Multimessenger Probes of the Cosmic Ray Origin

– High-Energy Neutrino Astrophysics & Astronomy –

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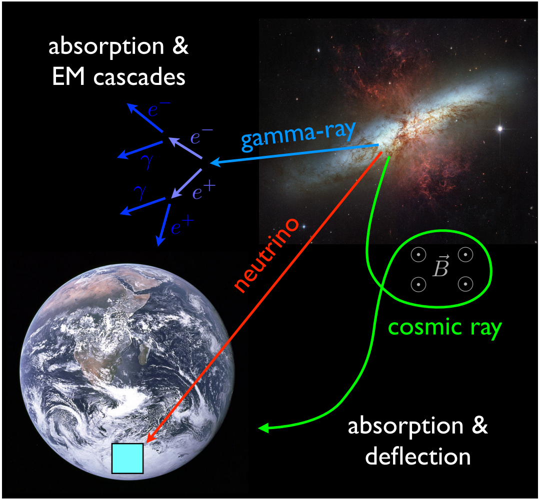
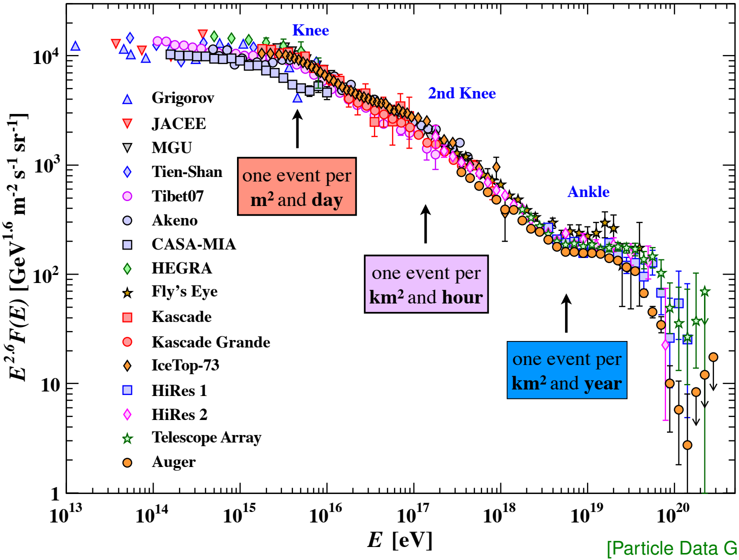
Multi-Messenger Astronomy

- Neutrino astronomy:
  - ✔ **natural extension**
  - ✔ closely **related** to cosmic rays (CRs) and γ-rays
  - ✔ **smoking-gun** of CR sources
  - ✔ **weak interaction** during propagation
  - ✔ **exclusive messenger** for 10 TeV-10 EeV telescopes
- Challenges:
  - ✘ **low** statistics
  - ✘ **large** backgrounds



The Cosmic “Beam”



[Particle Data Group’13]

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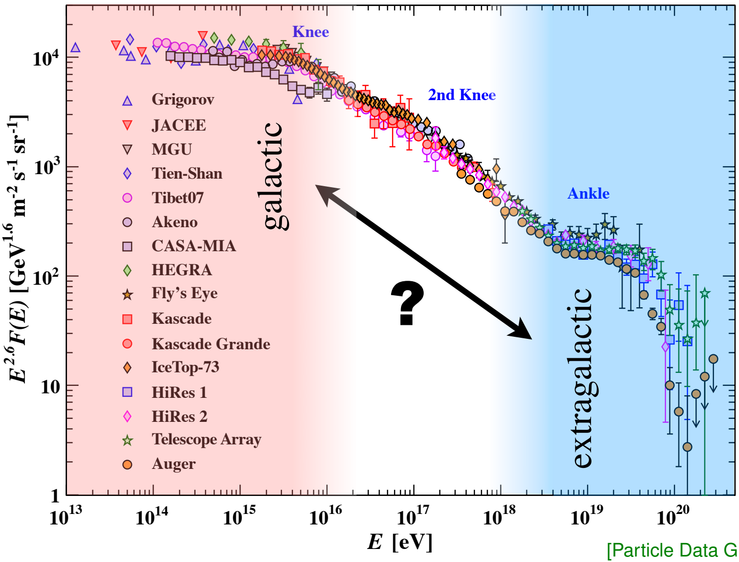


[Particle Data Group’13]

Galactic Cosmic Rays

- Galactic supernova (SN) remnants with $\mathcal{E}_{\rm ej} \simeq 10^{51}$ erg and 3 SNe per century

- Galactic CRs via diffusive shock acceleration (efficiency $\sim 10\%$)?

  [Baade & Zwicky'34]

$$\frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-(2.2-2.4)} \qquad \text{(at source)}$$

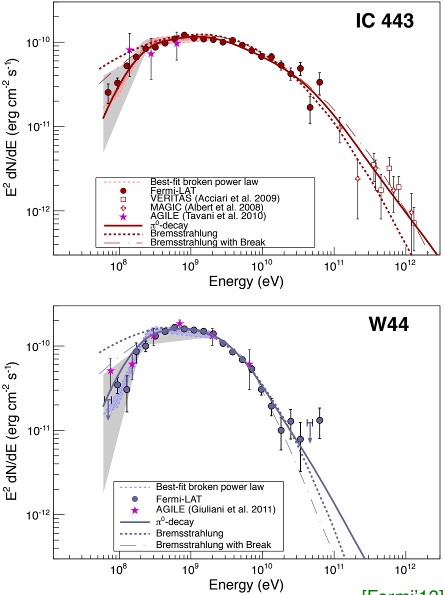
$$E_{p,\max} \simeq 4.5\,\text{PeV}\; \varepsilon_{B,-2}^{1/2} M_{\rm ej,\odot}^{-2/3} \mathcal{E}_{\rm ej,51} n_0^{1/6}$$

- energy-dependent **diffusive escape** from Galaxy

$$\frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-2.7} \qquad \text{(observed)}$$

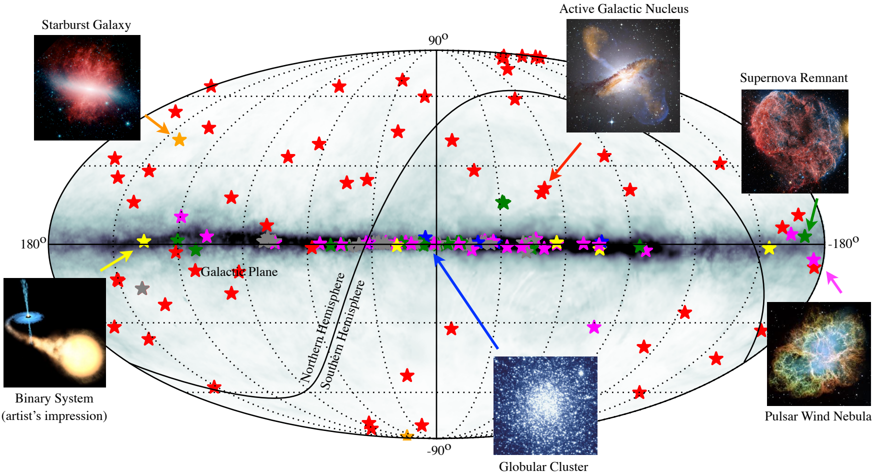
- indirect (diffuse) & direct ("pion bump") evidence via γ-ray radiation

  [Drury, Aharonian & Völk'94; Fermi'13]



[Fermi'13]

TeV γ-ray Observations



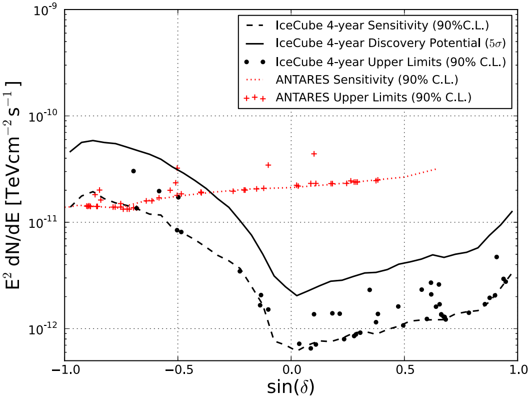
- **leptonic:** bremsstrahlung, synchrotron, inverse-Compton [TeVCat'14]
- **hadronic:** pion production in CR interaction with gas and radiation, $\pi^0 \rightarrow \gamma + \gamma$

Neutrino Point-Source Limits

- **upper flux limits and sensitivities** of Galactic neutrino sources with "classical" muon neutrino search ($\theta_{\rm res} \simeq 0.3^\circ$-$0.6^\circ$)
- sensitivity for **extended sources** weaker by $\sqrt{\Omega_{ES}/\Omega_{\rm PSF}} \simeq \theta_{\rm ES}/\theta_{\rm res}$
- strongest limits for sources in the Northern Hemisphere (IceCube FoV for upgoing ν's)
- **time-dependent** sensitivity:

[IceCube ApJ 744 (2012)]

$$E^2\Phi_{\nu_\mu} \simeq (0.1-1){\rm GeVcm}^{-2}$$



[IceCube 1406.6757]

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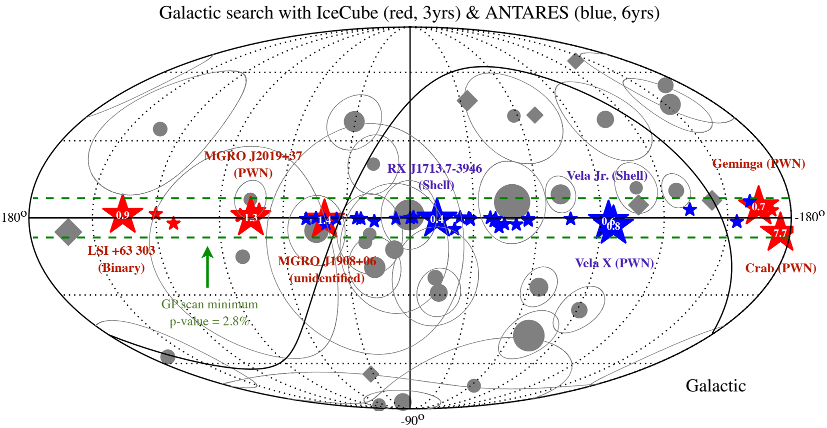


- relative strength of neutrino limits assuming hadronic TeV γ-ray emission (only shown for selected strong sources):

$$F_\gamma(E_\gamma > E_{\rm th})/F_\nu^{90CL}(E_\nu > E_{\rm th}/2)$$

✘ **caveats:** soft spectra, low energy cutoffs and extended emission

Ultra-High Energy Cosmic Rays

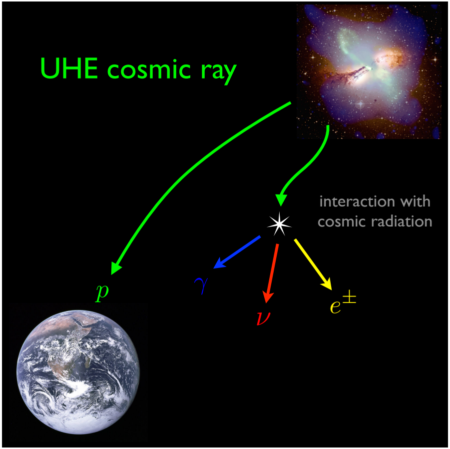
- particle confinement during acceleration requires: [Hillas'84]

$$E \lesssim 10^{18}\,\mathrm{EeV}\,(B/1\mu\mathrm{G})\;(R/1\mathrm{kpc})$$

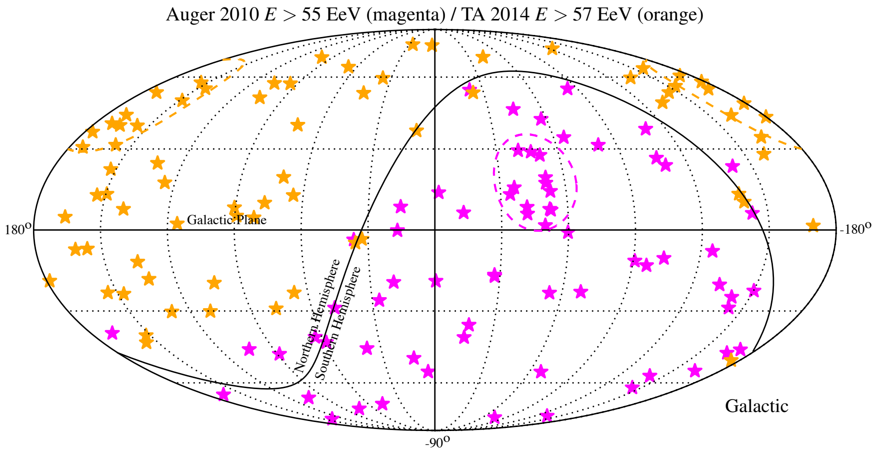
✘ *low statistics:* large uncertainties in chemical composition and spectrum!

✘ *"GZK" horizon* ($\lesssim 200$ Mpc): resonant interactions of CR nuclei with CMB photons [Greisen'66;Zatsepin &Kuzmin'66]

✔ "guaranteed flux" of **secondary γ-ray and neutrino emission** [Berezinsky&Zatsepin'70;Berezinsky&Smirnov'75]



Anisotropies of UHE CRs



- $\theta_{\rm rms} \simeq 1^\circ\ (D/\lambda_{\rm coh})^{1/2}(E/55{\rm EeV})^{-1}(\lambda_{\rm coh}/1{\rm Mpc})\ (B/1{\rm nG})$ [Waxman & Miralda-Escude'96]
- "hot spots" (dashed), but no significant auto-correlation in Auger and Telescope Array data
- no significant cross-correlation with source catalogs [Auger'10;TA'14]

Cosmogenic ("GZK") 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]

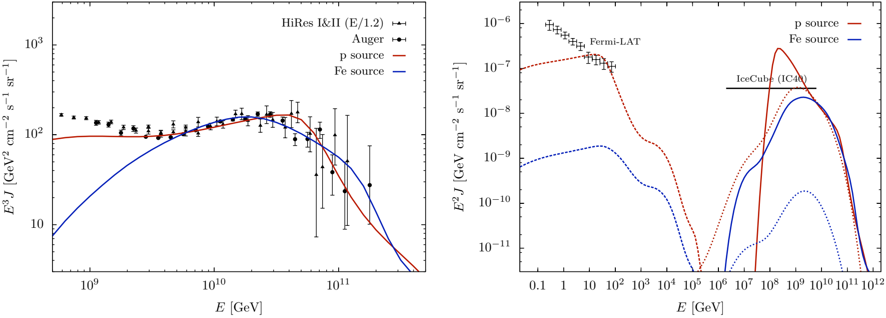
- "Guaranteed", but with many model uncertainties and constraints:
  - **(low cross-over) proton models + CMB (+ EBL)**

    [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]

Composition Dependence of UHE CRs



✘ large uncertainties on UHE CR mass composition

- UHE CR examples in plot: only proton or only iron on emission
- diffuse spectra of cosmogenic γ-rays (dashed lines) and neutrinos (dotted lines) **vastly different** [MA&Salvado'11]

➜ **neutrino limits** start to constrain most optimistic scenarios of proton-dominated UHE CR sources. [IceCube'13;ANITA'12]

Guaranteed Cosmogenic Neutrinos

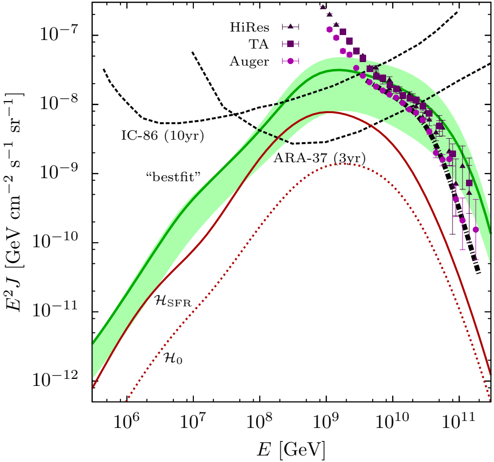
➜ neutrino emission depend on *nucleon spectrum*:

$$J_N(E_N) = \sum_i A_i^2 J_i(A_i E_N)$$

➜ **minimial** contribution can be estimated from observed mass composition

- dependence on cosmic evolution of sources:
  - no evolution (dotted)
  - star-formation rate (solid)

➜ **ultimate test** of UHE CR proton models with **ARA-37**



[MA&Halzen'12]

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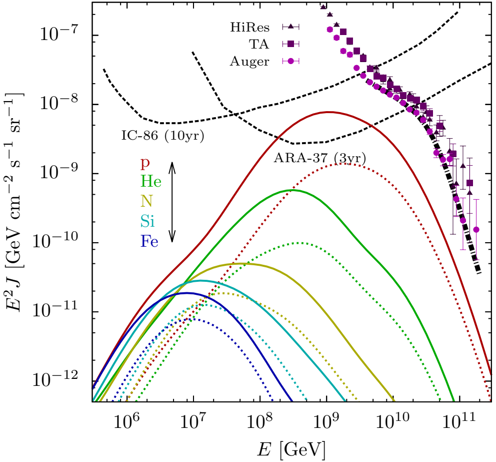


[MA&Halzen'12]

Astrophysical Neutrinos

- “smoking gun” of CR sources

✔ weak interaction during propagation . . .

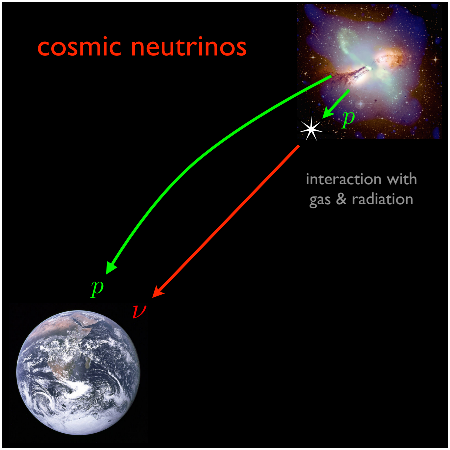
✘ . . . and detection!

- good angular resolution possible for muon neutrinos:
  neutrino clusters and/or associations?

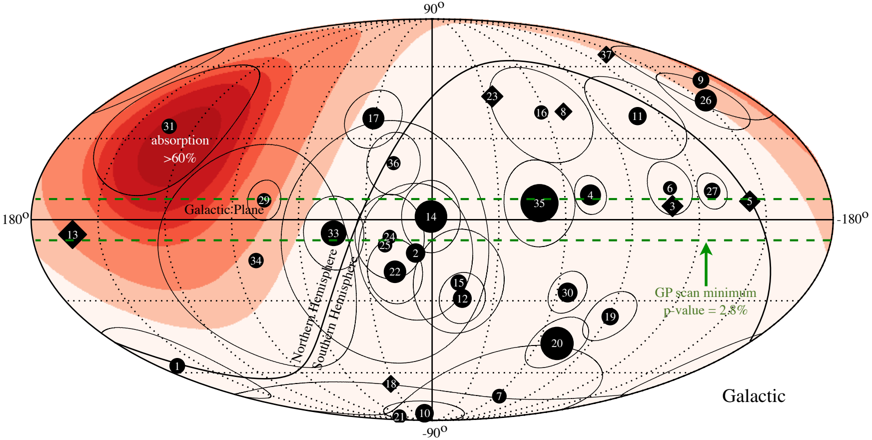
- recent IceCube observations of a diffuse flux of cosmic neutrinos
  [IceCube PRL 113 (2014)]

- **best-fit** E^{-2}-spectrum at $(0.1 - 1)\mathrm{PeV}$:

$$E_\nu^2 J_{\nu_\alpha}^{\rm IC} \simeq (0.95{\pm}0.3){\times}10^{-8}{\rm GeV s^{-1} cm^2 sr^{-1}}$$



Arrival Directions



- **28 "cascade events" (circles) and 7 "tracks events" (diamonds)**; size of symbols proportional to deposited energy (30 TeV to 2 PeV) [IceCube PRL 113 (2014)]

✘ **no significant spatial or temporal correlation of events**

Neutrino Flavors

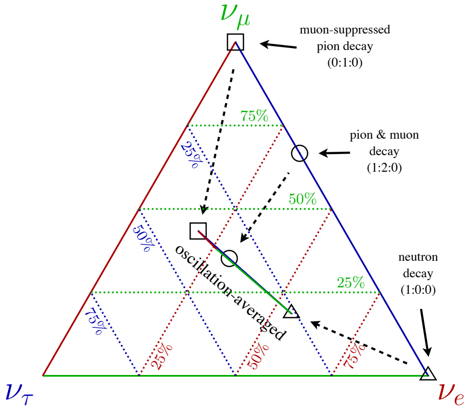
- oscillation-averaged probability:

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

- oscillation-averaged probability with *exotic neutrino decay*:
  [Beacom *et al.*'03;Barenboim & Quigg'03]

$$P_{\nu_\alpha \to \nu_\beta} \simeq \sum_{i,j} |U_{\alpha i}|^2 \mathrm{Br}_{i\to j} |U_{\beta j}|^2$$

➜ final state bounded by **mass triangle**



- "NuFit 1.3": $\sin^2\theta_{12} = 0.304$ / $\sin^2\theta_{23} = 0.577$ / $\sin^2\theta_{13} = 0.0219$ / $\delta = 251°$

✔ observed events **consistent with equal contributions of all neutrino flavors**

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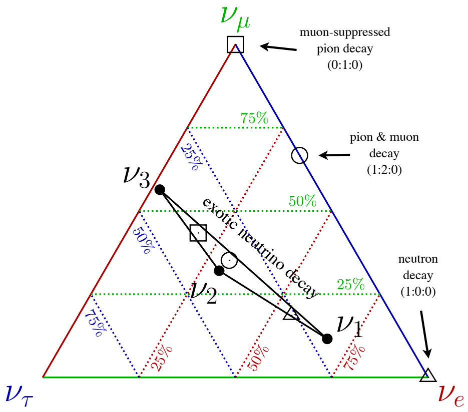

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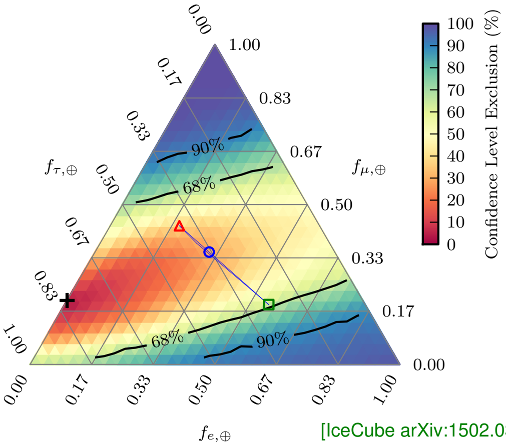

[IceCube arXiv:1502.033]

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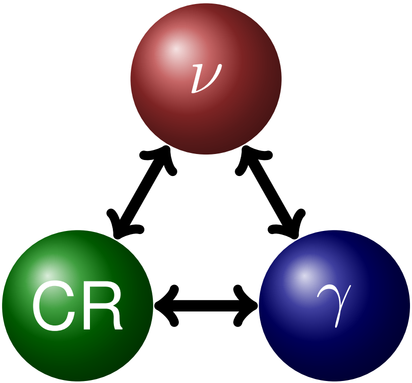
Multi-messenger Paradigm

- 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?



Proposed Source Candidates

- **Galactic:** (full or partial contribution)
  - diffuse or unidentified Galactic γ-ray emission [Fox, Kashiyama & Meszaros'13]
    [MA & Murase'13; Neronov, Semikoz & Tchernin'13;Neronov & Semikoz'14; Guo, Hu & Tian'14]
  - extended Galactic emission [Su, Slatjer & Finkbeiner'11; Crocker & Aharonian'11]
    [Lunardini & Razzaque'12;MA & Murase'13; Razzaque'13; Lunardini *et al.*'13]
    [Taylor, Gabici & Aharonian'14]
  - heavy dark matter decay [Feldstein *et al.*'13; Esmaili & Serpico '13; Bai, Lu & Salvado'13]
- **Extragalactic:**
  - association with sources of UHE CRs [Kistler, Stanev & Yuksel'13]
    [Katz, Waxman, Thompson & Loeb'13; Fang, Fujii, Linden & Olinto'14]
  - active galactic nuclei (AGN) [Stecker'91,'13;Kalashev, Kusenko & Essey'13]
    [Murase, Inoue & Dermer'14; Kimura, Murase & Toma'14;Kalashev, Semikoz & Tkachev'14]
  - gamma-ray bursts (GRB) [Murase & Ioka'13]
  - starburst galaxies [Loeb & Waxman'06; He *et al.*'13;Yoast-Hull, Gallagher, Zweibel & Everett'13]
    [Murase, MA & Lacki'13; Anchordoqui *et al.*'14; Chang & Wang'14]
  - hypernovae in star-forming galaxies [Liu *et al.*'13]
  - galaxy clusters/groups [Murase, MA & Lacki'13;Zandanel *et al.*'14]
  - ...

Diffuse vs. Point-Source

- (quasi-)diffuse flux fixes luminosity L:

$$F_{\rm diff} = \frac{1}{4\pi}\int {\rm d}z\,\frac{{\rm d}\mathcal{V}_C}{{\rm d}z}\,\mathcal{H}(z)\,\frac{L}{4\pi d_L^2(z)}$$

- point-source flux:

$$F_{\rm PS} = \frac{L}{4\pi d_{\rm L}^2(z)}$$

- typically, the density $\mathcal{H}$ of extra-galactic sources is:
    - $10^{-3} - 10^{-2}\,{\rm Mpc}^{-3}$ for **normal galaxies**
    - $10^{-5} - 10^{-4}\,{\rm Mpc}^{-3}$ for **active galaxies**
    - $10^{-7}\,{\rm Mpc}^{-3}$ for **massive galaxy clusters**
    - $> 10^{-5}\,{\rm Mpc}^{-3}$ for **UHE CR sources**

- PS flux based on IceCube flux:

$$F_{\rm PS}(E_\nu) \simeq 9\times10^{-13}\,{\rm TeV cm^{-2}s^{-1}}\left(\frac{\mathcal{H}_0}{10^{-5}{\rm Mpc}^{-3}}\right)^{-1}\left(\frac{r}{10{\rm Mpc}}\right)^{-2}\left(\frac{\xi_z}{2.4}\right)^{-1}$$

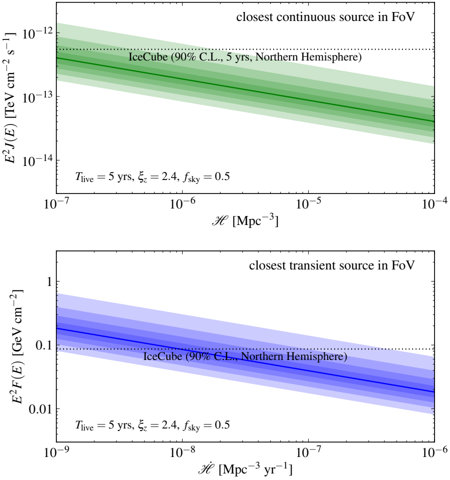
Neutrino Point-Source Limits

- Diffuse neutrino flux normalizes the contribution of individual sources
- dependence on local source density $\mathcal{H}$ (rate $\dot{\mathcal{H}}$) and redshift evolution ξ_z

➜ PS observation requires rare sources

- non-observation of individual neutrino sources exclude source classes, *e.g.*
  - ✘ flat-spectrum radio quasars ($\mathcal{H} \simeq 10^{-9}\mathrm{Mpc}^{-3}$ / $\xi_z \simeq 7$)
  - ✘ “normal” GRBs ($\dot{\mathcal{H}} \simeq 10^{-9}\mathrm{Mpc}^{-3}\mathrm{yr}^{-1}$ / $\xi_z \simeq 2.4$)

➜ stronger limits via source “stacking”

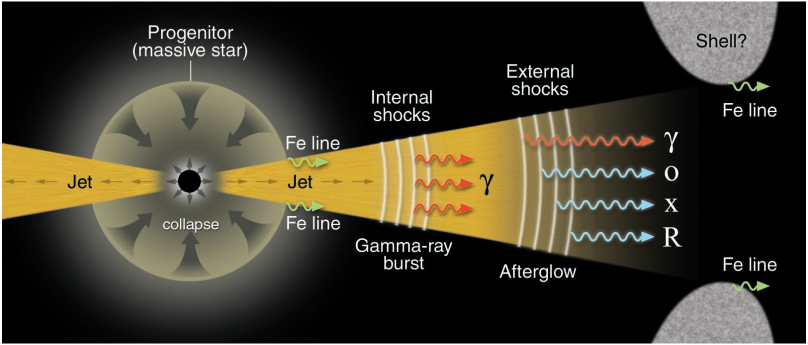


[MA&Halzen’14]

Example: GRB Neutrino Emission

- Neutrino production at various stages of gamma-ray burst (GRB), from precursor to afterglow [Waxman&Bahcall'97,'00;Razzaque,Meszaros&Waxman'03]
- Neutrino emission of GRBs is one of the best-tested models: [IceCube, Nature'12]

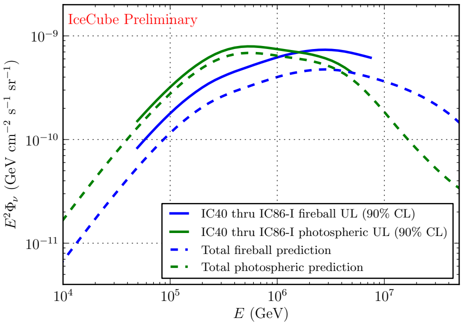
✔ **cosmological sources** ("one per day and 4π")
✔ **wealth of data** from Swift and Fermi
✔ good information on **timing and location** (➜ background reduction)



[Meszaros'01]

Example: GRB Neutrino Emission

- stacking limits exclude GRBs as the sources of the cosmic neutrino flux [IceCube Nature 484 (2012)]
- most recent **GRB** stacking:
  - 492 GRBs (2008–2012) in IceCube's FoV reported with GCN and Fermi GBM
  - ν_μ emission following the GRB "fireball" model
  - revised fireball calculation "`fireballet`" used by IceCube [MA'13]



[M.Richman ICRC 2013]

Leptonic and Hadronic Gamma-Rays

- **leptonic** γ-rays:
  inverse-Compton, bremsstrahlung & synchrotron emission
- **hadronic** γ-rays:
  pion production in CR interactions

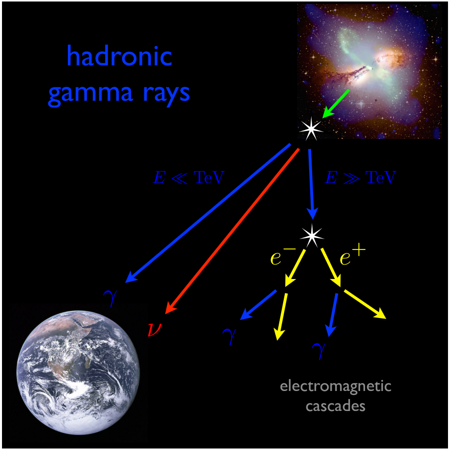
➜ linked to neutrino production

$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

✔ cross-correlation of γ-ray and neutrino sources

✘ electromagnetic cascades of super-TeV γ-rays in CMB

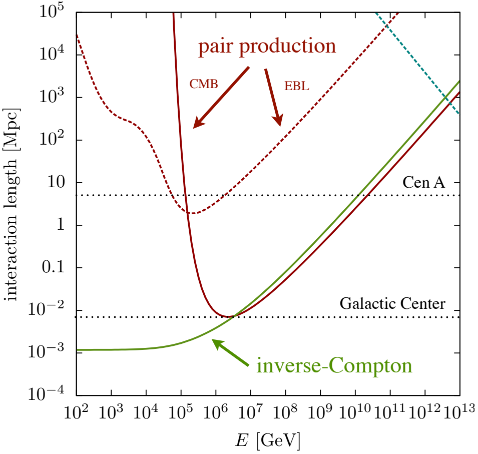


Electromagnetic Cascades

- CMB interactions **(solid lines)** dominate in casade:
  - inverse Compton scattering (ICS)
    $e^{\pm} + \gamma_{\rm CMB} \to e^{\pm} + \gamma$
  - pair production (PP)
    $\gamma + \gamma_{\rm CMB} \to e^{+} + e^{-}$
- extragalactic background light **(red dashed line)** determines the "edge" of the spectrum.

  [EBL: Franceschini *et al.* '08]
- rapid cascade interactions produce universal GeV-TeV emission

  [Berezinsky&Smirnov'75]



[MA'11]

Isotropic Diffuse Gamma-Ray Background (IGRB)

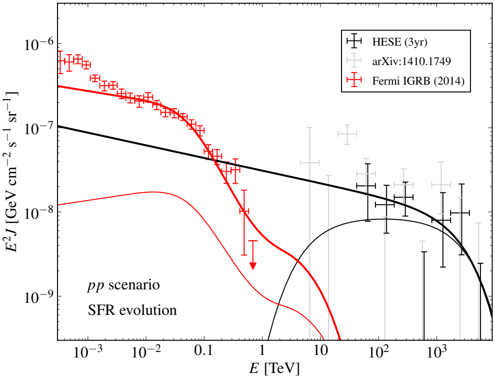
- neutrino and γ-ray fluxes in pp scenarios follow initial CR spectrum $\propto E^{-\Gamma}$

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

✘ constrained by IGRB
[Murase, MA & Lacki'13; Chang & Wang'14]

- extra-galactic emission (cascaded in EBL): $\Gamma \lesssim 2.15 - 2.2$

➜ $\gtrsim 10\%$ contribution to IGRB at $E_\gamma \gtrsim 100\mathrm{GeV}$



[MA; updated for IceCube-Gen2 1412.5106]

Open Questions

- Is there a **common origin** of the high-energy IGRB and diffuse neutrino emission?

- Is this source population (partially) **identified** by Fermi LAT? (➜ cross-correlation)
  [Padovani & Resconi'14;MA & Guetta, in preparation]

- Is secondary γ-ray emission "hidden" by **source dynamics**?

- Are there **Galactic** "contaminations" at $E_\nu \simeq 1 - 10$ TeV that effectively lead to a softening of the observed neutrino spectrum?
  [IceCube'15; Bai, Bargner, Lu & MA, in preparation]

- Are there **extended Galactic sources** dominating the neutrino emission, *e.g.* Fermi Bubbles, Galactic Halo or PeV dark matter decay? (➜ PeV γ-rays)

- The diffuse flux also saturates limits from **UHE CR sources**. Is this population also responsible for UHE CRs? [Katz, Waxman, Thompson & Loeb'13]

UHE CR association ?

- UHE CR proton emission rate density: [MA&Halzen'12]

$$E_p^2 Q_p(E_p) \simeq (1-2) \times 10^{44}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$$

- corresponding per flavor neutrino flux ($\xi_z \simeq 0.5 - 2.4$ and $K_\pi \simeq 1-2$):

$$E_\nu^2 J_\nu(E_\nu) \simeq f_\pi \frac{\xi_z K_\pi}{1+K_\pi}(2-4) \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr}$$

- **WB bound:** $f_\pi \leq 1$ [Waxman&Bahcall'98]
- $f_\pi \simeq 1$ requires efficient pion production

✘ how to reach $E_{\rm max} \simeq 10^{20}$ eV in environments of high energy loss?

➜ two-zone models: acceleration + CR "calorimeter"?

  - starburst galaxies [Loeb&Waxman'06]
  - galaxy clusters [Berezinsky,Blasi&Ptuskin'96;Beacom&Murase'13]

➜ "holistic" CR models: universal time-dependent CR sources?

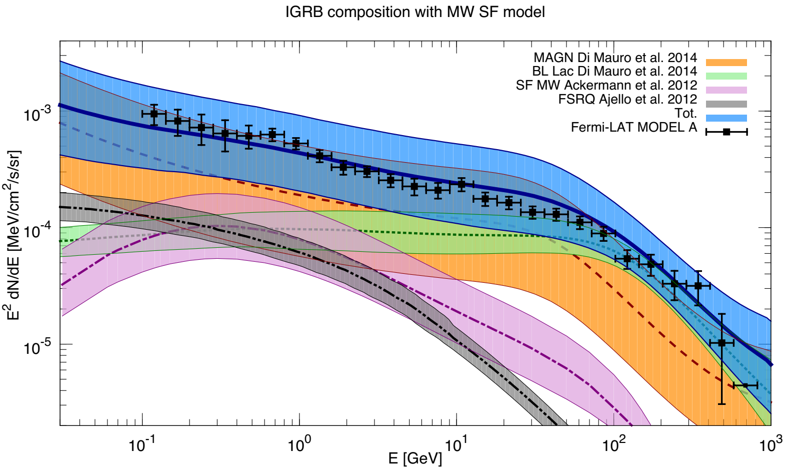
[Parizot'05;Aublin&Parizot'06;Katz,Waxman,Thompson&Loeb'13]

Summary

- Many aspects of cosmic rays (CRs), in particular at ultra-high energies (UHE) are still unknown.
- Multi-messenger studies with **hadronic gamma-rays and neutrinos** can help to decipher CR composition and origin.
- Neutrinos are **unique (pointing) probes** in the 10TeV-10EeV energy range.
- **Similar diffuse energy densities** of UHE CRs, γ-rays and neutrinos might indicate a common origin.
- Many open questions and opportunities concerning the recent neutrino observation, *e.g.*
  - Do we see **individual sources or just a diffuse background**?
  - How well can we determine the **spectrum** and **flavor composition**?
  - Is the corresponding CR population responsible for **UHE CRs** (WB saturation)?
  - Local **PeV γ-ray astronomy**?

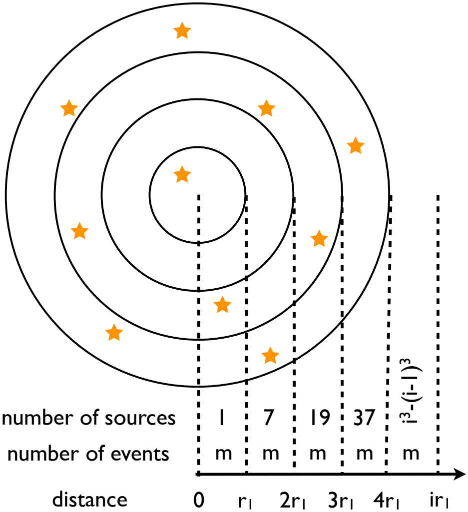
Appendix

Decomposition of IGRB



[Di Mauro & Donato'15]

Required Neutrino Sample



- total number of sources

$$n_s \simeq 10^6 - 10^7$$

- total number of "slices"

$$n_{\text{slice}} \simeq (n_s)^{\frac{1}{3}}$$

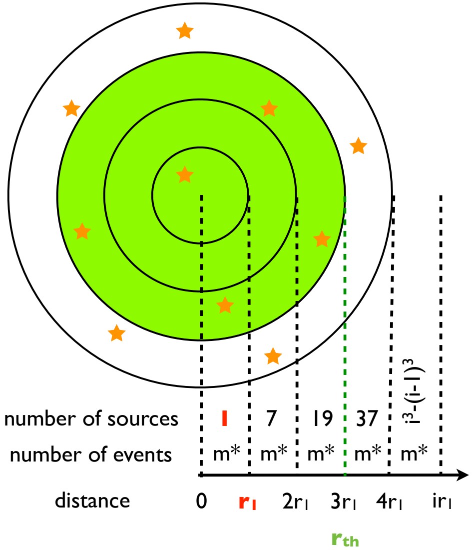
- total number of events

$$\bar{N} \simeq m \times n_{\text{slice}} = m \times (n_s)^{\frac{1}{3}}$$

- ✘ required number of events to see a doublet $(m = 2)$

$$\bar{N} \simeq 200 - 500$$

Required Neutrino Sample



- total number of **known** closeby ($r < r_{\rm th}$) sources, *e.g.*

$$n_{\rm cat} \simeq 100$$

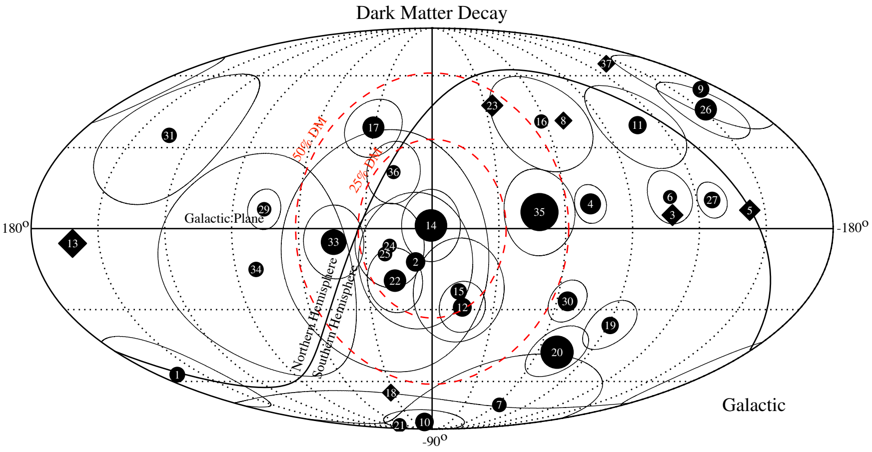
- total number of events

$$\bar{N} \simeq m^* \times n_{\rm slice} = m \times \left(\frac{n_s}{n_{\rm cat}}\right)^{\frac{1}{3}}$$

✔ required number of events to see an association ($m = 1$)

$$\bar{N} \simeq 20 - 50$$

DM decay


Dark Matter Decay
50% DM
25% DM
Galactic Plane
Northern Hemisphere
Southern Hemisphere
180°
-180°
-90°
Galactic
1
2
3
4
5
6
7
8
9
10
11
12
13
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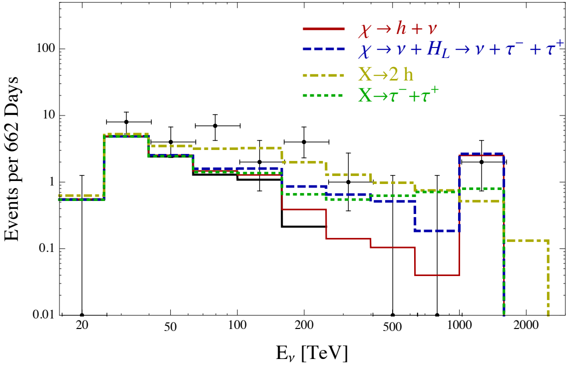
37

DM decay

- heavy (>PeV) DM decay?

  [Feldstein *et al.* 1303.7320; Esmaili & Serpico 1308.1105; Bai, Lu & Salvado 1311.5864]
- **initially** motivated by PeV “line-feature”, but continuum spectrum with/without line spectrum equally possible

➜ observable **PeV γ-rays** from the Milky Way halo?



[Bai, Lu & Salvado'13]

Contrast of DM decay

- Galactic neutrino flux from DM decay:

$$F_{\rm gal} = \frac{Q_\nu}{m_X\tau_X}\frac{1}{2}\int\limits_{-1}^{1}{\rm d}c_\alpha\int\limits_{0}^{\infty}{\rm d}s\,\rho_{\rm gal}(r(s,c_\alpha)) \simeq \frac{Q_\nu}{m_X\tau_X}\langle\rho_{\rm gal}\rangle d_{\rm halo}$$

- Extragalactic diffuse signal:

$$F_{\rm diff} = \frac{\Omega_{\rm DM}\rho_{\rm cr}}{4\pi m_X\tau_X}\int\limits_{0}^{\infty}\frac{{\rm d}z}{H(z)}Q_\nu((1+z)E_\nu) \simeq \frac{1}{4\pi}\frac{Q_\nu}{m_X\tau_X}\frac{\xi_z\Omega_{\rm DM}\rho_{\rm cr}}{H_0}$$

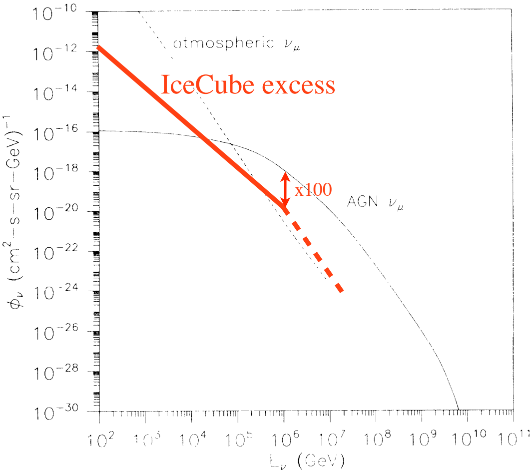
➜ flux ratio:

$$\frac{F_{\rm gal}}{4\pi F_{\rm diff}} \simeq \frac{\langle\rho_{\rm gal}\rangle}{\Omega_{\rm DM}\rho_{\rm cr}}\frac{d_{\rm halo}}{\xi_z/H_0} \simeq \mathbf{1}\left(\frac{d_{\rm halo}}{20{\rm kpc}}\right)\left(\frac{\xi_z}{0.5}\right)^{-1}$$

➜ **Similar contributions from Galactic and extragalactic DM decay.**

Active Galactic Nuclei

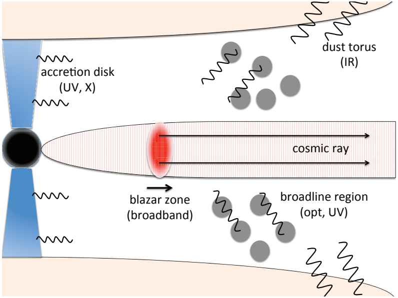
- neutrino interactions from $p\gamma$ interactions in AGN cores [Stecker*et al.*'91]
- AGN diffuse emission normalized to X-ray background
- revised model predicts 5% of original estimate [Stecker'05;'13]

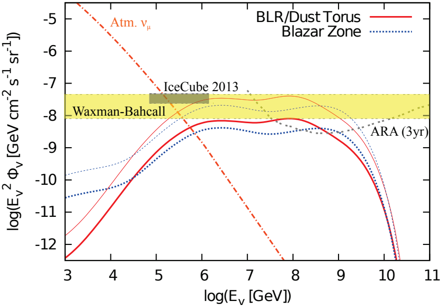


[Stecker *et al.*'91]

Active Galactic Nuclei

- neutrino from $p\gamma$ interactions in AGN jets [Mannheim'96; Halzen & Zas'97]
- complex spectra due to various photon backgrounds
- typically, deficit of sub-PeV and excess of EeV neutrinos

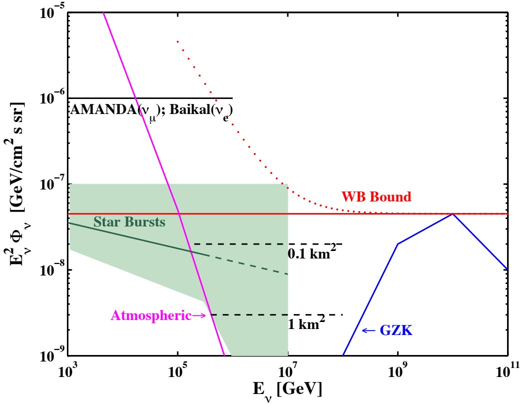




[Murase, Inoue & Dermer 1403.4089]

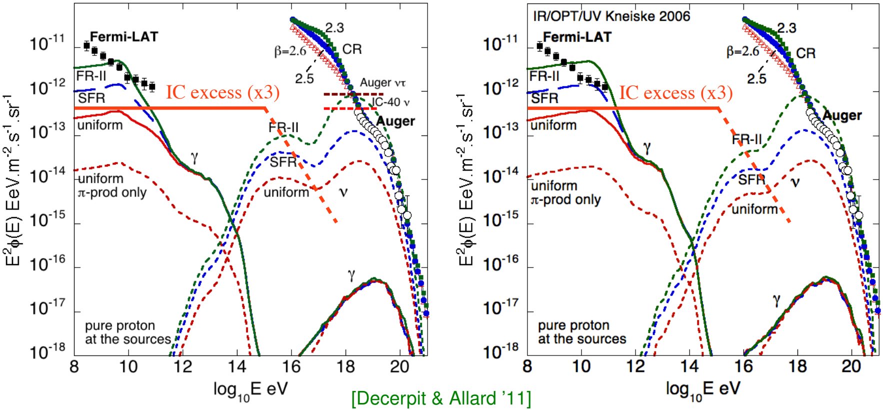
Starburst galaxies

- 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]

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

Cosmogenic neutrinos from heavy nuclei

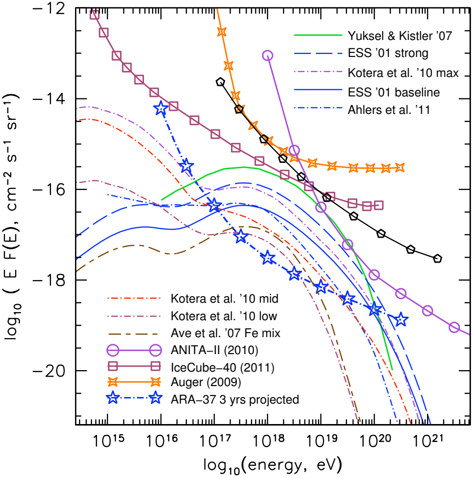


TABLE II: Expected numbers of events N_ν from several UHE neutrino models, comparing published values from the 2008 ANITA-II flight with predicted events for a three-year exposure for ARA-37.

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**!

Approximate* Scaling Law

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

*** disclaimer**:

- source composition 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
  $\omega_\gamma \propto 0.27 \times 0.5$

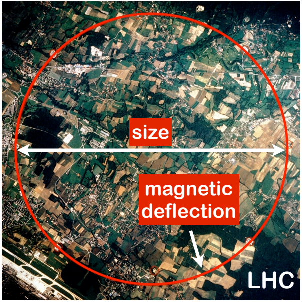
✔ **relative difference:** $\sim 82.$

Sources of UHE CRs?

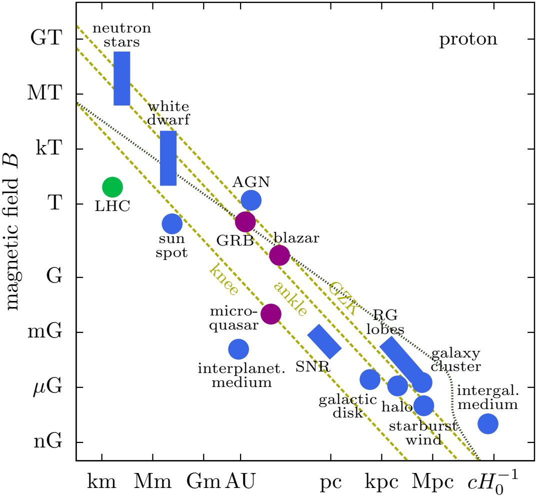
- fundamental energy bound on cosmic accelerators

➜ accelerators with size **R** and magnetic field strength **B**:

$$E_{\max} \simeq 0.9\beta Z\left(\frac{B}{\mu\mathrm{G}}\right)\left(\frac{R}{\mathrm{kpc}}\right)\mathrm{EeV}$$

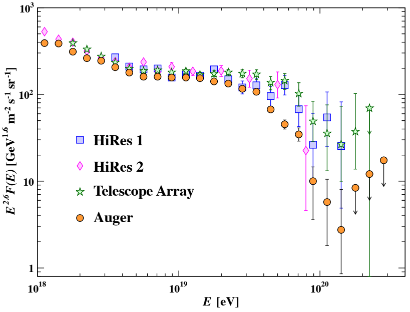


"Hillas plot"

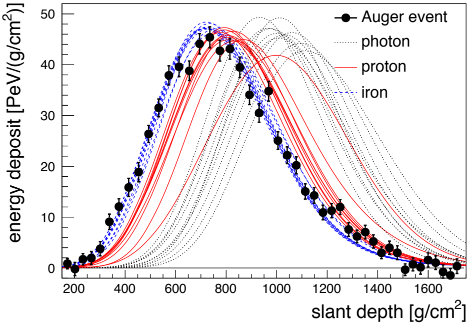


[after Hillas'84]

UHE CR composition



[PDG'13]

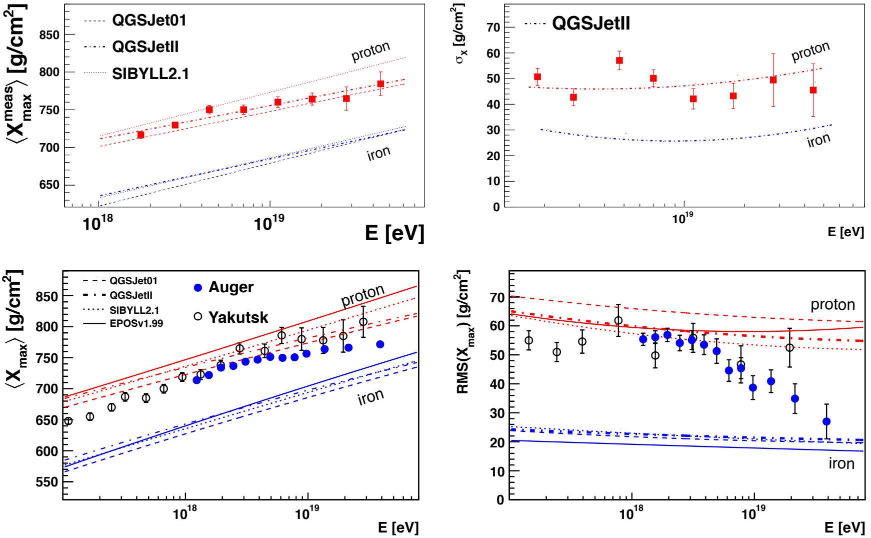


[Kampert&Unger'12]

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

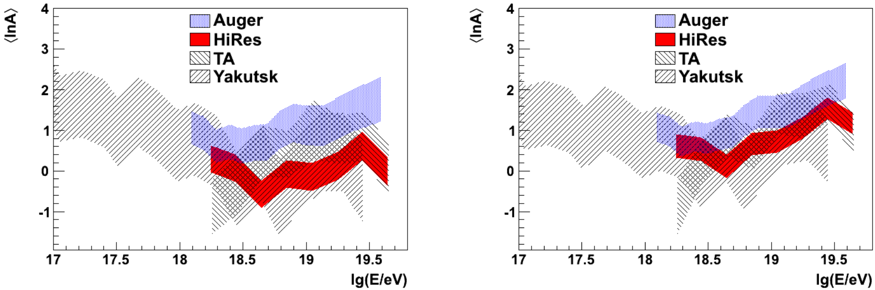
$$\langle \ln A\rangle = \frac{\langle X_{\max}\rangle_p - \langle X_{\max}\rangle_{\mathrm{data}}}{\langle X_{\max}\rangle_p - \langle X_{\max}\rangle_{\mathrm{Fe}}} \ln 56$$

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]

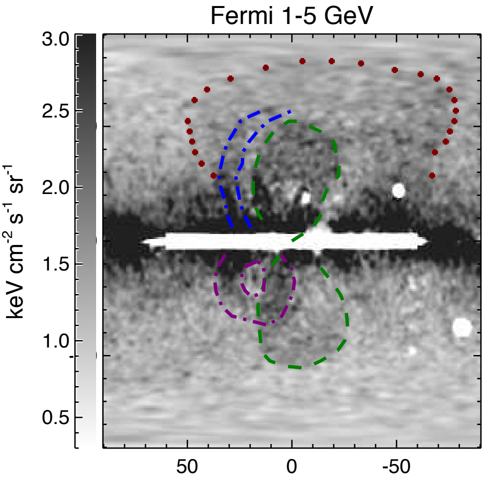
- inferred mass depend on hadronic interactions models
- large systematic uncertainties!

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

Fermi Bubbles

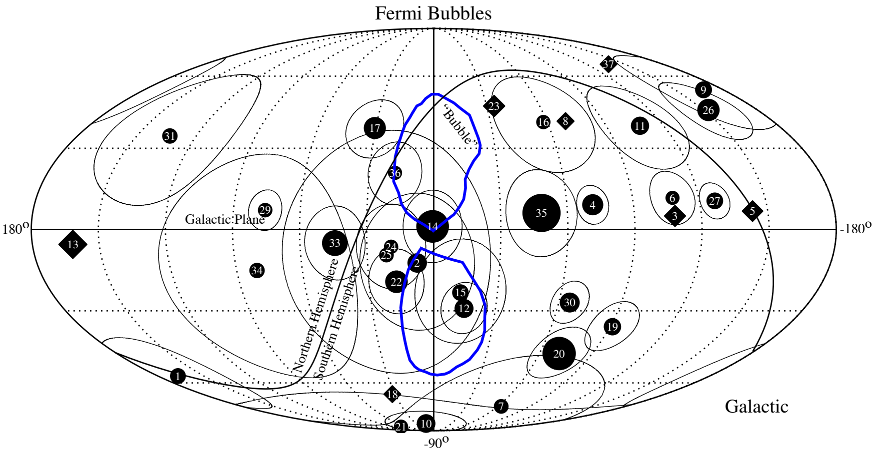
- two extended GeV γ-ray emission regions close to the Galactic Center [Su, Slatyer & Finkbeiner'10]
- hard spectra and relatively uniform emission
- some correlation with WMAP haze and X-ray observation
- model 1: hadronuclear interactions of CRs accelerated by star-burst driven winds and convected 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]

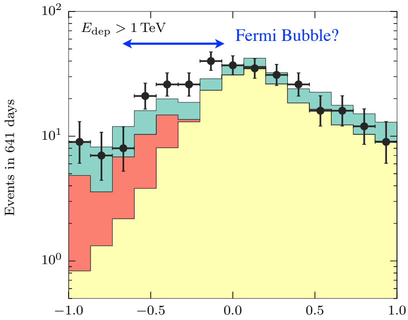


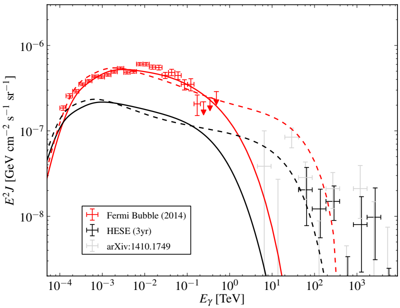
[Su, Slatyer & Finkbeiner'11]

Fermi Bubbles



Fermi Bubbles





[IceCube arXiv:1410.1749]

[MA & Murase 1309.4077; updated with Fermi ApJ 793 (2014)]

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

[Finkbeiner, Su & Slatyer'10; Crocker & Aharonian'11; Lunardini & Razzaque'12]

➜ extrapolation of hadronic γ-ray/neutrino responsible for an **"excess"** at 1-10 TeV?

Contrast of GC excess

- Galactic Center (GC) flux:

$$F_{\rm GC} \simeq \frac{L_{\rm GC}}{4\pi d_{\rm GC}^2}$$

- (quasi-)diffuse flux from similar galaxies:

$$F_{\rm diff} = \frac{1}{4\pi}\int {\rm d}z \, \frac{{\rm d}\mathcal{V}_C}{{\rm d}z}\,\mathcal{H}(z)\,\frac{L_{\rm GC}}{4\pi d_L(z)^2} \simeq \frac{L}{4\pi}\,\frac{\xi_z \mathcal{H}_0}{H_0}$$

➜ flux ratio depend on local source density $\mathcal{H}_0$ and evolution parameter ξ_z:

$$\frac{F_{\rm GC}}{4\pi F_{\rm diff}} \simeq \frac{H_0}{4\pi \xi_z \mathcal{H}_0 d_{\rm GC}^2} \simeq \mathbf{100}\left(\frac{\xi_z}{2.4}\right)^{-1}\left(\frac{\mathcal{H}_0}{10^{-3}}\right)^{-1}$$

- "benchmark" local density $\mathcal{H}_0 \simeq 10^{-3}$–$10^{-2}\,{\rm Mpc}^{-3}$ (normal galaxies)
- "benchmark" evolution $\xi_z \simeq 2.4$ (star-formation rate)

➜ **Additional component needed for full observation.**

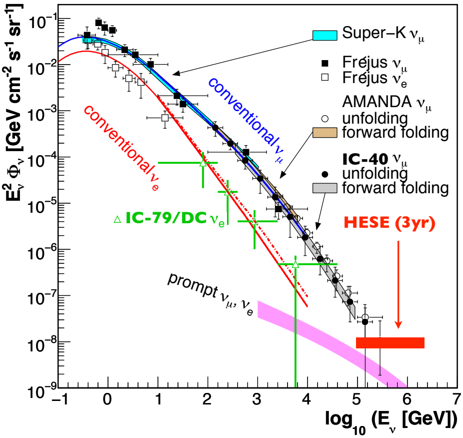
IceCube HESE Sample (3yrs)

- **High-Energy Starting Event (HESE)** sample: [IceCube Science 342 (2013)]
  - bright events ($E_{\rm th} \gtrsim 30$TeV) starting inside IceCube
  - efficient removal of atmospheric backgrounds by veto layer

- 37 events in about three years: [IceCube PRL 113 (2014)]
  - 28 **cascades** events
  - 8 **track** events
  - 1 **composite** event (removed)

- expected background events:
  - $6.6^{+5.9}_{-1.6}$ **atmospheric neutrinos**
  - $8.4^{+4.2}_{-4.2}$ **atmospheric muons**

- **significance** of 5.7σ above backgrounds



Spectrum

- E^{-2}-spectrum of the HESE 3yr sample within $(0.1 - 1)\mathrm{PeV}$: [IceCube PRL 113 (2014)]

$$E_\nu^2 \Phi_{\nu_\alpha} \simeq (0.95 \pm 0.3) \times 10^{-8} \mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

- "classical" muon-neutrino analysis (dominated by Northern Hemisphere) sees flux excess consistent with HESE sample [IceCube APS meeting'14]

- extended HESE sample with lower energy threshold indicates **softer spectrum**: [IceCube 1410.1749]

$$E^2 \Phi_{\nu_\alpha}(E) \simeq \left(2.06^{+0.4}_{-0.3}\right) \times 10^{-8} \left(\frac{E_\nu}{100\mathrm{TeV}}\right)^{-0.46 \pm 0.12}$$