The Abdus Salam International Centre for Theoretical Physics

2246-33

Workshop on Cosmic Rays and Cosmic Neutrinos: Looking at the Neutrino Sky

20 - 24 June 2011

Probing the UHE CR sky with neutrino observatories

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Probing the UHE CR sky with neutrino observatories

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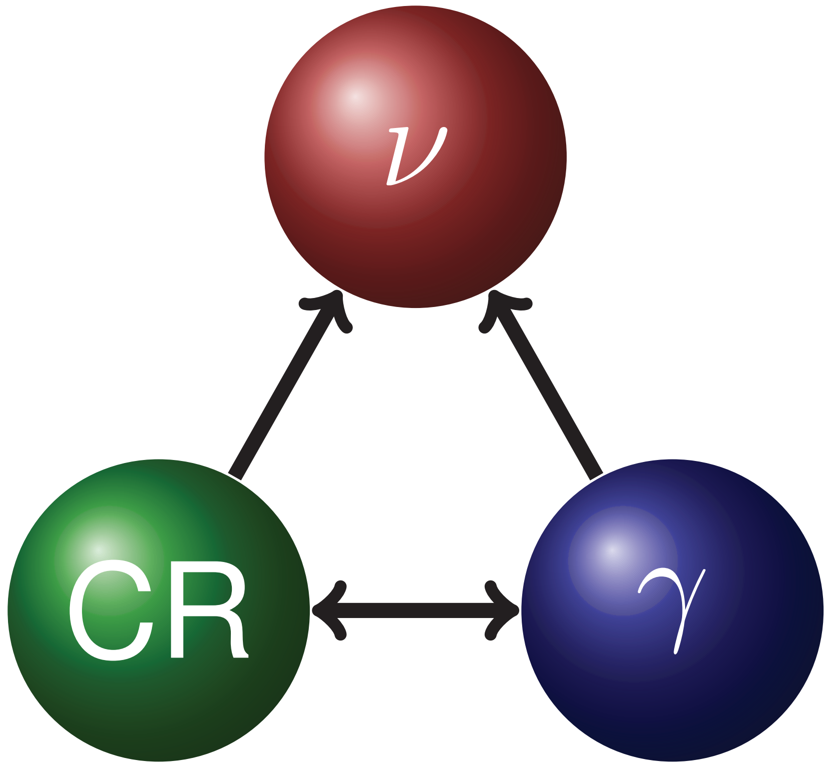
“Looking at the Neutrino Sky”, Trieste, June 20-24, 2011

Multi-messenger paradigm

- The multi-messenger triad:
  cosmic rays, γ-rays and ν's
- previous talks:
  - "*IceCube is the first detector which crossed the cascade upper bound and entered the physically allowed domain of cosmogenic neutrino fluxes.*" V.Berezinsky
  - "*Pushing below the Waxman-Bahcall limit in the 100TeV-10PeV range disfavors proton dominance in 1-100PeV range.*" T.Gaisser
  - "*IceCube sensitivity meets minimum requirements for detection of extragalactic sources.*" E.Waxman
  - "*IceCube (in the present configuration) will only just "scratch the surface" of neutrino astronomy.*" P.Lipari
  - . . .



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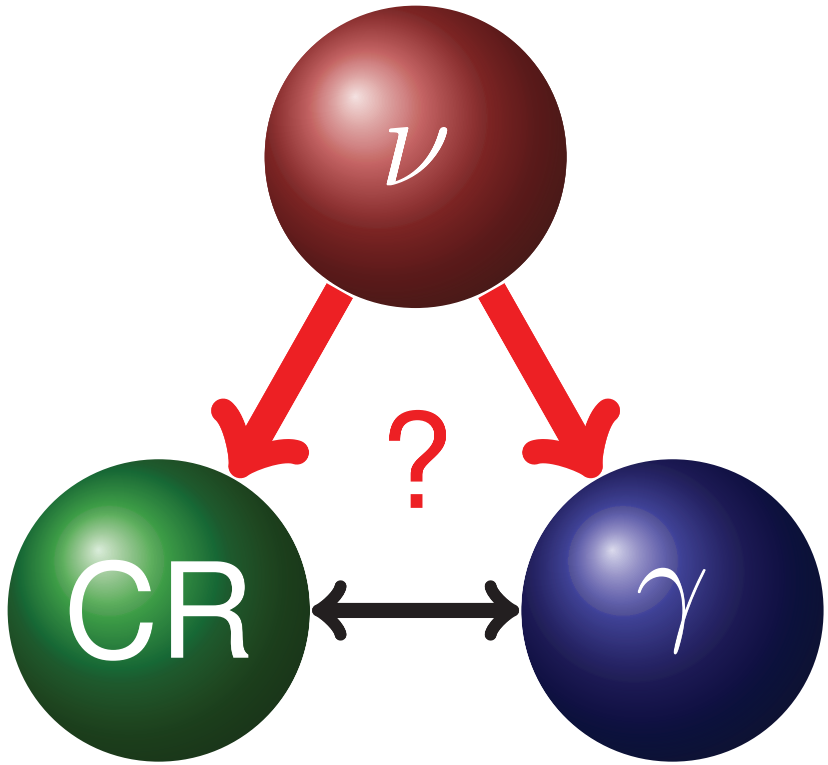
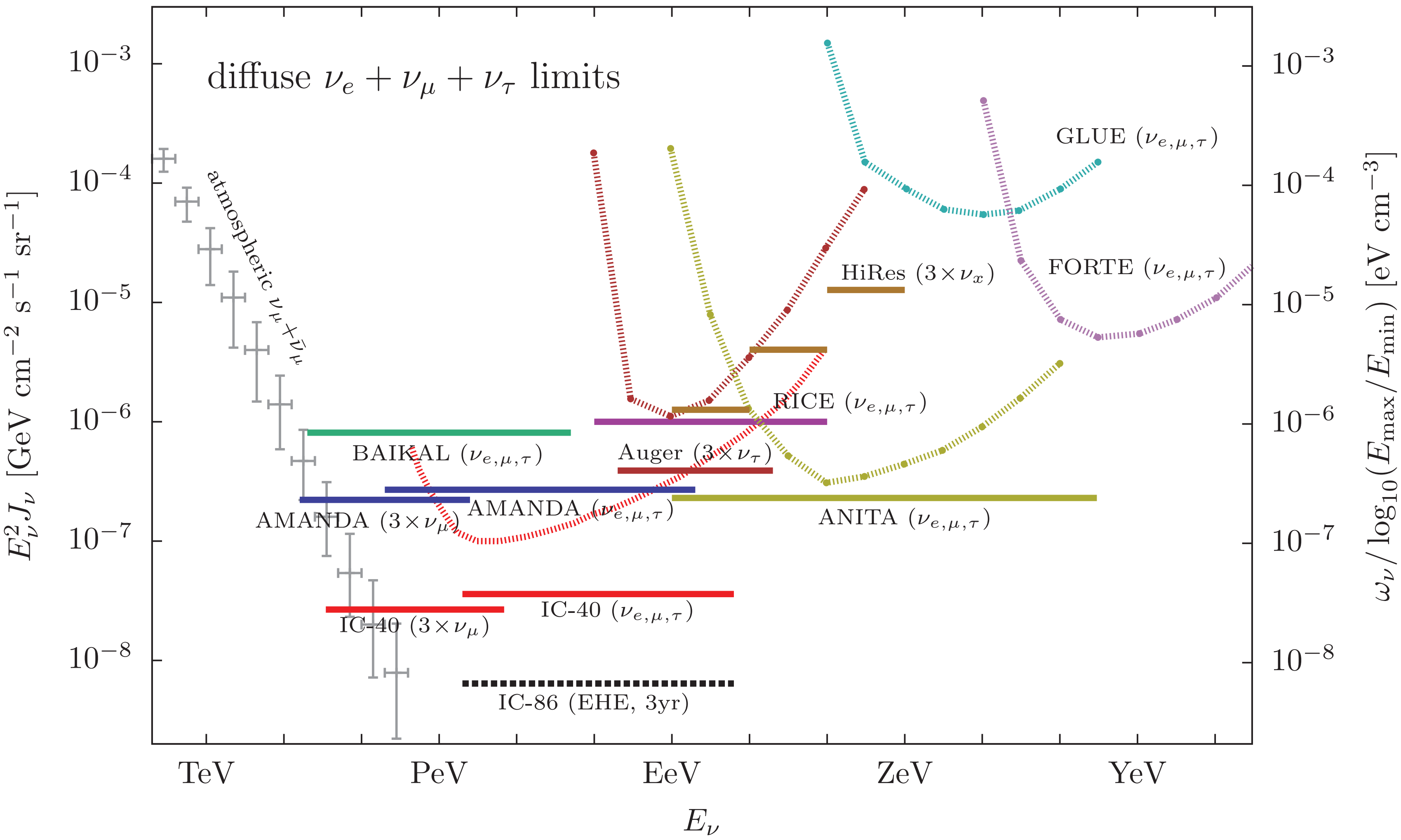


“Looking at the neutrino sky”



How dark is the neutrino sky?

- UHE CRs produced by astrophysical engine with ambient **gas and radiation**

➜ pion production in $p\gamma$ and/or pp interactions:

- $p\gamma : N_{\pi^\pm} : N_{\pi^0} \sim 1 : 1$
  (Δ-resonance with $N_{\pi^+} : N_{\pi^0} : N_{\pi^-} \sim 1 : 2 : 0$)
  (direct π^+ production on resonance about 1/5th)

- $pp : N_{\pi^\pm} : N_{\pi^0} \sim 2 : 1$
  ($N_{\pi^+} : N_{\pi^0} : N_{\pi^-} \sim 1 : 1 : 1$)

➜ relative abundance $K = N_{\pi^\pm}/N_{\pi^0}$: $K_{p\gamma} \simeq 1$ and $K_{pp} \simeq 2$

➜ **neutrino production** on decay:

$$\pi^+ \to \mu^+\nu_\mu \to e^+\nu_e\bar{\nu}_\mu\nu_\mu \qquad \& \qquad \pi^- \to \mu^-\bar{\nu}_\mu \to e^-\bar{\nu}_e\nu_\mu\bar{\nu}_\mu$$

➜ electromagnetic emission (assuming no B):

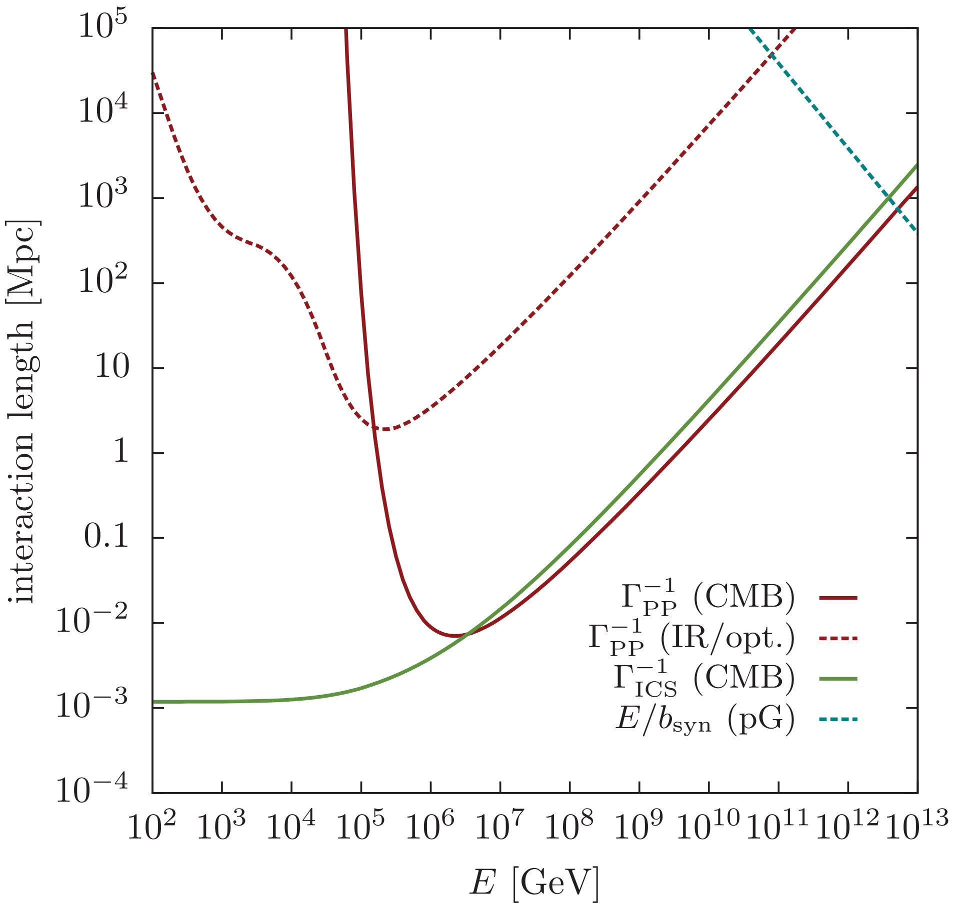
$$Q_\gamma(E_\gamma) = \frac{1}{3}\frac{1}{K}Q_\nu(E_\gamma/2) \qquad \& \qquad Q_e(E_e) = \frac{1}{3}Q_\nu(E_e)$$

➜ cascades in cosmic radiation background

✘ limited by extra-galactic **diffuse γ-ray background** [Berezinsky&Smirnov'75]

Diffuse GeV-TeV background

- CMB interactions **(solid lines)** dominate in casade:
  - inverse Compton scattering (ICS)
    $e^{\pm} + \gamma_{\rm CMB} \to e^{\pm} + \gamma$
  - pair production (PP)
    $\gamma + \gamma_{\rm CMB} \to e^{+} + e^{-}$
- PP in IR/optical background **(red dashed line)** determines the "edge" of the spectrum.
- this calculation:
  Franceschini *et al.* '08

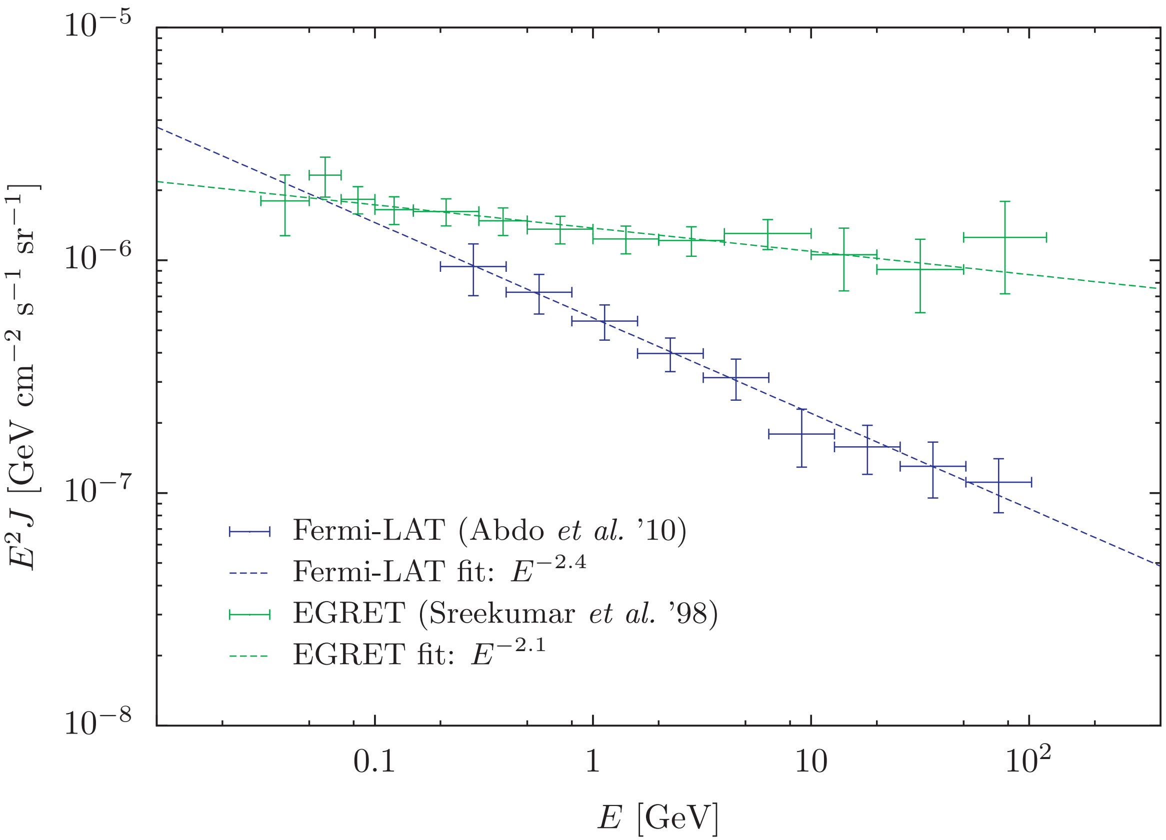


Rapid cascade interactions produce universel GeV-TeV emission (almost) independent of injection spectrum and source distribution.

Diffuse GeV-TeV background

- New diffuse γ-ray background measured by Fermi-LAT is significantly softer than the former measurement by EGRET.
- *Reduced* energy density sets stronger limits on multi-messenger models, in particular UHE CRs and cosmogenic neutrinos. [Berezinsky et al.'10]

$$\omega_{\rm cas} \leq 5.8 \times 10^{-7}\ {\rm eV/cm^3}$$



Test spectra

- scan over various neutrino energies via test-spectra:

$$Q_\nu(E; E_{\rm max}, E_{\rm min}) \propto E^{-1} \exp(-E/E_{\rm max}) \exp(-E_{\rm min}/E)$$

- "bin-wise" test of neutrino fluxes:

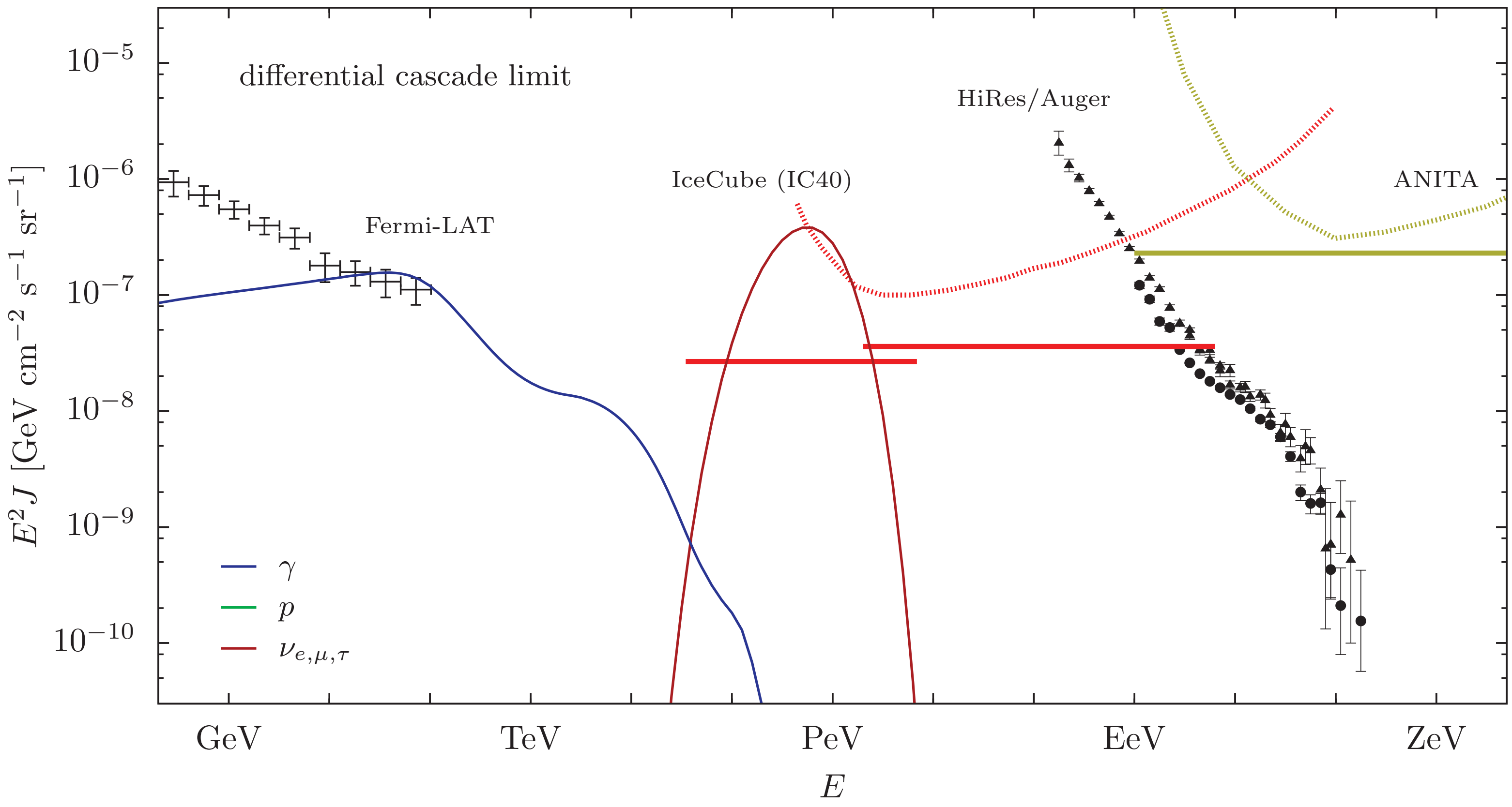
$$\log_{10}(E_{\rm max}/E_{\rm min}) = {\rm const} < 1$$

- serve as "basis", *e.g.* for power-law flux:

$$\int {\rm d}E_{\rm max}\, E_{\rm max}^{-\gamma}\, Q_\nu(E; E_{\rm max}) \propto E^{-\gamma}$$

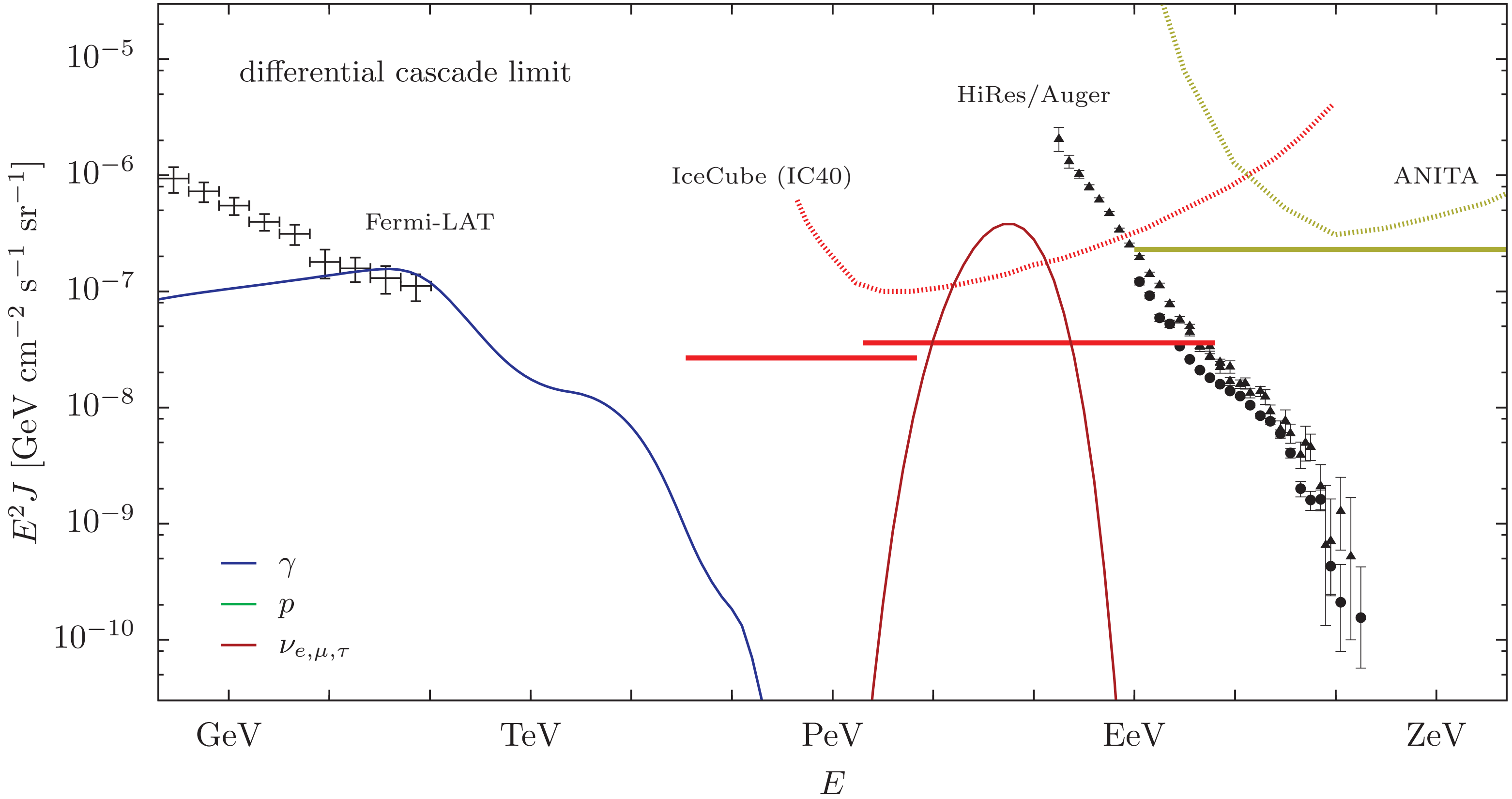
- diffuse production assuming homogeneous distribution of sources within $0 < z < 1$ and redshift evolution $(1+z)^3$

Cascade limit revisited



- test-spectra: $Q_\nu(E;E_{\rm max}) \propto E^{-1}e^{-E/E_{\rm max}}e^{-E_{\rm min}/E}$ with $\log_{10}(E_{\rm max}/E_{\rm min}) = 0.25$
- electromagnetic emission (with $K_{p\gamma} \simeq 1$) in GeV-TeV γ-rays normalized to Fermi-LAT (+1σ)

Cascade limit revisited



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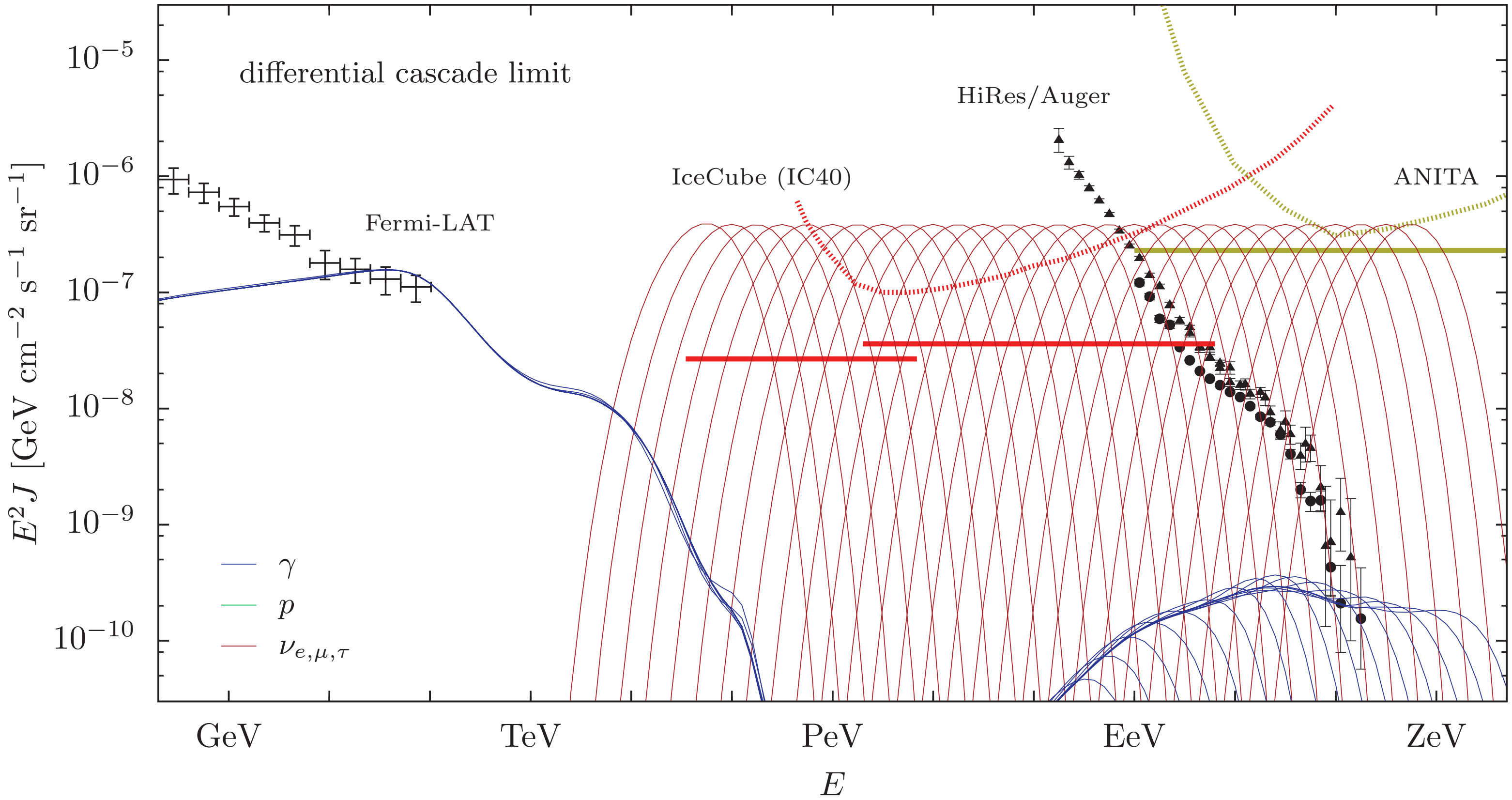
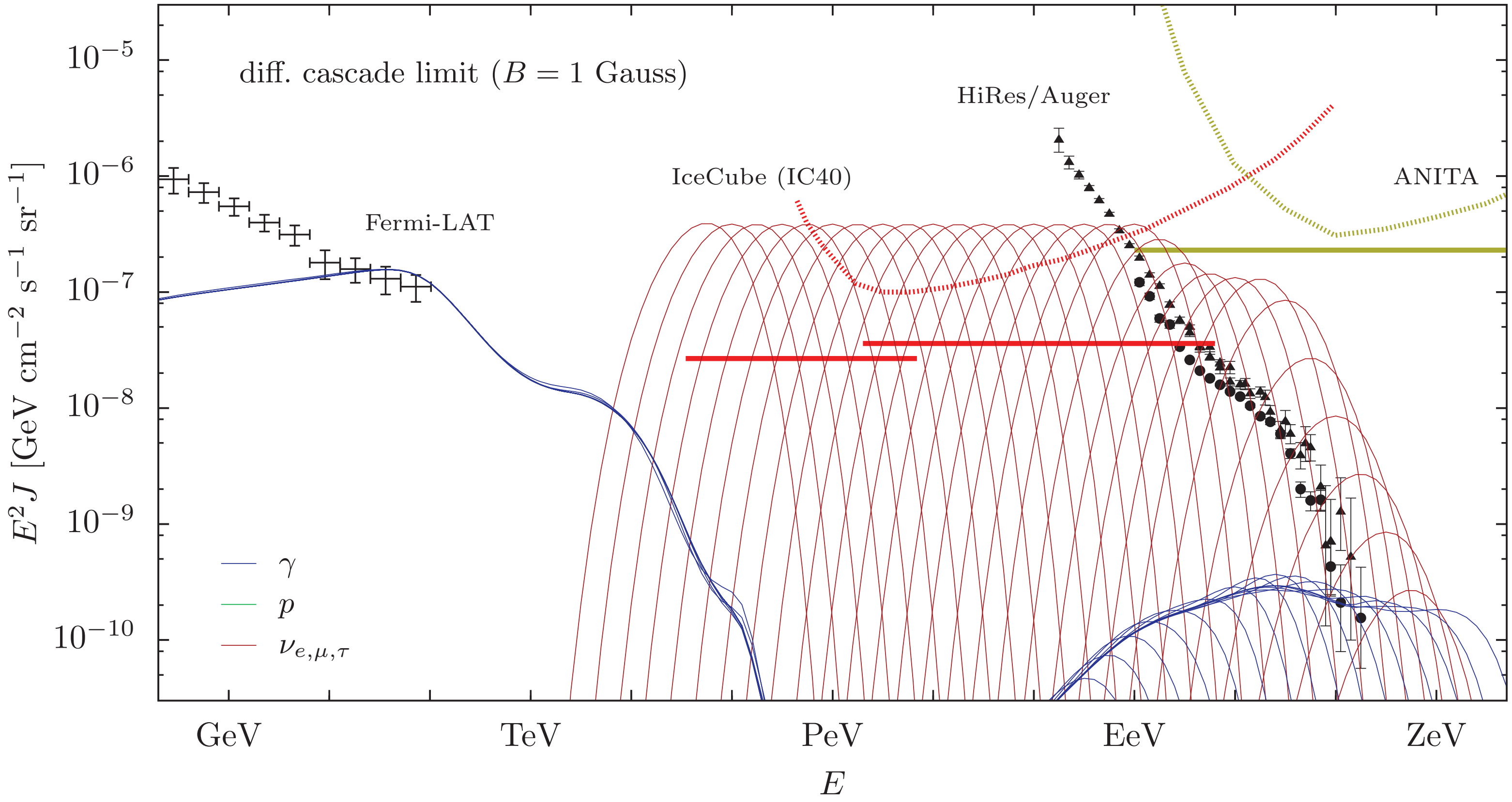


- envelope of test-function corresponds to a **differential** upper limit
- magnetic field at pion production ($\tau_{\rm syn} \ll \tau_\pi$?):

$Q_\nu(E_\nu) \to Q_\nu(E_\nu)/(1 + (E_\nu/E_b)^2)$ with $E_b \simeq \frac{1}{4}\frac{3}{4}\sqrt{\frac{m_\pi^2}{\pi\alpha^2 B^2 \tau_\pi}} \simeq 3\text{PeV}/B_{\rm T}$

Cascade limit revisited



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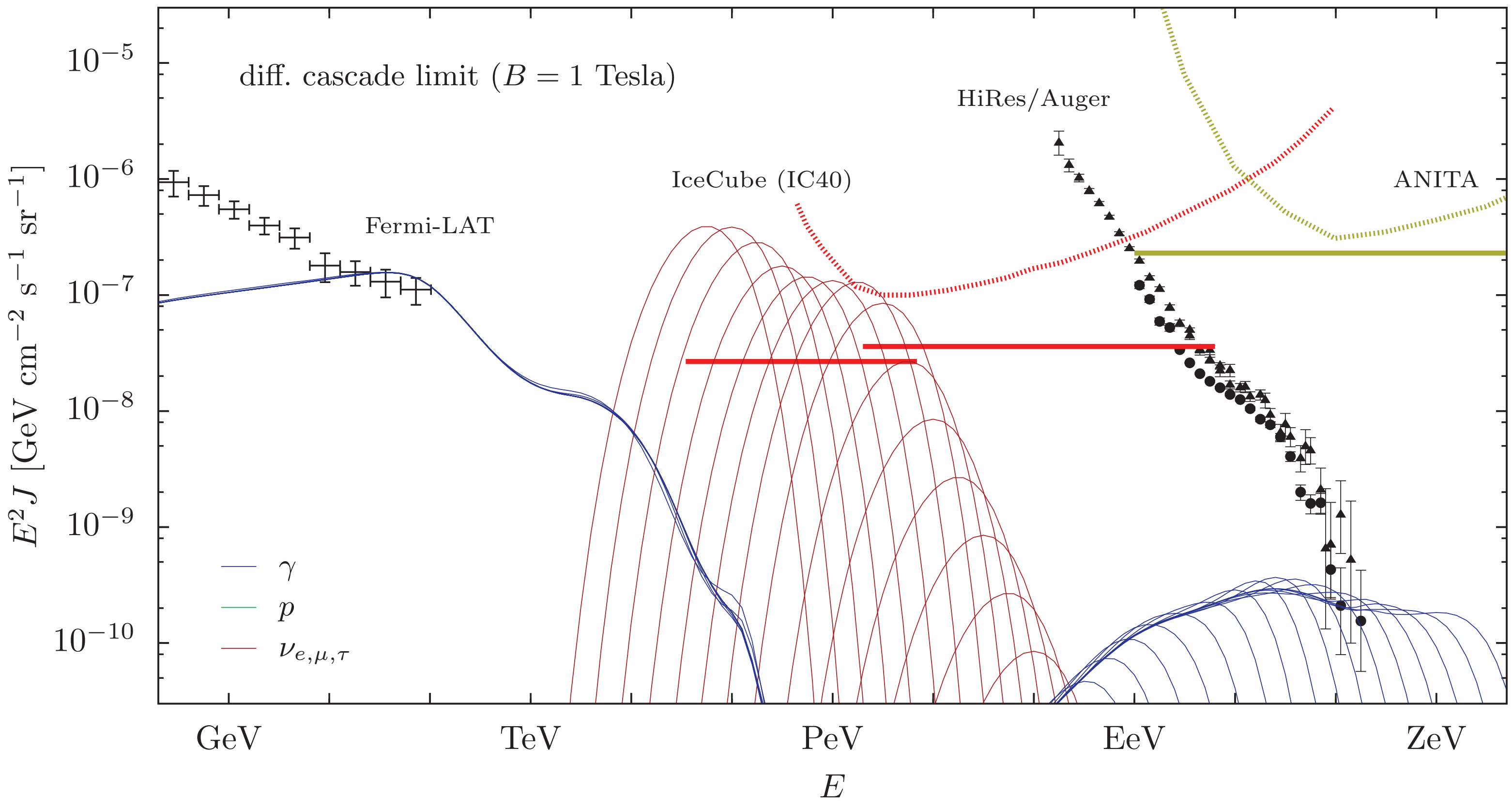

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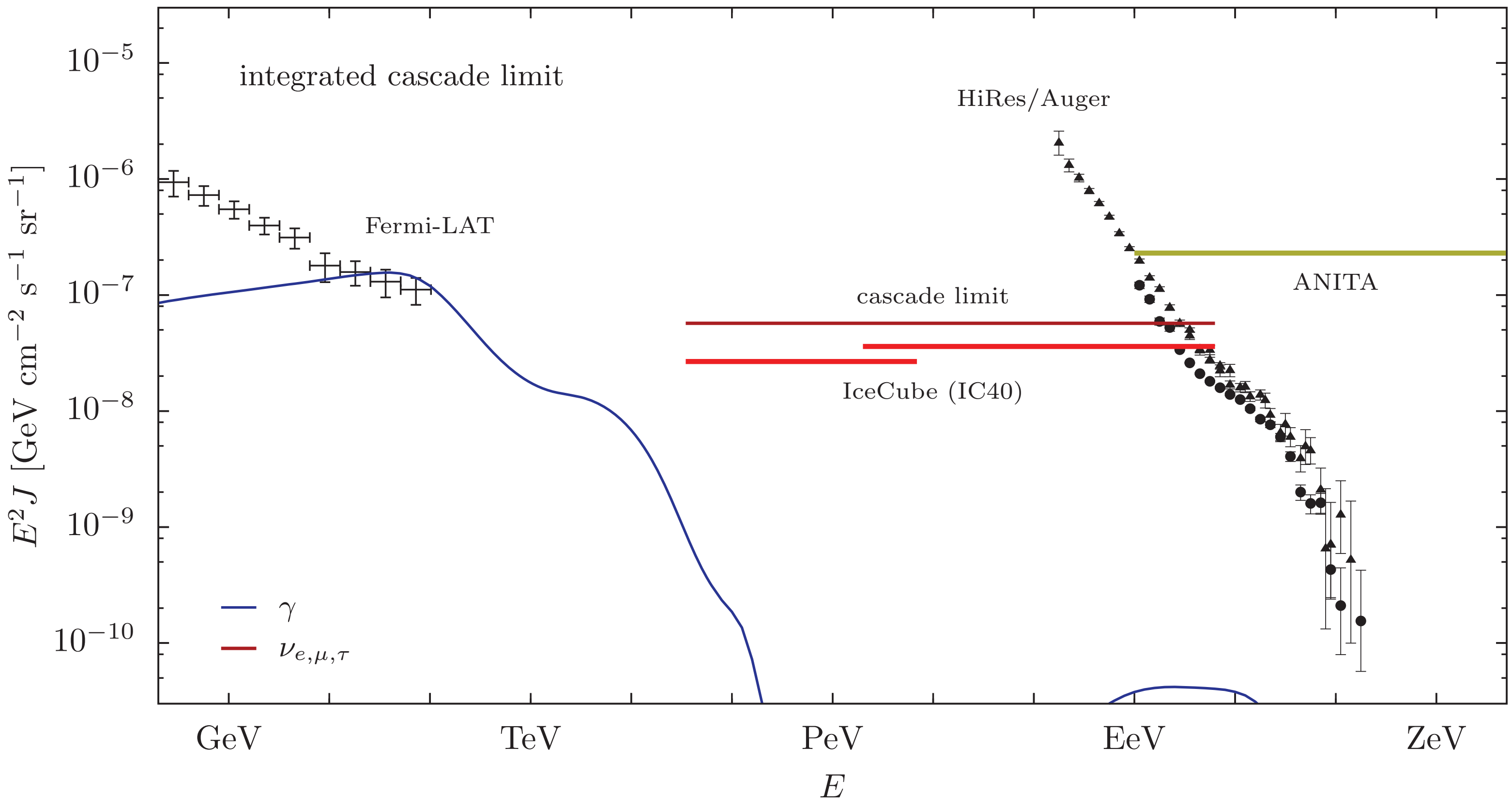
Integrated cascade limit

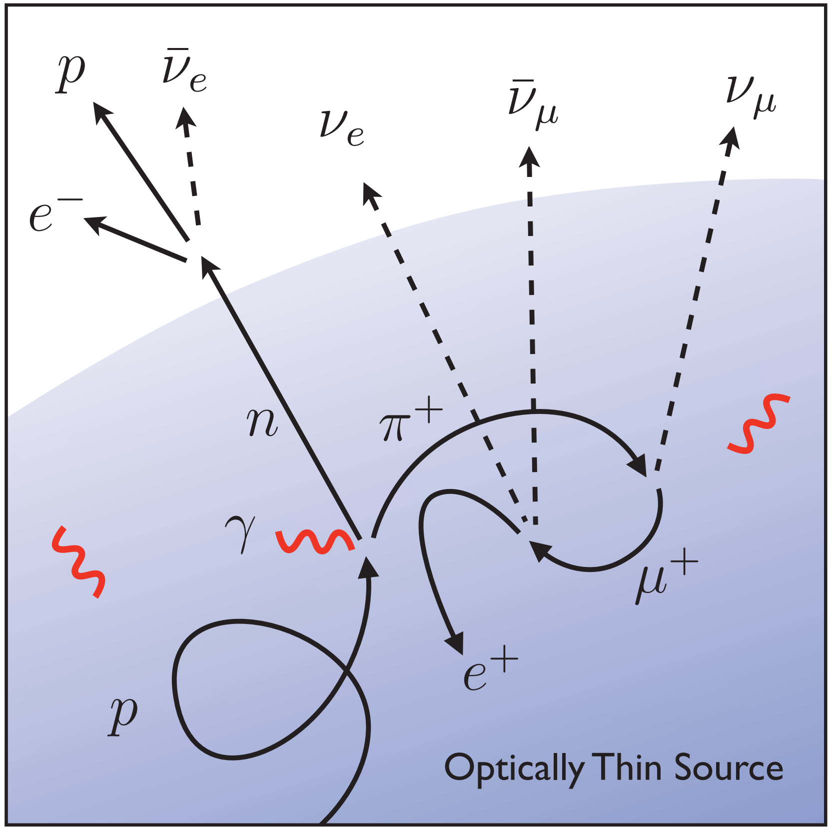


- **integrated** cascade limit assuming E^{-2} flux between E_- and E_+:

$$E^2\Phi_{\nu_{\rm tot}} \simeq 3 \times 10^{-7}\,(\log_{10}(E_+/E_-))^{-1}\,{\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

- **energy density**: $\omega_{\rm Fermi} \simeq 6 \times 10^{-7}\ {\rm eV/cm^3}$ vs. $\omega_{\rm IC40} \simeq 1 \times 10^{-7}\ {\rm eV/cm^3}$

Optically thin sources



(i) $t_{\rm acc} < \min(t_{\rm syn}, t_{p\gamma}, t_{pp}, t_{\rm dyn})$

(efficient CR **acceleration**)

(ii) $t_{p\gamma} \ll t_{pp}$ & $t_{\rm acc} < t_n$ & $t_{\rm dyn} \lesssim t_{p\gamma}$

(efficient **emission** of CR neutrons from $p\gamma$-interactions in optically thin source)

(iii) $t_{\pi/\mu} < t_{\rm syn}$

(synchrotron loss of pions and muons negligible)

$$\mathcal{L}_{\text{all }\nu}(z, E_\nu) \simeq \frac{\eta}{\epsilon}\,\mathcal{L}_n(z, E_\nu/\epsilon)$$

$$\eta = \frac{\langle N_\nu \rangle}{\langle N_n \rangle} \simeq 3 \quad \text{and} \quad \epsilon = \frac{\langle E_\nu \rangle}{\langle E_n \rangle} \simeq \frac{1}{20}$$

UHE CR model

- **spatially homogeneous and isotropic** distribution of sources
- Boltzmann equation of comoving number density ($Y = n/(1+z)^3$):

$$\dot{Y}_i = \partial_E(HEY_i) + \partial_E(b_i Y_i) - \Gamma_i\, Y_i + \sum_j \int \mathrm{d}E_j\, \gamma_{ji} Y_j + \mathcal{L}_i\,,$$

H : Hubble rate
b_i : continuous energy loss
γ_{ji} (Γ_i) : differential (total) interaction rate

- **power-law** proton emission rate:

$$\mathcal{L}_p(0,E) \propto (E/E_0)^{-\gamma} \exp(-E/E_{\rm max}) \exp(-E_{\rm min}/E)$$

- **redshift evolution** of source emission or distribution:

$$\mathcal{L}_p(z,E) = \mathcal{L}_p(0,E)(1+z)^n \Theta(z_{\rm max} - z)\Theta(z - z_{\rm min})$$

- **fixed in the following**: $z_{\rm min} = 0$, $z_{\rm max} = 1$ and $n = 3$.

Cosmogenic neutrinos & gamma-rays

- photopion production of protons

[Greisen'66;Zatsepin/Kuzmin'66]

[Berezinsky/Zatsepin'69]

$$p + \gamma_{\rm CMB} \to n + \pi^+ / p + \pi^0$$

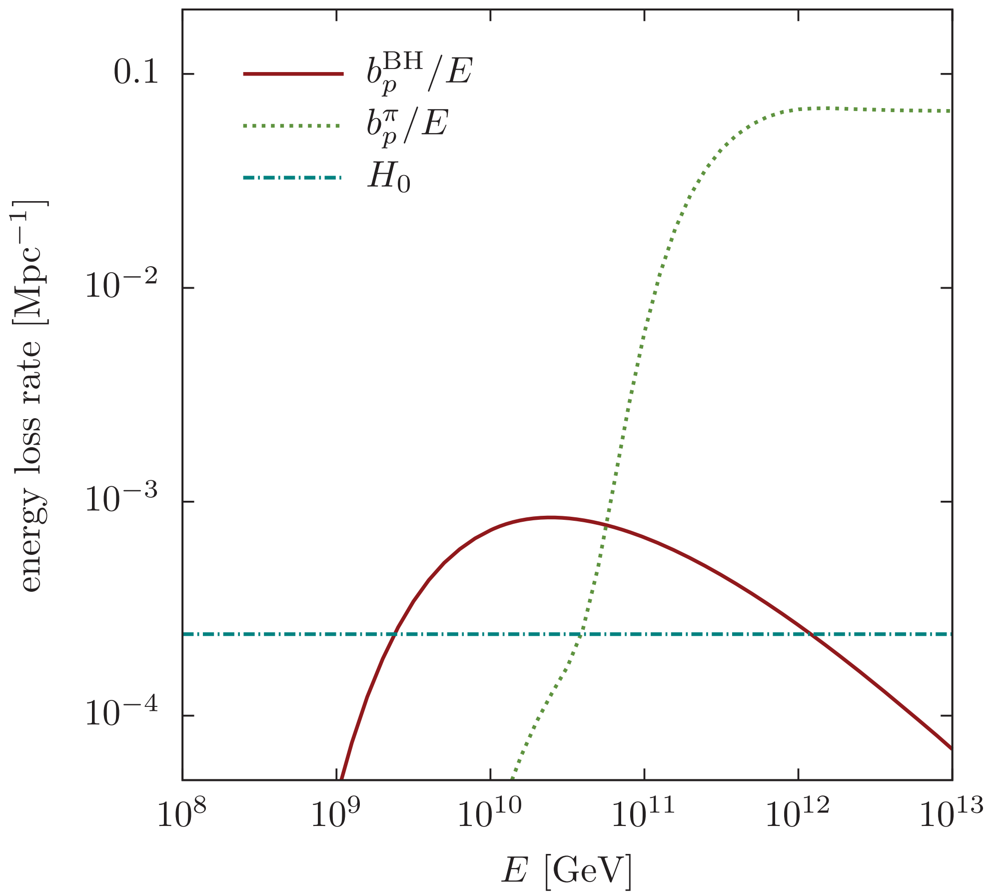
- Bethe-Heitler (BH) pair production:

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

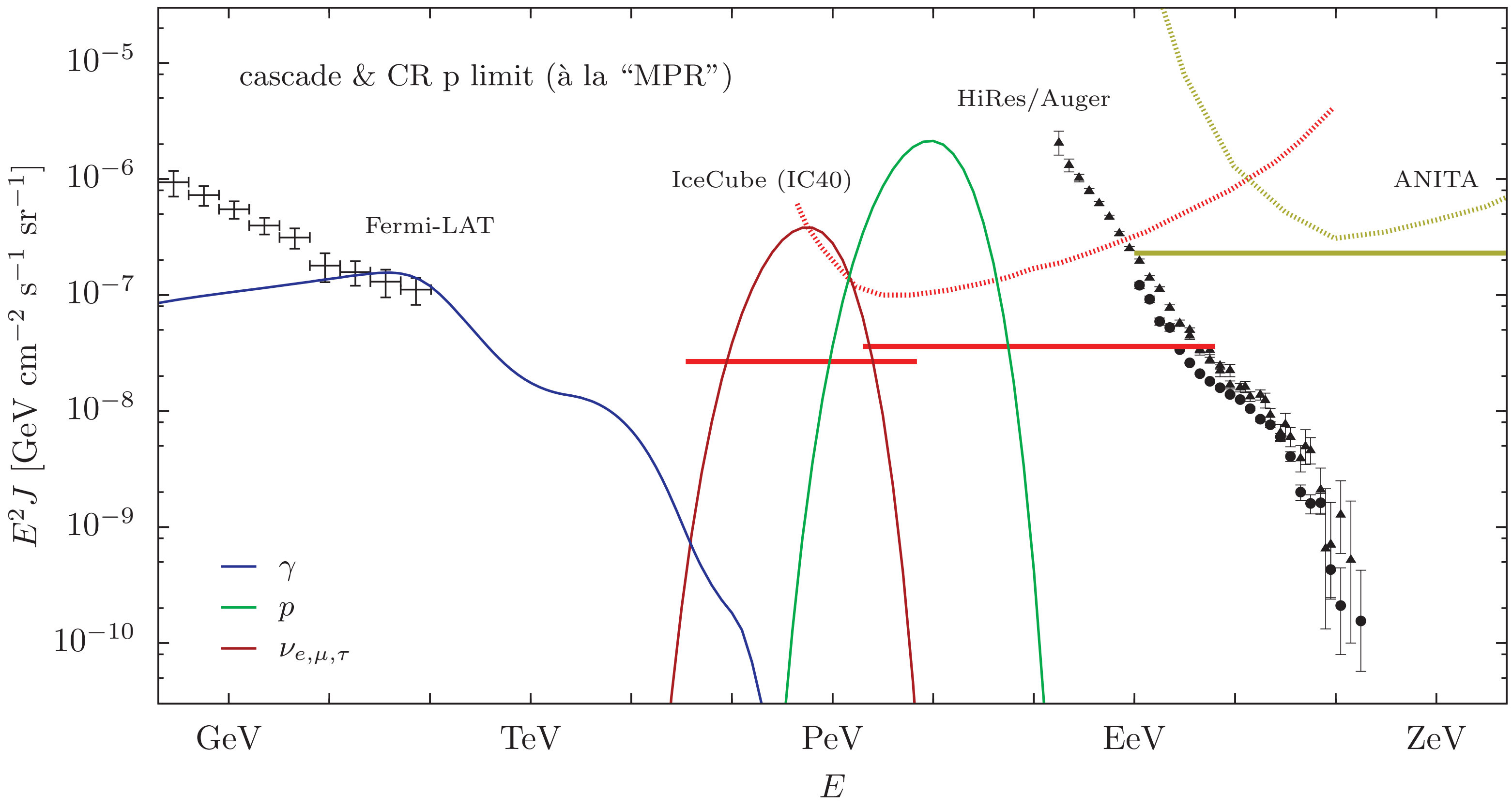
➜ dominant energy loss process for UHE CR protons at $\sim 2 \times 10^9 \div 2 \times 10^{10}$ GeV.

➜ **decreases** the cascade limit on cosmogenic neutrinos.

[Kalashev/Semikoz/Sigl'09]



MPR bound revisited



- CR emission via neutron production, Δ-approximation: $\epsilon_{p\gamma} \simeq 0.06$ & $\eta_{p\gamma} \simeq 3$
- CR propagation: cosmogenic emission (photo-pion & Bethe-Heitler)
- CR proton limited by UHE CR data (Auger & Hires)

➜ "reduced" cascade bound of optically thin sources [Mannheim/Protheroe/Rachen'98]

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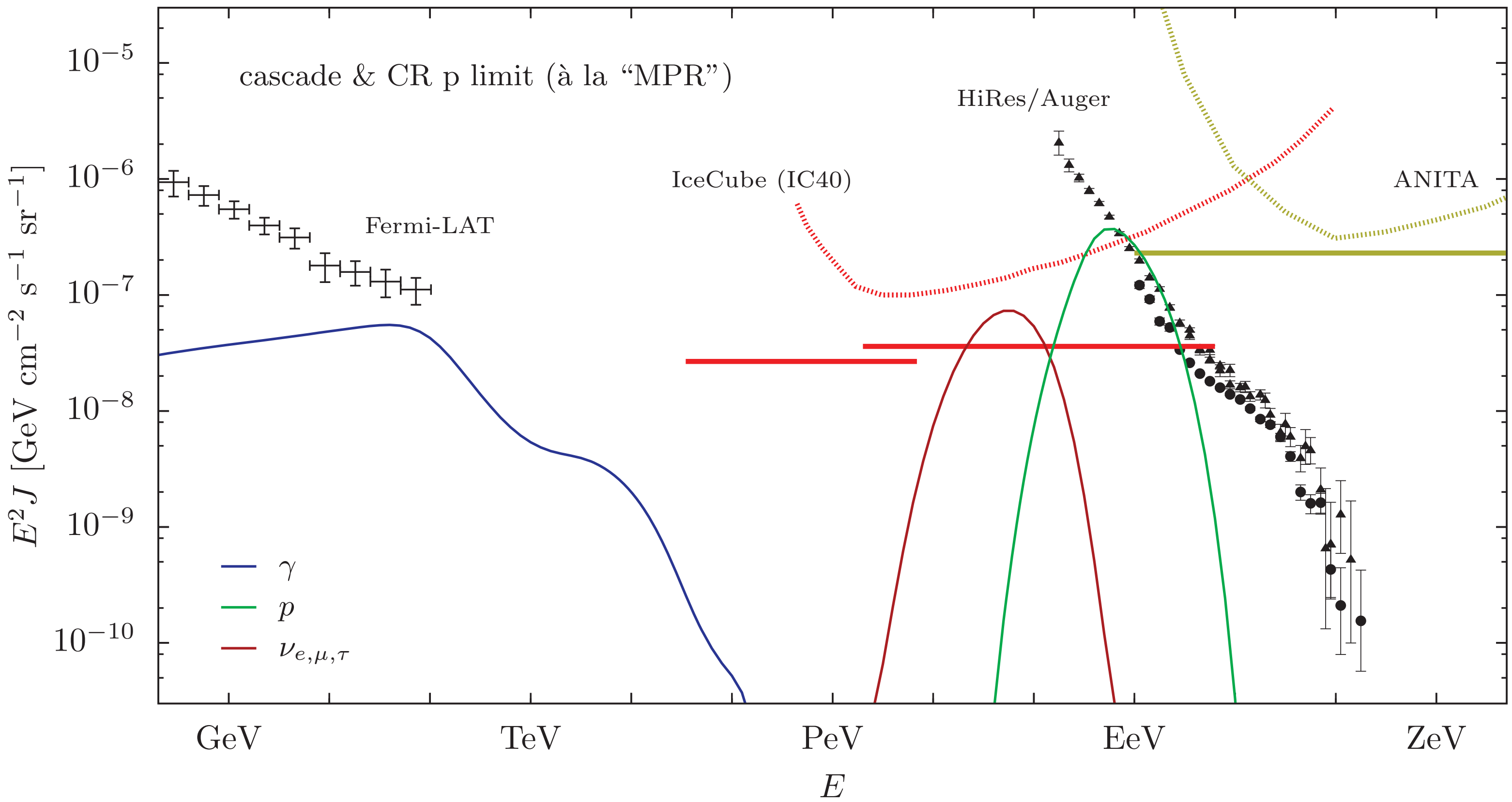

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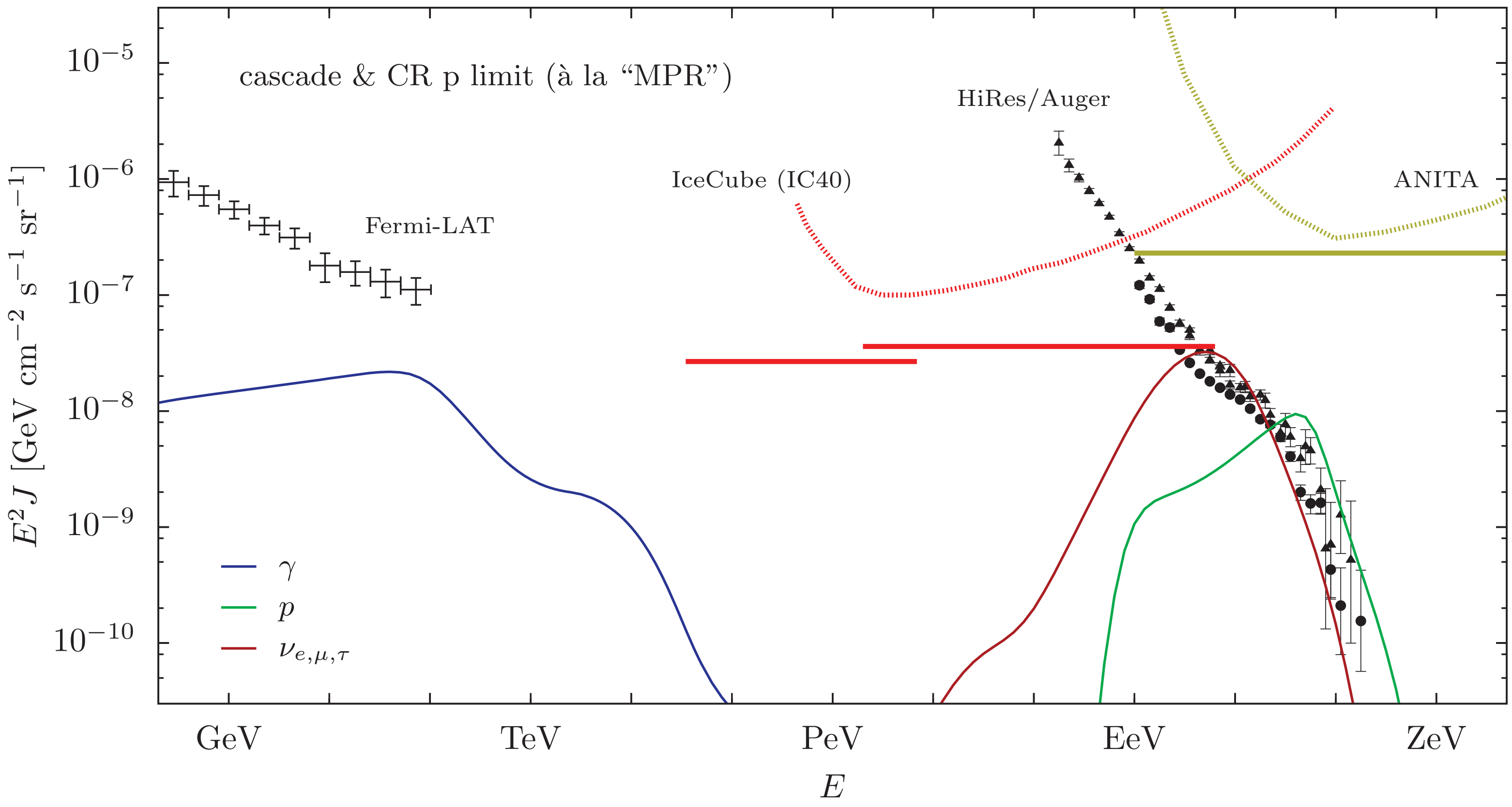

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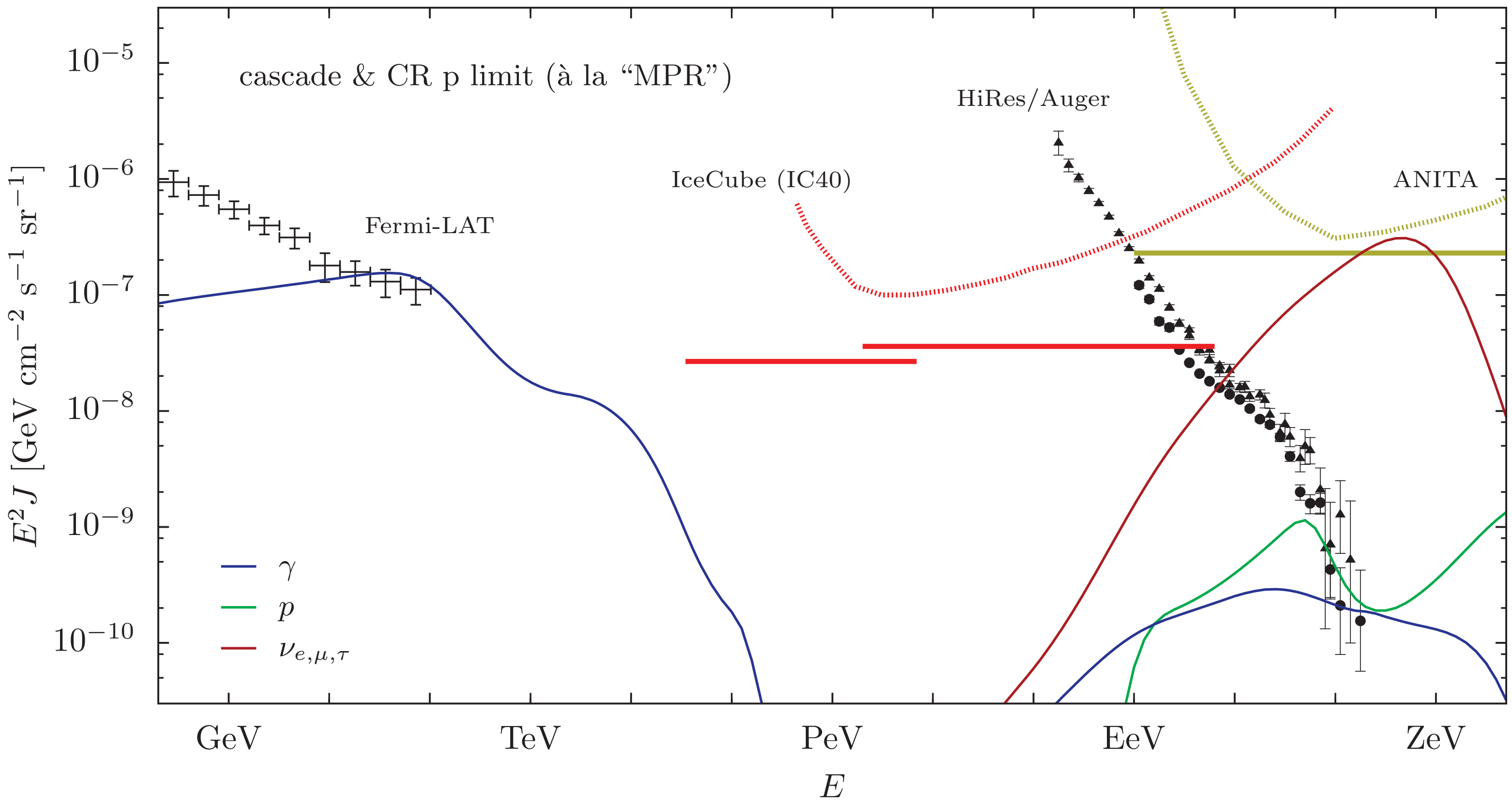

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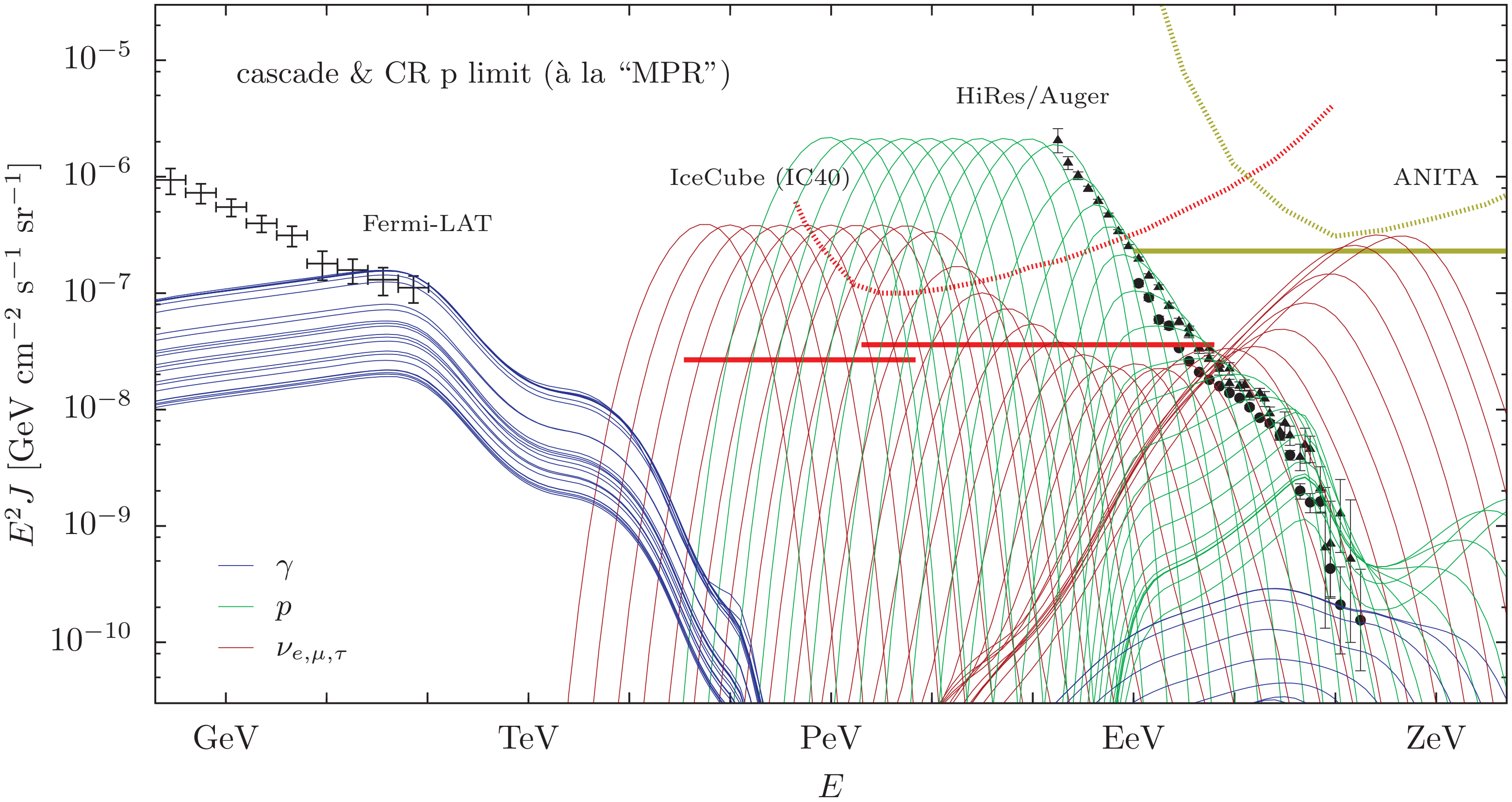

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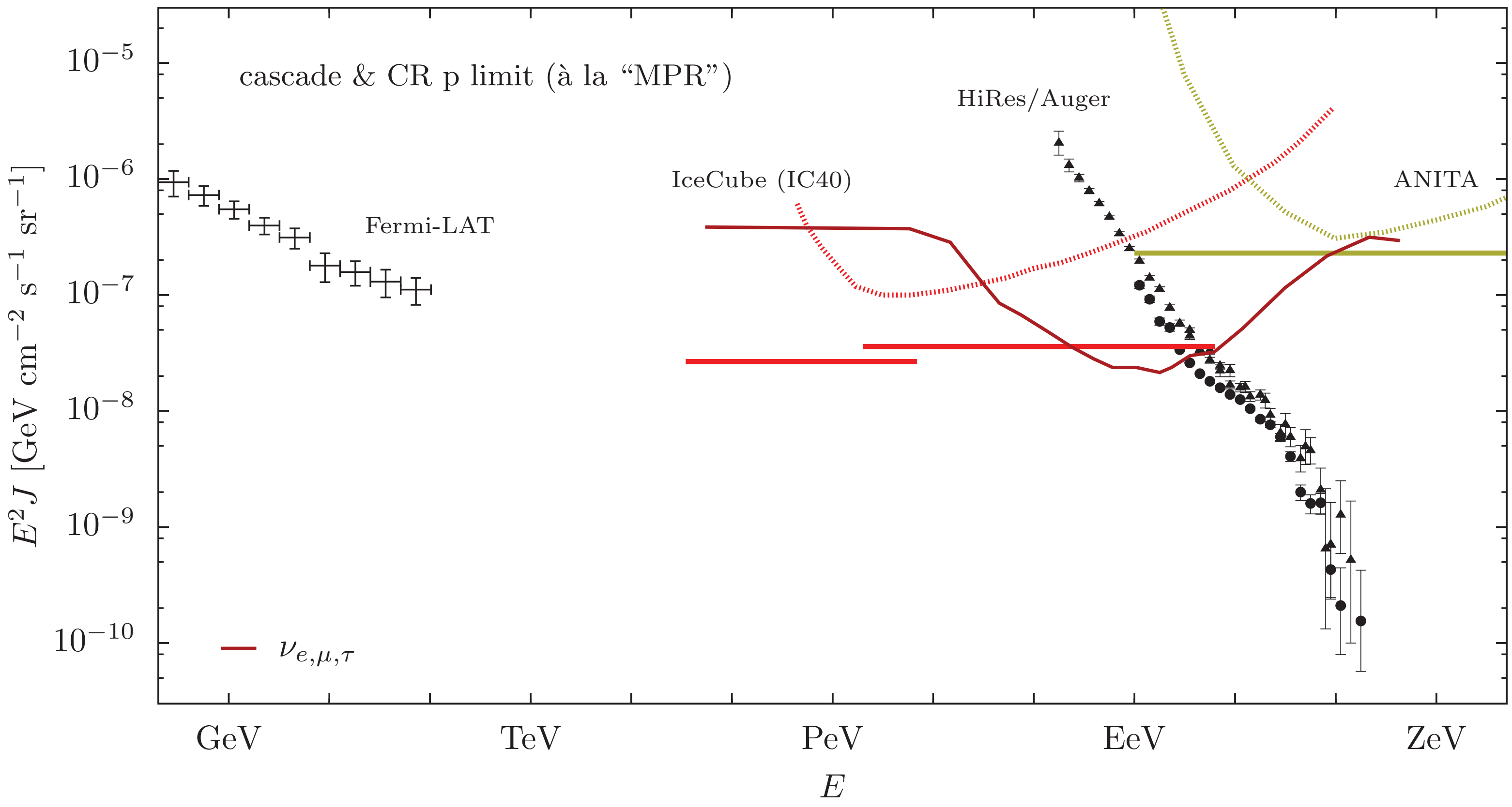

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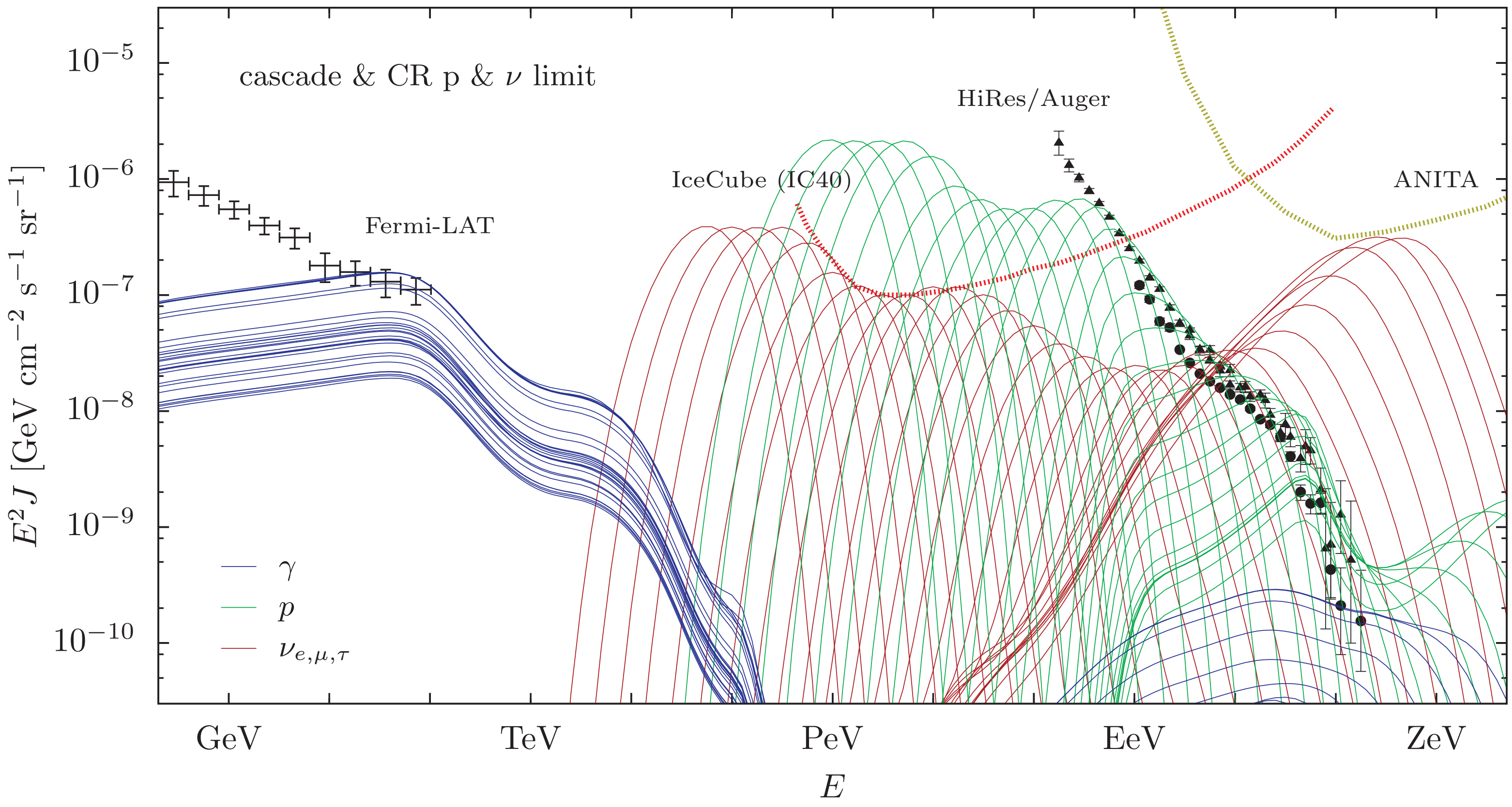

- Neutrino emission is further constraint by neutrino upper limits.

➜ Constraints proton fraction of UHE CRs! [MA/Anchordoqui/Sarkar'09]

- full IceCube after 3 years: "model-independent" limit on the proton fraction up to the ankle.

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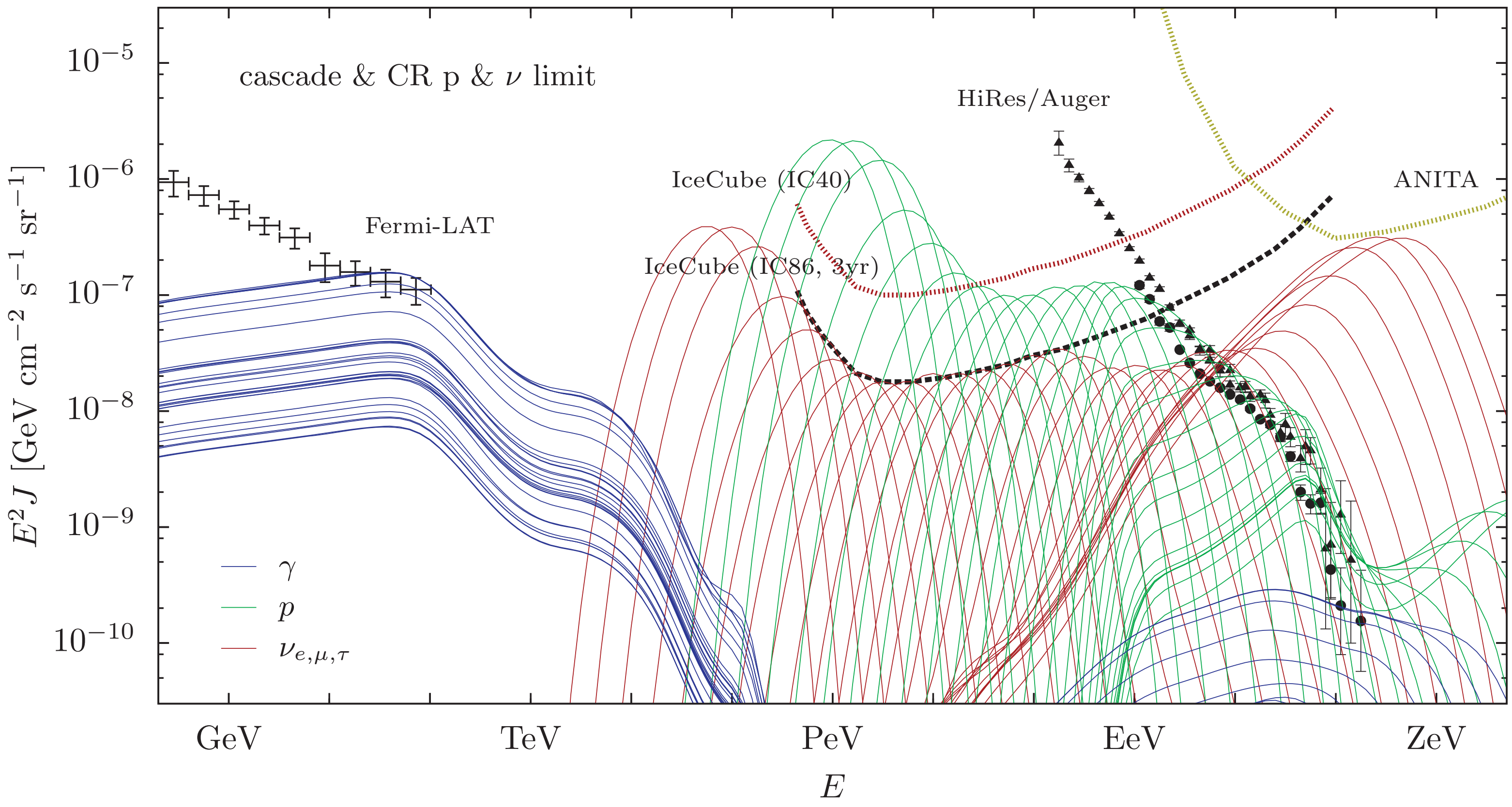

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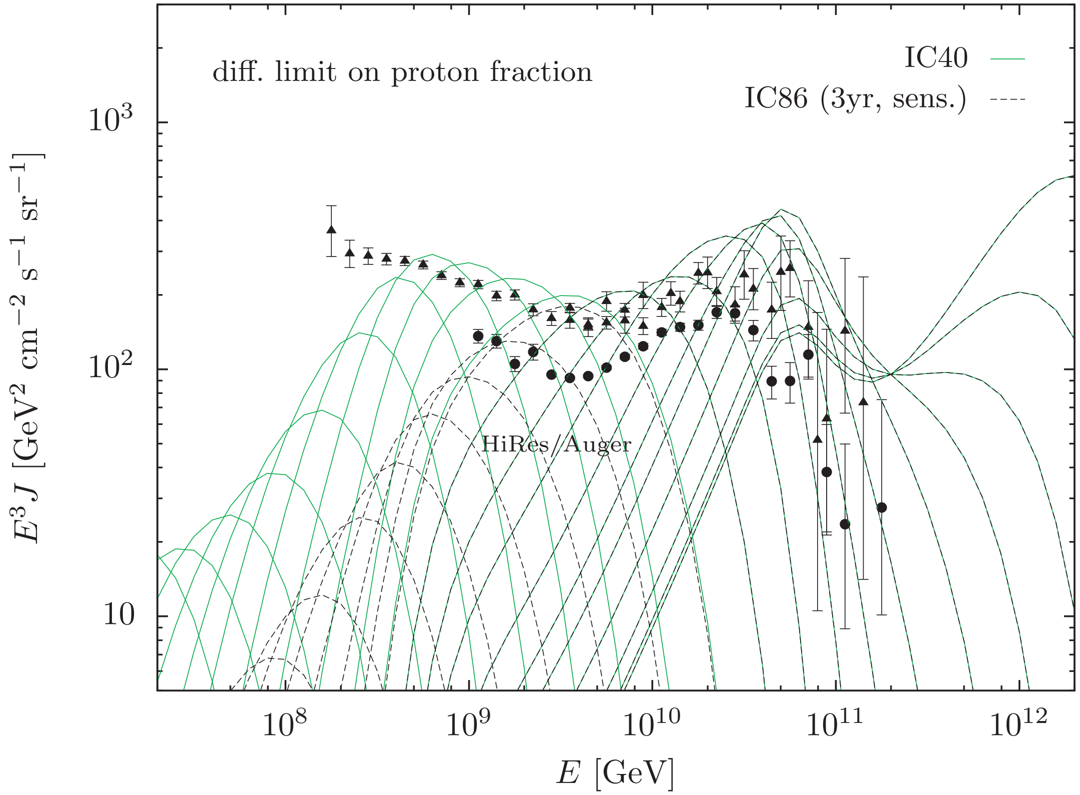

- differential upper limit on proton fraction from optically thin sources
- IC86 after 3 years is sensitive up to the ankle (for HiRes normalization)
- stronger (model-dependent) bounds possible from specific emission spectra

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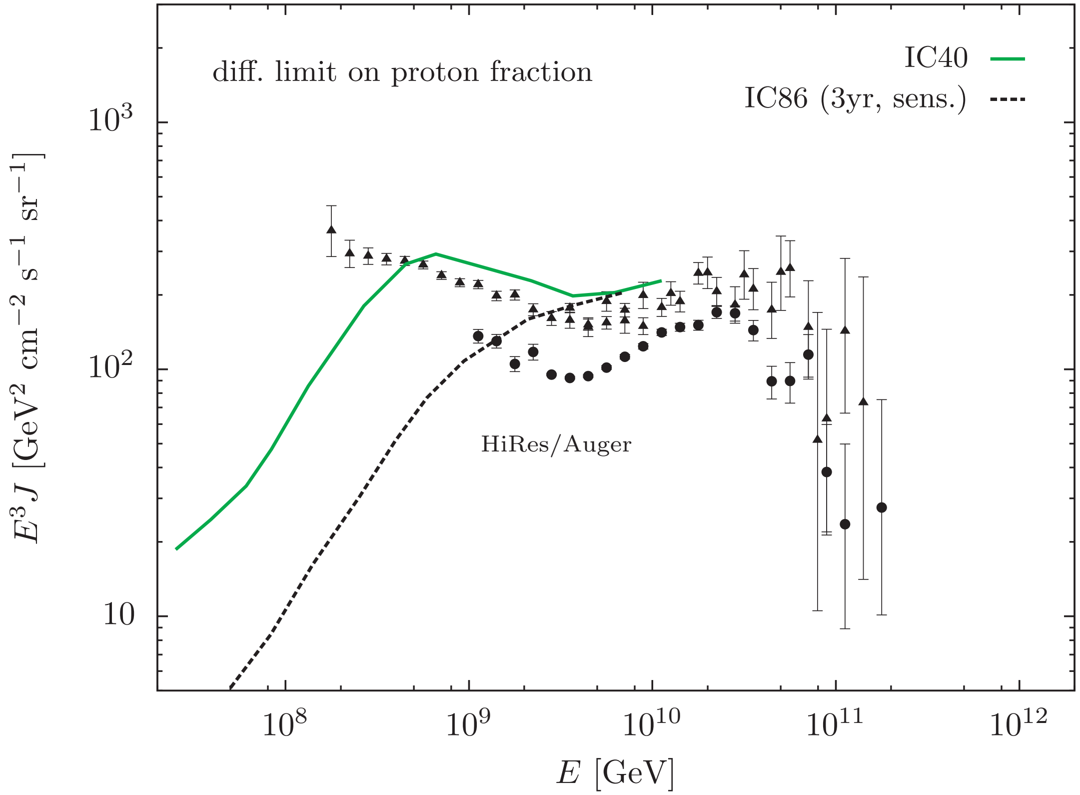

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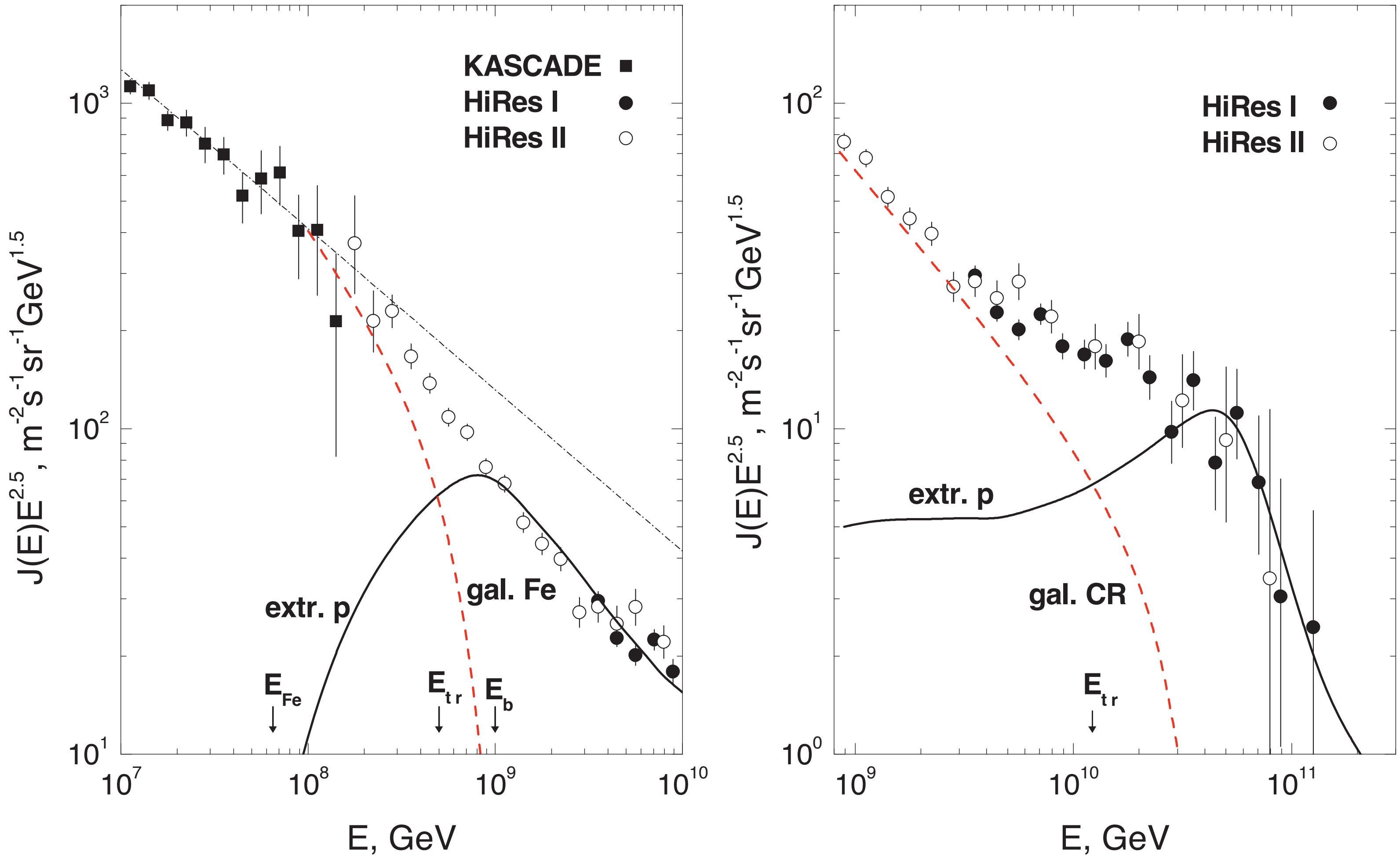
[MA/Anchordoqui/Sarkar'09]

Galactic to extragalactic crossover

"dip-transition" vs. "ankle-transition"

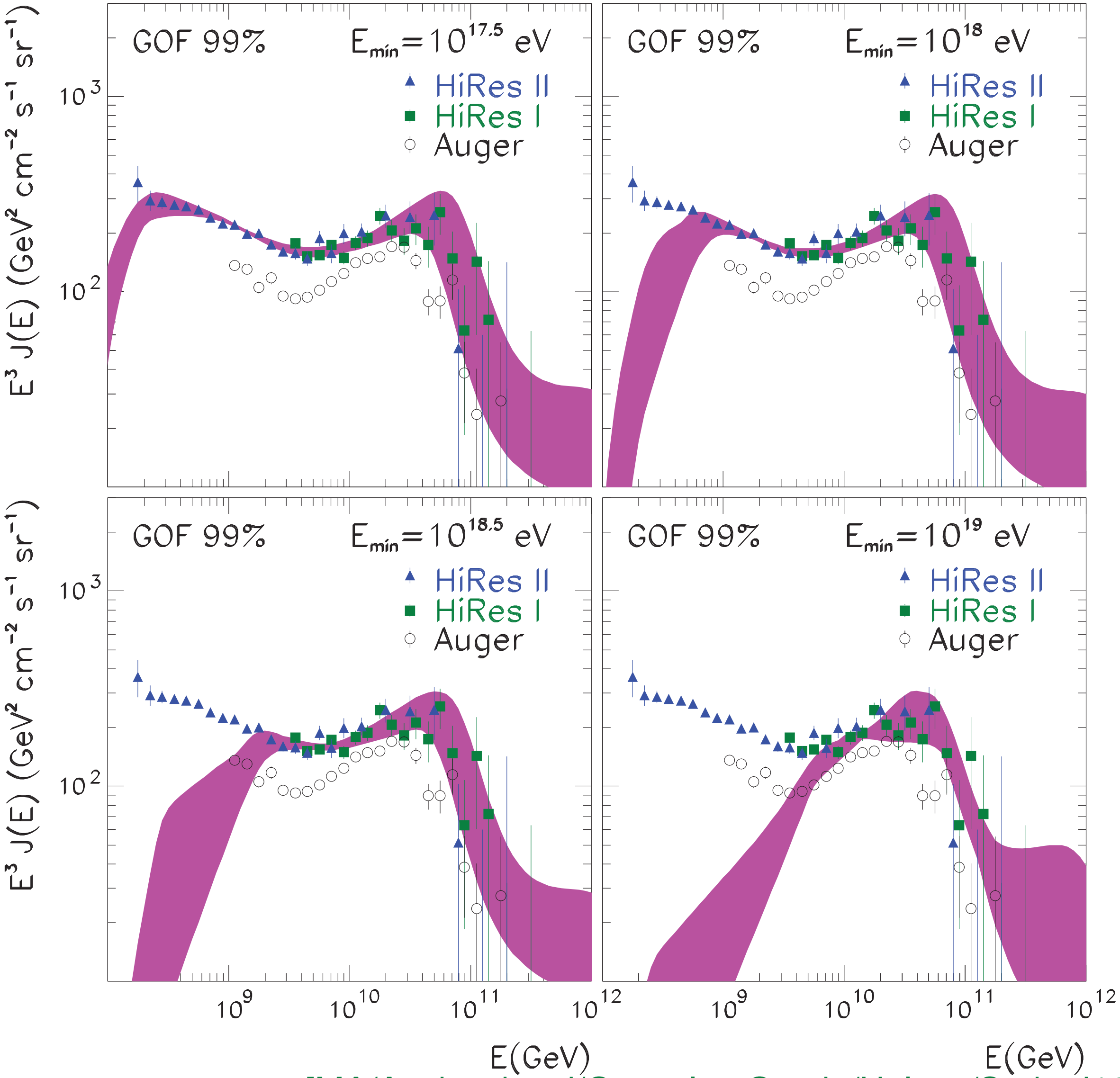


[*e.g.* Aloisio *et al.*'06]

Proton-dominance in UHE CRs?

- GoF based on Hires-I/II data ($\Delta E/E \simeq 25\%$)
- *fixed:*
  $E_{\max} = 10^{21}$ eV
  $z_{\min} = 0 \,/\, z_{\max} = 2$
- *priors:*
  $2.1 \leq \gamma \leq 2.9$
  $2 \leq n \leq 6$
  $\omega_{\rm cas} \leq \omega_{\rm Fermi}$
- *confidence levels:*
  68% **(pink)**
  95% **(blue)**
  99% **(magenta)**

➜ effect of $\omega_{\rm cas}$-prior shown as **black lines**



[MA/Anchordoqui/Gonzalez-Garcia/Halzen/Sarkar'10]

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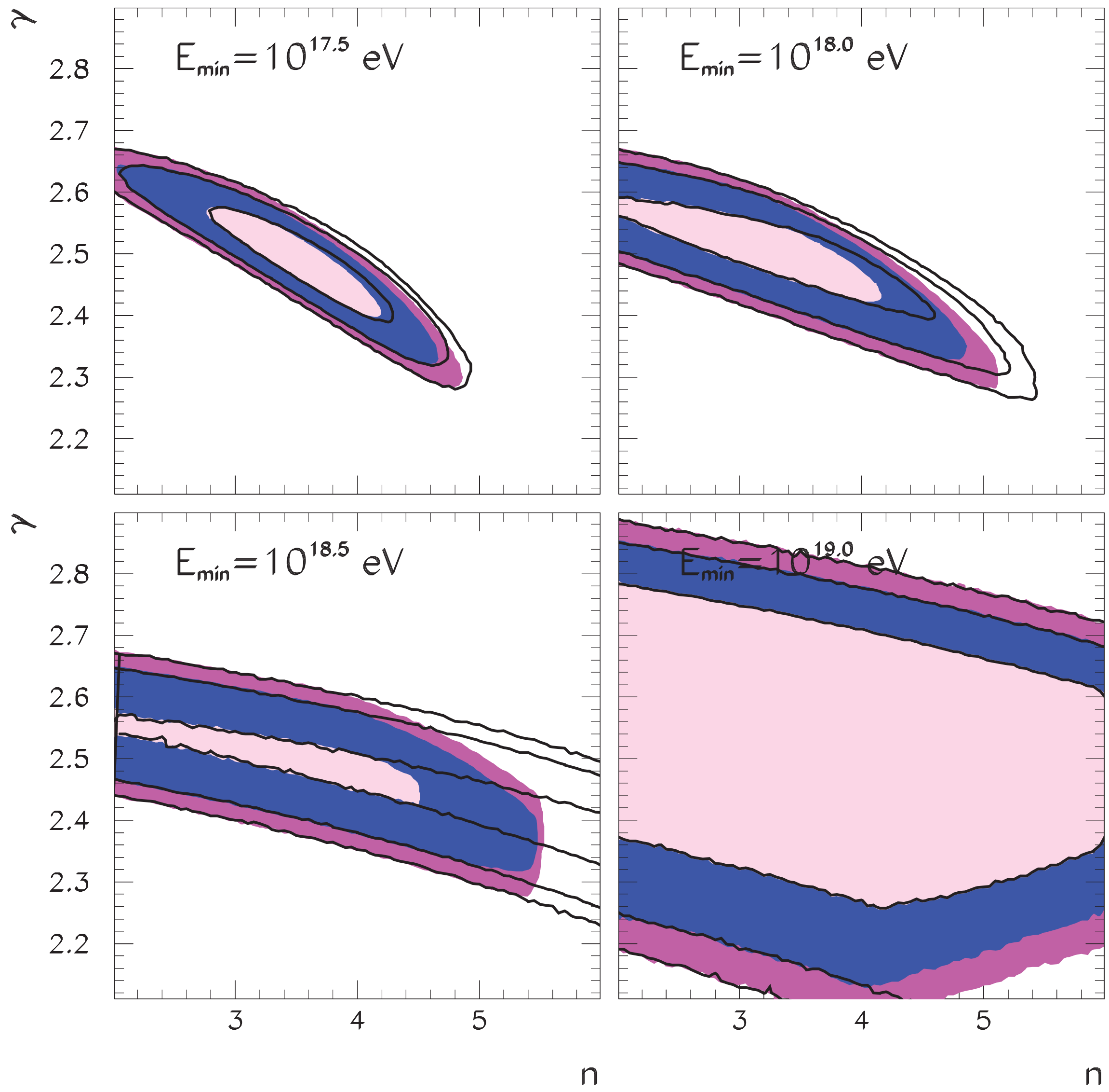
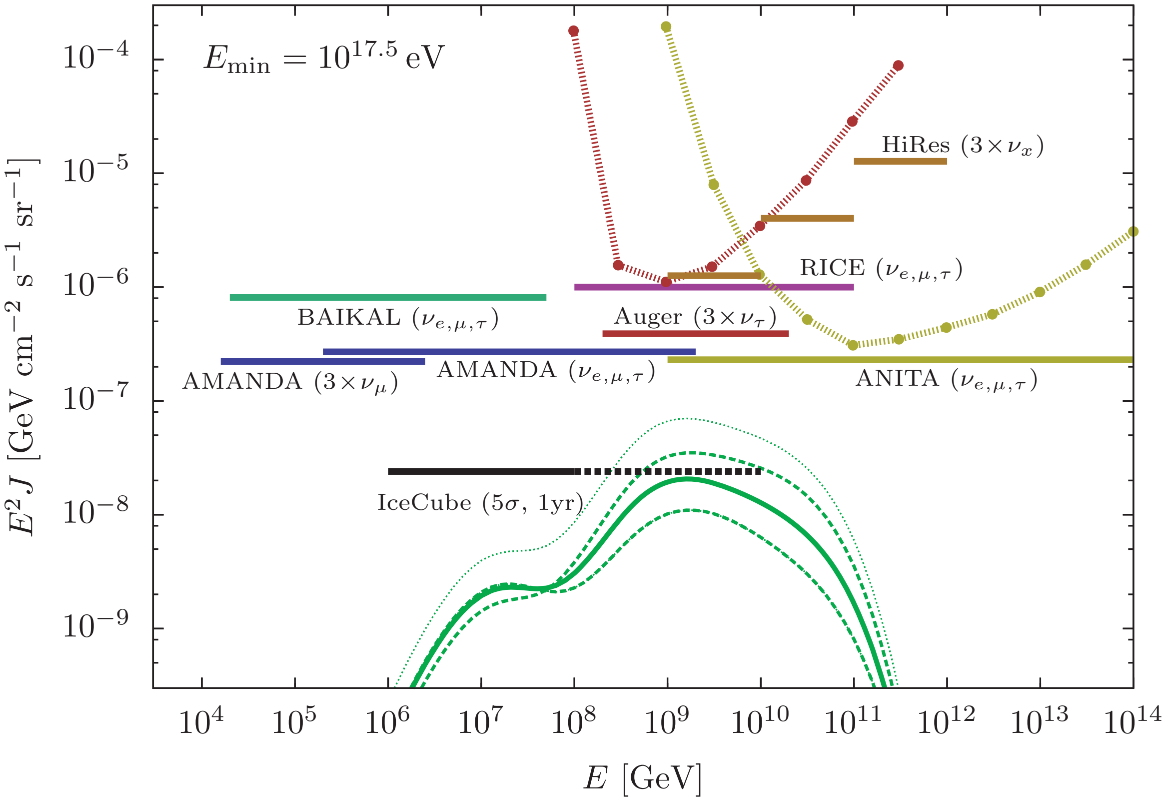


[MA/Anchordoqui/Gonzalez-Garcia/Halzen/Sarkar'10]

Cosmogenic Neutrinos

- Cascade bound, $\omega_{\rm cas} \leq \omega_{\rm Fermi}$, reduces the cosmogenic neutrino flux **(dotted green line)** by a factor 2-4.
- Range of cosmogenic neutrino fluxes increase along with the cross-over energy and lies *within reach of IceCube* **(black lines)**.



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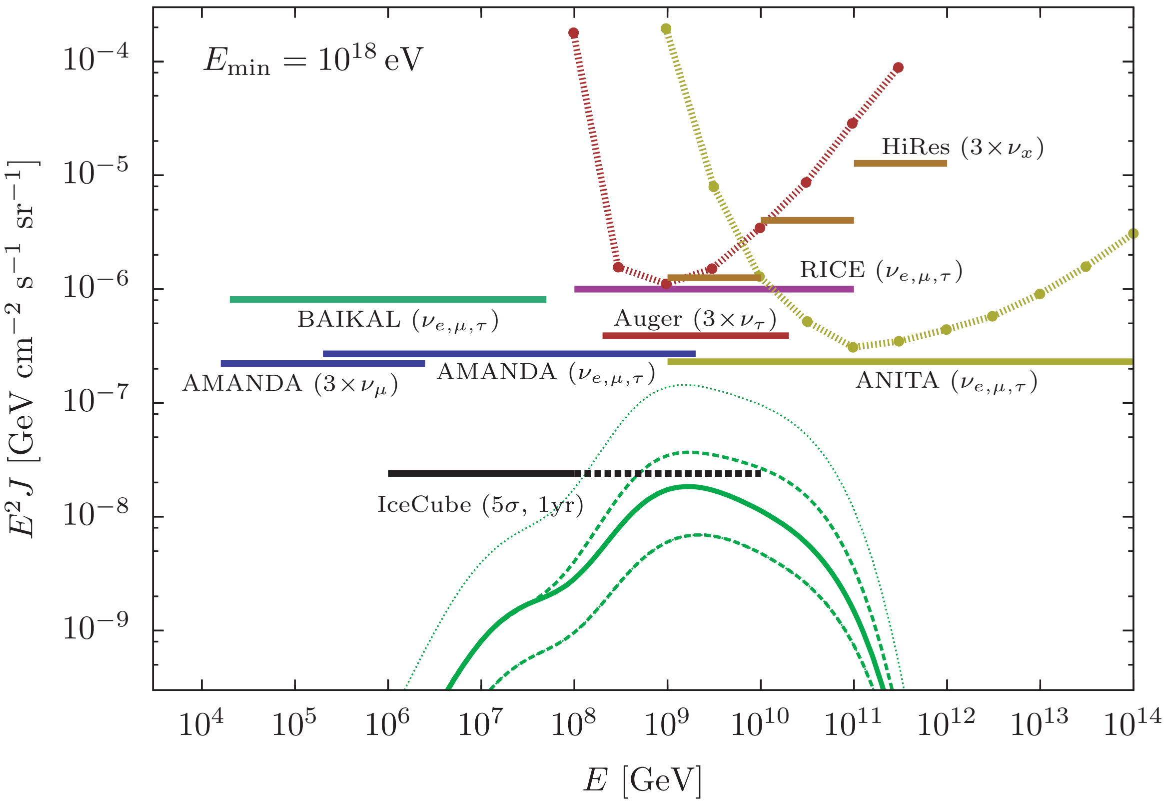

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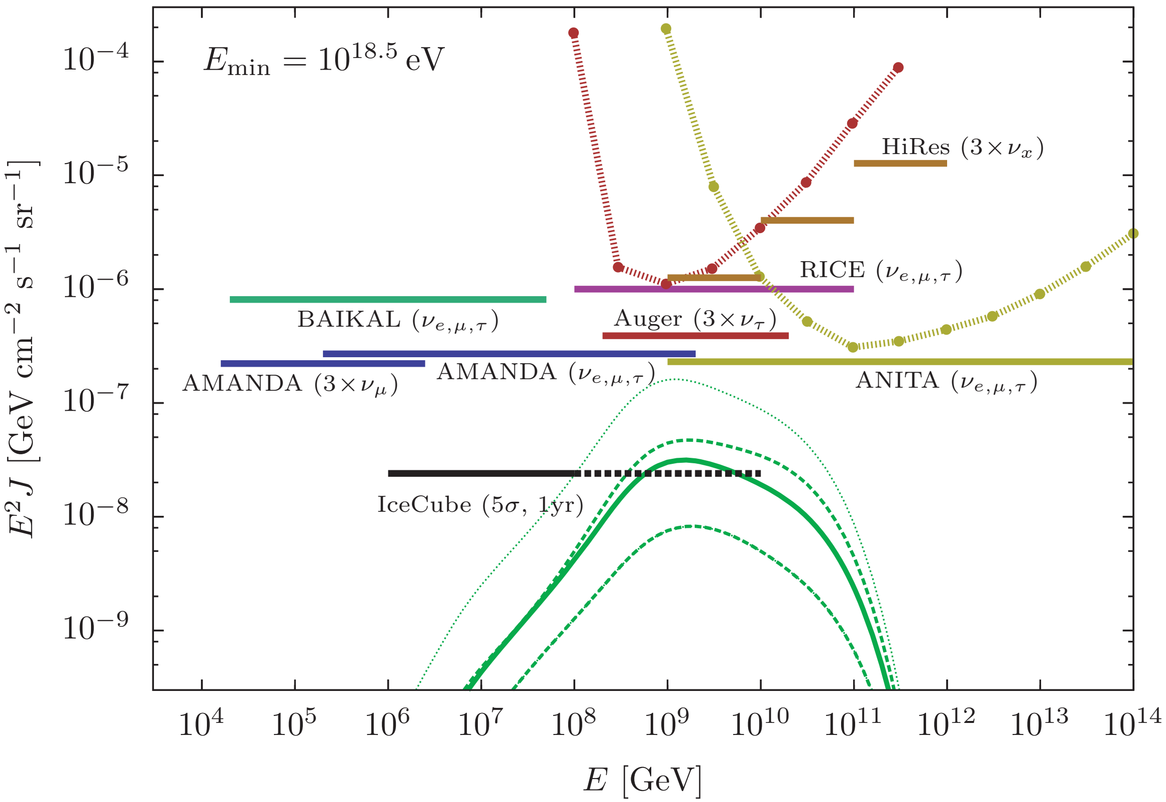

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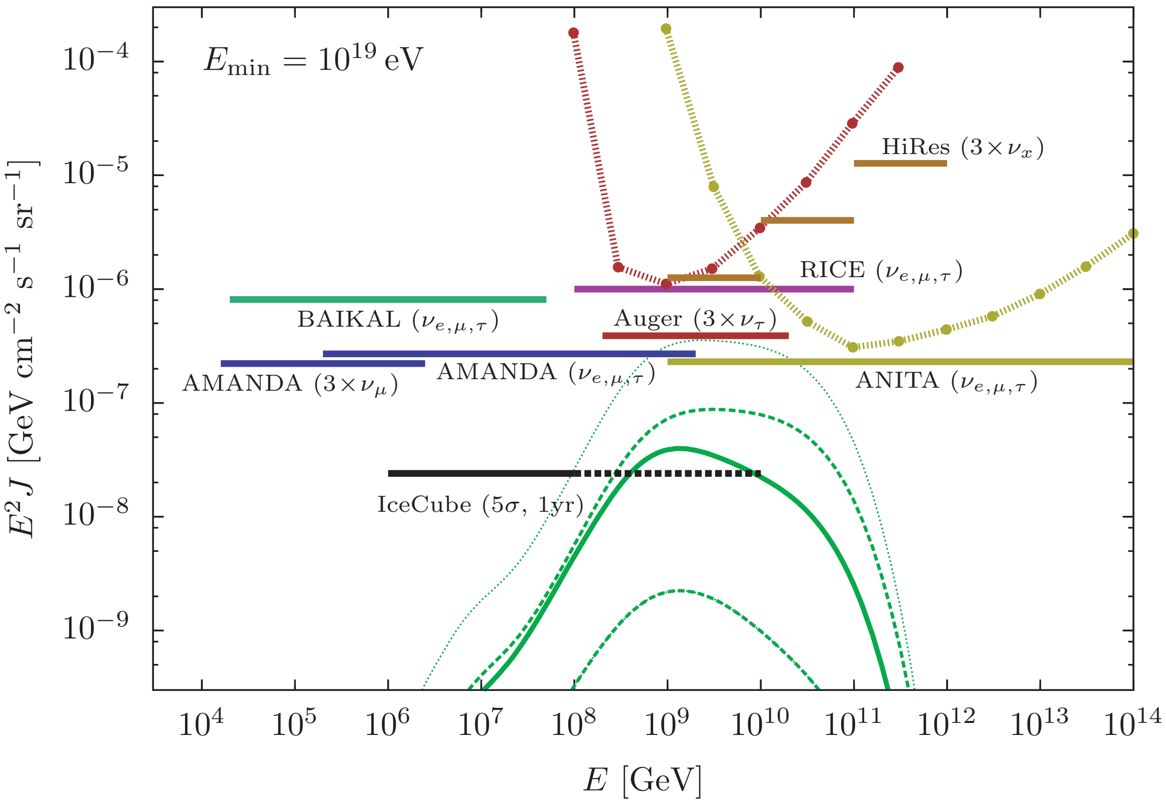

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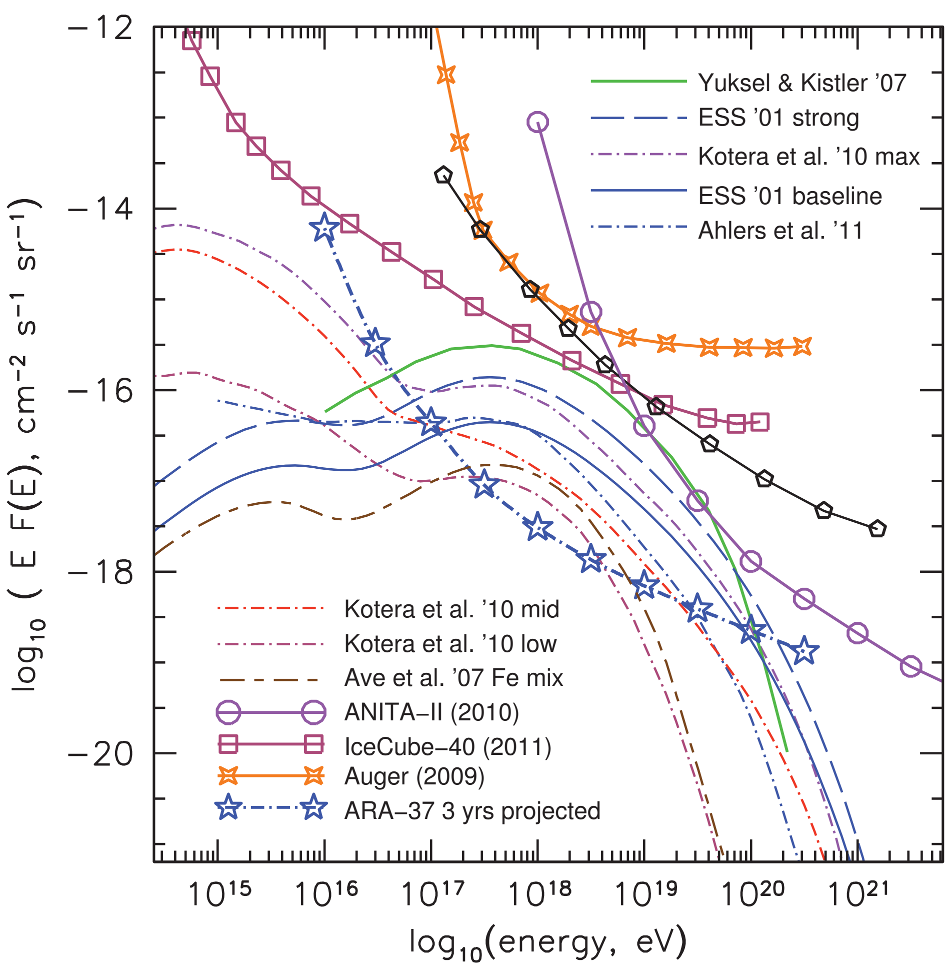


TABLE II: Expected numbers of events N_ν from several UHE neutrino models, comparing published values from the 2008 ANITA-II flight with predicted events for a three-year exposure for ARA-37.

Model & references N_ν:	ANITA-II, (2008 flight)	ARA, 3 years
Baseline cosmogenic models:		
Protheroe & Johnson 1996 [27]	0.6	59
Engel, Seckel, Stanev 2001 [28]	0.33	47
Kotera,Allard, & Olinto 2010 [29]	0.5	59
Strong source evolution models:		
Engel, Seckel, Stanev 2001 [28]	1.0	148
Kalashev *et al.* 2002 [30]	5.8	146
Barger, Huber, & Marfatia 2006 [32]	3.5	154
Yuksel & Kistler 2007 [33]	1.7	221
Mixed-Iron-Composition:		
Ave *et al.* 2005 [34]	0.01	6.6
Stanev 2008 [35]	0.0002	1.5
Kotera, Allard, & Olinto 2010 [29] upper	0.08	11.3
Kotera, Allard, & Olinto 2010 [29] lower	0.005	4.1
Models constrained by Fermi cascade bound:		
Ahlers *et al.* 2010 [36]	0.09	20.7
Waxman-Bahcall (WB) fluxes:		
WB 1999, evolved sources [37]	1.5	76
WB 1999, standard [37]	0.5	27

[ARA'11]

Cosmogenic Neutrinos

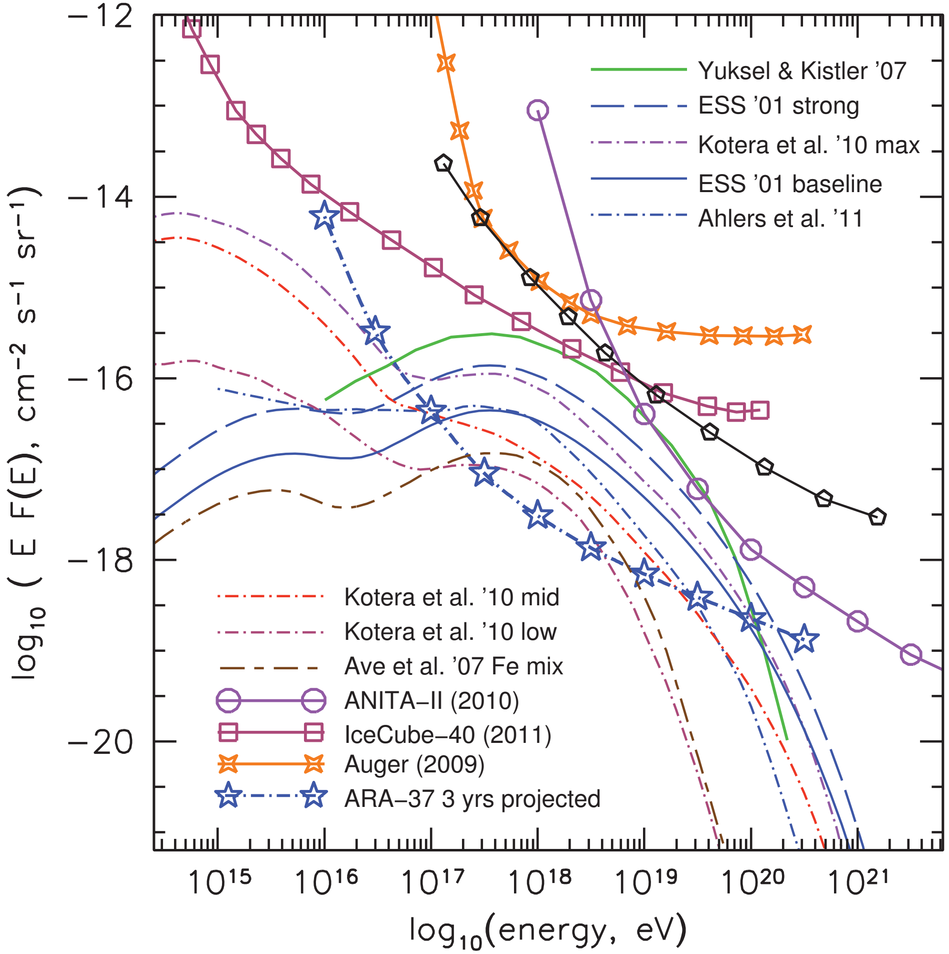


TABLE III. Expected numbers of events in 333.5 days from several cosmogenic neutrino models and top-down models. The confidence interval for exclusion by this observations is also listed where appropriate. The cosmogenic neutrino models (GZK 1-6) assume the cosmic-ray primaries to be protons and different spectral indices/cutoff energies at sources as well as different cosmological evolution parameters and extension in redshift for the sources. Representative models with moderate (GZK 3, 4, 6), moderately strong (GZK 1) and strong (GZK 2, 5) source evolution parameters are listed here.

Models	Event rate	C.L. %
GZK 1 [3]	0.57	···
GZK 2 [4]	0.91	53.4
GZK 3 ($\Omega_\Lambda = 0.0$) [5]	0.29	···
GZK 4 ($\Omega_\Lambda = 0.7$) [5]	0.47	···
GZK 5 (maximal) [6]	0.89	52.8
GZK 6 (the best fit) [6]	0.43	···
Top-down 1 (SUSY) [22]	1.0	55.7
Top-down 2 (no-SUSY) [22]	5.7	99.6
Z-burst [21]	1.2	66.4
WB bound (with evolution) [32]	4.5	···
WB bound (without evolution) [32]	1.0	···

GZK 1 : Yoshida&Teshima'93
GZK 2 : Kalashev/Kuzmin/Semikoz/Sigl'02
GZK 3/4 : Engel/Seckel/Stanev'01
GZK 5/6 : MA/Anchordoqui/Halzen/Gonzalez-Garcia/Sarkar'10

[IceCube'11]

Prompt neutrino emission of GRBs?

- acceleration of UHE CRs in internal shocks of GRBs? [Waxman'05;Vietri'95] (Lorentz factor Γ_i and variability t_v)
- prompt neutrino emission via $p\gamma$ interactions [Waxman&Bahcall'97]

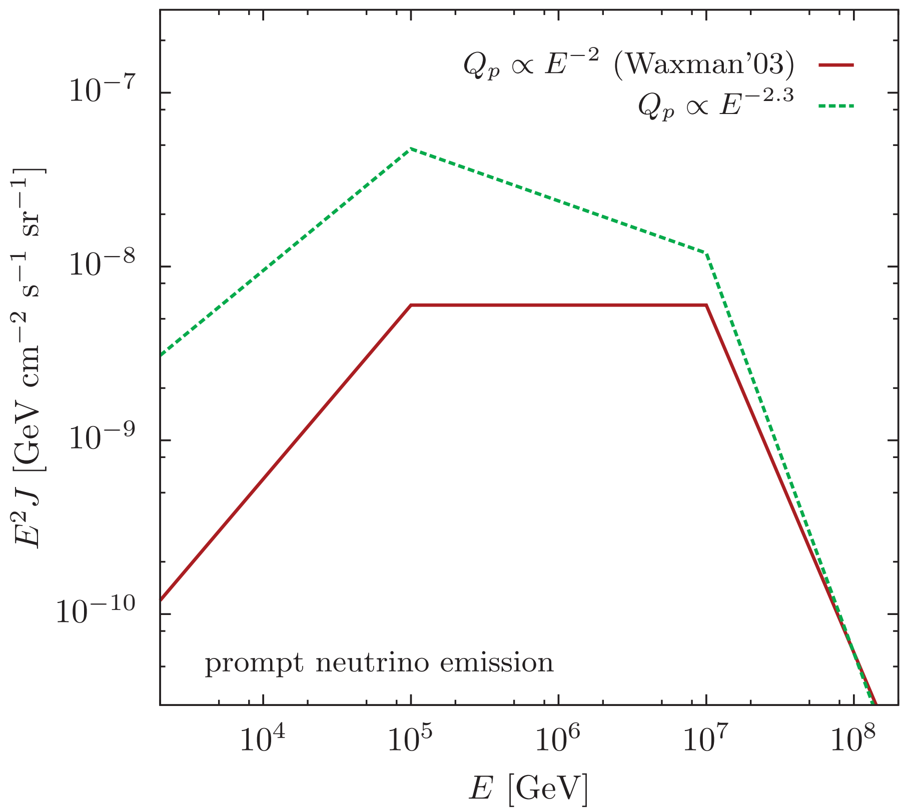
➜ neutrino spectrum follows CR spectrum $\propto E^{-\gamma}$ at PeV energies

- $p\gamma$ break in spectrum ($\epsilon_0 \sim 1$ MeV):

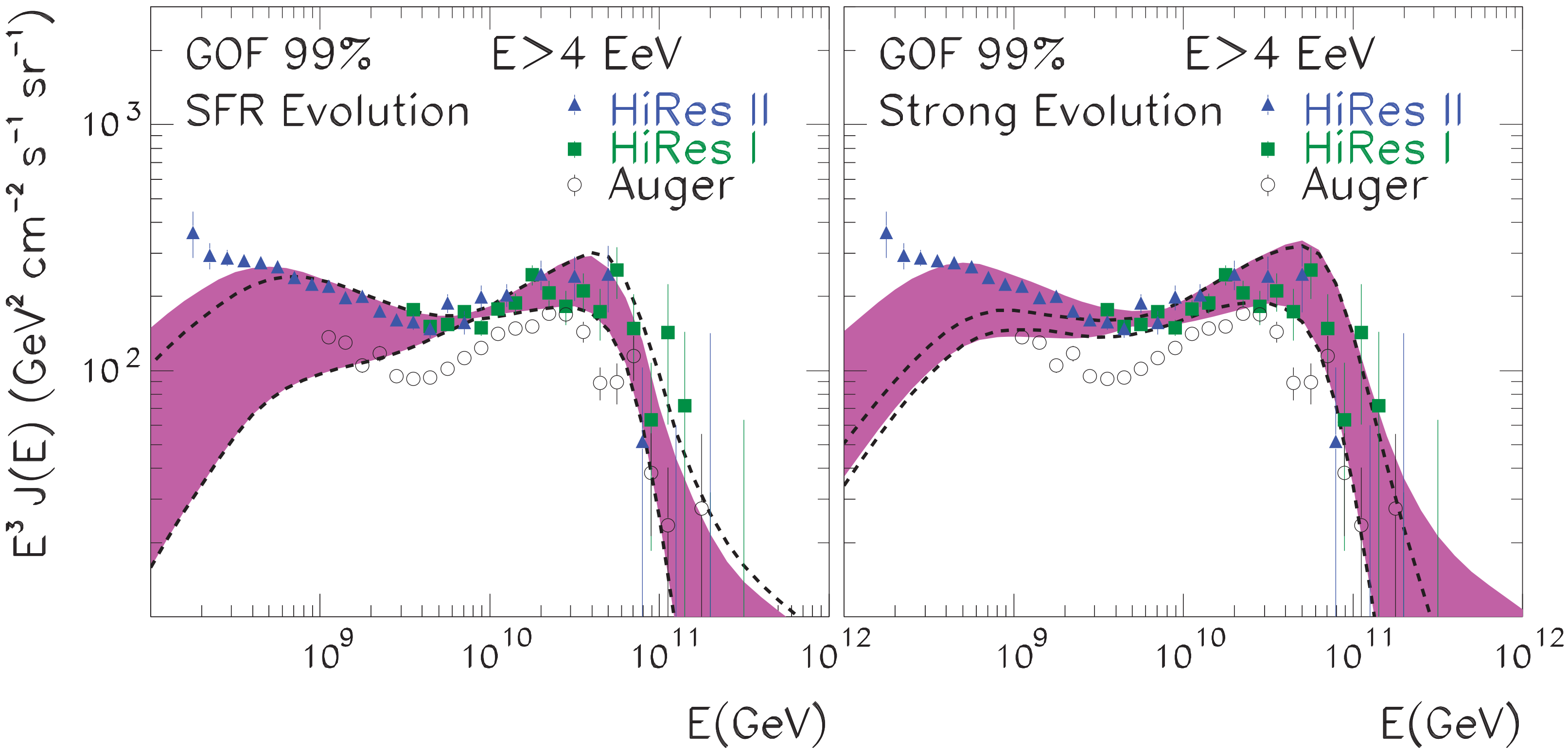
$$E_{\nu,\mathrm{b}} \simeq \frac{1}{20} E_{p,\mathrm{b}} \simeq 2 \times 10^{15} \frac{\Gamma_{i,2.5}^2}{\epsilon_{0,6}} \mathrm{eV}$$

- synchrotron knee of pions/muons:

$$E_{\nu,\mathrm{s}} = \left(\frac{\varepsilon_{e,-1} \Gamma_{i,2.5}^8 t_{v,-2}^2}{\varepsilon_{B,-1} L_{\gamma,52}} \right)^{1/2} \times \begin{cases} 2 \times 10^{17}\ \mathrm{eV} & (\nu_\mu) \\ 1 \times 10^{16}\ \mathrm{eV} & (\bar{\nu}_\mu, \nu_e) \end{cases}$$

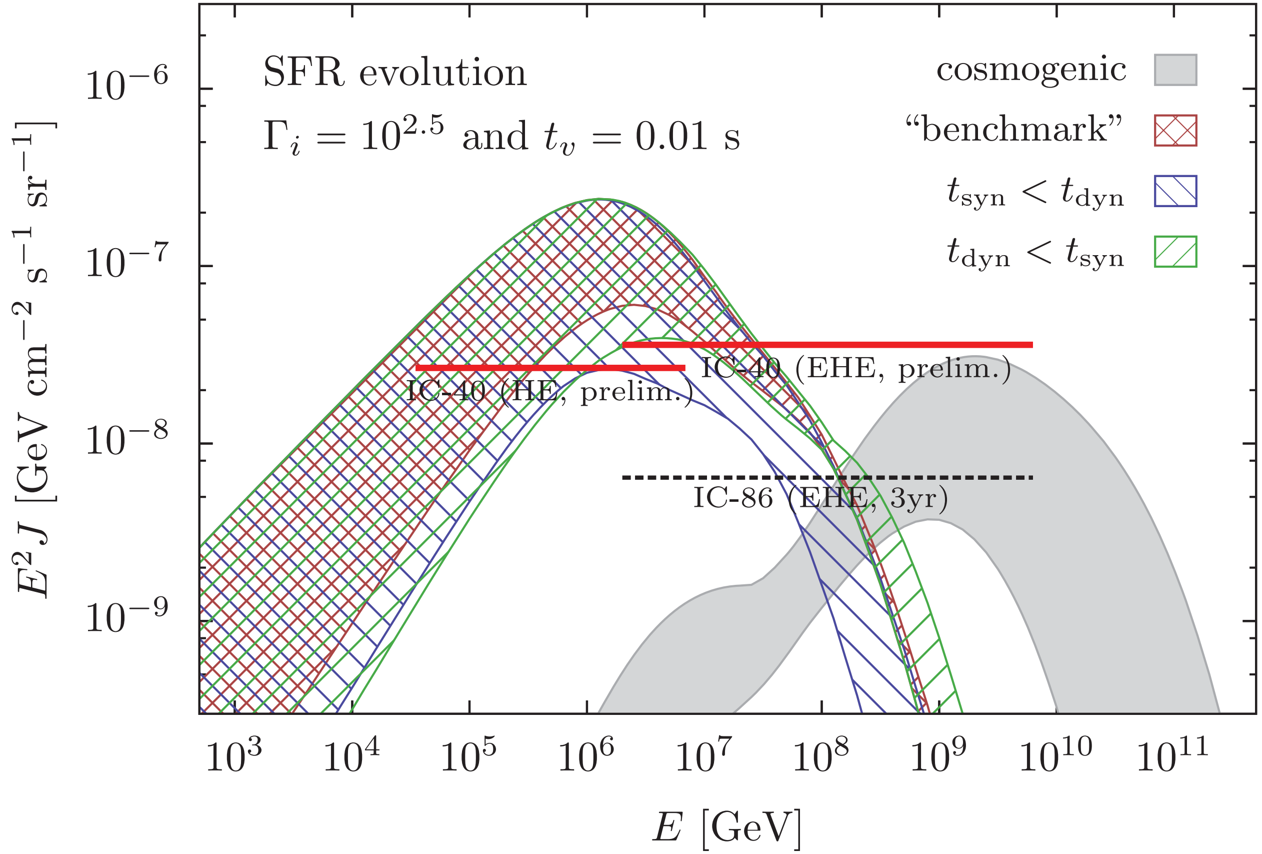


Prompt neutrino emission of GRBs?



- fit of spectrum to HiRes data above ankle: $\mathcal{L}(0,E) \propto E^{-\gamma}/(1+(E_{\rm p,b}/E))e^{-E/E_{\rm max}}$
- "SFR" : evolution following star formation rate [Hopkins&Beacom'06;Yuksel *et al.*'08]
- "strong" : $\mathcal{L}_{\rm strong}(z,E) = (1+z)^{1.4}\,\mathcal{L}_{\rm SFR}(z,E)$ [Yuksel&Kistler'06]

Prompt neutrino emission of GRBs?



- **hypothesis** : UHE CRs production in GRBs via neutron emission
- scan over luminosity range $0.1 < (\varepsilon_B/\varepsilon_e)L_{\gamma,52} < 10$

➜ probe of viable GRB parameters [MA/Gonzalez-Garcia/Halzen/Sarkar'11]

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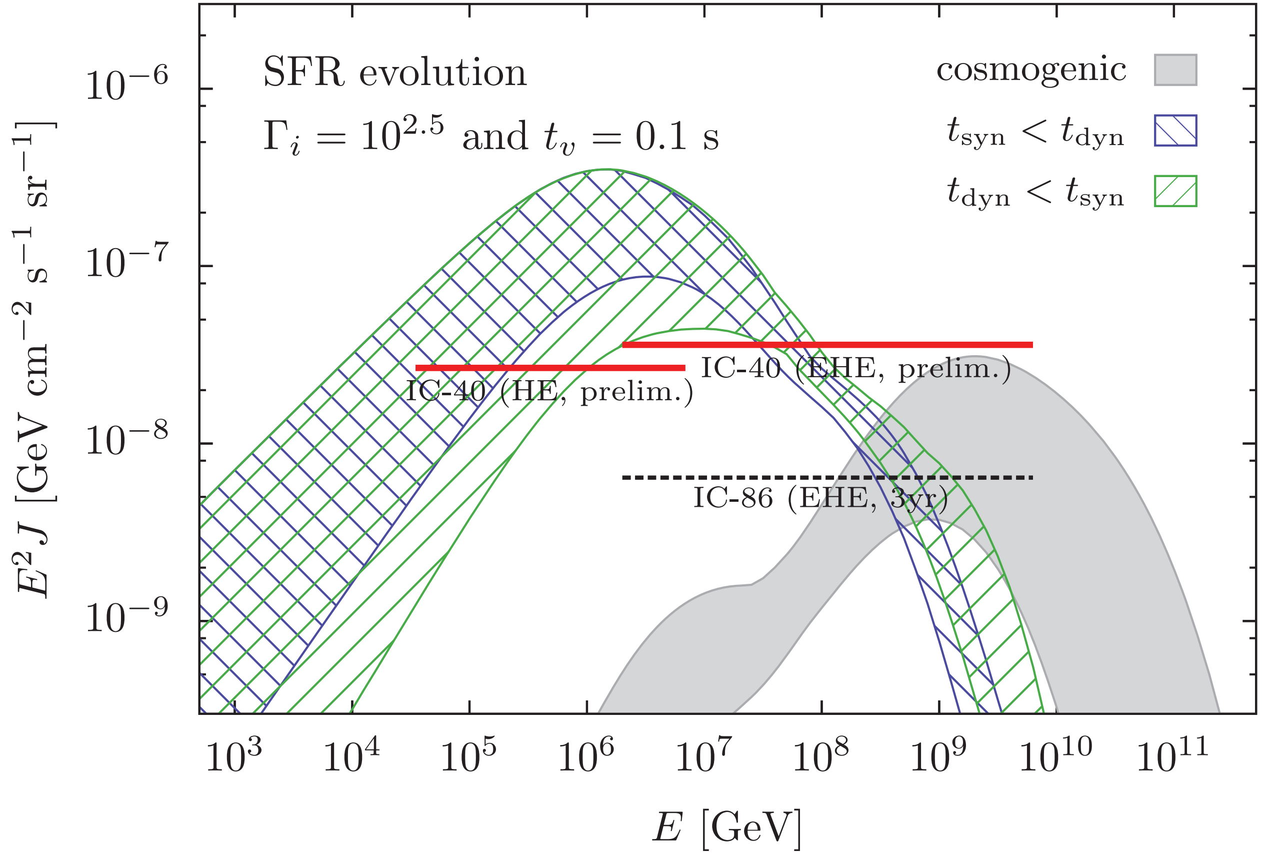

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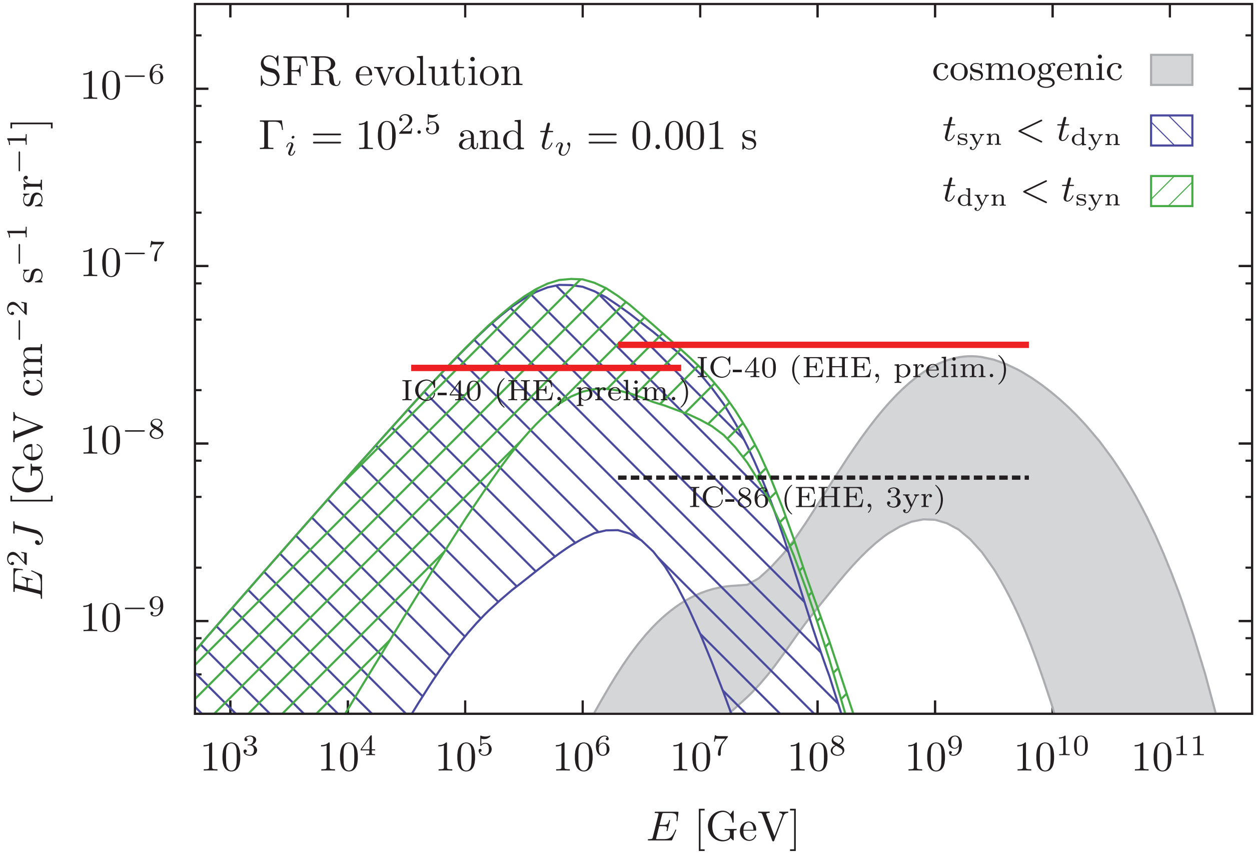

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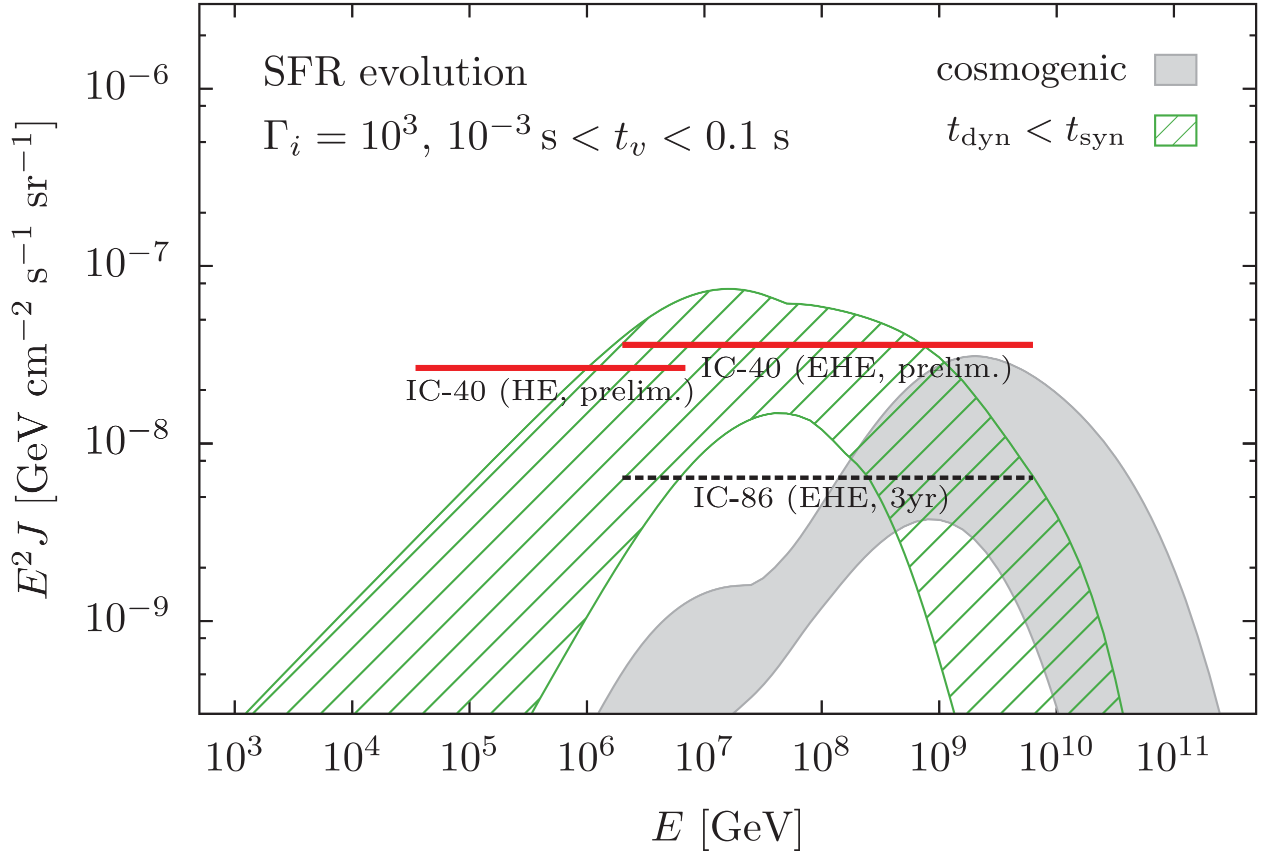

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Summary

- ✔ Neutrino sky looks dark so far, but a bright future might just be around the corner.

- ✔ Neutrino (non-)observatories have reached a sensitivity to constrain multi-messenger signals – γ-rays and UHE CRs – with "minimal" assumptions.

- ✔ Strong integral limit on diffuse emission set by IceCube (PeV-EeV):
  - $\omega_{\rm Fermi} \simeq 6 \times 10^{-7}\ {\rm eV/cm^3}$
  - $\omega_{\rm HiRes,E>4EeV} \simeq 4 \times 10^{44}{\rm erg/Mpc^3/yr} \times t_{\rm age} \simeq 1 \times 10^{-7}\ {\rm eV/cm^3}$
  - $\omega_{\rm IC40} \lesssim 1 \times 10^{-7}\ {\rm eV/cm^3}$

- ✔ Specific neutrino emission models, *e.g.* prompt neutrino emission of GRBs can already be tested by present limits, diffuse or point-source (➜ talk by Alexander).