Probing Anisotropies in the Arrival Directions of Astrophysical Neutrinos

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UW-Madison & WIPAC

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"Unveiling the Anisotropic Universe"

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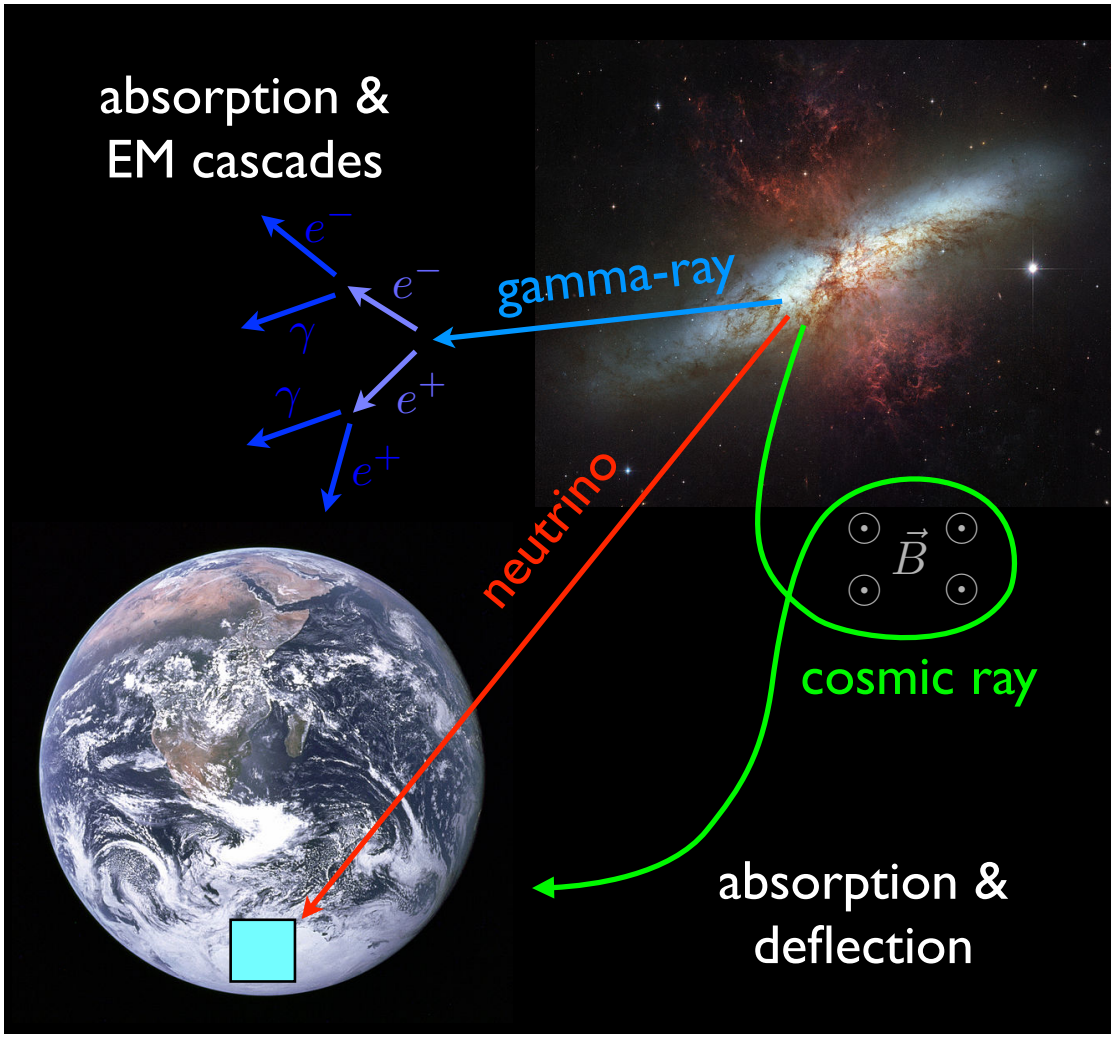
Multi-Messenger Astronomy

- 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



High-energy neutrino detection

- High energy neutrino collisions with nuclei are **rare**.

➜ Secondary charged particles can be detected by their **Cherenkov radiation** in transparent media.

- *back-of-the-envelope* ($E_\nu \sim 1\text{PeV} = 10^{15}$ eV):

- **flux of neutrinos** : $\dfrac{\mathrm{d}^2 N_\nu}{\mathrm{d}t\,\mathrm{d}A} \sim \dfrac{1}{\mathrm{cm}^2 \times 10^5 \mathrm{yr}}$

- **cross section** : $\sigma_{\nu N} \sim 10^{-33}\mathrm{cm}^2$

- **targets**: $N_N \sim N_A \times V/\mathrm{cm}^3$

➜ **rate of events** :

$$\dot{N}_\nu \sim N_N \times \sigma_{\nu N} \times \frac{\mathrm{d}^2 N_\nu}{\mathrm{d}t\,\mathrm{d}A} \sim \frac{1}{\mathrm{year}} \times \frac{V}{1\mathrm{km}^3}$$

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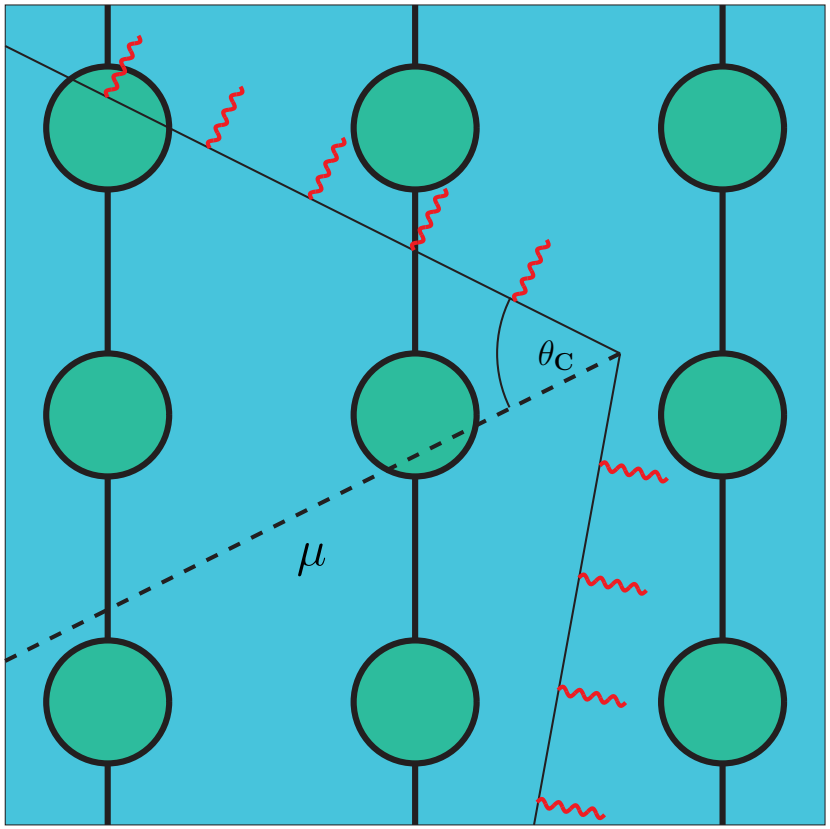
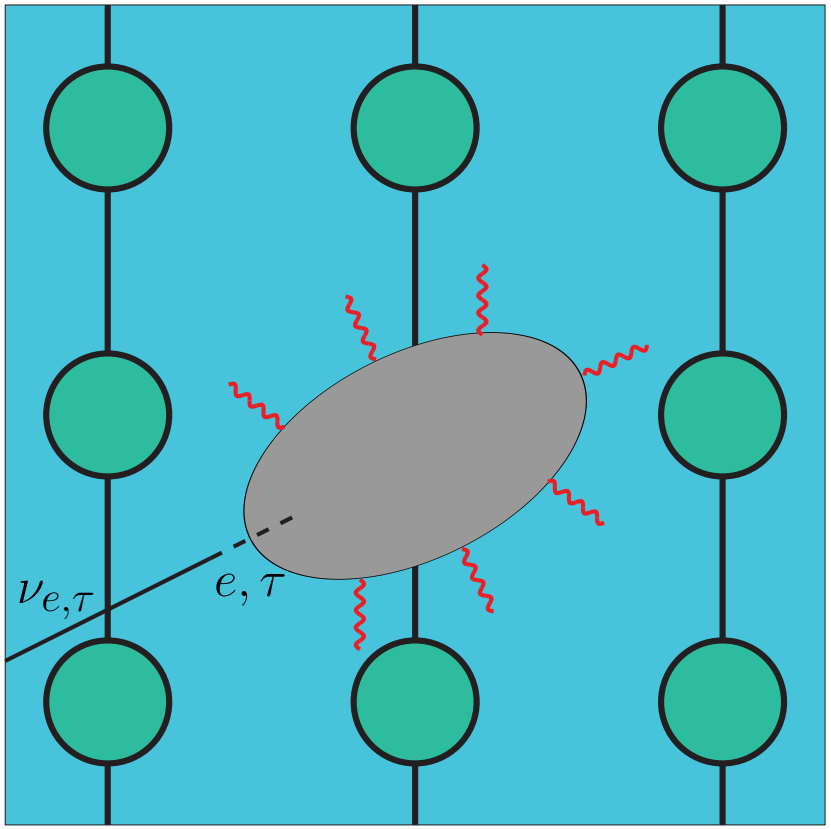
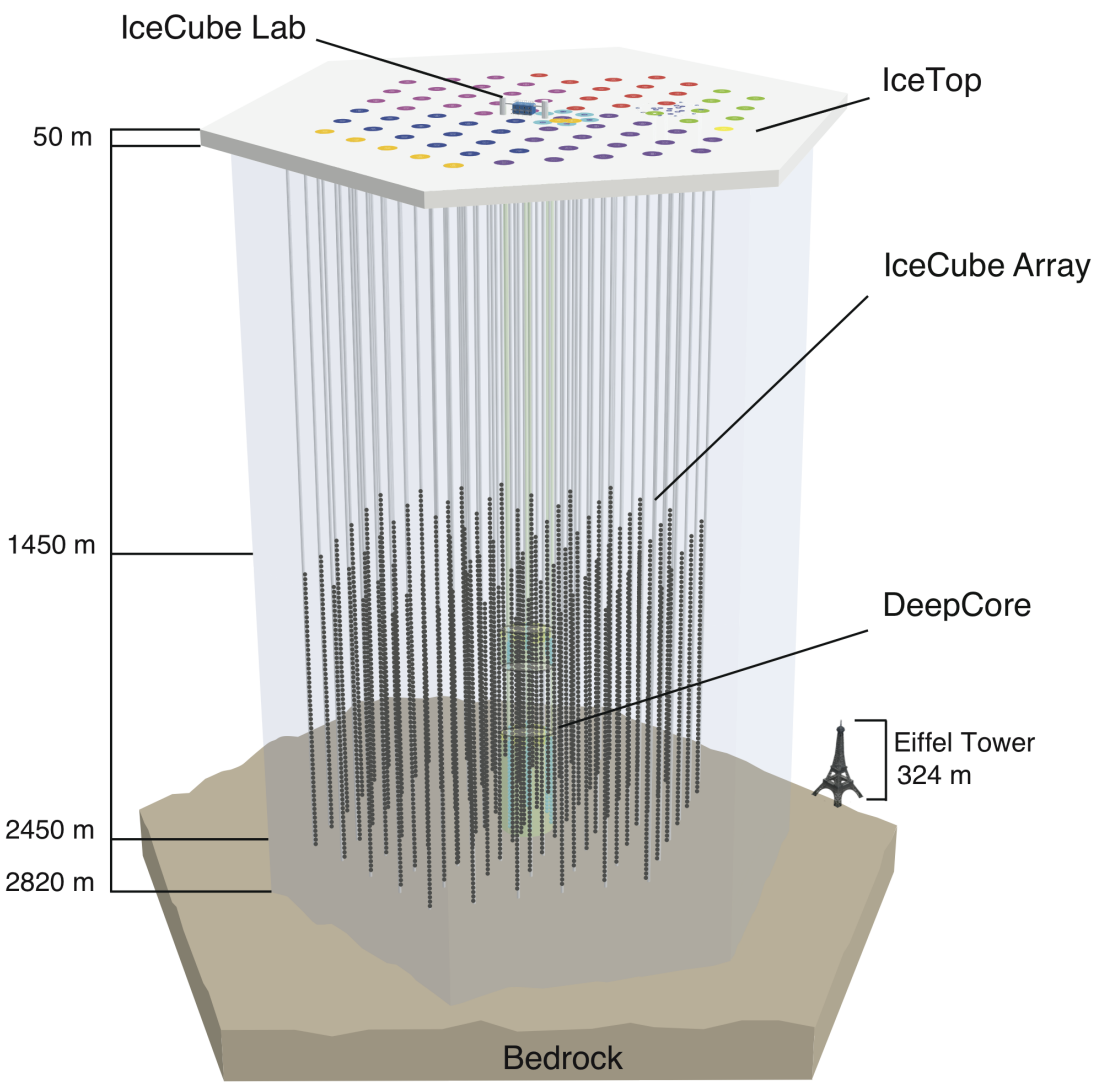
track event



cascade event



The IceCube Observatory

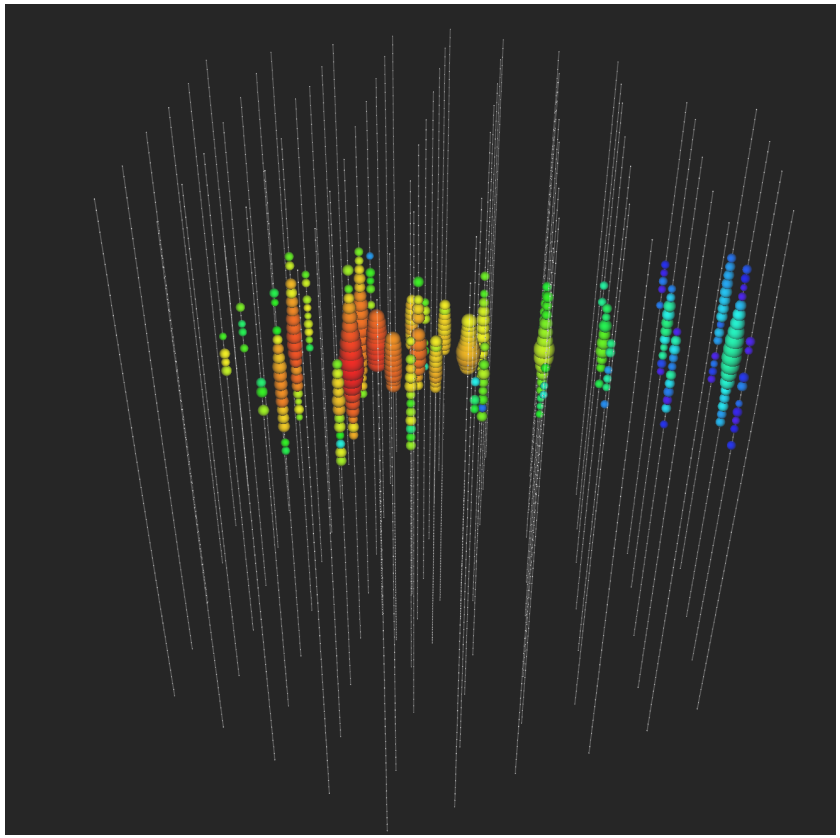


- Giga-ton **Cherenkov telescope** at the South Pole
- Collaboration of about 300 people at 43 intl. institutions
- 60 digital **optical modules** (DOMs) per string
- **78 IceCube strings**
  125 m apart on triangular grid
- **8 DeepCore strings**
  DOMs in particularly clear ice
- **81 IceTop stations**
  two tanks per station, two DOMs per tank
- 7 year construction phase (2004-2011)
- price tag: **30 Cents per ton**

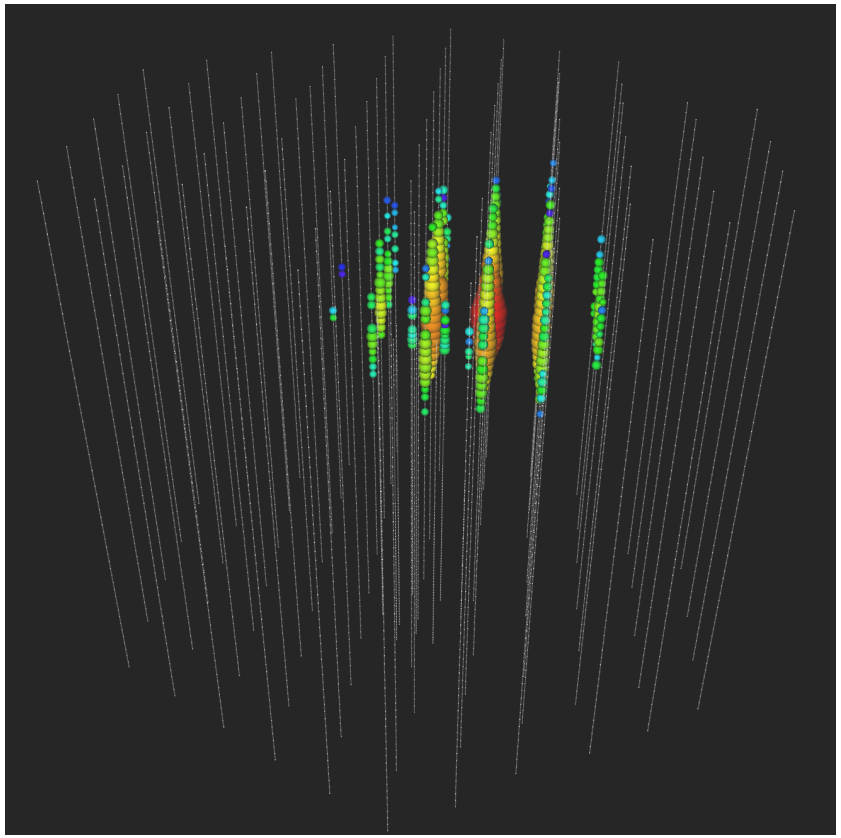
The IceCube Observatory

- "cascades": **good** energy, but **poor** angular resolution ($\Delta\theta > 10^\circ$)
- "muon tracks": **poor** energy, but **good** angular resolution ($\Delta\theta \lesssim 0.5^\circ$)
- **time-dependent** signal: early to late light detection

track event (IC-79)



cascade event (IC-86)

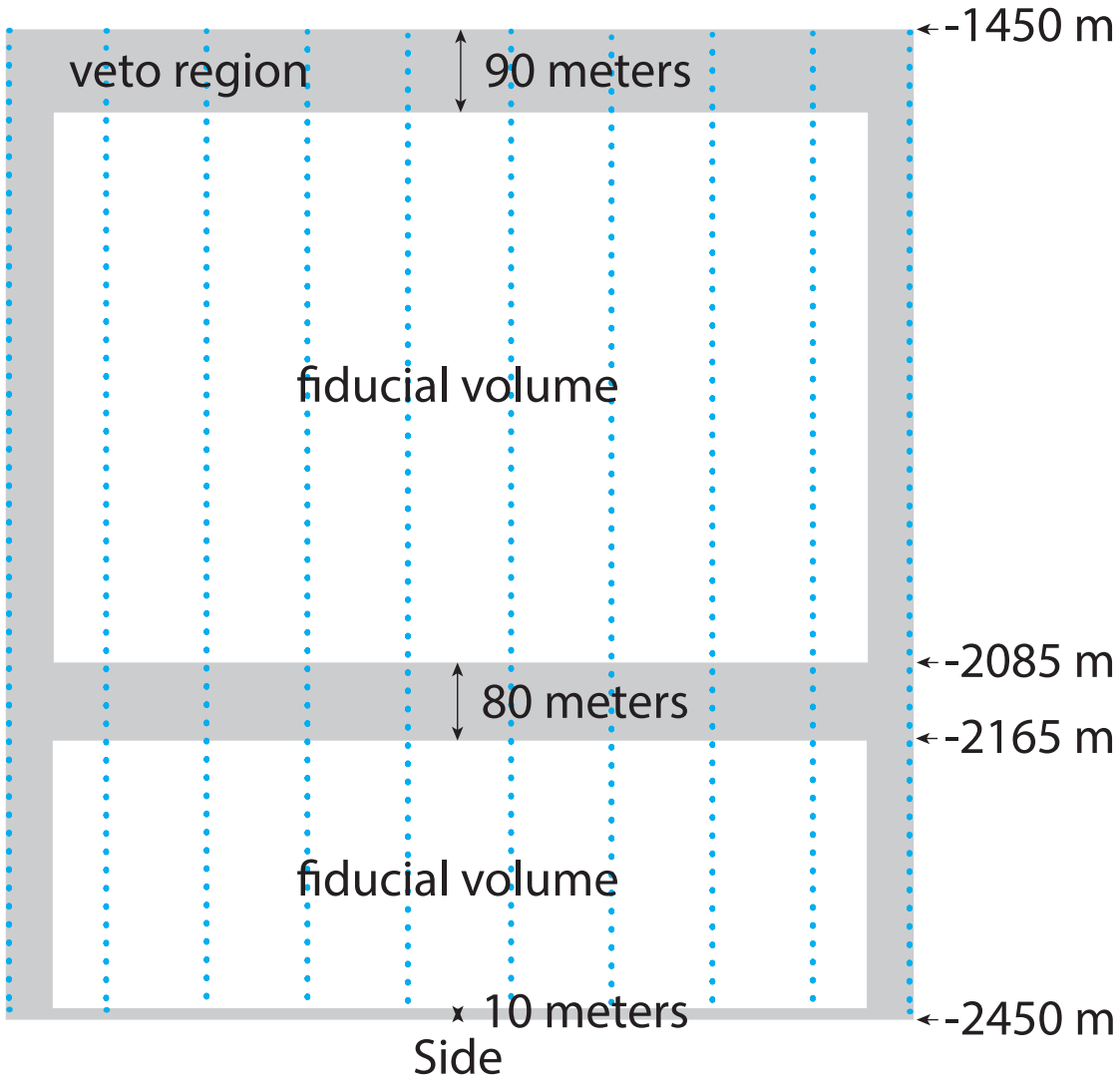


[two examples from the high-energy starting event (HESE) analysis; IceCube Science 342 (2013)]

High-energy starting event (HESE) analysis

- **veto region** marked as gray area (incl. dust layer)
- event passes if less than 3 of 250 first photo electrons (PE) are in veto region
- require high charge (> 6000 PE) to ensure high statistics
- background of atmospheric muons can be estimated from data
- high efficiency above 50-100 TeV

➜ **excess** beyond ~ 60 TeV



[IceCube Collaboration'15]

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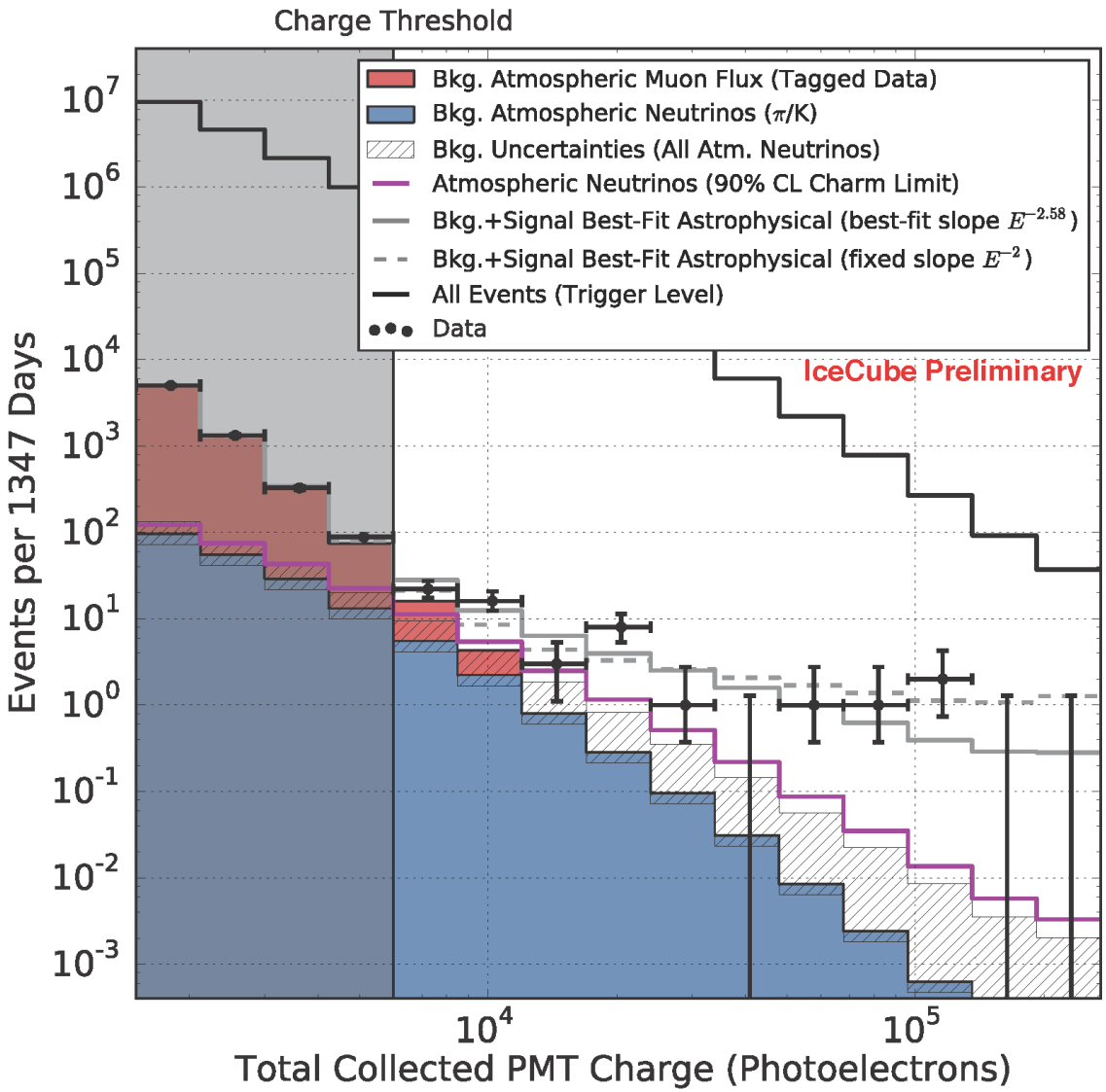


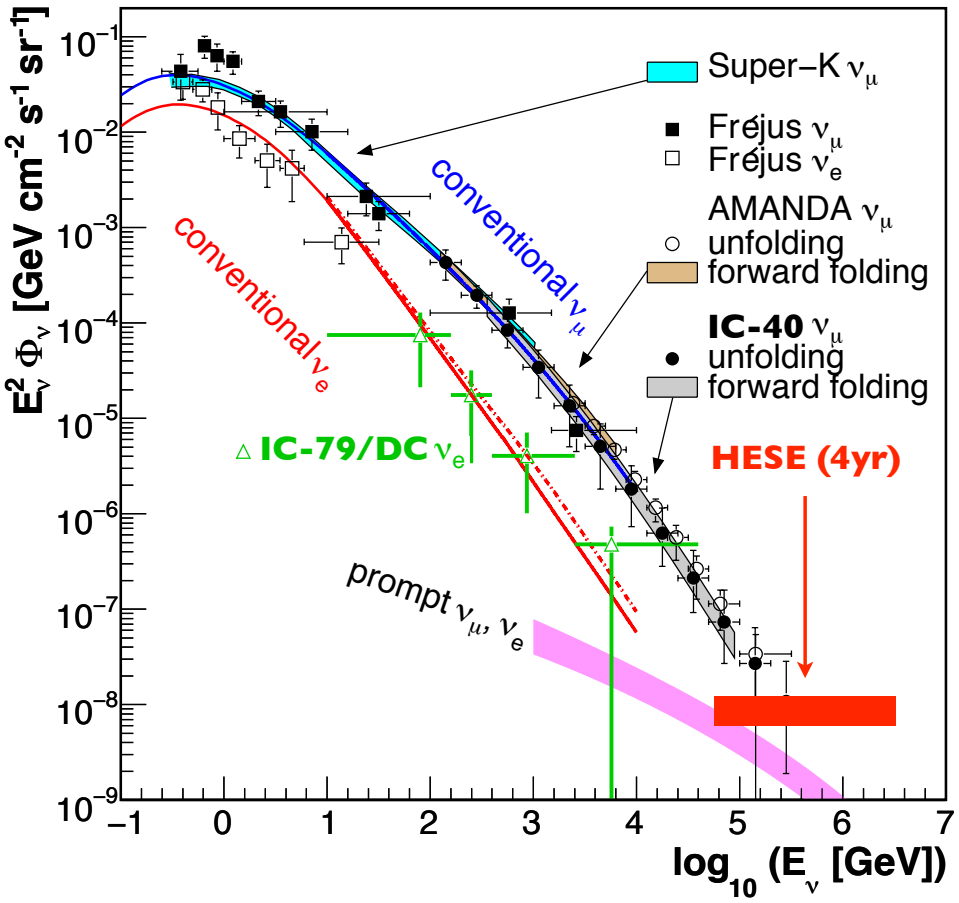
[IceCube Collaboration'15]

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:

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



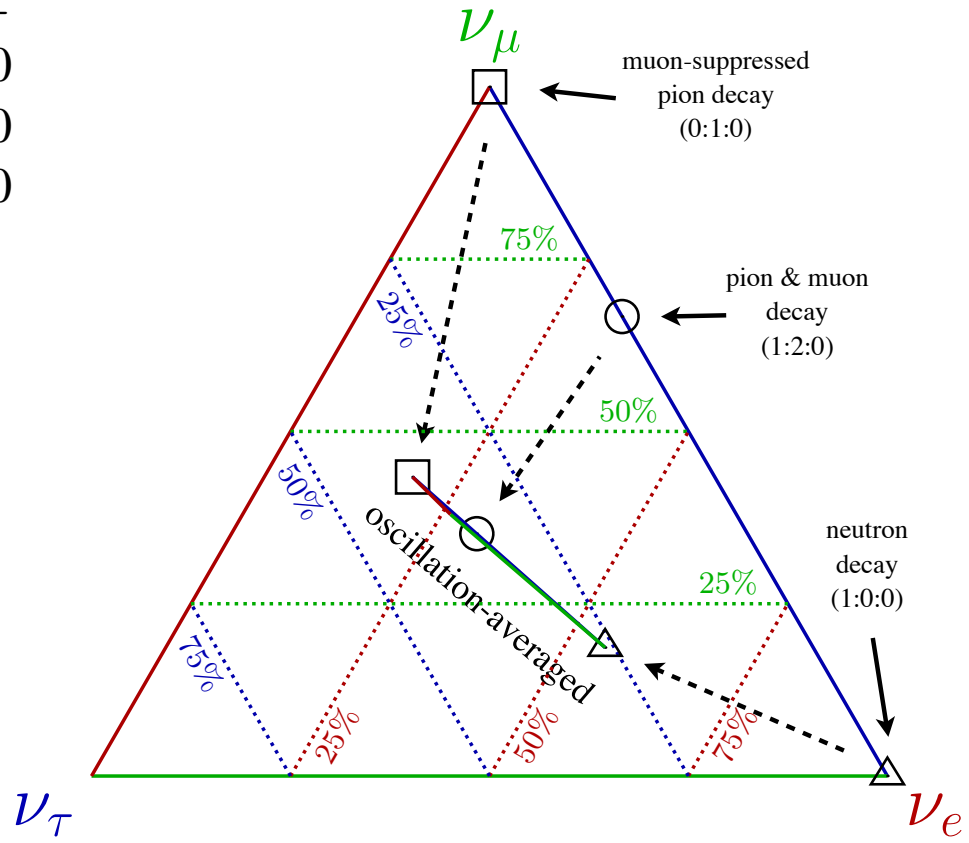
Neutrino Flavors

- 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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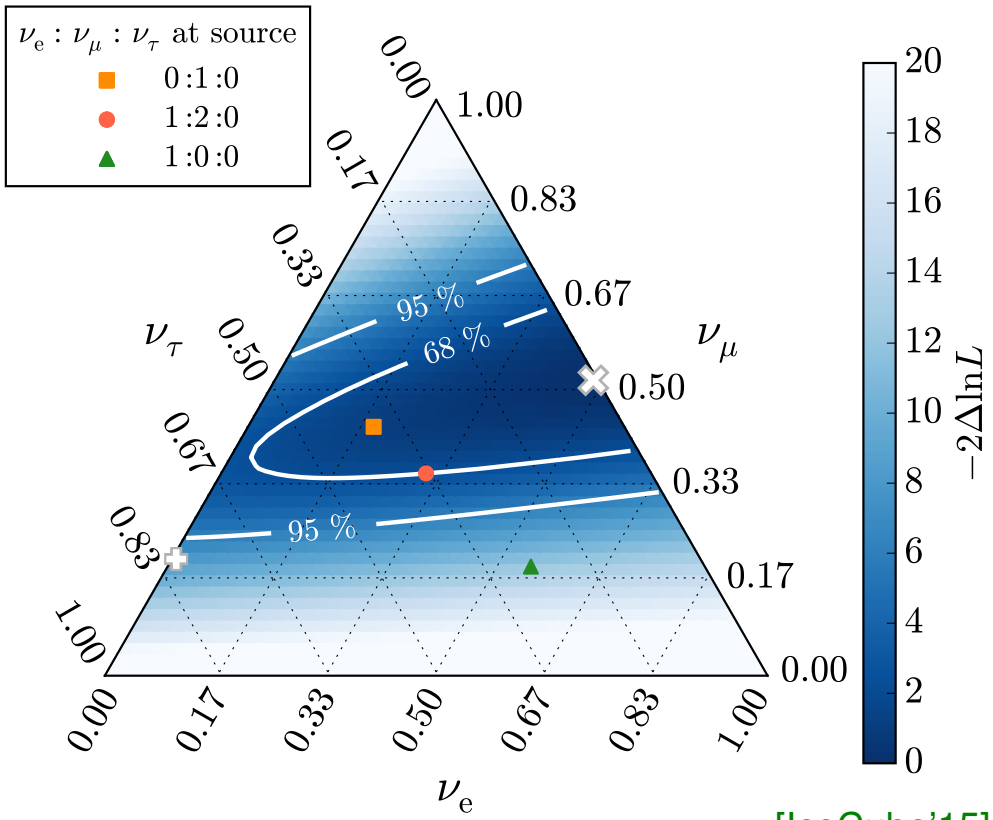

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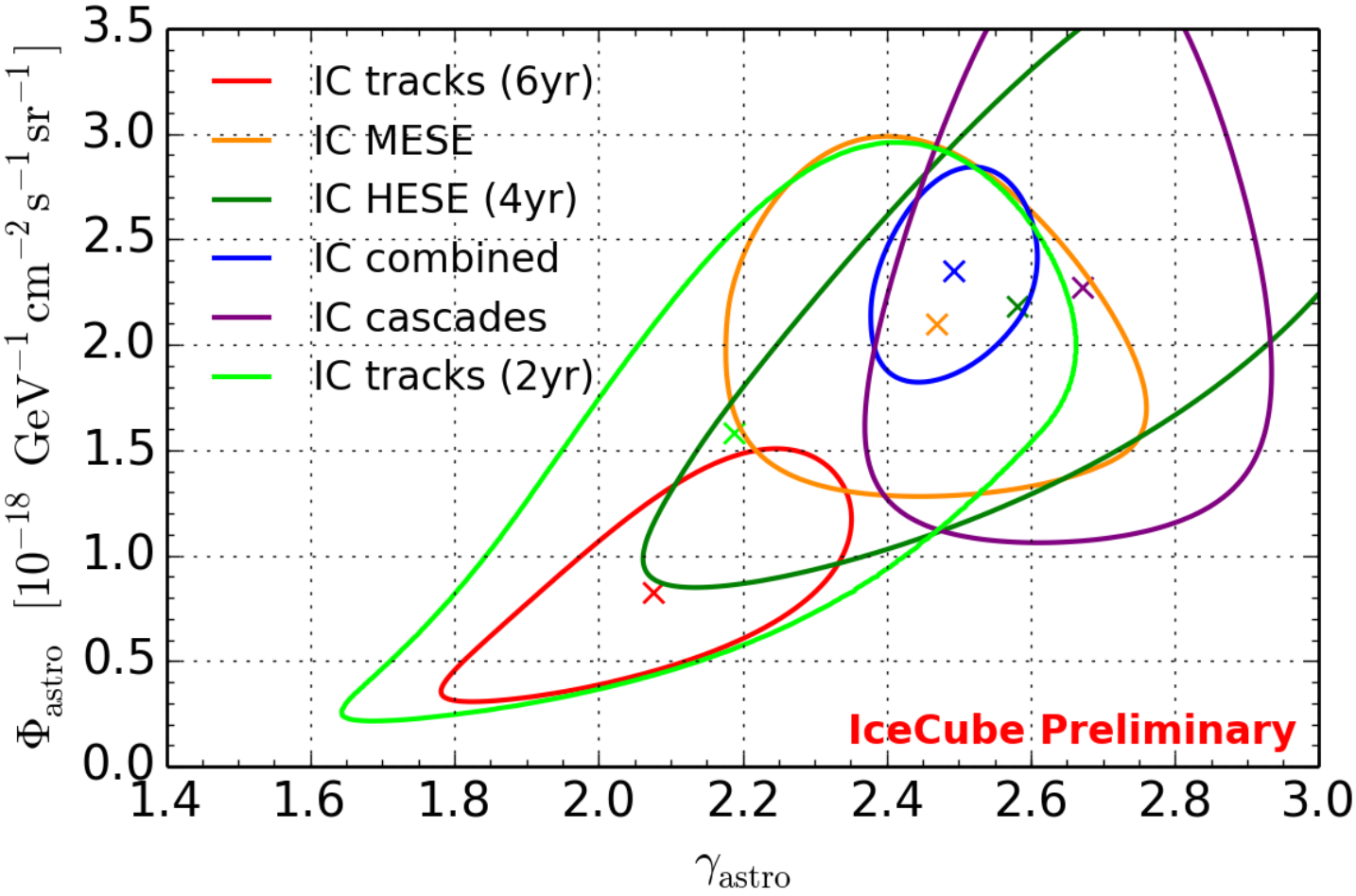
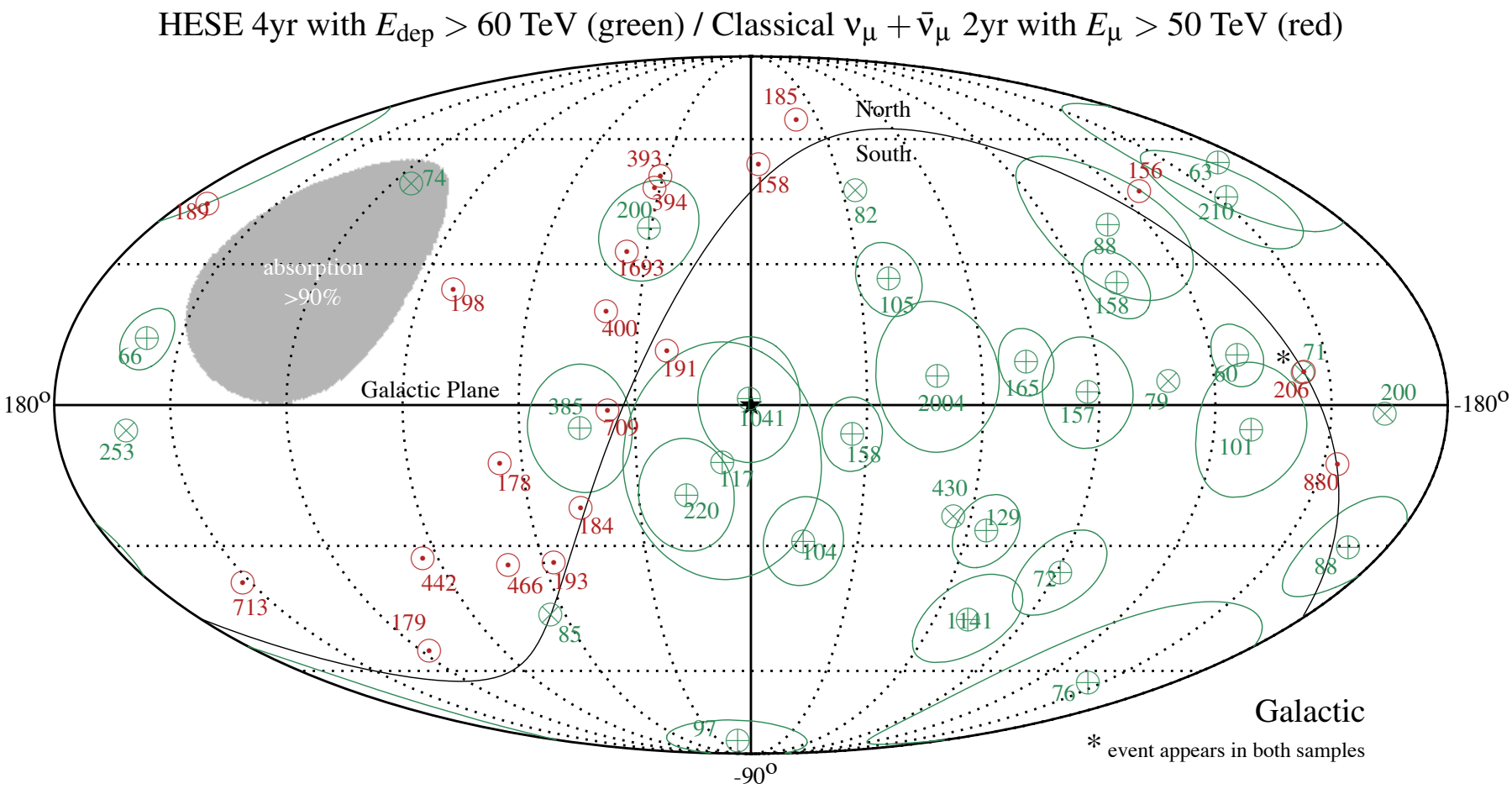
Best-Fit Power-Law Spectrum



- 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

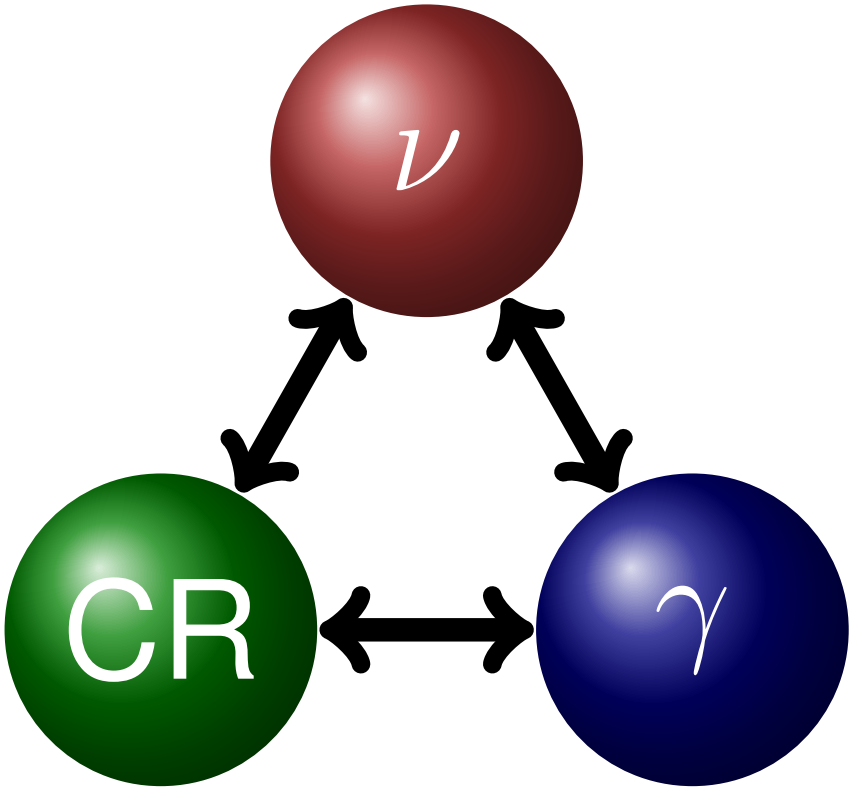
- Neutrino production is closely related to the production of cosmic rays (CRs) and γ-rays.

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

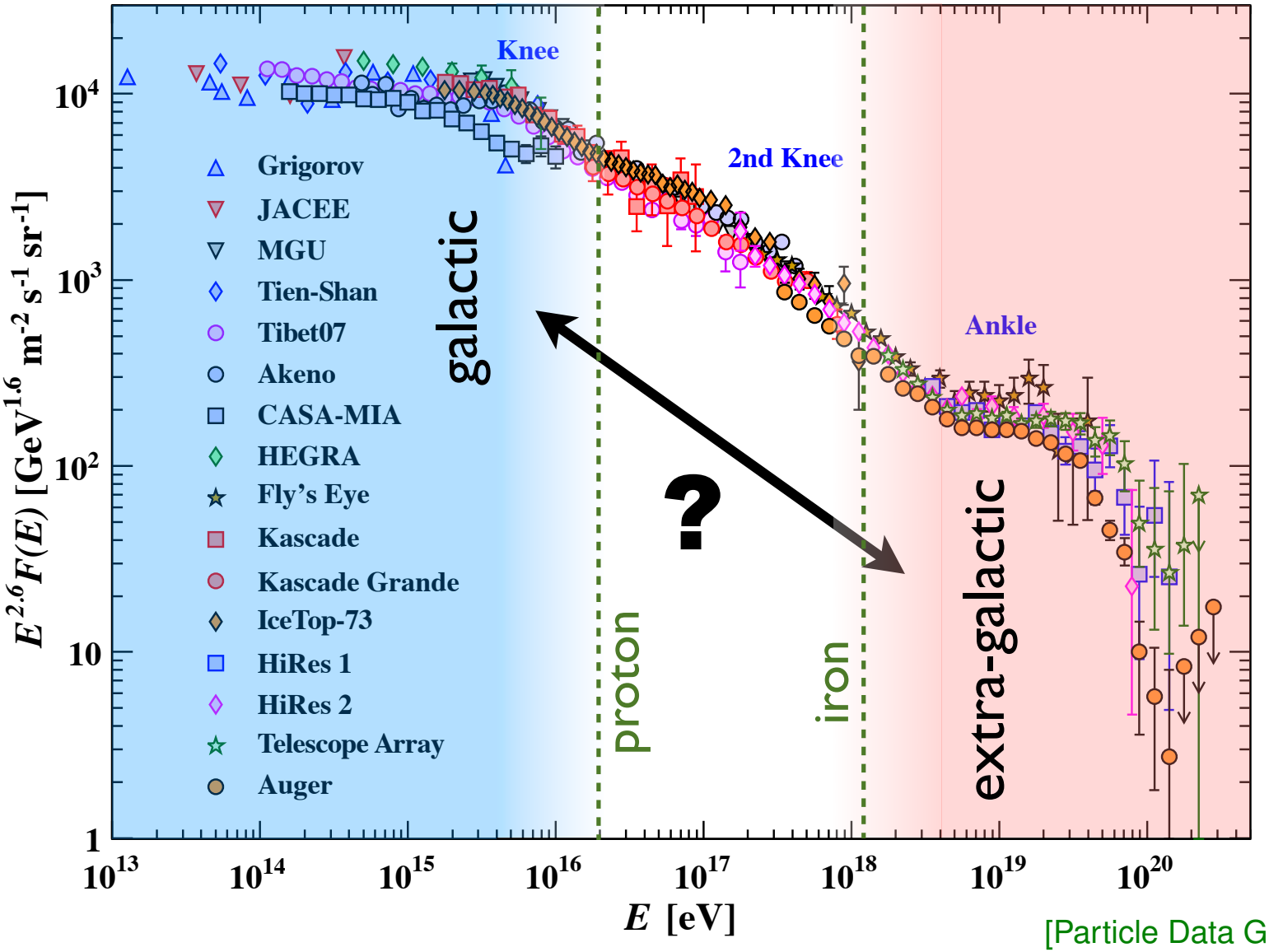
- 1 PeV neutrinos correspond to 20 PeV CR nucleons and 2 PeV γ-rays

➜ **very interesting** energy range:

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



The Cosmic “Beam”



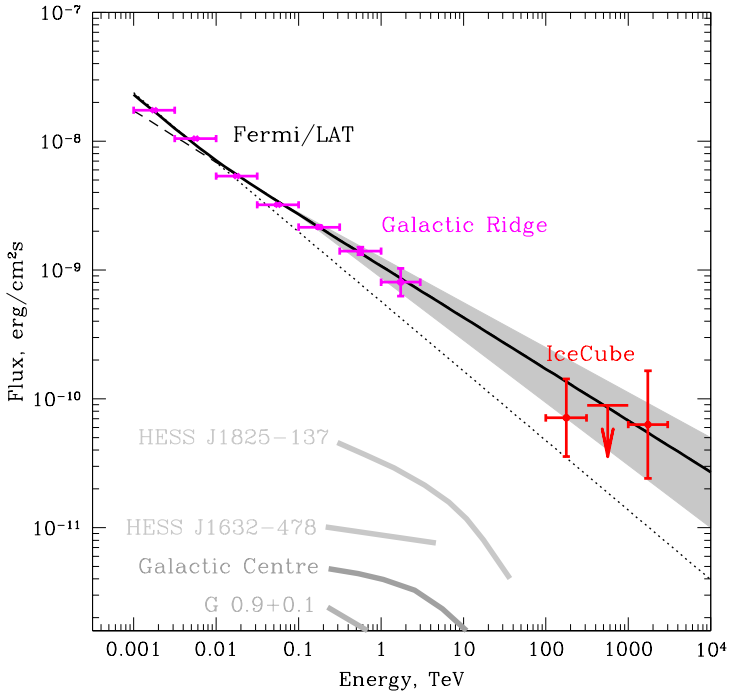
[Particle Data Group'13]

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; 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]

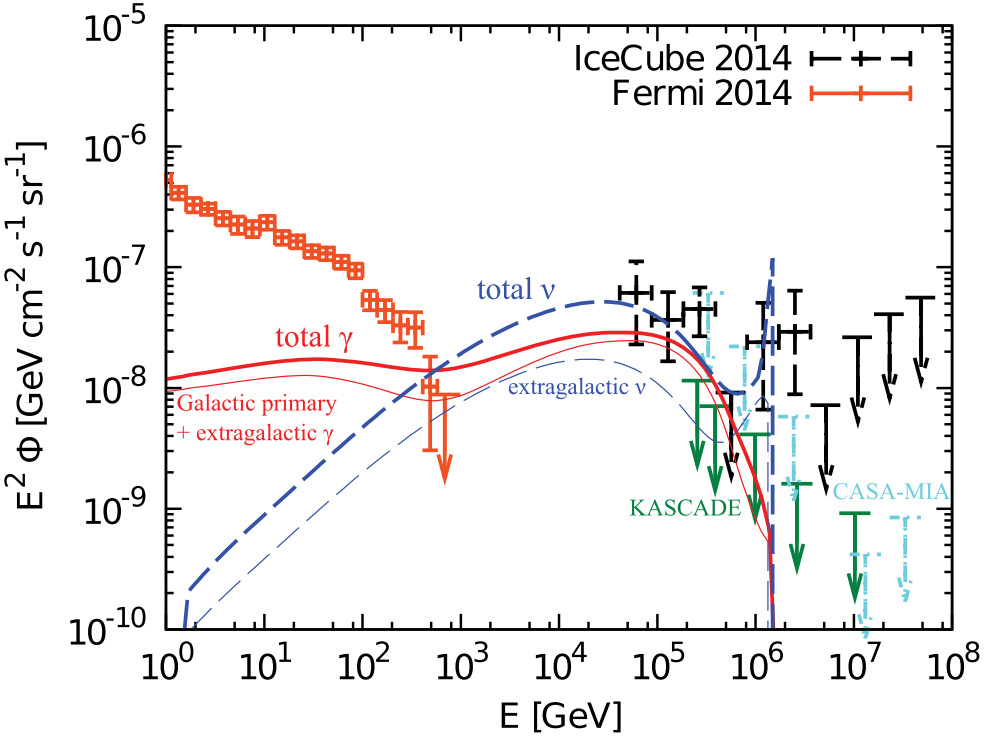
Galactic Emission Models: Two Examples

Hard Galactic Diffuse Emission



[Neronov, Semikoz & Tschernin'14]

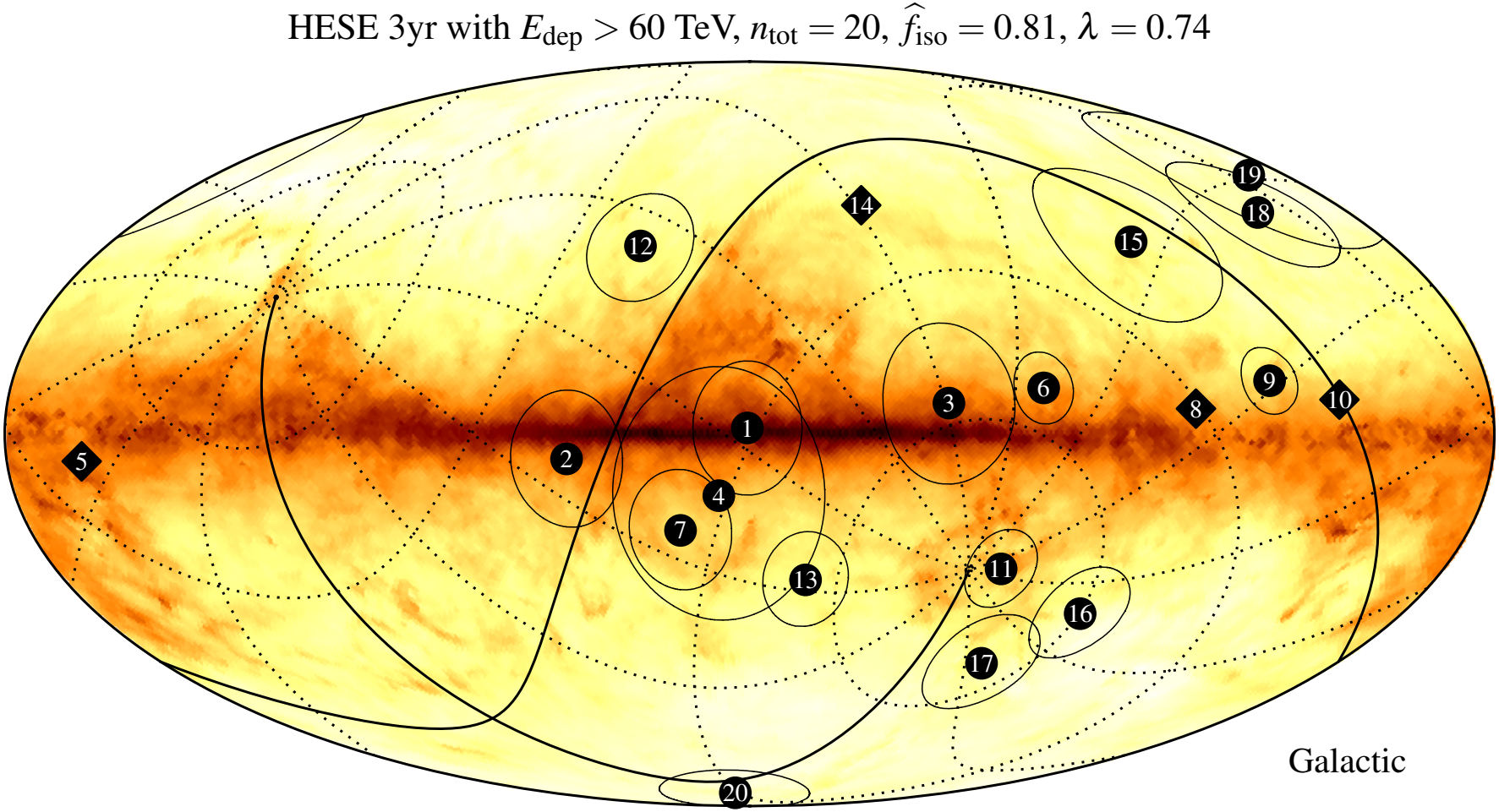
PeV Dark Matter Decay (*e.g.* DM$\to \nu\bar{\nu}/q\bar{q}$)



[*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

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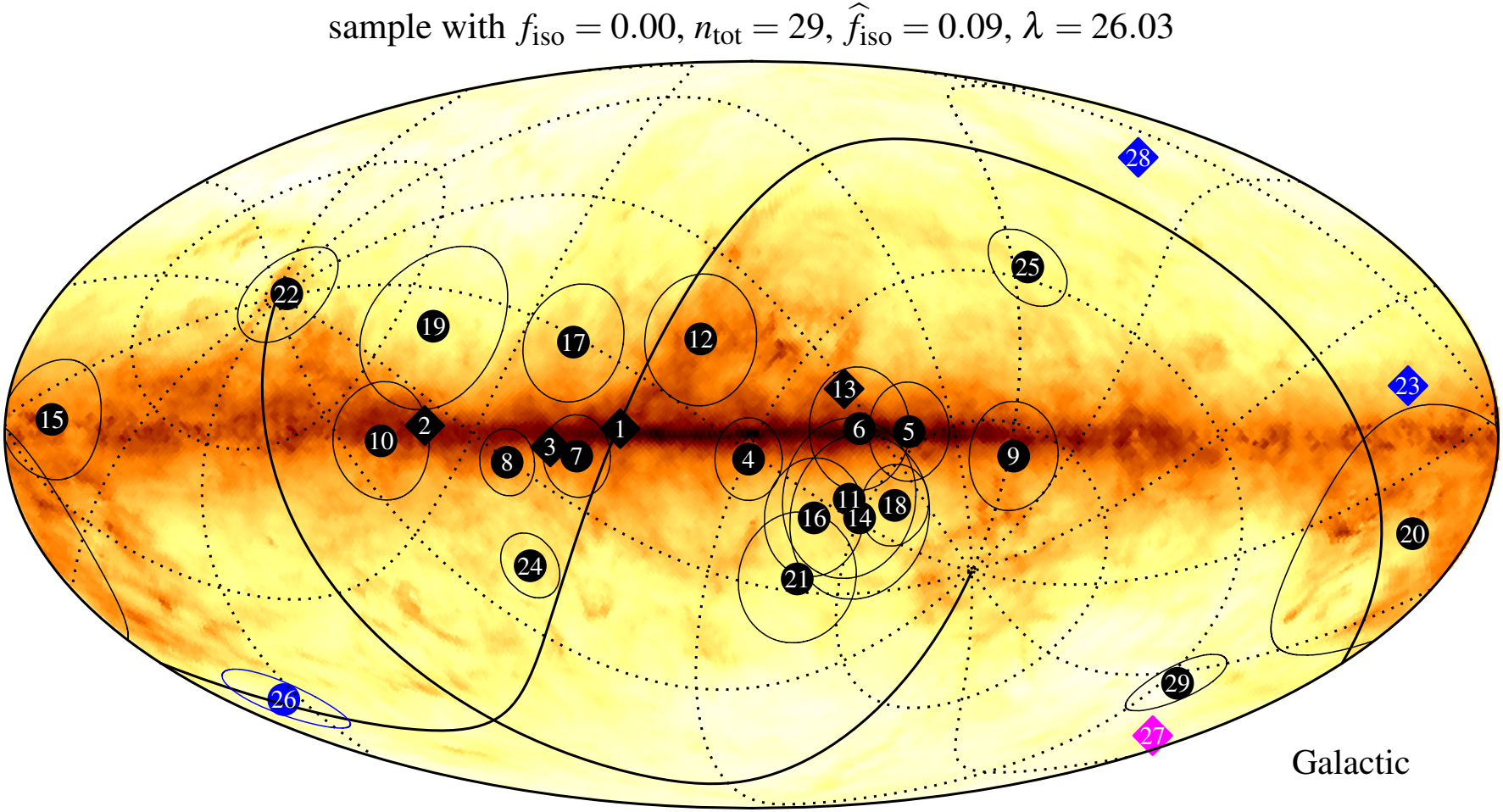

- Galactic diffuse emission template derived with GALPROP [Strong & Moskalenko'98]
- **simulated** map: $\diamond/\circ$: Galactic ν | $\diamond/\circ$: isotropic ν | $\diamond/\circ$: atmospheric ν | $\diamond/\circ$: atmospheric μ

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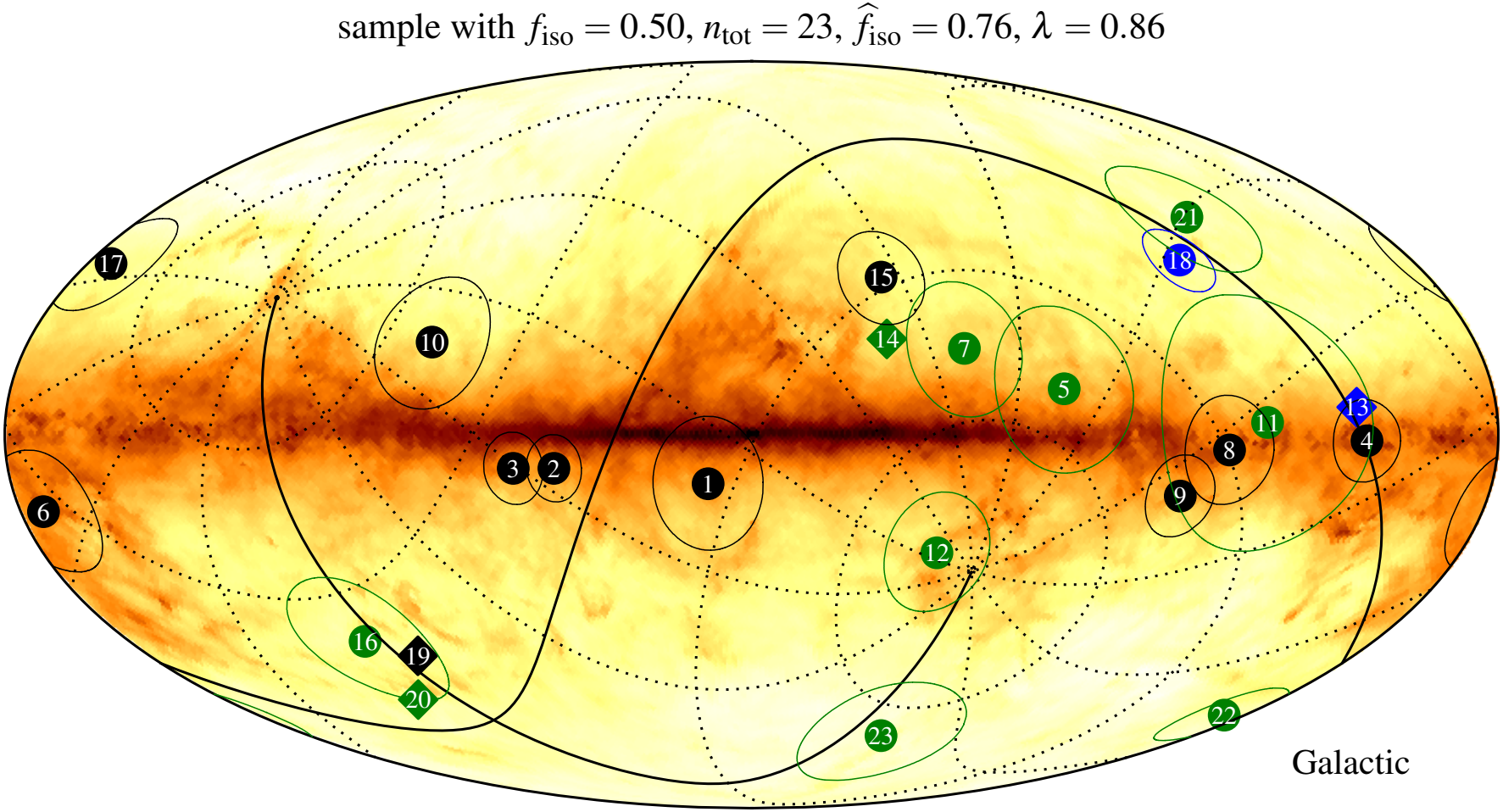

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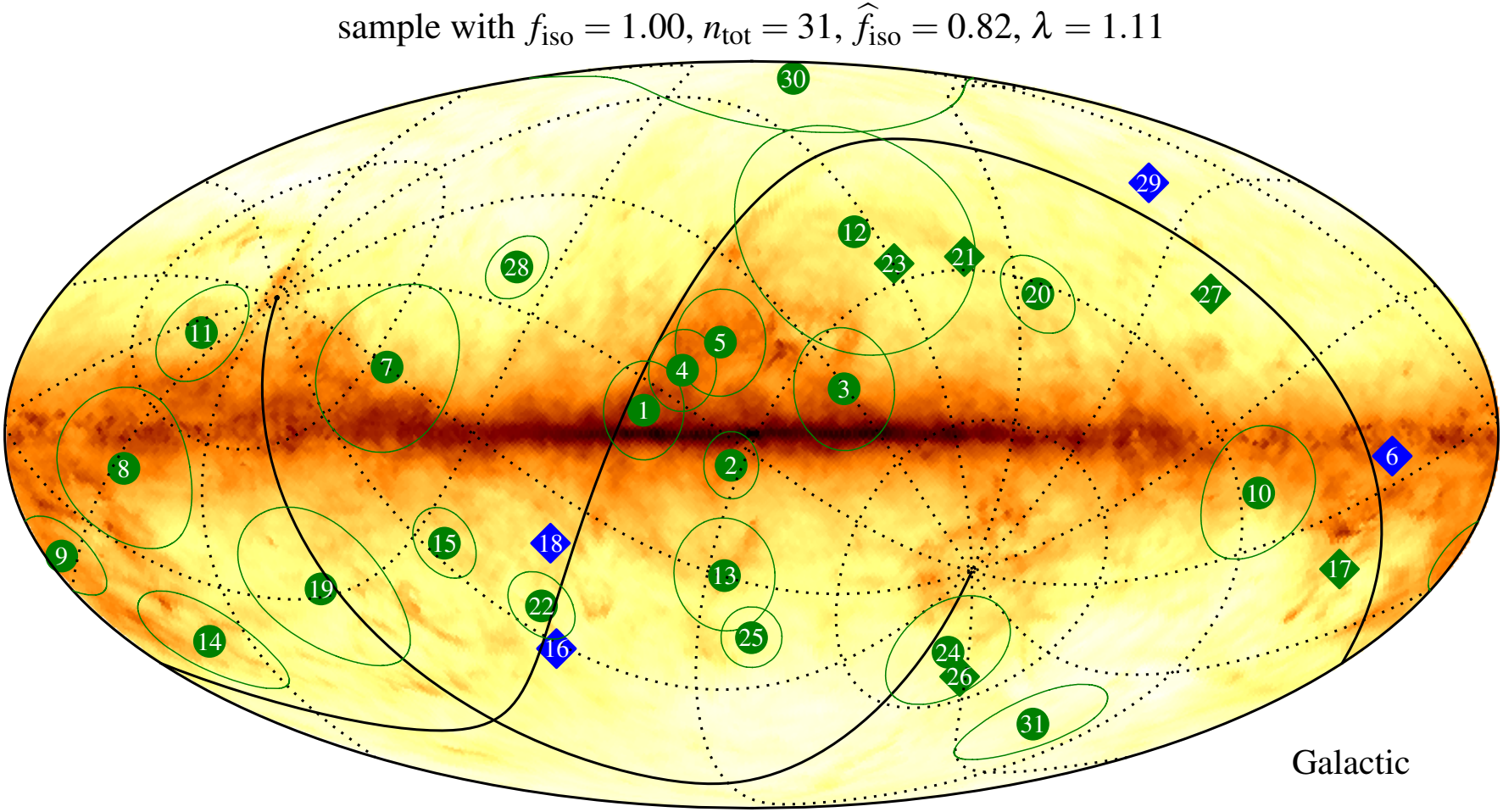

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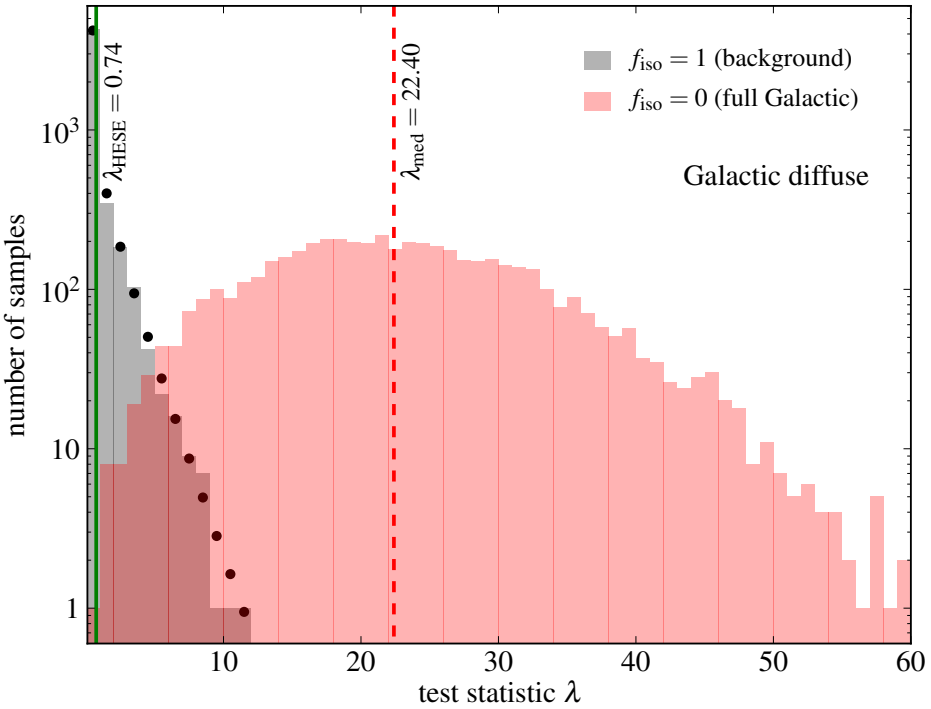
Anisotropy Test

- unbinned maximum LH test statistic:

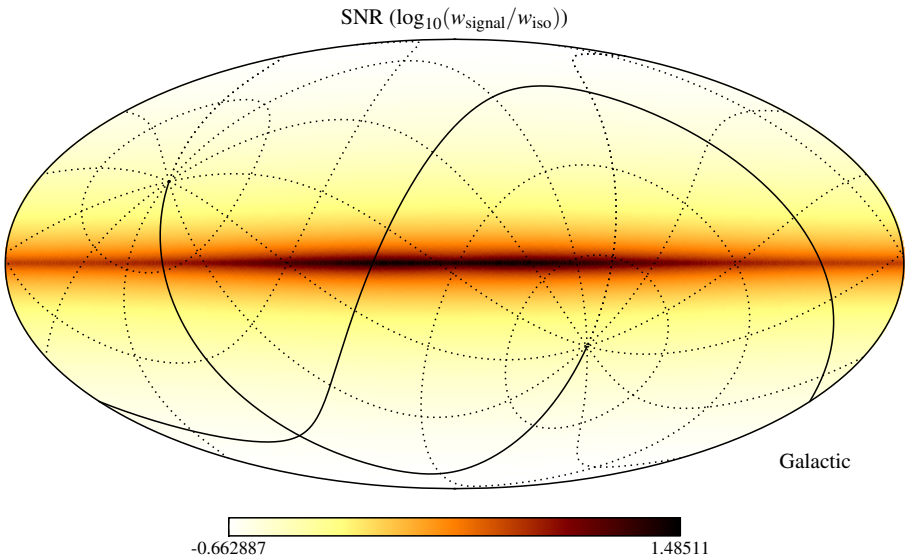
$$\lambda = 2 \ln \prod_{\text{event } j} \left[\frac{\mu_j^{\text{sig}}(\widehat{f}_{\text{iso}}) + \mu_j^{\text{bgr}}(\widehat{f}_{\text{iso}})}{\mu_j^{\text{bgr}}(1)} \right]$$

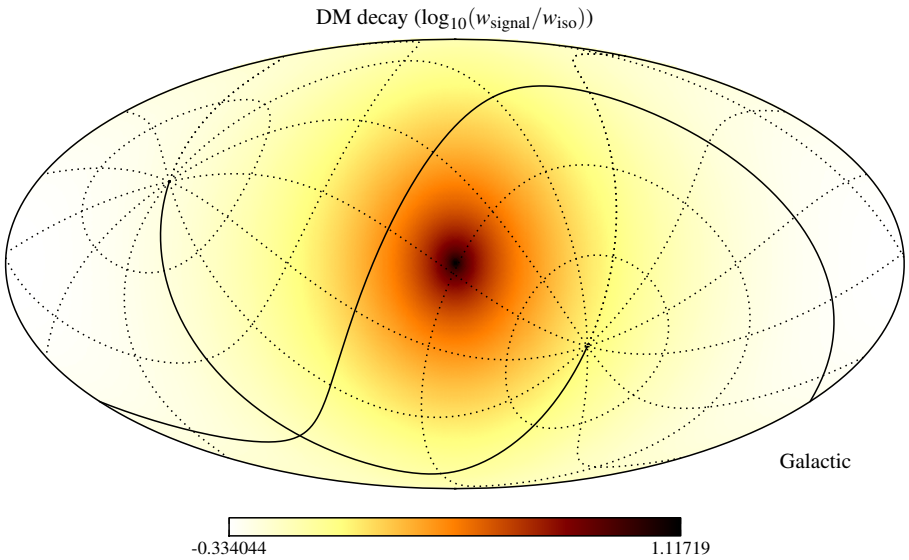
- $\widehat{f}_{\text{iso}}$: fraction of isotropic events at maximum LH
- 90% C.L. **sensitivity** :
  f_{iso} with 90% of samples $\lambda_{\text{MC}} > \lambda_{\text{med}}^{\text{bgr}}$
- 5σ C.L. **discovery potential** :
  f_{iso} with 50% of samples $\lambda_{\text{MC}} > \lambda_{5\sigma}^{\text{bgr}}$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

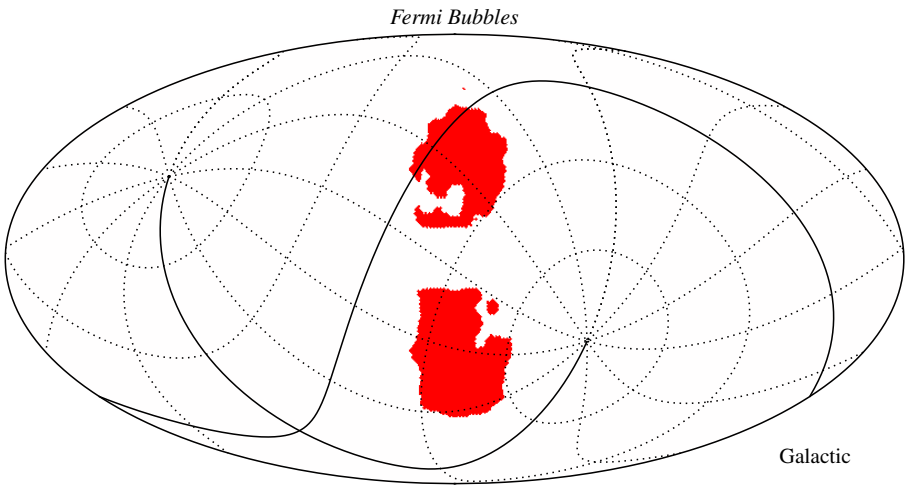


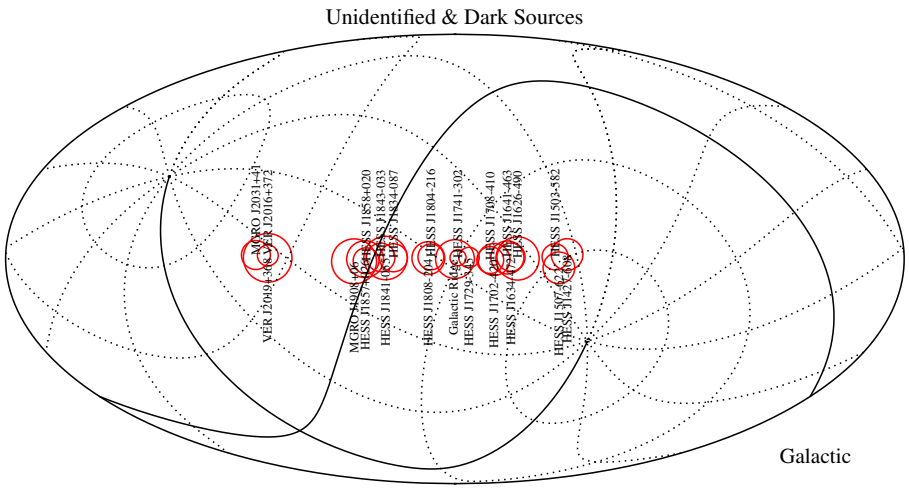
grey: background distribution ($f_{\text{iso}} = 1$)
red: maximal signal distribution ($f_{\text{iso}} = 0$)

Other Extended Galactic Emission

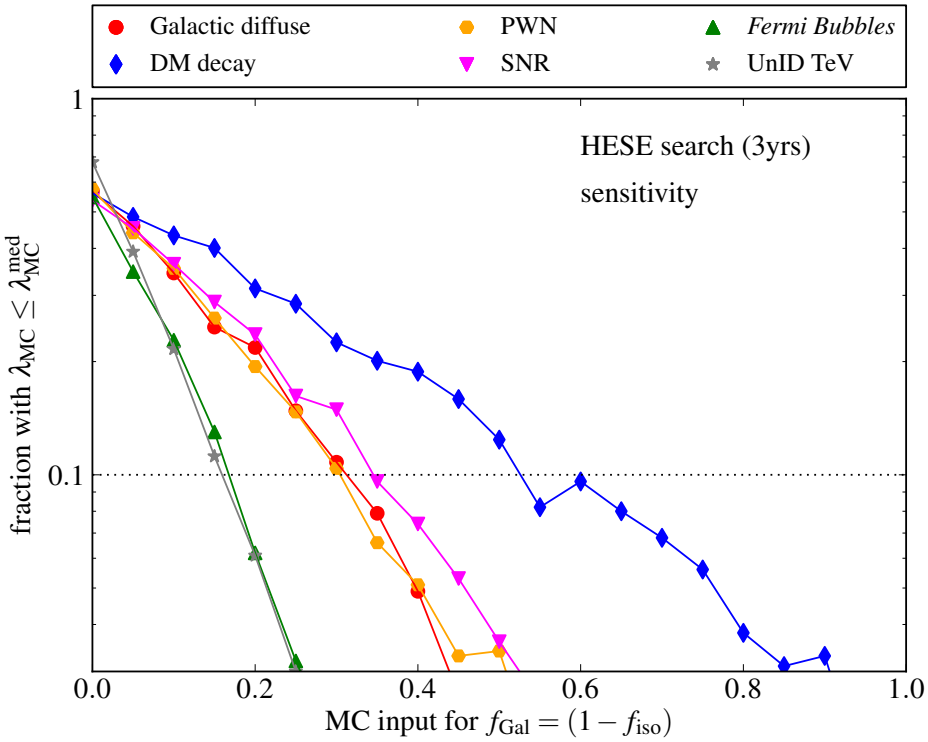


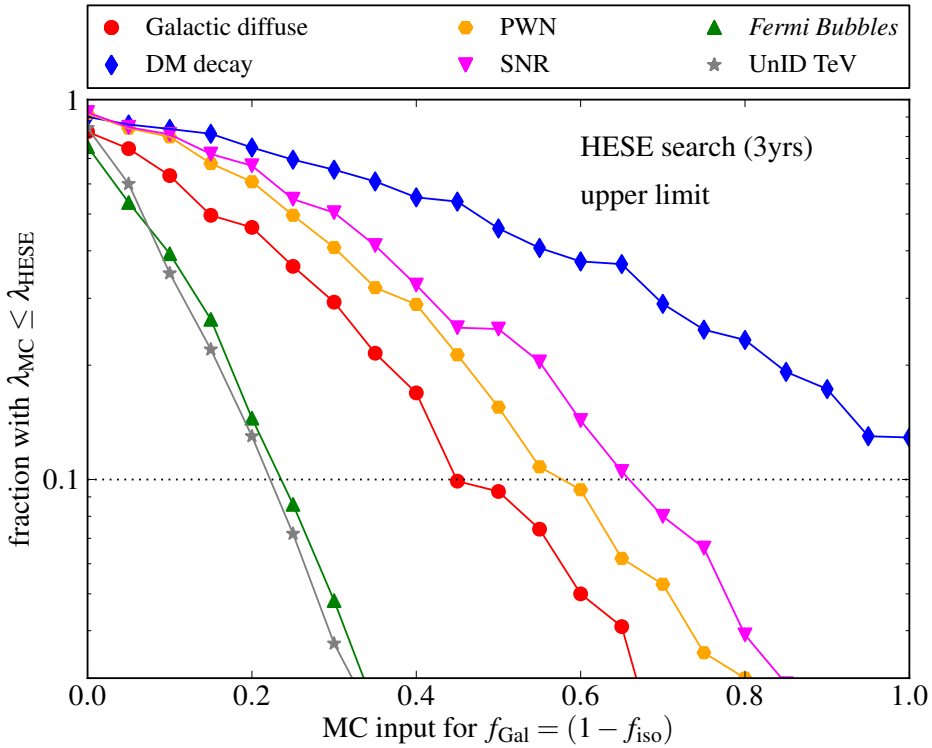






Sensitivity & Upper Limits





[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:
$\gamma + \gamma_{\rm CMB} \rightarrow e^+ + e^-$

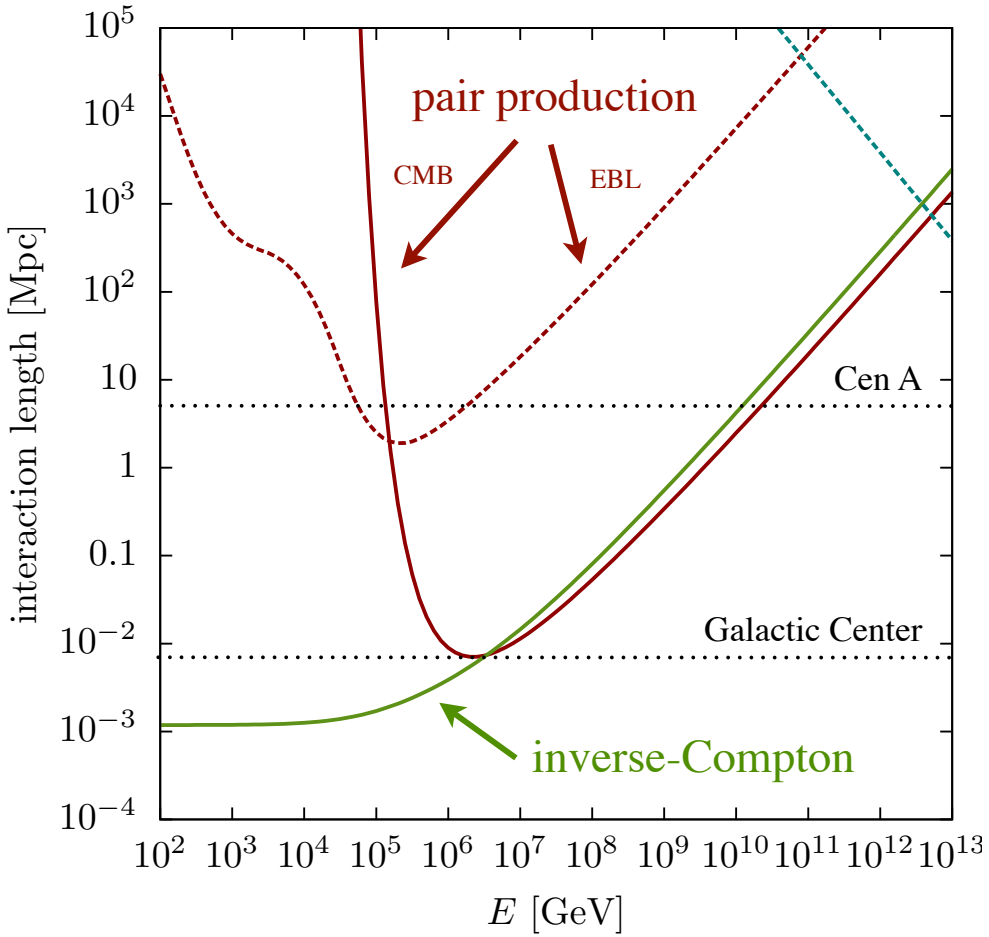
➜ PeV gamma-ray only observable locally ($\lesssim 10$kpc)

✔ 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]

➜ talk by Irene Tamborra



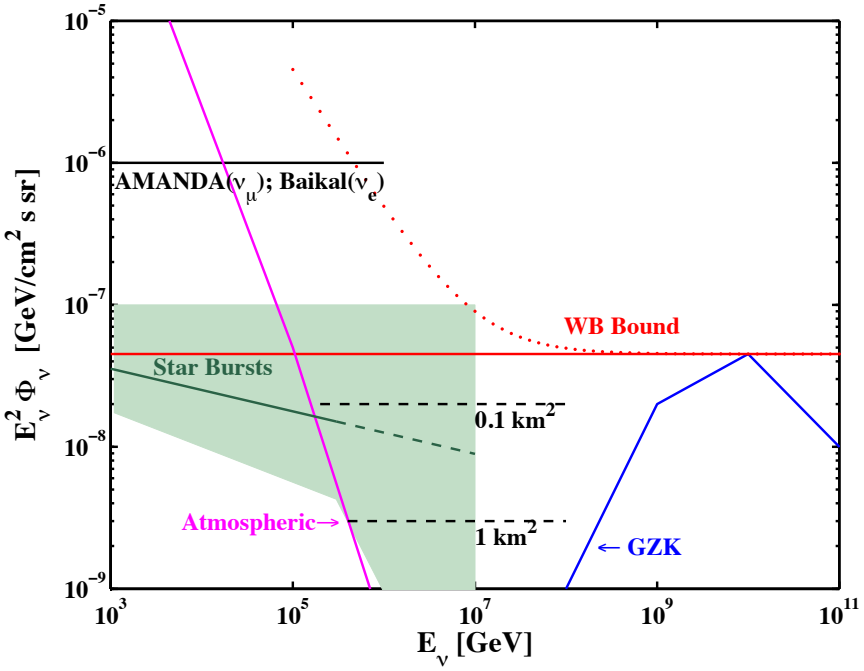
[MA'11]

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]
  - 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; Kadler *et al.*'16]
  - 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]
  - ...

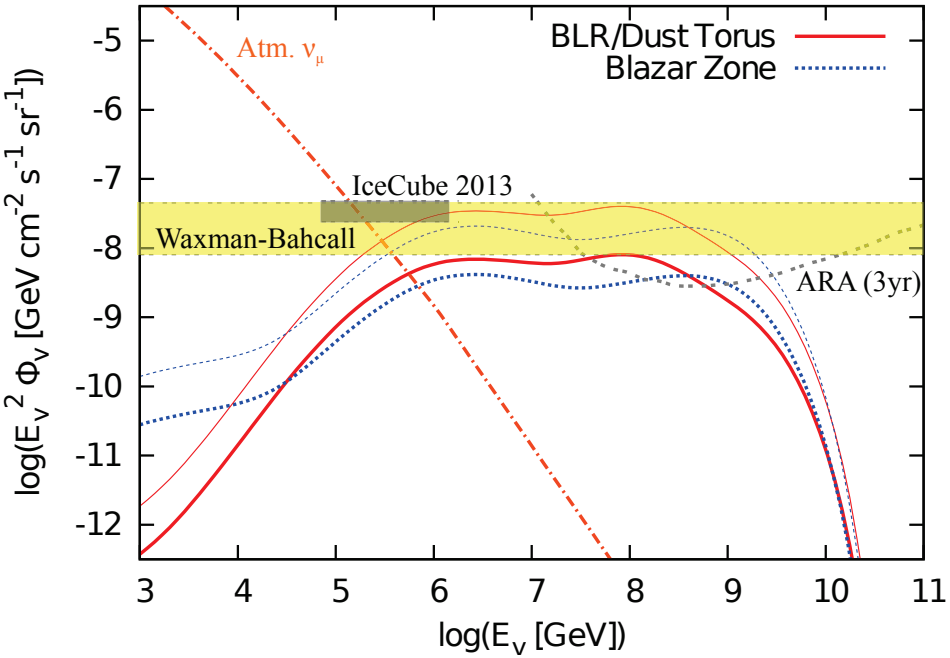
Extragalactic Emission Models: Two Examples

Starburst Galaxies ("pp" scenario)



[Loeb & Waxman'06]

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



[Mannheim'96; Halzen & Zas'97]

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

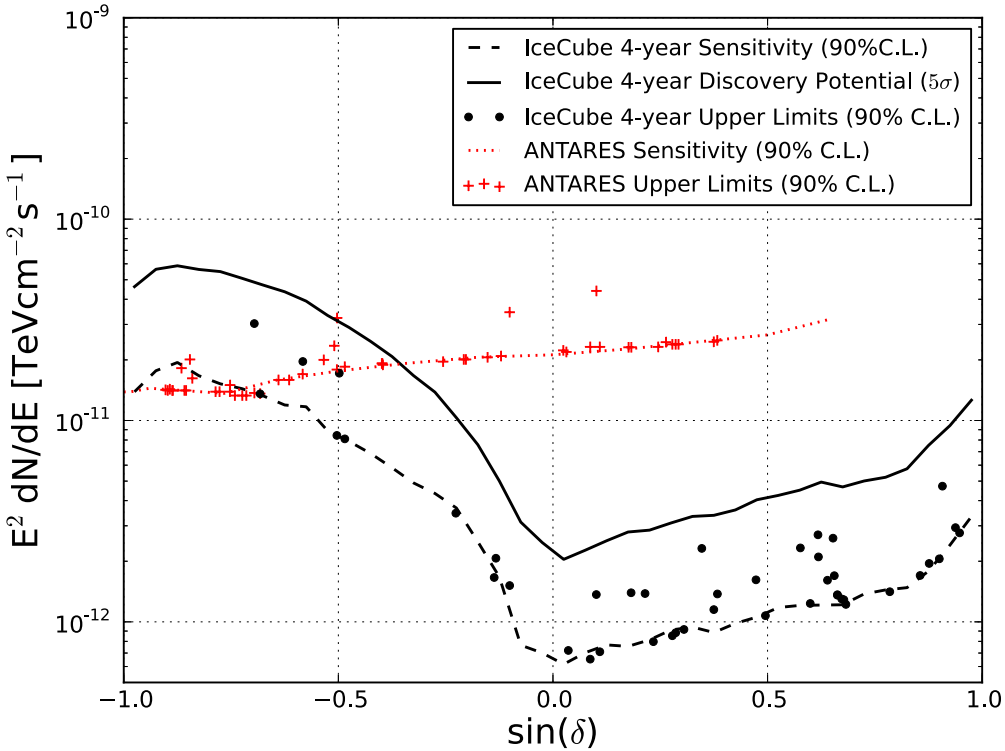
- CR-gas (pp) interactions: **mostly broken power-law** neutrino spectra.
- CR-photon ($p\gamma$) interactions: **strong spectral features** inherited from photon spectrum

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]

Neutrino Point-Source Limits

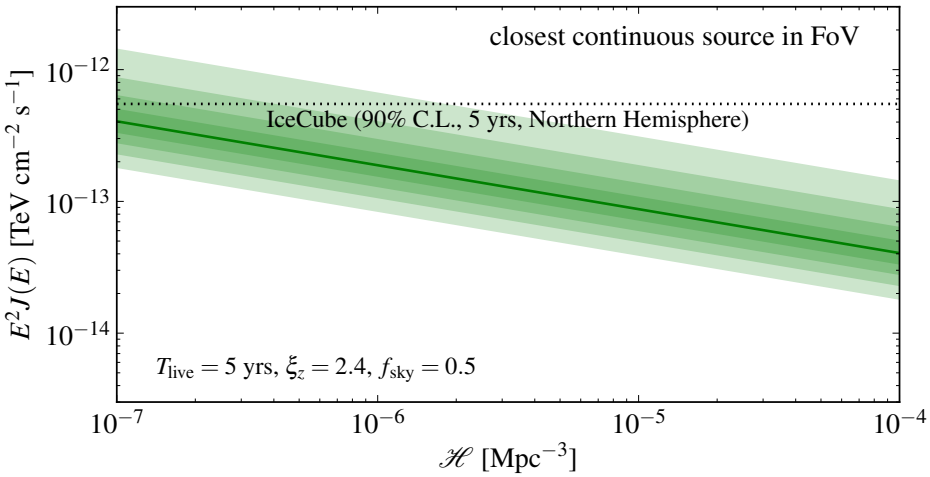
- Diffuse neutrino flux normalizes the contribution of individual sources
- dependence on local source density $\mathcal{H}$ (rate $\dot{\mathcal{H}}$) and redshift evolution ξ_z

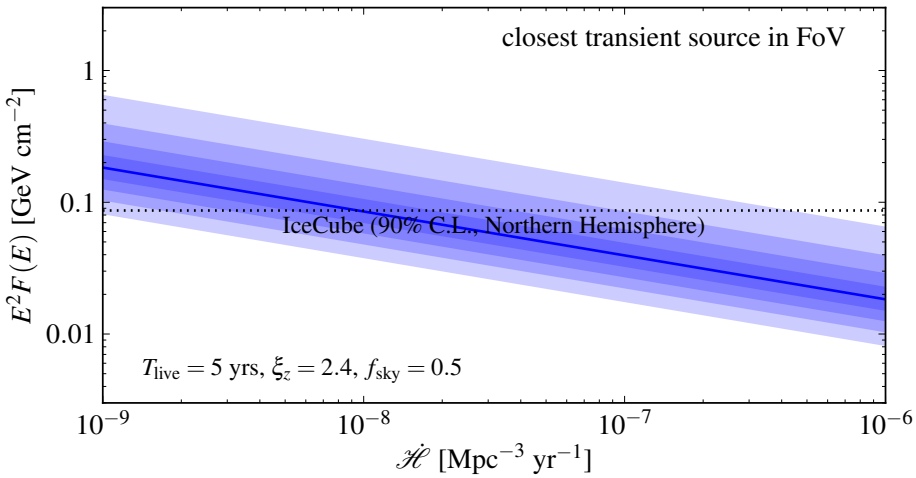
➜ PS observation requires rare sources

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

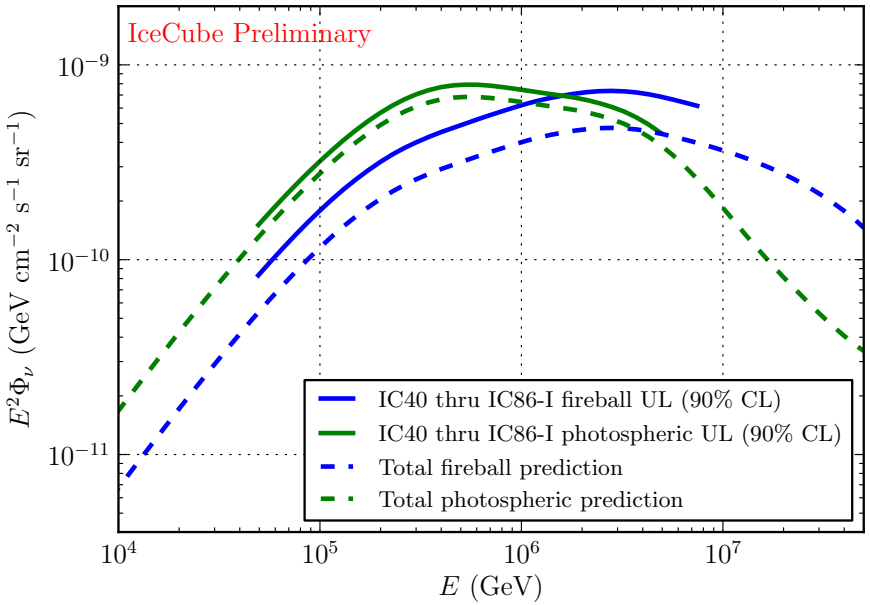




[MA&Halzen'14]

IceCube Stacking Searches

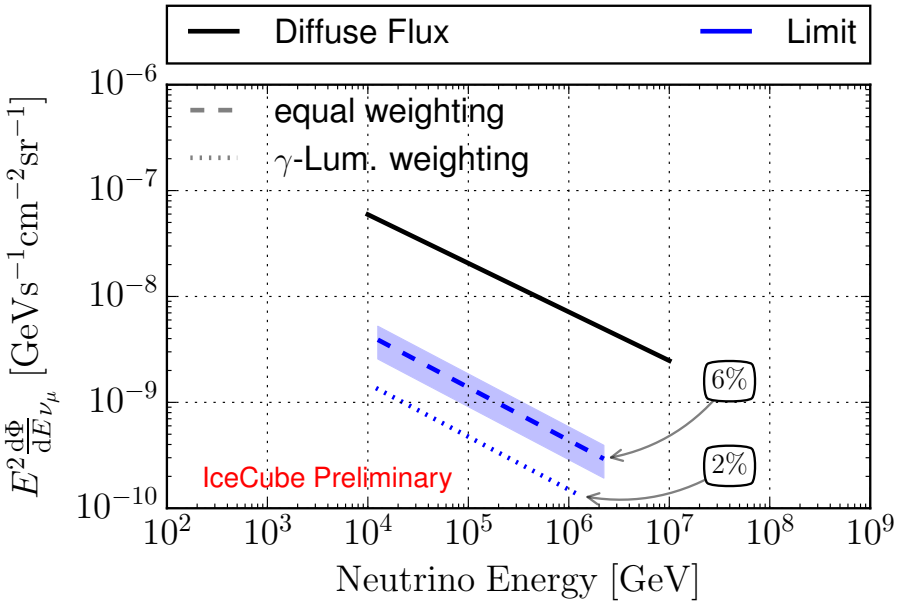
GRB Stacking



[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

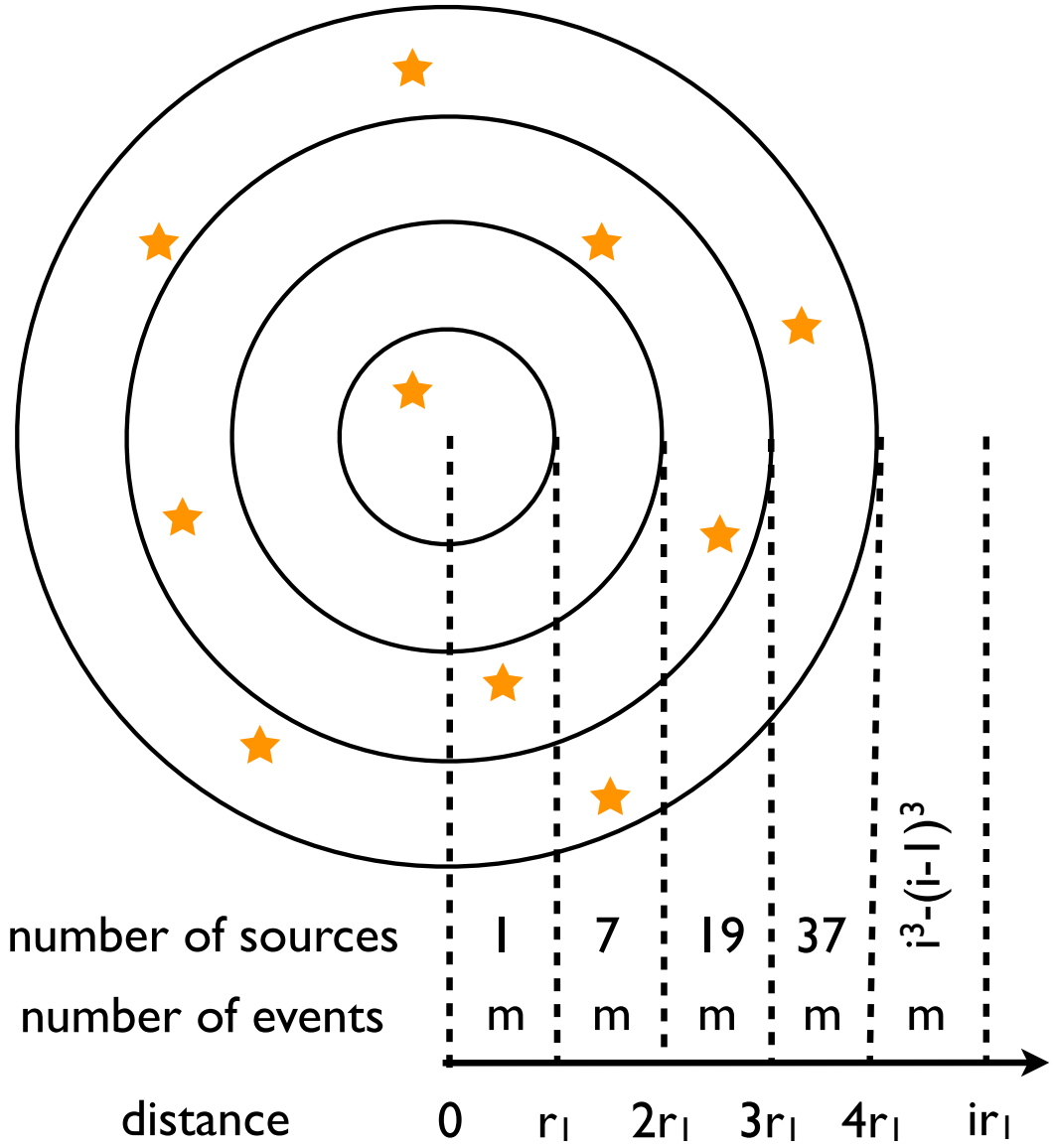
Blazar Stacking



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

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

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?

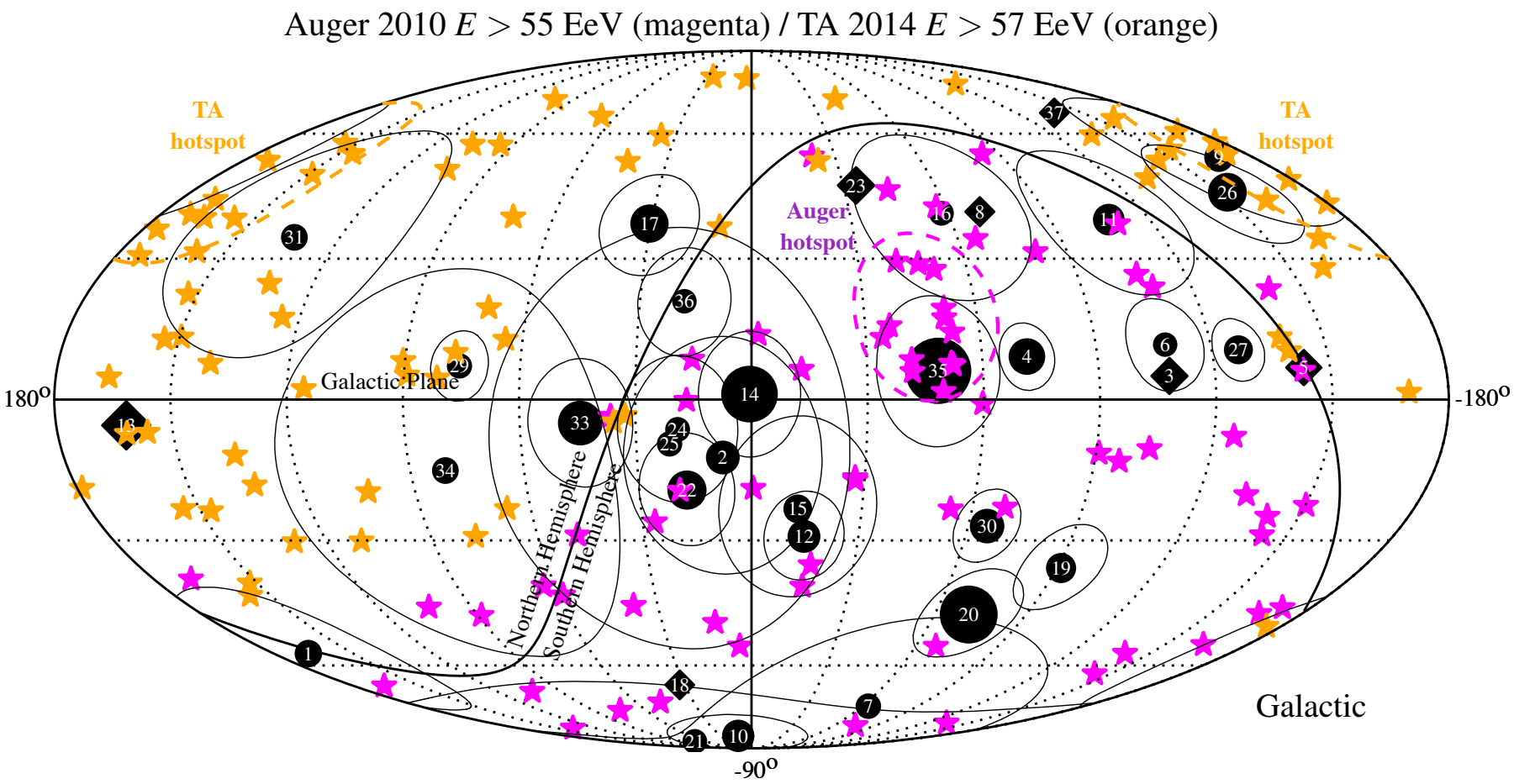
➜ two-zone models: acceleration + CR "calorimeter"?

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

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

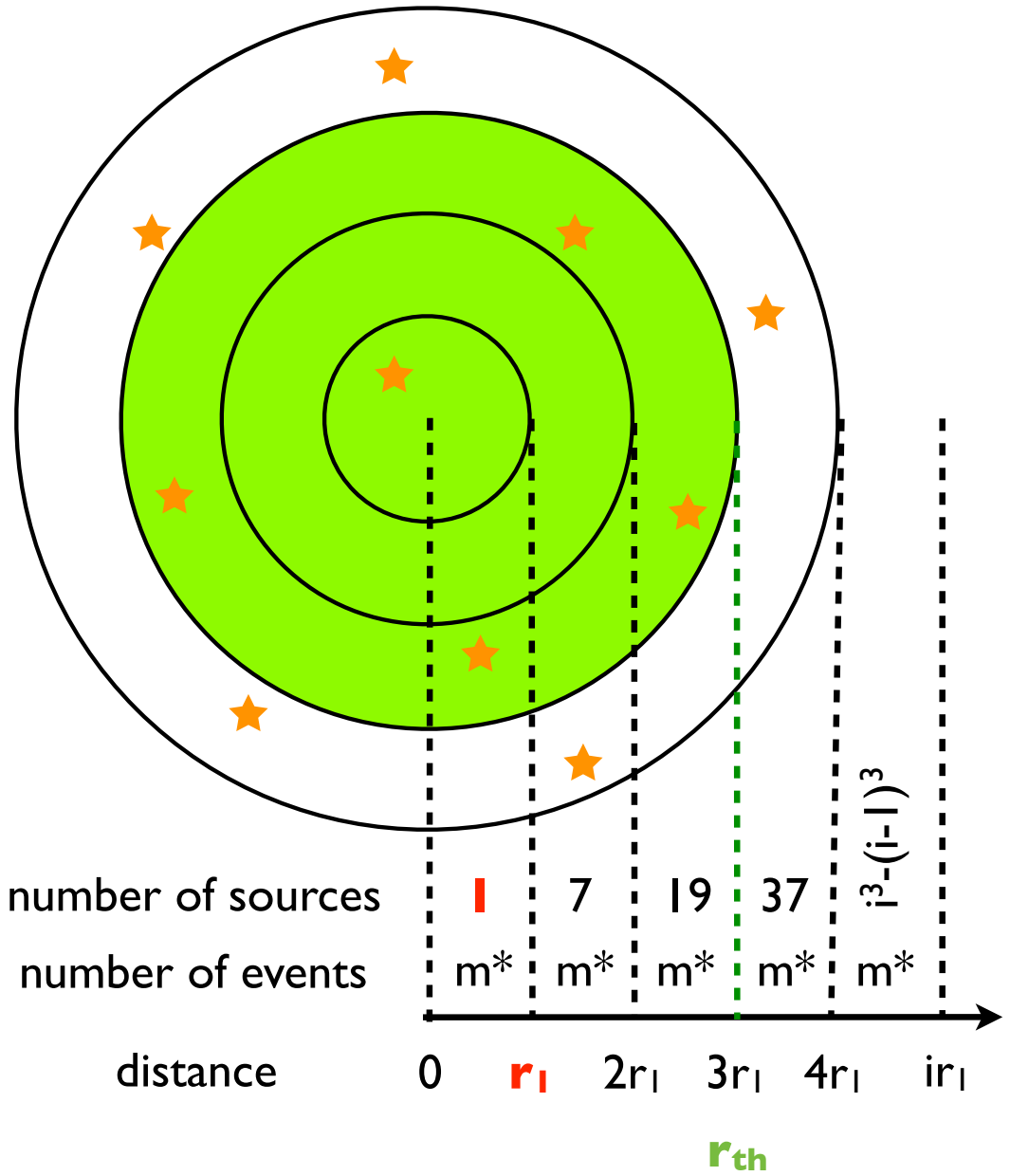
[Parizot'05; Aublin & Parizot'06; Katz, Waxman, Thompson & Loeb'13]

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

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,. . .

Summary & Outlook

- Neutrinos are **unique cosmic probes** for small-scale anisotropy and high-z tomography in the 10TeV-10EeV energy range.

✘ However, low statistics and poor angular reconstruction.

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

✔ Dedicated IceCube analyses of extended Galactic emission underway.

- **Similar diffuse energy densities** of UHE CRs, γ-rays and neutrinos might indicate a common extragalactic origin.

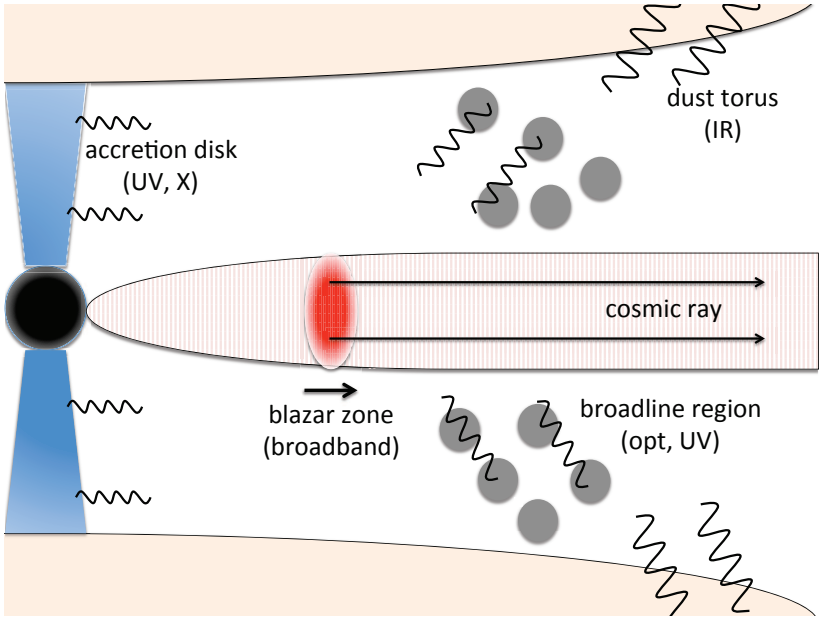
➜ **Multi-messenger cross-correlations** are the most promising scenario for point-source identification, in particular for transient sources.

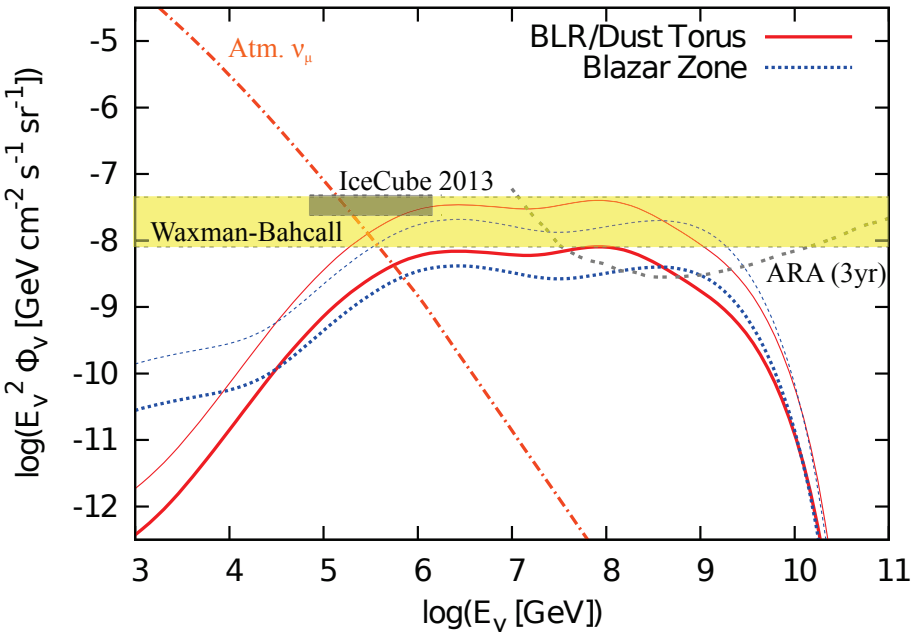
➜ more on statistical methods in talks by Kimberly Emig & Ke Fang

Appendix

AGN jets

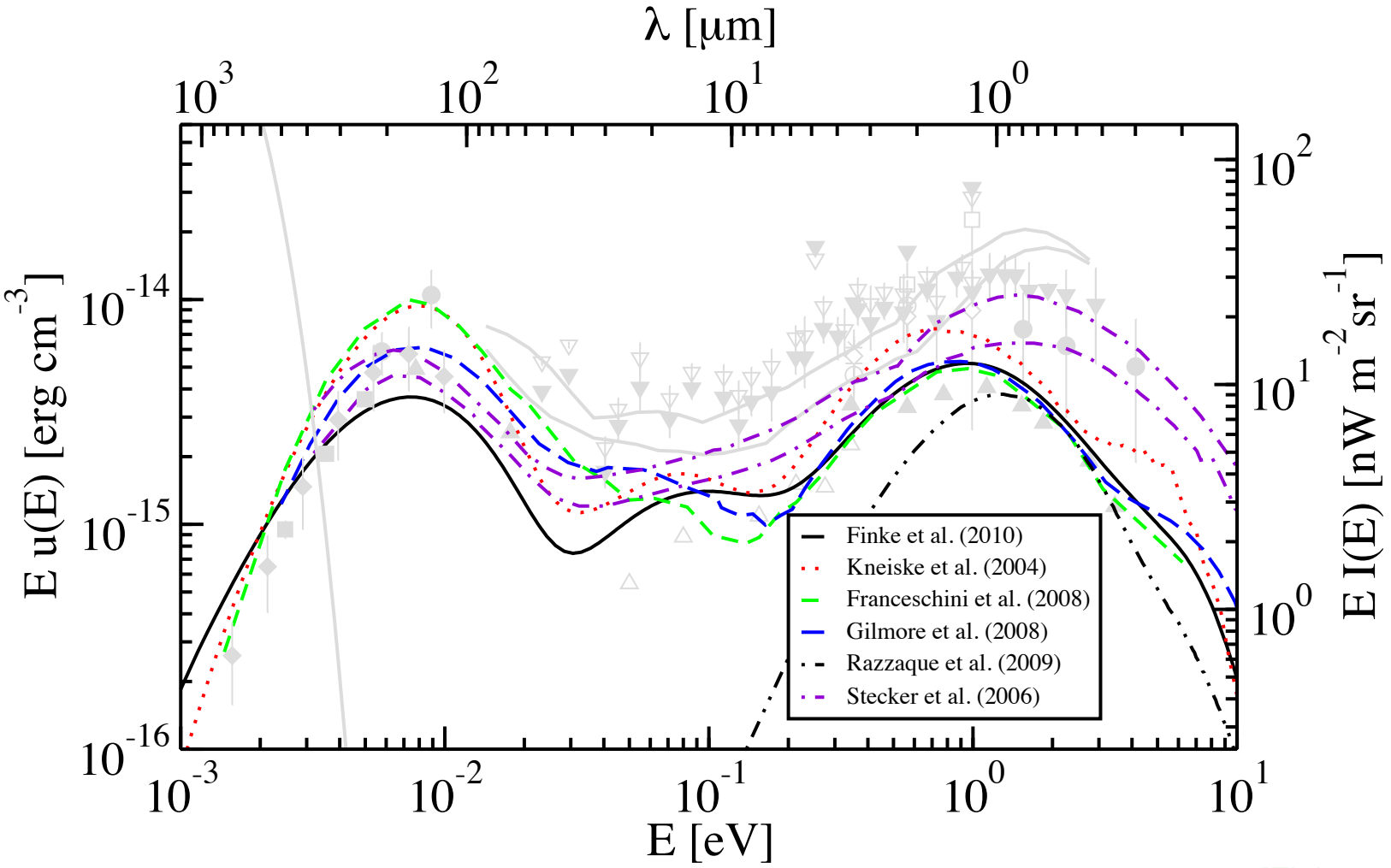
- neutrino from $p\gamma$ interactions in AGN jets [Mannheim'96; Halzen & Zas'97]
- complex spectra due to various photon backgrounds
- typically, deficit of sub-PeV and excess of EeV neutrinos





[Murase, Inoue & Dermer 1403.4089]

Extra-galactic background light (EBL)



[Finke *et al.* '10]

optical-UV background gives PeV neutrino peak

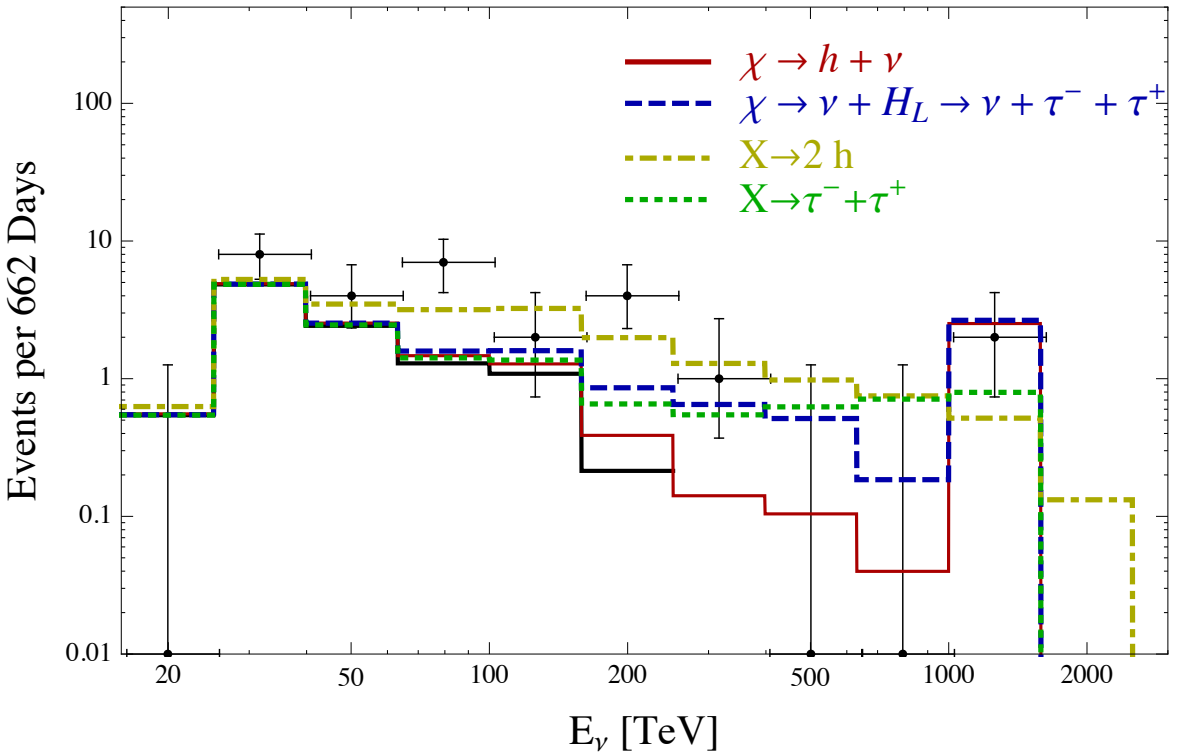
DM decay

- heavy (>PeV) DM decay?

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

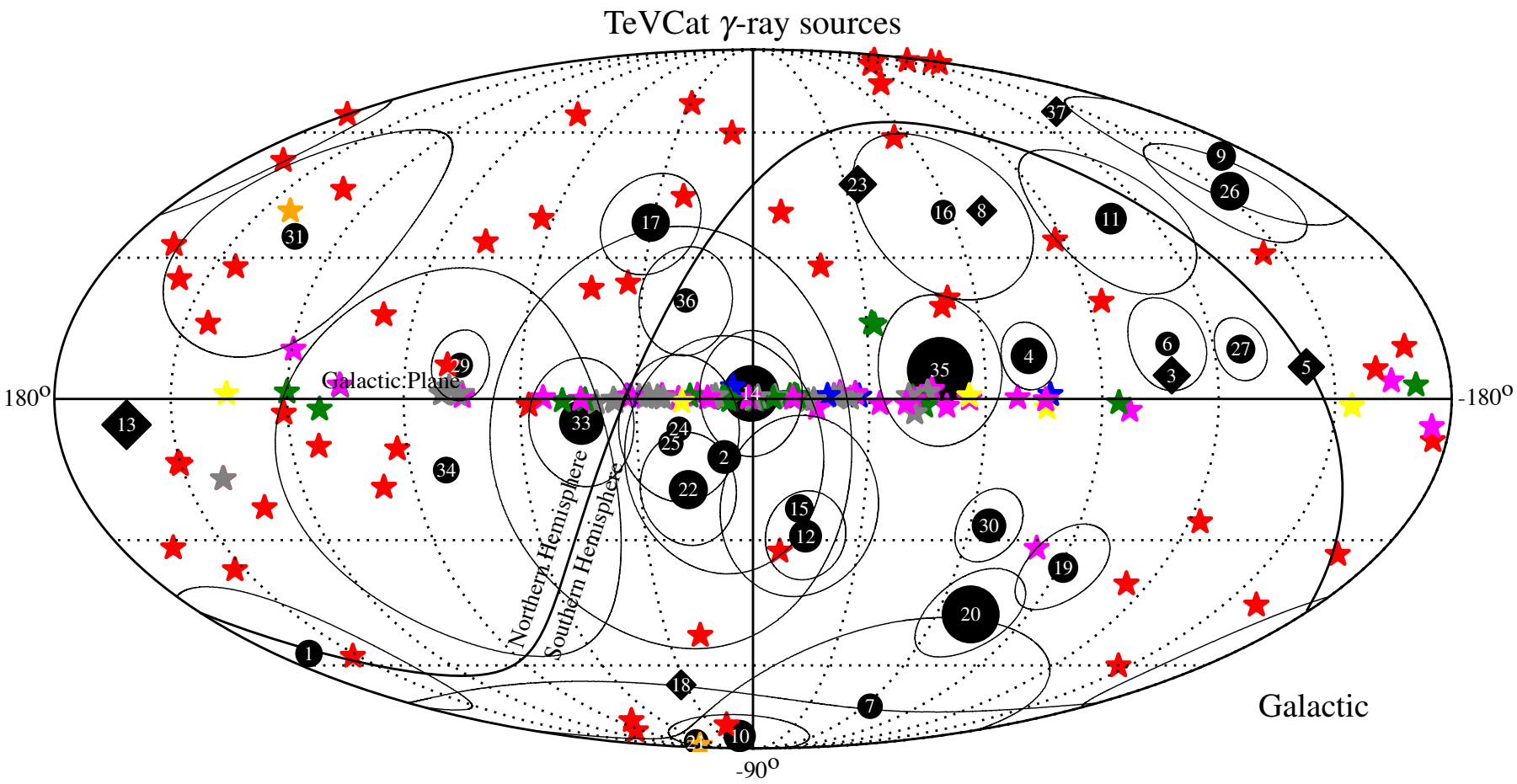
- **initially** motivated by PeV "line-feature", but continuum spectrum with/without line spectrum equally possible

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



[Bai, Lu & Salvado'13]

TeV Associations?



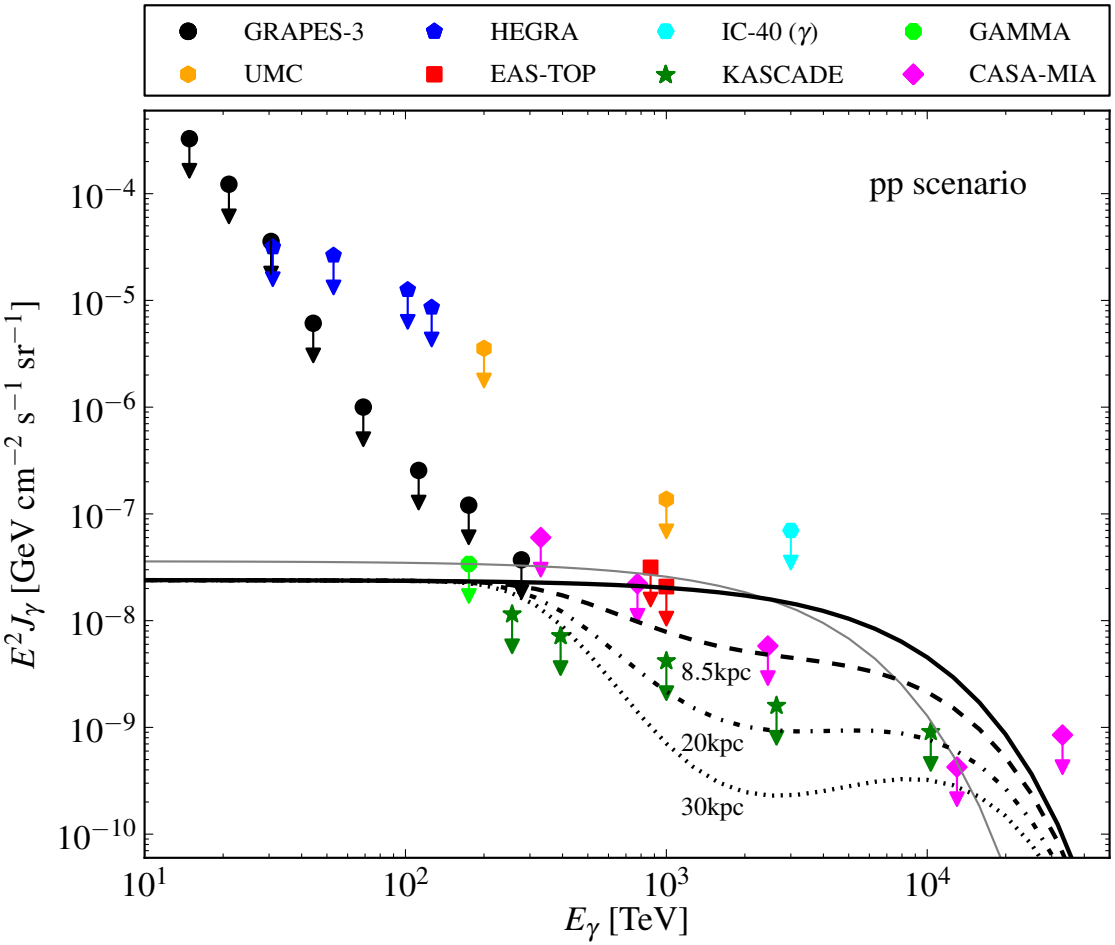
LBL, IBL, LBL, FRI, FSRQ Globular Cluster, Star Forming Region, Massive Star Cluster

Binary PWN Shell, SNR/Molec.Cloud, Composite SNR Starburst Others [TeVCat'14]

PeV γ-ray Associations?

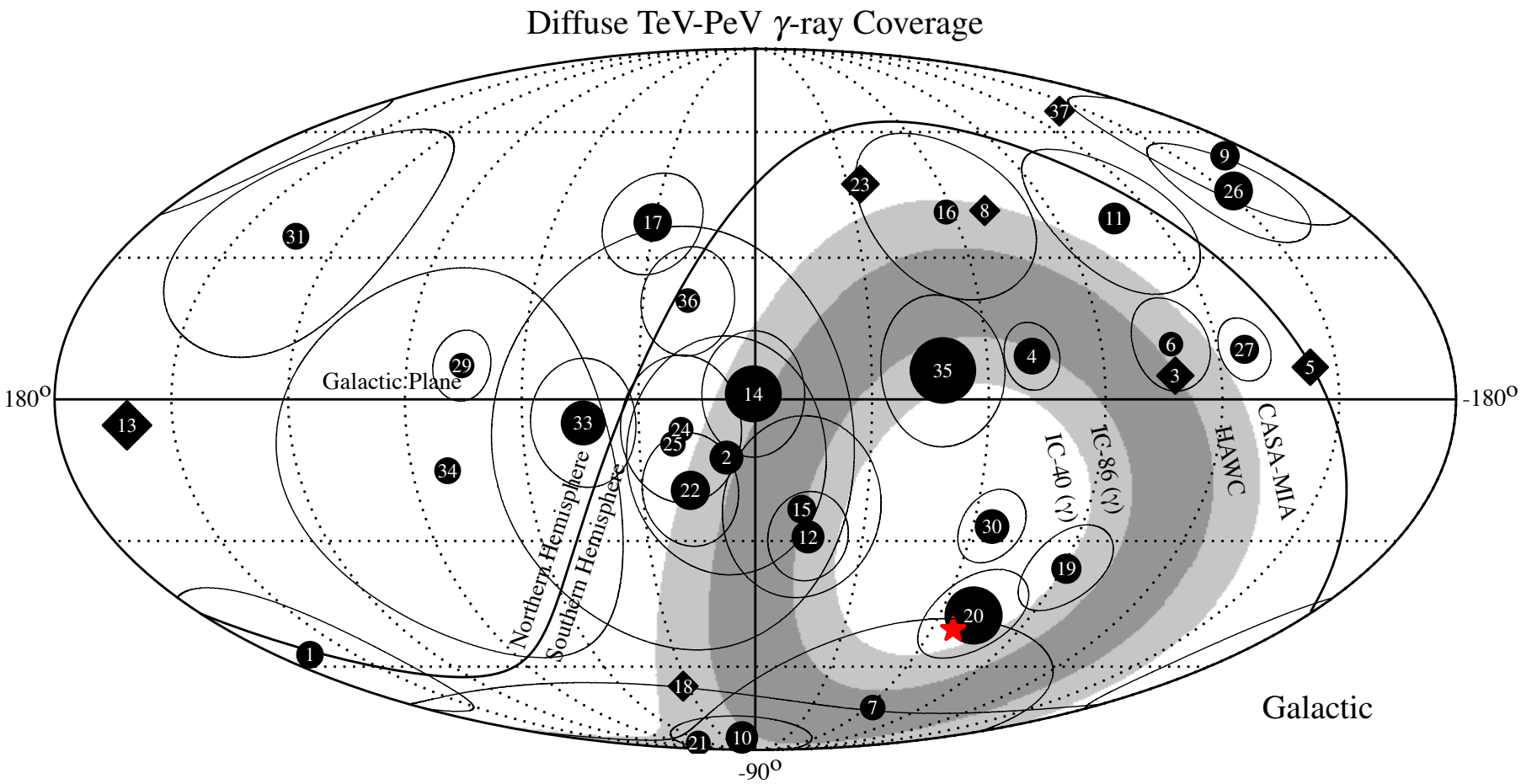
- ➜ PeV γ-rays from $\pi^0 \to 2\gamma$
- ✘ strong absorption via $\gamma\gamma_{\rm BG} \to e^+e^-$
  - effect strongest for CMB in PeV range: $\lambda_{\gamma\gamma} \simeq 10$ kpc
  - plot indicate absorption from 8.5 kpc (GC) to 30 kpc
- ➜ strong constraints on isotropic diffuse Galactic emission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

Extragalactic Gamma-Rays

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

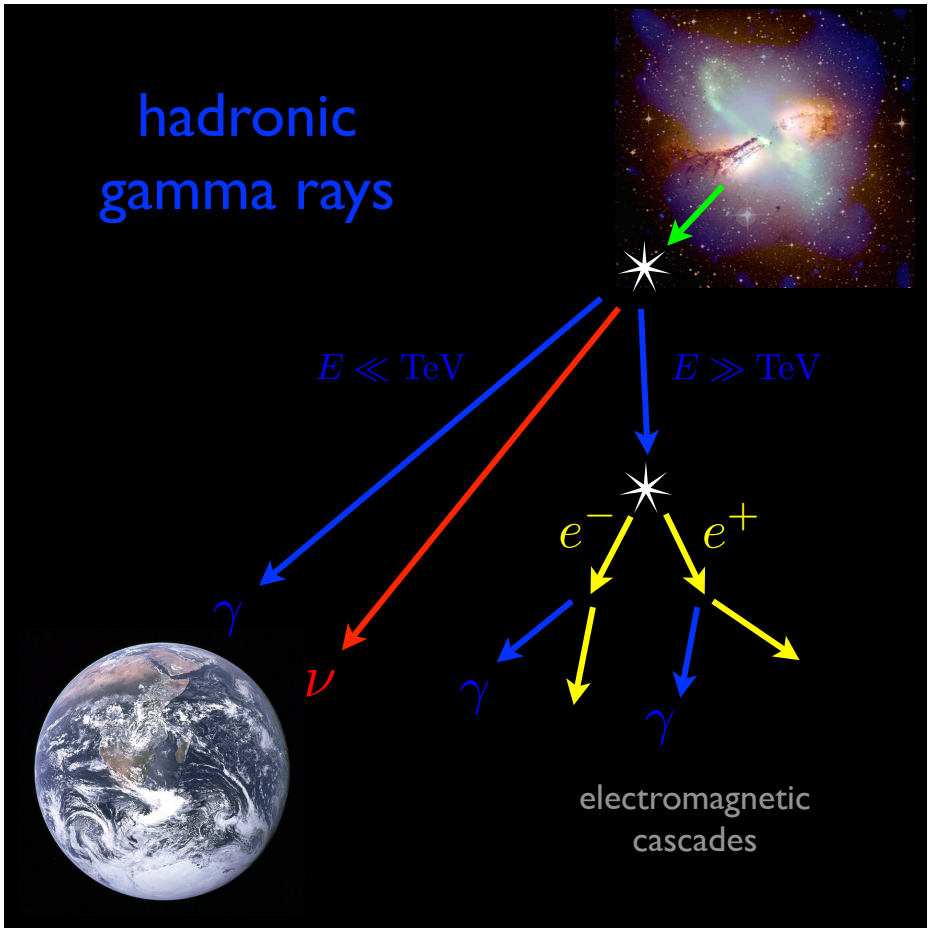
$$\pi^0 \rightarrow \gamma + \gamma$$

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

➜ 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

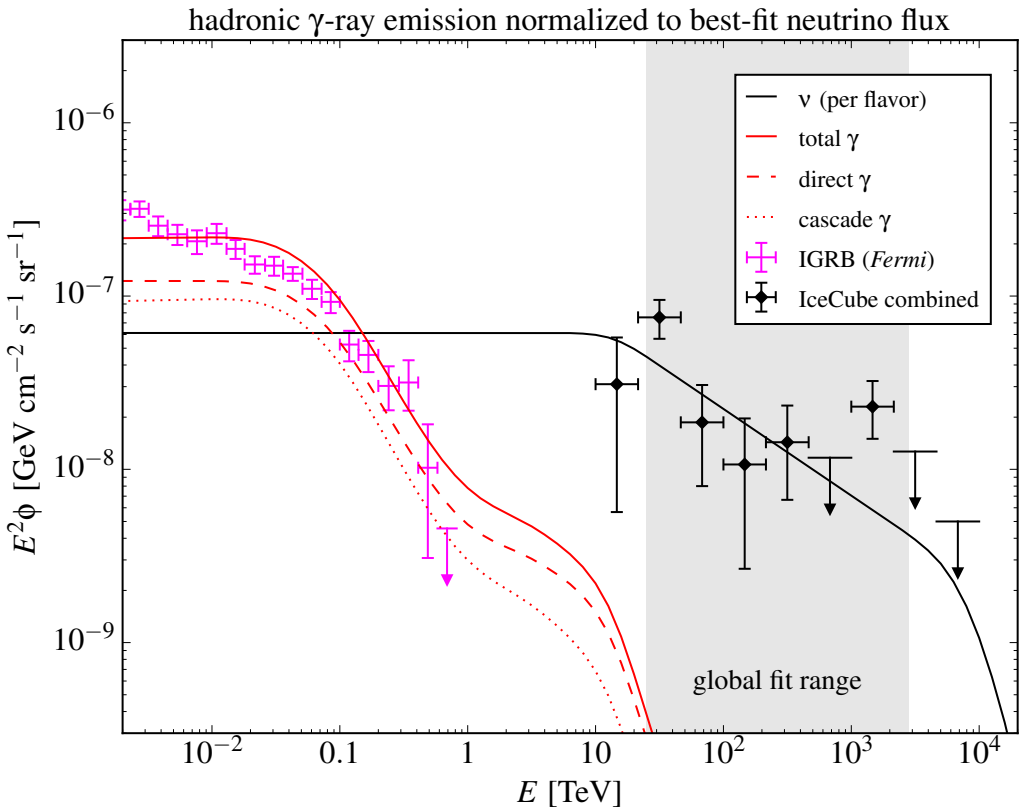
[Murase, MA & Lacki'13; Chang & Wang'14]

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

✘ Combined IceCube analysis:

$\Gamma \simeq 2.4 - 2.6$

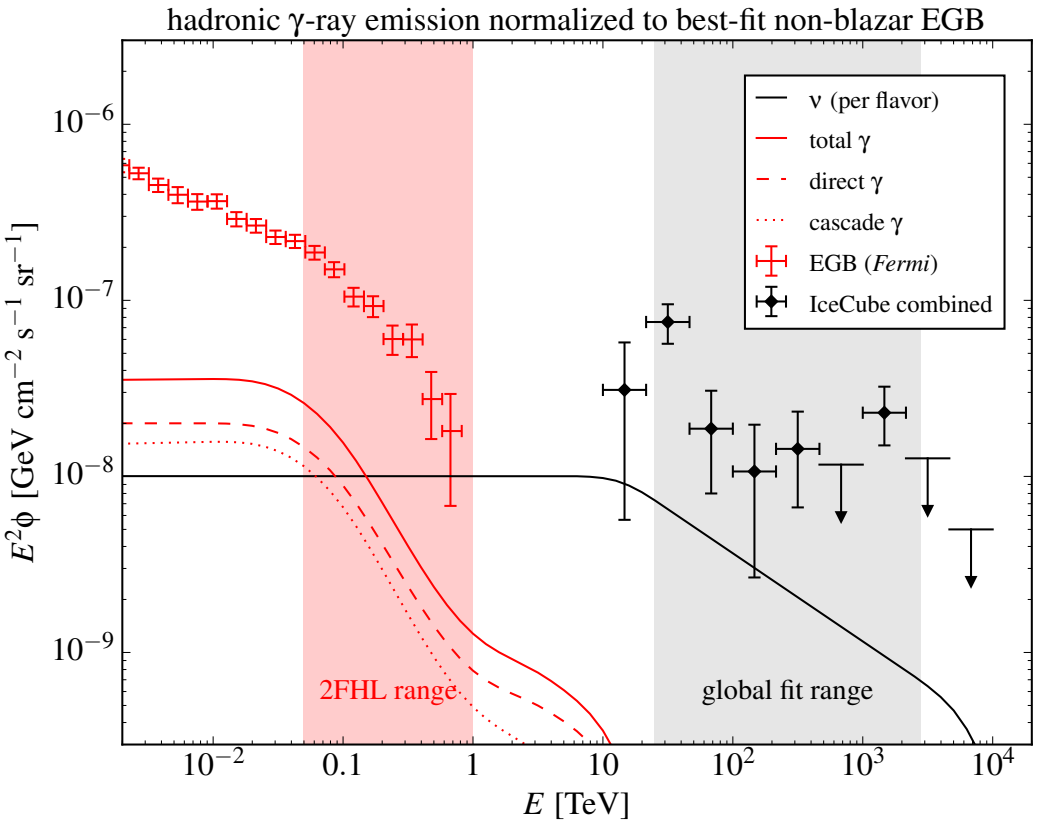
[IceCube'15]

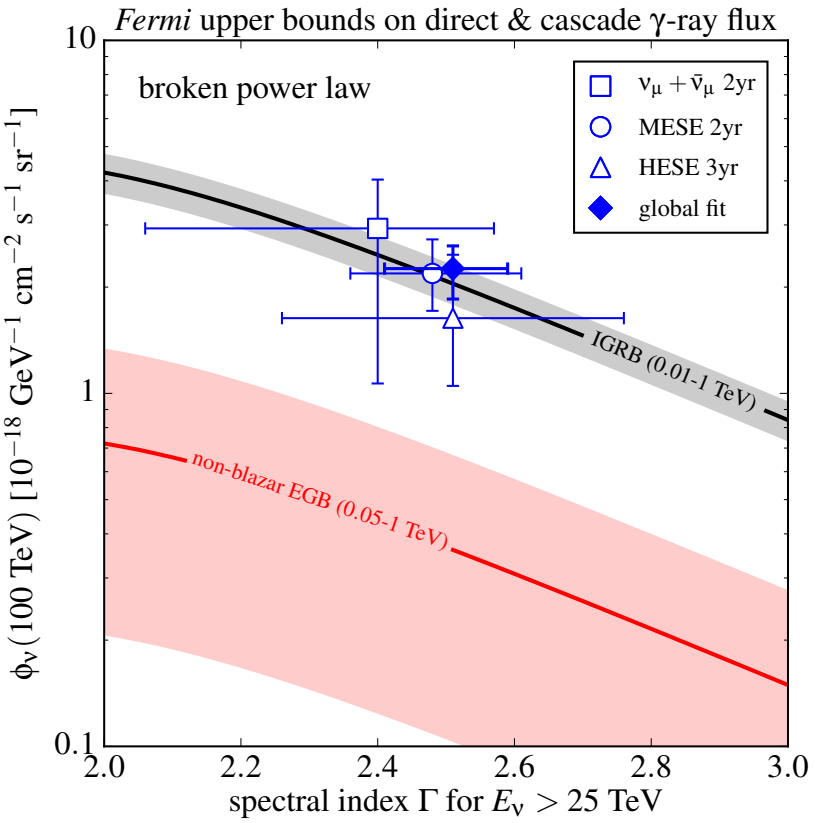


[Murase, MA & Lacki'14; Tamborra, Ando & Murase'14]

[Ando, Tamborra & Zandanel'15]

Non-Blazar Limits on Gamma-Ray Background





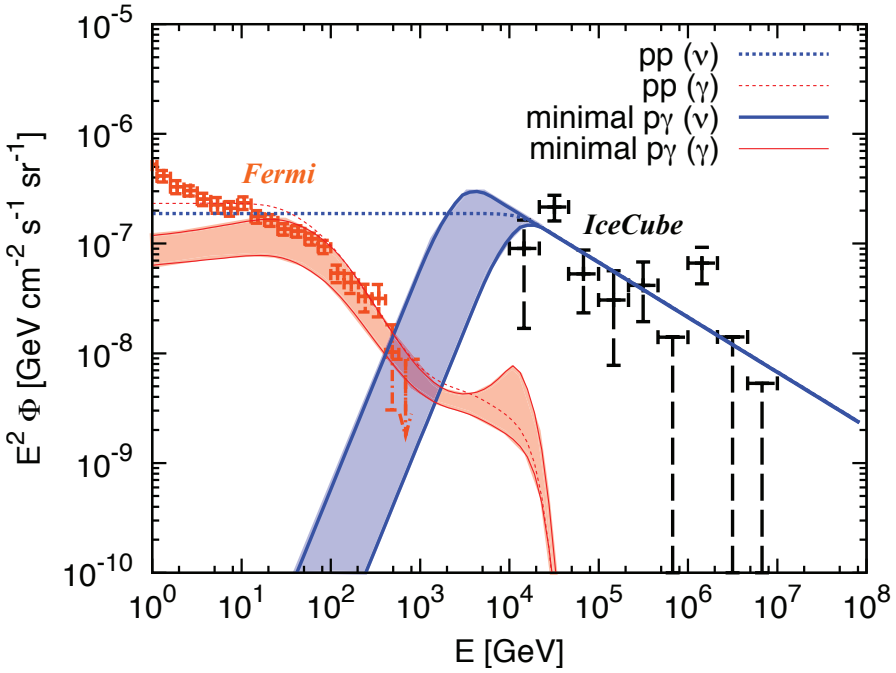
[Bechtol, MA, Ajello, Di Mauro & Vandenbroucke]

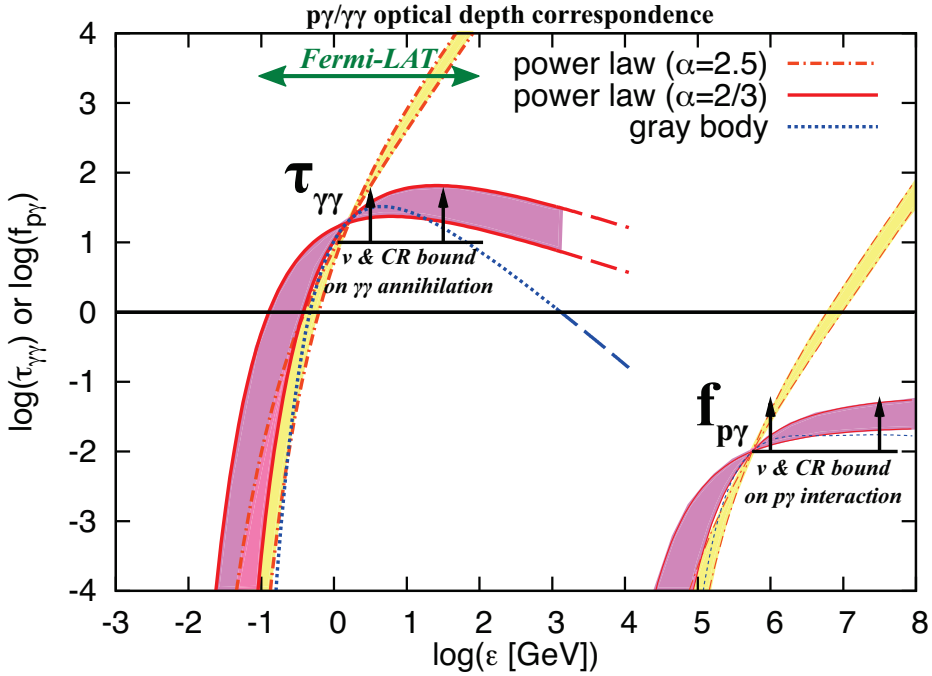
- Total γ-ray background above 50 TeV dominated by blazars ($\sim$ 86%) [Fermi'15]
- ✘ **strong tension** with IceCube observation

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?

Ultra-High Energy Cosmic Rays

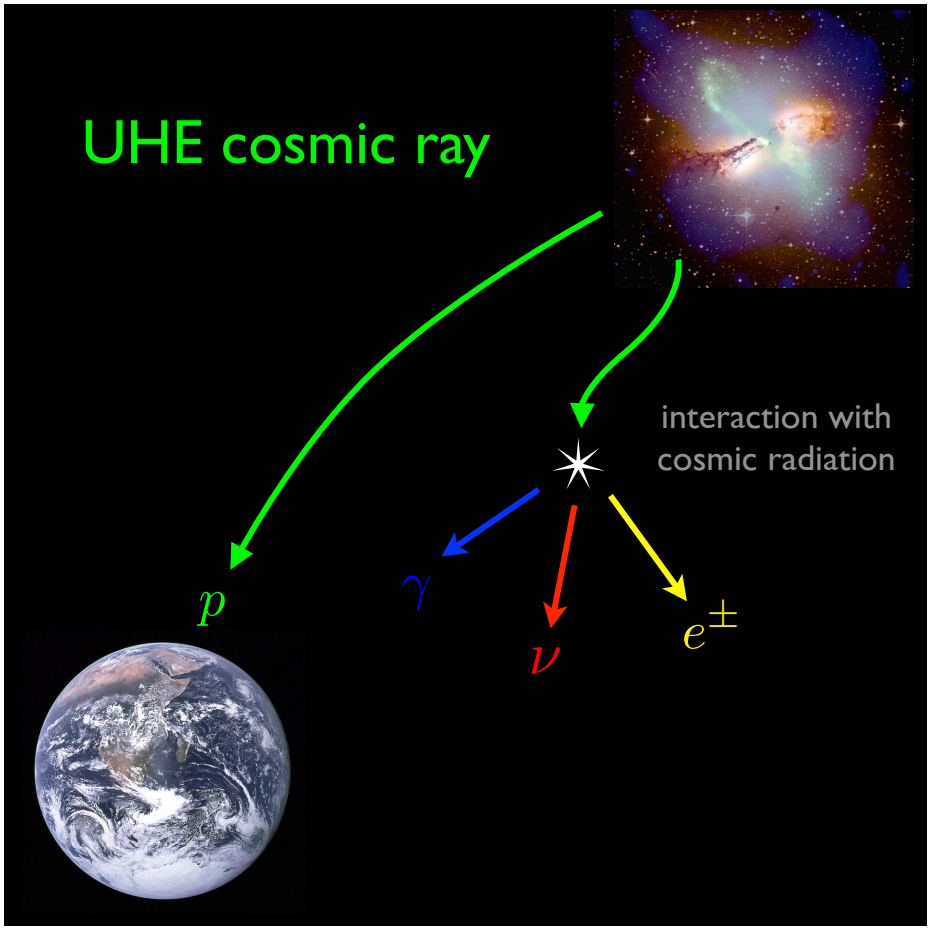
- particle confinement during acceleration requires: [Hillas'84]

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

✘ *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)**

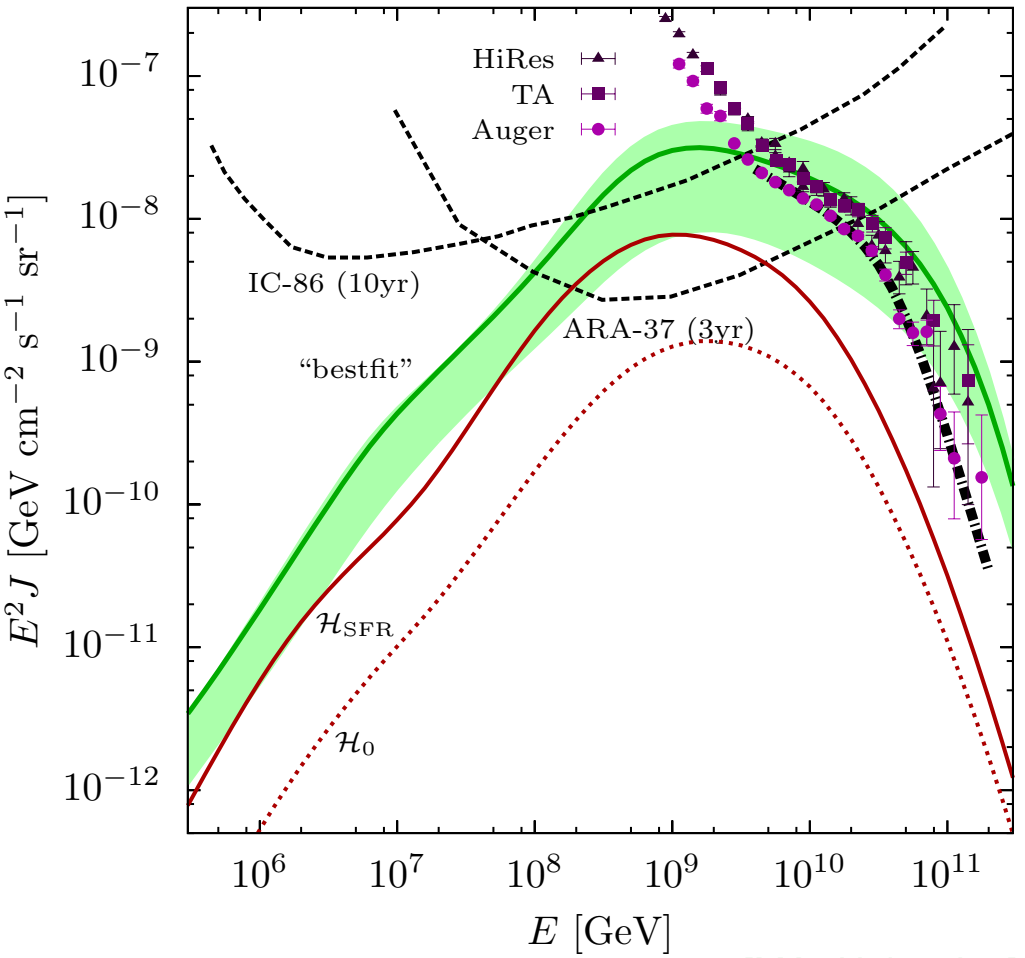
    [Berezinsky & Zatsepin'69; Yoshida & Teshima'93; Protheroe & Johnson'96; Engel, Seckel & Stanev'01; Fodor, Katz, Ringwald &Tu'03; Barger, Huber & Marfatia'06; Yuksel & Kistler'07; Takami, Murase, Nagataki & Sato'09, MA, Anchordoqui & Sarkar'09, Heinz, Boncioli, Bustamante & Winter'15]
  - **+ mixed compositions**

    [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]