Neutrino Connection with Cosmic Ray Origin

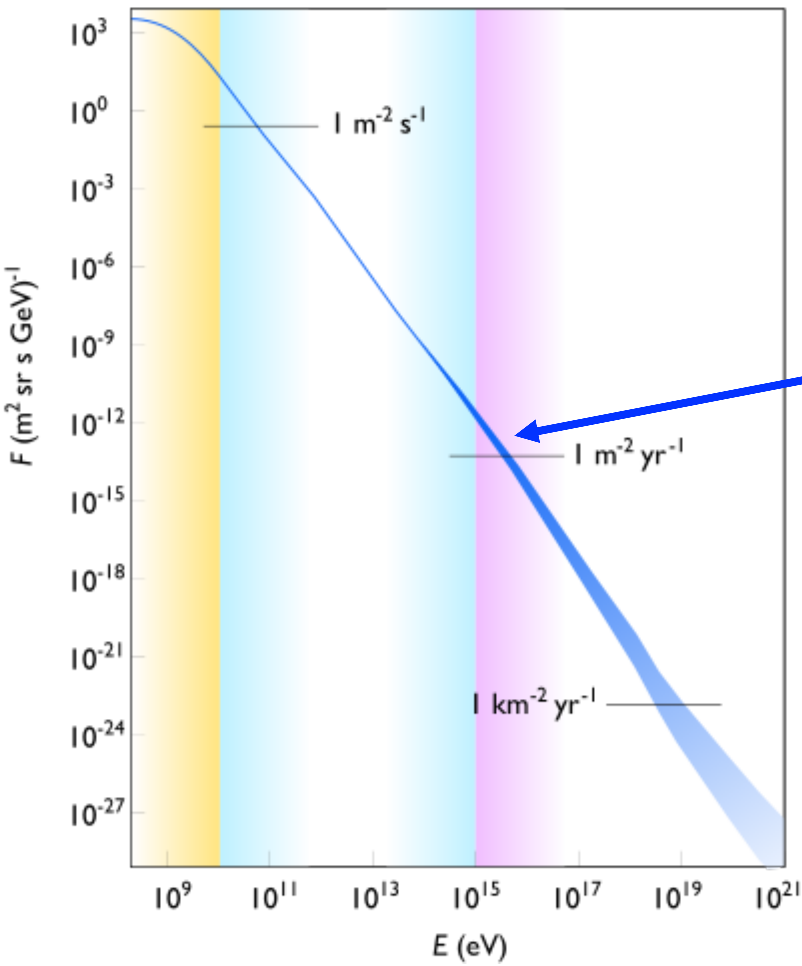
Hallsie Reno
University of Iowa

VHEPA2014, March 20, 2014

Cosmic ray flux

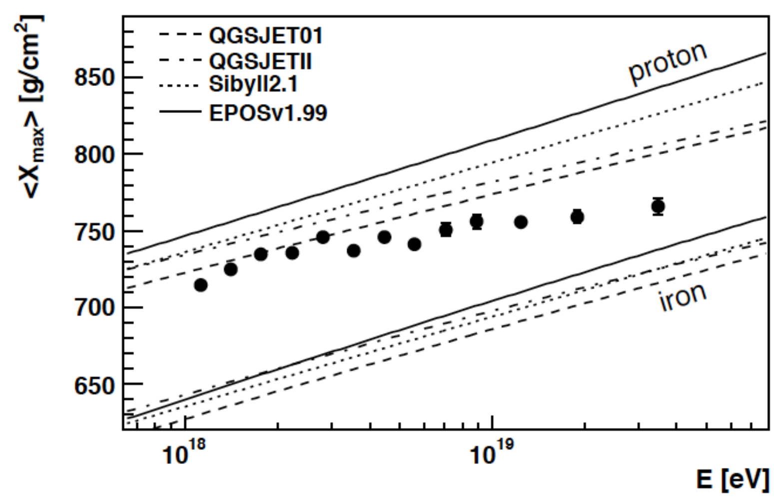
$\sim E^{-3}$

$$\phi \sim \frac{1.7}{E_{\rm GeV}^{2.7}} \frac{1}{{\rm cm^2\, s\, sr\, GeV}}$$



approximately isotropic above 30 GeV,

"knee", change in energy behavior



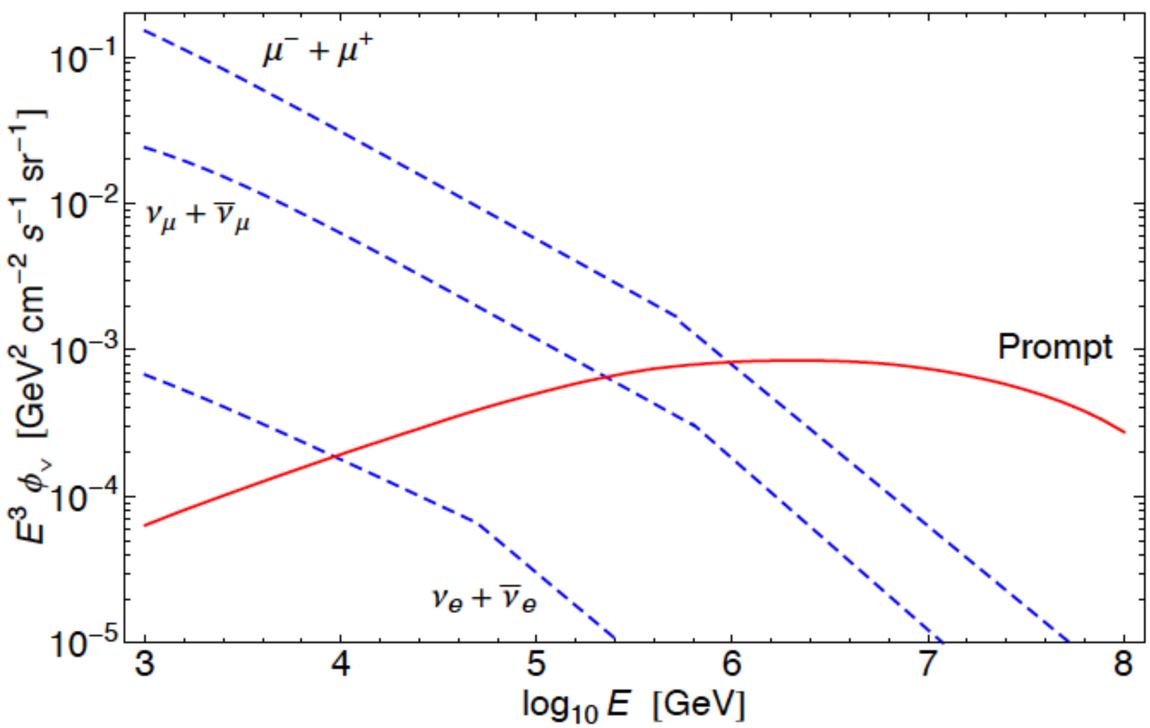
S. Lafebre, http://en.wikipedia.org/wiki/Cosmic_rays following S. Swordy.

Auger Collab, arXiv:1002.0699, uncertainties at highest energies.

Neutrinos are produced in association with cosmic rays

- Cosmic ray interactions in the atmosphere,
  "atmospheric neutrinos"
- Cosmic ray interactions in transit from their sources to us,
  "cosmogenic neutrinos, GZK neutrinos"
- Cosmic ray interactions at the site of their acceleration,
  "astrophysical neutrinos" which can be diffuse (sum of all sources) or point back to the source
- Results from IceCube about "extraterrestrial neutrinos" an important motivator

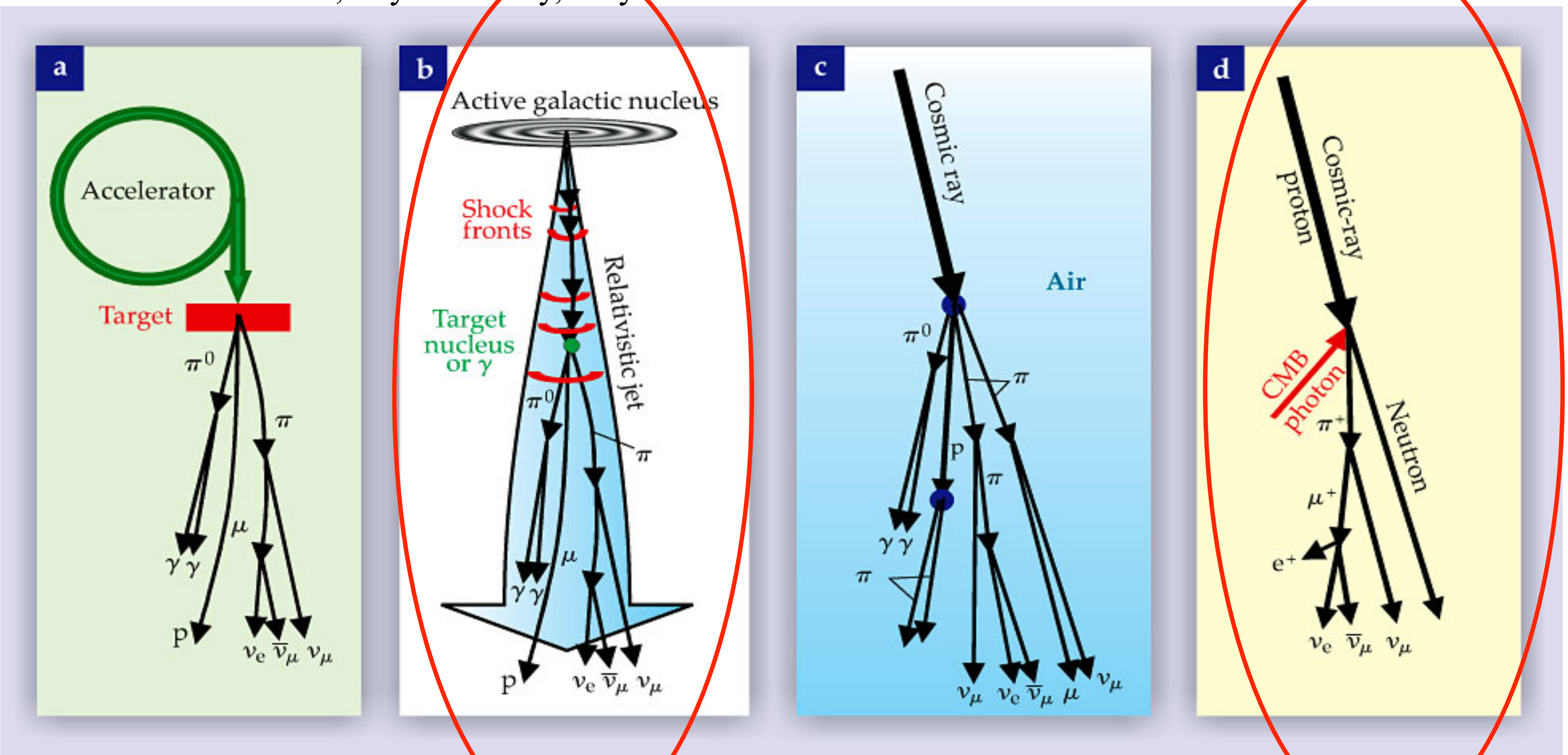
Atmospheric neutrino flux, the topic of a different talk…



Enberg, Reno, Sarcevic, PRD 78 (2008)

Neutrino production

F. Halzen and S. Klein, Physics Today, May 2008



Same production mechanism for accelerator beams, inside astrophysical objects, in the atmosphere, and for the cosmogenic neutrino flux.

Some references

- Some recent reviews, including
  - Anchordoqui et al, arXiv:1312.6587
  - Becker, Phys. Rept. 458 (2008)
- Long history of predictions for cosmogenic flux:

  Berezinsky and Zatsepin, Phys. Lett. B 28 (1969)

  Stecker, Ap. J. 228 (1979)

  Hill and Schramm, Phys. Leet. B 131 (1983)

  Engel, Seckel and Stanev, Phys. Rev. D64 (2001)

  Fodor, Katz, Ringwald and Tu, JCAP 0311 (2003)

  Anchordoqui, Goldberg, Hooper, Sarkar, Taylor, Phys. Rev. D76 (2007)

  Allard, Ave et al, JCAP 0609 (2006)

  Kotera, Allard & Olinto, JCAP 1010 (2010) 013

  Ahlers & Halzen, PRD 86 (2012) 083010
- Long history of predictions of neutrino fluxes from sources, incl.

  Stecker et al., PRL 66 (1991), Mannheim, Astron. Astrophys. 269 (1993), Stecker, PRD 72(2005), Manheim, Protheroe and Rachen, PRD 63 (2001), Guetta et al, Astropart. Phys. (2204), Alvarez-Muniz & Meszaros PRD70 (2004), … Murase & Ioka, PRL 111 (2013)

Starting point: neutrinos from pions

$$\pi^{\pm} \rightarrow \mu\nu_{\mu} \qquad \mu \rightarrow e\nu_e\nu_{\mu}$$

$$\pi^{\pm} \rightarrow e\nu_e\nu_{\mu}\nu_{\mu}$$

Qualitative features:

4 particles in final state, each roughly with

$$E \simeq E_{\pi}/4$$

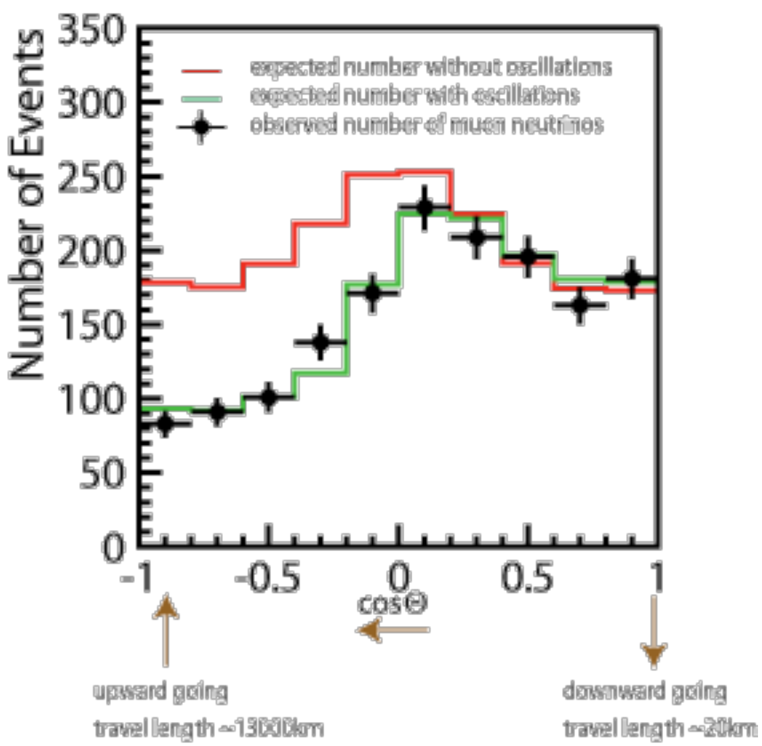
flavor ratio initially (neutrinos plus antineutrinos)

$$\nu_e : \nu_{\mu} : \nu_{\tau} = 1 : 2 : 0$$

Caveats: some dynamics mean energy distribution not exactly equal; not necessarily equal neutrinos & antineutrinos;

Neutrinos oscillate

- Atmospheric neutrinos with oscillation through Earth – discovery of neutrino mass and mixing



SuperKamiodande, Fukuda et al, PRL 81 (1998) 1562

Missing muon neutrinos, the right amount of electron neutrinos.

Oscillations

$$\frac{\delta m^2\, L}{E} \gg 1$$ over astrophysical distances.

Conversion/survival probabilities:

$$P_{\alpha\beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

$$\theta_{13} \simeq 0,\ \ \theta_{23} \simeq \pi/4 \implies 1:2:0 \to 1:1:1$$

Look for tau neutrinos! (Learned & Pakvasa, Astropart. Phys. 3 (1995) 267).

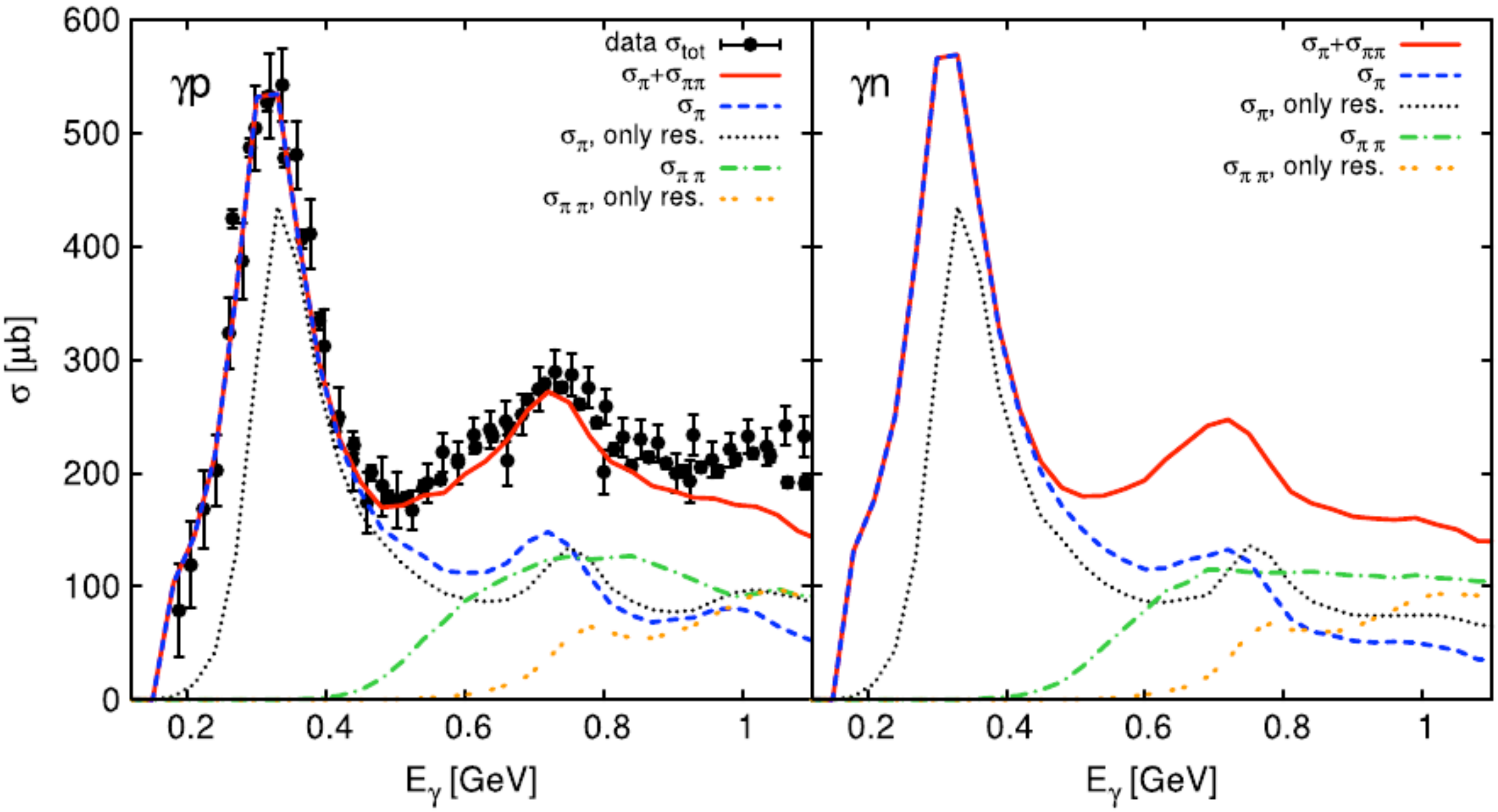
More on this later….

See, e.g., Pakvasa, arXiv:0803.1701

Plan:

- Cosmogenic neutrinos
  - Some predictions, depends on evolution of sources, cosmic ray composition
- Sources
  - Proton-gamma dominated
  - Proton-proton dominated
  - Multi-messenger theme to much of the recent literature
- Conclusions

Proton-photon interactions dominated by the Delta resonance



Lalakulich & Mosel, arXiv:1303.6677

$$m_\Delta = 1.23\ \mathrm{GeV}$$

Cosmogenic neutrinos – GZK cutoff

Key process: $p\gamma \rightarrow \Delta \rightarrow n\pi^+$ Neutrinos!

$p\gamma \rightarrow \Delta \rightarrow p\pi^0$

Target 3K photons have energy:

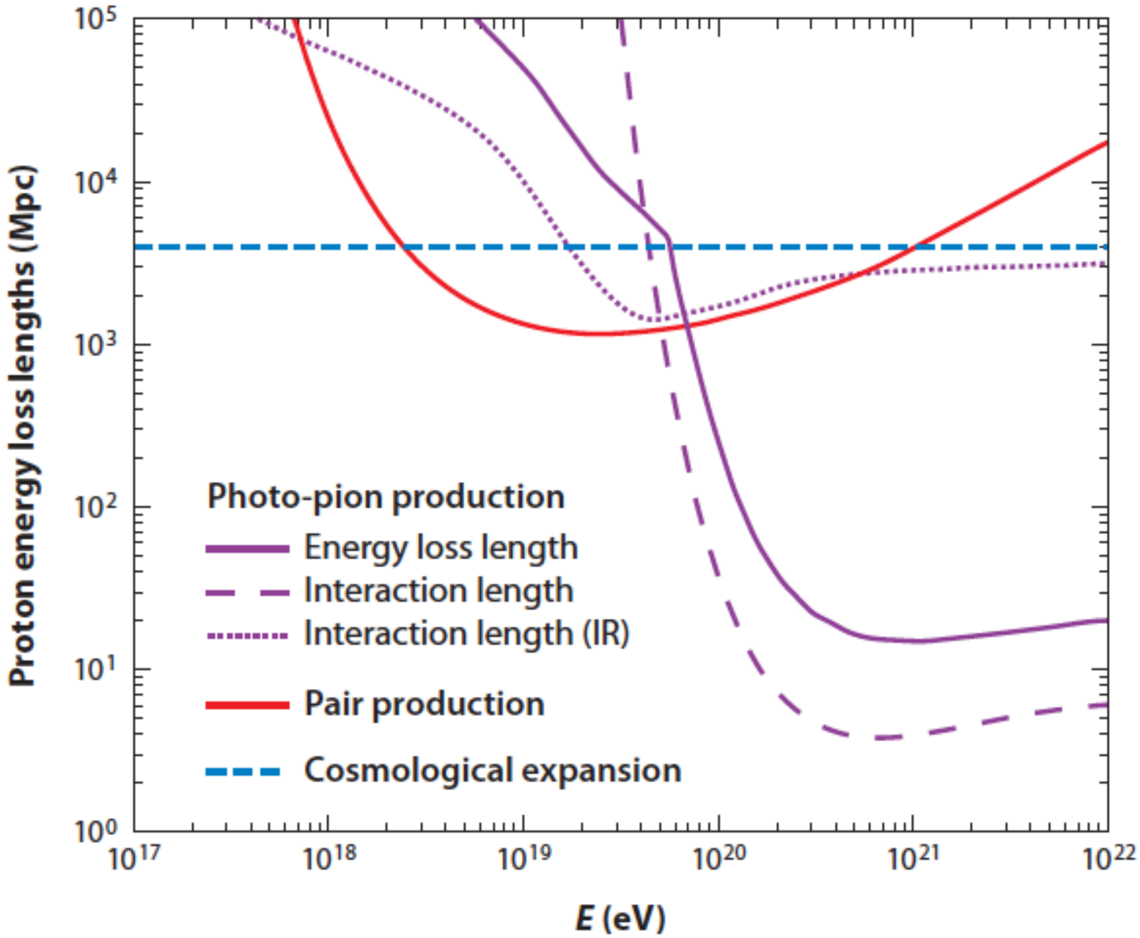
$$8.6 \times 10^{-5} \text{ eV}/K \times 3K = 2.6 \times 10^{-4} \text{ eV}$$

proton- 3K photon interactions:

$$\begin{aligned} s_{p\gamma} &\simeq (E_\gamma + E_p)^2 - (p_\gamma - p_p)^2 \\ &\simeq 4E_\gamma E_p = 10^{-12} \text{ GeV}^2 \; E_p/\text{GeV} \end{aligned}$$

Need this energy to be around Delta mass squared. Recall that there is a distribution of photons, also other energies from stellar sources, etc. so it is not a sharp threshold.

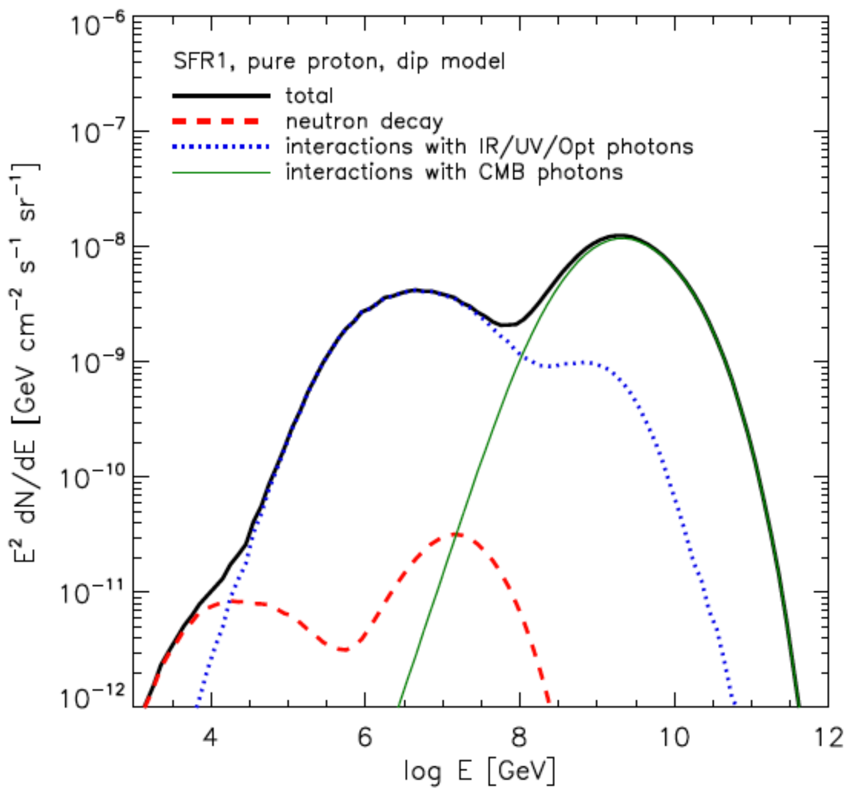
Cosmic ray propagation and neutrino production



Energy loss length, Fig. from Kotera & Olinto, Ann. Rev. Astron. Astrophys. 49 (2011).

Cosmogenic neutrinos

Cosmogenic Neutrinos: parameter space and detectabilty from PeV to ZeV



All protons, star formation rate type evolution (a la Hopkins & Beacom, 2006), dip model: transition of galactic to extragalactic CRs around

$$E \sim 10^{16.5-17.5} \text{ eV}$$

(Berezinsky et al. (2006)), maximum energy of

$$E_{p,max} = 10^{20.5} \text{ eV}$$

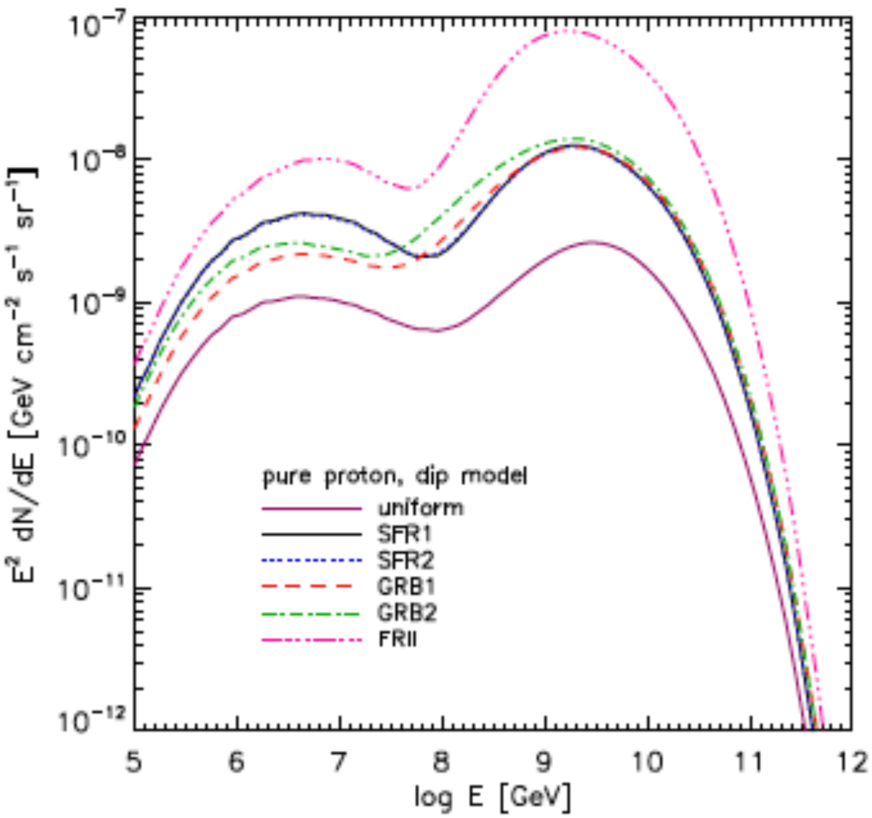
and power law spectrum,

$$\alpha = 2.5$$

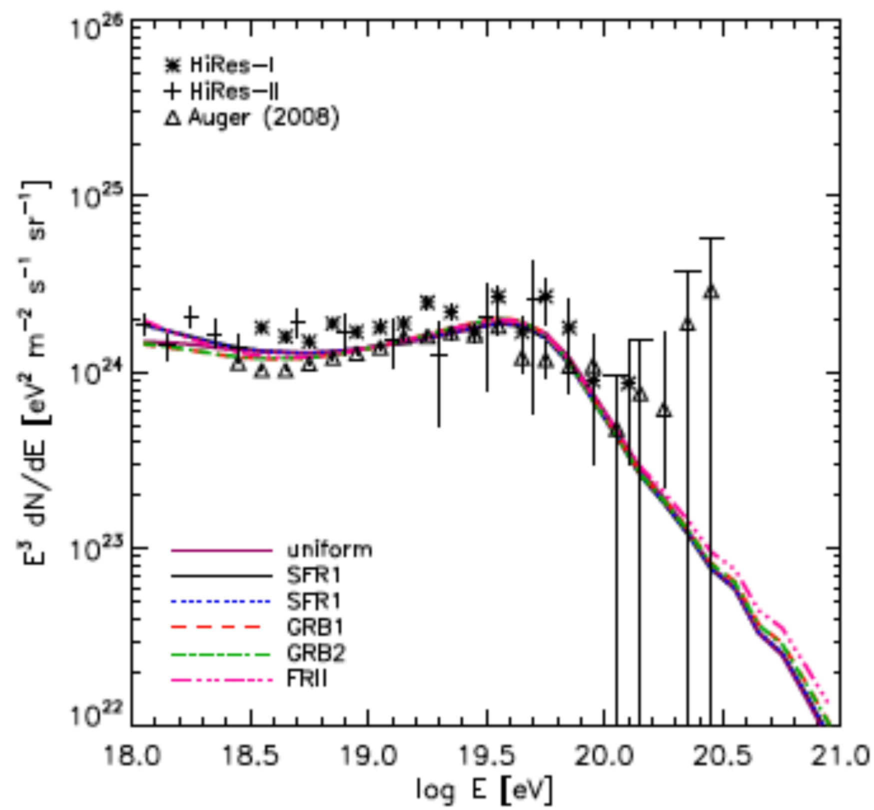
Kotera, Allard & Olinto, JCAP 1010 (2010) 013.

Source evolution

neutrinos



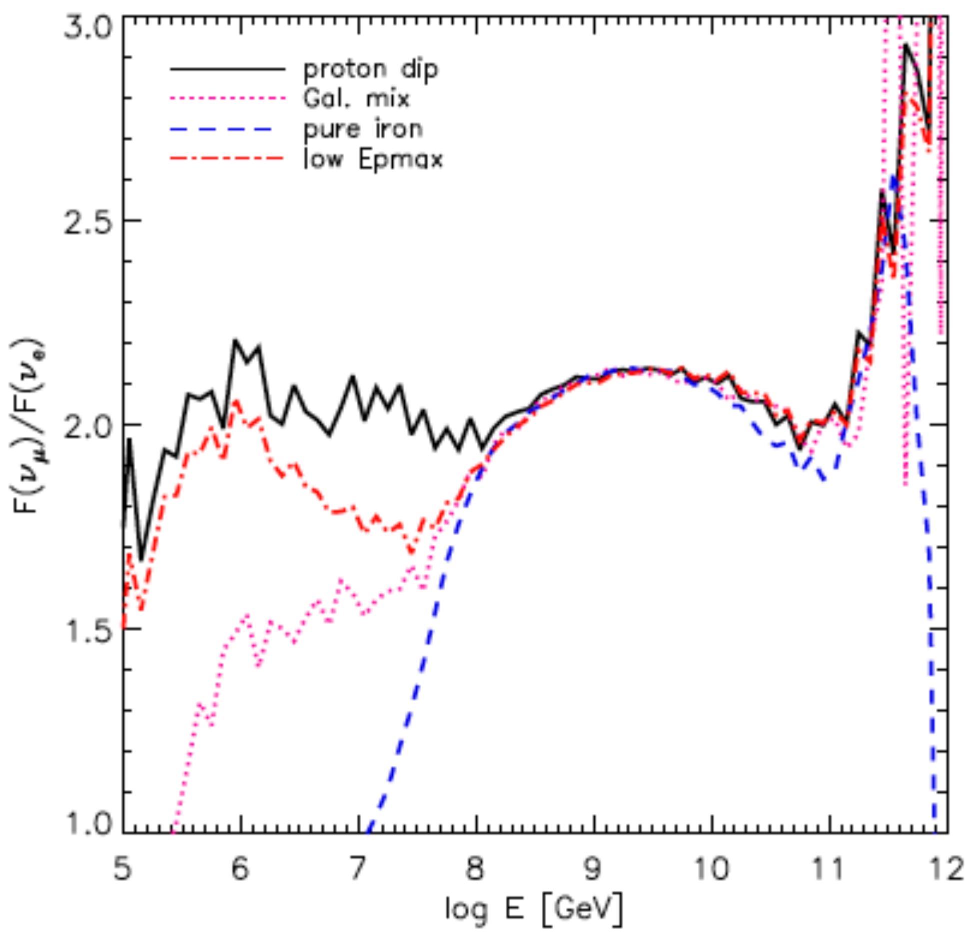
cosmic rays



Kotera, Allard & Olinto, JCAP 1010 (2010) 013.

Pure proton evolution, dip model

Neutrino flavor ratios before oscillation – cosmogenic neutrinos



Neutron decay at lower energies give more electron neutrinos; kaons at high energies give more muon neutrinos.

Refs: see also Pakvasa, Mod. Phys. Lett. A (2008) 1313.

Cosmogenic neutrinos: see also Ahlers & Halzen, PRD 86 (2012) 083010

Kotera, Allard & Olinto, JCAP 1010 (2010) 013.

Range of predictions – cosmogenic neutrino flux

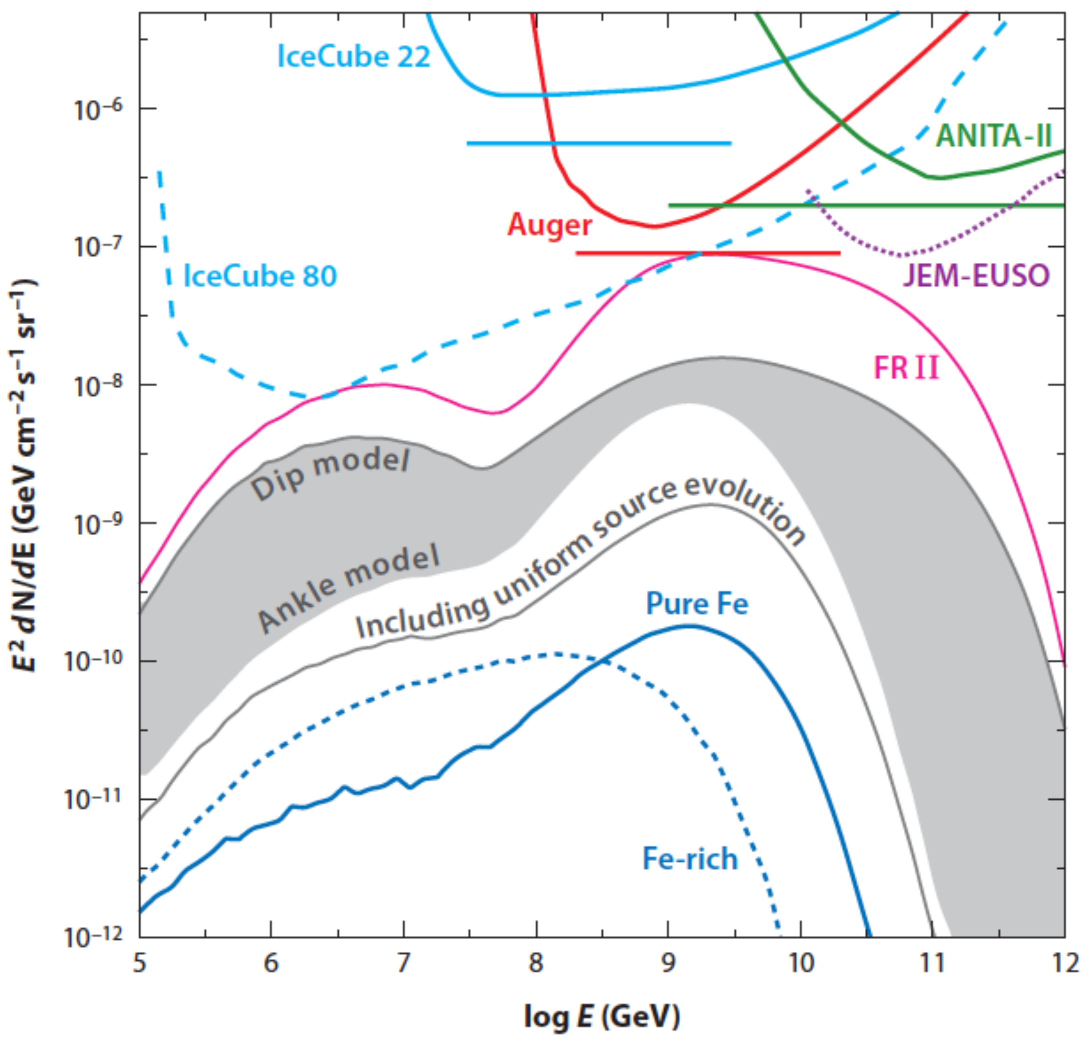


Fig. from Kotera & Olinto, Ann. Rev. Astron. Astrophys. 49 (2011).

Generic sources

Neutrinos can come from proton-proton or proton-photon interactions.

Much focus on proton-photon interactions: photon targets in many sources

Gamma ray bursts
Active galactic nuclei

Normalization depends on opacity of acceleration region, cosmic ray spectrum, distribution of sources… led to Waxman Bahcall bound.

Diffuse flux limits, CR protons with interactions with photons

- Waxman-Bahcall (PRD 59 (1999)) upper bound on diffuse flux. Relies on energy rate of production of cosmic rays. Claim:

$$\mathcal{R} = 10^{44} \ \frac{\mathrm{erg}}{\mathrm{Mpc^3 yr}}$$

- Cosmic rays produced at the source scale like: $\sim E_p^{-2}$
- Neutrino flux should scale like $\sim E_\nu^{-2}$
- Maximum neutrino intensity, neglect evolution and redshift dependence, assuming source size is shorter than photon-meson mean free path (protons get out):

$$I_{\max}^{\nu_\mu+\bar{\nu}_\mu} = \frac{1}{4}\frac{ct_H}{4\pi}\xi_Z\mathcal{R} = \xi_Z \times 1.5\times 10^{-8}\,\frac{\mathrm{GeV}}{\mathrm{cm^2 s\, sr}}$$

$$\frac{1}{4} \simeq \frac{n_{\pi^+}}{n_\pi}\frac{E_\nu}{E_{\pi^+}}$$

Diffuse neutrino flux limits, cont.

- Neutrino flux: (epsilon is ratio of protons that interact to protons that escape, set to 1 in limit)

$$E_\nu^2 \phi_\nu = \frac{1}{2} \epsilon I_{\rm max}^{\nu_\mu + \bar{\nu}_\mu}$$

- They looked at including redshift energy loss of neutrinos

$$E^0/(1+z)$$

- And included the possibility that there could be more sources of cosmic rays at earlier times.

$$\xi_Z \sim 0.6 - 3$$

$$E^2 \Phi_\nu < 2 \times 10^{-8} \frac{\rm GeV}{\rm cm^2 s\, sr}$$

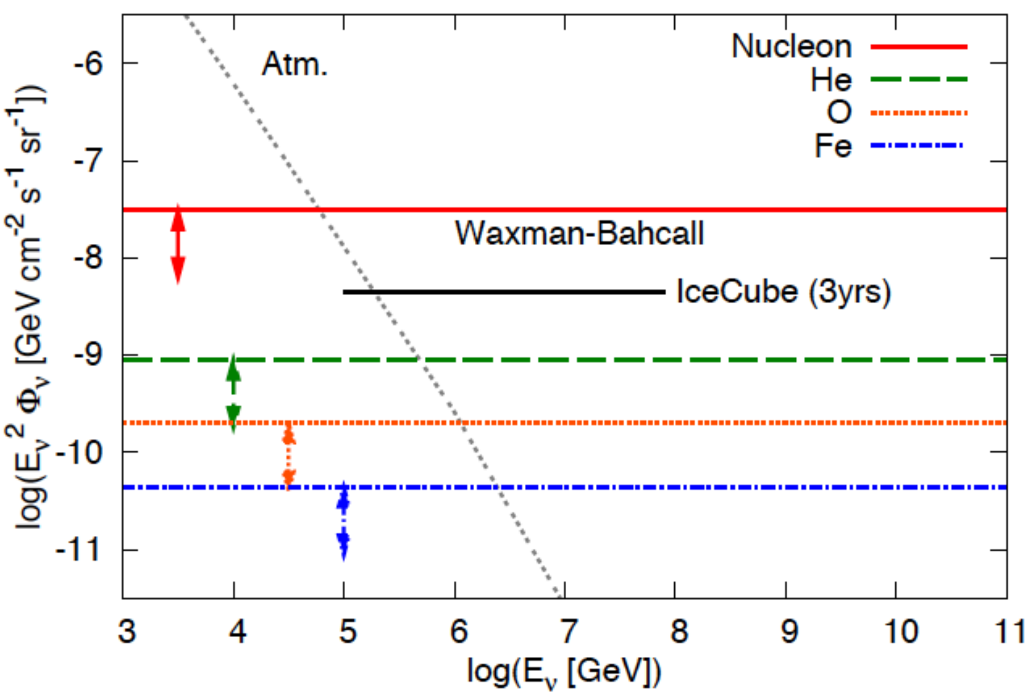
Waxman-Bahcall limit (1999), see also 2001 paper

Bounds -> Landmarks

Beacom and Murase, PRD 81 (2010) 123001 argue we should rename the W-B "limits" instead "landmarks" – reasonable scales in the argument, but not an observational requirement.
WB assume:

- Semi-transparent sources
- Spectral index = 2 for CR at source
- Magnetic fields don't change observed spectrum

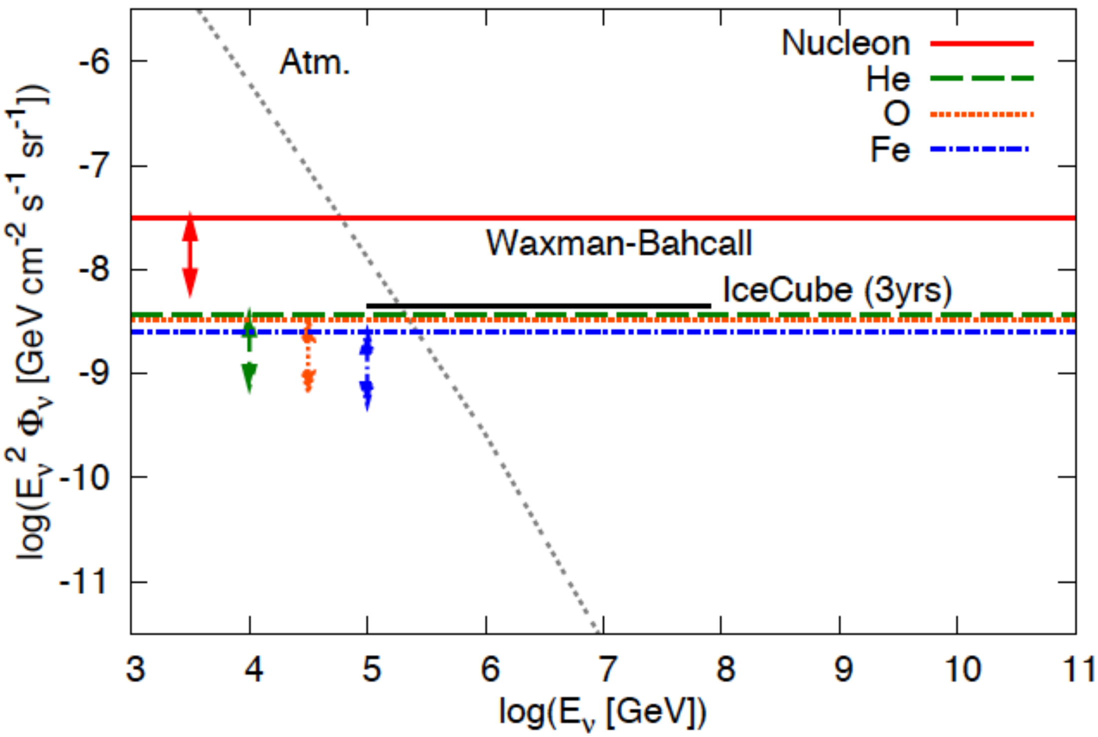
Diffuse flux "landmarks" if instead CR nuclei survive



Different nuclei, range shows for source evolution models, landmarks for complete nucleus survival.

Murase & Beacom, PRD 81 (2010) 123001; CR injection spectrum E^-2, photodisintegration via giant dipole resonance near threshold, fast redshift evolution. Relation between photodisintegration and photomeson production. Here assume optical depth for photodisintegration is: $\tau_{A\gamma} < 1$

Diffuse flux landmarks, mixed CR



Lower by one order of magnitude compared to protons

Murase & Beacom, PRD 81 (2010) 123001; CR injection spectrum E^-2, photodisintegration via giant dipole resonance near threshold, fast redshift evolution Here use the energy loss length rather than interaction length:

$$\kappa_{GDR}\tau_{A\gamma} < 1$$

$\kappa_{DGR} \sim 1/A$ is the fractional energy loss in first disintegration.

Photomeson production, from which the Waxman-Bahcall neutrino flux limits comes

$$p\gamma \to \Delta \to n\pi^+$$

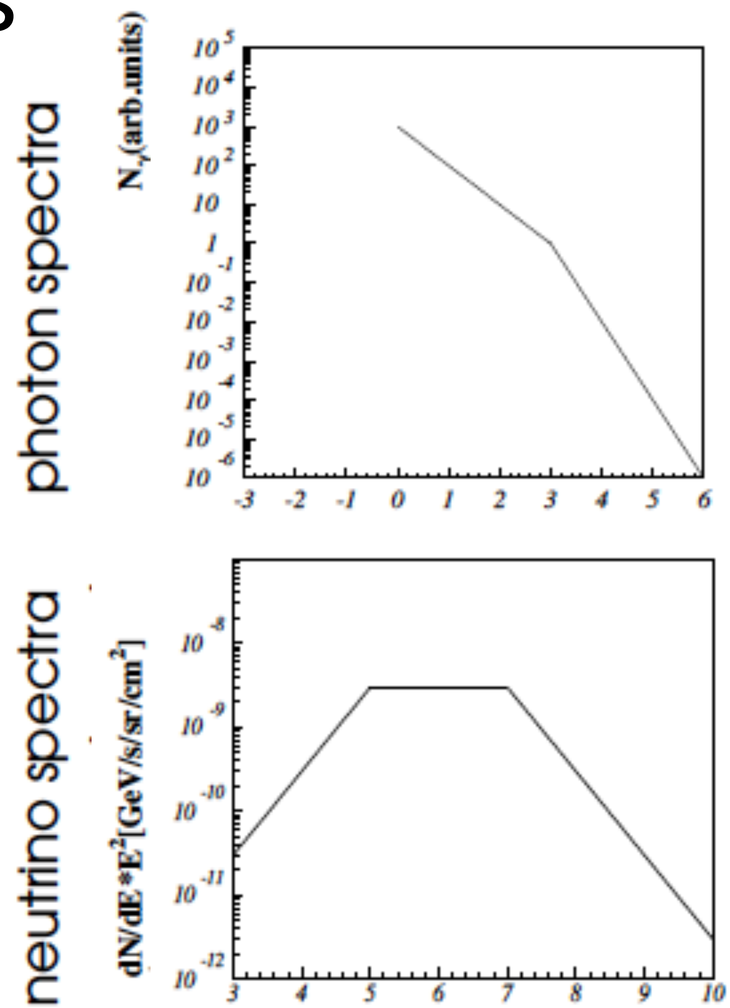
Sample source – Gamma Ray Bursts
Fig. from Becker, Phys. Rept. 0710.1557

$$4E_p E_\gamma \sim m_\Delta^2$$

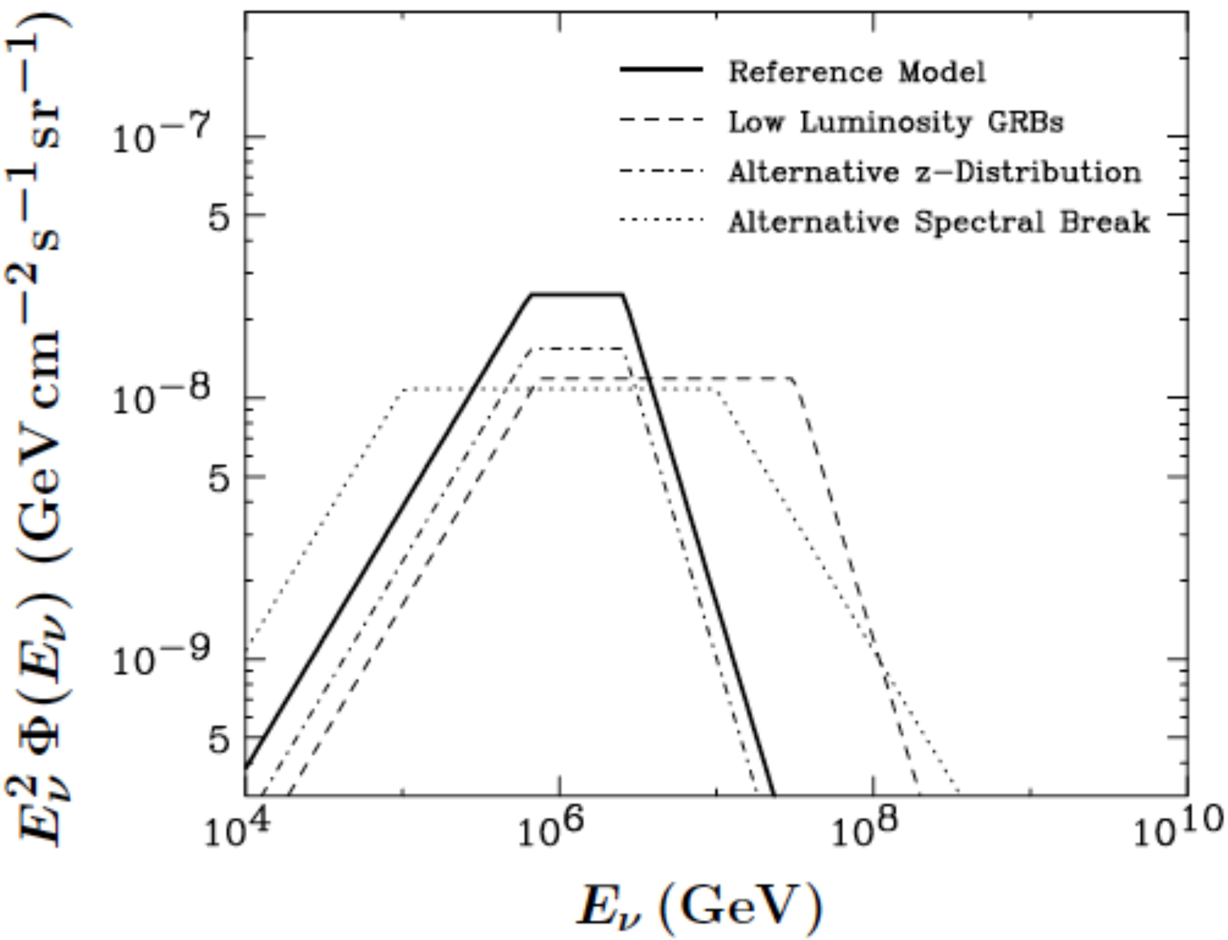
$$E_\nu \sim \frac{1}{20} E_p$$

$$E_\nu \propto E_\gamma^{-1}$$

Neutrino spectrum finally falls due to pion cooling.



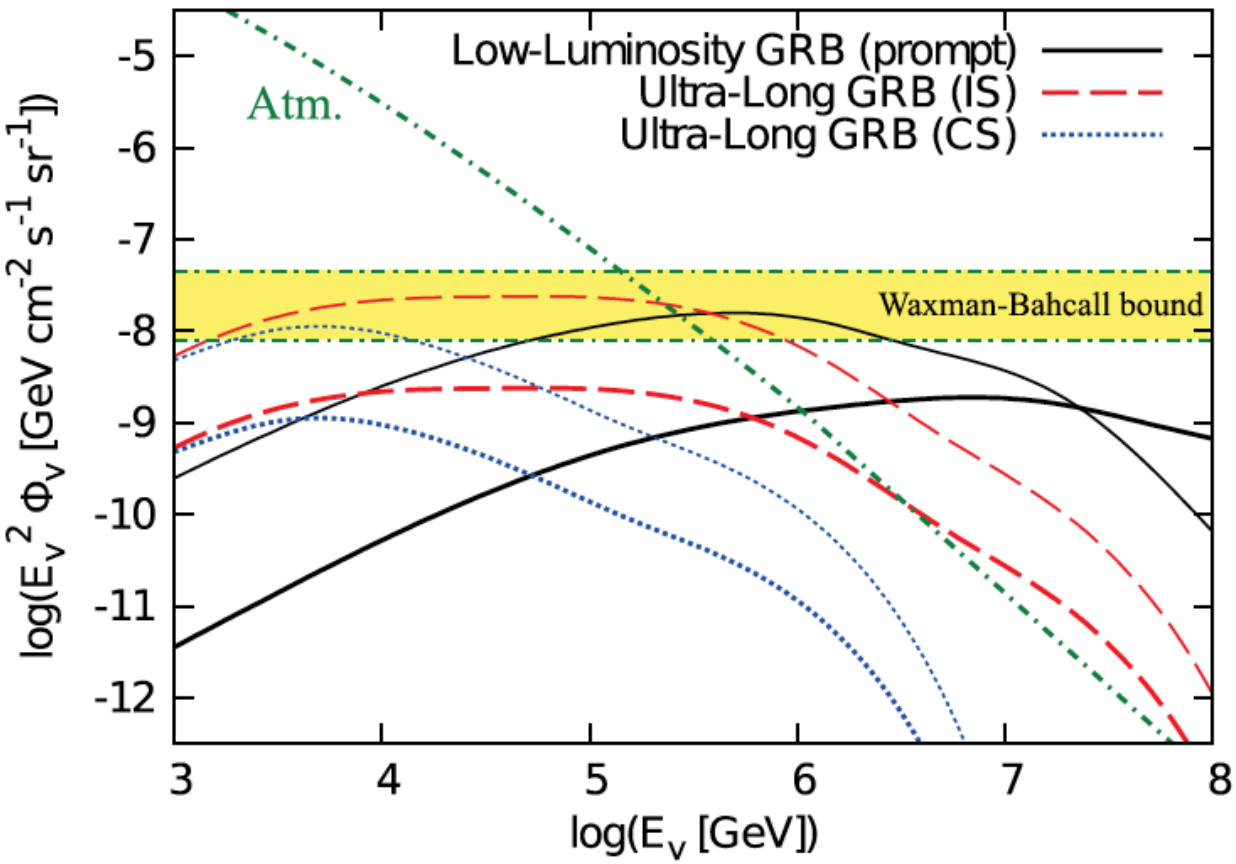
Gamma Ray Bursts, now normalized to IceCube event rate



Variations in luminosity, redshift distribution, location of the change in spectrum, each normalized to IceCube rate.

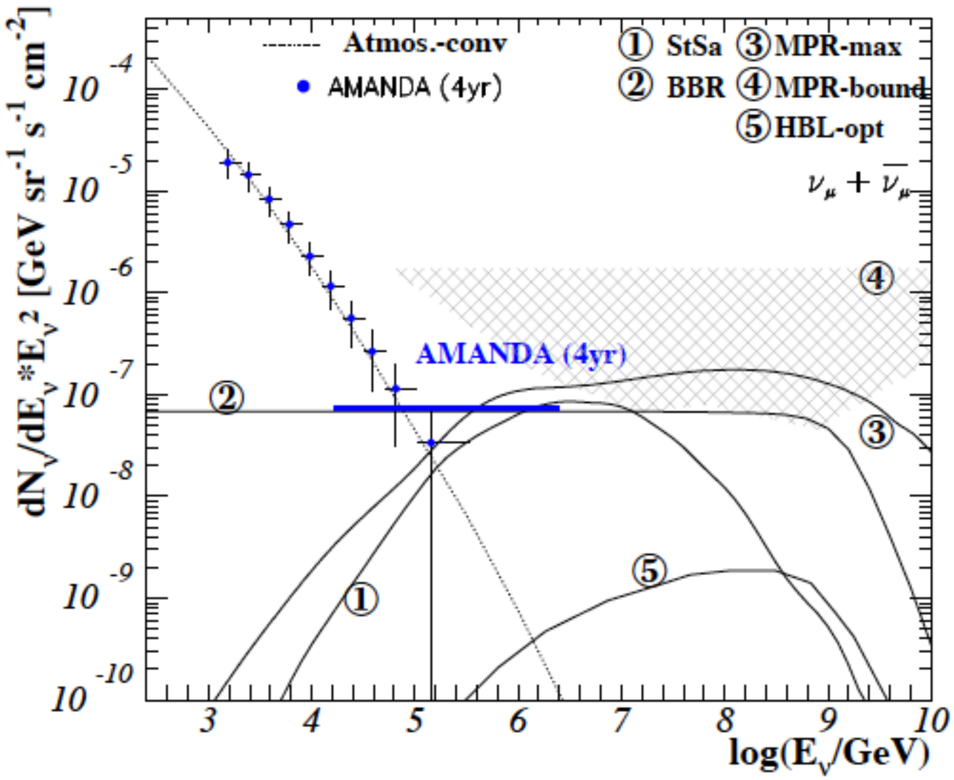
Cholis and Hooper, JCAP 06 (2013) 030; 1211.1974

Low power gamma ray bursts in jets?



Murase & Ioka, PRL 111 (2013) 121102,

Active galactic nuclei - historical



Cosmic rays or non thermal photons to normalize, from neutral pion decays.

Stecker: photomeson production by CR interactions in core of AGN, now normalized down, but energy behavior consistent.
Stecker, 1305.7404

Fig. from Becker, Phys. Rept. 0710.1557

Hadro-nuclear origin of neutrinos: proton-proton interactions

AGN, starburst galaxies could be sources. Need proton targets. E.g., Murase, Ahlers, Lacki PRD 88 (2013) 121301 look at connection between diffuse gamma-ray background and diffuse neutrino flux.

σ_{pp} nearly energy independent

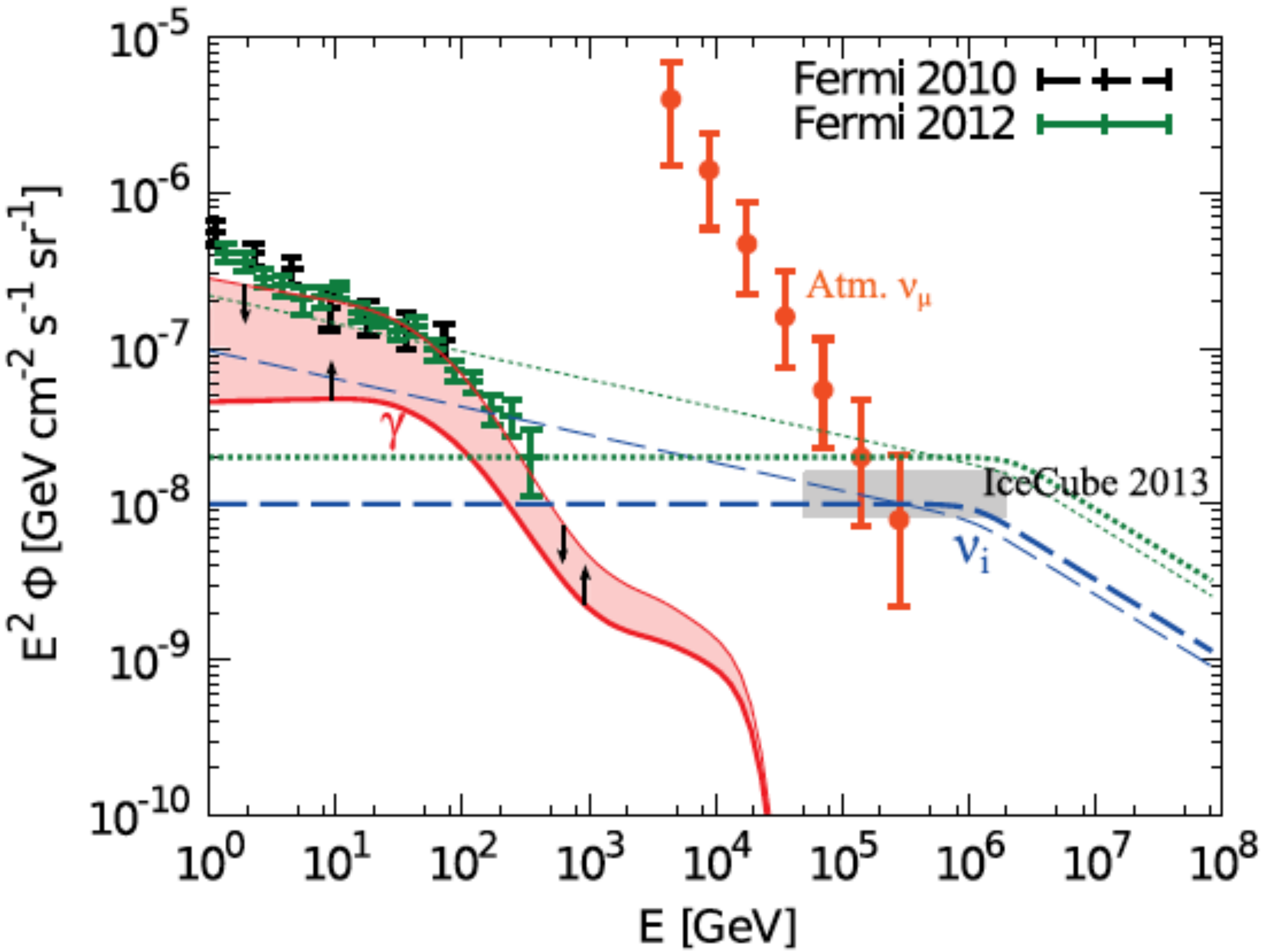
$\Phi_\nu \propto \Phi_{CR}$ scales like the CR flux at the source, so does gamma flux at source

Energetics:

$$\pi^\pm \to \mu\nu_\mu \to e\nu_e\nu_\mu\nu_\mu \qquad E_\nu \simeq \frac{1}{4}E_\pi$$

$$\pi^0 \to \gamma\gamma \qquad E_\gamma \simeq \frac{1}{2}E_\pi$$

Hadronuclear origin of neutrinos



$\Gamma = 2.0, 2.18$

Range shows spectral index range. Not much effect due to redshift evolution model.

Green dotted, before electromagnetic cascades:

$$E_\gamma^2 \Phi_\gamma \simeq 2(E_\nu \Phi_{\nu_i})|_{E_\nu = 0.5 E_\gamma}$$

Murase, Ahlers, Lacki, PRD 88 (2013) 121301

Hadronuclear origin

Murase, Ahlers, Lacki, PRD 88 (2013) 121301 conclusions for hadronuclear origin:

Spectral index, to be consistent with Fermi, IceCube:

$$\Gamma \leq 2.1 - 2.2$$

Minimal contribution to isotropic gamma ray flux:

$$\sim 30 - 40\%$$

Otherwise, neutrinos come for p-gamma, not pp interactions.

(Argue that the pp sources are transparent to gamma rays.)

Further connections, an example

Anchordoqui et al, 1306.5021: power law, spectral index 2.3, assume galactic sources:

Look at two different transition models for where galactic -> extragalactic cosmic rays:

Dip model with transition to extragalactic at 0.3 EeV, cuts of power law spectrum of neutrinos at lower energy (1-2 PeV) than if transition is at the ankle (8-10 PeV).

Look at CR knee as acceleration endpoint or from leakage of particles from the galaxy:

Translates to how the spectral index changes if knee due to one source at acceleration endpoint (or not, for Galaxy leakage) as a function of energy.

Flavor, particle/antiparticle diagnostics

$$p\gamma \to \Delta \to n\pi^+ \qquad \pi^0 : \pi^+ = 2 : 1$$

$$p\gamma \to \Delta \to p\pi^0 \qquad n + \pi^+ \to pe\bar{\nu}_e + e^+\nu_e\nu_\mu\bar{\nu}_\mu$$

Electron antineutrino energy much less than other neutrino energies (neutron decay), if we ignore the neutron decay:

$$1\nu_\mu : 1\bar{\nu}_\mu : 1\nu_e \qquad (\nu_\mu + \bar{\nu}_\mu) : (\nu_e + \bar{\nu}_e) = 2 : 1$$

Proton-proton interactions:

$$pp \to \pi X \qquad \pi^- : \pi^0 : \pi^+ = 1 : 1 : 1$$

$$2\nu_\mu : 2\bar{\nu}_\mu : 1\nu_e : 1\bar{\nu}_e \qquad (\nu_\mu + \bar{\nu}_\mu) : (\nu_e + \bar{\nu}_e) = 2 : 1$$

Astrophysical oscillation: $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0 \to 1 : 1 : 1$

See, e.g., Pakvasa, arXiv:0803.1701

Conditions in source

- Muon damping, $(\nu_\mu + \bar{\nu}_\mu) : (\nu_e + \bar{\nu}_e) = 1 : 0$
  pion decays but muon loses energy before it decays so the electron neutrinos are much lower energy

Astrophysical oscillation: $\nu_e : \nu_\mu : \nu_\tau = 0 : 1 : 0 \rightarrow 0.57 : 1 : 1$

- "Prompt beam" from heavy flavor,
  not just pions, $(\nu_\mu + \bar{\nu}_\mu) : (\nu_e + \bar{\nu}_e) = 1 : 1$

Astrophysical oscillation: $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 0 \rightarrow 1.27 : 1 : 1$

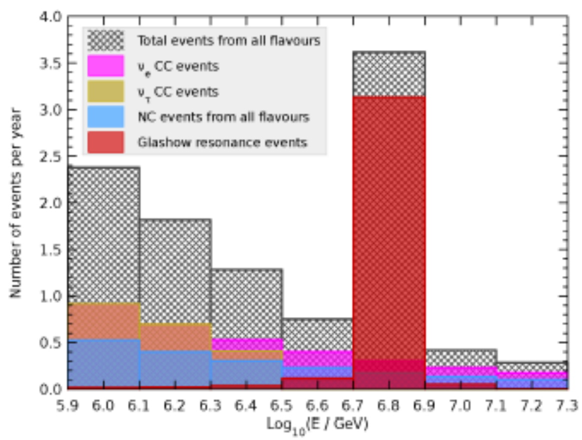
- Beta beam – only neutrons decay, $(\nu_\mu + \bar{\nu}_\mu) : (\nu_e + \bar{\nu}_e) = 0 : 1$

Astrophysical oscillation: $\nu_e : \nu_\mu : \nu_\tau = 1 : 0 : 0 \rightarrow 2.5 : 1 : 0$

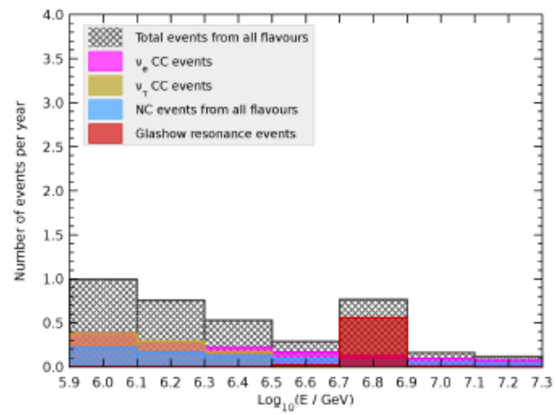
See, e.g., Pakvasa, arXiv:0803.1701

Glashow resonance, double bang

pp



$p\gamma$

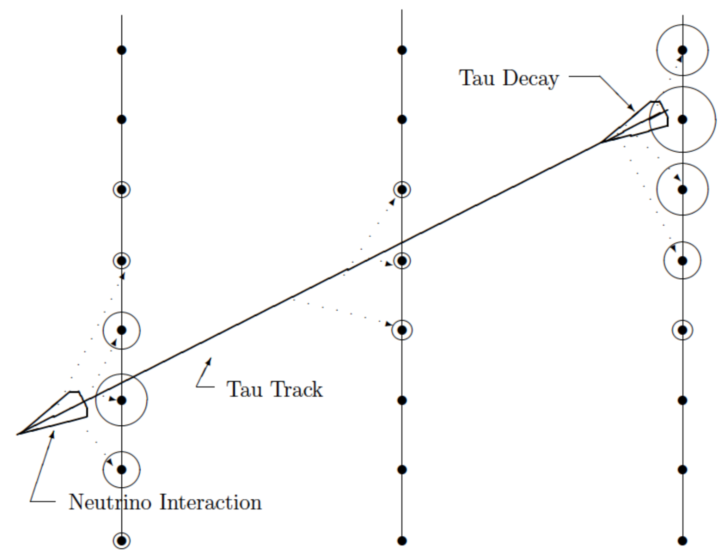


$$\bar{\nu}_e e \to W \to q\bar{q}'$$

$$\gamma c \tau_\tau \simeq \frac{E_\tau}{1\ \mathrm{PeV}} \times 50\ \mathrm{m}$$

E.g., Bhattacharya et al, JCAP 10 (2011) 017

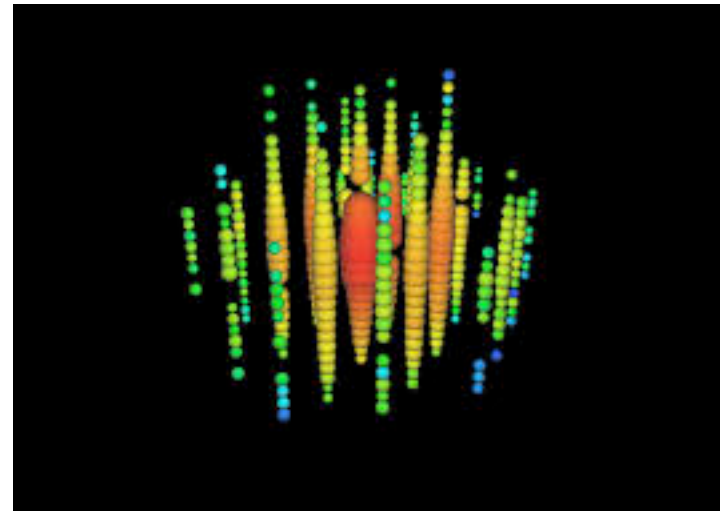
Look for Glashow resonance interaction of electron anti-neutrinos, double bang signature of HE tau neutrinos.



Learned & Pakvasa, Astropart. Phys. 3 (1995) 267

Potentially obscuring features

- Would like to cross correlate neutrinos and photons from the source. Not all sources allow photon to emerge.
- Photons can be produced elsewhere…cosmic rays can produce photons from interactions with extragalactic background light – distant blazers, Kalashev, Kusenko and Essey, arXiv:1303.0300 – is this too optimistic?
- Would like to cross correlate neutrinos and cosmic rays from the source. Not all sources allow cosmic rays to emerge (e.g., choked jets in AGN).
- (Potential for some neutrinos to be attenuated in some circumstances -)
- Could have sources in which both pp and pgamma interactions are important, in different energy regimes.



Roz Chast, from Symmetry publication, May 2007

IceCube: that neutrino is named Bert!

- Neutrino fluxes are definitely connected to cosmic ray origins – figuring out how is the challenge before us.
- The IceCube results (and results to come) gives a target neutrino normalization.