Hadronic processes at work in 5BZB J0630-2406

Sara Buson

A. Azzollini, M. Boughelilba, A. Bremer, M. Lincetto, S. Marchesi, L. Pfeiffer, J. Zaballa, D. Prokhorov, on behalf of the Fermi-LAT collaboration

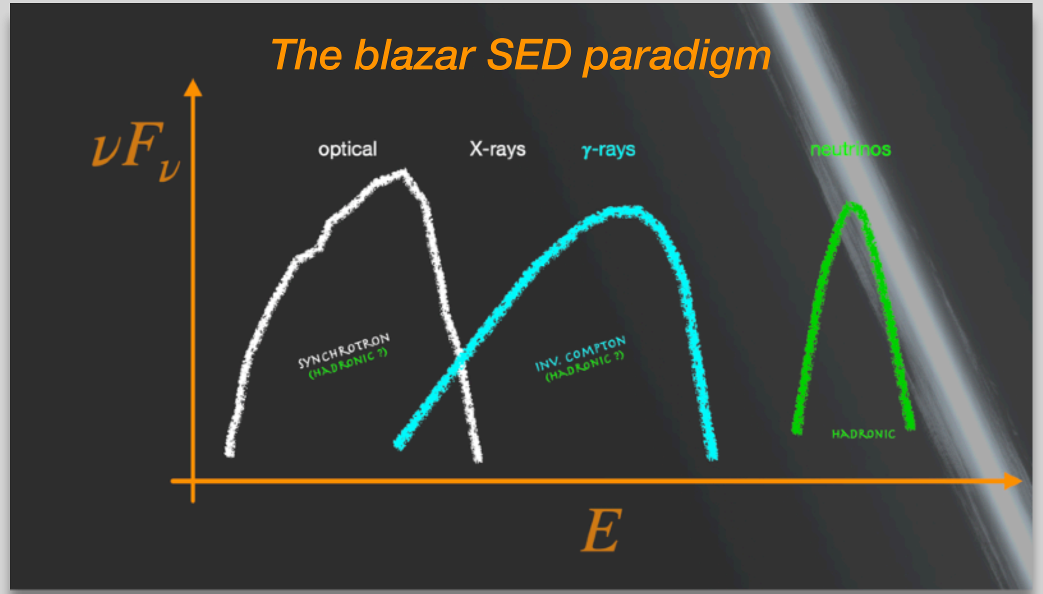
11th International Fermi Symposium, September 2024

MessMapp Research

1. **Neutrino** observational strategy (using the least number of assumptions as possible)

2. **Theoretical** angle (SED modeling: AM^3)

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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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 6×10^{-7}. Our statistical analysis provides the observational evidence that blazars are astrophysical neutrino factories and hence, extragalactic cosmic-ray accelerators.

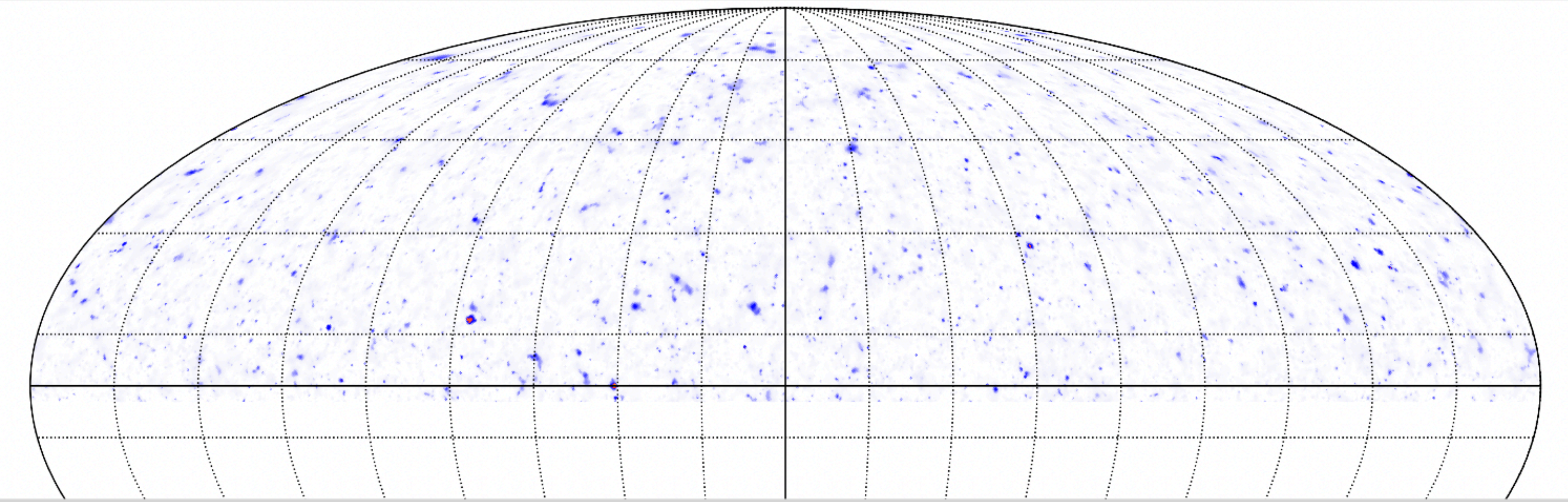
Unified Astronomy Thesaurus concepts: Neutrino astronomy (1100); Neutrino telescopes (1105); Blazars (164); Supermassive black holes (1663); Relativistic jets (1390); Cosmic ray astronomy (324)

IceCube Neutrino (p-value) sky-map

Informs about the level of anisotropy in the event spatial distribution

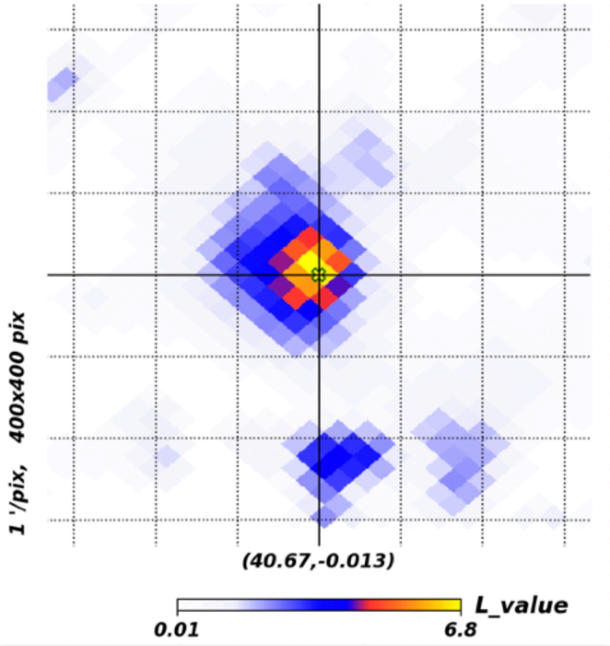
The smallest the local p-value, the highest the discrepancy from background expectations

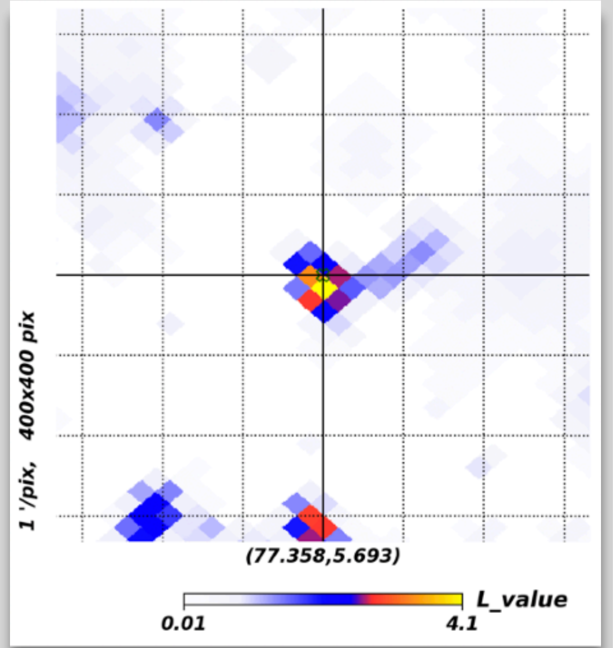
For convenience, we define: L-value = $-\log(\text{p-value}_{\text{Loc}})$



IceCube skymaps: sensitive to comic sources

Hotspots consistent with NGC 1068 and TXS 0506+056

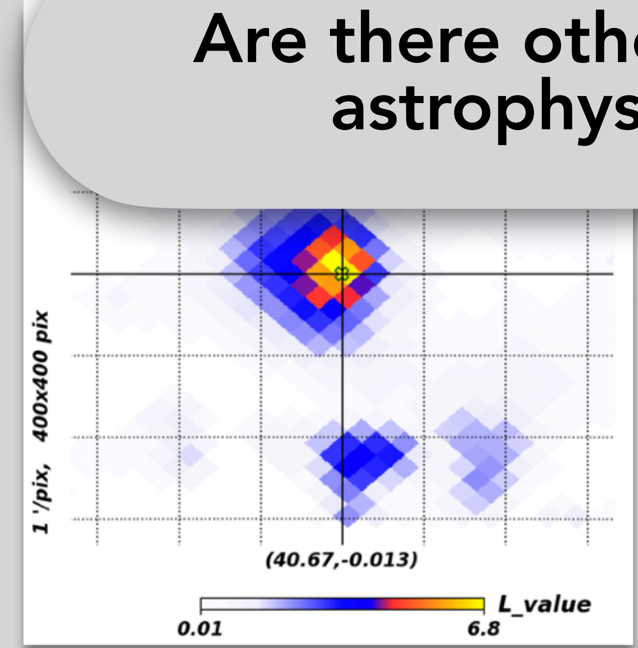


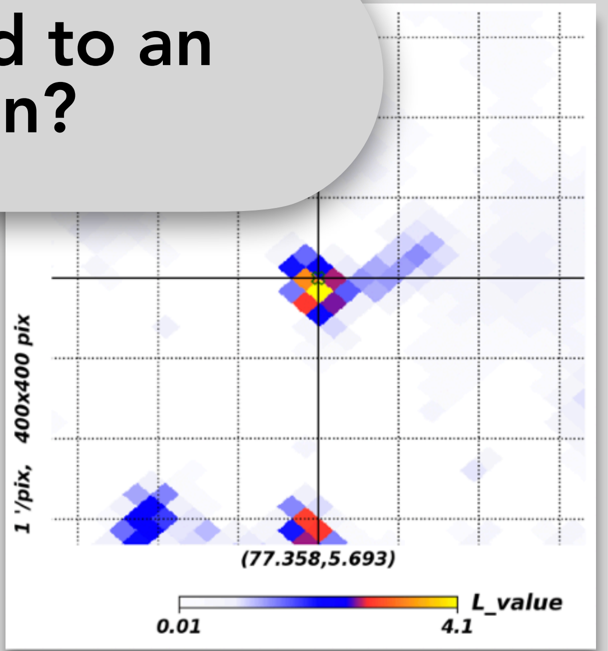


IceCube skymaps: sensitive to comic sources

Hotspots consistent with NGC 1068 and TXS 0506+056

Are there others linked to an astrophysical origin?



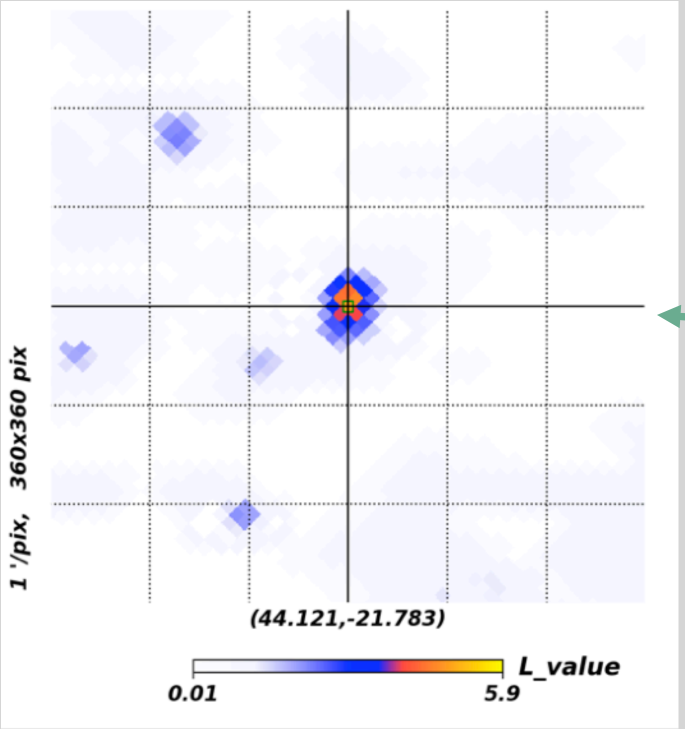


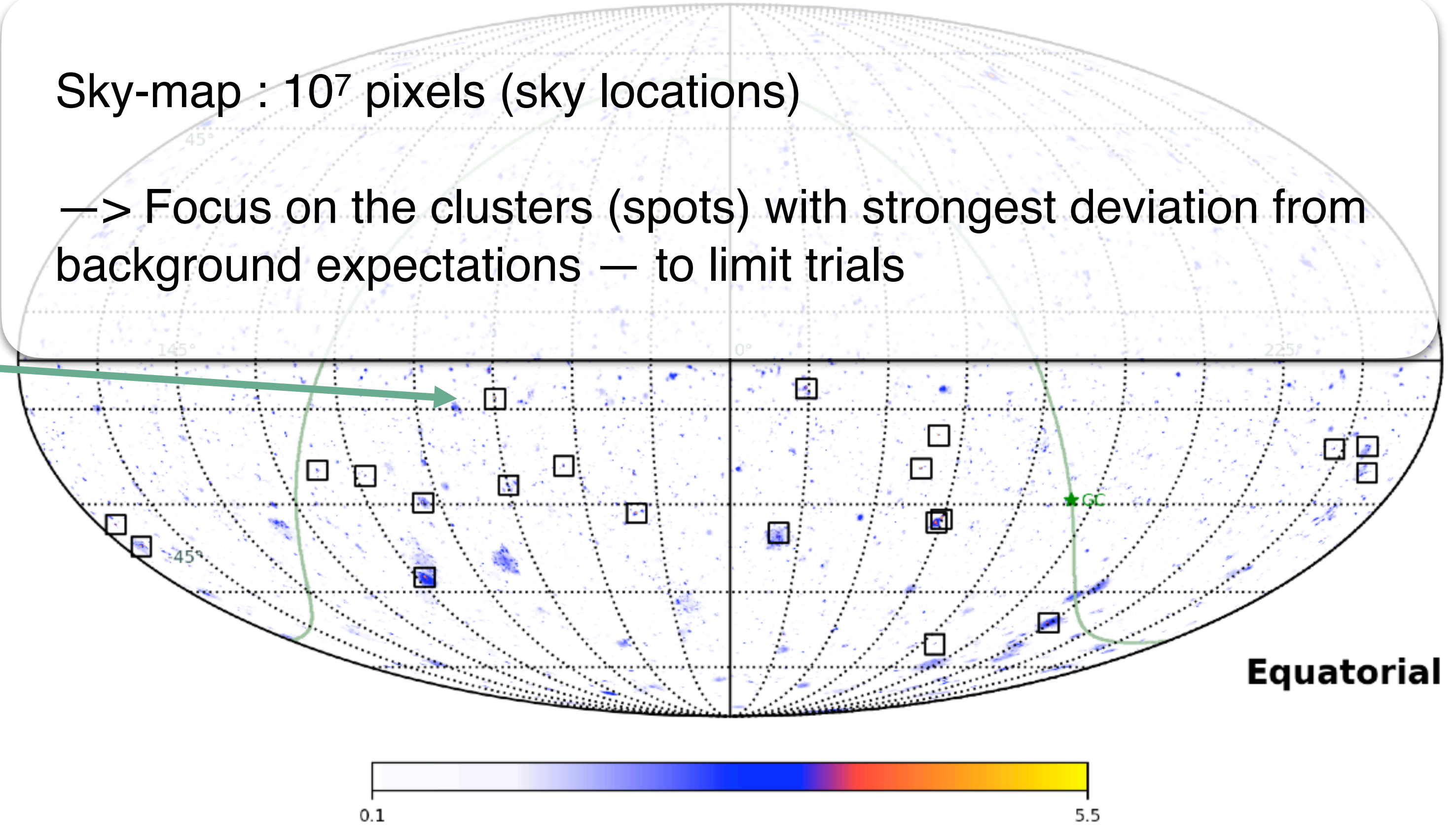
Skymap: Cross-correlation analysis

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 x 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 ($\sim$TeV/$\lesssim$ 0.1 PeV)	2130	66	42	5.12×10^{-4} (3.28σ)	6.79×10^{-3} (2.47σ)
South ($-85^\circ < \delta < -5^\circ$)	7 yr data ($\gtrsim$ 0.1 PeV)	1177	19	10	3×10^{-7} (4.99σ)	2×10^{-6} (4.5σ)
					$p_{\rm pre}^{\rm global}$	$p_{\rm post}^{\rm global}$
North + South		–	–	–	3.62×10^{-9} (5.78σ)	2.59×10^{-7} (5.02σ)

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[°]
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	–	–	–

Candidate PeVatron Blazar sample

Southern hemisphere candidate associations

IceCube hotspots				Blazar associations		
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IC J0628−4616	97.23	−46.28	4.987	–	–	–

Focus on one object which has broadband MWL data of good quality

5BZB J0630-2406

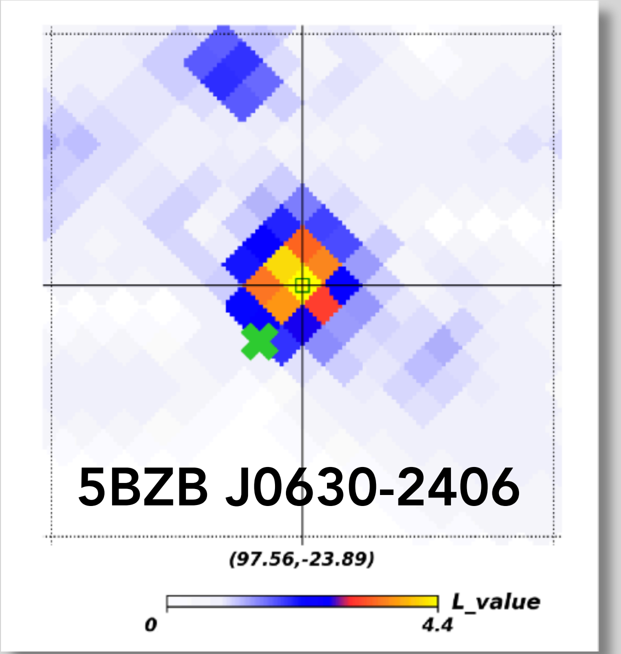
— May it be a plausible neutrino candidate?

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

IceCube skymap



Ghisellini+ 2011, 2012; Padovani+ 2012

Multi-Epoch Modeling

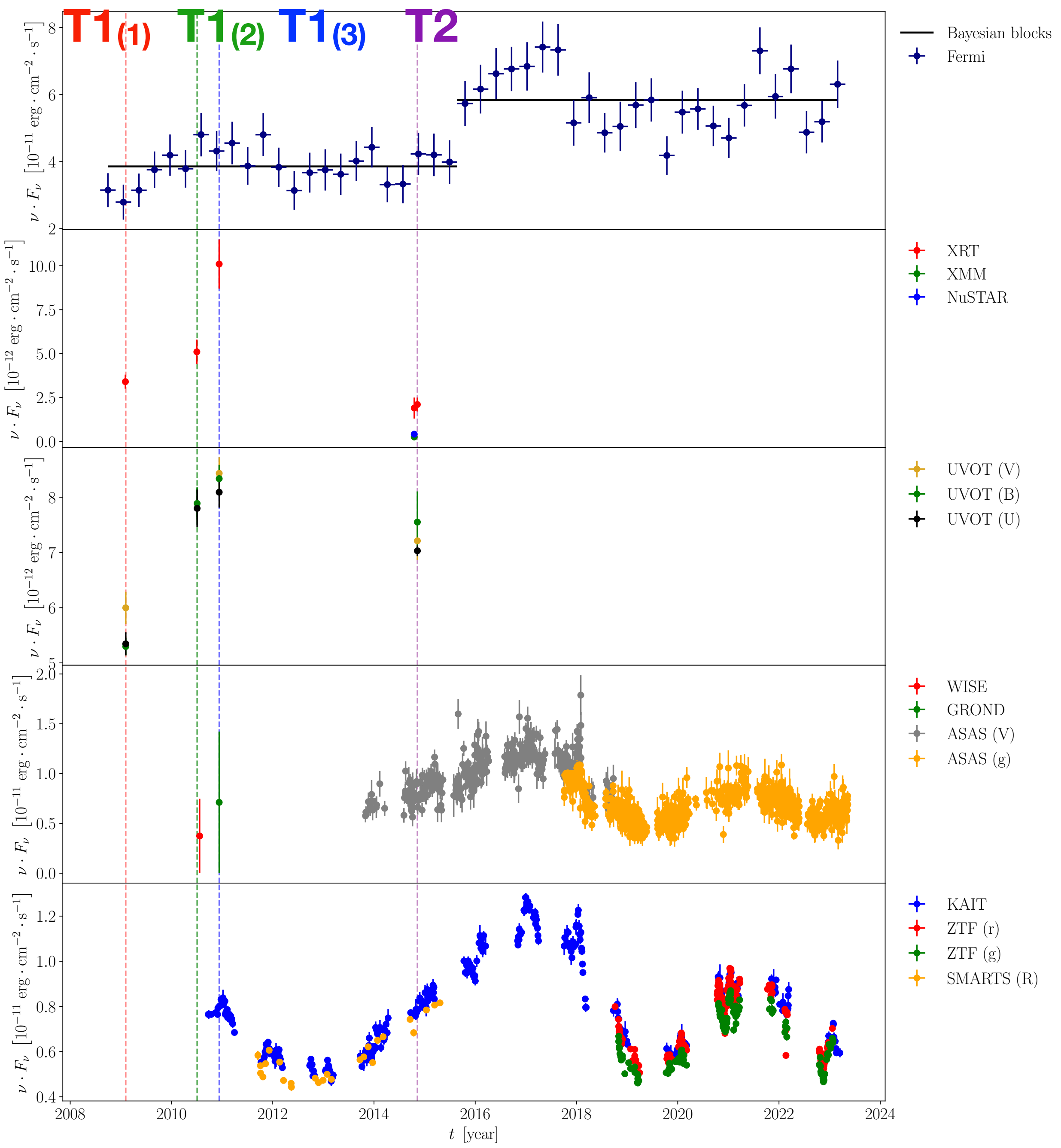
Good continuous coverage in optical and gamma rays

Four X-ray observations

Strong, correlated variability in all (available) bands

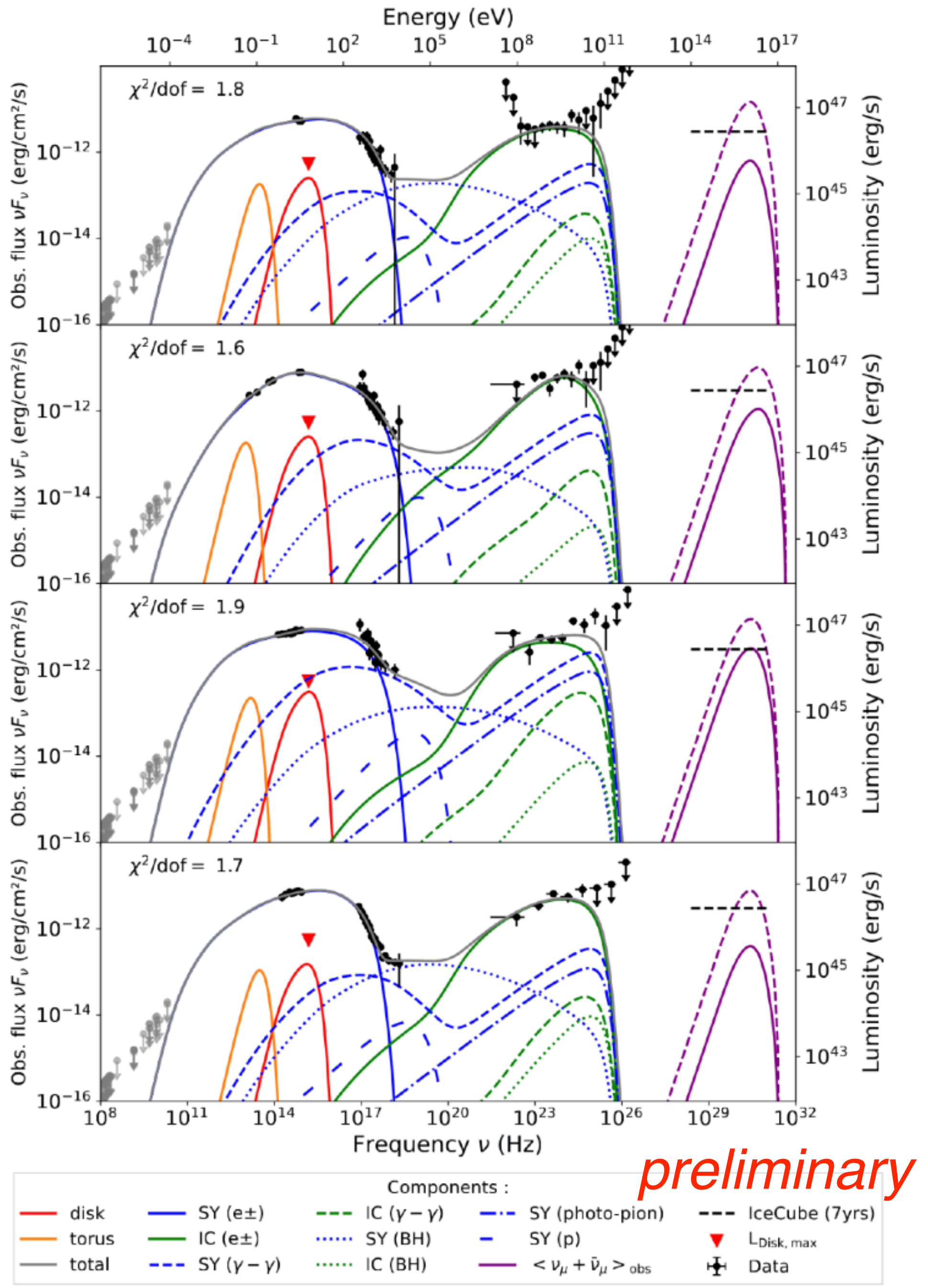
<u>Start from modelling the SED for T2:</u>

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



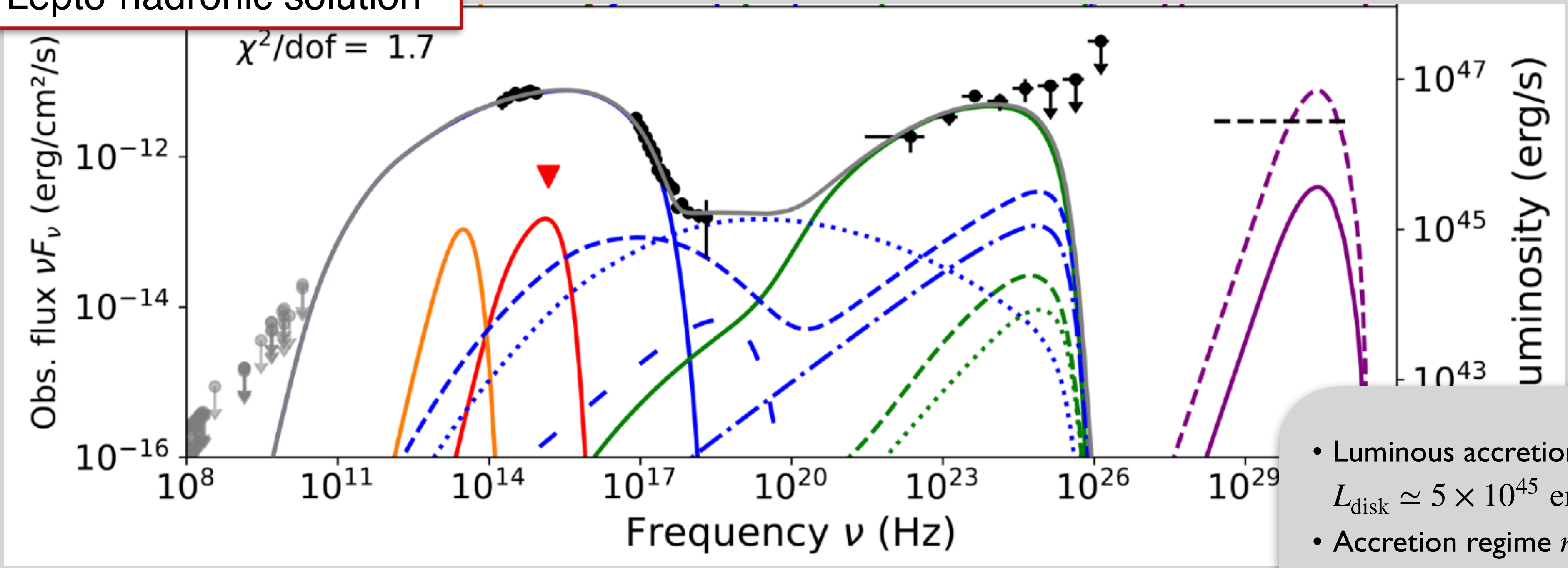
Multi-epoch modeling

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



Theoretical modeling
5BZB J0630-2406

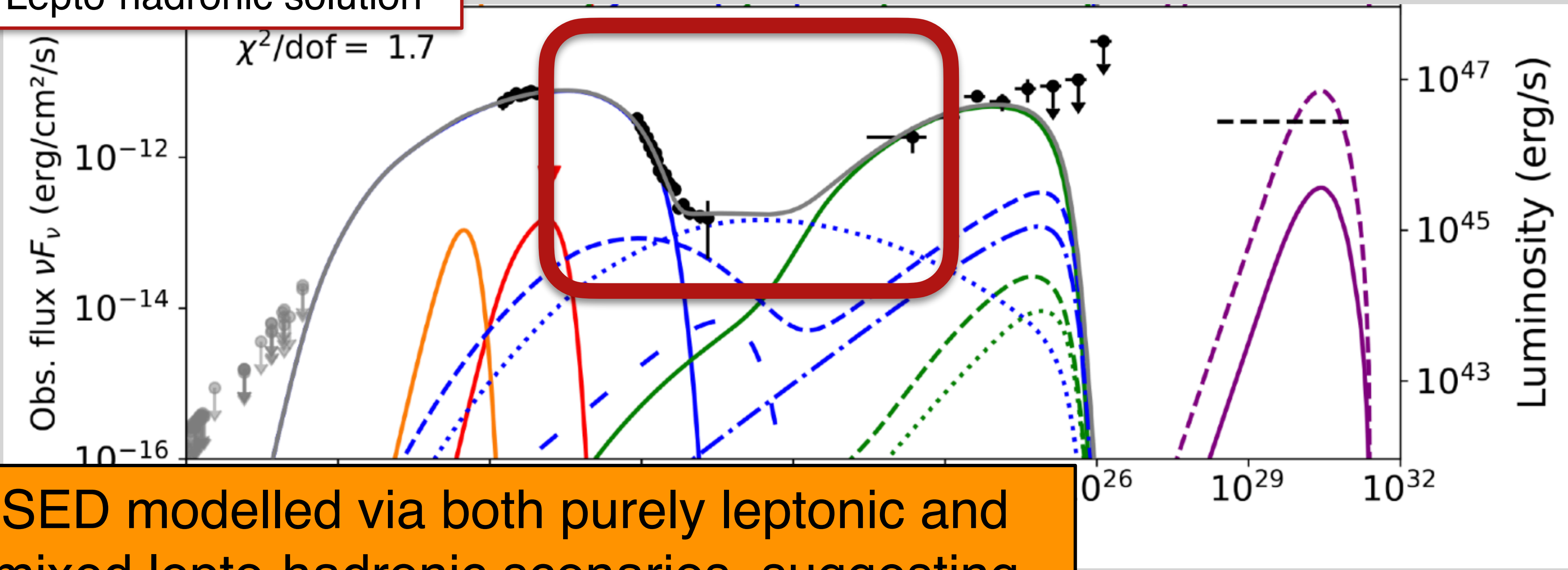
Lepto-hadronic solution



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

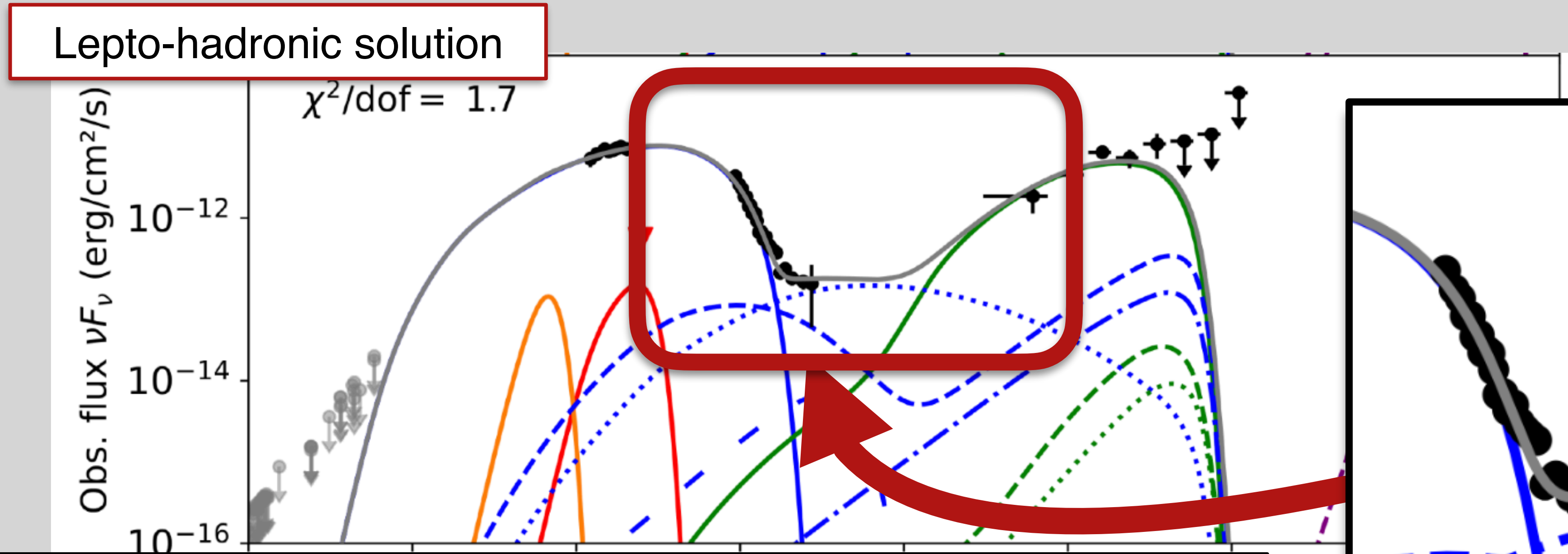
Theoretical modeling
5BZB J0630-2406

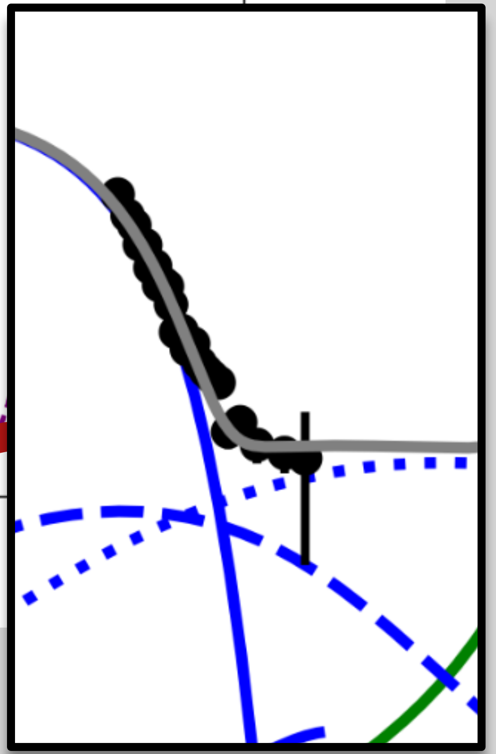
Lepto-hadronic solution



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

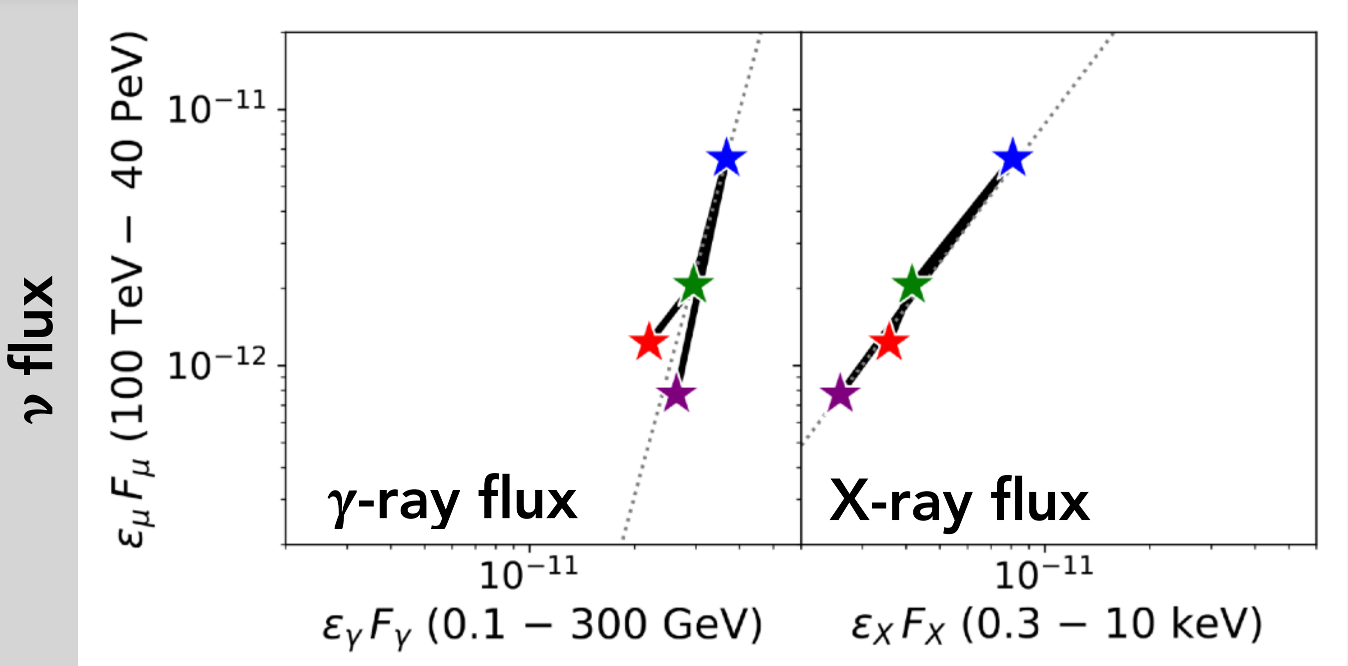




- **Evidence for a break in the X-ray** spectra (3 sigma).
- Standard leptonic models face challenges in reproducing it.
- Naturally explained by **the kick-in of the hadronic contribution**

Evolution of the neutrino emission

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



Neutrino predictions

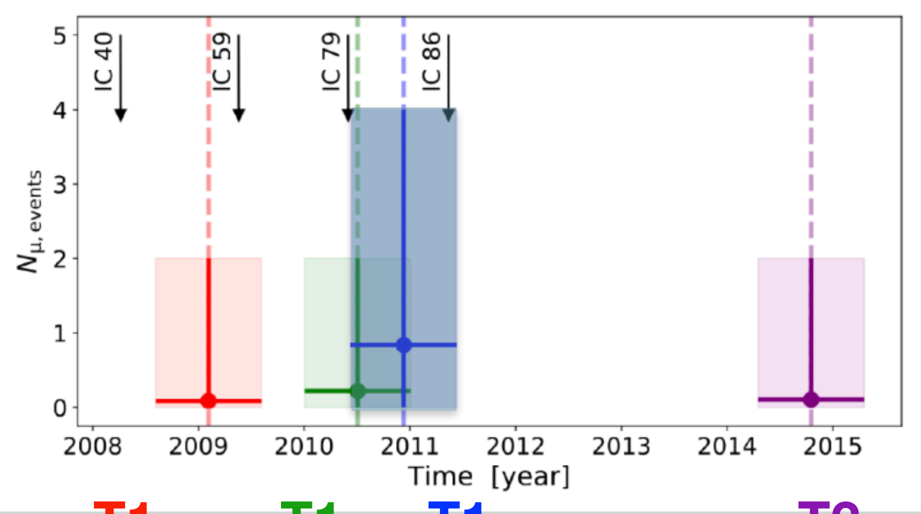
Neutrino predicted from theoretical modeling

Epoch	Period	IC	$N_{\mu,\mathrm{events}}$
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(ν_μ) predicted



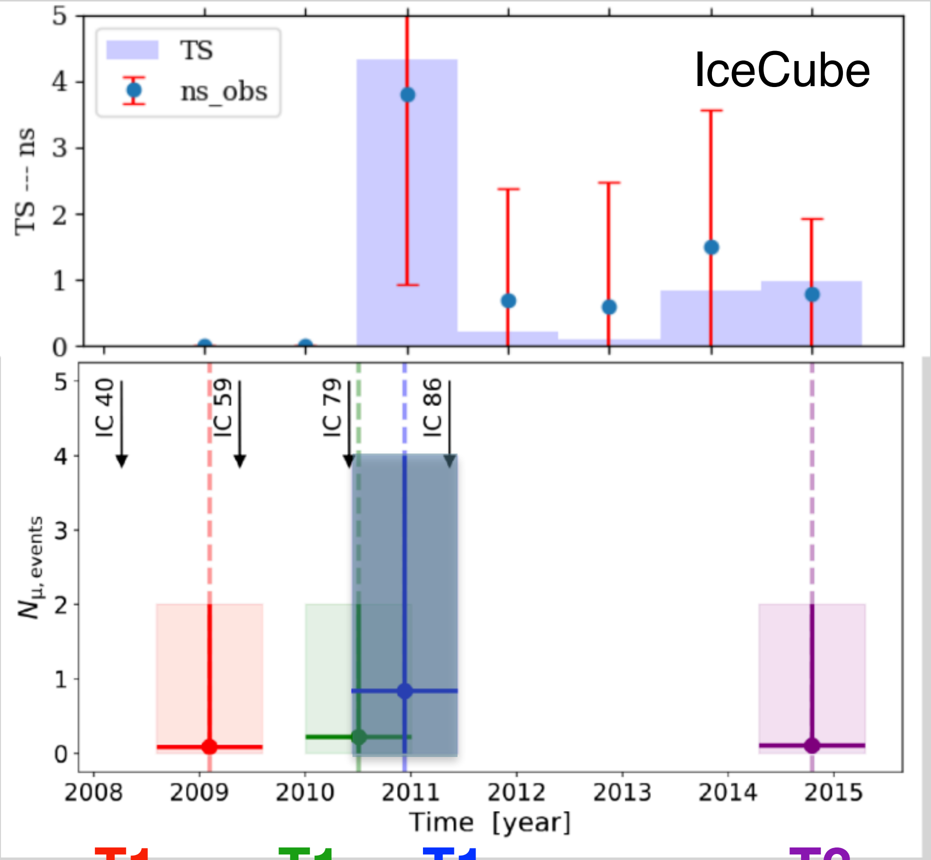
T1(1) T1(2) T1(3) T2

preliminary

Evolution of the neutrino emission

$N(\nu_\mu)$
observed

$N(\nu_\mu)$
predicted



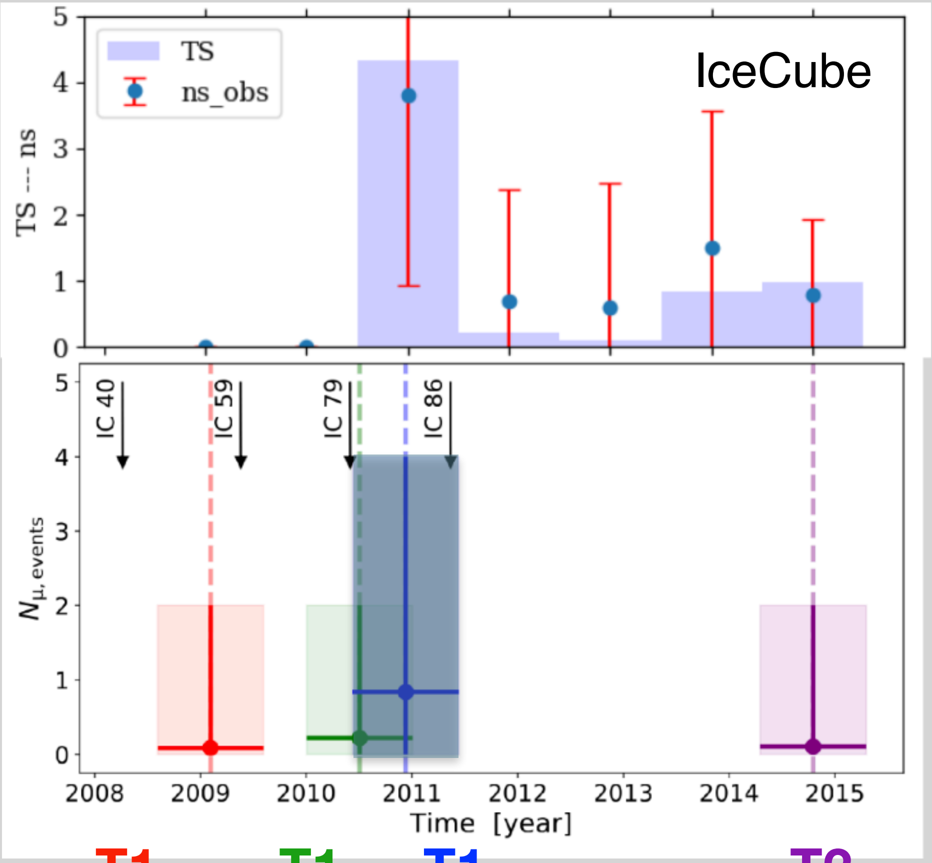
T1_1 T1_2 T1_3 T2

preliminary

Evolution of the neutrino emission

$N(\nu_\mu)$ observed

$N(\nu_\mu)$ predicted



T1_1 T1_2 T1_3 T2

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

preliminary

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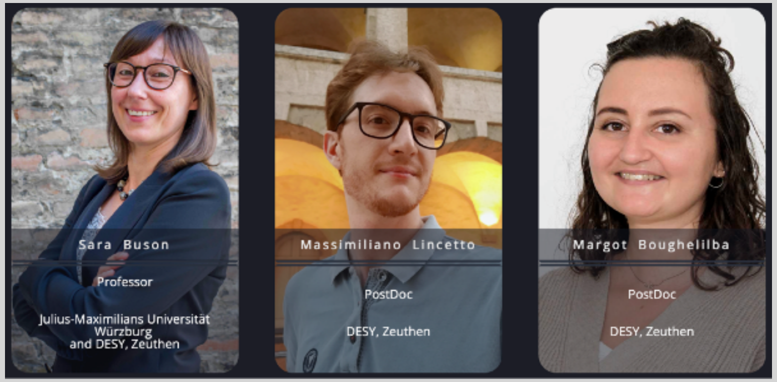
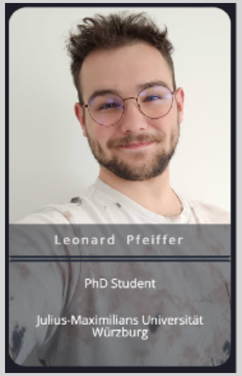
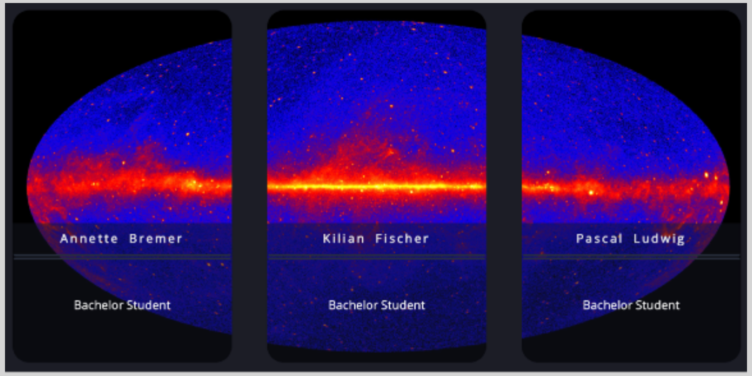
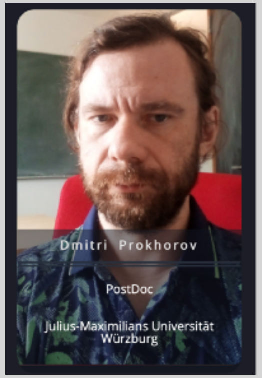








Current active members

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

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

Summary

- A subsample of candidate PeVatron blazars proposed as associated with IceCube neutrino hotspots; post-trial probability of ~2.59×10^{-7}.

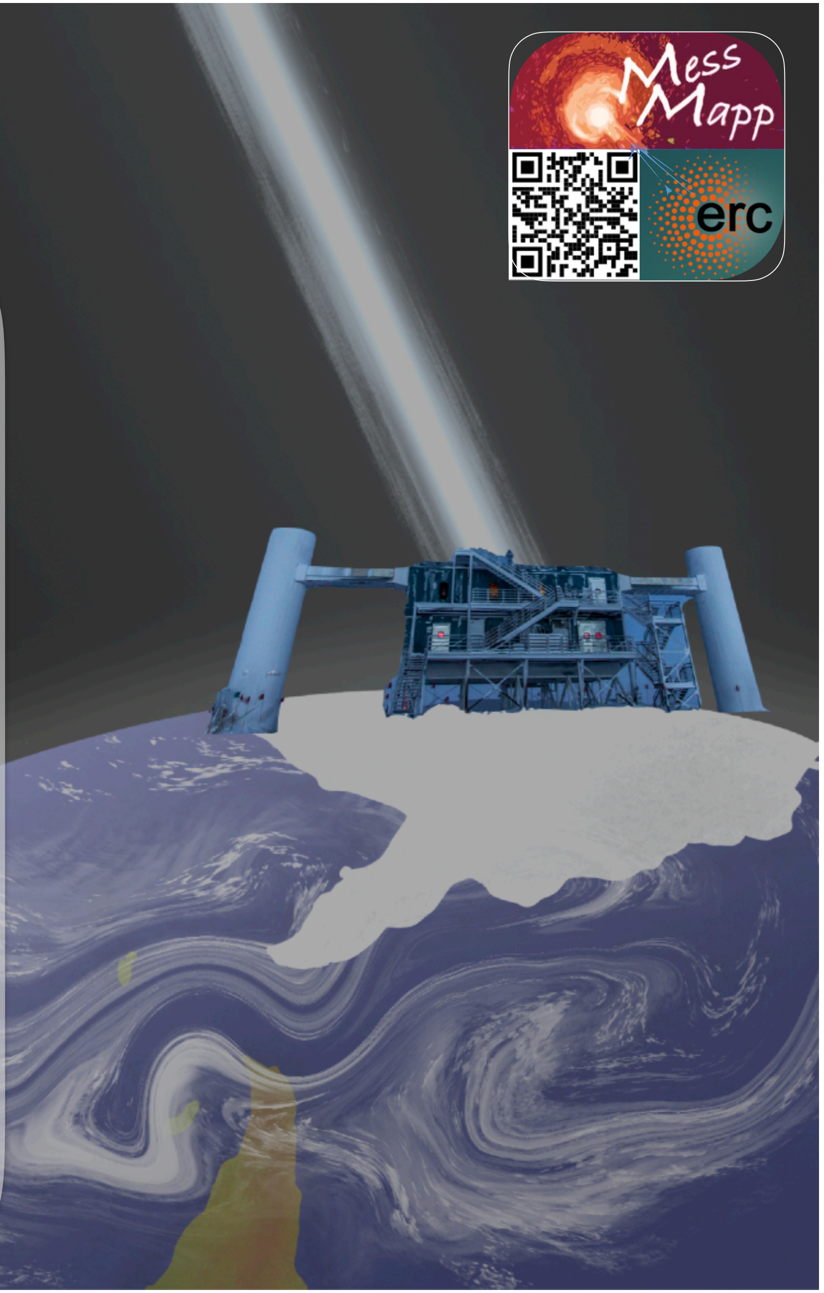
- Theoretical modelling of MWL SED confirms plausible neutrino emitter:

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

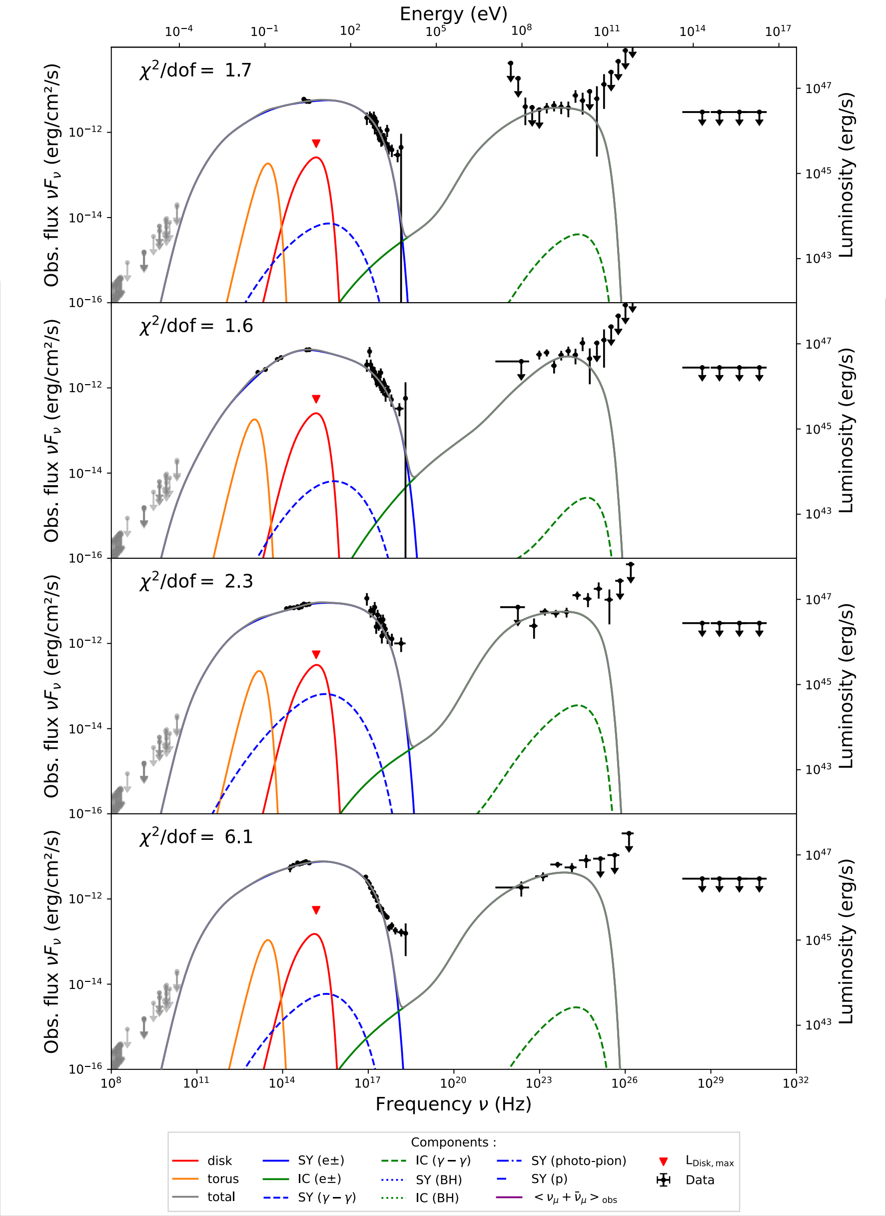
- Analysis and results fully reproducible:
  - Datasets available via e.g. Zenodo.
  - Software hosted e.g. in GitHub. First public release: AM^3.



Back up

Multi-epoch modeling

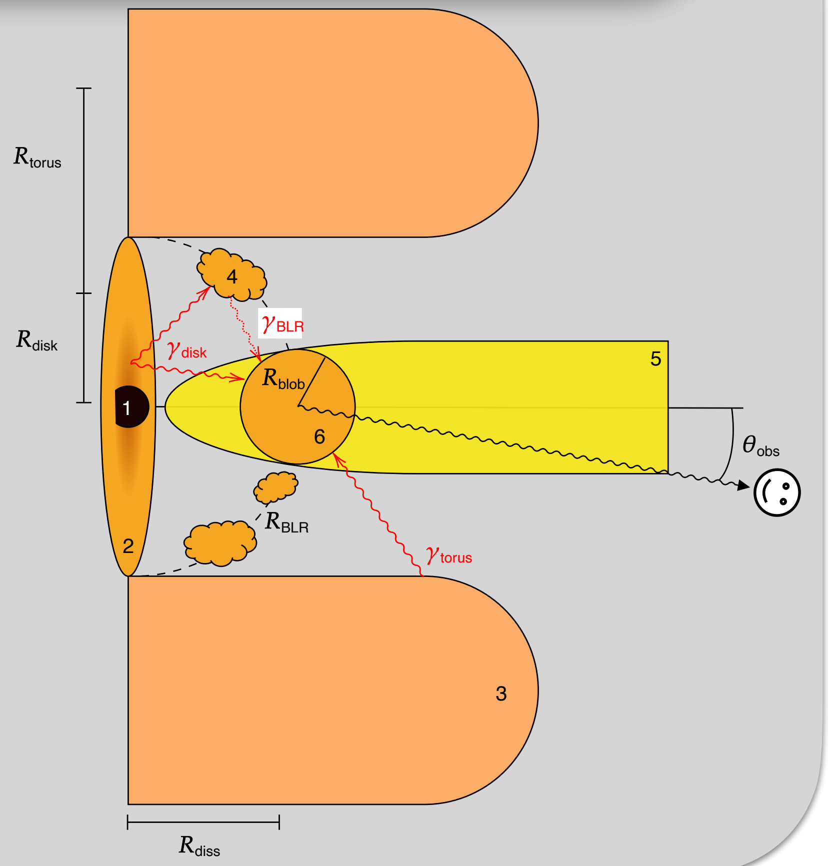
Leptonic solutions



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[3] 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 $\chi^2_{\mathrm{d.o.f}}$ between the simulated and the observed data.



Neutrino point-source Searches

Observational Approach

Blazar sample

5BZCat (Massaro+ 2015)

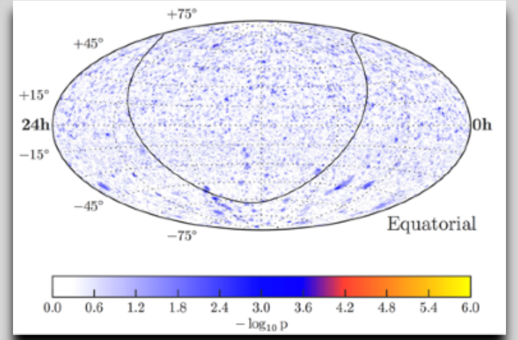
- no preferred selection

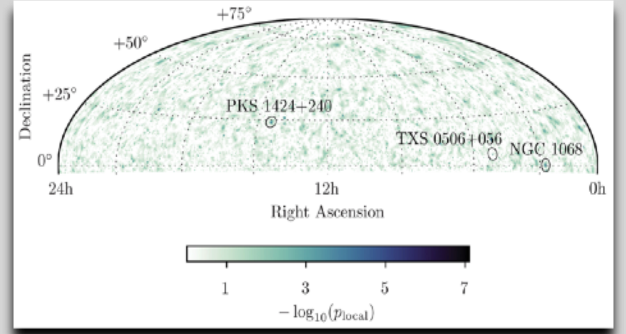
IceCube neutrino data

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

Test a few different (inclusive) neutrino samples

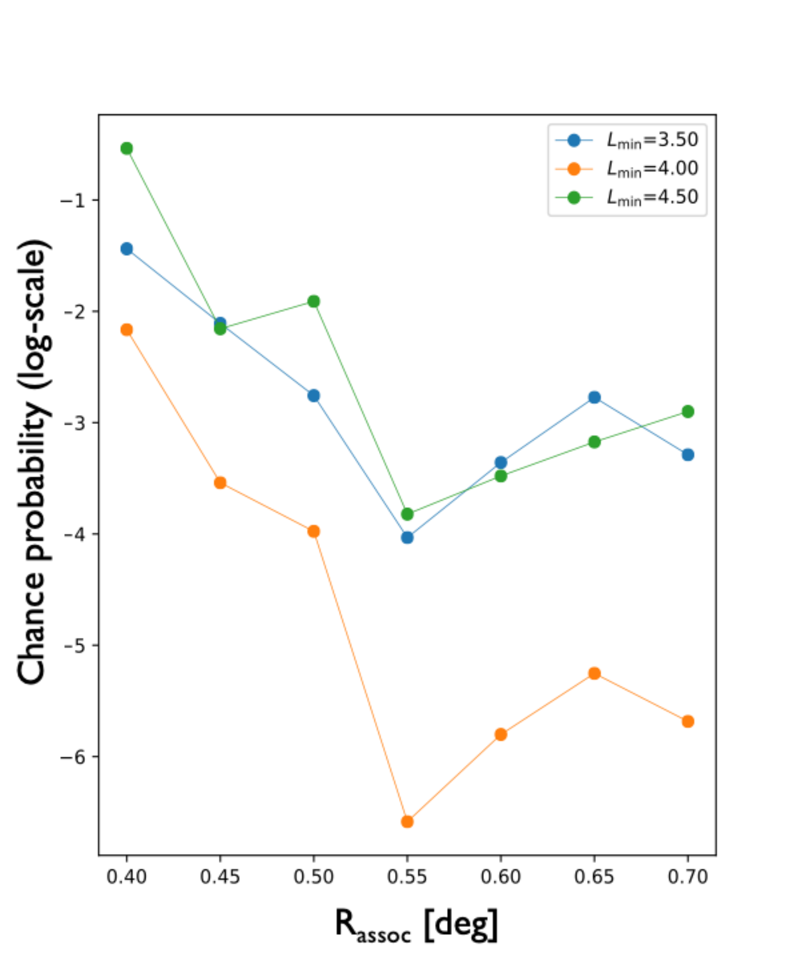
Southern hemisphere analysis

- Neutrino spot = i.e. sky-location (pixel-map)
  - 0.1° x 0.1° map resolution

- Lmin = {3.5, 4.0, 4.5}
  - 44, 19, 9 neutrino spots

- Rassoc = [0.4°, 0.7°] with steps of 0.05°
  - Driven by median angular resolution of the neutrino events

Buson+ 2022



IceCubePy an open software for neutrino data analysis

- IceCube released 10-yr (old, muon-track) dataset
- No public software available for the analyses of the data

IceCubePy

promising preliminary results

- based on simulations and cross-checks

e.g. TXS 0506+056 hotspot ———>

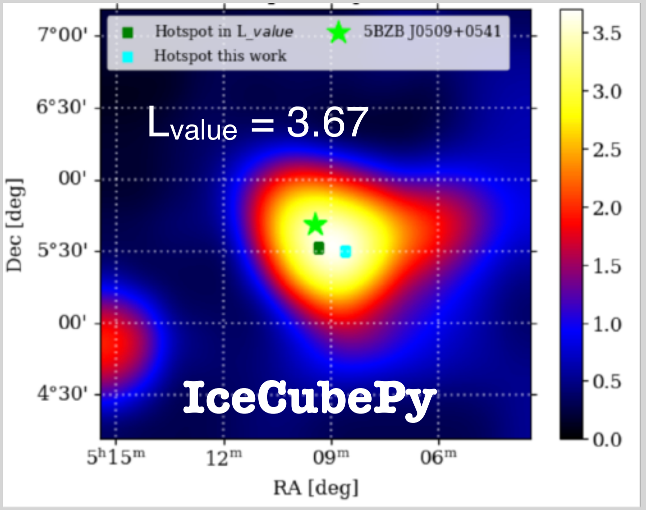
- **IceCube coll. (publication):**
  - **L_{value} = 3.7**

(planning public release in GitHub)

ICRC 2023

TXS 0506+056 region

(IceCube public dataset)



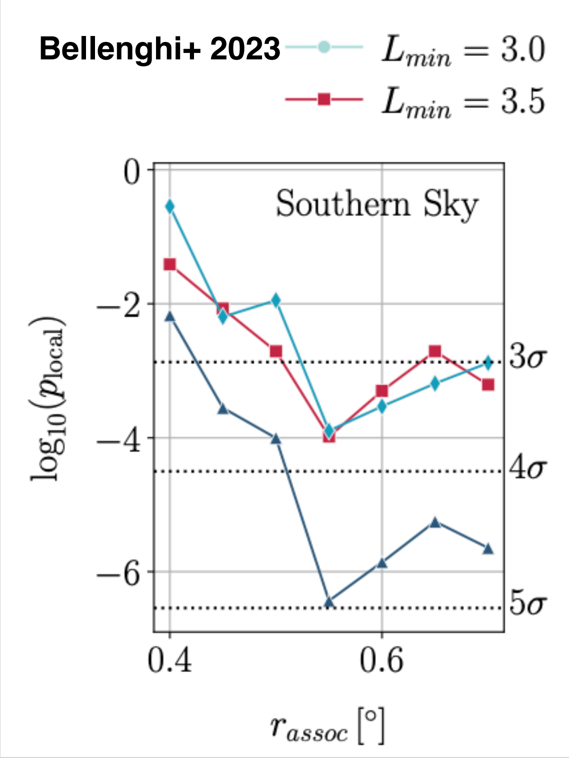
Independent confirmation

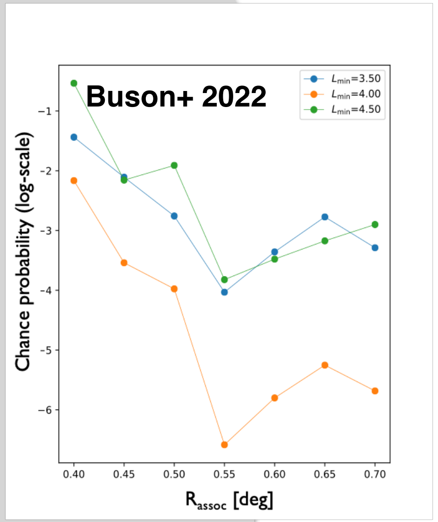
Independent works confirm the correlation reported in Buson+ 2022.

E.g. Bellenghi+ 2023, when using the "official" IceCube collaboration high-level data (i.e. skymaps), and same analysis strategy.

For the 7-yr southern skymap:

- Same hotspots (L_value > 4.0) are found
- Correlation between 5BZCat / hotspots :
  - post-trial p_value ~ 2 $\times 10^{-6}$ (~ 4.6σ)





Comparison with publicly available code/data

Discrepancy in the analysis results (southern hemisphere)

IceCube hotspots	α_{hs}[°]	δ_{hs}[°]	L	Blazar associations 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	–	–	–

Buson+ 2022

IC Hotspot	RA	Dec	SkyLLH L	IceCube L
IC J2242-0540	340.75	-5.68	3.301	4.012
IC J0359-0746	59.85	-7.78	3.574	5.565
IC J0256-2146	44.12	-21.78	3.015	4.873
IC J2037-2216	309.38	-22.27	3.125	4.664
IC J0630-2353	97.56	-23.89	3.363	4.420
IC J0359-2551	59.94	-25.86	2.530	4.356

Comparison between SkyLLH (Bellenghi+ 2023) and IceCube coll. publication (7-yr skymap)