PAHEN@Berlin
26 September 2019

Generic constraints on sources of the diffuse neutrino background

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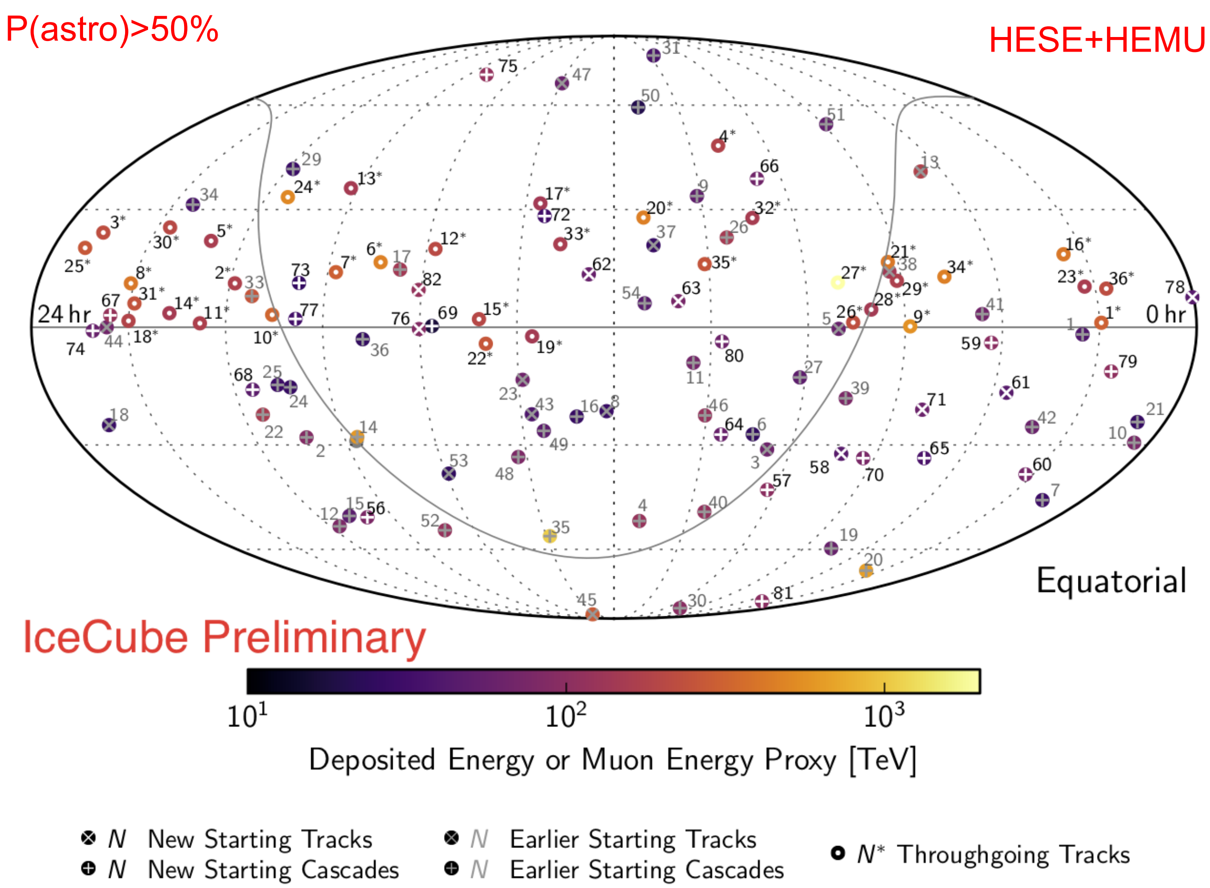
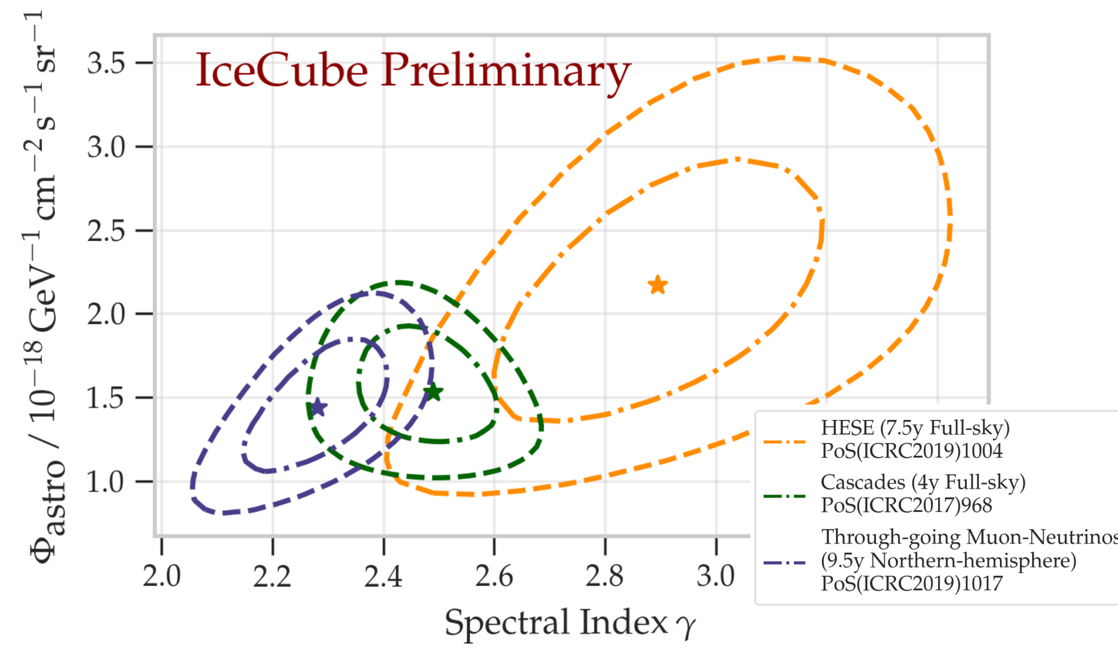
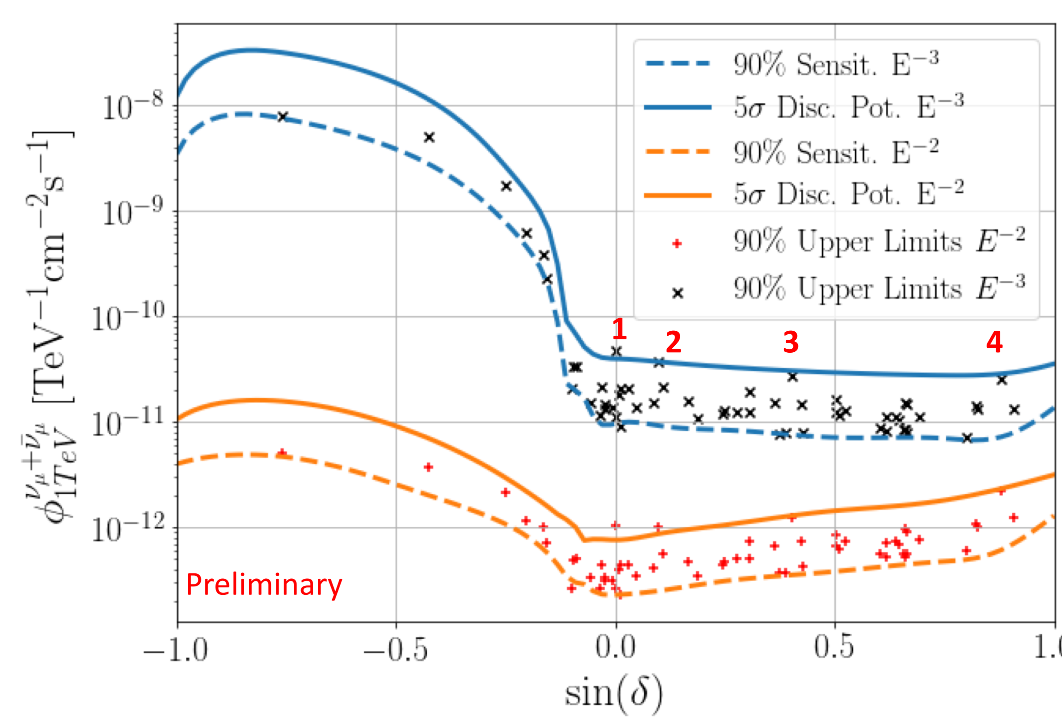
University of Amsterdam

GRAPPA
GRavitation AstroParticle Physics Amsterdam

High-energy neutrinos: Facts



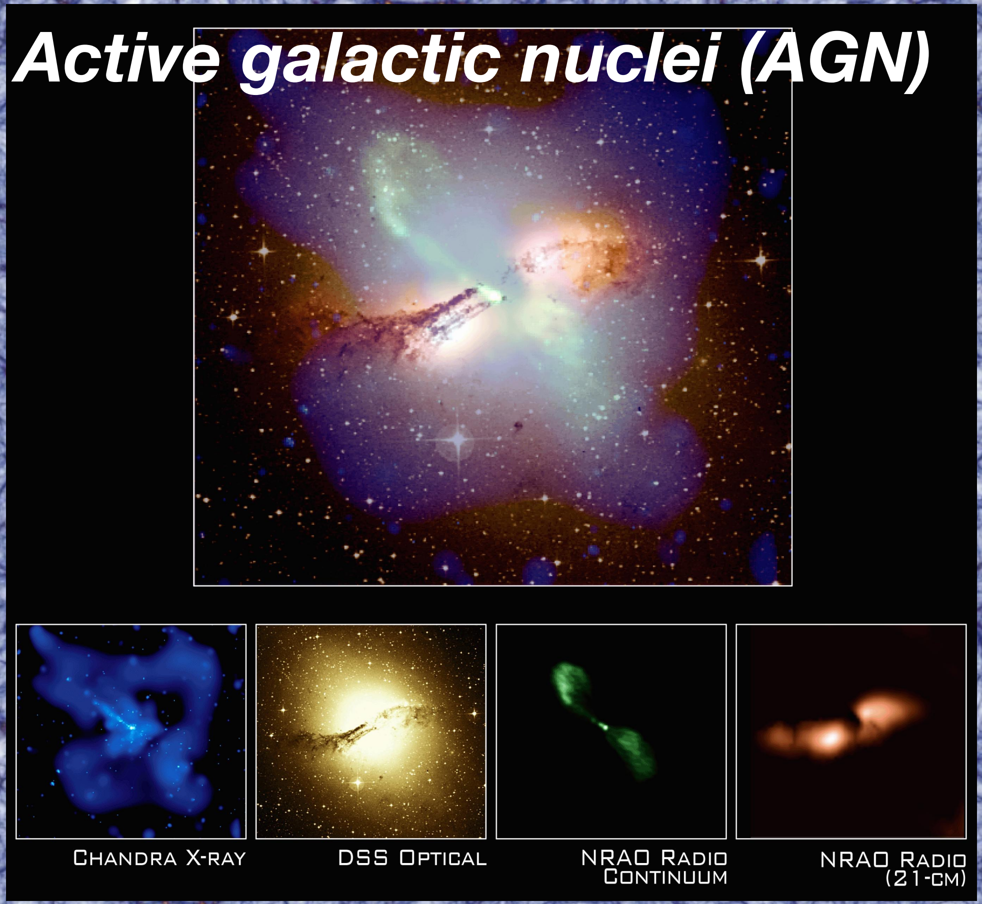




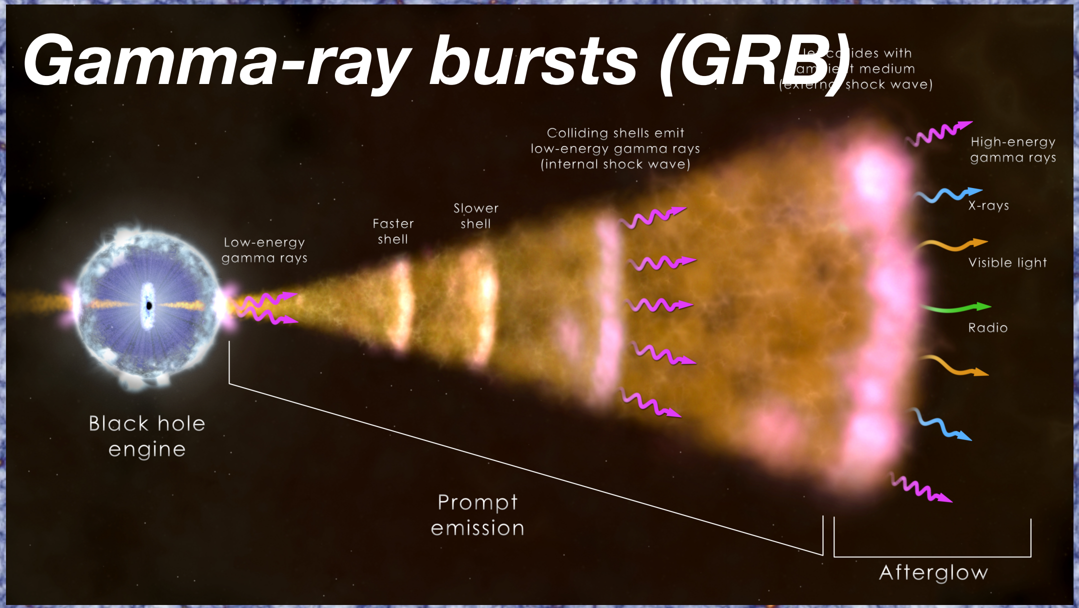
- Detected: Starting events and up-going muon events
- Their distribution is consistent with isotropy
- **No source has been identified yet**

Possible astrophysical explanations

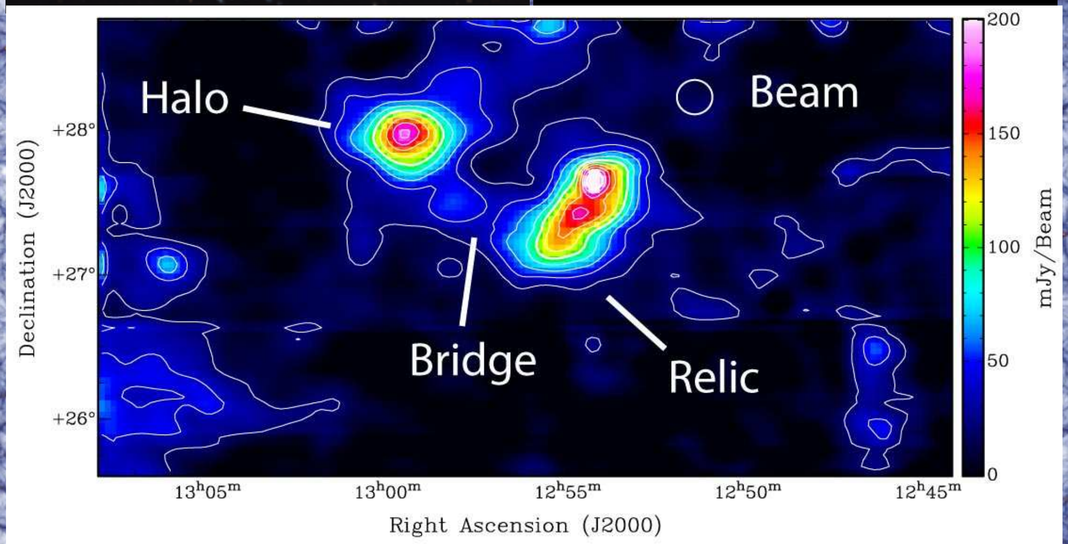
Active galactic nuclei (AGN)



Gamma-ray bursts (GRB)



Galaxy clusters



Star-forming galaxies (SFG)
Starburst galaxies (SB)

Unknown sources?
Particle dark matter?

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

$$\pi^0 \to 2\gamma$$

$$\pi^\pm \to \mu^\pm + \nu_\mu$$

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Generic consideration: Personal take

- Given no source has been detected, it is important to take unbiased, **model-independent** approach

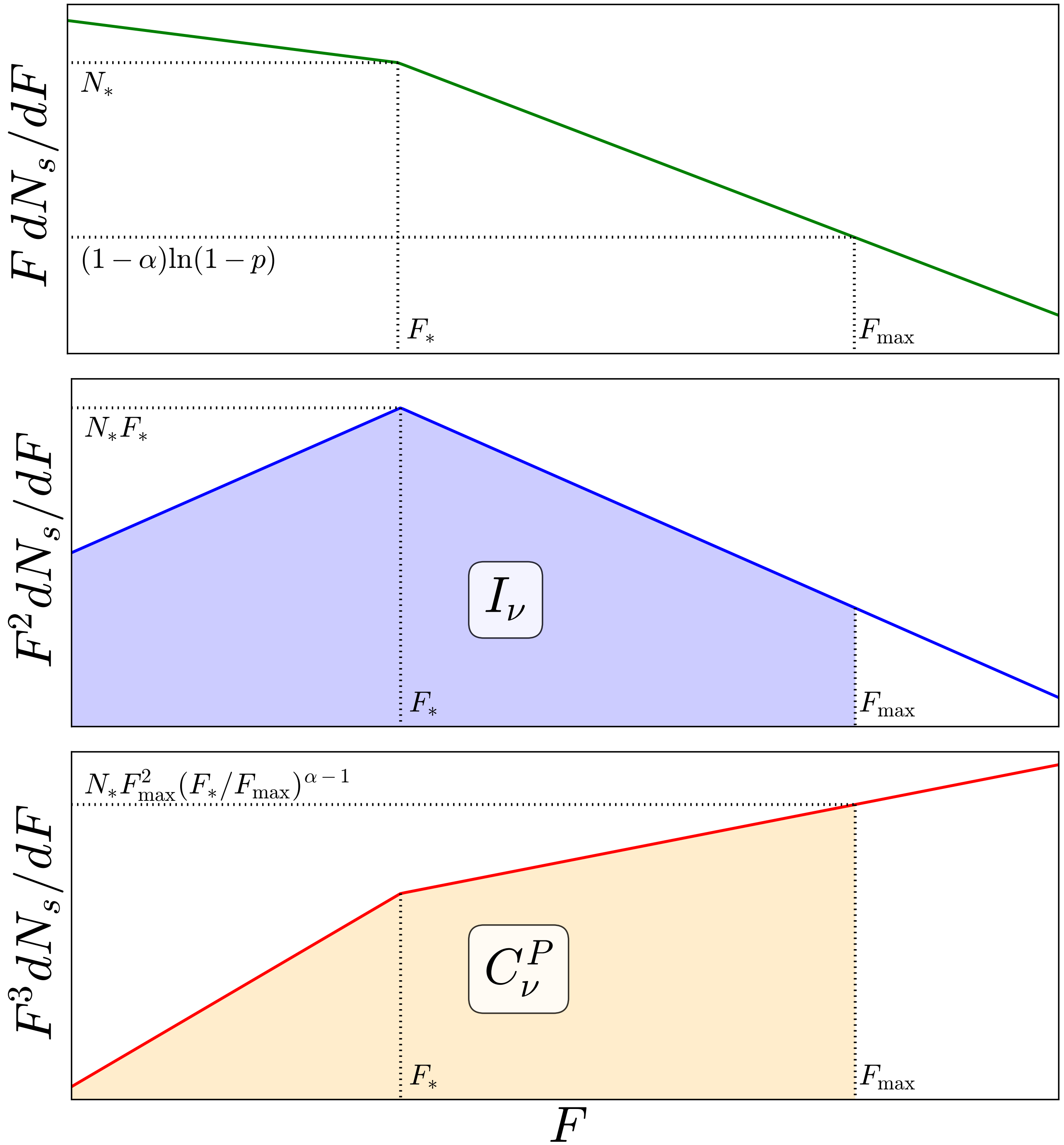
- Given we already have data, which will accumulate further, we want to adopt **data-driven** approaches

Traditional approaches

- Explain the **energy spectrum** of the diffuse neutrino background using models of astrophysical sources
- Look for **excess of events** in localized regions compared with global average (individual point source searches)
- Both these can be interpreted in terms of **flux distribution**

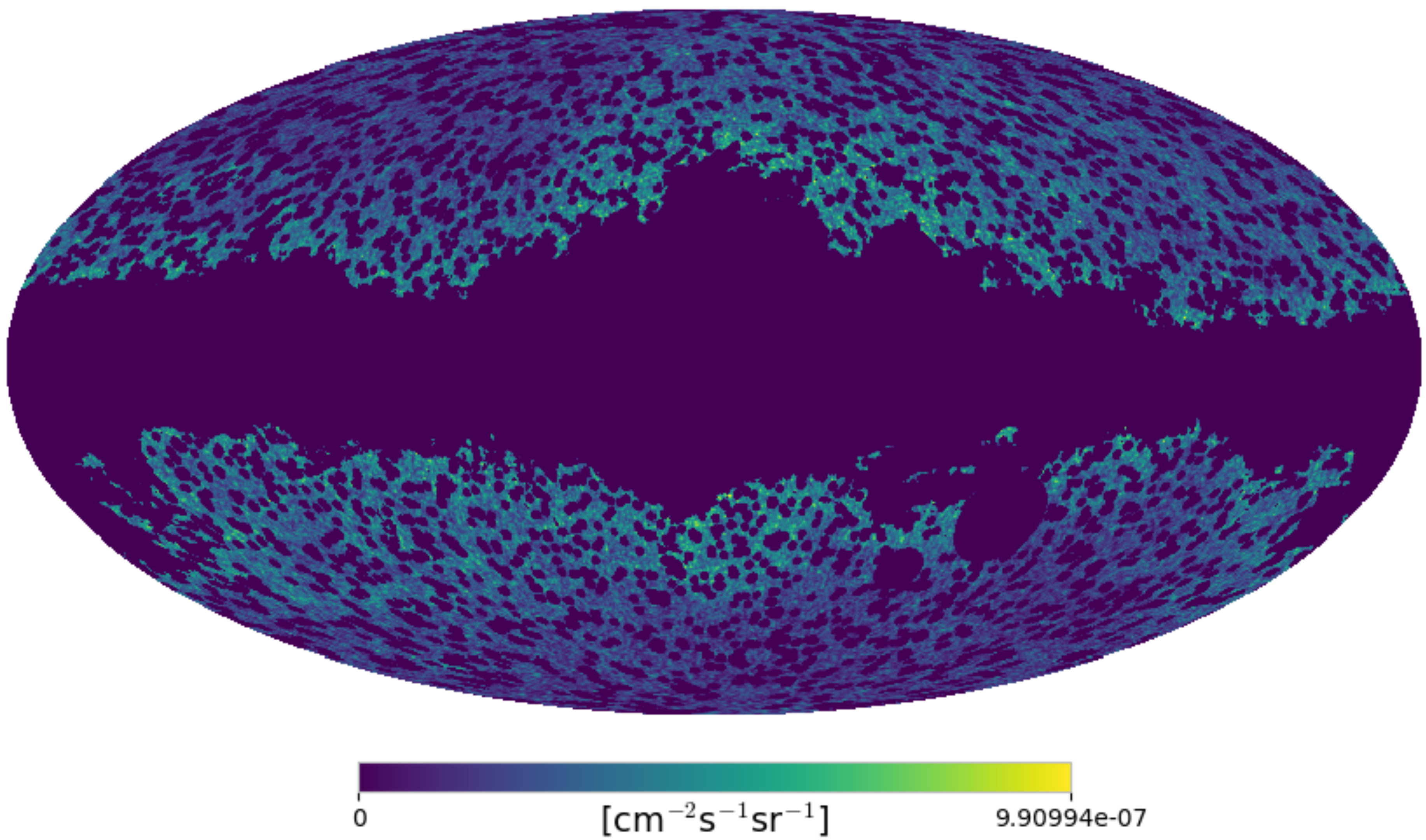
Flux distribution

Ando, Feyereisen, Fornasa, *Phys. Rev. D* **95**, 103003 (2017)



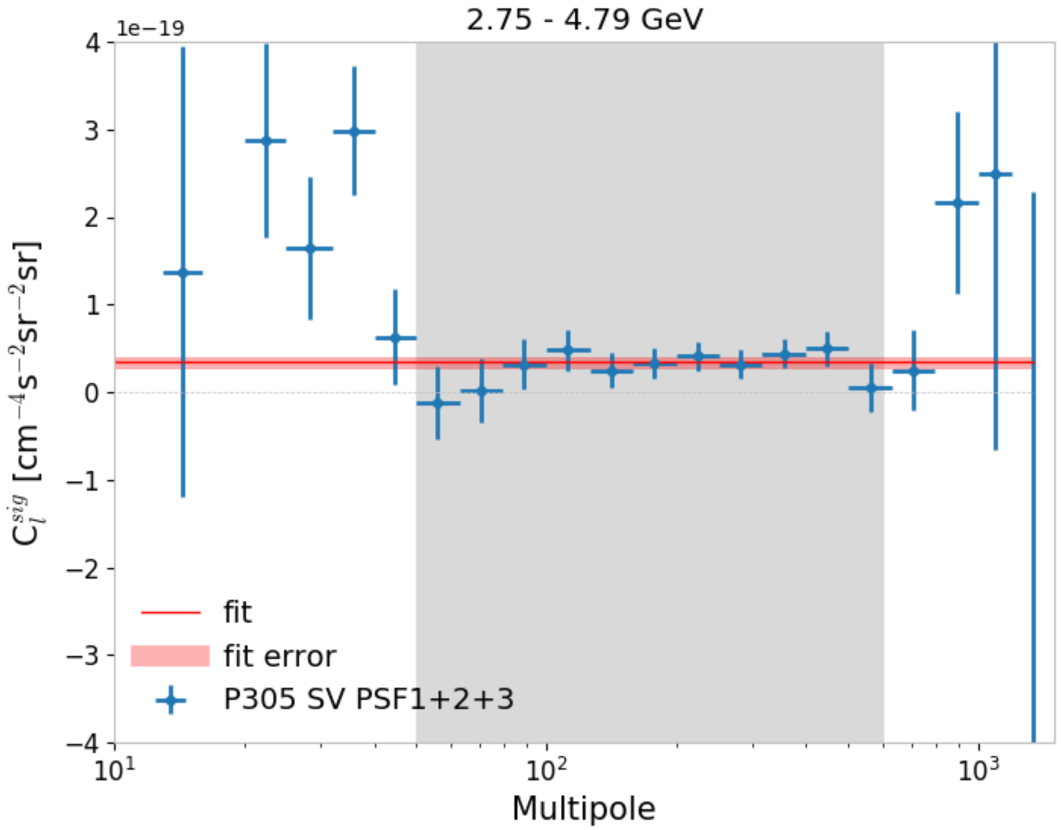
- **Number of detected sources:** Integral above flux threshold
  - At the moment, the threshold is higher than the flux of the brightest source
- **Energy spectrum:** first moment of the flux distribution below the flux threshold
- But we don't have to stop here!
- There are higher moments that can be used: e.g., **variance**

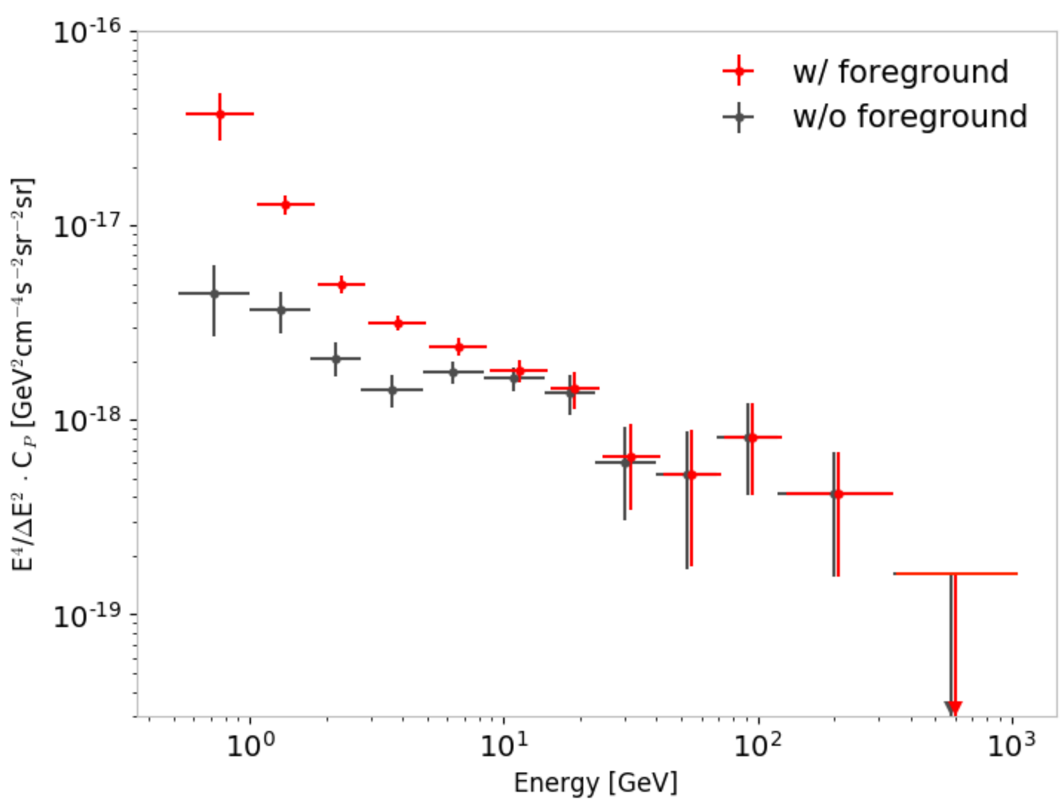
Anisotropies: Lessons from gamma rays



Fermi-LAT, *Phys. Rev. Lett.* **121**, 241101 (2018)

Angular power spectrum: Observations with Fermi





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  - Reanalyzed in 2016, 2018

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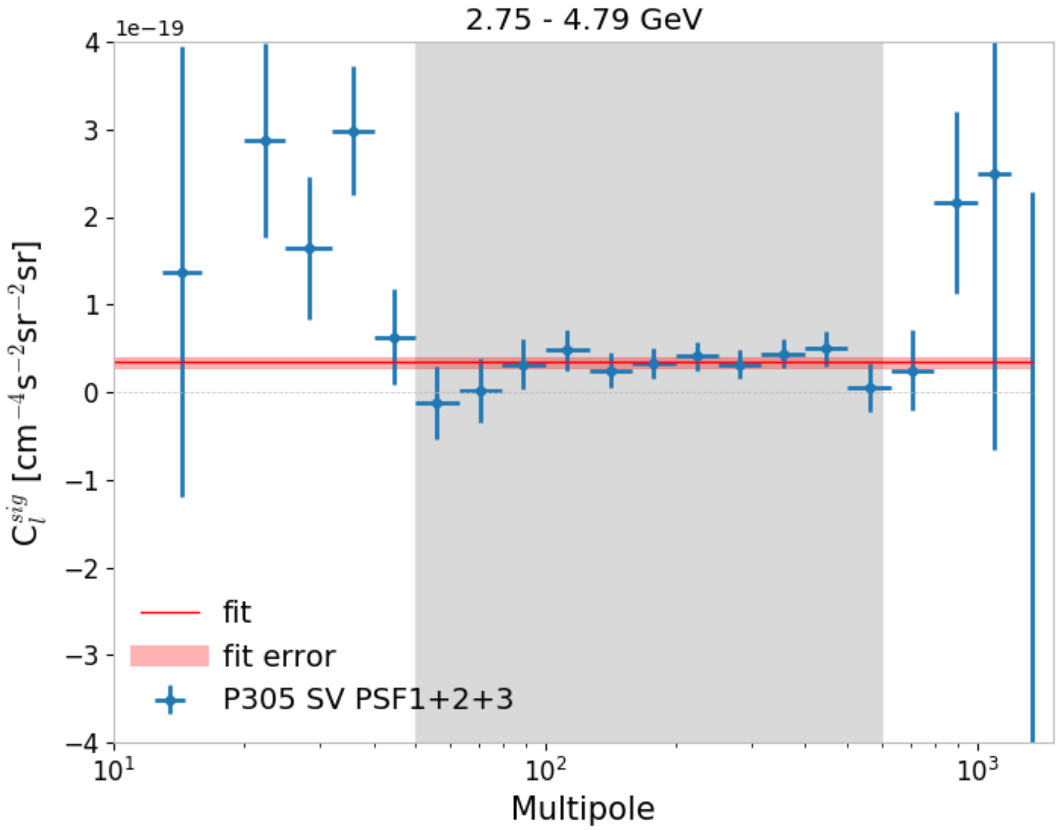

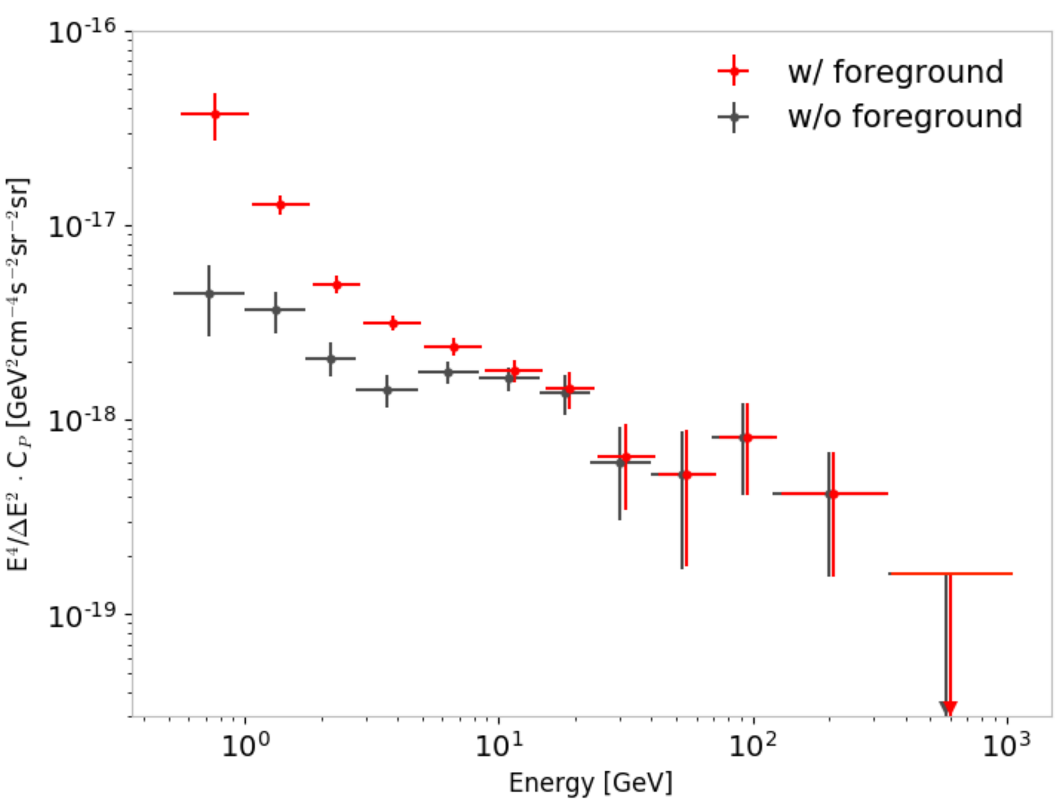

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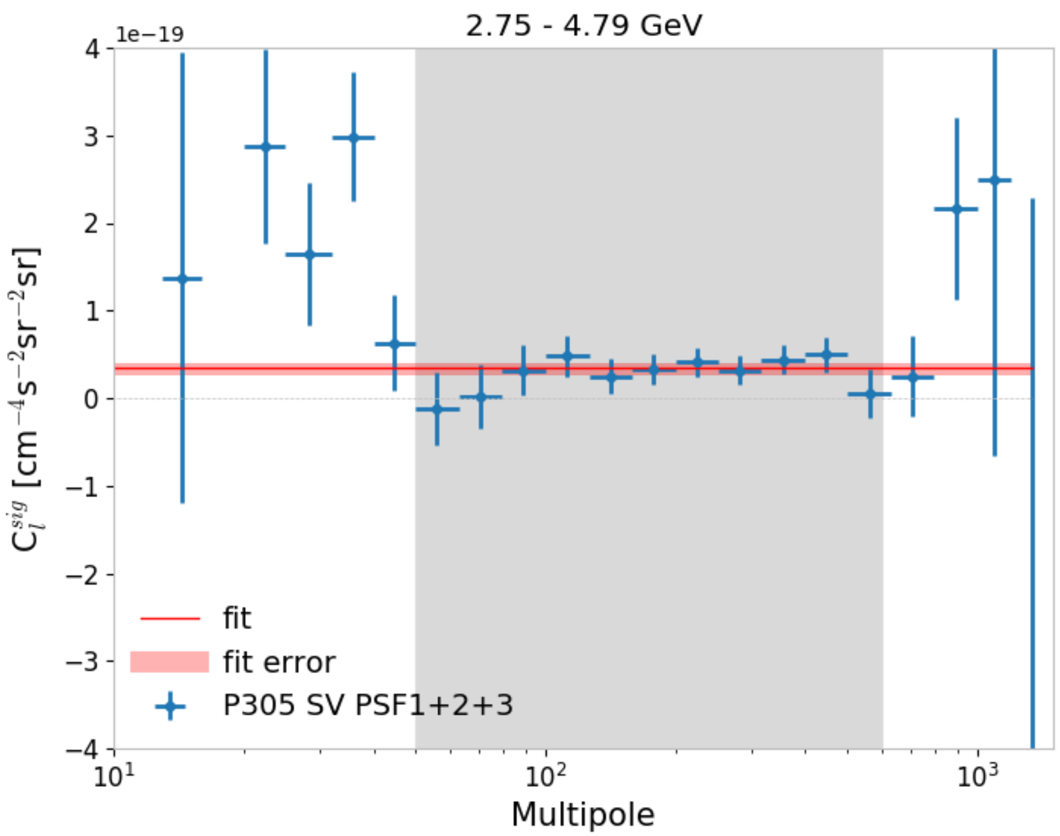

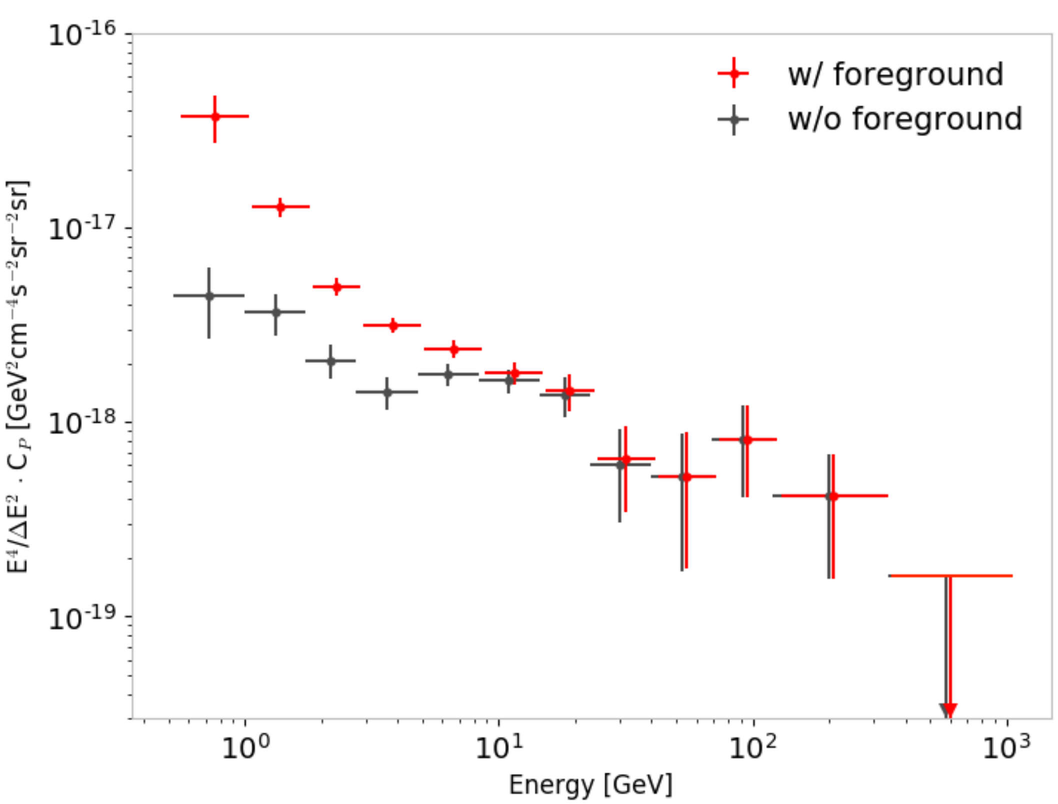

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$$C_\ell^{\rm total} = C_N + C_P + C_\ell^{\rm corr}$$

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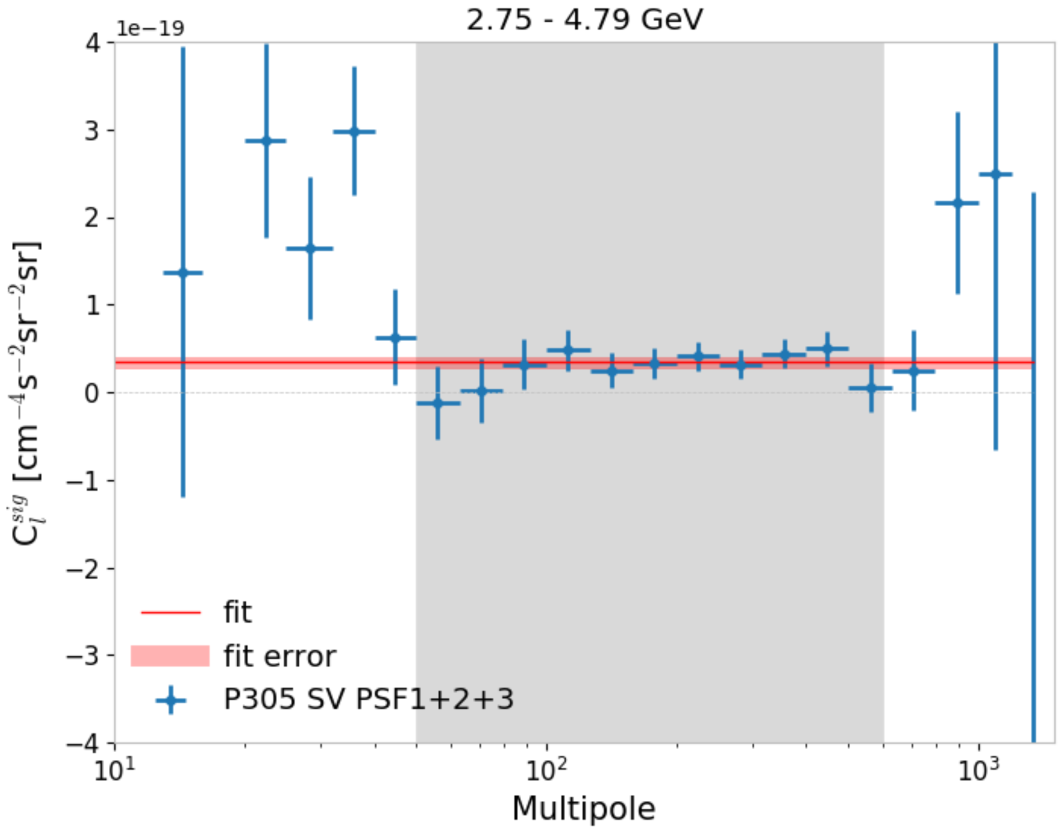

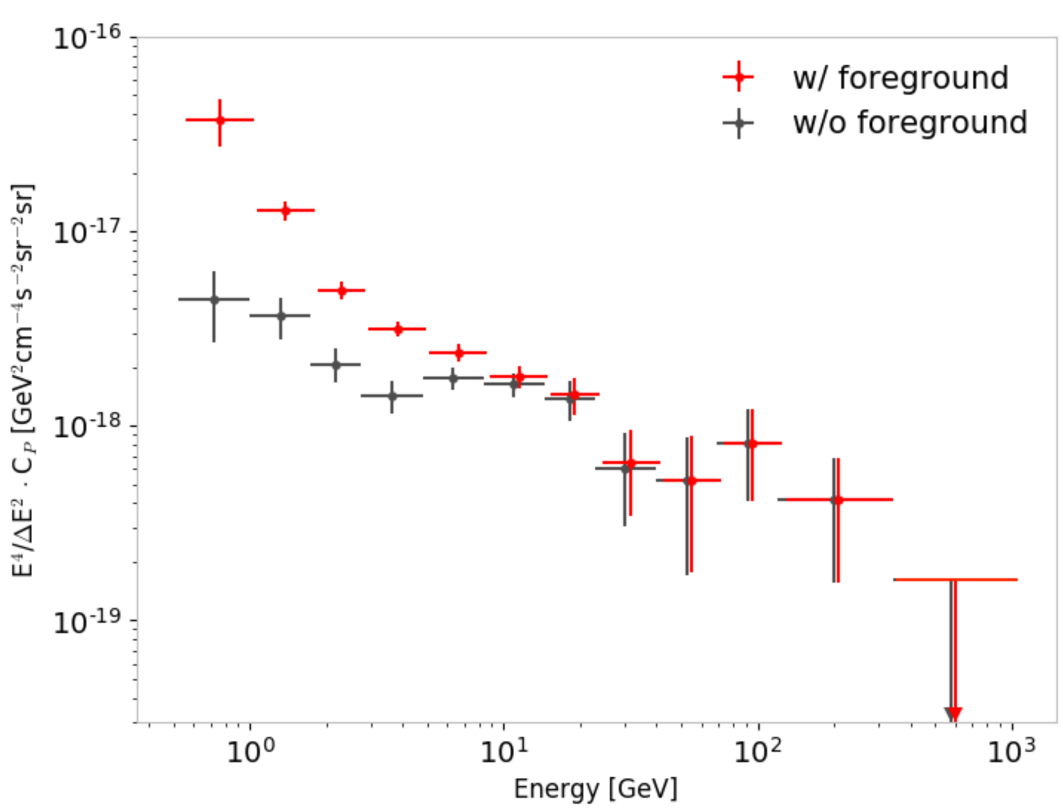

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$$C_\ell^{\rm total} = C_N + C_P + C_\ell^{\rm corr}$$

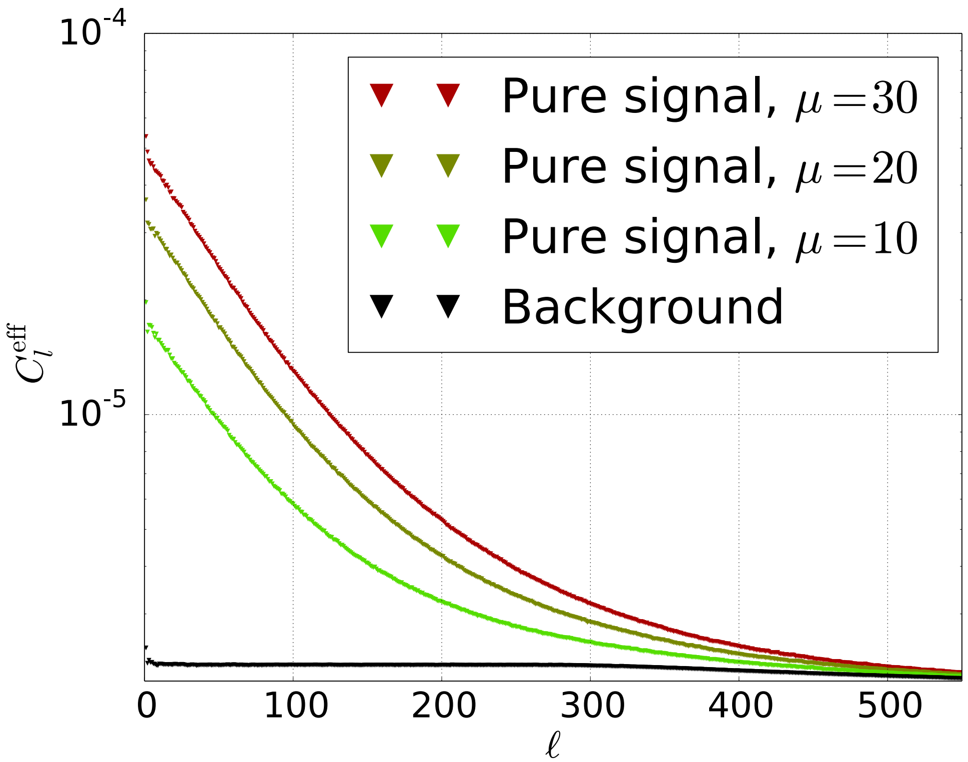
- Data are mostly **consistent with astrophysical expectations** (blazars; Ando et al. 2007)

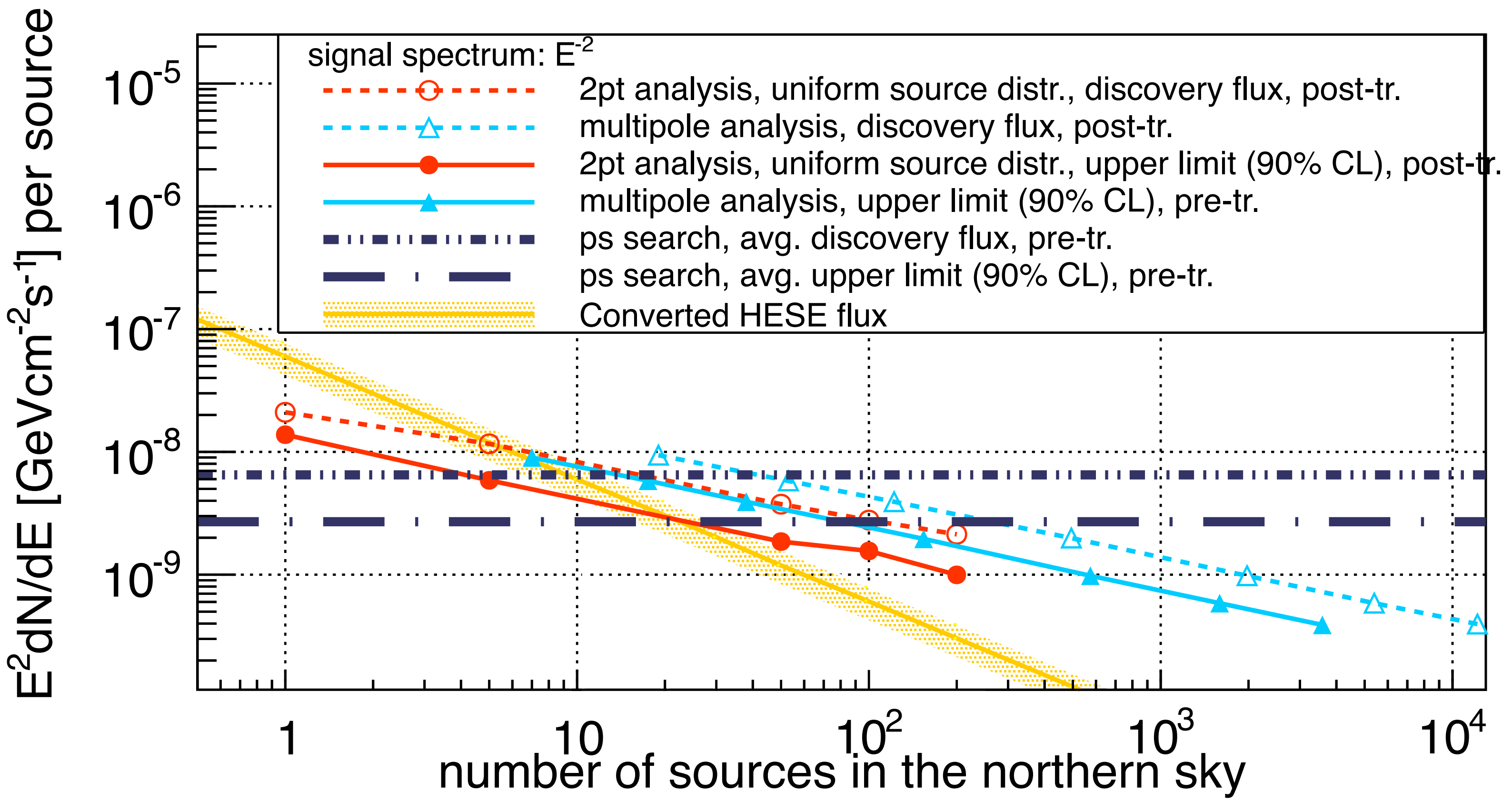
Implications

- Anisotropy analyses have already been established for GeV gamma rays
- Solid measurement of the angular power spectrum (variance) **implies (sub-threshold) point-source contribution**
- The source population that cannot be detected individually can be detected ***statistically***
- **Same technique can be used for high-energy neutrinos**, to identify ***sources***

Power spectrum analysis by IceCube

IceCube, *Astropart. Phys.* **66**, 39 (2015)

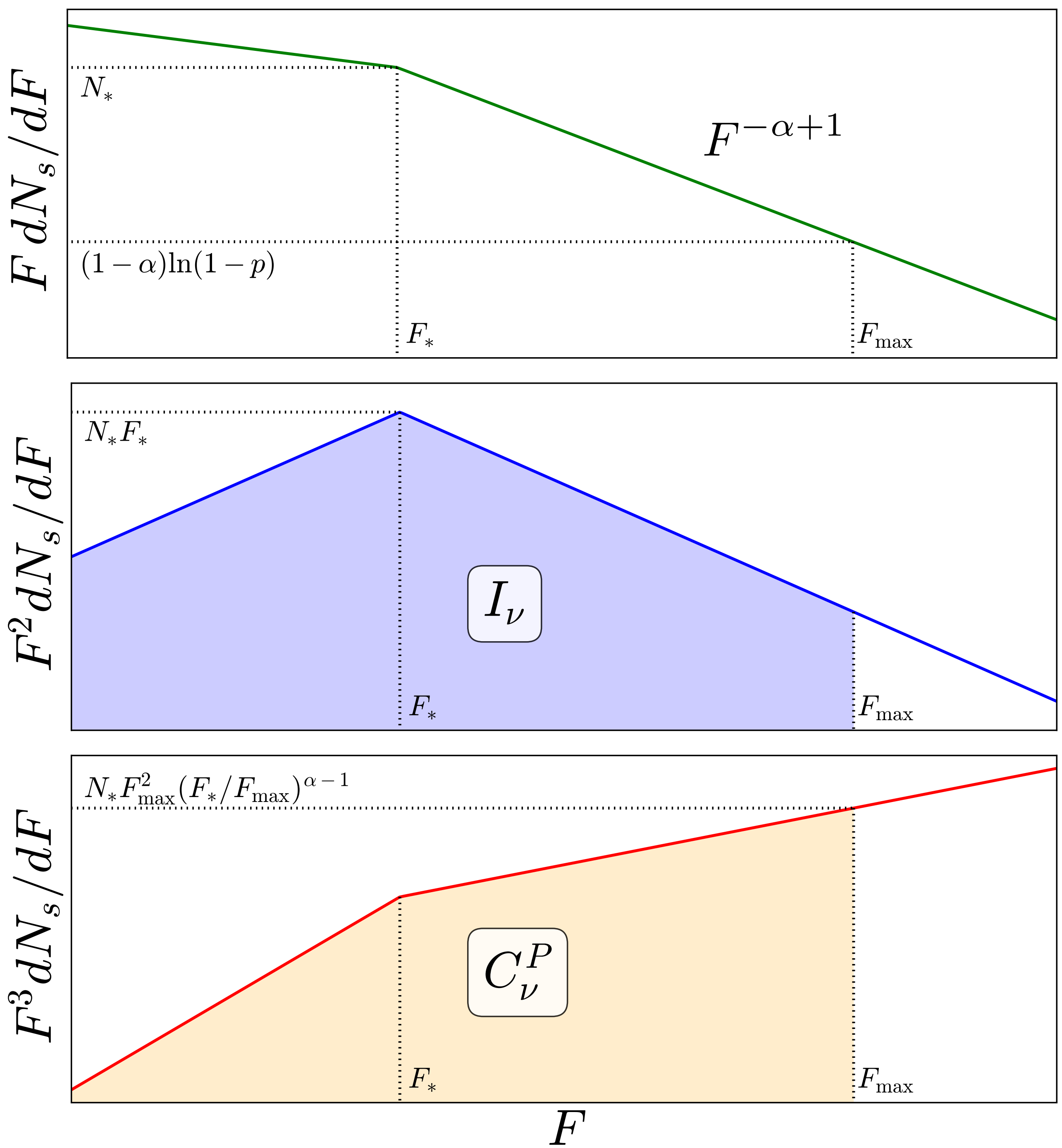




- No angular power was found (everything is consistent with diffuse the background model)
- It can exceed the point-source limit for more than 100 sources
- But it is assumed that all these sources have the **same** flux

Flux distribution and implications

Ando, Feyereisen, Fornasa, *Phys. Rev. D* **95**, 103003 (2017)



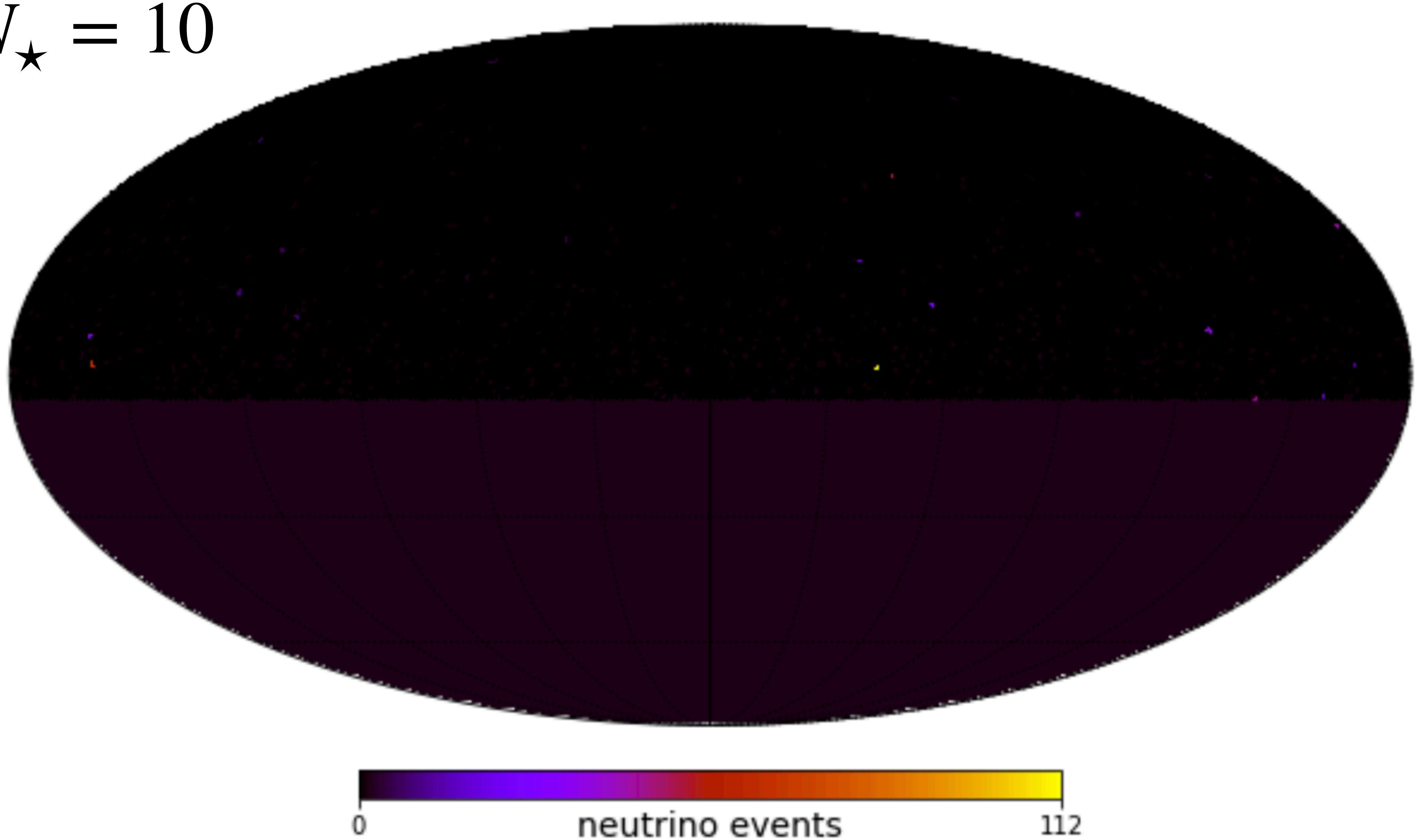
- Flux distribution of **any** astrophysical sources will follow a **power law**
  - Particularly $F^{-2.5}$ for high-flux region

Procedure:

1. Pick ***N**** as a parameter
2. From measured intensity ***I***, calculate ***F****, which will fix the distribution
3. Simulate neutrino data, calculate the power spectrum, and extract test statistic (TS) and TS distribution
4. Apply the method to the actual data to discuss what value of ***N**** is already excluded

Simulated neutrino data

$N_{\star} = 10$

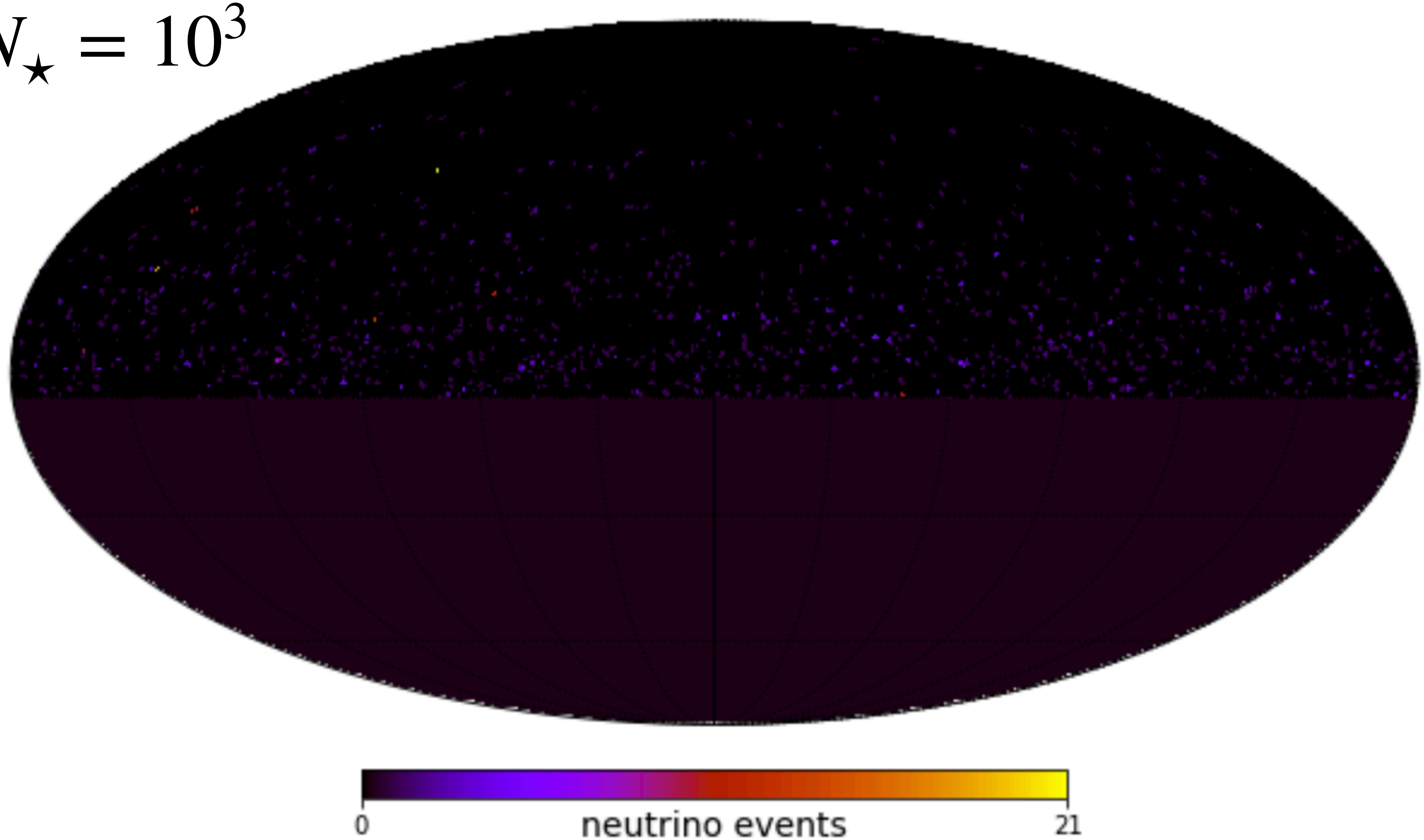


Dekker, Ando, *JCAP* **1902**, 002 (2019)

200 IceCube years

Simulated neutrino data

$N_\star = 10^3$

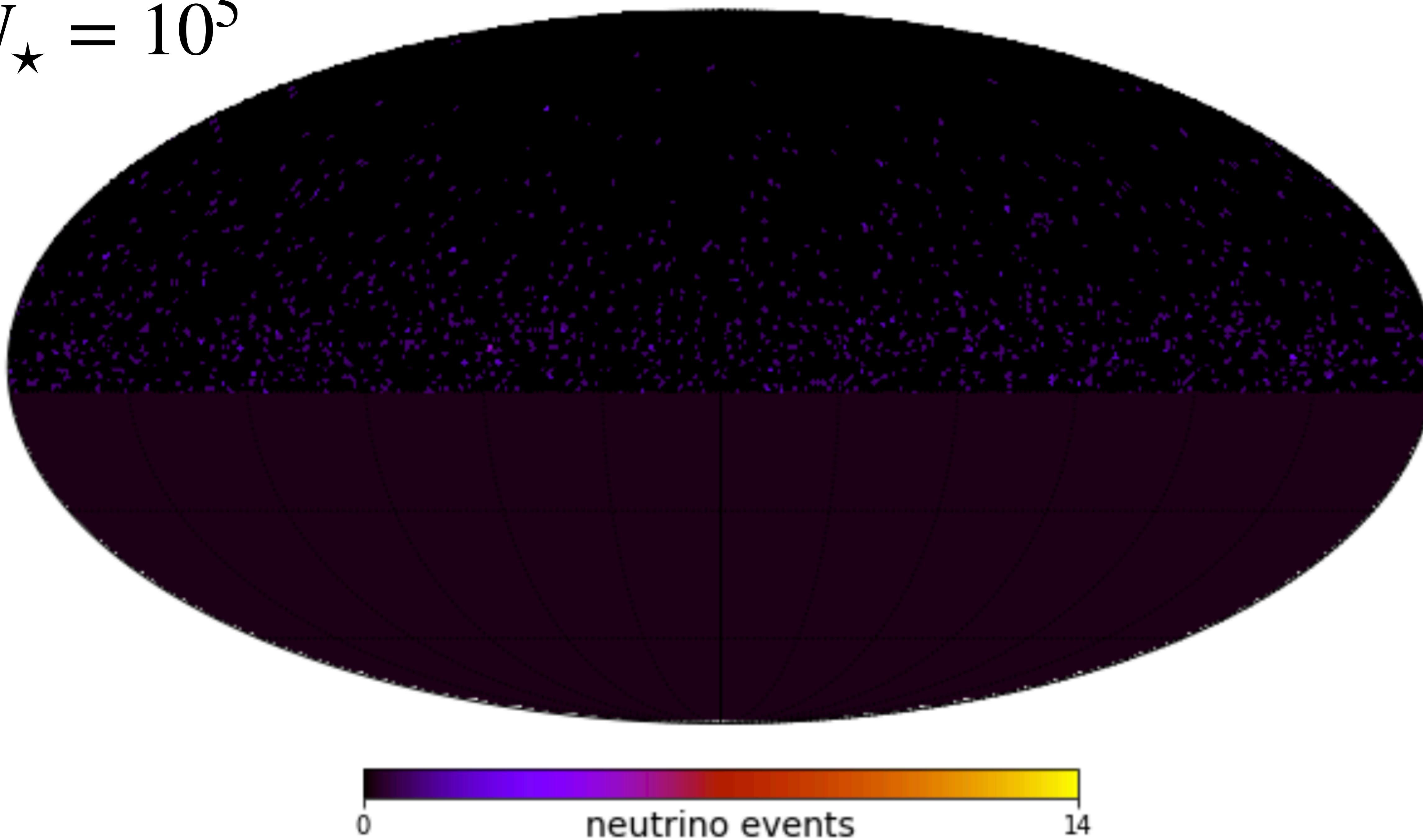


Dekker, Ando, *JCAP* **1902**, 002 (2019)

200 IceCube years

Simulated neutrino data

$N_\star = 10^5$

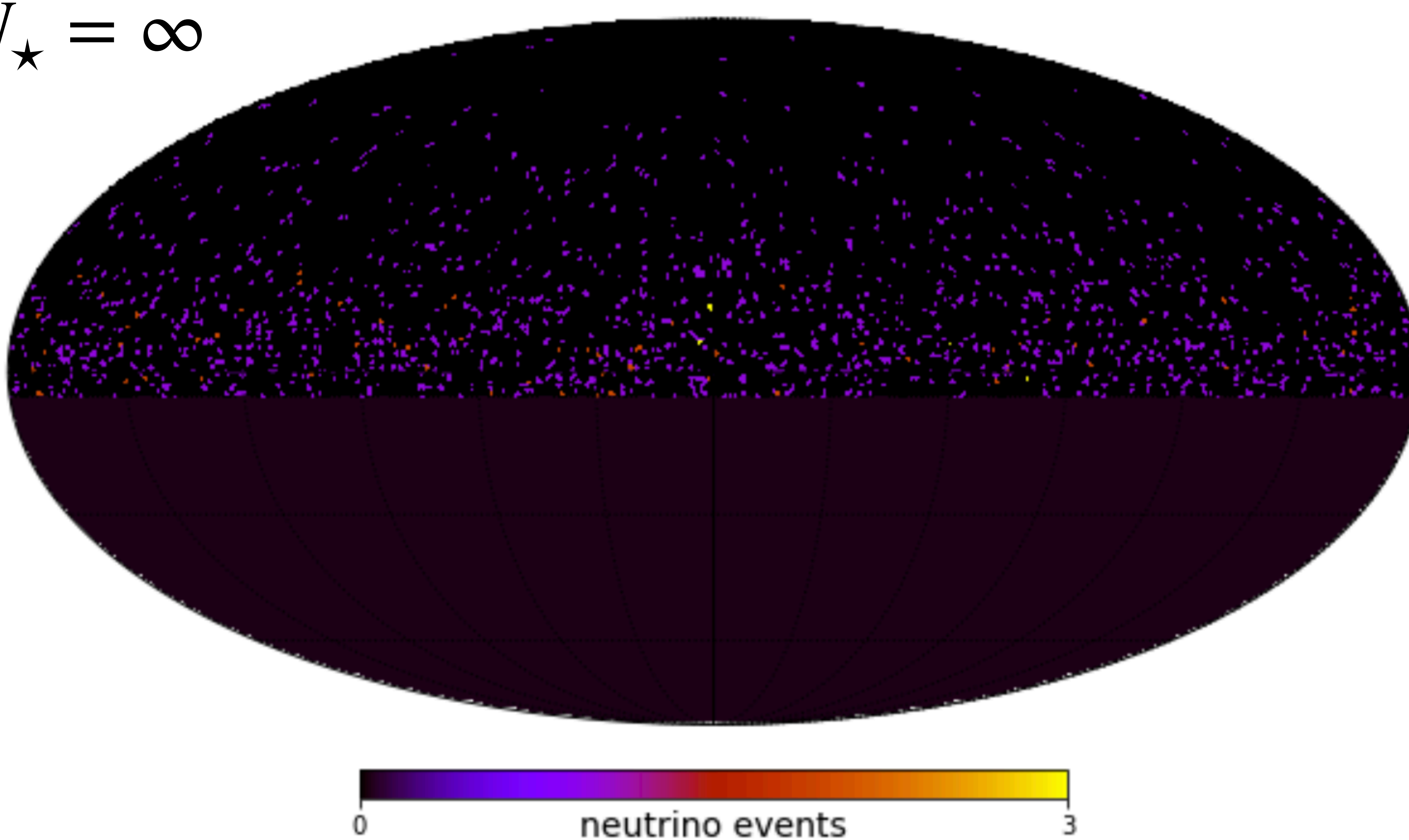


Dekker, Ando, *JCAP* **1902**, 002 (2019)

200 IceCube years

Simulated neutrino data

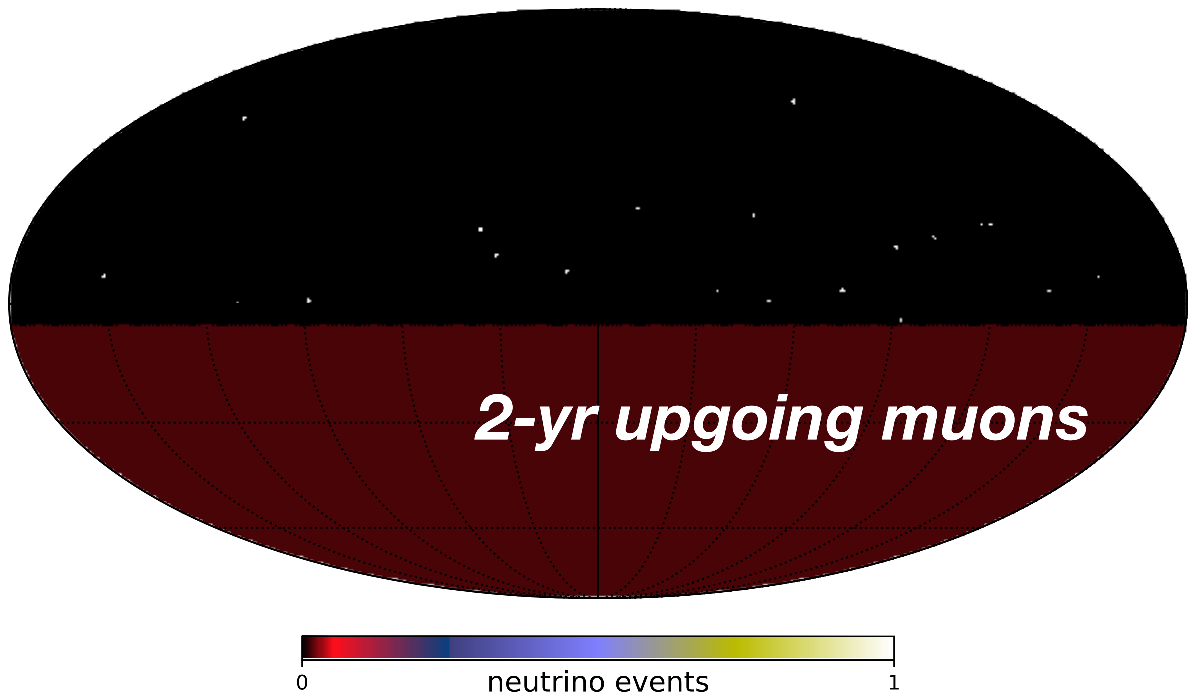
$N_{\star} = \infty$

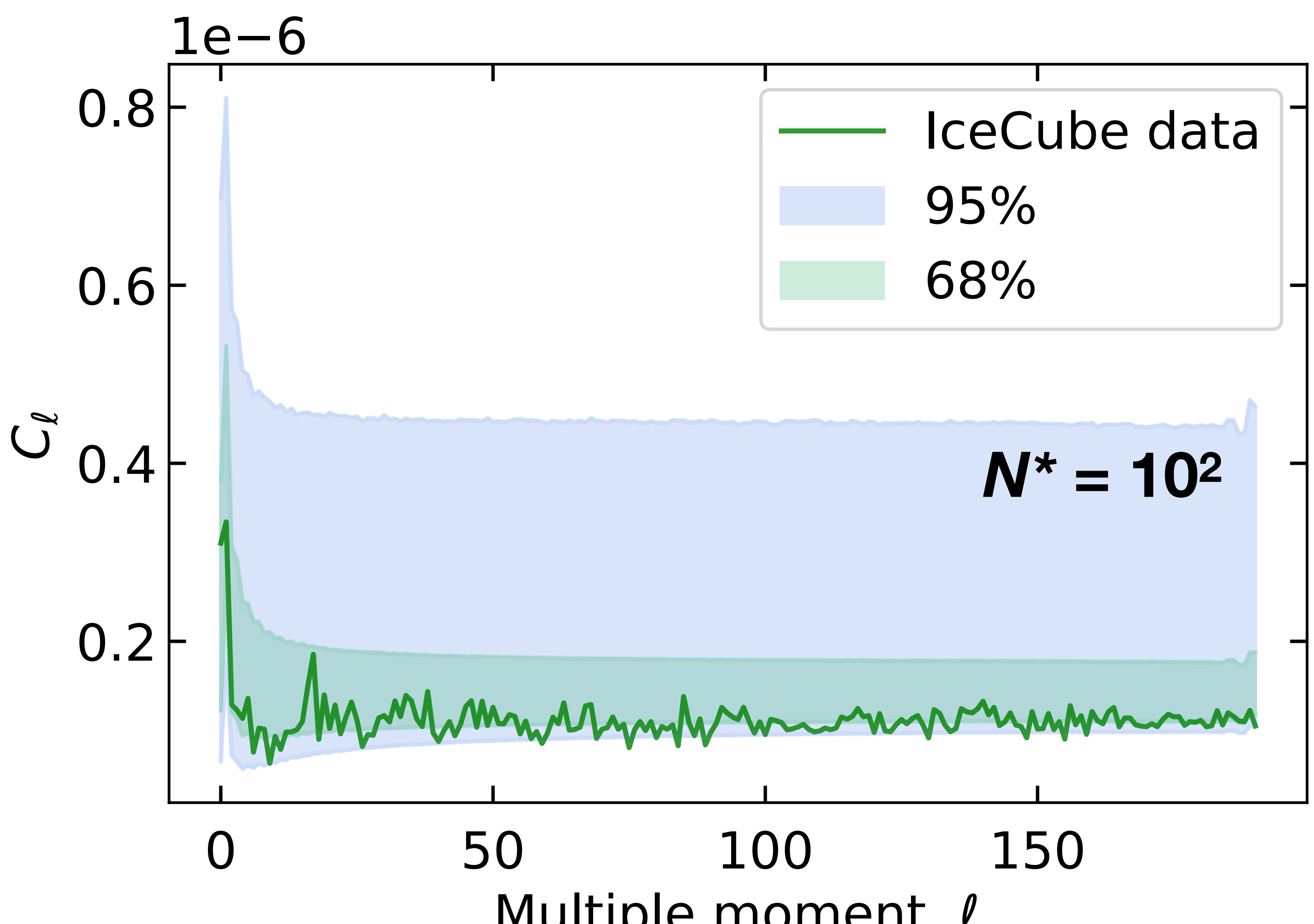


Dekker, Ando, *JCAP* **1902**, 002 (2019)

200 IceCube years

Angular power spectrum





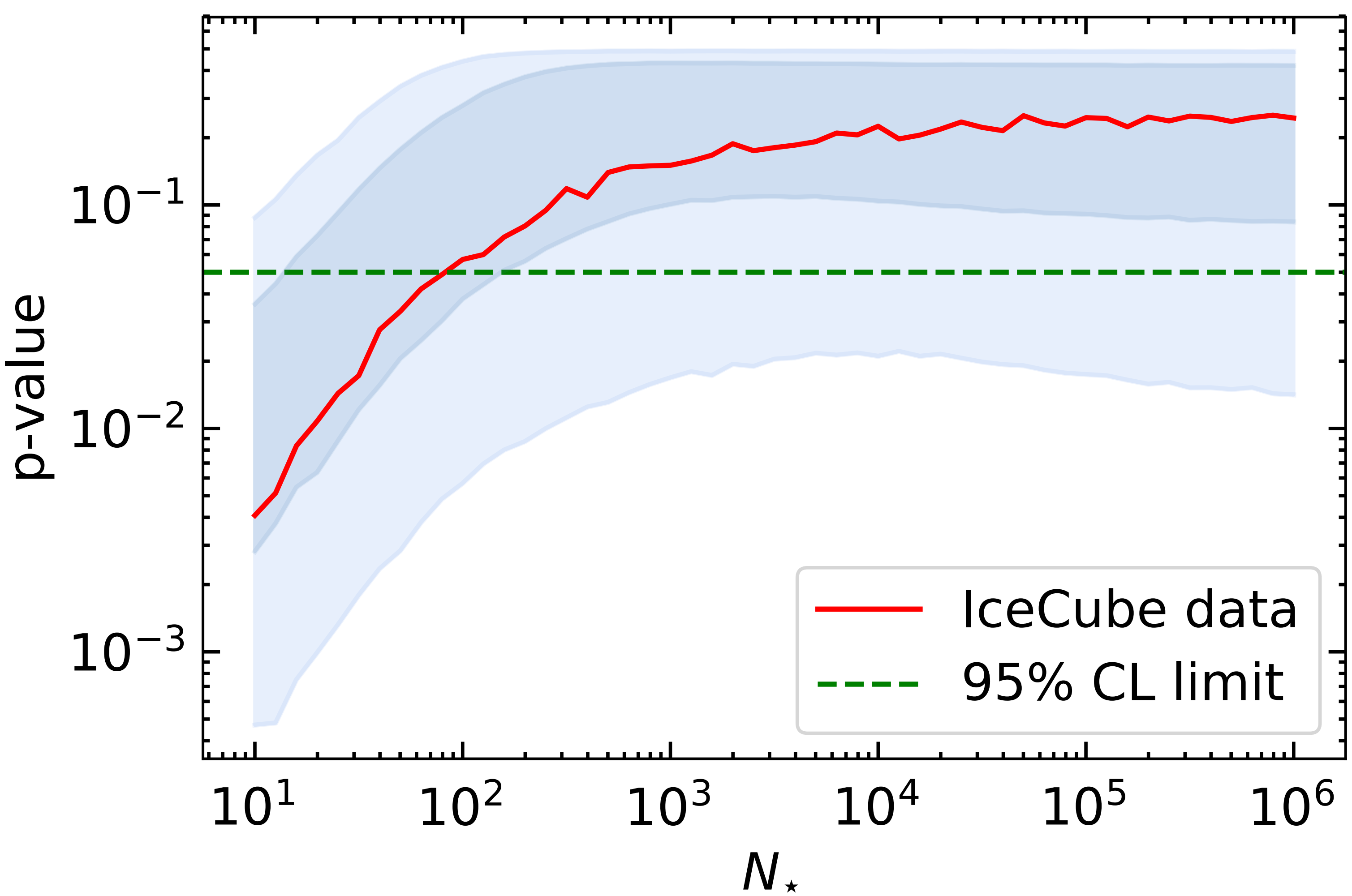
- For each simulated data set, we compute the angular power spectrum
- By repeating the procedure above, we construct the TS and its distribution

$$\chi^2 \left(C_\ell\right) = \sum_{\ell\ell'} \left(C_\ell - C_\ell^{\rm mean}\right) \left(\mathrm{Cov}_{\ell\ell'}\right)^{-1} \left(\mathrm{C}_{\ell'} - \mathrm{C}_{\ell'}^{\rm mean}\right)$$

- If the TS value of the actual data is found extreme, we can reject the value of *N**

Dekker, Ando, *JCAP* **1902**, 002 (2019)

IceCube constraints



Dekker, Ando, *JCAP* **1902**, 002 (2019)

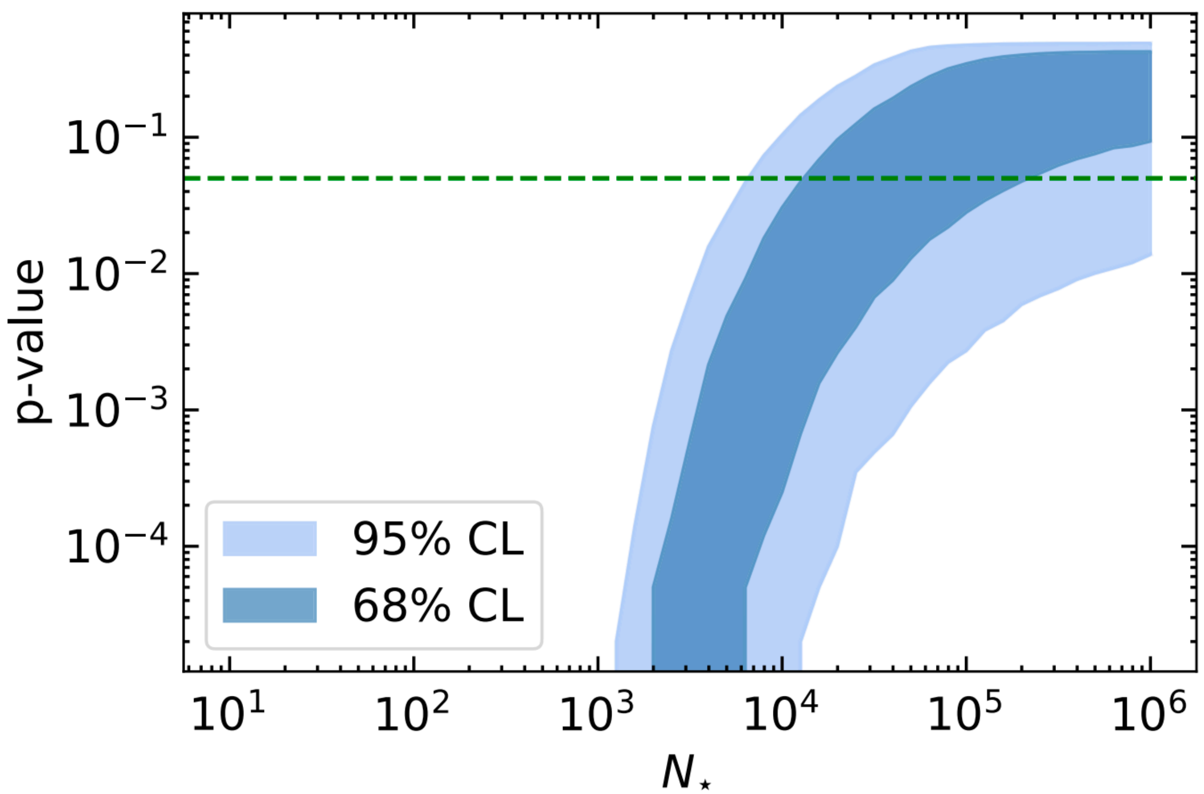
- 2 years of upgoing muon neutrino data from IceCube with energies $E_\mu > 50$ TeV: 21 events
- Source population with N^* < 82 is excluded at 95% CL

Source	***N****
Blazars	600
Radio galaxies	10^5
Starbursts	10^7

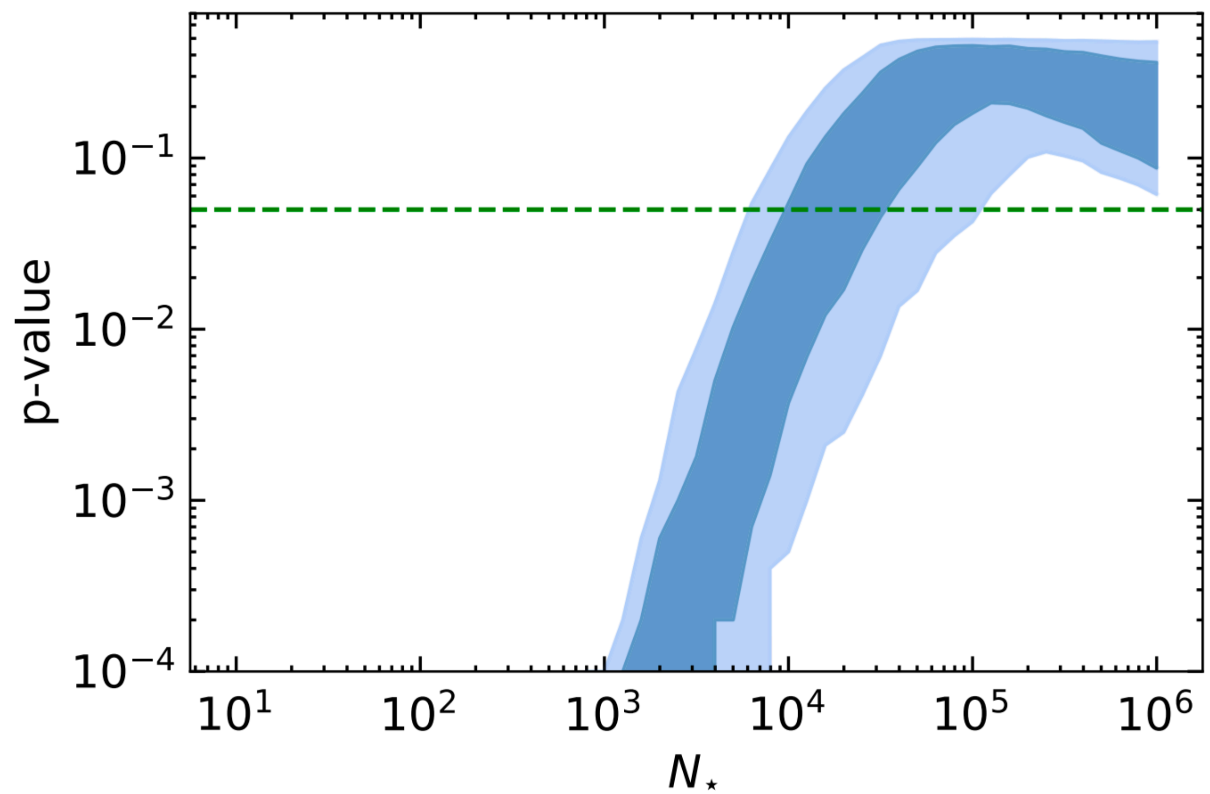
Future prospects

Case with $N^* = \infty$

IceCube-Gen2



KM3NeT



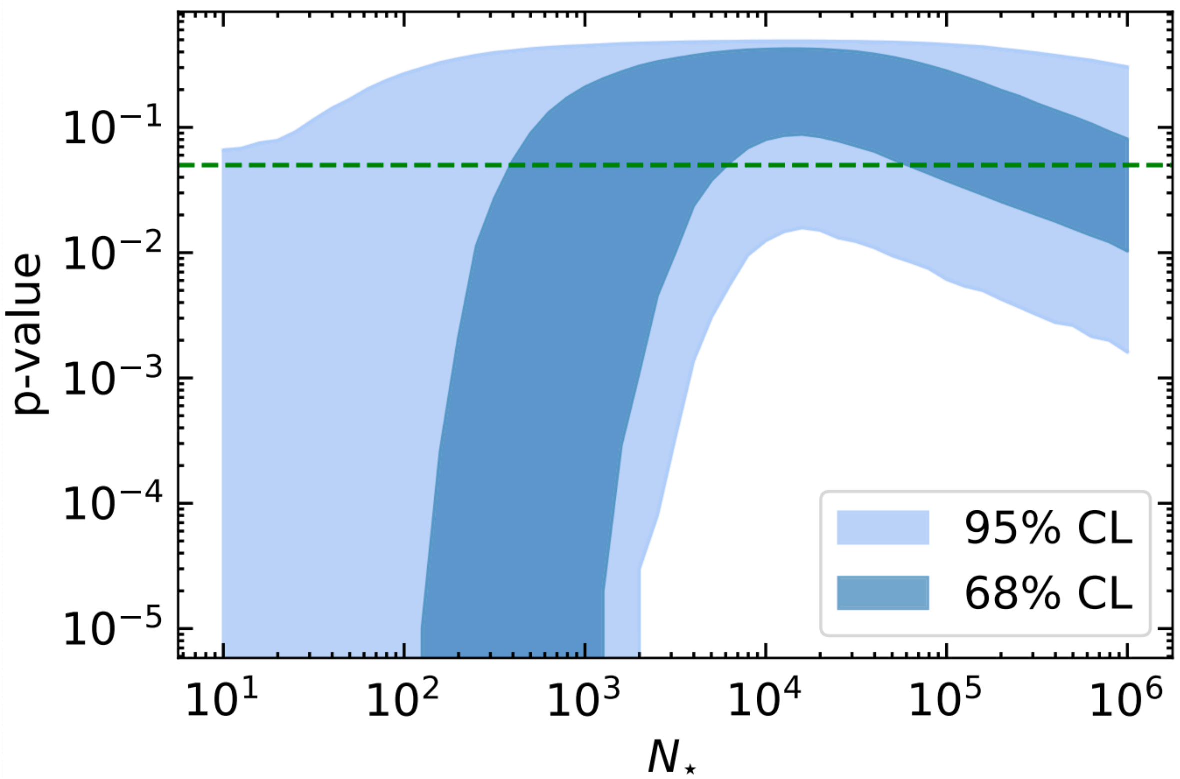
Dekker, Ando, *JCAP* **1902**, 002 (2019)

10-yr exposure

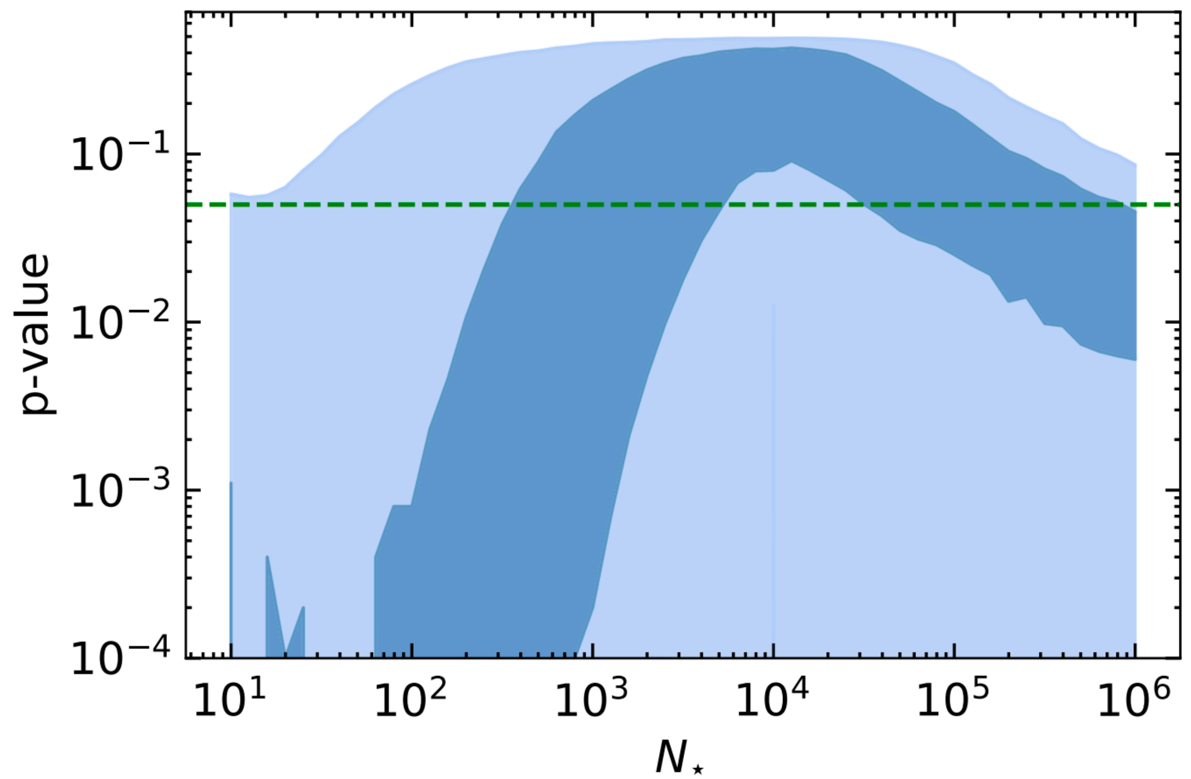
Future prospects

Case with $N^* = 10^4$

IceCube-Gen2



KM3NeT

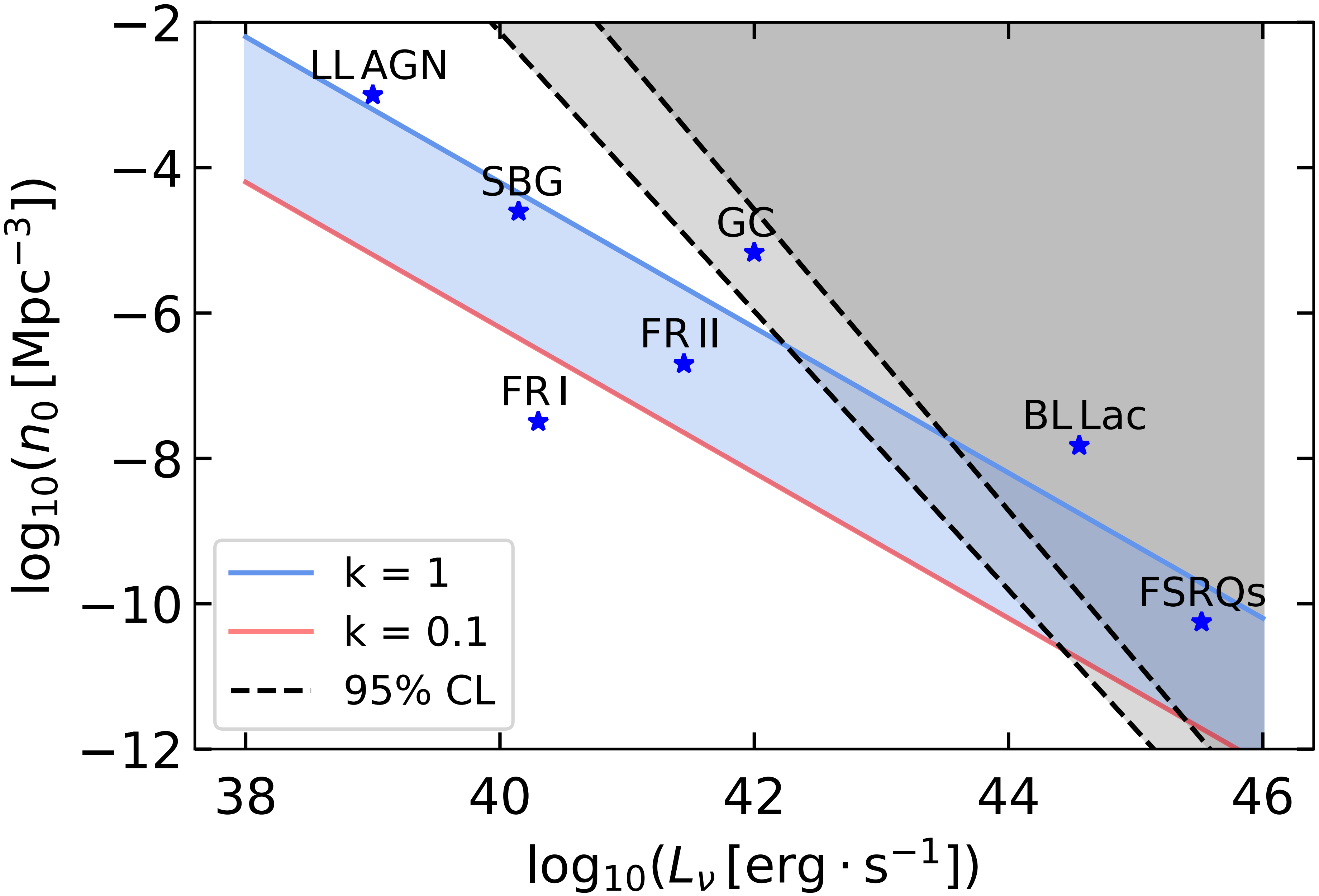


Dekker, Ando, *JCAP* **1902**, 002 (2019)

10-yr exposure

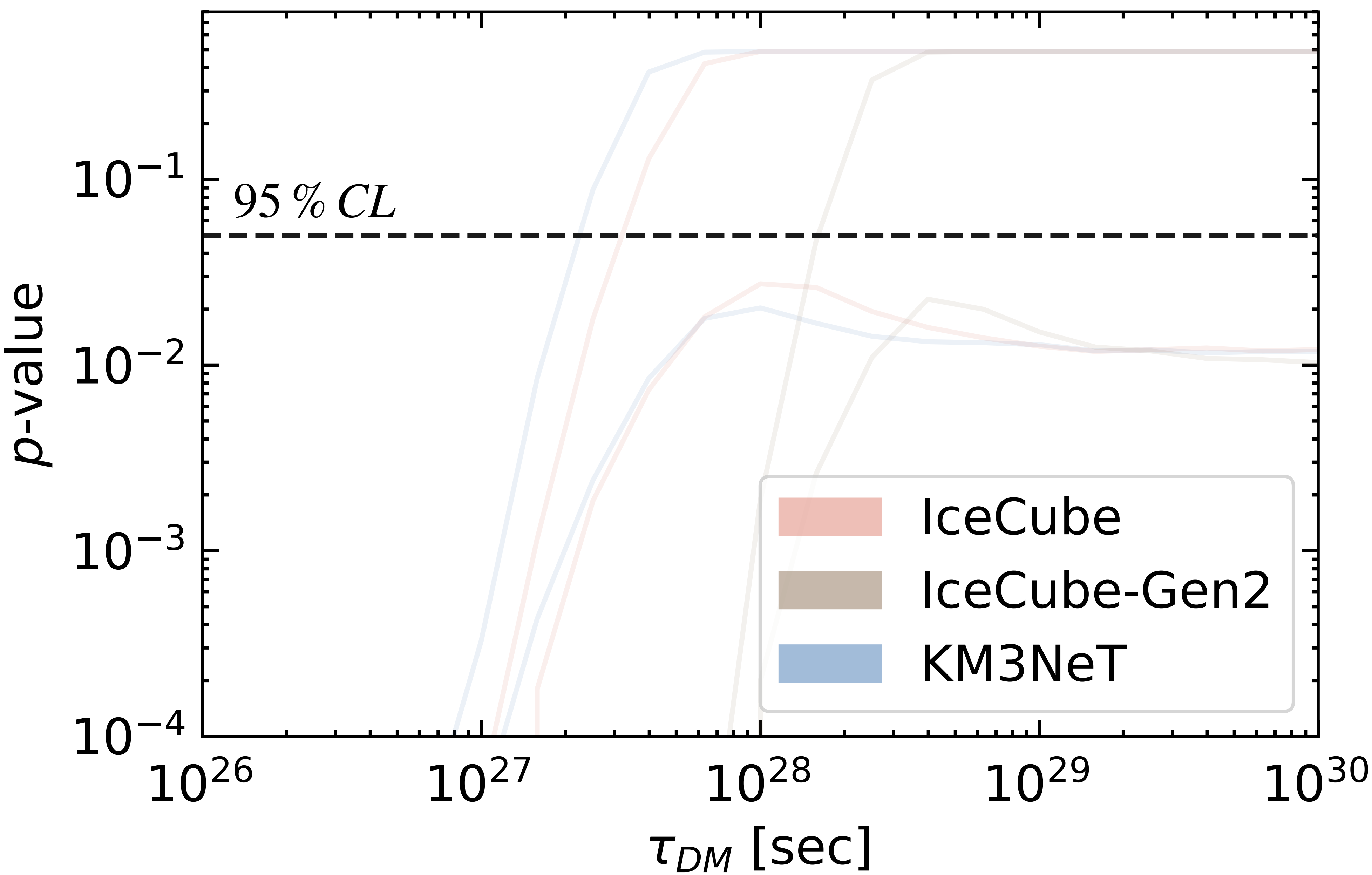
Constraints on source phase space

Dekker, Ando, *JCAP* **1902**, 002 (2019)



10-year IceCube-Gen2

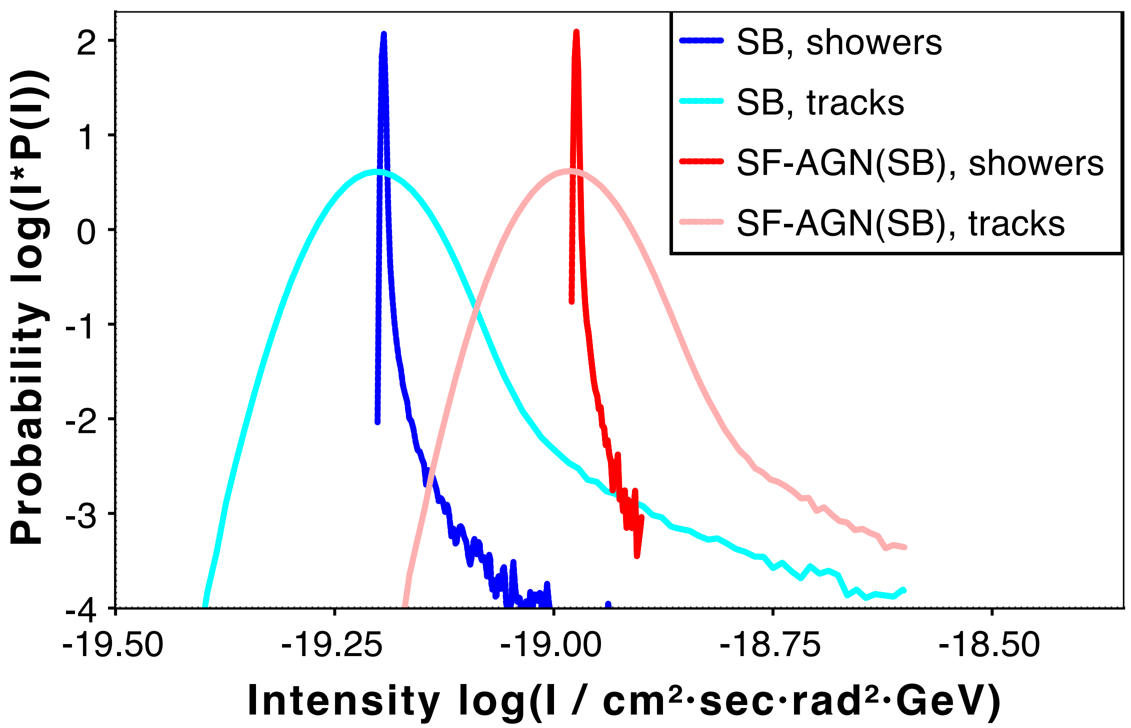
Application to heavy dark matter decay

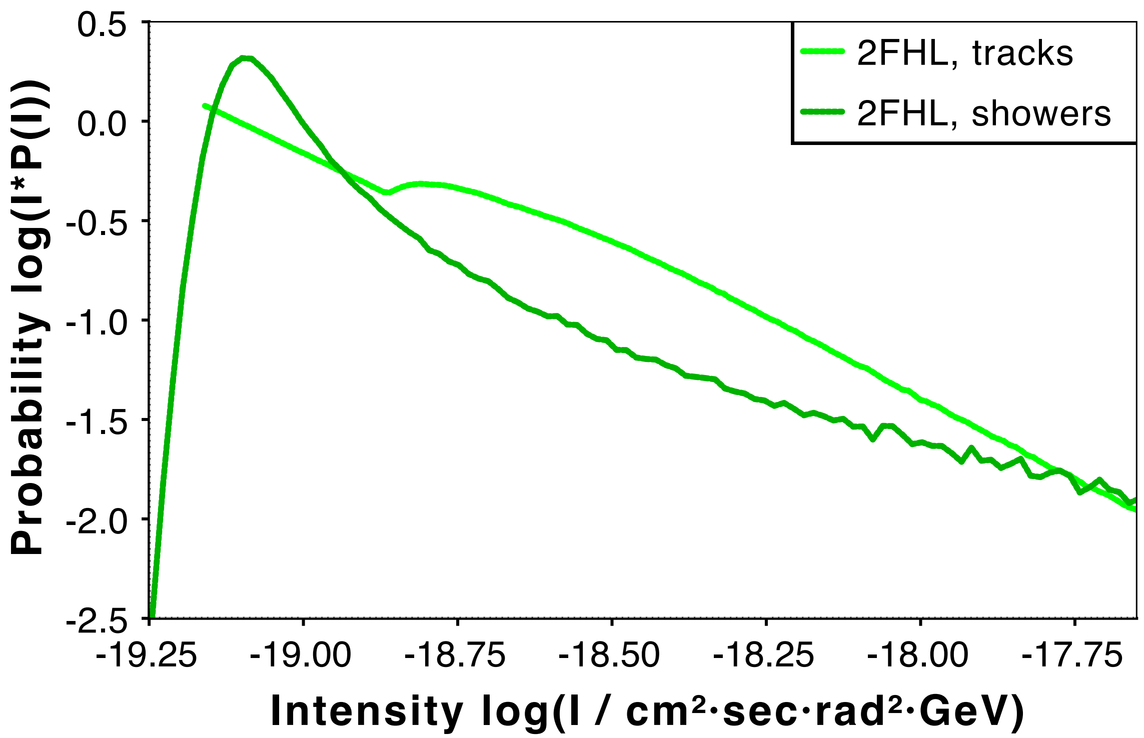


Dekker, Chianese, Ando, in preparation

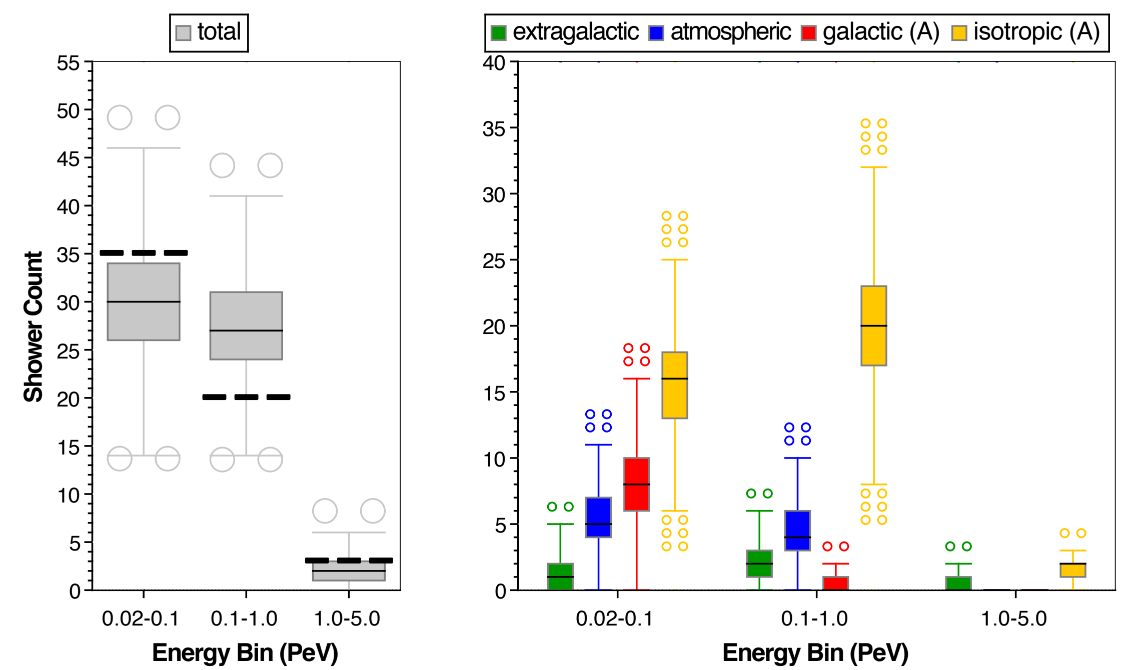
Beyond variance: One-point fluctuation analysis

Feyereisen, Tamborra, Ando, *JCAP* **03**, 057 (2017)





Feyereisen, Gaggero, Ando, *Phys. Rev. D* **97**, 103017 (2018)

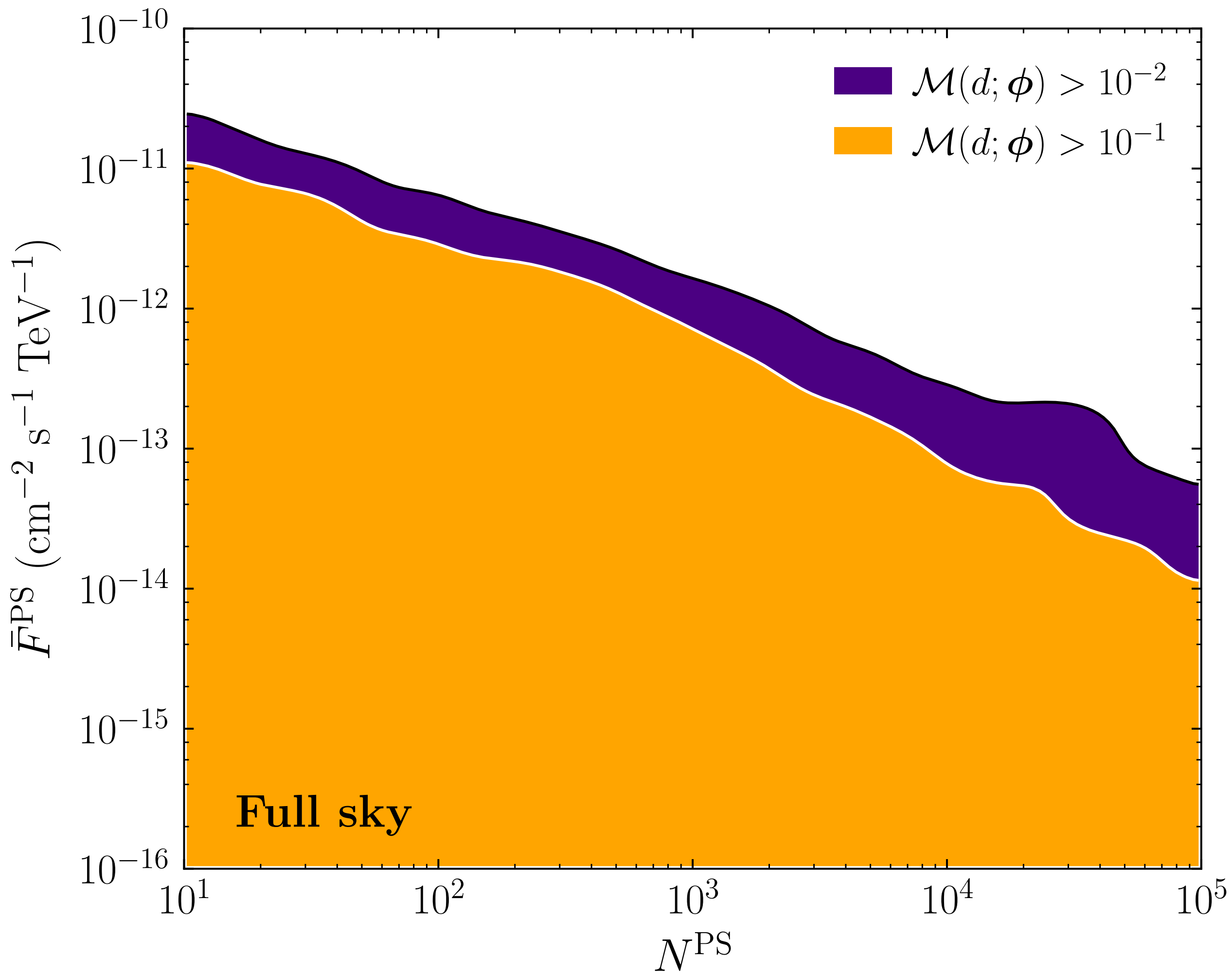


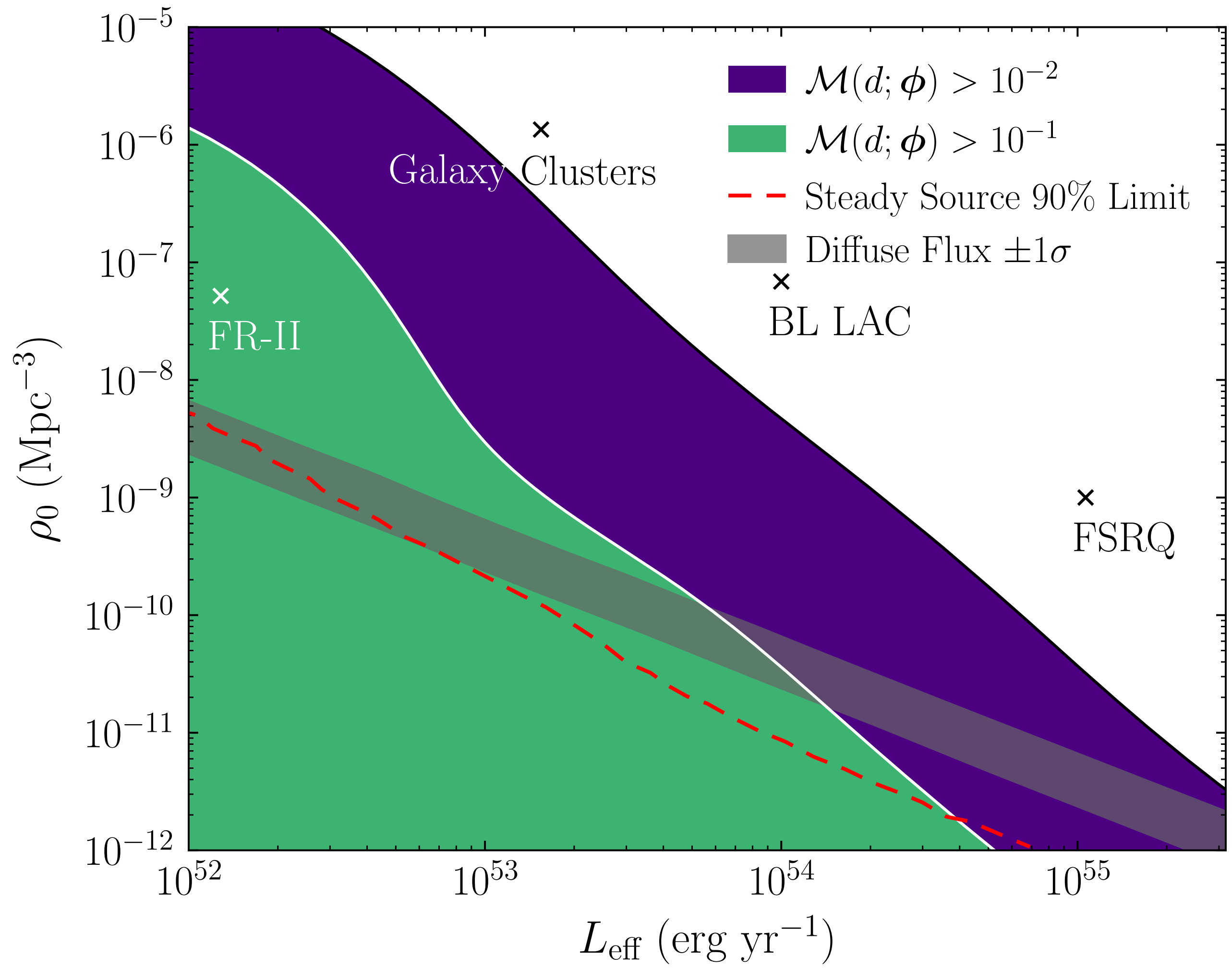
- One-point fluctuation analysis adopts all the information contained in the flux distribution
- Benefit is slim for now, but in the future can be large
    - E.g., test of Galactic component in the future KM3NeT data

Analysis by IceCube Collaboration

IceCube Collaboration, arXiv:1909.08623

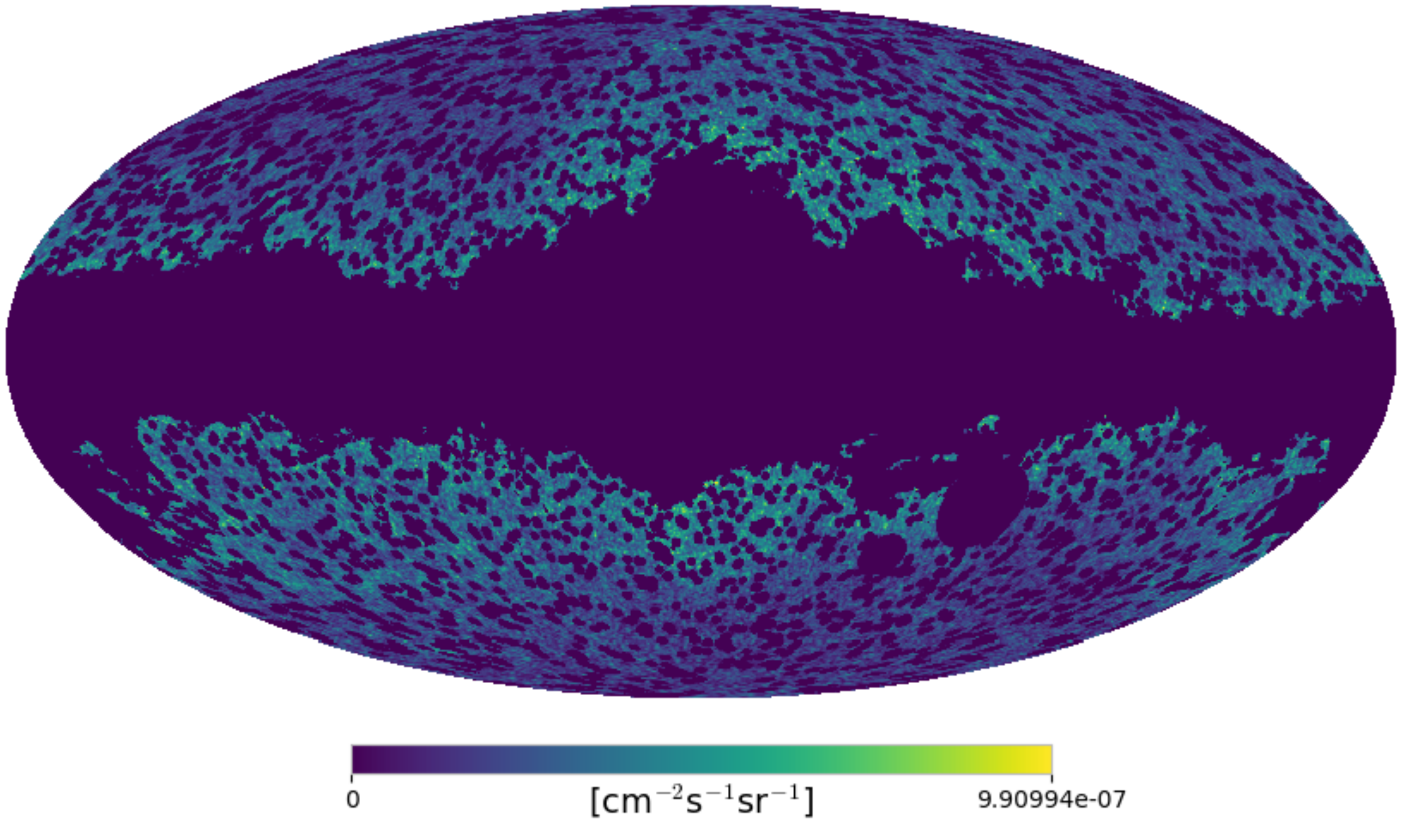
A Search for Neutrino Point-Source Populations in 7 Years of IceCube Data with Neutrino-count Statistics



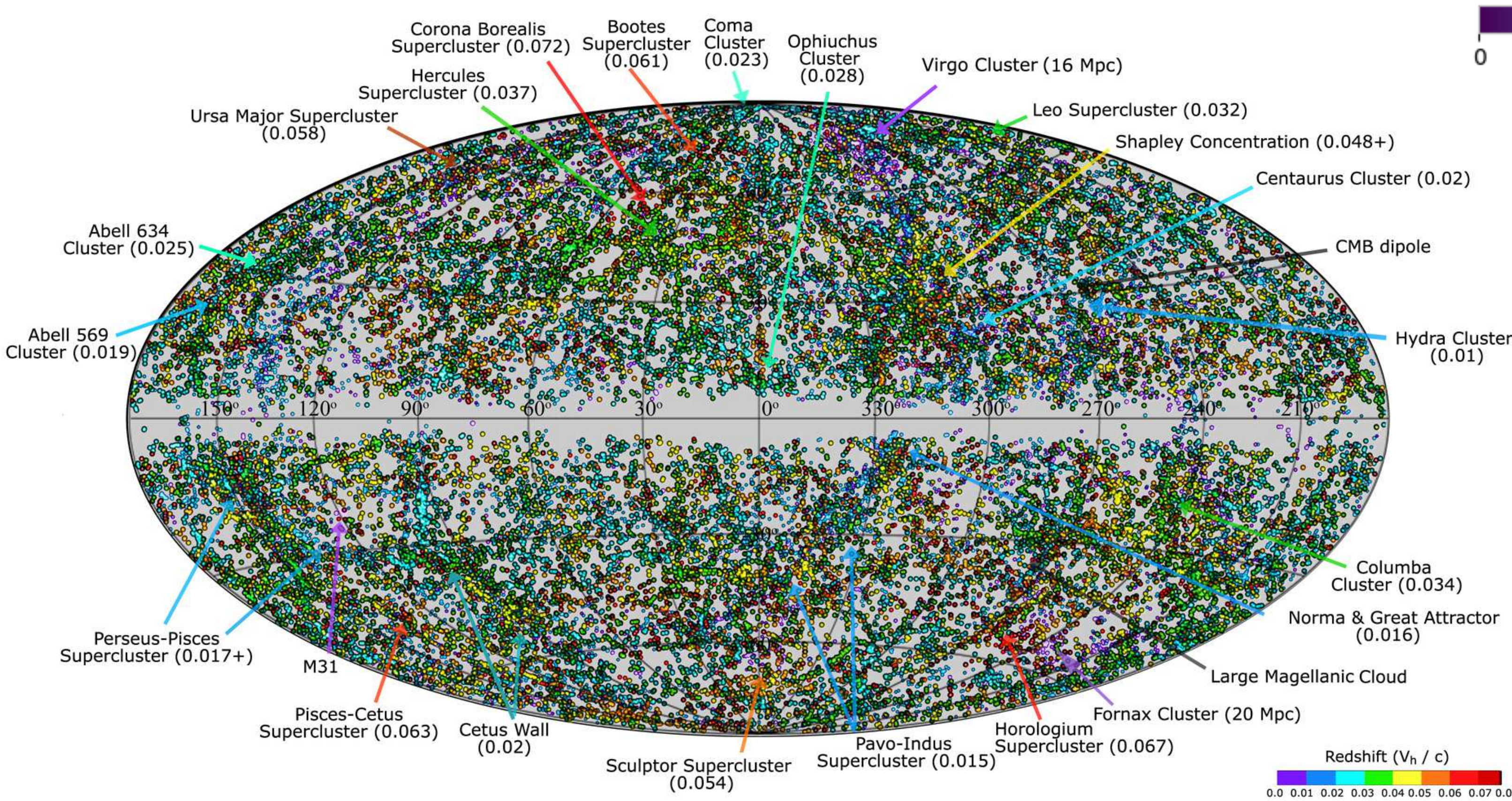


Constraints with two-point statistics

Cross correlation with galaxy distribution



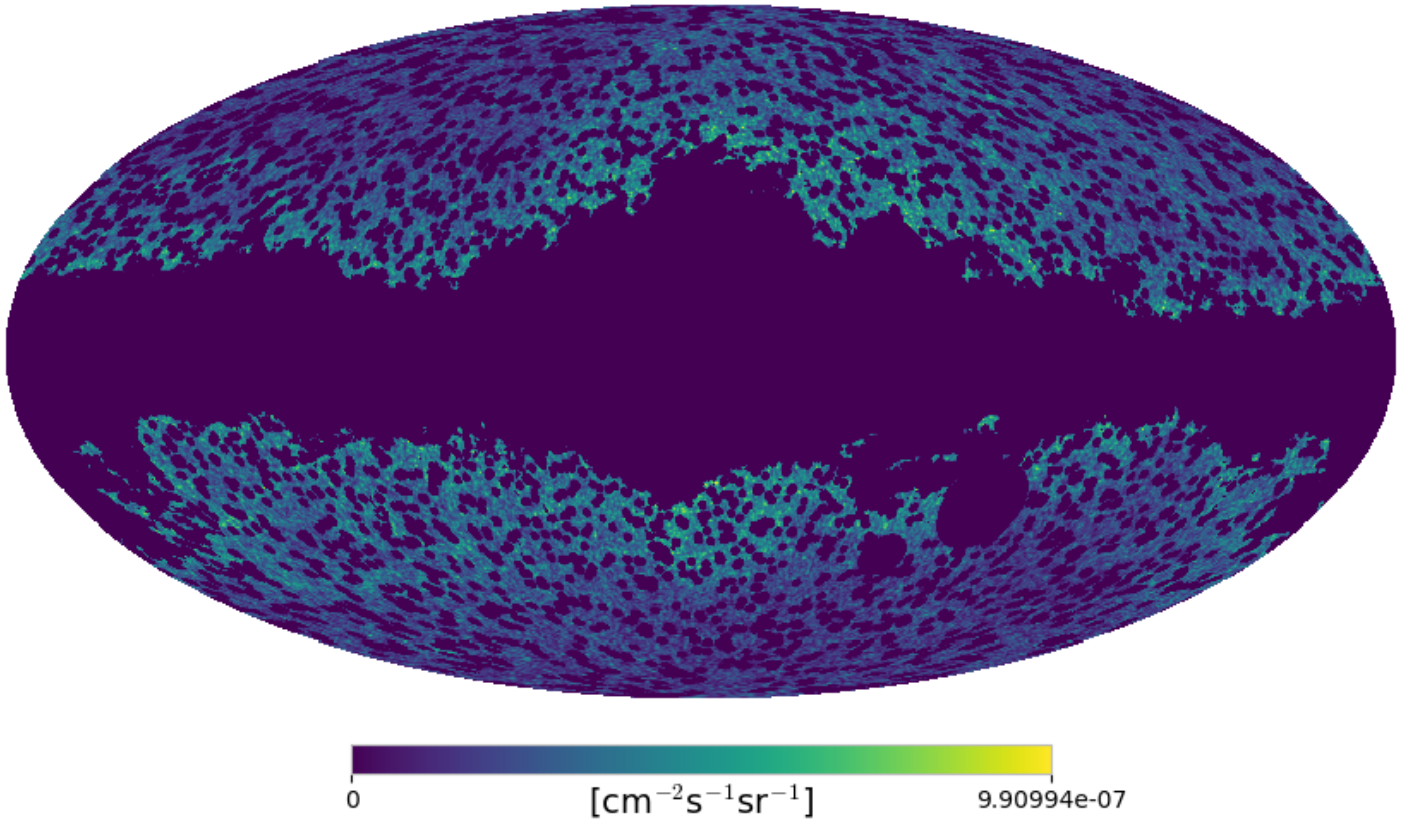
Fermi-LAT, *Phys. Rev. Lett.* **121**, 241101 (2018)



Huchra et al., *Astrophys. J. Suppl. Ser.* **199**, 26 (2011)

Cross correlation with galaxy distribution

Are these two maps similar to each other?



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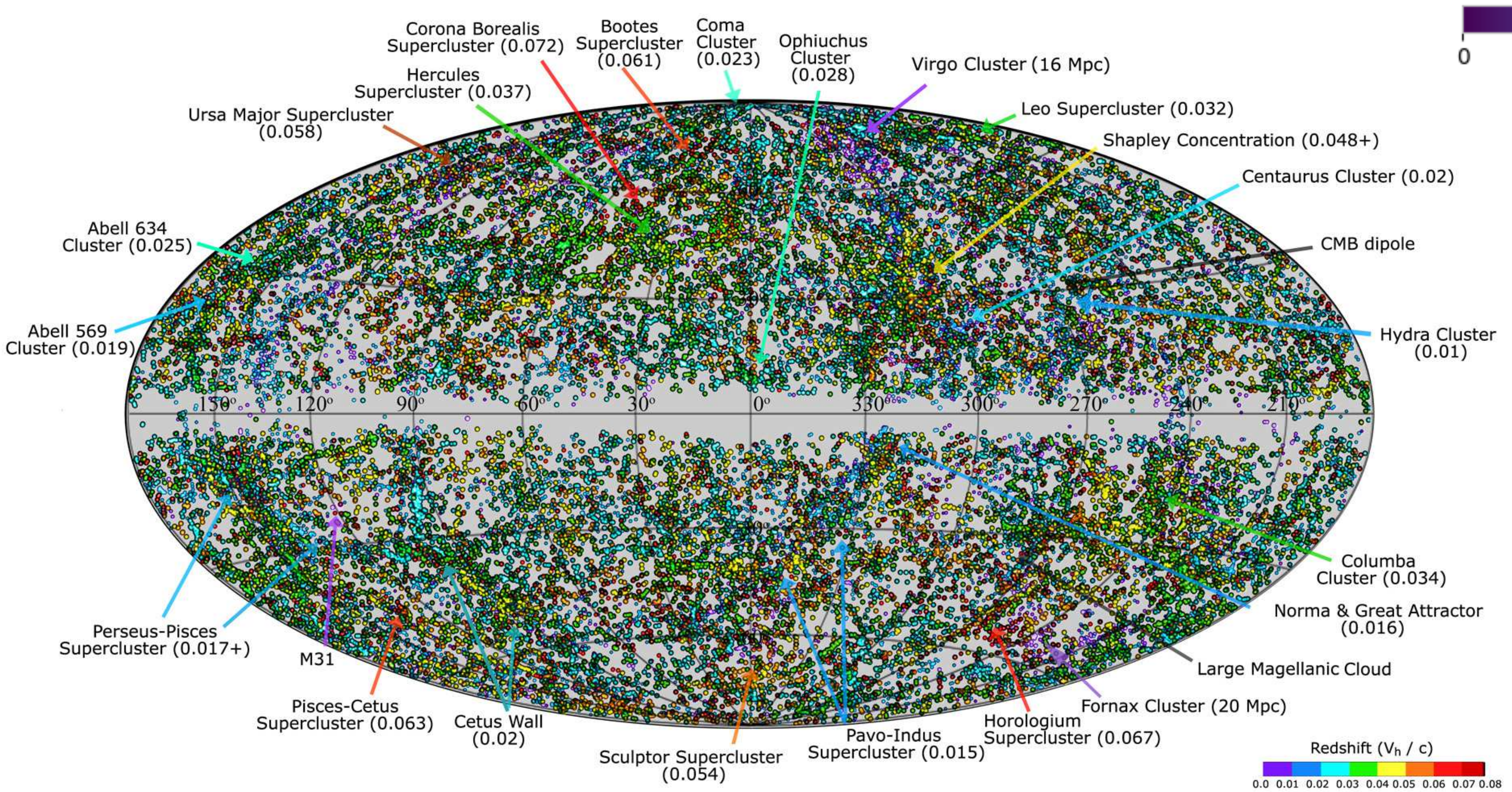

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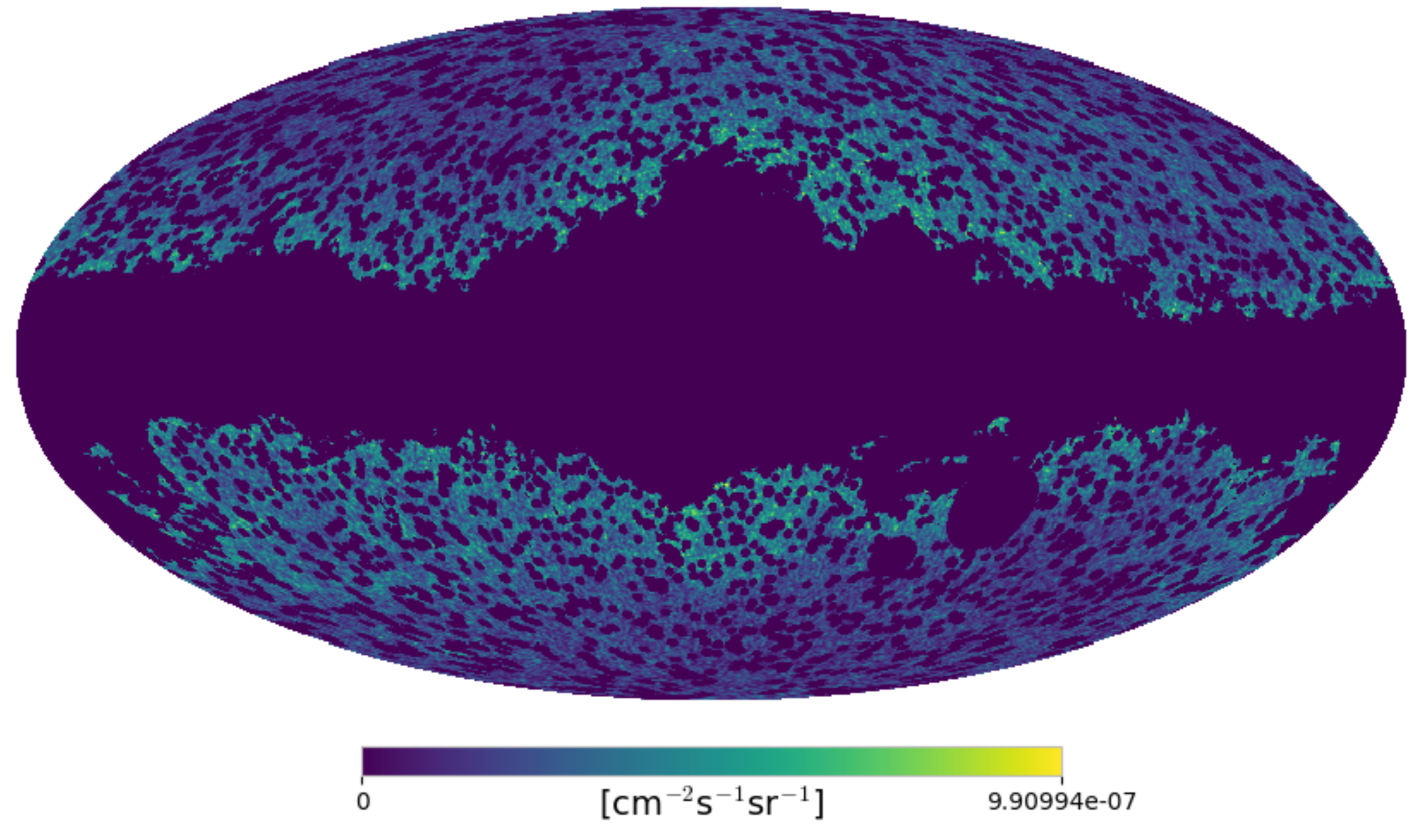
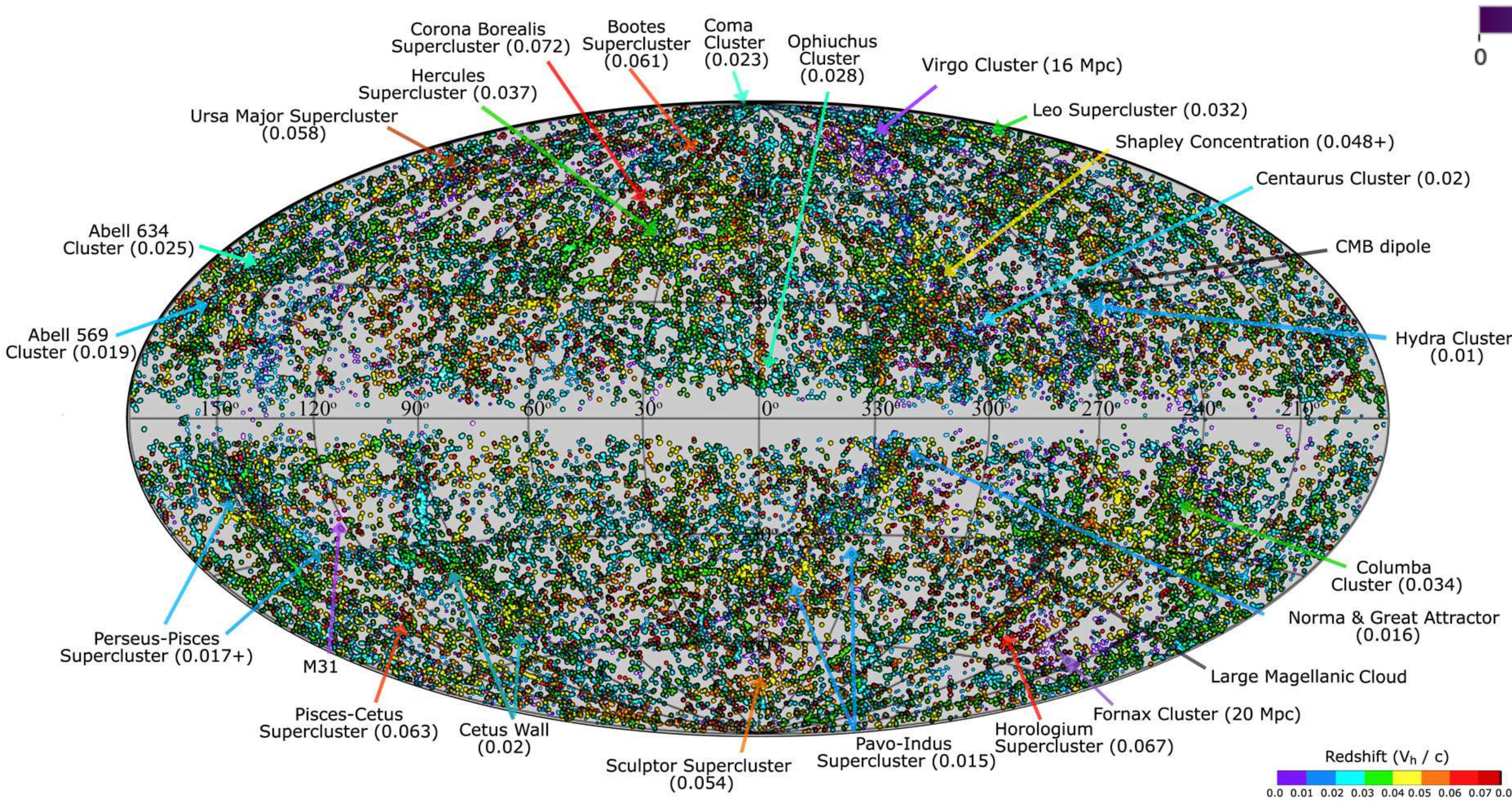


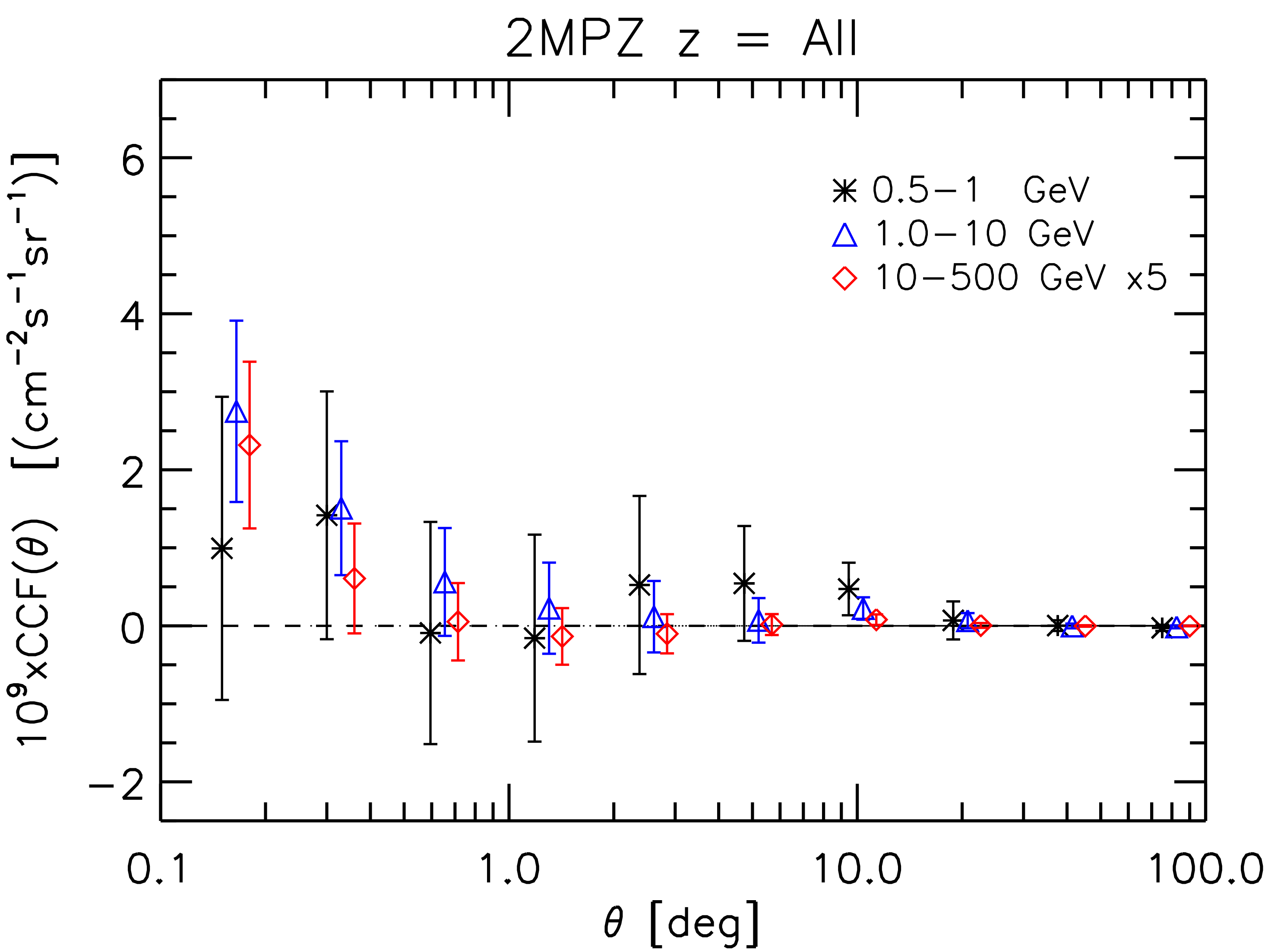
Fermi-LAT, *Phys. Rev. Lett.* **121**, 241101 (2018)



Huchra et al., *Astrophys. J. Suppl. Ser.* **199**, 26 (2011)

They must be, since both gamma-ray sources and galaxies trace dark matter distribution!

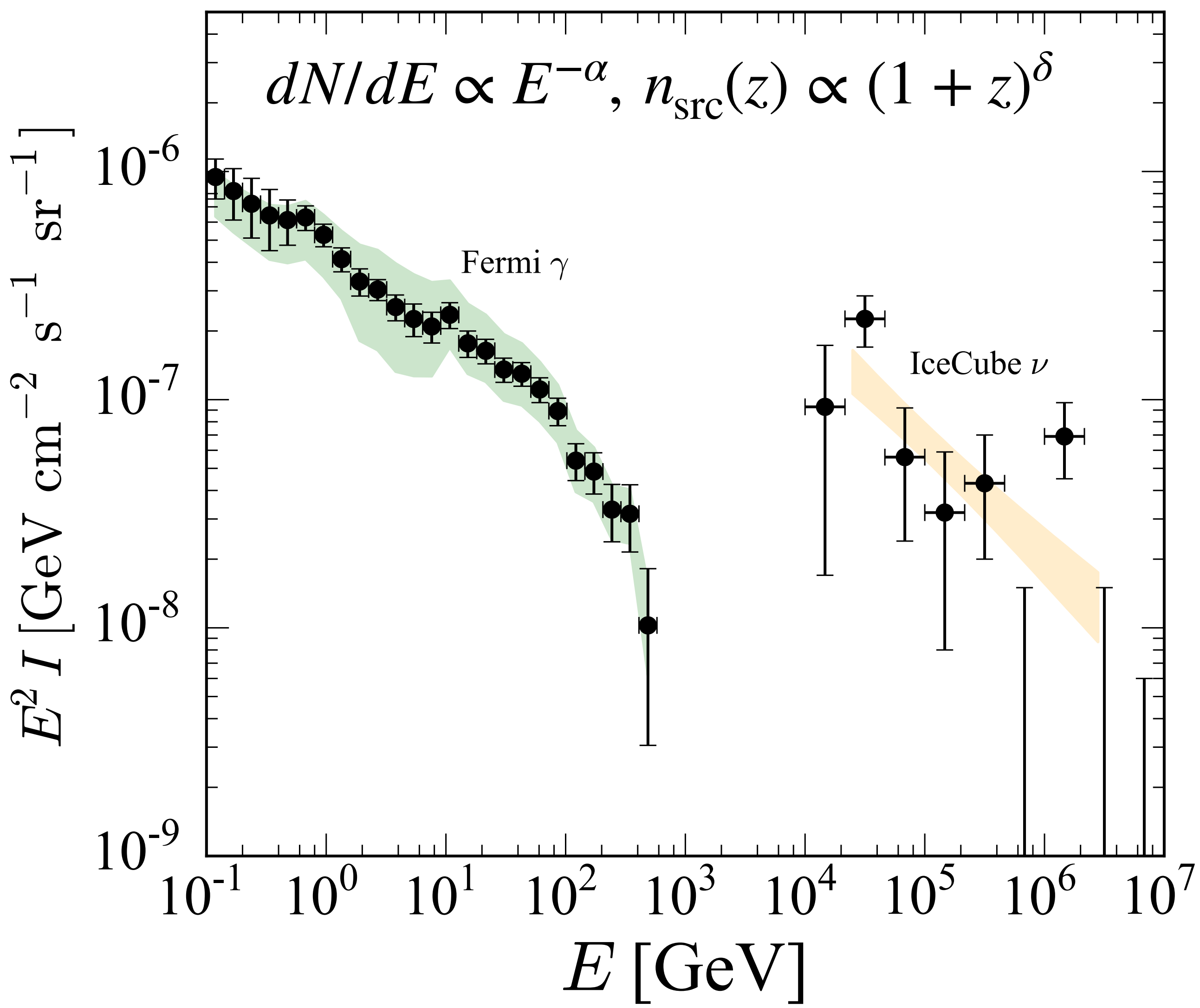
Cross correlation between IGRB and galaxies

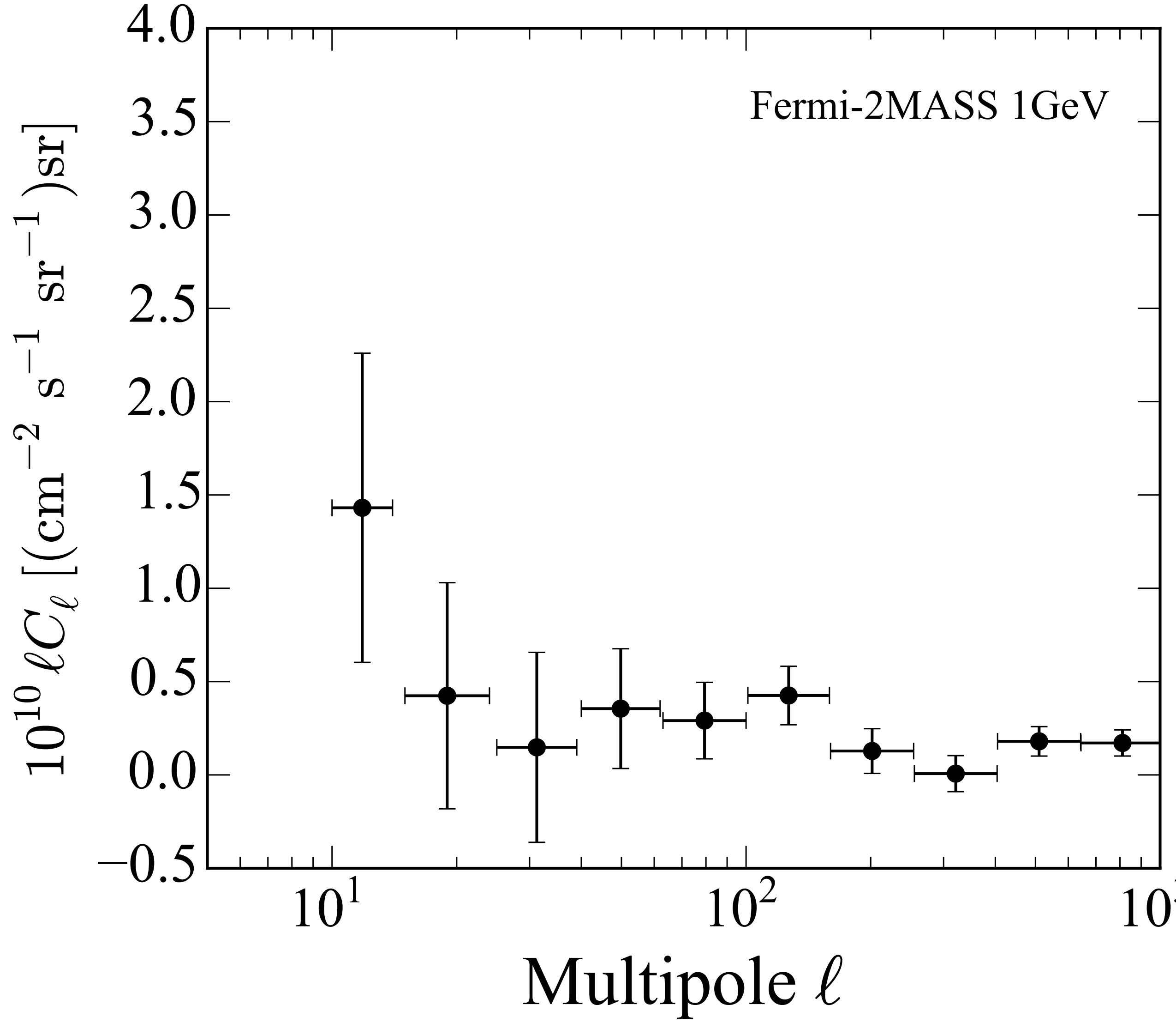


Cuoco et al., *Astrophys. J. Suppl. Ser.* **232**, 10 (2017)

- Yet another probe of gamma-ray sources due to measurements of cross correlations between IGRB and galaxy catalogs
- Originally proposed for dark matter annihilation (Ando et al. 2014) and was recently proven to be a strong probe
- *This can also be applied to any neutrino sources if they are of pp origin!*
    - The neutrino spectrum is very similar to that of gamma rays

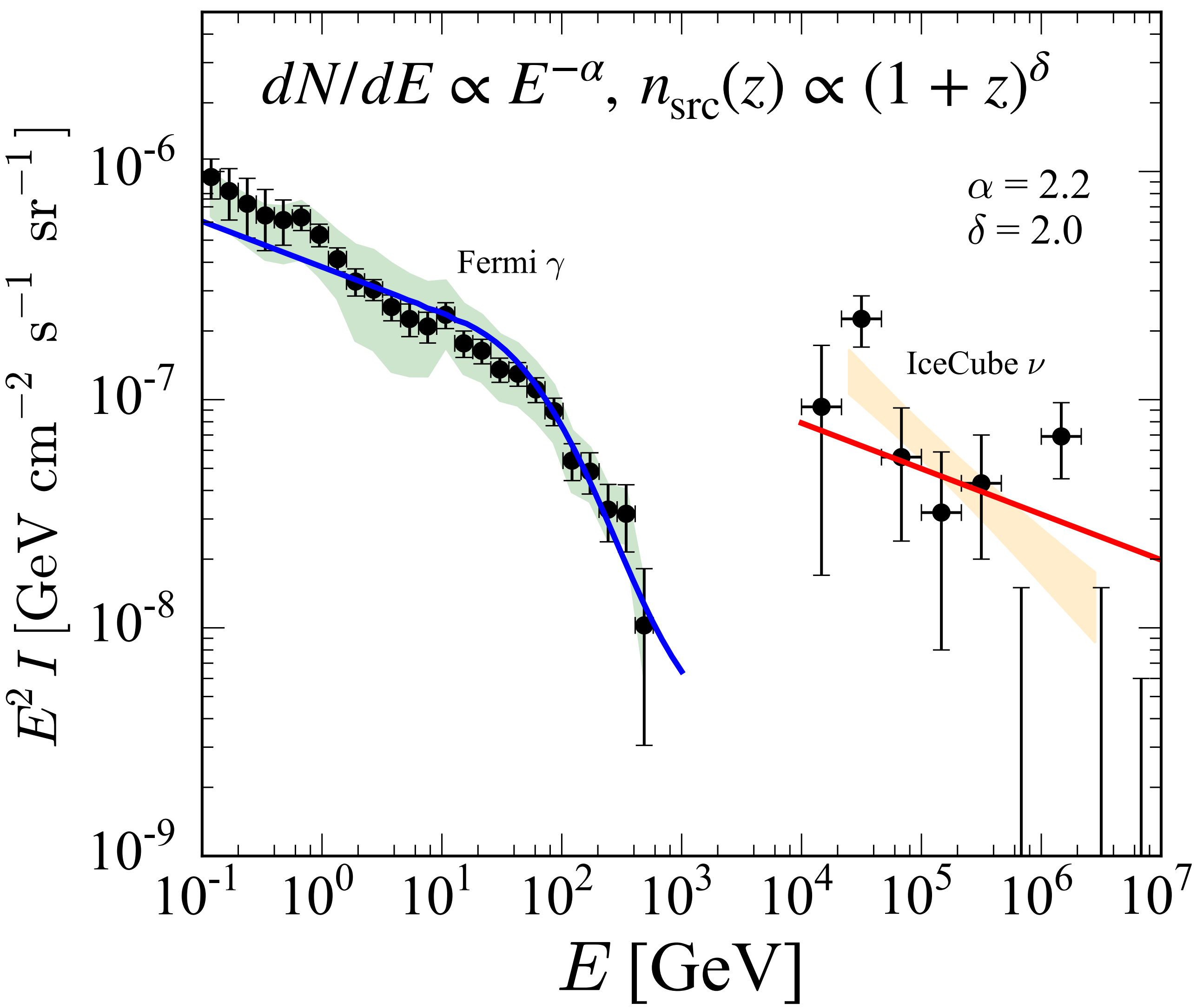
Spectral constraints

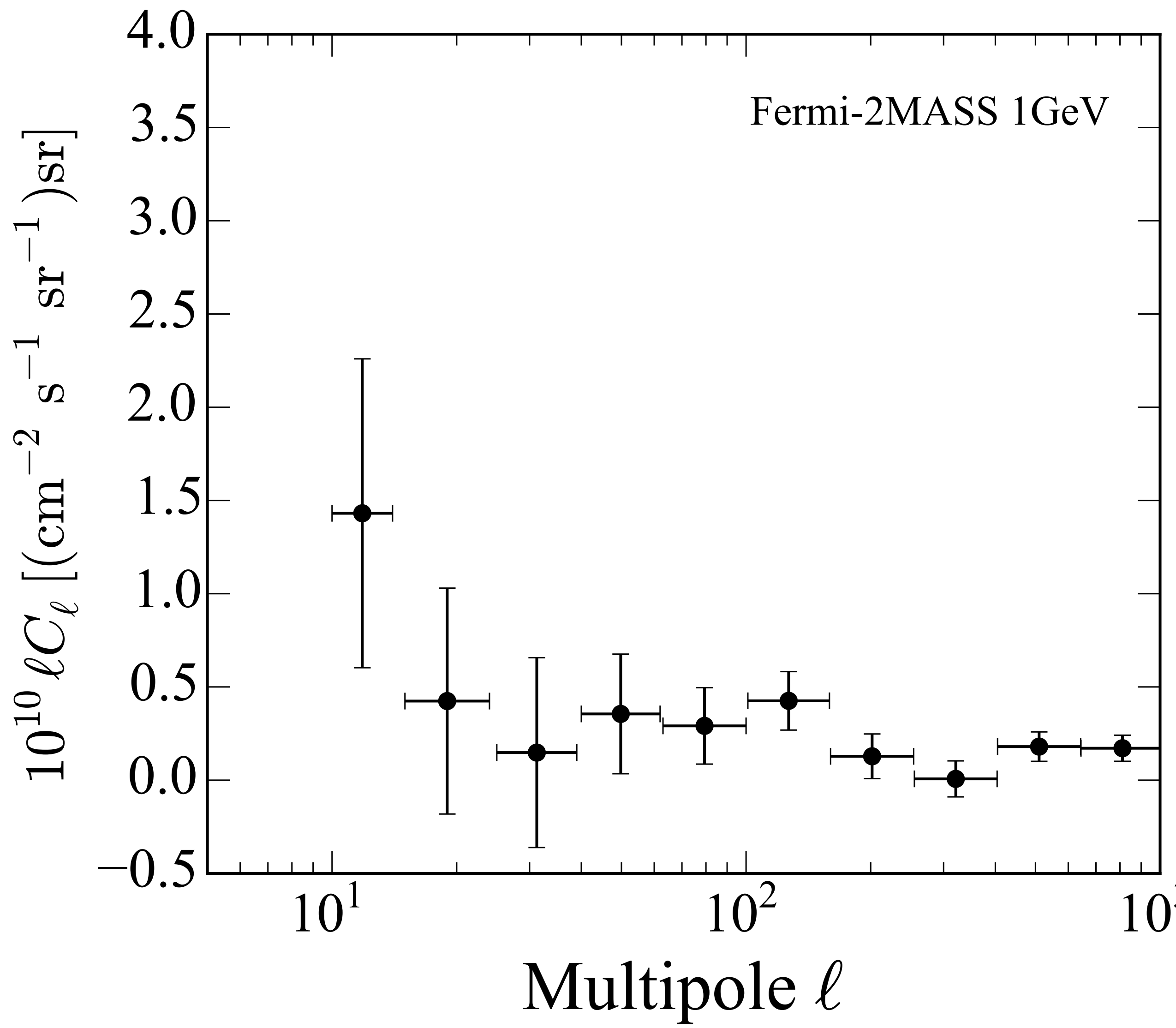




Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

Spectral constraints





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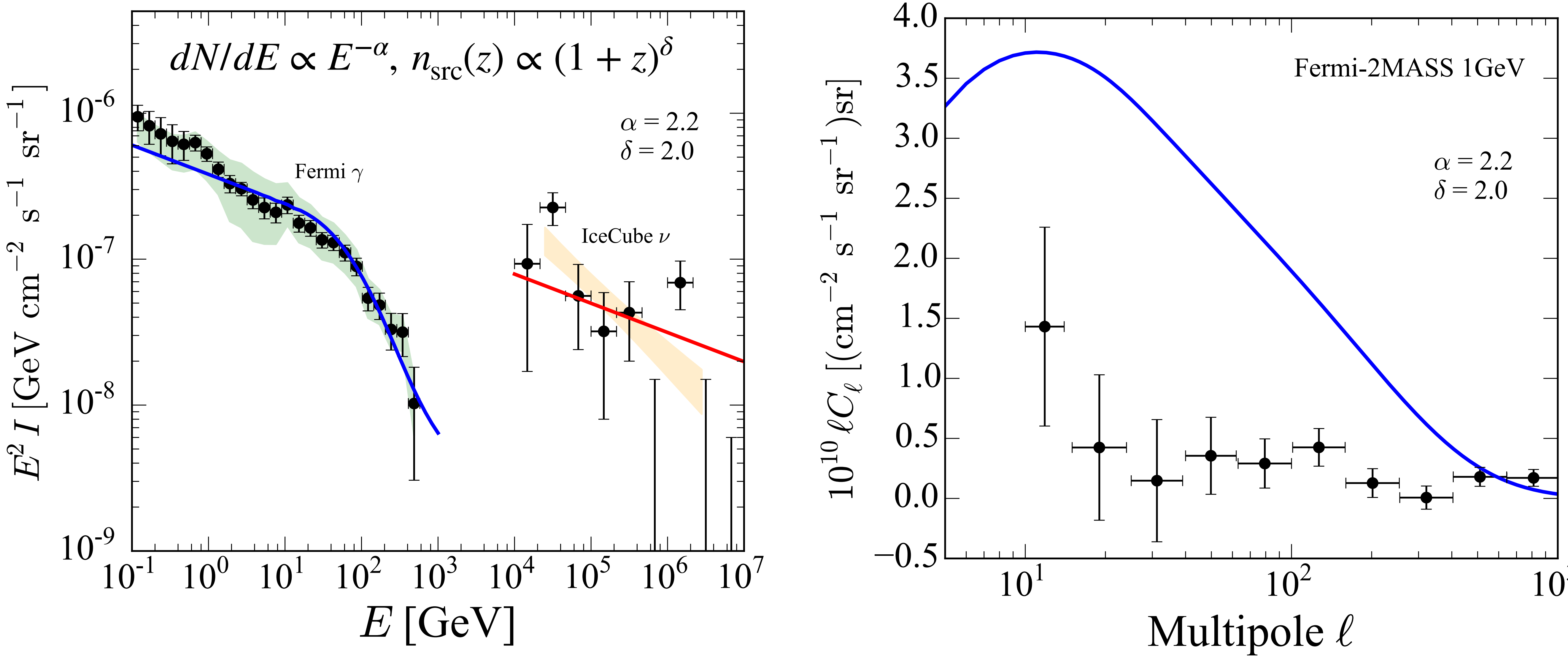
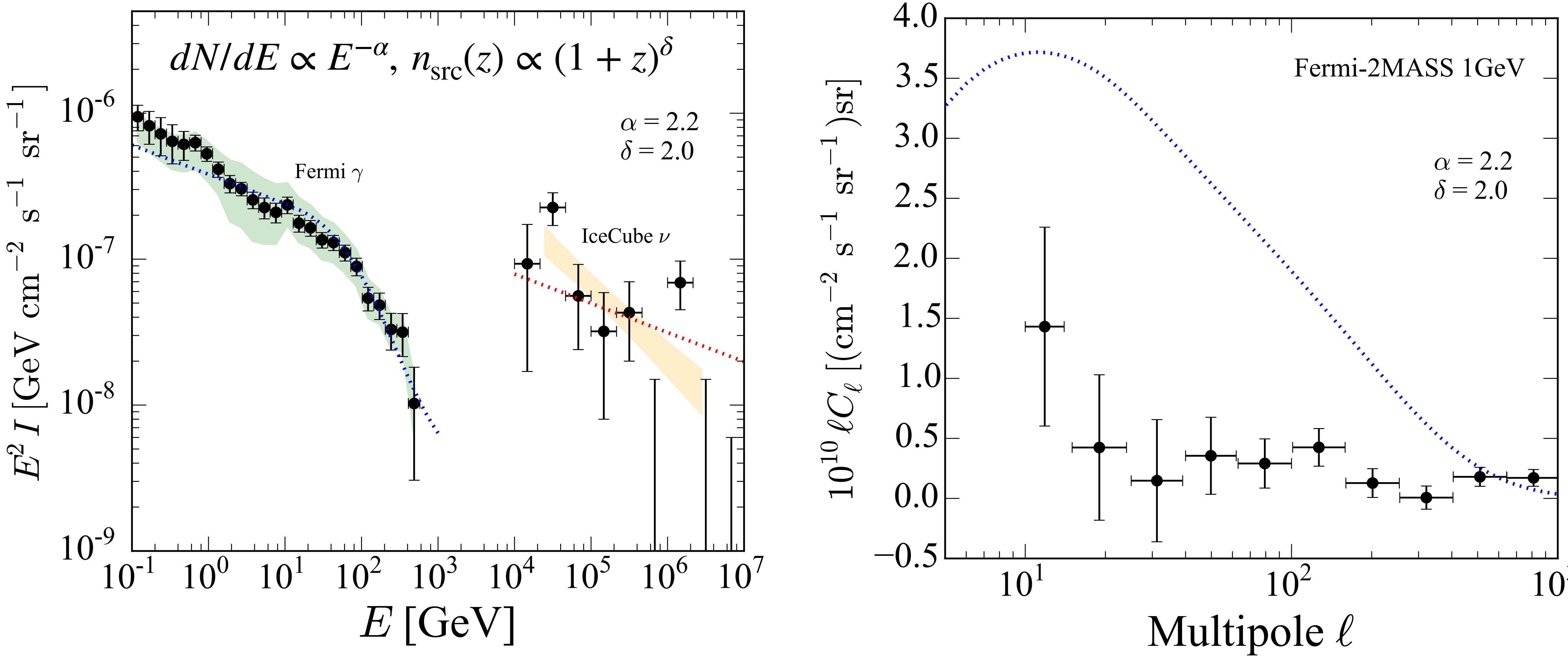


Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

Tomographic constraints



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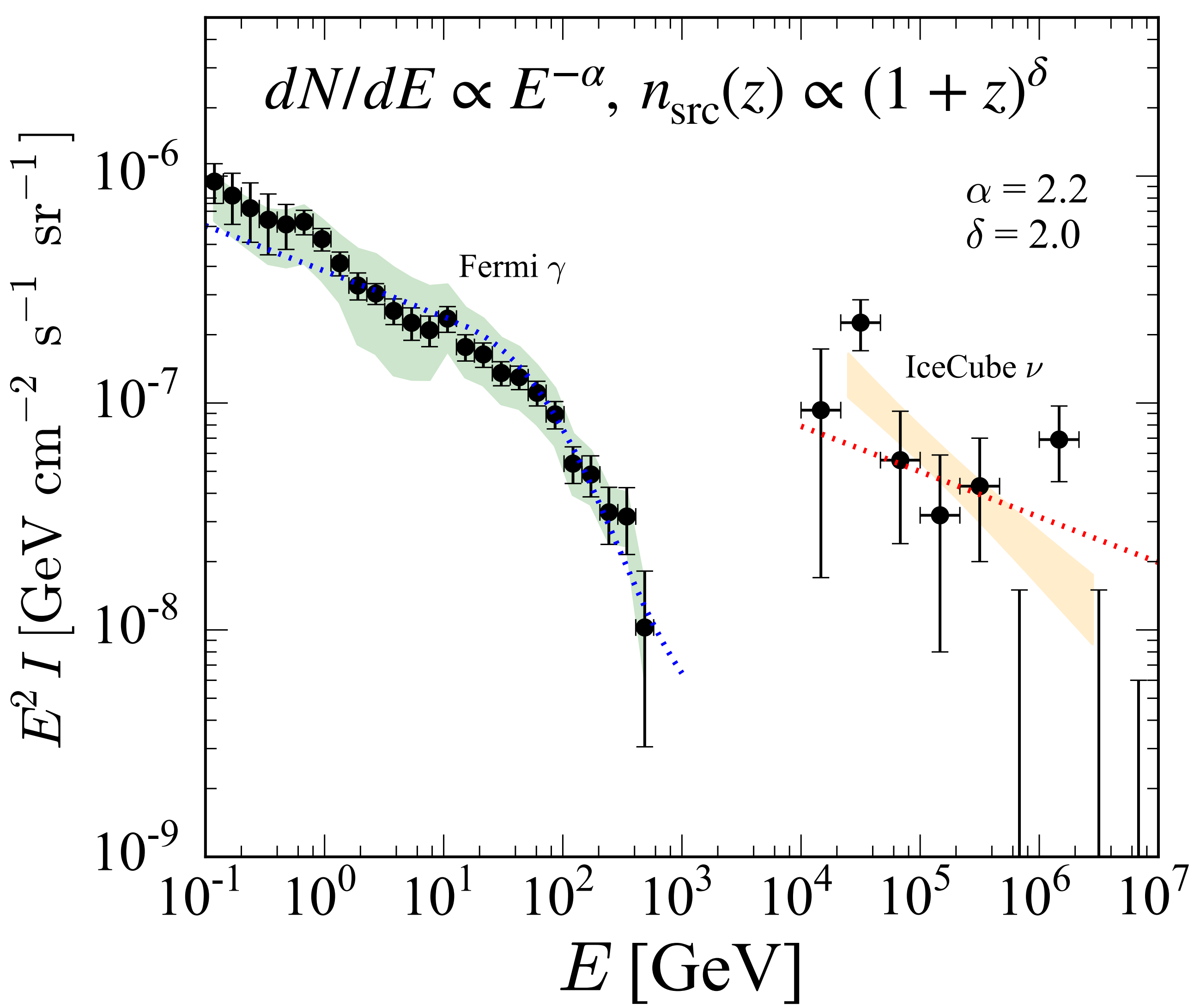
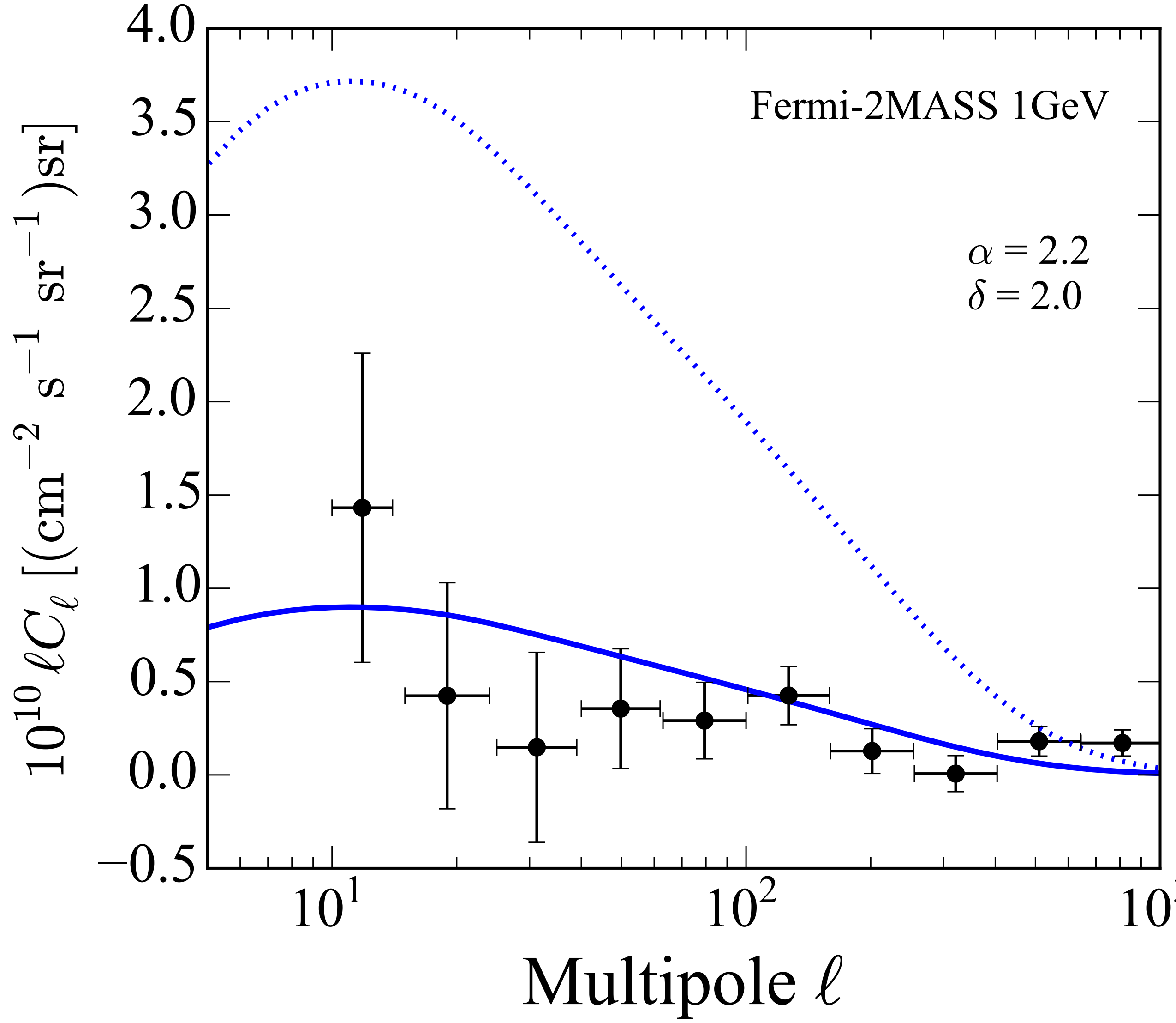
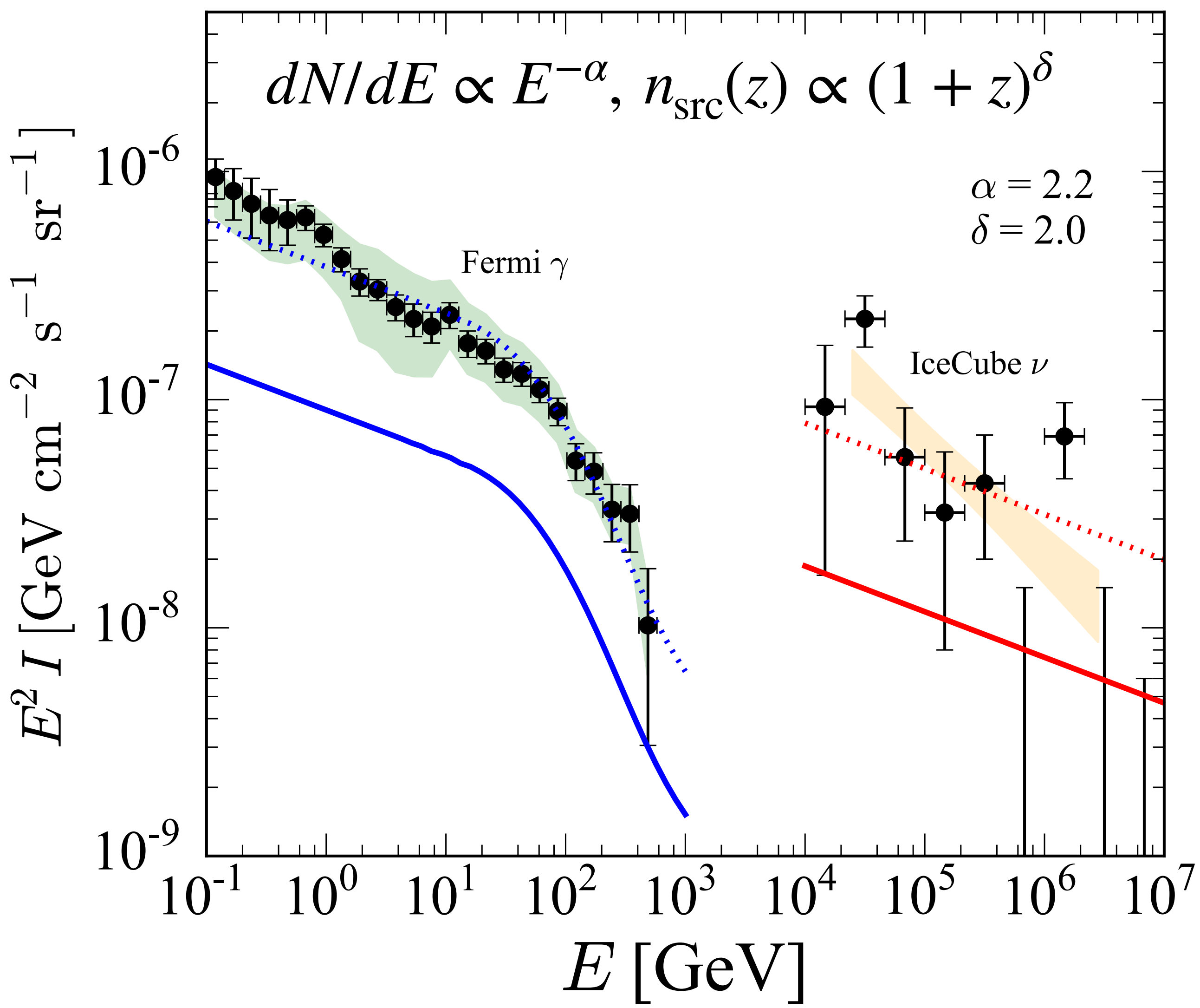
Tomographic constraints

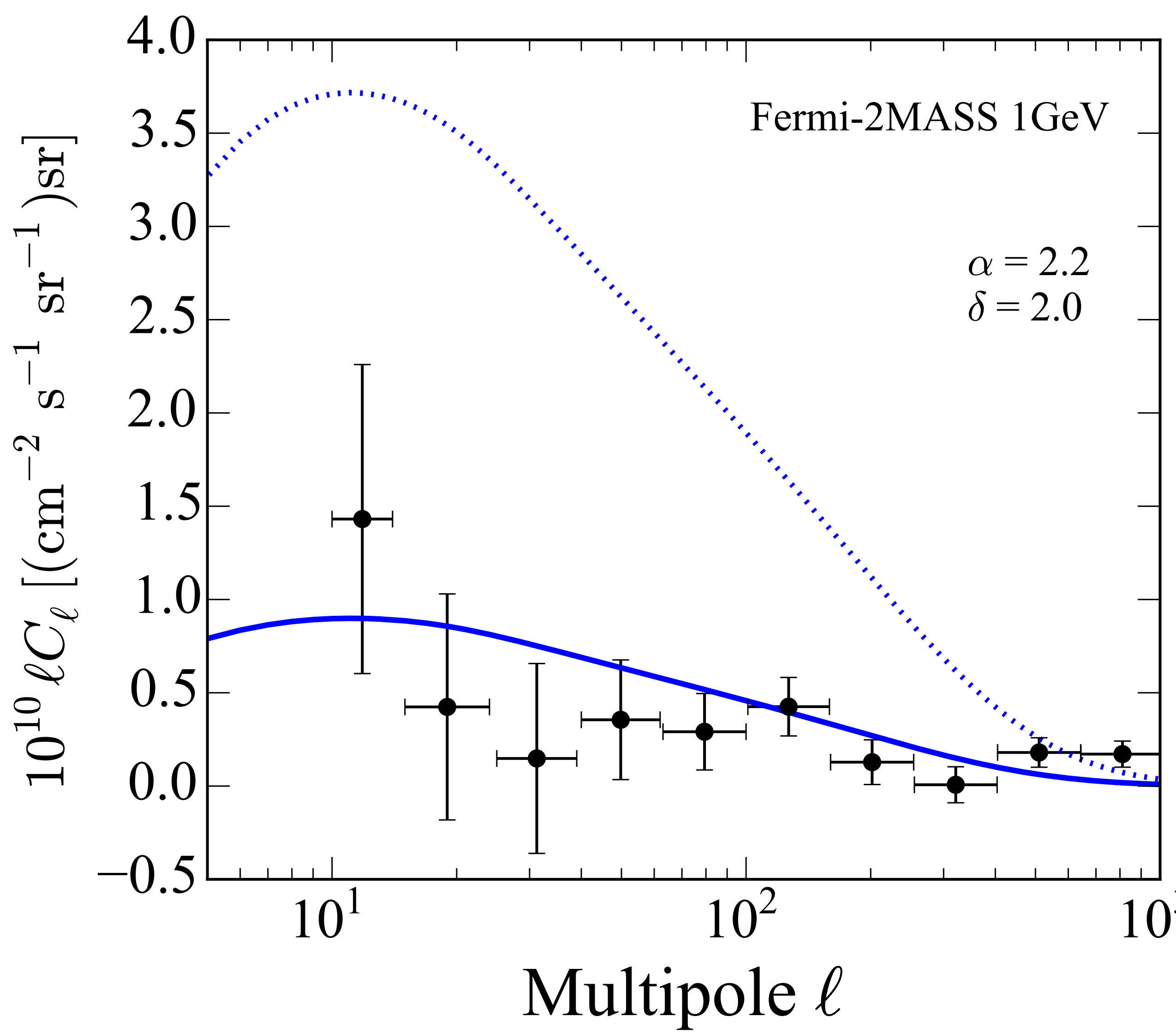




Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

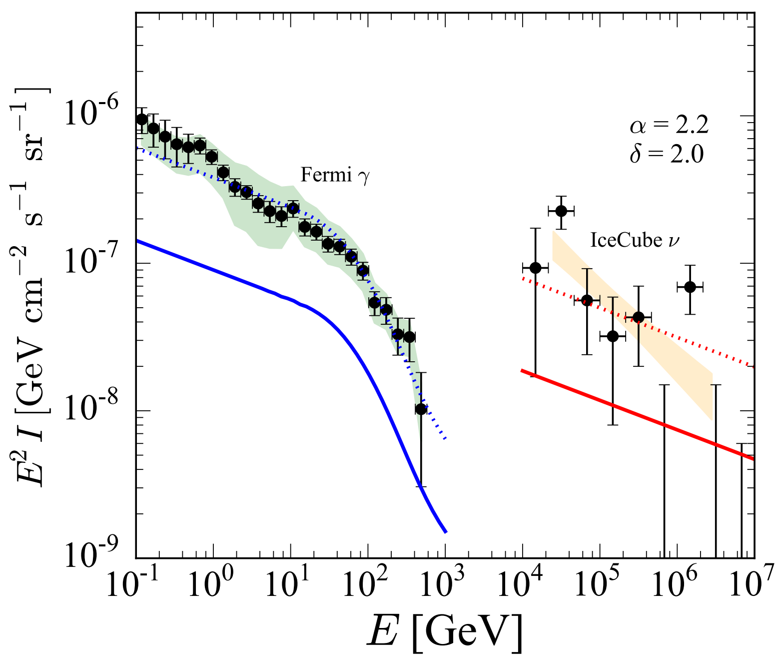
Tomographic constraints

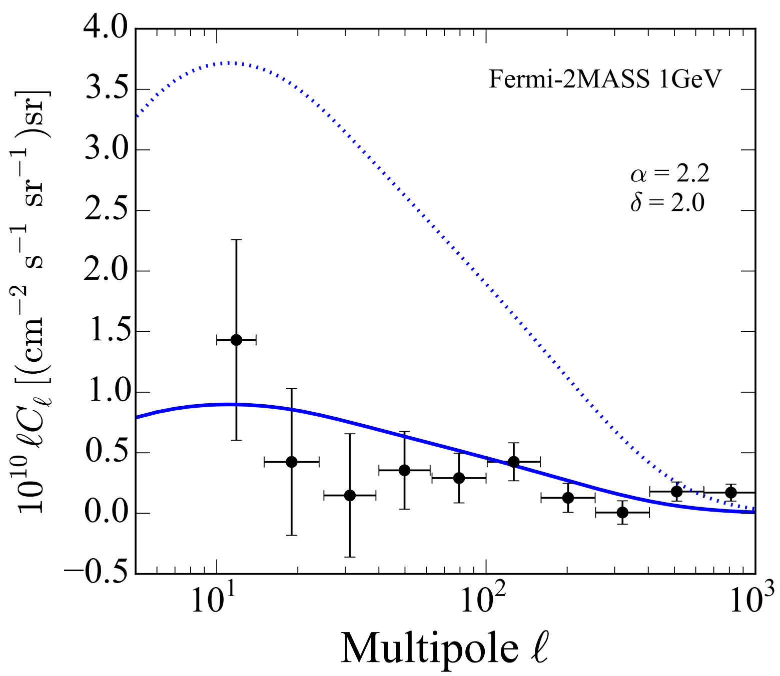




Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

Dependence on **α** and **δ**

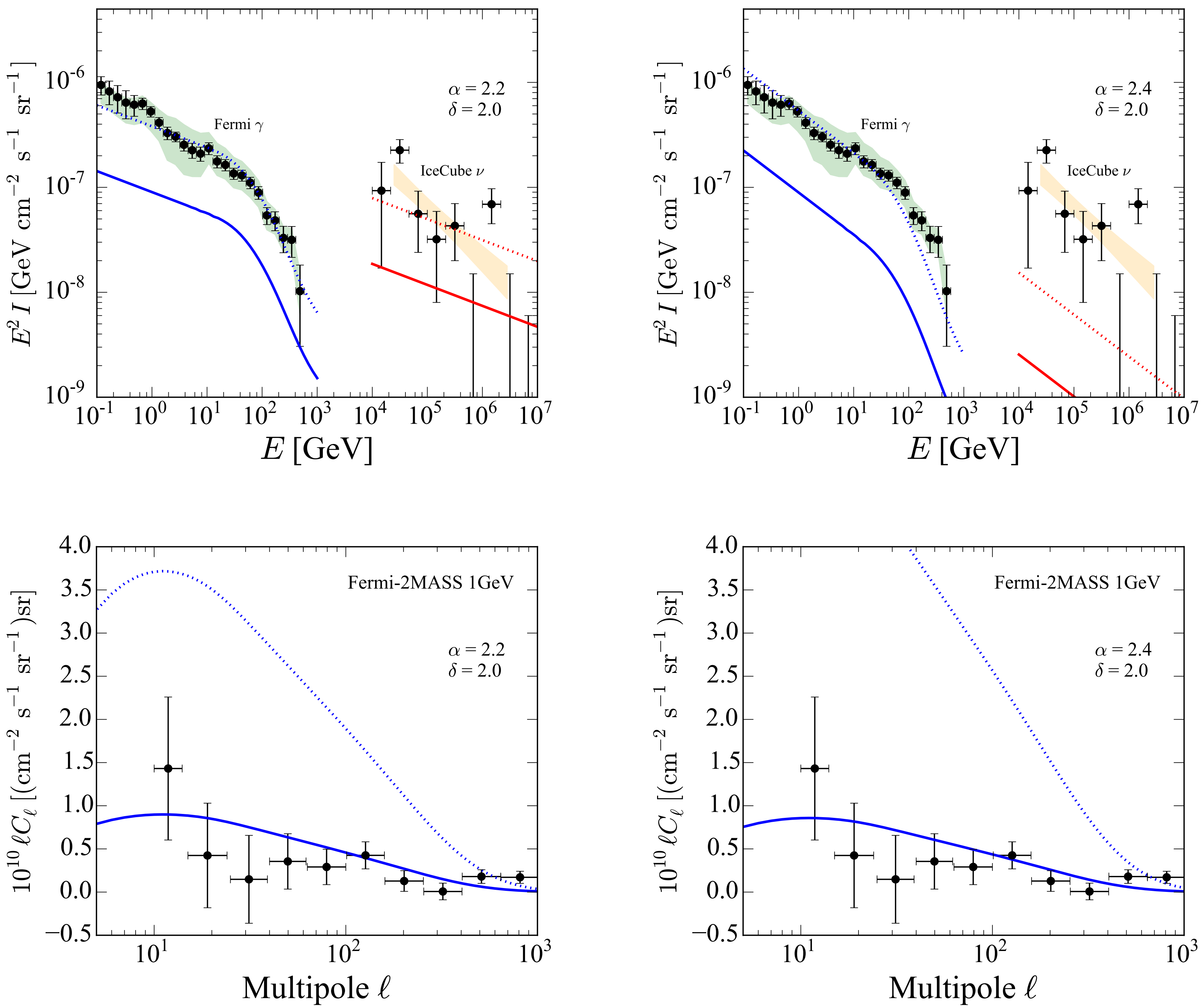




Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

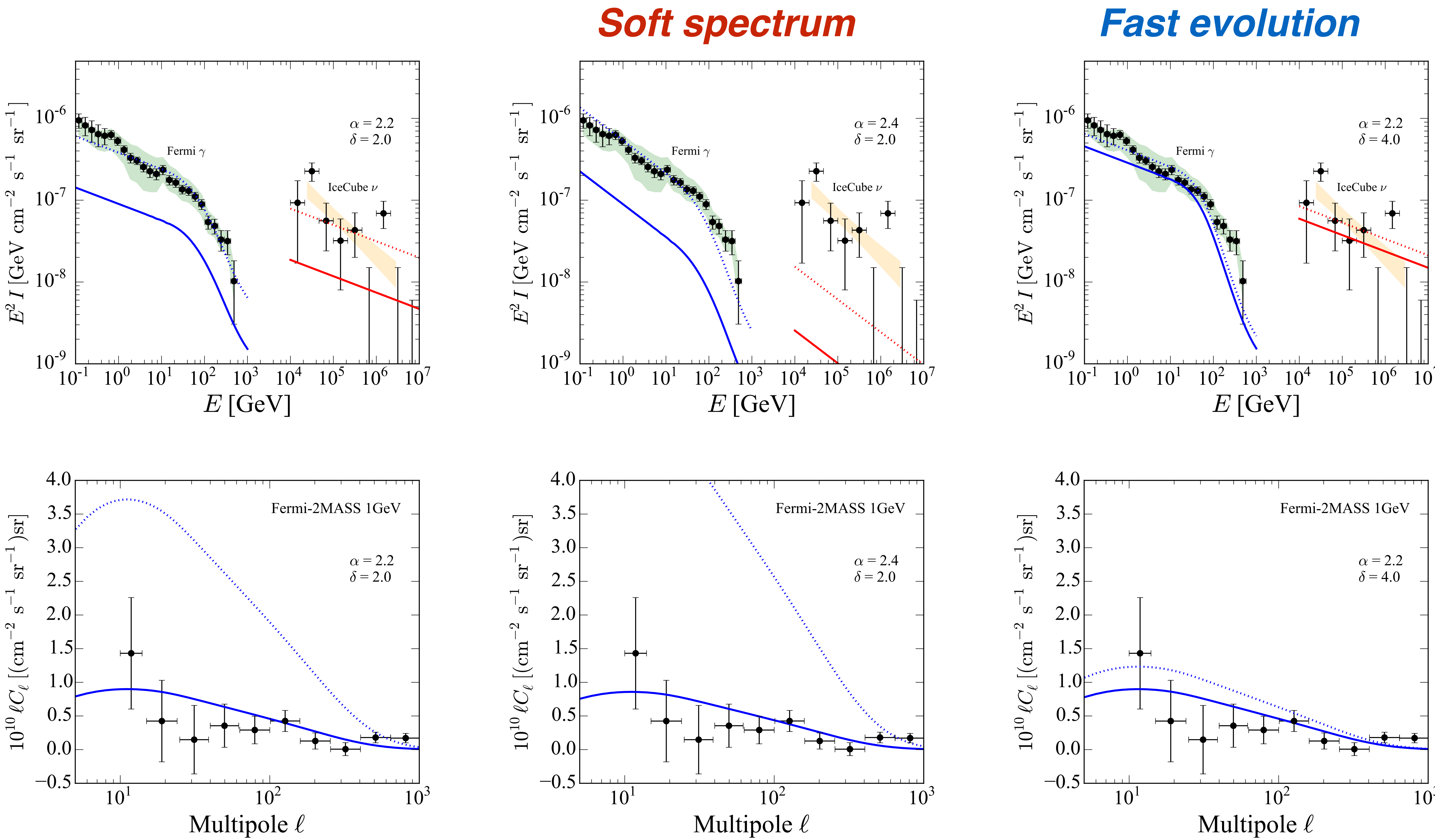
Dependence on **α** and **δ**

Soft spectrum



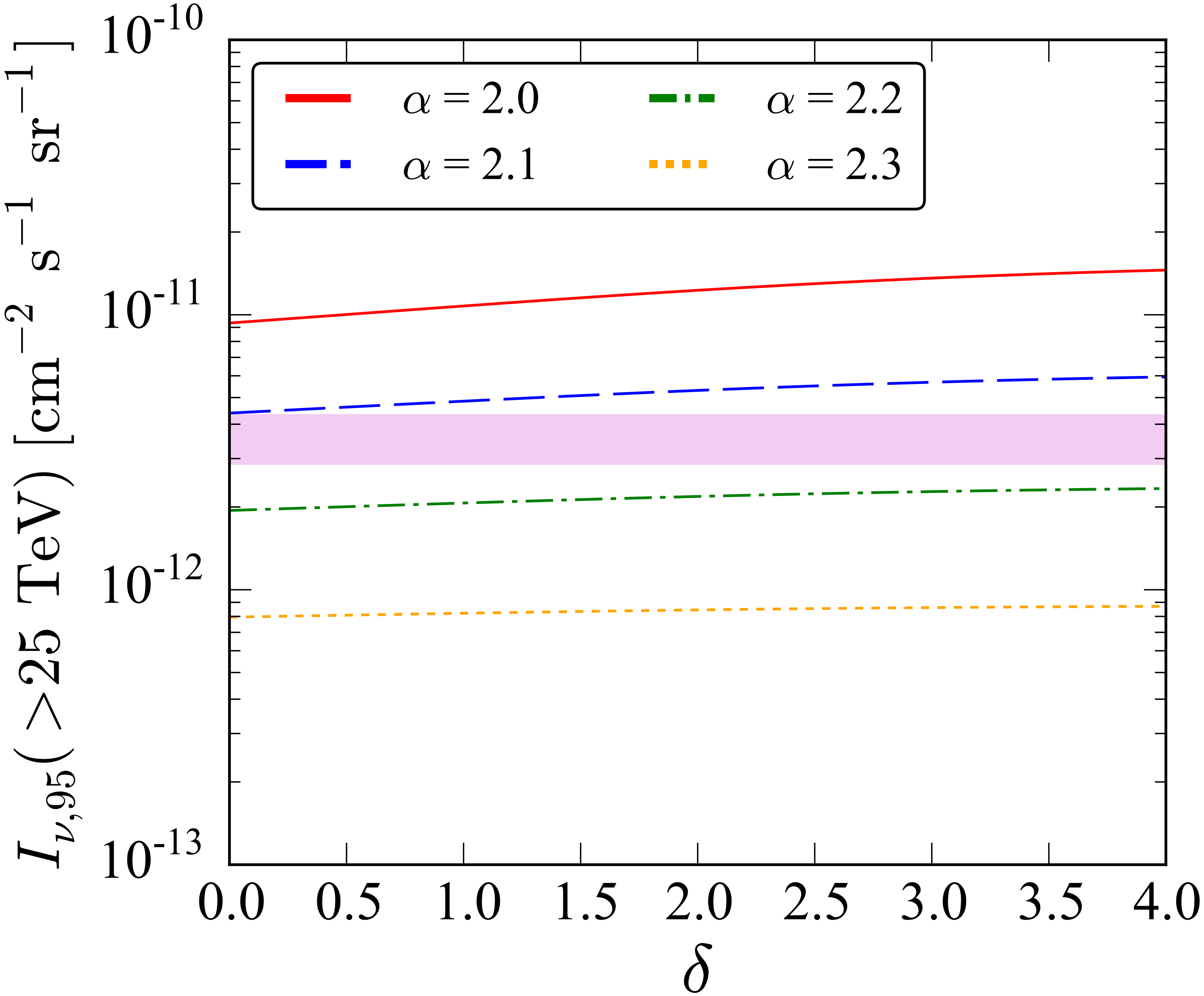
Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

Dependence on **α** and **δ**



Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

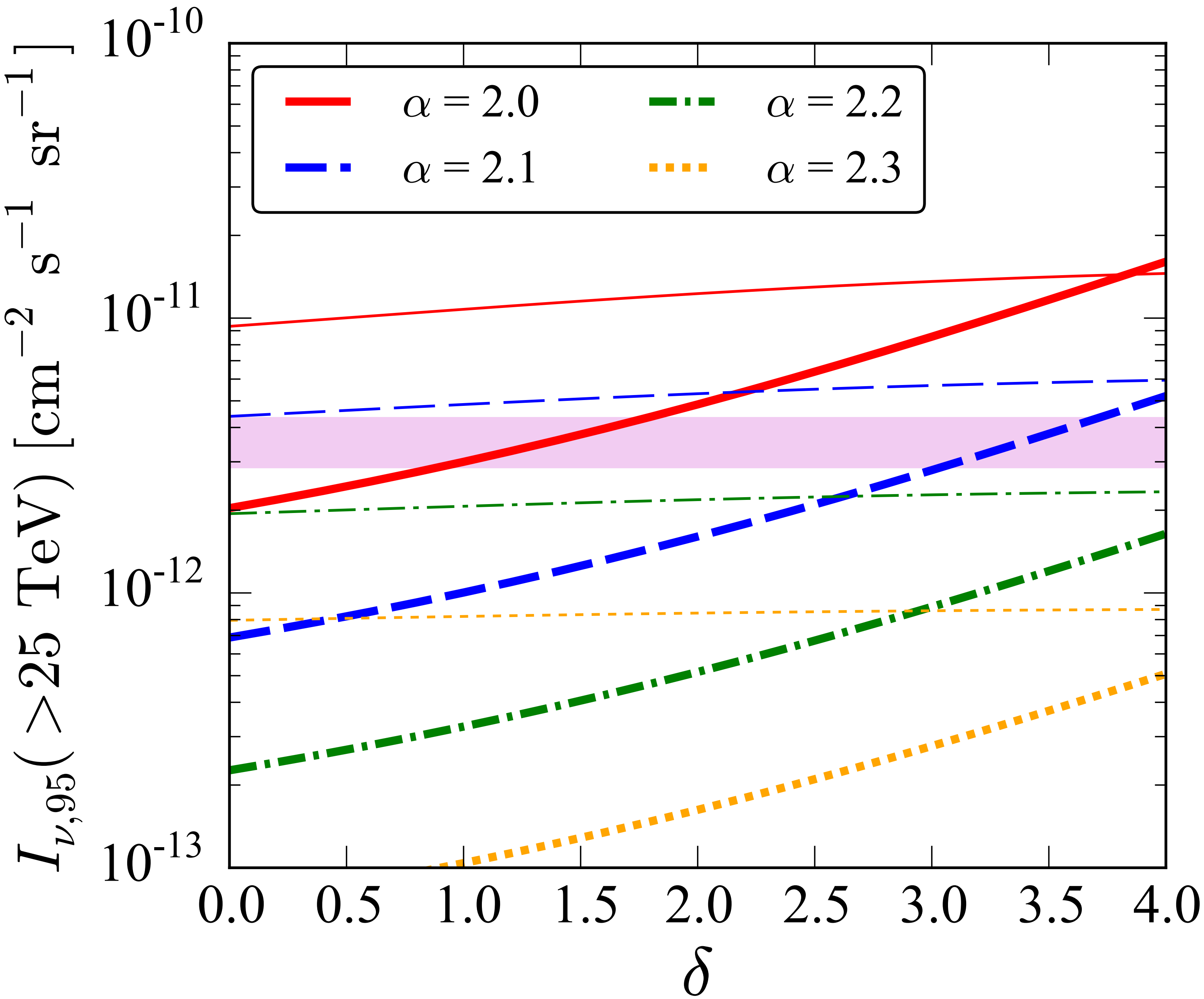
Constraints on high-energy neutrinos



- Spectral constraints: α has to be smaller than ~2.2 (cf. Murase, Ahlers, Lacki 2013)

Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

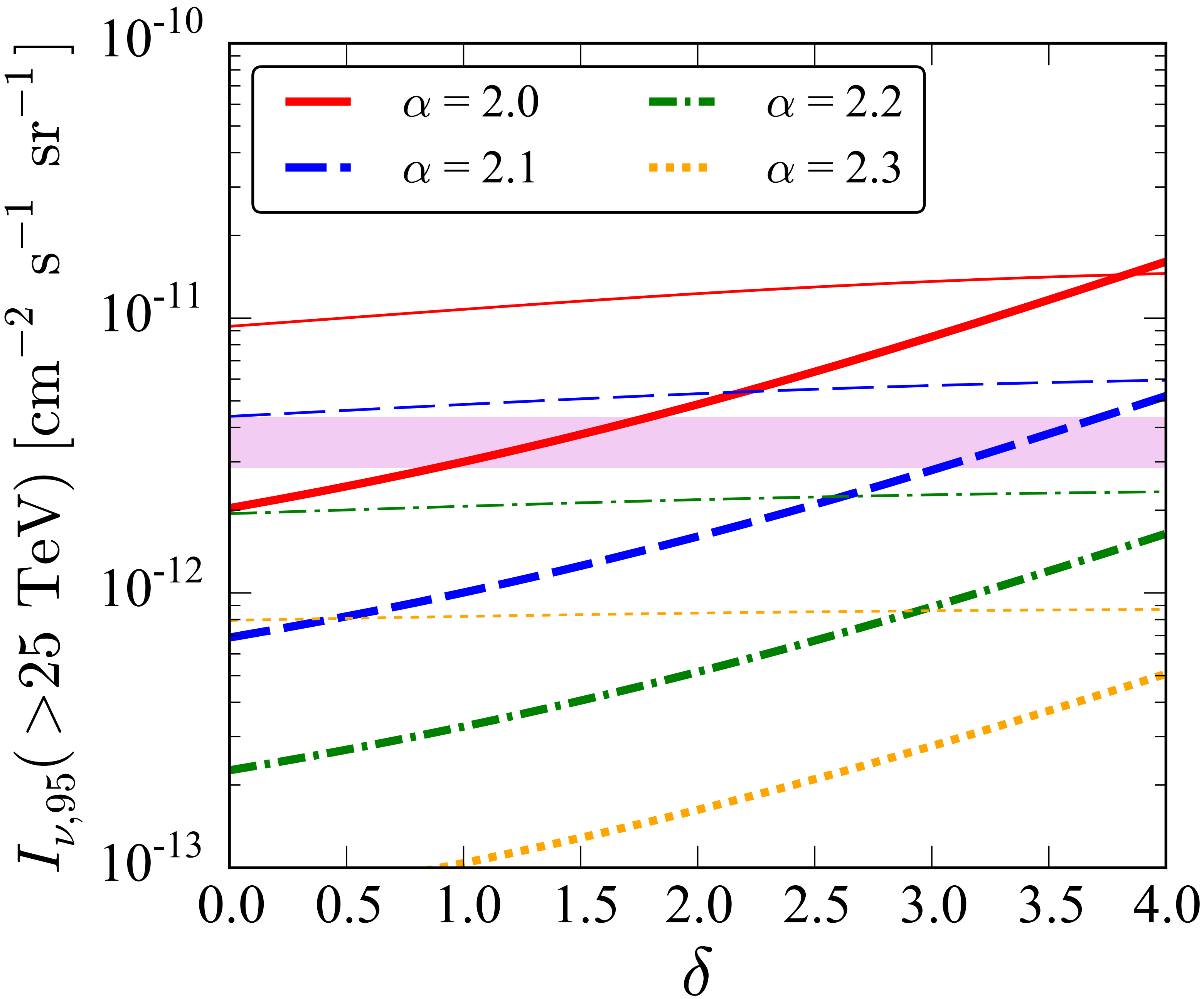
Constraints on high-energy neutrinos



- Spectral constraints: α has to be smaller than ~2.2 (cf. Murase, Ahlers, Lacki 2013)
- Tomographic constraints:

Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

Constraints on high-energy neutrinos



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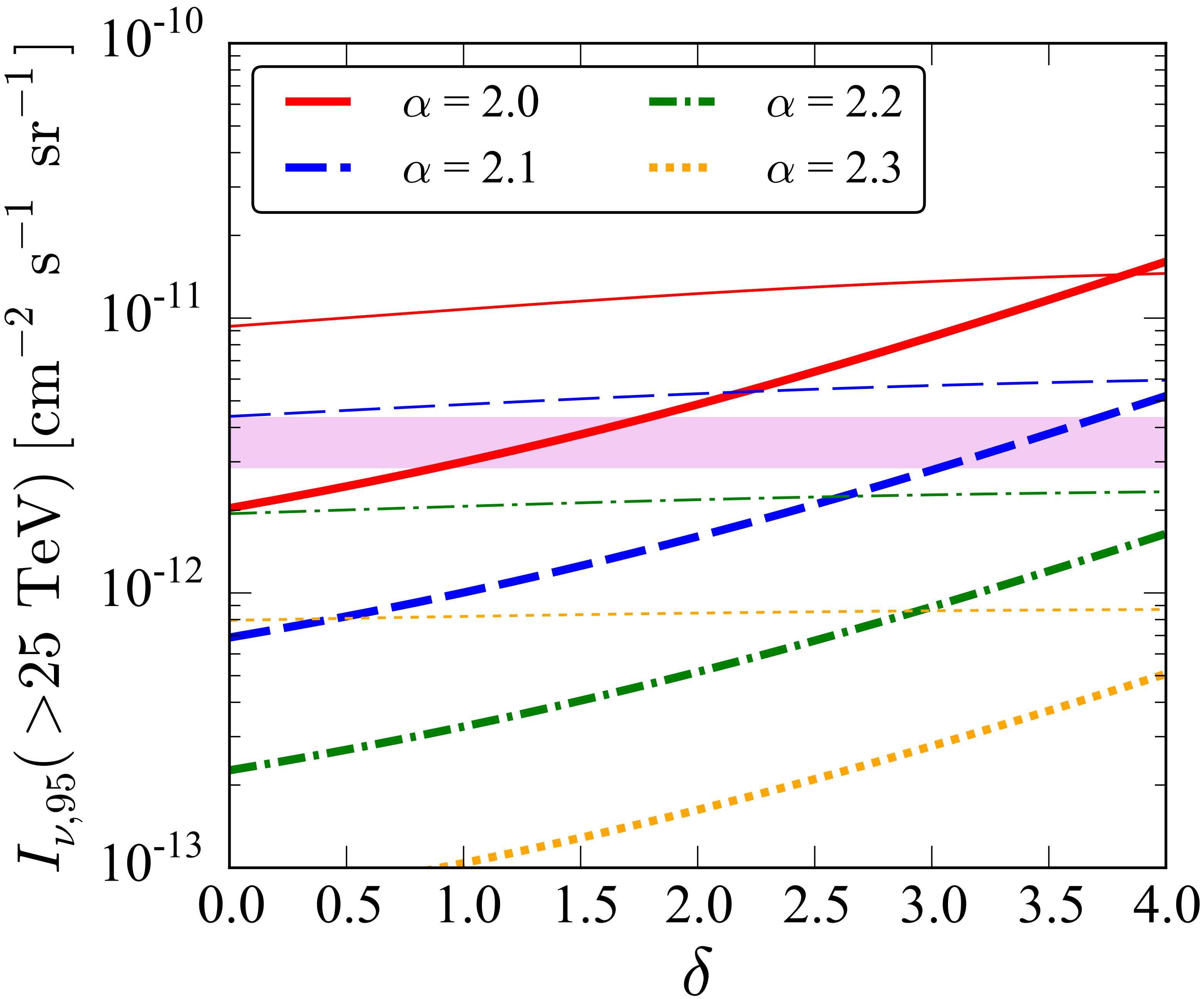
  - If δ is smaller than ~3, source with spectrum softer than $E^{-2.1}$ is disfavored

Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

Constraints on high-energy neutrinos

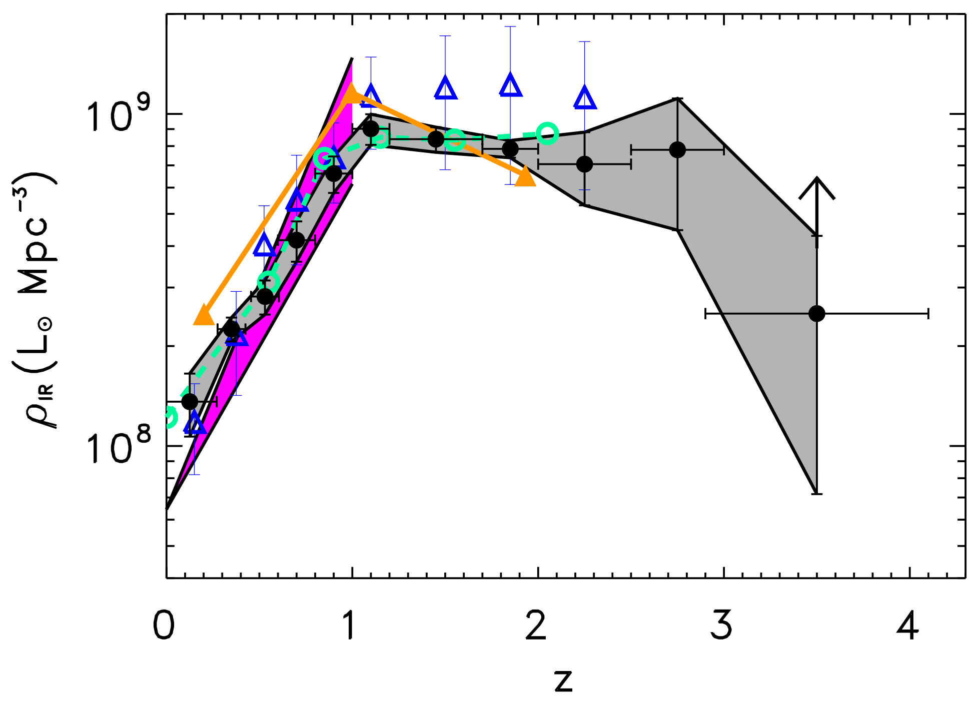


- Spectral constraints: α has to be smaller than ~2.2 (cf. Murase, Ahlers, Lacki 2013)
- Tomographic constraints:
  - If δ is smaller than ~3, source with spectrum softer than $E^{-2.1}$ is disfavored
- If δ ~ 4, both spectral and tomographic data give comparable constraints

Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

Possible pp sources

Star-forming/starburst galaxies



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

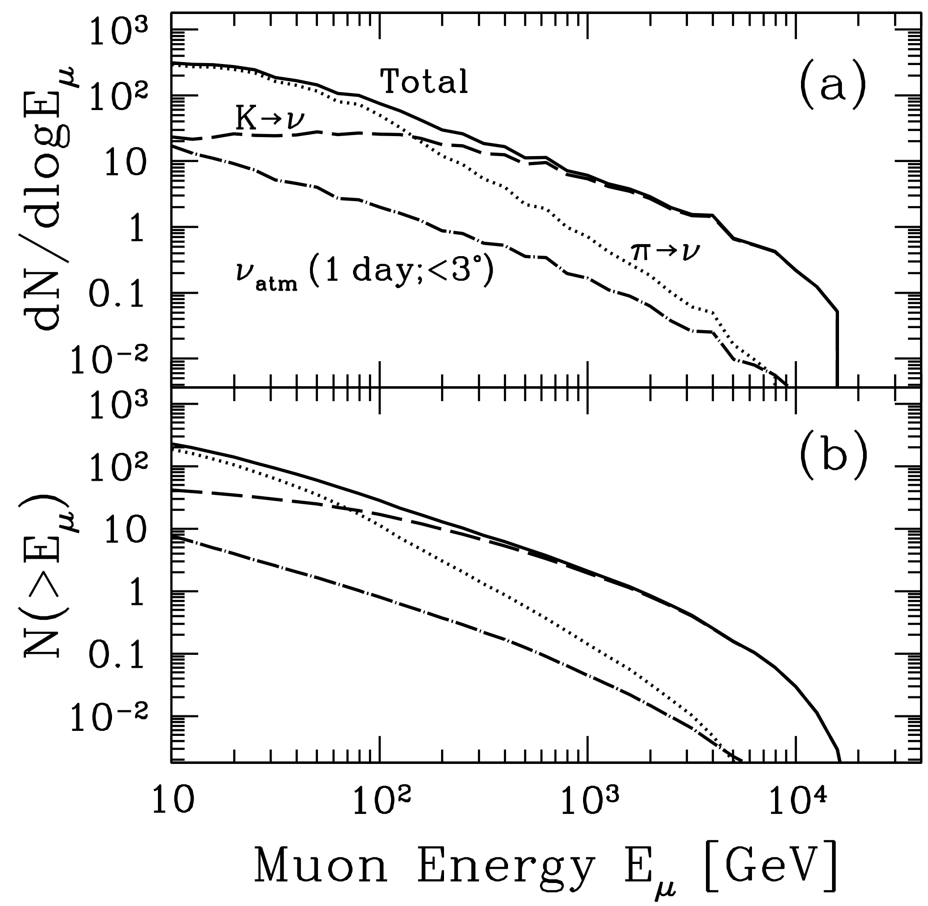
Gruppioni et al., *Mon. Not. R. Astron. Soc.* **432**, 23 (2013)

Clusters of galaxies

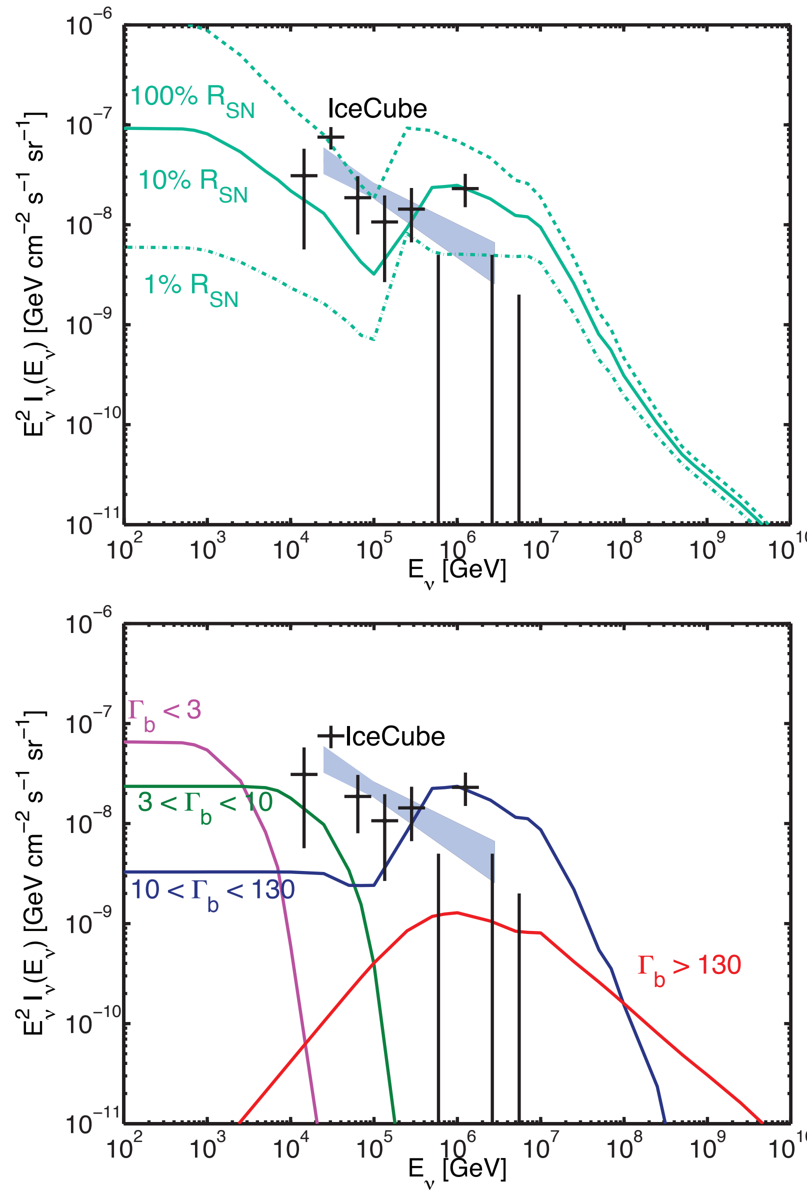
- Cosmic rays accelerated through large-scale-structure shocks or provided by sources (AGNs, galaxies)
- In both cases, δ is very small (i.e., clusters are found only in low-z)

Exception: Hidden pp sources?

Ando, Beacom, *Phys. Rev. Lett.* **95**, 061103 (2005)



Tamborra, Ando, *Phys. Rev. D* **93**, 053010 (2016)



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

Conclusions

- Given no source was detected, it is important to take **model-independent**, **data-drive** approaches
- Traditional approaches can be interpreted in terms of flux distribution: zeroth moment as number of sources; first moment as energy spectrum of diffuse flux
- **The second moment (variance)** can be adopted to constrain source populations: those with ***N**<100** are already excluded
- Two-point information is already available from **gamma-ray—galaxy cross correlations**, which can be applied to stringently constrain neutrino sources if they are of pp origin