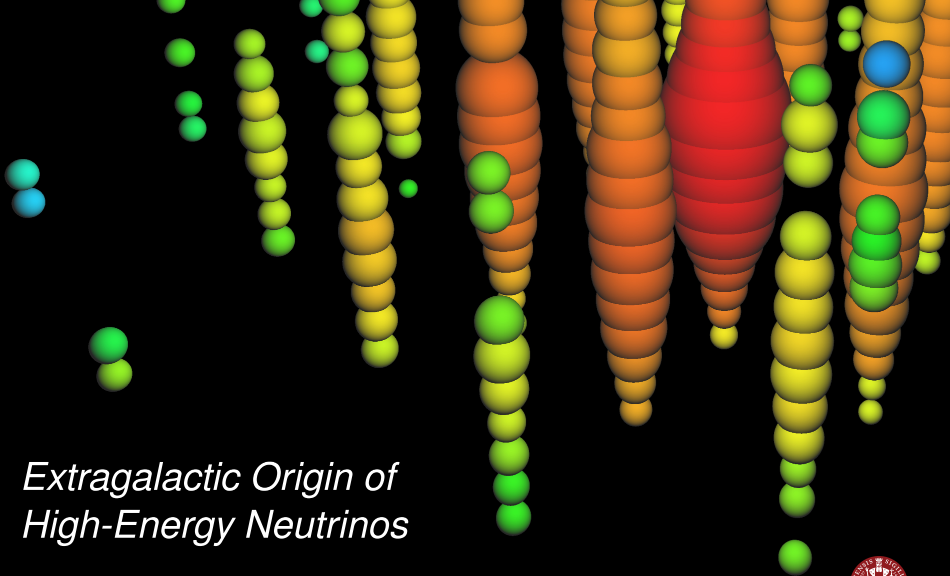


Extragalactic Origin of High-Energy Neutrinos

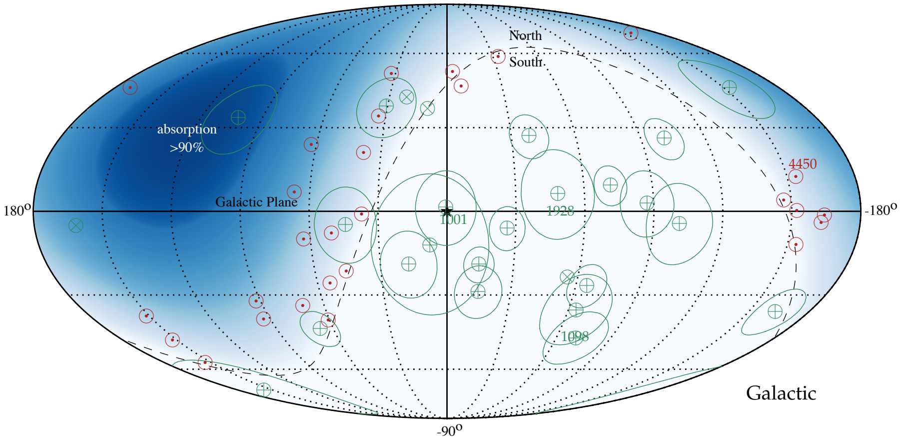
Markus Ahlers, Niels Bohr Institute

SuGAR, Brussels, January 23-26, 2018

UNIVERSITY OF COPENHAGEN

Neutrino Arrival Directions

Arrival directions of most energetic neutrino events (HESE 6yr (green) & $\nu_\mu + \overline{\nu}_\mu$ 6yr (red))



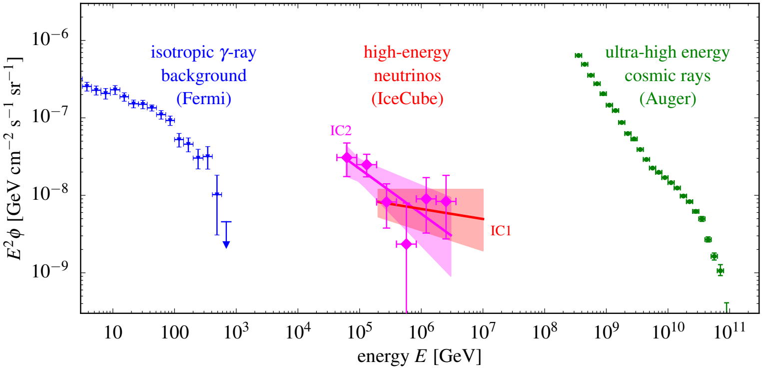
No significant correlation of neutrino events with Galactic structure.

Neutrino Arrival Directions

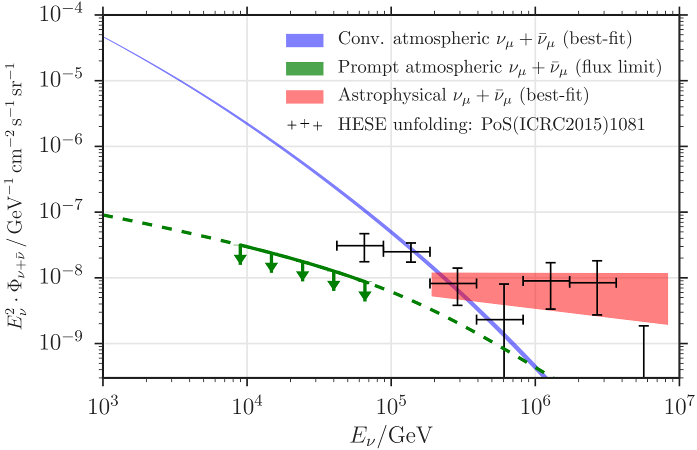
Extragalactic neutrino sources are **hiding in plain sight**.

Cosmic TeV-PeV Neutrinos

- **High-Energy Starting Events (HESE) (6.5σ 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 (5.6σ in 6yrs):** [Astrophys.J. 833 (2016)]
  - large effective volume due to ranging in tracks
  - efficient removal of atmospheric muon backgrounds by Earth-absorption

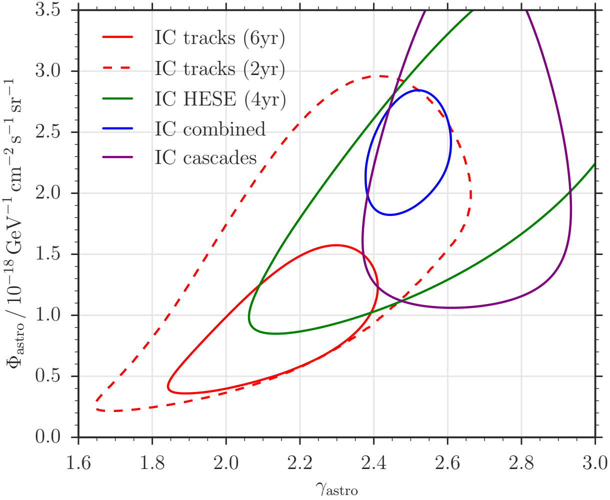


Fit of Power-Law Spectrum



Mild tension with cascade-dominated samples:
Indication of spectral features? [PRL 115 (2015) 081102]

Fit of Power-Law Spectrum



Mild tension with cascade-dominated samples:
Indication of spectral features? [PRL 115 (2015) 081102]

Multi-Messenger Paradigm

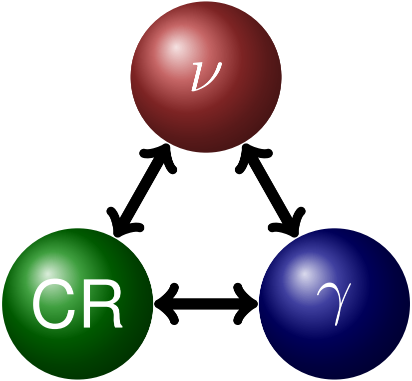
- Neutrino production is closely related to the production of cosmic rays (CRs) and γ-rays.

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

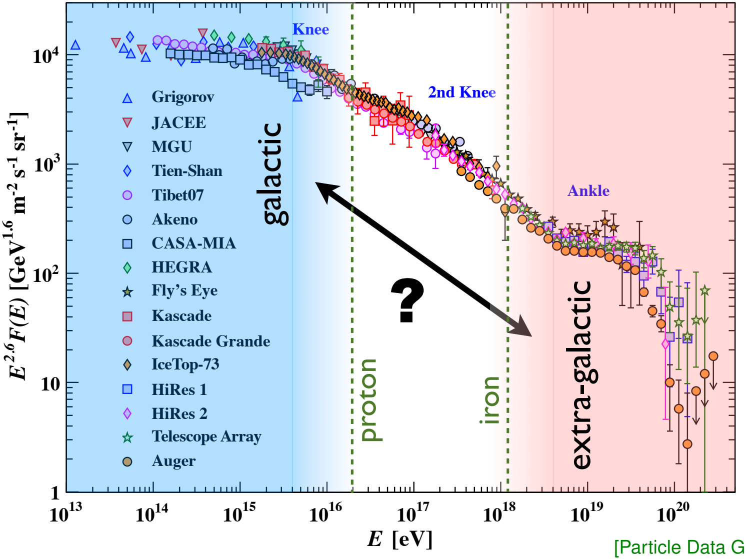
- 1 PeV neutrinos correspond to 20 PeV CR nucleons and 2 PeV γ-rays

➜ **very interesting** energy range:

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



The Cosmic "Beam"



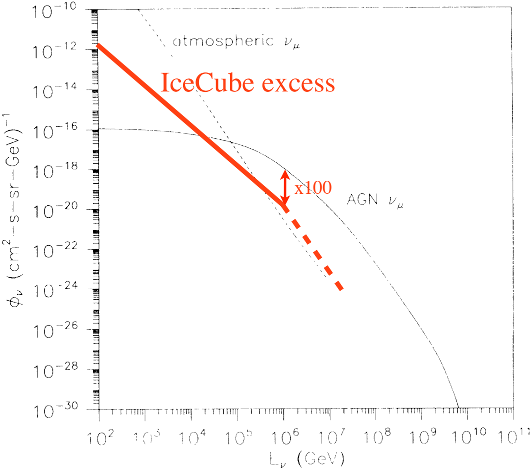
[Particle Data Group'13]

Extragalactic Source Candidates

- association with sources of UHE CRs [Kistler, Stanev & Yuksel'13]
  [Katz, Waxman, Thompson & Loeb'13; Fang, Fujii, Linden & Olinto'14;Moharana & Razzaque'15]
- association with diffuse γ-ray background [Murase, MA & Lacki'13]
  [Chang & Wang'14; Ando, Tamborra & Zandanel'15]
- 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 *et al.*'15; Padovani *et al.*'16; Kadler *et al.*'16; Wang & Loeb'16]
- gamma-ray bursts (GRB) [Murase & Ioka'13; Dado & Dar'14; Tamborra & Ando'15]
  [Senno, Murase & Meszaros'16]
- galaxies with intense star-formation (*e.g.* starbursts)
  [He, Wang, Fan, Liu & Wei'13; Yoast-Hull, Gallagher, Zweibel & Everett'13; Murase, MA & Lacki'13]
  [Anchordoqui, Paul, da Silva, Torres& Vlcek'14; Tamborra, Ando & Murase'14; Chang & Wang'14]
  [Liu, Wang, Inoue, Crocker & Aharonian'14; Senno, Meszaros, Murase, Baerwald & Rees'15]
  [Chakraborty & Izaguirre'15; Emig, Lunardini & Windhorst'15; Bechtol *et al.*'15]
- galaxy clusters/groups [Murase, MA & Lacki'13; Zandanel, Tamborra, Gabici & Ando'14]
- tidal disruption events (TDE) [Wang, Liu, Dai & Cheng'11; Senno, Murase & Més'aros'17]
  [Guépin, Kotera, Barausse, Fang & Murase'17; Biehl, Boncioli, Lunardini & Winter'17]

A) Active Galactic Nuclei

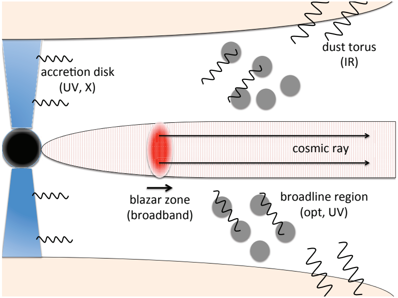
- neutrino production from $p\gamma$ interactions in AGN cores [Stecker *et al.*'91]
- AGN diffuse emission normalized to X-ray background
- revised model predicts 5% of original estimate [Stecker'05;'13]

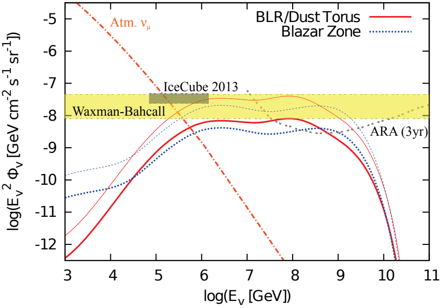


[Stecker *et al.*'91]

A) Active Galactic Nuclei

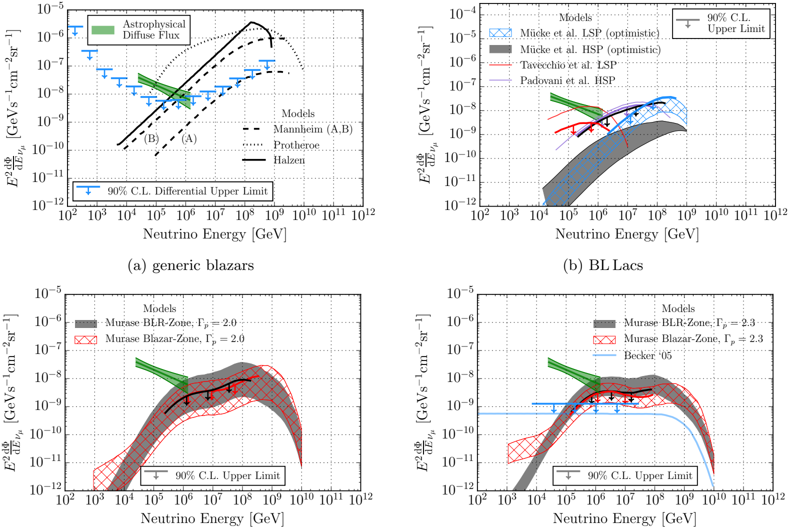
- neutrinos from $p\gamma$ interactions in AGN jets [Mannheim'96; Halzen & Zas'97]
- complex spectra due to various photon backgrounds
- typically, deficit of sub-PeV and excess of EeV neutrinos





[Murase, Inoue & Dermer'14]

A) Active Galactic Nuclei



(a) generic blazars

(b) BL Lacs

(c) FSRQs - 1

(d) FSRQs - 2

Blazar stacking limits derived from Fermi-LAT AGN catalogue (2LAC) [IceCube'16]

A) Blazar Flares?

nature physics

ARTICLES

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Coincidence of a high-fluence blazar outburst with a PeV-energy neutrino event

M. Kadler[1★], F. Krauß[1,2], K. Mannheim[1], R. Ojha[3,4,5], C. Müller[1,6], R. Schulz[1,2], G. Anton[7], W. Baumgartner[3], T. Beuchert[1,2], S. Buson[8,9], B. Carpenter[5], T. Eberl[7], P. G. Edwards[10], D. Eisenacher Glawion[1], D. Elsässer[1], N. Gehrels[3], C. Gräfe[1,2], S. Gulyaev[11], H. Hase[12], S. Horiuchi[13], C. W. James[7], A. Kappes[1], A. Kappes[7], U. Katz[7], A. Kreikenbohm[1,2], M. Kreter[1,7], I. Kreykenbohm[2], M. Langejahn[1,2], K. Leiter[1,2], E. Litzinger[1,2], F. Longo[14,15], J. E. J. Lovell[16], J. McEnery[3], T. Natusch[11], C. Phillips[10], C. Plötz[12], J. Quick[17], E. Ros[18,19,20], F. W. Stecker[3,21], T. Steinbring[1,2], J. Stevens[10], D. J. Thompson[3], J. Trüstedt[1,2], A. K. Tzioumis[10], S. Weston[11], J. Wilms[2] and J. A. Zensus[18]

individual objects are too low to make an unambiguous source association. Here, we report that a major outburst of the blazar PKS B1424–418 occurred in temporal and positional coincidence with a third petaelectronvolt-energy neutrino event (HESE-35) detected by IceCube. On the basis of an analysis of the full sample of γ-ray blazars in the HESE-35 field, we

There is a remarkable coincidence with the IceCube-detected petaelectronvolt-neutrino event HESE-35 with a probability of only ∼5% for a chance coincidence. Our model reproduces the

A) Blazar Flares?

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2017; 10:10 UT
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890, 10942

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

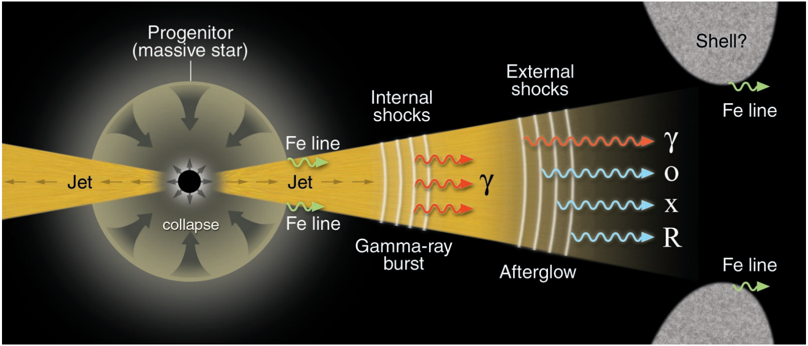
ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

B) Gamma-Ray Bursts

- Neutrino production at various stages of a gamma-ray burst (GRB).
  - → **precursor** pp and $p\gamma$ interactions in stellar envelope; also possible for "failed" GRBs [Razzaque,Meszaros&Waxman'03]
  - → **burst** $p\gamma$ interactions in internal shocks [Waxman&Bahcall'97]
  - → **afterglow** $p\gamma$ interactions in reverse external shocks [Waxman&Bahcall'00;Murase&Nagataki'06;Murase'07]

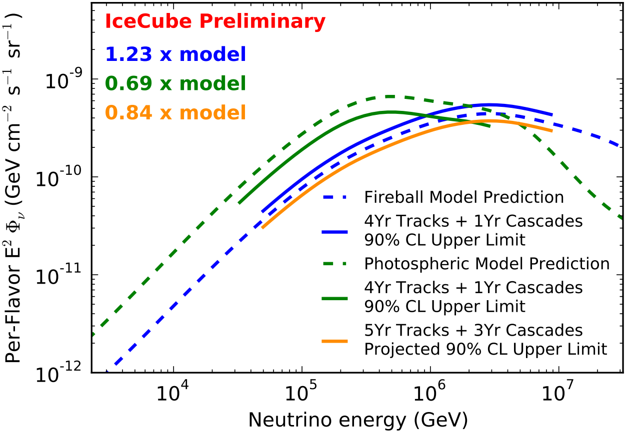


[Meszaros'01]

B) Gamma-Ray Bursts

- strong limits on neutrino emission associated with "fireball" model [Abbasi *et al.*'12]

➜ PeV neutrino flux exceeds GRB limit by one order of magnitude.



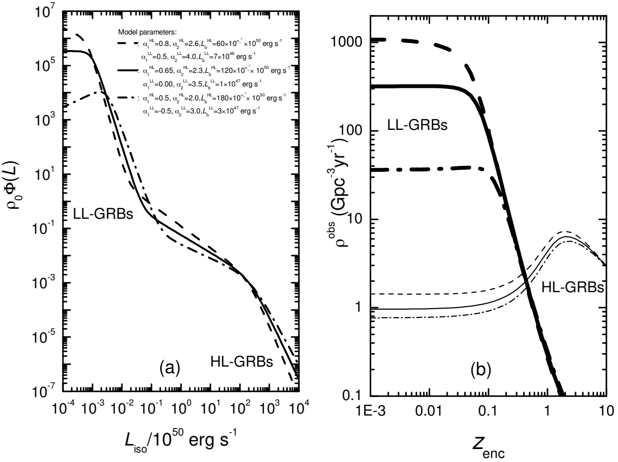
[IceCube'16]

B) Low-Luminosity Gamma-ray Bursts

- **loophole:** undetected low-luminosity γ-ray bursts (GRB)

  [Murase & Ioka'13; Senno, Murase & Mészáros'16]

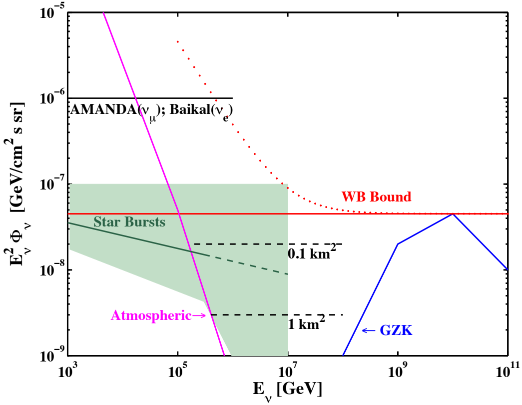
- *claim:* distinct population of LL-GRB more abundant in the local ($z \ll 1$) Universe



[Liang, Zhang, Virgili & Dai'06]

C) 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]

C) TeV Starburst Galaxies

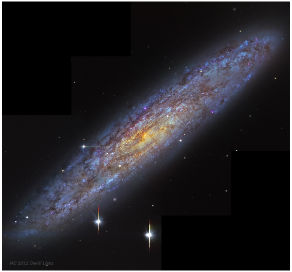
Messier 82 ($\delta \simeq 69°$)

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

$$E^2\phi_\nu(E) \lesssim 1.09 \times 10^{-12} \frac{\text{TeV}}{\text{cm}^2\text{s}}$$

[IceCube 7yr $\nu_\mu + \bar{\nu}_\mu$]

NGC 253 ($\delta \simeq -25°$)



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

no neutrino limit

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

D) Tidal Disruption Events

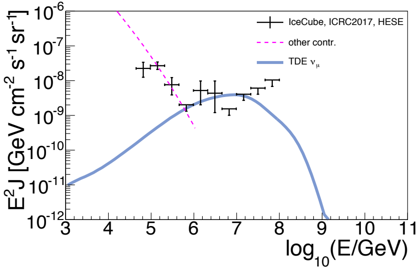
- Stars torn apart by tidal forces in the vicinity of a supermassive black holes can launch jet-like outflows.

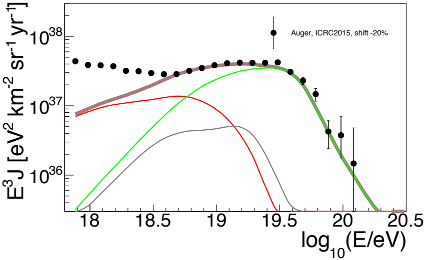
➜ good candidate sources of UHE CRs [Farrar & Gruzinov'09; Farrar & Piran'14]

- associate neutrino production via $p\gamma$ interactions:

[Wang, Liu, Dai & Cheng'11; Senno, Murase & Més'aros'17]

[Guépin, Kotera, Barausse, Fang & Murase'17; Biehl, Boncioli, Lunardini & Winter'17]





[*e.g.* Biehl, Boncioli, Lunardini & Winter'17]

E) 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]

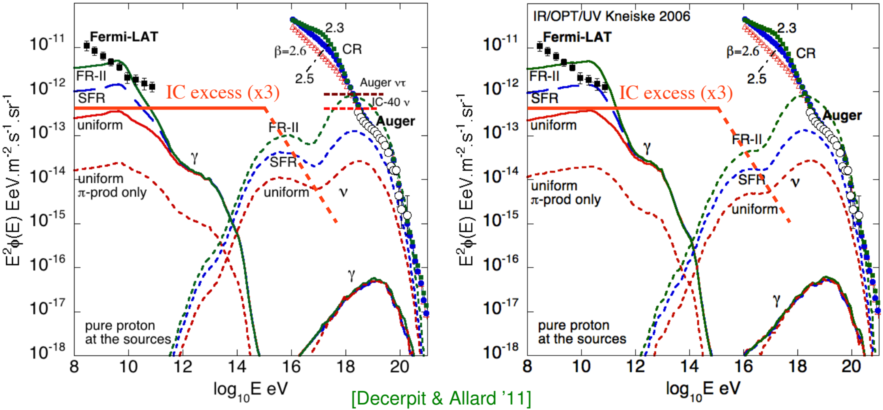
- “Guaranteed”, but with many model uncertainties and constraints:
  - **(low cross-over) proton models + CMB (+ EBL)**

    [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, Heinz, Boncioli, Bustamante & Winter’15]
  - **+ 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]

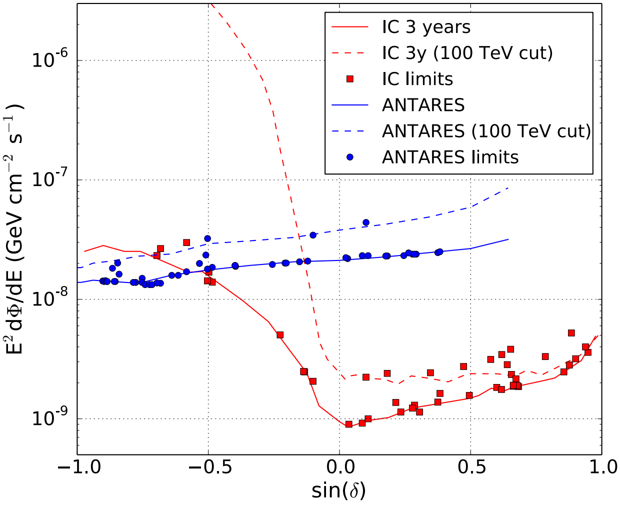
E) Cosmogenic ("GZK") Neutrinos



[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

Diffuse vs. Point-Source



90% CL limits for selected sources and sensitivities a function of the declination reported by ANTARES 5 years (blue) and IceCube 3 years (red) [IceCube & ANTARES'15]

Diffuse vs. Point-Source

- (quasi-)diffuse flux fixes luminosity L: [Lipari'08]

$$F_{\rm diff} = \frac{1}{4\pi}\int {\rm d}z\,\frac{{\rm d}\mathcal{V}_C}{{\rm d}z}\,\rho(z)\,\frac{L}{4\pi d_L^2(z)} \simeq \mathcal{O}(1)\frac{1}{4\pi}\frac{\rho(0)}{H_0}L$$

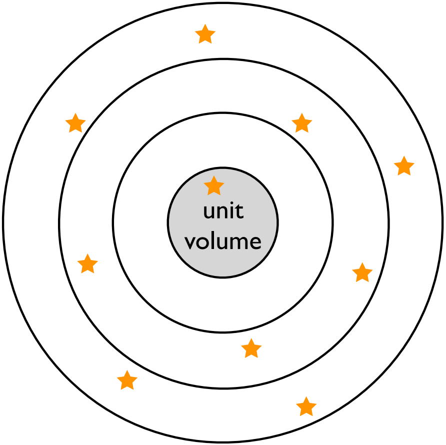
- point-source flux:

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

- *effective* local density $\rho(0)$ of extra-galactic sources is:
  - $\sim 10^{-3}\,{\rm Mpc}^{-3}$ for **low–luminosity AGN**
  - $\sim 10^{-5}\,{\rm Mpc}^{-3}$ for **starburst galaxies**
  - $\sim 10^{-5}\,{\rm Mpc}^{-3}$ for **galaxy clusters**
  - $\gtrsim 10^{-5}\,{\rm Mpc}^{-3}$ for **UHE CR sources**
  - $\sim 10^{-8} - 10^{-7}\,{\rm Mpc}^{-3}$ for **radio galaxies**
  - $\sim 10^{-8}\,{\rm Mpc}^{-3}$ for **BL Lacs**
  - $\sim 10^{-11} - 10^{-10}\,{\rm Mpc}^{-3}$ for **flat-spectrum radio quasars**

[Murase & Waxman'16; Mertsch, Rameez & Tamborra'16]

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**

Neutrino Point-Source Limits

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

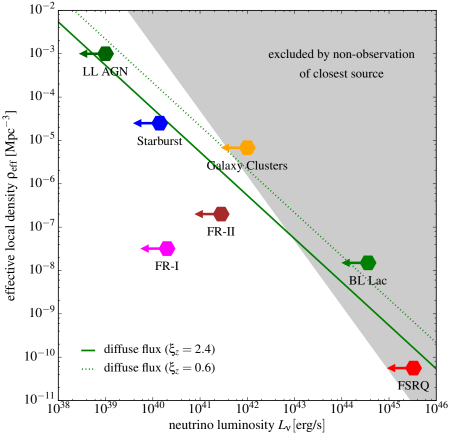
→ PS observation requires rare sources

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

  ✘ BL Lacs
  ($\rho_{\rm eff} \simeq 10^{-8}{\rm Mpc}^{-3}$)

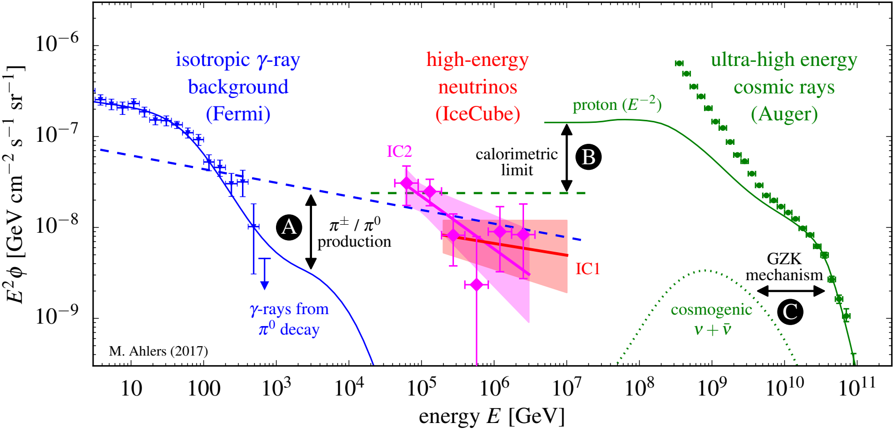
  ✘ "normal" GRBs
  ($\dot{\rho}_{\rm eff} \simeq 10^{-9}{\rm Mpc}^{-3}{\rm yr}^{-1}$)

→ **stronger limits** via source "stacking"



[Kowalski'06; Lipari'08; Murase, Beacom & Takami'12]
[MA & Halzen'14; Murase & Waxman'16]
[Mertsch, Rameez & Tamborra'16]

Multi-Messenger Interfaces



Further progress in source identification via **multi-messenger relations**.

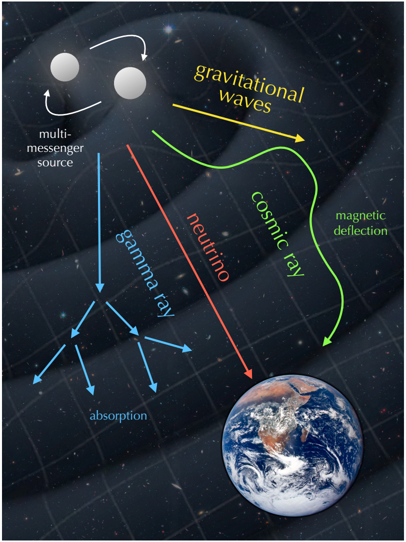
Hadronic Gamma-Ray Emission

- ➜ Inelastic collisions of **cosmic rays (CR)** with radiation or gas produce γ-rays and **neutrinos**.

$$\pi^0 \to \gamma + \gamma$$

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

- ➜ 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



Isotropic Diffuse Gamma-Ray Background (IGRB)

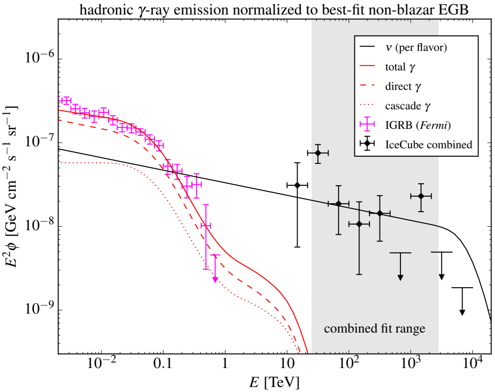
- neutrino and γ-ray fluxes in pp scenarios follow initial CR spectrum $\propto E^{-\Gamma}$

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

✘ constrained by *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]
[Ando, Tamborra & Zandanel'15]
[Bechtol, MA, Ajello, Di Mauro & Vandenbroucke'15]

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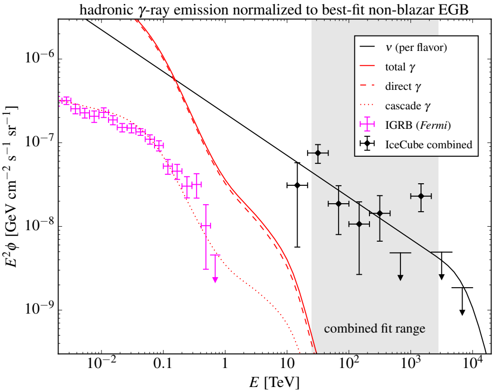

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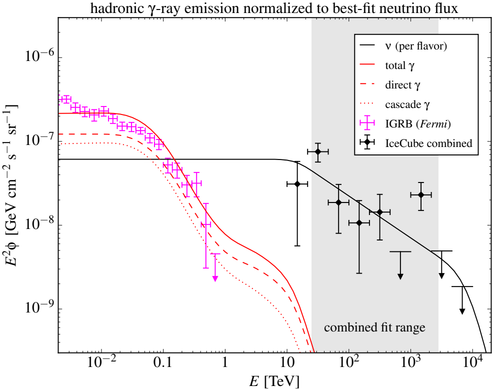


[Murase, MA & Lacki'14; Tamborra, Ando & Murase'14]
[Ando, Tamborra & Zandanel'15]
[Bechtol, MA, Ajello, Di Mauro & Vandenbroucke'15]

Non-Blazar Limits on Gamma-Ray Background

- **Photon fluctuation analyses** of Fermi data allow to constrain the source count distribution of blazars **below** the source detection threshold.
- inferred blazar contribution above 50 GeV:
  - Fermi Collaboration'15:

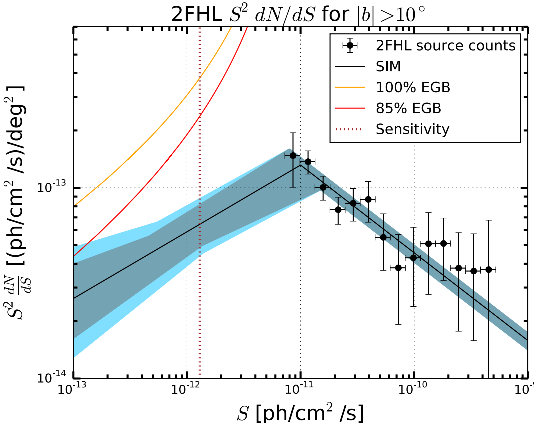
    $86^{+16}_{-14}\%$ of EGB

  - 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

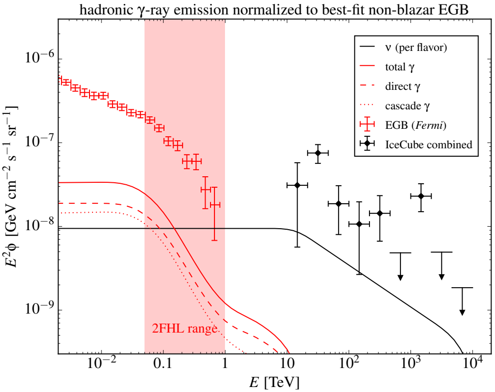
- non-blazar contribution above 50 GeV: [Fermi'15]

  $14^{+14}_{-14}\%$ 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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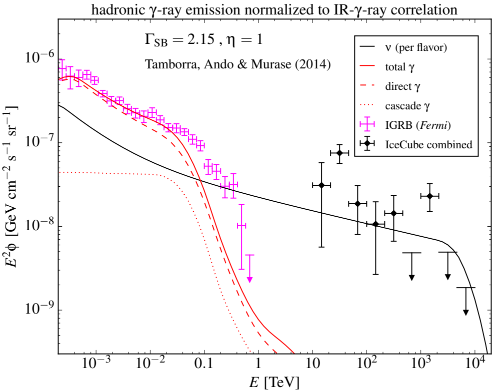

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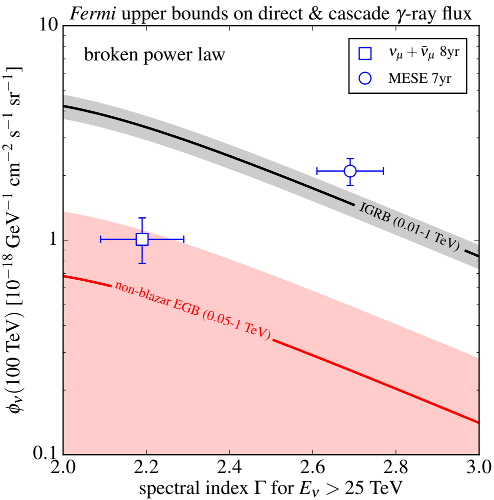

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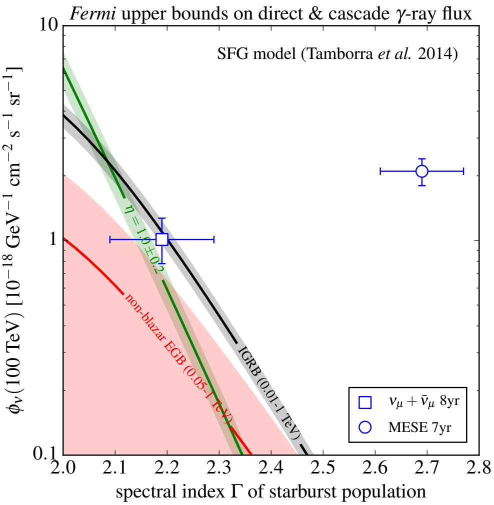


[Bechtol, MA, Ajello, Di Mauro & Vandenbroucke'15]

Comments & Consequences

- Strong limits apply to **CR calorimeters**, like starburst galaxies or galaxy clusters.
- Some direct γ-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 ν_μ (ν_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 γ-ray emission in the Fermi range **"hidden"**? [Murase, Guetta & MA'15]

UHE CR association?

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

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

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

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

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

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

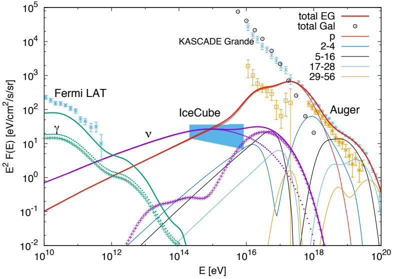
- **Waxman-Bahcall bound:** $f_\pi \leq 1$ [Waxman & Bahcall'98]

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

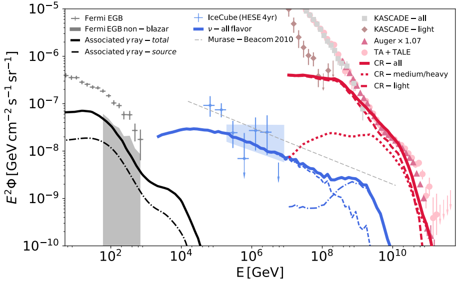
UHE CR association?

➜ **two-zone models**: CR accelerator + CR “calorimeter”?

- starburst galaxies [Loeb & Waxman’06]
- galaxy clusters [Berezinsky, Blasi & Ptuskin’96; Beacom & Murase’13]
- “unified” sources (UHE CRs, γ-ray & neutrinos):



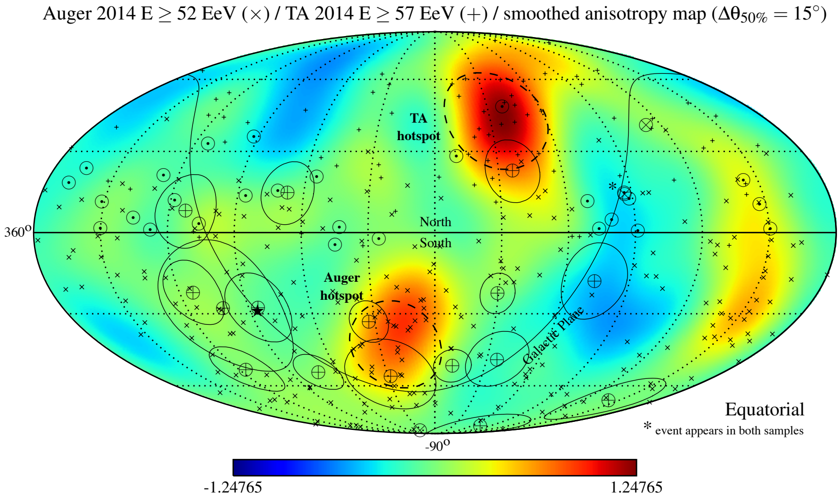
[Kachelriess, Kalashev, Ostapchenko & Semikoz’17]



[Fang & Murase’17]

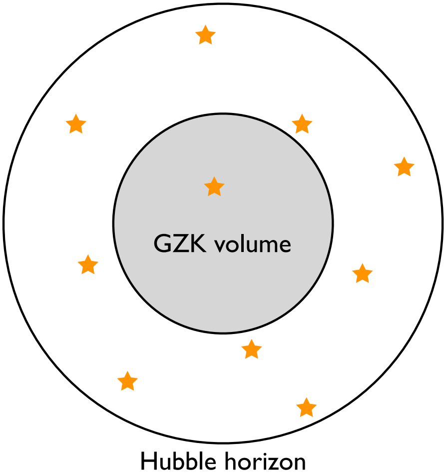
✘ **However,** $E_\nu < 100$ TeV neutrino data remains a challenge!

Correlation with 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

Identification of Extragalactic Point-Sources?



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

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

- neutrinos visible up to Hubble horizon

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

➜ maximal overlap:

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

- HESE 4yr : ca. 30 signal events

➜ $1-2$ neutrinos expected to correlate

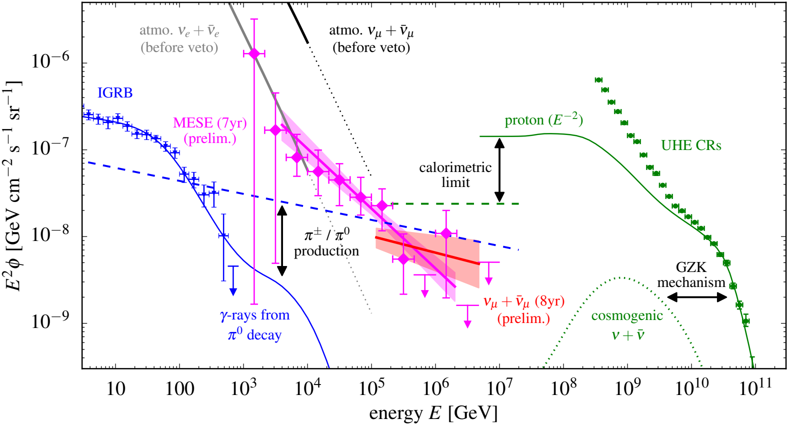
✘ magnetic deflections, angular resolution, incompleteness,. . .

Summary

- IceCube has identified a **diffuse flux of astrophysical neutrinos** in the TeV-PeV energy range of **unknown origin**.
- Galactic and Extragalactic Sources are candidate sources, but **absence of anisotropies** favours the latter.
- **No compelling scenario** for the TeV-PeV energy range.
- **High intensity** of the emission is comparable to that of ultrahigh-energy cosmic rays and γ-ray backgrounds.
- Large neutrino flux in the $1-10$ TeV range is **challenged** by constraints set by the extra-galactic γ-ray background observed by Fermi.
- **Saturation of calorimetric bounds** of UHE CR sources might indicate common origin.

Appendix

Updated Multi-Messenger Panorama



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

Cosmic Ray Accelerators?

- **Hillas bound:** [Hillas'84]

$$E/Z \lesssim 10^{11}\,\frac{\beta}{\Gamma}\left(\frac{B}{\mu\mathrm{G}}\right)\left(\frac{R}{100\ \mathrm{kpc}}\right)\mathrm{GeV}$$

- **luminosity bound:** [Waxman'95]

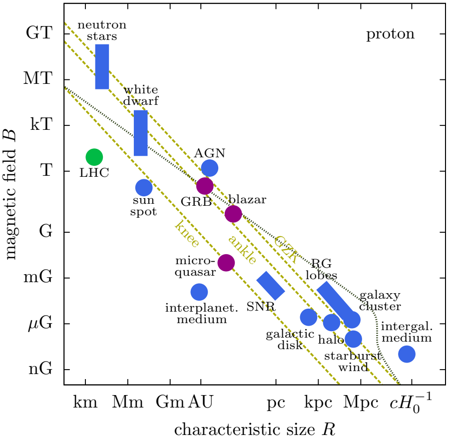
$$L_{\rm B} \gtrsim 10^{45.5}\,\frac{\Gamma^2}{\beta}\left(\frac{E/Z}{10^{11}\,\mathrm{GeV}}\right)^2\frac{\mathrm{erg}}{\mathrm{s}}$$

✘ few luminous source candidates within GZK horizon ($\simeq 200$ Mpc)

➜ **heavy composition** ($Z \gg 1$) and/or **transient** sources:

- gamma-ray bursts?
- tidal disruption events?

"Hillas plot"



[after Hillas'84]

Flux Distribution of a Standard Candle

- point-source flux F

$$F = \frac{L}{4\pi r^2} \quad \rightarrow \quad |\mathrm{d}F| = 2\frac{L}{4\pi r^3}\mathrm{d}r$$

- point-source number N per distance r

$$\mathrm{d}N = 4\pi r^2 \rho \mathrm{d}r$$

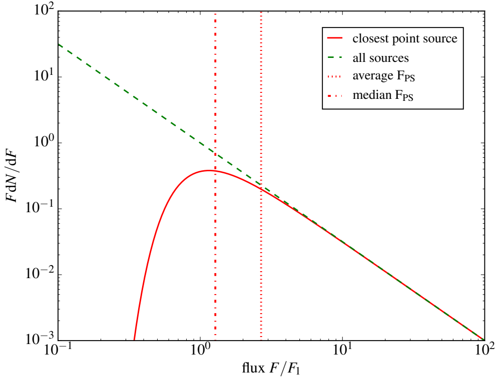
- flux distribution

$$\frac{\mathrm{d}N}{\mathrm{d}F} \propto r^5 \propto F^{-5/2}$$

- distribution of the closest source

[MA & Halzen'14]

$$F\frac{\mathrm{d}p}{\mathrm{d}F} = \frac{3}{2}\left(\frac{F_1}{F}\right)^{\frac{3}{2}} e^{-\left(\frac{F_1}{F}\right)^{\frac{3}{2}}}$$



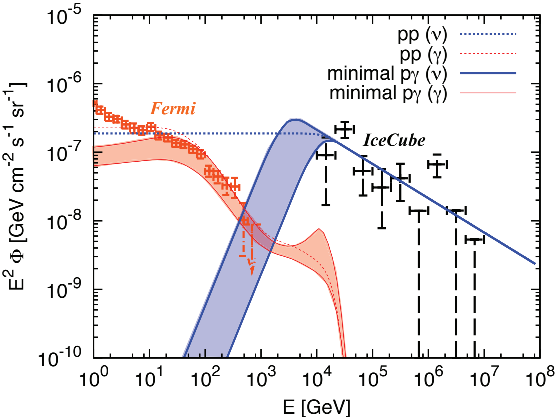
Fermi Bounds for $p\gamma$ Sources

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

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

2 **high pion production efficiency** implies strong γ-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:

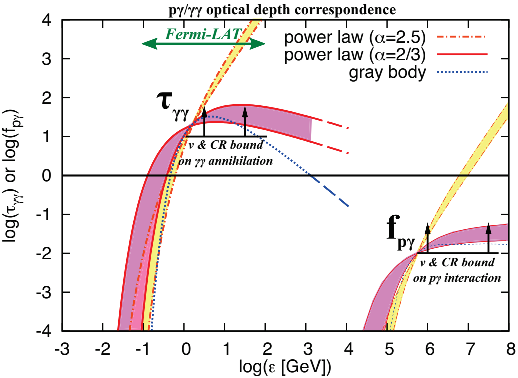
$$\varepsilon_t \sim 200\,{\rm keV}\left(\frac{\Gamma}{10}\right)^2\left(\frac{E_\nu}{3\,{\rm TeV}}\right)^{-1}$$

- **opacity relation**:

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

➜ strong internal γ-absorption:

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

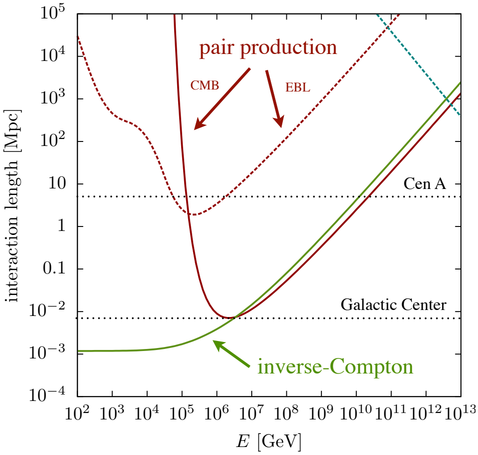


[Murase, Guetta & MA'15]

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]