GRAPPA
GRavitation AstroParticle Physics Amsterdam

Gamma Rays and Dark Matter
Obergurgl University Center
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Tomographic Constraints on High-Energy Neutrinos of Hadronuclear Origin

Shin'ichiro Ando
GRAPPA, University of Amsterdam

Ando, Tamborra, Zandanel, *PRL* **115**, 221101 (2015)

What are sources of TeV–PeV neutrinos?

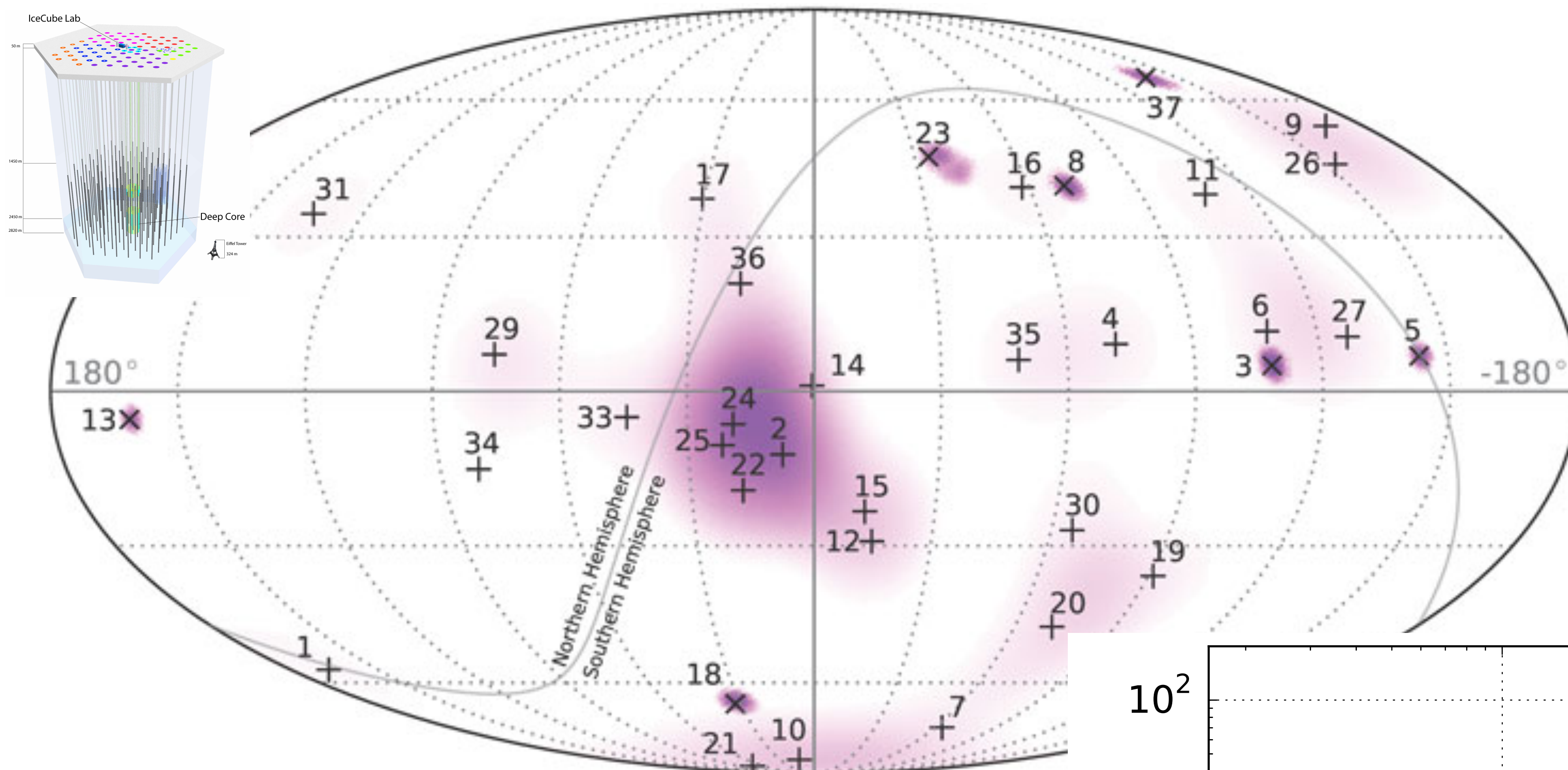
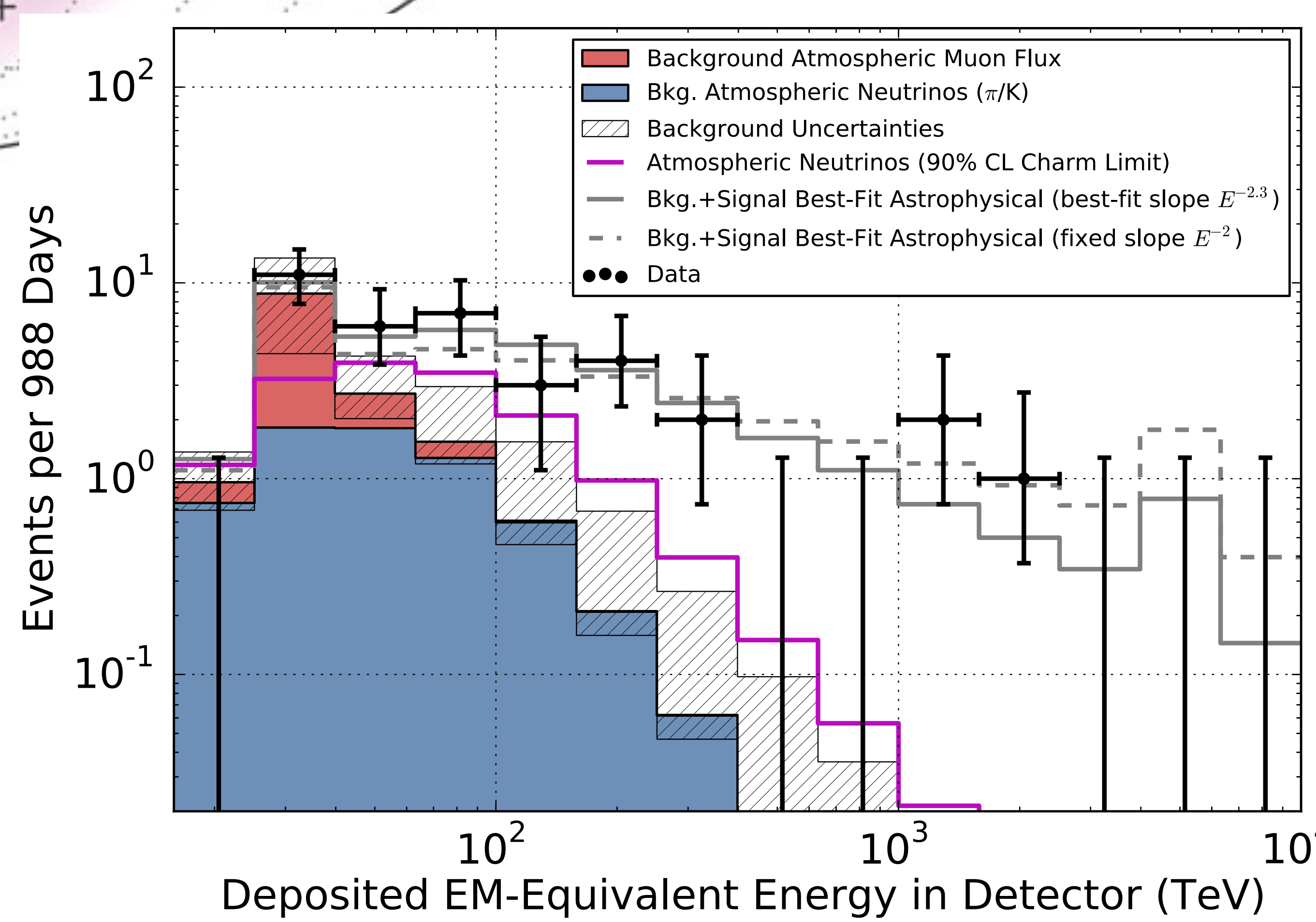


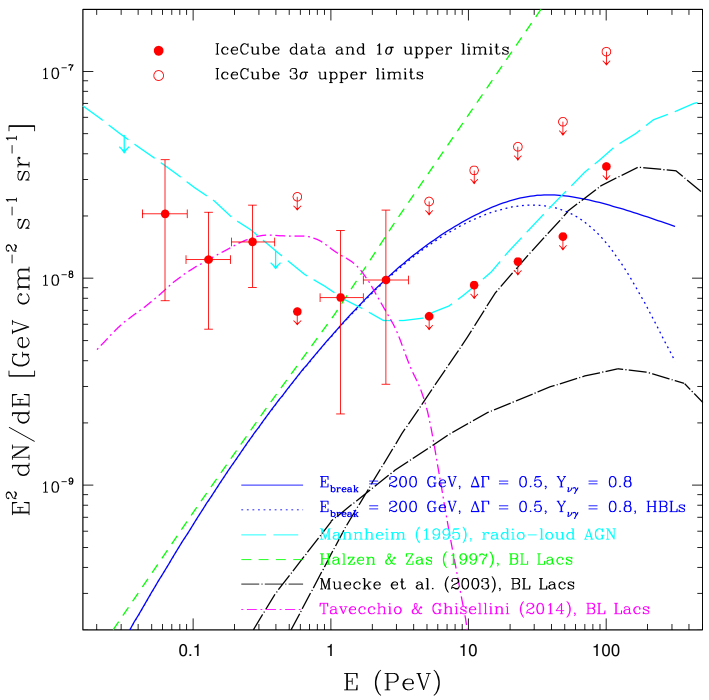
Image Credit: IceCube Collaboration



IceCube papers:
1304.5356, 1311.5238, 1405.5303, 1410.1749, 1507.03991, 1507.04005, etc.

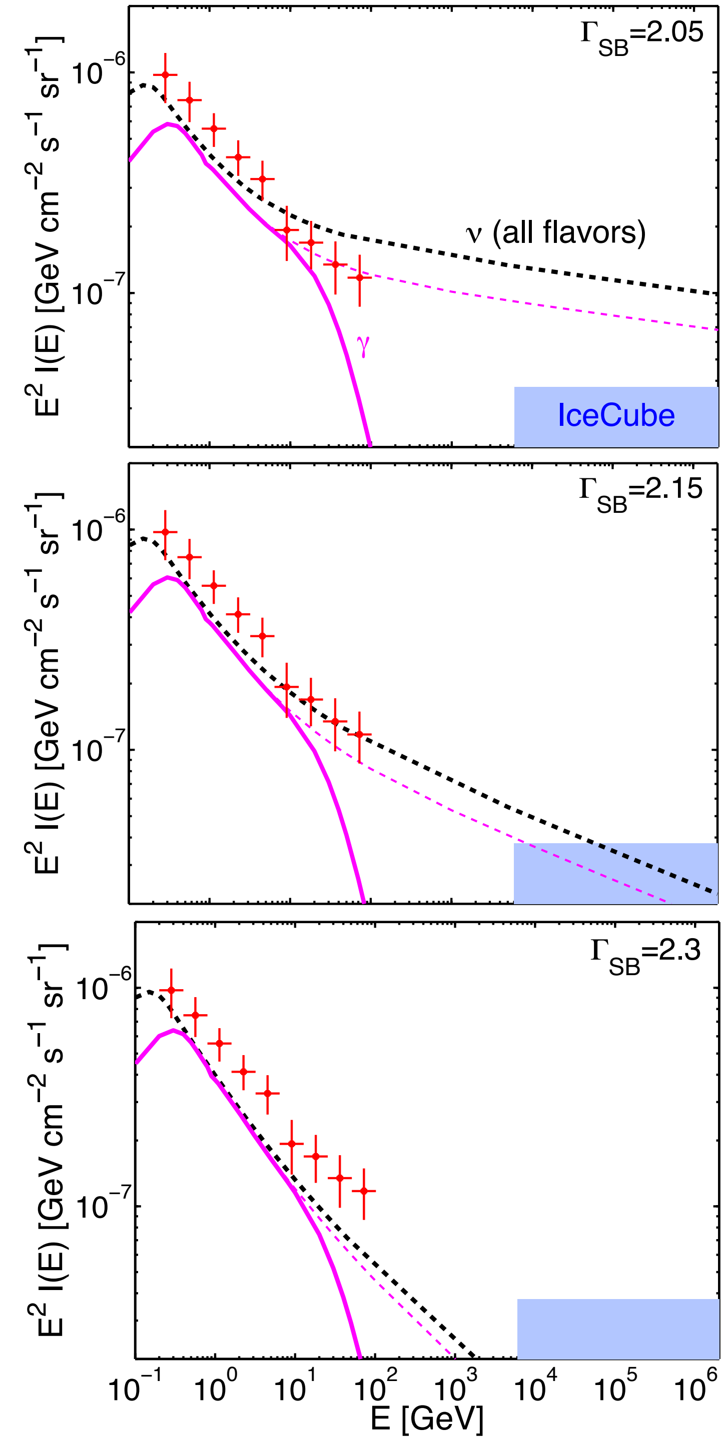
Possible astrophysical explanations

AGNs/blazars



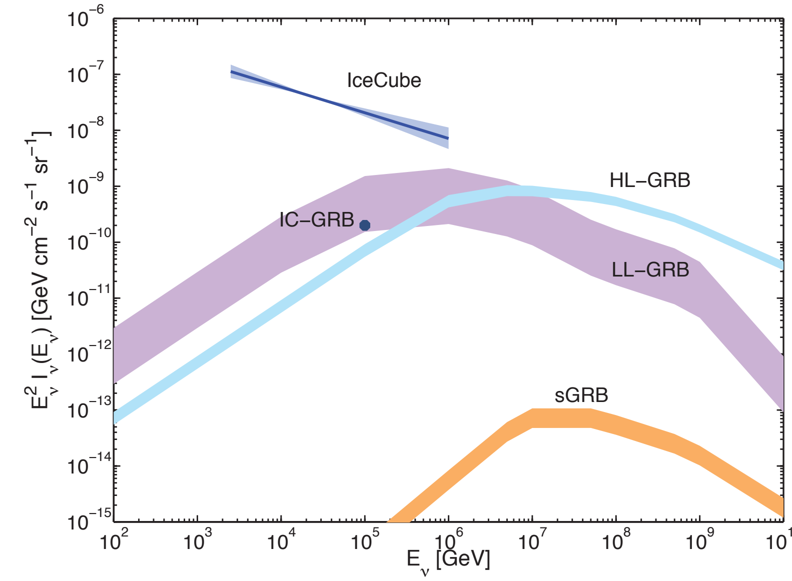
Padvani et al., 1506.09135

Star-forming galaxies



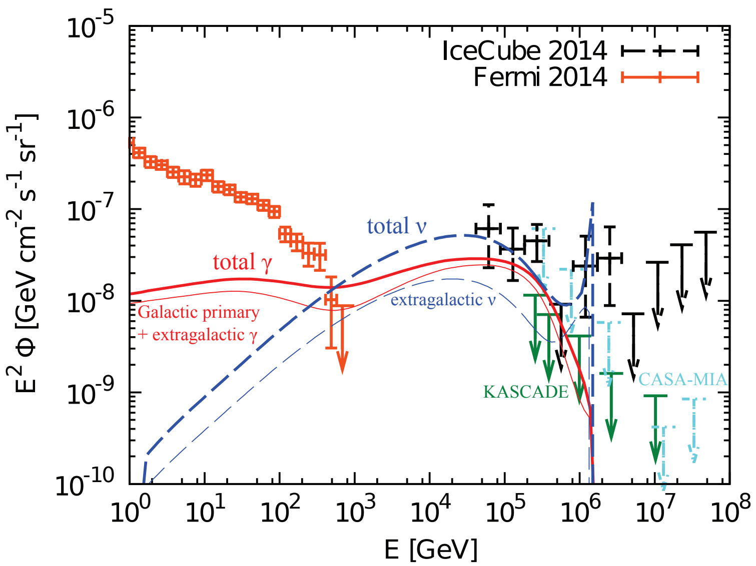
Tamborra et al., 1404.1189

GRBs



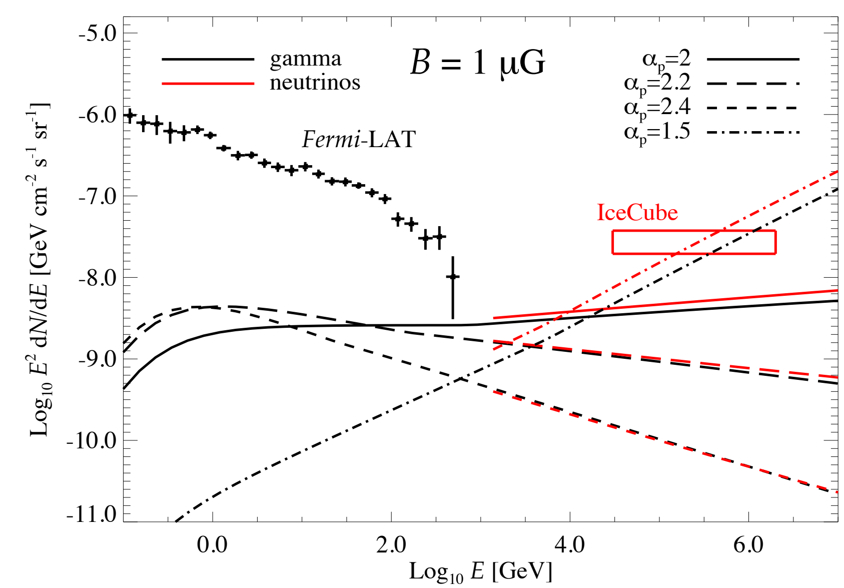
Tamborra, Ando, 1504.00107

Dark matter decay



Murase et al., 1503.04663

Galaxy clusters



Zandanel et al., 1410.8697

This work is

- **NOT** about
  - yet another modeling of whatever sources they are
- But, it is
  - ***model-independent*** study of any generic source of both gamma rays and neutrinos (i.e., **hadronuclear** source)

Two origins

Photohadron $p + \gamma \rightarrow \pi^0, \pi^\pm$

Usually, protons have to be very energetic, making pions very energetic too

Hadronuclear $p + p \rightarrow \pi^0, \pi^\pm$

Interaction can happen for low-energy protons

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Pion decays

$$\pi^0 \rightarrow 2\gamma$$

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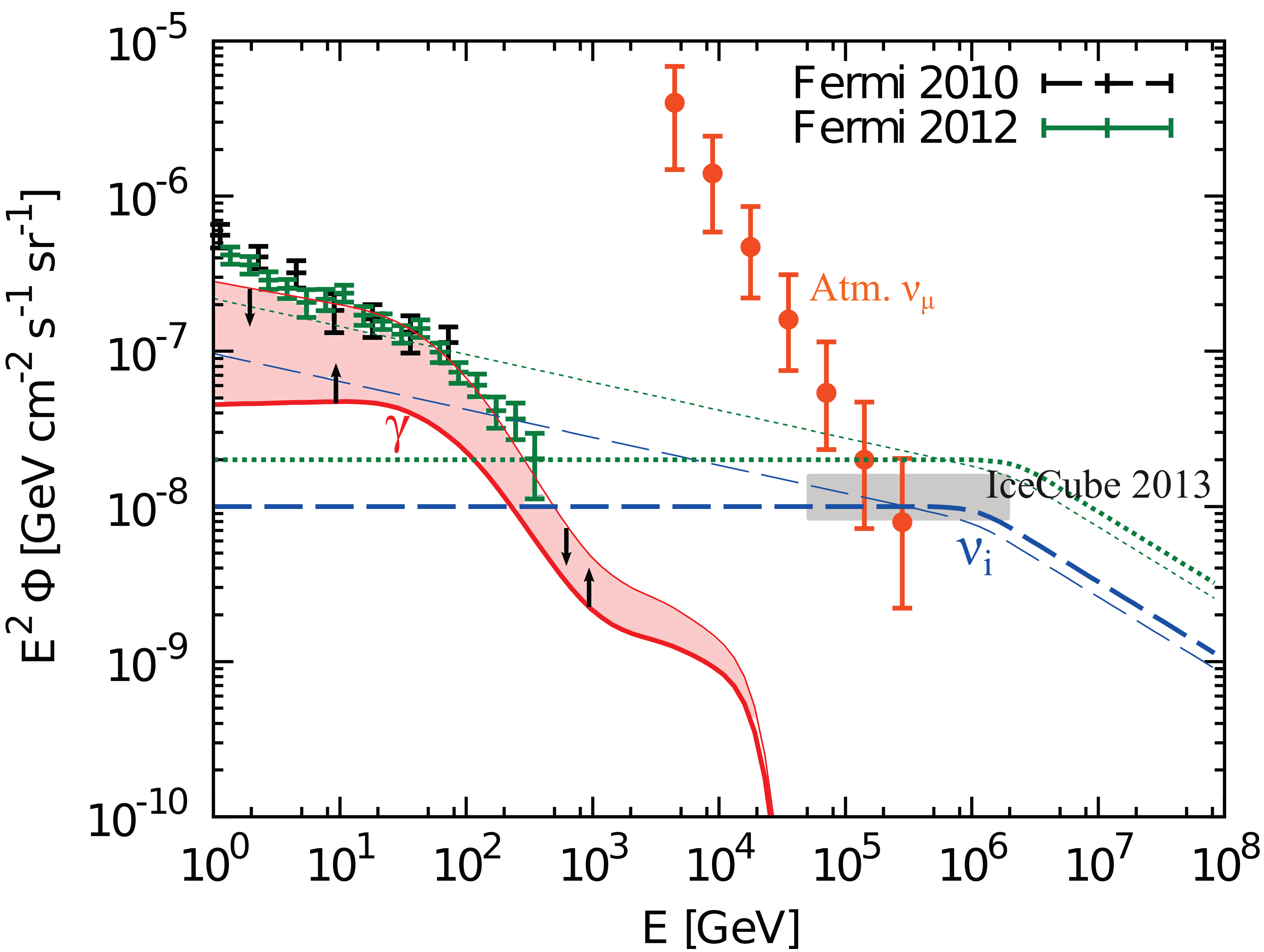
Any (optically thin) hadronuclear sources will produce both neutrinos and gamma rays down to GeV energies

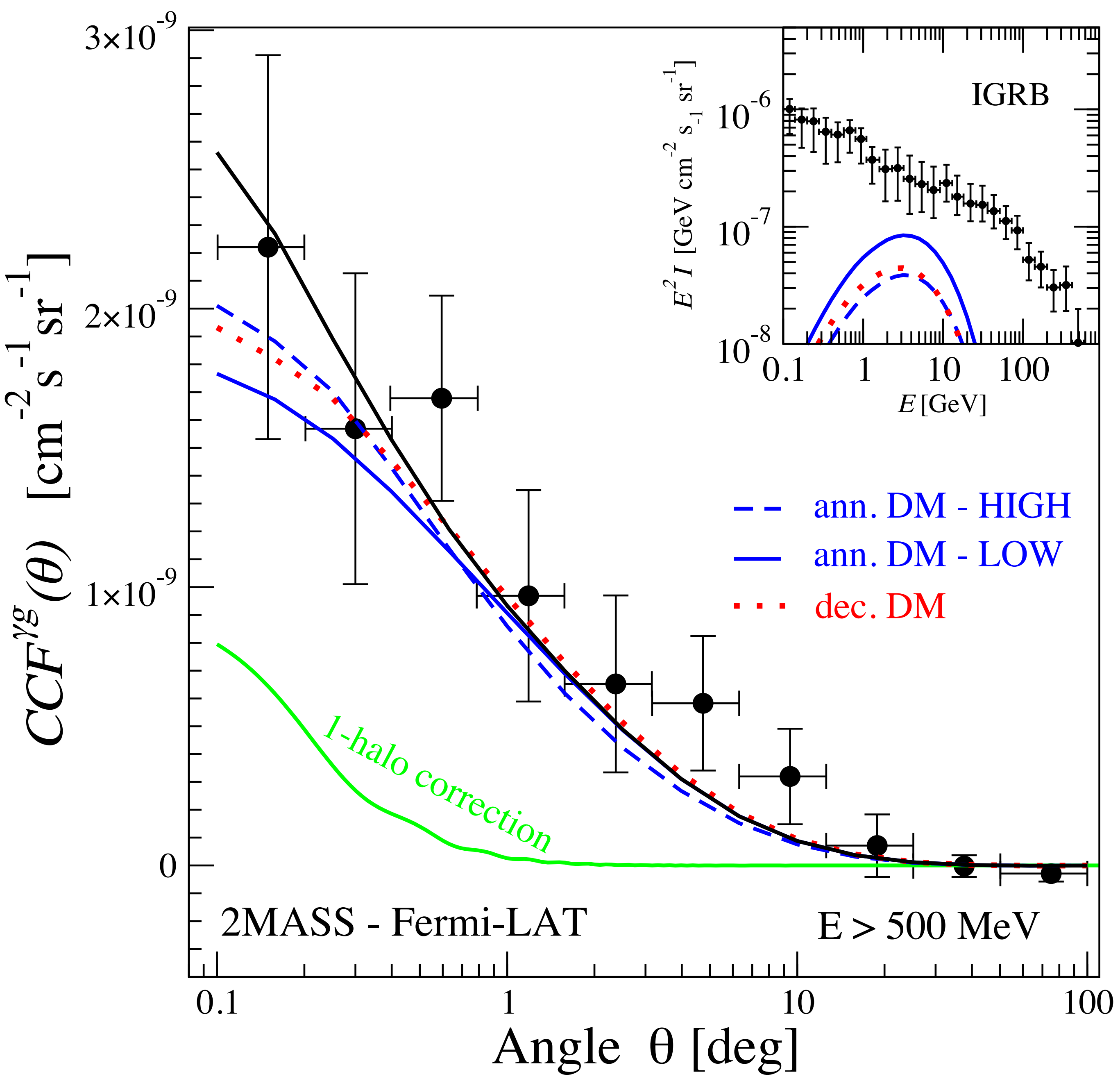
Spectral constraints

Murase, Ahlers, Lacki, 1306.3417



- If IceCube neutrinos are explained by hadronuclear sources, they will also produce GeV gamma rays
- These cannot overshoot the Fermi-LAT measurement of IGRB
- Implication: Spectrum cannot be softer than $E^{-2.2}$

Cross correlation between IGRB and galaxies



Xia et al., 1503.05918
Regis et al., 1503.05922
Cuoco et al., 1506.01030

- Yet another probe of gamma-ray sources due to recent measurements of cross correlations between IGRB and galaxy catalogs
- Proven to be strong probe of dark matter annihilation or decay
- *This can also be applied to neutrino sources if they are of hadronuclear origin!*

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$$\frac{dN}{dE} \propto E^{-\alpha}$$

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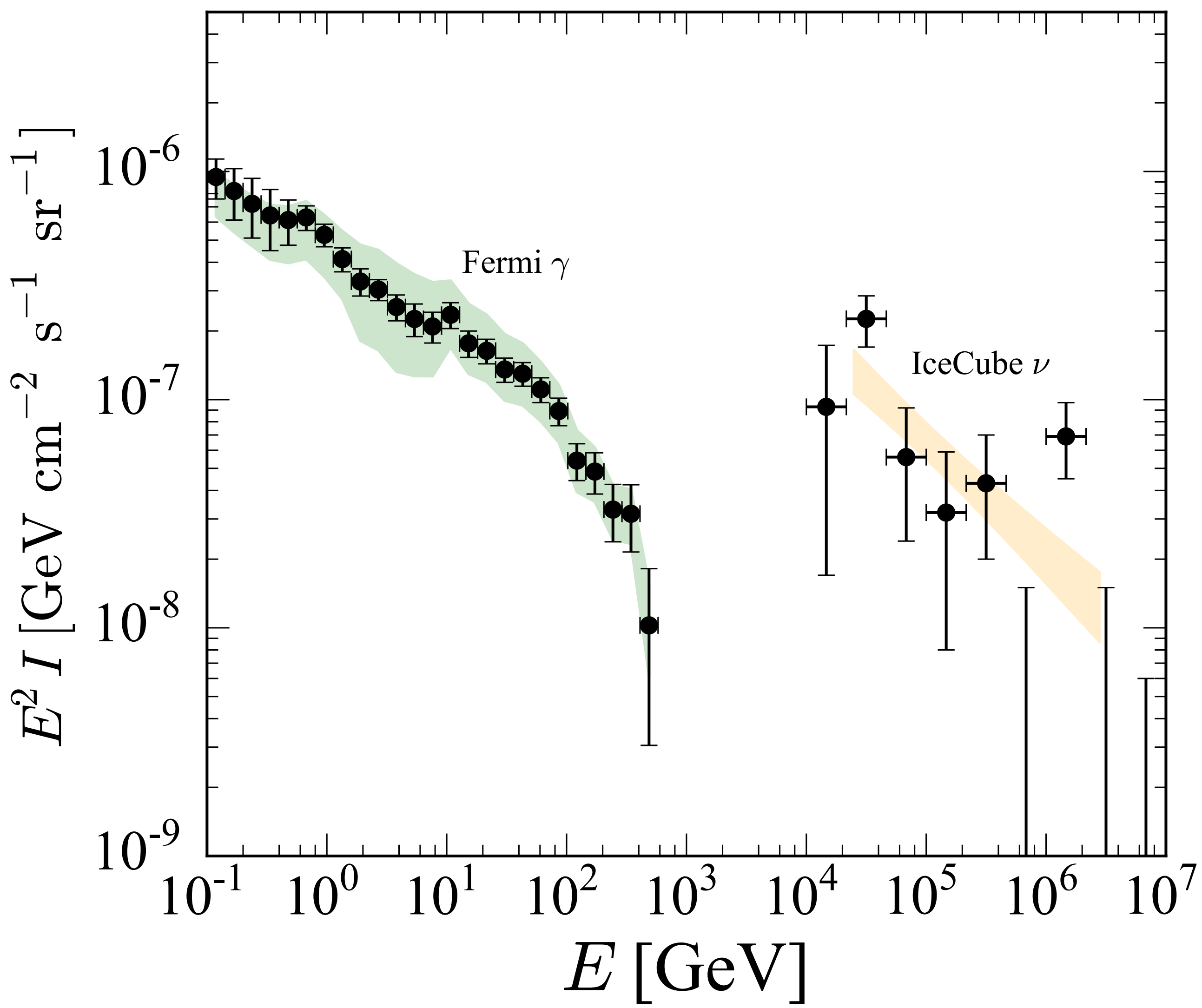
2. Source **luminosity density** evolves as power of 1+*z*

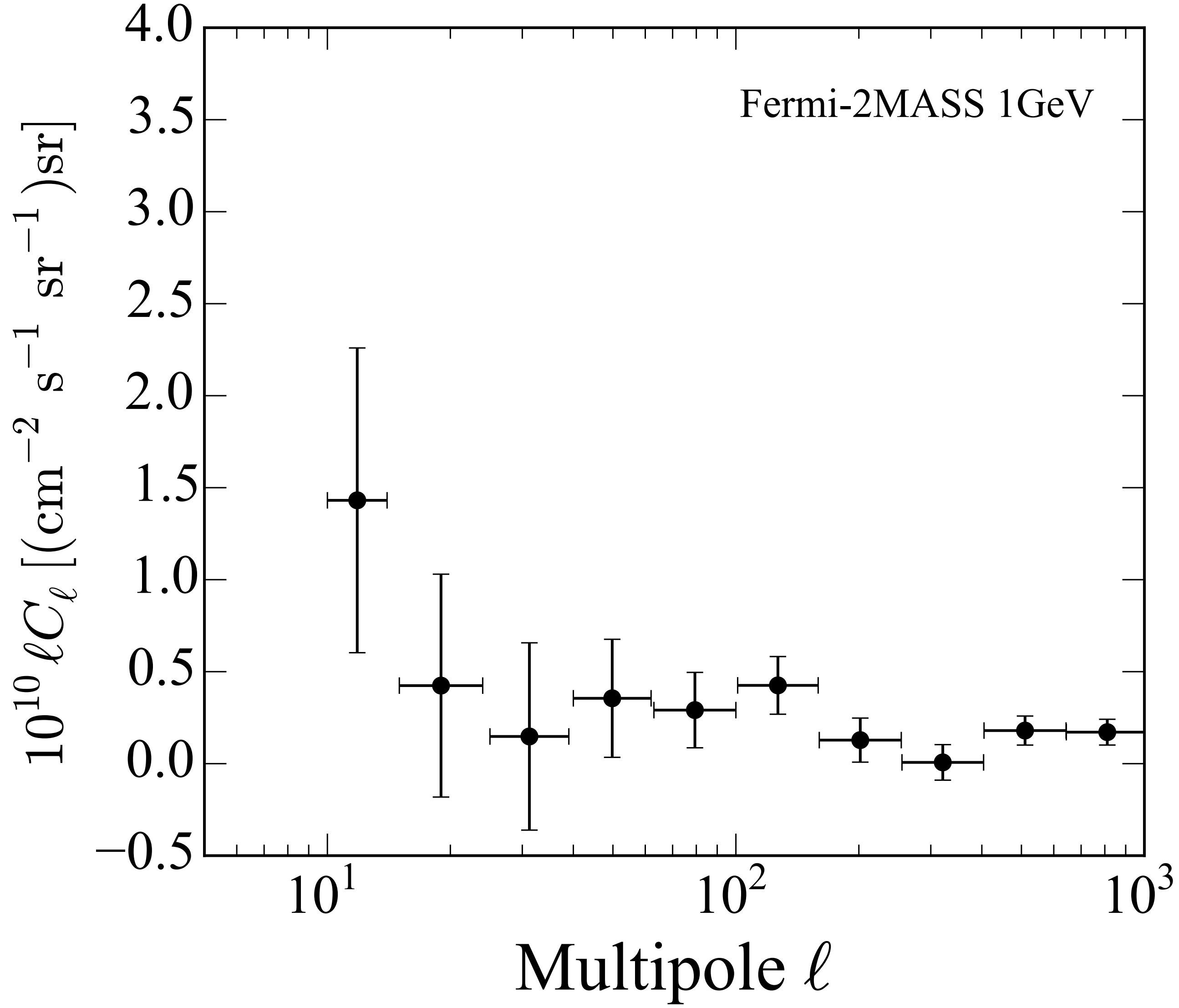
$$\mathcal{E} \propto (1+z)^{\delta}, \text{ for } z < 1.5$$

3. Sources **trace underlying dark matter** distribution in an unbiased way

$$P_{\gamma \mathrm{g}}(k,z) = b_\gamma b_\mathrm{g} P_\mathrm{m}(k,z) \text{ with } b_\gamma = 1$$

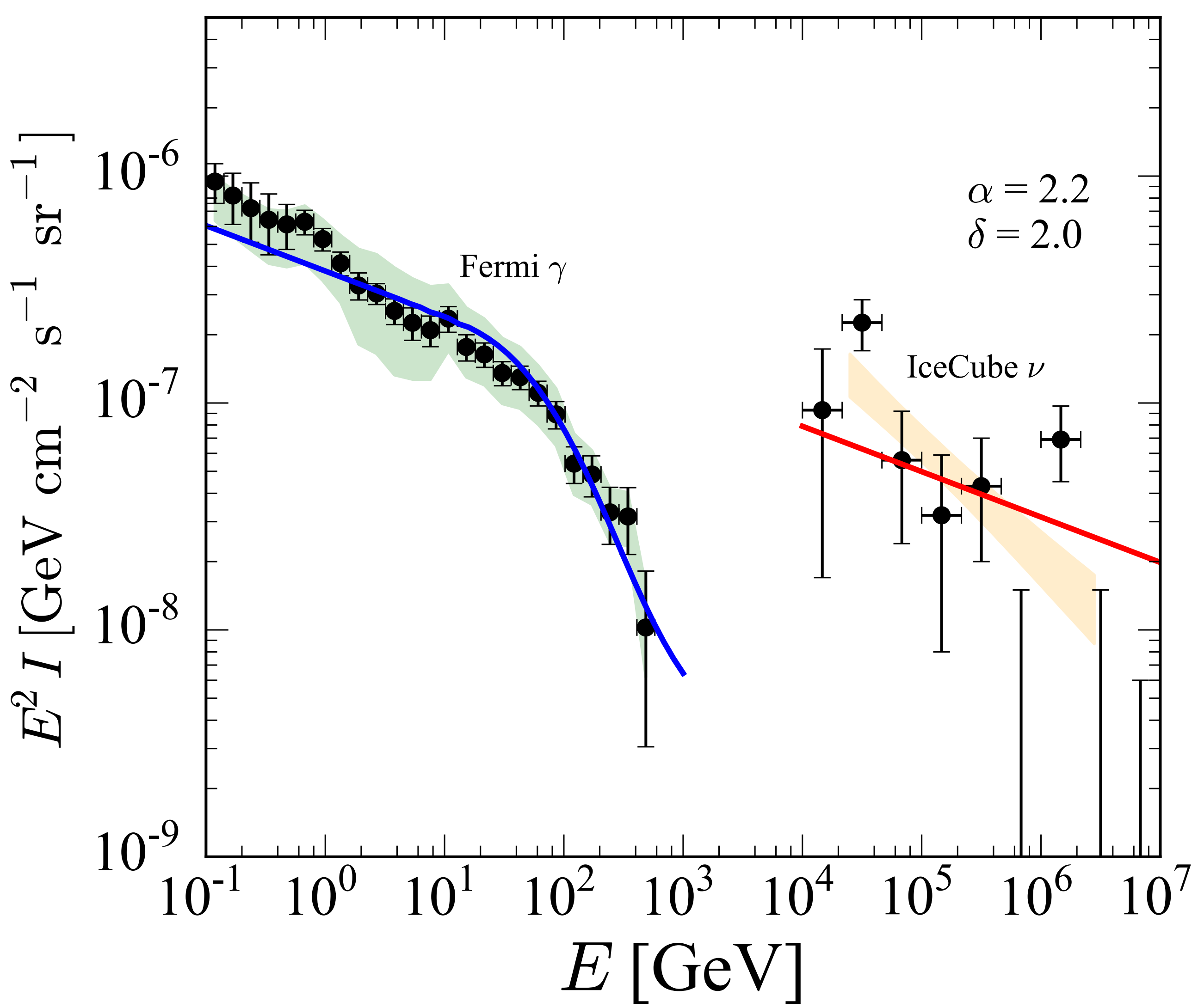
Spectral constraints

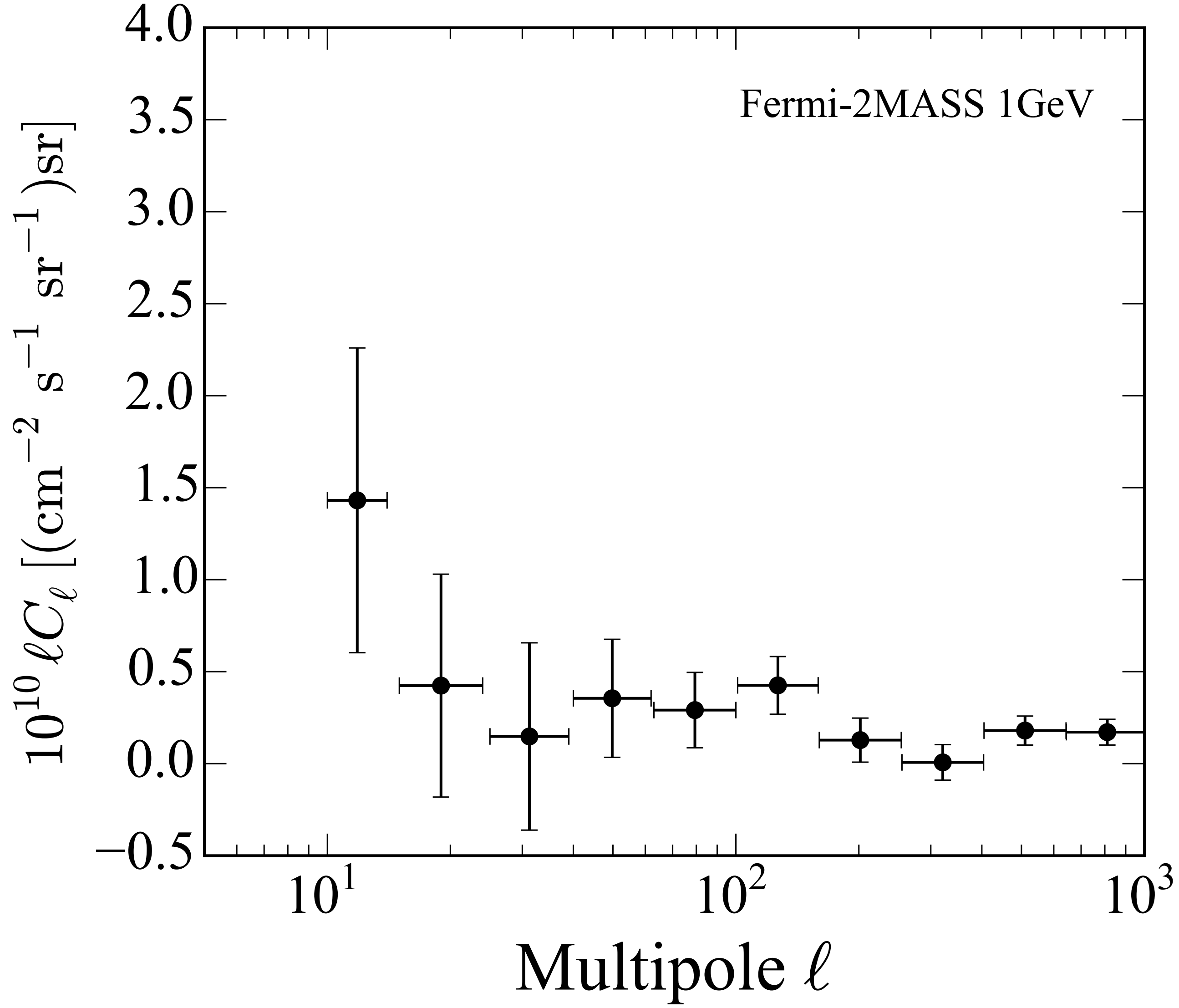




Ando, Tamborra, Zandanel, 1509.02444

Spectral constraints





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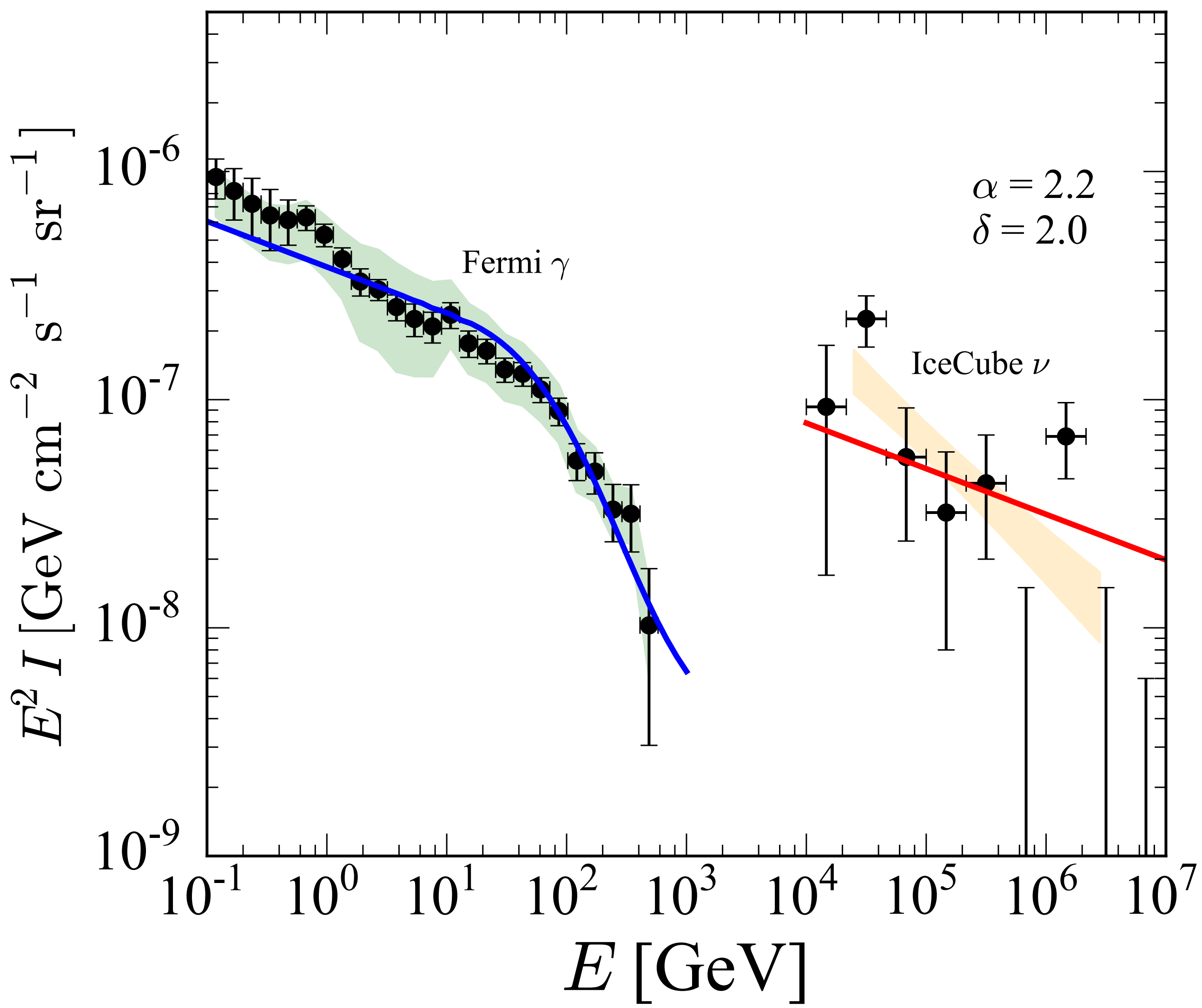
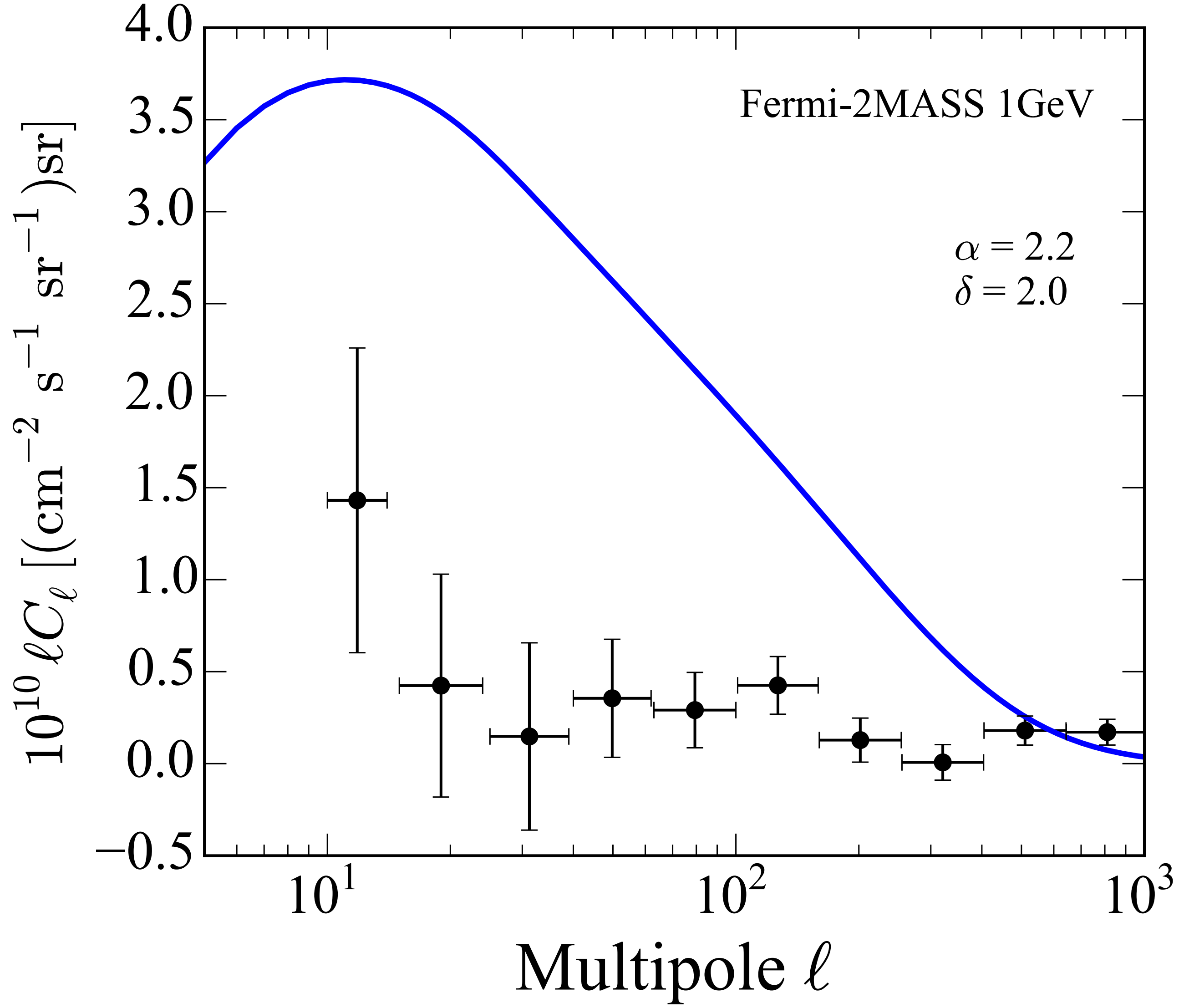
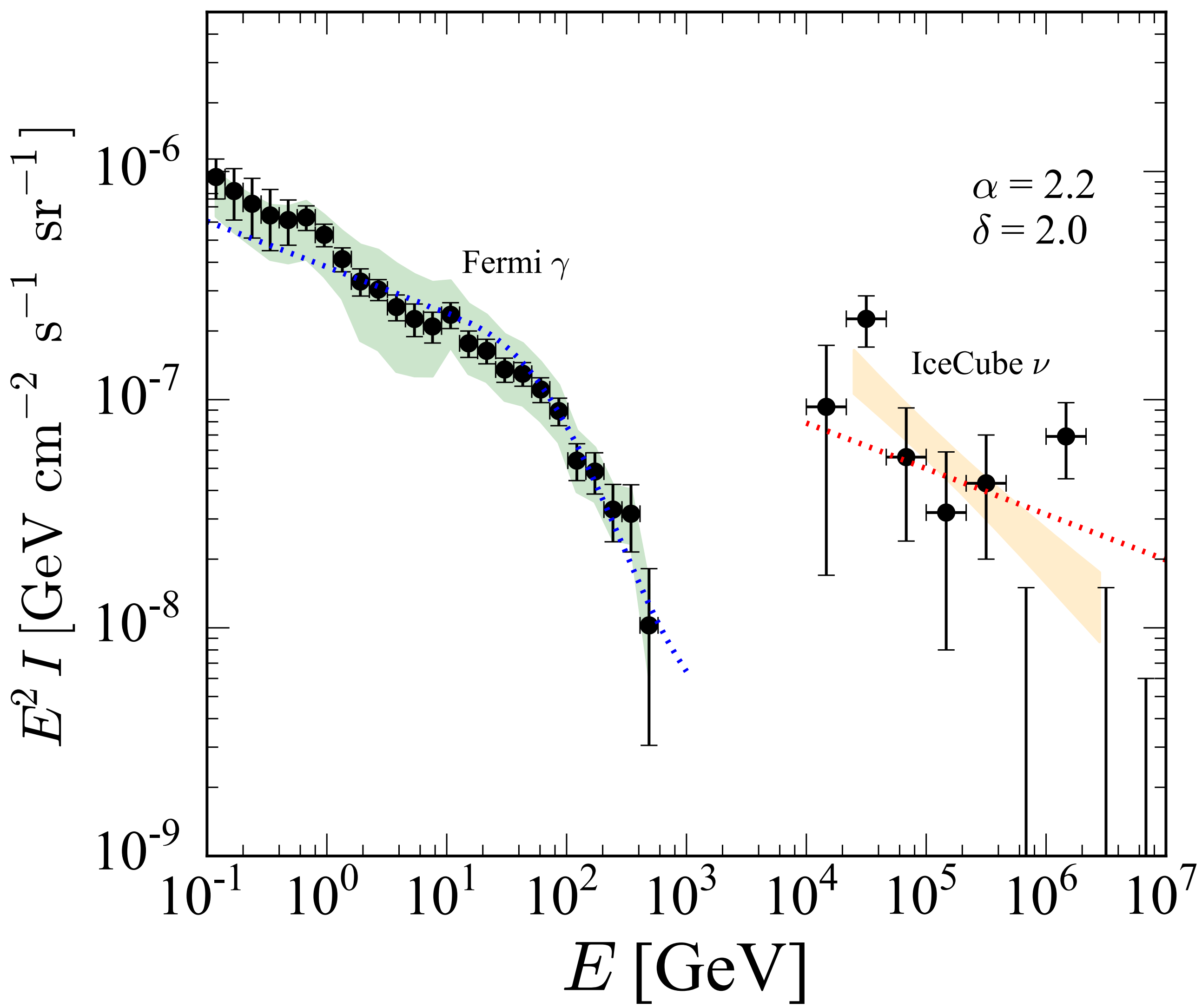
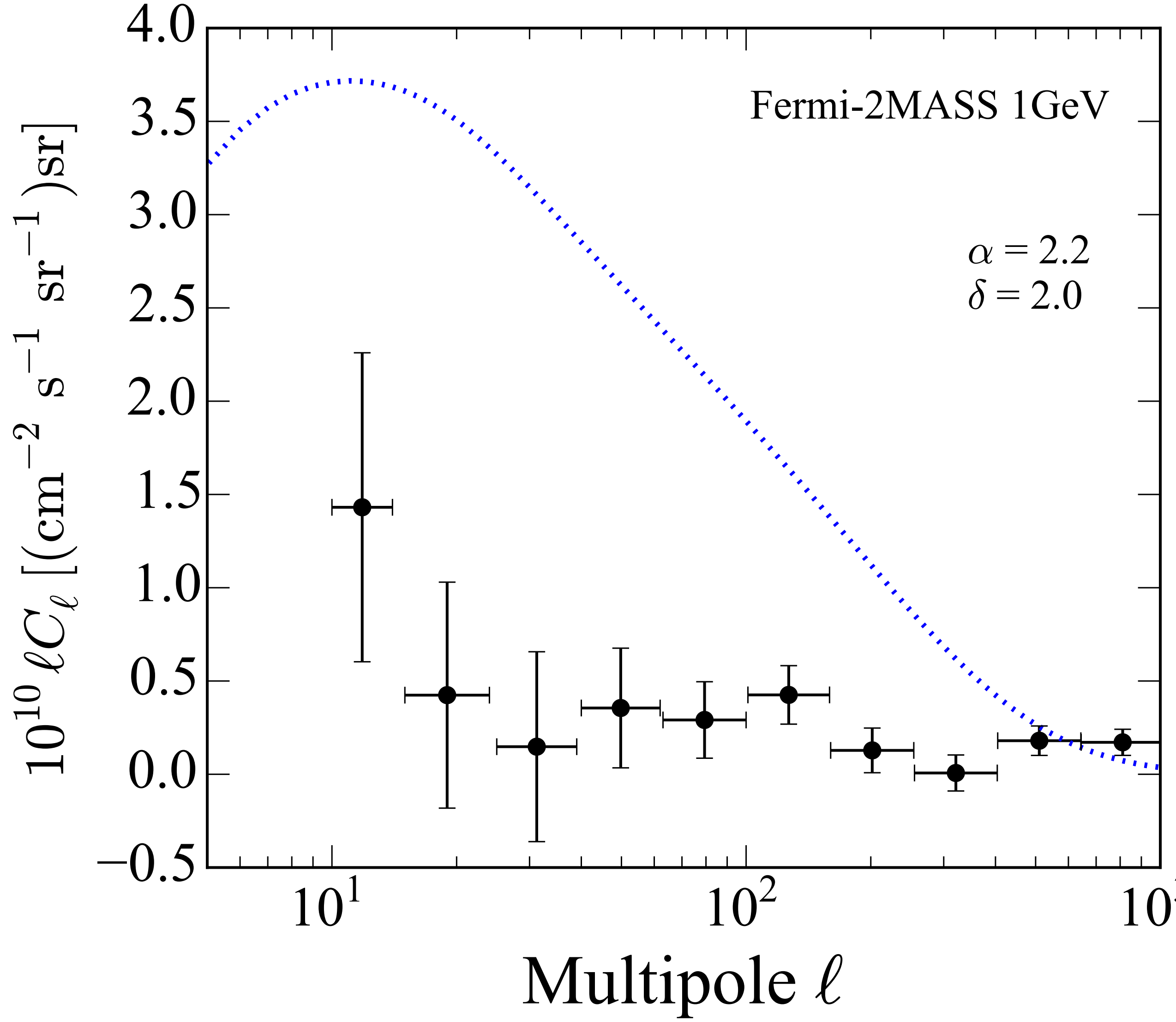




Ando, Tamborra, Zandanel, 1509.02444

Tomographic constraints





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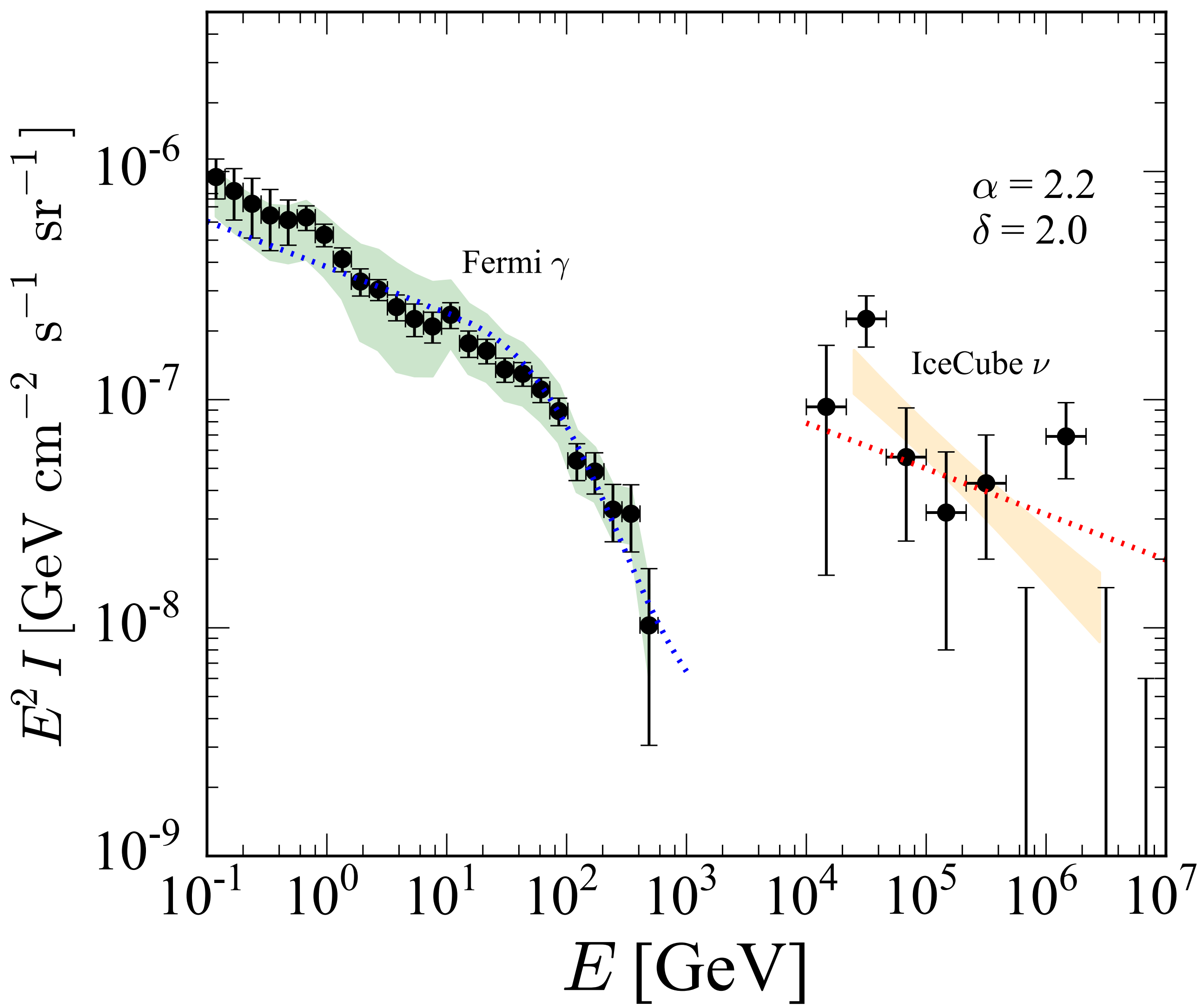

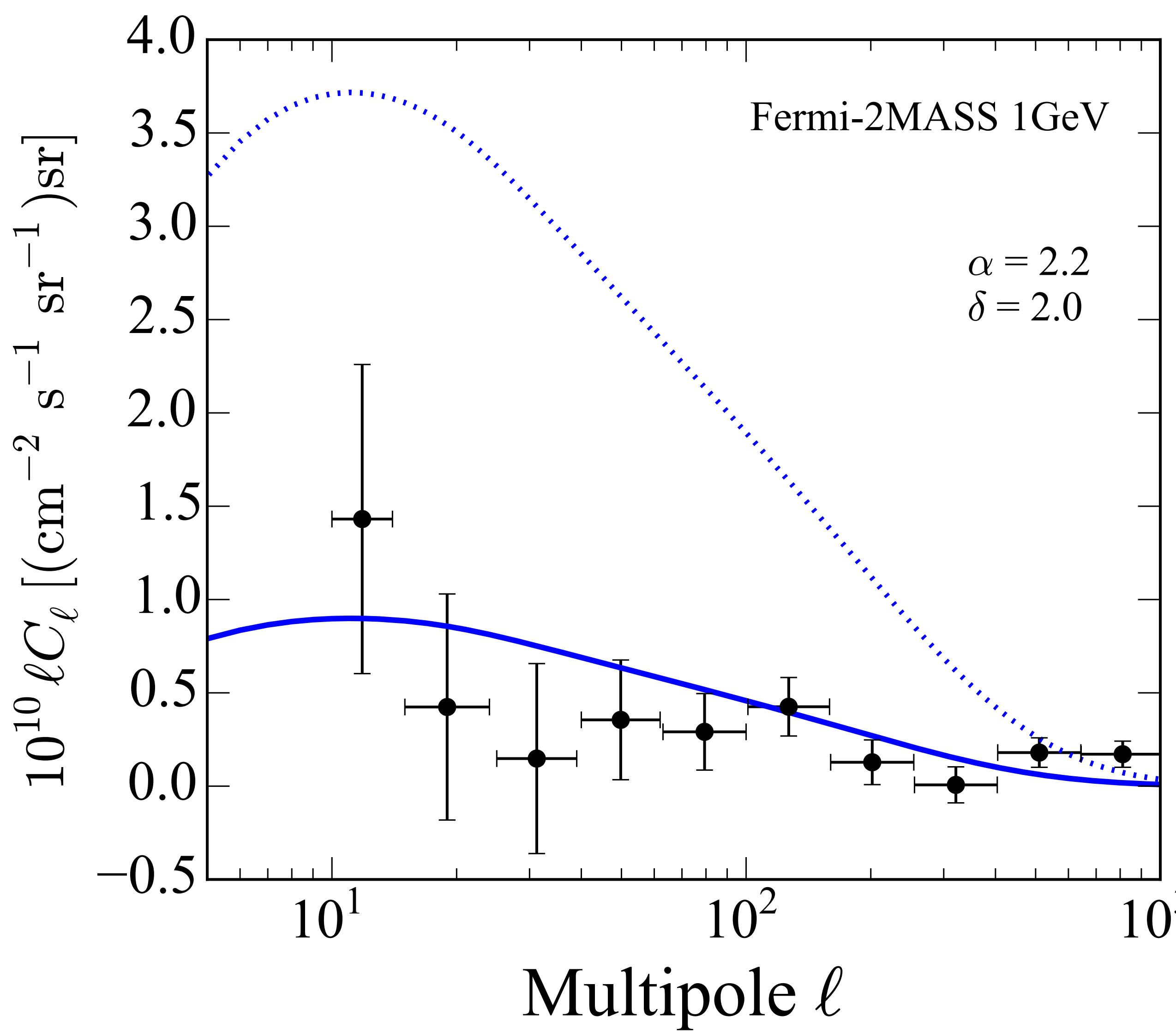

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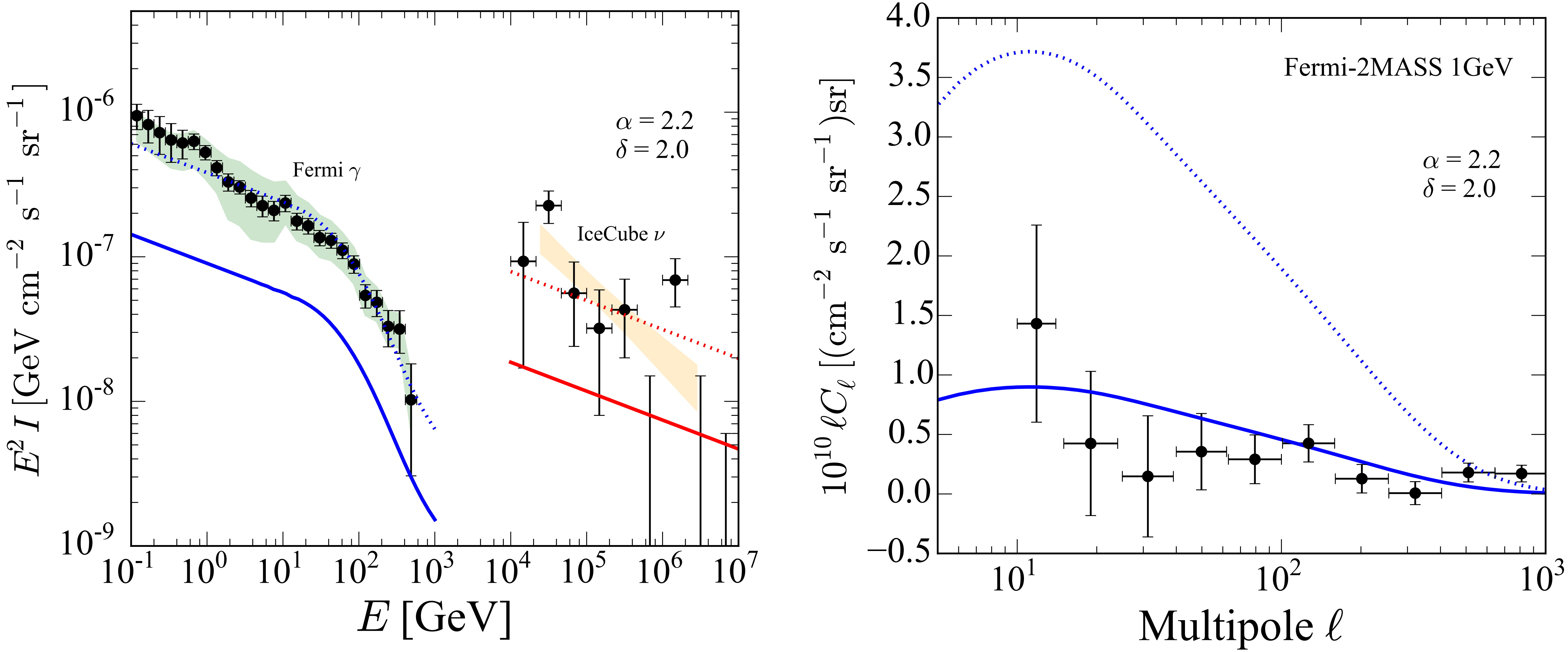
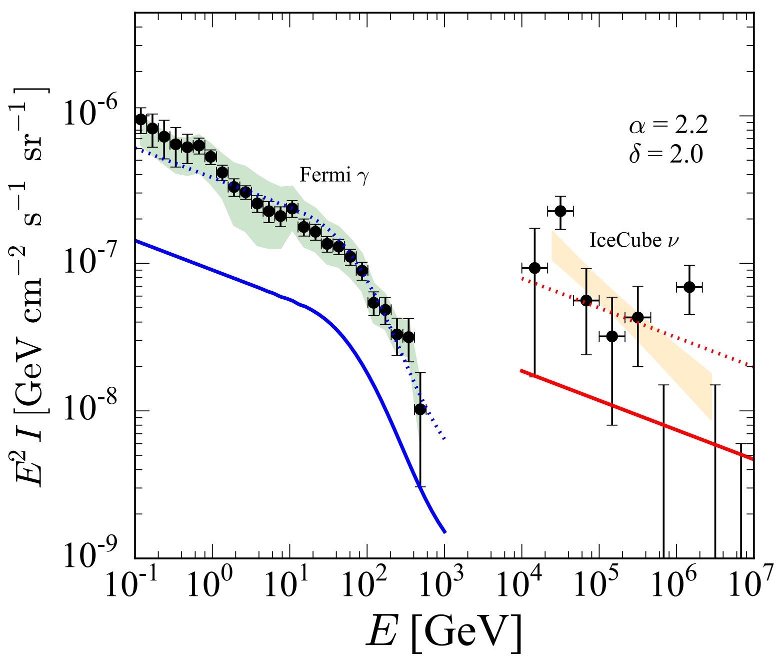
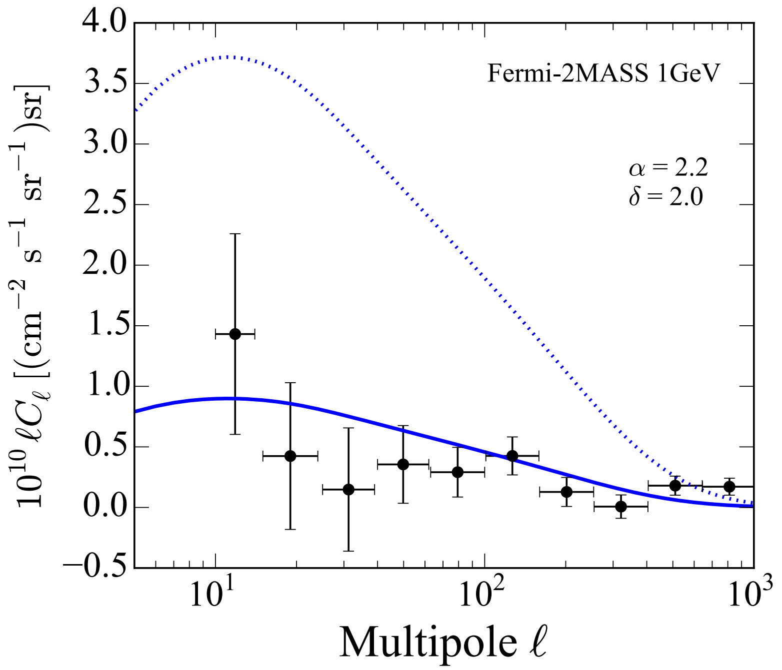


Ando, Tamborra, Zandanel, 1509.02444

Dependence on **α** and **δ**





Ando, Tamborra, Zandanel, 1509.02444

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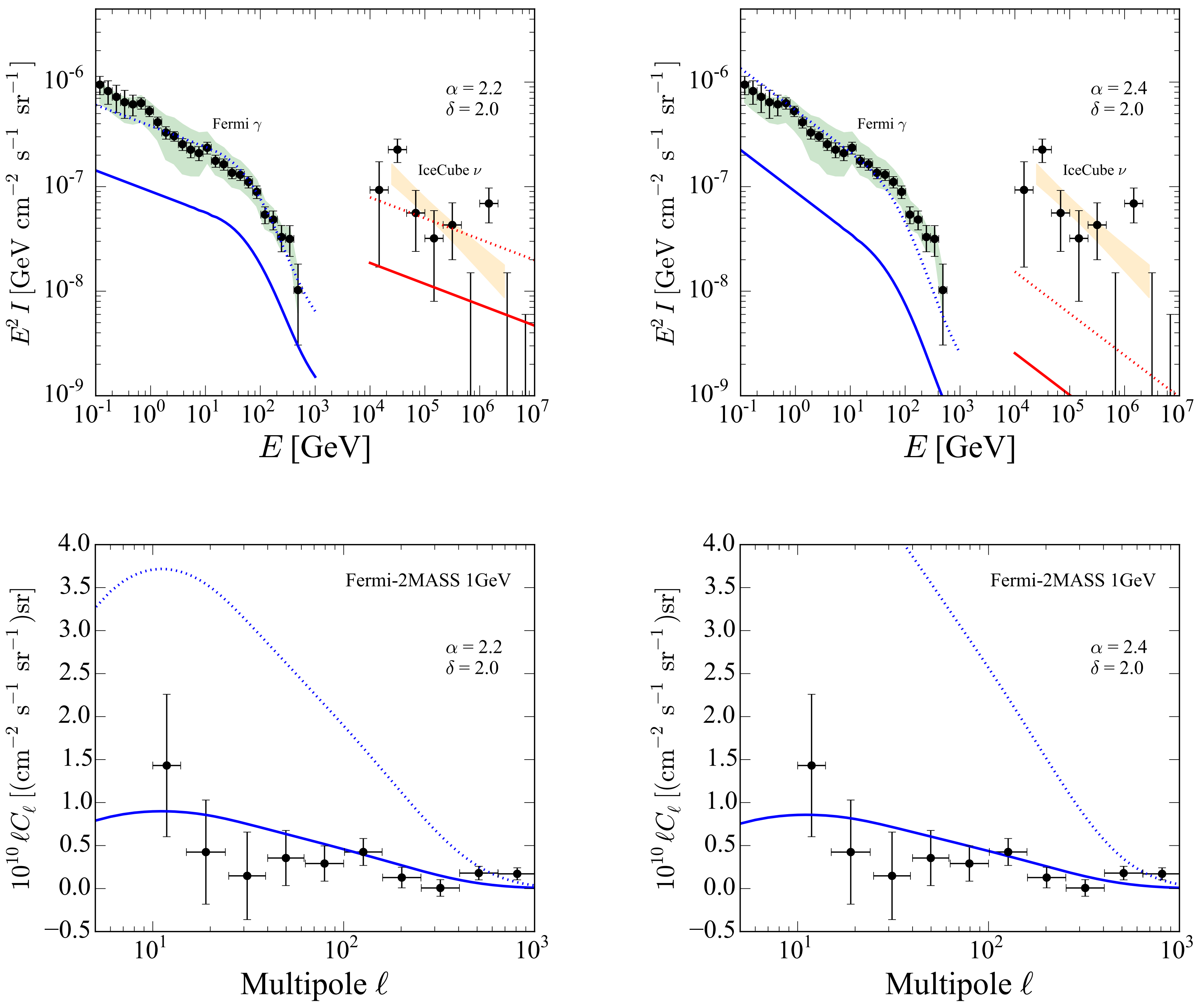
Soft spectrum



Ando, Tamborra, Zandanel, 1509.02444

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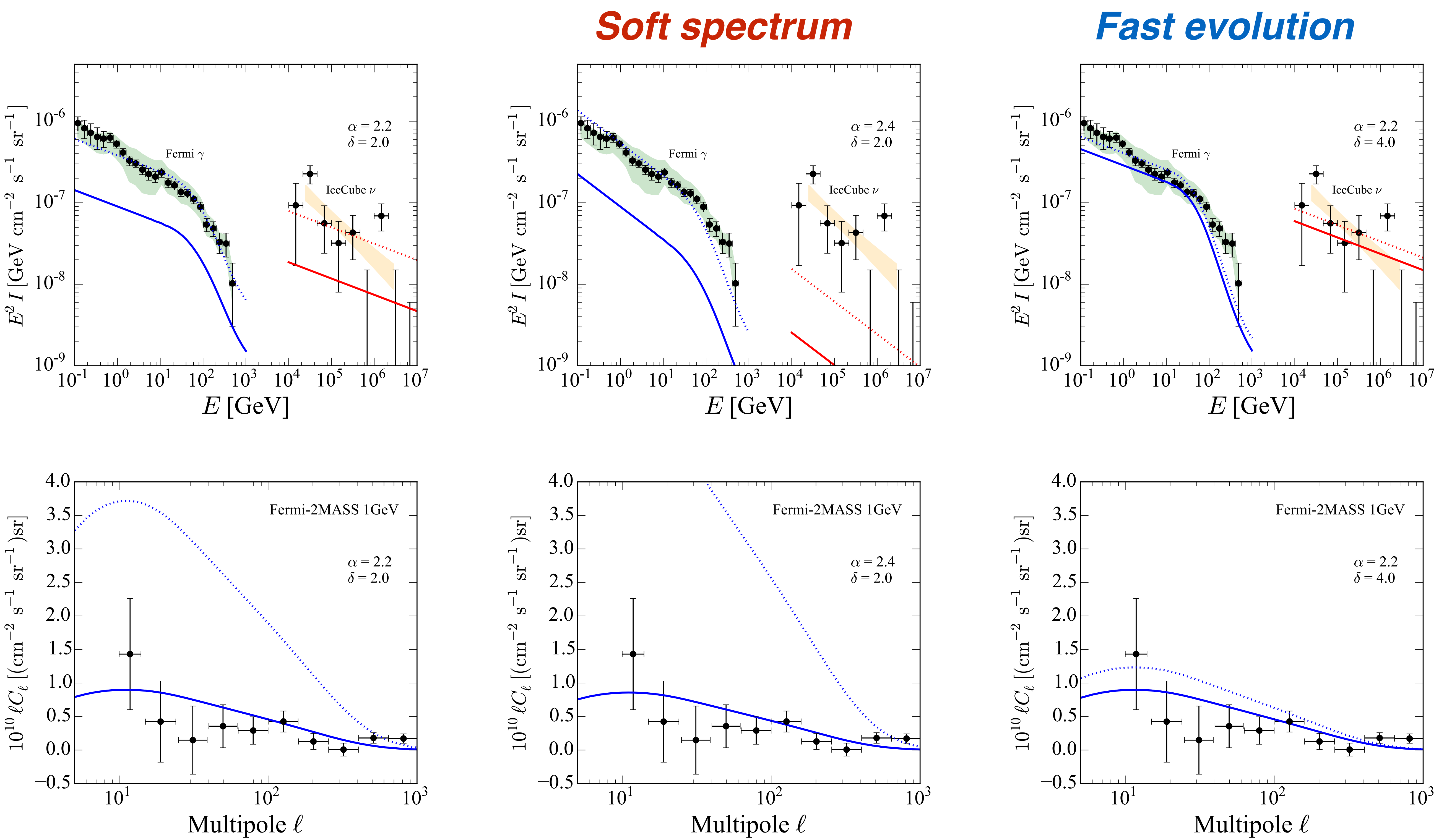
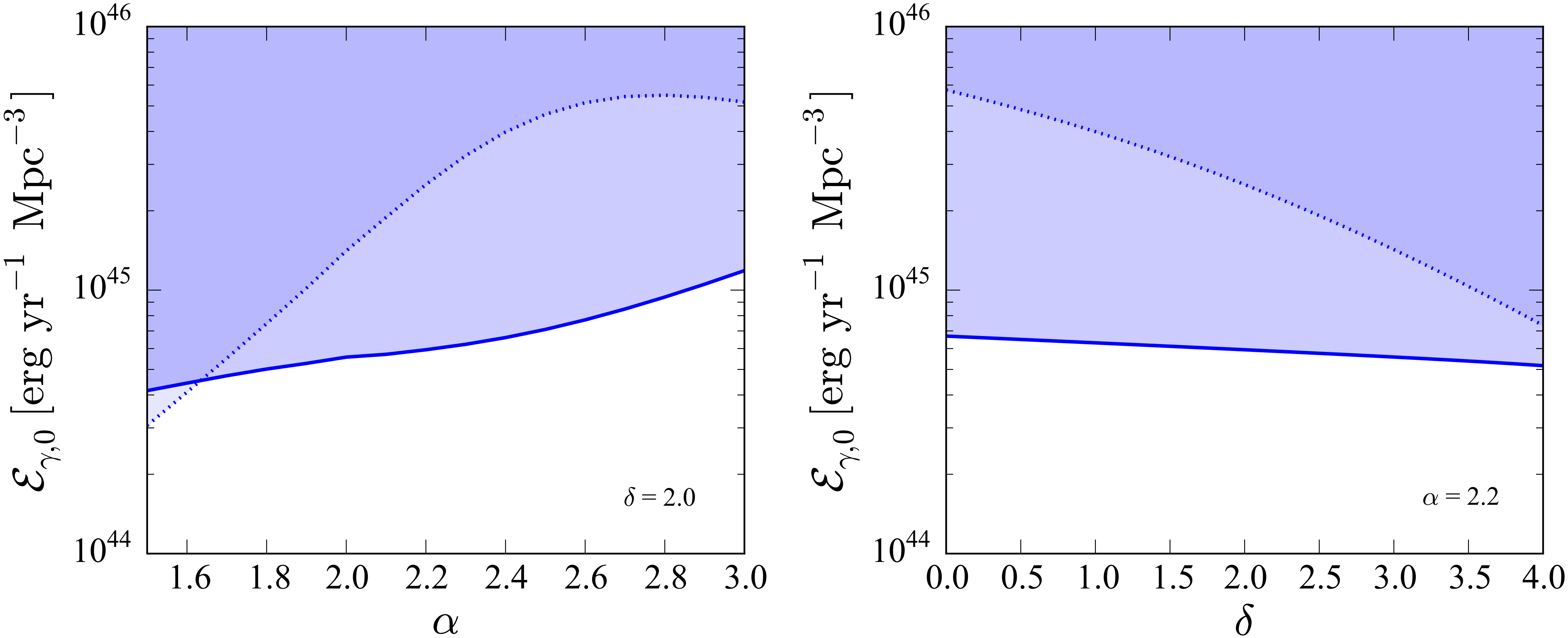


Ando, Tamborra, Zandanel, 1509.02444

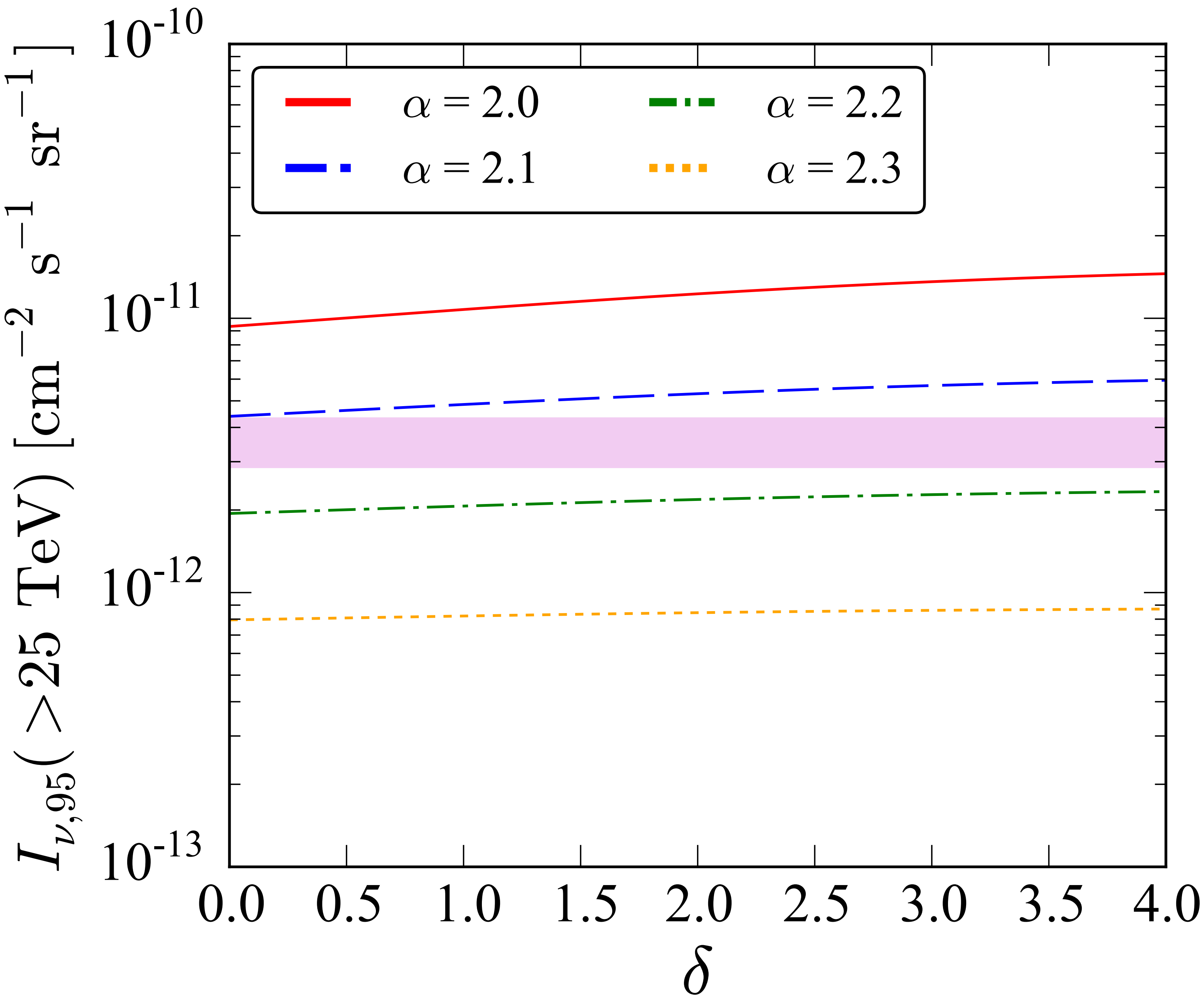
Constraints on gamma-ray luminosity density



Cross-correlation data give constraints tighter by ***up to 1 order of magnitude***!

Ando, Tamborra, Zandanel, 1509.02444

Constraints on high-energy neutrinos



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- Spectral constraints: α has to be smaller than ~2.2

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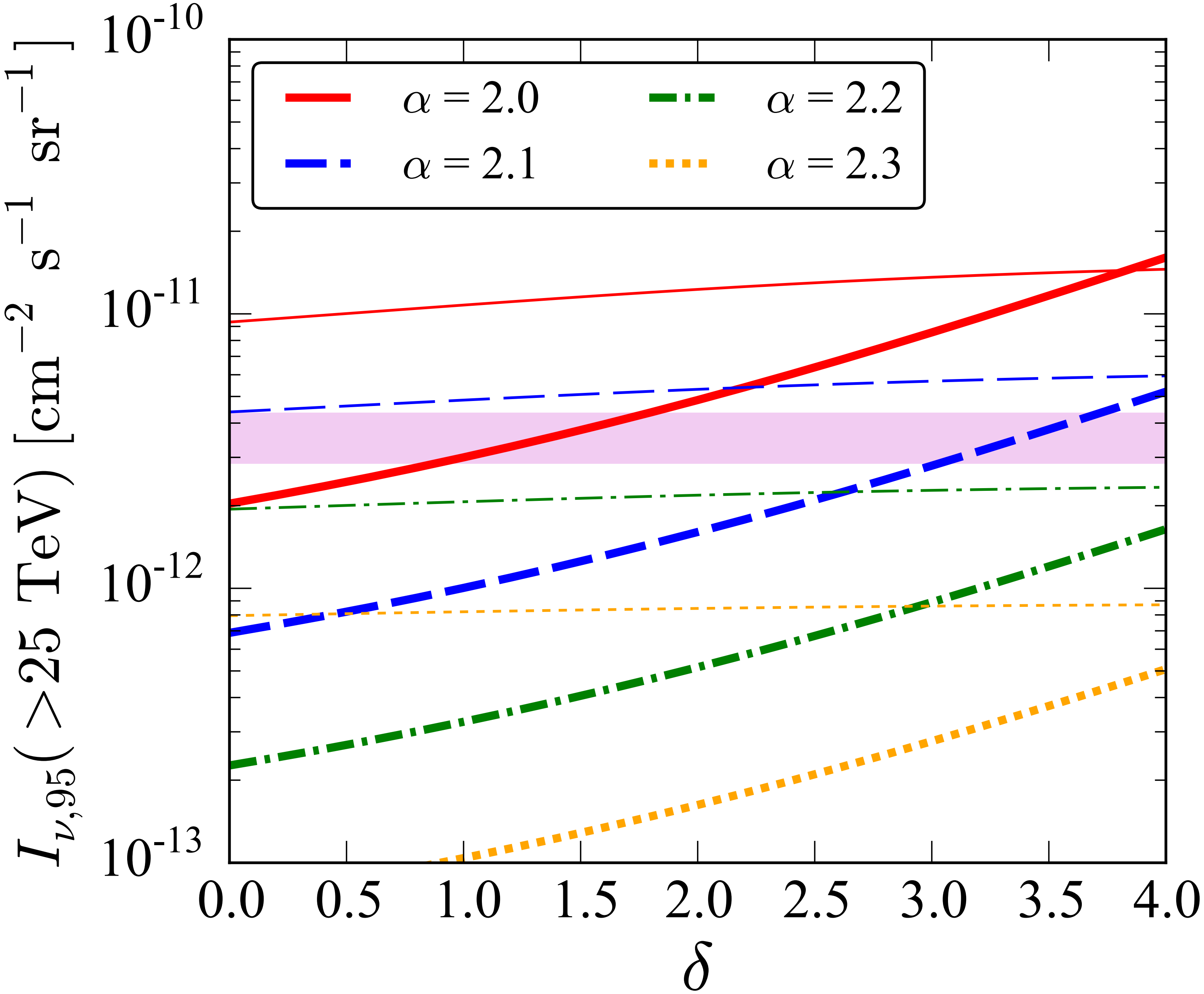

Ando, Tamborra, Zandanel, 1509.02444

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- Tomographic constraints:

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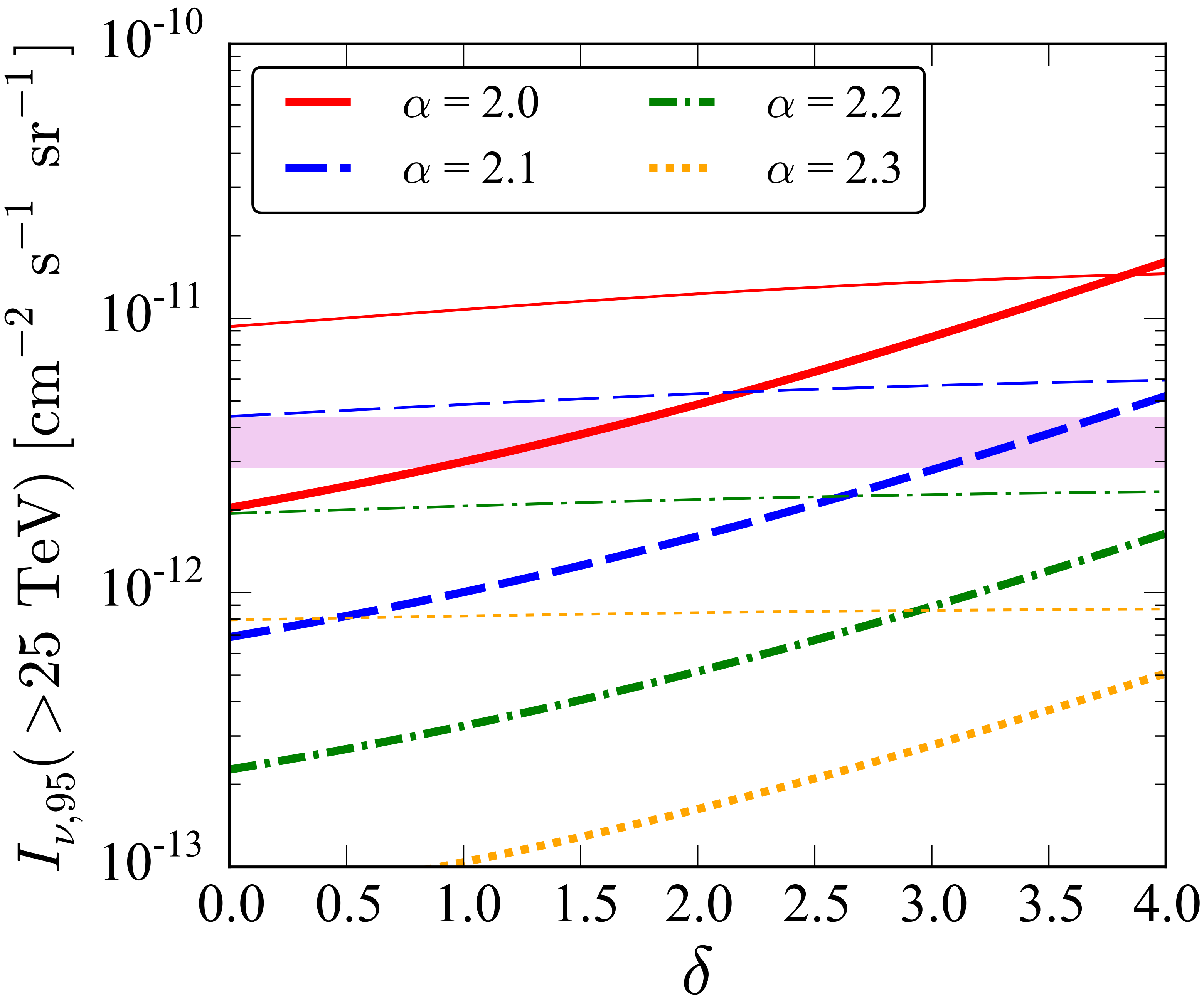

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- Tomographic constraints:
  - If δ is smaller than ~3, source with spectrum softer than $E^{-2.1}$ is disfavored

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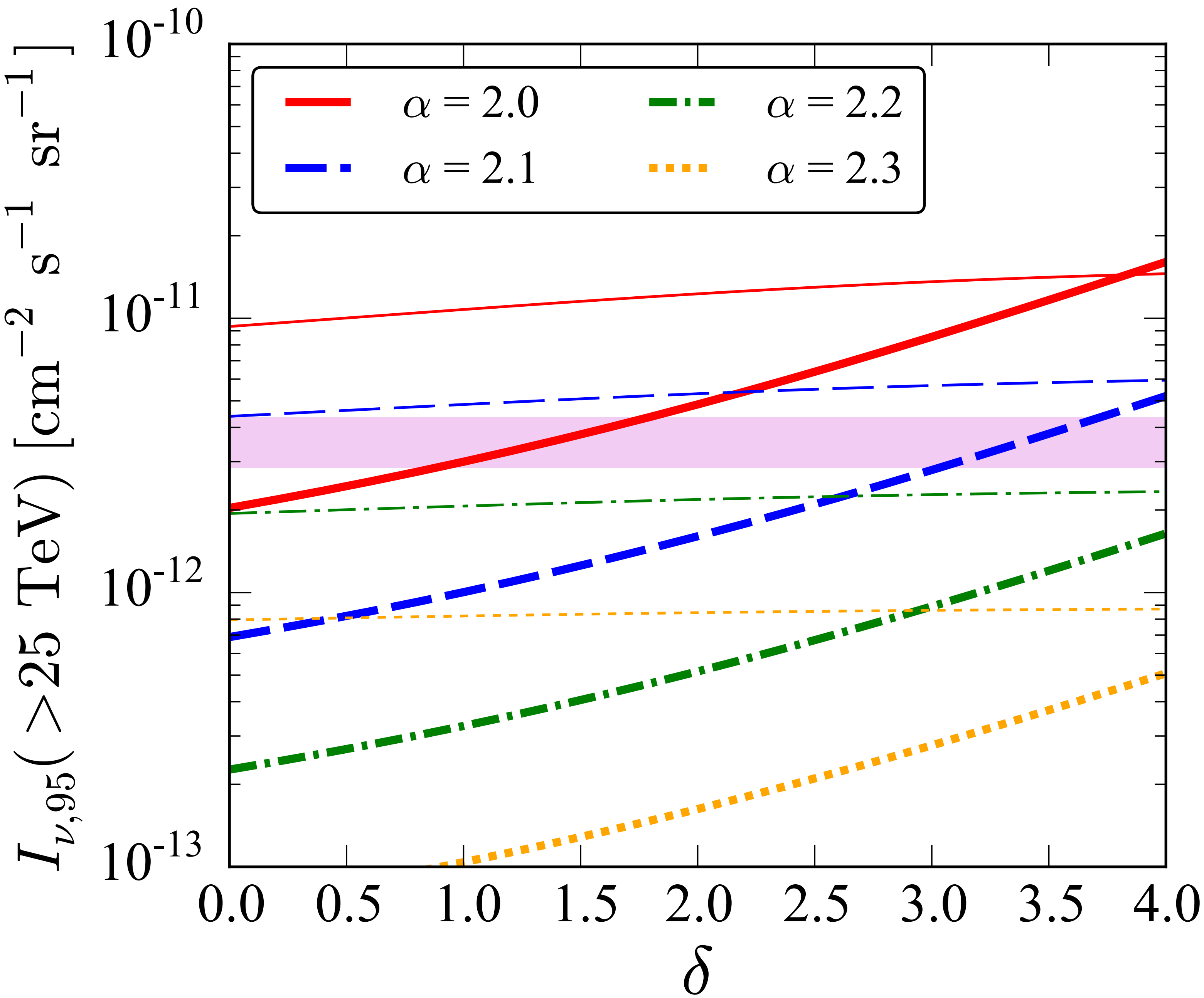
Constraints on high-energy neutrinos



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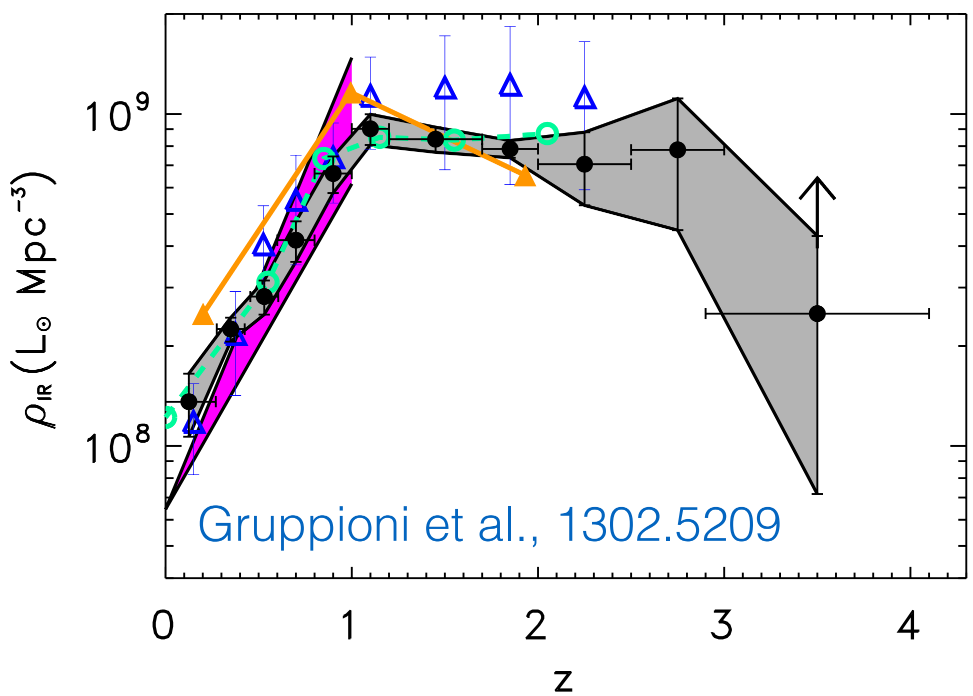
- Tomographic constraints:
  - If δ is smaller than ~3, source with spectrum softer than $E^{-2.1}$ is disfavored
- If δ ~ 4, both spectral and tomographic data give comparable constraints

Ando, Tamborra, Zandanel, 1509.02444

Possible pp sources

Star-forming/starburst galaxies



- No direct measurement of δ yet
- Infrared luminosity density suggests δ ~ 3–4

Clusters of galaxies

- Cosmic rays accelerated through large-scale-structure shocks or provided by sources (AGNs, galaxies)
- In both cases, δ is very small (i.e., clusters are found only in low-z)
- Very strongly disfavored; also independent constraints from radio number counts (Zandanel et al., 1410.8697)

What if blazars explain most IGRB data?

Ando, Tamborra, Zandanel, 1509.02444

- Blazars might be responsible for ~85% of IGRB spectrum above 50 GeV (Fermi-LAT, 1511.00693)

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Ando, Tamborra, Zandanel, 1509.02444

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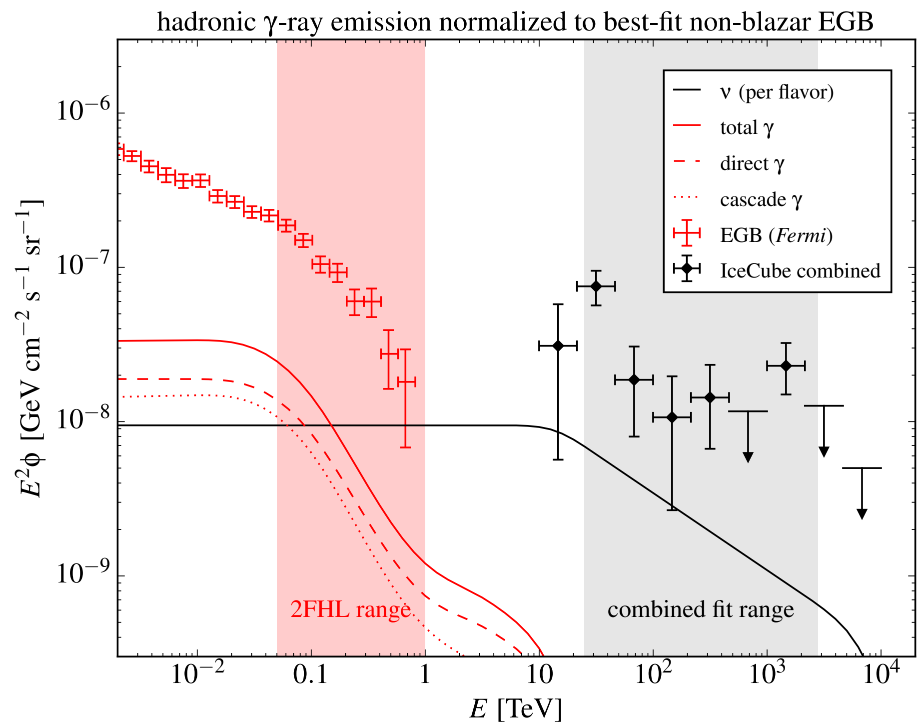

Bechtol et al., 1511.00688

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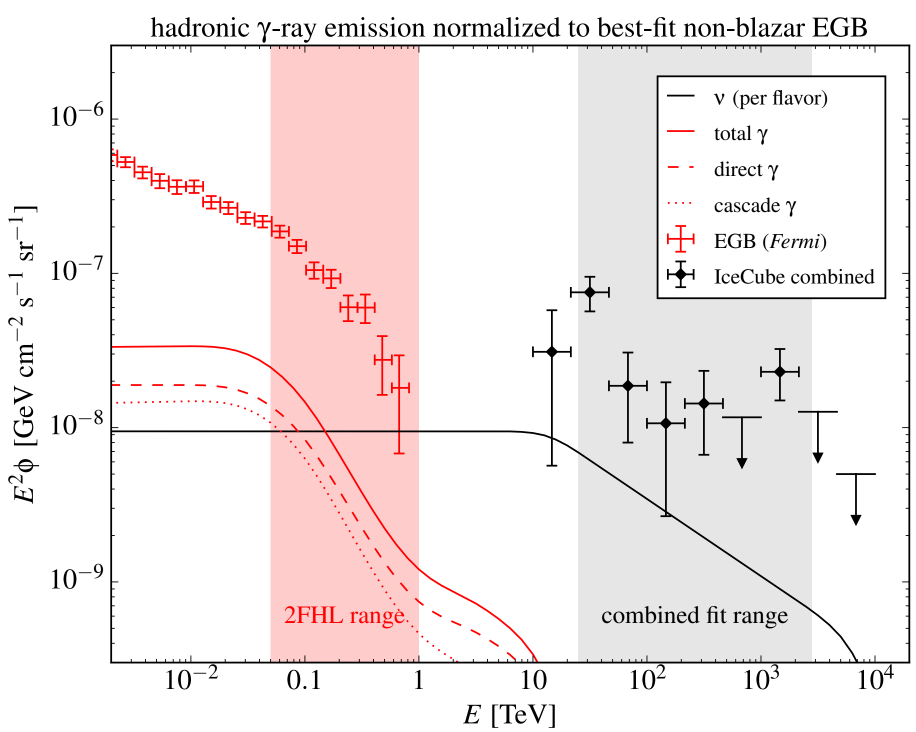

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  - If so, any pp sources are highly disfavored

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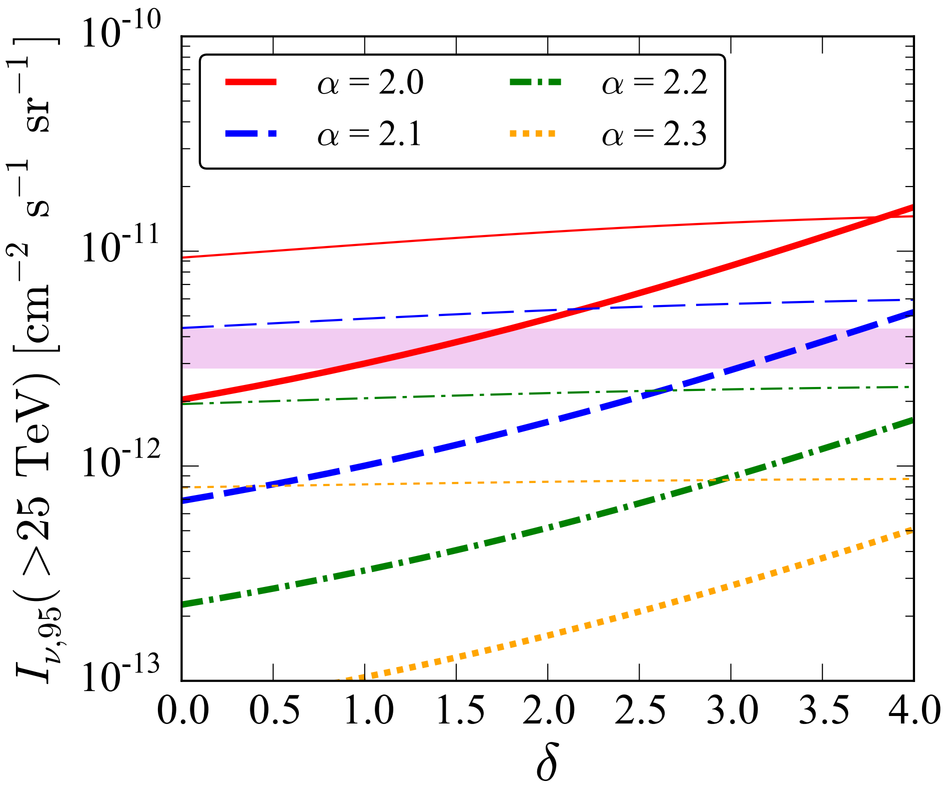

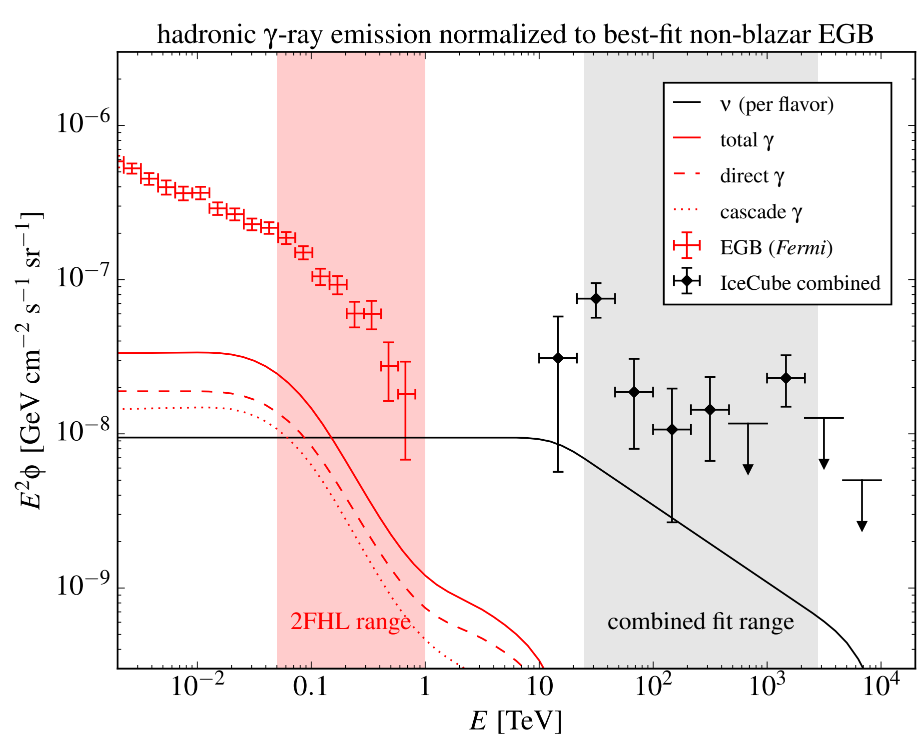

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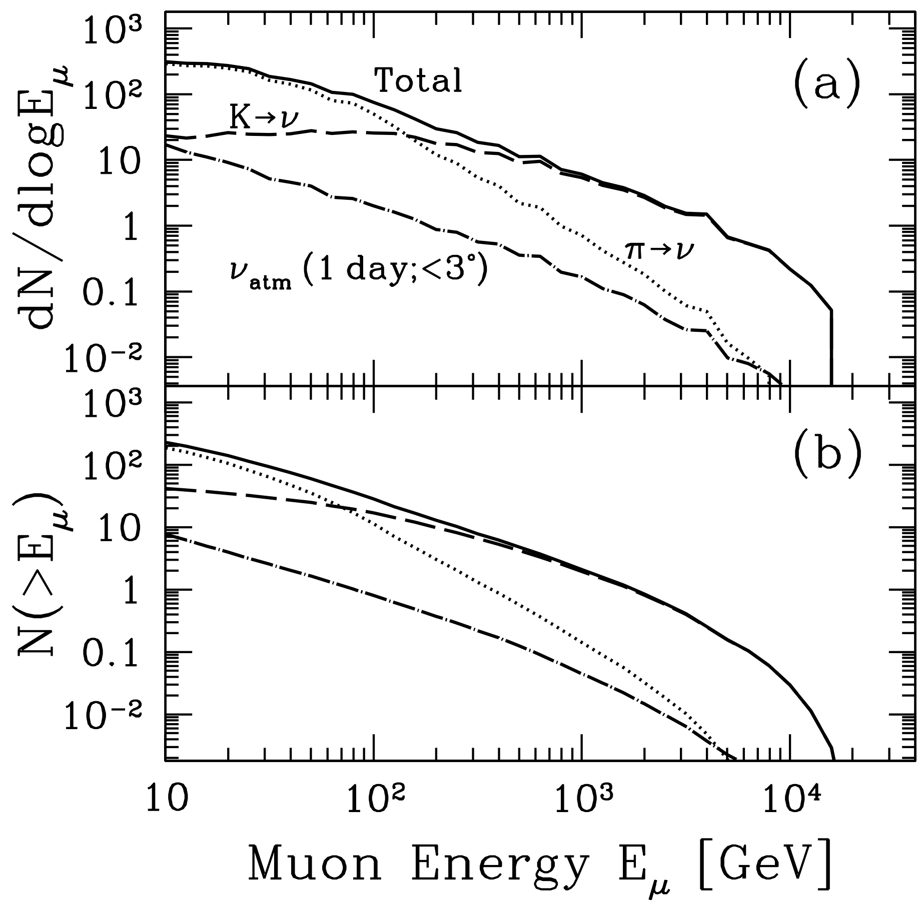
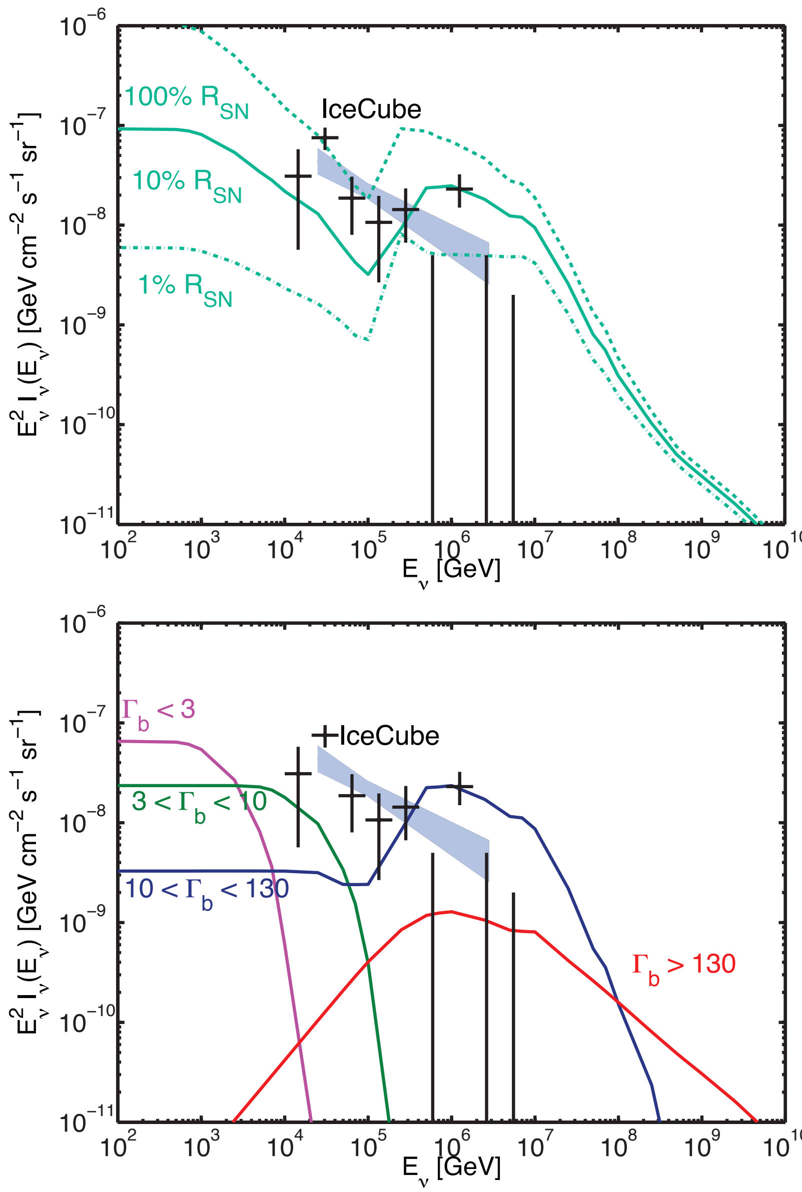
Exception: Hidden pp sources?

Ando, Beacom, astro-ph/0502521



Tamborra, Ando, 1512.01559



GRB-like jets, but richer with baryons (i.e., slower jets and optically thick): hence cannot be identified with gamma rays

Conclusions

- Hadronuclear (pp) interaction is a prime channel for production of high-energy neutrinos
- Contribution to IceCube neutrinos (TeV−PeV) can be constrained with Fermi-LAT gamma-ray data (GeV−TeV)
- New tomographic constraints are obtained with the galaxy-gamma cross-correlation measurements
- They exclude soft sources with relatively slow redshift evolution much more strongly than spectral constraints
- Sources with fast evolution (including starbursts) are still allowed, but they must have hard spectrum (E^{-2}) that can be tested