UHECR and NEUTRINOS: where are cosmogenic neutrinos ?

V. Berezinsky

INFN: GSSI and LNGS, Italy

UHE NEUTRINOS: PANORAMA

- **Cosmogenic neutrinos** *(produced by protons):* $p + \gamma_{\rm cmb} \to \pi^{\pm} + {\rm all}$
- **Resonant neutrinos** $\bar{\nu}_e + e \to W^- \to$ *hadrons: V.B, Gazizov 1977*
  $E_0 = m_W^2/2m_e = 6.3 \cdot 10^6$ *GeV,* $\nu_{\rm res} = 2\pi N_e \sigma_{\rm eff} I_{\bar{\nu}}(E_0)$
  (Breit-Wigner resonance) $\sigma_{\rm eff} = (3\pi/2)G_F = 3.0 \cdot 10^{-32}$ *cm*^{2}*.*
- **HE neutrinos from reionization epoch** *(*$z \sim 10$ *WMAP) V.B., Blasi 2011.*
- **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,
  Hidden jets: Razzaque, Smirnov 2010
- **Hidden Top-Down sources:**
  Annihilation of DM in the Earth and Sun,
  Mirror matter sources (oscillation of neutrinos)

UHECR and COSMOGENIC NEUTRINOS

UHE protons propagating through CMB produce cosmogenic neutrinos:

$$p + \gamma_{cmb} \rightarrow \pi^{\pm} + N$$

Spectral features of parent protons are:

pair-production dip and GZK cutoff

UHE nuclei are much less effective: $E_N = E_A/A$.

COSMOGENIC NEUTRINOS

$$p + \gamma_{CMB} \rightarrow \pi^{\pm} \rightarrow neutrinos$$

$$J_\nu(E) = \frac{2}{3} 3 \left(\frac{E_\nu}{E_p}\right)^{\gamma_g - 1} \frac{1}{1 - \alpha^{\gamma_g - 1}} \quad J_p^{unm}(E)$$

$$\frac{E_\nu}{E_p} \approx \frac{0.2}{4} = 0.05$$

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COSMIC RAYS AT ULTRA HIGH ENERGIES (NEUTRINO?)

V. S. BERESINSKY and G. T. ZATSEPIN

Academy of Sciences of the USSR. Physical Institute. Moscow

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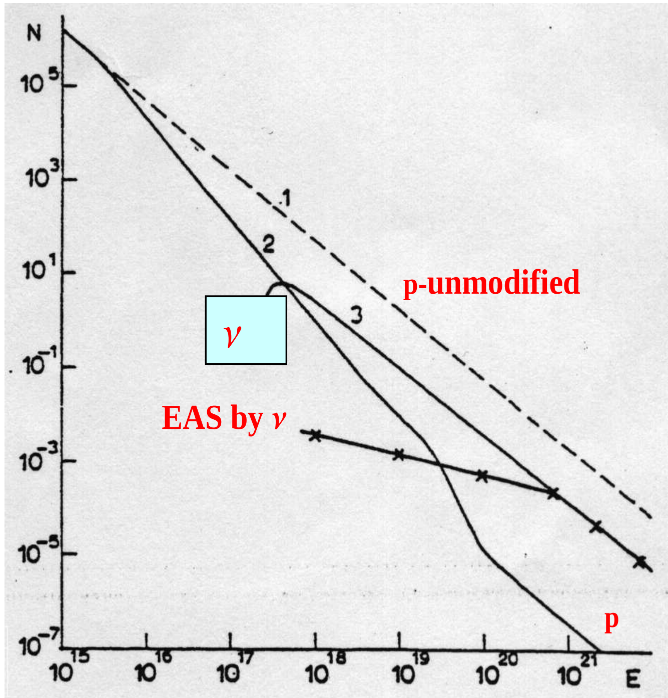
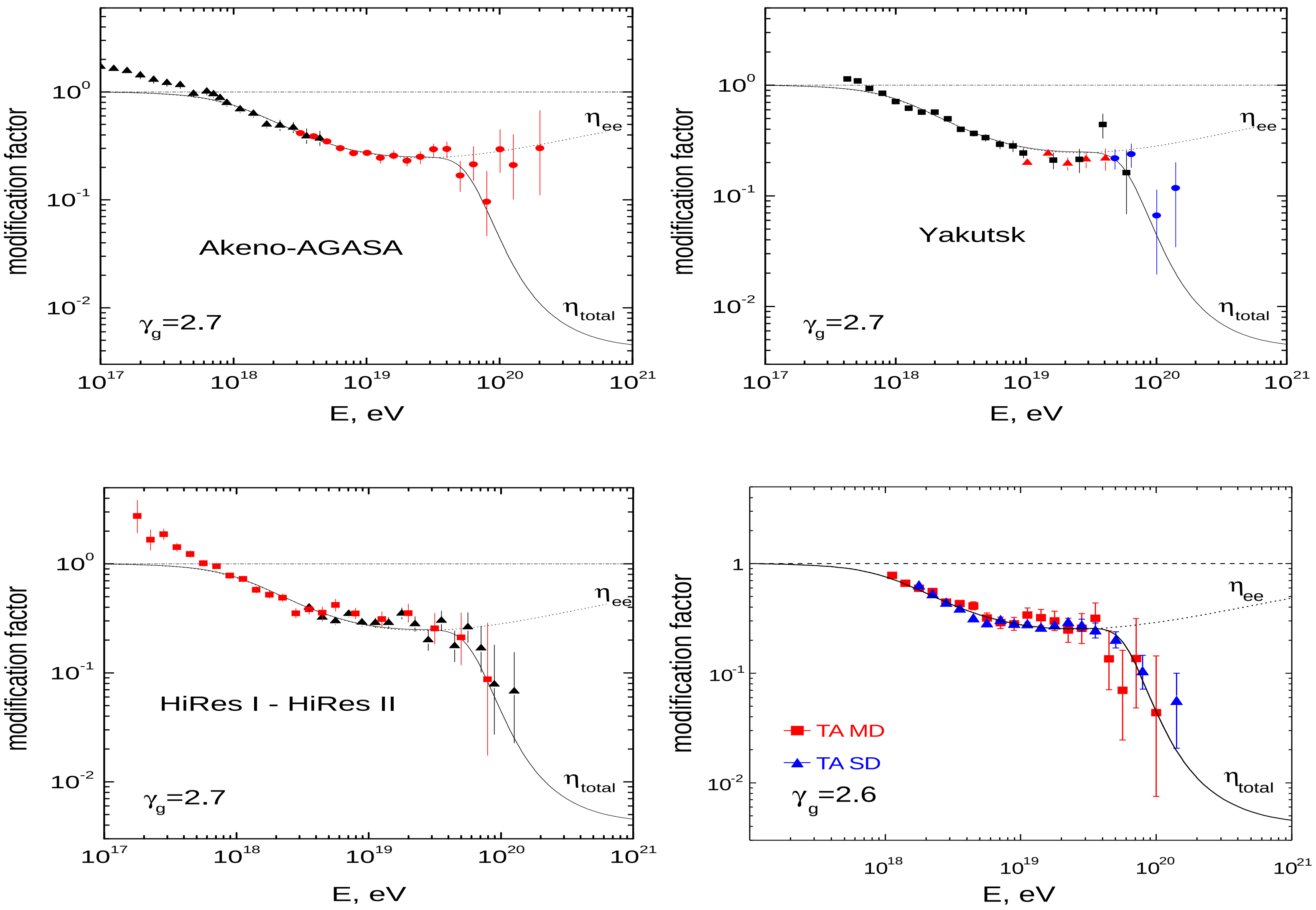
The neutrino spectrum produced by protons on microwave photons is calculated. A spectrum of extensive air shower primaries can have no cut-off at an energy E> 3 x 10^{19} eV. If the neutrino-nucleon total cross-section rises up to the geometrical one of a nucleon.

Greisen [1] and then Zatsepin and Kusmin [2] have predicted a rapid cut-off in the energy spectrum of cosmic ray protons near E~3x10^{19} eV because of pion production on 2.7° black body radiation. Detailed calculations of the spectrum were made by Hillas [3]. Recently there were observed [4] three extremely energetic extensive air showers with an energy of primary particles exceeding 5 x 10^{19} eV. The flux of these particles turned out of be 10 times greater than according to Hillas' calculations.

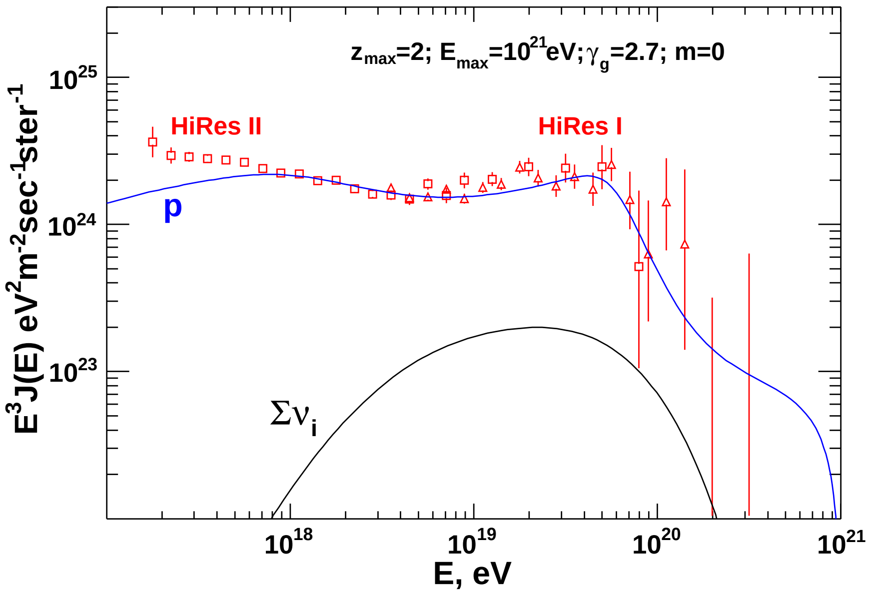
In the light of this it seems to be of some interest to consider the possibilities of absence of rapid (or any) fall in the energy spectrum of shower producing particles. A hypothetic possibility we shall discuss* consists of neutrinos being the shower producing particles at *E* > 3 x 10^{19} eV due to which the energy spectrum of shower producing particles cannot only have any fall but even some flattening.

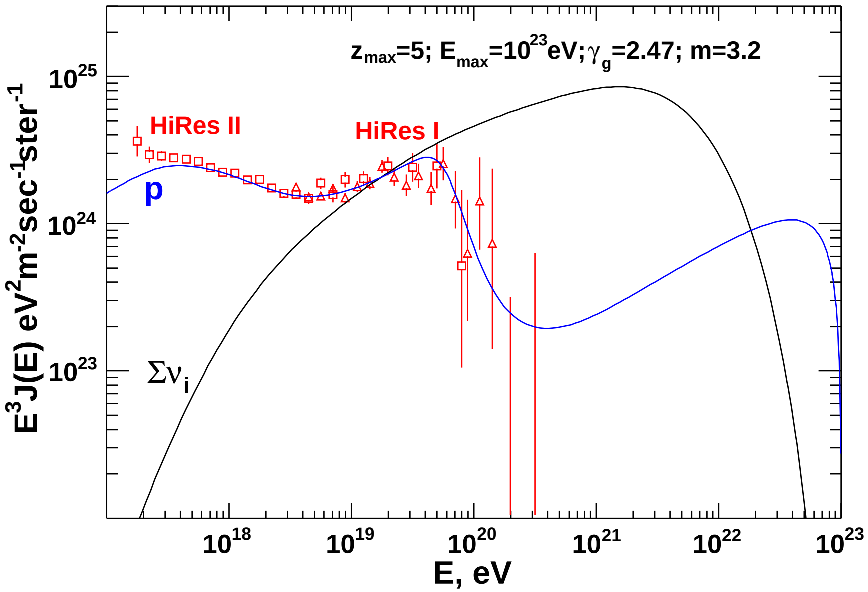


PAIR-PRODUCTION DIP MODEL

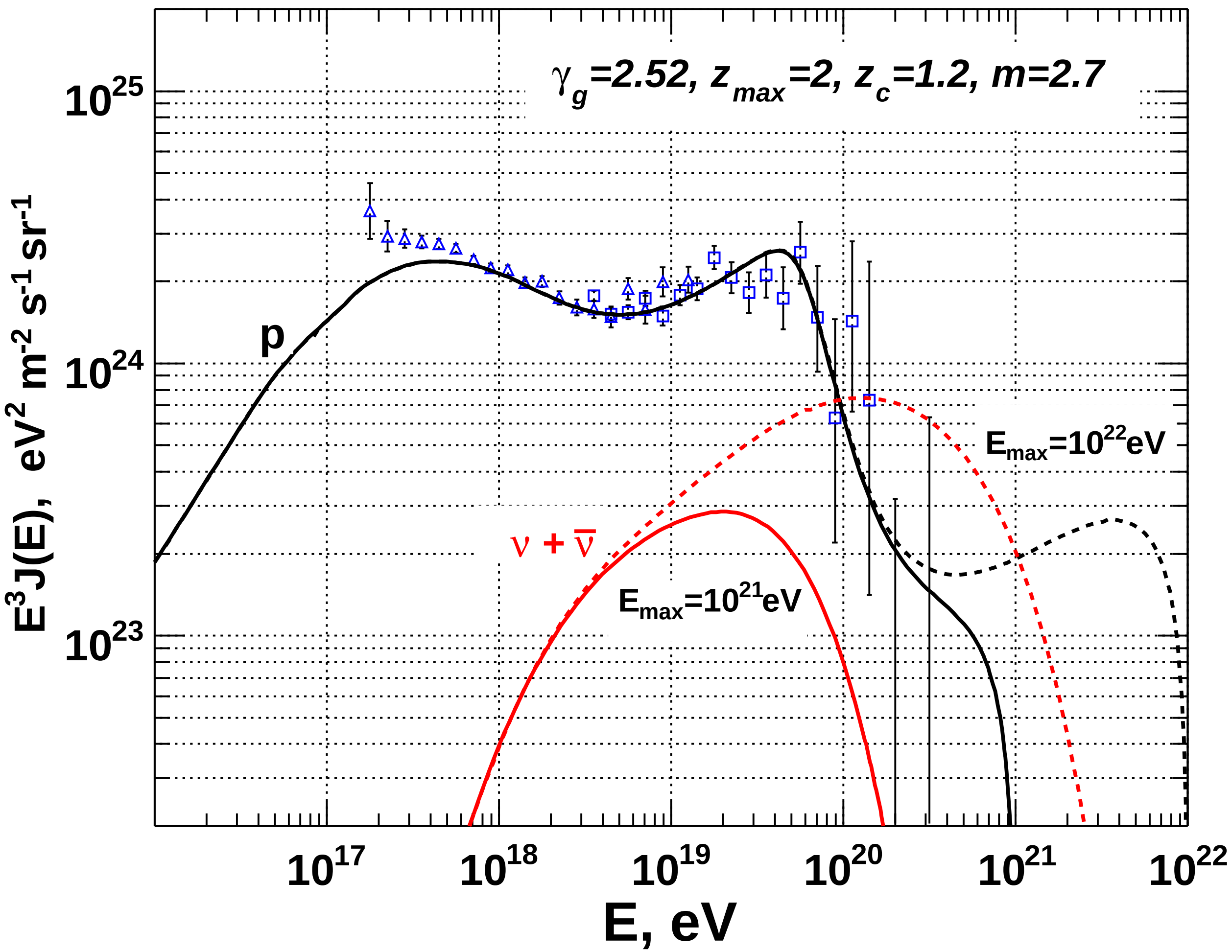


COSMOGENIC NEUTRINO FLUXES IN THE DIP MODEL



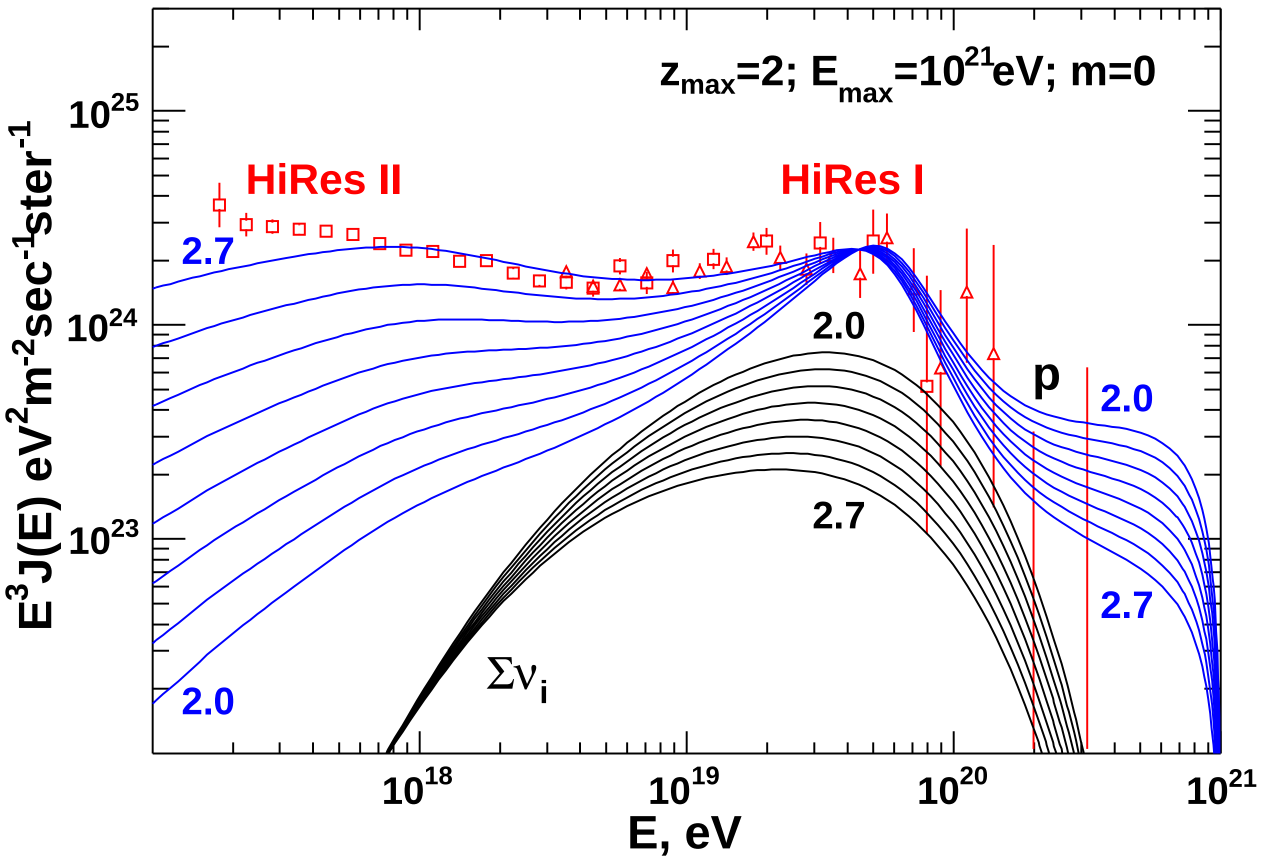


COSMOGENIC NEUTRINO FLUXES WITH AGN MODELS



LOWER LIMIT ON NEUTRINO FLUXES
IN THE PROTON MODELS

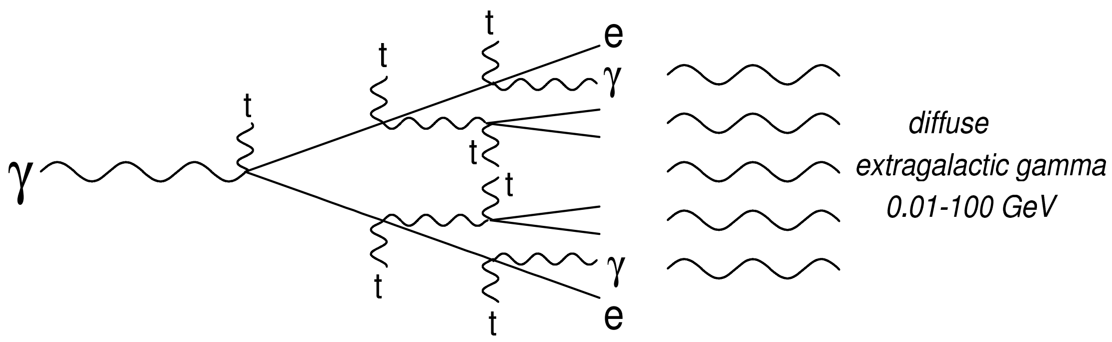
V.B. and A. Gazizov 2009



CASCADE UPPER LIMIT

V.B. and A.Smirnov 1975

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



Spectrum of cascade photons

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

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 $\omega_\gamma^{\rm obs} \sim 3 \times 10^{-6}$eV/cm^3 .
Fermi: V.B. Kalashev 2016, $m = 2.5$, $z_{\rm max} = 2$ $\omega_\gamma \lesssim 2 \cdot 10^{-7}$ eV/cm^3.

UPPER LIMIT ON NEUTRINO FLUX

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

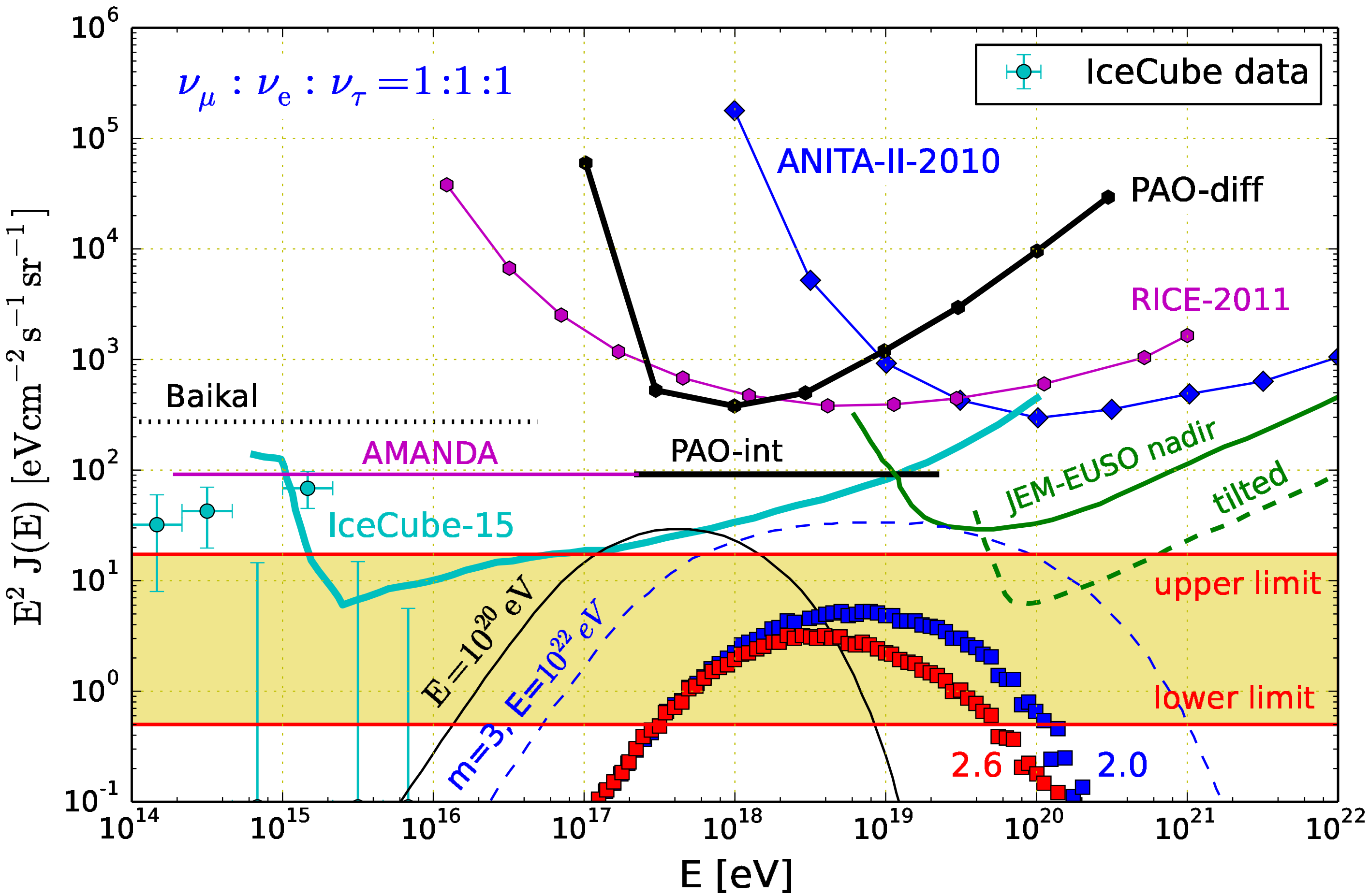
$$E^2 I_\nu(E) < \frac{c}{4\pi}\omega_{\rm cas.}$$

E^{-2}**- generation spectrum:**

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

OBSERVATIONAL AND THEORETICAL UPPER LIMITS

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



Reionization of Universe: Neutrino Bright Phase

Burst of first massive star formation

- Cooling of universe and recombination at $T_{\rm dec} \sim 3600$ K, $z_{\rm dec} \sim 1100$.
- **DARK AGES:** Evolution of DM structures with neutral hydrogen.
- Formation of the first **Pop III**
  Properties: metal poor, massive ($M \geq 100 M_\odot$), hot ($\varepsilon \sim 30$ eV), short-lived, strong wind, finishing evolution by SN explosion with W_{SN} up to 10^{53} erg.
- **Reionization** by Pop III radiation and by Pop III SN, observed by WMAP.
  For model of **Instantaneous reionization** $z_{\rm reion} = 11.0 \pm 1.4$ (WMAP).

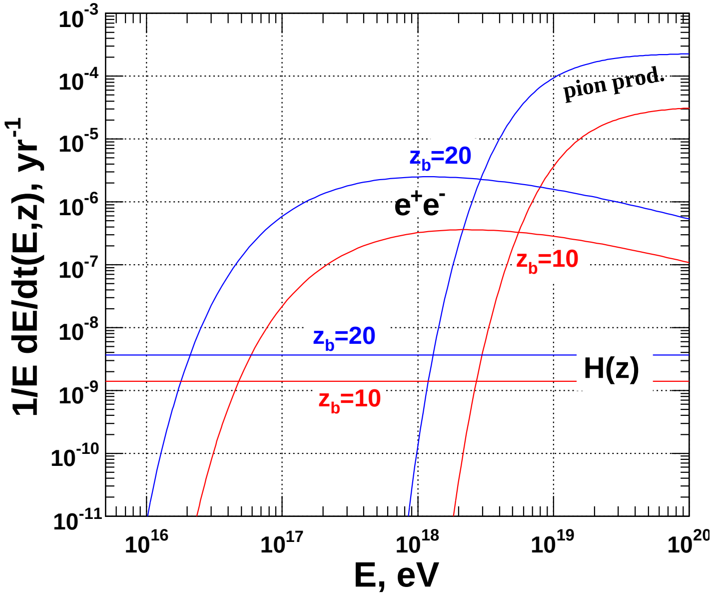
Pop III scenario fills several gaps:

- **Produce metals** needed for evolution of normal stars.
- Produce **reionization.**
- Produce **magnetic fields** in Universe.

UHE NEUTRINOS from REIONIZATION EPOCH

V.B., Blasi 2011.

At $z_b \sim 10 - 20$ CRs (mostly protons) are accelerated in Pop III SN.
Cosmogenic neutrinos are produced in $p\gamma_{\rm cmb}$.



Energy losses of protons at z_b.

Neutrino flux has a maximum at:

$$E_\nu \sim 0.05 \frac{E_{\rm GZK}}{(1+z_b)^2} \approx 7.5 \times 10^{15} \text{ eV},$$

$$E_\nu^{\max} \sim 0.05 \frac{E_p^{\max}}{(1+z_b)} \approx 2.5 \times 10^{17} \text{ eV}.$$

$$E_\nu^2 J_\nu(E) = 0.1 \frac{c}{4\pi} \frac{\omega_{\mathbf{p}}(\mathbf{z_b})}{(\mathbf{1}+\mathbf{z_b})^{\mathbf{4}}} \frac{1}{\ln E_{\max}/E_{\min}}$$

LOW FLUXES OF COSMOGENIC NEUTRINOS

Two kinds of data lower the flux of **extragalactic protons**:

(i)

Last bin ($E \approx 0.7$ TeV) in isotropic gamma radiation strongly limits the flux of UHE extragalactic protons.

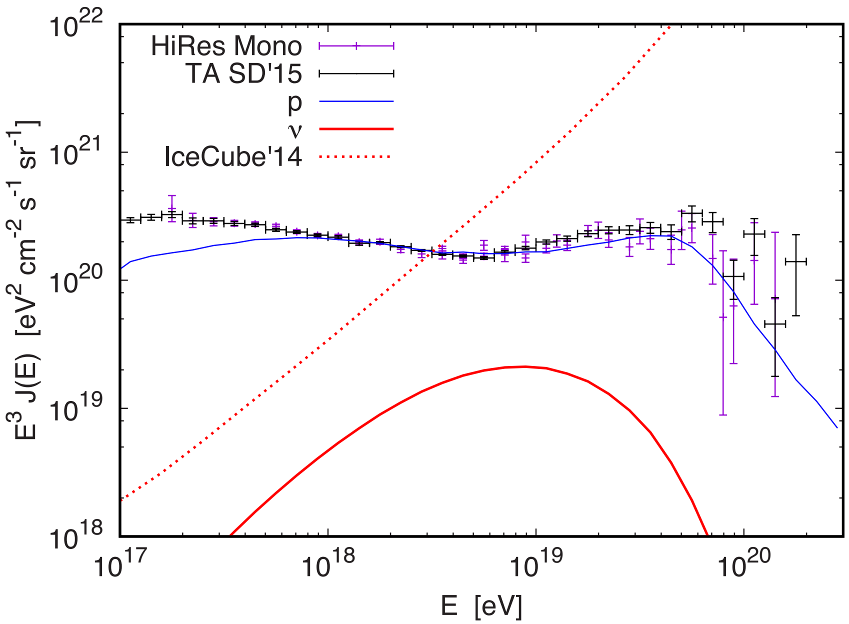
(ii)

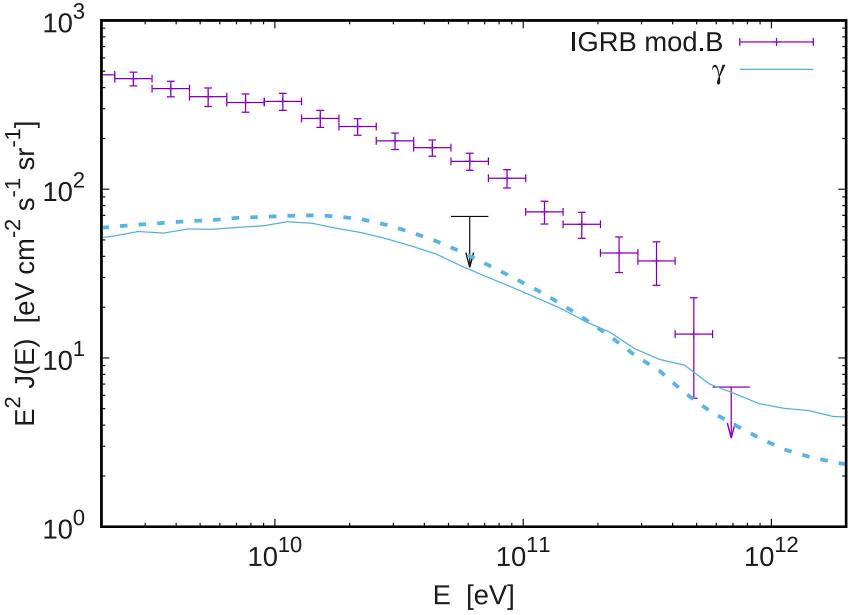
Recently (Sept. 2016) Auger collaboration using the correlation of muon flux with $X_{\max}$ lowred the proton flux at $(3-10)$ EeV.

Nuclei are less efficient in production of UHE neutrinos.

We calculated cosmogemic neutrino fluxes taking into account both effects.

Neutrino flux limited by Fermi LAT



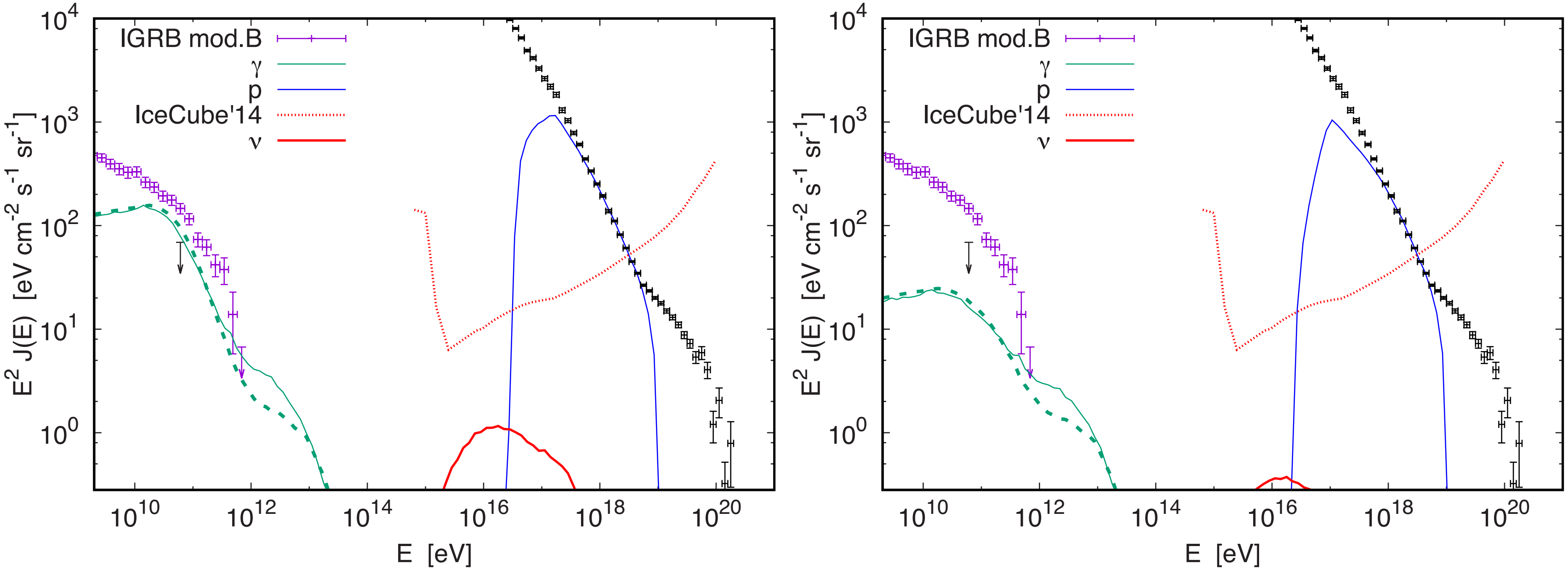


Left: UHE neutrino spectra produced by protons as observed by TA with generation spectrum given by $\gamma_g = 2.6$ and evolution of sources with $m = 1$ and $z_{\max} = 5$.

Right: The upper limit on neutrino flux is given by accompanying HE gamma-ray flux mainly by the last bin in the observed Fermi LAT spectrum.

Neutrino flux from protons at (1 - 4) EeV

All experiments agree on proton composition in this energy range.
Auger correlation data do not limit proton composition here.
Protons from this range gives reliable lower limit on neutrino flux:
VB, Gazizov, Kalashev 2016.



Left: proton evolution with $\gamma_g = 2.1,\ m = 3.9,\ z_{\max} = 2$
Right: proton evolution with $\gamma_g = 2.6,\ m = 0,\ z_{\max} = 3$

Mass composition in TA and Auger