TeV Particle Astrophysics
Columbus, OH
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How bright can the brightest neutrino source be?

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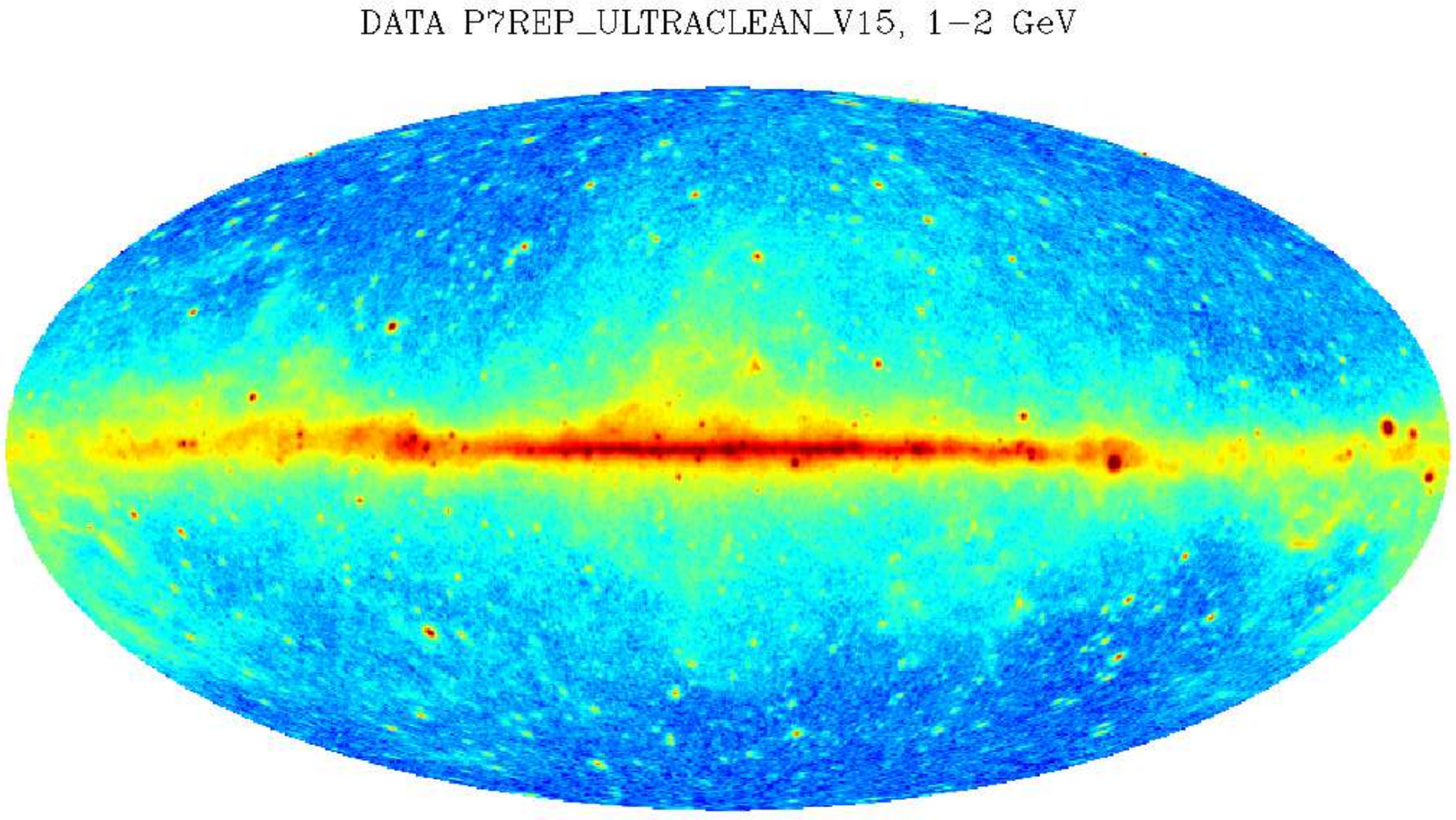
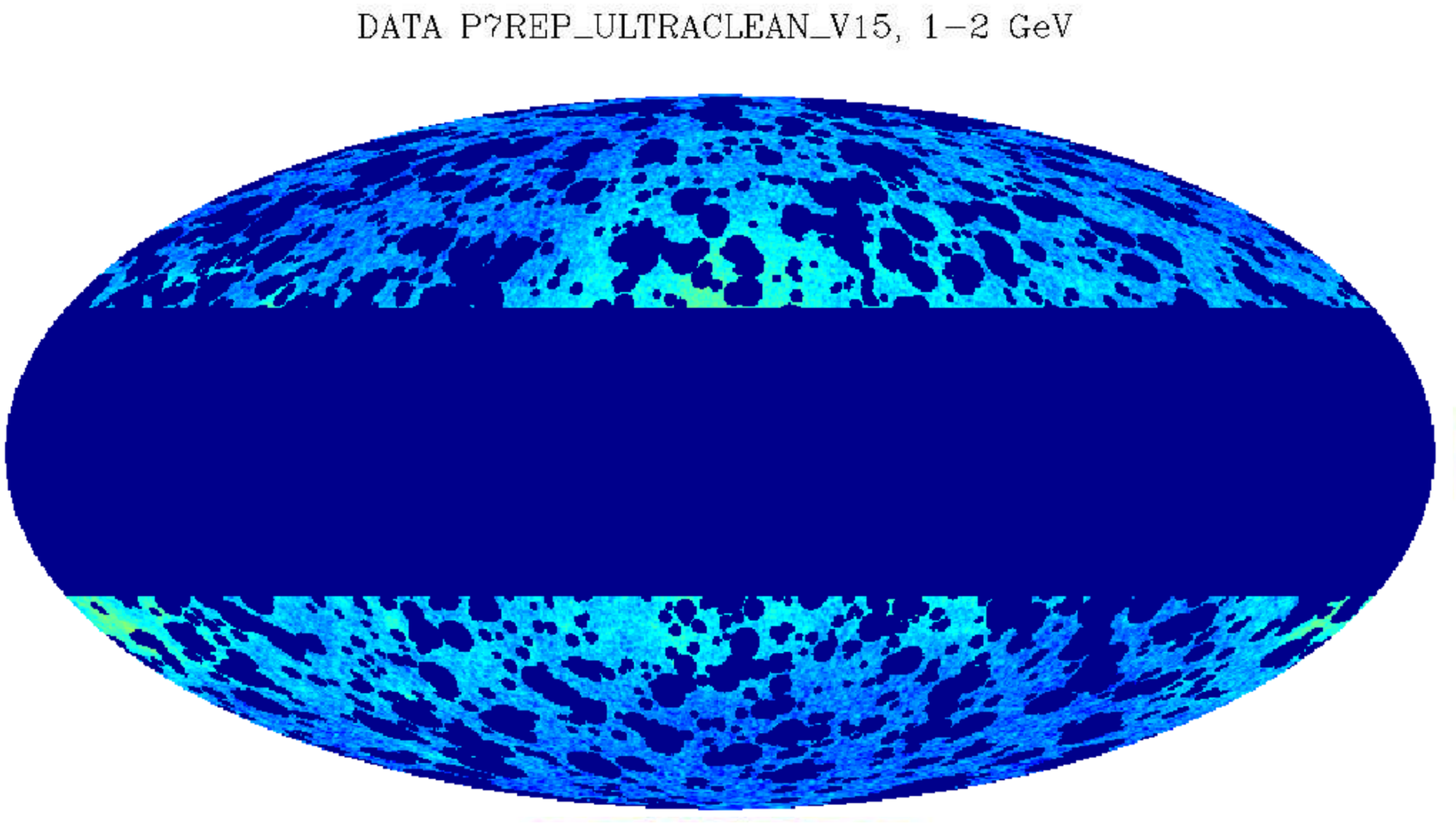
Ando, Feyereisen, Fornasa, *Phys. Rev. D* **95**, 103003 (2017)

Lessons from gamma rays



Fornasa et al. *Phys. Rev. D* **94**, 123005 (2016)

Lessons from gamma rays



Fornasa et al. *Phys. Rev. D* **94**, 123005 (2016)

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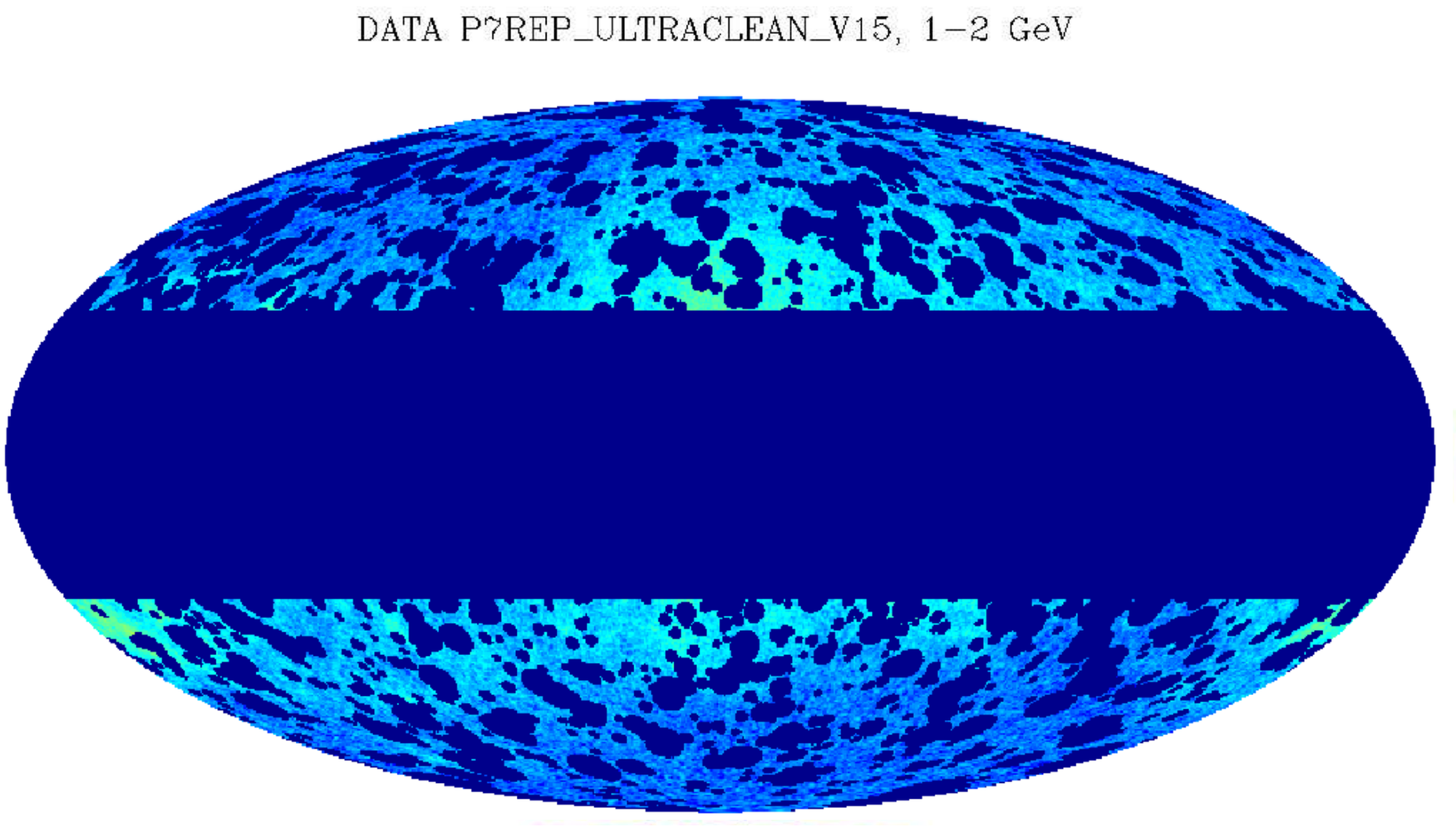
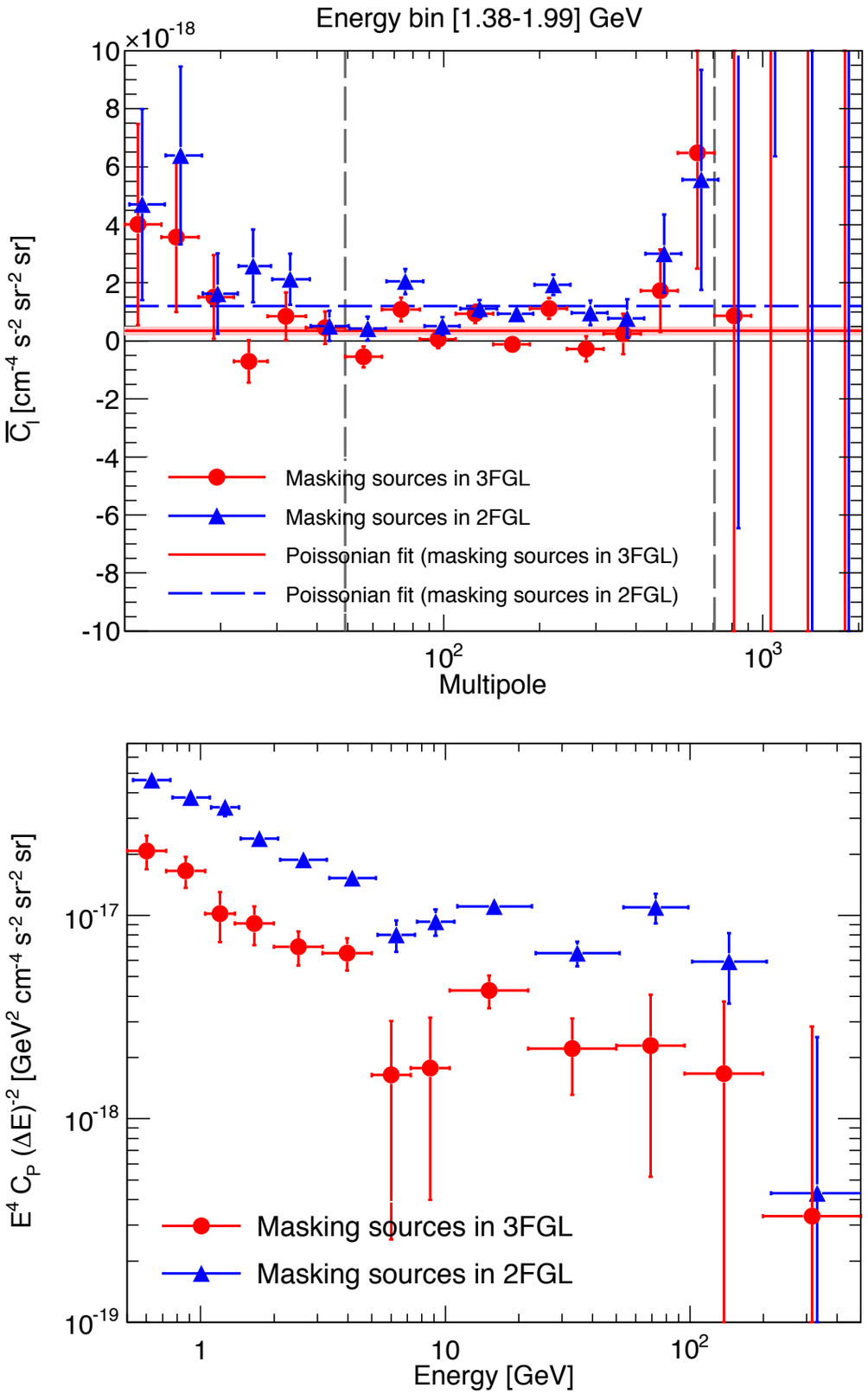


Fornasa et al. *Phys. Rev. D* **94**, 123005 (2016)

Is there signature of point sources here?

Angular power spectrum: Observations with Fermi



- Analysis of Fermi data for the angular power spectrum of the diffuse gamma-ray background in 2012 → **Discovery of small-scale anisotropies**
  - Reanalysed in 2016
- Almost constant excess compared with shot noise of the photons at $50 < l < 700$
- Data are more **consistent with discrete point sources rather than diffuse component** (blazars; Ando et al. 2007)

Fornasa et al. *Phys. Rev. D* **94**, 123005 (2016)
Ando et al. *Phys. Rev. D* **95**, 123006 (2017)

Implications

- Anisotropy analyses have already been established for GeV gamma rays

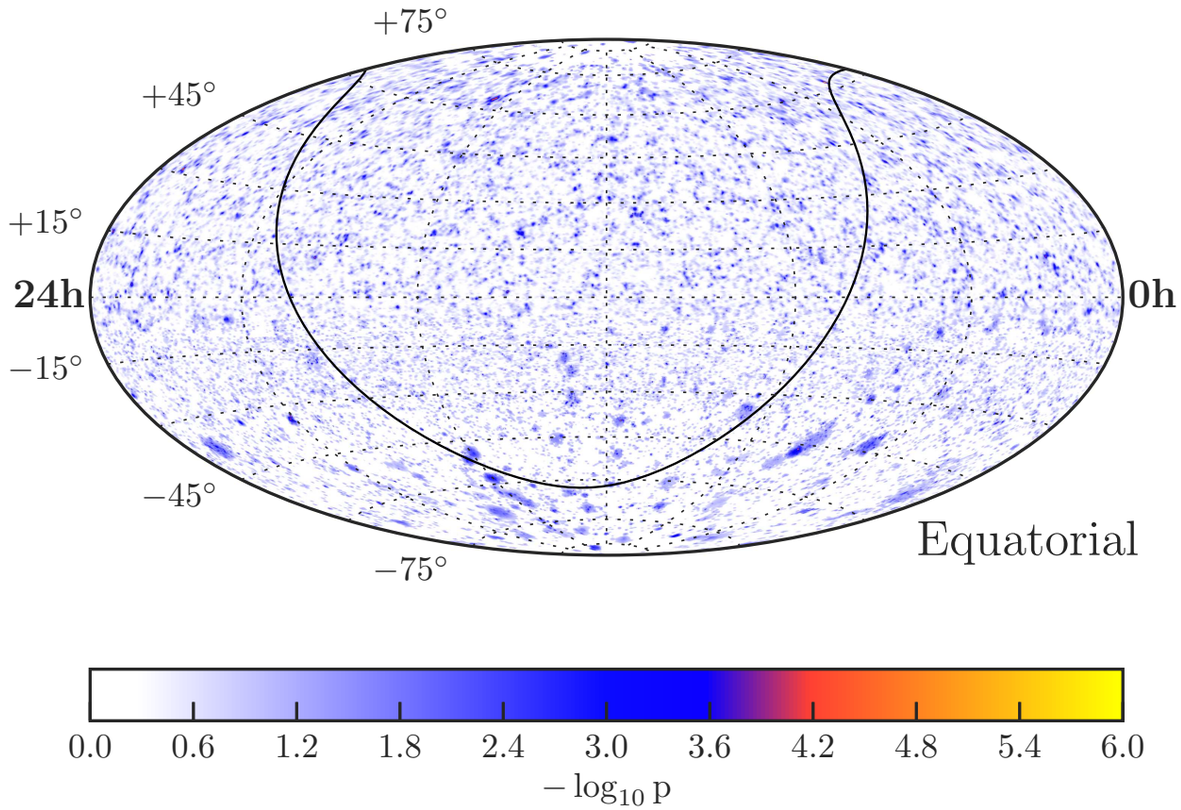
- Solid measurement of angular power spectrum **implies (sub-threshold) point-source contribution**

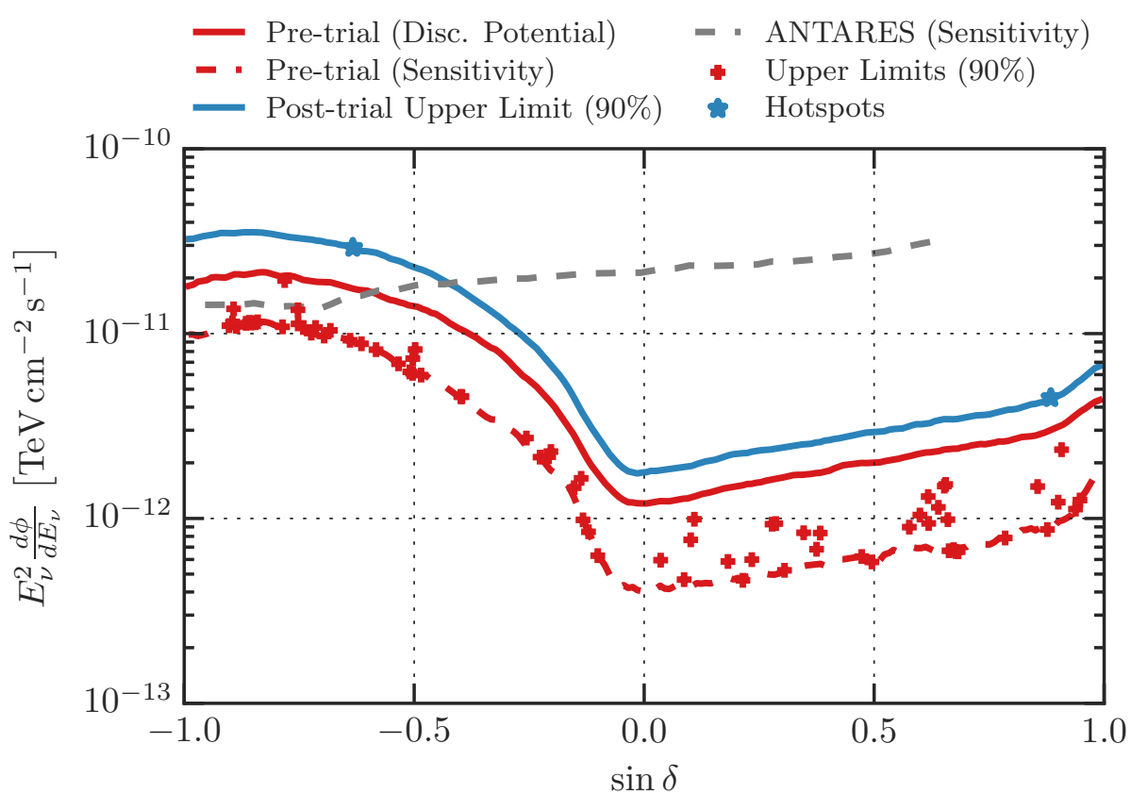
  - They can be identified, not individually but ***statistically***

- **Same technique can be used for high-energy neutrinos**, to identify ***source population***

High-energy neutrinos: Searches for point sources

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

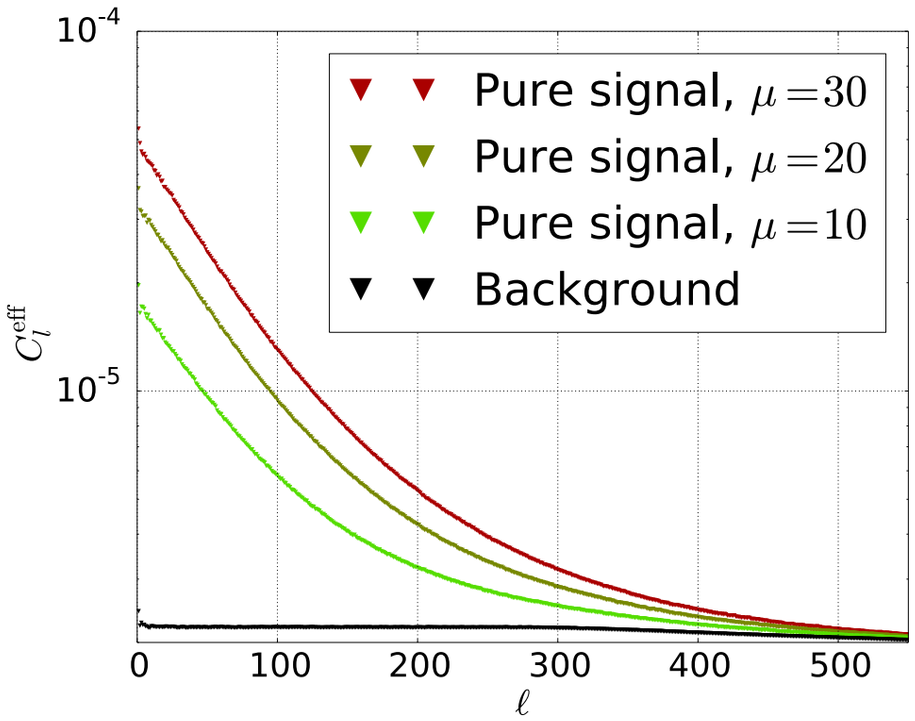


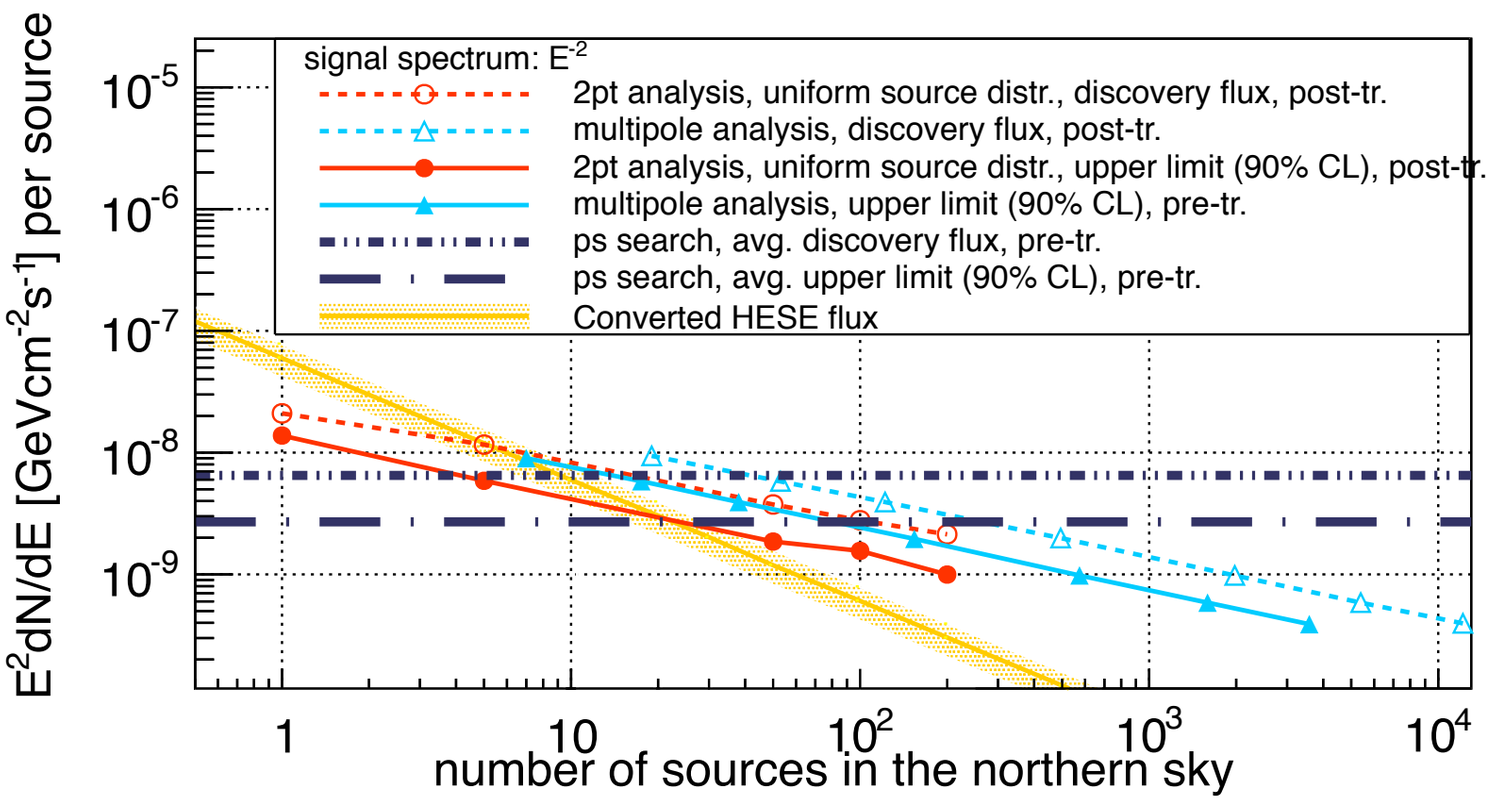


- No excess over the atmospheric backgrounds
- Roughly ~10^{-11} TeV/cm^2/s for the E^{-2} spectrum

Significant signal clustering? Angular power!

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

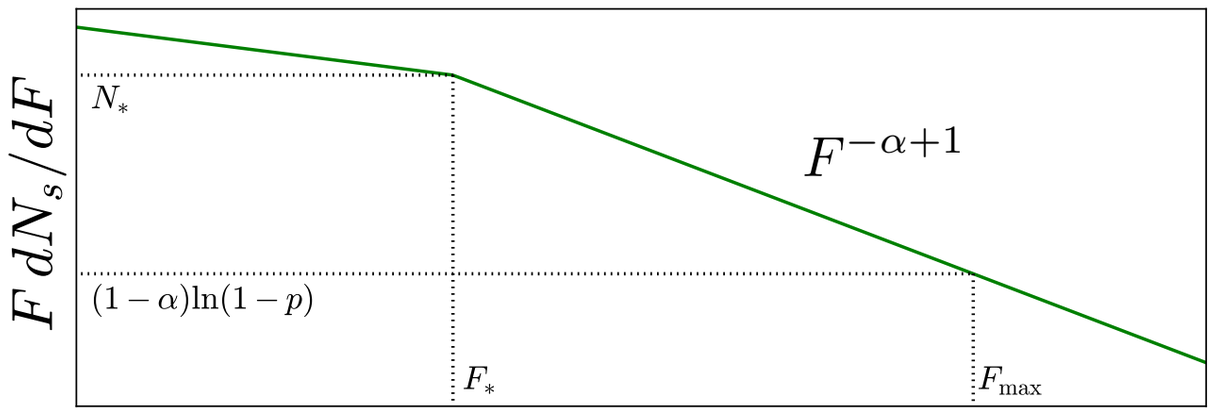


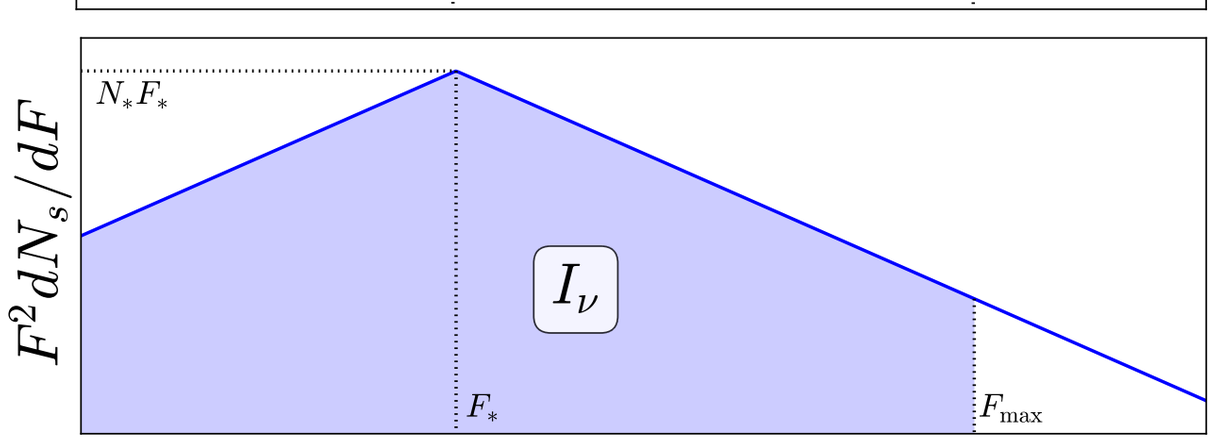


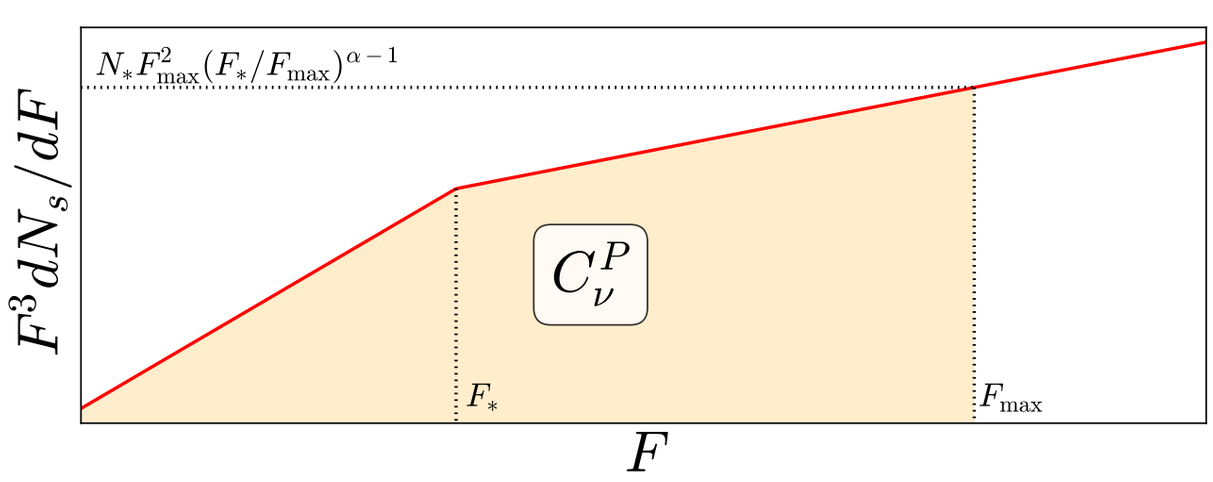
- No angular power was found (everything is consistent with diffuse the background model)
- It can exceed the point-source limit for more than 100 sources
- But it is assumed that all these sources have the **same** flux

Flux distribution and implications

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







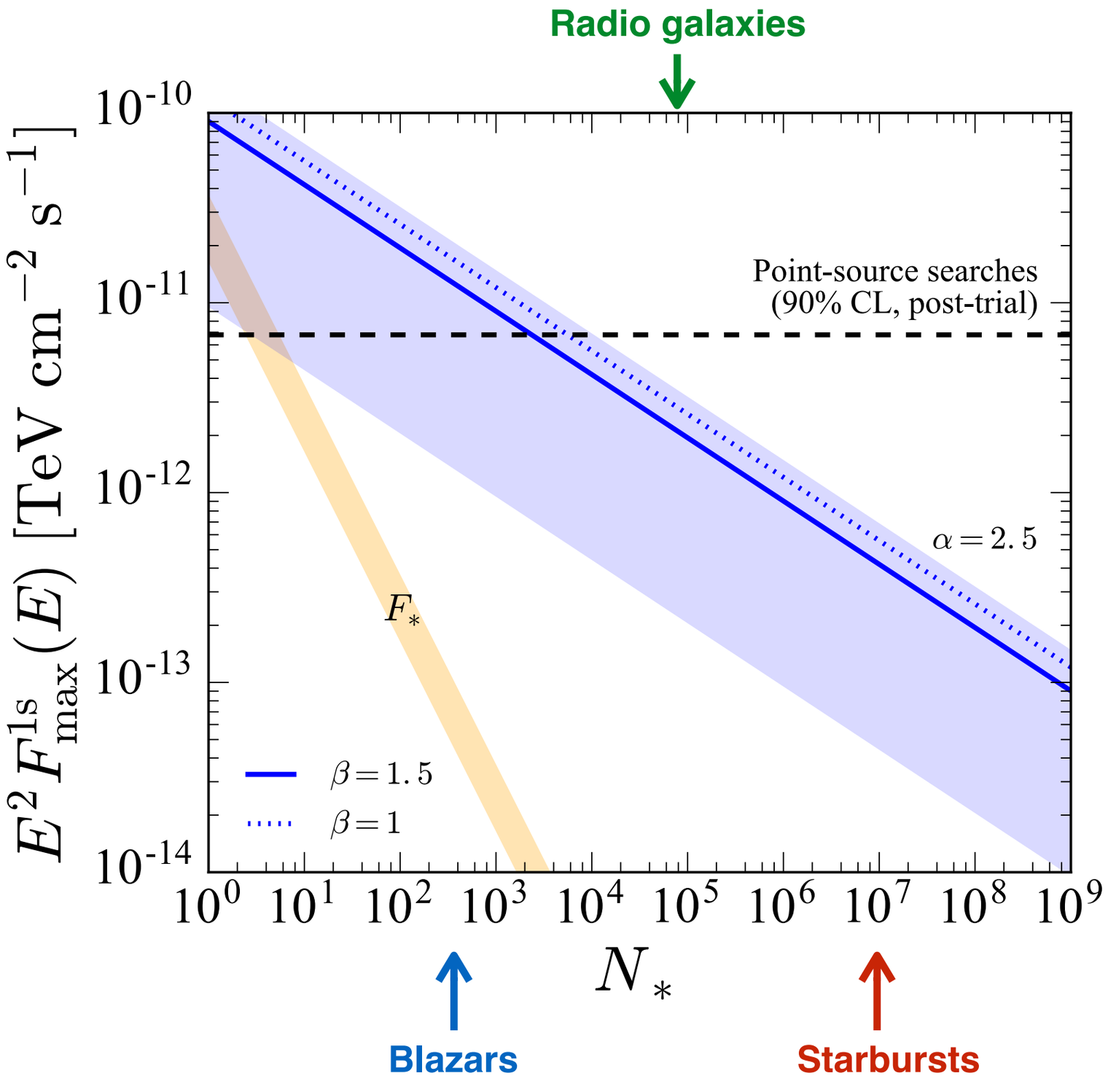
- Flux distribution of **any** astrophysical sources will follow a **power law**
  - Particularly $F^{-2.5}$ for high-flux region (cf., Olbers' paradox)
- First moment (mean): Intensity
- Second moment (variance): Angular power spectrum

Procedure:

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

One-source limit

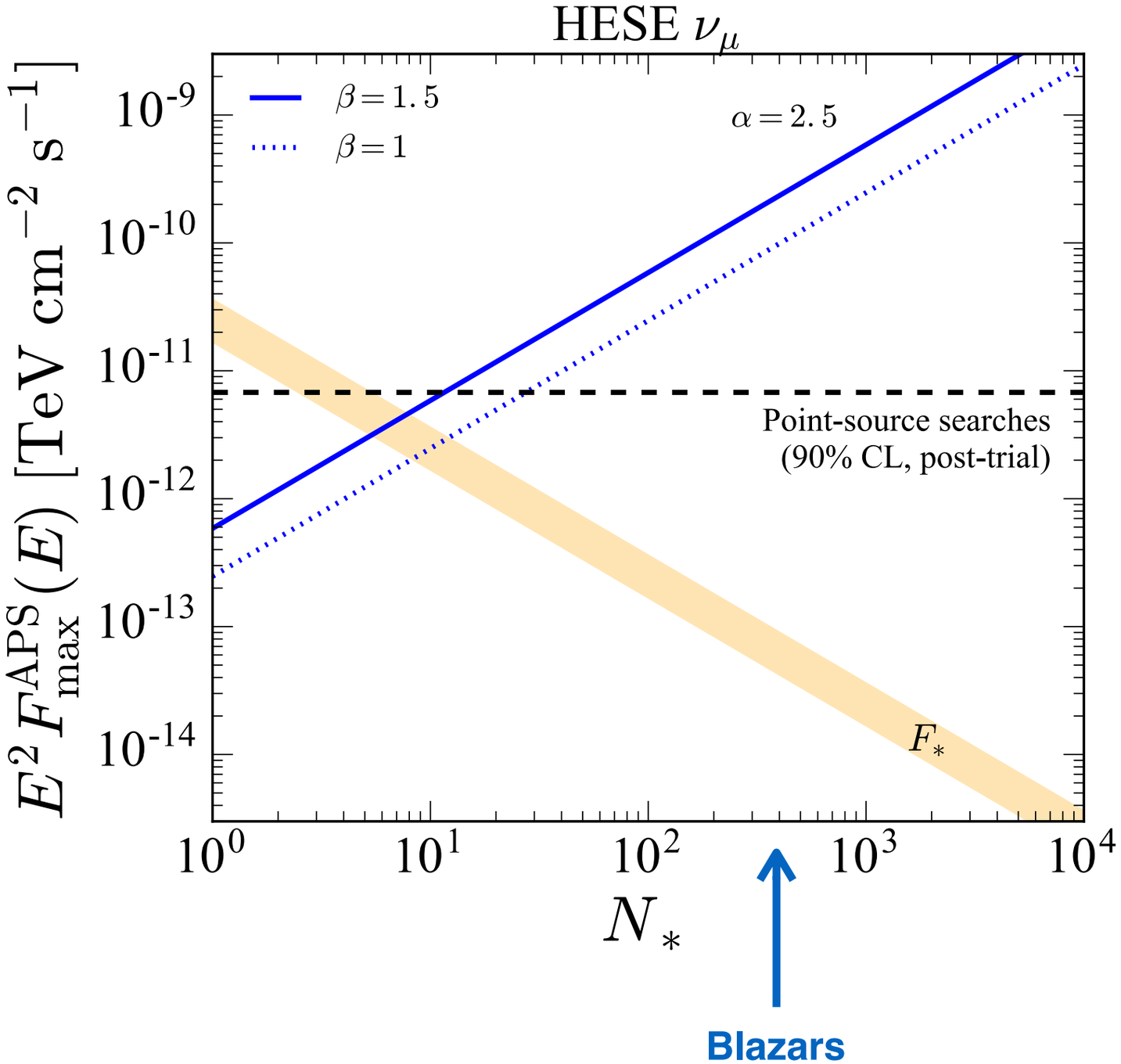
Ando, Feyereisen, Fornasa, *Phys. Rev. D* **95**, 103003 (2017)



- If 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 limit from the angular power spectrum: **HESE**

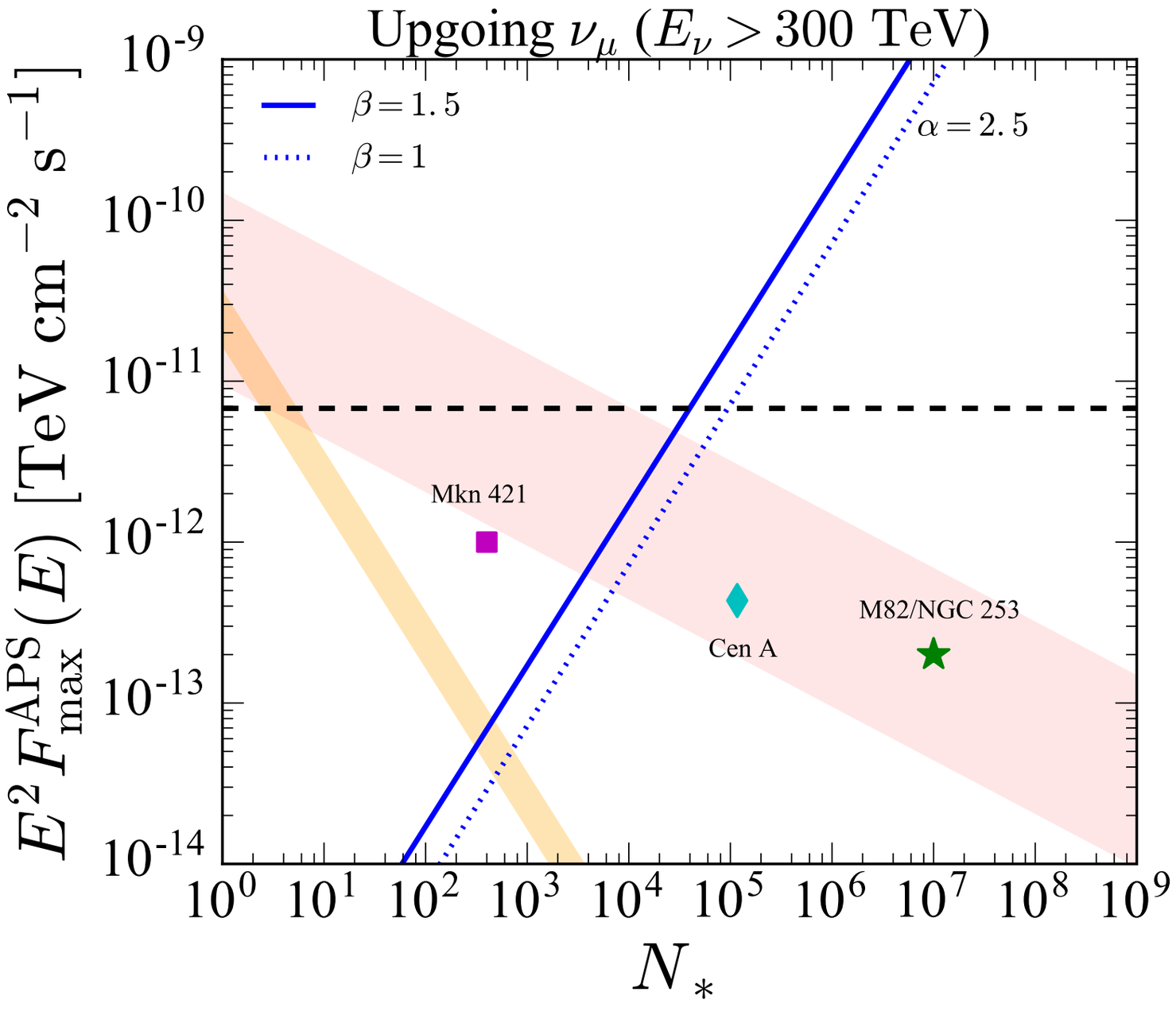
Ando, Feyereisen, Fornasa, *Phys. Rev. D* **95**, 103003 (2017)



- High-Energy Starting Events (HESE): 14 tracks, 39 showers
- 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

Flux limit from the angular power spectrum: **Upgoing ν_μ**

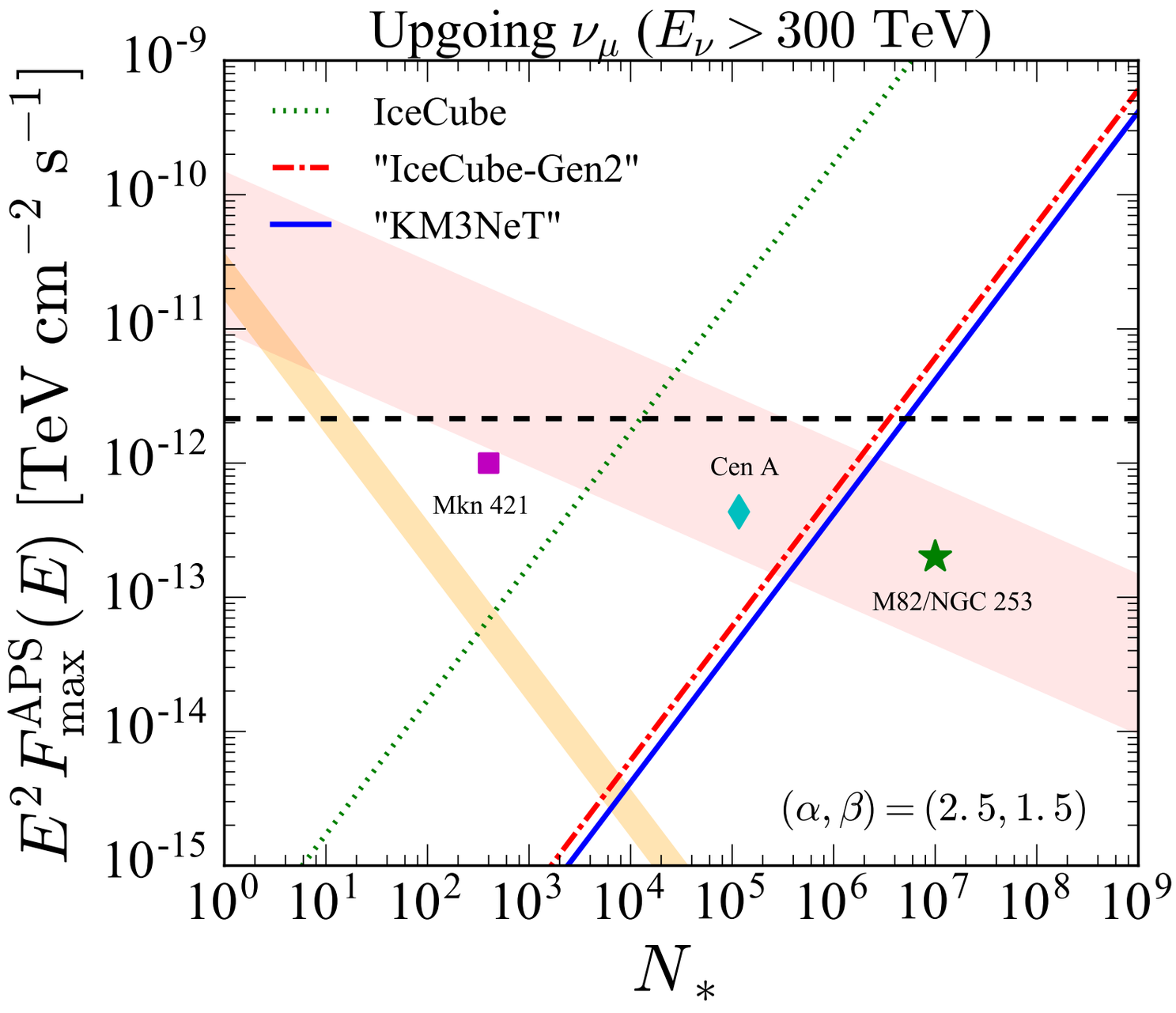
Ando, Feyereisen, Fornasa, *Phys. Rev. D* **95**, 103003 (2017)



- Projection for the ***current*** upgoing ν_μ events above 300 TeV: ~60 astro, 10 atmospheric
  - This doesn't change much even for 50 TeV threshold
- Constraints can already be very strong
  - Critical test of a scenario of blazar-domination for the diffuse flux
- Thanks to much larger exposure and better angular resolution

Flux sensitivity for the next generation

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

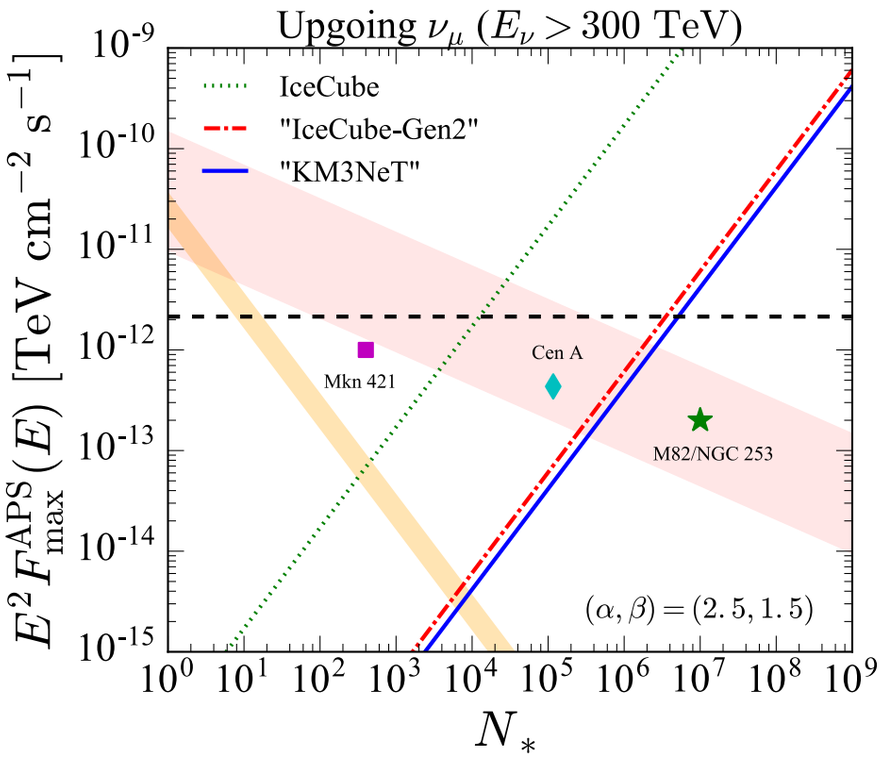


Detector	Strategy	$\mathcal{E}/\mathcal{E}_{\rm today}$	livetime	$\theta_{\rm psf}$ (tracks)
IceCube	HESE	1	4 yr	1°
	upgoing ν_μ	1	6 yr	0.5°
IceCube-Gen2	HESE	10	8 yr	0.5°
	upgoing ν_μ	10	12 yr	0.3°
KM3NeT	HESE	4	8 yr	0.2°
	upgoing ν_μ	4	12 yr	0.1°

- The angular power spectrum can test cases of any sources with ***N**** < **10^5–10^6** (blazars and radio galaxies)
- Similar sensitivities expected for “KM3NeT” and “IceCube-Gen2”

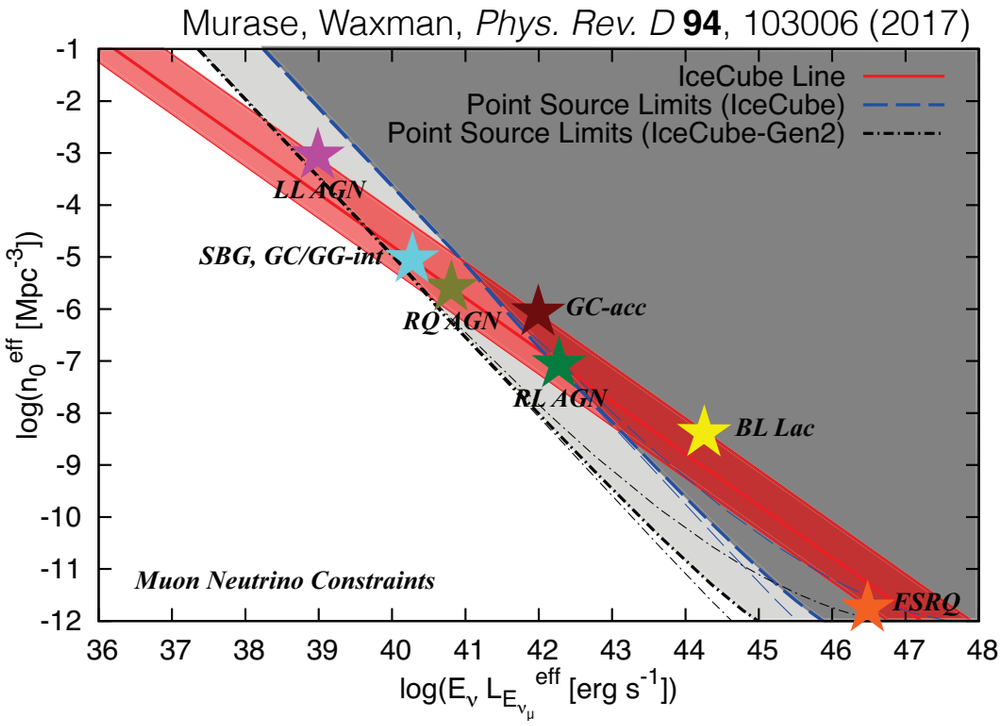
Relation with physical representation

Flux representation



- Phenomenological, but **model-independent**
- Contribution to the diffuse flux has to be assumed in advance
- **Power spectrum constraints nicely integrated**

Luminosity representation



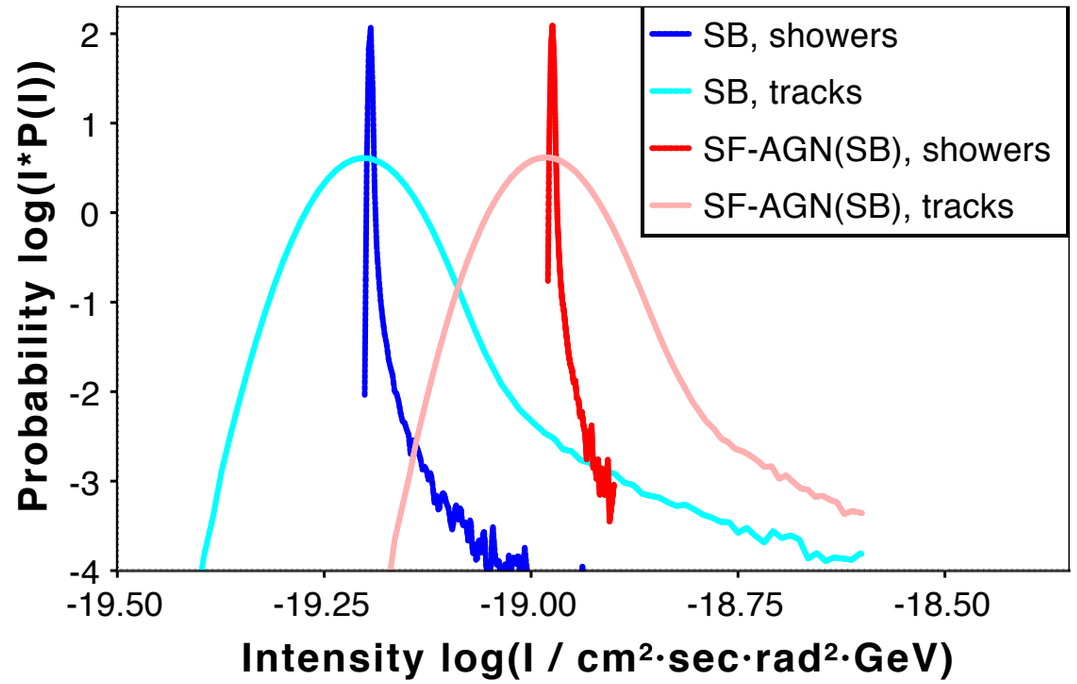
- Physical, but model dependent
- No assumption needed for fraction to the diffuse flux
- Power spectrum constraints not well integrated (so far)

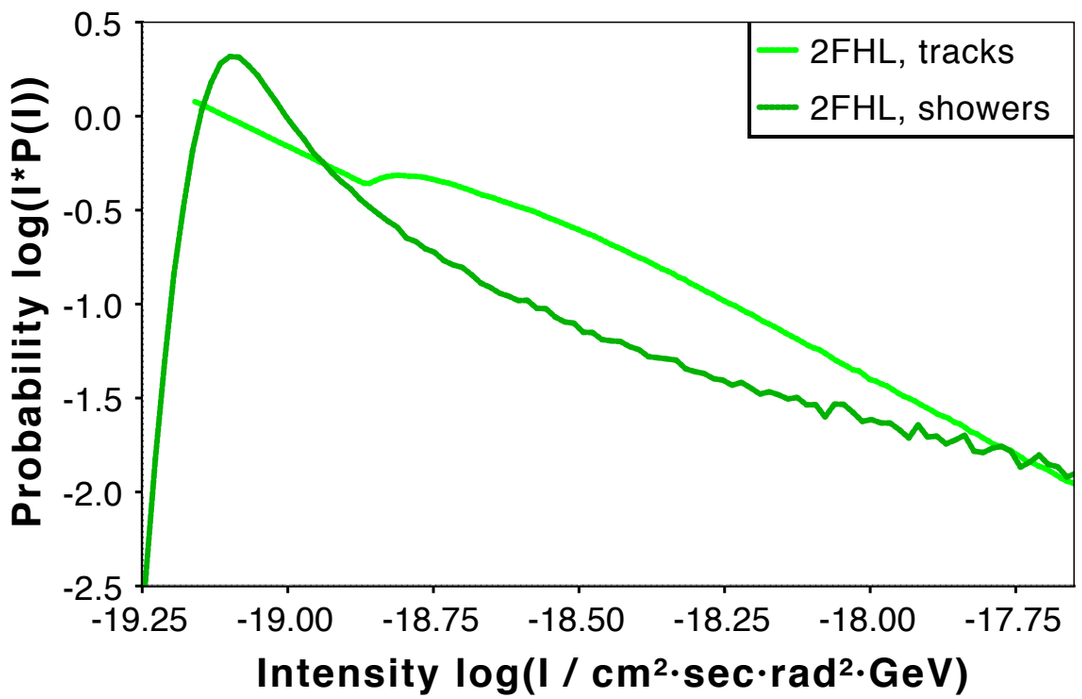
Conversion between the two straightforward (but model dependent)

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 (Feyereisen, Gaggero, Ando, in preparation)

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





Conclusions

- IceCube's detection of TeV-PeV neutrinos has 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** will be important to further constrain neutrino sources