BEGINNING A JOURNEY ACROSS THE UNIVERSE

THE DISCOVERY OF EXTRAGALACTIC NEUTRINO FACTORIES

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https://sarabuson.github.io/messmapp.html

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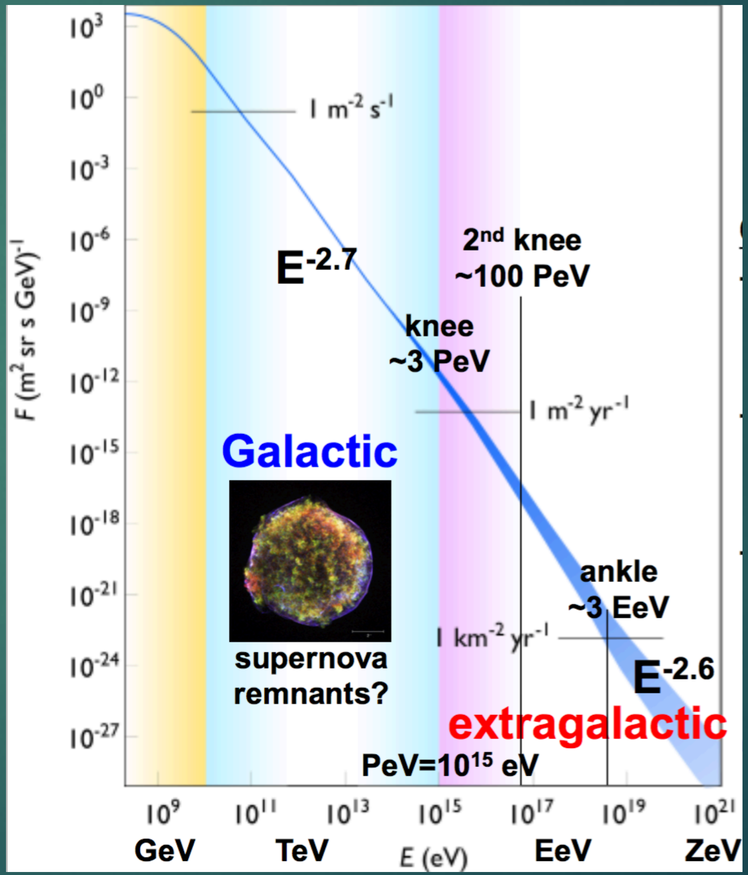
A Century Old Puzzle: Cosmic Rays
- neutrinos as indirect probes

How is the spectrum composed?

How are CRs accelerated?

How do CRs propagate?



Energy Density in the Universe in γ rays, neutrinos and cosmic rays is similar

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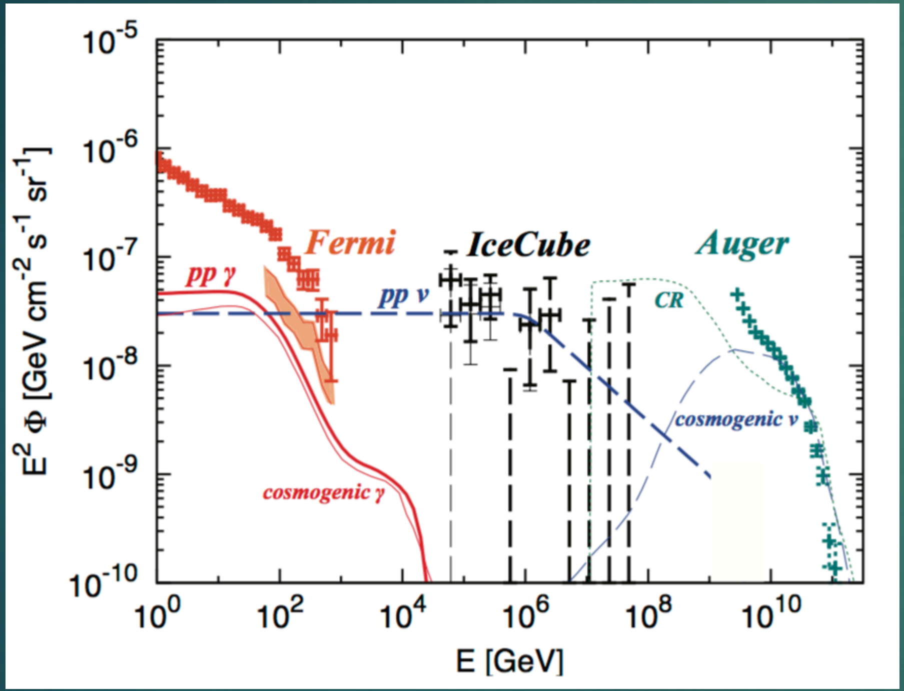

Murase & Waxam 2016

Diffuse energy fluxes of sub-TeV γ rays, PeV neutrinos, and UHECRs are all comparable, while particle energy spans over ten orders of magnitude.

Gamma-ray flaring blazar TXS 0506+056 possibly associated with one high-energy neutrino event (IceCube coll., Fermi-LAT coll., SB. et al. 2018, IceCube coll. 2018)

Neutrino point-source Searches: Status of Art

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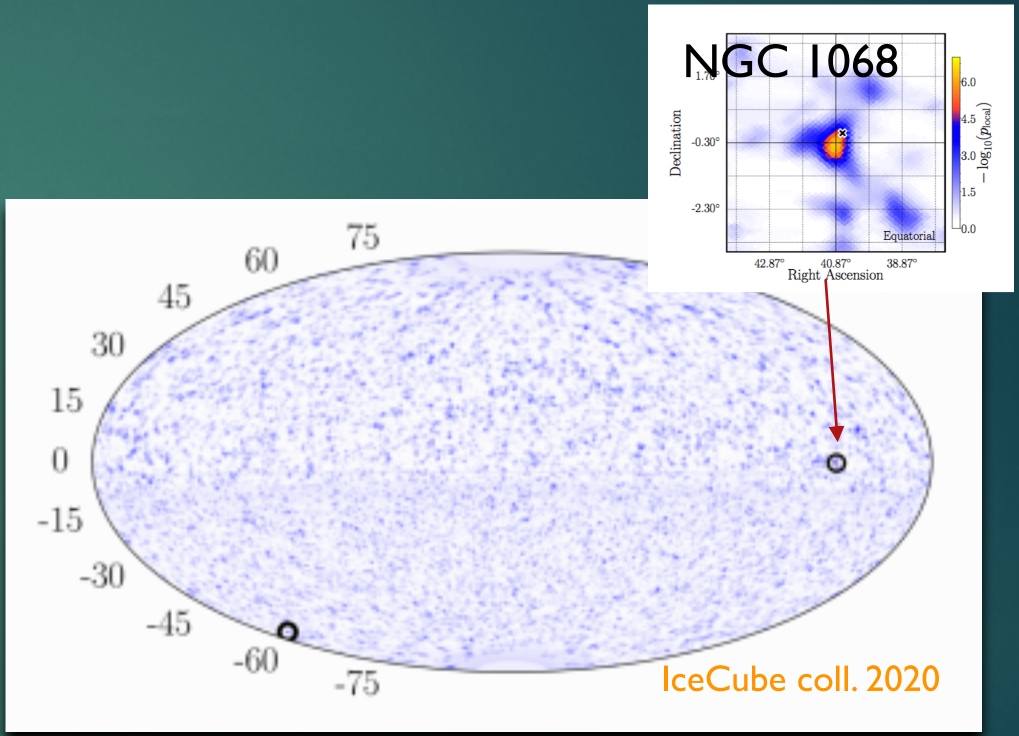
Latest (IceCube) searches

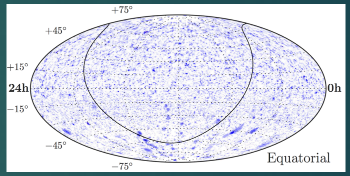
- Blind all-sky search (10-years IC data)
- Tested a list of extragalactic candidates. Most significant spots :
  - NGC 1068 (level of 2.9σ), PKS 1424+240, GB6 J1542+6129, TXS 0506+056
- Correlations with tested sources (northern catalog, level of 3.3σ)



- **Neither individual neutrino-source detected at high confidence, nor source classes**
- **Events isotropically distributed (favoring extragalactic origin)**

Hypothesis Primers

- IceCube neutrino data
  - the ‘highest-quality’ data for point-source searches publicly available



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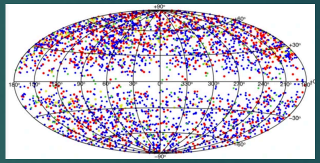
- Blazar sample



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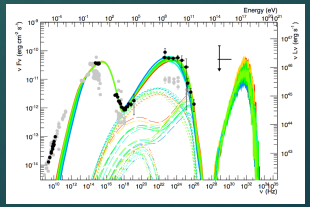
- Exploit blazar theoretical predictions



IceCube Neutrino sky-map

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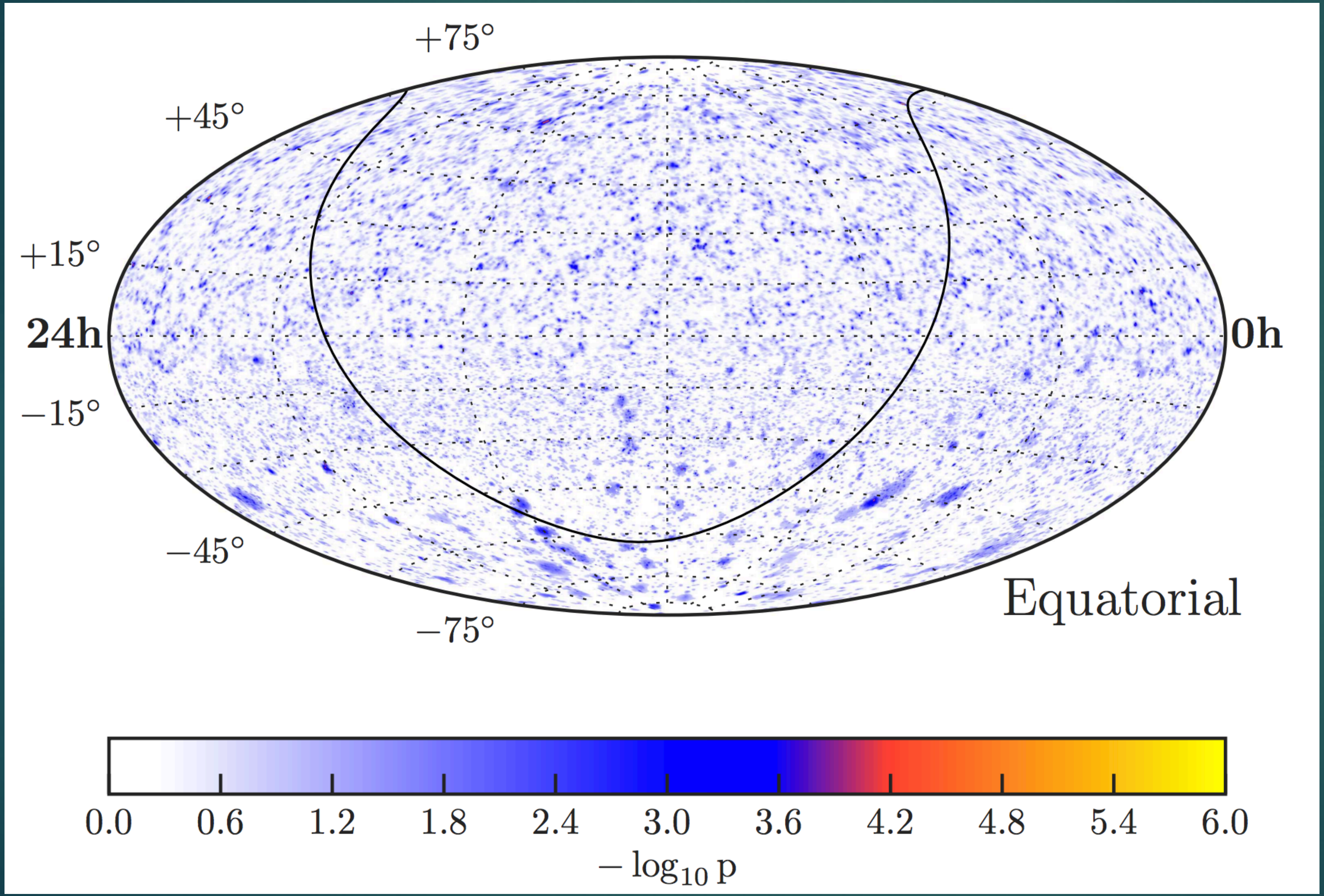

7-year sky map
- 2008 - 2015

IceCube coll. 2017

IceCube Neutrino sky-map

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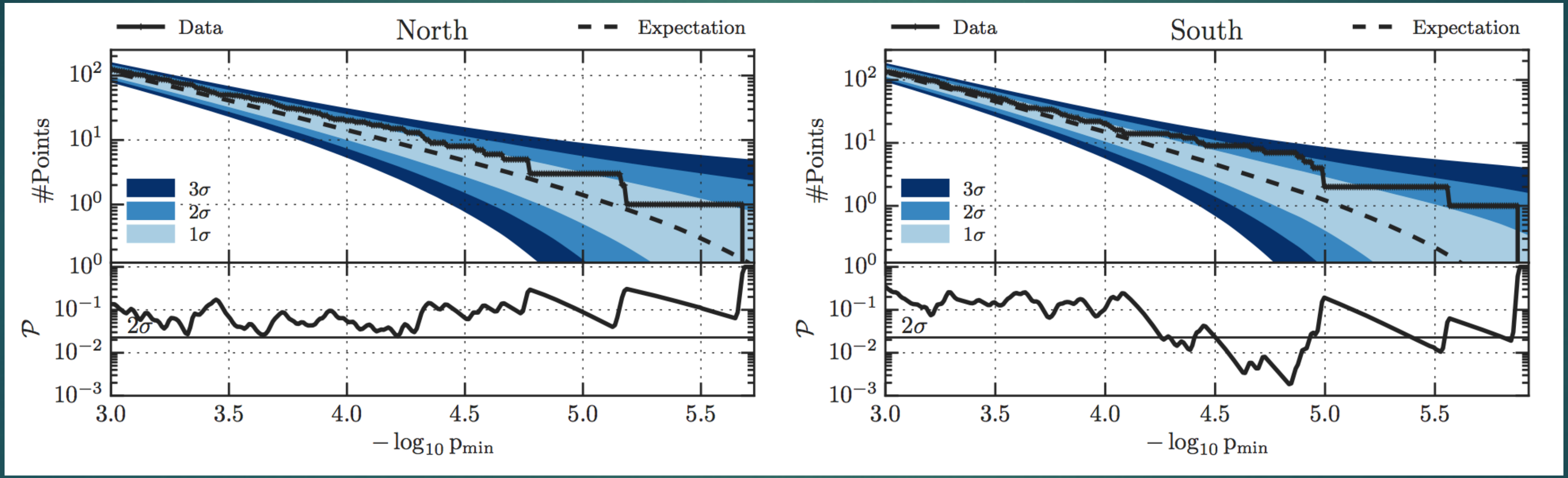
IceCube coll. Results:

- No significant excess in the hot-spot all-sky population analysis
  - Many trials, more than 10^7 sky locations tested



IceCube coll. 2017

The 7-year IceCube sky-map

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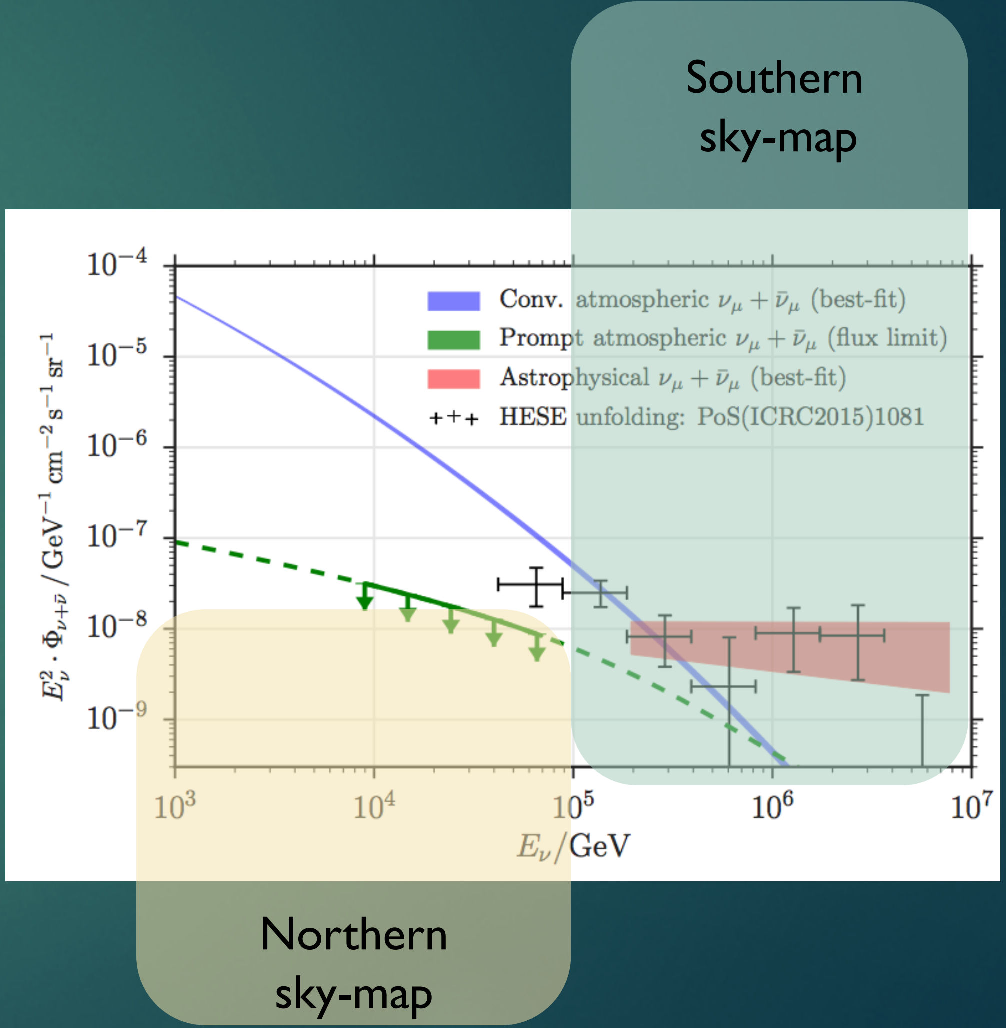
Hemisphere	*Northern*	*Southern*
Energy range	From **~TeV to <PeV**	From **≳ 100 TeV, beyond PeV**
PWL spectral index for event reconstruction	Trained with either -2 or -2.7	Fixed to -2
Data sensitive to	Both hard- & soft-spectrum point-sources	Optimized for hard-spectrum point-sources

Working Hypothesis:

- A significant astrophysical contribution is observed at the highest neutrino energies, ≳100 TeV
  - Diffuse neutrino emission analysis, Northern Hemisphere (2009 – 2015)
    - between 194 TeV and 7.8 PeV

- The observed spectrum is harder in comparison to previous IceCube analyses with lower energy thresholds which may **indicate a break** in the astrophysical neutrino spectrum of unknown origin



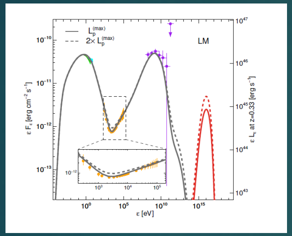
Working Hypothesis:

- If blazars are powered by hadronic processes (at least at some extent) :
  - The emerging spectrum is hard in the IceCube energy band (*many references)
    - Index <~ -2
    - NU peak foreseen at ~PeVs

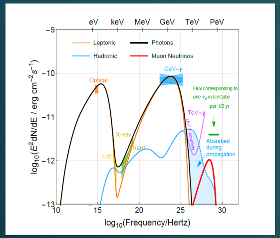
Many references (e.g. Mannheim 1993; Stecker 2013; Dermer et al. 2014; Murase et al. 2014; Petropoulou et al. 2015; Padovani et al. 2015)

Blazar (typical) Multi-Messenger SED

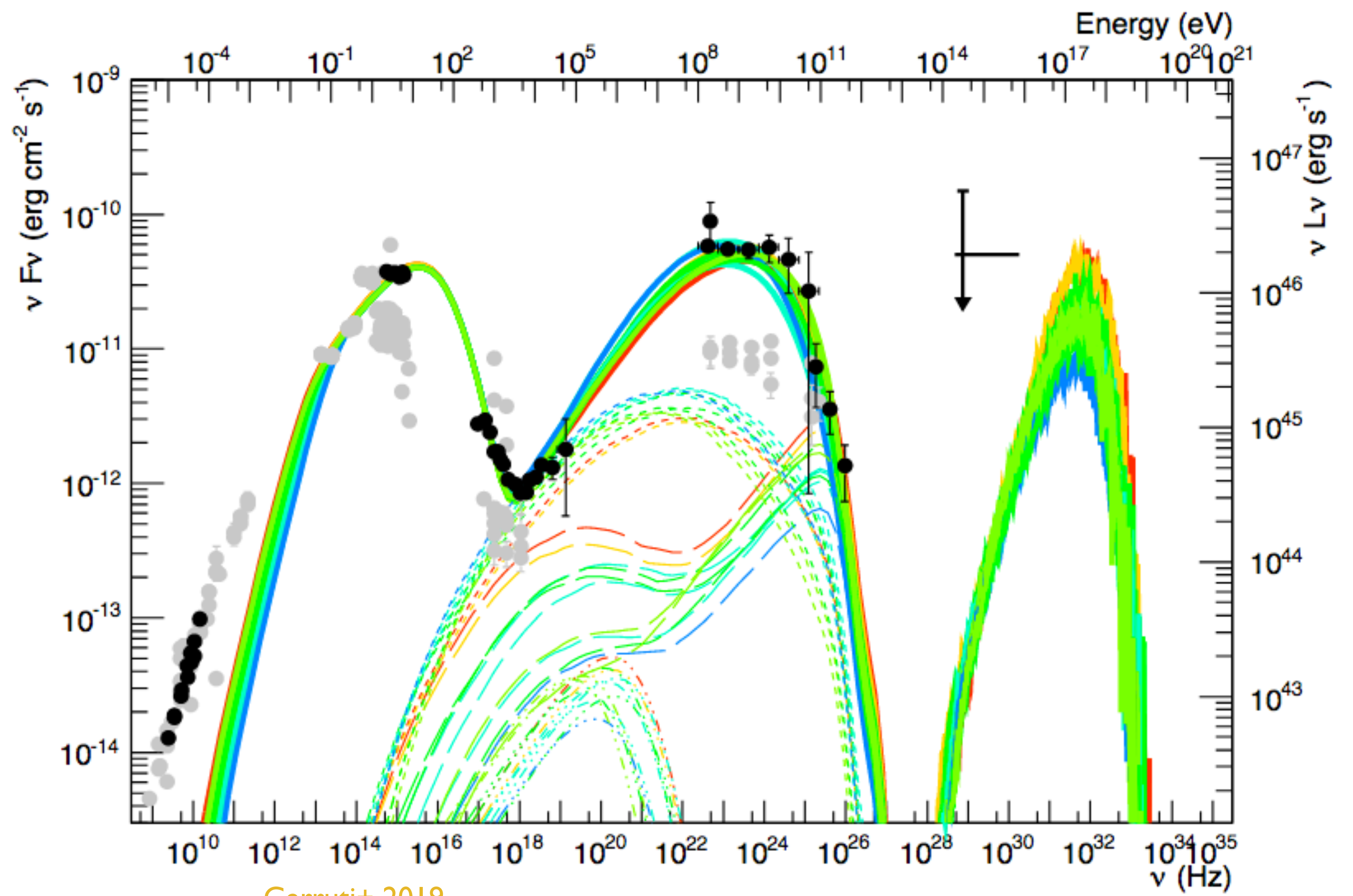
Similar for most blazar models



Keivani et al.:, 2018



Gao et al., 2018



Cerruti+ 2019

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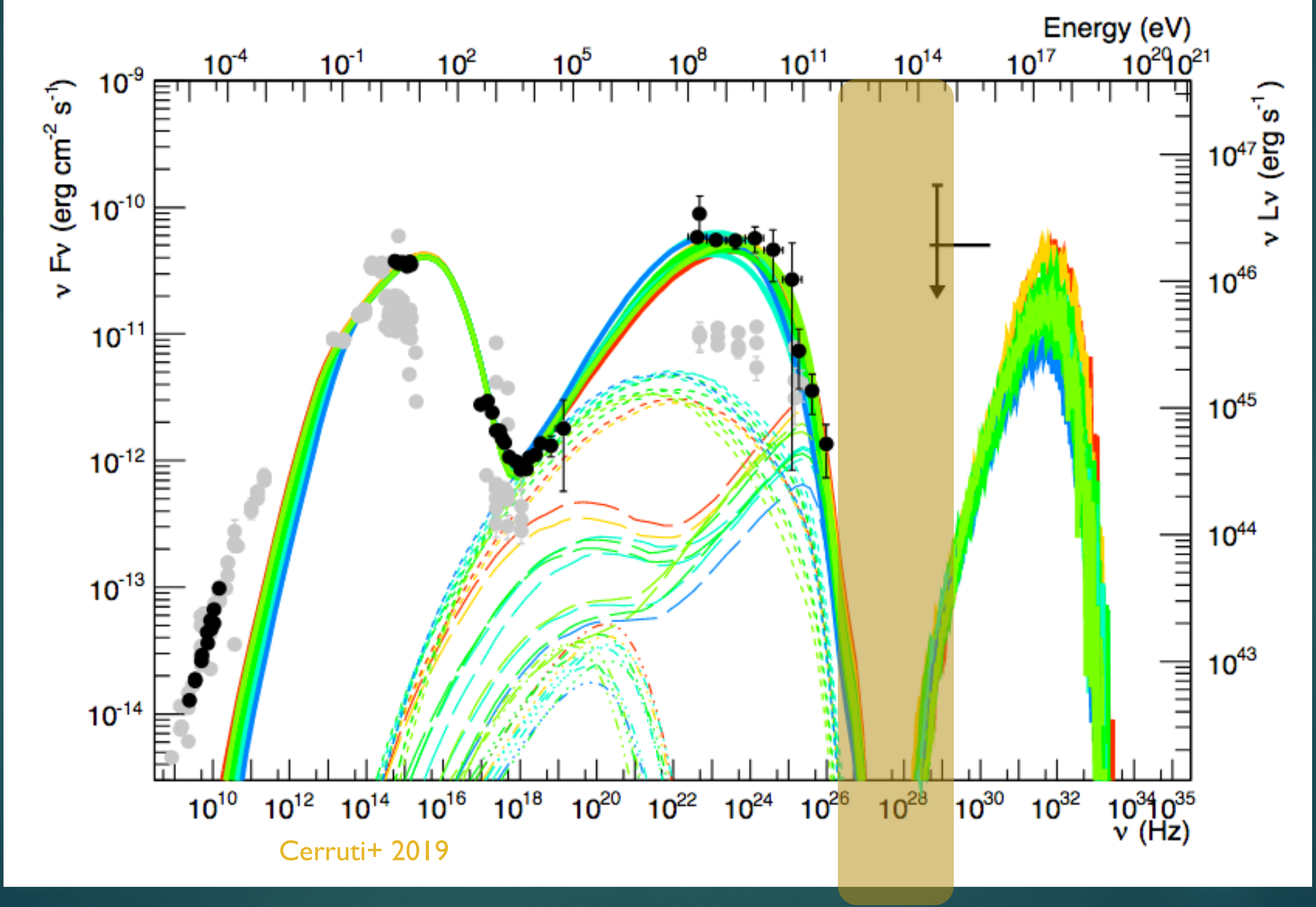
Blazar (typical) Multi-Messenger SED



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Northern sky-map

Blazar (typical) Multi-Messenger SED

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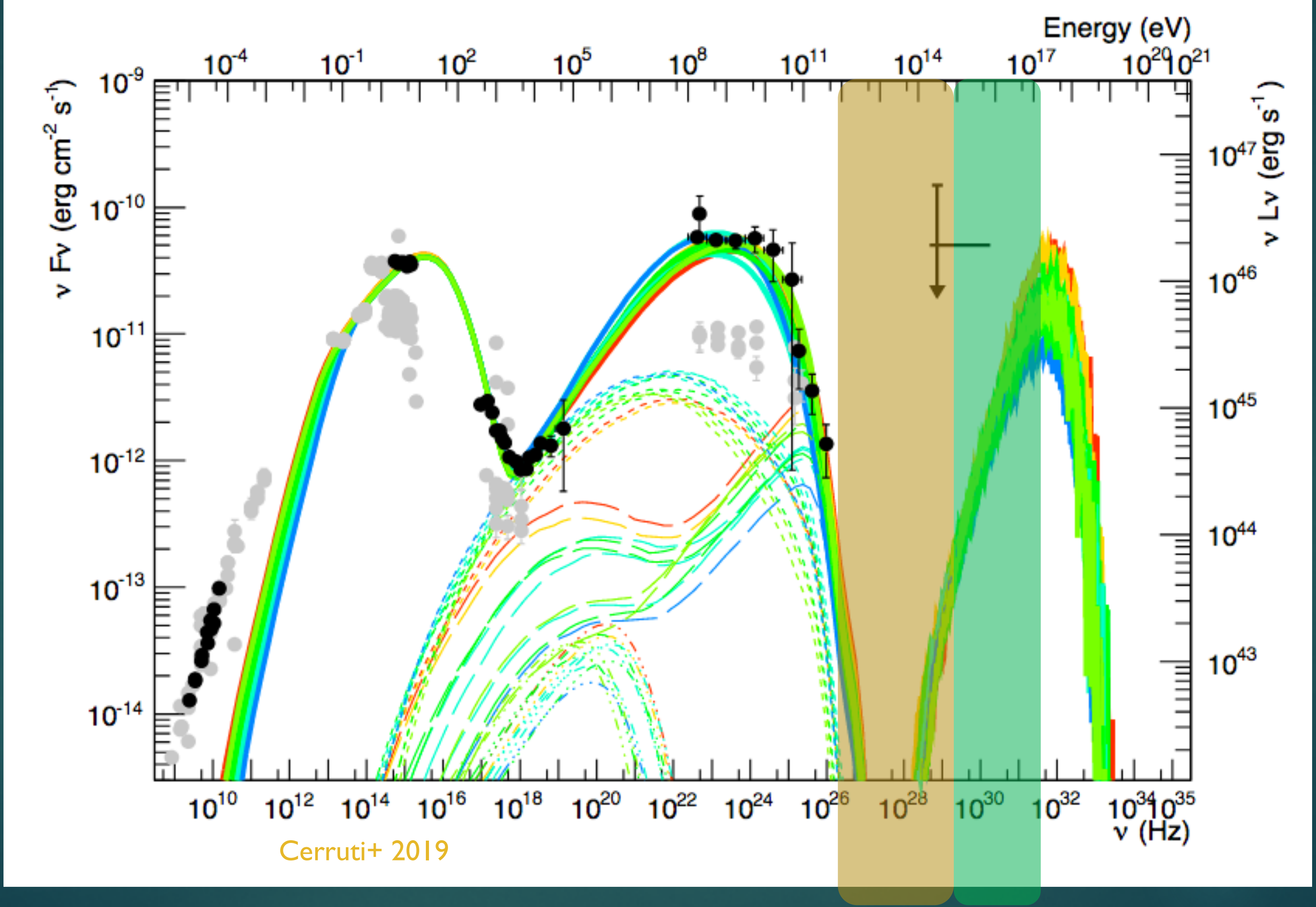

Cerruti+ 2019

Southern sky-map

Northern sky-map

Educated Guess

If blazars produce neutrinos,

given the data at hand,

the IceCube Southern celestial hemisphere is the most promising testing ground

Blazar sample : 5BZCat

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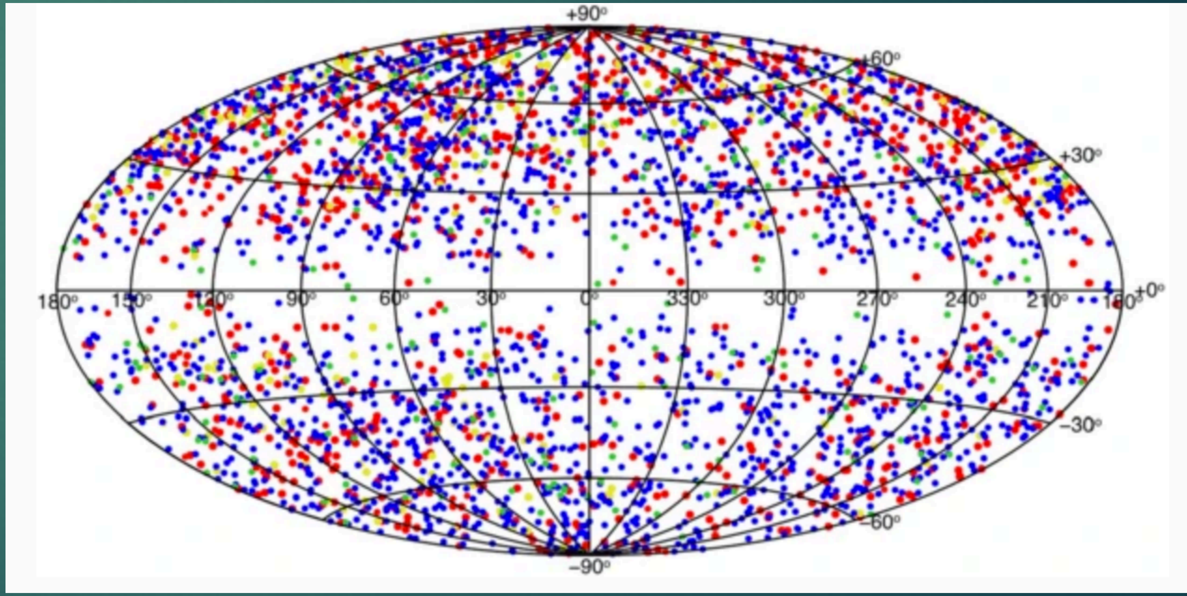
Well-defined sample of blazars
No preferred selection toward a particular wavelength or survey strategy

- 5BZCat : total of 3561 objects
- After cuts (|b|>10° dec= -5°) :
  - 2191 in northern hemisphere
  - 1177 in southern hemisphere



Neutrino sky-map (7 yr)

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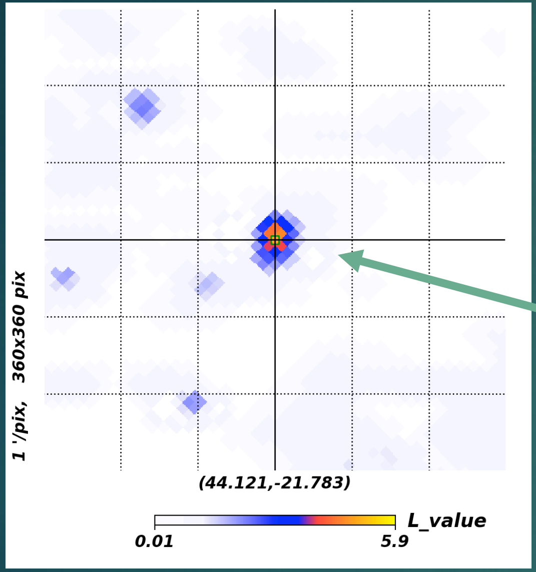
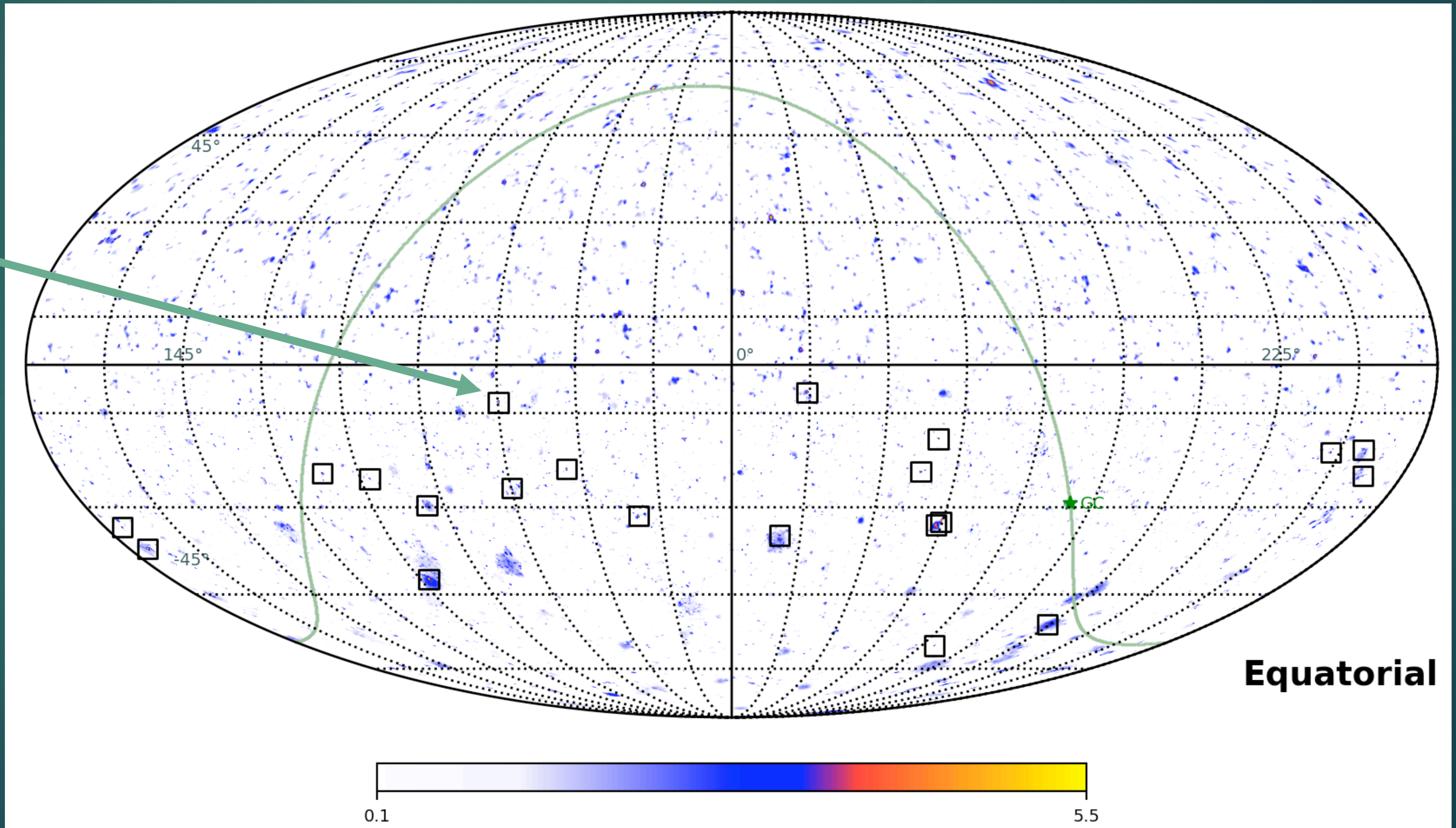
- Sky-map : 10^7 pixels (sky locations)

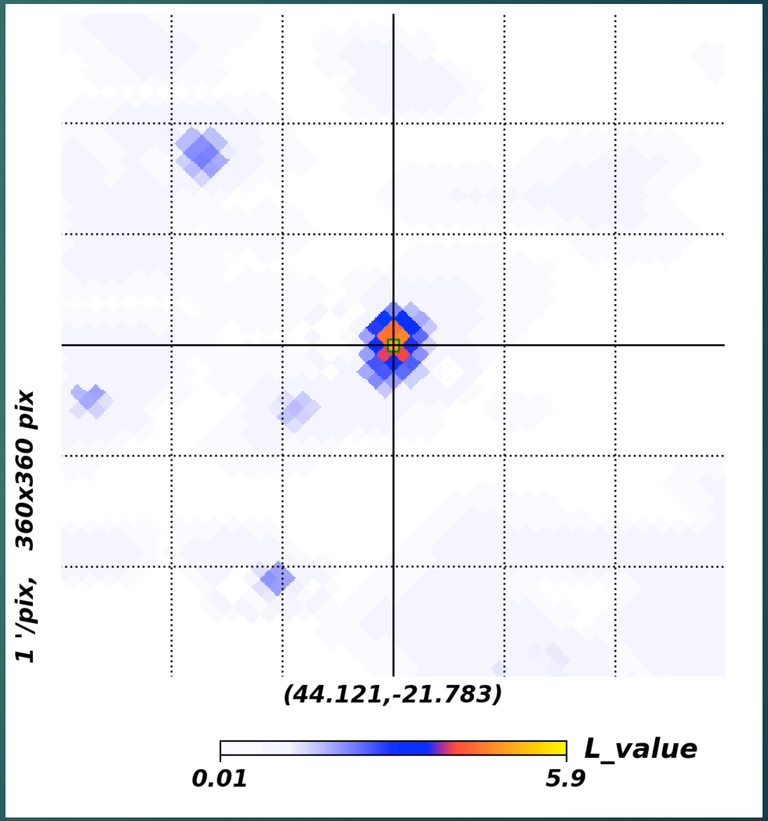
Focus on the neutrino clusters with strongest deviation from background expectations -- to limit trials





Test a few different (inclusive) neutrino samples

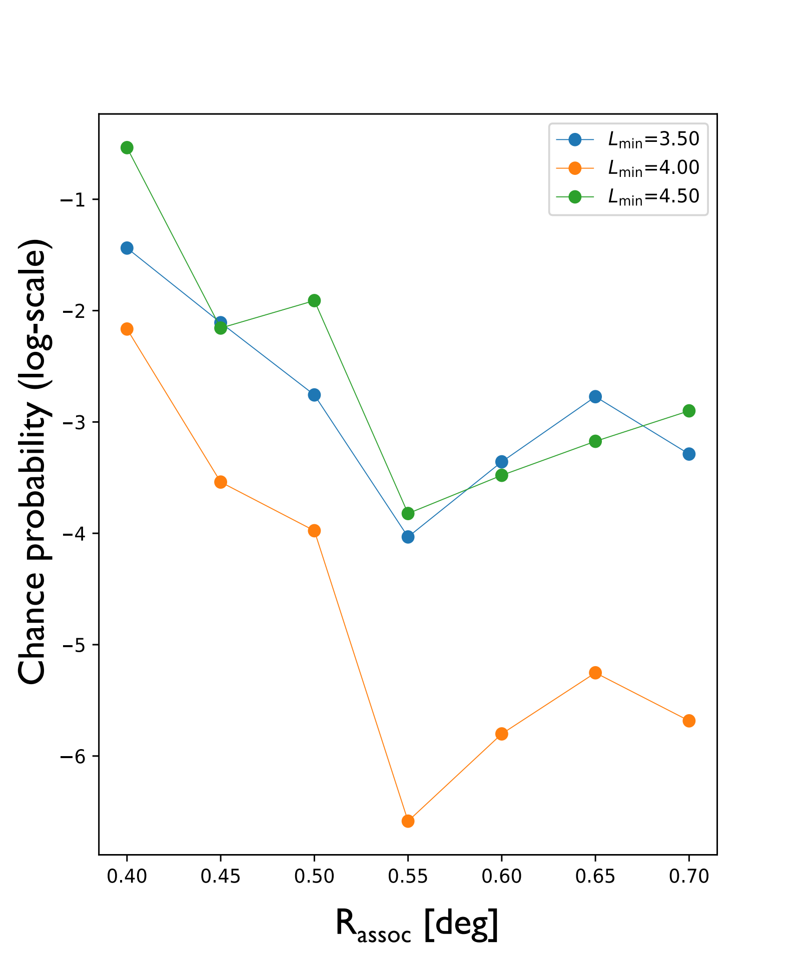
- Neutrino spot = i.e. sky-location (pixel-map)
  - 0.1° x 0.1° map resolution
- L_{min} = {3.5, 4.0, 4.5}
  - 44, 19, 9 neutrino spots
    - Out of > 10^7 pixels (sky locations)
- R_{assoc} = [0.4°, 0.7°] with steps of 0.05°
  - Driven by median angular resolution of the neutrino events



Cross-correlation analysis

- Perform positional cross-correlation analysis*

Sky region	5BZCat	Hotspots	Matches	pre-trial p-value	post-trial p-value
Southern sky ($L \geq 4$)	1177	19	10	3×10^{-7}	2×10^{-6}



*Similar to Finley & Westerhoff 2004; Pierre Auger Collaboration et al. 2008; Resconi et al. 2017; Plavin et al. 2021; Hovatta et al. 2021,…

Cross-correlation analysis

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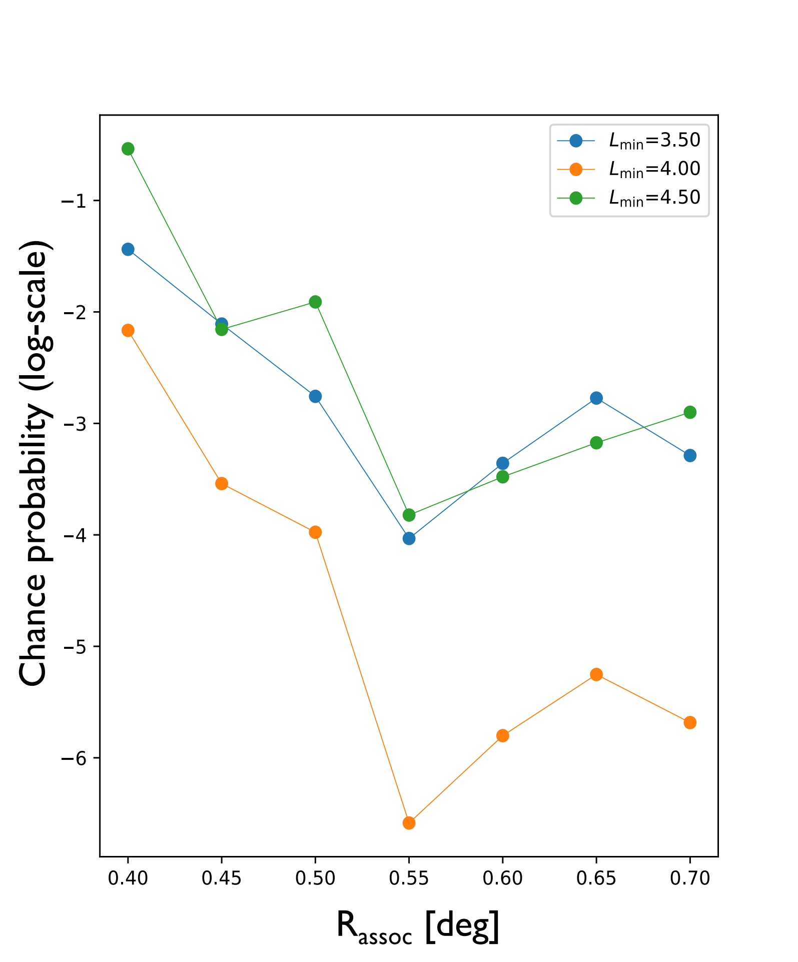
Southern sky ($L \geq 4$)	1177	19	10	3×10^{-7}	2×10^{-6}

- *The post-trial p-value is 2×10^{-6}*
- *The minimum pre-trial p-value, 3×10^{-7}, provides us **with the strongest potential correlation signal.***



*Similar to Finley & Westerhoff 2004; Pierre Auger Collaboration et al. 2008; Resconi et al. 2017; Plavin et al. 2021; Hovatta et al. 2021,…

Extragalactic neutrino factories

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The Astrophysical Journal Letters, 933:L43 (9pp), 2022 July 10 https://doi.org/10.3847/2041-8213/ac7d5b

CrossMark

Beginning a Journey Across the Universe: The Discovery of Extragalactic Neutrino Factories

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ABSTRACT

Neutrinos are the most elusive particles in the Universe, capable of travelling nearly unimpeded across it. Despite the vast amount of data collected, a long standing and unsolved issue is still the association of high-energy neutrinos with the astrophysical sources that originate them. Amongst the candidate sources of neutrinos there are blazars, a class of extragalactic sources powered by supermassive black holes that feed highly relativistic jets, pointed towards the Earth. Previous studies appear controversial, with several efforts claiming a tentative link between high-energy neutrino events and individual blazars, and others putting into question such relation. In this work we show that blazars are unambiguously associated with high-energy astrophysical neutrinos at unprecedented level of confidence, i.e. chance probability of 2×10^{-6}. Our statistical analysis provides the observational evidence that blazars are astrophysical neutrino factories and hence, extragalactic cosmic-ray accelerators.

Unified Astronomy Thesaurus concepts: Neutrino astronomy (1100); Neutrino telescopes (1105); Blazars (164); Supermassive black holes (1663); Relativistic jets (1390); Cosmic ray astronomy (324)


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The *PeVatron* Blazars

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IceCube hotspots				Blazar associations		
	α_{hs}[°]	δ_{hs}[°]	L	5BZCat	z	Separation[°]
IC J2243−0540	340.75	−5.68	4.012	5BZB J2243−0609	0.30[c]	0.47
IC J0359−0746	59.85	−7.78	5.565	5BZQ J0357−0751	1.05	0.42
IC J0256−2146	44.12	−21.78	4.873	5BZQ J0256−2137	1.47	0.17
IC J2037−2216	309.38	−22.27	4.664	5BZQ J2036−2146	2.299	0.51
IC J0630−2353	97.56	−23.89	4.420	5BZB J0630−2406[a,b]	>1.238[d]	0.28
IC J0359−2551	59.94	−25.86	4.356	5BZB J0359−2615[a]	1.47[e]	0.40
IC J0145−3154	26.28	−31.91	4.937	5BZU J0143−3200[a]	0.375	0.42
IC J2001−3314	300.41	−33.24	4.905	5BZQ J2003−3251	3.773	0.53
IC J2304−3614	346.03	−36.24	4.025	5BZQ J2304−3625	0.962	0.24
IC J1818−6315	274.50	−63.26	4.030	5BZU J1819−6345	0.063	0.53
IC J2024−1524	306.12	−15.40	4.454	–	–	–
IC J1256−1739	194.06	−17.66	4.407	–	–	–
IC J1329−1817	202.32	−18.29	4.040	–	–	–
IC J1241−2314	190.37	−23.24	4.288	–	–	–
IC J0538−2934	84.73	−29.57	4.994	–	–	–
IC J2006−3352	301.55	−33.87	4.698	–	–	–
IC J1140−3424	175.17	−34.41	4.082	–	–	–
IC J1138−3915[f]	174.64	−39.26	5.885	–	–	–
IC J0628−4616	97.23	−46.28	4.987	–	–	–

10 blazars confidently associated with IceCube neutrino clusters

Buson et al. 2022 (ApJL, 933, 43)

The *PeVatron* Blazars

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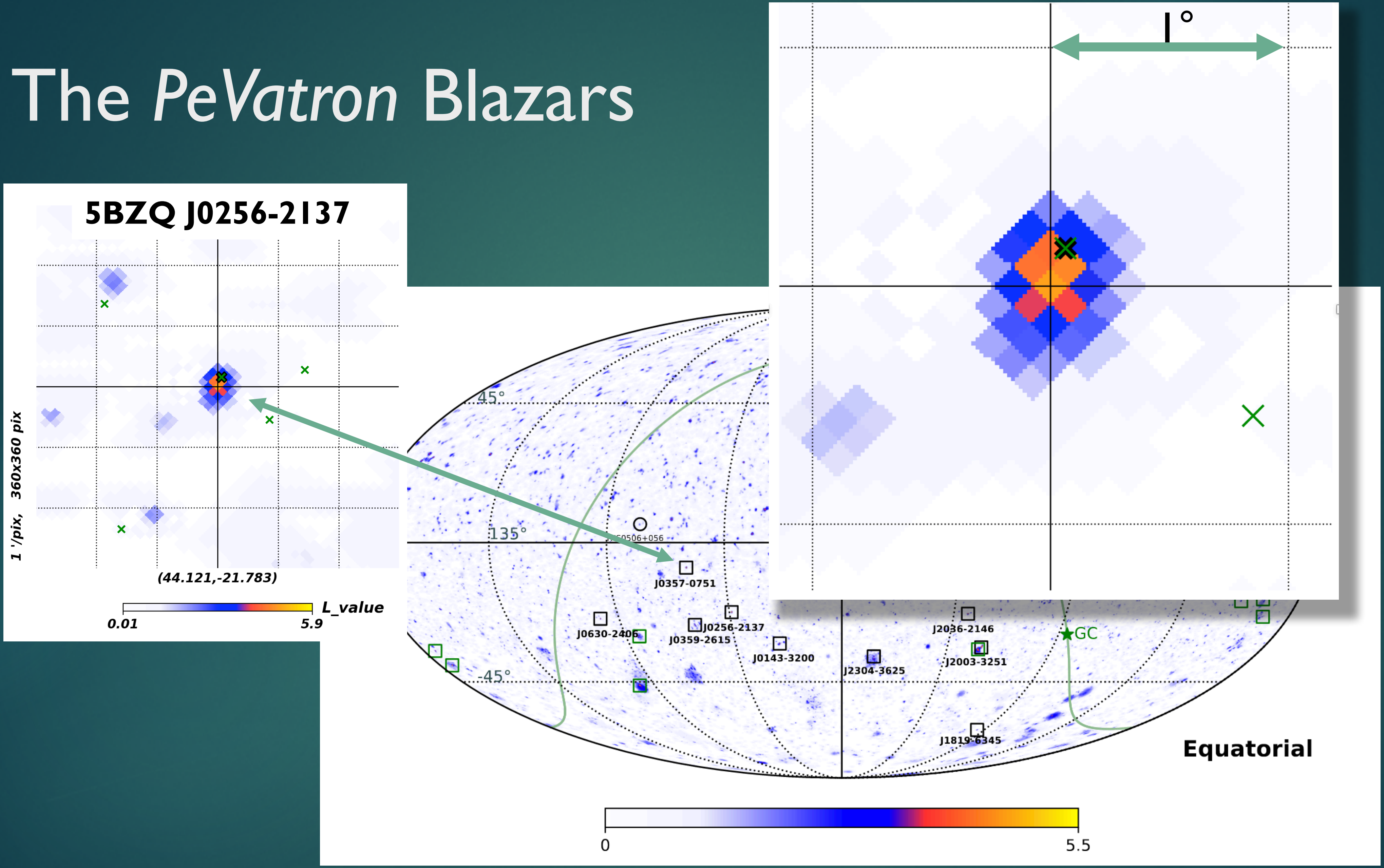
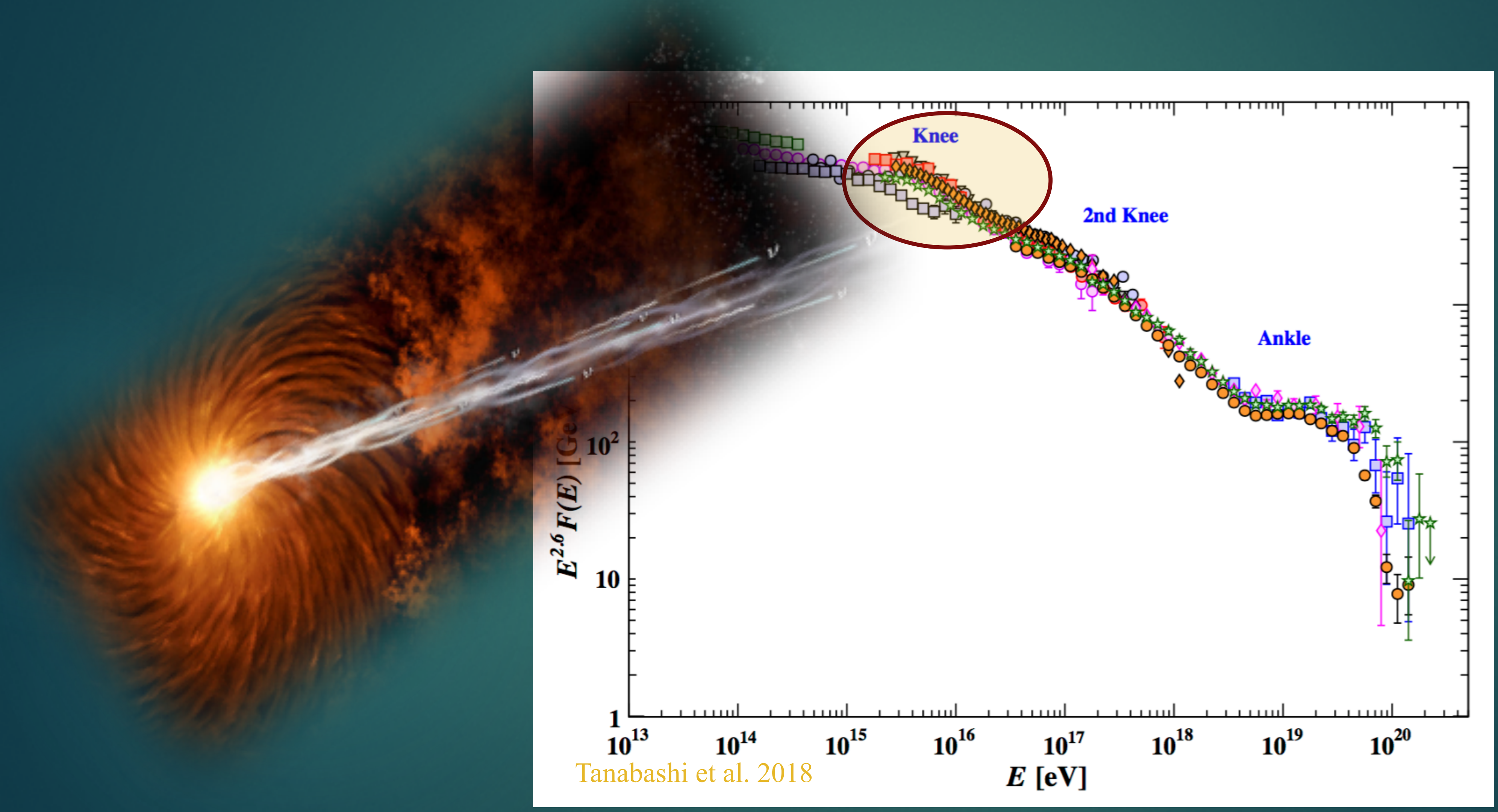


Implications to cosmic rays (& more)



Summary & Conclusions

- **10 PeVatron blazars associated with IceCube high-energy neutrino clusters**
  - post-trial probability of 2×10^{-6}
- In the blazars' engine, the neutrino emission is weakly related to the observed γ-ray emission, this implies :
  - Different emission sites for the bulk of neutrinos and gamma-rays
  - IceCube neutrinos most promisingly related to the X-ray / MeV (photon) regime
- **Firm indirect detection of extragalactic cosmic-ray factories**
  - In situ acceleration of cosmic rays to PeV energies and, possibly, up to the EeV regime
- '**Tip of the iceberg**' : IceCube may be soon sensitive to detect individual point-sources (possibly at high-confidence).

Buson et al. 2022, ApJL, 933, 43

Back UP

TXS 0506+056

E. TXS 0506+056: A PROMISING PEVATRON BLAZAR

Based on our work one may predict that the IceCube observatory will reach the sensitivity to detect individual astrophysical point-sources at high confidence in the near future. This behavior is yet observed at the location of TXS 0506+056, associated with the 5BZCat object 5BZB J0509+0541, and has been claimed to be a neutrino-emitter blazar (IceCube Collaboration et al. 2018). In the 7-year IceCube data utilised by this work, it appears in spatial agreement with a neutrino spot of $L = 2.2$. Since it is located in the northern hemisphere, this blazar is not included in our statistical analysis. However, we note that in the analysis of 10 (8) years of IceCube observations (Aartsen et al. 2020, 2019), i.e. 3 (2) additional years compared to the all-sky map used by us, the value of L in coincidence with TXS 0506+056 progressively increases to 3.72 (2.65), as expected for a truly astrophysical signal that keeps steadily increasing when deepening the observational sensitivity and acquiring more exposure. Besides, Aartsen et al. (2020) reports that the cumulative 10-year signal at the location of TXS 0506+056 is best-fitted by a hard powerlaw ($\propto E^{-2.1}$) neutrino spectrum, that is consistent with predictions of blazar hadronic models. This corroborates the hypothesis that this blazar may be a genuine astrophysical neutrino source. It would be interesting applying our analysis to the IceCube 10-year all-sky likelihood map, which has not been released publicly at the time of the writing.

Buson et al. 2022, ApJL, 933, 43