Cosmophenomenology of New Physics

(Cosmological impact of particle theory)

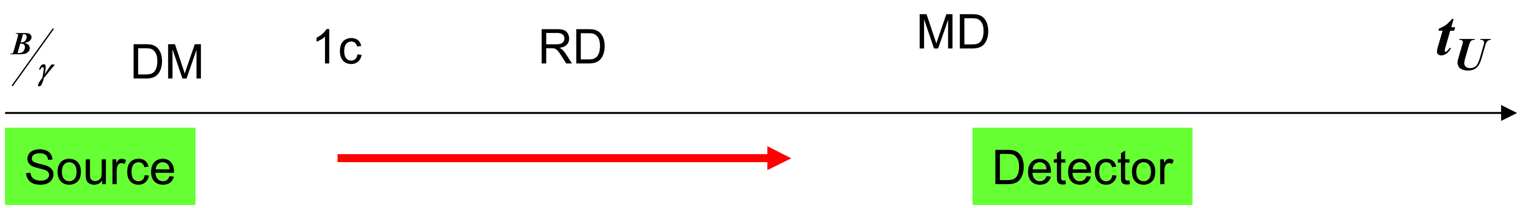
Lecture from course

“Introduction to Cosmoparticle Physics”

Outlines

- New stable particles as cosmological reflection of particle symmetry. Thermodynamics of early Universe. Decoupling, freezing out, nonthermal particle production (gravitino)
- Cosmological phase transitions and topological particle production (magnetic monopoles)
- Strong Primordial nonhomogeneities as cosmological reflection of particle symmetry. Primordial Black Holes (PBHs) and Massive PBH clusters.
- Antimatter as profound signature for nonhomogeneous baryosynthesis.

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 cosmological consequences of particle theory in the very Early Universe (in the 1 s of expension) are considered as the source, while their effects on later stages of expansion are considered as detector, fixing the signatures for these effects in the astrophysical data.



Possible forms of these sources are the subject of
Cosmophenomenology of New Physics

Cosmological Reflections of Microworld Structure

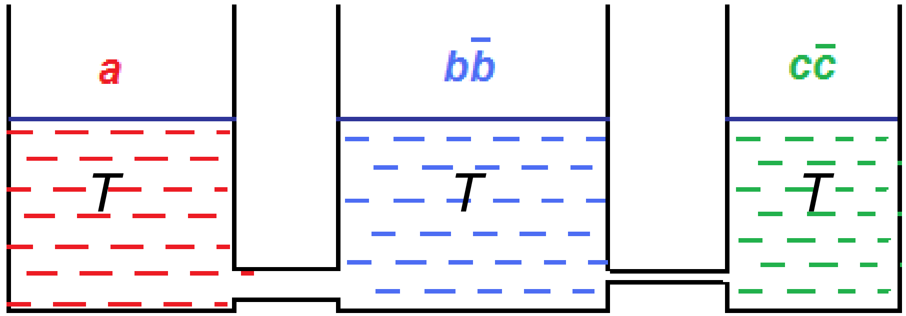
- (Meta-)stability of new particles reflects some Conservation Law, which prohibits their rapid decay. Following Noether's theorem this Conservation Law should correspond to a (nearly) strict symmetry of microworld. Indeed, all the particles - candidates for DM reflect the extension of particle symmetry beyond the Standard Model.
- In the early Universe at high temperature particle symmetry was restored. Transition to phase of broken symmetry in the course of expansion is the source of topological defects (monopoles, strings, walls…).
- Structures, arising from dominance of superheavy metastable particles and phase transitions in early Universe, can give rise to Black Holes, retaining in the Universe after these structures decay.

Particles in the Big Bang plasma

Equilibrium condition

$$\Gamma_{ab} = n_{ab}\sigma_{ab}v_{ab} >> \Gamma_{\substack{\text{macroscopic}\\ \text{conditions}}}$$

- condition of equilibrium between species a and b.



For matter in Universe, the change of macroscopic parameters is defined by the rate of its expansion:

$$\Gamma_{\substack{\text{macroscopic}\\ \text{conditions}}} = H \sim \frac{1}{t}$$

Equilibrium distribution

Under conditions of equilibrium, for gases of fermions and bosons we have

$$f = \frac{d^6 N}{d^3 x d^3 p} = \frac{1}{(2\pi\hbar)^3} \frac{g_S}{\exp\left(\frac{E-\mu}{T}\right) \pm 1}$$

$\hbar = c = k = 1$

$\mu \to 0$ *chemical potential is supposed to be 0: number of any species can be freely changed*

Using this distribution, we can find number and energy densities

$$n = \frac{d^3 N}{d^3 x} = \int f d^3 p \qquad \varepsilon = \int E \cdot f d^3 p$$

Number and energy densities

Ultrarelativistic case: E=p, d³p=4πE²dE

$$n = \frac{g_S}{(2\pi)^3}\int_0^\infty \frac{4\pi E^2 dE}{\exp\left(\frac{E}{T}\right)\pm 1} = \left(x \equiv \frac{E}{T}\right) = \frac{g_S T^3}{2\pi^2}\int_0^\infty \frac{x^2 dx}{e^x \pm 1} = \frac{g_S T^3}{2\pi^2} I_2^{(f/b)}$$

$$\varepsilon = \int E \cdot f d^3 p = \ldots = \frac{g_S T^4}{2\pi^2}\int_0^\infty \frac{x^3 dx}{e^x \pm 1} = \frac{g_S T^4}{2\pi^2} I_3^{(f/b)}$$

Notation is introduced: $$I_n^{(f/b)} \equiv \int_0^\infty \frac{x^n dx}{e^x \pm 1}$$

The given integrals are not trivial, however relation between them can be calculated

$$I_n^{(b)} - I_n^{(f)} \equiv \int_0^\infty \frac{x^n dx}{e^x - 1} - \int_0^\infty \frac{x^n dx}{e^x + 1} = \int_0^\infty \frac{2x^n dx}{e^{2x} - 1} = \left(y = 2x\right) = \frac{1}{2^n}\int_0^\infty \frac{y^n dy}{e^y - 1} = \frac{1}{2^n} I_n^{(b)}$$

$$\boxed{I_n^{(f)} = \left(1 - \frac{1}{2^n}\right) I_n^{(b)}}$$

Relativistic particles

From formula above we get in ultrarelativistic case

$$\boxed{n_f = \frac{3}{4} n_b \qquad \varepsilon_f = \frac{7}{8}\varepsilon_b}$$

Full calculation gives

Compare with Stefan-Boltzman law

$u = \varepsilon_\gamma / 4 = \sigma T^4$

$$\boxed{n = \begin{cases} \dfrac{\zeta(3) g_S T^3}{\pi^2} & \text{- for bosons -} \\[2ex] \dfrac{3\zeta(3) g_S T^3}{4\pi^2} & \text{- for fermions -} \end{cases}} \qquad \boxed{\varepsilon = \begin{cases} \dfrac{\pi^2 g_S T^4}{30} \\[2ex] \dfrac{7\pi^2 g_S T^4}{240} \end{cases}}$$

$\zeta(3) = 1.202$

Nonrelativistic particles

In non-relativistic case we have: E≈m>>T

$$n = \frac{g_S}{(2\pi)^3}\int \frac{4\pi p^2 dp}{\exp\left(\frac{m+E_{kin}}{T}\right)\pm 1} \approx \begin{pmatrix} e^{m/T} >> 1 \\ p = mv \\ E_{kin} = \frac{mv^2}{2} \end{pmatrix} \approx$$

$$\approx \frac{g_S m^3}{2\pi^2}\exp\left(-\frac{m}{T}\right)\cdot \underbrace{\int_0^\infty \exp\left(-\frac{mv^2}{2T}\right)v^2 dv}_{\sqrt{\frac{\pi}{2}}\left(\frac{T}{m}\right)^{3/2}} = g_S\left(\frac{Tm}{2\pi}\right)^{3/2}\exp\left(-\frac{m}{T}\right)$$

Thus

$$\boxed{n = g_S\left(\frac{mT}{2\pi}\right)^{3/2}\exp\left(-\frac{m}{T}\right)}$$

both for bosons and fermions

$$\boxed{\varepsilon = mn}$$

Multicomonent relativistic gas

$$\varepsilon_{tot}=\sum_b \varepsilon_b+\sum_f \varepsilon_f=\left(\sum_b g_{S(b)}+\frac{7}{8}\sum_f g_{S(f)}\right)\frac{\pi^2}{30}T^4=$$

$$=\underbrace{\left(1+\sum_{b\neq\gamma}\frac{g_{S(b)}}{2}+\frac{7}{8}\sum_f\frac{g_{S(f)}}{2}\right)}_{\kappa_\varepsilon}\bar{\sigma}T^4 \qquad \bar{\sigma}=4\sigma$$

$$\varepsilon^{(\mathrm{eq})}_{\text{non-rel}} << \varepsilon^{(\mathrm{eq})}_{\text{rel}}$$

In case of components with different temperatures:

$$\kappa_\varepsilon=1+\sum_{b\neq\gamma}\frac{g_{S(b)}}{2}\left(\frac{T_b}{T}\right)^4+\frac{7}{8}\sum_f\frac{g_{S(f)}}{2}\left(\frac{T_f}{T}\right)^4$$

Equation of state

The basic equations of state, as mentioned previously, are

$\boxed{p = 0}$ *-non-relativistic ("dust"-like) matter, the stage of dominance of such matter is called MD-stage*

$\boxed{p = \frac{\varepsilon}{3}}$ *- (ultra)relativistic (radiation-like) matter, the corresponding stage is called RD-stage*

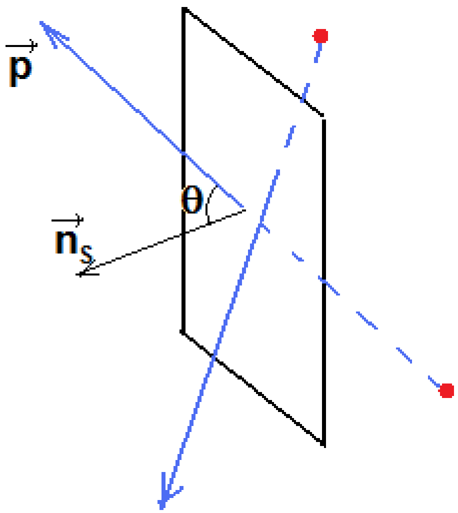
$\boxed{p = -\varepsilon}$ *- vacuum-like matter (vacuum energy), this stage leads to accelerated expansion (inflation)*

In the general case one can parameterize

$$\boxed{p = \gamma\varepsilon}$$

Derivation of p=ε/3

For the pressure of gas of photons we have



$$p \equiv \frac{F_\perp}{S} = \frac{\langle \vec{n}_S d\vec{P} / dt \rangle}{S} = \frac{\langle \vec{n}_S \cdot \vec{p} dN_\gamma / dt \rangle}{S}$$

$$dN_\gamma = n_\gamma \cdot S \cdot cdt \cdot \cos\theta$$

$$\vec{n}_S \vec{p} = |\vec{p}| \cos\theta = E / c \cos\theta$$

$$\Rightarrow \quad p = \langle E \cdot n_\gamma \cdot \cos^2\theta \rangle = \langle E \cdot n_\gamma \rangle \langle \cos^2\theta \rangle = \varepsilon \cdot \frac{1}{3}$$

$$\boxed{p = \frac{\varepsilon}{3}}$$

Basic relations

For the matter with equation of state $p=\gamma\varepsilon$, we can get from Friedmann equations

$$\boxed{\varepsilon \propto a^{-3(1+\gamma)} \propto \begin{cases} a^{-4} & \text{for relativistic matter} \\ a^{-3} & \text{for non-relativistic matter} \\ const & \text{for vacuum energy.} \end{cases}}$$

In early Universe density of CMB exceeded the density of matter.

=> Radiation Dominated (RD)-stage took place at $T>1$ eV.

For $\gamma \neq -1$

$$\varepsilon_{\text{crit}} = \frac{1}{6(1+\gamma)^2 \pi G} \frac{1}{t^2}$$

$$H = \frac{2}{3(1+\gamma)t}$$

$$\boxed{a \propto t^{\frac{2}{3(1+\gamma)}} = \begin{cases} t^{1/2} & \text{- for RD} \\ t^{2/3} & \text{- for MD} \end{cases}}$$

Note, that given relations take place for flat Universe ($K=0$ or $\Omega=1$) without Λ-term. Such approximation is justified, since the terms K/a^2 and, moreover, $2\Lambda/3$ in Friedmann equation

$$\left(\frac{\dot a}{a}\right)^2 - \frac{8\pi G\varepsilon}{3} = -\frac{K}{a^2} + \frac{2\Lambda}{3}$$

become negligible while a decreases even if $K, \Lambda \neq 0$.

Vacuum dominance

In case of γ=–1 we have

$$\varepsilon = -p = \frac{\Lambda}{8\pi G}$$

$$H = \sqrt{\frac{8\pi G\varepsilon}{3}}$$

$$a \propto \exp(Ht)$$

Λ-term is equivalent to the matter with e.s. $p=-\varepsilon$ (vacuum energy).

Density of Λ does not change with time.

=> *Then Λ-dominance can start only in a late period, provided that small Λ exists.*

Task: For homogeneous massive scalar field from general expression of energy-momentum tensor please show that it leads to vacuum equation of state at t<<1/m.

Temperature of early Universe

Since wavelength of free particle ~a, temperature of photons evolves as a^{-1}.

$$\boxed{T \propto \frac{1}{\lambda} \propto \frac{1}{a} \propto z+1}$$

However, before recombination (T>3000 K, z>1100) and, in particular, at RD stage, photons are not free and can get/give the energy from/to other matter with which they interact (are in equilibrium).

To define dependence of T from t at RD-stage, one writes

$$\varepsilon_{\text{crit}}(\gamma = 1/3) = \frac{3}{32\pi G}\frac{1}{t^2} = \kappa_\varepsilon \overline{\sigma} T^4$$

$$\Downarrow$$

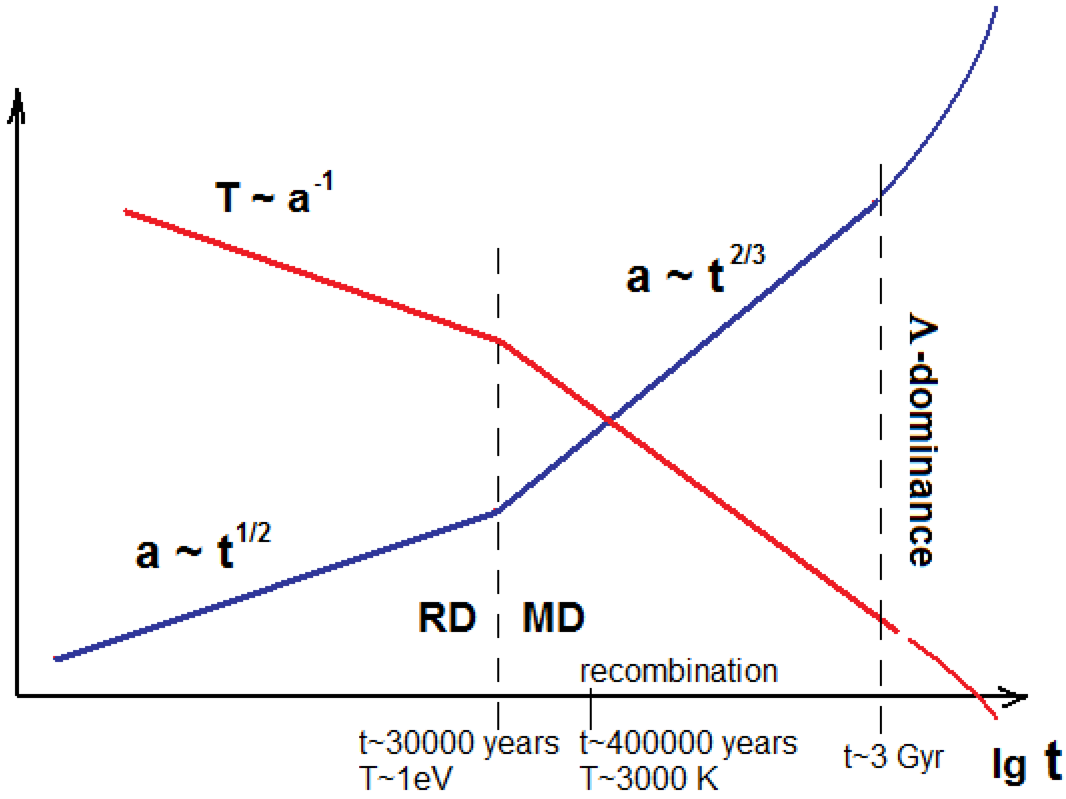
$$\boxed{T = \left(\frac{45}{32\pi^3 G}\right)^{1/4} \frac{1}{\kappa_\varepsilon^{1/4} t^{1/2}} \approx \left(\text{for } T \sim 1\,\text{MeV}\right) \approx 0.86\,\text{МэВ} \cdot \sqrt{\frac{1\text{с}}{t}}}$$

Contribution of species

$$\kappa_\varepsilon(T \sim 1\,\text{МэВ}) = 1 + \frac{7}{8}\left(2 \cdot \frac{2}{2}(e^{\pm}) + 3 \cdot 2 \cdot \frac{1}{2}(\nu\bar{\nu})\right) = \frac{43}{8}$$

- κ_ε depends on t (T) as soon as the number of relativistic species changes with T.
- Contribution of non-relativistic species at RD-stage is suppressed as $\exp(-m/T)$ or defined, as in case of nucleons, by small initial excess of their particles over antiparticles.

Evolution with time



Entropy

$$S = \int \frac{dQ}{T}$$

characterizes amount of states in phase space occupied by system.

$$\boxed{s = \frac{S}{V} = \frac{\varepsilon + p}{T} = \left(p = \frac{\varepsilon}{3} \right) = \frac{4\varepsilon}{3T}}$$

Gravitational energy is not taken into account

$$s \propto n$$

Entropy is conserved for reversible processes.

Entropy is conserved for any closed (sub)system in the absence of irreversible processes.

Examples of irreversible processes: radiation of hot bodies (stars), decays of particles, some phase transitions.

Entropy of multicomponent matter

For multicomponent matter we have:

$$s_{tot} = \sum_b s_b + \sum_f s_f = \frac{4}{3T}\varepsilon_{tot} = \underbrace{\left(1 + \sum_{b\neq\gamma}\frac{g_{S(b)}}{2} + \frac{7}{8}\sum_f \frac{g_{S(f)}}{2}\right)}_{\kappa_S}\frac{4}{3}\bar{\sigma}T^3$$

κ_S $= \kappa_\varepsilon$ *in case of* $T_i = T$

In case of components with different temperatures:

$$\kappa_s = 1 + \sum_{b\neq\gamma}\frac{g_{S(b)}}{2}\left(\frac{T_b}{T}\right)^3 + \frac{7}{8}\sum_f \frac{g_{S(f)}}{2}\left(\frac{T_f}{T}\right)^3$$

Freezing out and decoupling

Freezing out of particles a (and their antiparticles) takes place, when they go out of thermodynamic equilibrium with particles b. It happens when processes that maintain the equilibrium, including reactions changing number of particles a, are stopped ("frozen out") – become slower than the rate of cosmological expansion (H).

$$n_a \sigma_{a\bar{a}} v_{a\bar{a}} = H \quad \text{or} \quad n_a \sigma_{ab} v_{ab} = H$$

Decoupling of particles a from particles b takes place, when they go out of thermal (kinetic) equilibrium. It happens when energy exchange between a and b, carried out by their scattering processes, becomes ineffective – becomes slower than Universe expansion.

$$n_a \sigma_{ab} \frac{\Delta E_{ab}}{E_a} v_{ab} = H$$ It takes the form $$n_a \sigma_{ab} v_{ab} = H$$, if $\Delta E_{ab} \sim E_a$

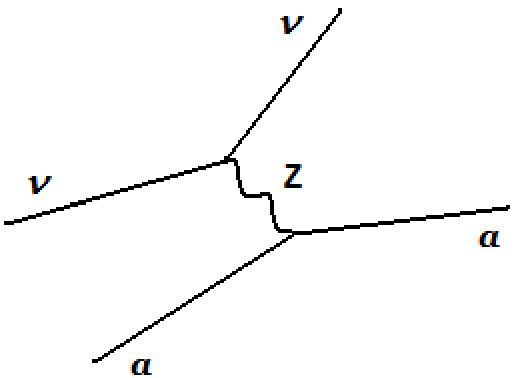
These notions play important role in particle physics of Big Bang Universe

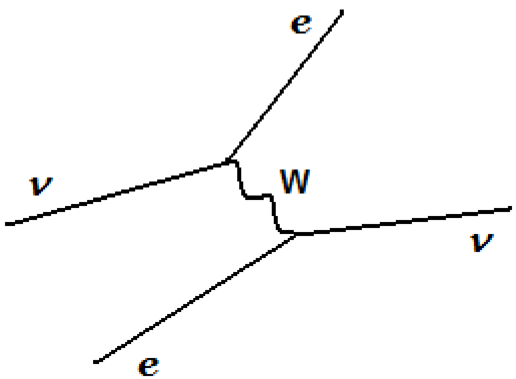
Neutrinos in early Universe

Let us consider conditions of equilibrium of neutrinos at $T \sim 1$ MeV

$$\overset{(\sim)}{\nu}_{e,\mu,\tau}\, a \leftrightarrow \overset{(\sim)}{\nu}_{e,\mu,\tau}\, a, \qquad a = \overset{(\sim)}{\nu}_{e,\mu,\tau}, e^{\pm}$$

$$\nu_e + \tilde{\nu}_e \leftrightarrow e^- + e^+$$





$$\left.\begin{array}{l} \tilde{\nu}_e + p \leftrightarrow e^+ + n \\ \nu_e + n \leftrightarrow e^- + p \end{array}\right\}$$

are not important for ν-equilibrium, because $n_{n,p} \ll n_{\nu,e}$

Decoupling of neutrinos

Condition of ν-decoupling (it coincides with freezing out of weak reactions) is

$$\boxed{n_a \sigma_{\nu a} \upsilon_{\nu a} = H}$$

$$\varepsilon_{\rm cr} = \frac{3H^2}{8\pi G} = \kappa_\varepsilon \overline{\sigma} T^4 \quad \Rightarrow \quad \left\{ \begin{array}{l} n_a \sim T^3 \qquad \text{- for relativistic species} \\ \sigma_{\nu a} \sim G_{\rm F}^2 E^2 \sim G_{\rm F}^2 T^2 \\ \upsilon_{\nu a} \sim 1 \\ H \sim \dfrac{\sqrt{\kappa_\varepsilon} T^2}{m_{\rm Pl}} \end{array} \right.$$

$$\Downarrow$$

$$\boxed{T \equiv T_* \sim \frac{\kappa_\varepsilon^{1/6}}{(G_{\rm F}^2 m_{\rm Pl})^{1/3}} \approx 1\,\mathrm{MeV}}$$

Accurate calculation gives close result.

Relic neutrinos

After decoupling, number of neutrinos (in comoving volume) does not change.

So, today we must have:

$$n_{\nu\bar{\nu}}^{(\mathrm{mod})} = n_{\nu\bar{\nu}}^{(*)} \cdot \left(\frac{a_*}{a_{\mathrm{mod}}} \right)^3$$

To find the ratio between the scale factors, corresponding to the moments $T=T_*\sim 1MeV$ and $T=T_{mod}=2.7\ K$, we need to relate a and T (photon temperature).

It can be done with the help of the law of entropy conservation.

Existence of gas of relic neutrinos is the inevitable consequence of a hot stages with $T>1MeV$

Abundance of relic neutrinos

Entropy conservation (being valid under supposition of absence of any entropy production (irreversible processes) during period of question) reads

$$S_* = S_{\mathrm{mod}}$$

After decoupling, neutrinos behave as a close system, therefore

$$\begin{cases} \cancel{S_{\nu\bar{\nu}}^{(*)}} + S_{e^\pm}^{(*)} + S_\gamma^{(*)} = \cancel{S_{\nu\bar{\nu}}^{(\mathrm{mod})}} + S_\gamma^{(\mathrm{mod})} \\ S_{\nu\bar{\nu}}^{(*)} = S_{\nu\bar{\nu}}^{(\mathrm{mod})} \end{cases}$$

In modern epoch relic photons and neutrinos are assumed to give dominant contribution into entropy (baryons, dark matter, light of stars are much less).

$$S \equiv s \cdot V \propto s \cdot a^3 \propto \kappa_s T^3 \cdot a^3$$

$$\left(1(\gamma) + \frac{7}{8} 2(e^\pm)\right) \cdot T_*^3 \cdot a_*^3 = 1(\gamma) \cdot T_{\mathrm{mod}}^3 \cdot a_{\mathrm{mod}}^3 \quad \Rightarrow \quad \left(\frac{a_*}{a_{\mathrm{mod}}}\right)^3 = \frac{4}{11} \frac{T_{\mathrm{mod}}^3}{T_*^3}$$

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

for one neutrino species

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

Using formally thermodynamic relations, we can define the temperature of relic neutrinos as:

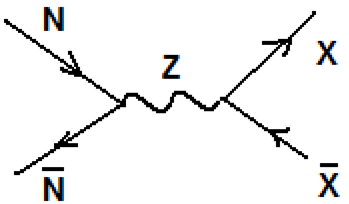
$$n_{\nu\bar{\nu}}^{(\mathrm{mod})} = \frac{3}{4} n_\gamma (T_{\nu\bar{\nu}}^{(\mathrm{mod})}) = \frac{3}{11} n_\gamma^{(\mathrm{mod})}$$

$$T_{\nu\bar{\nu}}^{(\mathrm{mod})} = \sqrt[3]{\frac{4}{11}} \cdot T_\gamma^{(\mathrm{mod})} \approx 2\,\mathrm{K}$$

Heavy neutrinos

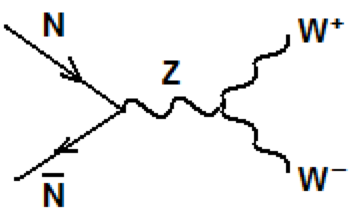
If heavy neutrinos (with mass m) existed, they might be in equilibrium in early Universe. At T<m their equilibrium number density would go down due to annihilation process.

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



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

In non-relativistic limit



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

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!*

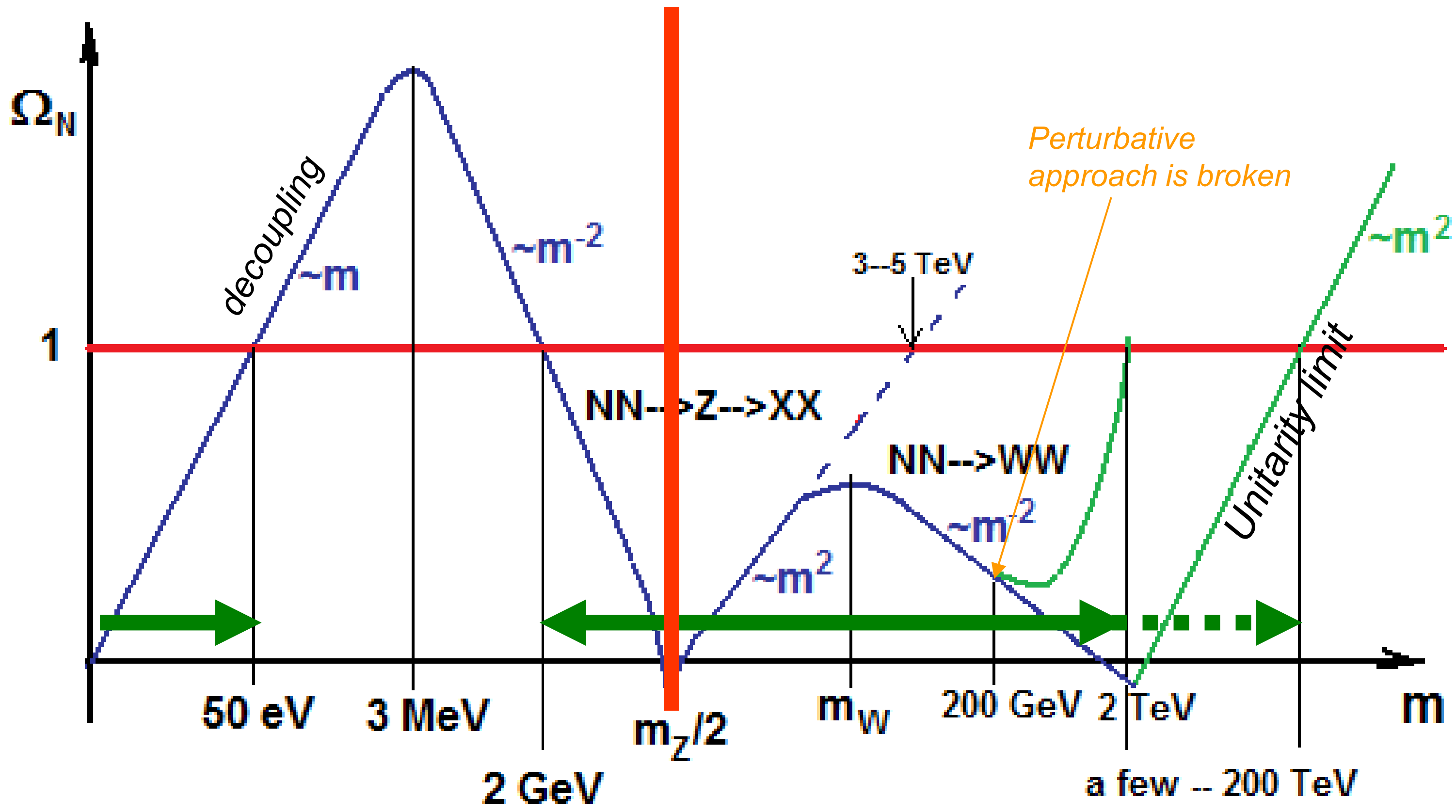
$$n_N^{(\text{mod})} = n_N^* \frac{a_*^3}{a_{\text{mod}}^3} \sim \frac{H}{\sigma_{N\bar{N}} \upsilon} \frac{T_{\text{mod}}^3}{T_*^3} \sim \frac{1}{\sigma_{N\bar{N}} \upsilon} \frac{T_*^2}{m_{\text{Pl}}} \frac{T_{\text{mod}}^3}{T_*^3} \sim \frac{T_{\text{mod}}^3}{m_{\text{Pl}} \cdot \sigma_{N\bar{N}}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

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

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

Density of massive neutrino

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



Thus 2 GeV < m < a few÷200 TeV is cosmologically allowable.

However m < 45 GeV is forbidden by accelerator data.

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 ~$G=m_{Pl}^{-1}$.

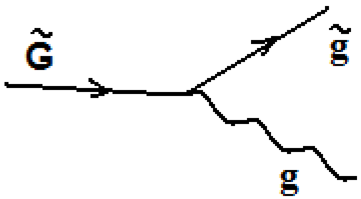
As a consequence, annihilation cross section is

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

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

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 $n_{i,j,\gamma} \sim T^3 \qquad dt \sim m_{\rm Pl} dT / T^3$

Cosmological Phase transitions 1.

- At high temperature $T > T_{cr}$ spontaneously broken symmetry is restored, owing to thermal corrections to Higgs potential

$$V(\varphi, T=0) = -\frac{m^2}{2}\varphi^2 + \frac{\lambda}{4}\varphi^4 \Rightarrow V(\varphi, T) = \left(C\lambda T^2 - \frac{m^2}{2}\right)\varphi^2 + \frac{\lambda}{4}\varphi^4$$

- When temperature falls down below

$$T = T_{cr} \cong \langle \varphi \rangle = \frac{m}{\sqrt{\lambda}}$$

transition to phase with broken symmetry takes place.

Cosmological Phase transitions 2.

- Spontaneously broken symmetry can be restored on chaotic inflationary stage, owing to corrections in Higgs potential due to interaction of Higgs field with inflaton

$$V(\varphi,\psi=0)=-\frac{m^2}{2}\varphi^2+\frac{\lambda}{4}\varphi^4 \Rightarrow V(\varphi,\psi)=\left(\varepsilon\psi^2-\frac{m^2}{2}\right)\varphi^2+\frac{\lambda}{4}\varphi^4$$

- When inflaton field rolls down below

$$\psi=\psi_{cr}\cong\frac{m}{\sqrt{\varepsilon}}$$

transition to phase with broken symmetry takes place.

Topological defects

- In cosmological phase transition false (symmetric) vacuum goes to true vacuum with broken symmetry. Degeneracy of true vacuum states results in formation of topological defects.
- Discrete symmetry of true vacuum $\langle\varphi\rangle = \pm f$ leads to domains of true vacuum with *+f* and *-f* and false vacuum wall on the border.
- Continuous degeneracy $\langle\varphi\rangle = f\exp(i\theta)$ results in succession of singular points surrounded by closed paths with $\Delta\theta = 2\pi$. Geometrical place of these points is line – cosmic string.
- SU(2) degeneracy results in isolated singular points – in GUTs they have properties of magnetic monopoles.

Magnetic monopoles in GUTs

Dirac suggested an existence of magnetic monopole with magnetic charge

$$g = (2e)^{-1}$$

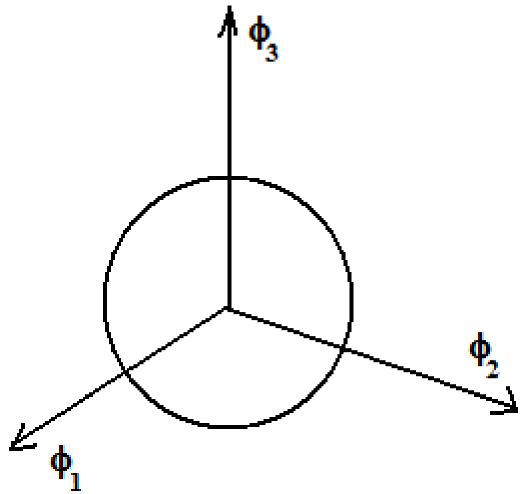
as condition of quantization of electric charge.

T'Hooft and Polyakov have shown, that in gauge models, in which $U(1)_{e/m}$ symmetry is included to SU(3) or wider compact symmetry group, magnetic monopole must appear in the result of spontaneous breaking of symmetry as a topological defect of respective Higgs' field. A.S. Schwartz has shown that it inevitably takes place in GUT models, embedding $U(1)_{e/m}$ in a compact group of GUT symmetry. The mass of GUT monopole was predicted to be

$$m_M \sim \Lambda_{\mathrm{GUT}} / \sqrt{\alpha} \qquad (\Lambda_{GUT} \sim 10^{15}\ \mathrm{GeV})$$

Formation of magnetic monopoles

In the isotopic space of Higgs' field, the minimum of potential corresponds to sphere. At the sphere, Higgs' field can be defined by angles θ and φ.



After phase transition (violation of SO(3) symmetry), at $T<T_{cr}\sim\upsilon$, Higgs' field acquires vacuum expectation value. In all (coordinate) space ϕ gets the value υ and different magnitudes of θ and φ, which vary within the length scale

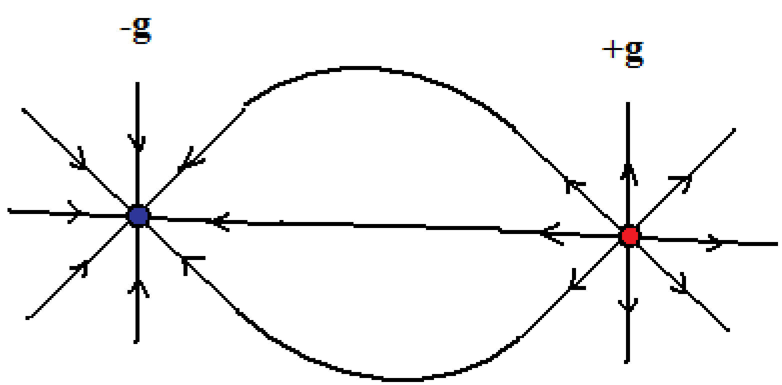
$$\Delta l \sim \frac{1}{e\upsilon}$$

However, it is not possible for θ and φ to vary continuously over 2π and not to get a singularity – the point where θ and φ are indefinite (like a pole on globe, "one cannot brush a hedgehog").

Magnetic monopole pairs

Such a singularity is topological defect – monopole. Its size is defined by Δl*. In its center* $\phi=0$*, it corresponds to non-zero energy density of* ϕ *(outside of minimum) – mass, pointed previously.*

Gradients of $\theta(x)$ *and* $\varphi(x)$*, issuing from singularity, define intensity of magnetic filed. This is accounted for by the fact that the field* ϕ *is connected with gauging of electromagnetic field. Singularity, where gradients of* $\theta(x)$ *and* $\varphi(x)$ *come to, corresponds to an antimonopole.*



Diffusion of magnetic monopoles

Two charge particles (with magnetic charge g) feel each other in plasma at distance when

$$\frac{g^2}{r} \sim E \sim T \quad \Rightarrow \quad r \sim r_0 \equiv \frac{g^2}{T}$$

Diffusive approximation is proved by condition

$$\lambda \ll r_0$$

where $\lambda \sim \frac{1}{n_a \sigma} \sim \frac{1}{T^3}\frac{Tm}{(ge)^2} \sim \frac{m}{T^2 (ge)^2}$ *is the scattering length.*

In this case annihilation rate is defined as

$$\frac{dn_M}{dt} = -n_M^2 \, 4\pi D r_0$$

where $D = \frac{1}{3}\lambda v$ *is diffusion coefficient.*

Magnetic monopole overproduction

Finally, for monopole relic density one finds

$$\Omega_M \sim m \frac{m}{g^5 (eg) m_{Pl}} \frac{n_\gamma^{(\mathrm{mod})}}{\varepsilon_{cr}} \sim 10^{15} \left(\frac{\Lambda_{GUT}}{10^{15}\, GeV} \right)^2$$

That is conclusion does not change in principle, the problem of overproduction of magnetic monopoles remains. In fact, diffusion slows down annihilation rate with respect to direct annihilation (in approximation of free monopole motion) and more monopoles should survive.

This problem either excludes magnetic monopole with given properties, or implies completely different conditions in very early Universe.

Primordial Black Holes

- Any object of mass M can form Black hole, if contracted within its gravitational radius.

$$\boxed{r \le r_g = \frac{2GM}{c^2}}$$

- It naturally happens in the result of evolution of massive stars (and, possibly, dense star clusters).
- In the early Universe Black hole can be formed, if expansion can stop within cosmological horizon [Zeldovich, Novikov, 1966]. It corresponds to strong nonhomogeneity in early Universe

$$\delta \equiv \frac{\delta\rho}{\rho} \sim 1$$

PBHs as indicator of early dust-like stages

- In homogeneous and isotropic Universe ($\delta_0 << 1$) with equation of state $p = k\varepsilon$ probability of strong nonhomogeneity $\delta \sim 1$ is exponentially suppressed

$$P(\delta) = A(\delta, \delta_0)\exp\left(-\frac{k^2\delta^2}{2\delta_0^2}\right)$$

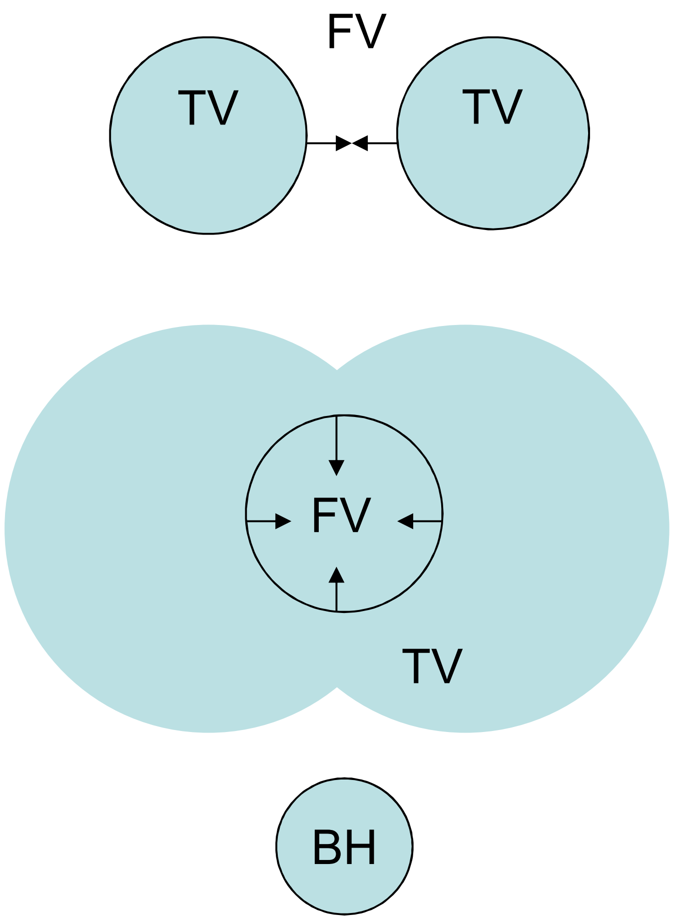
- At *k=0* on dust-like stage exponential suppression is absent. The minimal estimation is determined by direct production of BHs

$$A(\delta, \delta_0) \geq \left(\frac{\delta_0}{\delta}\right)^5 \left(\frac{\delta_0}{\delta}\right)^{3/2} = \left(\frac{\delta_0}{\delta}\right)^{13/2}$$

Dominance of superheavy particles

- Superheavy particles with mass *m* and relative concentration $r = n / n_{\gamma}$ dominate in the Universe at *T<r m.*
- Coherent oscillations of massive scalar field also behave as medium with *p*=0.
- They form BHs either directly from collapse of symmetric and homogeneous configurations, or in the result of evolution of their gravitationally bound systems (pending on particle properties they are like « stars » or « galaxies »).

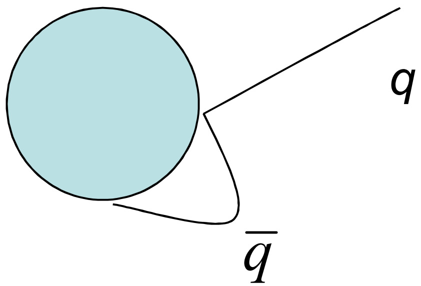
PBHs as indicator of first order phase transitions



- Collision of bubbles with True Vacuum (TV) state during the first-order phase transition results in formation of False Vacuum (FV) bags, which contract and collapse in Black Holes (BH).

PBH evaporation

- According to S. Hawking PBH with mass M evaporate due to creation of pairs by its nonstationary gravitational field. Products of evaporation have black body spectrum with



$$T_{PBH} \propto 1/r_g$$

$$T_{PBH} \approx 10^{13}\,GeV\left(\frac{1g}{M}\right)$$

- The rate of evaporation is given by

$$\frac{dM}{dt} = -\kappa T_{PBH}^{4}\, r_g^{2} \propto 1/r_g^{2} \propto 1/M^{2}$$

- The evaporation timescale is

$$t_{PBH} \approx 10^{27}\,s\left(\frac{M}{1g}\right)^{3}$$

Any particle with $m \leq T_{PBH}$ is created – UNIVERSAL source

Effects of Primordial Black Holes

- PBHs behave like a specific form of Dark Matter
- Since in the early Universe the total mass within horizon is small, it seems natural to expect that such Primordial Black holes should have very small mass (much smaller, than the mass of stars). PBHs with mass $M < 10^{15}\,g$ evaporate and their astrophysical effects are similar to effects of unstable particles.
- However, cosmological consequences of particle theory can lead to mechanisms of intermediate and even supermassive BH formation.

Strong nonhomogeneities in nearly homogeneous and isotropic Universe

- **The standard approach is to consider homogeneous and isotropic world and to explain development of nonhomogeneous structures by gravitational instability, arising from small initial fluctuations.**

$$\delta \equiv \delta\rho / \rho << 1$$

- **However, if there is a tiny component, giving small contribution to total**

$\rho_i << \rho$ **its strong nonhomogeneity** $\delta_i \equiv (\delta\rho / \rho)_i > 1$

is compatible with small nonhomogeneity of the total density

$$\delta = (\delta\rho_i + \delta\rho)/\rho \approx (\delta\rho_i / \rho_i)(\rho_i / \rho) << 1$$

Such components naturally arise as consequences of particle theory, shedding new light on galaxy formation and reflecting in cosmic structures the fundamental structure of microworld.

Strong Primordial nonhomogeneities from the early Universe

- Cosmological **phase transitions** in inflationary Universe can give rise to unstable cosmological defects, retaining a replica in the form of primordial **nonlinear** structures (massive PBH clusters, archioles).
- Nonhomogenous baryosynthesis (including spontaneous baryosynthesis and leptogensis) in its extreme form can lead to **antimatter** domains in baryon asymmetrical inflationary Universe.

Strong nonhomogeneities of total density and baryon density are severely constrained by CMB data at large scales (and by the observed gamma ray background in the case of antimatter). However, their existence at smaller scales is possible.

U(1) model

$$V(\psi) = \frac{\lambda}{2}\left(\psi^2 - f^2\right)$$

After spontaneous symmetry breaking infinitely degenerated vacuum

$$\psi = f e^{i\varphi/f}$$

experiences second phase transition due to the presence (or generation by instanton effects)

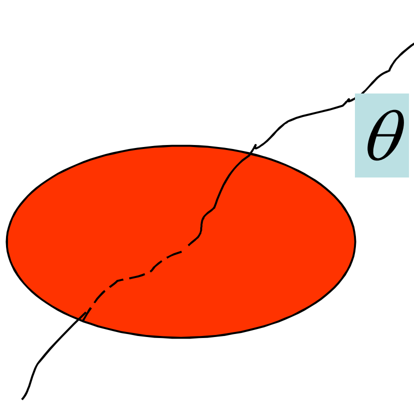
$$V(\varphi) = \Lambda^4\left(1 - \cos(\varphi/f)\right)$$

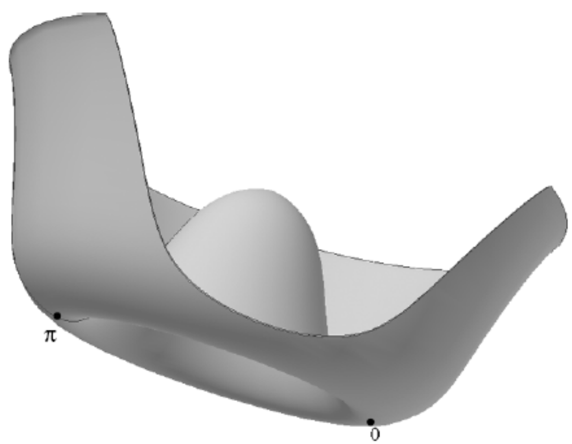
to vacuum states

$$\theta \equiv \varphi/f = 0, 2\pi, \ldots$$

In particular, this succession of phase transitions takes place in axion models

Topological defects



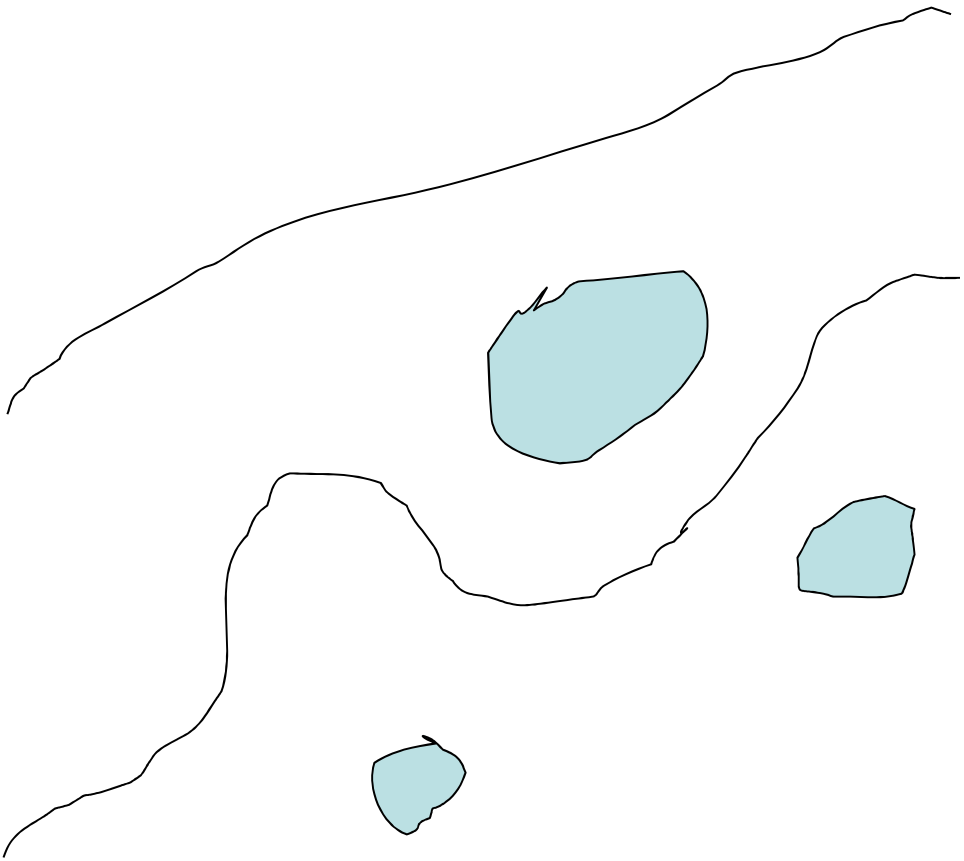


- Spontaneous breaking of U(1) symmetry results in the continuous degeneracy of vacua. In the early Universe the transition to phase with broken symmetry leads to formation of cosmic string network.
- The tilt in potential breaks continuous degeneracy of vacua. In the result string network converts into walls-bounded-by-strings structure in the second phase transition. This structure is unstable and decay, but the initial values of phase define the energy density of field oscillations.

Unstable topological defects

- This picture takes place in axion cosmology.
- The first phase transition gives rise to cosmic axion string network.
- This network converts in the second phase transition into walls-bounded-by-strings structure (walls are formed between strings along the surfaces $\alpha = \pi$), which is unstable.
- However, the energy density distribution of coherent oscillations of the field α follows the walls-bounded-by-strings structure.

Archioles structure

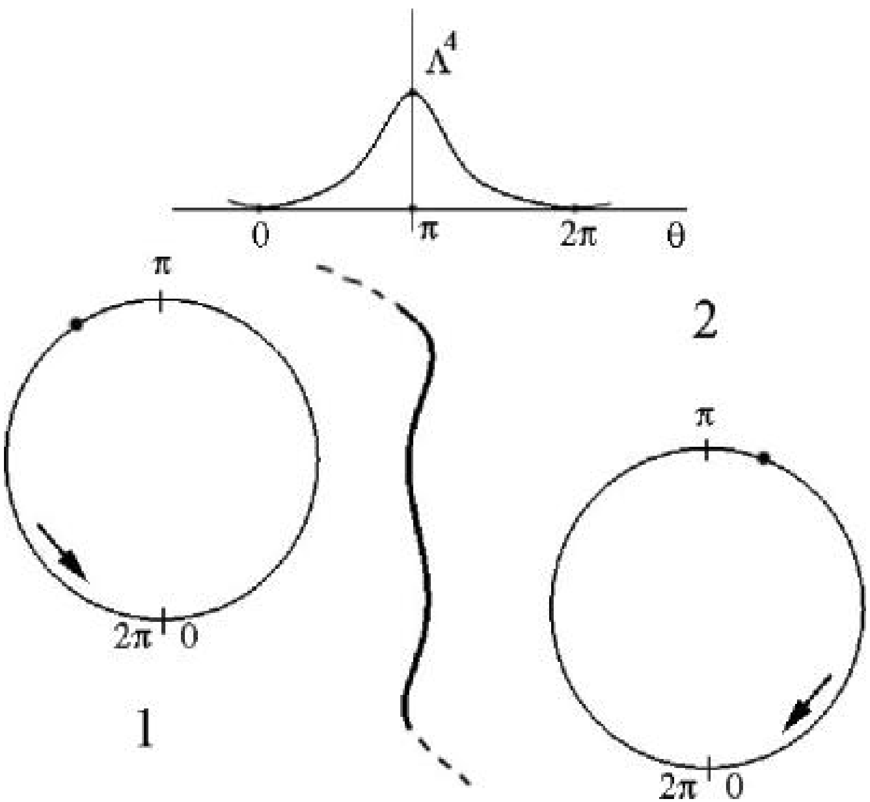


- Numerical studies revealed that ~80% of string length corresponds to infinite Brownian lines, while the remaining ~20% of this length corresponds to closed loops with large size loops being strongly suppressed. It corresponds to the well known scale free distribution of cosmic strings.
- The fact that the energy density of coherent axion field oscillations reflects this property is much less known. It leads to a large scale correlation in this distribution, called archioles.
- Archioles offer possible seeds for large scale structure formation.
- However, the observed level of isotropy of CMB puts constraints on contribution of archioles to the total density and thus puts severe constraints on axions as dominant form of Dark Matter.

Massive Primordial Black Holes

- Any object can form Black hole, if contracted within its gravitational radius. It naturally happens in the result of evolution of massive stars (and, possibly, star clusters).
- In the early Universe Black hole can be formed, if within cosmological horizon expansion can stop [Zeldovich, Novikov, 1966]. Since in the early Universe the total mass within horizon is small, it seems natural to expect that such Primordial Black holes should have very small mass (much smaller, than the mass of stars).
- However, cosmological consequences of particle theory can lead to mechanisms of intermediate and even supermassive BH formation.

Closed walls formation in Inflationary Universe



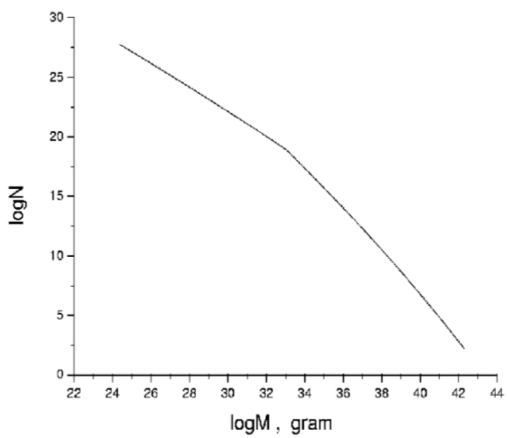
If the first U(1) phase transition takes place on inflationary stage, the value of phase θ , corresponding to e-folding N~60, fluctuates

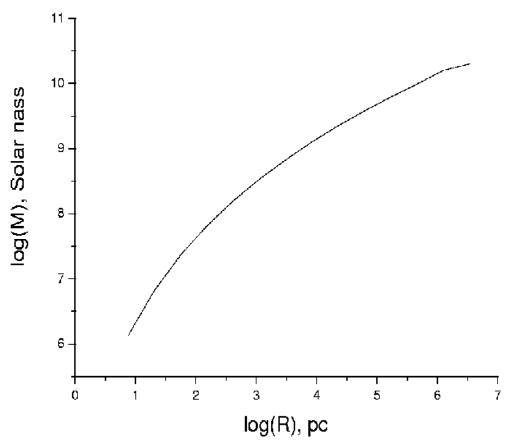
$$\Delta\theta \approx H_{\mathrm{infl}}/(2\pi f)$$

Such fluctuations can cross π

and after coherent oscillations begin,regions with $\theta > \pi$ occupying relatively small fraction of total volume are surrounded by massive walls

Massive PBH clusters





Each massive closed wall is accompanied by a set of smaller walls.
As soon as wall enters horizon, it contracts and collapses in BH.
Each locally most massive BH is accompanied by a cloud of less massive BHs.
The structure of such massive PBH clouds can play the role of seeds for galaxies and their large scale distribution.

Spectrum of Massive BHs

- The minimal mass of BHs is given by the condition that its gravitational radius exceeds the width of wall ($d \approx 2f/\Lambda^2$)

$$r_g = \frac{2M}{m_{Pl}^2} > d = \frac{2f}{\Lambda^2} \Rightarrow M_{\min} = f\left(\frac{m_{Pl}}{\Lambda}\right)^2$$

- The maximal mass is given by the condition that pieces of wall do not dominate within horizon, before the whole wall enters the horizon

$$R < \frac{3\sigma_w}{\rho_{tot}} \Rightarrow M_{\max} = f\left(\frac{m_{Pl}}{f}\right)^2\left(\frac{m_{Pl}}{\Lambda}\right)^2 \Rightarrow \frac{M_{\max}}{M_{\min}} = \left(\frac{m_{Pl}}{f}\right)^2$$

GW signals from closed wall collapse and BHs merging in clouds

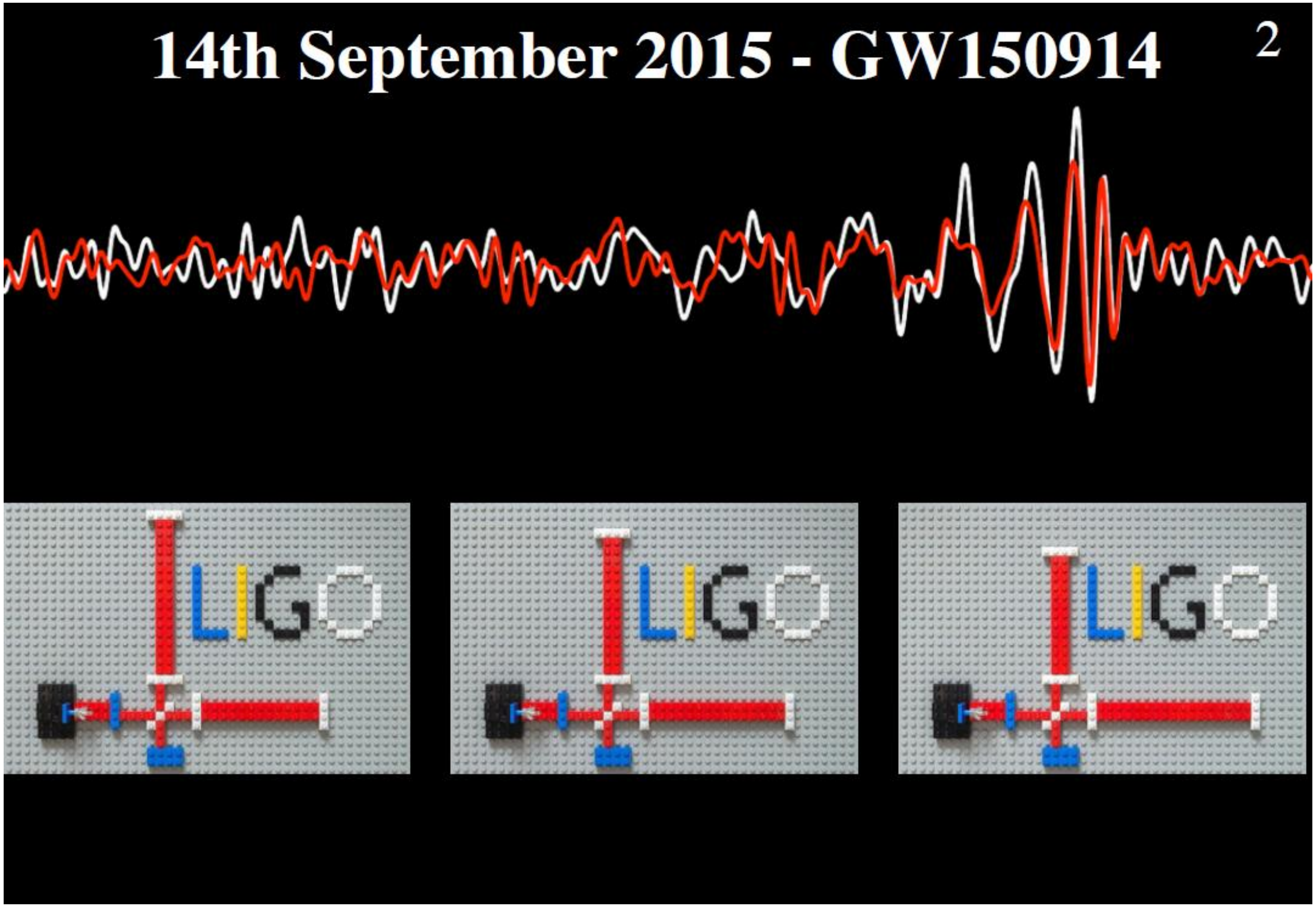
- Closed wall collapse leads to primordial GW spectrum, peaked at $\nu_0 = 3 \cdot 10^{11} (\Lambda / f) Hz$ with energy density up to

$$\Omega_{GW} \approx 10^{-4} \left(f / m_{Pl} \right)$$

- At $f \sim 10^{14}\, GeV$ $\Omega_{GW} \sim 10^{-9}$
- For $1 < \Lambda < 10^{8}\, GeV$ $3 \cdot 10^{-3}\, Hz < \nu_0 < 3 \cdot 10^{5}\, Hz$

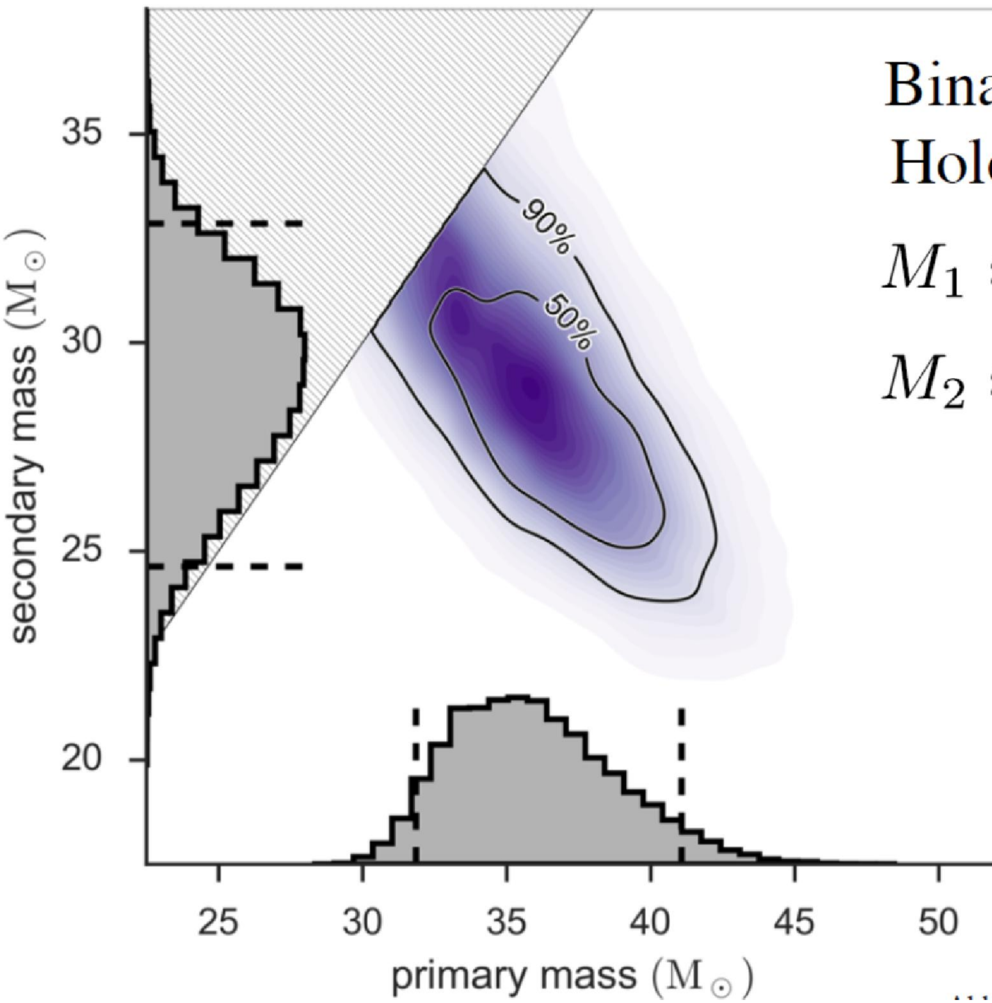
- Merging of BHs in BH cluster is probably detected by LIGO!.

The first GW signal!



From VIA talk 09.12.2016 by P.Lasky

Abbott et al. (2016) - GW150914



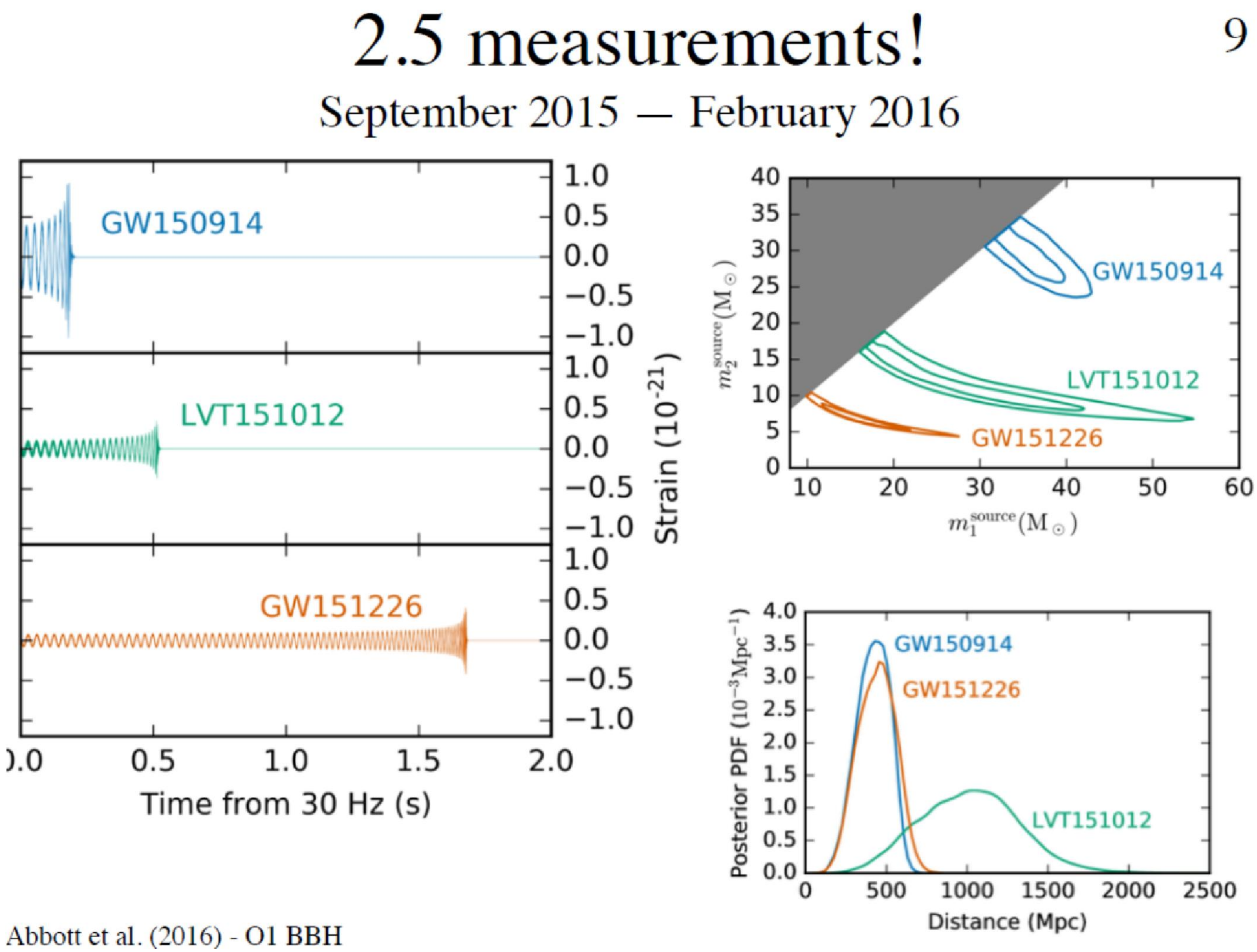
Binary Black Hole Merger

$M_1 \approx 36\, M_\odot$

$M_2 \approx 29\, M_\odot$

From VIA talk 09.12.2016 by P.Lasky

GW astronomy!



From VIA talk 09.12.2016 by P.Lasky

Binaries of massive PBHs?

- Massive PBHs are not distributed homogeneously in space, but are in clouds.
- It makes more probable formation of massive PBHs binaries.
- The problem of creation of stellar mass PBH clouds, their evolution and formation of BH binaries in them may be an interesting hot topic for a PhD thesis

Antimatter from nonhomogeneous baryosynthesis

- Baryon excess B>0 can be generated nonhomogeneously B(x).
- Any nonhomogeneous mechanism of BARYON excess generation B(x) leads in extreme form to ANTIBARYON excess in some regions.

Survival of antimatter domains

Diffusion of baryons and antibaryons to the border of domain results in eating of antimatter by surrounding baryonic matter.

$$\partial n_b/\partial t = D(t)\partial^2 n_b/\partial x^2 - \alpha n_b$$

where

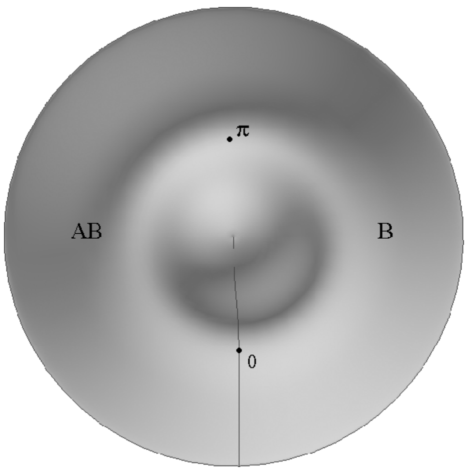
$$D(t) \approx \frac{3T_\gamma c}{2\rho_\gamma \sigma_T}$$

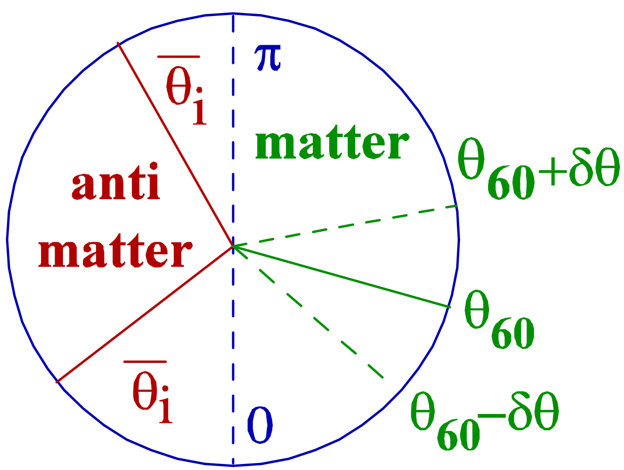
The minimal surviving scale is given by

$$d \approx \frac{c}{\sqrt{\frac{8\pi}{3}G\rho_0}} \frac{T_p}{m} \sqrt{\frac{m}{T_{rec}}} \int_{T_p/T_{rec}}^{1} \frac{dy}{y^{3/2}} = \frac{2c}{\sqrt{\frac{8\pi}{3}G\rho_0}} \sqrt{\frac{T_p}{m}}$$

which is about $d \sim 3/h$ kpc..

Nonhomogeneous spontaneous baryosynthesis





- Model of spontaneous baryosynthesis provides quantitative description of combined effects of inflation and nonhomogeneous baryosynthesis, leading to formation of antimatter domains, surviving to the present time.

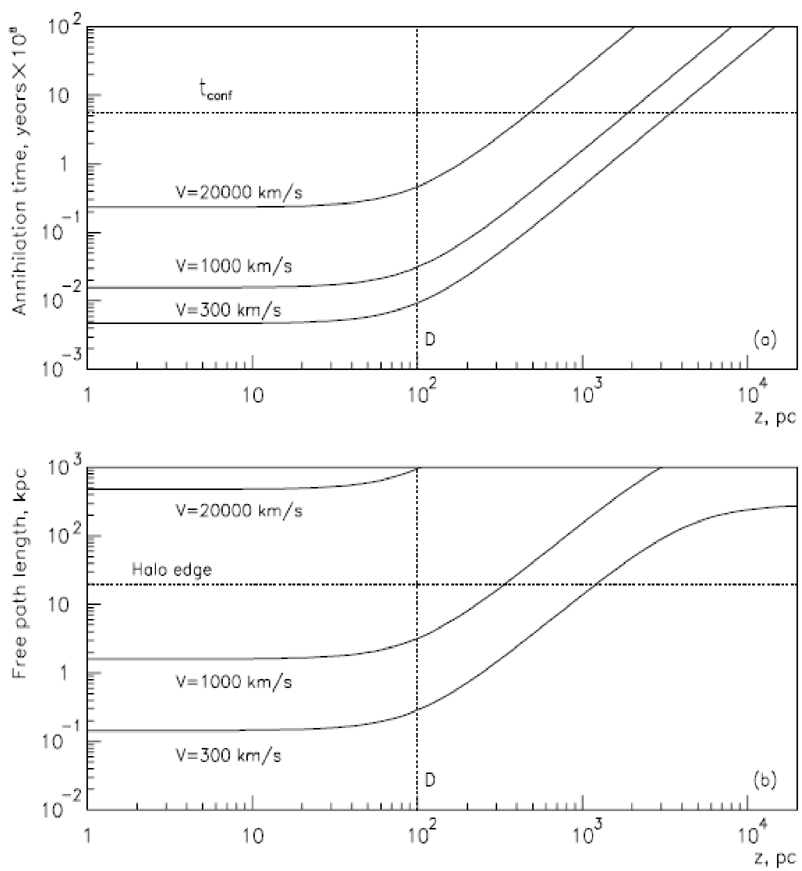
Antimatter in galaxies

Number of e-fold	Number of domains	Size of domain
59	0	$1103 Mpc$
55	$5.005 \cdot 10^{-14}$	$37.7 Mpc$
54	$7.91 \cdot 10^{-10}$	$13.9 Mpc$
52	$1.291 \cdot 10^{-3}$	$1.9 Mpc$
51	0.499	$630 kpc$
50	74.099	$255 kpc$
49	$8.966 \cdot 10^{3}$	$94 kpc$
48	$8.012 \cdot 10^{5}$	$35 kpc$
47	$5.672 \cdot 10^{7}$	$12 kpc$
46	$3.345 \cdot 10^{9}$	$4.7 kpc$
45	$1.705 \cdot 10^{11}$	$1.7 kpc$

Numerical simulations show that within the modern horizon possible amount of antimatter domains, with the size exceeding the survival scale and thus surviving to the present time, can be comparable with the total number of galaxies.

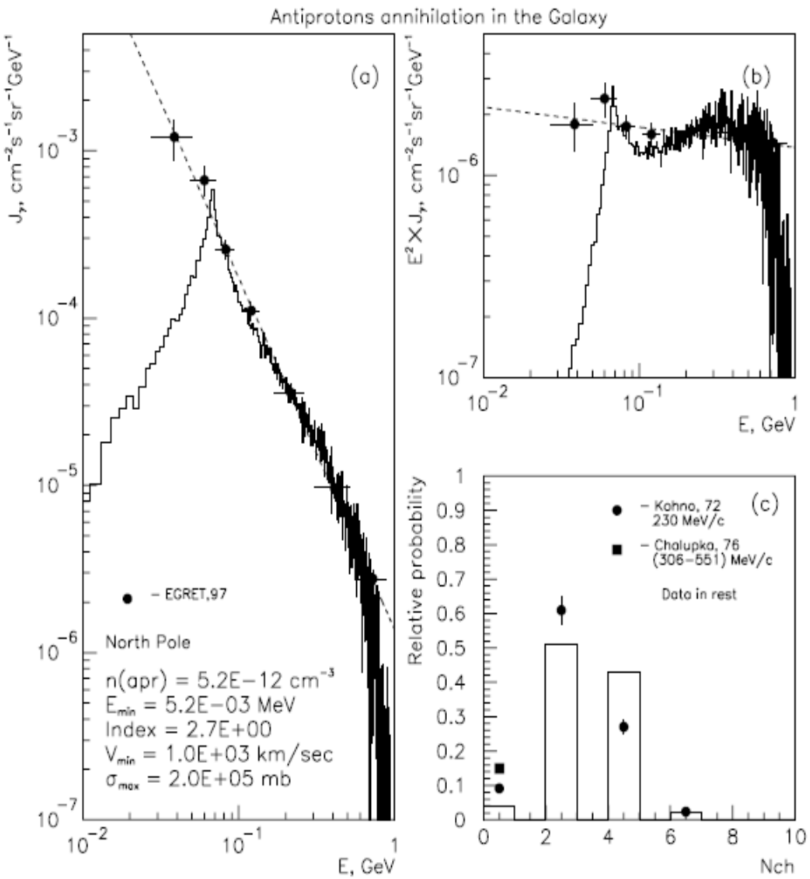
In our Galaxy from 1000 to 100000 antimatter stars can exist in a form of antimatter globular cluster (Khlopov, 1998). Being in halo, such cluster is a faint gamma ray source, but antimatter from it pollutes Galaxy and can be observed indirectly by annihilation, or directly as anti-meteorites or antinuclei in cosmic rays.

Antimatter pollution of Galaxy



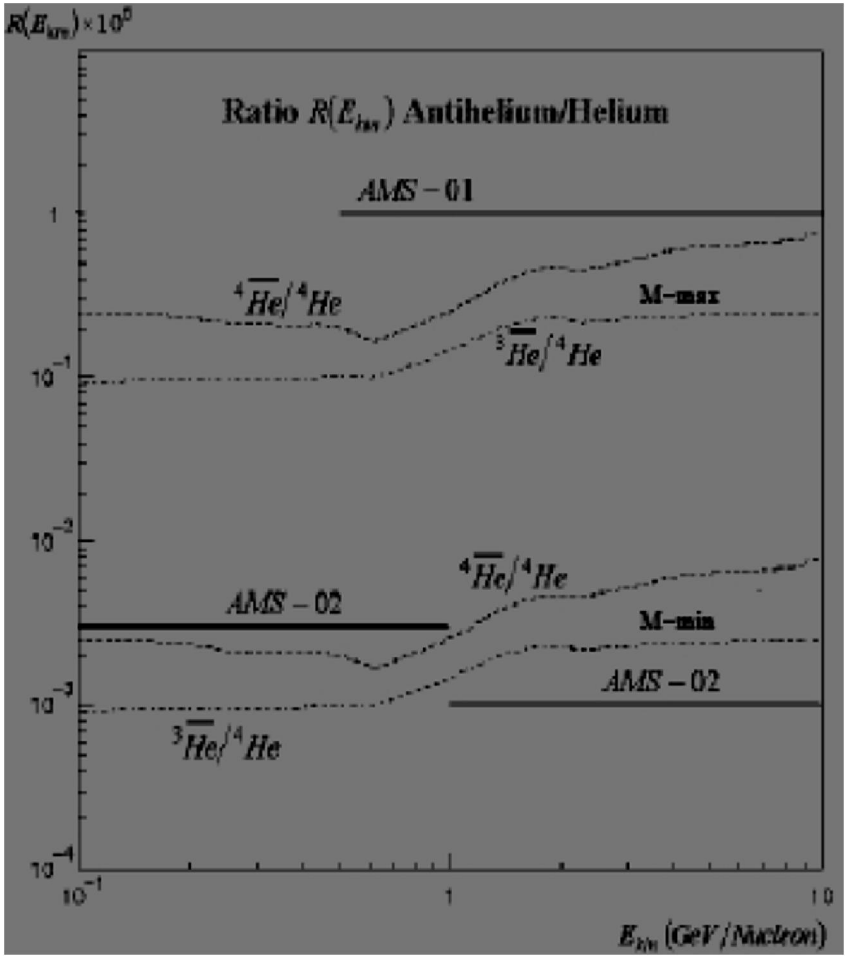
- Since antihydrogen is dominant in antimatter composition, the Galaxy is dominantly polluted by antiprotons.
- Their lifetime in Galaxy depends on their velocity and density of surrounding matter.

Gamma background from antimatter annihilation in Galaxy



- Antiproton annihilation can reproduce gamma background observed by EGRET in the range tens-hundreds MeV.
- It can not be considered as PROOF for existence of antimatter stars – only pieces of antimatter (antihelium nuclei, antimeteorites) can provide such PROOF.

Cosmic antihelium test for antimatter stars in Galaxy



- **Nonhomogeneous baryosynthesis in extreme form leads to antimatter domains in baryon asymmetrical Universe**
- **To survive in the surrounding matter domain should be sufficiently large, and to have sufficiently high internal antibaryon density to form stars. It gives minimal estimation of possible amount of antimatter stars in Galaxy**
- **The upper limit comes from observed gamma background**
- **Assuming that antihelium component of cosmic rays is proportional to the fraction of antimatter stars in the total mass of Galaxy, it is possible to test this hypothesis initially in PAMELA and then completely in AMS-02 experiment**

First signal from antimatter stars in AMS02?

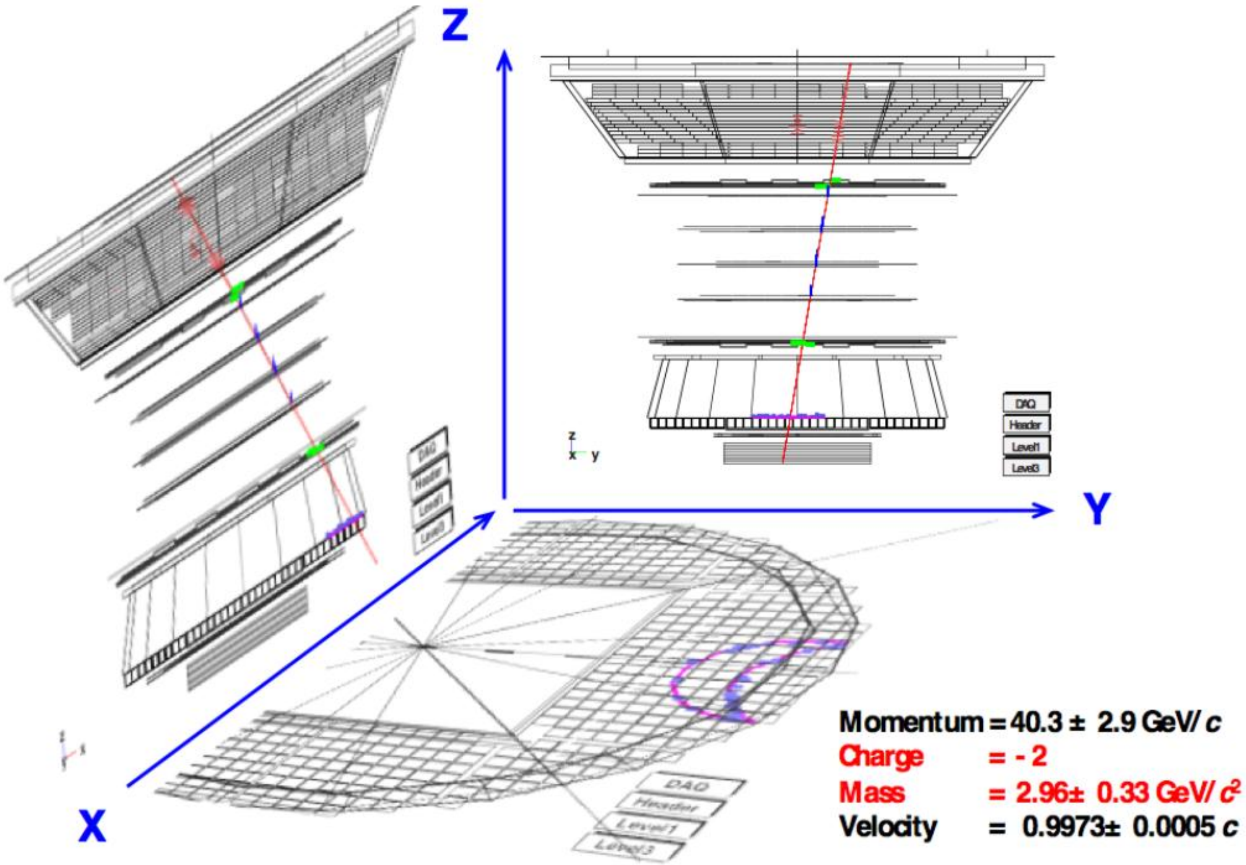


Figure 14. An antihelium candidate.

Presented in CERN on 08.12.2016 by Prof. S.Ting

Conclusions

• Pending on the strength of their interaction with plasma particles can freeze out in it or decouple from it. Primordial neutrinos, heavy leptons, gravitino and magnetic monopoles represent various mechanisms of particle production in very early Unvierse

•Strong primordial nonlinear structures (PBHs, massive BH clouds, strong nonhomogeneities of baryonic matter and even antimatter stars) link structure of microworld to cosmological structures and lead to experimentally accessible effects.

• The cosmological impact of primordial particles and structures give an example of fundamental relationship between micro- and macro worlds, studied by cosmoparticle physics.