Multi-Messenger Approaches to Cosmic Rays

– Neutrino Diagnostics –

Markus Ahlers

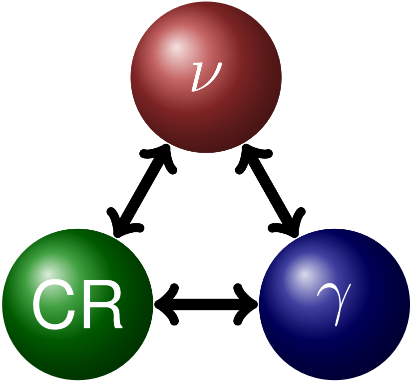
UW-Madison & WIPAC

MACROS 2013

Paris, November 28, 2013

Multi-messenger paradigm

- Neutrino astronomy:
  - ✔ **natural extension**:
    "optical"
    $+$ "multi-wavelength"
    $+$ "multi-messenger"
  - ✔ closely **related** to cosmic rays (CRs) and γ-rays
  - ✔ **smoking-gun** of CR sources
  - ✔ **weak interaction** during propagation
- Challenges:
  - ✘ **low** statistics
  - ✘ **large** backgrounds



High-energy neutrino detection

- ✘ High energy neutrino collisions with nuclei are **rare**.
- ✘ Backgrounds are huge and partially irreducible!

back-of-the-envelope ($E_\nu \sim 10^{15}$ eV):

- **flux of neutrinos** : $\frac{\mathrm{d}^2 N_\nu}{\mathrm{d}t\,\mathrm{d}A} \sim \frac{1}{\mathrm{cm}^2 \times 10^5 \mathrm{yr}}$
- **cross section** : $\sigma_{\nu N} \sim 10^{-33} \mathrm{cm}^2$
- **targets**: $N_N \sim N_A \times V/\mathrm{cm}^3$

→ **rate of events** :

$$\dot{N}_\nu \sim N_N \times \sigma_{\nu N} \times \frac{\mathrm{d}^2 N_\nu}{\mathrm{d}t\,\mathrm{d}A} \sim \frac{1}{\mathrm{year}} \times \frac{V}{1\mathrm{km}^3}$$

Multi-messenger paradigm

- pion production in CR interactions with ambient radiation & matter

$$\pi^+ \to \mu^+\nu_\mu \to e^+\nu_e\bar{\nu}_\mu\nu_\mu$$
$$\pi^0 \to \gamma\gamma$$

- inelasticity:

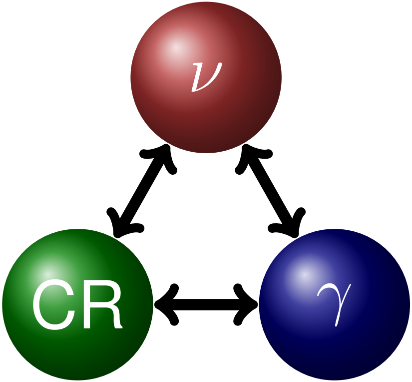
$$E_\nu \simeq E_\gamma/2 \simeq \kappa E_p/4$$

- relative multiplicity:

$$K = N_{\pi^\pm}/N_{\pi^0}$$

- pion fraction via optical depth:

$$f_\pi \simeq 1 - e^{-\kappa\tau}$$



Multi-messenger paradigm

- pion production in CR interactions with ambient radiation & matter

$$\pi^+ \to \mu^+\nu_\mu \to e^+\nu_e\bar{\nu}_\mu\nu_\mu$$
$$\pi^0 \to \gamma\gamma$$

- inelasticity:

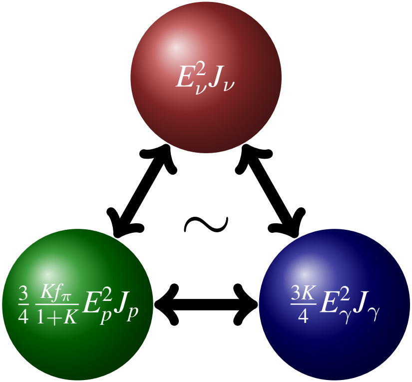
$$E_\nu \simeq E_\gamma/2 \simeq \kappa E_p/4$$

- relative multiplicity:

$$K = N_{\pi^\pm}/N_{\pi^0}$$

- pion fraction via optical depth:

$$f_\pi \simeq 1 - e^{-\kappa\tau}$$



($E_\nu^2 J_\nu \sim$ energy density ω)

Multi-messenger paradigm

- pion production in CR interactions with ambient radiation & matter

$$\pi^+ \to \mu^+\nu_\mu \to e^+\nu_e\bar{\nu}_\mu\nu_\mu$$
$$\pi^0 \to \gamma\gamma$$

- inelasticity:

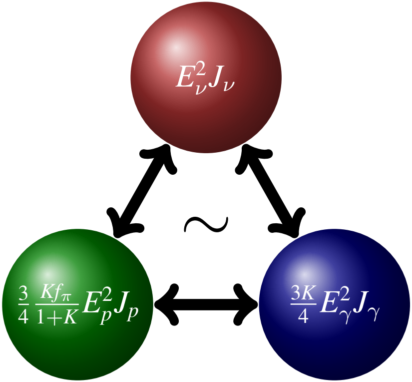
$$E_\nu \simeq E_\gamma/2 \simeq \kappa E_p/4$$

- relative multiplicity:

$$K = N_{\pi^\pm}/N_{\pi^0}$$

- pion fraction via optical depth:

$$f_\pi \simeq 1 - e^{-\kappa\tau}$$



$$\omega_{\gamma-\mathrm{bgr}} \simeq 6\times 10^{-7}\ \mathrm{eV/cm^3}$$
$$\omega_{\mathrm{UHECR}} \simeq 1\times 10^{-7}\ \mathrm{eV/cm^3}$$
$$\omega_{\nu_{\mathrm{all}}} \simeq 2\times 10^{-8}\ \mathrm{eV/cm^3}$$

“IceCube excess”

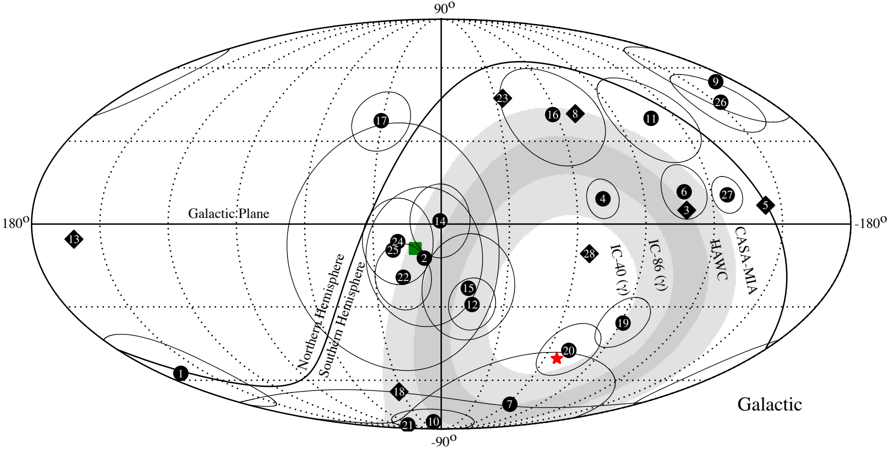
- IceCube observes 28 events over a period of two years, while $10.6^{+5.0}_{-3.6}$ are expected from atmospheric contributions.

  [➜ talk by C.Kopper; IceCube arXiv:1311.5238]

- flux excess at 4.1σ for combined 26+2 fit
- isotropic and flavor-universal
- no significant time-clustering
- 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

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

“IceCube excess”



[data from IceCube arXiv:1311.5238; MA & Murase arXiv:1309.4077]

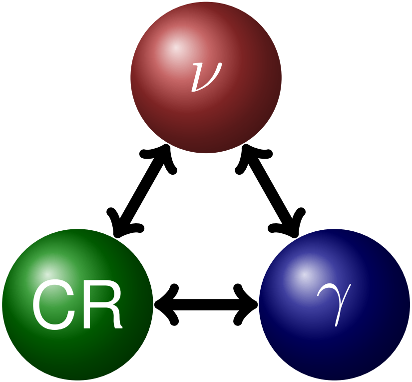
Multi-messenger paradigm

- Neutrino production is closely related to the production of cosmic rays (CRs) and γ-rays.

- 1 PeV neutrinos correspond to 20 PeV CR nucleons and 2 PeV γ-rays

→ **very interesting** energy range:

  - Glashow resonance?
  - galactic or extragalactic?
  - isotropic or point-sources?
  - chemical composition?
  - pp or $p\gamma$ origin?



Conceivable PeV neutrino fluxes

- more ν flux properties (**non-IceCube & preliminary data**):
  - ✘ "Glashow-excitement" [Barger, Learned & Pakvasa 1306.2309; Bhattacharya *et al.* 1209.2422]
  - spectral features [Laha *et al.* 1306.2309; Anchordoqui *et al.* 1306.5021;He *et al.* 1307.1450]
  - flavor composition [Winter 1307.2793]

- neutrinos form pp interactions follow CR spectrum: $E_{\nu,\max} \simeq \frac{1}{20} E_{p,\max}$

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

$$E_{\nu,\mathrm{pk}} \simeq \frac{1}{20}\Gamma^2 \frac{m_\Delta^2 - m_p^2}{4E_\gamma} \simeq 8\mathrm{PeV}\,\Gamma^2 \left(\frac{\mathrm{eV}}{E_\gamma}\right)$$

  - ✘ GZK neutrinos from optical-UV background ($\Gamma \simeq 1$ / $E_\gamma \simeq 10$ eV) [Berezinsky&Zatsepin'69; Roulet *et al.* 1209.4033]
  - ✘ prompt neutrino emission in GRBs ($\Gamma \simeq 300$ / $E_\gamma \simeq 1$ MeV) [Waxman&Bahcall'97]

- prompt neutrino contribution? [Enberg, Reno & Sarcevic'08; Lipari 1308.2086]

Conceivable PeV neutrino fluxes

- more ν flux properties (**non-IceCube & preliminary data**):
  - ✘ "Glashow-excitement" [Barger, Learned & Pakvasa 1306.2309; Bhattacharya *et al.* 1209.2422]
  - spectral features [Laha *et al.* 1306.2309; Anchordoqui *et al.* 1306.5021;He *et al.* 1307.1450]
  - flavor composition [Winter 1307.2793]

- neutrinos form pp interactions follow CR spectrum: $E_{\nu,\max} \simeq \frac{1}{20} E_{p,\max}$

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

$$E_{\nu,\mathrm{pk}} \simeq \frac{1}{20}\Gamma^2 \frac{m_\Delta^2 - m_p^2}{4E_\gamma} \simeq 8\mathrm{PeV}\,\Gamma^2 \left(\frac{\mathrm{eV}}{E_\gamma}\right)$$

  - ✘ GZK neutrinos from optical-UV background ($\Gamma \simeq 1$ / $E_\gamma \simeq 10$ eV) [Berezinsky&Zatsepin'69; Roulet *et al.* 1209.4033]
  - ✘ prompt neutrino emission in GRBs ($\Gamma \simeq 300$ / $E_\gamma \simeq 1$ MeV) [Waxman&Bahcall'97]

- prompt neutrino contribution? [Enberg, Reno & Sarcevic'08; Lipari 1308.2086]

Conceivable PeV neutrino fluxes

- more ν flux properties (**non-IceCube & preliminary data**):
  - ✘ "Glashow-excitement" [Barger, Learned & Pakvasa 1306.2309; Bhattacharya *et al.* 1209.2422]
  - spectral features [Laha *et al.* 1306.2309; Anchordoqui *et al.* 1306.5021;He *et al.* 1307.1450]
  - flavor composition [Winter 1307.2793]

- neutrinos form *pp* interactions follow CR spectrum: $E_{\nu,\max} \simeq \frac{1}{20} E_{p,\max}$

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

$$E_{\nu,\mathrm{pk}} \simeq \frac{1}{20}\Gamma^2 \frac{m_\Delta^2 - m_p^2}{4E_\gamma} \simeq 8\mathrm{PeV}\,\Gamma^2 \left(\frac{\mathrm{eV}}{E_\gamma}\right)$$

  - ✘ GZK neutrinos from optical-UV background ($\Gamma \simeq 1$ / $E_\gamma \simeq 10$ eV) [Berezinsky&Zatsepin'69; Roulet *et al.* 1209.4033]
  - ✘ prompt neutrino emission in GRBs ($\Gamma \simeq 300$ / $E_\gamma \simeq 1$ MeV) [Waxman&Bahcall'97]

- prompt neutrino contribution? [Enberg, Reno & Sarcevic'08; Lipari 1308.2086]

Conceivable PeV neutrino fluxes

- more ν flux properties (**non-IceCube & preliminary data**):
  - ✘ "Glashow-excitement" [Barger, Learned & Pakvasa 1306.2309; Bhattacharya *et al.* 1209.2422]
  - spectral features [Laha *et al.* 1306.2309; Anchordoqui *et al.* 1306.5021;He *et al.* 1307.1450]
  - flavor composition [Winter 1307.2793]

- neutrinos form *pp* interactions follow CR spectrum: $E_{\nu,\rm max} \simeq \frac{1}{20} E_{p,\rm max}$

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

$$E_{\nu,\rm pk} \simeq \frac{1}{20}\Gamma^2 \frac{m_\Delta^2 - m_p^2}{4E_\gamma} \simeq 8{\rm PeV}\,\Gamma^2 \left(\frac{\rm eV}{E_\gamma}\right)$$

  - ✘ GZK neutrinos from optical-UV background ($\Gamma \simeq 1$ / $E_\gamma \simeq 10$ eV) [Berezinsky&Zatsepin'69; Roulet *et al.* 1209.4033]
  - ✘ prompt neutrino emission in GRBs ($\Gamma \simeq 300$ / $E_\gamma \simeq 1$ MeV) [Waxman&Bahcall'97]

- prompt neutrino contribution? [Enberg, Reno & Sarcevic'08; Lipari 1308.2086]

Proposed source candidates

- **extragalactic sources:**
  - relation to the sources of UHE CRs [Kistler, Stanev & Yuksel 1301.1703]
  - GZK from low $E_{\max}$ blazars [Kalashev, Kusenko & Essey 1303.0300]
  - cores of active galactic nuclei (AGN) [Stecker *et al.*'91;Stecker 1305.7404]
  - low-power γ-ray bursts (GRB) [Murase & Ioka 1306.2274]
  - starburst galaxies [Loeb&Waxman'06; He *et al.* 1303.1253; Murase, MA & Lacki 1306.3417]
  - hypernovae in star-forming galaxies [Liu, Wang, Inoue, Crocker & Aharonian 1310.1263]
  - galaxy clusters/groups [Berezinksy, Blasi & Ptuskin'97; Murase, MA & Lacki 1306.3417]
- **Galactic sources:**
  - heavy dark matter decay [Feldstein *et al.* 1303.7320; Esmaili & Serpico 1308.1105]
  - peculiar hypernovae [Fox, Kashiyama & Meszaros 1305.6606; MA & Murase 1309.4077]
  - diffuse Galactic γ-ray emission [*e.g.* Ingelman & Thunman'96; MA & Murase 1309.4077]
- **γ-ray association:**
  - unidentified Galactic TeV γ-ray sources [Fox, Kashiyama & Meszaros 1306.6606]
  - sub-TeV diffuse Galactic γ-ray emission [Neronov, Semikoz & Tchernin 1307.2158]

Proposed source candidates

- **extragalactic sources:**
  - relation to the sources of UHE CRs [Kistler, Stanev & Yuksel 1301.1703]
  - GZK from low $E_{\max}$ blazars [Kalashev, Kusenko & Essey 1303.0300]
  - cores of active galactic nuclei (AGN) [Stecker *et al.*'91;Stecker 1305.7404]
  - low-power γ-ray bursts (GRB) [Murase & Ioka 1306.2274]
  - starburst galaxies [Loeb&Waxman'06; He *et al.* 1303.1253; Murase, MA & Lacki 1306.3417]
  - hypernovae in star-forming galaxies [Liu, Wang, Inoue, Crocker & Aharonian 1310.1263]
  - galaxy clusters/groups [Berezinksy, Blasi & Ptuskin'97; Murase, MA & Lacki 1306.3417]

- **Galactic sources:**
  - heavy dark matter decay [Feldstein *et al.* 1303.7320; Esmaili & Serpico 1308.1105]
  - peculiar hypernovae [Fox, Kashiyama & Meszaros 1305.6606; MA & Murase 1309.4077]
  - diffuse Galactic γ-ray emission [*e.g.* Ingelman & Thunman'96; MA & Murase 1309.4077]

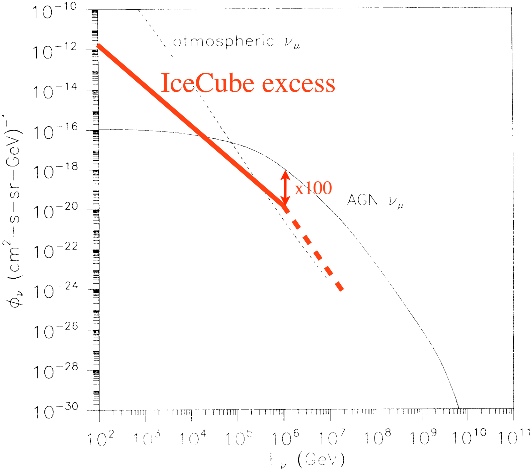
- **γ-ray association:**
  - unidentified Galactic TeV γ-ray sources [Fox, Kashiyama & Meszaros 1306.6606]
  - sub-TeV diffuse Galactic γ-ray emission [Neronov, Semikoz & Tchernin 1307.2158]

Proposed source candidates

- **extragalactic sources:**
  - relation to the sources of UHE CRs [Kistler, Stanev & Yuksel 1301.1703]
  - GZK from low $E_{\max}$ blazars [Kalashev, Kusenko & Essey 1303.0300]
  - cores of active galactic nuclei (AGN) [Stecker *et al.*'91;Stecker 1305.7404]
  - low-power γ-ray bursts (GRB) [Murase & Ioka 1306.2274]
  - starburst galaxies [Loeb&Waxman'06; He *et al.* 1303.1253; Murase, MA & Lacki 1306.3417]
  - hypernovae in star-forming galaxies [Liu, Wang, Inoue, Crocker & Aharonian 1310.1263]
  - galaxy clusters/groups [Berezinksy, Blasi & Ptuskin'97; Murase, MA & Lacki 1306.3417]
- **Galactic sources:**
  - heavy dark matter decay [Feldstein *et al.* 1303.7320; Esmaili & Serpico 1308.1105]
  - peculiar hypernovae [Fox, Kashiyama & Meszaros 1305.6606; MA & Murase 1309.4077]
  - diffuse Galactic γ-ray emission [*e.g.* Ingelman & Thunman'96; MA & Murase 1309.4077]
- **γ-ray association:**
  - unidentified Galactic TeV γ-ray sources [Fox, Kashiyama & Meszaros 1306.6606]
  - sub-TeV diffuse Galactic γ-ray emission [Neronov, Semikoz & Tchernin 1307.2158]

A. Active Galactic Nuclei

- neutrino interactions from $p\gamma$ interactions in AGN cores [Stecker *et al.*'91]
- AGN diffuse emission normalized to X-ray background
- revised model predicts 5% of original estimate [Stecker'05;'13]



[Stecker *et al.*'91]

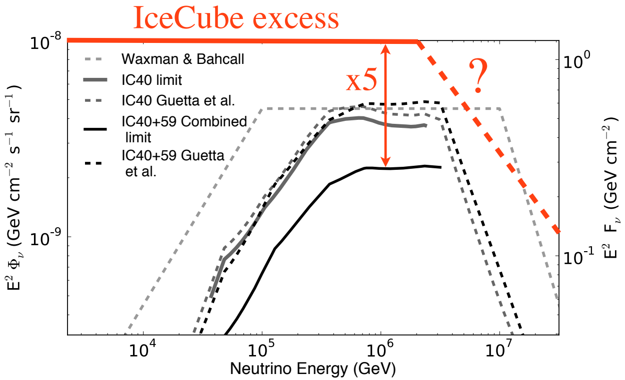
B. Gamma-ray Bursts

- strong limits on neutrino emission associated with the fireball model [Abbasi *et al.*'12]

➜ IceCube excess exceeds IC40+59 limit by factor ~ 5

- **loophole:** undetected low-power γ-ray bursts (GRB) [Murase & Ioka 1306.2274]

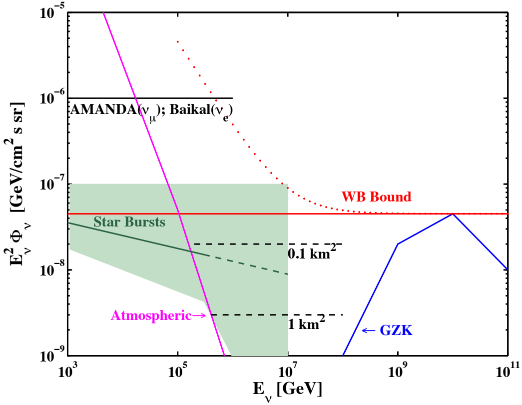
➜ talk by X.Y.Wang in this session



[modified from Abbasi *et al.*'12]

C. Starburst galaxies

- intense CR interactions (and acceleration) in dense starburst galaxies
- cutoff/break feature $(0.1 - 1)$ PeV at the CR knee (of these galaxies), but very uncertain
- plot shows muon neutrinos on production $(3/2$ of total)



[Loeb & Waxman'06]

D. Cosmogenic neutrinos

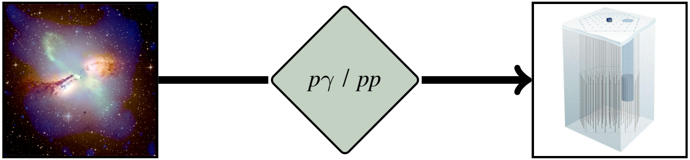
- *cos-mo-gen-ic* (adj.): "produced by cosmic rays"

✘ 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.*

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



(e.g. Centaurus A)

propagation

D. Cosmogenic neutrinos

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

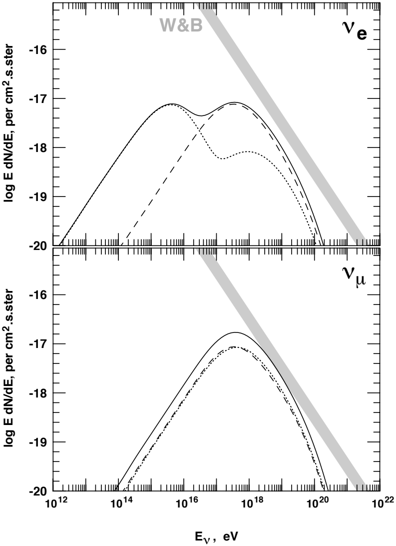
- "GZK"-neutrinos at EeV energies from pion decay [Berezinsky/Zatsepin'69]

- 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]

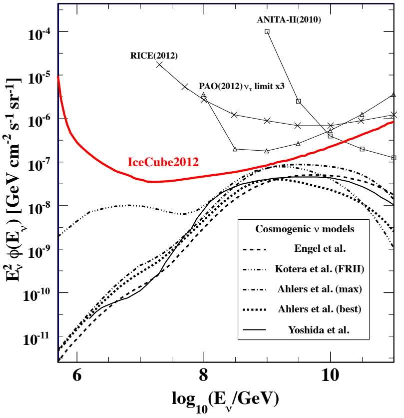
D. Cosmogenic neutrinos

- 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^+:

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

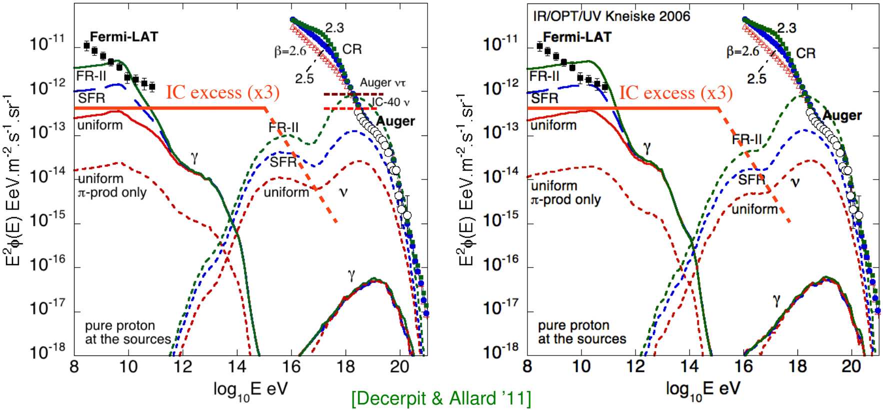
- one neutrino from neutron decay:

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



[IceCube'13]

D. Cosmogenic neutrinos



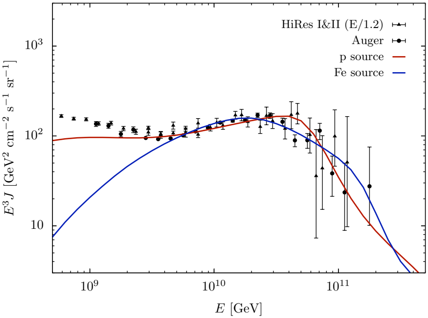
[Decerpit & Allard '11]

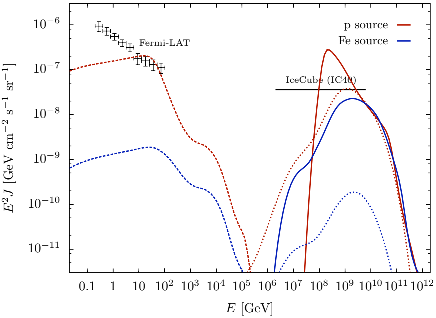
➜ neutrino flux depend on source **evolution model** (strongest for "FR-II") and **EBL model** (highest for "Stecker" model)

✘ "Stecker" model disfavored by Fermi observations of GRBs

✘ strong evolution disfavored by Fermi diffuse background

E. GZK neutrinos from heavy nuclei





- 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]

E. GZK neutrinos from heavy nuclei

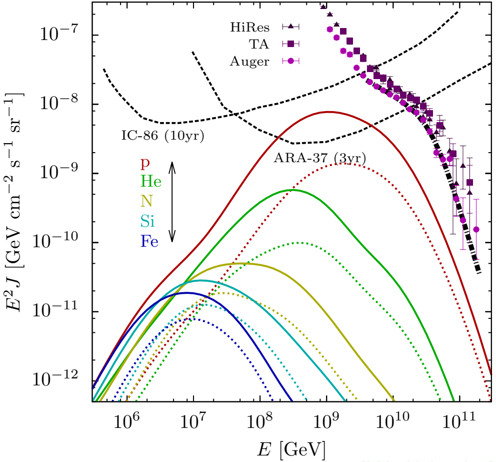
➜ nucleon spectrum for observed mass number $A_{\rm obs}$:

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

- lower limit by "indefinite" back-tracking of nuclei
- dependence on cosmic evolution of sources:
  - no evolution (dotted)
  - star-formation rate (solid)

➜ 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]

E. GZK neutrinos from heavy nuclei

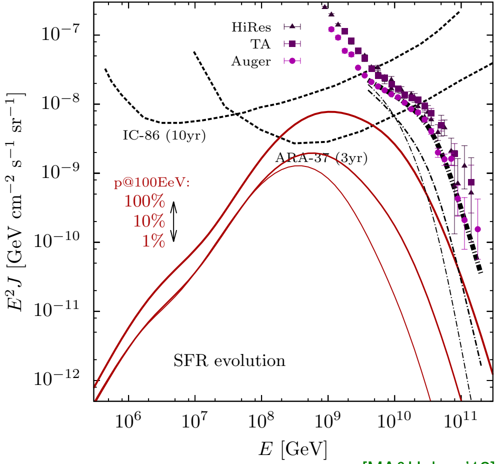
➜ nucleon spectrum for observed mass number $A_{\rm obs}$:

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

- lower limit by "indefinite" back-tracking of nuclei
- dependence on cosmic evolution of sources:
  - no evolution (dotted)
  - star-formation rate (solid)

➜ 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]

F. GeV-TeV γ-ray limits on pp scenario

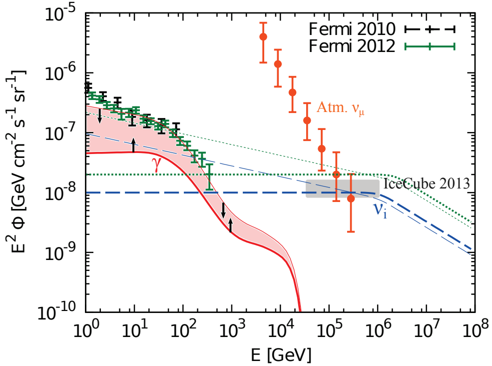
- neutrino flux in pp scenario follows CR spectrum $\propto E^{-\Gamma}$

➜ low energy tail of GeV-TeV neutrino/γ-ray spectra

✘ constraint by extragalactic γ-ray background

- extra-galactic emission: $\Gamma \lesssim 2.2$
- Galactic emission: $\Gamma \lesssim 2.0$

✔ limits insensitive to redshift evolution effects



[Murase, MA & Lacki'13]

Outlook

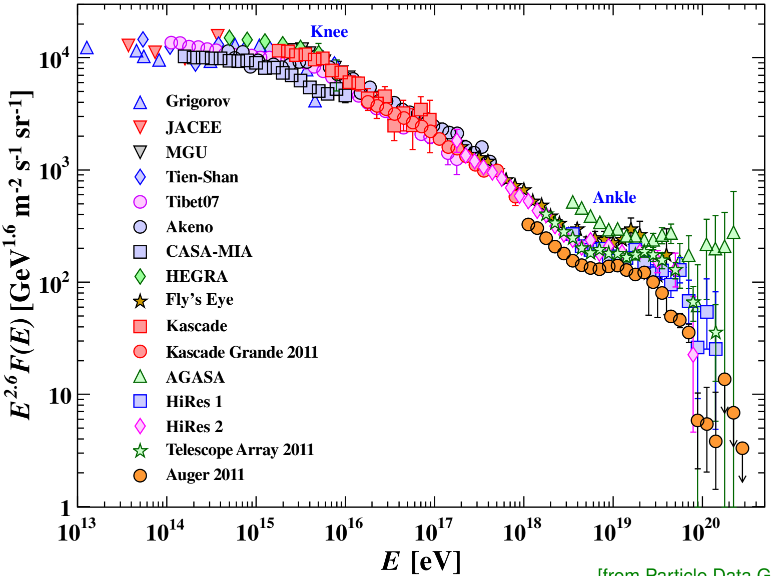
- The IceCube excess marks the birth* of HE neutrino astronomy!

* (4.1σ background probability: $\sim$4 in 100000)

- What's next: ➜ talk by C.Finley after coffee
  - Do we see individual sources or just a diffuse background?
  - What can we learn from spectrum (in particular a possible PeV-ish break) and flavor composition? ➜ next talk by R.Laha
  - Is the corresponding CR population responsible for UHE CRs?
- Neutrino astronomy also closes in on cosmogenic neutrino fluxes.
- Will be already see the first hints with IceCube or do we have to wait for future EeV neutrino upgrades (ARA, ARIANNA,...)?
- Full power of multi-messenger astronomy lies in the combination of all messengers, in particular γ-rays! ➜ γ-ray afternoon session

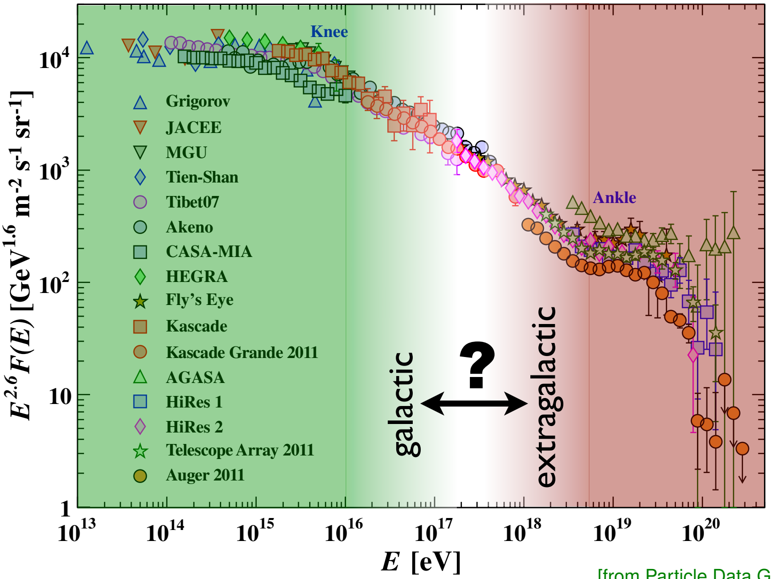
Appendix

Cosmic ray spectrum



[from Particle Data Group'12]

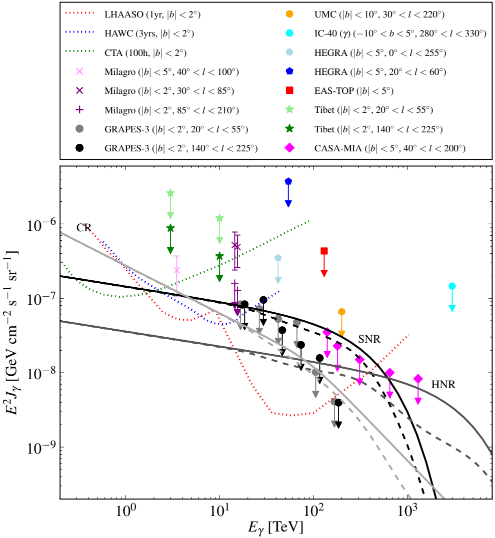
Cosmic ray spectrum



[from Particle Data Group'12]

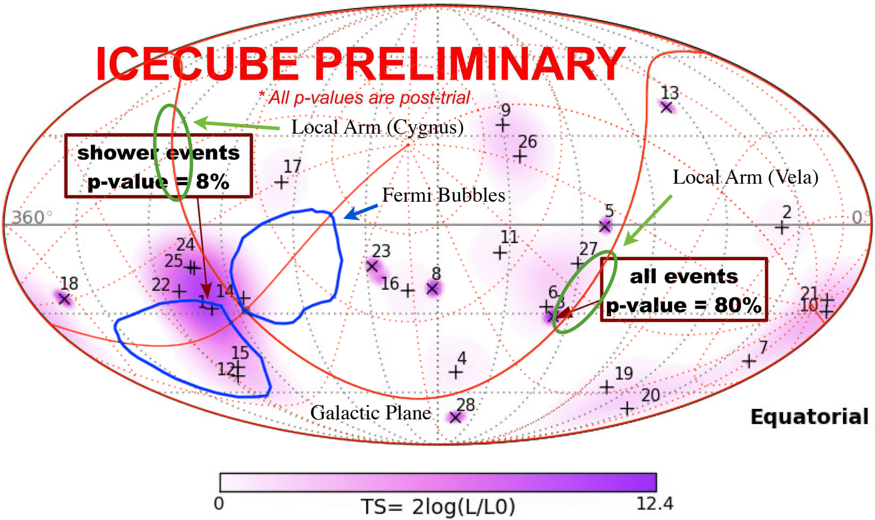
Galactic Plane diffuse fluxes

- diffuse γ-ray emission from CR propagation ($|b| < 2°$)
- supernova remnants (SNR):
  $R_{\rm SN} \simeq 0.03 {\rm yr}^{-1}$
  $\mathcal{E}_{\rm ej} \simeq 10^{51}$ erg
  $N_{\rm SNR} \simeq 1200$
- hypernova remnants (HNR):
  $R_{\rm HN} \simeq 0.01 R_{\rm SN}$
  $\mathcal{E}_{\rm ej} \simeq 10^{52}$ erg
  $N_{\rm HNR} \simeq 20$
- flux concentrated in Galactic Plane:
  $J \propto 30\%$ for $|b| < 10°$
  $J \propto 15\%$ for $|b| < 30°$
- however, this does not account for **local fluctuation**

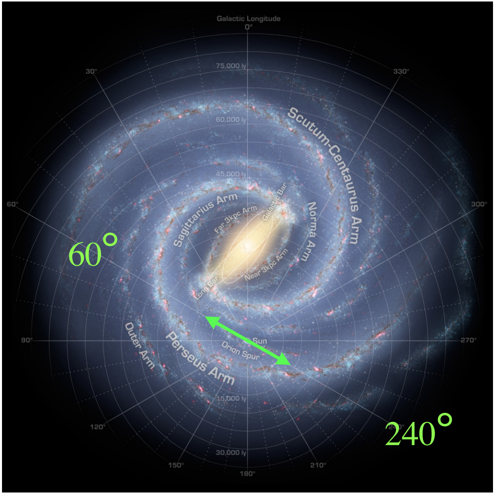


[MA & Murase 1309.4077]

Extended Galactic sources?



Milky Way and Local Arm

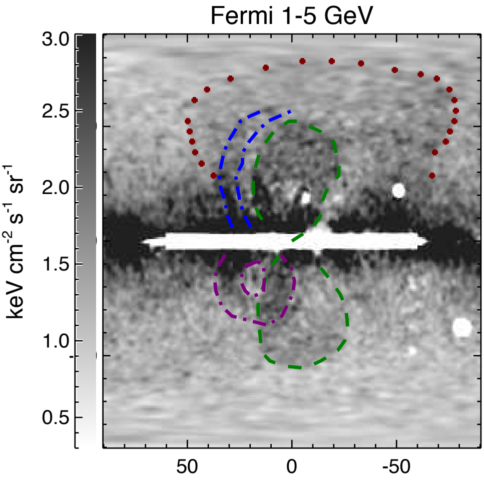


Close-by sources in the Local Arm can show up as high-latitude hot spots!

Fermi Bubbles

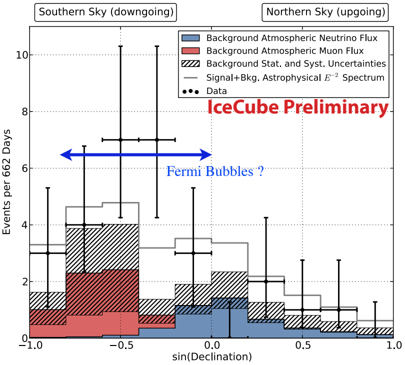
- two extended GeV γ-ray emission regions close to the Galactic Center [Su, Slatyer & Finkbeiner'10]
- hard spectra and relatively uniform emission
- some correlation with WMAP haze and X-ray observation
- model 1: hadronuclear interactions of CRs accelerated by star-burst driven winds and convected over few 10^9 years [Crocker & Aharonian'11]
- model 2: leptonic emission from 2nd order Fermi acceleration of electrons [Mertsch & Sarkar'11]

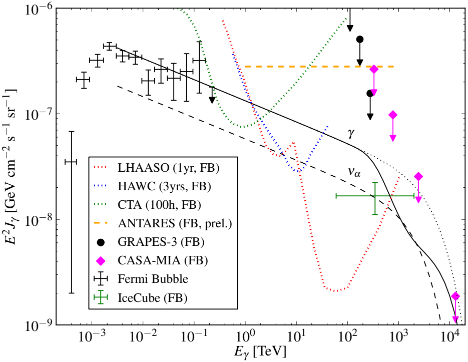
➜ probed by associated neutrino production [Lunardini & Razzaque'12]



[Su, Slatyer & Finkbeiner'11]

Fermi Bubbles





[MA & Murase 1309.4077]

- small zenith "excess" in IceCube excess (but not significant)
- Galactic Center source(s) of extended source, *e.g.* "Fermi Bubbles"?

  [Finkbeiner, Su & Slatyer'10]

- FB "excess" in agreement with GeV-PeV neutrino & γ-ray observations and limits assuming $\Gamma \simeq 2.2$

Glashow resonance

➜ resonant interactions with in-ice electrons:

$$\bar{\nu}_e e^- \to W \to X$$

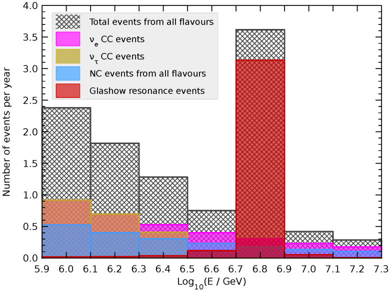
- hadronic (70%) or leptonic (30%) decay

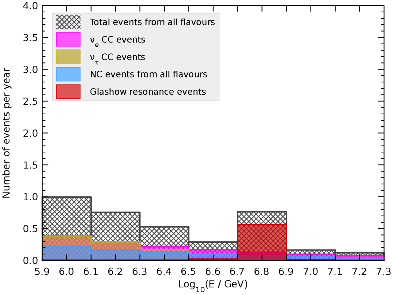
- pp (top plot) and $p\gamma$ (bottom plot) with different flavor ratios and E^{-2}-flux
  [Bhattacharya, Gandhi, Rodejohann & Watanabe'11]

- early "Glashow-excitement" after *Neutrino* 2012, Kyoto
  [Barger, Learned & Pakvasa 1207.4571]
  [Bhattacharya *et al.* 1209.2422]

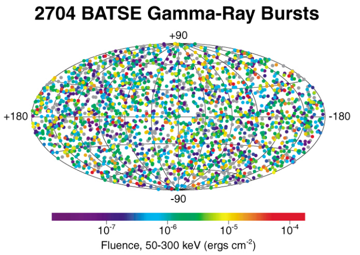
✘ Where are the Glashow events?

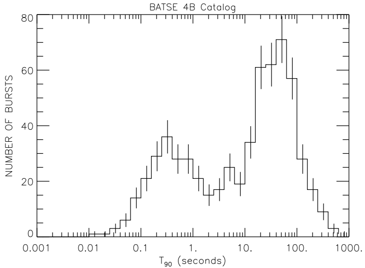
➜ flavor composition and spectral features
[Laha *et al.* 1306.2309; Anchordoqui *et al.* 1306.5021]
[He *et al.* 1307.1450; Winter 1307.2793]

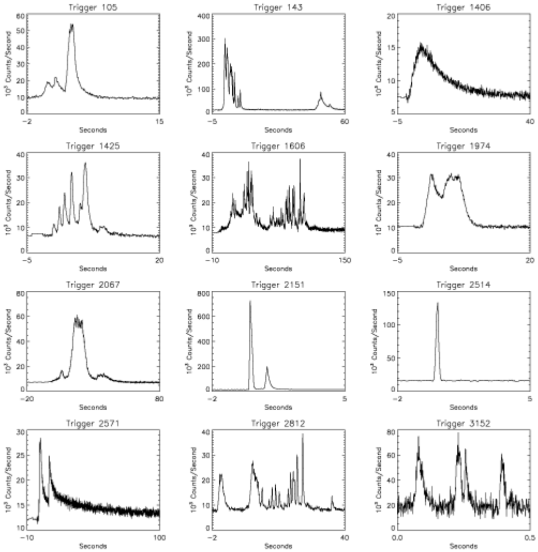




Gamma-ray bursts (GRBs)







IC40+59 results

- Limits on neutrino emission coincident with 215 (85) northern (southern) sky GRBs between April 2008 and May 2010 (“IC40+59”). [Abbasi *et al.*’11;’12]

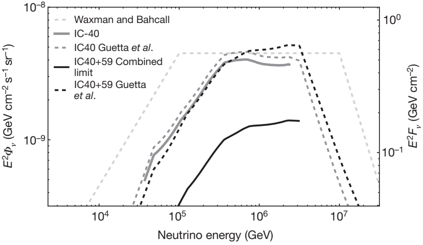
➜ **Model-dependent** limit for prompt emission model.

➜ **Model-independent** limit for general neutrino coincidences (no spectrum assumed) with sliding time window $\pm\Delta t$ from burst.

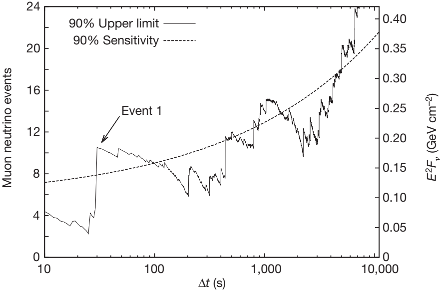
- **Stacked flux** below “benchmark” prediction of burst neutrino emission by a factor 3-4. [Guetta *et al.*’04]

➜ **conversion to diffuse flux** via cosmic GRB rate.

“model-dependent”



“model-independent”



IC40+59 results

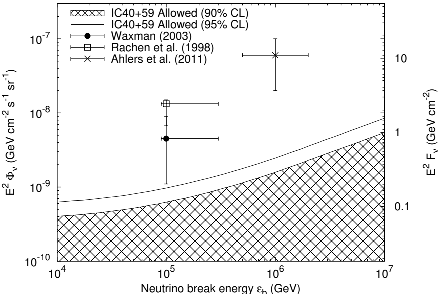
- IceCube limit below **benchmark diffuse models** normalized to UHE CR data. [Waxman&Bahcall'03; Rachen *et al.*'98]

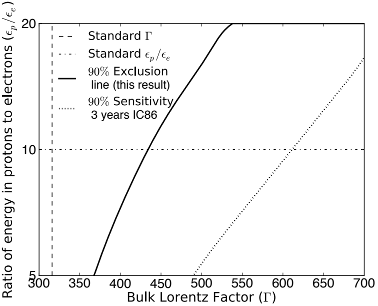
➜ **IceCube's results challenge GRBs as the sources of UHE CRs!**

- **Limit** on burst neutrino emission depends on neutrino break energy "$\varepsilon_b \propto \Gamma^2$" (break in optical depth).

- Results from model-dependent analysis translate into bounds of GRB parameters. [Guetta *et al.*'04]

➜ **Neutron emission models largely ruled out.** [MA, Gonzalez-Garcia & Halzen'11]





GRB flux normalization

- Neutrino predictions depend on model and normalization:

A GRB as **the** source of UHE CRs?

→ calculate the pion energy fraction f_π in $p\gamma$ interactions
→ normalize to UHE CRs [Waxman & Bahcall'97]

A' GRB as **the** source of UHE CR neutrons?

→ independent of f_π
→ normalize to UHE CRs [Rachen & Mészáros'98; MA, Gonzalez-Garcia & Halzen'11]

B GRB as **one** source of (UHE) CRs?

→ use bolometric energy arguments about internal energy densities U in shock

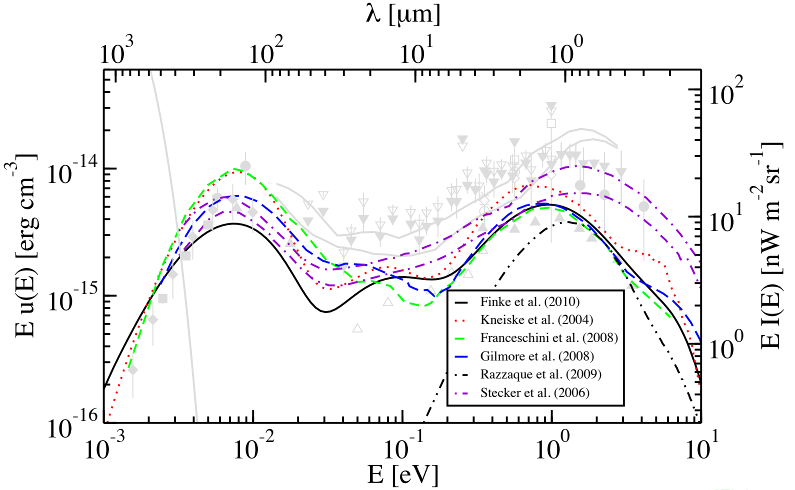
$$U_B = \epsilon_B U_{\rm tot} \qquad U_e = \epsilon_e U_{\rm tot} \qquad U_p = \epsilon_p U_{\rm tot}$$

→ by construction, $\epsilon_B + \epsilon_e + \epsilon_p \lesssim 1$, but otherwise **not well constrained**
→ calculate the pion energy fraction f_π in $p\gamma$ interactions
→ normalize to CRs in individual bursts, $U_p = (\epsilon_p/\epsilon_e)U_{\rm burst}$ [Guetta *et al.*'04;He *et al.*'12]

GRB model-dependence

- The parameters Γ_i, ϵ_p and ϵ_e are in general fudge-factors; some indirect observation by GRB afterglow emission.
- Model hierarchy: "**A ➜ B**" or "**not B ➜ not A**"
- Heavy nuclei acceleration in internal shocks?
  - issues for model **A**; large internal shock radii and/or large Lorentz factors needed to reach UHEs [Wang,Razzaque&Meszaros'08;Murase *et al.*'08]
  - generally lower neutrino luminosity due to limited photon density
- Diffuse limits have also dependence on the stochasticity of the tested GRB ensemble. [Baerwald,Hümmer&Winter'11]
- Revised calculations of pion fraction f_π produce *lower values* than the standard parametrization [Li'11; Baerwald,Hümmer&Winter'11;He *et al.*'12]
- CR production via neutron emission (model **A'**) relates neutrinos and CR protons *independent* of the absolute value f_π; scenario largely ruled out by IC40+59. [MA/Gonzalez-Garcia/Halzen'11]

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

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

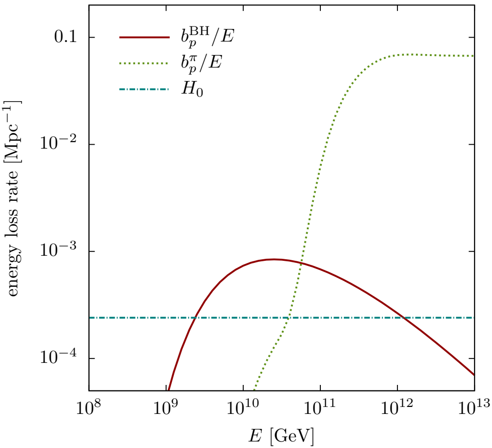
- Bethe-Heitler (BH) pair production:

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

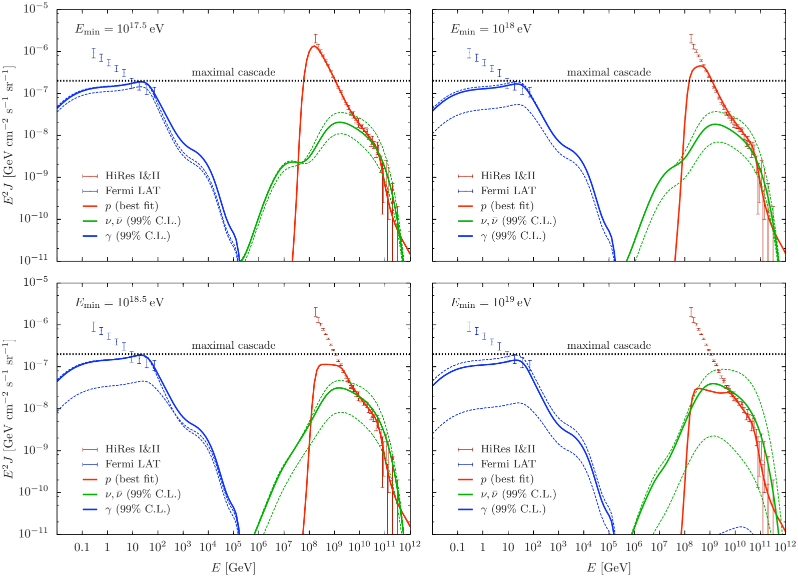
➜ BH is dominant energy loss process for UHE CR protons at $\sim 2 \times 10^{9} \div 2 \times 10^{10}$ GeV.

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

[Berezinsky&Smirnov'75]



Cosmogenic neutrinos from EBL



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

Propagation of CR nuclei

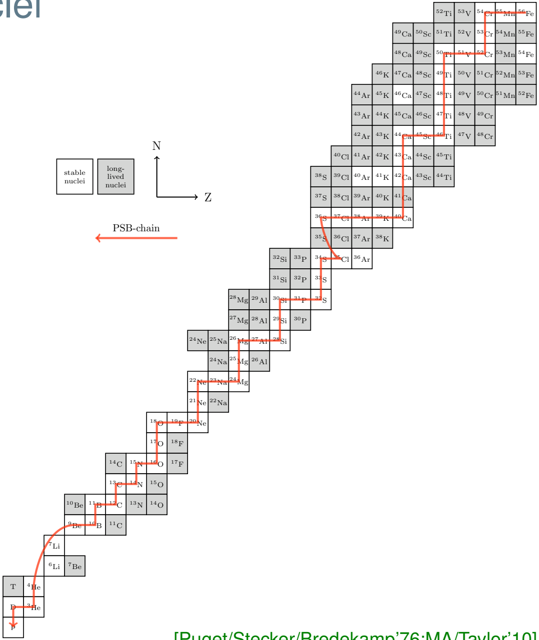
- fast photo-disintegration of nuclei (mass number $A = N + Z$) beyond the giant dipole resonance (GDR):

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

✘ 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]

Approximate* scaling law of energy densities

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

* **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 ($z_{\max} = 2$ & $\gamma = 2.3$):

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

✔ **relative difference:** $\sim 82.$

Nucleon cascade

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

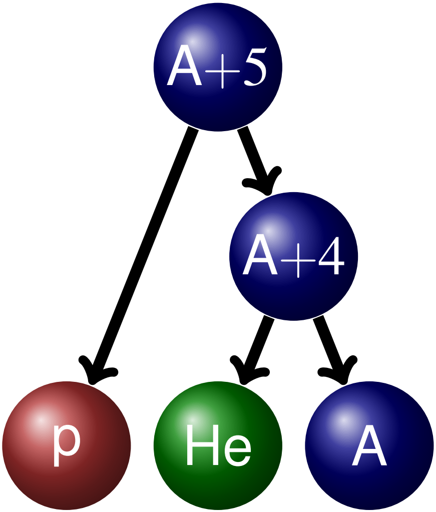
✘ Bethe-Heitler (BH) loss breaks this approximation

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

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

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

➜ **minimal** nucleon emissivity



Nucleon cascade

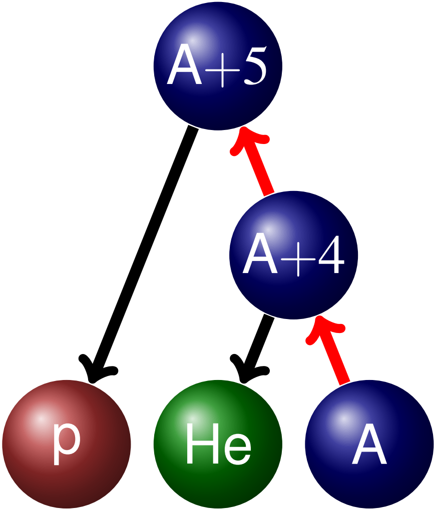
- Observed composition is result of source composition and nucleon cascades.
- **Backtracking** conserves energy per nucleon.
- ✗ Bethe-Heitler (BH) loss breaks this approximation

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

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

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

  ➜ **minimal** nucleon emissivity



Cosmogenic neutrinos from heavy nuclei

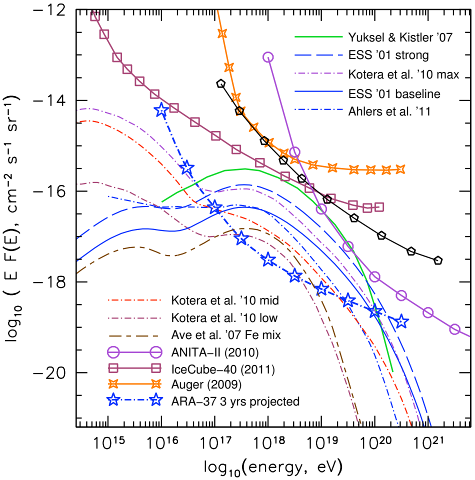


TABLE II: Expected numbers of events N_ν from several UHE neutrino models, comparing published values from the 2008 ANITA-II flight with predicted events for a three-year exposure for ARA-37.

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.