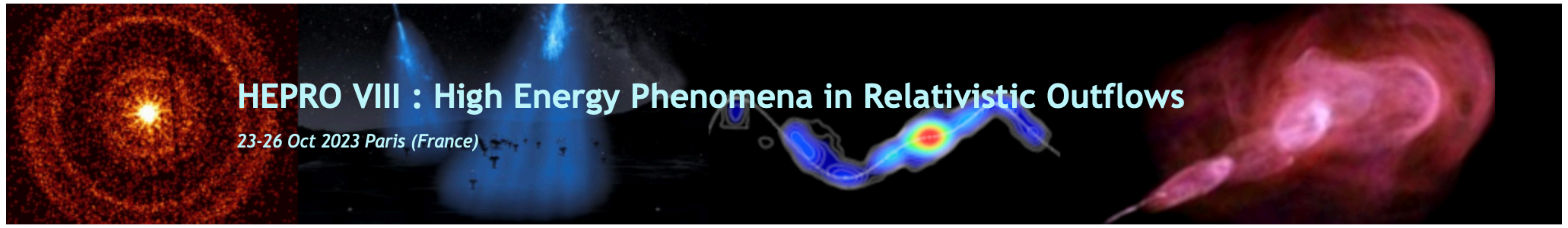

Hadronic processes at work in 5BZB J0630-2406

Gaëtan Fichet de Clairfontaine*, Julius-Maximilians-Universität Würzburg, Fakultät für Physik und Astronomie, Emil-Fischer-Str. 31, D-97074 Würzburg, Germany.

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

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].
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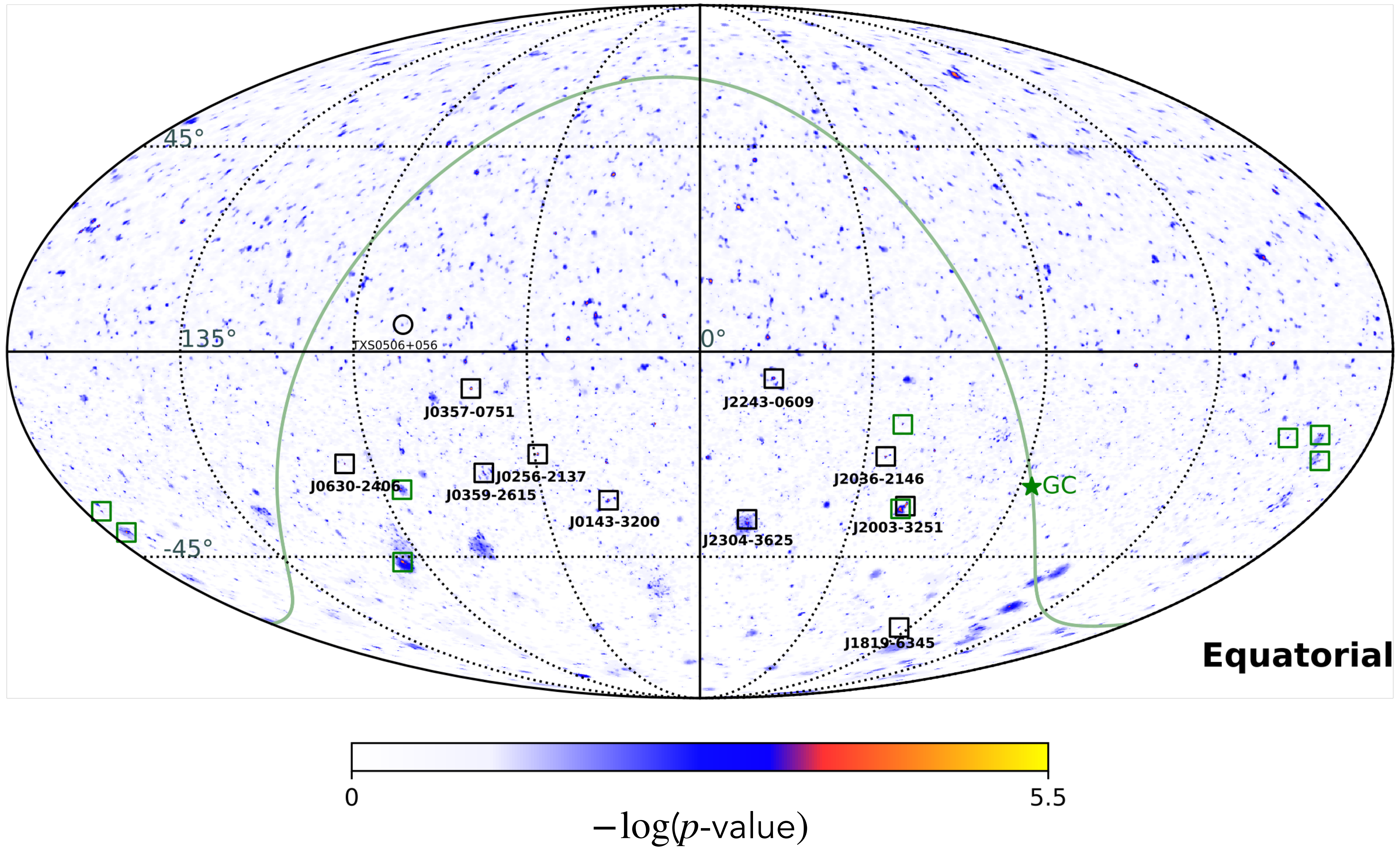

In the IceCube sky map, the positions of the 5BZCat blazars associated with neutrino spots, i.e. the ***PeVatron blazars***, are pinpointed as black squares.

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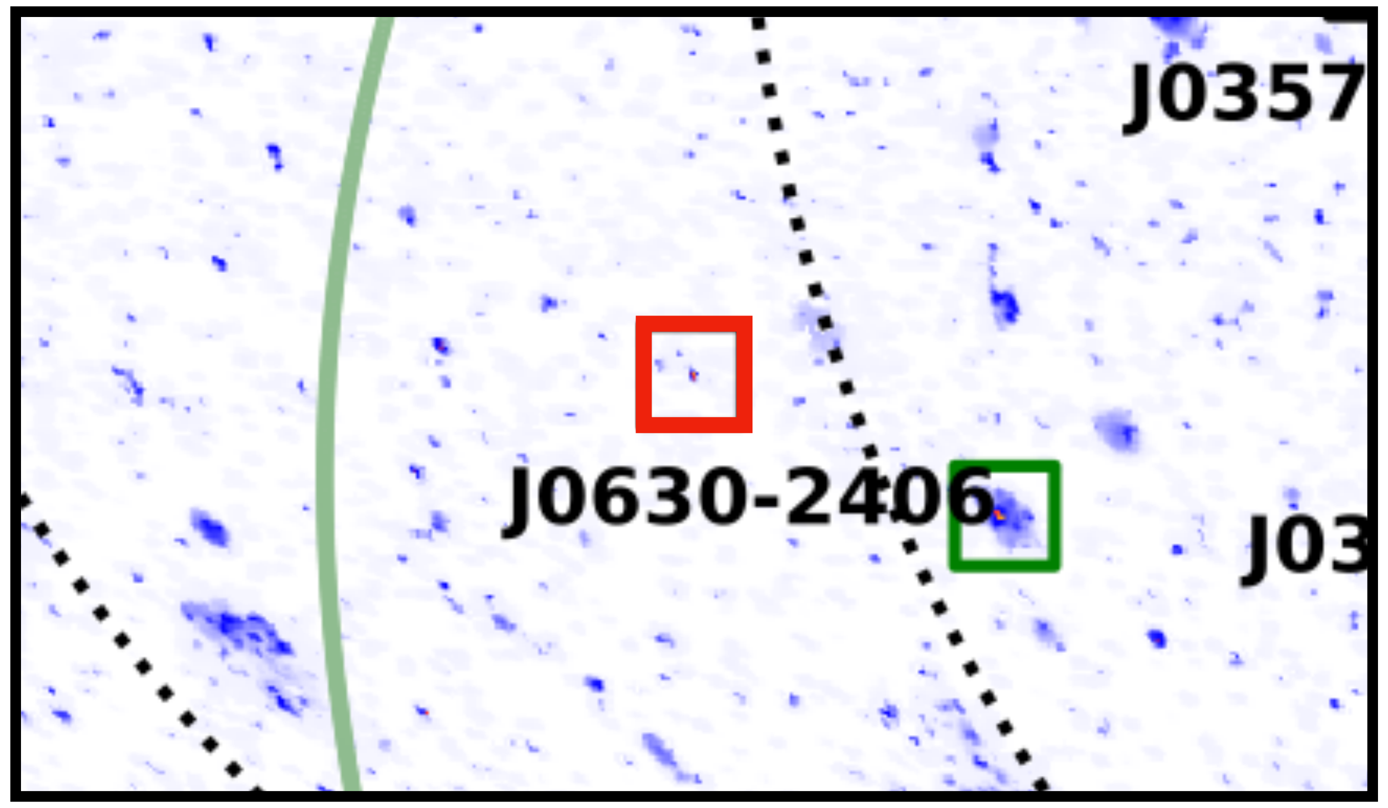

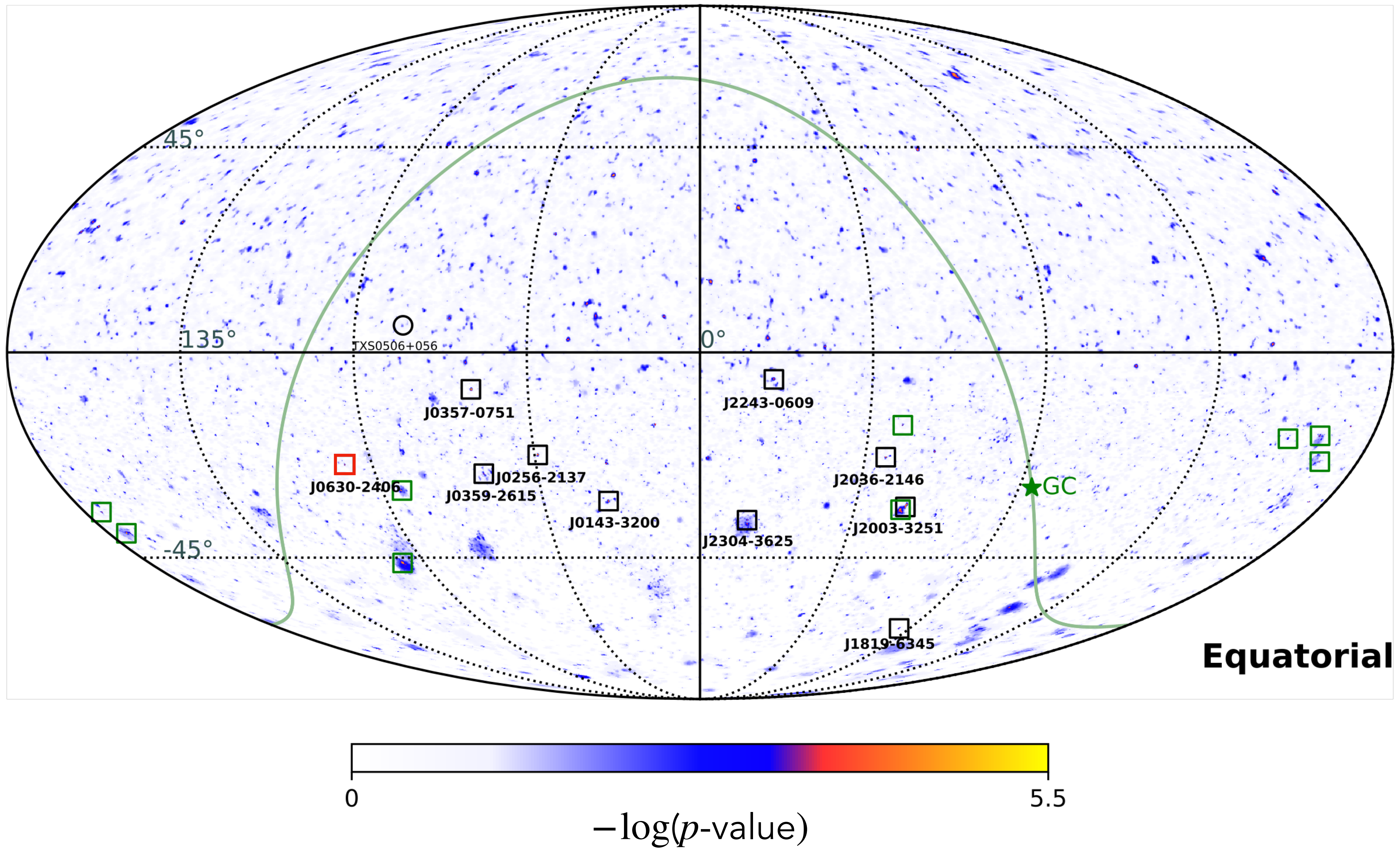

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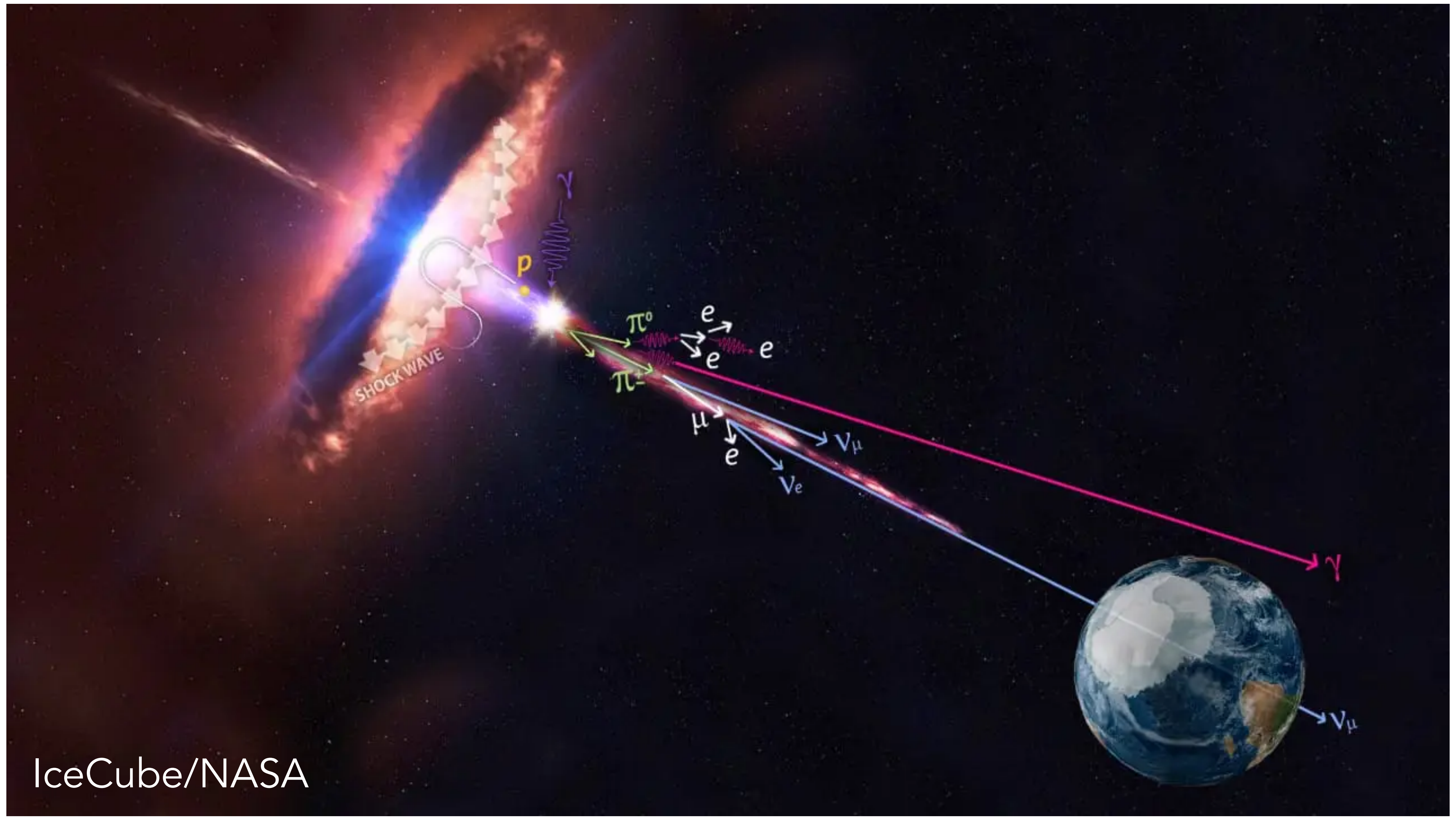
Our target : 5BZB J0630-2406

- 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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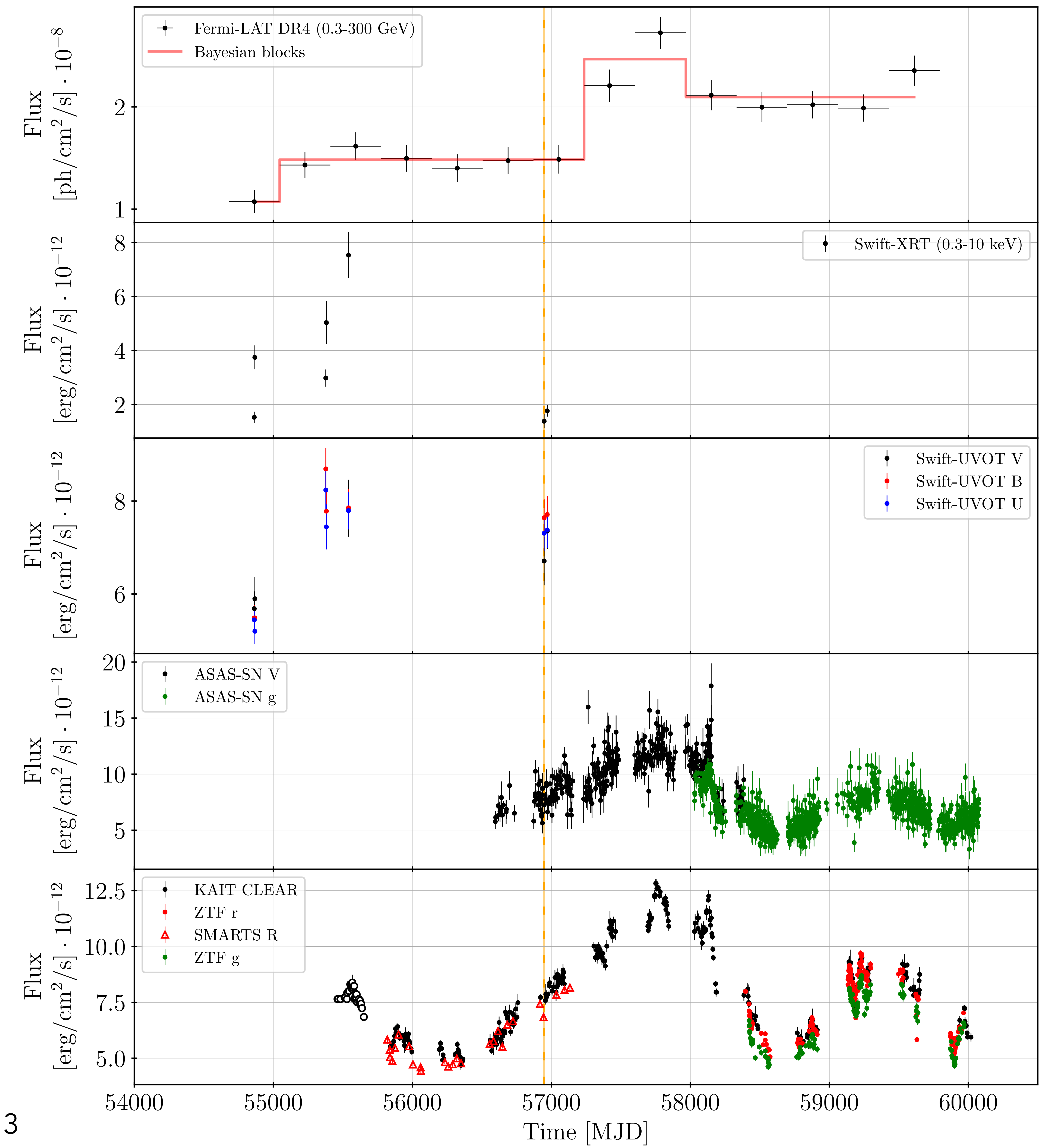

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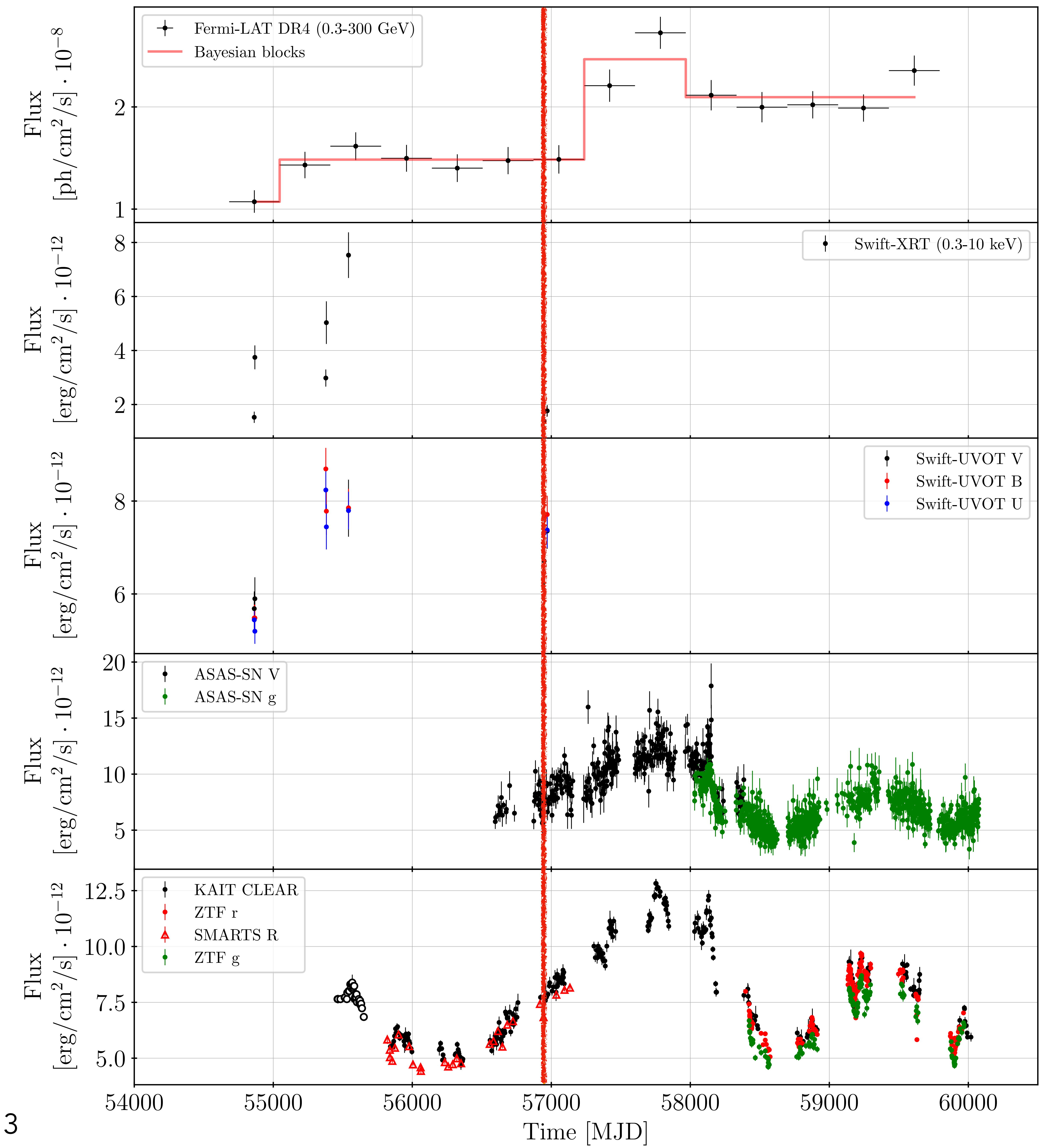


The blob-in-jet model

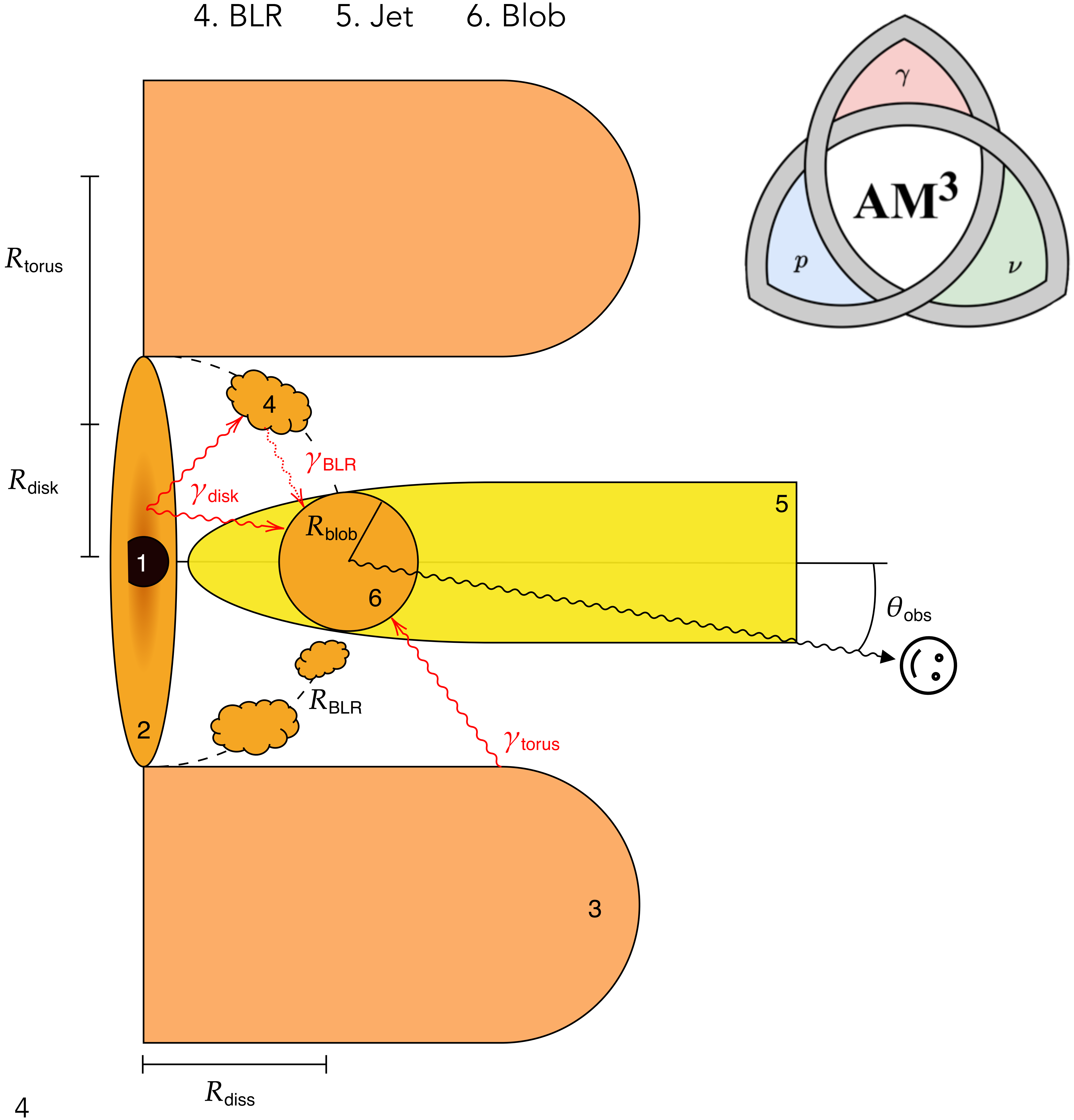
- Simulation of the acceleration and the cooling of electrons and / or protons inside of a spherical region (blob) with the AM³ code [Gao et al. 2017].

- 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.

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



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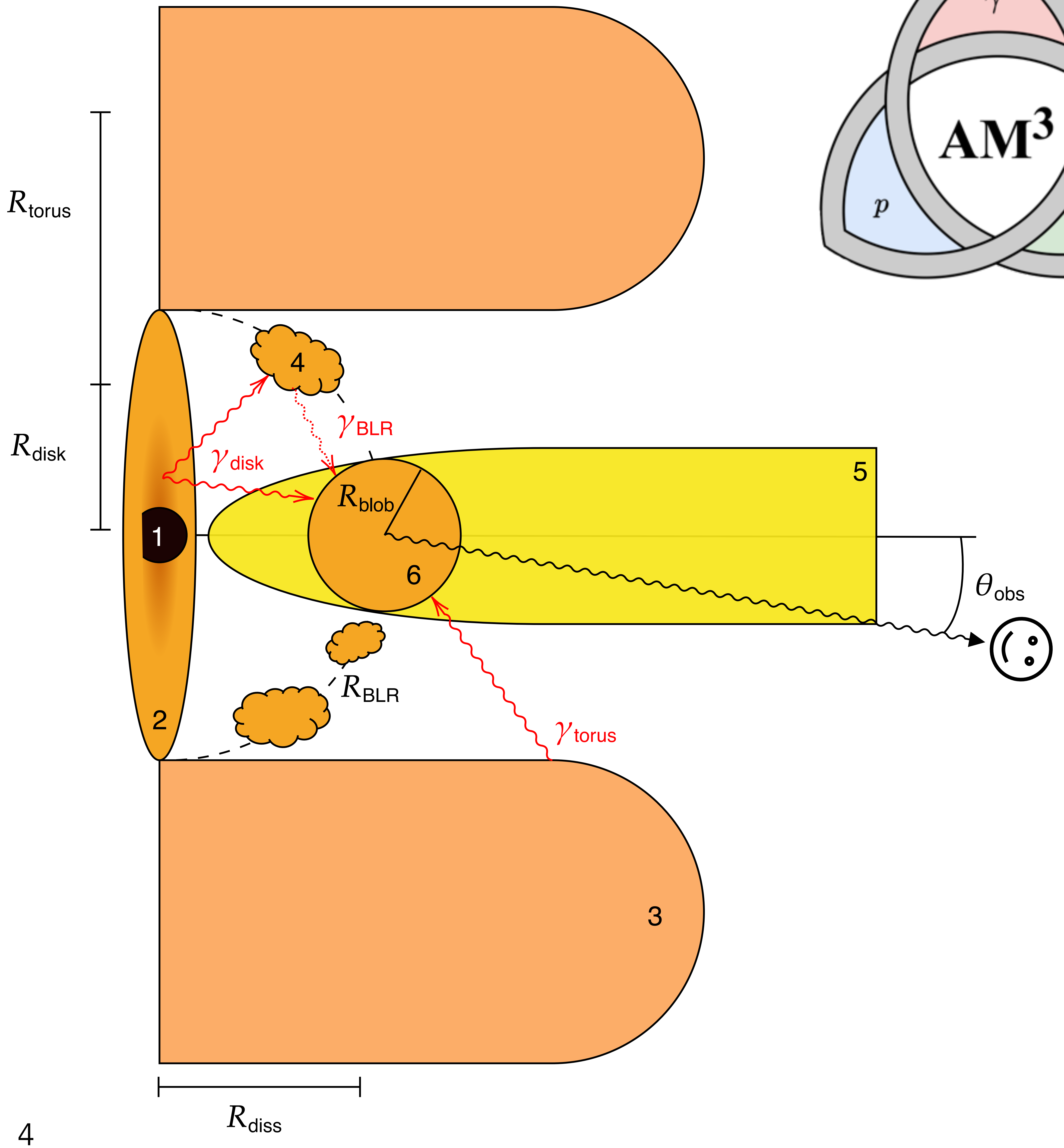
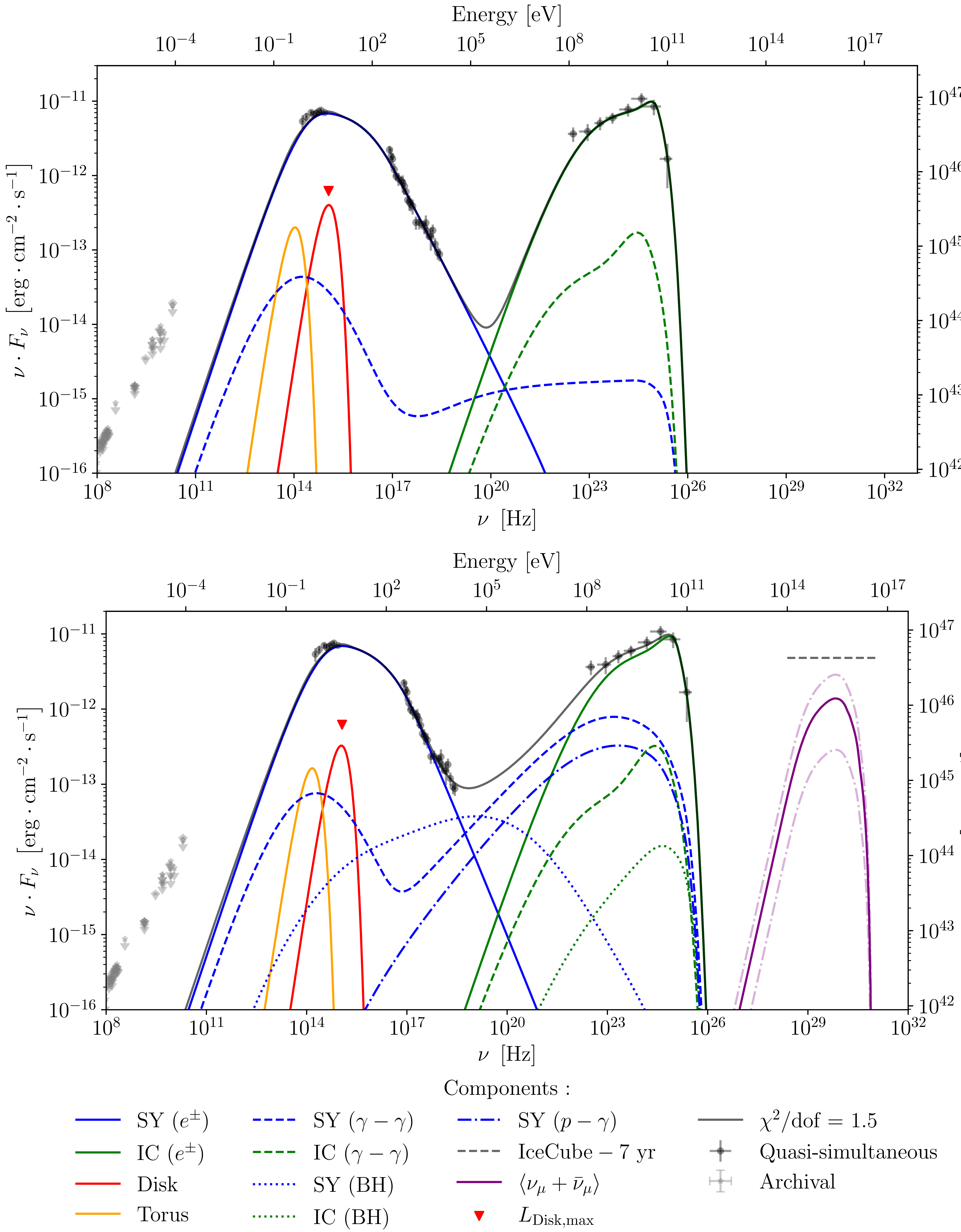


SED : leptonic and lepto-hadronic models

- Solutions display luminous accretion disk $L_{\rm disk} \simeq 5 \times 10^{45}\ \mathrm{erg \cdot s^{-1}}$ (below the upper-limit) with intermediate accretion regime $\eta \sim 2 \times 10^{-4}$, $L_\gamma / L_{\rm Edd} = 0.15$.
- Both models can explain the SED - only the hadronic model can explain the broken spectral shape in the X-ray SED.



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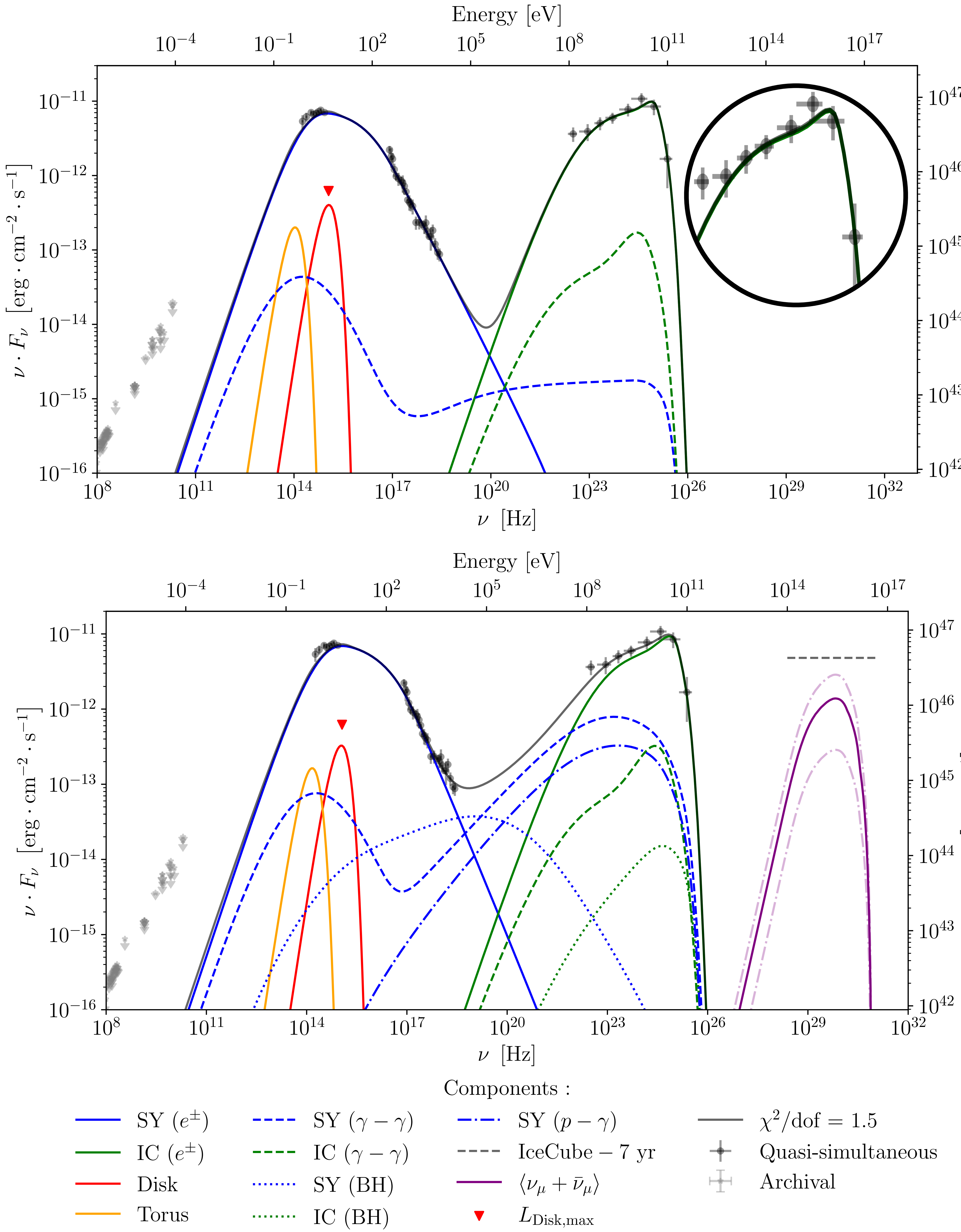

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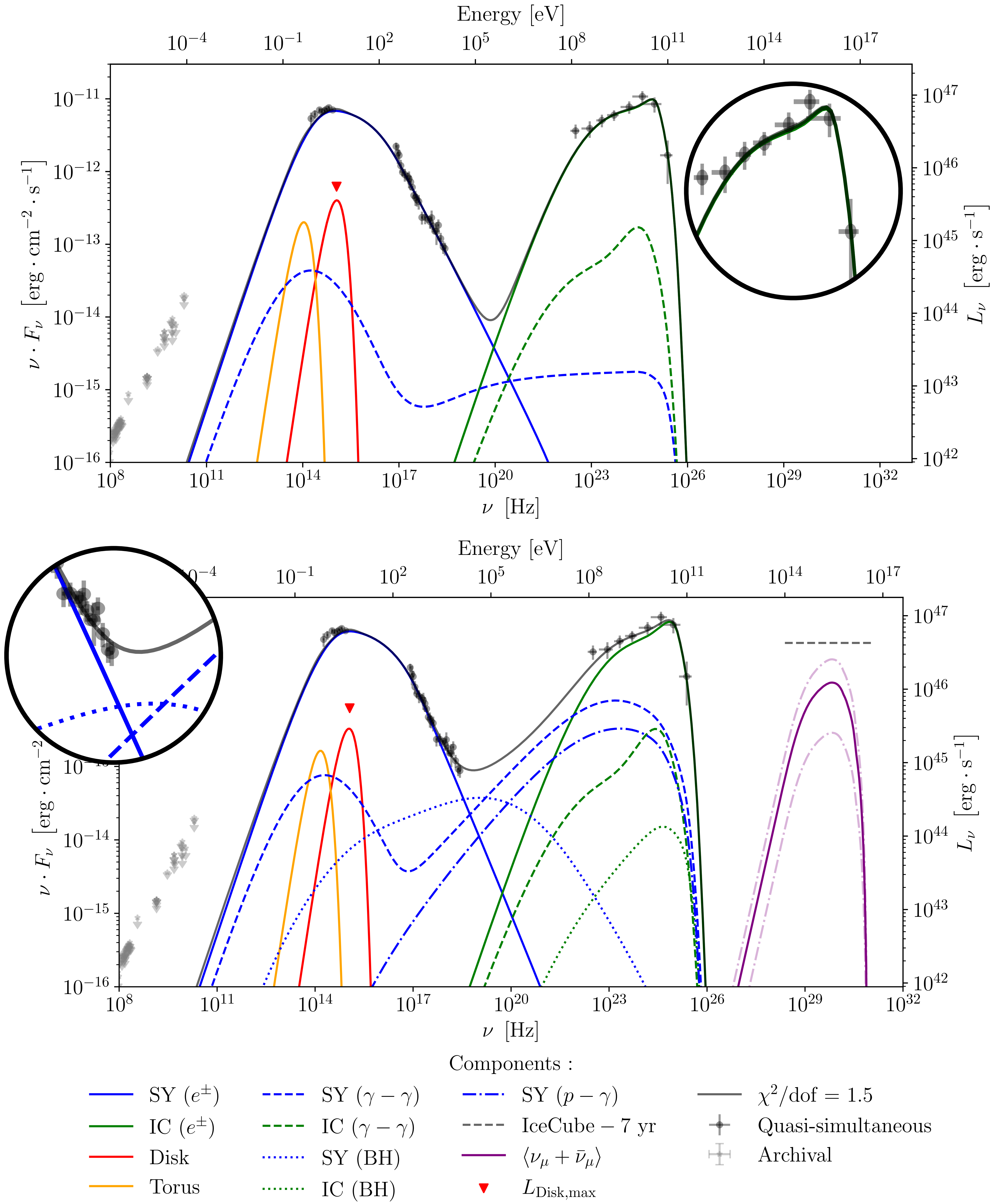

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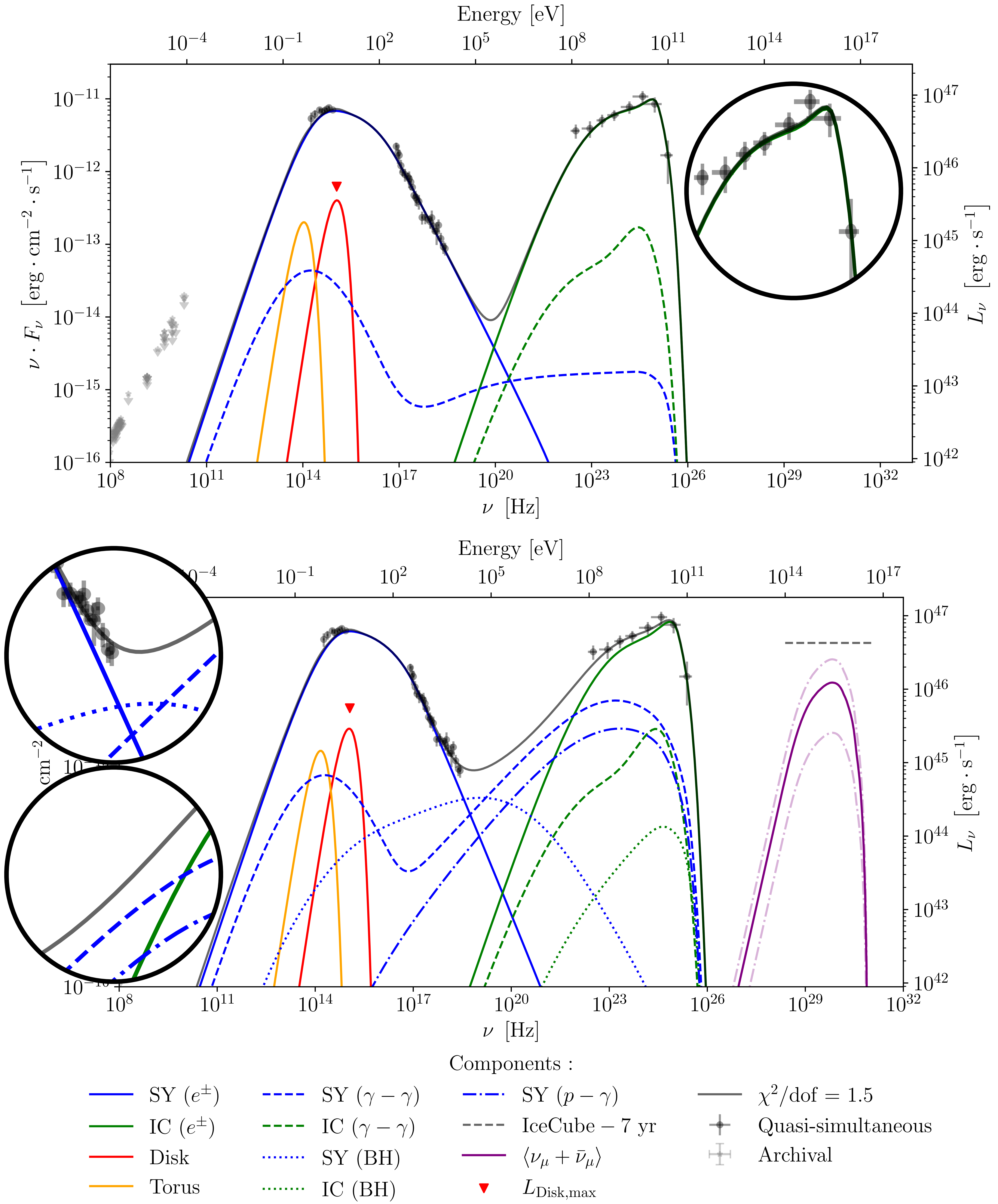


What can we learn from this?

5BZB J0630-2406 as a high-power FSRQ

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

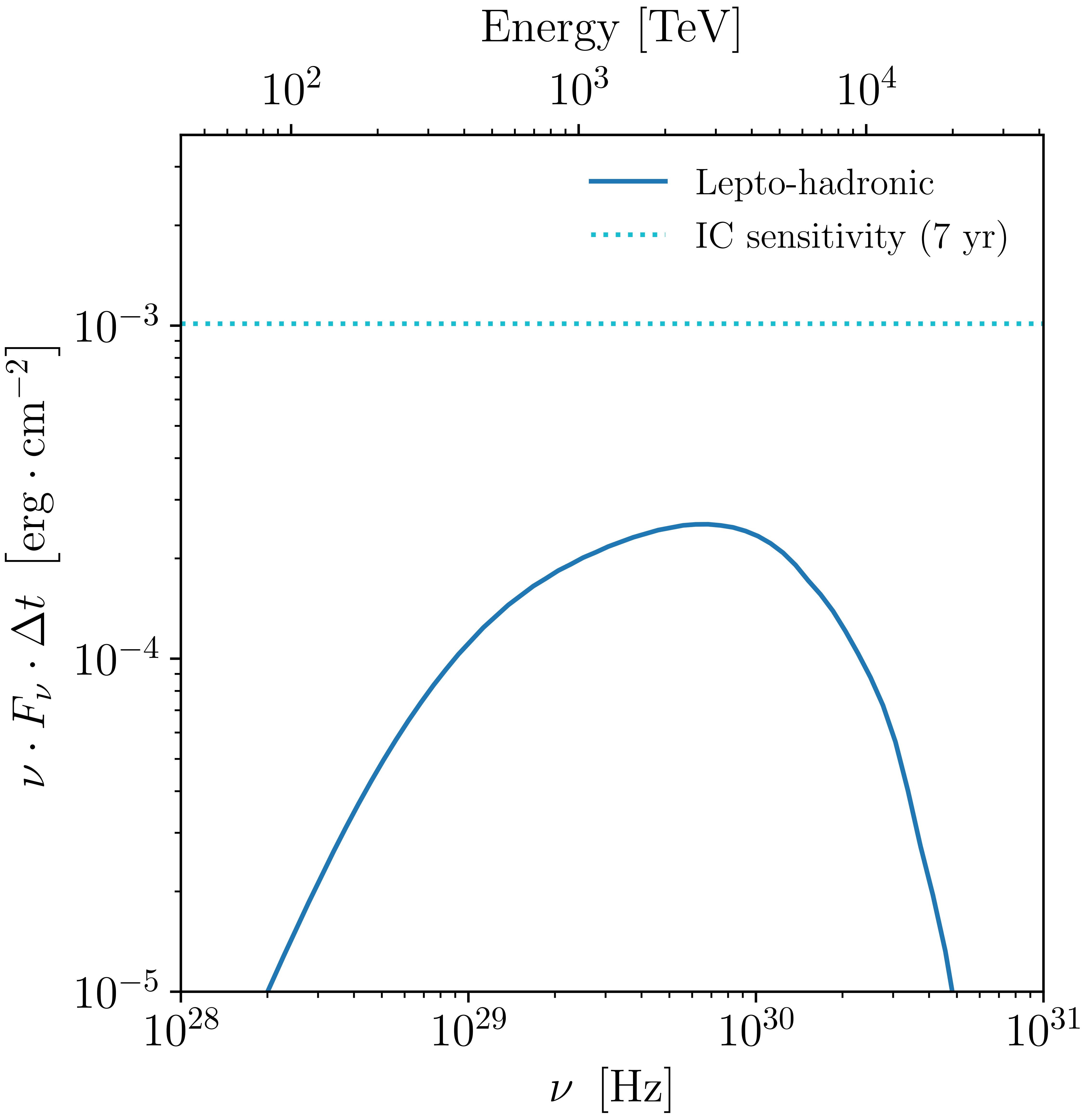
✓ Hosting a luminous accretion disk with relatively high accretion rate $\eta \sim 2 \times 10^{-4} \Rightarrow$ In between BL Lac / FSRQ [Sbarrato et al. 2012].

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

✓ Dissipation radius is on the outer edge of the BLR $\Rightarrow$ 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 live time 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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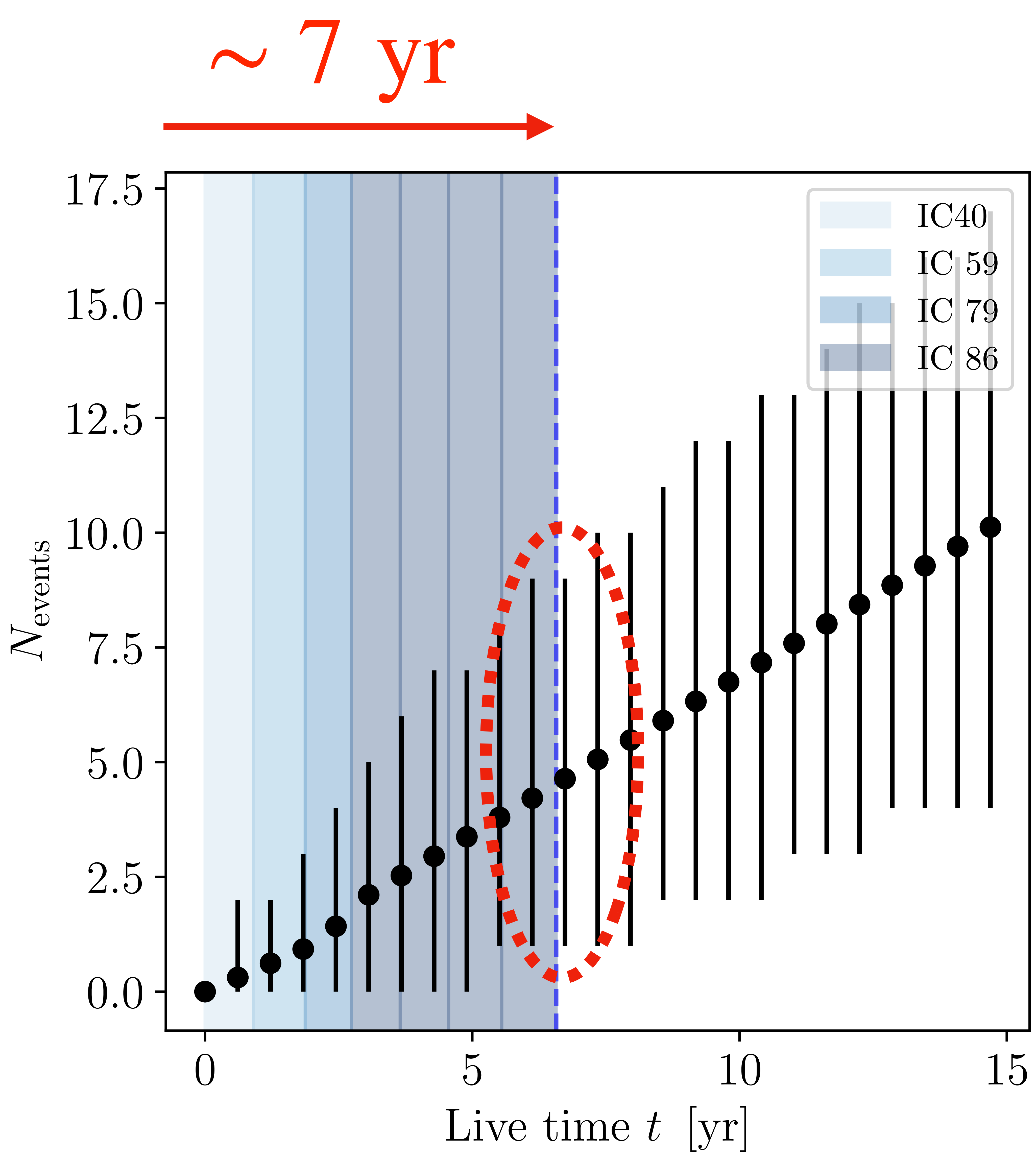

What can we learn from this?

5BZB J0630-2406 as a neutrino emitter

✓ Hints of an intrinsic X-ray break in the SED, reproducible only with the lepto-hadronic scenario.

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

✓ $N_{\text{events}} = 4.82^{+5.18}_{-3.82}$ 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

Building a larger picture

High power, Radiatively Efficient Blazar

Building a larger picture

High power, Radiatively Efficient Blazar

PeVatron Blazar Sample

5BZB J0630-2406

TXS 0506+056, PKS 1424+240,

5BZB J0035+1515, …

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Putting into question the traditional FSRQ / BL Lac classification.

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Origin of Unique Characteristics

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

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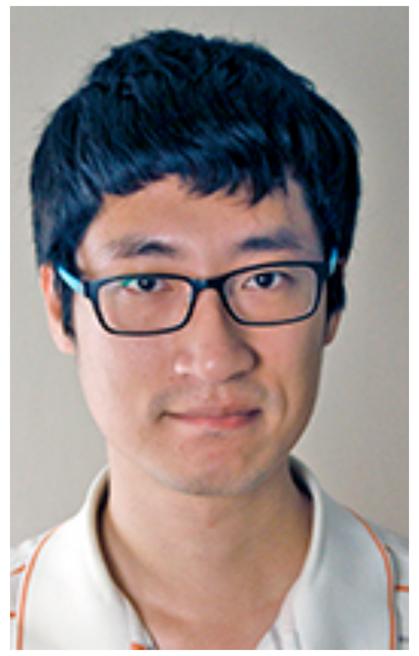
Ongoing Research

Fichet DC et al. (in press., arXiv:2310.03698) & Azzollini et al. (in prep) studying PeVatron

Public release of AM^3

- Solve transport equations - time dependent!
- For protons, electrons, photons
  + pions, muons, neutrinos.
- Syn, IC, pair-prod., $p\gamma$,pp, Bethe-Heitler, decays,…
- Speed optimized (steady state in ~10s)
- Written in C++, interface to Python.
- Used already for blazars (initially Gao++ 2017), GRBs, TDEs, …
- Including documentation and examples!

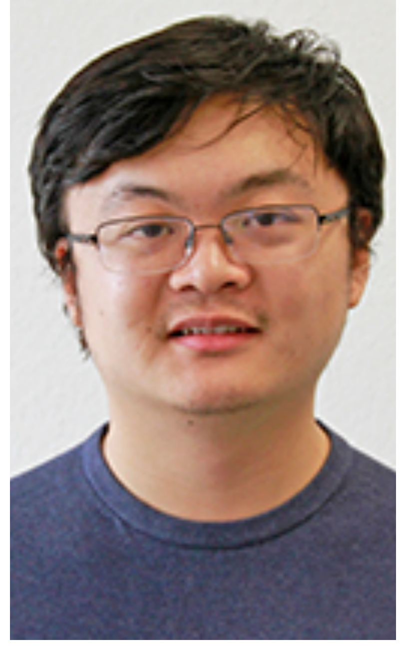
Astrophysical Multi-Messenger Modeling


Gao


Klinger


Rudolph


Rodrigues


Yuan

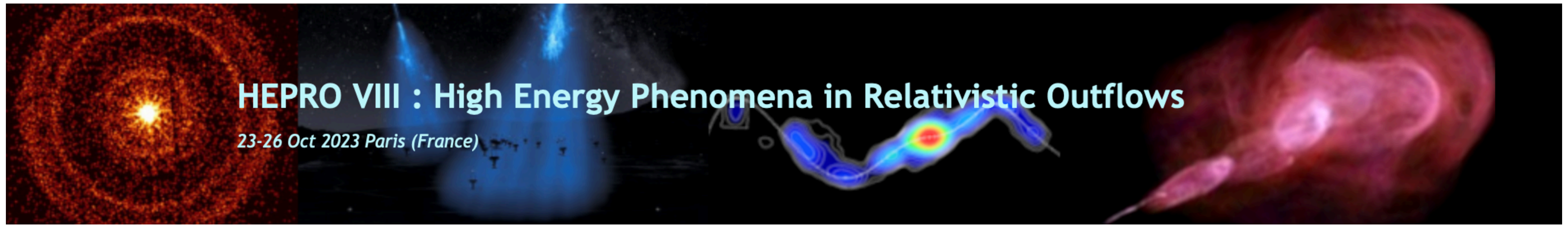

Fichet De Clairfontaine


Fedynitch


Winter


Pohl

gitlab.desy.de/am3/am3



Thank you for your attention!
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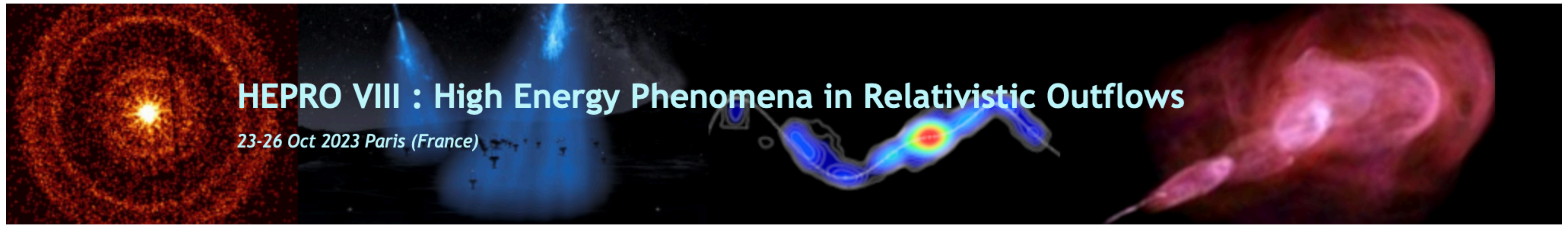

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Ackermann et al. 2016, ApJ, 820, 72.

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

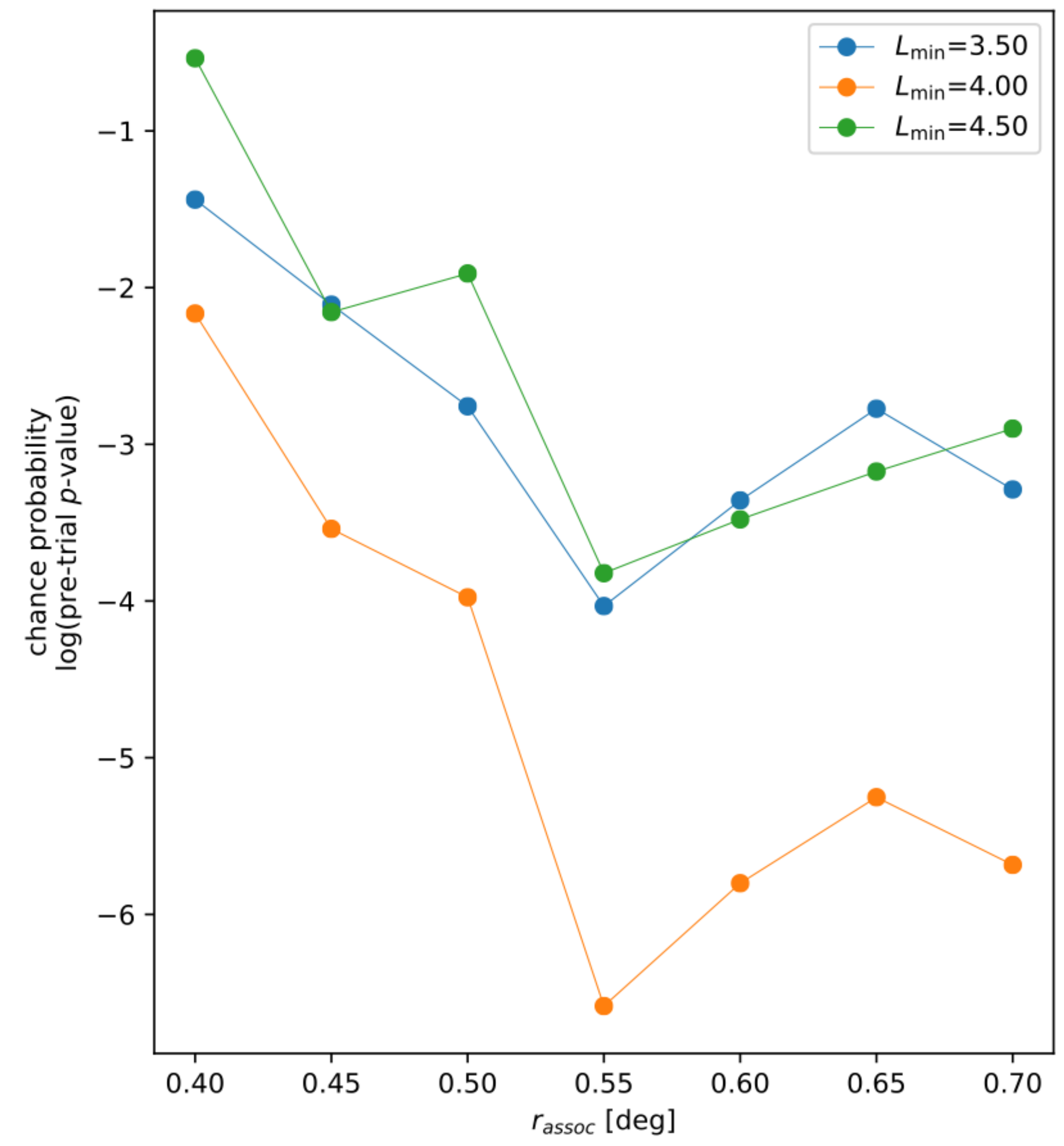
Aartsen et al. 2017, ApJ, 835, 151.

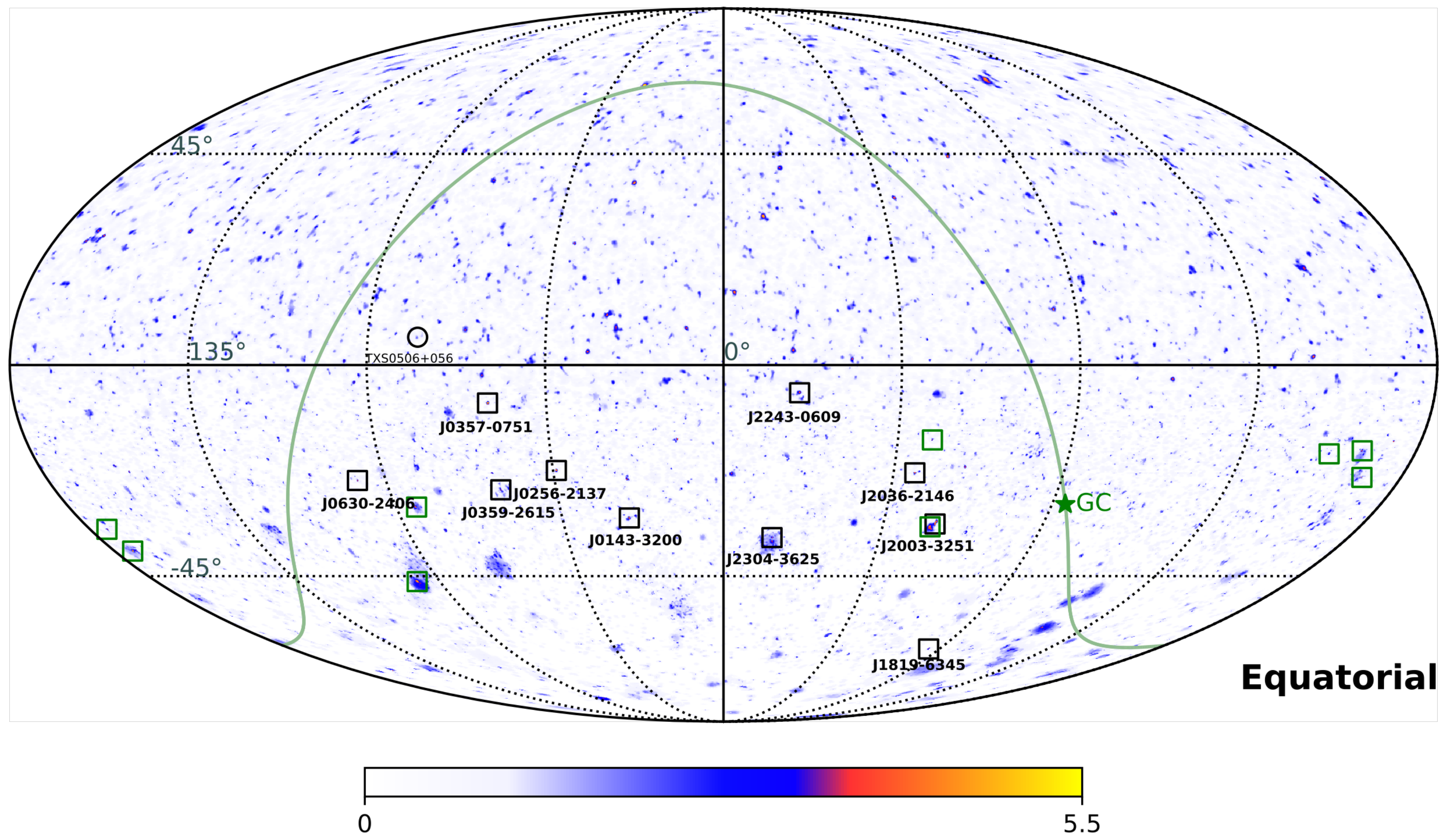
Peña-Herazo et al. 2011, AJ, 161, 196.

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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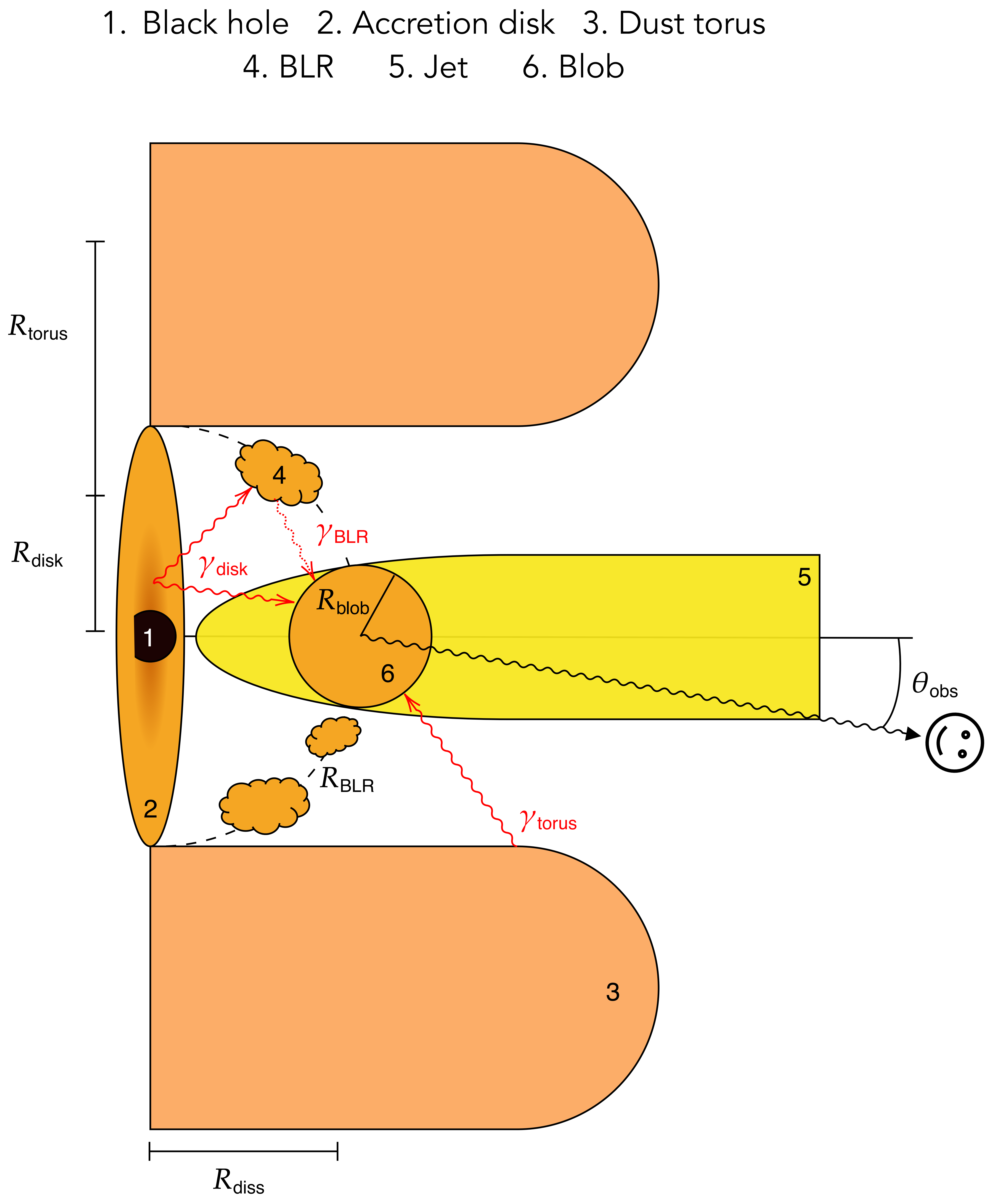
Parameters table

	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 $\left[\mathrm{erg} \cdot \mathrm{cm}^{-3}\right]$	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 $\left[\mathrm{erg} \cdot \mathrm{cm}^{-3}\right]$	6.4×10^{-4}	6.3×10^{-4}
u'_e/u'_b	3.9	2.3
L'_e $\left[\mathrm{erg} \cdot \mathrm{s}^{-1}\right]$	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 $\left[\mathrm{erg} \cdot \mathrm{cm}^{-3}\right]$	–	1.5
u'_p/u'_b	–	5.3×10^3
L'_p $\left[\mathrm{erg} \cdot \mathrm{s}^{-1}\right]$	–	1.0×10^{45}
L_{disk} $\left[\mathrm{erg} \cdot \mathrm{s}^{-1}\right]$	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



$\chi^2_{\mathrm{d.o.f.}}$: parameter space research

- Parallel parameter space research on multiple cpus.
- Best solution is re-injecting with Gaussian noises at each step.