MIRROR MATTER
AND
MIRROR NEUTRINOS

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Based on:

V.B., A. Vilenkin, Phys.Rev. D 62, 083512, 2000;

V.B., M. Narayan, F. Vissani, Nucl. Phys. B658, 245, 2003.

THEORETICAL CONCEPT OF MIRROR MATTER

Lee and Yang 1956, Landau 1957, Salam 1957, Kobzarev, Pomeranchuk and Okun 1966

assumption:

PARTICLE (HILBERT) SPACE IS A REPRESENTATION OF EXTENDED LORENTZ GROUP.

Extended Lorentz group includes reflection: $\vec{x} \to -\vec{x}$.

In particle space it corresponds to inversion operation I_r.

Reflection $\vec{x} \to -\vec{x}$ and time shift $t \to t + \Delta t$ commute as coordinate transformations.

In the particle space the corresponding operators must commute, too:

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

i.e. eigenvalues of operator I_r must be conserved.

$I_r = P$ (parity operator) is not conserved.

definition: $$P\psi(x_\mu) = \gamma_0 \psi(x_0, -\vec{x});$$ $$P\phi(x_\mu) = \pm\phi(x_0, -\vec{x}).$$

- Lee and Yang: $I_r = P \cdot R$, where R transfers particle to the new state (mirror particle).
- Landau: $I_r = CP$ where C transfers particle to antiparticle. This hypothesis has been dismissed by discovery of CP violation.

MIRROR PARTICLE SPACE is generated by R-transformation with the same particle content and interactiions (symmetries). $\Psi_L \to \Psi'_R$, $\Psi_R \to \Psi'_L$, $SU_2(L) \times U(1) \to SU'_2(R) \times U'(1)$, with a new photon ($\gamma'$), new gauge bosons and with vev = vev′, $\alpha_i = \alpha'_i$, $i = 1, 2, 3$.

Kobzarev, Pomeranchuk, Okun suggested that ordinary and mirror sectors communicate only gravitationally. The mirror matter in the universe may exist as the mirror stars and mirror galaxies.

COMMUNICATION TERMS can be written as

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

where $\bar{\psi}_L = (\bar{l}_L, \bar{\nu}_L)$ and $\phi = (\phi_0^*, -\phi_+^*)$.

After SSB, Eq.(1) results in mixing of ordinary and mirror (sterile) neutrinos.

$$\frac{v_{\text{EW}}^2}{M_{\text{Pl}}} \bar{\nu}_L \nu'_R, \tag{2}$$

with $\mu \equiv v_{\text{EW}}^2 / M_{\text{Pl}} = 2.5 \cdot 10^{-6}$ eV.

Eq.(2) implies oscillations between ν and ν'.

MIRROR NEUTRINOS AS STERILE NEUTRINOS

UNBROKEN MIRROR SYMMETRY

Foot, Volkas 1985

Communication of ordinary and mirror sectors - through neutrino mixing

BROKEN MIRROR SYMMETRY

Berezhiani, Mohapatra 1985 :

COMMUNICATION TERM:

$$\frac{h}{\Lambda}(\psi_L\phi)(\psi'_R\phi')$$

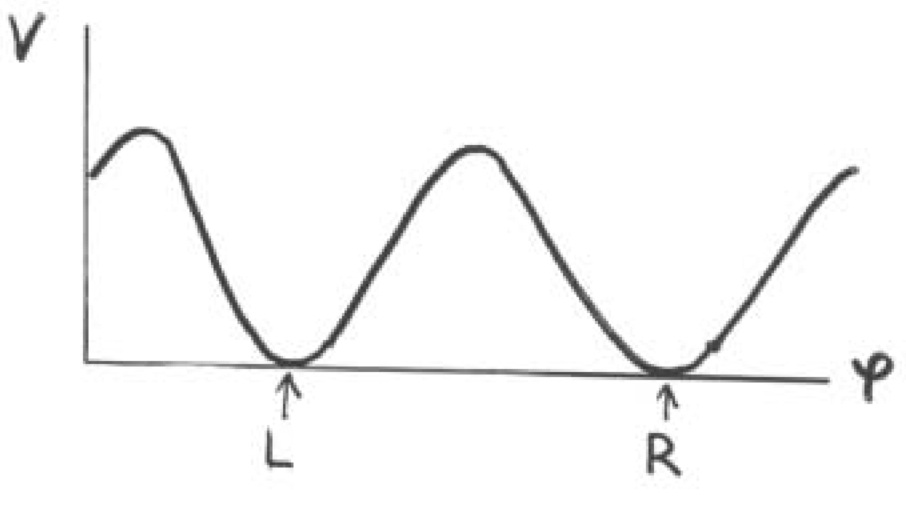
with $\Lambda = M_{\mathrm{Pl}}$ for some fields, and $\Lambda < M_{\mathrm{Pl}}$ for others.

MIRROR SYMMETRY IS BROKEN SPONTANEOUSLY

$$\mathrm{vev} \neq \mathrm{vev}'$$

MASSES m and m' BECOME DIFFERENT

How to do it?



COSMOLOGICAL RESTRICTIONS: BING-BANG NUCLEOSYNTHESIS

PROBLEM: additional light particles γ', ν'_e, ν'_μ, ν'_τ

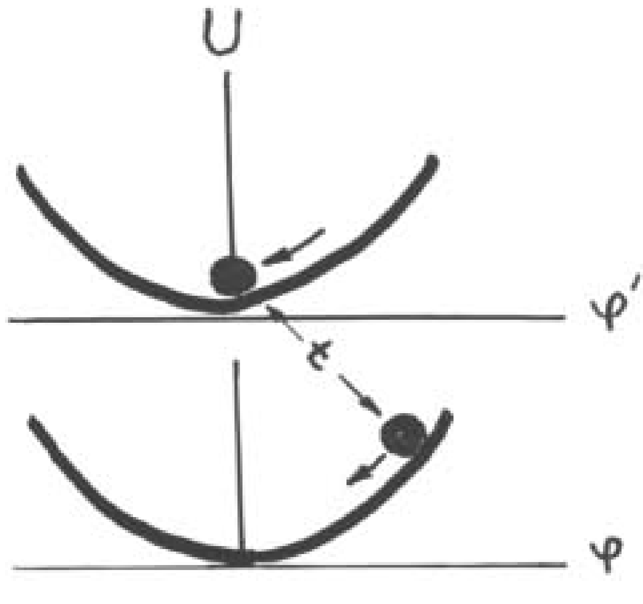
T′ MUST BE SUPPRESSED

ONE-INFLATON MODEL (BDM)

$$\Gamma'_{\phi\to \mathrm{mirr}} < \Gamma_{\phi\to \mathrm{ord}}$$

$$T'_R = \sqrt{\Gamma' M_{\mathrm{Pl}}} < T_R = \sqrt{\Gamma M_{\mathrm{Pl}}}$$

TWO-INFLATON MODEL (V.B., Vilenkin 2000)



MIRROR DENSITY IS INFLATED BY ϕ: $T' < T$

SOME RECENT WORKS

Berezhiani, Dolgov, Mohapatra 1996

Foot and Volkas 1997

Berezhiani 1996

Mohapatra, Teplitz 1997

Foot 1999

Silagadze 1999

Kirillova, Chizhov 1999.

MIRROR NEUTRINOS IN SOLAR-NEUTRINO OBSERVATIONS

V.B., Narayan, Vissani 2003

Unbroken mirror symmetry with gravitational communication:

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

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

$M' = M$ due to mirror symmetry. It makes mirror model most natural one for sterile neutrinos.

$m = 0 : M = \text{diag}(M_1,\ M_2,\ M_3)$ are generated by usual see-saw mechanism.

Diagonalization in case $m \neq 0$ results in 6 mass eigenstates ν_i^+ and ν_i^-

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

with mass eigenstates $M_{\pm i} = M_i \pm \tilde{m}_{ii}$

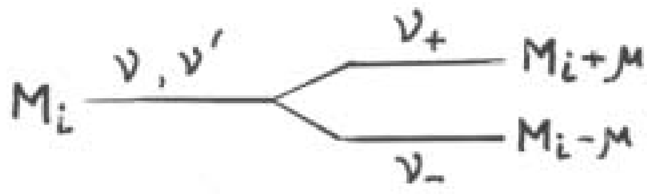
$\tilde{m} = U^t m U$, where U diagonalizes M.

ILLUSTRATIVE CASE OF TWO NEUTRINOS

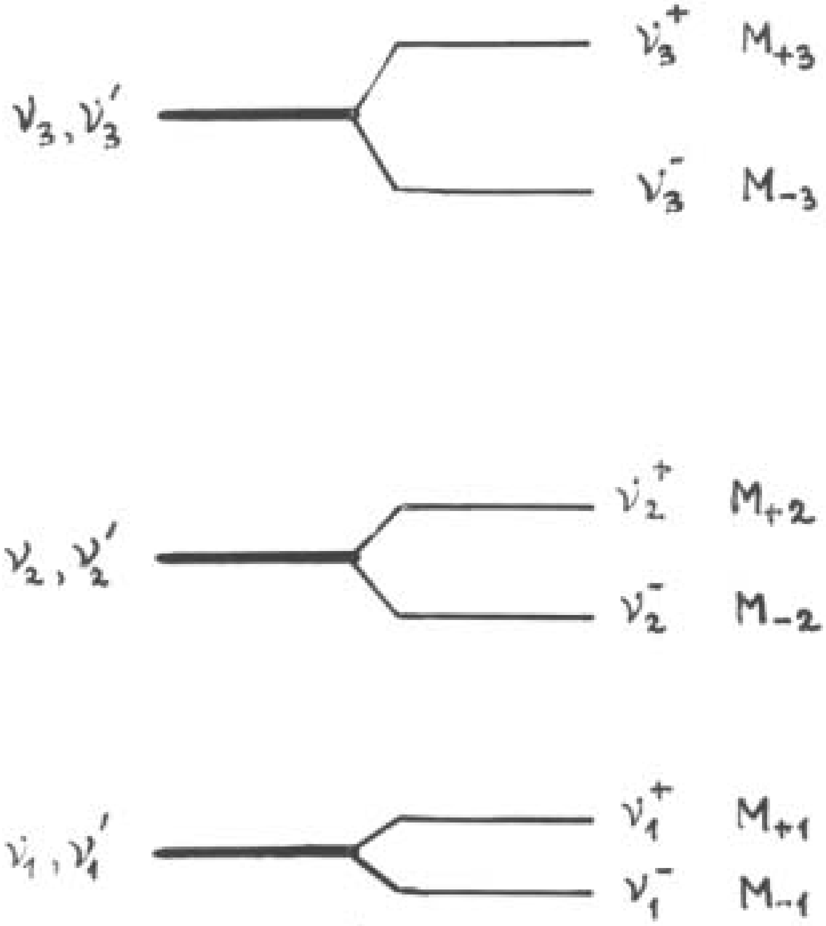
$$(\nu, \nu') \begin{pmatrix} M_i & \mu \\ \mu & M_i \end{pmatrix} \begin{pmatrix} \nu \\ \nu' \end{pmatrix}$$

DIAGONALIZATION RESULTS IN MAXIMAL MIXING

$\sin 2\theta = 1$, $m_{1,2} = M_i \pm \mu$ AND $\Delta m^2 = 4 M_i \mu$.



MASS SPLITTING



$$\Delta m_i^2 = 4M_i\tilde{m}_{ii}$$

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

SOLAR-NEUTRINO OSCILLATION

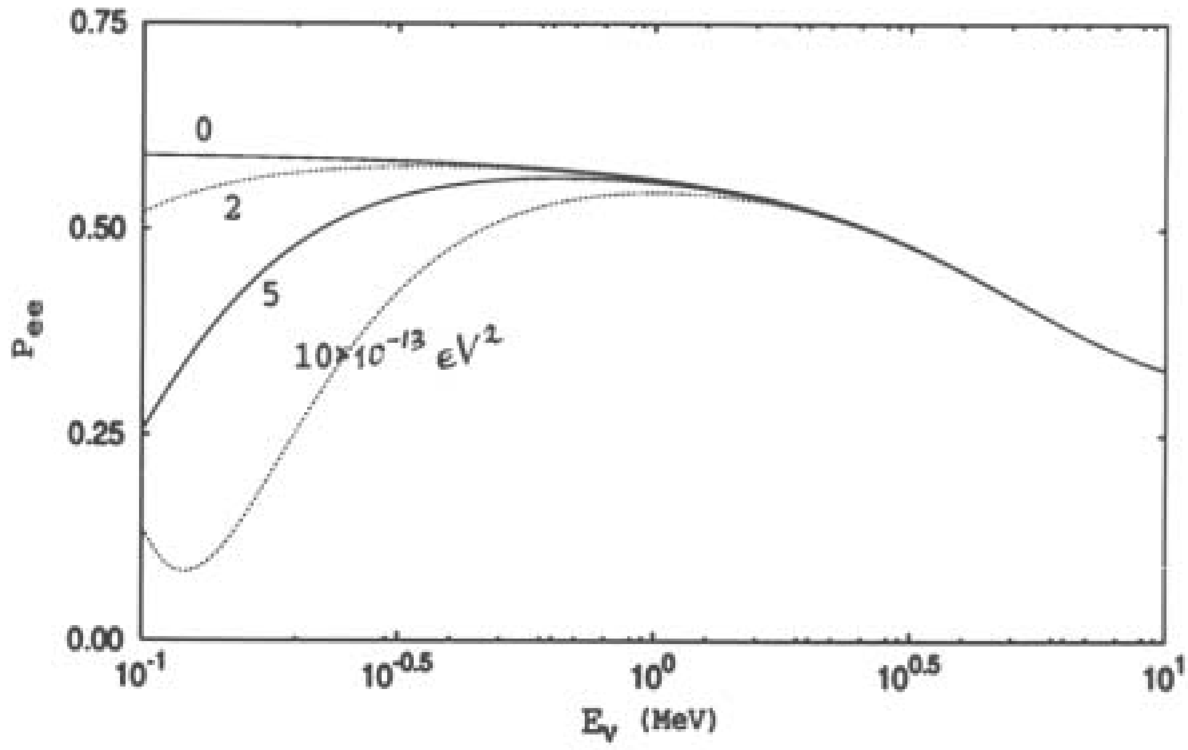
CONSIDER THE CASE OF LMA IN UNPERTURBATIVE REGIME AND $\Delta m_1^2 \gg \Delta m_2^2$

HIGH ENERGY REGIME

$P_{ee} = \sin^2\omega$: standard LMA

LOW ENERGY REGIME

$P_{ee} = P_{ee}^{\mathrm{LMA}} - \cos^4\omega \sin^2\delta$, where $\delta = \frac{\Delta m_1^2 L}{4E}$



ANOMALOUS SEASONAL VARIATION $\sim 20-30\%$ from geometrical one

SN NEUTRINOS

DISAPPERANCE OF ACTIVE NEUTRINOS

$$F_\alpha = \frac{1}{2} F_\alpha^0, \qquad \text{where } \alpha = e,\ \mu,\ \tau$$

$$\mathcal{E}_{\text{obs}} \sim \frac{1}{2} \mathcal{E}_{\text{theor}}$$

ACTIVE NEUTRINOS FROM MIRROR SN

(NOISELESS COLLAPSE)

$$\nu' \to \nu$$

UHE NEUTRINOS FROM MIRROR MATTER

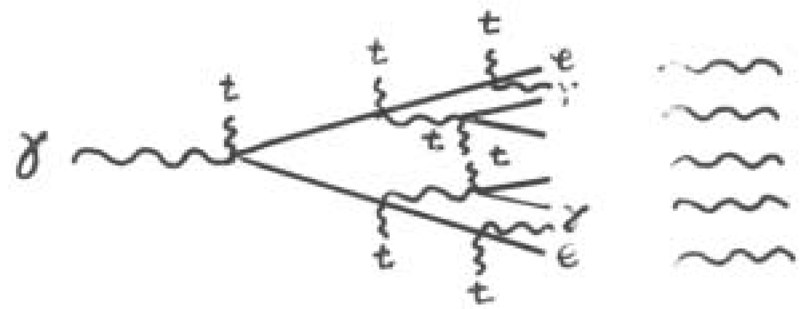
CASCADE UPPER LIMIT

ON HE NETRINO FLUX

(V.B. and A.Smirnov 1975)

E-M CASCADE ON TARGET PHOTONS

$$\gamma + \gamma_{\text{tar}} \rightarrow e^+ + e^-$$
$$e + \gamma_{\text{tar}} \rightarrow e' + \gamma'$$



diffuse
extragalactic gam
0.01 – 100 GeV

EGRET: $\omega_\gamma^{\text{obs}} \sim (2-3) \times 10^{-6} \text{eV/cm}^3$

UPPER LIMIT ON HE NEUTRINO FLUX

$$\omega_{cas} > \omega_\nu(>E) = \frac{4\pi}{c}\int_E^\infty E I_\nu(E)\, dE > \frac{4\pi}{c} E \int_E^\infty I_\nu(E)\, dE \equiv \frac{4\pi}{c} E I_\nu(>E)$$

$$E^2 I_\nu(E) < \frac{4\pi}{c}\omega_{\text{cas}}$$

where $\omega_{\text{cas}} \leq \omega_\gamma^{\text{obs}}$

UPPER LIMIT ON MIRROR NEUTRINO FLUX

Production of mirror neutrinos is not accompanied by visible particles.

Visible neutrinos appear due to $\nu' \to \nu$ oscillation.

$$\nu + \bar{\nu}_{\rm DM} \to Z^0 \to hadrons \to \textbf{e-m cascade}$$

$$E_0 = \frac{m_Z^2}{2m_\nu} = 1.8 \times 10^{22} \left(\frac{0.23\ \rm eV}{m_\nu}\right)\ \rm eV$$

$$\dot{n}_Z = 4\pi\ \sigma_{tot}\ n_{\nu_i}\ I_\nu(E_0)\, E_0$$

$$\omega_{\rm cas} = 0.5 E_0\, \dot{n}_Z\, t_0\, f_h/f_{tot}, \quad f_h/f_{\rm tot} = 0.7.$$

$$I_\nu(E_0) \le \frac{f_{\rm tot}}{f_h}\ \frac{\omega_{\rm cas}}{\sigma_{\rm tot}\, n_{\nu_i}\, t_0}\, \frac{m_\nu{}^2}{m_Z^4}.$$

The strongest limit is imposed by lightest neutrino, if corresponding $E_\nu = m_Z^2/2m_\nu$ is available.

Ratio of upper limits:

$$\frac{I_\nu^{mirr}(E_0)}{I_\nu^{cas}(E_0)} = 8\,\frac{f_{\rm tot}}{f_h}\,\frac{1}{\sigma_{tot}\, n_{\nu_i}\, t_0} = 1.3 \cdot 10^3.$$

UHE NEUTRINOS FROM MIRROR TDs

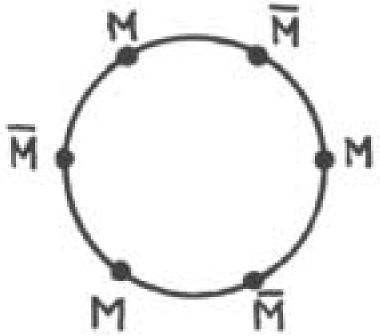
In two-inflatons scenario with curvature-driven phase transition there can be:

$$\rho'_{\rm matter} \ll \rho_{\rm matter}, \quad \rho'_{\rm TD} \gg \rho_{\rm TD}$$

V.B., A.Vilenkin 2000

HE ν PRODUCTION IN ORDINARY / MIRROR TDs

e.g. **NECKLACES:** $G \to H \times U(1) \to H \times Z_2$
V.B., A.Vilenkin 1997



strings shrink and monopoles inevitably annihilate:

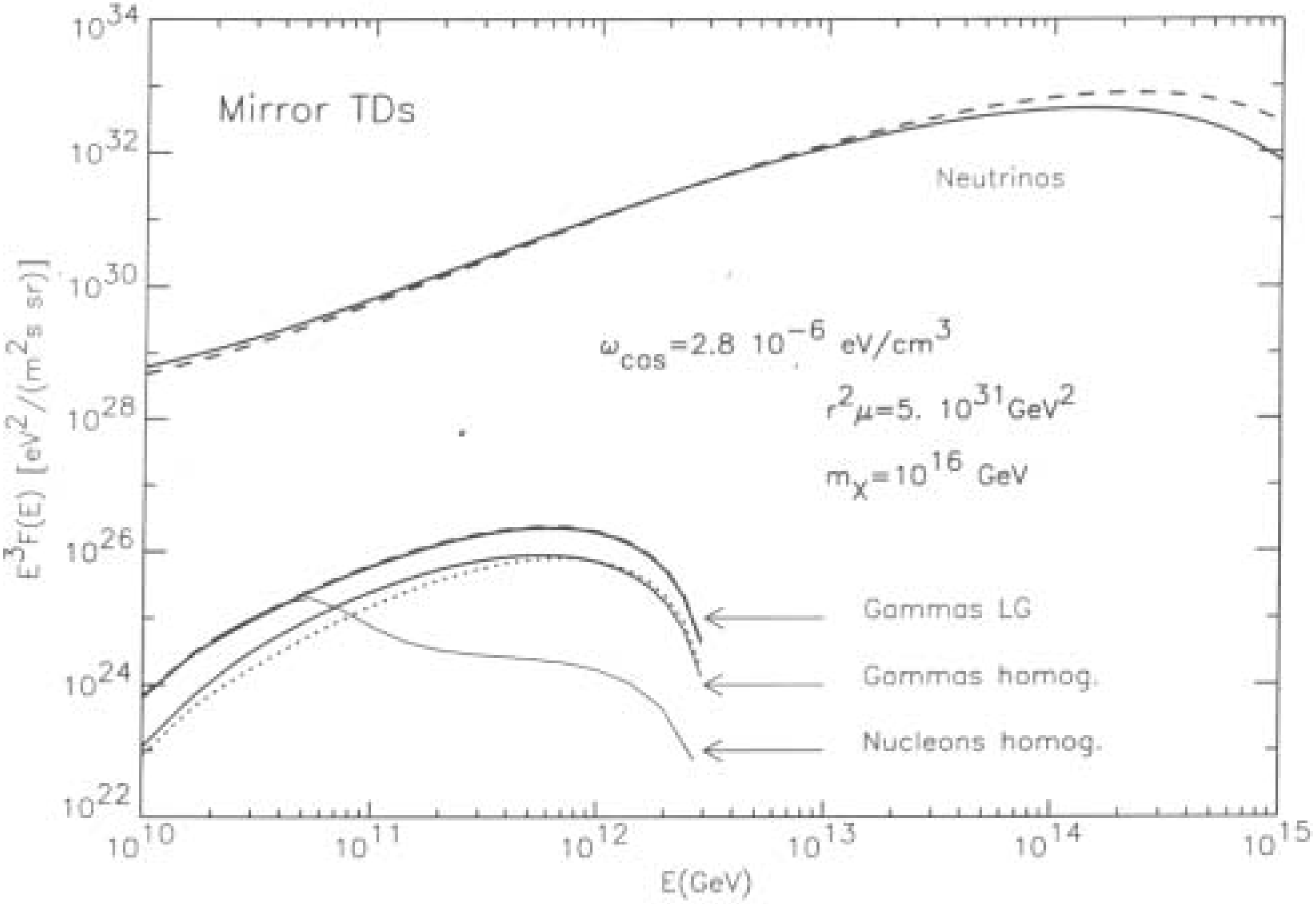
$$M + \bar{M} \to G, H \to \text{hadrons} \to \text{neutrinos}$$

From all particles produced, only neutrinos (due to $\nu' \to \nu$) are visible.

$$L_{\rm osc} \sim \frac{E}{4M_i\mu} \sim 10 \;\frac{E}{10^{20}\ \text{eV}}\; \frac{7\cdot 10^{-3}\ \text{eV}}{M_\nu}\ \text{kpc}$$

Probability of oscillation: $P_{\nu'\to\nu} = 1/2$

SUPERGZK NEUTRINOS FROM MIRROR TD



CONCLUSIONS

- Mirror matter has deep theoretical motivation

- $\nu_a \to \nu_s$ oscillations can be interesting subdominant process in atm and solar neutrino physics

- To provide $\nu_a \to \nu_s$ oscillations, 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

- Gravitational communication between visible and mirror matter provides mixing of mirror and ordinary neutrinos with parameter

$$\mu \sim v_{\rm EW}^2/M_{\rm Pl} = 5 \times 10^{-6}\ \text{eV}$$

which results in observable effect in solar-neutrino, SN-neutrino and HE-neutrino experiments

➡ IN SOLAR NEUTRINOS: suppression of low energy $E_\nu < 1$ MeV neutrino fluxes and small anomalous seasonal variation in MSW solution

➡ IN HIGH ENERGY NEUTRINOS: very large diffuse neutrino fluxes