

MIRROR MATTER AND MIRROR NEUTRINOS

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Abstract

Theoretical concept of mirror matter is discussed. Mirror matter is considered as interacting with ordinary matter only gravitationally. Oscillation of mirror and active neutrinos is studied at low and high energies. In solar-neutrino physics it results in subdominant effects, which can be observed in future low-energy experiments. Much attention is given to UHE neutrinos. Oscillation of mirror neutrinos to active neutrinos can provide very large neutrino fluxes, above the cascade limit. Some new results are included.

1 Introduction

If not by Borges (1941),¹ mirror particles were first suggested by Lee and Yang [1] in 1956 to save the conservation of parity in the whole enlarged particle space. This concept was discussed in the different form by Landau [2] and Salam [3], but in fact it has been clearly formulated only later, in 1966, by Kobzarev, Okun and Pomeranchuk [4], who consistently introduced mirror symmetry, mirror particles and mirror matter. They introduced the

¹“The visible universe is an illusion. Mirrors ... are hateful because they multiply it”. Jorge Luis Borges, *The Garden of Forking Paths* (1941).

mirror particle space as a hidden sector, which interacts with visible one only gravitationally (Okun [5] considered also communication due to new very weak forces). It was indicated there that mirror matter can exist in the form of stars and planets. Later the idea of two weakly interacting sectors, visible and hidden, found interesting development [6] and astrophysical and cosmological applications [7]. It has been boosted in 1980s by superstring theories with $E_8 \times E_8$ symmetry. The particle content and symmetry of interactions in each of the E_8 groups are identical, and thus the mirror world has naturally emerged. The most recent reincarnation of hidden-sector models is in the context of D-branes. In this approach, light particles are associated with the endpoints of open strings which are attached to D-branes. Ordinary and hidden-sector particles live on different branes which are embedded in a higher-dimensional compactified space.

In 1985 *mirror neutrinos* were suggested as sterile neutrinos in two pioneering works by Berezhiani and Mohapatra [8] and by Foot and Volkas [9]. In these works two basic versions of mirror matter scenarios have been developed.

In the *symmetric* version [9], like in early works, the Lagrangian which describes the particles and their interactions in the visible and mirror sectors, \mathcal{L}_{vis} and $\mathcal{L}_{\text{mirr}}$, are perfectly symmetric and transforms into each other when $\vec{x} \rightarrow -\vec{x}$, accompanying by all left states transforming into right and vice versa: $\psi_L \rightarrow \psi'_R$ and $\psi_R \rightarrow \psi'_L$, where primes denote the mirror states. The vacuum expectation values (vev's) of the Higgs fields are also identical in both sectors. Parity is conserved in the enlarged space of ordinary and mirror states. The two sectors (ordinary and mirror) communicate through the Higgs potential and mixing of neutrinos. Neutrino masses and mixings in each sector are induced by the usual see-saw mechanism, and mixing of neutrinos of different sectors are postulated as e.g. $m' \bar{\nu}_L \nu'_R$, where mirrors neutrinos are denoted by primes. As demonstrated in [9] the most general mixing terms compatible with parity conservation results in maximal mixing of ordinary and sterile neutrinos.

In the *asymmetric* version [8] it was suggested that mirror symmetry is spontaneously broken. While all coupling constants in the two sectors are identical, the vev's are different and break the parity. The ratio $\zeta = v'/v$ of electroweak vev's ($\langle \phi \rangle = v$ and $\langle \phi' \rangle = v'$) gives the scaling factor for ratios of masses in the ordinary and mirror worlds, such as masses of gauge bosons, leptons and quarks. The basic communication between the two sectors is gravitational. It is taken in the form of universal dimension 5 operators,

suppressed by the Planckian mass M_{Pl} . Operating inside each sector and between them, these terms give neutrino masses and mixings. However, to describe the desired neutrino masses, the authors assume also additional communication through the singlet superheavy fields, which results in the similar dimension 5 operators suppressed by superheavy mass $\Lambda < M_{\text{Pl}}$.

A similar model—with asymmetric mirror sector—was studied in Ref.[10]. The mirror symmetry is broken spontaneously. The potential with two degenerate minima is the same in both sectors, but mirror and ordinary scalars choose the different minima at $\phi' = v'$ and $\phi = v$, respectively. The communication of the two sectors is described by a dimension 5 operator with superheavy mass Λ in the denominator. The neutrinos in this model are found to be maximally mixed and mass degenerate. The neutrino masses and mixings are obtained with help of dimension 5 operators with one scale Λ , with two different electroweak vev's, v and v' , in the visible and mirror sectors, respectively, and using vev's of two SU(2) singlets $\langle\phi\rangle = v$ and $\langle\phi'\rangle = v'$.

Mirror neutrinos and various applications of mirror matter have been intensively studied during the past several years in the context of explanation of atmospheric and solar neutrino problems [8, 9, 11], cosmological problems, including inflation and nucleosynthesis [12, 13, 14, 11, 10], dark matter and galaxy formation [12, 13, 15, 16], extra dimensions [17] and high energy neutrinos [10].

Three subjects of mirror neutrinos will be reviewed here: subdominant effects in solar neutrino experiments [18], mirror neutrinos from SN [18] and high energy mirror neutrinos [10, 18].

2 Theoretical concept of mirror matter

Why Lee, Yang, Landau and Salam thought that observed parity violation implies the mirror matter? It can be explained in the following way.

Particle space is a representation of the Poincare group. This basic theoretical assumption demands that *inversion* operator in particle space, I_s , which describes the space reflection $\vec{x} \rightarrow -\vec{x}$, commutes with Hamiltonian

$$[\mathcal{H}, I_r] = 0 \tag{1}$$

Indeed, reflection $\vec{x} \rightarrow -\vec{x}$ and time shift $t \rightarrow t + \Delta t$ commute as coordinate transformations. Then the corresponding operators in the particle space, I_r

and \mathcal{H} , must commute, too.

Eq. (1) implies that eigenvalues of operators I_r must be conserved. What is this operator?

The first candidate is *parity* operator P .

It is defined by the transformation of spinors $\psi(x)$ and scalars $\phi(x)$ as [19]

$$\begin{aligned} P\psi(x_0, \vec{x}) &= \gamma_0\psi(x_0, -\vec{x}) \\ P\phi(x_0, \vec{x}) &= \pm\phi(x_0, -\vec{x}) \end{aligned} \quad (2)$$

It is easy to see that operator P with these properties transforms left states into right ones and vice versa as it should be for inversion operator. However, according to Eq.(1) this operator must be conserved, while experiments show that it is not.

Lee and Yang suggested that $I_r = P \cdot R$, where R transfers particle to the new state (mirror particle).

In fact, the assumption of Landau is similar: one may say that he assumed $R = C$, i.e. the mirror space is a space of antiparticles, and then the conserved operator is $I_r = CP$. Discovery of CP violation dismissed this hypothesis.

Mirror particle space is generated by R -transformation with the same particle content and interactions (symmetries):

$$\begin{aligned} \psi_L &\rightarrow \psi'_R, & \psi_R &\rightarrow \psi'_L \\ SU_2(L) \times U(1) &\rightarrow SU'_2(R) \times U'(1) \end{aligned}$$

with a new (mirror) photon, γ' , new (mirror) gauge bosons and with equal vev's and coupling constants:

$$\alpha_i = \alpha'_i, \quad (i = 1, 2, 3), \quad \text{vev} = \text{vev}'$$

Kobzarev, Okun and Pomeranchuk suggested that ordinary and mirror sectors communicate only gravitationally.

For leptons communication term can be written as

$$\mathcal{L}_{\text{comm}} = \frac{1}{M_{\text{Pl}}} (\bar{\psi}_L \phi) (\psi'_R \phi'), \quad (3)$$

where ψ and ϕ are $SU(2)$ doublets: $\bar{\psi}_L = (\bar{l}_L, \bar{\nu}_L)$ and $\phi = (\phi_0^*, -\phi_+^*)$. After EW spontaneous symmetry breaking, Eq. (3) results in mixing of ordinary

and mirror (sterile) neutrinos:

$$\frac{v_{\text{EW}}^2}{M_{\text{Pl}}} \bar{\nu}_L \nu'_R = \mu \bar{\nu}_L \nu'_R, \quad (4)$$

with $\mu = v_{\text{EW}}^2/M_{\text{Pl}} = 2.5 \times 10^{-6}$ eV, where $v_{\text{EW}} = 174$ GeV is vev of the standard EW group.

Eq.(4) implies oscillation between ν and ν' . As illustrative example one can consider the case of two neutrinos ν and ν' . The 2×2 mass matrix in this case is given by

$$\mathcal{M} = \begin{pmatrix} M_i & \mu \\ \mu & M_i \end{pmatrix}. \quad (5)$$

When the interaction between the two sectors is switched off, $\mu = 0$, neutrinos are mass degenerate with masses M_i . With μ taken into account, the mixing is maximal $\sin 2\theta = 1$ and the mass eigenvalues split to $m_{1,2} = M_i \pm \mu$, so that $\Delta m^2 = 4M_i\mu$ (more precisely, in case of three neutrinos $\Delta m^2 = 4\text{Re}(M_i m^*)$, since neutrino oscillations depend on the product of neutrino mass matrix and its hermitian conjugate). The transition between the splitted levels results in $\nu_\alpha \rightarrow \nu_s$ oscillation with small Δm^2 .

This feature survives in the three neutrino case which will be considered in the next Section.

In the early works (e.g. [8, 9]) the authors have studied $\nu\nu'$ oscillations in the specific models trying to find explanation for solar and atmospheric neutrino experiments. In our work [18] we accepted neutrino mixing (4) as it is given by gravitational communication of mirror and visible sectors, in attempt to find subdominant, though observable effects. Such effects, even weak, can result in discovery of mirror neutrinos.

3 Mirror neutrinos in solar-neutrino observations

Following the work [18] we shall consider here distortion of solar-neutrino spectrum due to oscillation of visible to mirror neutrinos, in case of Majorana neutrinos.

Generalizing Eq. (4) to the case of three neutrinos one can write mixing term as

$$\mathcal{L}_{\text{mix}} = \lambda_{\alpha\beta} \frac{v^2}{M_{\text{Pl}}} \nu_\alpha \nu'_\beta, \quad (6)$$

where $v=174$ GeV is EW vev, which is due to mirror symmetry is the same for $SU(2)$ and $SU(2)'$ groups. Here and everywhere below we use the Greek letters $\alpha, \beta = e, \mu, \tau$ for flavor states, and Latin letters $i, k = 1, 2, 3$ for mass states.

Coefficients $\lambda_{\alpha\beta}$ can be either $\lambda_{\alpha\beta} = 1$ (flavor-blind interaction) or $\lambda_{\alpha\beta} \sim \mathcal{O}(1)$ (broken flavor blindness). There are some arguments in favor of the latter case, but our ignorance in theory of quantum gravity does not allow to make a choice.

The neutrino mass matrix in the flavor representation can be written as

$$\mathcal{L}_{\nu \text{ mass}} = -\frac{1}{2}(\nu, \nu') \begin{pmatrix} M & m \\ m^t & M' \end{pmatrix} \begin{pmatrix} \nu \\ \nu' \end{pmatrix} + h.c., \quad (7)$$

where ν and ν' are three-neutrino states, and M, m are 3×3 matrices, with $M = M'$. The models of sterile neutrinos must explain the (almost) exact equality of active and sterile neutrino masses. In the mirror model this equality follows from mirror symmetry, as $M = M'$. When $m = 0$ $M = M' = \text{diag}(M_1, M_2, M_3)$ are assumed to be generated by usual see-saw mechanism. Diagonalization in case $m \neq 0$ results in 6 mass eigenstates ν_i^+ and ν_i^- :

$$\nu_i^\pm = \frac{1}{\sqrt{2}}(\nu'_i \pm \nu_i) \quad (8)$$

The analysis is convenient to perform in terms of matrix

$$\bar{m} = U^t m U, \quad (9)$$

where matrix U diagonalizes $M = M'$.

The non-diagonal terms of \bar{m} provide the short-wave oscillations connected with large mass splittings $M_i - M_j$. These oscillations are strongly suppressed and in practice are negligible.

The diagonal terms of \bar{m} remove degeneracy of M_i values ($M_i = M'_i$) and the masses of mass eigenstates (8) becomes

$$M_{\pm i} = M_i \pm \bar{m}_{ii} \quad (10)$$

The corresponding mass splitting between M_{+i} and M_{-i} is characterized by

$$\Delta m_i^2 = 4M_i \bar{m}_{ii} \quad (11)$$

The probability of transition can be calculated as

$$P_{\text{long}}(\nu_\alpha \rightarrow \text{mirror}) = \sum_i |U_{\alpha i}|^2 \sin^2 \left(\frac{\Delta m_i^2 L}{4E} \right), \quad (12)$$

where $U_{\alpha i}$ connects flavor and mass eigenstates $\nu_\alpha = U_{\alpha i} \nu_i$.

The scheme of mass splitting is shown in Fig. 1. The degenerate levels $M_i = M'_i$ in absence of interaction, $m = 0$, are shown by thick lines. The unsuppressed oscillations described by Eq. (12) occurs only inside the narrow windows. To proceed with calculation of observable quantities in our model,

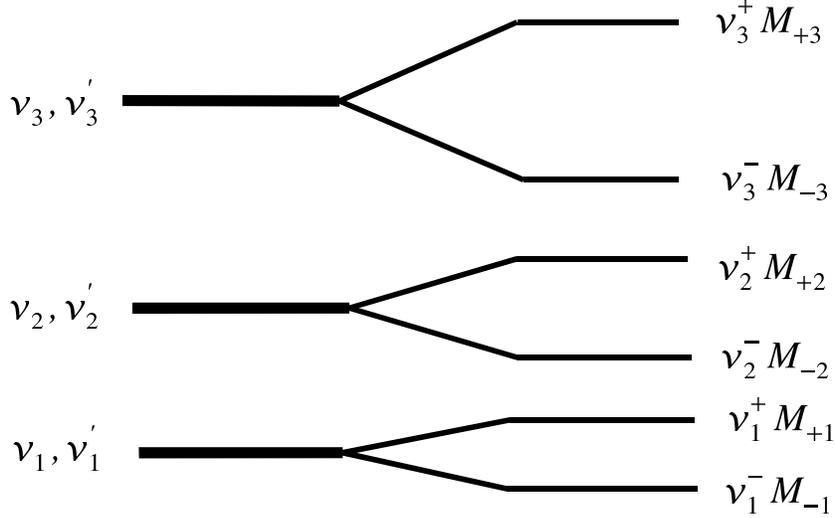


Figure 1: Degeneracy between ordinary and mirror neutrino mass eigenstates (ν_i and ν'_i , respectively, with $i = 1, 2, 3$) is lifted due to communication interaction. The new mass eigenstates, denoted as ν_i^+ and ν_i^- , are maximal superpositions of ν_i and ν'_i : $\nu_i^+ = (\nu_i + \nu'_i)/\sqrt{2}$ and $\nu_i^- = (\nu'_i - \nu_i)/\sqrt{2}$. Long-wavelength oscillations occur only between splitted states in windows.

we must fix the matrix m in the flavor representation, i.e. the values $\lambda_{\alpha\beta}$ from Eq.(6). Several possibilities are considered in Ref. [18], including the case of exact flavor blindness $\lambda_{\alpha\beta} = 1$. We shall describe here another specific case. Our method consists in choosing \bar{m} and then finding matrix m in flavor representation. We qualify a choice as acceptable, if it corresponds to $\lambda_{\alpha\beta} \sim \mathcal{O}(1)$. Let us consider the case when $\bar{m} = \mu \text{diag}(1, 0, 0)$, i.e. when

oscillations occur only in the first (lowest) window in Fig. 1. The splitting $\Delta m_1^2 = 4M_1\bar{m}_{ii}$ can be taken arbitrarily small because the smallest neutrino mass in unperturbative case M_1 is not determined experimentally.

We shall demonstrate, that this specific case arises from a class of initial textures of matrix m with all elements of order one, as implied by Lagrangian (6) with $\lambda_{\alpha\beta} \sim 1$. We perform rotation of \bar{m} to m using the usual mixing matrix U with $U_{e3} = \sin\phi = 0$, with the maximal atmospheric neutrino mixing angle, i.e. $\psi = 45^\circ$, and with a large solar angle ω , namely

$$U = \begin{pmatrix} c_\omega & s_\omega & 0 \\ -\frac{s_\omega}{\sqrt{2}} & \frac{c_\omega}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{s_\omega}{\sqrt{2}} & -\frac{c_\omega}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}, \quad (13)$$

where $s_\omega = \sin\omega$ and $c_\omega = \cos\omega$ and the common notation for the angles is $\omega = \theta_{12}$, $\phi = \theta_{13}$, $\psi = \theta_{23}$. Using Eq. (9), we obtain the communication matrix m which has all elements $\mathcal{O}(1)$, as should be provided by $\lambda_{\alpha\beta} \sim 1$:

$$m = \begin{pmatrix} c_\omega^2 & -\frac{1}{\sqrt{8}}s_{2\omega} & \frac{1}{\sqrt{8}}s_{2\omega} \\ -\frac{1}{\sqrt{8}}s_{2\omega} & \frac{1}{2}s_\omega^2 & -\frac{1}{2}s_\omega^2 \\ \frac{1}{\sqrt{8}}s_{2\omega} & -\frac{1}{2}s_\omega^2 & \frac{1}{2}s_\omega^2 \end{pmatrix}, \quad (14)$$

This property remains true *generically*, even for other values of the starting matrix, e.g. $\bar{m} = \mu \text{diag}(1, i, 3)$ (i here is $\sqrt{-1}$), and actually, this happens even when \bar{m} is non-diagonal. In other words, we may have very small or negligible oscillations in the second window, without violating the condition that the elements of m are of order unity.

The electron neutrino survival probability can be calculated with the MSW effect taken into account. In low-energy regime it is given by [18]

$$P_{ee} = P_{ee}^{LMA} - \cos^4\omega \sin^2\delta. \quad (15)$$

where P_{ee}^{LMA} is the standard survival probability at low energies of the LMA solution.

At high energy regime it is given by

$$P_{ee} = \sin^2\omega. \quad (16)$$

which is the standard survival probability at high energies of the LMA solution.

Therefore, the crucial feature of our model is that its predictions coincide with the standard MSW solution at high energies but are affected by the subdominant sterile oscillations at low energies: The standard MSW solution is modified at low energies, and most noticeably at pp neutrinos energies. One can see it from Fig. 2. Survival probabilities, P_{ee} (and hence neutrino spectrum) are presented there for different values of Δm_1^2 , which are arbitrary in our model since M_1 is a free parameter. One can observe the suppression of spectrum at low energies when Δm_1^2 varies from 0 to $10 \times 10^{-13} \text{ eV}^2$.

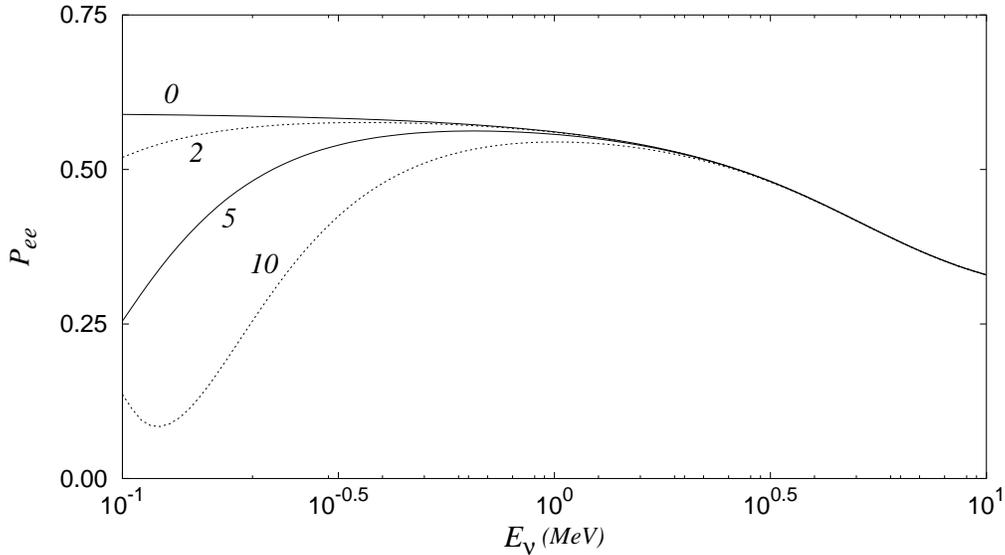


Figure 2: Distortion of LMA survival probability by the the oscillation into mirror neutrinos. The values of Δm_1^2 are indicated at the curves, in units of 10^{-13} eV^2 . Note the sizeable spectral distortion at low energies.

Another signature of this model is anomalous seasonal variations at low energies.

The predicted distortion of low energy spectrum and anomalous seasonal variations can be observed in future solar neutrino experiments, e.g. in LENS.

4 Supernova neutrinos

Oscillations between active neutrinos may result in the observable effects, most notably in appearance of ν_e and $\bar{\nu}_e$ with higher energies due to oscillations with ν_μ and ν_τ .

Oscillation into mirror neutrinos affects strongly the flux of neutrinos from SN explosion when the phase $\phi = \Delta m^2 l / 4E$ becomes large (l is a distance to SN). This condition can be written as

$$\Delta m^2 \gg 1.3 \times 10^{-19} \text{eV}^2 \left[\frac{1 \text{ kpc}}{l} \right] \left[\frac{E}{20 \text{ MeV}} \right]. \quad (17)$$

This condition is reliably satisfied for the mirror models with gravitational communication for a case of Galactic SN with the typical distance $l \sim 10$ kpc and neutrino energies $1 < E < 100$ MeV. We shall shortly discuss two effects: disappearance of active neutrinos in case of ordinary SN and their appearance in case of mirror SN.

Disappearance of supernova neutrinos.

For the distance l typical for Galactic SN, the phase ϕ is large, $\sin^2 \phi = 1/2$ and due to maximal mixing of mirror and ordinary neutrinos all neutrino flavors are suppressed by the same factor $1/2$ (see Eq.(12) which results in $P_{\text{long}}(\nu_\alpha) = 1/2$). Therefore, oscillation to mirror (sterile) neutrinos does not change the flavor ratios, and the effect of this oscillation is described entirely by decreasing the total energy of the detected neutrinos \mathcal{E}_ν by factor 2. At present, \mathcal{E}_ν cannot be predicted theoretically with such accuracy. But one must keep in mind that in case of future Galactic SN many measurements of SN parameters will be available, and \mathcal{E}_ν can be fixed theoretically with better accuracy.

Appearance of neutrinos from mirror SN.

Explosion of mirror SN in our Galaxy will result, due to oscillation, in the flux of active neutrinos, not accompanied by any other radiations. Energy spectrum and flavor ratios will be a signature of SN neutrinos, while the absence of any other signal from given direction will be an indication to mirror SN.

5 UHE mirror neutrinos

The mirror sources in the universe can provide the large fluxes of high-energy neutrinos, not accompanied by other visible radiations. In contrast, the diffuse flux from ordinary neutrino sources is restricted most notably by *cascade limit*, which can be given as [20, 21]

$$E^2 I_\nu(E) \leq \frac{c}{4\pi} \omega_{cas}, \quad (18)$$

where $I_\nu(E)$ is high energy neutrino flux and ω_{cas} is energy density of cascade e-m radiation initiated by high energy electrons and photons, which always accompany production of high energy neutrinos. Electromagnetic cascade is developed due to collisions of the cascade particles with microwave photons. The energy density of the cascade radiation is limited by EGRET observation as $\omega_{cas} \leq (1 - 2) \times 10^{-6}$ eV/cm³.

Oscillations

The mirror sources produce active neutrinos due to oscillation. The oscillations of mirror neutrinos into the visible ones are characterized by oscillation length $l_{osc} \sim E/\Delta m^2$, much shorter than the typical cosmological distance $l \sim 100$ Mpc. The only exceptional case is given by oscillation of the resonant neutrinos with $E_0 \approx 1 \times 10^{13}$ GeV in the first “window” (see the Fig. 1), where Δm_1^2 can be as small as 1×10^{-13} eV². Therefore, the average suppression due to oscillation length is given by factor $\frac{1}{2}$.

The conversion of the sterile neutrinos into visible ones occurs through two stages. Let us consider a sterile neutrino ν'_α born with a flavor α and energy E . On the short length scale $l_{short} \sim E/\Delta M^2$, where $\Delta M^2 = M_i^2 - M_k^2$ is the mass squared difference of the unperturbed states, ν'_α oscillates into two other sterile flavors, and we have all three sterile neutrinos ν'_β with $\beta = e, \mu, \tau$. On much longer scale $l_{long} \sim E/\Delta m^2$, where Δm^2 is a scale of the window splittings, sterile neutrinos oscillate into visible ones. Taking into account that suppression factors due to oscillation length is $1/2$, we can calculate the probabilities $P_{\nu'_\alpha \nu_\beta}$ for conversion of mirror neutrino ν'_α into visible neutrino ν_β , using Eqs. (12) and (13). In particular, for conversion of mirror muon neutrino ν'_μ we obtain the probabilities

$$P_{\nu'_\mu \nu_e} = \frac{\sin^2 2\omega}{8}, \quad P_{\nu'_\mu \nu_\mu} = P_{\nu'_\mu \nu_\tau} = \frac{1}{4} - \frac{\sin^2 2\omega}{16}, \quad (19)$$

which depend only on the solar mixing angle ω . For conversion of mirror tau neutrino ν'_τ one should replace ν'_μ by ν'_τ in Eq. (19). For completeness we also

give the relevant probabilities for the mirror electron neutrino ν'_e conversion.

$$P_{\nu'_e\nu_\mu} = P_{\nu'_e\nu_\tau} = \frac{\sin^2 2\omega}{8}, \quad P_{\nu'_e\nu_e} = \frac{1}{2} - \frac{\sin^2 2\omega}{4}. \quad (20)$$

Note, that as follows from Eq. (12) the probability of conversion $P_{\nu'_\alpha\nu_\beta}$ summed over all visible neutrinos ν_β is equal to $\frac{1}{2}$. It means that for Z-burst production when all neutrino flavors participate in the resonant reaction, the total oscillation suppression $P(\nu'_\alpha \rightarrow \nu) = \frac{1}{2}$.

Cascade limit for mirror neutrinos.

Mirror neutrinos oscillate into visible ones. An upper bound on the flux of these neutrinos is provided by the resonant interaction of UHE neutrinos with relic cosmological neutrinos, $\nu + \bar{\nu} \rightarrow Z^0 \rightarrow \text{pions}$. As a result, one obtains the cascade energy density as

$$\omega_{cas} = 2\pi \frac{f_h}{f_{tot}} \sigma_t n_{\nu_i} t_0 E_0^2 I_\nu(E_0), \quad (21)$$

where

$$E_0 = \frac{m_Z^2}{2m_\nu} = 1.81 \cdot 10^{13} \left(\frac{0.23 \text{ eV}}{m_\nu} \right) \text{ GeV}$$

is the resonant neutrino energy, n_{ν_i} is the density of DM neutrinos, f_{tot} and f_{had} are total and hadron widths of Z^0 decay, respectively, and

$$\sigma_t = 48\pi f_\nu G_F = 1.29 \cdot 10^{-32} \text{ cm}^2, \quad (22)$$

is the effective $\nu\bar{\nu}$ -cross-section in the resonance.

Eq. (21) gives the upper bound on $I_\nu(E_0)$ which is very weak, due to factor $\sigma_t n_{\nu_i} t_0$, as compared with that for visible neutrinos.

Fluxes of UHE neutrinos from mirror Topological Defects (TD).

I will follow here the cosmological scenario of Ref. [10], in which the density of mirror matter (including photons and neutrinos) is suppressed, while mirror topological defects are dominant as compared with visible sector. The crucial feature of this cosmological model is existence of two inflatons, one interacting with ordinary matter and another - with mirror matter. One inflaton reaches potential minimum earlier than the other, and the matter produced by it is diluted by the other inflaton which is still rolling down. The matter produced by the first inflaton is by the definition the mirror one. As demonstrated in Ref. [18] in case of gravitational interaction of mirror and ordinary matter,

Δm^2 for neutrino masses is too small to regenerate mirror neutrinos due oscillations.

Despite the suppression of mirror matter, mirror topological defects can dominate over the ordinary ones, as it is illustrated in Ref. [10] by curvature driving phase transition. In this model, mirror topological defects are produced in a phase transition during inflation, when the mirror inflaton ϕ' is already at the minimum of its potential. The phase transition is triggered when the spacetime curvature (which is driven by the ordinary inflaton potential) decreases to some critical value. If this happens sufficiently close to the end of inflation, the resulting defects are not strongly inflated. The corresponding phase transition in the ordinary matter occurs much earlier, and ordinary topological defects are almost completely diluted by inflation.

The mirror TD can provide UHE neutrino fluxes of order of upper limit given by Eq. (18). As an example, we shall calculate here, following Ref. [10], the neutrino fluxes from mirror necklaces, which can be very efficient HE neutrino sources.

Necklaces are hybrid TDs formed by monopoles (M) and antimonopoles (\bar{M}), each being attached to two strings. The monopole mass m and the mass per unit length of string μ are determined by the corresponding symmetry breaking scales, η_s and η_m ,

$$m \sim 4\pi\eta_m/e, \quad \mu \sim 2\pi\eta_s^2 \quad (23)$$

where e is the gauge coupling. The evolution of necklaces depends on the parameter

$$r = m/\mu d \quad (24)$$

which gives the ratio of the monopole mass to the average mass of string between two monopoles (d is the average string length between the monopoles). It cannot exceed $r_{max} \sim \eta_m/\eta_s$. As it is argued in Ref. [23], necklaces might evolve towards a scaling solution with a constant $r \gg 1$, possibly approaching $r \sim r_{max}$. Monopoles and antimonopoles trapped in the necklaces inevitably annihilate in the end, producing superheavy Higgs and gauge bosons (X particles) of mass $m_X \sim e\eta_m$. The rate of X -particle production per unit volume and time is

$$\dot{n}_X \sim r^2\mu/t^3m_X \quad (25)$$

It is easy to estimate neutrino fluxes, assuming power-law energy spectrum of neutrinos produced at the decay of X-particles. Normalizing neutrino flux by energy density of mirror neutrinos, ω_ν^{mirr} we have

$$I_\nu(E) = (2 - p)x_{\text{max}}^{p-2} \frac{c}{4\pi} \frac{\omega_\nu^{\text{mirr}}}{m_X^2} \left(\frac{E}{m_X} \right)^{-p} P, \quad (26)$$

where $x_{\text{max}} = E_\nu^{\text{max}}/m_X$ at the decay of X-particle, and $P = 1/2$ is probability of oscillation to ordinary neutrino. The approximate power-law spectrum of particles produced in X-decays is seen in MC simulations and DGLAP calculations [22]. The exponent of spectrum $p \approx 1.9$. Energy density of mirror neutrinos can be estimated using Eq. (25) as

$$\omega_\nu^{\text{mirr}} = \frac{1}{2} f_\pi \dot{n}_X m_X t_0, \quad (27)$$

with $f_\pi \approx 0.7$ being fraction of pions in X-decays [22]. In Fig. 3 we present UHE neutrino flux calculated with help of MC and DGLAP methods [22] for $r^2\mu = 5 \times 10^{31} \text{ GeV}^2$ and $m_X = 1 \times 10^{14} \text{ GeV}$. The calculated flux exceeds the cascade upper limit for ordinary neutrino sources.

6 Conclusions

Mirror matter has a deep theoretical motivation, and it has a natural realization in models with $G \times G'$ symmetry, in particular in superstring models $E_8 \times E'_8$. The mirror symmetry can be exact, but it can be spontaneously broken by different vev's in ordinary and visible sectors. The most natural communication between mirror and ordinary sectors is given by gravitational interaction. It provides mixing of mirror and ordinary neutrinos with parameter $\mu \sim v_{\text{EW}}^2/M_{\text{Pl}} = 2.5 \times 10^{-6} \text{ eV}$. Mirror neutrino is an excellent candidate for sterile neutrino ν_s . To provide observable oscillation between active and sterile neutrinos, $\nu_a \leftrightarrow \nu_s$, all known models of sterile neutrinos must have m_{ν_s} fine tuned to m_{ν_a} . Mirror neutrinos meet this requirement naturally due to mirror symmetry. Mirror neutrinos with gravitational mixing result in subdominant, but observable effects in solar-neutrino physics: suppression of low-energy ($E < 1 \text{ MeV}$) neutrino fluxes and small anomalous seasonal variation in MSW solution.

Another possible manifestation of mirror matter is existence of large fluxes of UHE neutrinos with energies higher than 1 EeV. Production of neutrinos

by mirror matter is not accompanied by other visible particles: all of them have only gravitational interaction in detectors, and only mirror neutrinos oscillate into active ones. The upper limit to flux of UHE active neutrinos from mirror matter is induced only by resonant interaction with relic cosmological neutrinos ($\nu_{\text{UHE}} + \nu_{\text{rel}} \rightarrow Z^0$). This limit is a factor ~ 300 higher than cascade upper limit for ordinary neutrinos.

The large fluxes of UHE neutrinos from mirror matter can be realized in two-inflaton cosmological scenario. In this model there are two inflatons, ϕ and ϕ' , interacting with ordinary and mirror matter, respectively. One of the inflatons reaches minimum of its potential earlier than the other. The matter produced by it, is strongly diluted by another inflaton, which is still rolling down to the potential minimum. The less abundant matter is called the mirror one, as definition. Such suppression of mirror matter (including the mirror photons and neutrinos) solves the problem of extra light particles in cosmological nucleosynthesis. Reproduction of mirror neutrinos due to oscillation is suppressed in scenario with gravitational communication by smallness of Δm^2 . Despite the suppression of mirror matter in two-inflaton scenario, the mirror topological defects can dominate over the ordinary ones. It occurs, for example, in a curvature-driven phase transition. The mirror topological defects can provide UHE neutrino fluxes up to upper bound given by resonant Z^0 production.

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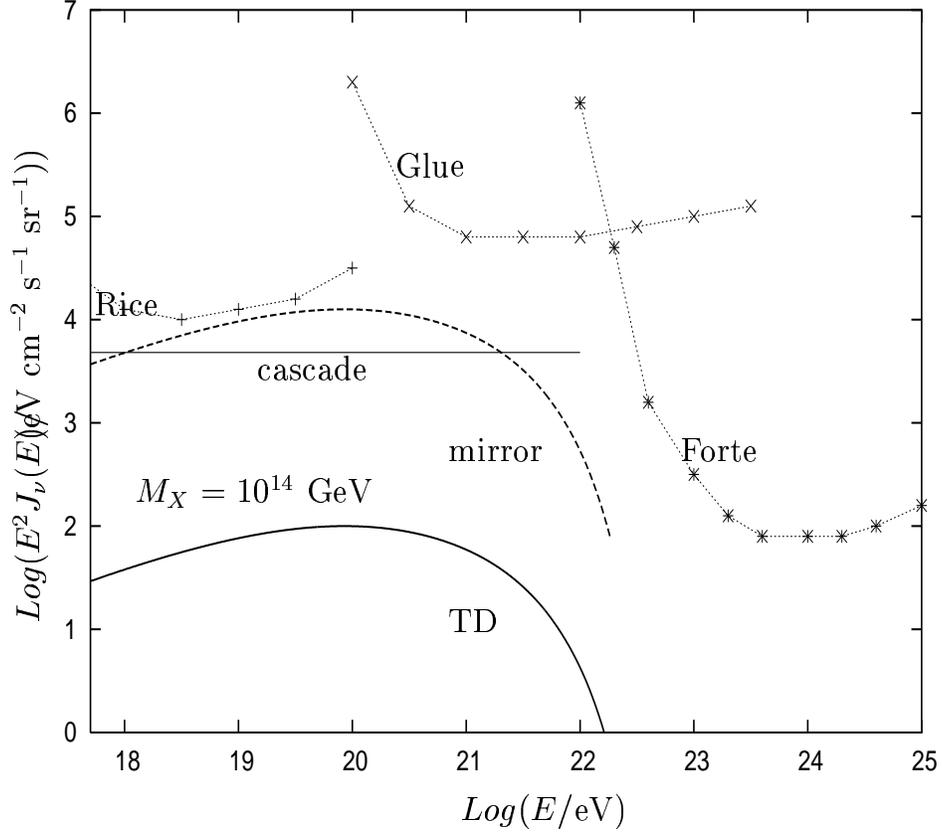


Figure 3: UHE active-neutrino flux (curve “mirror”) from mirror necklaces with $r^2\mu = 5 \times 10^{31} \text{ GeV}^2$ and $m_X = 1 \times 10^{14} \text{ GeV}$. Cascade limit for ordinary neutrino sources and upper limits on UHE neutrino fluxes from Rice, Glue and Forte experiments are also shown.