UHE COSMIC NEUTRINOS: the view from 2014

V. Berezinsky

INFN: GSSI and LNGS, Italy

Content:

- **Astrophysical neutrinos: production and sources.**
- **UHE neutrino interaction.**
- **2013 breakthrough: TeV-PeV neutrino detection by IceCube.**
- **Upper limit on UHE neutrino flux.**
- **Cosmogenic neutrinos .**
- **Topological defects.**
- **Future experiments.**

UHE NEUTRINOS: PRODUCTION and SOURCES

- **Astrophysical (acceleration) neutrinos**
  pp: $p + N_{\rm tar} \to \pi^{\pm} + {\rm all}$, **p$\gamma$:** $p + \gamma_{\rm tar} \to \pi^{\pm} + {\rm all}$
- **Cosmogenic neutrinos (produced by CRs):** $p + \gamma_{\rm cmb} \to \pi + N$
- **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)
- **Bright phase (Pop III stars at $z \sim 10-20$, $z_{\rm reion} = 11.0 \pm 0.14$ WMAP).**
  V.B., Ozernoy 1981, V.B.,Blasi 2012.

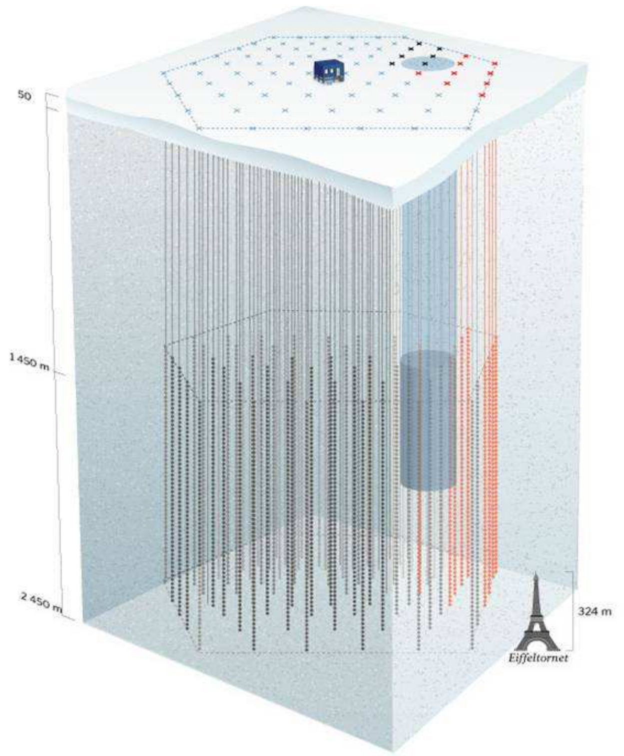
UHE NEUTRINO DETECTION

- **Muon production:** $\nu_\mu + N \to \mu + \text{all}.$
  Shower production: $\nu_e + N \to e + \text{hadrons}.$
- τ**-production:** $\nu_\tau + N \to \tau + \text{hadrons}$, followed by $\tau \to \nu_\tau + \mu + \bar{\nu}_\mu$ (three signals).
- **Glashow resonance:**
  $\bar{\nu}_e + e^- \to W^- \to \mu^- + \bar{\nu}_\mu$ **(Glashow 1960)**
  $\bar{\nu}_e + e^- \to W^- \to \text{hadrons}$ **(VB, A.Gazizov 1977)**
  resonance energy: $E_0 = m_W^2/2m_e = 6.3$ PeV
- **Neutrino flavour oscillation:**
  oscillation length: $L(E) = \frac{4E}{\Delta m^2} = 25 \left(\frac{E}{10^{11}\text{GeV}}\right) \left(\frac{10^{-4}\text{eV}^2}{\Delta m^2}\right)$ pc
  Typical flavour ratio: $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ (equipartition)
- Z**-bursts:** $\nu + \bar{\nu}_{\text{bcgr}} \to Z_0 \to \text{hadrons}$
  $E_0 = m_Z^2/2m_\nu = 1.7 \times 10^{22} (0.23\text{eV}/m_\nu))$ eV
- **Neutrino absorption in early universe:**
  $z_{\text{abs}} = 7.9 \times 10^4 (E_{\nu 0})/1\text{ TeV})^{-1/3}$

IceCube: Historical breakthrough

86 strings with 5160 PMT at depth 2450 km,
Two PeV events detected in 616 days of observ.:
$E = 1.04 \pm 0.16$ PeV and $E = 1.4 \pm 0.17$ PeV.
2.8 σ above atm ν background in base-line model.
Additional 26 events 30 - 250 TeV with interaction vertices within detector volume.
Combined 28 TeV - PeV events are 4σ significant.
Difficulties in interpretation:

- no correlations with known astrophysical sources,
- energies are smaller than expected,
- majority of events are shower-like.



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

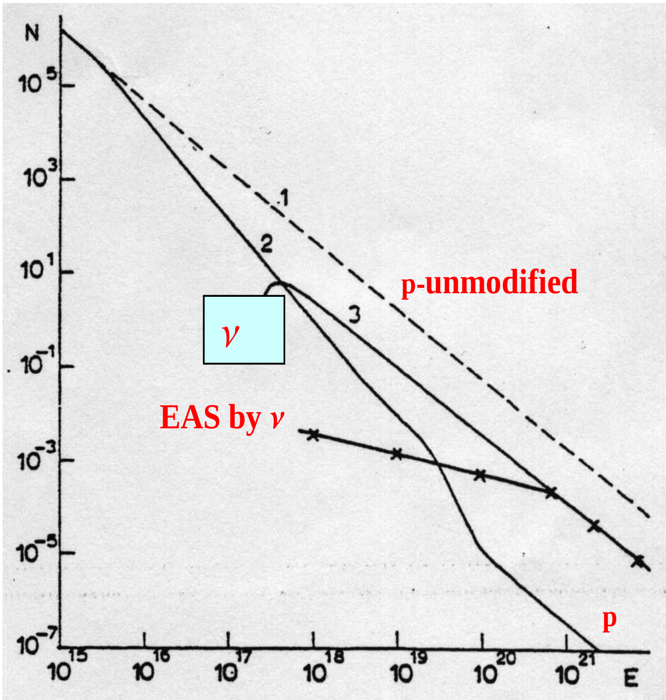
Academy of Sciences of the USSR. Physical Institute. Moscow

Received 8 November 1968

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.



UHECR and COSMOGENIC NEUTRINOS

UHE protons propagating through CMB produce cosmogenic neutrinos:

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

Spectral signatures of this propagation are:

pair-production dip and GZK cutoff

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:

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

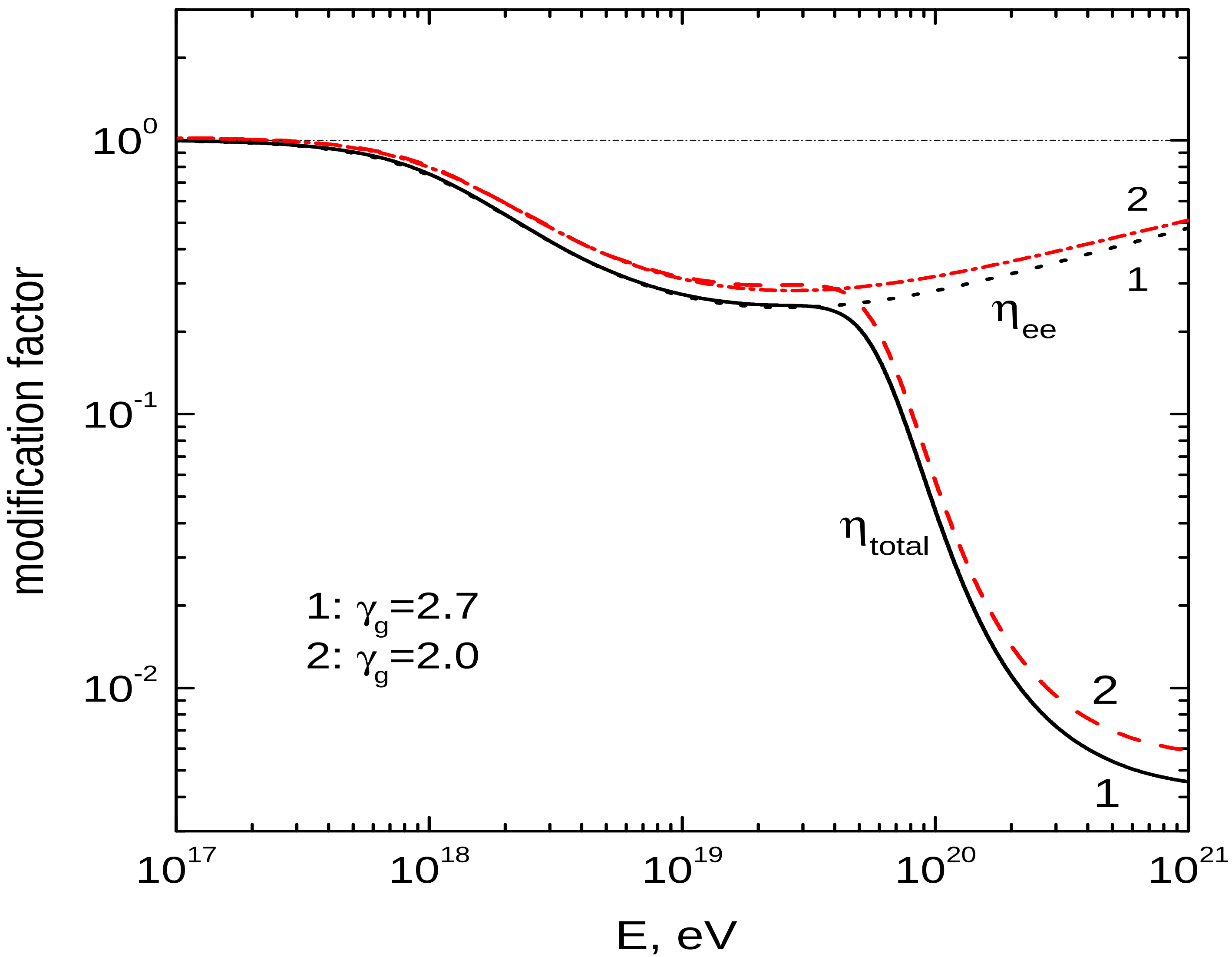
Dip is a faint spectral feature, seen better in terms of **modification factor**

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

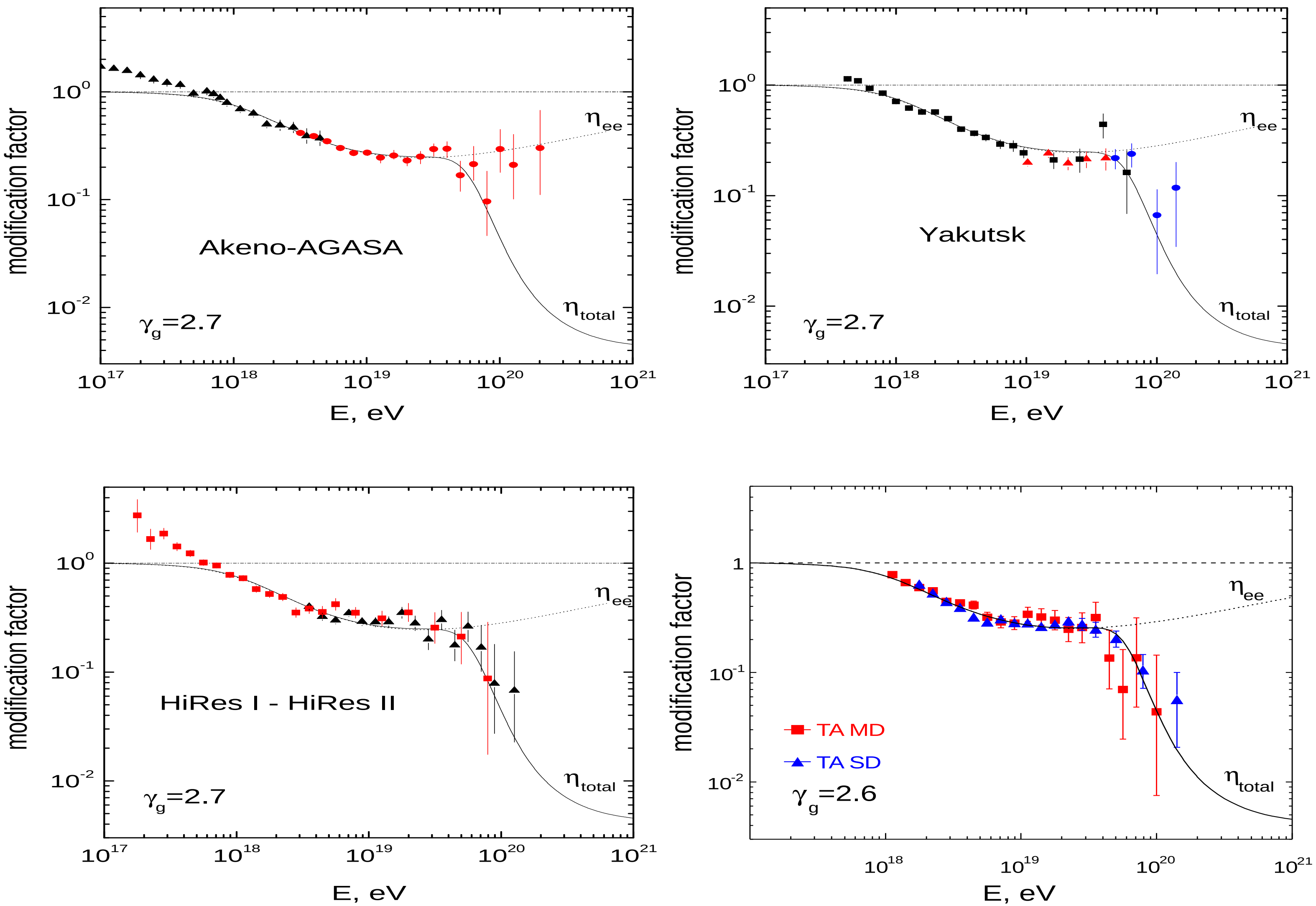
where $J_p^{\rm unm}(E) = KE^{-\gamma_g}$ includes only adiabatic energy losses (redshift),

and $J_p(E)$ all energy losses.

DIP AND GZK CUTOFF IN TERMS OF MODIFICATION FACTOR

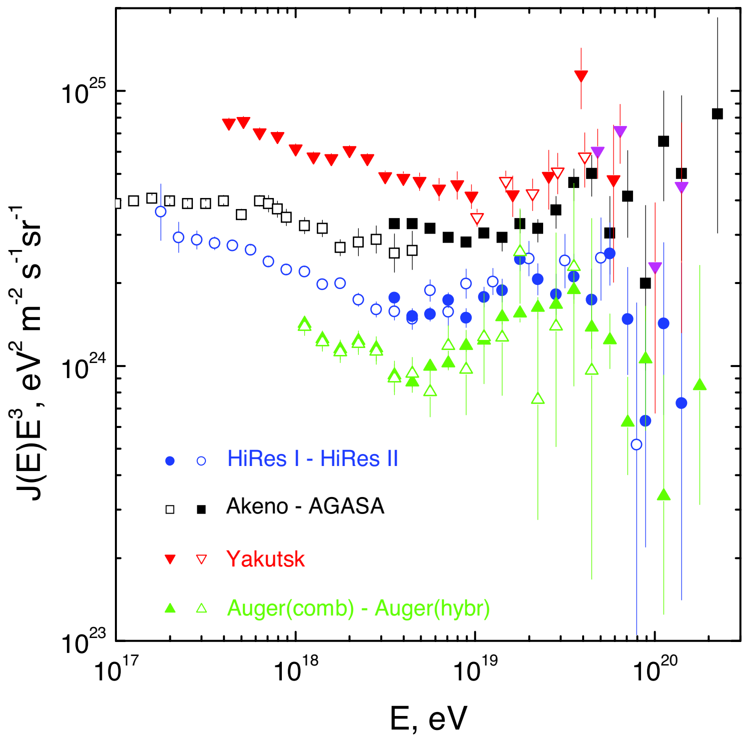


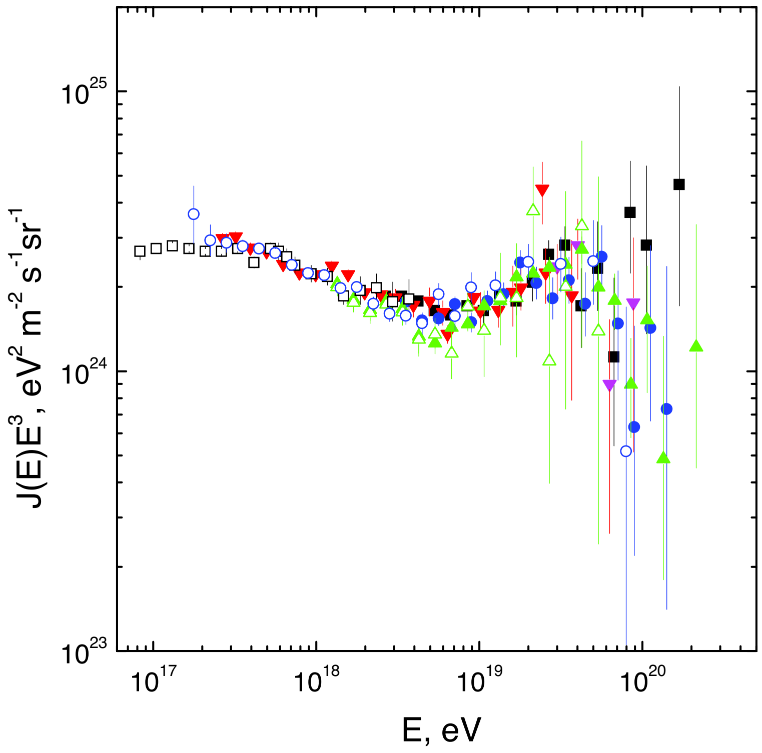
COMPARISON OF PAIR-PRODUCTION DIP WITH OBSERVATIONS



RECALIBRATION of AUGER, HIRES, AGASA, YAKUTSK FLUXES

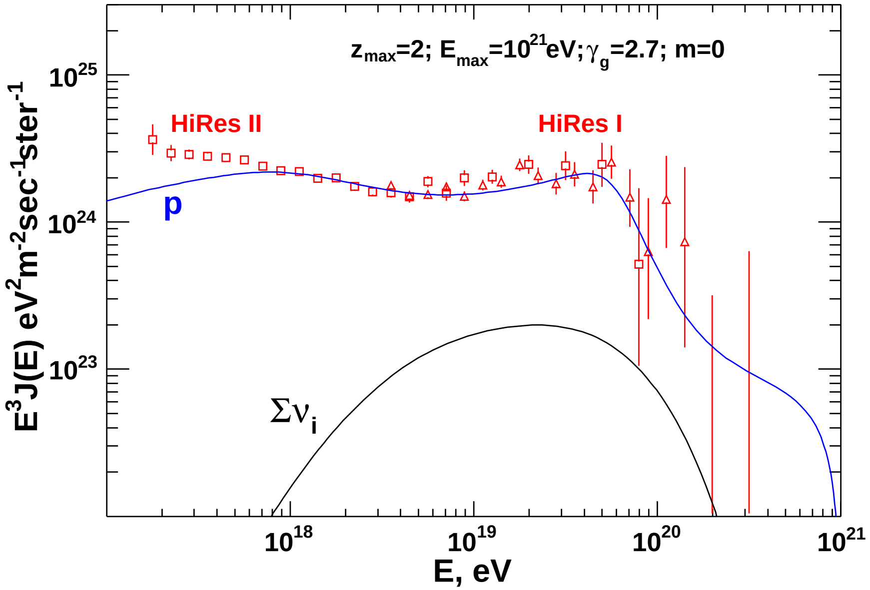
V.B., A. Gazizov, S. Grigorieva

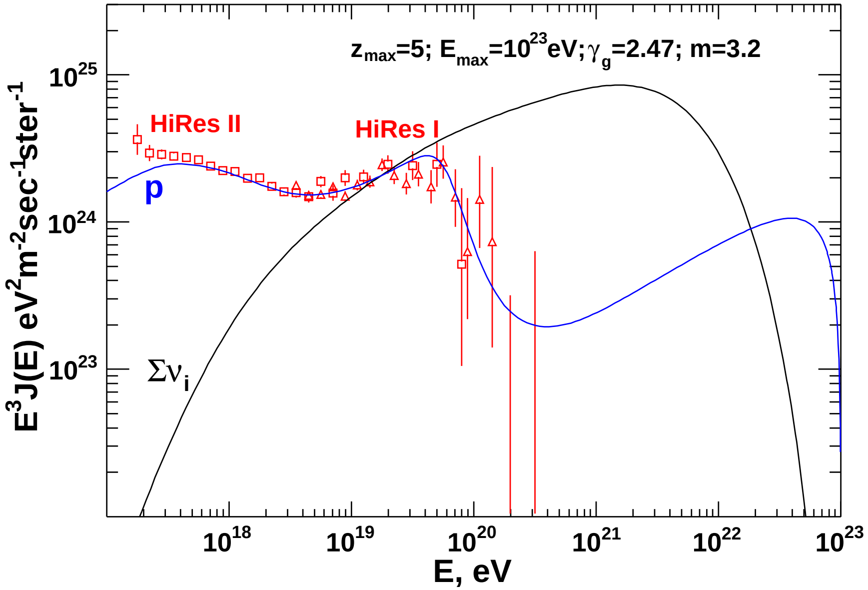




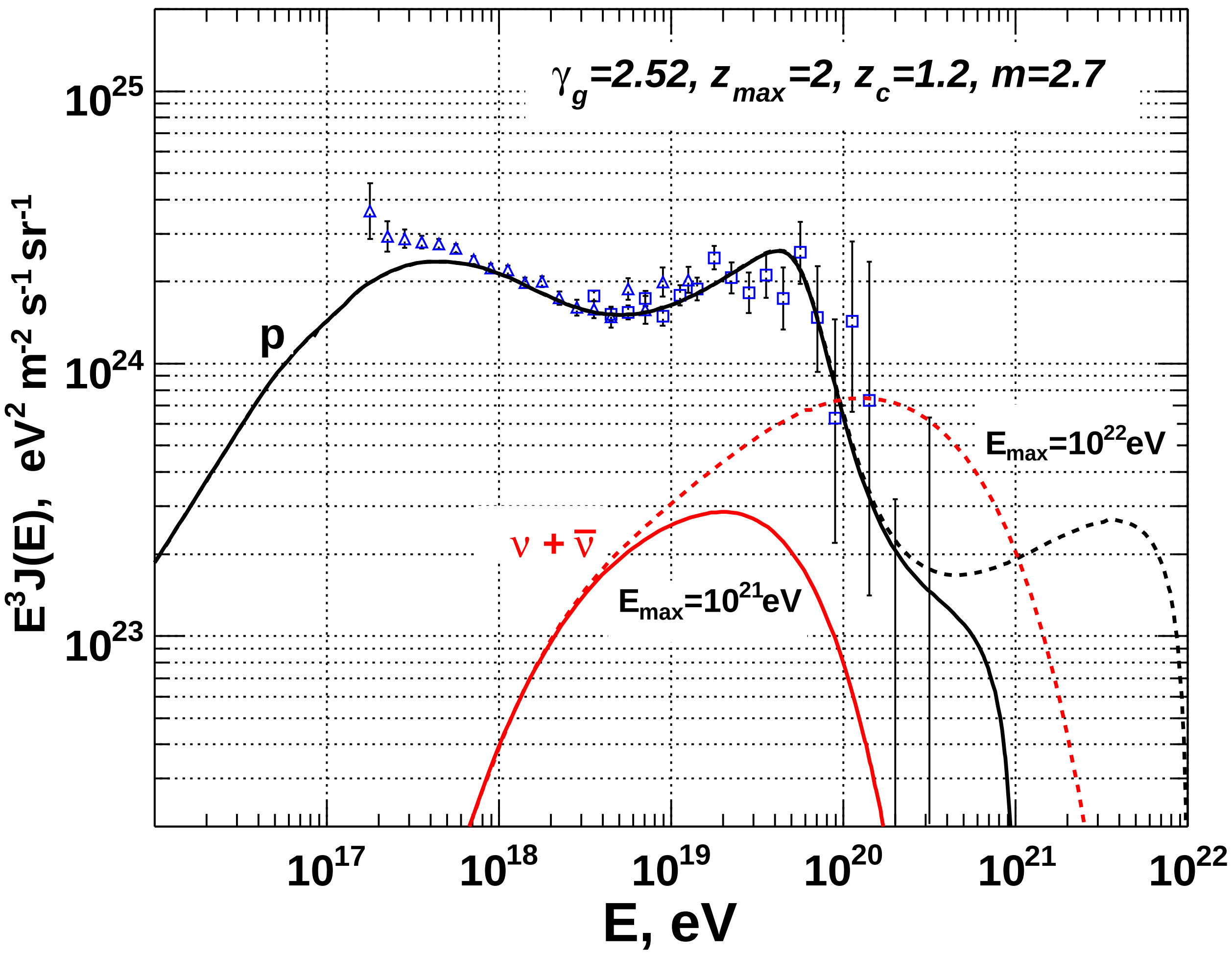
Recalibration factors: $\lambda = 1.2$ (Auger), $\lambda = 1.0$ (HiRes), $\lambda = 0.75$ (AGASA), $\lambda = 0.625$ (Yakutsk).

COSMOGENIC NEUTRINO FLUXES IN THE DIP MODEL



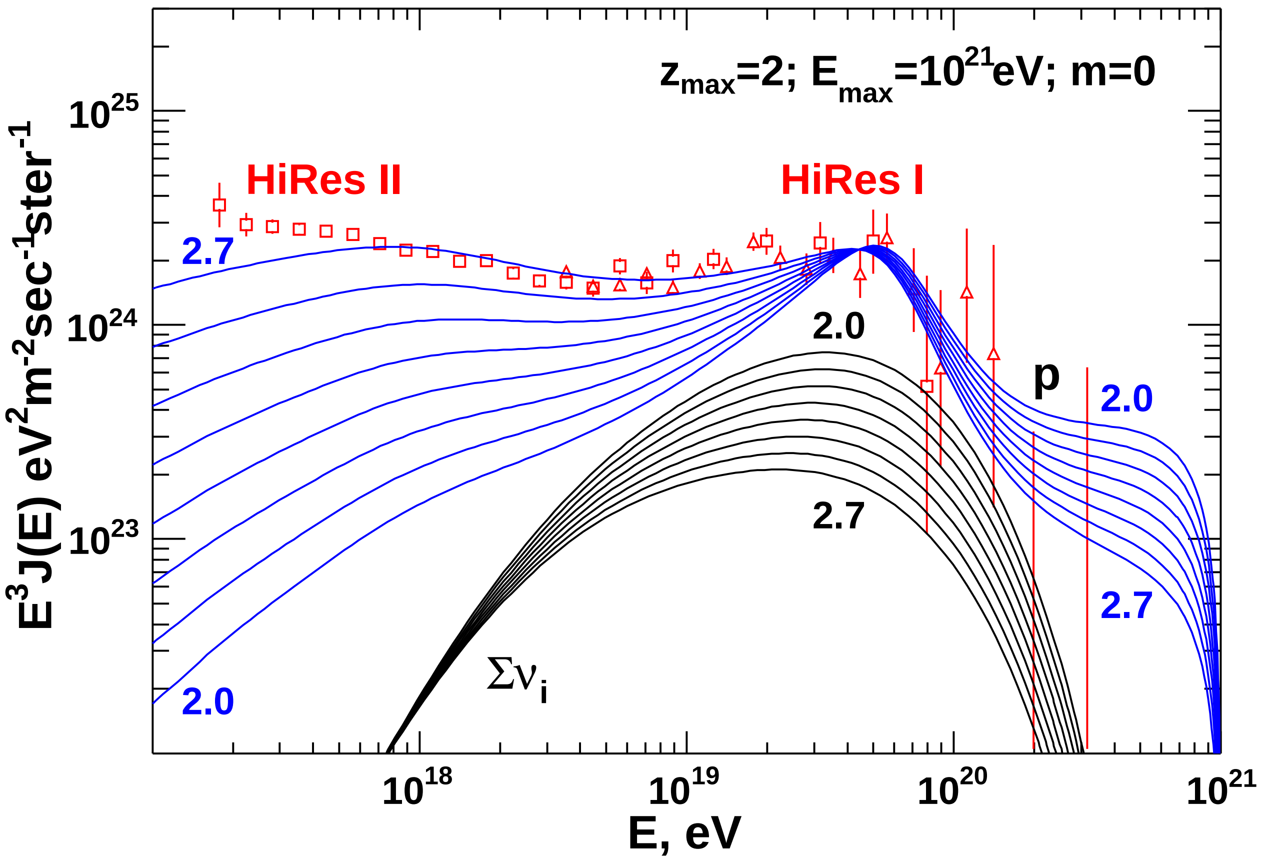


COSMOGENIC NEUTRINO FLUXES FROM AGN



LOWER LIMIT ON NEUTRINO FLUXES IN THE PROTON MODELS

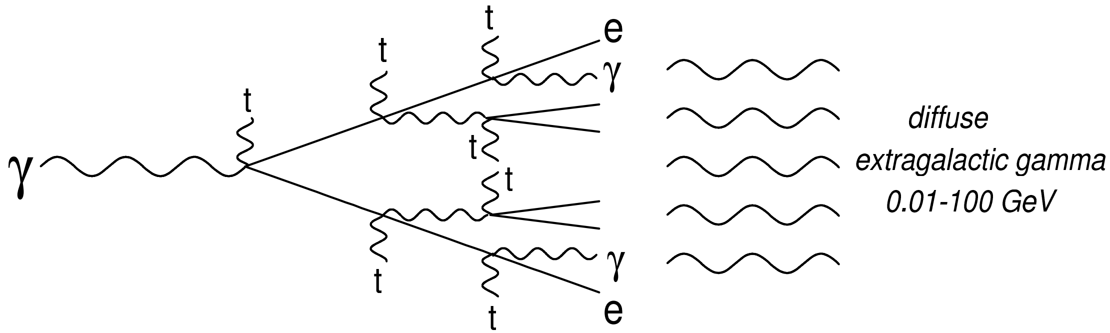
V.B. and A. Gazizov 2009



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

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

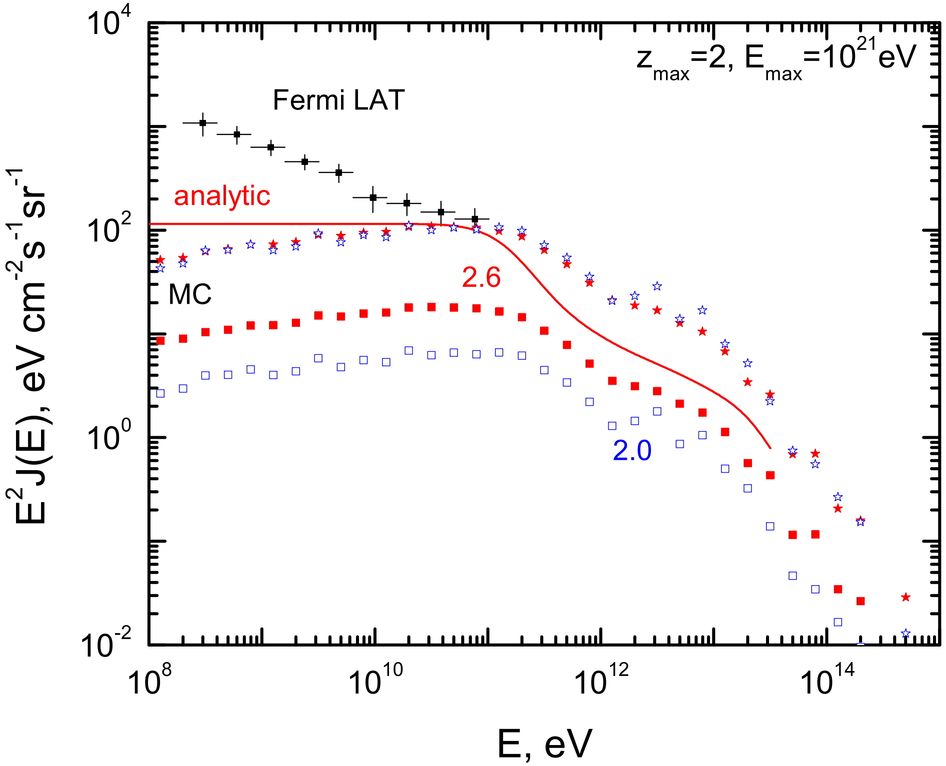
$$E^2 I_\nu(E) < \frac{c}{4\pi} \omega_{\rm cas.}$$

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

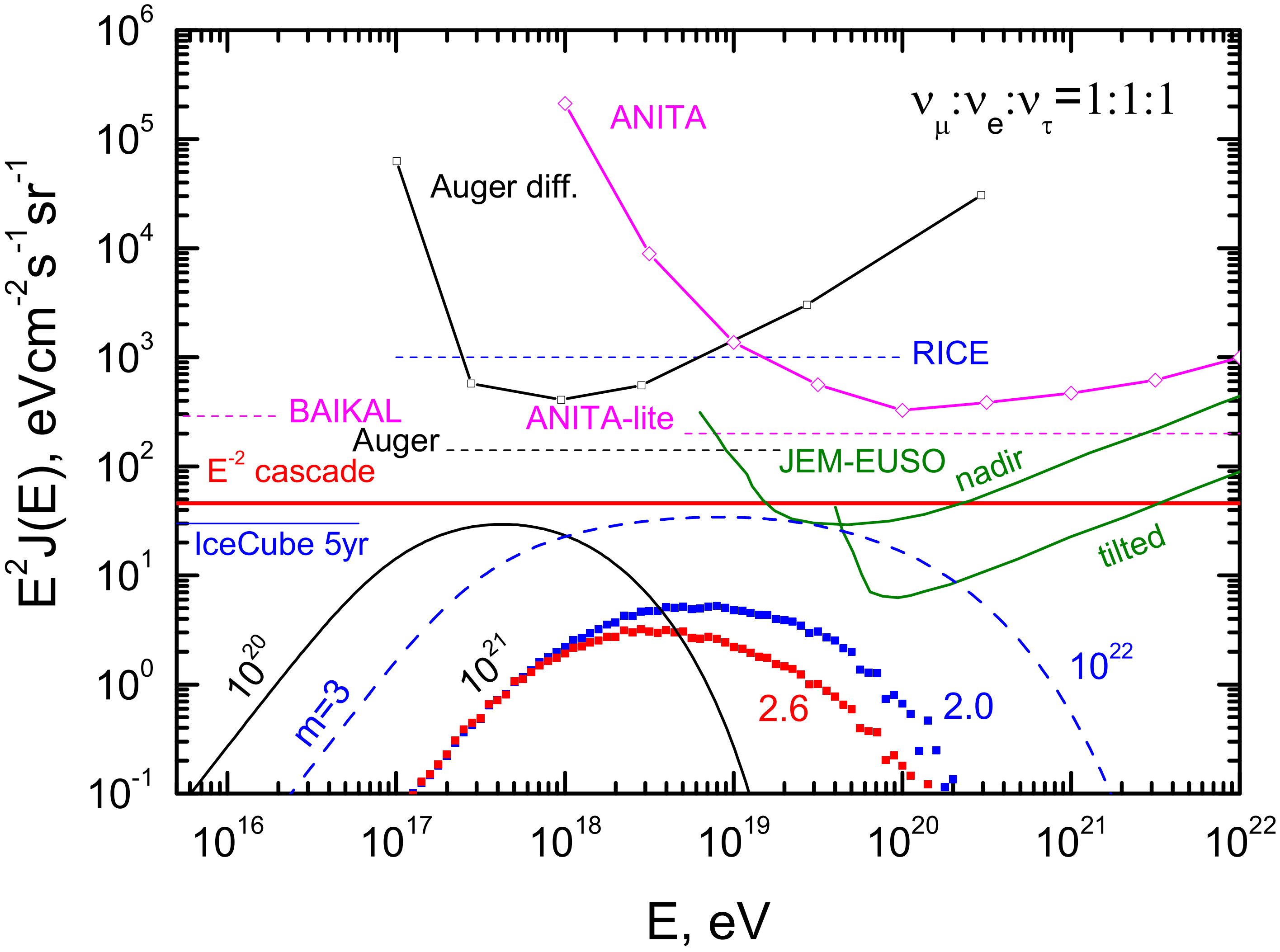
V.B., Gazizov, Kachelriess, Ostapchenko Phys. Lett. B 695 (2011) 13.
Ahlers, Anchordoqui, Gonzales-Garcia, Halzen, Sarkar Astrop. Phys. 34 (2010) 106.
G. Gelmini, O. Kalashev, D. Semikoz arXiv:1107.1672



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

OBSERVATIONAL AND THEORETICAL UPPER LIMITS

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



Reionization of Universe: 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.
- Cooling of baryonic gas by H_2 formation $z \leq 20 - 30$
- Formation of the first **Pop III** stars hosted by $M \sim 10^6 M_\odot$ DM halos.
  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).

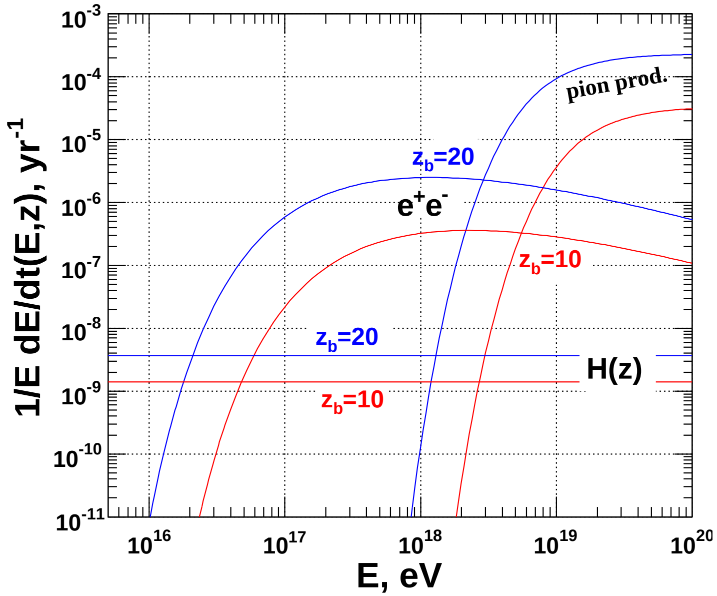
Pop III scenario fills several gaps:

- **Produce metals** needed for evolution of normal stars.
- Produce **reionization.**
- Produce **magnetic fields** in Universe.
  Pioneering proposal: Bisnovatiy-Kogan, Ruzmaikin, Syunyaev 1973.
  The other mechanisms: **Weibel** and **Kelvin-Helmholtz** instabilities. Production of magnetic field without pre-existing seed: **Resistive magnetic field generation** by Miniati and Bell.
  Shock may develop without magnetic field (Spitkovsky).

UHE NEUTRINOS from BRIGHT PHASE

V.B., Ozernoy 1981; Gao et al 2011, 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:

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

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

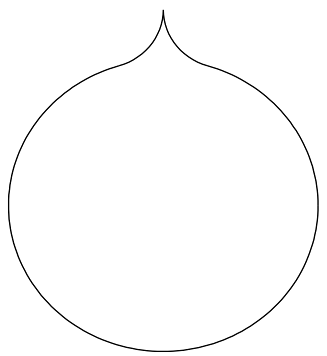
$$E_\nu^2 J_\nu(E) = 0.1 \frac{c}{4\pi} \frac{\omega_{\mathbf{p}}(\mathbf{z_b})}{(\mathbf{1}+\mathbf{z_b})^{\mathbf{4}}} \frac{1}{\ln E_{\max}/E_{\min}}$$

The value of basic parameter $\frac{\omega_p(z_b)}{(1+z_b)^4} = 9.5 \times 10^{-7}$ eV/cm^3 corresponds to future IceCube sensitivity $E^2 J_\nu(E) = 3 \times 10^{-9}$ GeV/cm^2 s sr and respects the Fermi upper limit $\omega_{\rm cas}^{\max} = 5.8 \times 10^{-8}$ eV/cm^3.

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



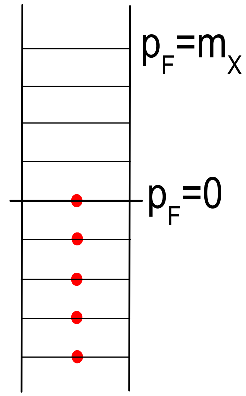
Produced at $U(1)$ symmetry breaking.
Particles are massless inside the string.
η is symmetry breaking scale, e.g. 10^9 GeV, and $\mu \sim \eta^2$ is tension.
Loop oscillates with periodically produced cusp ($v = c$) and with large Lorentz factors, e.g. above 10^{10}, at nearby points.
Particles escaping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

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

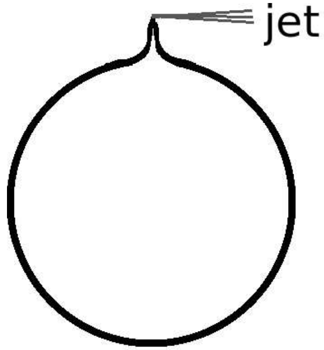
$n_X = \frac{p_F}{2\pi}, \;\; \frac{dJ}{dt} = e^2\mathcal{E}$ (superconductivity)

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

Clusters of galaxies dominate.

$I \sim e^2 B\ell, \quad I_{\rm cusp} \sim \gamma_c I, \quad I_{\rm cusp}^{\rm max} \sim i_c e\eta.$

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 2010

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.

2. UHE neutrinos emitted from ordinary strings via dilatons and moduli.
VB, Sabancilar, Vilenkin, 2011 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

- **In 2013 IceCube announced the first detection of UHE extraterrestrial neutrinos, two events with $E \approx 1$ PeV and 26 with energies $30 - 250$ TeV. They do not correlate with known sources, and for predicted diffuse fluxes they have too low energies. Many exotic models have been recently proposed.**

- **Cosmogenic neutrinos remain the reliable model for diffuse UHE neutrino flux. The large fluxes are predicted for proton mass composition in case of large maximum energy of acceleration $E_{\rm max}$. The predicted fluxes are undetectable by IceCube. However, IceCube can detect (and maybe detected) cosmogenic neutrinos from bright phase. The cosmogenic neutrinos normally have $E \gg 1$ PeV. For the bright phase (reionization) these energies are $(1 + z_{\rm reion})^2$ times lower, and two PeV events can be naturally explained by cosmogenic neutrinos produced at the bright phase.**

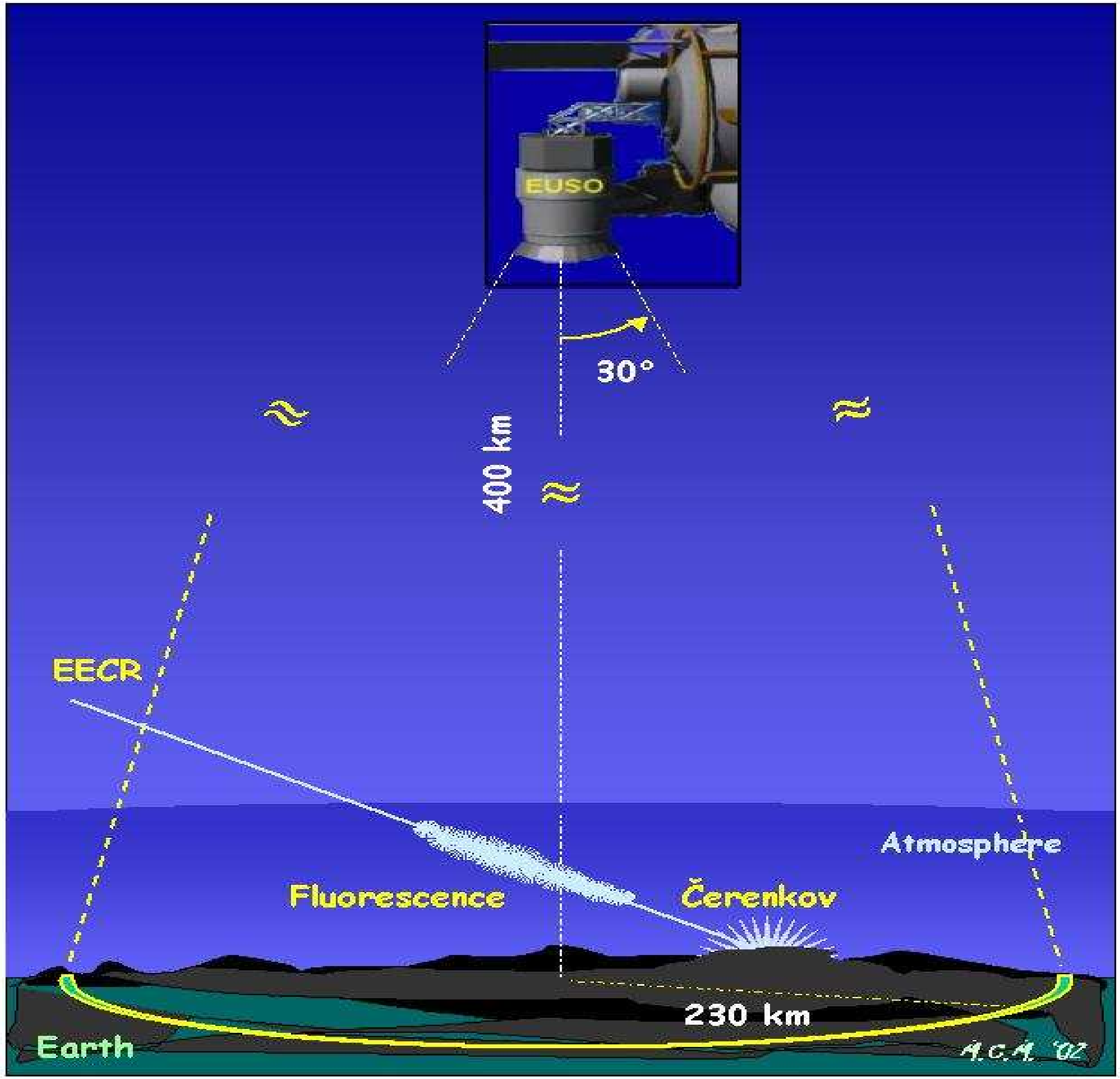
- **In the light of new stronger cascade limit on diffuse fluxes of UHE neutrinos search for the sources becomes the priority goal of neutrino astronomy with JEM-EUSO and IceCube detectors. This task is viable even if protons constitute a small part of primary cosmic ray radiation. Discovery of HE neutrino 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 $G\mu \lesssim 10^{-6}$.**

FUTURE NEUTRINO DETECTORS

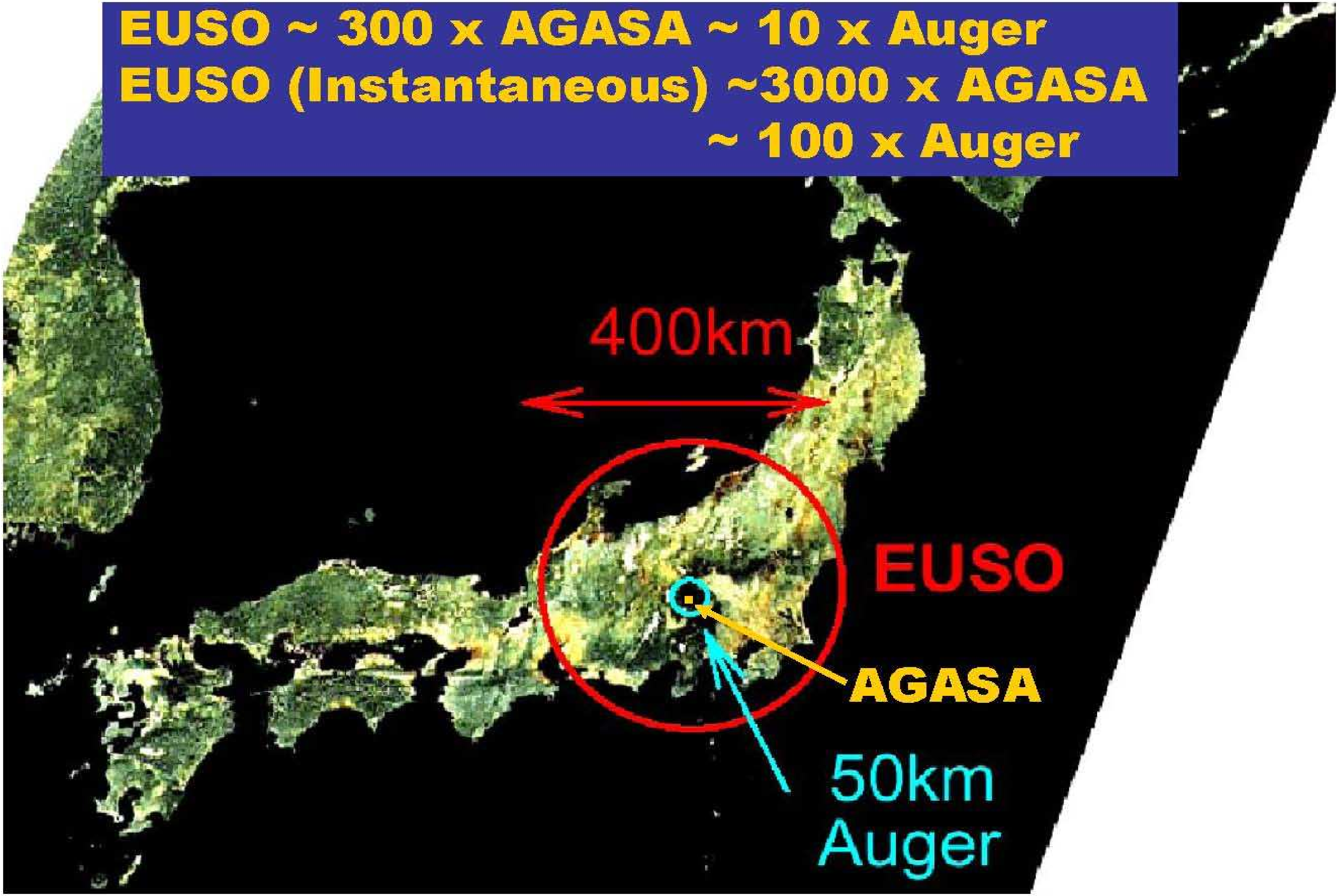
KM3 ($1\ \mathrm{km}^3$) European detector and JEM-EUSO

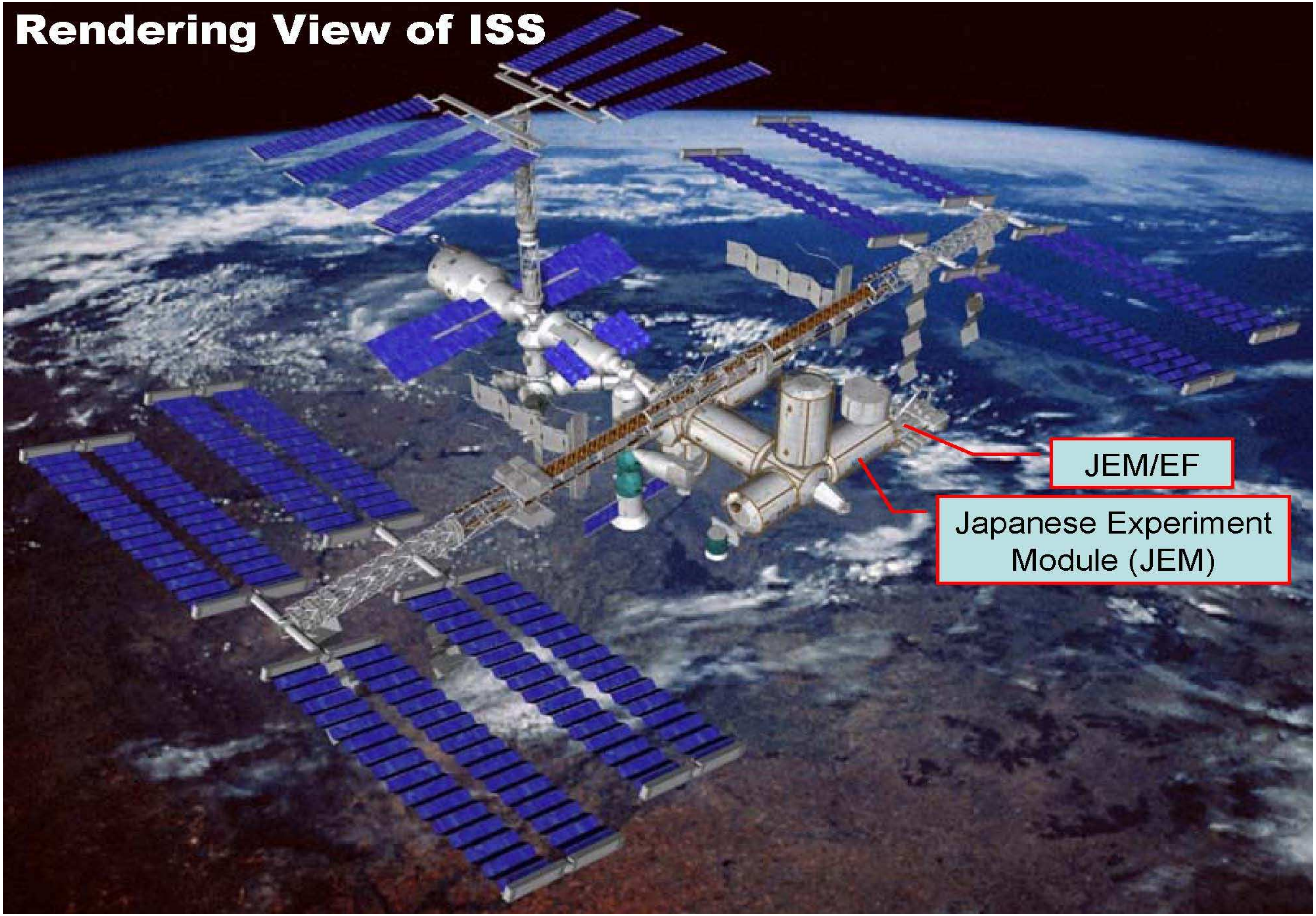
PRINCIPLES OF EUSO OBSERVATIONS



Field of View of EUSO

EUSO ~ 300 x AGASA ~ 10 x Auger
EUSO (Instantaneous) ~3000 x AGASA
~ 100 x Auger




Rendering View of ISS
JEM/EF
Japanese Experiment Module (JEM)

H-IIA Launch Vehicle

Nov. 29, 2003
Accident happened for the H-IIA Launch Vehicle No 6

Feb. 26, 2005
The H-IIA Launch Vehicle No. 7 with MTSAT-1R was launched successfully.

Jan. 24, 2006
The H-IIA Launch Vehicle No. 8 with the Advanced Land Observing Satellite "Daichi“ (ALOS) was launched successfully.

Feb. 18, 2006
The H-IIA Launch Vehicle No. 9 with the Multi-functional Transport Satellite 2 (MTSAT-2) was launched successfully.