Neutrino Forum@Nikhef
10 February 2017

High-energy cosmic neutrinos

How bright can the brightest neutrino source be?

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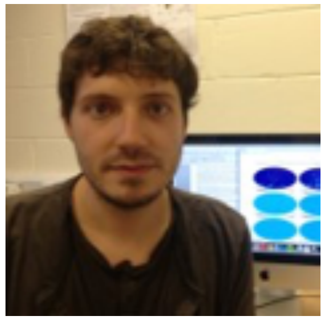
Neutrino branch of the group

PhDs

Michael Feyereisen
One-point fluctuation analysis

Niki Klop
Flavour oscillations and interactions with dark sector

Postdocs



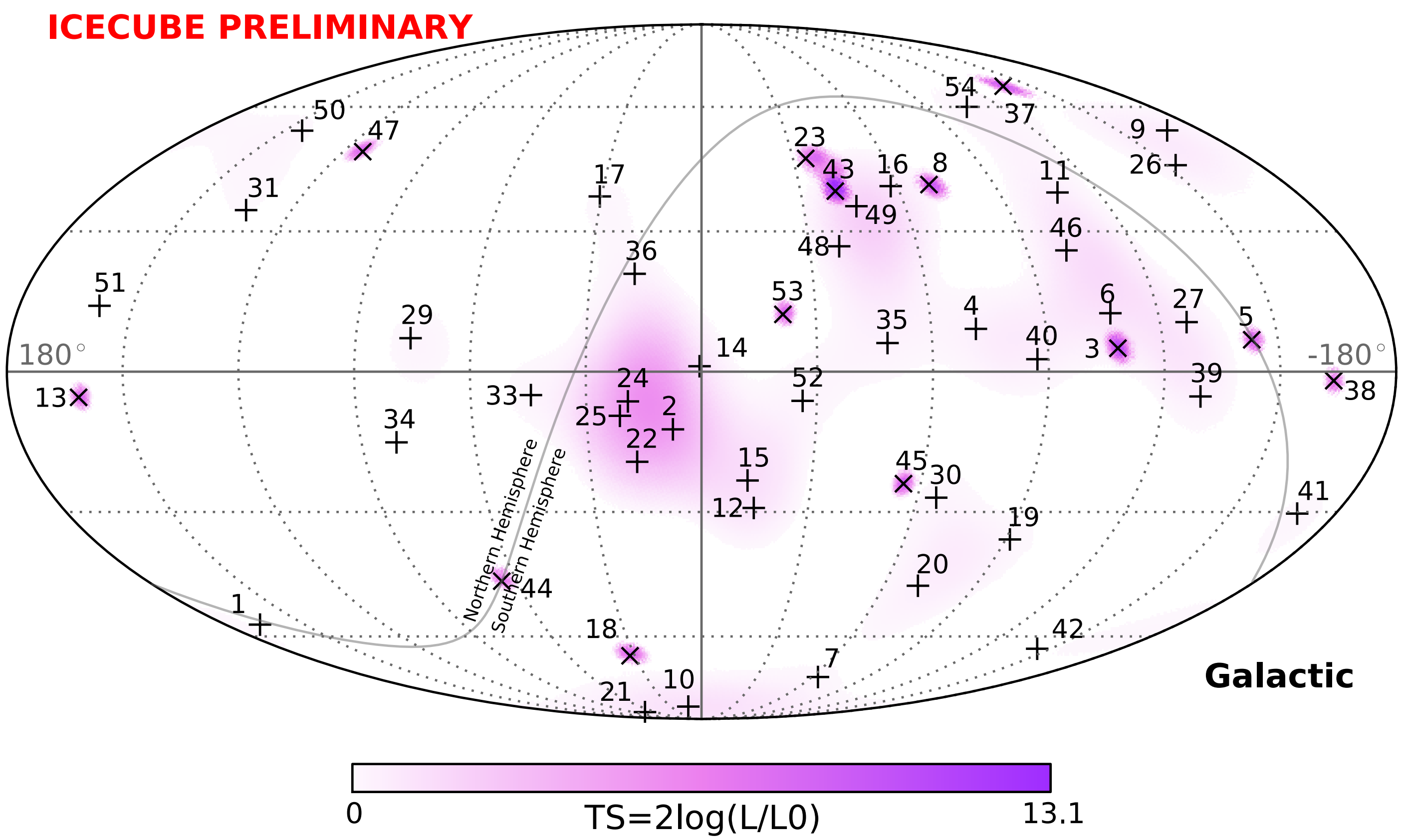
Mattia Fornasa

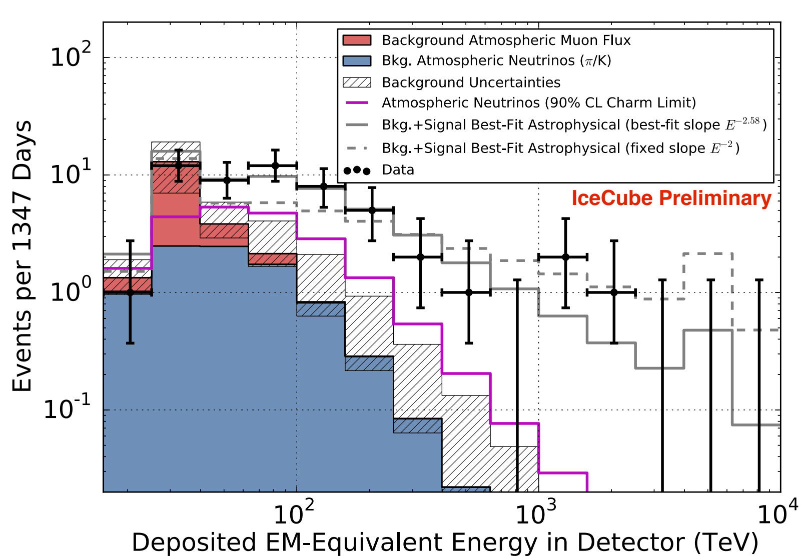
Fabio Zandanel

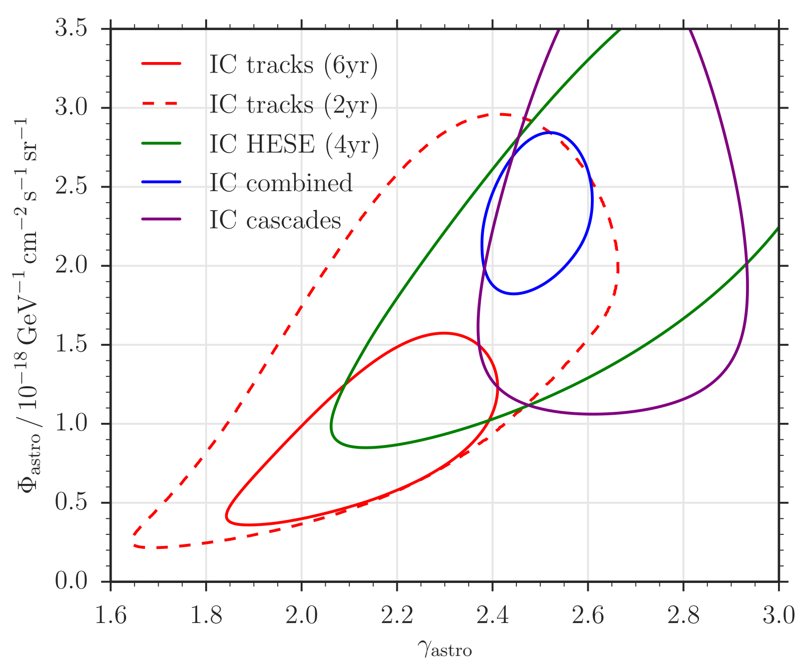
Ex-postdoc

Irene Tamborra (U. Copenhagen)

IceCube neutrinos







IceCube,
ICRC Proceedings (2015)

- 54 High-Energy Starting Events (HESE)
  - 39 showers, 14 tracks
  - Best-fit spectrum: $E^{-2.6}$
- Different data sets exist
- Consistent with isotropic distribution of the sources
- No point-like (or extended) sources identified
- No significant correlation with any catalog of known sources
- Consistent with 1:1:1 flavour ratio

Two origins of high-energy neutrinos

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

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

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

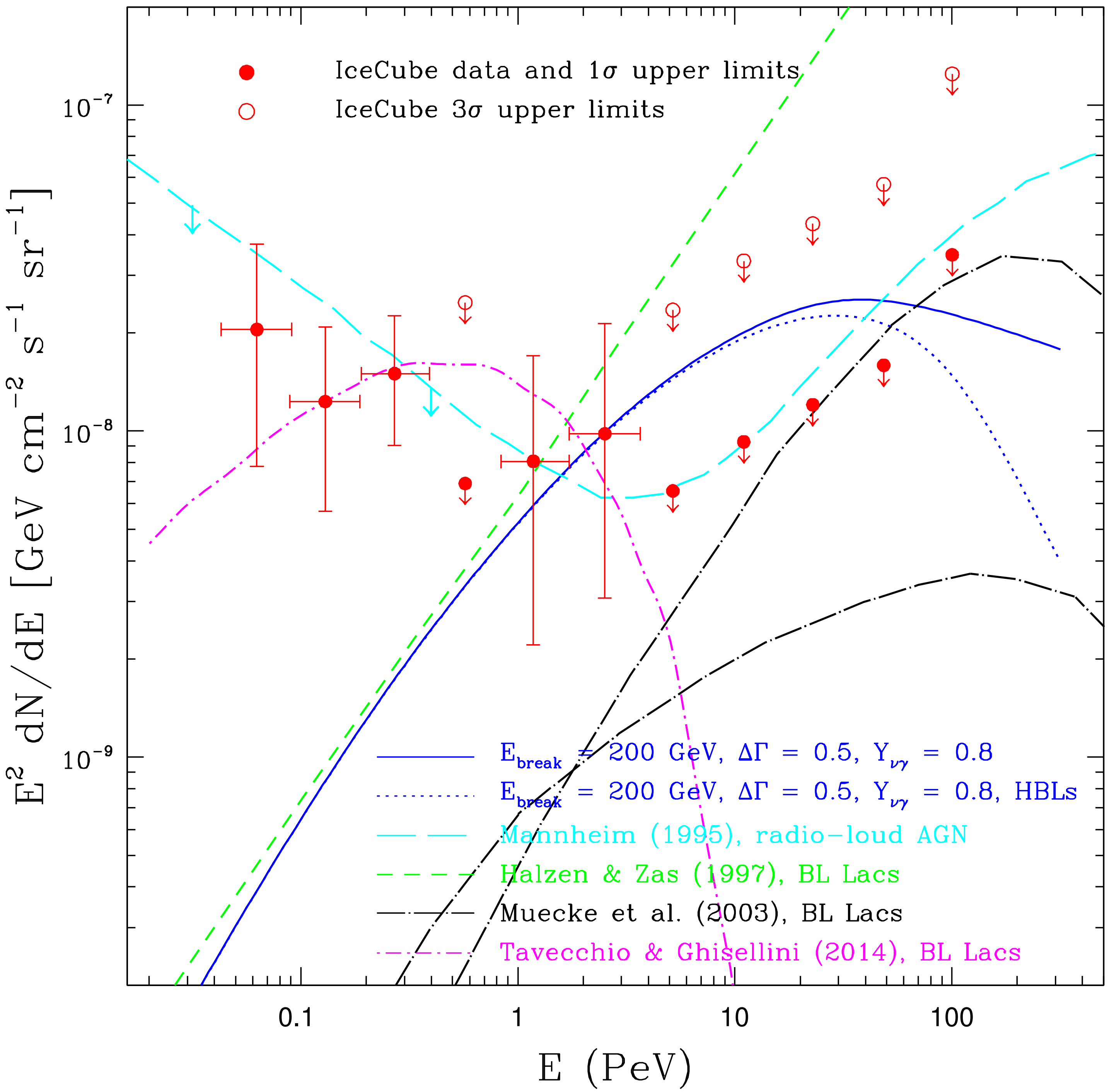
Interaction can happen for low-energy protons

Pion decays

$$\pi^0 \to 2\gamma$$
$$\pi^\pm \to \mu^\pm + \nu_\mu$$
$$\mu^\pm \to e^\pm + \nu_e + \nu_\mu$$

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

Blazars: pγ source

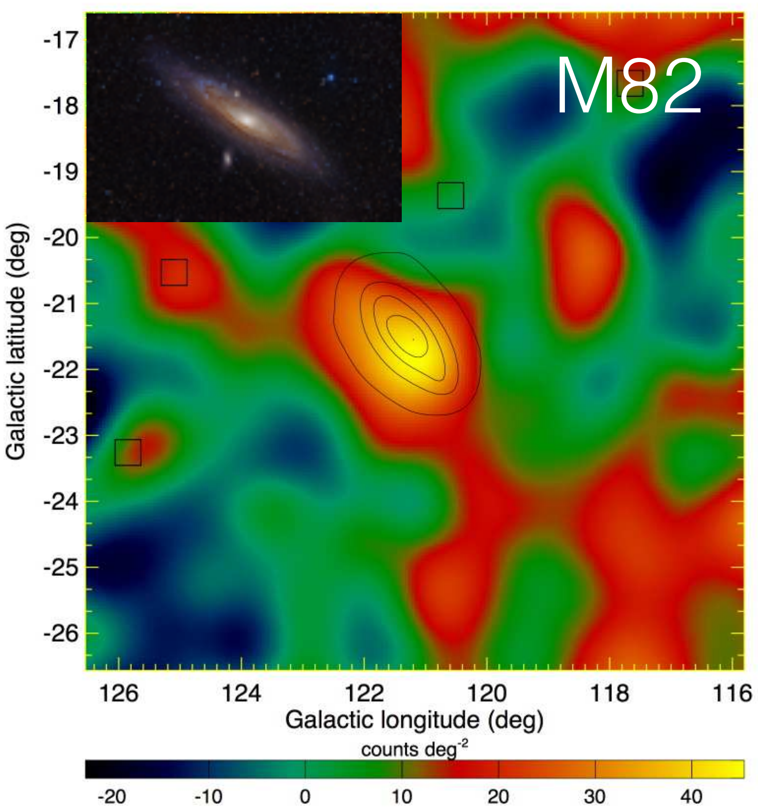


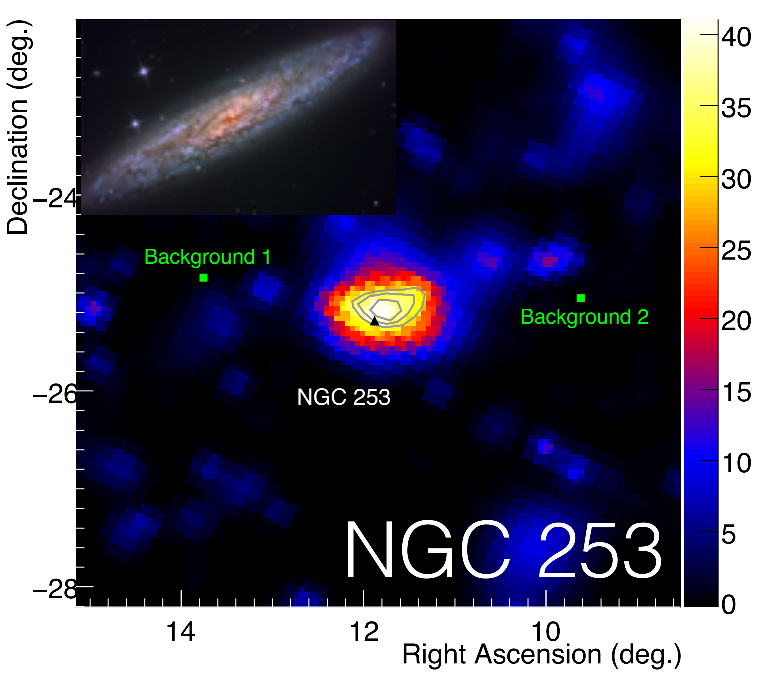
Padvani et al., *Mon. Not. R. Astron. Soc.* **452**, 1877 (2015)

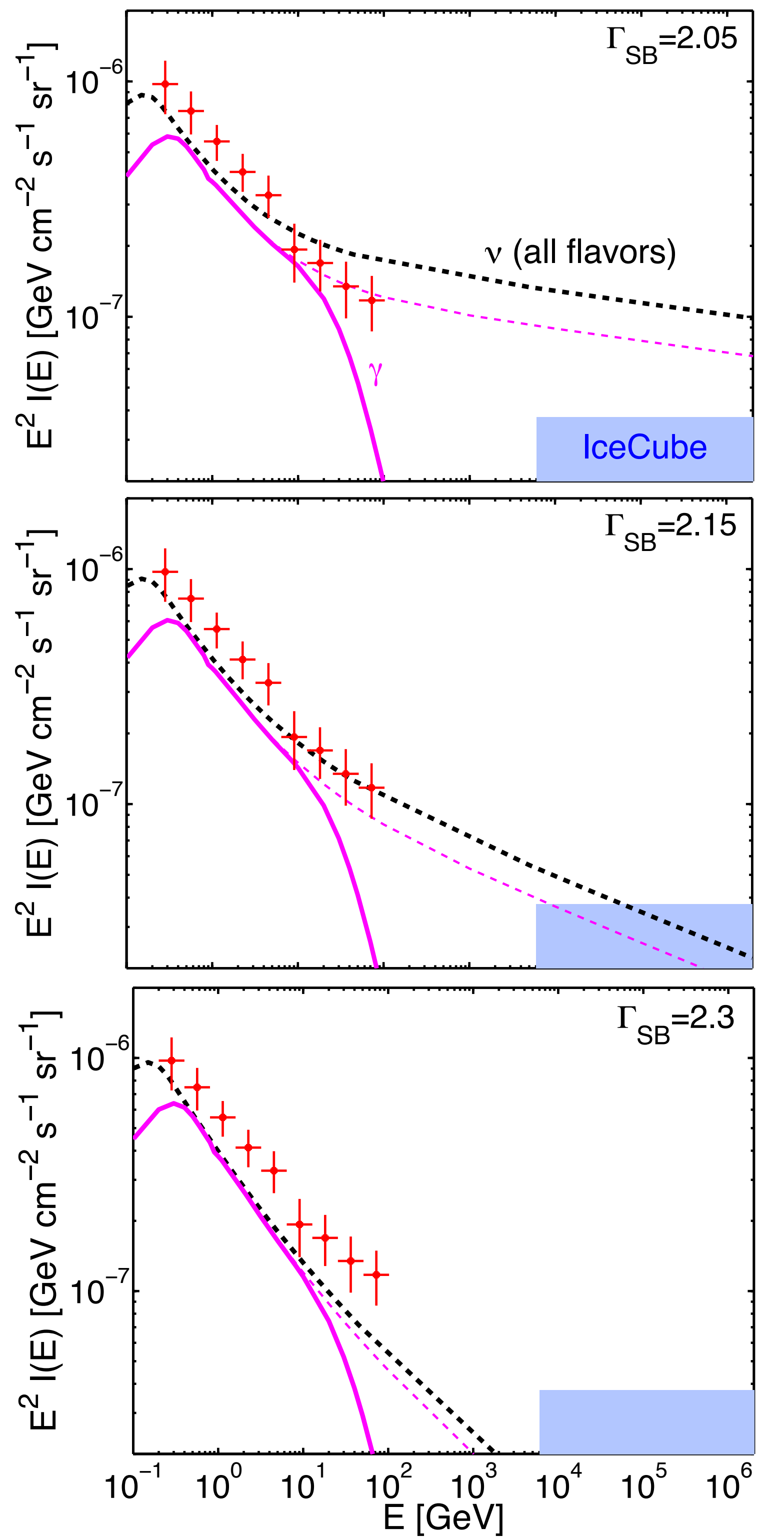
- The cosmic ray protons accelerated in jets interact with surrounding photons
- The neutrino spectrum depends on that of seed photons
- Consequences are in general much more model dependent

Starburst galaxies: pp source

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



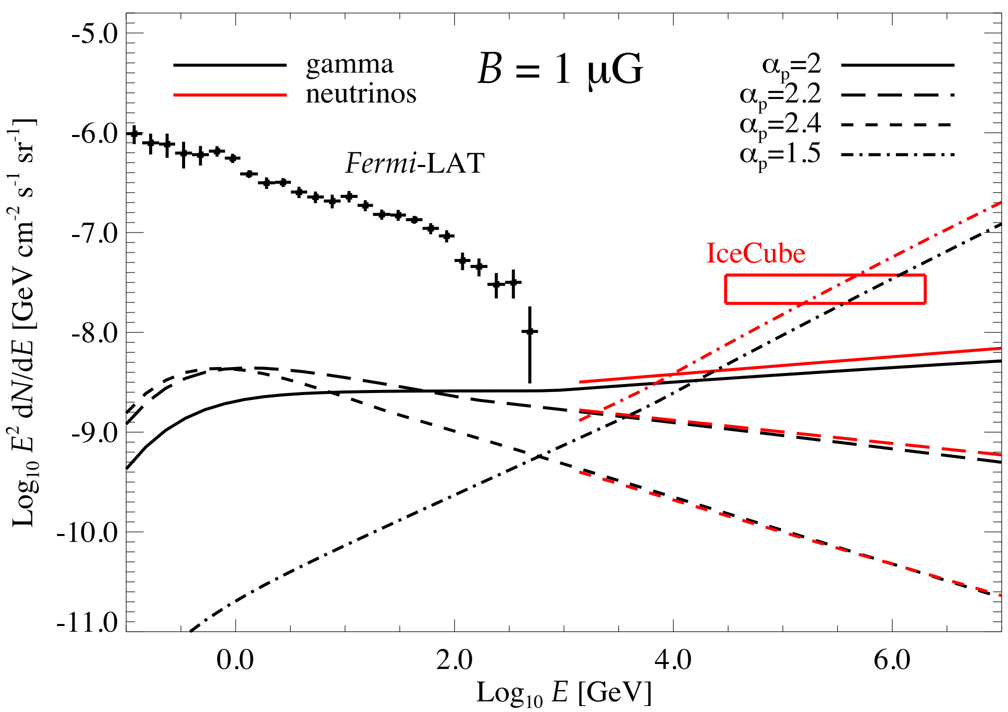




- Starbursts are bright in gammas (M82 and NGC 253 at ~3 Mpc)
- Gamma-ray spectrum roughly follows $E^{-2.2}$
- Modelling the gamma-ray and neutrino luminosity functions using
  - IR luminosity function (Herschel)
  - IR-gamma correlation (Fermi)

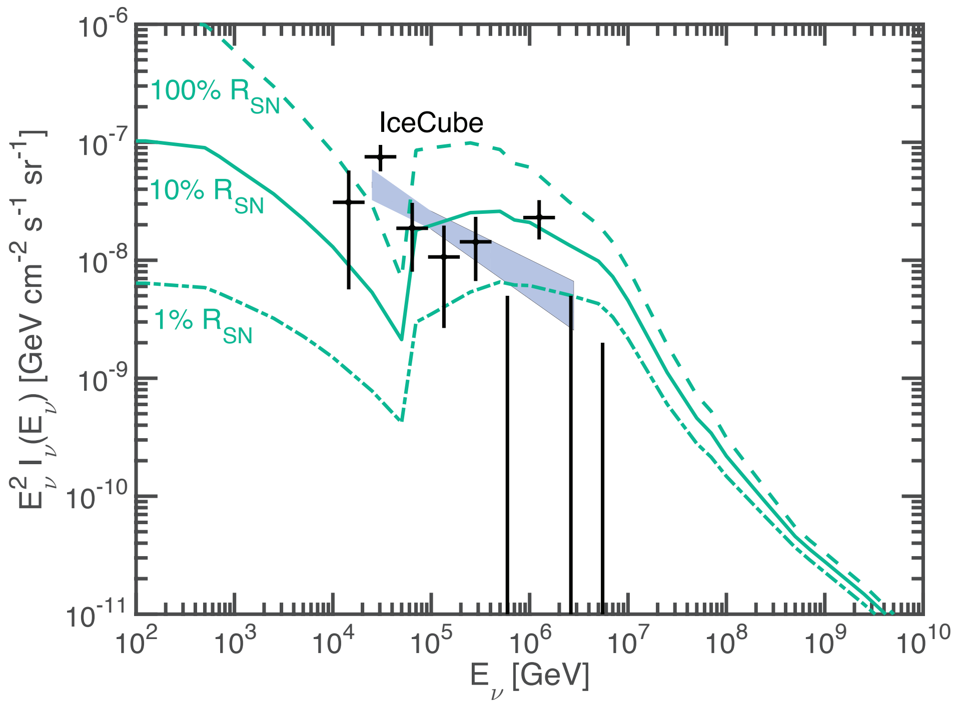
Galaxy clusters, GRBs, dark matter…

Galaxy clusters



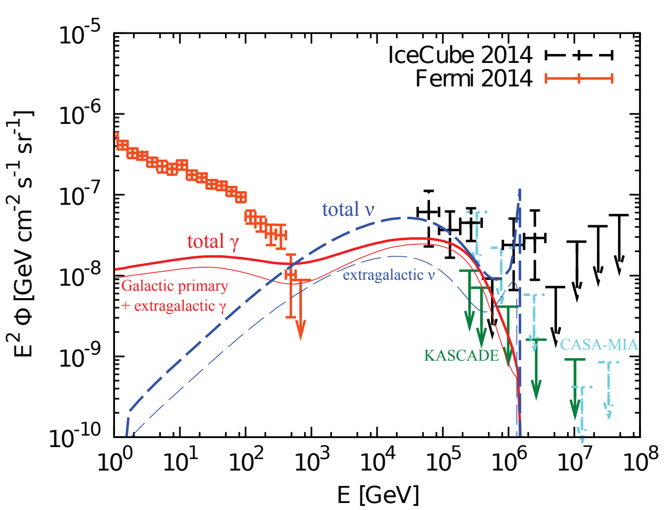
Zandanel, Tamborra, Gabici, Ando,
Astron. Astrophys. **578**, A32 (2015)

GRBs (successful or failed)



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

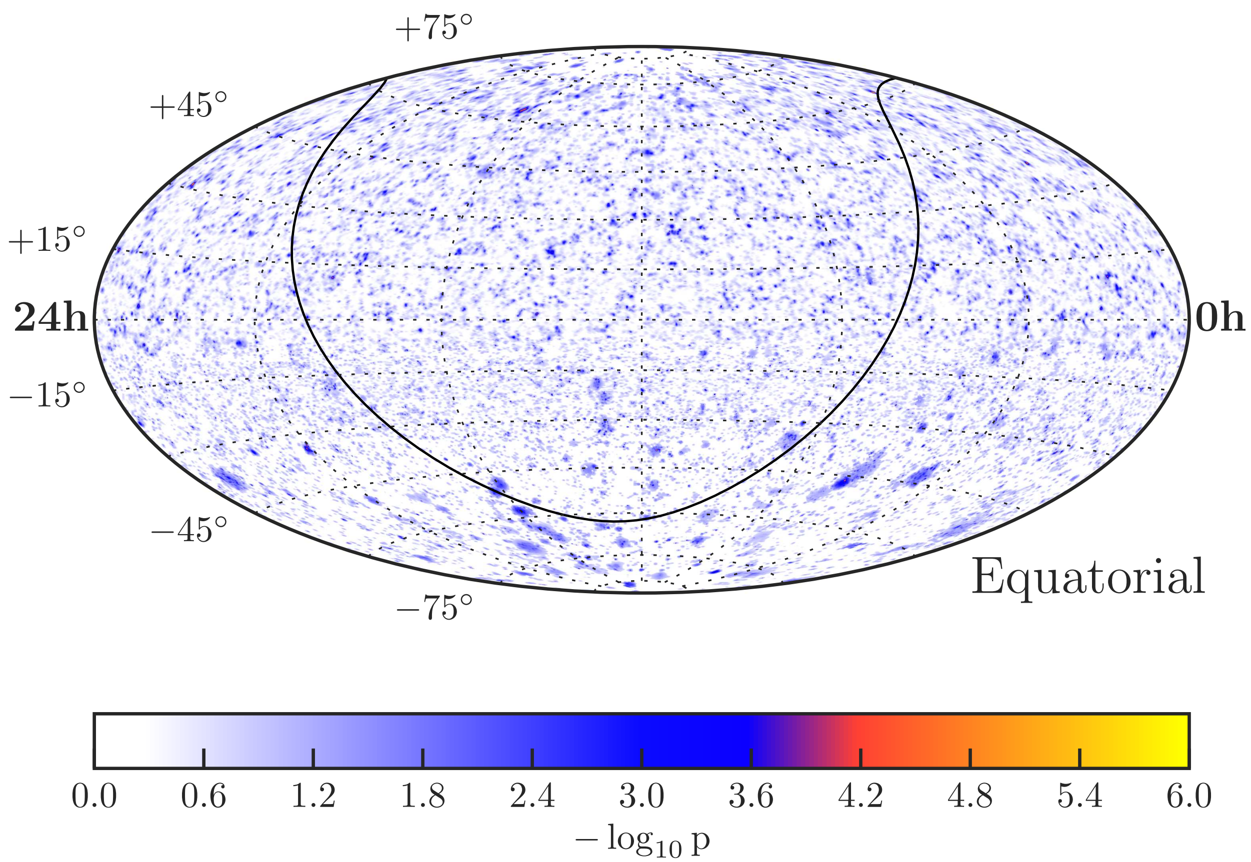
Dark matter decay

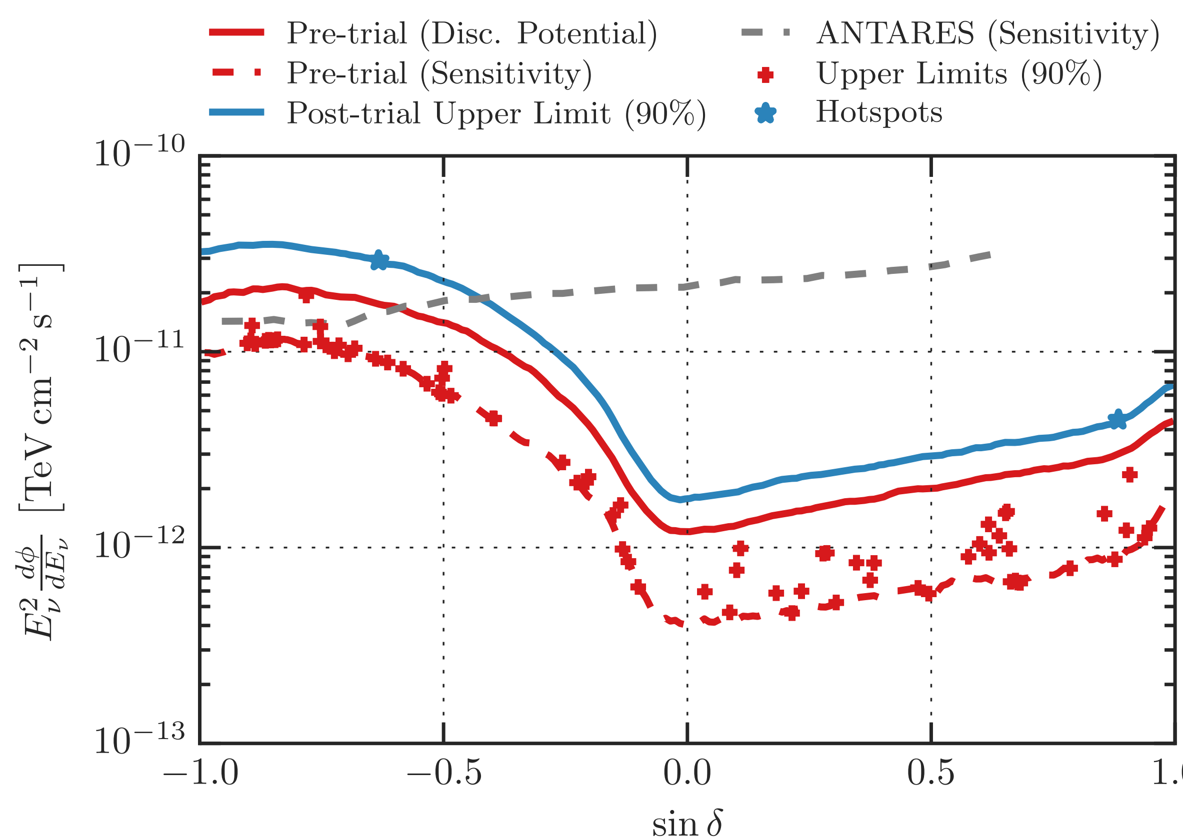


Murase, Laha, Ando, Ahlers, *Phys. Rev. Lett.* **115**, 071301 (2015)

Searches for point sources

IceCube, *Astrophys. J.* **835**, 151 (2017)

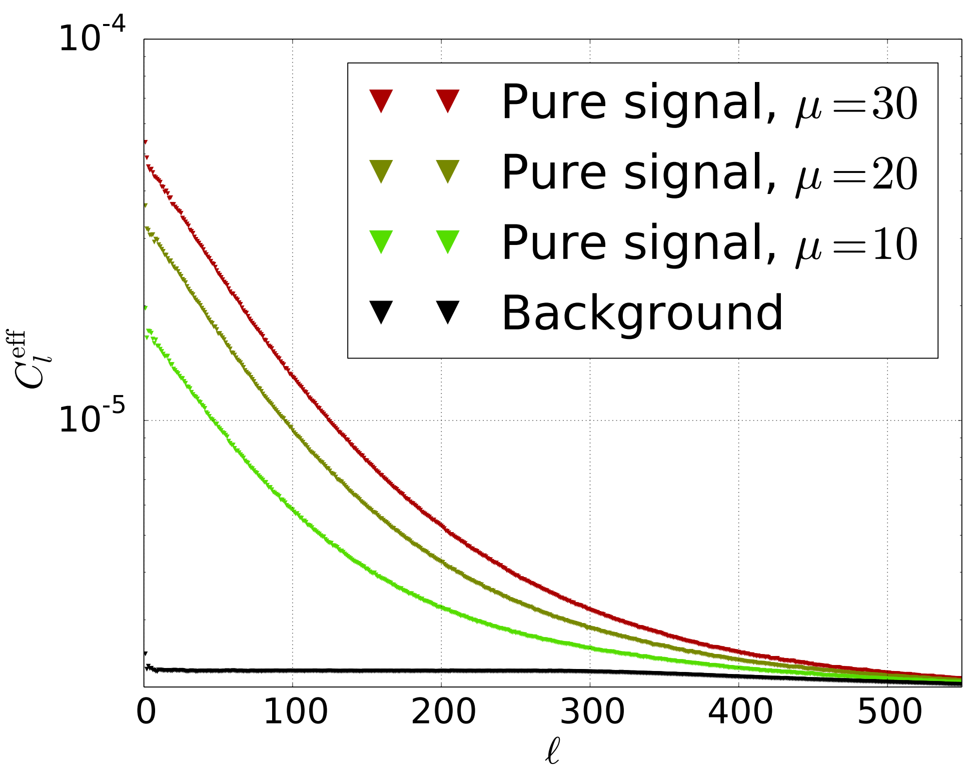


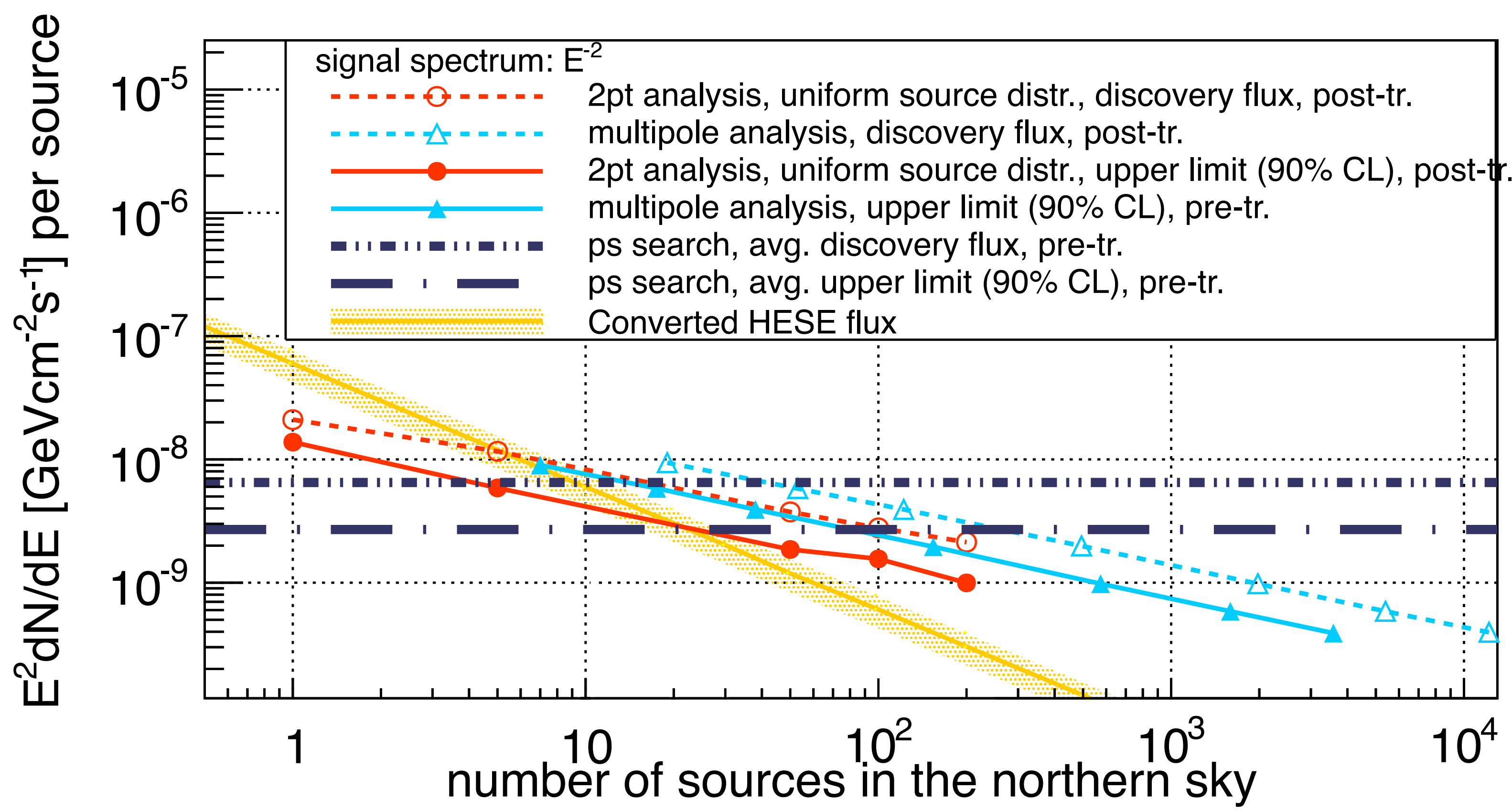


- No excess over the atmospheric backgrounds
- Roughly ~10^{-11} TeV/cm^2/s for the E^{-2} spectrum

Significant signal clustering? Angular power!

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

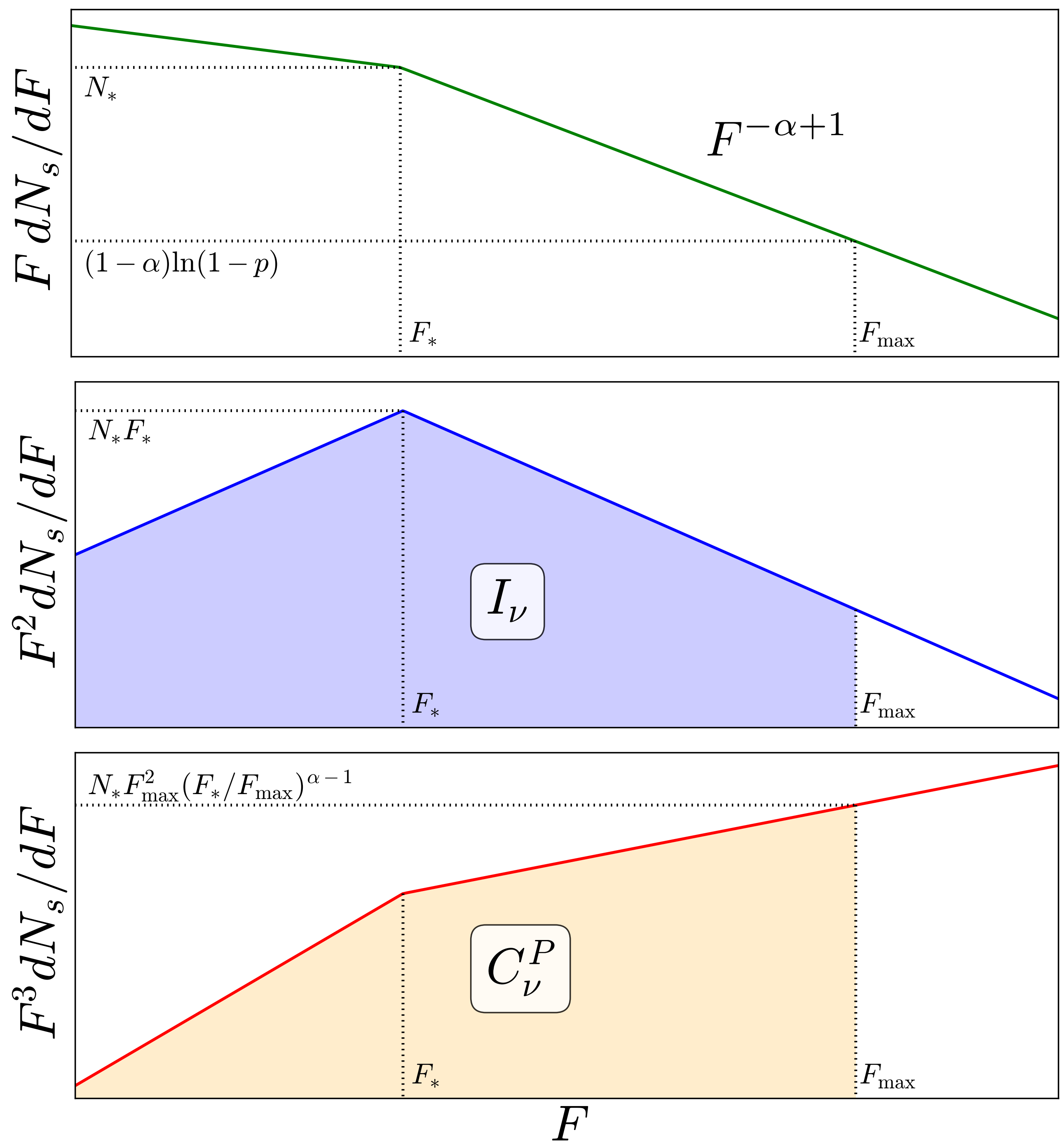




- No angular power was found (everything is consistent with diffuse the background model)
- It can exceed the point-source limit for more than 100 sources
- My comment: It's **nonsense** to think about ~10^3 sources with the **same** flux!!

Flux distribution and implications

Ando, Feyereise, Fornasa, arXiv:1701.02165 [astro-ph.HE]



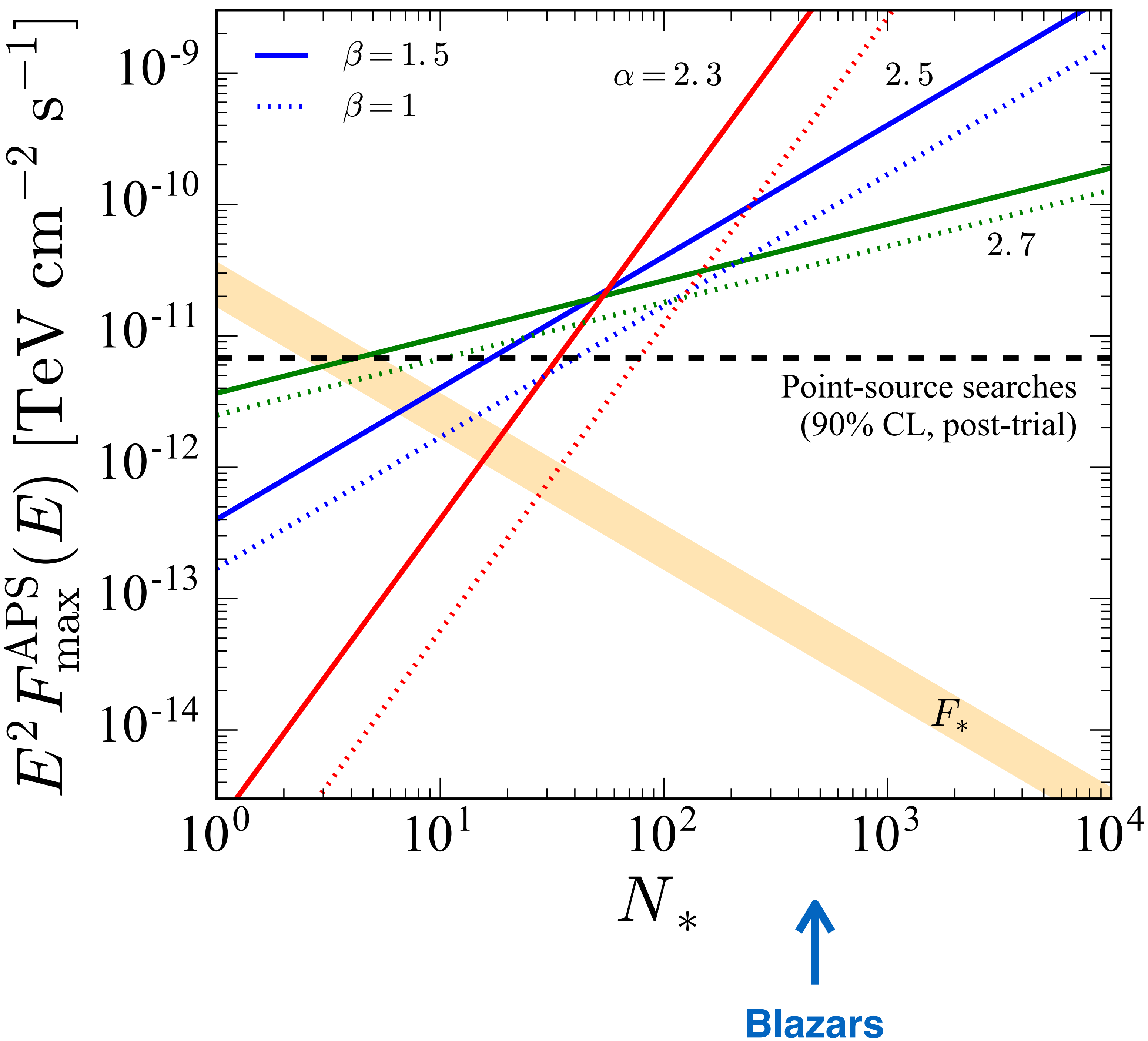
- Flux distribution of **any** astrophysical sources will follow a **power law**
  - Particularly $F^{-2.5}$ for high-flux region (cf., Olbers' paradox)
- First moment (mean): Intensity
- Second moment (variance): Angular power spectrum

Procedure:

1. Pick ***N**** as a parameter
2. From measured intensity ***I***, calculate ***F****
3. Discuss what constraints we have on $\boldsymbol{F_{\rm max}}$

Flux limit from the angular power spectrum

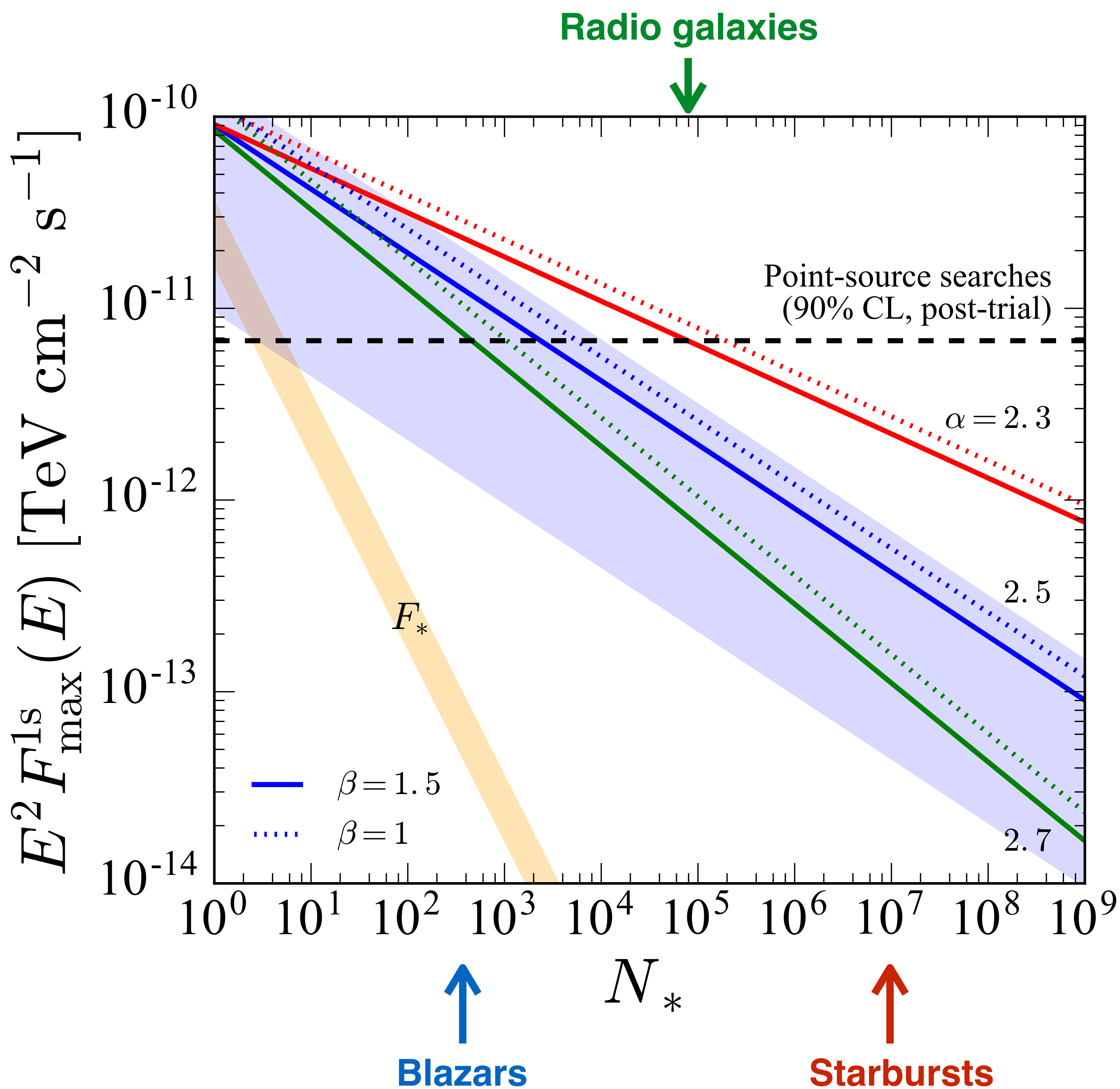
Ando, Feyereise, Fornasa, arXiv:1701.02165 [astro-ph.HE]



- Particularly important for small ***N****
- So far it is not very constraining
  - Given that there are only 14 track events (HESE; 1 deg angular resolution), this is not surprising
- The sensitivity will however improve as exposure squared

One-source limit

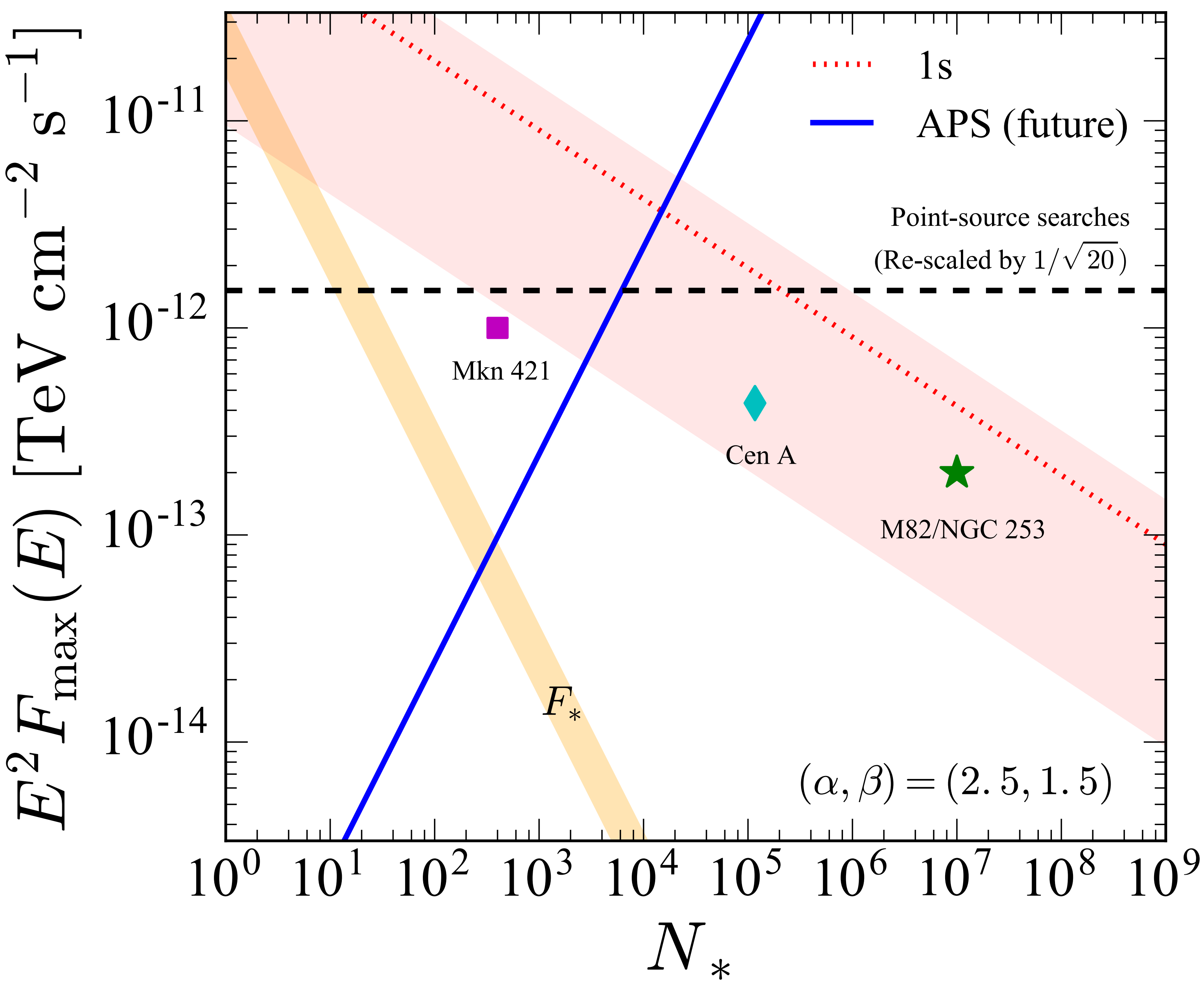
Ando, Feyereise, Fornasa, arXiv:1701.02165 [astro-ph.HE]



- If $\boldsymbol{F_{max}}$ gets too large, the expected number of the source at this flux gets significantly smaller than 1
- This one-source limit is much stronger than the point-source flux limit for $N^* > 10^4$

Flux sensitivity from the angular power spectrum

Ando, Feyereise, Fornasa, arXiv:1701.02165 [astro-ph.HE]

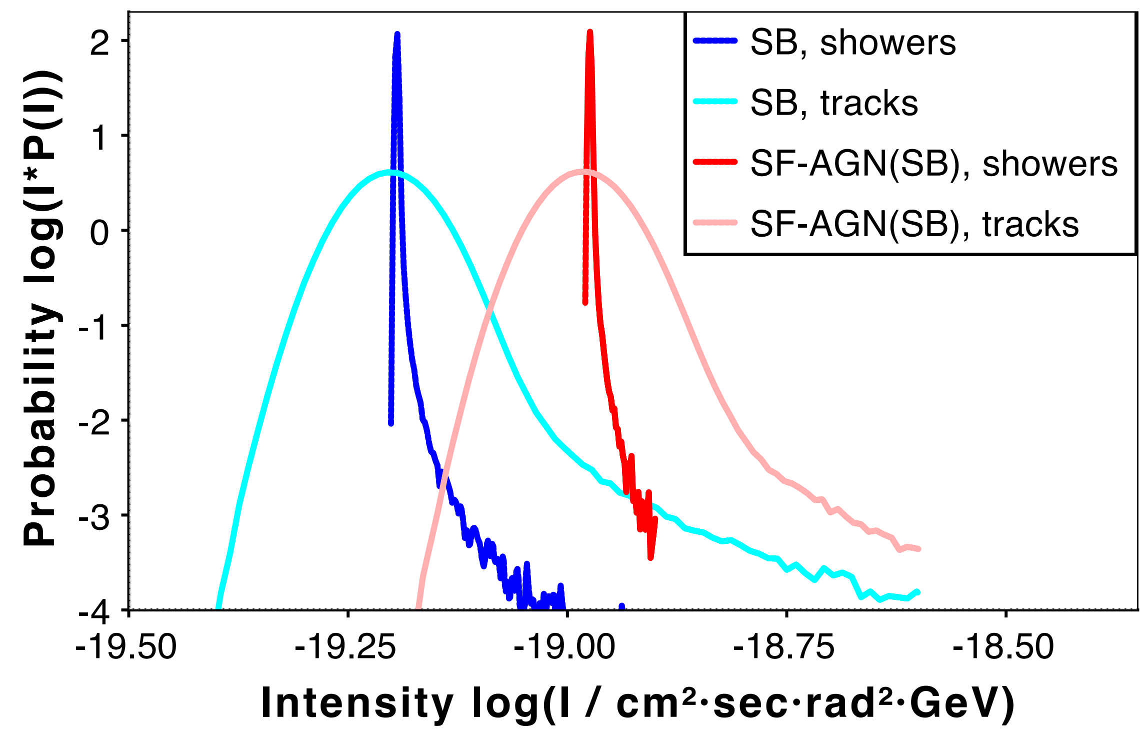


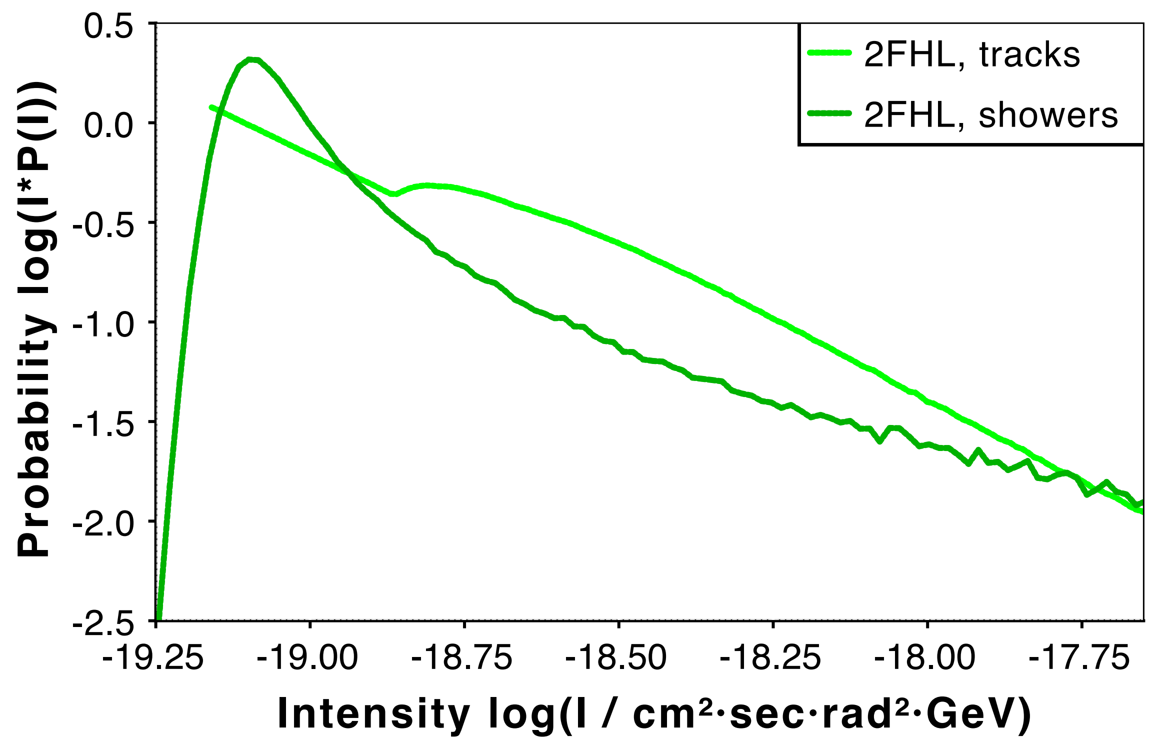
- Assumption: 20 times exposure than 4-yr IceCube, and 0.5 deg angular resolution
- The angular power spectrum can test blazar scenario

Beyond variance: One-point fluctuation analysis

- Flux PDF is highly non-Gaussian, featuring long power-law tail
- Power spectrum does *not* capture all the statistical information
- One-point fluctuation analysis utilise all the information contained in full PDF
- Benefit is slim for now, but in the future will be large
    - E.g., test of Galactic component in the future KM3NeT data

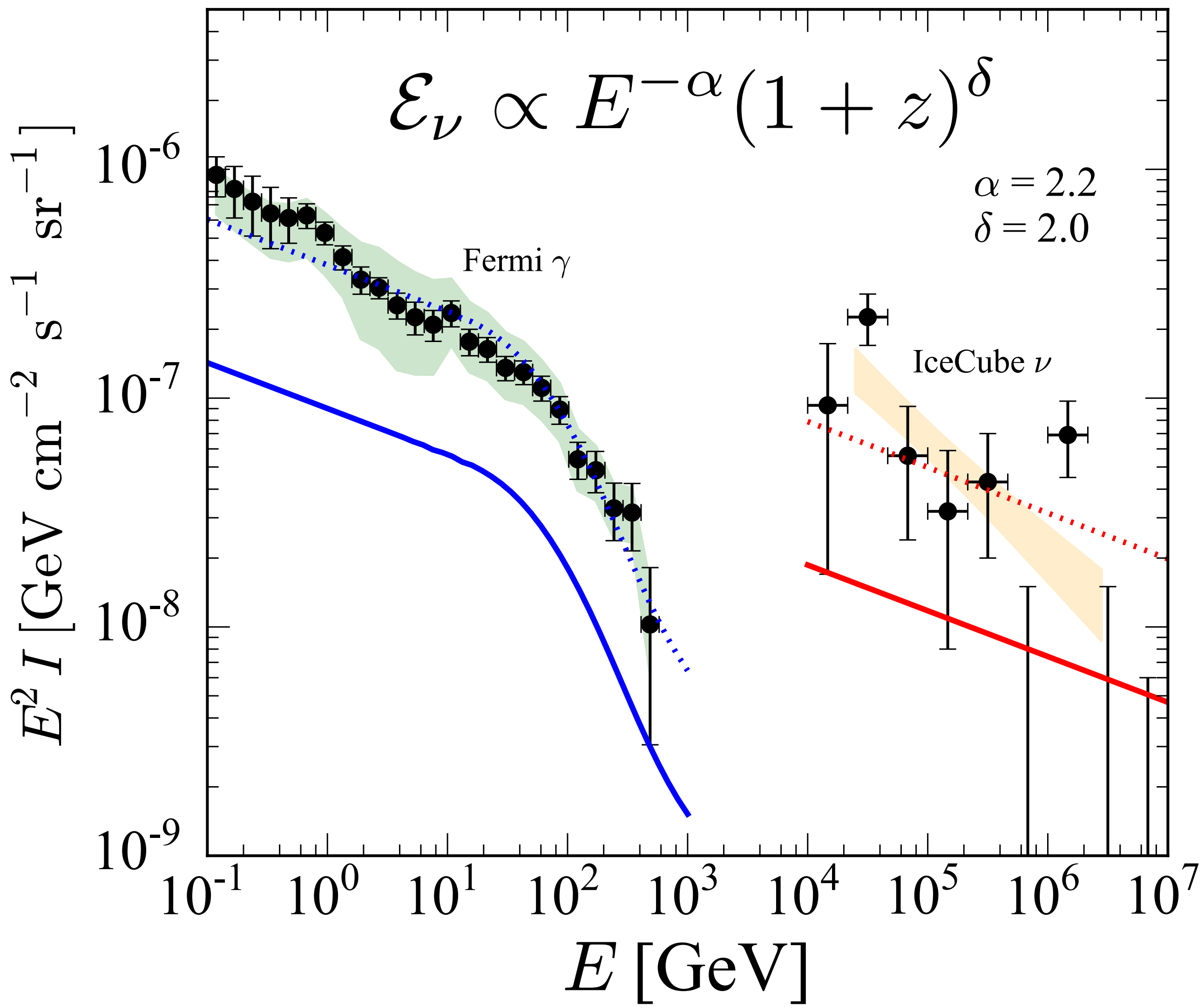
Feyereise, Tamborra, Ando, arXiv:1610.01607 [astro-ph.HE]

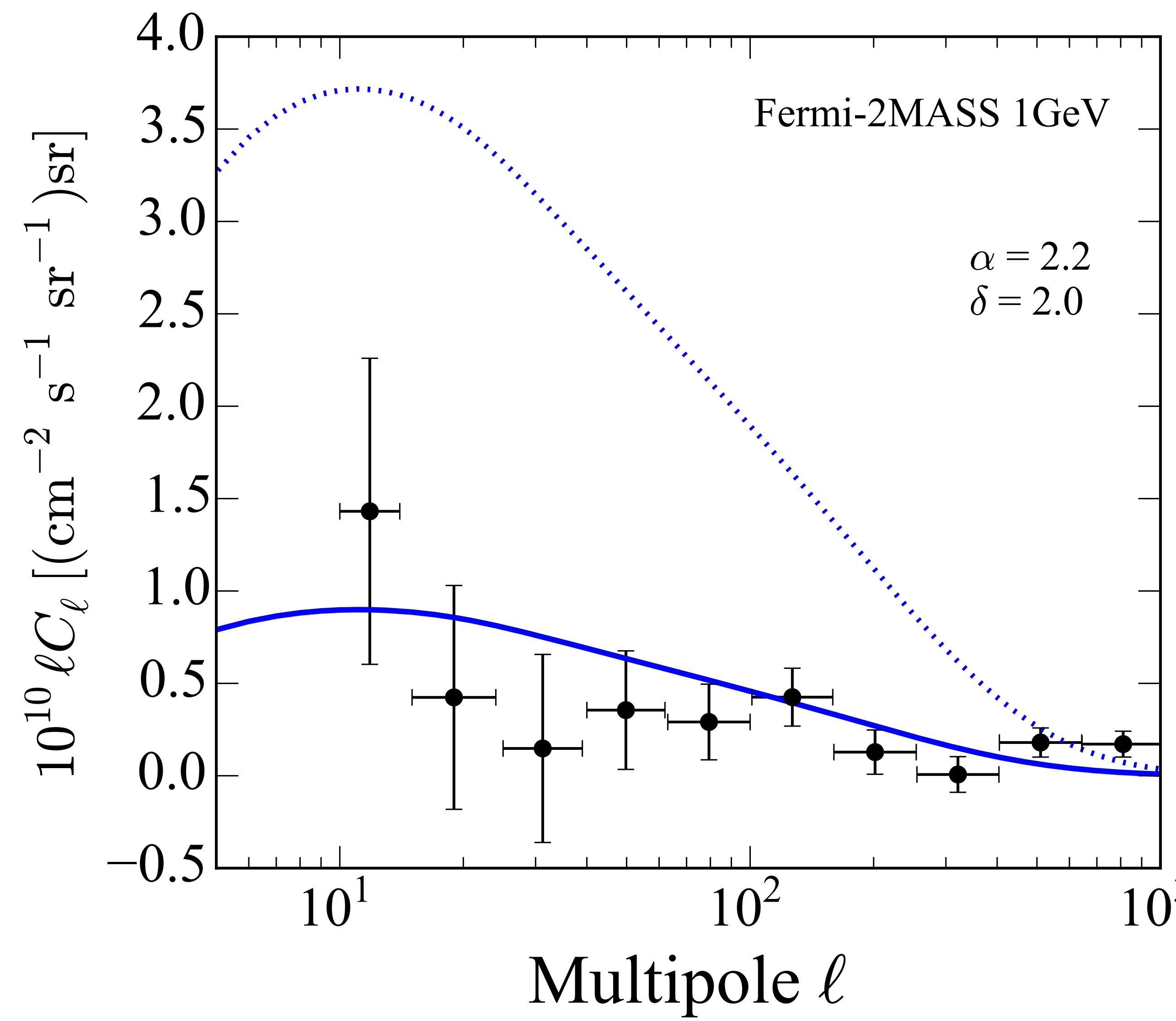




Tomographic constraints on hadronuclear sources

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





- For (transparent) pp sources, we can use constraints from gamma rays in GeV energies (Fermi-LAT)
- Cross correlation between Fermi data and 2MASS galaxies give stringent constraints on sources with soft spectrum and mild redshift evolution (galaxy clusters disfavoured)

Summary and prospects

- IceCube's detection of TeV-PeV neutrinos launched high-energy neutrino astrophysics
- The next question to be answered: ***What are the sources?***
- Given that there will be many more events (KM3NeT, IceCube-Gen2, etc.), **it is important to go beyond the mean of the flux PDF (i.e., intensity energy spectrum)**
- Simple discussions of the PDF such as the angular power spectrum already show good prospects; e.g., testing blazar contribution
- **Full usage of one-point PDF** as well as **information from gamma-ray data** will be important to further constrain neutrino sources