

ASTROPHYSICAL IMPLICATIONS OF THE MIRROR WORLD WITH BROKEN MIRROR PARITY*,**

Z.G. BEREZHIANI

INFN Sezione di Ferrara, I-44100 Ferrara, Italy

and

Institute of Physics, Georgian Academy of Sciences, Tbilisi, Georgia

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We discuss the physics of the mirror (shadow) world which is completely analogous to the visible one except that its 'weak' scale is larger by one or two orders of magnitude than the weak scale in the standard model. The mirror neutrinos can mix the ordinary ones through the Planck scale induced higher order operators, which can help to reconcile the present neutrino puzzles that are the solar and atmospheric neutrino deficits, the recent LSND anomaly and the need in the \sim eV mass neutrino as the hot dark matter. In particular, the oscillation of ν_e into its mirror partner ν'_e emerges with parameters naturally in the MSW range. The nucleosynthesis constraint on the extra light particle species can be fulfilled by assuming the asymmetric postinflationary reheating between the usual and mirror worlds. One implication of our proposal is that bulk of the dark matter in the universe may be a warm dark matter consisting of the keV range mirror neutrinos rather than the conventional cold dark matter, while the mirror baryons can also contribute as dissipative dark matter. Implications of the mirror Machos for microlensing experiments are also discussed.

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1. Neutrino puzzles

Direct measurements show no evidence for any of the neutrinos to be massive. However, there have been indirect "positive" signals for neutrino masses and mixing accumulated during the past years. These are:

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- A. *Solar neutrino problem* (SNP). The solar ν_e deficit indicated by the solar neutrino experiments [3] cannot be explained by nuclear or astrophysical reasons (see [4] and references therein). The most popular and natural solution is provided by the MSW oscillation of ν_e into another neutrino ν_x in solar medium [5]. It requires the oscillation parameters in the range $\delta m_{ex}^2 \sim 10^{-5} \text{ eV}^2$ and $\sin^2 2\theta_{ex} \sim 10^{-3} - 10^{-2}$. Another possible solution is related to the long wavelength “just-so” oscillation from Sun to Earth [6], which requires a parameter range $\delta m_{ex}^2 \sim 10^{-10} \text{ eV}^2$ and $\sin^2 2\theta_{ex} \sim 1$.
- B. *Atmospheric neutrino problem* (ANP). There is an evidence for a significant depletion of the atmospheric ν_μ flux by almost a factor of 2 [7]. This points to $\nu_\mu - \nu_x$ oscillation, with $\delta m_{\mu x}^2 \sim 10^{-2} \text{ eV}^2$ and $\sin^2 2\theta_{\mu x} \sim 1$.
- C. *Dark matter problem* (DMP). The COBE measurements of the cosmic microwave background anisotropy suggests that cosmological dark matter consists of two components, cold dark matter (CDM) being a dominant component and hot dark matter (HDM) being a smaller admixture [8, 9]. The latter role can be naturally played by neutrinos with mass of few eV's. As for the CDM, there are several candidates, *e.g.* the lightest supersymmetric particle (LSP) or the axion condensate. However, it is of certain interest to think of it as also consisting of some heavier (keV range) neutrinos with correspondingly small concentration, so called warm dark matter (WDM) [10].
- D. *LSND result*: Direct evidence of $\bar{\nu}_\mu - \bar{\nu}_e$ oscillation from the recent Los Alamos experiment [11], with $\delta m_{e\mu}^2 \geq 0.3 \text{ eV}^2$ and $\sin^2 2\theta_{e\mu} = 10^{-3} - 10^{-2}$.

If all these hints (or at least first three of them) will indeed be confirmed in future experiments, then three standard neutrinos ν_e, ν_μ and ν_τ would not suffice for their explanation. Since existence of the fourth active neutrino is excluded by the LEP measurements of the invisible decay width of Z -boson, one has to introduce an extra light sterile neutrino ν_s . It was shown [12] that only one possible texture is compatible with all the above mentioned data, which requires that $m_{\nu_{e,s}} \ll m_{\nu_{\mu,\tau}}$. In this case the SNP can be explained by the $\nu_e - \nu_s$ oscillation and the ANP by the $\nu_\mu - \nu_\tau$ oscillation. In addition, the ν_μ and ν_τ with mass $\simeq 2.4 \text{ eV}$ provide the cosmological HDM and can also explain the LSND result.

One can question, from where the sterile neutrino comes from and how it can be so light when it is allowed to have a large mass by the gauge symmetry of the standard model. We suggest [1] that the sterile neutrino is in fact a neutrino of a shadow world which is the mirror duplicate of our visible world, but its ‘electroweak’ scale v' is by a factor of $\zeta \sim 30$ larger

than the standard electroweak scale v . Thus, the mirror neutrinos $\nu'_{e,\mu,\tau}$ should be light by the same reason as the usual ones $\nu_{e,\mu,\tau}$: their mass terms are suppressed by the accidental B-L symmetry resulting from the gauge symmetry and field content of the theory¹.

This framework can provide a plausible solution to all present neutrino puzzles. We suppose that the dominant entries ($\sim \text{eV}$) in the neutrino mass matrix have origin in some intermediate scale physics which respects an approximate global ZKM-type lepton number $\bar{L} = L_e + L_\mu - L_\tau$ conservation in both sectors. This fixes the neutrino mass texture needed for reconciling the HDM requirement, the ANP and the LSND oscillation, while the ν_e and ν'_e states are left massless. The masses and mixing of the latter and thereby the oscillation $\nu_e - \nu'_e$ then can be induced by the Planck scale effects [15, 16], which for $\zeta \sim 30$ properly reproduce the parameter range needed for the MSW solution to the SNP. The question arises, what is a possible role played by two other mirror neutrinos $\nu'_{\mu,\tau}$. In the framework presented below they have masses in the keV range and constitute the WDM of the universe.

The concept of the hidden mirror world has been considered in several earlier papers [17]. A key difference of our approach [1, 2] from the earlier ones is that we consider a case of the spontaneously broken mirror parity between two worlds, so that the weak scales v and v' are different. This can allow also to reconcile the Big Bang nucleosynthesis (BBN) constraints on the effective number of the light neutrinos [18]. The mirror photons and neutrinos could apriori give a large contribution considerably exceeding $N_\nu = 3$. Therefore, their abundances at the BBN epoch must be appropriately reduced. To achieve this goal, we assume an asymmetric inflationary reheating between the two universes, which can naturally occur once the mirror parity is spontaneously broken. In particular, if the mirror universe reheats to a lower temperature than our universe, then BBN constraint can be satisfied. We also address some cosmological implications of the mirror particles.

2. Within the visible world

Apparently, three known neutrinos are not enough to explain all the present neutrino puzzles [12]. The key difficulty is related to the SNP, while the other puzzles can be easily reconciled. One can assume that the neutrino mass matrix in flavour basis $\nu_{e,\mu,\tau}$ has a texture obeying the approximate

¹ For some other proposals for light ν_s invoking extra global symmetries, see [13, 14].

$\bar{L} = L_e + L_\mu - L_\tau$ conservation:

$$\hat{m}_\nu = \begin{pmatrix} 0 & 0 & m \sin \theta_{e\mu} \\ 0 & 0 & m \cos \theta_{e\mu} \\ m \sin \theta_{e\mu} & m \cos \theta_{e\mu} & \varepsilon m \end{pmatrix} \quad (1)$$

with say $m \simeq 2.4$ eV and $\varepsilon \simeq 10^{-3}$. Then it has one massless eigenstate $\nu_1 \simeq \nu_e$ and two almost degenerate eigenstates $\nu_{2,3} \simeq \frac{1}{\sqrt{2}}(\nu_\mu \pm \nu_\tau)$, with masses $m_{2,3} \approx m(1 \pm \frac{\varepsilon}{2})$. The latter will play a role of the HDM [9], while the ANP can be explained by the oscillation $\nu_\mu - \nu_\tau$ with $\sin 2\theta_{\mu\tau} \approx 1$ and $\delta m_{\mu\tau}^2 \approx 2\varepsilon m^2 \simeq 10^{-2}$ eV², and the oscillation $\bar{\nu}_\mu - \bar{\nu}_e$ with $\delta m_{e\mu}^2 = m^2 \simeq 6$ eV² can explain the LSND result, if $\sin \theta_{e\mu} \simeq 0.02$. Thus, only the SNP remains unresolved.

One can build a simple seesaw model that could naturally implement the above structure. Let us introduce beyond the left-handed lepton doublets $l_{e,\mu,\tau}$ and the right-handed charged leptons e, μ, τ of the standard model, also two right-handed neutrinos N and S (subscripts L and R are omitted). We prescribe the global lepton number $\bar{L} = 1$ to states $l_{e,\mu}$, e, μ and N , and $\bar{L} = -1$ to states l_τ , τ and S . Let us also introduce a gauge singlet scalar Φ with $\bar{L} = -2$. Then the relevant Lagrangian has a form

$$(g_e \bar{l}_e \phi e + g_\mu \bar{l}_\mu \phi \mu + g_\tau \bar{l}_\tau \phi \tau) + (g_1 \bar{l}_e \tilde{\phi} N + g_2 \bar{l}_\mu \tilde{\phi} N + g_3 \bar{l}_\tau \tilde{\phi} S) \\ + MNCS + g_N \Phi NCN + g_S \Phi^* SCS + \text{h.c.}, \quad (2)$$

where ϕ is a standard Higgs doublet with a VEV $v = 174$ GeV ($\tilde{\phi} = i\tau_2 \phi^*$), and C is the charge conjugation matrix. We assume that the scalar Φ develops a nonzero VEV $\langle \Phi \rangle = V \ll M$, which spontaneously breaks the \bar{L} -invariance and gives rise to majoron in the particle spectrum. We also assume that the Yukawa constants $g_{N,S} \sim 1$ while $g_{1,2,3}$ have the same pattern as $g_{e,\mu,\tau}$, so that the Dirac mass terms of neutrinos emerge with approximately the same magnitudes as masses of the charged leptons: $m_{1,2,3}^D \sim m_{e,\mu,\tau}$. Clearly, this model provides a texture resembling (1). One neutrino eigenstate ν_1 (an admixture of ν_e and ν_μ with angle $\theta_{e\mu} = m_1^D/m_2^D \sim 10^{-2}$) is left massless while two other eigenstates $\nu_{2,3}$ get masses $m \simeq m_2^D m_3^D/M$ through the seesaw mixing to the heavy states N, S , with small splitting $\varepsilon \sim (m_3^D/m_2^D)(V/M)$.

Then m in the eV range corresponds to $M \sim 10^8$ GeV, while $\varepsilon \sim 10^{-3}$ demands that $V \sim 10^4$ GeV. Interestingly, the latter value fulfills the upper bound on the spontaneous lepton number breaking scale which arises if the the Planck scale effects on the majoron are taken into account [19]. This is important, since the Planck scale effects will play a crucial role in our further considerations.

3. Introducing the mirror world

Having in mind the $E_8 \times E_8'$ string theory, one can imagine that in the field-theoretical limit it reduces to a gauge theory given by the product of two identical groups $G \times G'$, where $G = \text{SU}(3) \times \text{SU}(2) \times \text{U}(1)$ stands for the standard model describing particles of the visible world: quarks and leptons $q_i, u_i^c, d_i^c; l_i, e_i^c$ and the Higgs doublet ϕ , and $G' = [\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)]'$ is its mirror counterpart with analogous particle content: $q_i', u_i'^c, d_i'^c; l_i', e_i'^c$ and ϕ' ($i = 1, 2, 3$ is a family index). Let us suppose also that there exists a discrete mirror parity $P(G \leftrightarrow G')$ interchanging all particles in corresponding representations of G and G' . It implies that all coupling constants (gauge, Yukawa, Higgs) have the same pattern in both sectors. Let us also assume that there is some mechanism that spontaneously breaks P parity at lower energies and thus allows the weak interaction scales $\langle \phi \rangle = v$ and $\langle \phi' \rangle = v'$ to be different; below we assume that $v'/v \sim 30$. Thus the fermion mass and mixing pattern in the mirror world is completely analogous to that of the visible world, but all fermion masses are scaled up by the factor $\zeta = v'/v$. The W', Z' boson and mirror Higgs masses are also scaled up by factor ζ , while photons and gluons remain massless in both systems.

We suppose that two worlds communicate only through gravity and possibly also via some superheavy gauge singlet matter. It is also essential that at higher energies the $\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)$ factors in both sectors should be embedded into some simple gauge groups: otherwise, kinetic terms of the two $\text{U}(1)$ gauge fields can mix which would induce arbitrary electric charges to the particles [17]. *E.g.* one can consider (SUSY) GUT like $\text{SU}(5) \times \text{SU}(5)'$ without mixed representations, which then breaks down to $G \times G'$ at higher energies. We also assume that the mirror parity P is not broken at the GUT scales and its breaking is essentially related to the electroweak symmetry breaking scales v and v' .

Concerning the strong interactions, it is clear that a big difference between the weak scales v' and v will not cause as big difference between the confinement scales in two worlds. As far as P parity is valid at higher scales, the strong coupling constant will evolve down in energies with same value in both sectors until it reaches threshold of the mirror-top (t') mass. Below it α'_s will have a different slope than α_s . It is then very easy to calculate the value of the scale Λ' at which α'_s becomes large. This value will of course depend on ζ . By taking $\Lambda = 200$ MeV for the ordinary QCD, then for $\zeta \sim 30$ we find $\Lambda' \simeq 280$ MeV. On the other hand, for $\zeta \sim 30$ the masses of 'light' mirror quarks $m'_{u,d} = \zeta m_{u,d}$ do not exceed the value of Λ' and thus they should develop condensates $\langle \bar{q}' q' \rangle$ as their visible partners do. So, the mirror π -mesons should have masses rather close to that of our K -mesons. Also the mirror nucleons are not much heavier than the usual proton and

neutron, $m'_{p,n} \sim 1.5m_{p,n}$. However, the mirror light quarks have ~ 200 MeV masses and thus we expect the mass difference between the mirror neutron and proton of 100 MeV or so, while the mirror electron mass is $m'_e = \zeta m_e \sim 15$ MeV. Then unlike in our world, in the mirror world all bound neutrons will be unstable against β decay and the mirror hydrogen will be the only stable nucleus.

As for neutrinos, they can acquire nonzero masses only via operators bilinear in the Higgs fields and cutoff by some large scale M . As far as the P parity breaking is a lower energy phenomenon, it should be respected by these operators. For example, one can directly extend the model of previous section, by introducing along with the heavy neutral states N, S also their mirror partners N', S' , with the same mass $M \sim 10^8$ GeV. Then the neutrino mass operators in two sectors are:

$$\frac{h_{ij}}{M}(l_i\phi)C(l_j\phi) + \frac{h'_{ij}}{M}(l'_i\phi')C(l'_j\phi') + \text{h.c.} \quad (3)$$

with constants h_{ij} obeying the approximate $L_e + L_\mu - L_\tau$ symmetry. In doing so, the $\nu_{2,3}$ states get almost degenerate masses $m \sim \text{few eV}$ and thus can constitute HDM, and the ANP and LSND problems are also solved. Then for $\zeta \sim 30$, mass of their mirror partners $\nu'_{2,3}$, $m' = \zeta^2 m$, is in the keV range and thus the latter could constitute the WDM of the universe.

The ν_e and ν'_e states are left massless. However, they can get masses from the Planck scale effects which explicitly violate the global lepton number, and can also induce the neutrino mixing between two sectors [16]. The relevant operators are:

$$\frac{\alpha_{ij}}{M_{Pl}}(l_i\phi)C(l_j\phi) + \frac{\alpha'_{ij}}{M_{Pl}}(l'_i\phi')C(l'_j\phi') + \frac{\beta_{ij}}{M_{Pl}}(l_i\phi)C(l'_j\phi') + \text{h.c.} \quad (4)$$

with constants $\alpha, \beta \sim 1$. Then ν_e and ν'_e acquire masses respectively $\sim \mathring{m}$ and $\sim \zeta^2 \mathring{m}$, and their mixing term is $\sim \zeta \mathring{m}$, where $\mathring{m} = v^2/M_{Pl} = 3 \cdot 10^{-6}$ eV. Hence, parameters of the oscillation $\nu_e - \nu'_e$ are in the range:

$$\delta m^2 \sim \left(\frac{\zeta}{30}\right)^4 \times 8 \cdot 10^{-6} \text{ eV}^2, \quad \sin^2 2\theta \sim \left(\frac{30}{\zeta}\right)^2 \times 5 \cdot 10^{-3}, \quad (5)$$

which for $\zeta \sim 30$ perfectly fits the small mixing angle MSW solution to the SNP [5]. More generally, by taking into account the solar model uncertainties [4, 5], as well as the possible order of magnitude spread in constants α, β , the relevant range for ζ can be extended to $\zeta \sim 10 - 100$ [1]. Alternatively, for $\zeta \sim 1$ we get $\delta m^2 \sim 10^{-10} \text{ eV}^2$ and $\sin^2 2\theta \sim 1$, which corresponds to the 'just-so' solution [6].

4. Spontaneous parity breaking and asymmetric inflation

The simplest possibility to spontaneously break the mirror parity $P(G \leftrightarrow G')$ is to introduce a P -odd real scalar η with VEV $\langle \eta \rangle = \mu$ at some intermediate scale [20]. Then the Higgs potential has a form:

$$\begin{aligned} \mathcal{V}(\eta) + m^2(|\phi|^2 + |\phi'|^2) + \lambda(|\phi|^4 + |\phi'|^4) \\ + g\mu\eta(|\phi|^2 - |\phi'|^2) + h\eta^2(|\phi|^2 + |\phi'|^2), \end{aligned} \quad (6)$$

so that after the non-zero VEV of η emerges, the effective mass terms of ϕ and ϕ' become different and their VEVs v and v' will be different as well. As for the gauge and Yukawa coupling constants, they will not be affected and thus will maintain the same pattern in both worlds. Hence, the particle spectrum in the mirror world will have the same shape as that of the visible one but scaled up by the factor $\zeta = v'/v$.

On the other hand, the P -parity breaking can be related to the possibility of asymmetric postinflationary “reheating” between two worlds². In fact, it is natural to assume that the field η itself plays a role of the inflaton [1, 2], provided that potential $\mathcal{V}(\eta)$ is sufficiently flat and satisfies all necessary ‘inflationary’ conditions [22]. As far as P -parity is broken, then it should be violated also in the inflaton couplings to visible and mirror Higgses: *e.g.* constants of trilinear couplings of the inflaton to ϕ and ϕ' become respectively $(h \pm g)\mu$. Then the inflaton will decay into the visible and mirror particles with different rates, so that the two thermal baths can be established having different temperatures T_R and T'_R . One has also to assume that already at the reheating stage two worlds are decoupled from each other. In particular, this means that couplings like $a|\phi|^2|\phi'|^2$, in principle allowed by symmetry, should be strongly suppressed: $a < 10^{-7}$. In this way, the initial cosmological abundance of the mirror particles can be smaller than that of their visible partners. For more detailed discussion of asymmetric reheating and possible realistic supersymmetric models see Ref.[2].

Let us discuss now constraints on the difference of the reheating temperatures T_R and T'_R . The most serious bound emerges from the BBN constraint on the effective number of the light particle species [18]. As far as the two worlds are decoupled already at the inflationary reheating epoch, dur-

² The idea of using inflation to provide a temperature difference between ordinary matter and mirror or other forms of hidden matter was first discussed in Ref. [21].

ing the universe expansion they evolve with separately conserved entropy³. Then the T_R, T'_R are related to the temperatures T, T' respectively of the usual and mirror photons at the BBN era as

$$\frac{T'_R}{T_R} = \left(\frac{2 + 5.25x^3}{10.75} \right)^{\frac{1}{3}} \frac{T'}{T}, \quad x = \frac{T'_\nu}{T'} \quad (7)$$

where T'_ν is a temperature of the mirror neutrinos.

In standard cosmology effective number of the light degrees of freedom at the BBN era is $g_* = 10.75$ as it is contributed by photons, electrons and three neutrino species $\nu_{e,\mu,\tau}$, in a remarkable agreement with the observed abundances of light elements [18]. In our case, the mirror photons γ' and neutrinos $\nu'_{e,\mu,\tau}$ would also contribute the effective number of the light particles, as

$$\Delta g_* = 1.75 \Delta N_\nu = (2 + 5.25x^4) \left(\frac{T'}{T} \right)^4. \quad (8)$$

The value of x is determined by the temperature T'_D at which ν' decouple from the mirror plasma. It approximately scales as $T'_D \sim \zeta^{4/3} T_D$, where $T_D = 2 - 3$ MeV is the decoupling temperature of the usual neutrinos. For smaller values of ζ , when $T'_D < A'$, ν' decouple after the mirror QCD phase transition, so that the mirror electrons e' contribute the heating of γ' after the ν' freezing out and we arrive to the standard result $x = (4/11)^{1/3} = 0.71$. For sufficiently large ζ , T'_D can be larger than both the QCD scale A' and the light mirror quark masses $m'_{u,d} = \zeta m_{u,d}$. Then u', d' and the mirror gluons will also contribute and we obtain $x = (4/53)^{1/3} = 0.36$. Thus, for x in the interval $0.71 - 0.36$ from Eqs. (8) and (7) we obtain:

$$\frac{T'}{T} < (0.85 - 0.96)(\Delta N_\nu)^{1/4} \quad \implies \quad \frac{T'_R}{T_R} < (0.60 - 0.57)(\Delta N_\nu)^{1/4}. \quad (9)$$

Therefore, by taking the conservative bound $\Delta N_\nu < 1$ or very strong limit $\Delta N_\nu < 0.1$, we obtain that reheating temperature in the mirror sector has to be about 2 or 3 times smaller than that of the visible world.

A somewhat stronger bound can be derived from the overclosure constraint of the universe. Since in our model almost degenerate ν_μ and ν_τ have masses $m \sim \text{few eV}$, they form the HDM of the universe with

³ In fact, this applies if the expansion goes adiabatically in both sectors and only the second order phase transitions occur. At the presence of the first order phase transitions in both sectors this relation would change due to additional entropy production [2].

$\Omega_\nu = 2m/(94h^2 \text{ eV})$. Then their mirror partners $\nu'_{\mu,\tau}$ being ζ^2 times heavier would contribute the cosmological energy density as $\Omega'_\nu = r\zeta^2 \Omega_\nu$, where $r = n'_\nu/n_\nu$ stands for the present abundance of mirror neutrinos relative to ordinary ones: $r = (xT'/T)^3$, and h is the Hubble constant in units $100 \text{ Km s}^{-1} \text{ Mpc}^{-1}$. Then by taking rather conservatively that $\Omega_\nu + \Omega'_\nu < 1$ (bearing in mind that other particles like LSP or mirror baryons could also contribute the present energy density), we obtain

$$\frac{T'}{T} < \frac{1}{x\zeta^{2/3}}(\Omega_\nu^{-1} - 1)^{1/3} = 0.29 \left(\frac{0.36}{x}\right) \left(\frac{30}{\zeta}\right)^{2/3} (\Omega_\nu^{-1} - 1)^{1/3}. \quad (10)$$

Therefore, if $\Omega_\nu \simeq 0.2$ [8], then for $\zeta \approx 30$ we get that $T'/T < 0.46$ and $T'_R/T_R < 0.27$, which limits are comparable to that of Eqs. (9) for $\Delta N_\nu = 0.05$!

5. Cosmological implications of the mirror particles

Thus, the concept of the mirror universe suggests a natural possibility for solving the DMP with dark matter components entirely consisting of neutrinos. Indeed, in the most interesting case the electroweak scale v' in the mirror sector should be by factor $\zeta \sim 30$ larger than the standard electroweak scale $v = 174 \text{ GeV}$, while the reheating temperature of the mirror universe should be 3-4 times smaller than that of the visible one. Hence, if the usual neutrinos with $m \sim \text{few eV}$ form the HDM component, then bulk of the dark matter can be the WDM component consisting of their mirror partners with $m' = \zeta^2 m \sim \text{few keV}$. Clearly, the latter could form the halo dark matter even in dwarf spheroidal galaxies where the Tremaine-Gunn limit is most stringent ($m'_\nu > 0.3 - 0.5 \text{ keV}$).

Implications of the WDM for the shape of the large scale structure are rather similar [10] to that of the currently popular CDM made upon the heavy ($m \sim 100 \text{ GeV}$) particles or axion condensate. However, more detailed observational data on the distribution of matter in the universe may make it possible to discriminate between warm and cold dark matter. Moreover, dark matter consisting of sterile neutrinos invalidates direct searches of the CDM candidates via superconducting detectors or axion haloscopes. High energy neutrino fluxes from the Sun and from the Galactic center which are expected from the annihilation of LSP's if they dominate in the universe, will also be absent. In supersymmetric versions of our scheme, however, CDM as well could exist in the form of the LSP.

An interesting question is what is the amount and form of the mirror baryonic dark matter in the universe. Most likely, baryogenesis in the mirror universe proceeds through the same mechanism as in the visible one and we

may expect that the baryon asymmetries in both worlds should be nearly the same. Since mirror nucleons are not much heavier than the usual ones, their fraction in the present energy density, $\Omega_{B'}$, would be about the same as Ω_B , that is around a few percent.

Let us discuss now cosmological evolution of mirror baryonic matter. Since the binding energy of the mirror hydrogen atom is thirty times larger than that of the ordinary hydrogen, its recombination occurs much before the usual recombination era. Hence, the evolution of density fluctuations in the mirror matter would be more efficient than in the visible one. (From the viewpoint of the visible observer mirror baryons behave as a dissipative dark matter.) As a result, one can expect that the distribution of mirror baryons in galactic discs should be more clumped towards the center. It is noteworthy that mirror dark matter may show antibiasing behaviour ($b < 1$) which is considered unphysical for normal dark matter. Recent data on the dark matter distribution in dwarf spiral galaxies obtained at smaller distances from the center and with a better resolution, do not agree with the assumption of purely collisionless dark matter and may indicate the existence of dissipative dark matter [23].

On the other hand, since mirror hydrogen is the only stable nucleus in the mirror world, nuclear burning could not be ignited and luminous (in terms of γ') mirror stars cannot be formed. Therefore, nothing can prevent the sufficiently big protostars to collapse and in dense galactic cores a noticeable fraction of mirror baryons should form the black holes. Recent observational data indeed suggest a presence of giant black holes with masses $\sim 10^{6-7} M_\odot$ in galactic centers. In addition, easier formation of mirror black holes may explain the early origin of quasars.

The remaining fraction of the mirror baryons could fragment into smaller objects like white dwarves (or possibly neutron stars) which can maintain stability due to the pressure of degenerate fermions. For the mirror stars consisting entirely of hydrogen, the Chandrasekhar limit is $M'_{\text{Ch}} = 5.75(m_p/m'_p)^2 M_\odot \simeq 3M_\odot$. For smaller mirror objects the evaporation limit should be 2 – 3 orders of magnitude smaller than for the visible ones because the Bohr radius of the mirror hydrogen is 30 times smaller than that of the usual one.

These mirror objects, being dark for the normal observer, could be observed as Machos in the gravitational microlensing experiments (for a review, see *e.g.* Ref. [24]). In principle they can be distinguished from the Machos of the visible world. The latter presumably consist of the dim compact objects (brown dwarves) too light to burn hydrogen, with masses ranging from the evaporation limit ($\sim 10^{-7} M_\odot$) to the ignition limit ($\sim 10^{-1} M_\odot$) [25]. As for the mirror Machos, their mass spectrum can extend from the smaller evaporation limit $\sim 10^{-9} M_\odot$ up to the Chandrasekhar

limit $\sim 3M_{\odot}$. The present data on the microlensing events are too poor to allow any conclusion on the presence of such heavy (or light) objects. An unambiguous determination of the Macho mass for each event is impossible, and only the most probable mass can be obtained, depending of the spatial and velocity distribution of Machos. The optical depth or the fraction of the sky covered by the Einstein disks of Machos, is nearly independent of their mass: the Einstein disk surface is proportional to M , while the number of deflectors for a given total mass decreases as M^{-1} . However, larger event statistics will allow to find the Macho mass distribution with a better precision.

As noted earlier, the distribution of mirror baryonic matter in galaxies should be more shifted towards their centers as compared to the visible matter. Thus one can expect that mirror stars in our Galaxy would significantly contribute to the microlensing events towards the galactic bulge, while their weight in the microlensing events in halo should be smaller than that of usual Machos. Interestingly, the event rates in the galactic bulge observed by OGLE and MACHO experiments are about twice larger than the expected value deduced from the low mass star population in the Galactic disk [26]. Barring accidental conspiracies like a presence of bar (elongated dense stellar distribution along the line of sight), this can be explained by the contribution of mirror stars, which could naturally increase the optical depth towards the galaxy bulge by factor 2 or so.

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