High Energy Neutrinos as Probes of Quantum Gravity (2nd part of WG4 review)

1. Observations
2. Secondary Neutrinos and Gamma-Rays
3. Tests of Lorentz Symmetry

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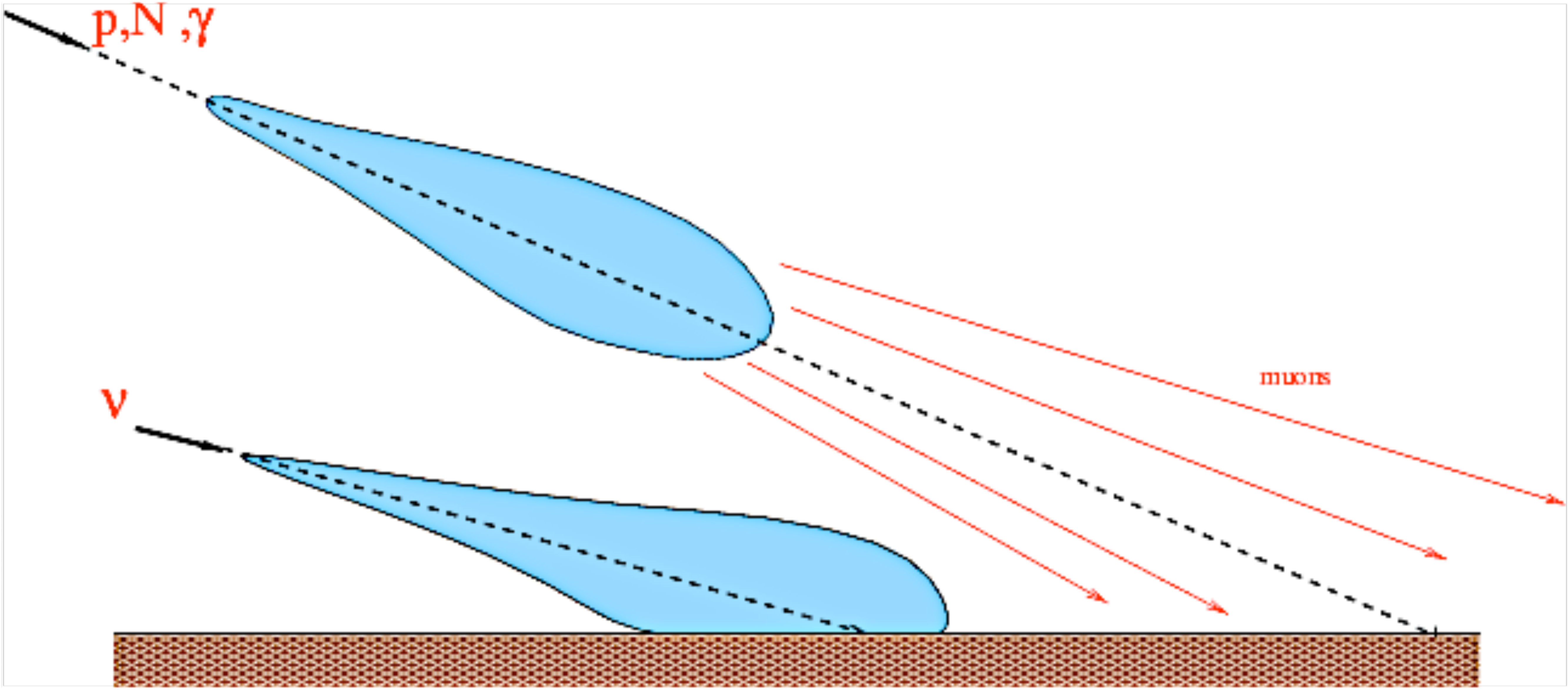
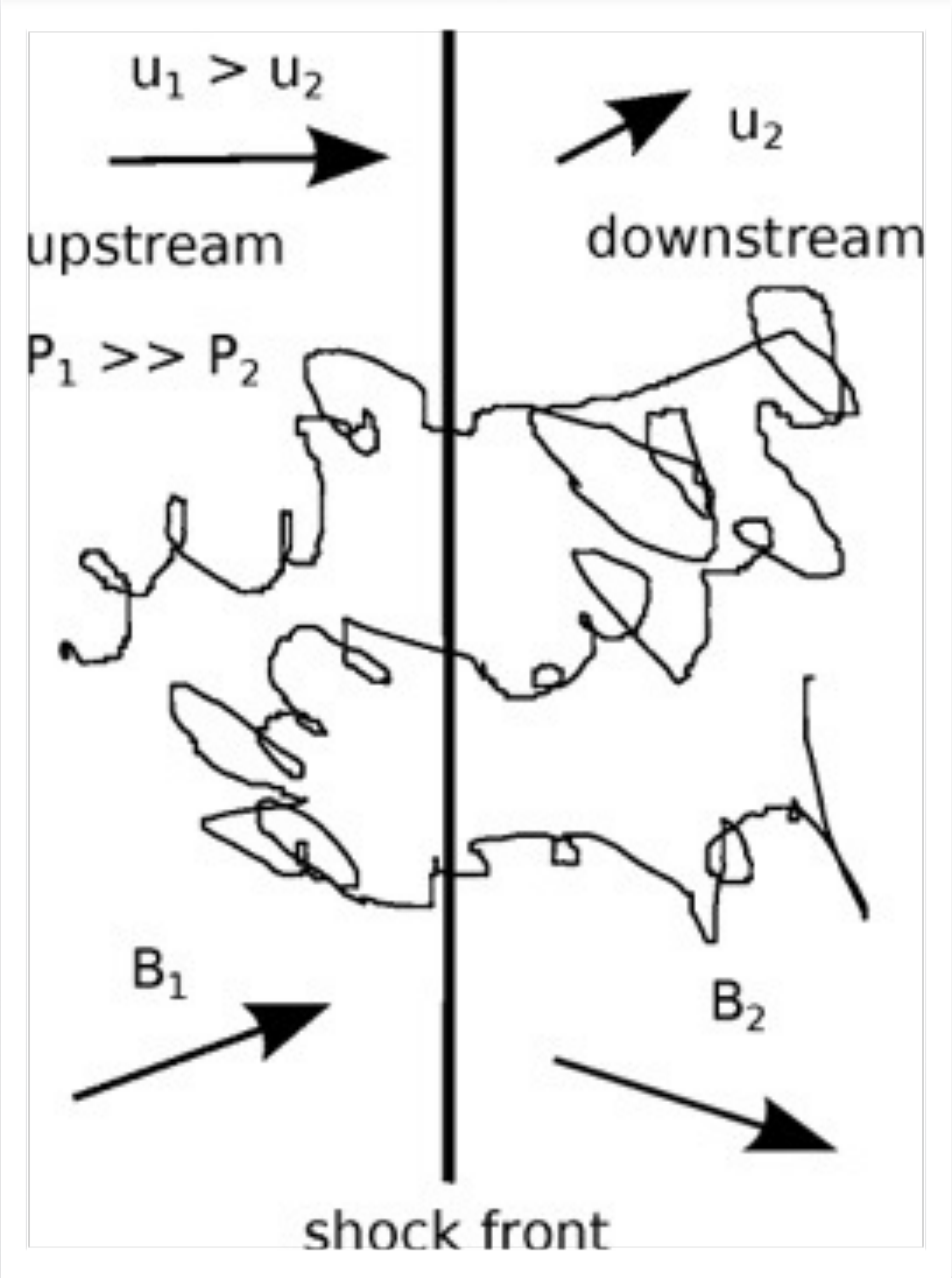
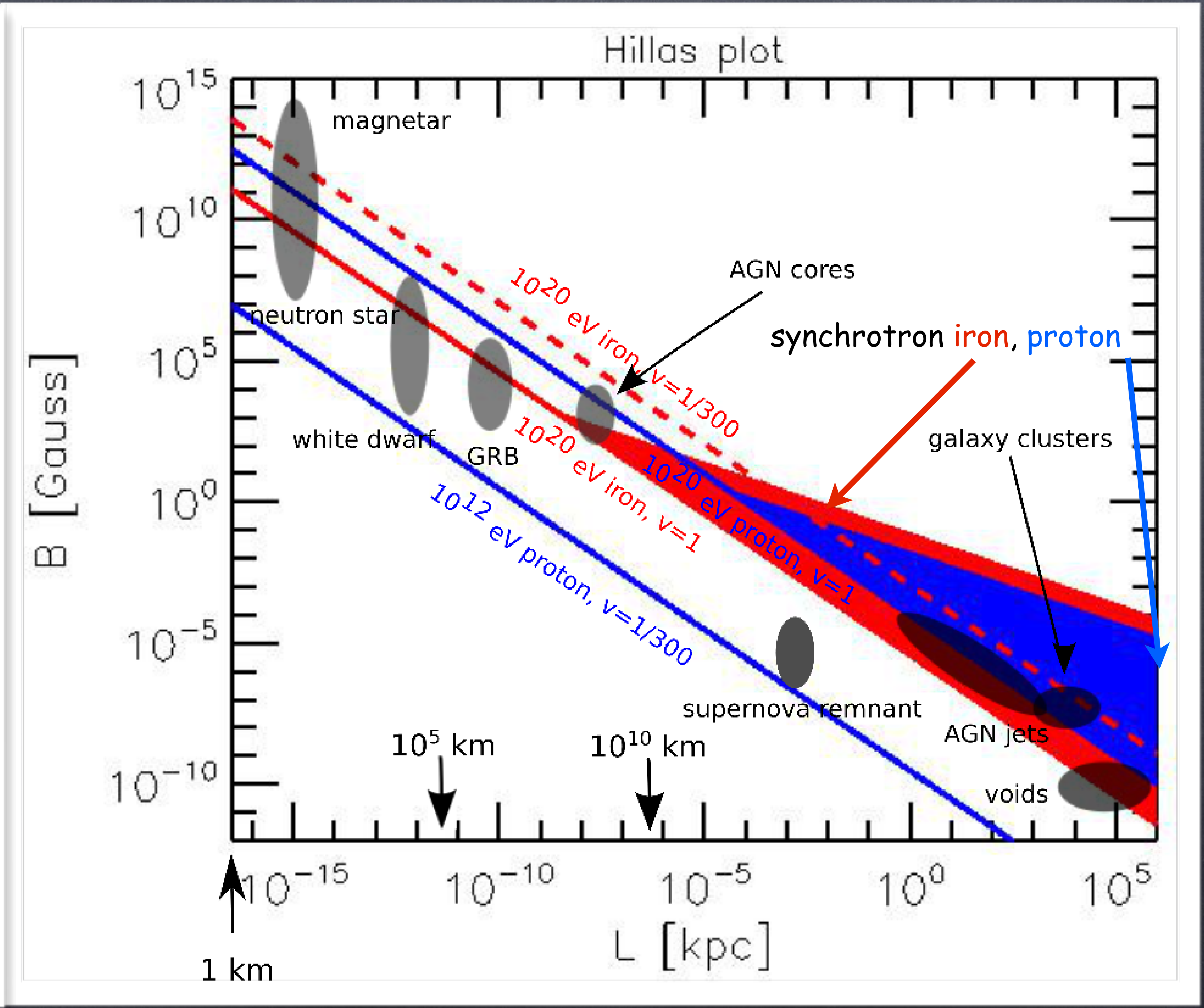
Cosmic ray versus neutrino induced air showers



1^{st} Order Fermi Shock Acceleration





Fractional energy gain per shock crossing $\sim u_1 - u_2$ on a time scale r_L/u_2 .

Together with downstream losses this leads to a spectrum E^{-q} with $q > 2$ typically.

Confinement, gyroradius < shock size, and energy loss times define maximal energy

Some general Requirements for Sources

Accelerating particles of charge eZ to energy E_{max} requires induction $\varepsilon > E_{max}/eZ$. With $Z_0 \sim 100\Omega$ the vacuum impedance, this requires dissipation of minimum power of

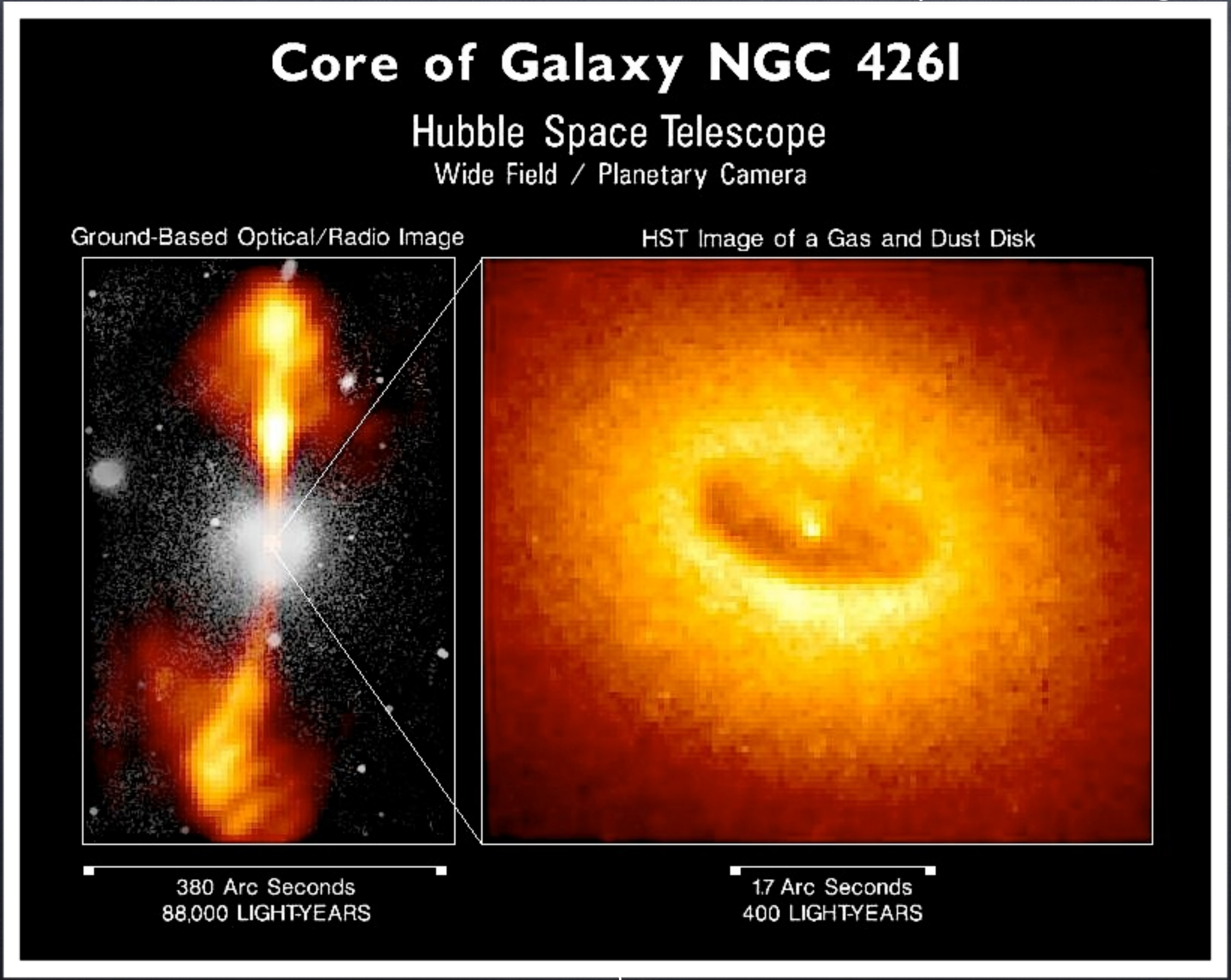
$$L_{\rm min} \sim \frac{\epsilon^2}{Z_0} \simeq 10^{45}\, Z^{-2} \left(\frac{E_{\rm max}}{10^{20}\,{\rm eV}}\right)^2 \;{\rm erg\,s^{-1}}$$

This „Poynting" luminosity can also be obtained from $L_{min} \sim (BR)^2$ where BR is given by the „Hillas criterium":

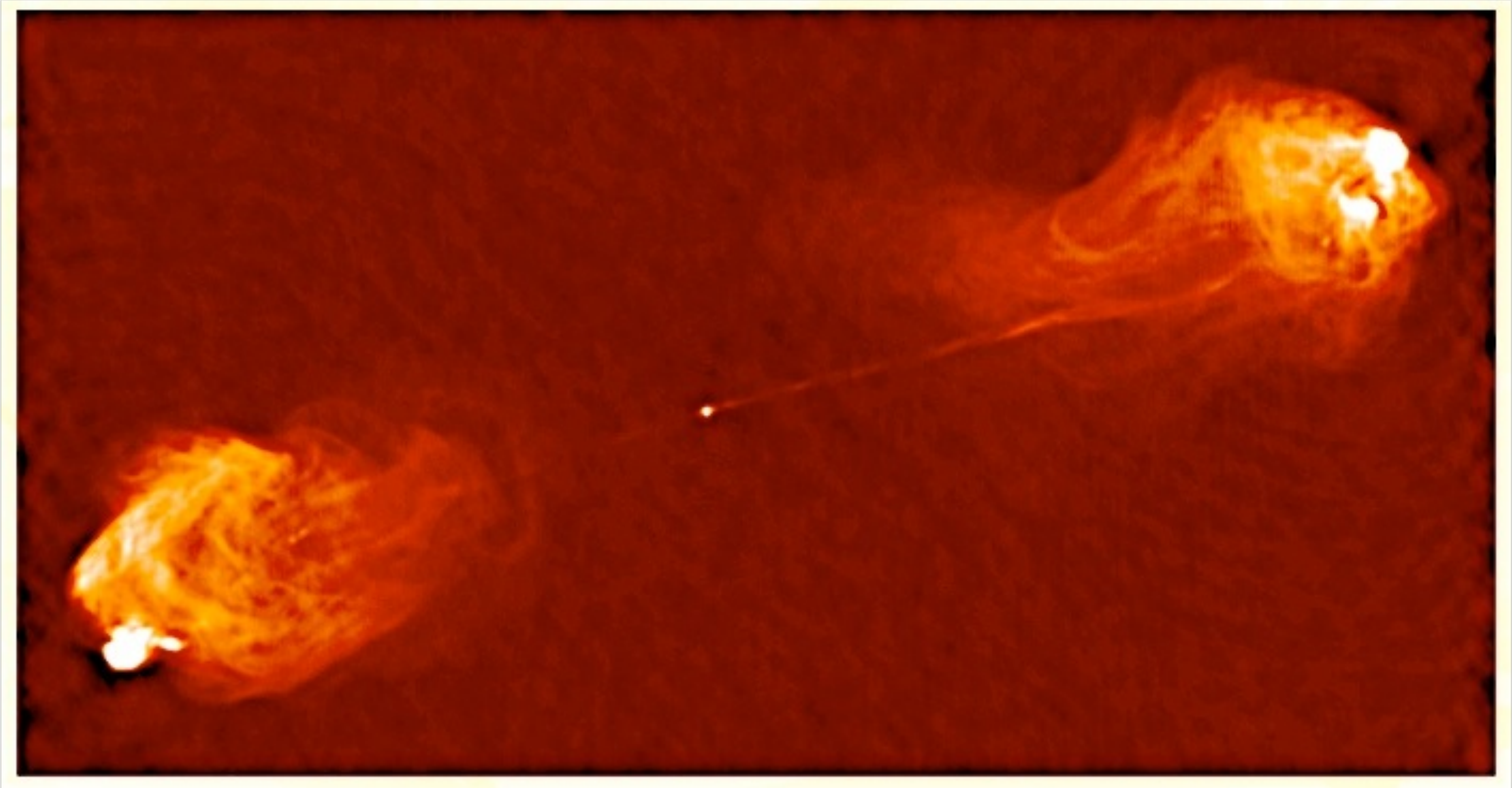
$$BR > 3\times 10^{17}\,\Gamma^{-1}\left(\frac{E_{\rm max}/Z}{10^{20}\,{\rm eV}}\right)\;{\rm Gauss\,cm}$$

where Γ is a possible beaming factor.
If most of this goes into electromagnetic channel, only AGNs and maybe gamma-ray bursts could be consistent with this.

A possible acceleration site associated with shocks in hot spots of active galaxies

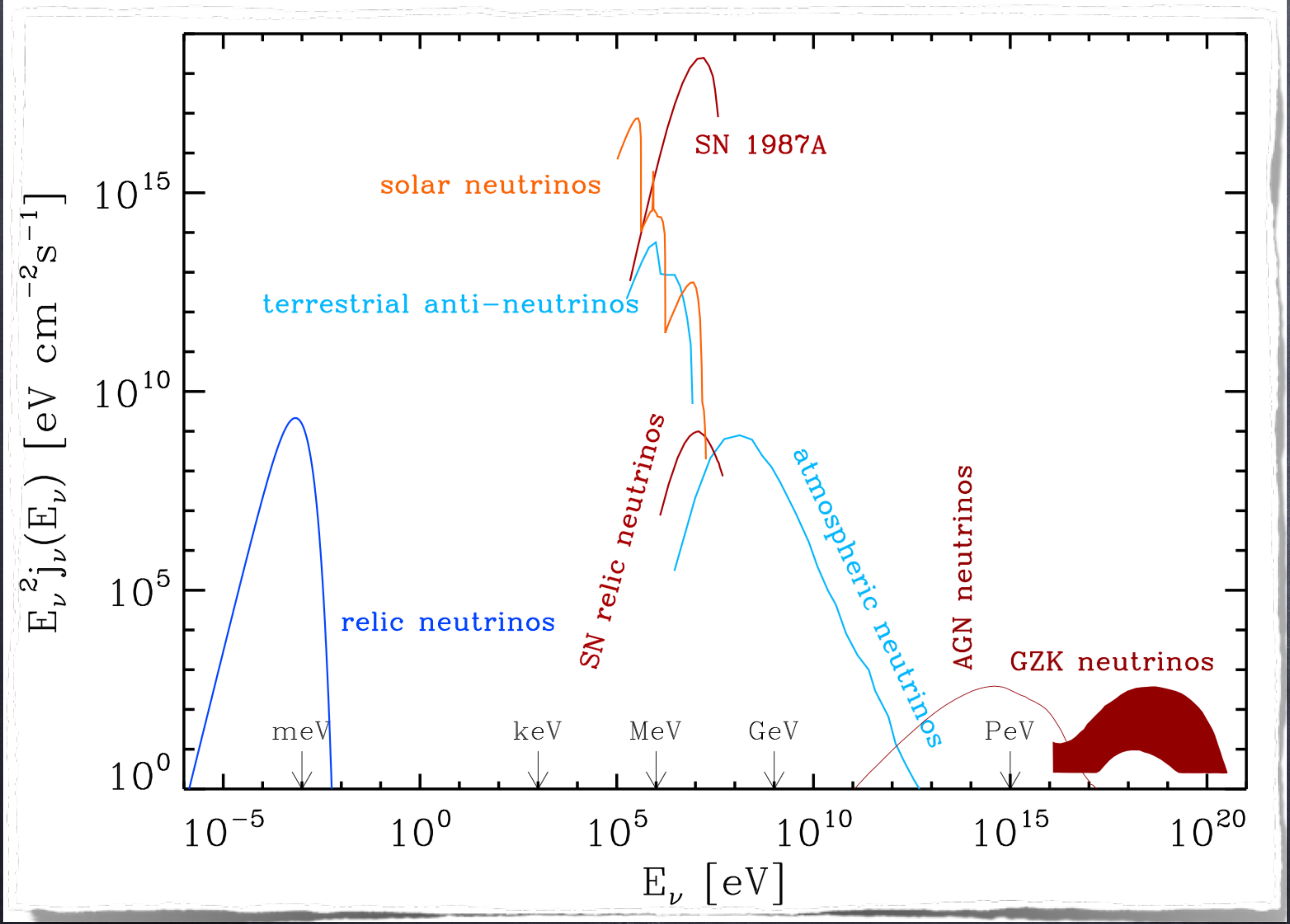


Or Cygnus A



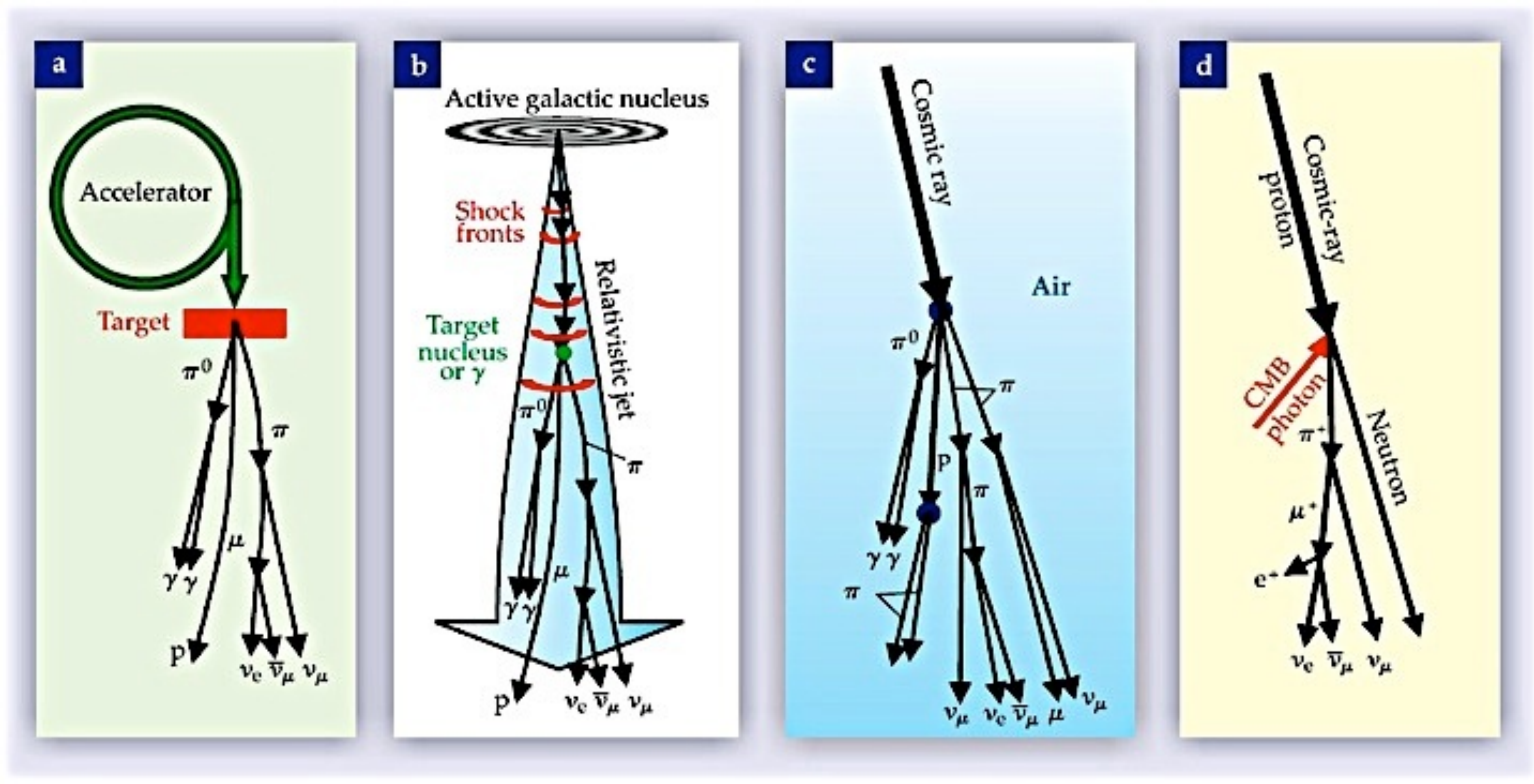
Very High High Energy Neutrinos

The „grand unified“ differential neutrino number spectrum

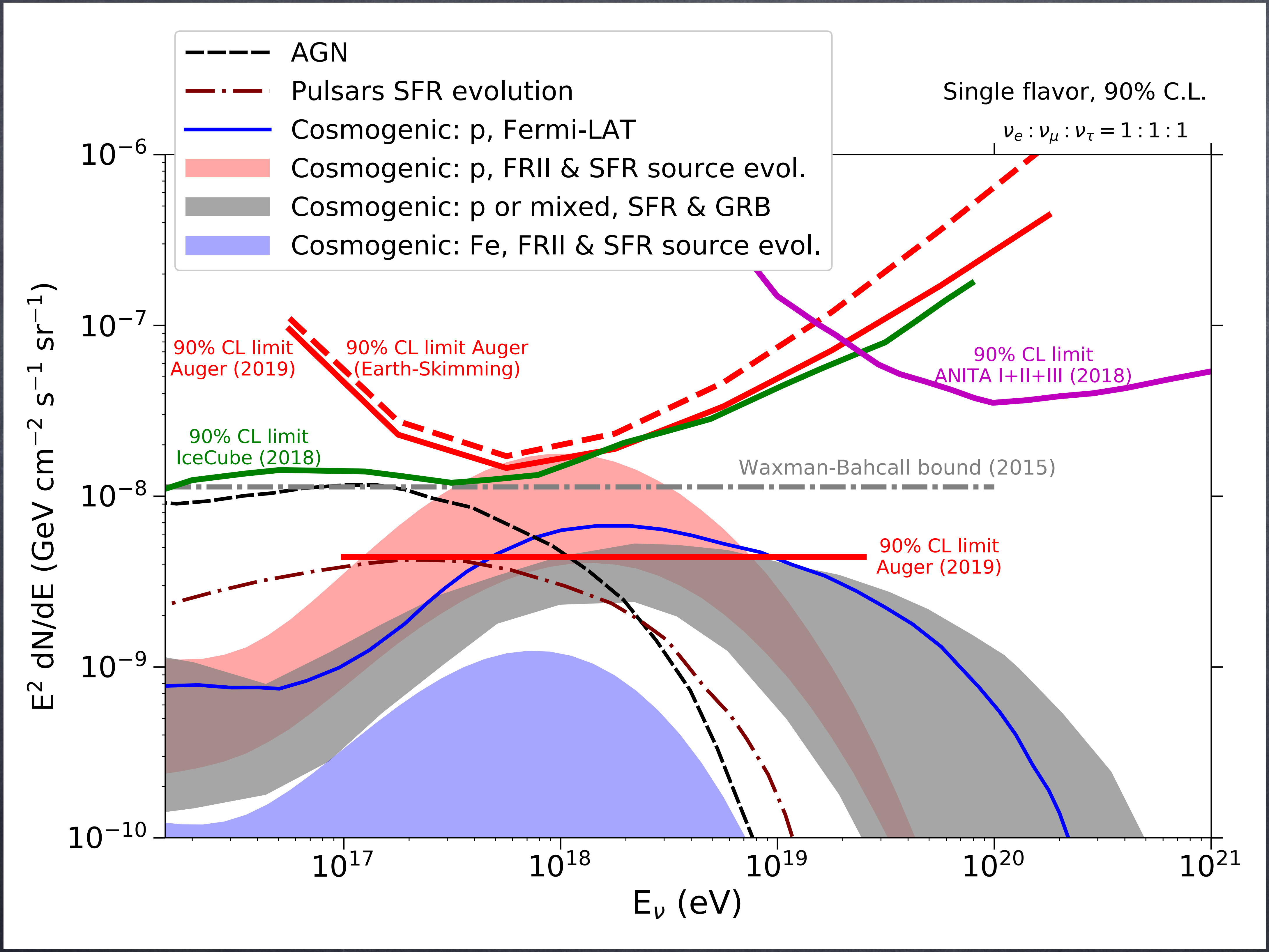


G. Sigl, book
"Astroparticle Physics:
Theory and Phenomenology",
Atlantis Press/Springer 2016

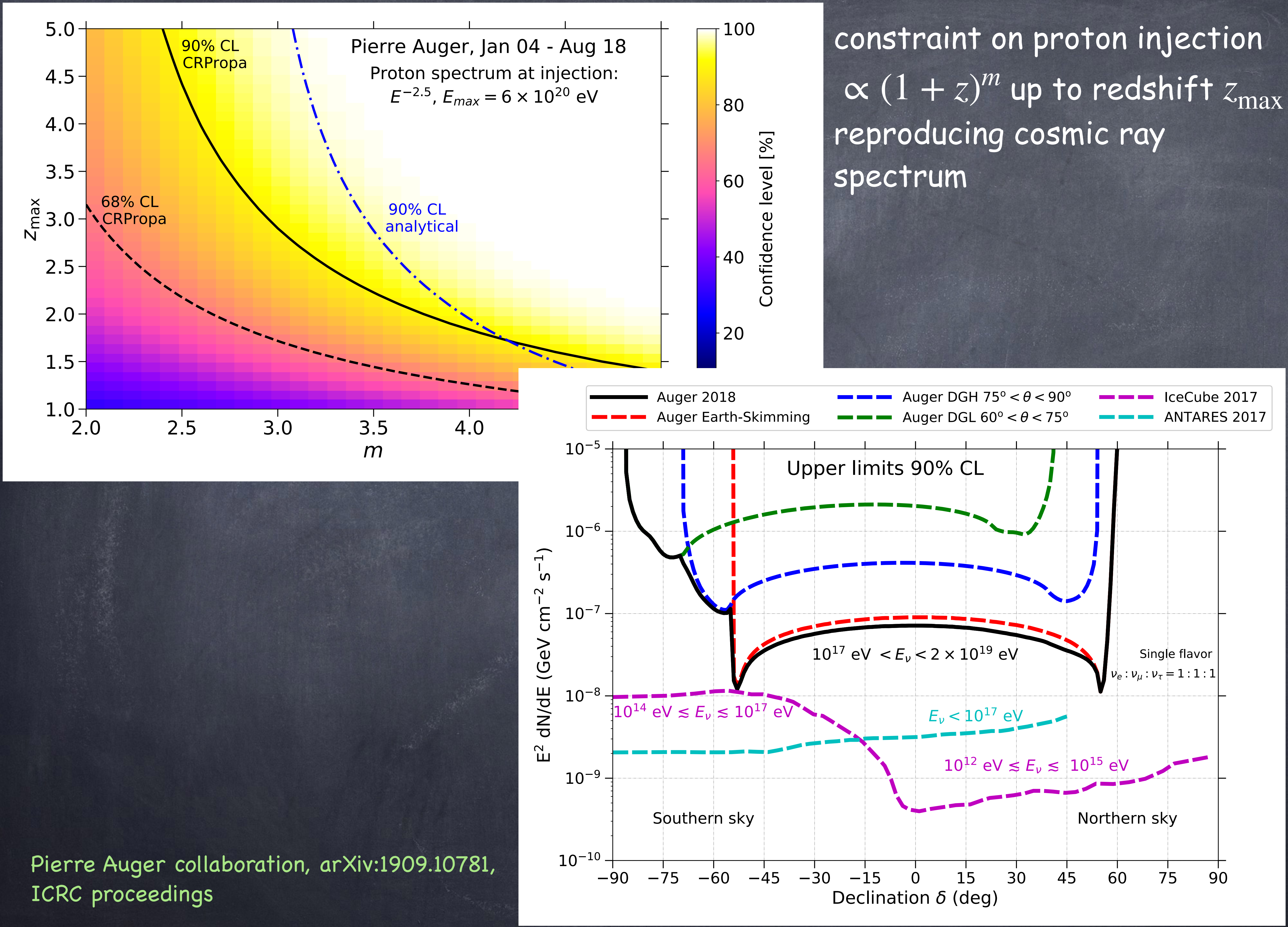
Summary of neutrino production modes



From Physics Today

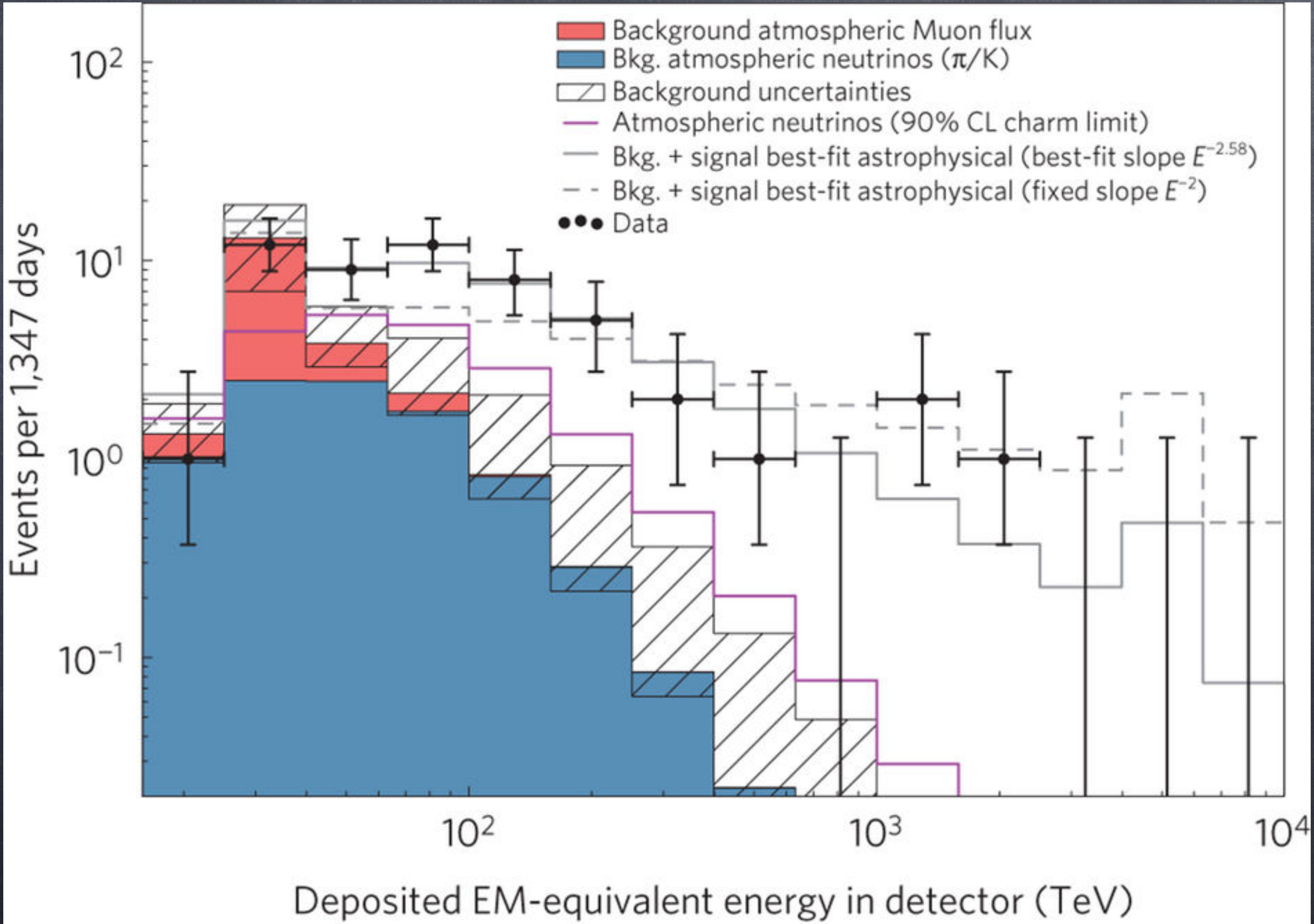


Pierre Auger collaboration, arXiv:1909.10781, ICRC proceedings constraint on proton injection $\propto (1+z)^m$ up to redshift $z_{\max}$ reproducing cosmic ray spectrum



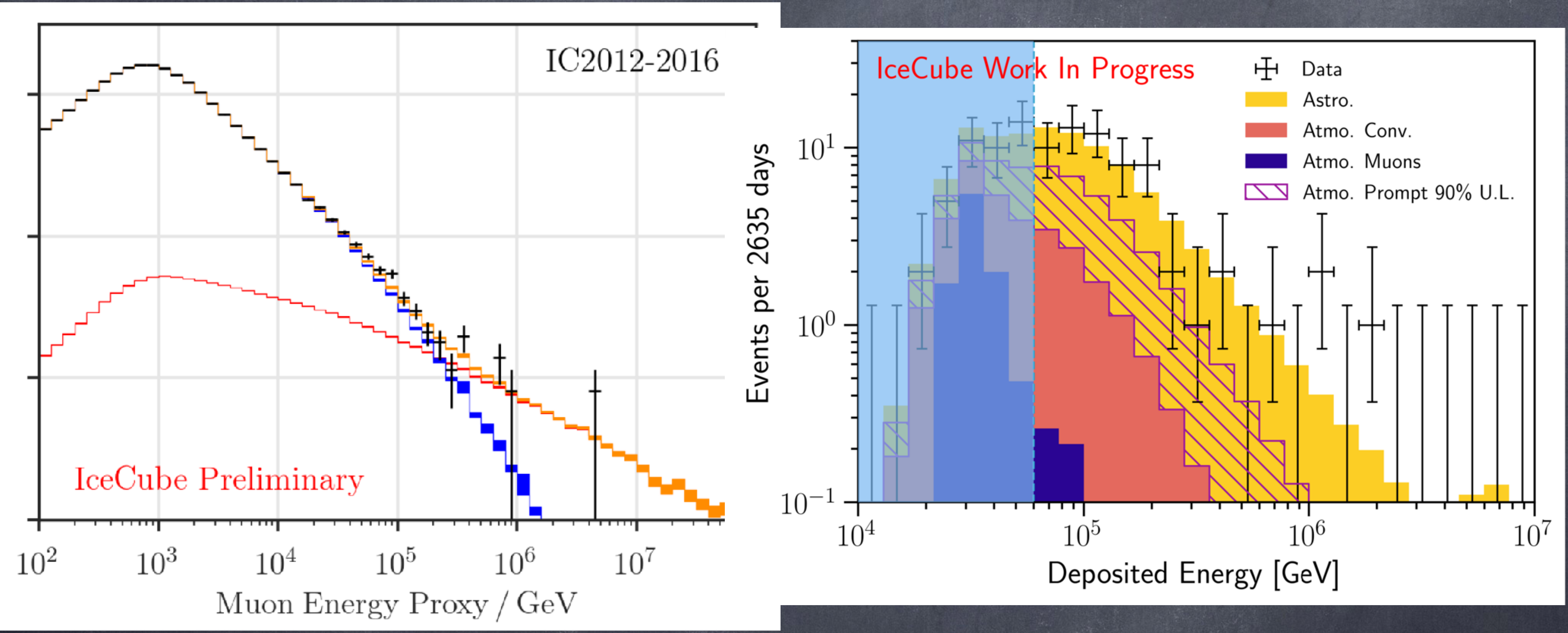
Pierre Auger collaboration, arXiv:1909.10781, ICRC proceedings

IceCube observed about 50 events above atmospheric background



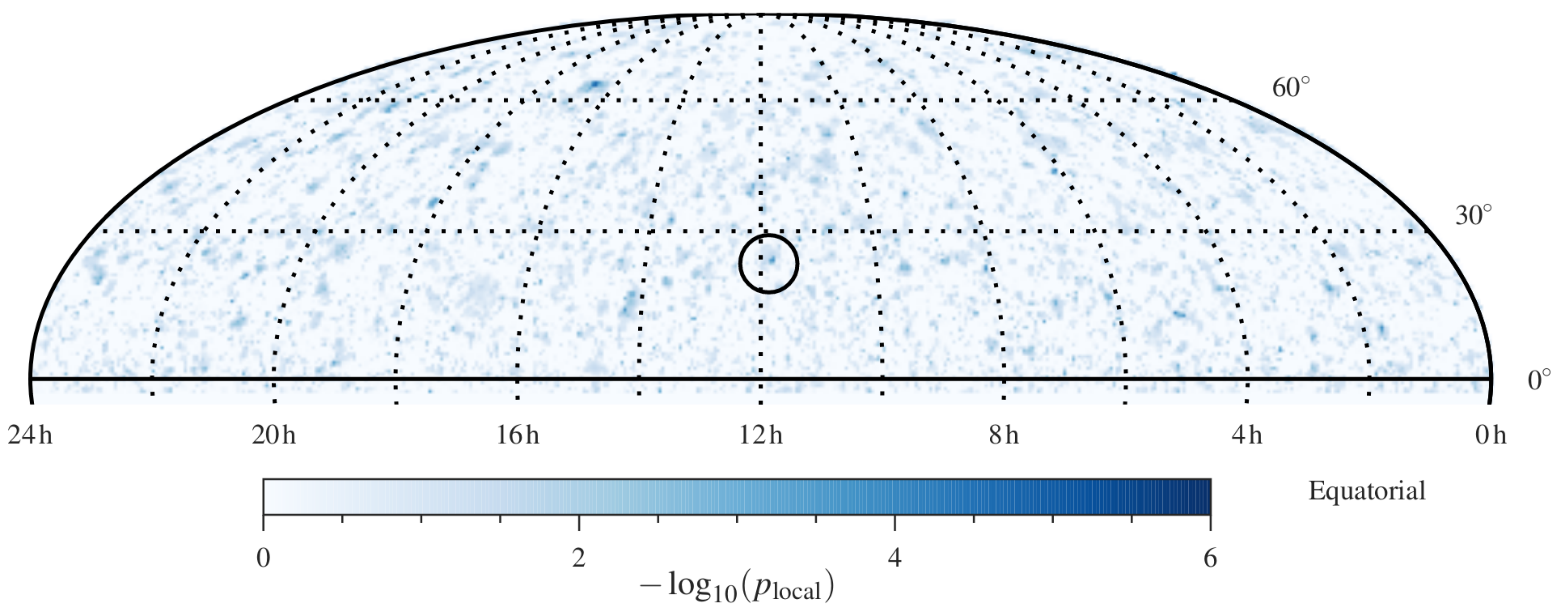
F. Halzen, Nature Physics 13 (2016) 232

IceCube observed about 50 events above atmospheric background



number of observed through-going tracks (left panel) and high energy starting events (right panel)

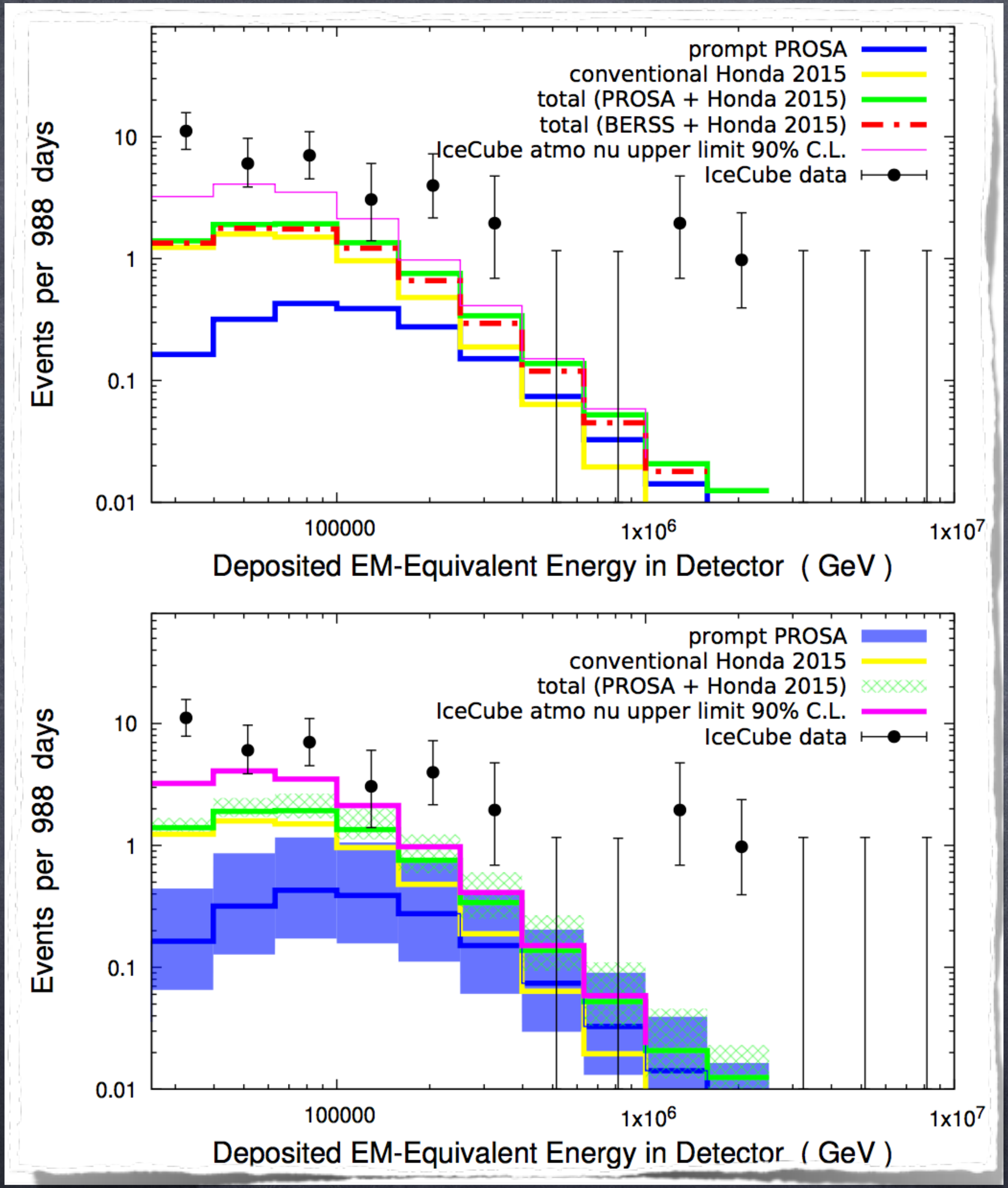
IceCube collaboration, arXiv:1909.12182



significance of search for time-integrated, point-like neutrino emission using through-going track events as function of possible source position

IceCube collaboration, arXiv:1909.12182

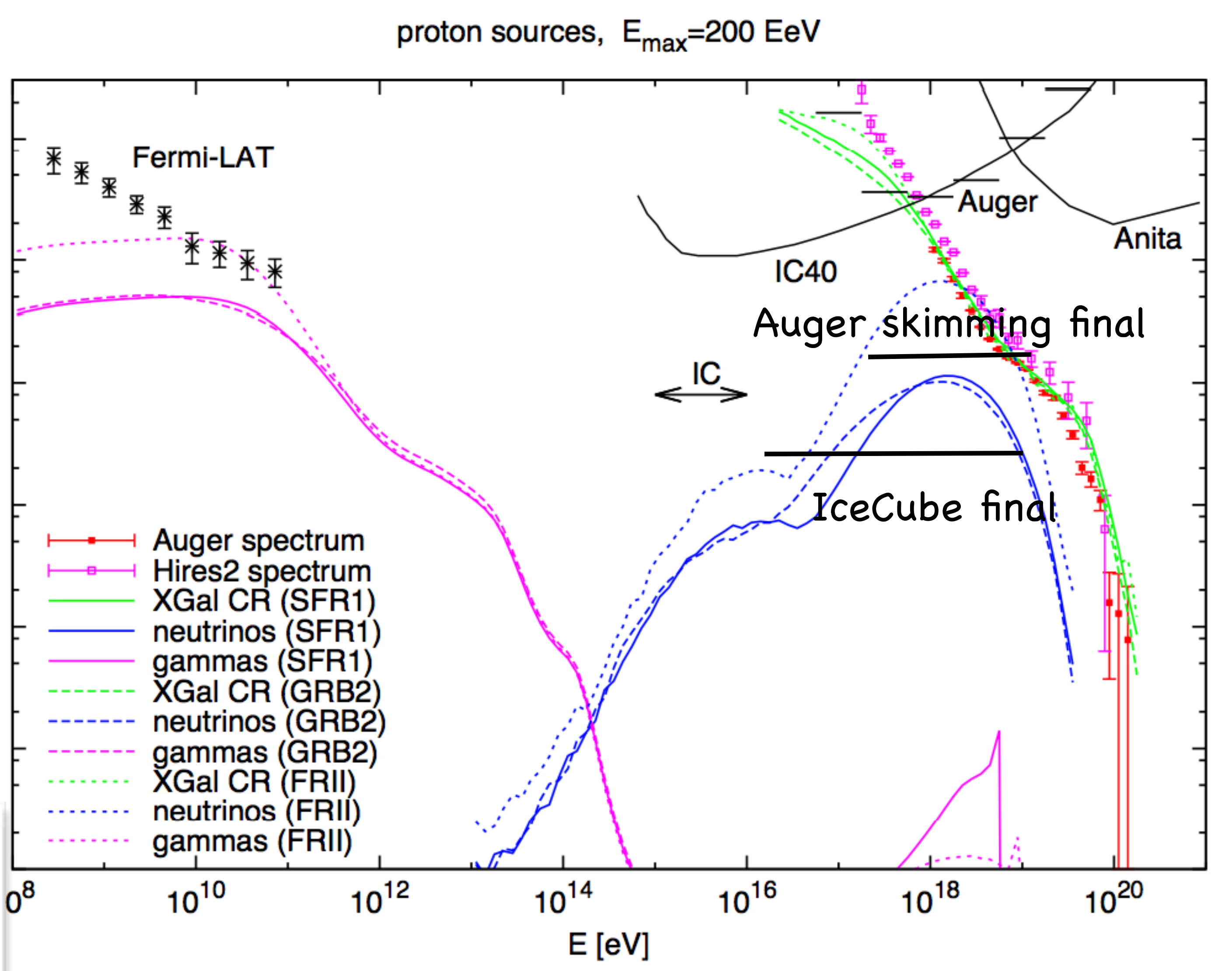
predicted and observed IceCube neutrino fluxes based on PROSA (Proton Structure Analysis in Hadronic Collisions) PDF



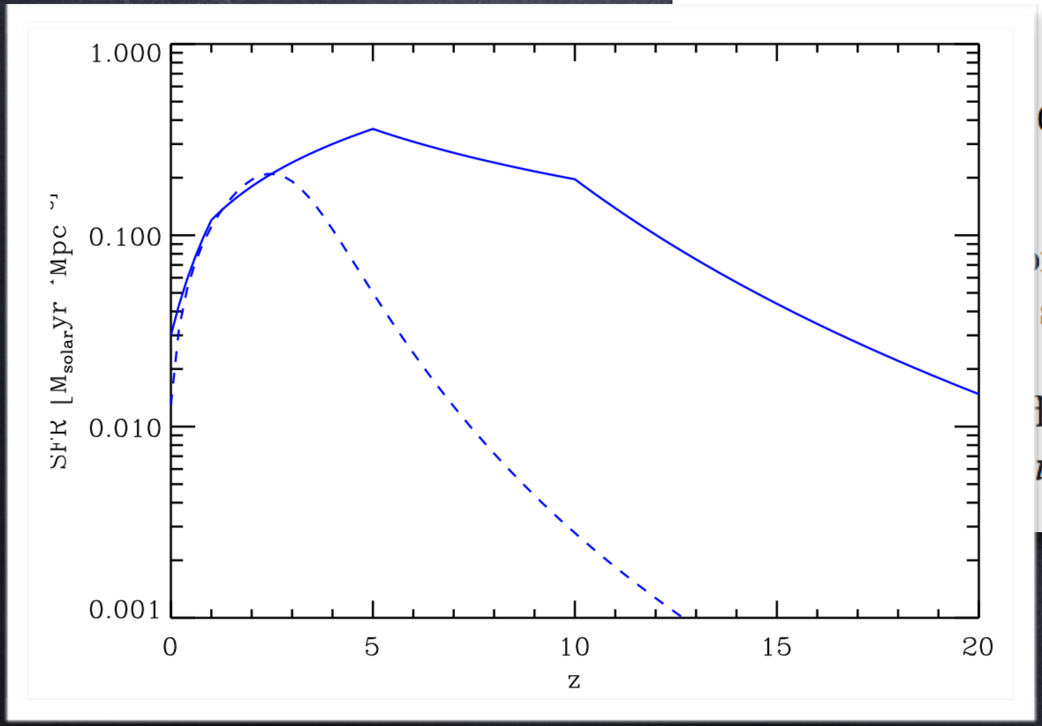
M. Garzelli et al., JHEP 05 (2017) 004

Cosmogenic Neutrinos: Maximal Fluxes for Pure Proton Injection insufficient to explain IceCube neutrinos

- Including secondary photons
- strong source evolution is here constrained by Fermi-LAT results



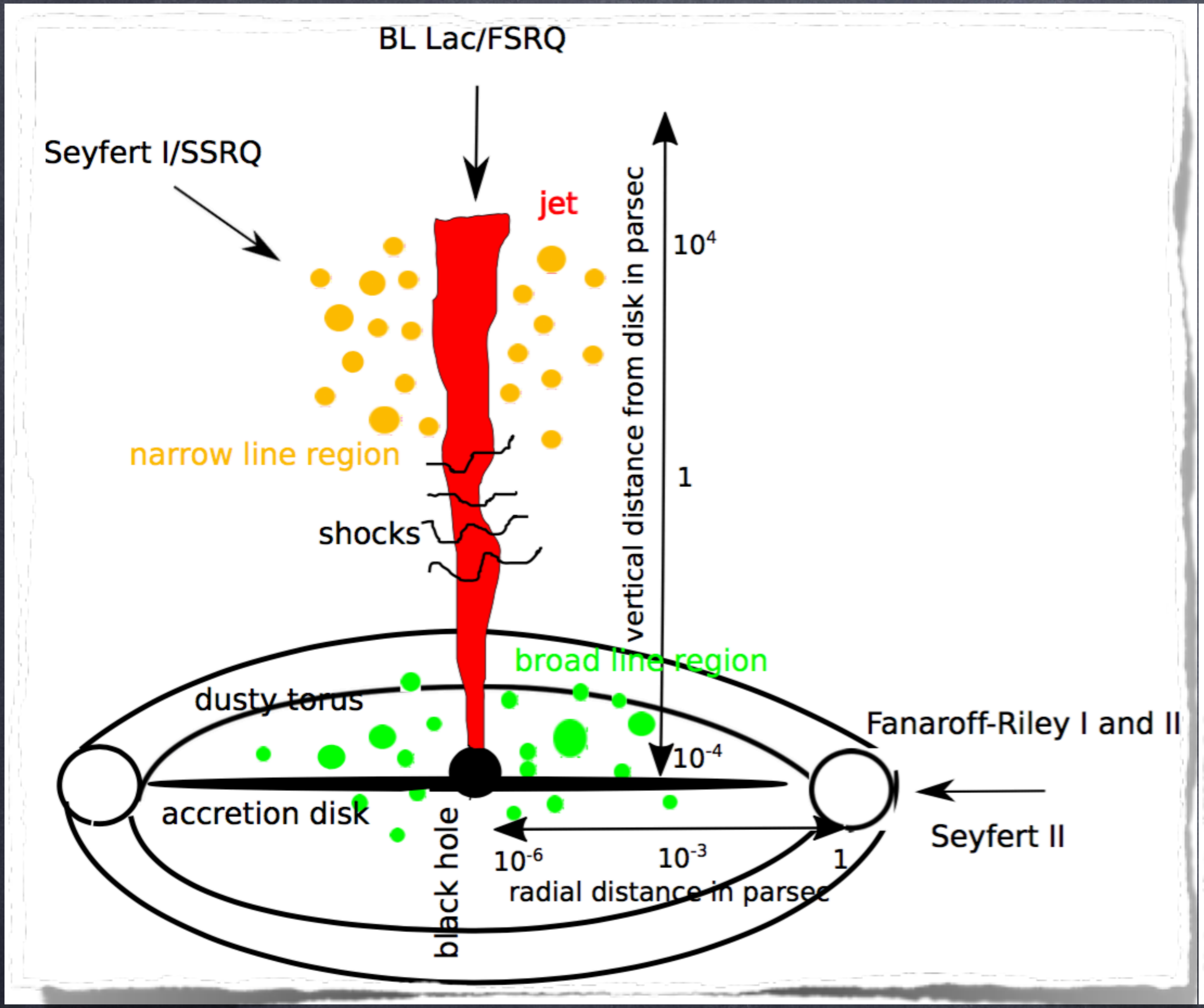
n scenario with $E_{\max} = 200\,\text{EeV}$ for different source evolution models (SFR1, GRB2 source spectral index is $\alpha = 2.4$ for the SFR1 and GRB2 models, while $\alpha = 2.2$ for Indicated are the propagated proton spectrum, the resulting (all flavor) neutrino luxes. The photon background measured by Fermi-LAT [10] is indicated, besides the ν bounds included in figure 1.

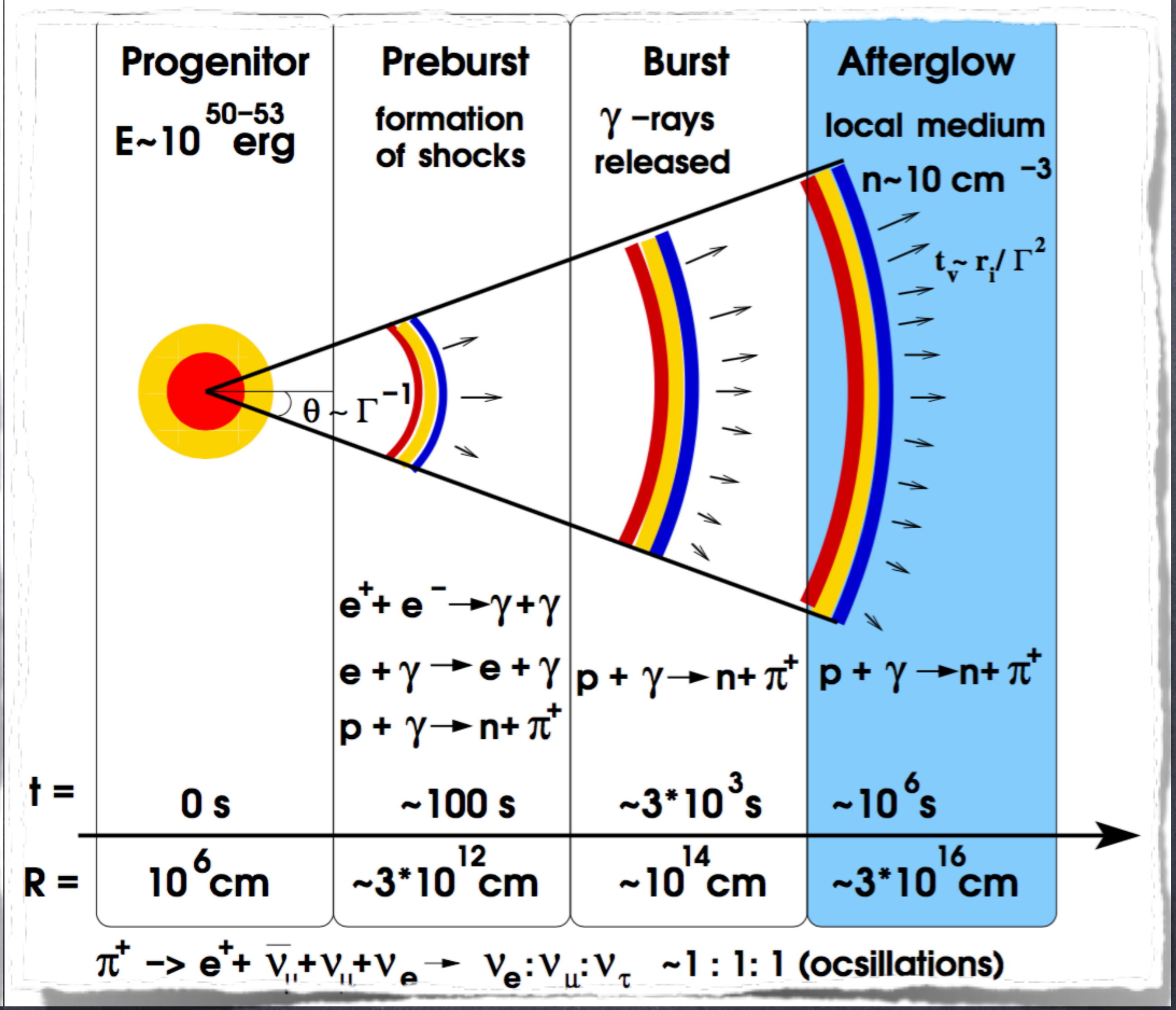


Roulet, Sigl, van Vliet, Mollerach, JCAP 1301, 028

Discrete Extragalactic High Energy Neutrino Sources

IceCube neutrinos should be produced mostly within sources, not during propagation





active galaxies **gamma ray bursts**

Figures adapted from J. Becker-Tjus, Phys.Rep. 458 (2008) 173

Neutrino Fluxes from Gamma-Ray Bursts

GRBs are optically thick to charged cosmic rays and nuclei are disintegrated
=> only neutrons escape and contribute to the UHECR flux by decaying back into protons

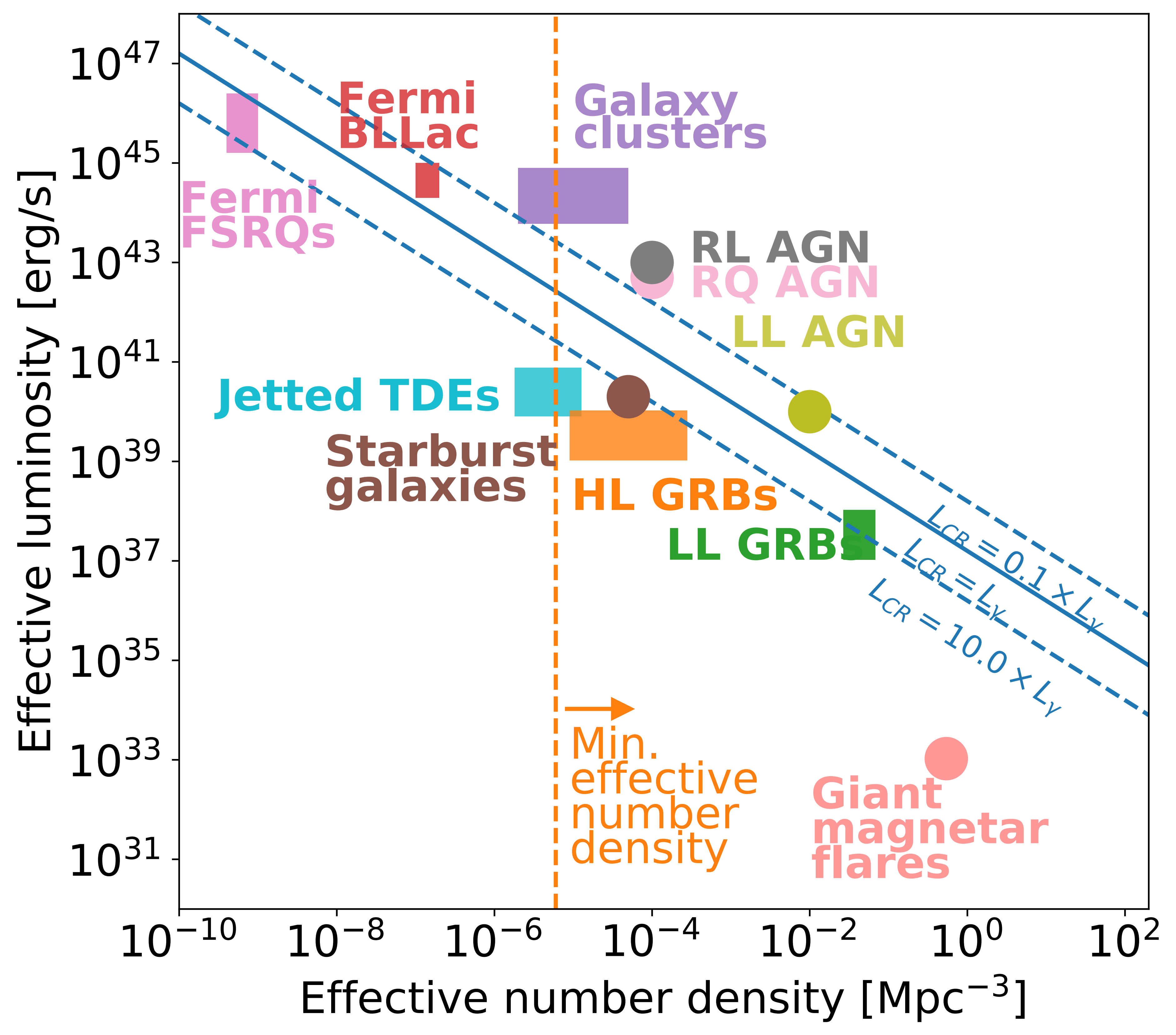
Diffuse neutrino flux from GRBs can thus be linked to UHECR flux (if it is dominantly produced by GRBs)

$$\Phi_\nu(E_\nu) \sim \frac{1}{\eta_\nu}\Phi_p\left(\frac{E}{\eta_\nu}\right) ,$$

where $\eta_\nu \simeq 0.1$ is average neutrino energy in units of the parent proton energy.

Above ~ 10^{17} eV neutrino spectrum is steepened by one power of E_ν because pions/muons interact before decaying

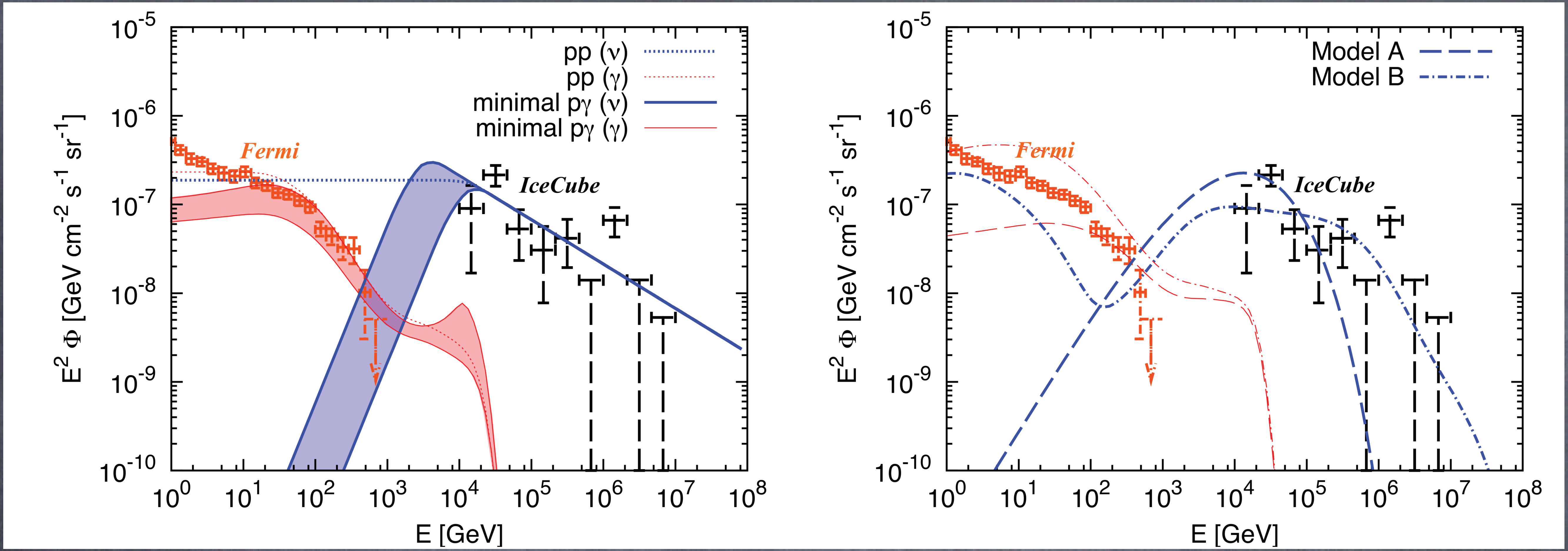
Correlation studies with GRBs now constrain the GRB contribution to observed diffuse neutrino flux to < 1%, see IceCube collaboration Astrophys.J. 824 (2016) 115 [arXiv:1601.06484];
the relation above then also implies subdominant contribution of GRBs to ultra-high energy cosmic rays



luminosity versus number density for continuous sources or (total energy released)/T versus (rate per volume)*T for intermittent sources with effective time delay T=3x10^5 y:

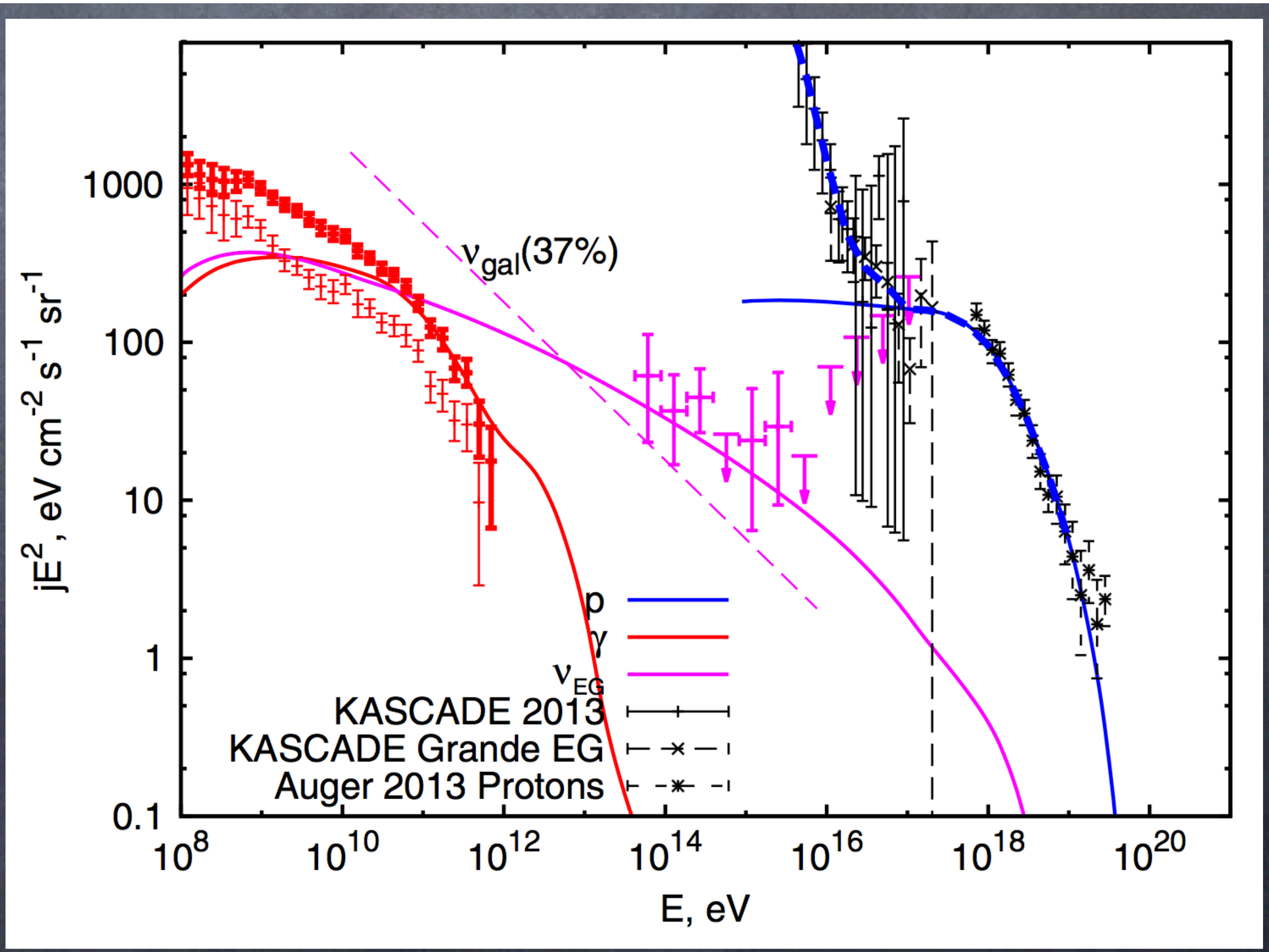
diagonal lines from UHECR flux, minimal number density from lack of significant UHECR clustering

Alves Batista et al., ``Open Questions in Cosmic Ray Research at ultra-high energies”, Front.Astron.Space Sci. 6 (2019) 23 [arXiv:1903.06714]



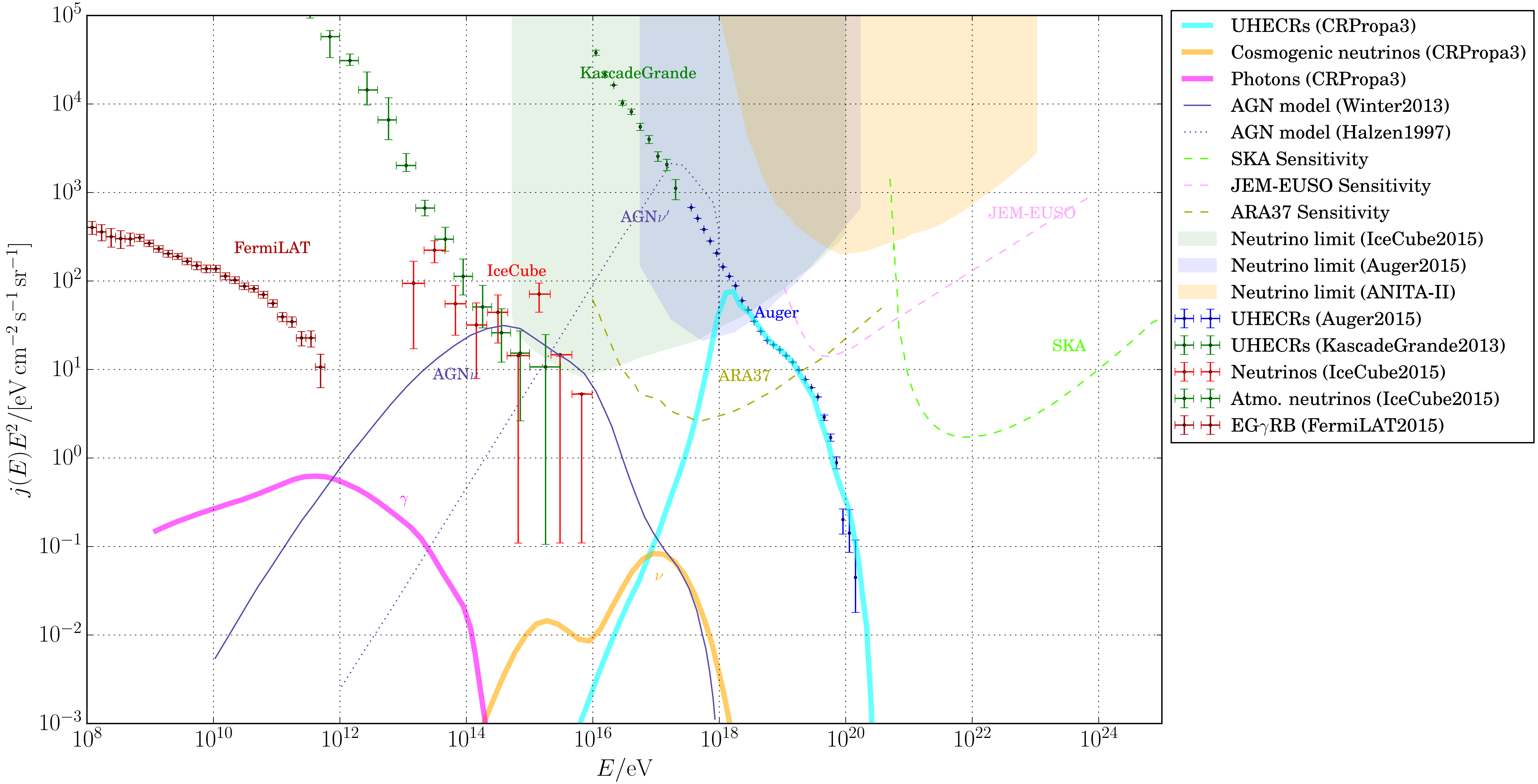
Murase, Guetta, Ahlers, PRL 116}, 071101 (2016)

Sources may have to be “hidden” in gamma-rays and primary cosmic rays to be consistent with other data



Giacinti, Kachelrieß, Kalashev, Neronov, Semikoz, PRD 92}, 083016 (2015)

Multi-Messengers: The Big Picture



A. Dundovic, G. Sigl

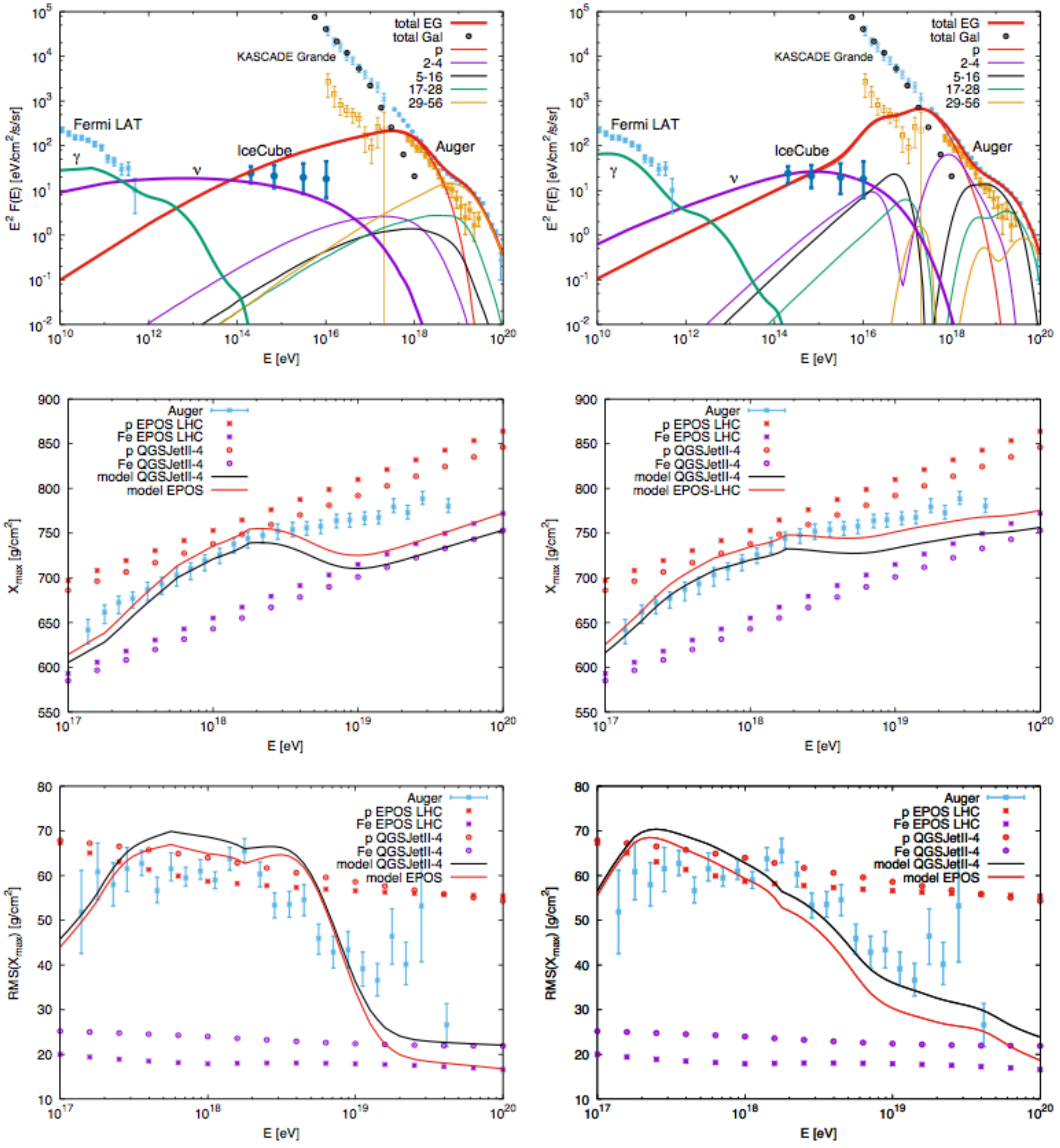


FIG. 1: Predictions for the diffuse flux (top) of five elemental groups together with the proton (orange errorbars) and total (blue errorbars) flux from KASCADE, KASCADE-Grande [9] and Auger (black errorbars) [8, 33], the EGRB from Fermi-LAT (red errorbars) [2], and the high-energy neutrino flux from IceCube (magenta errorbars) [3]; the middle and lower panels compare predictions for $X_{\max}$and RMS($X_{\max}$) using the EPOS-LHC [35] and QGSJET-II-04 [26] models to data from Auger [34]. Left panels for only hadronic interactions with $\alpha = 1.8$, $E_{\max} = 3 \times 10^{18}$ eV and BL Lac evolution. Right panels for both $A\gamma$ and Ap interactions with $\alpha = 1.5$, $E_{\max} = 6 \times 10^{18}$ eV, $\tau^{p\gamma} = 0.29$ and AGN evolution. The hadronic interaction depth is normalised as $\tau_0^{pp} = 0.035$.

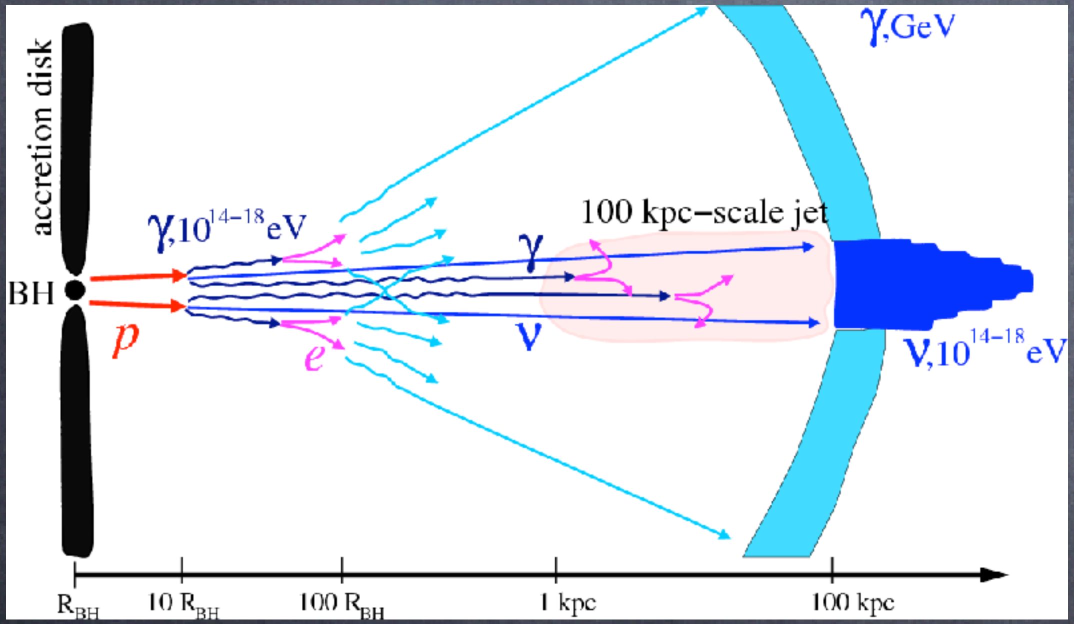
a recent “minimal” model that explains diffuse spectra of primary cosmic rays, secondary gamma-rays and neutrinos in which primary cosmic rays interact hadronically and/or photo-hadronically around the sources

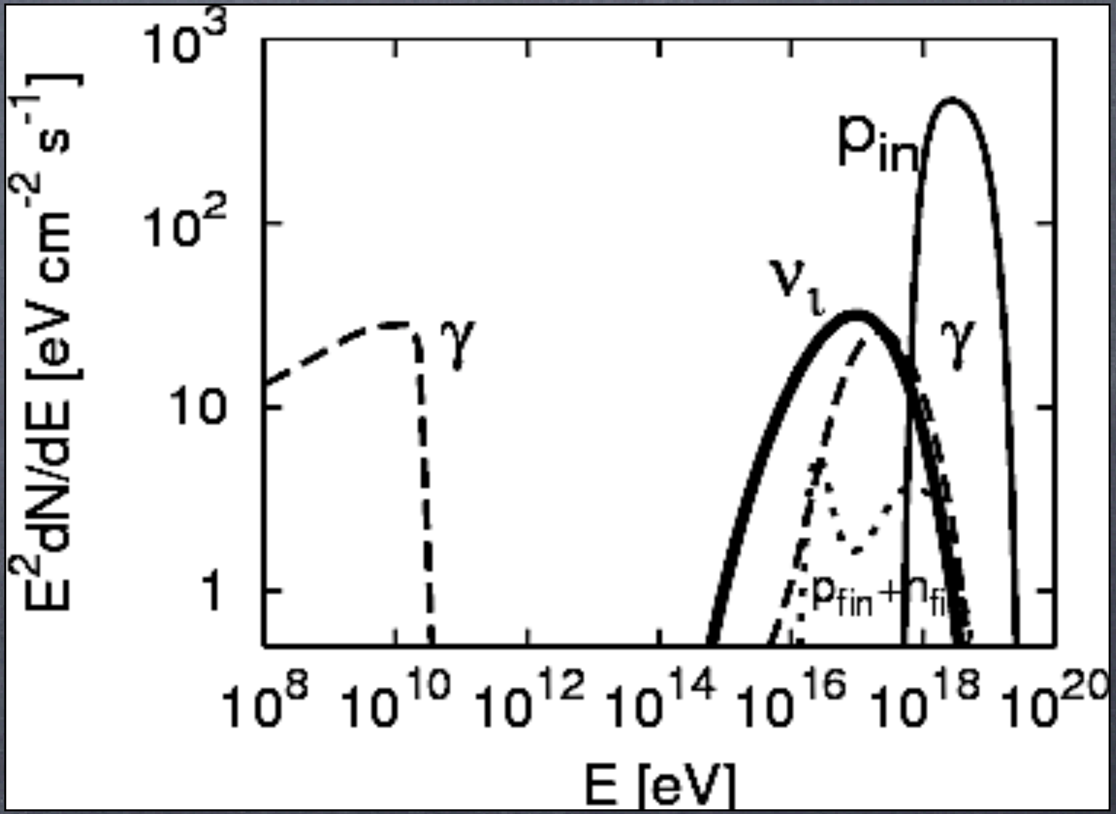
M. Kachelriess et al., Phys.Rev. D96 (2017) 083006 [arXiv: 1704.06893]

General Multi-Messenger Aspects

Blazars emitting significant neutrino fluxes should be loud in GeV γ-rays, but NOT in γ-rays above TeV.

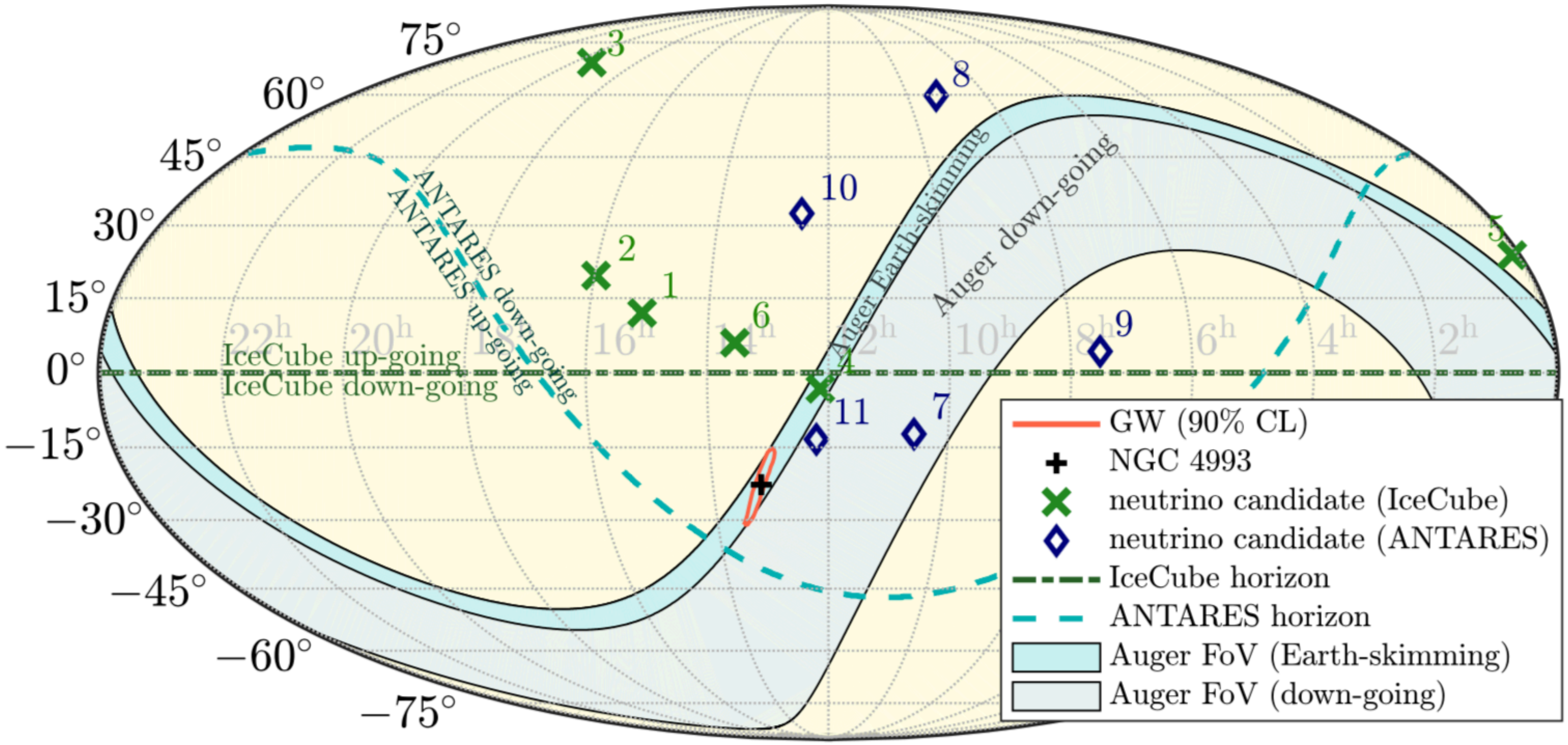
This is because TeV γ-rays pair produce with “blue bump” photons of ~10 eV energy with a cross section $\sim\sigma_{Th} \sim 1$ b about a factor 10^4 larger than the pγ cross section that produces the neutrinos => If loud in > TeV γ-rays, optical depth for neutrino production would be very small.





Neronov and Semikoz, Phys.Rev.D66 (2002) 123003

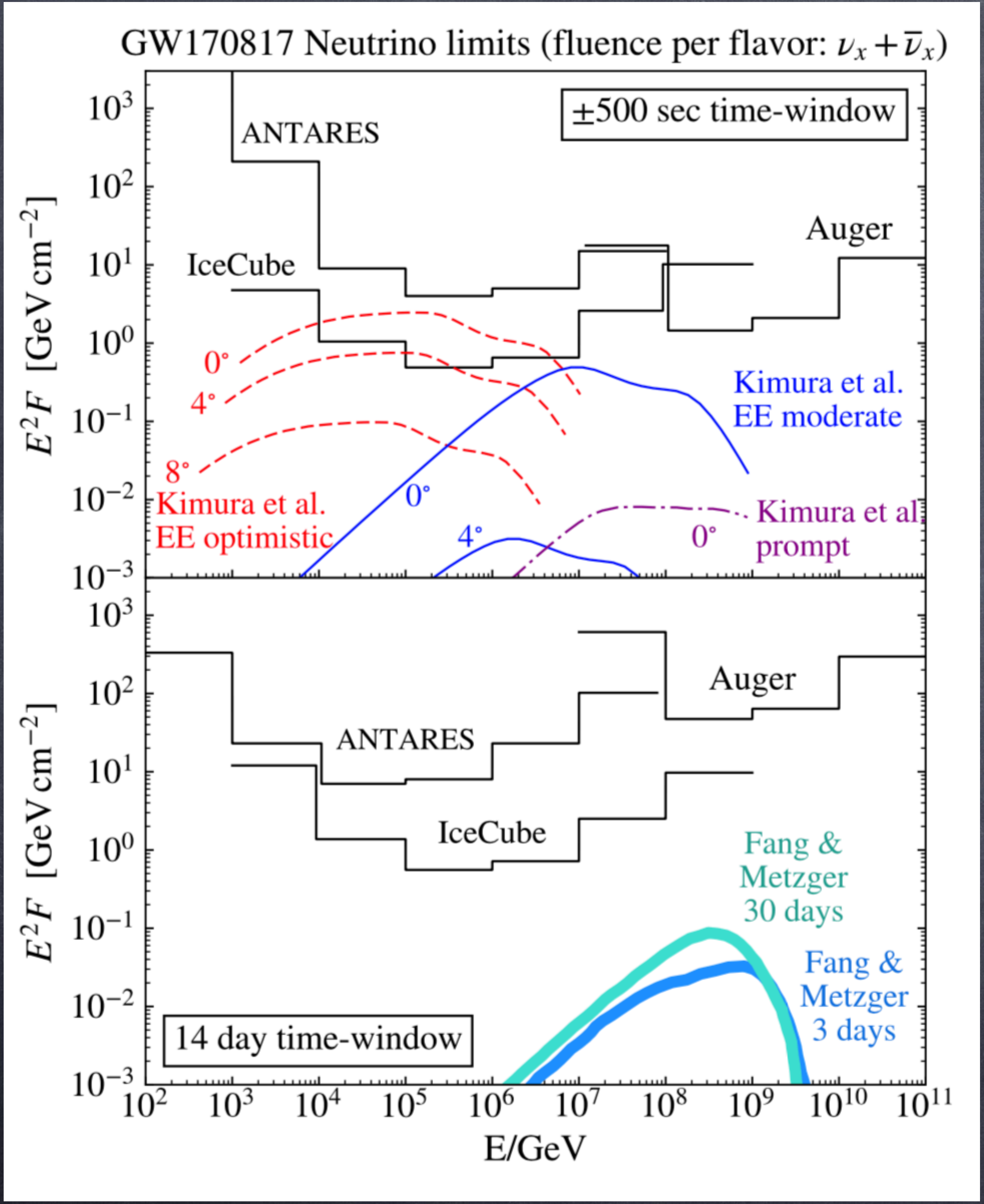
High Energy Neutrinos and Gravitational Waves



Antares, IceCube, Auger, LIGO, Virgo, arXiv:1710.05839, to appear in ApJ Lett

Figure 1. Localizations and sensitive sky areas at the time of the GW event in equatorial coordinates: GW 90% credible-level localization (red contour; Abbott et al. 2017c), direction of NGC 4993 (black plus symbol; Coulter et al. 2017a), directions of IceCube's and ANTARES's neutrino candidates within 500 s of the merger (green crosses and blue diamonds, respectively), ANTARES's horizon separating down-going (north of horizon) and up-going (south of horizon) neutrino directions (dashed blue line), and Auger's fields of view for Earth-skimming (darker blue) and down-going (lighter blue) directions. IceCube's up-going and down-going directions are on the northern and southern hemispheres, respectively. The zenith angle of the source at the detection time of the merger was 73.8° for ANTARES, 66.6° for IceCube, and 91.9° for Auger.

curiously, around the time of GW170817 Auger was in "Earth skimming mode" with maximal sensitivity, allowing relatively strong constraints



main message: most optimistic models start to be constrained

Antares, IceCube, Auger, LIGO, Virgo, Astrophys.J. 850 (2017) L35 [arXiv:1710.05839]

Probes of Quantum Gravity Effects with Neutrinos

Dispersion relation between energy E, momentum p, and mass m may be modified by non-renormalizable effects at the Planck scale M_{Pl},

$$p^2 + m^2 = E^2 \left[1 - \sum_{n=1}^{\infty} \xi_n \left(\frac{E}{M_{\rm Pl}} \right)^n \right]$$

where most models, e.g. critical string theory, predict ξ=0 for lowest order.

For the i-th neutrino mass eigenstate this gives

$$p_i \simeq E + \frac{m_i^2}{2E} + \frac{1}{2} \sum_{n=1}^{\infty} \xi_n^{(i)} \frac{E^{n+1}}{M_{\rm Pl}}$$

The « standard » oscillation term becomes comparable to the new terms at energies

$$E \simeq M_{\rm Pl} \left(\frac{\Delta m^2}{M_{\rm Pl}^2 \xi_n} \right)^{\frac{1}{n+2}} \simeq 0.2\,,\, 2 \times 10^4\,,\, 1.8 \times 10^7\,,\, 1.7 \times 10^9\,\mathrm{GeV}$$

for $\xi_n \sim 1$, n=1, 2, 3, 4, respectively, and $\Delta m^2=10^{-3}$ eV^2, for which ordinary oscillation length is ~2.5(E/MeV) km.

See, e.g., Christian, Phys.Rev.D71 (2005) 024012

Other possible effects: Decoherence of oscillation amplitude with $\exp(-\alpha L)$:
Assume galactic neutron sources, L~10 kpc, giving exclusively electron-anti-neutrinos before oscillation. After oscillation the flavor ratio becomes 1:0:0 -> 0.56:0.24:0.20 without decoherence, but 0.33:0.33:0.33 with decoherence.

At E~1 TeV one has a sensitivity of $\alpha \sim 10^{-37}$ GeV (somewhat dependent on energy dependence of α)

Hooper, Morgan, Winstanley, Phys.Lett.B609 (2005): 206

We consider mass dimension 5 and 6 (non-renormalisable) operators for fermion fields ψ involving a time-like 4-vector field u^μ within a local effective field theory description,

$$\overline{\psi}\Big[-\frac{1}{M_{\rm Pl}}(u\cdot D)^2(\alpha_L^{(1)}P_L+\alpha_R^{(1)}P_R)-\frac{i}{M_{\rm Pl}^2}(u\cdot D)^3(u\cdot\gamma)(\alpha_L^{(2)}P_L+\alpha_R^{(2)}P_R)$$
$$-\frac{i}{M_{\rm Pl}^2}(u\cdot D)\,\Box\,(u\cdot\gamma)(\tilde\alpha_L^{(2)}P_L+\tilde\alpha_R^{(2)}P_R)\Big]\psi\ ,$$

with $\alpha_{R,L}^{(d)},\tilde\alpha_{R,L}^{(d)}$ dimensionless constant and the right- and left-chiral projectors $P_{R,L}=(1\pm\gamma_5)/2$ and D_μ the gauge-invariant derivative and $u\cdot D=u^\mu D_\mu$ etc.
In the ultra-relativistic limit one can relabel to helicity states, $\alpha_+^{(d)}=\alpha_R^{(d)},\alpha_-^{(d)}=\alpha_L^{(d)}$, yielding the dispersion relations

$$E^2=p^2+m^2+f_\pm^{(0)}p^2+f_\pm^{(2)}\frac{p^4}{M_{\rm Pl}^2}\,,$$

with $f_\pm^{(0)}=\dfrac{m}{M_{\rm Pl}}(\alpha_-^{(1)}+\alpha_+^{(1)})\,,f_\pm^{(2)}=2\alpha_\pm^{(2)}+\alpha_-^{(1)}\alpha_+^{(1)}.$

We consider a more general dispersion relation of the form

$$E^2 - p^2 - (m_i)^2 = p^2 \sum_n \xi_i^{(n)} \left(\frac{p}{M_{\rm Pl}} \right)^n , \quad E^2 - p^2 - (m_i)^2 = p^2 \sum_n (-1)^n \xi_i^{(n)} \left(\frac{p}{M_{\rm Pl}} \right)^n$$

for mass eigenstate i for neutrinos and anti-neutrinos, respectively, see. e.g., Maccione, Liberati, Mattingly, JCAP 03 (2013) 039.

Sometimes the quantity

$$\delta_i = \sum_n \xi_i^{(n)} \left(\frac{p}{c_0 M_{\rm Pl}} \right)^n$$

is used because it is directly proportional to velocity differences. Also, the mass scales

$$M_i^{(n)} \equiv M_{\rm Pl} \left[\xi_i^{(n)} \right]^{-1/n}$$

are used in terms of which terms in the dispersion relation read $\left[p/M_i^{(n)} \right]^n$.

Time of flight differences over distance L:

$$\Delta T(p) = \frac{\Delta v}{c_0^2} L = \left[-\frac{c_0^2 m_i^2}{2p^2} + \xi_i^{(n)} \frac{n+1}{2} \left(\frac{p}{c_0 M_{\rm Pl}} \right)^n \right] \frac{L}{c_0}$$

For example, the coincident observation of gamma-ray (by MAGIC) and neutrino (by IceCube) emission from a flare of the blazar TXS 0506+056 can be translated into the constraint

$$\xi^{(1)} \lesssim 300\,, \quad M^{(1)} \gtrsim 3 \times 10^{16}\,\mathrm{GeV}$$
$$\xi^{(2)} \lesssim 10^{16}\,, \quad M^{(2)} \gtrsim 10^{11}\,\mathrm{GeV}$$

see Ellis et al., Phys. Lett. B789 (2019) 352.

Effects on neutrino oscillations: Additional oscillation phases have the form

$$\Delta\phi_{\rm LIV} = \frac{\Delta v}{c_0} \frac{EL}{4\hbar c_0}\,.$$

Anomalous reactions

neutrino Cherenkov emission, $\nu \to \nu\gamma$,

$$\tau_{\nu\gamma} \simeq \xi_n^{-2} \left(\frac{E}{1\ \mathrm{PeV}}\right)^{-(2n+5)} \quad 10^{26n-34}\ \mathrm{s}$$

neutrino splitting, $\nu \to \nu\nu\bar{\nu}$,

$$\tau_{\nu-\mathrm{splitting}} \simeq \frac{64\pi^3}{3G_F^2E^5}\xi_n^{-3}\left(\frac{M_{\mathrm{Pl}}}{E}\right)^{3n}, \quad \mathrm{e.g.\ for}\ n=1 \quad \tau_{\nu-\mathrm{splitting}} \simeq 10^{38}\xi_1^{-3}\left(\frac{E_\nu}{10\ \mathrm{GeV}}\right)^{-8} \mathrm{s}\,.$$

neutrino pair emission, $\nu \to \nu e^+e^-$,

$$\tau_{\nu-\mathrm{pair}} \simeq G_F^{-2}E^{-5}\xi_n^{-3}\left(\frac{M_{\mathrm{Pl}}}{E}\right)^{3n} \quad \mathrm{for}\ E > E_{\mathrm{pair}} = m_e\left(\frac{2}{\delta}\right)^{1/2}\,.$$

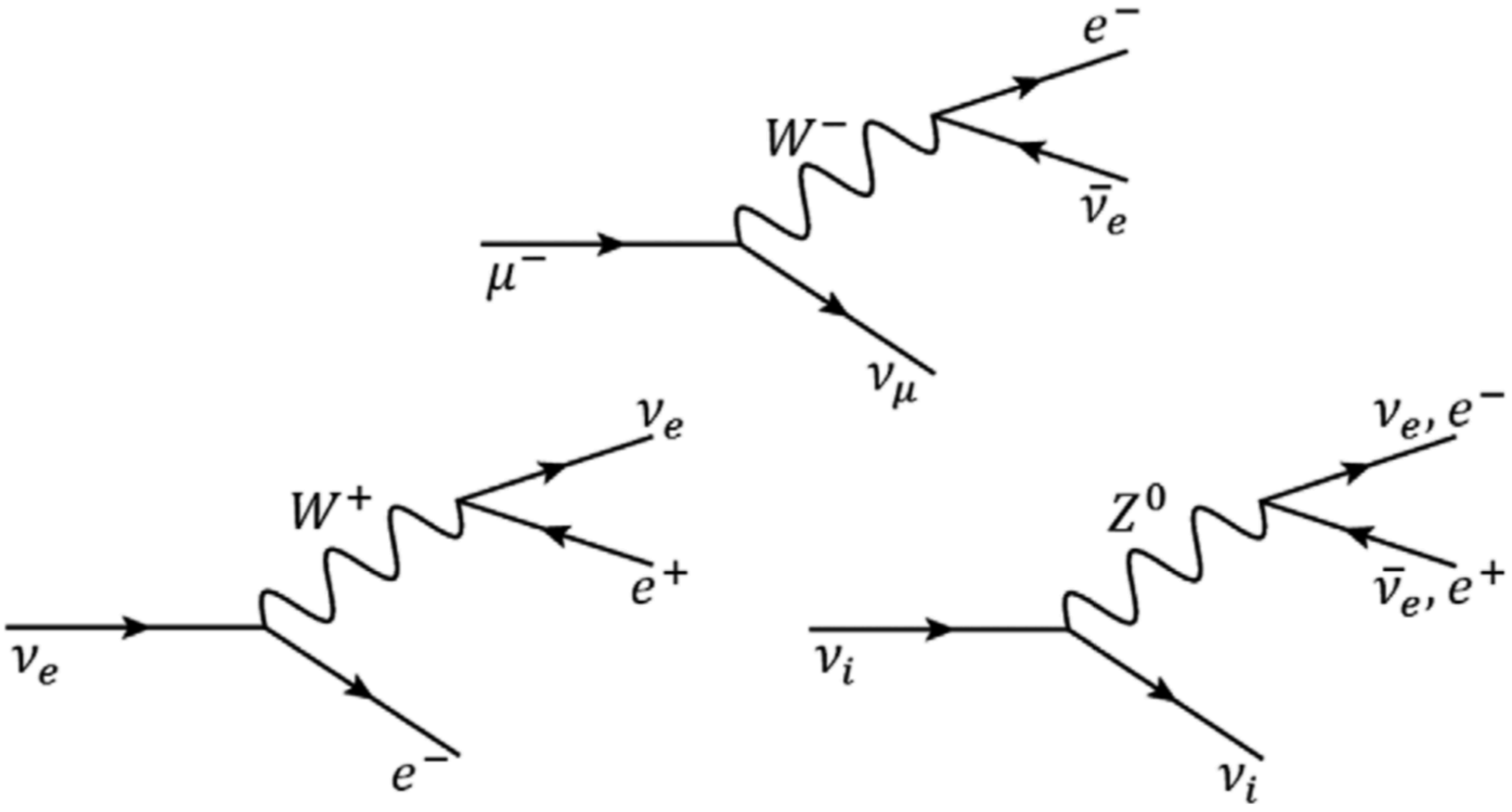
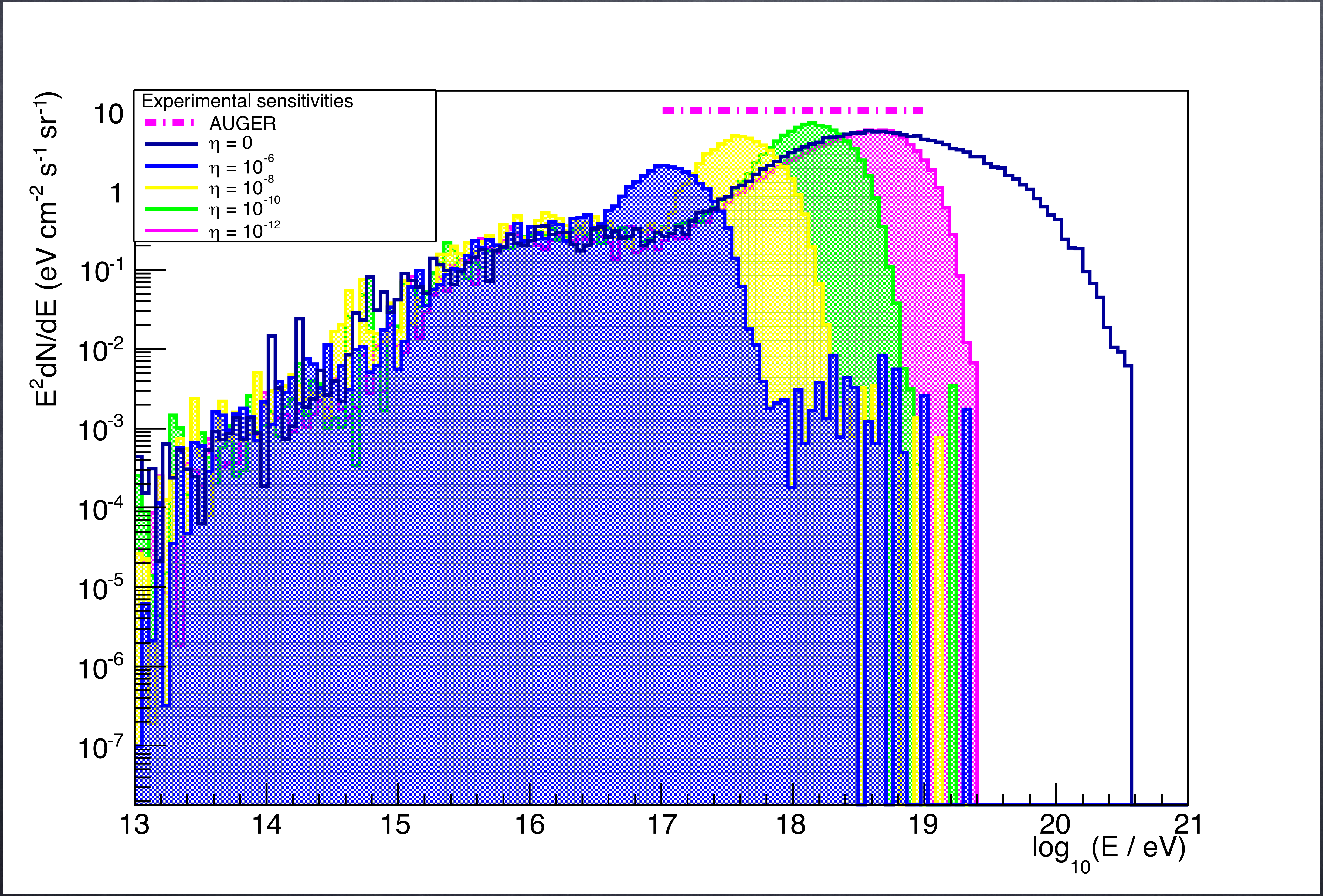


FIG. 1. Diagrams for muon decay (top), charged current mediated VPE (bottom left), and neutral current mediated neutrino splitting/VPE (bottom right). Time runs from left to right and the flavor index i represents e, μ, or τ neutrinos.

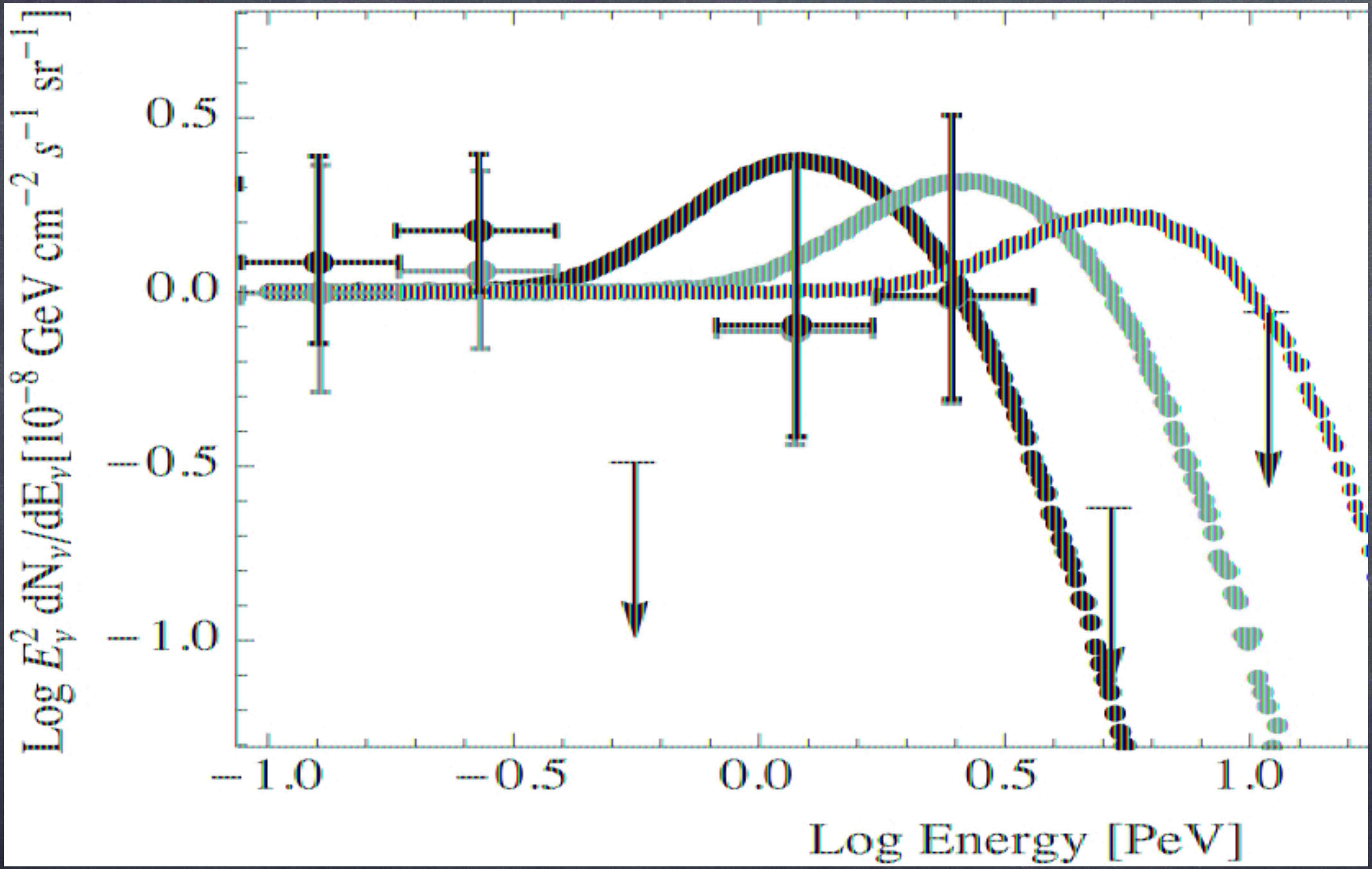
from Stecker et al., Phys. Rev. D 91 (2015) 045009

EeV Neutrino Fluxes



Maccione, Liberati, Mattingly, JCAP 03 (2013) 039

PeV Neutrino Fluxes



Stecker et al., Phys. Rev. D 91 (2015) 045009

Predicted spectra for $n = 2$, including all anomalous reactions, for $E_{\text{pair}} = 10\,\text{PeV(black)}\,,20\,\text{PeV(green)}\,,40\,\text{PeV(blue)}$ compared to IceCube data.

Interpreting the suggested cutoff as due to Lorentz symmetry violation would imply $\delta \simeq 5.2 \times 10^{-21}$. For $n = 2$ this would correspond to $\xi_2 \simeq 7.8 \times 10^3$ (superluminal neutrinos). Otherwise, if there is no cutoff due to LIV this constitutes an upper limit,
see Stecker et al., Phys. Rev. D 91 (2015) 045009

Lorentz Deformation/Doubly Special Relativity

Following. e.g., Amelino-Camelia, Symmetry 2 (2010) 230,

(La$*$): The laws of physics, and in particular the laws of transformation between inertial observers, involve a fundamental/observer-independent small (possibly Planckian) length scale L, which can be measured by each inertial observer by determining the dispersion relation for photons. This relation has the form

$$E^2 - c_0^2 p^2 + f(E, p, L) = 0\,,$$

where the function f is the same for all inertial observers and in particular all inertial observers agree on the leading L dependence of f,

$$f(E, p, L) \simeq L c_0 p^2 E\,.$$

(Lb): The laws of physics, and in particular the laws of transformation between inertial observers, involve a fundamental/observer-independent velocity scale c_0 as the infrared limit, $pL \to 0$, of the speed of light.

Note: in contrast to the other dispersion-relation modification scenarios, there is no preferred frame in Lorentz deformation scenarios; rather Lorentz transformations are realised in a nonlinear fashion.

If such scenarios are constrained by the effects discussed above depends on the specific scenario, but generally effects on observables tend to be smaller because Lorentz symmetry is still realised.

Conclusions

1.) IceCube neutrinos already constrain their sources which should be sufficiently numerous: Gamma-ray bursts are unlikely as main sources

2.) Multi-messenger modeling sources including gamma-rays and neutrinos start to constrain the source and acceleration mechanisms

3.) Highest Energy Cosmic Rays, Gamma-rays, and Neutrinos give the strongest constraints on violations of Lorentz symmetry => terms suppressed to first and second order in the Planck mass would have to be unnaturally small for gamma-rays, less so for neutrinos