Astrophysical Interpretations of the IceCube Excess

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“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.
- 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

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

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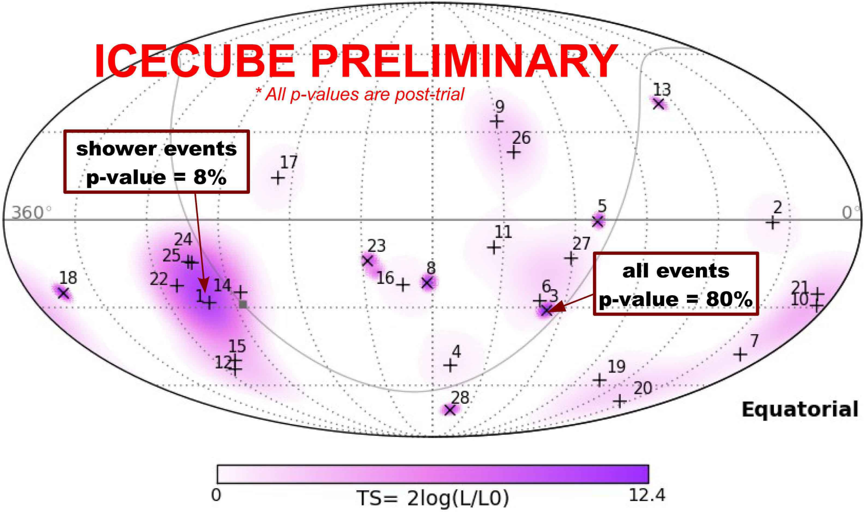


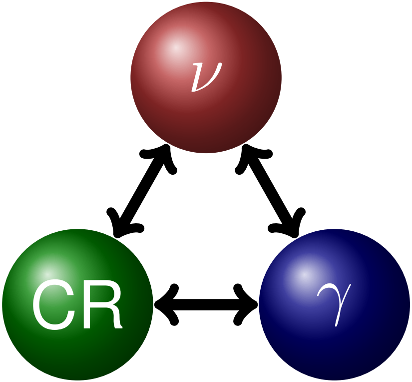
[C.Kopper, N.Kurahashi & N.Whitehorn, IPA’13]

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]

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Proposed source candidates

- **extragalactic sources:**
  - relation to the sources of UHE CRs [Kistler, Stanev & Yuksel 1301.1703]
  - GZK from low $E_{\rm max}$ 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 *et al.* 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]

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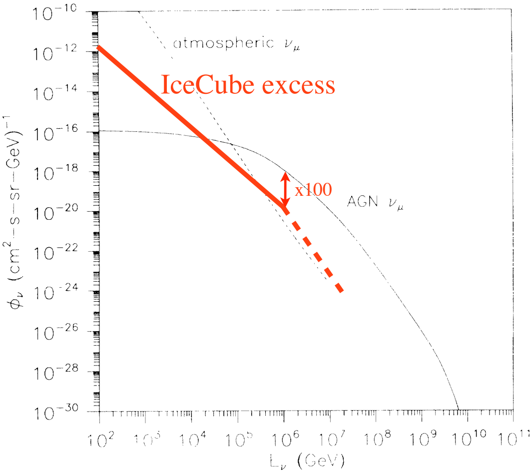
A. Active Galactic Nuclei

- 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]



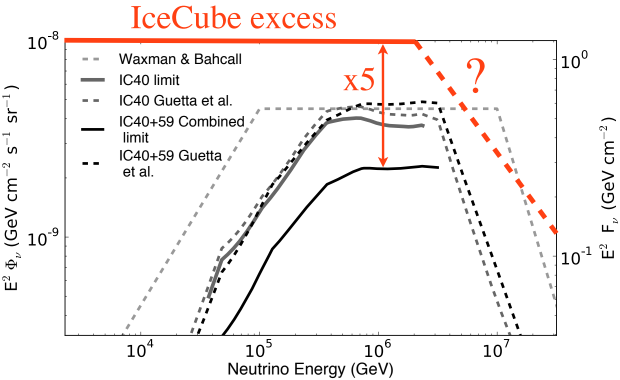
[Stecker *et al.*'91]

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

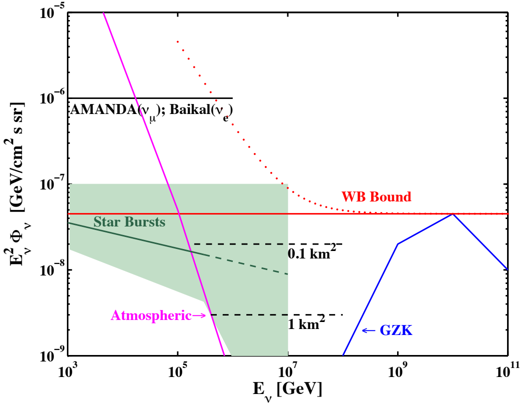
- **loophole:** undetected low-power γ-ray bursts (GRB) [Murase & Ioka 1306.2274]



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

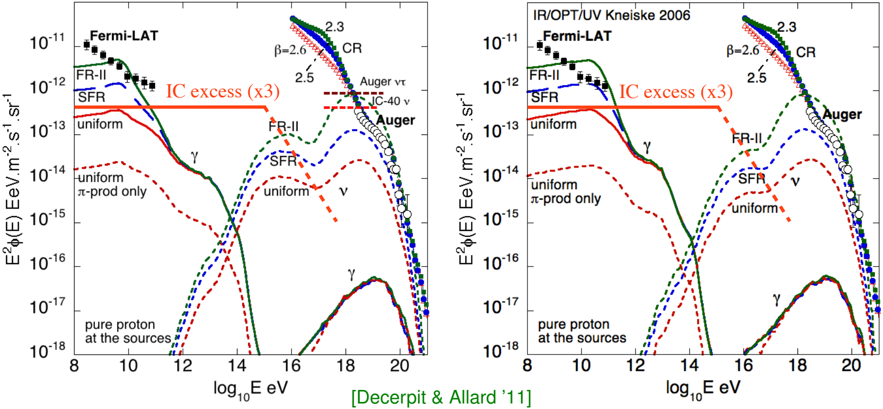
C. Starburst galaxies

- 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



[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

Neutrino and γ-ray connection

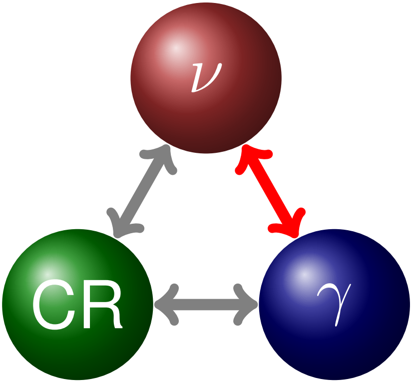
➜ related production of charged and neutral pions:

$$\left.\begin{matrix} pp \\ p\gamma \end{matrix}\right\} \rightarrow \left\{\begin{matrix} X + \pi^{\pm} \\ X + \pi^{0} \end{matrix}\right.$$

- simple related production spectra:

$$E_\gamma Q_\gamma(E_\gamma) \simeq \frac{2}{K}\frac{1}{3}\sum_{\nu_\alpha} E_\nu Q_{\nu_\alpha}(E_\nu)$$

- neutrino energy: $E_\nu \simeq E_\gamma/2$
- pion ratio: $K = \frac{N_{\pi^\pm}}{N_{\pi^0}}$
- $K \simeq 2$ ($K \simeq 1$) for pp ($p\gamma$) scenario



GeV-TeV γ-ray limits on pp scenario

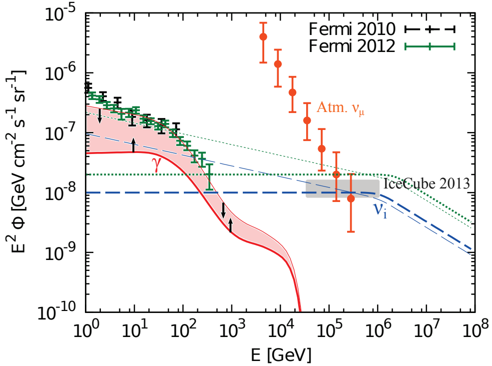
- neutrino flux in pp scenario follows CR spectrum $\propto E^{-\Gamma}$

➜ 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]

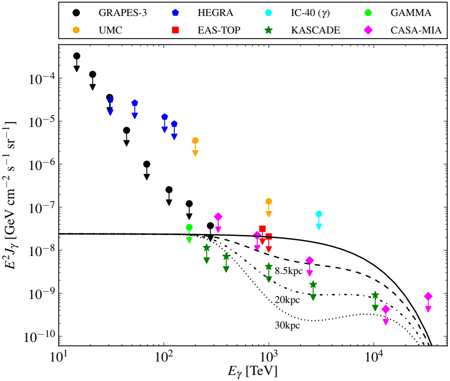
Isotropic diffuse TeV-PeV γ-ray limits

- IceCube-equivalent diffuse γ-ray flux:

$$E_\gamma J_\gamma(E_\gamma) \simeq e^{-\frac{d}{\lambda_{\gamma\gamma}}} \frac{2}{K} \frac{1}{3} \sum_{\nu_\alpha} E_\nu J^{\rm IC}_{\nu_\alpha}(E_\nu)$$

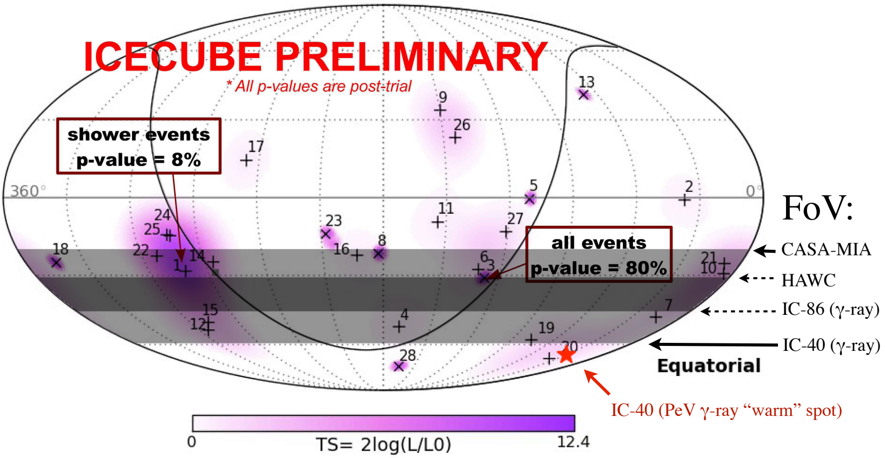
- absorption length $\lambda_{\gamma\gamma}$ via $\gamma\gamma \to e^+e^-$
- effect strongest for CMB in PeV range: $\lambda_{\gamma\gamma} \simeq 10$ kpc
- plot shows distance d from 8.5 kpc (GC) to 30 kpc

➜ strong constraints of isotropic diffuse Galactic emission from γ-ray observatories [Gupta 1305.4123]



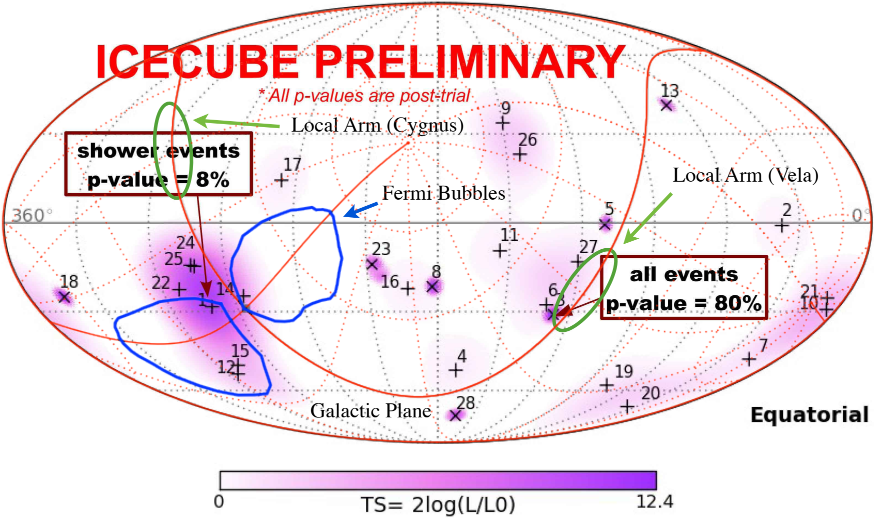
[MA & Murase 1309.4077]

Isotropic diffuse TeV-PeV γ-ray limits

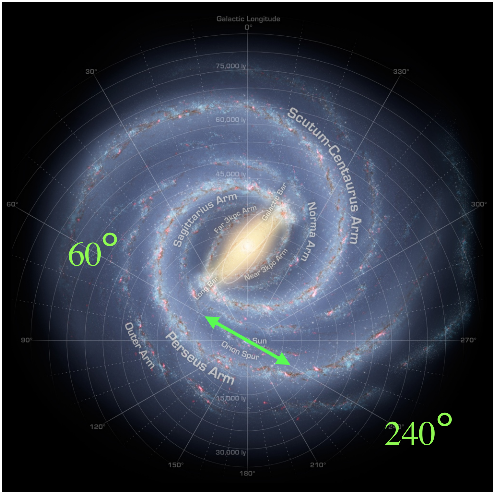


- 15 events lie in TeV-PeV "blind spot"
- one PeV event ("Ernie") within 10° of PeV γ-ray "warm spot" [IceCube'12]

Extended Galactic sources



Milky Way and Local Arm

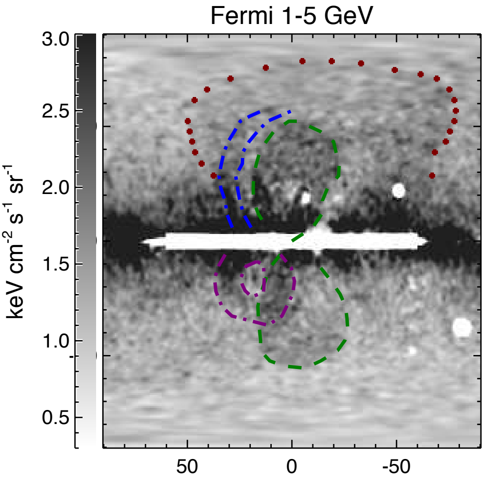


Close-by sources in the Local Arm can show up as high-latitude hot spots!

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]

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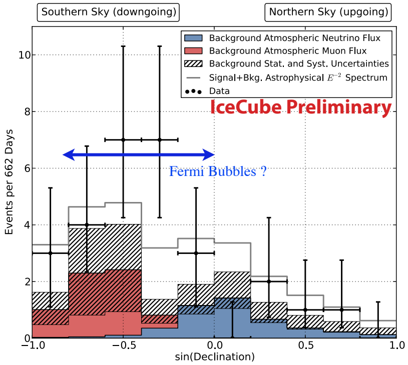
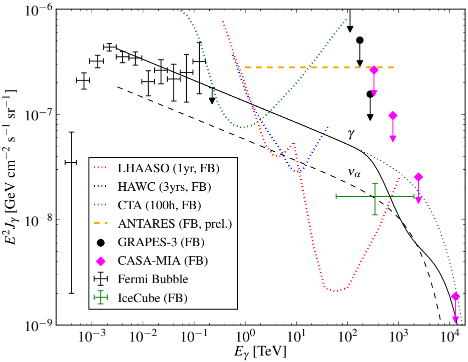




[MA & Murase 1309.4077]

- 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 $\Gamma \simeq 2.2$

Summary

✔ IceCube Excess marks the beginning of HE neutrino astronomy.

✔ PeV neutrino signal connects to an interesting multi-messenger energy region:

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

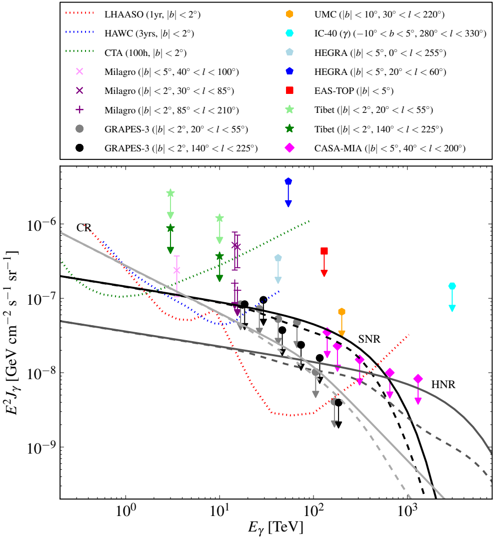
➜ Diffuse γ-ray observations serve as a diagnostic tool.

- limits on diffuse TeV-PeV γ-ray emission challenge the contribution of local sources
- hints for GeV-TeV γ-ray counterparts? (Cygnus region, Fermi Bubbles,. . .)
- however, TeV-PeV "blind spot" due to lack of Southern observatories

Backup

Galactic Plane diffuse fluxes

- diffuse γ-ray emission from CR propagation ($|b| < 2^\circ$)
- 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 $|b| < 10^\circ$
  $J \propto 15\%$ for $|b| < 30^\circ$
- however, this does not account for **local fluctuation**



[MA & Murase 1309.4077]

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]

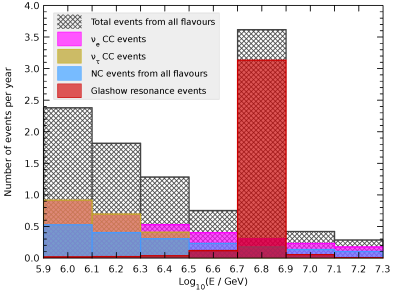
  [Bhattacharya *et al.* 1209.2422]

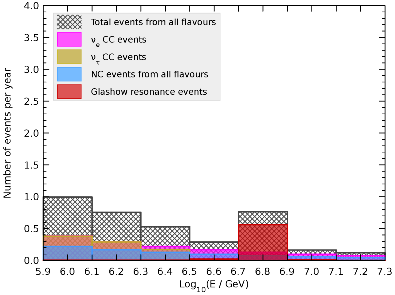
✘ Where are the Glashow events?

➜ flavor composition and spectral features

[Laha *et al.* 1306.2309; Anchordoqui *et al.* 1306.5021]

[He *et al.* 1307.1450; Winter 1307.2793]





Cosmogenic neutrinos

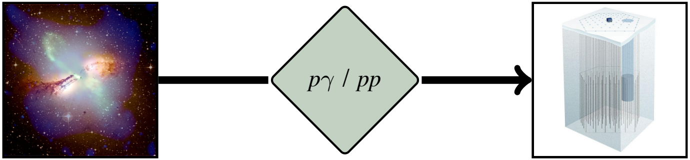
- Can these events have a **cosmogenic** origin?
- *cos-mo-gen-ic* (adj.): “produced by cosmic rays”

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

➜ “our” **definition**: 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

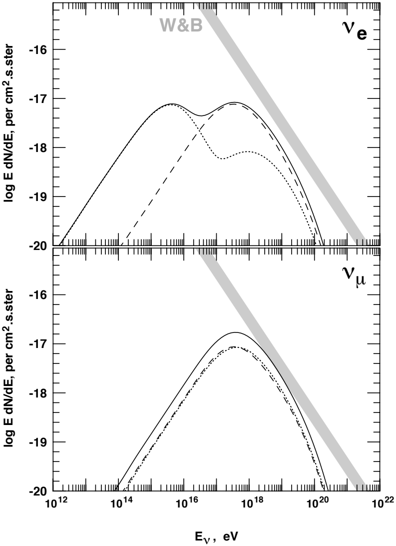
GZK neutrinos from CMB

- 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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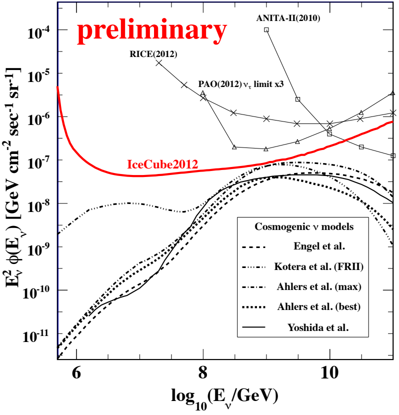
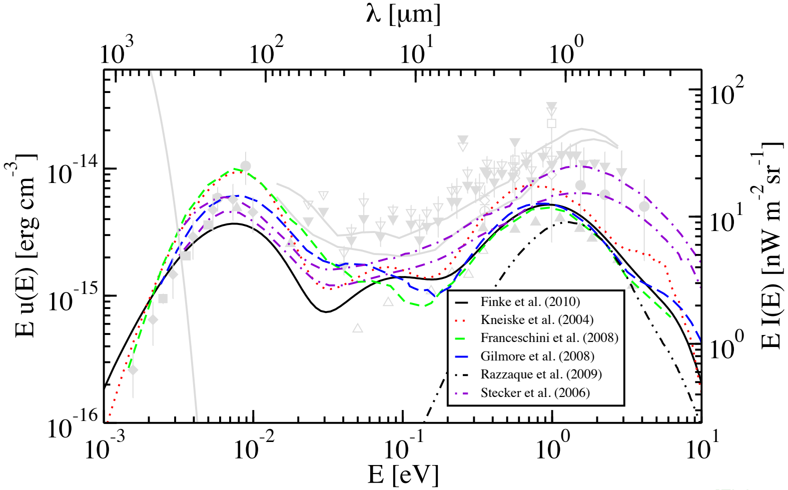


Extra-galactic background light (EBL)



[Finke *et al.* '10]

optical-UV background gives PeV neutrino peak

Cosmogenic neutrinos & gamma-rays

- GZK interactions produce neutral and charged pions

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

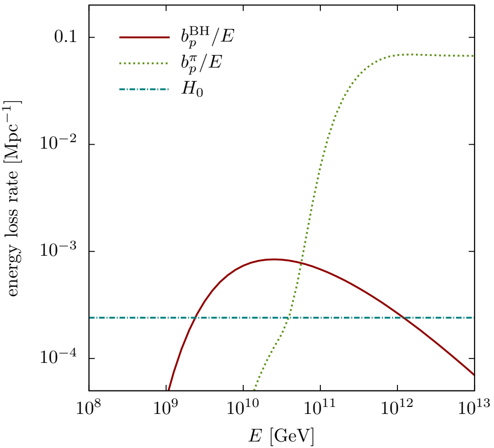
- Bethe-Heitler (BH) pair production:

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

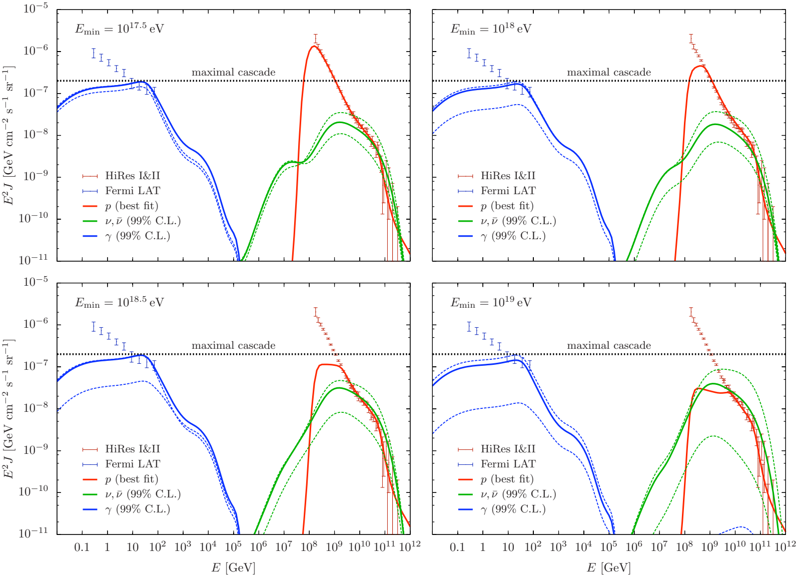
➜ BH is dominant energy loss process for UHE CR protons at $\sim 2 \times 10^{9} \div 2 \times 10^{10}$ GeV.

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

[Berezinsky&Smirnov'75]

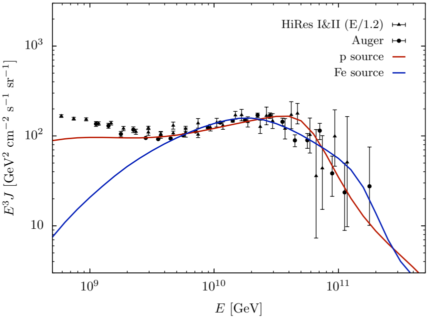


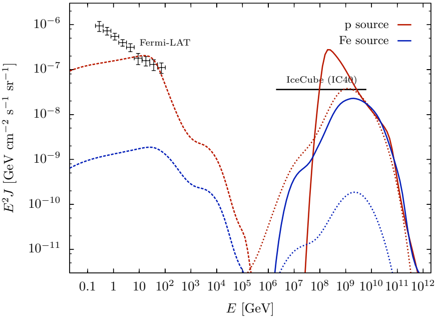
Cosmogenic neutrinos from EBL



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

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]

Cosmogenic neutrinos from heavy nuclei

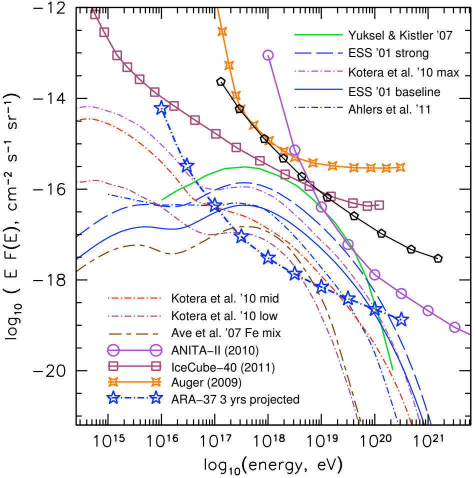


TABLE II: Expected numbers of events N_ν from several UHE neutrino models, comparing published values from the 2008 ANITA-II flight with predicted events for a three-year exposure for ARA-37.

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.