The physical properties of candidate neutrino-emitter blazars

Alessandra Azzollini*

On behalf of: Sara Buson, Alexis Coleiro, Gaëtan Fichet de Clairfontaine, Leonard Pfeiffer, Jose Maria Sanchez Zaballa, Margot Boughelilba, Massimiliano Lincetto

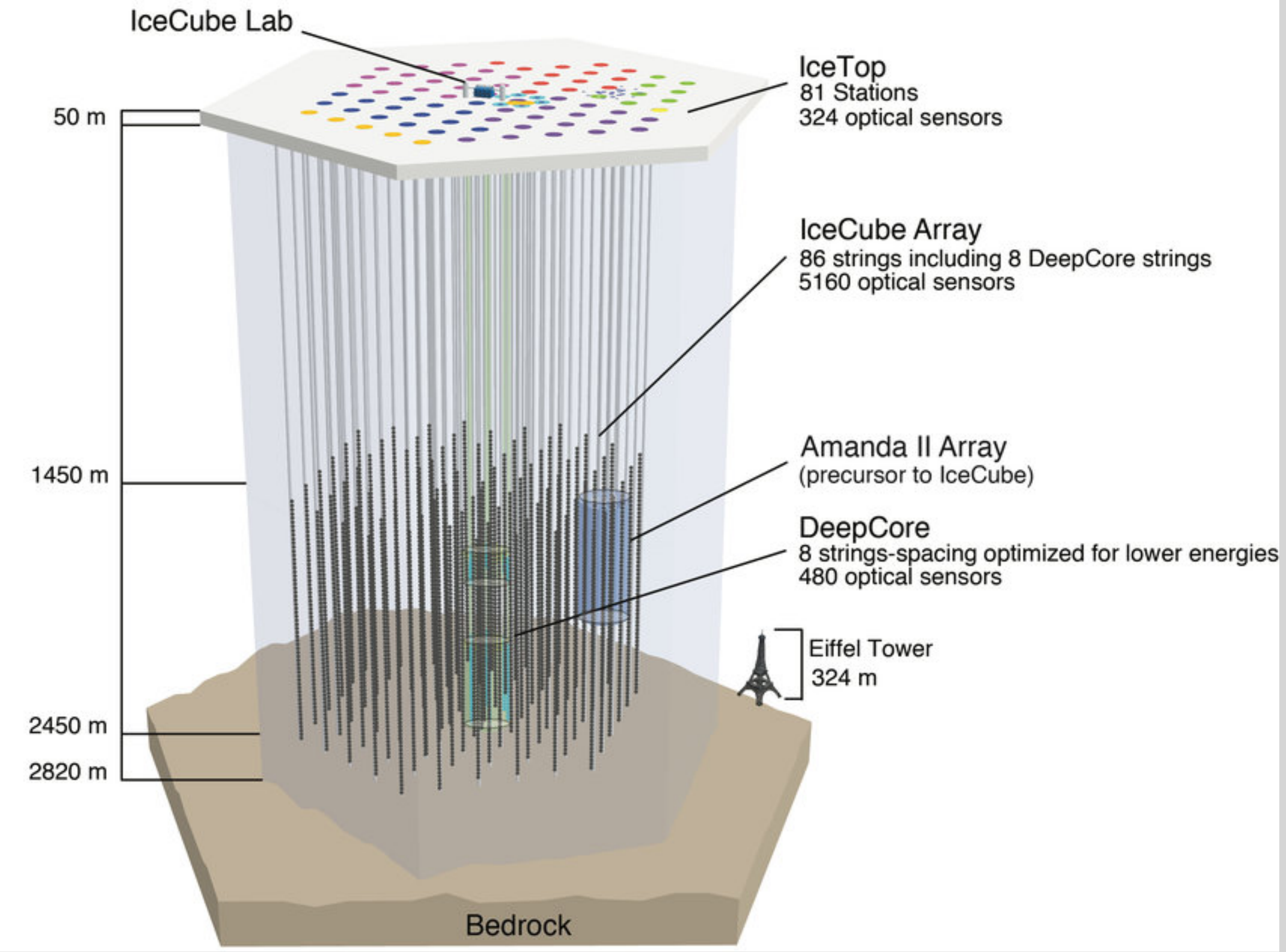
September 26th, 2024 - Frascati

9th edition of the Roma International Conference on AstroParticle Physics (RICAP 2024)

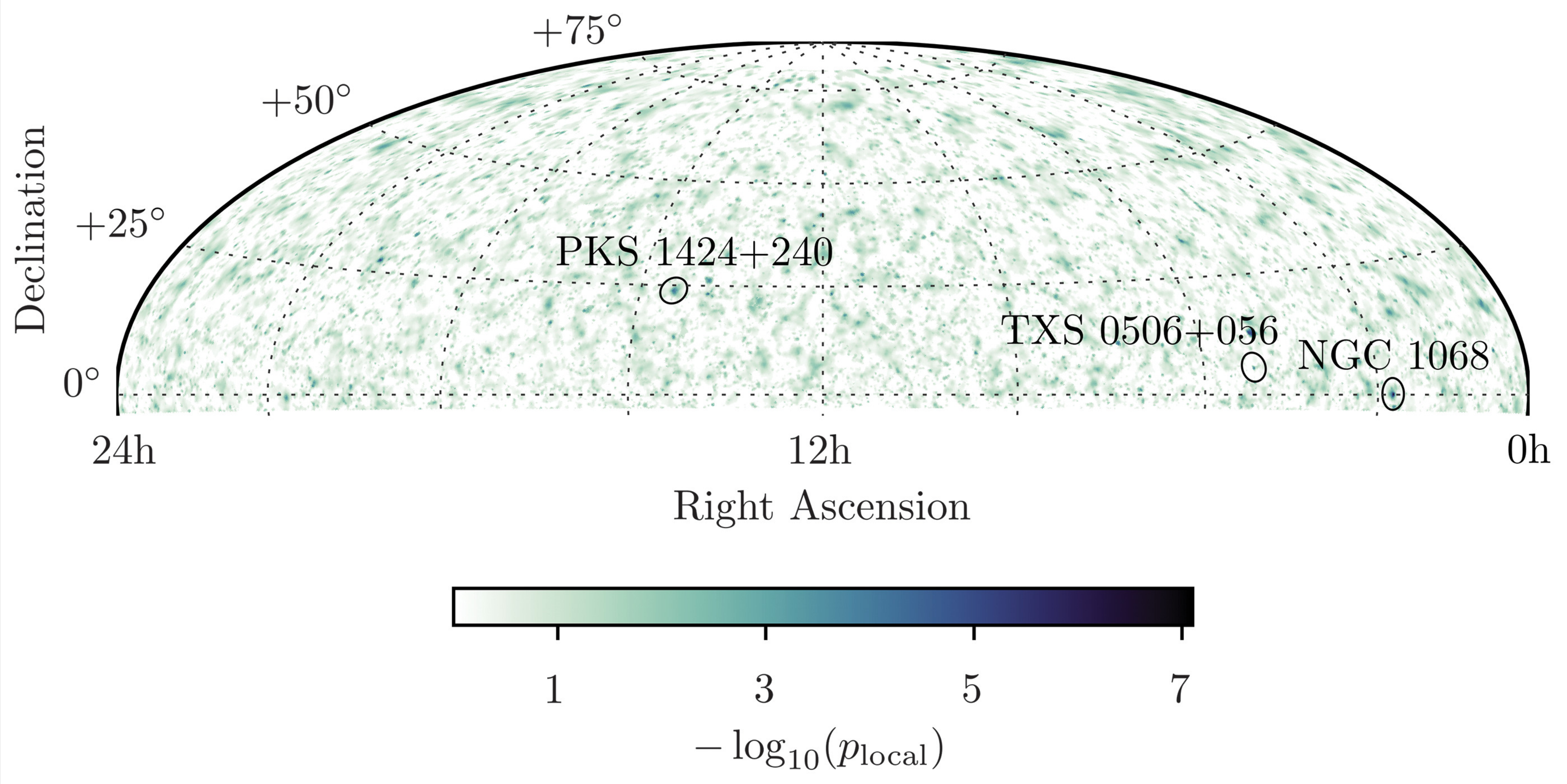
**alessandra.azzollini@uni-wuerzburg.de*

The puzzle of high-energy neutrinos

Nearly massless
Very challenging to detect
Indirect probes of cosmic rays



Credits: IceCube Collaboration



IceCube Collaboration (2022)

Yet to be unveiled:

Which astrophysical **sources** produce them

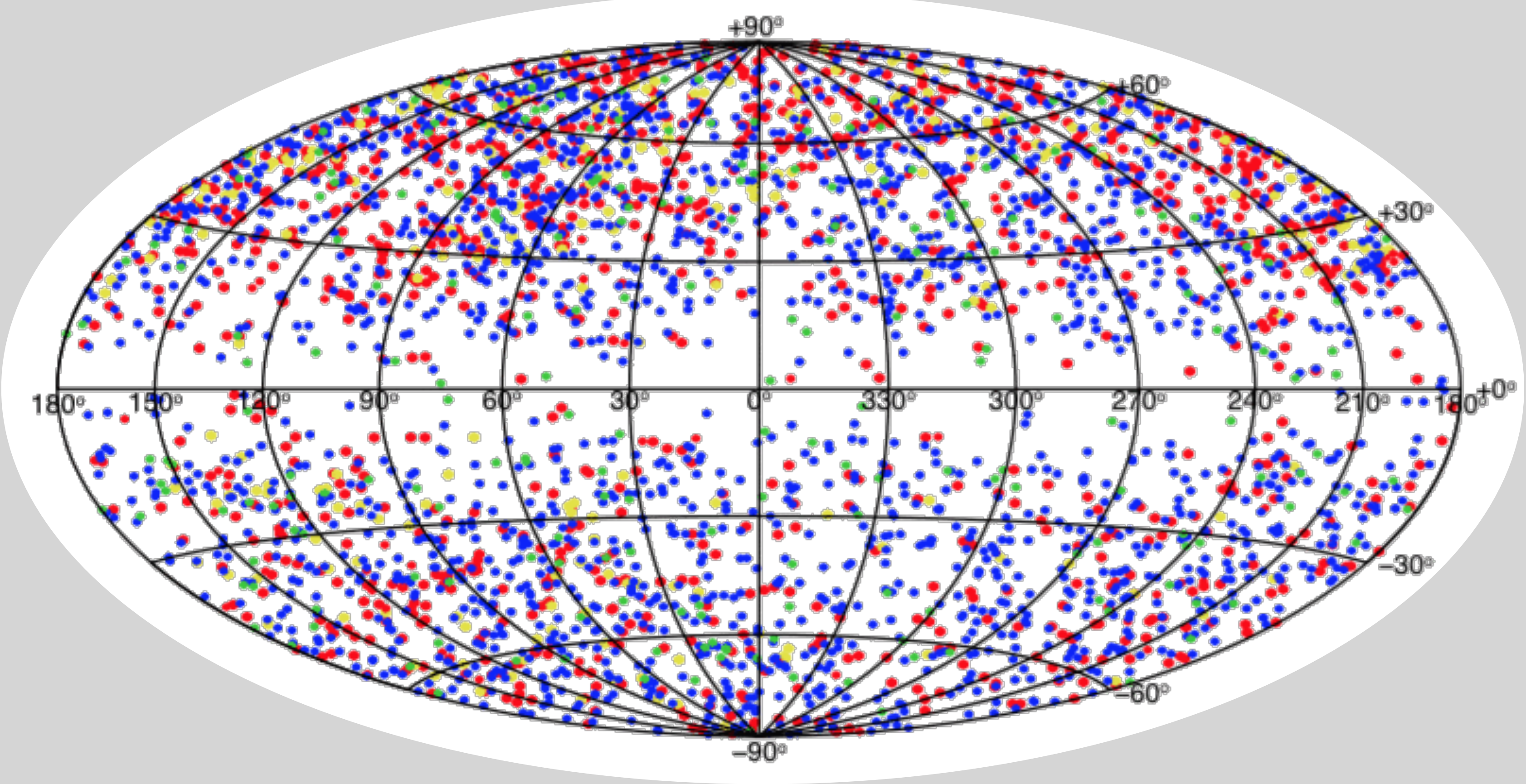
Which **processes** originate them

The connection between blazars and neutrinos: further clues

Positional cross-correlation analysis

Blazar sample

5th Edition of Roma-5BZCat catalog
- no preferred selection

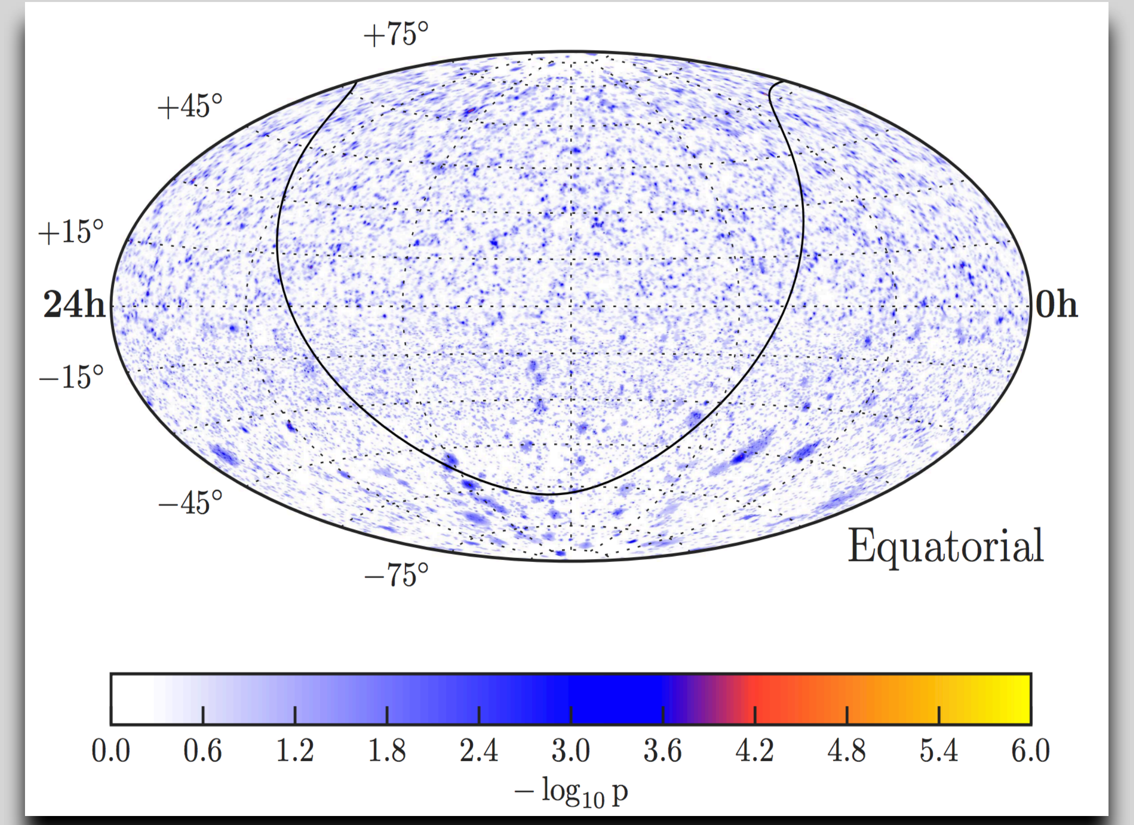


Massaro et al. (2015)

See Sara Buson's talk tomorrow!

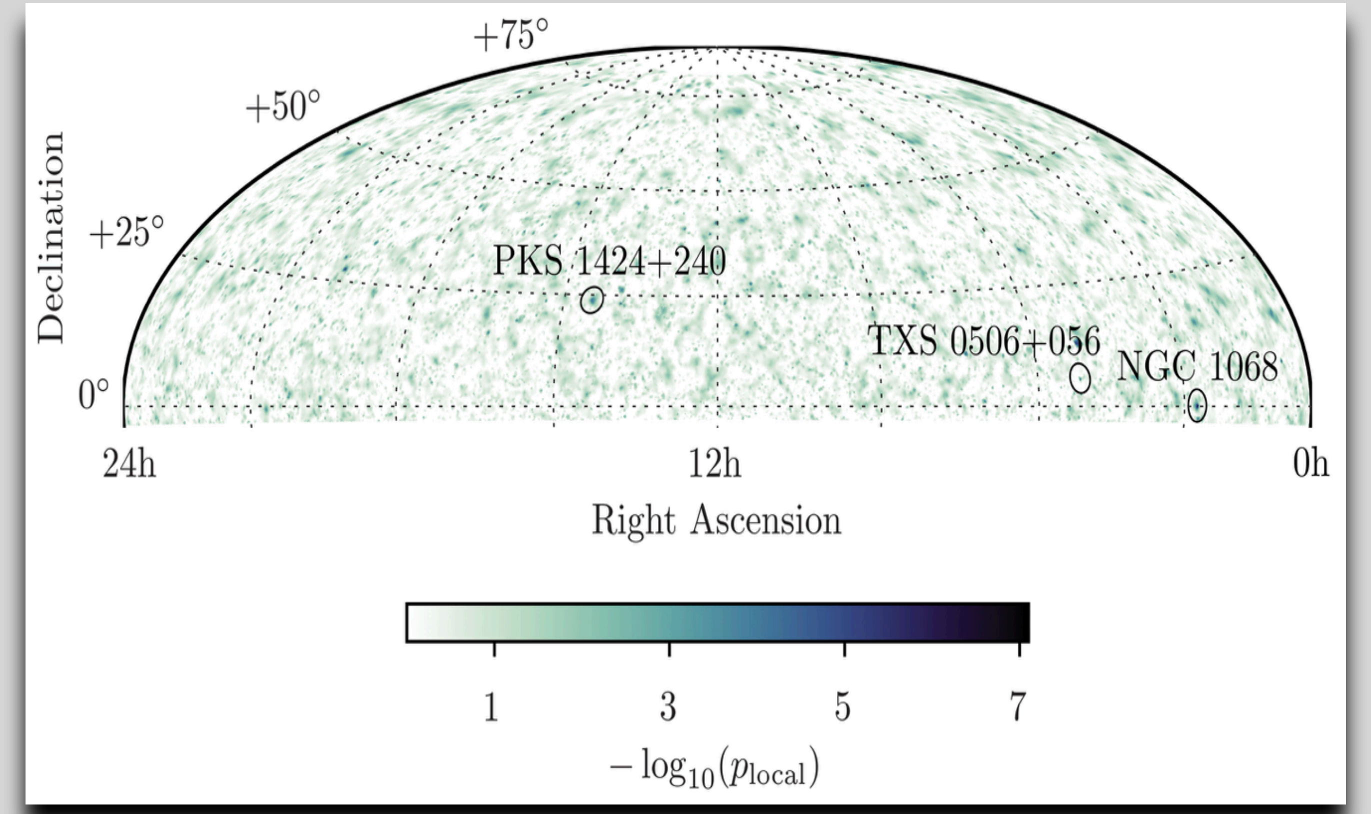
IceCube neutrino data

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)

The connection between blazars and neutrinos: further clues

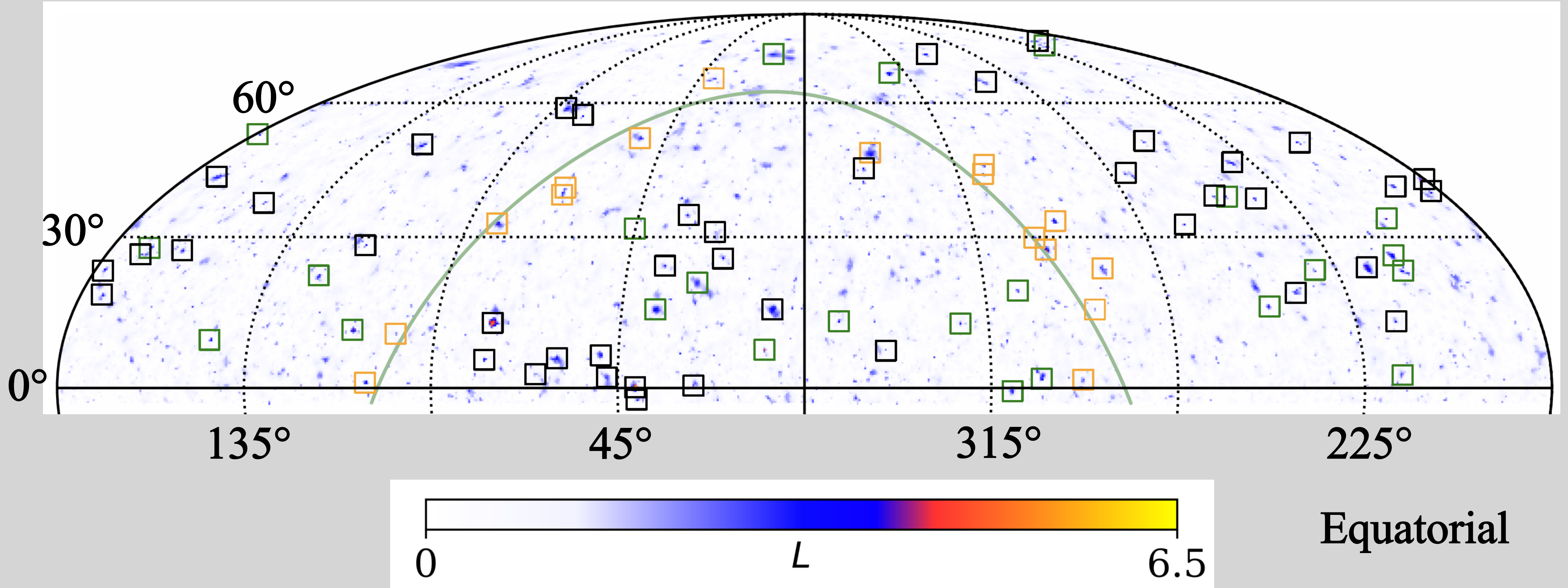
The candidate “PeVatron blazars” sample

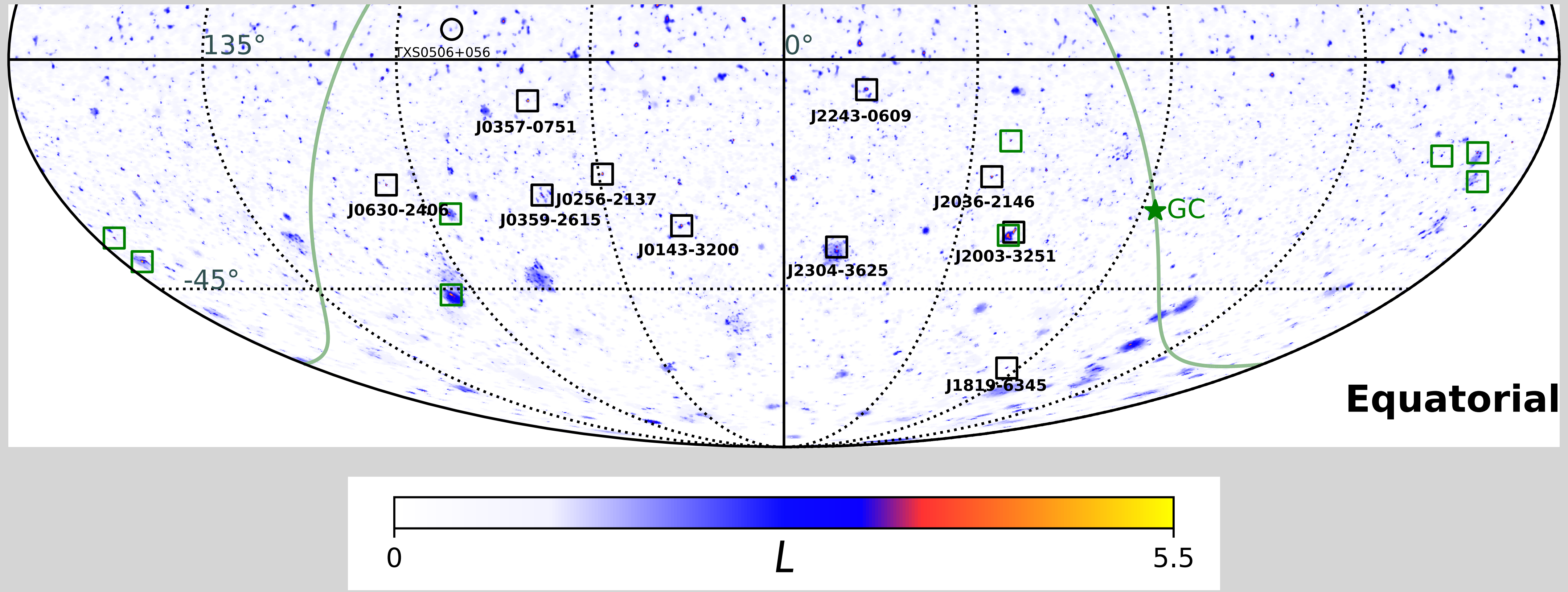
52 BZCat blazars

10 southern
$-85^{\circ} < \delta < -5^{\circ}$

42 northern
$-3^{\circ} \leq \delta \leq 81^{\circ}$

Buson et al. (2022a, 2022b)
Buson et al. (2023)
See also Bellenghi et al. (2023)





Diving into the properties of the sample

Do the 52 candidate neutrino-emitter blazars share similar chacteristics?
How do they behave compared to the overall population of blazars?

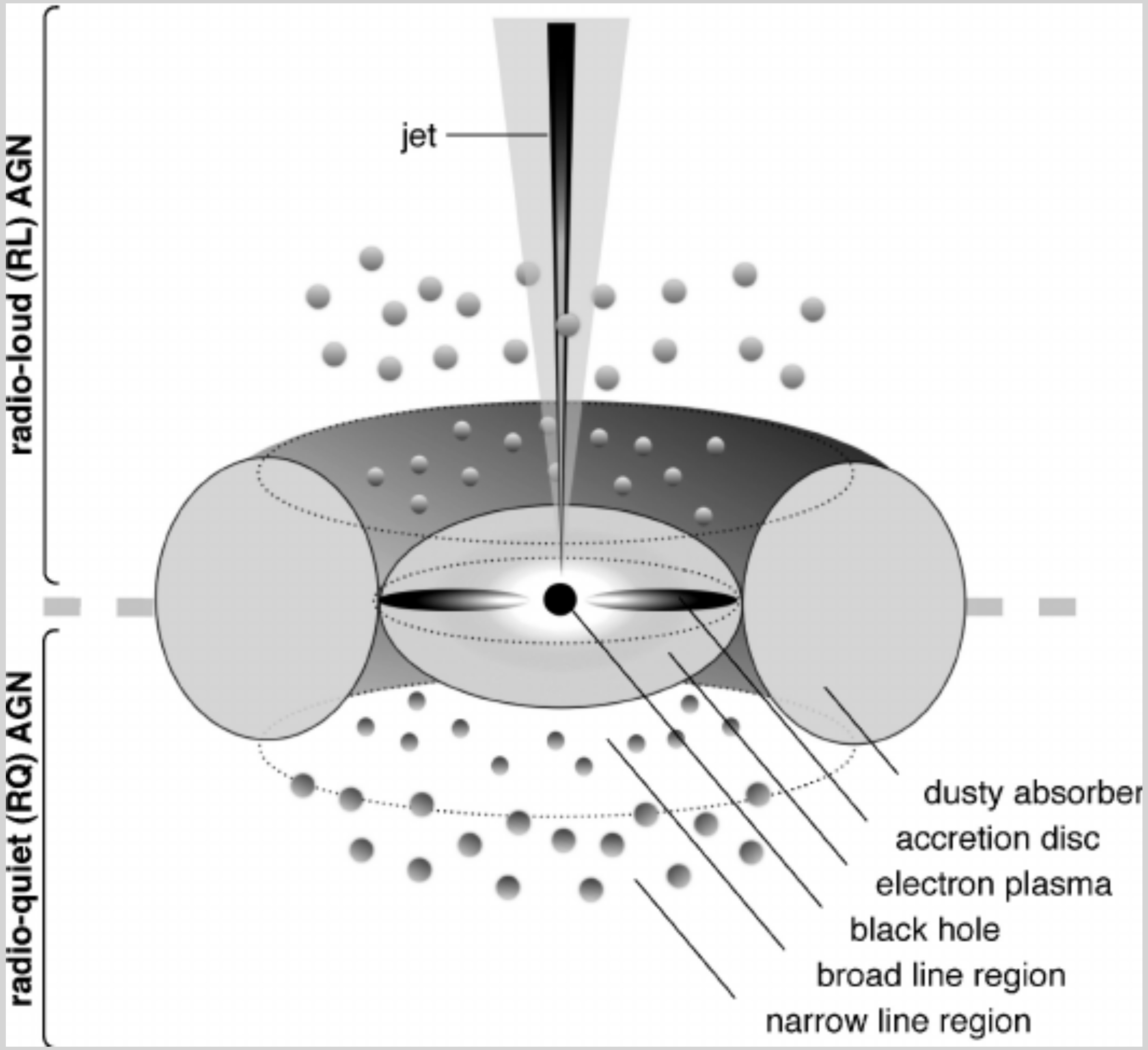
Physical properties from MWL observations

Radio

Optical

ɣ-rays

Active Galactic Nuclei (AGN): the unified model



Beckmann & Shrader (2012)
Urry & Padovani (1995)

Accretion onto a supermassive black hole

$M \sim 10^6 - 10^9 \, M_\odot$

Very **powerful** objects

$L_{\text{bol}} \sim 10^{46} - 10^{48} \, \text{erg} \cdot \text{s}^{-1}$

Emission up to ~ Mpc scales

Rapid **variability** ~ min - yr

Observed **boosted** emission from the jet spans the whole electromagnetic spectrum:

- Infrared (IR) - obscuring material, dust
- Optical/Ultraviolet (UV) - accretion disc
- X-rays (XRs) - corona
- Radio, γ-rays - non-thermal jet related radiation

Active Galactic Nuclei (AGN): the unified model

Historical classification of radio-loud blazars

Flat spectrum radio quasars (FSRQs)

- *Prominent* emission lines in the optical spectrum
- *Highly* beamed jets closely aligned with line of sight
- *High* radio luminosities
- *High* redshifts
- *High* accretion efficiency ("cold-mode")
- *Less massive* black holes

BL Lacertae objects (BL Lacs)

- *Weak* or *absent* emission lines in the optical spectrum
- *Less* beamed jets more closely aligned with line of sight
- *Low* radio luminosities
- *Low* redshifts
- *Low* accretion efficiency ("hot-mode")
- *More massive* black holes

Best & Heckman (2014)

The transitional blazars and the need for a new nomenclature

Blue FSRQs (masquerading BL Lacs)

Ambiguous properties between the two classes

High synchrotron peak, **featureless** optical spectrum

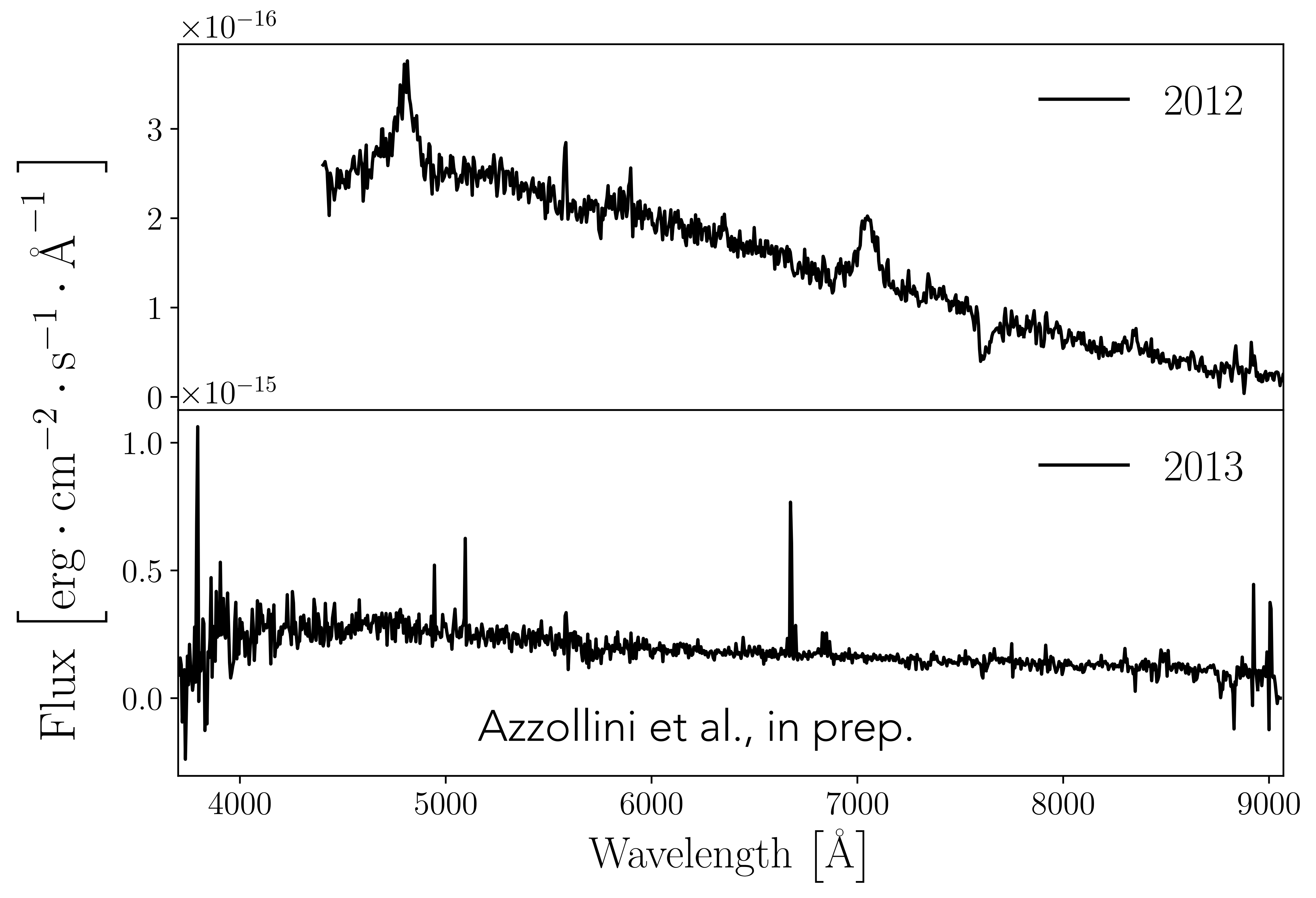
Intrinsically FSRQs with optical lines **swamped** by jet's emission

TXS 0506+056 (5BZB J0509+0541)
PKS 1424+240 (5BZB J1427+2348)
5BZB J0630-2406

Ghisellini et al. (2012)
Padovani et al. (2012, 2019, 2022)
Fichet de Clairfontaine et al. (2023)

Changing-look blazars

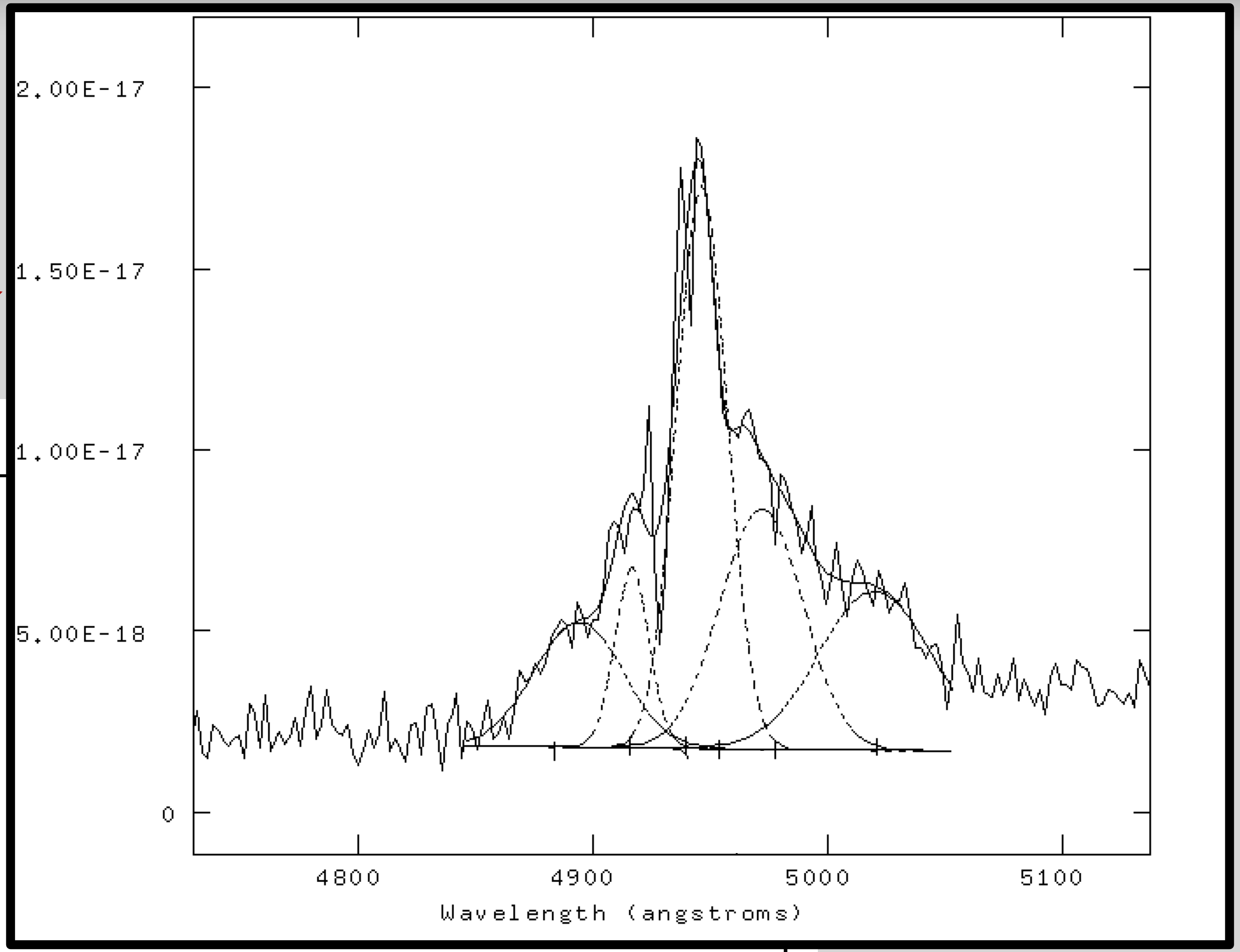
Observational **transitions** between classes

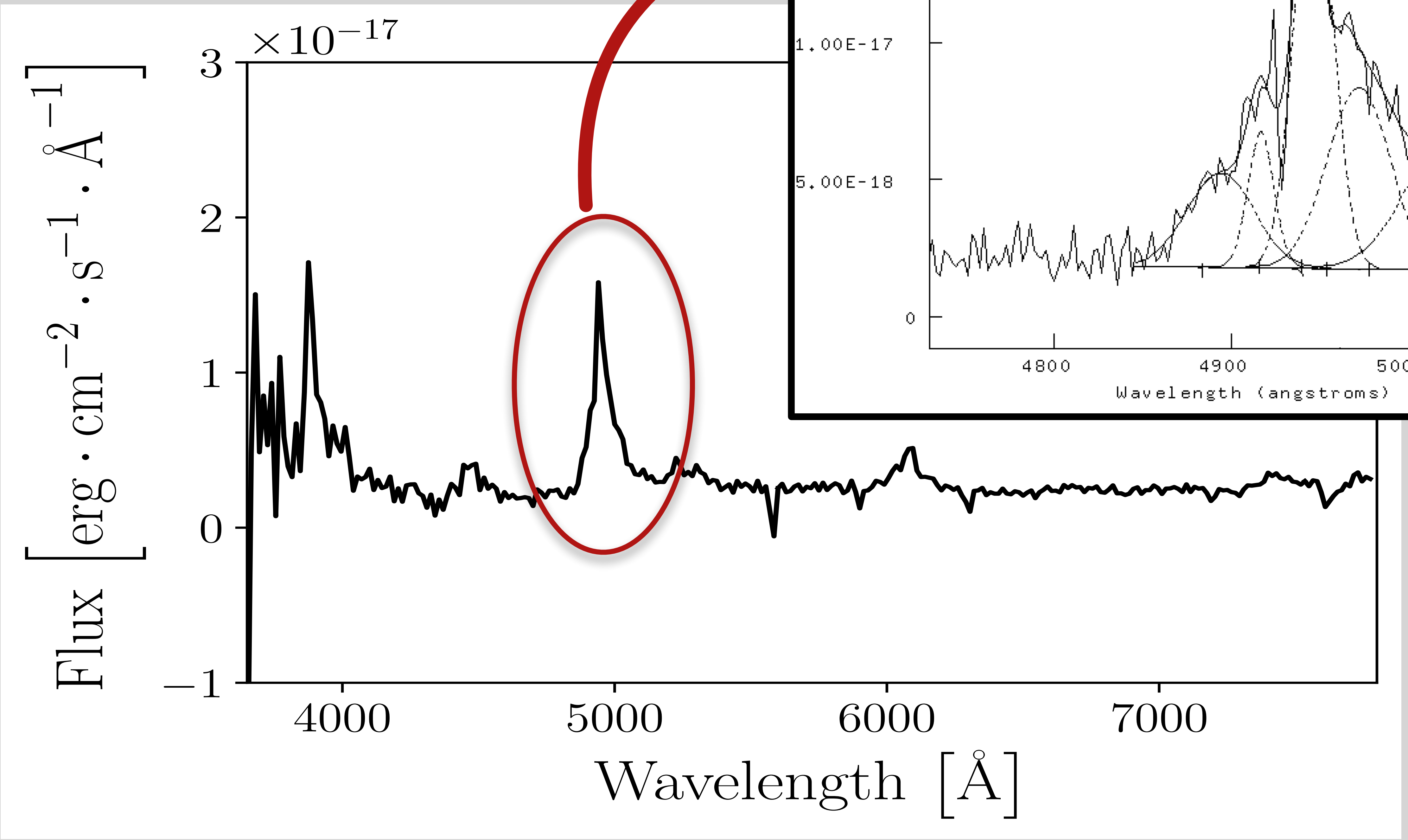


Probing the accretion properties

Through optical spectroscopy

Azzollini et al., submitted





Emission lines from the **BLR**:

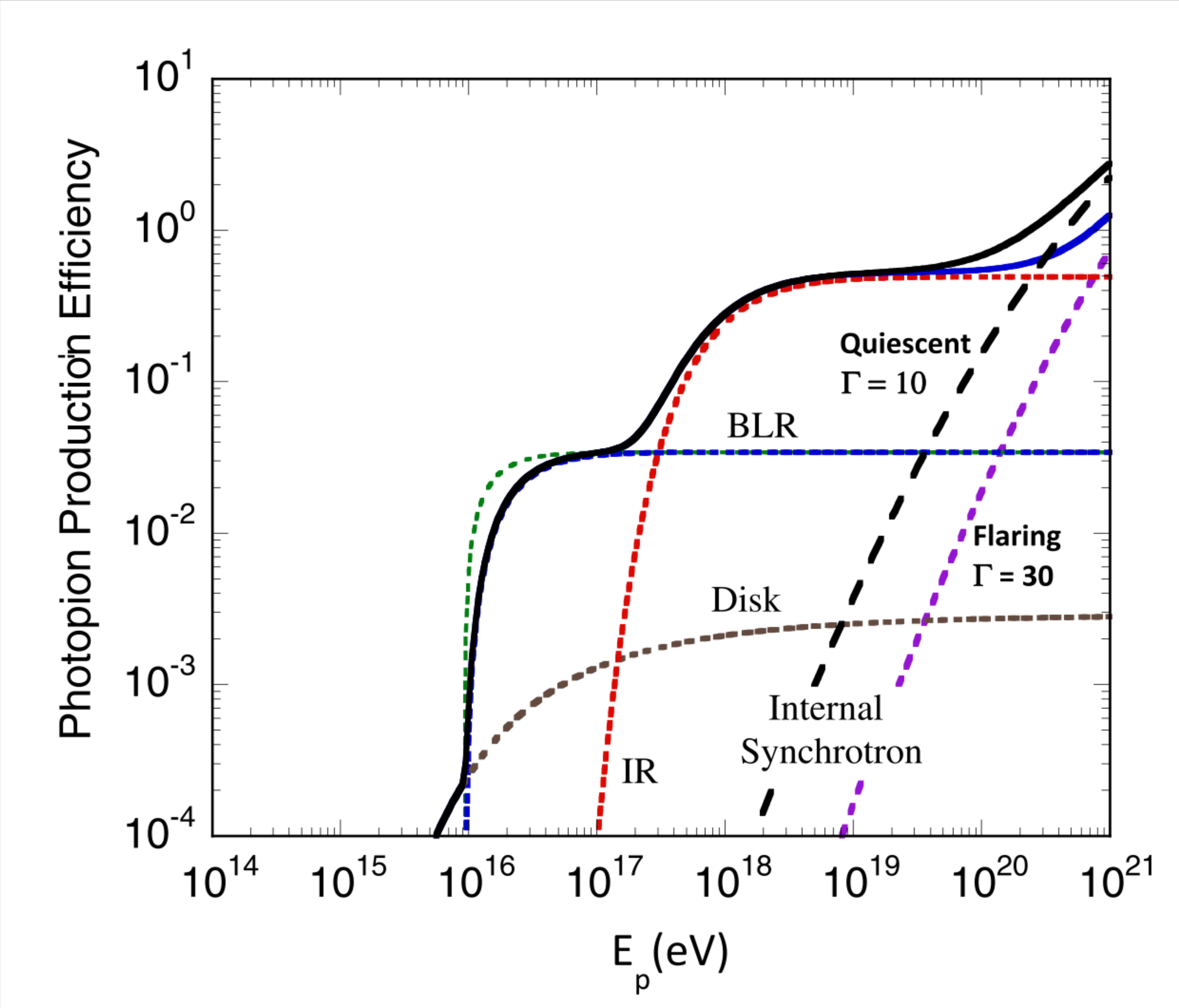
Hα, Hβ, Mg II, C IV

Detections or upper limits

- Luminosity of the BLR
- Luminosity of the accretion disk
- Bolometric luminosity
- Mass of the central black hole
- Eddington luminosity
- Radii of the BLR and DT

Why the accretion regime?

In lepto-hadronic frameworks: tight relation between neutrino production properties and radiation fields



Dermer et al. (2014)

A physically-driven classification

"Radiative-mode" AGN
High-excitation radio galaxies
(**HERGs**)

Radiatively **efficient** accretion:

$$L_{\mathrm{BLR}}/L_{\mathrm{Edd}} \gtrsim 5 \times 10^{-4}$$

$$L_{\gamma}/L_{\mathrm{Edd}} \gtrsim 0.1$$

High radio power:

$$P_{1.4\,\mathrm{GHz}} \gtrsim 10^{26}\,\mathrm{W} \cdot \mathrm{Hz}^{-1}$$

"Jet-mode" AGN
Low-excitation radio galaxies
(**LERGs**)

Radiatively **inefficient** accretion:

$$L_{\mathrm{BLR}}/L_{\mathrm{Edd}} \lesssim 5 \times 10^{-4}$$

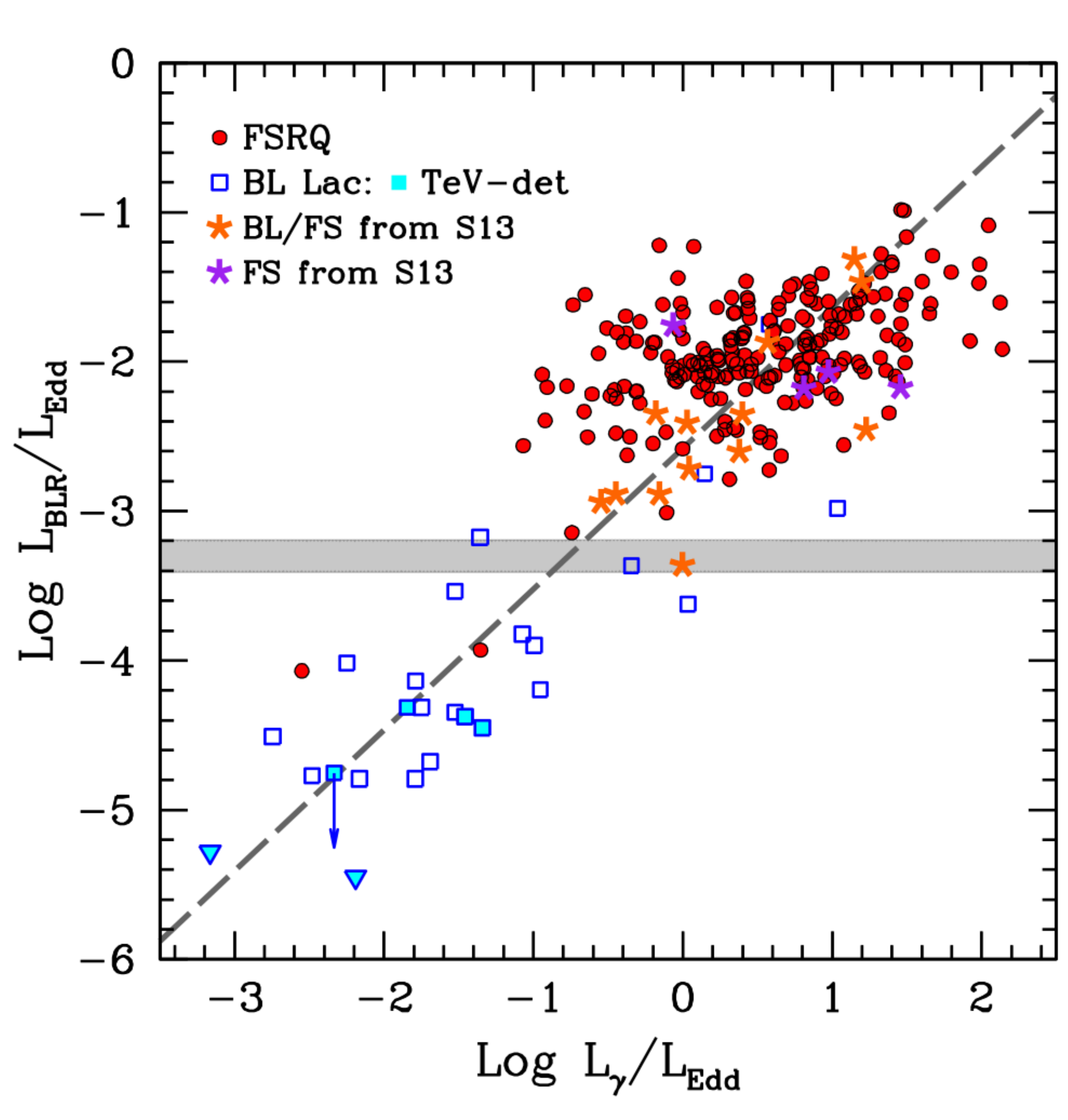
$$L_{\gamma}/L_{\mathrm{Edd}} \lesssim 0.1$$

Low radio power:

$$P_{1.4\,\mathrm{GHz}} \lesssim 10^{26}\,\mathrm{W} \cdot \mathrm{Hz}^{-1}$$

Best & Heckman (2014); Giommi et al. (2012); Padovani et al. (2022); Ghisellini et al. (2011)

A physically-driven classification



Sbarrato et al. (2014)
Ghisellini et al. (2014)

Results: the accretion regime

L_{BLR}/L_{Edd} vs . L_γ/L_{Edd}

- Mild tendency towards *intense radiation fields* and *radiatively efficient accretion*:

~60% HERG-like

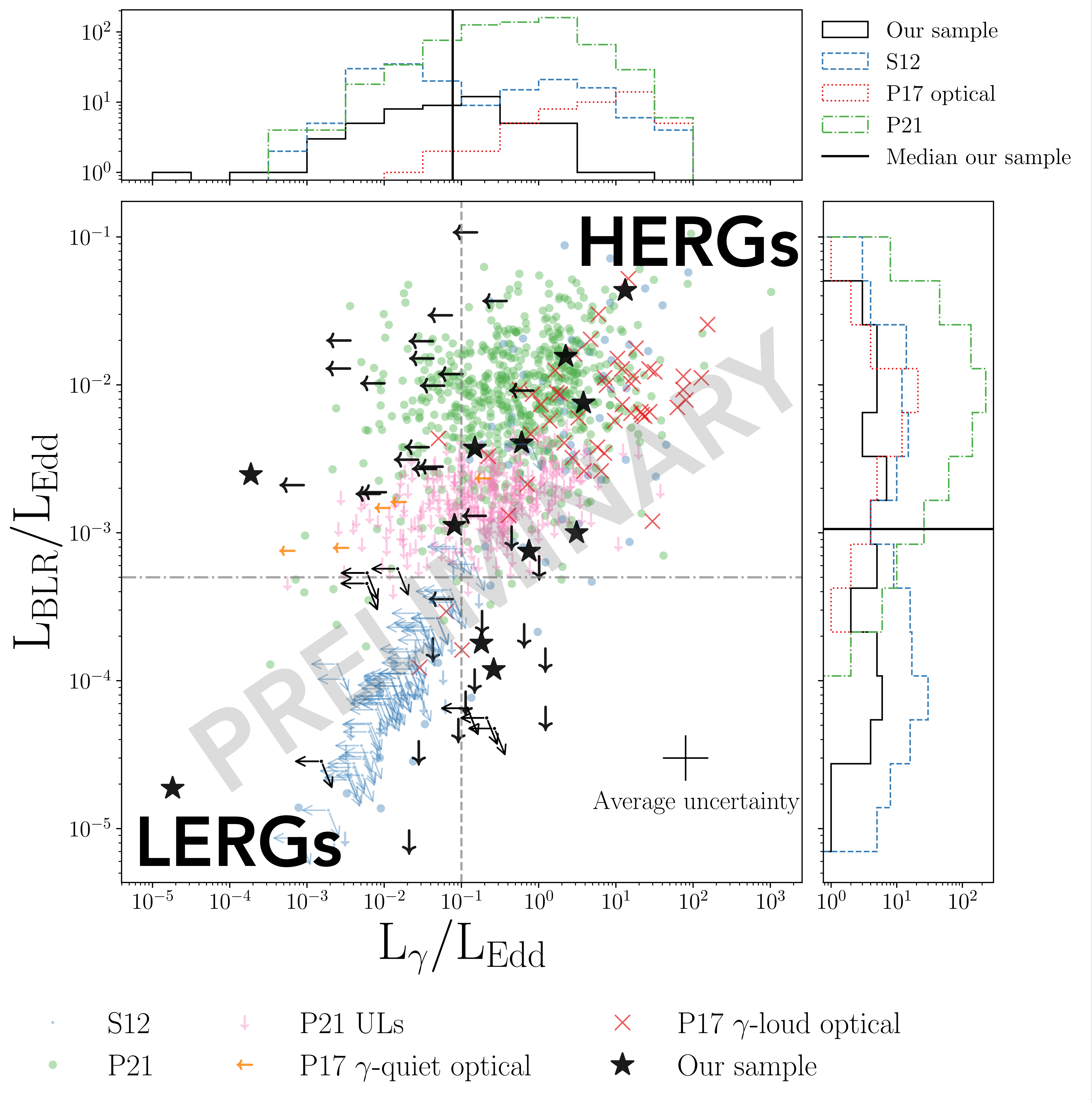
- 50% with Fermi-LAT detection:

$$L_\gamma \in \left[1.43 \times 10^{42}, 1.21 \times 10^{48}\right] \mathrm{erg \cdot s^{-1}}$$

- **Compatible** with overall population of blazars (Anderson-Darling statistical test)

Azzollini et al., submitted

Comparison samples:
Sbarrato et al. (2012, S12)
Paliya et al. (2017, P17)
Paliya et al. (2021, P21)



Results: the accretion regime

L_{BLR}/L_{Edd} vs . L_γ/L_{Edd}

- Mild tendency towards *intense radiation fields* and *radiatively efficient accretion*:

  ~60% HERG-like

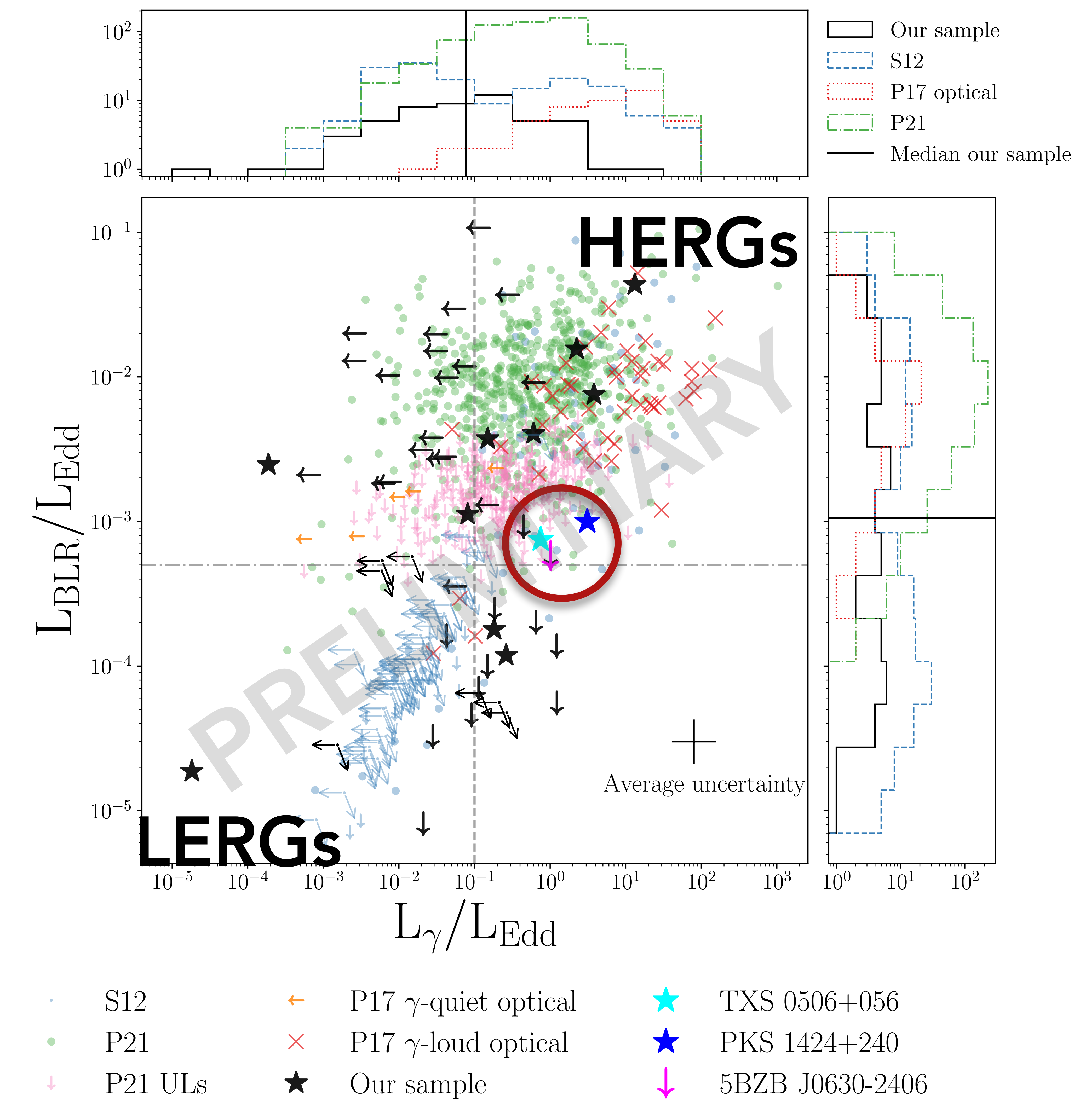
- 50% with Fermi-LAT detection:

  $L_\gamma \in \left[1.43 \times 10^{42}, 1.21 \times 10^{48}\right]$ erg $\cdot$ s^{-1}

- **Compatible** with overall population of blazars (Anderson-Darling statistical test)

Azzollini et al., submitted

Comparison samples:
Sbarrato et al. (2012, S12)
Paliya et al. (2017, P17)
Paliya et al. (2021, P21)



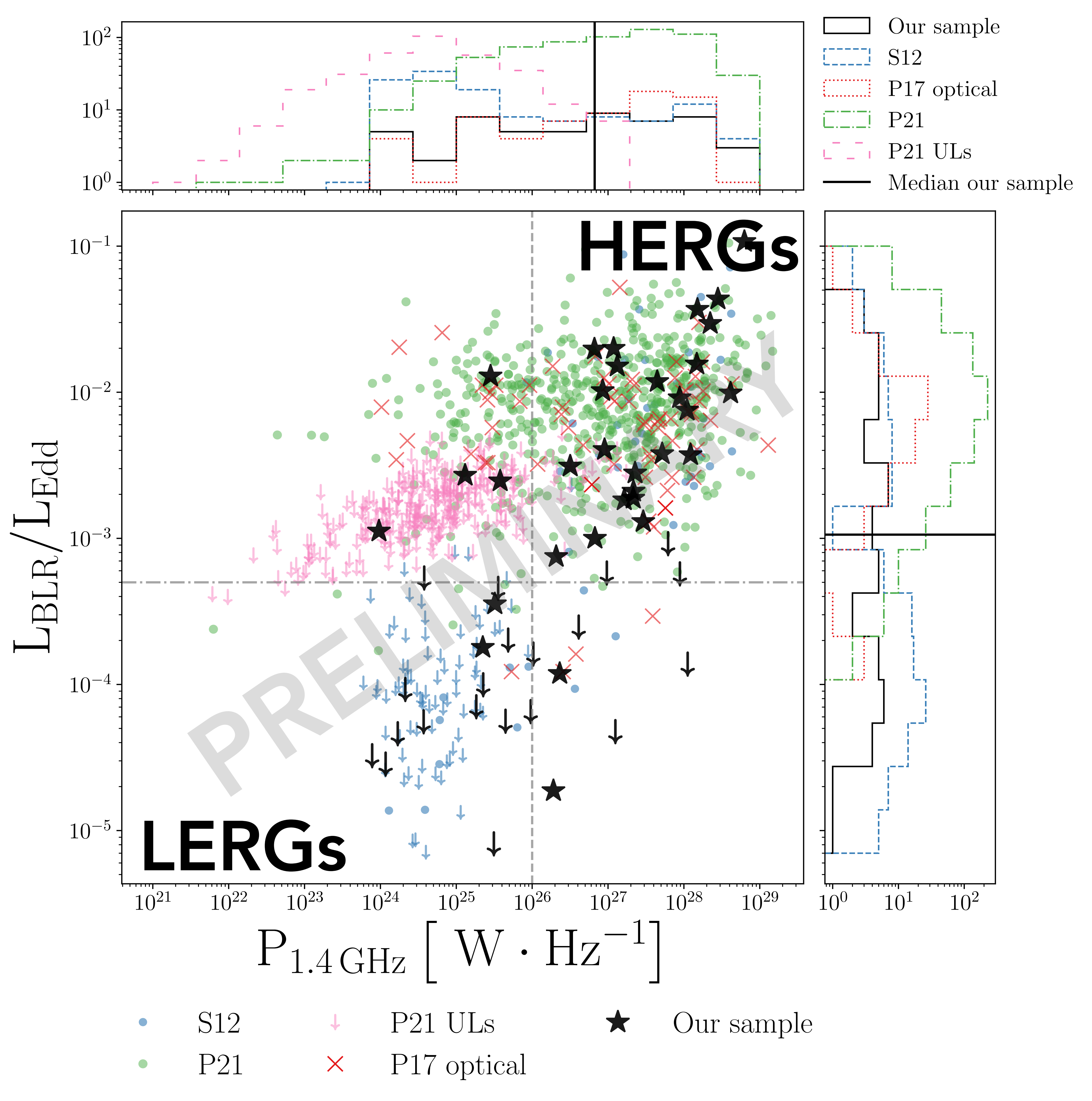
Results: the radio power

L_{BLR}/L_{Edd} vs . $P_{1.4\,GHz}$

- Mild tendency towards *powerful jets* and *high radio power*:

  ~60% HERG-like

- **Compatible** with overall population of blazars (Anderson-Darling statistical test)



Azzollini et al., submitted

Comparison samples:
Sbarrato et al. (2012, S12)
Paliya et al. (2017, P17)
Paliya et al. (2021, P21)

Results: the radio power

L_{BLR}/L_{Edd} vs . $P_{1.4\,GHz}$

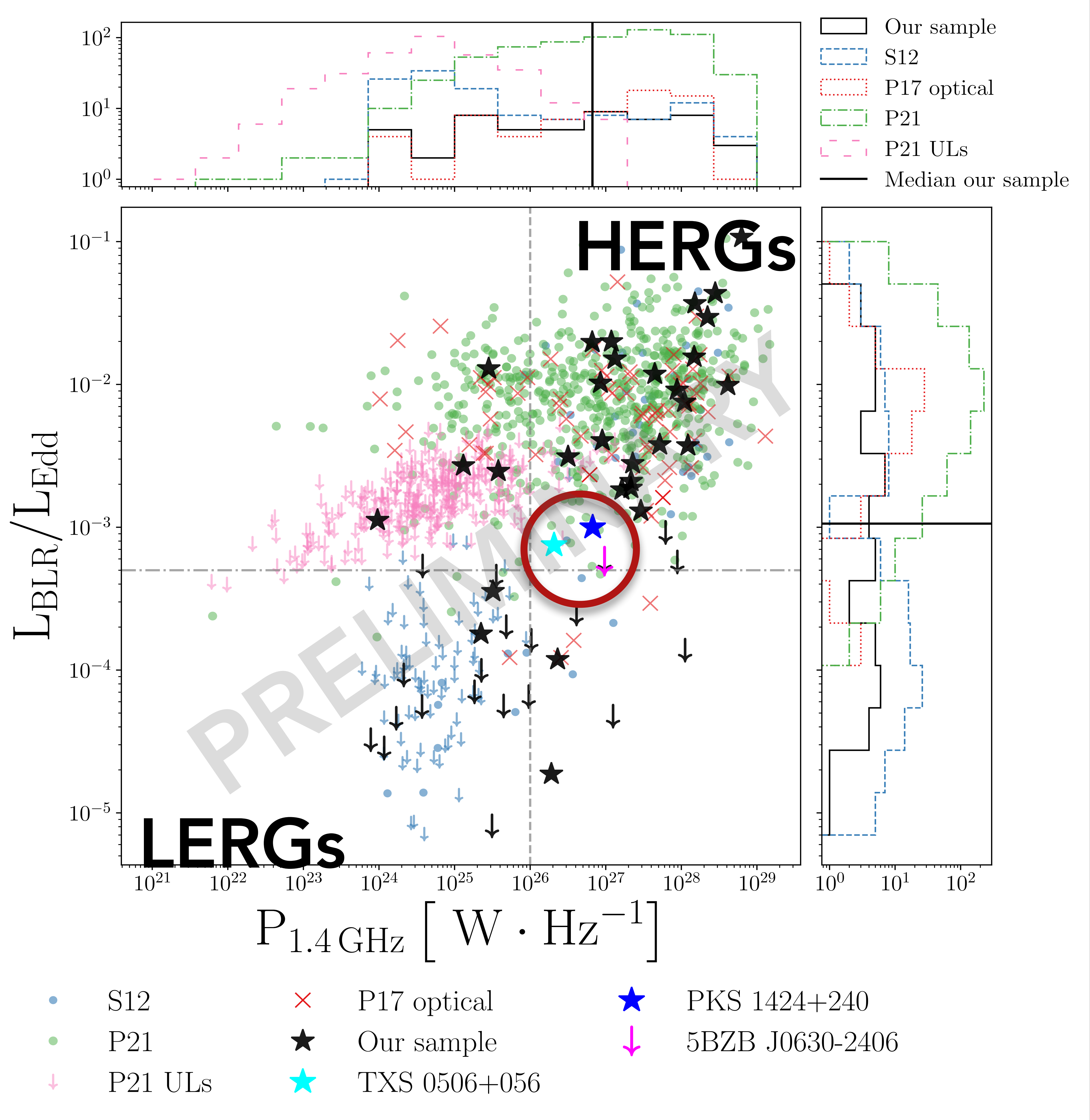
- Mild tendency towards *powerful jets* and *high radio power*:

  ~60% HERG-like

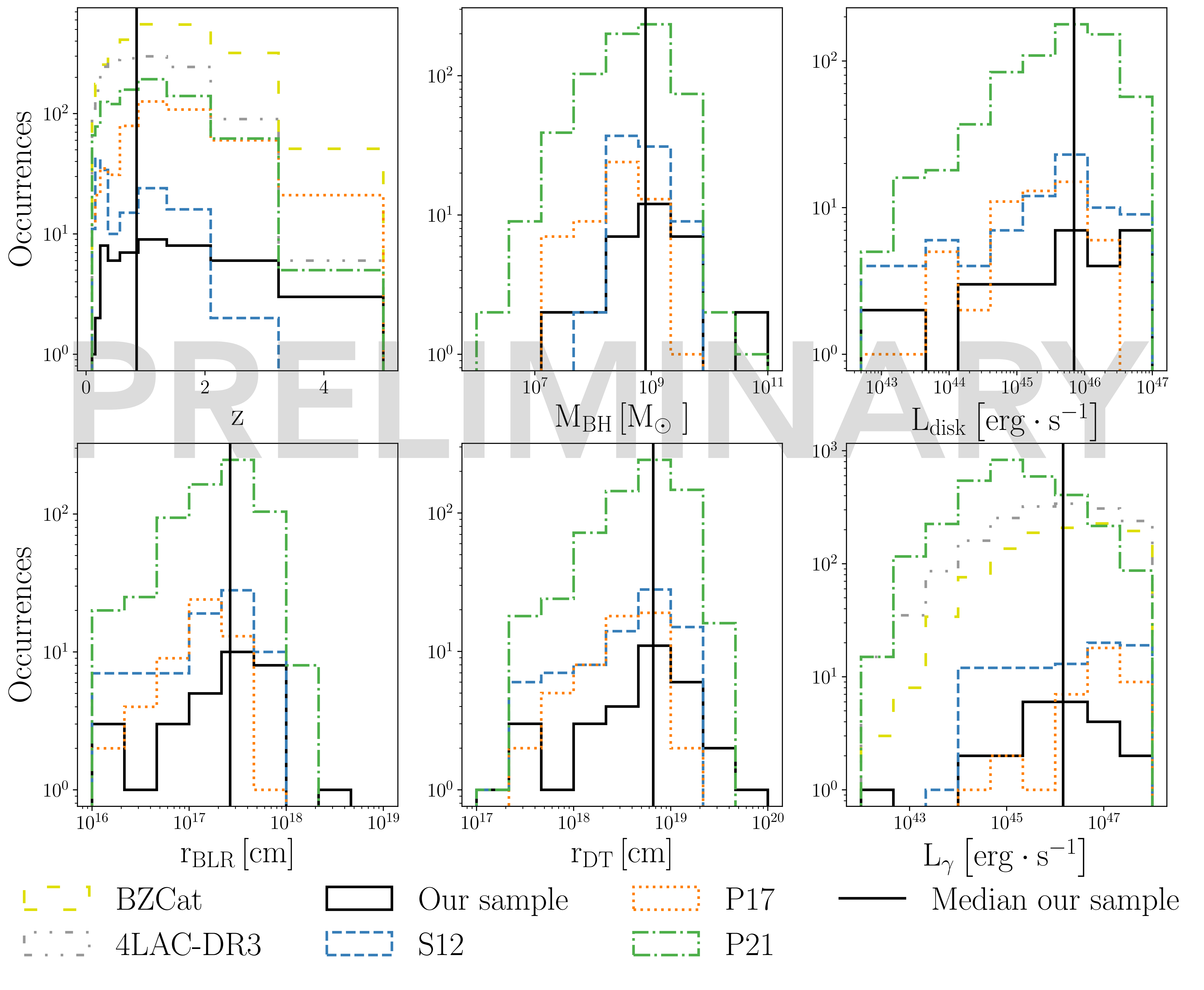
- **Compatible** with overall population of blazars (Anderson-Darling statistical test)

Azzollini et al., submitted

Comparison samples:
Sbarrato et al. (2012, S12)
Paliya et al. (2017, P17)
Paliya et al. (2021, P21)



Results: other properties



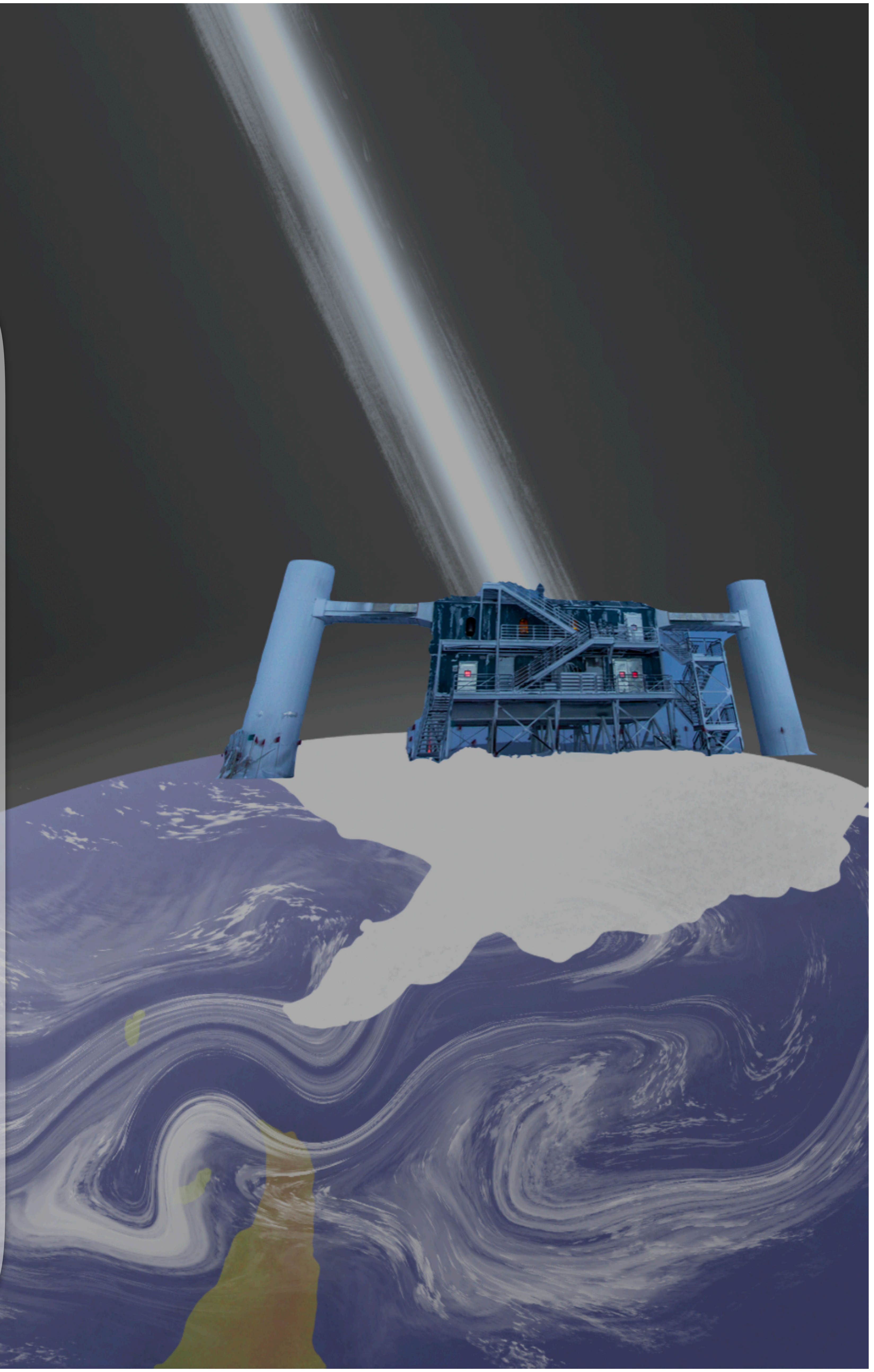
Azzollini et al., submitted

Summary

- A subsample of blazars proposed as associated with IceCube neutrino hotspots.

- Multi-wavelength analysis:
  - Proprietary and archival data.
  - Optical spectroscopy: key tool to study the intrinsic physical properties.
  - Mild tendency toward radiatively efficient accretion, strong external radiation fields and powerful relativistic jets (HERGs).
  - Compatible with the overall population of blazars.

- No definitive conclusions can be drawn from the full candidates sample.
  - Forthcoming dedicated studies tackling the genuineness of the associations.



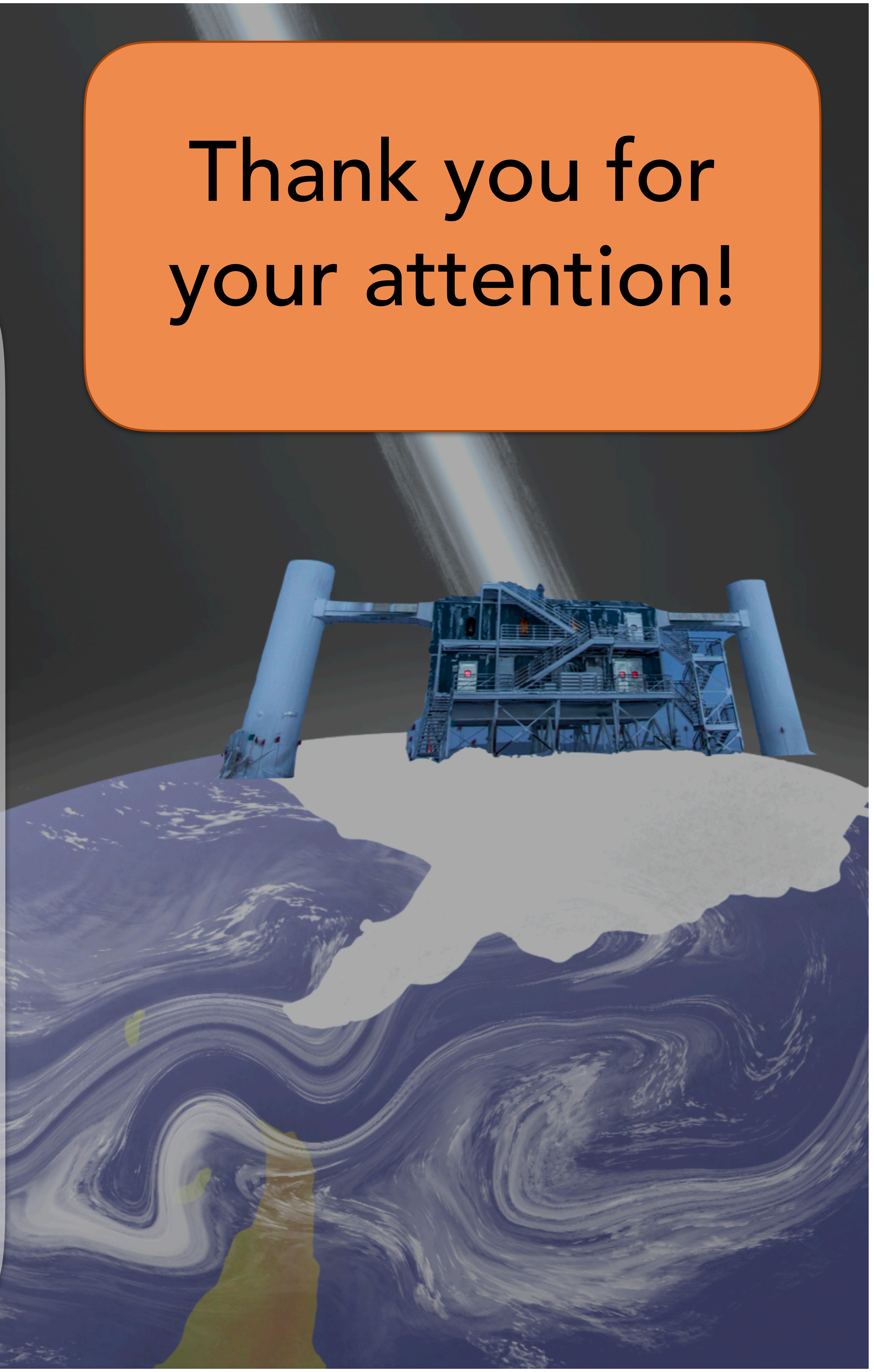
Summary

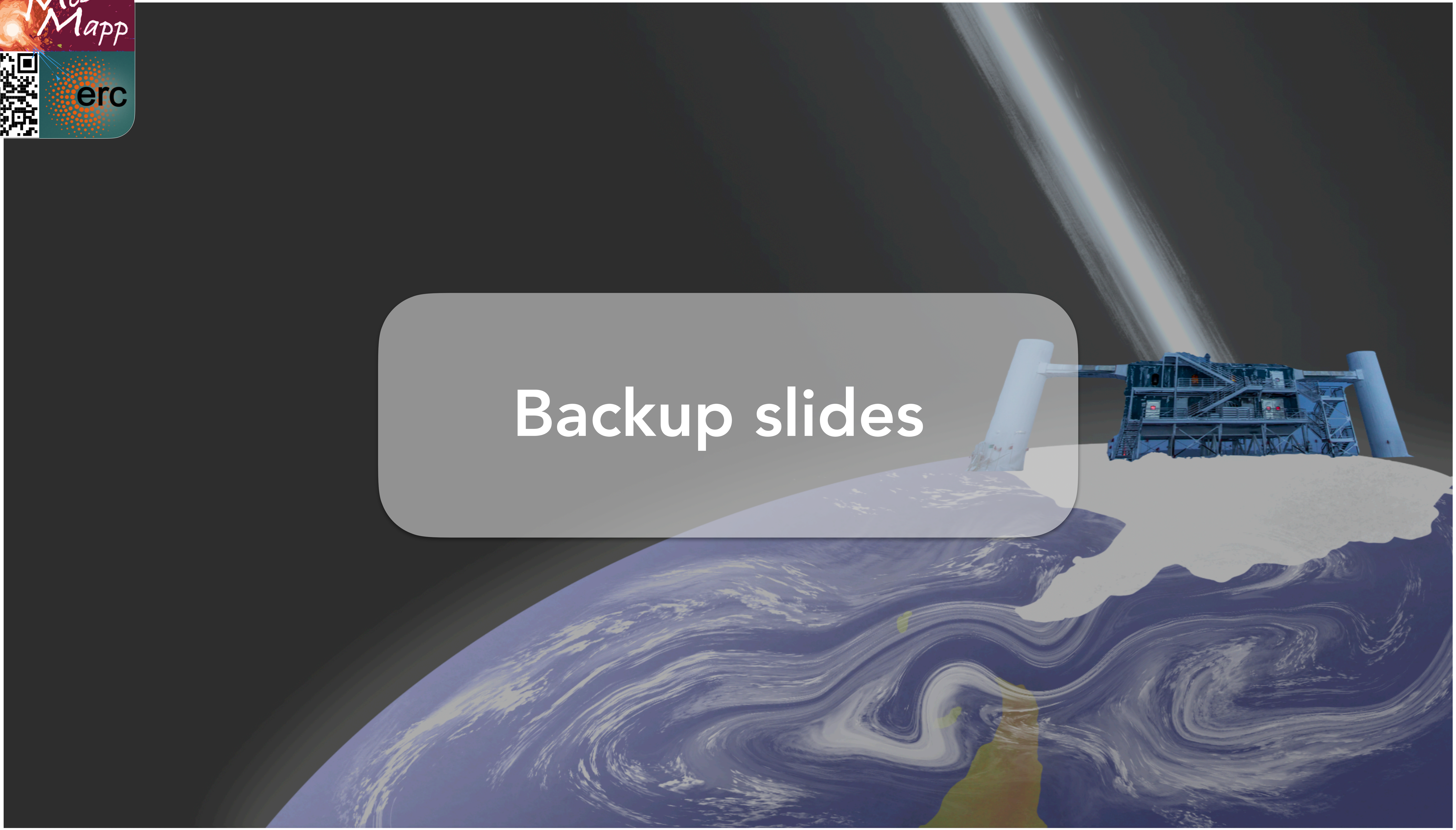
- A subsample of blazars proposed as associated with IceCube neutrino hotspots.

- Multi-wavelength analysis:
  - Proprietary and archival data.
  - Optical spectroscopy: key tool to study the intrinsic physical properties.
  - Mild tendency toward radiatively efficient accretion, strong external radiation fields and powerful relativistic jets (HERGs).
  - Compatible with the overall population of blazars.

- No definitive conclusions can be drawn from the full candidates sample.
  - Forthcoming dedicated studies tackling the genuineness of the associations.

Thank you for your attention!

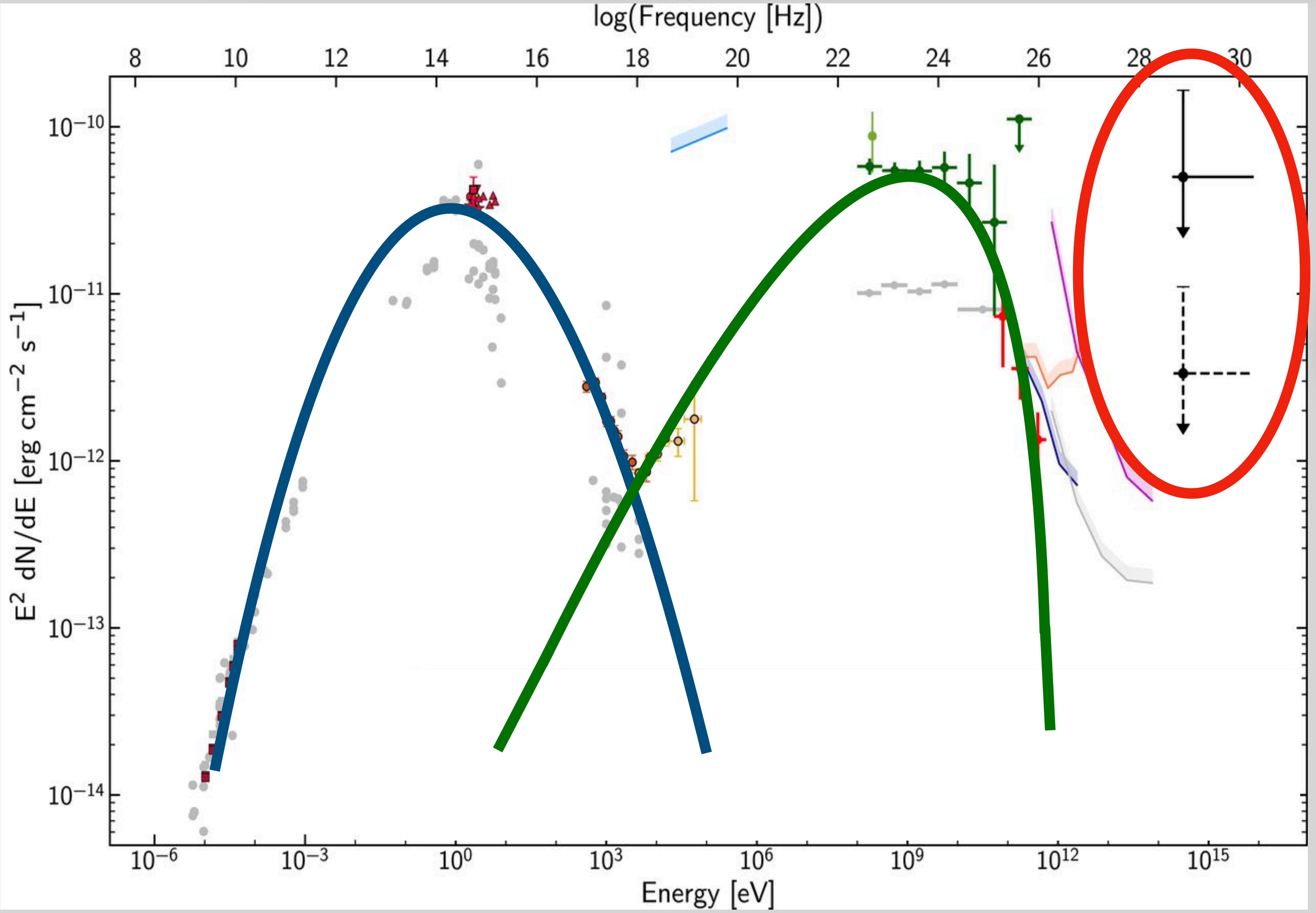




Backup slides

Blazar properties: the spectral energy distribution (SED)

Double-humped shape



SED of TXS 0506+056

IceCube Collaboration (2018)

Leptonic scenario

First peak
Low energy (IR - XRs)
Synchrotron radiation

Second peak
High energy (hard XRs - ɣ-rays)
Inverse Compton radiation

Lepto-hadronic/
Hadronic scenario

Hadrons contribution to the MWL SED

Neutrinos

The production of neutrinos in blazars

p-ɣ interaction

$$p + \gamma \rightarrow \begin{cases} n + \pi^+ \\ p + \pi^0 \end{cases}$$

p-p interaction

$$p + p \rightarrow \begin{cases} p + p + \pi^0 \\ p + n + \pi^+ \\ p + p + \pi^+ + \pi^- + \dots \end{cases}$$

$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

Blazars' relativistic jets are able to accelerate electrons and hadrons

Mannheim (1993)
Böttcher et al. (2013)
Dermer et al. (2014)

The physical properties estimation

$$z \implies d \implies L_{\rm line} = 4 \cdot \pi \cdot d^2 \cdot F_{\rm line}$$

$$\log\left(\frac{M_{\rm BH}}{M_\odot}\right) = \mathrm{a} + \mathrm{b} \cdot \log\left(\frac{\lambda \cdot \mathrm{L}}{10^{44}\ \mathrm{erg \cdot s^{-1}}}\right) + \mathrm{c} \cdot \log\left(\frac{\mathrm{FWHM}}{\mathrm{km \cdot s^{-1}}}\right)$$

$$(\mathrm{a,b,c}) = \begin{cases} (0.379, 0.43, 2.1) & \text{for H}\alpha\,, \\ (0.672, 0.61, 2.0) & \text{for H}\beta\,, \\ (0.740, 0.62, 2.0) & \text{for Mg II}\,, \\ (0.660, 0.53, 2.0) & \text{for C IV}\,, \end{cases}$$

$$L_{\rm BLR} = L_{\rm line} \cdot \frac{< L_{\rm BLR} >}{L_{\rm rel.\,frac.}} \sim 10\,\%\, L_{\rm disk}$$

$$\mathrm{L_{rel.frac.}} = \begin{cases} 77 & \text{for H}\alpha\,, \\ 22 & \text{for H}\beta\,, \\ 34 & \text{for Mg II}\,, \\ 63 & \text{for C IV}\,, \end{cases}$$

$$L_{\rm Edd} = 3 \times 10^4 \cdot \left(\frac{M}{M_\odot}\right) \cdot L_\odot$$

$$r_{\rm BLR} = 10^{17} \cdot \left(\frac{L_{\rm disk}}{10^{45}\ \mathrm{erg \cdot s^{-1}}}\right)^{1/2}\ \mathrm{cm}$$

$$r_{\rm DT} = 2 \times 10^{18} \cdot \left(\frac{L_{\rm disk}}{10^{45}\ \mathrm{erg \cdot s^{-1}}}\right)^{1/2}\ \mathrm{cm}$$

Francis et al. (1991; Celotti et al. (1997; Sbarrato et al. (2012) Ghisellini et al. (2014); Shen et al. (2011) McLure & Dunlop (2004); Vestergaard & Osmer (2009); Ghisellini & Tavecchio (2008); Ghisellini et al. (2017)

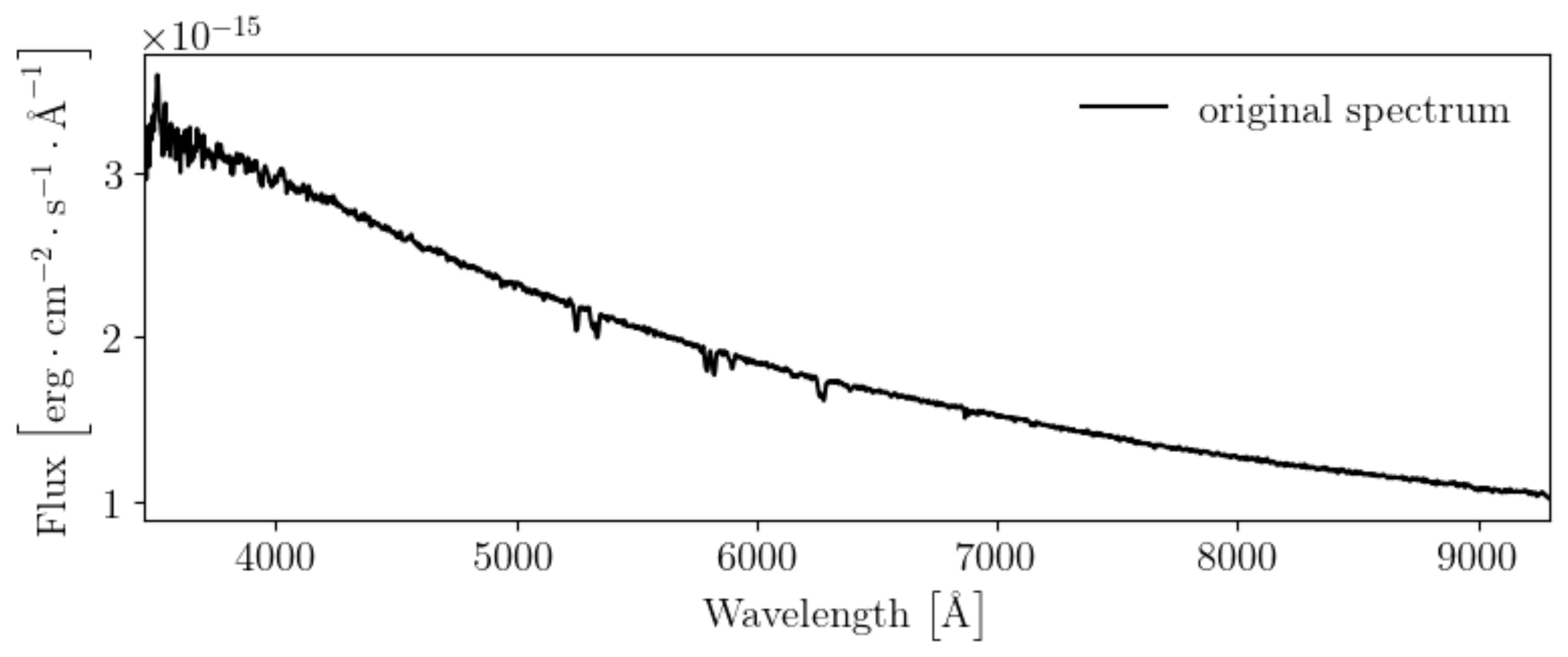
Upper limits on the not-detected lines

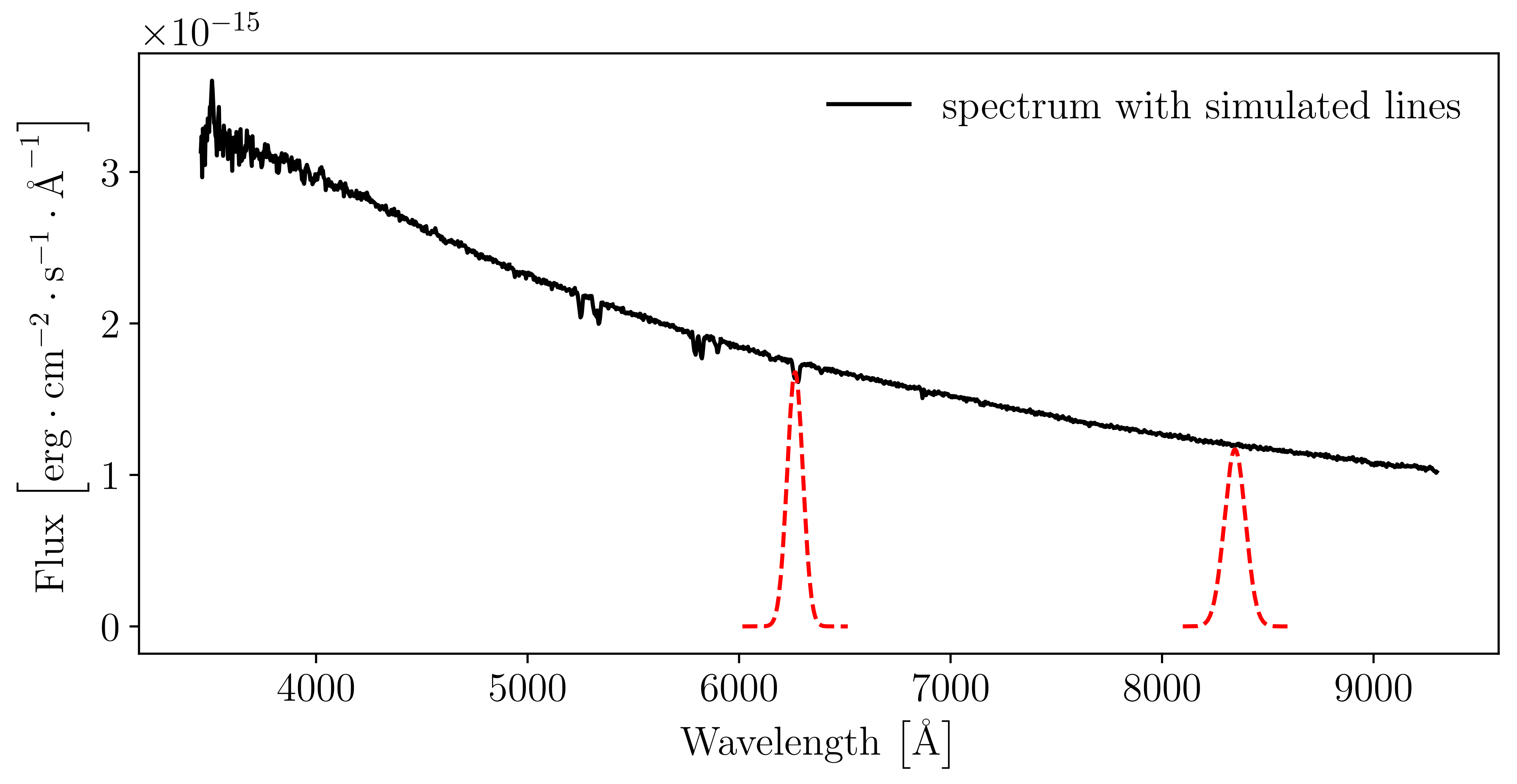
Power-law fit of *continuum* in range 500 Å around expected line position

Line as additional **Gaussian** with $v_{\mathrm{FWHM}} = 4000\,\mathrm{km}\cdot\mathrm{s}^{-1}$ and variable F_{line}

Accept F_{line} *when* $\chi^2 < \chi^2\,(99\,\%)$

Sbarrato et al. (2012)
Azzollini et al., submitted





Probing the intrinsic power of the relativistic jet

Complementary information at radio and ɣ-rays

Radio power at 1.4 GHz

NVSS, FIRST catalogs

HERG/LERG dividing value:

$$P_{1.4\,\mathrm{GHz}} \sim 10^{26}\,\mathrm{W \cdot Hz^{-1}}$$

Best & Heckman (2014)

ɣ-ray luminosity

Fermi-LAT 4LAC-DR3 catalog

HERG/LERG dividing value:

$$L_\gamma / L_{\mathrm{Edd}} \sim 0.1$$

The comparison samples

S12

Blazars with SDSS-DR7 spectrum and 1LAC counterpart; BL Lacs from Plotkin et al. (2011) with no Fermi-LAT detection; intermediate objects between FSRQs/BL Lacs with 1LAC counterpart

Measurements + upper limits in both optical, ɣ-rays

Sbarrato et al. (2012)

P17

Blazars from CGRaBS with counterpart in a Fermi catalog up to 3FGL

ɣ-loud, ɣ-quiet

Several methods to derive physical properties:
54 sources via optical spectroscopy (emission lines)

Only measurements in optical, measurements + upper limits in ɣ-rays

Paliya et al. (2017)

P21

Blazars from 4FGL-DR3 with SDSS-DR16 counterpart

Only measurements in ɣ-rays, measurements + upper limits in optical

Paliya et al. (2021)

The results of the Anderson-Darling test

Quantity	Compared samples	# sources	pvalue
$L_{\rm BLR}/L_{\rm Edd}$	Our sample vs. P21	32 vs. 664	$< 10^{-3}$ ($> 3.29\sigma$)
	Our sample vs. P17	32 vs. 54	0.14 (1.48σ)
	Our sample vs. S12	32 vs. 79	0.25 (1.15σ)
$L_\gamma\,[{\rm erg\cdot s^{-1}}]$	our sample vs. P21	26 vs. 1006	0.25 (1.15σ)
	our sample vs. P17	26 vs. 314	$< 10^{-3}$ ($> 3.29\sigma$)
	our sample vs. S12	26 vs. 101	0.07 (1.78σ)
	our sample vs. BZCat	26 vs. 1137	0.17 (1.36σ)
	our sample vs. 4LAC-DR3	26 vs. 1872	0.25 (1.15σ)
$P_{1.4\,{\rm GHz}}\,[{\rm W\cdot Hz^{-1}}]$	our sample vs. P21	52 vs. 966	0.09 (1.69σ)
	our sample vs. P17	52 vs. 468	0.02 (2.23σ)
	our sample vs. S12	52 vs. 126	$< 10^{-3}$ ($> 3.29\sigma$)
	our sample vs. BZCat	52 vs. 2799	0.25 (1.15σ)
z	our sample vs. P21	50 vs. 1006	0.05 (1.97σ)
	our sample vs. P17	50 vs. 505	0.05 (1.99σ)
	our sample vs. S12	50 vs. 163	$< 10^{-3}$ ($> 3.29\sigma$)
	our sample vs. BZCat	50 vs. 2803	0.25 (1.15σ)
	our sample vs. 4LAC-DR3	50 vs. 1872	0.01 (2.68σ)
$L_\gamma/L_{\rm Edd}$	our sample vs. P21	12 vs. 664	0.22 (1.24σ)
	our sample vs. P17	12 vs. 49	1.15×10^{-3} (3.25σ)
	our sample vs. S12	12 vs. 79	0.12 (1.55σ)
$L_{\rm disk}\,[{\rm erg\cdot s^{-1}}]$	our sample vs. P21	32 vs. 664	0.09 (1.70σ)
	our sample vs. P17	32 vs. 54	3.16×10^{-3} (2.95σ)
	our sample vs. S12	32 vs. 79	0.18 (1.35σ)
$M_{\rm BH}\,[M_\odot]$	our sample vs. P21	32 vs. 664	0.01 (2.46σ)
	our sample vs. P17	32 vs. 54	$< 10^{-3}$ ($> 3.29\sigma$)
	our sample vs. S12	32 vs. 79	0.02 (2.34σ)
$r_{\rm BLR}$ [cm]	our sample vs. P21	32 vs. 664	0.09 (1.67σ)
	our sample vs. P17	32 vs. 54	3.19×10^{-3} (2.95σ)
	our sample vs. S12	32 vs. 79	0.18 (1.34σ)
$r_{\rm DT}$ [cm]	our sample vs. P21	32 vs. 664	0.09 (1.68σ)
	our sample vs. P17	32 vs. 54	3.16×10^{-3} (2.95σ)
	our sample vs. S12	32 vs. 79	0.19 (1.32σ)

Azzollini et al., submitted