Mapping highly-energetic Messengers throughout the Universe

Hadronic processes at work in 5BZB J0630-2406

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On behalf of the MessMapp group, Sara Buson, Leonard Pfeiffer, Stefano Marchesi, Alessandra Azzollini, Vardan Baghmanyan, Andrea Tramacere, Eleonora Barbano and Lenz Oswald.

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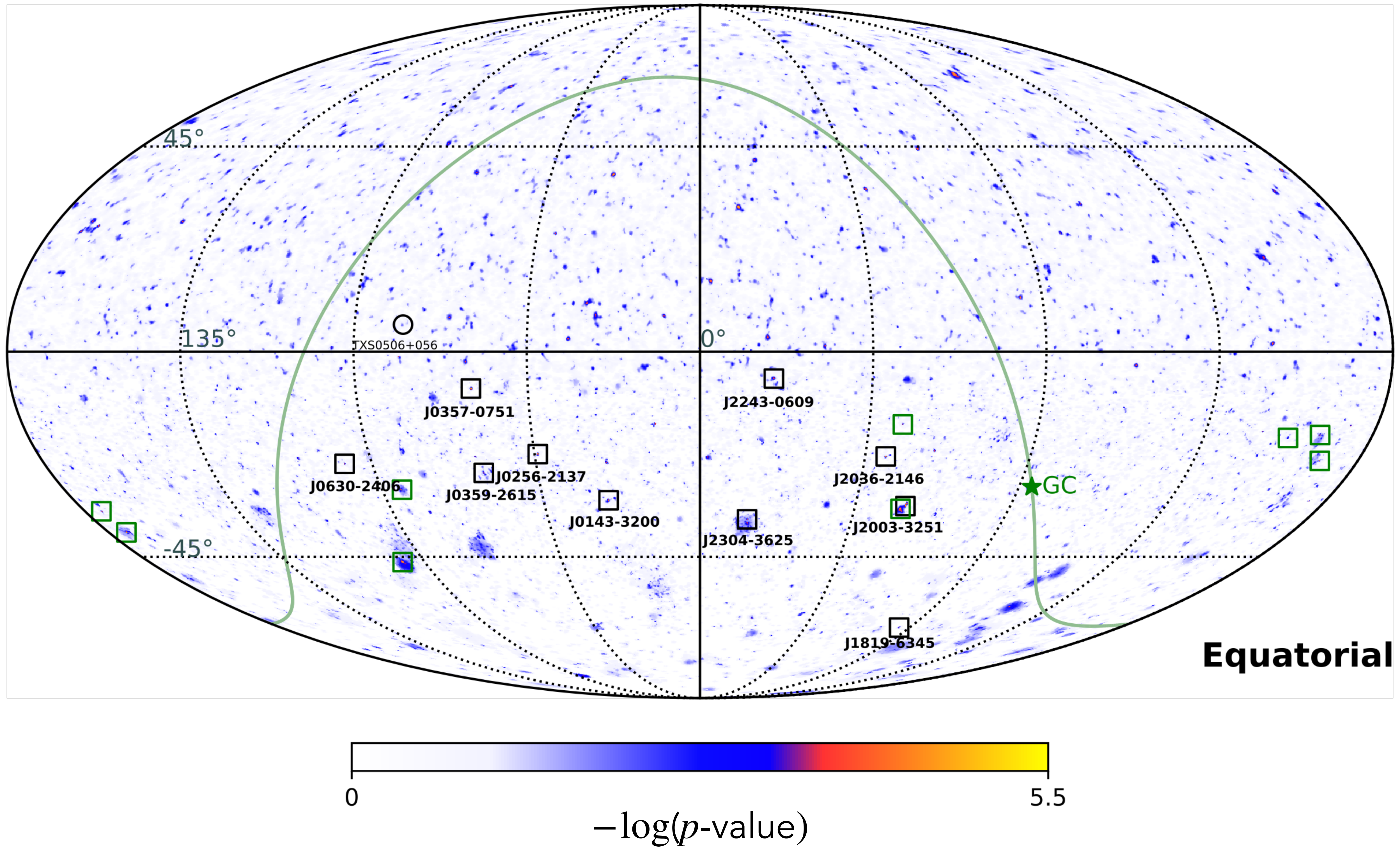
The blazar - neutrino association

Radiatively efficient blazar with powerful jets : fosters the production of neutrinos [Dermer et al. 2014].

- Significant correlation (p-value $= 2 \times 10^{-6}$) between blazars spatial positions and IceCube neutrinos p-value hotspots [Buson et al. 2022].
- 10 blazars suggested as potential sources of neutrinos, referred as PeVatron blazars.
- Plausible association with 5BZB J0630-2406 and p-value hotspot.



In the IceCube sky map, the positions of the 5BZCat blazars associated with neutrino spots, i.e. the ***PeVatron blazars***, are pinpointed as black squares.

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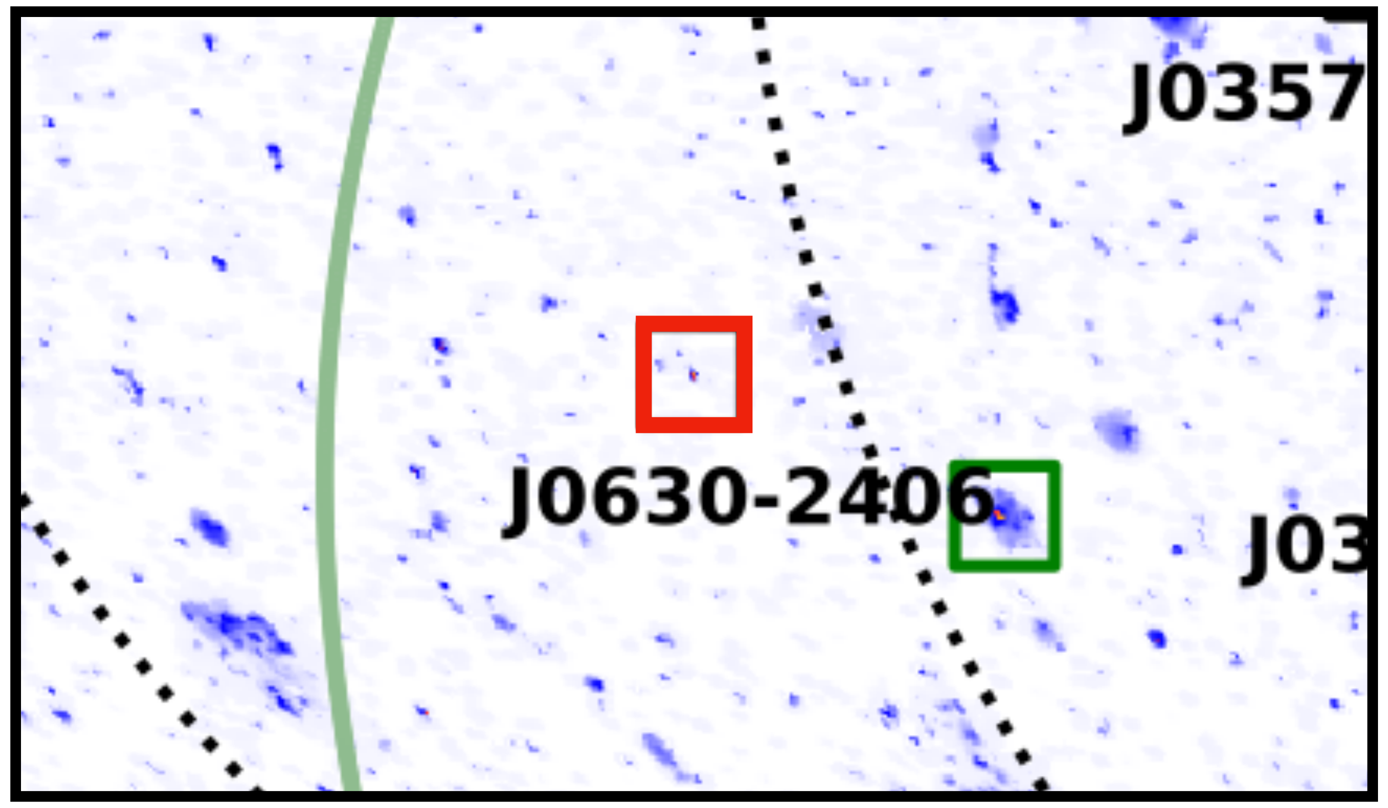

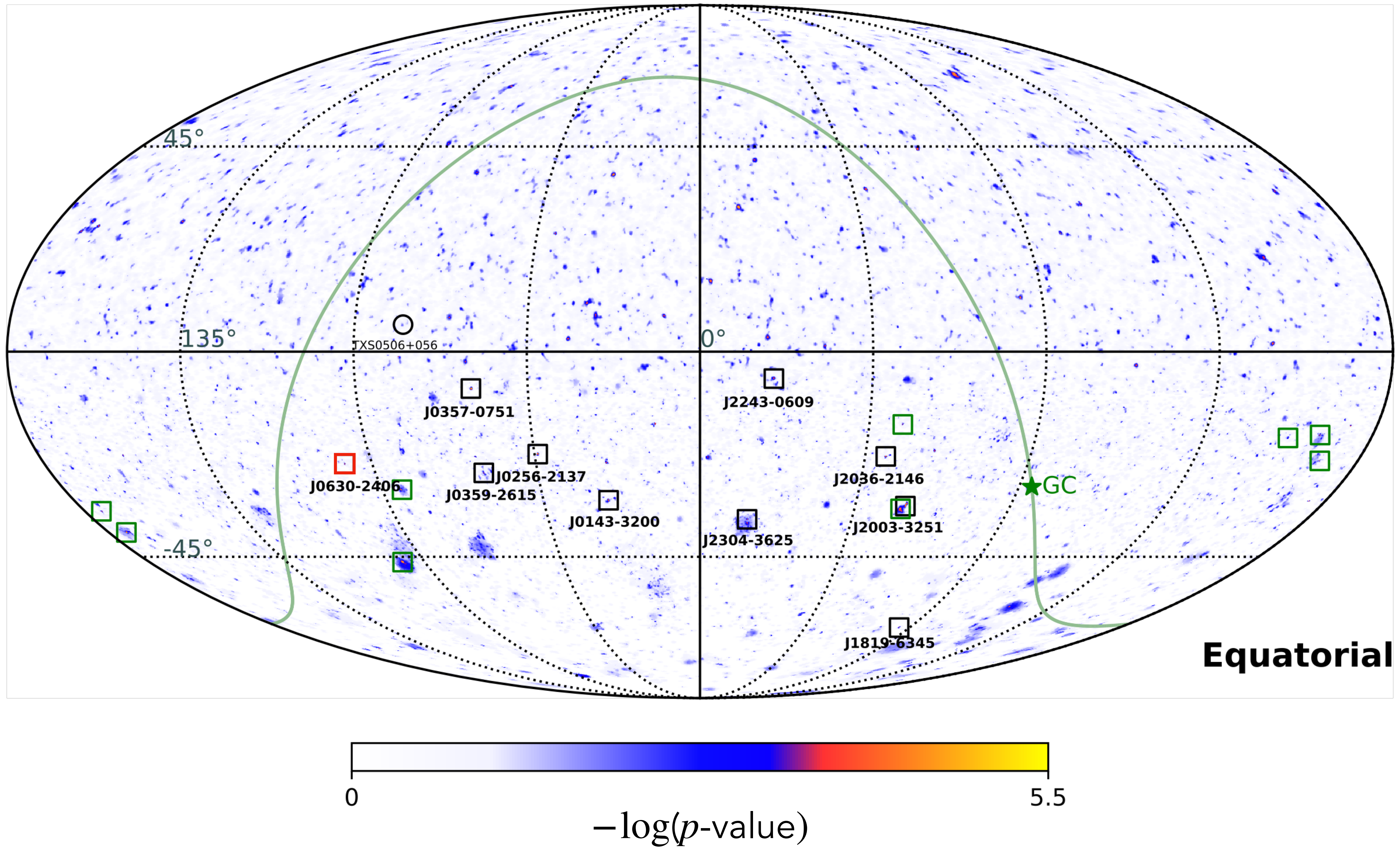

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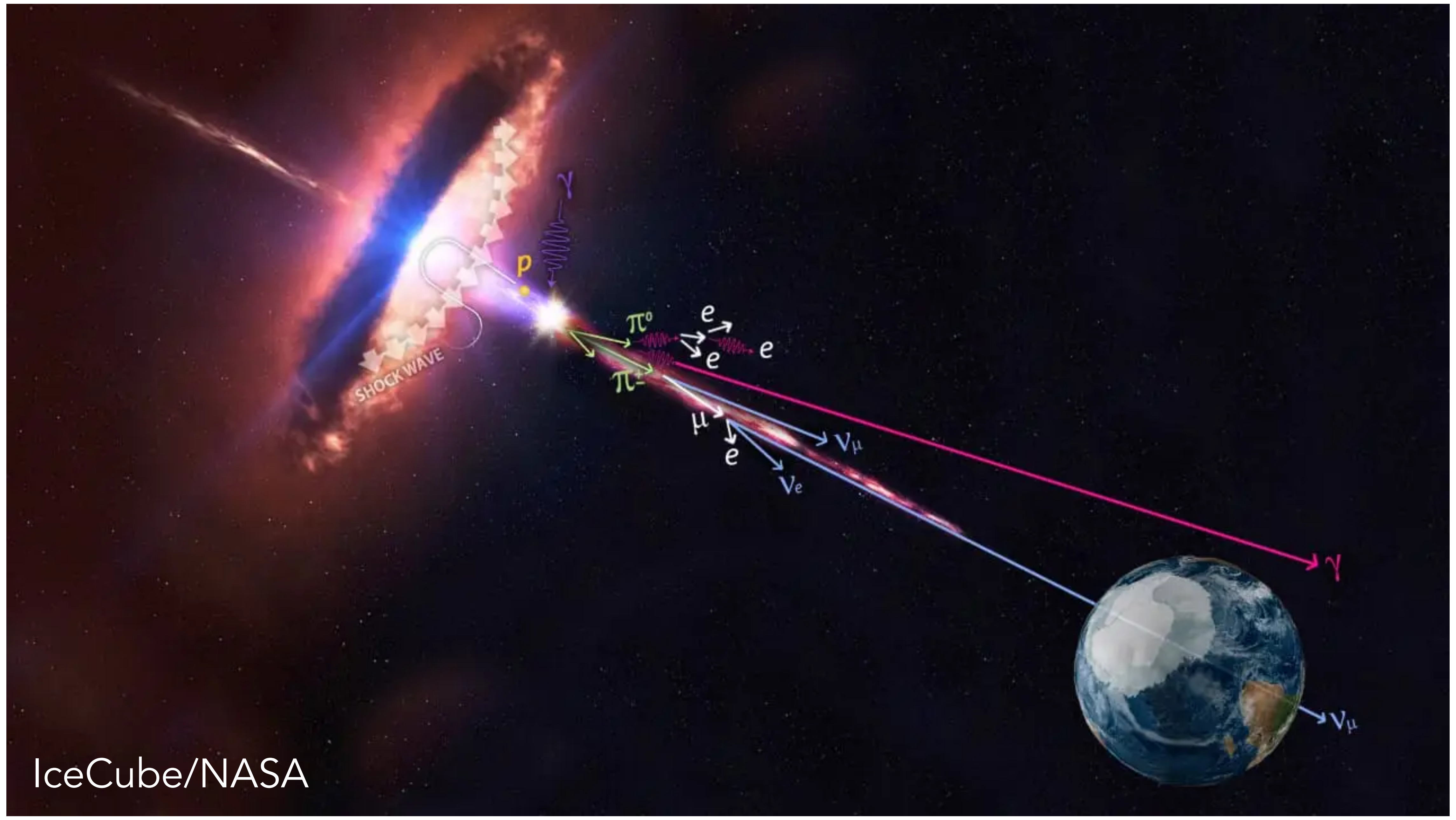
Our target : 5BZB J0630-2406

- Source redshift $z \geq 1.23$.
- Proposed as a BL Lac object : lack of emission lines, high synchrotron peak.
- Hints of a luminous accretion disk [Ghisellini et al. 2012] with broad emission lines swapped by the jet synchrotron (similar to "masquerading BL Lacs").

- Quasi-simultaneous data taken in October 17. 2014 (MJD : 56948) ⇒ good MWL coverage.
  - Optical : GROND and KAIT.
  - X-ray : XMM-Newton and NuSTAR ⇒ evidence of a broken spectral shape ($\geq 3\sigma$)
  - γ-ray : Fermi-LAT data from [Ackermann et al. 2016].



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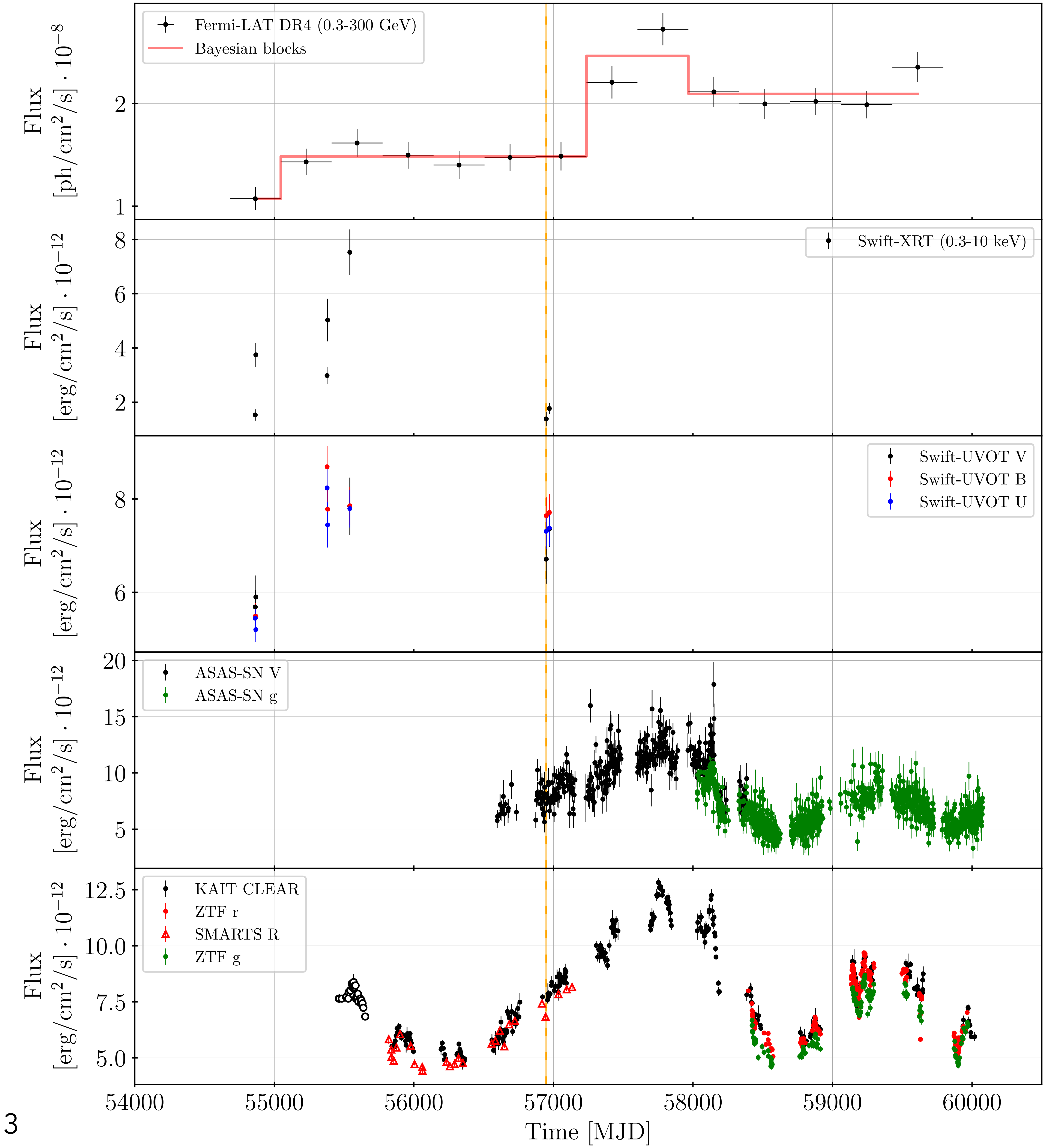


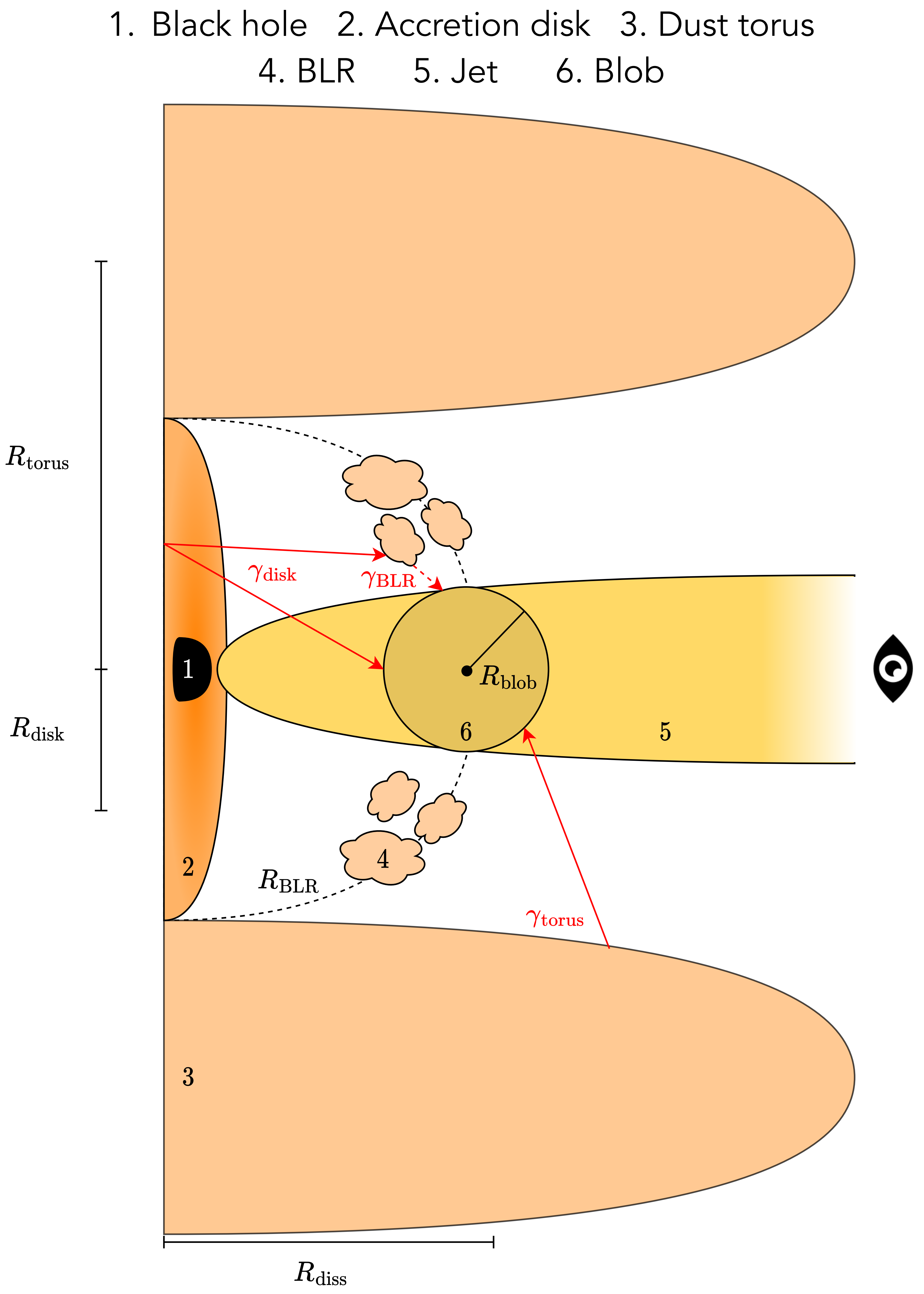
The blob-in-jet model

- Simulation of the acceleration and the cooling of electrons and / or protons inside of a spherical region (blob) with the AM³ code [Gao et al. 2017].

- Spherical region moving at relativistic speed inside the jet surrounded by an accretion disk and a dust torus emitted as black bodies.

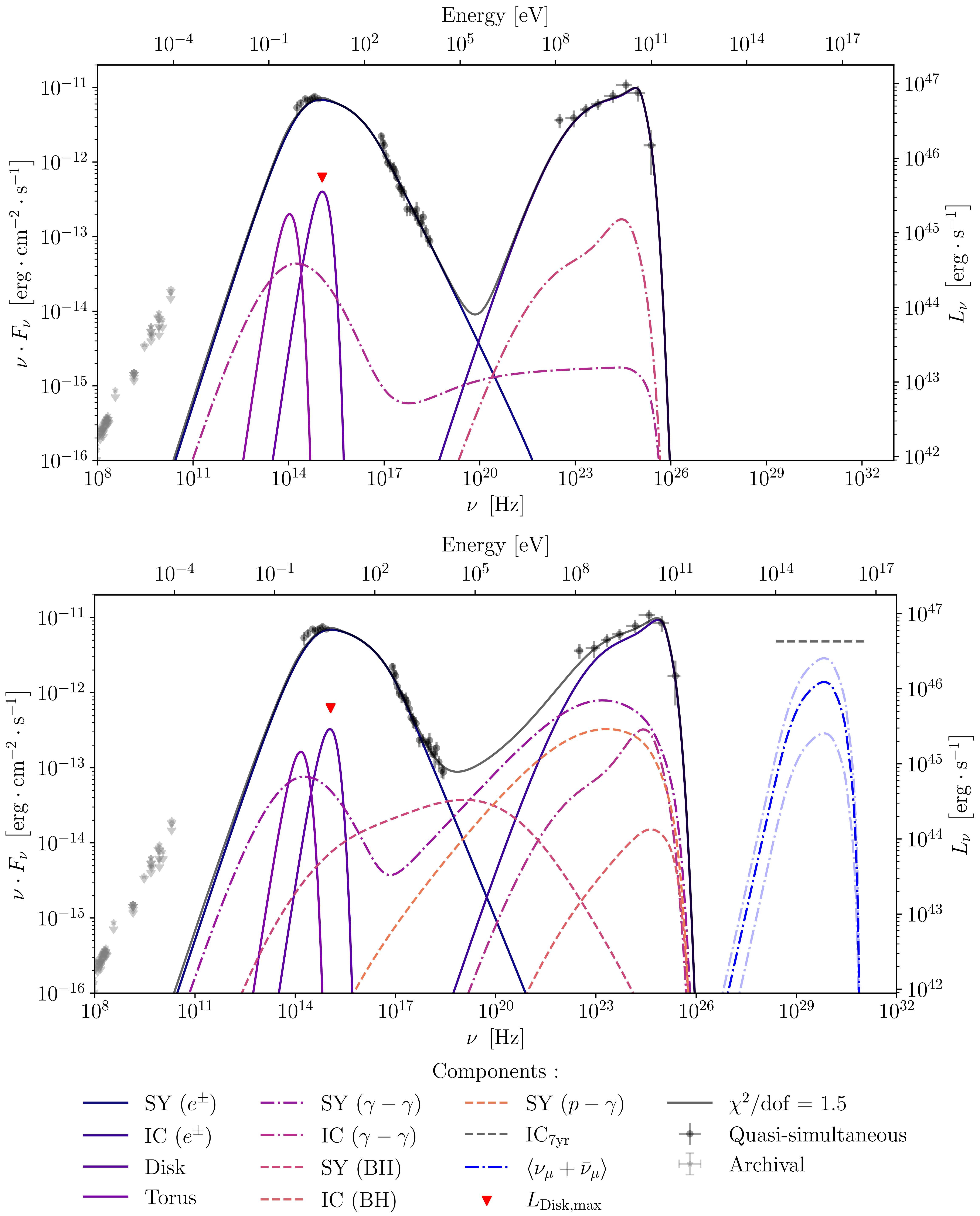
- Emission from the accretion disk is reprocessed by the BLR.

- Parameters are fitted to reproduce the SED by minimising the $\chi^2_{\mathrm{d.o.f}}$ between the simulated and the observed data.



SED : leptonic and lepto-hadronic models

- Solutions display luminous accretion disk $L_{\text{disk}} \simeq 5 \times 10^{45}\ \text{erg} \cdot \text{s}^{-1}$ (below the upper-limit) with intermediate accretion regime $\eta \sim 2 \times 10^{-4}$.
- Both models can explain the SED - only the hadronic model can explain the broken spectral shape in the X-ray SED.



What can we learn from this?

5BZB J0630-2406 as a high-power FSRQ

✓ High synchrotron peak with $\nu_{\rm pk}^{\rm sy} \sim 10^{15}$ Hz.

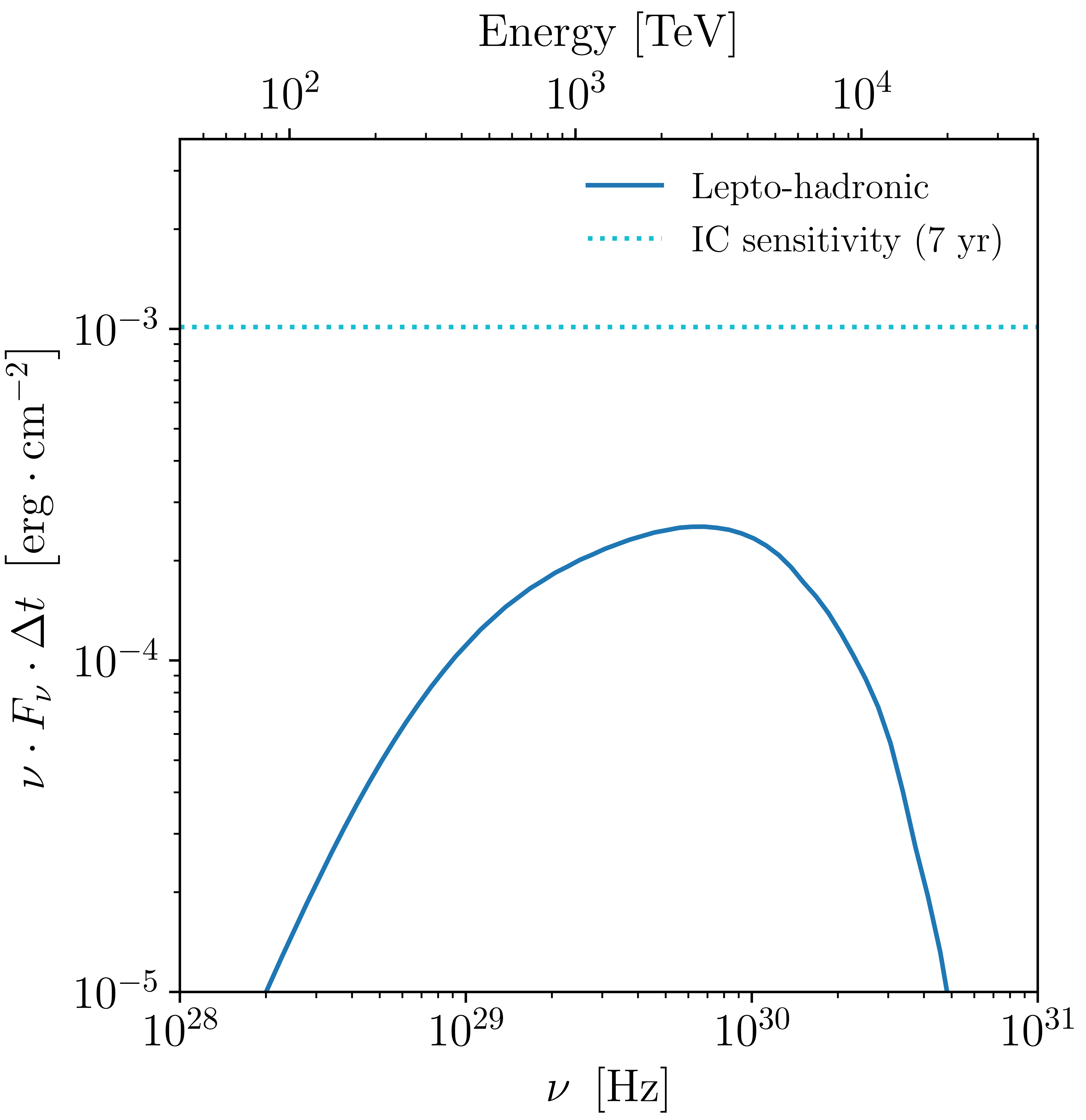
✓ Hosting a luminous accretion disk with relatively high accretion rate $\eta \sim 2 \times 10^{-4}$ ⇒ In between BL Lac / FSRQ [Sbarrato et al. 2012].

✓ Efficient γ-ray production from external Compton due to the BLR $L_\gamma / L_{\rm Edd} \sim 0.15$ ⇒ FSRQ [Sbarrato et al. 2012].

✓ Dissipation radius is on the outer edge of the BLR ⇒ limited $\gamma - \gamma$ absorption and efficient neutrino production.

Expected neutrino production

- Convolution with the detector response matrix over time (various strings configurations) [Aartsen et al. 2017].
- Over a livetime period of 7 years, we expect $N_{\text{events}} = 4.82^{+5.18}_{-3.82}$ muon neutrinos.
- Testing the non-detection hypothesis, a p-value of 3% is derived.



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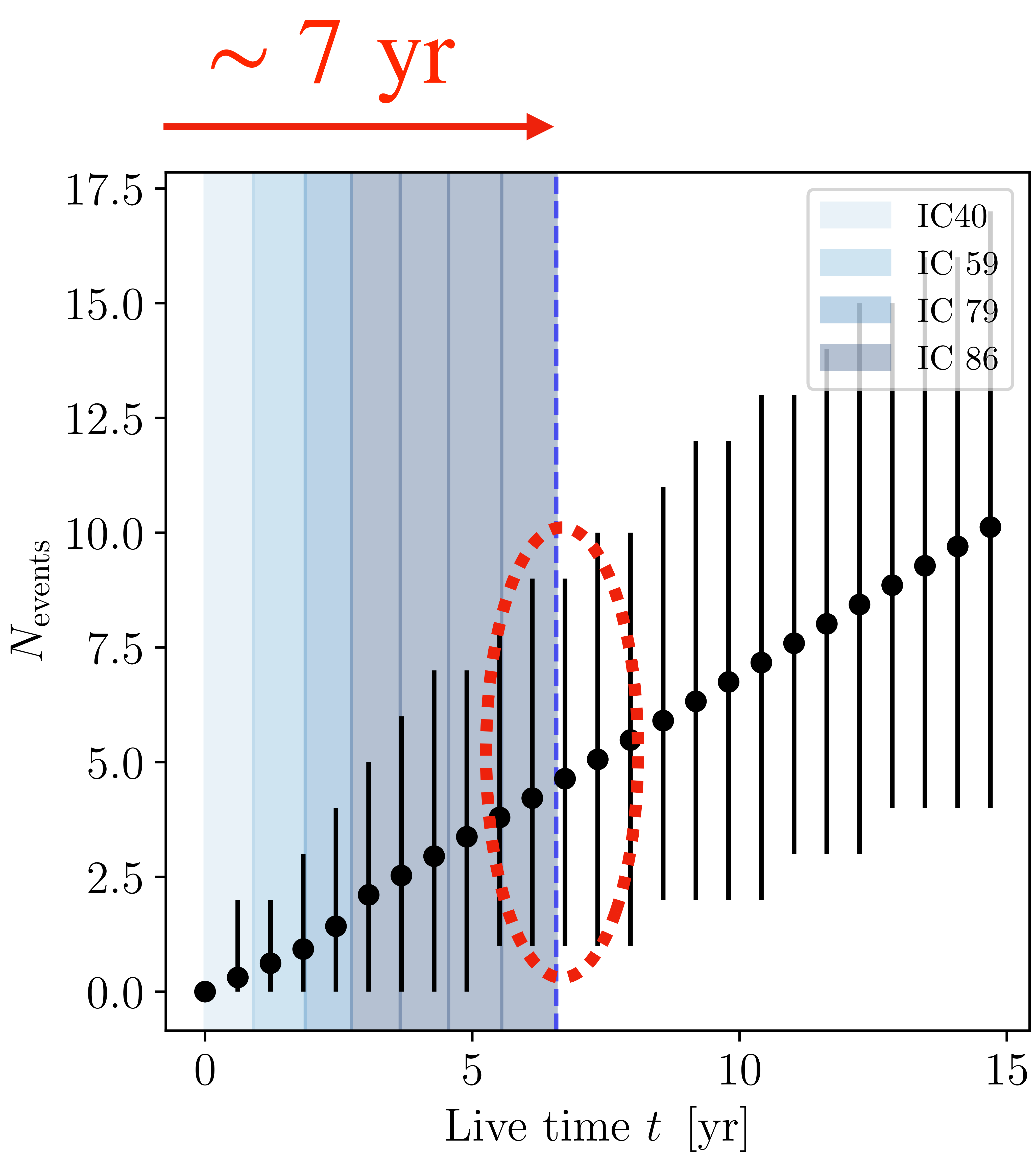

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5BZB J0630-2406 as a neutrino emitter

✓ Hints of an intrinsic X-ray break in the SED, reproducible only with the lepto-hadronic scenario ⇒ see *Xavier Rodrigues* talk.

✓ Predicted muon neutrino flux close to the IceCube flux sensitivity [Aartsen et al. 2017].

✓ $N_{\rm events} = 4.82^{+5.18}_{-3.82}$ with a p-value of 3% over a livetime of 7 yr suggests a mild conflict with the non-detection hypothesis.

✓ Neutrino hotspot observed in the IceCube 7yr data consistent with the blazar.

Building a larger picture

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High power, Radiatively Efficient Blazar

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PeVatron Blazar Sample

5BZB J0630-2406

TXS 0506+056, PKS 1424+240,

5BZB J0035+1515, …

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Origin of Unique Characteristics

"Changing-look blazars" [Peña-Herazo et al. 2011] or shifts in dissipation region [Ghisellini et al. 2013].

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Ongoing Research

Fichet DC et al. (in prep) & Azzollini et al. (in prep) studying PeVatron blazar sample.

Public release of AM³

- C++ code with efficient hybrid solver combining analytical and numerical approaches.
- Source code with tutorials on various astrophysical objects,
  - AGN.
  - Gamma-ray bursts.
  - Tidal disruption events.
- Join with turn-key installations (Docker) on Linux and Mac OS systems.
- **Soon to be published - stay tuned!**

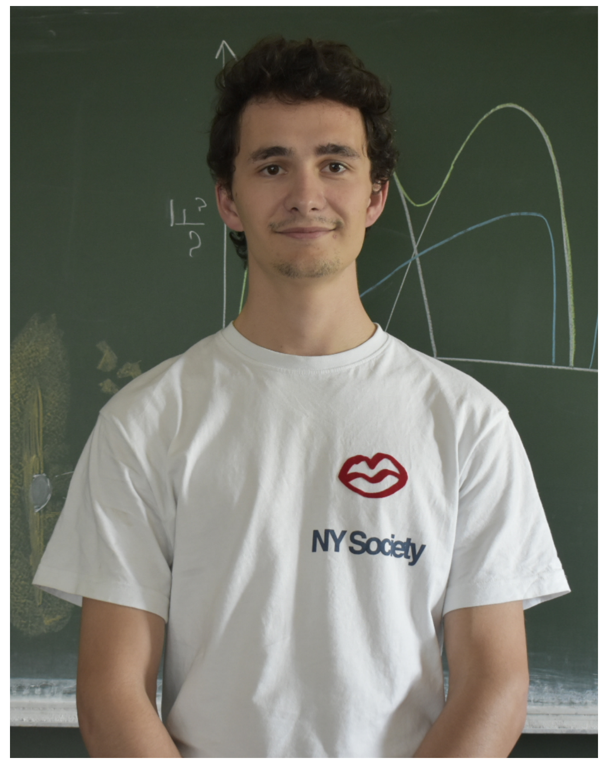
AM³ : An open-source tool for time-dependent lepto-hadronic modelling of astrophysical sources

Xavier Rodrigues - ESO

Annika Rudolph - Niels Bohr Institute

Marc Klinger - DESY

Chengchao Yuan - DESY



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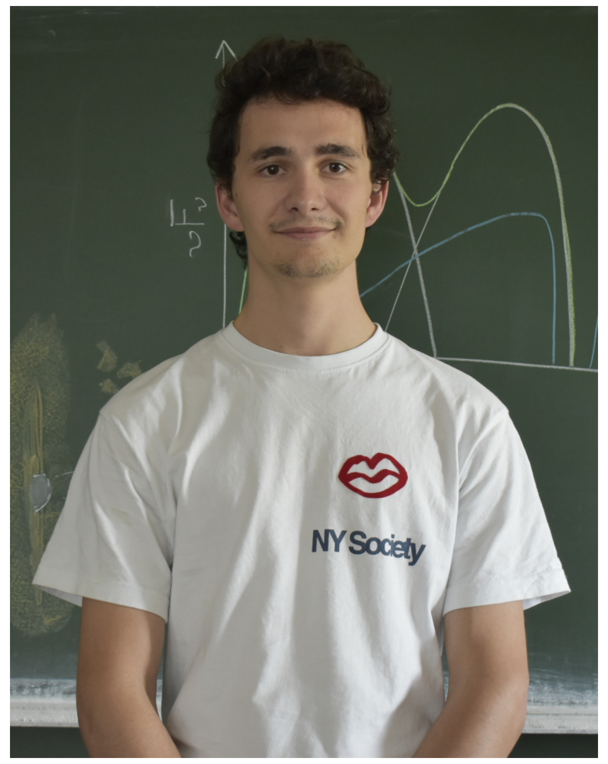

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Thank you for your attention!
Questions?

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Bibliography

Buson et al. 2022, ApJL, 933, L43.

Buson et al. 2022, ApJL, 934, L38.

Ghisellini et al. 2011, MNRAS, 414, 2674.

Ghisellini et al. 2012, MNRAS, 425, 1371.

Padovani et al. 2012, MNRAS, 422, L48.

Padovani et al. 2019, MNRAS, 484, L104.

Ackermann et al. 2016, ApJ, 820, 72.

Gao et al. 2017, ApJ, 843, 109.

Aartsen et al. 2017, ApJ, 835, 151.

Peña-Herazo et al. 2011, AJ, 161, 196.

Ghisellini et al. 2013, MNRAS, 432, L66.

The blazar - neutrino association

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}

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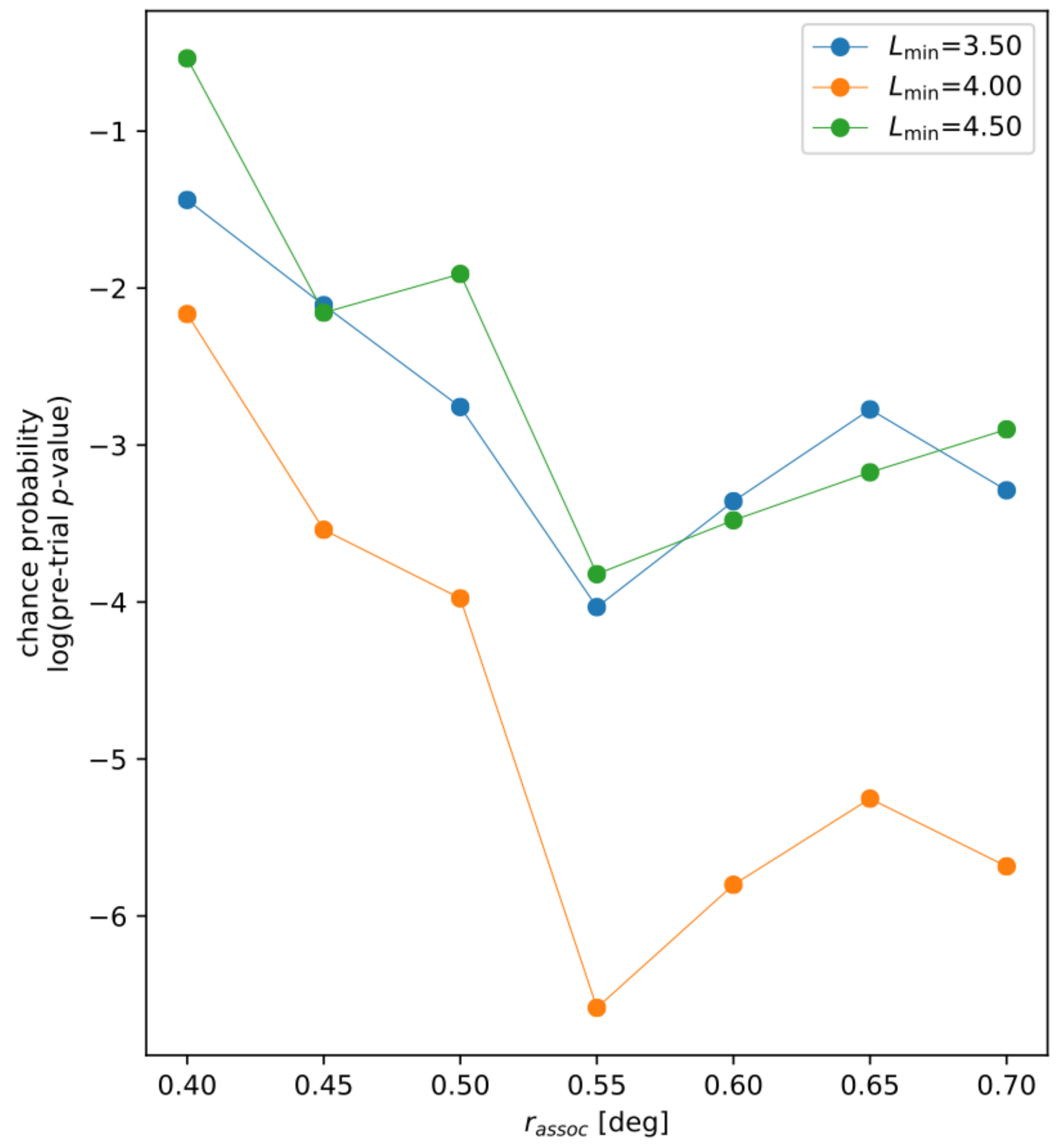

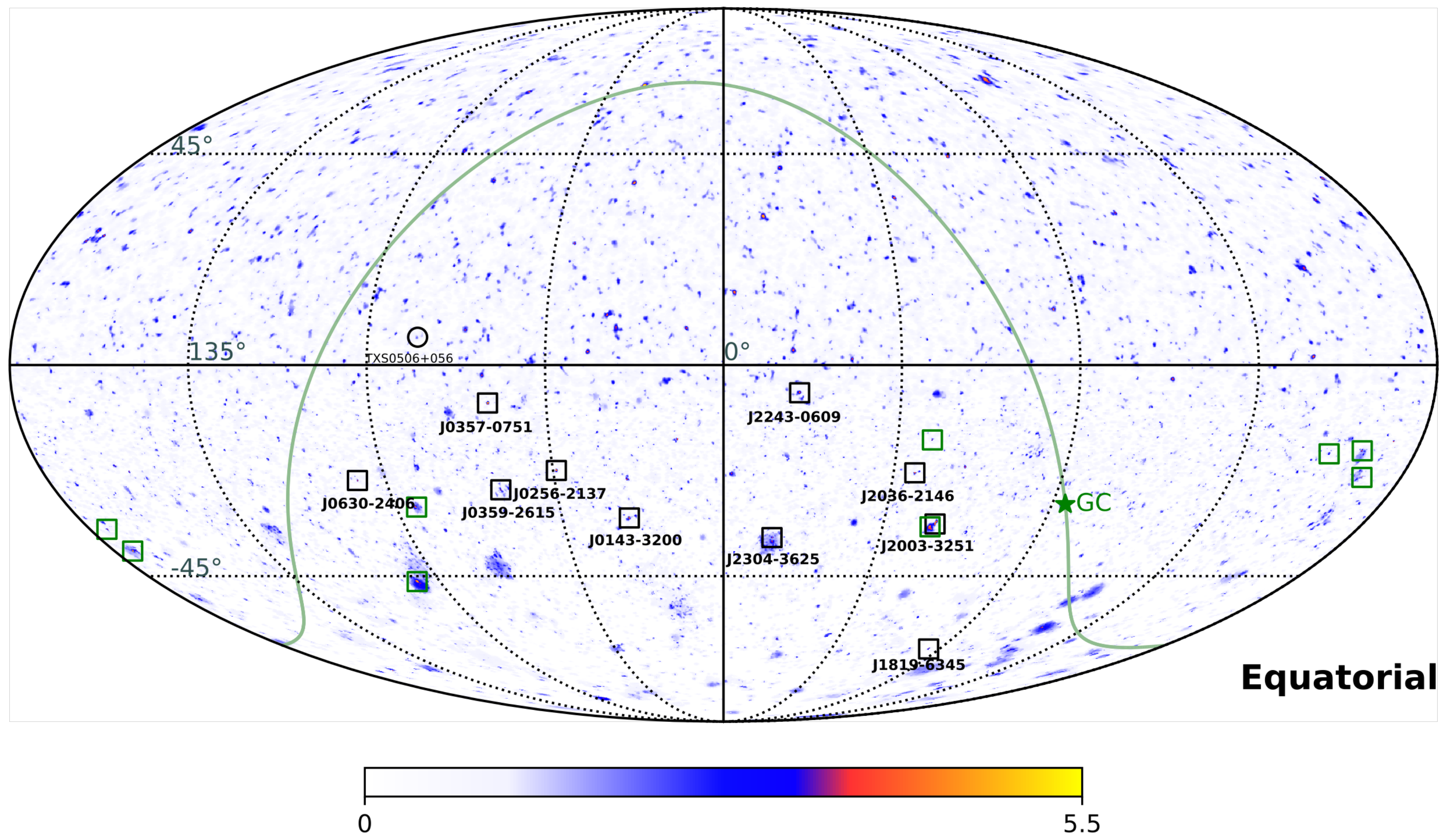

Parameters table

	L	LH
δ_D	22.7	22.5
R'_b [cm]	1.1×10^{17}	9.8×10^{16}
τ_{var} [days]	3.7	3.3
B' [G]	6.4×10^{-2}	8.3×10^{-2}
u'_b $\left[\mathrm{erg \cdot cm^{-3}}\right]$	2.7×10^{-4}	3.1×10^{-4}
$\gamma_{e,min}$	10^4	10^4
$\gamma_{e,brk}$	1.1×10^5	1.3×10^5
$\gamma_{e,max}$	9.6×10^7	1.0×10^8
$p_{e,1}$	2.71	2.73
$p_{e,2}$	3.84	4.26
u'_e $\left[\mathrm{erg \cdot cm^{-3}}\right]$	6.4×10^{-4}	6.3×10^{-4}
u'_e/u'_b	3.9	2.3
L'_e $\left[\mathrm{erg \cdot s^{-1}}\right]$	1.2×10^{42}	1.0×10^{42}
$\gamma_{p,min}$	–	90
$\gamma_{p,max}$	–	1.0×10^7
p_p	–	2.0
u'_p $\left[\mathrm{erg \cdot cm^{-3}}\right]$	–	1.5
u'_p/u'_b	–	5.3×10^3
L'_p $\left[\mathrm{erg \cdot s^{-1}}\right]$	–	1.0×10^{45}
L_{disk} $\left[\mathrm{erg \cdot s^{-1}}\right]$	4.8×10^{45}	3.9×10^{45}
T_{disk} [K]	1.4×10^4	1.3×10^4
T_{torus} [K]	1.3×10^3	1.3×10^3
R_{diss}/R_{BLR}	1.7	1.6
N_{events} per year	–	$0.68^{+2.32}_{-0.68}$
N_{events} (total)	–	$4.82^{+5.18}_{-3.82}$
χ^2/d.o.f.	1.5	1.5

1. Black hole 2. Accretion disk 3. Dust torus
4. BLR 5. Jet 6. Blob