

# High Energy Neutrinos from Blazars

Hadronic processes at work in 5BZB J0630-2406

*Sara Buson*

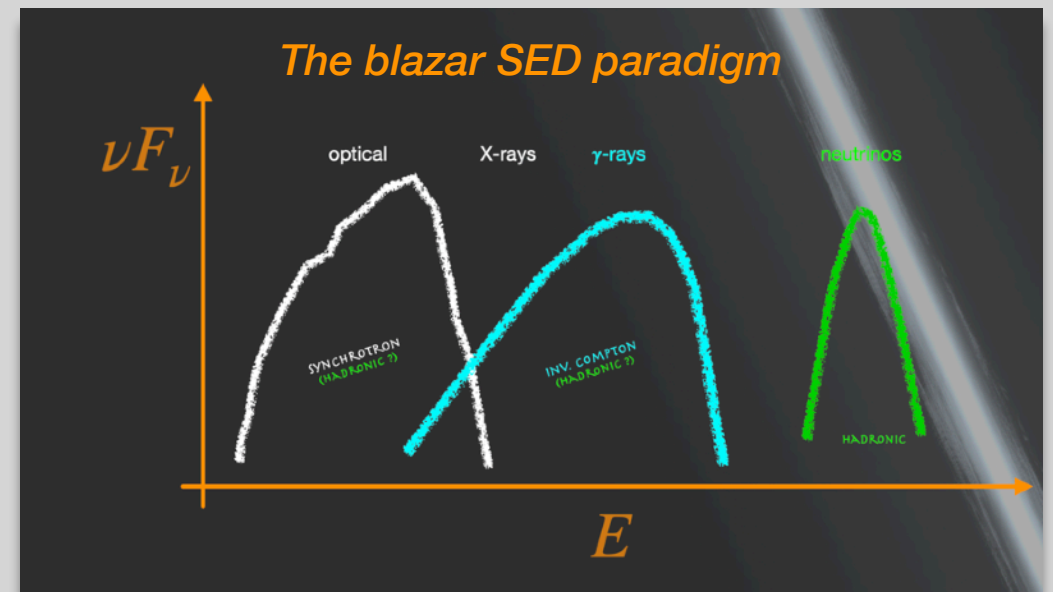
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on behalf of the Fermi-LAT collaboration*

*9th Roma International Conference on Astro-Particle Physics, September 2024*



# MessMapp Research

1. **Neutrino** observational strategy (using the least number of assumptions as possible)
2. **Theoretical** angle (SED modeling: AM<sup>3</sup>)
3. **Multi-wavelength** (photon) observations strategy, including time-evolution information and #1/#2 (when possible)



# Blazar / neutrino correlation

THE ASTROPHYSICAL JOURNAL LETTERS, 933:L43 (9pp), 2022 July 10

<https://doi.org/10.3847/2041-8213/ac7d5b>








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

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*Received 2022 May 13; revised 2022 June 20; accepted 2022 June 28; published 2022 July 14*

### Abstract

Neutrinos are the most elusive particles in the universe, capable of traveling 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. Among the candidate sources of neutrinos, there are blazars, a class of extragalactic sources powered by supermassive black holes that feed highly relativistic jets, pointed toward 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 an unprecedented level of confidence, i.e., a chance probability of  $6 \times 10^{-7}$ . Our statistical analysis provides the observational evidence that blazars are astrophysical neutrino factories and hence, extragalactic cosmic-ray accelerators.

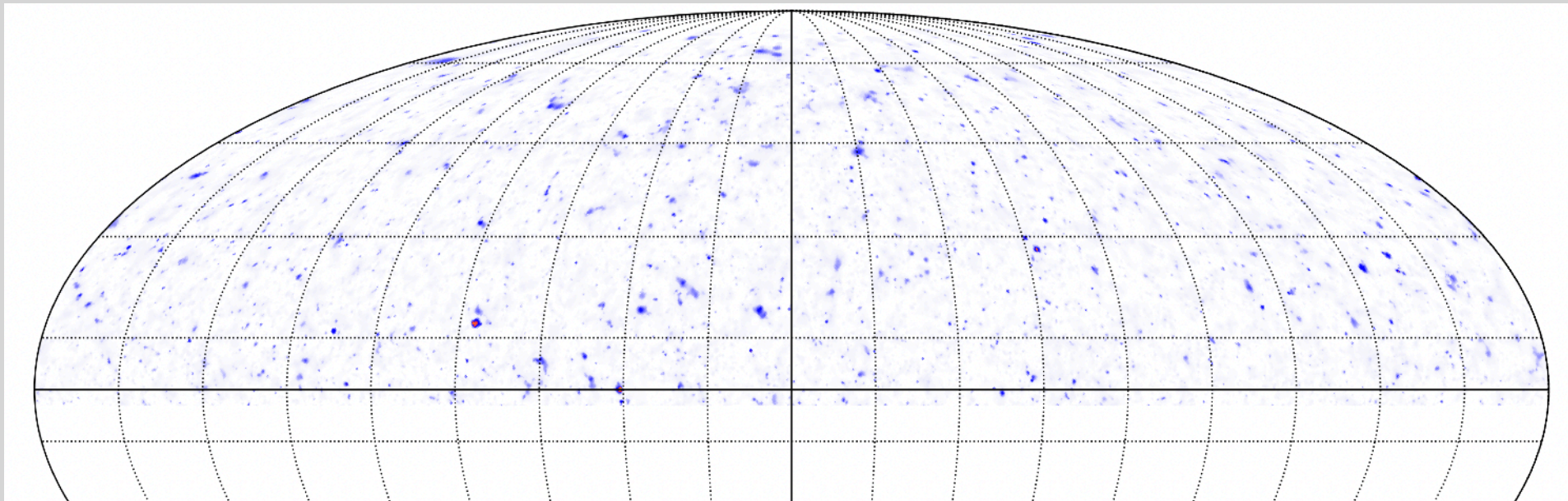
*Unified Astronomy Thesaurus concepts:* [Neutrino astronomy \(1100\)](#); [Neutrino telescopes \(1105\)](#); [Blazars \(164\)](#); [Supermassive black holes \(1663\)](#); [Relativistic jets \(1390\)](#); [Cosmic ray astronomy \(324\)](#)

# IceCube Neutrino (p-value) sky-map

**Informs about the level of anisotropy in the event spatial distribution**

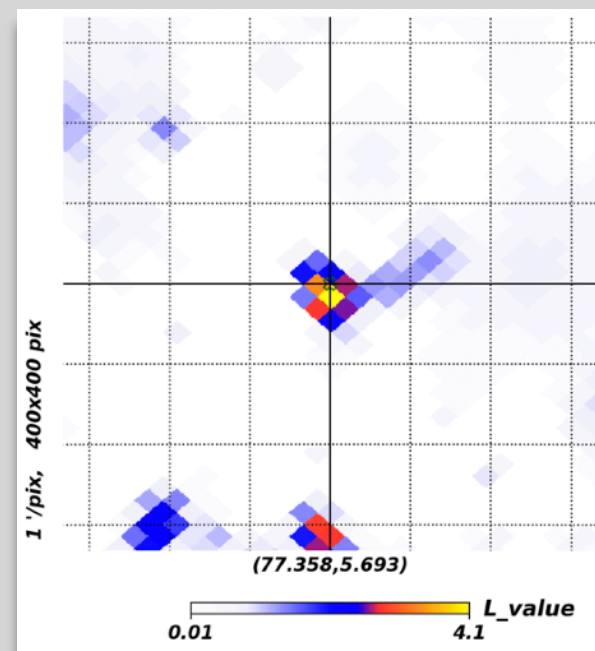
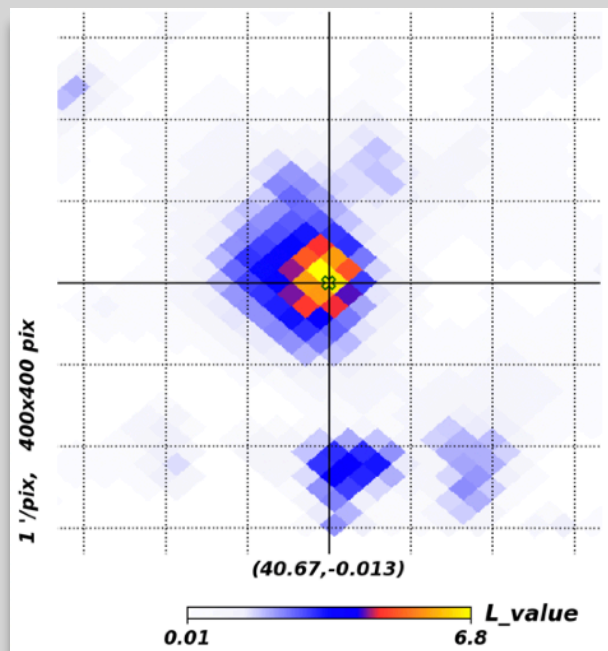
The smallest the local p-value, the highest the discrepancy from background expectations

For convenience, we define:  $L\text{-value} = -\log(\text{p-value}_{\text{Loc}})$



# IceCube skymaps: sensitive to comic sources

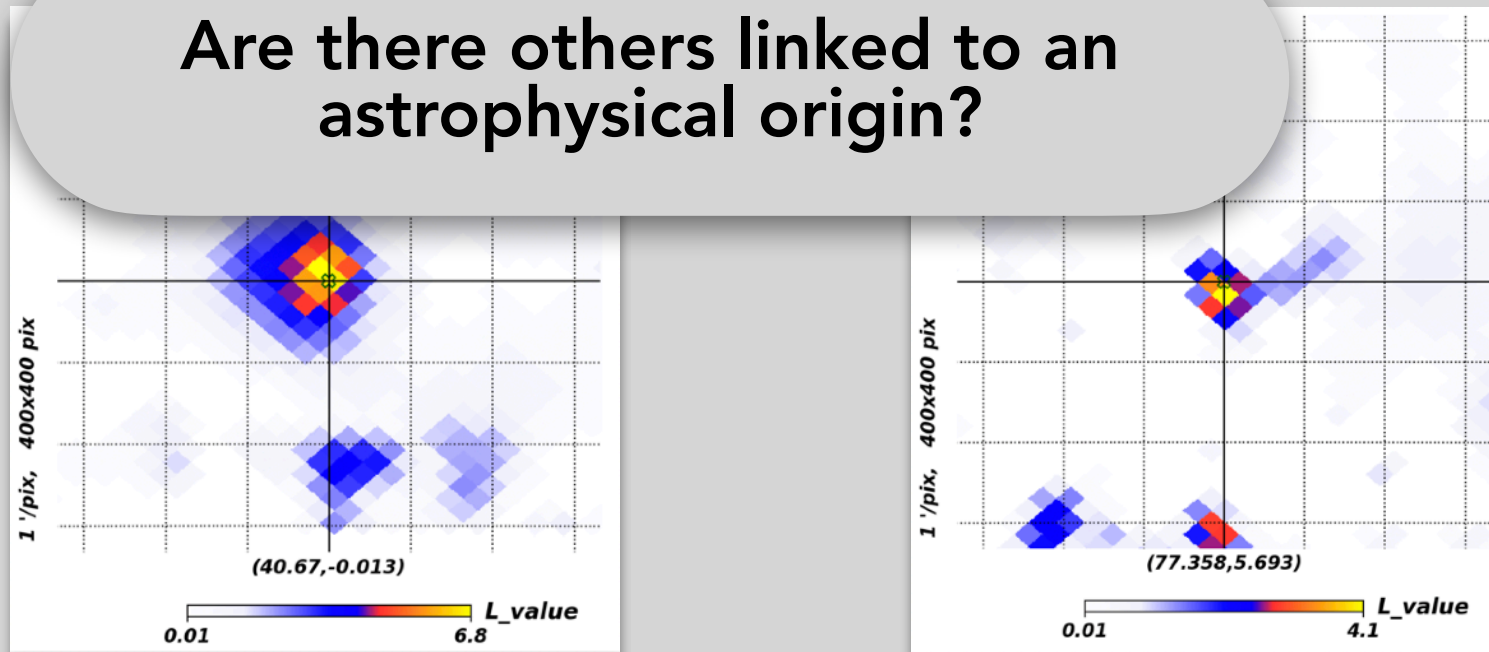
Hotspots consistent with NGC 1068 and TXS 0506+056



# IceCube skymaps: sensitive to comic sources

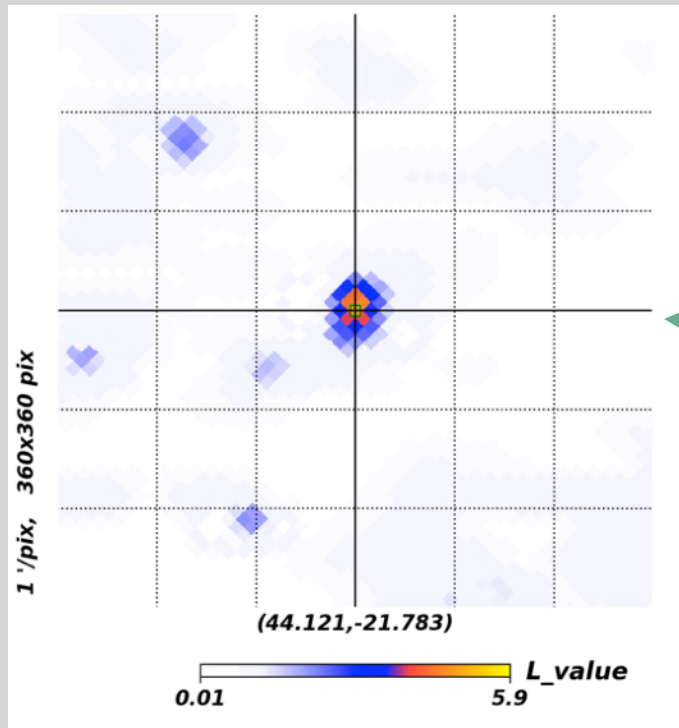
Hotspots consistent with NGC 1068 and TXS 0506+056

Are there others linked to an astrophysical origin?



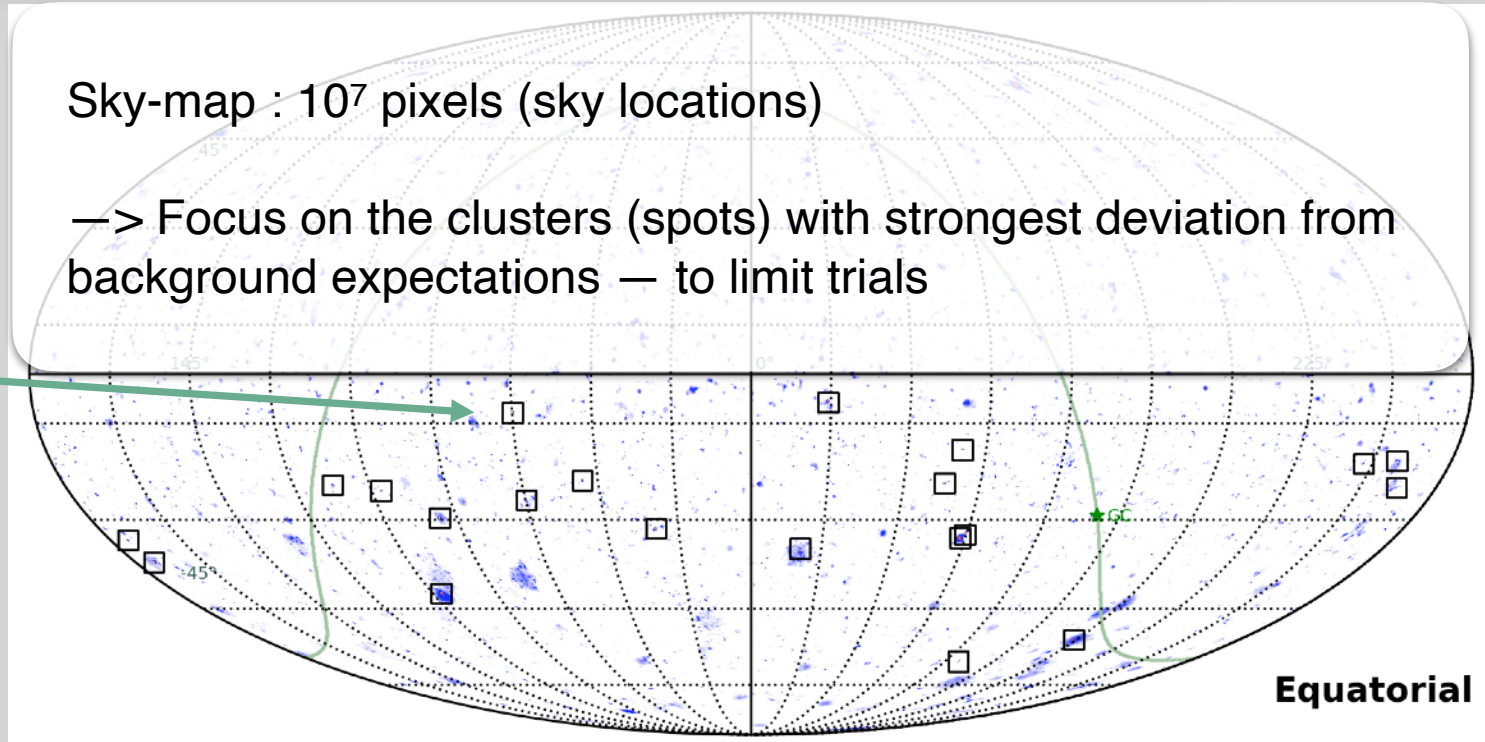
# Skymap: Cross-correlation analysis

Northern and southern hemispheres treated separately



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

—> Focus on the clusters (spots) with strongest deviation from background expectations — to limit trials



# Skymap: Cross-correlation analysis

## Summary of findings

Perform positional cross-correlation analysis, between blazar sample and neutrino spot sample.

Combining the (independent) north and south analysis, the global post-trial p-value for the chance correlation is  $2.59 \times 10^{-7}$ .

Sky region	Dataset (energies)	5BZCat	Hotspots	Matches	Pre-trial p-value	Post-trial p-value
North ( $-3^\circ \leq \delta \leq 81^\circ$ )	9 yr data ( $\sim \text{TeV}/\lesssim 0.1 \text{ PeV}$ )	2130	66	42	$5.12 \times 10^{-4}$ ( $3.28\sigma$ )	$6.79 \times 10^{-3}$ ( $2.47\sigma$ )
South ( $-85^\circ < \delta < -5^\circ$ )	7 yr data ( $\gtrsim 0.1 \text{ PeV}$ )	1177	19	10	$3 \times 10^{-7}$ ( $4.99\sigma$ )	$2 \times 10^{-6}$ ( $4.5\sigma$ )
North + South		–	–	–	$3.62 \times 10^{-9}$ ( $5.78\sigma$ )	$2.59 \times 10^{-7}$ ( $5.02\sigma$ )

Buson+ 2022  
Buson+ 2023

also confirmed by independent studies, e.g.  
Bellenghi+, when using the same IceCube skymap



# Candidate PeVatron Blazar sample

## Southern hemisphere candidate associations

See Alessandra's poster



IceCube hotspots	Blazar associations					
	$\alpha_{hs} [^\circ]$	$\delta_{hs} [^\circ]$	$L$	5BZCat	$z$	Separation $[^\circ]$
IC J2243–0540	340.75	–5.68	4.012	5BZB J2243–0609	0.30 <sup>c</sup>	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 <sup>a,b</sup>	>1.238 <sup>d</sup>	0.28
IC J0359–2551	59.94	–25.86	4.356	5BZB J0359–2615 <sup>a</sup>	1.47 <sup>e</sup>	0.40
IC J0145–3154	26.28	–31.91	4.937	5BZU J0143–3200 <sup>a</sup>	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 <sup>f</sup>	174.64	–39.26	5.885	–	–	–
IC J0628–4616	97.23	–46.28	4.987	–	–	–

# Candidate PeVatron Blazar sample

## Southern hemisphere candidate associations

IceCube hotspots			Blazar associations			
	$\alpha_{hs} [^\circ]$	$\delta_{hs} [^\circ]$	$L$	5BZCat	$z$	Separation $[^\circ]$
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Focus on one object  
which has broadband  
MWL data of good quality

### 5BZB J0630–2406

— May it be a plausible neutrino candidate?

IC J0628–4616	97.23	–46.28	4.987	–	–	–
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# Physical properties

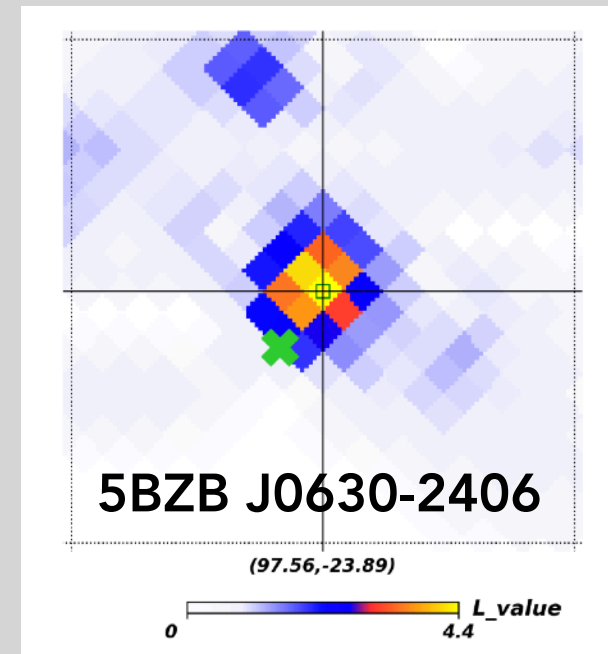
## 5BZB J0630-2406

### Classification

- Source at redshift  $z \geq 1.23$
- Historically classified as a BL Lac object : lack of emission lines, high synchrotron peak
- Hints of a luminous accretion disk with broad emission lines swapped by the jet synchrotron (Ghisellini+12).
  - High-power, radiatively efficient blazar, i.e. a **blue flat spectrum radio quasars**, broad lines and a standard accretion disk (a.k.a. **masquerading BL Lacs**)
- Properties similar to TXS 0506+056 and PKS 1424+240

Ghisellini+ 2011, 2012; Padovani+ 2012

### IceCube skymap

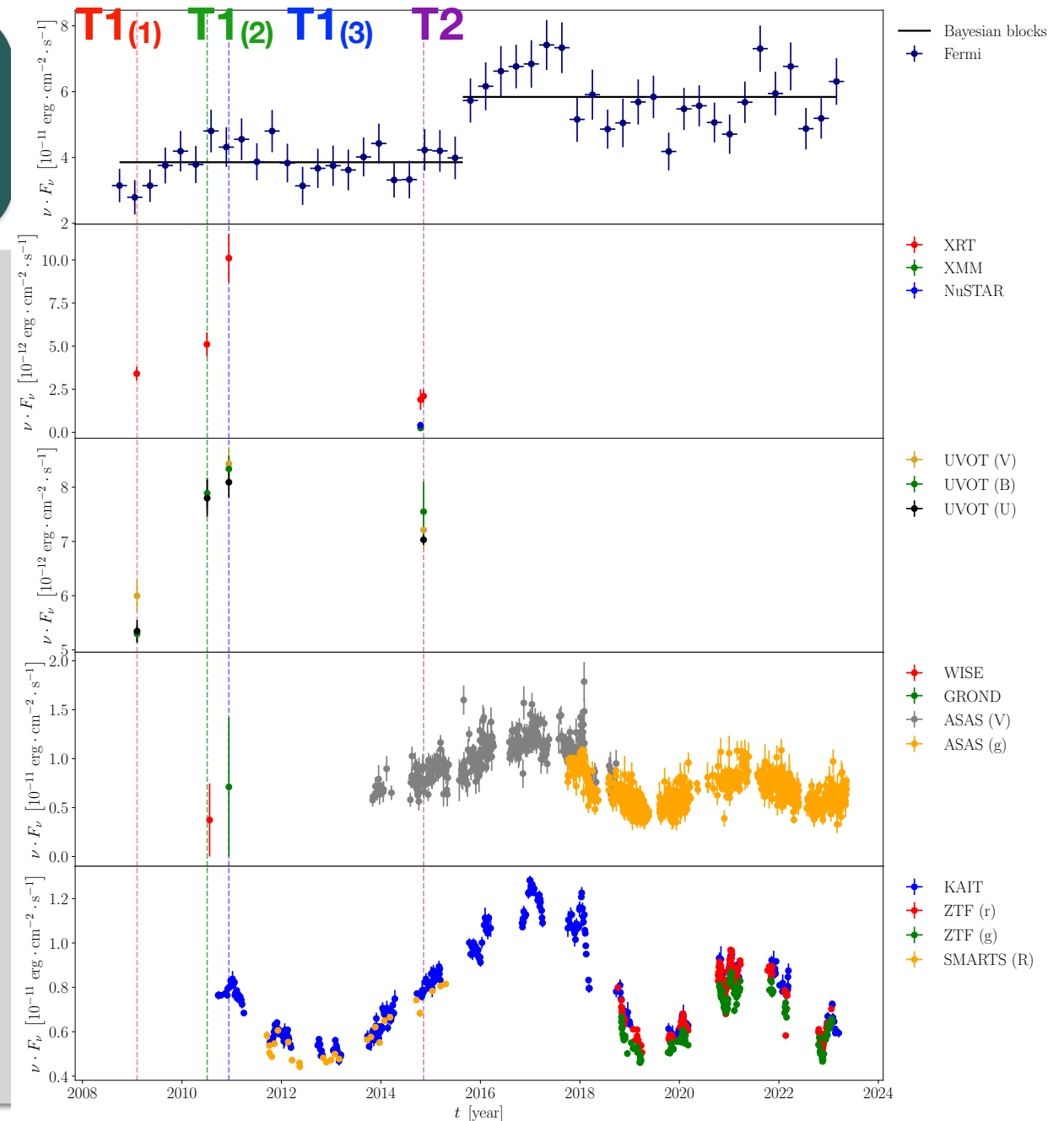


# Multi-Epoch Modeling

Good continuous coverage in optical and gamma rays  
Four X-ray observations  
Strong, correlated variability in all (available) bands

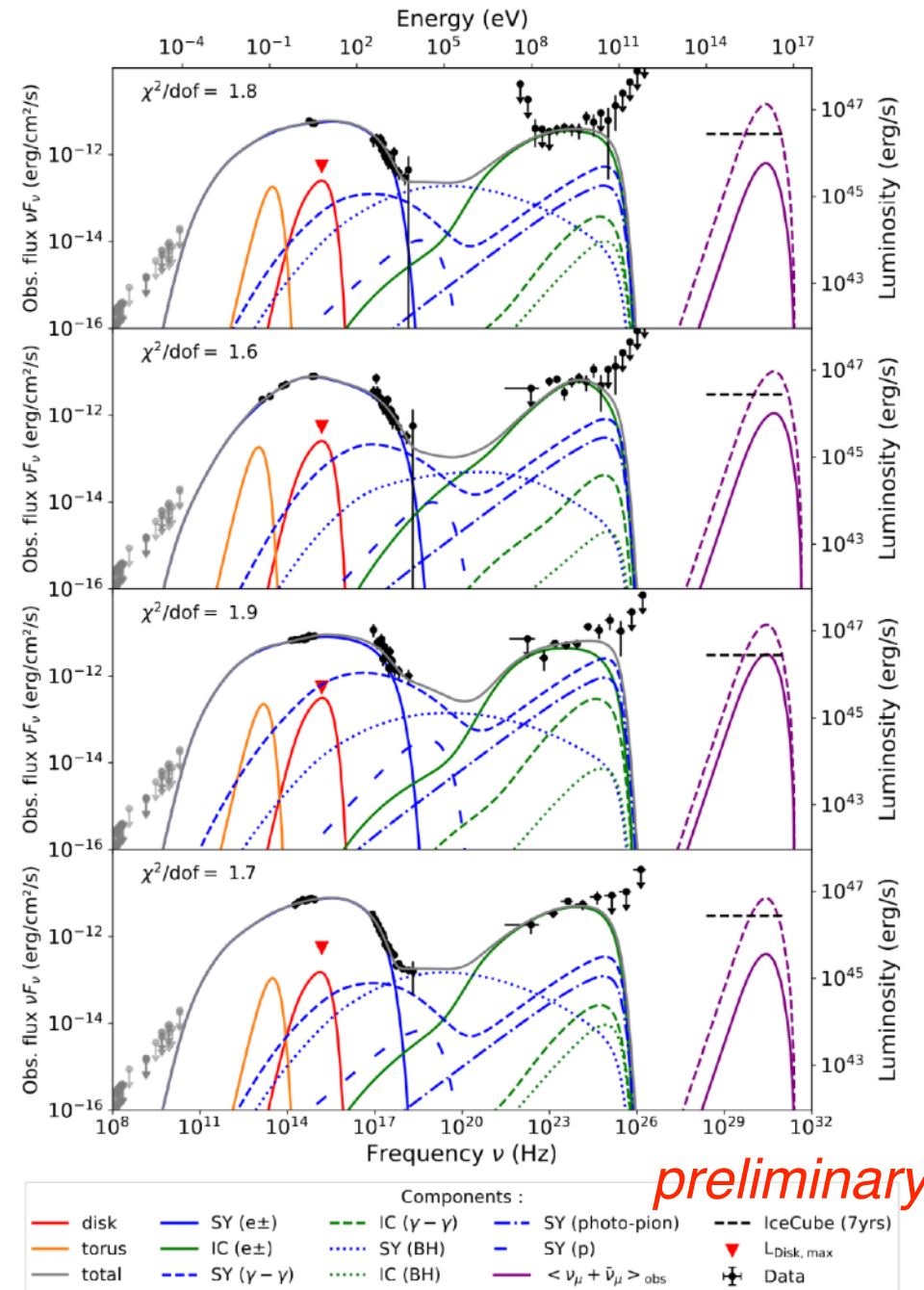
Start from modelling the SED for T2:

- Serendipitous simultaneous data in the X-ray band:
  - Swift / XMM / NuSTAR
- Complementary optical and Fermi-LAT



# Multi-epoch modeling

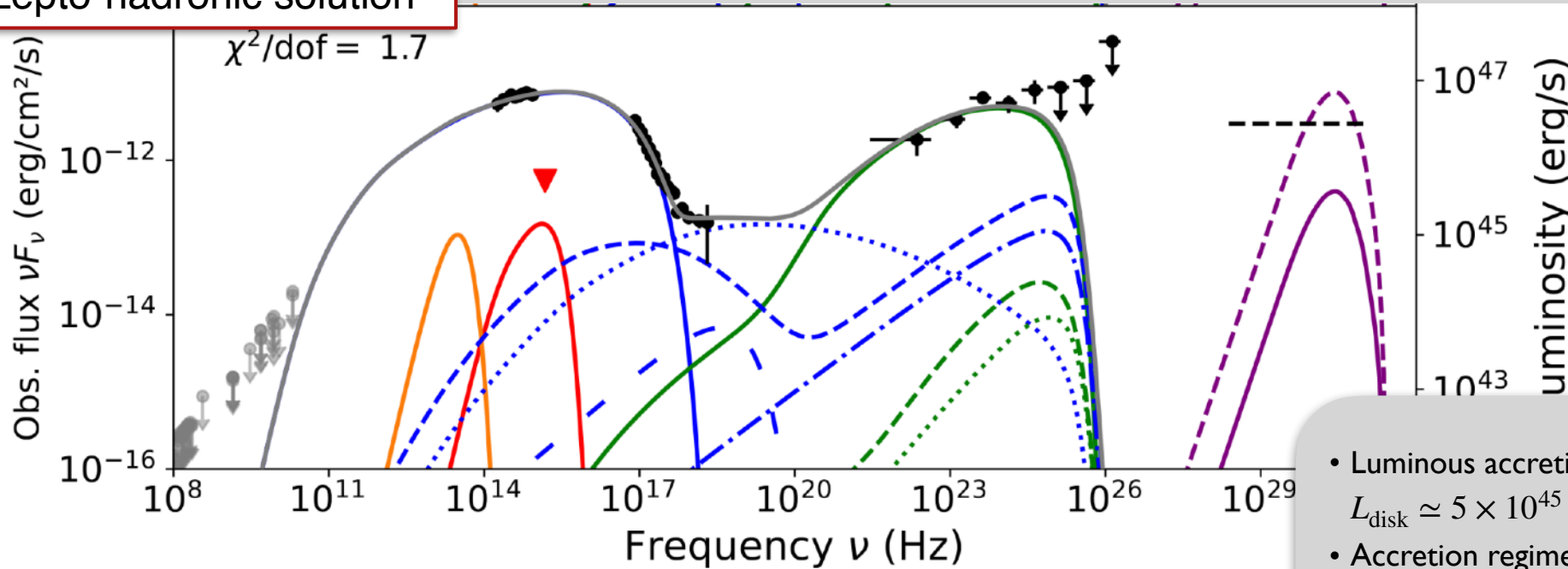
—	unit	T1 (1)	T1 (2)	T1 (3)	T2
$R'_{\text{blob}}$	cm	$2.5 \times 10^{16}$	$1.8 \times 10^{16}$	$2.7 \times 10^{16}$	$2.6 \times 10^{16}$
$B'$	G	$1.1 \times 10^0$	$7.4 \times 10^{-1}$	$1.7 \times 10^0$	$1.1 \times 10^0$
$\delta$	—	49	49	49	49
$\tau_{\text{var}}$	days	0.44	0.31	0.48	0.46
$\gamma'_{\text{e,min}}$	—	$8.2 \times 10^1$	$1.4 \times 10^2$	$9.0 \times 10^1$	$8.2 \times 10^1$
$\gamma'_{\text{e,brk}}$	—	$9.9 \times 10^2$	$3.0 \times 10^3$	$4.0 \times 10^2$	$3.1 \times 10^3$
$\gamma'_{\text{e,max}}$	—	$5.1 \times 10^4$	$9.7 \times 10^4$	$4.9 \times 10^4$	$3.7 \times 10^4$
$p_e^1$	—	1.85	1.5	1.54	1.85
$p_e^2$	—	2.14	2.71	2.09	2.07
$u'_e/u'_b$	—	$8.2 \times 10^{-3}$	$6.4 \times 10^{-2}$	$2.2 \times 10^{-3}$	$8.0 \times 10^{-3}$
$L'_e$	$\text{erg} \cdot \text{s}^{-1}$	$1.3 \times 10^{41}$	$2.0 \times 10^{41}$	$1.4 \times 10^{41}$	$1.5 \times 10^{41}$
$\gamma'_{\text{p,min}}$	—	1	1	1	1
$\gamma'_{\text{p,max}}$	—	$1.4 \times 10^7$	$2.7 \times 10^7$	$1.5 \times 10^7$	$1.5 \times 10^7$
$p_p$	—	1.75	1.51	1.53	1.87
$u'_p/u'_b$	—	$2.1 \times 10^1$	$7.7 \times 10^1$	$5.4 \times 10^0$	$2.0 \times 10^1$
$L'_p$	$\text{erg} \cdot \text{s}^{-1}$	$1.8 \times 10^{44}$	$1.6 \times 10^{44}$	$1.3 \times 10^{44}$	$1.8 \times 10^{44}$
$L_{\text{disk}}$	$\text{erg} \cdot \text{s}^{-1}$	$2.8 \times 10^{45}$	$2.8 \times 10^{45}$	$3.4 \times 10^{45}$	$1.7 \times 10^{45}$
$\dot{M}$	$M_{\odot} \cdot \text{year}^{-1}$	$4.9 \times 10^{-1}$	$5.0 \times 10^{-1}$	$6.0 \times 10^{-1}$	$2.9 \times 10^{-1}$
$\eta$	—	$2.2 \times 10^{-3}$	$2.2 \times 10^{-3}$	$2.7 \times 10^{-3}$	$1.3 \times 10^{-3}$
$M_{\text{BH}}$	$M_{\odot}$	$1.0 \times 10^9$	$1.0 \times 10^9$	$1.0 \times 10^9$	$1.0 \times 10^9$
$R_{\text{diss}}/R_{\text{BLR}}$	—	2.1	2.0	1.8	2.1
$T_{\text{torus}}$	K	$3.8 \times 10^2$	$1.3 \times 10^2$	$1.9 \times 10^2$	$3.8 \times 10^2$



# Theoretical modeling

## 5BZB J0630-2406

Lepto-hadronic solution



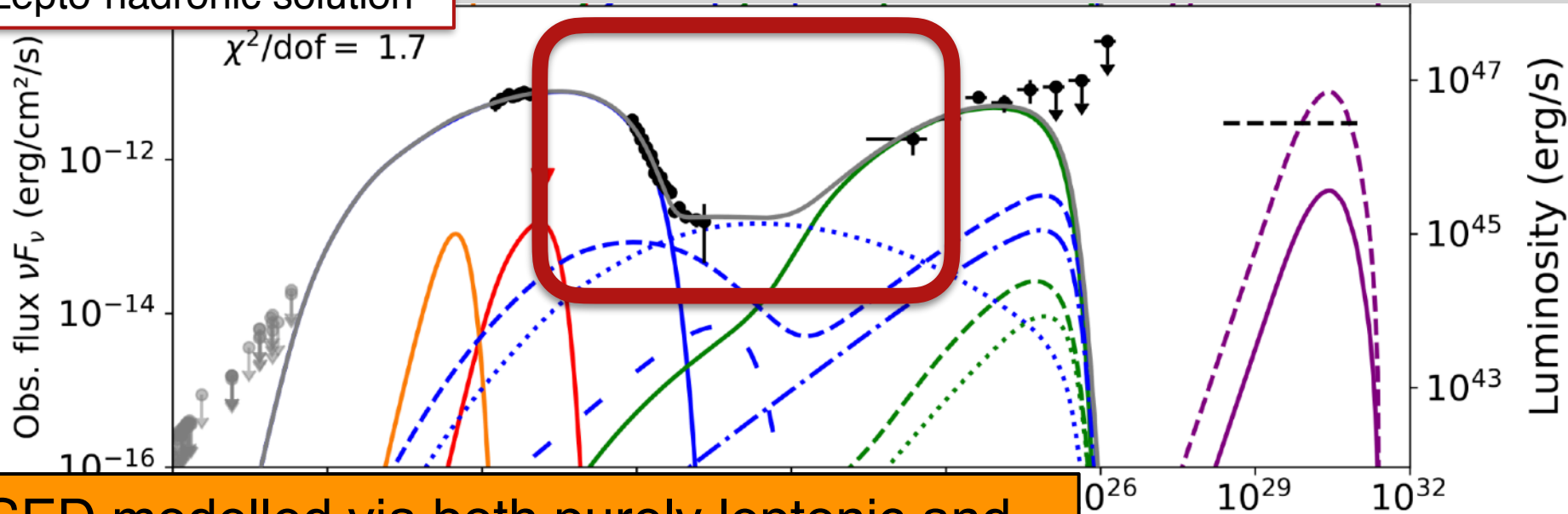
- Luminous accretion disk  
 $L_{\text{disk}} \simeq 5 \times 10^{45} \text{ erg} \cdot \text{s}^{-1}$
- Accretion regime  $\eta \sim 2 \times 10^{-4}$ ,  
 $L_\gamma/L_{\text{Edd}} = 0.15$ .
- Dissipation radius is on the outer edge of the BLR
  - Combination of limited absorption and efficient neutrino production.

# Theoretical modeling

## 5BZB J0630-2406

Lepto-hadronic solution

$\chi^2/\text{dof} = 1.7$



SED modelled via both purely leptonic and mixed lepto-hadronic scenarios, suggesting that the hadronic component is subdominant, **except in the X-ray and the MeV bands.**

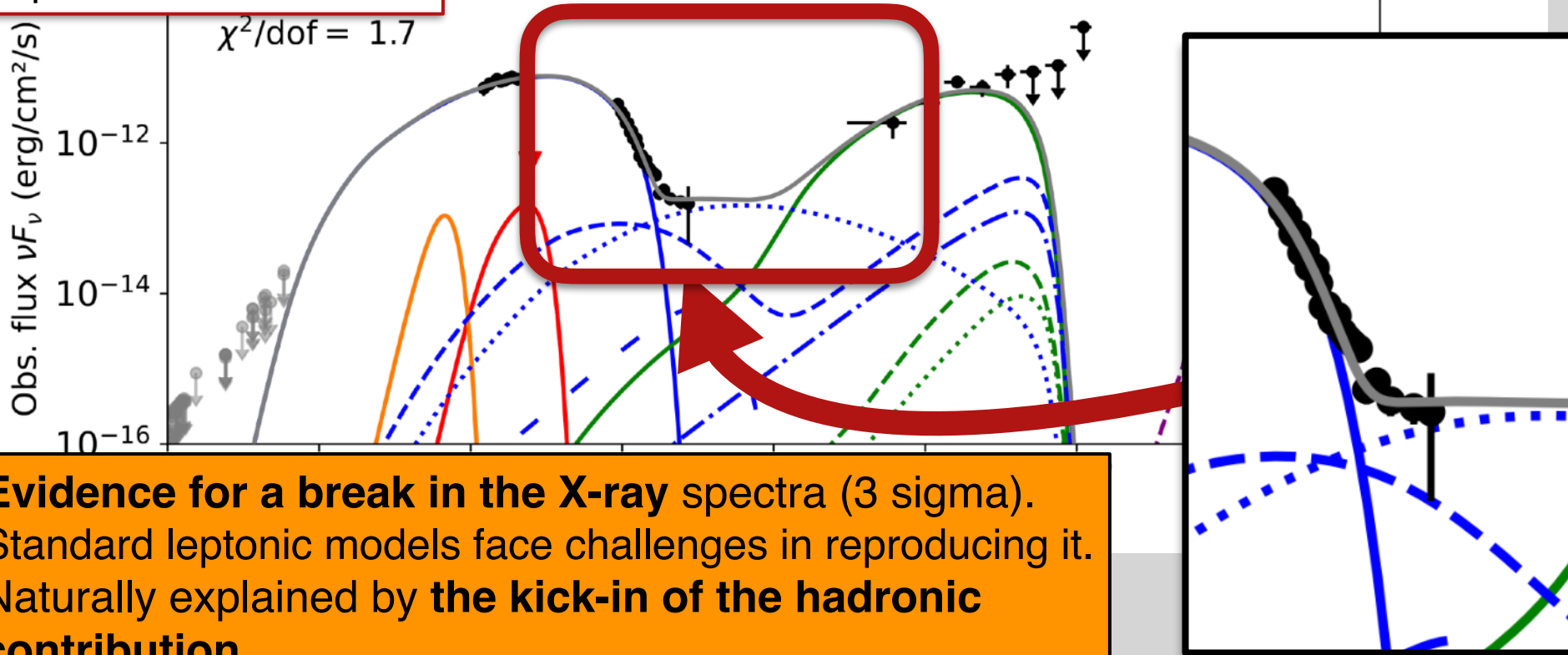
# Theoretical modeling

## 5BZB J0630-2406

Lepto-hadronic solution

Obs. flux  $\nu F_\nu$  (erg/cm<sup>2</sup>/s)

$\chi^2/\text{dof} = 1.7$

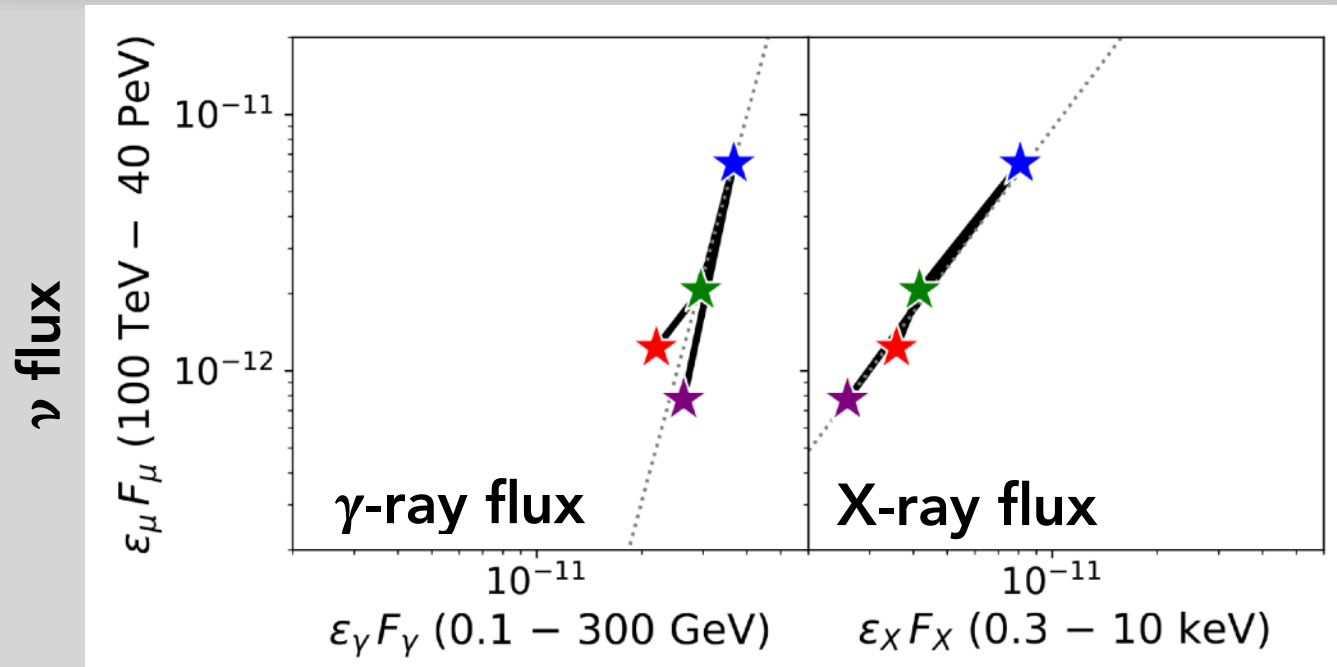


- **Evidence for a break in the X-ray spectra (3 sigma).**
- Standard leptonic models face challenges in reproducing it.
- Naturally explained by **the kick-in of the hadronic contribution**



# Evolution of the neutrino emission

Increase in neutrino emission relates to change in X-rays  
**X-rays better proxy for neutrinos than gamma  $\gamma$  rays**



# Neutrino predictions

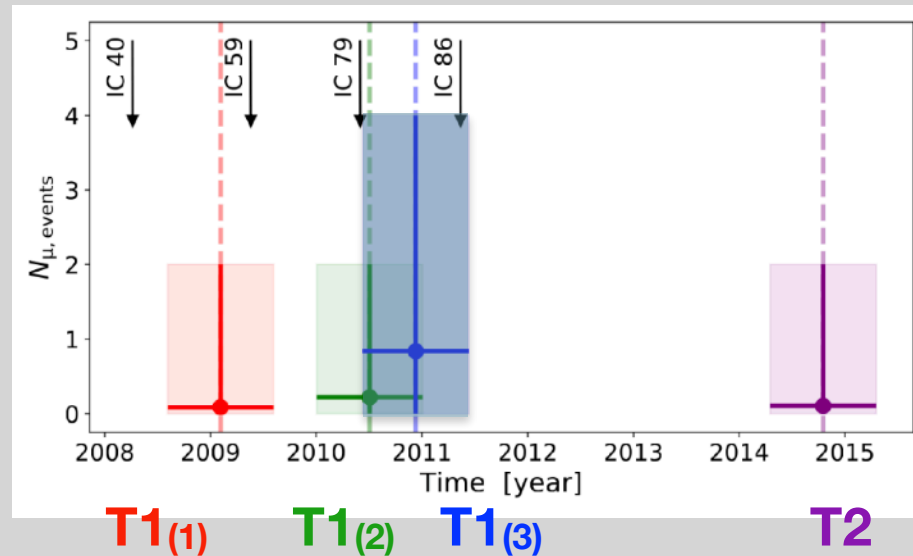
## Neutrino predicted from theoretical modeling

Epoch	Period	IC	$N_{\mu,events}$
T1 (1)	August 2008 - August 2009	40 / 59	$0.09^{+1.91}_{-0.09}$
T1 (2)	January 2010 - January 2011	59 / 79	$0.21^{+1.79}_{-0.21}$
T1 (3)	June 2010 - June 2011	79 / 86	$0.84^{+3.16}_{-0.84}$
T2	April 2014 - April 2015	86	$0.11^{+1.89}_{-0.11}$

*preliminary*

# Evolution of the neutrino emission

$N(\nu_\mu)$   
predicted

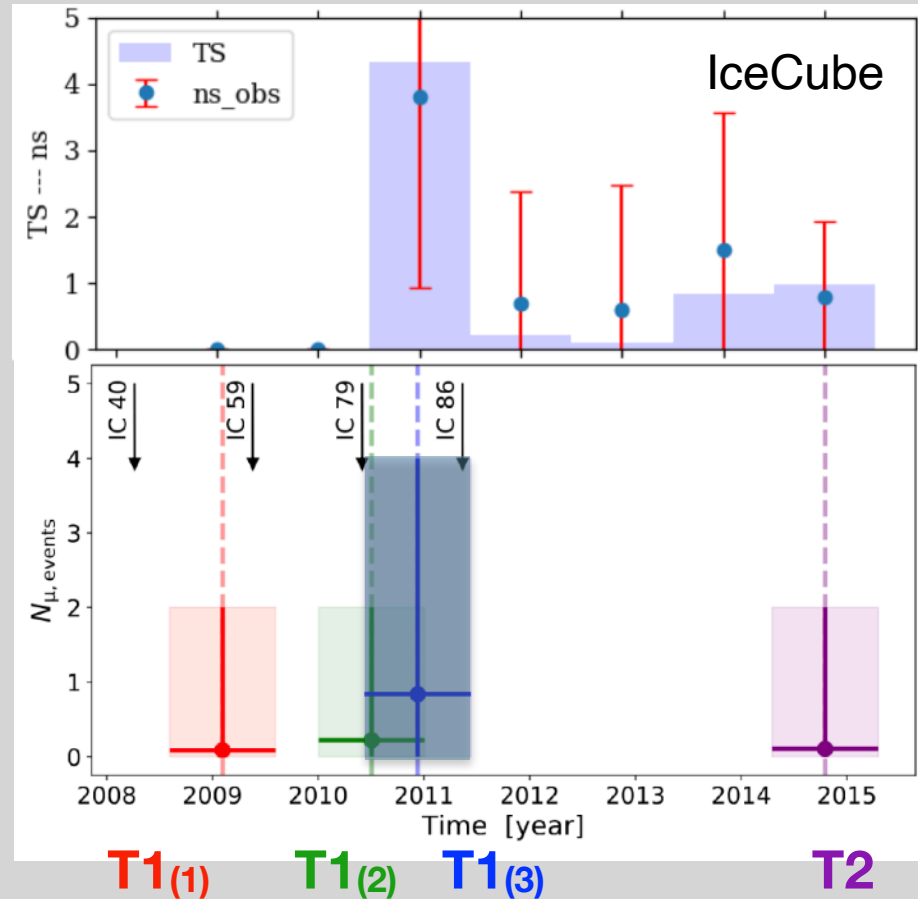


*preliminary*

# Evolution of the neutrino emission

$N(\nu_\mu)$   
observed

$N(\nu_\mu)$   
predicted

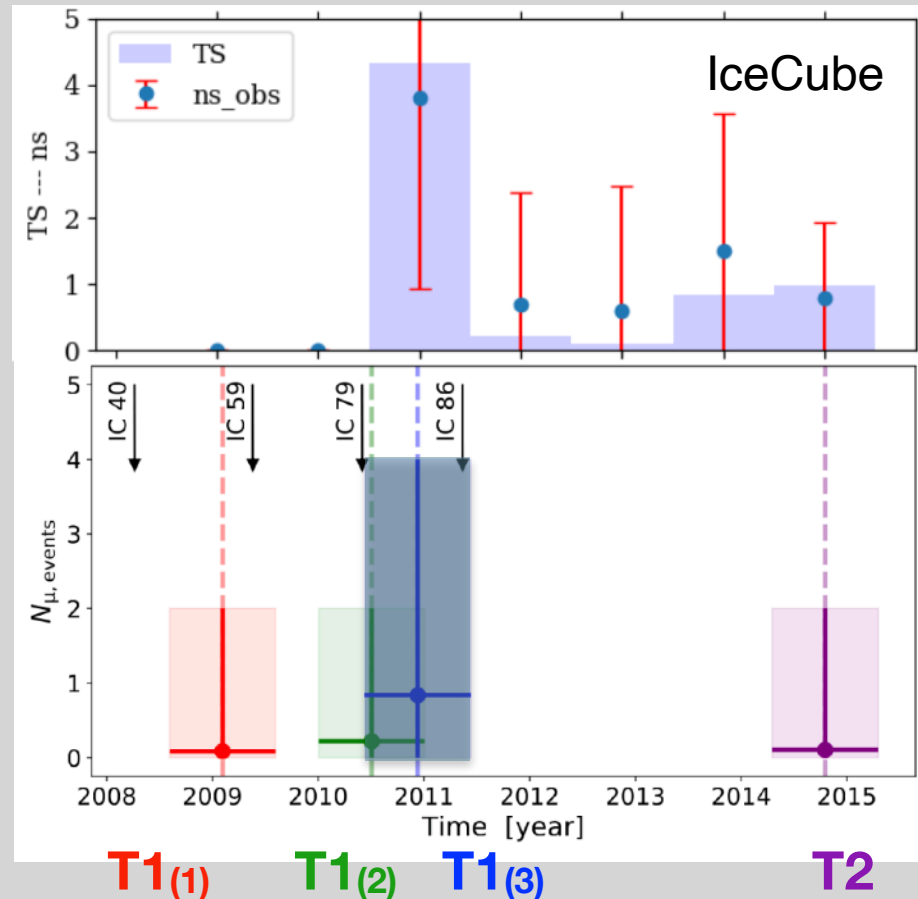


*preliminary*

# Evolution of the neutrino emission

$N(\nu_\mu)$   
observed

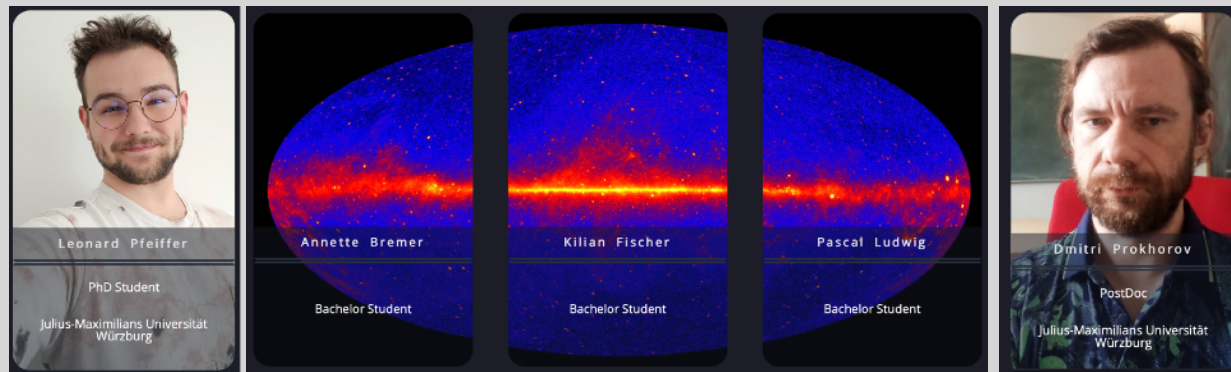
$N(\nu_\mu)$   
predicted



Extending the neutrino observation time-window does not necessarily result in a (stronger) detection

*preliminary*

# MessMapp Research Group



*Collaborators:  
M. Ajello, A. Coleiro, G. Illuminati, S. Marchesi, M. Santander, A. Tramacere  
F. Vazza*

Current active members

Full list of contributors : <https://messmapp.github.io/group.html>

# Summary

- A subsample of candidate PeVatron blazars proposed as associated with IceCube neutrino hotspots; post-trial probability of  $\sim 2.59 \times 10^{-7}$ .
- Theoretical modelling of MWL SED confirms plausible neutrino emitter: Candidate association, 5BZB J0630-2406:
  - X-ray flare happening during the 7yr IceCube observation
  - SED modeling predicts variable neutrino emission
  - Consistent with an increase in the observed neutrino event rate
  - Overall properties similar to TXS 0506+056; contributing  $<1\%$  to the diffuse neutrino flux
- *'Tip of the iceberg'* : other individual sources may be already detectable in the 15-yr (proprietary) IceCube datasets
- Analysis and results fully reproducible:
  - Datasets available via e.g. Zenodo.
  - Software hosted e.g. in GitHub. First public release: AM<sup>3</sup>.

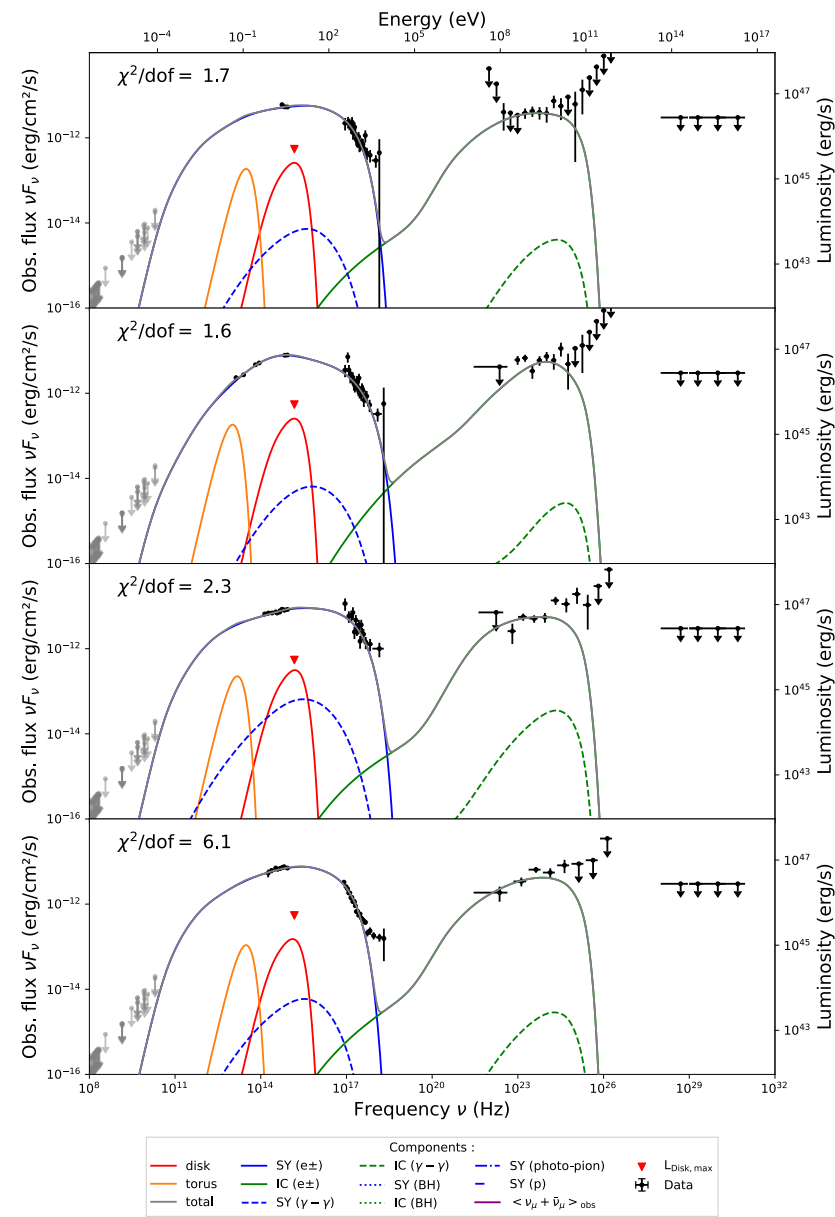


# Back up



# Multi-epoch modeling

## Leptonic solutions

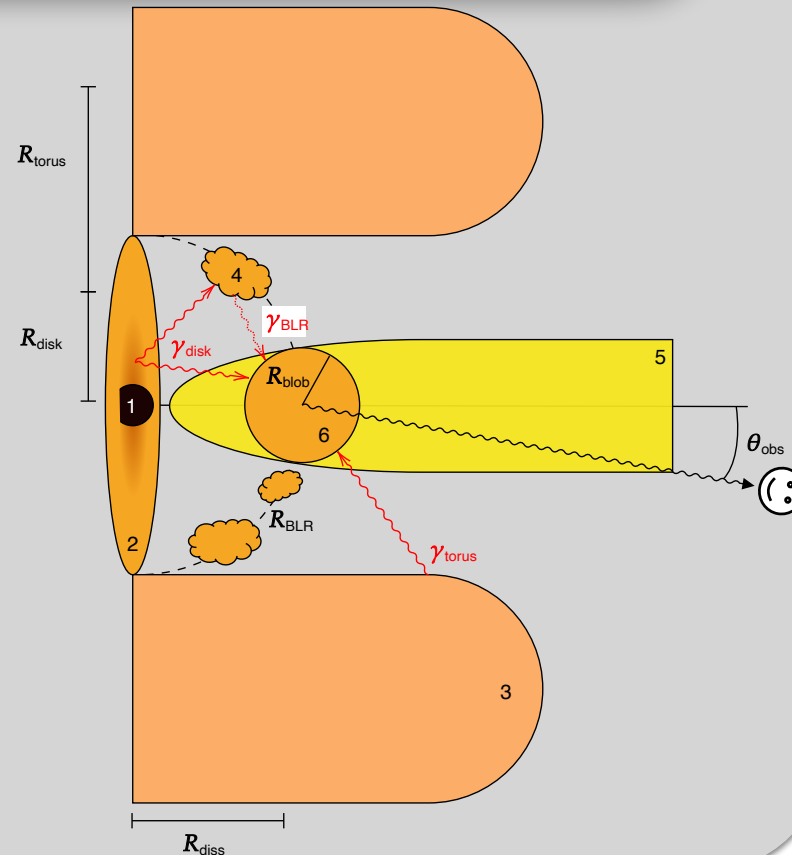


# Theoretical modeling

## 5BZB J0630-2406

### Leptonic / Lepton-hadronic modeling

- Simulation of the acceleration and the cooling of electrons and / or protons inside of a spherical region (blob) with the AM<sup>3</sup> code (Gao+ 2017, Klinger+ 2023).
- Spherical region moving at relativistic speed inside the jet surrounded by an accretion disk and a dust torus emitted as black bodies.
- Emission from the accretion disk is reprocessed by the BLR.
- Parameters are fitted to reproduce the SED by minimising the  $\chi^2_{\text{d.o.f}}$  between the simulated and the observed data.



# Neutrino point-source Searches

## Observational Approach

### Blazar sample

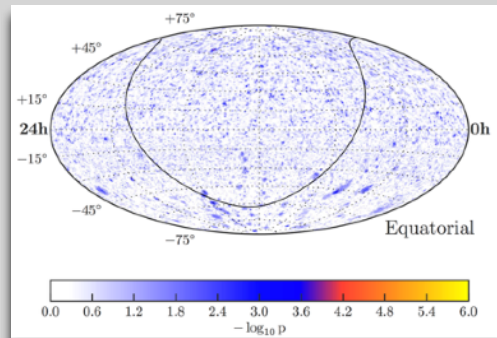
- 5BZCat (Massaro+ 2015)
- no preferred selection

### IceCube neutrino data

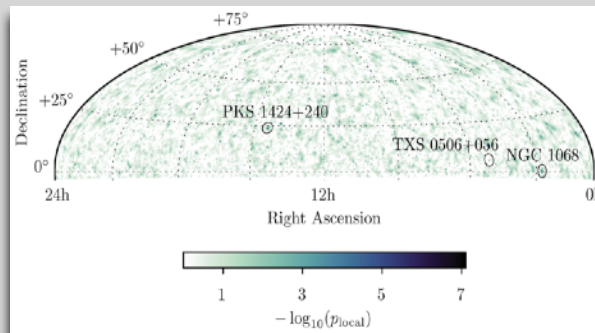
The 'highest-quality' data for point-source searches publicly available

### Southern hemisphere

- 7-year sky map
- 2008 - 2015



IceCube coll. 2017



### Northern hemisphere

- 10-year sky map
- 2011 - 2020

IceCube coll. 2022