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SUMMER SCHOOL ON PARTICLE PHYSICS

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ASTROPARTICLE PHYSICS

Lecture V

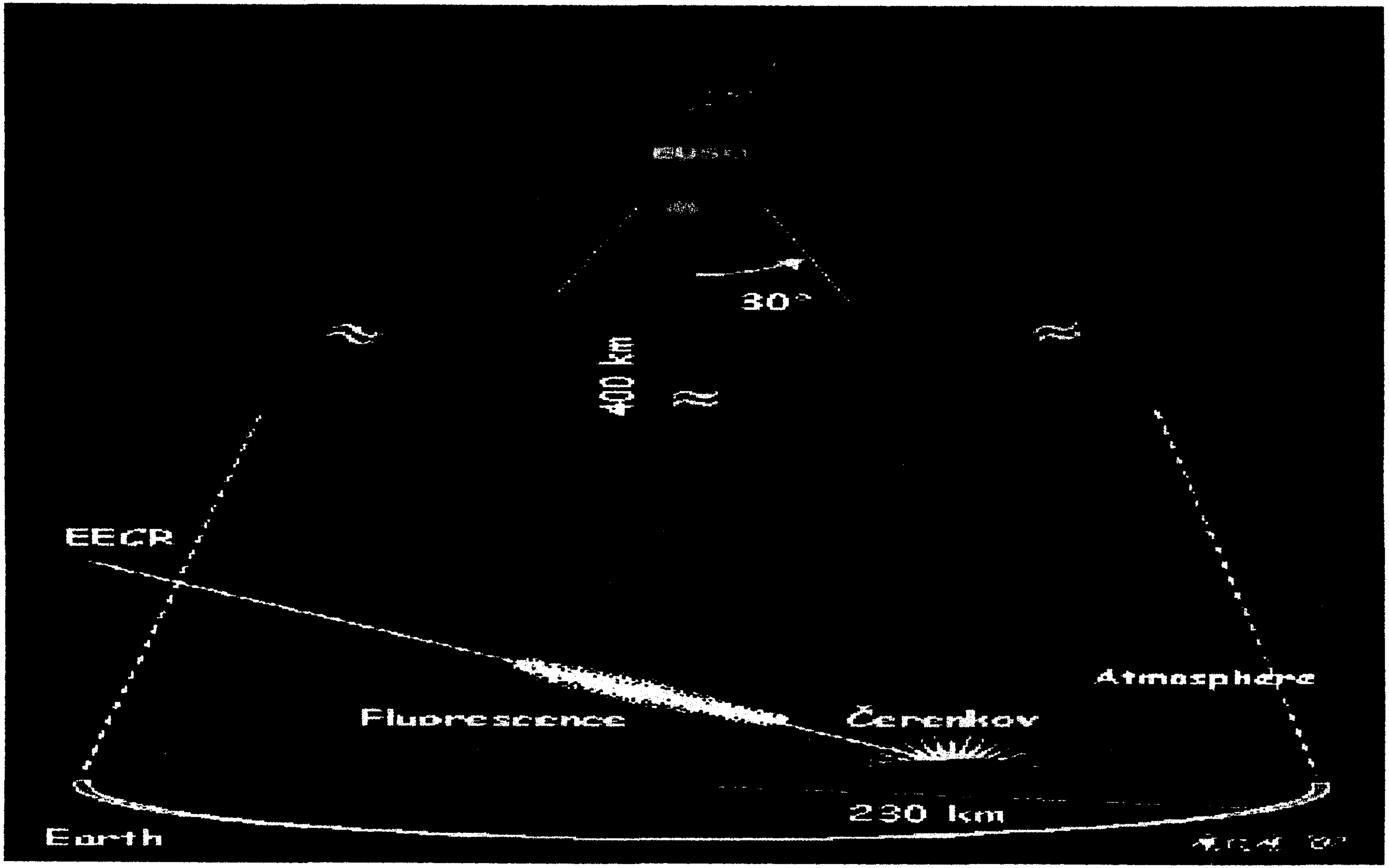
V. BEREZINSKY
I.N.F.N.
Laboratorio Nazionale del Gran Sasso (L.N.G.S.)
Assergi, L'Aquila
ITALY

SuperGZK NEUTRINOS
TESTING PHYSICS BEYOND SM

V. Berezinsky
LNGS, Laboratori Nazionali del Gran Sasso

SuperGZK NEUTRINOS $(E_\nu > 10^{20}\,eV)$

MOTIVATION: SPACE DETECTORS (EUSO and OWL)



SuperGZK NEUTRINOS: SOURCES

- ACCELERATION to $E \gg 10^{20}\,eV$ IS A CHALLENGE FOR ASTROPHYSICAL MECHANISMS.

- TOPOLOGICAL DEFECTS and SUPERHEAVY DARK MATTER NATURALLY PROVIDE THESE ENERGIES.

→ DECAY OF SUPERHEAVY PARTICLES (DM and TD) $E_\nu^{max} \sim 0.1\, m_X$

→ CUSPS IN SUPERCONDUCTING STRINGS.

→ RADIATION BY MONOPOLES IN NETWORKS

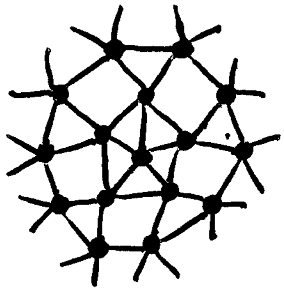
V.B., X. Martin, A. Vilenkin PR D56, 2024, 1997

MONOPOLES CONNECTED BY STRINGS

$$G \underset{\eta_m}{\longrightarrow} H \times U(1) \underset{\eta_s}{\longrightarrow} H \times Z_N$$

MASS OF MONOPOLE: $m = 4\pi\eta_m/e$ TENSION $\mu = 2\pi\eta_s^2$

MS NETWORK



DUE TO COSMOLOGICAL EVOLUTION MONOPOLES BECOME RELATIVISTIC AT $t \sim t_0$: $V_0 \sim c$, $\Gamma_0 \gg 1$

MONOPOLES OSCILLATE DUE TO $f = \mu$ AND OBTAIN A PROPER ACCELERATION $a \sim \mu/m$

HARMONIC OSCILLATION: $x = x_0 \sin \Omega t$

$$a_{max} = \frac{2}{3\sqrt{3}} \Gamma_0^2 \Omega$$

RADIATION OF MASSLES GAUGE BOSONS

$$P \sim q^2 a^2$$

$$\langle P \rangle = \frac{9}{8} \frac{1}{\Gamma_0} q^2 a_m^2 = \frac{1}{6} q^2 \Gamma_0^3 \Omega^2$$

RADIATION OF HEAVY GAUGE BOSONS

CLASSICALLY MOVING MONOPOLE RADIATES QUANTUM FIELD

MONOPOLE HAS CHROMOMAGNETIC CHARGE g

$$(\Box + M^2) A_\mu = j_\mu \qquad (1)$$

CLASSICAL CURRENT $j_\mu = g \frac{p_\mu}{p_0} \delta^3(\vec{r} - \vec{r}_M(t))$

$$T_{\mu\nu} = -2(\partial_\mu A_\lambda)(\partial_\nu A^\lambda) - \mathcal{L} g_{\mu\nu}$$

FOR ONE-DIMENSION MOTION THERE ARE ONLY TWO COMPONENTS, A_0 AND A_3.

RADIAL FLUX:

$$S_r = -(\partial_0 A_0)(\partial_r A_0) - (\partial_0 A_3)(\partial_r A_3)$$

RADIATED POWER FOR PERIODIC MOTION

$$P = r^2 \int \frac{dt}{T} \int d\Omega \, S_r(t)$$

METHOD: SOLUTION OF EQ.(1)

CASE $a \gg M$ (M IS BOSON MASS)

$$P = \frac{g^2}{16\sqrt{6}\pi^2} \Gamma_0^3 \Omega^2$$

CLASSICAL CASE

$$E_{max} \sim \Gamma_0 a_{max} = \frac{\pi^2}{3} \Gamma_0^3 \Omega$$

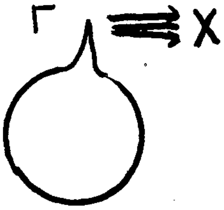
CASE $a \ll M$

$$P = \sqrt{\frac{2\pi}{3}} \frac{g^2}{2\pi^2} \frac{\Gamma_0^3 \Omega^2}{V_0^4} \left(\frac{MV_0}{a_{max}}\right)^{1/2} \exp\left(-\frac{2}{3} \frac{MV_0}{a_{max}}\right)$$

$$E_{max} \sim \Gamma_0 M$$

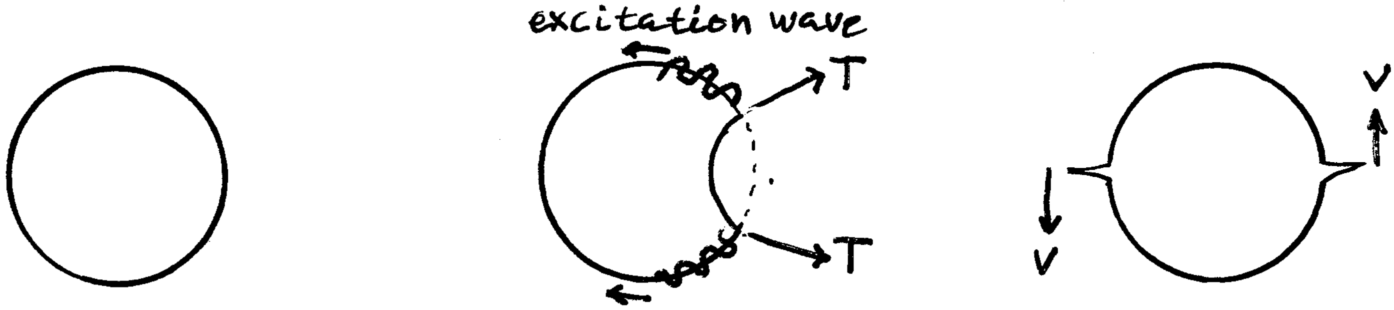
E_{max} REACHES PLANCKIAN SCALE!

SUPERCONDUCTING CUSPS



CUSP IS A POINT ON A STRING MOVING WITH $V \approx C$

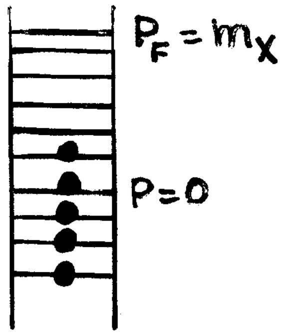
ORIGIN OF CUSP



LOOP

TENSION $T = \mu$

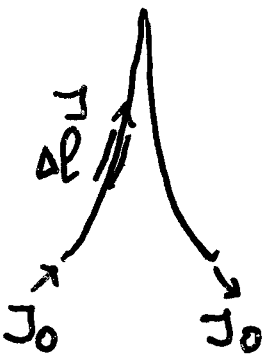
SUPERCONDUCTING STRING



$$p = e\mathcal{E}t \qquad P_c = m_X$$

$$J = en = e^2\mathcal{E}t \qquad J_c = e m_X$$

STRUCTURE OF THE CUSP



INVARIANT LENGTH $\Delta l \sim \frac{J}{J_0} l$

LORENTZ FACTOR $\Gamma \sim \frac{J}{J_0}$

$$E_{max} \sim \gamma_c m_X \sim \frac{J_c}{J_0} m_X = \frac{e m_X^2}{J_0}$$

$$\dot{N}_X \sim \Delta l \frac{J_0}{e} \frac{1}{\tau} \sim \frac{J_0}{J_c} l \frac{J_0}{e} \frac{1}{\tau} \sim \frac{J_0^2}{e J_c} \sim \frac{J_0^2}{e^2 m_X}$$

MIRROR MATTER AS A HIDDEN NEUTRINO SOURCE

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

IN EMPTY SPACE REFLECTION $\vec{x} \to -\vec{x}$ AND TIME SHIFT $t \to t + \Delta t$ COMMUTE.

IN THE PARTICLE SPACE THE CORRESPONDING OPERATORS MUST COMMUTE, TOO

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

i.e. EIGENVALUE OF OPERATOR I_r MUST BE CONCERVED

$I_r = P$ (PARITY OPERATOR) IS NOT CONSERVED

DEFINITION: $P\Psi(x_\mu) = \gamma_0 \Psi(x_0, -\vec{x})$; $P\varphi(x_\mu) = \pm \varphi(x_0, -\vec{x})$

- Lee and Yang: $I_r = PR$ WHERE R TRANSFERS PARTICLE TO THE NEW STATE (MIRROR PARTICLE)

- Landau: $I_r = PC$, 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 INTERACTIONS (SYMMETRIES). SINCE $L \to R'$ AND $R \to L'$ (e.g. $I_r \Psi_L(t, \vec{x}) = \Psi'_R(t, -\vec{x})$) $SU_2(L) \times U(1) \to SU'_2(R) \times U'(1)$ WITH NEW PHOTON (γ') AND NEW GAUGE BOSONS.

Kobzarev, Pomeranchuk and Okun SUGGESTED THAT ORDINARY AND MIRROR SECTORS COMMUNICATE ONLY GRAVITATIONALY. THE MIRROR MATTER IN THE UNIVERSE MAY EXIST AS THE MIRROR STARS AND MIRROR GALAXIES.

COMMUNICATION TERMS CAN BE WRITTEN e.g. AS

$$\mathcal{L}_{comm} = \frac{1}{M_{Pl}} (\bar{\Psi}_L \varphi)(\Psi'_R \varphi') \qquad (1)$$

WHERE $\bar{\Psi}_L = (\bar{\ell}_L, \bar{\nu}_L)$ AND $\varphi = (\varphi_0^*, -\varphi_+^*)$.

AFTER SSB (1) RESULTS IN MIXING OF ORDINARY AND MIRROR (STERILE) NEUTRINOS.

$$\frac{V_{EW}^2}{M_{Pl}} \bar{\nu}_L \nu'_R$$

FOR OTHER PARTICLES V_{EW}^2/M_{Pl} IS TOO SMALL IN COMPARISON WITH THEIR MASSES

$$\mu = \frac{V_{EW}^2}{M_{Pl}} = 2.5 \cdot 10^{-6}\, eV$$

THE MOST GENERAL NEUTRINO MASS MATRIX

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

where M and m are 3×3 matrices.

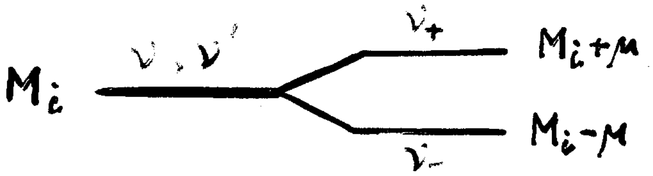
MIRROR SYMMETRY GIVES $M = M'$.

ILLUSTRATIVE CASE OF TWO NEUTRINOS ν AND ν':

$$\begin{pmatrix} M_i & \mu \\ \mu & M_i \end{pmatrix}$$

DIAGONALIZATION RESULTS IN MAXIMAL MIXING

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



COSMOLOGICAL RESTRICTIONS: BING-BANG NUCLEOSYNTHESIS

PROBLEM: additional light particles $\gamma', \nu'_e, \nu'_\mu, \nu'_\tau$

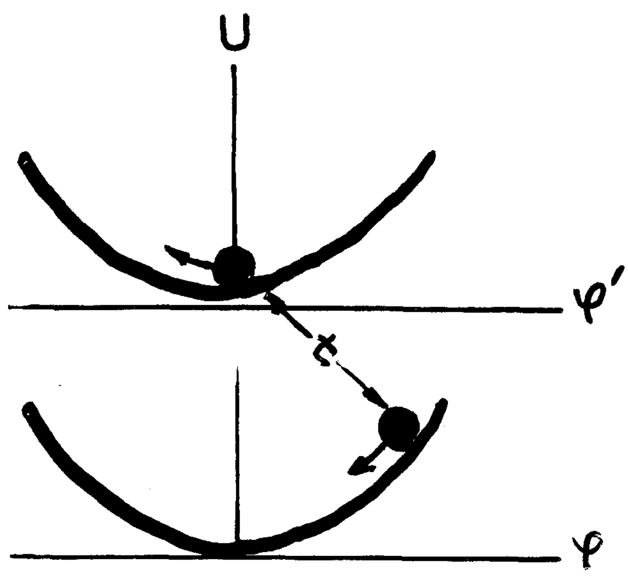
T′ MUST BE SUPPRESSED

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: $T' < T$

MIRROR TOPOLOGICAL DEFECTS

DENSITY OF MIRROR TDs CAN BE MUCH LARGER THAN THAT OF ORDINARY TDs.

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

HOW IT CAN BE IF ORDINARY AND MIRROR SECTORS ARE SYMMETRIC

TWO-INFLATON SCENARIO CREATES NON-SYMMETRIC INITIAL CONDITIONS.

CURVATURE-DRIVEN PHASE TRANSITION

$$R = 12H^2 = 16\pi\left(\frac{m_\varphi}{m_{Pl}}\right)^2(\varphi^2 + \varphi'^2)$$

φ and φ' ARE INFLATON FIELDS

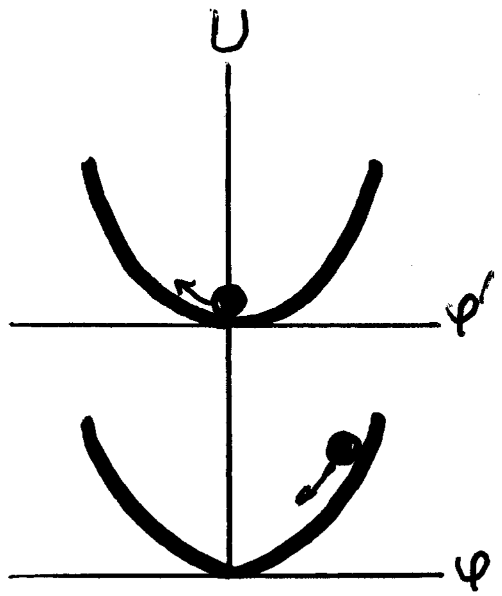
$$V(\chi) = \frac{1}{4}\lambda(\chi^2 - v^2)^2 - \frac{1}{2}g\varphi^2\chi^2 + \frac{1}{2}\xi R\chi^2$$

COEFFICIENT IN FRONT OF χ^2 IS m^2_{eff}

$$m^2_\chi = -\lambda v^2 - g\varphi^2 + \xi R$$

$$m^2_{\chi'} = -\lambda v^2 + \xi R$$

$R = \frac{\lambda}{\xi}v^2$: PHASE TRANSITION



$$m^2_\chi = -\lambda v^2 - g\varphi^2 + \xi R = -\lambda v^2 - g\varphi^2\left(1 - \frac{\xi}{g}16\pi\frac{m^2_\varphi}{m^2_{Pl}}\right)$$: NO PHASE TRANSITION

UHE NEUTRINOS FROM MIRROR TDs

CALCULATION OF MIRROR ν-FLUX FROM TD IS IDENTICAL TO THE CASE OF ORDINARY NEUTRINOS

FROM ALL PARTICLES PRODUCED BY X_{mirr}-DECAYS ONLY ν's (DUE TO $\nu_{mirr} \to \nu_{act}$ OSCILLATIONS) ARE VISIBLE.

$$L_{osc}(E) \sim \frac{E}{\Delta m^2} \sim \frac{E}{4M_{if}} \sim 10 \, \frac{E}{10^{20}\,eV} \, \frac{7 \cdot 10^{-3}\,eV}{M_\nu} \text{ kpc}$$

PROBABILITY OF OSCILLATION: $P_{\nu' \to \nu} = 1/2$

UPPER LIMIT ON MIRROR NEUTRINO FLUX

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

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

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

$$\omega_{cas} = E_0 \dot{n}_Z t_0 \frac{1}{2} \frac{f_h}{f_{tot}} \qquad \frac{f_h}{f_{tot}} \approx 0.7$$

$$I_\nu(E_0) \leq \frac{2}{\pi} \frac{f_{tot}}{f_h} \frac{\omega_{cas}}{\sigma_t n_{\nu_i} t_0} \frac{m_\nu^2}{m_Z^4}$$

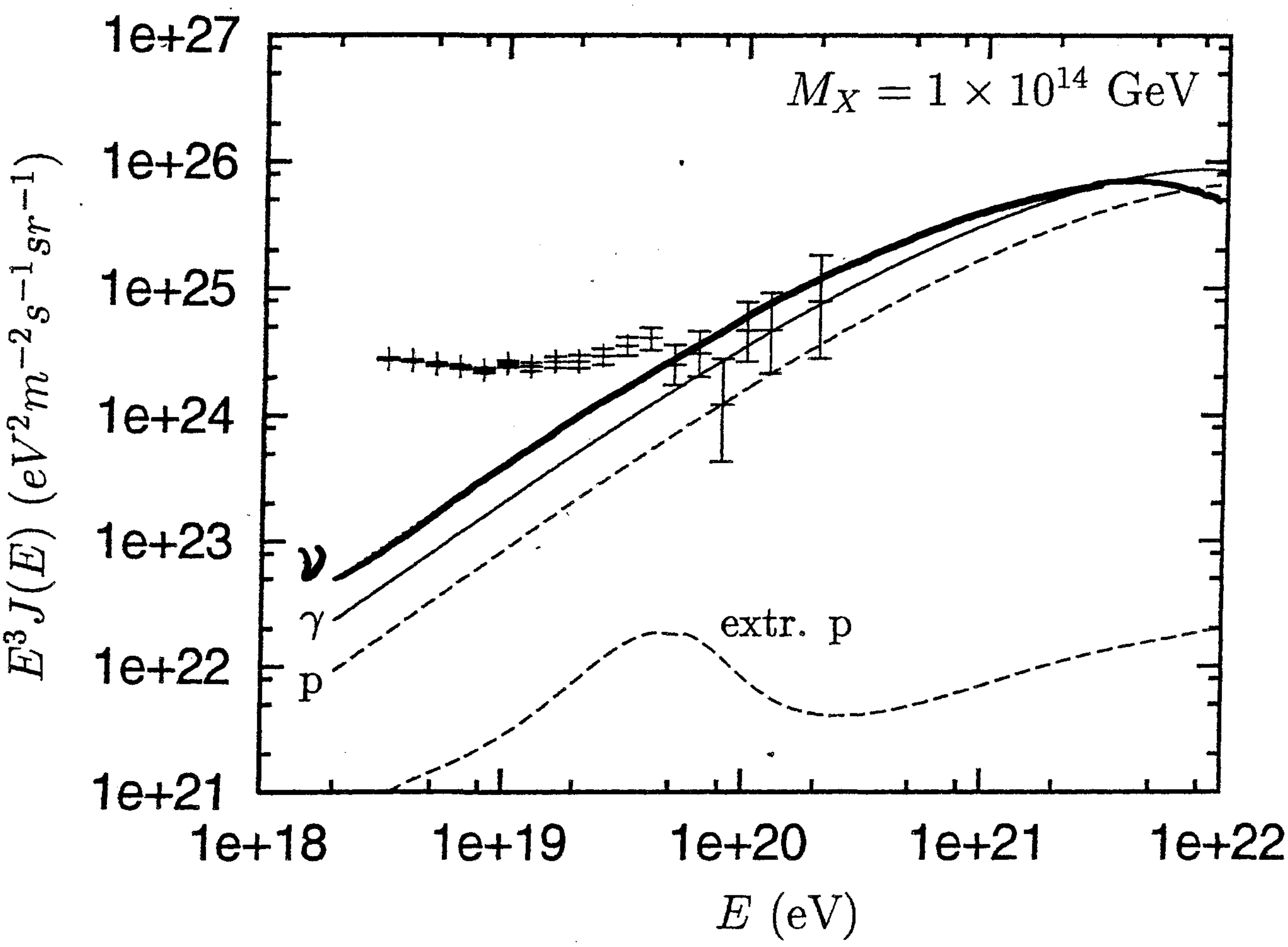
THE STRONGEST LIMIT IS IMOPED BY LIGHTEST NEUTRINO, IF $E_\nu = m_Z^2/2m_\nu$ IS AVAILABLE

RATIO OF UPPER LIMITS:

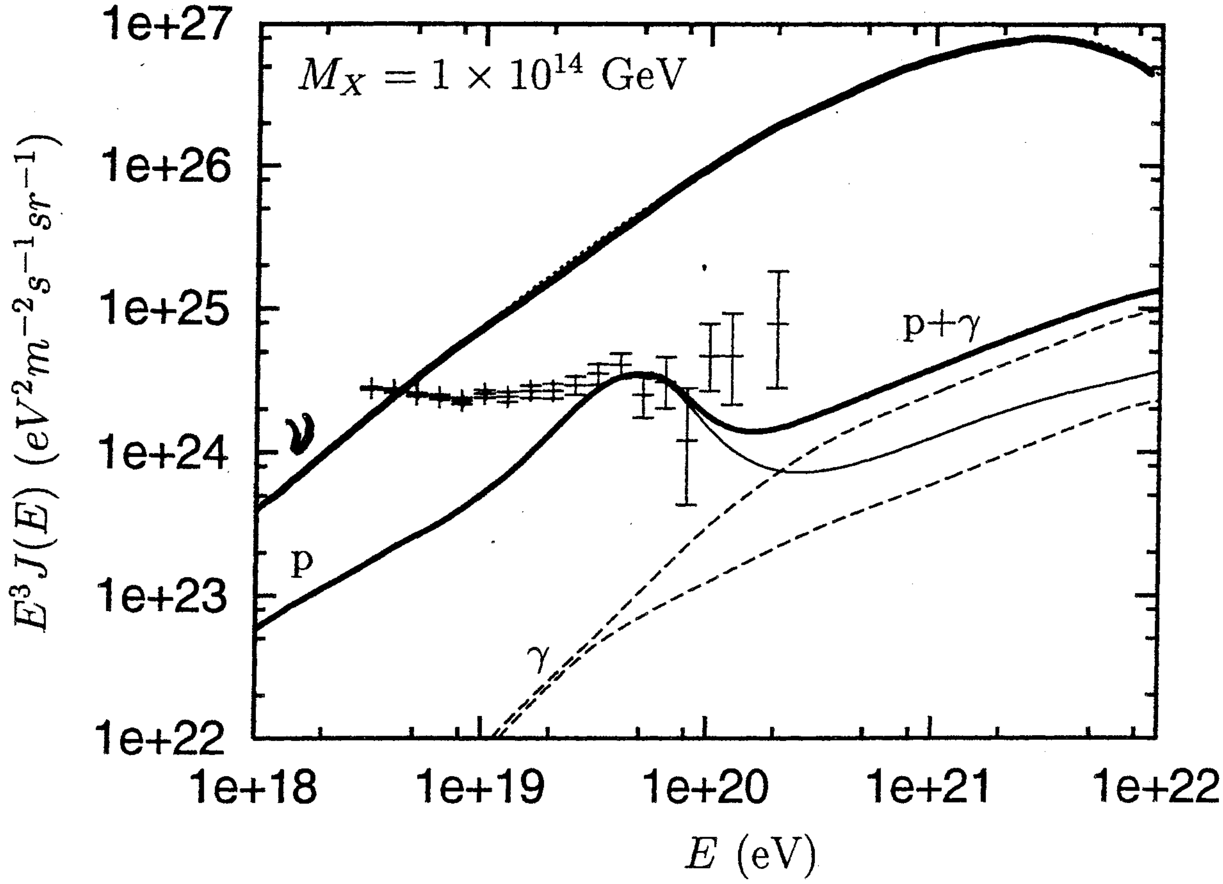
$$\frac{I_\nu^{mirr}(E_0)}{I_\nu^{cas}(E_0)} = 8 \, \frac{f_{tot}}{f_h} \, \frac{1}{\sigma_t n_{\nu_i} t_0} = 1.3 \cdot 10^3$$

SUPERGZK NEUTRINO FLUXES

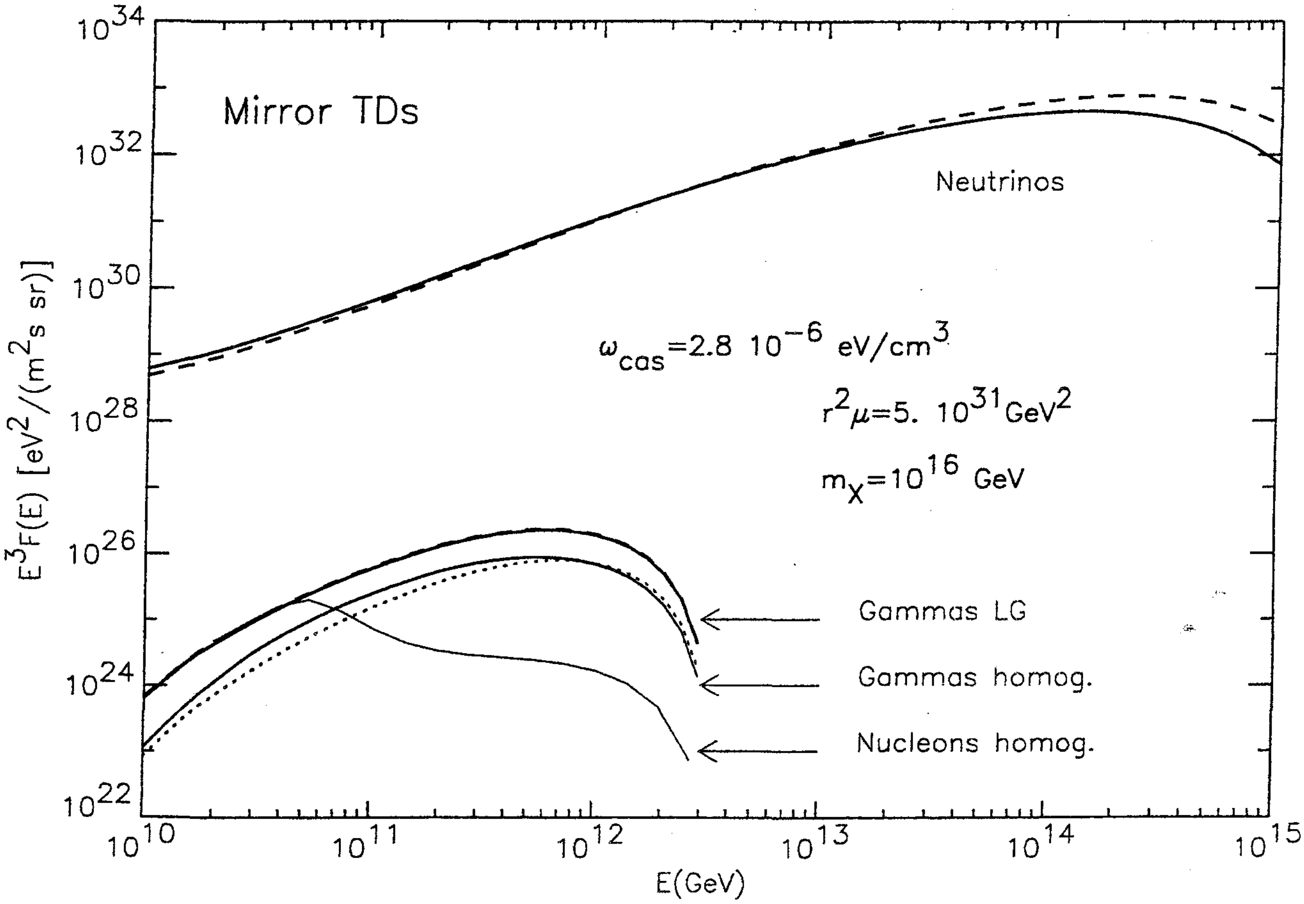
SUPERGZK NEUTRINOS FROM SHDM



SUPER GZK NEUTRINOS FROM NECKLACES



SUPERGZK NEUTRINOS FROM MIRROR TD



CONCLUSIONS

- HE NEUTRINOS IS A TRACER OF HE PHENOMENA IN THE UNIVERSE: ACCELERATION TO HE, DECAY AND ANNIHILATION OF HEAVY PARTICLES. TECHNICALLY, HE NEUTRINO ASTRONOMY IS A SEARCH FOR HIGH ENERGY PIONS IN THE SOURCES.

- SEVERAL TASKS OF HE NEUTRINO ASTRONOMY ARE AIMED TO FUNDAMENTAL PHYSICS:
  (i) DETECTION OF HE NEUTRINOS FROM THE SUN IMPLIES DISCOVERY OF DM AND SUPERSYMMETRY
  (ii) DETECTION OF DIFFUSE FLUX OF SuperGZK NEUTRINOS WITH FLUX HIGHER THAN CASCADE LIMIT IMPLIES DISCOVERY OF MIRROR SYMMETRY.
  (iii) IT IS POSSIBLE TO HAVE INDICATIONS FOR TD's AND SHDM

- THE DETECTABLE DIFFUSE FLUXES CAN BE PRODUCED BY CLUSTERS OF GALAXIES, AGN, GRB, TDs, MIRROR MATTER etc

- THE RIGOROUS UPPER LIMIT ON DIFFUSE FLUXIS GIVEN BY CASCADE ENERGY DENSITY MEASURED BY EGRET. THIS LIMIT DOES NOT DEPEND ON HE PROTON SPECTRUM AND VALID FOR NON-ACCELERATOR SOURCES. THE ONLY EXCEPTION IS GIVEN BY HIDDEN SOURCES.

- CR LIMITS(BASED ON OBSEVED CR FLUXES) ARE LESS GENERAL (NOT VALID FOR MANY SOURCES) BUT FOR SOME SOURCES THEY ARE STRONGER THAN CASCADE LIMIT

- SuperGZK NEUTRINOS AND EUSO ARE TESTING MAINLY THE NEW PHYSICS: TDs, SUPERHEAVY DM AND MIRROR MATTER.

COSMOLOGICAL RESTRICTIONS: OSCILLATIONS

EVEN IF $T' \ll T$ STERILE NEUTRINOS ARE PRODUCED DUE TO $\nu \to \nu'$ OSCILLATION AND CAN VIOLATE NUCLEOSYNTHESIS LIMIT.

BOUND ON Δm^2 FOR MAXIMAL MIXING (strongest for ν_e):

$$\Delta m^2_{\nu_e \nu'} \leq 10^{-9} - 10^{-8}\ \mathrm{eV}^2$$

THIS BOUND BECOMES MUCH WEAKER IN CASE OF LARGE LEPTON ASYMMETRY $L = (n_\nu - n_{\bar{\nu}})/n_\gamma$

$$\Delta m^2 < 4 \times 10^2 |L_e|\ \mathrm{eV}^2$$

NATURAL LEPTON ASYMMETRY IS $L_e \sim B \sim 10^{-10}$, BUT $L_e \sim 10^{-5}$ IS NOT EXLUDED.