Interpretation of Results on Cosmic Neutrinos

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Workshop on Perspectives on the Extragalactic Frontier:
From Astrophysics to Fundamental Physics

Trieste, May 3, 2016

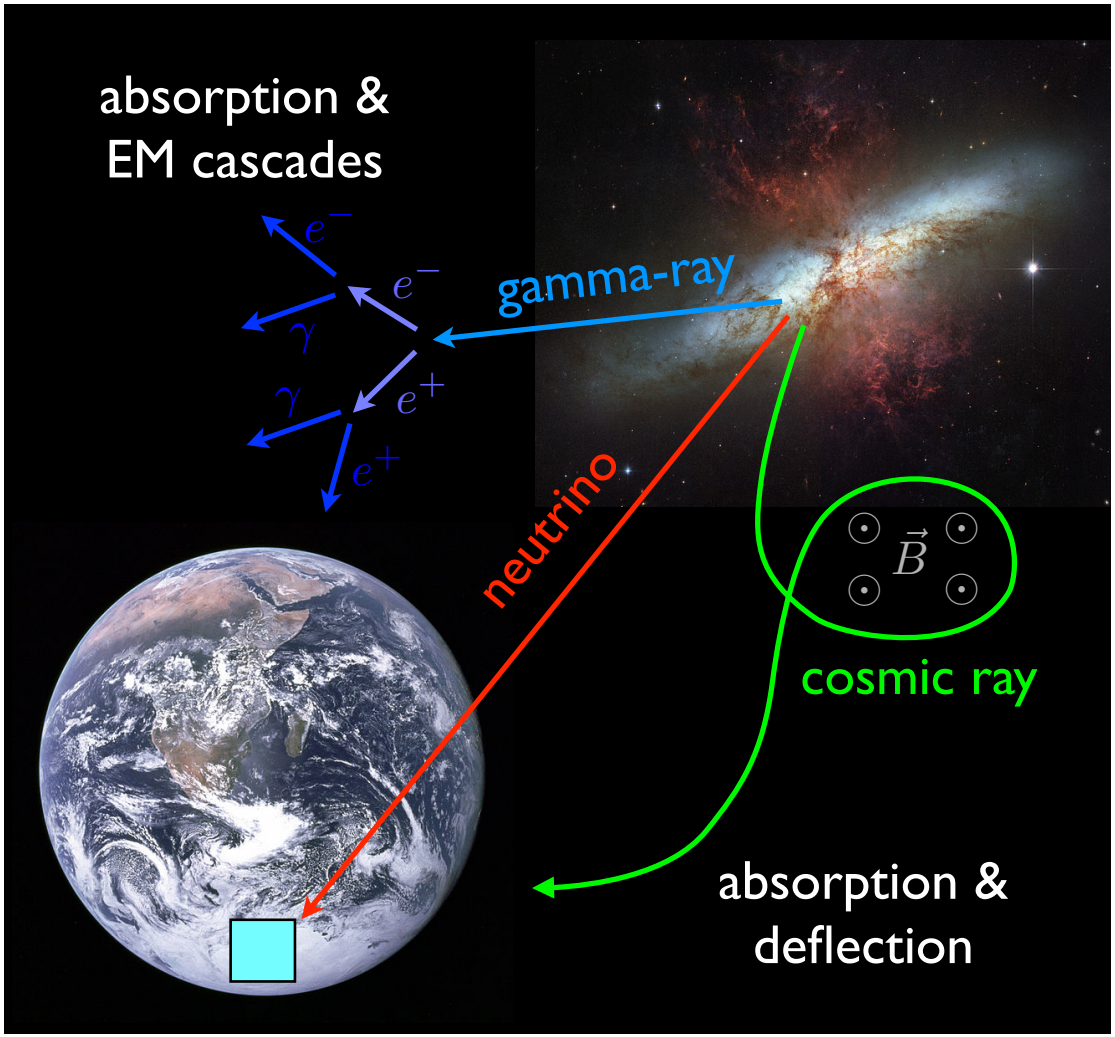
Multi-Messenger Astronomy

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

➜ Neutrino astronomy:

- ✔ closely **related** to cosmic rays (CRs) and γ-rays
- ✔ **weak interaction** during propagation
- ✔ **ideal probe** for 10 TeV-10 EeV anisotropy and tomography

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

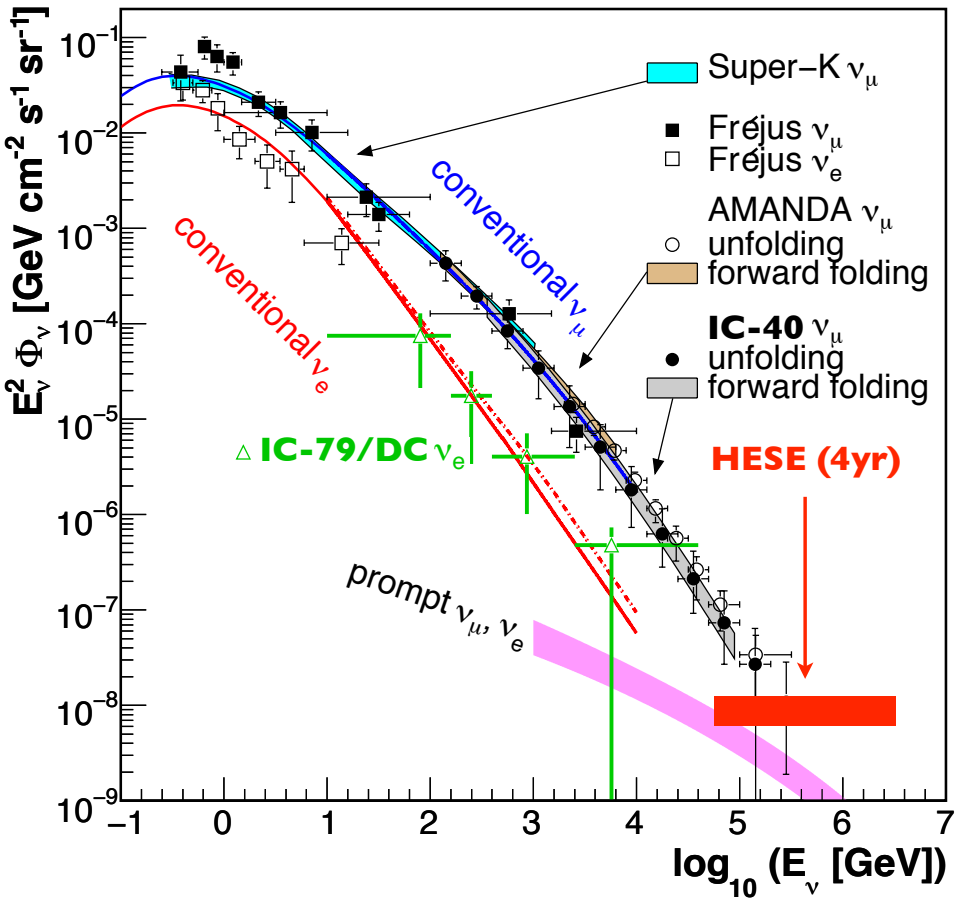


IceCube HESE (4yr)

- **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 60TeV-3PeV (6.5σ):

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



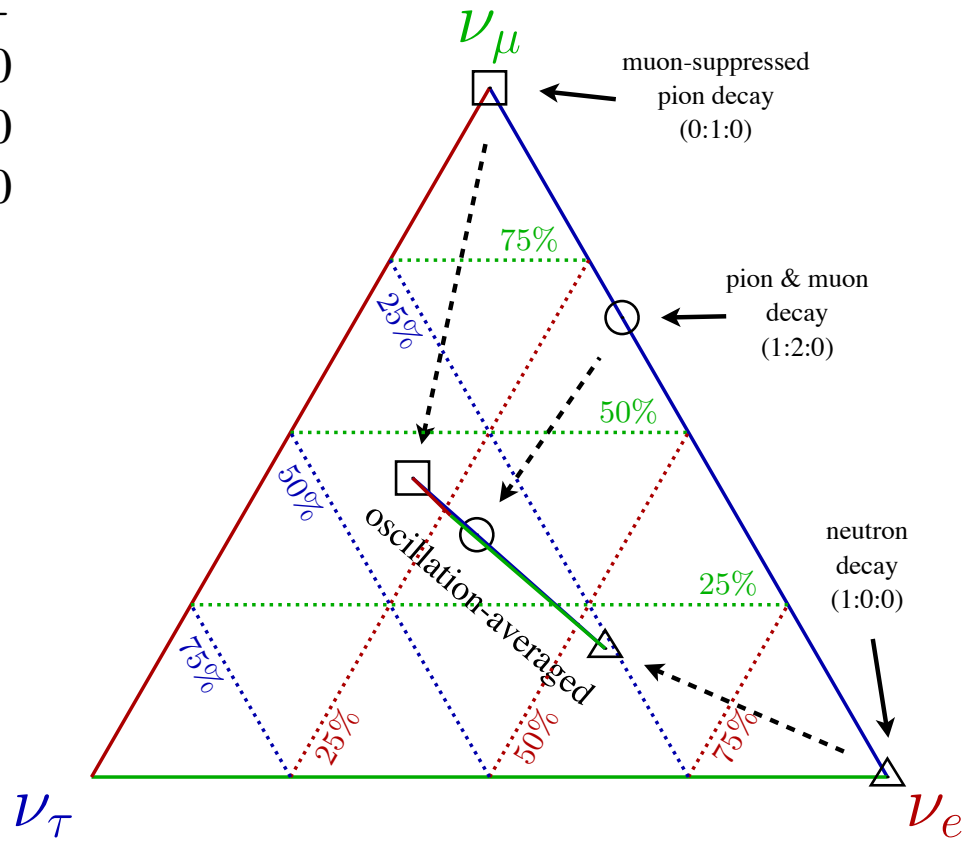
Neutrino Flavors

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

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

- oscillation-averaged probability:

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



- "NuFit 1.3": $\sin^2\theta_{12} = 0.304$ / $\sin^2\theta_{23} = 0.577$ / $\sin^2\theta_{13} = 0.0219$ / $\delta = 251°$

✔ observed events **consistent with equal contributions of all neutrino flavors**

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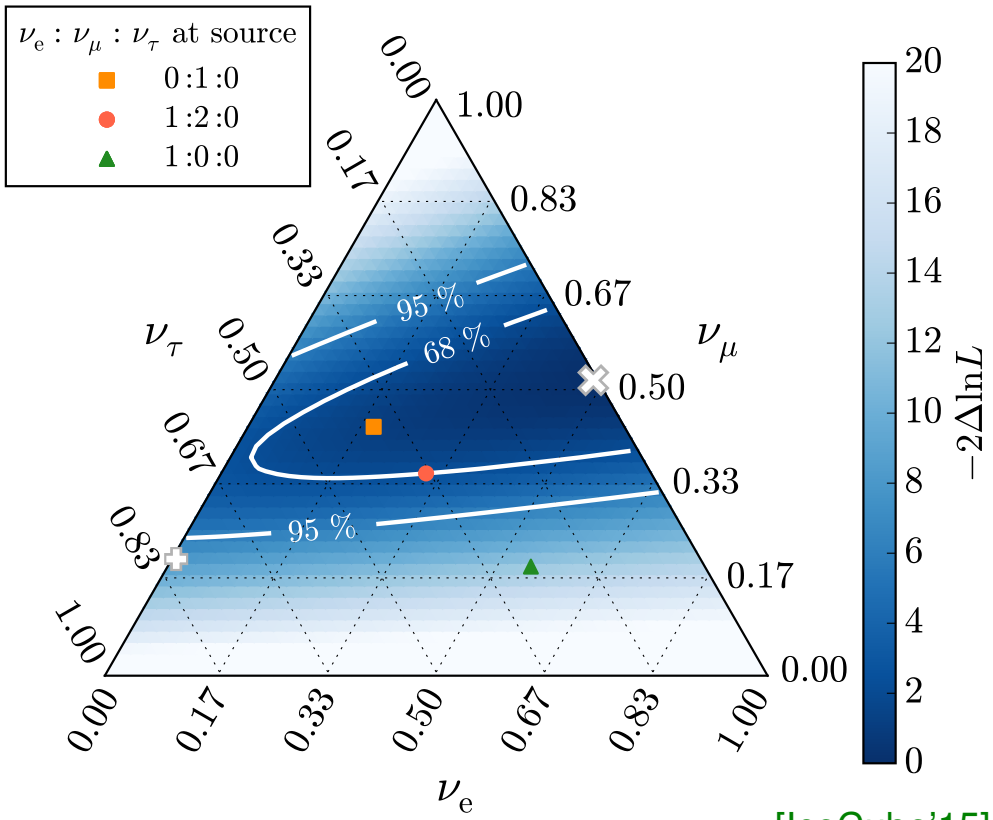

[IceCube'15]

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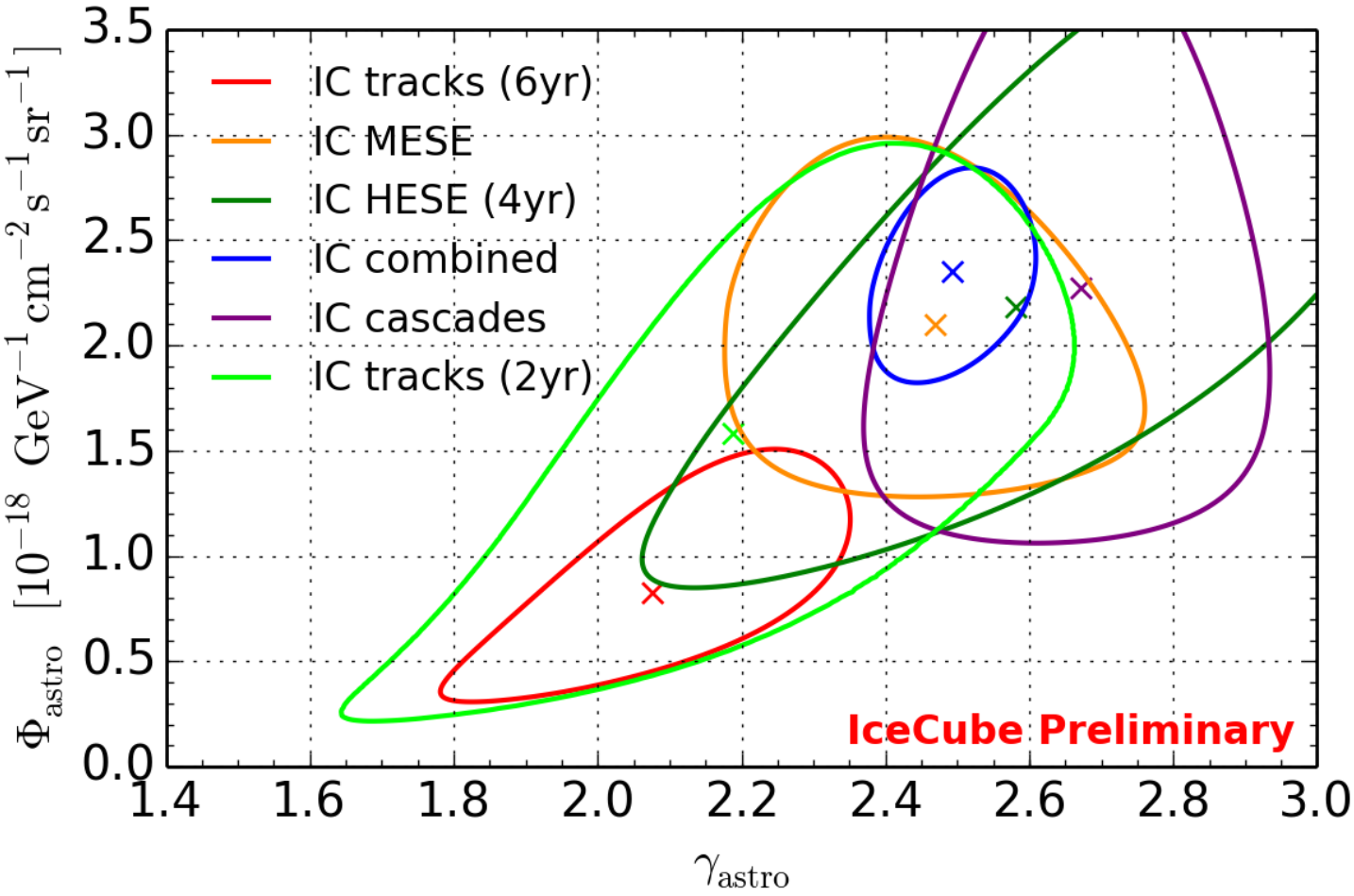
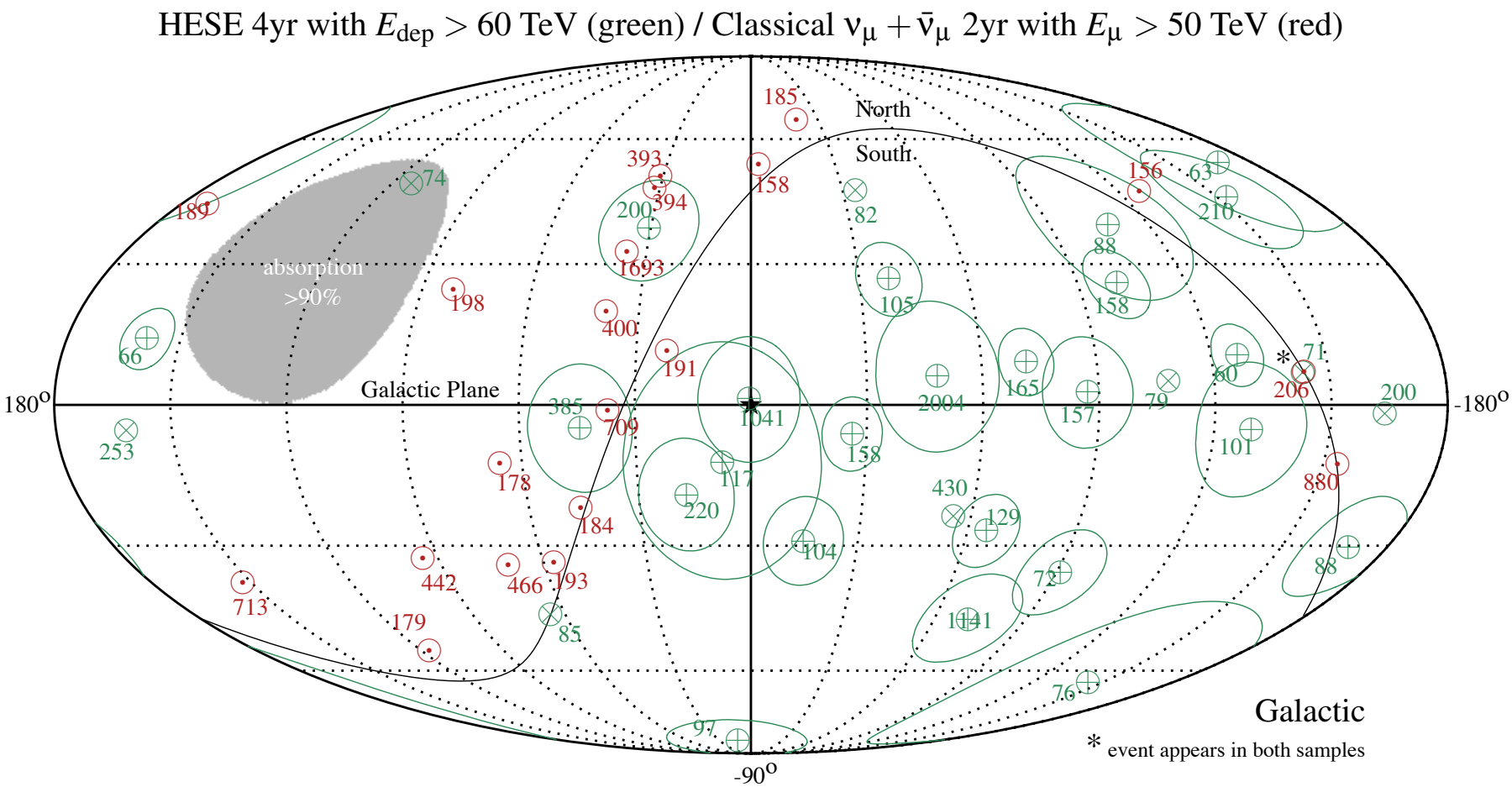
Best-Fit Power-Law Spectrum



- 6yr $\nu_\mu + \bar{\nu}_\mu$ analysis (preliminary)
- individual analysis:
  PRD 91 (2015) 022001, PoS(IRCR2015)1081 , PoS(IRCR2015)1109, PRL 115 (2015) 081102
- combined fit: PoS(IRCR2015)1066

Neutrino Arrival Directions



- **24 "cascade events" (circles) and 8 "tracks events" (diamonds)** with $E_{dep} \gtrsim 60$ 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**

Multi-messenger Paradigm

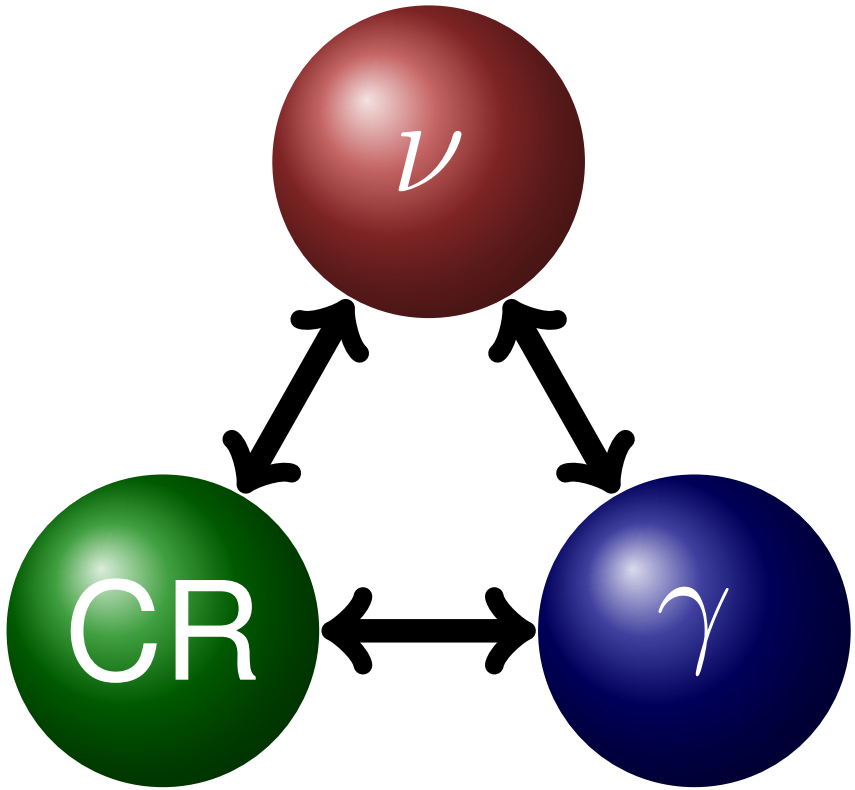
- Neutrino production is closely related to the production of cosmic rays (CRs) and γ-rays.

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

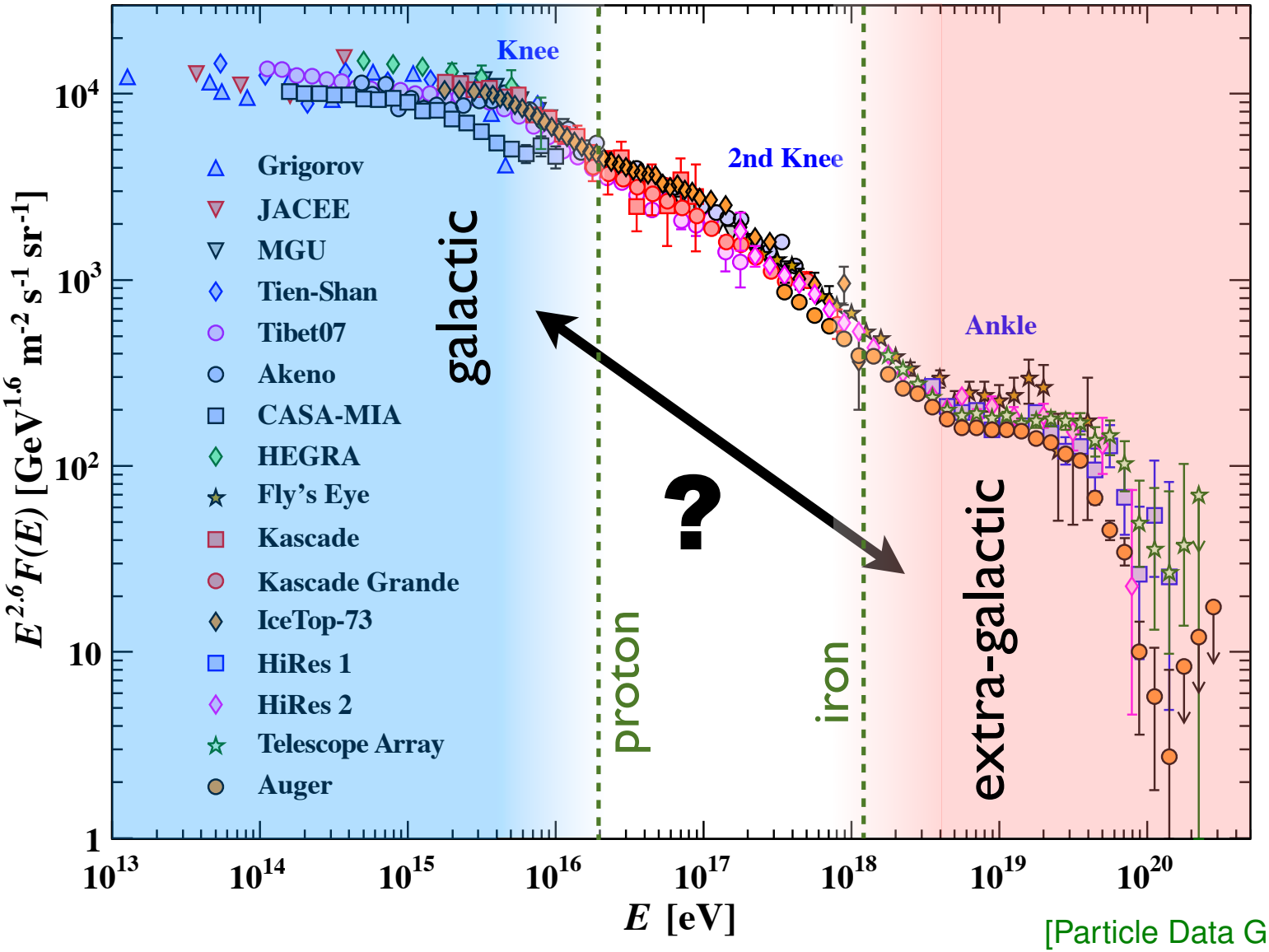
- 1 PeV neutrinos correspond to 20 PeV CR nucleons and 2 PeV γ-rays

➜ **very interesting** energy range:

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



The Cosmic "Beam"



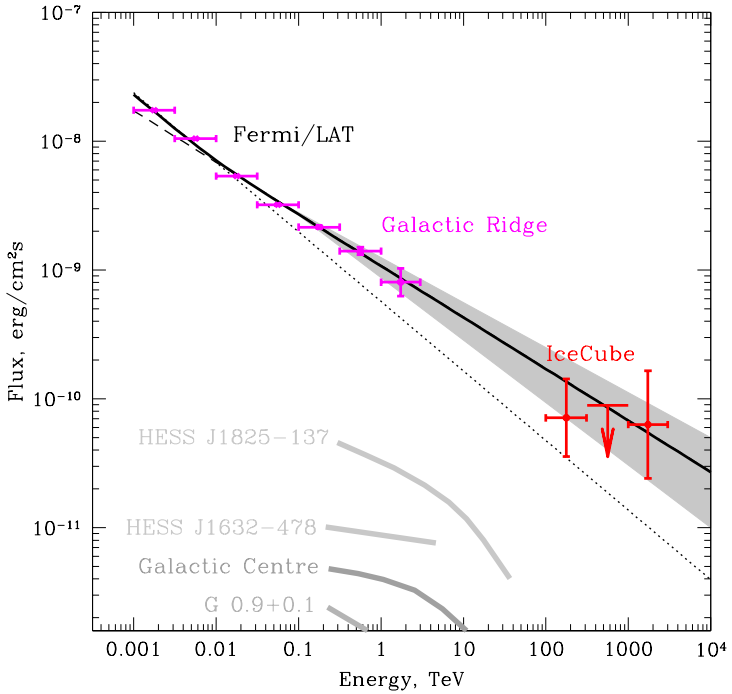
[Particle Data Group'13]

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]
  - 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]

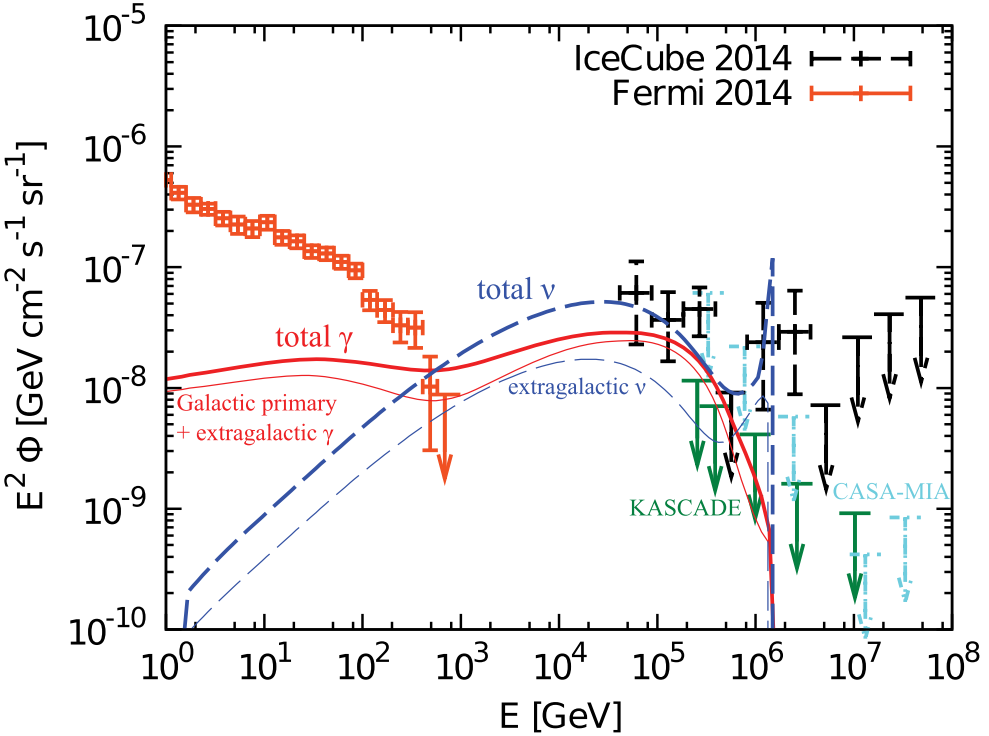
Galactic Emission Models: Two Examples

Hard Galactic Diffuse Emission



[Neronov, Semikoz & Tchernin'14]

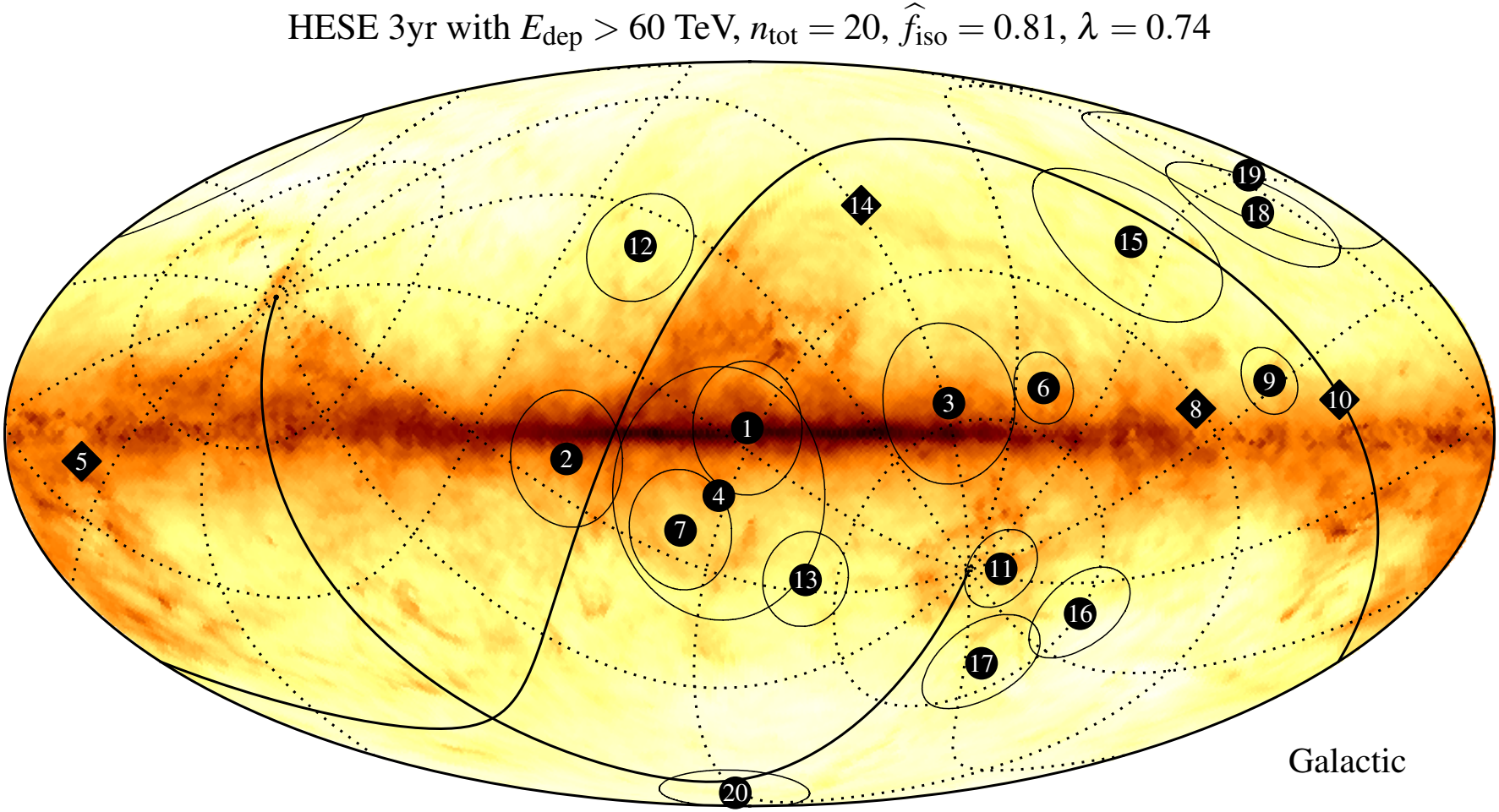
PeV Dark Matter Decay (*e.g.* DM$\to \nu\bar{\nu}/q\bar{q}$)



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

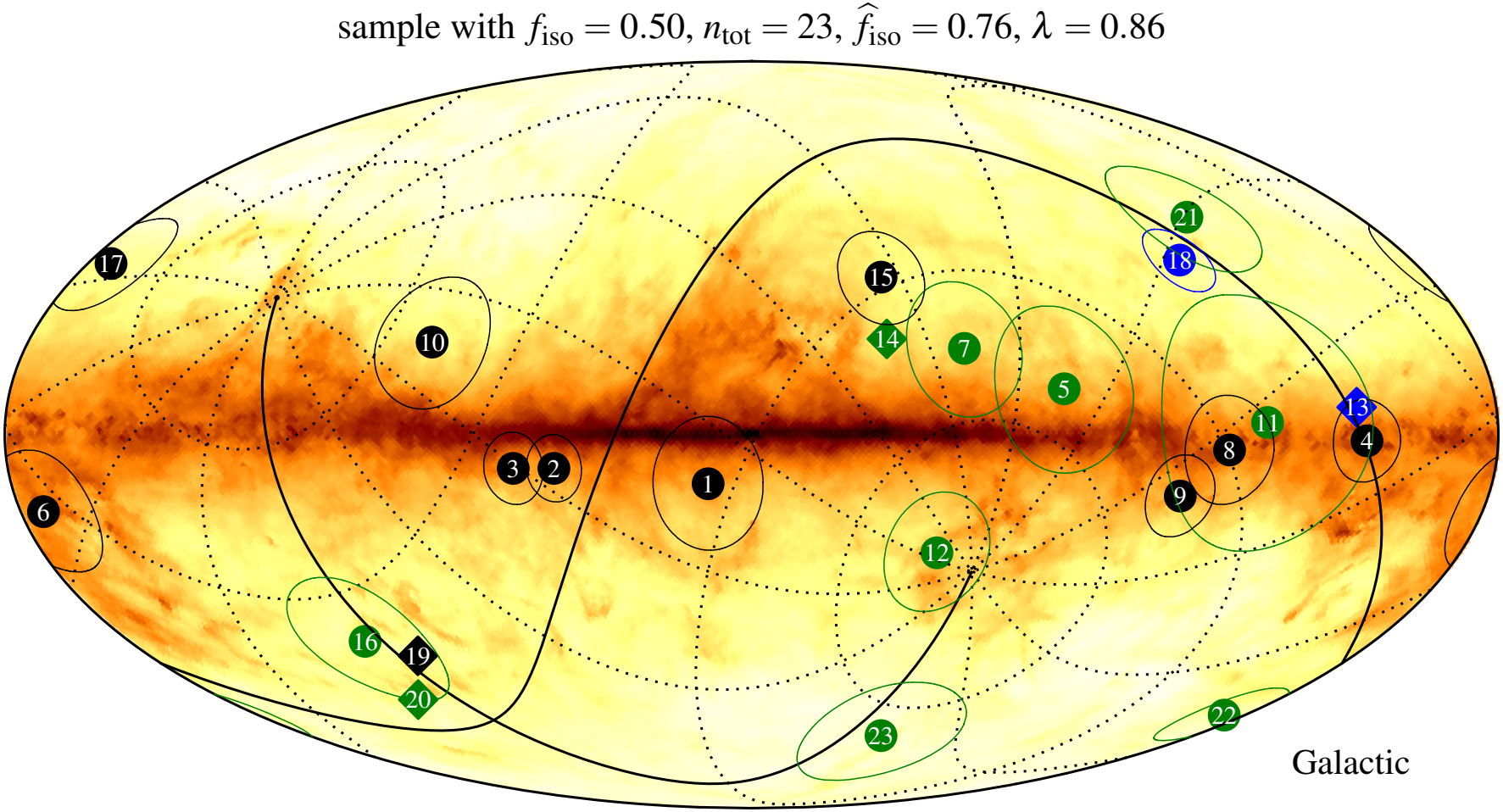
- anisotropy limits on Galactic emission [MA & Bai, Barger & Yang'15]
- limits on Galactic contribution from PeV γ-ray observation [Gupta'14; MA & Murase'14]

Example: Galactic Diffuse Emission



- Strong Galactic diffuse emission up to PeV? [Neronov, Semikoz & Tchernin'13'14]
- **actual** map: tracks ($\diamond$) and cascades ($\circ$) from HESE 3yr with $E_{\rm dep} > 60$ TeV

Example: Galactic Diffuse Emission



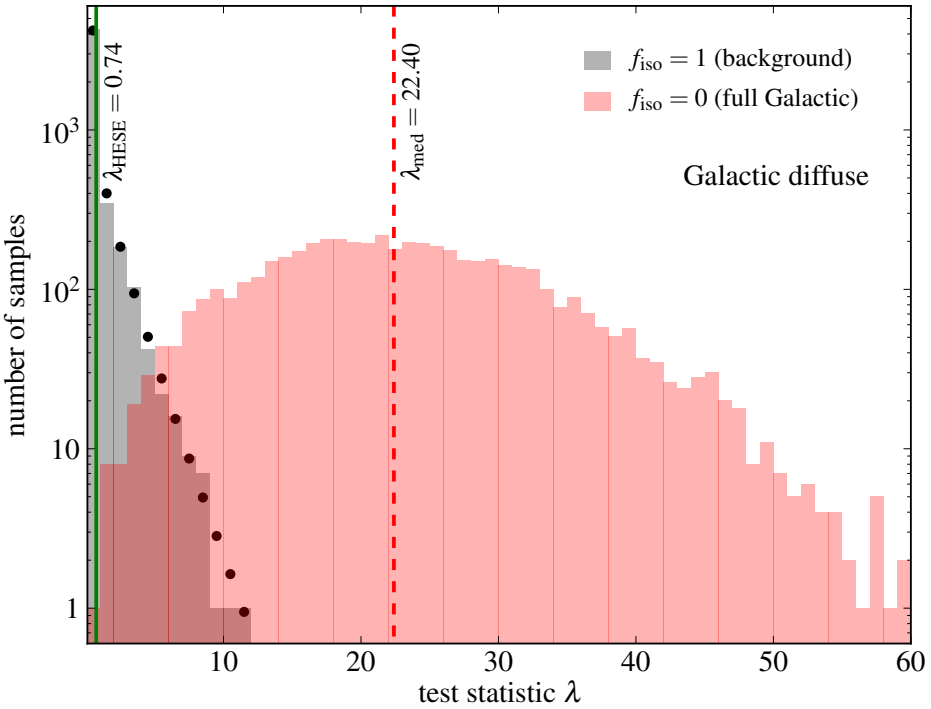
- Galactic diffuse emission template derived with GALPROP [Strong & Moskalenko'98]
- **simulated** map: $\diamond/\circ$: Galactic ν | $\diamond/\circ$: isotropic ν | $\diamond/\circ$: atmospheric ν | $\diamond/\circ$: atmospheric μ

Anisotropy Test

- unbinned maximum LH test statistic:

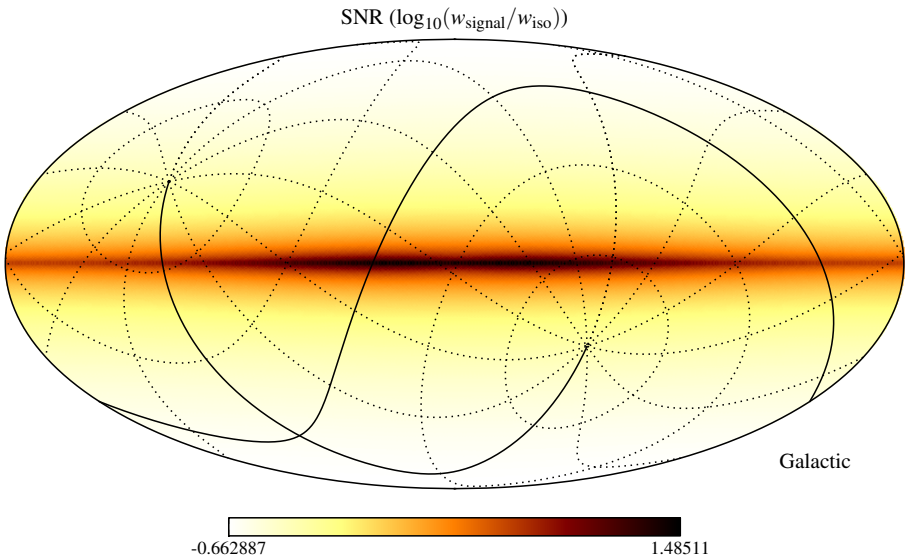
$$\lambda = 2 \ln \prod_{\text{event } j} \left[\frac{\mu_j^{\text{sig}}(\widehat{f}_{\text{iso}}) + \mu_j^{\text{bgr}}(\widehat{f}_{\text{iso}})}{\mu_j^{\text{bgr}}(1)} \right]$$

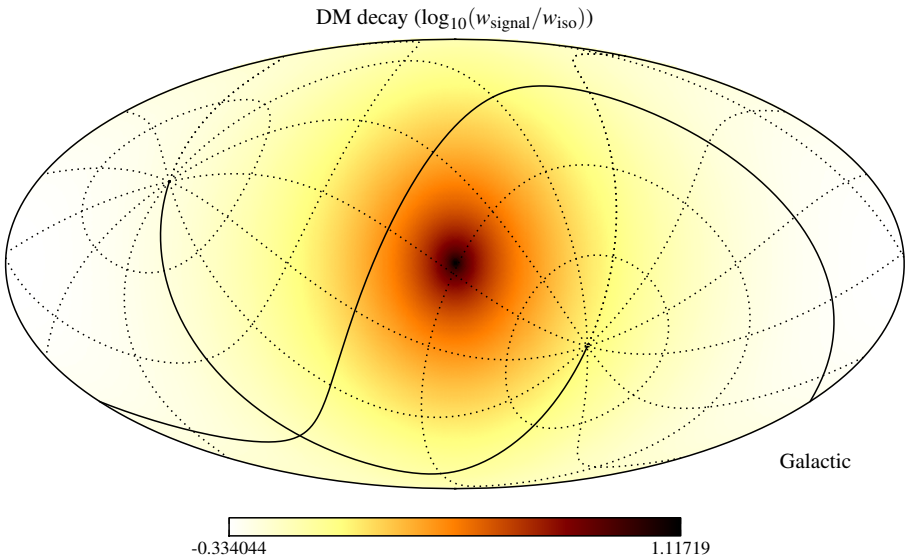
- $\widehat{f}_{\text{iso}}$: fraction of isotropic events at maximum LH
- 90% C.L. **sensitivity** :
  f_{iso} with 90% of samples $\lambda_{\text{MC}} > \lambda_{\text{med}}^{\text{bgr}}$
- 5σ C.L. **discovery potential** :
  f_{iso} with 50% of samples $\lambda_{\text{MC}} > \lambda_{5\sigma}^{\text{bgr}}$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

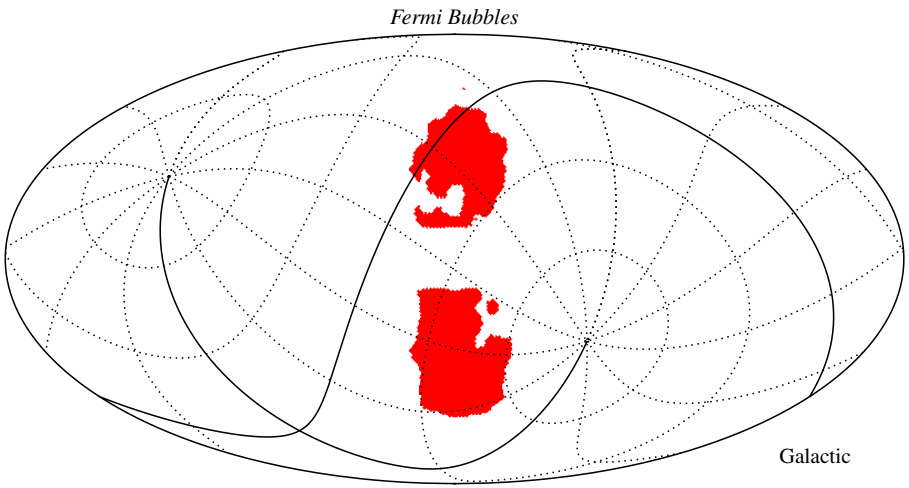


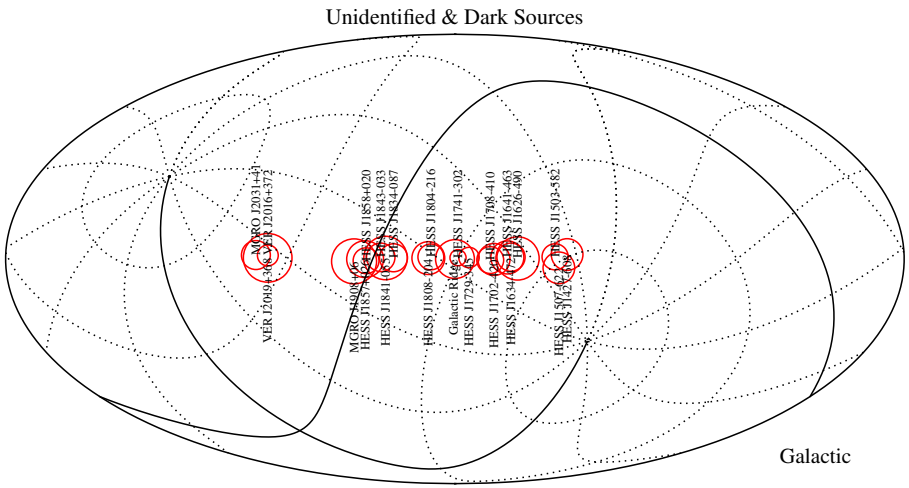
grey: background distribution ($f_{\text{iso}} = 1$)
red: maximal signal distribution ($f_{\text{iso}} = 0$)

Other Extended Galactic Emission

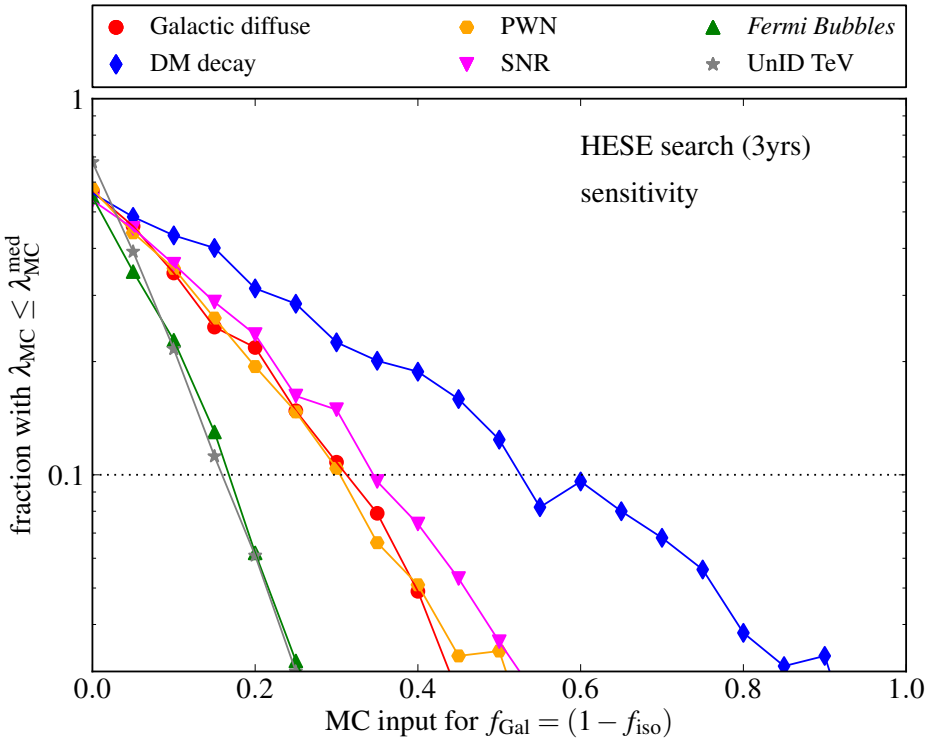


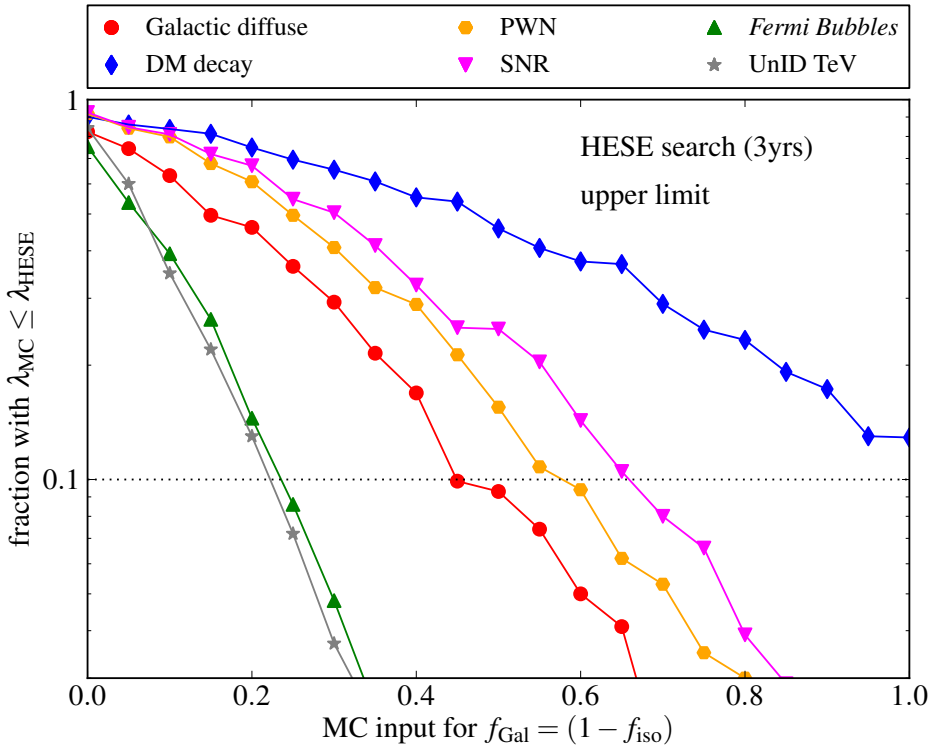






Sensitivity & Upper Limits





[MA, Bai, Barger & Lu'15]

- PWN : source distribution following pulsars [Lorimer *et al.*'98]
- SNR : source distribution following supernova [Case *et al.*'06]
- UnID TeV : unidentified TeV gamma-ray sources [Fox, Kashiyama & Meszaros'13]
- *Fermi Bubbles* : uniform gamma-ray emission [Ackermann *et al.*'14]
- DM decay : Galactic DM distribution (Einasto profile) [Graham *et al.*'06]

Sensitivity & Upper Limits

template	HESE 3yr observation λ	p-value*	$\widehat{f}_{\mathrm{Gal}}{}^{\star}$	$f_{\mathrm{Gal}}^{90\%\star}$	sensitivity for $f_{\mathrm{Gal}}{}^{\star}$ HESE 3 yr	HESE 10 yr	Northern ν_μ 3 yr
Galactic diffuse ν #	0.74	0.19	0.19	0.50	0.30	0.15	0.25
SNR [65]	1.68	0.10	0.34	0.65	0.35	0.20	0.30
PWN [66]	1.77	0.09	0.30	0.60	0.30	0.15	0.25
DM decay [81]	1.48	0.11	0.46	–	0.60	0.30	0.85
Fermi Bubbles [74]	0.36	0.27	0.07	0.25	0.20	0.10	–
UnID TeV [7]	0.43	0.25	0.07	0.25	0.20	0.10	–

The emission template is using `GALPROP`. We estimate the systematic uncertainty of f_{Gal} from the diffusion model to be at the level of $\pm 10\%$.

* The p-value is calculated from λ assuming a background distribution $[\delta(\lambda) + \chi^2_1(\lambda)]/2$.

⋆ The Galactic fraction is defined as $f_{\mathrm{Gal}} = 1 - f_{\mathrm{iso}}$.

- **stronger** sensitivity in combination with spectral and flavor analysis ➜ ongoing IceCube analysis
- classical $\nu_\mu + \bar{\nu}_\mu$ search with good angular resolution (but limited FoV)
- PeV γ-ray emission?

Gamma-Ray Opacity

- production and decay of neutral pions into gamma rays

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

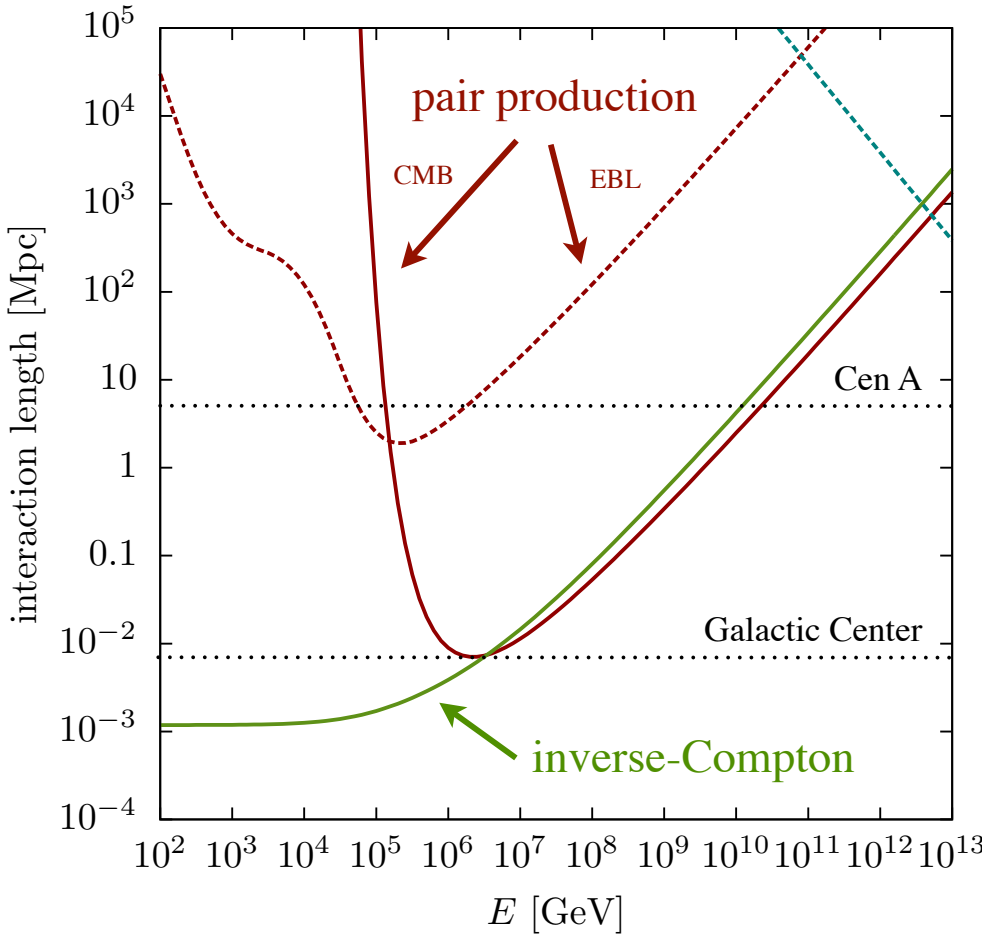
➜ PeV gamma-ray only observable locally ($\lesssim 10$kpc)

✔ recyling of gamma-rays via inverse Compton scattering (ICS):
$e^\pm + \gamma_{\rm CMB} \rightarrow e^\pm + \gamma$

- rapid cascade interactions produce universal GeV-TeV emission

[Berezinsky&Smirnov'75]

➜ more on this later



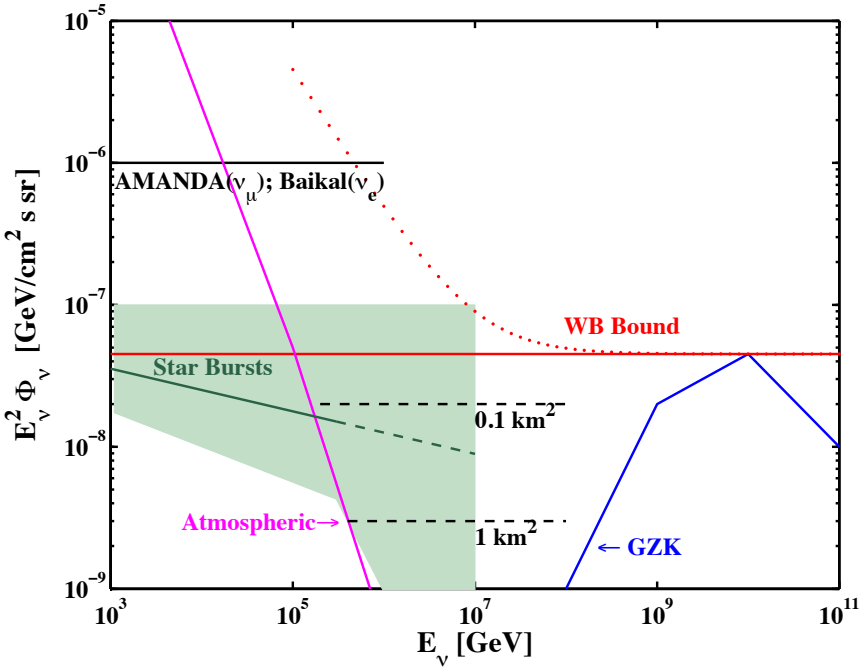
[MA'11]

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]
  - 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]
  - ...

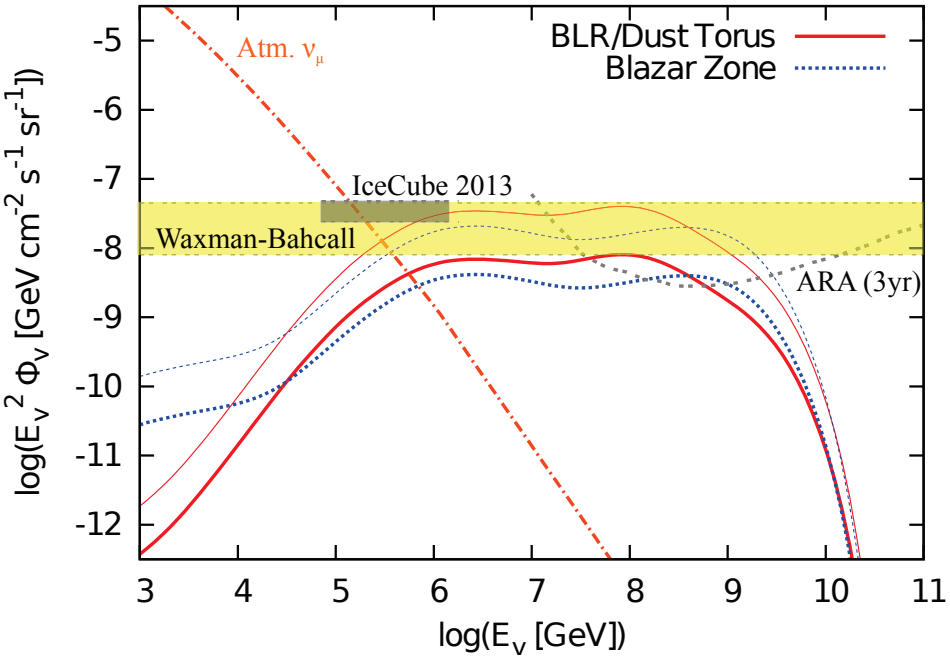
Extragalactic Emission Models: Two Examples

Starburst Galaxies ("pp" scenario)



[Loeb & Waxman'06]

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



[Mannheim'96; Halzen & Zas'97]

[*e.g.* Murase, Inoue & Dermer'14]

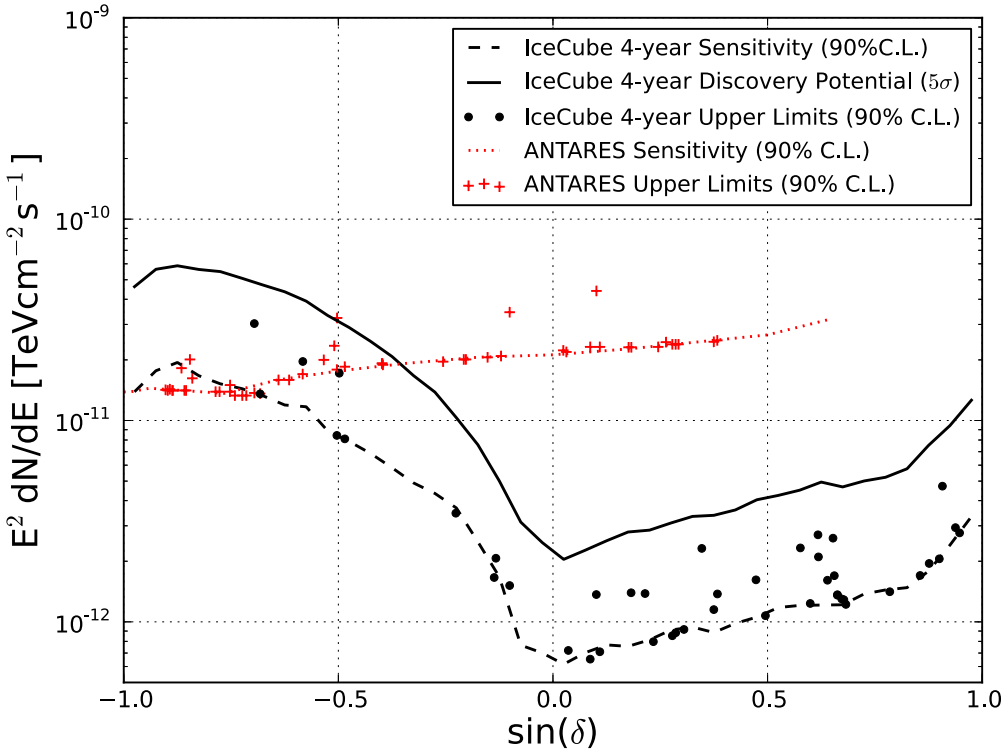
- CR-gas (pp) interactions: **mostly broken power-law** neutrino spectra.
- CR-photon ($p\gamma$) interactions: **strong spectral features** inherited from photon spectrum

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)]

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



[IceCube arXiv:1406.6757]

Neutrino Point-Source Limits

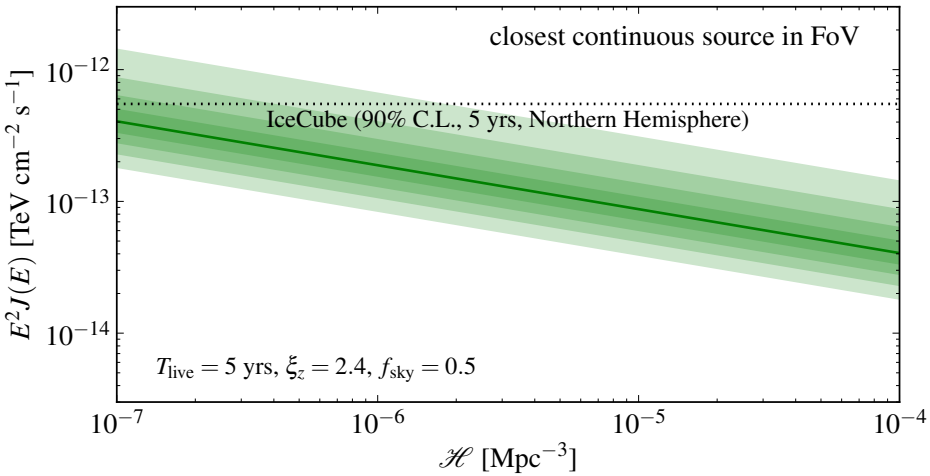
- Diffuse neutrino flux normalizes the contribution of individual sources
- dependence on local source density $\mathcal{H}$ (rate $\dot{\mathcal{H}}$) and redshift evolution ξ_z

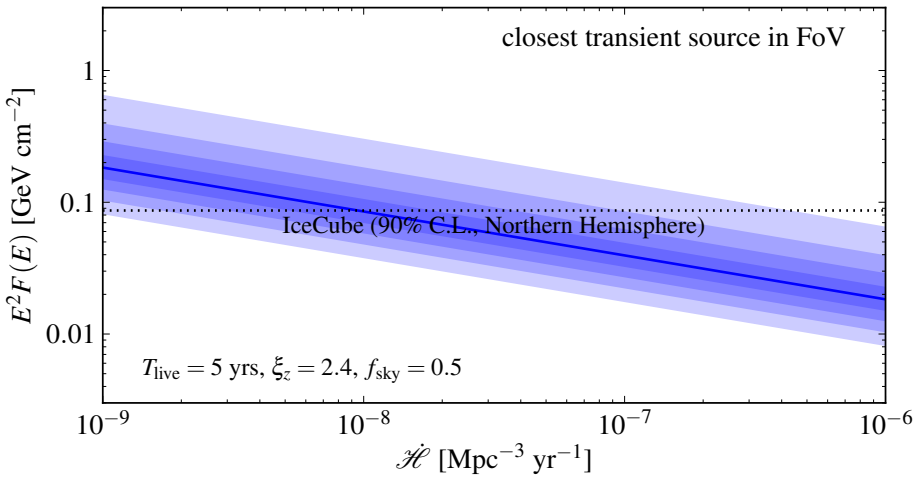
➜ PS observation requires rare sources

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

  ✘ flat-spectrum radio quasars ($\mathcal{H} \simeq 10^{-9}\mathrm{Mpc}^{-3}$ / $\xi_z \simeq 7$)

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

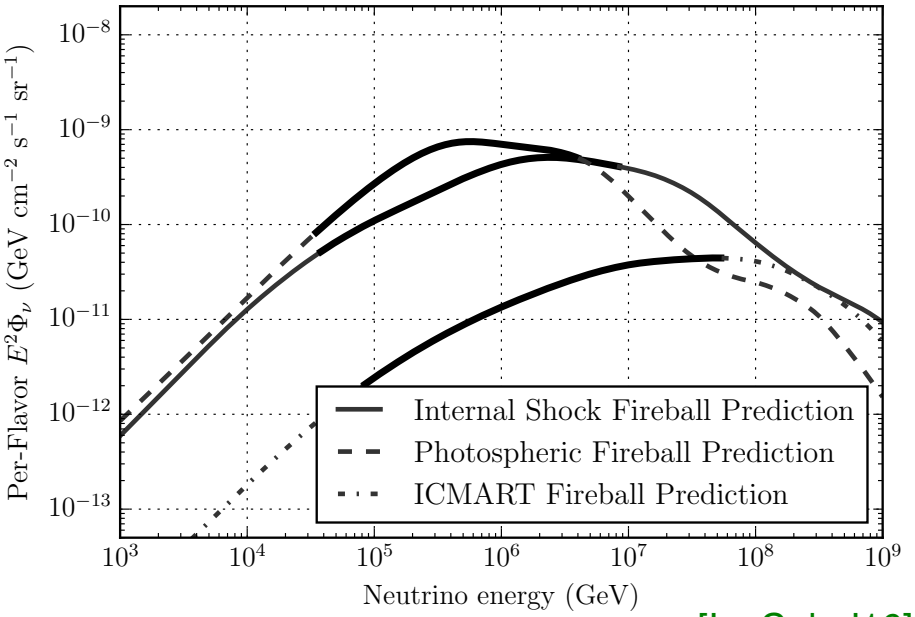




[MA&Halzen'14]

IceCube Stacking Searches

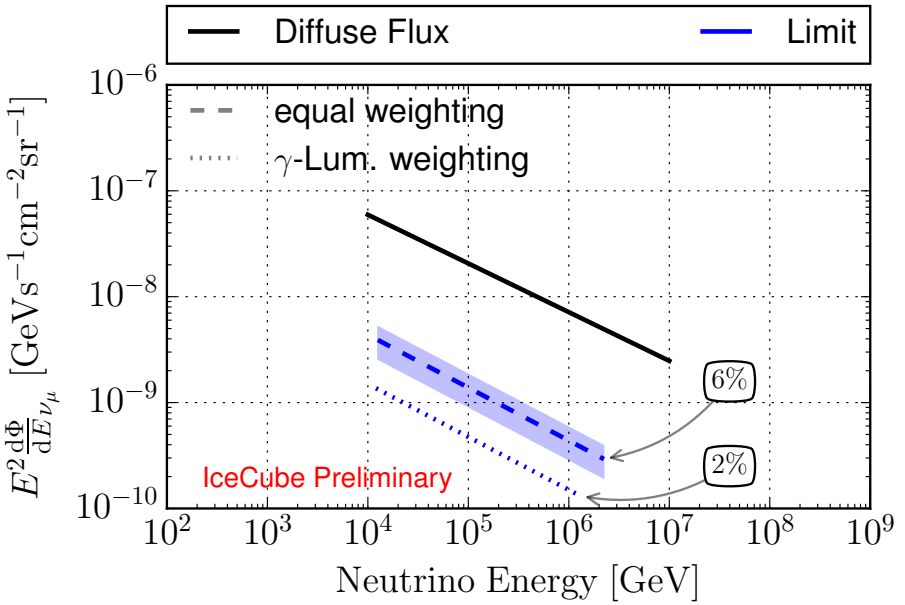
GRB Stacking



[IceCube'16]

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

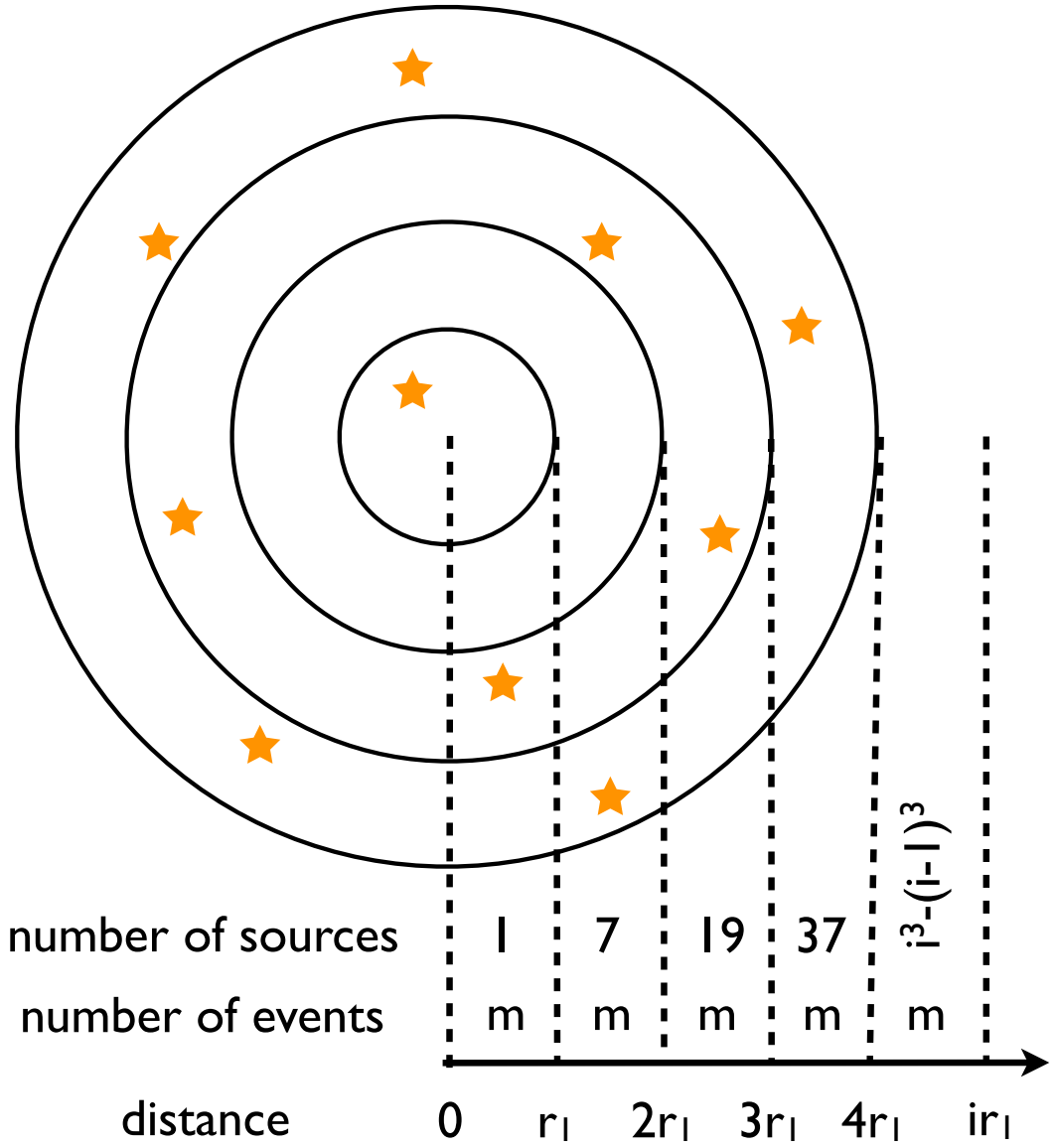
Blazar Stacking



[arXiv:1502.03104]

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

Identification of Extragalactic Point-Sources?



- total number of sources up to Hubble horizon, *e.g.* mAGN

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

- total number of "shells" contributing as much as the closest source

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

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

$$\bar{N} = m \times (n_s)^{\frac{1}{3}} \simeq 200 - 500$$

✘ random clusters are very likely with bad angular resolution!

➜ **multi-messenger cross-correlations**!

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 $E_{\mathrm{max}} \simeq 10^{20}$ eV in environments of high energy loss?

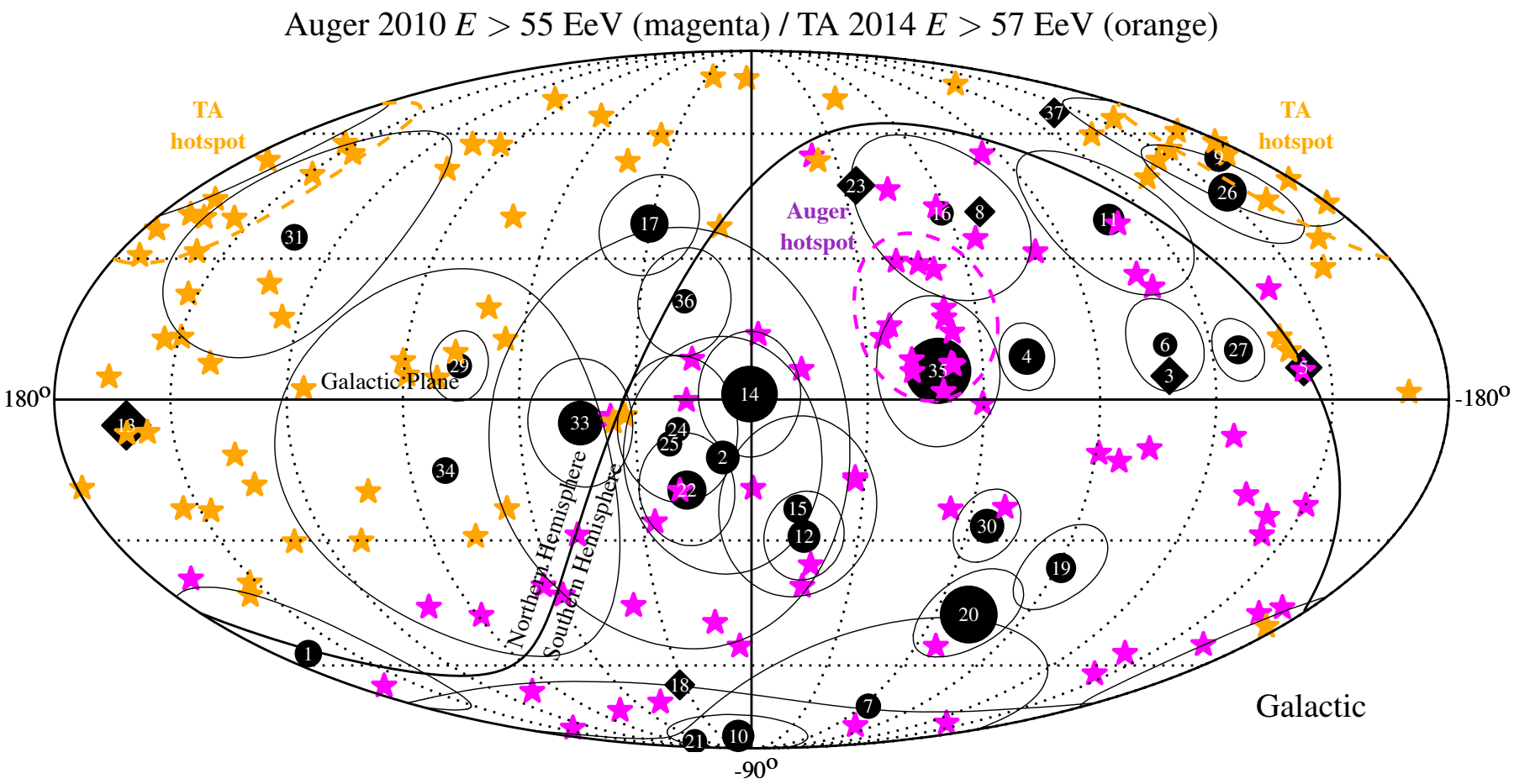
➜ two-zone models: acceleration + CR "calorimeter"?

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

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

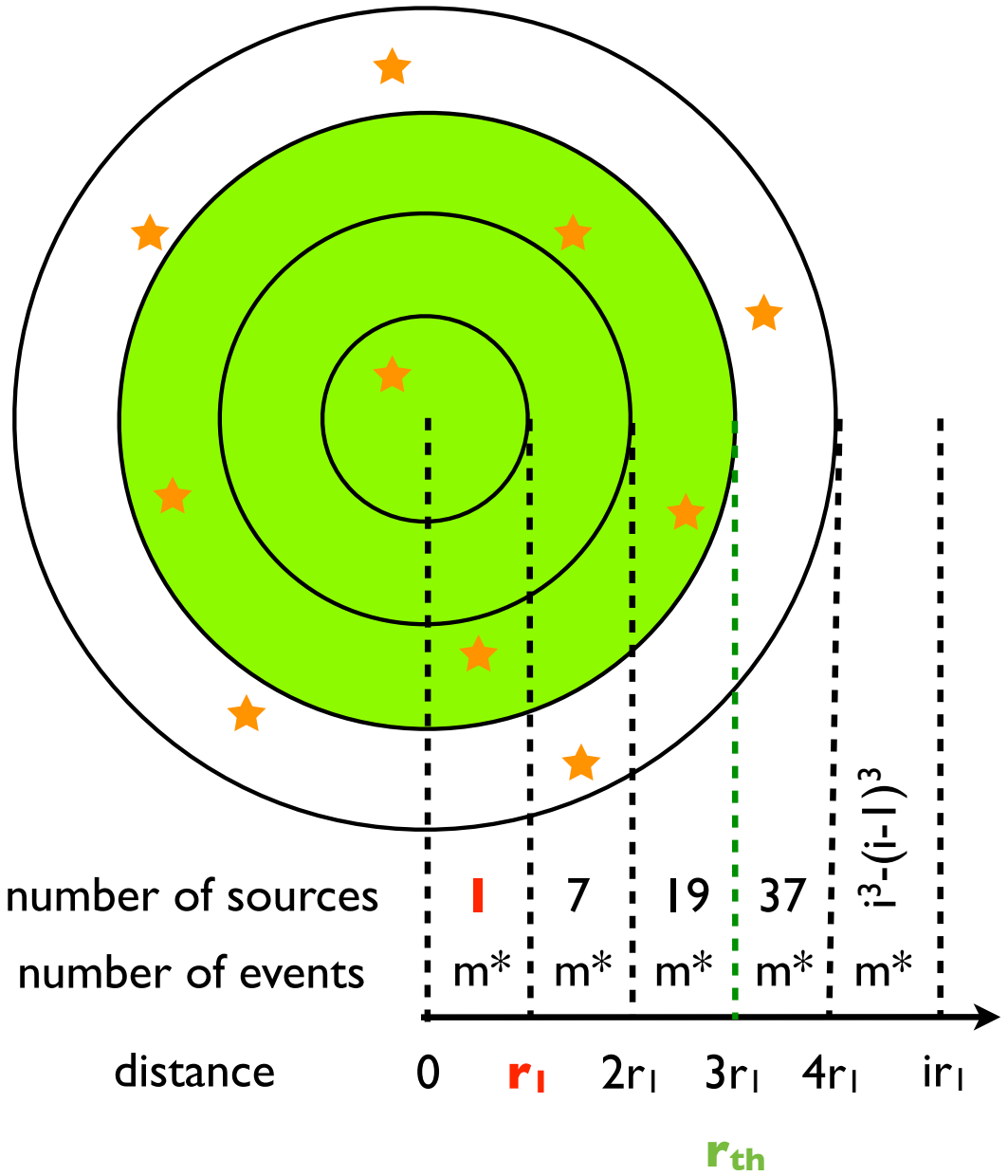
[Parizot'05; Aublin & Parizot'06; Katz, Waxman, Thompson & Loeb'13]

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 $r_{\mathrm{th}} = \lambda_{\mathrm{GZK}} \simeq 200$ Mpc
- Neutrinos visible up to Hubble horizon $\lambda_{\mathrm{Hubble}} \simeq 4.4$ Gpc

➜ maximal overlap:

$$\frac{\lambda_{\mathrm{GZK}}}{\lambda_{\mathrm{Hubble}}} \sim 5\%$$

- HESE 4yr : ca. 30 signal events

➜ $1-2$ neutrinos expected to correlate

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

Extragalactic Gamma-Rays

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

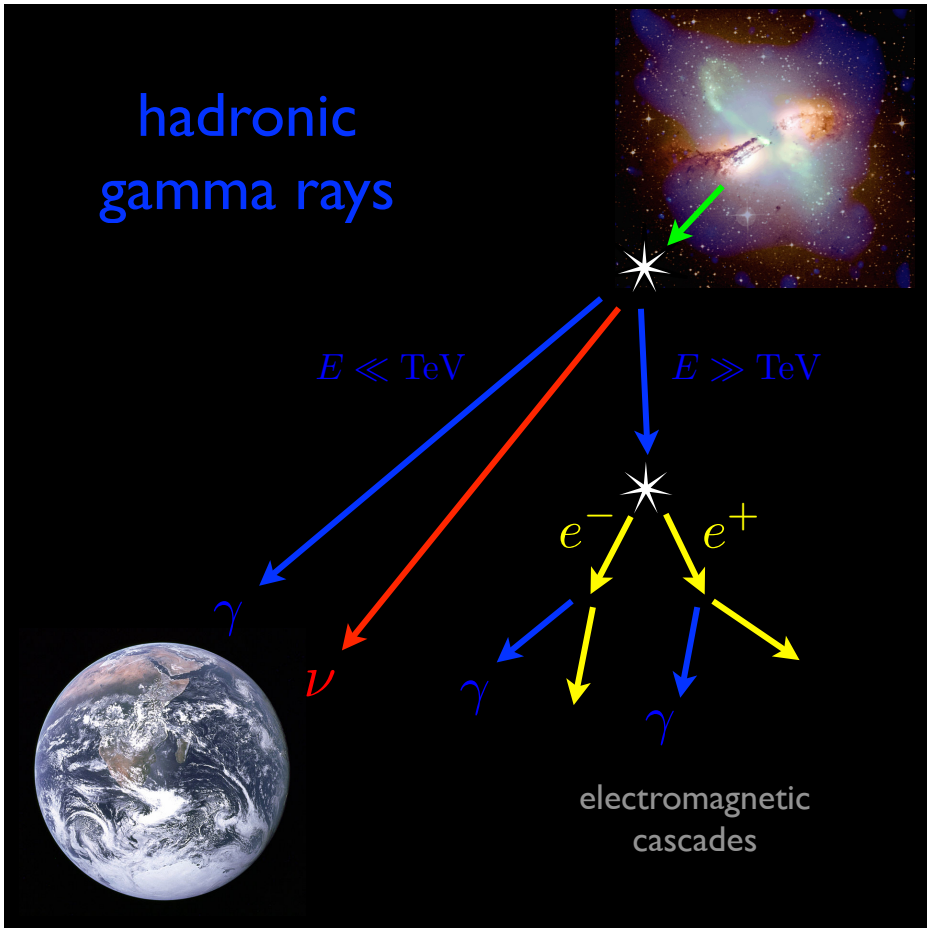
$$\pi^0 \to \gamma + \gamma$$

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

➜ 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



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

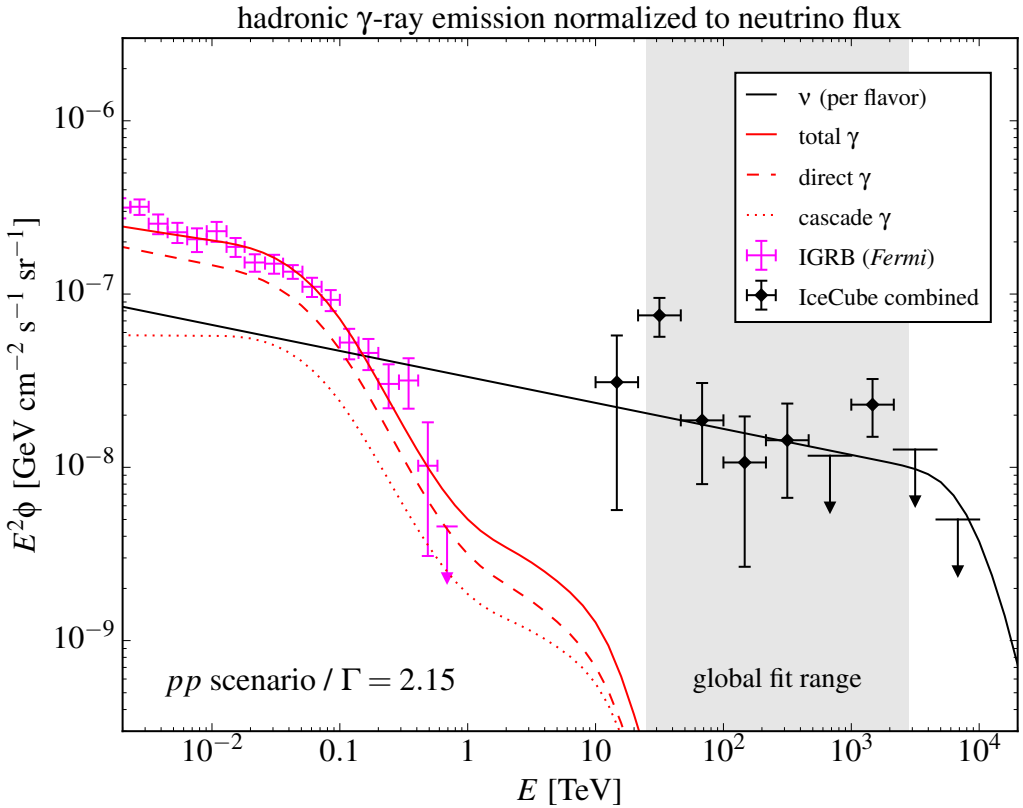
[Murase, MA & Lacki'13; Chang & Wang'14]

- 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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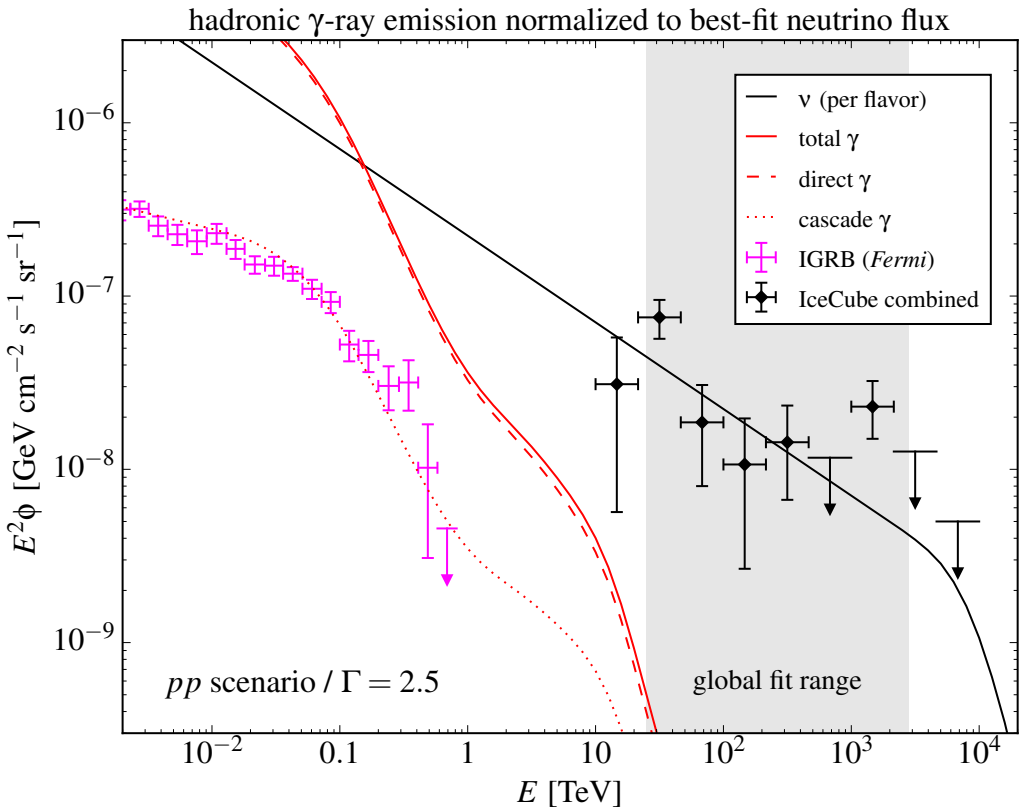

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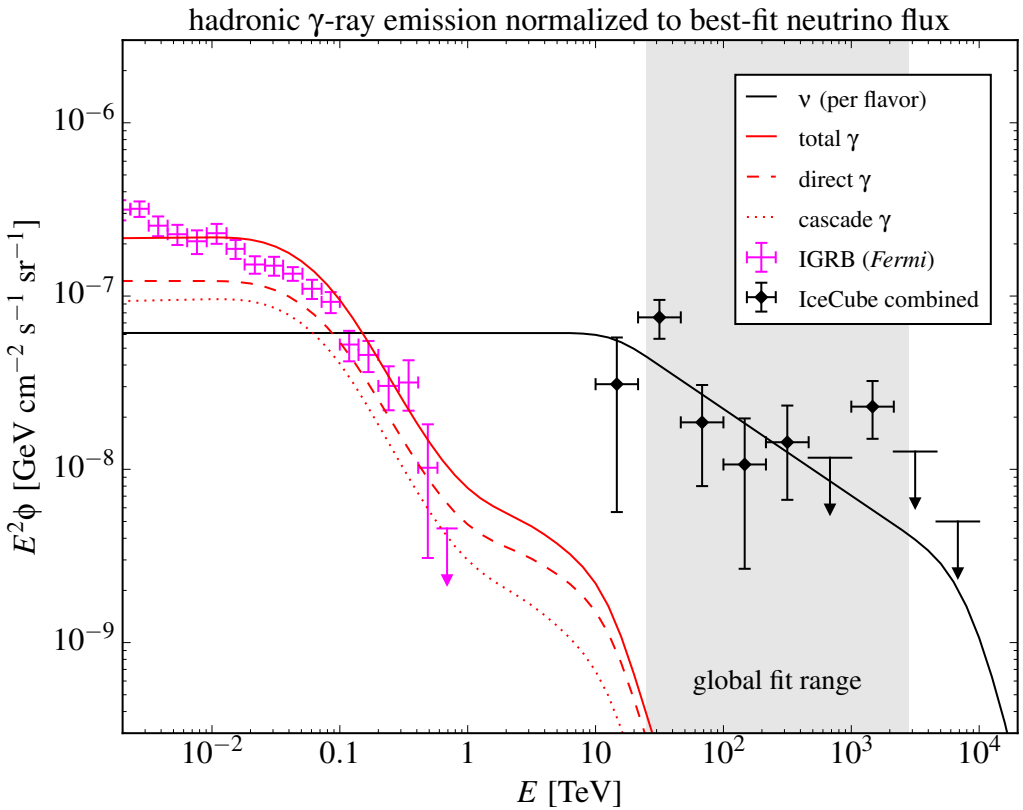
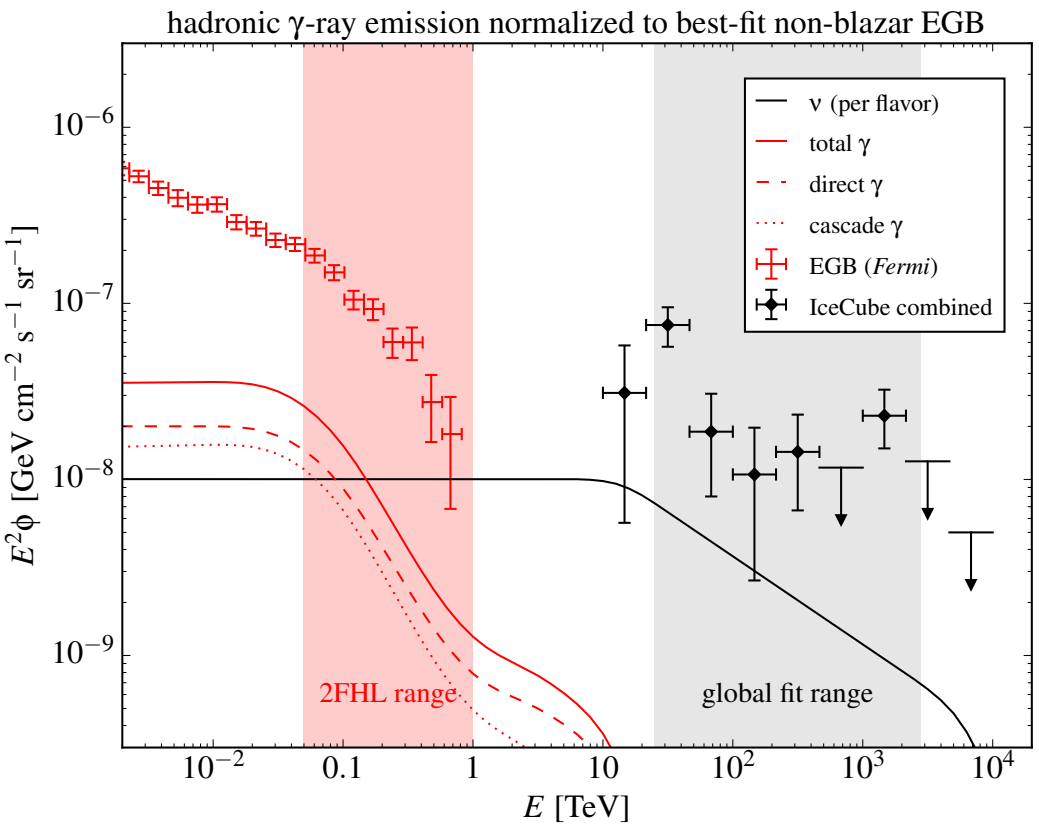
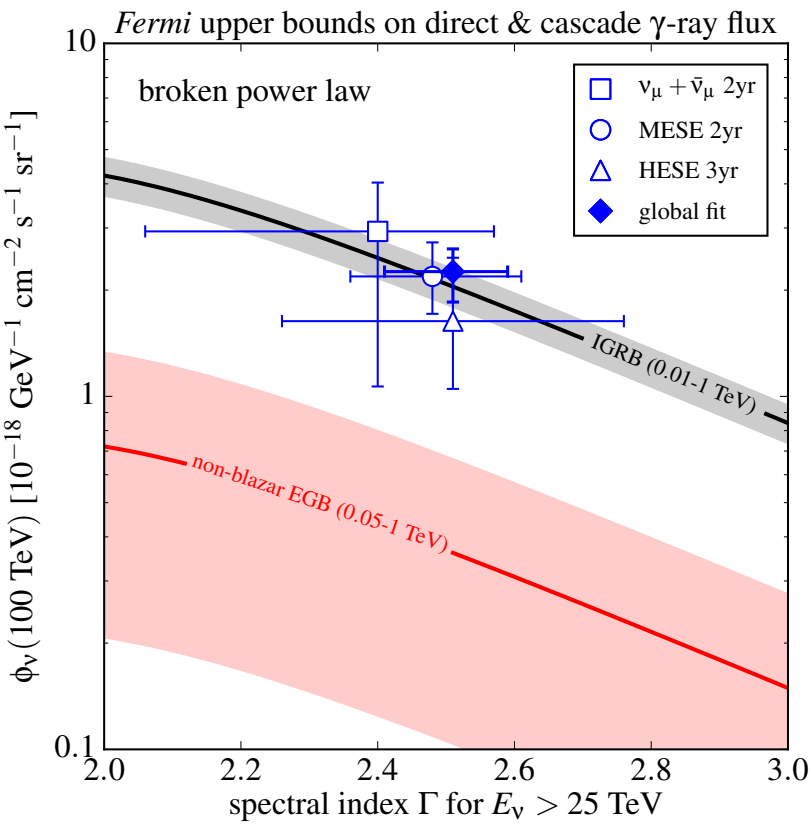


[Murase, MA & Lacki'14; Tamborra, Ando & Murase'14]

[Ando, Tamborra & Zandanel'15]

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]
- 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]

Summary

- Neutrinos are **unique pointing probes** in the 10TeV-10EeV energy range.
- **No (statistically significant) correlation yet** of neutrino events with known extragalactic and Galactic sources.

➜ excludes fireball GRB scenario, starts to test AGN correlations, prefers weak individual sources

- Fit of diffuse power-law fluxes in different energy region show **mild tension**.

➜ more complex emission, i.e. $p\gamma$ scenarios and/or multiple components?

- **High intensity** of 10TeV neutrino data is in tension with extragalactic γ-ray backgrounds.

➜ hidden sources or Galactic contribution?

- **Patience is of the essence!** Let's not over-emphasize $2\text{-}3\sigma$ results prematurely!

Appendix

Blazar Correlations?

nature physics

ARTICLES

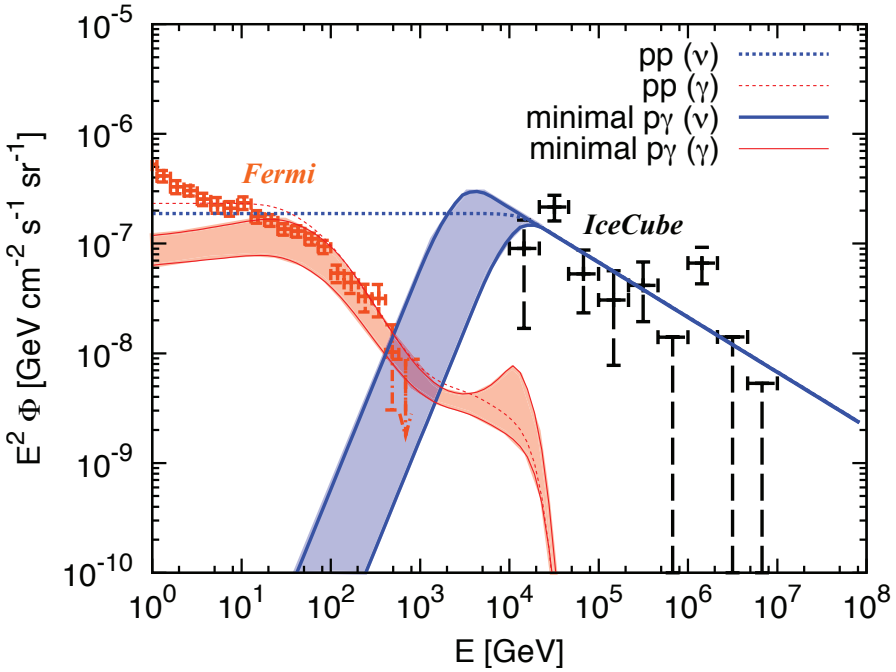
PUBLISHED ONLINE: 18 APRIL 2016 | DOI: 10.1038/NPHYS3715

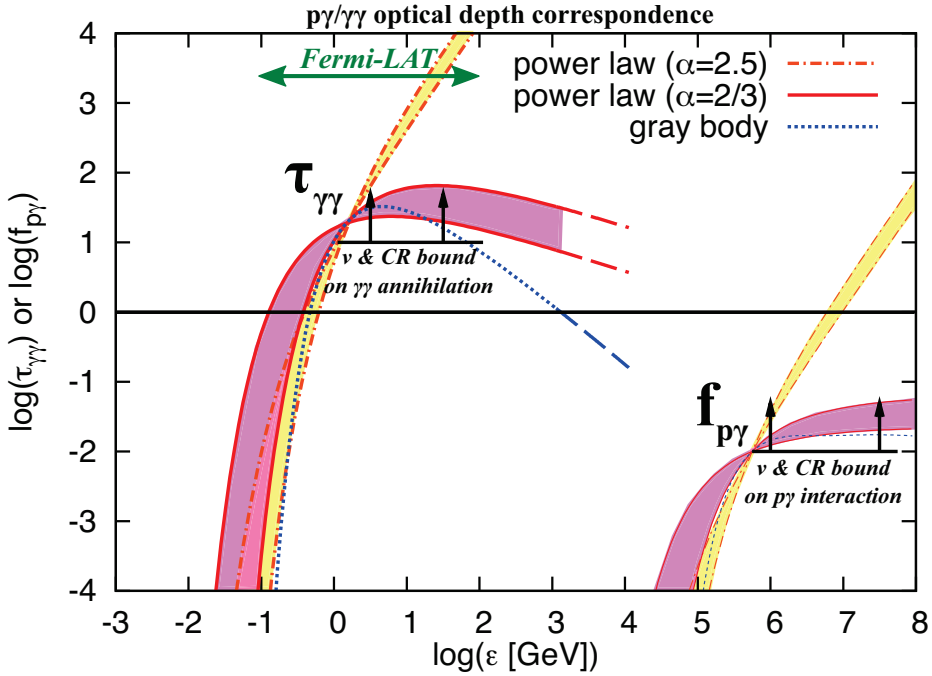
Coincidence of a high-fluence blazar outburst with a PeV-energy neutrino event

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]

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

Fermi IGRB and $p\gamma$ Scenarios?





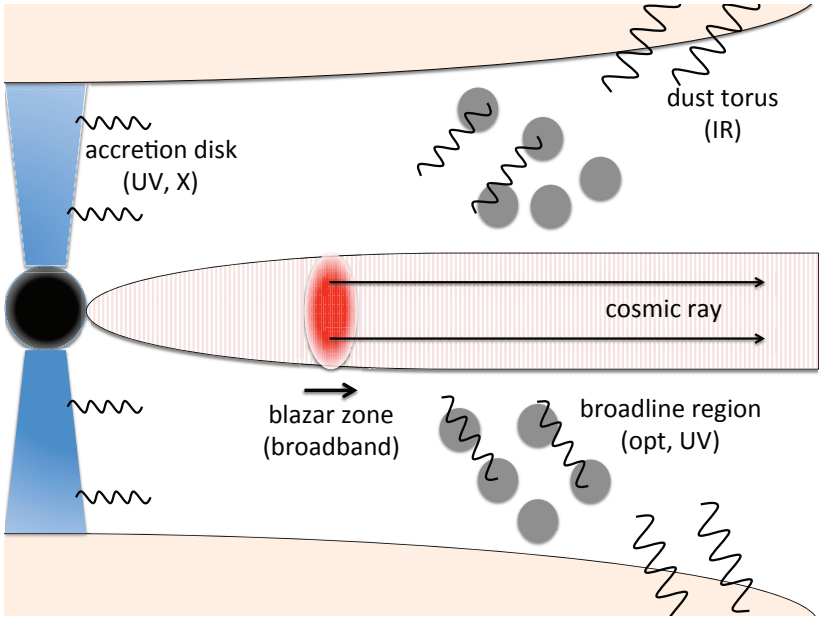
[Murase, Guetta & MA'15]

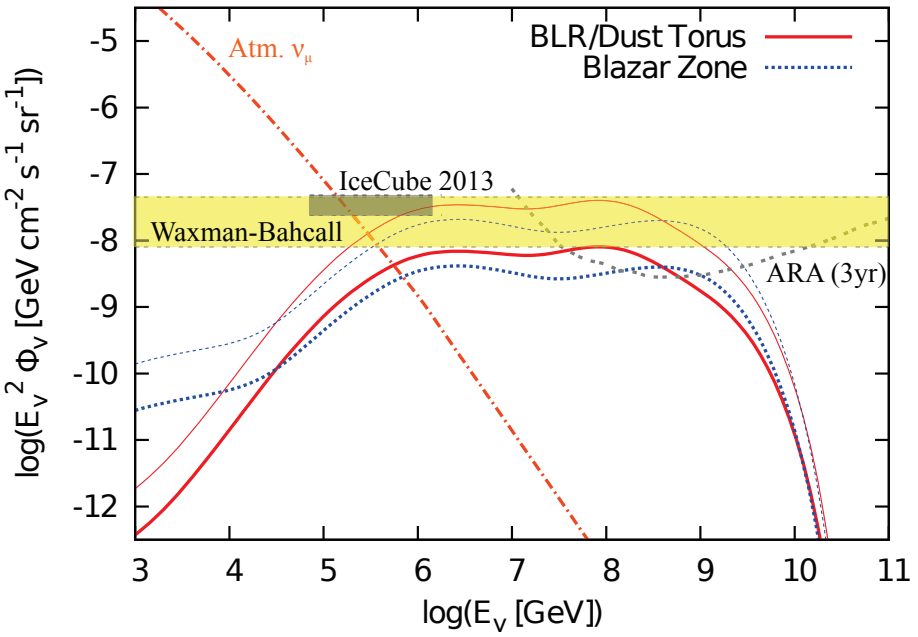
- also strong constraints from cascade emission of $p\gamma$ scenarios
- However, **high pion production efficiency** implies strong $\gamma\gamma$ absorption in sources!

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

AGN jets

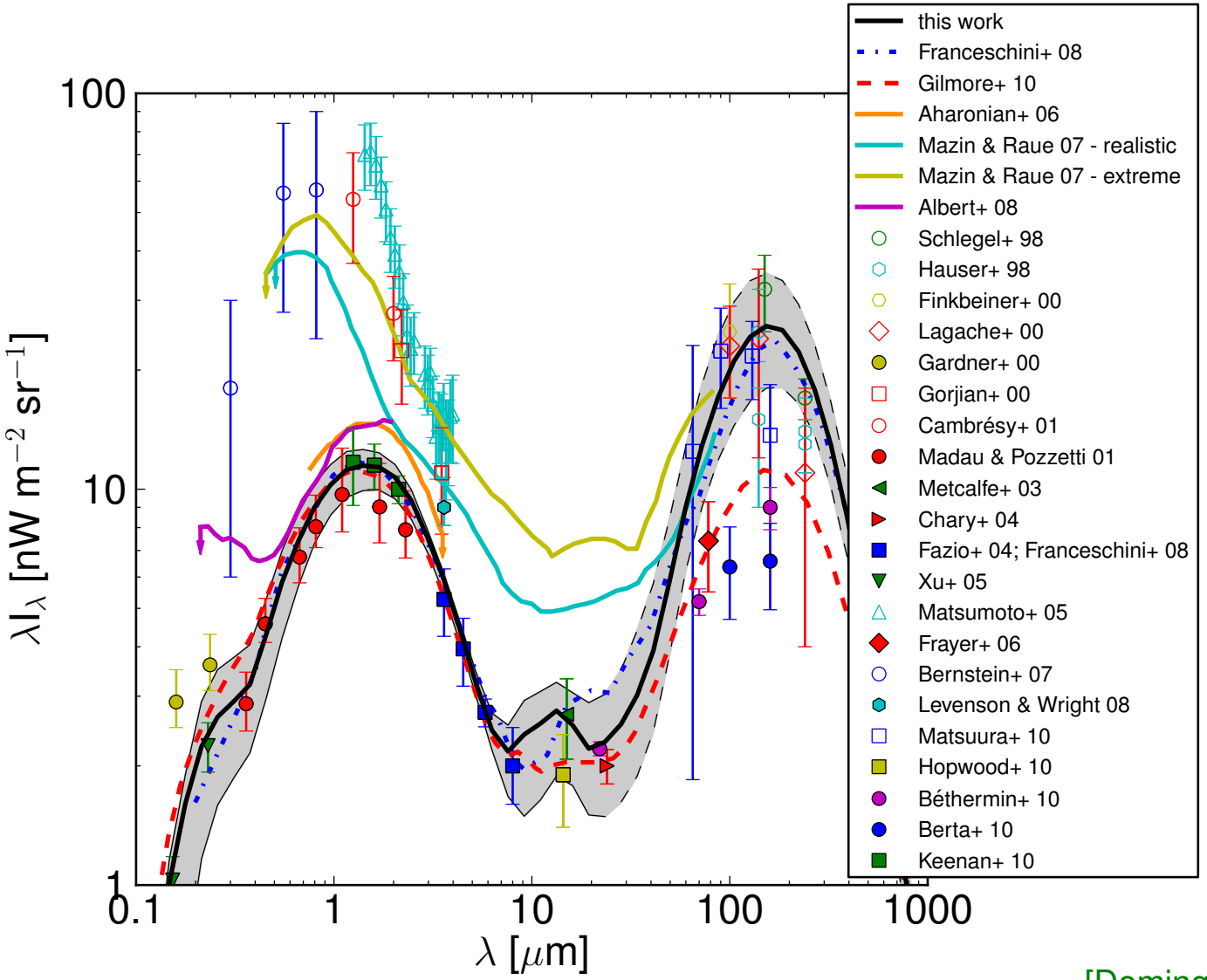
- neutrino from $p\gamma$ interactions in AGN jets [Mannheim'96; Halzen & Zas'97]
- complex spectra due to various photon backgrounds
- typically, deficit of sub-PeV and excess of EeV neutrinos





[Murase, Inoue & Dermer'14]

Extra-galactic background light (EBL)



[Dominguez *et al.* '10]

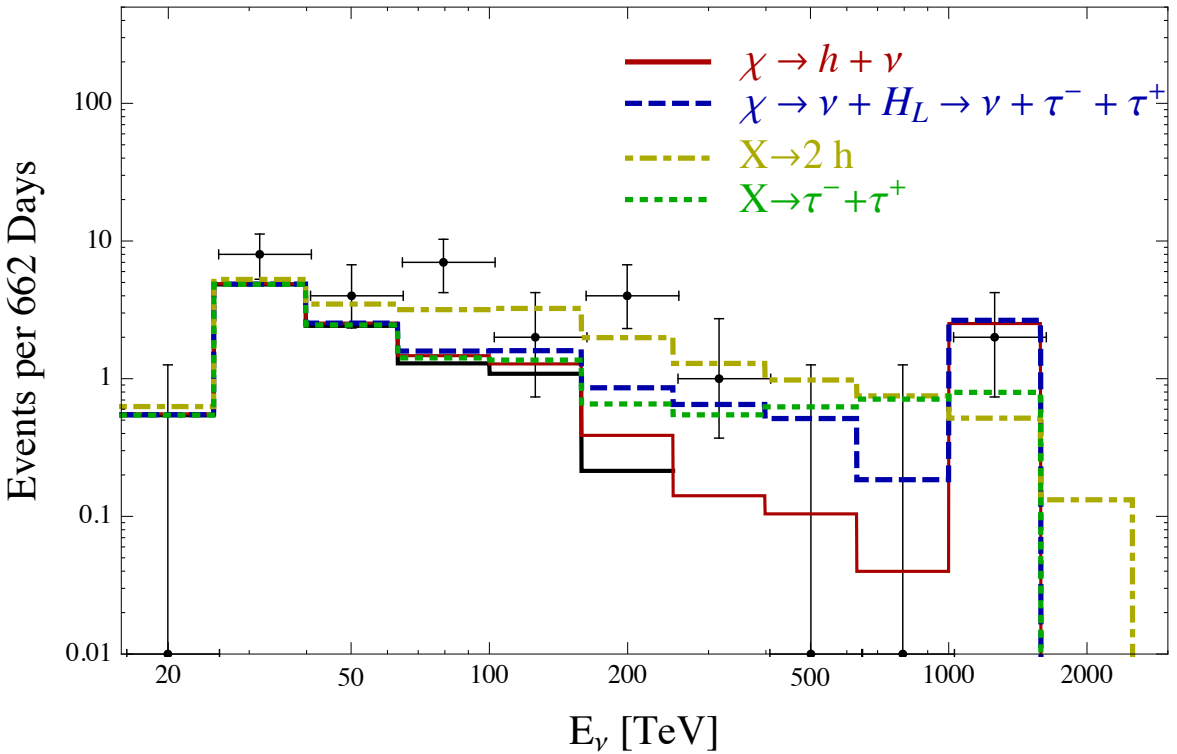
DM decay

- heavy (>PeV) DM decay?

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

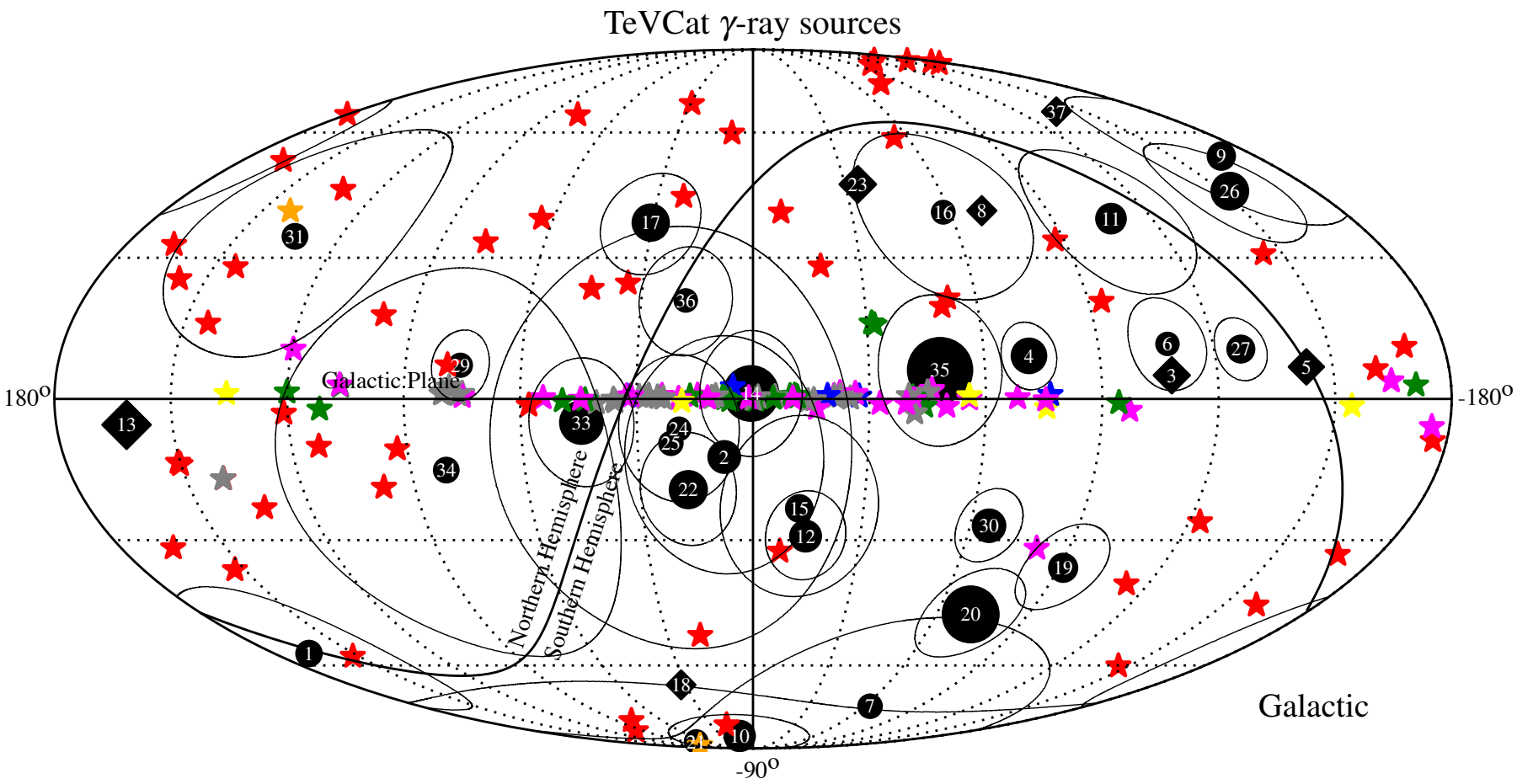
- **initially** motivated by PeV "line-feature", but continuum spectrum with/without line spectrum equally possible

➜ 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

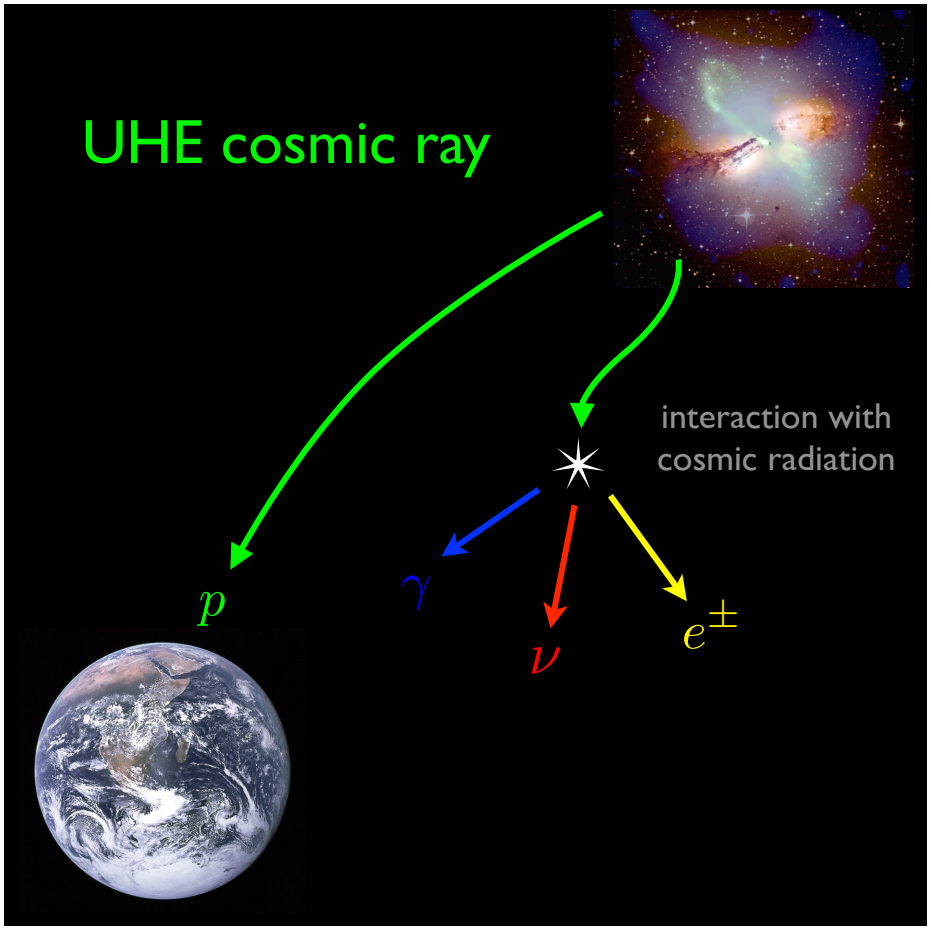
- particle confinement during acceleration requires: [Hillas'84]

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

✘ *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**

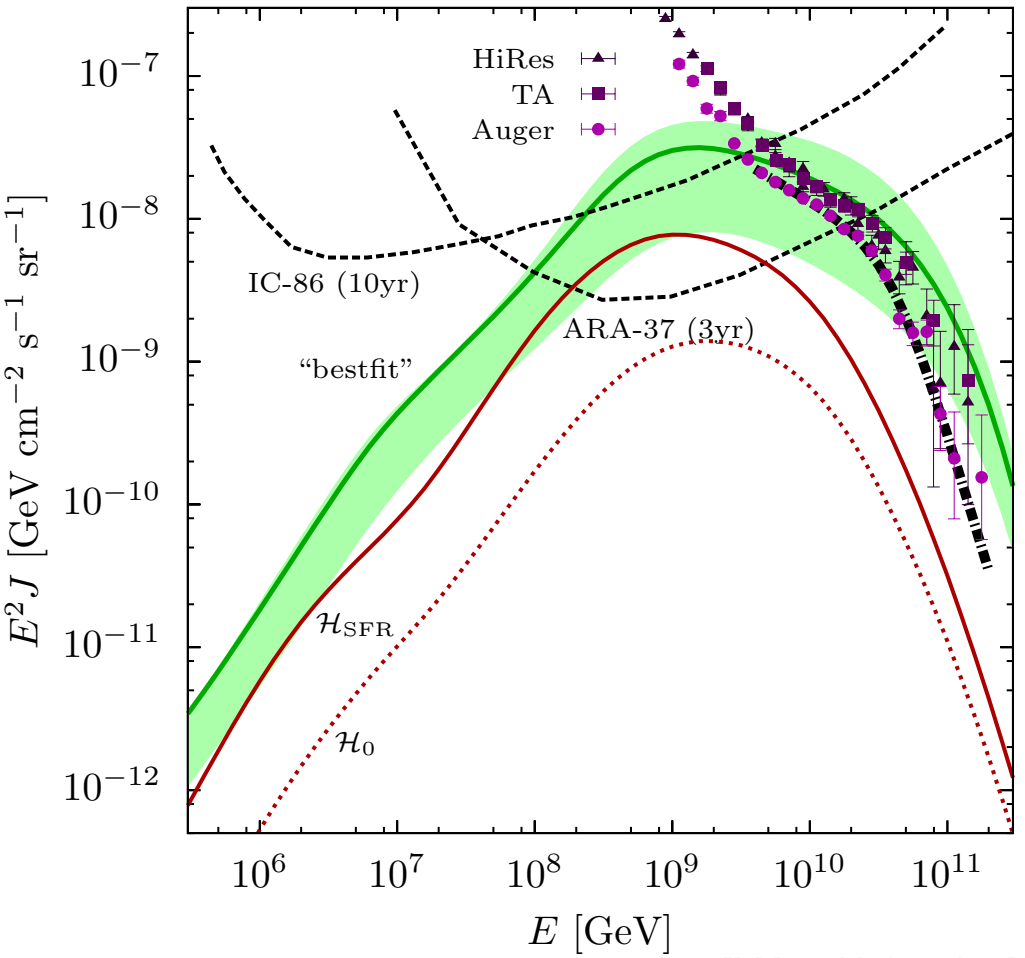
    [Berezinsky & Smirnov'75; Mannheim, Protheroe & Rachen'01; Keshet, Waxman, & Loeb'03; Berezinsky, Gazizov, Kachelriess & Ostapchenko'10; MA, Anchordoqui, Gonzalez–Garcia, Halzen & Sarkar'10; MA & Salvado'11; Gelmini, Kalashev & Semikoz'12]

Guaranteed Cosmogenic Neutrinos

- ➜ **minimal** GZK flux from proton dominated models can be estimated from observed spectrum

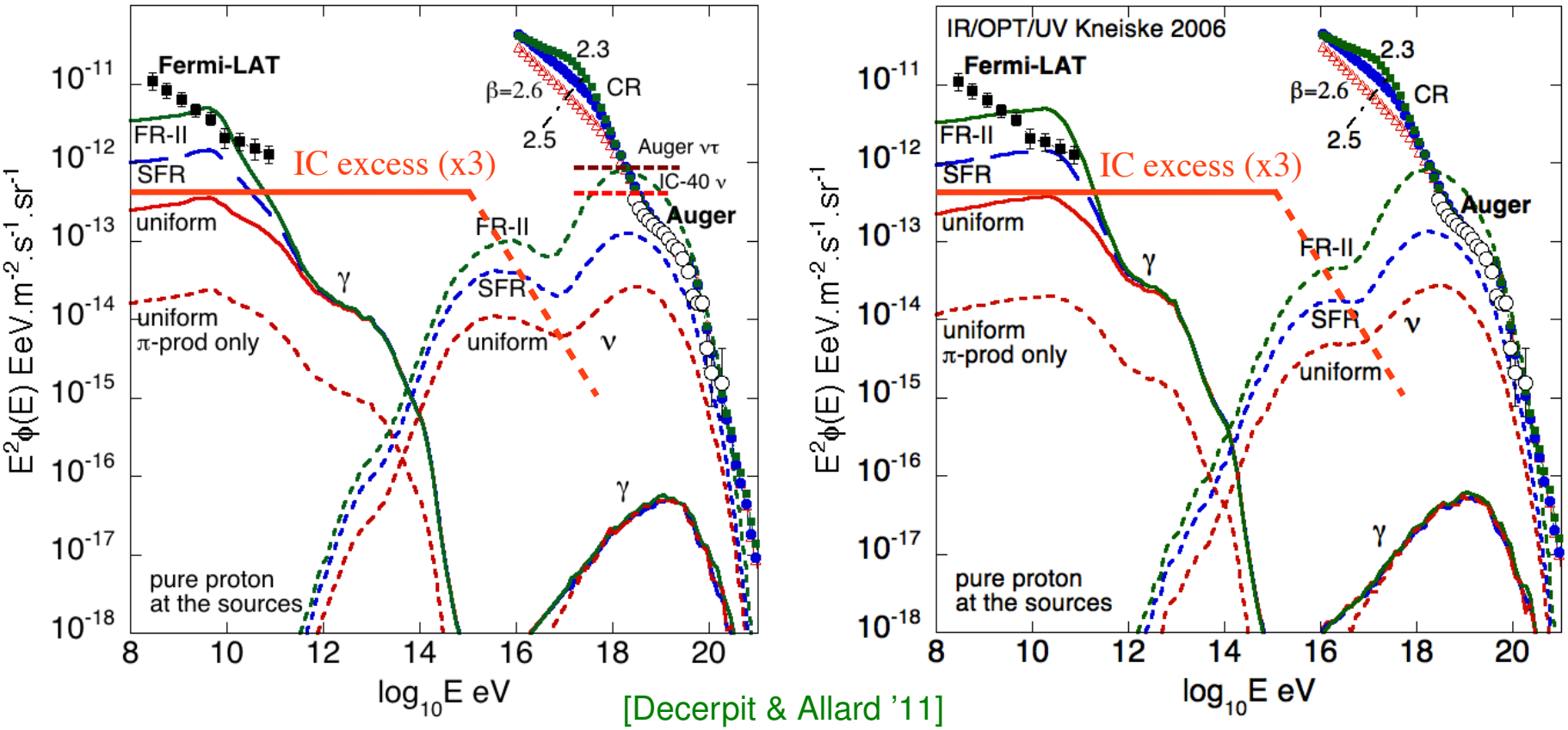
  - dependence on cosmic evolution of sources:
    - no evolution (dotted)
    - star-formation rate (solid)

- ➜ **ultimate test** of UHE CR proton models feasible with future observatories like ARA.



[MA & Halzen'12]

Cosmogenic PeV Neutrinos?



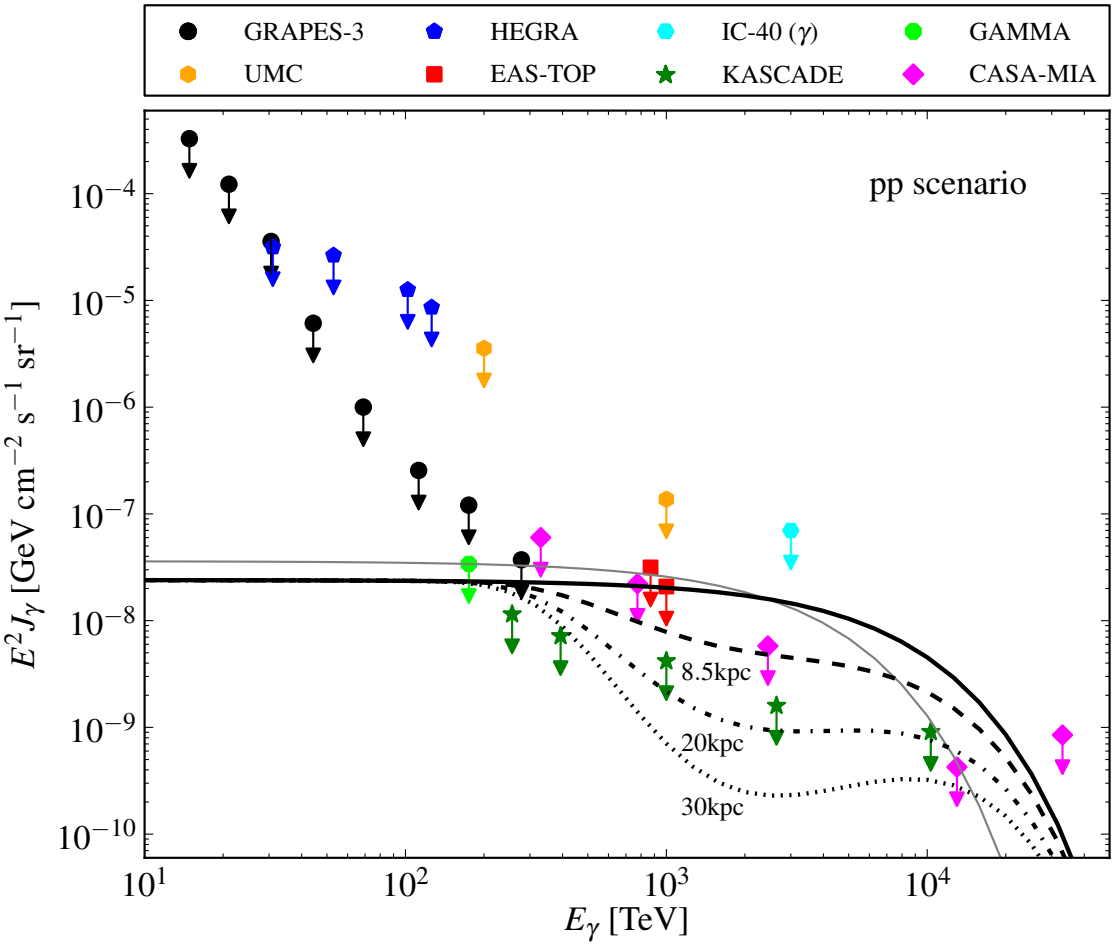
[Decerpit & Allard '11]

- ➜ 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

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]