The neutrino sky at very high energies

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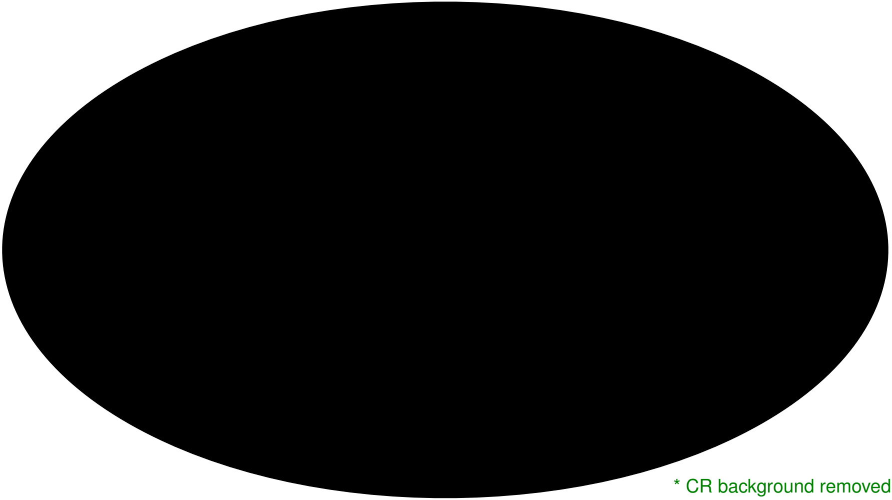
"5th Workshop on Very-Large Volume Neutrino Telescopes",
Erlangen, October 12-14, 2011

Neutrino sky map* at very high energies

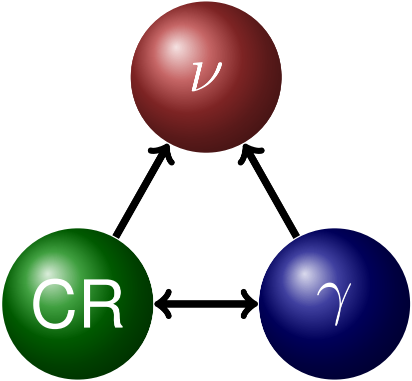


* CR background removed

Multi-messenger paradigm

- Neutrino production closely related to the production of cosmic rays (CRs) and γ-rays.
- Flux predictions are based on CR and γ-ray observation.
- A brief status summary:
  - ✘ No “surprises” yet.
  - ✔ Sensitivity has reached the level of “serious” models.

➜ Implications of neutrino limits on multi-messenger production.



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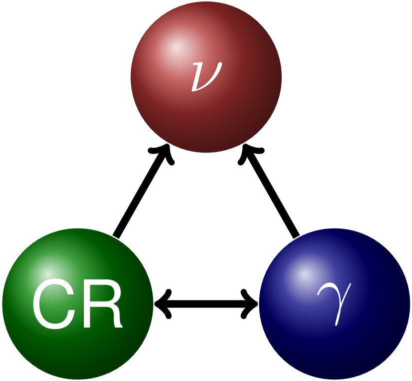

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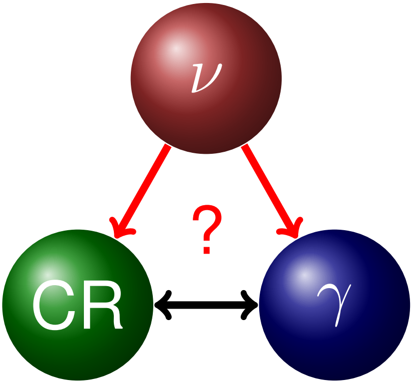
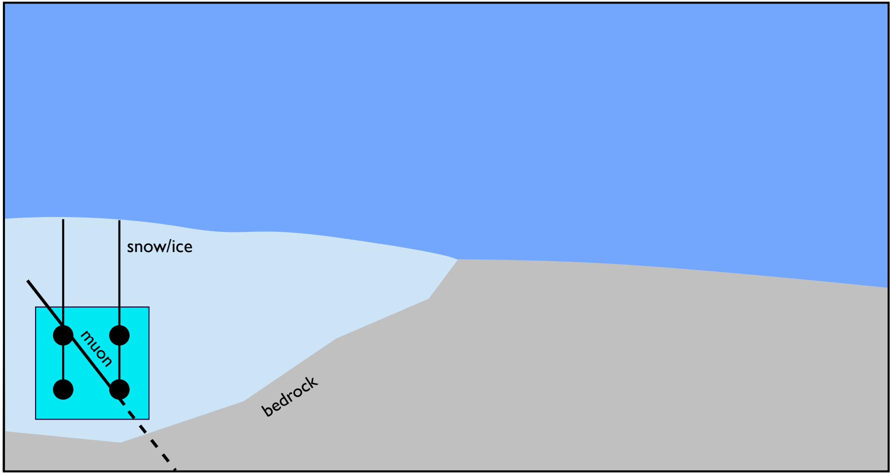


Neutrino observation at very high energies



[MA'11]

Cherenkov radiation in transparent media (glaciers, lakes, oceans,. . .).

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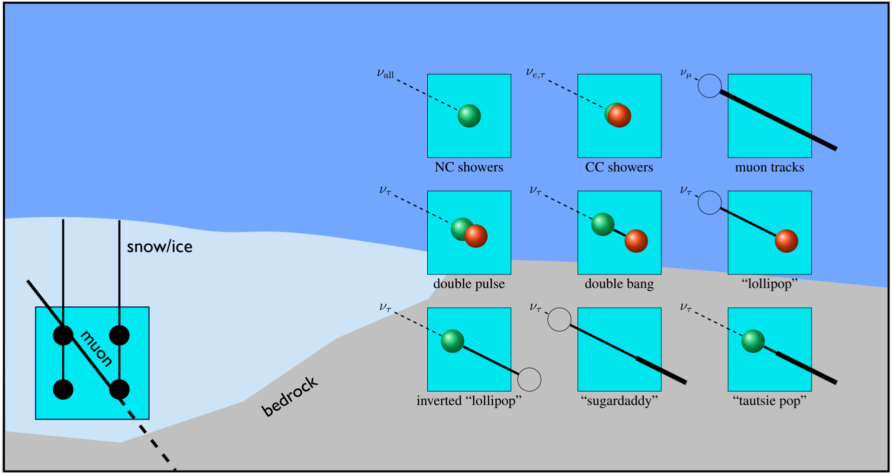

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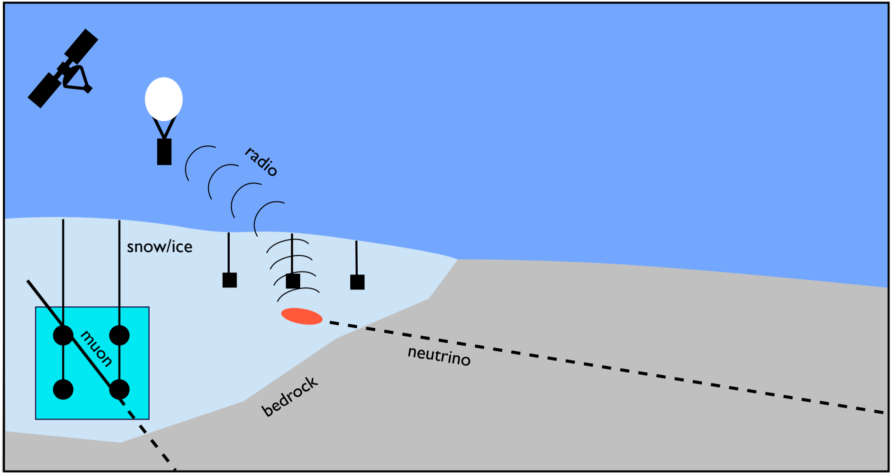
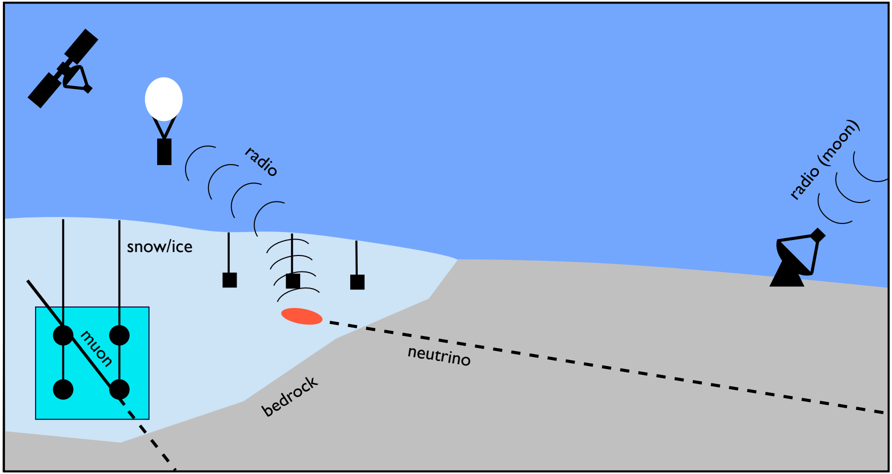


[MA'11]

Coherent radio Cherenkov emission (Askaryan effect).
Observation in-situ, balloons or satellites.

Neutrino observation at very high energies



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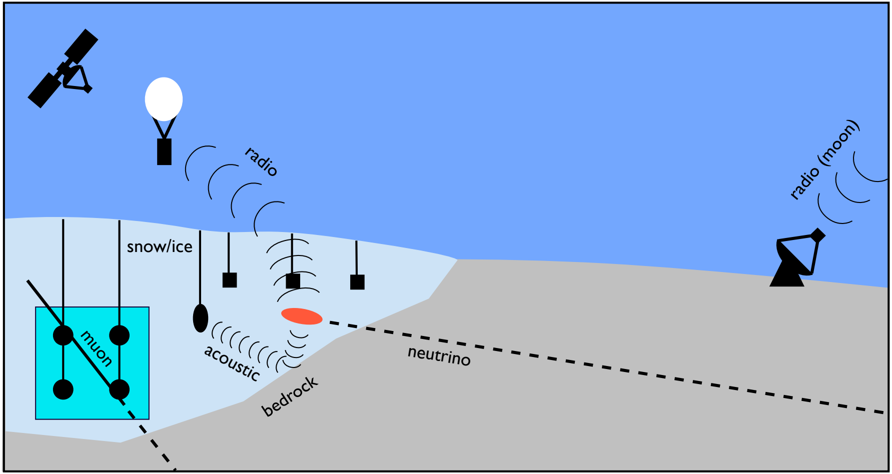
Observation from lunar regolith.

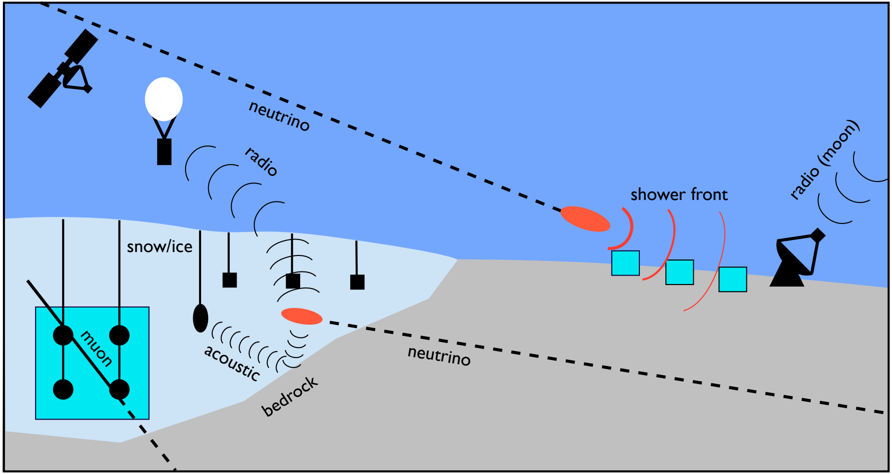
Neutrino observation at very high energies



[MA'11]

Acoustic detection?

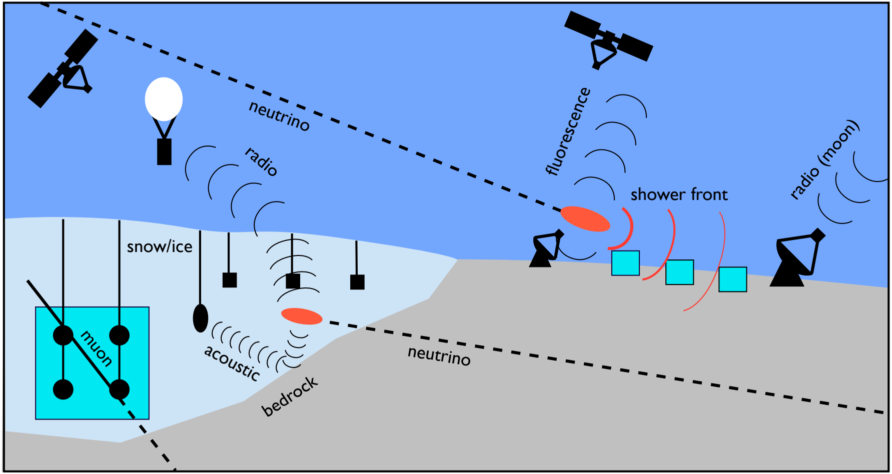
Neutrino observation at very high energies



[MA'11]

Deeply penetrating quasi-horizontal showers.
Observation by CR surface arrays.

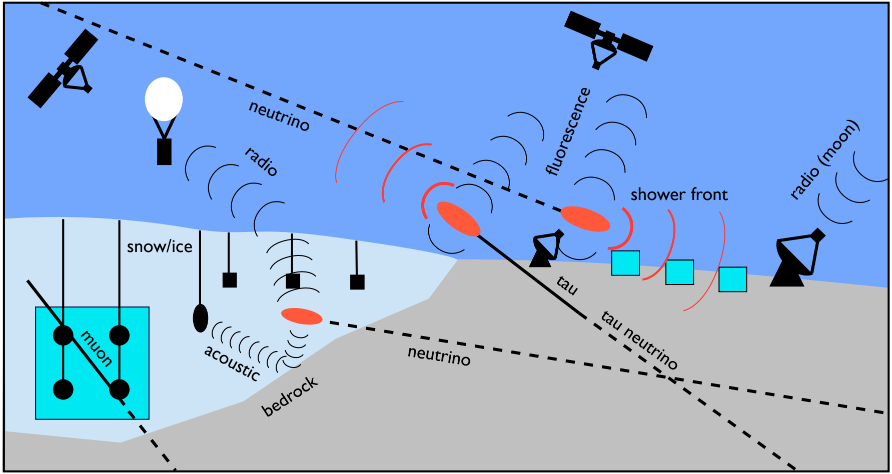
Neutrino observation at very high energies



[MA'11]

Observation by CR surface arrays and/or fluorescence detectors/satellites.

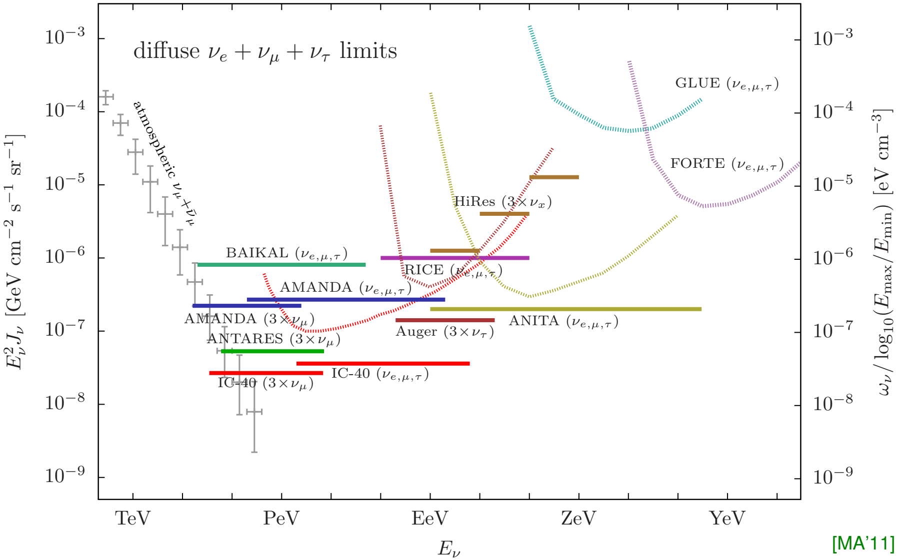
Neutrino observation at very high energies



[MA'11]

Earth-skimming tau neutrinos.

Neutrino limits at very high energies



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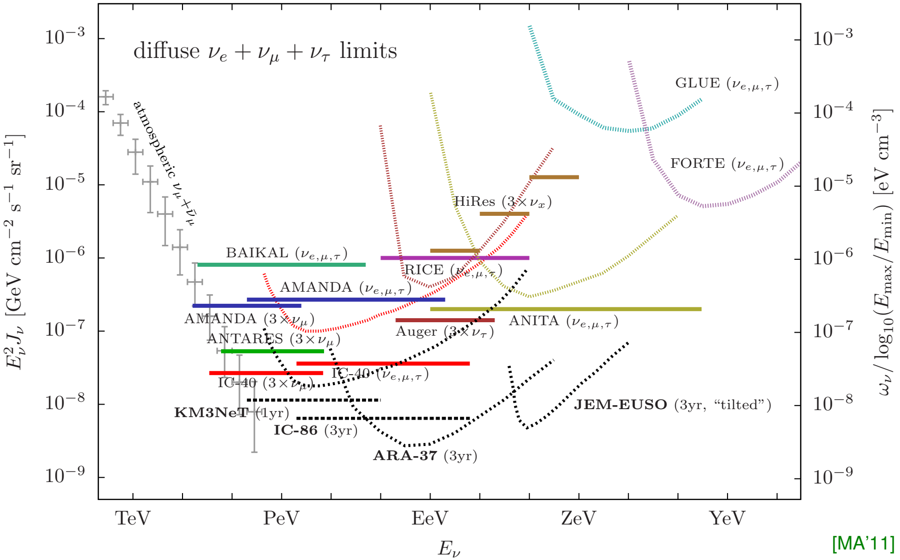


[MA'11]

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):

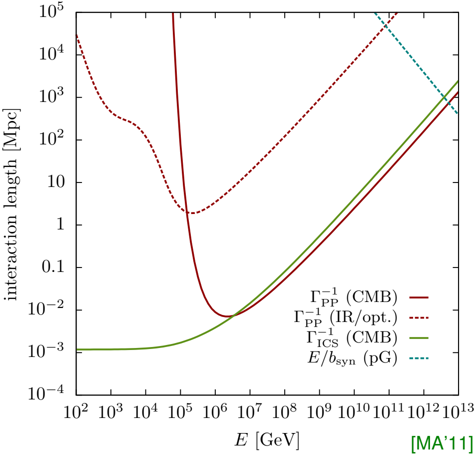
$$Q_\gamma(E_\gamma) = \frac{1}{3}\frac{1}{K}Q_\nu(E_\gamma/2) \qquad \& \qquad Q_e(E_e) = \frac{1}{3}Q_\nu(E_e)$$

➜ cascades in cosmic radiation background

✘ limited by extragalactic **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



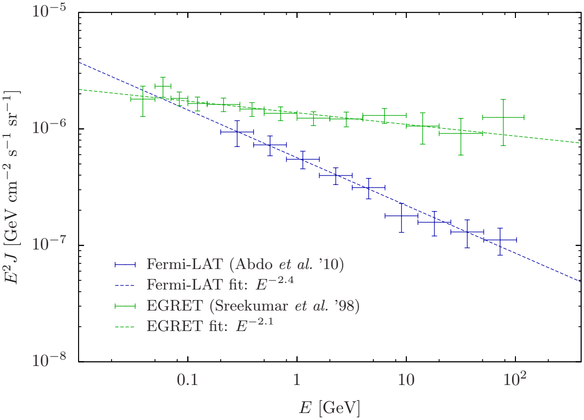
[MA'11]

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

Study of multi-messenger relations over various CR energies via test-spectra:

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

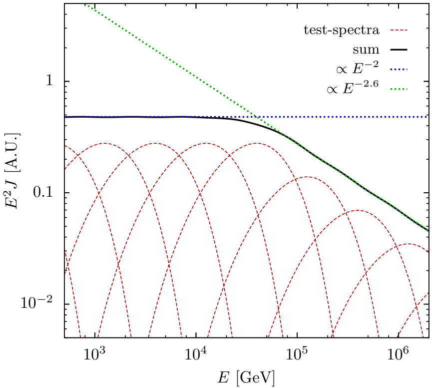
- "bin-wise" test of neutrino fluxes:

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

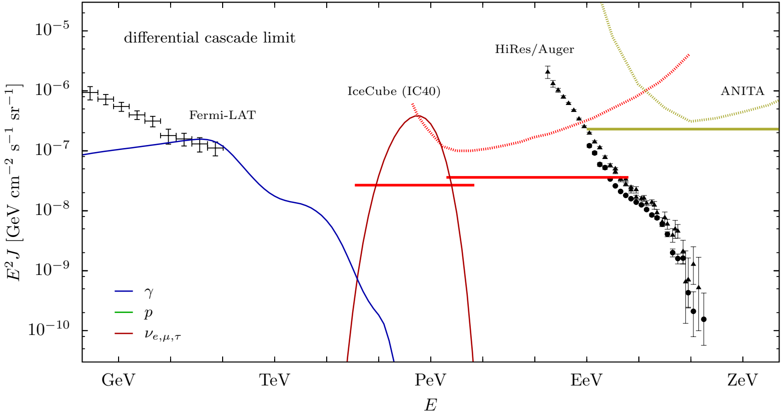
- serves as "basis", *e.g.* for power-law flux:

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

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



Cascade limit revisited



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

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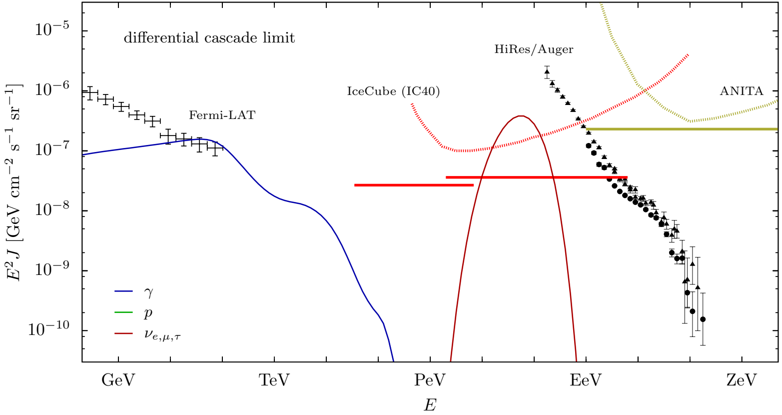

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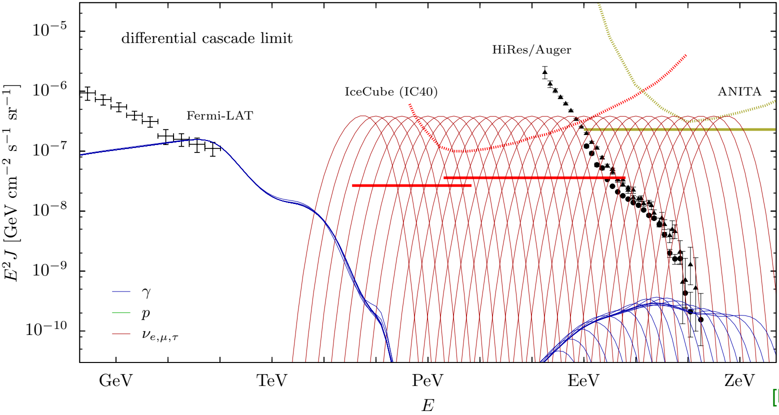

[MA'11]

- envelope of test-function corresponds to a **differential** upper limit
- magnetic field at pion production ($\tau_{syn} \ll \tau_\pi$?):
  $Q_\nu(E_\nu) \to Q_\nu(E_\nu)/(1 + (E_\nu/E_b)^2)$ with $E_b \simeq \frac{1}{4}\frac{3}{4}\sqrt{\frac{m_\pi^2}{\pi\alpha^2 B^2 \tau_\pi}} \simeq 3\mathrm{PeV}/B_\mathrm{T}$

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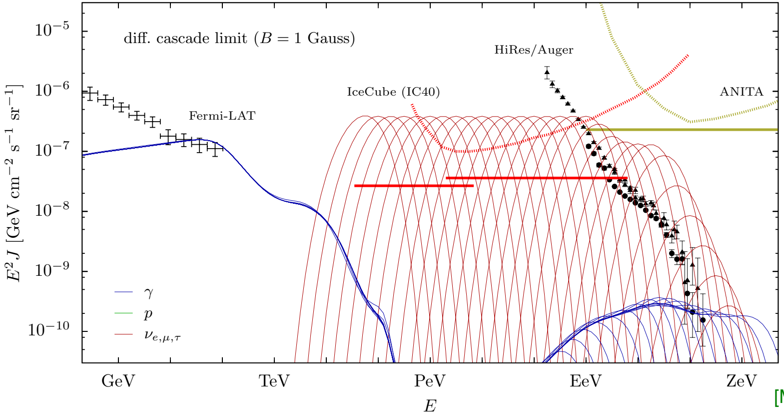

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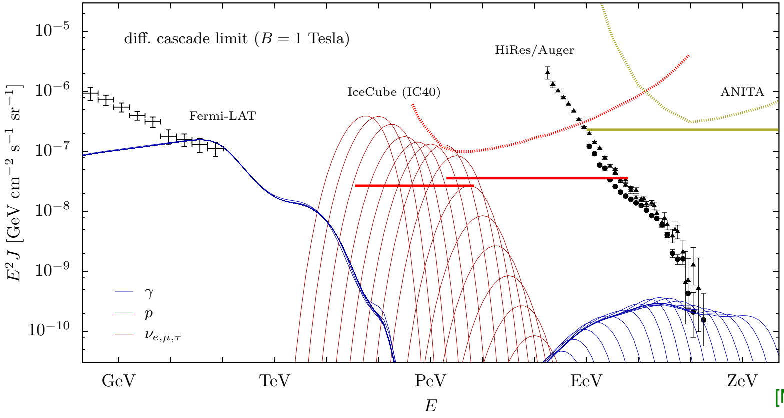

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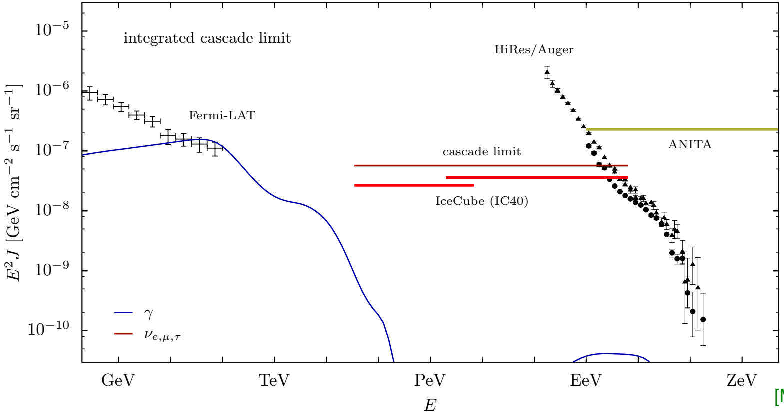
Integrated cascade limit



[MA'11]

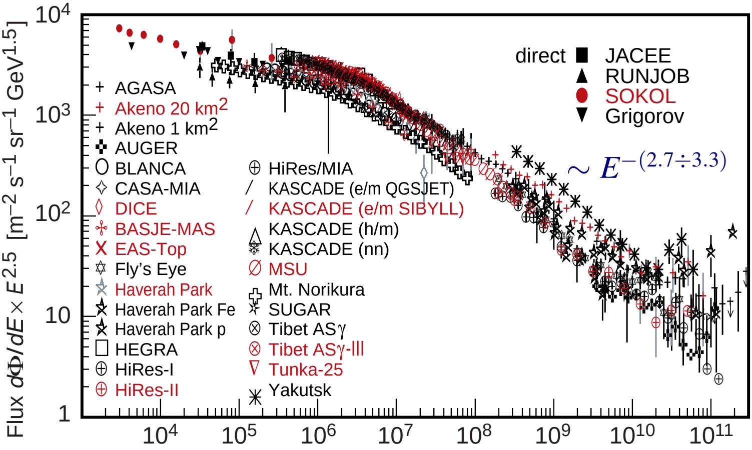
- **integrated** cascade limit assuming E^{-2} flux between E_- and E_+:

$$E^2\Phi_{\nu_{\rm tot}} \simeq 3\times10^{-7}\,(\log_{10}(E_+/E_-))^{-1}\,{\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

- **energy density**: $\omega_{\rm Fermi} \simeq 6\times10^{-7}\ {\rm eV/cm^3} \quad {\rm vs.} \quad \omega_{\rm IC40}\simeq 1\times10^{-7}\ {\rm eV/cm^3}$

The cosmic leg

The all-particle spectrum (as $E^{2.5} \times F$) of cosmic rays.



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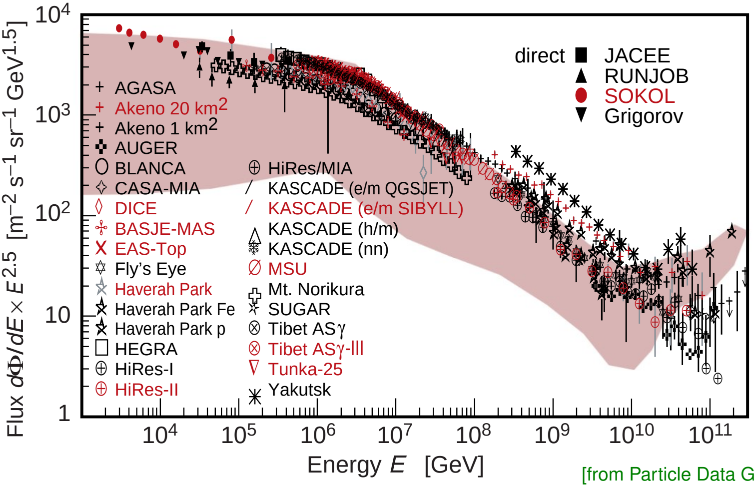

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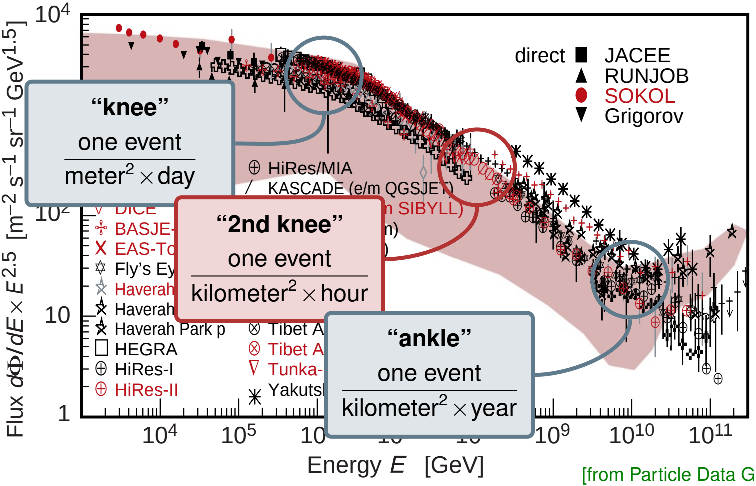

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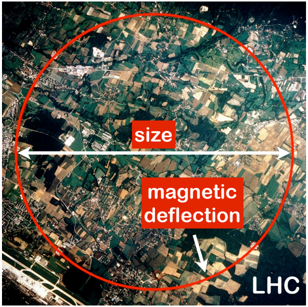
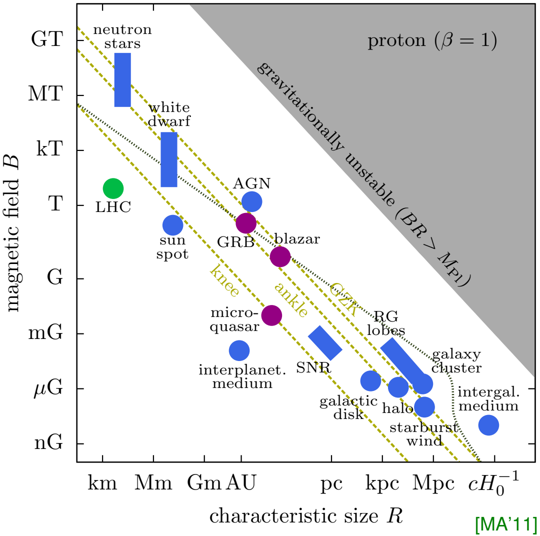
Where do they come from?

- CR acceleration is (most likely) a continuous process.

➜ Accelerators need to confine the particle by magnetic fields.

- $E_{\max} \sim$ size $\times$ field strength





[MA'11]

Conceivable neutrino fluxes

- Typical neutrino energy from $p\gamma$ interactions (in boosted environments):

$$E_\nu \simeq \frac{1}{40}\frac{\Delta^2\Gamma^2}{(1+z)^2E_\gamma} \simeq 4\times10^{19}\ \mathrm{eV}\times\frac{\Gamma^2}{(1+z)^2}\times\left(\frac{E_\gamma}{\mathrm{meV}}\right)^{-1}$$

  - cosmogenic neutrinos ($\Gamma = 1$ / $E_\gamma \simeq 10$ meV): $E_\nu \simeq 1$ EeV
    [Berezinsky&Zatsepin'69]
  - prompt neutrino emission in GRBs ($\Gamma \simeq 300$ / $E_\gamma \simeq 1$ MeV): $E_\nu \simeq 1$ PeV
    [Waxman&Bahcall'97]
  - afterglow emission in GRBs ($\Gamma \simeq 100$ / $E_\gamma \simeq 1$ keV): $E_\nu \simeq 1$ EeV
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  - external radiation in line-emitting blazars ($\Gamma \simeq 10$ / $E_\gamma \simeq 0.1$ MeV): $E_\nu \simeq 10$ TeV
    [Atoyan&Dermer'01]
  - UV emission from AGN disk ($\Gamma \simeq 1$ / $E_\gamma \simeq 10$ eV): $E_\nu \simeq 1$ PeV
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  - internal synchrotron emission in AGN jets ($\Gamma \simeq 10$ / $E_\gamma \simeq 1$ meV): $E_\nu \simeq 1$ ZeV
    [Mannheim/Stanev/Biermann'92]
  - ...

- Neutrinos form pp interactions $E_\nu \lesssim 0.05E_p$ can dominate in dense environments:
  - precursor neutrinos of GRBs: $E_\nu \lesssim 100$ TeV
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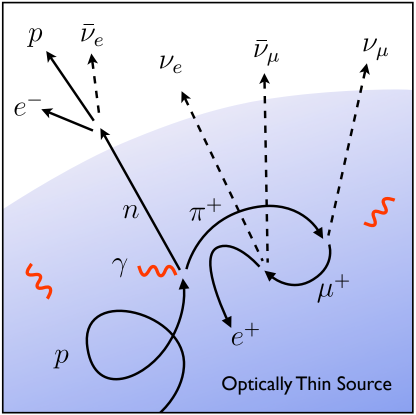
Optically thin sources



(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]

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

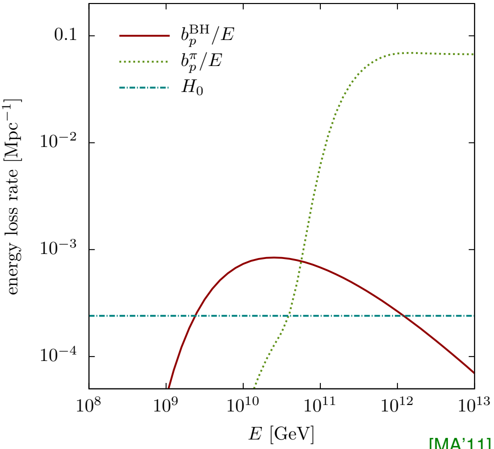
- Bethe-Heitler (BH) pair production:

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

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

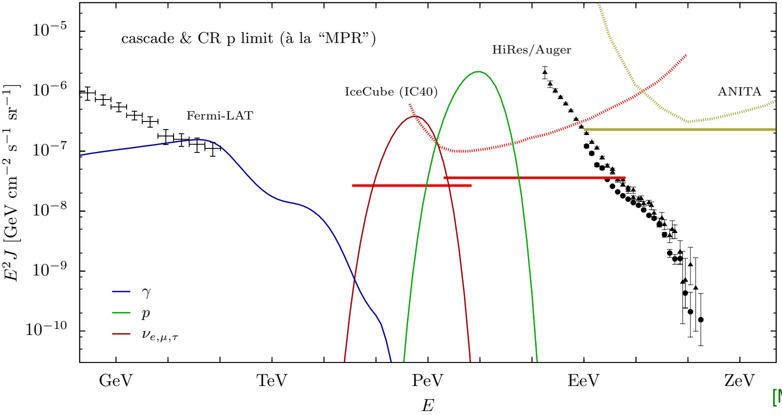
➜ **decreases** the cascade limit on cosmogenic neutrinos.

[Kalashev/Semikoz/Sigl'09]



[MA'11]

MPR bound revisited



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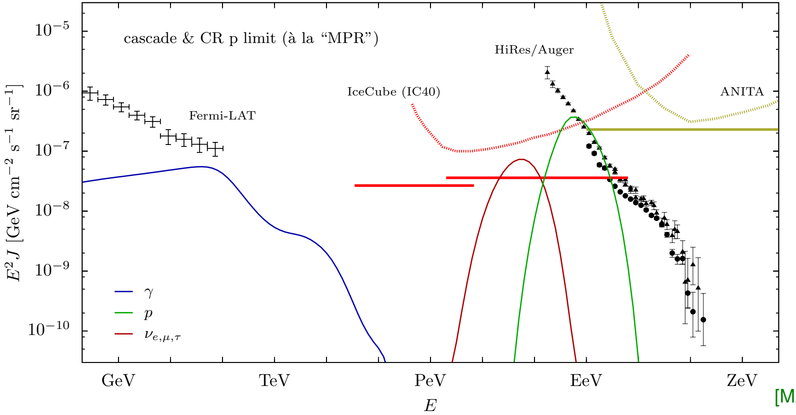
➜ "reduced" cascade bound of optically thin sources [Mannheim/Protheroe/Rachen'98]

MPR bound revisited



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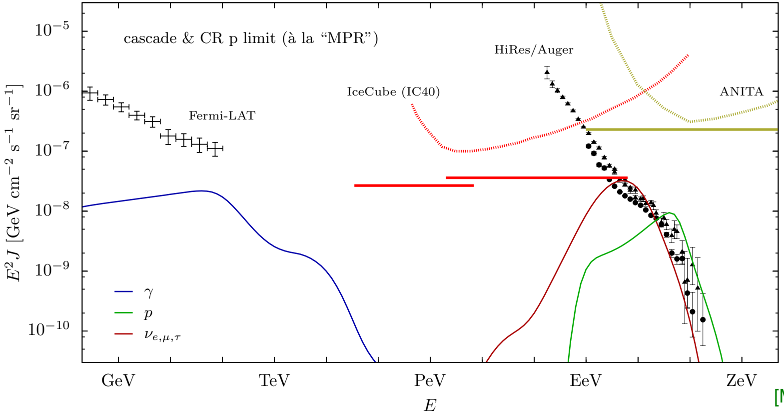

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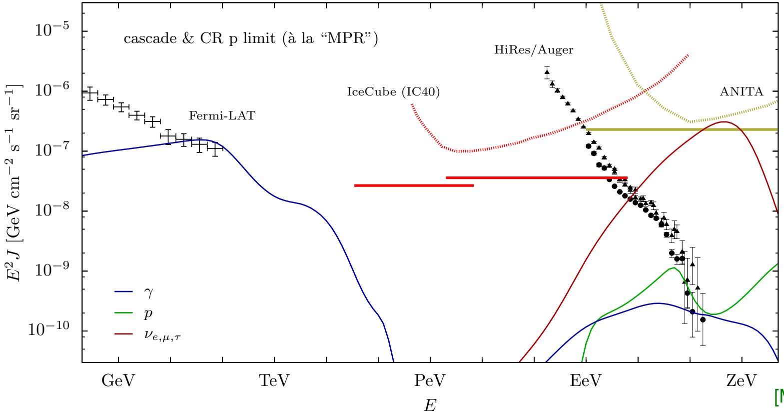

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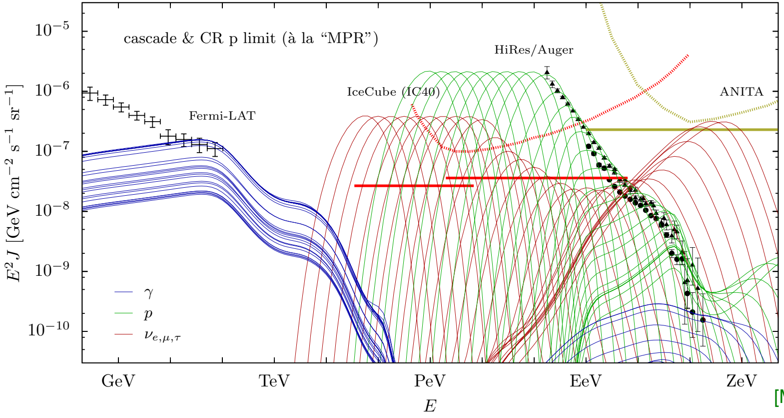

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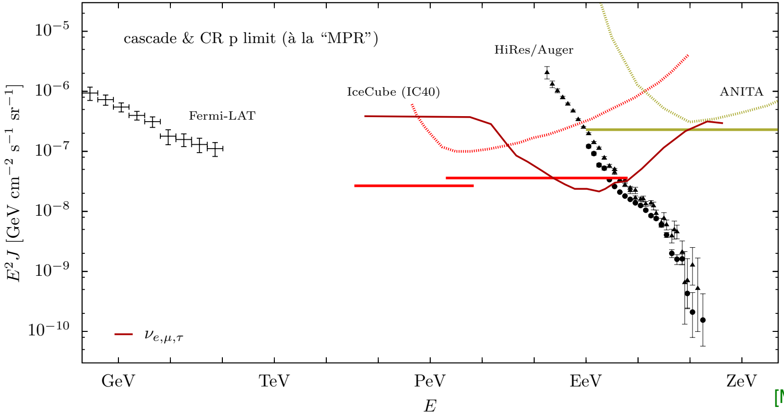

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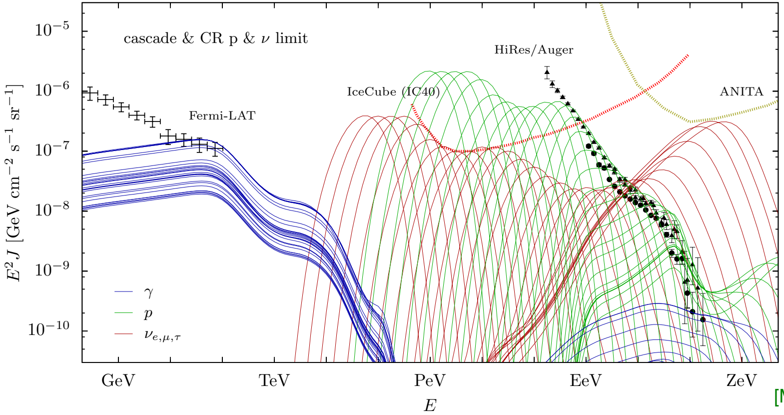

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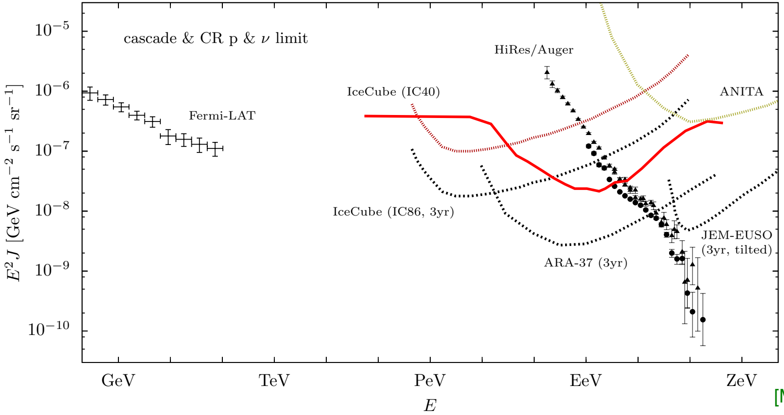
- Neutrino emission is further constraint by neutrino upper limits.

➜ 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.

CR proton bound



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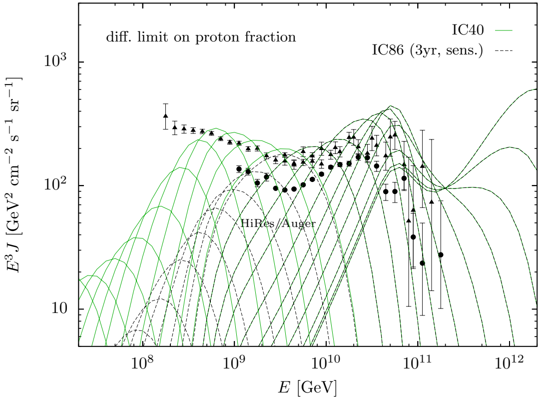

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- differential upper limit on proton fraction from optically thin sources
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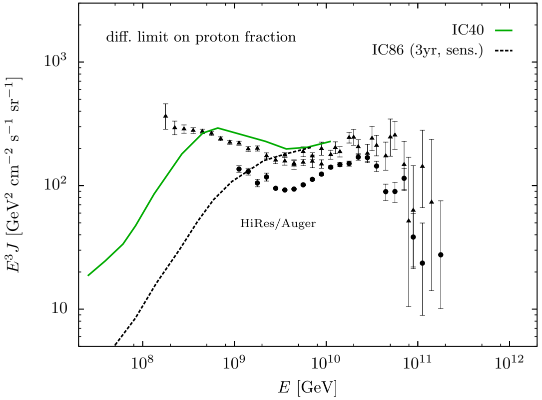

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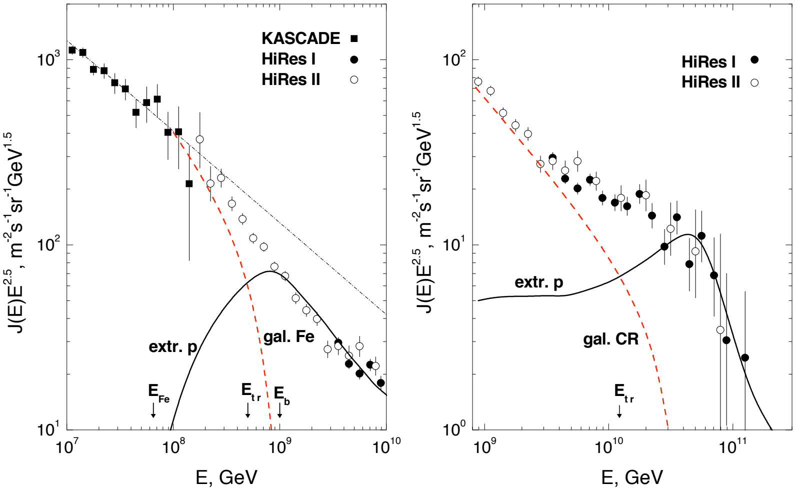
Galactic to extragalactic crossover

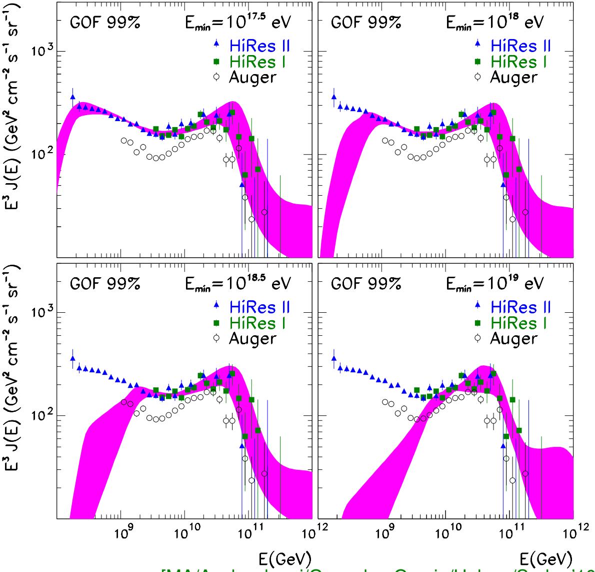
“dip-transition” vs. “ankle-transition”



[*e.g.* Aloisio *et al.*’06]

Proton-dominance in UHE CRs?

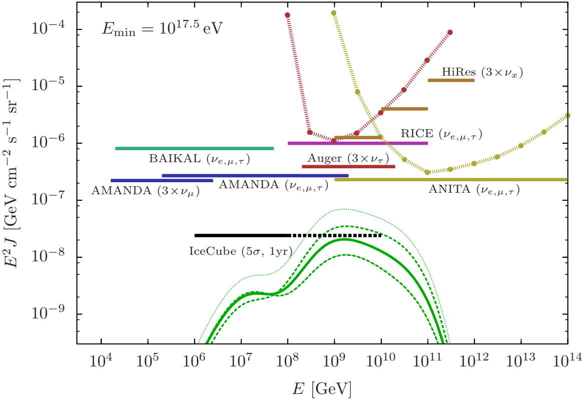
- GoF based on Hires-I/II data ($\Delta E/E \simeq 25\%$)
- *fixed:*
  $E_{\rm max} = 10^{21}$ eV
  $z_{\rm min} = 0$ / $z_{\rm max} = 2$
- *priors:*
  $2.1 \leq \gamma \leq 2.9$
  $2 \leq n \leq 6$
  $\omega_{\rm cas} \leq \omega_{\rm Fermi}$
- range of spectra: 99% C.L.
- increasing crossover energy from 2nd knee to ankle



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

Cosmogenic neutrinos from CR protons

- 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 **(dashed green line)** increase along with the cross-over energy and lies within reach of present & future neutrino observatories.



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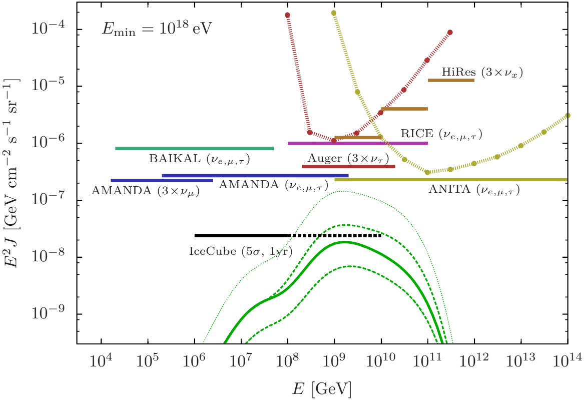

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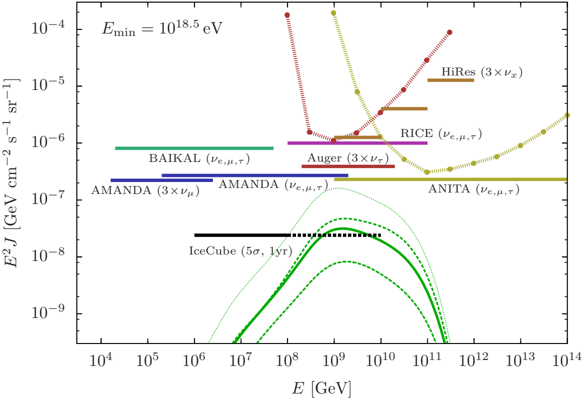

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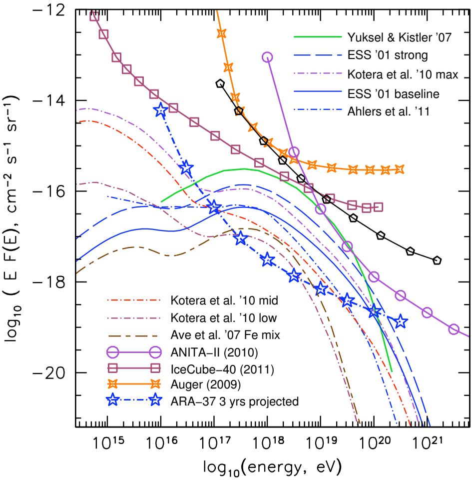


TABLE II: Expected numbers of events N_ν from several UHE neutrino models, comparing published values from the 2008 ANITA-II flight with predicted events for a three-year exposure for ARA-37.

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]

Best-fit range of GZK neutrino predictions (∼two orders of magnitude!) cover various evolution models and source compositions.

Cosmogenic neutrinos from CR protons

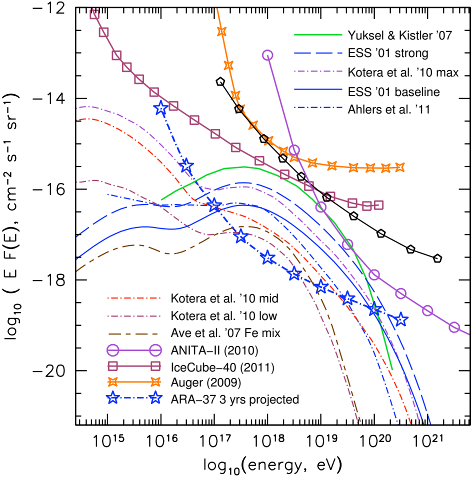


TABLE III. Expected numbers of events in 333.5 days from several cosmogenic neutrino models and top-down models. The confidence interval for exclusion by this observations is also listed where appropriate. The cosmogenic neutrino models (GZK 1-6) assume the cosmic-ray primaries to be protons and different 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.

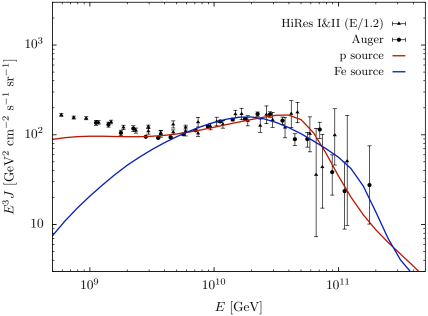
Models	Event rate	C.L. %
GZK 1 [3]	0.57	· · ·
GZK 2 [4]	0.91	53.4
GZK 3 ($\Omega_\Lambda = 0.0$) [5]	0.29	· · ·
GZK 4 ($\Omega_\Lambda = 0.7$) [5]	0.47	· · ·
GZK 5 (maximal) [6]	0.89	52.8
GZK 6 (the best fit) [6]	0.43	· · ·
Top-down 1 (SUSY) [22]	1.0	55.7
Top-down 2 (no-SUSY) [22]	5.7	99.6
Z-burst [21]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

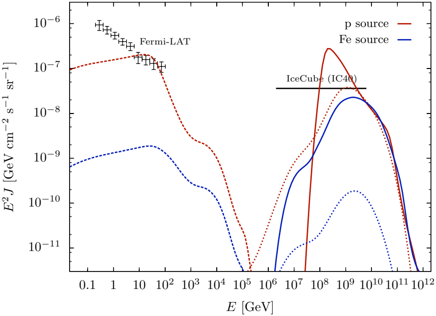
GZK 1 : Yoshida&Teshima'93
GZK 2 : Kalashev/Kuzmin/Semikoz/Sigl'02
GZK 3/4 : Engel/Seckel/Stanev'01
GZK 5/6 : MA/Anchordoqui/Halzen/Gonzalez-Garcia/Sarkar'10

[IceCube'11]

Best-fit range of GZK neutrino predictions (∼two orders of magnitude!) cover various evolution models and source compositions.

“Guaranteed” model dependence





Two “extreme models”: [MA&Salvado’11]

- 100% proton: $n = 5$ & $z_{\max} = 2$ & $\gamma = 2.3$ & $E_{\max} = 10^{20.5}$ eV
- 100% iron: $n = 0$ & $z_{\max} = 2$ & $\gamma = 2.3$ & $E_{\max} = 26 \times 10^{20.5}$ eV

➜ “Guaranteed” diffuse spectra of **gamma-rays** (dashed lines) and **cosmogenic neutrinos** (all flavor, dotted lines).

➜ Absolute neutrino limits from diffuse γ-ray background (Fermi-LAT).

Propagation of CR nuclei

- strong photo-disintegration of nuclei (mass number A) beyond the giant dipole resonance (GDR):

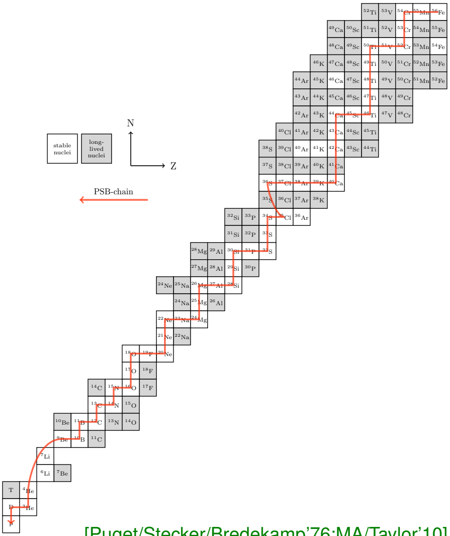
$$E^A_{\rm GDR} \simeq A \times 2 \times \epsilon^{-1}_{\rm meV} \times 10^{10}\ \text{GeV}$$

➜ strong influence of mass composition at very high energy, **but** conserves total number of nucleons with nucleon energy E/A.

- energy loss rates via Bethe-Heitler (BH) and photo-pion ($\gamma\pi$) production:

$$b_{A,{\rm BH}}(E) \simeq Z^2 \times b_{p,{\rm BH}}(E/A)$$

$$b_{A,\gamma\pi}(E) \simeq A \times b_{N,\gamma\pi}(E/A)$$



[Puget/Stecker/Bredekamp'76;MA/Taylor'10]

Approximate* scaling law for GZK neutrinos

$$\omega_{\rm GZK} \propto \underbrace{\sum_i f_i A_i^{2-\gamma_i}}_{\text{composition}} \times \underbrace{\int_0^{z_{\rm max}} {\rm d}z \frac{(1+z)^{n+\gamma_i-3}}{\sqrt{\Omega_\Lambda + \Omega_{\rm m}(1+z)^3}}}_{\text{evolution}}$$

*** disclaimer**:

- source composition $\{f_i\}$ ($\sum_i f_i = 1$) with mass number A_i and index γ_i
- applies only to models with large rigidity cutoff $E_{{\rm max},i} \gg A_i \times E_{\rm GZK}$
- applies to total relative energy density; below the peak ($10^{18} - 10^{19}$ eV) it is more model dependent/less predictable

previous examples ($z_{\rm max} = 2$ & $\gamma = 2.3$):

- 100% proton: $n = 5$ & $E_{\rm max} = 10^{20.5}$ eV
  $\omega_{\rm GZK} \propto 0.3 \times 0.8$
- 100% iron: $n = 0$ & $E_{\rm max} = 26 \times 10^{20.5}$ eV
  $\omega_{\rm GZK} \propto 1 \times 28$

➜ **relative difference:** ~ 120.

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]

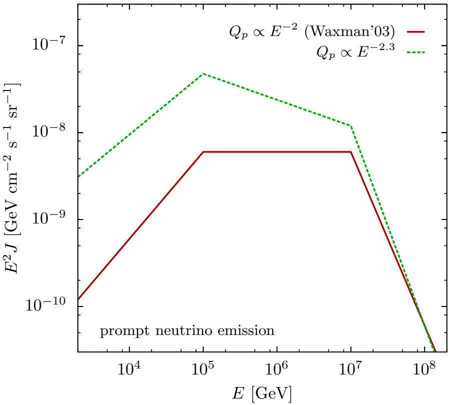
➜ neutrino spectrum follows CR spectrum $\propto E^{-\gamma}$ at PeV energies

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

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

- synchrotron knee of pions/muons:

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



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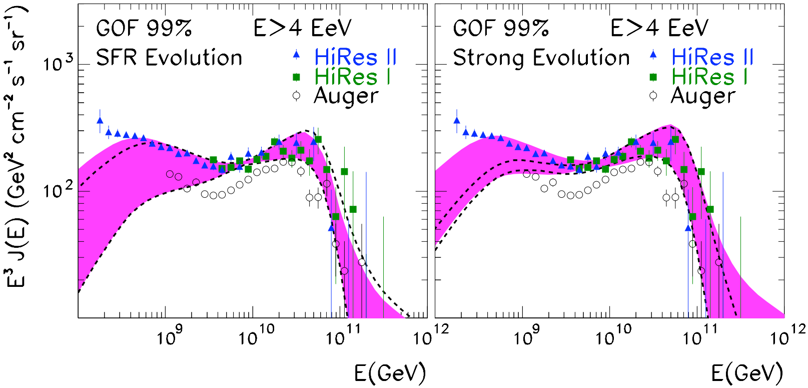

- fit of spectrum to HiRes data above ankle: $\mathcal{L}(0,E) \propto E^{-\gamma}/(1+(E_{\rm p,b}/E))e^{-E/E_{\rm max}}$
- "SFR" : evolution following star formation rate [Hopkins&Beacom'06;Yuksel *et al.*'08]
- "strong" : $\mathcal{L}_{\rm strong}(z,E) = (1+z)^{1.4}\,\mathcal{L}_{\rm SFR}(z,E)$ [Yuksel&Kistler'06]

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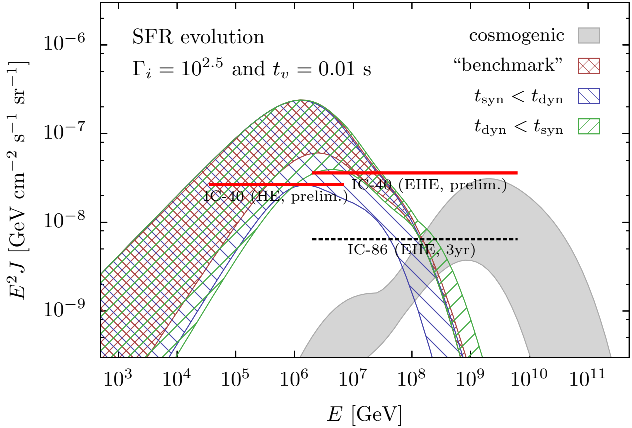

- **hypothesis** : UHE CRs production in GRBs via neutron emission
- scan over luminosity range $0.1 < (\varepsilon_B/\varepsilon_e)L_{\gamma,52} < 10$

➜ probe of viable GRB parameters

[MA/Gonzalez-Garcia/Halzen'11]

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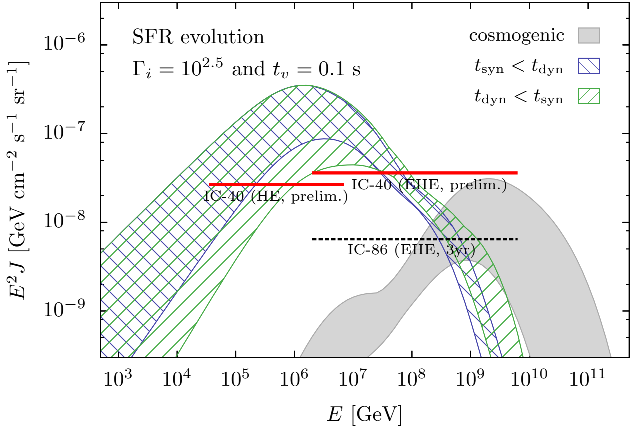

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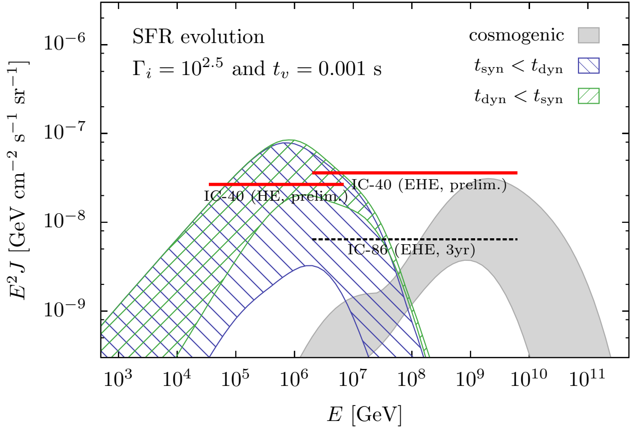

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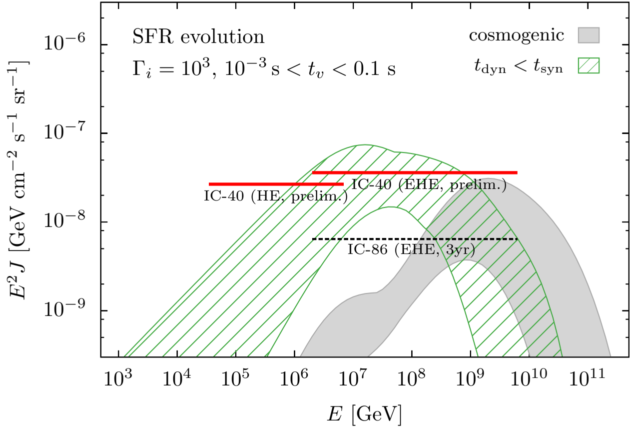

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[MA/Gonzalez-Garcia/Halzen'11]

Summary

✘ **No surprises yet:** very high energy neutrino sky looks dark.

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

✔ Cosmogenic neutrinos of proton-dominated models **in reach**, even with stronger bounds on diffuse γ-ray emission from Fermi-LAT.

✘ However, there are **model uncertainties**, in particular evolution of CR sources.

✔ 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.