# High-Energy Neutrinos in Light of Fermi-LAT

Markus Ahlers

UW-Madison & WIPAC

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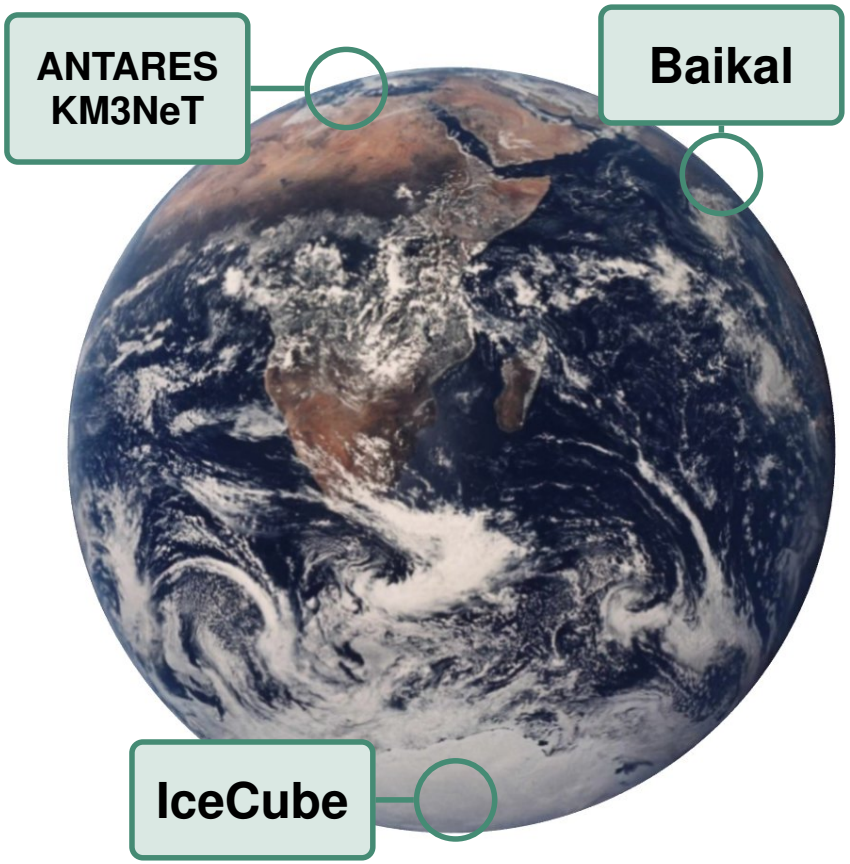
# Neutrino Cherenkov Telescopes

Astrophysical neutrinos are an important addition to **multi-messenger** astronomy (no deflection & absorption in space; “smoking-gun” of cosmic rays)




**detector requirements:**

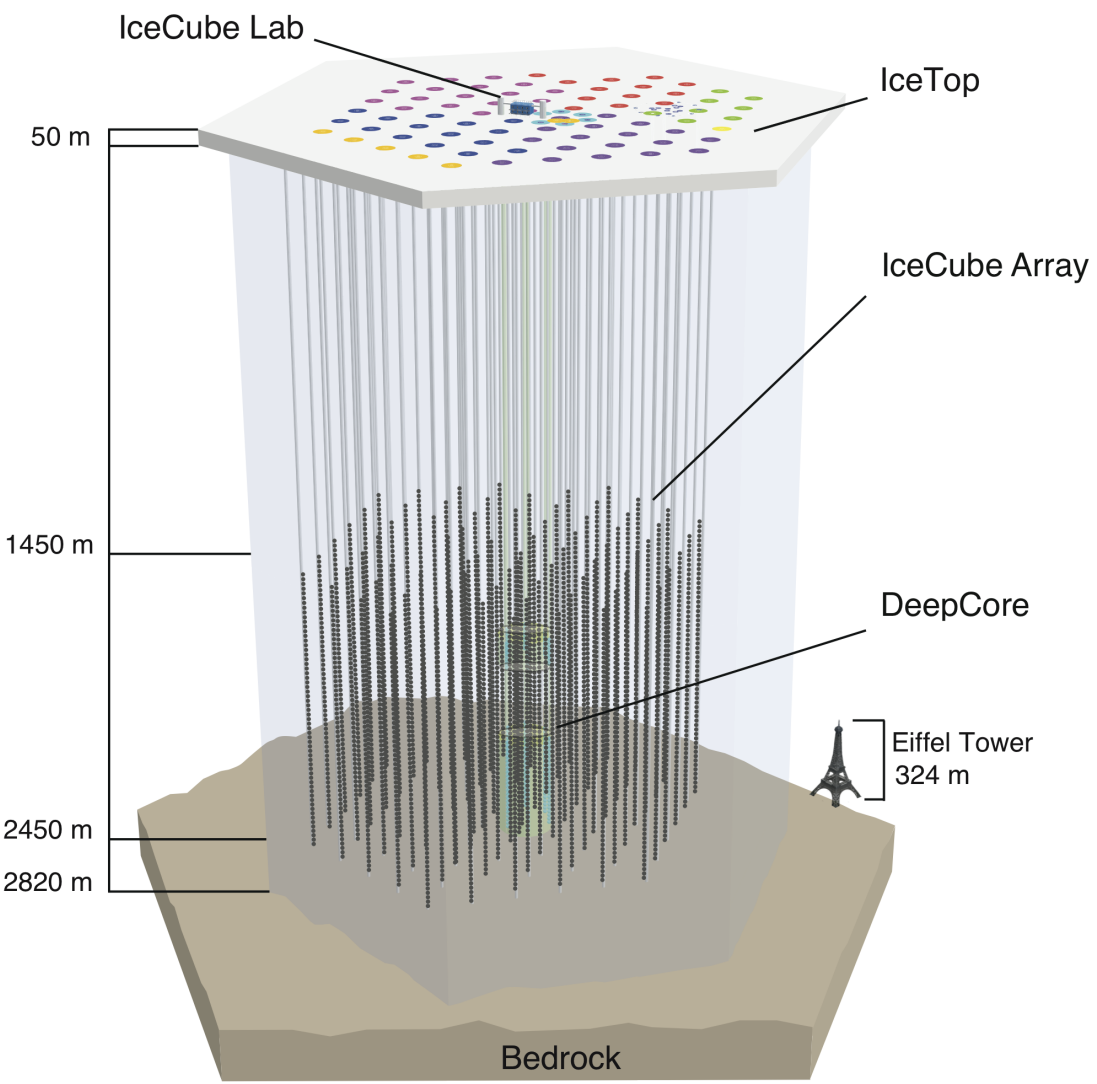
$$N_N \times \sigma_{\nu N} \times \frac{\mathrm{d}^2 N_\nu}{\mathrm{d}t\,\mathrm{d}A} \sim \frac{1}{\mathrm{year}} \times \frac{V}{1\mathrm{km}^3}$$

$$\rightarrow \; M_{\mathrm{det}} \simeq V \times m_p \sim 1\,\mathrm{Gton}$$

**realization:**

Observation of **Cherenkov light** in $\mathrm{km}^3$-volumes of deep ocean water (Mediterranean), fresh water (Lake Baikal) or ice (Antarctic).

# The IceCube Observatory

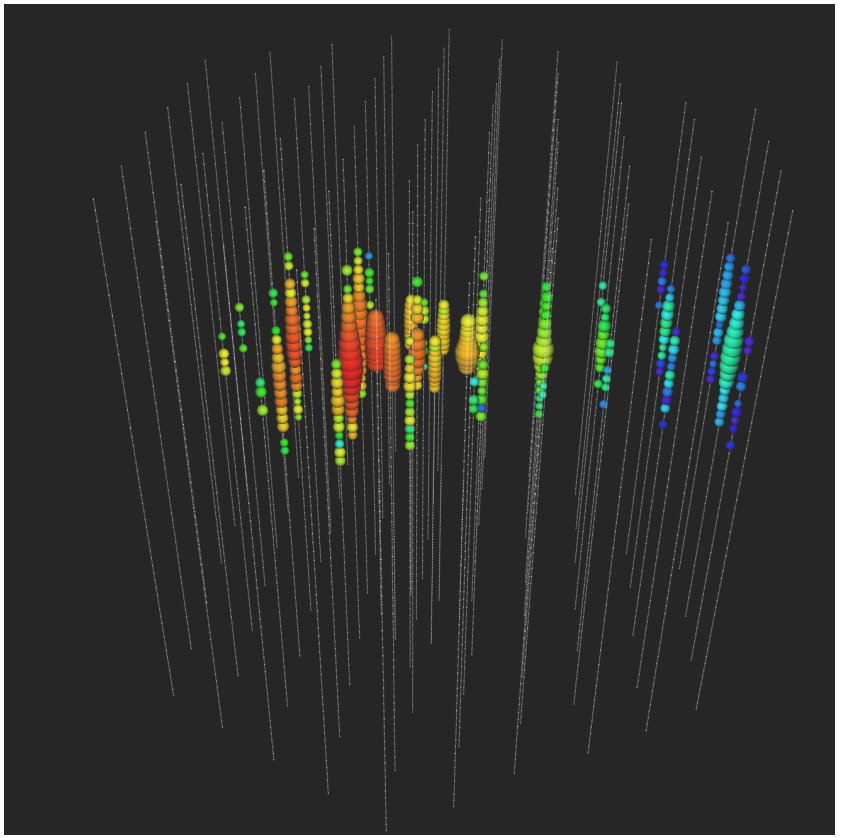



- Giga-ton telescope at the South Pole
- Collaboration of about 250 people at 43 intl. institutions
- 60 digital **optical modules** (DOMs) per string
- **78 IceCube strings**
  125 m apart on triangular grid
- **8 DeepCore strings**
  DOMs in particularly clear ice
- **81 IceTop stations**
  two tanks per station, two DOMs per tank
- 7 year construction phase (2004-2011)
- price tag: **30 Cents per ton**

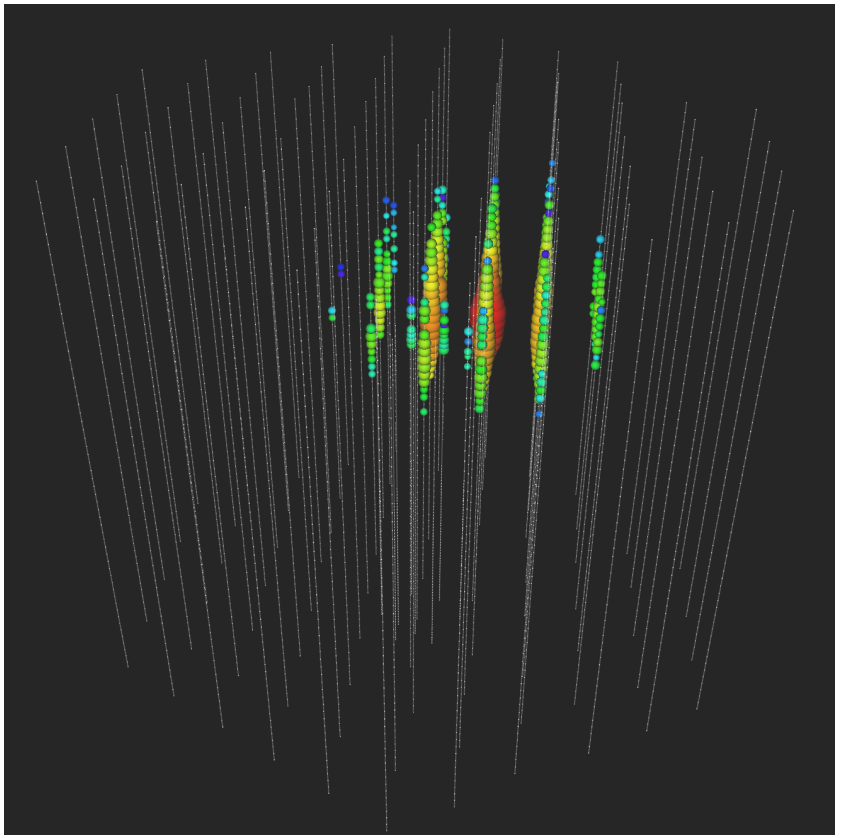
# The IceCube Observatory

- "cascades": **good** energy, but **poor** angular resolution ($\Delta\theta > 10^\circ$)
- "tracks": **poor** energy, but **good** angular resolution ($\Delta\theta \lesssim 1^\circ$)
- **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)]

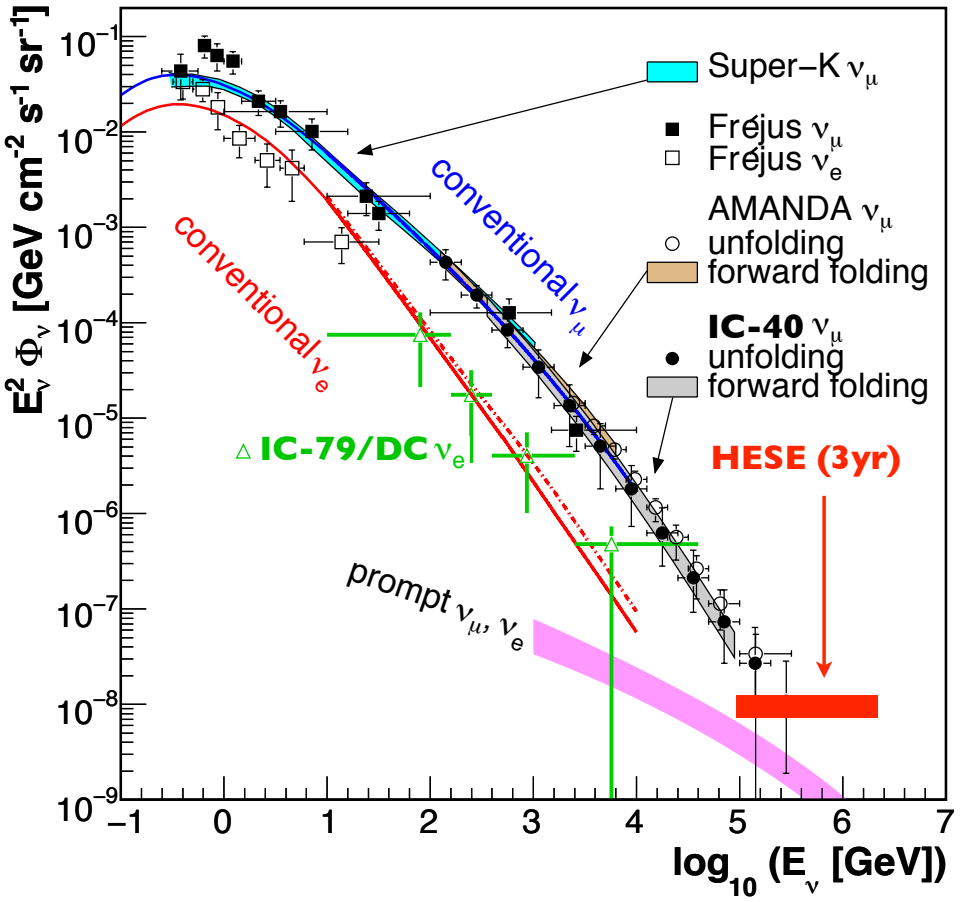
# IceCube HESE Sample (3yrs)

- **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

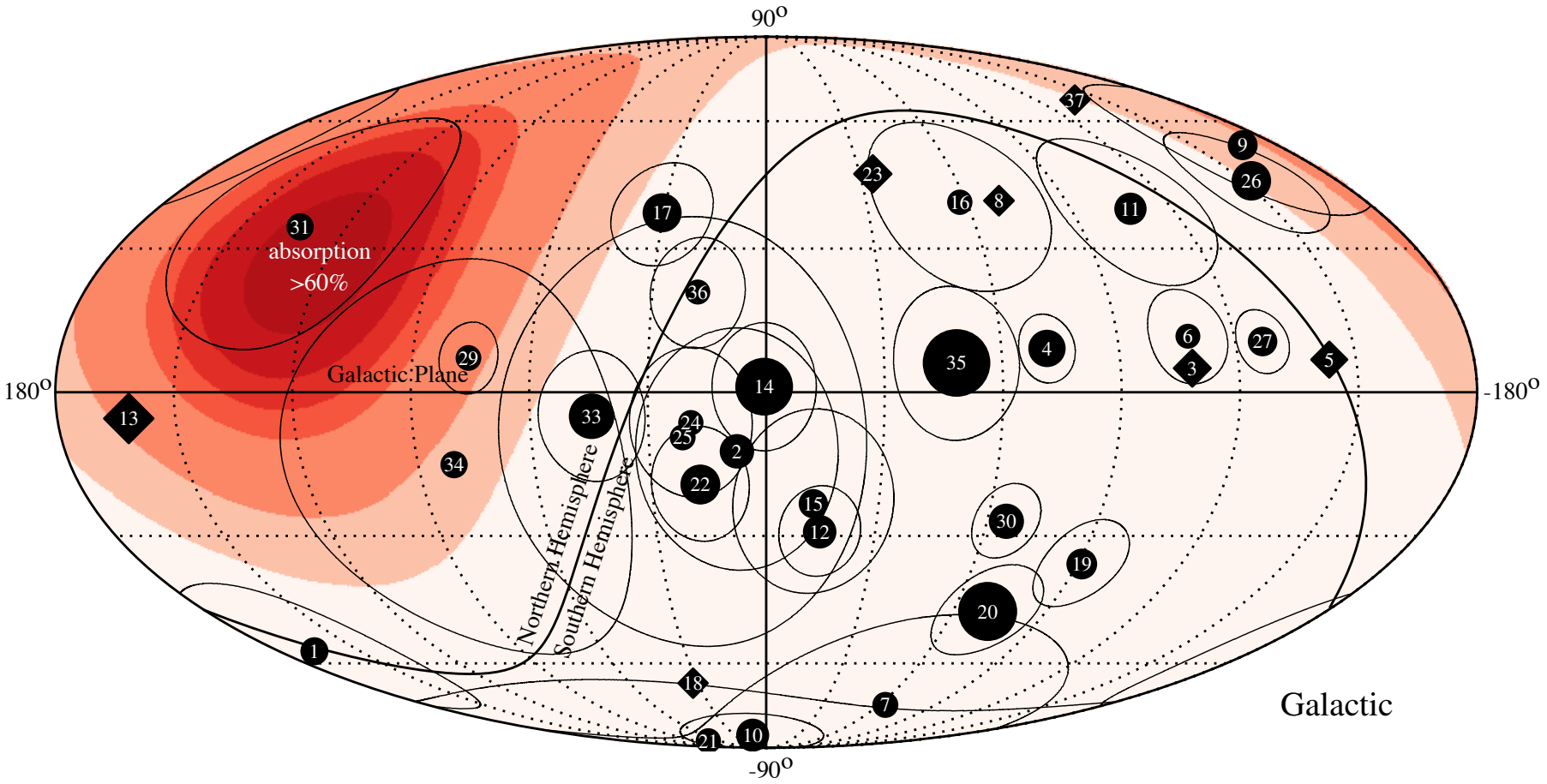
- 37 events in about three years: [IceCube PRL 113 (2014)]
  - 28 **cascades** events
  - 8 **track** events
  - 1 **composite** event (removed)

- expected background events:
  - $6.6^{+5.9}_{-1.6}$ **atmospheric neutrinos**
  - $8.4^{+4.2}_{-4.2}$ **atmospheric muons**

- **significance** of $5.7\sigma$ above backgrounds



# Arrival Directions




- **28 "cascade events" (circles) and 7 "tracks events" (diamonds)**; size of symbols proportional to deposited energy (30 TeV to 2 PeV) [IceCube PRL 113 (2014)]

✘ **no significant spatial or temporal correlation of events**

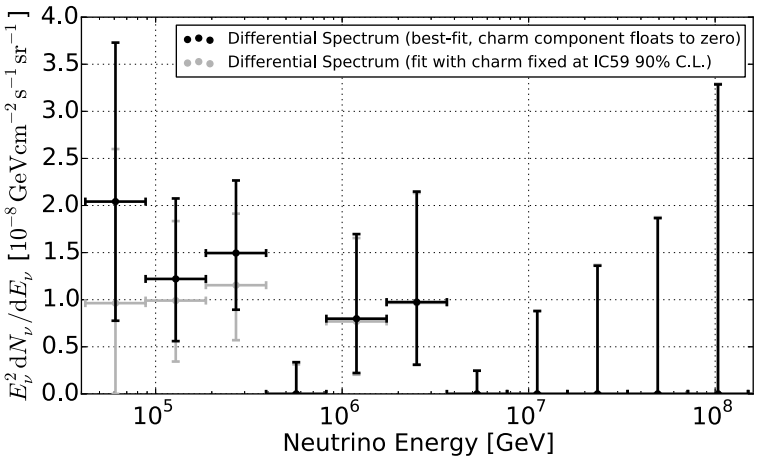
# Spectrum

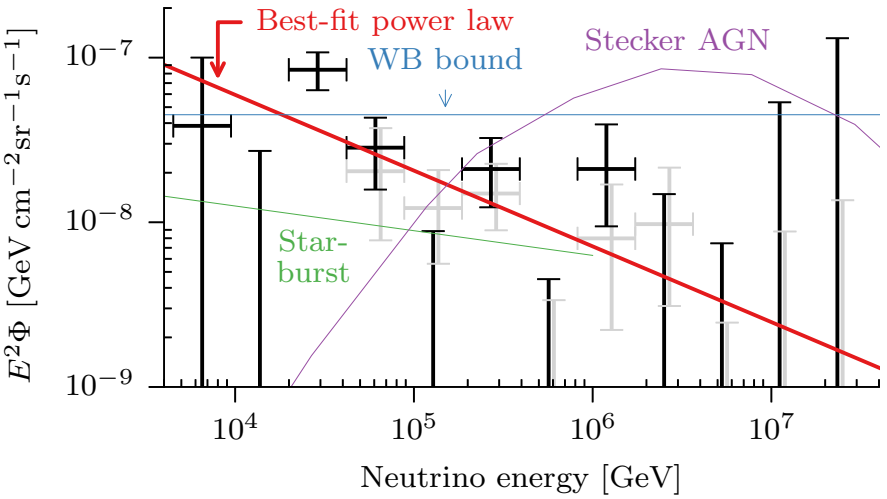
- $E^{-2}$-spectrum of the HESE 3yr sample within $(0.1 - 1)\mathrm{PeV}$: [IceCube PRL 113 (2014)]

$$E_\nu^2 \Phi_{\nu_\alpha} \simeq (0.95 \pm 0.3) \times 10^{-8} \mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

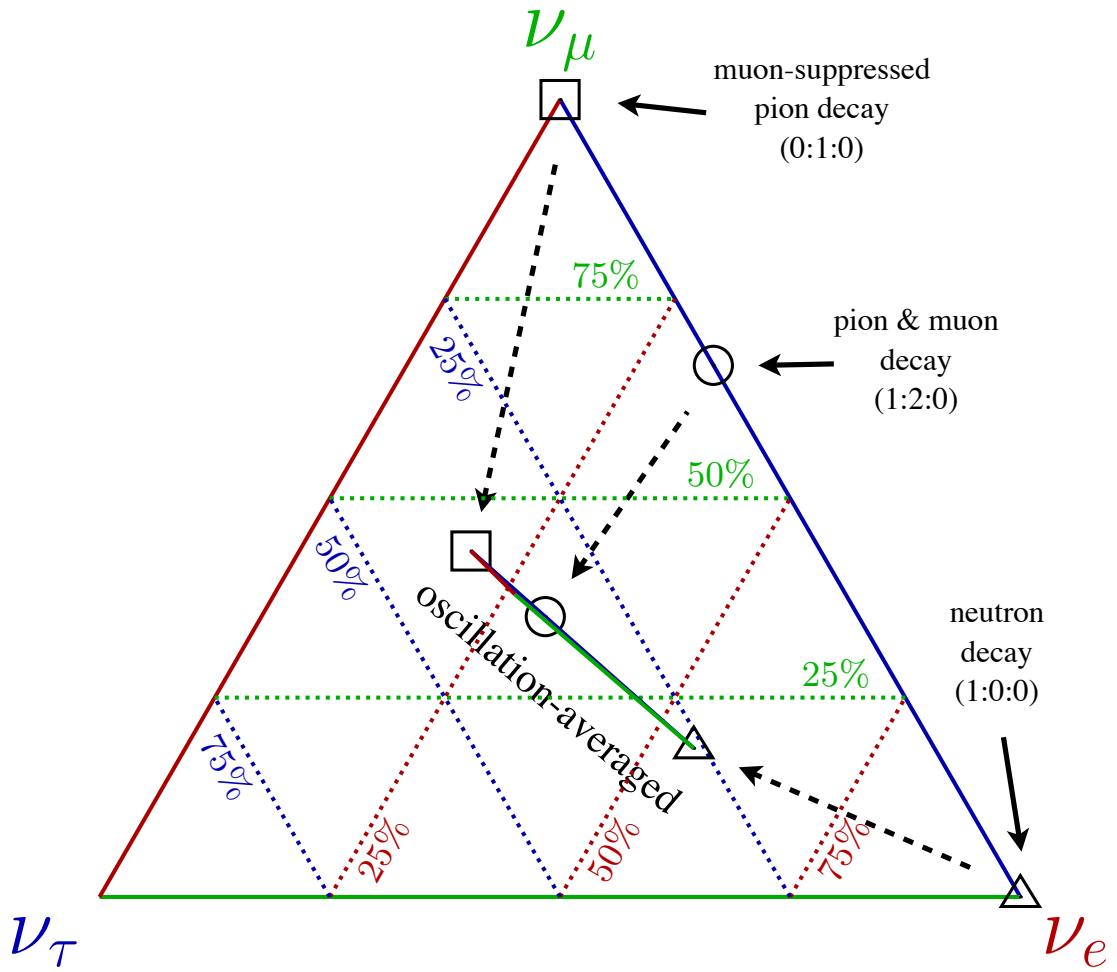
- "classical" muon-neutrino analysis (dominated by Northern Hemisphere) sees flux excess consistent with HESE sample [IceCube APS meeting'14]
- extended HESE sample with lower energy threshold indicates **softer spectrum**: [IceCube 1410.1749]

$$E^2 \Phi_{\nu_\alpha}(E) \simeq \left(2.06^{+0.4}_{-0.3}\right) \times 10^{-8} \left(\frac{E_\nu}{100\mathrm{TeV}}\right)^{-0.46 \pm 0.12} \mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$



# Neutrino Flavors




- "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**

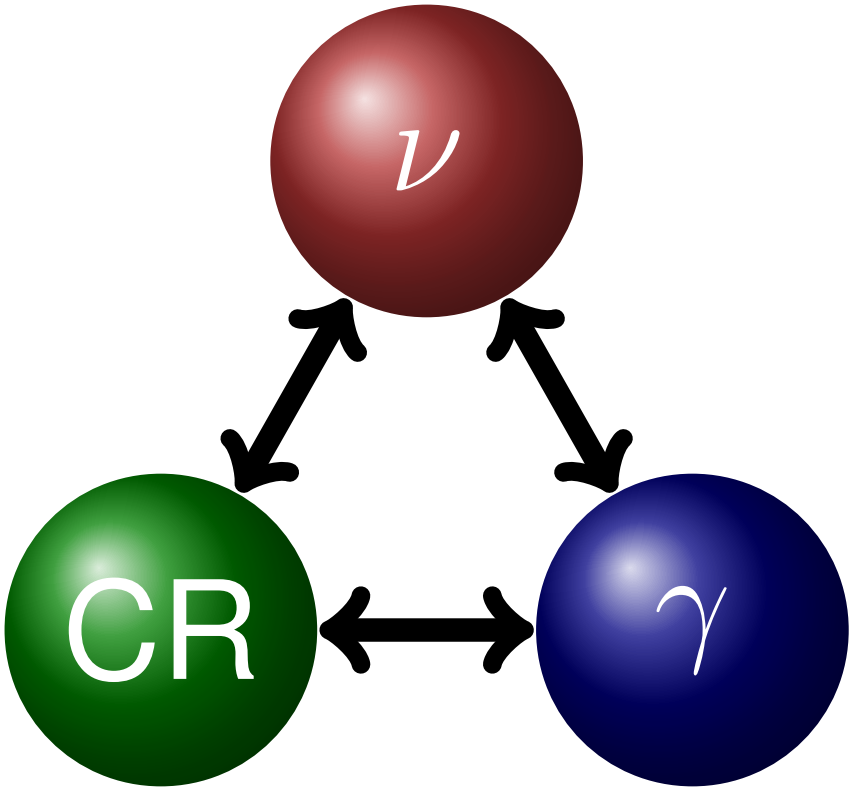
# Multi-messenger paradigm

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

- 1 PeV neutrinos correspond to 20 PeV CR nucleons and 2 PeV $\gamma$-rays

➜ **very interesting** energy range:

  - Glashow resonance?
  - galactic or extragalactic?
  - isotropic or point-sources?
  - chemical composition?
  - $pp$ or $p\gamma$ origin?



# Proposed Source Candidates

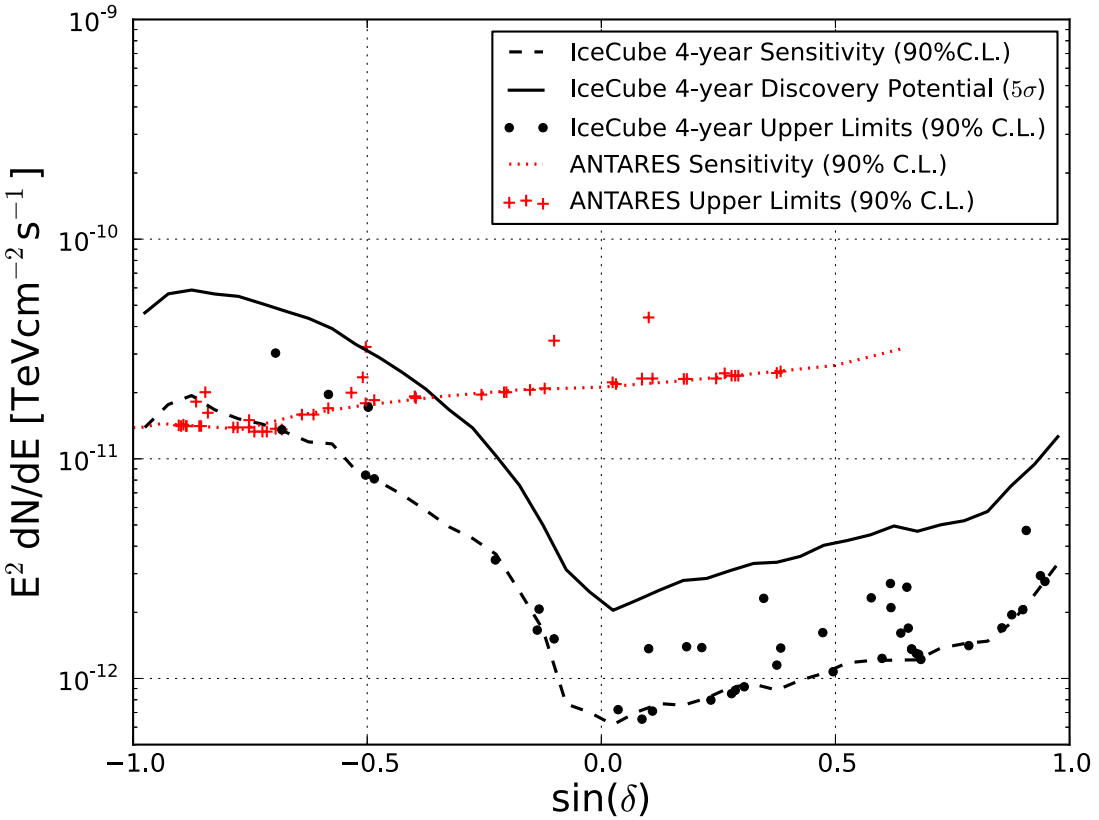
- **Galactic:** (full or partial contribution)
  - heavy dark matter decay [Feldstein *et al.* 1303.7320; Esmaili & Serpico 1308.1105]
  - peculiar hypernovae [Fox, Kashiyama & Meszaros 1305.6606; MA & Murase 1309.4077]
  - diffuse Galactic $\gamma$-ray emission [*e.g.* Ingelman & Thunman'96; MA & Murase 1309.4077]
  - unidentified Galactic TeV $\gamma$-ray sources [Fox, Kashiyama & Meszaros 1306.6606]
  - sub-TeV diffuse Galactic $\gamma$-ray emission [Neronov, Semikoz & Tchernin 1307.2158]
  - "Fermi bubbles" [Su, Slatjer & Finkbeiner'11; Crocker & Aharonian'11; Lunardini & Razzaque'12] [MA & Murase'13; Razzaque'13; Lunardini *et al.*'13 ]
- **Extragalactic:**
  - association with sources of UHE CRs [Kistler, Stanev & Yuksel 1301.1703] [Katz, Waxman, Thompson & Loeb 1311.0287; Fang, Fujii, Linden & Olinto 1404.6237]
  - GZK from low $E_{\rm max}$ blazars [Kalashev, Kusenko & Essey 1303.0300]
  - cores of active galactic nuclei (AGN) [*e.g.* Stecker *et al.*'91;Stecker 1305.7404]
  - AGN jets [*e.g.* Murase, Inoue & Dermer 1403.4089; 1406.2633]
  - low-power $\gamma$-ray bursts (GRB) [Murase & Ioka 1306.2274]
  - starburst galaxies [*e.g.* Loeb & Waxman'06; He *et al.* 1303.1253] [ Murase, MA & Lacki 1306.3417; Anchordoqui *et al.* 1405.7648; Chang & Wang 1406.1099]
  - hypernovae in star-forming galaxies [Liu, Wang, Inoue, Crocker & Aharonian 1310.1263]
  - galaxy clusters/groups [Berezinksy, Blasi & Ptuskin'97; Murase, MA & Lacki 1306.3417]

# 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 $\nu$'s)
- **time-dependent** sensitivity:

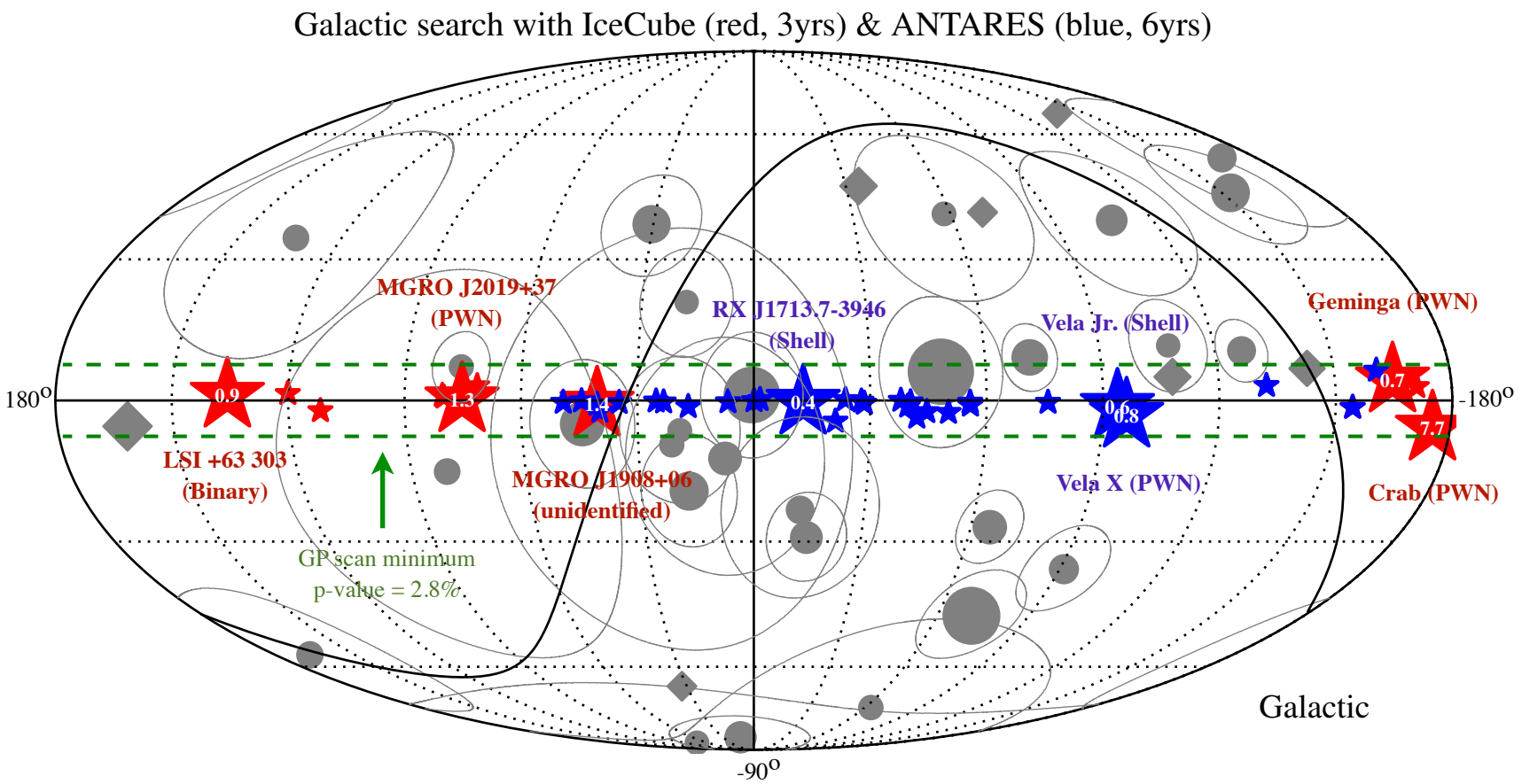
[IceCube ApJ 744 (2012)]

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




[IceCube 1406.6757]

# Neutrino Point-Source Limits




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

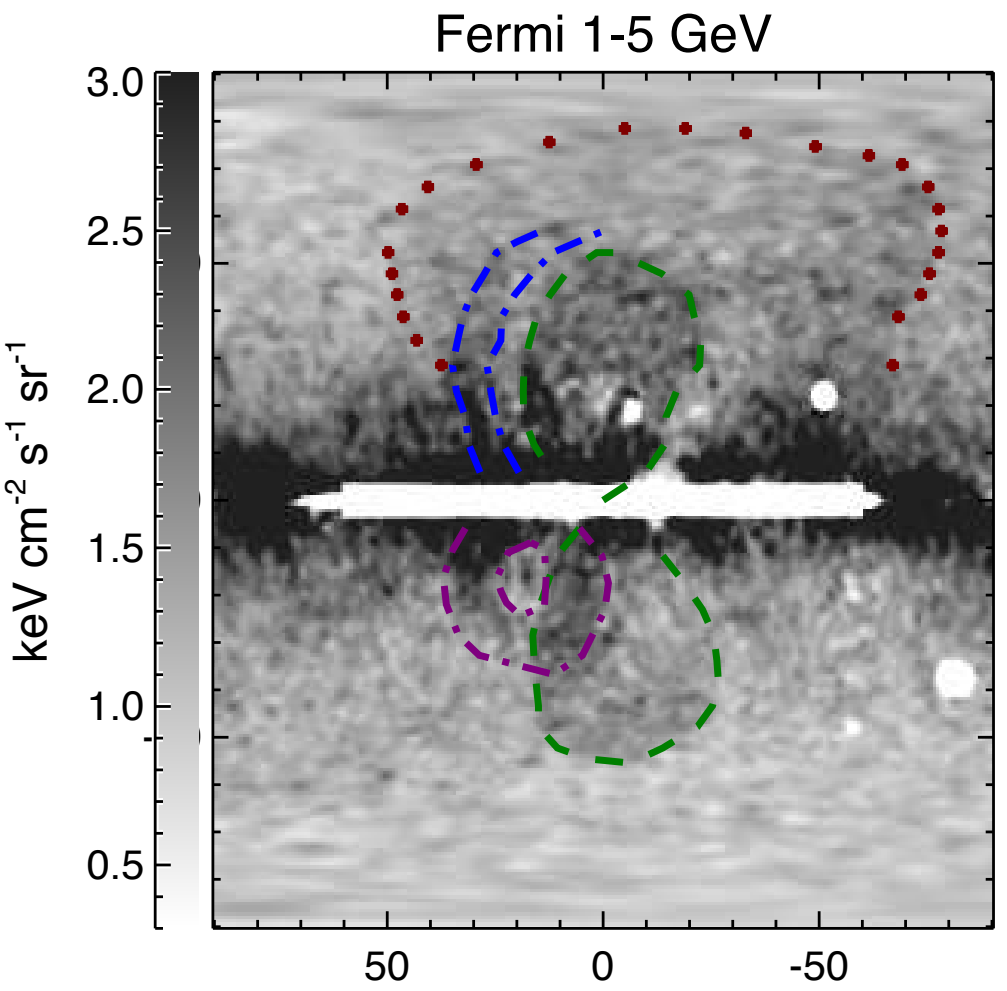
$$F_\gamma(E_\gamma > E_{\rm th})/F_\nu^{90CL}(E_\nu > E_{\rm th}/2)$$

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

# Fermi Bubbles

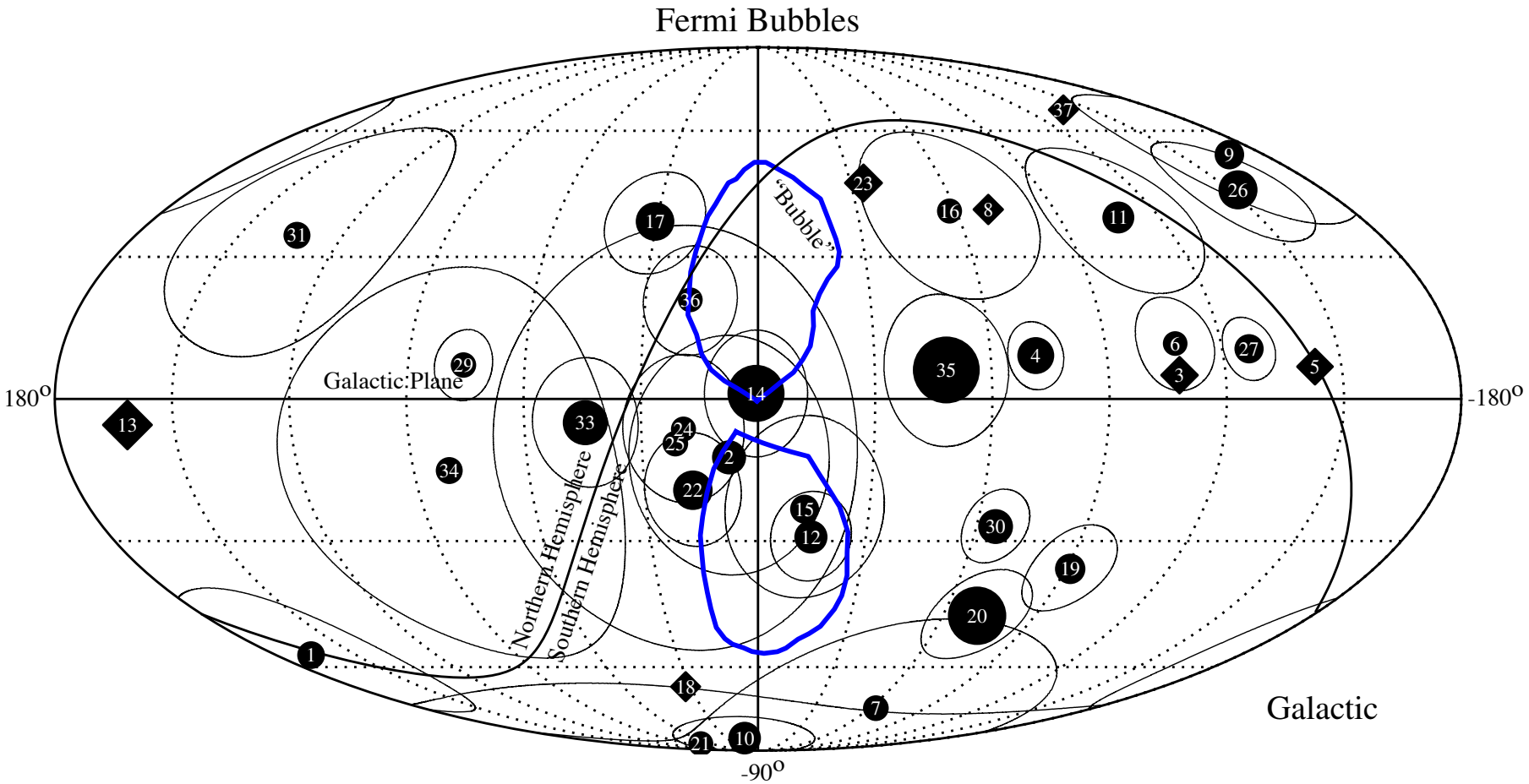
- two extended GeV $\gamma$-ray emission regions close to the Galactic Center [Su, Slatyer & Finkbeiner'10]
- hard spectra and relatively uniform emission
- some correlation with WMAP haze and X-ray observation
- model 1: hadronuclear interactions of CRs accelerated by star-burst driven winds and convected 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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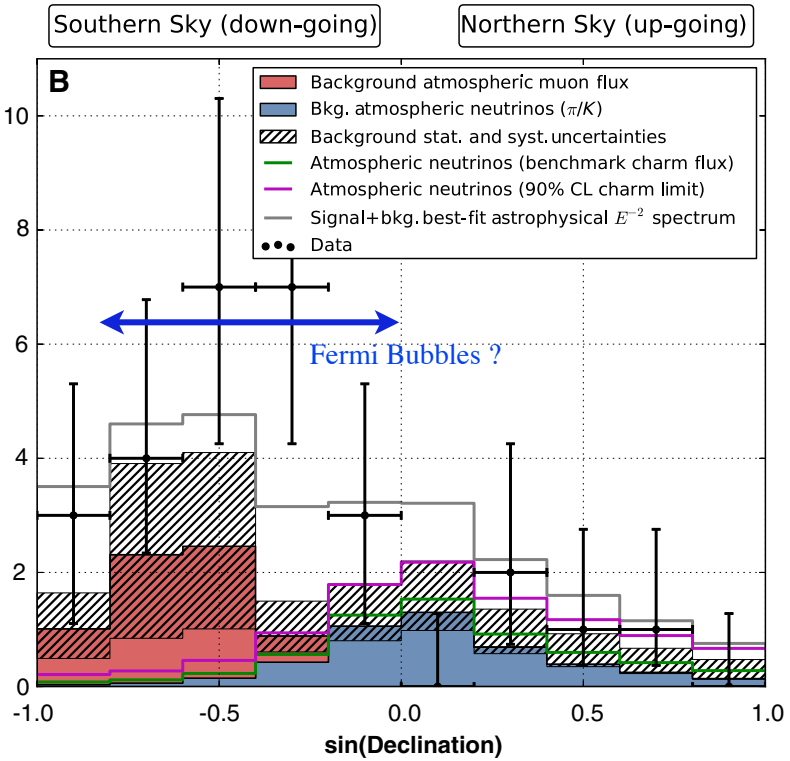
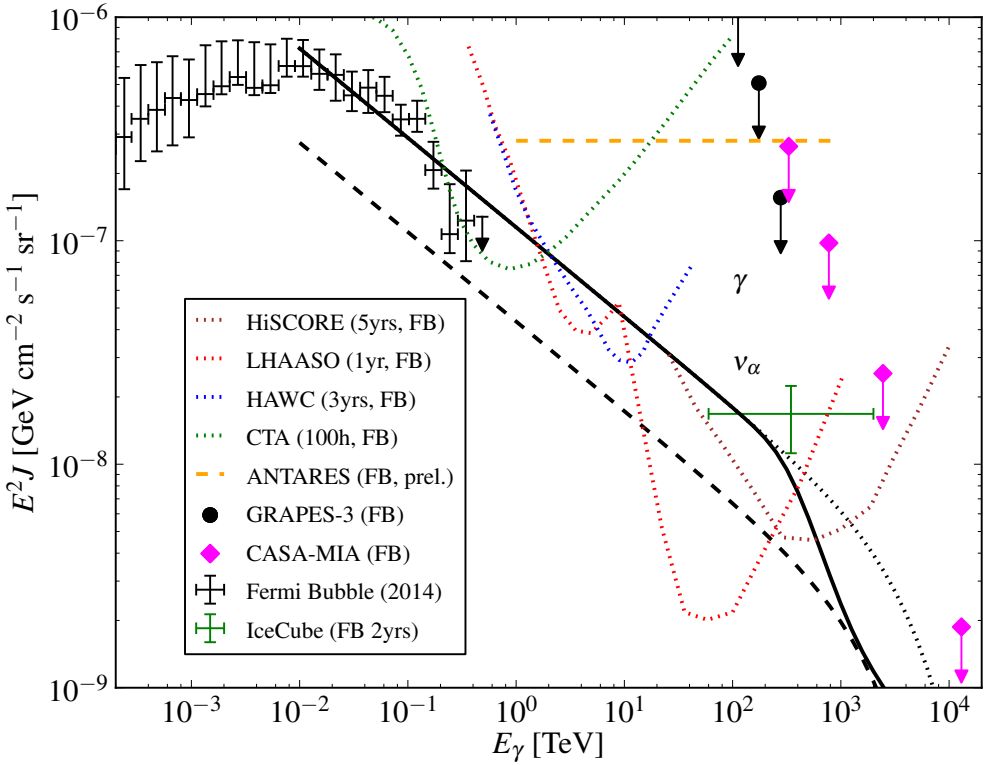



[MA & Murase 1309.4077; updated with Fermi ApJ 793 (2014)]

- small zenith "excess" in IceCube HESE 2yr sample (but not significant)
- Galactic Center source(s) of extended source, *e.g.* "Fermi Bubbles"?

[Finkbeiner, Su & Slatyer'10]

✘ $\Gamma = 2.4$ extrapolation of hadronic $\gamma$-ray/neutrino flux unlikely to produce an "excess" at 100 TeV to PeV in FB region

# Diffuse vs. Point-Source flux

- point-source flux:

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

- (quasi-)diffuse flux:

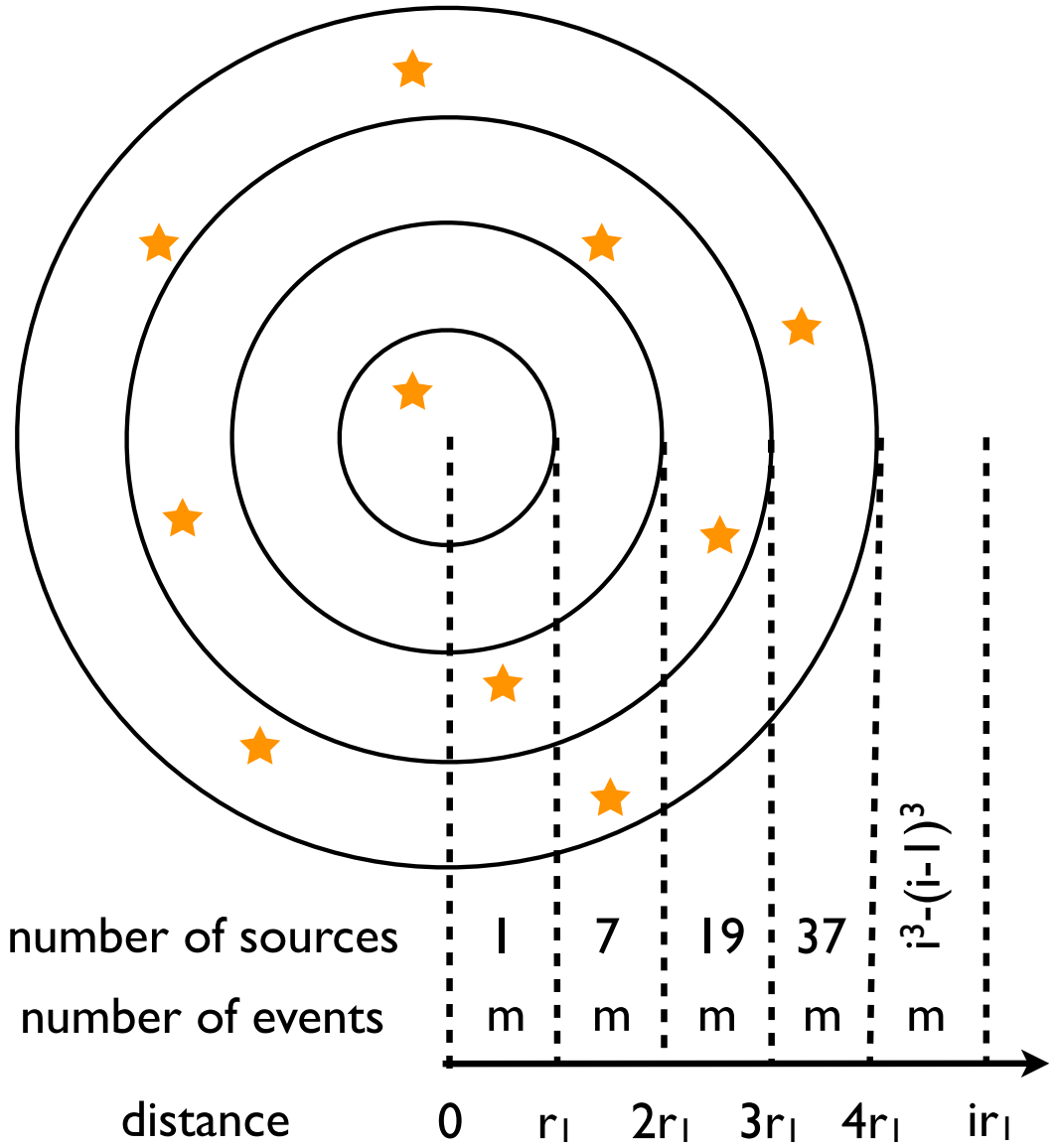
$$F_{\rm diff} = \frac{1}{4\pi} \int {\rm d}z \, \frac{{\rm d}\mathcal{V}_C}{{\rm d}z} \, \mathcal{H}(z) \, \frac{L}{4\pi d_L(z)^2} \simeq \frac{L}{4\pi} \int_0^{1/H_0} {\rm d}r \, \mathcal{H}(r)$$

- typically, the density $\mathcal{H}$ of extra-galactic sources is:
  - $10^{-3} - 10^{-2}\,{\rm Mpc}^{-3}$ for **normal galaxies**
  - $10^{-5} - 10^{-4}\,{\rm Mpc}^{-3}$ for **active galaxies**
  - $10^{-7}\,{\rm Mpc}^{-3}$ for **massive galaxy clusters**
  - $> 10^{-5}\,{\rm Mpc}^{-3}$ for **UHE CR sources**

- PS flux based on HESE measurement:

$$F_{\rm PS}(E_\nu) \simeq 9 \times 10^{-13}\,{\rm TeV cm^{-2} s^{-1}} \left(\frac{\mathcal{H}_0}{10^{-5}{\rm Mpc}^{-3}}\right)^{-1} \left(\frac{r}{10{\rm Mpc}}\right)^{-2} \left(\frac{\xi_z}{2.4}\right)^{-1}$$

# Identification of Extragalactic Point-Sources?




- total number of sources

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

- total number of "slices"

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

- total number of events

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

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

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

✘ random clusters are very likely with bad angular resolusion!

# Identification of Extragalactic Point-Sources?

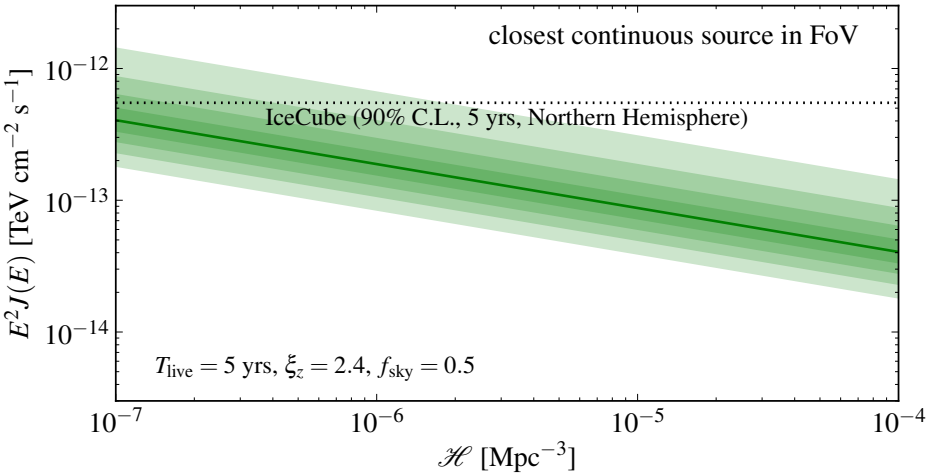
- IceCube flux normalizes the contribution of individual sources
- dependence on local source density $\mathcal{H}$ (rate $\dot{\mathcal{H}}$) and redshift evolution $\xi_z$

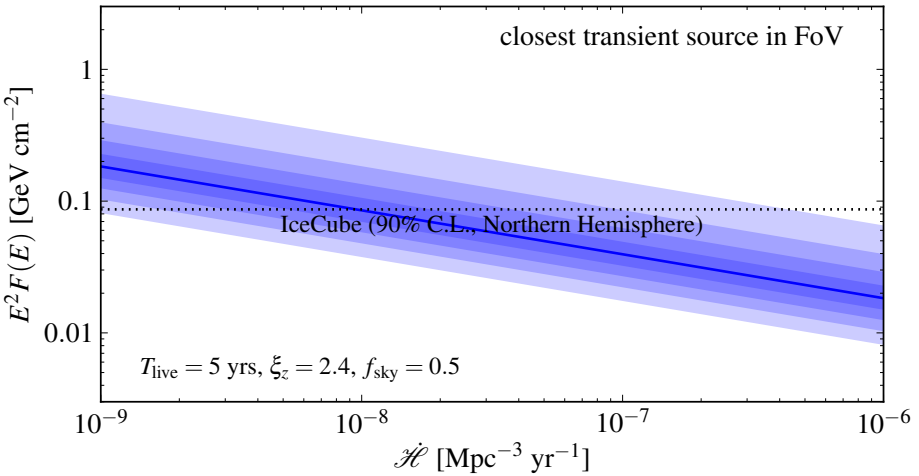
➜ PS observation requires rare sources

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

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

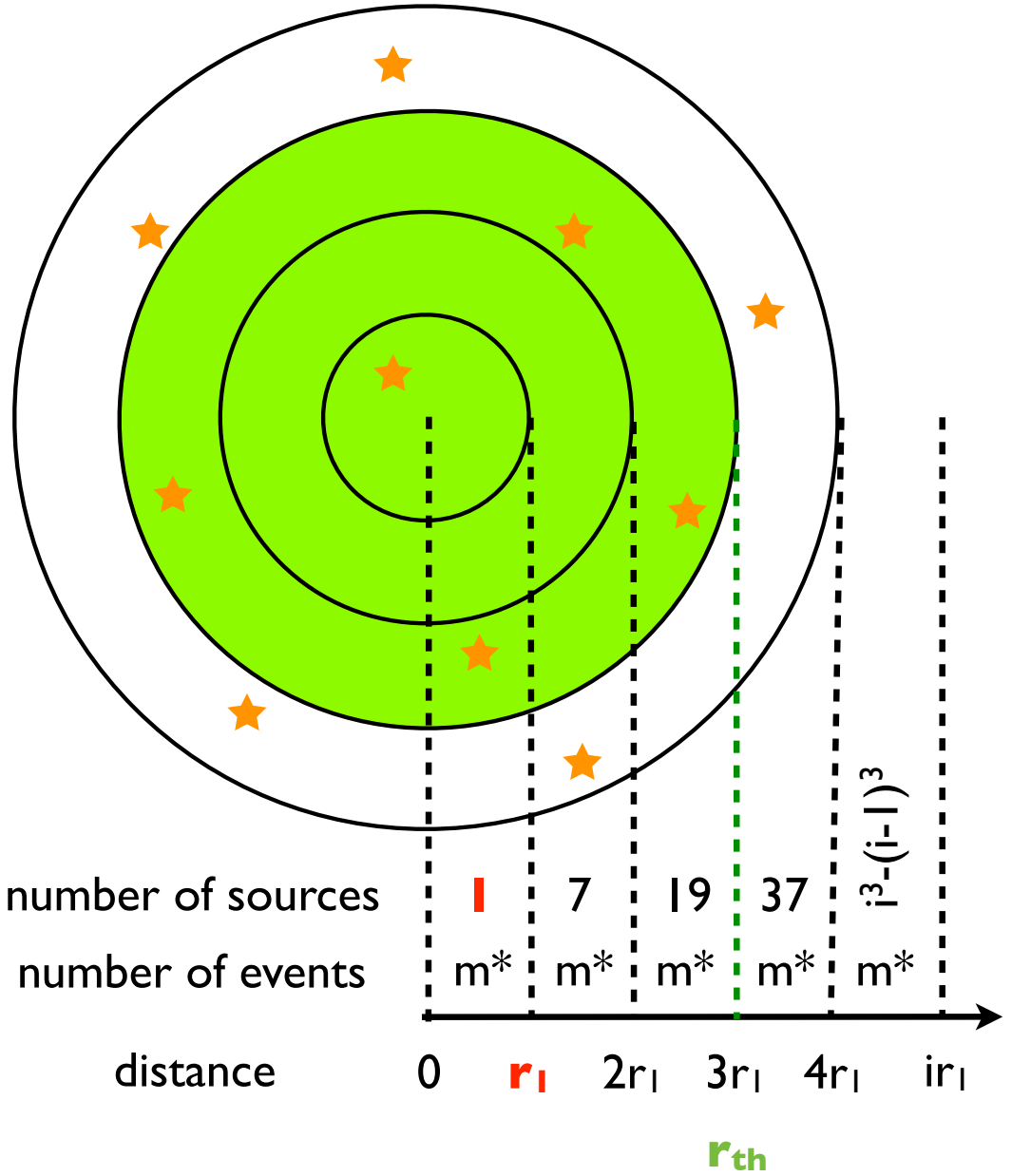
  ✘ “normal” GRBs
  ($\dot{\mathcal{H}} \simeq 10^{-9}\mathrm{Mpc}^{-3}\mathrm{yr}^{-1}$ / $\xi_z \simeq 2.4$)




[MA&Halzen’14]

# Association with Known Sources?




- total number of **known** closeby ($r < r_{\rm th}$) sources, *e.g.*

$$n_{\rm cat} \simeq 100$$

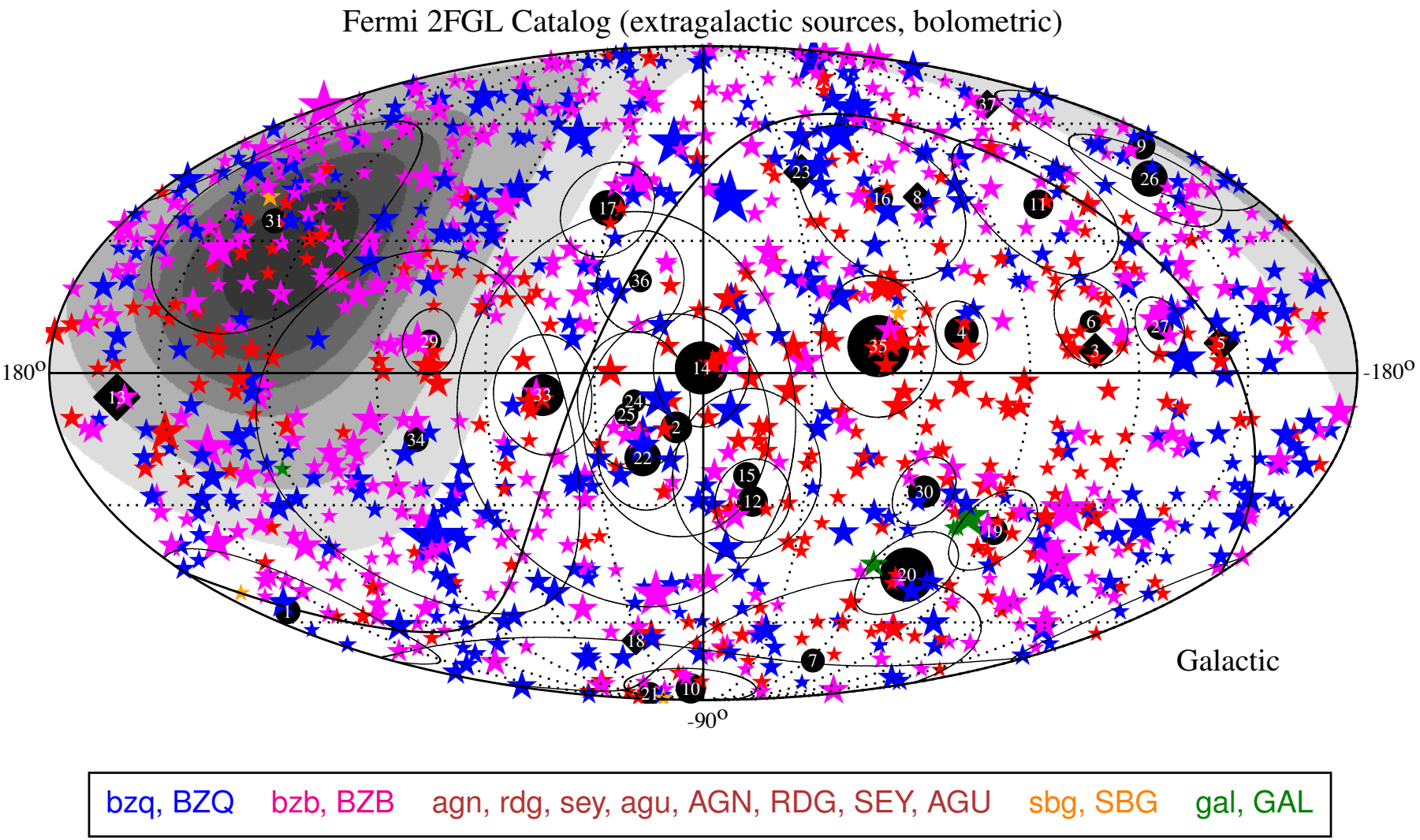
- total number of events

$$\bar{N} \simeq m^* \times n_{\rm slice} = m \times \left(\frac{n_s}{n_{\rm cat}}\right)^{\frac{1}{3}}$$

✔ required number of events to see an association ($m = 1$)

$$\bar{N} \simeq 20 - 50$$

# Association with Known Sources?



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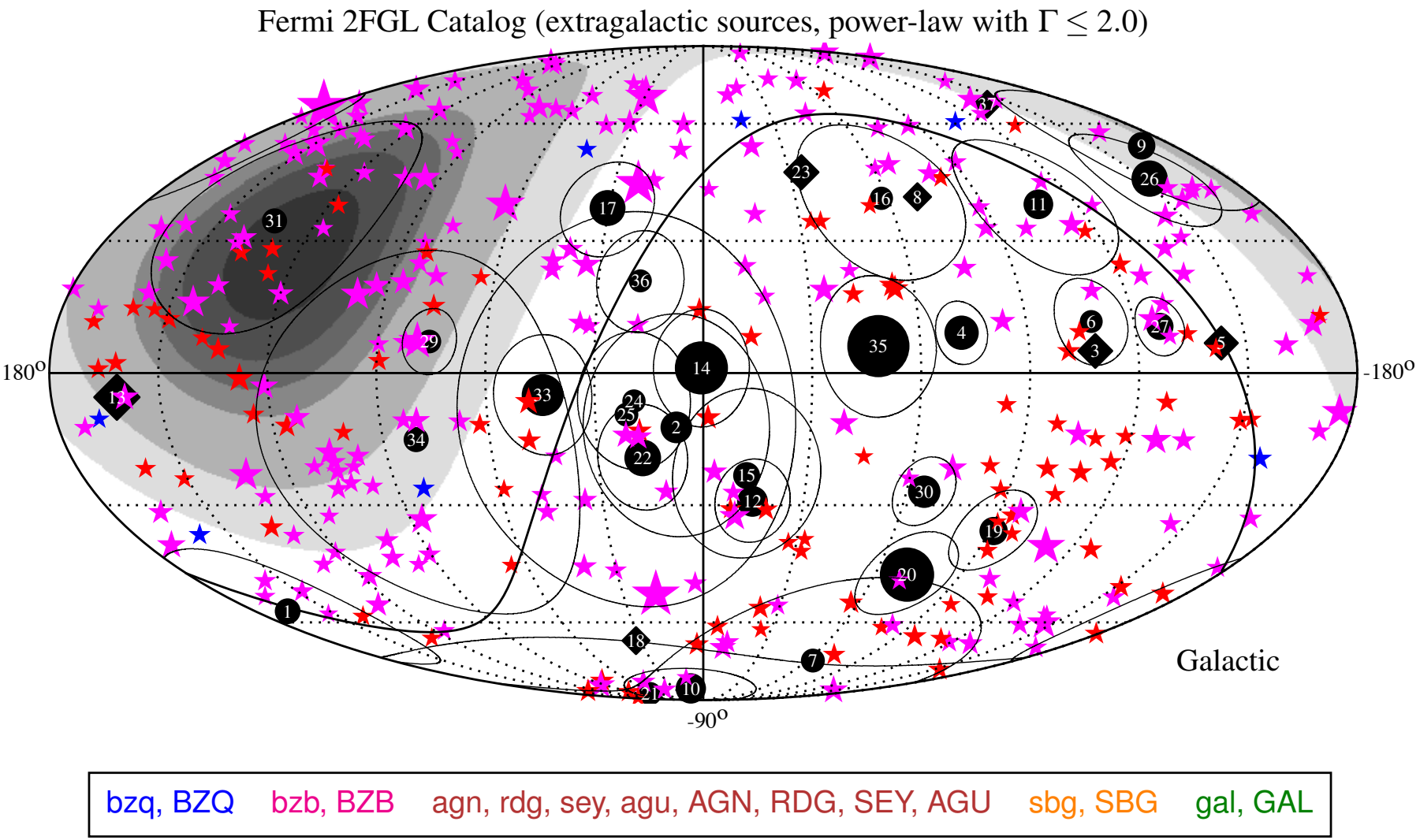
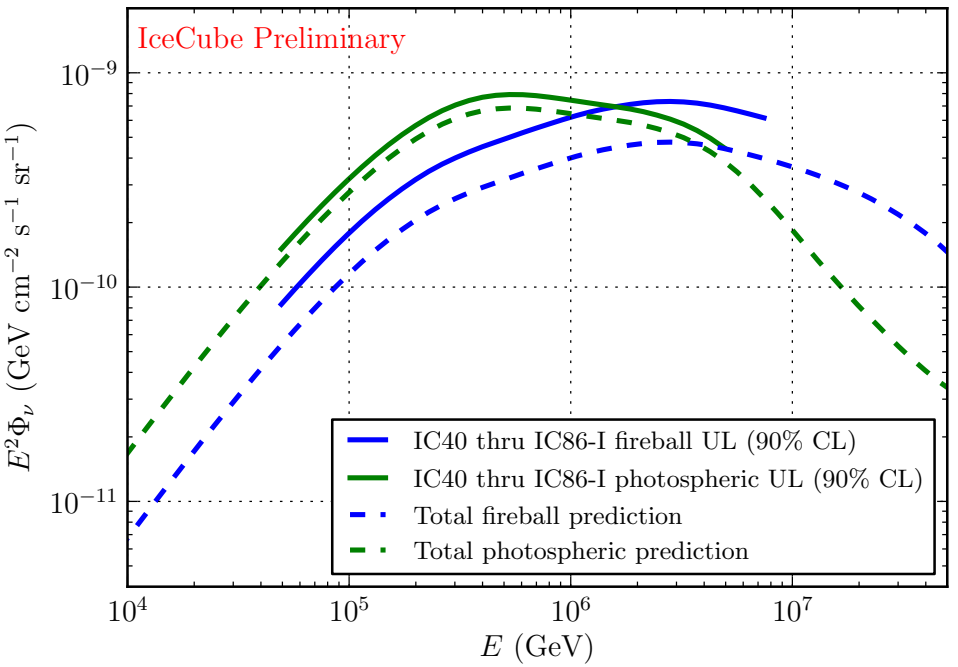


# IceCube Stacking Searches

- **GRB** stacking (right plot)
  - $\nu_\mu$ emission following the GRB "fireball" model
  - 492 GRBs (2008–2012) in IceCube's FoV reported with GCN and Fermi GBM
- **Fermi blazar** stacking

  [IceCube 1406.6757]
  - weighting with Fermi $\gamma$-ray flux
  - 33 FSRQs:
    $E^2\Phi_{\nu_\mu} < 3.5 \times 10^{-12}\mathrm{TeVcm}^{-2}\mathrm{s}^{-1}$
  - 27 LSP BL Lacs:
    $E^2\Phi_{\nu_\mu} < 5.2 \times 10^{-12}\mathrm{TeVcm}^{-2}\mathrm{s}^{-1}$
  - 37 hard $\gamma$-spectrum BL Lacs:
    $E^2\Phi_{\nu_\mu} < 3.7 \times 10^{-12}\mathrm{TeVcm}^{-2}\mathrm{s}^{-1}$




[IceCube Nature 484 (2012); M.Richman ICRC'2013]

# Isotropic Diffuse Gamma-Ray Background (IGRB)

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

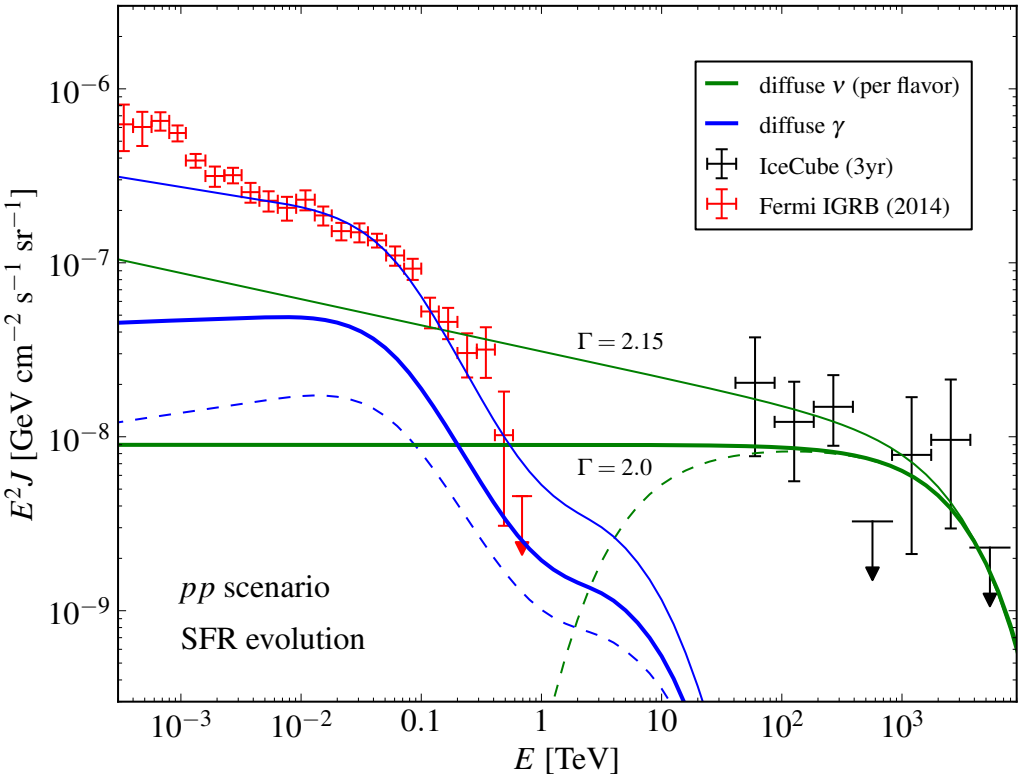
➜ low energy tail of GeV-TeV neutrino/$\gamma$-ray spectra

✘ constraint by IGRB

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

- extra-galactic emission (cascaded in EBL): $\Gamma \lesssim 2.15 - 2.2$
- Galactic emission: $\Gamma \lesssim 2.0$

➜ $\gtrsim$ 10% contribution to IGRB at $E_\gamma \gtrsim 100\mathrm{GeV}$




[Murase, MA & Lacki'13; updated with Fermi 1410.3696]

# Summary & Outlook

- IceCube 4th year HESE data to be unblinded soon.
- Refined analysis strategies with reduced atmospheric backgrounds and lower energy threshold under development.
- Do we see **individual sources or just a diffuse background**?

➜ Input from $\gamma$-ray astronomy will be **essential** to identify extragalactic source populations.

- How well can we determine the **spectrum** and **flavor composition**?
- Is the corresponding CR population responsible for **UHE CRs** (WB saturation)?
- Local **PeV $\gamma$-ray astronomy**?
- Extragalactic contributions of **EeV neutrinos** (GZK)?
- Studies of possible future extensions of IceCube underway.