High-Energy Cosmogenic Neutrinos

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Cosmogenic neutrinos

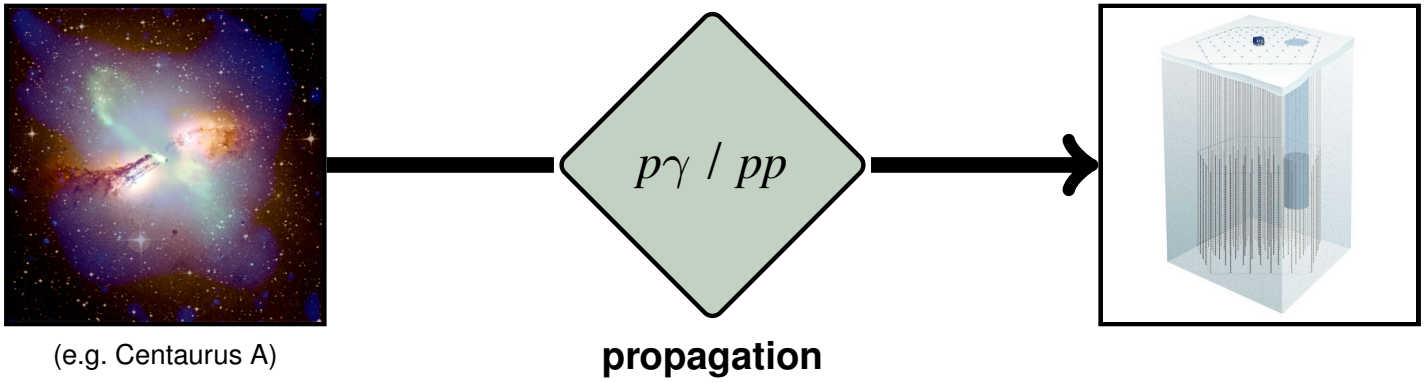
- *cos-mo-gen-ic* (adj.): “produced by cosmic rays”

✘ but this is true for all high-energy neutrinos. . .

➜ **more specifically**: not in the source or atmosphere, but during **CR propagation**

- most plausibly via pion production in $p\gamma$ interactions, *e.g.*

$$p + \gamma_{\rm bgr} \to \Delta \to n + \pi^+$$
$$\pi^+ \to \mu^+ \nu_\mu \quad \& \quad \mu^+ \to e^+ \bar{\nu}_\mu \nu_e$$



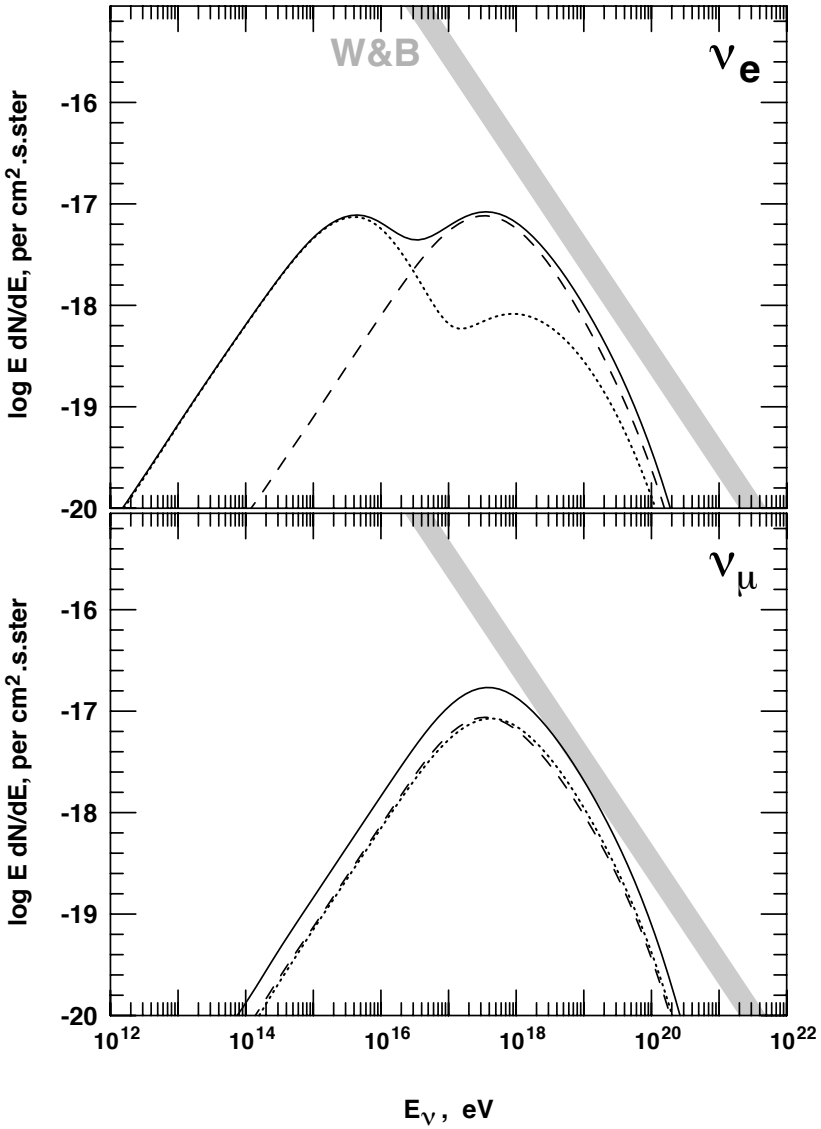
GZK neutrinos from CMB

- Greisen-Zatsepin-Kuzmin (GZK) interactions of ultra-high energy CRs with cosmic microwave background (CMB) [Greisen'66;Zatsepin/Kuzmin'66]
- "GZK"-neutrinos at EeV energies from pion decay [Berezinsky/Zatsepin'69]
- three neutrinos ($\nu_\mu/\bar{\nu}_\mu/\nu_e$) from π^+:

$$E_{\nu_\pi} \simeq \frac{1}{4}\langle x\rangle E_p \simeq \frac{1}{20}E_p$$

- one neutrino from neutron decay:

$$E_{\bar{\nu}_e} \simeq \frac{m_n - m_p}{m_n}E_p \simeq 10^{-3}E_p$$



[Engel, Stanev & Seckel'01]

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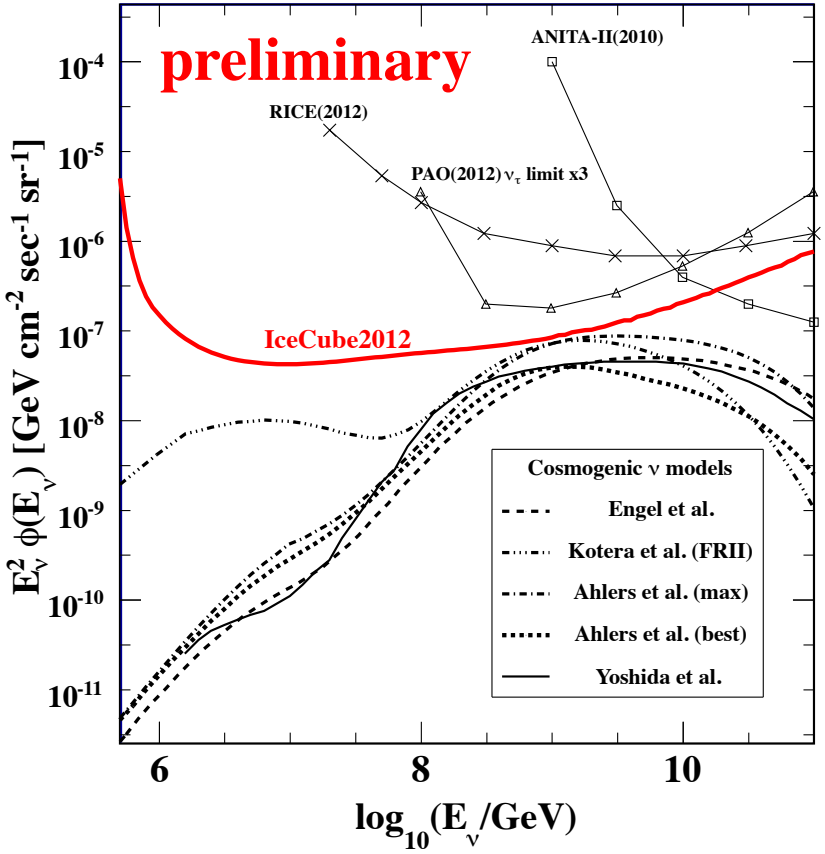
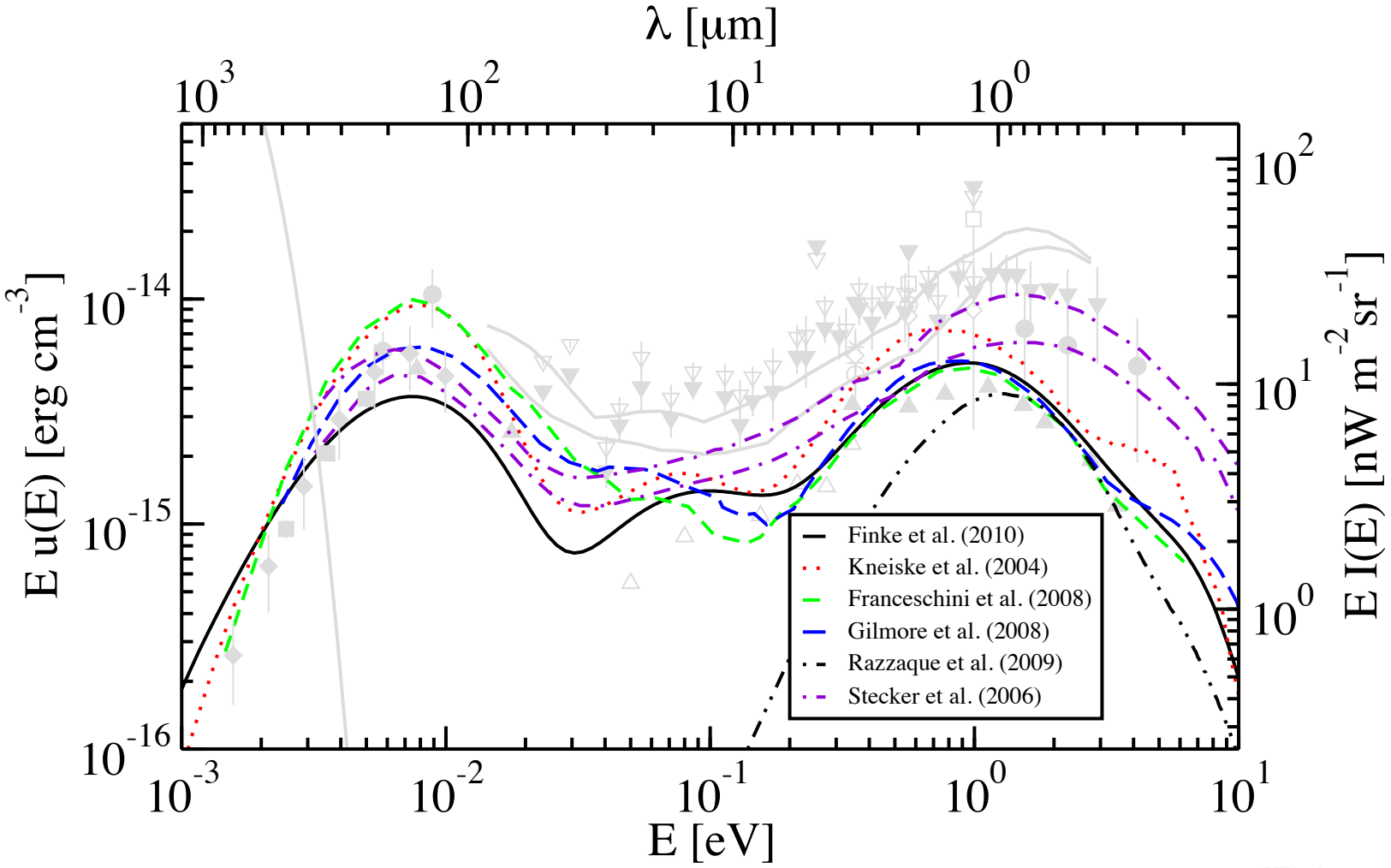


Extra-galactic background light (EBL)



[Finke *et al.* '10]

optical-UV background gives PeV neutrino peak

Cosmogenic neutrinos & gamma-rays

- GZK interactions produce neutral and charged pions

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

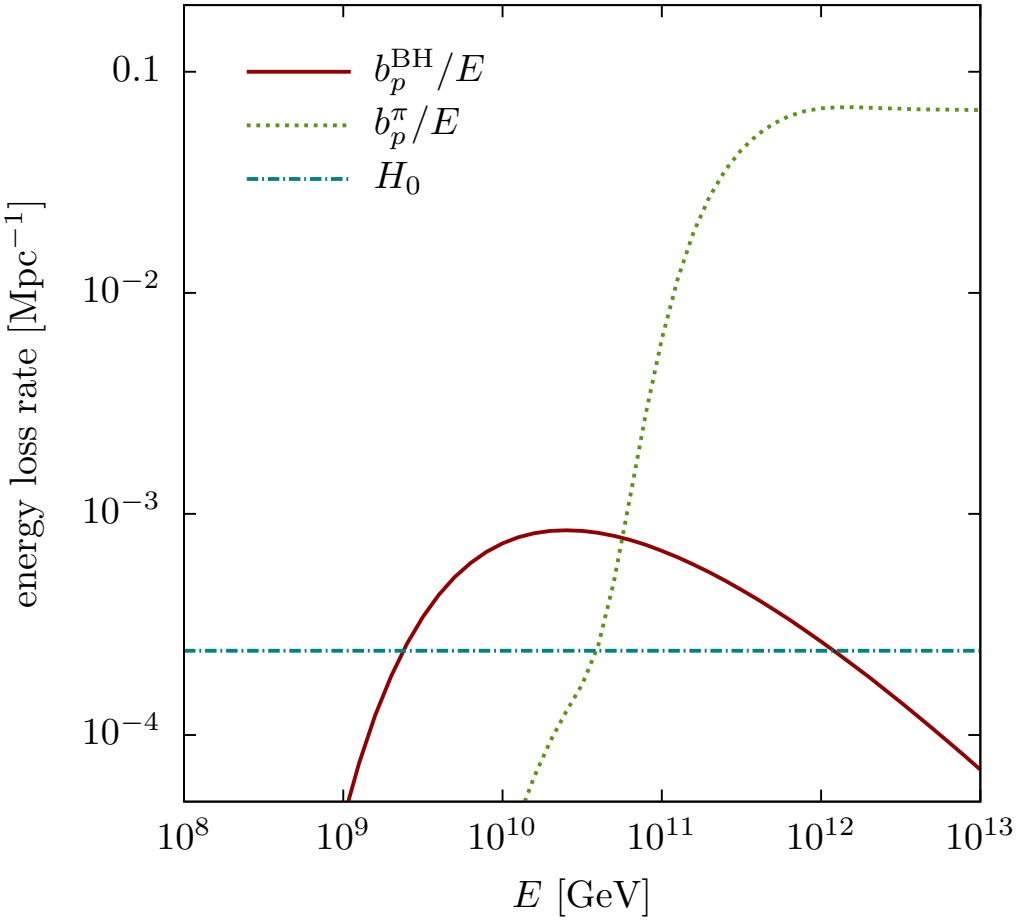
- Bethe-Heitler (BH) pair production:

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

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

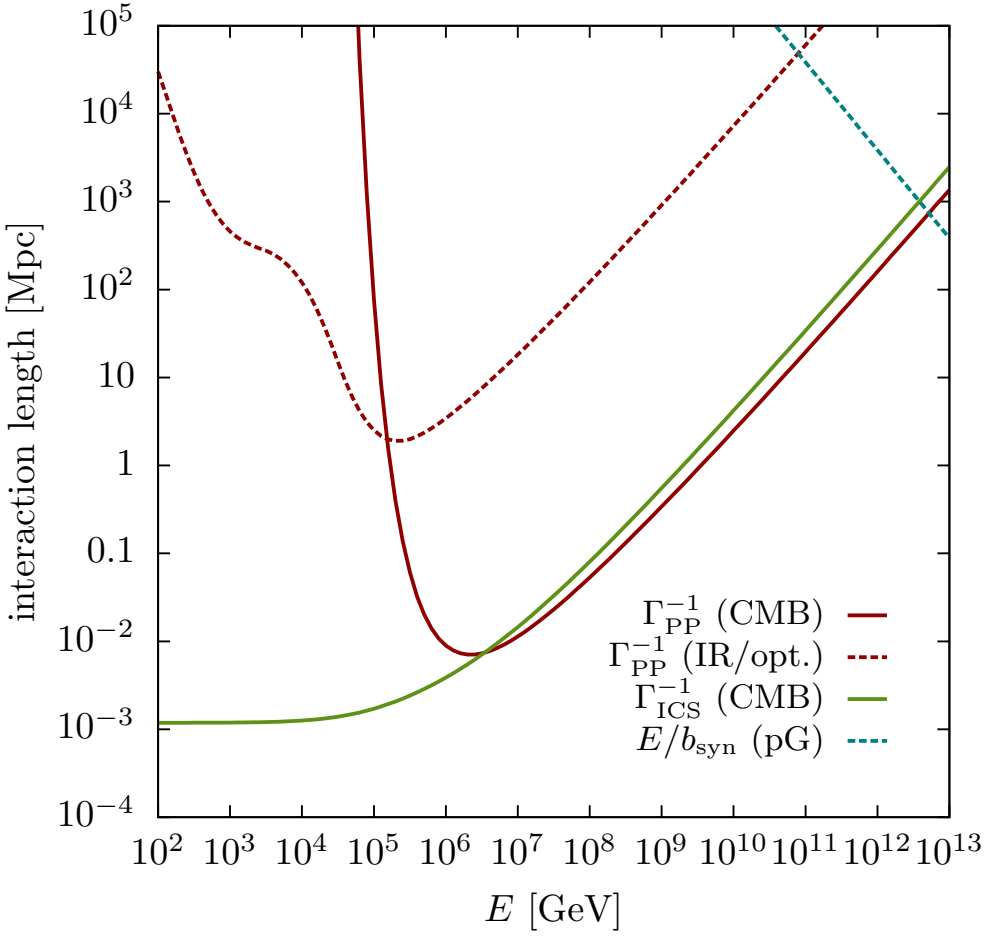
- EM components cascade in CMB/EBL and contribute to GeV-TeV γ-ray background

[Berezinsky&Smirnov'75]



Gamma-ray cascades

- 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 universal GeV-TeV emission (almost) independent of injection spectrum and source distribution.
➜ **"cascade bound" for neutrinos** [Berezinsky&Smirnov'75]

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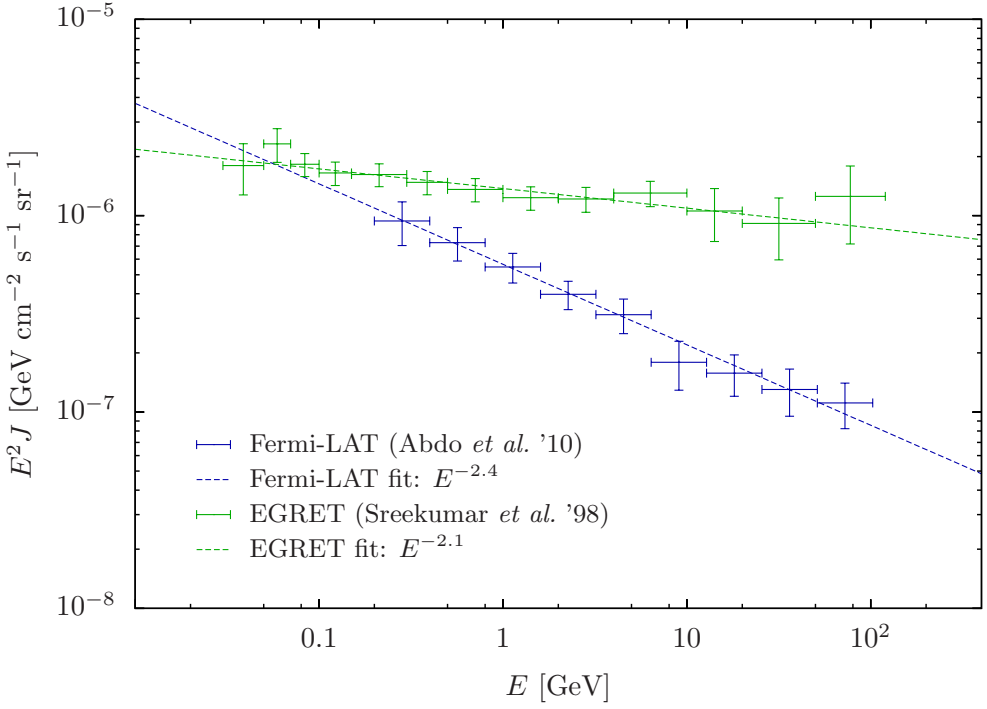
diffuse γ-ray background



Rapid cascade interactions produce universal GeV-TeV emission (almost) independent of injection spectrum and source distribution.
➜ **"cascade bound" for neutrinos** [Berezinsky&Smirnov'75]

Diffuse CR fluxes

- **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:

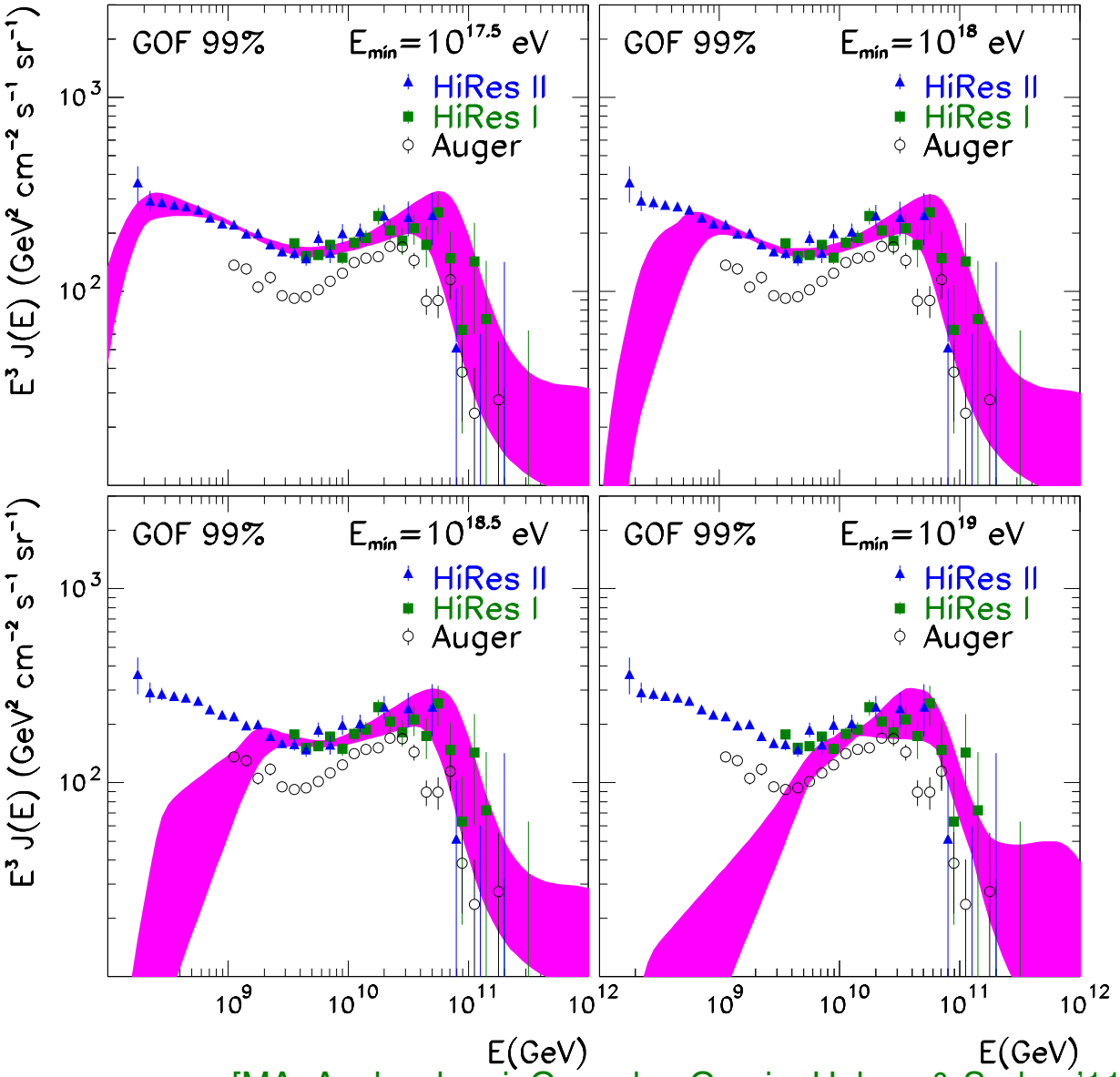
$$\mathcal{L}_p(0,E) \propto (E/E_0)^{-\gamma} \exp(-E/E_{\mathrm{max}}) \exp(-E_{\mathrm{min}}/E)$$

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

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

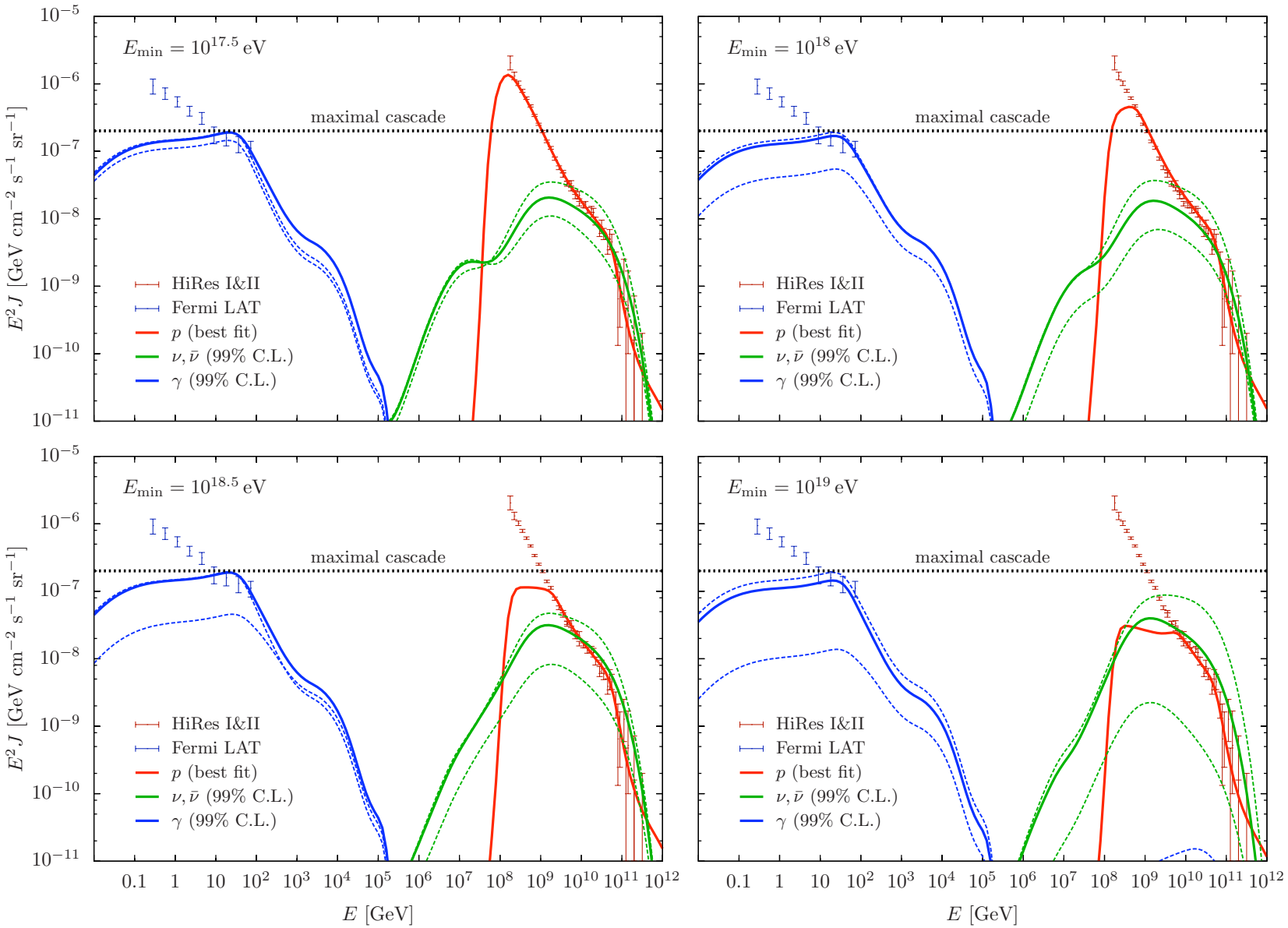
Proton-dominance in UHE CRs?

- 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:*
  $2.1 \leq \gamma \leq 2.9$
  $2 \leq n \leq 6$
  $\omega_{\text{cas}} \leq \omega_{\text{Fermi}}$
- range of spectra: 99% C.L.
- increasing crossover energy from 2nd knee to ankle



[MA, Anchordoqui, Gonzalez-Garcia, Halzen & Sarkar '11]

Cosmogenic neutrinos from CR protons



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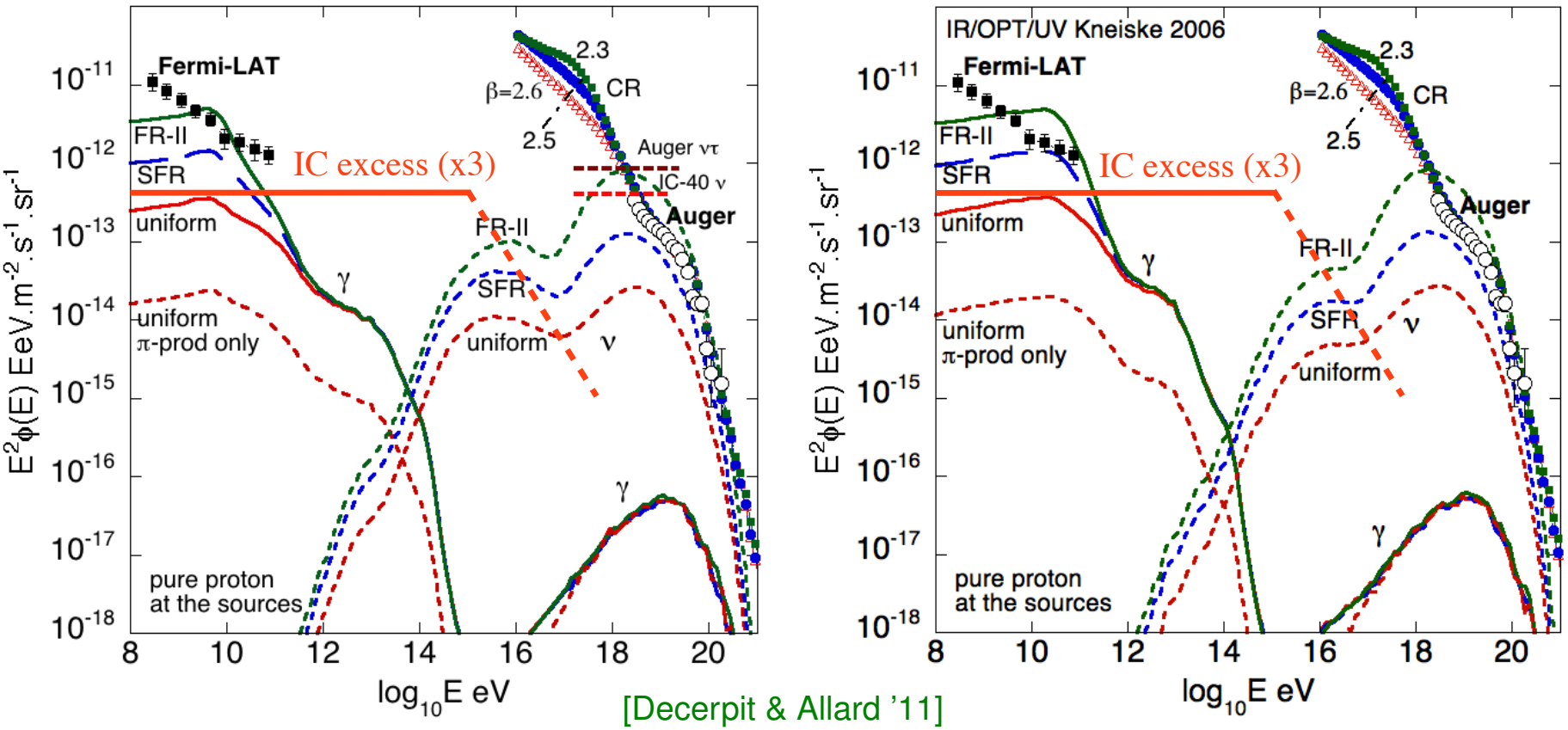
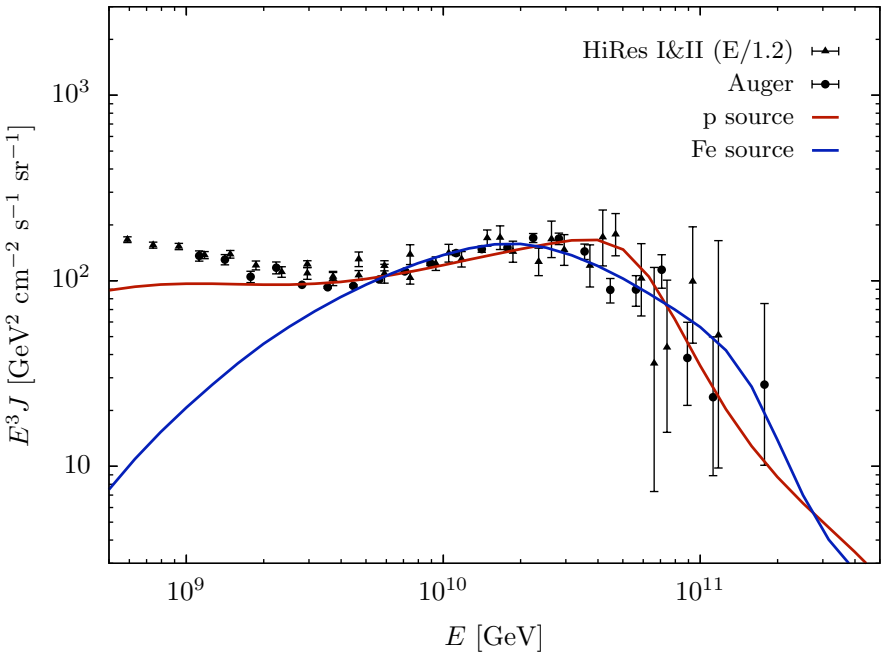
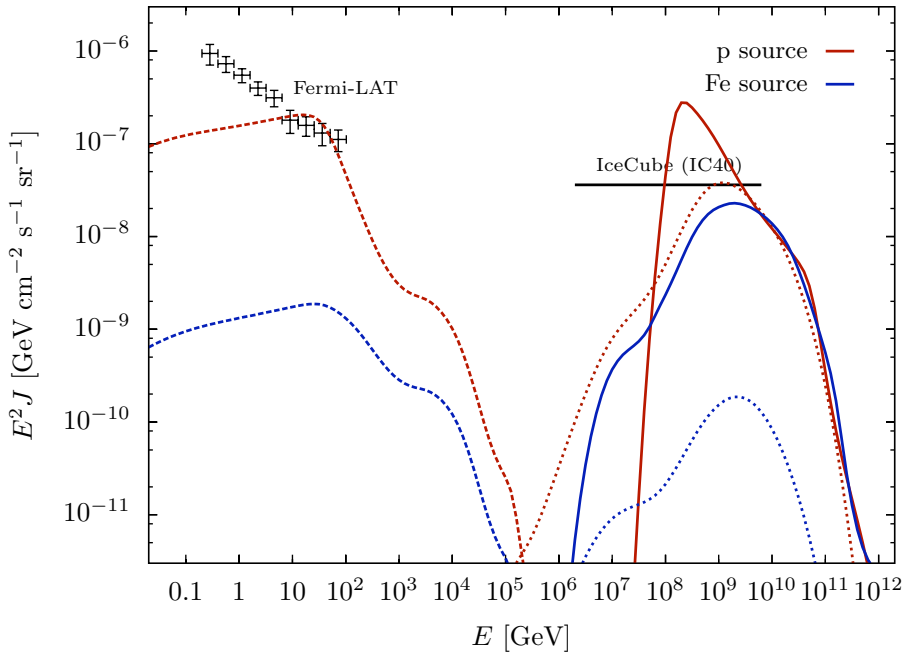


[Decerpit & Allard '11]

- ➜ neutrino flux depend on source **evolution model** (strongest for "FR-II") and **EBL model** (highest for "Stecker" model)
- ✘ "Stecker" model disfavored by Fermi observations of GRBs
- ✘ strong evolution disfavored by Fermi diffuse background

Composition dependence of UHE CR sources





- UHE CR emission toy-model:
  - 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
- Diffuse spectra of cosmogenic γ-rays (dashed lines) and neutrinos (dotted lines) **vastly different**. [MA&Salvado'11]

Cosmogenic neutrinos from heavy nuclei

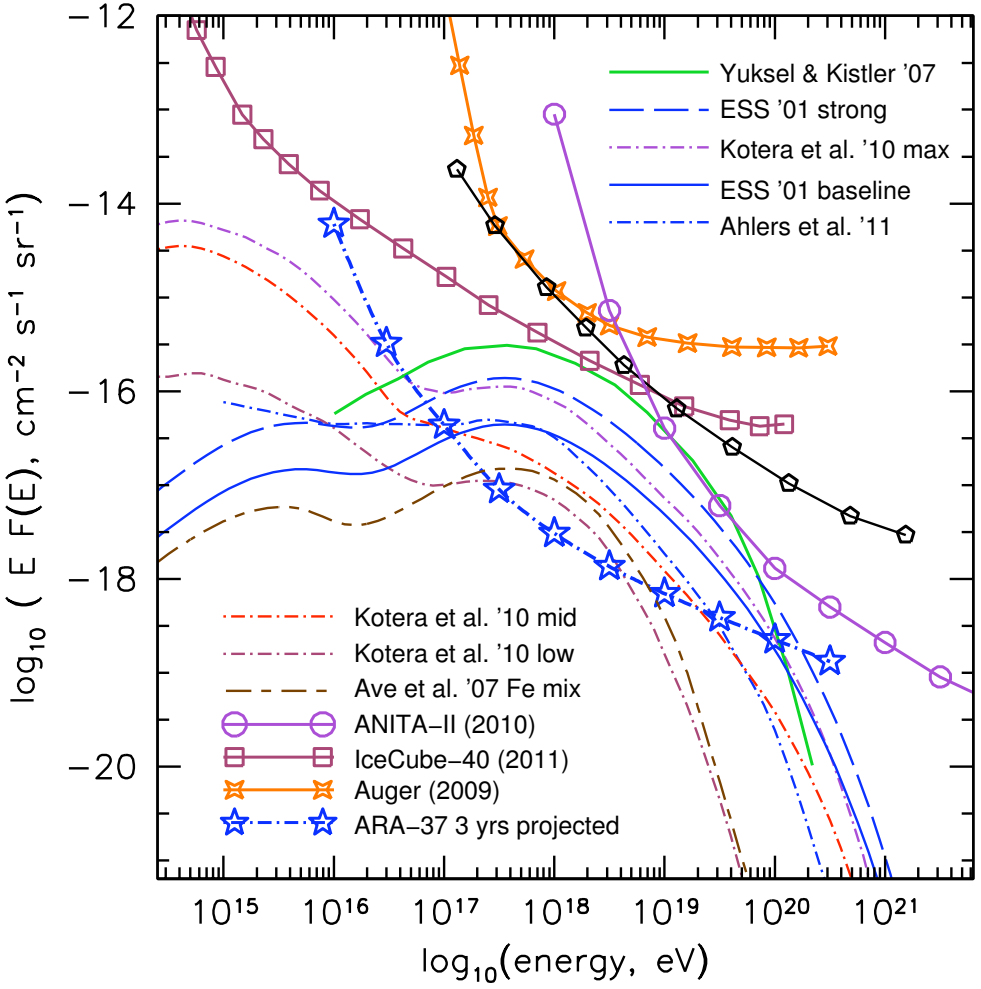


TABLE II: Expected numbers of events N_ν from several UHE neutrino models, comparing published values from the 2008 ANITA-II flight with predicted events for a three-year exposure for ARA-37.

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.

Propagation of CR nuclei

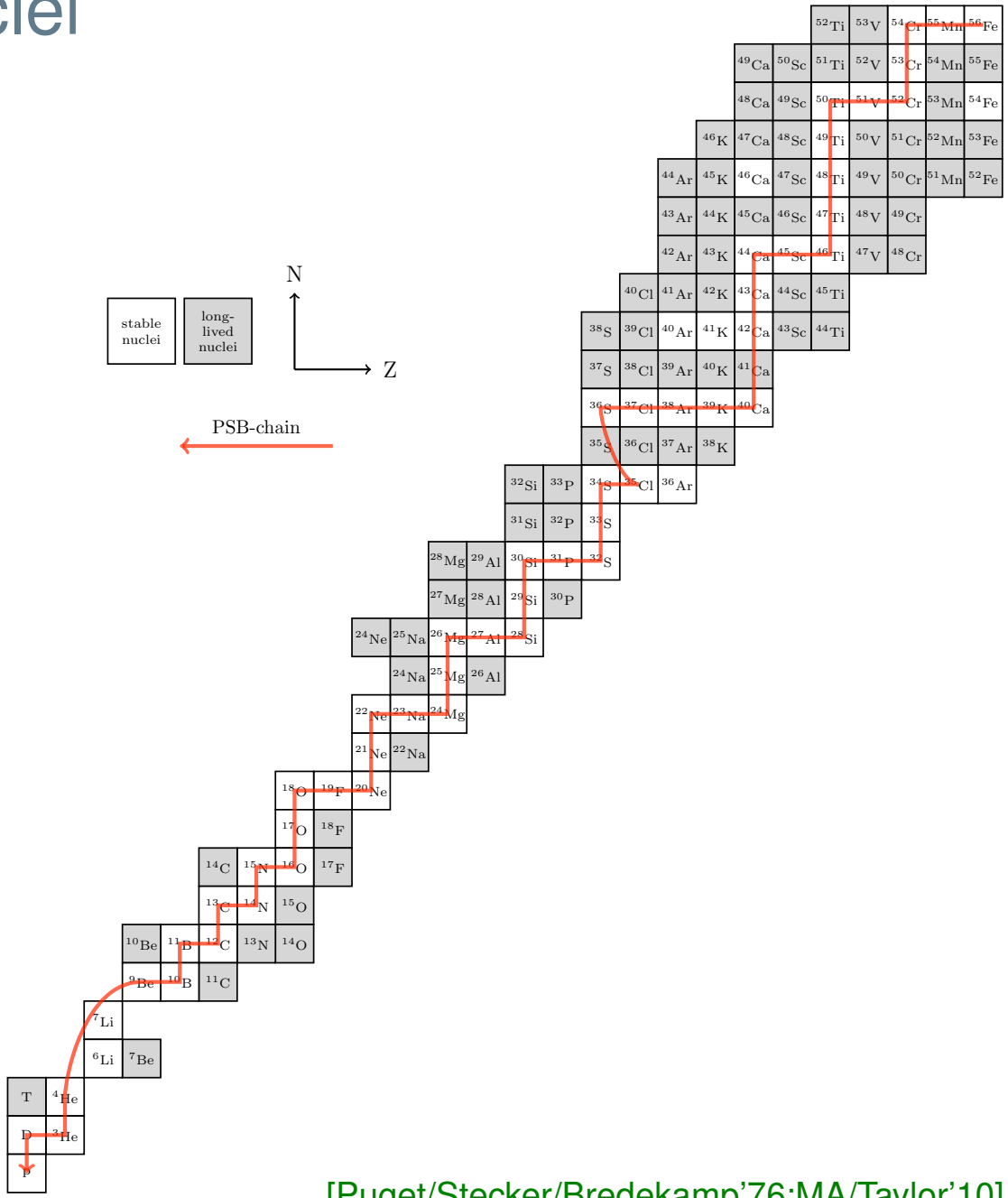
- fast photo-disintegration of nuclei (mass number $A = N + Z$) beyond the giant dipole resonance (GDR):

$$\lambda_{\mathrm{GDR}} \sim \frac{4}{A}\ \mathrm{Mpc}$$

✘ strong influence of mass composition at very high energy

➜ BUT: **conserves total number of nucleons** with nucleon energy E/A!

➜ **Neutrino production (mostly) via γ-nucleon interaction!**



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

Approximate* scaling law of energy densities

$$\omega_\nu \propto \underbrace{\sum_i A_i^{2-\gamma_i} \frac{E_{\rm th}^2 \mathcal{Q}_i(E_{\rm th})}{2-\gamma_i}}_{\text{composition}} \times \underbrace{\int_0^{z_{\rm max}} {\rm d}z \frac{(1+z)^{n+\gamma_i-4}}{H(z)}}_{\text{evolution}}$$

*** disclaimer**:

- source composition $\mathcal{Q}_i$ with mass number A_i and index γ_i
- applies only to models with large rigidity cutoff $E_{{\rm max},i} \gg A_i \times E_{\rm GZK}$

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

- 100% proton: $n = 5$ & $E_{\rm max} = 10^{20.5}$ eV
  $\omega_\gamma \propto 1 \times 12$
- 100% iron: $n = 0$ & $E_{\rm max} = 26 \times 10^{20.5}$ eV
  $\omega_\gamma \propto 0.27 \times 0.5$

✔ **relative difference:** ~ 82.

Nucleon cascade

- Observed composition is result of source composition and nucleon cascades.
- **Backtracking** conserves energy per nucleon.

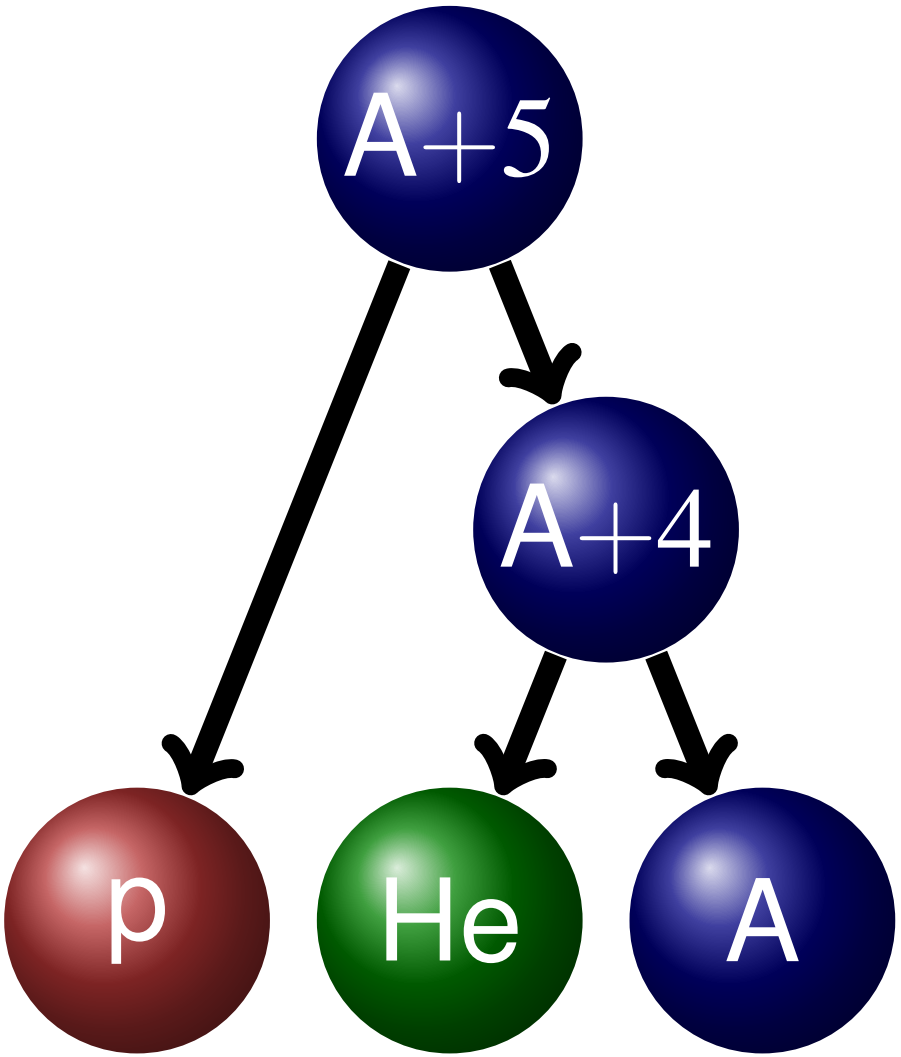
✘ Bethe-Heitler (BH) loss breaks this approximation

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

➜ **Minimal cosmogenic neutrino** production from fit to Auger data assuming:

- **maximal** backtracking
- **minimal** BH loss

➜ **minimal** nucleon emissivity



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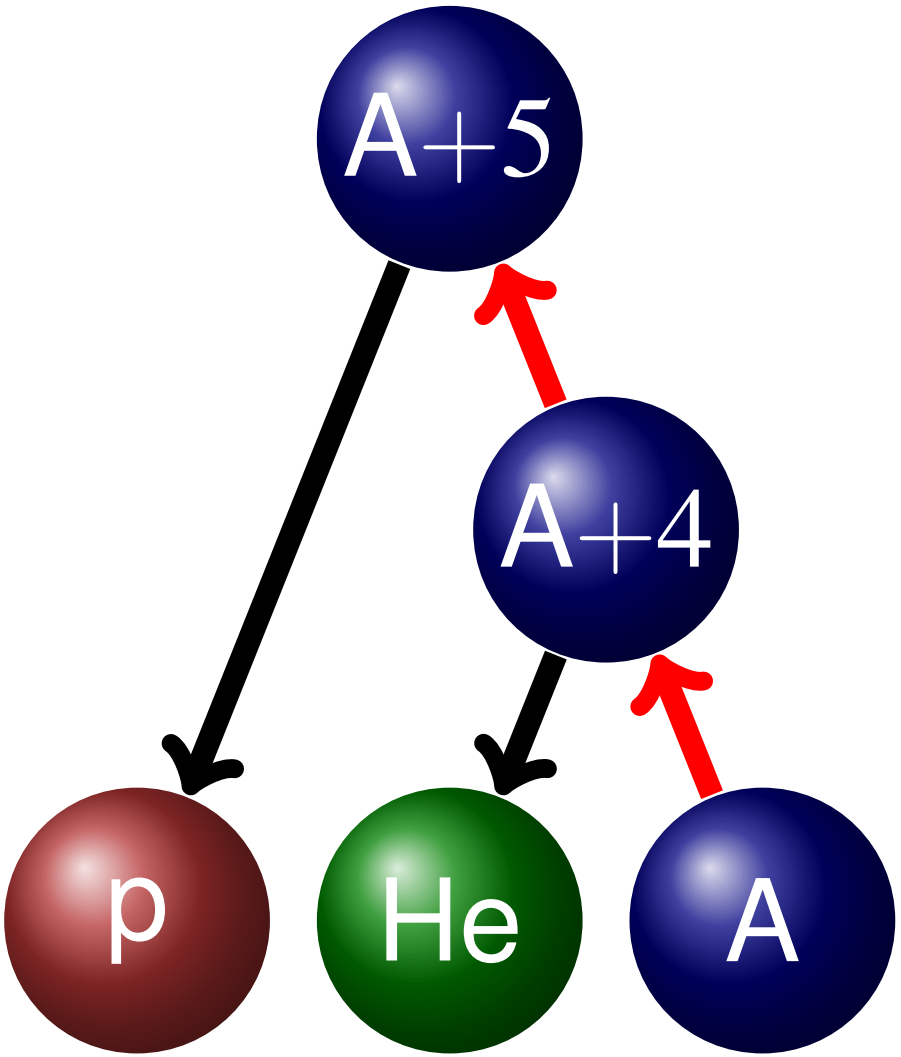


Guaranteed cosmogenic neutrinos

- ➜ nucleon spectrum for observed mass number $A_{\rm obs}$:

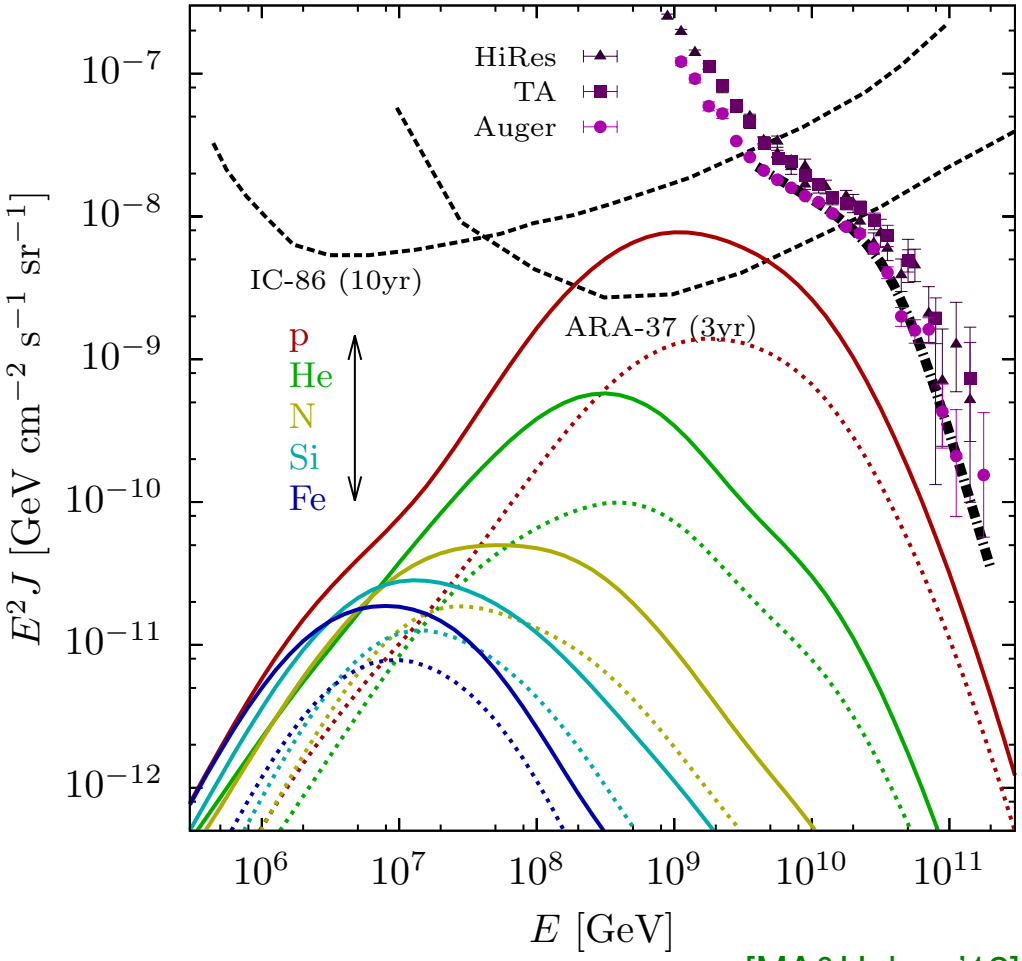
$$J_N^{\rm min}(E_N) = A_{\rm obs}^2 J_{\rm CR}(A_{\rm obs}E_N)$$

  - dependence on cosmic evolution of sources:
    - no evolution (dotted)
    - star-formation rate (solid)

- ➜ **ultimate test** of UHE CR proton models with **ARA-37**

- ➜ generalization to arbitrary composition via

$$J_N^{\rm min}(E_N) = \sum_i f_i(A_i E_N) A_{\rm i}^2 J_{\rm CR}(A_i E_N)$$



[MA&Halzen'12]

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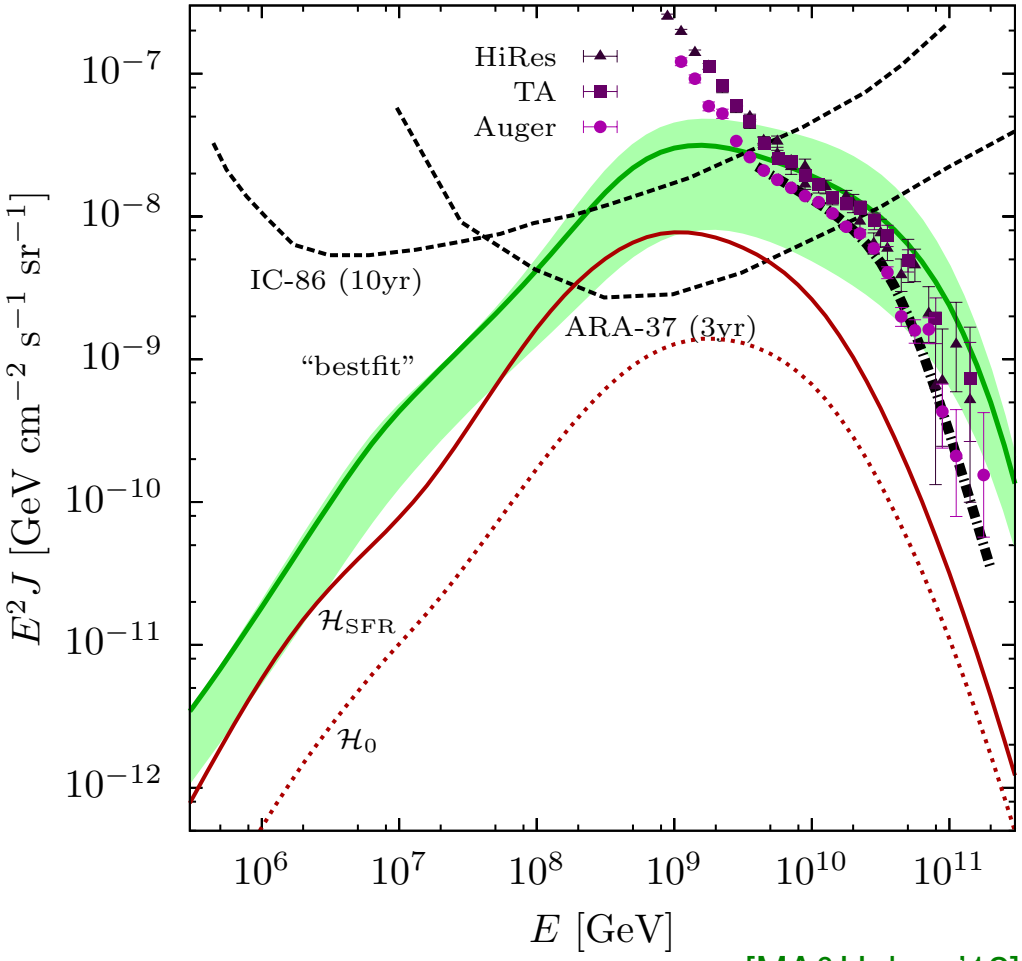

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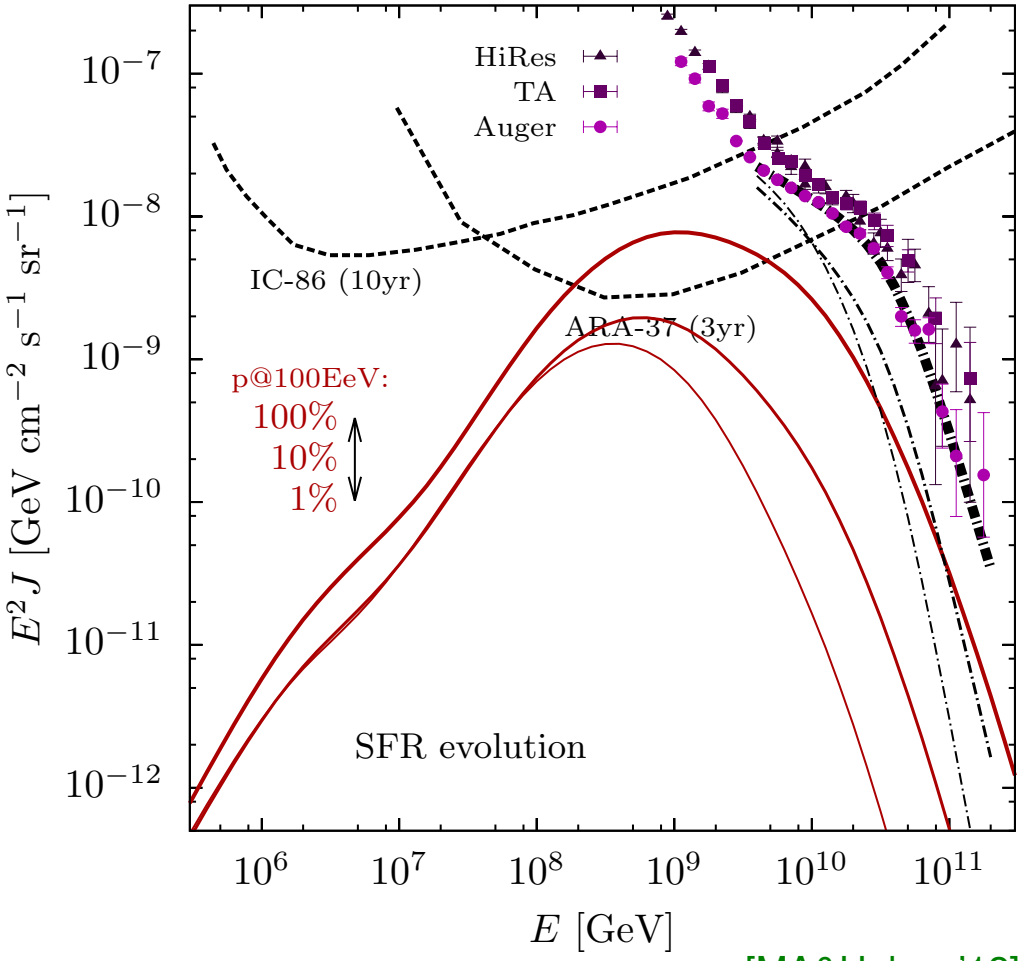


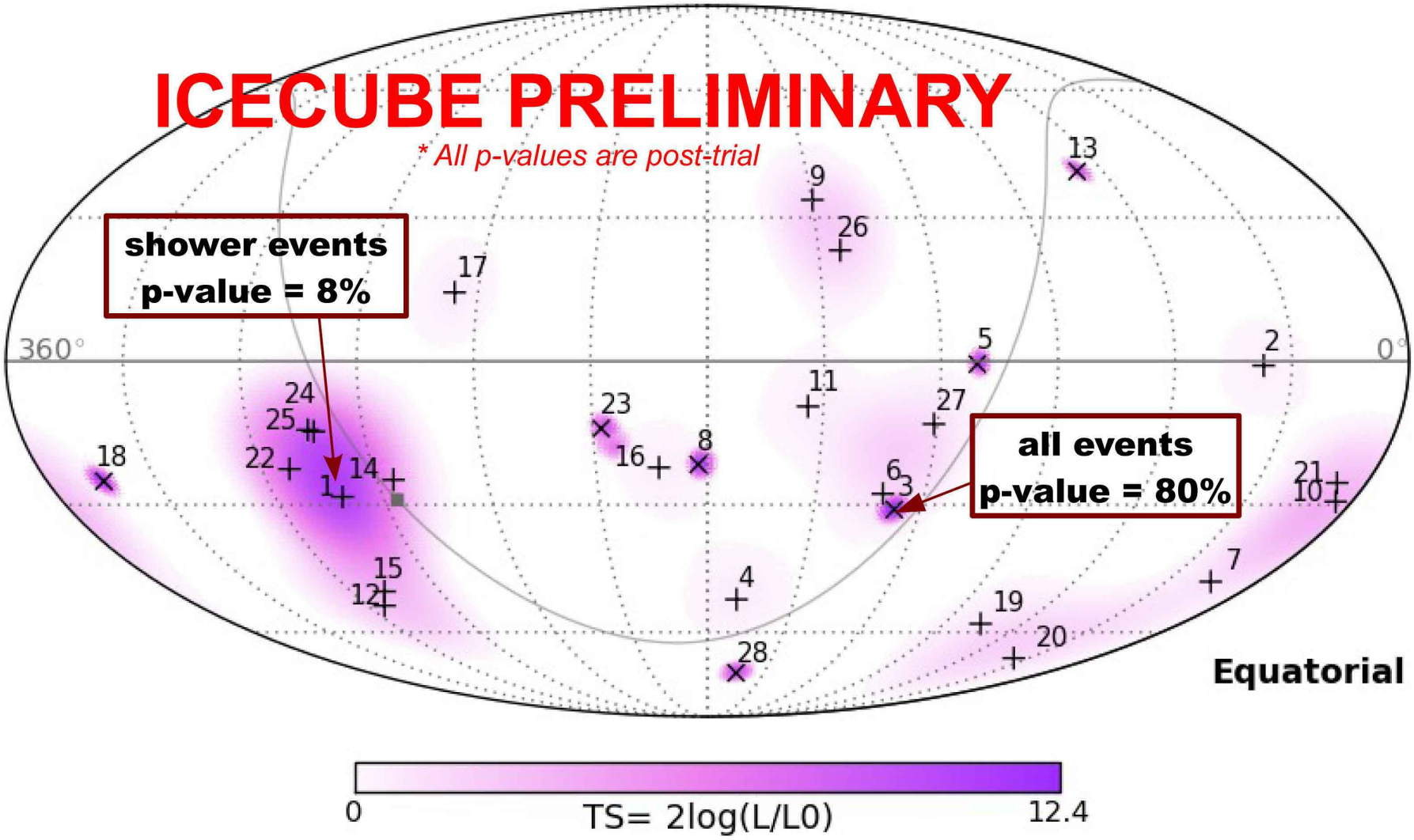
[MA&Halzen'12]

Summary

- Cosmogenic neutrinos **guarantee** a diffuse flux of UHE neutrinos.
- Present neutrino limits start to **constrain** optimistic (proton-dominated) model.
- A cosmogenic origin of the IceCube “excess” at TeV-PeV energies is **very unlikely**.
- **Model uncertainties** of predictions are large (UHE CR source composition and evolution).
- Future EeV neutrino observatories (ARA or ARIANNA) will be able to **probe** proton-dominated CR models.

Backup

“IceCube excess”



[C.Kopper, N.Kurahashi & N.Whitehorn, IPA’13]

“IceCube excess”

- IceCube observes 28 events over a period of two years, while $10.6^{+5.0}_{-3.6}$ are expected from conventional atmospheric contributions.

  [M.Ackermann’s & C.Koppers’s talks at this meeting]

- flux excess at 4.1σ for combined 26+2 fit
- isotropic and flavor-universal
- small excess in the Southern Hemisphere even after correction for zenith angle dependent acceptance
- E^{-2} spectrum favors cutoff/break at $2-5$ PeV
- “best-fit” of the HESE spectrum

$$E_\nu^2 J_{\nu_\alpha}^{\rm IC} \simeq (1.2 \pm 0.4) \times 10^{-8} {\rm GeV s^{-1} cm^2 sr^{-1}}$$

➜ **interpretation as GZK neutrino flux unlikely** [Roulet *et al.* 1209.4033]