Multi-Messenger Aspects of Cosmic Neutrinos

Markus Ahlers

UW-Madison & WIPAC

Next-Generation Techniques for UHE Astroparticle Physics

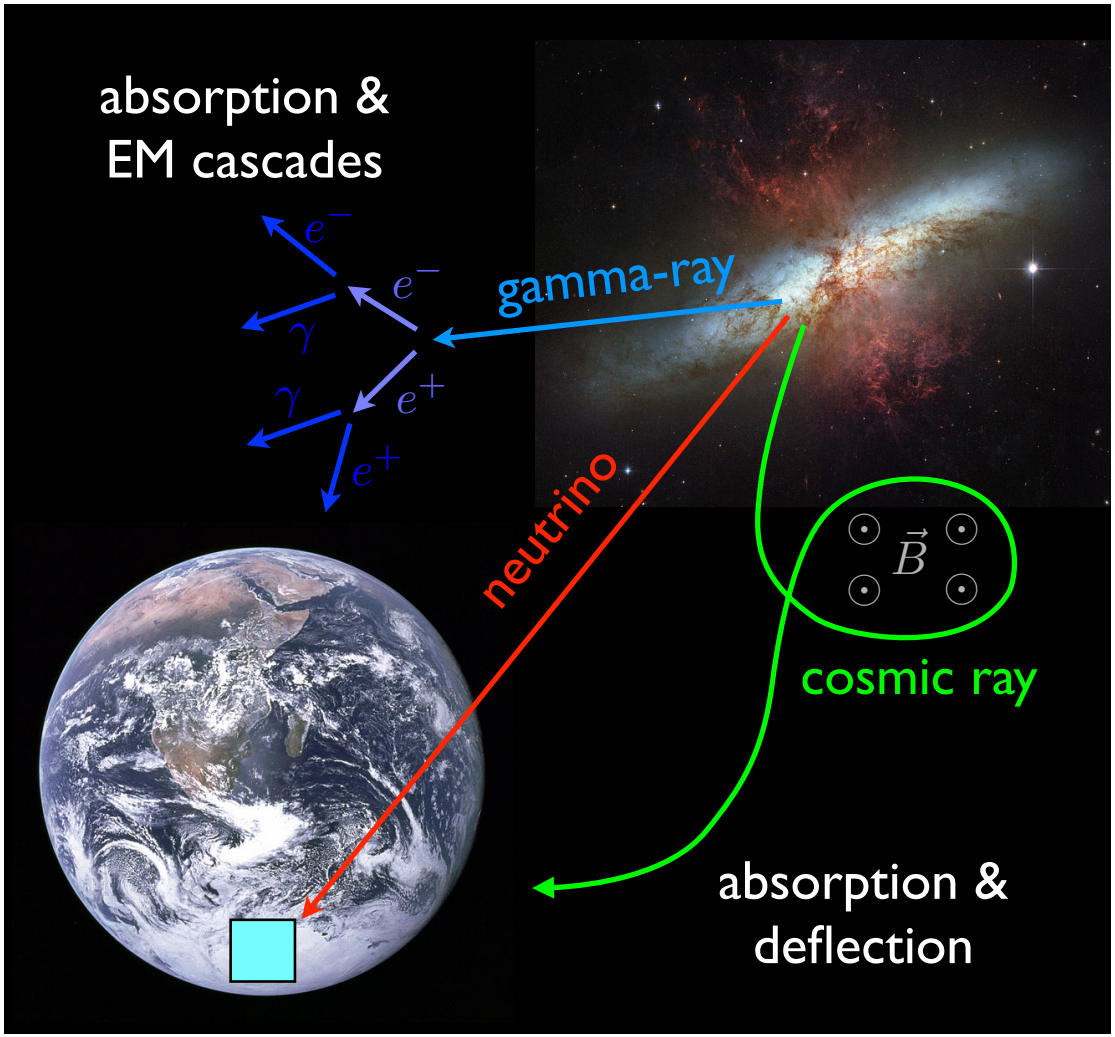
Chicago, March 2, 2015

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

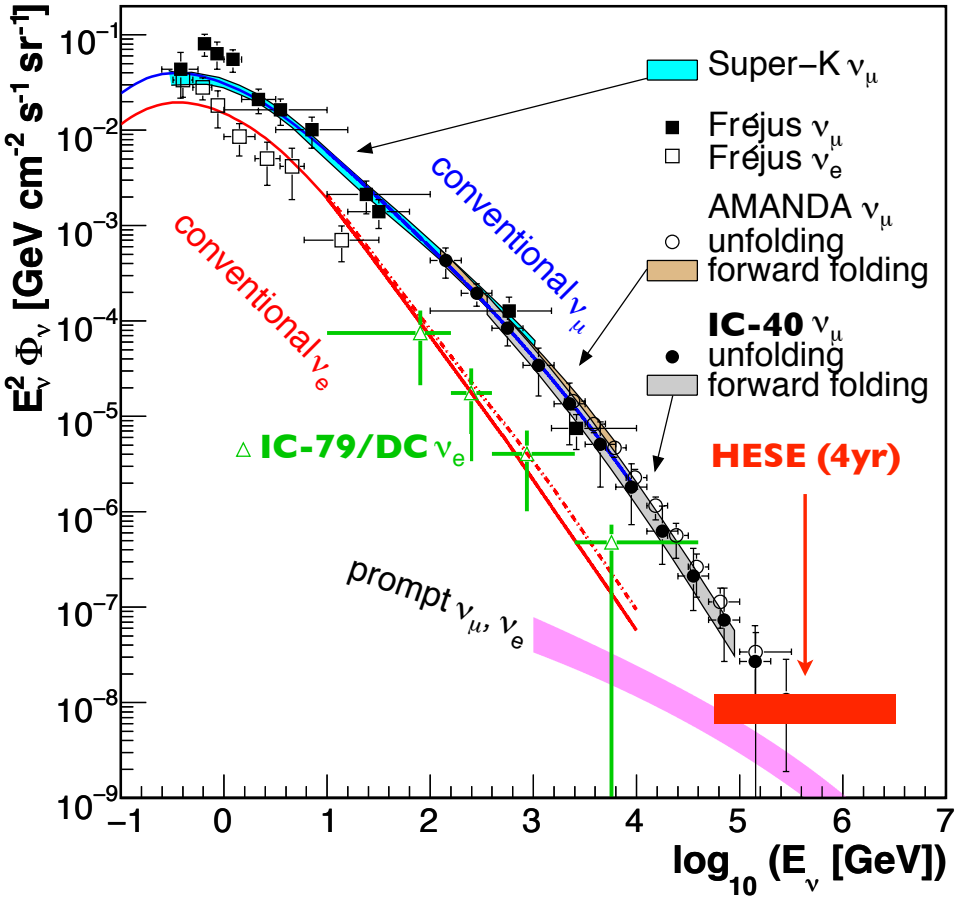


IceCube HESE (4yr)

- **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

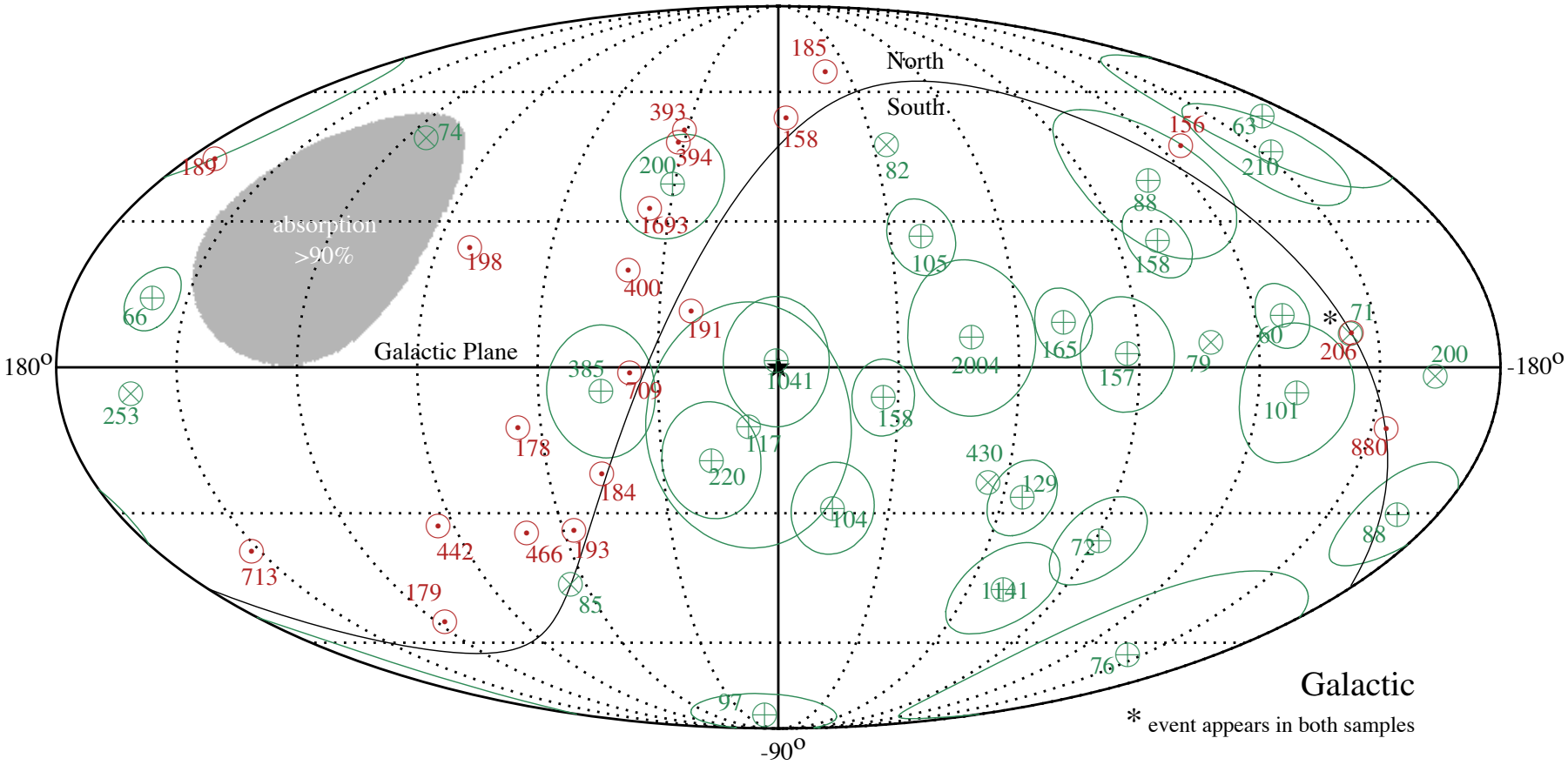
- 54 events in about four years: [IceCube ICRC'15]
  - 39 **cascades** events
  - 14 **track** events
  - 1 **composite** event (removed)
- expected background events:
  - $9.0^{+8.0}_{-2.2}$ **atmospheric neutrinos**
  - 12.6 ± 5.1 **atmospheric muons**
- **best-fit** E^{-2}-flux $(0.06 - 3)$PeV:

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



IceCube Diffuse Flux

HESE 4yr with $E_{\rm dep} > 60$ TeV (green) / Classical $\nu_\mu + \bar{\nu}_\mu$ 2yr with $E_\mu > 50$ TeV (red)



- **24 "cascade events" (circles) and 8 "tracks events" (diamonds)** with $E_{\rm dep} \gtrsim 60$ TeV
- **20 up-going muon neutrino** events with $E_\mu \gtrsim 50$ TeV [IceCube PRL 115 (2015)]
- ✘ **no significant spatial or temporal correlation of events**

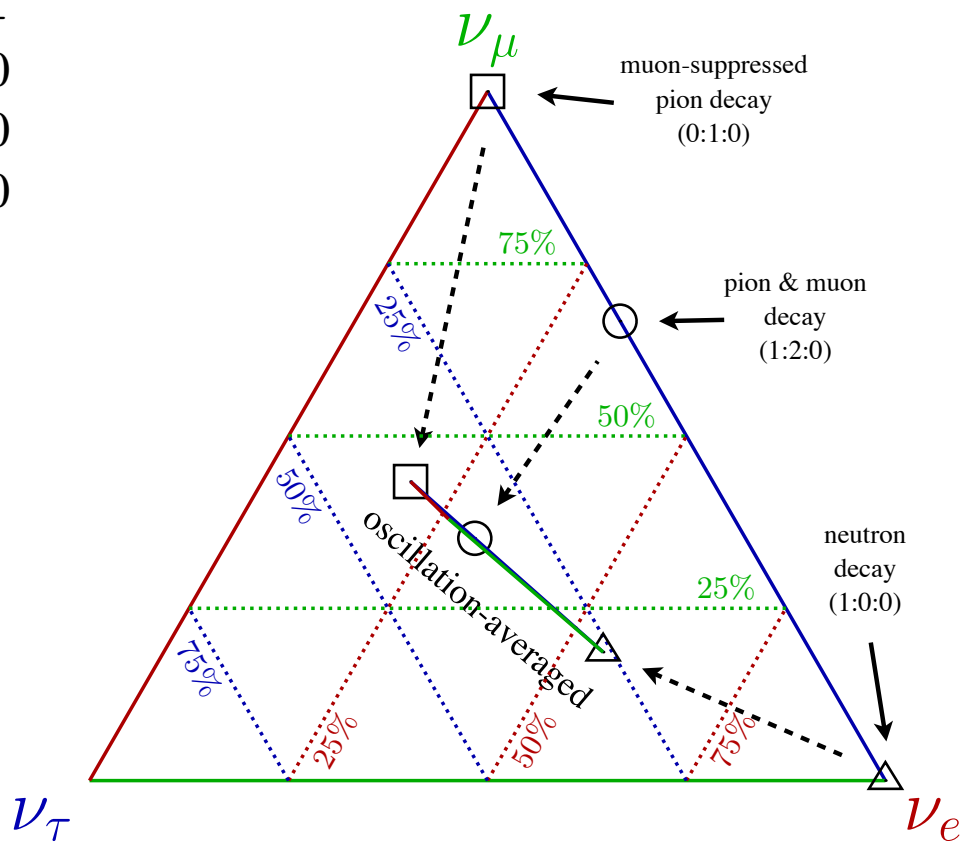
Neutrino Flavors

- 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**

➜ talk by Mauricio Bustamante

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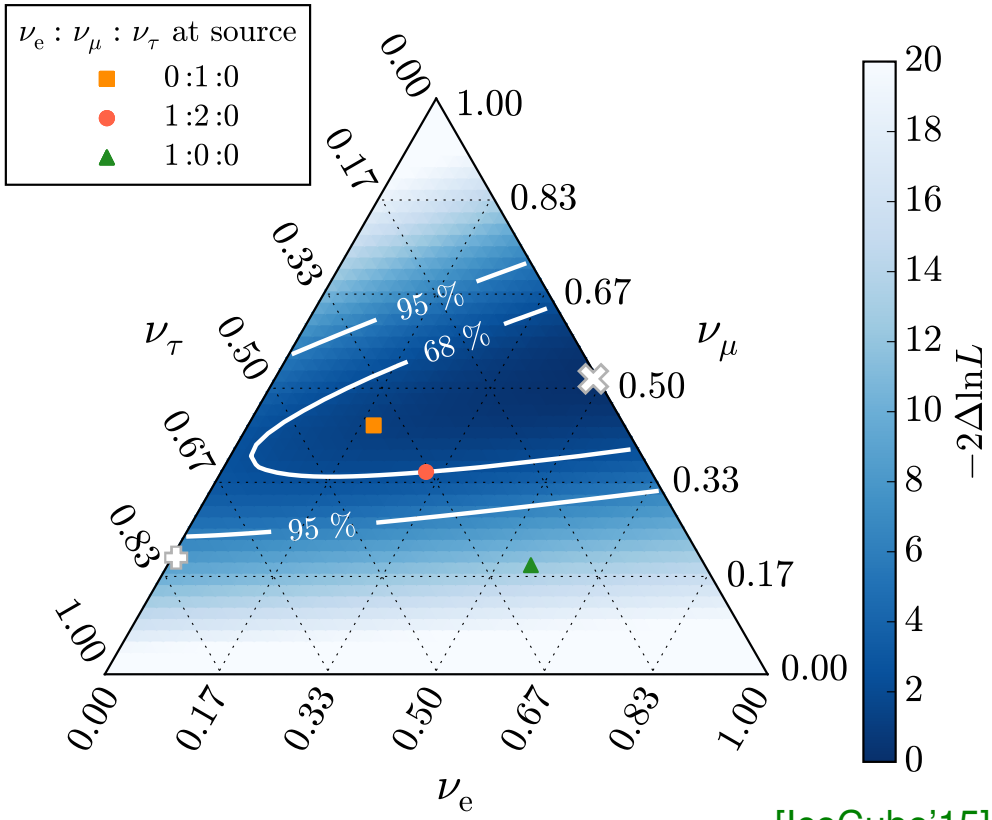

[IceCube'15]

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Multi-messenger Paradigm

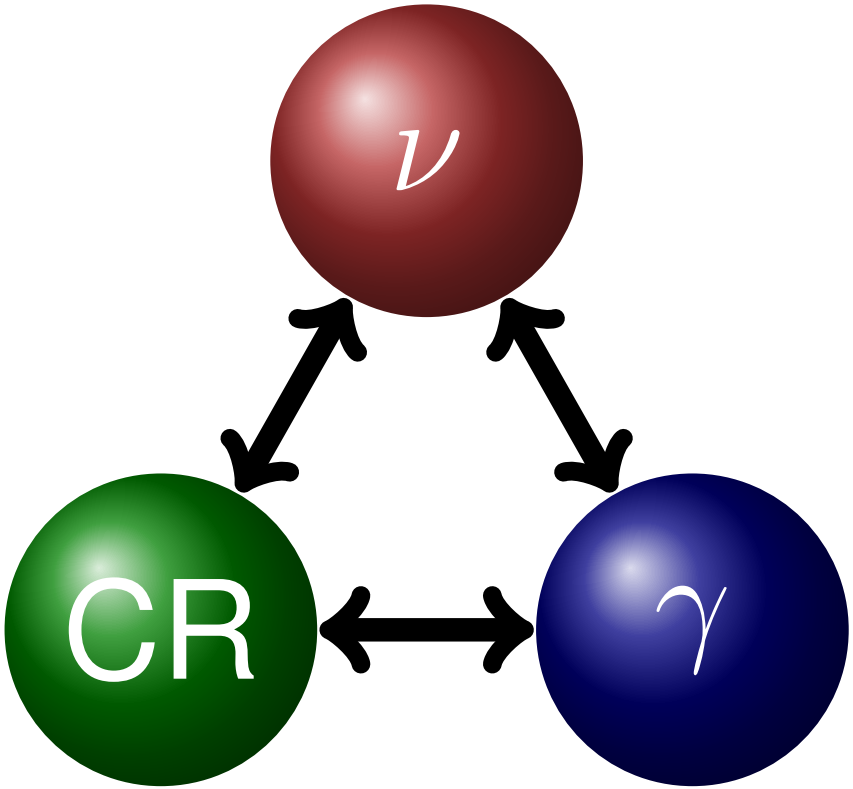
- Neutrino production is closely related to the production of cosmic rays (CRs) and γ-rays.

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

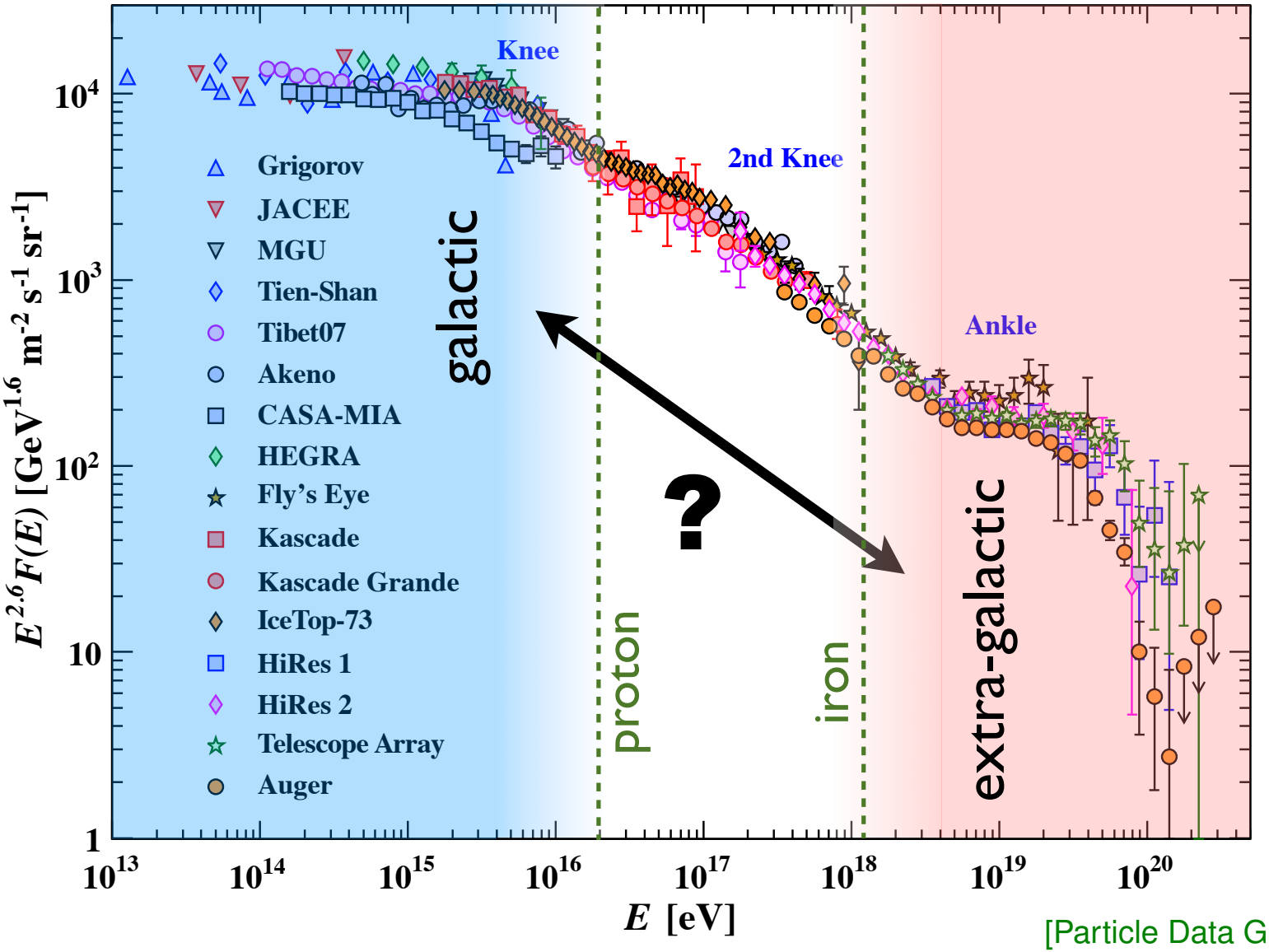
- 1 PeV neutrinos correspond to 20 PeV CR nucleons and 2 PeV γ-rays

➜ **very interesting** energy range:

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



The Cosmic "Beam"



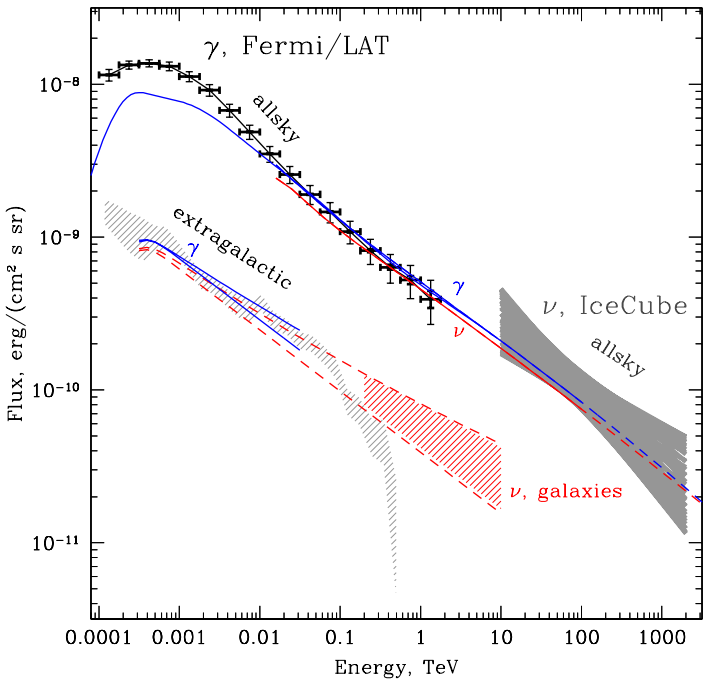
[Particle Data Group'13]

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 and Ostapchenko'14; Neronov, Semikoz & Tchernin'13] [Neronov & Semikoz'14; Guo, Hu & Tian'14; Gaggero, Grasso, Marinelli, Urbano & Valli'15]
  - unidentified Galactic γ-ray emission [Fox, Kashiyama & Meszaros'13] [Gonzalez-Garcia, Halzen & 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]

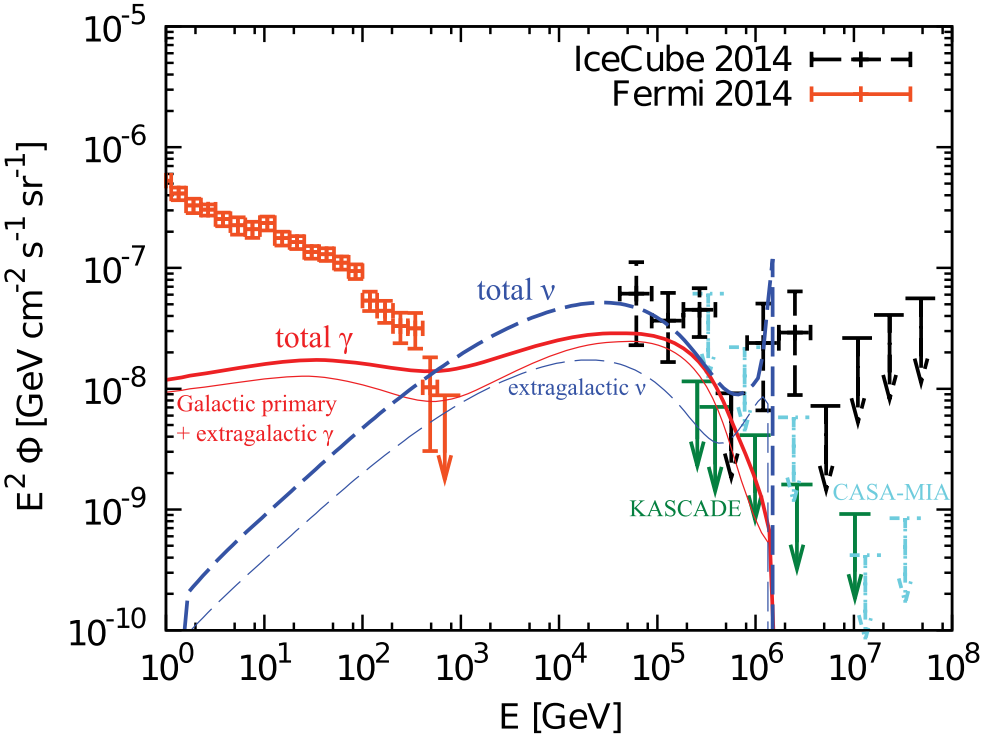
Galactic Emission Models: Two Examples

Hard Galactic Diffuse Emission



[Neronov & Semikoz'14]

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

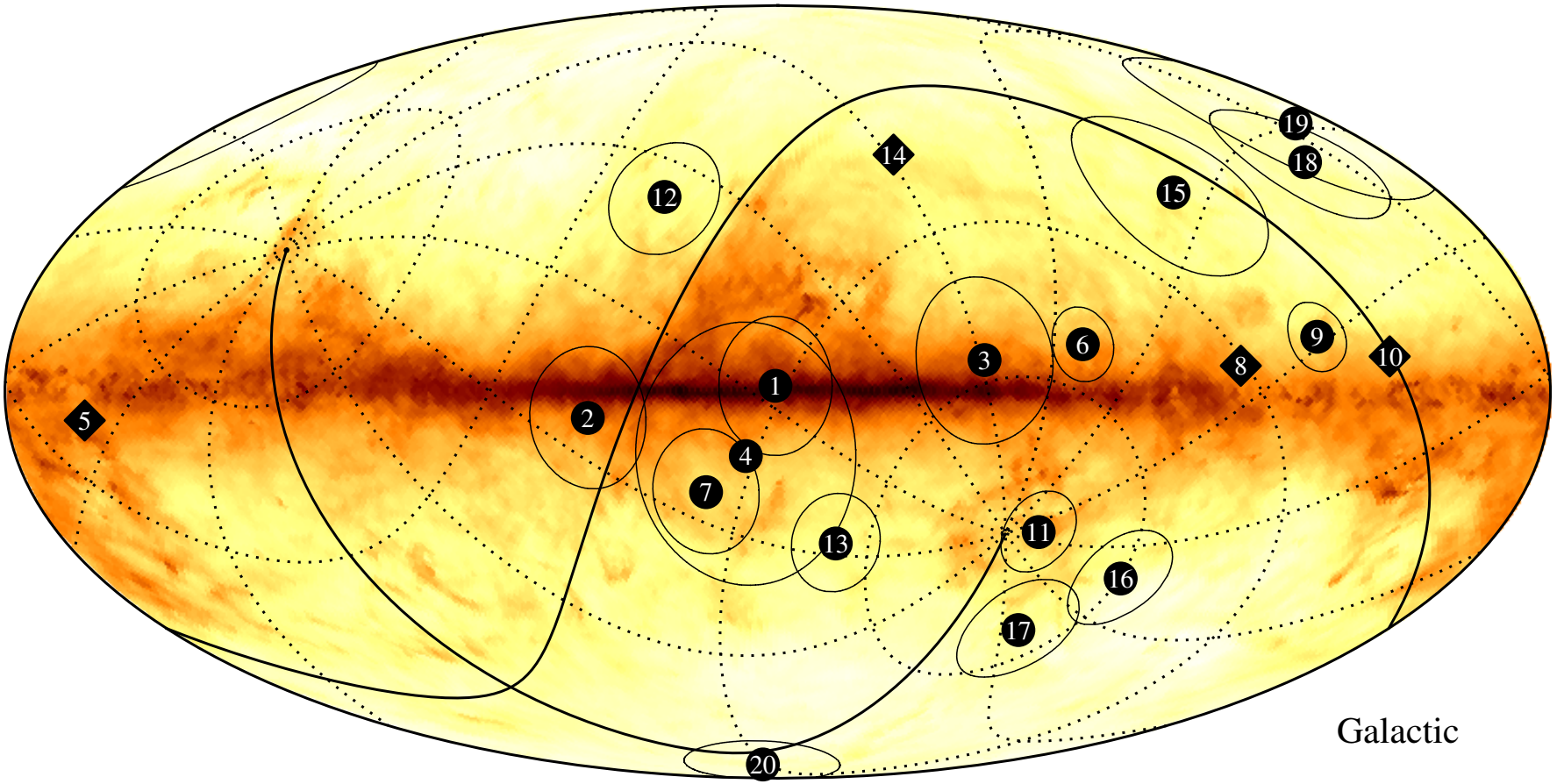


[*e.g.* Murase, Laha, Ando & MA'15]

- 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

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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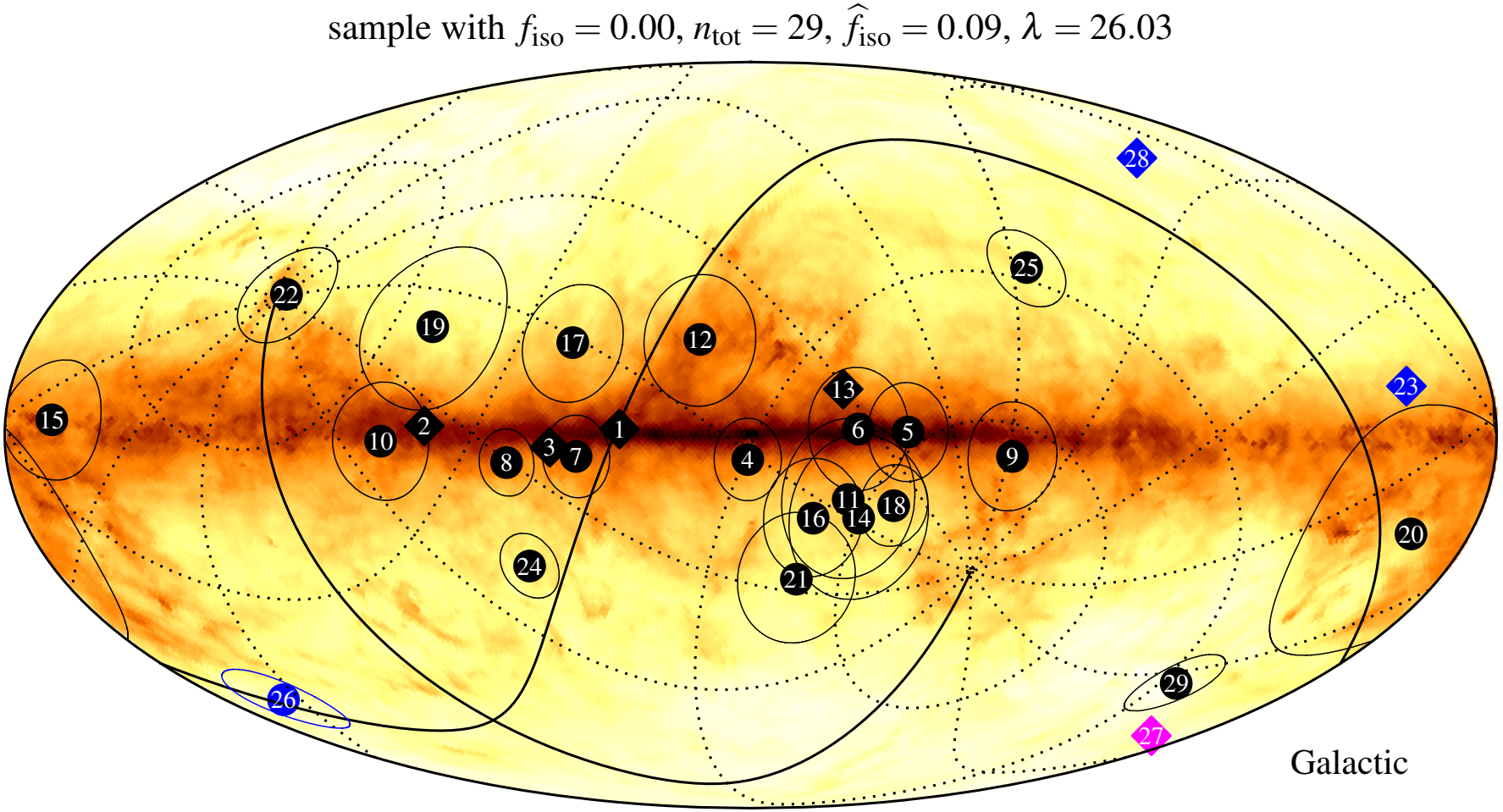

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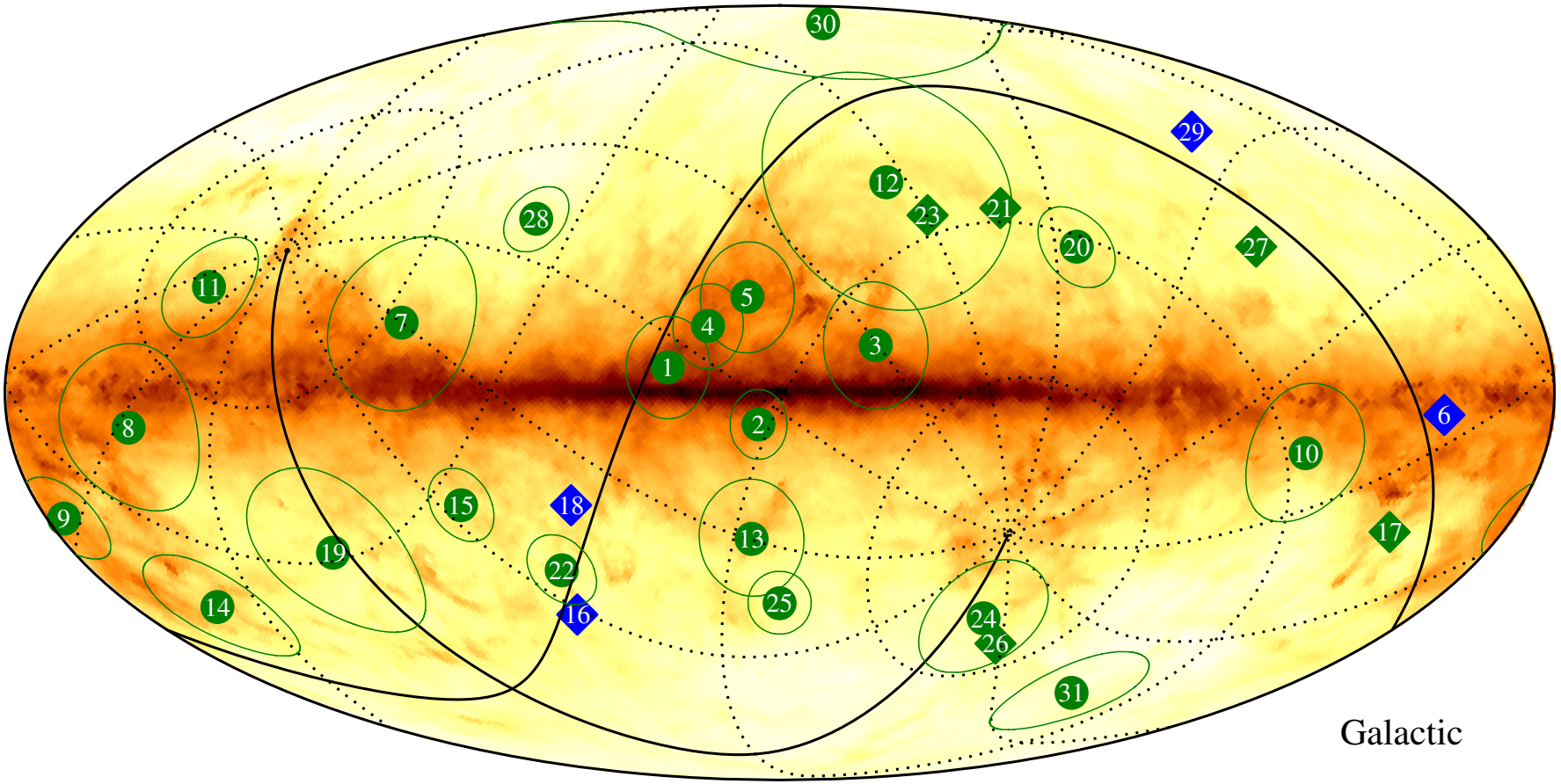
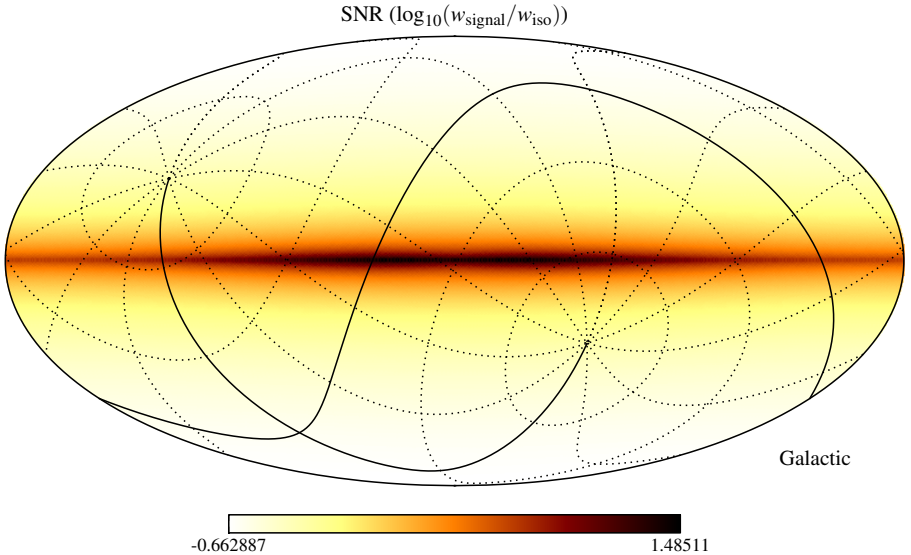
Example: Galactic Diffuse Emission

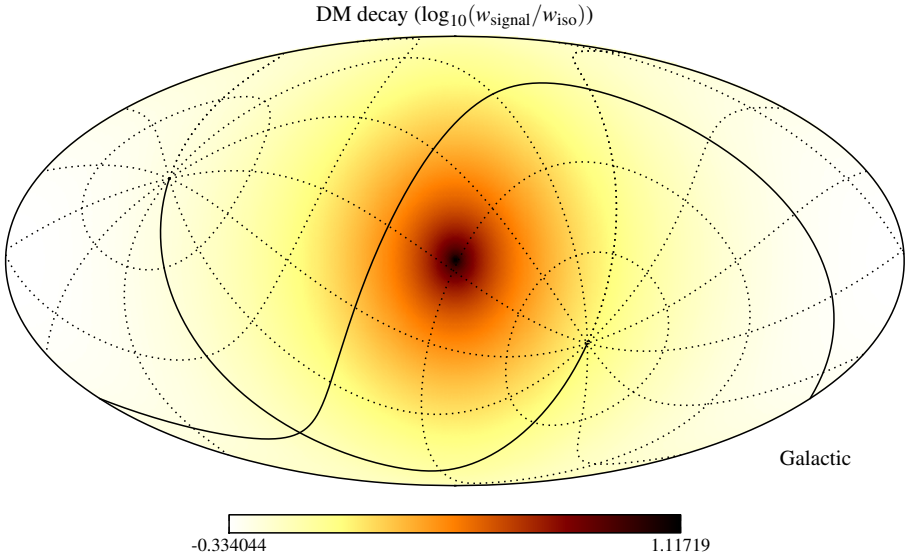
sample with $f_{\rm iso} = 1.00$, $n_{\rm tot} = 31$, $\widehat{f}_{\rm iso} = 0.82$, $\lambda = 1.11$

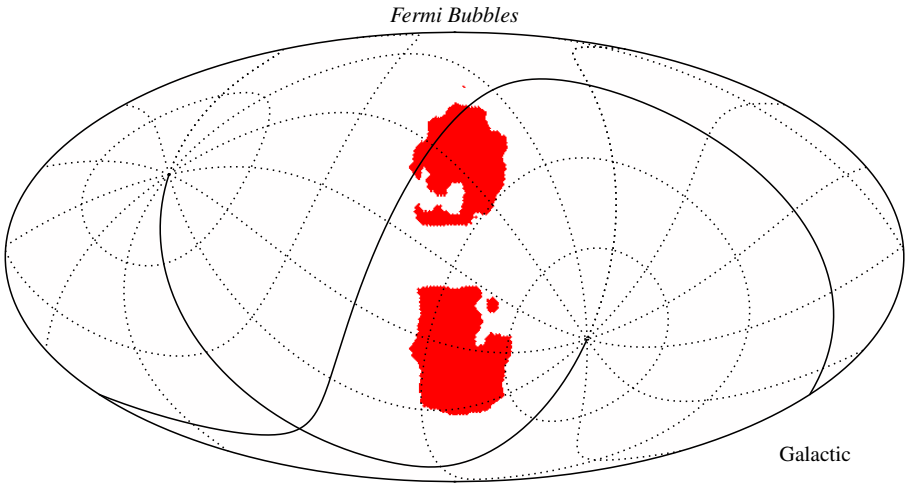


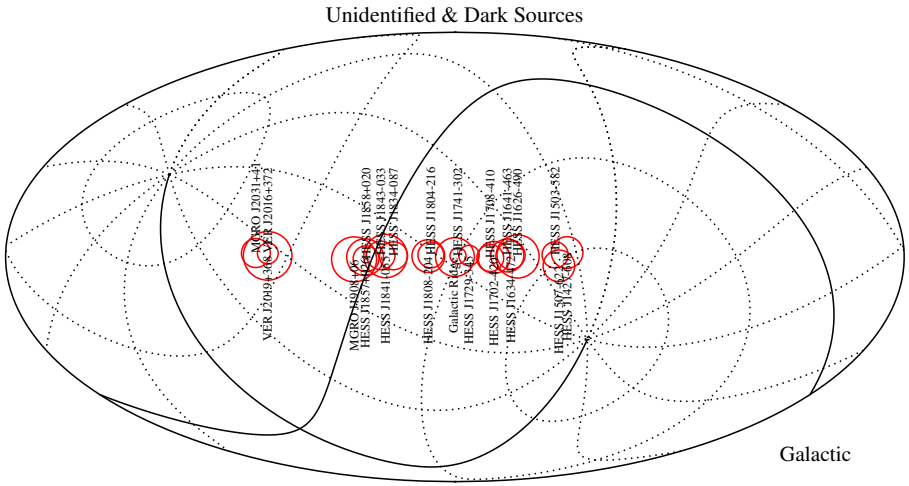
- Strong Galactic diffuse emission up to PeV? [Neronov, Semikoz & Tchernin'13]
- simulated map: $\diamond/\circ$: Galactic ν | $\diamond/\circ$: isotropic ν | $\diamond/\circ$: atmospheric ν | $\diamond/\circ$: atmospheric μ

Other Extended Galactic Emission



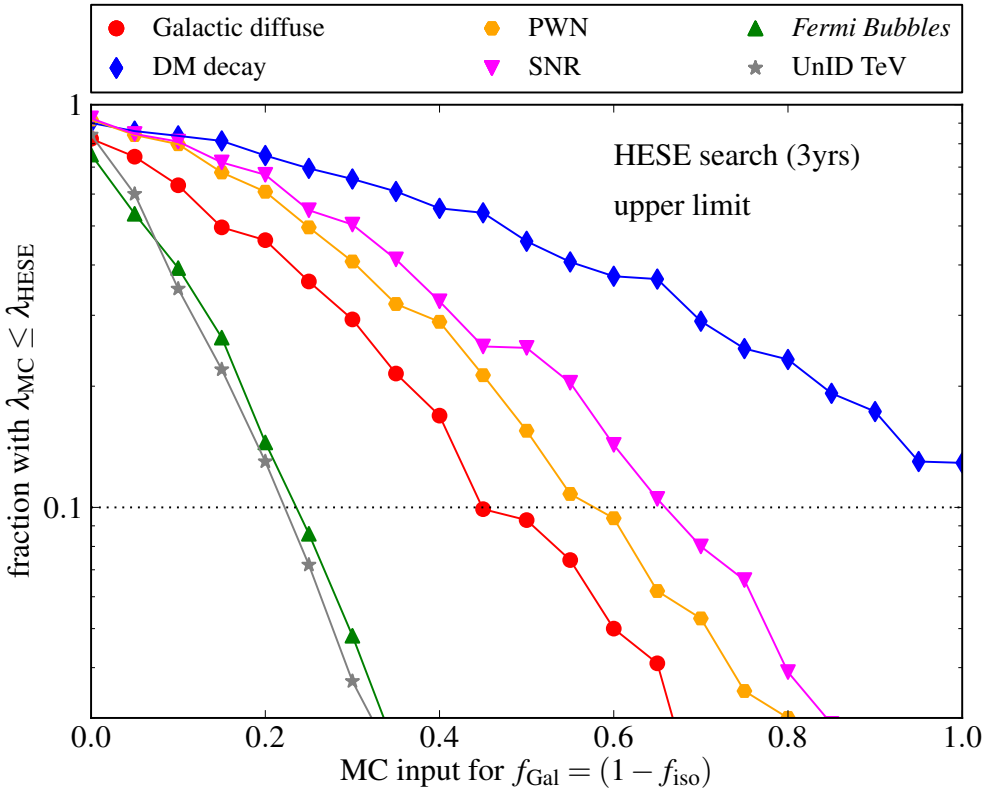






Galactic Limits

- 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?

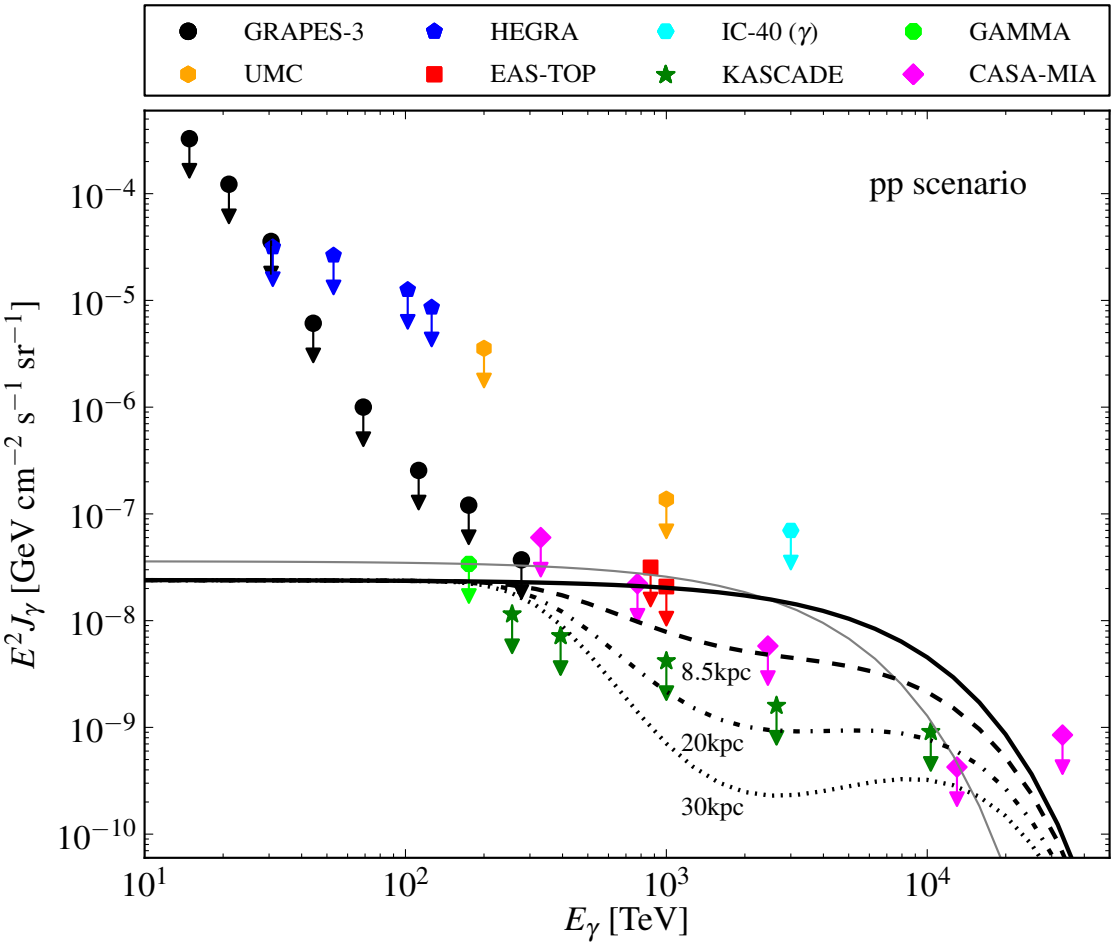


[MA, Bai, Barger & Lu'15]

PeV γ-ray Associations?

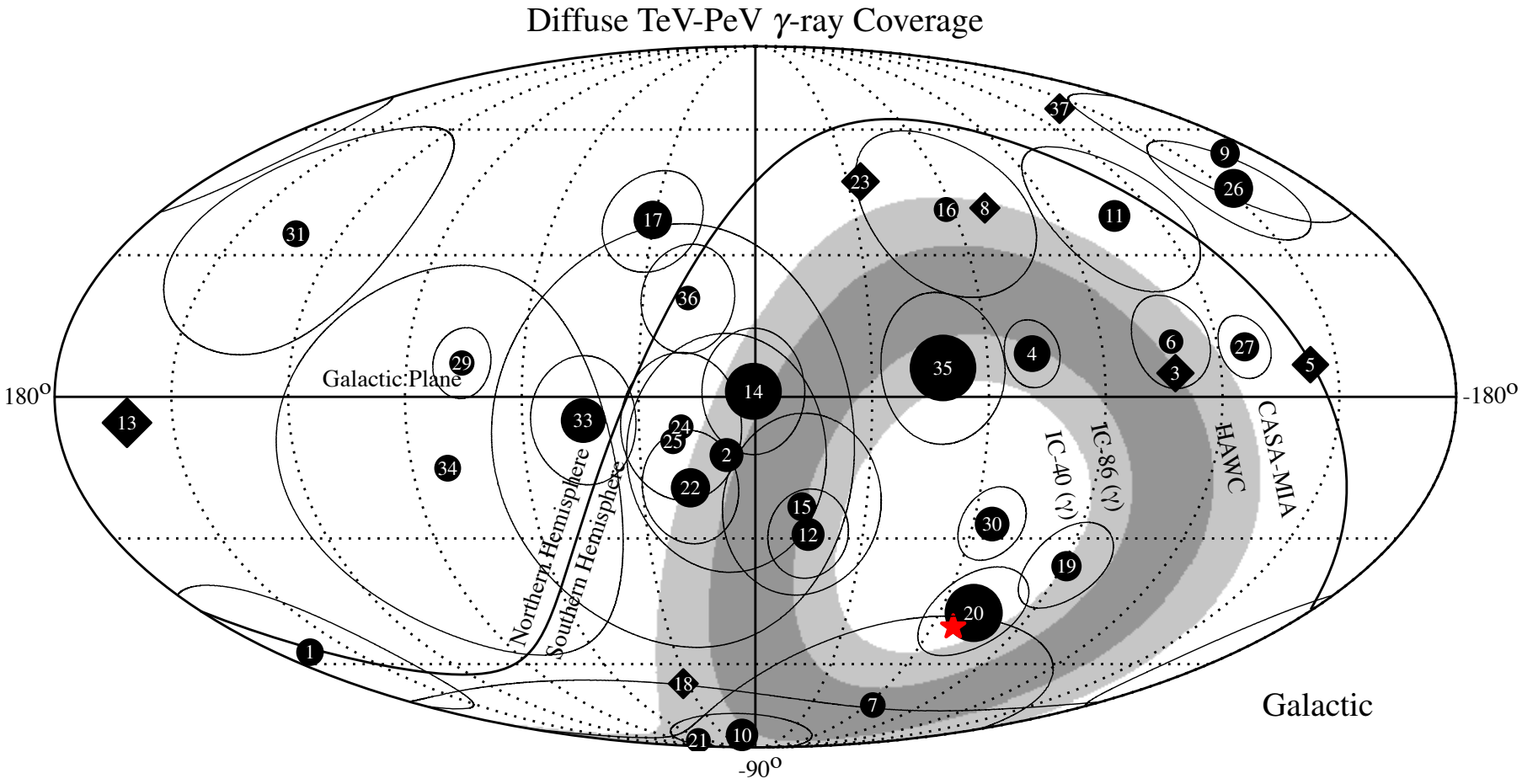
- ➜ PeV γ-rays from $\pi^0 \to 2\gamma$
- ✘ strong absorption via $\gamma\gamma_{\rm BG} \to e^+e^-$
  - effect strongest for CMB in PeV range: $\lambda_{\gamma\gamma} \simeq 10$ kpc
  - plot indicate absorption from 8.5 kpc (GC) to 30 kpc
- ➜ strong constraints on isotropic diffuse Galactic emission from γ-ray observatories

[Gupta'13, MA & Murase'13]



[MA & Murase'13]

PeV γ-ray Associations?



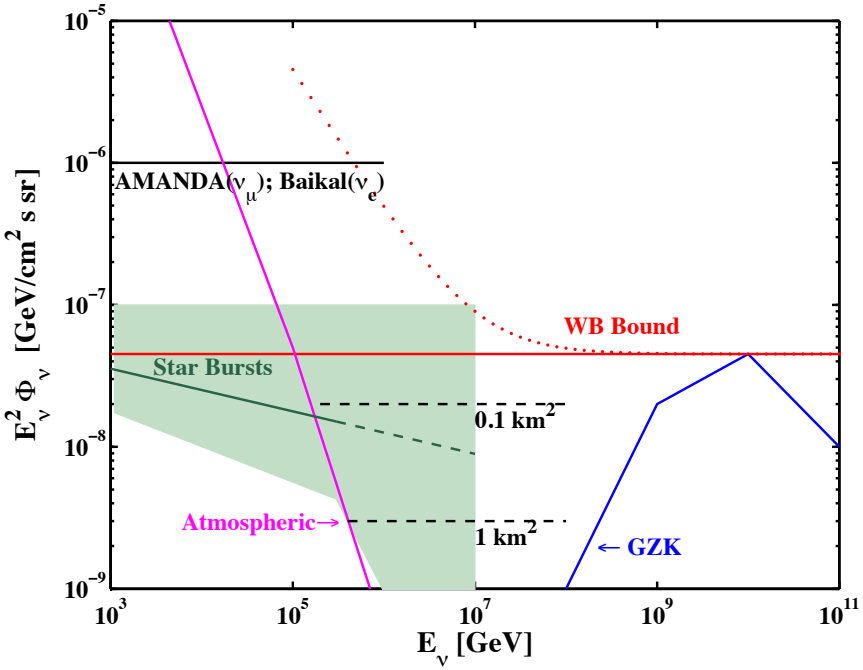
- large overlap of HESE events with TeV-PeV "blind spot"
- one PeV event ("Ernie") within 10° of PeV γ-ray "warm spot" [IceCube'12]

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; 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, Dimitrakoudis, Padovani, Mastichiadis & Resconi'15]
  - gamma-ray bursts (GRB) [Murase & Ioka'13; Dado & Dar'14; Tamborra & Ando'15]
  - 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]
  - galaxy clusters/groups [Murase, MA & Lacki'13; Zandanel, Tamborra, Gabici & Ando'14]
  - ...

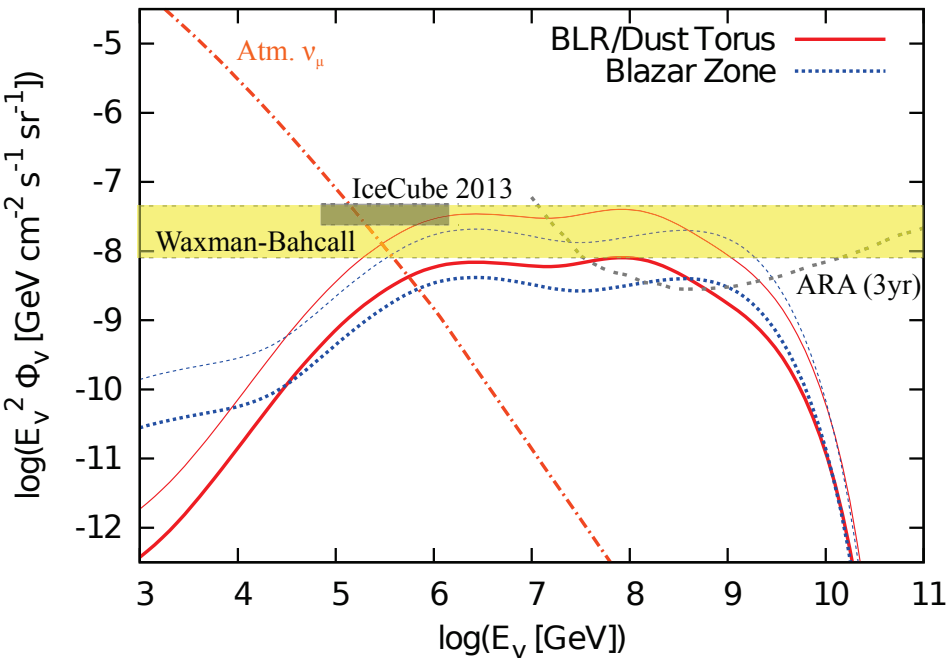
Extragalactic Emission Models: Two Examples

Starburst Galaxies ("pp" scenario)



[Loeb & Waxman'06]

Active Galactic Nuclei ("$p\gamma$" scenario)

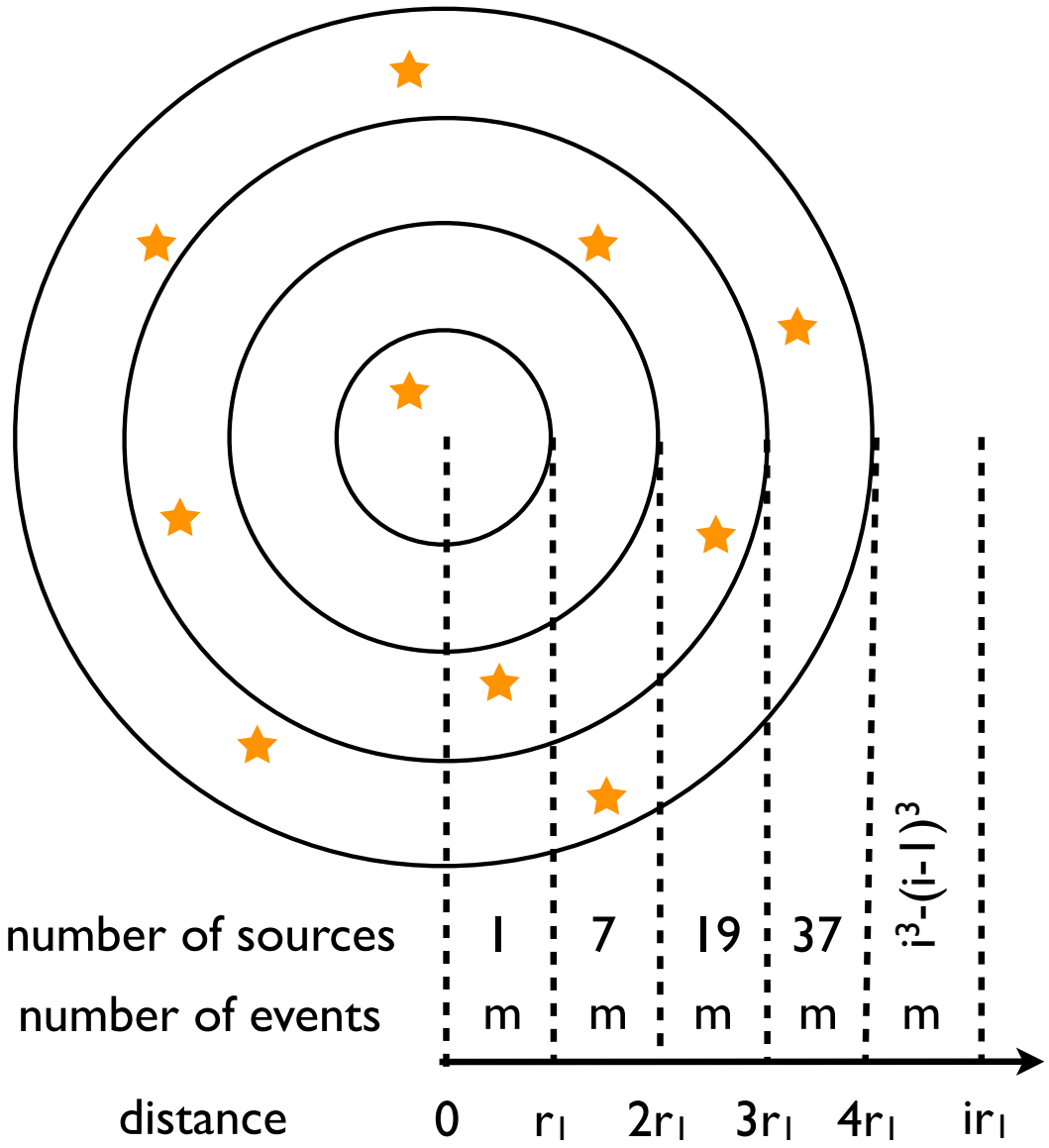


[Mannheim'96; Halzen & Zas'97]

[*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

Identification of Extragalactic Point-Sources?



- total number of sources

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

- total number of "shells"

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

- total number of events

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

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

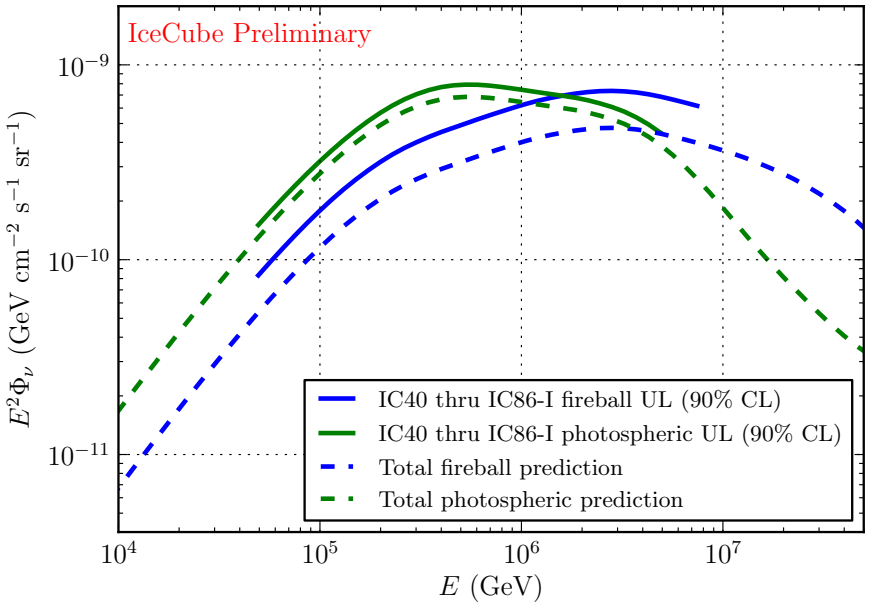
$$\bar{N} \simeq 200 - 500$$

✘ random clusters are very likely with bad angular resolution!

➜ **multi-messenger correlations**!

IceCube Stacking Searches

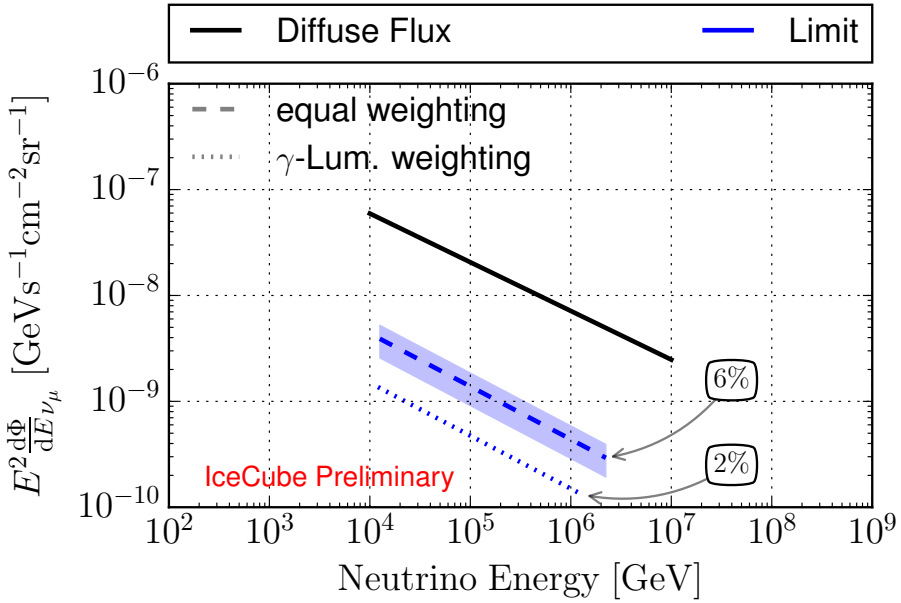
GRB Stacking



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

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

Blazar Stacking



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

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

Extragalactic Gamma-Rays

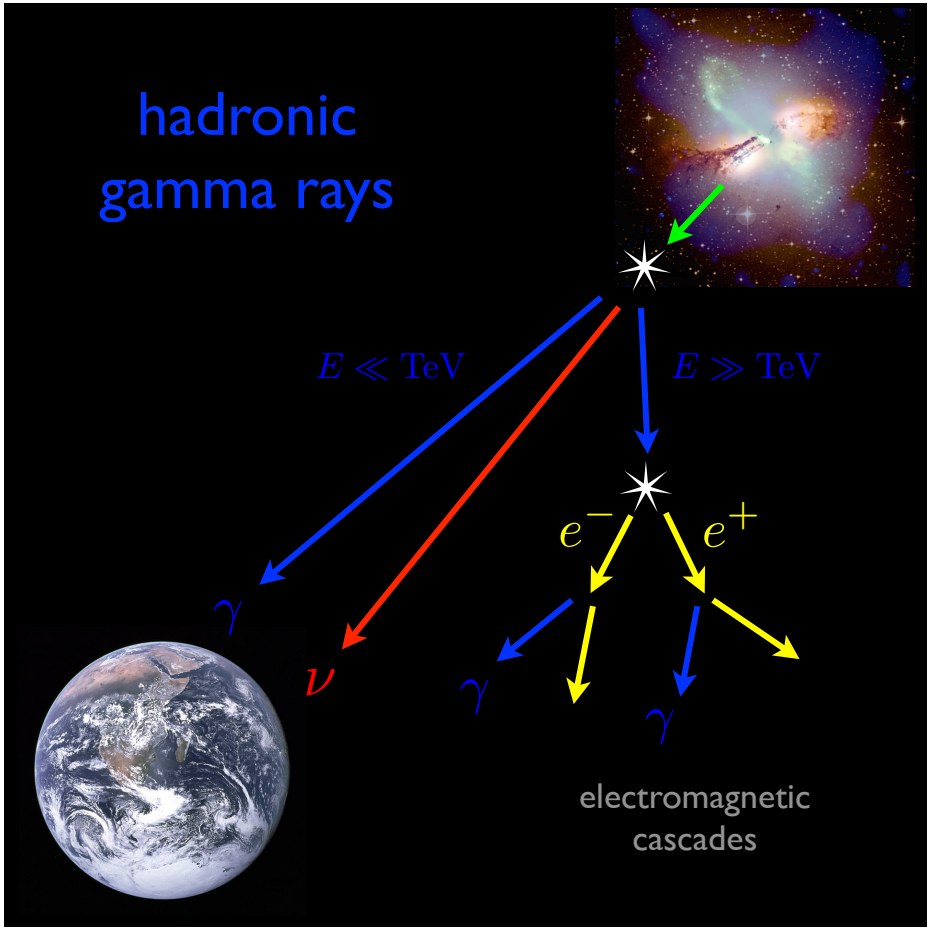
- **hadronic** γ-rays:
  pion production in CR interactions

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

➜ 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

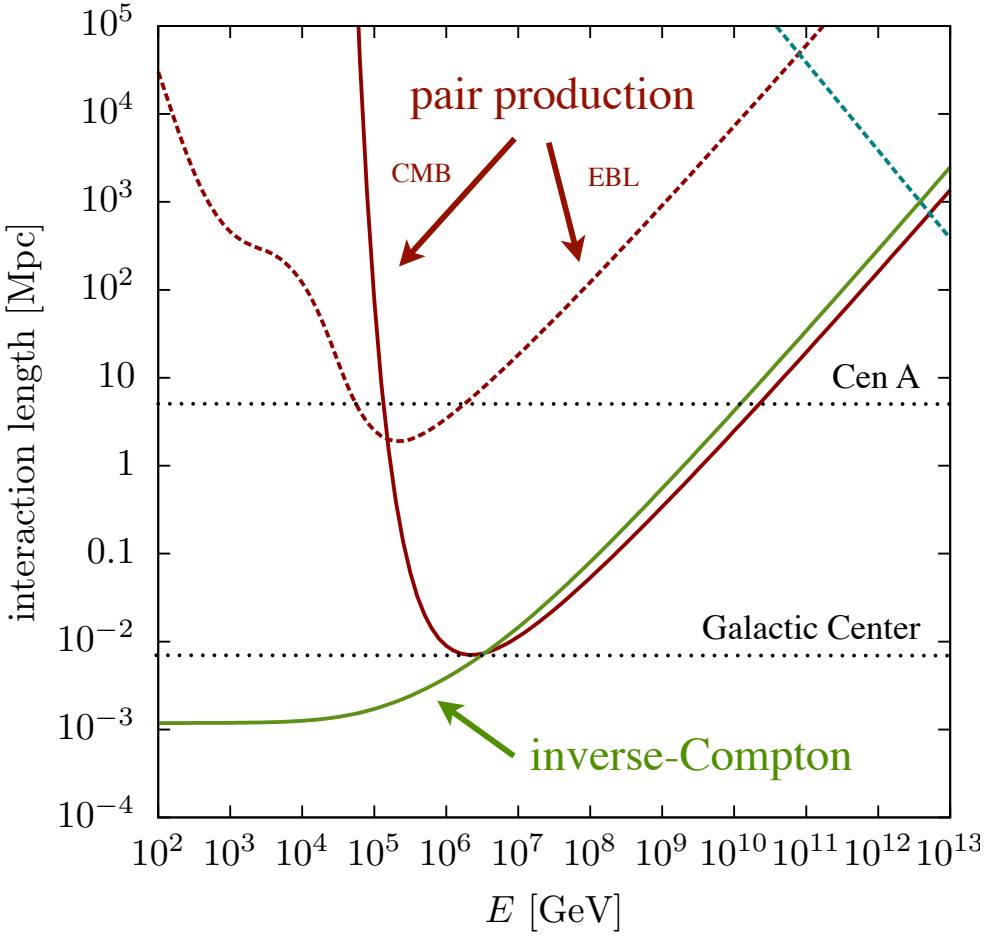


Electromagnetic Cascades

- 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 *Fermi* IGRB

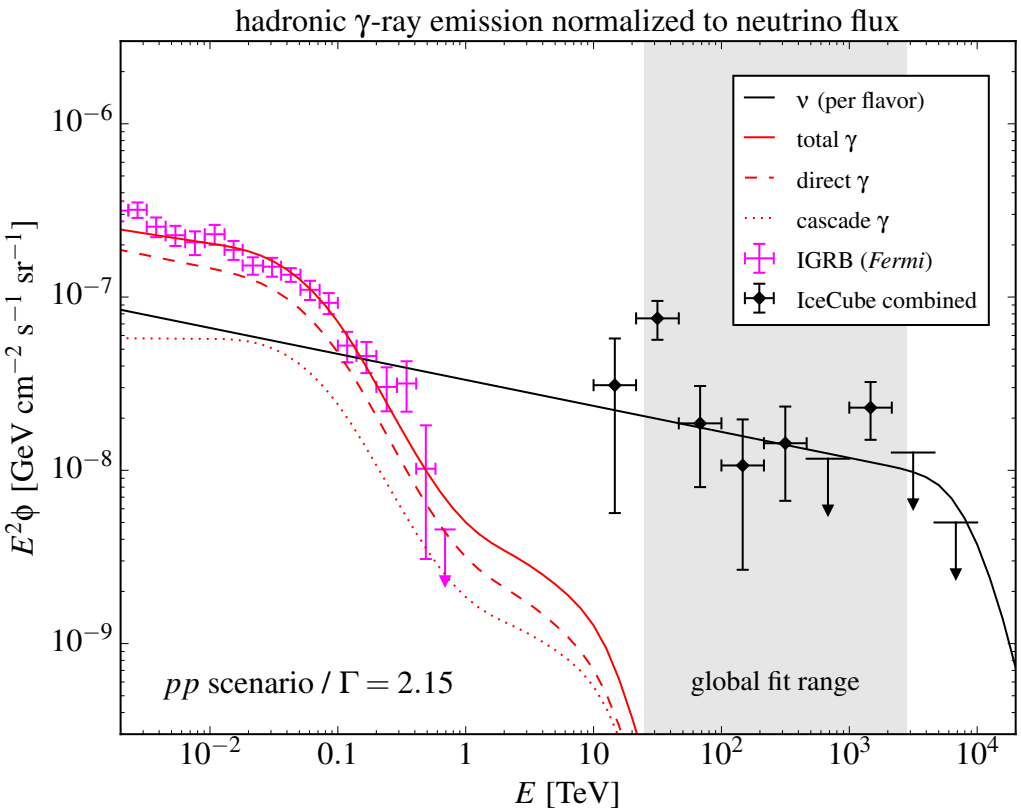
[Murase, MA & Lacki'13; Chang & Wang'14]

- 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]

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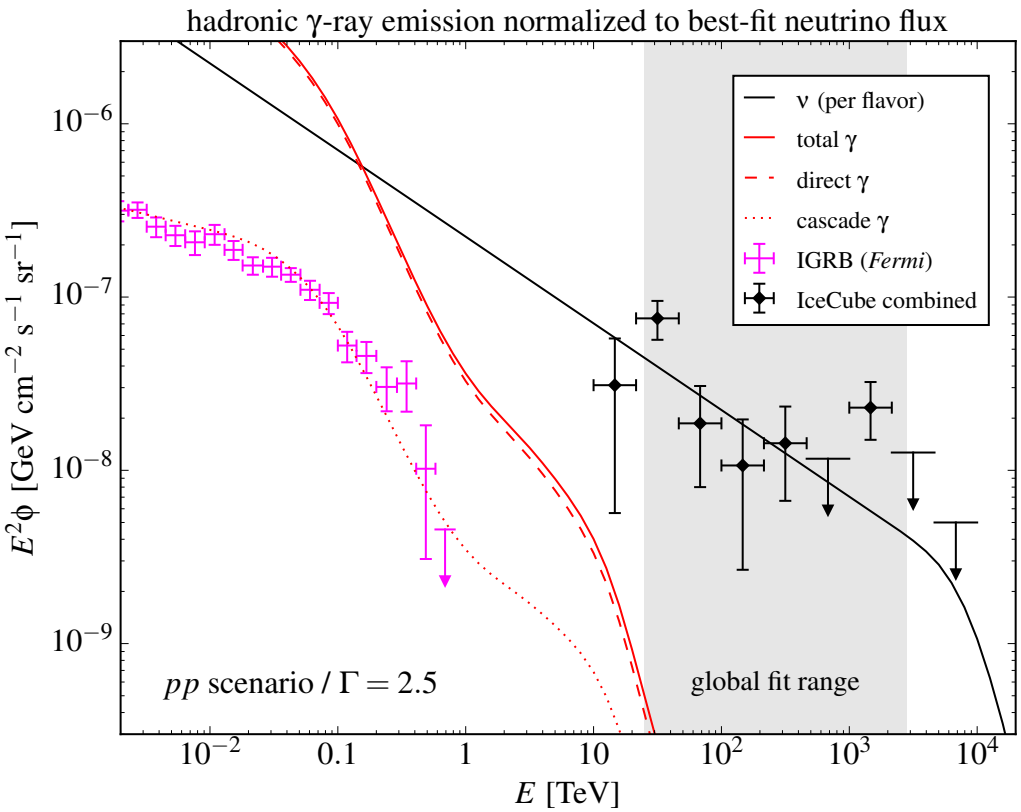

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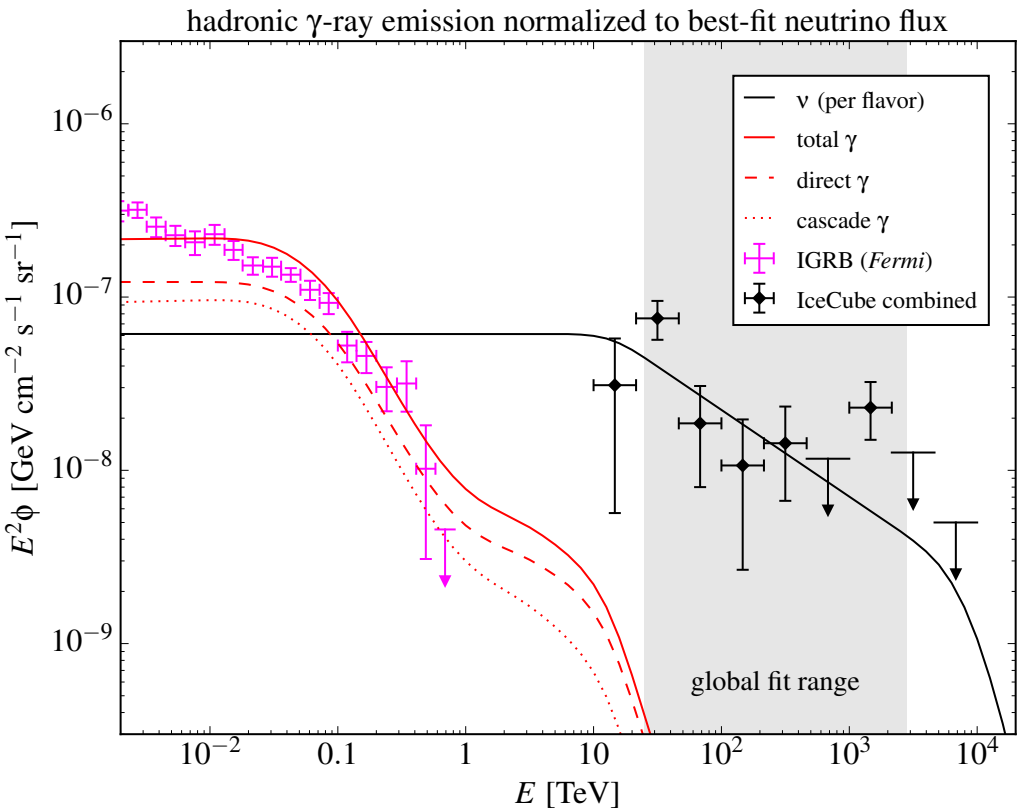

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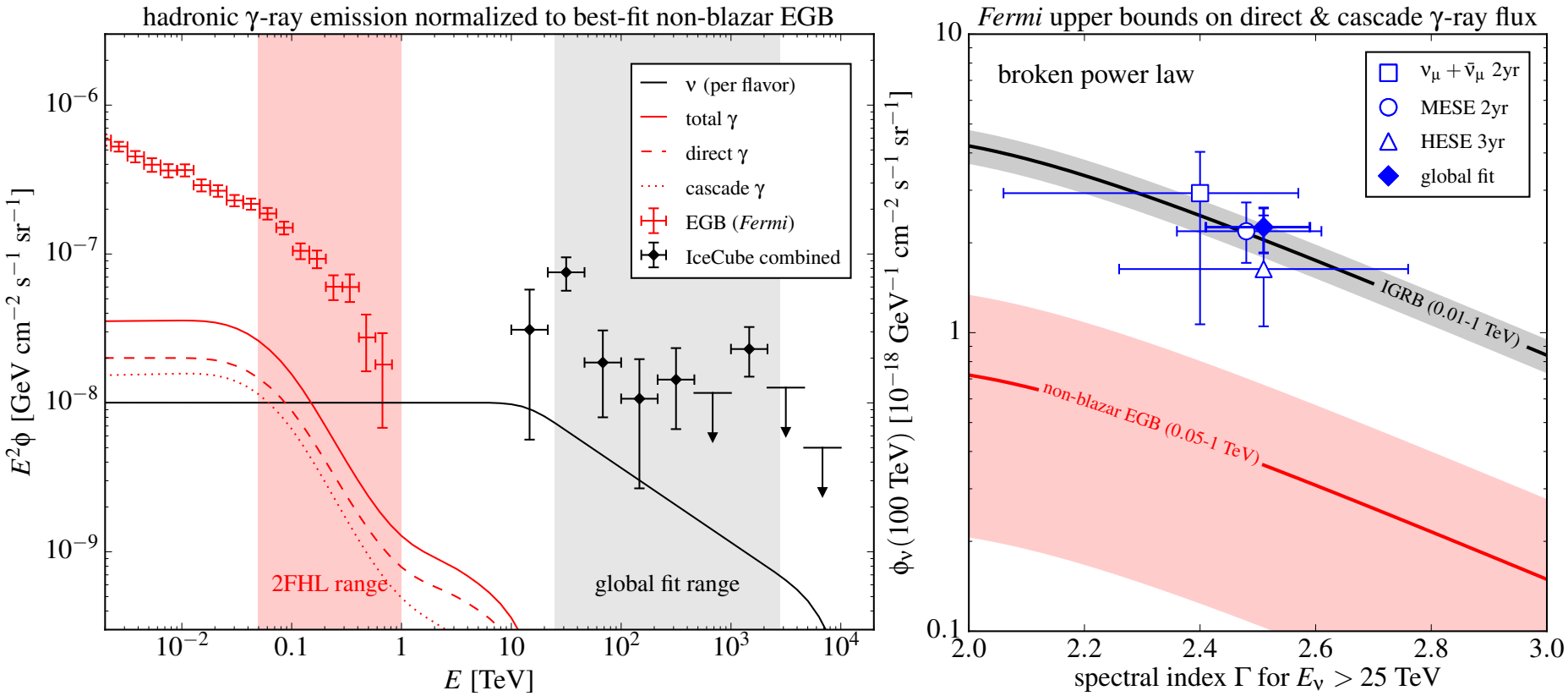
Non-Blazar Limits on Gamma-Ray Background



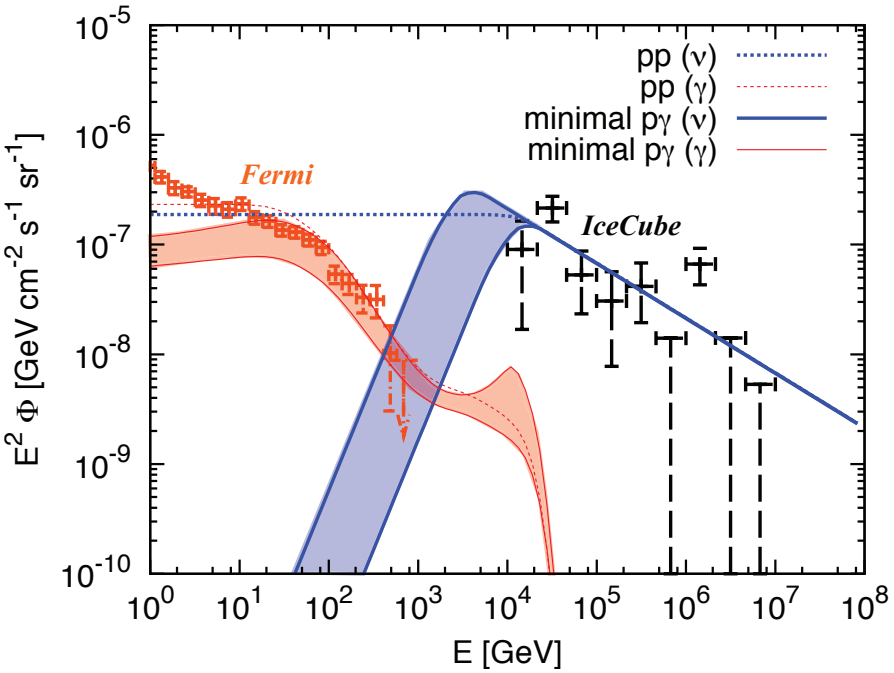
[Bechtol, MA, Ajello, Di Mauro & Vandenbroucke]

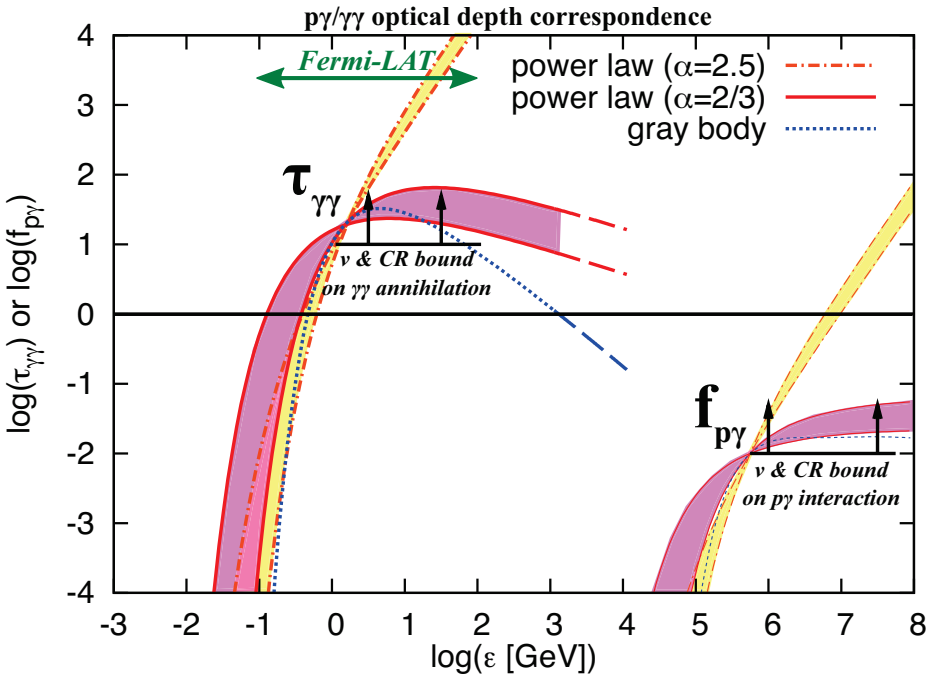
- Total γ-ray background above 50 TeV dominated by blazars ($\sim 86\%$) [Fermi'15]
- ✘ **strong tension** with IceCube observation

Comments & Consequences

- Strong limits apply to **CR calorimeters**, like starburst galaxies or galaxy clusters.
- Some direct γ-ray emission can be reduced in $\gamma\gamma_{\rm BG}$ interactions in sources. [Chang & Wang'14]
- Cascade emission alone contributes at the level of 10% above 100 GeV to the IGRB.
- Is **blazar emission** above 50 GeV dominated by **hadronic interactions**?
- 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]
- Is secondary γ-ray emission "hidden" by **source radiation backgrounds**? [Murase, Guetta & MA'15]
- The diffuse flux also saturates limits from **UHE CR sources**. Is this population also responsible for UHE CRs? [Katz, Waxman, Thompson & Loeb'13]

Fermi IGRB and $p\gamma$ Scenarios?





[Murase, Guetta & MA'15]

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

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

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

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

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

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

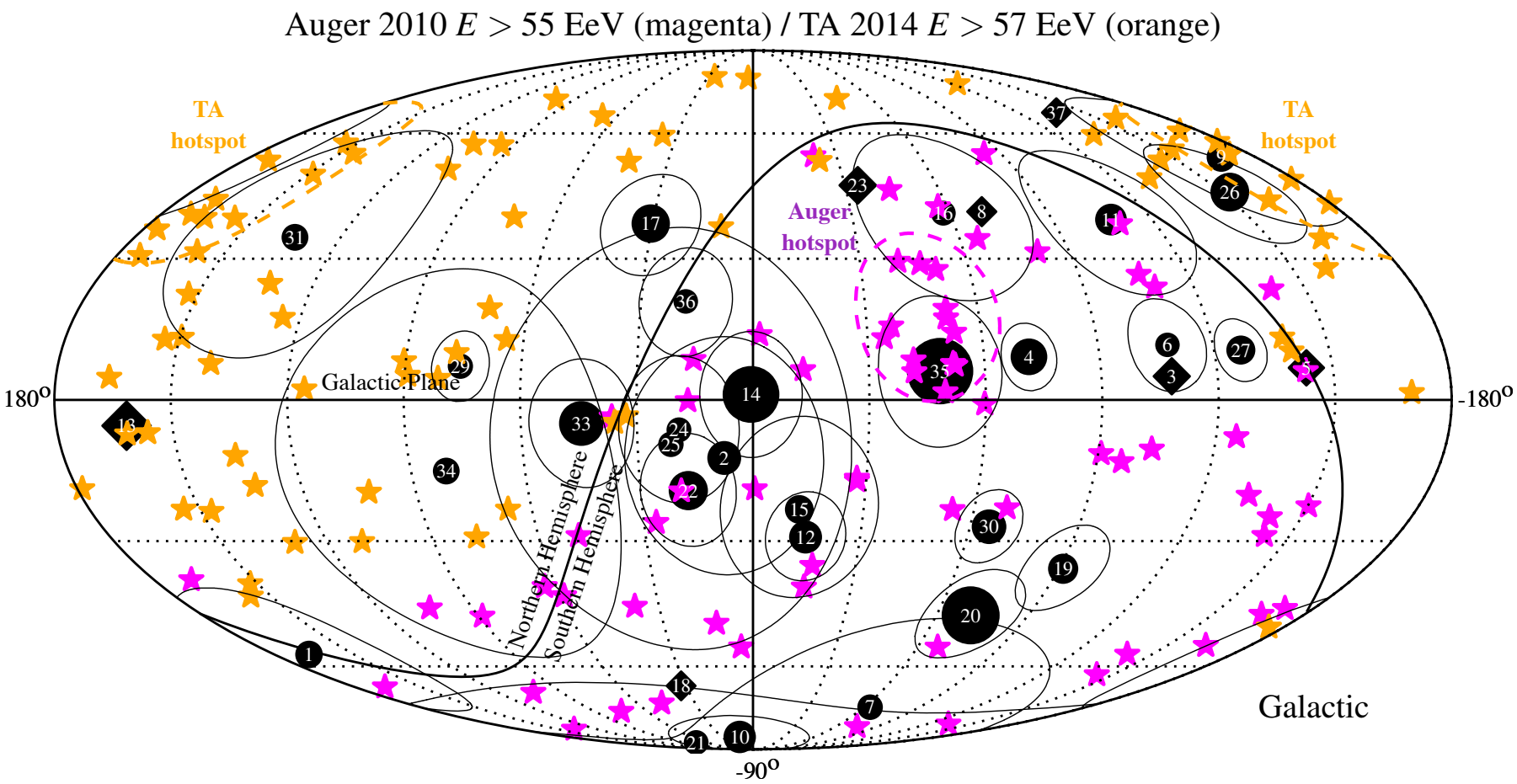
➜ two-zone models: acceleration + CR "calorimeter"?

  - 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]

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
- cross correlation? **only expected for $\lambda_{\rm GZK}/\lambda_{\rm Hubble} \sim 5\%$ of neutrino events**

Ultra-High Energy Cosmic Rays

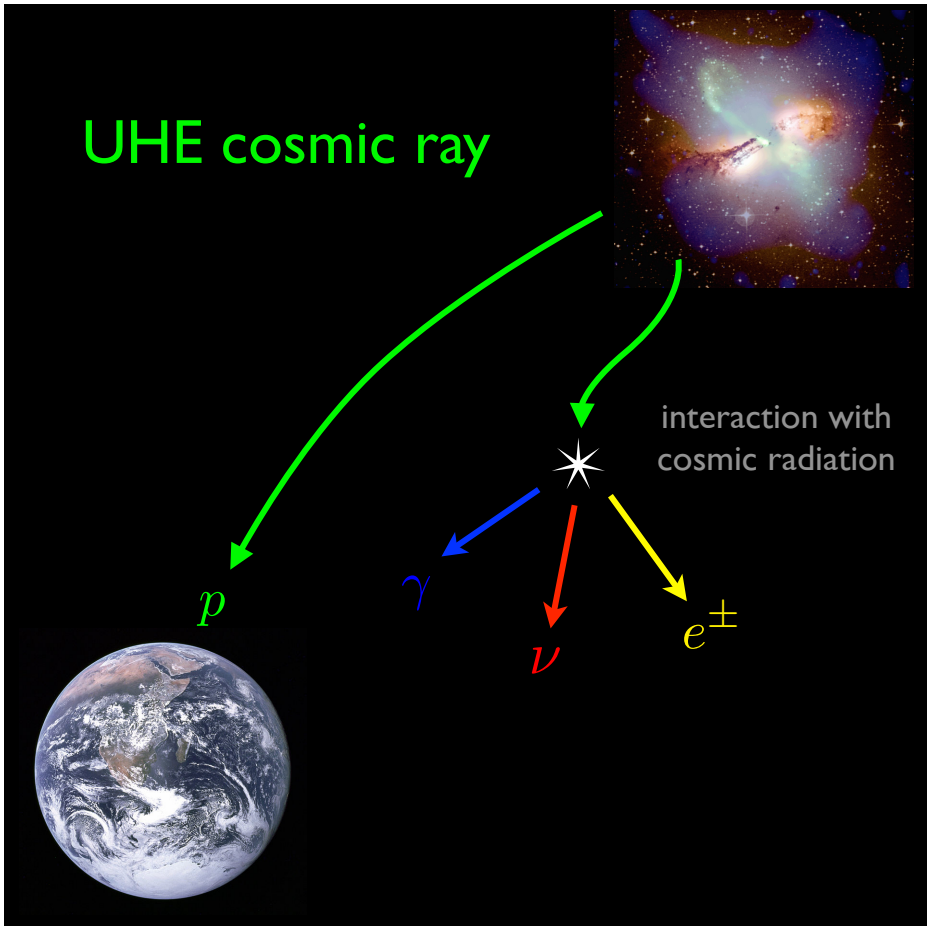
- particle confinement during acceleration requires: [Hillas'84]

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

✘ *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**

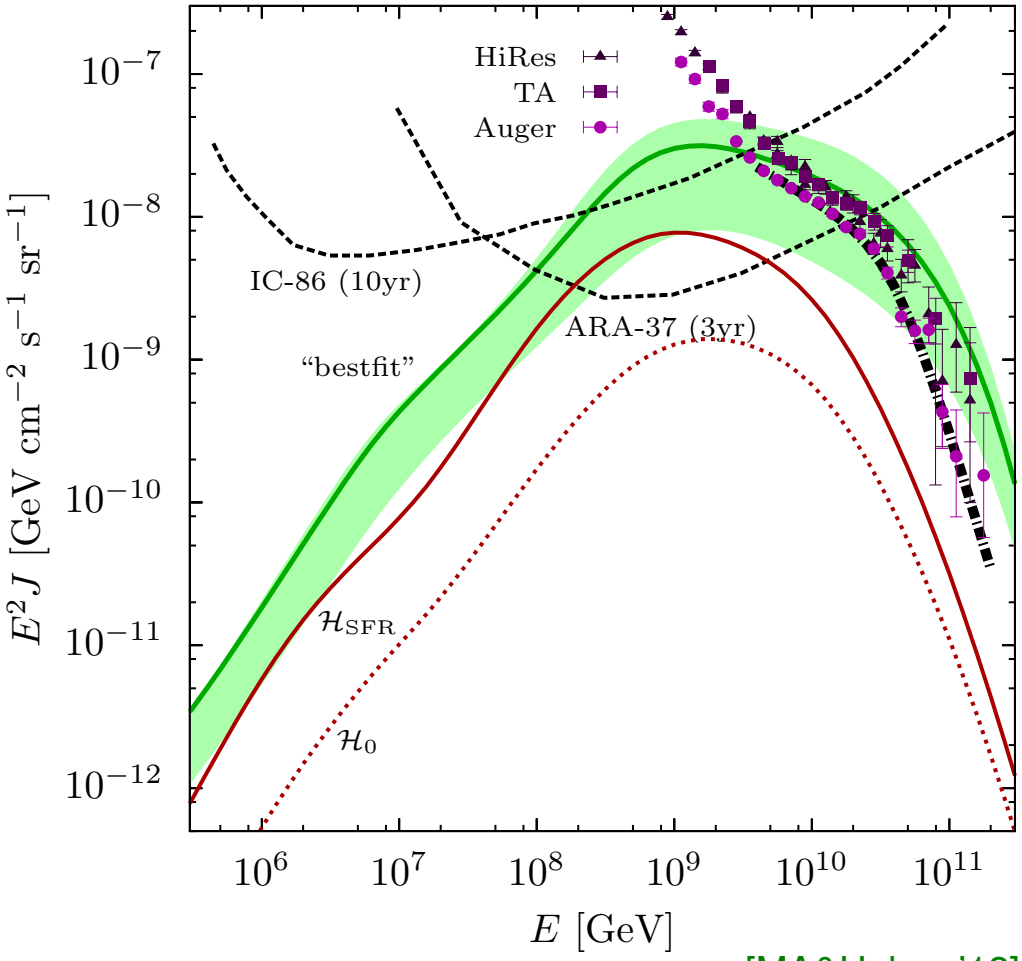
    [Berezinsky & Smirnov'75; Mannheim, Protheroe & Rachen'01; Keshet, Waxman, & Loeb'03; Berezinsky, Gazizov, Kachelriess & Ostapchenko'10; MA, Anchordoqui, Gonzalez–Garcia, Halzen & Sarkar'10; MA & Salvado'11; Gelmini, Kalashev & Semikoz'12]

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]

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.
- Local **PeV γ-ray astronomy**?

➜ **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**?

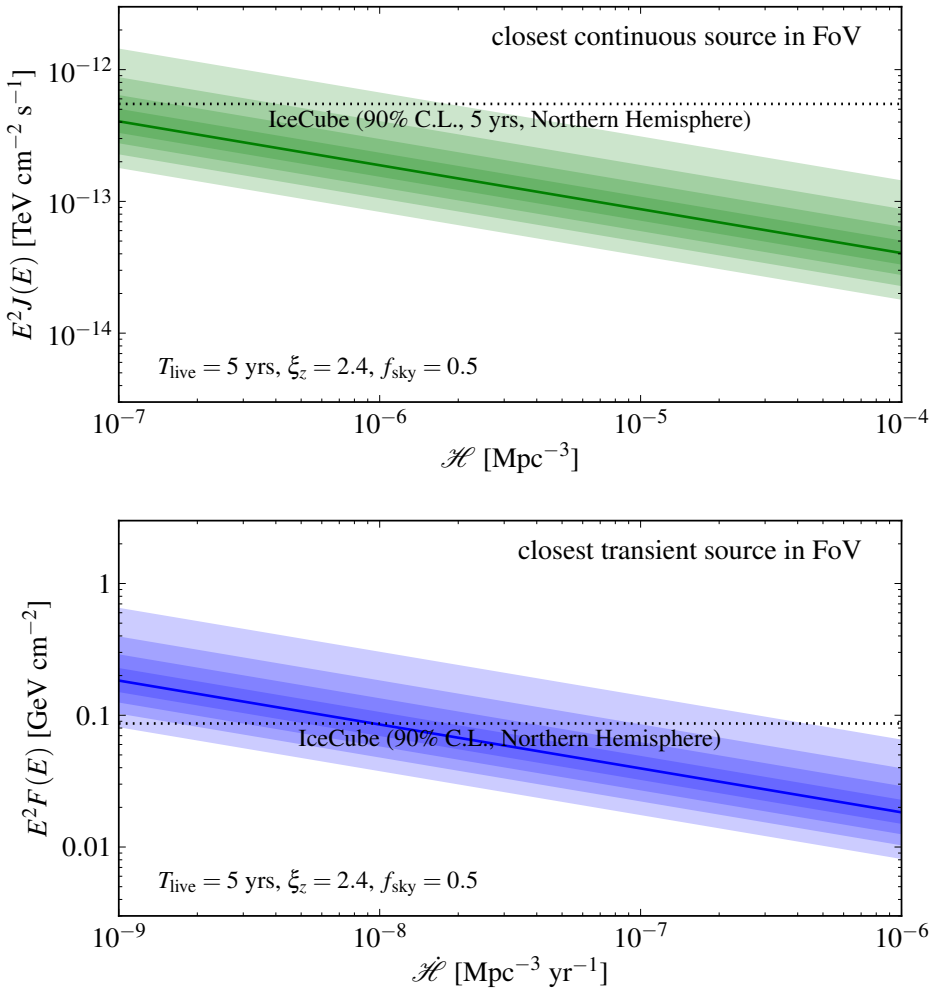
Appendix

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 ξ_z

➜ PS observation requires rare sources

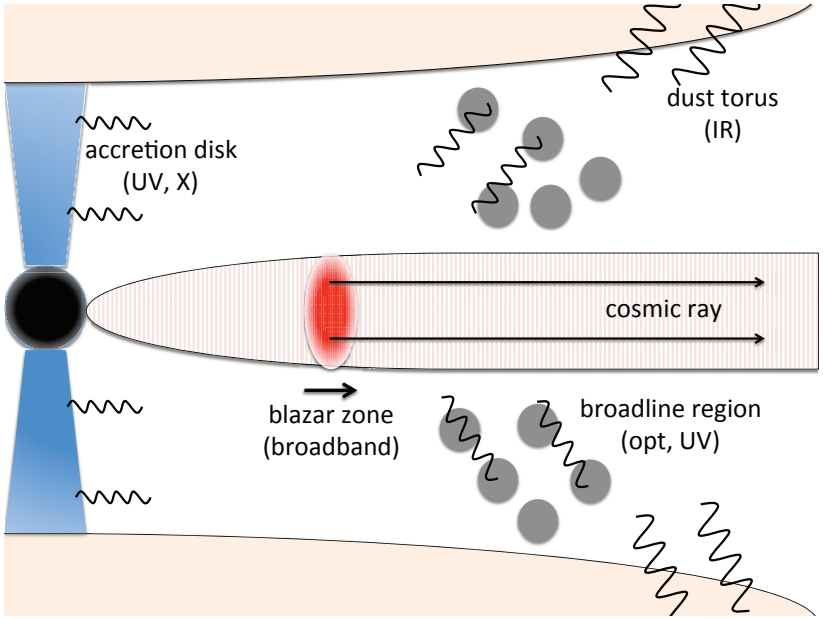
- non-observation of individual neutrino sources exclude source classes, *e.g.*
  - ✘ flat-spectrum radio quasars ($\mathcal{H} \simeq 10^{-9}\mathrm{Mpc}^{-3}$ / $\xi_z \simeq 7$)
  - ✘ "normal" GRBs ($\dot{\mathcal{H}} \simeq 10^{-9}\mathrm{Mpc}^{-3}\mathrm{yr}^{-1}$ / $\xi_z \simeq 2.4$)

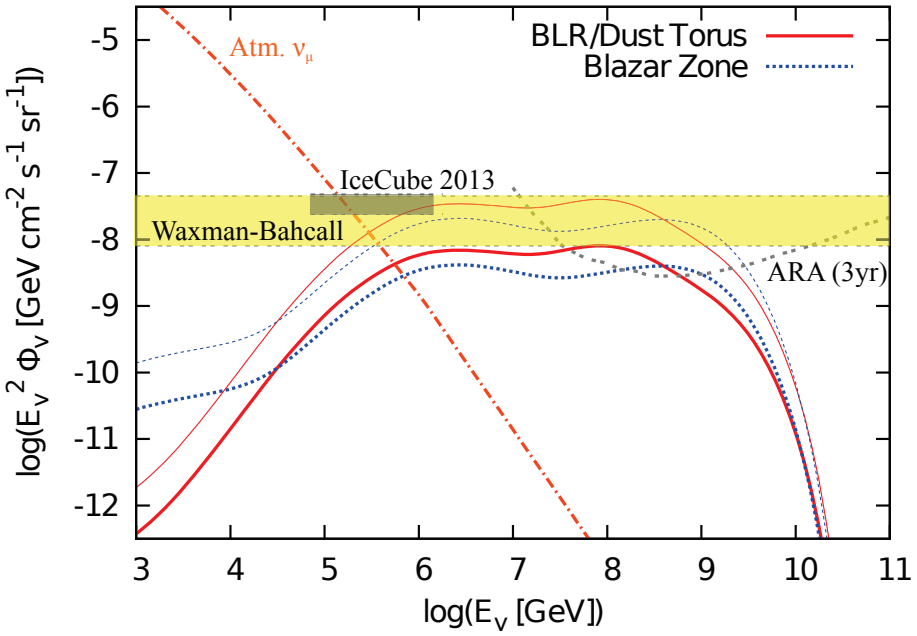


[MA&Halzen'14]

AGN jets

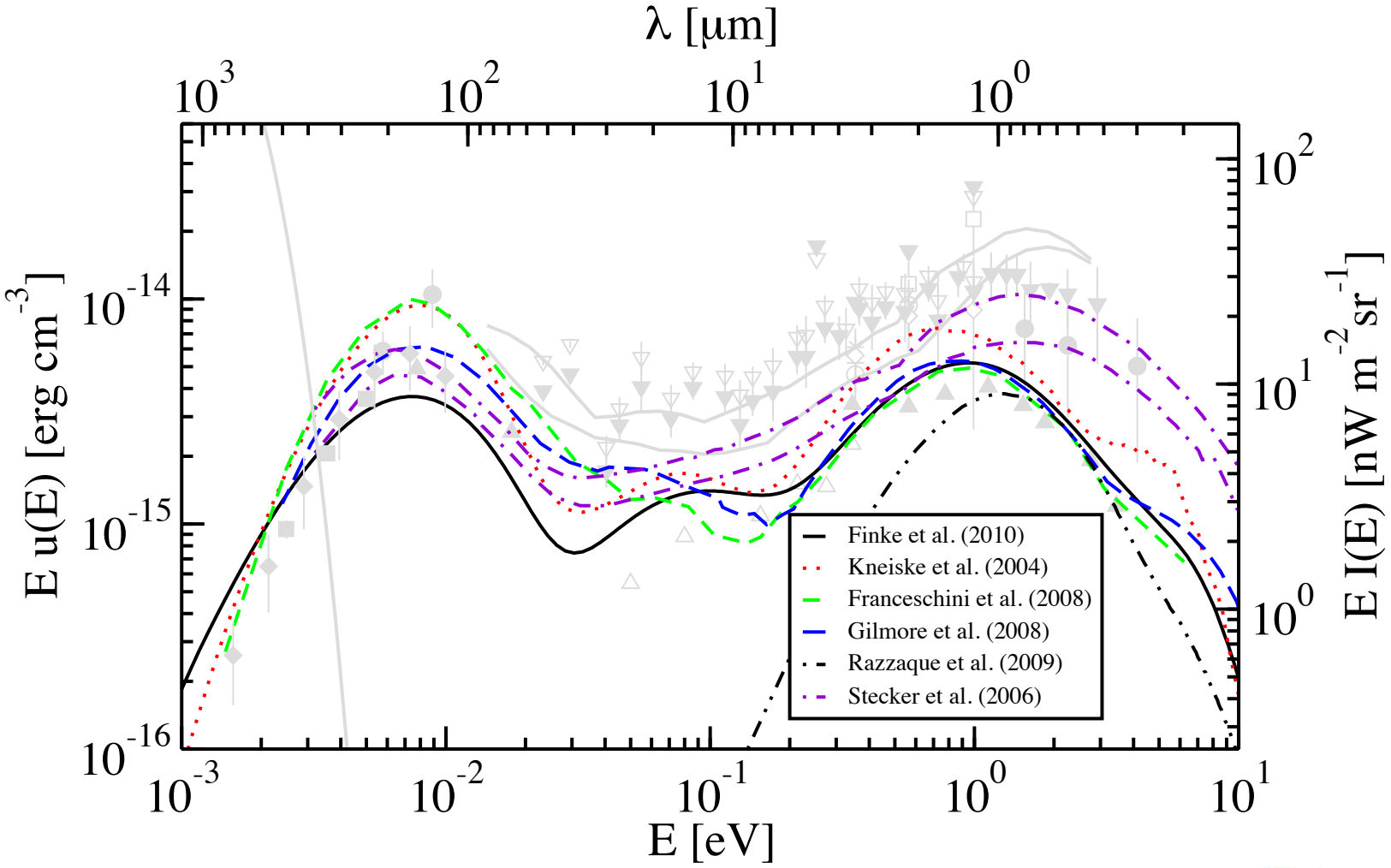
- neutrino from $p\gamma$ interactions in AGN jets [Mannheim'96; Halzen & Zas'97]
- complex spectra due to various photon backgrounds
- typically, deficit of sub-PeV and excess of EeV neutrinos





[Murase, Inoue & Dermer 1403.4089]

Extra-galactic background light (EBL)



[Finke *et al.* '10]

optical-UV background gives PeV neutrino peak

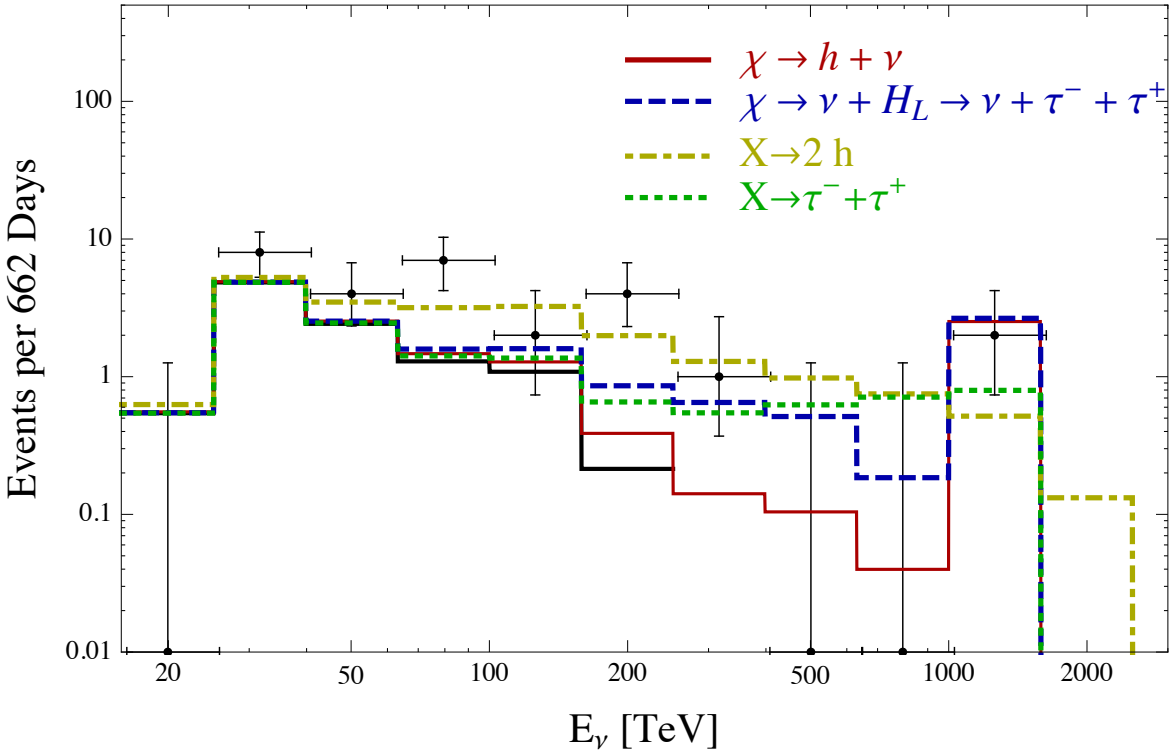
DM decay

- heavy (>PeV) DM decay?

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

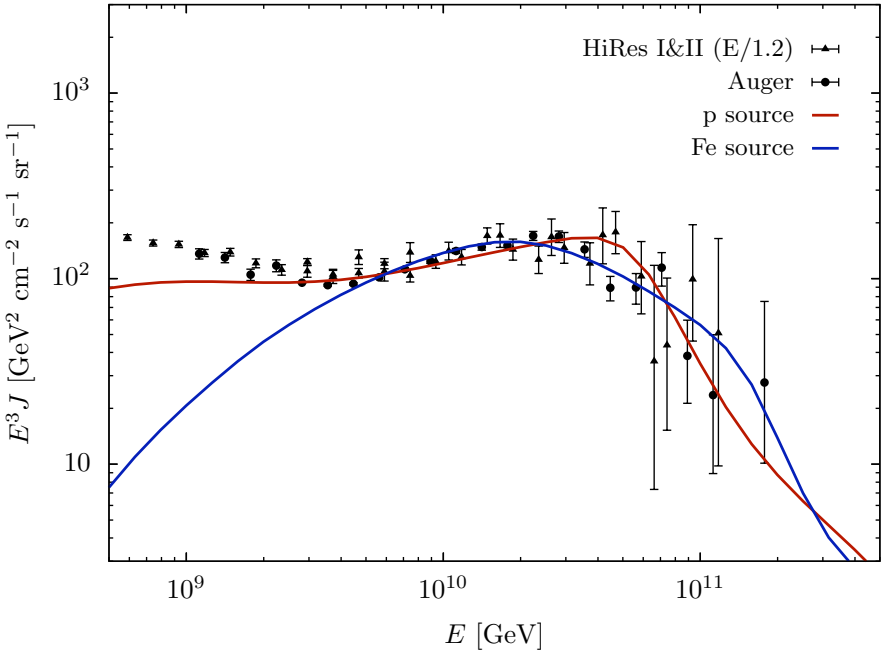
- **initially** motivated by PeV "line-feature", but continuum spectrum with/without line spectrum equally possible

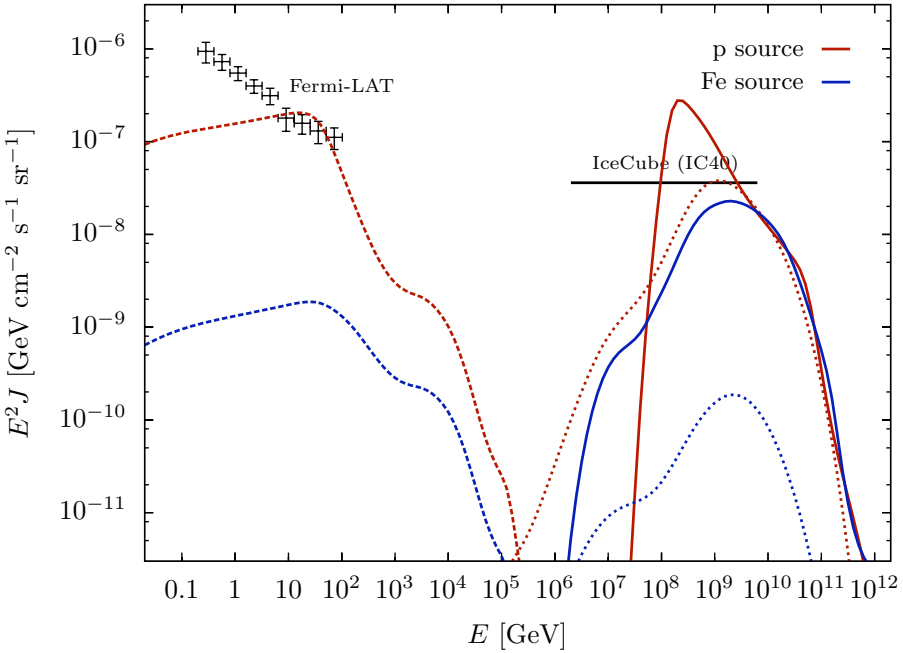
➜ observable **PeV γ-rays** from the Milky Way halo?



[Bai, Lu & Salvado'13]

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]

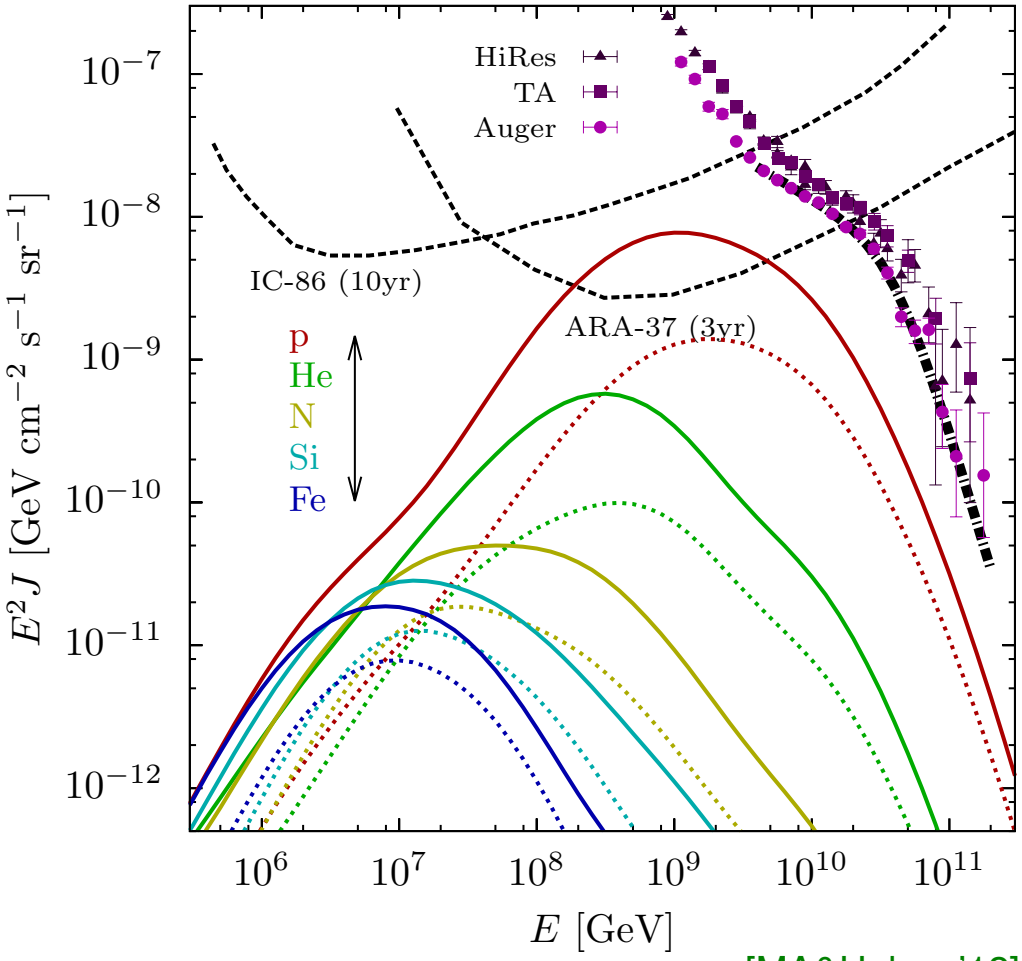
➜ **neutrino limits** start to constrain most optimistic scenarios of proton-dominated UHE CR sources. [IceCube'13;ANITA'12]

Guaranteed Cosmogenic Neutrinos

- ➜ neutrino emission depend on *nucleon spectrum*:

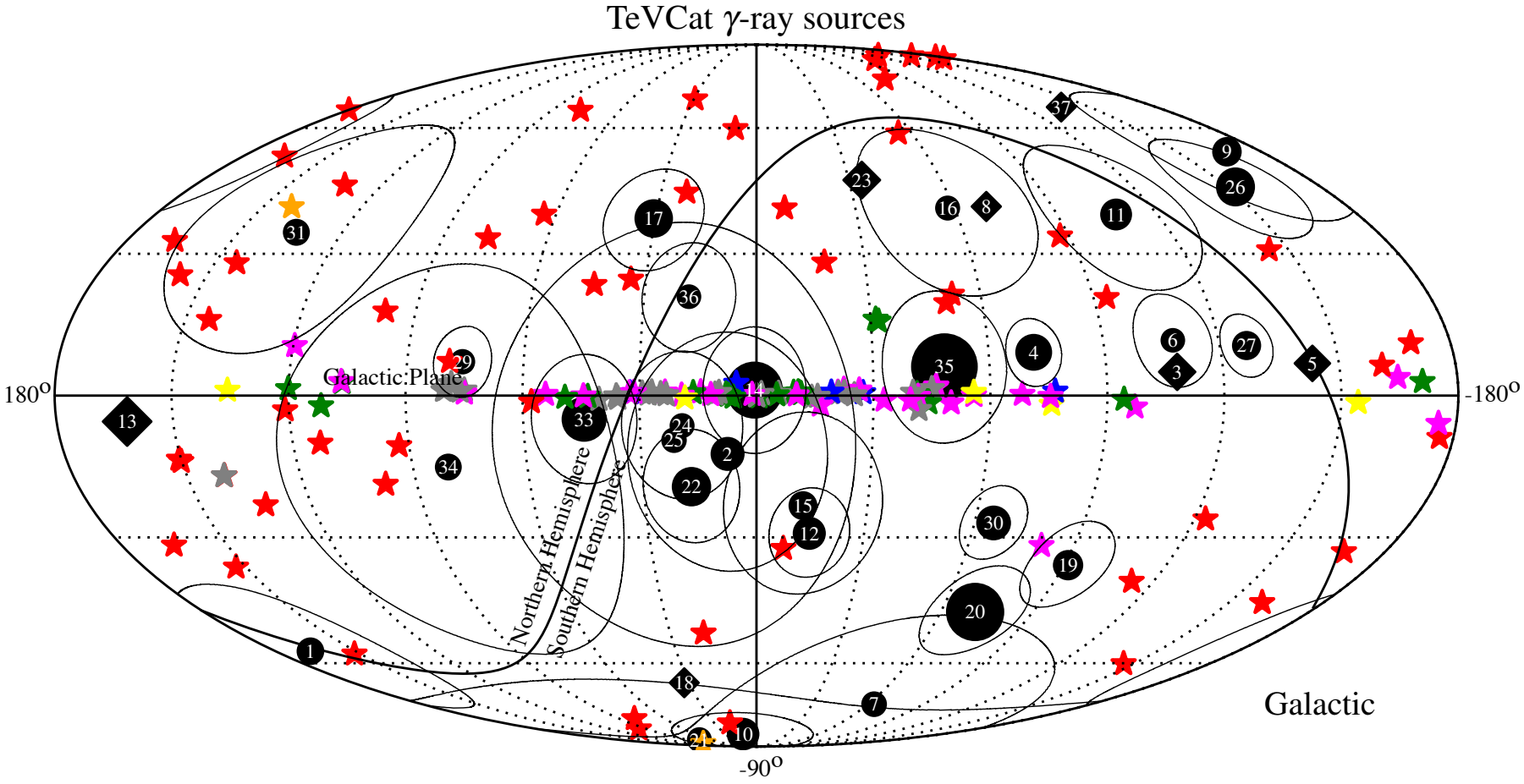
$$\phi_N(E_N) = \sum_i A_i^2 \phi_i(A_i E_N)$$

- ➜ **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]

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]