COSMOGENIC AND TOP-DOWN UHE NEUTRINOS

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UHE NEUTRINOS at $E > 10^{17}$eV

Cosmogenic neutrinos:

Reliable prediction **of existence** is guaranteed by observations of UHECR.

Production: $p + \gamma_{\rm CMB} \to \pi^{\pm} \to$ neutrinos.

Limited maximum energy: $E_\nu^{\rm max} < E_{\rm acc}^{\rm max} < 10^{22}$ eV.

Neutrinos in top-down models:

Signature: high $E_\nu^{\rm max}$ up to $M_{\rm GUT} \sim 10^{25}$ eV and above.

- **Topological Defects**
- **Superheavy Dark Matter**
- **Mirror Matter**

COSMOGENIC NEUTRINOS: FLUX CALCULATIONS

- Berezinsky and Zatsepin 1969, 1970
- Engel, Seckel, Stanev 2001
- Kalashev, Kuzmin, Semikoz, Sigl 2002
- Fodor, Katz, Ringwald , Tu 2003
- VB, Gazizov, Grigorieva 2003
- Hooper et al. 2004
- Allard et al. 2006

APPROACH and RESULTS:

- **Normalization by the observed UHECR flux**
- **Neutrino flux is SMALL in non-evolutionary models with $E_{\max} \leq 10^{21}$ eV**
- **Neutrino flux is LARGE in evolutionary models with $E_{\max} \geq 10^{22}$ eV**

COSMOGENIC NEUTRINOS

IN THE DIP MODEL FOR UHECR

The **dip** is a feature in the spectrum of UHE protons propagating through CMB:

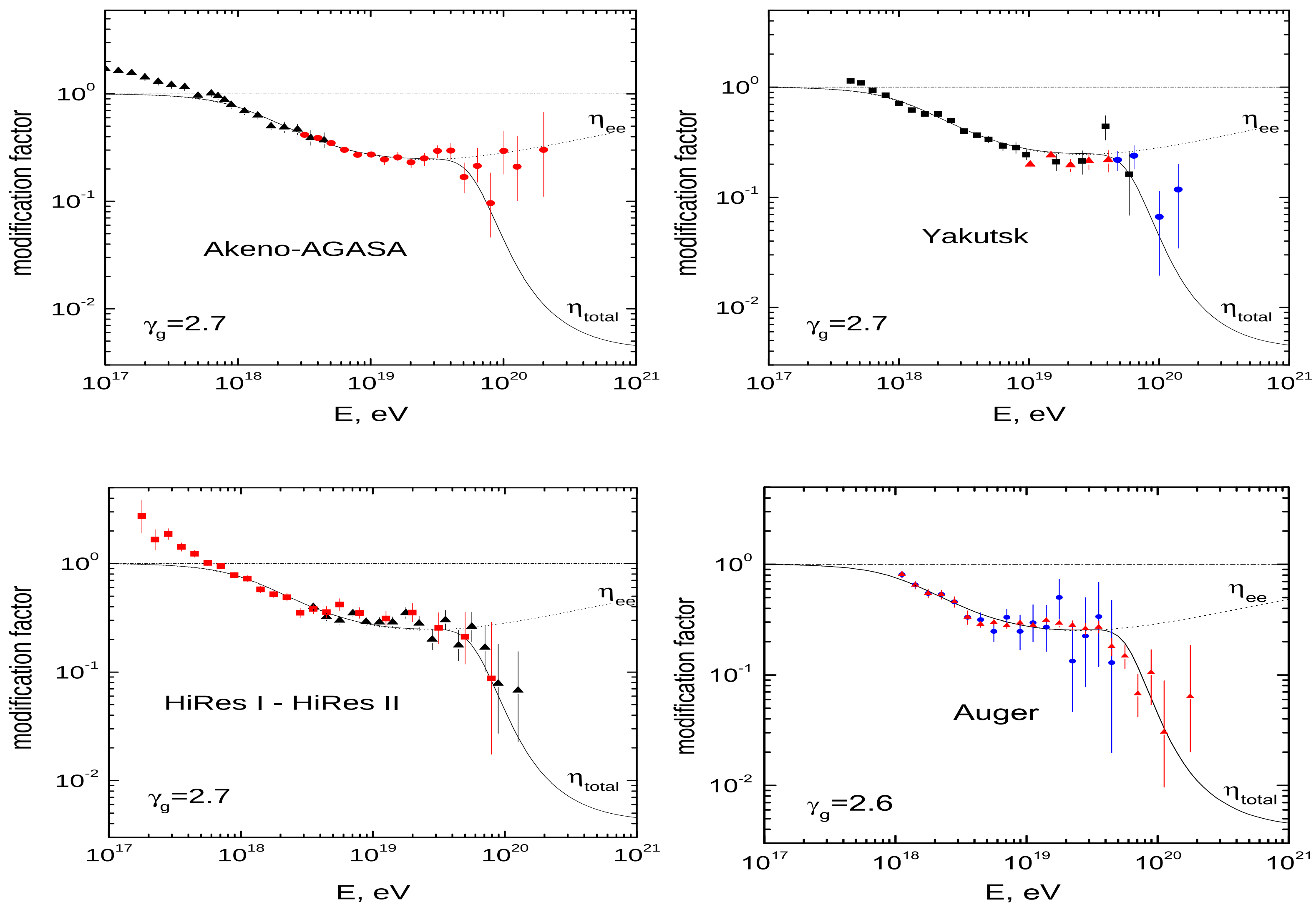
$$\mathbf{p} + \gamma_{\rm CMB} \to \mathbf{e}^+ + \mathbf{e}^- + \mathbf{p}$$

Calculated in the terms of **modification factor** $\eta(E)$ the dip is seen in all observational data.

$$\eta(\mathbf{E}) = \frac{\mathbf{J_p(E)}}{\mathbf{J_p^{\rm unm}(E)}},$$

where $J_p^{\rm unm}(E)$ includes only adiabatic energy losses and $J_p(E)$ - all energy losses.

COMPARISON OF DIP WITH OBSERVATIONS



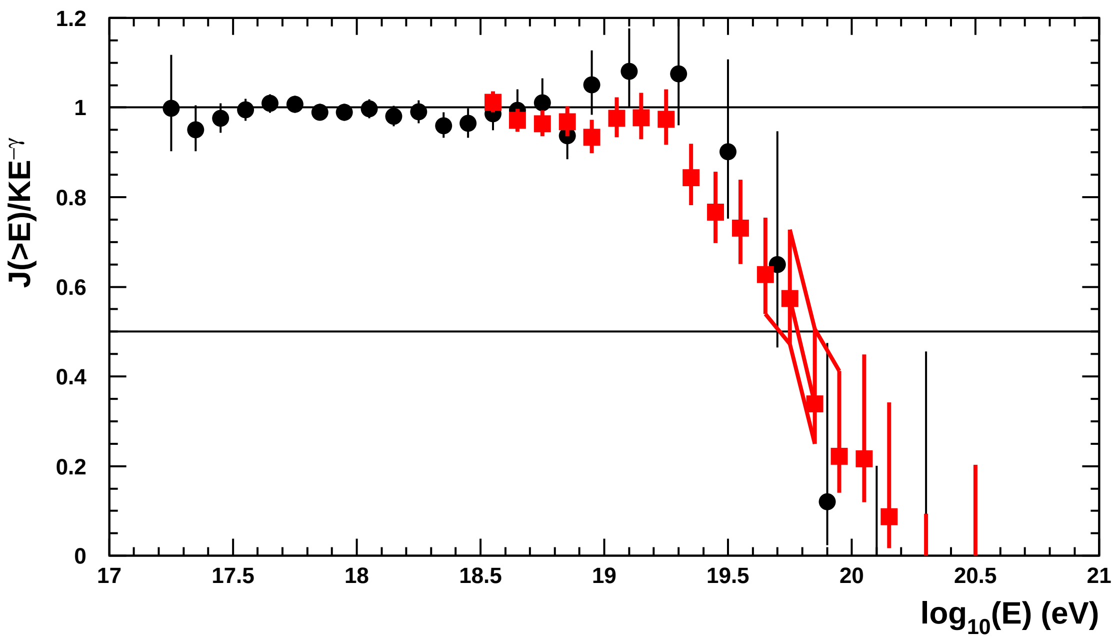
GZK CUTOFF IN HiRes DATA

In the integral spectrum GZK cutoff is numerically characterized by energy $E_{1/2}$ where the calculated spectrum $J(>E)$ becomes half of power-law extrapolation spectrum $KE^{-\gamma}$ at low energies. As calculations (V.B.&Grigorieva 1988) show

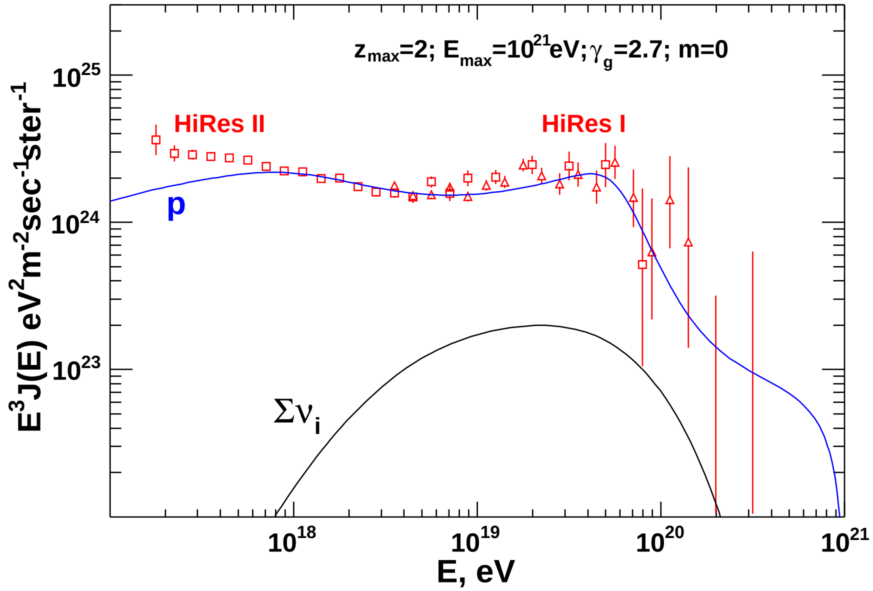
$$E_{1/2} = 10^{19.72}\ \mathrm{eV}$$

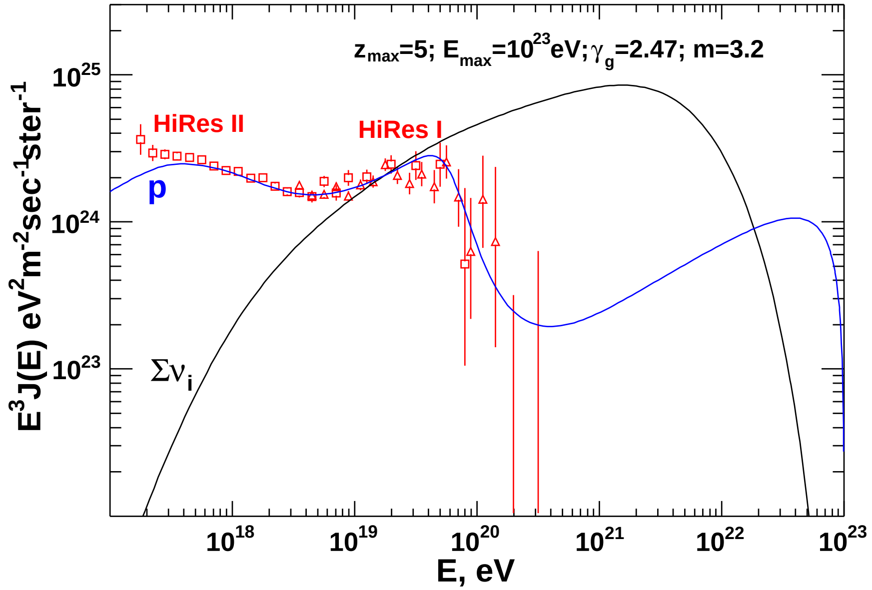
valid for a wide range of generation indices from 2.1 to 2.8. HiRes obtained:

$$E_{1/2} = 10^{19.73 \pm 0.07}\ \mathrm{eV}$$

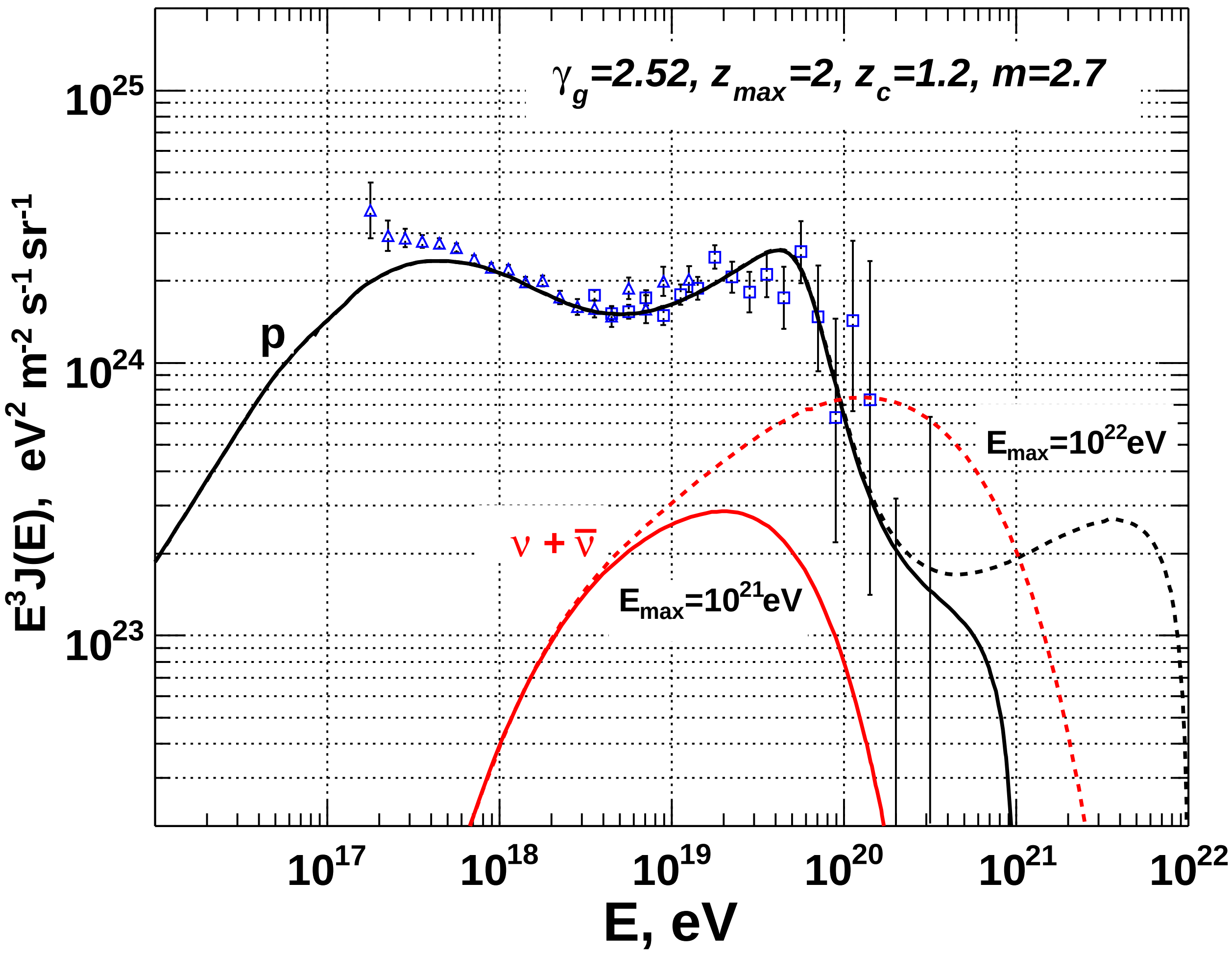


COSMOGENIC NEUTRINO FLUXES IN THE DIP MODEL



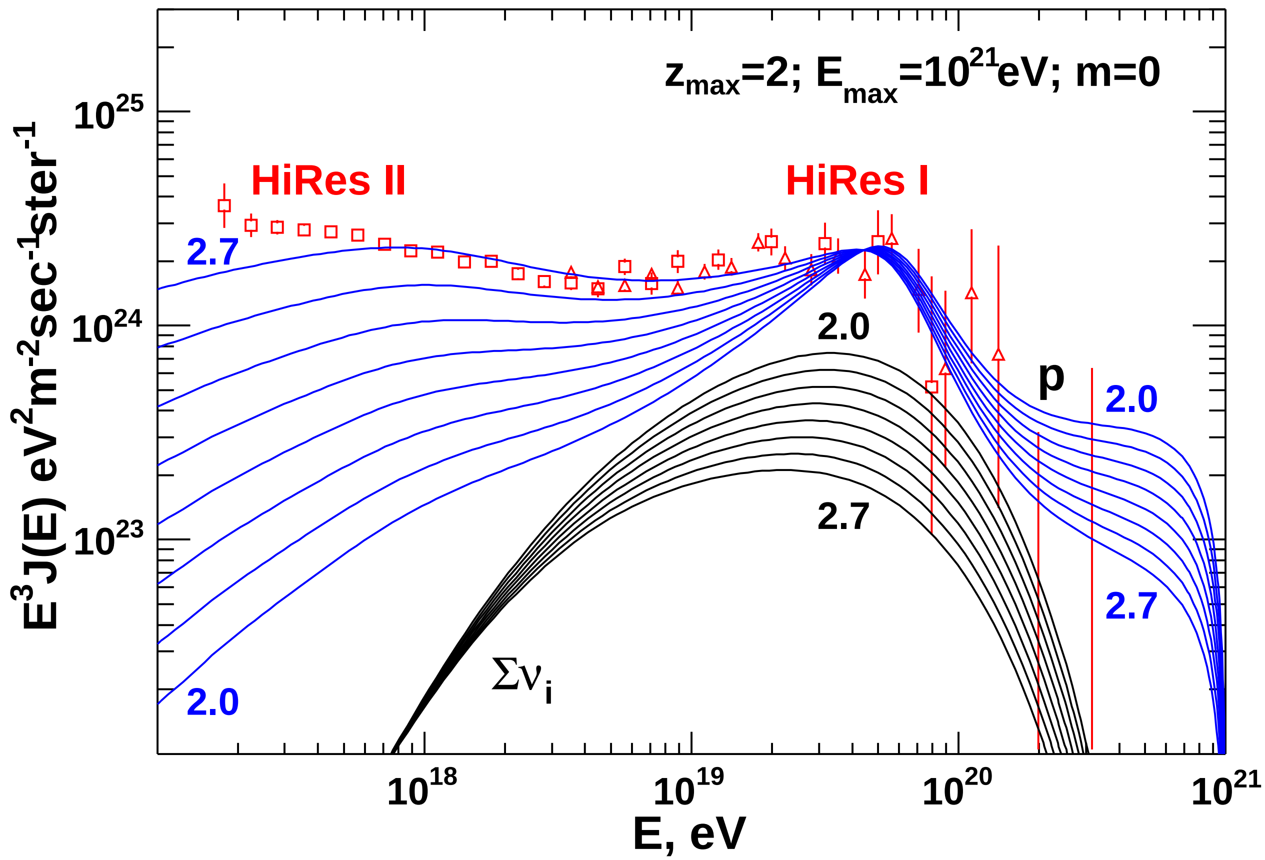


COSMOGENIC NEUTRINO FLUXES FROM AGN



LOWER LIMIT ON NEUTRINO FLUXES IN THE PROTON MODELS

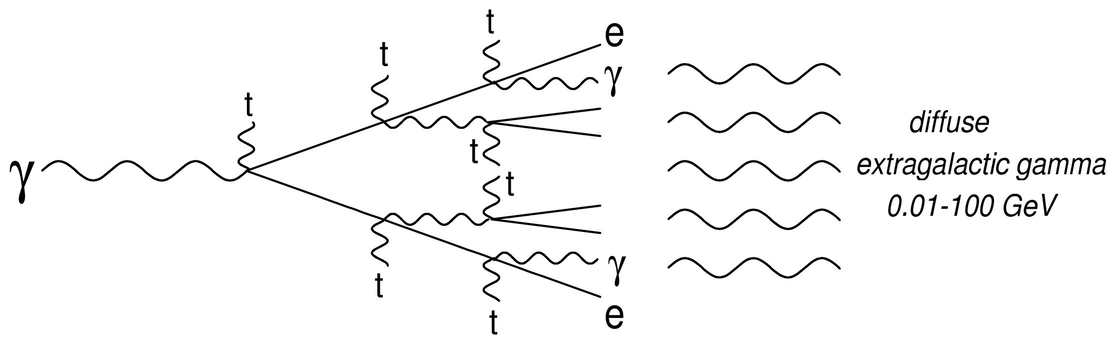
V.B. and A. Gazizov 2009



CASCADE UPPER LIMIT

V.B. and A.Smirnov 1975

$$\text{e}-\text{m cascade on target photons}: \begin{cases} \gamma + \gamma_{\rm tar} \to e^+ + e^- \\ e + \gamma_{\rm tar} \to e' + \gamma' \end{cases}$$



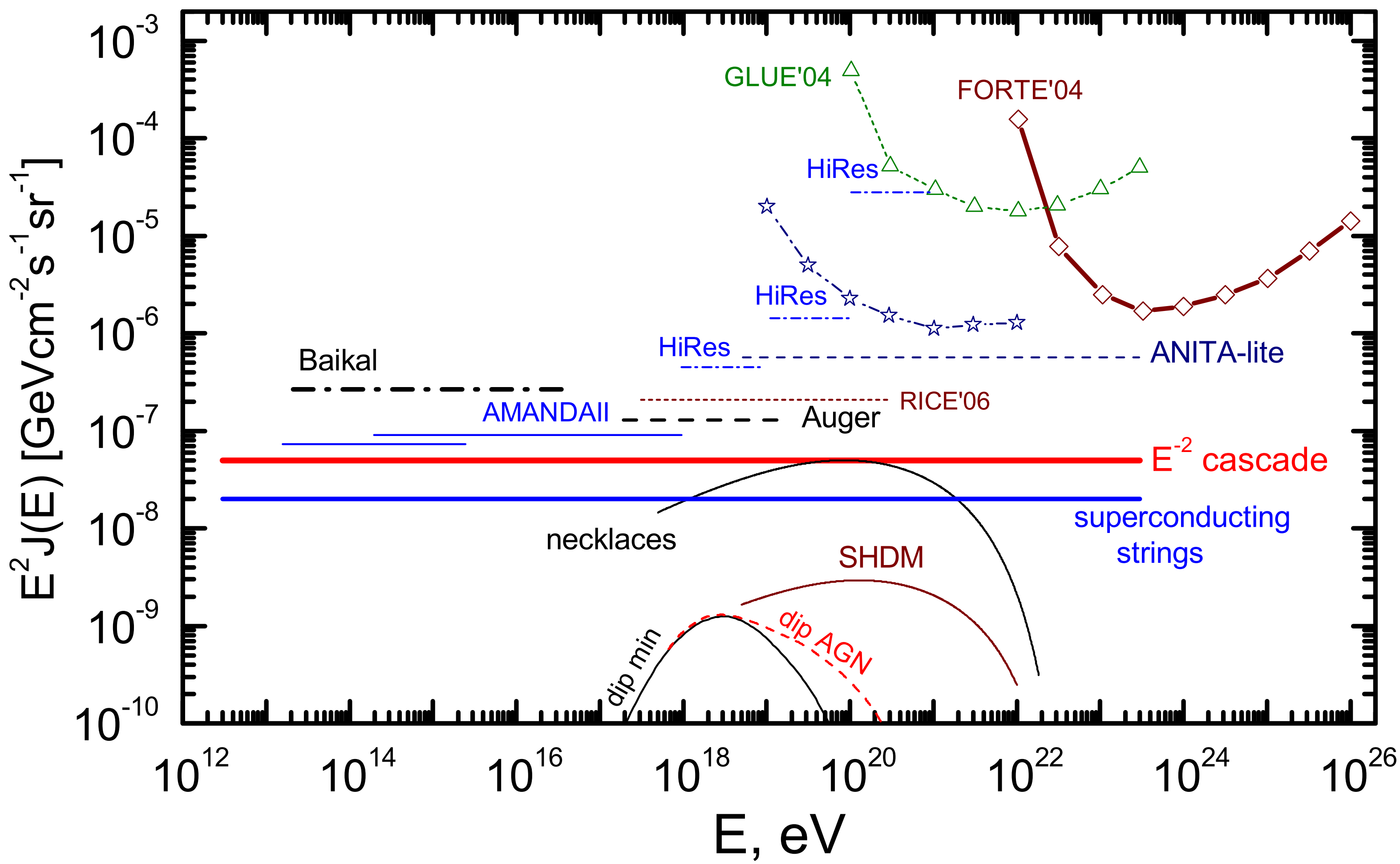
EGRET: $\omega_\gamma^{\rm obs} \sim (2-3)\times 10^{-6}\text{eV/cm}^3$.

$$\omega_{\rm cas} > \frac{4\pi}{c}\int_E^\infty EJ_\nu(E)dE > \frac{4\pi}{c}E\int_E^\infty J_\nu(E)dE \equiv \frac{4\pi}{c}EJ_\nu(>E)$$

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

$$E^{-2}-\text{generation spectrum}: E^2 J_{\nu_i}(E) < \frac{c}{12\pi}\frac{\omega_{\rm cas}}{\ln E_{\rm max}/E_{\rm min}},\ i=\nu_\mu+\bar\nu_\mu\ \text{ etc.}$$

OBSERVATIONAL UPPER LIMITS



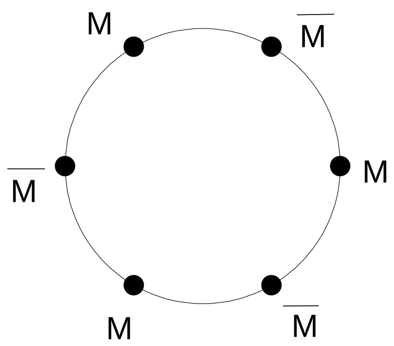
UHE NEUTRINOS FROM TOPOLOGICAL DEFECTS

Symmetry breaking in early universe results in phase transitions, which are accompanied by Topological Defects.

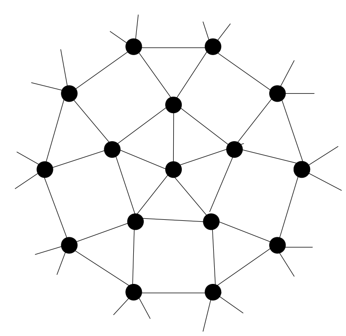
TDs OF INTEREST FOR UHE NEUTRINOS.

- **Ordinary strings:** $U(1)$ **breaking**
- **Superconducting strings:** $U(1)$ **breaking**
- **Monopoles:** $G \rightarrow H \times U(1)$
- **Monopoles connected by strings:** $G \rightarrow H \times U(1) \rightarrow H \times Z_n$
  e.g. necklaces $Z_n = Z_2$.

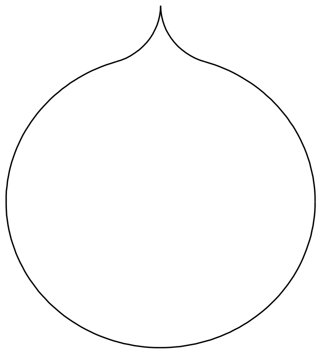
NECKLACE



MS NETWORK



ORDINARY and SUPERCONDUCTING STRINGS



Ordinary strings are produced at $U(1)$ symmetry breaking, i.e. by the Higgs mechanism: $\mathcal{L} = \lambda(\phi^+\phi - \eta^2)^2$.

They are produced as **long strings** and **closed loops**.

The fundamental property of a loop is **oscillation** with periodically produced **cusp**, where $v \to c$.

In a wide class of particle physics strings are **superconducting** (Witten 1985)

$$\mathbf{dJ/dt \propto e^2E}$$

If a string moves through magnetic field the electric current is induced

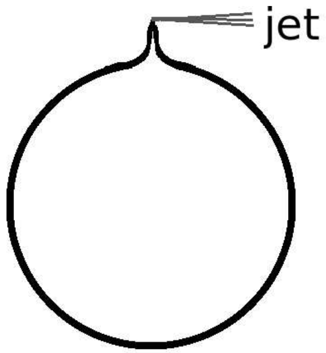
$$\mathbf{J \sim e^2vBt}$$

The charge carriers X are massless inside the string, and massive outside.
When current exceeds the critical value $J_c \sim em_X$, the charge carriers X can escape.
Energy of released particles is $E_X \sim \gamma_c m_X$, they are emitted in a cone $\theta \sim 1/\gamma_c$.

In ordinary strings the neutral particles, e.g. Higgses, can escape through a cusp, too.

UHE neutrino jets from superconducting strings

V.B., K.Olum, E.Sabancilar and A.Vilenkin 2009



Basic parameter: symmetry breaking scale $\eta \gtrsim 1 \times 10^9$ GeV.

Lorentz factor of cusp $\gamma_c \sim 10^{12}$.

Electric current is generated in magnetic fields $(B,\ f_B)$.

Clusters of galaxies dominate.

$J \sim e^2 Bl, \quad J_{\rm cusp} \sim \gamma_c J, \quad J_{\rm cusp}^{\rm max} \sim i_c e\eta.$

Particles are ejected with energies $E_X \sim i_c \gamma_c \eta \sim 10^{22}$ GeV.

Diffuse neutrino flux :

$$E^2 J_\nu(E) = 2 \times 10^{-8} i_c B_{-6} f_{-3}\ \ {\rm GeV cm^{-2} s^{-1}}$$

does not depend on η in a range $\eta > 1 \times 10^9$ GeV.

Signatures:

- **Correlation of neutrino flux with clusters of galaxies.**
- **Detectable flux of 10 TeV gamma ray flux from Virgo cluster.**
- **Multiple simultaneous neutrino induced EAS in field of view of JEM-EUSO.**

NECKLACES

V.B., Vilenkin, 1997, V.B., Blasi, Vilenkin 1998

$$G \underset{\eta_m}{\longrightarrow} H \times U(1) \underset{\eta_s}{\longrightarrow} H \times Z_2$$

mass of monopole: $m = 4\pi\eta_m/e$, tension: $\mu = 2\pi\eta_s^2$

Due to gravitational radiation, strings shrink, and monopoles inevitably annihilate.

$$M + \bar{M} \to A_\mu, H \to \text{pions} \to \text{neutrinos}$$

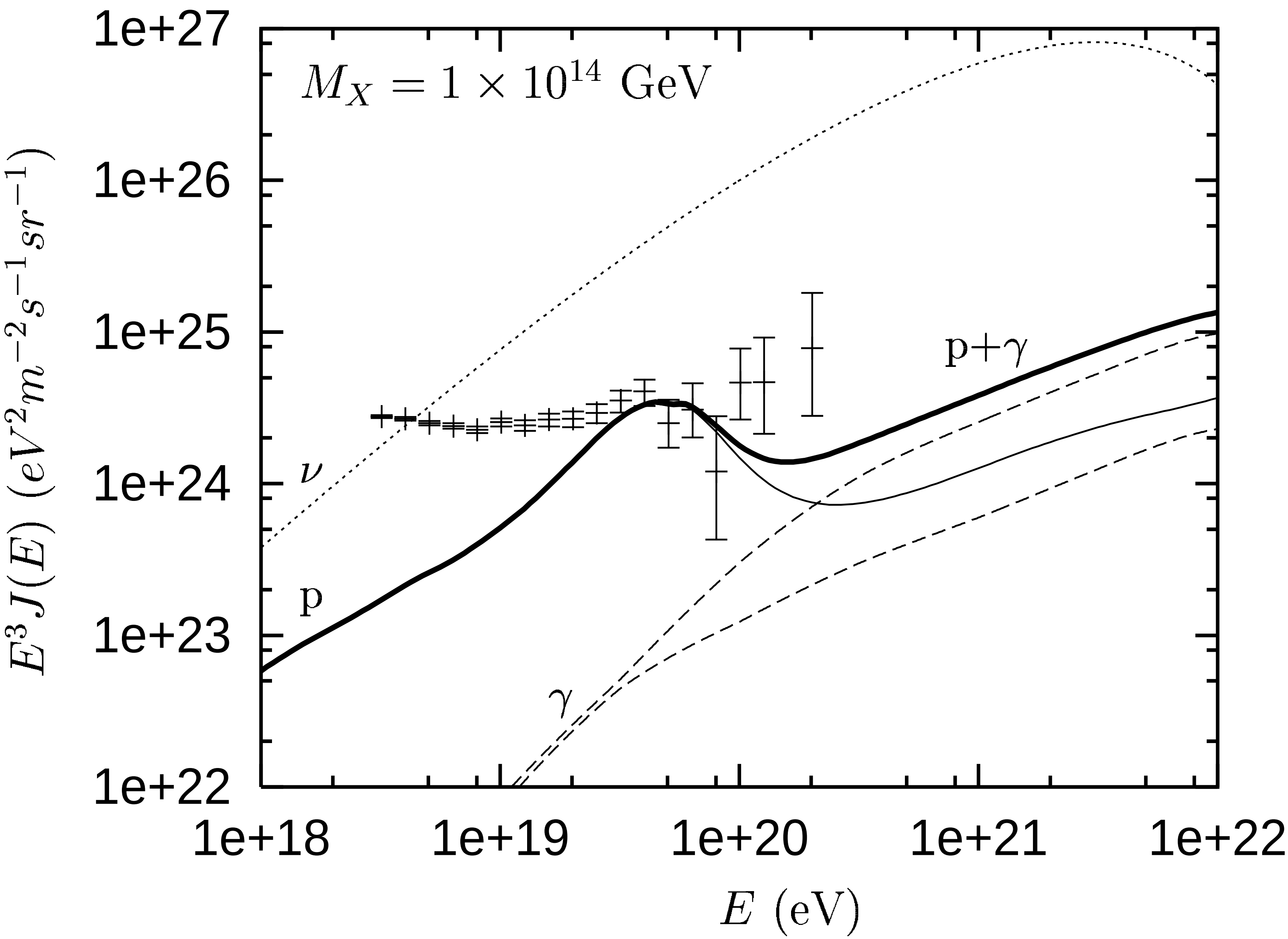
Production rate of X-particles: $\dot{n}_X \sim r^2\mu/t^3 m_X$, where $r = m/\mu d$.
Energy density $\omega \sim m_X \dot{n}_X t$ must be less 2×10^{-6} eV/cm^3 (EGRET).

$$r^2\mu \leq 8.5 \times 10^{27}\ \text{GeV}^2$$

Neutrino energy: $E_\nu^{\max} \sim 0.1 m_X \sim 10^{13}(m_X/10^{14})$ GeV

UHE NEUTRINOS FROM NECKLACES

Aloisio, V.B., Kachelriess 2004



SUPERHEAVY DARK MATTER ($m_X \gtrsim 10^{13}$ GeV)

(V.B., Kachelrieß, Vilenkin 1997, Kuzmin, Rubakov 1998).

Basic idea:

Thermal equilibrium is not reached for SHDM particles even in early universe.
Ratio $\rho_{\rm shdm}/\rho_{\rm rel} \sim a(t)/a_0 = 1/(1+z)$ and it is enough to produce a tiny quantity of SHDM in early universe, i.e. at small $a(t)$, to be a dominant component now.

Production:

Gravitational production at the end of inflation is enough (Chung, Kolb, Riotto 1998; Kuzmin, Tkachev 1998). $m_X < H(t) < m_{\rm inflaton} \sim 10^{13}$ GeV. Many other mechanisms at preheating or reheating stages may give additional contribution.

Accumulation in galactic halo :

SHDM is gravitationally accumulated in halo with overdensity $\rho_{\rm halo}/\bar{\rho}_{\rm univ} \approx 2.5 \times 10^5$.

Observational signal:

At decay or annihilation $X \to {\rm partons} \to {\rm pions} \to \gamma + \nu$.
Gamma-ray signal from halo dominates.

Particle candidates:

Particles from hidden sectors (e.g. cryptons, Ellis et al 1999, Yanagida et al. 1999).
Superheavy neutralino (V.B., Kachelrieß, Solberg 2008).

UHE MIRROR NEUTRINOS

1. CONCEPT OF MIRROR MATTER

Mirror matter is based on the theoretical concept of the space reflection, as first suggested by Lee and Yang (1956) and developed by Landau (1956), Salam (1957), Kobzarev, Okun, Pomeranchuk (1966) and Glashow (1986, 1987): see review by Okun hep-ph/0606202

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

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

Hence, I_r must correspond to the conserved value.

- Lee and Yang: $I_r = P \cdot R$, where R transfers particle to mirror particle:

$$I_r \Psi_{\rm L} = \Psi'_{\rm R} \quad \text{and} \quad I_r \Psi_{\rm R} = \Psi'_{\rm L}$$

- Landau: $I_r = C \cdot P$, where C transfers particle to antiparticle.

2. OSCILLATION OF MIRROR AND ORDINARY NEUTRINOS

Kobzarev, Okun, Pomeranchuk (1966) suggested that ordinary and mirror sectors communicate only gravitationally.

COMMUNICATION TERMS include EW SU(2) singlet interaction term:

$$\mathcal{L}_{\rm comm} = \frac{1}{M_{\rm Pl}}(\bar{\psi}\phi)(\psi'\phi') \qquad (1)$$

where $\psi_L = (\nu_L,\ \ell_L)$ and $\phi = (\phi_0^*,\ -\phi_+^*)$.
After SSB, Eq.(1) results in mixing of ordinary and mirror neutrinos.

$$\mathcal{L}_{\rm mix} = \frac{v_{\rm EW}^2}{M_{\rm Pl}}\nu\nu',$$

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

It implies oscillations between ν and ν'.

Pioneering works: Berezhiani, Mohapatra (1995) and Foot, Volkas (1995).
Mirror model appears in superstring theory based on $E_8 \times E_8'$ symmetry.

3. UHE NEUTRINOS FROM MIRROR TDs

Two-inflaton scenario with curvature-driven phase transition (V.B., Vilenkin 2000):

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

HE mirror ν's are produced by mirror TDs and oscillate into visible ν's.

All other HE mirror particles which accompany neutrino production remain invisible.

Oscillations are studied by V.B, Narayan, Vissani 2003 in:

Symmetric mirror model with gravitational communication

$$P_{\nu'_\mu \nu_e} = \frac{1}{8}\sin^2 2\theta_{12}\ , \quad P_{\nu'_\mu \nu_\mu} = P_{\nu'_\mu \nu_\tau} = \frac{1}{4} - \frac{1}{6}\sin^2 2\theta_{12}\ , \quad \sum_\alpha P_{\nu'_\mu \nu_\alpha} = \frac{1}{2}.$$

Signature: diffuse flux exceeds cascade upper limit.

CONCLUSIONS

- UHE neutrino astronomy has a balanced program of observations of reliably existing cosmogenic neutrinos, and top-down neutrinos predicted by the models beyond SM (e.g. topological defects or SHDM).

- Energies of cosmogenic neutrinos are expected below $E_\nu \sim 10^{21}$ eV. Acceleration to $E_p^{\rm max} \sim 1 \times 10^{22}$ eV is a problem in astrophysics. Energies in top-down models can be much higher.

- Fluxes of cosmogenic neutrinos are high and detectable in case of UHECR proton composition (confirmed by observations of dip and GZK cutoff). Neutrino flux lower than the minimum flux in the dip model indicates presence of nuclei as primaries.

- Fluxes of cosmogenic neutrinos are much lower in case of heavy-nuclei composition and could be undetectable by EUSO if source evolution is absent and/or $E_{\rm max}$ is small.

- Neutrinos with $E_\nu > 10^{21} - 10^{22}$ eV are a signal for a new physics.