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Nonstandard cosmologies from BSM physics

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« What comes Beyond the Standard Model »
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The bedrocks of modern cosmology

Our current understanding of structure and evolution of the Universe implies three necessary elements of Big Bang cosmology that can not find physical grounds in the standard model of elementary particles. They are:

- Inflation
- Dark matter/energy
- Baryosynthesis

These standards of the modern cosmology based on physics Beyond the Standard Model of elementary particles are inevitably accompanied by model dependent nonstandard cosmological consequences that are the subject of the present talk

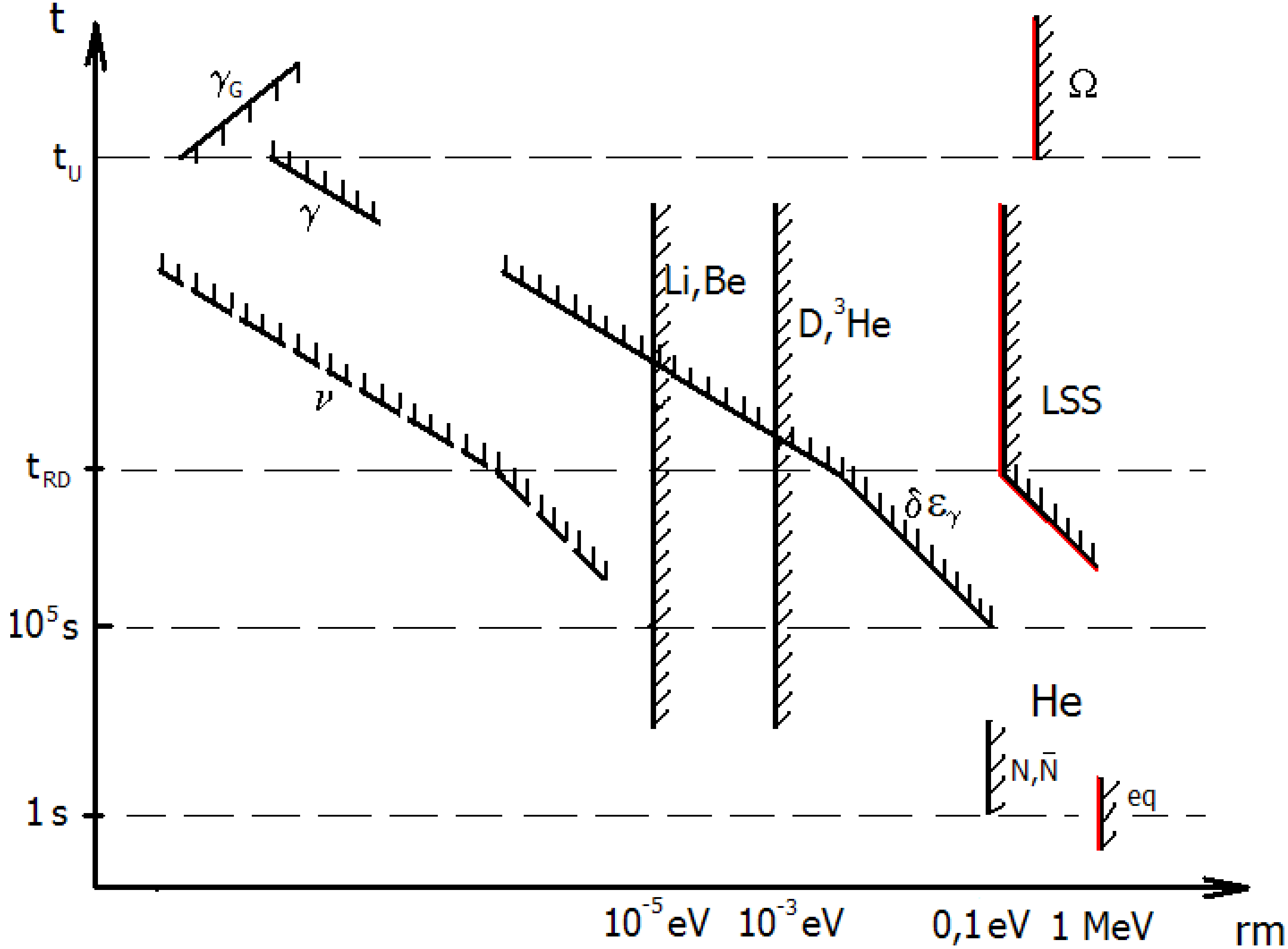
Outlines

- Decaying metastable particles as reflection of approximate particle symmetry
- 4th generation with new U(1) gauge charge (charge symmetric case): neutrino binding and annihilation and OHe neutrino binding in charge asymmetric case
- Strong Primordial nonhomogeneities as cosmological reflection of particle symmetry
- Primordial Black Holes (PBHs)
- Massive PBH clusters.
- Antimatter as profound signature for nonhomogeneous baryosynthesis.

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. Metastable particles reflect approximate symmetry. Next to the lightest new particles, being unstable, may be sufficiently longliving.
- 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…). Phase transitions on inflationary stage can give rise to primordial nonlinear structures like surviving antimatter domains or priordial seeds for AGNs.
- Structures, arising from dominance of superheavy metastable particles and phase transitions in early Universe, can give rise to Black Holes, remaining in the Universe after these structures decay.

Laboratory of the Universe



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

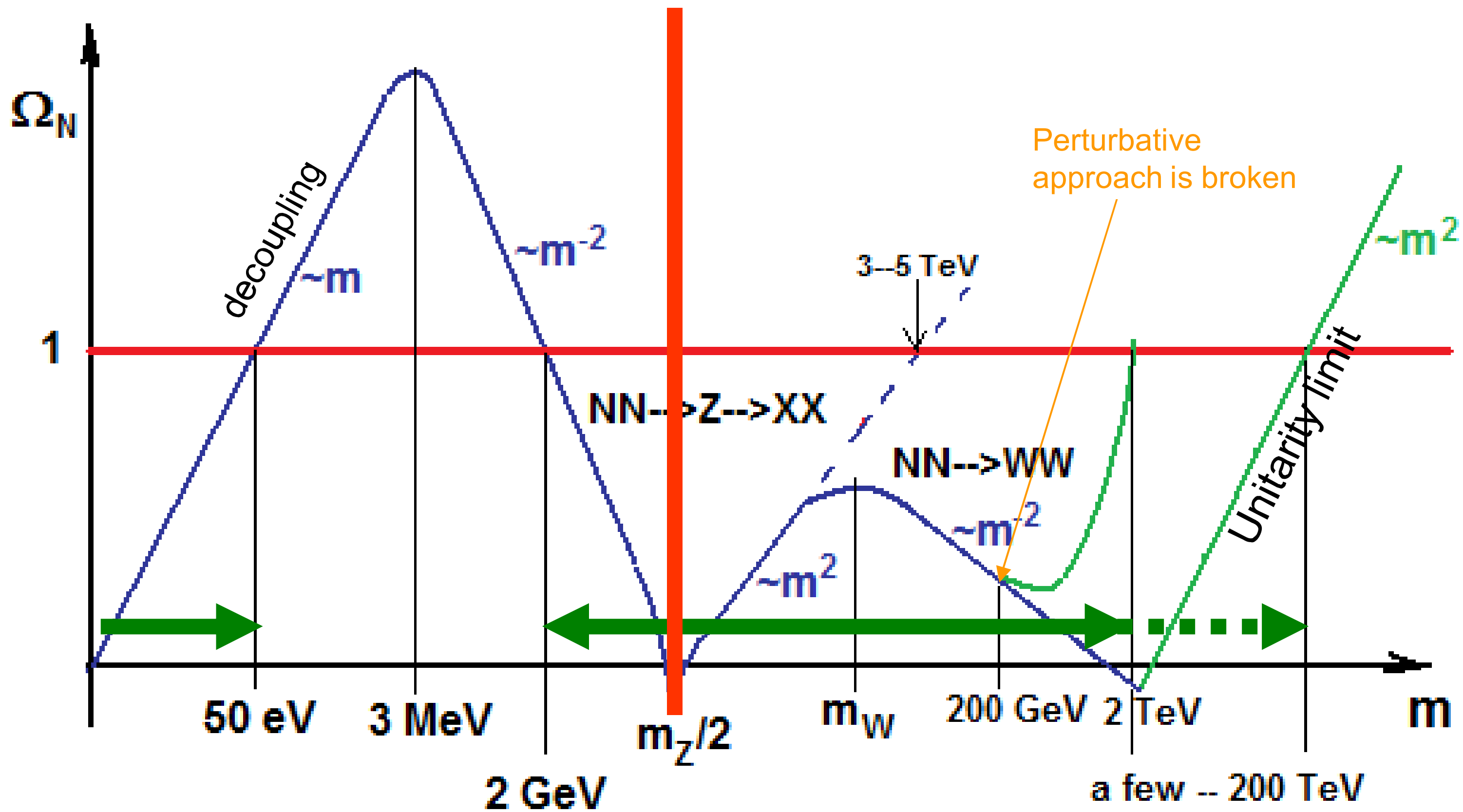
Mass of neutrino and physics beyond SM

- Majorana mass of neutrino – lepton number violation
- Dirac mass – new state of right handed neutrino

Physics of neutrino mass goes beyond the Standard Model

Constraint on the mass of neutrino

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



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

However *m* < 45 GeV is forbidden by accelerator data.

4th family with new U(1) gauge charge

4th family from heterotic string phenomenology

- 4th family can follow from heterotic string phenomenology as naturally as SUSY.
- GUT group E_6 has rank (number of conserved quantities) 6, while SM, which it must embed, has rank 4. This difference means that new conserved quantities can exist.
- Euler characterics of compact manifold (or orbifold) defines the number of fermion families. This number can be 3, but it also can be 4.
- The difference of the 4th family from the 3 known light generations can be explained by the new conserved quantity, which 4th generation fermions possess.
- If this new quantum number is strictly conserved, the lightest fermion of the 4th generation (4th neutrino, N) should be absolutely stable.
- The next-to-lightest fermion (which is assumed to be U-quark) can decay to N owing to GUT interaction and can have life time, exceeding the age of the Universe.
- If baryon asymmetry in 4th family has negative sign and the excess of anti-U quarks with charge -2/3 is generated in early Universe, composite dark matter from 4th generation can exist and dominate in large scale structure formation.

Suppression of Higgs couplings

4th family is more massive, what appeals to its mass generation different from the one for the three known families.

So its coupling to 125 GeV Higgs boson should be suppressed.

The example of a two photon decay channel shows, that with such suppression the SM prediction can be reproduced.

$$R = \frac{\sigma_{\mathrm{SM4}}(gg \to H)\,\Gamma_{\mathrm{SM4}}(H \to \gamma\gamma)}{\sigma_{\mathrm{SM}}(gg \to H)\,\Gamma_{\mathrm{SM}}(H \to \gamma\gamma)}$$

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SM prediction can be reproduced

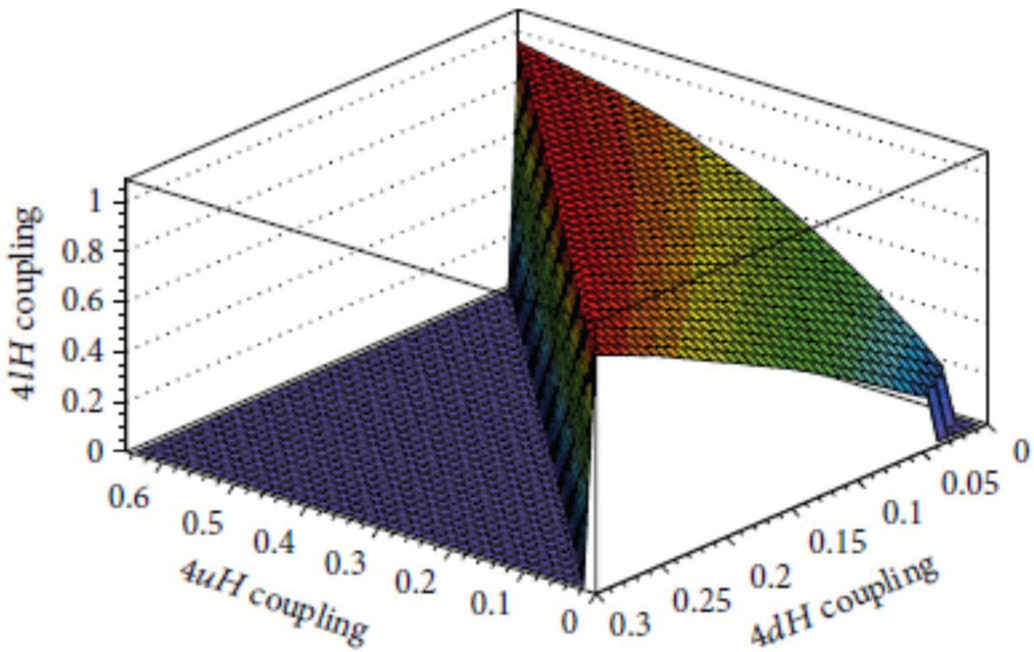

FIGURE 10: The surface in the space of parameters of the suppression factors $4dH$, $4uH$, and $4lH$ in the Higgs coupling to the quarks and leptons of the 4th generation, at which the value of ratio $R = 1$, corresponding to the Standard model prediction, is reproduced.

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RECOMBINATION AND ANNIHILATION OF U(1) CHARGED NEUTRINOS

Recombination

- In charge symmetric case at $T<T_{rec}$ neutrino and antineutrino recombine and annihilate.
- The rate of recombination exceeds the rate of expansion due to strong temperature dependence of classical dipole radiative capture, proposed in [Zeldovich, Khlopov,1978] for free monopole-antimonopole capture.
- It results in strong suppression of relic U(1) charged heavy neutrino density and electromagnetic energy release at dark ages

Recombination of heavy neutrinos

Effects of new long-range interaction: Recombination of relic Heavy neutrinos and antineutrinos

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Abstract

If stable Heavy neutrinos of 4th generation possess their own Coulomb-like interaction, recombination of pairs of Heavy neutrinos and antineutrinos can play important role in their cosmological evolution and lead to observable consequences. In particular, effect of this new interaction in the annihilation of neutrino-antineutrino pairs can account for γ-flux observed by EGRET.

1 Introduction

This work begins systematic study of model of subdominant component of dark matter in form of Heavy neutrinos [1] in the special case when this component possesses its own long range interaction. It is supposed that new interaction is Coulomb-like, being described with unbroken $U(1)$-gauge group. We call it y-interaction. Its massless gauge boson and charge are called y-photon and y-charge, respectively. The

SUPPRESSION OF U(1) CHARGED NEUTRINOS

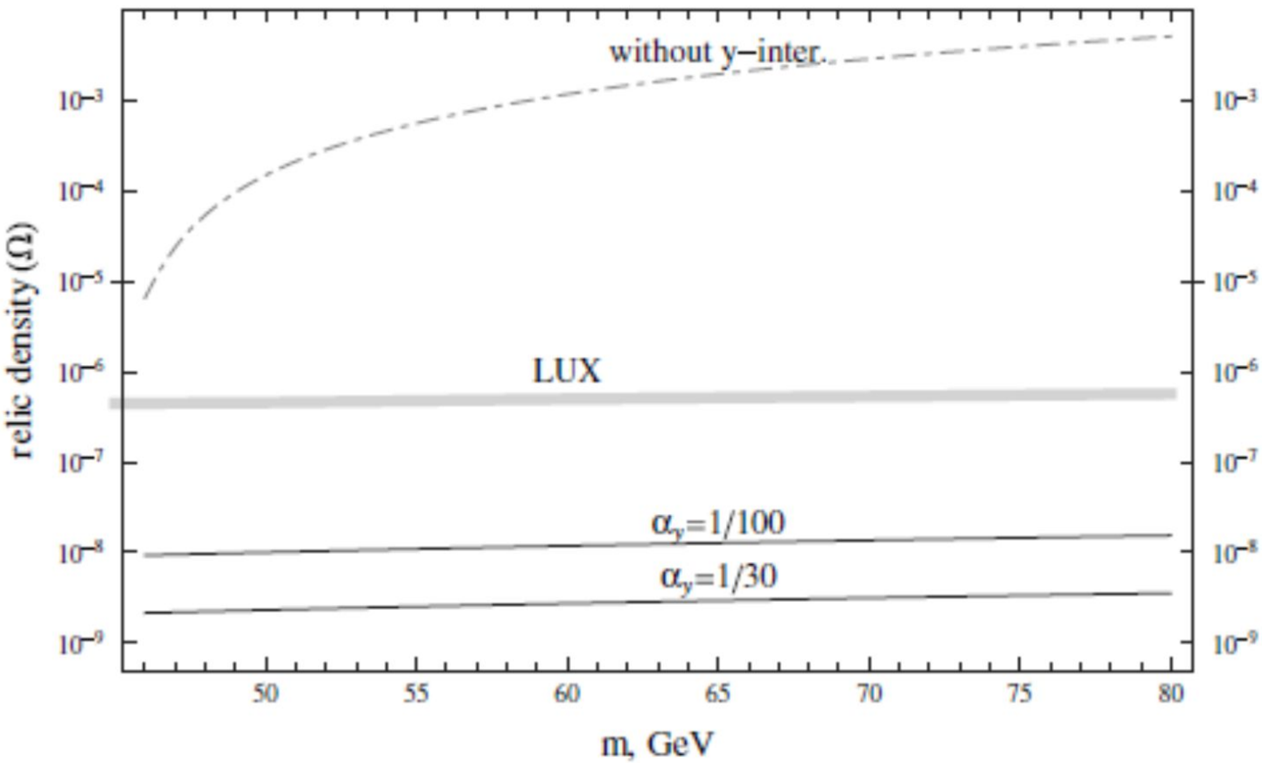

Fig. 1. Relic densities of fourth neutrinos in the galaxy in units of critical density for the cases without and with y-interaction. In the latter case, $\alpha_y = 1/30$ and $1/100$ were taken.

K.M. Belotsky, E. A. Esipova, M. Yu. Khlopov and M. N. Laletin. “Dark Coulomb Binding of Heavy Neutrinos of 4th family”. IJMP D Vol. 24, No. 13 (2015) 1545008 (9 pages)

SAVING OF 4TH NEUTRINOS IN OHE COSMOLOGY

OHE – N recombination

- In charge asymmetric case, when dark matter is explained by excessive anti-U quarks, U(1) charge conservation implies the corresponding N excess.
- Then at $T<T_{rec}$ free N are captured by OHe and hidden in it under its helium nuclear shell. Such « molecule » has nuclear interaction with matter, and most of N are elusive for WIMP searches.

SUPPRESSION OF FREE U(1) CHARGED NEUTRINOS

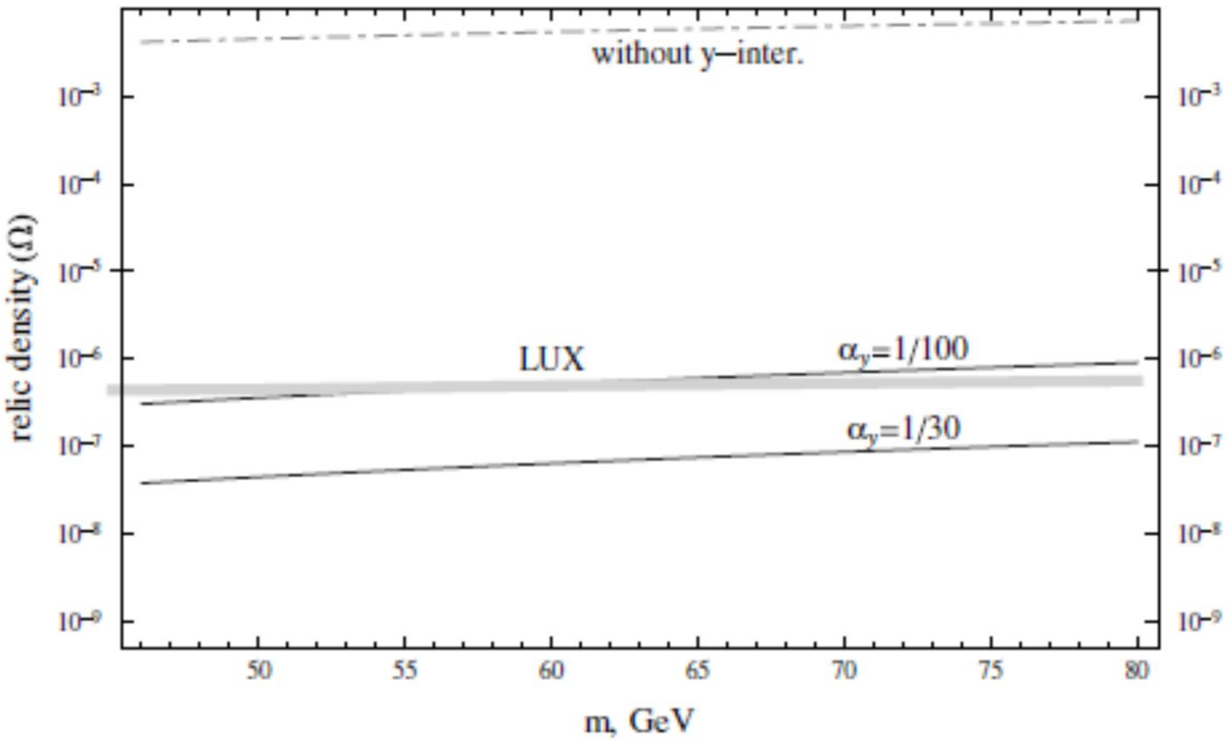

Fig. 2. The same as on Fig. 1 but for the cases of N-$\bar{U}\bar{U}\bar{U}$ charge asymmetric dark matter.

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Cosmological phase transitions as the reflection of particle symmetry breaking

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.

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

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

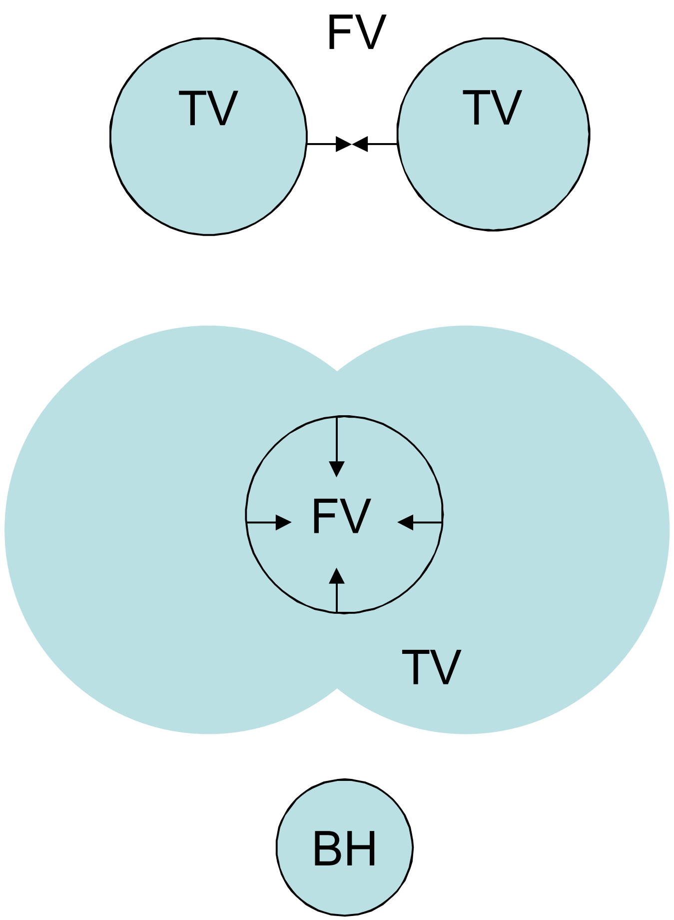
- At *k=0* on dust-like stage exponential suppression is absent. The minimal estimation is determined by direct production of BHs

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

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 »).

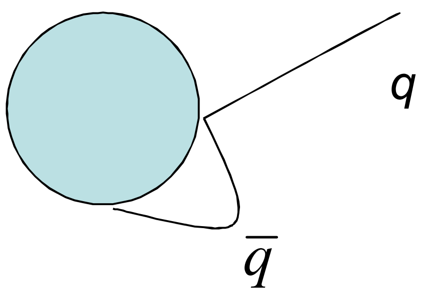
PBHs as indicator of first order phase transitions



- 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)

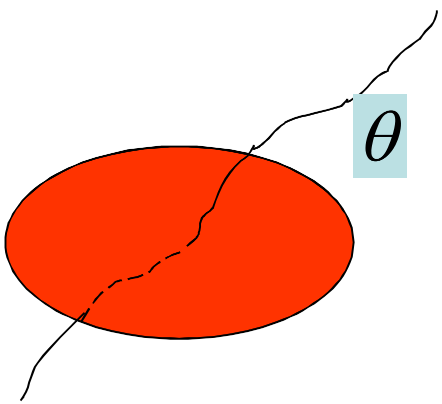
$$V(\varphi) = \Lambda^4\left(1 - \cos(\varphi/f)\right)$$

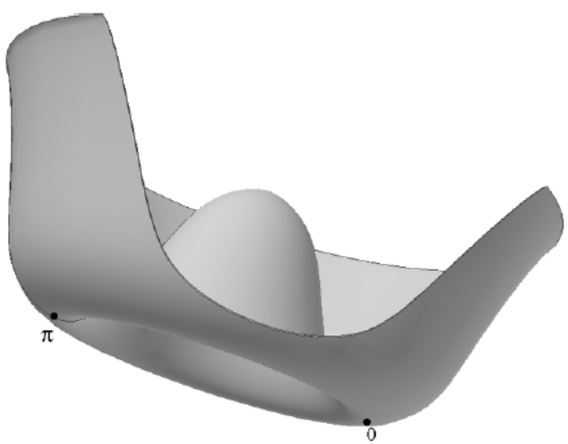
to vacuum states

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

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.

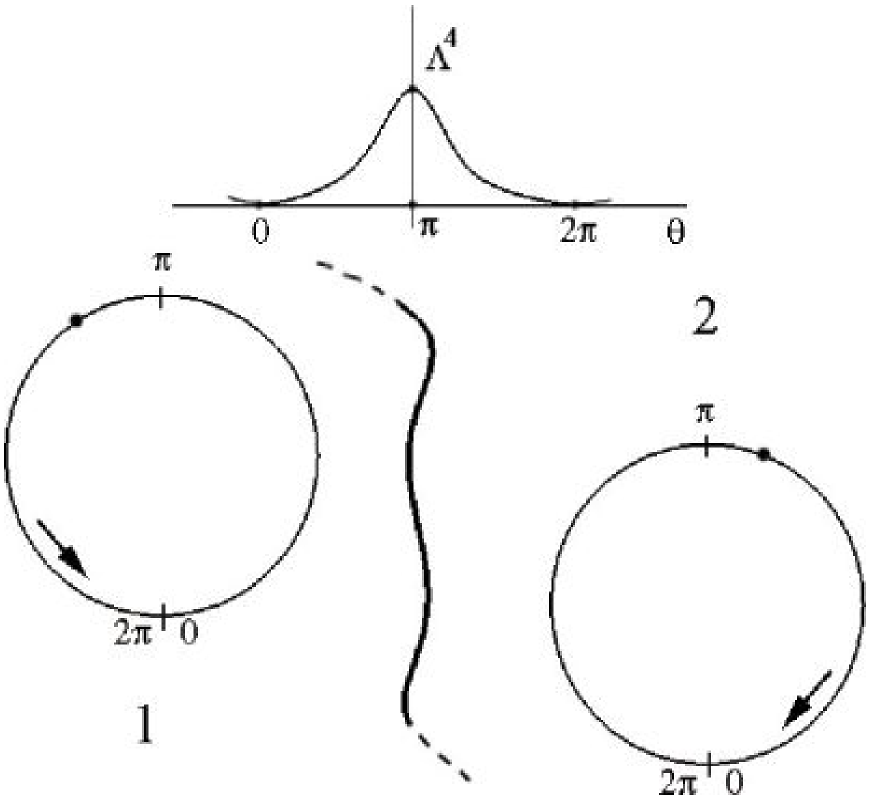
Archioles structure

- 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



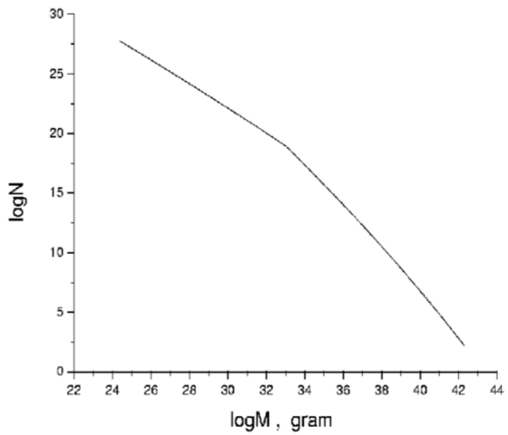
If the first U(1) phase transition takes place on inflationary stage, the value of phase θ , corresponding to e-folding N~60, fluctuates

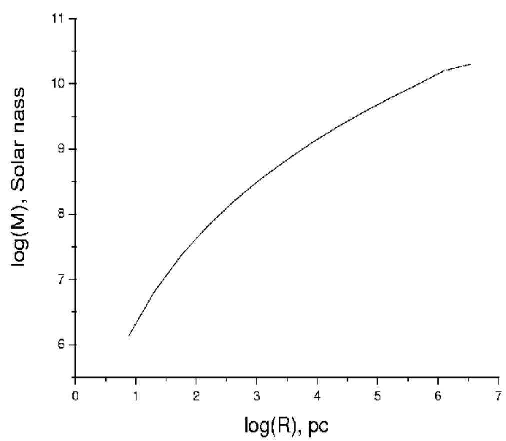
$$\Delta\theta \approx H_{\text{infl}} / (2\pi f)$$

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

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

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

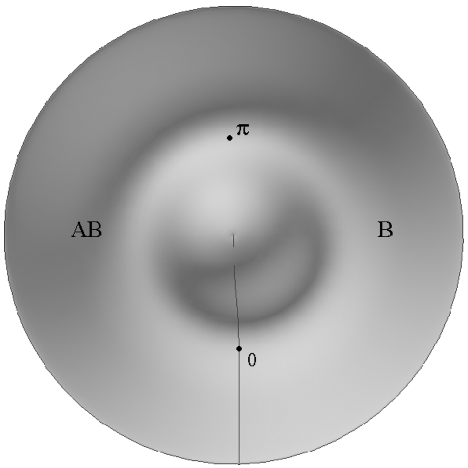
$$D(t) \approx \frac{3T_\gamma c}{2\rho_\gamma \sigma_T}$$

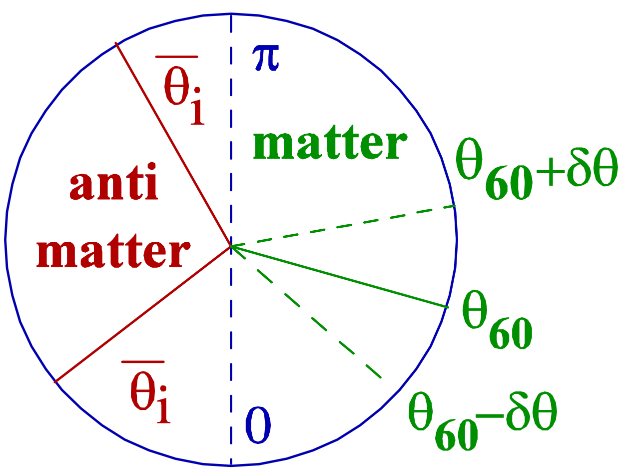
The minimal surviving scale is given by

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

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.

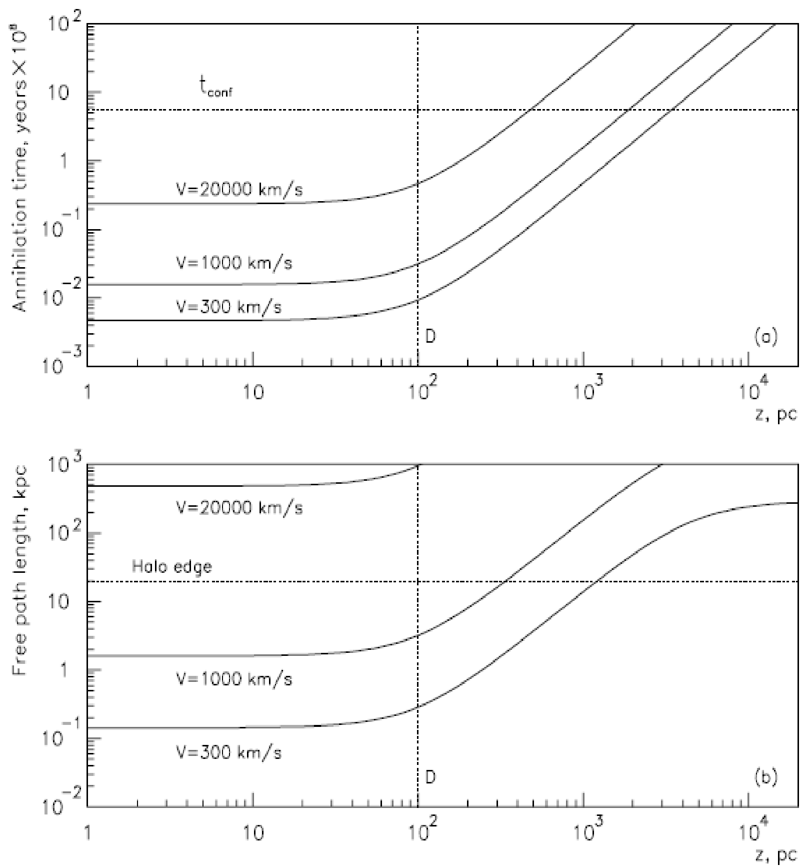
Antimatter in galaxies

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.

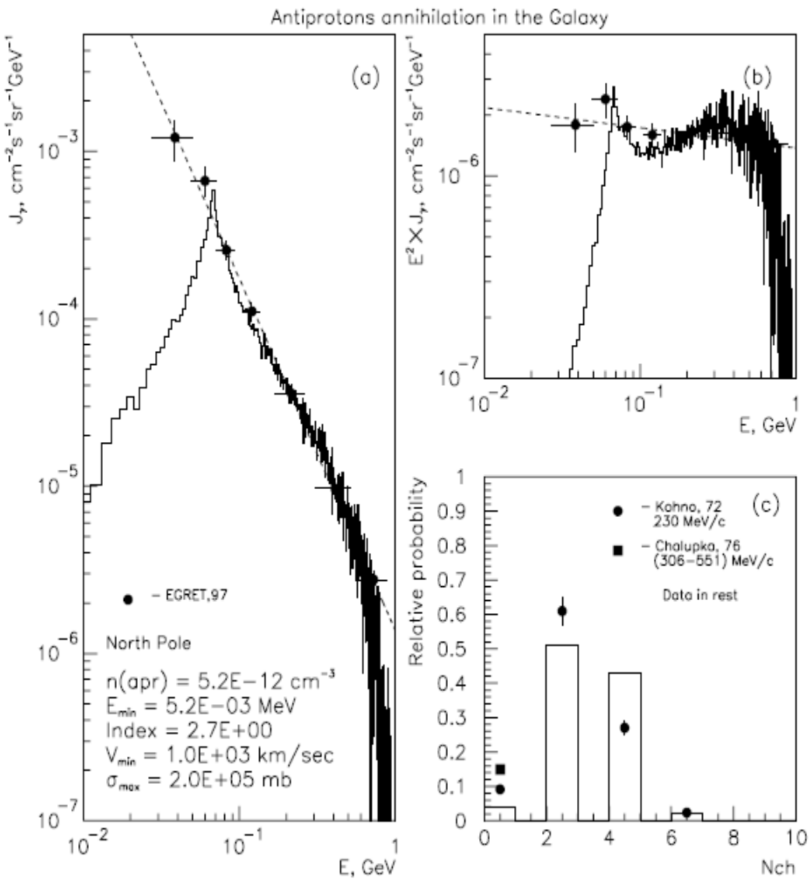
In our Galaxy from 1000 to 100000 antimatter stars can exist in a form of antimatter globular cluster (Khlopov, 1998). Being in halo, such cluster is a faint gamma ray source, but antimatter from it pollutes Galaxy and can be observed indirectly by annihilation, or directly as anti-meteorites or antinuclei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

Antimatter pollution of Galaxy



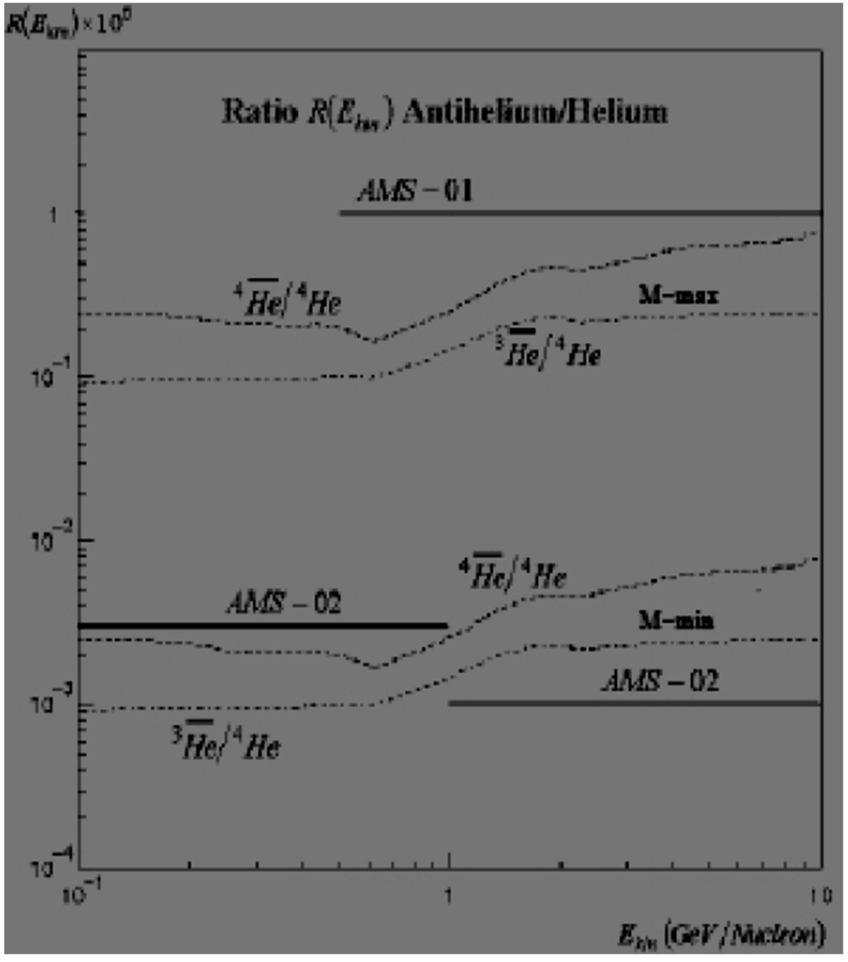
- Since antihydrogen is dominant in antimatter composition, the Galaxy is dominantly polluted by antiprotons.
- Their lifetime in Galaxy depends on their velocity and density of surrounding matter.

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

Conclusions

• Next to the lightest new particles can be metastable and decay with the effect of CMB distorsions.

•4th family with stable heavy neutrino can manage to escape severe constraints from direct dark matter searches, if it possess a new strictly conserved U(1) charge. Their recombination and annihilation leads to electromagnetic energy release in dark ages. In charge asymmetric case of OHe cosmology free U(1) charged neutrinos are bound with OHe, what reduces their cosmic abundance below the experimental upper limits.

•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 observable effects.

• These effects and structures are examples of fundamental relationship between micro- and macro worlds, studied by cosmoparticle physics, on which nonstandard cosmological scenarios are based.