

Multi-Messenger Tests of the IceCube Excess

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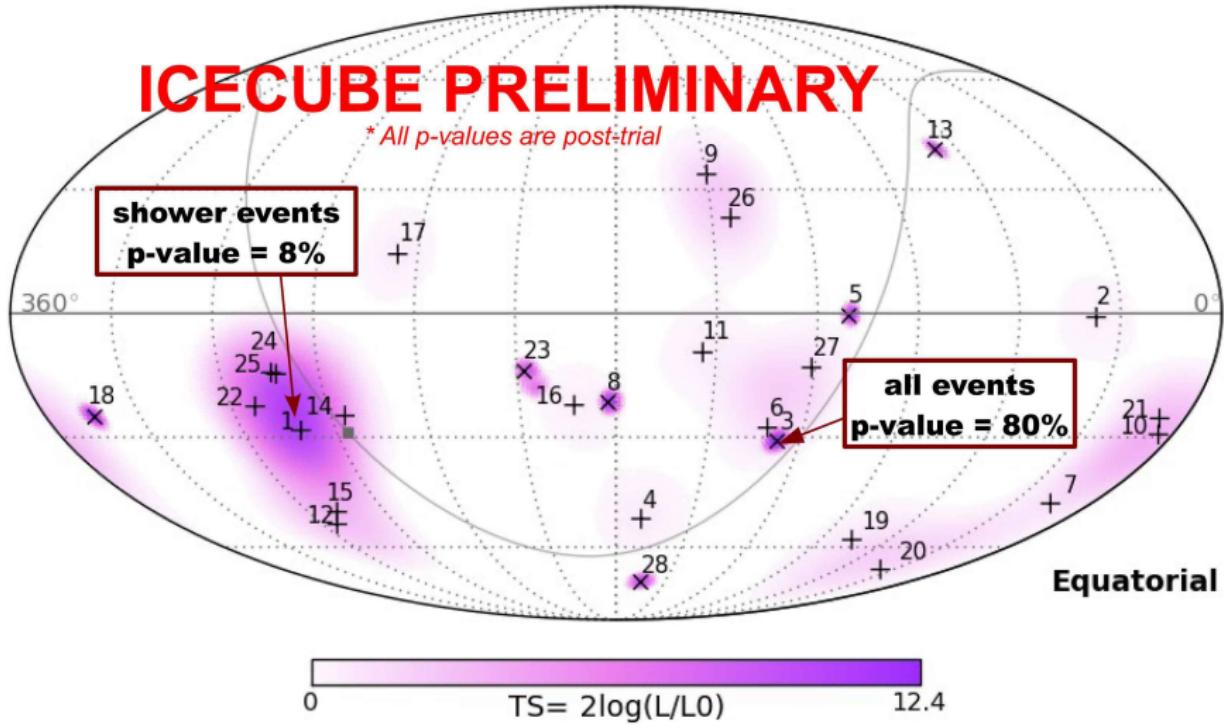
“IceCube excess”

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

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

ICECUBE PRELIMINARY

* All p-values are post-trial



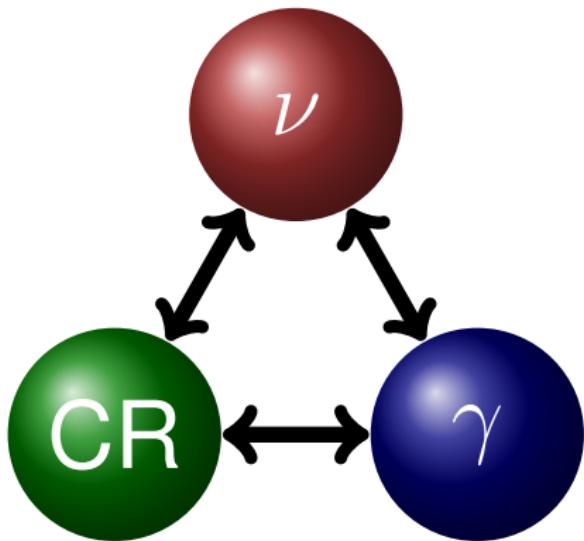
[C.Kopper, N.Kurahashi & N.Whitehorn, IPA'13]

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 from $p\bar{p}$ interactions follow CR spectrum: $E_{\nu,\text{max}} \simeq \frac{1}{20} E_{p,\text{max}}$
- typical neutrino energy from $p\gamma$ interactions (in boosted environments):
$$E_{\nu,\text{pk}} \simeq \frac{1}{20} \Gamma^2 \frac{m_\Delta^2 - m_p^2}{4E_\gamma} \simeq 8\text{PeV} \Gamma^2 \left(\frac{\text{eV}}{E_\gamma} \right)$$
 - ✗ GZK neutrinos from optical-UV background ($\Gamma \simeq 1 / E_\gamma \simeq 10 \text{ eV}$)
[Berezinsky&Zatsepin'69; Roulet *et al.* 1209.4033]
 - ✗ prompt neutrino emission in GRBs ($\Gamma \simeq 300 / E_\gamma \simeq 1 \text{ MeV}$) [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_{\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]
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- **Galactic sources:**

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

- **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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Neutrino and γ -ray connection

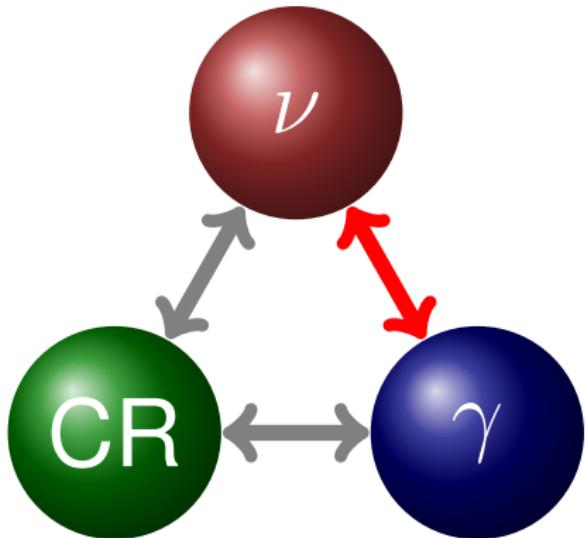
- related production of charged and neutral pions:

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

- simple related production spectra:

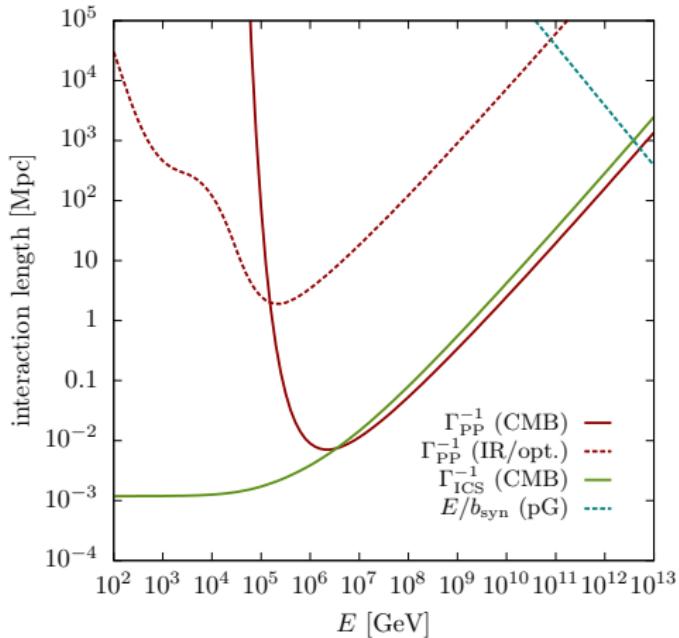
$$E_\gamma Q_\gamma(E_\gamma) \simeq \frac{2}{K} \frac{1}{3} \sum_{\nu_\alpha} E_\nu Q_{\nu_\alpha}(E_\nu)$$

- 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



Gamma-ray cascades

- CMB interactions (**solid lines**) dominate in cascade:
 - inverse Compton scattering (ICS)
 $e^\pm + \gamma_{\text{CMB}} \rightarrow e^\pm + \gamma$
 - pair production (PP)
 $\gamma + \gamma_{\text{CMB}} \rightarrow e^+ + e^-$
- PP in IR/optical background (**red dashed line**) determines the “edge” of the spectrum.
- this calculation:
Franceschini *et al.* '08



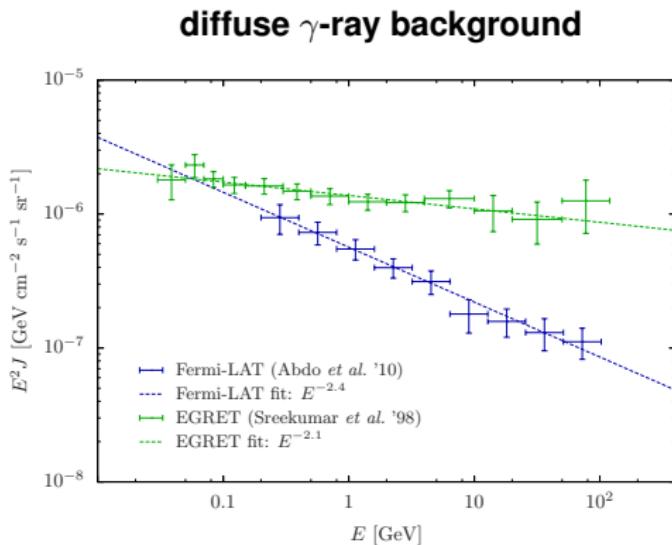
Rapid cascade interactions produce universal GeV-TeV emission (almost) independent of injection spectrum and source distribution.

→ “cascade bound” for neutrinos

[Berezinsky&Smirnov'75]

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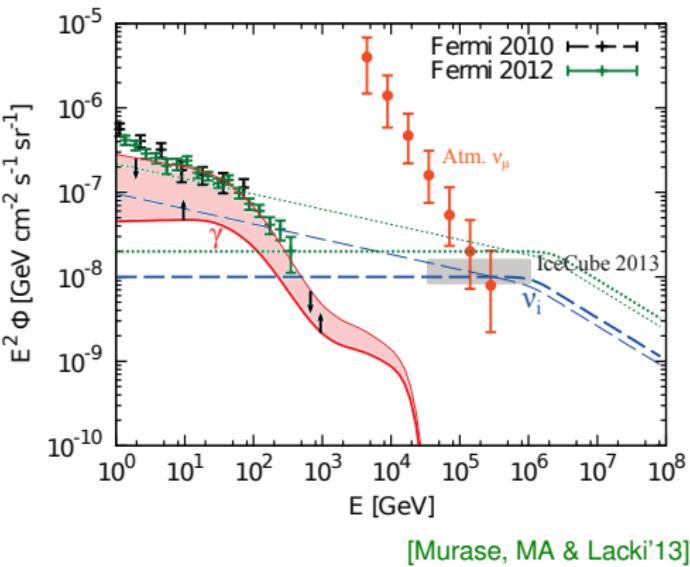
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[Berezinsky&Smirnov'75]

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

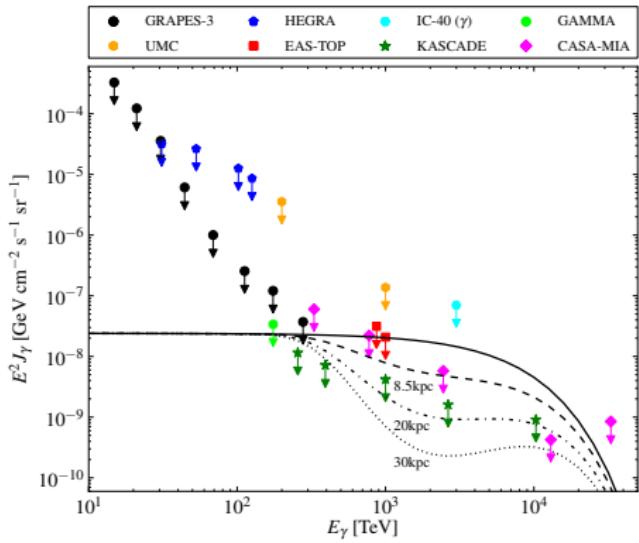


Isotropic diffuse TeV-PeV γ -ray limits

- IceCube-equivalent diffuse γ -ray flux:

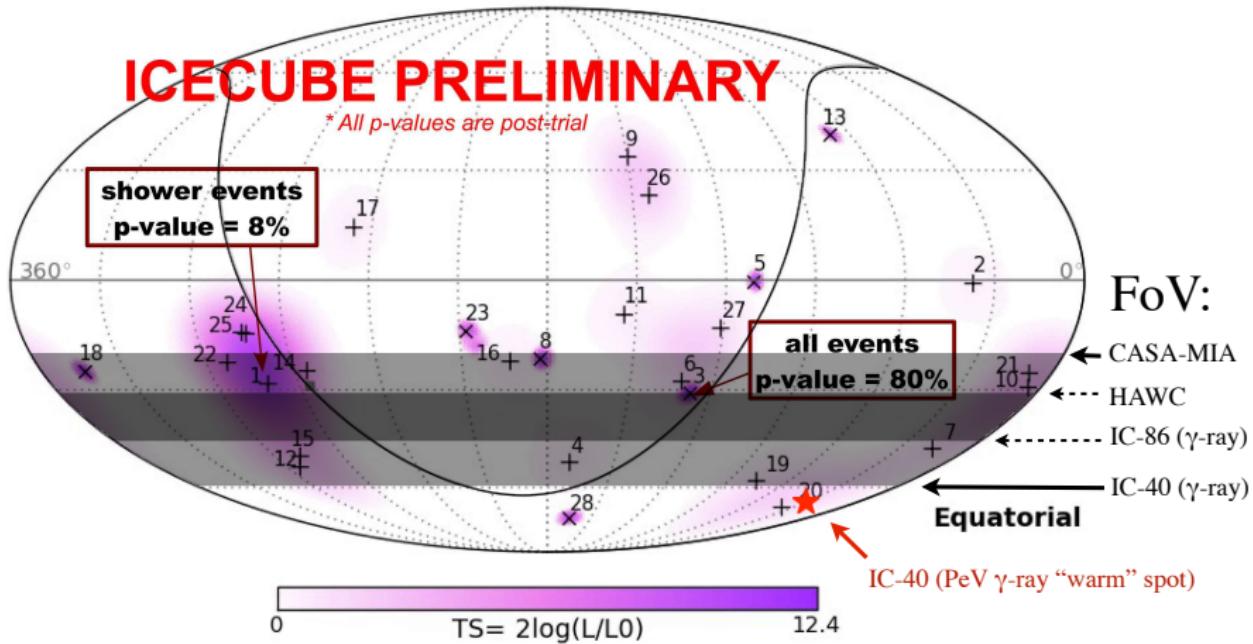
$$E_\gamma J_\gamma(E_\gamma) \simeq e^{-\frac{d}{\lambda_{\gamma\gamma}}} \frac{2}{K} \frac{1}{3} \sum_{\nu_\alpha} E_\nu J_{\nu_\alpha}^{\text{IC}}(E_\nu)$$

- absorption length $\lambda_{\gamma\gamma}$ via $\gamma\gamma \rightarrow e^+e^-$
- effect strongest for CMB in PeV range:
 $\lambda_{\gamma\gamma} \simeq 10 \text{ kpc}$
- 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]



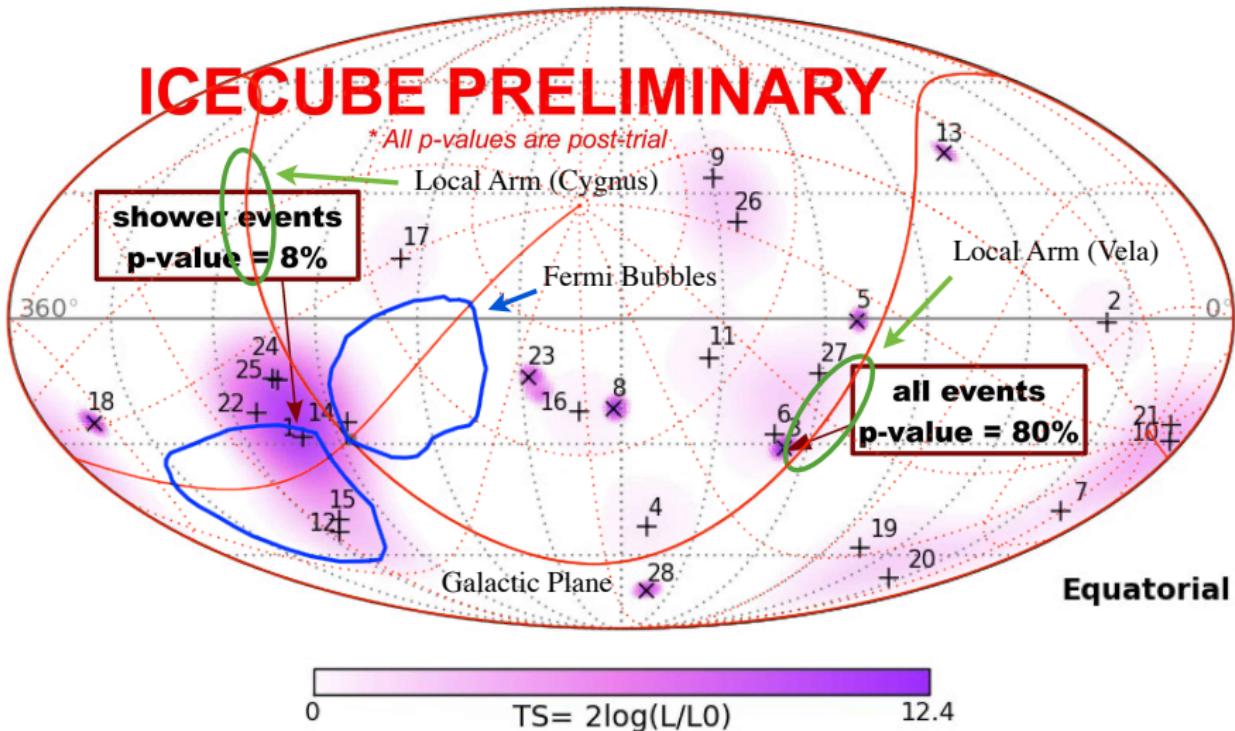
[MA&Murase (to be published)]

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



Galactic Plane diffuse fluxes

- **diffuse γ -ray emission from CR propagation ($|b| < 2^\circ$)**

- **supernova remnants (SNR):**

$$R_{\text{SN}} \simeq 0.03 \text{yr}^{-1}$$

$$\mathcal{E}_{\text{ej}} \simeq 10^{51} \text{ erg}$$

$$N_{\text{SNR}} \simeq 1200$$

- **hypernova remnants (HNR):**

$$R_{\text{HN}} \simeq 0.01 R_{\text{SN}}$$

$$\mathcal{E}_{\text{ej}} \simeq 10^{52} \text{ erg}$$

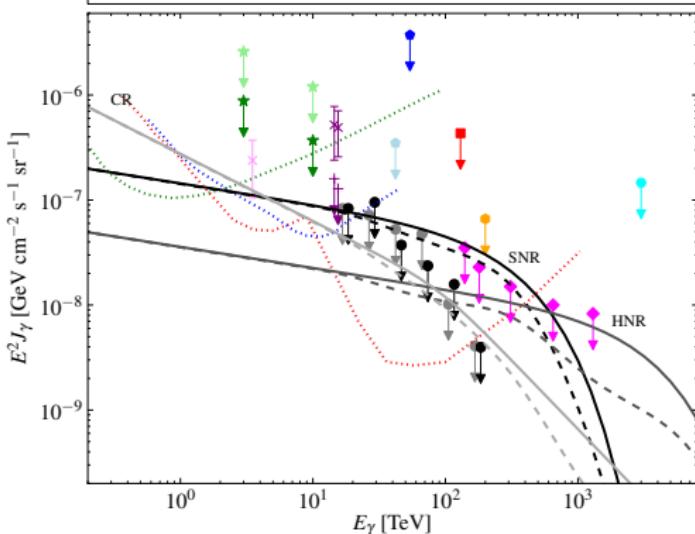
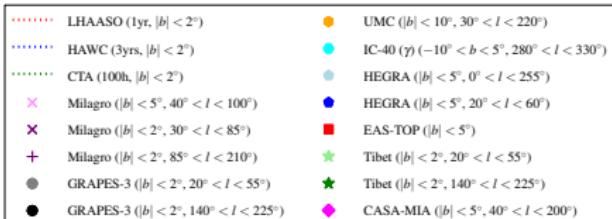
$$N_{\text{HNR}} \simeq 20$$

- flux concentrated in Galactic Plane:

$$J \propto 30\% \text{ for } |b| < 10^\circ$$

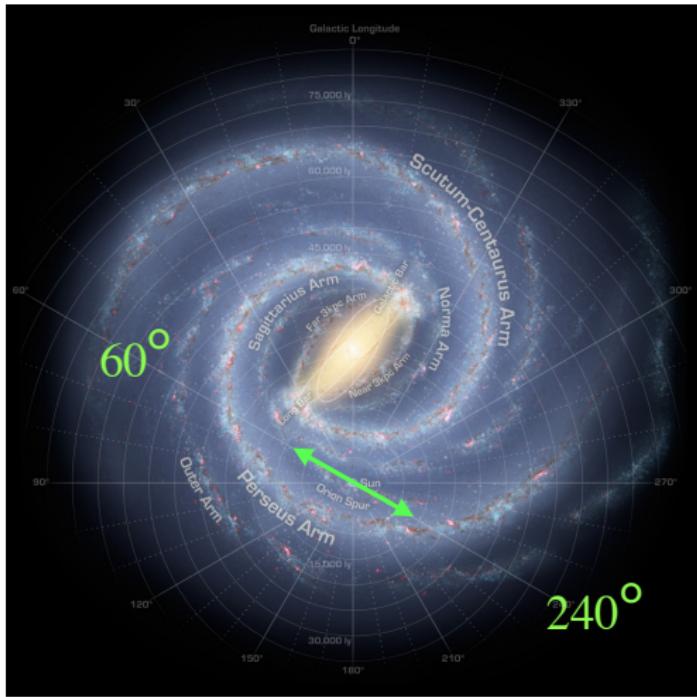
$$J \propto 15\% \text{ for } |b| < 30^\circ$$

- however, this does not account for **local fluctuation**



[MA & Murase (in prep.)]

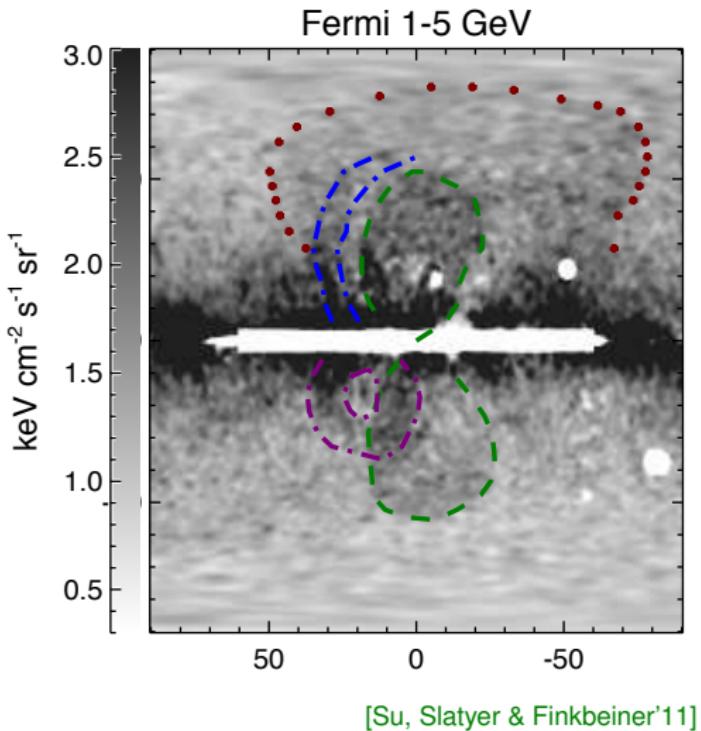
Milky Way and Local Arm



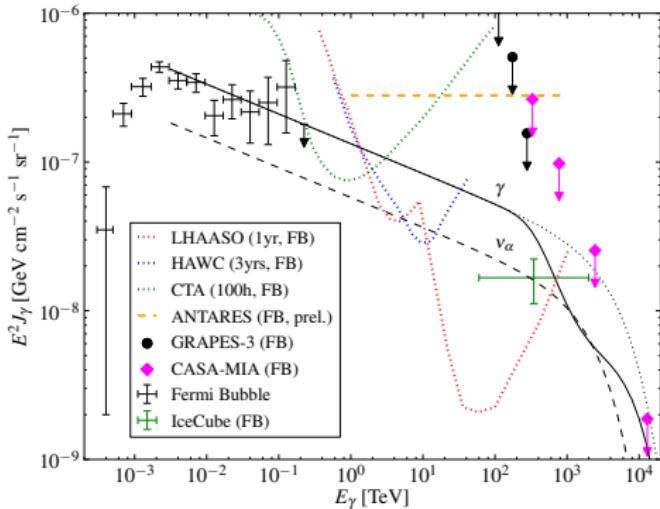
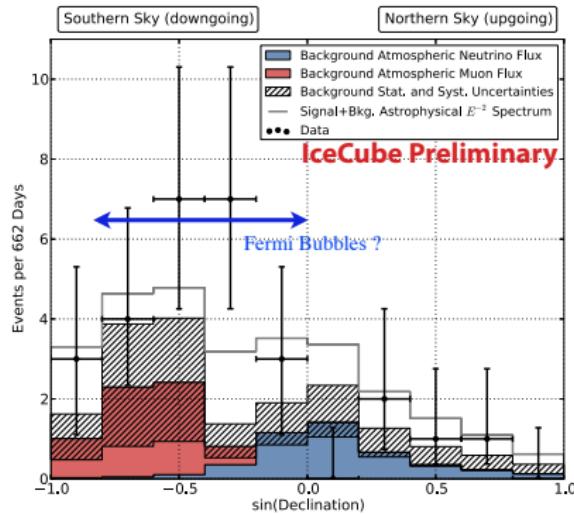
Close-by sources in the Local Arm can show up as high-latitude hot spots!

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]



Fermi Bubbles



[MA&Murase (to be published)]

- 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

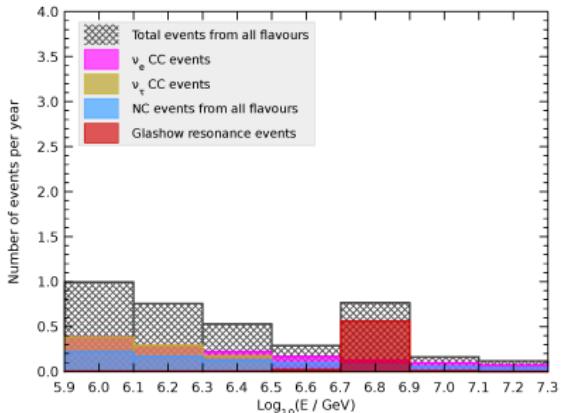
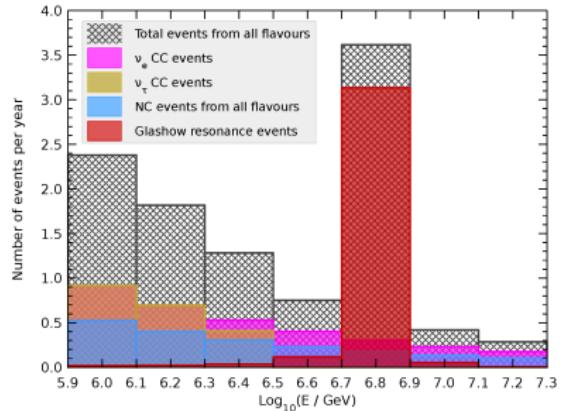
Backup

Glashow resonance

- resonant interactions with in-ice electrons:

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

- hadronic (70%) or leptonic (30%) decay
- $p p$ (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]



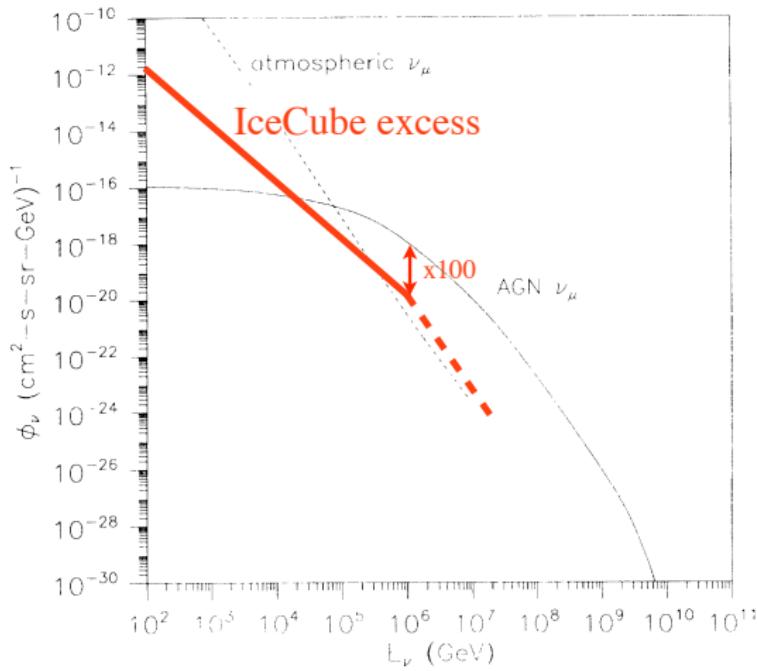
- ✗ Where are the Glashow events?
- flavor composition and spectral features
[Laha *et al.* 1306.2309; Anchordoqui *et al.* 1306.5021]
[He *et al.* 1307.1450; Winter 1307.2793]

Active Galactic Nuclei

- neutrino interactions from $p\gamma$ interactions in AGN cores
- AGN diffuse emission normalized to X-ray background
- revised model predicts 5% of original estimate

[Stecker et al.'91]

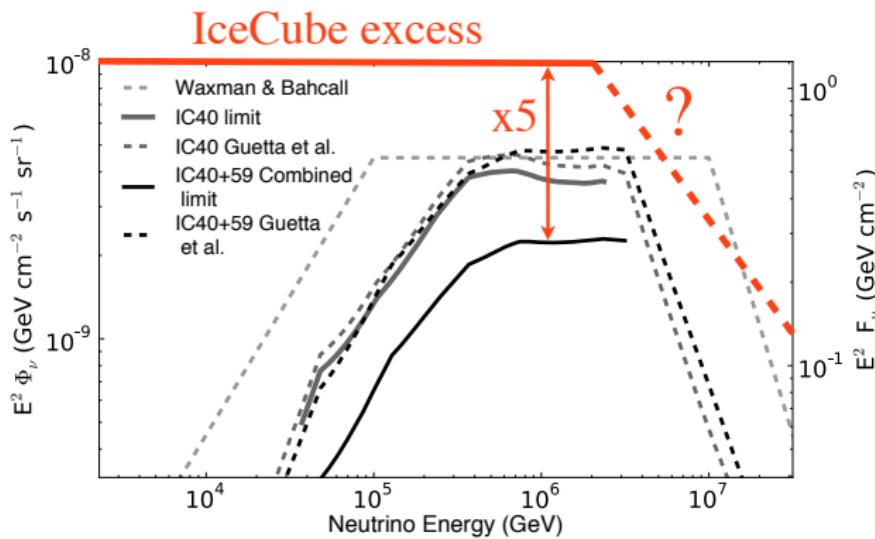
[Stecker'05,'13]



[Stecker et al.'91]

Gamma-ray Bursts

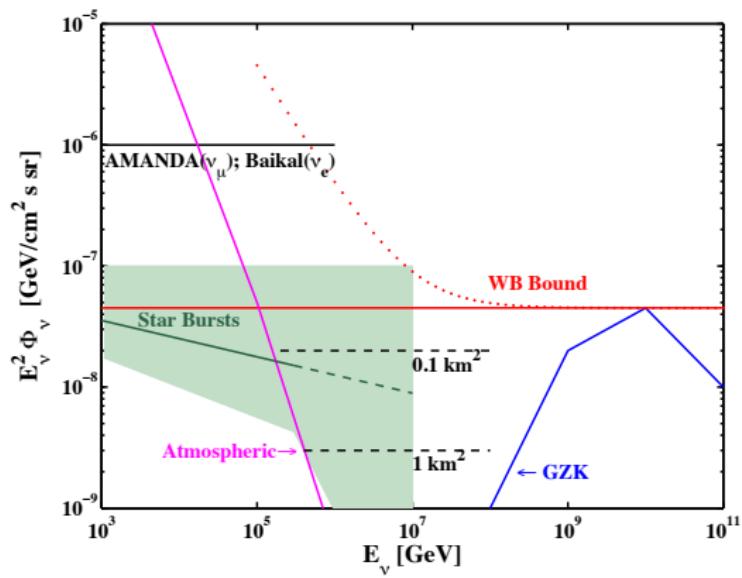
- strong limits on neutrino emission associated with the fireball model [Abbasi et al.'12]
- IceCube excess exceeds IC40+59 limit by factor ~ 5
- **loophole:** undetected low-power γ -ray bursts (GRB) [Murase & Ioka 1306.2274]



[modified from Abbasi et al.'12]

Starburst galaxies

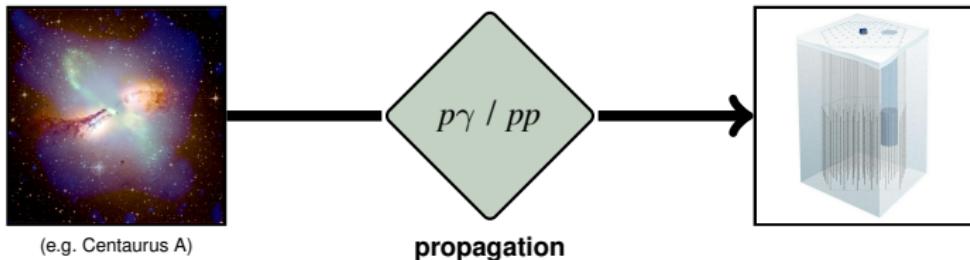
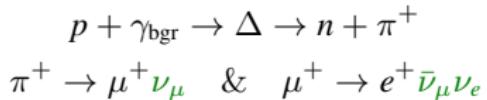
- intense CR interactions (and acceleration) in dense starburst galaxies
- cutoff/break feature (0.1 – 1) PeV at the CR knee (of these galaxies), but very uncertain
- plot shows muon neutrinos production (3/2 of total)



[Loeb & Waxman'06]

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.



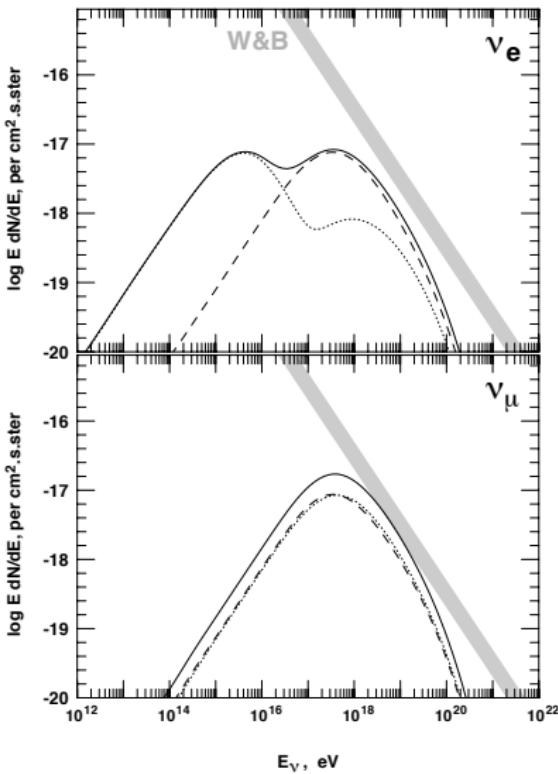
GZK neutrinos from CMB

- 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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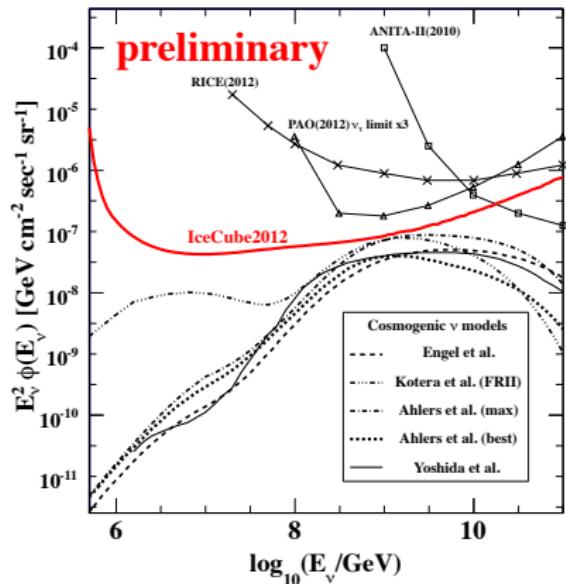
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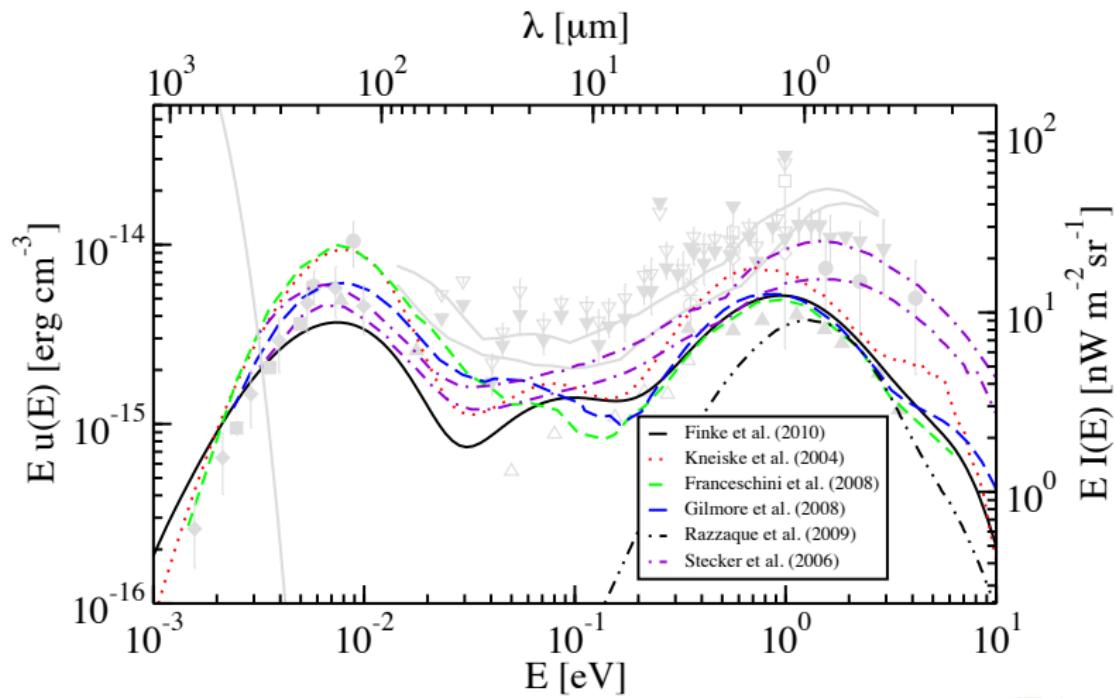
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Extra-galactic background light (EBL)

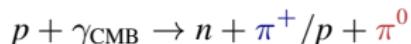


[Finke *et al.* '10]

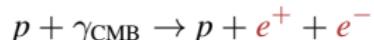
optical-UV background gives PeV neutrino peak

Cosmogenic neutrinos & gamma-rays

- GZK interactions produce neutral and charged pions



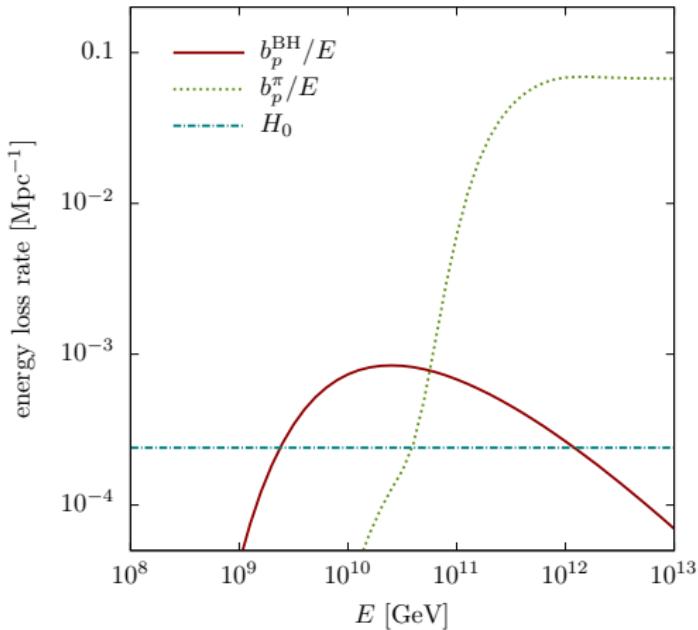
- Bethe-Heitler (BH) pair production:



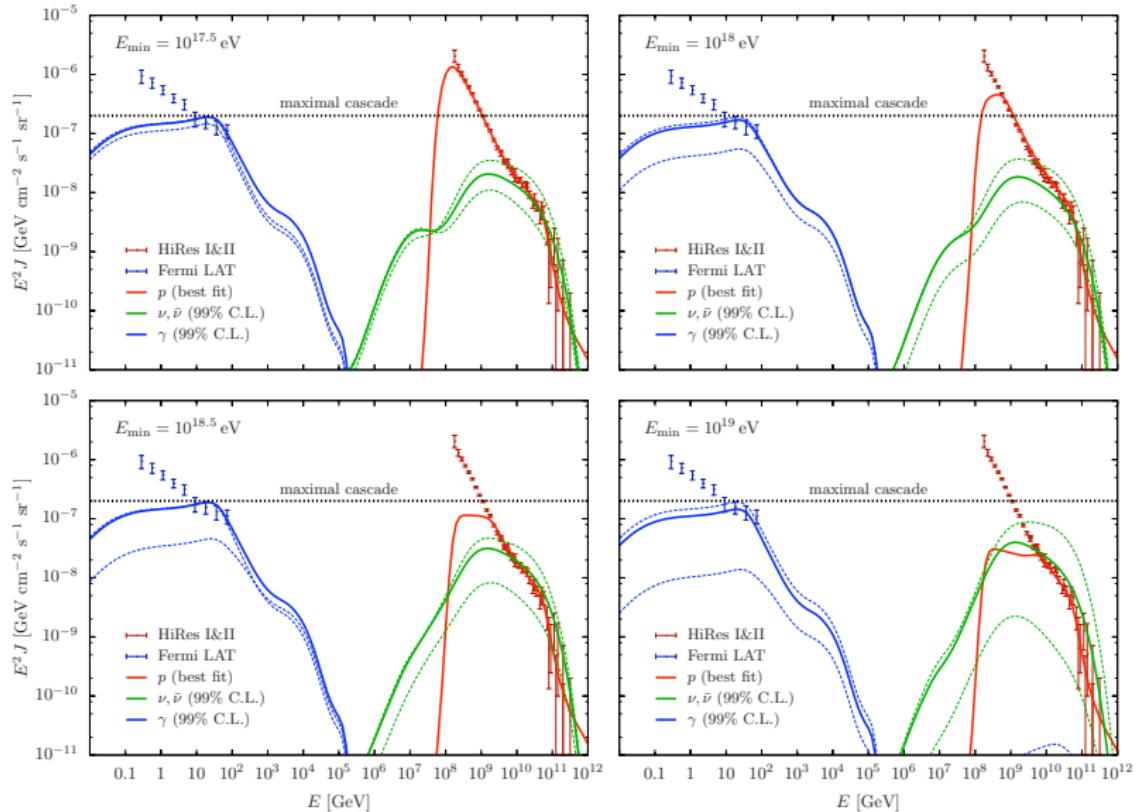
→ BH is dominant energy loss process for UHE CR protons at $\sim 2 \times 10^9 \div 2 \times 10^{10}$ GeV.

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

[Berezinsky&Smirnov'75]

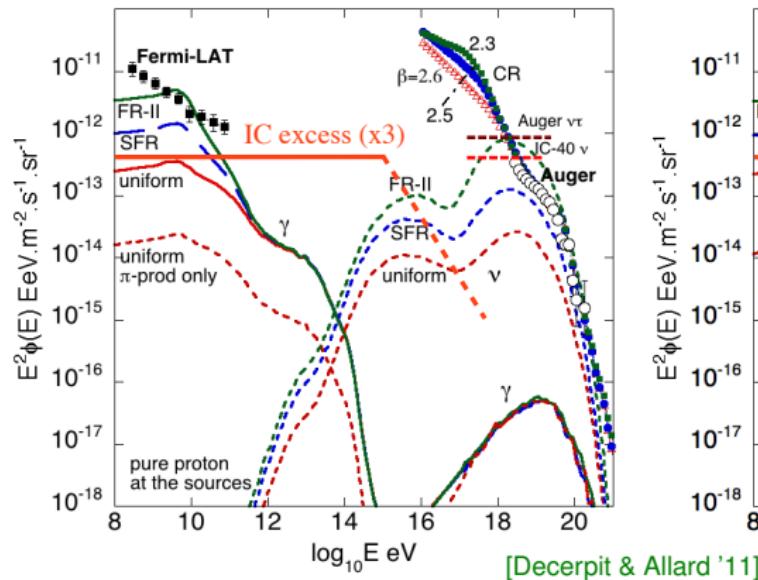


Cosmogenic neutrinos from EBL

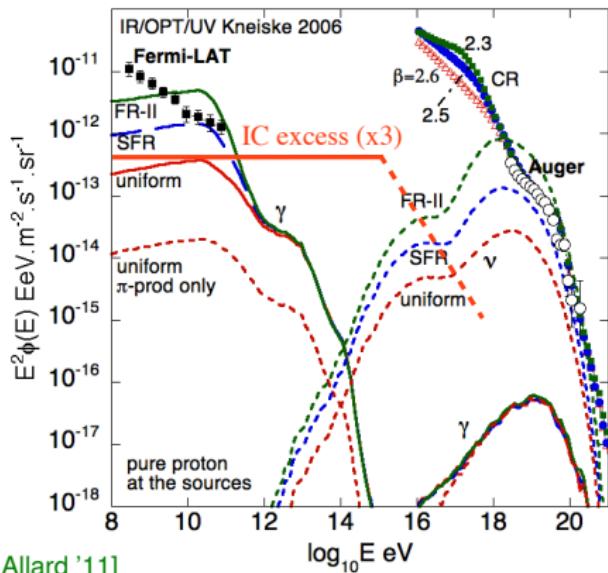


[MA, Anchordoqui, Gonzalez-Garcia, Halzen & Sarkar '11]

Cosmogenic neutrinos from EBL

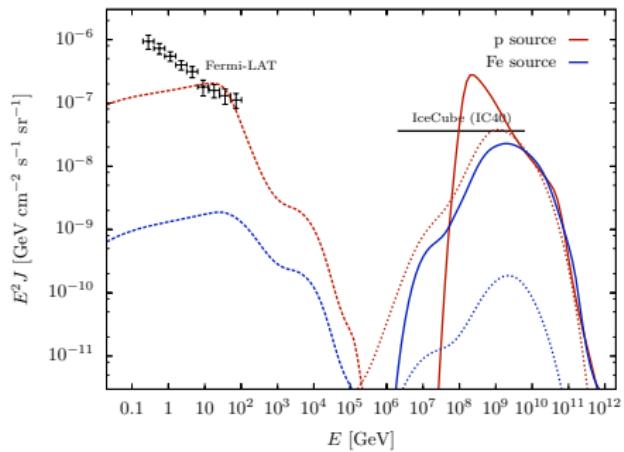
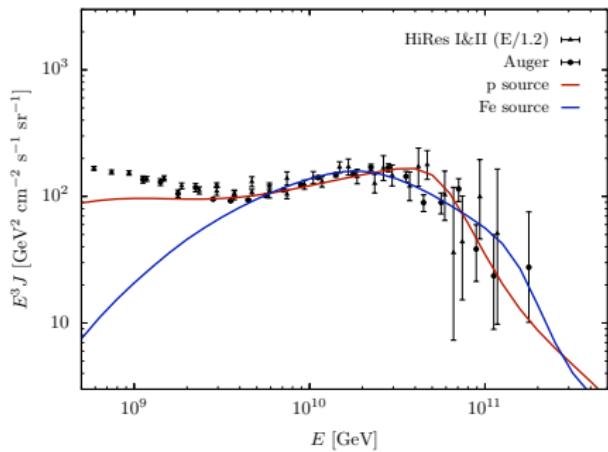


[Decerprit & Allard '11]



- 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: $n = 5$ & $z_{\text{max}} = 2$ & $\gamma = 2.3$ & $E_{\text{max}} = 10^{20.5}$ eV
 - 100% iron: $n = 0$ & $z_{\text{max}} = 2$ & $\gamma = 2.3$ & $E_{\text{max}} = 26 \times 10^{20.5}$ eV
- Diffuse spectra of cosmogenic γ -rays (dashed lines) and neutrinos (dotted lines) vastly different.

[MA&Salvado'11]

Cosmogenic neutrinos from heavy nuclei

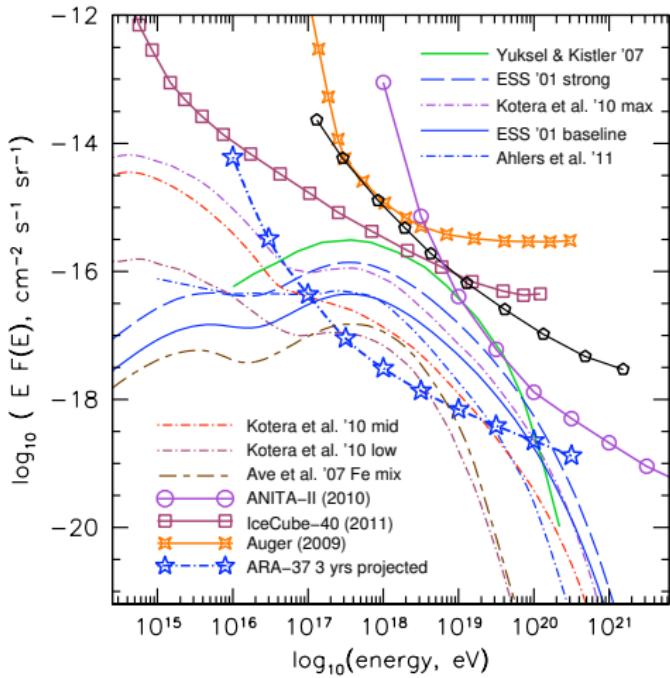


TABLE II: Expected numbers of events N_ν from several UHE neutrino models, comparing published values from the 2008 ANITA-II flight with predicted events for a three-year exposure for ARA-37.

Model & references	N_ν :	ANITA-II, (2008 flight)	ARA, 3 years
<i>Baseline cosmogenic models:</i>			
Protheroe & Johnson 1996 [27]	0.6	59	
Engel, Seckel, Stanev 2001 [28]	0.33	47	
Kotera,Allard, & Olinto 2010 [29]	0.5	59	
<i>Strong source evolution models:</i>			
Engel, Seckel, Stanev 2001 [28]	1.0	148	
Kalashev <i>et al.</i> 2002 [30]	5.8	146	
Barger, Huber, & Marfatia 2006 [32]	3.5	154	
Yuksel & Kistler 2007 [33]	1.7	221	
<i>Mixed-Iron-Composition:</i>			
Ave <i>et al.</i> 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	
<i>Models constrained by Fermi cascade bound:</i>			
Ahlers <i>et al.</i> 2010 [36]	0.09	20.7	
<i>Waxman-Bahcall (WB) fluxes:</i>			
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.