# Multimessenger Aspects of Cosmic Neutrinos

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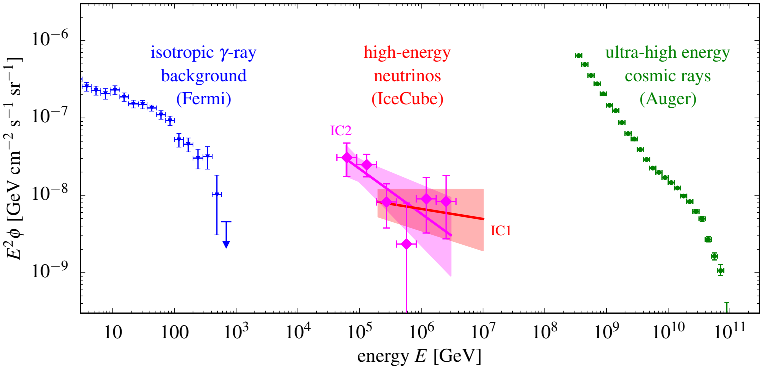
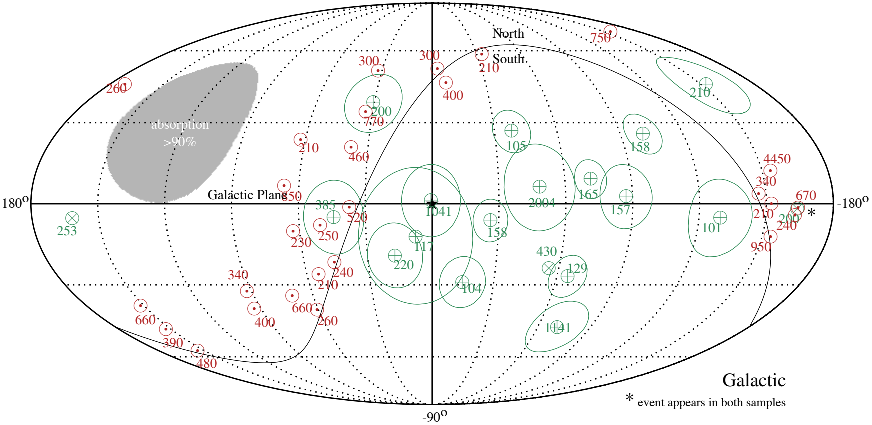
# Cosmic TeV-PeV Neutrinos

- **High-Energy Starting Events (HESE) (6.5$\sigma$ in 4yrs):** [Science 342 (2013)]
  - bright events ($E_{\rm th} \gtrsim 30$TeV) starting inside IceCube
  - efficient removal of atmospheric backgrounds by veto layer
- **Up-going muon-neutrino tracks (5.6$\sigma$ in 6yrs):** [Astrophys.J. 833 (2016)]
  - large effective volume due to ranging in tracks
  - efficient removal of atmospheric muon backgrounds by Earth-absorption



# Neutrino Arrival Directions

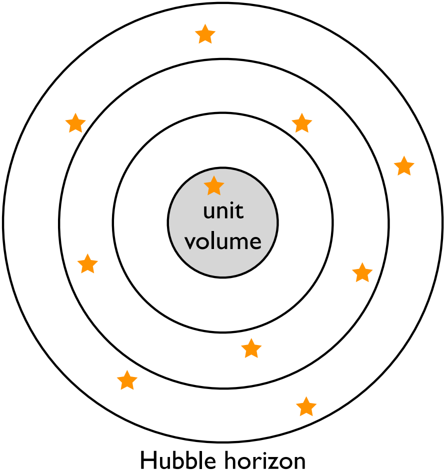
HESE 4yr with $E_{\text{dep}} > 100$ TeV (green) / Classical $\nu_\mu + \bar{\nu}_\mu$ 6yr with $E_\mu > 200$ TeV (red)




- **16 "cascade events" (circles) and 3 "tracks events" (diamonds)** with $E_{\text{dep}} \gtrsim 100$ TeV
- **28(+1) up-going muon neutrino** events with $E_\mu \gtrsim 200$ TeV [IceCube'15]

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

# Revisiting Olbers' Paradox




- expect one source per unit volume:

$$\frac{4\pi f_{\rm sky}}{3} d^3 \rho_0 = 1$$

**A** total number of "unit shells" contributing as much as the closest source

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

➜ e.g., required number of events to see a **doublet** from radio galaxies

$$\bar{N} = 2 \times (n_{\rm source})^{\frac{1}{3}} \simeq 100 - 300$$

**B** brightest source at distance

$$d \simeq \left(\frac{3}{4\pi f_{\rm sky} \rho_0}\right)^{\frac{1}{3}}$$

➜ compare to **point-source sensitivity**

# Multi-messenger Paradigm

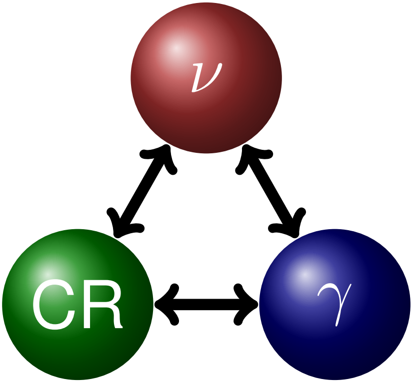
- Neutrino production is closely related to the production of cosmic rays (CRs) and $\gamma$-rays.

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

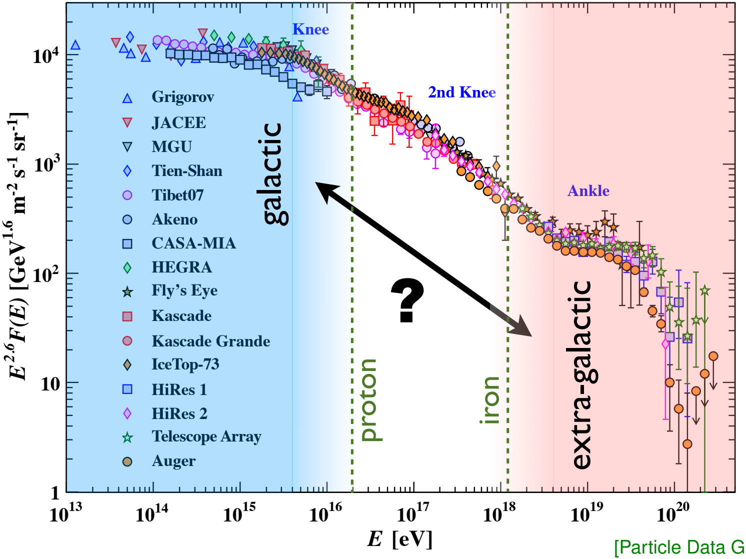
- 1 PeV neutrinos correspond to 20 PeV CR nucleons and 2 PeV $\gamma$-rays

➜ **very interesting** energy range:

  - Galactic or extragalactic CRs?
  - Galactic PeV $\gamma$-rays?
  - isotropic or point-sources?
  - probe of $\bar{\nu}_e$ via Glashow resonance?
  - or exotic origin, e.g. DM decay?



# The Cosmic “Beam”




[Particle Data Group’13]

# Hadronic Gamma-Ray Emission

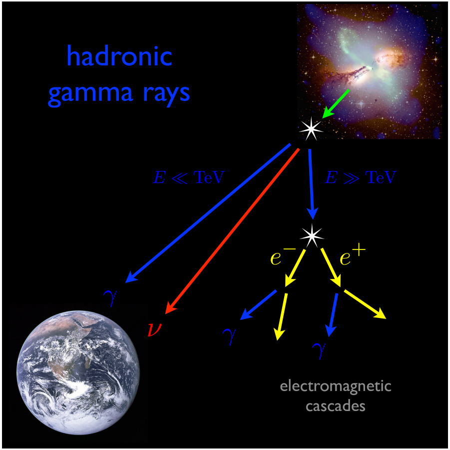
- **hadronic** $\gamma$-rays:
  *pion production in CR interactions*

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

➜ cross-correlation of $\gamma$-ray and neutrino sources

✘ electromagnetic cascades of super-TeV $\gamma$-rays in CMB

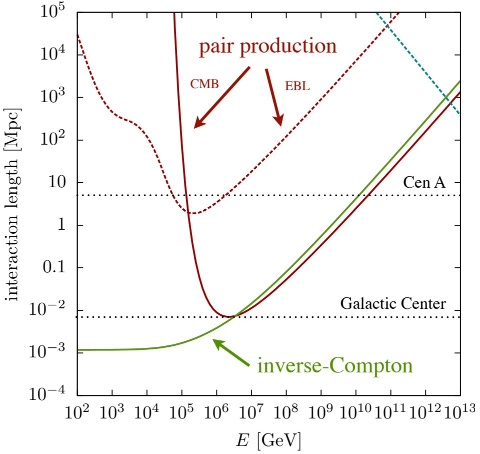
✔ Isotropic Diffuse Gamma-Ray Background (IGRB) constraints the energy density of hadronic $\gamma$-rays & neutrinos



# Gamma-Ray Opacity

- production and decay of neutral pions into gamma rays
- ✘ strong pair production (PP) in CMB: $\gamma + \gamma_{\rm CMB} \to e^+ + e^-$
- ➜ PeV gamma-ray only observable locally ($\lesssim$ 10kpc)
- ✔ recyling of gamma-rays via inverse Compton scattering (ICS): $e^\pm + \gamma_{\rm CMB} \to e^\pm + \gamma$
- rapid cascade interactions produce universal GeV-TeV emission

[Berezinsky&Smirnov'75]




[MA'11]

# Isotropic Diffuse Gamma-Ray Background (IGRB)

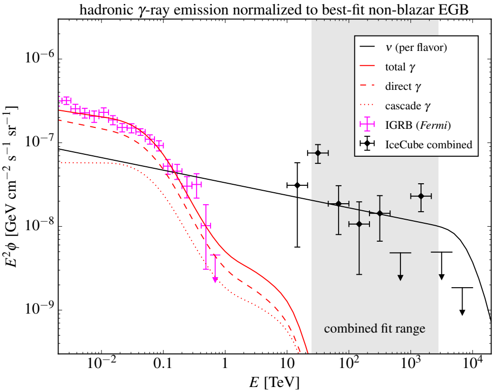
- neutrino and $\gamma$-ray fluxes in $pp$ scenarios follow initial CR spectrum $\propto E^{-\Gamma}$

➜ low energy tail of GeV-TeV neutrino/$\gamma$-ray spectra

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

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

✘ combined IceCube analysis:
$\Gamma \simeq 2.4 - 2.6$
[IceCube'15]




[Murase, MA & Lacki'14; Tamborra, Ando & Murase'14]
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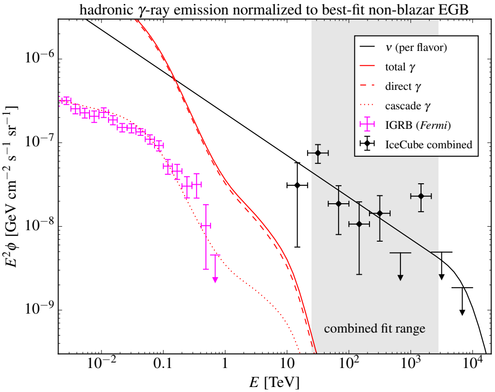


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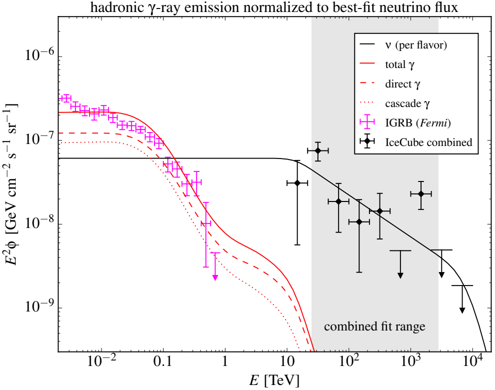


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# Non-Blazar Limits on Gamma-Ray Background

- **Photon fluctuation analyses** of Fermi data allow to constrain the source count distribution ($\mathrm{d}N/\mathrm{d}S$) of blazars **below** the source detection threshold.
- inferred blazar contribution above 50 GeV:
  - Fermi Collaboration'15:

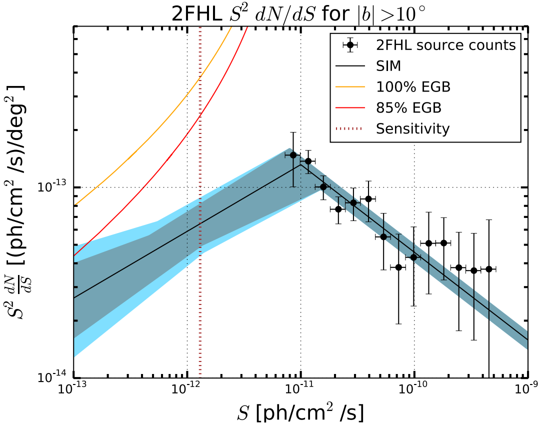
    $$86^{+16}_{-14}\%$$ of EGB

  - Lisanti *et al.*'16:

    $$68^{+9}_{-8}(\pm 10)_{\rm sys}\%$$ of EGB

  - Zechlin *et al.*'16

    $$81^{+52}_{-19}\%$$ of EGB




[Fermi'15]

# Non-Blazar Limits on Gamma-Ray Background

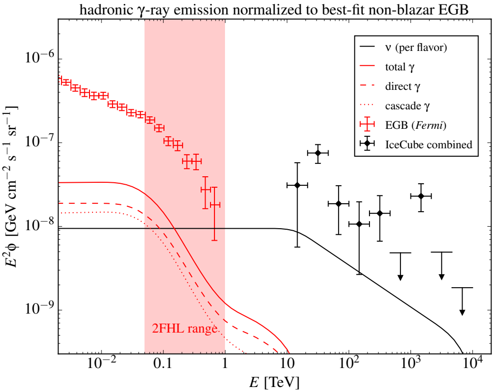
- non-blazar contribution above 50 GeV: [Fermi'15]

$$14^{+14}_{-14}\% \text{ of EGB}$$

✘ **strong tension** with IceCube observation ($E_\nu \lesssim 100$ TeV)

- limits apply to generic **cosmic ray calorimeters**

✘ even **stronger tension** for individual calorimeters, *e.g.* star-forming galaxies




[Bechtol, MA, Ajello, Di Mauro & Vandenbroucke'15]

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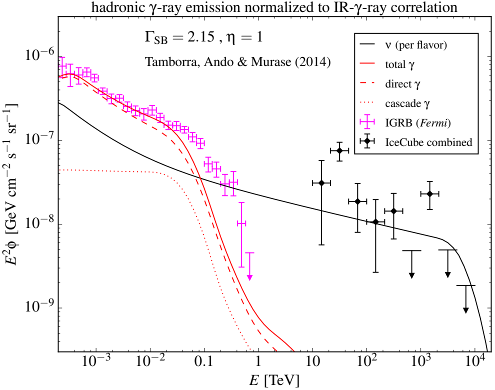
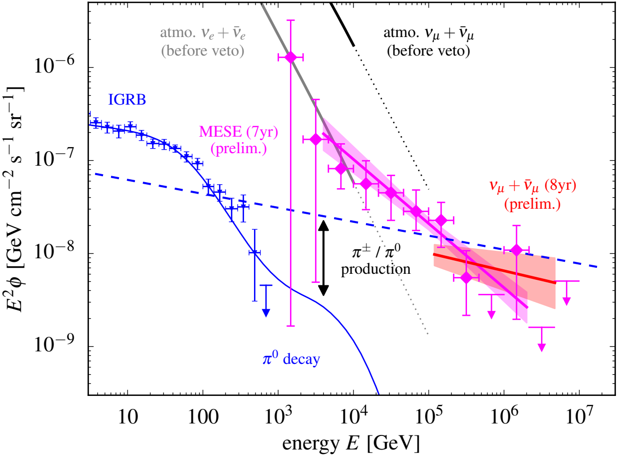



[Bechtol, MA, Ajello, Di Mauro & Vandenbroucke'15]

# Updated Neutrino Fluxes




| | | |
|---|---|---|
| MESE (7yr) | $\Gamma = 2.69 \pm 0.08$ | $[E^2\phi]_{100\text{TeV}} = (2.1^{+0.3}_{-0.3}) \times 10^{-8}$GeV/cm$^2$/s/sr |
| $\nu_\mu + \bar{\nu}_\mu$ (8yr) | $\Gamma = 2.19 \pm 0.1$ | $[E^2\phi]_{100\text{TeV}} = (1.01^{+0.26}_{-0.23}) \times 10^{-8}$GeV/cm$^2$/s/sr |

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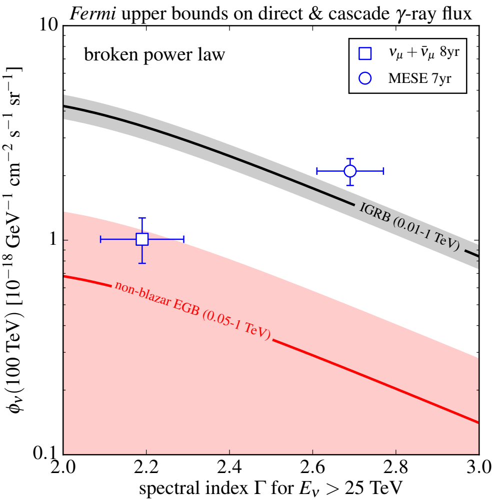


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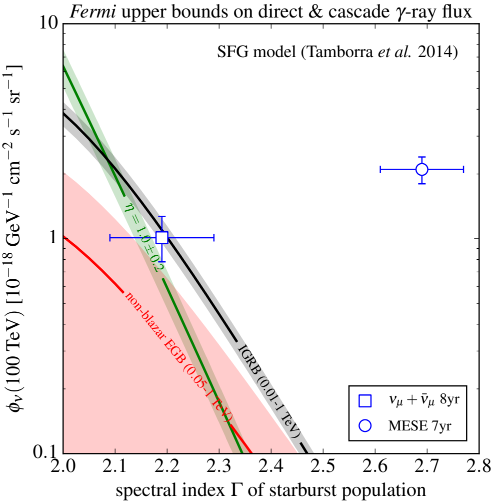



[Bechtol, MA, Ajello, Di Mauro & Vandenbroucke'15]

# Comments & Consequences

- Strong limits apply to **CR calorimeters**, like starburst galaxies or galaxy clusters.
- Some direct $\gamma$-ray emission can be reduced by **absorption** ($\gamma\gamma_{\rm BG}$) in sources.
  [Chang & Wang'14]
- Neutrino flux at $10$ TeV at the level of 10% (100%) of atmospheric $\nu_\mu$ ($\nu_e$) background: **failure of veto mechanism**? [Gaisser, Jero, Karle & van Santen'14]
- Broken power-law would be a natural consequence of a combination of **multiple diffuse neutrino source populations**.
- The diffuse neutrino flux at $E_\nu \gtrsim 100$ TeV saturates limits from **UHE CR sources**. Is this population also responsible for UHE CRs? [Katz, Waxman, Thompson & Loeb'13]
- Is secondary $\gamma$-ray emission in the Fermi range **"hidden"**? [Murase, Guetta & MA'15]

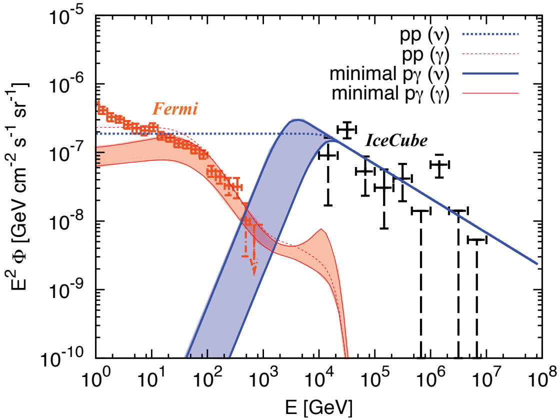
# Fermi Bounds for $p\gamma$ Sources

- Fermi constraints less severe for $p\gamma$ scenarios:

1 **no power-law extrapolation** to Fermi energy range

2 **high pion production efficiency** implies strong $\gamma$-absorption in sources

- source candidates:
  - AGN cores [Stecker'91;'13] [Kimura, Murase & Toma'14]
  - choked GRB jets [Mészáros & Waxman'01] [Senno, Murase & Mészáros'16]




[Murase, Guetta & MA'15]

# Corresponding Opacities

- required cosmic ray energy:

$$E_{\rm CR} \sim 20 E_\nu$$

- required target photon energy:

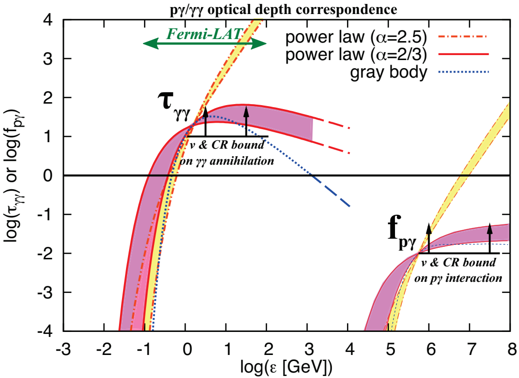
$$\varepsilon_t \sim 200\,{\rm keV}\left(\frac{\Gamma}{10}\right)^2\left(\frac{E_\nu}{3\,{\rm TeV}}\right)^{-1}$$

- **opacity relation**:

$$\tau_{\gamma\gamma}(E_\gamma) \sim 1000\, f_{p\gamma}(E_p)$$

➜ strong internal $\gamma$-absorption:

$$E_\gamma \gtrsim 100\,{\rm MeV}\left(\frac{E_\nu}{3\,{\rm TeV}}\right)$$




[Murase, Guetta & MA'15]

# UHE CR association?

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

$$[E_p^2 Q_p(E_p)]_{10^{19.5}\mathrm{eV}} \simeq 8 \times 10^{43}\,\mathrm{erg\,Mpc}^{-3}\,\mathrm{yr}^{-1}$$

- UHE nucleon emission rate density (local minimum at $\Gamma \simeq 2.04$) [Auger'16]

$$[E_N^2 Q_N(E_N)]_{10^{19.5}\mathrm{eV}} \simeq 2.2 \times 10^{43}\,\mathrm{erg\,Mpc}^{-3}\,\mathrm{yr}^{-1}$$

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

$$E_\nu^2 \phi_\nu(E_\nu) \simeq f_\pi \frac{\xi_z K_\pi}{1 + K_\pi} 1.5 \times 10^{-8}\,\mathrm{GeV\,cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}$$

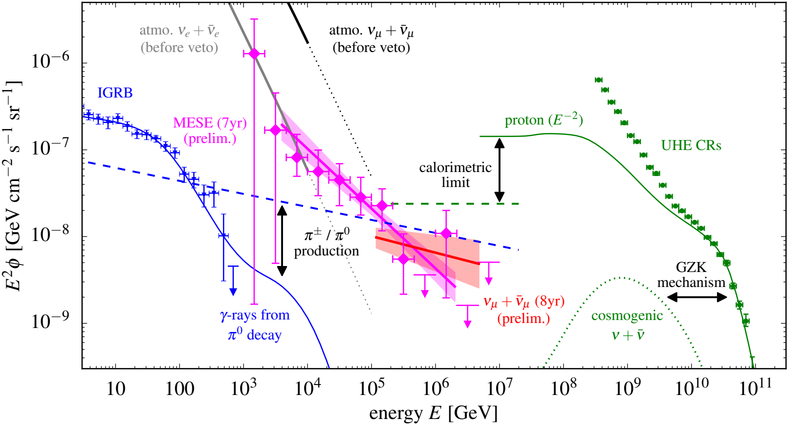
- **Waxman-Bahcall bound:** $f_\pi \leq 1$ [Waxman & Bahcall'98]

✘ how to reach $E_{\rm max} \simeq 10^{20}$ eV in environments of high energy loss ($f_\pi \simeq 1$)?

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

  - starburst galaxies [Loeb & Waxman'06]
  - galaxy clusters [Berezinsky, Blasi & Ptuskin'96; Beacom & Murase'13]
  - "unified" sources [Kachelriess, Kalashev, Ostapchenko & Semikoz'17; Fang & Murase'17]

# Updated Multi-Messenger Panorama

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# Correlation with UHE CRs?

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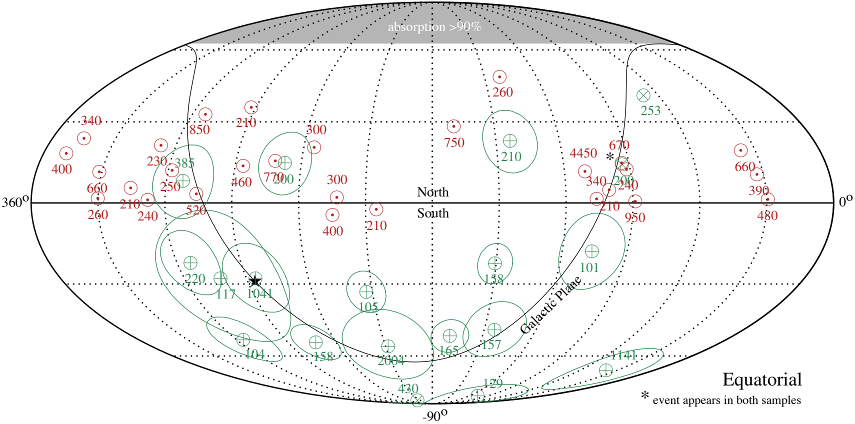


- $\theta_{rms} \simeq 1^\circ \, (D/\lambda_{coh})^{1/2} (E/55\mathrm{EeV})^{-1} (\lambda_{coh}/1\mathrm{Mpc}) \, (B/1\mathrm{nG})$ [Waxman & Miralda-Escude'96]
- "hot spots" (dashed), but no significant auto-correlation in Auger and Telescope Array data

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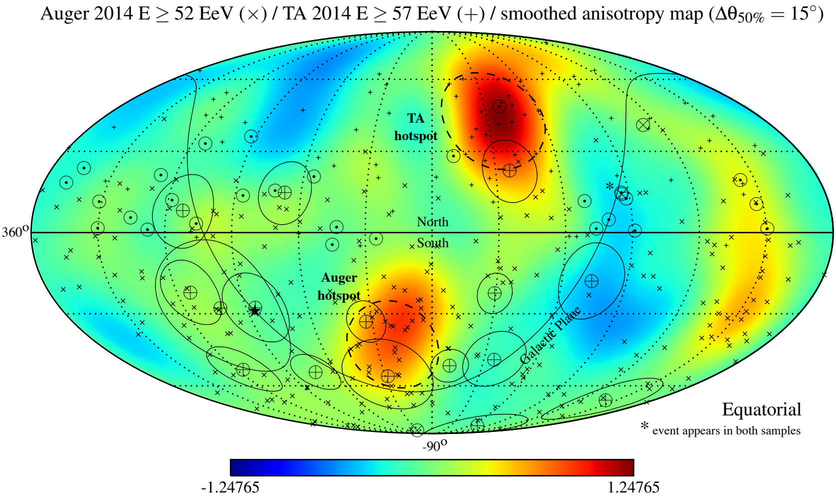


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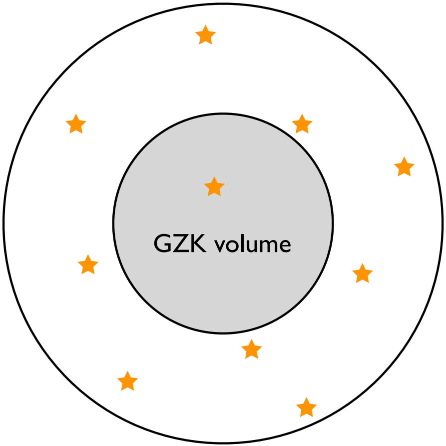
# Identification of Extragalactic Point-Sources?




- Do astrophysical neutrinos correlate with sources of UHE CRs?
- UHE CRs trace sources within

$$\lambda_{\rm GZK} \simeq 200 \text{ Mpc}$$

- neutrinos visible up to Hubble horizon

$$\lambda_{\rm Hubble} \simeq 4.4 \text{ Gpc}$$

➜ maximal overlap:

$$\lambda_{\rm GZK}/\lambda_{\rm Hubble} \sim 5\%$$

- HESE 4yr : ca. $30$ signal events

➜ $1-2$ neutrinos expected to correlate

✘ magnetic deflections, angular resolution, incompleteness,. . .

# Summary

- IceCube has identified a **diffuse flux of astrophysical neutrinos** in the TeV-PeV energy range of **unknown origin**.

- **High intensity** of the emission is comparable to that of ultrahigh-energy cosmic rays and $\gamma$-ray backgrounds.

- Large neutrino flux in the $1-10$ TeV range is **challenged** by constraints set by the extra-galactic $\gamma$-ray background observed by Fermi.

- This motivates a class of neutrino sources **"hidden"** in $\gamma$-rays.

  ➜ Natural implication for $p\gamma$ sources with target photons in the **hard x-ray to soft $\gamma$-ray range**.

  ➜ **New avenues** for neutrino cross-correlation studies.

- **Saturation of calorimetric bounds** of UHE CR sources might indicate common origin.

# Appendix

# 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 $\xi_z$

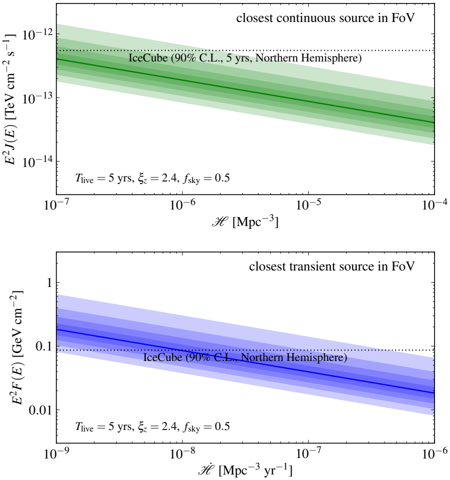
➜ PS observation requires rare sources

- **non-observation** of individual neutrino sources exclude source classes, *e.g.*

  ✘ flat-spectrum radio quasars ($\mathcal{H} \simeq 10^{-9}\mathrm{Mpc}^{-3}$)

  ✘ "normal" GRBs ($\dot{\mathcal{H}} \simeq 10^{-9}\mathrm{Mpc}^{-3}\mathrm{yr}^{-1}$)

➜ **stronger limits** via source "stacking"




[MA&Halzen'14]