Cosmoarcheology (cosmological probes for particle physics)

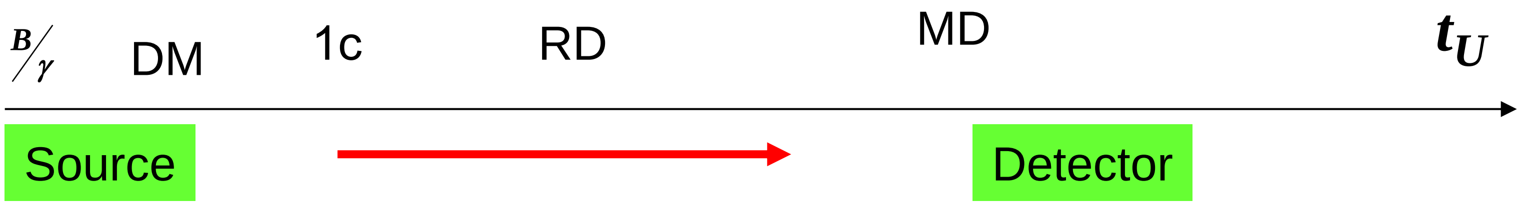
Lecture from course

“Cosmoparticle Physics”

Outlines

- Constraints on neutrino mass
- « Integral » detectors of the Universe: Age of the Universe, Primordial helium abundance, LSS and PBHs
- « Differential detectors » of the Universe
- Non-equilibrium particles
- Experimental nuclear cosmoarcheology
- Astro-nuclear experiment ASTROBELIX
- Problem of primordial gravitino

Cosmoarcheology treats the set of astrophysical data as the experimental sample shedding light on possible properties of new physics. Its methods provide *Gedanken Experiment*, in which cosmophenomenology of new physics is considered as the source, while its effects on later stages of expansion are considered as detector, fixing the signatures for these effects in the astrophysical data.



These « detectors of the Universe » can be « integral » (sensitive to very existence of new forms of matter) and « differential » (sensitive to some particular effect of such forms of matter)

Detectors of the Universe

- Integral detectors (age of the Universe, primordial He, LSS, PBH) are sensitive to the contribution of a new form of matter (or products of its decay) to the total cosmological density.
- Differential detectors are sensitive to presence of decay products of definite type ($\bar{p}, \gamma, \nu ...$).

Integral detectors

Indicators of the very fact of presence of any form of matter in the Universe

Age of the Universe

$$t_U\left(\Omega, p(\rho)\right)$$

Lower limit on the age of the Universe puts upper limit on the total cosmological density

WMAP, PLANCK

$$\Omega = 1$$

Any new form of matter can not give larger contribution to the total density. At large value of the Hubble constant the estimated age of the Universe favors the presence of “dark energy” and the acceleration of the modern cosmological expansion

Stable particles from Big Bang

- Stable particles should be created in very early Universe and remain at successive stages
- If theory predicts new stable particles, they should obey this rule.
- Their presence in the Universe should not contradict its observed properties

Cosmochronology

Very early Universe

***T*~1 MeV, *t*~1 s**

n/p freezing out,
ν-decoupling

***T*~0.1 MeV, *t*~100 s**

Nucleosynthesis

***T*~1 eV, *t*~30000 yr**

RD->MD

***T*~3000 K,**
***t*~400000 yr**

Recombination

***t*~1 Gyr**

Galaxy
formation

t~3 Gyr

Λ-dominance

***t*~10 Gyr**

Modern
epoch

Constraint on number of neutrino species

Constraint on the mass of neutrino

Relic neutrinos

Primordial neutrinos are inevitable relic of hot stages with T>1MeV. Their modern concentration is related with the concentration of relic photons

$$n_{\nu\bar{\nu}}^{(\mathrm{mod})} = \frac{4}{11}\frac{T_{\mathrm{mod}}^3}{T_*^3} n_{\nu\bar{\nu}}^{(*)} = \frac{4}{11}\frac{T_{\mathrm{mod}}^3}{T_*^3}\frac{3}{4} n_{\gamma}^{(*)} = \frac{3}{11} n_{\gamma}^{(\mathrm{mod})}$$

for one neutrino species

$$n_{\nu\bar{\nu}}^{(\mathrm{mod})} = \frac{3}{11} n_{\gamma}^{(\mathrm{mod})} \approx 110\,\mathrm{cm}^{-3}$$

If these neutrinos have nonzero mass one can take product of their mass and concentration and compare it with total density.

Density of massive neutrinos

Contribution of massive neutrinos into the total density should in no case exceed this density. For massive (non-relativistic) neutrinos it leads to constraint on neutrino mass

$$\Omega_\nu = \frac{\sum\limits_{\text{types of }\nu} m_\nu n_{\nu\bar{\nu}}^{(\text{mod})}}{\varepsilon_{\text{cr}}} < \Omega_{\text{tot}}$$

$$\sum_{\text{types of }\nu} m_\nu < 50\,\text{eV} \cdot \Omega_{\text{tot}}$$

Constraints on neutrino mass

In 1970th, an upper limit on the total density was set from the estimation of age of Universe by the method of Nuclear Cosmochronology. It is based on analysis of nuclear isotope compositions. It gave *t*>5 Gyr, whence

$$\Omega_{\text{tot}} < 2 \qquad \sum_{\text{types of } \nu} m_\nu < 100\,\text{eV}$$

The modern estimation of total density give

$$\Omega_{\text{tot}} \approx 1 \qquad \sum_{\text{types of } \nu} m_\nu < 50\,\text{eV}$$

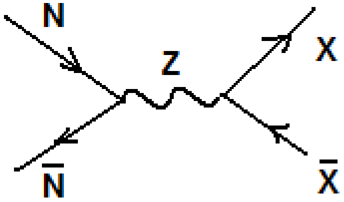
Theory of formation of Large Scale Structure (galaxies) of Universe allows to restrict contribution into density of neutrinos along with all the Hot Dark Matter (HDM), to be discussed in future, as

$$\Omega_\nu \le \Omega_{\text{HDM}} < 0.015 \qquad \sum_{\text{types of } \nu} m_\nu < 0.8\,\text{eV}$$

Heavy neutrinos

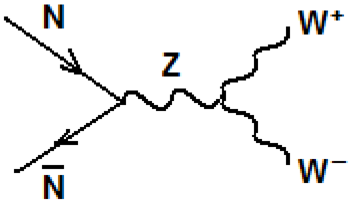
If heavy neutrinos (with mass *m*) existed, they might be in equilibrium in early Universe. At $T<m$ their equilibrium number density would go down due to annihilation process.

m must be >~1 MeV in order Heavy neutrinos had time to become non-relativistic before they decoupled



$$\sigma_{N\bar{N}}\upsilon \approx \frac{\sum_{channels} Z_X}{4\pi}\frac{G_F^2 m_Z^4 m^2}{(4m^2-m_Z^2)^2+m_Z^2\Gamma_Z^2} \sim \begin{cases} \frac{m^2}{m_Z^4}, & m \ll m_Z/2 \\ \frac{1}{m^2}, & m \gg m_Z/2 \end{cases}$$

In non-relativistic limit



$$\sigma_{N\bar{N}}\upsilon \approx \frac{G_F^2 m^2}{8\pi} \sim \frac{m^2}{m_Z^4}, \quad m \gg m_W$$

At *m*~200 GeV perturbative approach becomes invalid (since Yukawa couplings to the Higgs filed, defining masses of both *N* and *W* participating in the process of question, become >1).

At *m*~2 TeV **unitarity limit** is reached, which gives

$$\sigma_{N\bar{N}}\upsilon \approx \frac{4\sqrt{\pi m/T_*}}{m^2} \sim \frac{1}{m^2}$$

Freezing out of Heavy neutrinos

Neutrinos are frozen when: $n_N \sigma_{N\bar{N}} \upsilon = H$ ⇒ $T_* \sim 10^{-1} m$.

$$n_N^* = \frac{H}{\sigma_{N\bar{N}} \upsilon}$$

Note, frozen out density is **inverse** proportional to annihilation cross section!

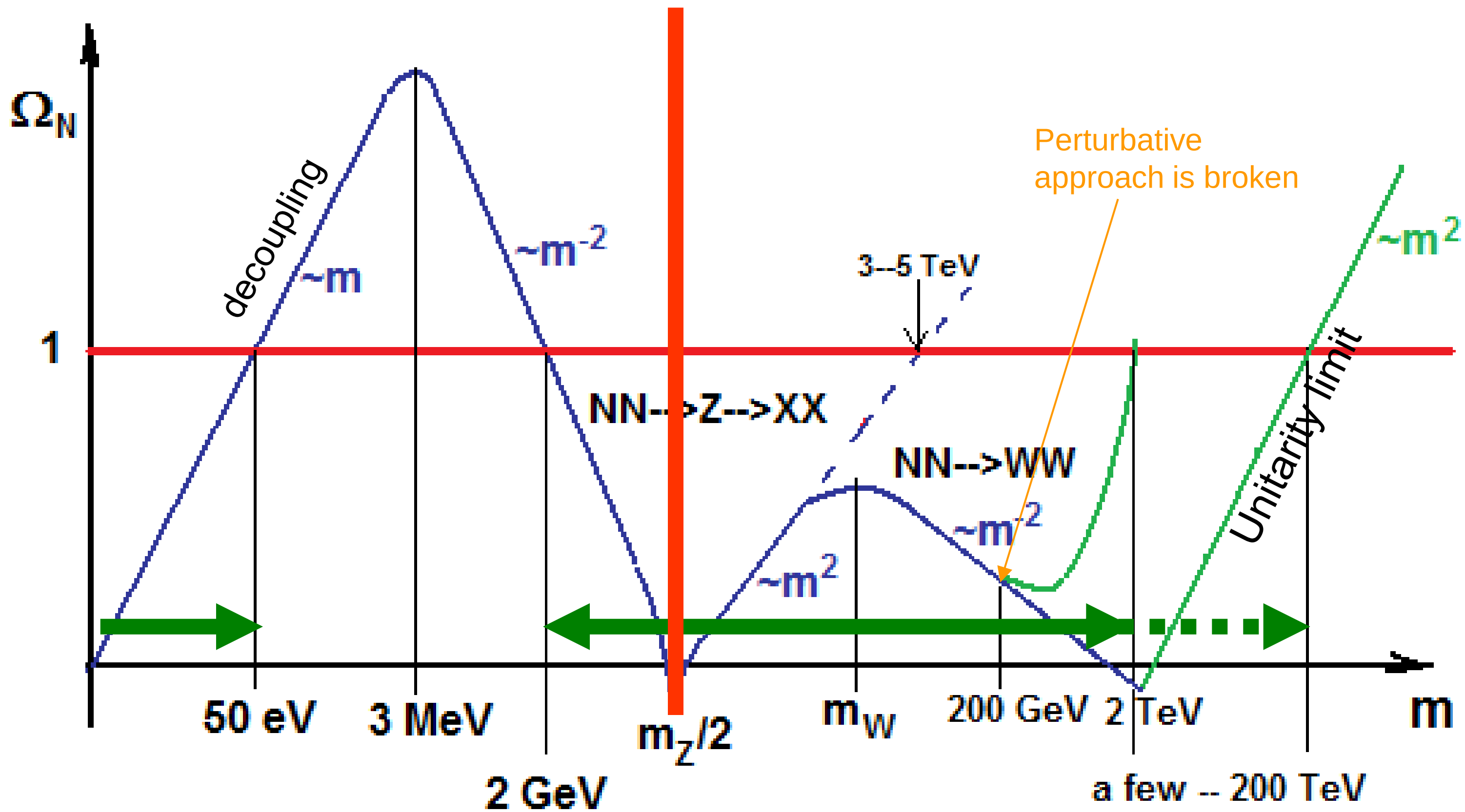
$$n_N^{(\mathrm{mod})} = n_N^* \frac{a_*^3}{a_{\mathrm{mod}}^3} \sim \frac{H}{\sigma_{N\bar{N}} \upsilon} \frac{T_{\mathrm{mod}}^3}{T_*^3} \sim \frac{1}{\sigma_{N\bar{N}} \upsilon} \frac{T_*^2}{m_{\mathrm{Pl}}} \frac{T_{\mathrm{mod}}^3}{T_*^3} \sim \frac{T_{\mathrm{mod}}^3}{m_{\mathrm{Pl}} \cdot \sigma_{N\bar{N}} \upsilon \cdot T_*} \sim \frac{n_\gamma^{(\mathrm{mod})}}{m_{\mathrm{Pl}} \cdot \sigma_{N\bar{N}} \upsilon \cdot m}$$

$$r_N^{(\mathrm{mod})} \equiv \frac{n_N^{(\mathrm{mod})}}{n_\gamma^{(\mathrm{mod})}} \sim \frac{1}{m_{\mathrm{Pl}} \cdot \sigma_{N\bar{N}} \upsilon \cdot m} \sim \begin{cases} \dfrac{m_Z^4}{m_{\mathrm{Pl}} m^3}, & m << \dfrac{m_Z}{2} \\ \dfrac{m}{m_{\mathrm{Pl}}}, & \dfrac{m_Z}{2} << m < m_W \\ \dfrac{m_Z^4}{m_{\mathrm{Pl}} m^3}, & m >> \dfrac{m_Z}{2} \end{cases}$$

$$\Omega_N \propto m r_\gamma^{(\mathrm{mod})} \sim \frac{1}{m_{\mathrm{Pl}} \cdot \sigma_{N\bar{N}} \upsilon}$$

Constraint on the mass of neutrino

$$\Omega_N \sim \begin{cases} \frac{m_Z^4}{m_{Pl} m^2}, & m << \frac{m_Z}{2} \\ \frac{m^2}{m_{Pl}}, & \frac{m_Z}{2} << m < m_W \\ \frac{m_Z^4}{m_{Pl} m^2}, & m >> m_W \end{cases}$$



Thus 2 GeV < *m* < a few÷200 TeV is cosmologically allowable.
However *m* < 45 GeV is forbidden by accelerator data.

Freezing out of n/p ratio

The ratio between the numbers of neutrons and protons in early Universe was regulated by reactions

$$\tilde{\nu}_e + p \leftrightarrow e^+ + n$$

$$\nu_e + n \leftrightarrow e^- + p$$

which were frozen out together with other weak interaction processes at

$$T_* \sim \frac{\kappa_\varepsilon^{1/6}}{(G_F^2 m_{Pl})^{1/3}} \approx 1\,\mathrm{MeV}$$

This corresponds to

$t_* \sim 1$ s

If more relativistic species were present, freezing out of n/p took place at smaller t and larger T.

Primordial He and the equilibrium for beta processes

$$\frac{n}{p} = \exp\left\{-\frac{\Delta m}{T}\right\}$$ is in equilibrium at $$T < \Delta m = m_n - m_p$$

The equilibrium ratio is provided by beta processes

$$\nu_e + n \Leftrightarrow e + p$$

$$\bar{\nu}_e + p \Leftrightarrow e^+ + n$$

When the rate of expansion exceeds the rate of beta processes

$$R = \kappa_0^{1/2} \frac{T^2}{m_{Pl}} \geq (n_l \sigma v) = G_F^2 T^5$$ at

$$T_f = \left(\frac{\kappa}{\kappa_0}\right)^{1/6} \left(G_F^2 m_{Pl}\right)^{-1/3} \approx \left(\frac{\kappa}{\kappa_0}\right)^{1/6} \left(\frac{10^{-10}}{m_p^4} 10^{19} m_p\right)^{-1/3} \approx 10^{-3} m_p \left(\frac{\kappa}{\kappa_0}\right)^{1/6} \approx 1 MeV \left(\frac{\kappa}{\kappa_0}\right)^{1/6}$$

This ratio is frozen out and virtually all the frozen out neutrons go during *the first three minutes* in primordial helium

Primordial helium abundance

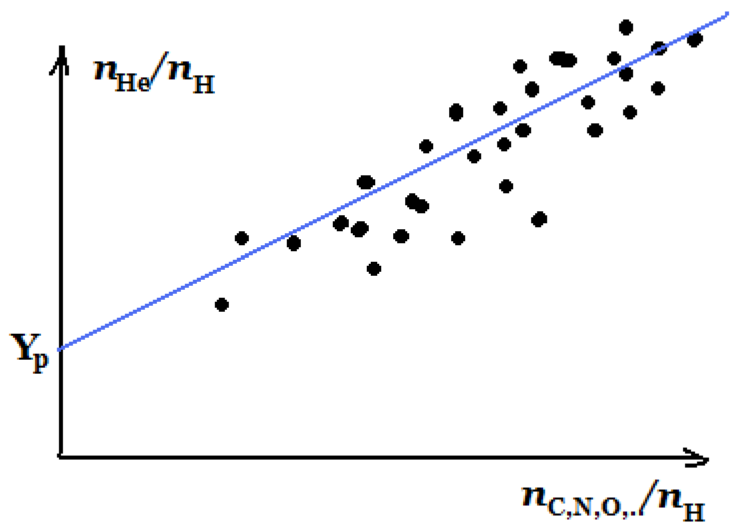
All reactions of Big Bang Nucleosynthesis took place at t~100 s, in the result of which a primordial chemical composition has been established, in which virtually all frozen out neutrons entered primordial helium-4:

$$\frac{\rho_{\mathrm{He}}}{\rho_{\mathrm{B}}} \equiv Y_p \approx \frac{2(n/p)}{1+n/p} \approx 0.25$$

This abundance should be compared with observed abundance of He-4. However, we don't observe primordial helium. The modern helium abundance also includes products of nuclear burning in stars. Special analysis of observations is needed to deduce the primordial component of helium.

Y_p from observation

The observed Helium is of both primordial and secondary (star) origin. To define primordial amount (Y_p), to be compared with prediction of BBN theory, an observed dependence of helium amount from amount of secondary elements (O, C, N,… - called *metalicity*) is extrapolated to the zero.



$$Y_p^{(obs)} = 0.249 \pm 0.004 \pm 0.018$$

Primordial He and the number of species of relativistic particles

$$\frac{n}{p} = \exp\left\{-\frac{\Delta m}{T_f}\right\}$$ and the freezing out temperature $$T_f \propto \left(\frac{\kappa}{\kappa_0}\right)^{1/6}$$

Any new species of relativistic particles increases the frozen our concentration of neutrons and correspondingly of primordial helium

$$Y_{prim} = 0.25 \Rightarrow \Delta n_\nu < 1$$

For a long time the opinion was widely spread that the abundance of primordial helium does not admit more than 3 types of light neutrinos.
Recently the systematic errors in determination of this abundance acquire more attention and less restrictive limits are discussed.
In any case even the most conservative estimation of primordial helium abundance puts severe constraint on the expansion rate of the Universe at 1 s of expansion and on the presence of any unknown form of matter in this period.

Number of neutrino species

Number of ultrarelativistic species affects the number of neutrons and, correspondingly, predicted primordial Helium abundance (Y_p):

$$\frac{n_n}{n_p} = \exp\left(-\frac{\Delta m (G_F^2 m_{Pl})^{1/3}}{\kappa_\varepsilon^{1/6}} \right)$$

The larger number of neutrinos N_ν, the larger κ_ε is, the larger n/p is, the larger Y_p.

From comparison with the Y_p deduced from observation one gets

$$2.0 < N_\nu < 4.5$$

If to take into account only statistical errors, then $2.8 < N_\nu < 3.5$.

Constraint on mirror world

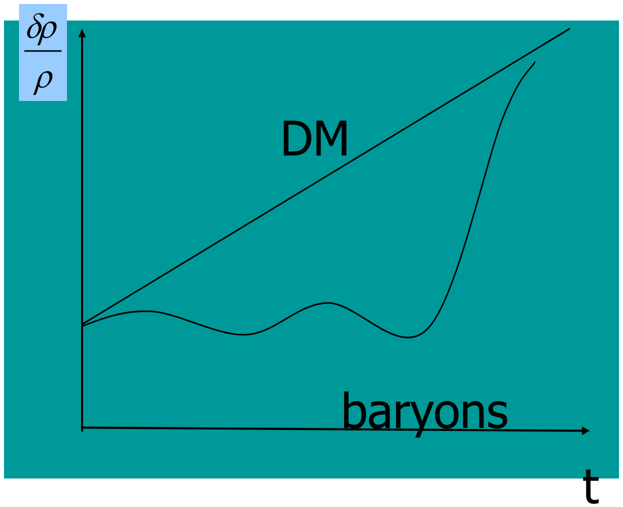
Data on primordial Helium-4 restricts number of any possible unknown species of particles. Hypothesis on mirror world existence implies doubling all known particle species. As a consequence for primordial Helium amount (Y_p) we should have:

$$Y_{\mathrm{p}}^{(\mathrm{mirror})} \approx 0.28$$

However, it is forbidden by observational data.

Hypothesis on mirror world to be viable should be modified either by asymmetry in initial conditions, or by asymmetry in its particle content and/or interactions relative to ordinary particles **=> Shadow world**

The condition of formation of the cosmological Large Scale Structure (LSS)



$$\frac{\delta\rho}{\rho} \Rightarrow \frac{\delta T}{T}$$

Formation of the Large Scale structure of the Universe due to growth of small initial density fluctuations needs long dust-like stage of expansion, at which these small fluctuations grow.

Unstable particles, decaying in that period to Relativistic particles, should not prevent this growth of density fluctuations.

Primordial Black Holes (PBH) – indicators of physics of very early Universe

- Existence of superheavy metastable particles in the very early Universe leads to stages of their dominance, at which growth of their density fluctuations leads to formation of their gravitationally bound systems, including black holes.
- Black holes, formed at this stage , must retain in the Universe after decay of particles, which have formed them, and at the mass $M > 10^{15} g$ must be present in the modern Universe as a specific form of dark matter.
- Black holes of smaller mass evaporate by mechanism of Hawking
- Effect s of their evaporation are similar to effects of decay of unstable paticles with one important difference – the products of evaporation are all the existing particles with mass, smaller than the temperature of evaporation.

Differential detectors

Indicators of specific modes of new particle decay

Non-equilibrium particles

- Decays of unstable particles, antimatter domain annihilation, PBH evaporation… are the source of particles with energy E>>T or of such particles, which are absent in equilibrium at this temperature T (e.g. antiprotons in baryon asymmetrical Universe after the first microsecond of expansion).
- Late sources of non-equilibrium particles directly contribute in fluxes of cosmic rays.
- If the source of particles acts sufficiently early, interaction of non-equilibrium particles with plasma and radiation can lead to observable effect

Nuclear cosmoarcheology

- **After BBN primordial chemical composition is created in the Universe: 75% H, 25% He-4 with a small fraction of other elements:**

$$X_D = 2.5 \cdot 10^{-5}; X_{^3He} = 4.2 \cdot 10^{-5}; X_{^7Li} = 2 \cdot 10^{-9}$$

- **Destruction by non-equilibrium particles of even small fracion (<1%) of primordial He-4 can lead to excessive abundance of light elements (D and He-3). Antinucleons in the Universe after BBN (from sources of nucleon-antinucleon pairs or survived in antimatter domains) are a profound example of non-equilibrium particles:**

$$\bar{p} + {}^4He \Rightarrow n + ...; n + p \Rightarrow D + \gamma; \bar{p} + {}^4He \Rightarrow D + N + pions$$

$$\bar{p} + {}^4He \Rightarrow {}^3H + pions; \bar{p} + {}^4He \Rightarrow {}^3He + pions$$

Experimental nuclear cosmoarcheology

- **There was an incomplete link in the cosmoarcheoLOGICAL chain between comophenomenology of new physics and observed light element abundance. The yield of D,T and He-3 was not known in reactions**

$$\bar{p} + {}^4He \Rightarrow D + N + pions$$

$$\bar{p} + {}^4He \Rightarrow {}^3H + pions$$

$$\bar{p} + {}^4He \Rightarrow {}^3He + pions$$

This information was obtained in special experiment PS179 at Low Energy Antiproton Ring (LEAR) in CERN. The measured yield of He-3 (20%) provided a set of severe constraints on the sources of nonequilibrium particles after BBN.

- **Analysis of Li and Be formation by nonequilibrium nuclear fragments (D, He-3, T) strengthened these constraints by 2 orders of magnitude. The progress was achieved in the result of Astro-nuclear experiment ASTROBELIX**

$$\bar{p} + {}^4He \Rightarrow D + ...; D + {}^4He \Rightarrow {}^6Li + \gamma$$

$$\bar{p} + {}^4He \Rightarrow {}^3H + ...; {}^3H + {}^4He \Rightarrow {}^6Li + n$$

$$\bar{p} + {}^4He \Rightarrow {}^3He + ...; {}^3He + {}^4He \Rightarrow {}^7Be + \gamma$$

Astro-nuclear experiment ASTROBELIX

- The project was aimed to join astronomers and physicists in studies of nuclear cosmoarcheology
- Measurement of momentum distribution for secondary He-3, D, T from antiproton-helium interaction in experiment OBELIX at LEAR CERN.
- Astronomical measurement of pregalactic abundance of light elements (by narrow band distorsions in CMB spectrum).
- Theoretical analysis of nuclear cosmoarcheological chain

Gravitino

In models mSUGRA, gravitino has typically the following properties:

is Majorana fermion with spin 3/2

$$m_{\tilde{G}} \sim 100 \div 1000\,\mathrm{GeV}$$

Interaction amplitude ~$G=m_{\mathrm{Pl}}^{-1}$.

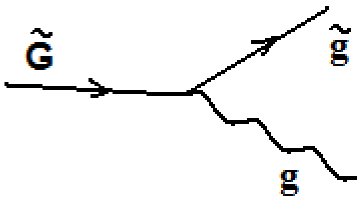
As a consequence, annihilation cross section is

$$\sigma_{ann} v \sim \frac{1}{m_{Pl}^2}$$

and, if gravitino is unstable, its lifetime

$$\tau_{\tilde{G}} \sim \frac{m_{\mathrm{Pl}}^2}{m_{\tilde{G}}^3} \sim \mathrm{yr}\left(\frac{100\ \mathrm{GeV}}{m_{\tilde{G}}}\right)^3$$

That is gravitino is long-lived particle.



Possible decay mode

Constraint on relic gravitinos

Processes of gravitational interactions should be frozen out soon after Plankian temperature $T=T_*<m_{Pl}$. Given so, (relativistic) gravitinos are decoupled from plasma at $T=T_*$. Standard estimation of modern relic density of gravitinos (see the part about light neutrinos) formally gives:

$$\Omega_{\tilde{G}}^{(\mathrm{mod})} = \frac{m_{\tilde{G}} n_{\tilde{G}}^{(\mathrm{mod})}}{\varepsilon_{\mathrm{cr}}^{(\mathrm{mod})}} = r_{\tilde{G}*} \cdot \frac{\kappa_s^{(\mathrm{mod})}}{\kappa_s^*} \cdot \frac{m_{\tilde{G}} n_\gamma^{(\mathrm{mod})}}{\varepsilon_{\mathrm{cr}}^{(\mathrm{mod})}} \sim 10^8 \frac{m_{\tilde{G}}}{100\,\mathrm{GeV}}$$

Comparison with observational data put strong constraint

$$\boxed{m_{\tilde{G}} < 1\,\mathrm{keV}}$$

which strongly disfavours minimal framework of SUGRA model.

Nonthermal relic gravitinos

Another way to reach agreement between mSUGRA and cosmological data is to assume that no period of $T \sim m_{Pl}$ took place in our Universe.

Let us suppose that initial temperature of primordial plasma had been equal to

$$T_R \ll m_{Pl}$$

In this case, thermal production of gravitinos in plasma (in collisions of particles of view $i + j \to \tilde{G} + X$) become suppressed (due to very small interaction constant), but not vanishing.

Let us estimate production rate. For it we have in the comoving volume V

$$\dot{N}_{\tilde{G}} = n_i n_j \left\langle \sigma_{ij \to \tilde{G}X} \upsilon_{ij} \right\rangle V$$

The volume changes as $V = N_\gamma / n_\gamma$

For other we have $n_{i,j,\gamma} \sim T^3 \qquad dt \sim m_{Pl} dT / T^3$

Constraint on Very Hot Universe

For modern moment we obtain

$$\frac{n_{\tilde{G}}}{n_\gamma} = \int\limits_{t(T=T_\mathrm{R})}^{t(T\sim m_G)} \frac{\dot{N}_{\tilde{G}}}{N_\gamma} dt \sim \int\limits_{T=m_{\tilde{G}}}^{T_\mathrm{R}} T^6 m_\mathrm{Pl}^{-2} T^{-3} \frac{m_\mathrm{Pl} dT}{T^3} = \frac{T_\mathrm{R}}{m_\mathrm{Pl}}$$

$$\boxed{\Omega_{\tilde{G}} = \frac{m_{\tilde{G}} n_{\tilde{G}}}{\varepsilon_\mathrm{cr}} \sim \frac{m_{\tilde{G}} n_\gamma}{\varepsilon_\mathrm{cr}} \frac{T_\mathrm{R}}{m_\mathrm{Pl}}}$$

If gravitino is stable, then to satisfy data on modern density we get constraint on parameter of cosmological model T_R (for m_G~100 GeV)

$$\boxed{T_\mathrm{R} < 10^{9\div 10}\ \mathrm{GeV}}$$

Gravitino in SUSY models

- Local SUSY models predict SUSY partner of graviton with spin 3/2 – gravitino, having semi-gravitational interaction $\propto 1/m_{Pl}$
- In a wide variety of models gravitino mass is determined by SUSY breaking scale (~100 GeV)
- In such models gravitino is unstable with lifetime

$$\tau = a\left(\frac{m_{Pl}}{m_G}\right)^3 \frac{1}{m_{Pl}} \approx 10^8 s\left(\frac{100GeV}{m_G}\right)^3$$

- If created in early Universe it should decay at $t = \tau$ and give rise to non-equilibrium particles from decay channels

$$G \to g\tilde{g}; \gamma\tilde{\gamma} \Rightarrow g \to hadrons$$

Problem of primordial gravitino

- **Due to superweak semi-gravitational interaction gravitino could not be in equilibrium in early Universe, but it could be produced in reactions with SUSY particles.**
- **Abundance of primordial gravitino mass is determined by reheating temperature**

$$r_G = \frac{n_G}{n_\gamma} \approx \frac{T_{reheating}}{m_{Pl}}$$

- **Hadronic cascades from gravitino decay induce Li production**

$$G \to \tilde{g}g \Rightarrow g \to N\overline{N} \Rightarrow \overline{N}\,{}^4He \to T + \ldots \Rightarrow T + {}^4He \to {}^6Li + n$$

- **From observed lithium abundance follows** $T_{reheating} < 4 \cdot 10^6\, GeV$
- **Problem of primordial gravitino (baryogenesis?)**

Weak and strong non-equilibrium sources

- If energy density of non-equilibrium particles is of the order or larger than the energy density of equilibrium radiation the source is strong.
- If their energy density is much smaller, than the total (equilibrium) energy density the source is weak.

Kinetics of non-equilibrium processes

- System of kinetic equations of non-equilibrium processes is given by

$$\frac{\partial F_i}{\partial t} + 2HF_i - Hp_i \frac{\partial F_i}{\partial p_i} = I^+ - I^- + Q_i$$

Here *H(t)* is Hubble constant in the period *t*, $Q(p,t,\tau)$ – the distribution function of source, characterized by the time scale τ, *I* – collision terms and *F* - distribution functions.

Distribution function for weak sources

- The condition of weak source is given by

$$\sum_i \int \varepsilon_i Q_i \left(p_i, t, \tau \right) dp_i \Delta t \ll \varepsilon_\gamma;$$

- The distribution function $F_i = f_i + \varphi_i$ takes into account both thermal equilibrium f_i and non-equilibrium φ_i components for particles of type *i*.

Kinetic equation for weak sources

- For non-equilibrium particles of *i*-th type the equation runs

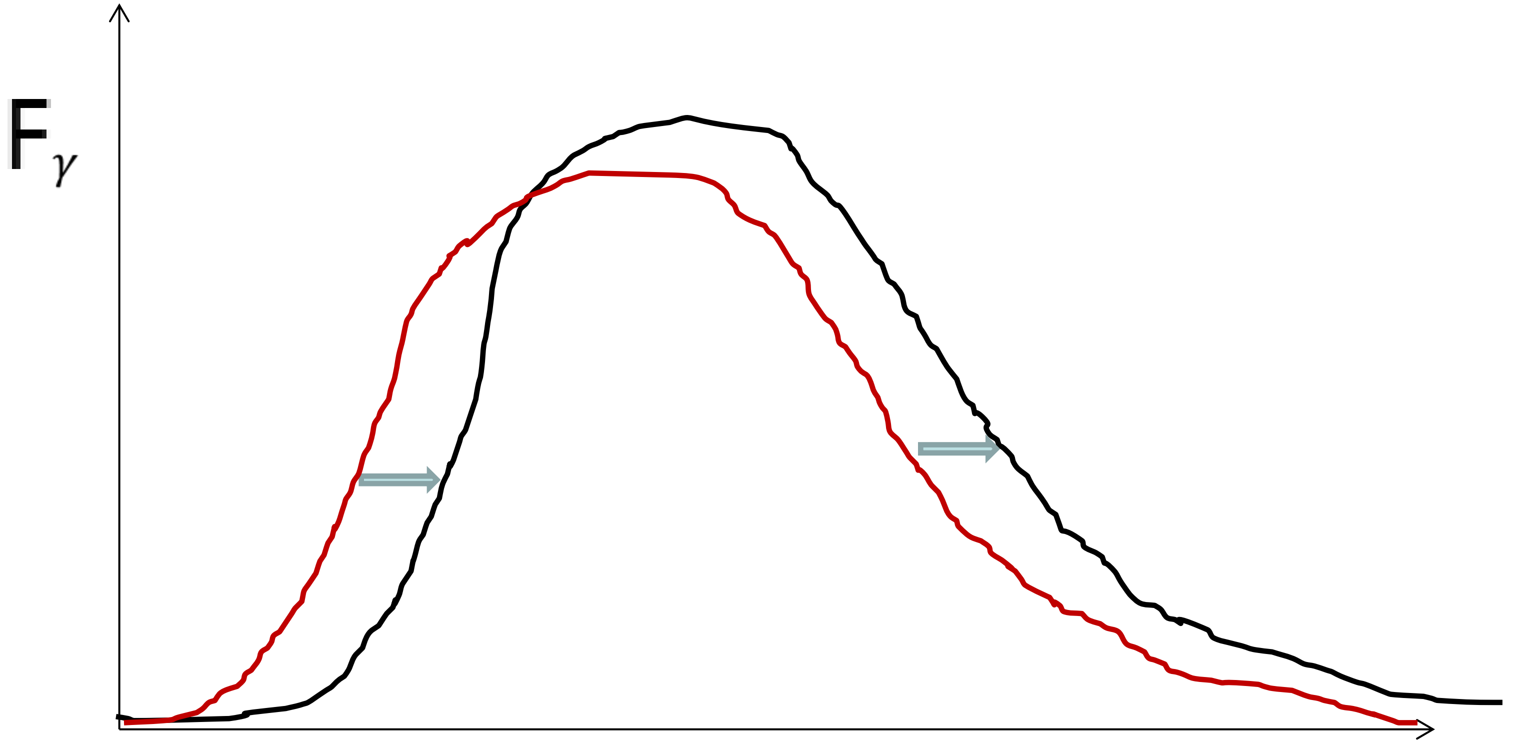
$$\frac{\partial \varphi_i}{\partial t} = \sum_{j,k} \varphi_j F_k \frac{d\left(\sigma v\right)^{i}_{jk}}{dp_i} dp_j dp_k + \sum_j \varphi_j \frac{d\Gamma_j}{dp_i} -$$

$$-\varphi_i \left(\Gamma_i + \sum_j \left(n_j \left(\sigma v\right)^{ij} \left(p_i\right) + \int \varphi_j \left(\sigma v\right)^{ij} dp_j \right) \right) + Q_i\left(p_i, t, \tau\right)$$

CMB spectrum as electromagnetic calorimeter

- If electromagnetic energy release takes place at $z > 10^8 \Omega_b^{1/2}$, Planck form of spectrum is restored due to $\gamma e \to 2\gamma e$ or $\gamma Z \to 2\gamma Z$ processes.
- When the rate of expansion exceeds the rate of these processes black body spectrum is distorted. The distortion is proportional to the energy release relative to the total energy density of the thermal background radiation.

Effect of energy release in CMB spectrum



The energy release reduces low frequency (RJ) and increases high frequency (W) parts of spectrum ω

Bose-Einstein distortion

- Early energy release at $4 \cdot 10^4 \Omega_b^{1/2} < z < 10^8 \Omega_b^{1/2}$

leads to equilibrium distribution at fixed number of photons – i.e. to the Bose-Einstein distribution with photon chemical potential proportional to energy release:

$$F_{em}(\nu) = \frac{2h\nu^3}{c^2} \frac{1}{\exp\left\{\frac{h\nu + \mu k T_e}{k T_e}\right\} - 1}$$

Measurements of SMB spectrum provide the constraint

$$\frac{\delta\varepsilon}{\varepsilon_\gamma} < \frac{1}{3}|\mu| < 1.1 \cdot 10^{-4}$$

y-distortions of CMB spectrum

- Late energy release at

$$z < 4 \cdot 10^4 \, \Omega_b^{1/2}$$

cannot support equilibrium Bose – Einstein distribution and spectral *y* distortions are determined by kinetics of heating of photon gas by hot electrons. COBE data give

$$\frac{\delta\varepsilon}{\varepsilon_\gamma} < 12|y| < 3 \cdot 10^{-4}$$

High energy neutrino background from decays of superheavy particles

- If superheavy particles of mass *M* decay in early Universe after 1 s, high energy neutrinos – their decay products and high energy neutrinos from interaction of decay products quarks and leptons with thermal neutrino background form high energy neutrino background.
- Interaction of high energy neutrinos with thermal neutrino background and their redshift put upper limit on the maximal energy of these high energy neutrinos in the modern Universe:

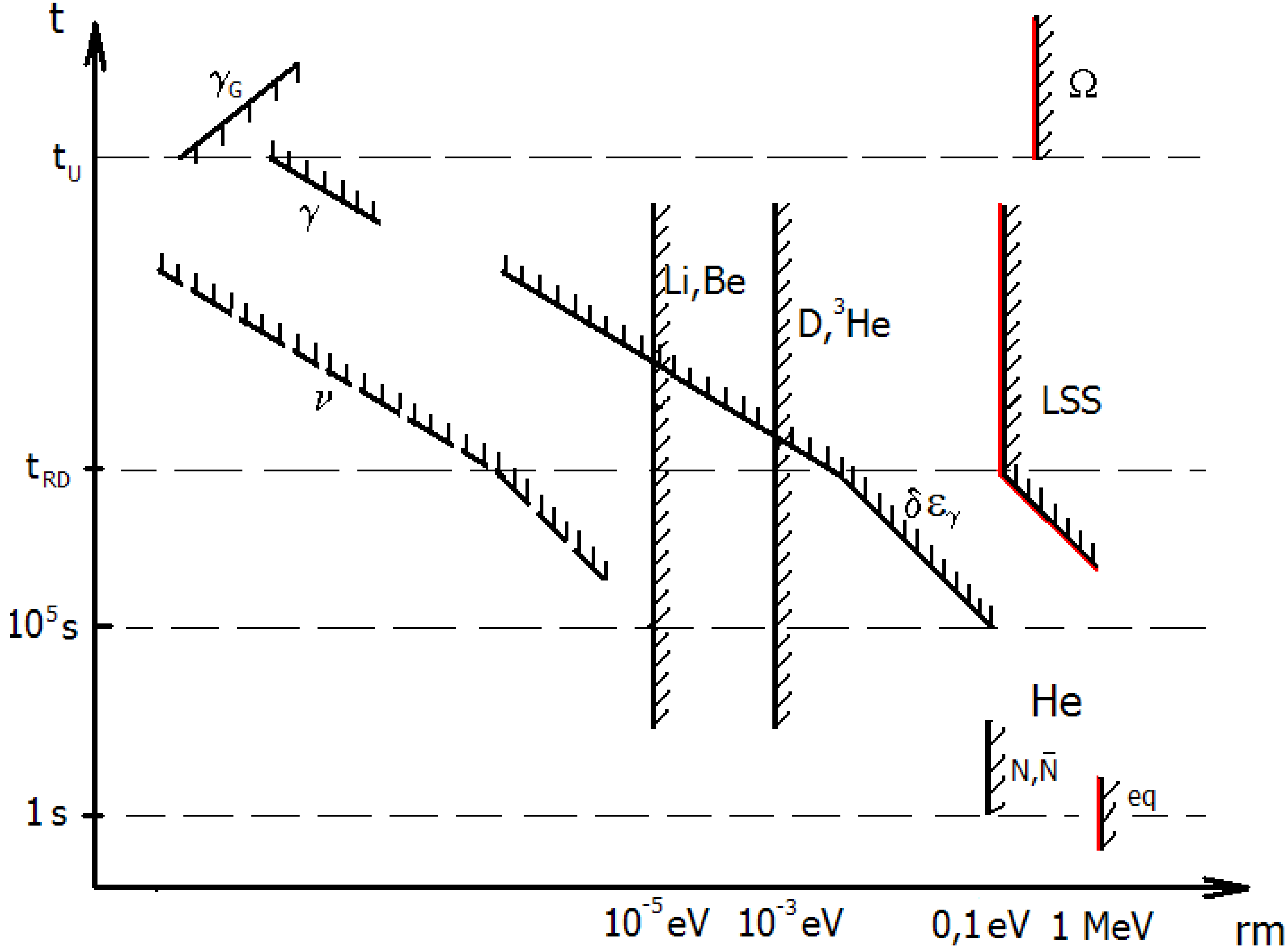
$$E_{\max}^{\text{mod}} = 2 \cdot 10^{-10}\ \text{GeV} \left(\frac{\tau}{1\text{s}} \right)^{3/2}$$

For $\tau > 10^5\ s$

such neutrinos can be detected in neutrino observatories.

Laboratory of the Universe

$$r \equiv \frac{n_X}{n_\gamma}$$



Conclusions

- « Integral detectors » of the Universe are sensitive only to the fact of presence of new particles. They are: the age of the Universe; primordial light element abundance, existence of the LSS and the PBH link to the physics of very early Universe.

- « Differential detectors » of the Universe are sensitive to non-equilibrium particles.
- Results of non-equilibrium cosmological nucleosynthesis directly depend on cross sections of reactions with such particles. It
- implies new level of relationship between experimental particle physics and cosmology
- Any given cosmoarcheological chain constrains new physics from the astrophysical data. To provide realistic scenario all the data should be reproduced.