UHE COSMIC NEUTRINOS: view from 2011

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UHE NEUTRINOS: PRODUCTION and SOURCES

- **Astrophysical neutrinos** **(produced by CRs)**
  pp: $p + N_{\rm tar} \to \pi^{\pm} + {\rm all}$**,** **p$\gamma$:** $p + \gamma_{\rm tar} \to \pi^{\pm} + {\rm all}$

- **Top-Down neutrinos** **(direct pion production :)**
  TDs, annihilation of DM, decay of SHDM, oscillation of mirror neutrinos.

- **Hidden astrophysical sources:**
  Cocooned black hole: VB, Ginzburg 1981,
  Stecker AGN model: Stecker et al 1991,
  Collapsing galactic nuclei: VB, Dokuchaev 2001,
  Hidden jets: Razzaque, Smirnov 2010

- **Hidden Top-Down sources:**
  Annihilation of DM in the Earth and Sun,
  Mirror matter sources (oscillation of neutrinos)

- **Bright phase** **(Pop III stars at** $z \sim 10-20$ **,** $z_{\rm reion} = 11.0 \pm 0.14$ **WMAP).**
  V.B., Ozernoy 1981, Gao, Toma, Meszaros 2011.

UHECR and COSMOGENIC NEUTRINOS BEFORE 2009

“ Damals bei uns daheim” (Hans Fallada)

COSMOGENIC NEUTRINOS
IN THE DIP MODEL FOR UHECR

V.B. and Grigorieva 1988; V.B., Gazizov, Grigorieva 2005 - 2006.

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

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

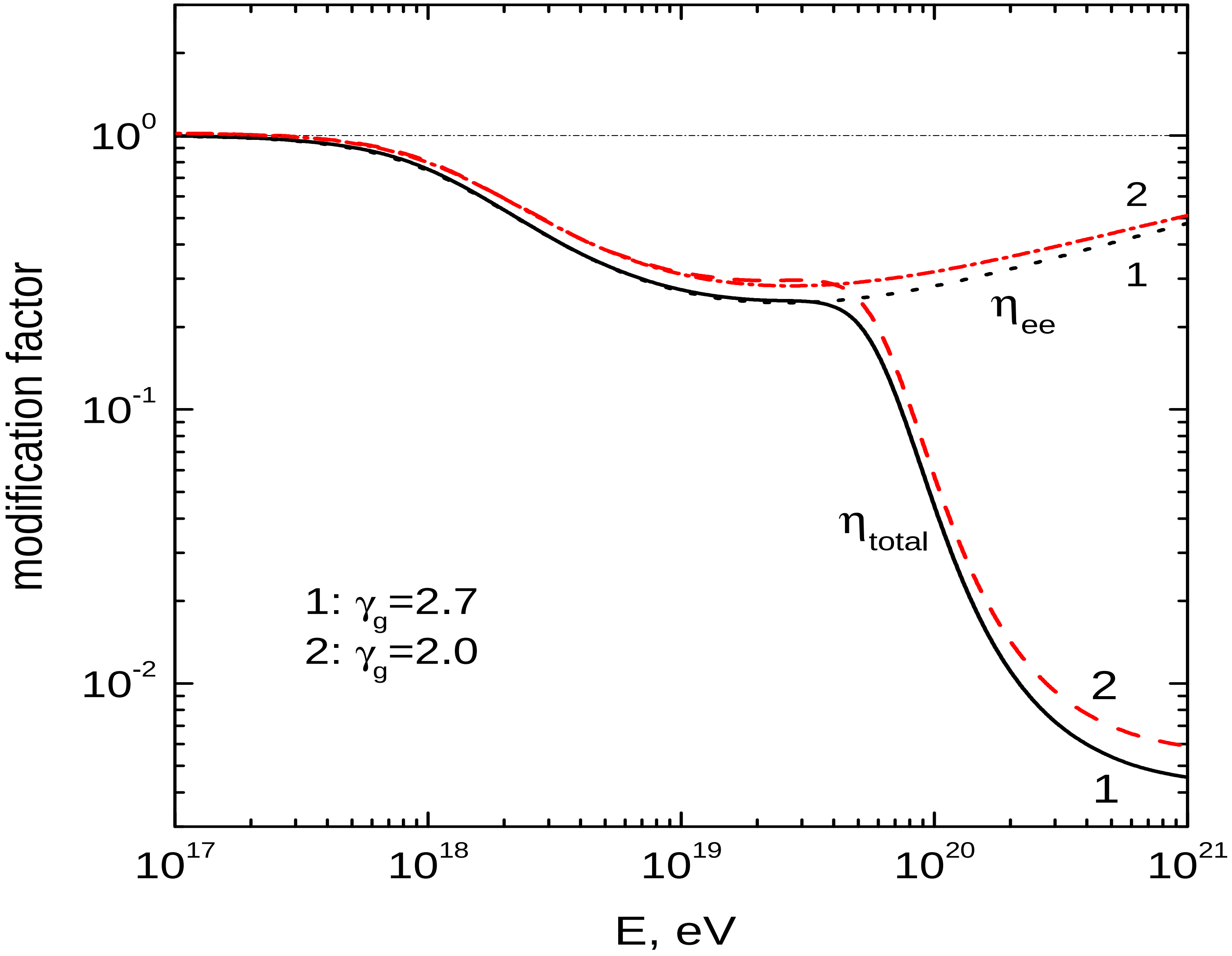
Calculated in the terms of **modification factor** $\eta(E)$ the dip is seen in all observational data.

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

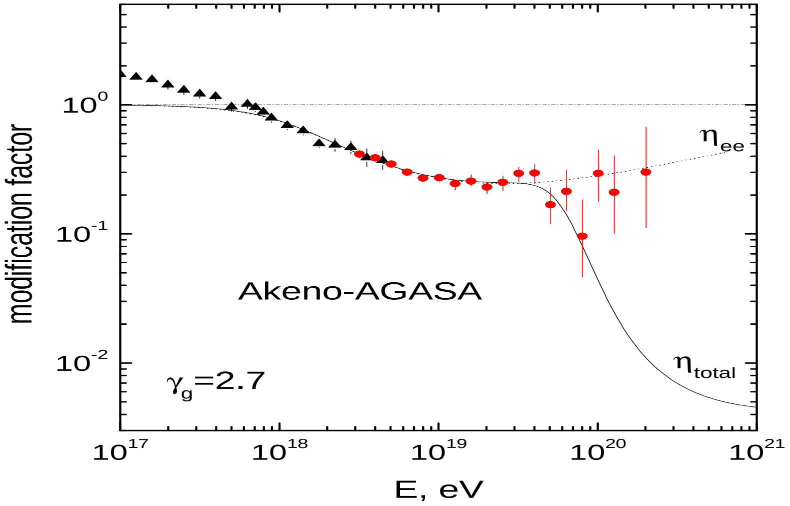
where $J_p^{\rm unm}(E) = KE^{-\gamma_g}$ includes only adiabatic energy losses (redshift),

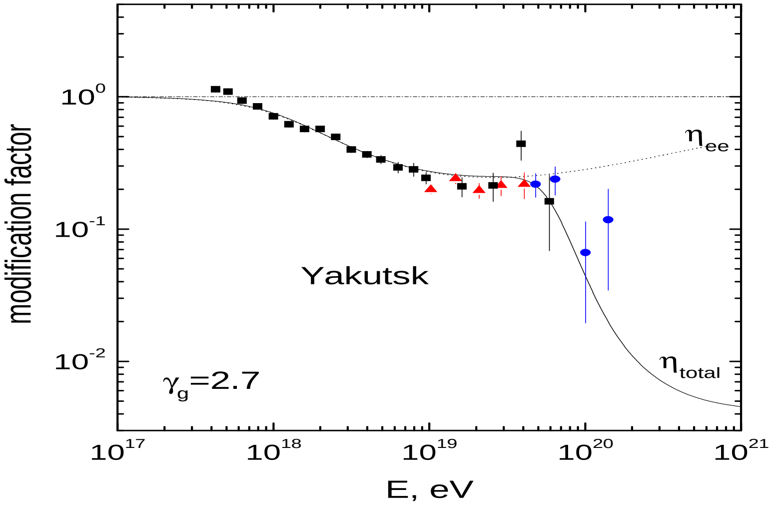
and $J_p(E)$ all energy losses.

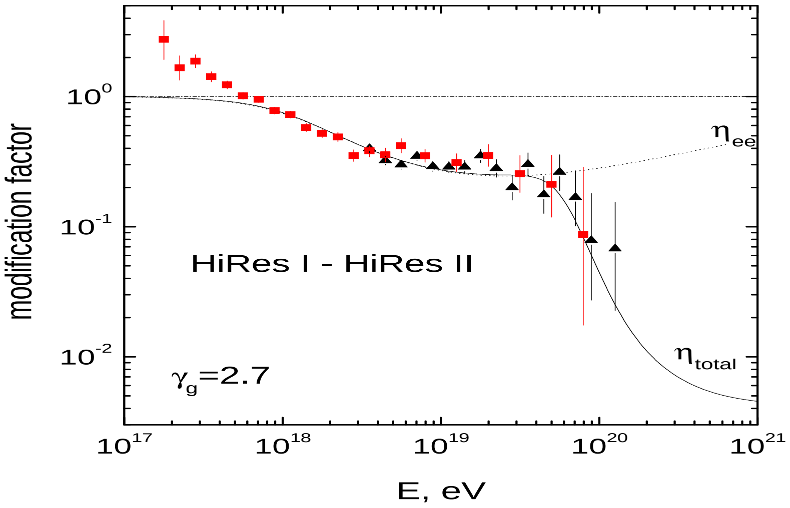
DIP AND GZK CUTOFF IN TERMS OF MODIFICATION FACTOR

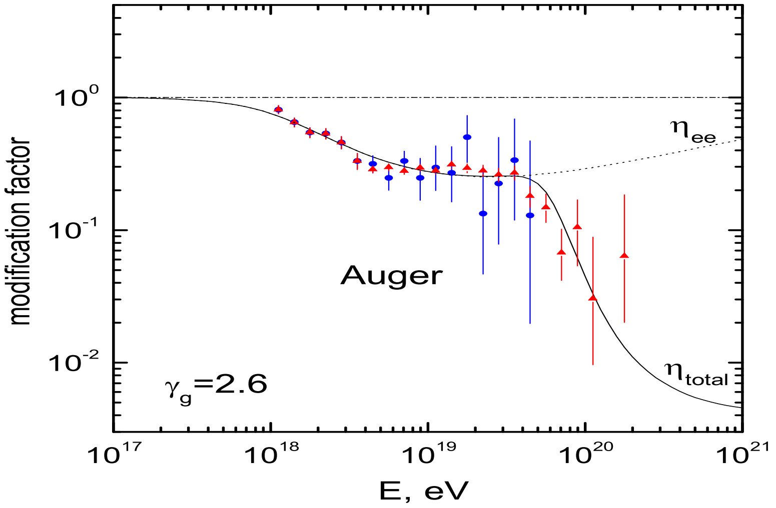


COMPARISON OF DIP WITH OBSERVATIONS OF 2007.

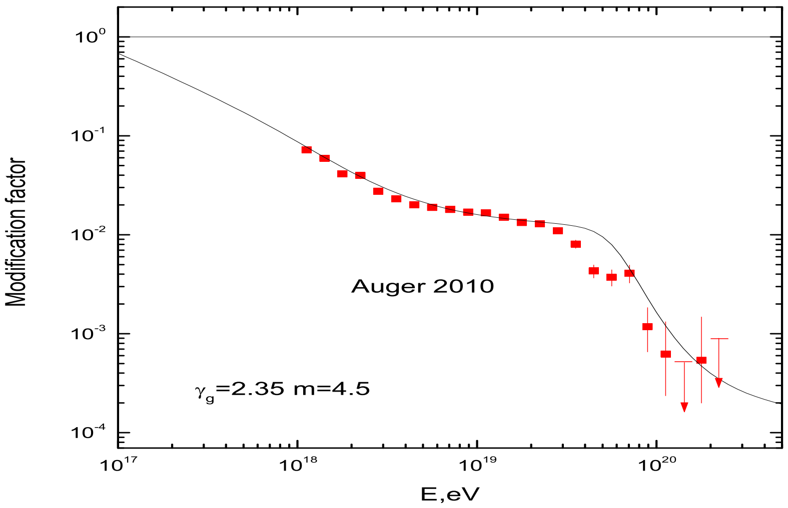


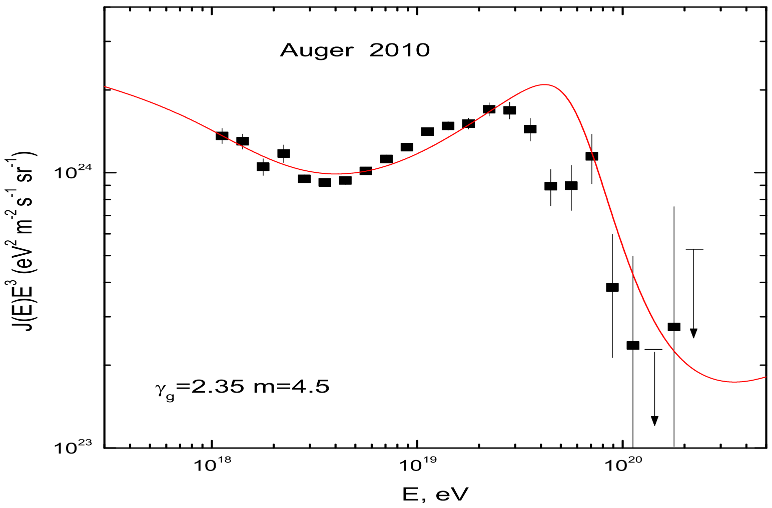


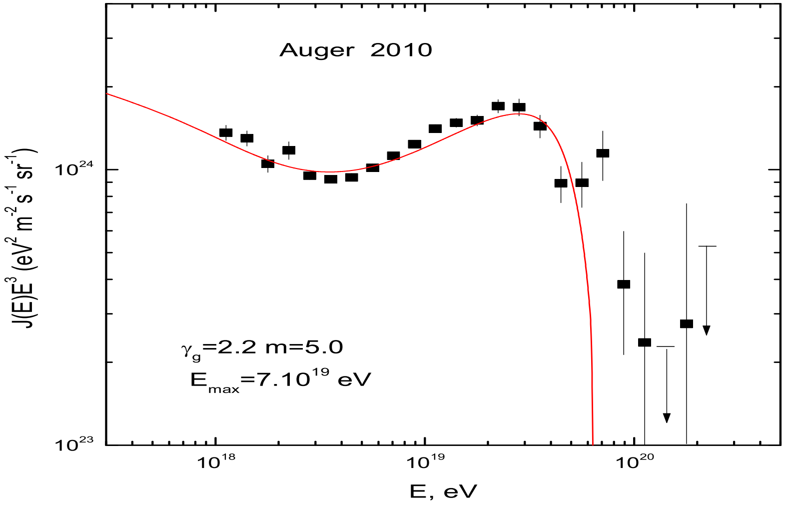


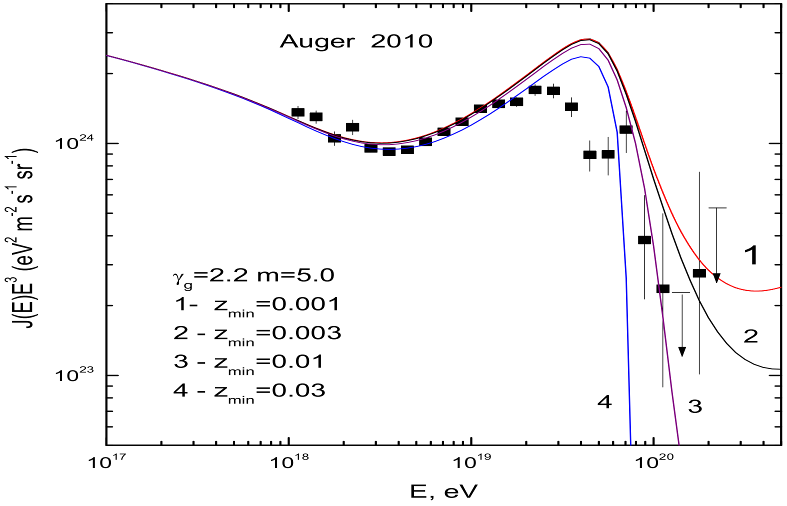


AUGER DATA 2010









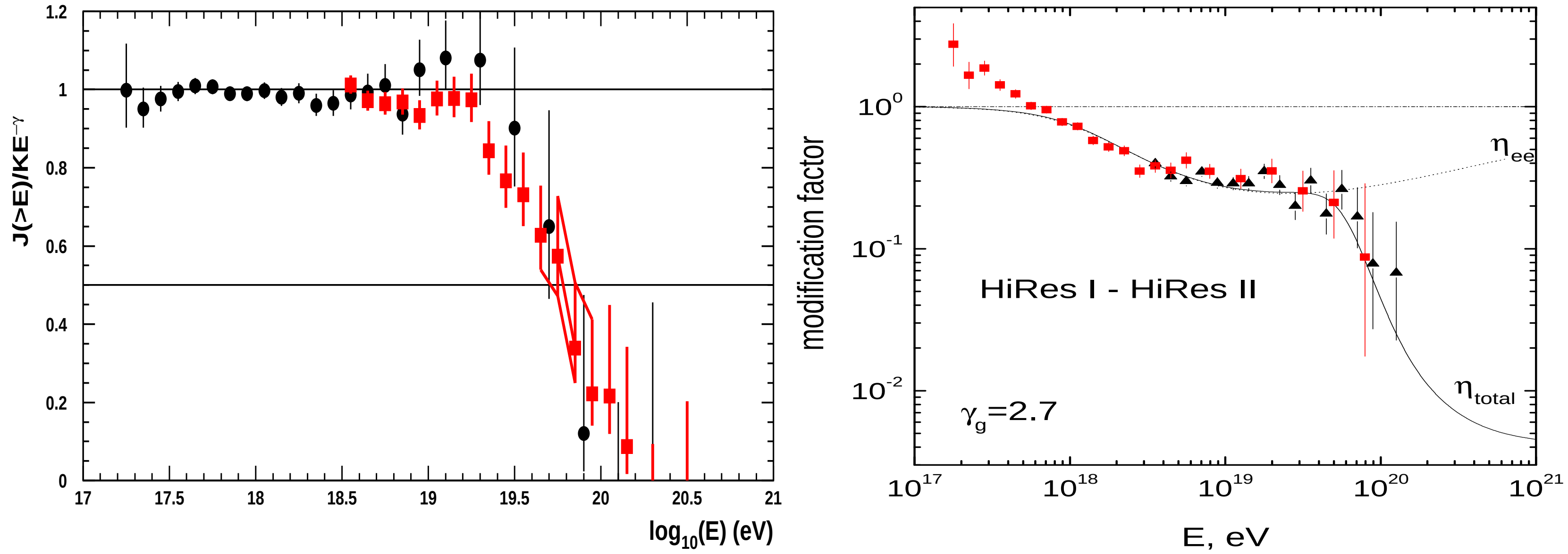
GZK CUTOFF IN HiRes DATA

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

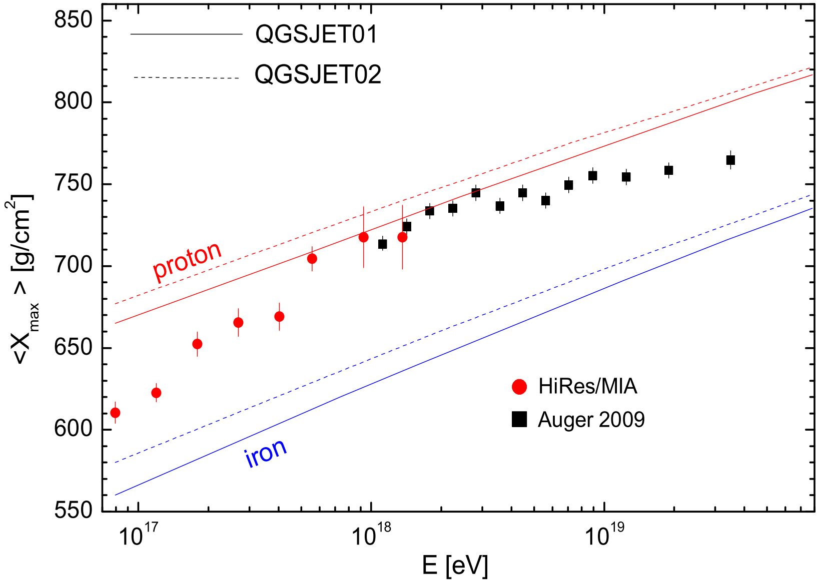
$$\mathrm{E}_{\mathbf{1/2}} = \mathbf{10^{19.72}}\ \mathrm{eV}$$

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

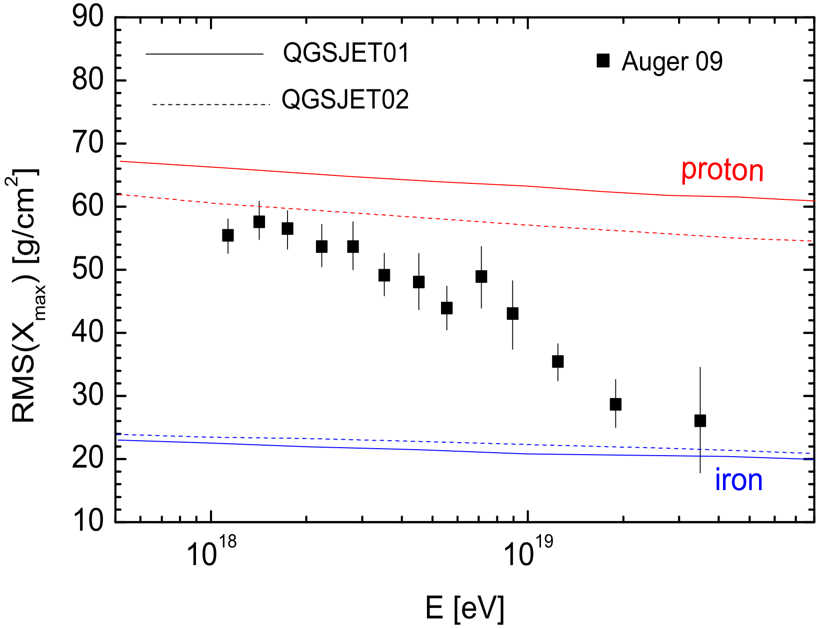
$$\mathrm{E}_{\mathbf{1/2}} = \mathbf{10^{19.73 \pm 0.07}}\ \mathrm{eV}$$



Auger mass composition

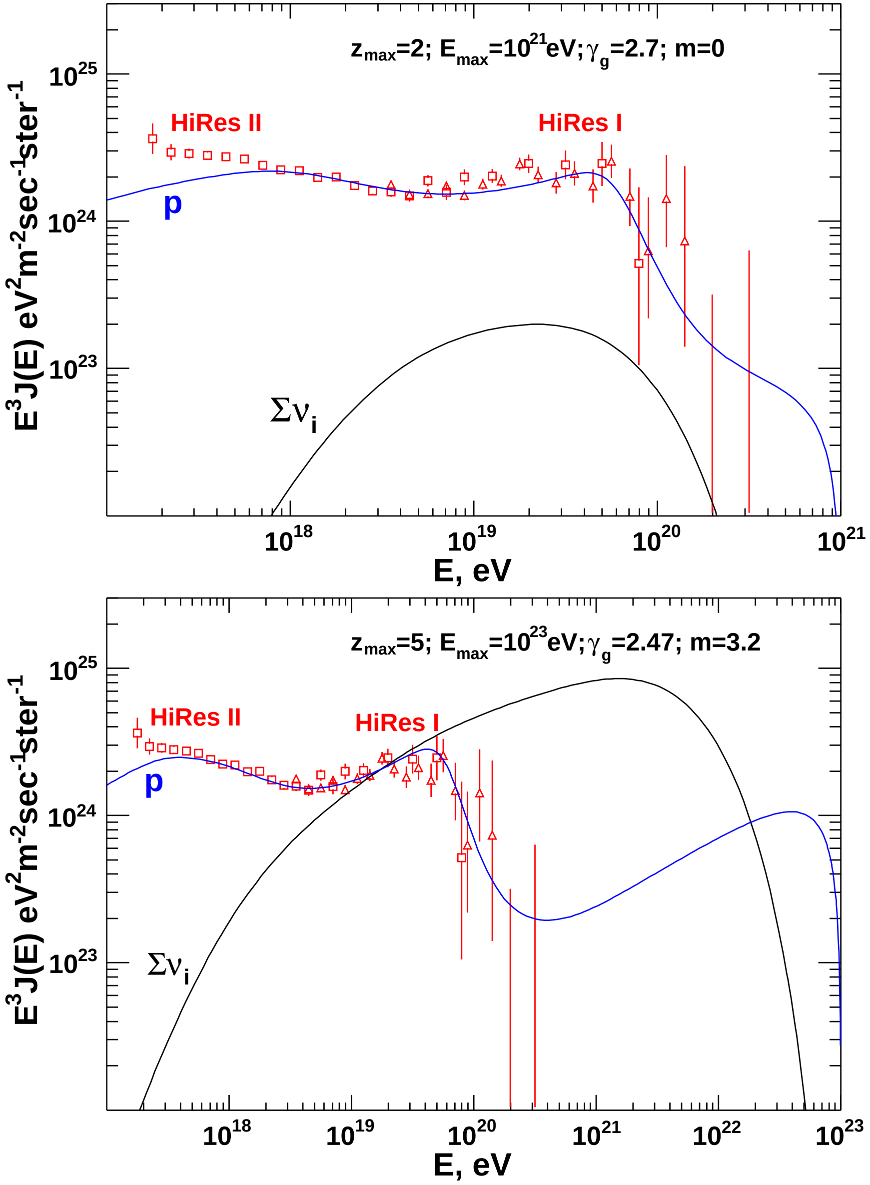


$X_{\max}$ as function of energy

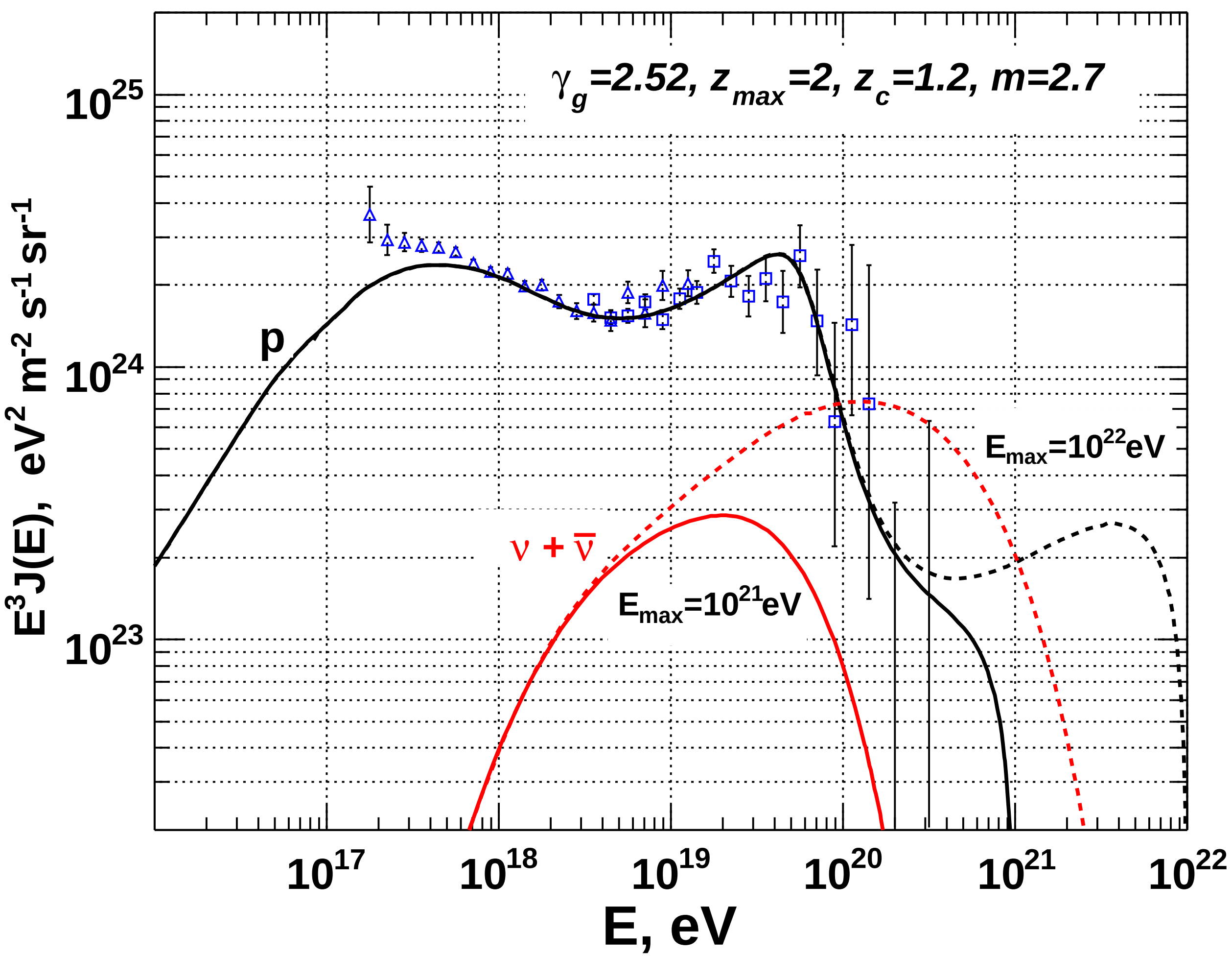


RMS as function of energy.

COSMOGENIC NEUTRINO FLUXES IN THE DIP MODEL

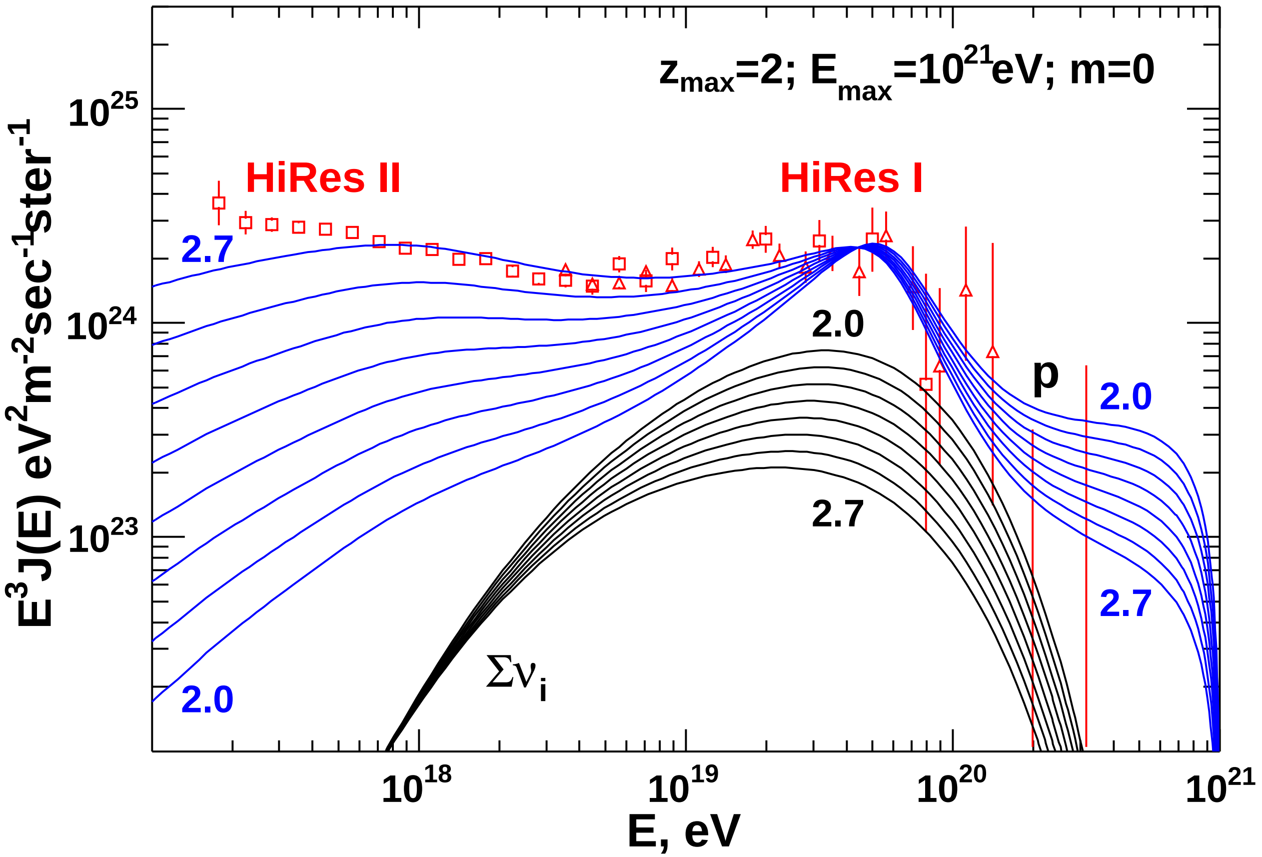


COSMOGENIC NEUTRINO FLUXES FROM AGN



LOWER LIMIT ON NEUTRINO FLUXES IN THE PROTON MODELS

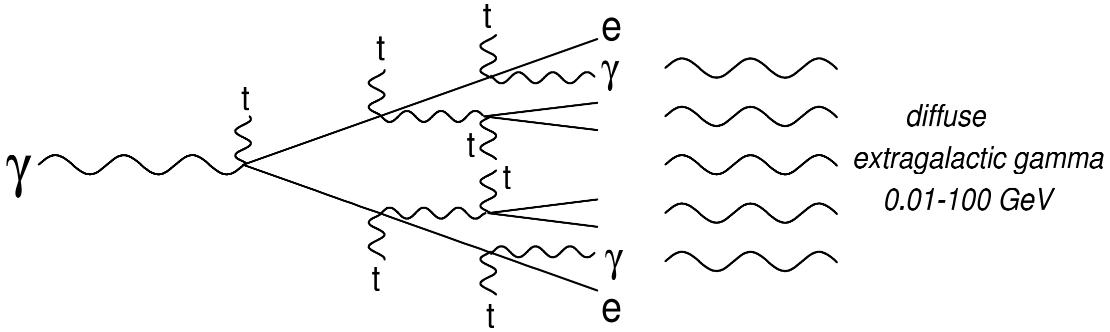
V.B. and A. Gazizov 2009



CASCADE UPPER LIMIT

V.B. and A.Smirnov 1975

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



Spectrum of cascade photons

$$J_\gamma^{\rm cas}(E) = \begin{cases} K(E/\varepsilon_X)^{-3/2} & \text{for} \quad E \le \varepsilon_X\,, \\ K(E/\varepsilon_X)^{-2} & \text{for} \quad \varepsilon_X \le E \le \varepsilon_a\,, \end{cases} \tag{1}$$

with a steepening at $E > \varepsilon_a$, and $\varepsilon_X = 1/3\,(\varepsilon_a/m_e)^2\,\varepsilon_{\rm cmb}$.

EGRET: agreement with spectrum (1) and $\omega_\gamma^{\rm obs} \sim 3 \times 10^{-6}{\rm eV/cm^3}$.

UPPER LIMIT ON NEUTRINO FLUX

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

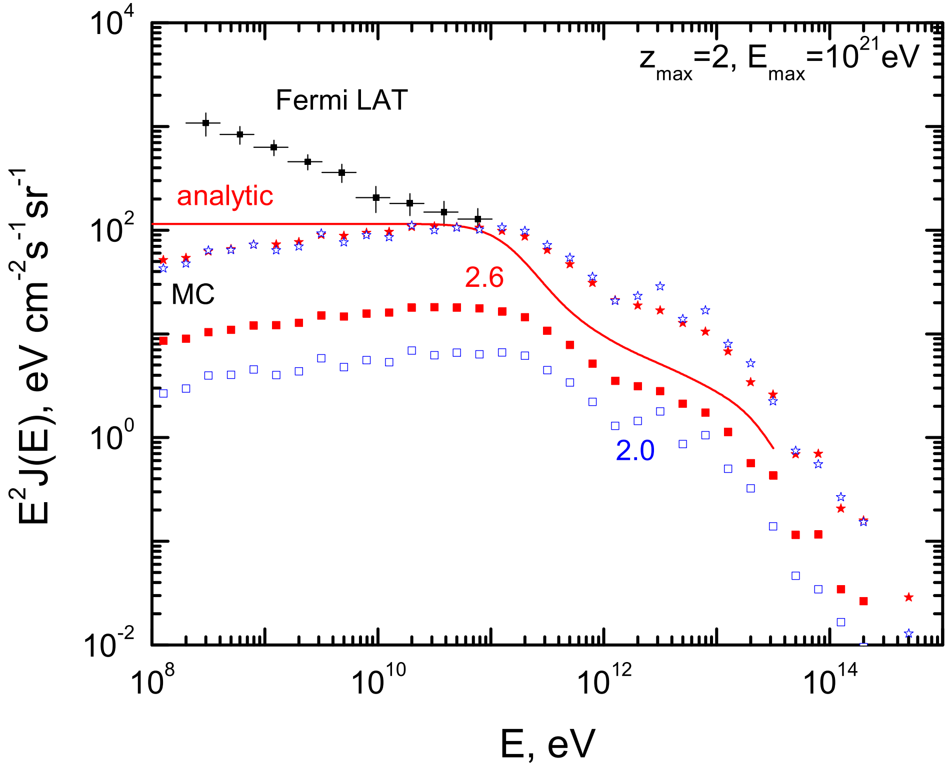
$$E^2 I_\nu(E) < \frac{c}{4\pi}\omega_{\rm cas.}$$

E^{-2}- generation spectrum:

$$E^2 J_\nu(E) < \frac{c}{4\pi}\frac{\omega_{\rm cas}}{\ln E_{\rm max}/E_{\rm min}}.$$

CASCADE UPPER LIMIT FROM FERMI LAT

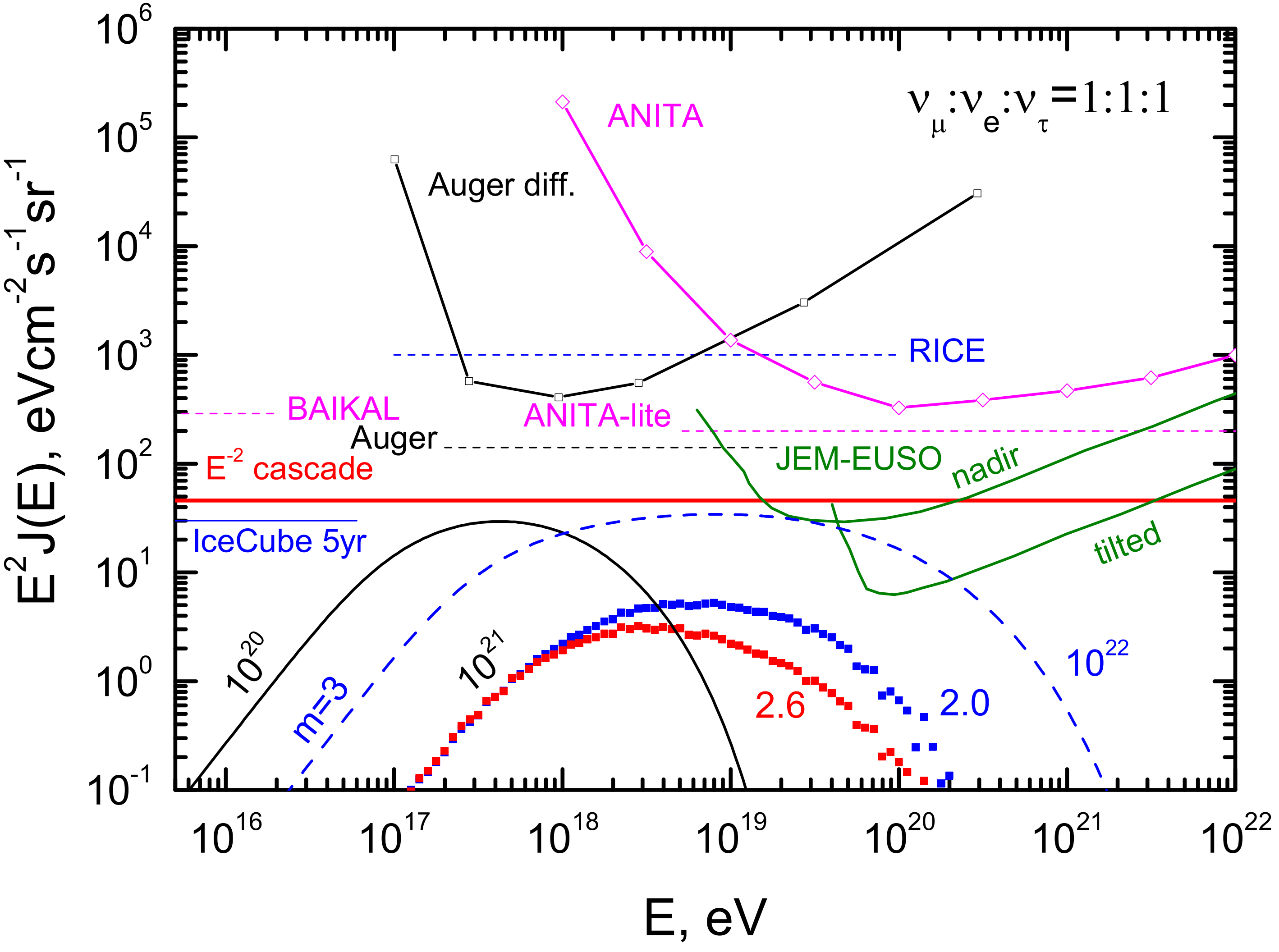
V.B., Gazizov, Kachelriess, Ostapchenko Phys. Lett. B 695 (2011) 13.
Ahlers, Anchordoqui, Gonzales-Garcia, Halzen, Sarkar Astrop. Phys. 34 (2010) 106.



$$\omega_{\rm cas}^{\rm max} = 5.8 \times 10^{-7}\ {\rm eVcm}^{-3}$$

OBSERVATIONAL AND THEORETICAL UPPER LIMITS

V.B., Gazizov, Kachelriess, Ostapchenko 2010.



BRIGHT PHASE

Burst of first massive star formation at $z_b \sim 20$

Partridge and Peebles 1967, M. Rees (Pop III stars) 1976.

Burst of CR and neutrino production, VB, Ozernoy 1981:
At $z_b \sim 20$ CRs are accelerated in massive SN from Pop III stars. Cosmogenic neutrinos from $p\gamma_{cmb}$.
HE proton space density at $z = 0$:

$$n_p(E) = \frac{\omega_p(z_b)}{(1+z_b)^4} \frac{1}{\ln E_{\rm max}/E_{\rm min}} E^{-2}, \qquad E_\nu \approx \frac{1}{20} E_p$$

HE neutrino space density at $z = 0$:

$$n_\nu(E) = 0.1 \frac{\omega_p(z_b)}{(1+z_b)^4} \frac{1}{\ln E_{\rm max}/E_{\rm min}} E^{-2}, \qquad E^2 J_\nu(E) = \frac{c}{4\pi} n_\nu(E)$$

Detectability by IceCube $E^2 J_\nu(E) = 3 \times 10^{-9}$ GeV/cm^{2}s sr, provided by $\omega_p(z_b)$, is within capability of Pop III stars.

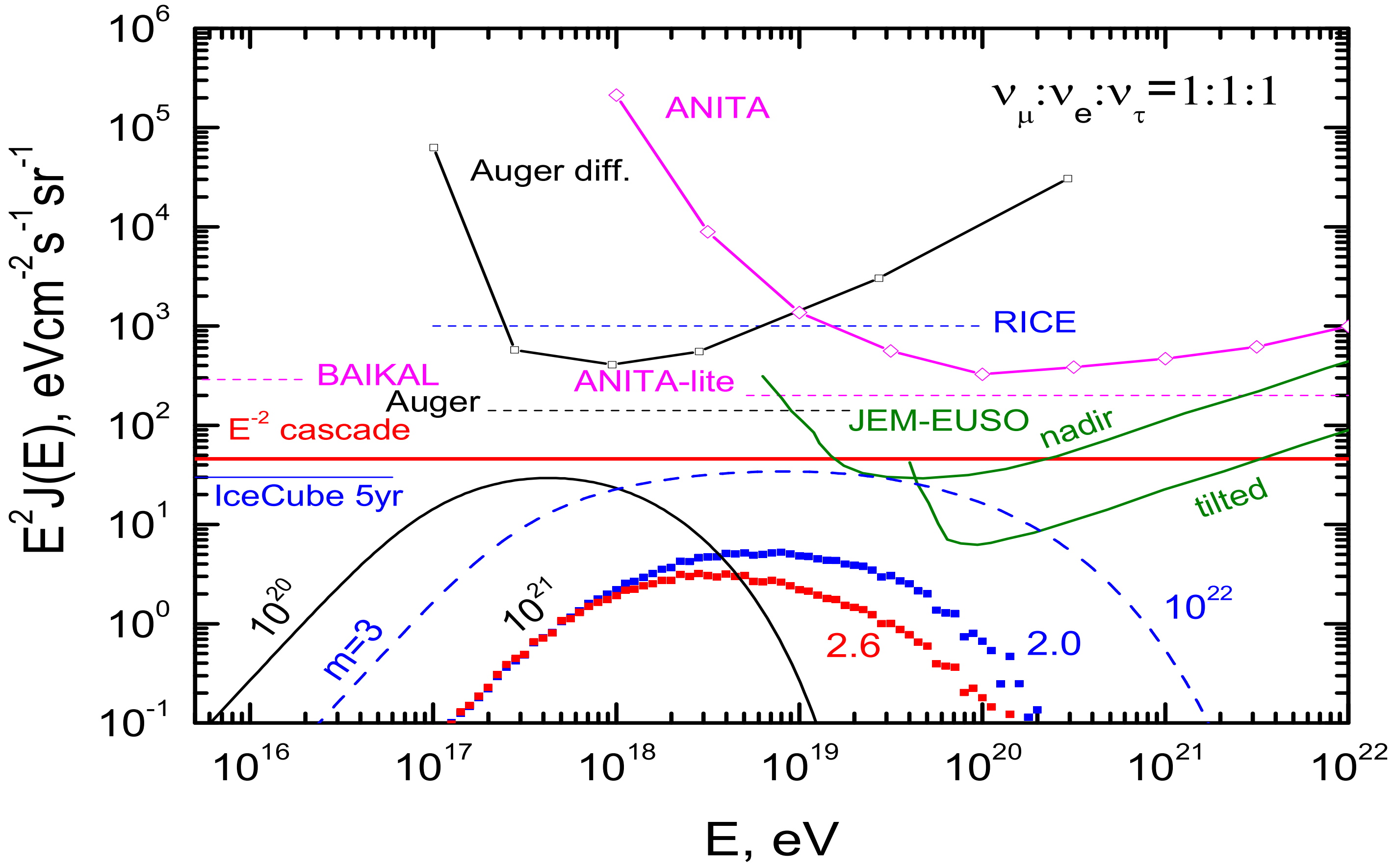
Maximum flux is at $E_\nu \sim 0.05\, E_{\rm GZK}/(1+z_b)^2 \sim 5 \times 10^{15}$ eV.

Maximum energy $E_{\rm max} \approx 0.05\, E_p^{\rm max}\, /(1+z_b) \approx 2.5 \times 10^{18}$ eV.

GRBs from Pop III stars

Gao, Toma, Meszaros 2011

- Collapsed stars produce relativistic jets.
- Protons are accelerated at forward shock with E^{-2} spectrum.
- Neutrinos are produced in $p\gamma$ collisions with GRB photons.
- Both individual GRBs and diffuse neutrinos may be detectable by IceCube.



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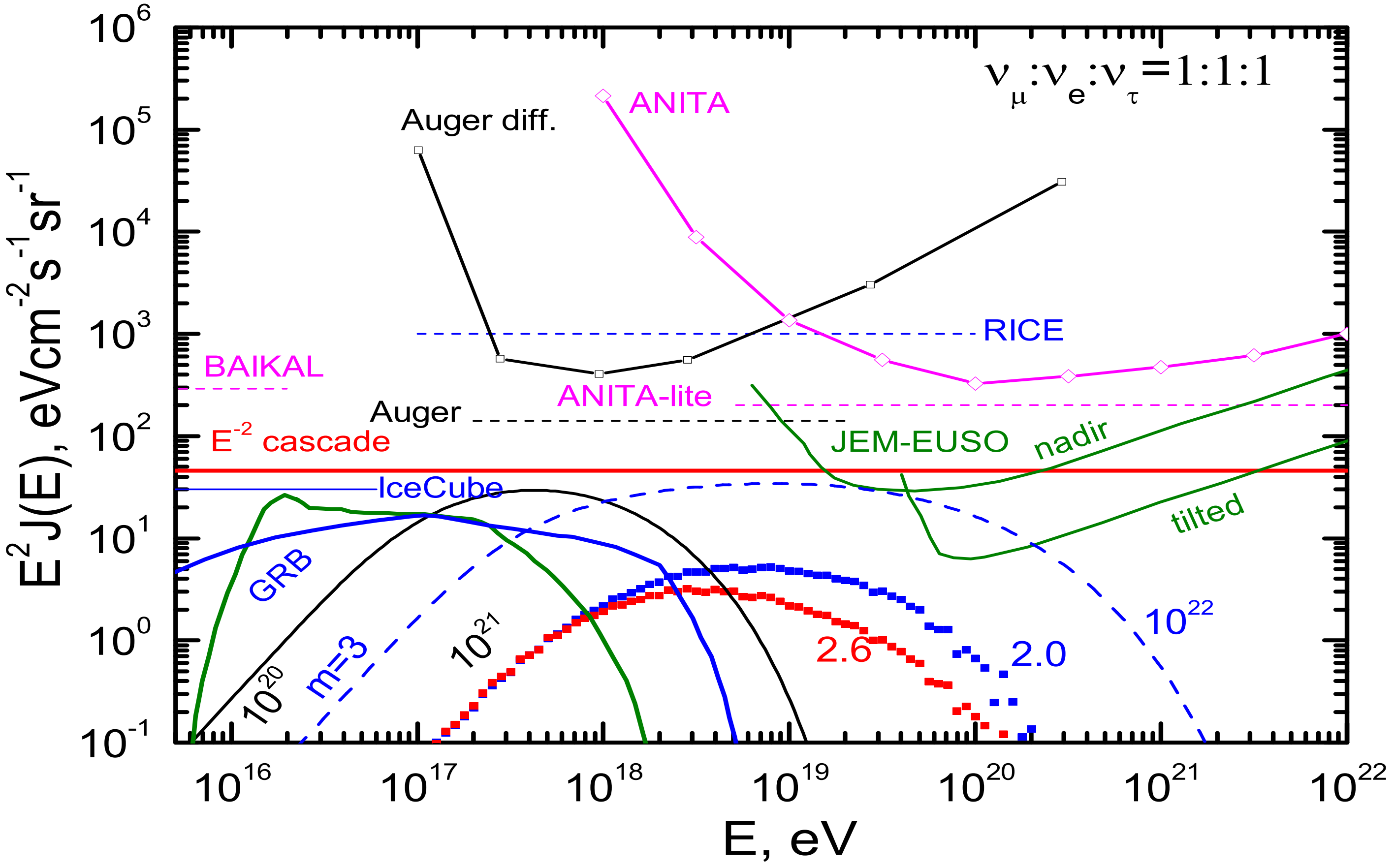
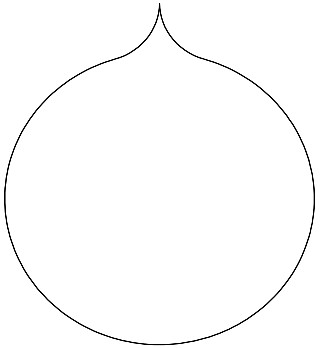


TOPOLOGICAL DEFECTS

Symmetry breaking in early universe results in phase transitions (D.A. Kirzhnitz 1972), accompanied by TDs. Their common feature is production of HE particles.

Ordinary and superconducting strings



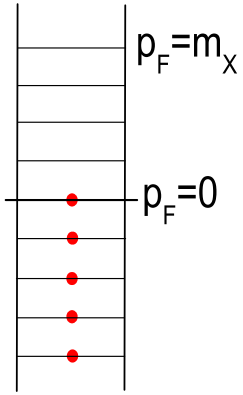
Produced at $U(1)$ symmetry breaking.
Particles are massless inside the string.
η is symmetry breaking scale, e.g. 10^9 GeV, and $\mu \sim \eta^2$ is tension.
Loop oscillates with periodically produced cusp ($v = c$) and with large Lorentz factors, e.g. above 10^{10}, at nearby points.
Particles escaping from cusp segment have energy $E \sim \Gamma m_X$, which can exceed the Planck scale.

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

$\frac{dp}{dt} = e\mathcal{E}, \quad p_F = e\mathcal{E}t \sim m_X$ (exit)

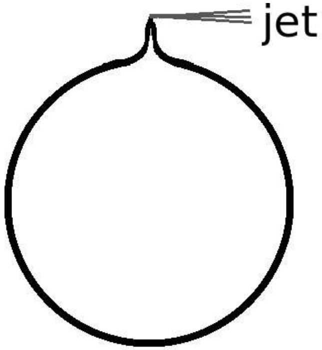
$n_X = \frac{p_F}{2\pi}, \quad \frac{dJ}{dt} = e^2\mathcal{E}$ (superconductivity)

If a string moves through magnetic field the electric current is induced $J \sim e^2 vBt$



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 $\gamma_c \sim 1 \times 10^{12} i_c \eta_{10}^{-1} B_{\mu G}^{-1}$, $\mathbf{i_c} \lesssim 1.$
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 :

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

UHE neutrino flux is generated at $z \lesssim 4 - 5$.
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.**

UHE NEUTRINOS FROM ORDINARY STRINGS.

1. Ordinary strings with EW Higgs condensate. Vachaspati, PRD 81(2010)043531

Interaction of EW Higgs ϕ with the string field Φ (κ is coupling constant):

$$S_{\rm int} = \kappa \int d^4x(\Phi^+\Phi - \eta^2)\phi^+\phi$$

After GUT symmetry breaking ($< \Phi >= \eta$):

$$S_{\rm int} = -\kappa\eta \int d^2\sigma\sqrt{-\gamma}\ \phi,$$

where $d^2\sigma$ is string world-sheet space, γ_{ab} is the world-sheet metric.
The higgses are emitted through the cusp.

1. UHE neutrinos emitted from ordinary strings via dilatons and moduli.

VB, Sabancilar, Vilenkin, in preparation, following Damour and Vilenkin 1997.

$$S_{\rm int} = (\sqrt{4\pi}\alpha/M_{\rm Pl}) \int d^4x\ \phi\ T^{\nu}_{\nu},$$

$$T^{\nu}_{\nu}(x) = -2\eta^2 \int d^2\sigma\sqrt{-\gamma}\ \delta^4(x^\alpha - x^\alpha(\sigma))$$

is the trace of energy-momentum tensor of string.
Dilatons and moduli are produced as radiation quanta from the cusp.
In terms of the Fourier momenta k : $dN(k) = \alpha^2 G\eta^4\ell^{2/3}k^{-7/3}dk.$

CONCLUSIONS

- **Predicted fluxes of diffuse cosmogenic neutrinos strongly depend on the mass composition of UHECR measured by HiRes and Auger detectors. According to Auger data mass composition becomes steadily heavier with increasing energy, which dramatically decreases the predicted neutrino flux.**

- **HiRes data are compatible with pure proton composition and with large fluxes of cosmogenic neutrinos. However, these fluxes are strongly bounded by the cascade upper limit with the new extragalactic gamma-ray background radiation measured by Fermi-LAT. With this upper limit detectability of neutrino flux depends on maximum acceleration energy $E_{\rm max}$. Acceleration to $E_p^{\rm max} \sim 1 \times 10^{22}$ eV is a problem in astrophysics. With this $E_p^{\rm max}$ cosmogenic neutrinos can be detected only marginally by JEM-EUSO in the extreme models.**

- **IceCube detector also can detect only marginally cosmogenic fluxes in case of extreme models with strong cosmological evolution and soft spectra (large $E_{\rm max}$ is not needed). However, IceCube can detect cosmogenic neutrinos and diffuse flux of GRBs neutrinos from the bright phase. These fluxes are limited weaker by the cascade upper bound.**

- **IceCube is the first detector which crossed the cascade upper bound and entered the physically allowed domain of cosmogenic neutrino fluxes.**

- **In the light of new stronger limit on diffuse flux of cosmogenic neutrinos search for the sources becomes the priority goal of neutrino astronomy and JEM-EUSO and IceCube detectors. This task is viable even if protons constitute a small part of primary radiation. Discovery of HE neutrino radiation from SNR (in case of IceCube) will give the final proof of GCR SM, from AGN and GRB - proof of UHECR sources.**

- **There is an impressive progress in theoretical study of TDs as UHE neutrino sources: The ordinary cosmic strings, which are the simplest TDs, can produce the large fluxes with extremely high $E_{\max}$. This prediction directly follows from fundamental properties of the strings: existence of cusp, gravitational interaction of intermediate particles (higgses, dilatons, moduli) with the string field Φ and basic string parameter $\eta^2 = \mu$, satisfying $G\mu \gtrsim 10^{-20}$, while observational limits are $G\mu \lesssim 10^{-6}$.**