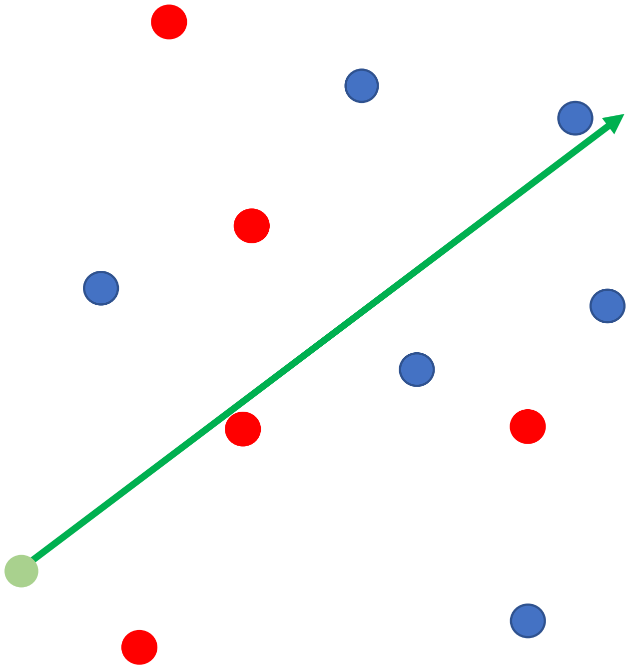
Neutrino mass density in today's Universe is

$$\rho_\nu \simeq m_\nu\ n_\nu \simeq 10^{-29} \left(\frac{m_\nu}{100\ \mathrm{eV}}\right) \frac{\mathrm{g}}{\mathrm{cm}^3}$$

Neutrino masses (rest energies) are below $1\ \mathrm{eV}$, so that neutrinos cannot constitute the dark matter.

PTOLEMY experiment plans to use measurement of the energy spectrum of electrons from beta-decays of atomic nuclei to catch events of "induced" beta decay initiated by interactions of the cosmological neutrinos

Weakly interacting massive particles



Consider neutrino-like particles that participate in the Weak interactions, with cross-section

$$\sigma_w \sim G_F^2 \langle E \rangle^2$$

But are much more massive than neutrinos, perhaps $M \gg m_\nu$. Such particles should have also been in thermal equilibrium in the Early Universe, as long as their interaction time scale

$$t_{int} = \frac{1}{\sigma_w \, v n} < t_H$$

If, at the moment of decoupling ($t_{int} \sim t_H$) the particles are already non-relativistic ($Mc^2 > T$), their number density is given by the Maxwell-Boltzmann distribution:

$$n = \left(\frac{MT}{2\pi}\right)^{3/2} \exp\left(-\frac{M}{T}\right); \quad \frac{Mv^2}{2} = \frac{3}{2} T$$

The moment of decoupling is then

$$\frac{1}{\sigma_w} \left(\frac{M}{3T}\right)^{\frac{1}{2}} \left(\frac{2\pi}{MT}\right)^{\frac{3}{2}} \exp\left(\frac{M}{T}\right) = \frac{1}{G_N^{\frac{1}{2}} T^2}$$

$$T_* \sim \frac{M}{\ln(G_N^{-\frac{1}{2}} \, \sigma_w M)} \sim \frac{M}{\ln(G_F^2 M^3 M_{Pl})} \sim 0.1\, M \quad \left(M_{pl} = G_N^{-\frac{1}{2}}\right)$$

At the moment of decoupling,

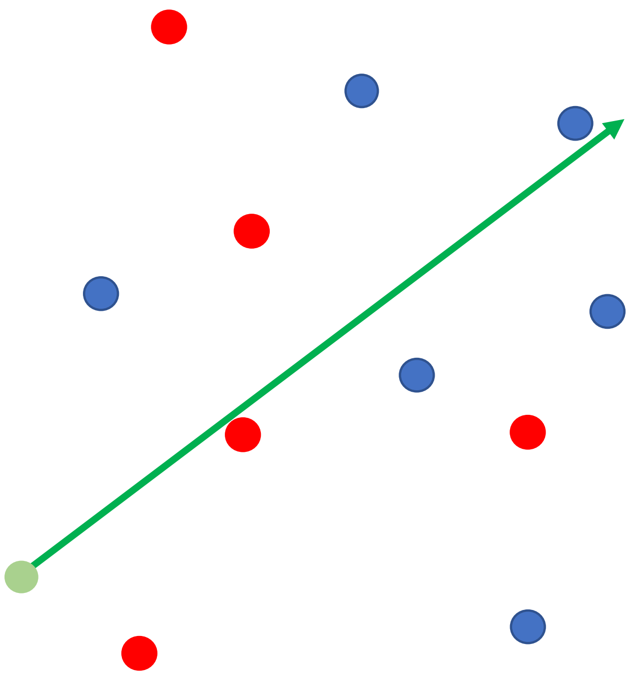
$$n_* \sim \frac{G_N^{1/2}\, T_*^2}{\sigma_w v}$$

Today:

$$n_0 = \left(\frac{R_*}{R_0}\right)^3 n_* \sim \left(\frac{T_0}{T_*}\right)^3 \frac{G_N^{\frac{1}{2}}\, T_*^2}{\sigma_w v}; \; \rho_0 = M n_0 \sim \frac{G_N^{\frac{1}{2}}\, T_0^3}{\sigma_w v} \frac{M}{T_*} \sim 0.1 \frac{G_N^{\frac{1}{2}}\, T_0^3}{\sigma_w v} \simeq 10^{-29} \left(\frac{\sigma v}{10^{-25} \mathrm{cm}^3/\mathrm{s}}\right) \frac{\mathrm{g}}{\mathrm{cm}^3}$$

The mass density of "weakly interacting massive particles" depends only on their cross-section!

Exercise: baryon asymmetry of the Universe



Concentrations of quarks and antiquarks in thermal equilibrium are equal. change, this leads to equal concentrations of baryons and antibaryons. Baryons and antibaryons annihilate with cross-section $\sigma_\pi v \propto m_\pi^{-2}$ ($m_\pi c^2 \simeq 100$ MeV is the rest energy of pions, particles made of two quarks).

The annihilation process has stopped at some T_* of decoupling ($t_{int} \sim t_H$) when the particles were already non-relativistic ($m_p c^2 > T$), ($m_p \simeq 1$ GeV, proton mass). Find this temperature. Find the ratio η of number densities of protons and neutrons to the number density of photons at the moment of decoupling.

Starting from this decoupling moment, the value of η does not change: both baryon and photon number density are changing inversely proportionally to the volume.

Use this fact to the expected mass density of baryons today, as a fraction of the critical density. Is this number consistent with $\Omega_b \simeq 0.05$?