Horizontal unification

Lecture from course

"Introduction to Cosmoparticle Physics"

Outlines

- **Gauge model of family symmetry breaking.**
- **Neutrino mass, archion.**
- **Cosmology of horizontal unification.**
- **Cosmology of invisible axion. Archioles.**
- **Massive BHs from horizontal phase transitions**
- **Unstable dark matter. Hierarchical neutrino decay scenario.**
- **Complete cosmological scenario from horizontal unification.**

Problem of quark-lepton families

- There are free families of quarks and leptons with apparent symmetry of their interactions and apparent hierarchy of their mass states.

$$\begin{pmatrix} \nu_e \\ e \\ u \\ d \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \\ c \\ s \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \\ t \\ b \end{pmatrix}$$

Masses of fermions are determined by EW scale.

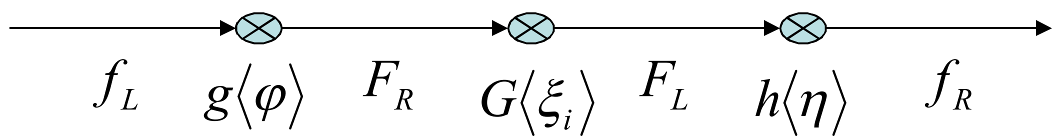
Masses of H-gauge bosons must be much heavier than this scale, due to the absence of flavor changing neutral currents (FCNC)

Gauge model of broken family symmetry

- To avoid symmetric mass terms L- and R-handed states of fermions should belong to different representations. It excludes orthogonal and vector-like groups of family symmetry and reduces the choice to SU(3) for 3 generations [8 H gauge bosons].
- Heavy partners F of ordinary fermions f acquire mass by Yukawa coupling with Higgs fields [3 multiplets $\langle \xi_i \rangle$ and singlet $h\langle \eta \rangle = \mu$]. Mixing of F and f induces SU(3) symmetry breaking pattern in mass pattern of quarks and leptons.
- To compensate anomalies heavy partners N of neutrinos are necessary. It provides the mechanism of neutrino mass.
- Natural choice of Higgs potential leads to additional global U(1) symmetry. It links physics of axion to physics of broken family symmetry.

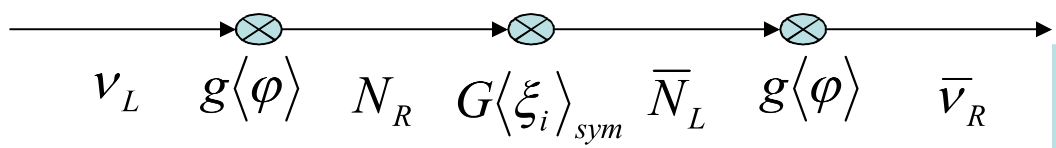
Fermion masses

- Dirac see-saw mechanism of mass generation for quarks and charged leptons



$$m_f = \frac{h\langle\eta\rangle}{G\langle\xi_i\rangle} g_f \langle\varphi\rangle$$

- Maiorana see-saw mechanism for neutrino mass.



$$m_\nu = \frac{g_f\langle\varphi\rangle}{G\langle\xi_i\rangle} g_f\langle\varphi\rangle = m_f \frac{g_f\langle\varphi\rangle}{h\langle\eta\rangle}$$

- Pattern of symmetry breaking

$$SU(3)\otimes U(1) \xrightarrow[\langle\xi_0\rangle]{} SU(2)\otimes U'(1) \xrightarrow[\langle\xi_1\rangle]{} U''(1) \xrightarrow[\langle\xi_2\rangle \equiv V]{} I$$

- Results in mass pattern

$$m_i \propto \langle\xi_i\rangle^2$$

Reduction of number of parameters

Hierarchy of masses is not given by hands, but follows from pattern of family symmetry breaking

	e	μ	τ
e	m_e	s_{12}	s_{13}
μ	s_{12}	m_μ	s_{23}
τ	s_{13}	s_{23}	m_τ

	e	μ	τ
e	0	p	0
μ	p	0	q
τ	0	q	r

3 parameters instead of 9

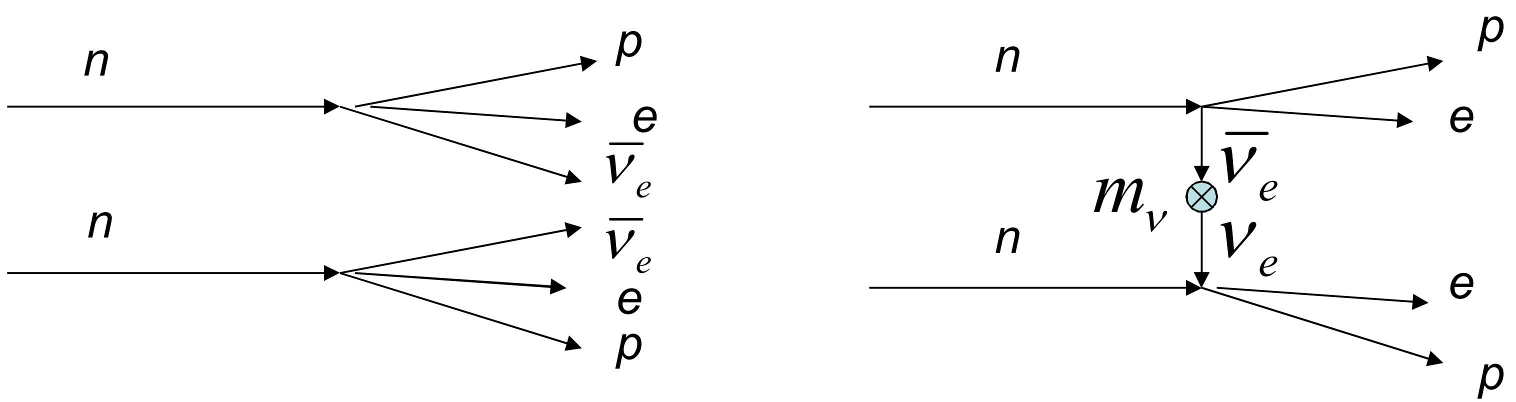
Archion

- The assumption that Higgs potential contains only terms, which can be generated by radiative effects of gauge and Yukawa couplings excludes the term $\propto p\xi_i\xi_j\xi_k$.
- It leads to additional global U(1) symmetry. Breaking of this symmetry results in the existence of Goldstone boson α .
- This boson shares the properties of Majoron, familon and axion and was called archion.
- Archion couplings are proportional to 1/V and its mass is given by

$$m_\alpha = C \frac{f_\pi}{V} m_\pi$$

Physical consequences

- FCNC, due to H-bosons $K \to \mu e; \bar{D}^0 \leftrightarrow D^0; \ldots$
- Mass of neutrino $m_\nu \propto V^{-1}$, neutrino oscillations, double neutrinoless beta-decay due to Majorana mass



- Archion decays $K \to \pi\alpha; \mu \to e\alpha; \ldots$
- Archion decays of massive neutrinos

$$\nu_H \to \nu_L \alpha \qquad \tau = \frac{V^2}{a_{HL}^2 m_H^3} \propto V^5$$

Astrophysical consequences

- Archion emission speeds up stellar evolution

$$t_s = \frac{Q}{L + L_\alpha} < t_s = \frac{Q}{L} \qquad L_\alpha \propto 1/V^2$$

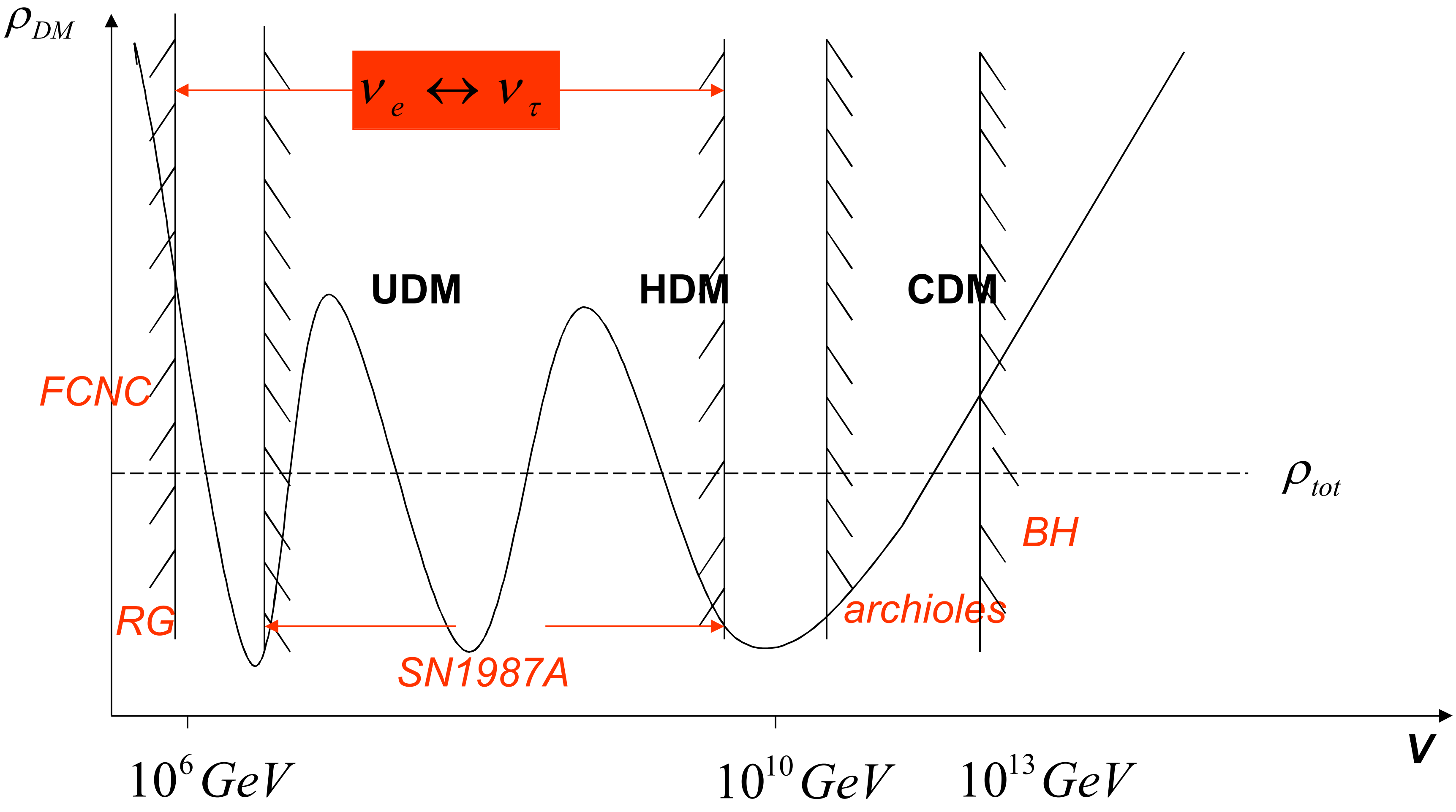
It puts lower limit $V > 10^6 GeV$ from observation of red giants.

- Neutrino radiation from collapsing stars is suppressed due to energy loss by archion emission
- Detection of neutrino from SN1987A constrains $10^{10} GeV > V \geq 3 \cdot 10^6 GeV$ (at low *V* archion energy losses decrease due to opacity of stellar matter)

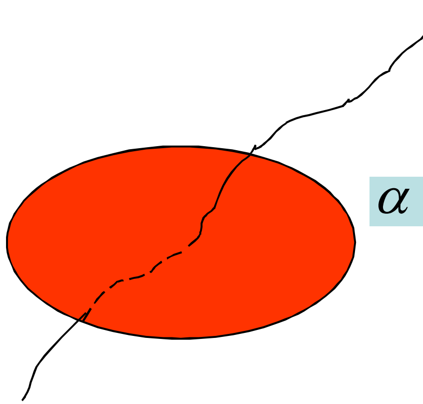
Dark matter candidates

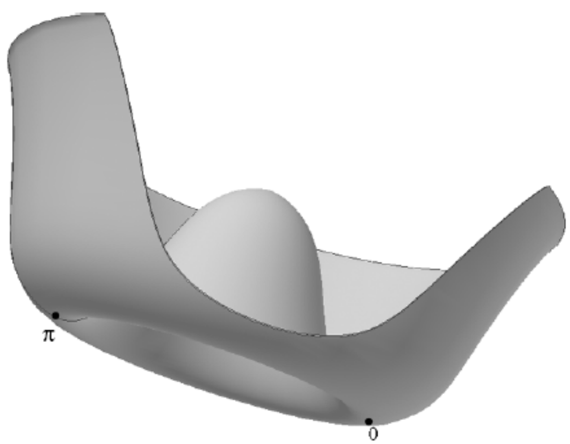
- Massive neutrinos $n_\nu = \frac{3}{11} n_\gamma, \quad \rho_\nu = m_\nu n_\nu \propto V^{-1}$
- Unstable massive neutrinos. Due to strong dependence $\tau(\nu_H \to \nu_L \alpha) \propto V^5$ at lower V neutrino lifetime can become $\tau < t_U$
- Primordial archion field oscillations $\rho_\alpha \propto V$
- Density of all the candidates is determined by the same scale of family symmetry breaking V and they can be treated within the unique framework.

Unified model of dark matter



Topological defects in axion cosmology



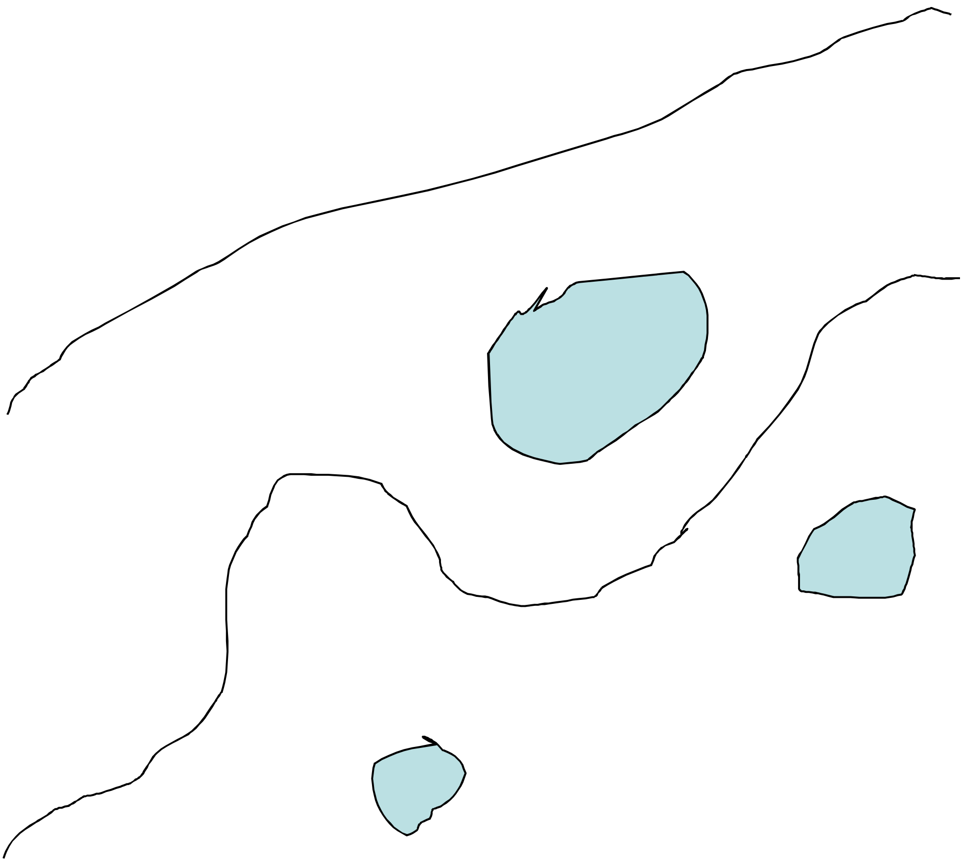


- **Spontaneous breaking of U ’’(1) symmetry results in the continuous degeneracy of vacua. In the early Universe the transition to phase with broken symmetry leads to formation of axion cosmic string network.**
- **The tilt in potential, generated by instanton effects at T~1GeV breaks continuous degeneracy of vacua. In the result axion field acquires mass, while string network converts into walls-bounded-by-strings structure in this second phase transition.**

Unstable topological defects

- 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.

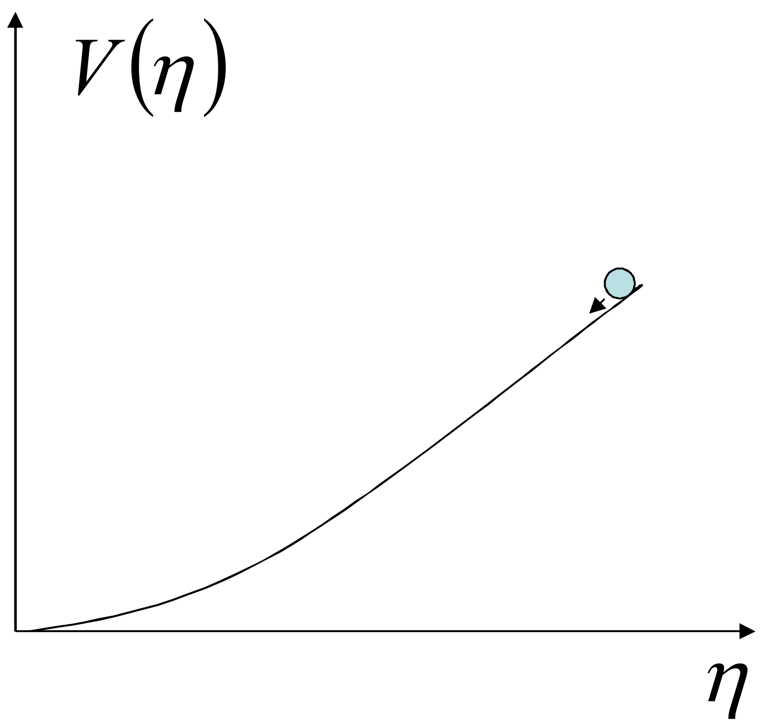
Archioles structure



- 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.

Inflation from horizontal unification

- Gauge theory of broken family symmetry also provides mechanisms for inflation and baryogenesis. It provides horizontal unification of physical basis for cosmology.



Singlet field η can play the role of inflaton and provide the mechanism for chaotic inflation. At large values of

$$\langle \xi_i \rangle > 10^{13}\,GeV$$

horizontal phase transitions can take place on inflationary stage, thus preventing formation of archioles.

Effects of horizontal phase transitions on inflationary stage

- After horizontal phase transition on inflationary stage closed circles, along which $\Delta\alpha = 2\pi$, inflate exponentially and axion string network can not arise on scale of the modern cosmological horizon, preventing archioles formation.
- However, such phase transitions provide several mechanisms for massive, intermediate and even supermassive BH formation.

Peaks of density fluctuations from phase transitions

- Owing to weak $\nu\eta^2\xi^2; \nu > \frac{h^2 G^2}{8\pi^2}$ interaction, on chaotic

inflationary stage corrections in Higgs potential

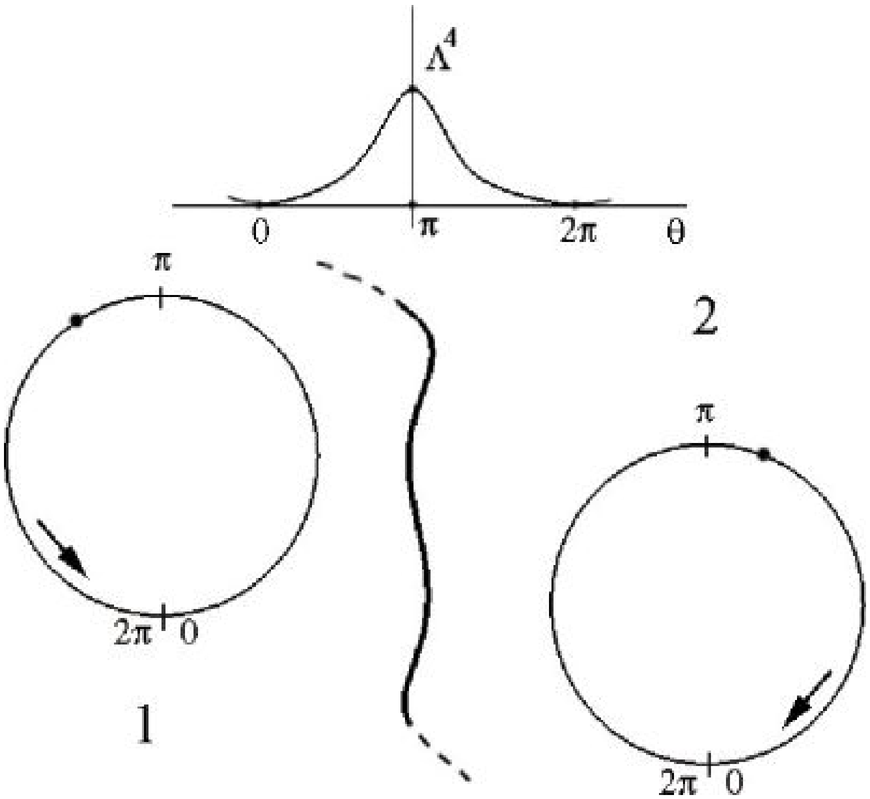
$$V(\xi,\eta) = \nu\xi^2\eta^2 - \frac{m^2}{2}\varphi^2 + \frac{\lambda}{4}\varphi^4 \Rightarrow V(\xi,\eta) = \left(\nu\eta^2 - \frac{m^2}{2}\right)\xi^2 + \frac{\lambda}{4}\xi^4$$

result in horizontal phase transition, when inflaton field rolls down below

$$\eta = \eta_{cr} \cong \frac{m}{\sqrt{2\nu}}$$

It leads to peaks with $\delta_0 \geq 0.1$ on corresponding scales in spectrum of density fluctuations. Such peaks give rise to copius production of massive BHs.

Closed walls formation in Inflationary Universe



If horizontal phase transition takes place on inflationary stage, the value of phase α , corresponding to e-folding N~60, fluctuates

$$\Delta\alpha \approx H_{\text{infl}} / (2\pi V)$$

Such fluctuations can cross π and after coherent oscillations begin, regions with $\alpha > \pi$ occupying relatively small fraction of total volume are surrounded by massive walls. Collapse of such walls also lead to massive BH formation

Baryogenesis from leptogenesis

- EW baryon charge nonconservation washes out baryon asymmetry with B-L=0.
- Majorana mass of neutrino corresponds to

$$\Delta L = 2$$

- Leptogenesis: CP violating effects in nonequilibrium L-nonconserving decays of N can lead to generation of lepton excess. Due to EW baryon charge nonconservation baryon excess is generated from lepton excess in processes, making

$$B + L \Rightarrow 0$$

Cosmological reflection of fundamental physical parameters

- Inflation driven by singlet field η is related to the mechanism of quark-charged leptons mass generation.
- Mechanism of neutrino Majorana mass is related to mechanism of baryosynthesis.
- Cold, warm and hot forms of dark matter, both stable and unstable follow from the unique theoretical framework and are realised pending of the scale *V* of family symmetry breaking.
- This model can hardly explain the dominant form of dark matter, but it illustrates methods of cosmoparticle physics.

Hierarchical neutrino decay scenario (excluded by neutrino oscillations)

- **Formation of Large Scale Structure (LSS) in succession of stages of dominance of massive neutrinos and their decay products.**
- **Dominance of ν_τ with mass *m*=1 keV at $10^8 s < t < 10^{11} s$ provides growth of fluctuations on galactic scales.**
- **Dominance of ν_μ with mass *m*=100 eV at $10^{12} s < t < 10^{16} s$ provides growth of fluctuations on scales of LSS. The structure is formed by equal fractions of primordial ν_μ having after ν_τ dominance spectrum, typical for particles with mass 1 keV, and of non-equilibrium ν_μ from $\nu_\tau \rightarrow \nu_\mu + \alpha$ decays, which have spectrum of fluctuations typical for hot particles with mass ~1eV**
- **Products of decay of ν_μ form homogeneously distributed dark matter, which can be alternative to dark energy.**

UDM versus LCDM

- **UDM:**
- H<50, age of Universe does not need Lamda
- LSS evolution slows down **absolutely** due to decrease of density in it
- Homogeneously distributed dark matter – products of decay of unstable dark matter
- SN data are interpreted in terms of non-accelerated expansion

- **LCDM:**
- H>50, age of Universe needs Lamda
- LSS evolution slows down **relative** to accelerated expansion
- Homogeneous dark energy is provided by Lambda-term, quintessence…
- SN data are interpreted in terms of accelerated expansion

Conclusions

• Gauge model of broken family symmetry extends standard model to explain mass hierarchy and mixing between families.

•It offers unique framework for neutrino mass and axion solution for CP-nonconservation in QCD, linking them to broken family symmetry.

•It demonstrates how the choice of cosmological scenario follows from the choice of fundamental physical scale (scale of horizontal symmetry breaking).

•It provides mechanism for chaotic inflation and generation of baryon asymmetry from leptogenesis.

•It demonstrates that realistic model, underlying inflation, barygenesis and dark matter is NEVER reduced to these phenomena ONLY.

• It does not contain SUSY, GUTs, shadow matter… and being incomplete can hardly pretend to explain all the set of observational data, but it gives us the flavor of what cosmoparticle physics can be.

Basic ideas of cosmoparticle physics in studies of horizontal unification

- **Physics beyond the Standard model can be studied in combination of indirect physical, astrophysical and cosmological effects**
- **New symmetries imply new conserved charges. Strictly conserved charge implies stability of the lightest particle, possessing it.**
- **New stable particles should be present in the Universe. Breaking of new symmetries implies cosmological phase transitions. Cosmological and astrophysical constraints are supplementary to direct experimental search and probe the fundamental structure of particle theory**
- **Combination of physical, cosmological and astrophysical effects provide an over-determined system of equations for parameters of particle theory**

Extremes of physical knowledge converge in the mystical Uhrohboros wrong circle of problems, which can be resolved by methods of Cosmoparticle physics