Multi-Messenger Aspects of Cosmic Neutrinos

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Inνisibles15

Madrid, June 25, 2015

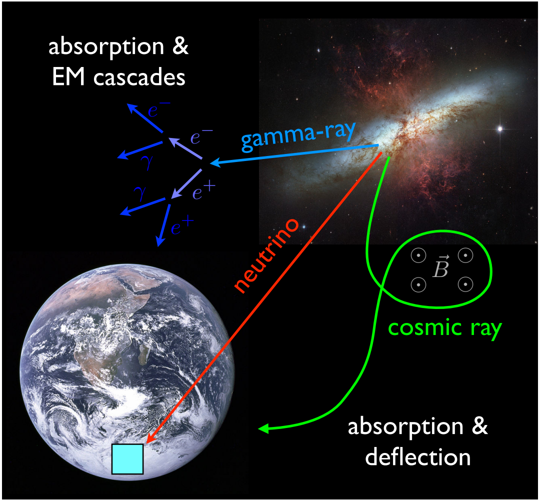
Multi-Messenger Astronomy

- Cosmic Messengers:
  - ✔ Cosmic Rays
  - ✔ Gamma-Rays
  - ✔ Neutrinos
  - ? Gravitational Waves

➜ Neutrino astronomy:

- ✔ closely **related** to cosmic rays (CRs) and γ-rays
- ✔ **weak interaction** during propagation
- ✔ **exclusive messenger** for 10 TeV-10 EeV telescopes

- Challenges:
  - ✘ **low** statistics
  - ✘ **large** backgrounds



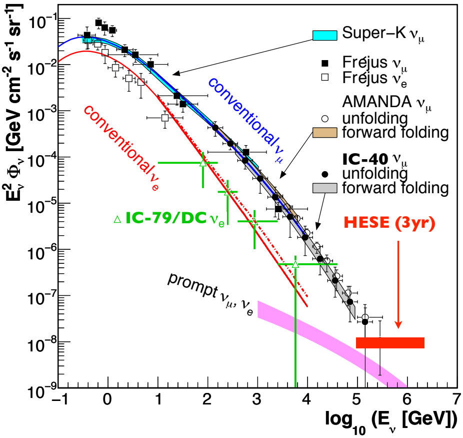
IceCube HESE Sample (3yrs)

- **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

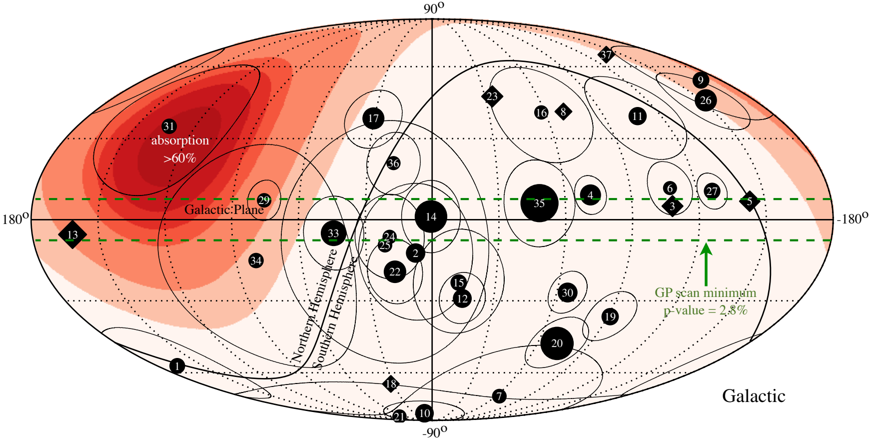
- 37 events in about three years: [IceCube PRL 113 (2014)]
  - 28 **cascades** events
  - 8 **track** events
  - 1 **composite** event (removed)

- 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



IceCube 3 year Results



- **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**

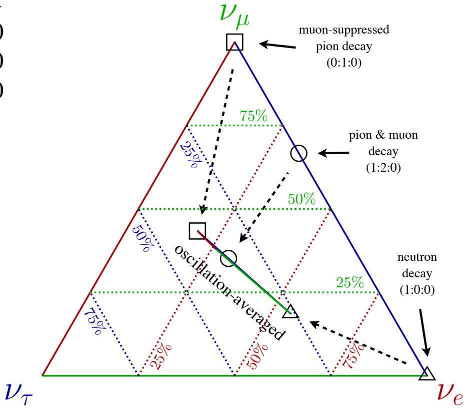
Neutrino Flavors

- initial composition: $\nu_e : \nu_\mu : \nu_\tau$
  pion & muon decay: $1 : 2 : 0$
  neutron decay: $1 : 0 : 0$
  muon-damped pion decay: $0 : 1 : 0$

$$p + p \to \pi^+ + X$$
$$\hookrightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

- oscillation-averaged probability:

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



- "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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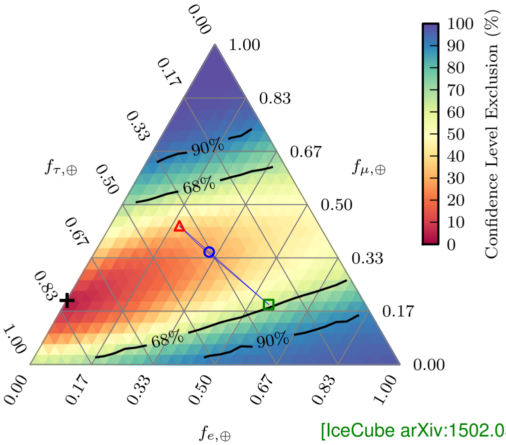

[IceCube arXiv:1502.033]

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Multi-messenger Paradigm

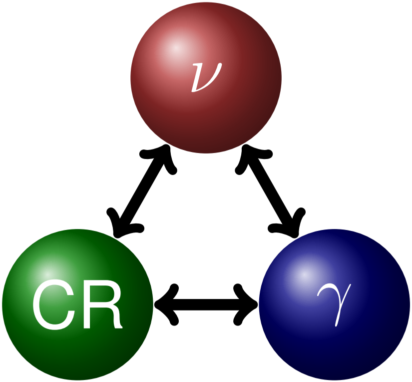
- Neutrino production is closely related to the production of cosmic rays (CRs) and γ-rays.

➜ pion production in CR interactions with gas ("pp") or radiation ("$p\gamma$"); neutrinos with about 5% of CR nucleon energy

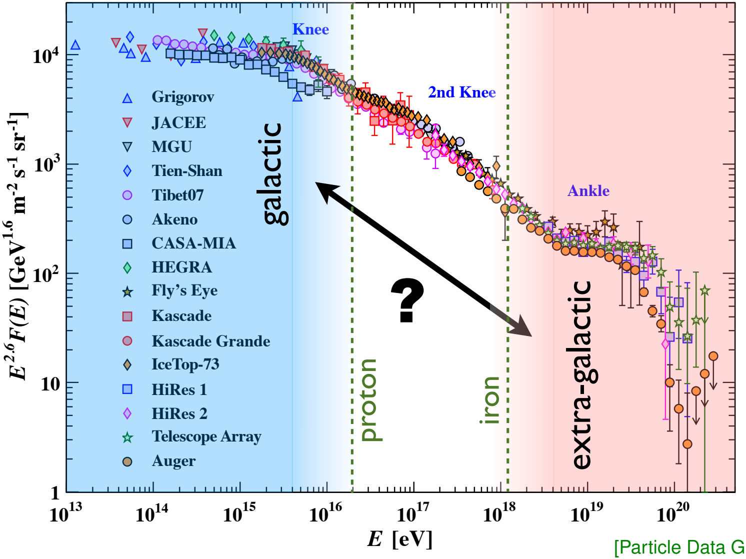
- 1 PeV neutrinos correspond to 20 PeV CR nucleons and 2 PeV γ-rays

➜ **very interesting** energy range:

  - Glashow resonance?
  - galactic or extragalactic?
  - isotropic or point-sources?



The Cosmic "Beam"



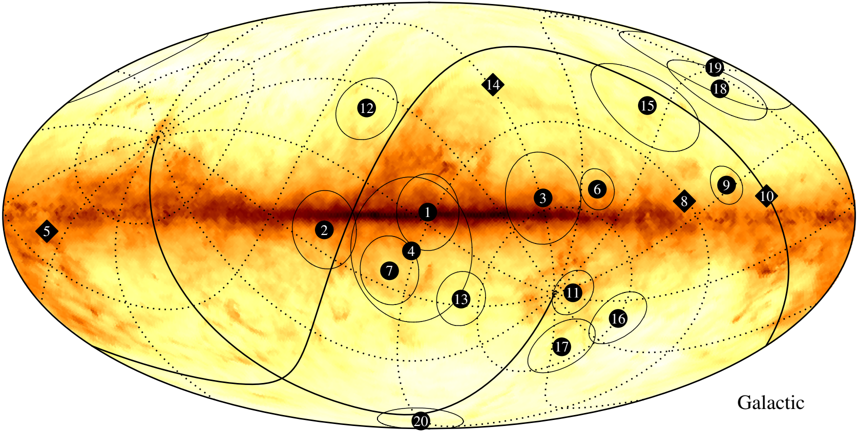
[Particle Data Group'13]

Proposed Source Candidates I

- **Galactic:** (full or partial contribution)
  - diffuse Galactic γ-ray emission [MA & Murase'13; Joshi J C, Winter W and Gupta'13] [Kachelriess M and Ostapchenko'14; Neronov, Semikoz & Tchernin'13] [Neronov & Semikoz'14; Guo, Hu & Tian'14]
  - unidentified Galactic γ-ray emission [Fox, Kashiyama & Meszaros'13] [Gonzalez-Garcia M, Halzen F and Niro'14]
  - supernova remnants [Mandelartz & Tjus'14]
  - pulsars [Padovani & Resconi'14]
  - microquasars [Anchordoqui, Goldberg, Paul, da Silva & Vlcek'14]
  - Sagitarius A* [Bai, Barger, Barger, Lu, Peterson & Salvado'14; Fujita, Kimura & Murase'15]
  - *Fermi Bubbles* [MA & Murase'13; Razzaque'13] [Lunardini, Razzaque, Theodoseau & Yang'13; Lunardini, Razzaque & Yang'15]
  - Galactic Halo [Taylor, Gabici & Aharonian'14]
  - heavy dark matter decay [Feldstein, Kusenko, Matsumoto & Yanagida'13] [Esmaili & Serpico '13; Bai, Lu & Salvado'13; Cherry, Friedland & Shoemaker'14]

Example: Galactic Diffuse Emission

HESE 3yr with $E_{\rm dep} > 60$ TeV, $n_{\rm tot} = 20$, $\widehat{f}_{\rm iso} = 0.81$, $\lambda = 0.74$



- Strong Galactic diffuse emission up to PeV? [Neronov, Semikoz & Tchernin'13]
- simulated map: ◇/○ : Galactic ν | ◇/○ : isotropic ν | ◇/○ : atmospheric ν | ◇/○ : atmospheric μ

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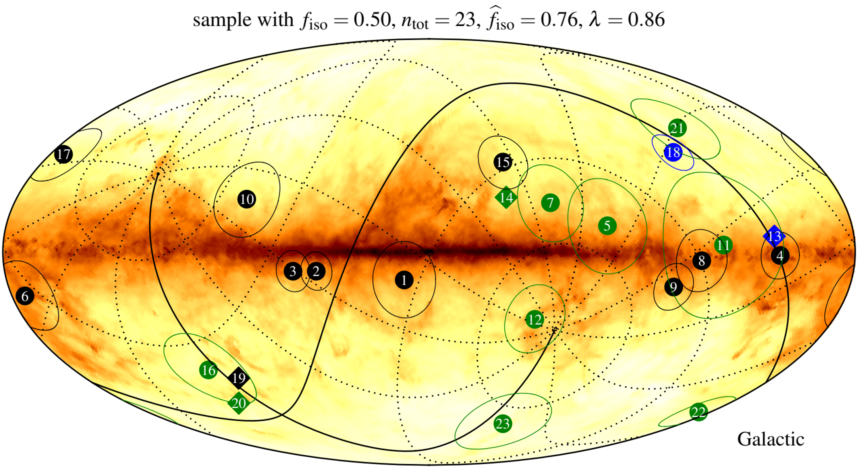

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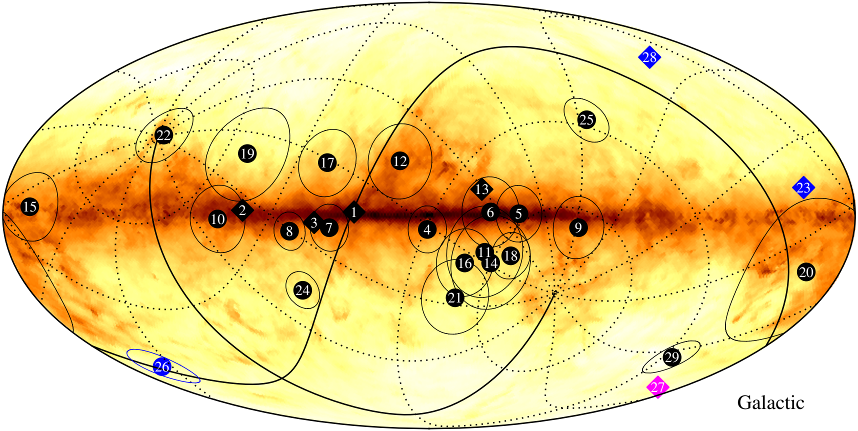
Example: Galactic Diffuse Emission

sample with $f_{\rm iso} = 0.00$, $n_{\rm tot} = 29$, $\widehat{f}_{\rm iso} = 0.09$, $\lambda = 26.03$



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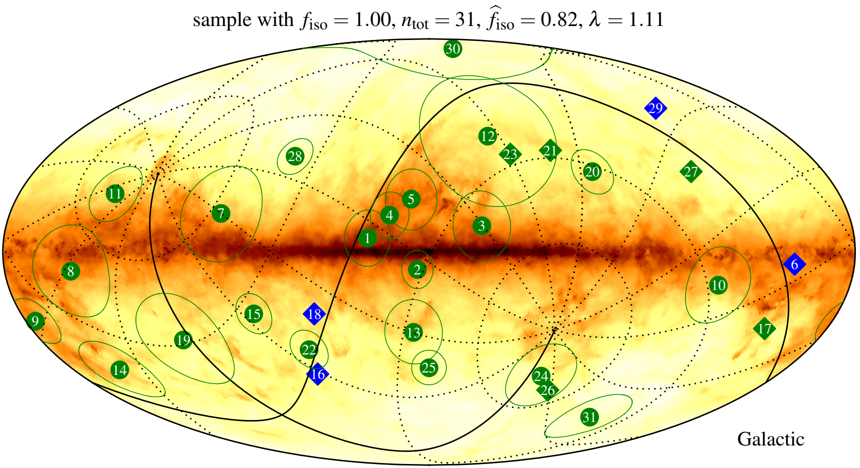

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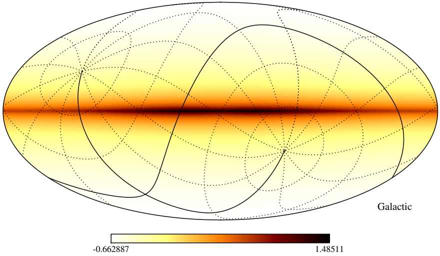
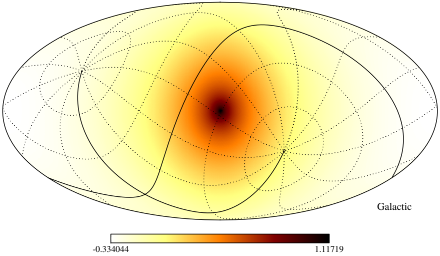
Other Extended Galactic Emission

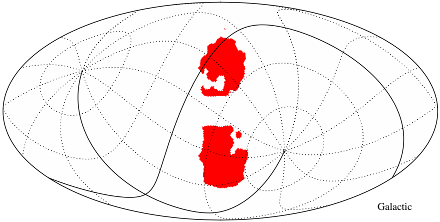
SNR ($\log_{10}(w_{\rm signal}/w_{\rm iso})$)



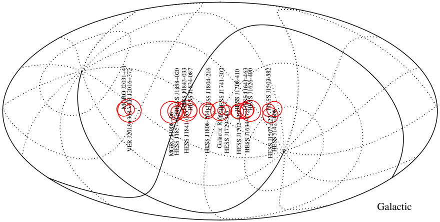
DM decay ($\log_{10}(w_{\rm signal}/w_{\rm iso})$)



Fermi Bubbles

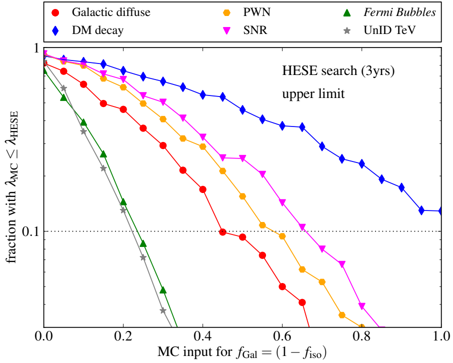


Unidentified & Dark Sources



Galactic Limits

- maximum likelihood-ratio test for Galactic emission (signal)
- **IceCube 3yr limits** ($E_{\rm dep} > 60$ TeV & 90% C.L.):
  - *Fermi Bubbles*: $< 25\%$
  - unidentified TeV γ-ray sources: $< 25\%$
  - Galactic diffuse emission: $< 50\%$
  - cumulative distribution of sources: $< 65\%$
  - PeV DM decay: *unconstrained*
- **stronger** limits possible:
  - spectral and flavor analysis
  - classical $\nu_\mu + \bar{\nu}_\mu$ search
  - PeV γ-ray emission?



[MA, Bai, Barger & Lu'15]

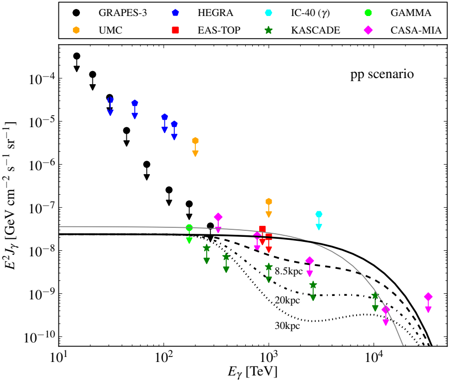
PeV γ-ray Associations?

- IceCube-equivalent diffuse γ-ray flux:

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

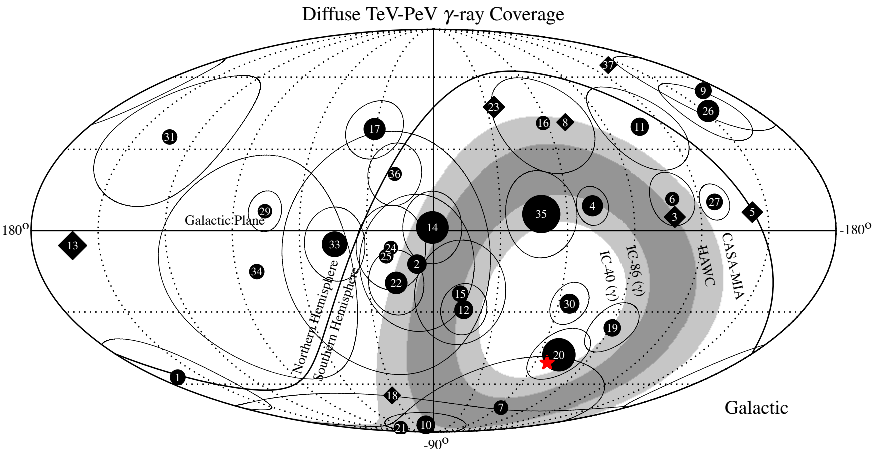
- absorption length $\lambda_{\gamma\gamma}$ via $\gamma\gamma \to e^+e^-$
- effect strongest for CMB in PeV range: $\lambda_{\gamma\gamma} \simeq 10$ kpc
- plot shows distance d from 8.5 kpc (GC) to 30 kpc

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



[MA & Murase'13]

PeV γ-ray Associations?

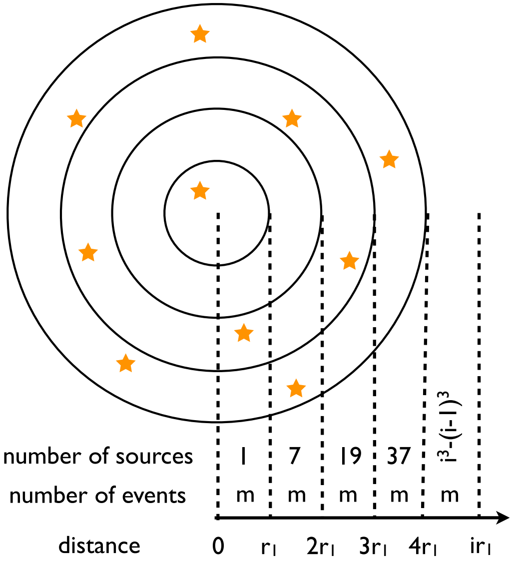


- 16 events lie in TeV-PeV "blind spot" [MA & Murase'13]
- one PeV event ("Ernie") within 10° of PeV γ-ray "warm spot" [IceCube'12]

Proposed Source Candidates II

- **Extragalactic:**
  - association with sources of UHE CRs [Kistler, Stanev & Yuksel'13]
    [Katz, Waxman, Thompson & Loeb'13; Fang, Fujii, Linden & Olinto'14]
  - association with diffuse γ-ray background [Murase, MA & Lacki'13; Chang & Wang'14]
  - active galactic nuclei (AGN) [Stecker'13;Kalashev, Kusenko & Essey'13]
    [Murase, Inoue & Dermer'14; Kimura, Murase & Toma'14; Kalashev, Semikoz & Tkachev'14]
    [Padovani & Resconi'14; Petropoulou, Dimitrakoudis, Padovani, Mastichiadis & Resconi'15]
  - gamma-ray bursts (GRB) [Murase & Ioka'13; Dado & Dar'14]
  - galaxies with intense star-formation
    [He, Wang, Fan, Liu & Wei'13; Yoast-Hull, Gallagher, Zweibel & Everett'13]
    [Murase, MA & Lacki'13; Anchordoqui, Paul, da Silva, Torres& Vlcek'14]
    [Chang & Wang'14; Liu, Wang, Inoue, Crocker& Aharonian'14]
    [Senno, Meszaros, Murase, Baerwald & Rees'15; Chakraborty & Izaguirre'15]
  - galaxy clusters/groups [Murase, MA & Lacki'13; Zandanel, Tamborra, Gabici & Ando'14]
  - . . .

Identification of Extragalactic Point-Sources?



- total number of sources

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

- total number of "shells"

$$n_{\rm shell} \simeq (n_s)^{\frac{1}{3}}$$

- total number of events

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

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

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

✘ random clusters are very likely with bad angular resolution!

➜ **multi-messenger correlations**!

Diffuse vs. Point-Source

- (quasi-)diffuse flux fixes luminosity L:

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

- point-source flux:

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

- 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 HESE E^{-2}-flux:

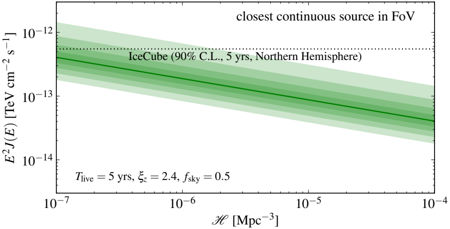
$$\phi_{\rm PS}(E_\nu) \simeq 9\times 10^{-13}\,{\rm TeV cm^{-2} s^{-1}} \left(\frac{\mathcal{H}_0}{10^{-5}{\rm Mpc}^{-3}}\right)^{-1} \left(\frac{r}{10{\rm Mpc}}\right)^{-2} \left(\frac{\xi_z}{2.4}\right)^{-1}$$

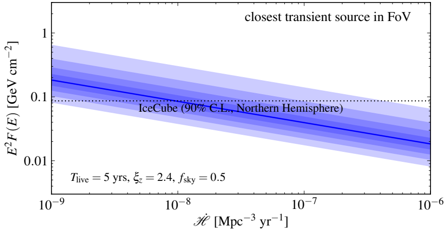
Neutrino Point-Source Limits

- 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 ($\dot{\mathcal{H}} \simeq 10^{-9}\mathrm{Mpc}^{-3}\mathrm{yr}^{-1}$ / $\xi_z \simeq 2.4$)

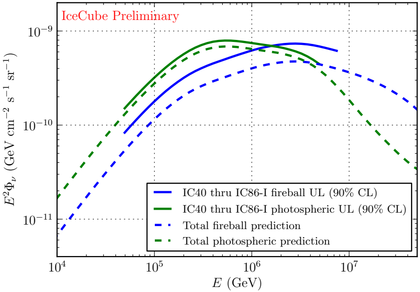




[MA&Halzen’14]

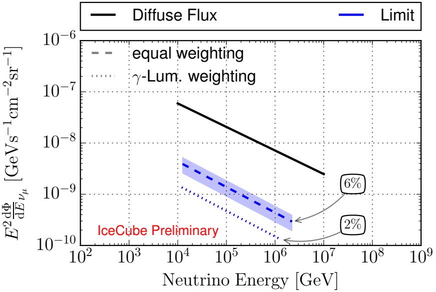
IceCube Stacking Searches

GRB Stacking



[M.Richman ICRC'13; arXiv:1412.6510]

Blazar Stacking



[Th.Gluesenkamp RICAP'14; arXiv:1502.03104]

- ν_μ emission following the GRB "fireball" model
- 492 GRBs (2008–2012) in IceCube's FoV reported with GCN and Fermi GBM

- Fermi blazar stacking
- plot shows limit on 310 FSRQ
- all 2LAC blazar limits of similar strength

Extragalactic Gamma-Rays

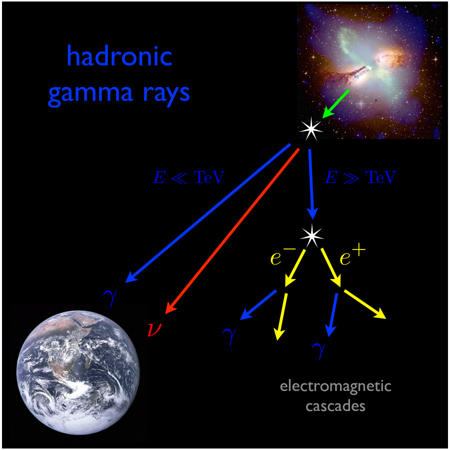
- **hadronic** γ-rays:
  pion production in CR interactions

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

➜ cross-correlation of γ-ray and neutrino sources

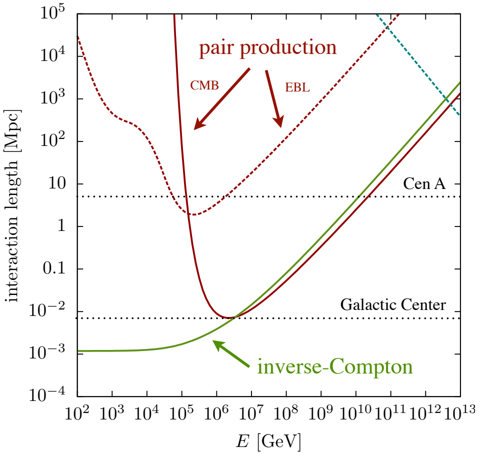
✘ electromagnetic cascades of super-TeV γ-rays in CMB

✔ Isotropic Diffuse Gamma-Ray Background (IGRB) constraints the energy density of hadronic γ-rays & neutrinos



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)

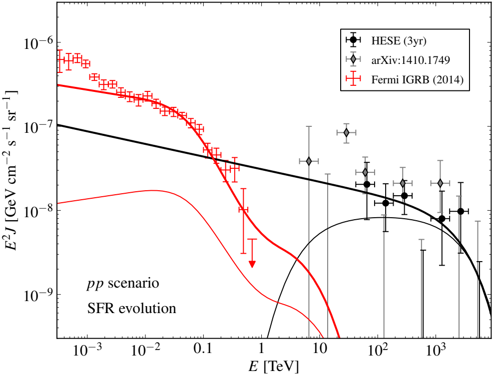
- neutrino and γ-ray fluxes in pp scenarios follow initial CR spectrum $\propto E^{-\Gamma}$

➜ 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 $E_\gamma \gtrsim 100\text{GeV}$

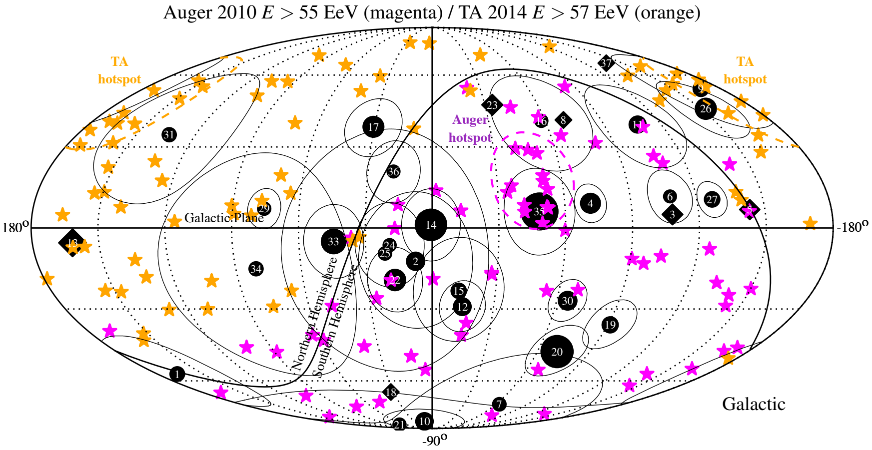


[Murase, MA & Lacki'14 ; IceCube-Gen2 1412.5106]

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]
- 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; MA, Bai, Bargner & Lu'15]
- The diffuse flux also saturates limits from **UHE CR sources**. Is this population also responsible for UHE CRs? [Katz, Waxman, Thompson & Loeb'13]

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]

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 $K_\pi \simeq 1 - 2$):

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

- **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"?

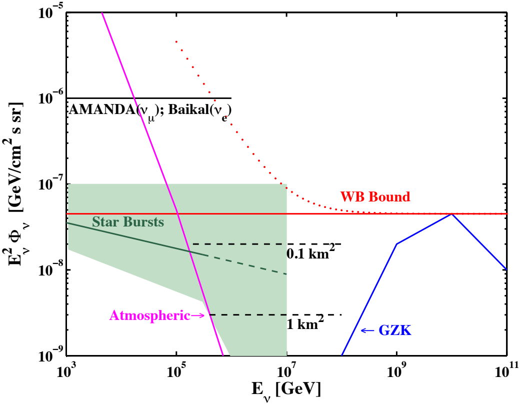
  - starburst galaxies [Loeb&Waxman'06]
  - galaxy clusters [Berezinsky,Blasi&Ptuskin'96;Beacom&Murase'13]

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

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

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]

TeV Starburst Galaxies

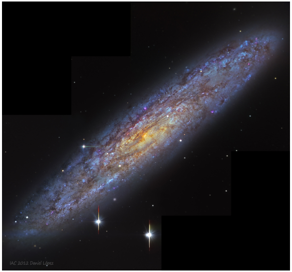
Messier 82

$$E^2\phi_\gamma(E) \simeq 3.3 \times 10^{-13}\left(\frac{E}{\text{TeV}}\right)^{-0.5}\frac{\text{TeV}}{\text{cm}^2\text{s}}$$

$$E^2\phi_\nu(E) \lesssim 3 \times 10^{-12}\frac{\text{TeV}}{\text{cm}^2\text{s}}$$

[IceCube 4yr]

NGC 253



$$E^2\phi_\gamma(E) \simeq 9.6 \times 10^{-13}\left(\frac{E}{\text{TeV}}\right)^{-0.14}\frac{\text{TeV}}{\text{cm}^2\text{s}}$$

no neutrino limit

expected from pp interactions: $E_\nu^2\phi_{\nu_\mu}(E_\nu) \simeq \frac{1}{2}E_\gamma^2\phi_\gamma(E_\gamma)$

Summary & Outlook

- Neutrinos are **unique cosmic (pointing) probes** in the 10TeV-10EeV energy range (six orders of magnitude!).
- Identification of PeV neutrino sources is *challenging*.
- Galactic neutrino emission unlikely the main source of the PeV diffuse flux.

➜ **Multi-messenger correlations** are the most promising scenario for point-source detection, in particular for transient sources.

- **Similar diffuse energy densities** of UHE CRs, γ-rays and neutrinos might indicate a common extragalactic origin.

➜ Input from γ-ray astronomy will be **essential** to identify extragalactic source populations.

- How well can we determine the **spectrum** and **flavor composition**?
- Local **PeV γ-ray astronomy**?
- IceCube 4th year HESE data to be published soon.
- Studies of possible future extensions of IceCube underway.

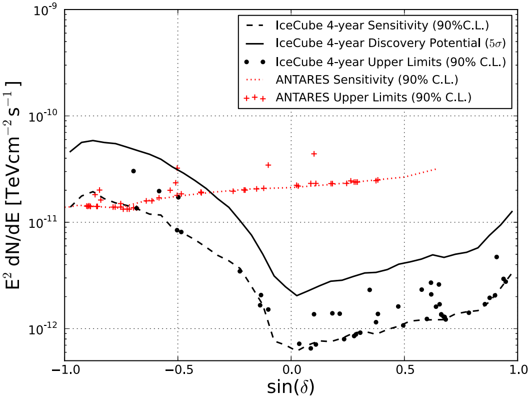
Appendix

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:

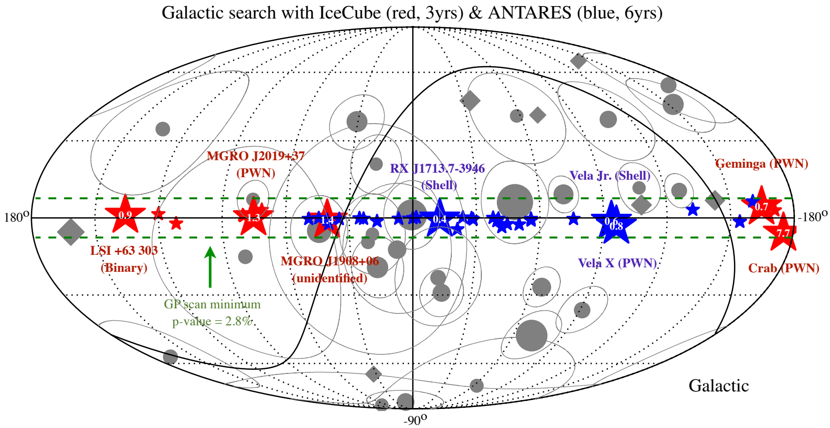
[IceCube ApJ 744 (2012)]

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



[IceCube 1406.6757]

Neutrino Point-Source Limits



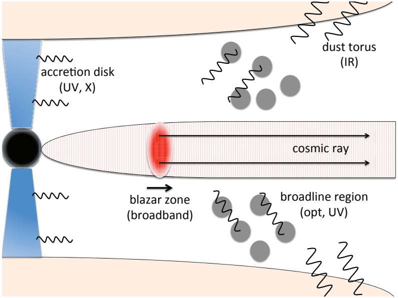
- relative strength of neutrino limits assuming hadronic TeV γ-ray emission (only shown for selected strong sources):

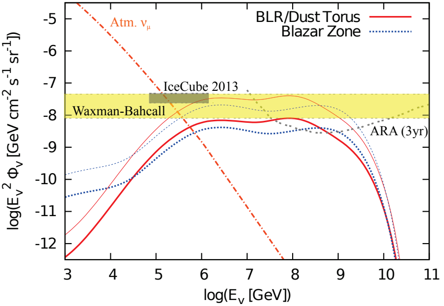
$$F_\gamma(E_\gamma > E_{\rm th})/F_\nu^{90CL}(E_\nu > E_{\rm th}/2)$$

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

AGN jets

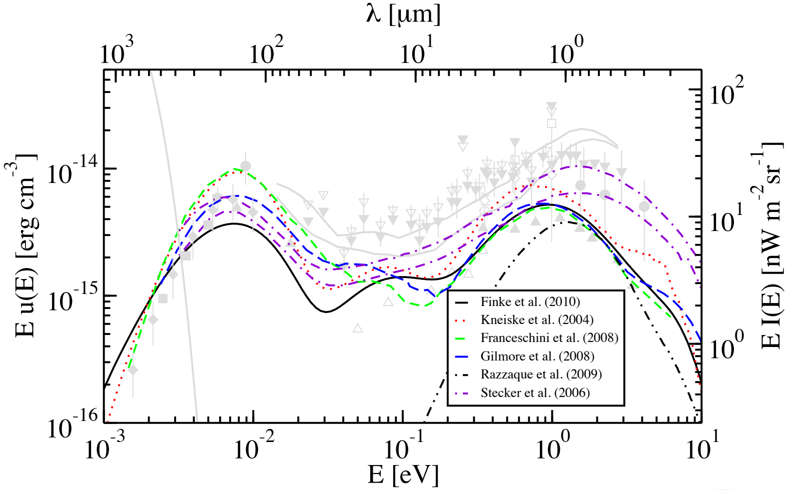
- neutrino from $p\gamma$ interactions in AGN jets [Mannheim'96; Halzen & Zas'97]
- complex spectra due to various photon backgrounds
- typically, deficit of sub-PeV and excess of EeV neutrinos





[Murase, Inoue & Dermer 1403.4089]

Extra-galactic background light (EBL)



[Finke *et al.* '10]

optical-UV background gives PeV neutrino peak

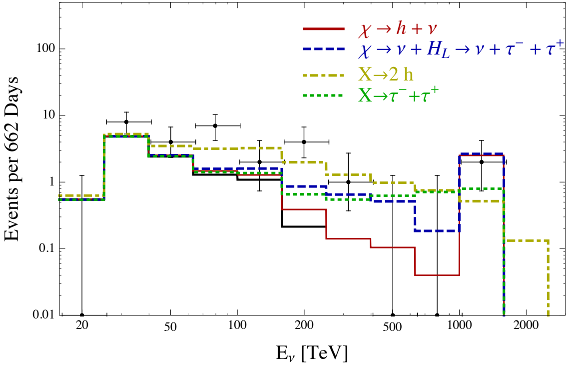
DM decay

- 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]

Ultra-High Energy Cosmic Rays

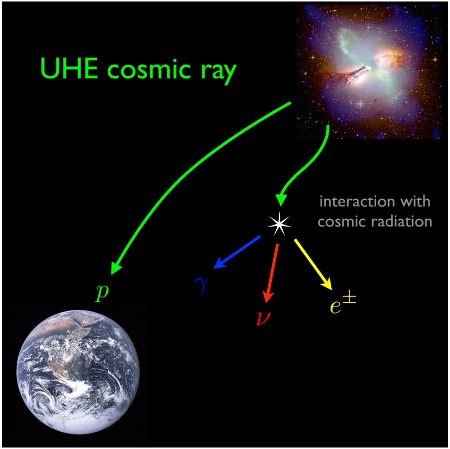
- particle confinement during acceleration requires: [Hillas'84]

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

✘ *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]



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]

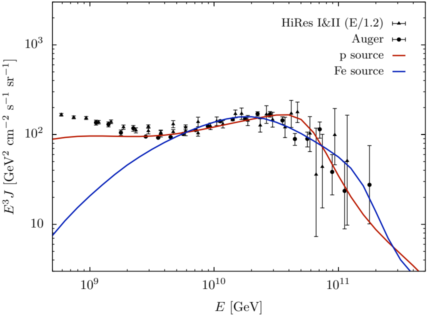
- "Guaranteed", but with many model uncertainties and constraints:
  - **(low cross-over) proton models + CMB (+ EBL)**

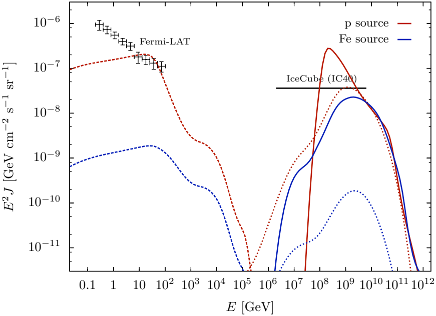
    [Berezinsky & Zatsepin'69; Yoshida & Teshima'93; Protheroe & Johnson'96; Engel, Seckel & Stanev'01; Fodor, Katz, Ringwald &Tu'03; Barger, Huber & Marfatia'06; Yuksel & Kistler'07; Takami, Murase, Nagataki & Sato'09, MA, Anchordoqui & Sarkar'09]
  - **+ mixed compositions**

    [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]

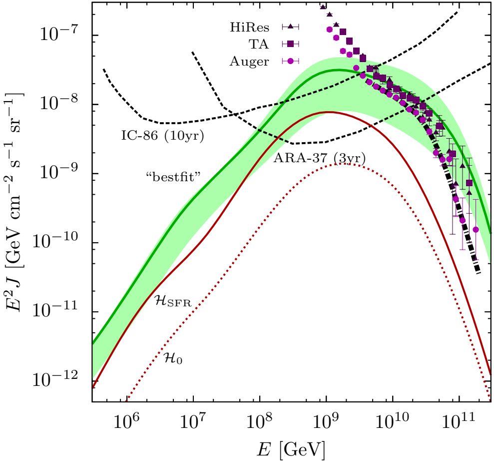
➜ **neutrino limits** start to constrain most optimistic scenarios of proton-dominated UHE CR sources. [IceCube'13;ANITA'12]

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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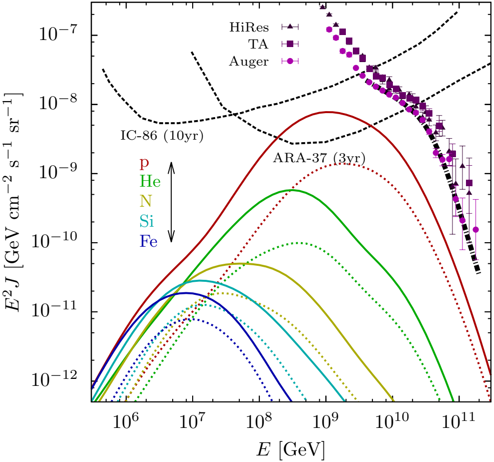
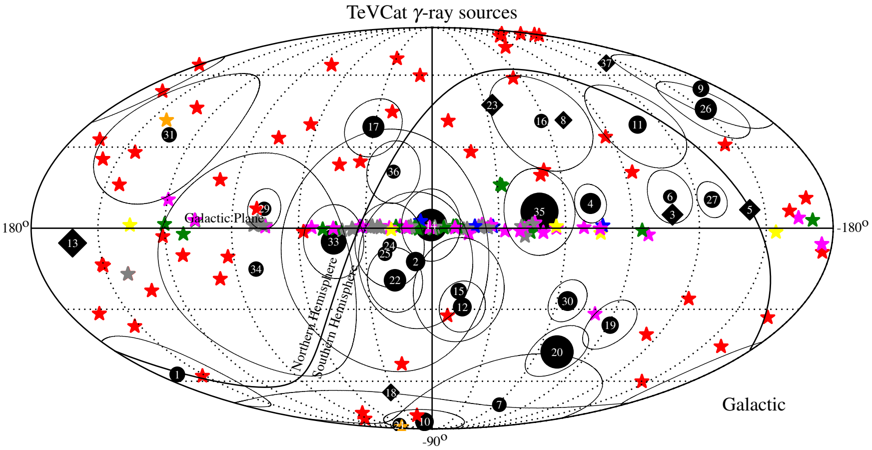


[MA&Halzen'12]

TeV Associations

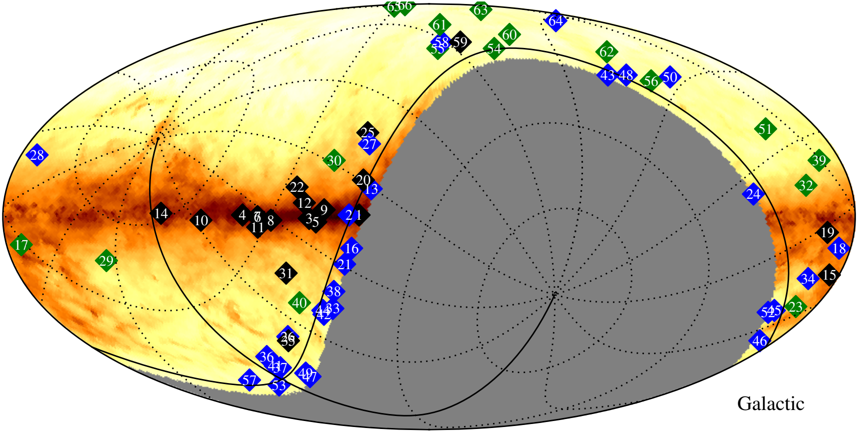


LBL, IBL, LBL, FRI, FSRQ   Globular Cluster, Star Forming Region, Massive Star Cluster

Binary   PWN   Shell, SNR/Molec.Cloud, Composite SNR   Starburst   Others   [TeVCat'14]

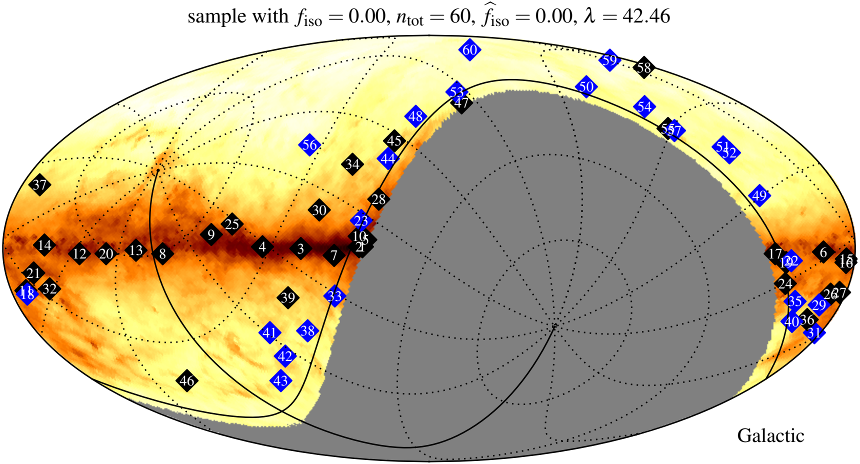
Classical $\nu_\mu + \bar{\nu}_\mu$ Sensitivity

sample with $f_{\text{iso}} = 0.50$, $n_{\text{tot}} = 66$, $\widehat{f}_{\text{iso}} = 0.33$, $\lambda = 24.30$



- Classical $\nu_\mu + \bar{\nu}_\mu$ search in the Northern Hemisphere compared to HESE (all 3yr).
- simulated map: $\diamond/\circ$: Galactic ν | $\diamond/\circ$: isotropic ν | $\diamond/\circ$: atmospheric ν | $\diamond/\circ$: atmospheric μ

Classical $\nu_\mu + \bar{\nu}_\mu$ Sensitivity



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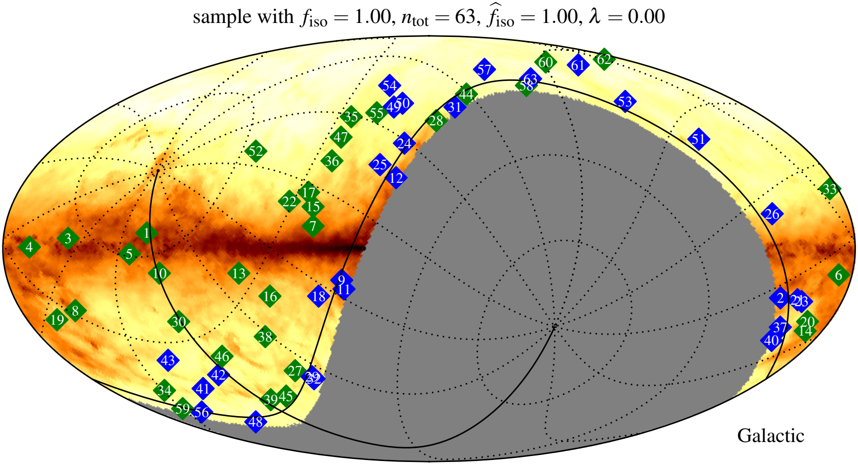

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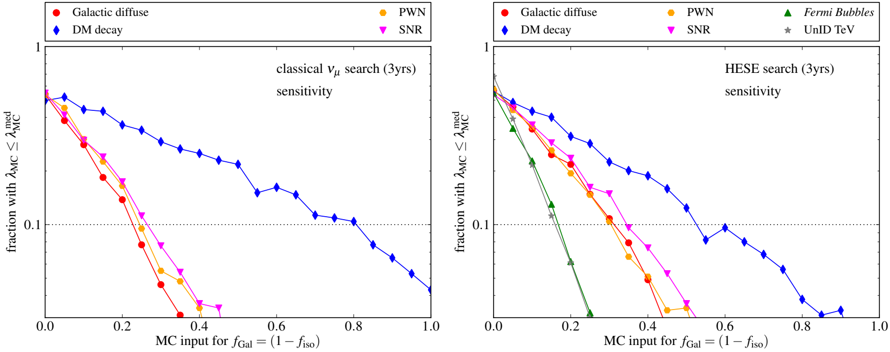

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