Interpretation of Astrophysical Neutrinos

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Sources of Galactic Cosmic Rays

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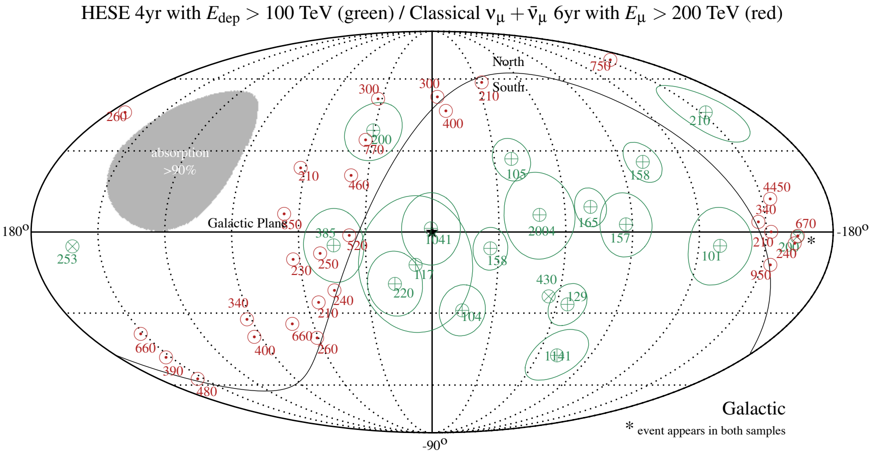
Neutrino Arrival Directions



- **16 "cascade events" (circles) and 3 "tracks events" (diamonds)** with $E_{\mathrm{dep}} \gtrsim 100$ TeV
- **28(+1) up-going muon neutrino** events with $E_\mu \gtrsim 200$ TeV [IceCube'15]
- ✘ **no significant spatial or temporal correlation of events**

Multi-messenger Paradigm

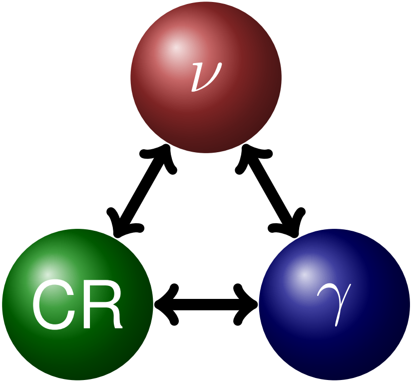
- Neutrino production is closely related to the production of cosmic rays (CRs) and γ-rays.

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

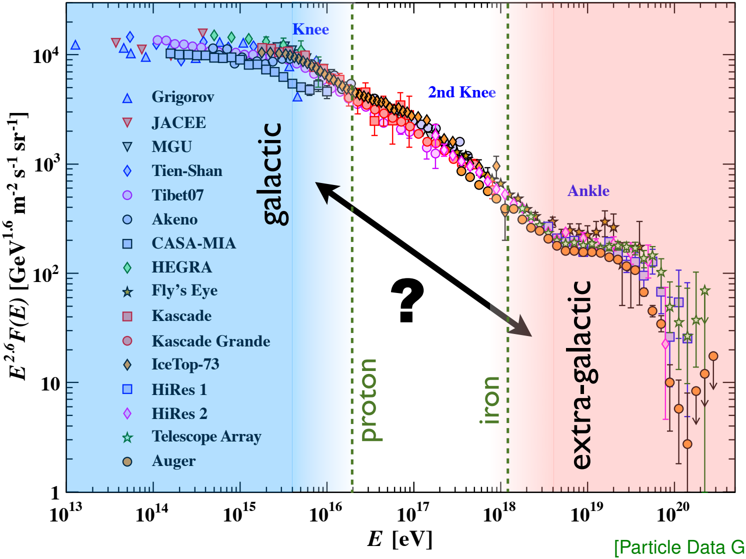
- 1 PeV neutrinos correspond to 20 PeV CR nucleons and 2 PeV γ-rays

➜ **very interesting** energy range:

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



The Cosmic "Beam"



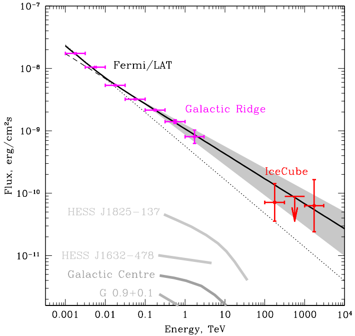
[Particle Data Group'13]

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 and Ostapchenko'14; Neronov, Semikoz & Tchernin'13] [Neronov & Semikoz'14,'16; Guo, Hu & Tian'14; Gaggero, Grasso, Marinelli, Urbano & Valli'15]
  - unidentified Galactic γ-ray emission [Fox, Kashiyama & Meszaros'13] [Gonzalez-Garcia, Halzen & Niro'14]
  - *Fermi Bubbles* [MA & Murase'13; Razzaque'13] [Lunardini, Razzaque, Theodoseau & Yang'13; Lunardini, Razzaque & Yang'15]
  - 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,'16]
  - Galactic Halo [Taylor, Gabici & Aharonian'14; Kalashev & Troitsky'16]
  - heavy dark matter decay [Feldstein, Kusenko, Matsumoto & Yanagida'13] [Esmaili & Serpico '13; Bai, Lu & Salvado'13; Cherry, Friedland & Shoemaker'14] [Murase, Laha, Ando, MA'15; Boucenna *et al.*'15 ; Chianese, Miele, Morisi & Vitagliano'16]

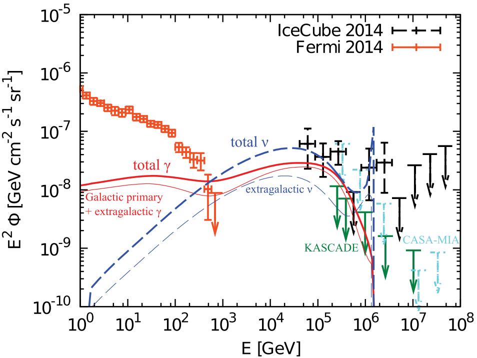
Galactic Emission Models: Two Examples

Hard Galactic Diffuse Emission



[Neronov, Semikoz & Tchernin'14]

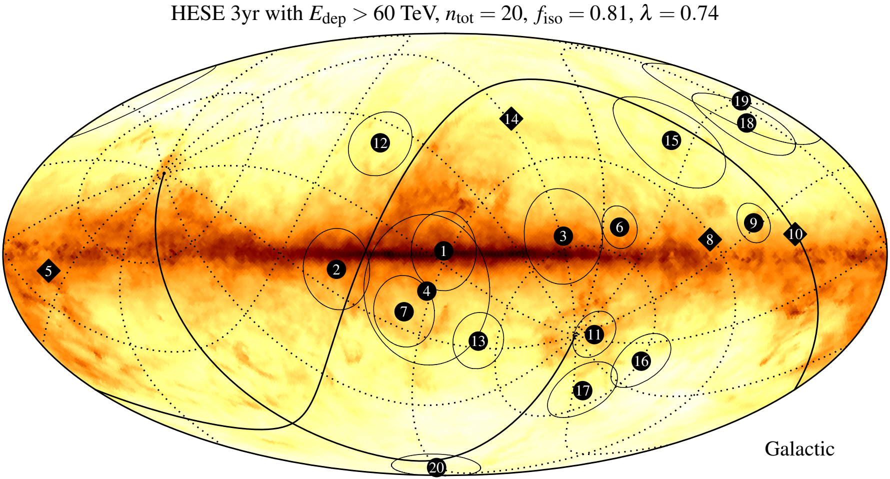
PeV Dark Matter Decay (*e.g.* DM$\rightarrow \nu\bar{\nu}/q\bar{q}$)



[*e.g.* Murase, Laha, Ando & MA'15]

- anisotropy limits on Galactic emission [MA & Bai, Barger & Yang'15]
- limits on Galactic contribution from PeV γ-ray observation [Gupta'14; MA & Murase'14]

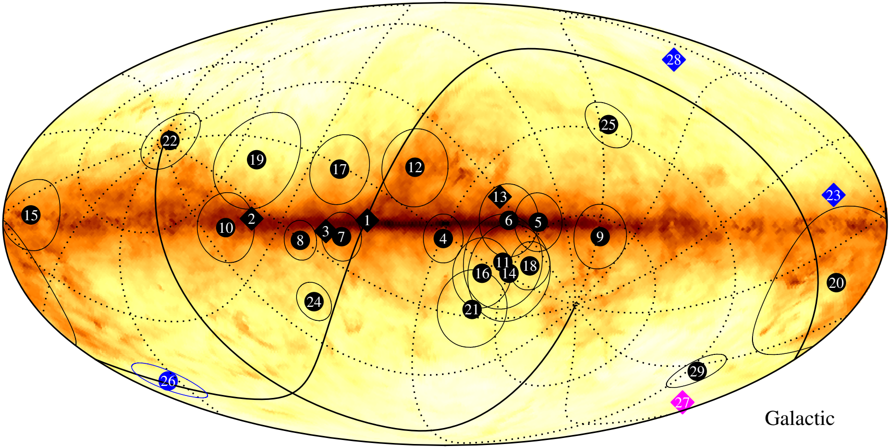
Example: Galactic Diffuse Emission



- Strong Galactic diffuse emission up to PeV? [Neronov & Semikoz'15'16]
- tracks (◇) and cascades (○) from HESE 3yr with $E_{\rm dep} > 60$ TeV; circles indicate angular uncertainty

Example: Galactic Diffuse Emission

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



- Galactic diffuse emission template derived with GALPROP [Strong & Moskalenko'98]
- **simulated** map: ◇/○ : Galactic ν | ◇/○ : isotropic ν | ◇/○ : atmospheric ν | ◇/○ : atmospheric μ

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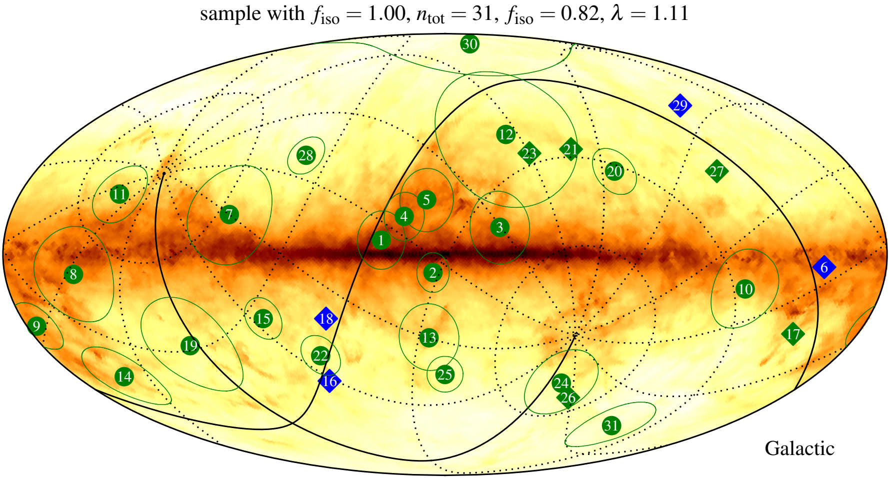

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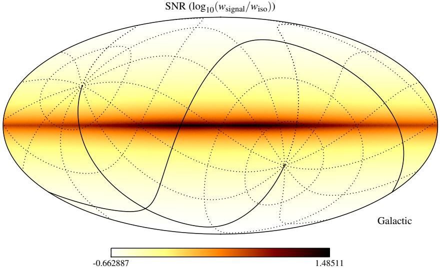
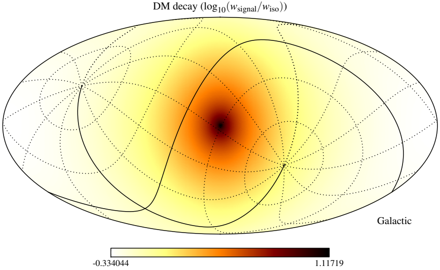
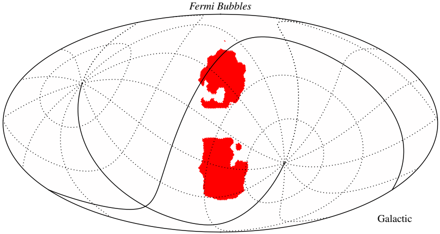
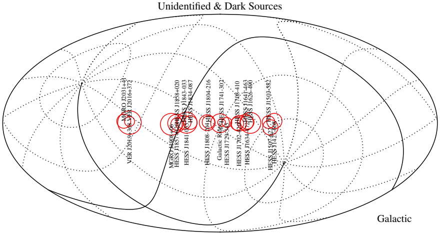
Other Extended Galactic Emission





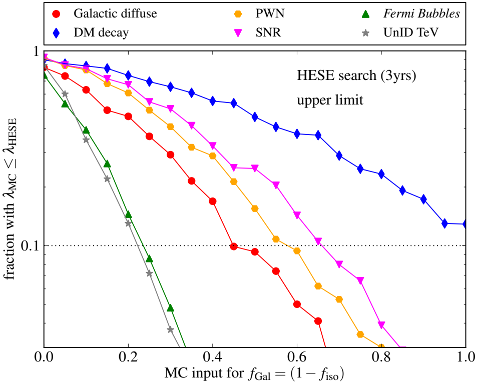




Galactic Limits

- maximum likelihood-ratio test for Galactic emission (signal)
- **IceCube 3yr HESE 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 Galactic sources: $< 65\%$
  - PeV DM decay: *unconstrained*
- **stronger** limits possible:
  - spectral and flavor analysis
  - classical $\nu_\mu + \bar\nu_\mu$ search
  - PeV γ-ray emission

➜ **ongoing IceCube analysis**



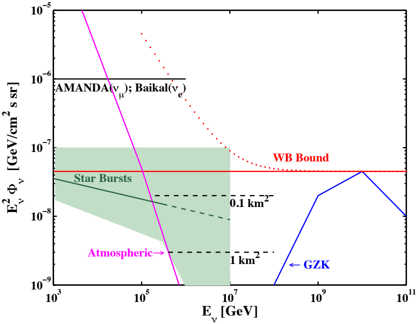
[MA, Bai, Barger & Lu'15]

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;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]
  - tidel disruption events [Wang & Liu'16; Dai & Fang'16; Senno, Murase & Meszaros'16]
  - gamma-ray bursts (GRB) [Murase & Ioka'13; Dado & Dar'14; Tamborra & Ando'15]
    [Senno, Murase & Meszaros'16]
  - 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; 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]
  - ...

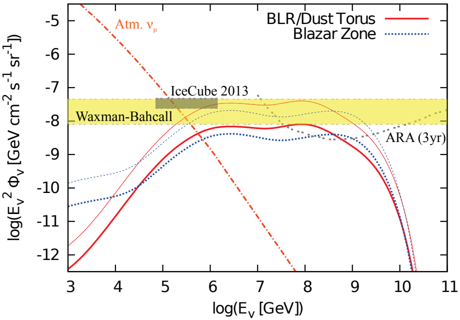
Extragalactic Emission Models: Two Examples

Starburst Galaxies (“*pp*” scenario)



[Loeb & Waxman’06]

Active Galactic Nuclei (“$p\gamma$” scenario)



[Mannheim’96; Halzen & Zas’97]

[*e.g.* Murase, Inoue & Dermer’14]

- CR-gas (*pp*) interactions: **mostly broken power-law** neutrino spectra.
- CR-photon ($p\gamma$) interactions: **strong spectral features** inherited from photon spectrum

Diffuse vs. Point-Source

- (quasi-)diffuse flux fixes luminosity L:

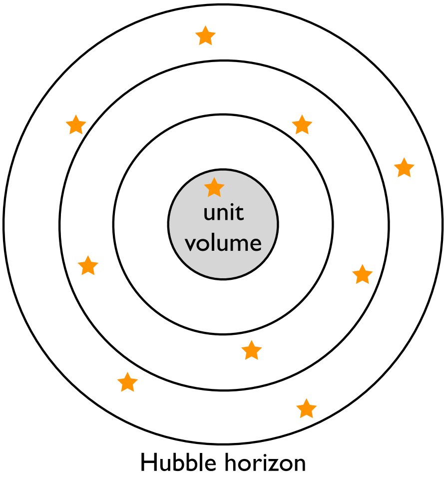
$$F_{\rm diff} = \frac{1}{4\pi}\int \mathrm{d}z\,\frac{\mathrm{d}\mathcal{V}_C}{\mathrm{d}z}\,\mathcal{H}(z)\,\frac{L}{4\pi d_L^2(z)} \simeq \mathcal{O}(1)\,\frac{1}{4\pi}\,\frac{\mathcal{H}(0)}{H_0}L$$

- point-source flux:

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

- local density $\mathcal{H}(0)$ of extra-galactic sources is:
  - $\sim 10^{-3}\,\mathrm{Mpc}^{-3}$ for **star-forming galaxies**
  - $\sim 10^{-4}\,\mathrm{Mpc}^{-3}$ for **starburst galaxies**
  - $\gtrsim 10^{-5}\,\mathrm{Mpc}^{-3}$ for **UHE CR sources**
  - $\sim 10^{-6} - 10^{-5}\,\mathrm{Mpc}^{-3}$ for **radio galaxies**
  - $\sim 10^{-8} - 10^{-7}\,\mathrm{Mpc}^{-3}$ for **BL Lacs**
  - $\sim 10^{-9}\,\mathrm{Mpc}^{-3}$ for **flat-spectrum radio quasars**

Identification of Extragalactic Point-Sources?



- expect one source per unit volume:

$$\frac{4\pi f_{\rm sky}}{3} d^3 \mathcal{H}(0) = 1$$

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

$$d \simeq \left(\frac{3}{4\pi f_{\rm sky}\mathcal{H}(0)}\right)^{\frac{1}{3}}$$

➜ compare to **point-source sensitivity**

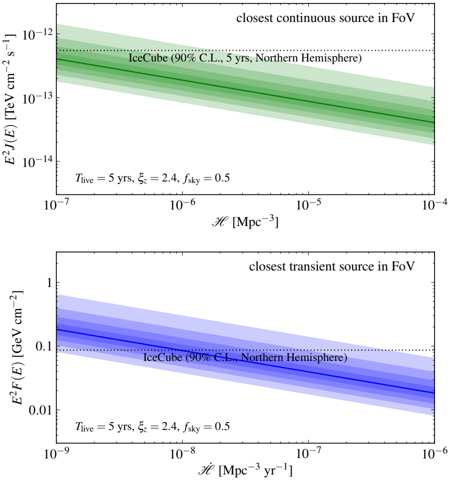
Neutrino Point-Source Limits

- Diffuse neutrino flux **normalizes** the contribution of individual sources
- dependence on local source density $\mathcal{H}$ (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 ($\mathcal{H} \simeq 10^{-9}\mathrm{Mpc}^{-3}$)
  - ✘ "normal" GRBs ($\dot{\mathcal{H}} \simeq 10^{-9}\mathrm{Mpc}^{-3}\mathrm{yr}^{-1}$)

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



[MA&Halzen'14]

Hadronic Gamma-Ray Emission

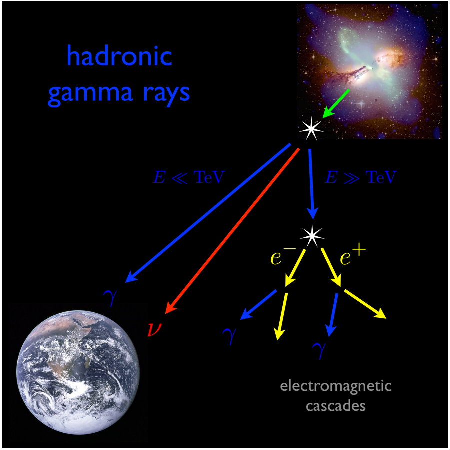
- **hadronic** γ-rays:
  pion production in CR interactions

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

➜ 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



Gamma-Ray Opacity

- production and decay of neutral pions into gamma rays

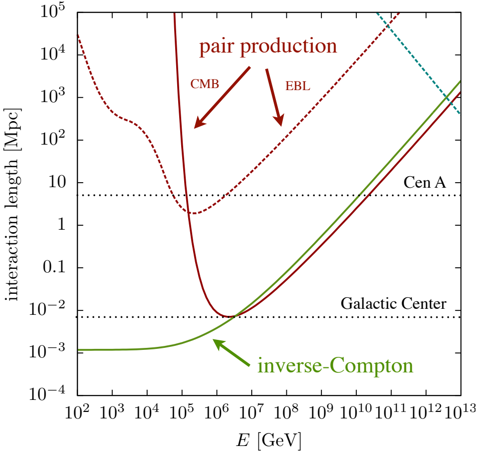
✘ strong pair production (PP) in CMB:
$\gamma + \gamma_{\rm CMB} \to e^+ + e^-$

➜ 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)

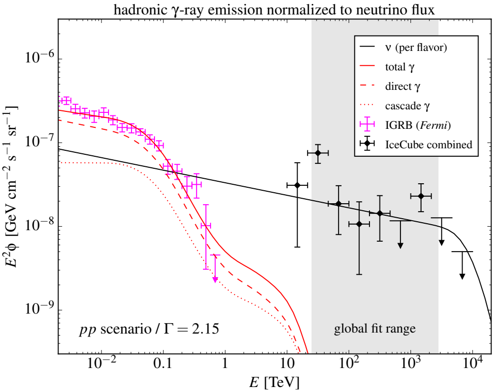
- neutrino and γ-ray fluxes in pp scenarios follow initial CR spectrum $\propto E^{-\Gamma}$

➜ 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]
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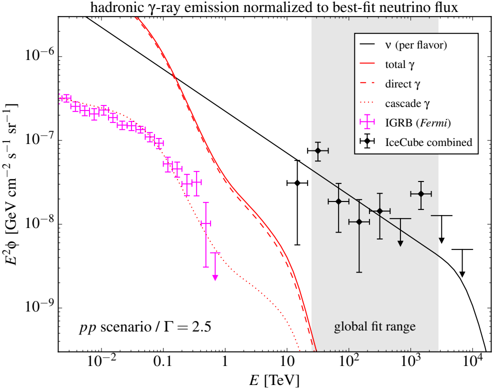

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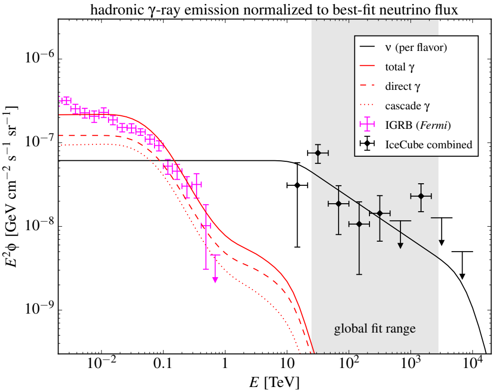

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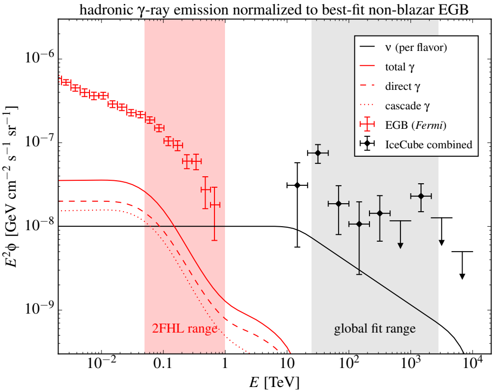
Non-Blazar Limits on Gamma-Ray Background

- Total γ-ray background above 50 TeV dominated by blazars ($\sim 86\%$) [Fermi'15]

✘ **strong tension** with IceCube observation

- limits apply to **CR calorimeters**, *e.g.*, **starburst galaxies**

➜ loop-holes:
  - γ-absorption in source? [Chang & Wang'14]
  - dominance of high-redshift sources? [Wang & Loeb'16]
  - extra-galactic background light estimates?



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

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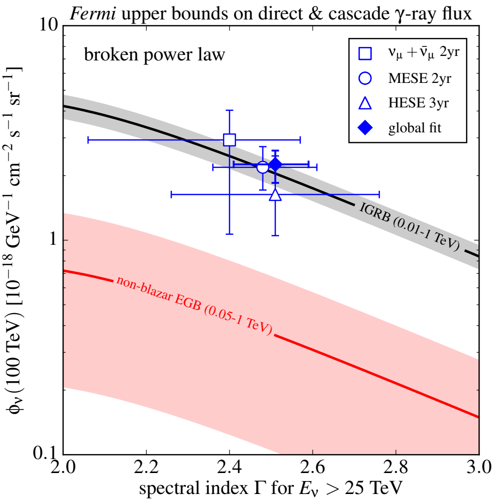


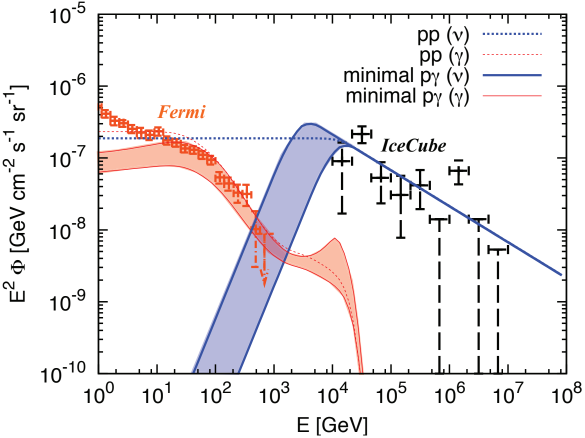
[Bechtol, MA, Ajello, Di Mauro & Vandenbroucke'15]

Fermi IGRB and $p\gamma$ Scenarios?

- also strong constraints from cascade emission of $p\gamma$ scenarios
- **high pion production efficiency** implies strong $\gamma\gamma$ absorption in sources

➜ Are strong neutrino sources **hidden** in γ-rays?

[Murase, Guetta & MA'15]



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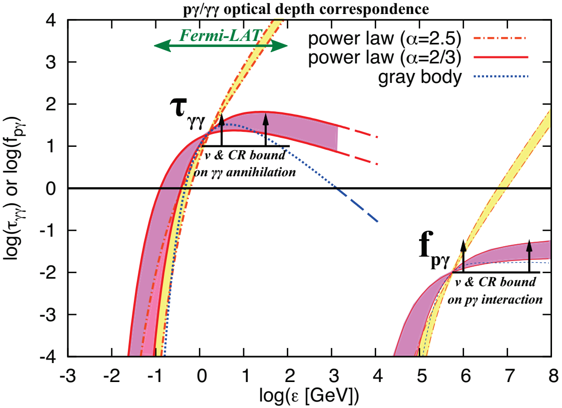


UHE CR association?

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

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

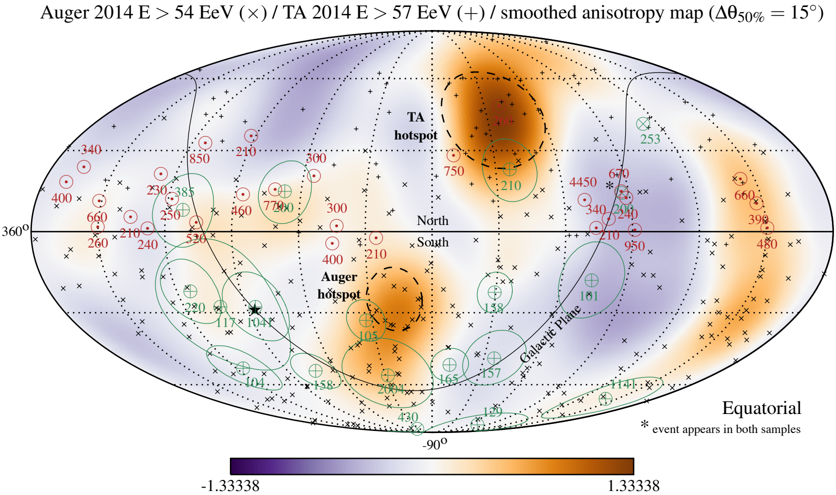
- **Waxman-Bahcall bound:** $f_\pi \leq 1$ [Waxman & Bahcall'98]
- $f_\pi \simeq 1$ requires efficient pion production

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

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

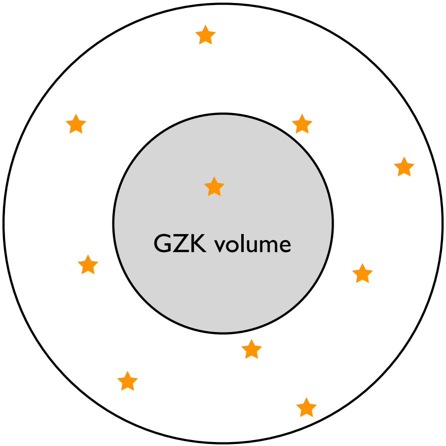
  - starburst galaxies [Loeb & Waxman'06]
  - galaxy clusters [Berezinsky, Blasi & Ptuskin'96; Beacom & Murase'13]

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

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

- 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 & Outlook

- Identification of PeV neutrino sources is *challenging*.
- Galactic neutrino emission unlikely the main source of the PeV diffuse flux.

➜ Pending IceCube analyses & and new data soon!

- **Absence of anisotropies** favor extragalactic scenarios!

➜ Is the **weak tension** of best–fit spectral indices indicating spectral features?

- **Rare sources excluded** by the non–observation of point sources.
- Soft neutrino spectra challenged by **diffuse γ-ray background**.

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

Appendix

Blazar Correlations?

nature physics

ARTICLES

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

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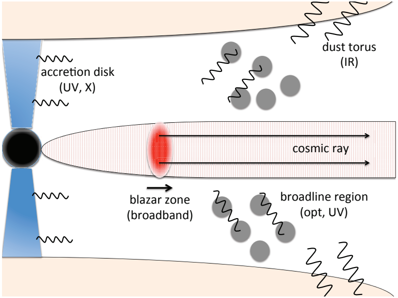
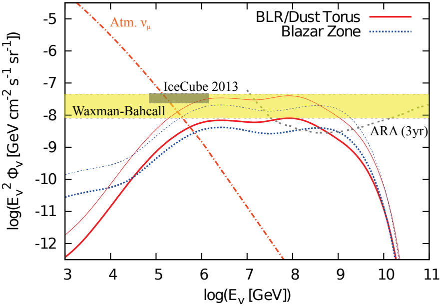
to explain an observed coinciding petaelectronvolt-neutrino event. There is a remarkable coincidence with the IceCube-detected petaelectronvolt-neutrino event HESE-35 with a probability of only ~5% for a chance coincidence. Our model reproduces the measured rate of petaelectronvolt events detected over the whole

AGN jets

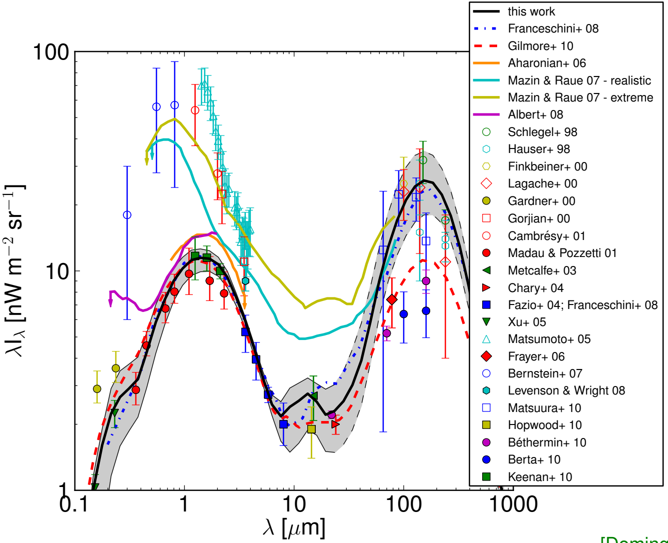
- neutrino from $p\gamma$ interactions in AGN jets [Mannheim'96; Halzen & Zas'97]
- complex spectra due to various photon backgrounds
- typically, deficit of sub-PeV and excess of EeV neutrinos





[Murase, Inoue & Dermer'14]

Extra-galactic background light (EBL)



[Dominguez *et al.* '10]

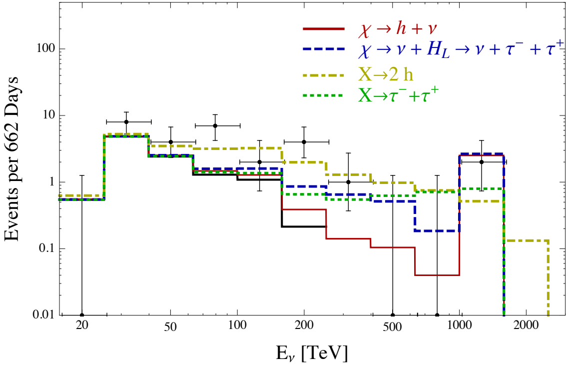
DM decay

- heavy (>PeV) DM decay?

  [Feldstein *et al.* 1303.7320; Esmaili & Serpico 1308.1105; Bai, Lu & Salvado 1311.5864]

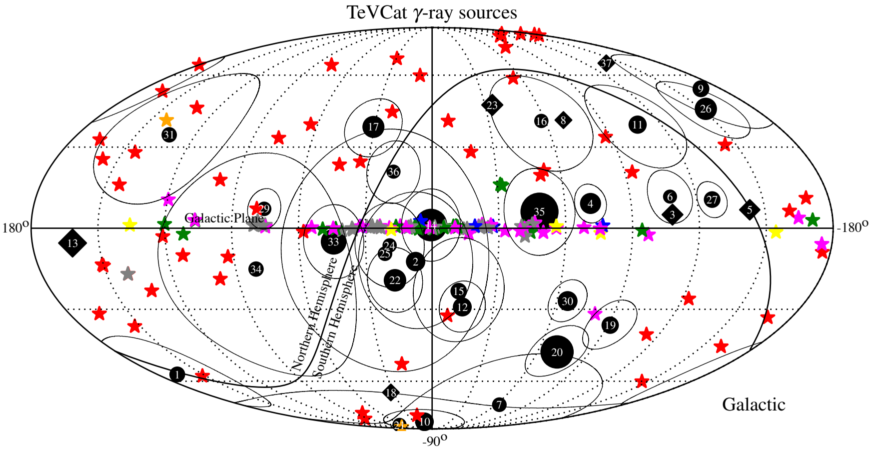
- **initially** motivated by PeV "line-feature", but continuum spectrum with/without line spectrum equally possible

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



[Bai, Lu & Salvado'13]

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]

Ultra-High Energy Cosmic Rays

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

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

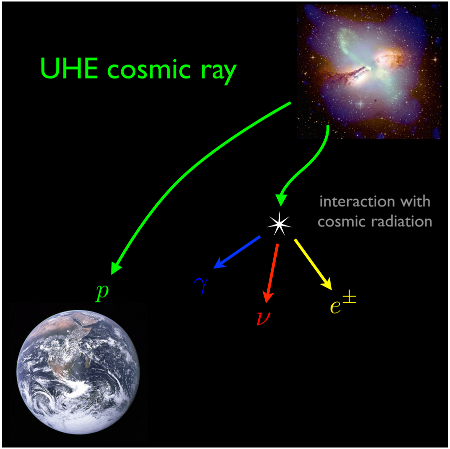
✘ *low statistics:* large uncertainties in chemical composition and spectrum!

✘ *"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)**

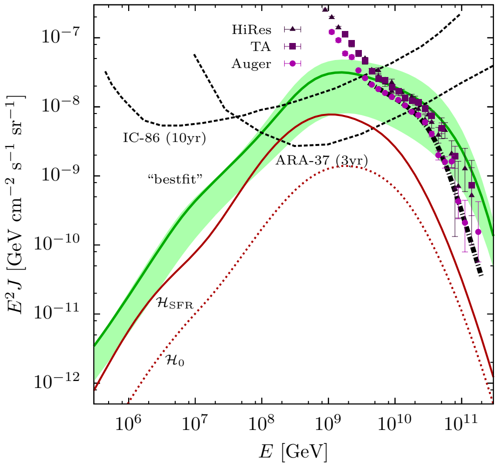
    [Berezinsky & Zatsepin'69; Yoshida & Teshima'93; Protheroe & Johnson'96; Engel, Seckel & Stanev'01; Fodor, Katz, Ringwald &Tu'03; Barger, Huber & Marfatia'06; Yuksel & Kistler'07; Takami, Murase, Nagataki & Sato'09, MA, Anchordoqui & Sarkar'09, Heinz, Boncioli, Bustamante & Winter'15]
  - **+ mixed compositions**

    [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]

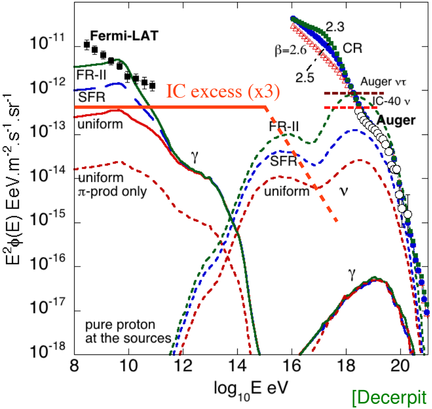
Guaranteed Cosmogenic Neutrinos

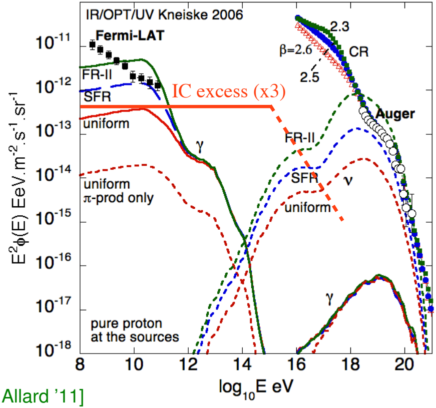
- ➜ **minimal** GZK flux from proton dominated models can be estimated from observed spectrum
  - dependence on cosmic evolution of sources:
    - no evolution (dotted)
    - star-formation rate (solid)
- ➜ **ultimate test** of UHE CR proton models feasible with future observatories like ARA.



[MA & Halzen'12]

Cosmogenic PeV 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

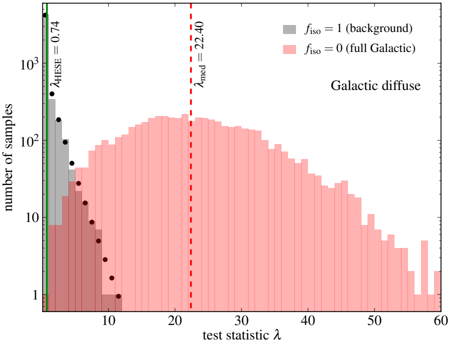
✘ strong evolution disfavored by Fermi diffuse background

Anisotropy Test

- unbinned maximum LH test statistic:

$$\lambda = 2\ln \prod_{\text{event } j} \left[\frac{\mu_j^{\text{sig}}(\widehat{f}_{\text{iso}}) + \mu_j^{\text{bgr}}(\widehat{f}_{\text{iso}})}{\mu_j^{\text{bgr}}(1)} \right]$$

- $\widehat{f}_{\text{iso}}$: fraction of isotropic events at maximum LH
- 90% C.L. **sensitivity** :
  f_{iso} with 90% of samples $\lambda_{\text{MC}} > \lambda^{\text{bgr}}_{\text{med}}$
- 5σ C.L. **discovery potential** :
  f_{iso} with 50% of samples $\lambda_{\text{MC}} > \lambda^{\text{bgr}}_{5\sigma}$
- 90% C.L. **upper limit** :
  f_{iso} with 90% of samples $\lambda_{\text{MC}} > \lambda_{\text{HESE}}$



grey: background distribution ($f_{\text{iso}} = 1$)
red: maximal signal distribution ($f_{\text{iso}} = 0$)

Neutrino Point-Source Limits

- **upper flux limits and sensitivities** of Galactic neutrino sources with “classical” muon neutrino search ($\theta_{\rm res} \simeq 0.3^\circ$-$0.6^\circ$)

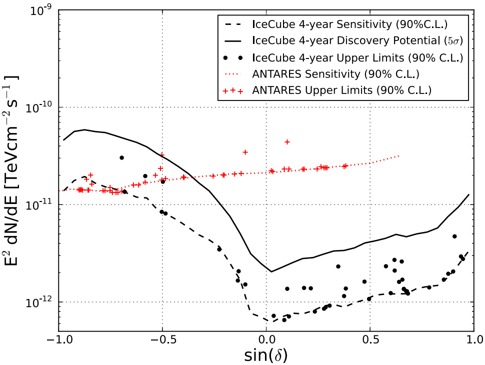
- sensitivity for **extended sources** weaker by $\sqrt{\Omega_{ES}/\Omega_{\rm PSF}} \simeq \theta_{\rm ES}/\theta_{\rm res}$

- strongest limits for sources in the Northern Hemisphere (IceCube FoV for upgoing ν's)

- **time-dependent** sensitivity:

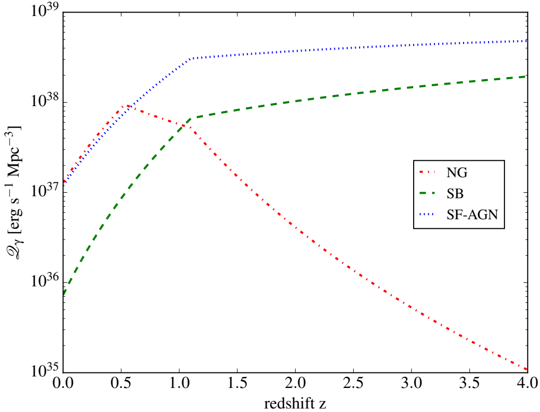
[IceCube ApJ 744 (2012)]

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



[IceCube arXiv:1406.6757]

Example: Star-Forming Galaxies



- explicit case of star-forming galaxies following the scaling relation between γ-ray and IR luminosities [Ackermann *et al.* '12; Tamborra, Ando & Murase'14]
- only soft spectra ($\Gamma \simeq 2.3$) consistent with γ-ray background, but undershoot IceCube data [Bechtol, MA, Ajello, Di Mauro & Vandenbroucke'15]

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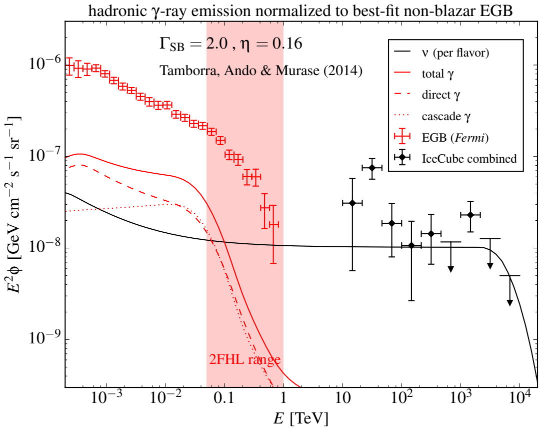

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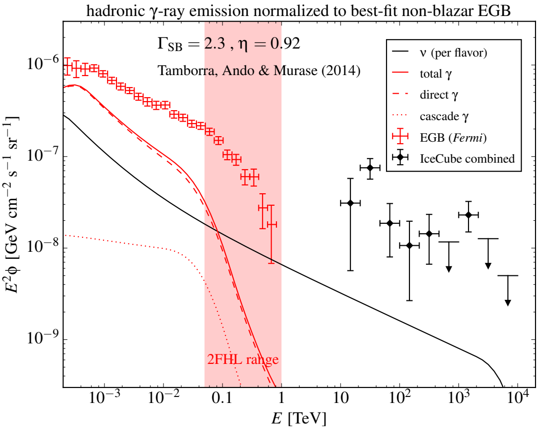

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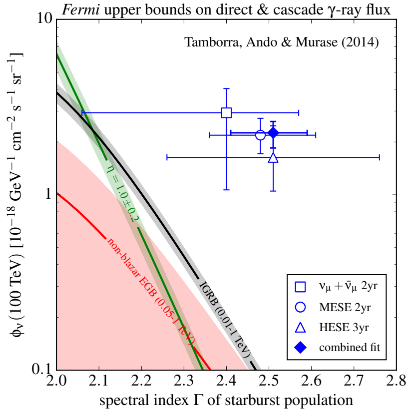

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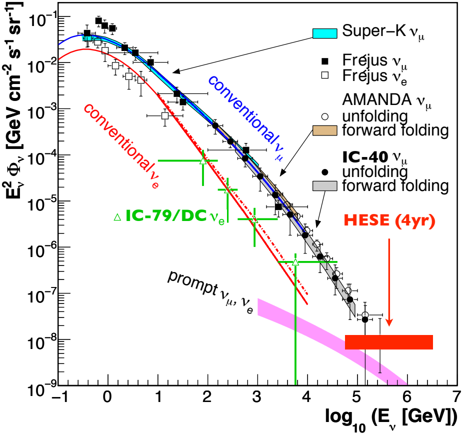
IceCube HESE (4yr)

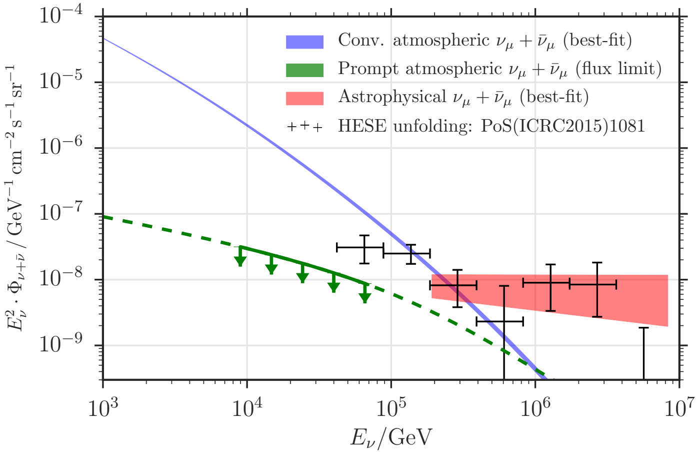
- **High-Energy Starting Event (HESE)** sample: [IceCube Science 342 (2013)]
  - bright events ($E_{\rm th} \gtrsim 30$TeV) starting inside IceCube
  - efficient removal of atmospheric backgrounds by veto layer

- 54 events in about four years: [IceCube ICRC'15]
  - 39 **cascades** events
  - 14 **track** events
  - 1 **composite** event (removed)
- expected background events:
  - $9.0^{+8.0}_{-2.2}$ **atmospheric neutrinos**
  - 12.6 ± 5.1 **atmospheric muons**
- best-fit E^{-2}-flux 60TeV-3PeV (6.5σ):

$$E_\nu^2 \phi_{\nu_\alpha} \simeq (0.84 \pm 0.3) \times 10^{-8} \frac{\text{GeV}}{\text{s cm}^2 \text{ sr}}$$



Fit of Power-Law Spectrum



- update of $\nu_\mu + \bar{\nu}_\mu$ search ("IC tracks") [PRL 115 (2015) 081102; arXiv:1607.08006]

➜ mild tension with cascade-dominated samples: **indication of spectral features?**

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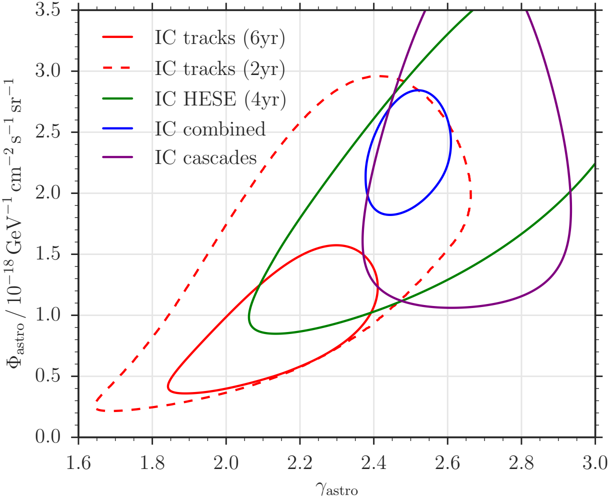

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