Multi-Messenger Signatures of UHE CRs

Markus Ahlers

UW-Madison & WIPAC

TeVPA/IDM Conference 2014

Amsterdam, June 23–28, 2014

Cosmogenic neutrinos

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

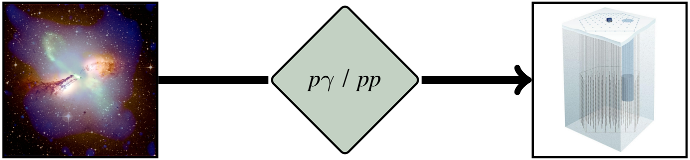
✘ but this is true for all high-energy neutrinos…

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

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

$$p + \gamma_{\rm bgr} \to \Delta \to n + \pi^+$$

$$\pi^+ \to \mu^+ + \nu_\mu \quad \& \quad \mu^+ \to e^+ + \bar\nu_\mu + \nu_e \quad \& \quad n \to p + e^- + \bar\nu_e$$

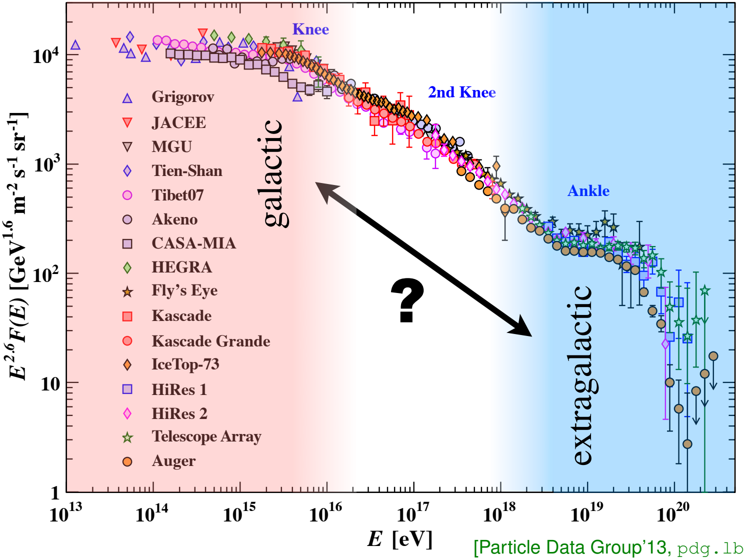


(e.g. Centaurus A)

propagation

(e.g. IceCube)

Ultra-High Energy (UHE) Cosmic Rays (CRs)



[Particle Data Group'13, pdg.lbl.gov]

Cosmogenic neutrinos

- Observation of UHE CRs and extragalactic radiation backgrounds "guarantee" a flux of high-energy neutrinos, in particular via resonant production in CMB.

  [Berezinsky & Zatsepin'69]

- "Guaranteed", but with many model uncertainties and constraints:
  - **(low cross-over) proton models + CMB (+ EBL)**
    [Berezinsky & Zatsepin'69; Yoshida & Teshima'93; Protheroe & Johnson'96; Engel, Seckel & Stanev'01; Fodor, Katz, Ringwald &Tu'03; Barger, Huber & Marfatia'06; Yuksel & Kistler'07; Takami, Murase, Nagataki & Sato'09, MA, Anchordoqui & Sarkar'09]
  - **+ mixed compositions**
    [Hooper, Taylor & Sarkar'05; Ave, Busca, Olinto, Watson & Yamamoto'05; Allard, Ave, Busca, Malkan, Olinto, Parizot, Stecker & Yamamoto'06; Anchordoqui, Goldberg, Hooper, Sarkar & Taylor'07; Kotera, Allard & Olinto'10; Decerprit & Allard'11; MA & Halzen'12]
  - **+ extragalactic γ-ray background limits**
    [Berezinsky & Smirnov'75; Mannheim, Protheroe & Rachen'01; Keshet, Waxman, & Loeb'03; Berezinsky, Gazizov, Kachelriess & Ostapchenko'10; MA, Anchordoqui, Gonzalez–Garcia, Halzen & Sarkar'10; MA & Salvado'11; Gelmini, Kalashev & Semikoz'12]

GZK neutrinos from CMB

- Greisen-Zatsepin-Kuzmin (GZK) interactions of ultra-high energy CRs with cosmic microwave background (CMB) [Greisen'66;Zatsepin/Kuzmin'66]

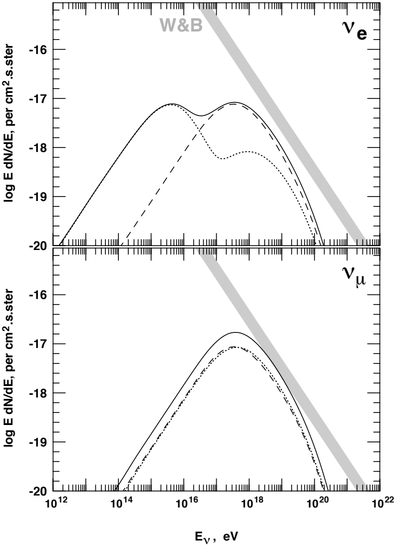
- "GZK"-neutrinos at EeV energies from pion decay [Berezinsky/Zatsepin'69]

- 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]

Flavor Composition

- in general, **initial flavor ratio** (ν_e:ν_μ:ν_τ) depend on process and environment

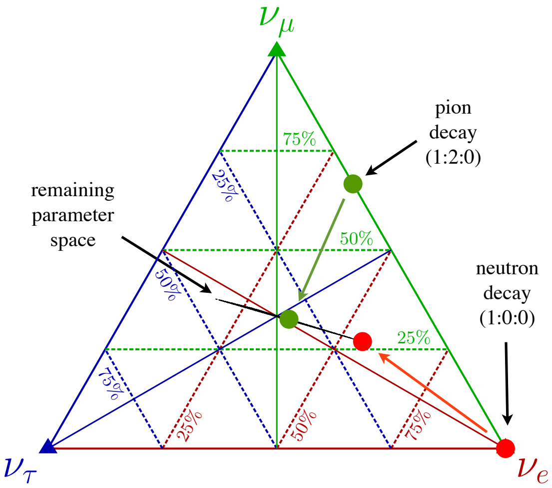
- mixing between flavor and mass eigenstates

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j}|\nu_j\rangle,$$

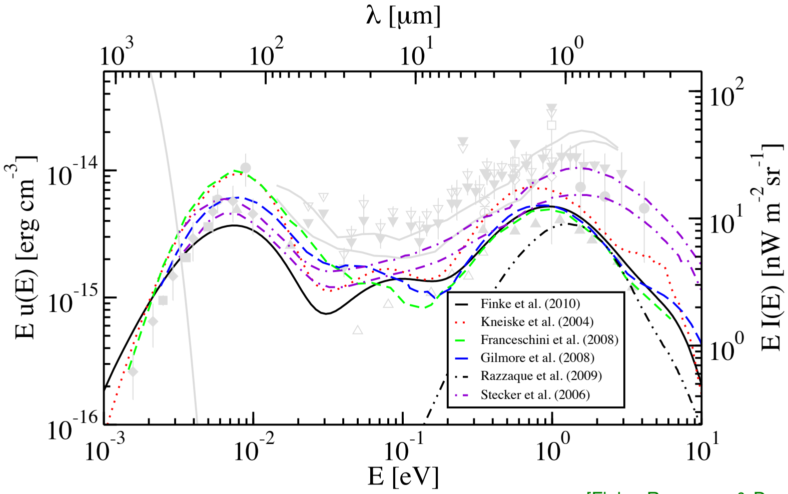
- flavor oscillations **average out** over cosmic distances

$$P_{\nu_\alpha \to \nu_\beta} \simeq \sum_i |U_{\alpha i}\, U_{\beta i}|^2$$

➜ remaining phase space thin black line crossing (1:1:1)



Extra-galactic background light (EBL)



[Finke, Razzaque & Dermer'10]

PeV cosmogenic neutrinos via optical-UV background: $E_\nu \simeq 8\mathrm{PeV}\,(\mathrm{eV}/E_\gamma)$

Cosmogenic neutrinos & gamma-rays

- GZK interactions produce neutral and charged pions

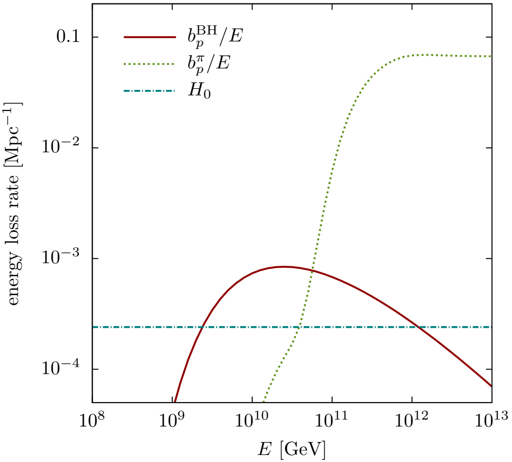
$$p + \gamma_{\mathrm{CMB}} \to n + \pi^+ / p + \pi^0$$

- Bethe-Heitler (BH) pair production:

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

- EM components cascade in CMB/EBL and contribute to GeV-TeV γ-ray background
  [Berezinsky&Smirnov'75]

- . . . except **UHE γ-rays**. . .
  [Gelmini, Kalashev & Semikoz'05,'07]



Photon fraction in UHE CRs

- ✘ **top-down** scenarios ("SHDM" & "TD") mostly ruled out

  [Ellis, Mayes & Nanopoulos'05]

  [Risse & Homola'07]

- ✔ **Z Burst** scenario

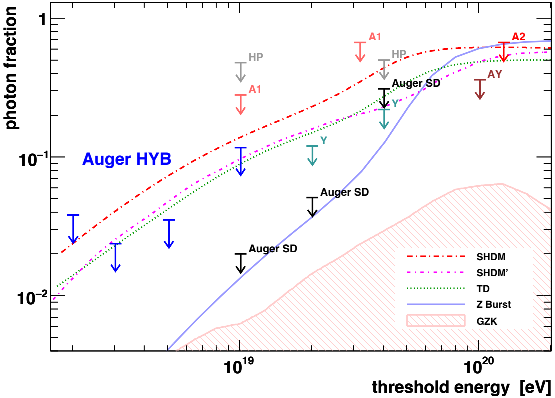
  $\nu + \nu_{\rm bgr} \to Z \to X$

  marginally consistent

  [Weiler'82]

- ✔ **cosmogenic** γ-rays (GZK) consistent with limits

  [Gelmini, Kalashev & Semikoz'07]



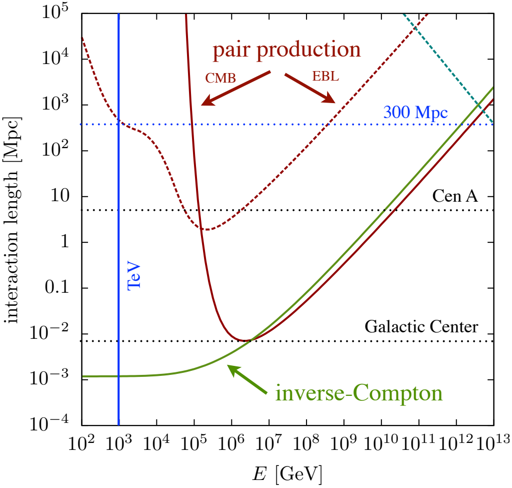
[plot by Auger'09]

[AGASA (A), AGSAS-Yakutsk (AY), Yakutsk (Y), Haverah Park (HP)]

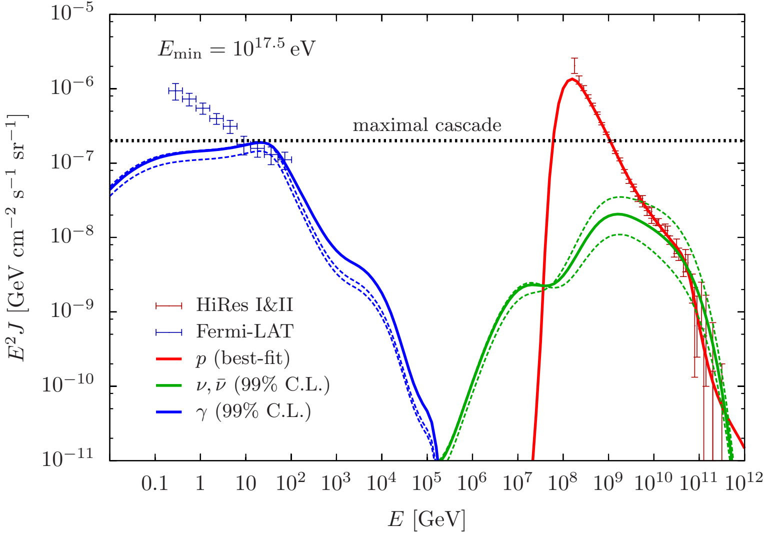
Gamma-ray cascades

- 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.
  [e.g. Franceschini *et al.* '08]

➜ **cascade bound** for neutrino production of UHE CRs
[Berezinsky&Smirnov'75]

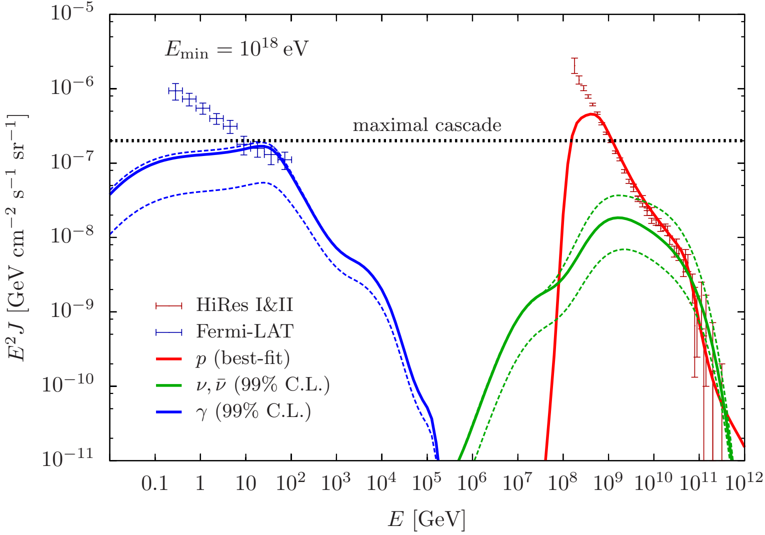


Cosmogenic neutrinos from CR protons



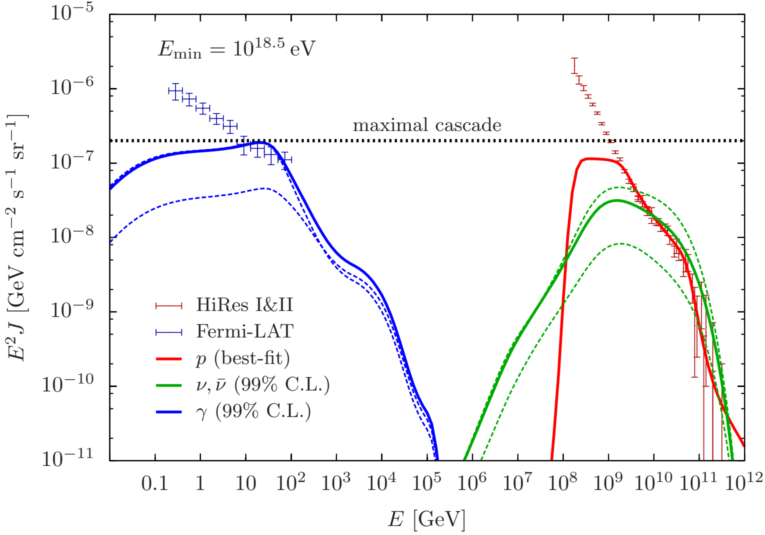
[MA, Anchordoqui, Gonzalez-Garcia, Halzen & Sarkar '11]

Cosmogenic neutrinos from CR protons



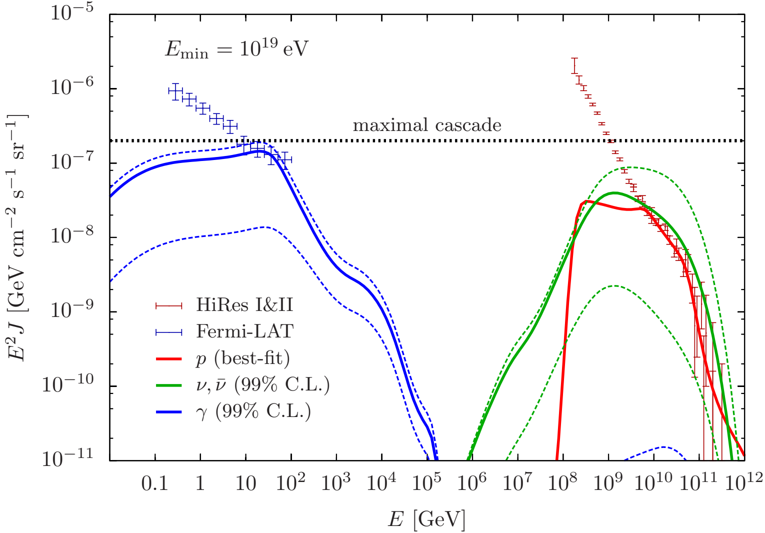
[MA, Anchordoqui, Gonzalez-Garcia, Halzen & Sarkar ’11]

Cosmogenic neutrinos from CR protons



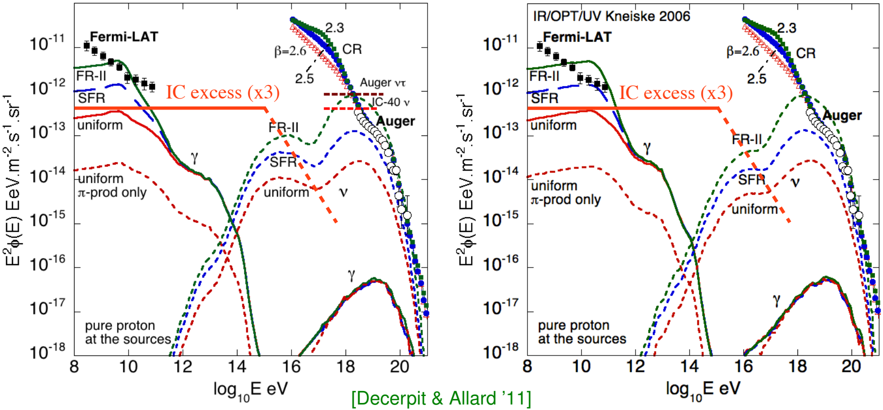
[MA, Anchordoqui, Gonzalez-Garcia, Halzen & Sarkar '11]

Cosmogenic neutrinos from CR protons



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

Cosmogenic neutrinos from CR protons



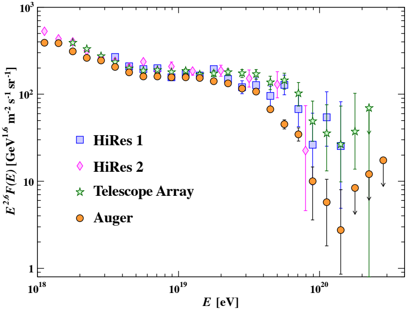
[Decerpit & Allard '11]

➜ neutrino flux depend on source **evolution model** (strongest for "FR-II") and **EBL model** (highest for "Stecker" model)

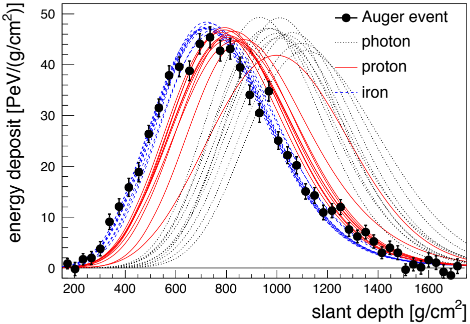
✘ "Stecker" model disfavored by Fermi observations of GRBs

✘ strong evolution disfavored by Fermi diffuse background

UHE CR composition



[PDG'13]

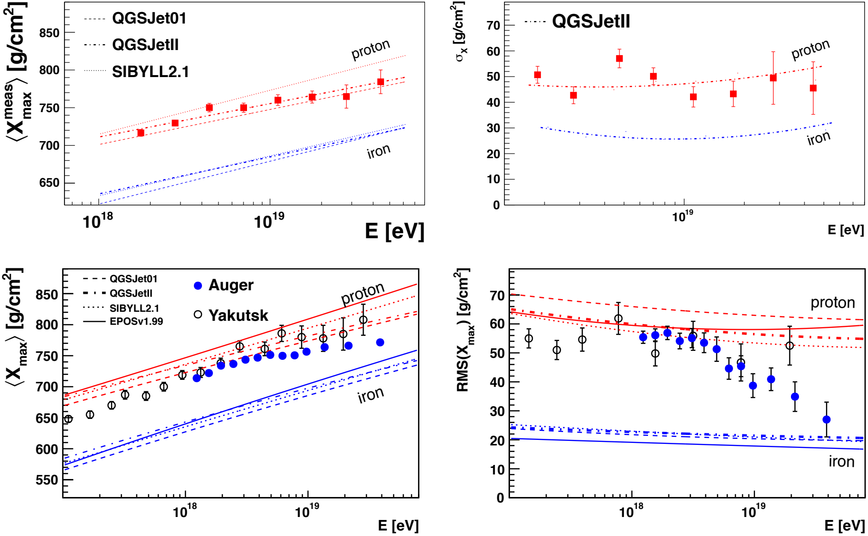


[Kampert&Unger'12]

- composition measurement on a statistical basis
- first two moments: $\langle X_{\rm max}\rangle$ & $\mathrm{RMS}(X_{\rm max})$
- average mass inferred, *e.g.* from $\langle X_{\rm max}\rangle$:

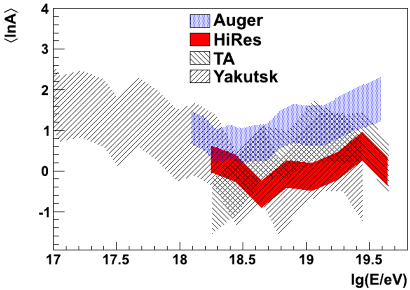
$$\langle \ln A\rangle = \frac{\langle X_{\rm max}\rangle_p - \langle X_{\rm max}\rangle_{\rm data}}{\langle X_{\rm max}\rangle_p - \langle X_{\rm max}\rangle_{\rm Fe}} \ln 56$$

UHE CR composition

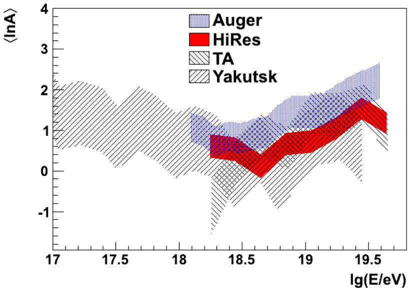


[Mass Composition Working Group Report '13; arXiv:1306.4430]

UHE CR composition



(a) using QGSJet-II model.



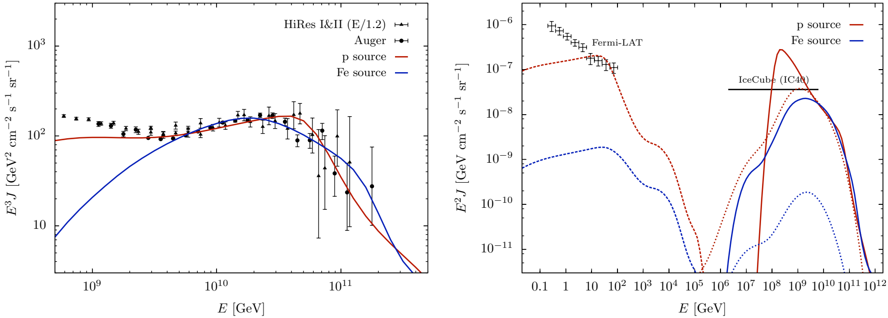
(b) using SIBYLL model.

[Mass Composition Working Group Report '13; arXiv:1306.4430]

- inferred mass depend on hadronic interactions models
- large systematic uncertainties!

➜ "*Auger results are consistent within systematic uncertainties with TA and Yakutsk, but not fully consistent with HiRes.*" [arXiv:1306.4430]

Composition dependence of UHE CR sources



- UHE CR emission toy-model:
  - 100% proton: $n = 5$ & $z_{\rm max} = 2$ & $\gamma = 2.3$ & $E_{\rm max} = 10^{20.5}$ eV
  - 100% iron: $n = 0$ & $z_{\rm max} = 2$ & $\gamma = 2.3$ & $E_{\rm max} = 26 \times 10^{20.5}$ eV
- Diffuse spectra of cosmogenic γ-rays (dashed lines) and neutrinos (dotted lines) **vastly different**. [MA&Salvado'11]

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 $E_{\max,i} \gg A_i \times E_{\rm GZK}$

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:** $\sim 82.$

Cosmogenic neutrinos from heavy nuclei

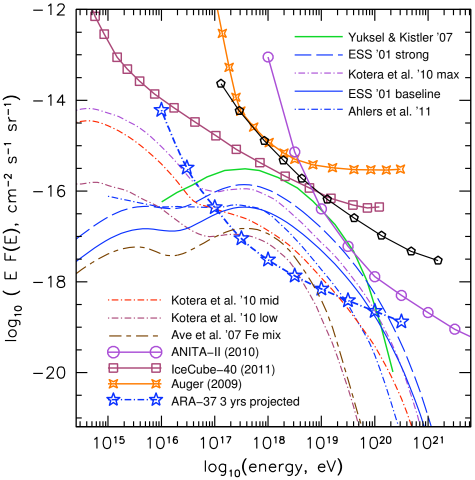


TABLE II: Expected numbers of events N_ν from several UHE neutrino models, comparing published values from the 2008 ANITA-II flight with predicted events for a three-year exposure for ARA-37.

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]

Range of GZK neutrino predictions of various evolution models and source compositions range over **two orders of magnitude**!

Nucleon cascade

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

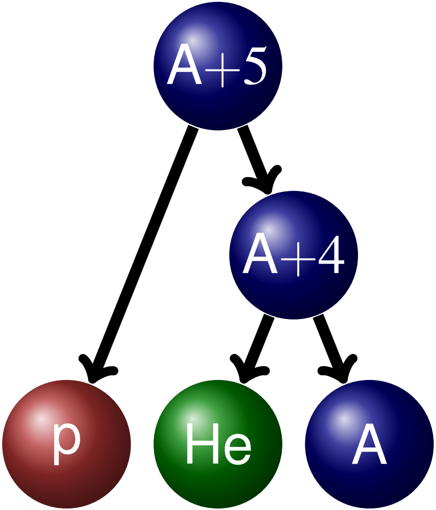
✘ Bethe-Heitler (BH) loss breaks this approximation

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

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

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

➜ **minimal** nucleon emissivity



Nucleon cascade

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

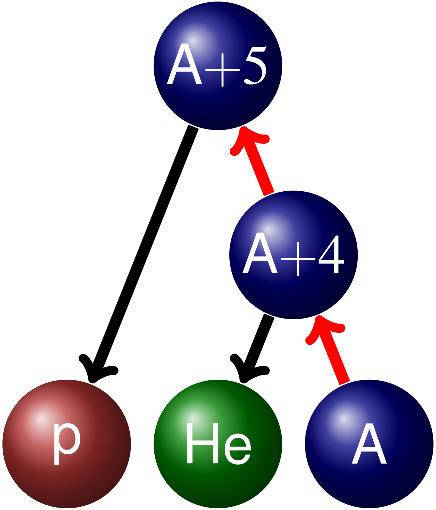
✘ Bethe-Heitler (BH) loss breaks this approximation

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

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

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

➜ **minimal** nucleon emissivity



Guaranteed cosmogenic neutrinos

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

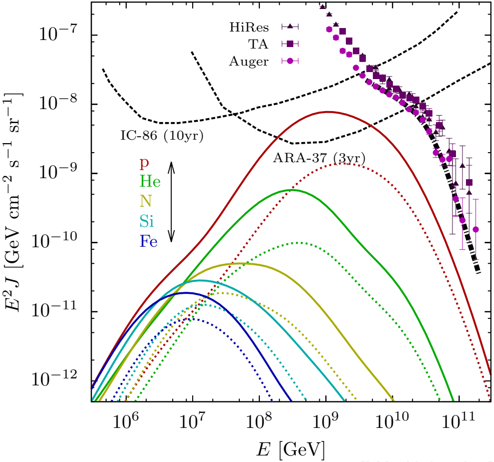
$$J_N^{\rm min}(E_N) = A_{\rm obs}^2 J_{\rm CR}(A_{\rm obs}E_N)$$

- 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

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



[MA&Halzen'12]

Guaranteed cosmogenic neutrinos

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

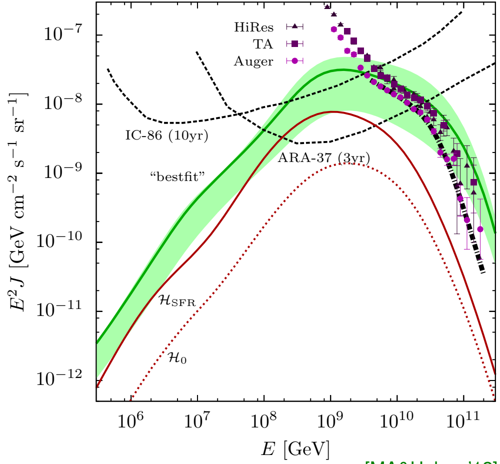
$$J_N^{\rm min}(E_N) = A_{\rm obs}^2 J_{\rm CR}(A_{\rm obs}E_N)$$

- 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

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



[MA&Halzen'12]

Guaranteed cosmogenic neutrinos

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

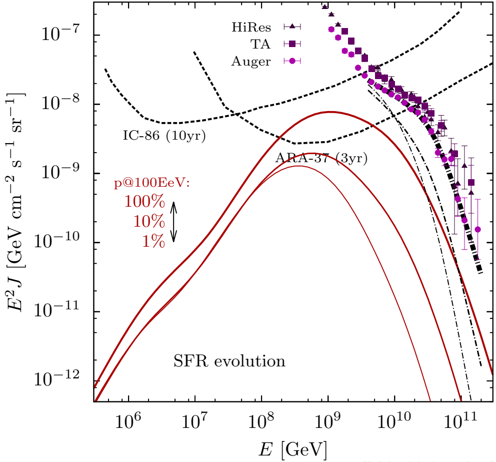
$$J_N^{\rm min}(E_N) = A_{\rm obs}^2 J_{\rm CR}(A_{\rm obs}E_N)$$

- 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

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



[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

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:

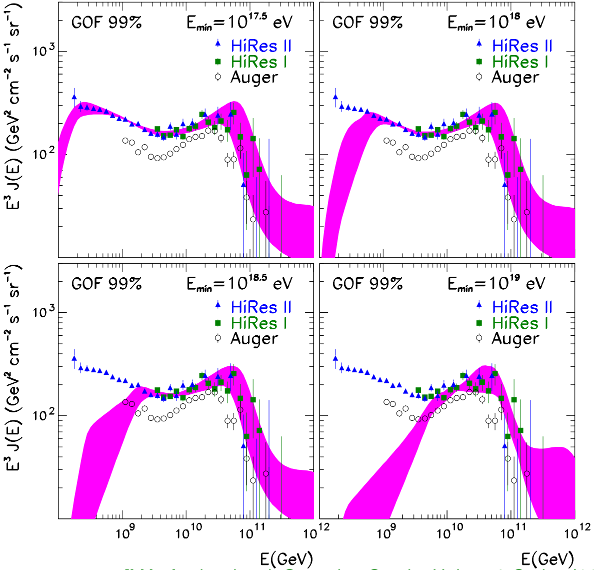
$$\mathcal{L}_p(0,E) \propto (E/E_0)^{-\gamma} \exp(-E/E_{\max}) \exp(-E_{\min}/E)$$

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

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

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 '11]

Propagation of CR nuclei

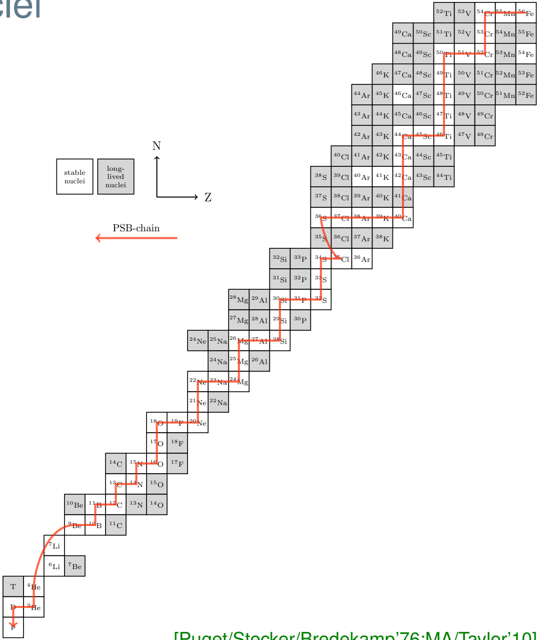
- fast photo-disintegration of nuclei (mass number $A = N + Z$) beyond the giant dipole resonance (GDR):

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

✘ 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]