NuPhys@London
16 December 2019

Astrophysical neutrino theory

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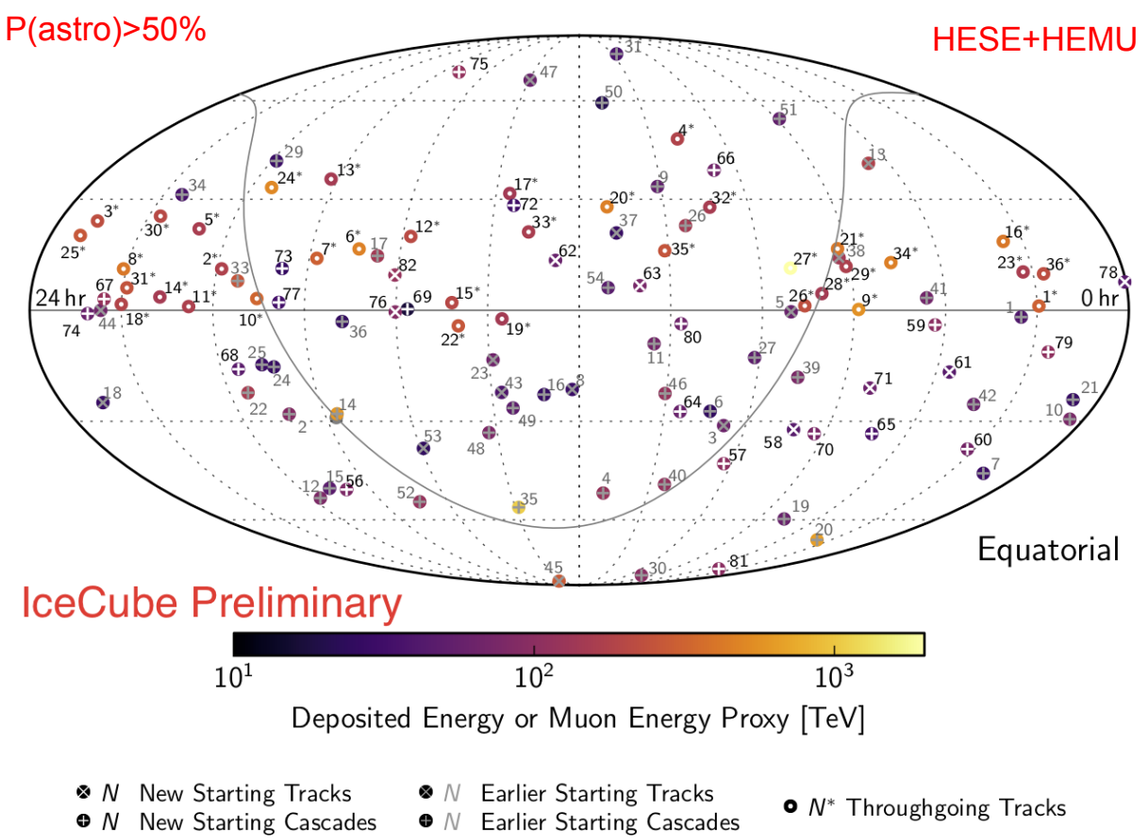
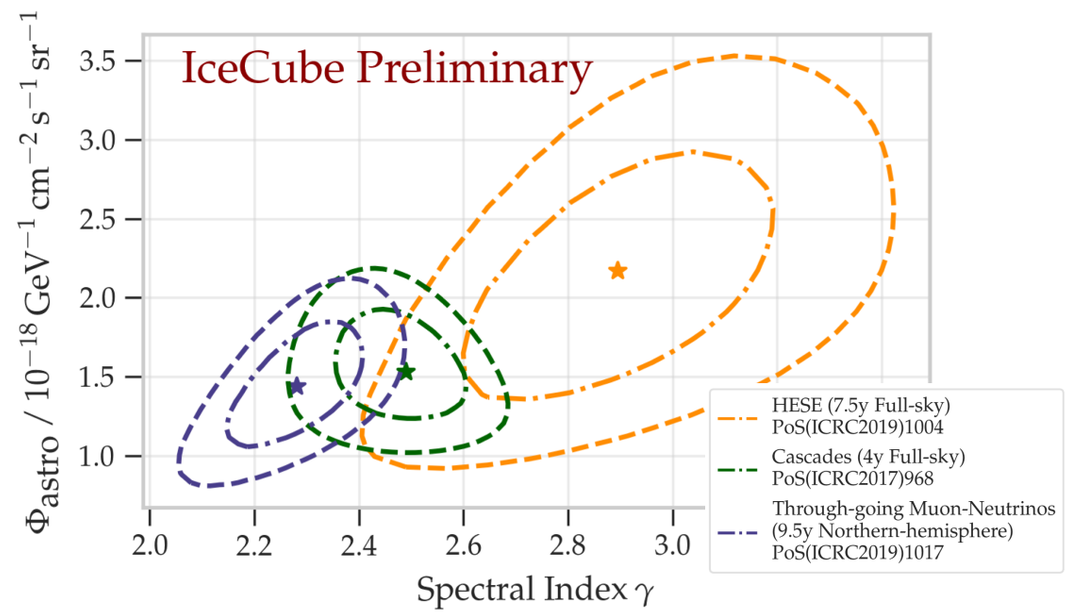
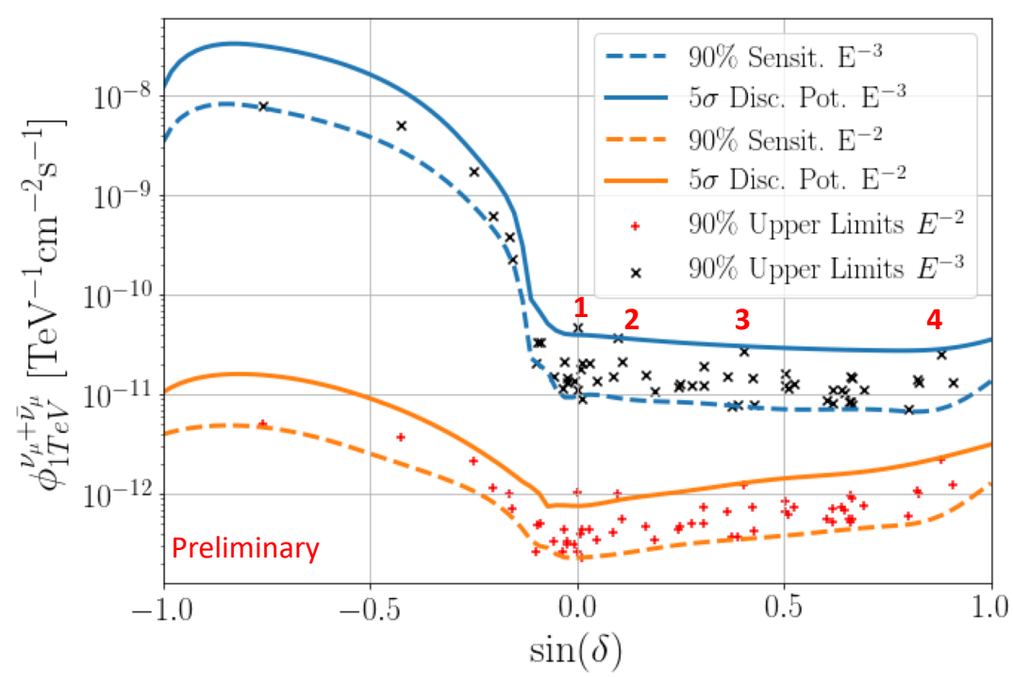
University of Amsterdam

GRAPPA
GRavitation AstroParticle Physics Amsterdam

High-energy neutrinos: Facts

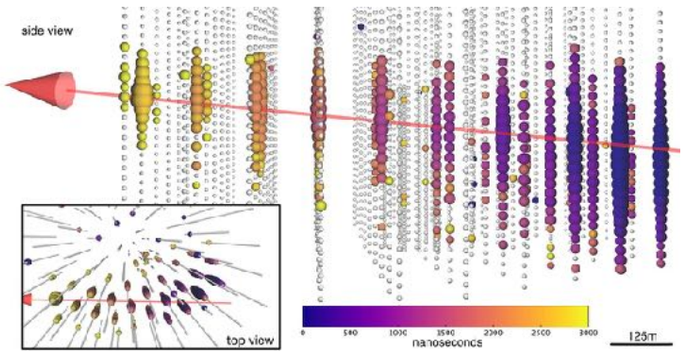


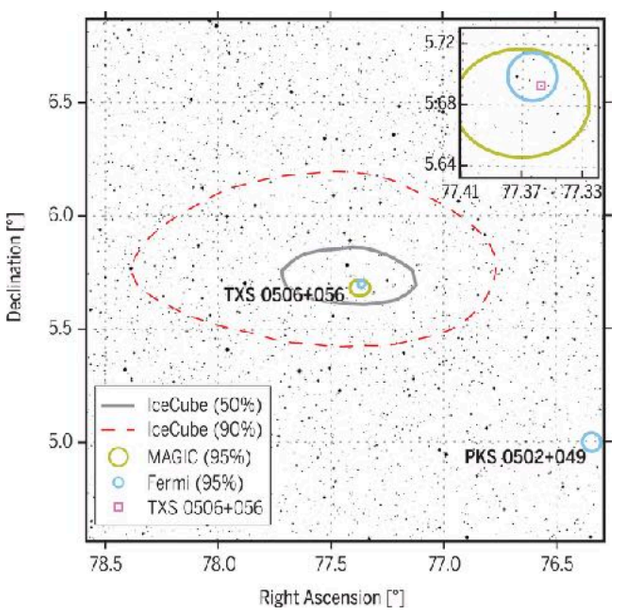




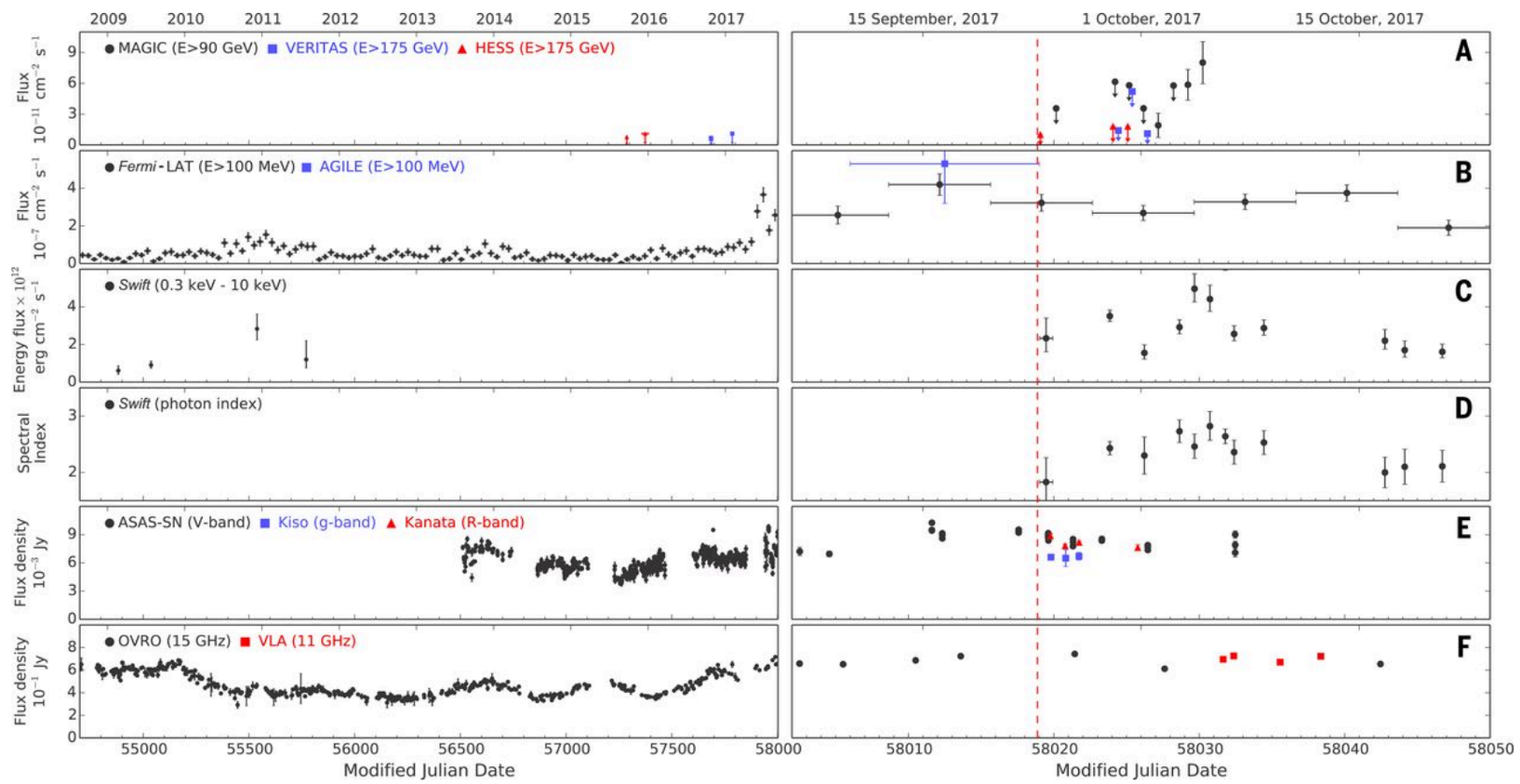
- Detected: Starting events and up-going muon events
- Their distribution is consistent with isotropy
- **No source has been identified yet**

Neutrinos from TXS 0506+056?



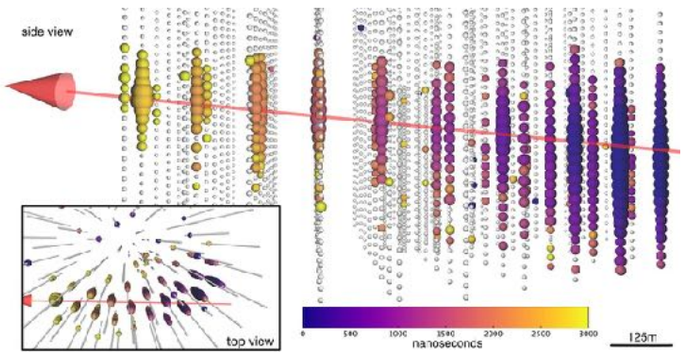


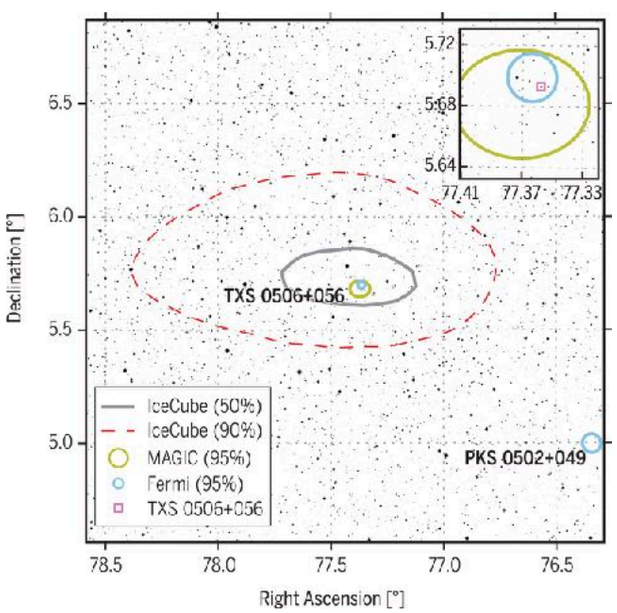
A neutrino event (IceCube-170922A) at ~290 TeV coincident with gamma-ray flare **(3σ)**



Science **361**, eaat1378 (2018)

Neutrinos from TXS 0506+056?





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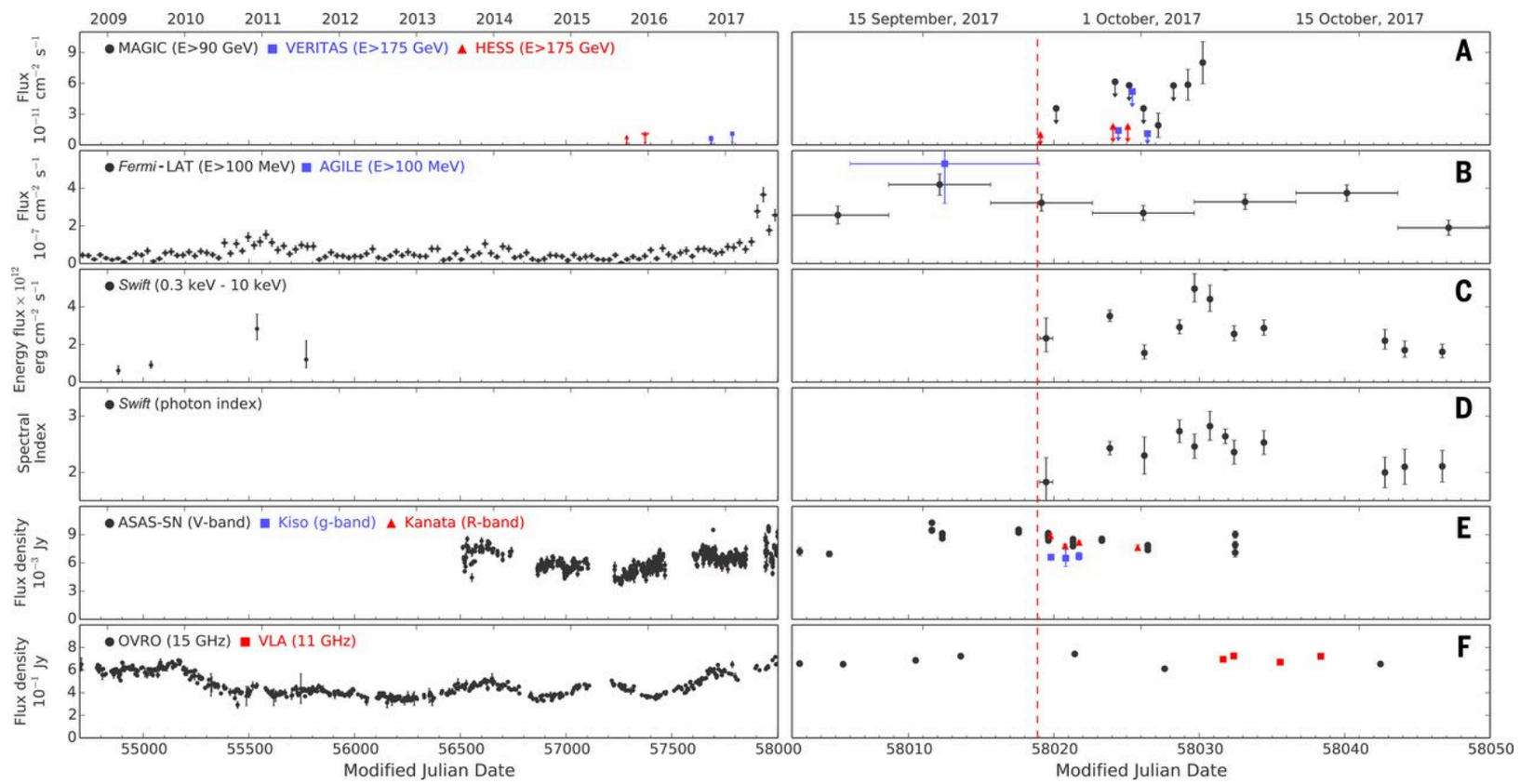
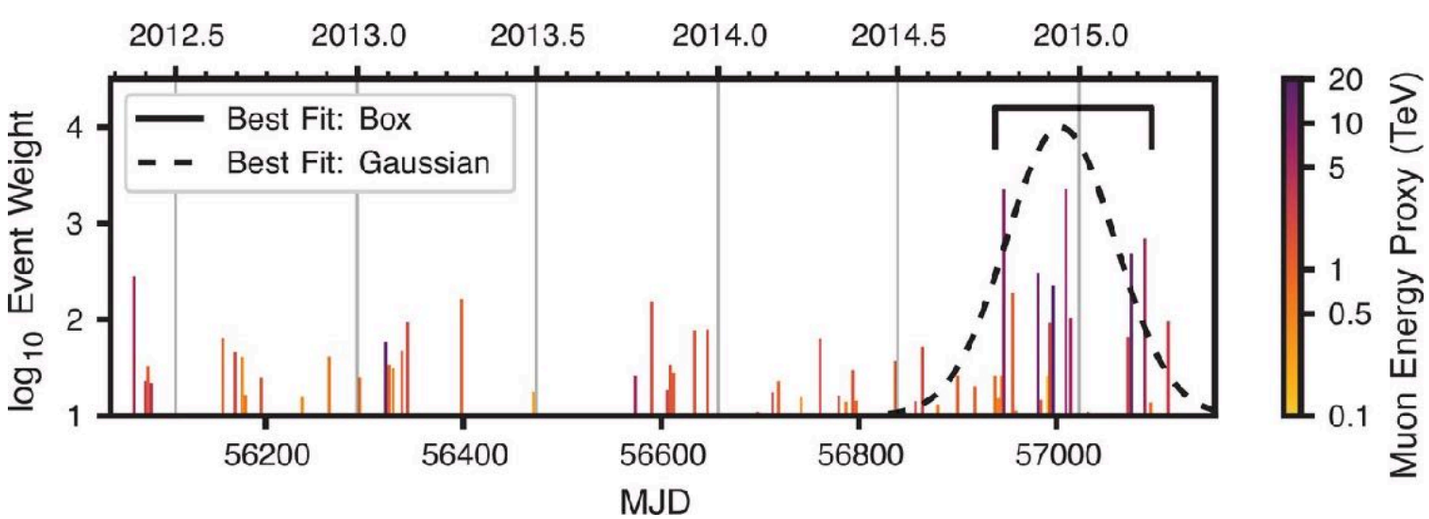


Science **361**, eaat1378 (2018)



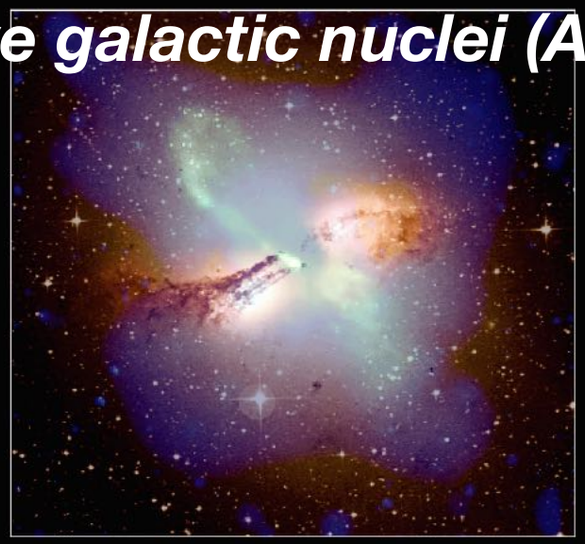
13±5 neutrinos above backgrounds in 2014-2015 (3.5σ)

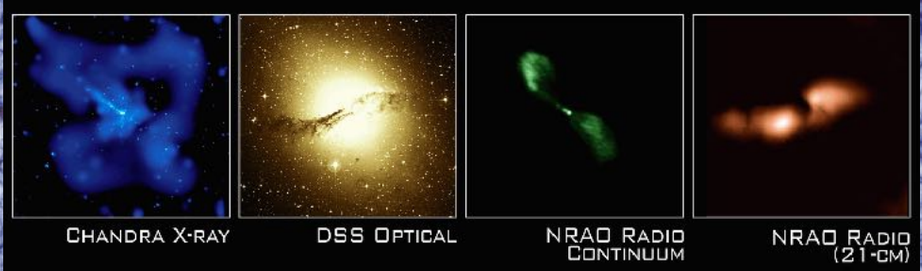
But no gamma-ray counterpart

Science **361**, 147 (2018)

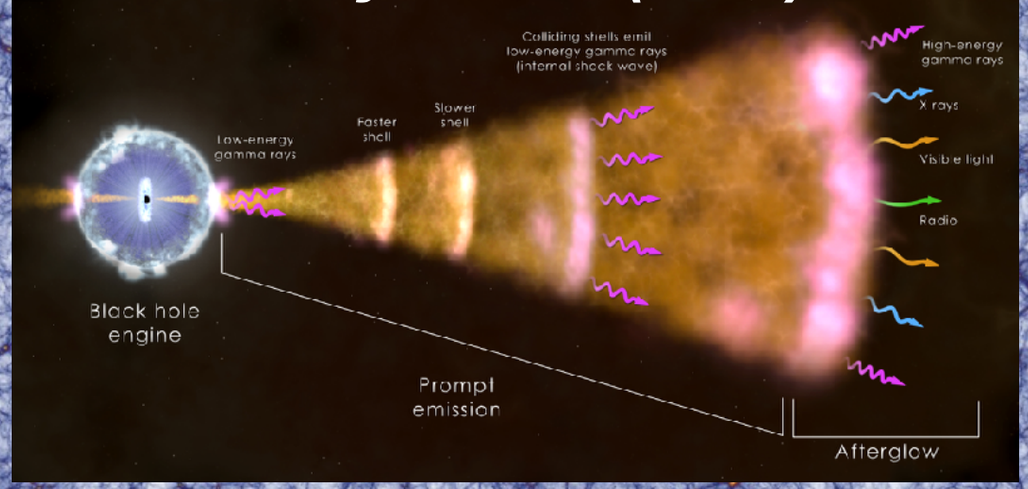
Possible astrophysical explanations

Active galactic nuclei (AGN)

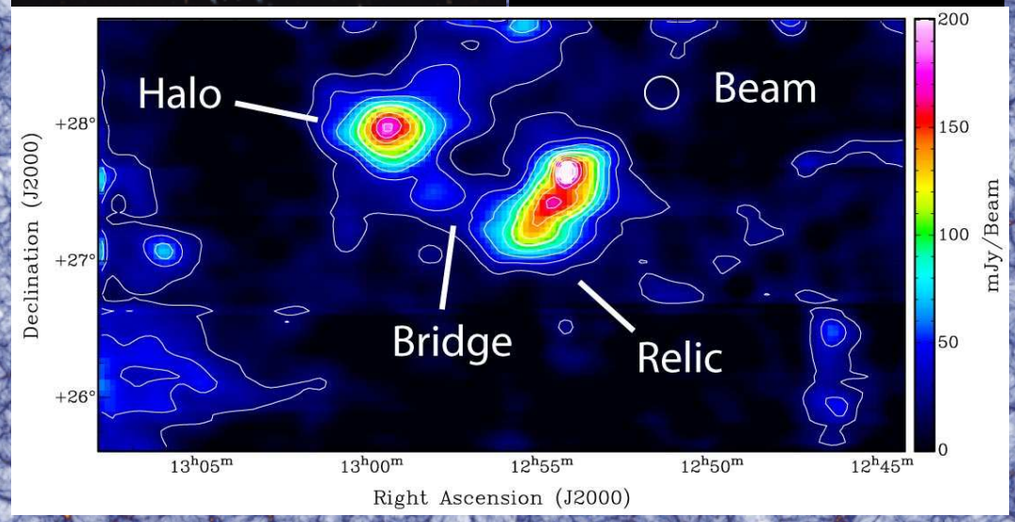




Gamma-ray bursts (GRB)



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

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

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

$$\mu^\pm \rightarrow e^\pm + \nu_e + \nu_\mu$$

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Pion decays

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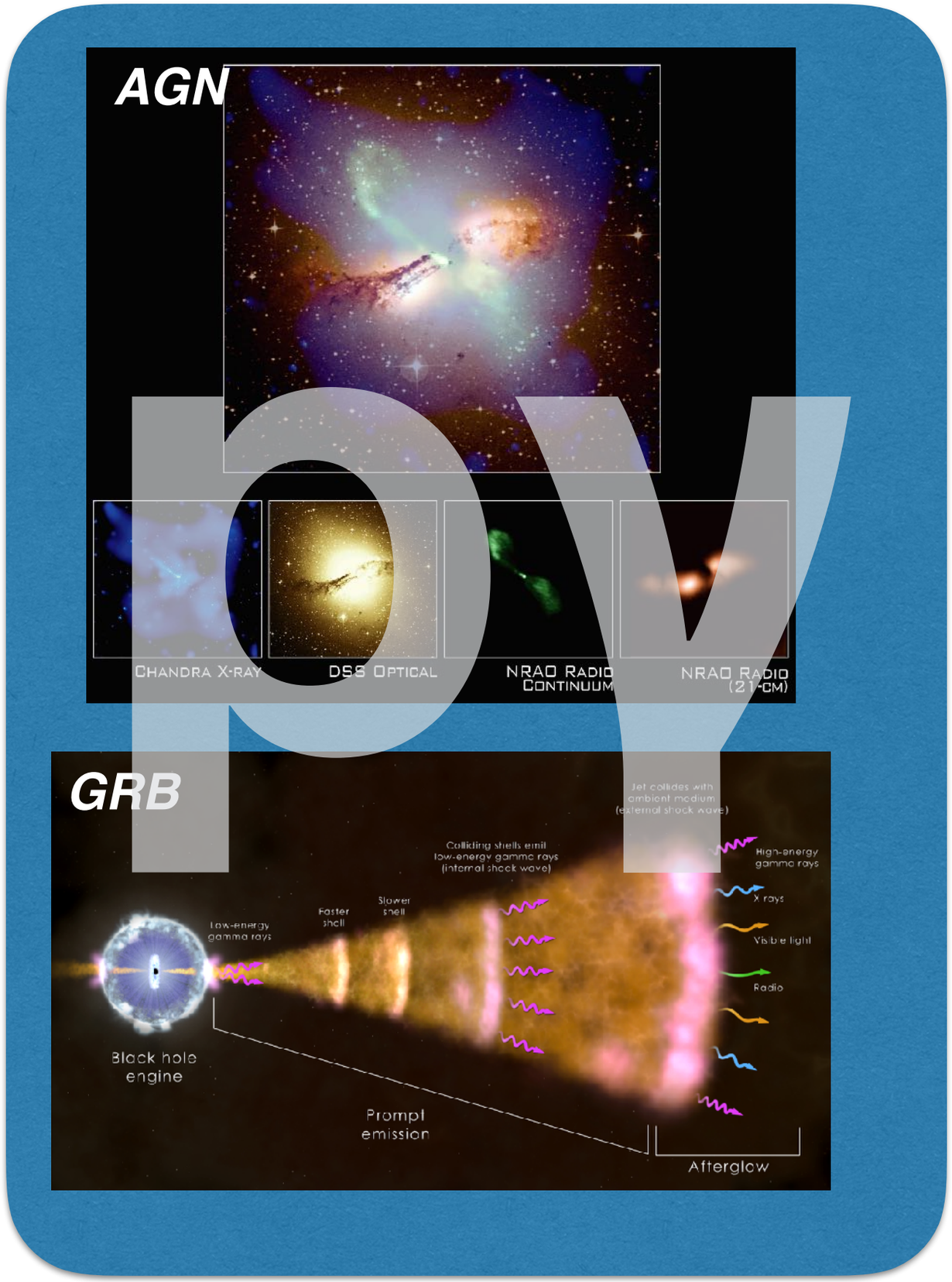
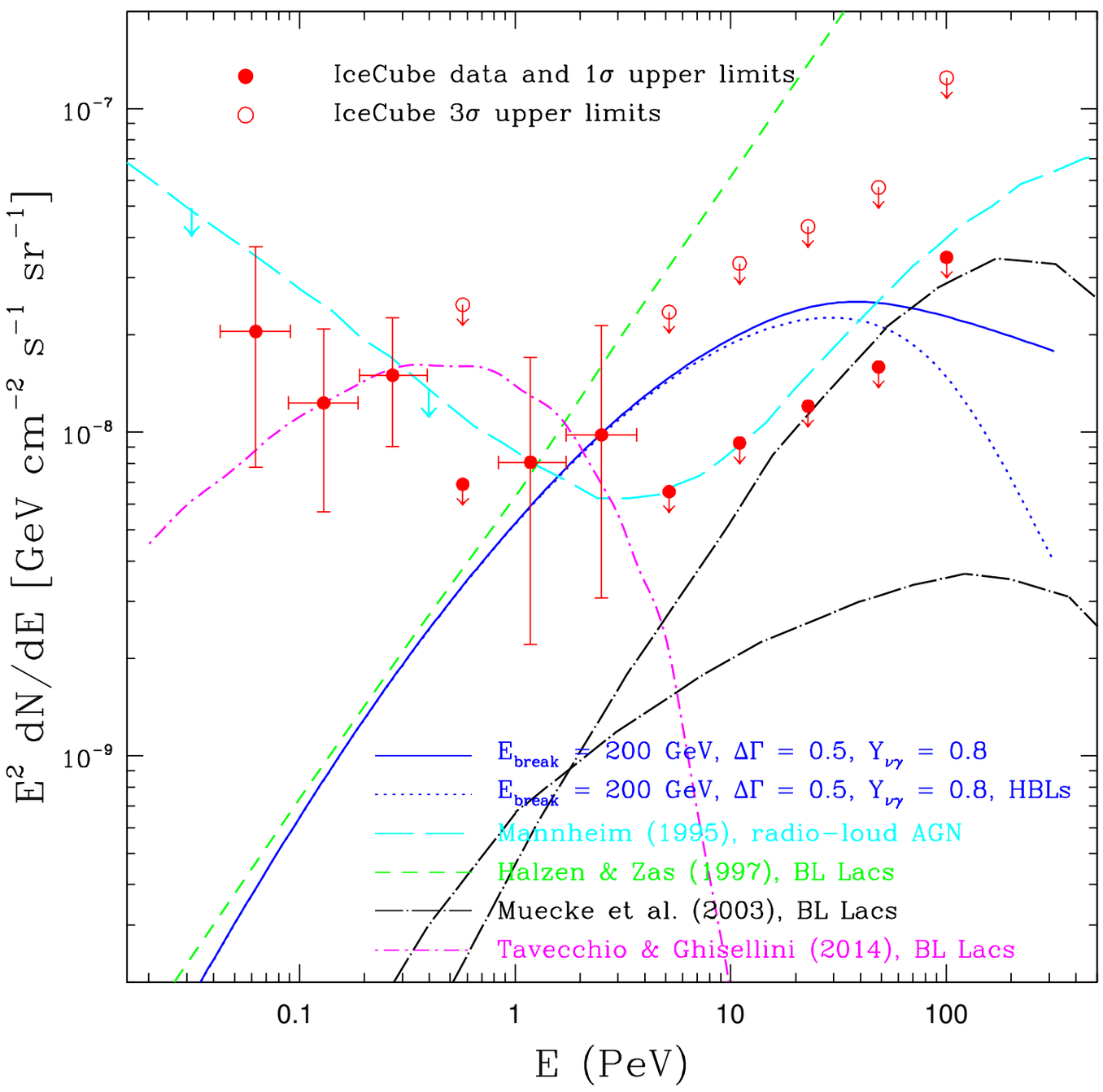
pp and pγ sources: 0th order classification



Blazars: pγ source

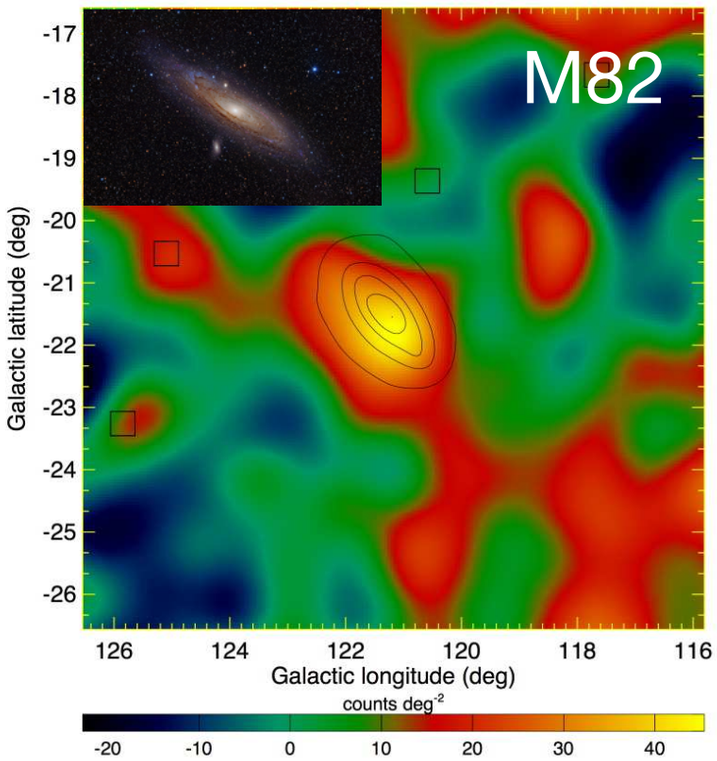


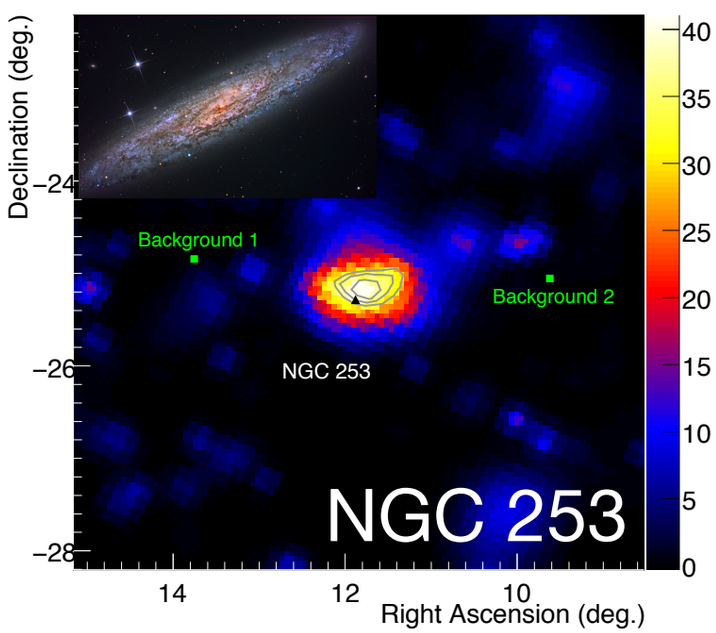
Padvani et al., *Mon. Not. R. Astron. Soc.* **452**, 1877 (2015)

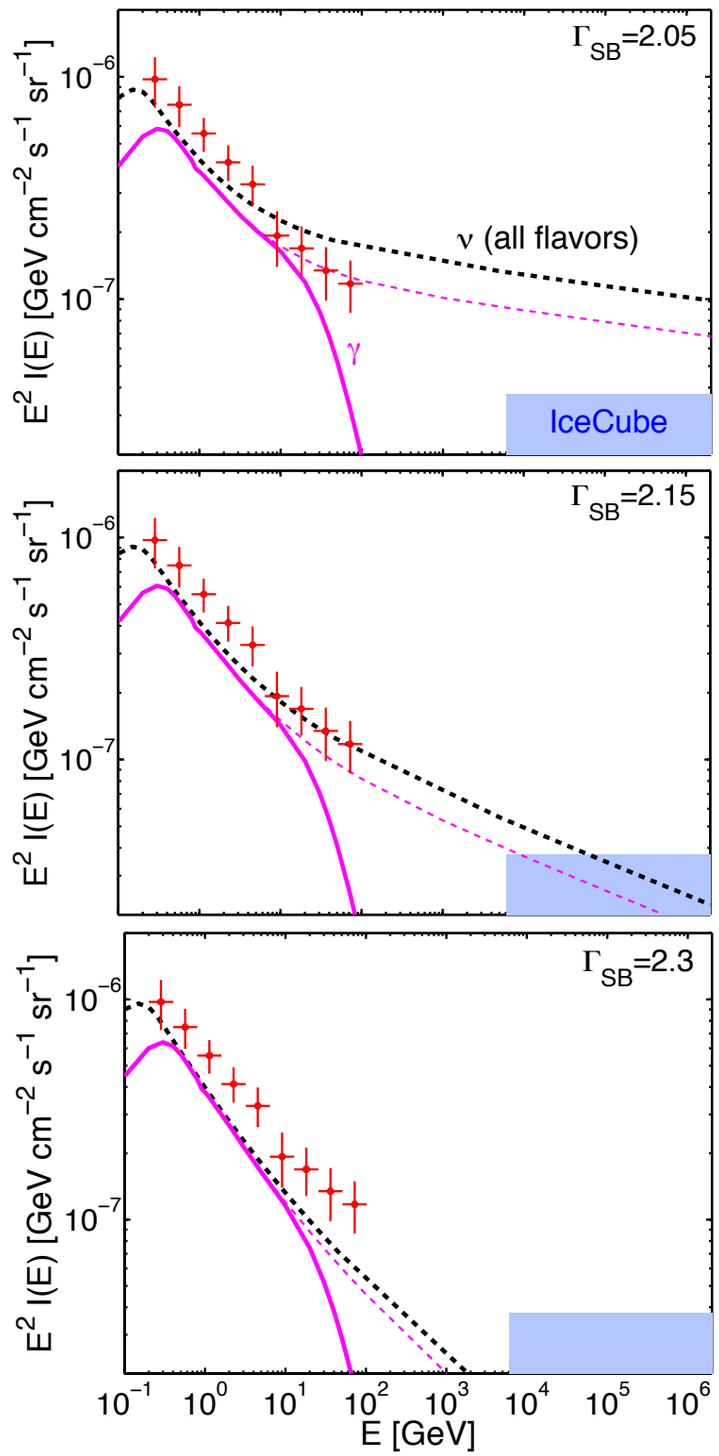
- The cosmic ray protons accelerated in jets interact with surrounding photons
- The neutrino spectrum depends on that of seed photons
- Consequences are in general much more model dependent

Starburst galaxies: pp source

Tamborra, Ando, Murase, *JCAP* **09**, 043 (2014)

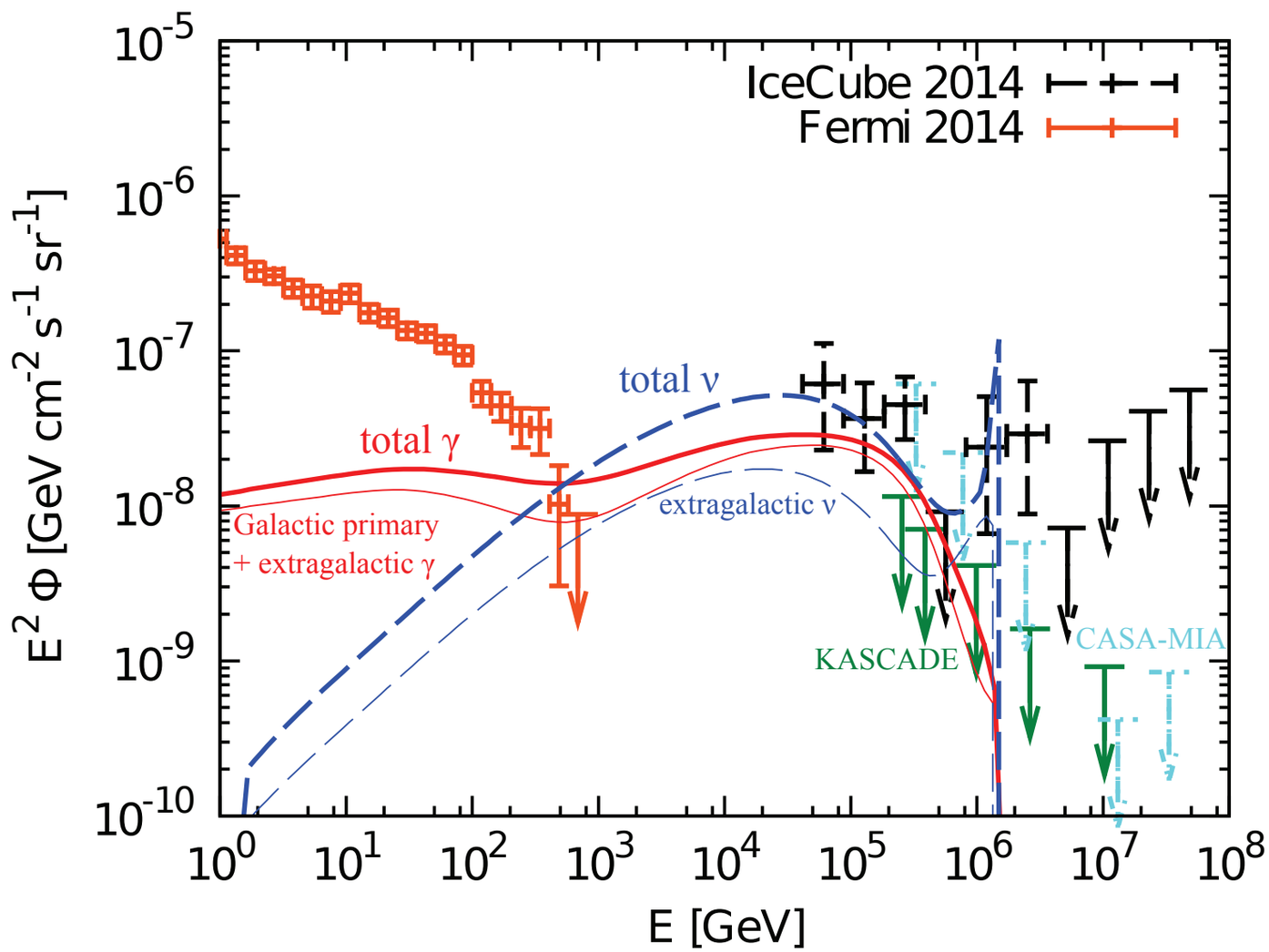






- Starbursts are bright in gammas (M82 and NGC 253 at ~3 Mpc)
- Gamma-ray spectrum roughly follows $E^{-2.2}$
- Modeling the gamma-ray and neutrino luminosity functions using
  - IR luminosity function (Herschel)
  - IR-gamma correlation (Fermi)

Exotic scenario: Dark matter decay



Murase, Laha, Ando, Ahlers, *Phys. Rev. Lett.* **115**, 071301 (2015)

Generic consideration: Personal take

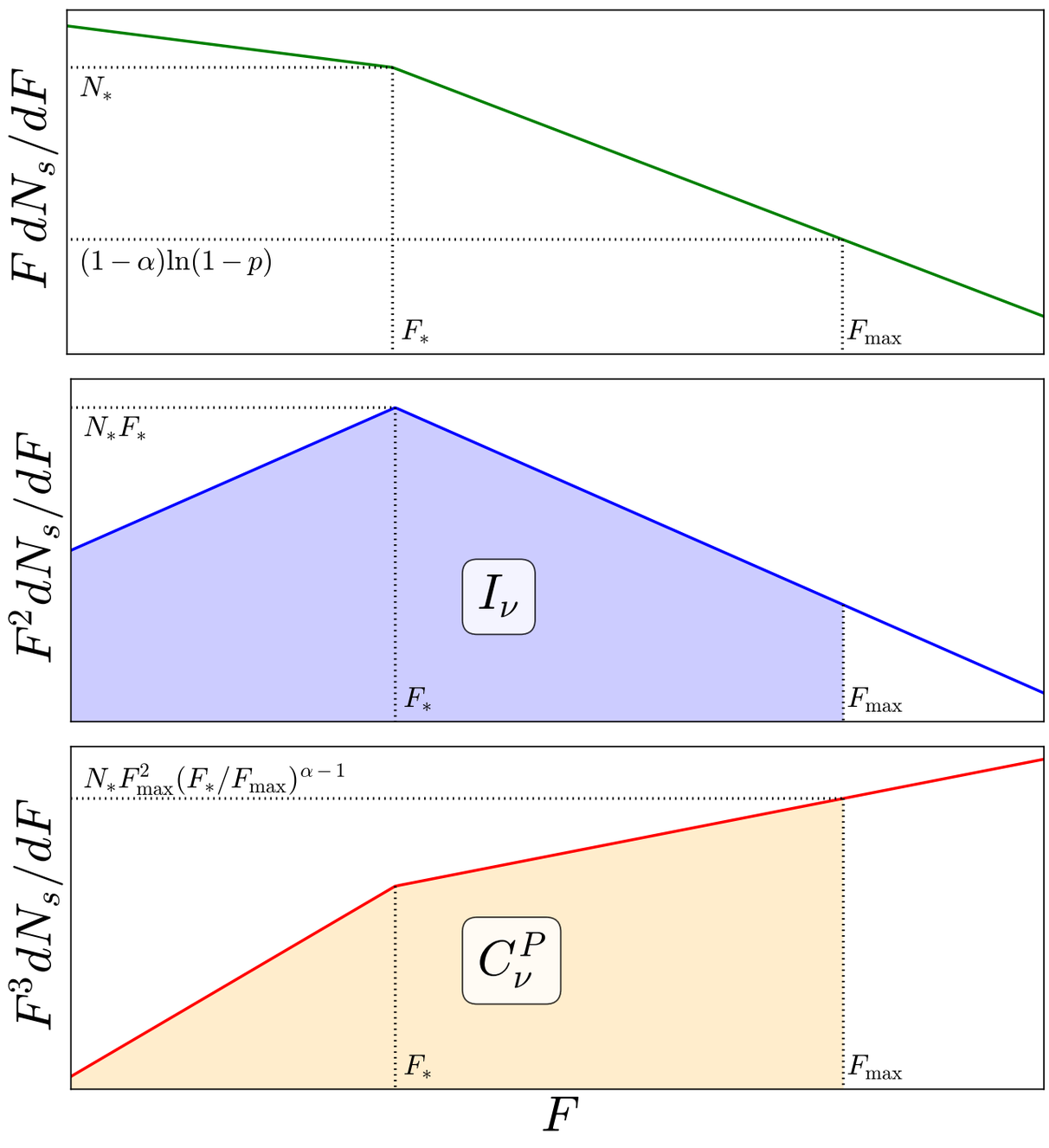
- Given no source has been detected, it is important to take unbiased, **model-independent** approach
- Given we already have data, which will accumulate further, we want to adopt **data-driven** approaches

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)

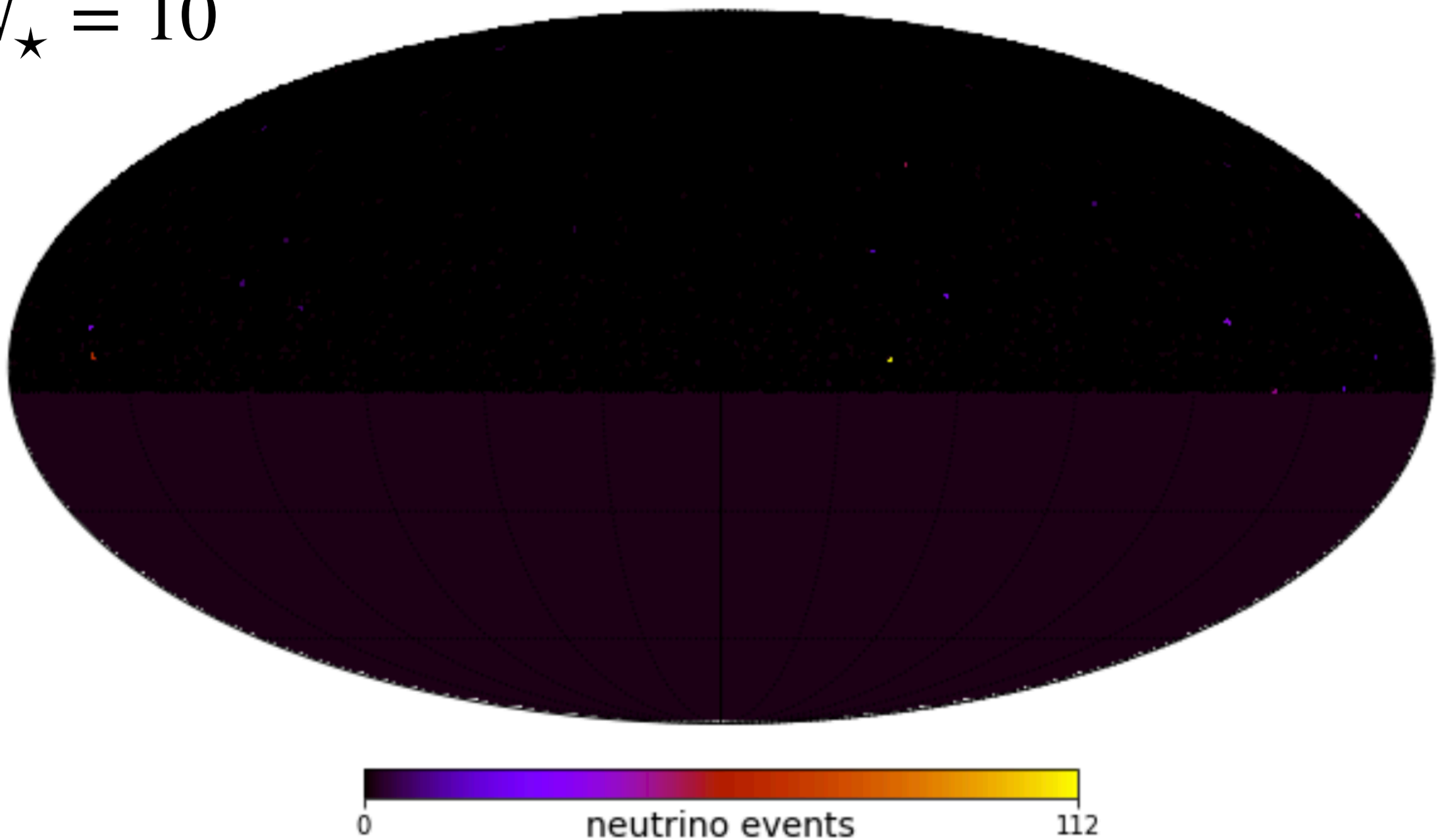


- **Number of detected sources**: Integral above flux threshold
  - At the moment, the threshold is higher than the flux of the brightest source
- **Energy spectrum:** first moment of the flux distribution below the flux threshold
- But we don't have to stop here!
- There are higher moments that can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

Simulated neutrino data

Characteristic number of sources: *N**

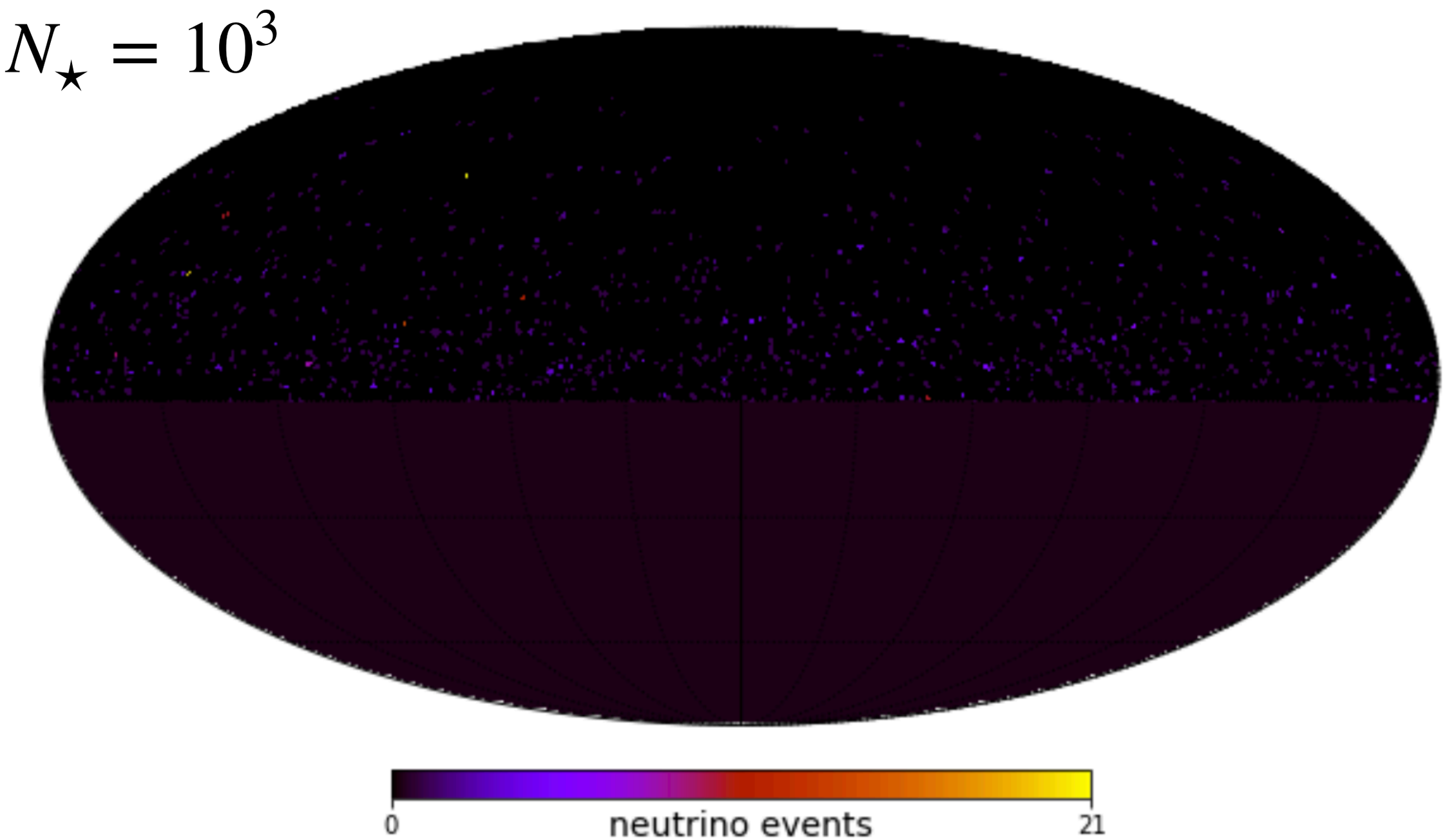
$$N_\star = 10$$



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

200 IceCube years

Simulated neutrino data



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

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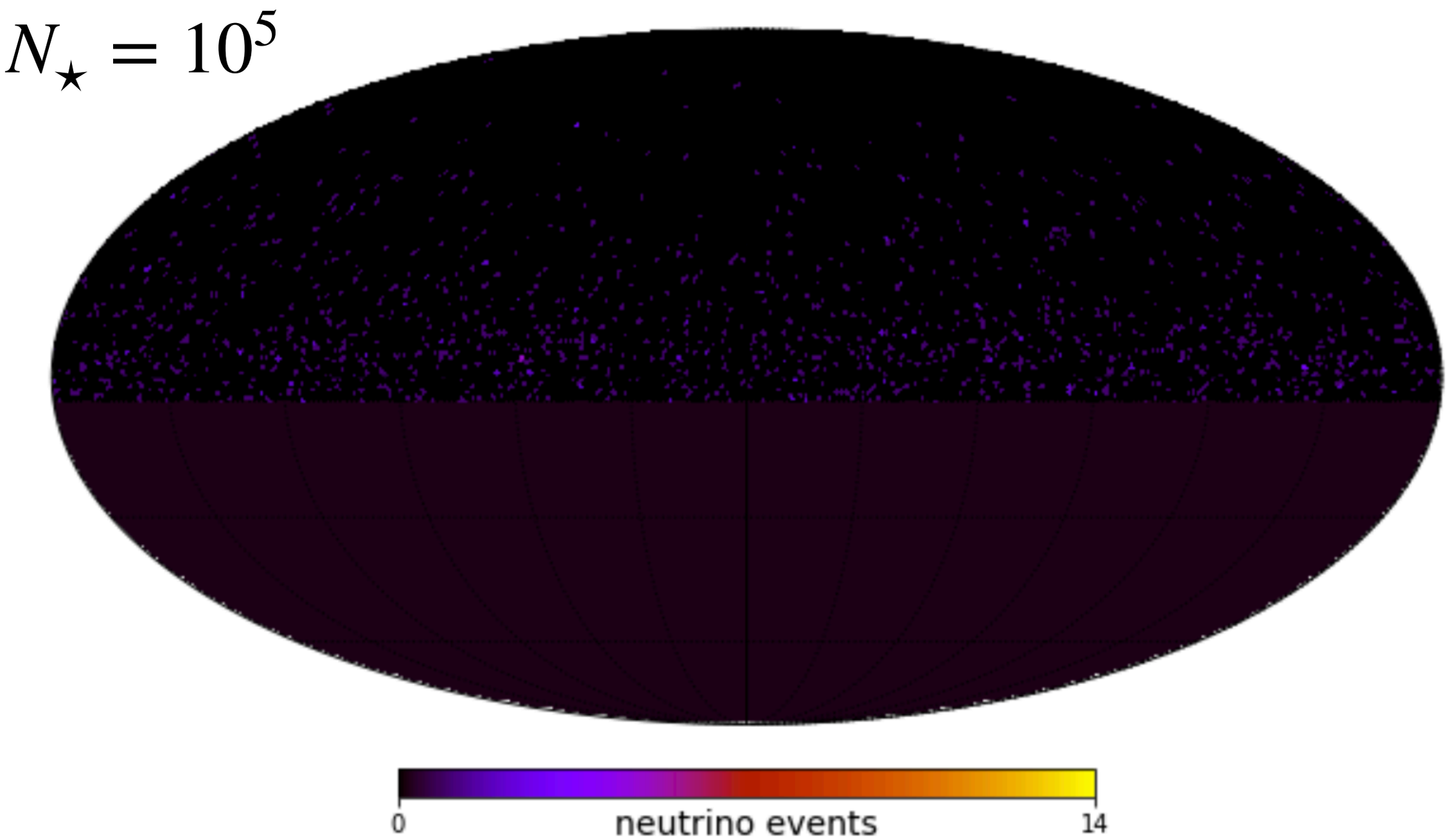
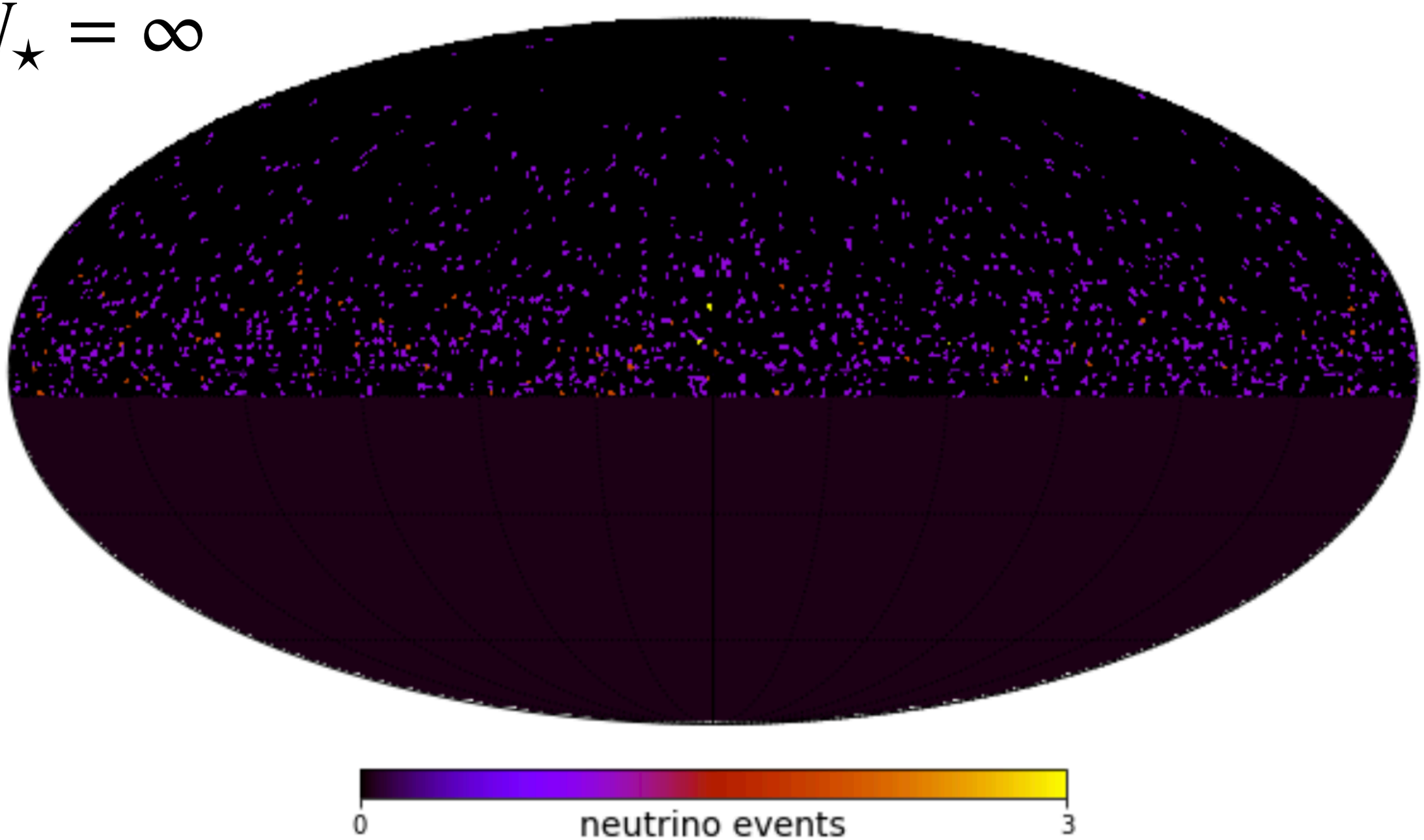


Dekker, Ando, *JCAP* **1902**, 002 (2019)

200 IceCube years

Simulated neutrino data

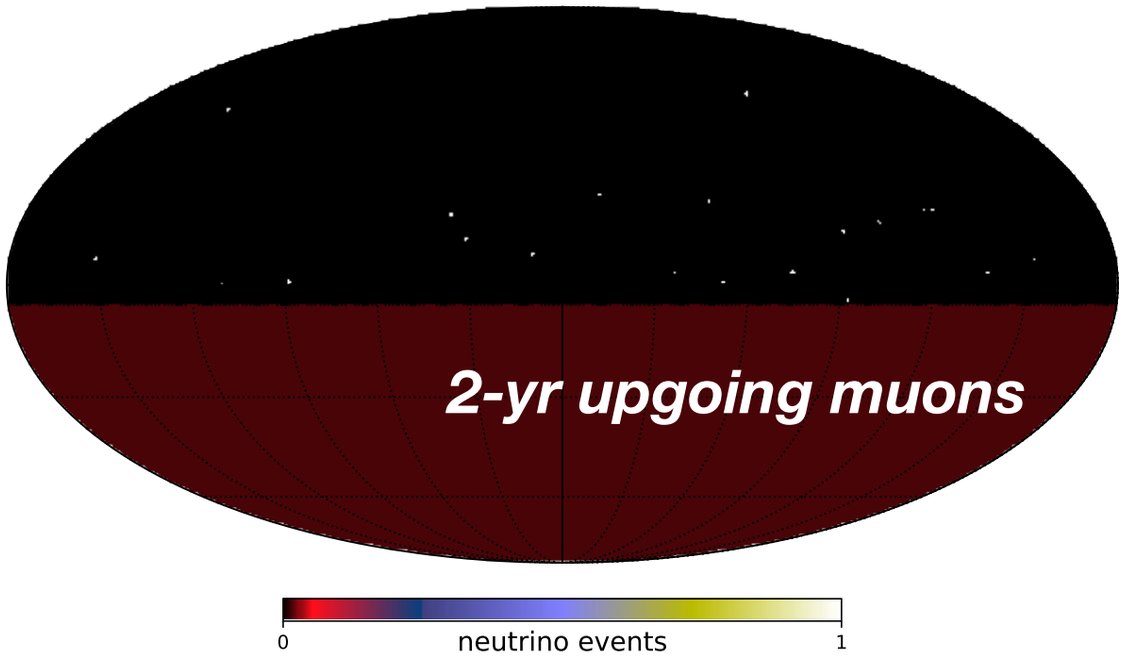
$N_\star = \infty$

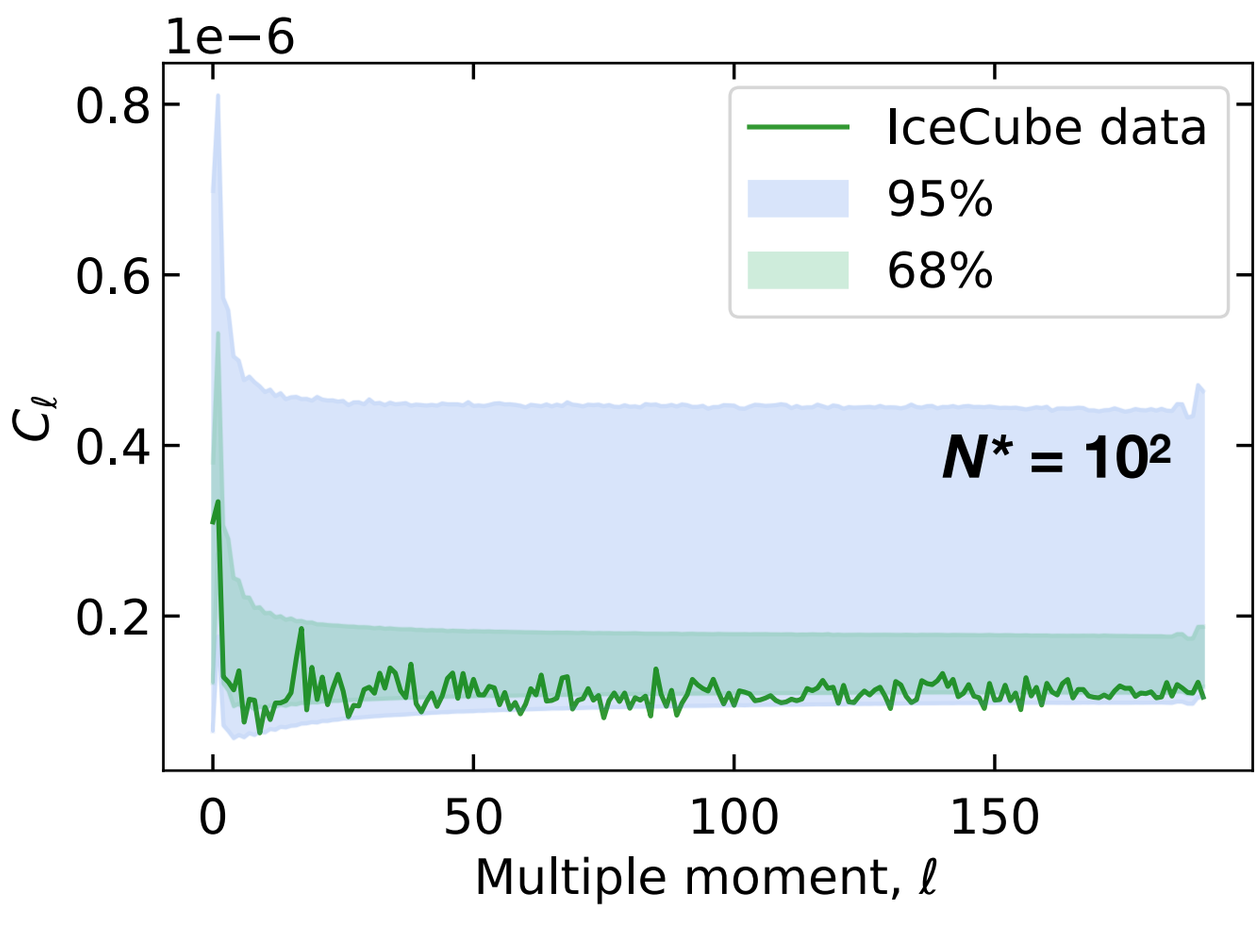


Dekker, Ando, *JCAP* **1902**, 002 (2019)

200 IceCube years

Angular power spectrum





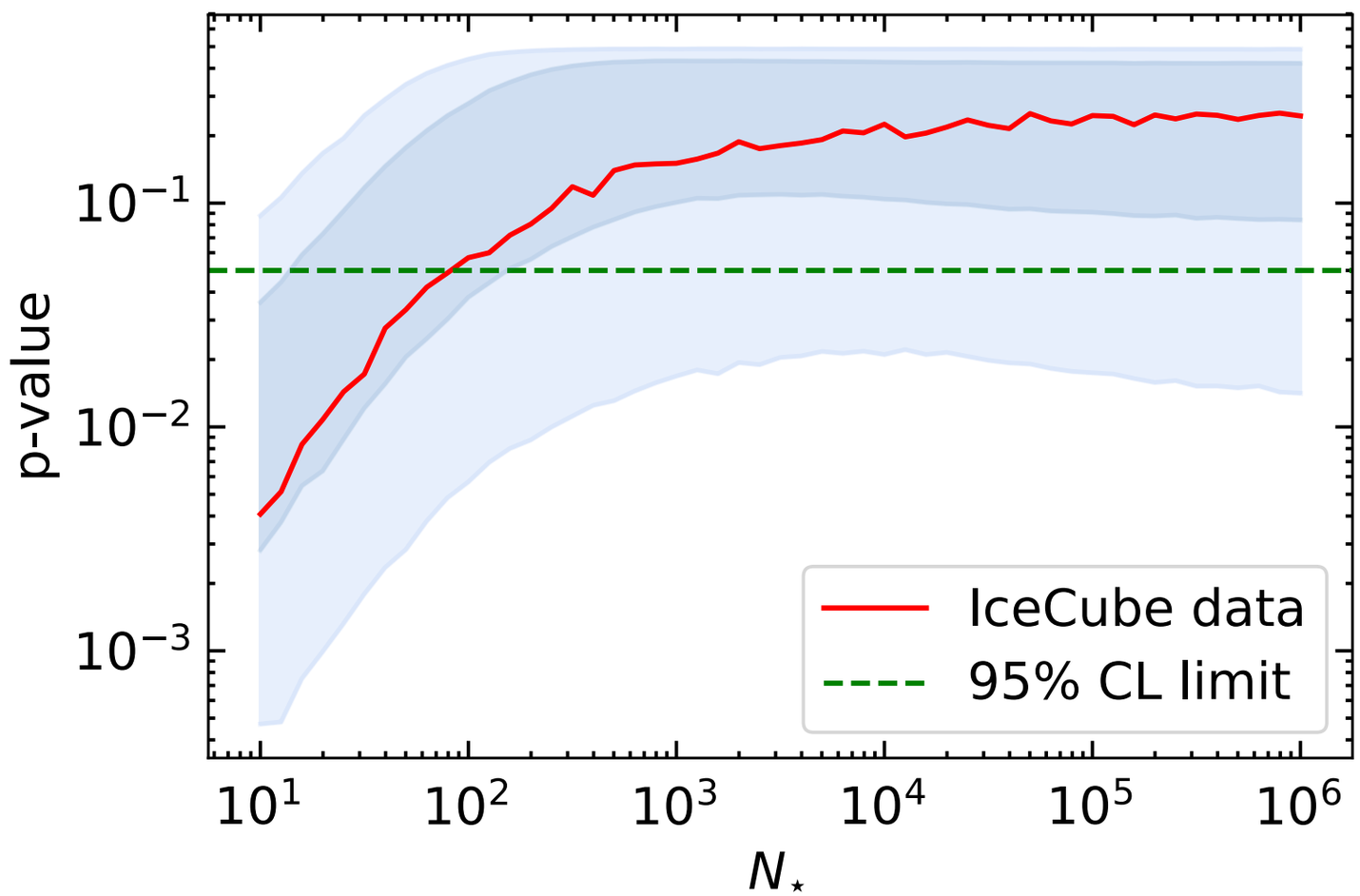
- For each simulated data set, we compute the angular power spectrum, i.e., variance
- By repeating the procedure above, we construct the TS and its distribution

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

- 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)

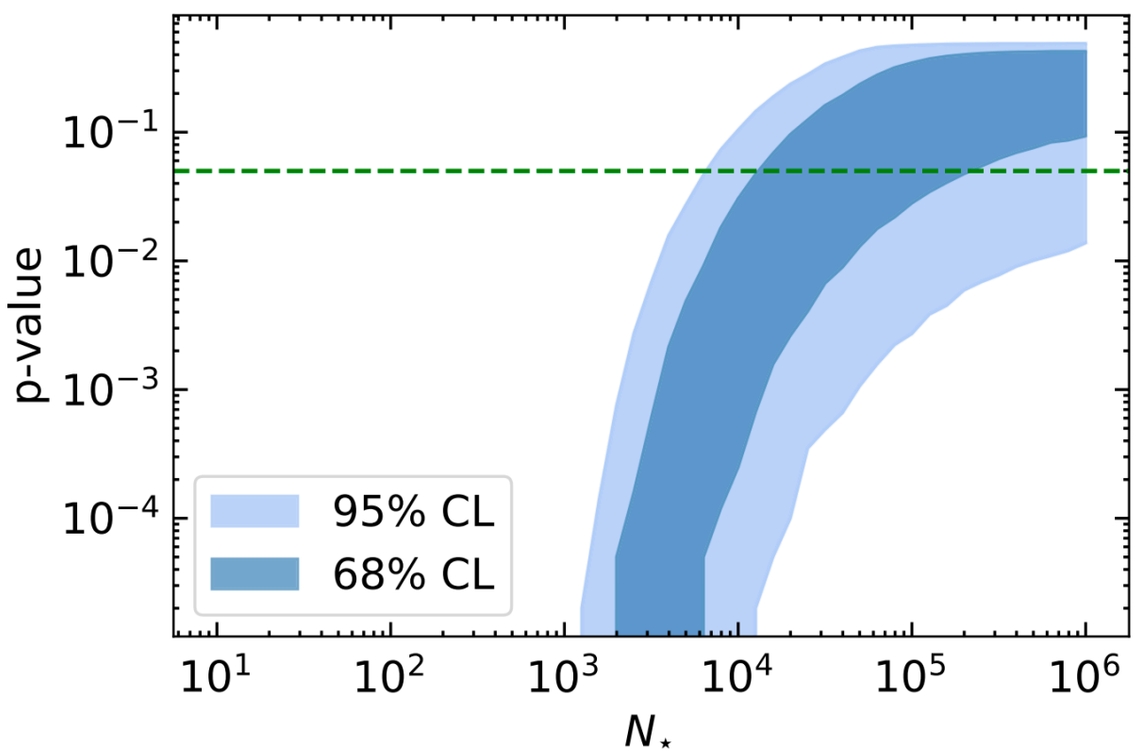
- 2 years of upgoing muon neutrino data from IceCube with energies $E_\mu > 50$ TeV: 21 events
- Source population with $N^* < 82$ is excluded at 95% CL

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

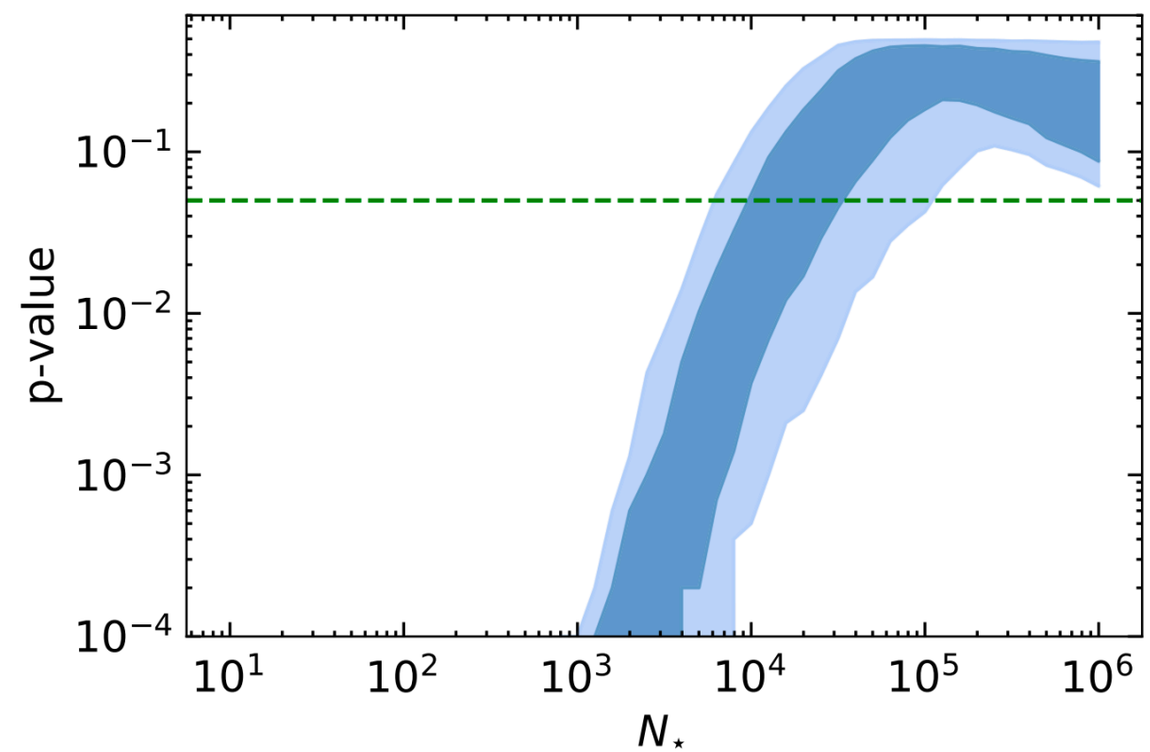
Future prospects

Case with $N^* = \infty$

IceCube-Gen2



KM3NeT



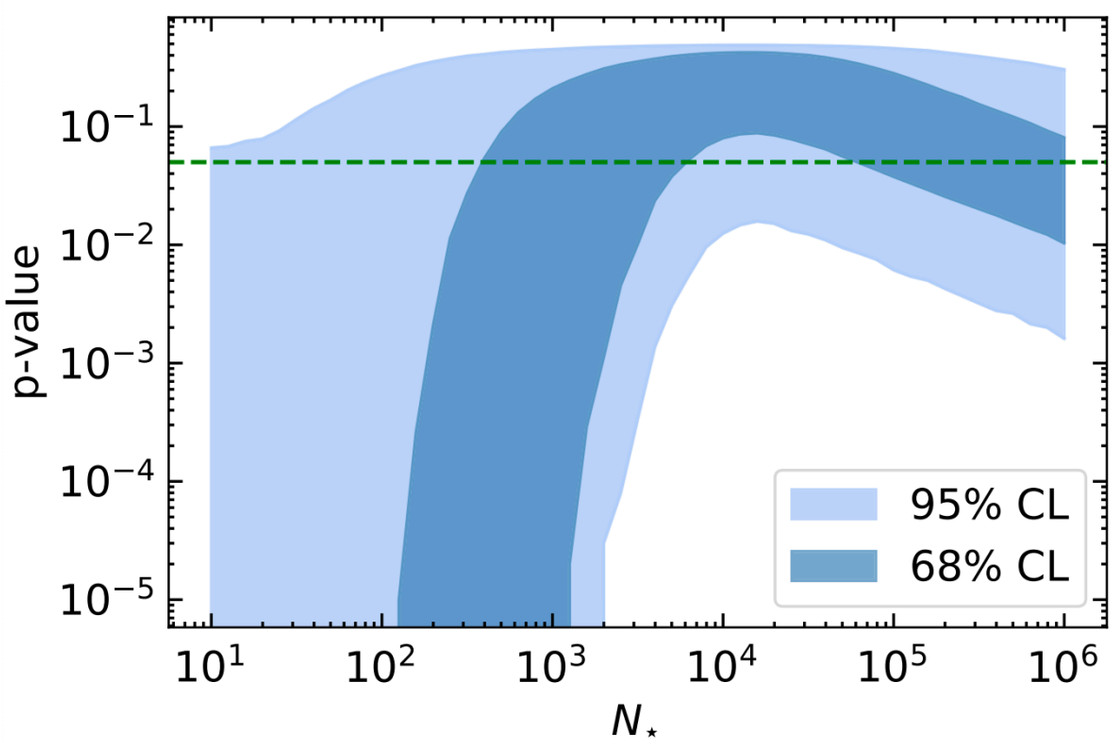
Dekker, Ando, *JCAP* **1902**, 002 (2019)

10-yr exposure

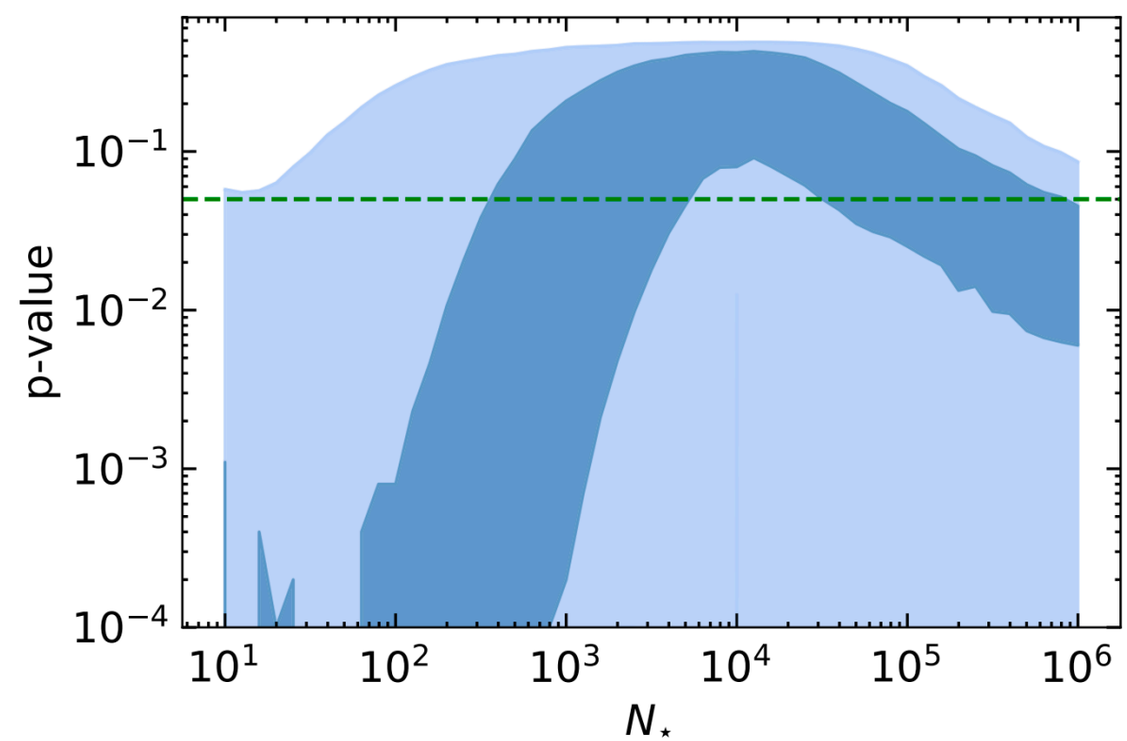
Future prospects

Case with $N^* = 10^4$

IceCube-Gen2



KM3NeT

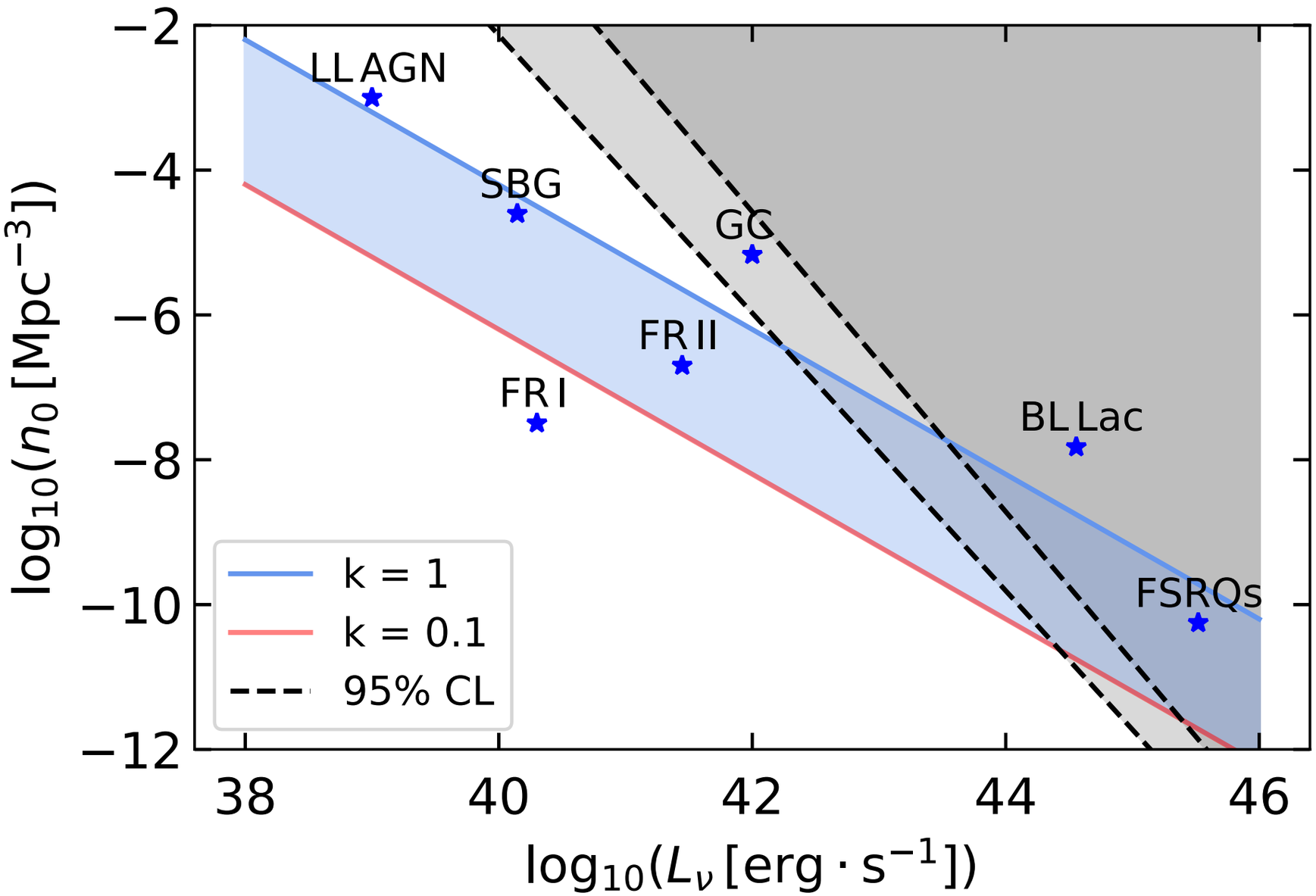


Dekker, Ando, *JCAP* **1902**, 002 (2019)

10-yr exposure

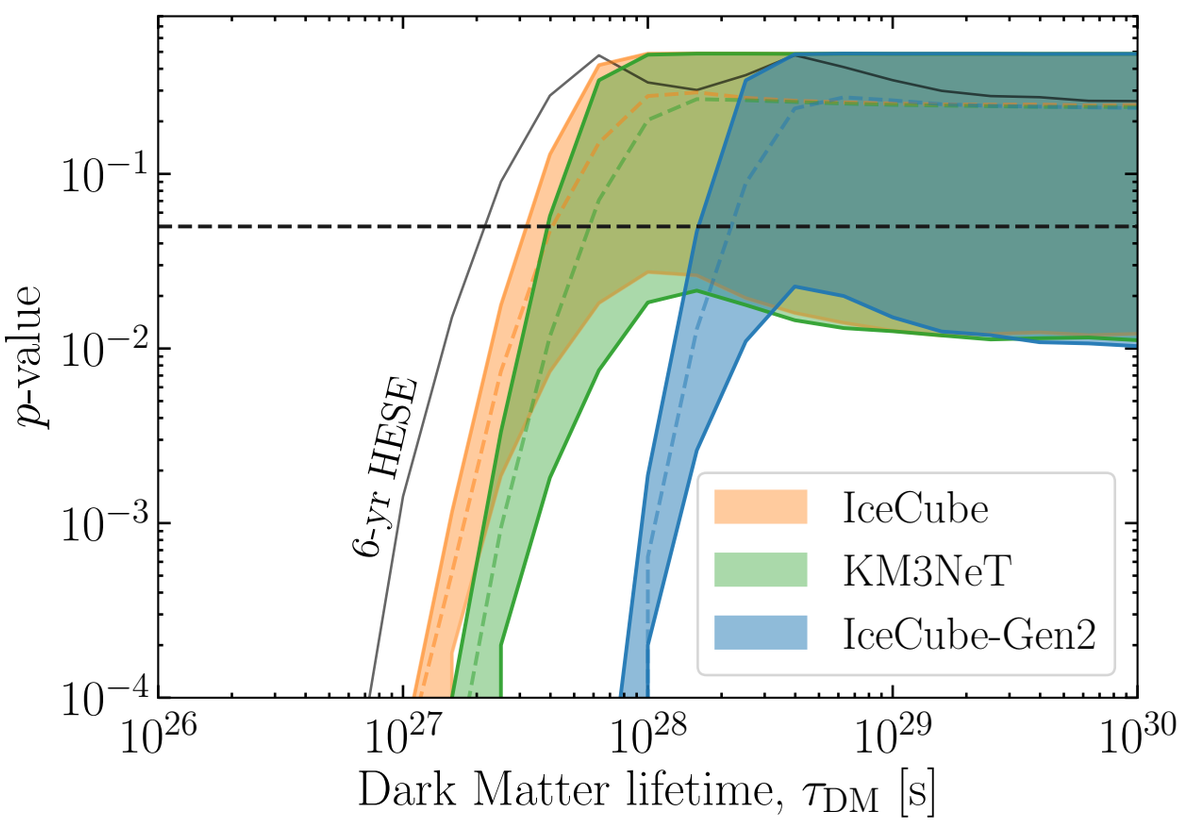
Constraints on source phase space

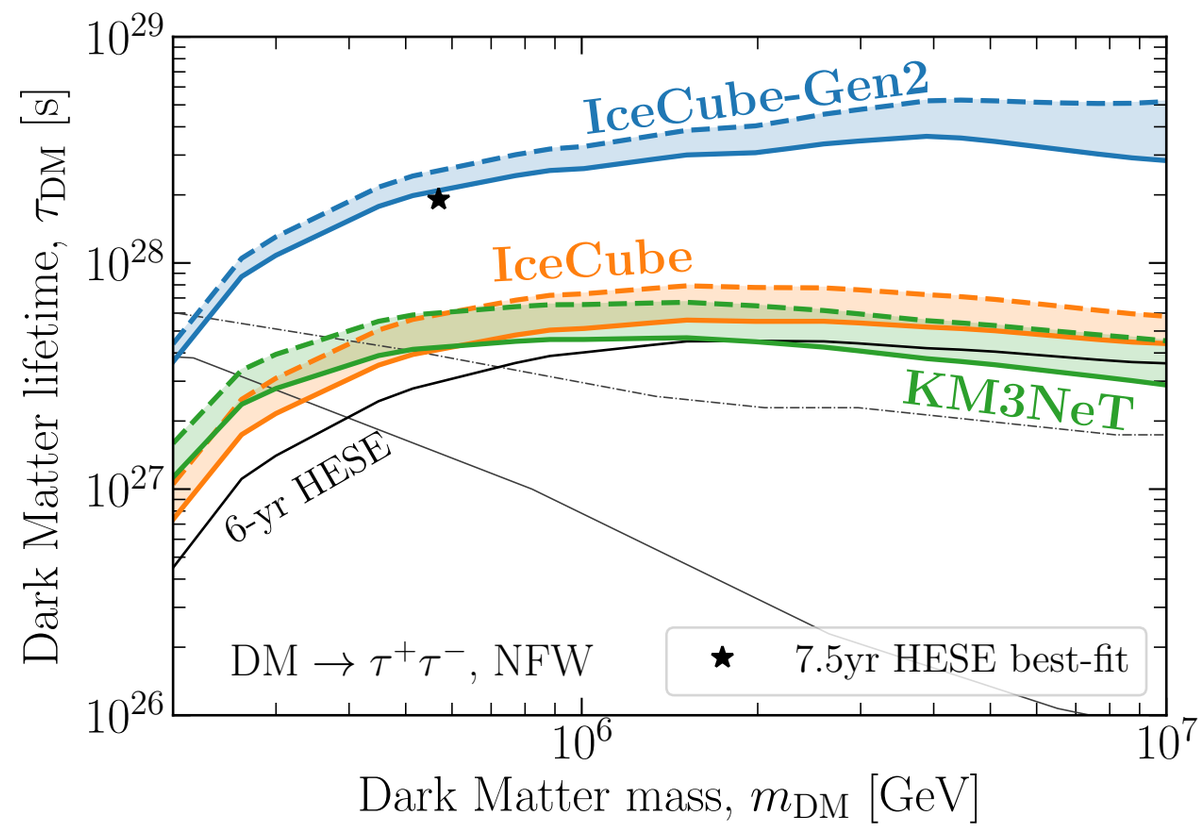
Dekker, Ando, *JCAP* **1902**, 002 (2019)



10-year IceCube-Gen2

Application to heavy dark matter decay

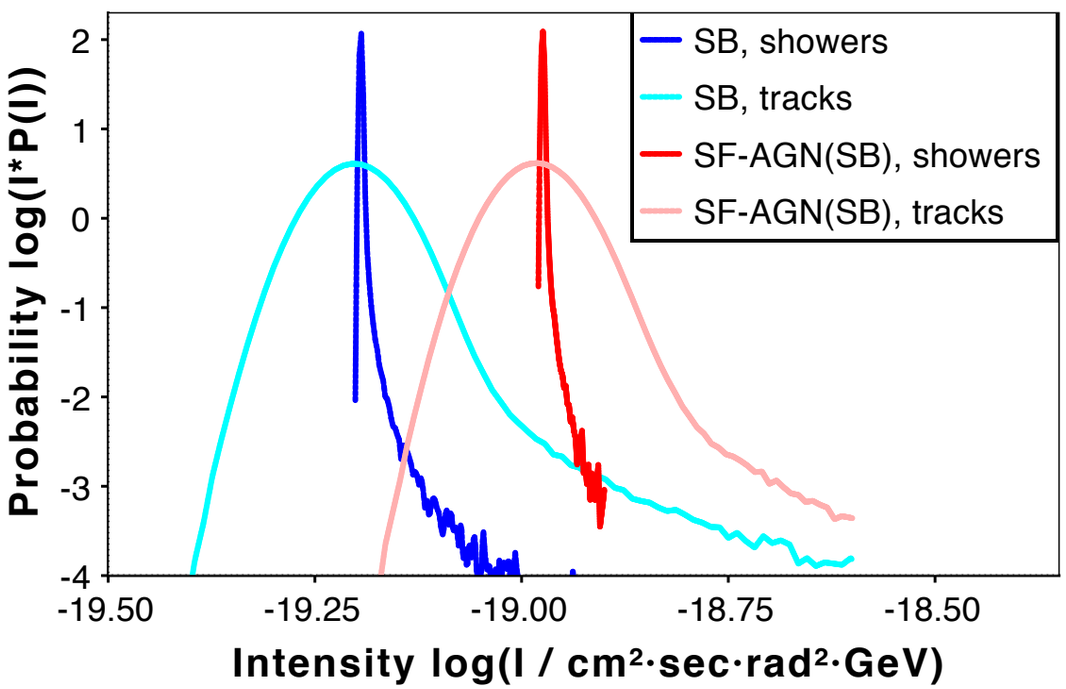


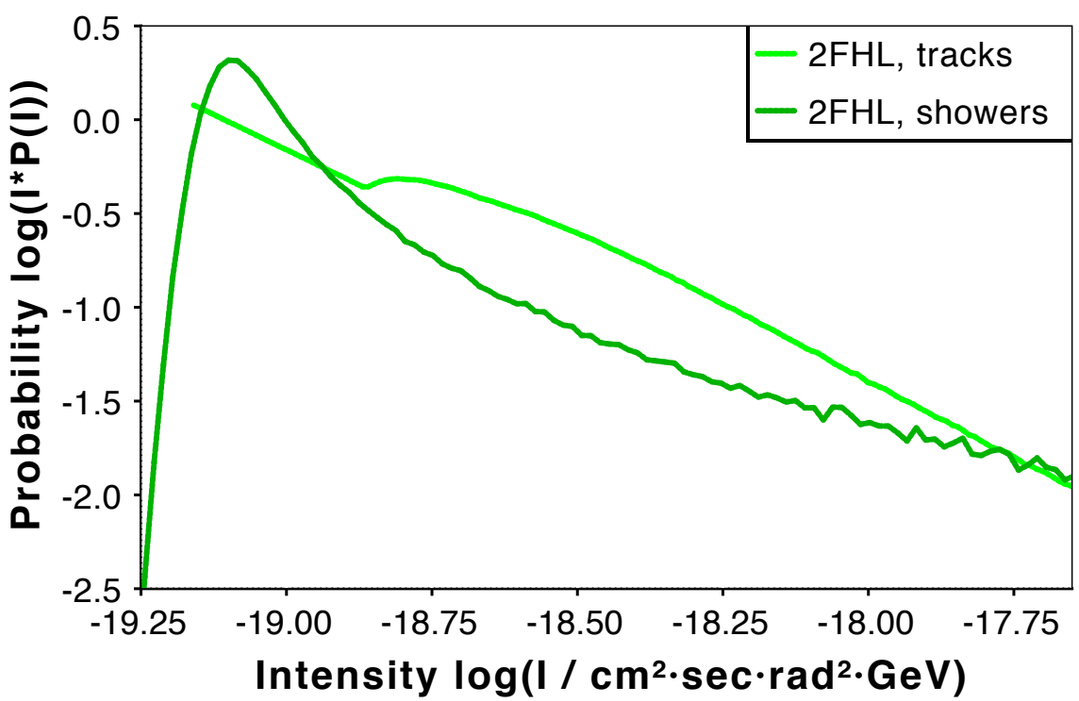


Dekker, Chianese, Ando, arXiv:1910.12917 [hep-ph]

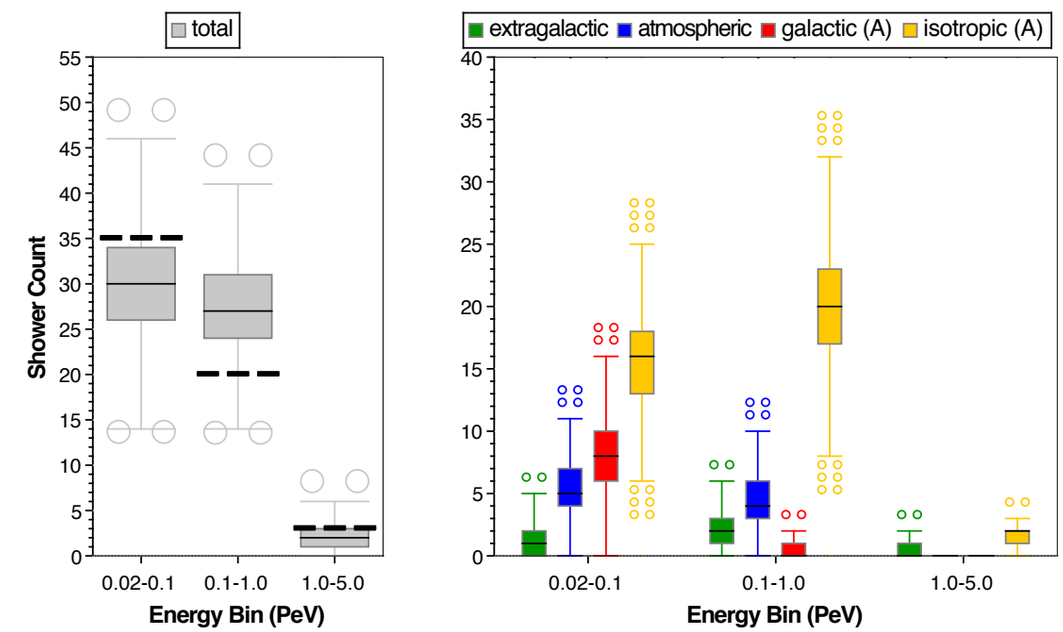
Beyond variance: One-point fluctuation analysis

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





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

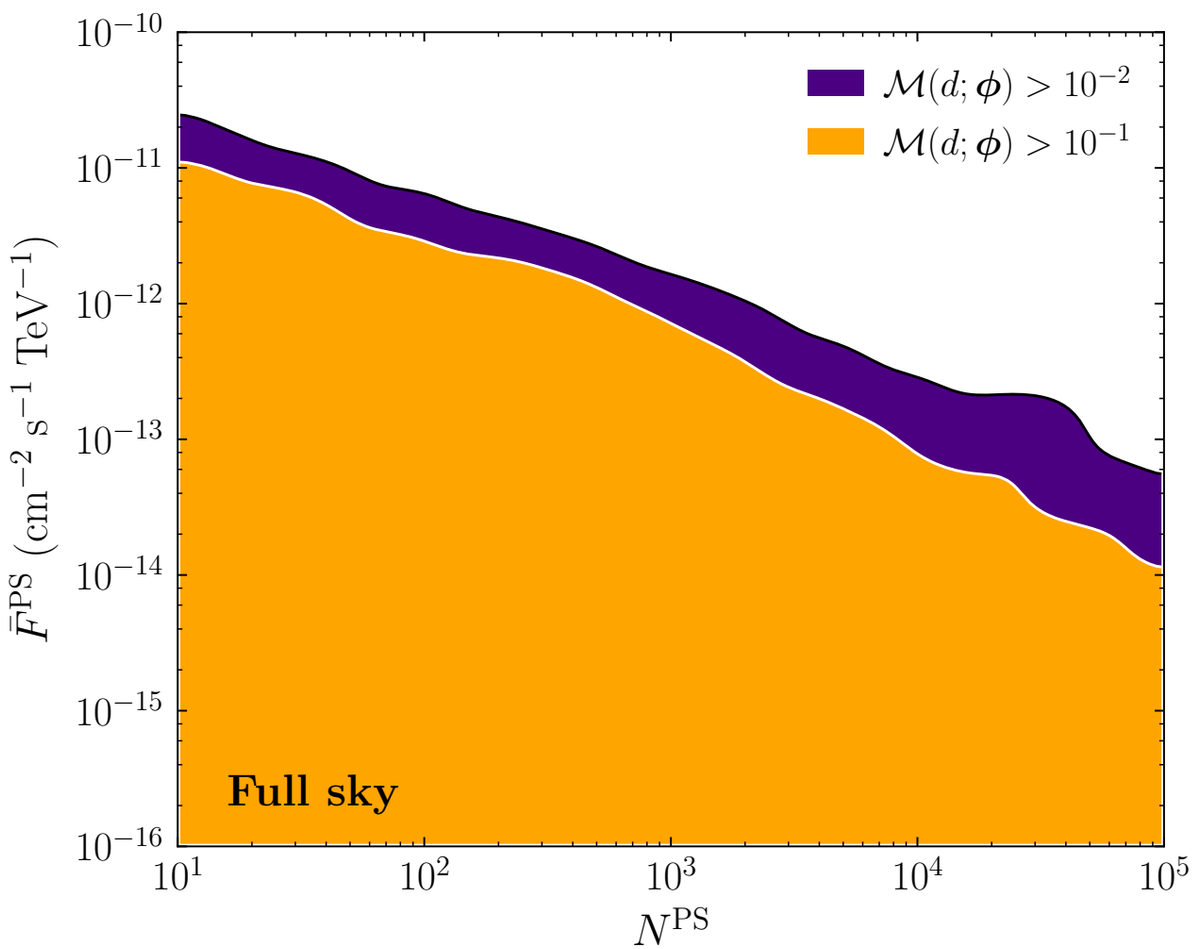


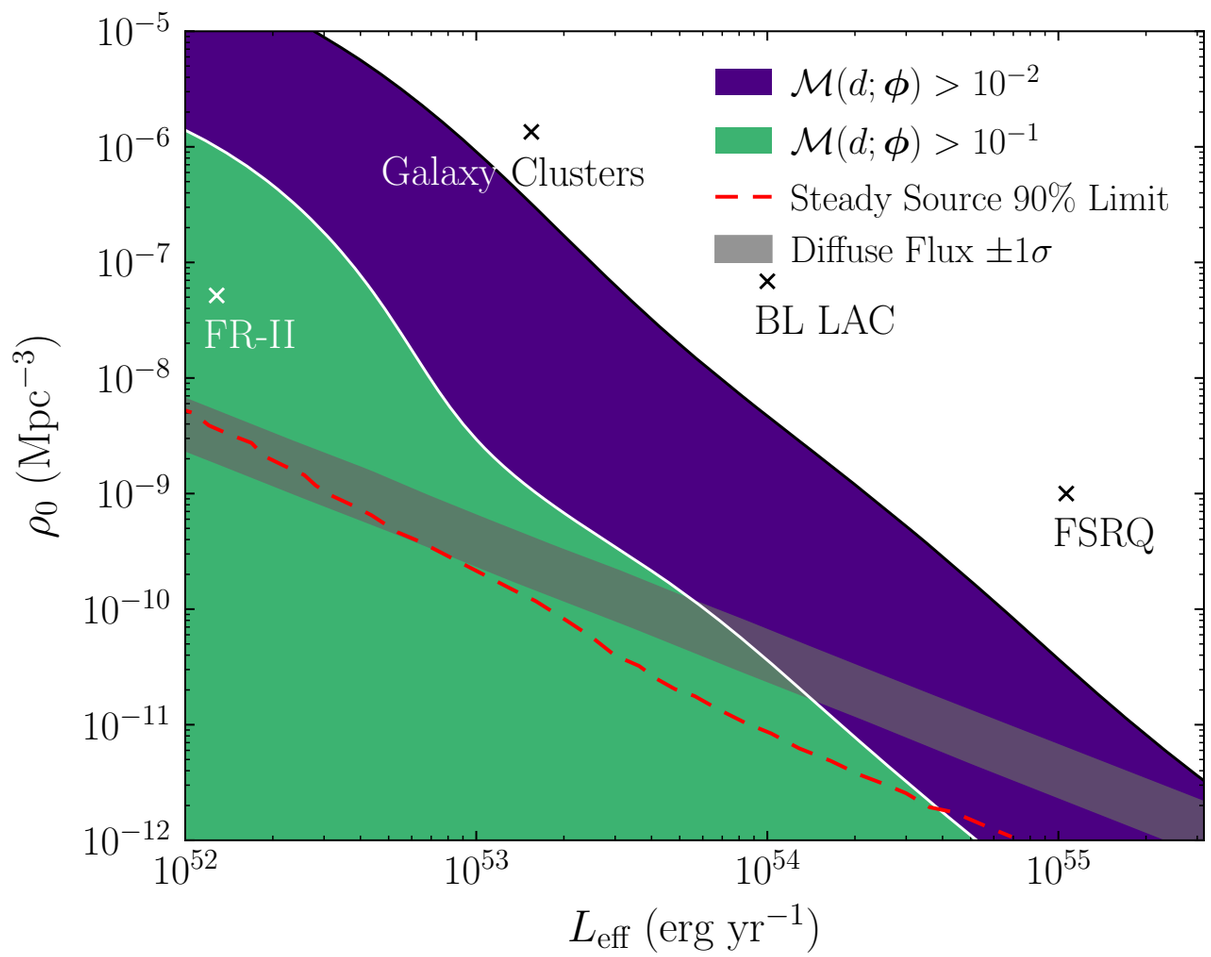
- One-point fluctuation analysis adopts all the information contained in the flux distribution
- Benefit is slim for now, but in the future can be large
  - E.g., test of Galactic component in the future KM3NeT data

Analysis by IceCube Collaboration

IceCube Collaboration, arXiv:1909.08623

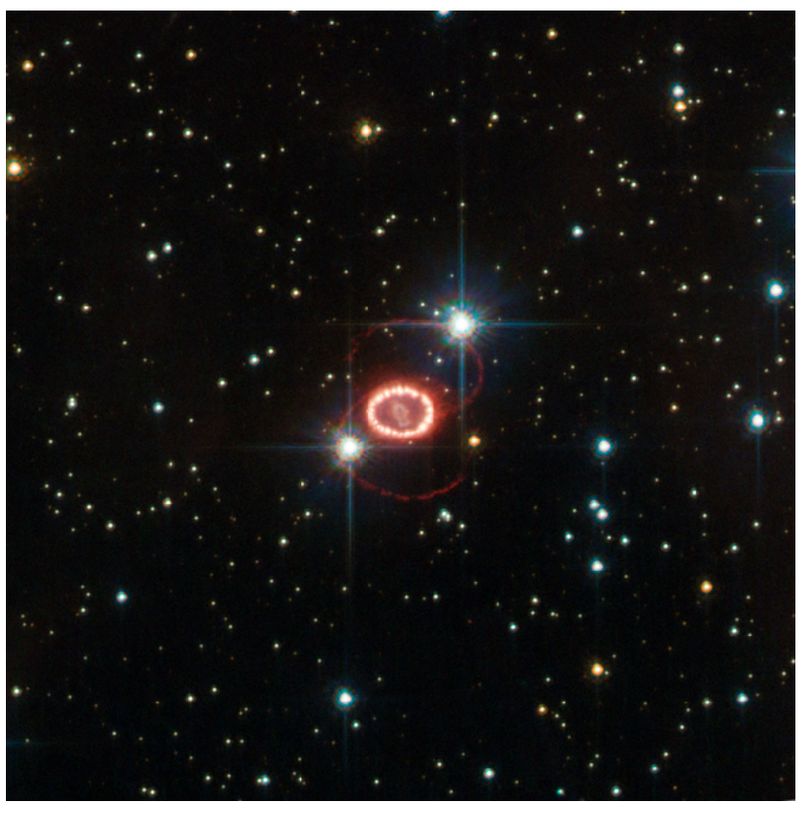
A Search for Neutrino Point-Source Populations in 7 Years of IceCube Data with Neutrino-count Statistics



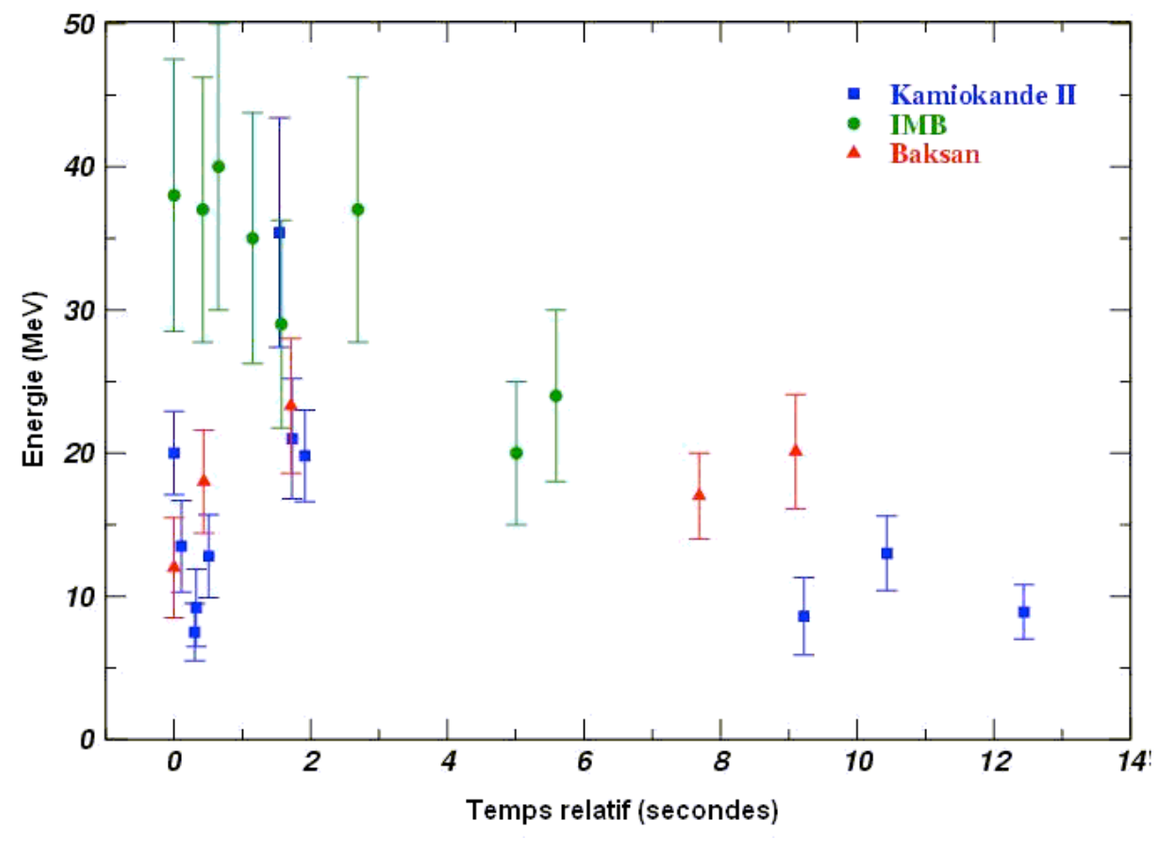


Diffuse supernova neutrino background

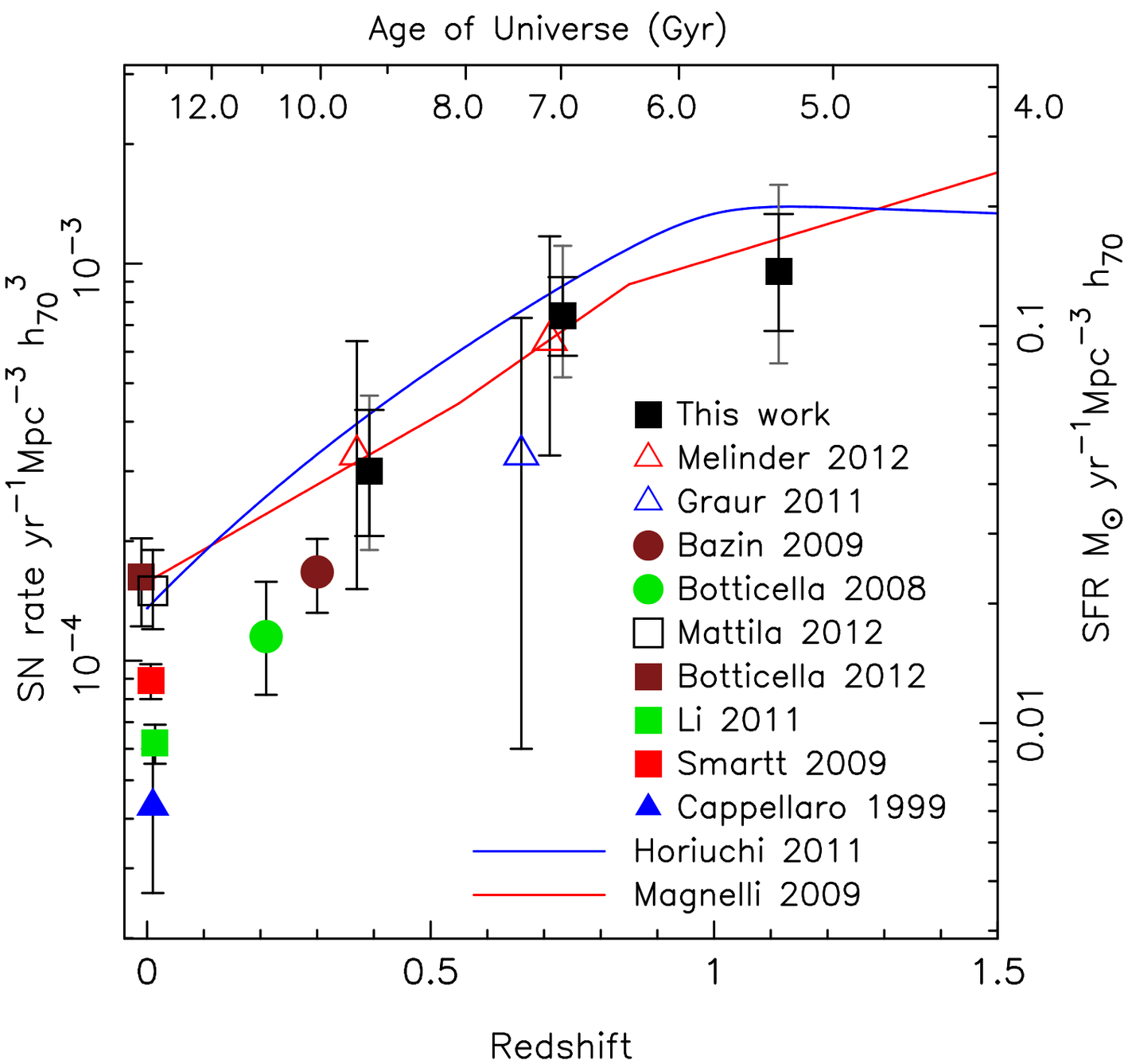
Stars do explode and emit neutrinos



- SN 1987A in LMC: tens of neutrinos detected with Kamiokande II and IMB
- Corresponds to ~10^{53} erg total energy released as a form of neutrinos



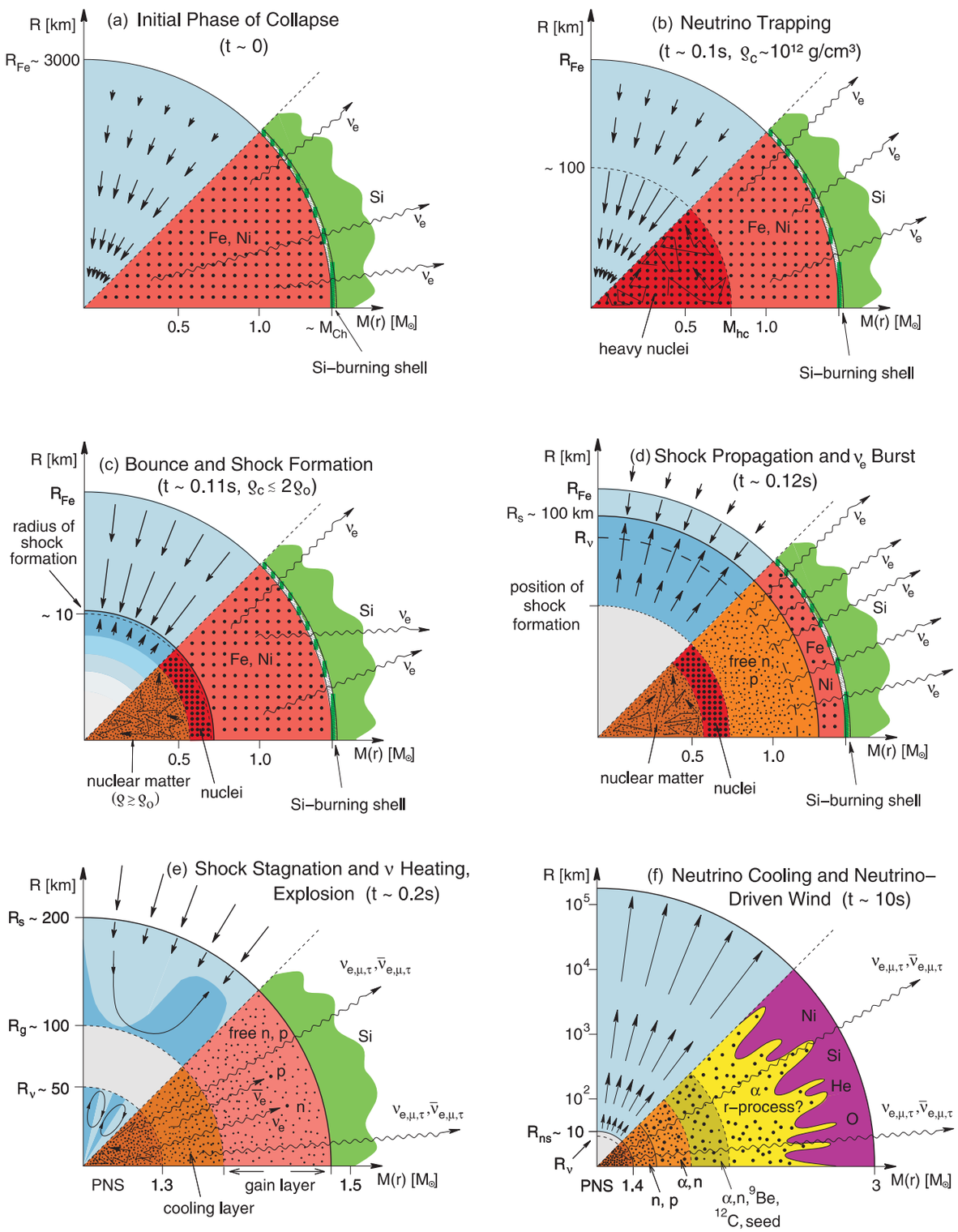
Stars do explode: Now and in the past



Dahlen et al., *Astrophys. J.* **757**, 70 (2012)

- Local rate: a few per century (^{26}Al decay line, etc.)
- Supernova rate increases as a function of redshift
- It is consistent with star formation rate and stellar initial mass function, assuming that stars for 8-50 M_{sun} explode as a supernova

Supernova explosion: A rough sketch



Janka et al. *Phys. Rep.* **442**, 38 (2007)

- Core collapse stars when iron can no longer sustain mass
- It stops when EOS stiffens, and bounces falling matter back
- Shocks wave stall until they are pushed further by neutrino wind
- The explosion leaves a neutron star or black hole as its remnant
- Gravitational binding energy:

$$E_B = \frac{3GM_{\rm NS}^2}{5R_{\rm NS}} \approx 3 \times 10^{53}\ \text{erg}$$

99%	MeV neutrinos
1%	Shock waves
0.01%	Photons

Diffuse supernova neutrinos: How bright is the Universe?

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- Galactic supernova rate is ~0.02 yr^{-1} (e.g., Diehl et al. 2006), which corresponds to global rate of ~2×10^{-4} yr^{-1} Mpc^{-3} (as galaxy density is 10^{-2} Mpc^{-3})

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- Supernovae continuously inject neutrinos for the age of the Universe, ~14 billion years

Diffuse supernova neutrinos: How bright is the Universe?

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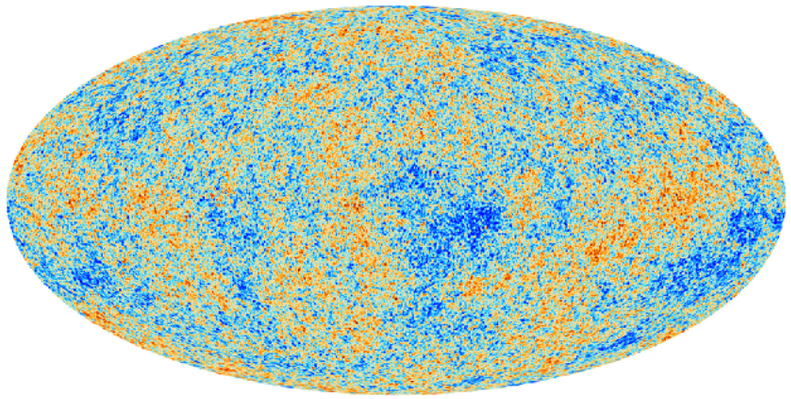
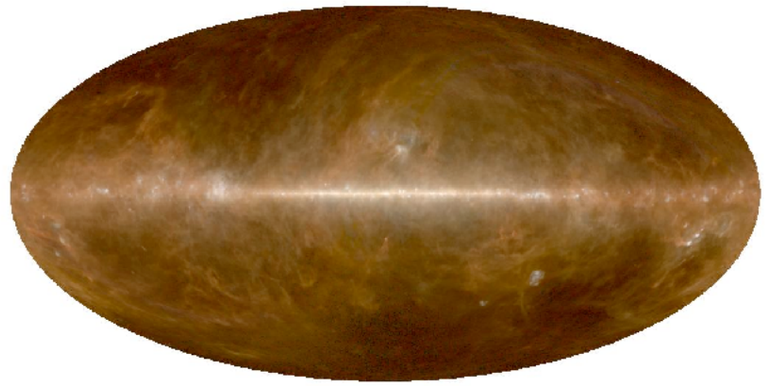
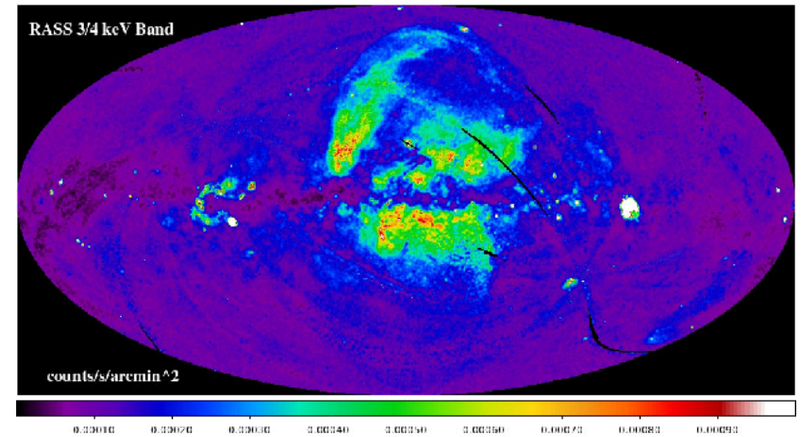
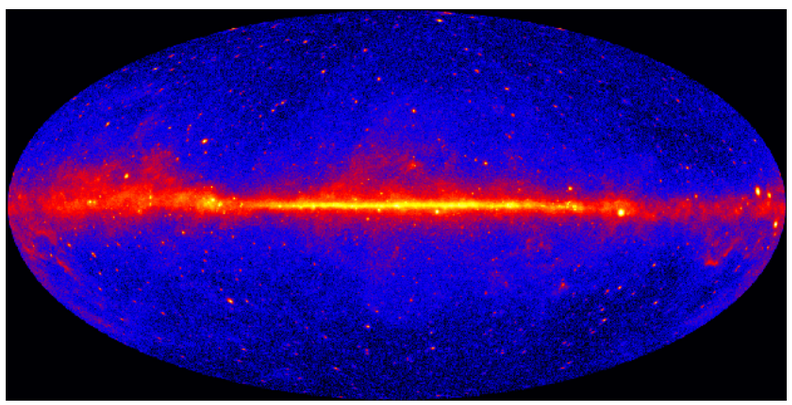
Energy/SN Global SN rate Cosmic age

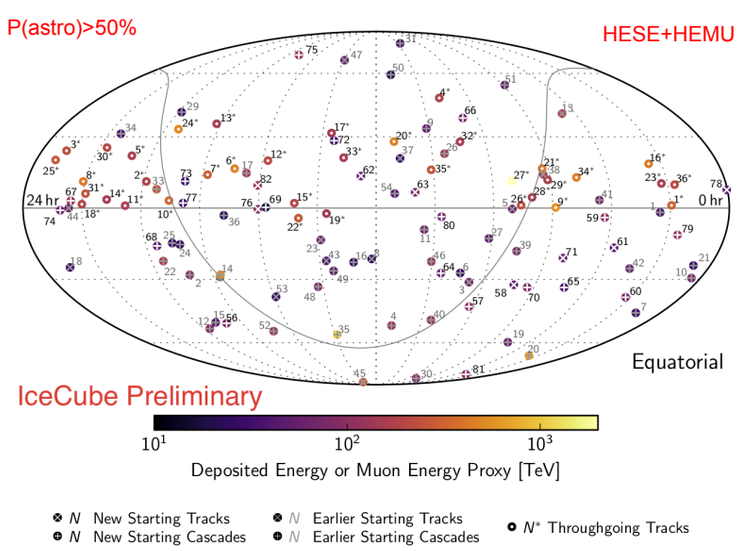
How bright is the Universe?







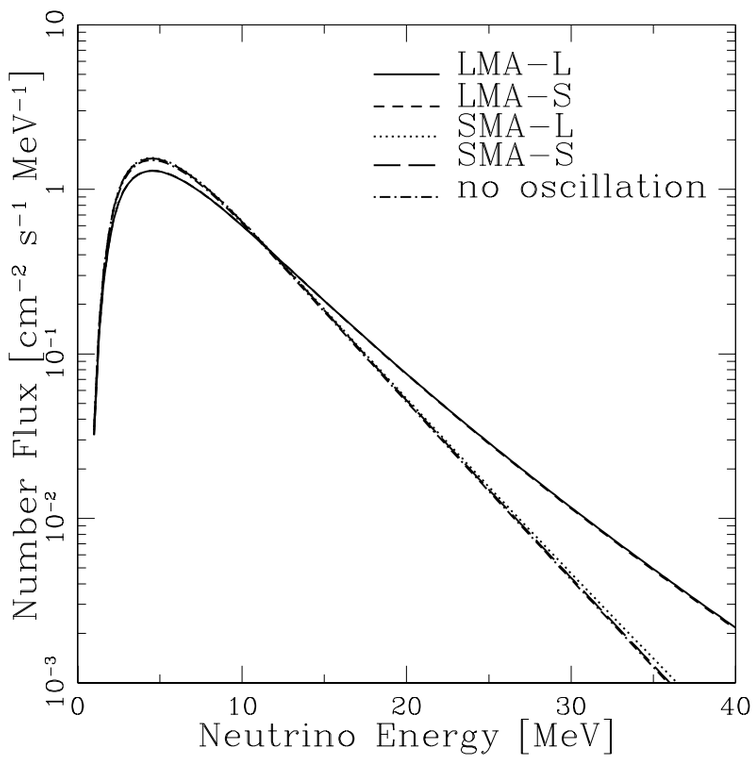




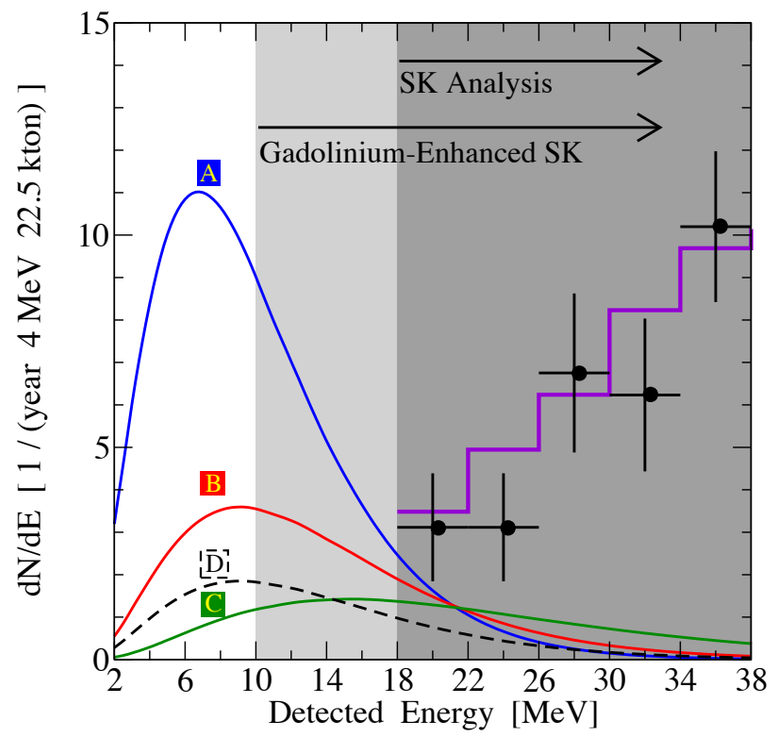
	Energy density
CMB	4×10^{-13} erg cm^{-3}
CIB/EBL	$(2–3) \times 10^{-14}$ erg cm^{-3}
CXB	10^{-16} erg cm^{-3}
CGB	10^{-17} erg cm^{-3}
DSNB	**3×10^{-14} erg cm^{-3}**
TeVvB	10^{-19} erg cm^{-3}

Spectrum of supernova neutrino background

Ando, Sato, Totani,
Astropart. Phys. **18**, 307 (2003)

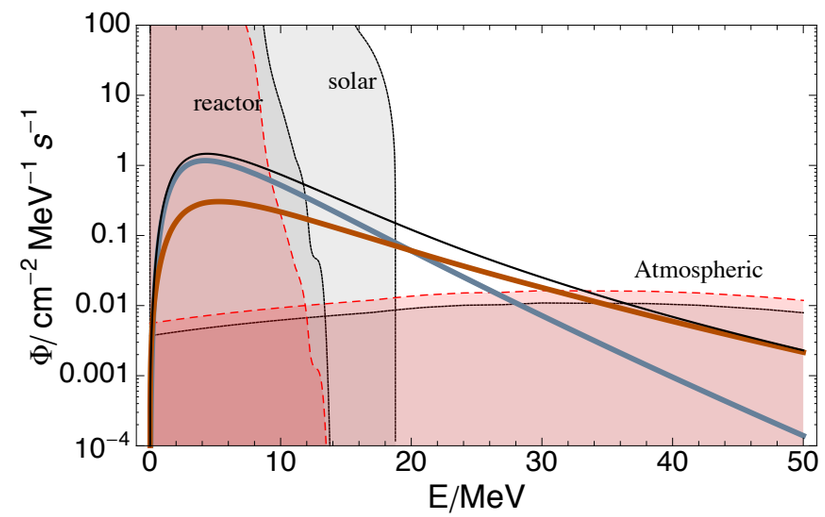


Neutrino physics



Yuksel, Ando, Beacom,
Phys. Rev. C **74**, 015803 (2006)

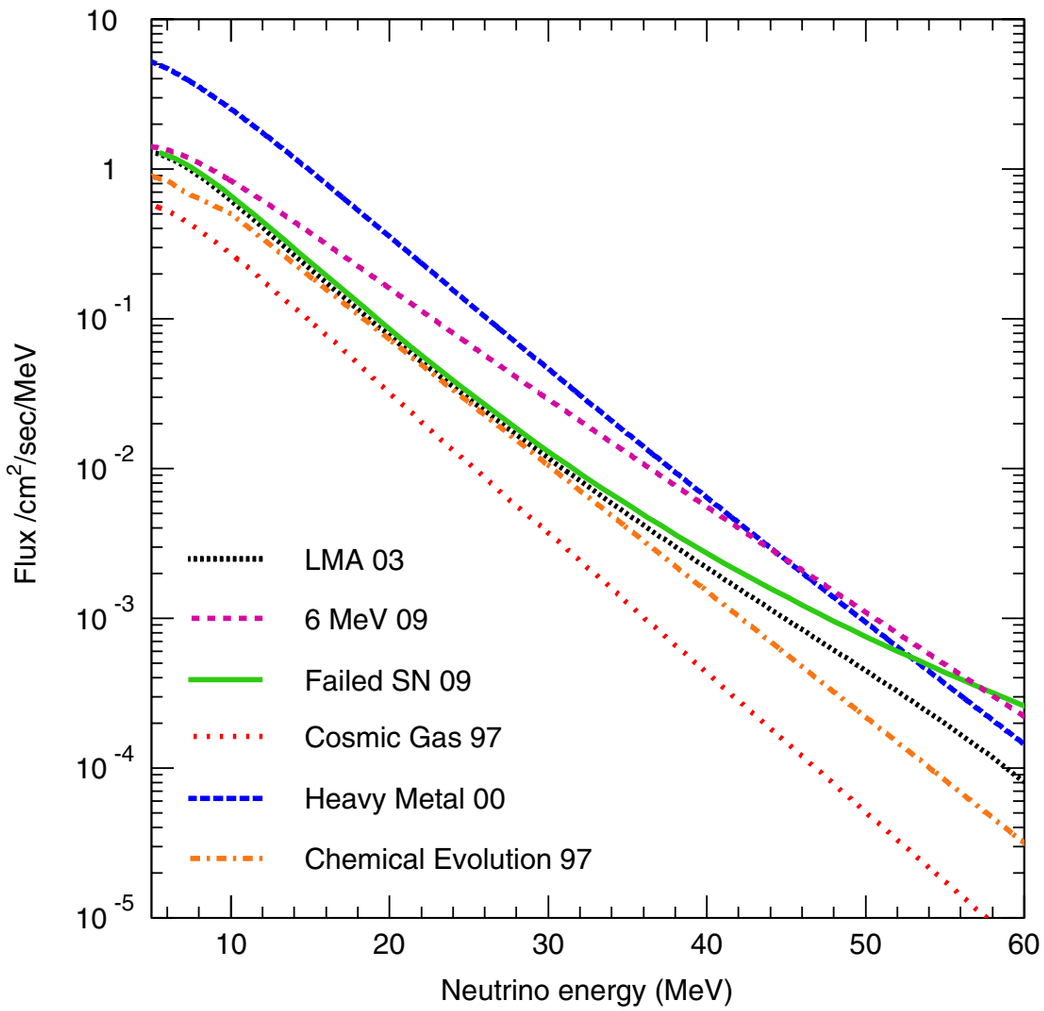
Keehn, Lunardini
Phys.Rev. D **85** (2012) 043011

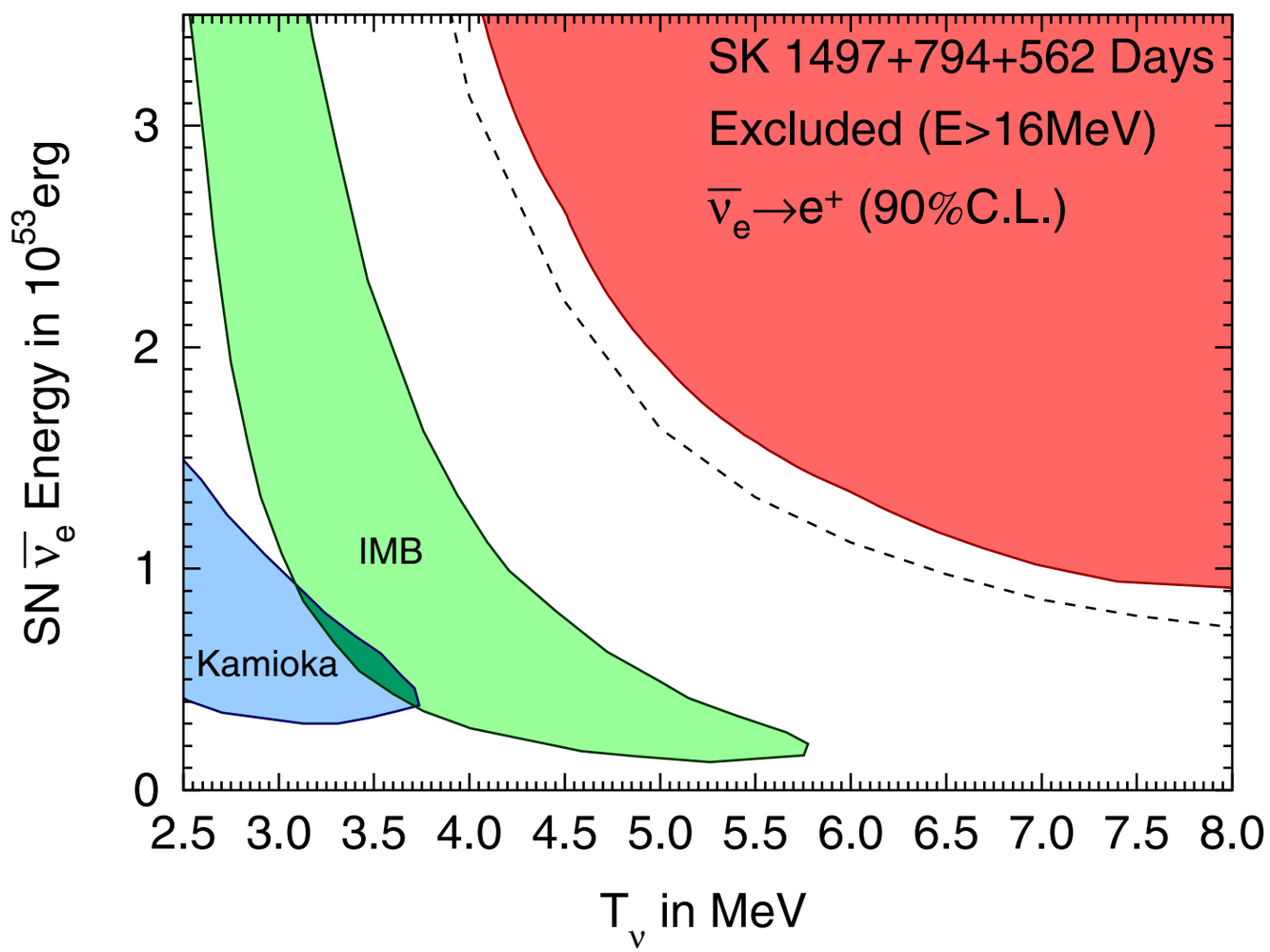


Black-hole formation

Supernova model

DSNB: Observational constraints





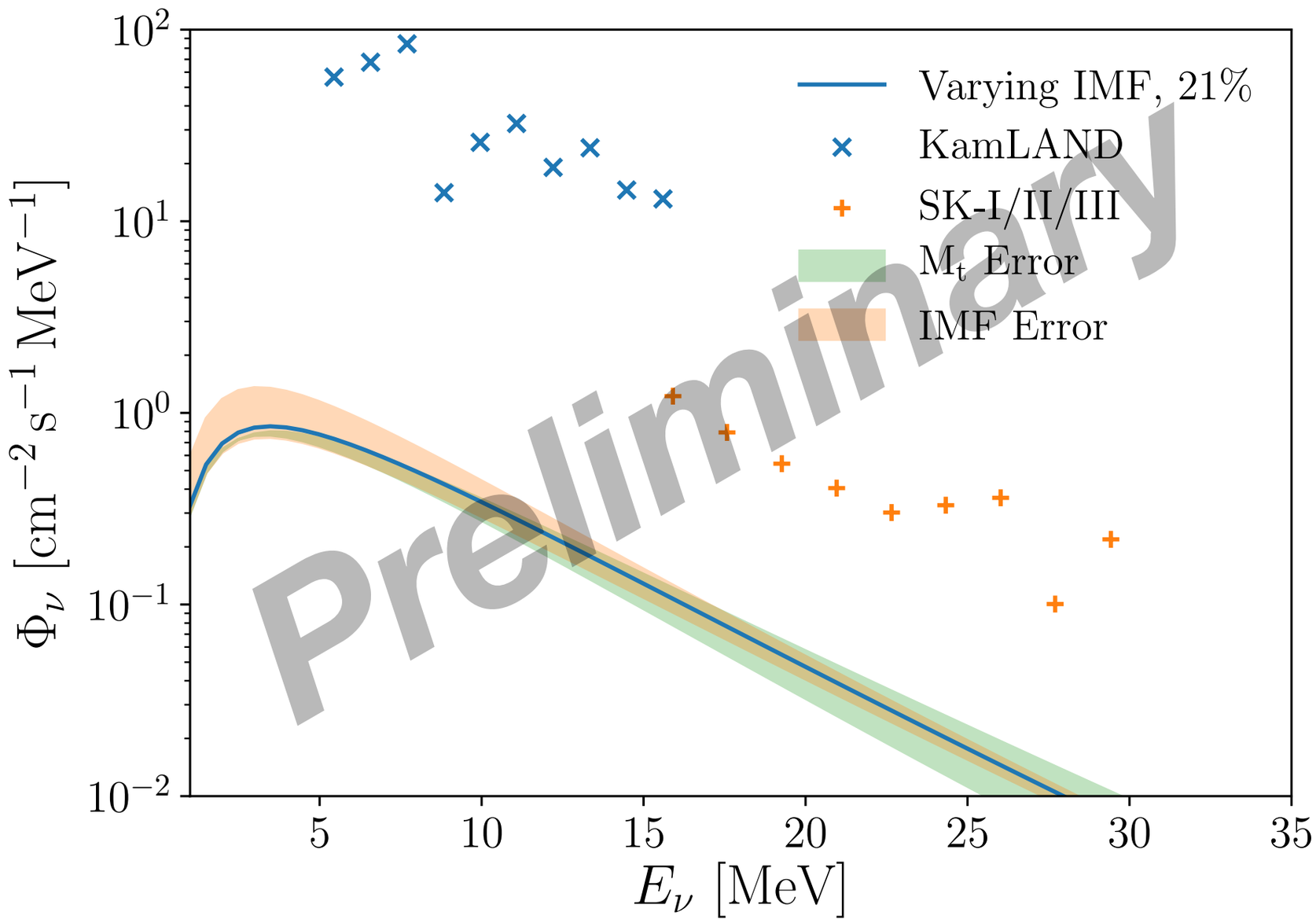
Super-K, *Phys. Rev. D* **85**, 052007 (2012)

Model	SK-I	SK-II	SK-III	All	Predicted
Gas infall (97)	<2.1	<7.5	<7.8	<2.8	0.3
Chemical (97)	<2.2	<7.2	<7.8	<2.8	0.6
Heavy metal (00)	<2.2	<7.4	<7.8	<2.8	<1.8
LMA (03)	<2.5	<7.7	<8.0	<2.9	1.7
Failed SN (09)	<2.4	<8.0	<8.4	<3.0	0.7
6 MeV (09)	<2.7	<7.4	<8.7	<3.1	1.5

90 % C.L. flux limit ($\bar{\nu}$ cm^{-2} s^{-1}), $E_\nu > 17.3$ MeV

- Latest upper limits with Super-K are about factor 2-3 above predictions
- Good prospects for Super-K+Gd or large-volume scintillation detectors (e.g., LENA)

DSNB: Astrophysical uncertainties



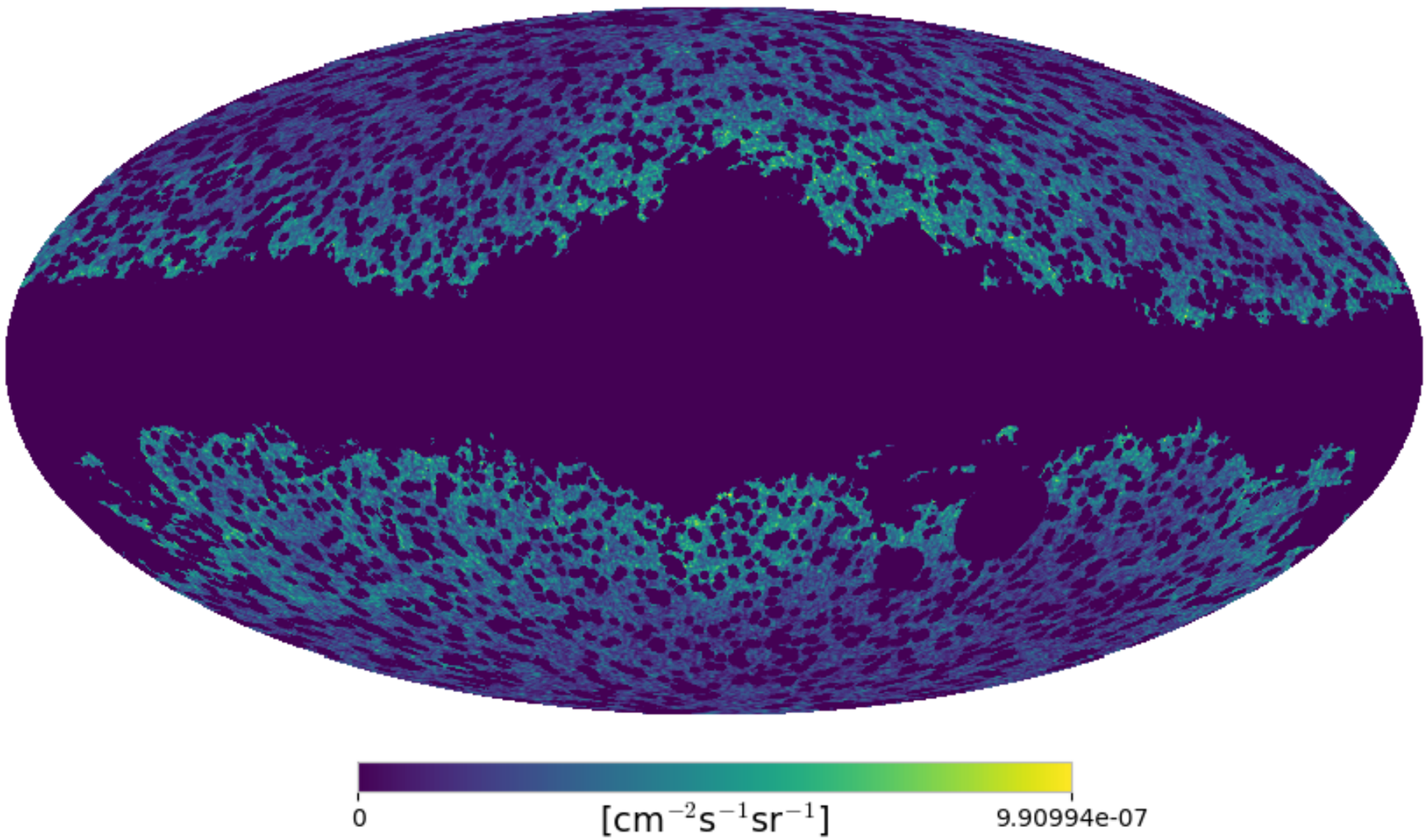
Work in preparation with **Thomas Edwards**, Shunsaku Horiuchi, Anna Suliga, Irene Tamborra

Conclusions

- IceCube detected TeV-PeV neutrinos, but **no source has been identified**
- Potential sources include blazars, starburst galaxies, radio galaxies, etc.
- Given no source was detected, however, 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
- Supernovae power non-thermal activities in the Universe, and can be probed with neutrinos; **detection of diffuse supernova neutrino background is just around the corner**

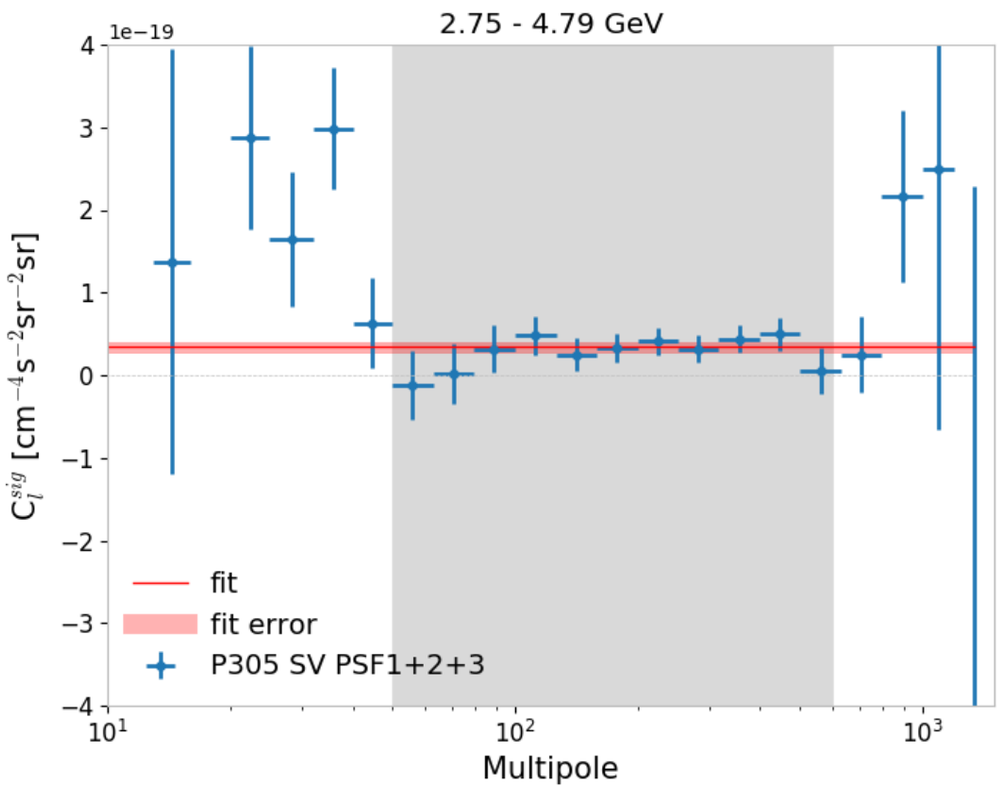
Backup

Anisotropies: Lessons from gamma rays



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

Angular power spectrum: Observations with Fermi



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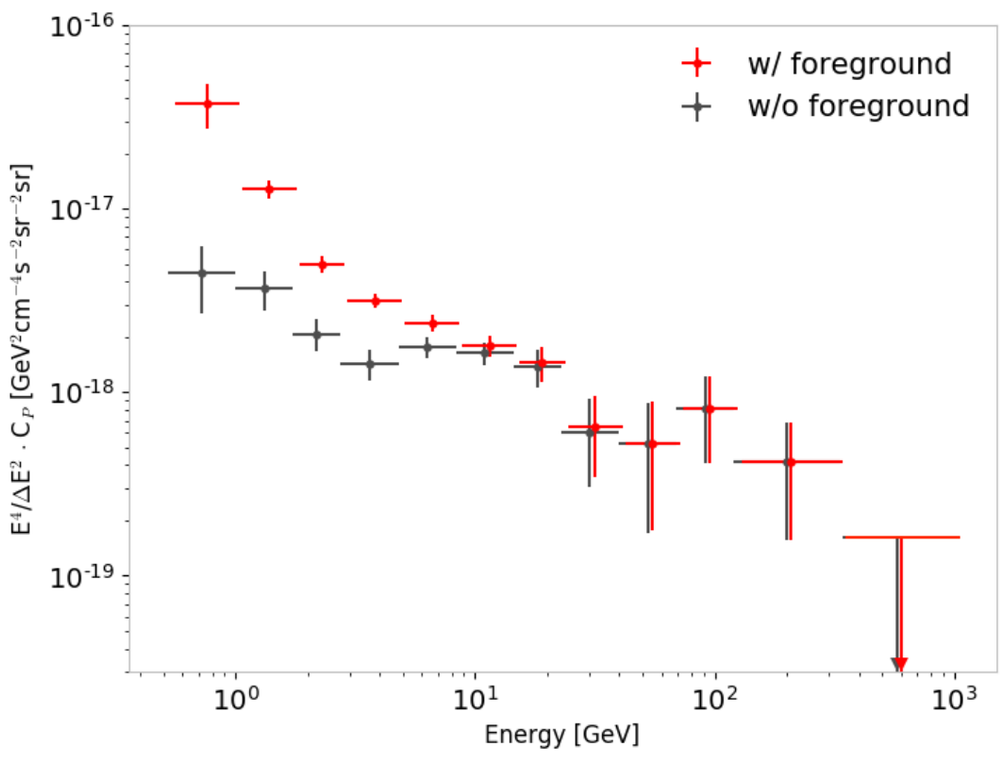

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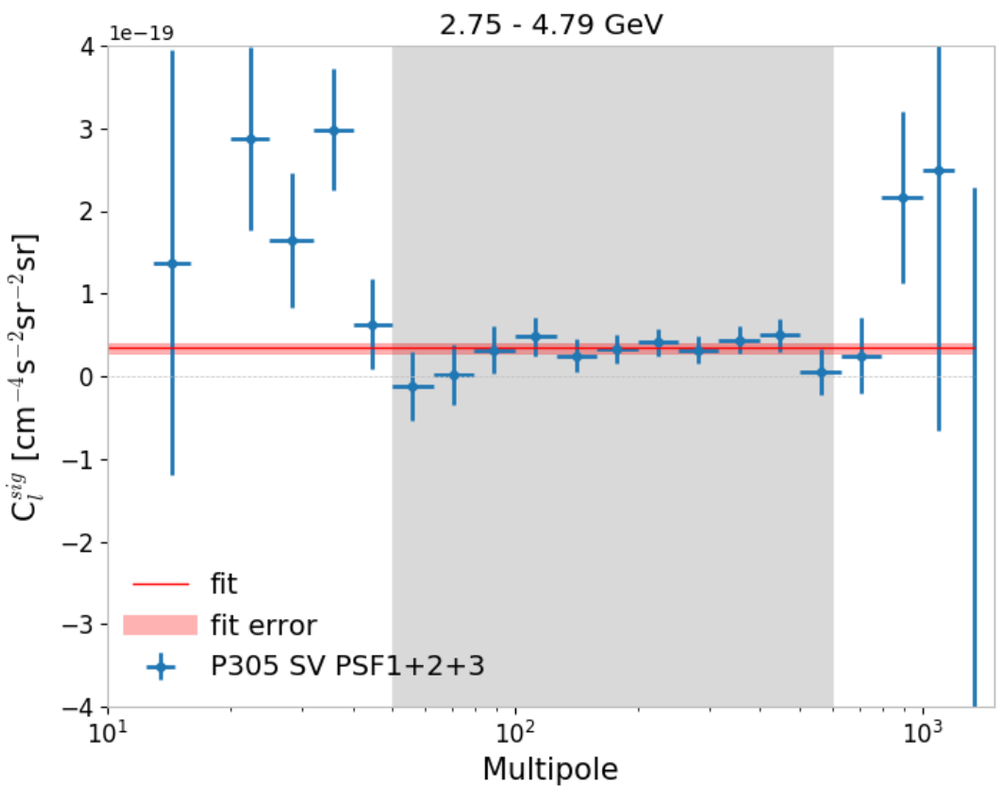

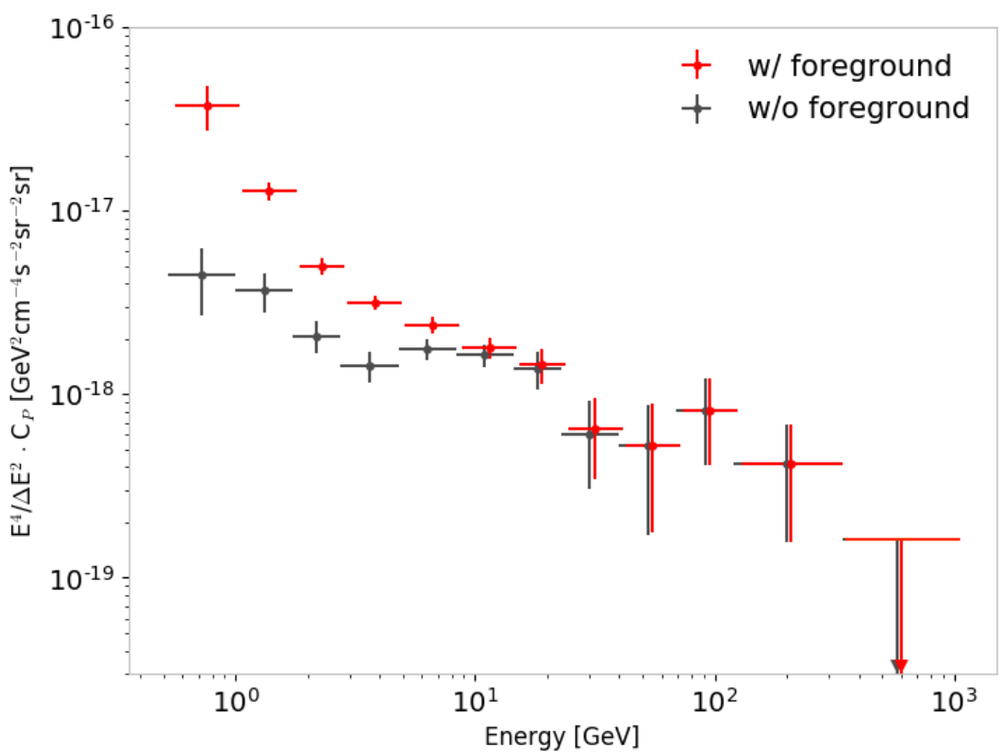

Fermi-LAT, *Phys. Rev. Lett.* **121**, 241101 (2018)

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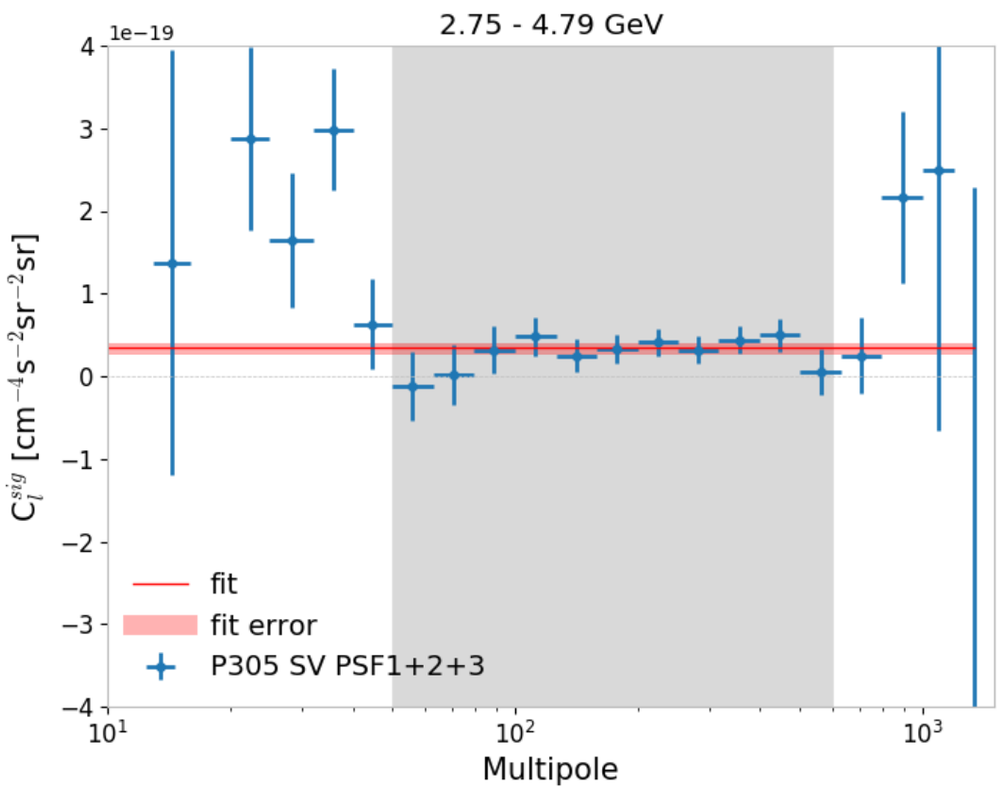

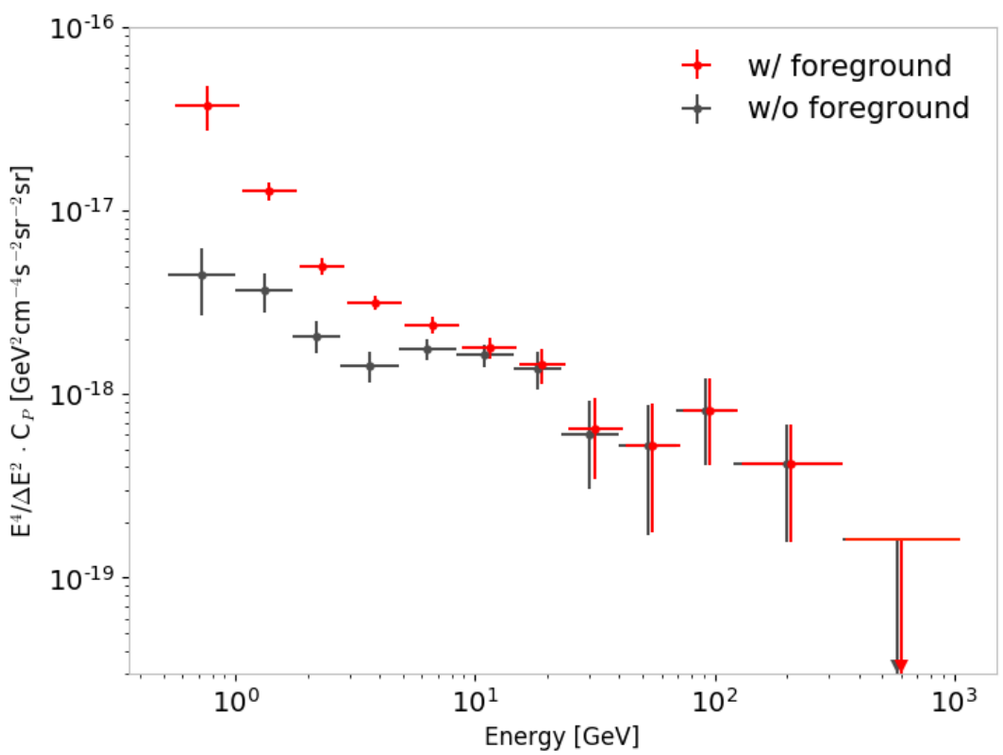

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$$C_\ell^{\rm total} = C_N + C_P + C_\ell^{\rm corr}$$

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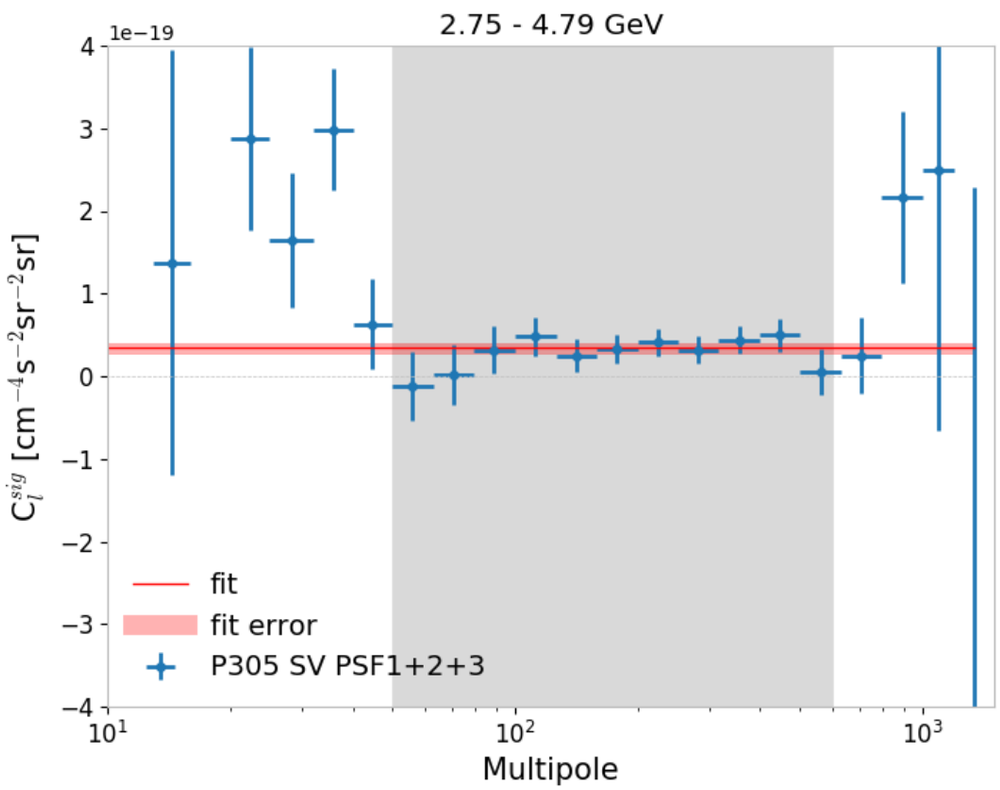

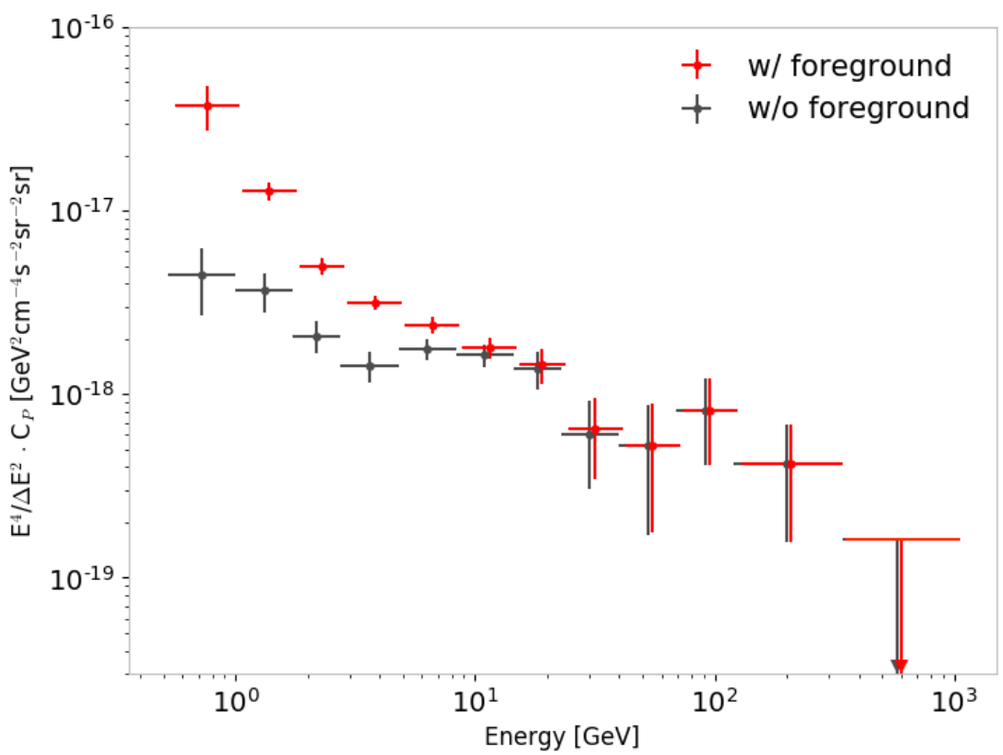

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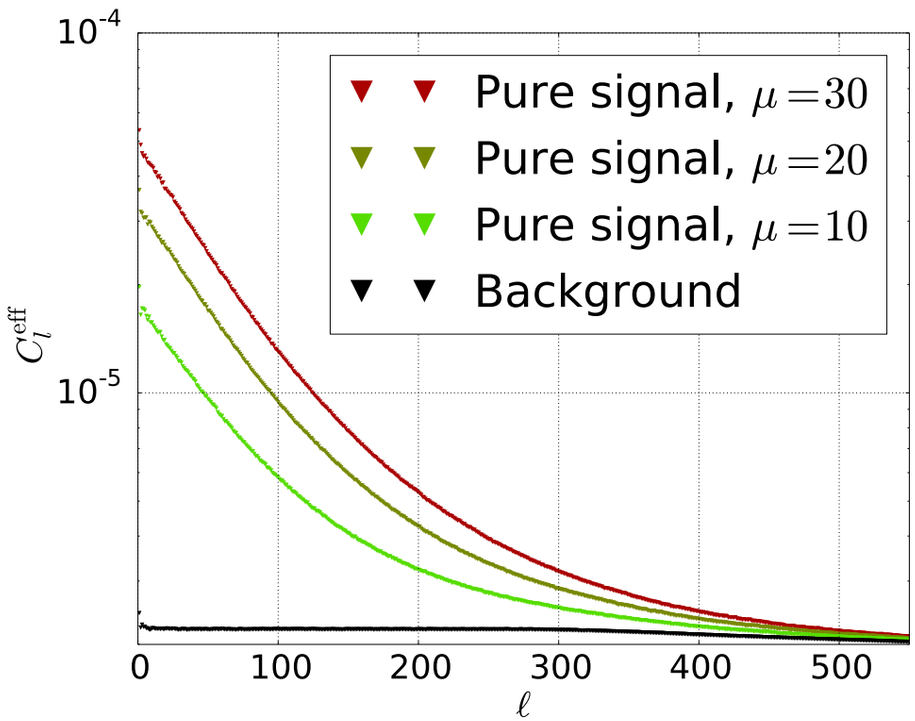
- Data are mostly **consistent with astrophysical expectations** (blazars; Ando et al. 2007)

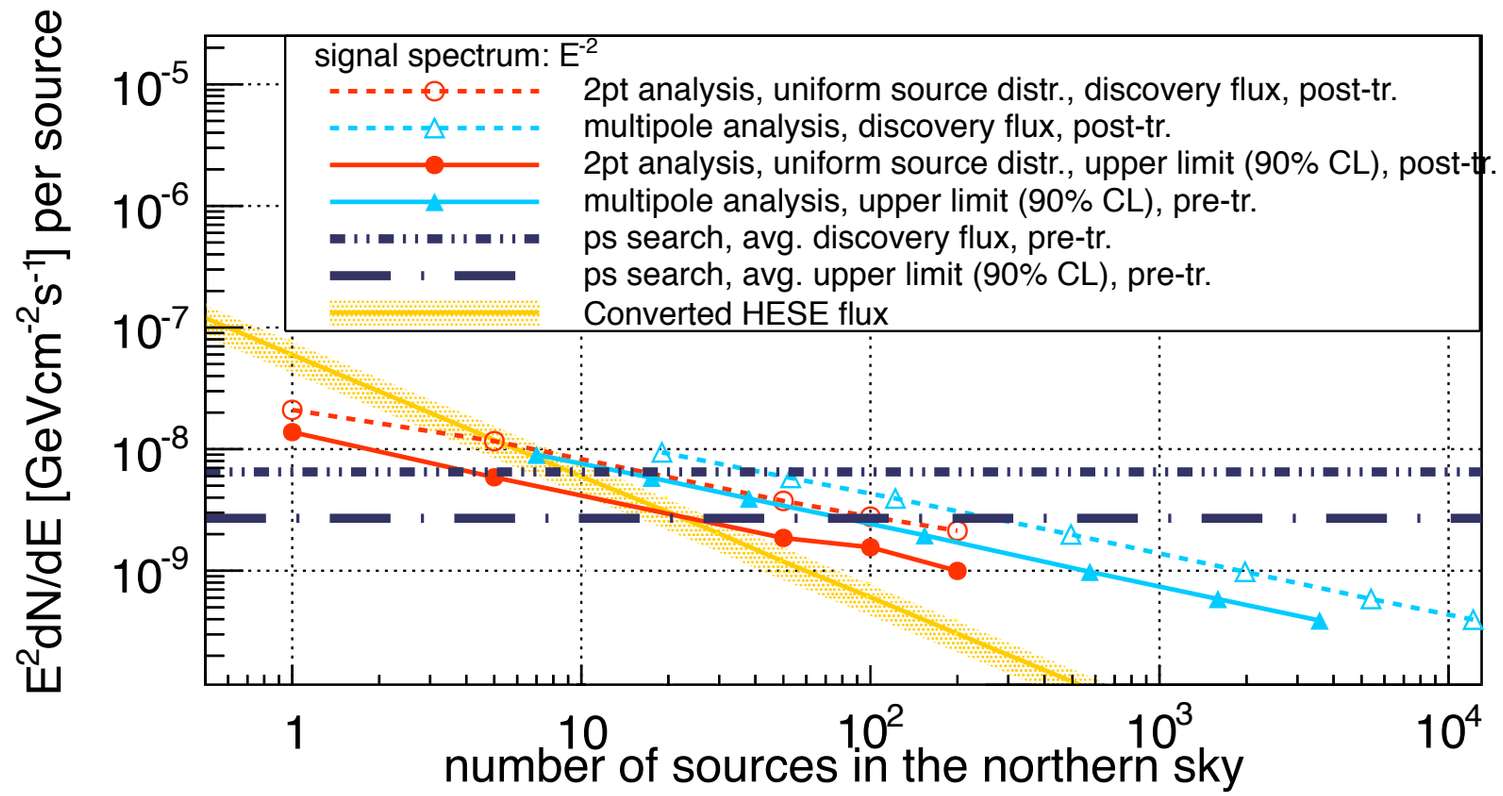
Implications

- 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)

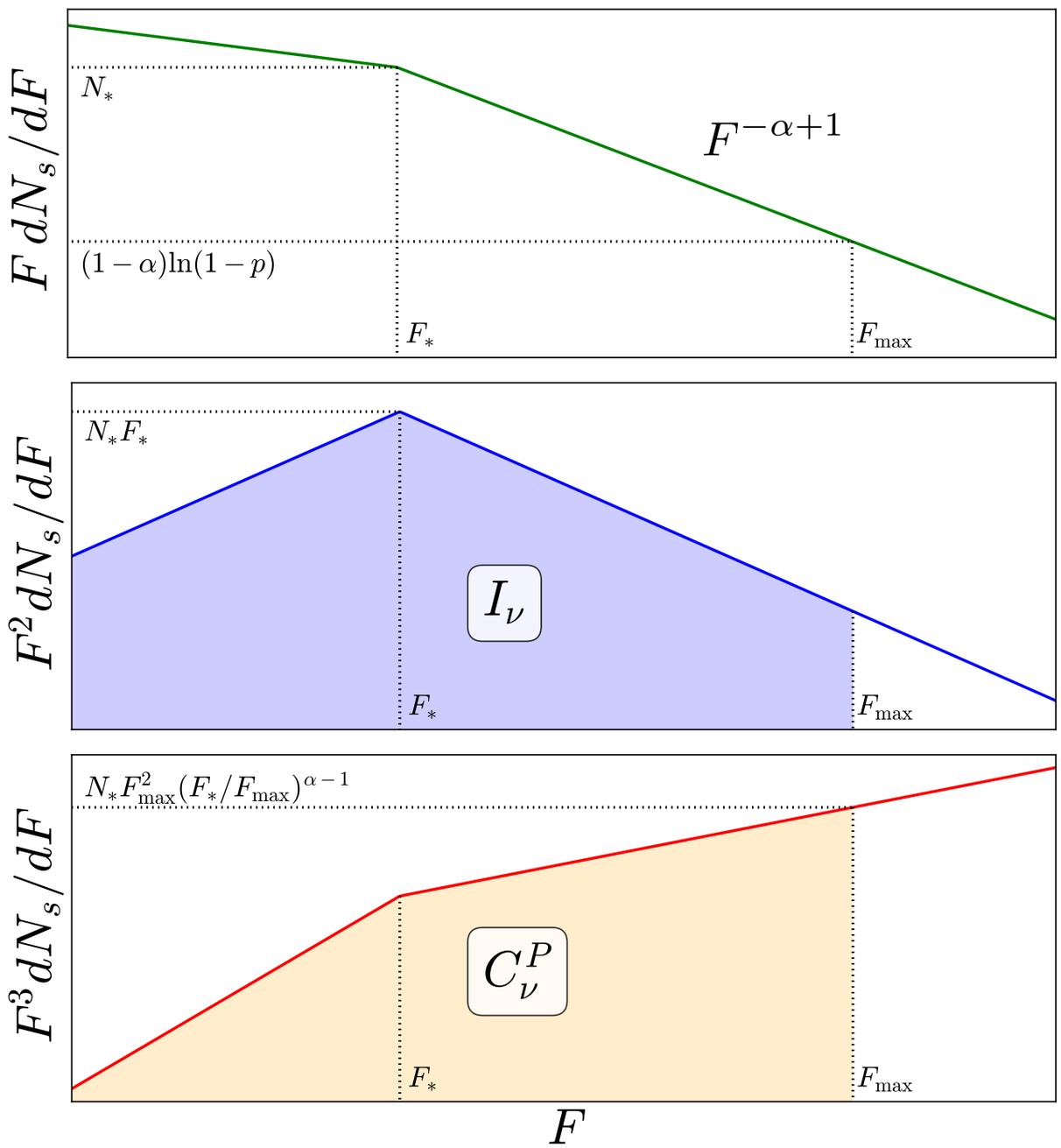




- No angular power was found (everything is consistent with diffuse the background model)
- It can exceed the point-source limit for more than 100 sources
- But it is assumed that all these sources have the **same** flux

Flux distribution and implications

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

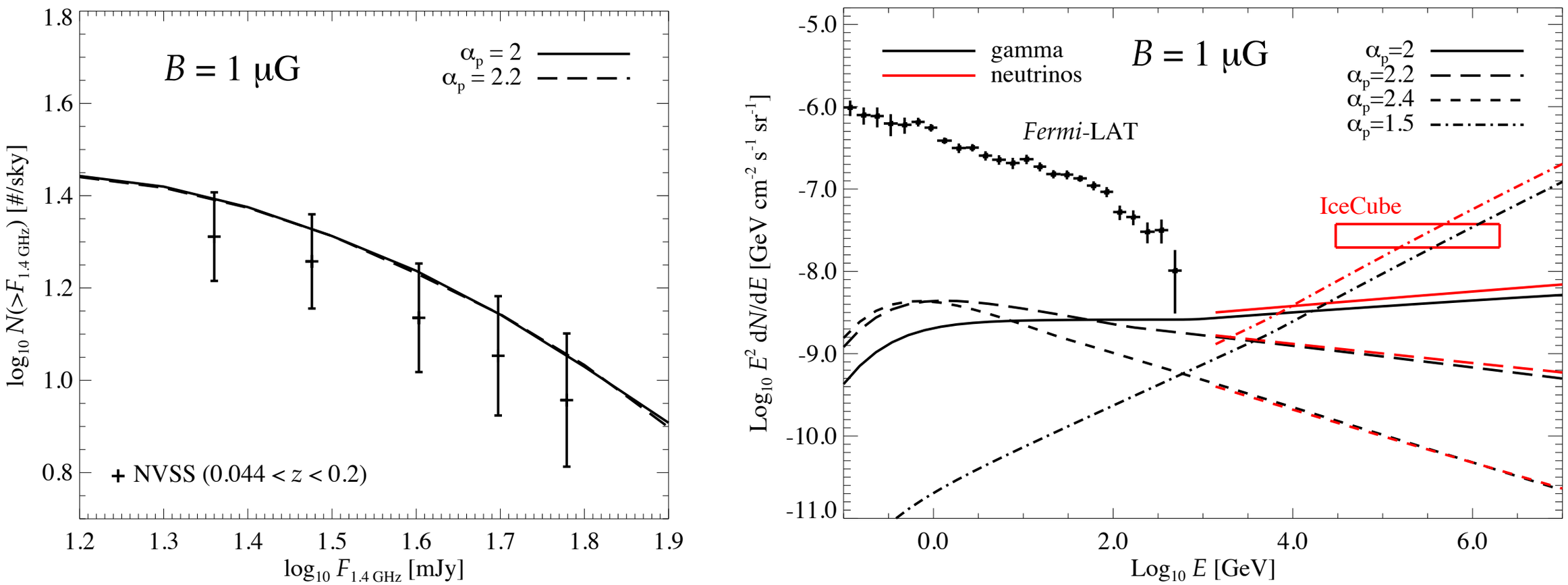


- Flux distribution of **any** astrophysical sources will follow a **power law**
  - Particularly $F^{-2.5}$ for high-flux region

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

Galaxy clusters: Radio constraints

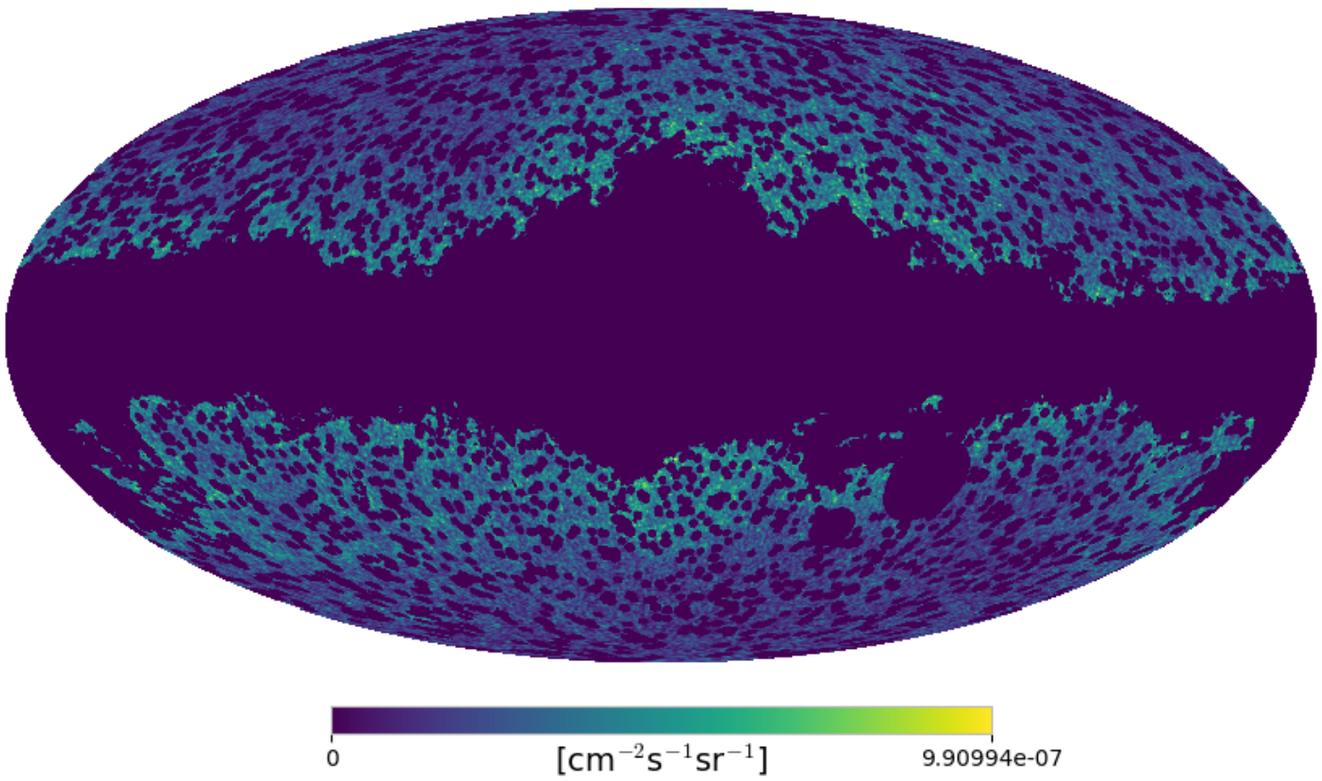


Zandanel, Tamborra, Gabici, Ando, *Astron. Astrophys.* **578**, A32 (2015)

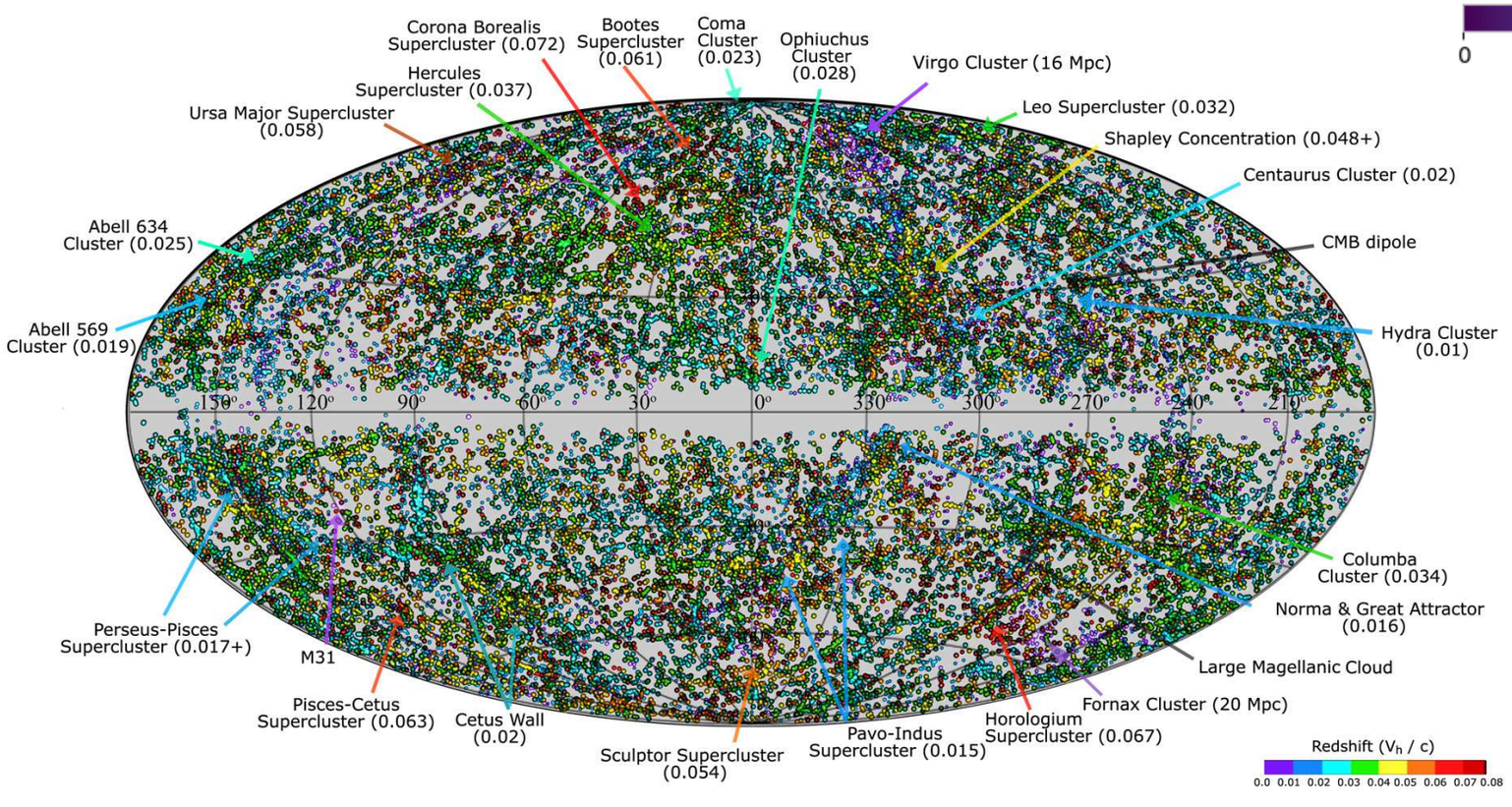
- pp interaction will produce electrons/positrons that will make clusters bright in radio in the cluster magnetic fields (~1 μG)
- Radio constraints are very tight, and clusters **cannot** contribute to γ & ν backgrounds strongly

Constraints with two-point statistics

Cross correlation with galaxy distribution



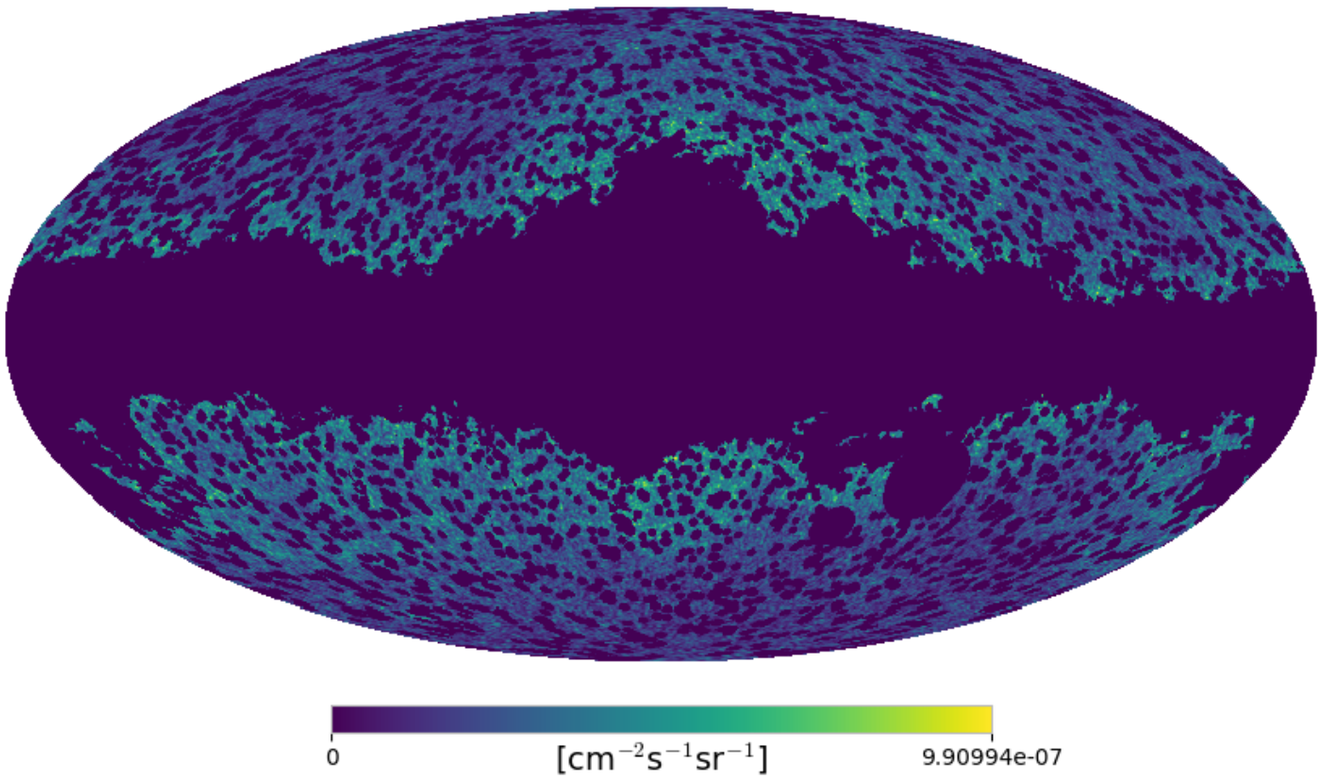
Fermi-LAT, *Phys. Rev. Lett.* **121**, 241101 (2018)



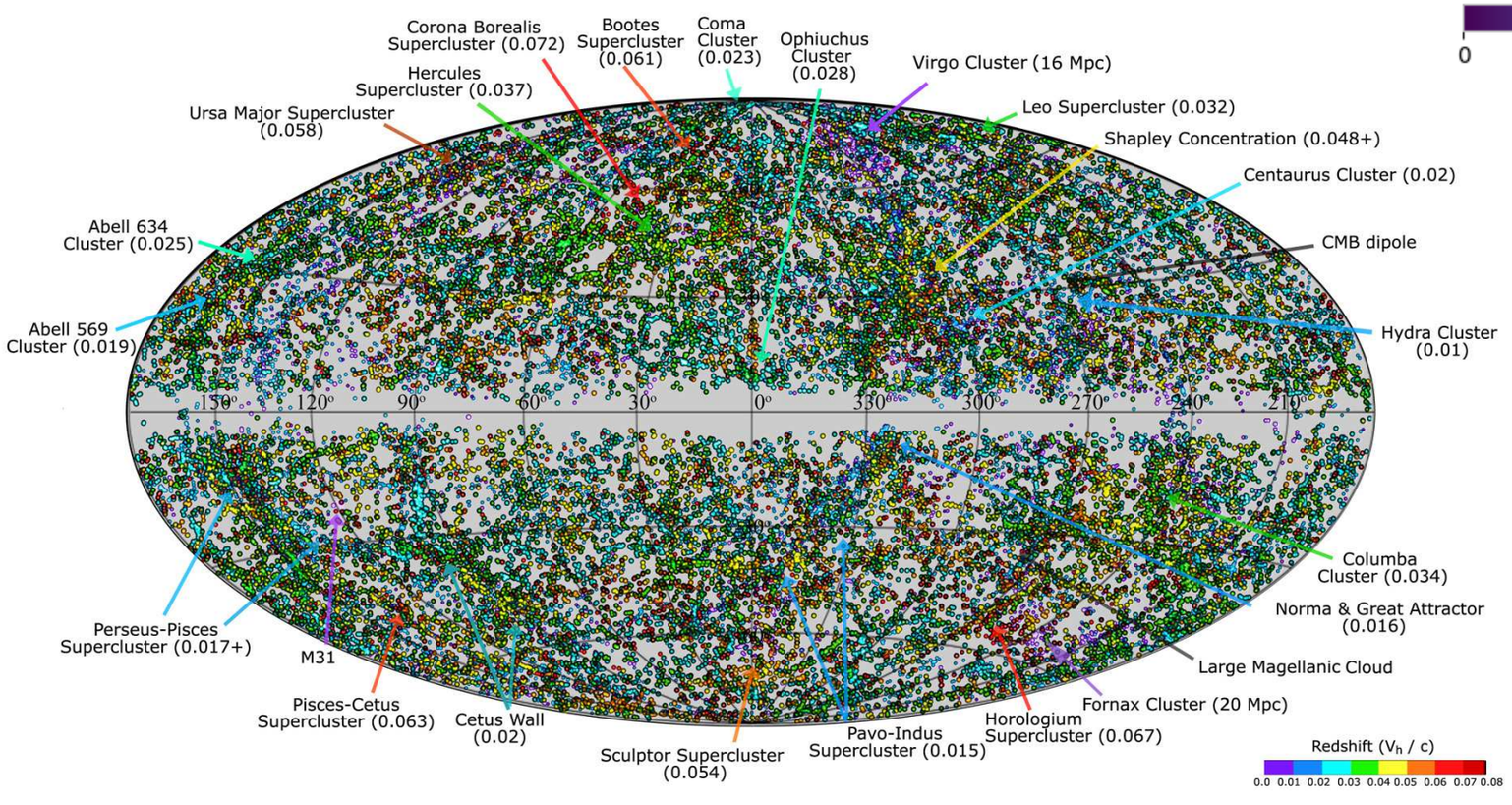
Huchra et al., *Astrophys. J. Suppl. Ser.* **199**, 26 (2011)

Cross correlation with galaxy distribution

Are these two maps similar to each other?



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



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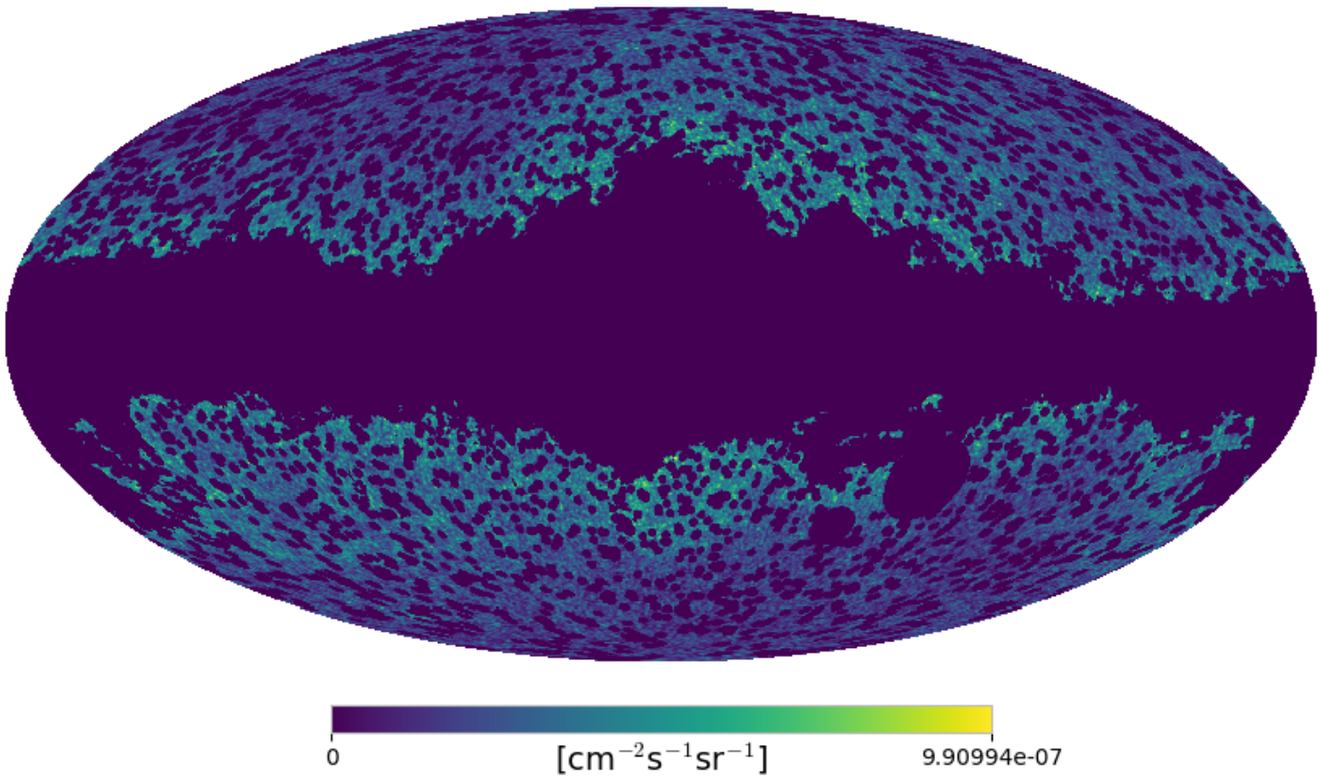

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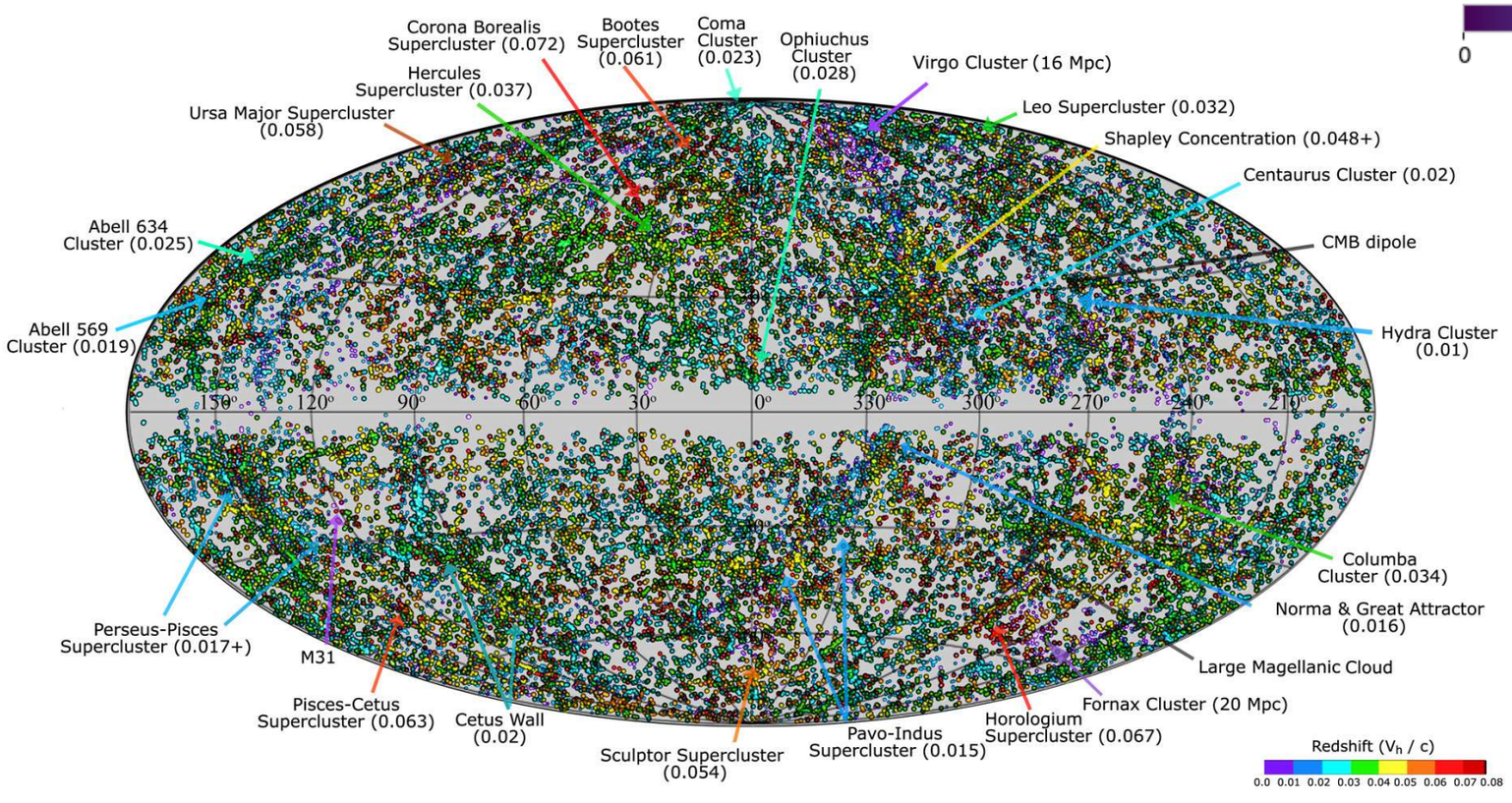
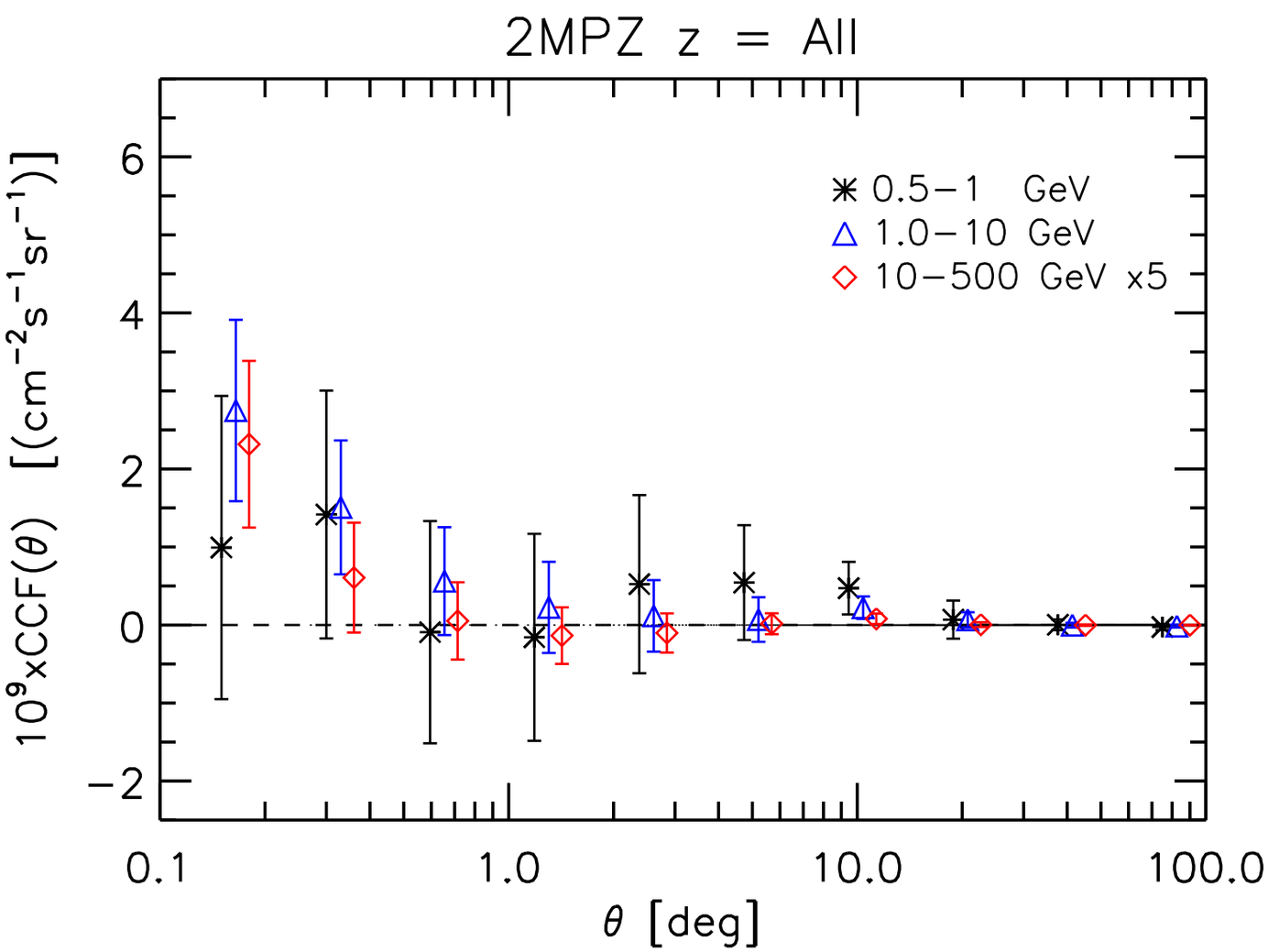


Huchra et al., *Astrophys. J. Suppl. Ser.* **199**, 26 (2011)

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

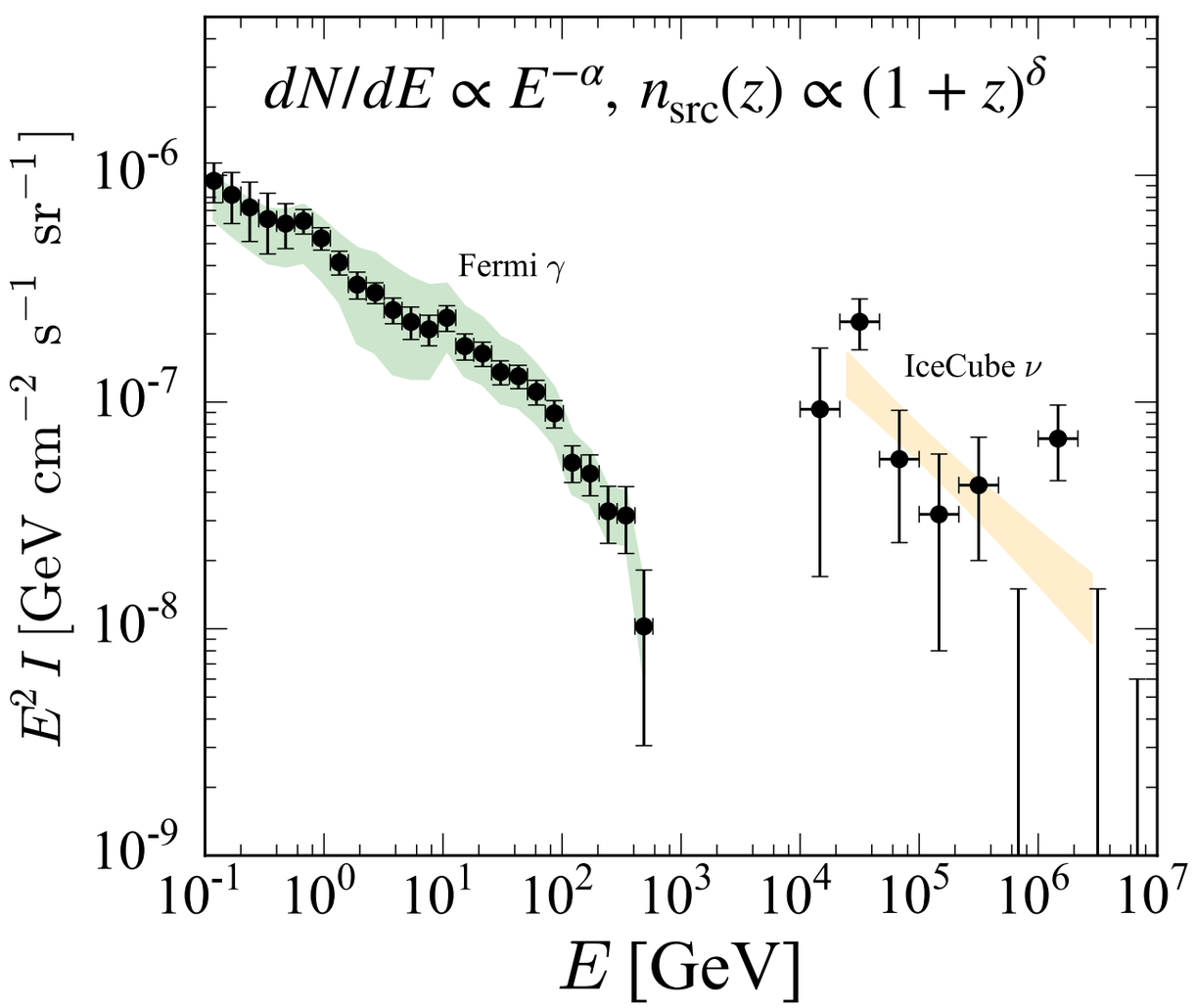
Cross correlation between IGRB and galaxies

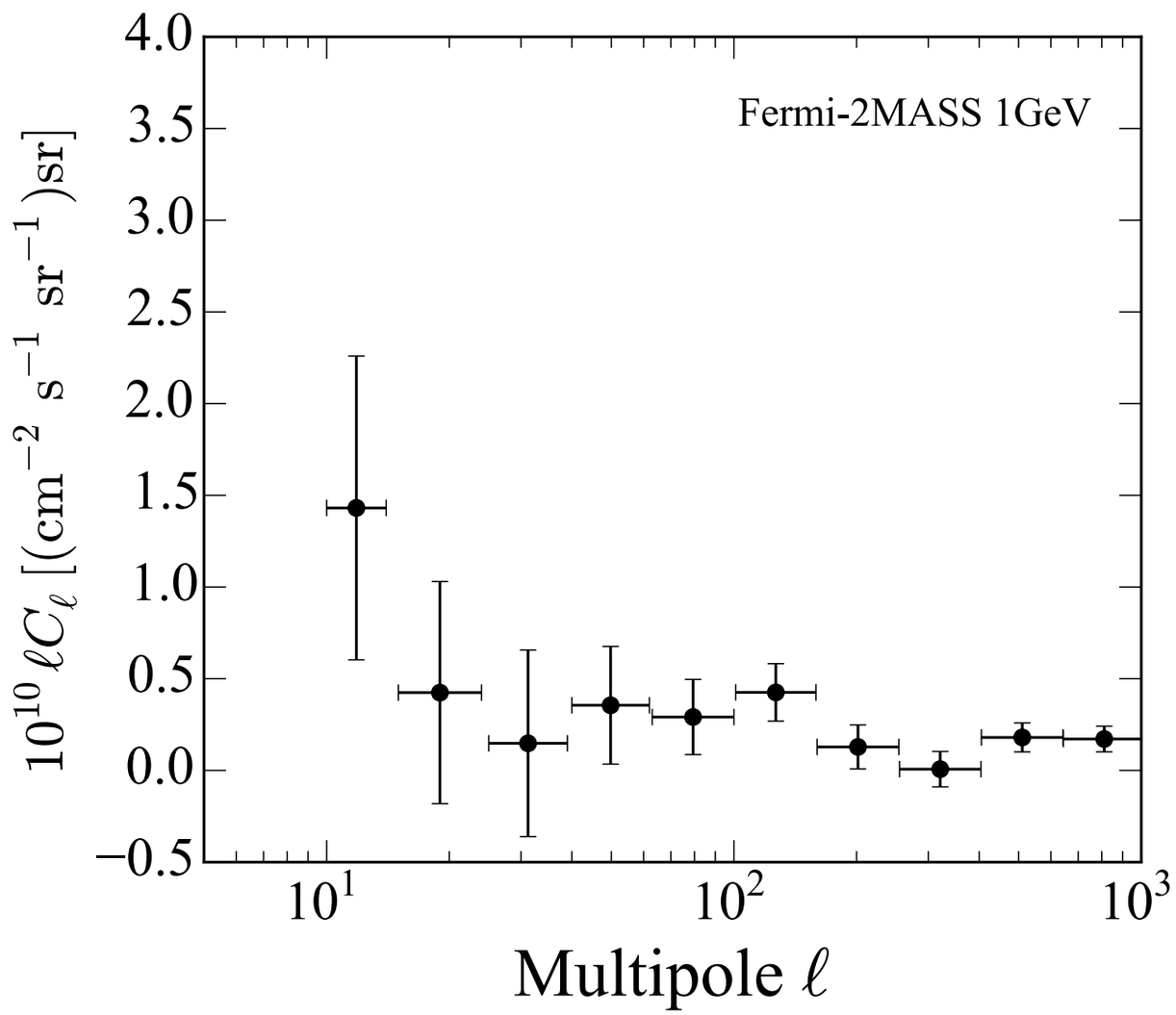


Cuoco et al., *Astrophys. J. Suppl. Ser.* **232**, 10 (2017)

- 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

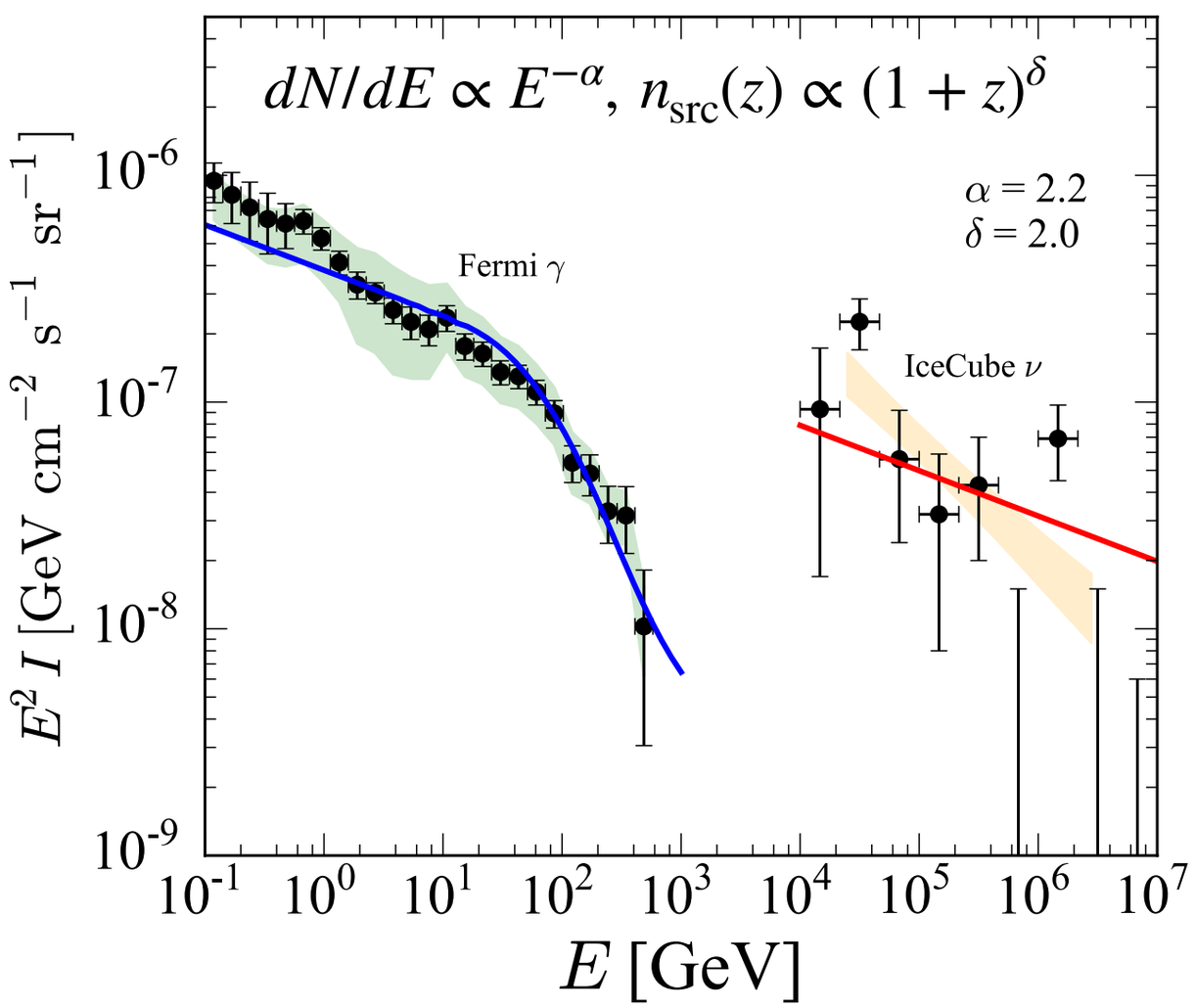
Spectral constraints

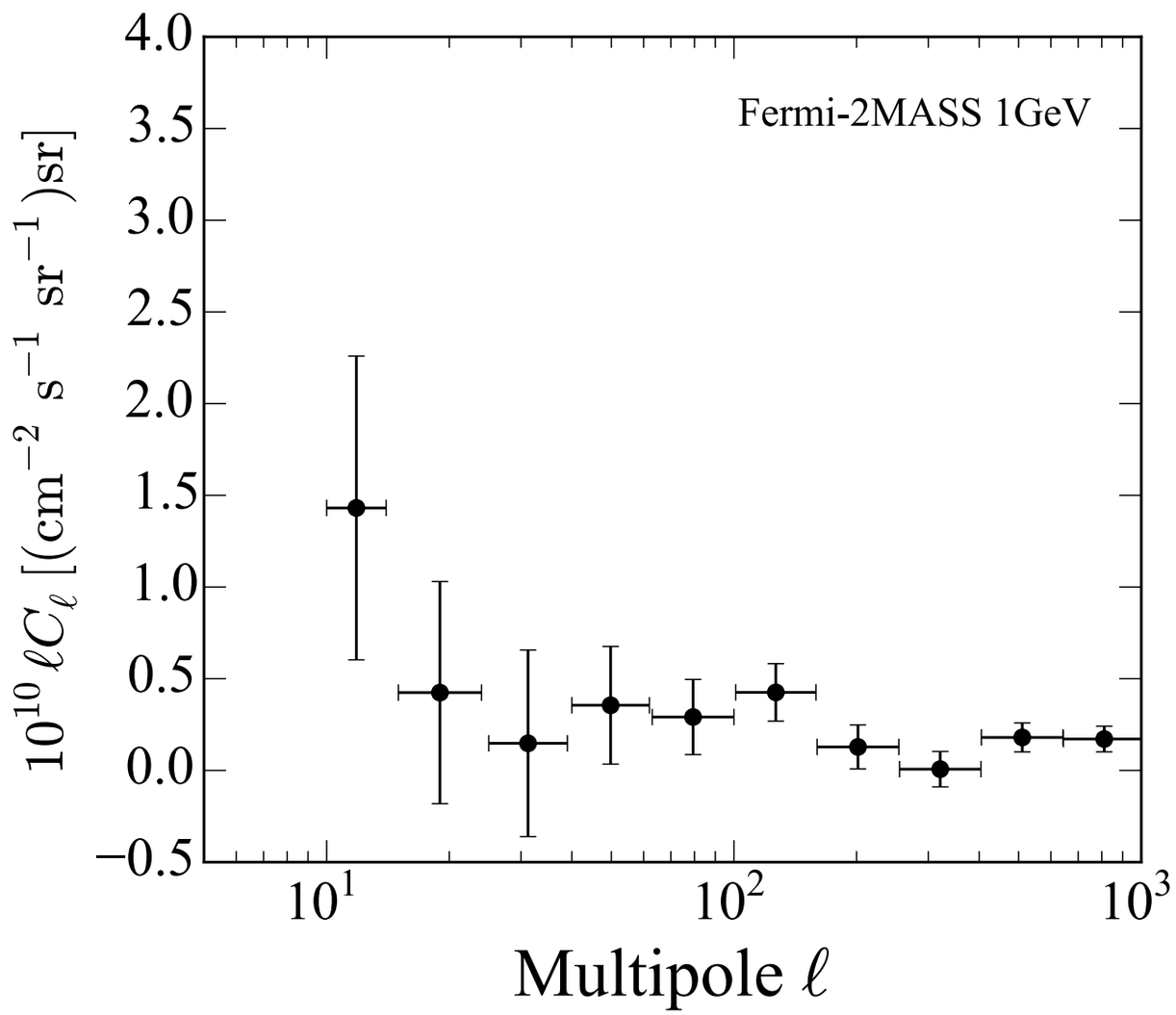




Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

Spectral constraints





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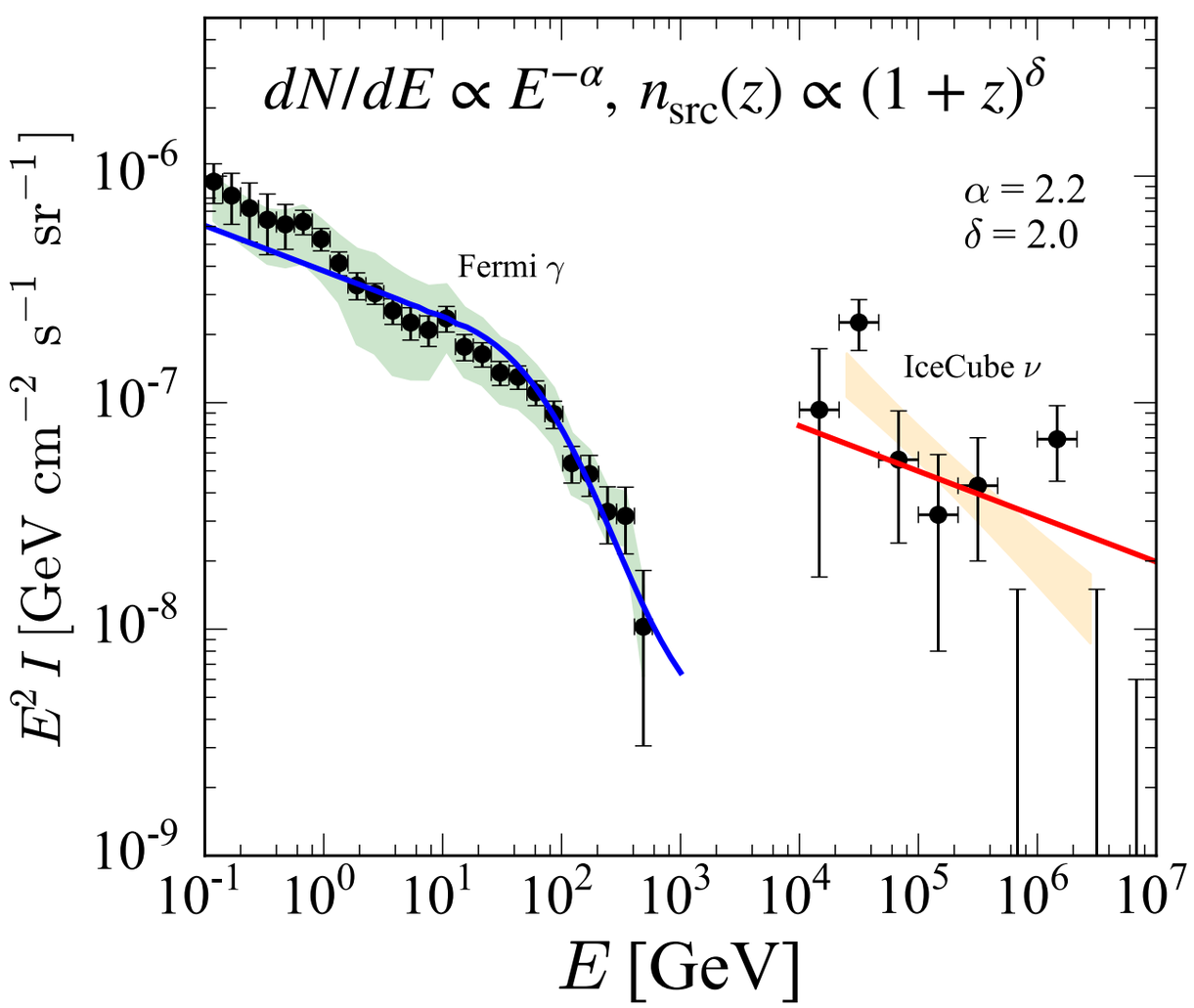

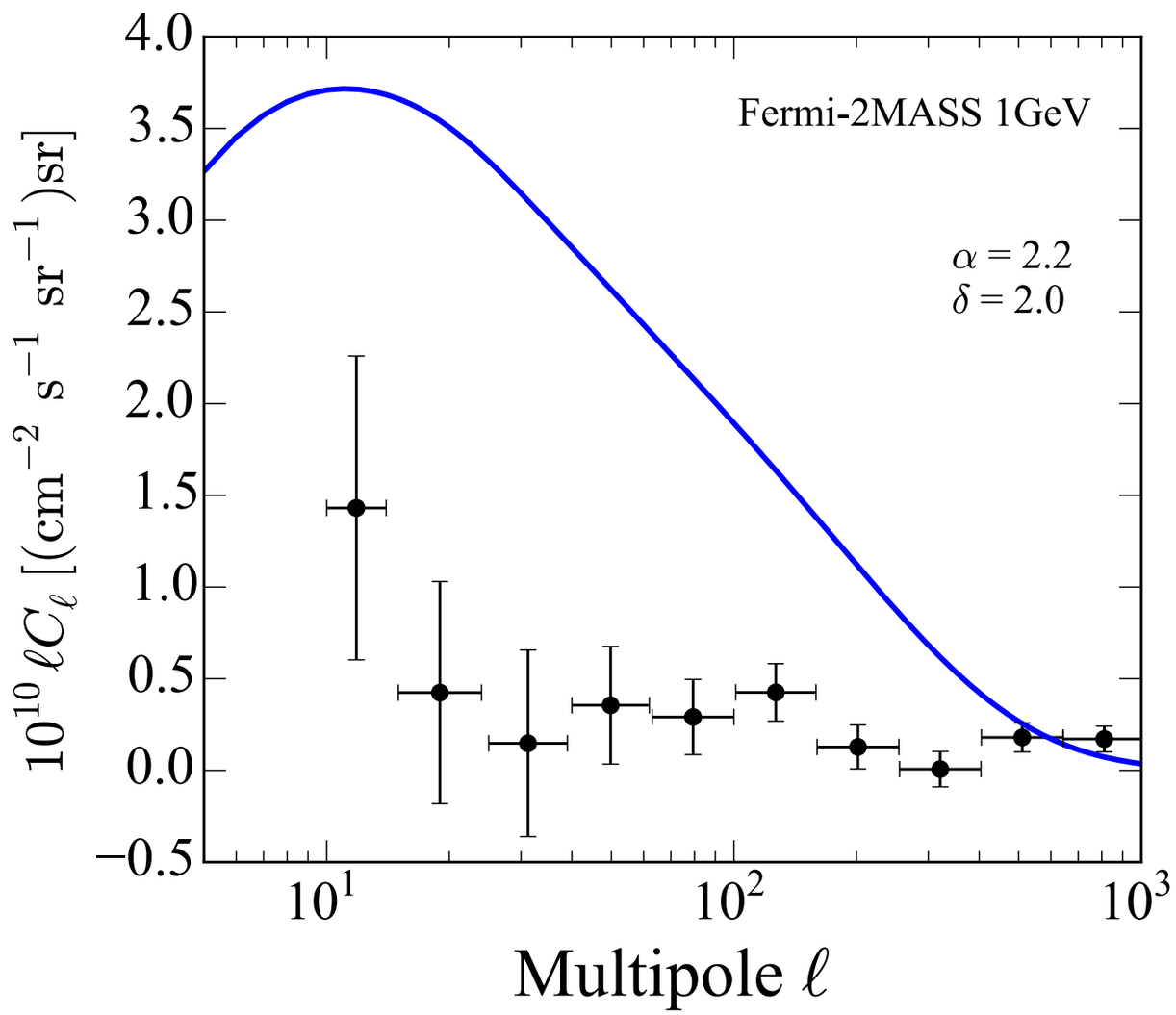

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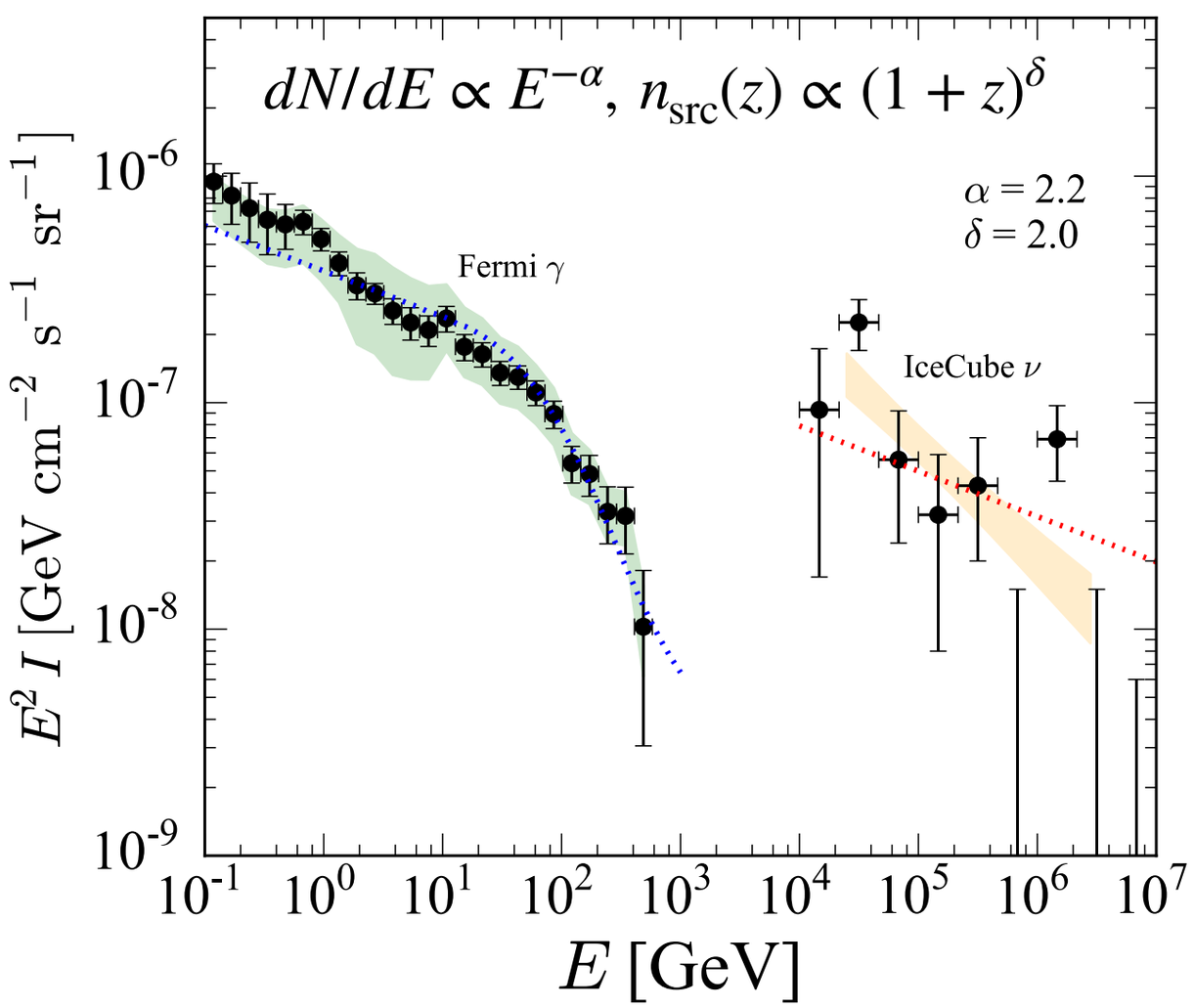
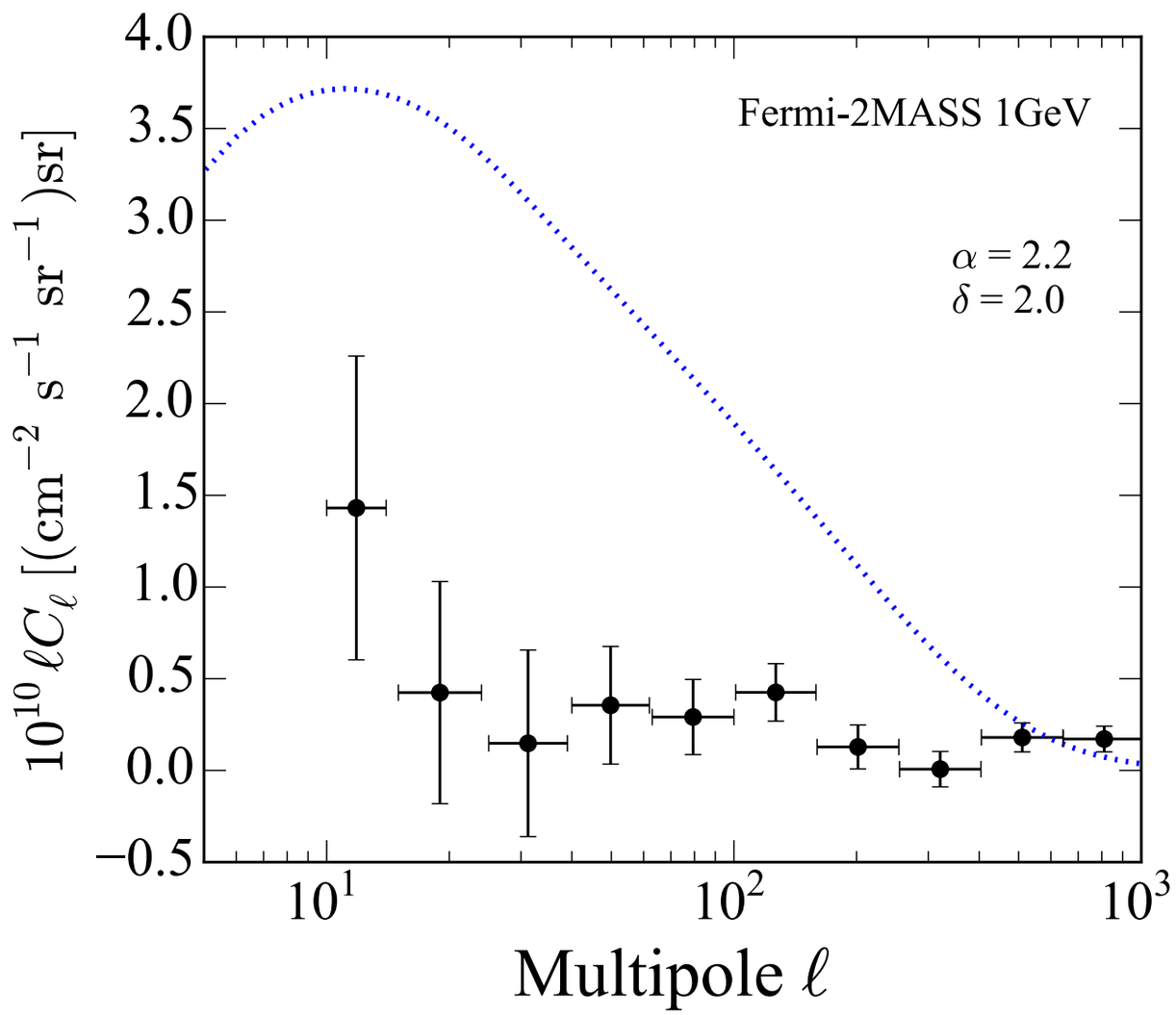
Tomographic constraints





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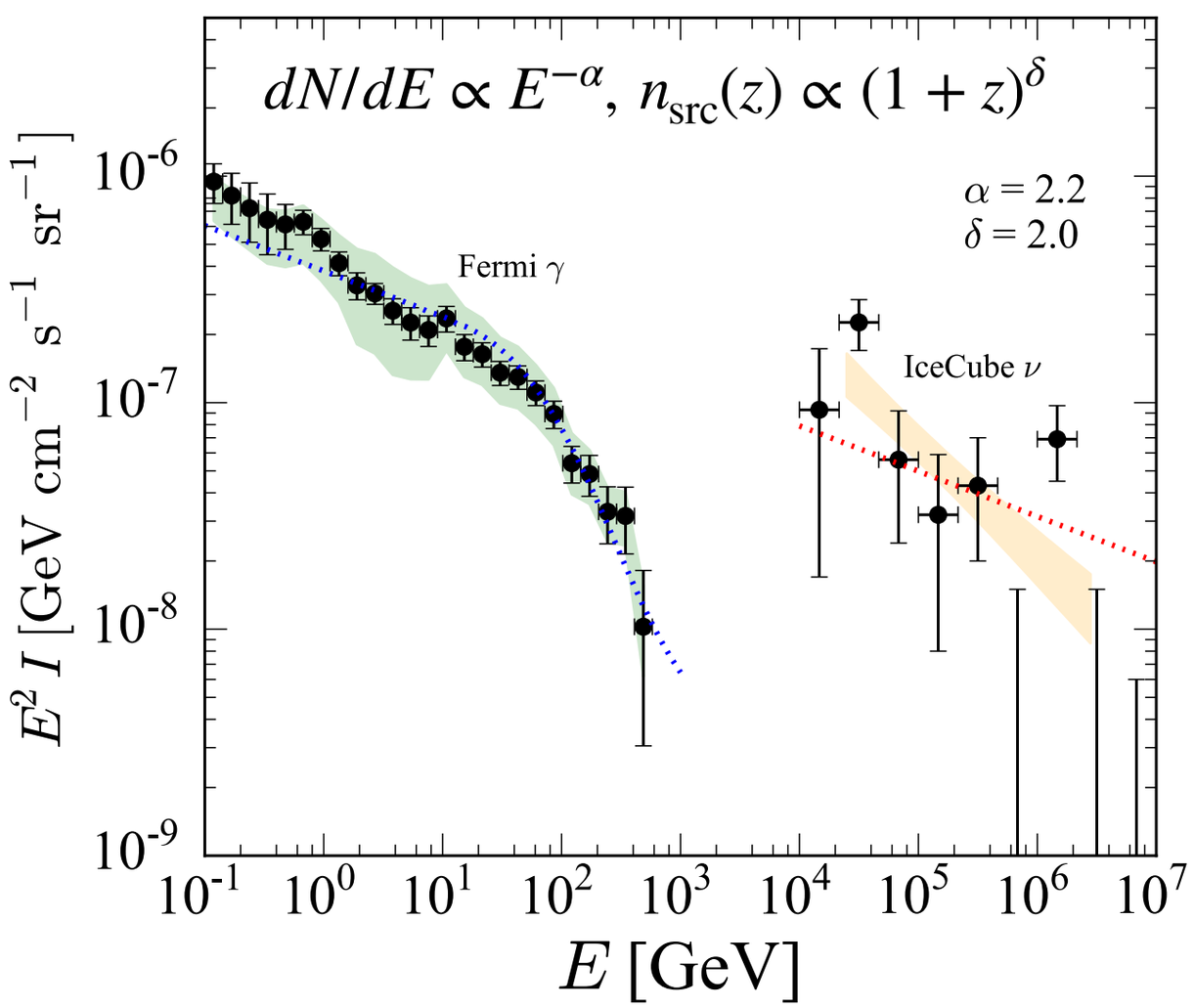
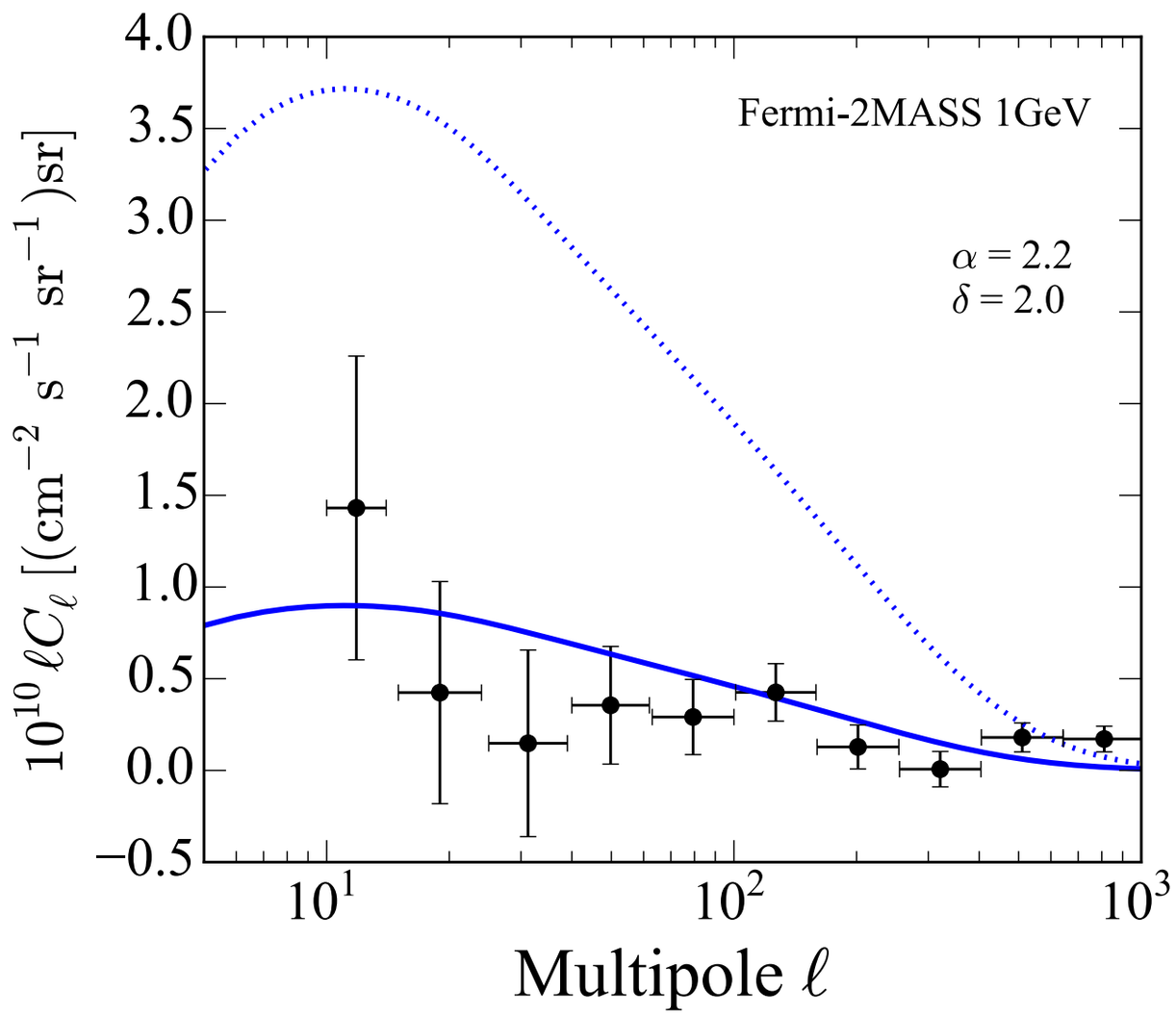
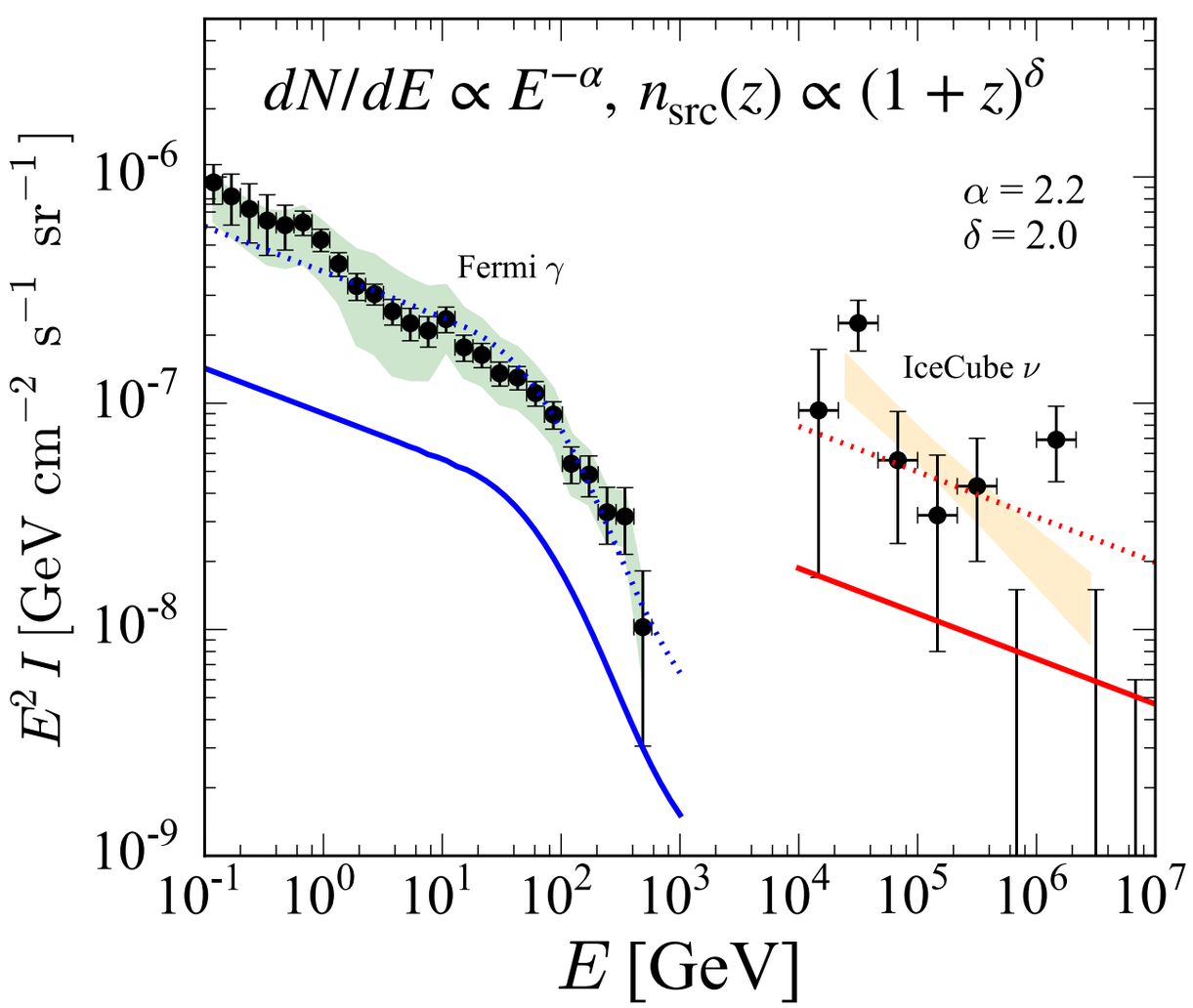
Tomographic constraints

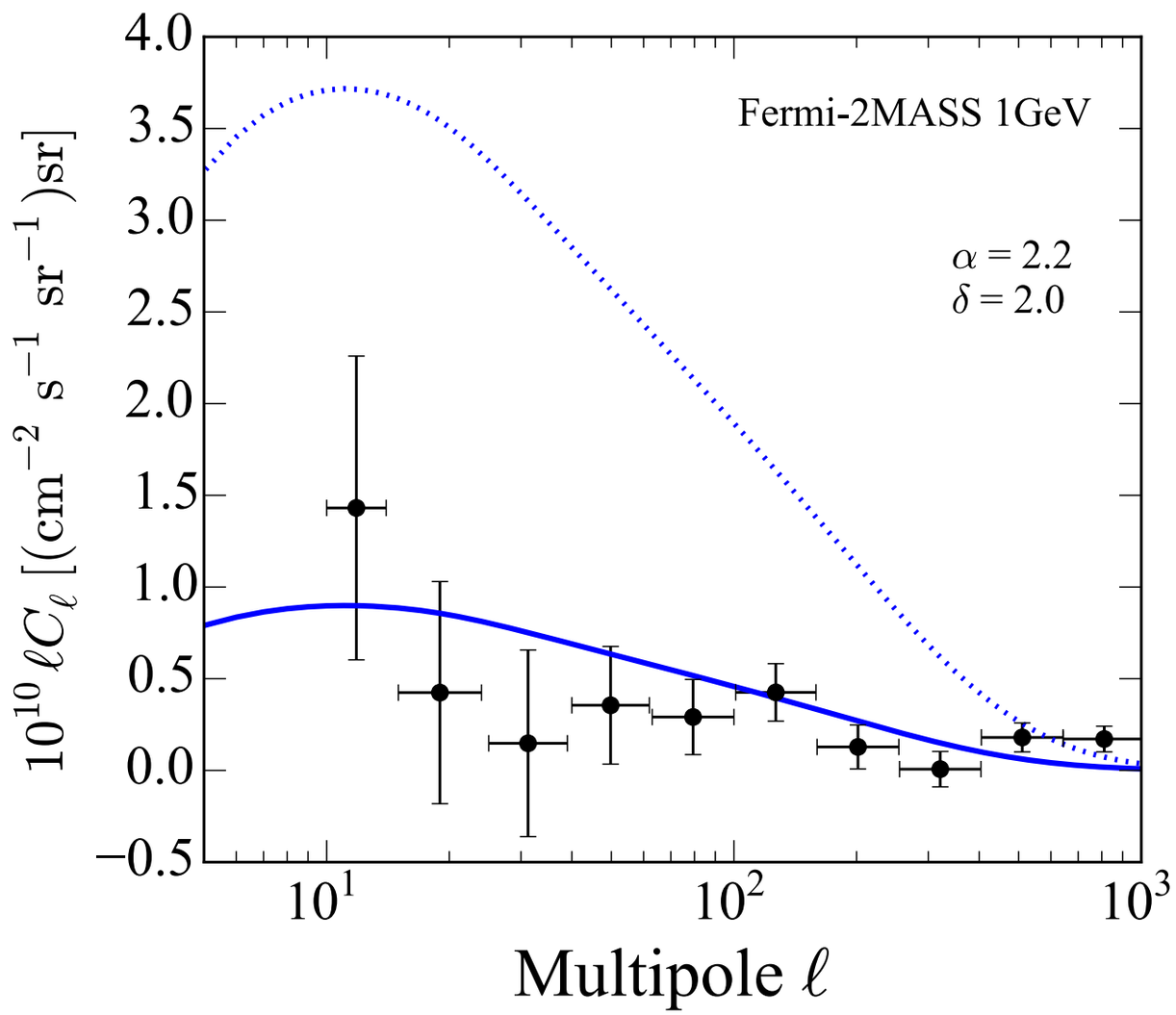




Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

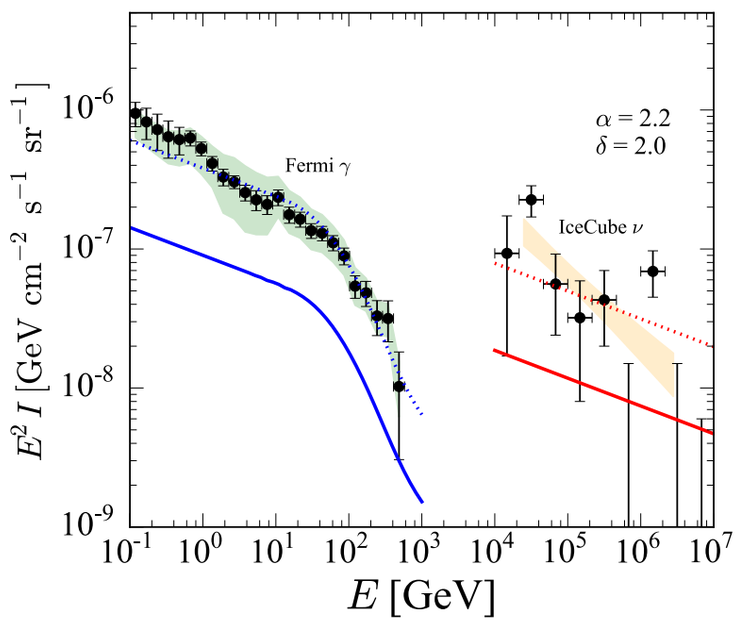
Tomographic constraints

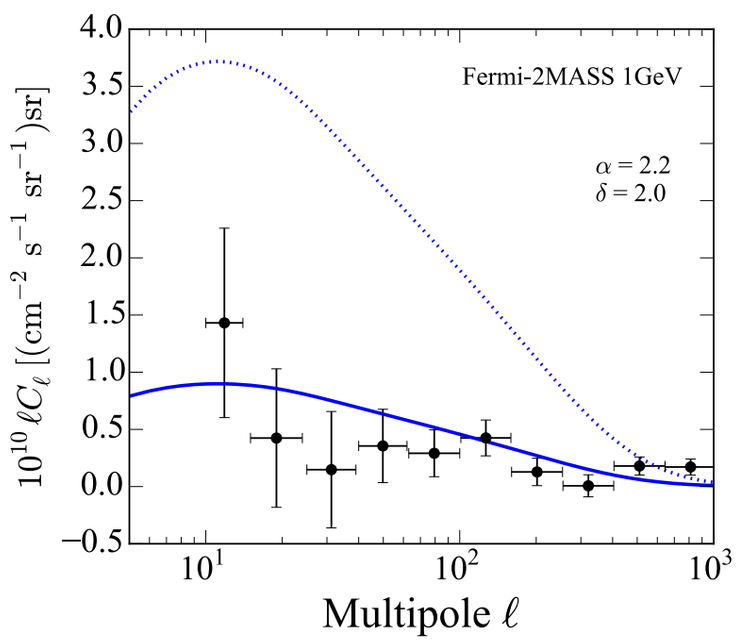




Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

Dependence on α and δ

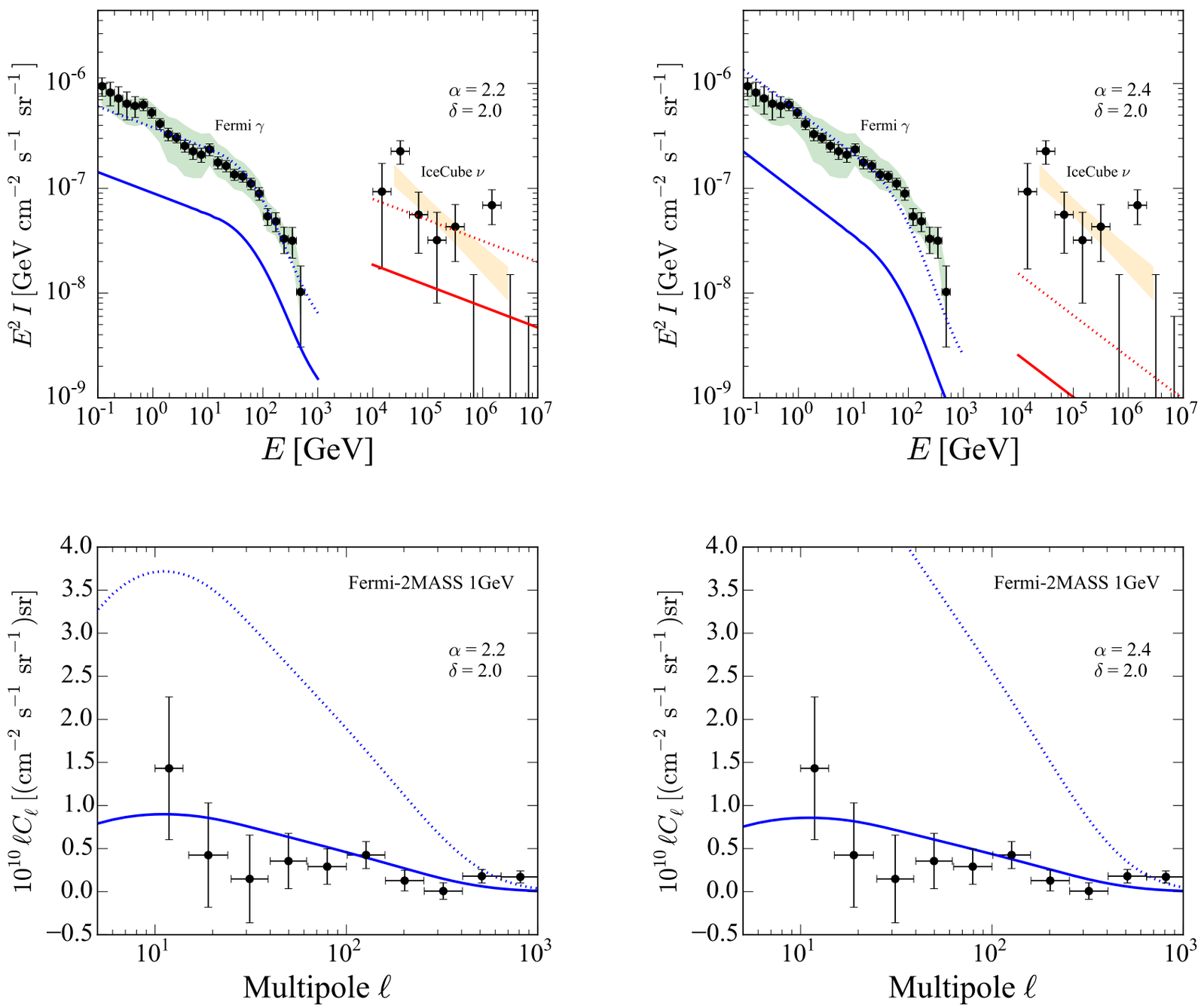




Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

Dependence on α and δ

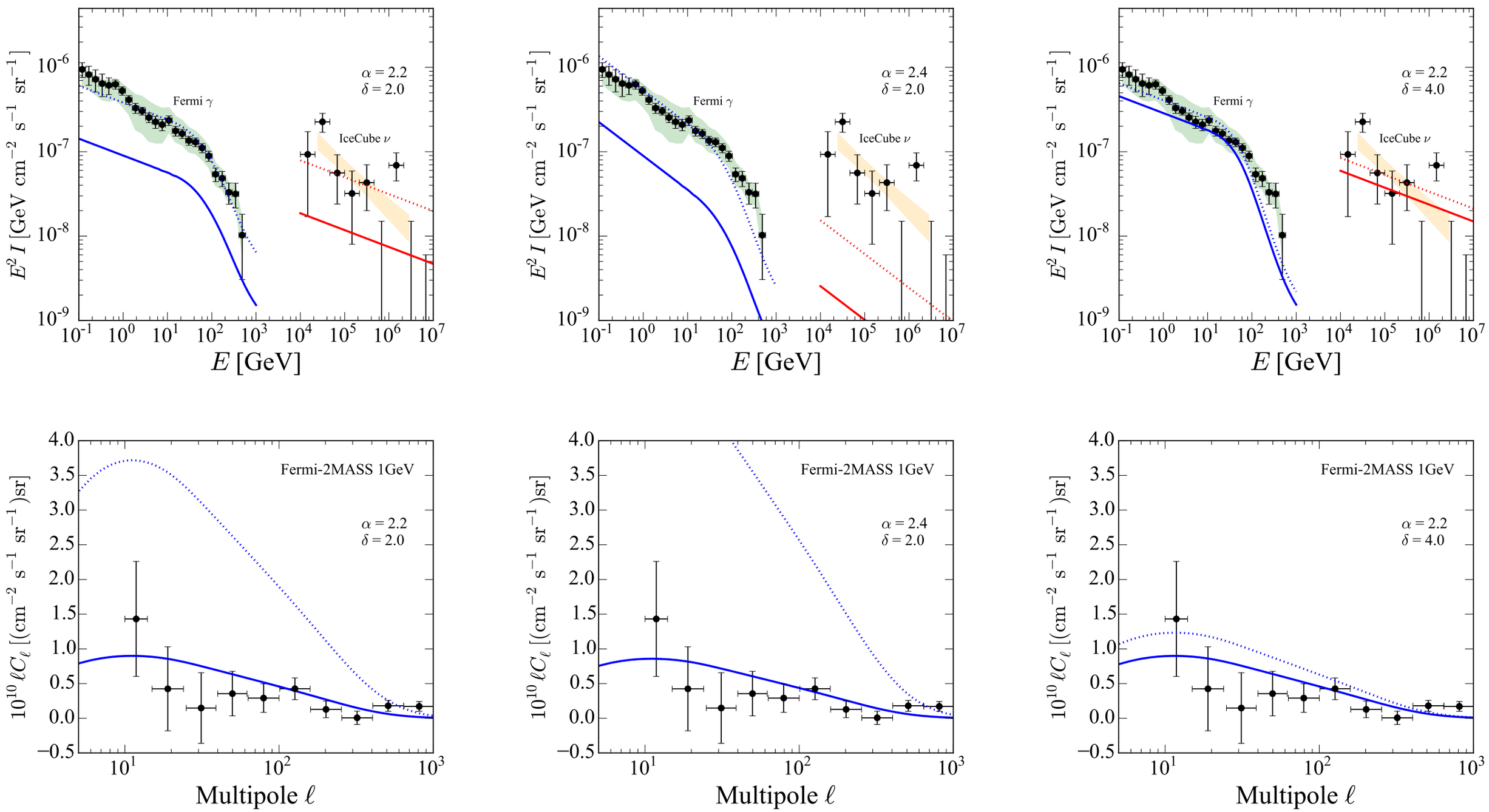
Soft spectrum



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

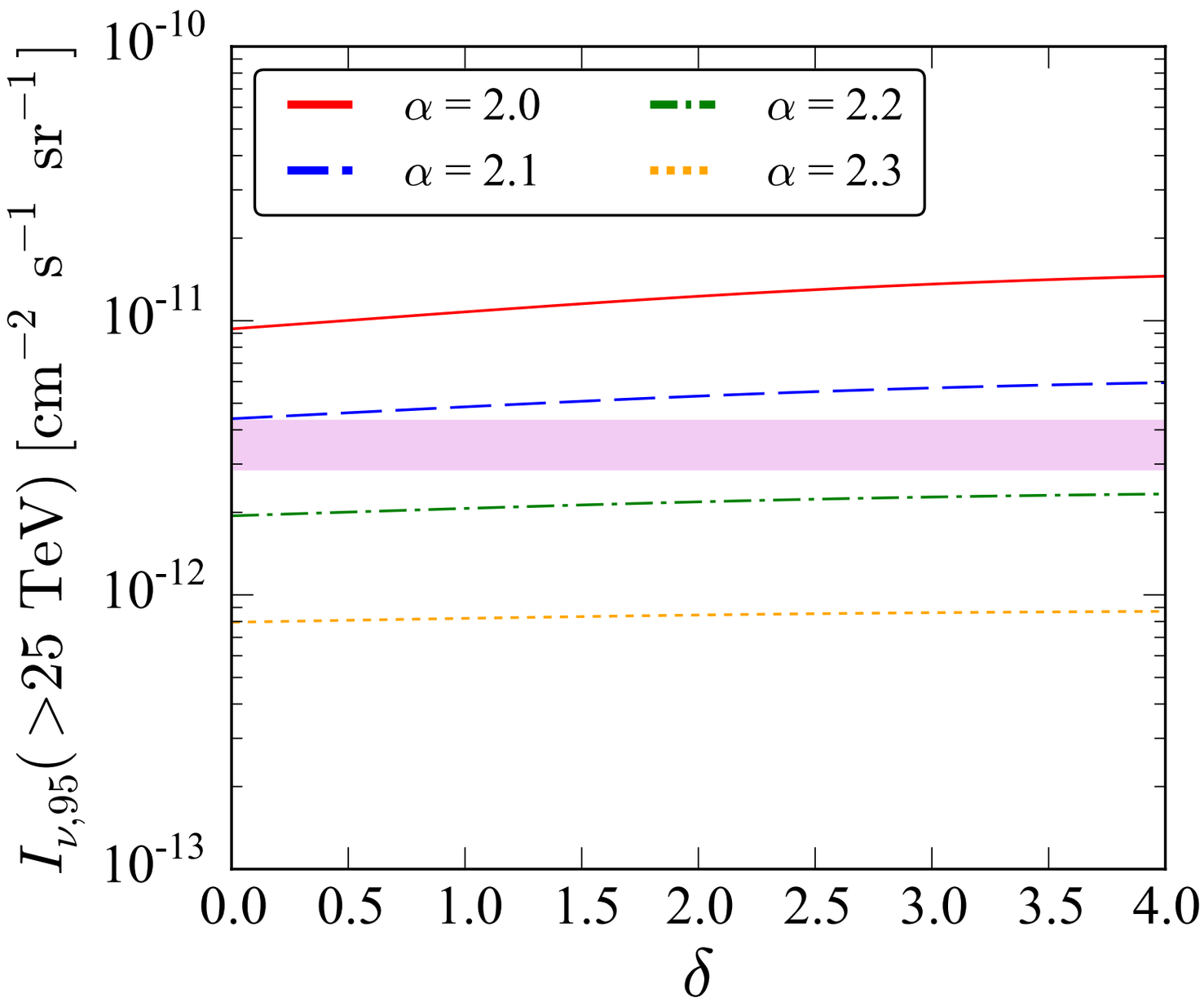
Dependence on α and δ

Soft spectrum ***Fast evolution***



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

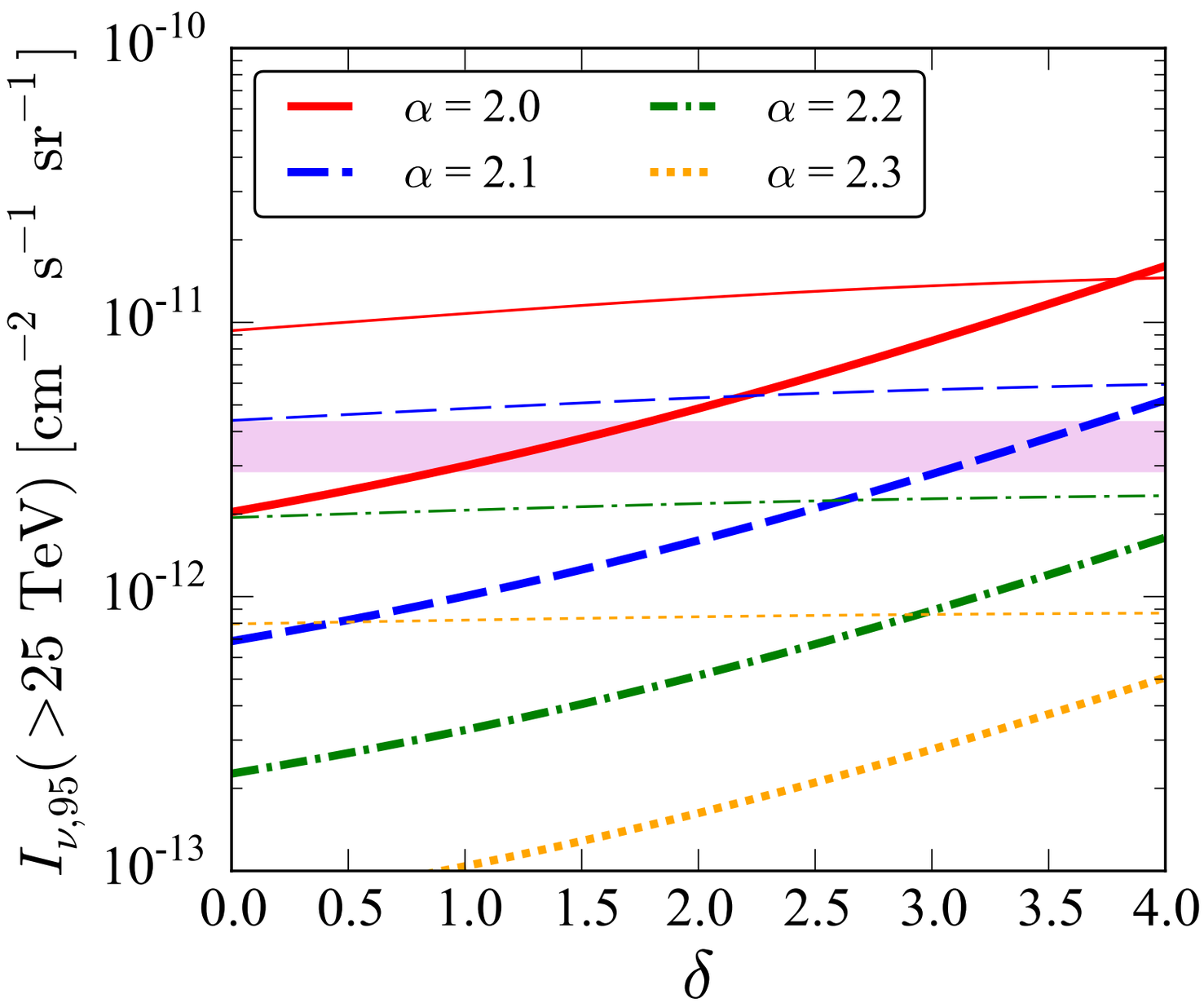
Constraints on high-energy neutrinos



- 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



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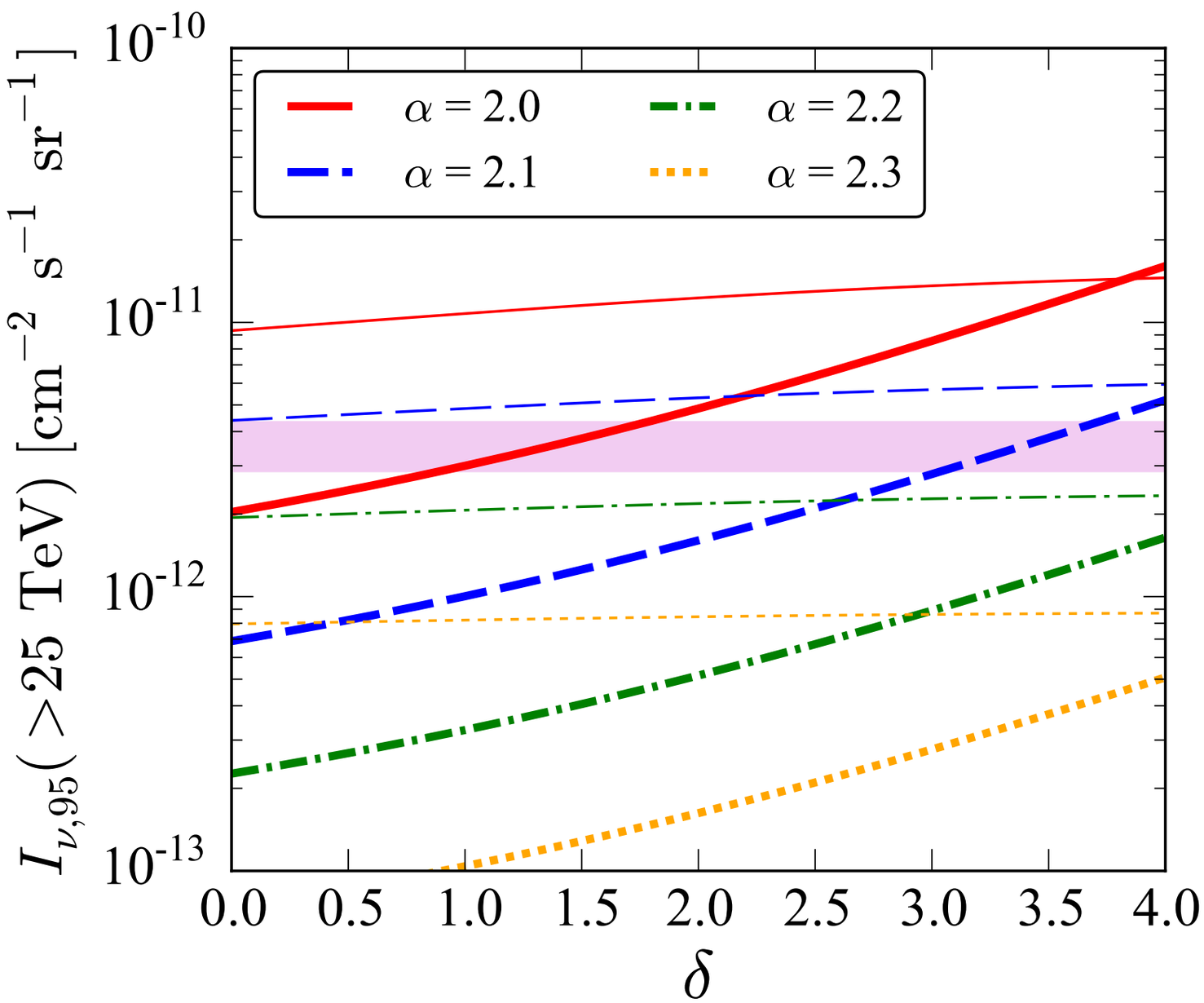
- Tomographic constraints:

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

Constraints on high-energy neutrinos



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- Tomographic constraints:
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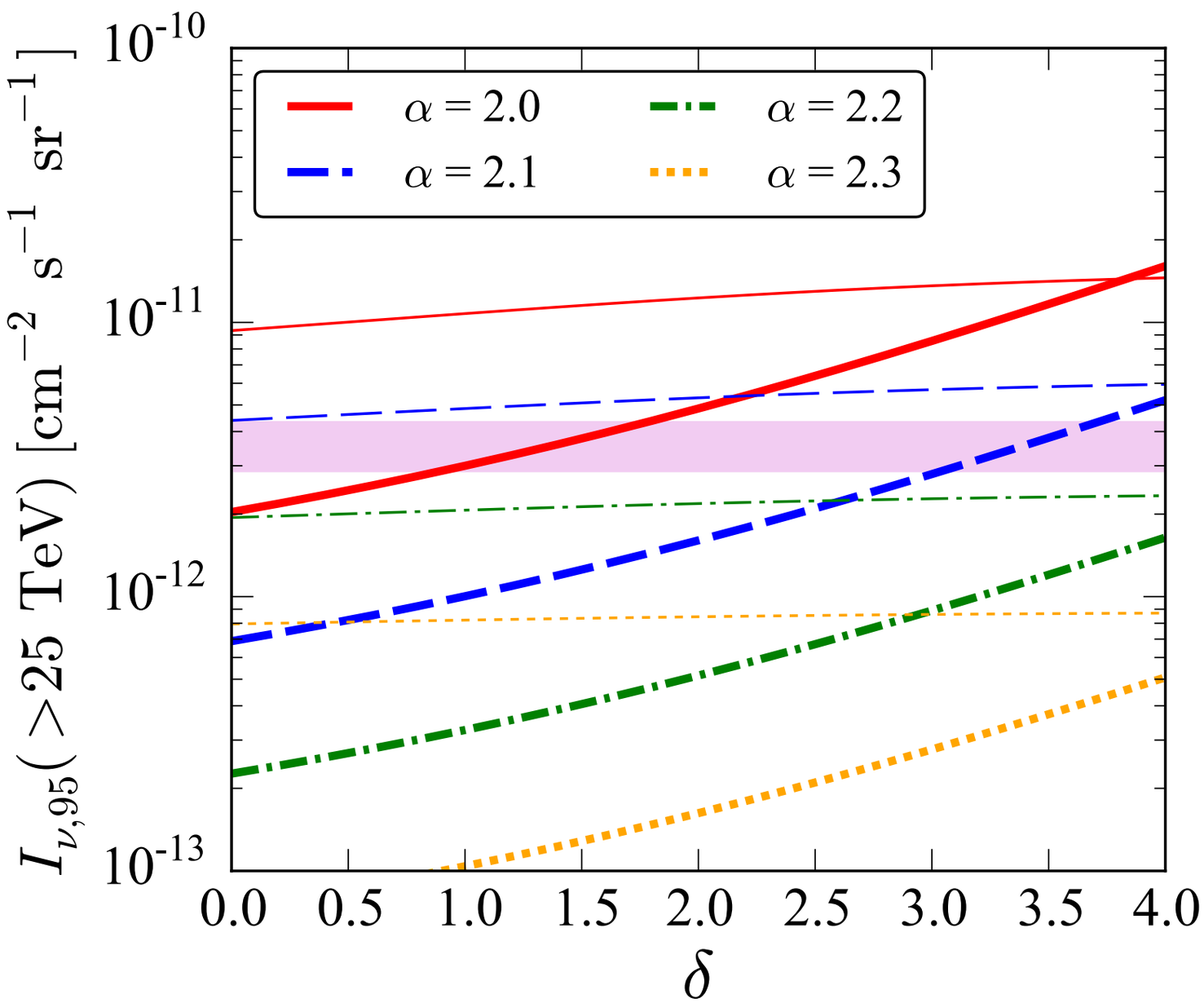
Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

Constraints on high-energy neutrinos

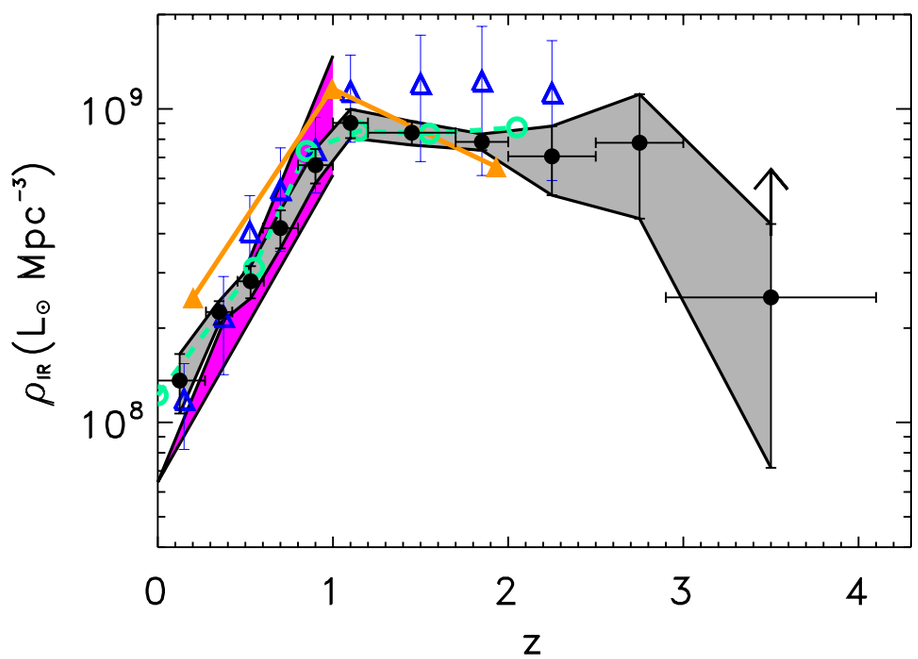


- Spectral constraints: α has to be smaller than ~2.2 (cf. Murase, Ahlers, Lacki 2013)
- Tomographic constraints:
  - If δ is smaller than ~3, source with spectrum softer than $E^{-2.1}$ is disfavored
- If δ ~ 4, both spectral and tomographic data give comparable constraints

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

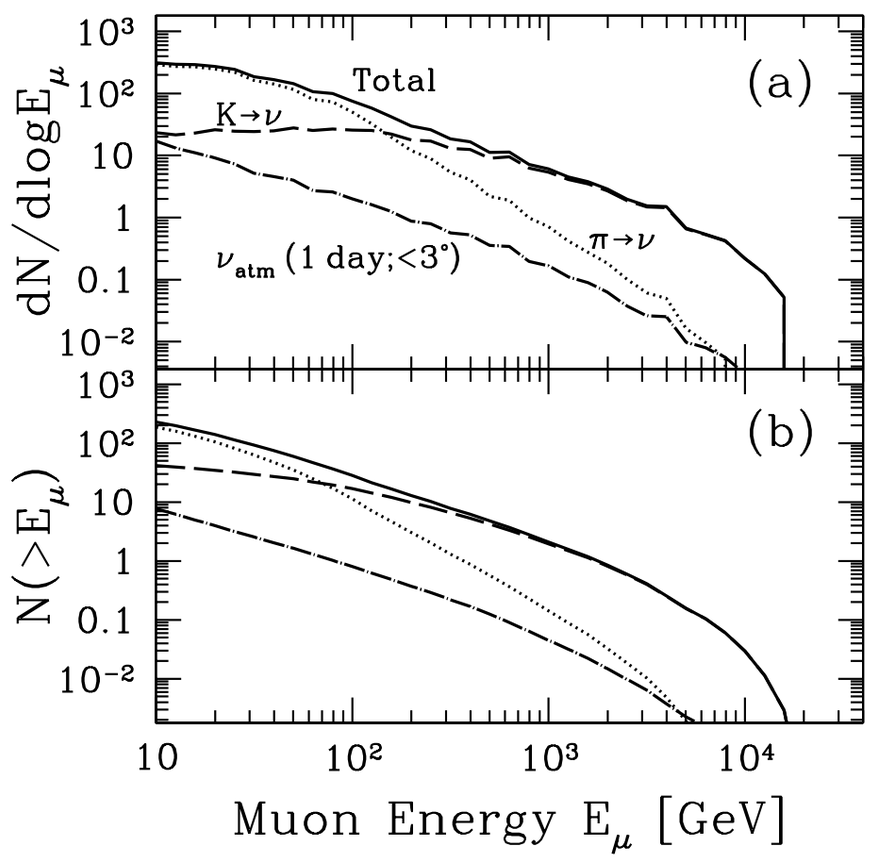
Gruppioni et al., *Mon. Not. R. Astron. Soc.* **432**, 23 (2013)

Clusters of galaxies

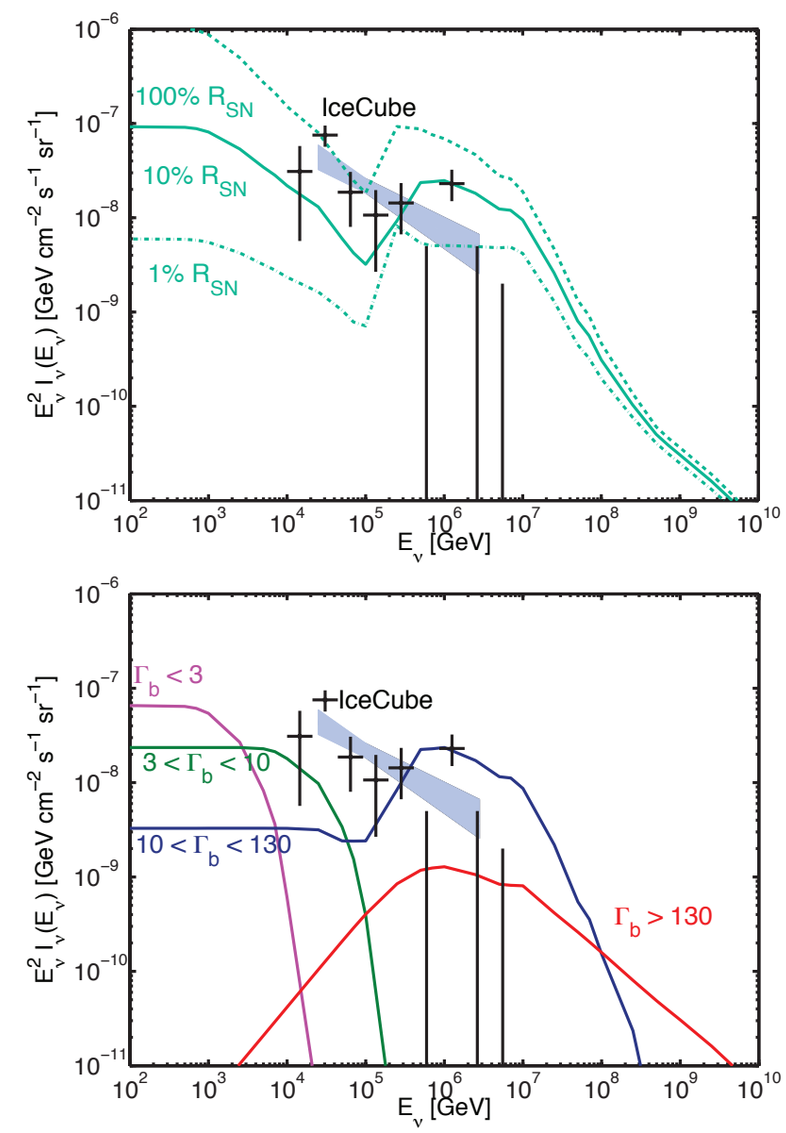
- Cosmic rays accelerated through large-scale-structure shocks or provided by sources (AGNs, galaxies)
- In both cases, δ is very small (i.e., clusters are found only in low-z)

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