GRAPPA
GRavitation AstroParticle Physics Amsterdam

Particle and Astroparticle Theory Seminar
MPIK, Heidelberg
18 January 2016

High-energy astrophysical neutrinos
Potential sources and gamma-ray constraints

Shin'ichiro Ando
GRAPPA, University of Amsterdam

What are sources of TeV–PeV neutrinos?

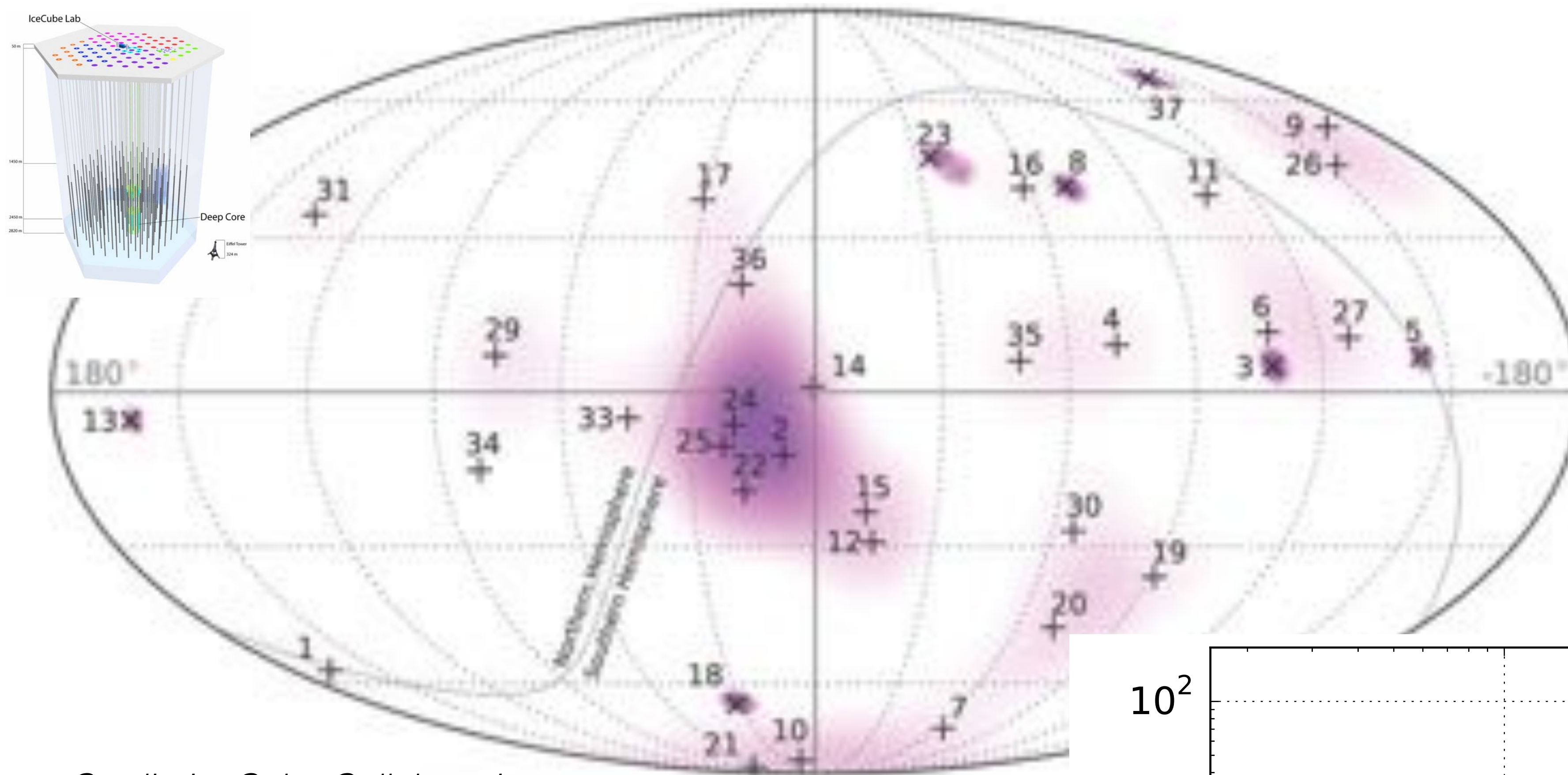
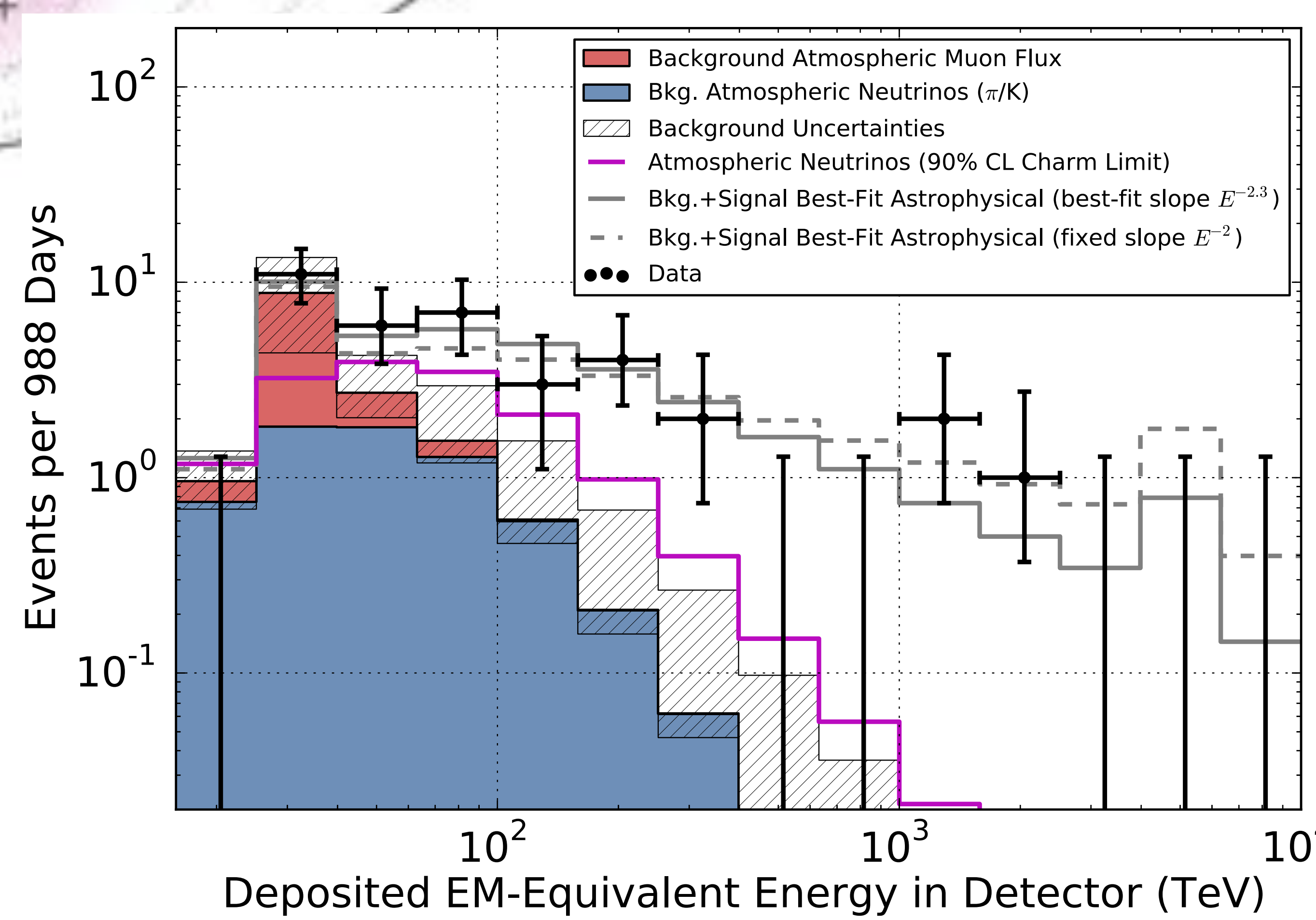
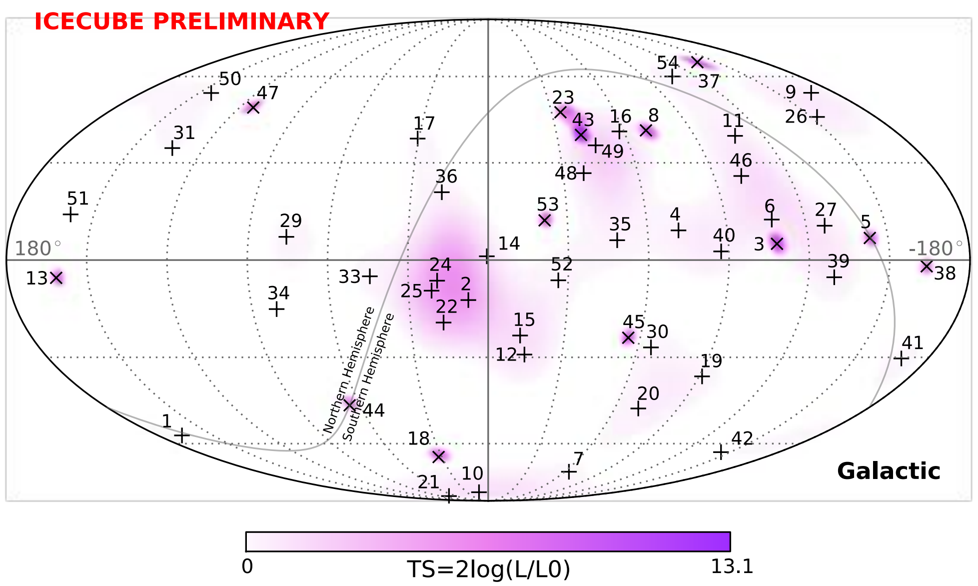


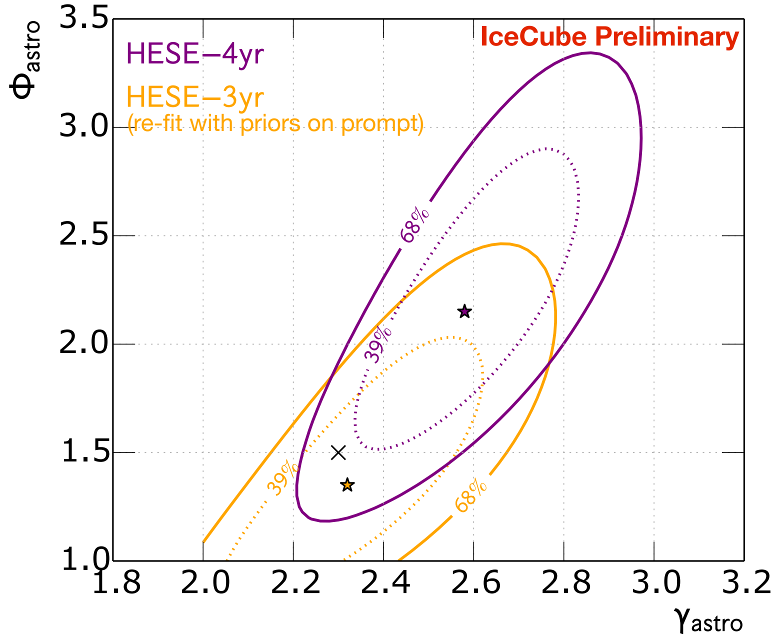
Image Credit: IceCube Collaboration

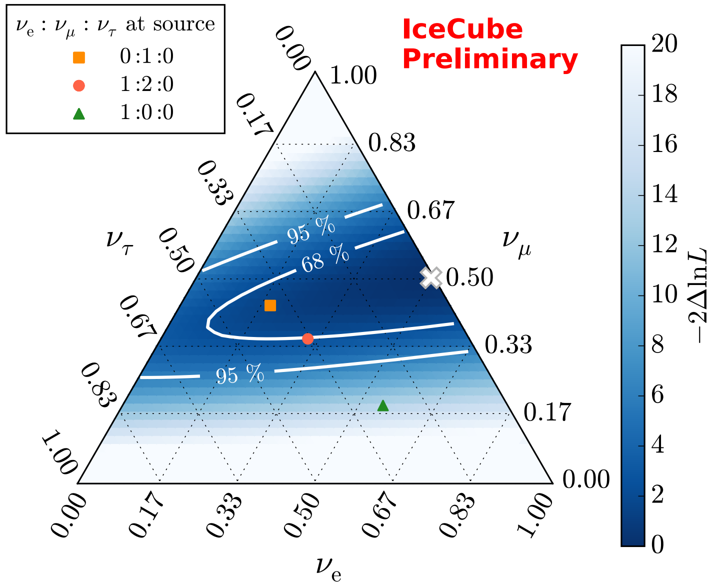


IceCube papers:
1304.5356, 1311.5238, 1405.5303,
1410.1749, 1507.03991, 1507.04005, etc.

Quick summary of IceCube neutrinos



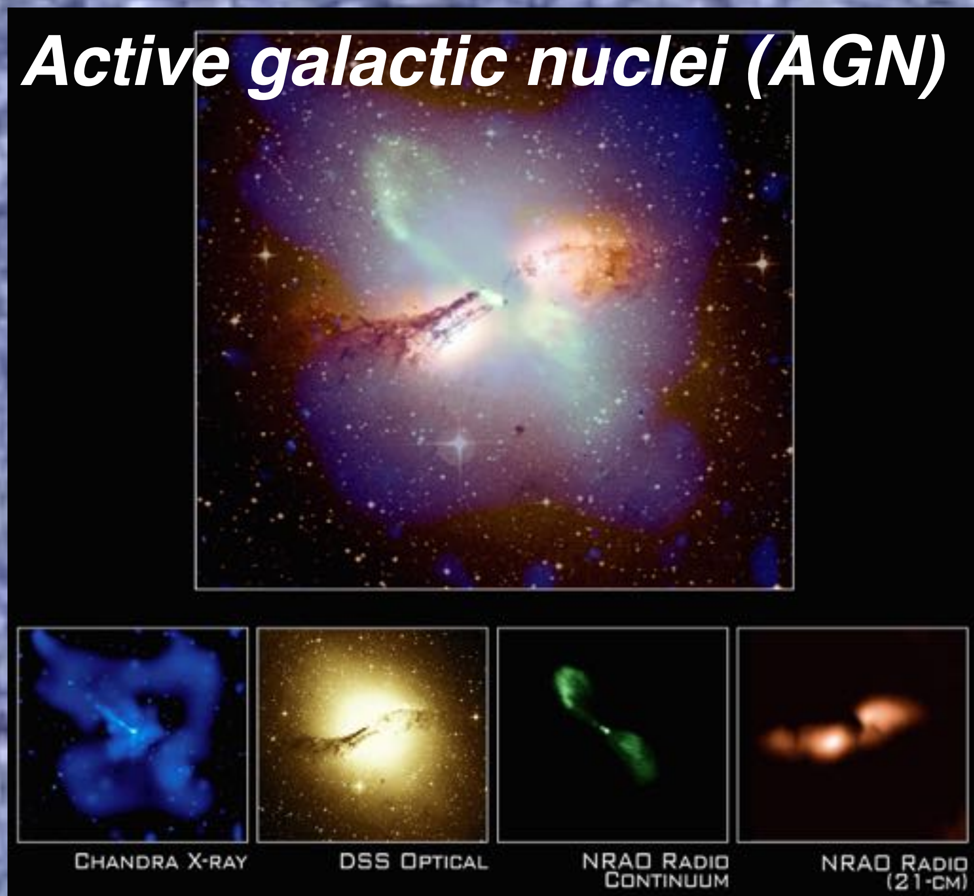


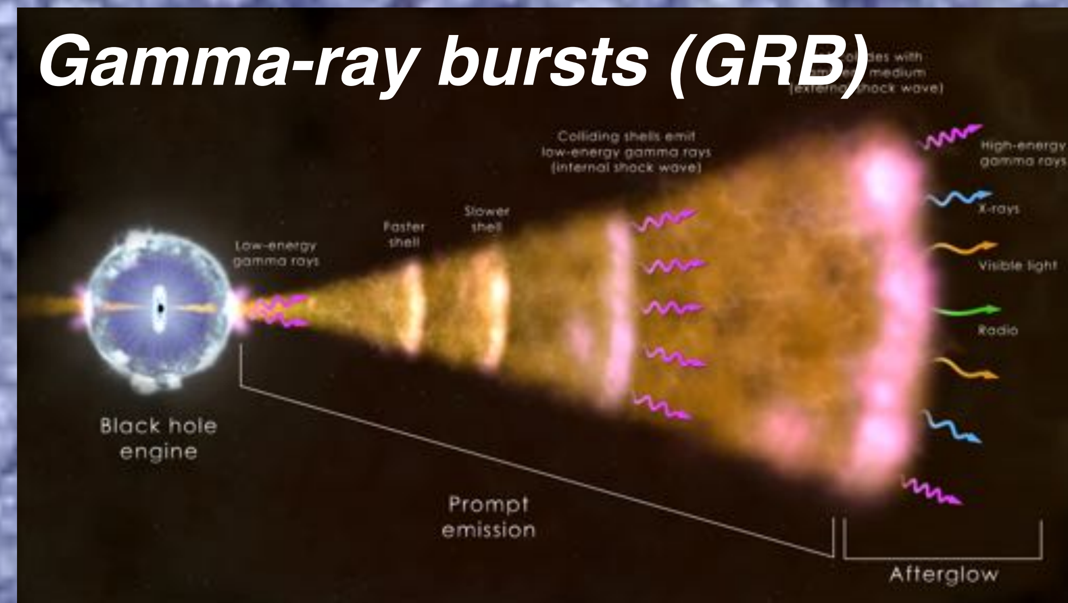


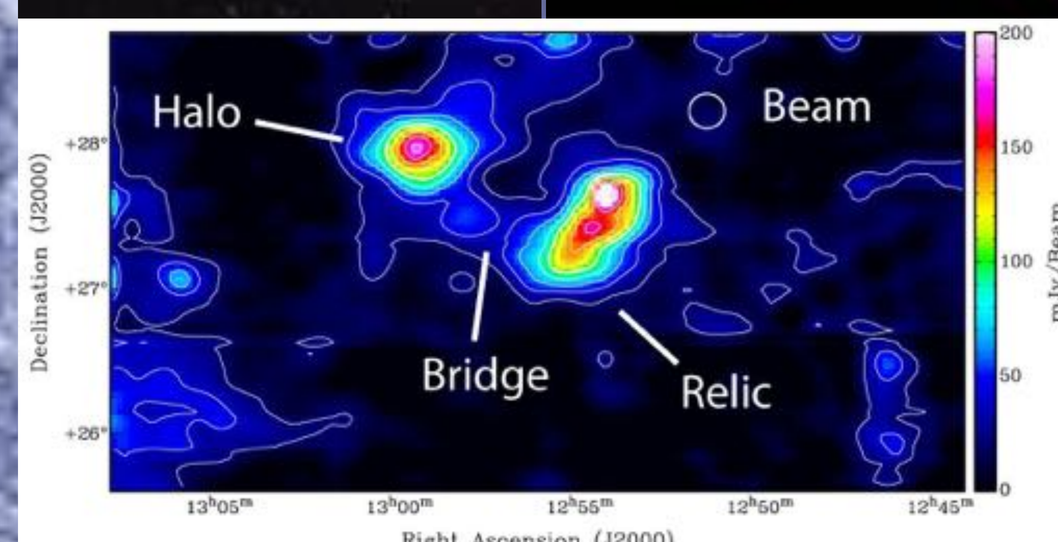
ICRC 2015 [1510.05223]

- From tens of TeV to a few PeV
- Tens of events: 37 in published paper, 17 more in preliminary results
- Atmospheric neutrino origin is excluded
- Consistent with isotropic distribution and no sign of spatial clustering
- Consistent with flavour equipartition

Possible astrophysical explanations



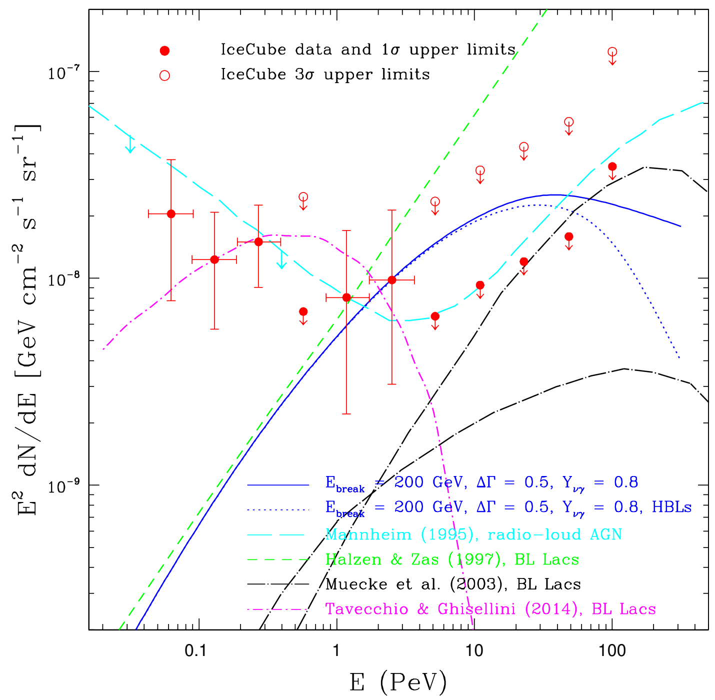




Particle dark matter

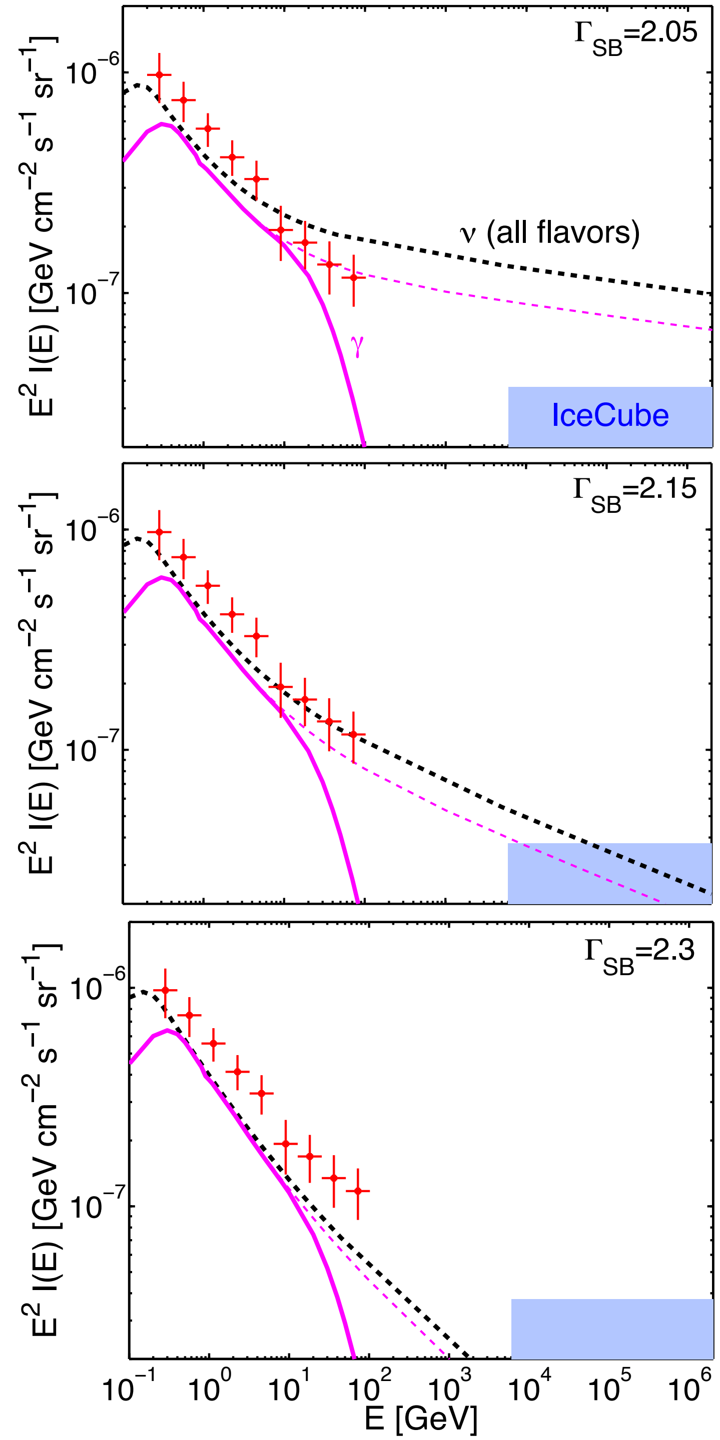
Possible astrophysical explanations

AGN



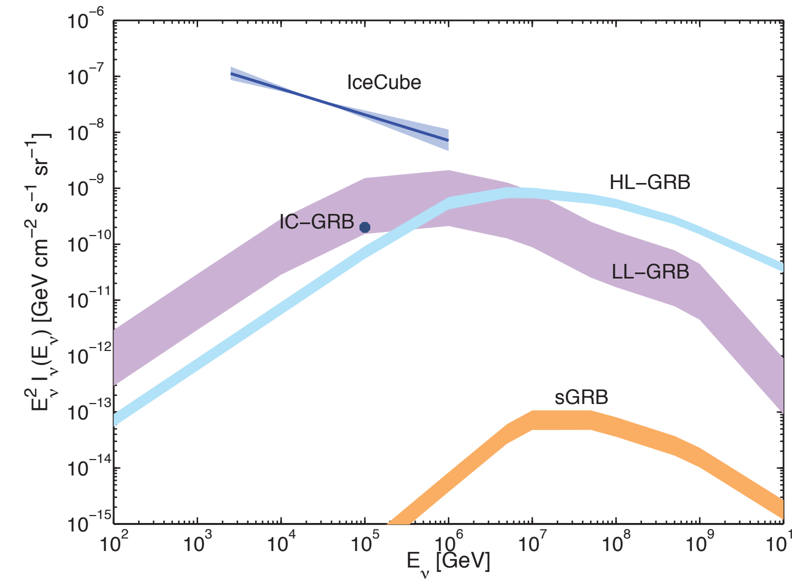
Padvani et al., 1506.09135

SFG/SB



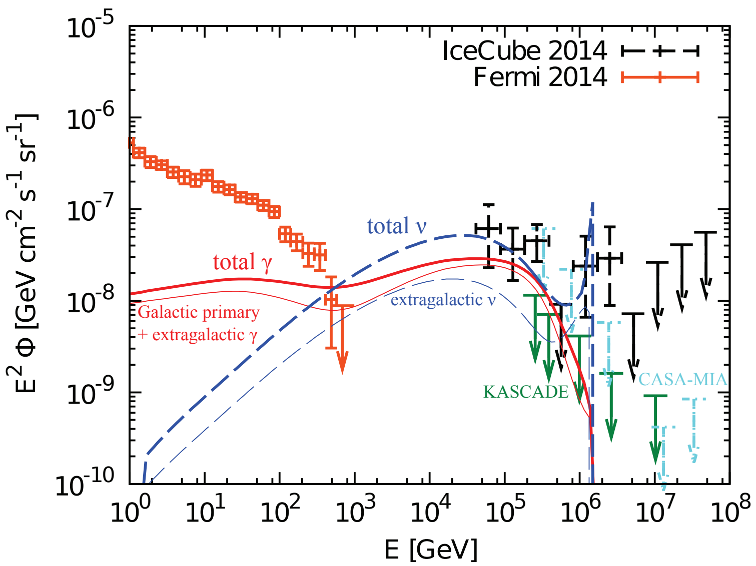
Tamborra et al., 1404.1189

GRB



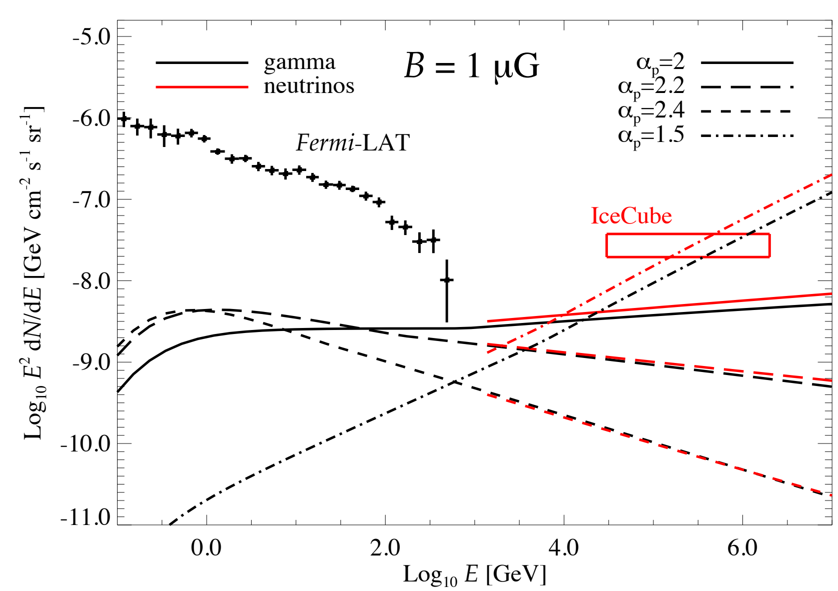
Tamborra, Ando, 1504.00107

Dark matter decay



Murase et al., 1503.04663

Galaxy clusters



Zandanel et al., 1410.8697

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

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

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

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

GeV gamma rays: Fermi-LAT

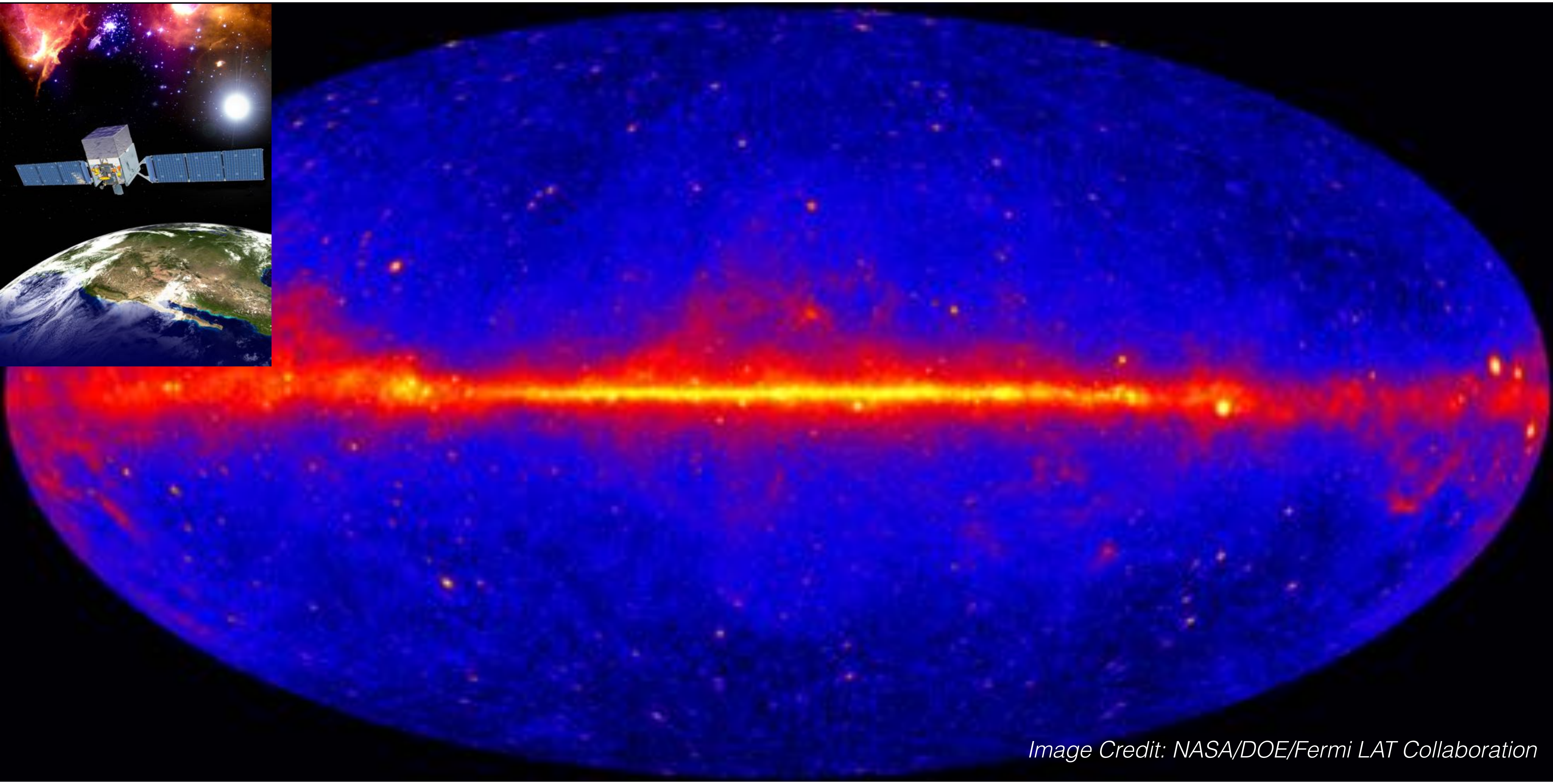
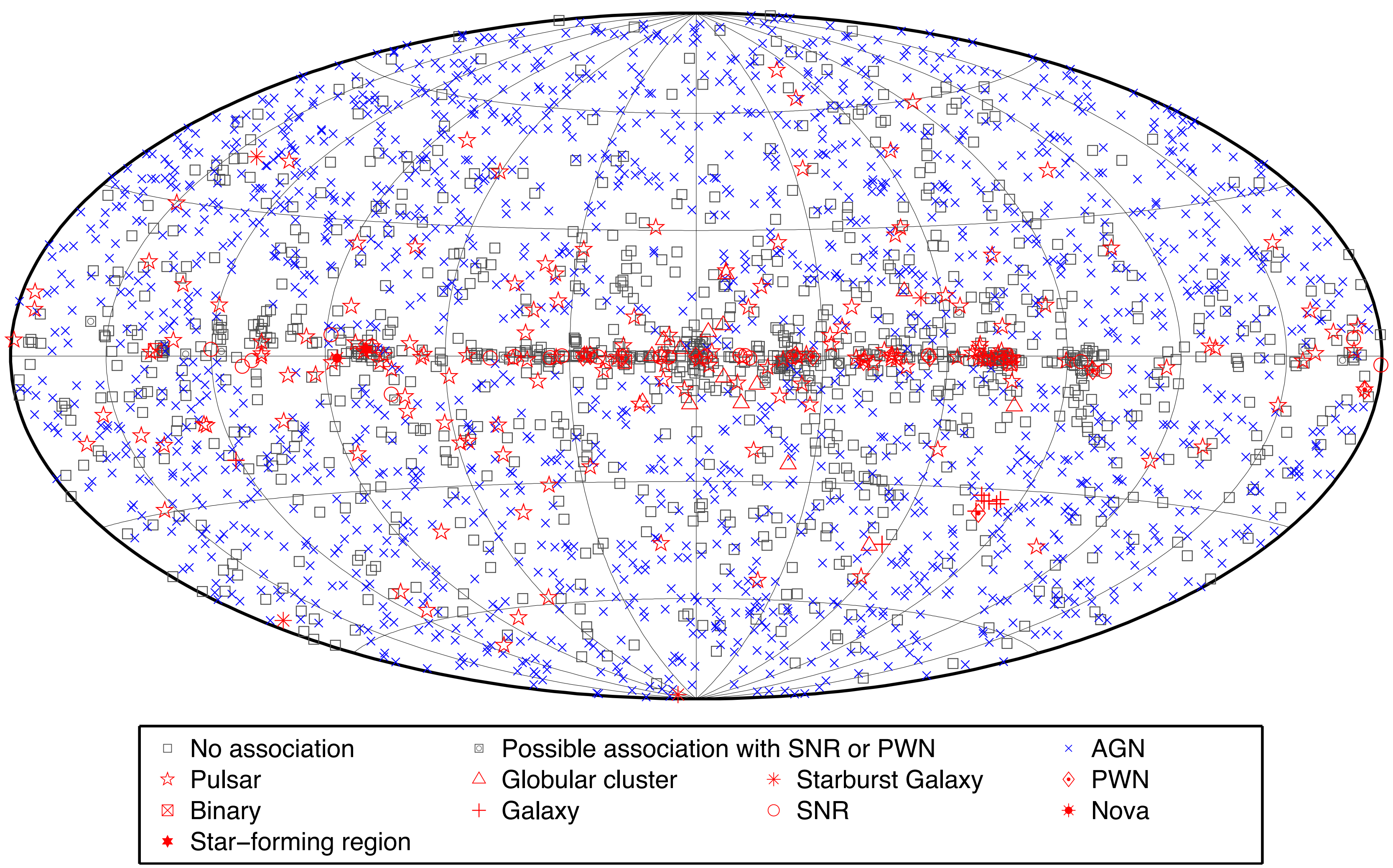


Image Credit: NASA/DOE/Fermi LAT Collaboration

What constitutes the gamma-ray sky?

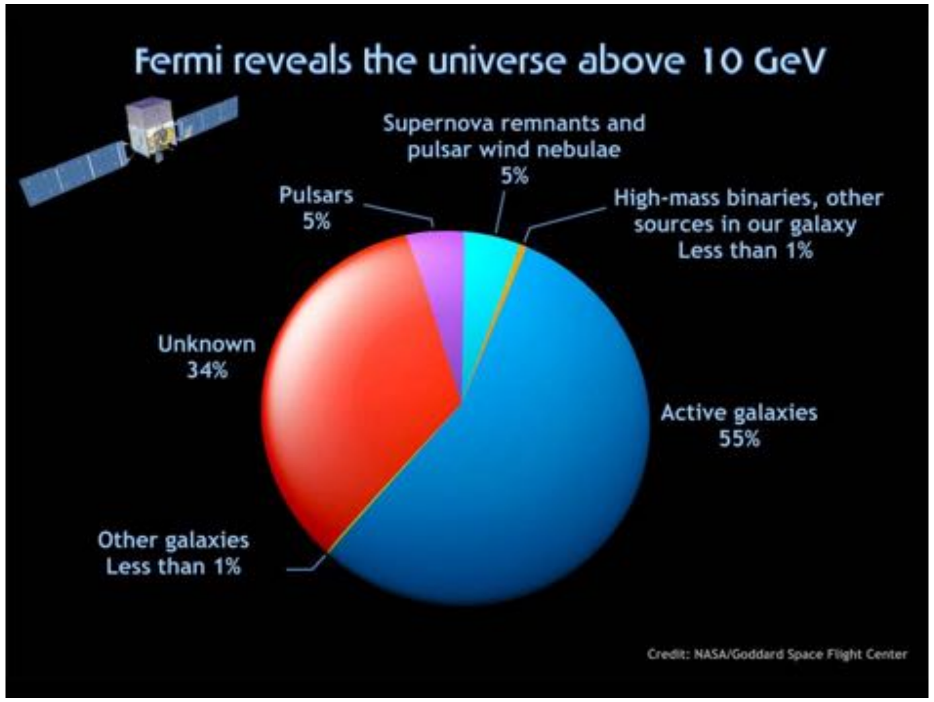
Fermi-LAT, arXiv:1501.02003 [astro-ph.HE]



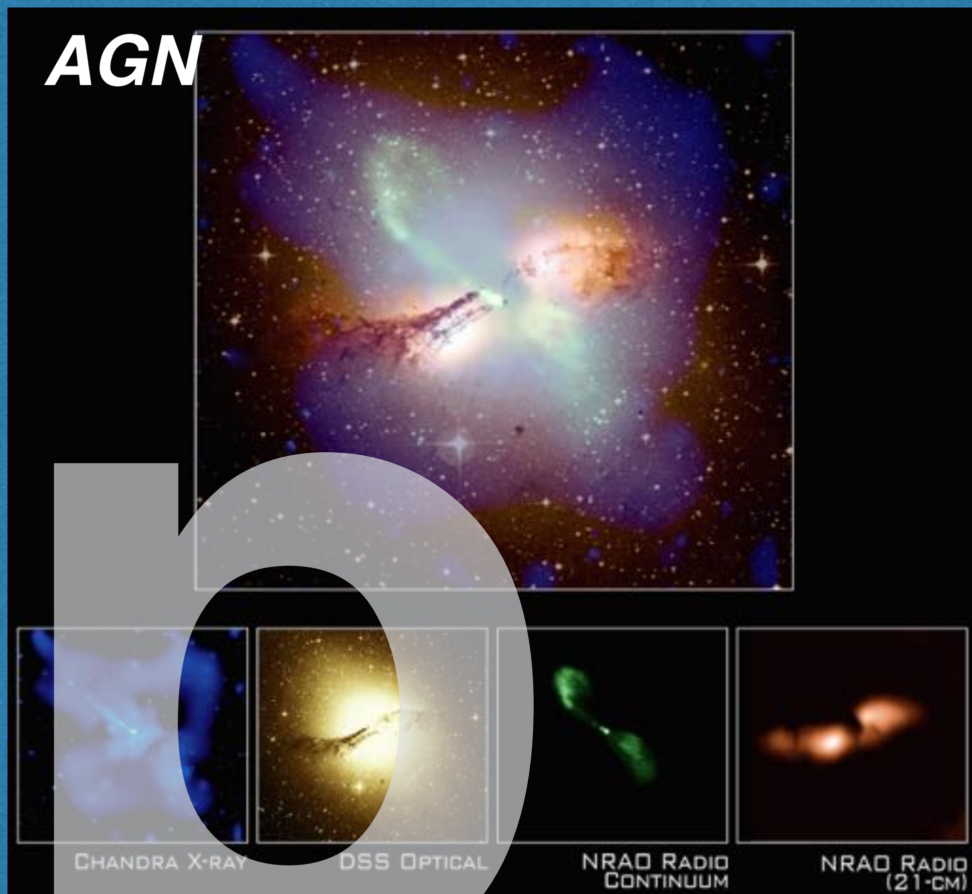
Emission from our Galaxy

+

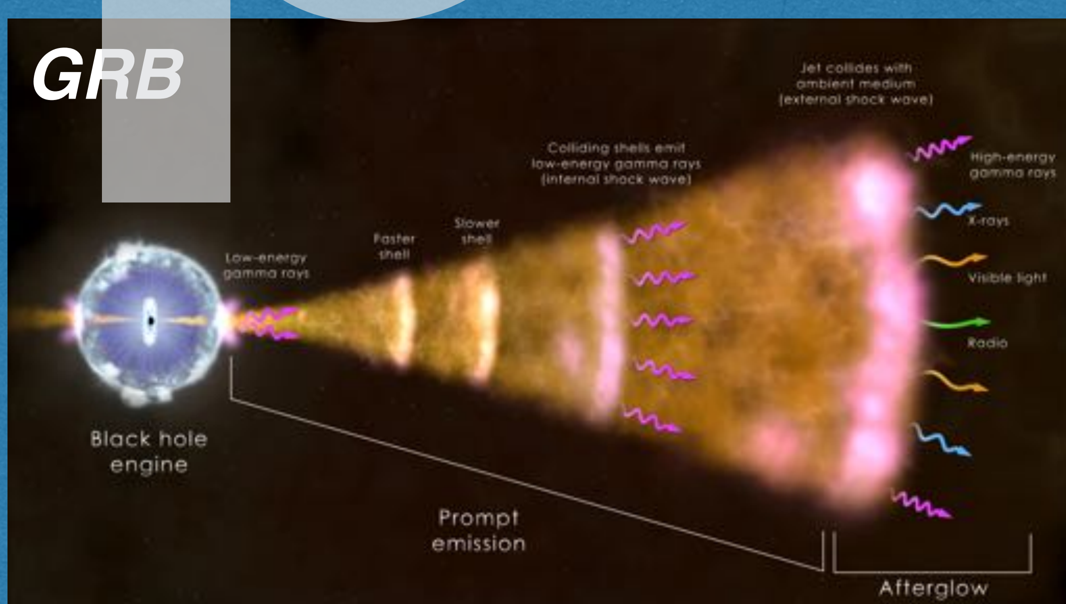
3FGL sources (3033 in catalog)



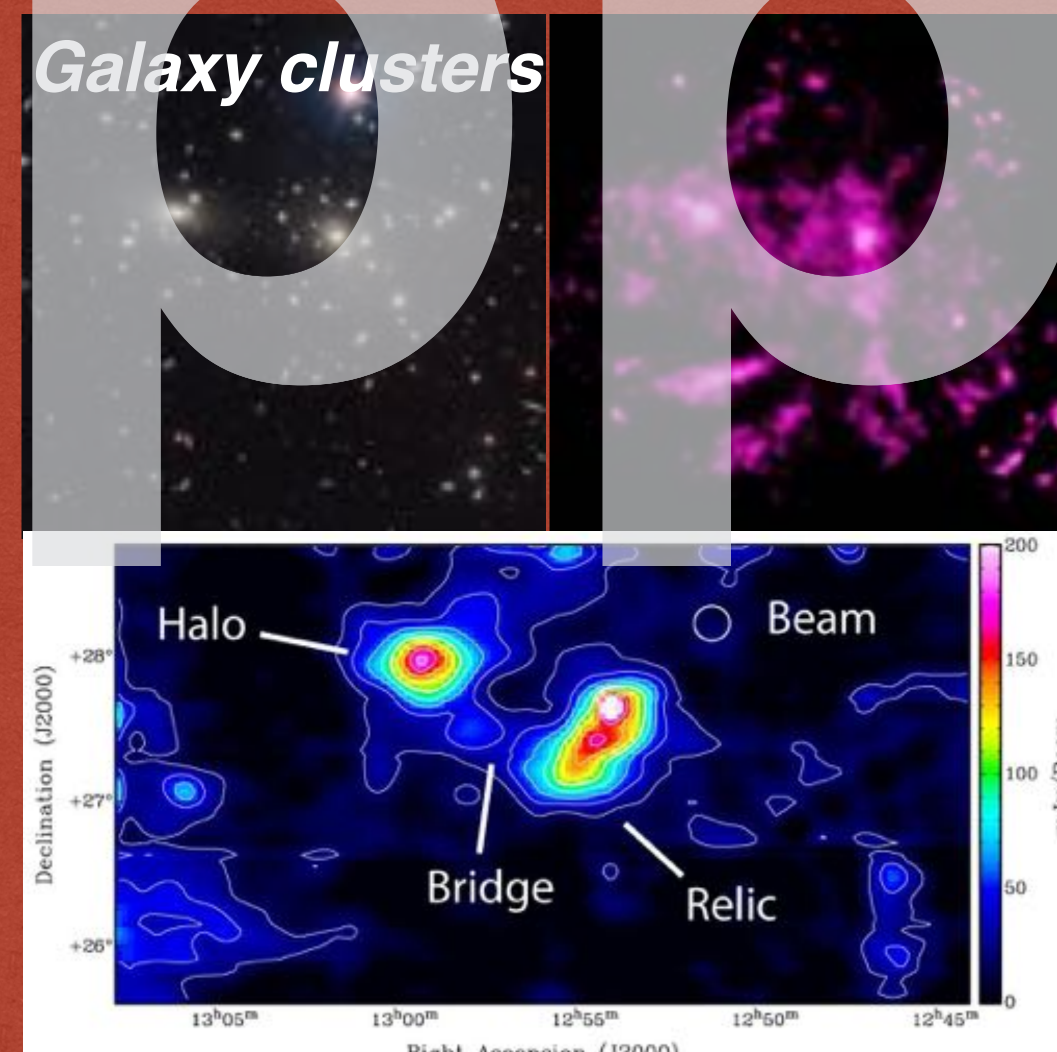
pp and pγ sources: 0th order classification



p



pp



Three ***constraints*** discussed

	SFG/SB	Galaxy clusters	Other pp sources	Conclusion
Gamma-ray (non)detection	✓	✓		SB preferred
Radio number count		✓		Clusters disfavored
Cross correlation with galaxies	✓	✓	✓	SB preferred; Clusters disfavored

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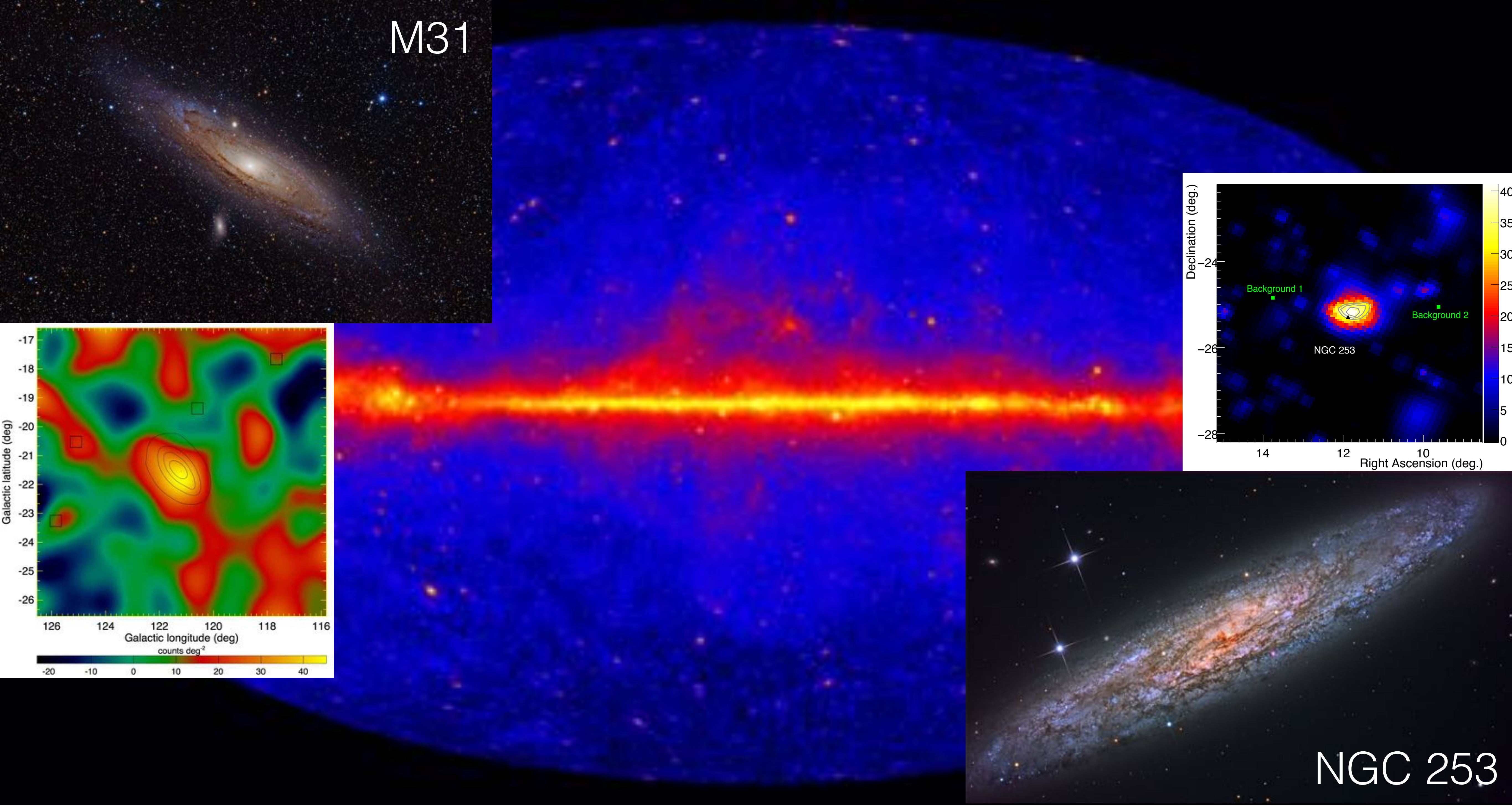


Star-forming and starburst galaxies

A guaranteed source class

Recipe for computation

$$I(E) = \int dz \frac{d^2V}{d\Omega dz} \int dL \; \Phi(L, z) F[L, (1+z)E, z]$$

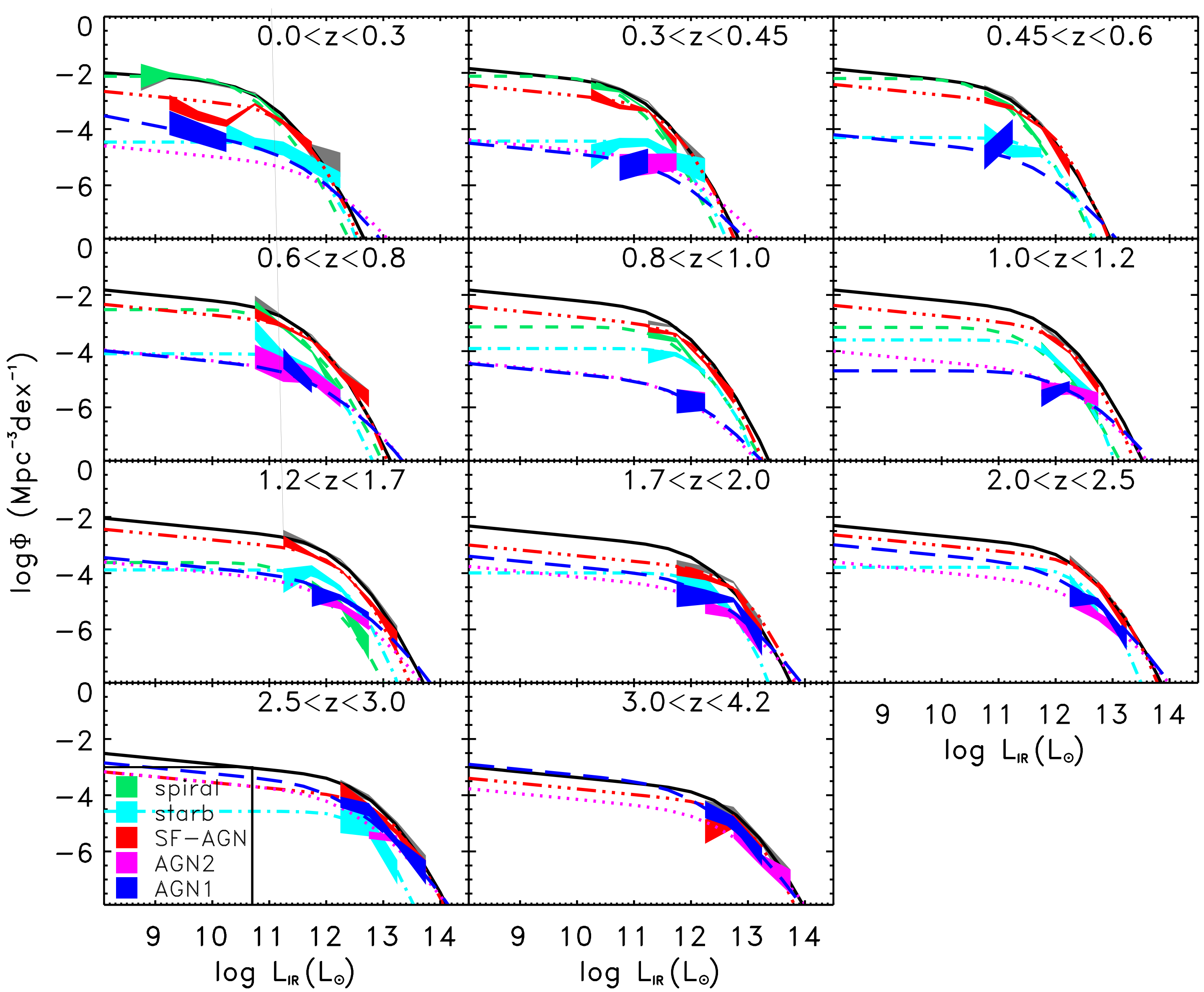
$d^2V/d\Omega dz$: volume element (depends only on cosmology)

Φ: luminosity function; source density per L ~ L+dL

F: flux from a source L at z and energy (1+z)E

- Roughly speaking: **(flux per source) * (source number)**
- More precisely: integration over flux *F* weighed by luminosity function Φ and volume element

Infrared luminosity function of galaxies



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

- Herschel PEP/HerMES luminosity function up to z ~ 4
- Constructed for several different sub-classes
  - Spiral galaxies
  - Starbursts
  - Star-forming galaxies including AGN
- Well fitted with modified Schechter function with evolving density and luminosity parameters

$L_{\rm IR}$-L_γ correlation, and relation to L_ν

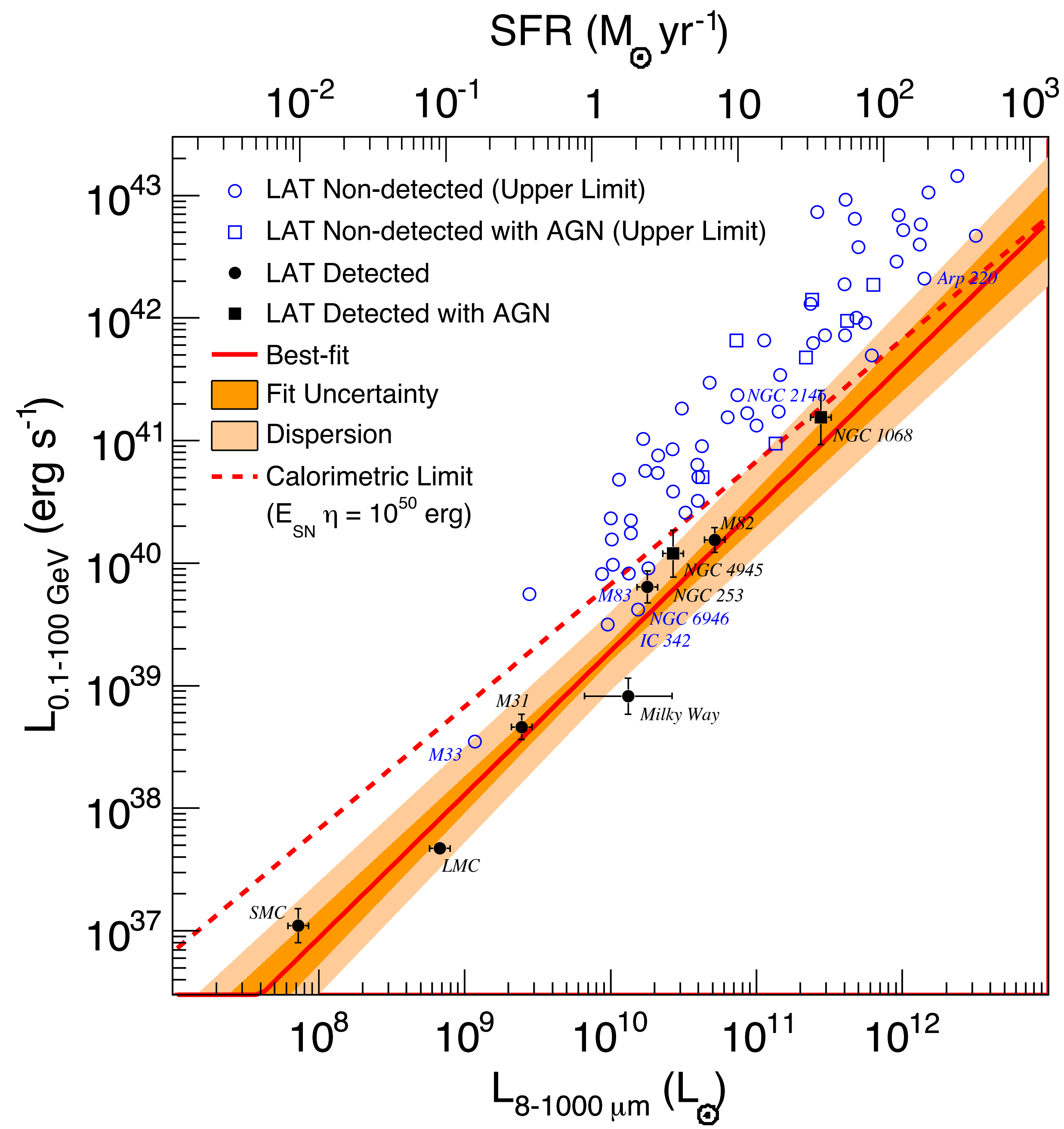
- To obtain gamma-ray luminosity function from IR luminosity function, one needs $L_{\rm IR}$-L_γ relation

$$\Phi_\gamma(L_\gamma) = \Phi_{\rm IR}(L_{\rm IR}(L_\gamma))\frac{dL_{\rm IR}}{dL_\gamma}$$

- Well calibrated for wide luminosity range with *Fermi*-LAT

- L_ν-L_γ relation:

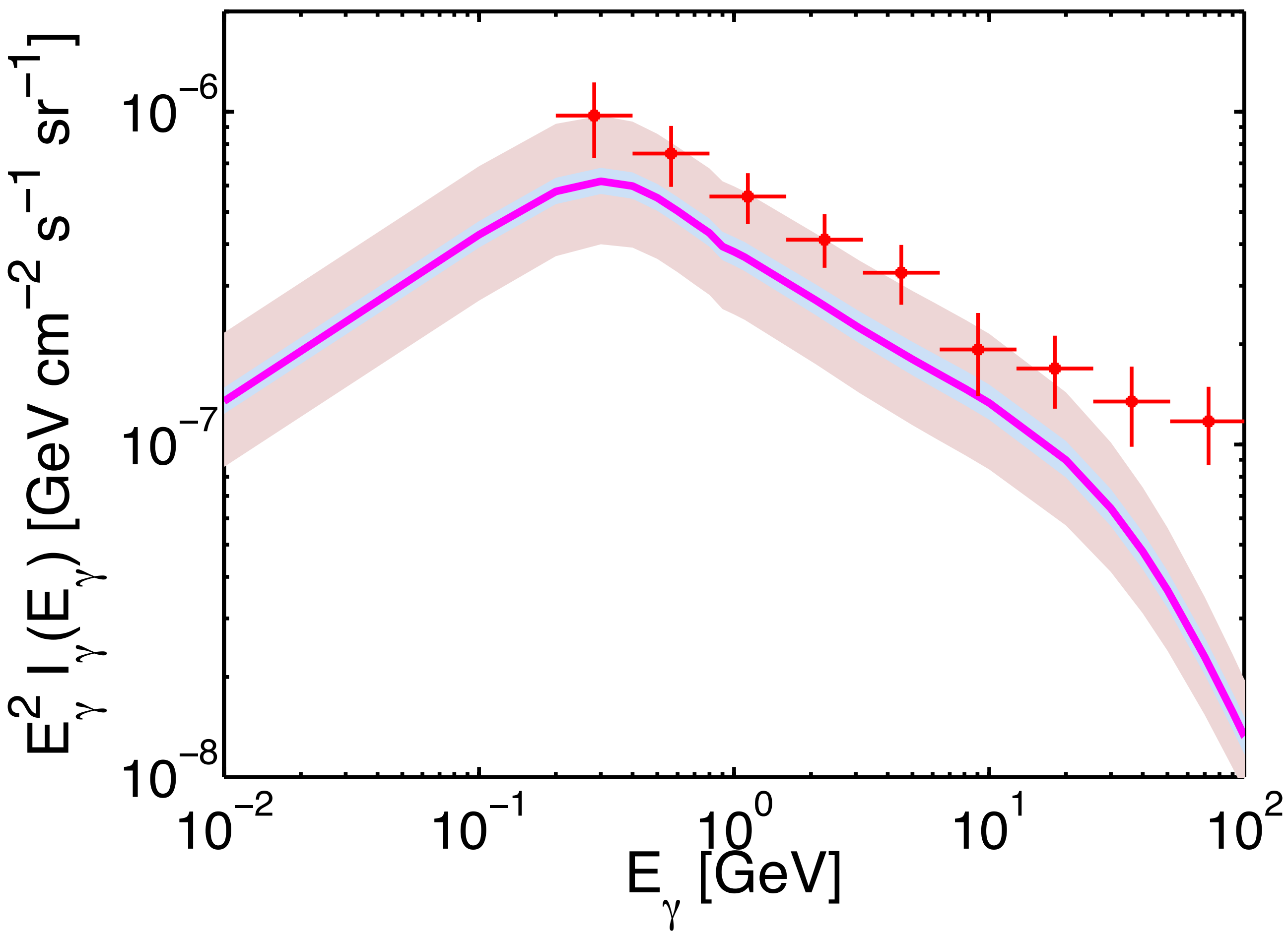
$$\sum_\alpha L_{\nu_\alpha}(E_\nu) \simeq 6L_\gamma(E_\gamma = 2E_\nu)$$

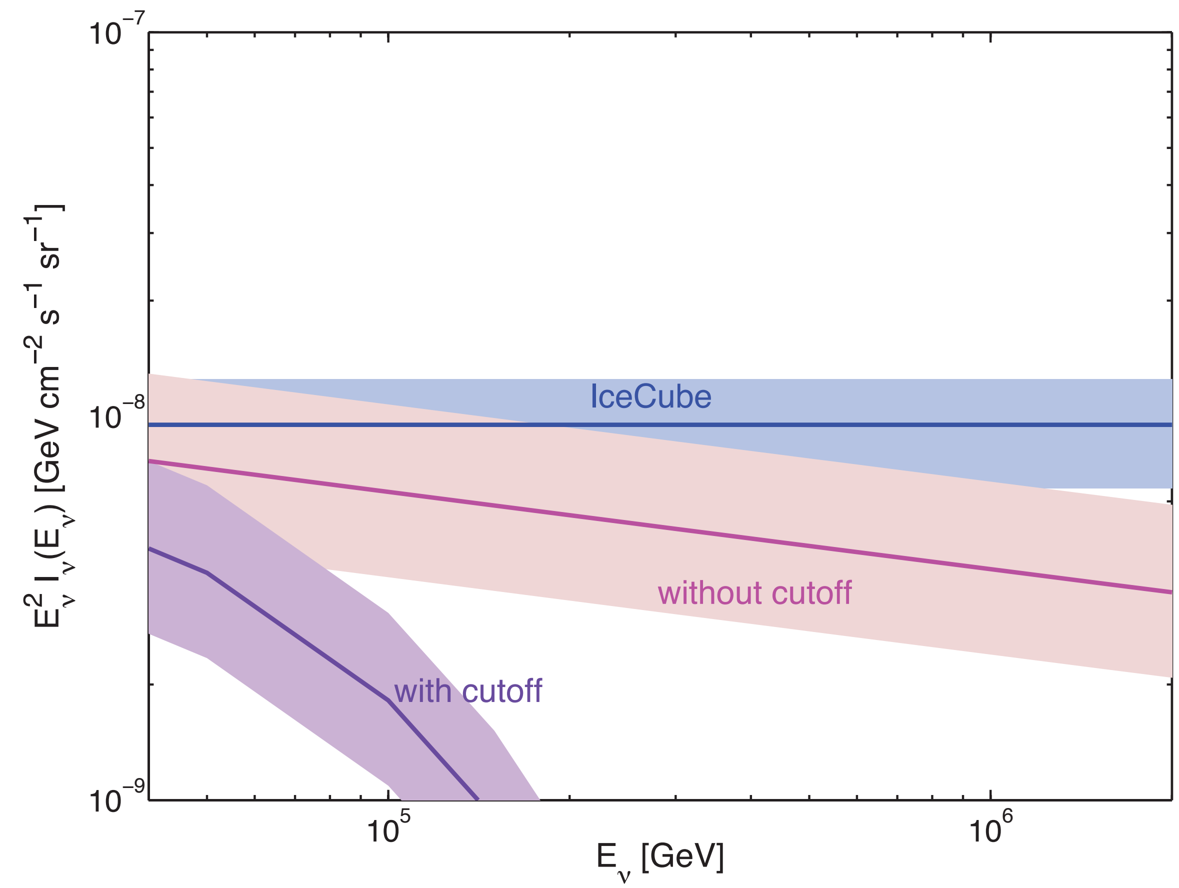


Fermi-LAT, *Astrophys. J.* **755**, 164 (2012)

Galaxy contributions to γ & ν backgrounds

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

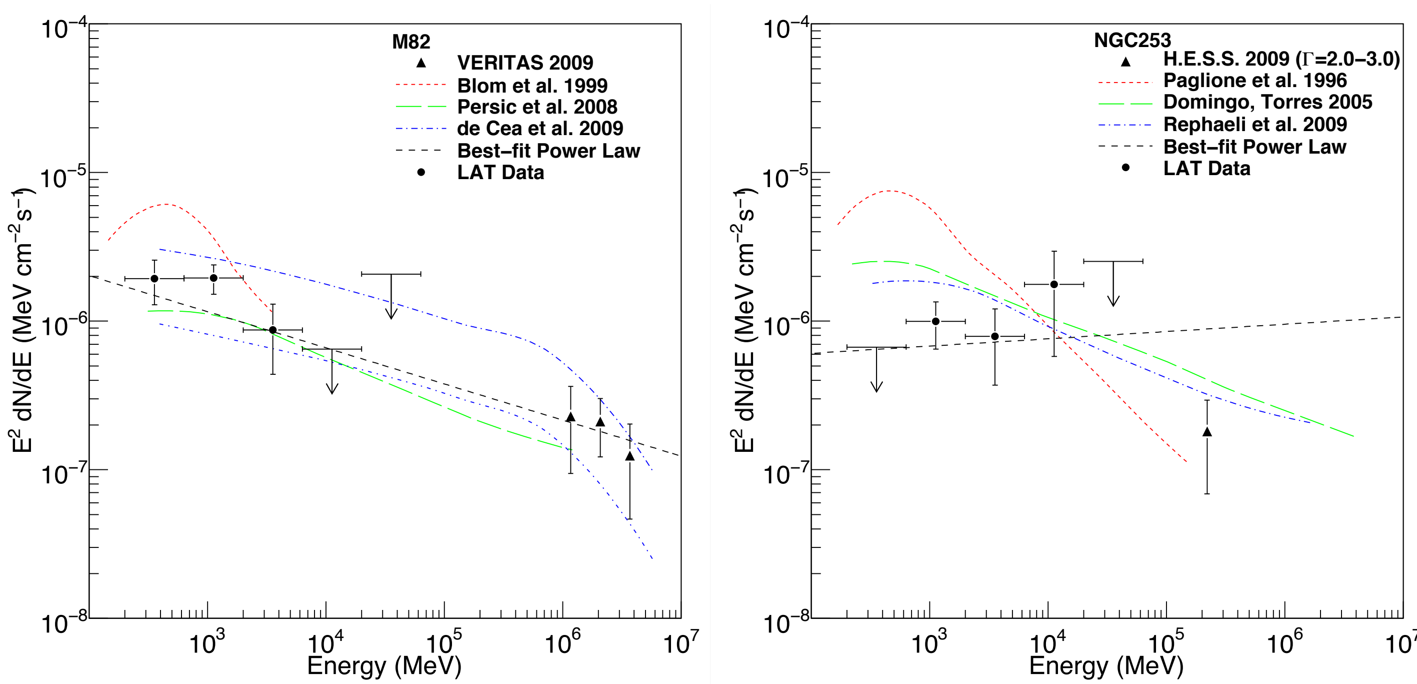


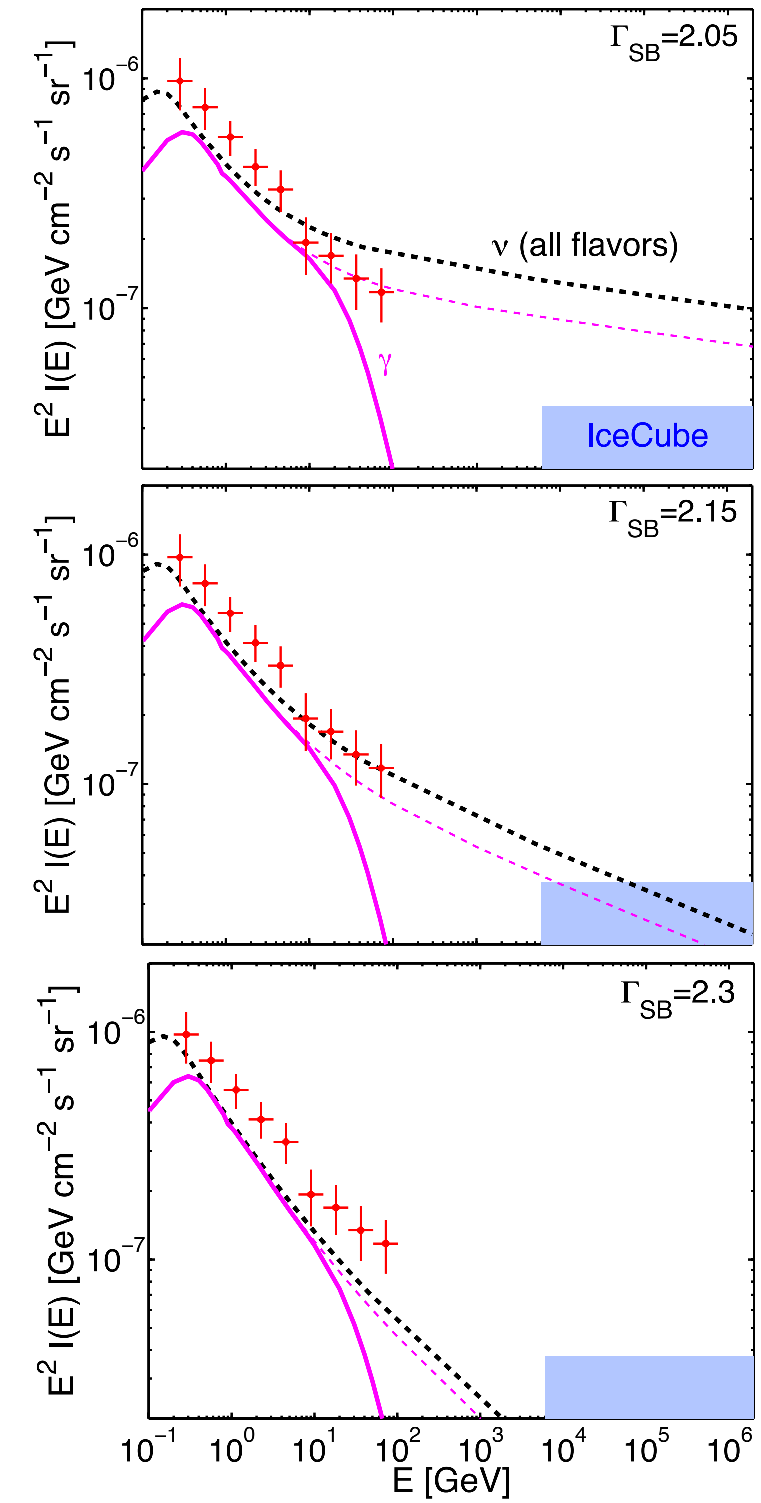


- Assumed spectral index: –2.7 for spirals, –2.2 for starbursts
- If there is no cutoff, starbursts can explain IceCube neutrinos (and Fermi IGRB)

Dependence on starburst spectra

Fermi-LAT, *Astrophys. J.* **709**, L152 (2010)

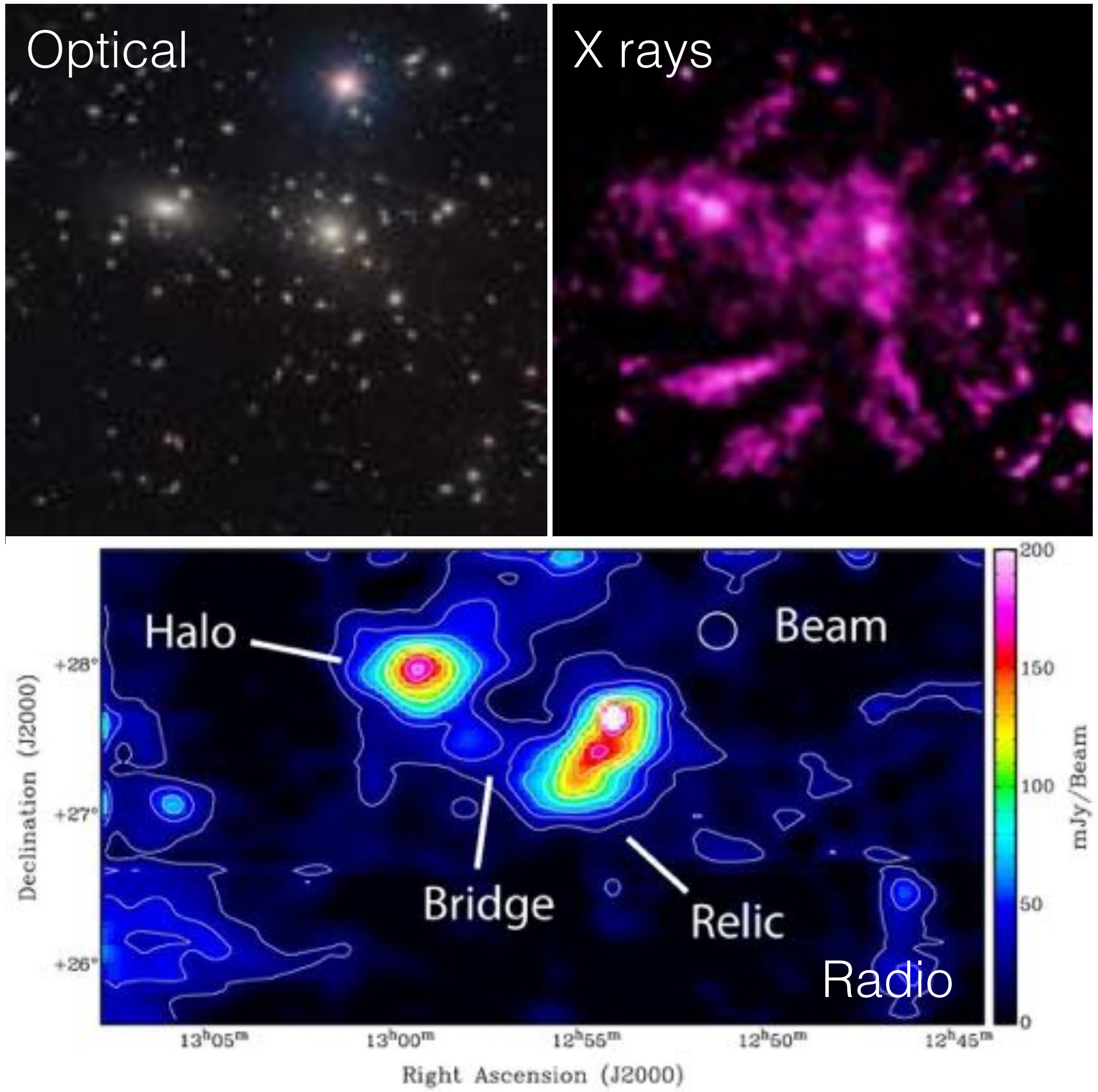


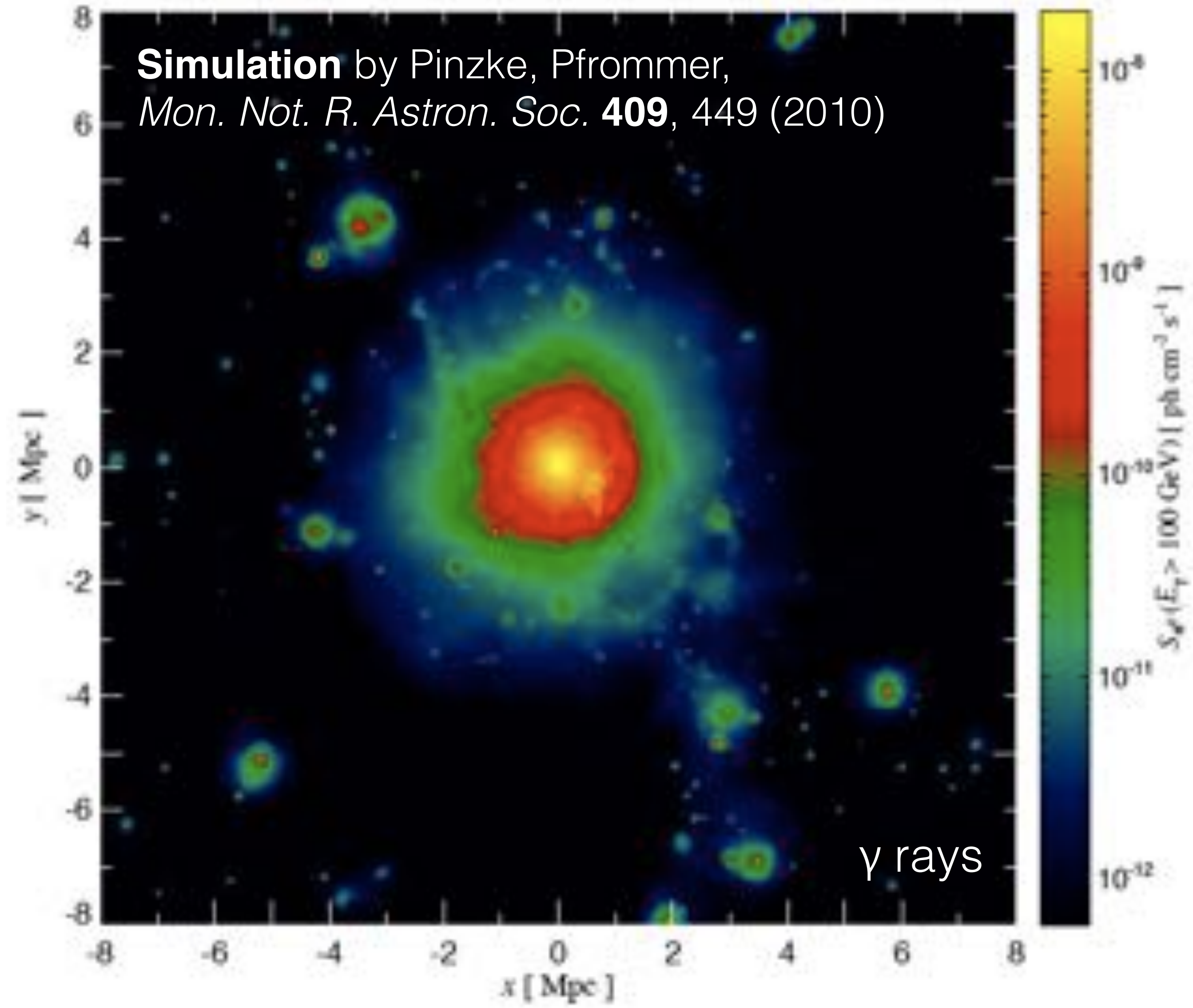


Tamborra, Ando, Murase, *JCAP* **09**, 043 (2014)

- Γ_{SB}: spectral index for starbursts, still uncertain
- Harder spectrum for starbursts (>−2.15) is *excluded* with IceCube

Coma galaxy cluster





Clusters of galaxies

Constraints from gamma-ray non-detections and radio counts

Clusters of Galaxies

Largest gravitationally bound systems in the Universe with mass of $10^{14} - 10^{15}\ M_\odot$ and radius of few Mpc

Actively evolving objects

Cosmic energy reservoirs

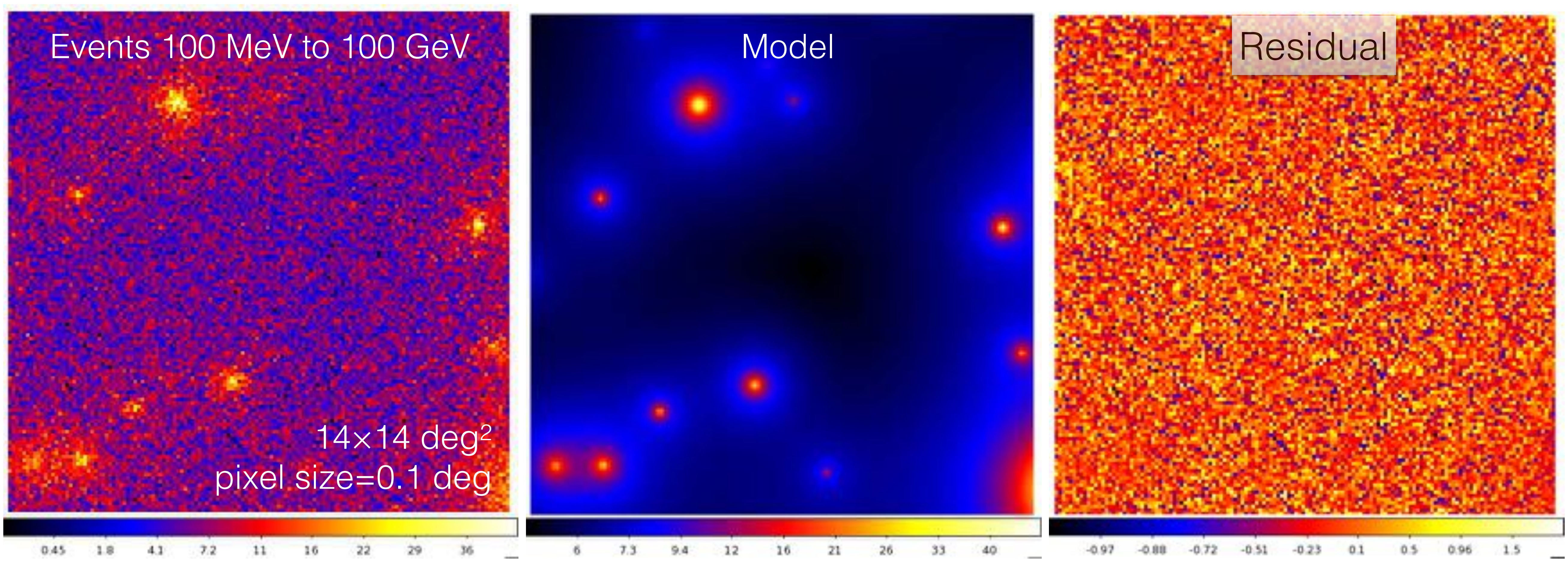
Expected to contain substantial populations of cosmic rays (CRs) and dark matter → can generate non-thermal emission from radio to gamma-ray frequencies

Powerful cosmological tools to test models on the origin and evolution of the Universe → via thermal X-ray emission and Sunyaev-Zel'dovich effect

From F. Zandanel

But clusters are not bright in gamma rays!

Analysis of **Coma cluster** with 63-month *Fermi*-LAT data

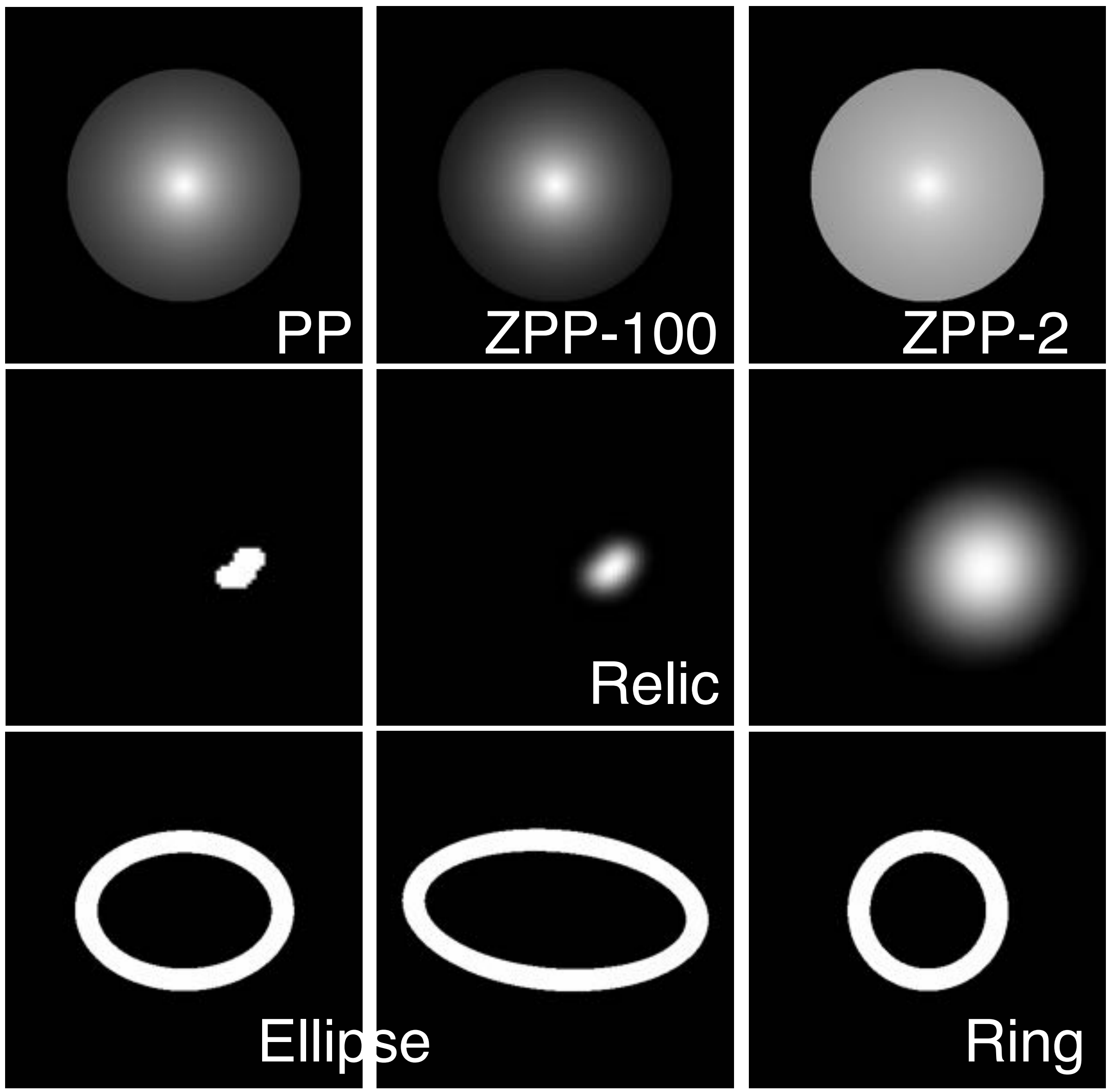


Zandanel, Ando, *Mon. Not. R. Astron. Soc.* **440**, 663 (2014)

No detection so far (TS < 4)

But see Selig et al. (2015) for claim of positive signature (other clusters)

Templates for Coma and upper limits



model	notes	TS	Γ	F_{UL} $[\times 10^{-9}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}]$
PS		0.0	-2	0.62
PP		0.3	-	1.08
ZPP-100	$\gamma_{tu} = 100$	0.1	-	0.92
ZPP-2	$\gamma_{tu} = 2$	1.3	-	1.81
Relic		0.0	-1.18^{*}	0.09
Ellipse		0.0	-2	2.49
Ellipse	tilted	0.0	-2	1.74
Ring		0.2	-2	2.59
Disk		1.5	-2	2.91

Zandanel, Ando, *Mon. Not. R. Astron. Soc.* **440**, 663 (2014)

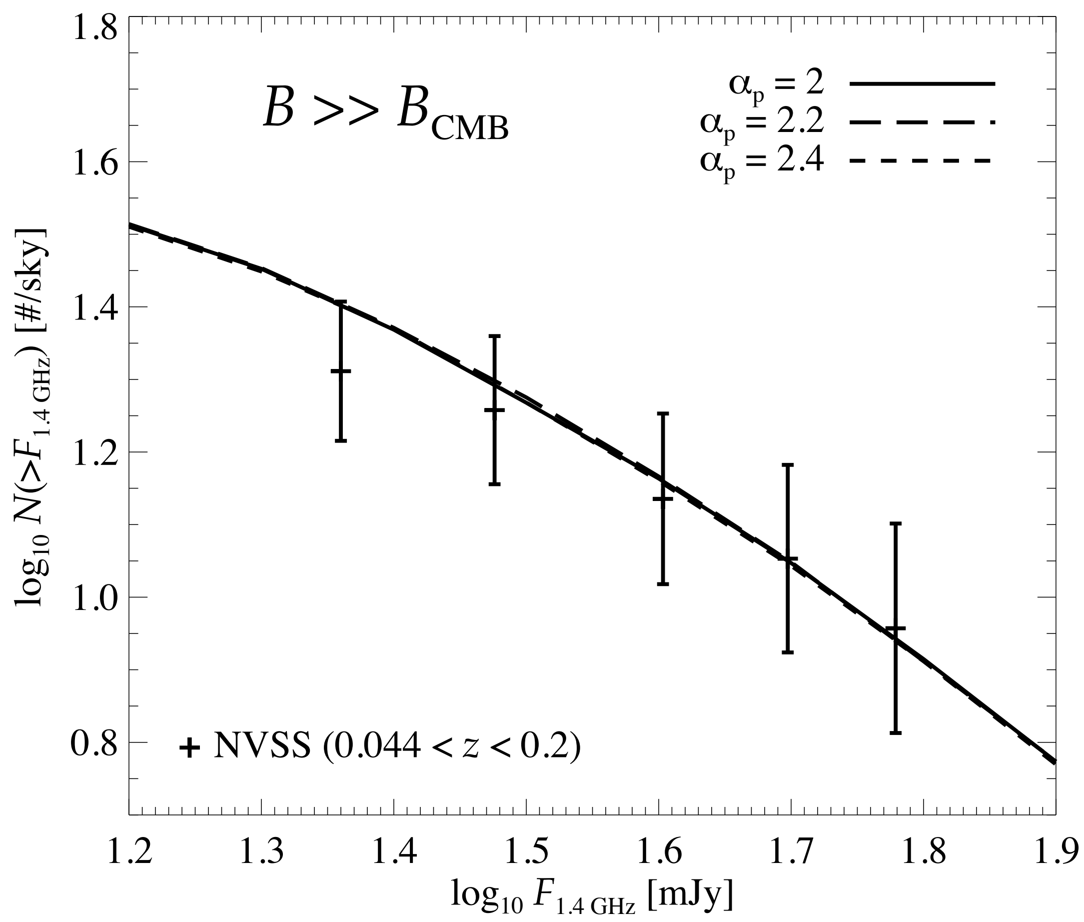
- Implications
  - Protons maximum acceleration efficiency at shocks < 20%
  - CR-to-thermal pressure < 0.5%

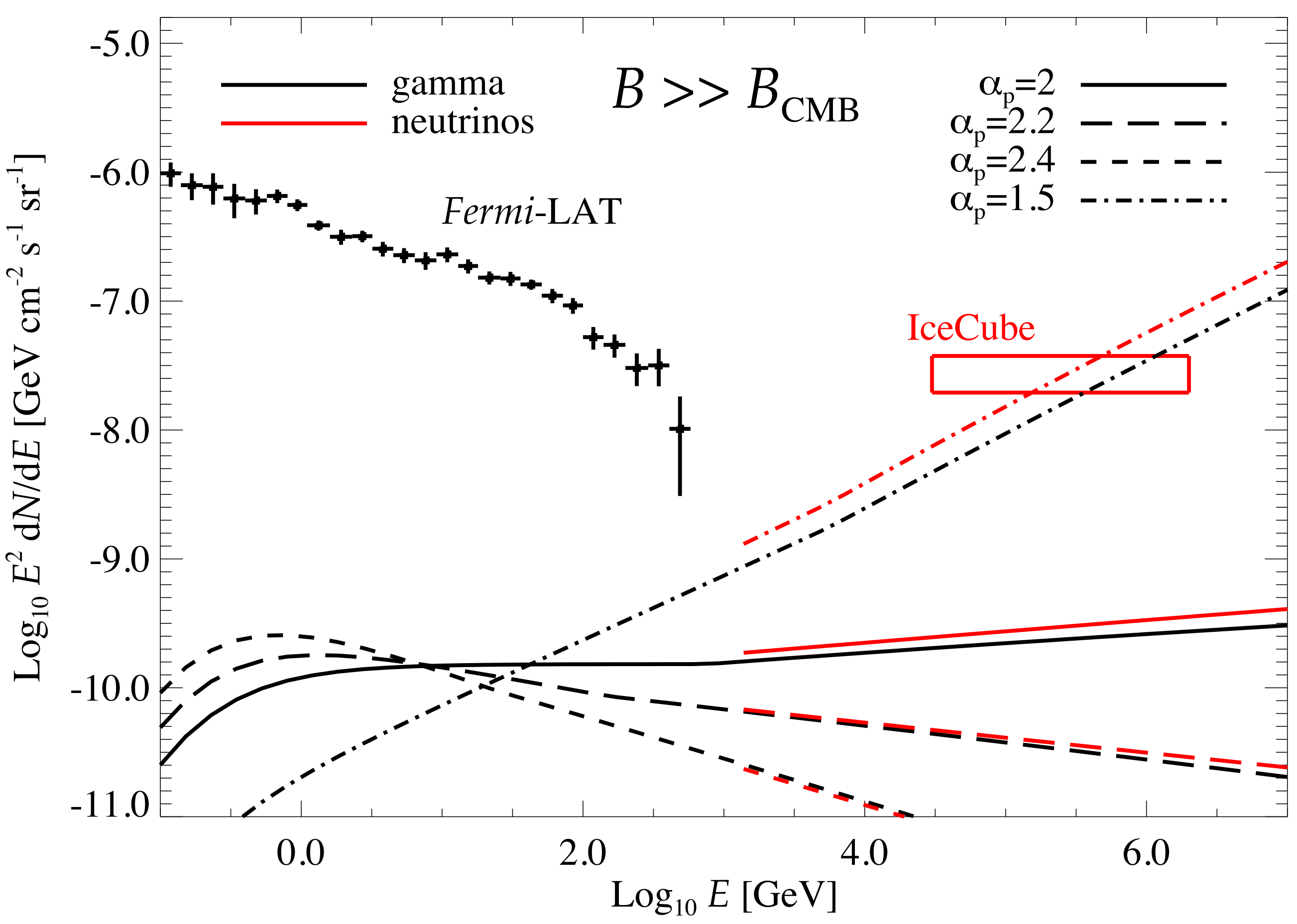
Contribution to γ & ν backgrounds

$$I(E) = \int dz \frac{d^2V}{d\Omega dz} \int dM_{500} \frac{dn(M_{500}, z)}{dM_{500}} F[L(M_{500}), (1+z)E, z]$$

- Use halo mass function dn/dM_{500} instead of luminosity function
- Luminosity-mass relation $L(M_{500})$ is unknown, but expected to be $L \sim (M_{500})^{5/3}$
- Correlation between γ and radio luminosities is expected (radio from synchrotron from secondary electrons) → radio measurements can be used for γ & ν!

Contribution to γ & ν backgrounds





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

- Radio constraints are very tight, and clusters **cannot** contribute to γ & ν backgrounds strongly

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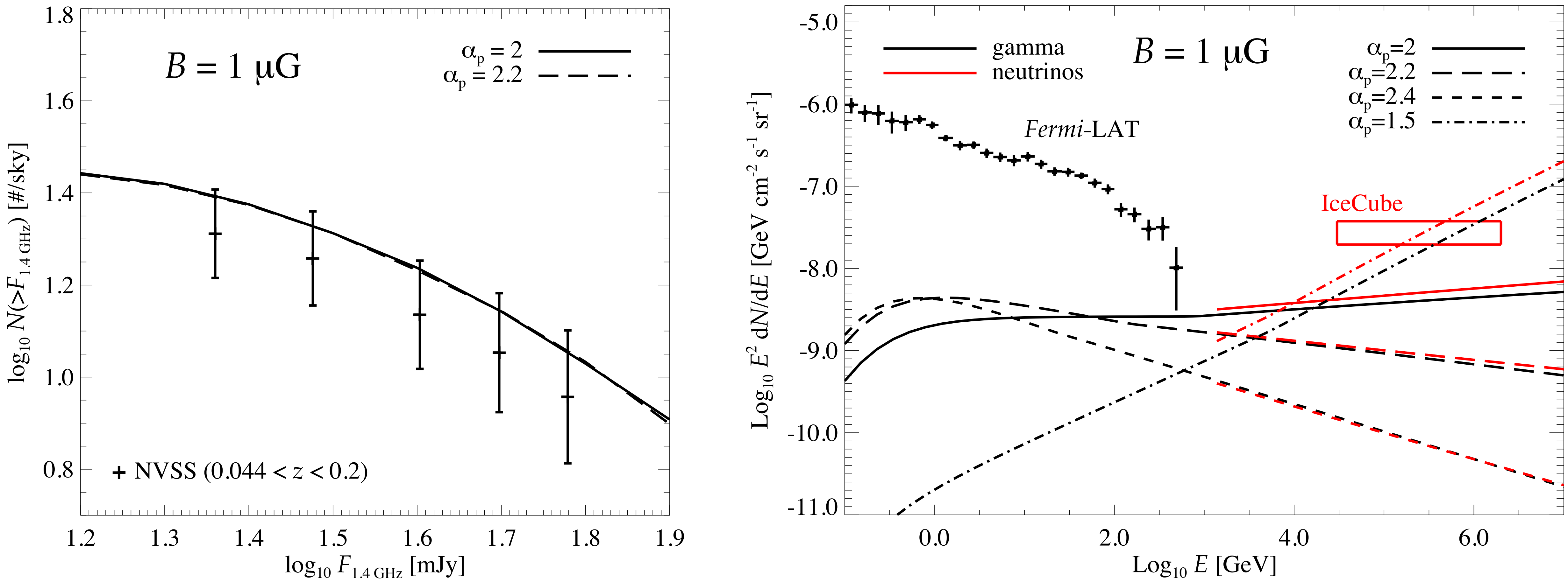

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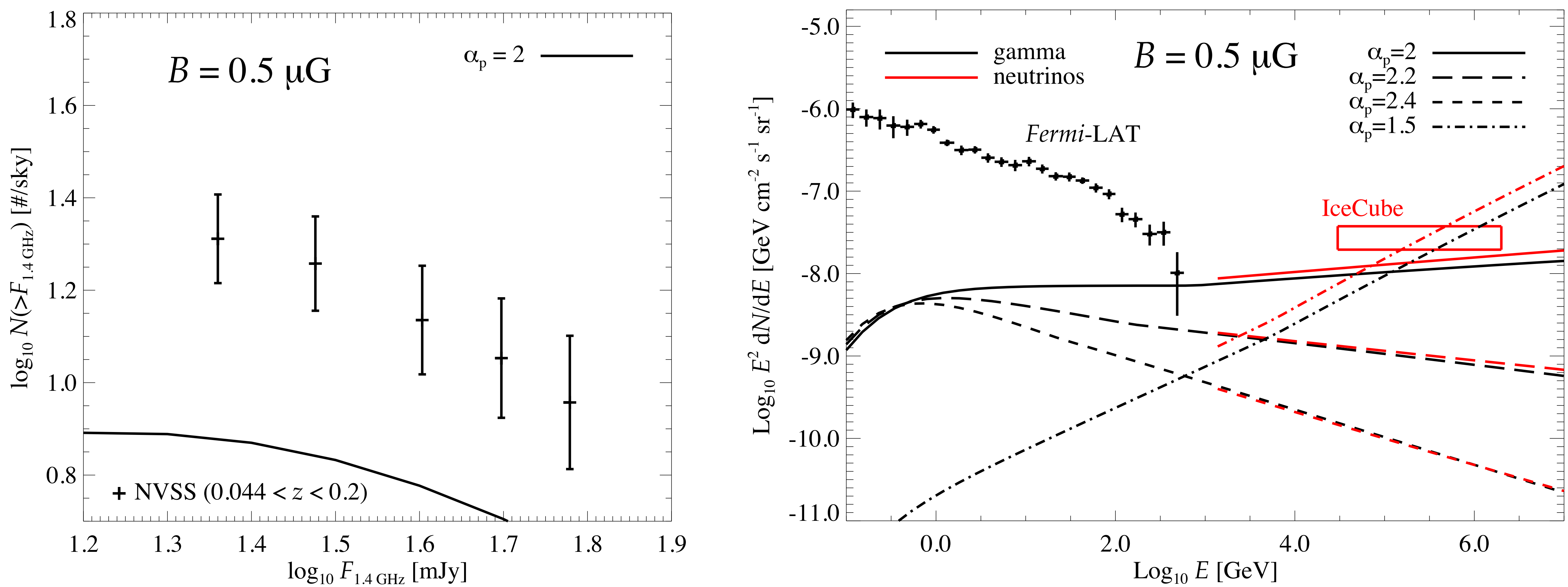

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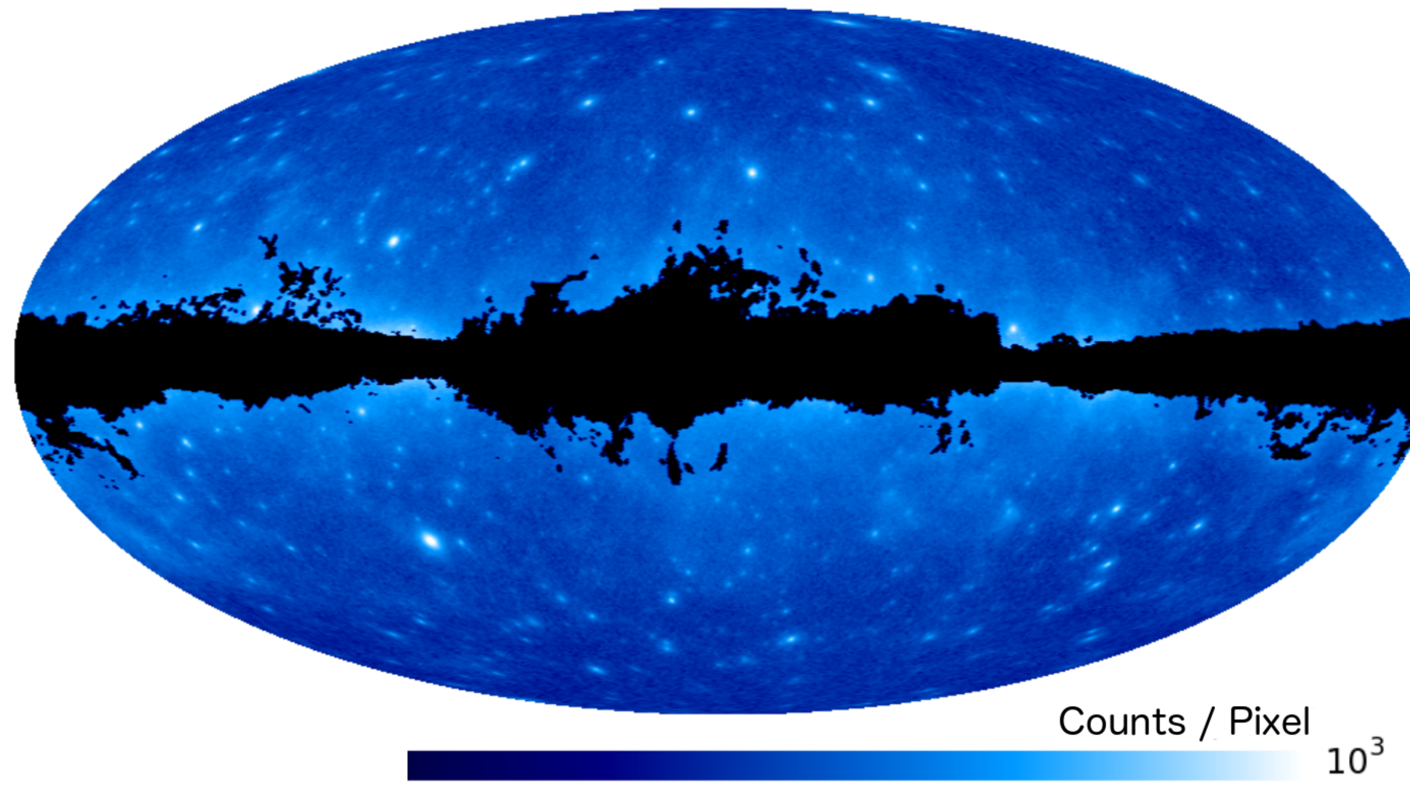
Take-home message 1

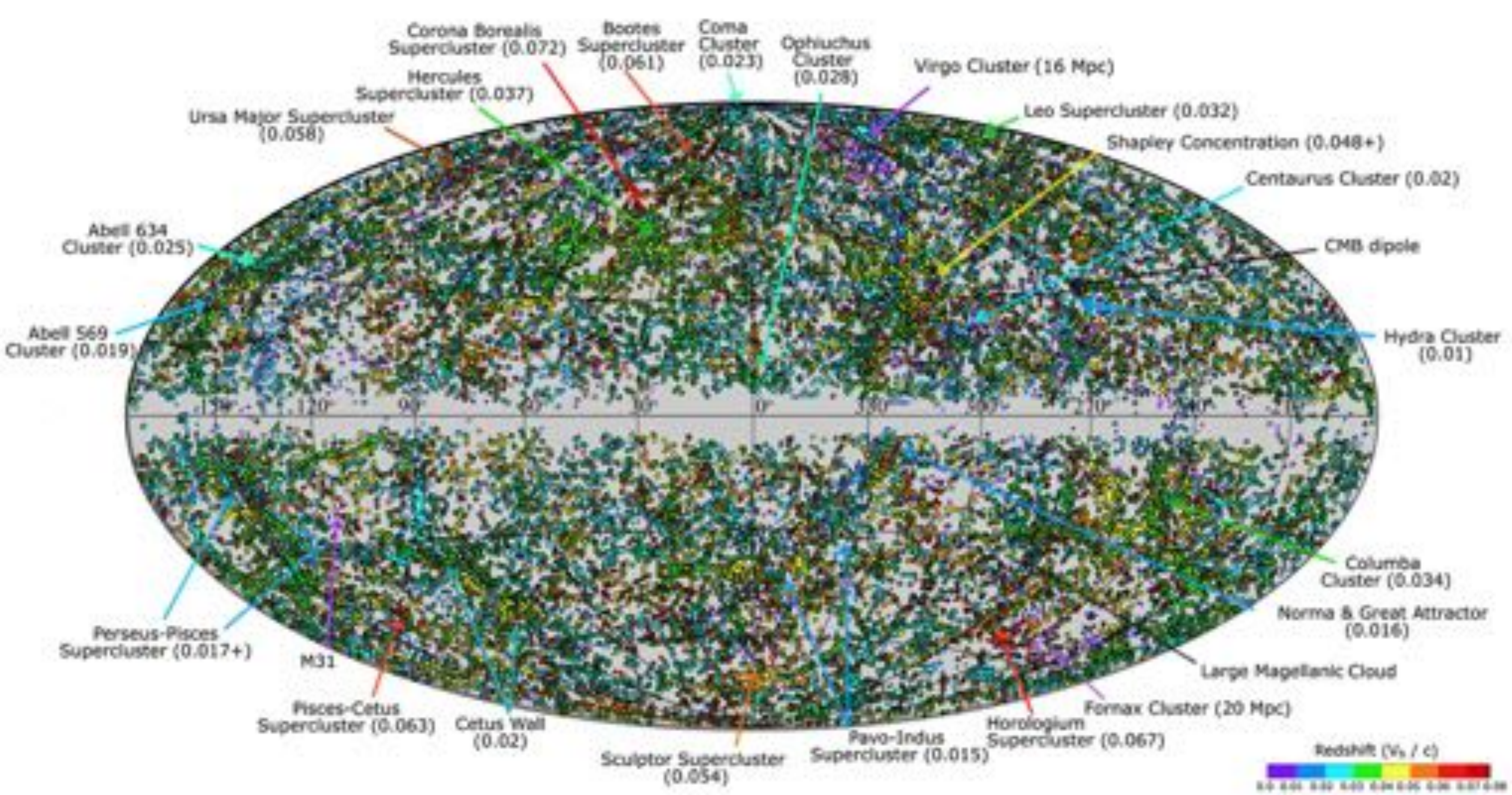
- Fermi and IceCube found diffuse backgrounds of gamma rays and neutrinos, respectively
- Star-forming and **starburst galaxies can explain the IceCube neutrinos**, if protons can be accelerated up to tens of PeV, as well as the IGRB
- **Clusters of galaxies**, formerly believed to be a strong high-energy emitter, **cannot contribute to the both backgrounds significantly**, because of radio and gamma-ray constraints for individual sources (such as Coma)

Cross correlation with galaxy distribution

Tomographic constraints on neutrinos



Fermi-LAT, *Astrophys. J.* **799**, 86 (2015)

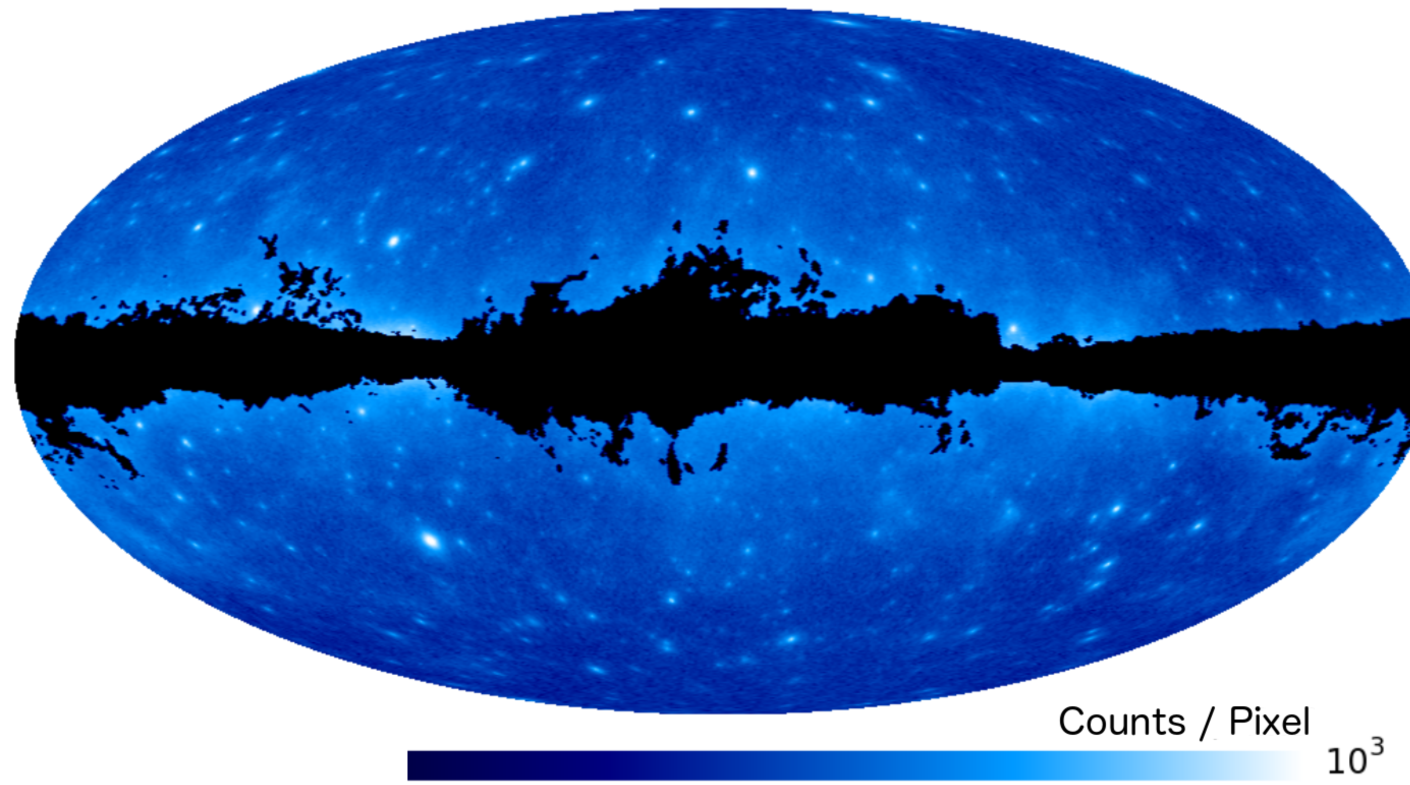


Huchra et al., *Astrophys. J. Suppl. Ser.* **199**, 26 (2011)

Cross correlation with galaxy distribution

Tomographic constraints on neutrinos

Are these two maps similar to each other?



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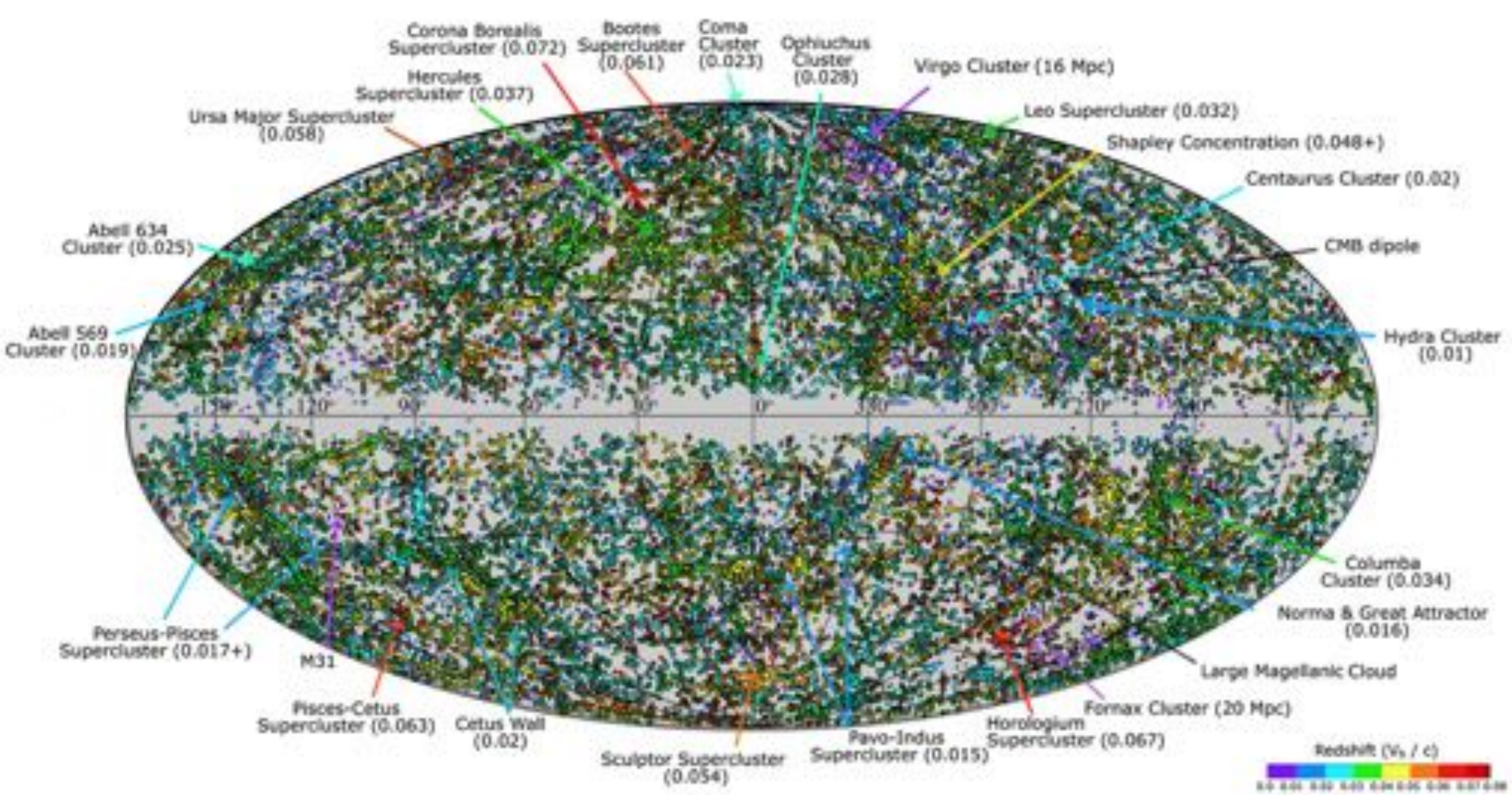

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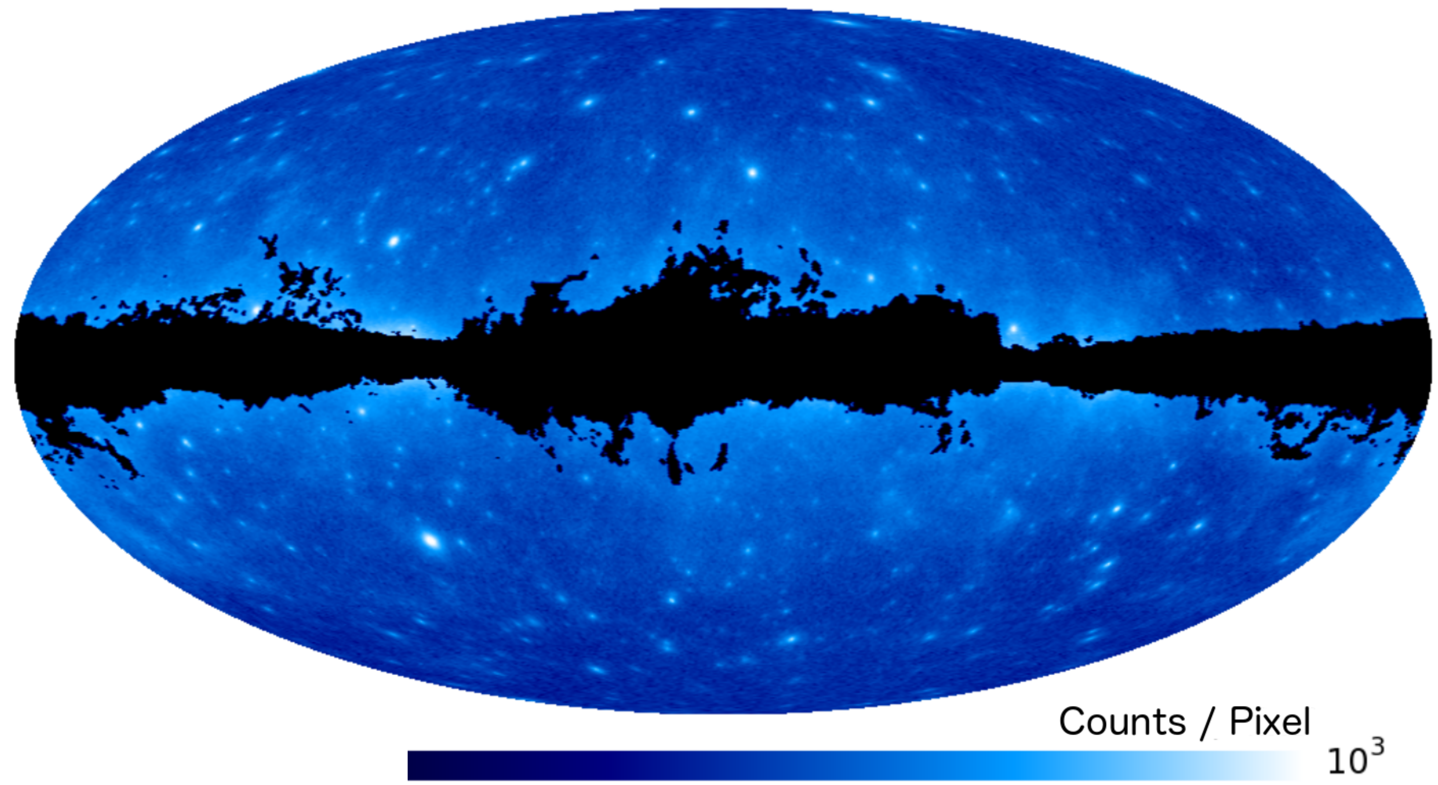
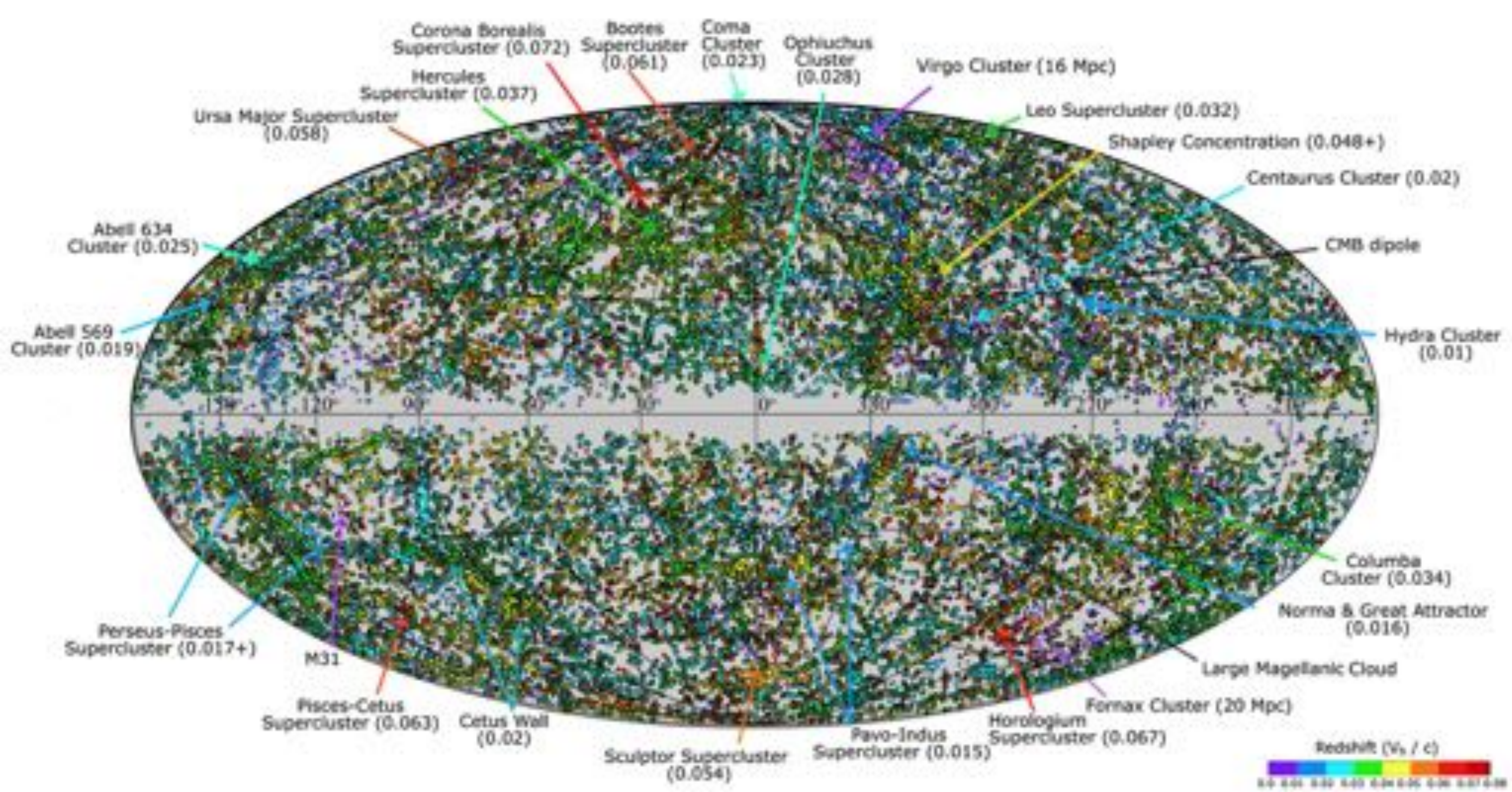


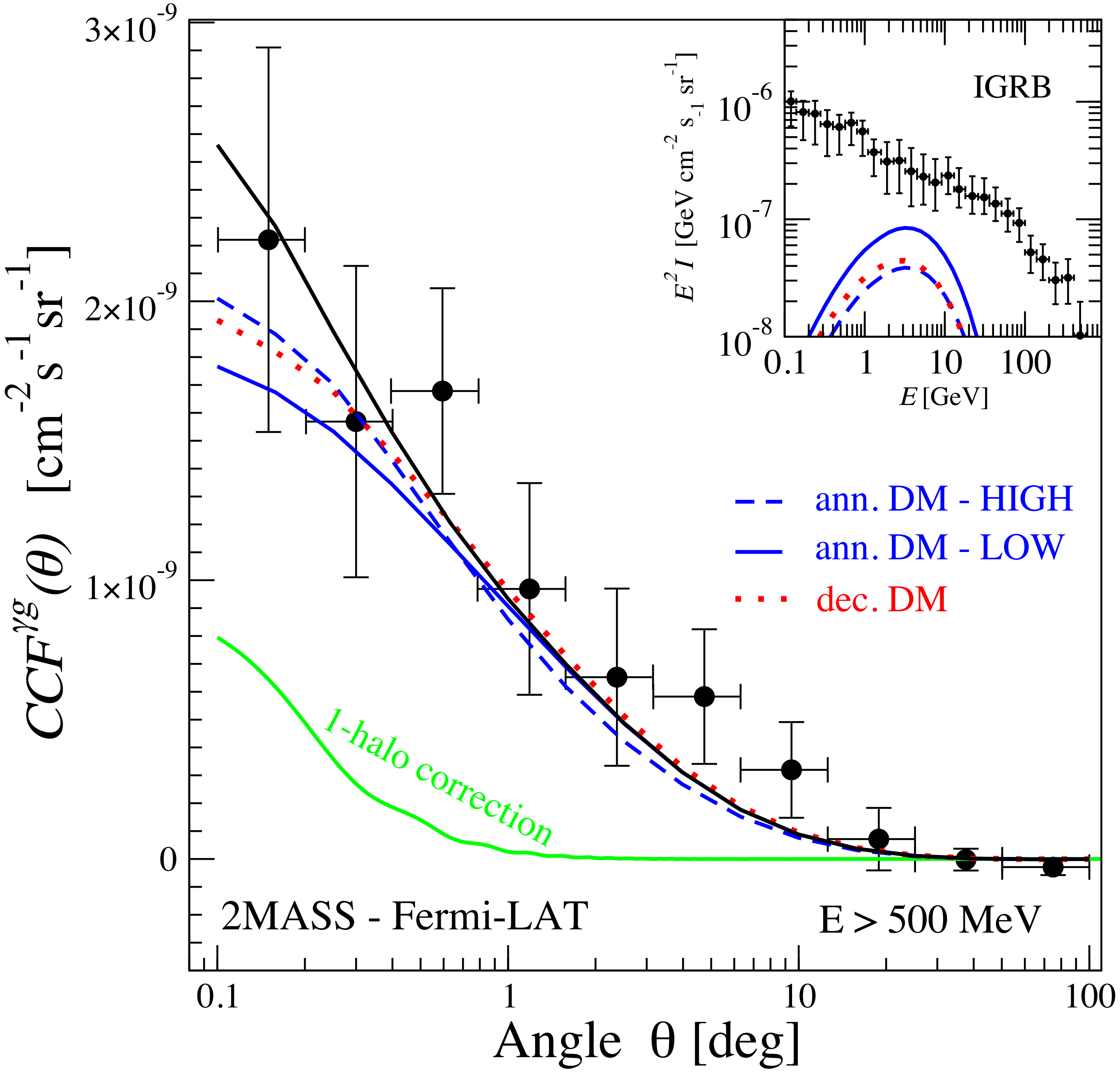
Fermi-LAT, *Astrophys. J.* **799**, 86 (2015)



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



Regis et al., *Phys. Rev. Lett.* **114**, 241301 (2015)

- Yet another probe of gamma-ray sources due to recent 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!*

Application to neutrinos: Assumptions

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1. Energy **spectrum** is power law

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

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

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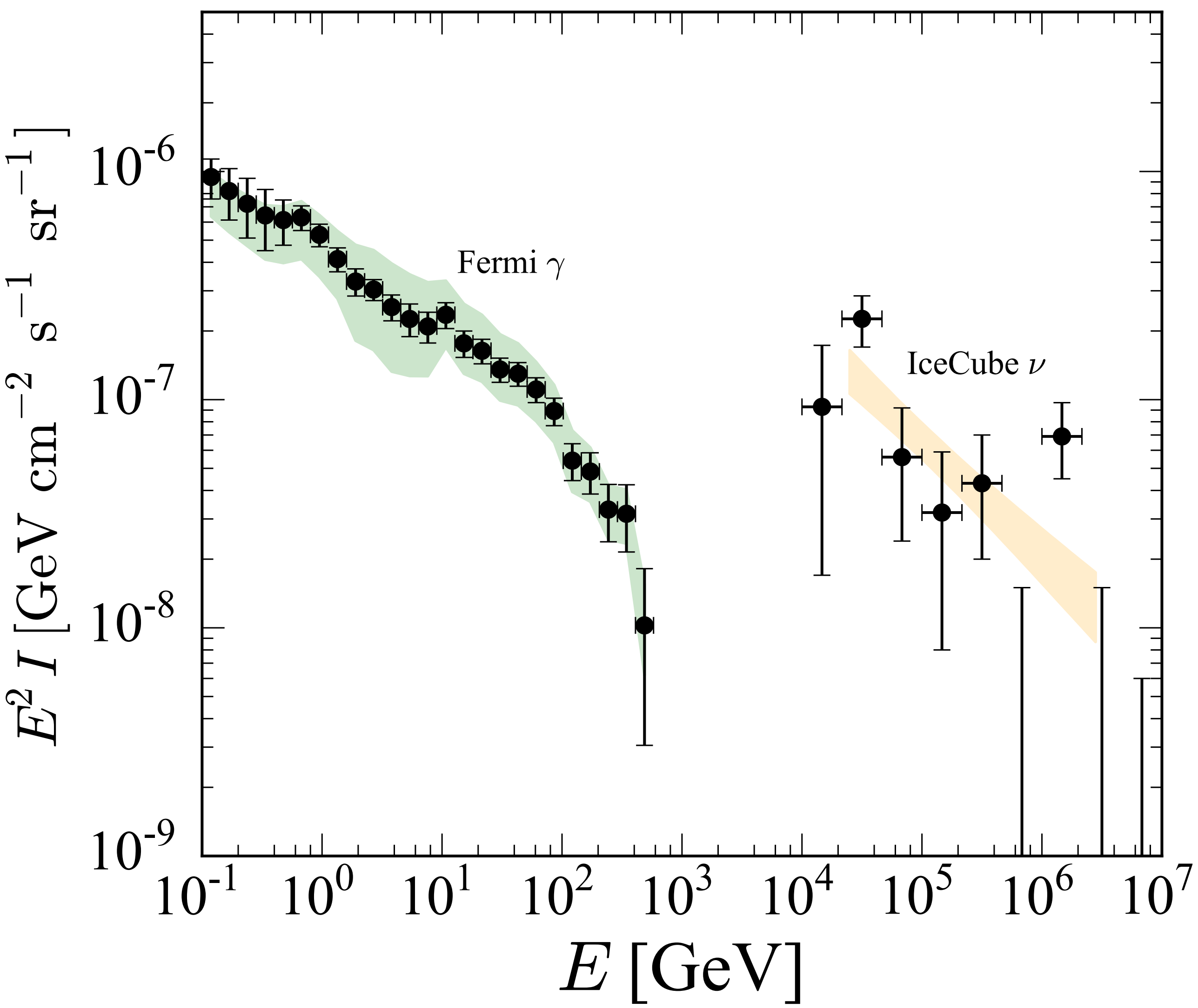
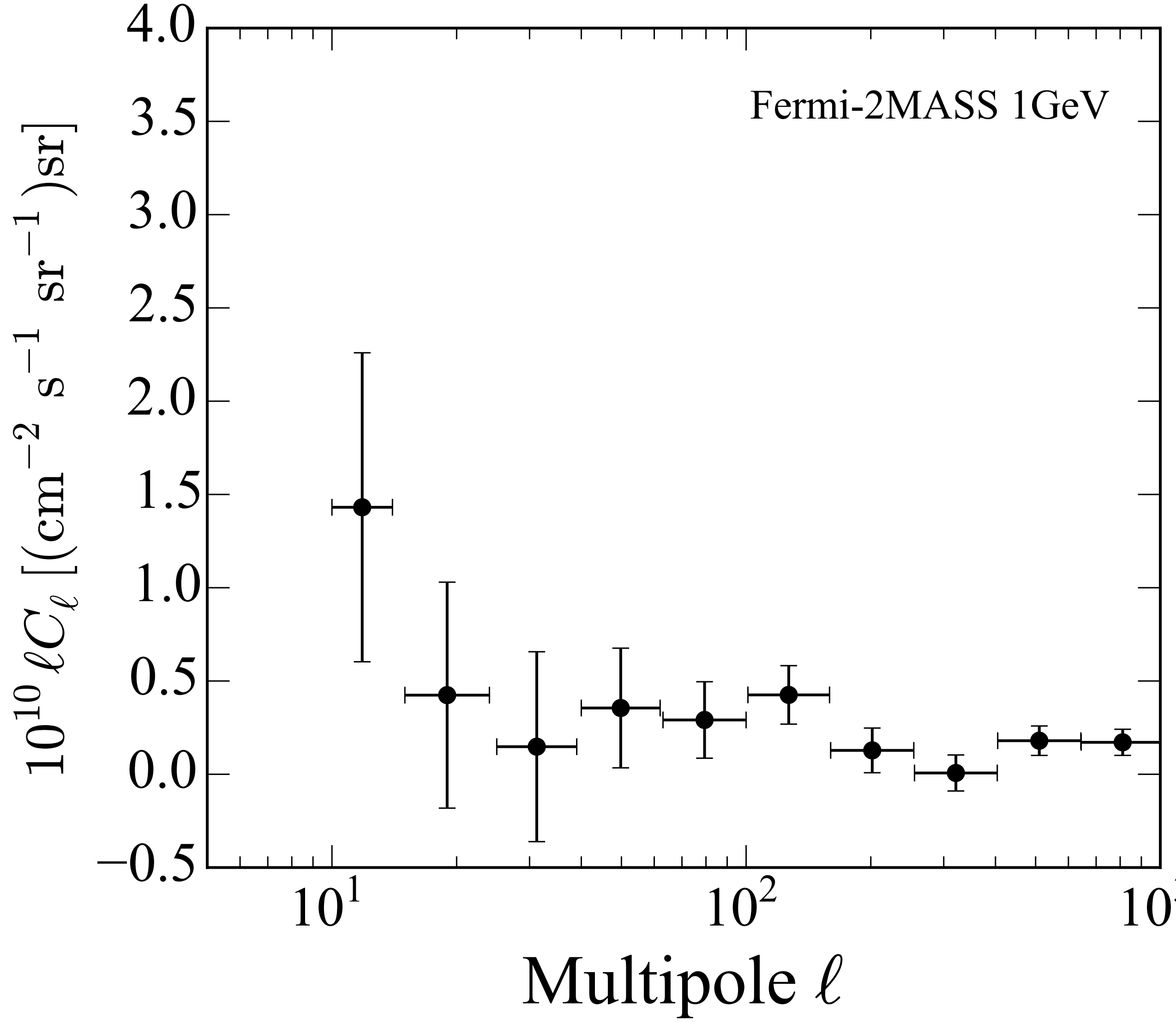
3. Sources **trace underlying dark matter** distribution in an unbiased way

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

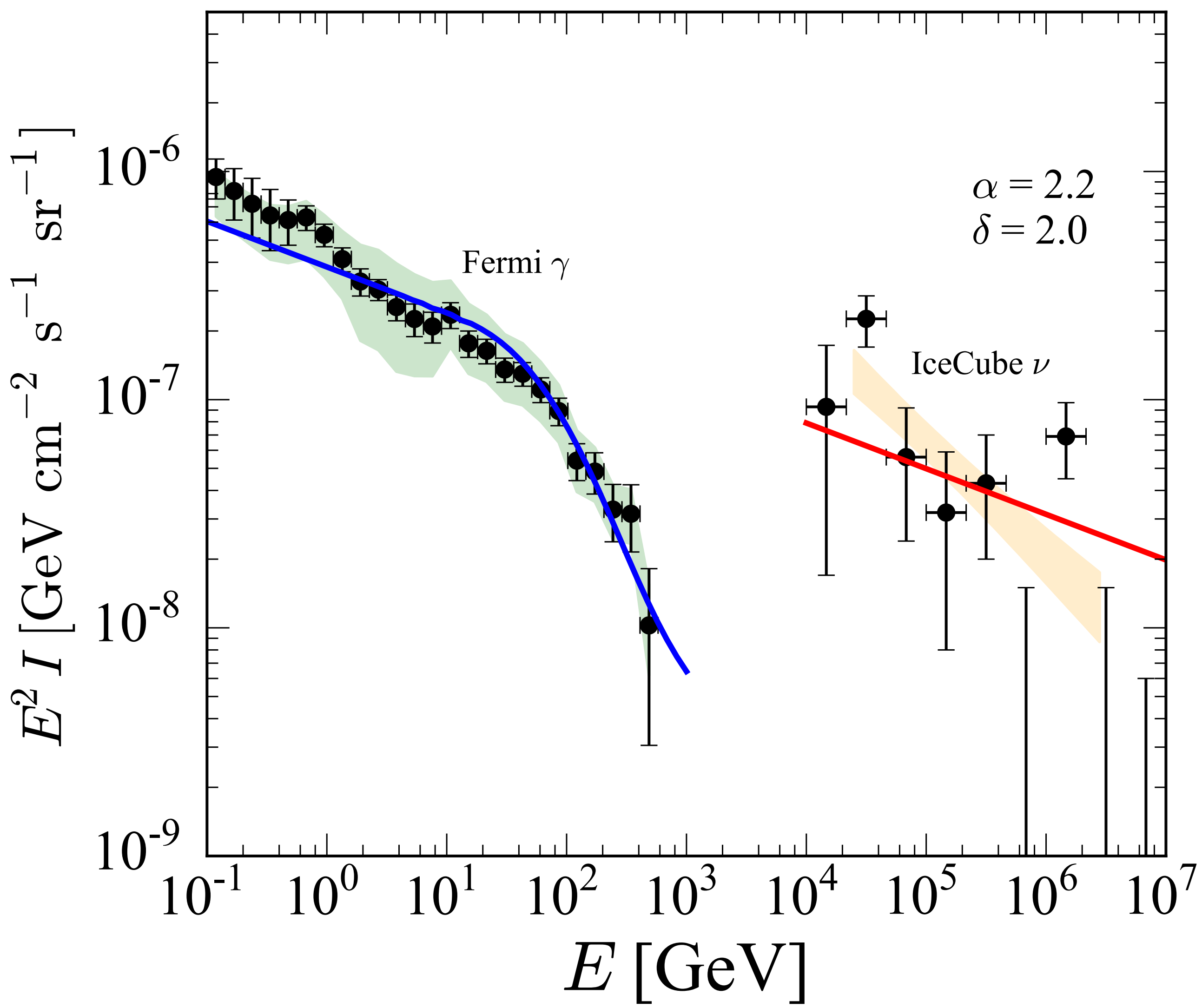
Spectral constraints

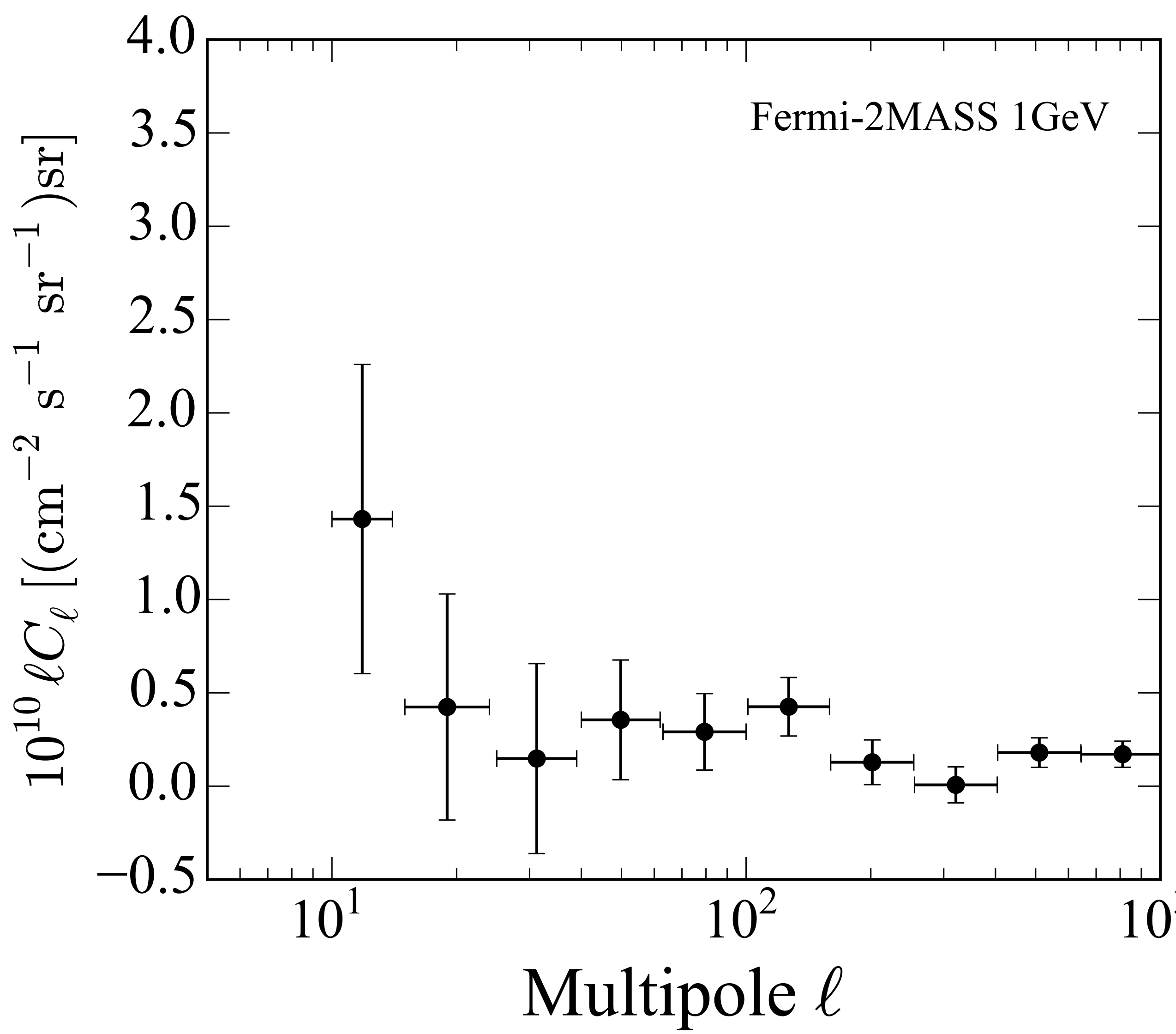




Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

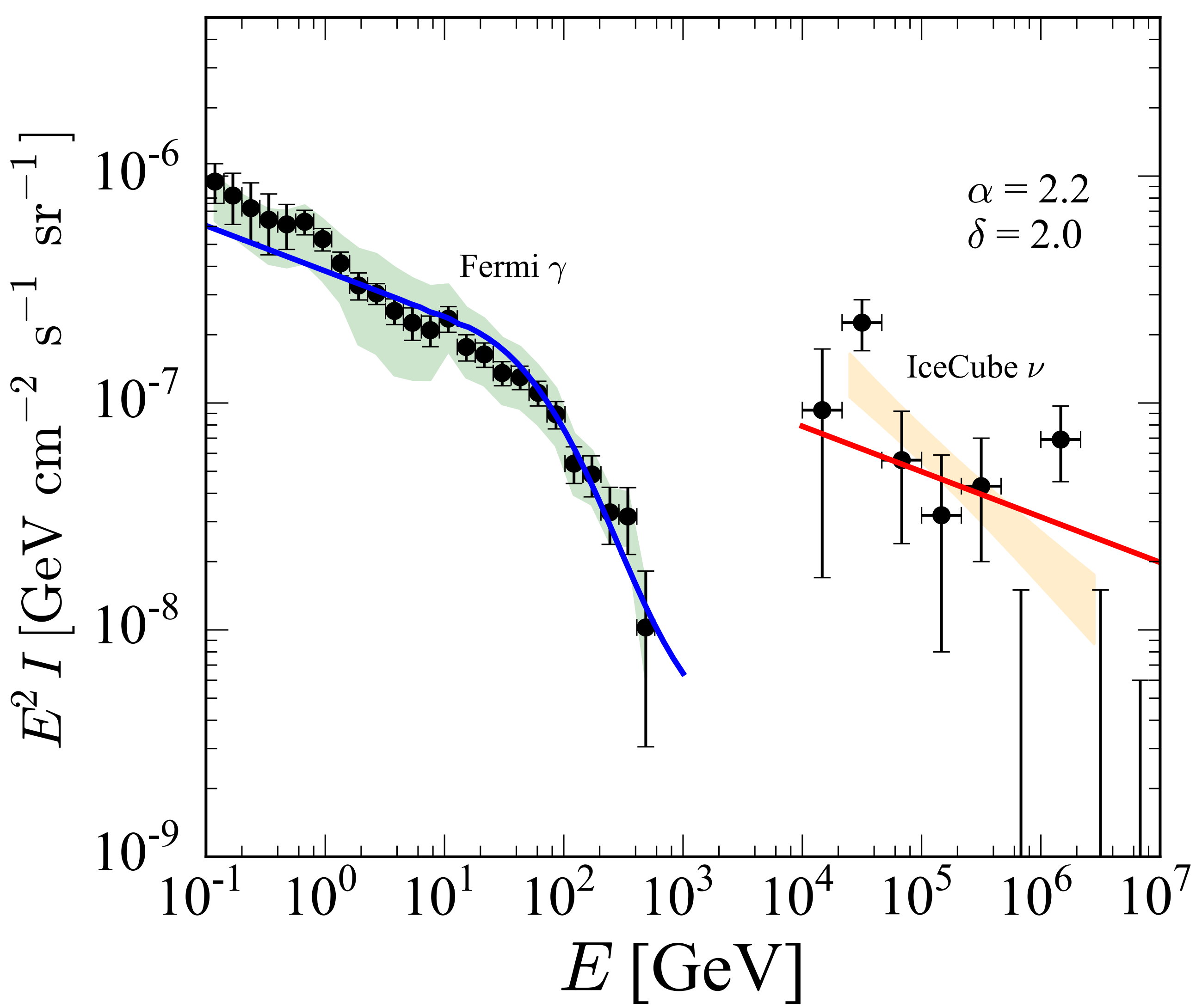
Spectral constraints

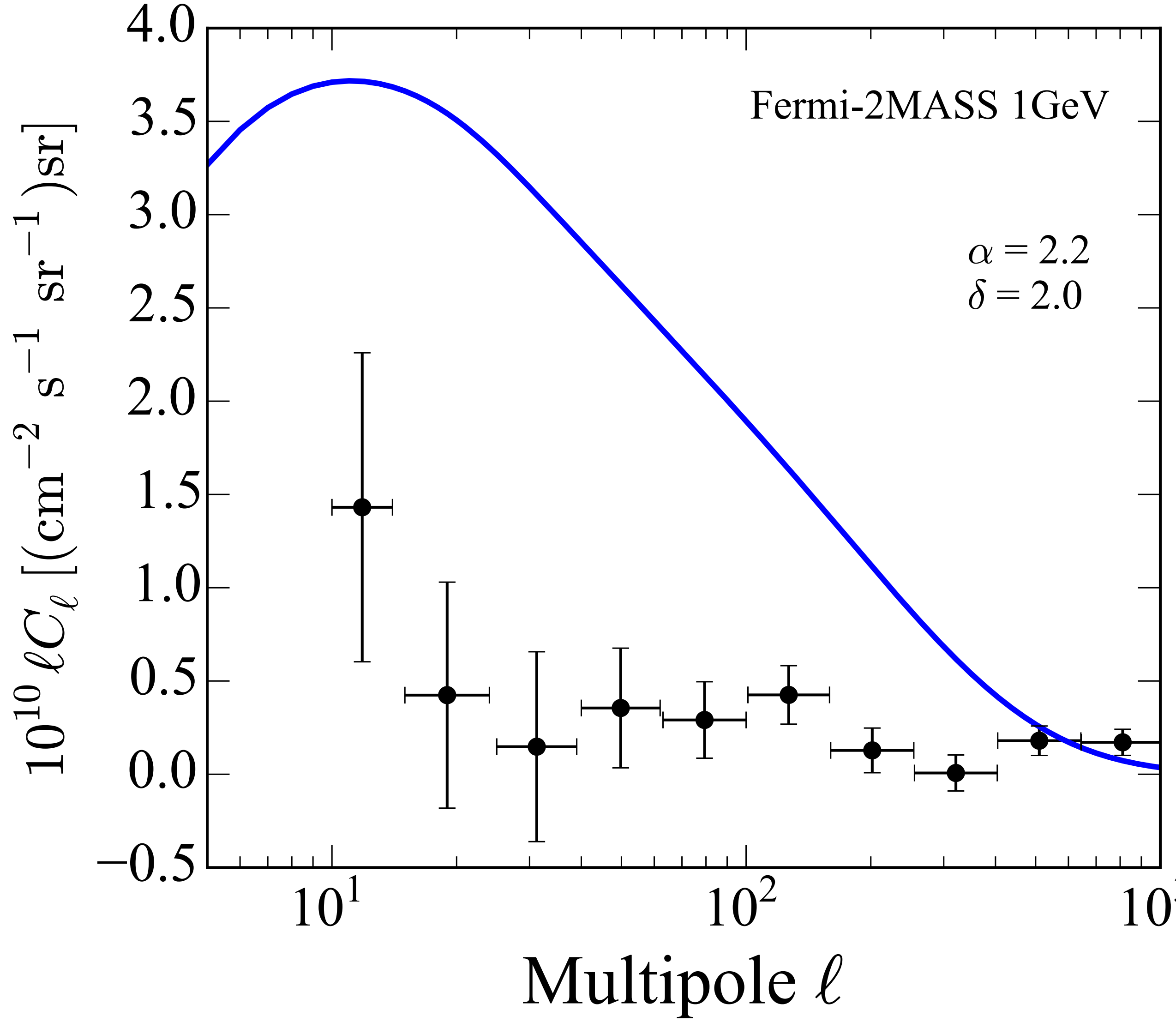




Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

Spectral constraints





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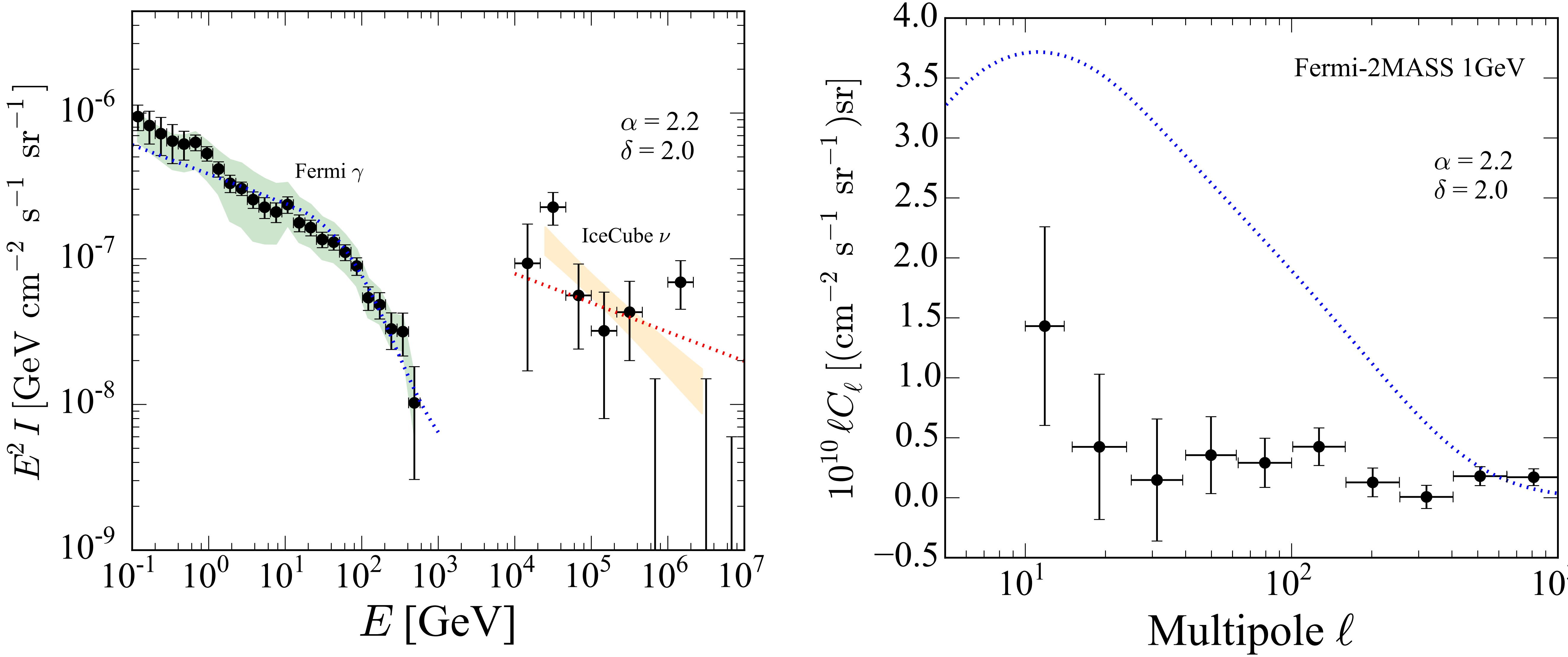
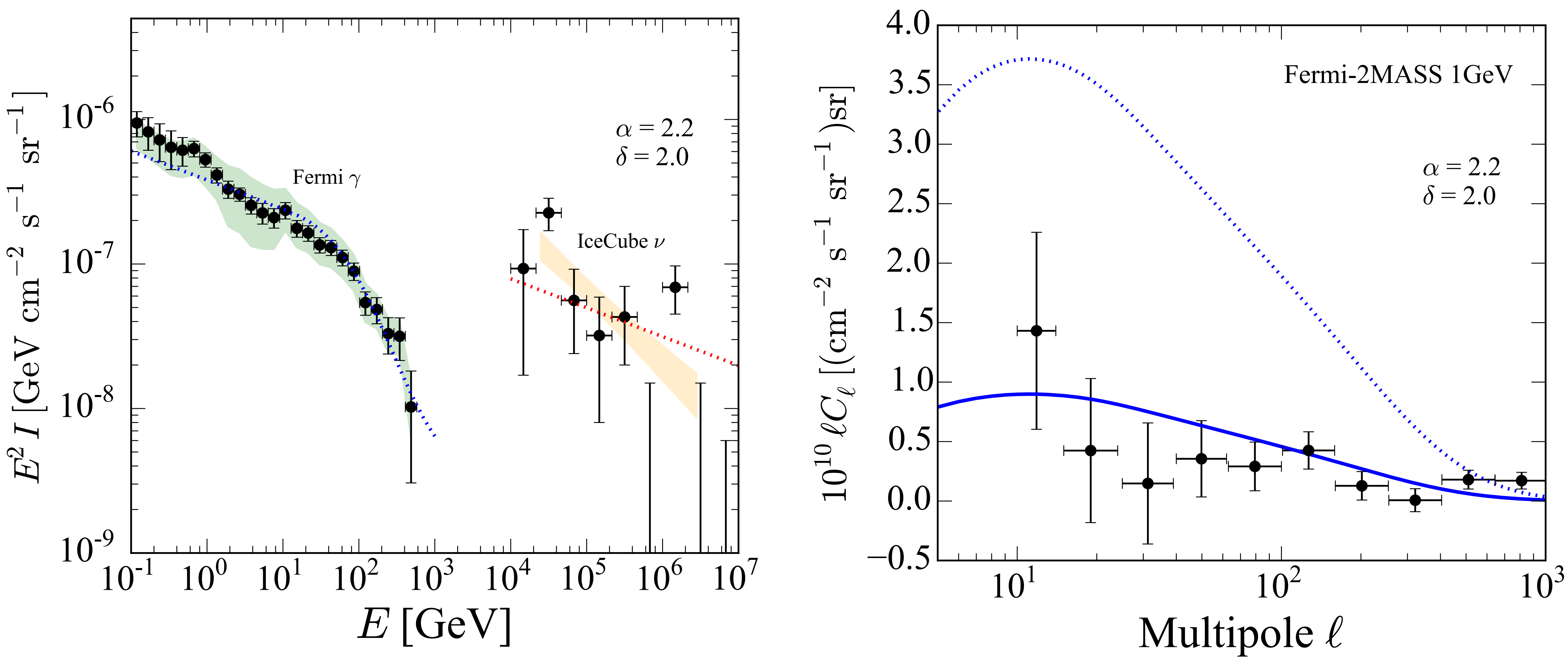
Tomographic constraints



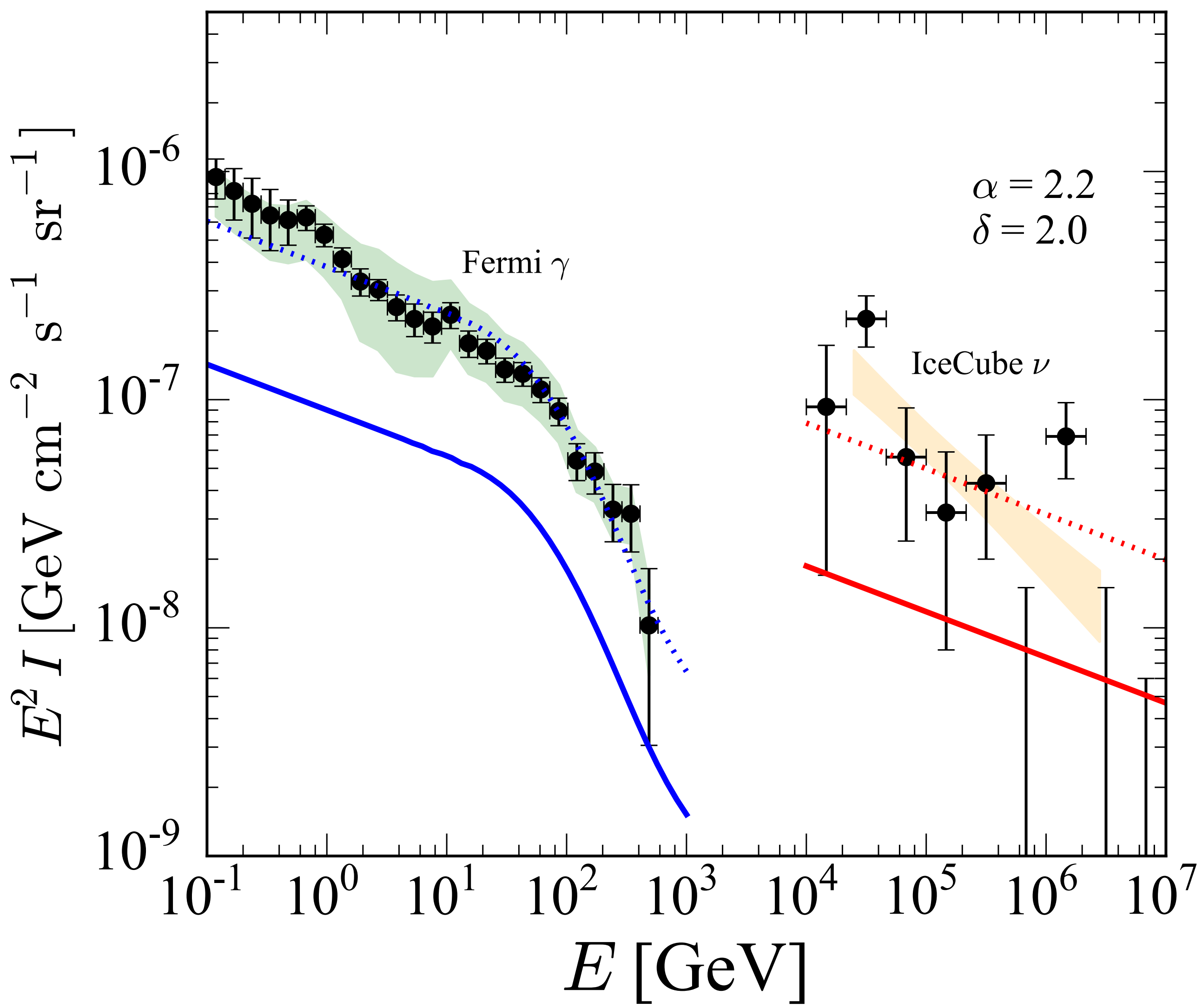
Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

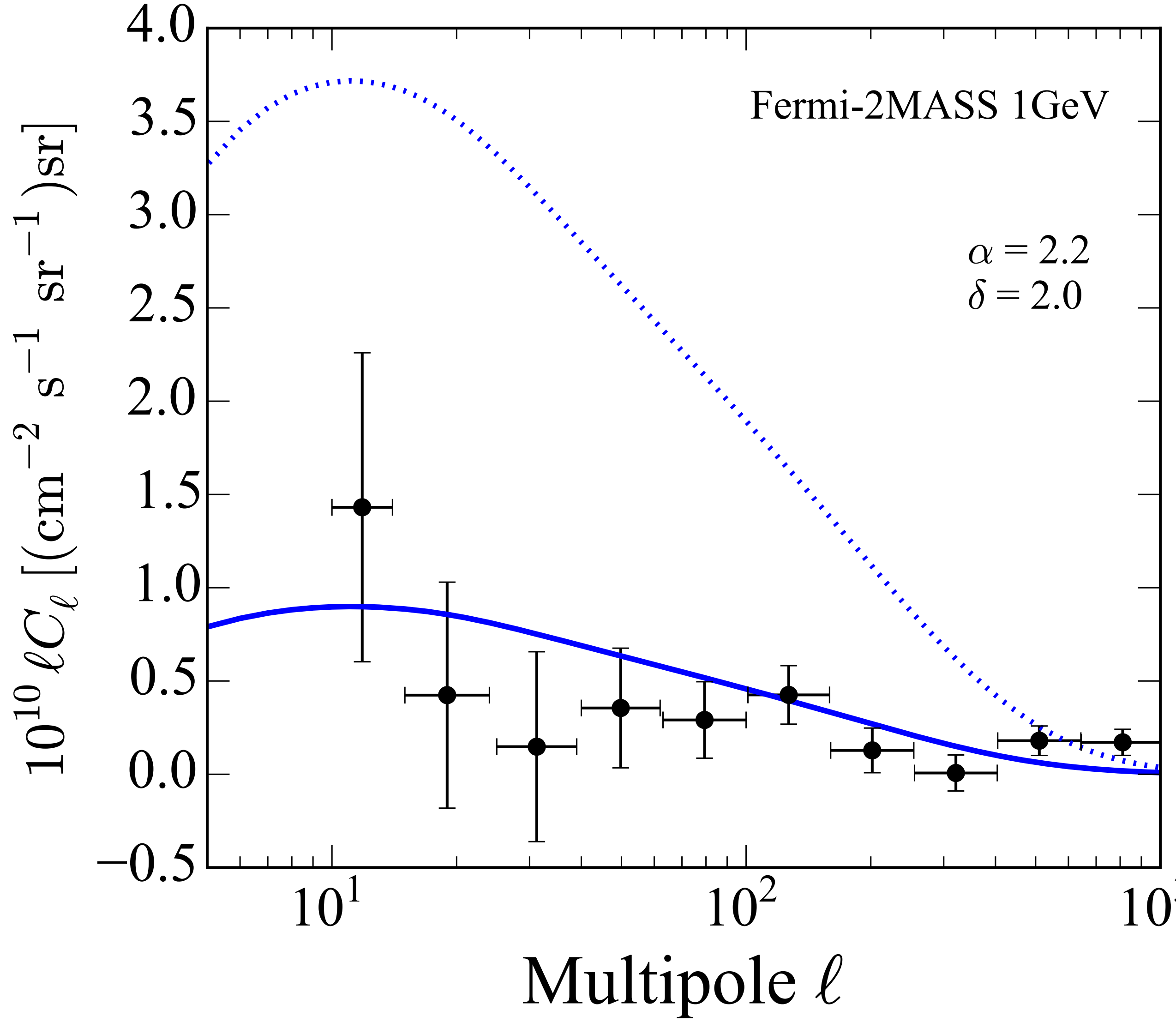
Tomographic constraints



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

Tomographic constraints





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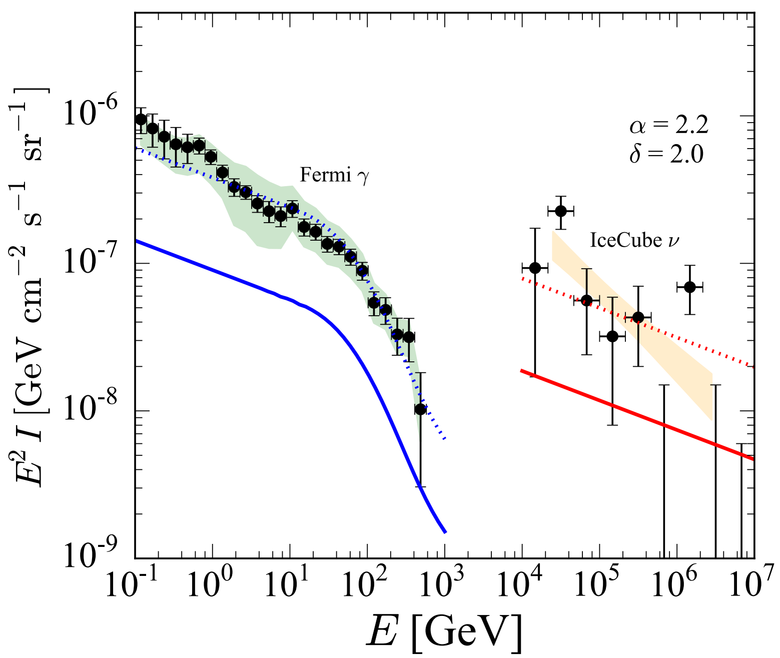
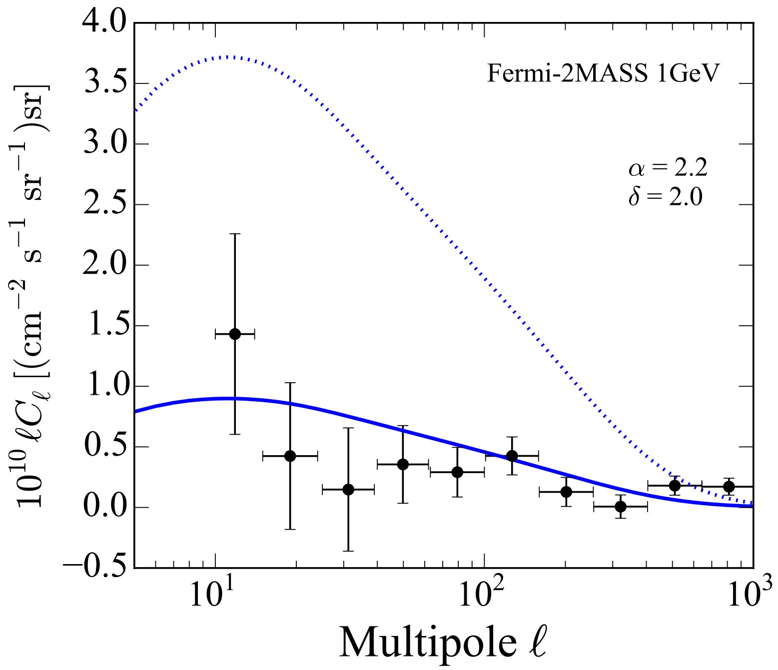
Dependence on **α** and **δ**

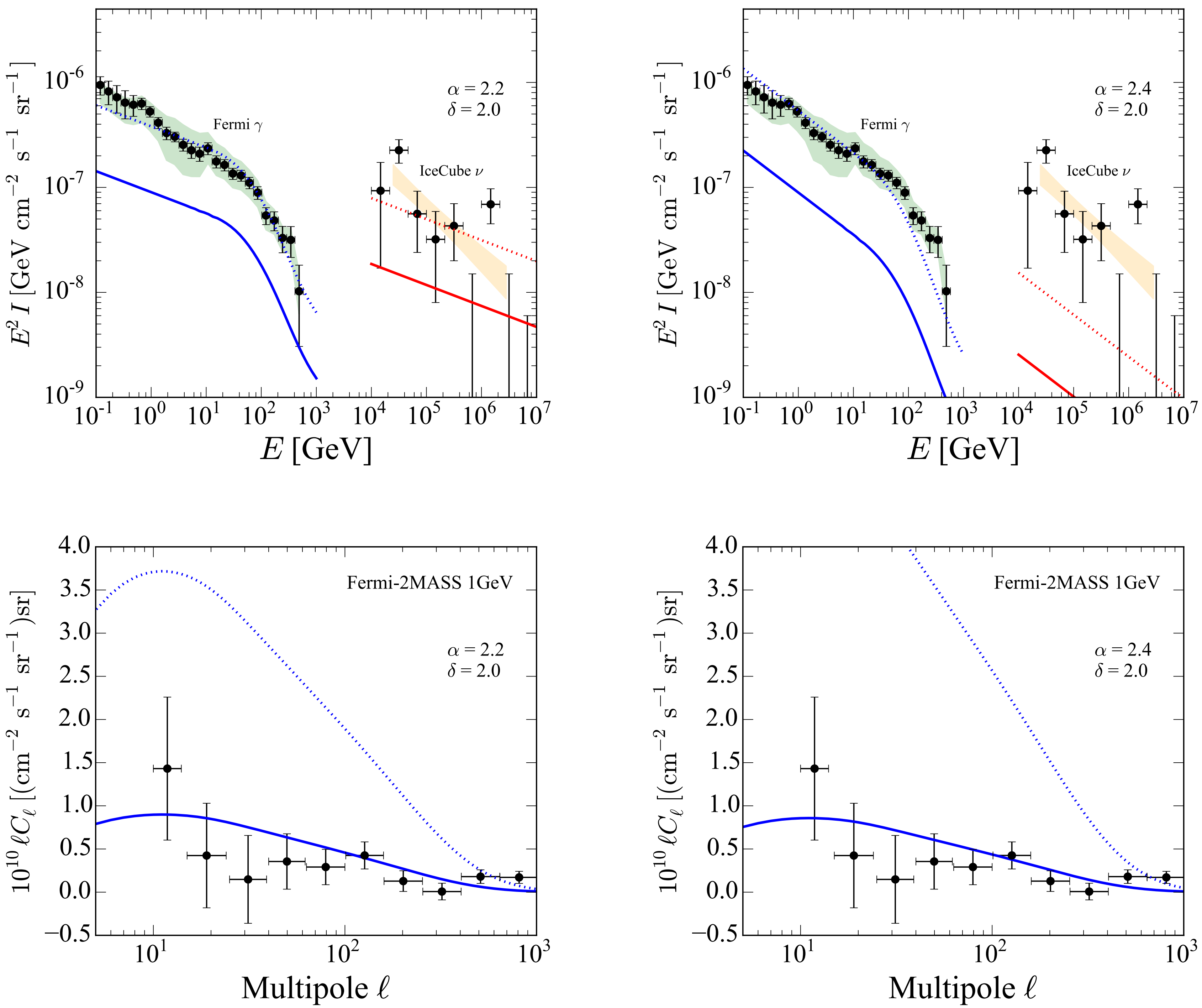




Ando, Tamborra, Zandanel, *Phys. Rev. Lett.* **115**, 221101 (2015)

Dependence on **α** and **δ**

Soft spectrum



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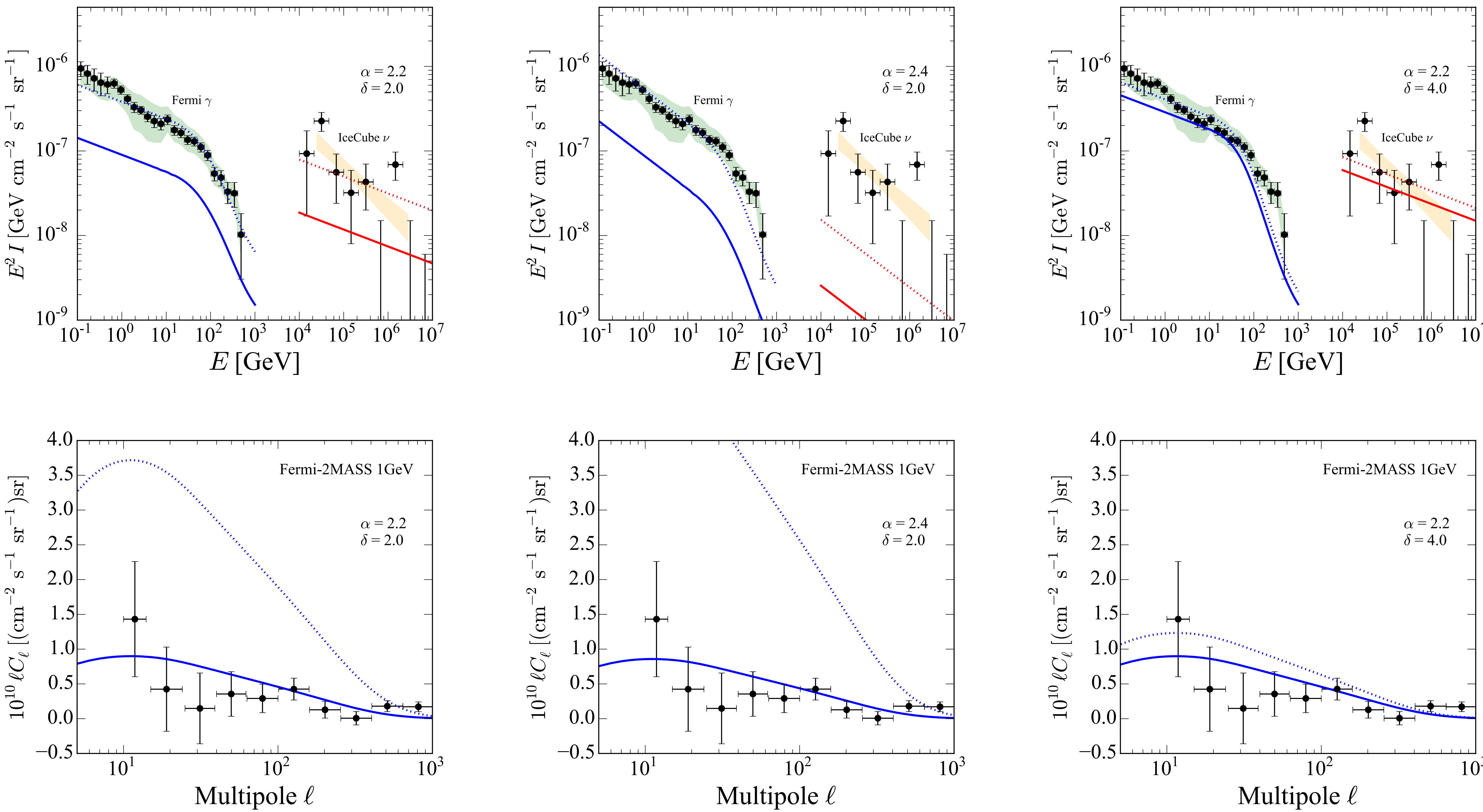
Dependence on α and δ

Soft spectrum | **Fast evolution**



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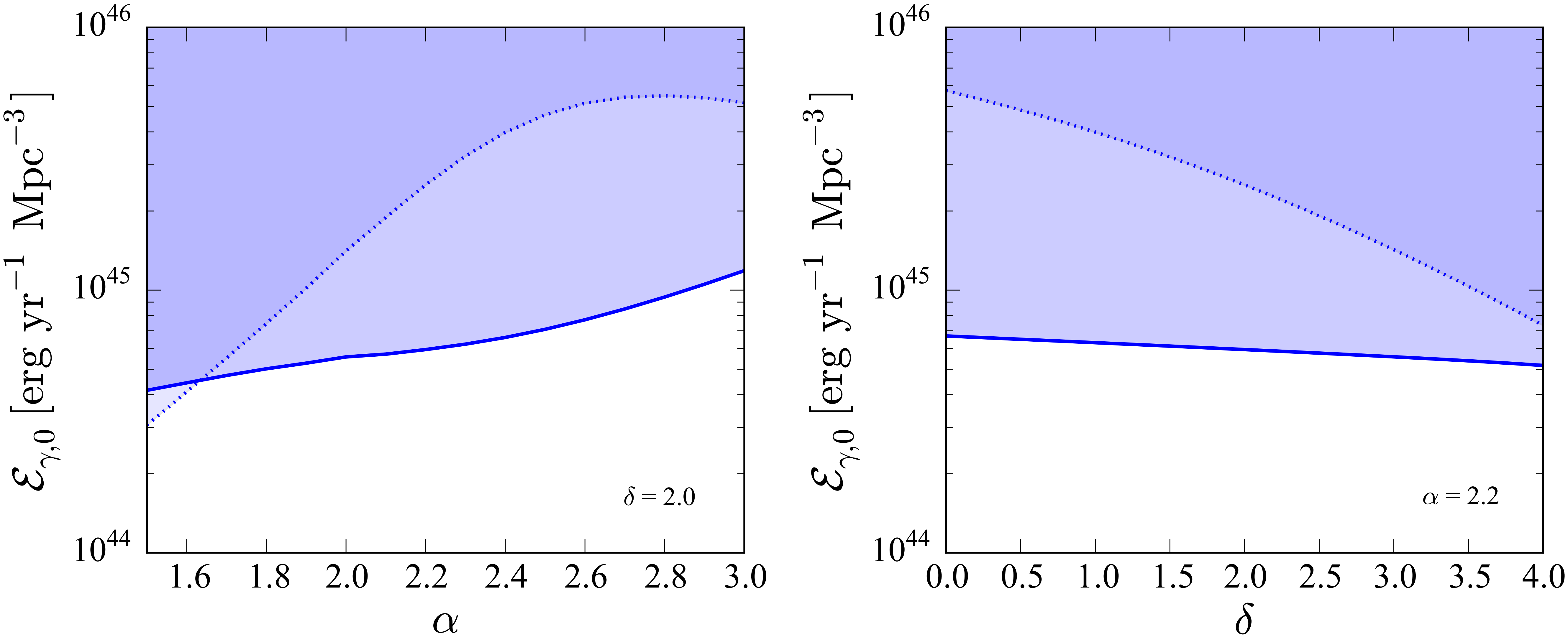
Constraints on gamma-ray luminosity density



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

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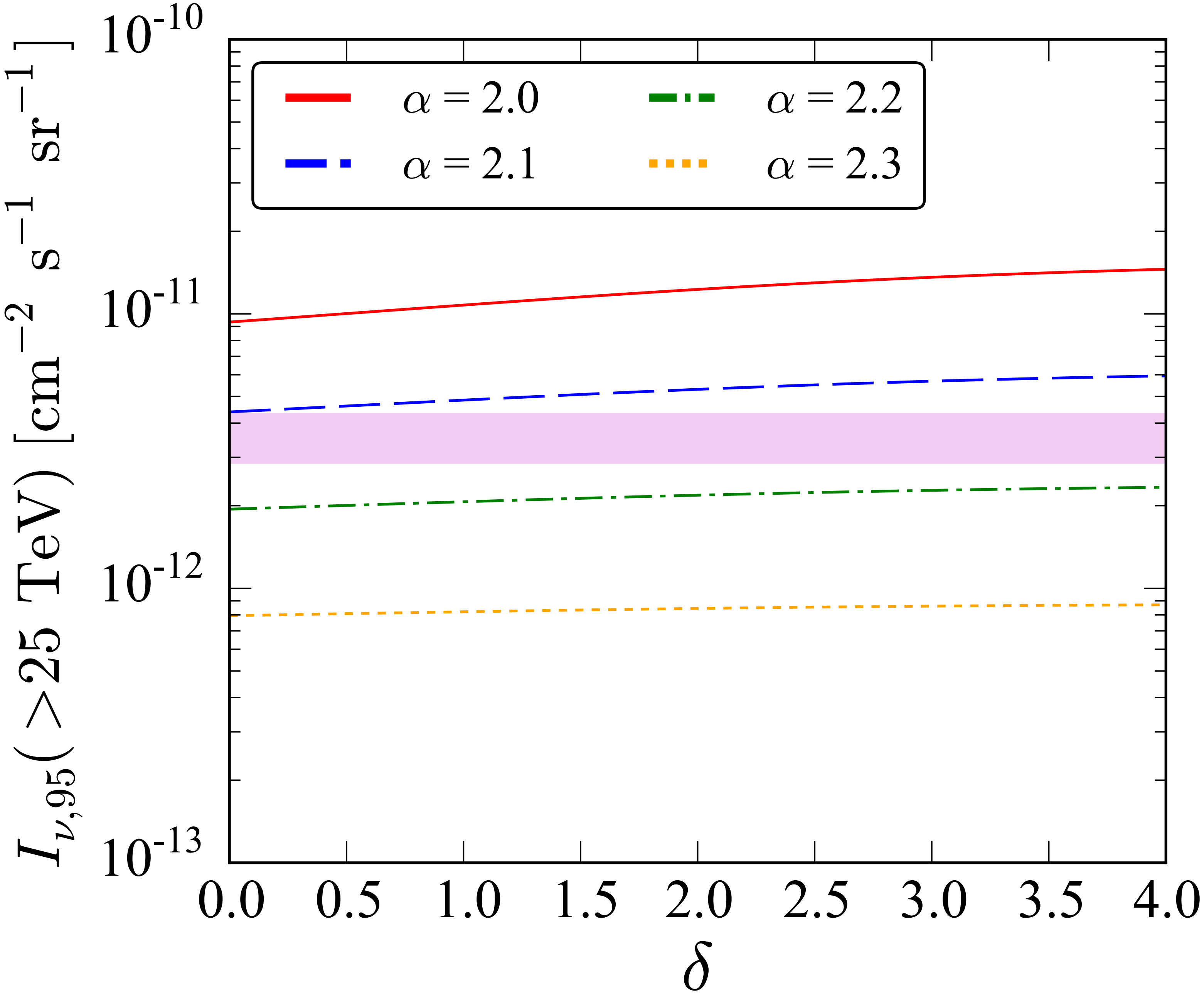
Constraints on high-energy neutrinos



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

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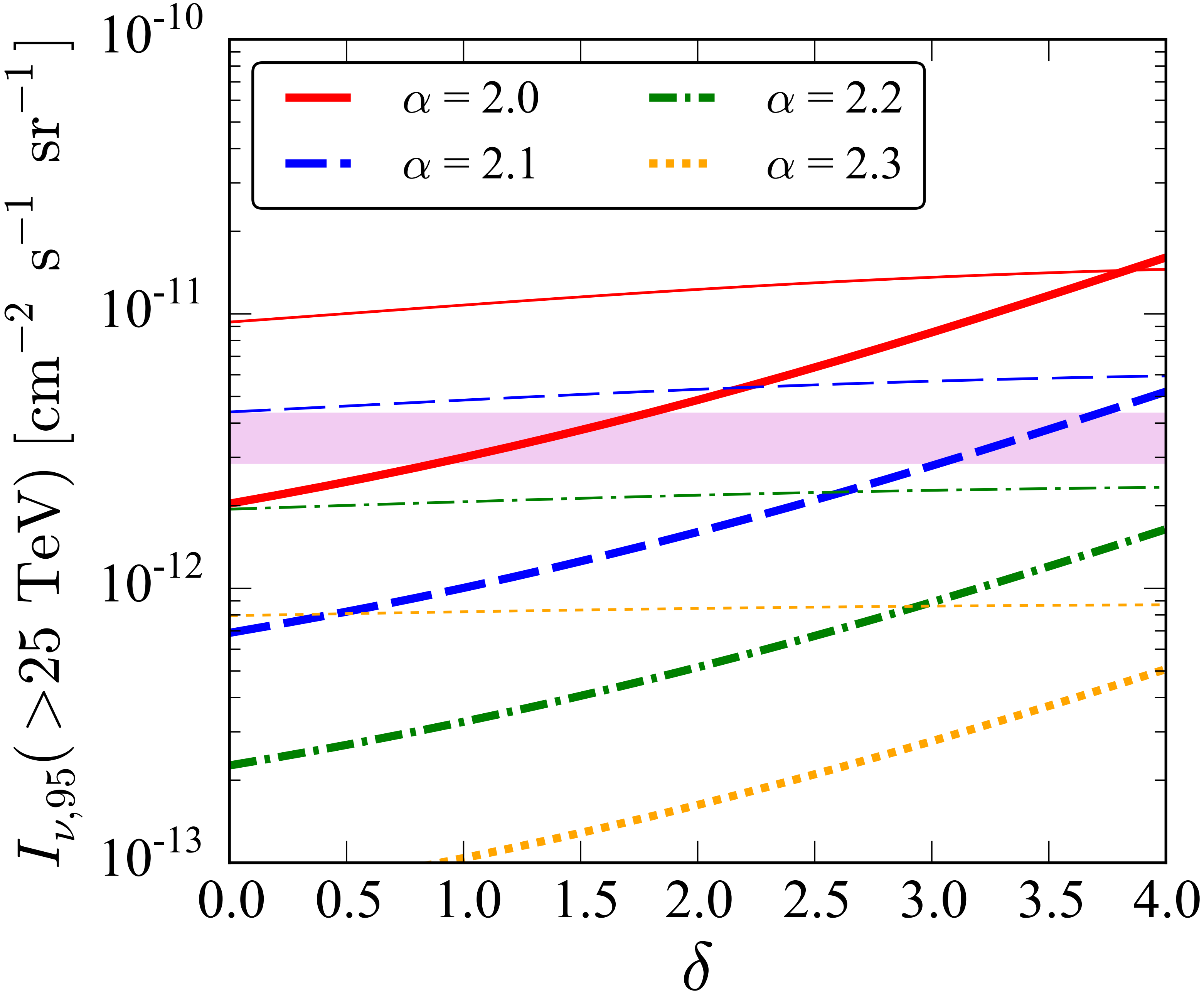
Constraints on high-energy neutrinos



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

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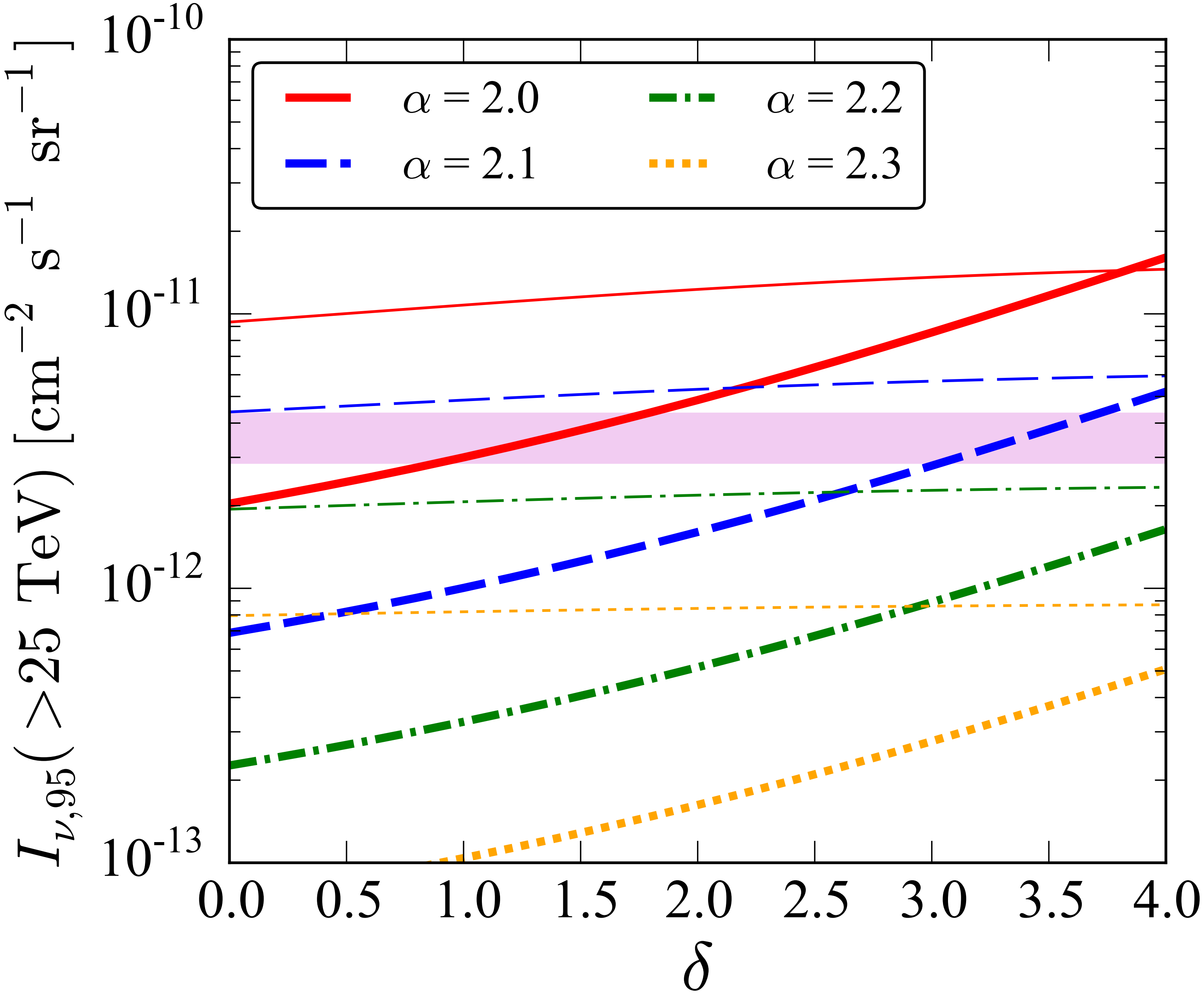
Constraints on high-energy neutrinos



- Spectral constraints: α has to be smaller than ~2.2
- Tomographic constraints:
  - If δ is smaller than ~3, source with spectrum softer than $E^{-2.1}$ is disfavored

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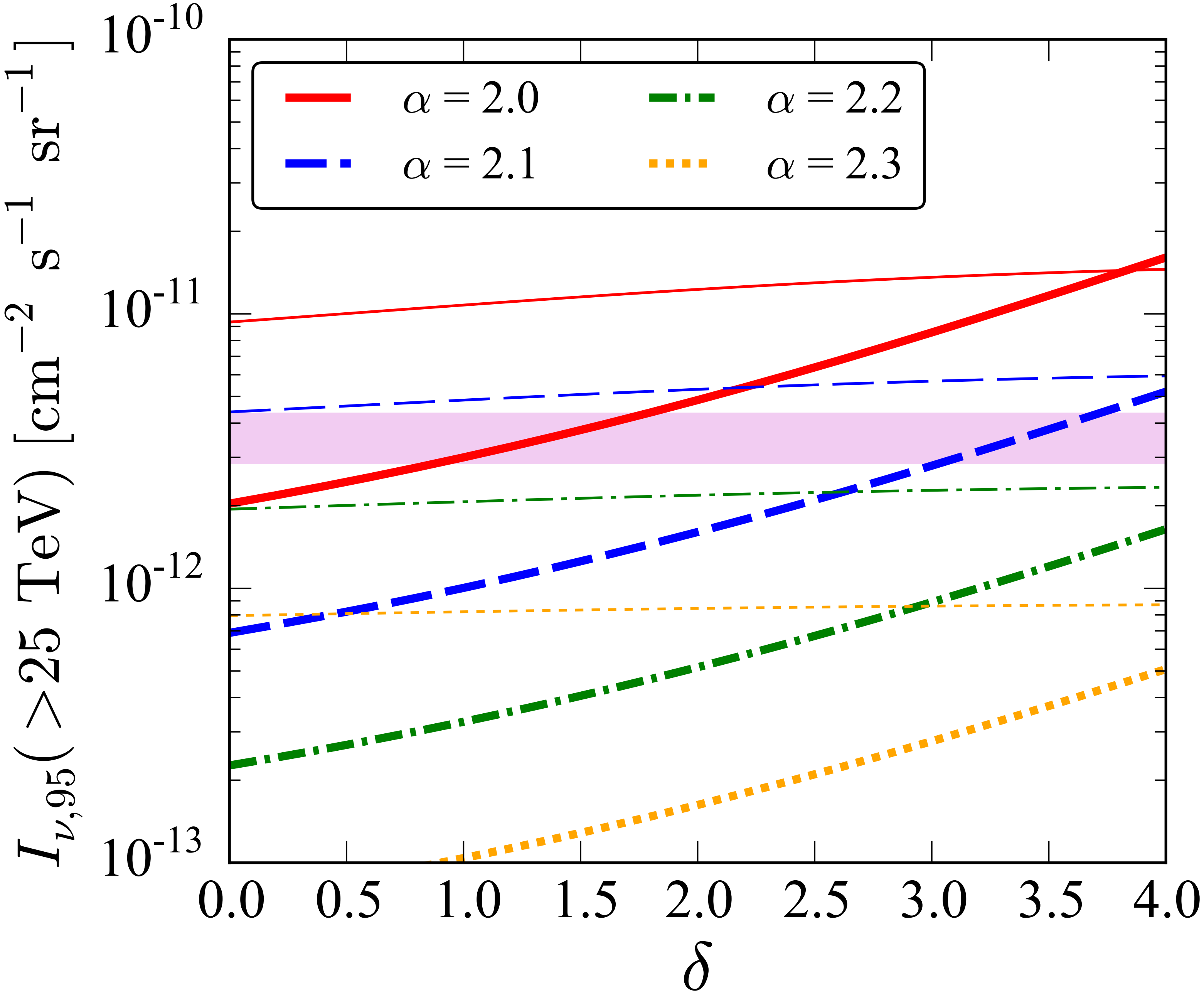
Constraints on high-energy neutrinos



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

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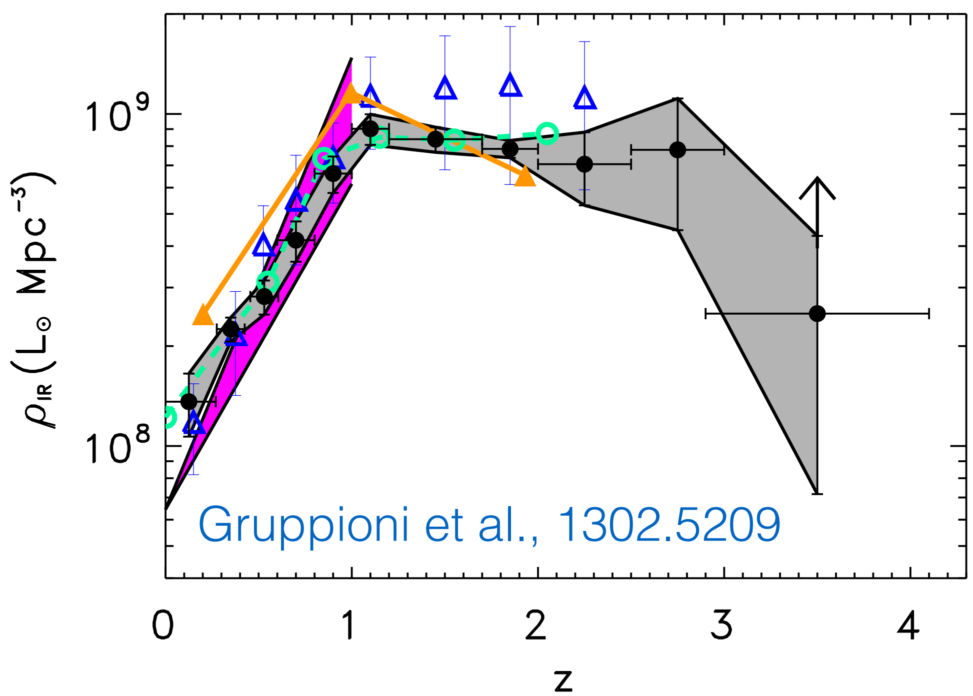
Possible pp sources

Star-forming/starburst galaxies

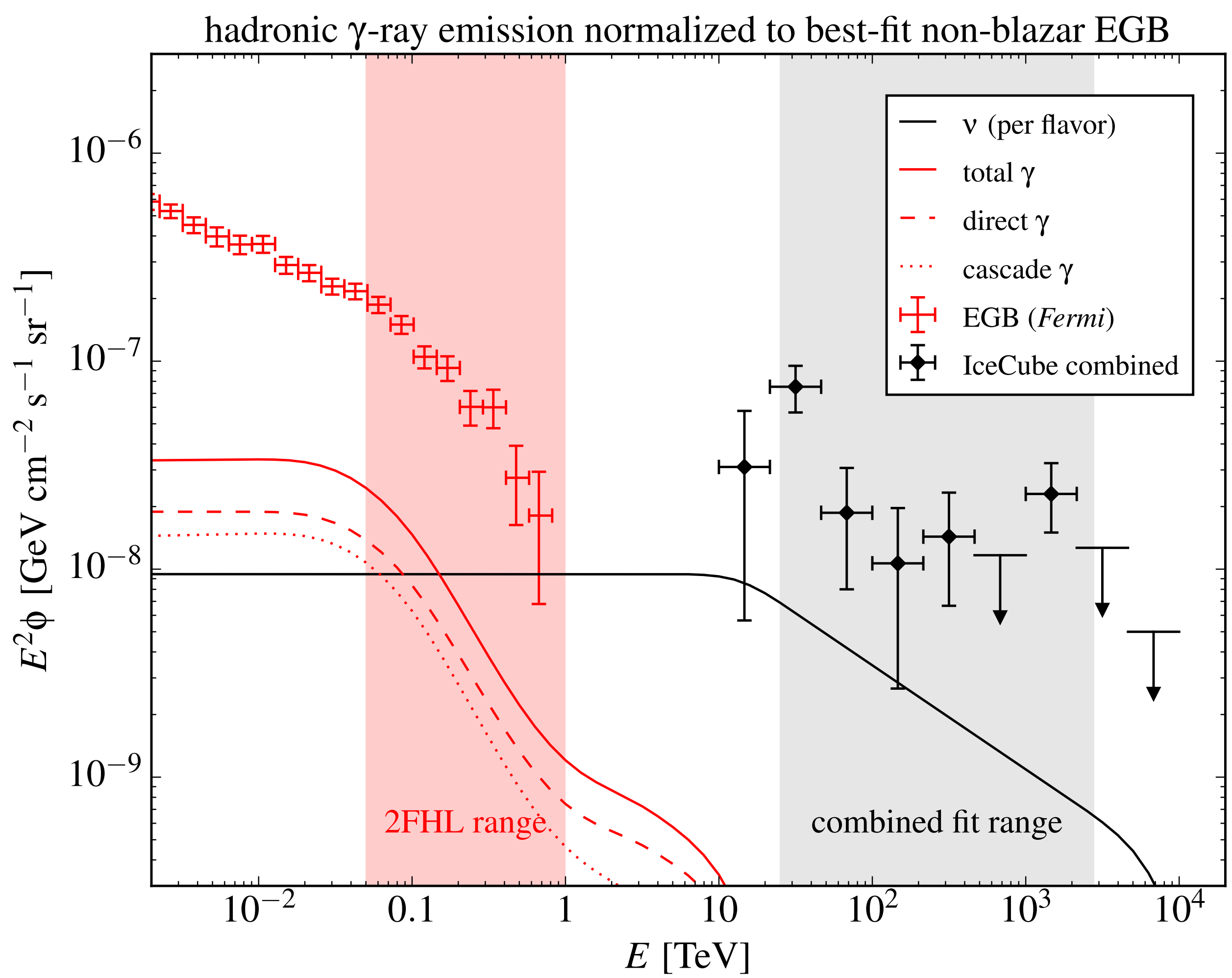


- No direct measurement of δ yet
- Infrared luminosity density suggests δ ~ 3–4

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)

What if blazars explain most IGRB data?

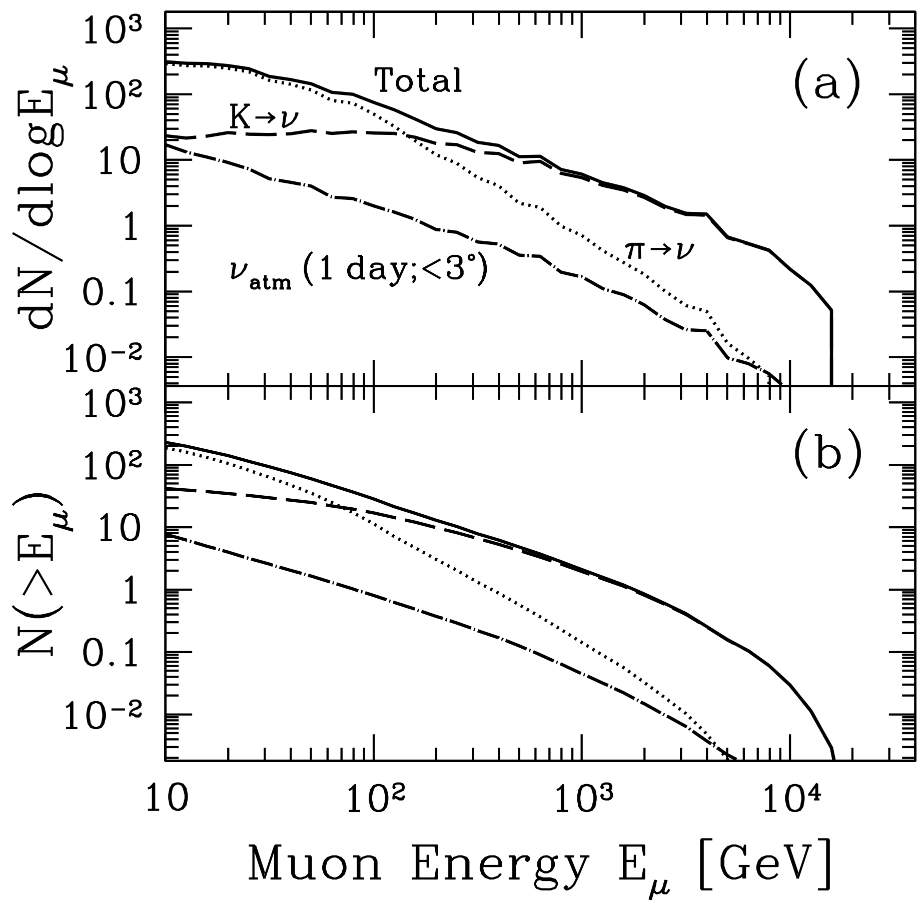


Bechtol et al., 1511.00688

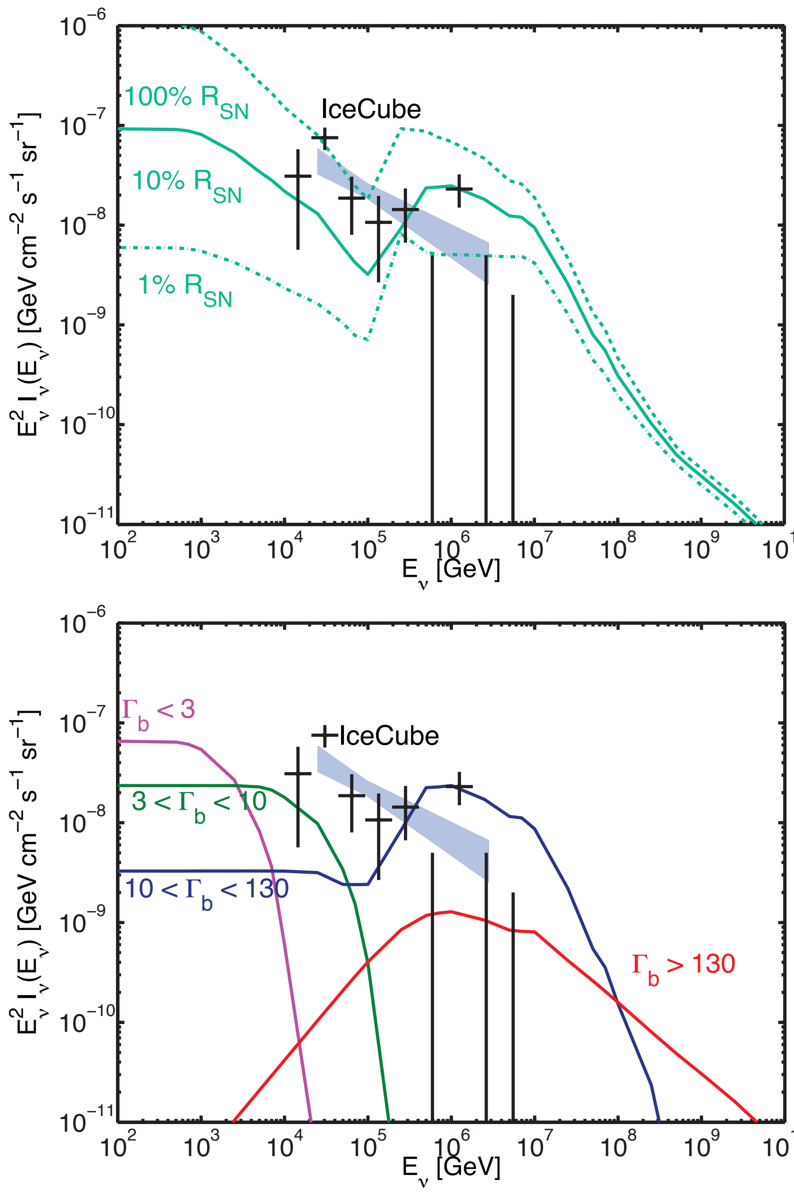
- Blazars might be responsible for ~85% of IGRB spectrum above 50 GeV (Fermi-LAT, 1511.00693)
  - If so, only very hard sources (α ~ 2) are allowed as the origin of the IceCube neutrinos
- Maybe such hard sources are disfavoured by IceCube data??
  - If so, any pp sources are highly disfavoured

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

Take-home message 2

- 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})

Three ***constraints*** discussed

	SFG/SB	Galaxy clusters	Other pp sources	Conclusion
Gamma-ray (non)detection	✓	✓		SB prefrred
Radio number count		✓		Clusters disfavored
Cross correlation with galaxies	✓	✓	✓	SB preferred; Clusters disfavored

Conclusions

- Interesting era for high-energy gamma-ray and neutrino astrophysics
- Study of astrophysical sources that contribute to the backgrounds started going into more quantitative argument
- Coherent picture of gamma rays and neutrinos and their interplay are important
- This might also lead to groundbreaking discovery of new physics (e.g., dark matter annihilation)!