Minimal models of UHECR, gamma-rays and neutrino sources

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Cosmic Rays and Neutrinos in the Multi-Messenger Era, 7-11 December 2020, IPGP

With single scenario we try to explain

- Ultra-high energy cosmic ray flux
- UHECR mass composition
- Observed neutrino flux in IceCube
- Satisfy diffuse gamma-ray limit

Neutrino production

connection to γ and cosmic rays

$$N + \gamma_b \Rightarrow N' + \sum \pi^i$$

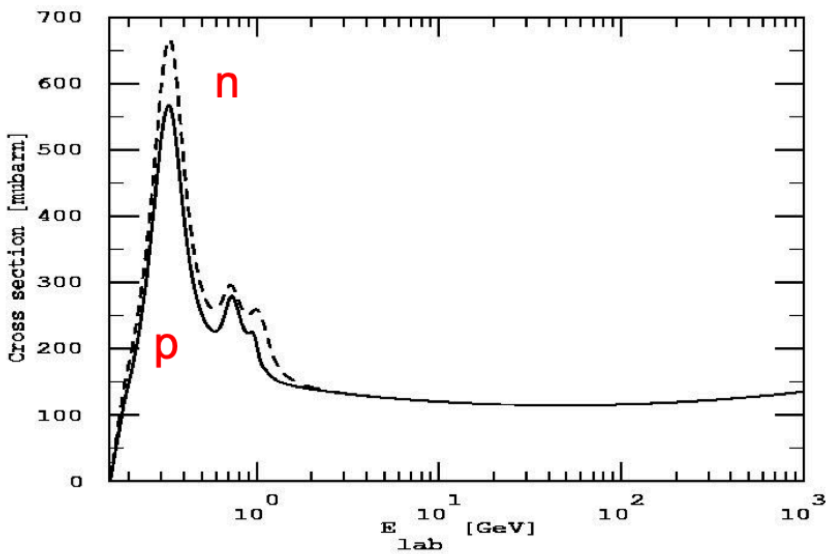
$$N + A_b \Rightarrow N' + \sum \pi^i$$

$$\pi^0 \Rightarrow 2\gamma$$

$$\pi^\pm \Rightarrow \mu^\pm + \nu_\mu$$

$$\mu^\pm \Rightarrow e^\pm + \overline{\nu}_e + \nu_\mu$$

$$n \Rightarrow p + e^- + \overline{\nu}_e$$



Cosmic ray, photon and neutrino fluxes are connected in well-defined way.
If we know one of them we can estimate other ones:

$$E_\gamma \simeq E_\nu$$

Diffuse γ ray background

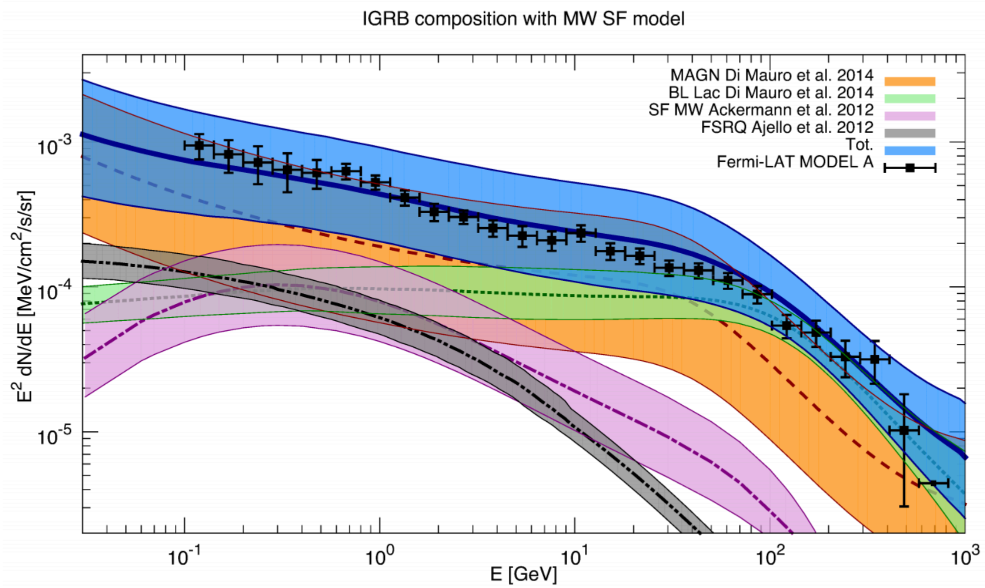
expected contributions

- Unresolved sources

mainly BL Lacs, also FSRQs, misaligned AGNs,

star forming galaxies

at least 84% of γ ray flux above 50GeV. *Fermi LAT 2016*



BL Lacs give main contribution to high energy part of diffuse gamma-ray flux

Neronov, Semikoz 2012

M. Di Mauro et al 2013

Diffuse γ ray background

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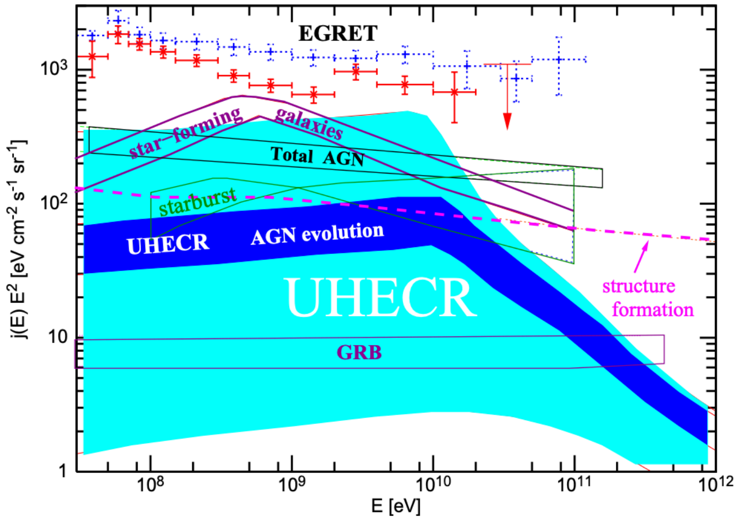
- Ultra-high energy cosmic rays

may saturate flux above few 100 GeV (constraints on proton-dominated models)

minimal flux is not negligible



O.K., D.Semikoz, G. Sigl 2007

Processes contributing to EM cascade:

$$A\gamma_b \to Ae^+e^-$$

$$N\gamma_b \to N' \sum \pi^i$$

Diffuse γ ray background

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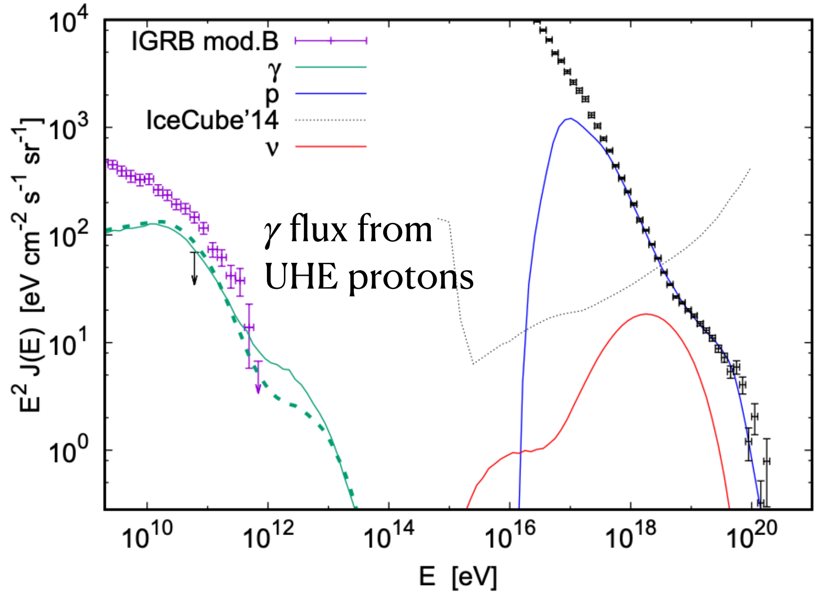
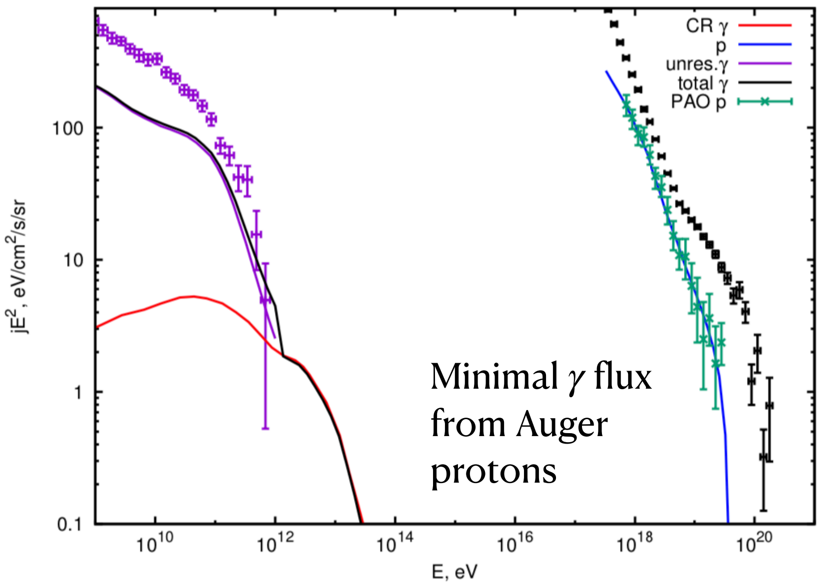


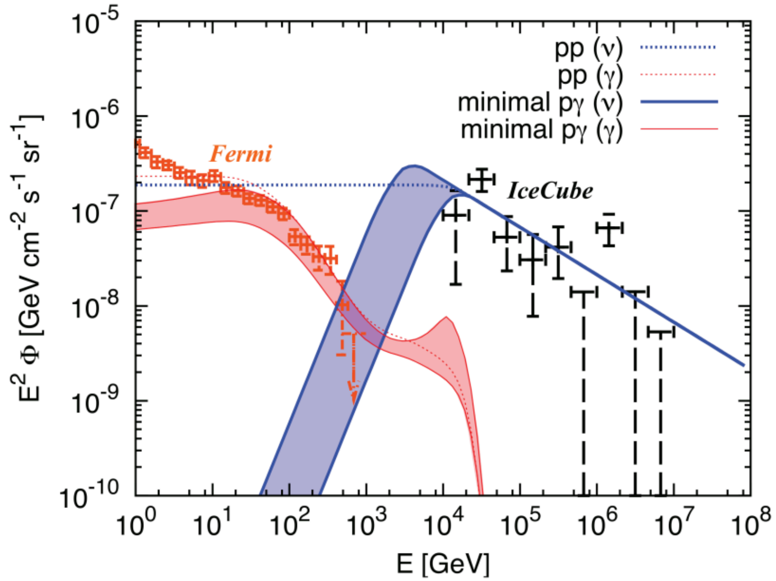
Berezinsky, Gazizov, O.K. 2016



O.K. 2016

Diffuse γ ray background

expected contributions



K.Murase, D.Guetta, M.Ahlers 2015

- Unresolved sources

mainly BL Lacs, also FSRQs, misaligned AGNs,

star forming galaxies

at least 84% of γ ray flux above 50GeV. *Fermi LAT 2016*

- Ultra-high energy cosmic rays

may saturate flux above few 100 GeV (constraints on proton-dominated models)

minimal flux is not negligible

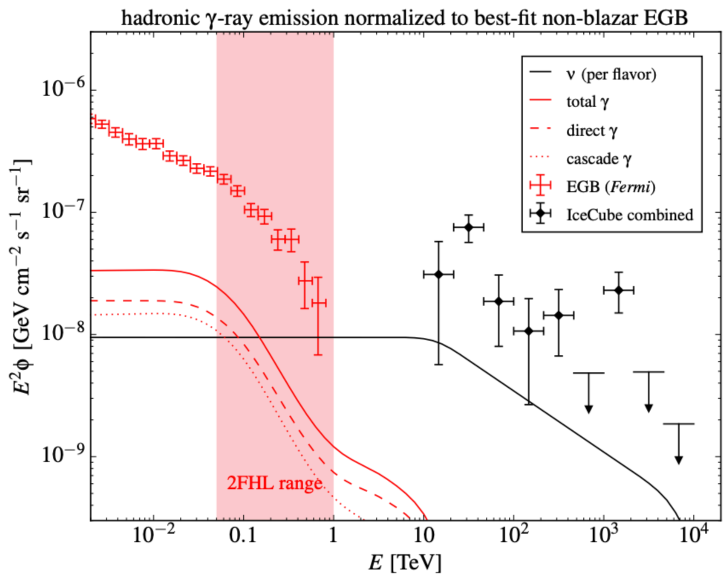
- Neutrino sources

may saturate flux above 10 GeV

sources opaque to 1–100 GeV γ rays are preferable

contribution of star forming galaxies is limited

no ν correlation with Fermi BL Lacs was found (27% or less between around 10 TeV and 2 PeV), *IceCube 2016*

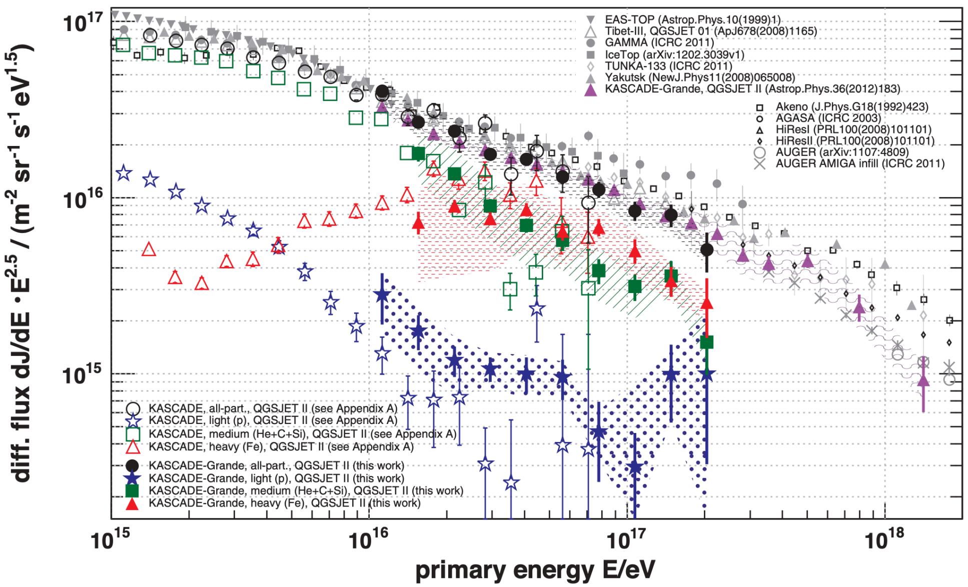


K. Bechtol et al 2017

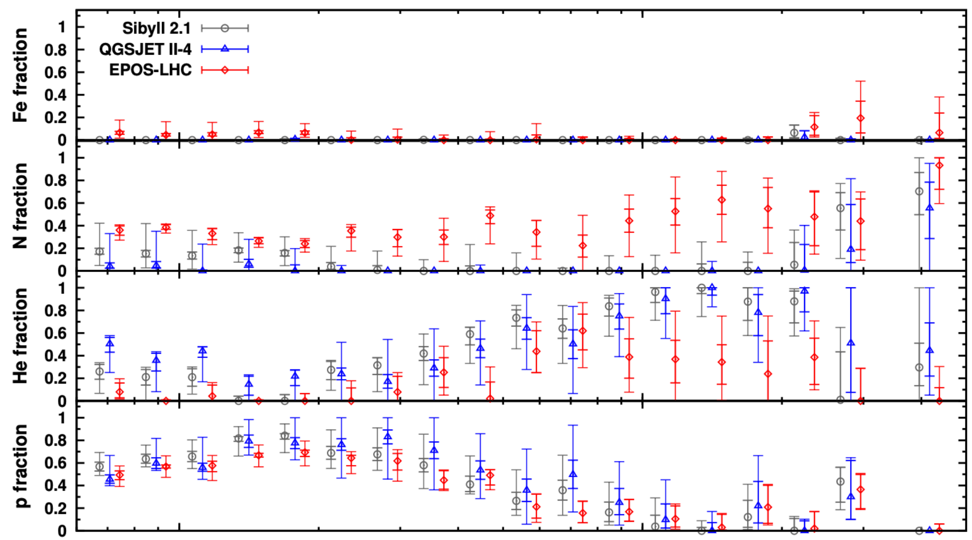
Model constraints.

Composition

- Mass composition below 0.2 EeV by CASCADE-Grande
- Limits on 4 element fractions above 0.6 EeV by Auger



W. D. Apel et al. [KASCADE-Grande Collaboration], Astropart. Phys. 47, 54 (2013).



A. Aab et al. [Pierre Auger Collaboration], Phys. Rev. D 90, no. 12, 122006 (2014)

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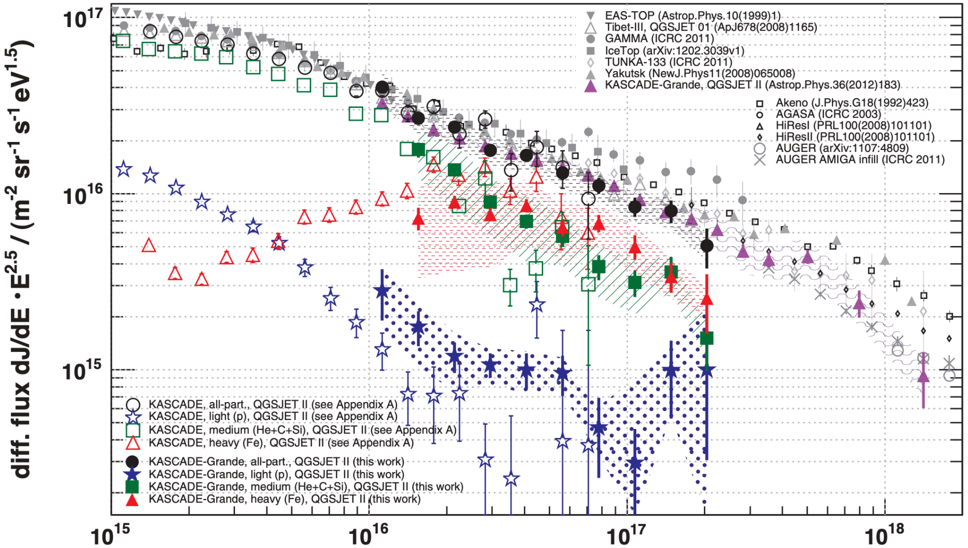
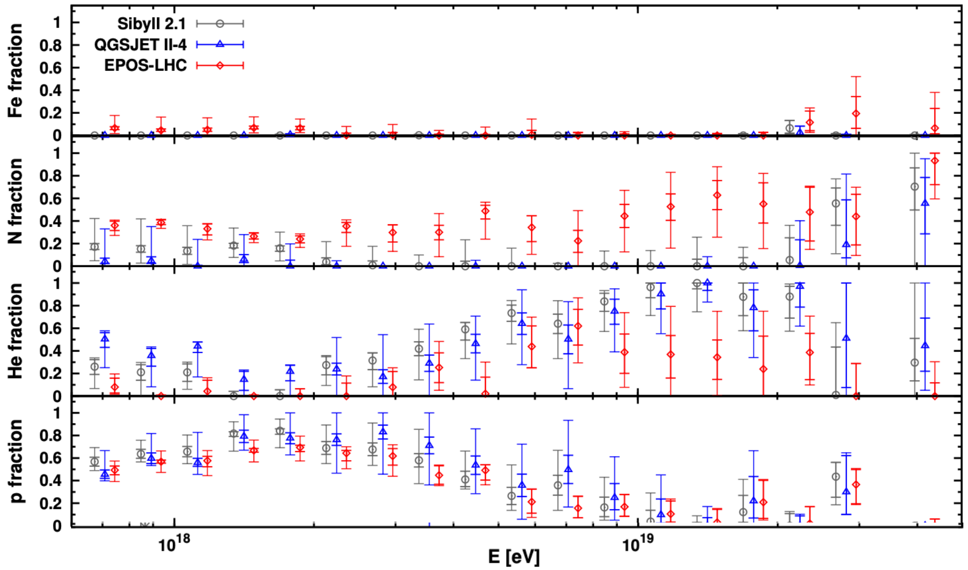




- Proton fraction 40-60% for 0.7 < E/EeV < 7
- Above 7 EeV
  - proton fraction decreases
  - intermediate elements fraction increases
- Fe fraction is limited by 15-20% for 0.7<E/EeV<20
- Galactic component ends around 0.7 EeV (escape model)

Model summary

Acceleration close to the SMBH:

- shock acceleration in accretion shocks [Kazanas, Ellison 1986]
- acceleration in regular fields close to the SMBH [Blandford 1976]

Energy spectrum after acceleration:

$$j_{\mathrm{inj}}(E) \propto E^{-\alpha} \exp[-E/(ZE_{\mathrm{max}})]$$

Attenuation:

- zone I - photohadronic interactions of nuclei
- zone II - interactions with gas
- propagation via intergalactic space after escaping the source

Zone I

Photo-hadronic interactions

- Thermal emission from dust surrounding the SMBH - main source of attenuation
- Model parameters:

  T - radiation temperature

  $\tau_0^{p\gamma} = R_{\mathrm{int}}/R_{\mathrm{esc}}$ - interaction depth for protons with $E_0 = 10\,EeV$

  $R_{\mathrm{esc}} \propto (E/Z)^{\delta_{p\gamma}}$ - escape rate (neutrons escape freely)

- Modelled using kinetic equations in one dimension with rates multiplied by the escape times.

Zone II

Interactions with gas

- Model parameters:

  $\tau_0^{pp} = R_{\text{int}}/R_{\text{esc}}$ - interaction depth for protons with $E_0 = 10$ EeV

  $R_{\text{esc}} \propto (E/Z)^{\delta_{pp}}$ - escape rate (neutrons escape freely)

- Modelled with Monte Carlo using QGSJET-II-04 in leaky-box approximation

Observable spectra calculation

- Use output from zone II as effective source spectrum
- Calculate total diffuse flux from a distribution of sources taking into account propagation effects:
  - interactions with EBL
  - redshift
- Model parameters:
  - source distribution (or evolution)
  - EBL spectrum

Observable spectra calculation

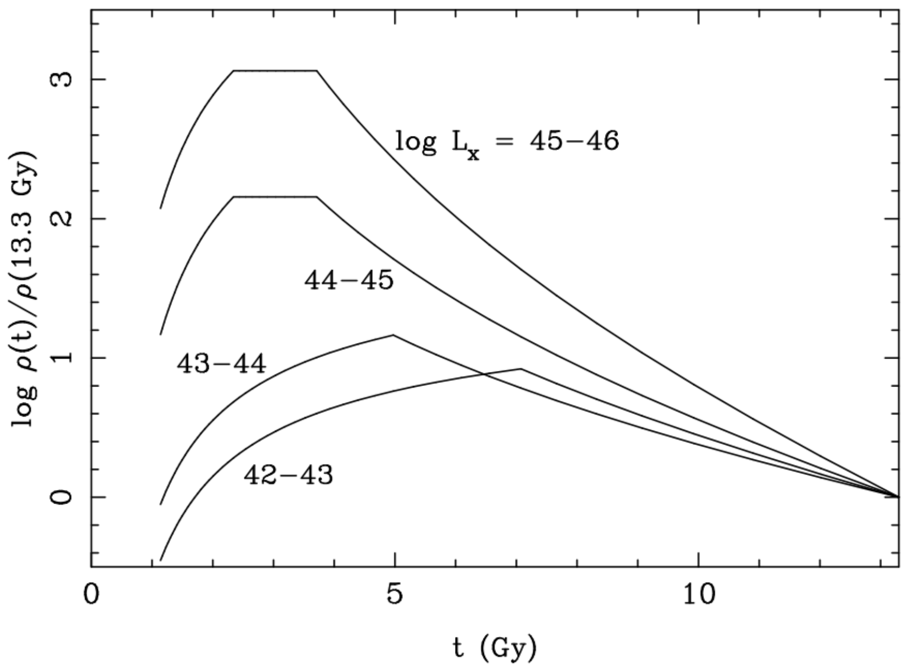
Source Distribution

Option I. Using luminosities in X-rays for AGN

Hasinger et al. Astron. Astrophys. 441, 417 (2005)

$$\rho(z) = \begin{cases} (1+z)^m & \text{for } z < z_c, \\ (1+z_c)^m & \text{for } z_c < z < z_d, \\ (1+z_c)^m 10^{k(z-z_d)} & \text{for } z > z_d, \end{cases}$$

$\log L_{\mathrm{x}}$	42.5	43.5	44.5	45.5
m	4.0 ± 0.7	3.4 ± 0.5	5.0 ± 0.2	7.1 ± 1.0
z_{c}	0.7	1.2	1.7	1.7
z_{d}	0.7	1.2	2.7	2.7
k	-0.32	-0.32	-0.43	-0.43



Observable spectra calculation

Source Distribution

Option II. Using γ-ray Luminosity-Dependent Density Evolution for FR I / BL Lac sources

M.Di Mauro et al. 2014 ApJ 786 129

$$N_c(z) \propto \int_{L_\gamma^{min}}^{L_\gamma^{max}} \rho(z, L_\gamma) L_\gamma dL_\gamma$$

$$\rho(z, L_\gamma) = \rho(L_\gamma)\, e(z, L_\gamma)$$

$$\rho(L_\gamma) = \frac{A}{\log(10) L_\gamma} \left[\left(\frac{L_\gamma}{L_c} \right)^{\gamma_1} + \left(\frac{L_\gamma}{L_c} \right)^{\gamma_2} \right]^{-1}$$

Peaks at low redshift:

Z < 1

$$e(z, L_\gamma) = \left[\left(\frac{1+z}{1+z_c(L_\gamma)} \right)^{p_1} + \left(\frac{1+z}{1+z_c(L_\gamma)} \right)^{p_2} \right]^{-1}$$

Observable spectra

Hadronic interactions only

Injection power-low $\alpha = 1.8$

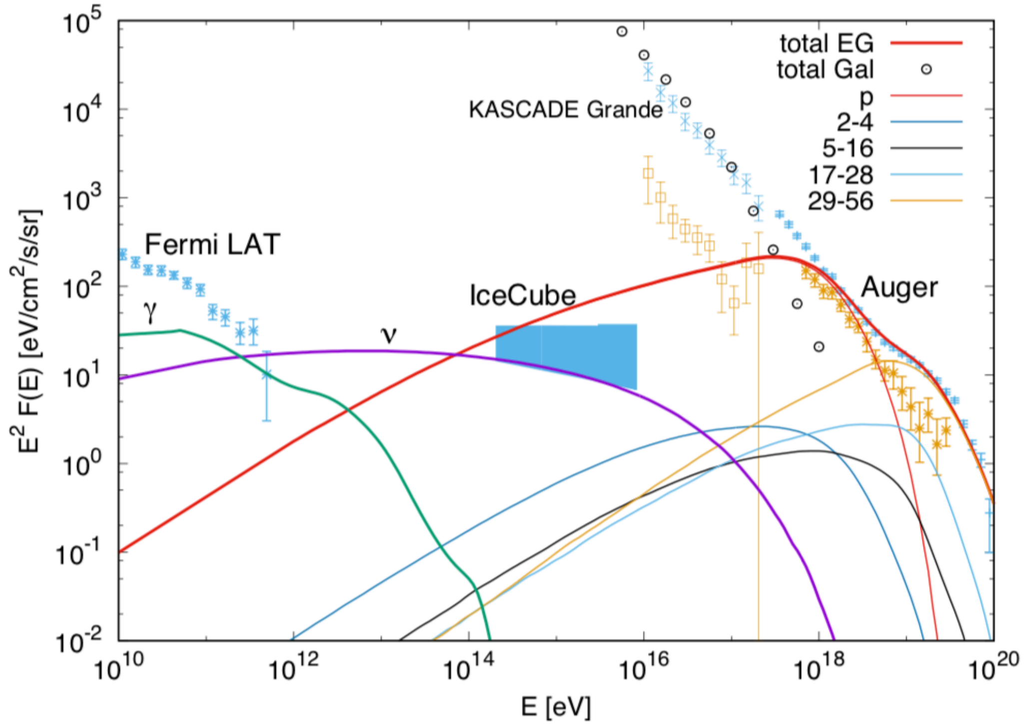
Maximal energy $E_{max} = 3$ EeV

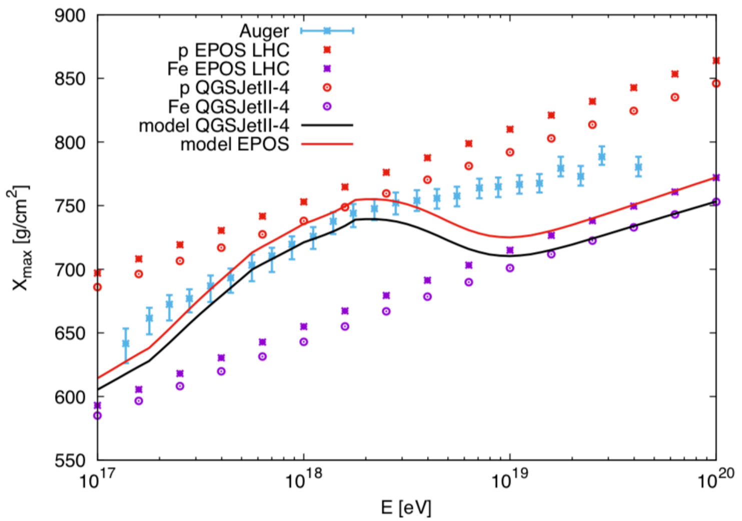
Evolution: BL Lac

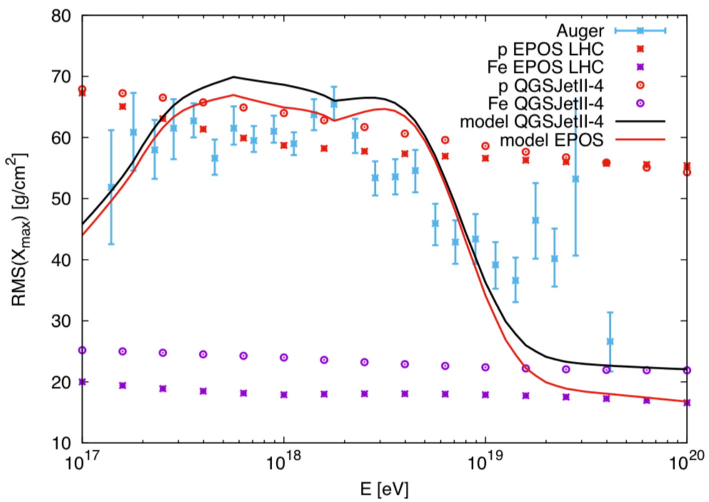
Interaction depth $\tau_0^{pp} = 0.035$

Diffusion:

$\delta_{Ap} = 0.5$ (Kraichnan turbulence)

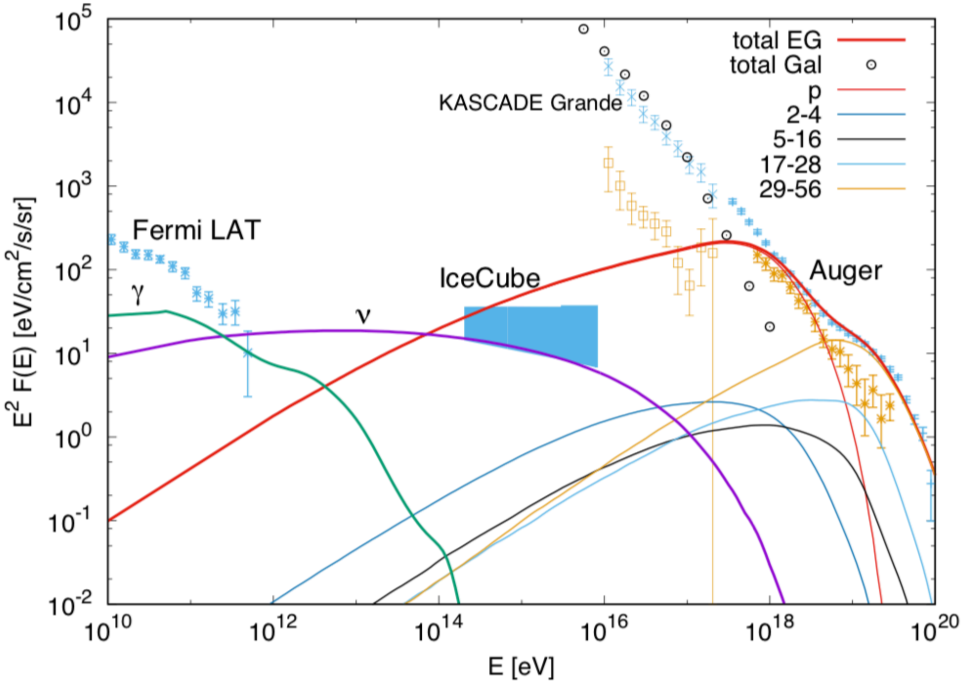


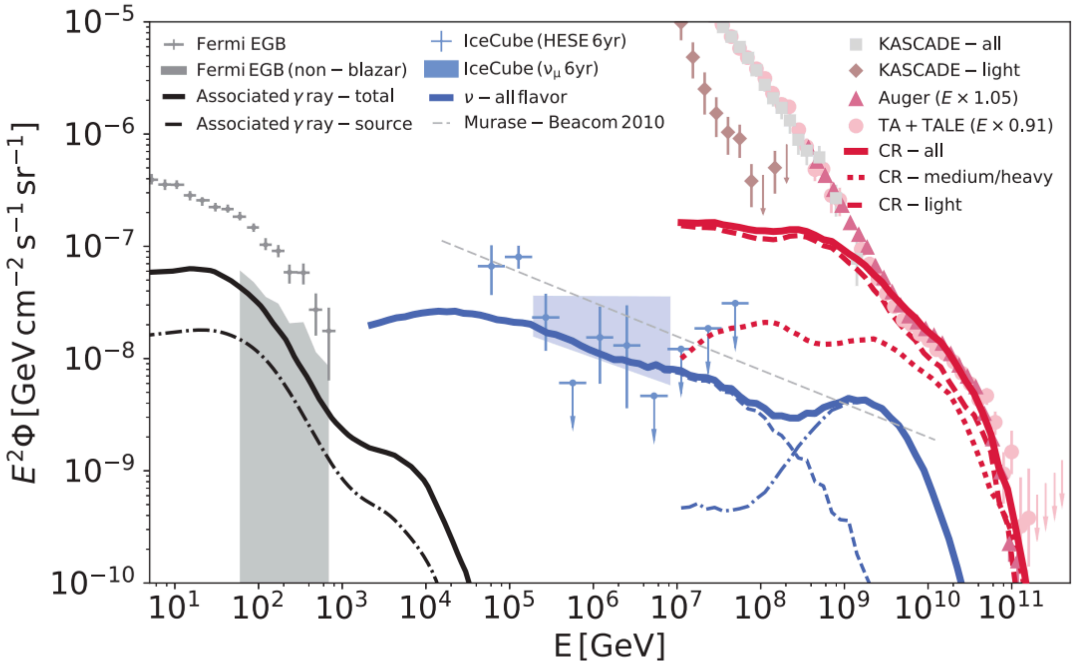


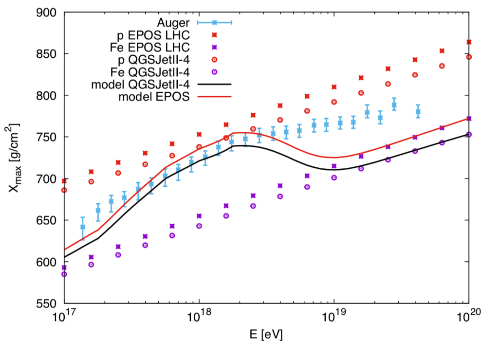


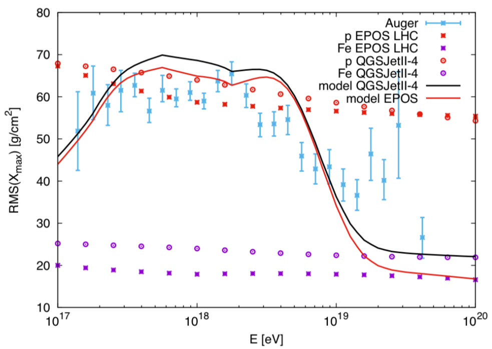
Observable spectra

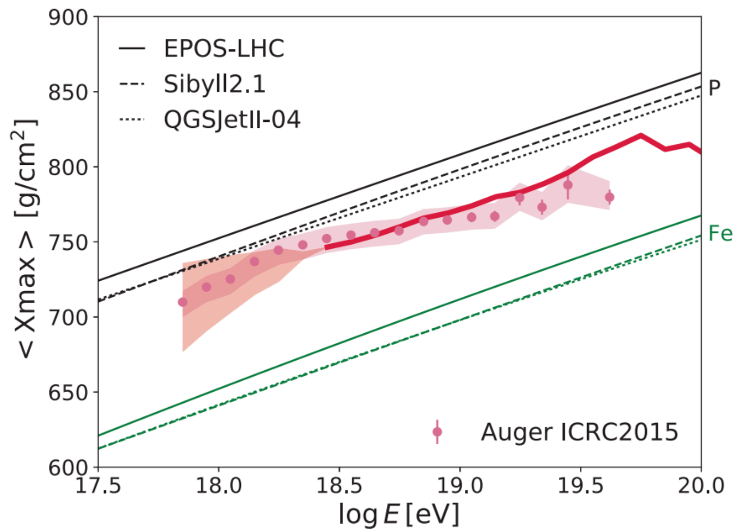
K. Fang, K. Murase 2018











Observable spectra calculation

Photo-hadronic and hadronic interactions

Injection power-low $\alpha = 1.5$

Maximal energy $E_{max} = 6$ EeV

Evolution: AGN with $LogL_X = 43.5$

Photon temperature $T = 850$ K

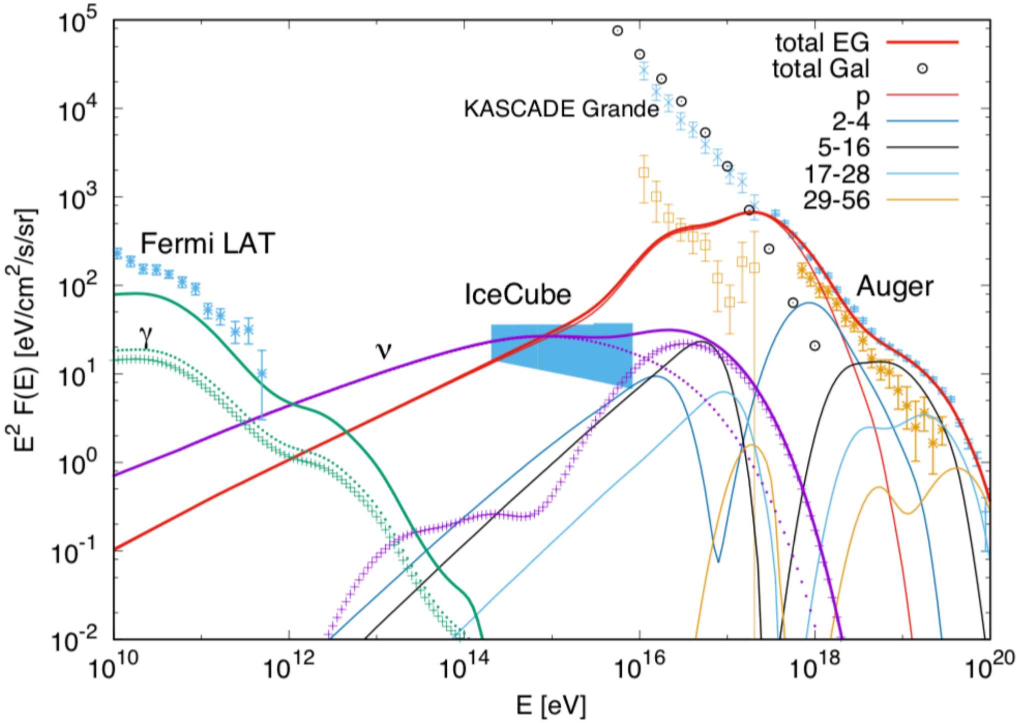
Interaction depth $\tau_0^{pp} = 0.035$

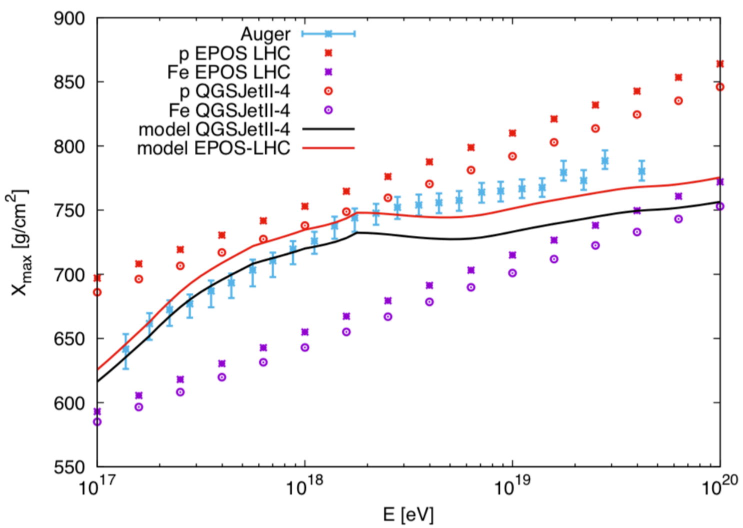
Interaction depth $\tau_0^{p\gamma} = 0.29$

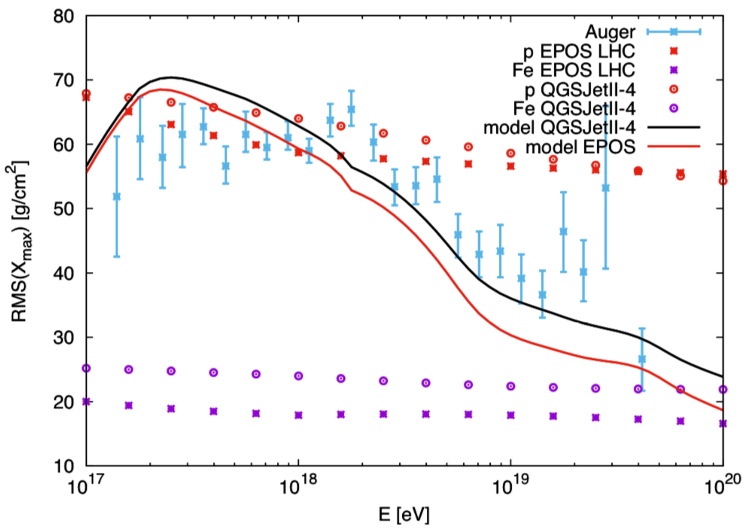
Diffusion:

$\delta_{Ap} = 0.5$

$\delta_{A\gamma} = 0.77$







Conclusion

We demonstrated the toy scenario explaining astrophysical neutrino flux above 200 TeV along with UHECR cosmic ray spectrum and mass composition. The predicted contribution to the EGRB is of order 30%