Beginning a Journey Across the Universe

the Discovery of Extragalactic Neutrino Factories

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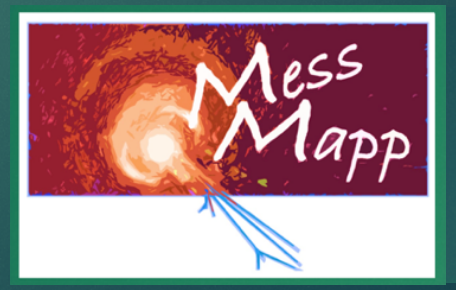


Caltech/IPAC Seminar series, *15.03.2023*

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

Outline

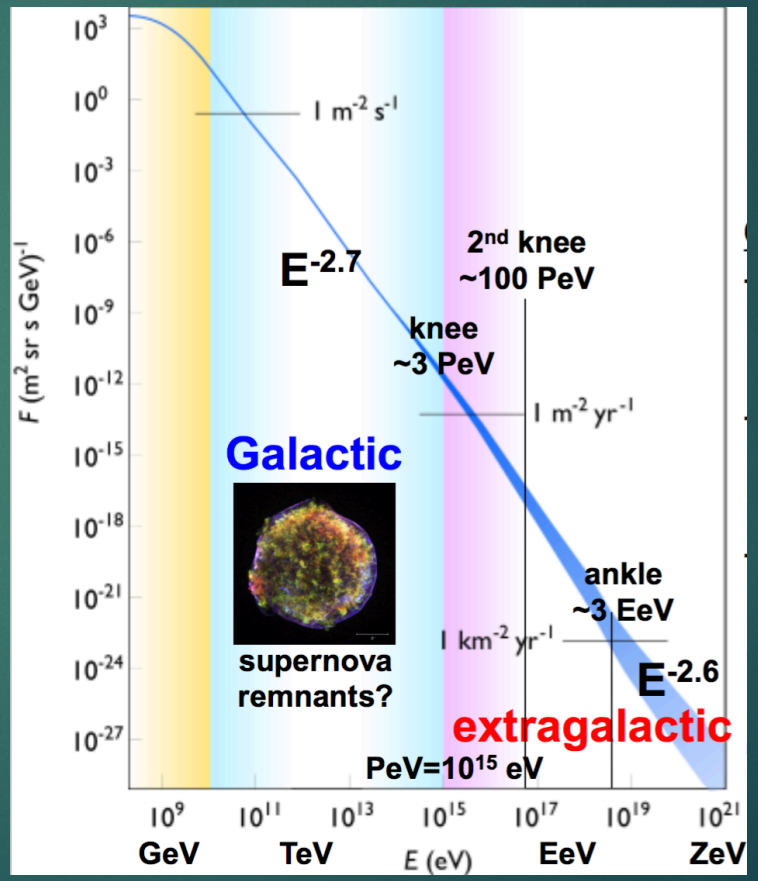
- The multi-messenger panorama (cosmic ray / neutrino dichotomy)
  - Astrophysical sources of neutrinos (focus on blazars)
- Status of art for astrophysical neutrino searches
- A promising next step forward
  - *PeVatron* blazars

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

How is the spectrum composed?

How are CRs accelerated?

How do CRs propagate?



Astrophysical Extragalactic Scenarios - neutrino production

Cosmic-ray Accelerators

Neutrinos produced within the CR source, mesons are typically produced by interactions of CRs with radiation

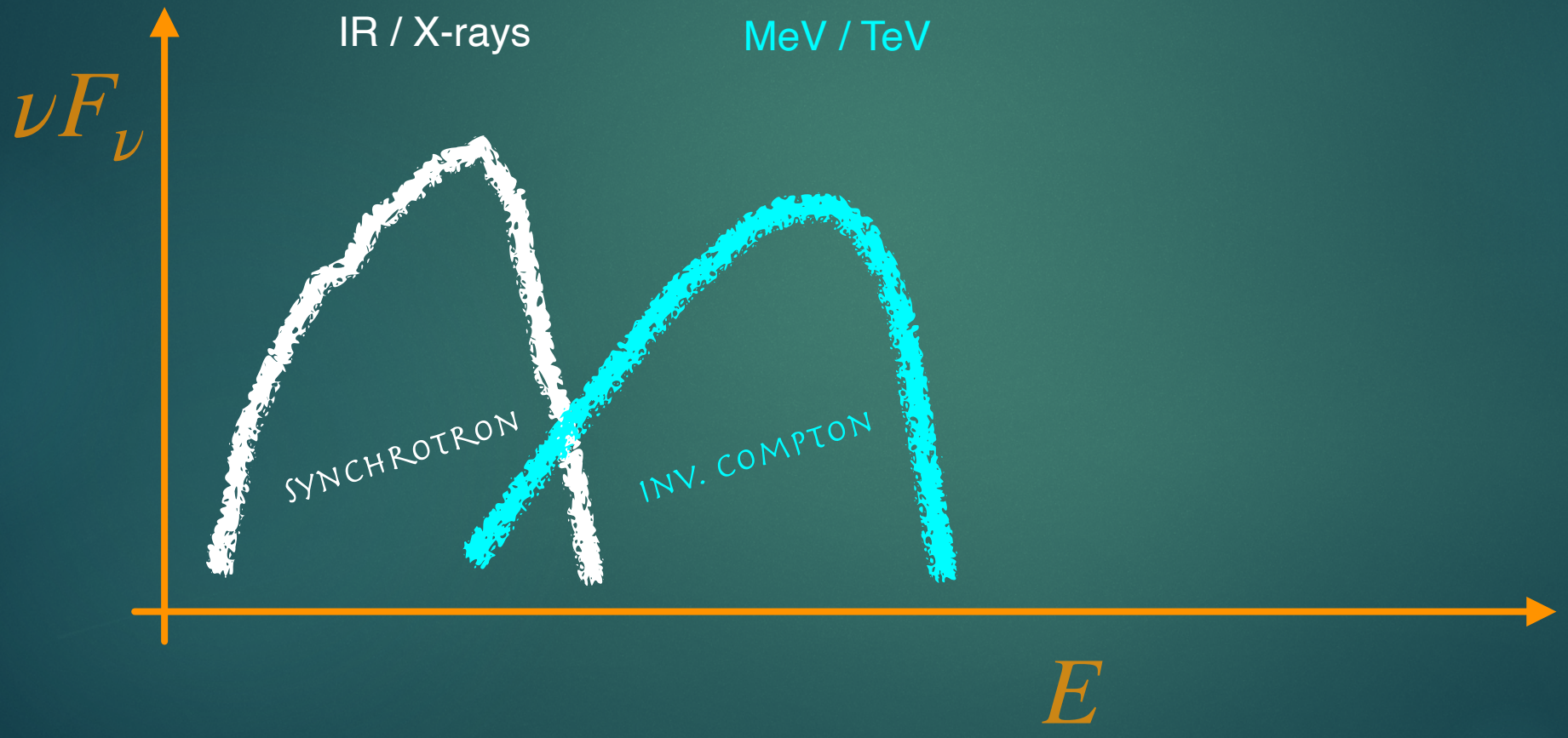
- **Gamma-ray bursts**
  - e.g. Waxman & Bahcall 97, Murase et al. 06, Cholis & Hooper 13, Liu & Wang 13, Murase & Ioka 13, Winter 13, Senno, Murase & Meszaros 16
- **Active Galactic Nuclei**
  - e.g. Mannheim et al. 98, Stecker et al. 91, Mannheim 93/95, Reimer 2012, Kalashev, Kusenko & Essey 13, Stecker 13, Murase, Inoue & Dermer 14, Dermer, KM & Inoue 14, Tavecchio et al. 14, Kimura, Murase & Toma 15, Padovani et al. 15, Wang & Li 1, Lamastra 2017

Cosmic-ray Reservoirs

Neutrinos produced by inelastic hadronuclear collisions while confined within the environment surrounding the CR source

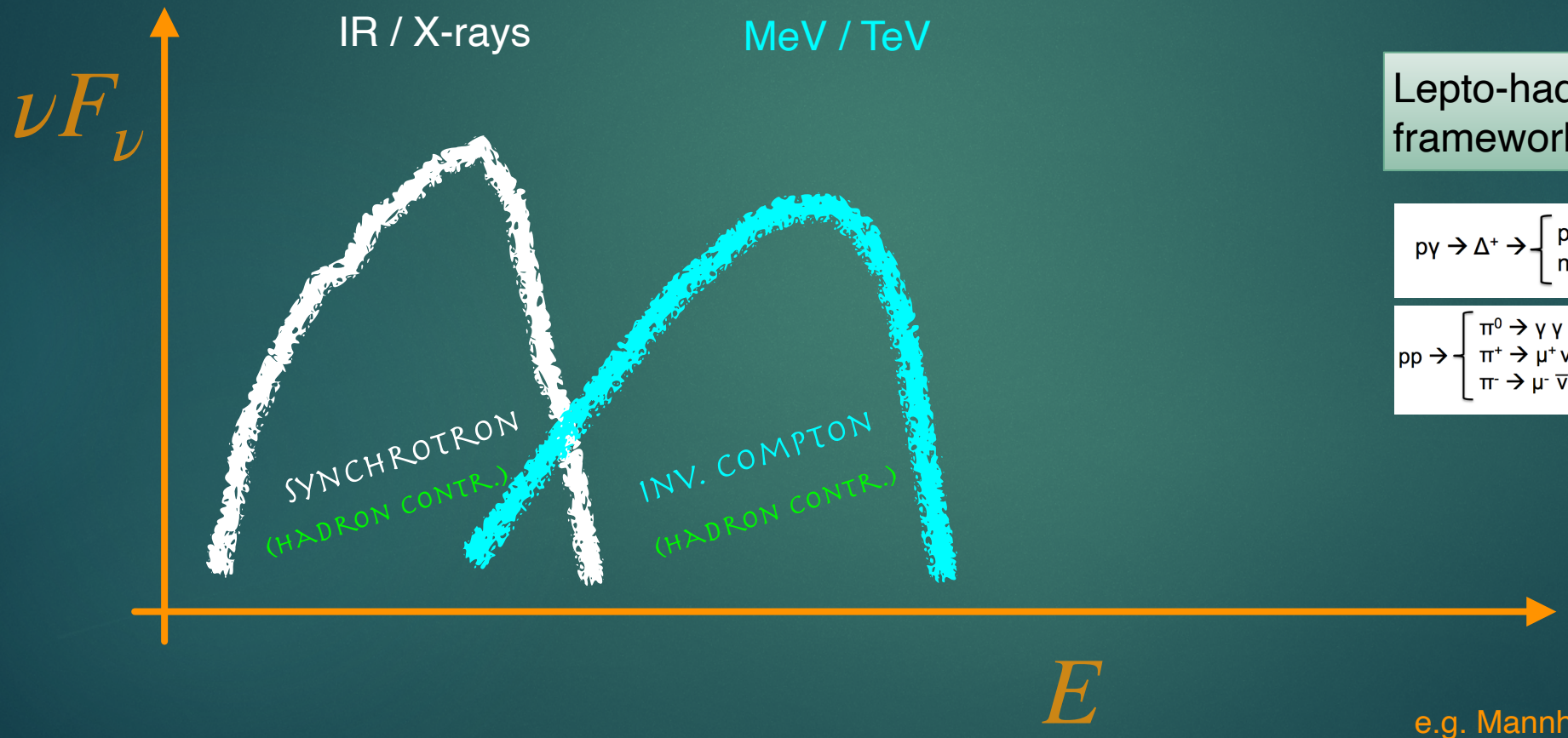
- **Starburst galaxies**
  - e.g., Loeb & Waxman 06, Thompson+ 07; Murase, Ahlers & Lacki 13, Katz et al. 13, Liu+ 14, Tamborra, Ando & Murase 14, Anchordoqui+ 14, Senno+ 15
- **Galaxy groups/clusters**
  - e.g., Berezinsky+ 97, KM et al. 08, Kotera+ 09, Murase, Ahlers & Lacki 13, Fang & Olinto 16

Blazar Spectral Energy Distribution



Blazar Spectral Energy Distribution

The proton blazar



Lepto-hadronic / hadronic frameworks

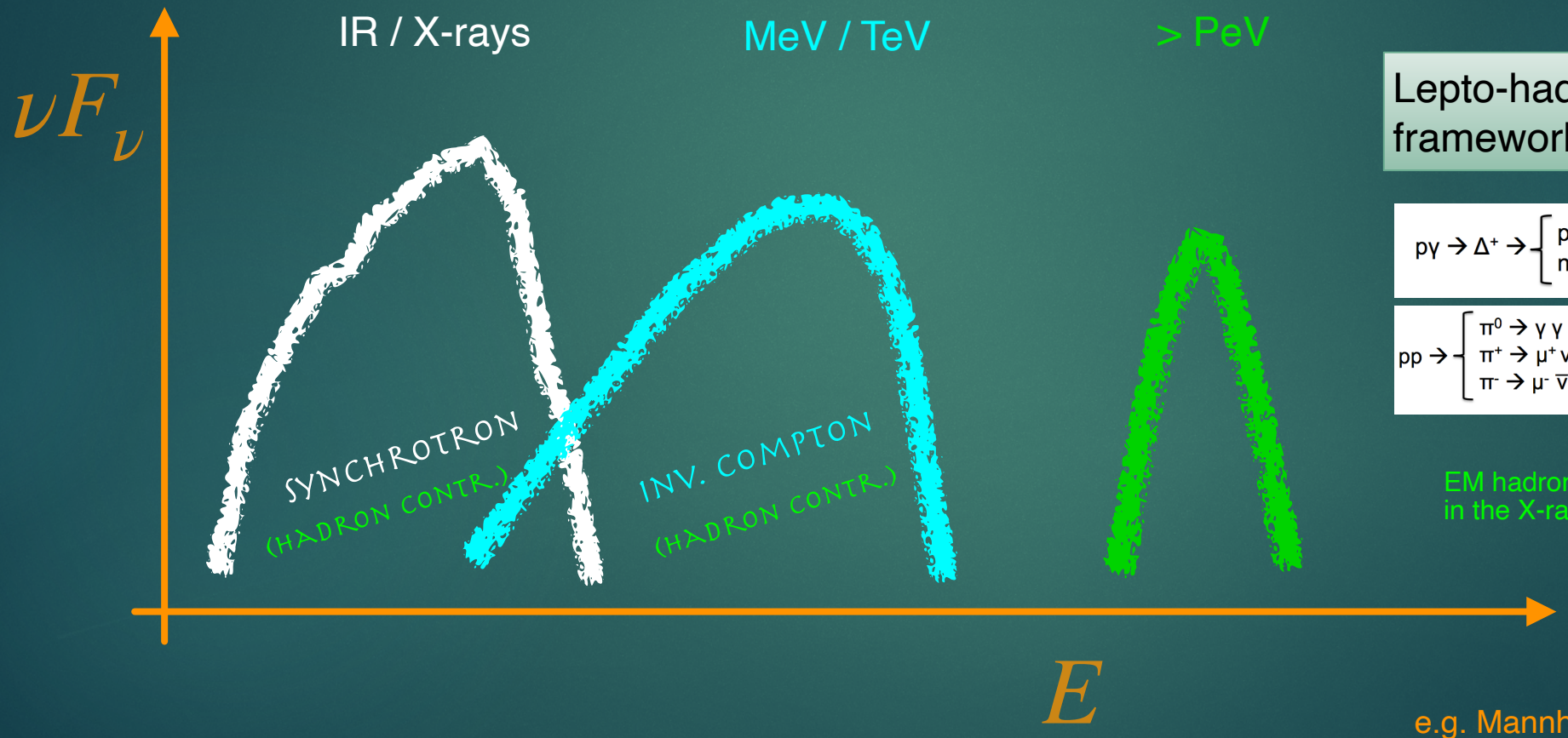
$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\,\pi^0 \rightarrow p\,\gamma\,\gamma \\ n\,\pi^+ \rightarrow n\,\mu^+\,\nu_\mu \rightarrow n\,e^+\,\nu_e\,\bar{\nu}_\mu\,\nu_\mu \end{cases}$$

$$pp \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\,\gamma \\ \pi^+ \rightarrow \mu^+\,\nu_\mu \rightarrow e^+\,\nu_e\,\nu_\mu\,\bar{\nu}_\mu \\ \pi^- \rightarrow \mu^-\,\bar{\nu}_\mu \rightarrow e^-\,\bar{\nu}_e\,\bar{\nu}_\mu\,\nu_\mu \end{cases}$$

e.g. Mannheim 1993

Blazar Spectral Energy Distribution

The proton blazar



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EM hadronic signatures imprinted in the X-ray / MeV band

e.g. Mannheim 1993

Neutrino Searches: Status of Art

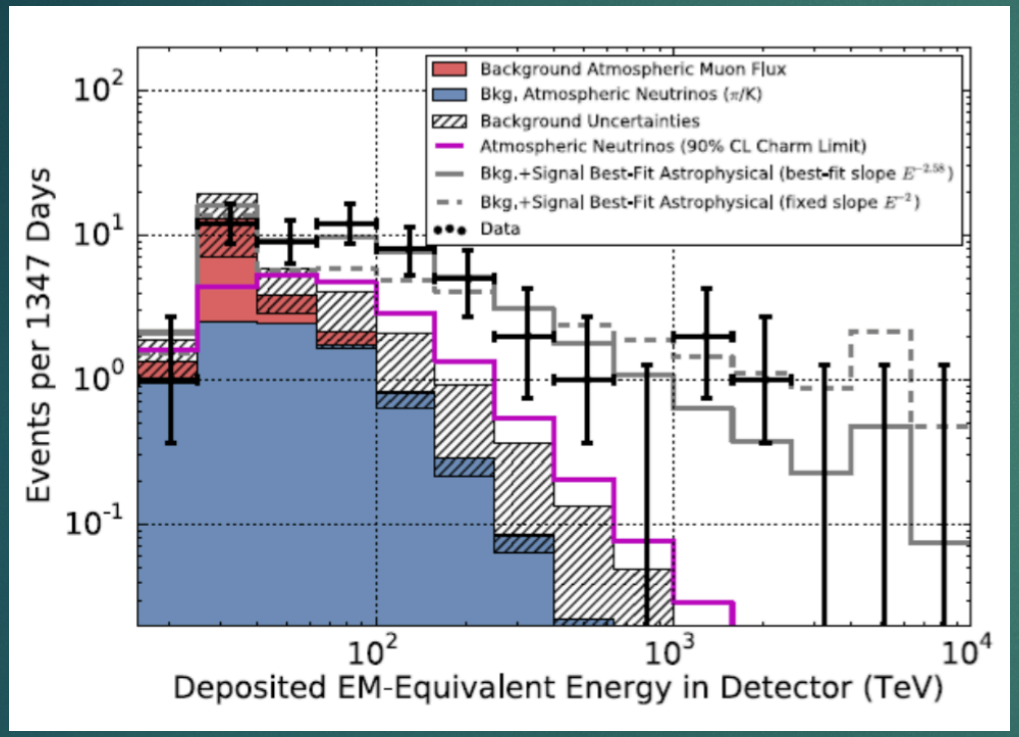
Main approaches:

— **diffuse astrophysical flux studies**

— time dependent studies (variable point sources)

— time integrated studies (steady point sources)

Neutrino Searches: Status of Art
— Diffuse



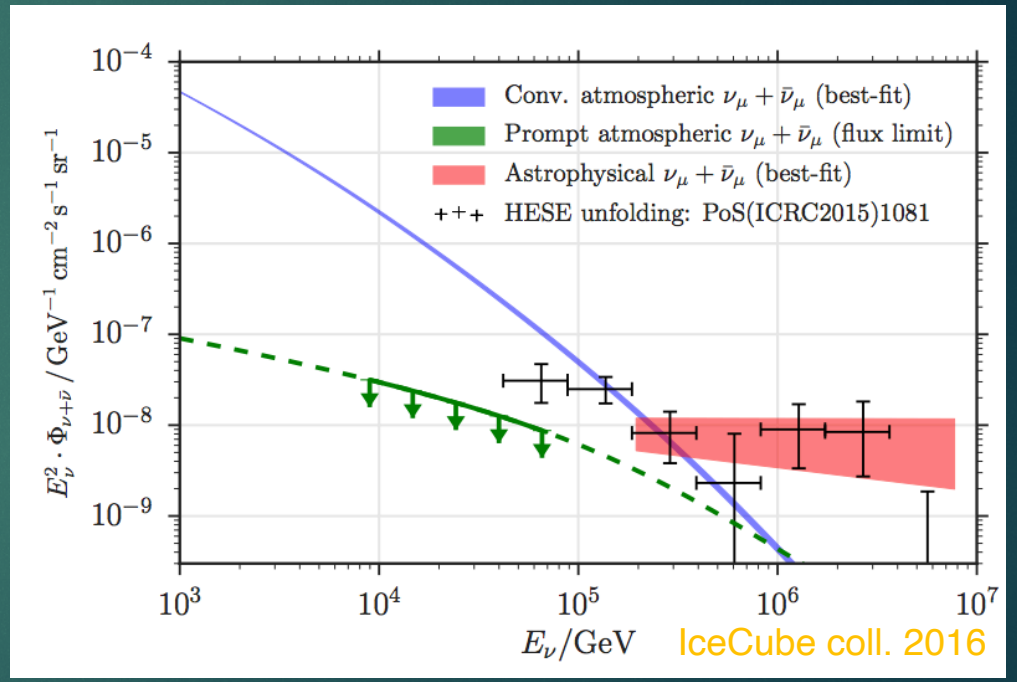
IceCube established a flux of astrophysical neutrinos at high statistical significance above the known atmospheric backgrounds

IceCube collaboration
Science 342, 2013

- an exciting step forward detecting cosmic neutrinos -

Neutrino Searches: Status of Art — Diffuse

- 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
  - break is not statistically significant



Neutrino Searches: Status of Art

Main approaches:

— diffuse astrophysical flux studies

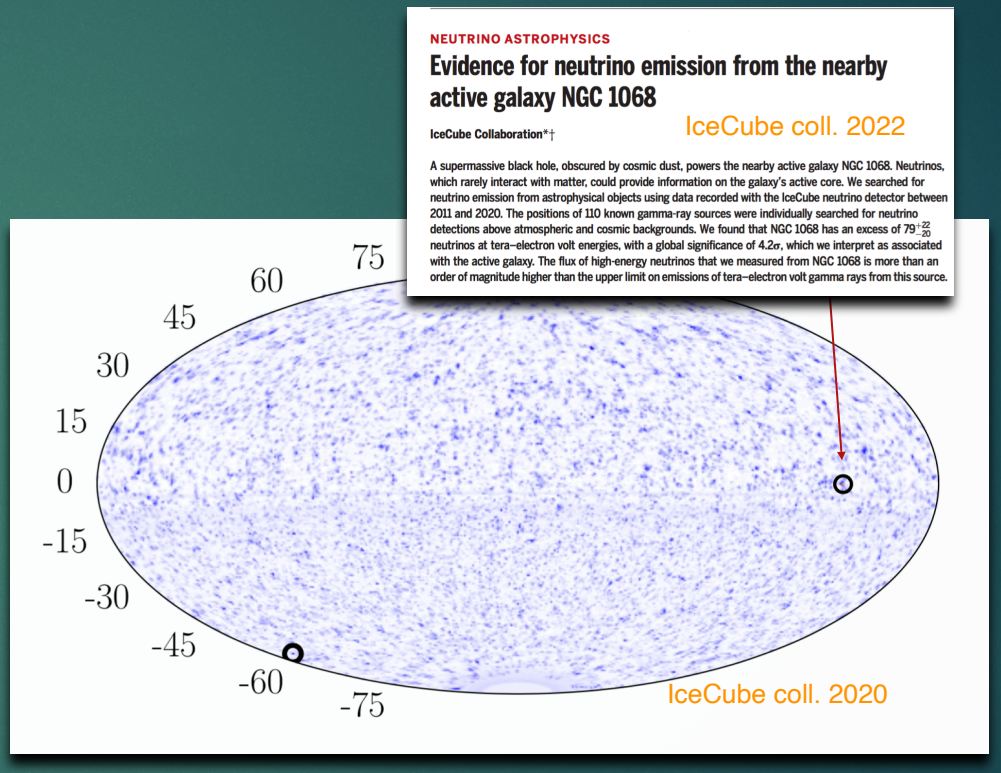
— time dependent studies (variable point sources)

— time integrated studies (steady point sources)

Neutrino Searches: Status of Art — time integrated

Latest searches

- Blind all-sky search (~10-years IC data)
- Binomial test on a list of extragalactic candidates (northern catalog) : level of 3.4σ
  - Most significant spots :
    - NGC 1068 (4.2σ), PKS 1424+240, TXS 0506+056

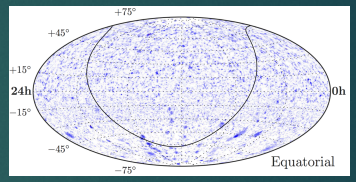


- **Neither individual neutrino-source detected at high confidence, nor source classes**
- **Events are isotropically distributed (favoring extragalactic origin)**

a new approach

Hypothesis Primers

- IceCube neutrino data
  - the ‘highest-quality’ data for point-source searches publicly available
- Blazar sample
- Exploit blazar theoretical predictions



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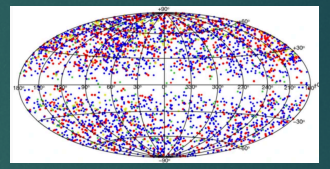

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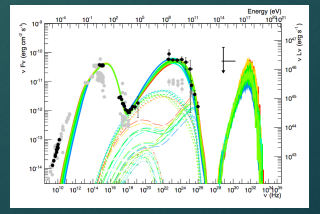

IceCube Neutrino sky-map

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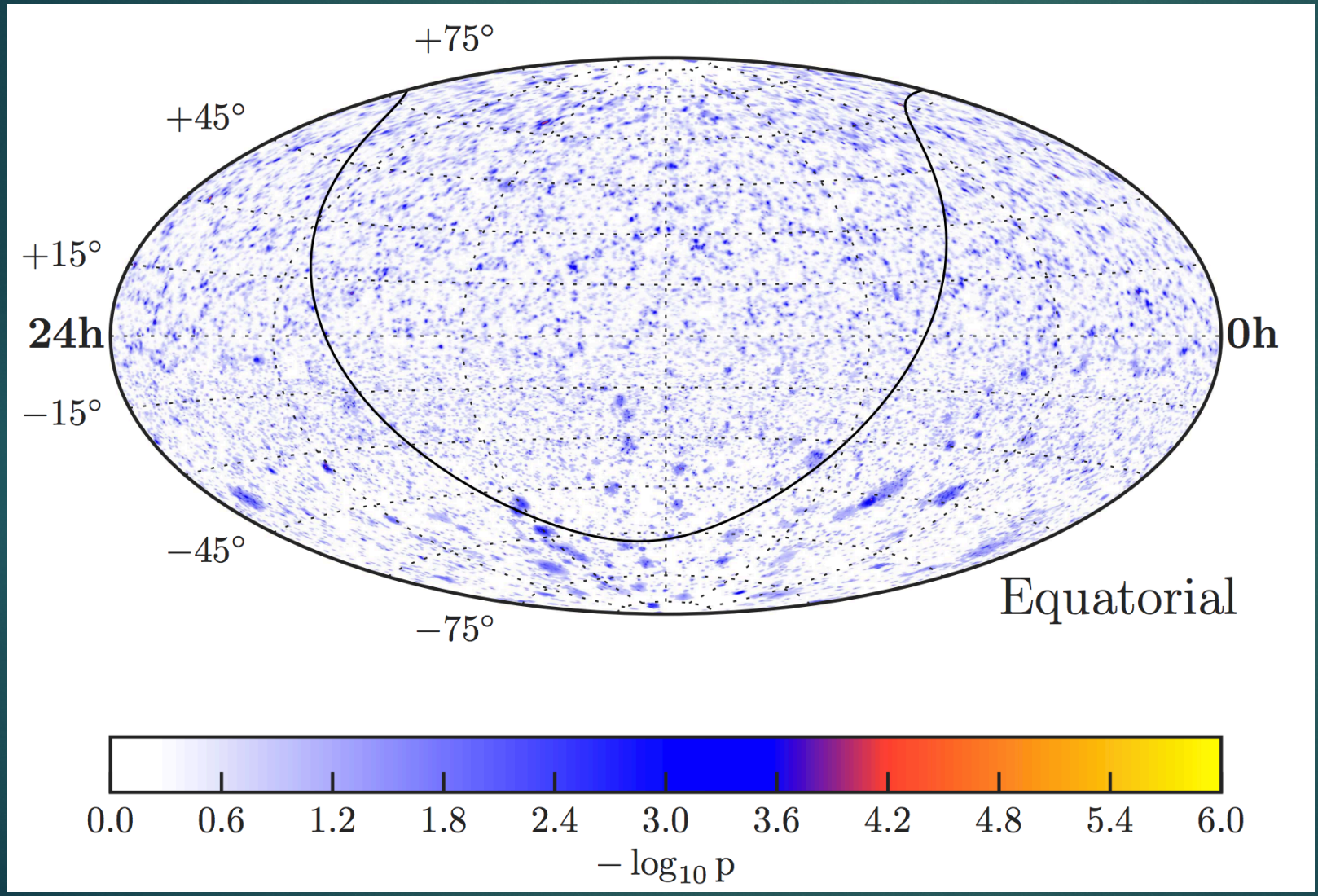


7-year sky map

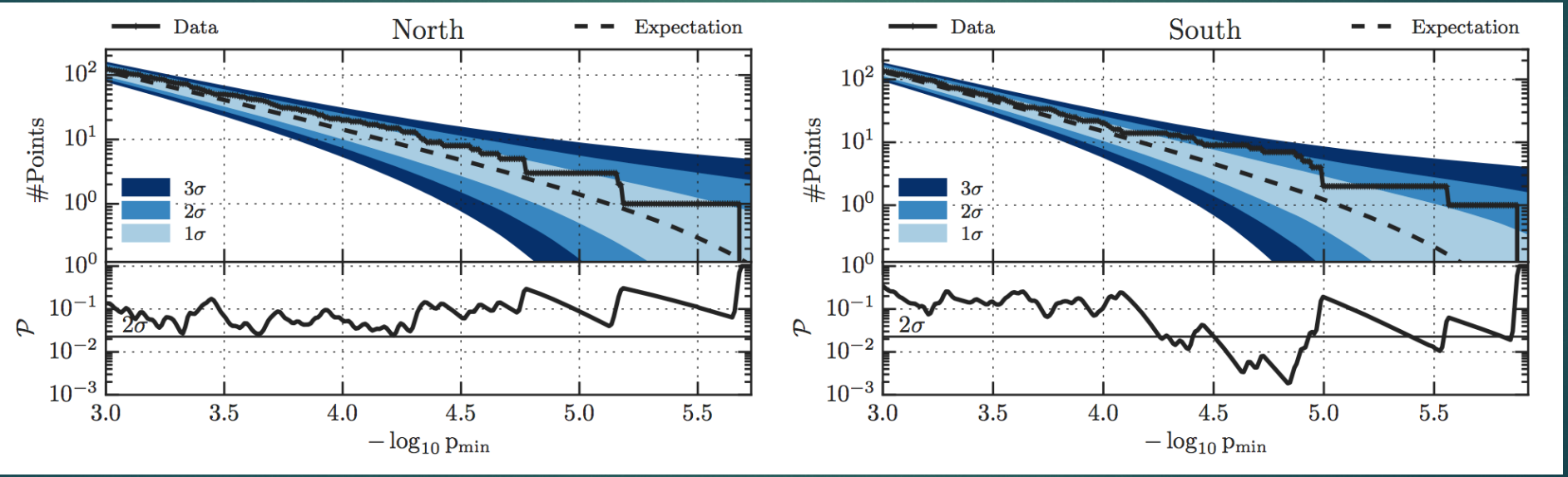
- 2008 - 2015

IceCube coll. 2017

IceCube Neutrino sky-map
- *note*

IceCube coll. results:

- No significant excess in the hot-spot all-sky population analysis
  - Caveat: many trials, more than 10^7 sky locations tested (!)

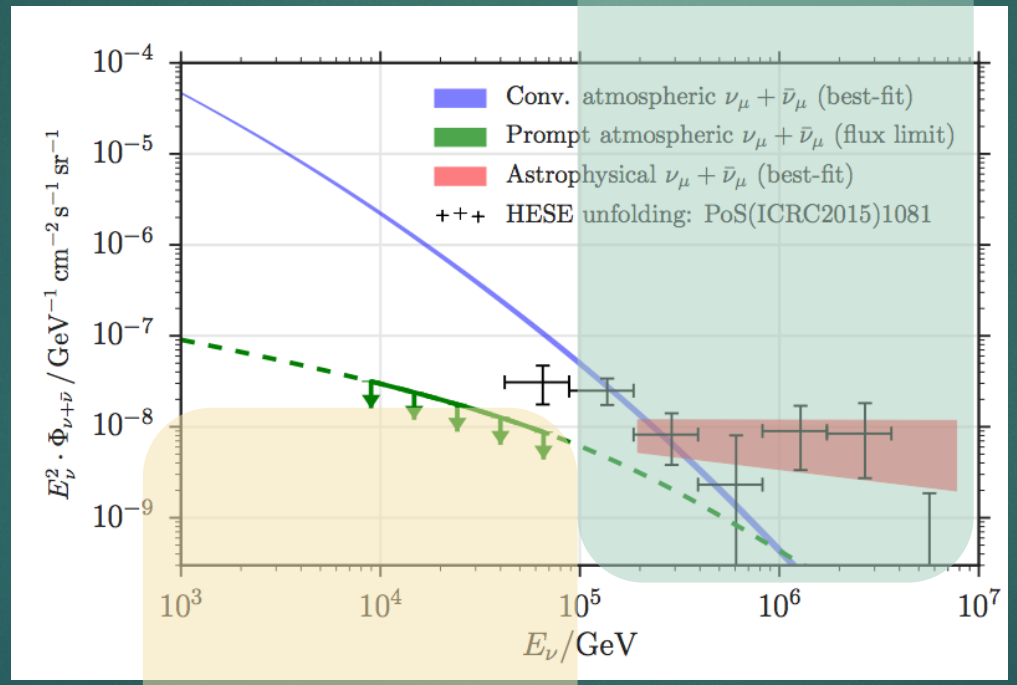


IceCube coll. 2017

The 7-year IceCube sky-map

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

Astrophysical diffuse neutrinos



Southern sky-map

Northern sky-map

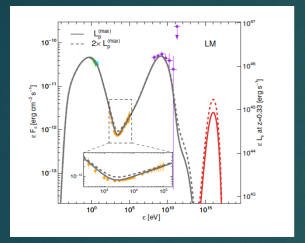
Working Hypothesis:

- If blazars are powered by hadronic processes[1]
  - The emerging spectrum[2] is hard in the IceCube energy band
    - Index <~ -2
    - NU energy peak foreseen at ~PeVs

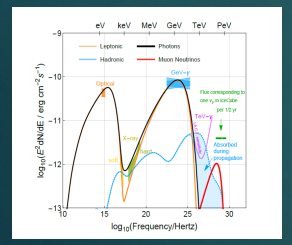
1) **At least at some extent**
2) **Many references**, e.g. Mannheim 1993; Stecker 2013; Dermer et al. 2014; Murase et al. 2014; Petropoulou et al. 2015; Padovani et al. 2015, Reimer 2015, Keivani et al. 2018, Cerruti et al. 2019, Rodrigues et al. 2021, ..

Blazar (typical) Multi-Messenger SED

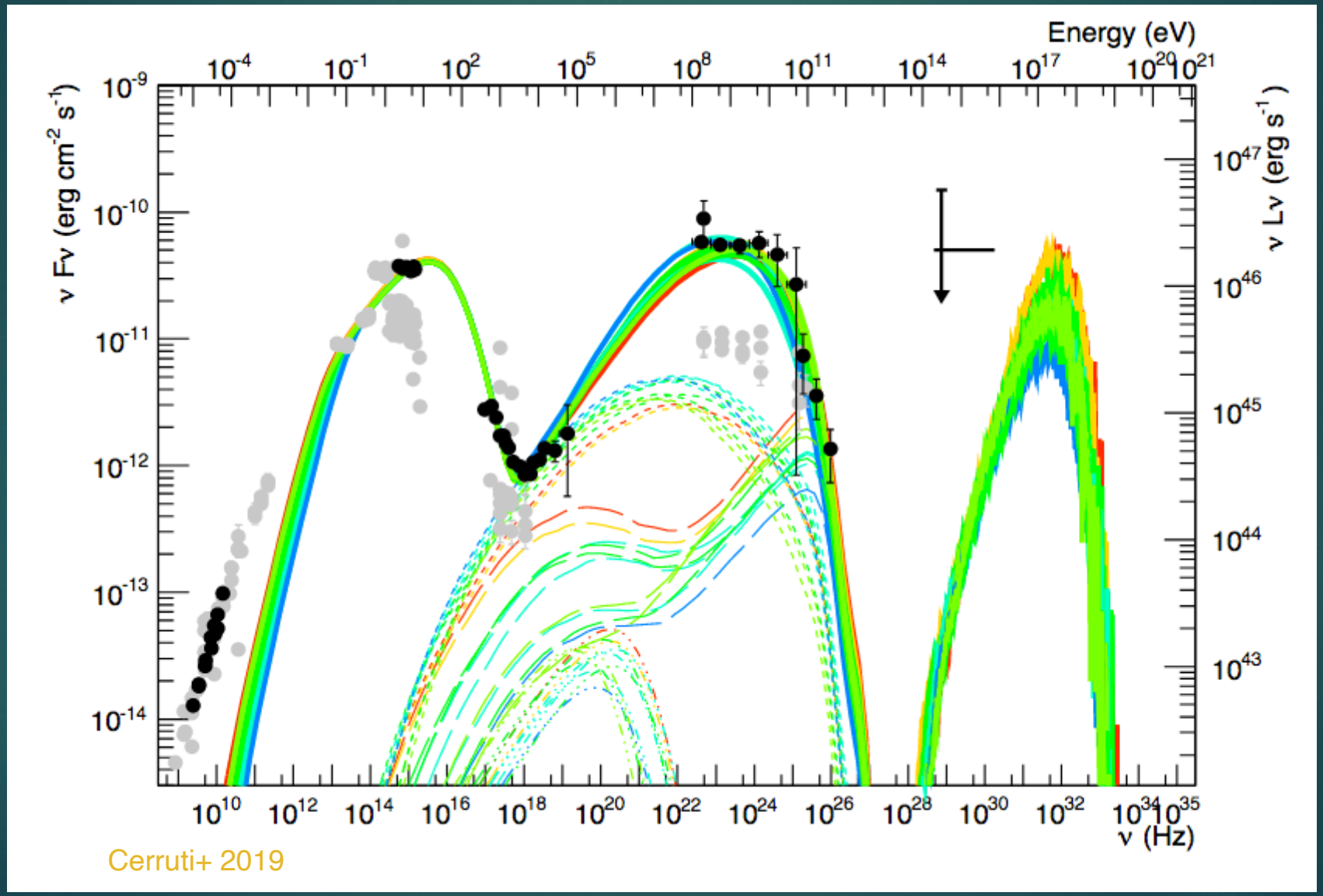
Similar for most blazar models



Keivani et al.:, 2018

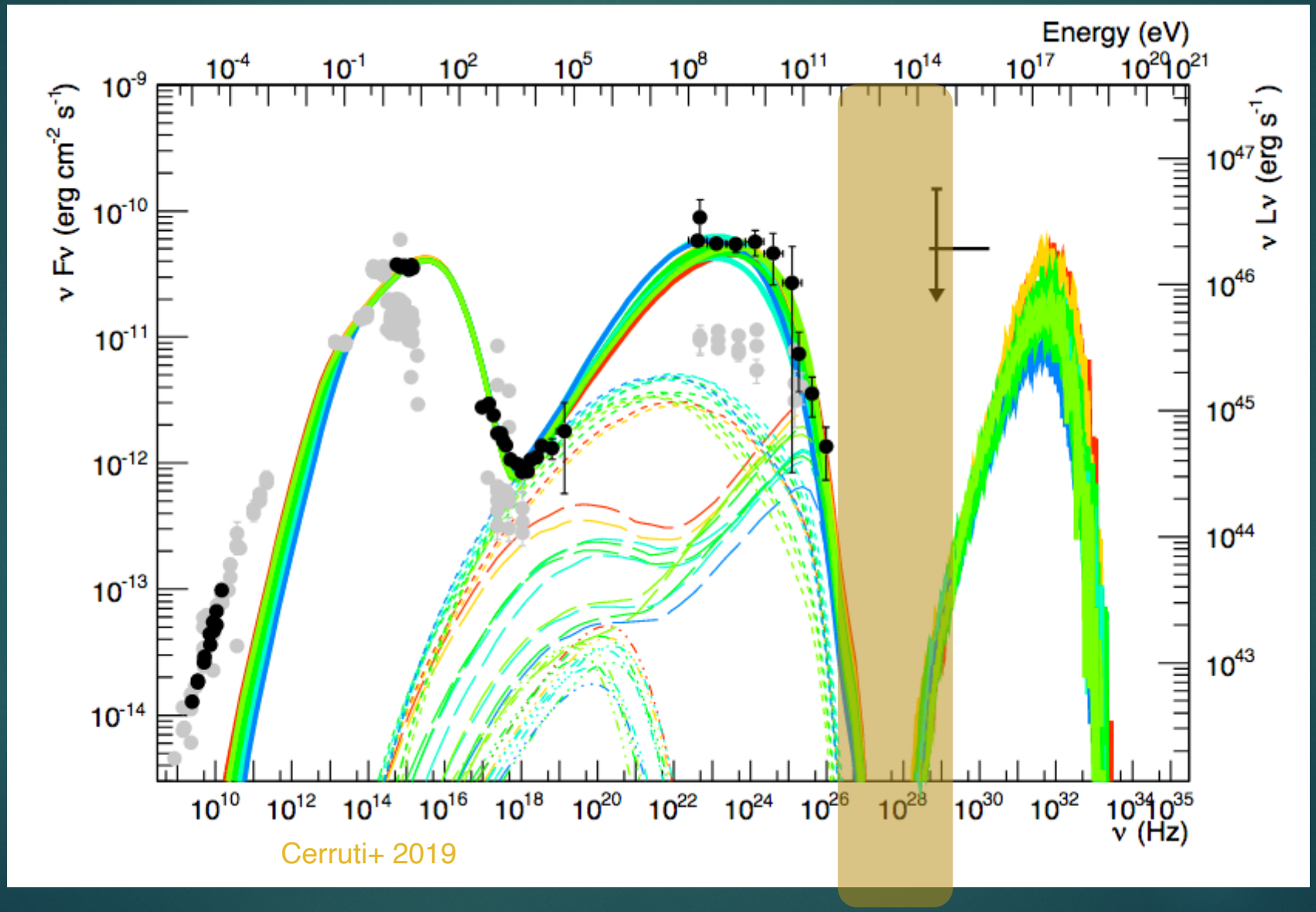


Gao et al., 2018



Cerruti+ 2019

Blazar (typical) Multi-Messenger SED



Cerruti+ 2019

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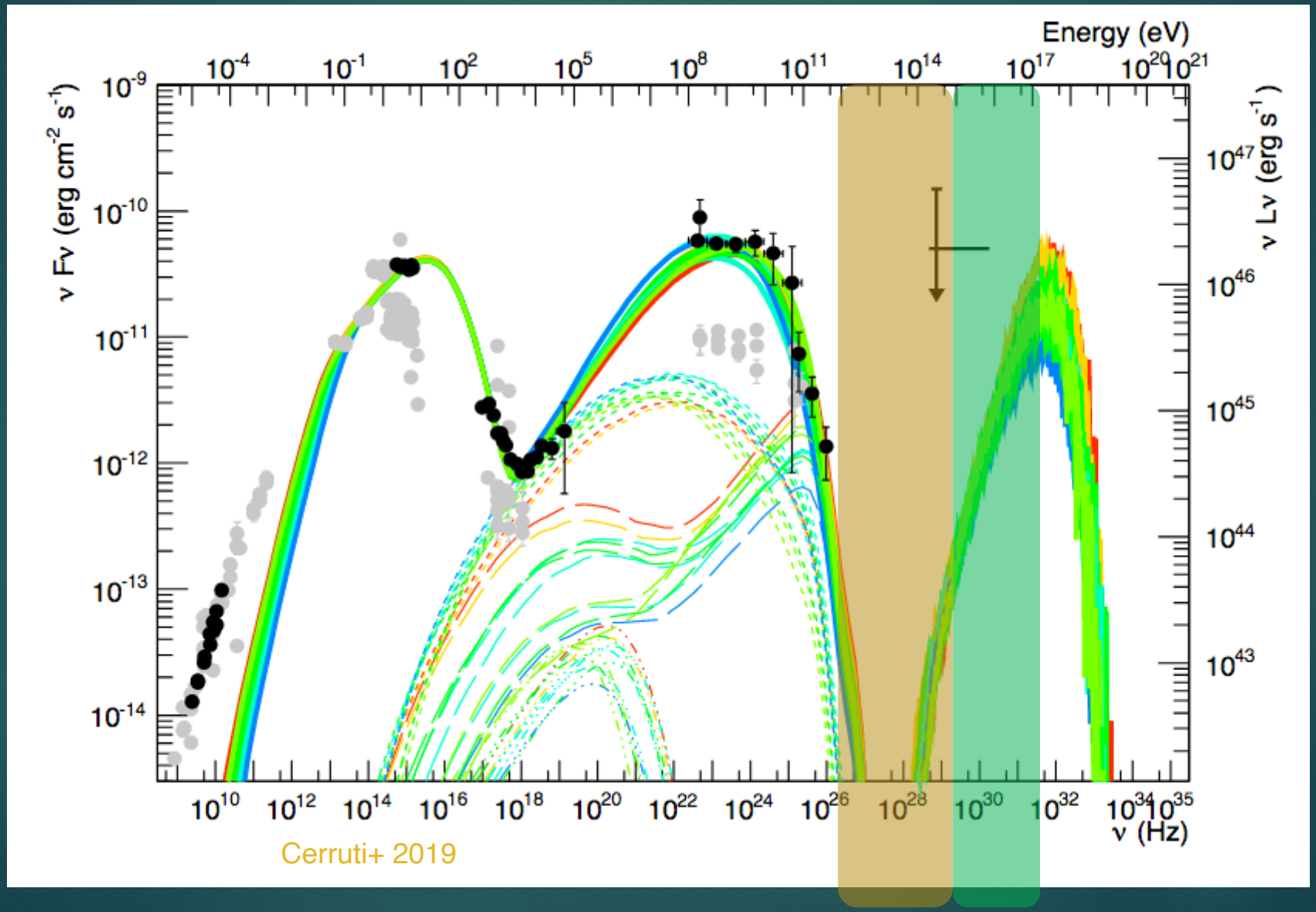
Northern sky-map

Blazar (typical) Multi-Messenger SED



Southern sky-map

Northern sky-map

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Educated Guess

If blazars produce neutrinos,

given the data at hand,

*the **IceCube Southern celestial hemisphere** may be the most promising testing ground*

Blazar sample : 5BZCat

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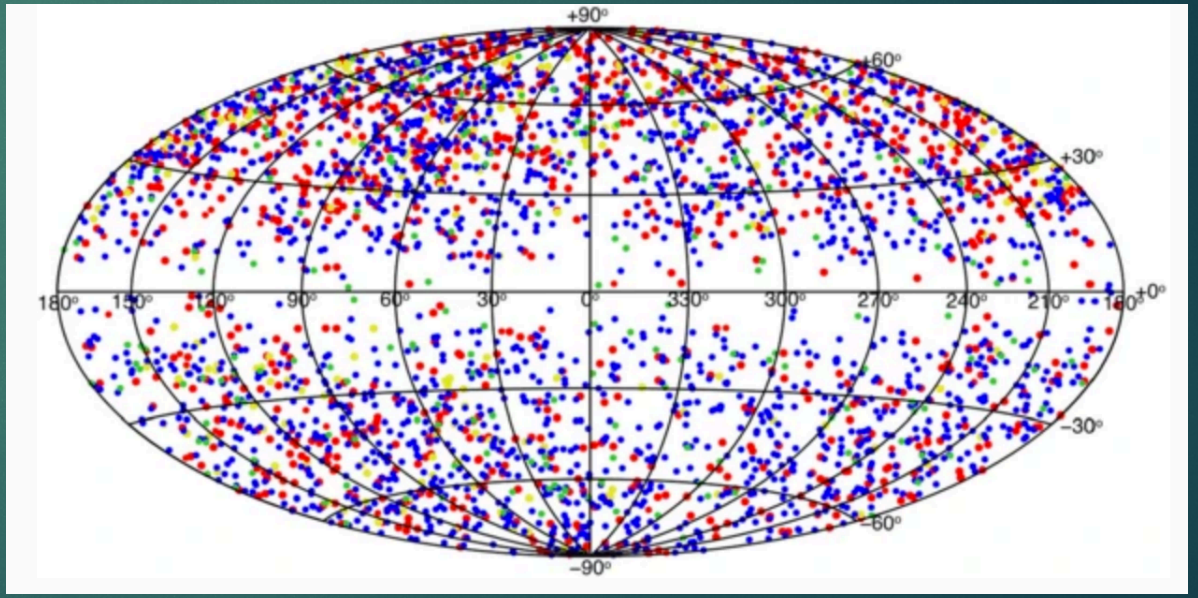
Well-defined sample of blazars
No preferred selection toward a particular wavelength or survey strategy

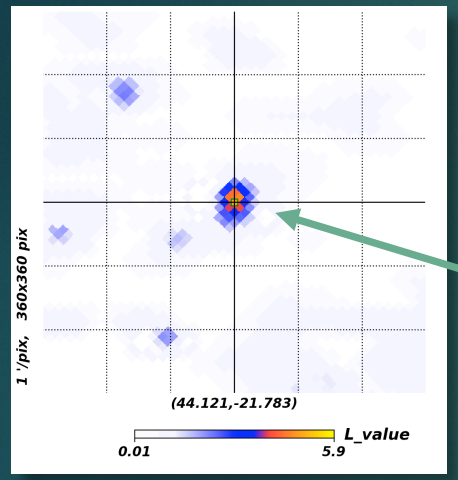
- 5BZCat : total of 3561 objects
- After cuts (|b|>10° dec= -5°) :
  - 2191 in northern hemisphere
  - 1177 in southern hemisphere

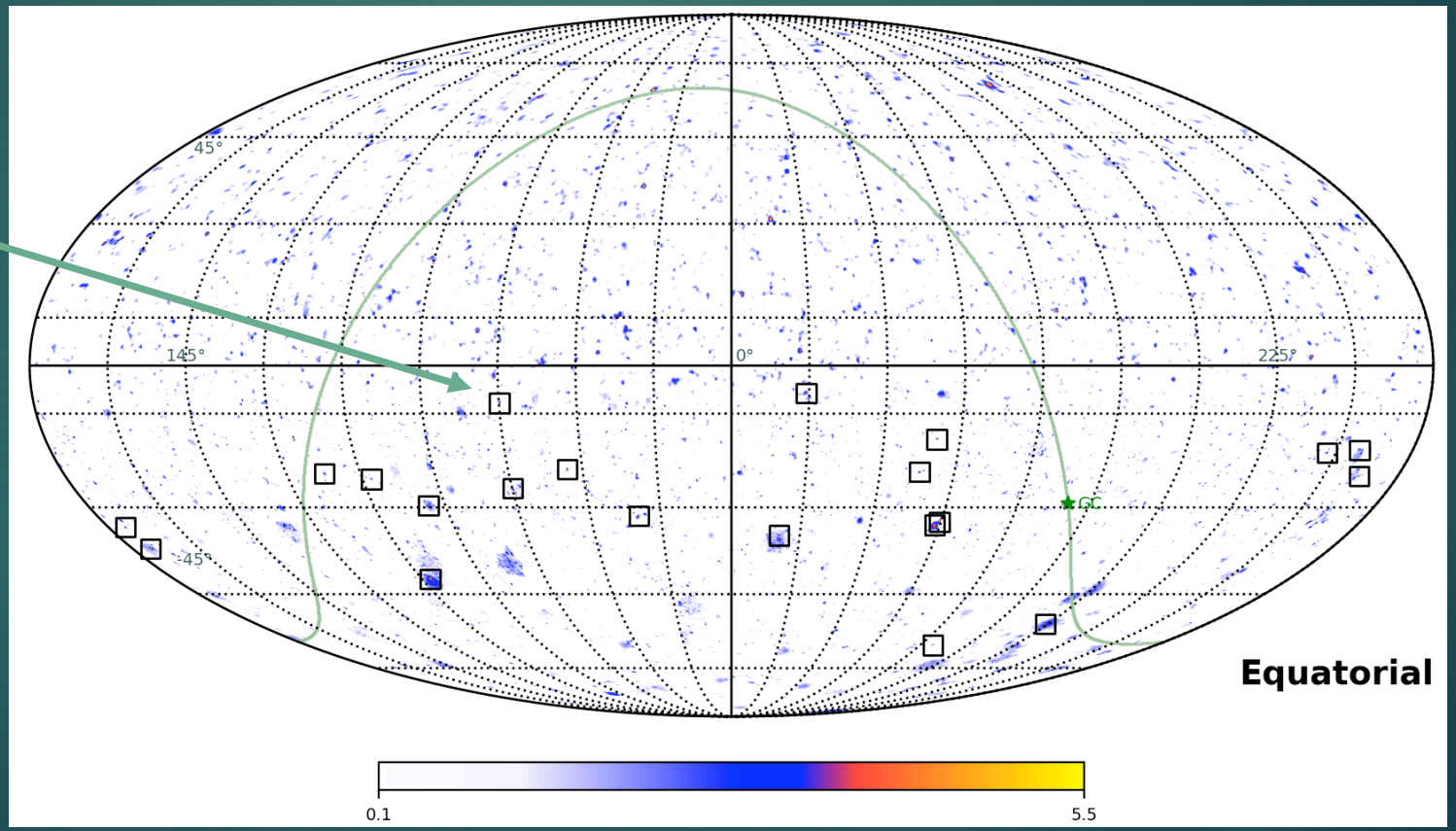


Neutrino sky-map (7 yr)

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

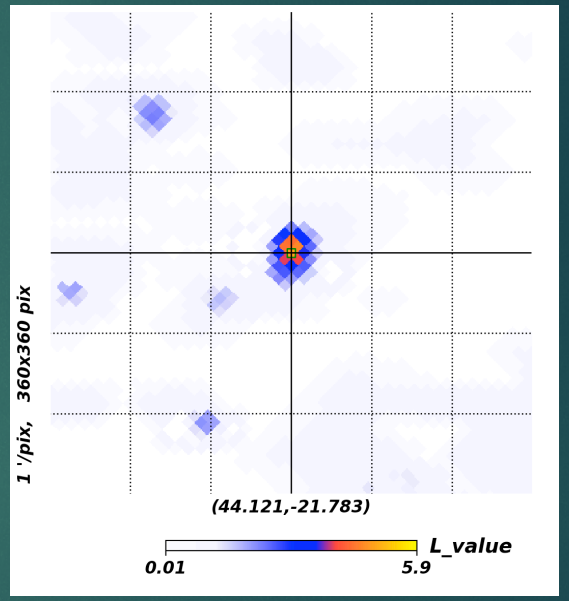
Focus on the neutrino clusters with strongest deviation from background expectations -- to limit trials





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

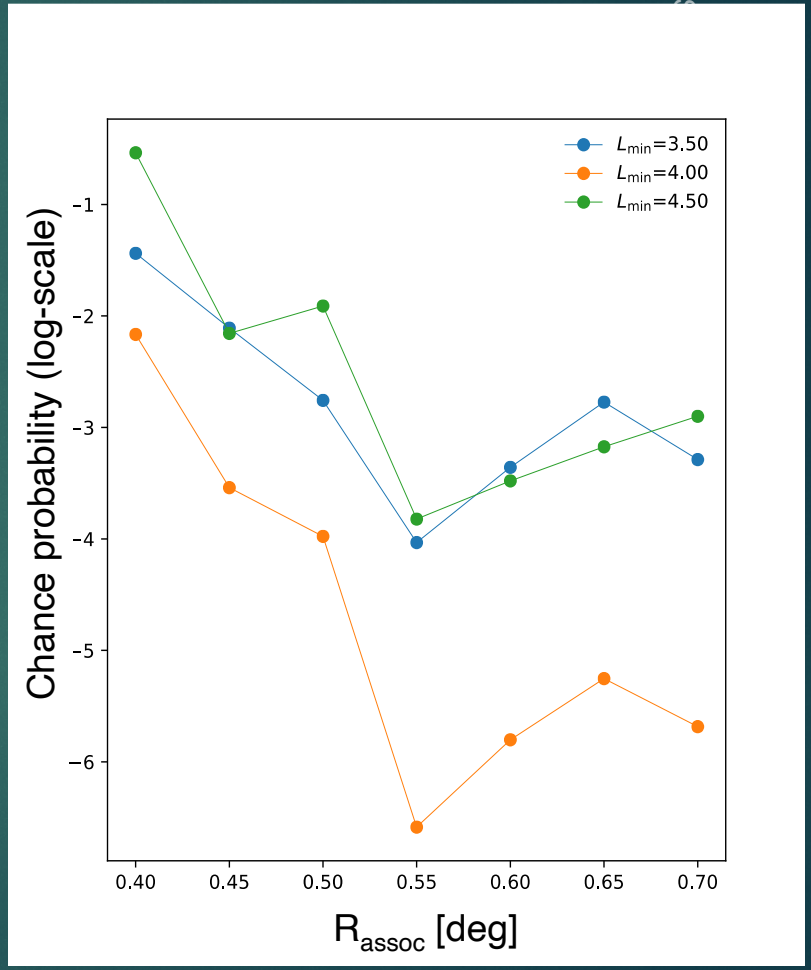


Perform positional cross-correlation analysis

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}



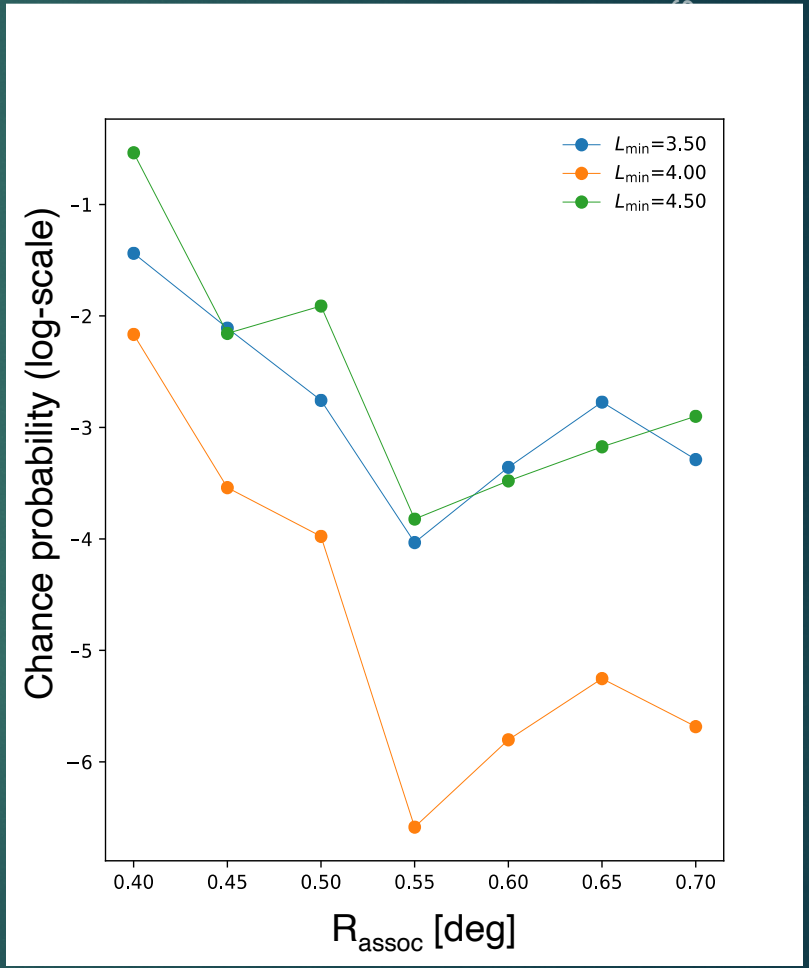
*Similar to Finley & Westerhoff 2004; Pierre Auger Collaboration et al. 2008; IceCube Coll. 2016; Resconi et al. 2017; Plavin et al. 2021; Hovatta et al. 2021,…

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}

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



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Extragalactic neutrino factories

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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)

A. Tramacere

L. Pfeiffer , L. Oswald

R. De Menezes

The *PeVatron* Blazars

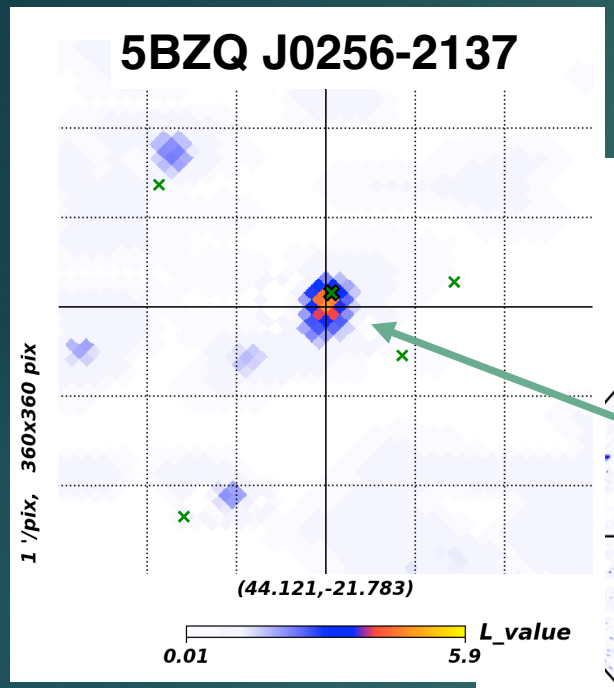
IceCube hotspots				Blazar associations		
	α_{hs}[°]	δ_{hs}[°]	L	5BZCat	z	Separation[°]
IC J2243−0540	340.75	−5.68	4.012	5BZB J2243−0609	0.30[c]	0.47
IC J0359−0746	59.85	−7.78	5.565	5BZQ J0357−0751	1.05	0.42
IC J0256−2146	44.12	−21.78	4.873	5BZQ J0256−2137	1.47	0.17
IC J2037−2216	309.38	−22.27	4.664	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	–	–	–

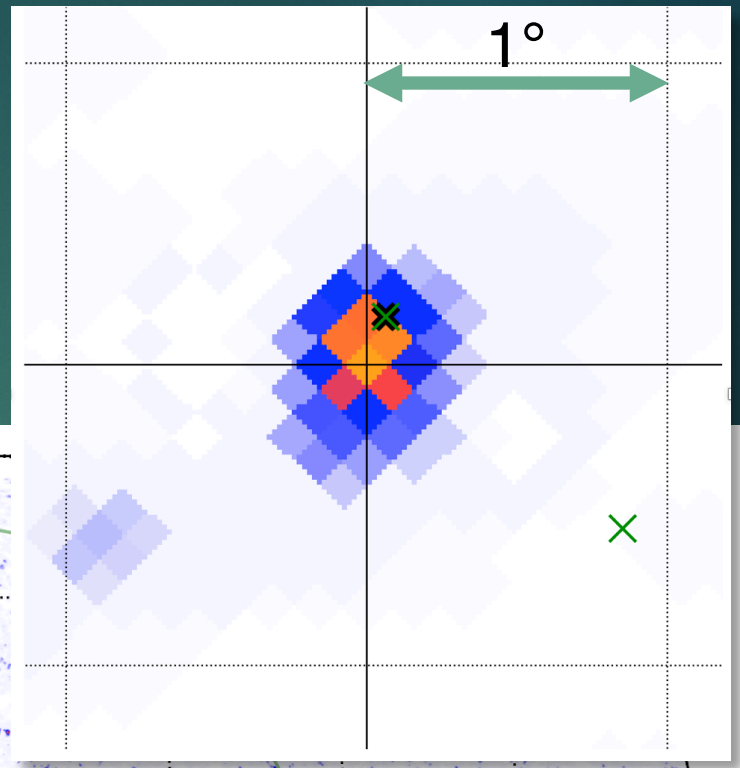
a) Blazars listed as γ-ray emitters in 4FGL-DR2 b) Blazar listed in 2LAC

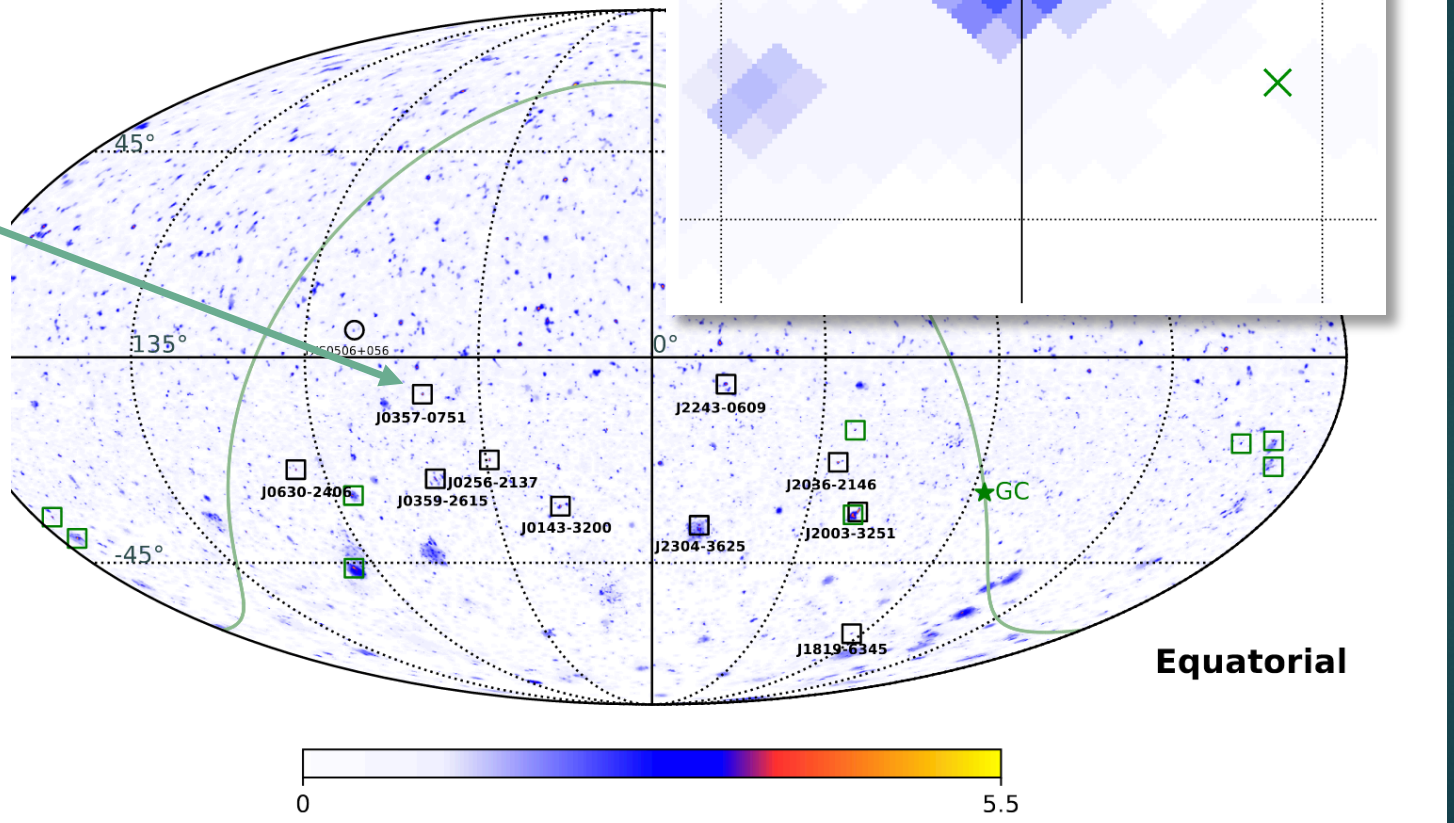
10 blazars highly likely associated with clusters of IceCube neutrinos

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

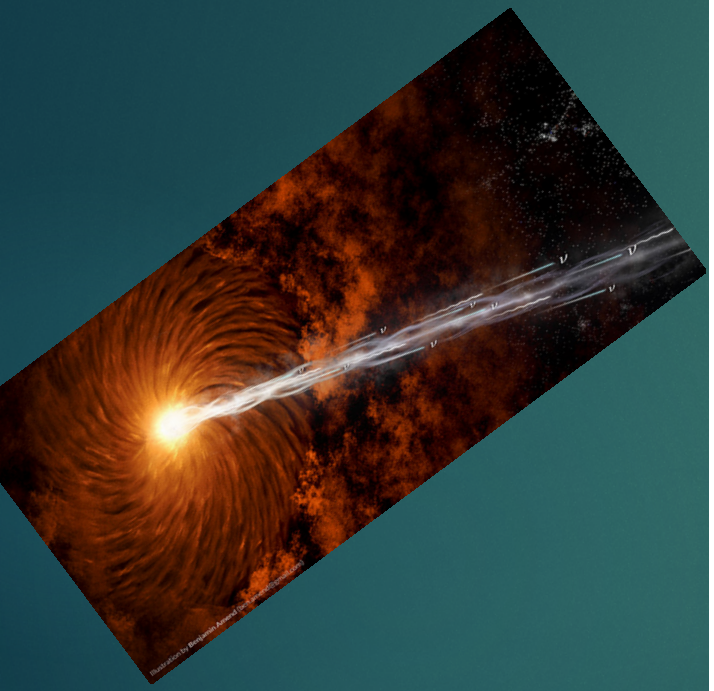
The *PeVatron* Blazars

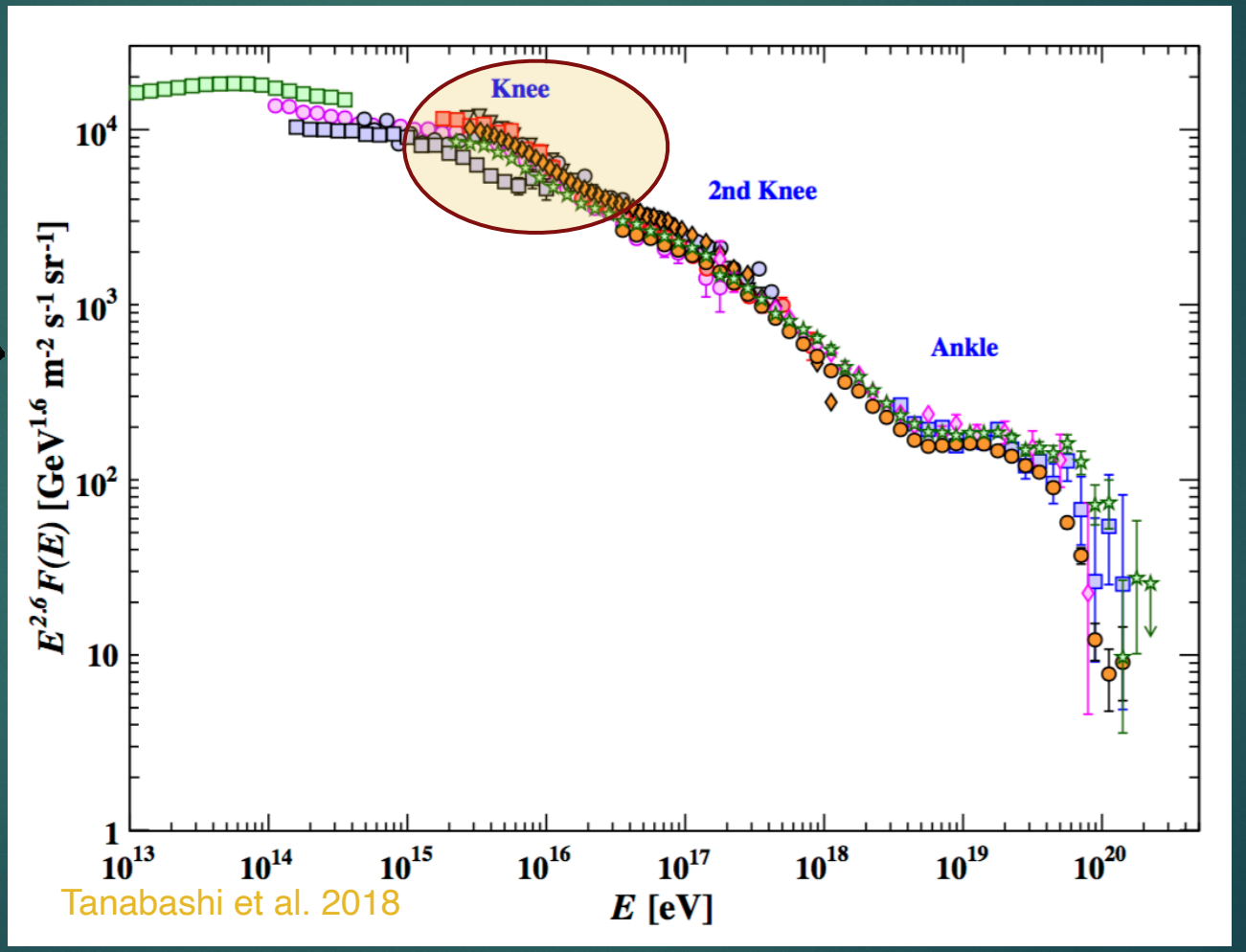






Implications to cosmic rays (& more)





Tanabashi et al. 2018

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