Galactic Sources of High-Energy Neutrinos

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Multi-messenger paradigm

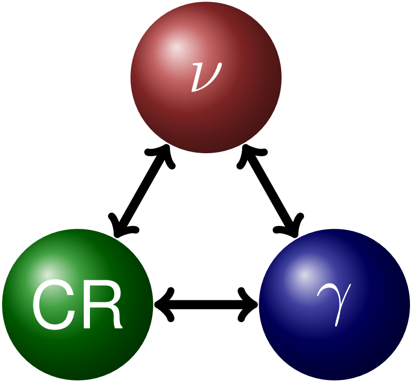
- Neutrino production is closely related to the production of cosmic rays (CRs) and γ-rays.
- **Pion production** of CRs with gas and radiation followed by:

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

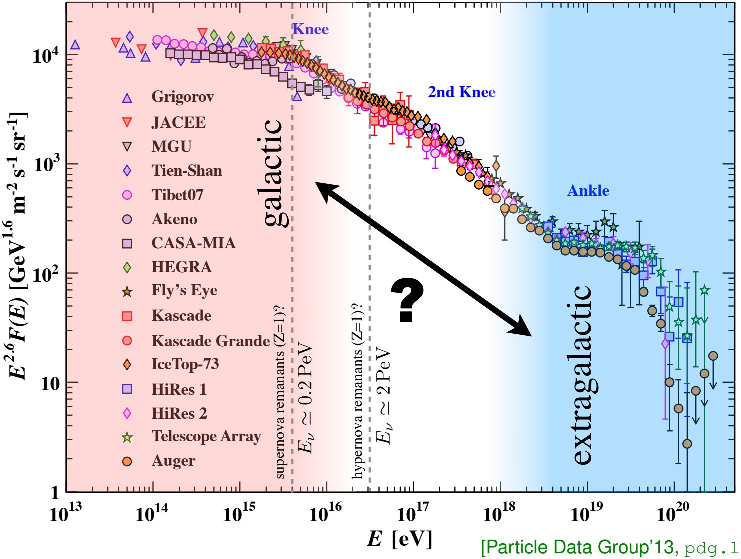
➜ Neutrinos are **smoking-gun** messengers of CR sources.

- typtical energy relations:

$$E_\nu \simeq \frac{1}{2} E_\gamma \simeq \frac{1}{20} E_{\rm N}$$

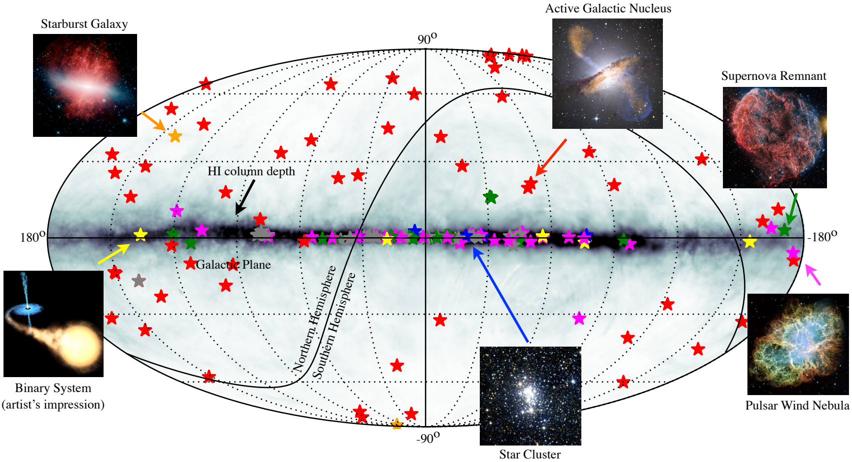


Very-High-Energy Cosmic Rays (CRs)



[Particle Data Group'13, pdg.lbl.gov]

Very-High Energy γ-rays



LBL, IBL, HBL, FRI, FSRQ Globular Cluster, Star Forming Region, Massive Star Cluster
Binary PWN Shell, SNR/Molec.Cloud, Composite SNR Starburst Others [TeVCat'14]

Galactic Cosmic Rays

- Galactic supernova (SN) remnants with 10^{51} erg and 3 SNe per century

- Galactic CRs via diffusive shock acceleration (efficiency $\sim 10\%$)?

  [Baade & Zwicky'34]

$$\frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-(2.2-2.4)} \qquad \text{(at source)}$$

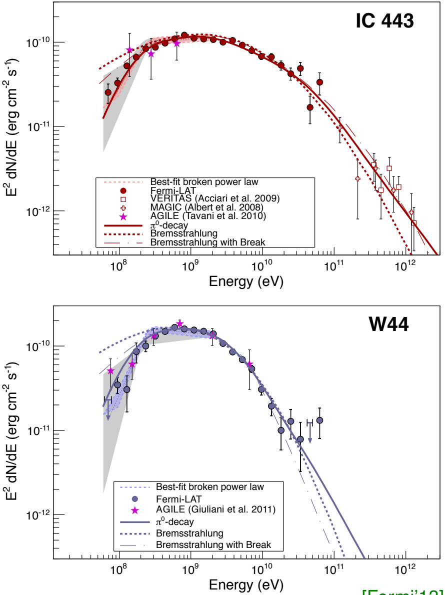
$$E_{p,\mathrm{max}} \simeq 4.5\ \mathrm{PeV}\ \varepsilon_{B,-2}^{1/2} M_{\mathrm{ej},\odot}^{-2/3} \mathcal{E}_{\mathrm{ej},51} n_0^{1/6}$$

- energy-dependent **diffusive escape** from Galaxy

$$\frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-2.7} \qquad \text{(observed)}$$

- indirect (diffuse) & direct ("pion bump") evidence via γ-ray radiation

  [Drury, Aharonian & Völk'94; Fermi'13]



[Fermi'13]

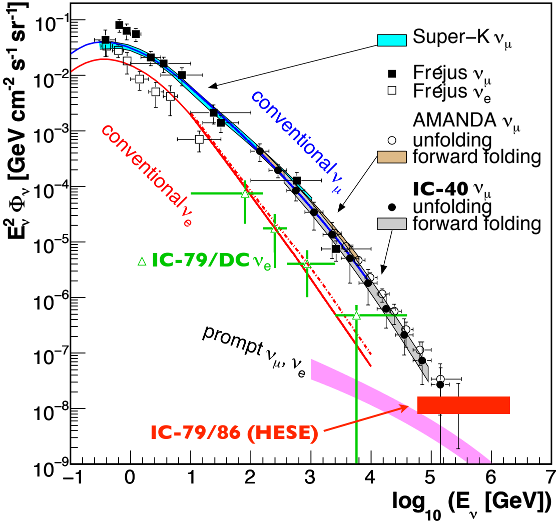
Galactic sources of HE Neutrinos

- SNR and molecular clouds [Gabici & Aharonian'07]
- x-ray binaries / microquasars [Levinson & Waxman'01; Distefano *et al.*'02; Anchordoqui *et al.*'03]
- pulsars / magnetars
  [Goldreich & Julian'69; Blasi, Epstein & Olinto'00; Arons'03; Murase, Meszaros & Zhang'09]
- hypernovae [Fox, Kashiyama & Meszaros'13; MA & Murase'13; Liu *et al.*'14]
- TeV associations (point-source & extended)
  [*e.g.* Kistler & Beacom'06; Gabici *et al.*'08; Halzen, Kappes & Ó Murchadha'08]
  [Fox, Kashiyama & Meszaros'13; Neronov, Semikoz & Tchernin'13]
- diffuse Galactic Plane emission [Stecker'78; Berezinsky *et al.*'92; Ingelman & Thunman'96]
  [MA & Murase'13; Kachelriess & Ostapchenko'14]
- diffuse Galactic Halo emission [Feldmann, Hooper & Gnedin'12; Taylor, Gabici & Aharonian'14]
- "Fermi bubbles" [Su, Slatjer & Finkbeiner'11; Crocker & Aharonian'11; Lunardini & Razzaque'12]
  [MA & Murase'13; Razzaque'13; Lunardini *et al.*'13]
- PeV dark matter decay [Feldstein *et al.*'13; Esmaili & Serpico'13; Bai, Lu & Salvado'13]

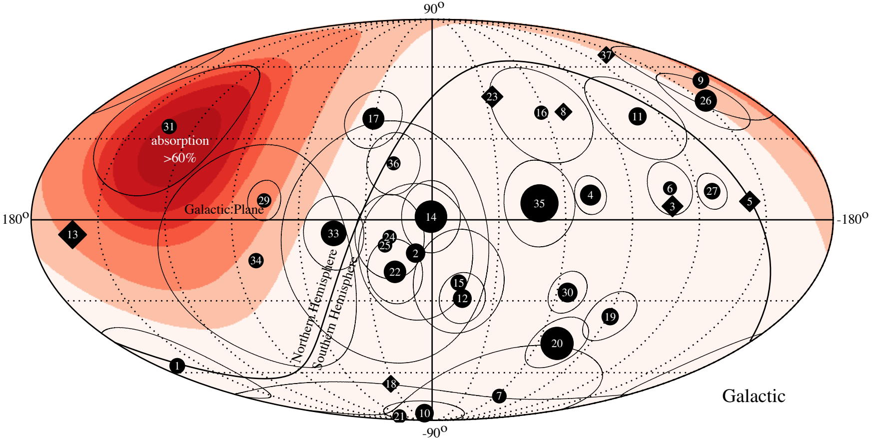
Very-High Energy Neutrinos

- high-energy atmospheric ν_μ/ν_e-spectrum as seen by **IC-40** & **IC-79/DC**
  [IceCube'11,'12]
- irreducible background for PS studies at $E_\nu \lesssim 1$ TeV
- predicted prompt atmospheric ν-fluxes (charmed meson decay)
  [Enberg *et al.*'08]

➜ high-energy starting event (HESE) analysis
  [IceCube Science'13]



“IceCube excess” (3yrs)



28 “cascade events” (circles) and 7 “tracks events” (diamonds); size of symbols proportional to deposited energy (30 TeV to 2 PeV); data from [`arXiv:1405.5303`]

“IceCube excess” (3yrs)

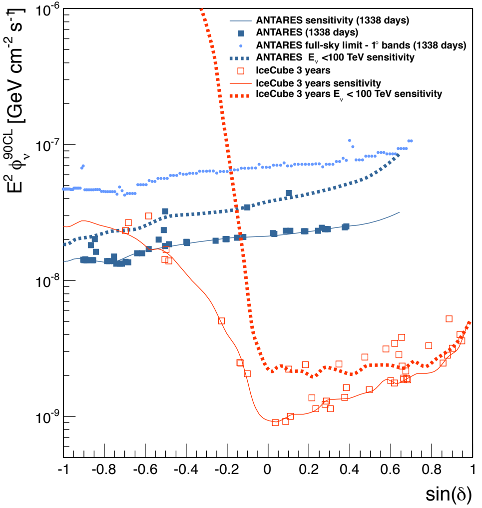
- IceCube observes $36(+1)$ **events** over a period of **three years**, while $6.6^{+5.9}_{-1.6}$ and $8.4^{+4.2}_{-4.2}$ are expected from atmospheric neutrinos and muons, respectively. [IceCube’13,’14]
- flux excess at 4.8σ for combined 35+2 fit
- **isotropic and flavor-universal**
- **no significant time-clustering**
- E^{-2} spectrum favors **cutoff/break** at $2-5$ PeV
- **best-fit** of the HESE E^{-2}-spectrum:

$$E_\nu^2 J^{\rm IC}_{\nu_\alpha} \simeq (0.95 \pm 0.3) \times 10^{-8} {\rm GeV s^{-1} cm^2 sr^{-1}}$$

- Consistent with classical diffuse analysis of muon neutrinos (IC-79/86)!

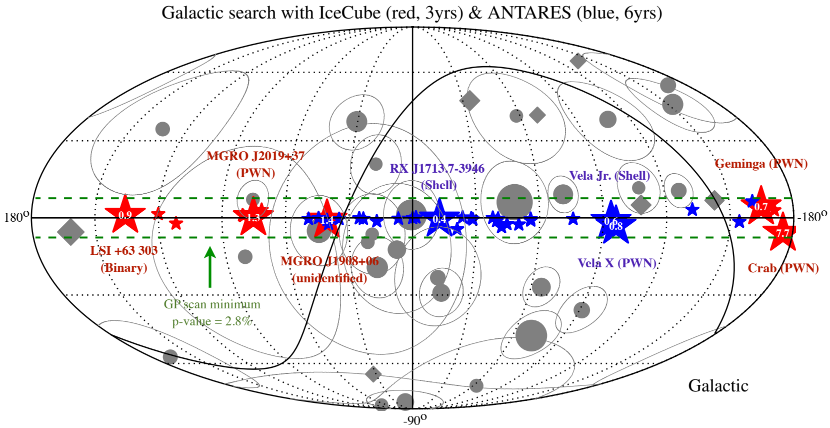
Galactic Neutrino Limits

- **upper flux limits and sensitivities** of Galactic neutrino sources with "classical" muon neutrino search
- point sources: $\theta_{\rm res} \simeq 0.3^\circ - 0.6^\circ$
- discrimination w.r.t. background from spatial (& time) clustering and energy
- sensitivity for **extended sources** increases 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)



[summary plot by ANTARES'14]

Galactic Neutrino Limits



- relative strength of neutrino limits assuming hadronic TeV γ-ray emission (only shown for selected strong sources):

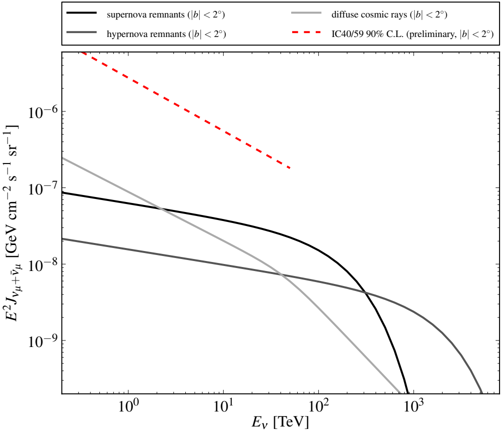
$$F_\gamma(E_\gamma > E_{\rm th})/F_\nu^{90CL}(E_\nu > E_{\rm th}/2)$$

✘ **caveats:** soft spectra, low energy cutoffs and extended emission

Diffuse emission in GP

- diffuse γ-ray & ν emission from CR propagation ($|b| < 2^\circ$)
- unresolved supernova remnants:
  $R_{\rm SN} \simeq 0.03{\rm yr}^{-1}$
  $\mathcal{E}_{\rm ej} \simeq 10^{51}$ erg
  $N_{\rm SNR} \simeq 1200$
- unresolved hypernova remnants:
  $R_{\rm HN} \simeq 0.01 R_{\rm SN}$
  $\mathcal{E}_{\rm ej} \simeq 10^{52}$ erg
  $N_{\rm HNR} \simeq 20$
- flux concentrated in Galactic Plane:
  $J \propto 50\%$ for $|b| < 5^\circ$
  $J \propto 30\%$ for $|b| < 10^\circ$
- however, this does not account for **local fluctuation**

[MA & Murase 1309.4077]



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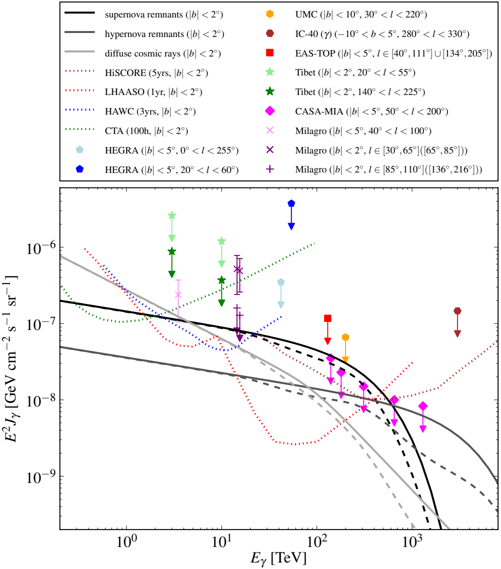

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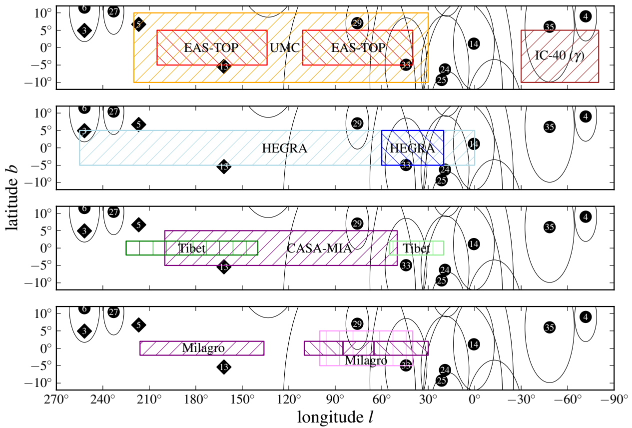


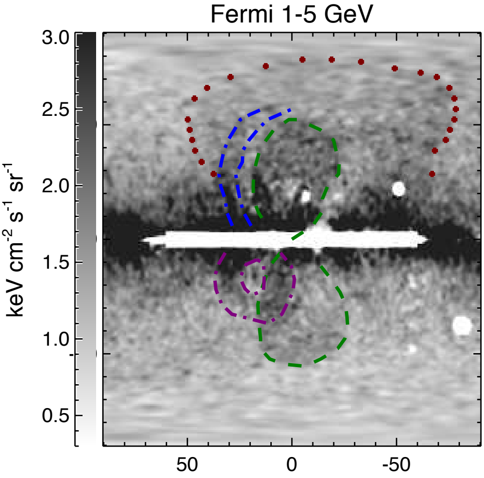
- on-source search regions of TeV-PeV diffuse γ-rays from Galactic Plane
- no significant overlap [MA & Murase 1309.4077]

➜ talk by **Anna Bernhard** (IceCube) on ν search in Cygnus region

Fermi Bubbles

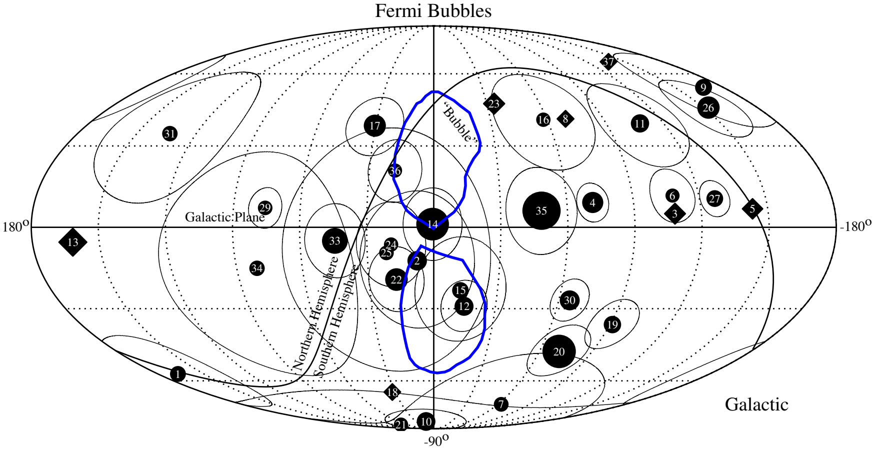
- two extended GeV γ-ray emission regions close to the Galactic Center [Su, Slatyer & Finkbeiner'10]
- hard spectra and relatively uniform emission
- some correlation with WMAP haze and X-ray observation
- model 1: hadronuclear interactions of CRs accelerated by star-burst driven winds and convected over few 10^9 years [Crocker & Aharonian'11]
- model 2: leptonic emission from 2nd order Fermi acceleration of electrons [Mertsch & Sarkar'11]

➜ probed by associated neutrino production [Lunardini & Razzaque'12]



[Su, Slatyer & Finkbeiner'11]

Fermi Bubbles



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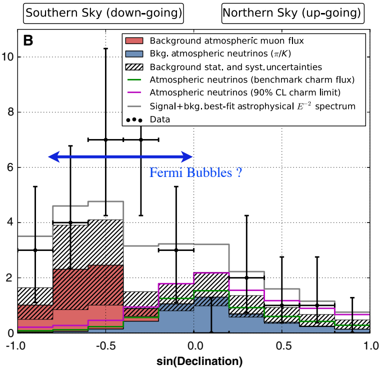
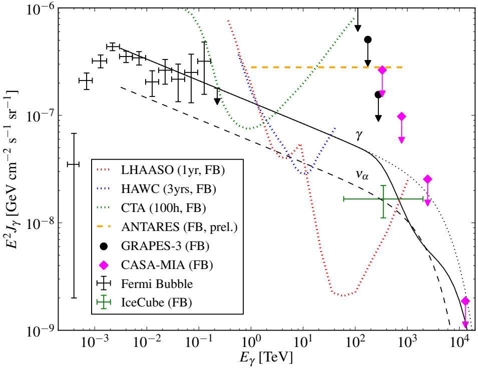




[MA & Murase 1309.4077]

- small zenith "excess" in IceCube excess (but not significant)
- Galactic Center source(s) of extended source, *e.g.* "Fermi Bubbles"?

[Finkbeiner, Su & Slatyer'10]

- FB "excess" in agreement with GeV-PeV neutrino & γ-ray observations and limits assuming $\Gamma \simeq 2.2$

Contrast of GC excess

- Galactic Center (GC) flux:

$$F_{\rm GC} \simeq \frac{L_{\rm GC}}{4\pi d_{\rm GC}^2}$$

- (quasi-)diffuse flux from similar galaxies:

$$F_{\rm diff} = \frac{1}{4\pi}\int {\rm d}z \frac{{\rm d}\mathcal{V}_C}{{\rm d}z}\mathcal{H}(z)\,\frac{L_{\rm GC}}{4\pi d_L(z)^2} \simeq \frac{L}{4\pi}\frac{\xi_z\mathcal{H}_0}{H_0}$$

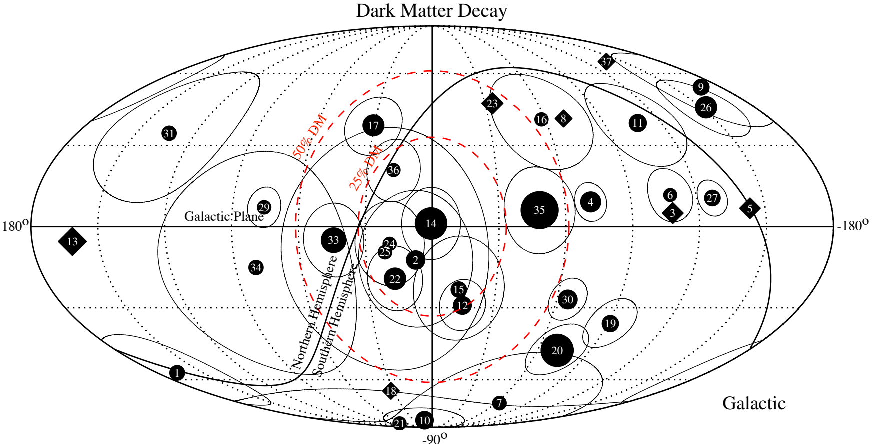
➜ flux ratio depend on local source density $\mathcal{H}_0$ and evolution parameter ξ_z:

$$\frac{F_{\rm GC}}{4\pi F_{\rm diff}} \simeq \frac{H_0}{4\pi\xi_z\mathcal{H}_0 d_{\rm GC}^2} \simeq \mathbf{100}\left(\frac{\xi_z}{2.4}\right)^{-1}\left(\frac{\mathcal{H}_0}{10^{-3}}\right)^{-1}$$

- “benchmark” local density $\mathcal{H}_0 \simeq 10^{-3}$–$10^{-2}\,{\rm Mpc}^{-3}$ (normal galaxies)
- “benchmark” evolution $\xi_z \simeq 2.4$ (star-formation rate)

➜ **Additional component needed for full observation.**

DM decay


Dark Matter Decay
180°
-180°
-90°
Galactic Plane
Galactic
50% DM
25% DM
Northern Hemisphere
Southern Hemisphere
1
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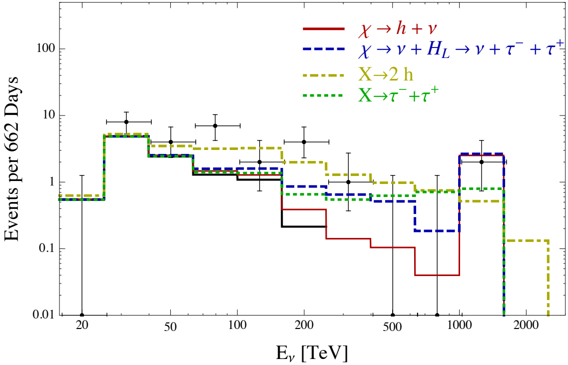
DM decay

- 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]

Contrast of DM decay

- Galactic neutrino flux from DM decay:

$$F_{\rm gal} = \frac{Q_\nu}{m_X\tau_X}\frac{1}{2}\int_{-1}^{1}{\rm d}c_\alpha\int_0^\infty {\rm d}s\,\rho_{\rm gal}(r(s,c_\alpha)) \simeq \frac{Q_\nu}{m_X\tau_X}\langle\rho_{\rm gal}\rangle d_{\rm halo}$$

- Extragalactic diffuse signal:

$$F_{\rm diff} = \frac{\Omega_{\rm DM}\rho_{\rm cr}}{4\pi m_X\tau_X}\int_0^\infty\frac{{\rm d}z}{H(z)}Q_\nu((1+z)E_\nu) \simeq \frac{1}{4\pi}\frac{Q_\nu}{m_X\tau_X}\frac{\xi_z\Omega_{\rm DM}\rho_{\rm cr}}{H_0}$$

➜ flux ratio:

$$\frac{F_{\rm gal}}{4\pi F_{\rm diff}} \simeq \frac{\langle\rho_{\rm gal}\rangle}{\Omega_{\rm DM}\rho_{\rm cr}}\frac{d_{\rm halo}}{\xi_z/H_0} \simeq \mathbf{1}\left(\frac{d_{\rm halo}}{20{\rm kpc}}\right)\left(\frac{\xi_z}{0.5}\right)^{-1}$$

➜ **Similar contributions from Galactic and extragalactic DM decay.**

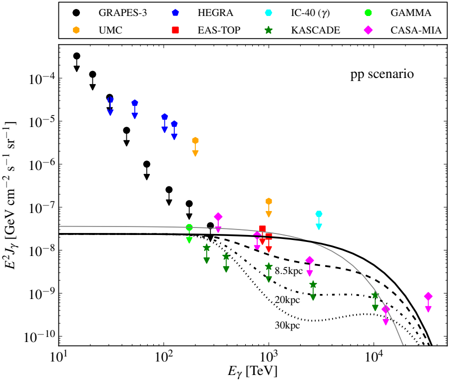
PeV γ-ray associations (isotropic)

- IceCube-equivalent diffuse γ-ray flux:

$$E_\gamma J_\gamma(E_\gamma) \simeq e^{-\frac{d}{\lambda_{\gamma\gamma}}} \frac{2}{K}\frac{1}{3}\sum_{\nu_\alpha} E_\nu J^{\rm IC}_{\nu_\alpha}(E_\nu)$$

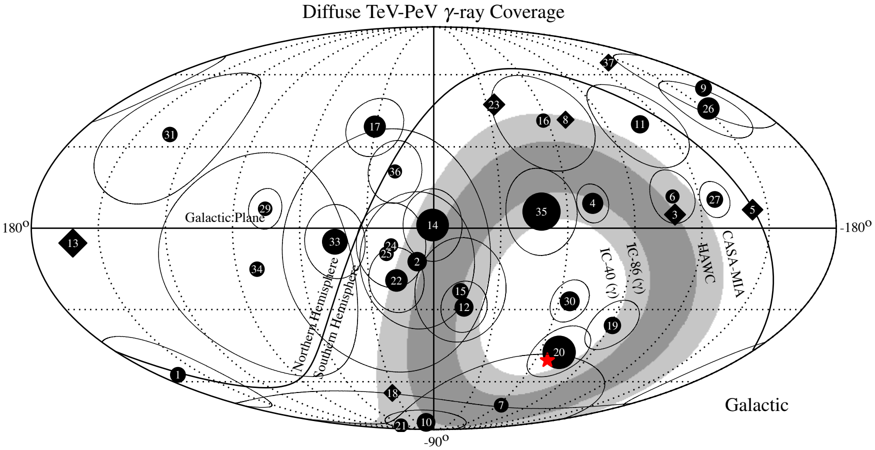
- absorption length $\lambda_{\gamma\gamma}$ via $\gamma\gamma \to e^+e^-$
- effect strongest for CMB in PeV range: $\lambda_{\gamma\gamma} \simeq 10$ kpc
- plot shows distance d from 8.5 kpc (GC) to 30 kpc

➜ strong constraints of isotropic diffuse Galactic emission from γ-ray observatories [Gupta 1305.4123]



[MA & Murase 1309.4077]

PeV γ-ray associations (isotropic)



- 16 events lie in TeV-PeV "blind spot" [MA & Murase 1309.4077]
- one PeV event ("Ernie") within 10° of PeV γ-ray "warm spot" [IceCube'12]

Conclusions

- Presence of Galactic CR sources requires the existence of high-energy neutrino sources.
- Non-observation is consistent with present indirect limits from γ-ray observatories, but sensitivity can target “Crab”-like hadronic fluxes.
- Neutrino detector with ~ 5 times effective area (~ 10 times volume) sensitive to neutrino production in Cygnus region.
- Galactic **origin of** or **contribution to recent IceCube observation** is challenging, but possible.
- If present, Galactic sources could emerge as spatial anisotropy and/or via PeV γ-ray emission.