How bright can the brightest neutrino source be?

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Lessons from gamma rays

DATA P7REP_ULTRACLEAN_V15, 1–2 GeV

Lessons from gamma rays

DATA P?REP_ULTRACLEAN_V15, 1–2 GeV

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)

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


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

- 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 $F_{\text{max}}$
One-source limit

- If $F_{\text{max}}$ 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**

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


Blazars

![Graph showing $E^2 F_{\text{APS}}(E)$ vs $N^*$]
Flux limit from the angular power spectrum: **Upgoing $\nu_\mu$**


- Projection for the **current** upgoing $\nu_\mu$ events above 300 TeV: $\sim$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)

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

**Flux representation**

![Flux representation diagram](image)

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

**Luminosity representation**

![Luminosity representation diagram](image)

- 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)
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.