PhD Summer School on Neutrinos

Here, There & Everywhere

July 17-21, 2023

Niels Bohr Institute, Copenhagen

# Studying the physical properties of the engines of neutrino-emitter blazars


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On behalf of: Sara Buson, Alexis Coleiro, Gaëtan Fichet de Clairfontaine, Vardan Baghmanyan, Leonard Pfeiffer, Lenz Oswald, Eleonora Barbano, Stefano Marchesi, Andrea Tramacere


July 18th, 2023

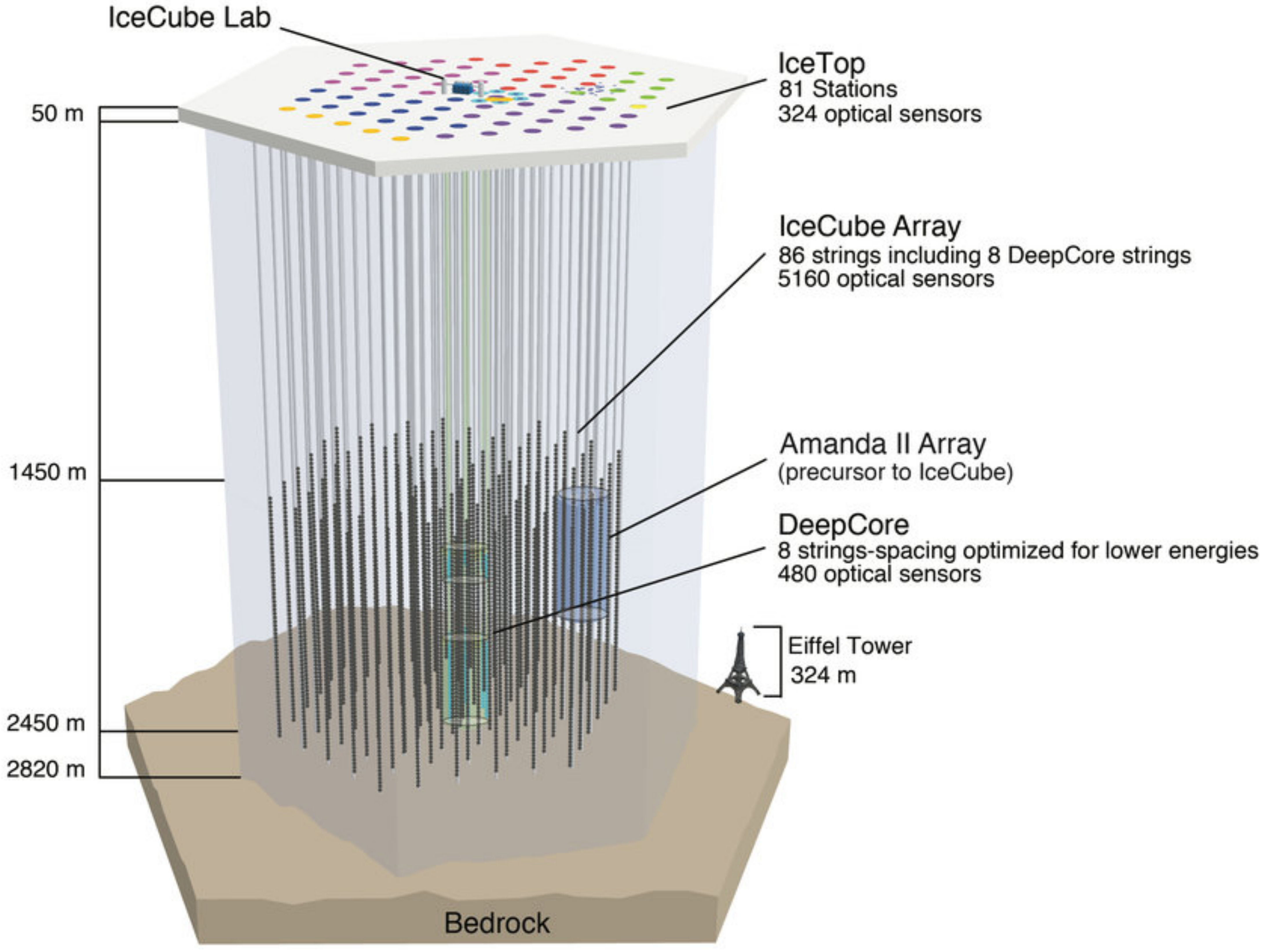
Copenhagen

# The puzzle of high-energy neutrinos

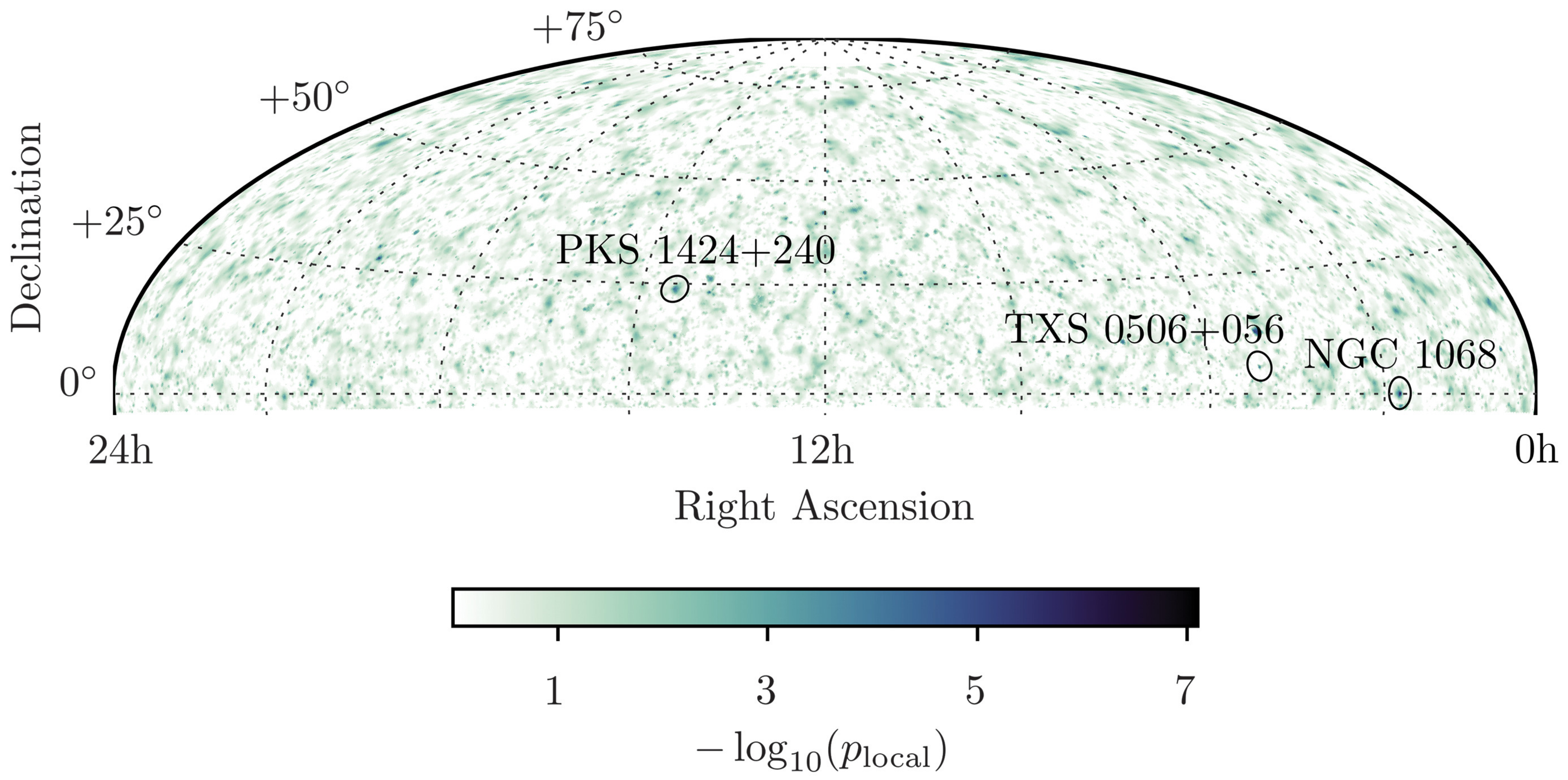
Nearly massless

Very challenging to detect

Indirect probes of cosmic-rays




Credits: IceCube Collaboration



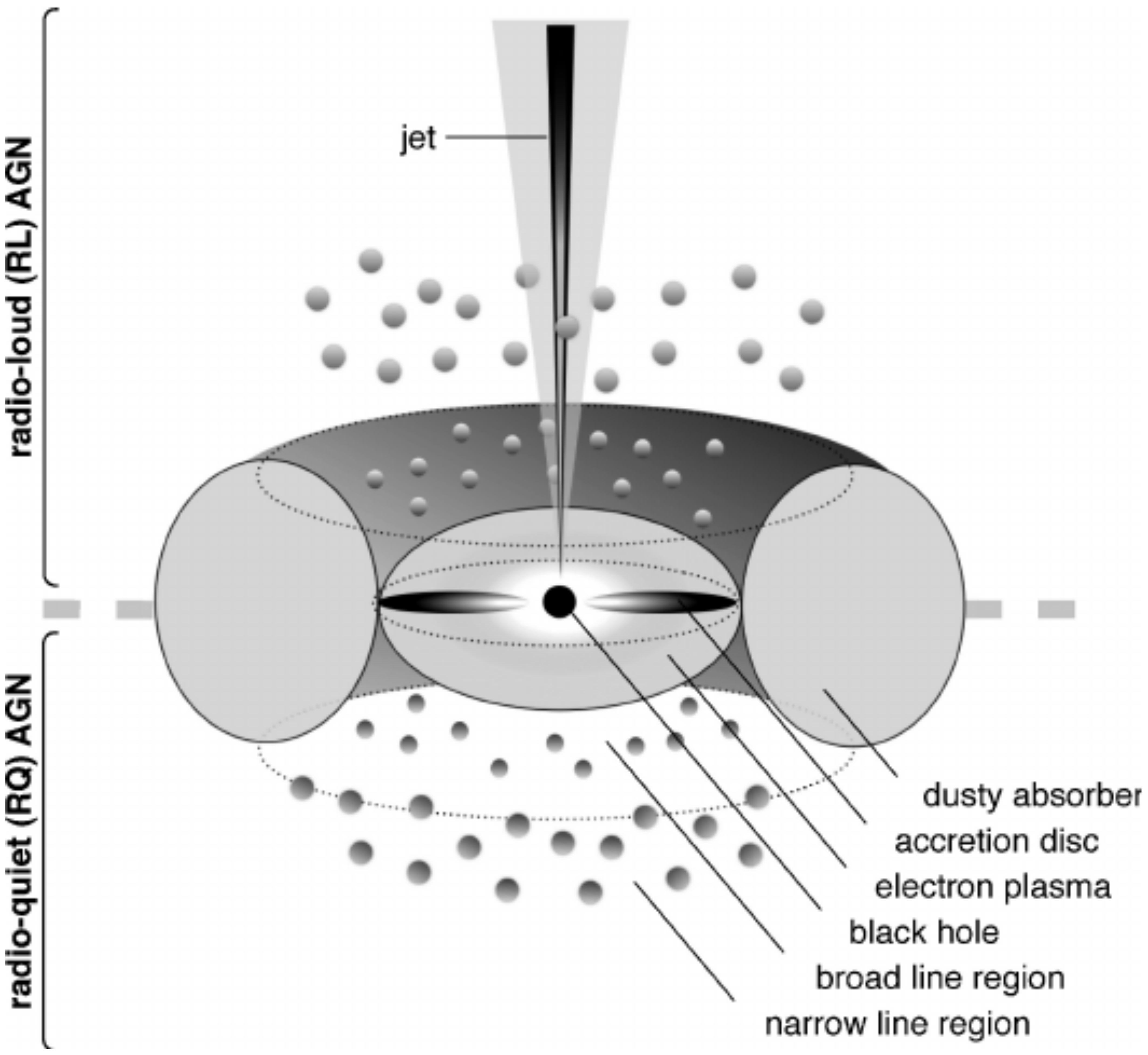

IceCube Collaboration (2022), Science 378, I6619, pp.538-543

Yet to be unveiled:

Which astrophysical **sources** produce them

Which **processes** originate them

# Active Galactic Nuclei (AGN): the unified model




Beckmann & Shrader (2012), Active Galactic Nuclei, Wiley-VCH Verlag GmbH
Urry & Padovani (1995), Publications of the Astronomical Society of the Pacific, v.107, p.803

Accretion onto a supermassive black hole

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

Very powerful objects

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

Emission up to ~ Mpc scales

Rapid variability ~ min - yr

The 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, $\gamma$-rays - non-thermal jet related radiation

# The classification of radio-loud blazars

**Flat spectrum radio quasars (FSRQs)**

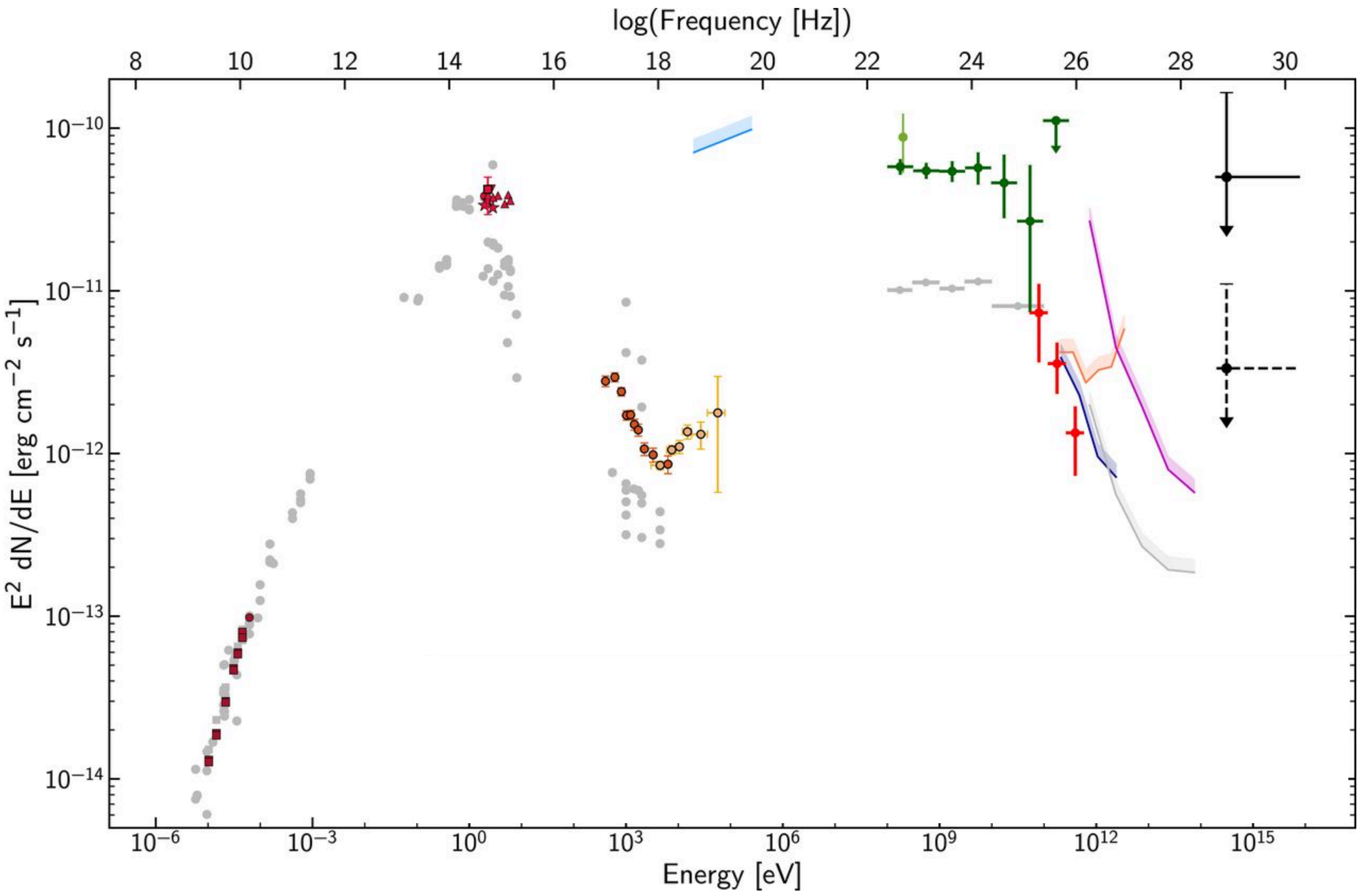
- *Prominent* emission lines in the optical spectrum
- *Highly* beamed jets closely aligned with line of sight
- *High* radio luminosities
- *High* redshifts
- *High* accretion efficiency ("cold-mode")
- *Less massive* black holes

**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), Annual Review of Astronomy and Astrophysics, Vol. 52:589-660

# Blazars properties: the spectral energy distribution (SED)




SED of TXS 0506+056

IceCube Collaboration (2018), Science, v. 361, I6398, id. eaat1378

**Double-humped** shape

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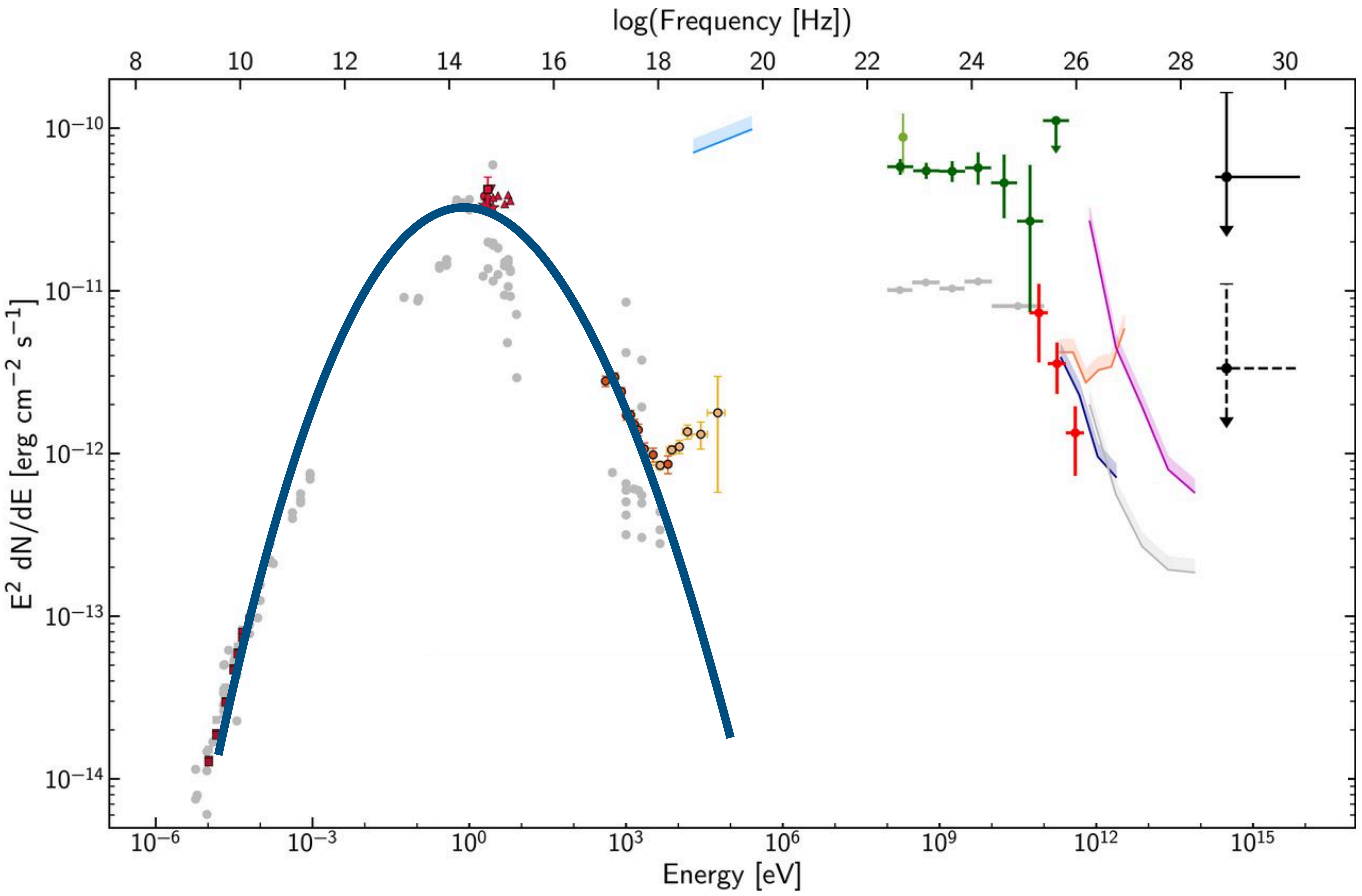


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**Leptonic** scenario

**First peak**

- Low-energy (IR - X-rays)
- **Synchrotron** radiation

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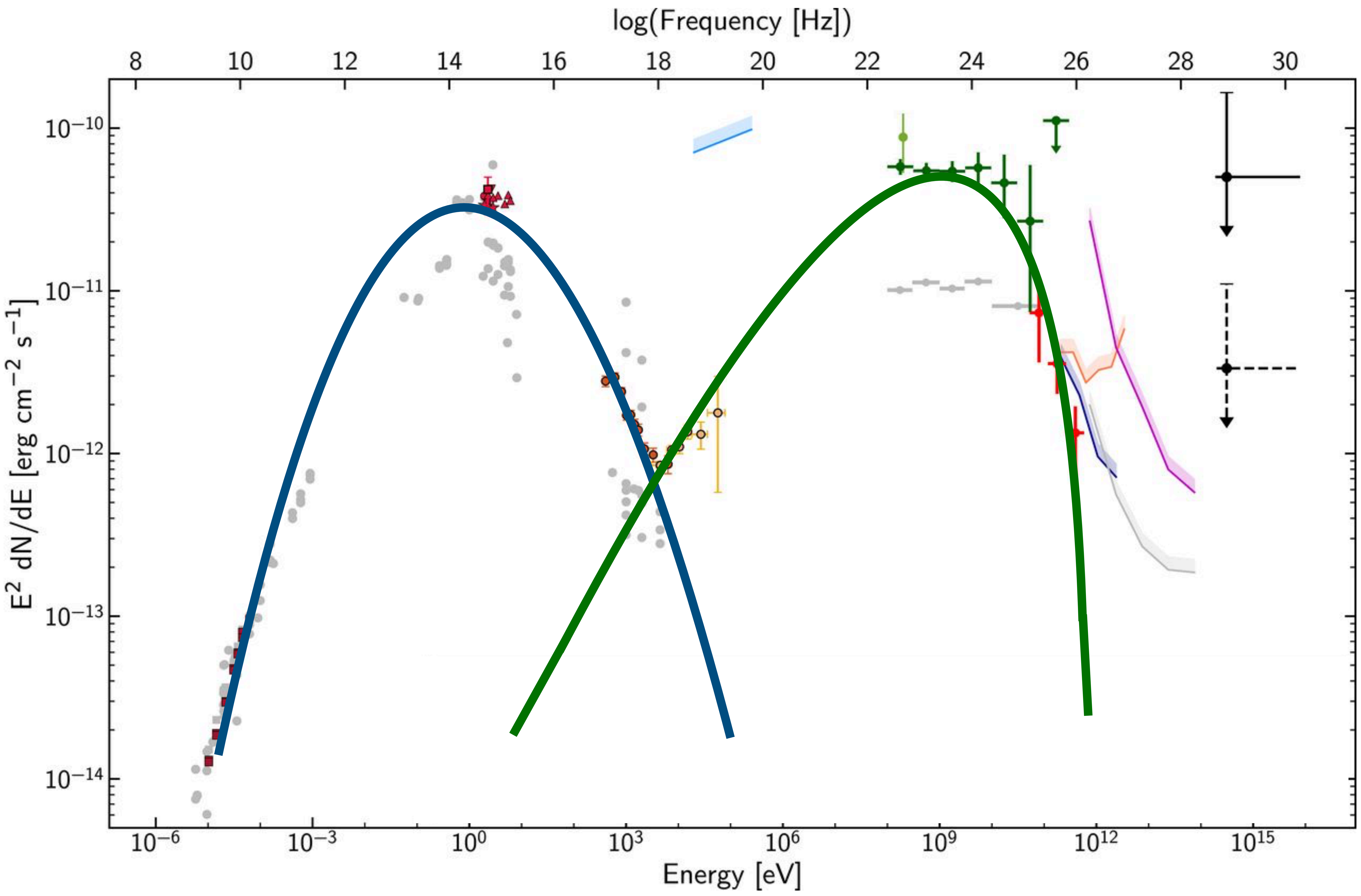


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**Second peak**

- High-energy (X-rays/$\gamma$-rays)
- **Inverse Compton** radiation

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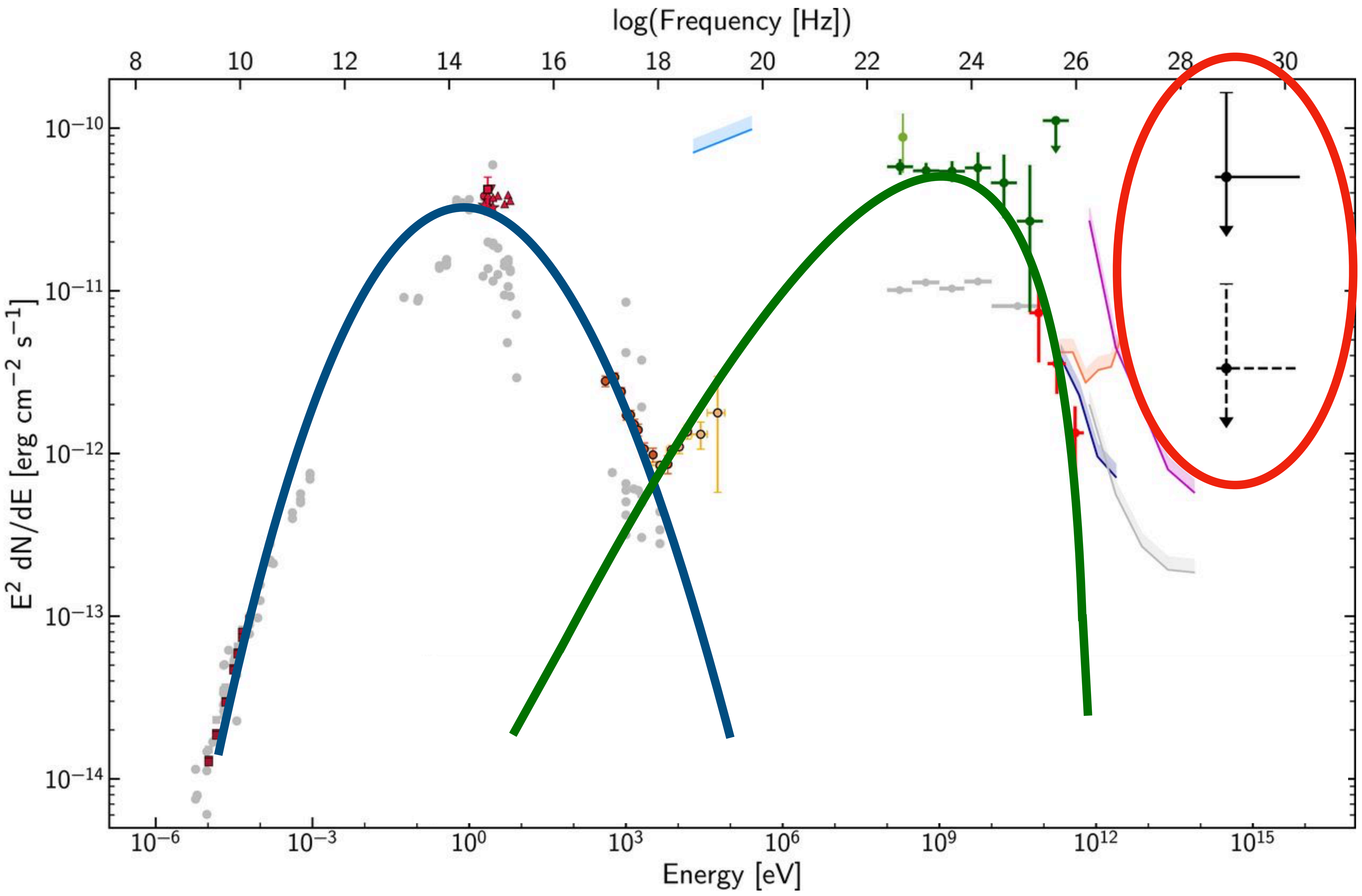


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- Synchrotron radiation

Second peak

- High-energy (X-rays/$\gamma$-rays)
- Inverse Compton radiation

**Lepto-hadronic / hadronic** scenario

Hadrons contribution to the multi-wavelength SED

+

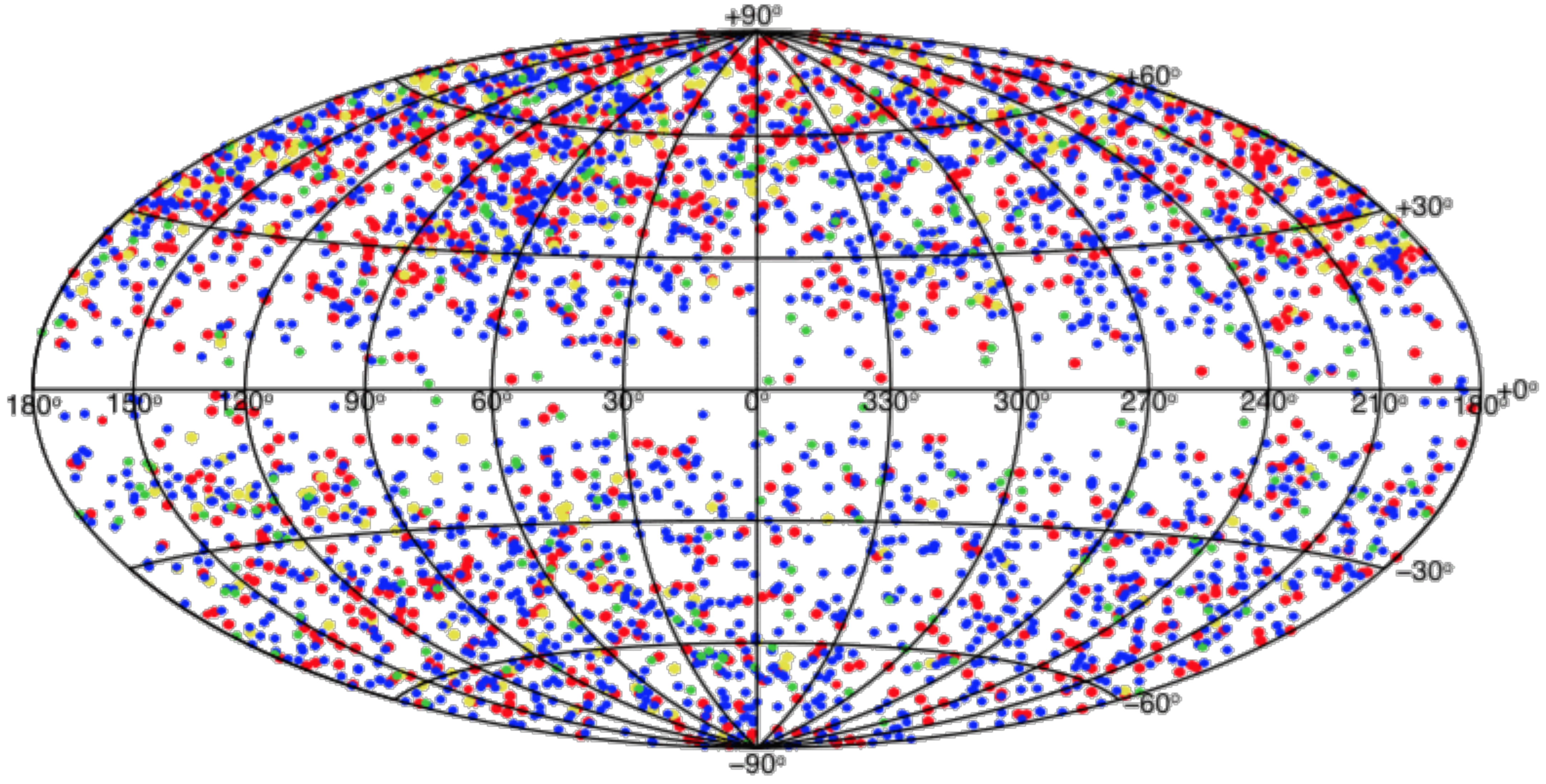
**neutrinos**

# The connection between neutrinos and blazars: further clues

The "PeVatron blazars" sample

Based on positional cross-correlation statistical analysis between 5BZCat and IceCube data

52 5BZCat blazars




Massaro et al. (2015), Astrophysics and Space Science, Vol. 357, I1, 75

Buson et al. (2022), Astrophysical Journal Letters, Vol. 933, I2, L43
Buson et al. (2022), Astrophysical Journal Letters, Vol. 934, I2, L38
Buson et al. (2023), submitted, eprint arXiv:2305.11263

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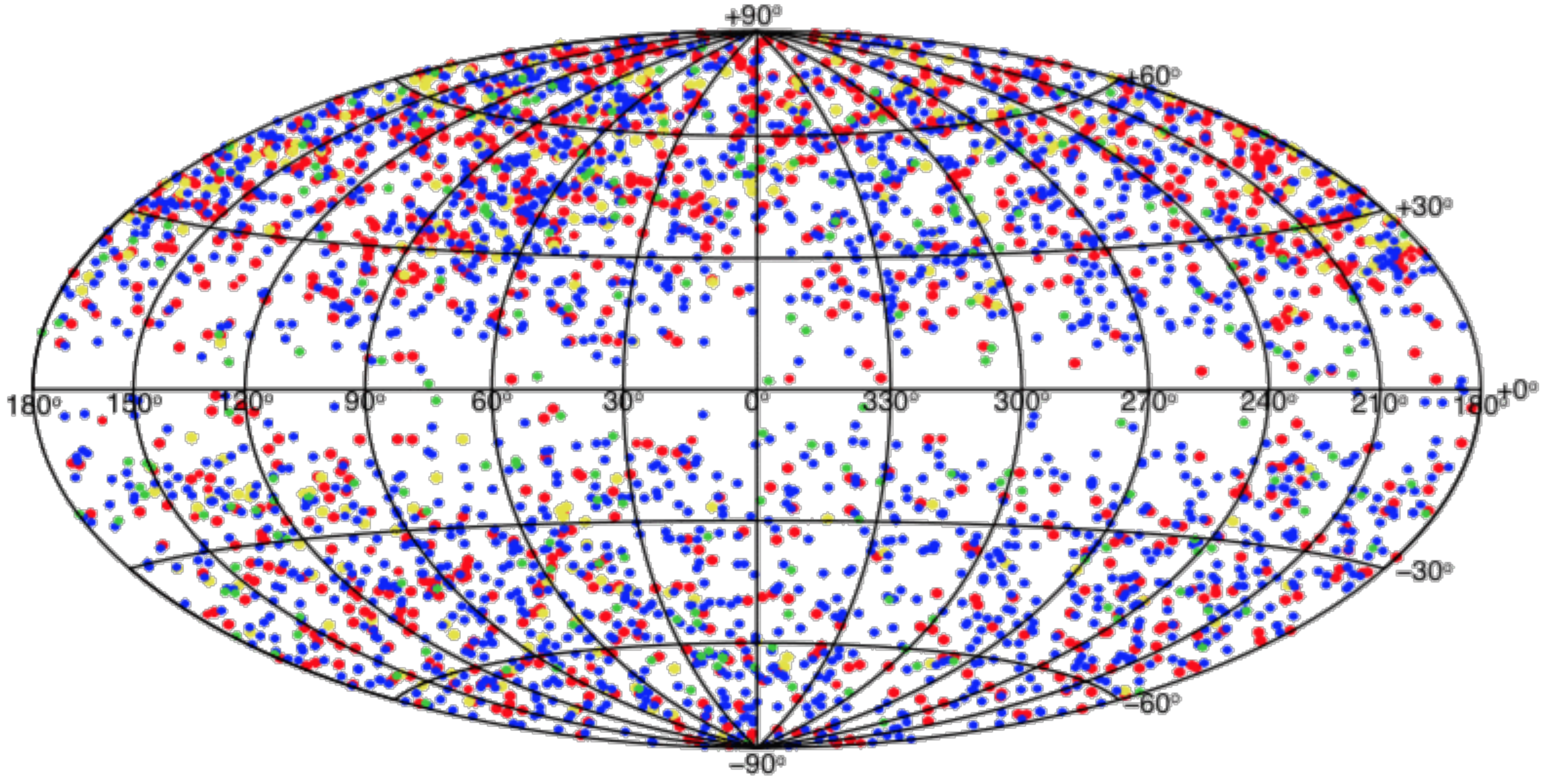
52 5BZCat blazars

10 Southern
$-85^\circ < \delta < -5^\circ$

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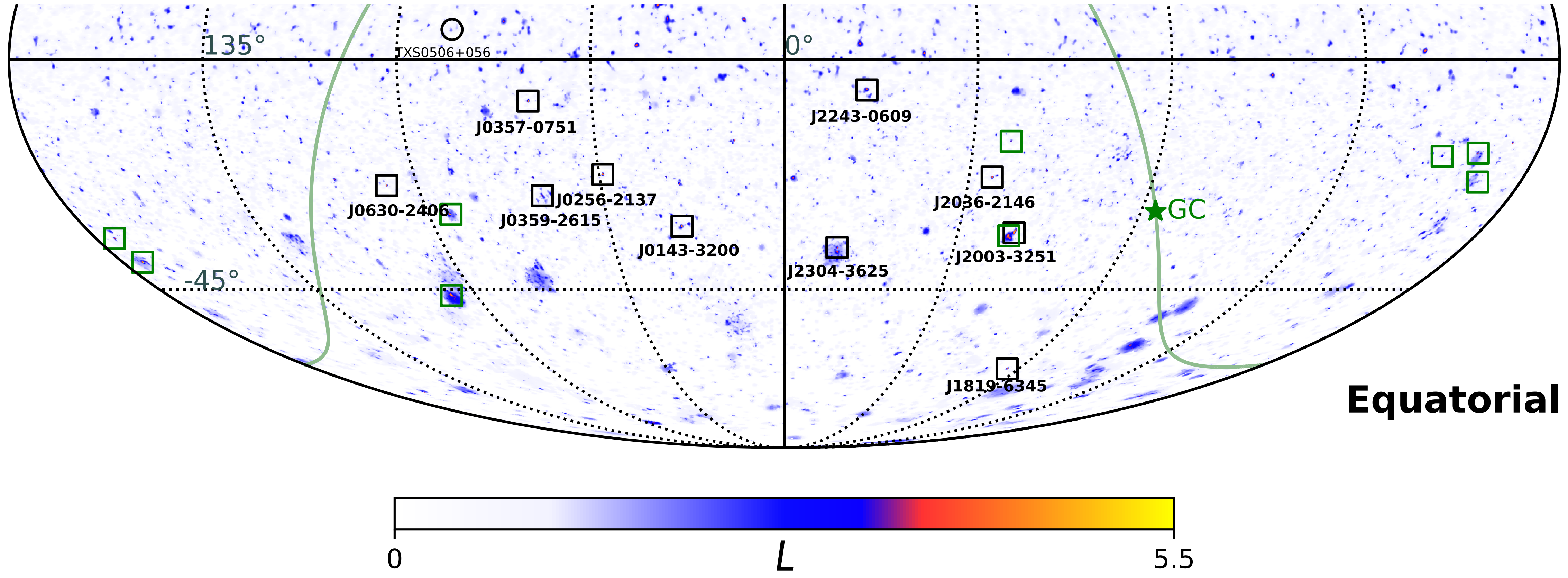


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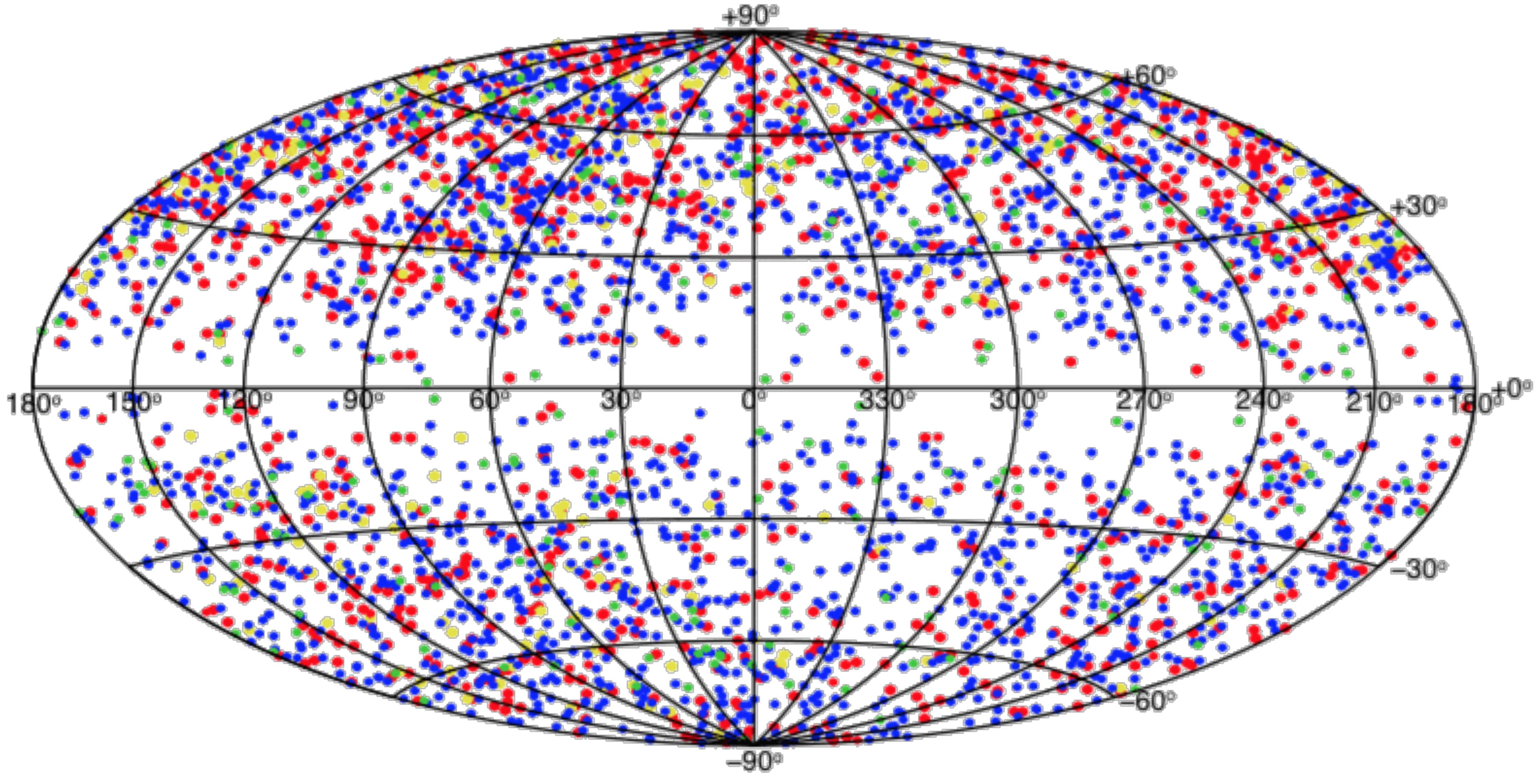
# The connection between neutrinos and blazars: further clues

The “PeVatron blazars” sample

52 5BZCat blazars

→ 42 Northern $-3^\circ \leq \delta \leq 81^\circ$

→ 10 Southern $-85^\circ < \delta < -5^\circ$

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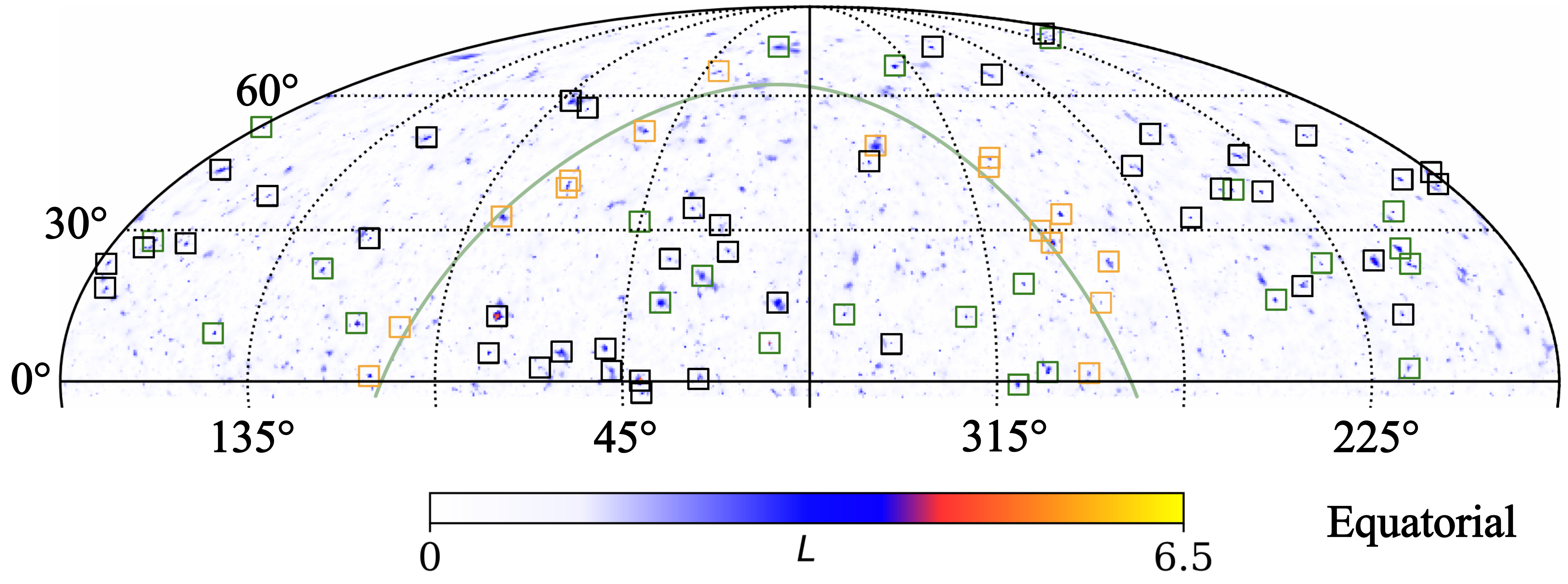


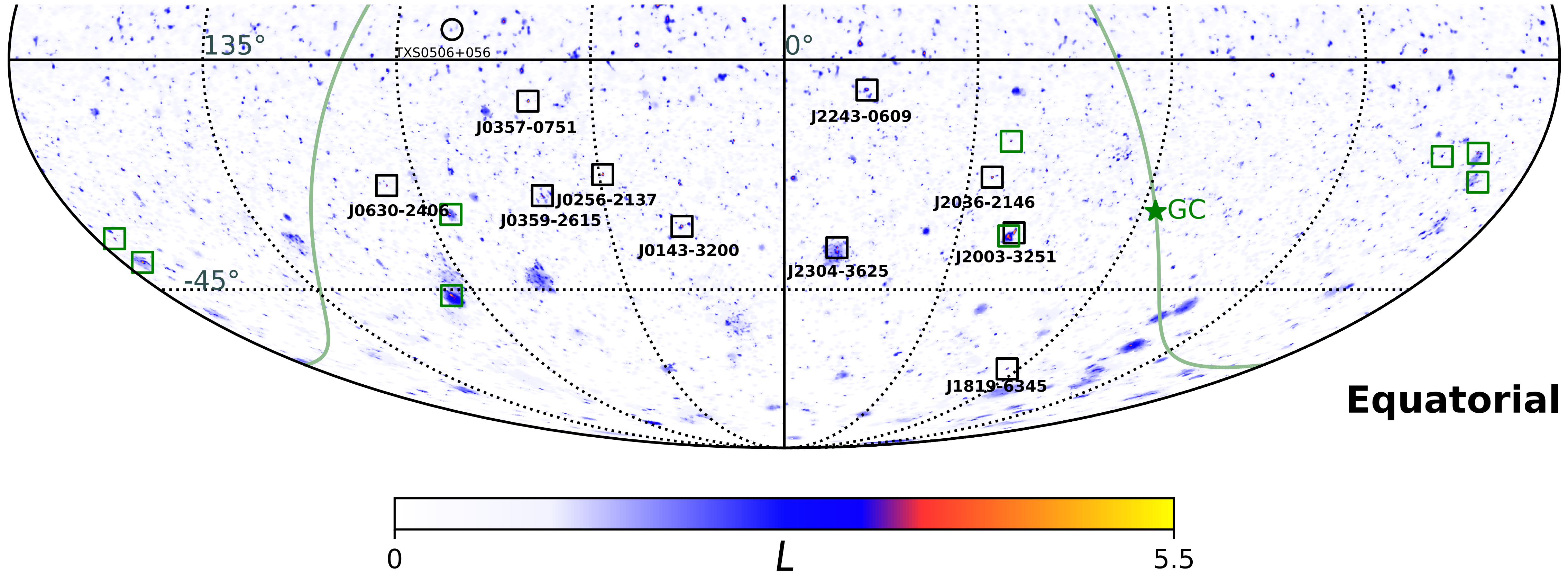


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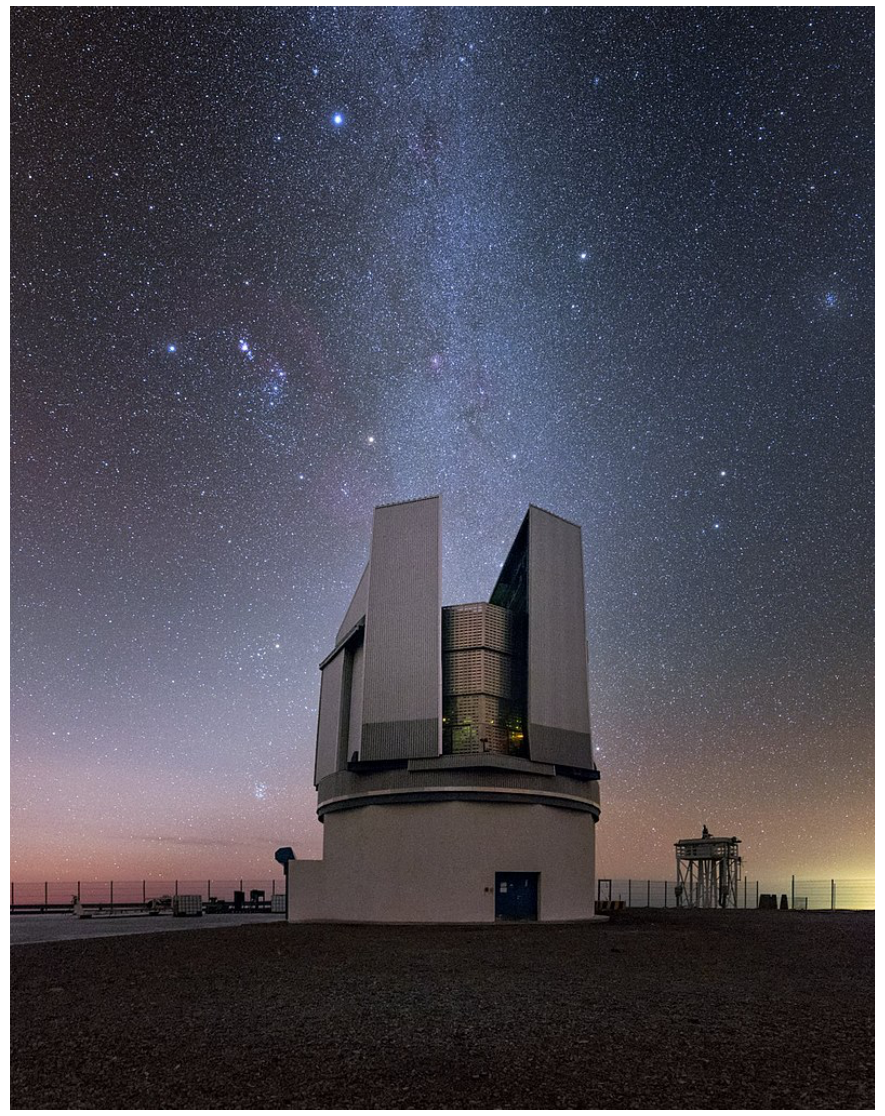
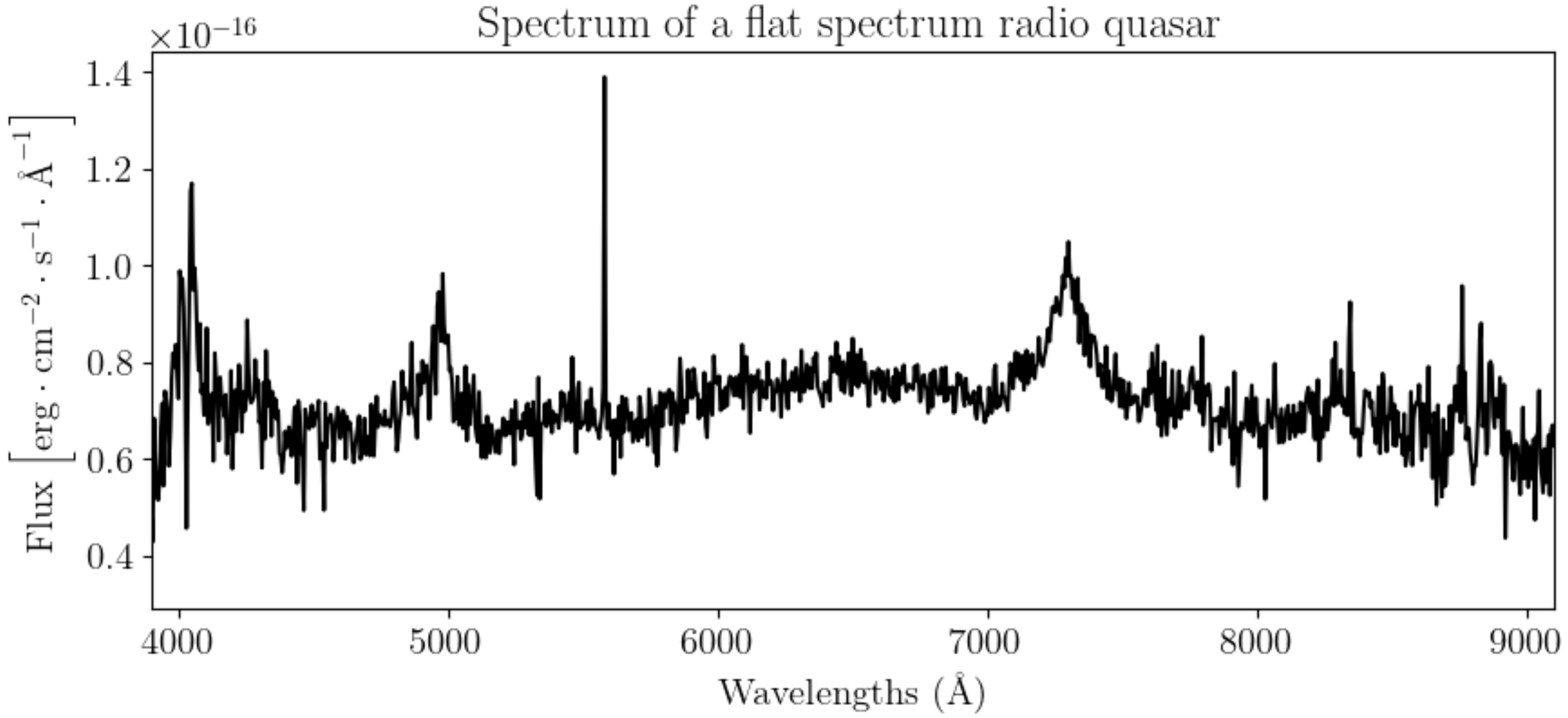
# Optical spectroscopy: probing the accretion properties

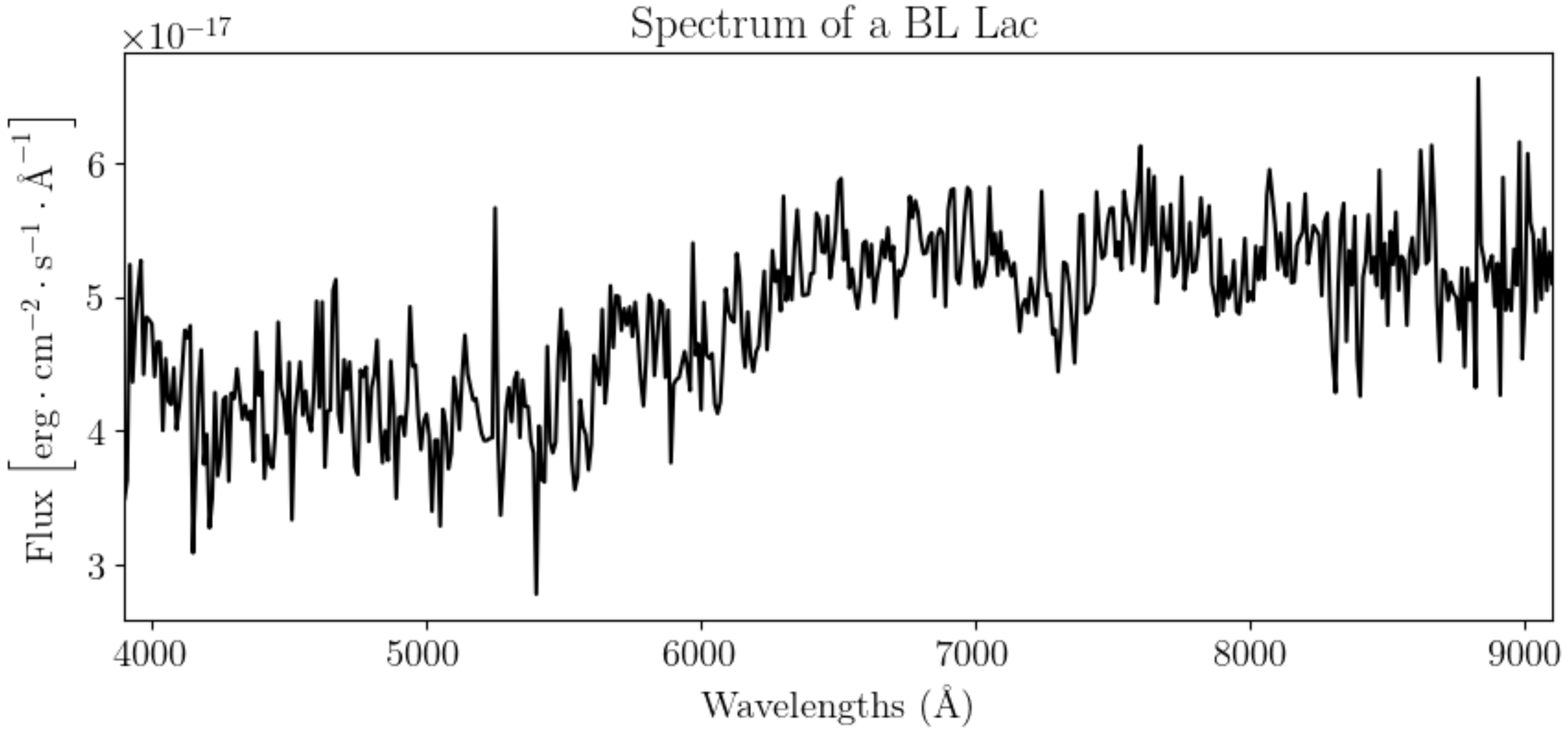
ESO Very Large Telescope (VLT)



Gemini South

Apache Point Observatory (APO)




Emission lines from the BLR:
**H$\alpha$, H$\beta$, C IV, Mg II**

↓

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

*Redshift* and distance:

$$z = \frac{\lambda_{th} - \lambda_{obs}}{\lambda_{th}} = \frac{v}{c} = H_0 \cdot d$$

$$EW = \int \left(1 - \frac{F_S}{F_C}\right) d\lambda$$

↓

Traditional taxonomy
FSRQ - BL Lacs

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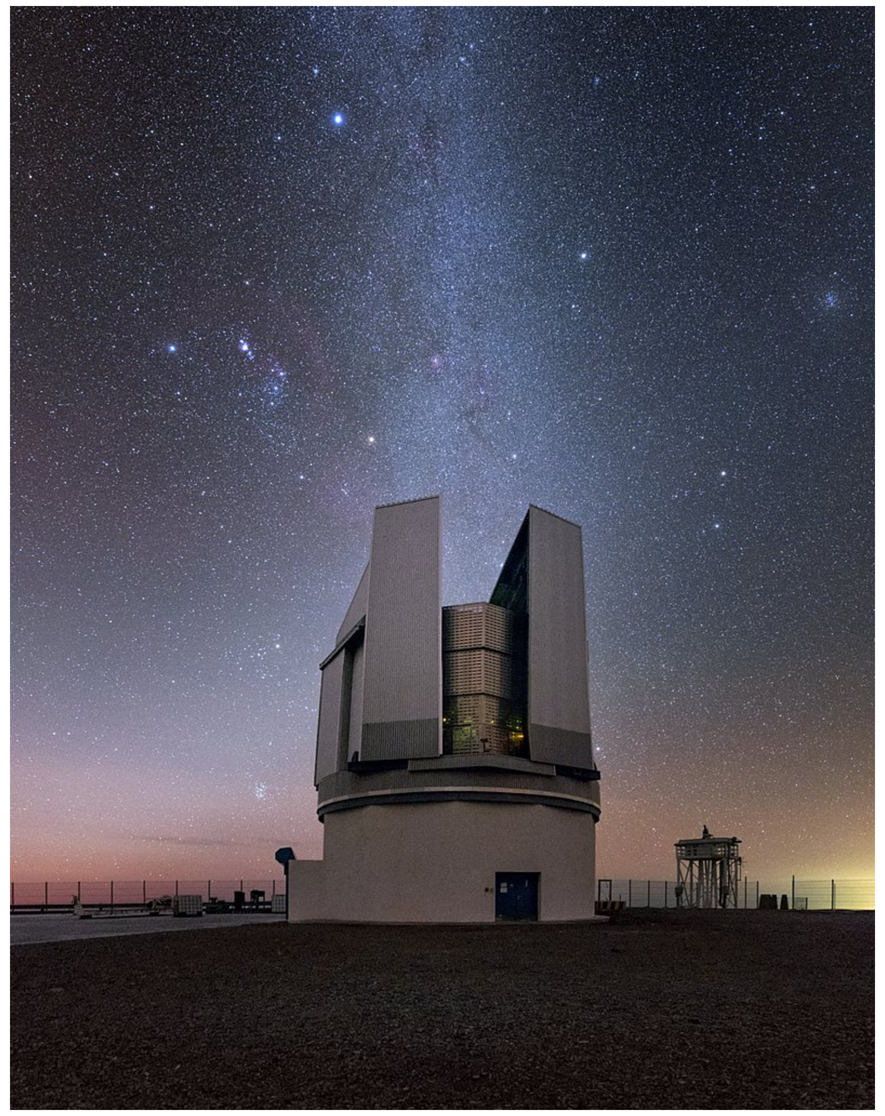

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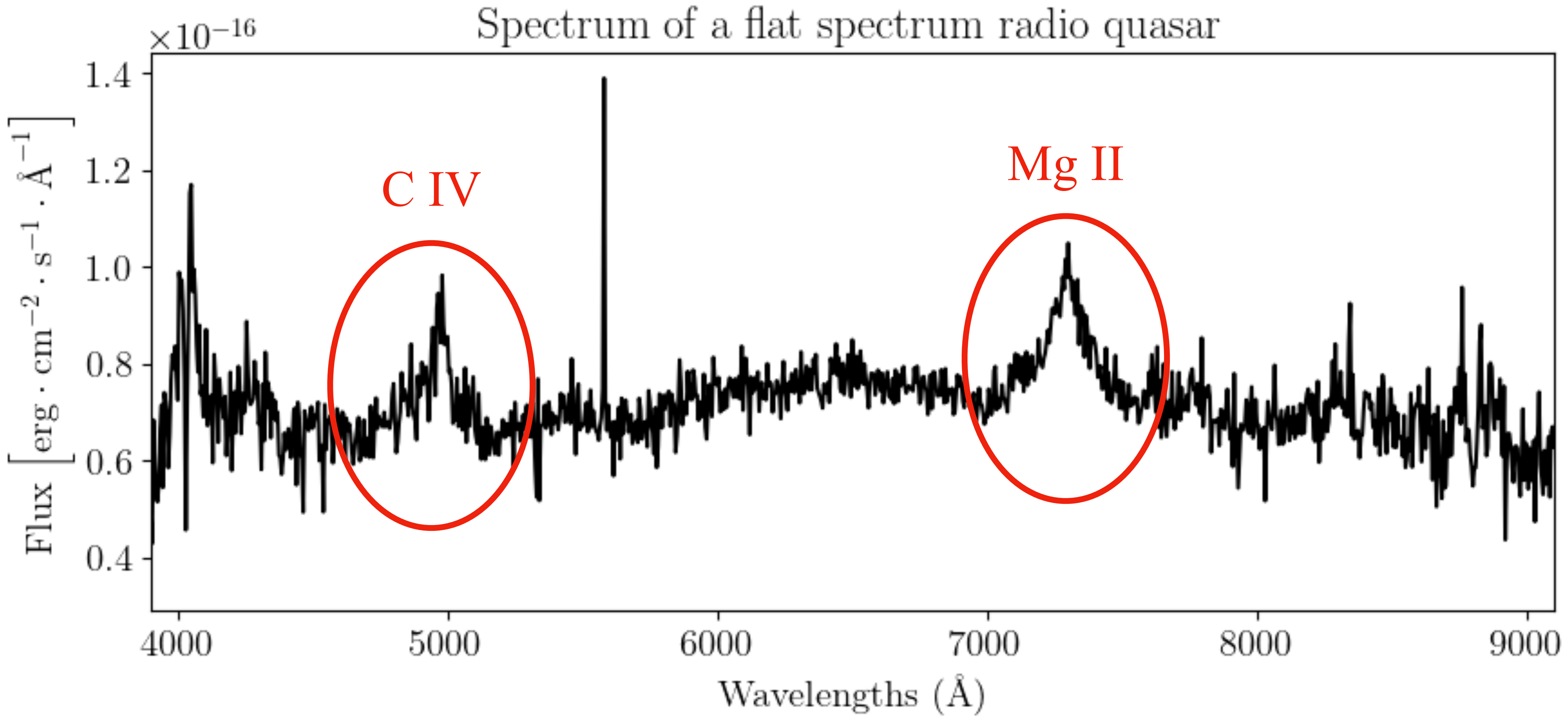


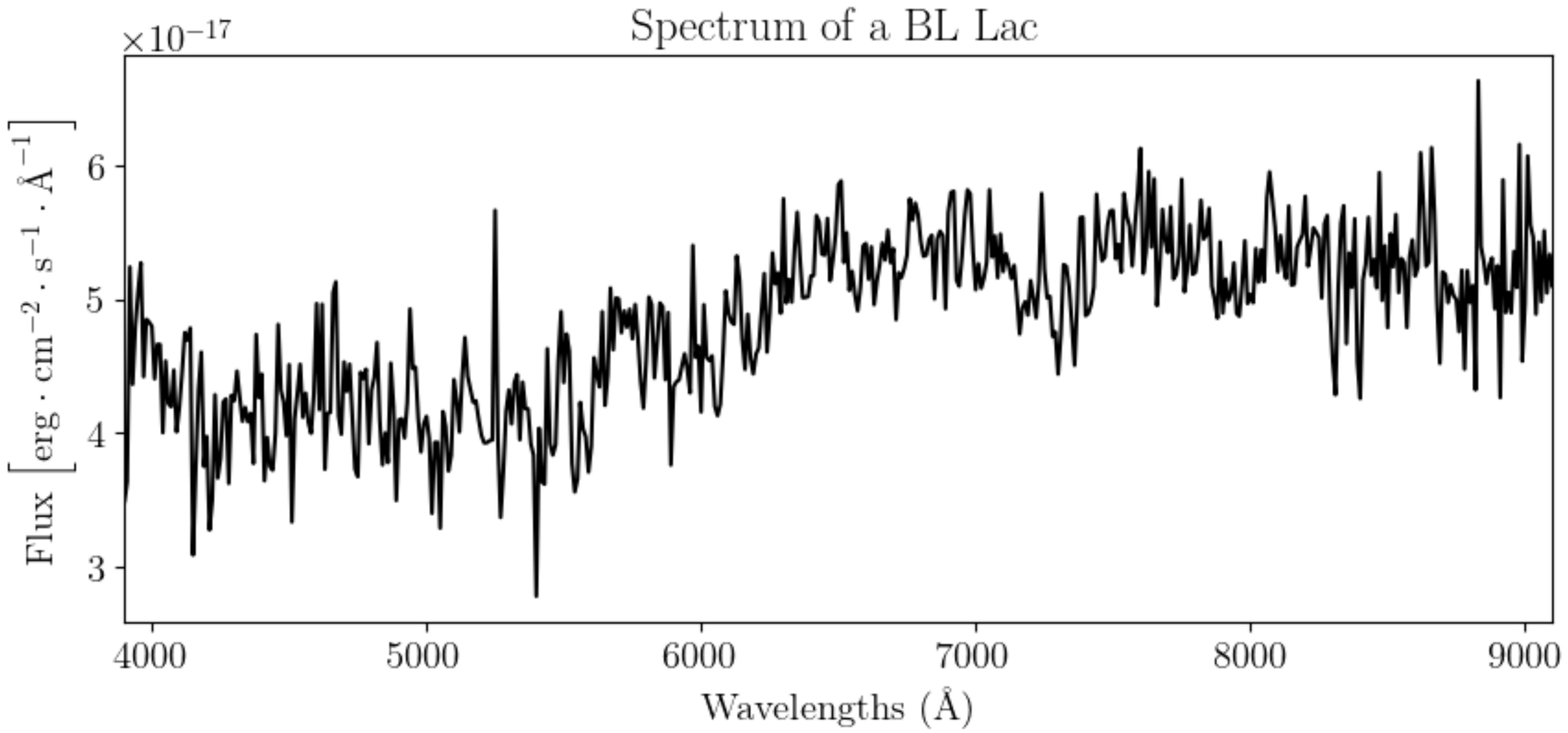


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Luminosity of the *BLR*
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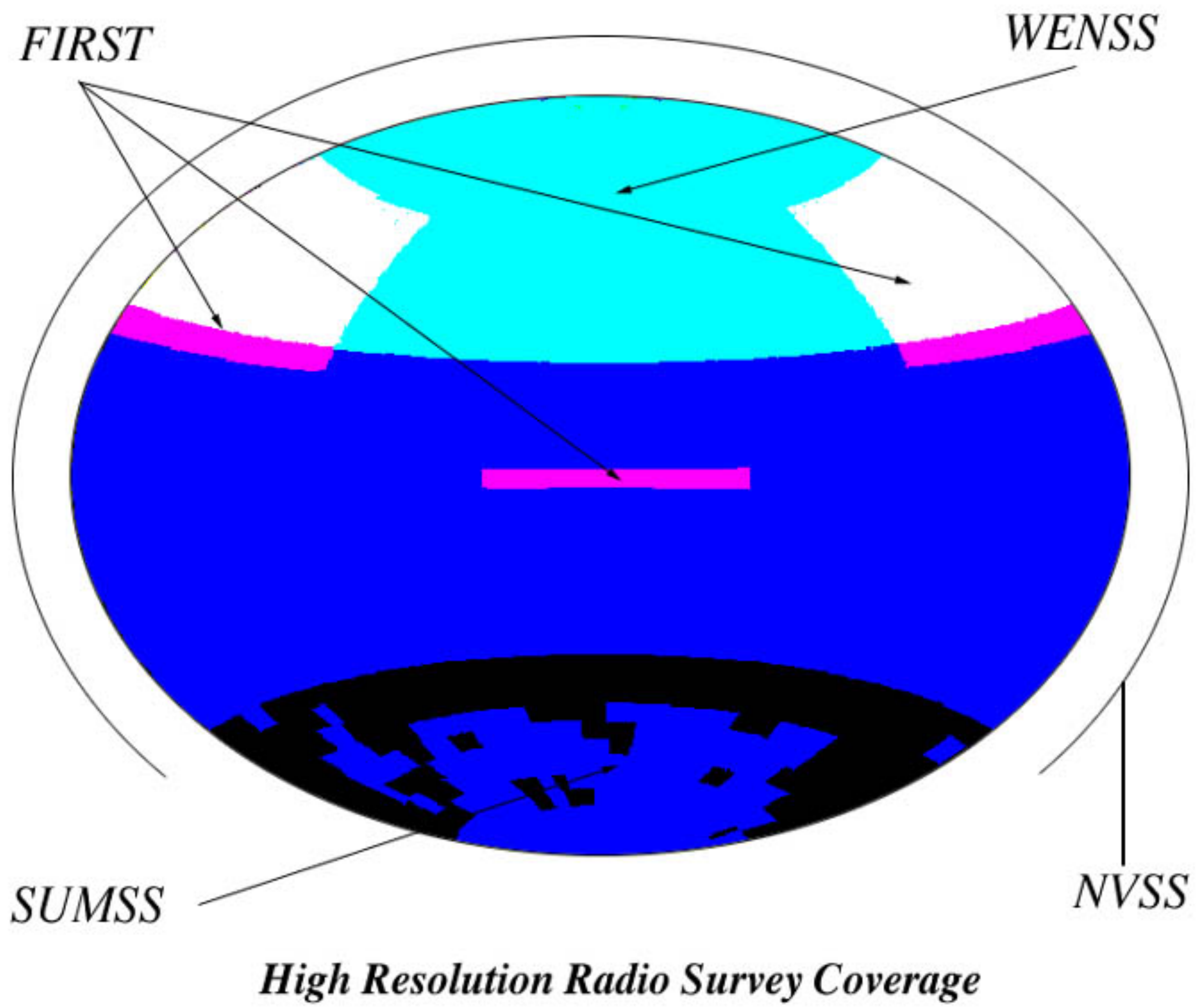
# Radio and $\gamma$-rays: probing the power of the jet

Each 5BZCat object has a detection in radio

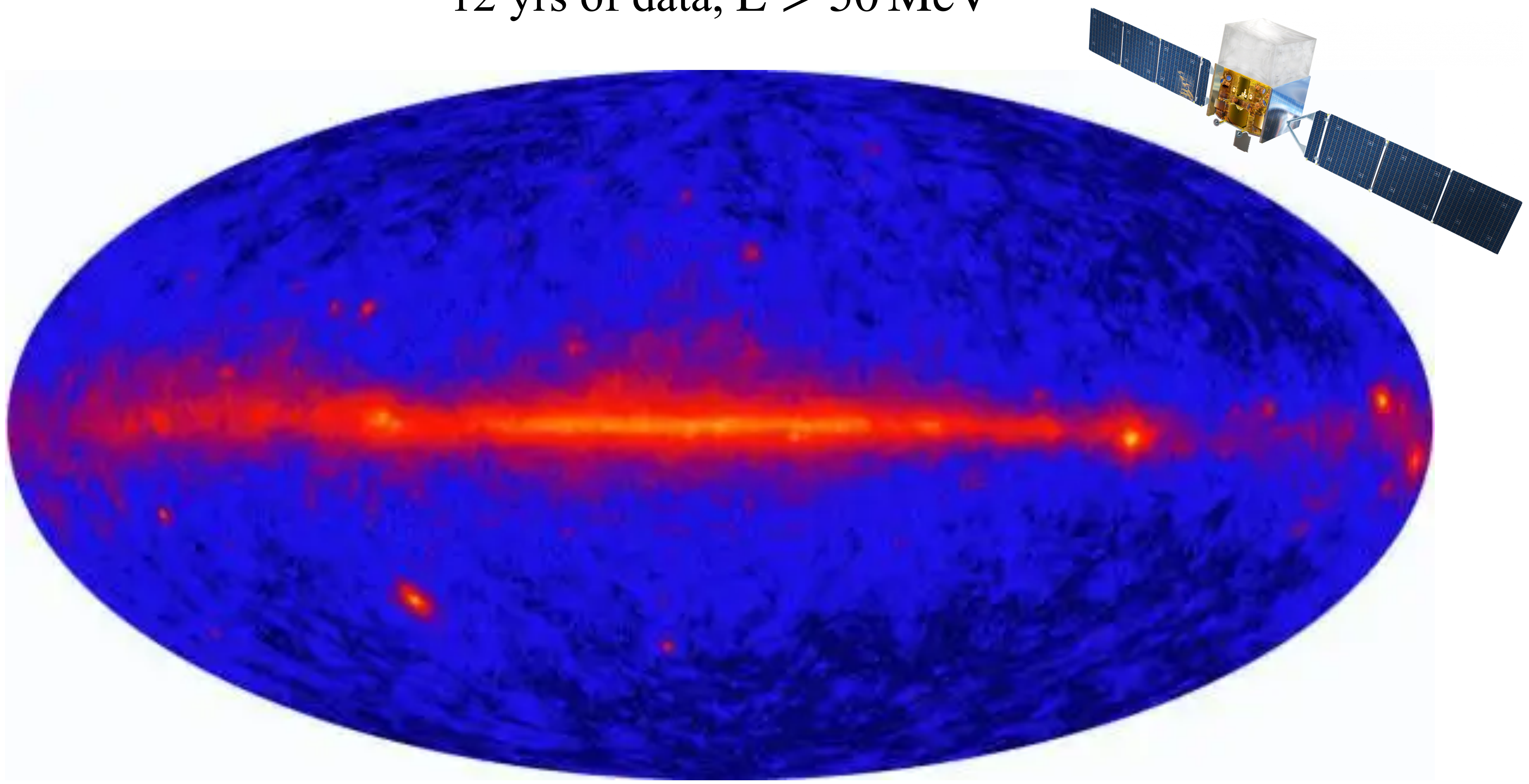



SkyView High Resolution Radio Coverage map
https://skyview.gsfc.nasa.gov/v3.4.5/cgi/survey.pl

**Radio power** at 1.4 GHz

*Fermi* Fourth Catalog of Active Galactic Nuclei
detected by the LAT (4LAC-DR3)

12 yrs of data, E > 50 MeV



Ajello et al. (2022), ApJSS 263, I2, 24, 9 pp.

26 detected sources:

- $F_\gamma$ in range [50 MeV, 1000 GeV]
- **Measured** $L_\gamma$

26 undetected sources:

- LAT sensitivity for $F_\gamma$
- **Upper limit on** $L_\gamma$

# Adopted approach for the data analysis of our work

Collection of data and information from **public** archives

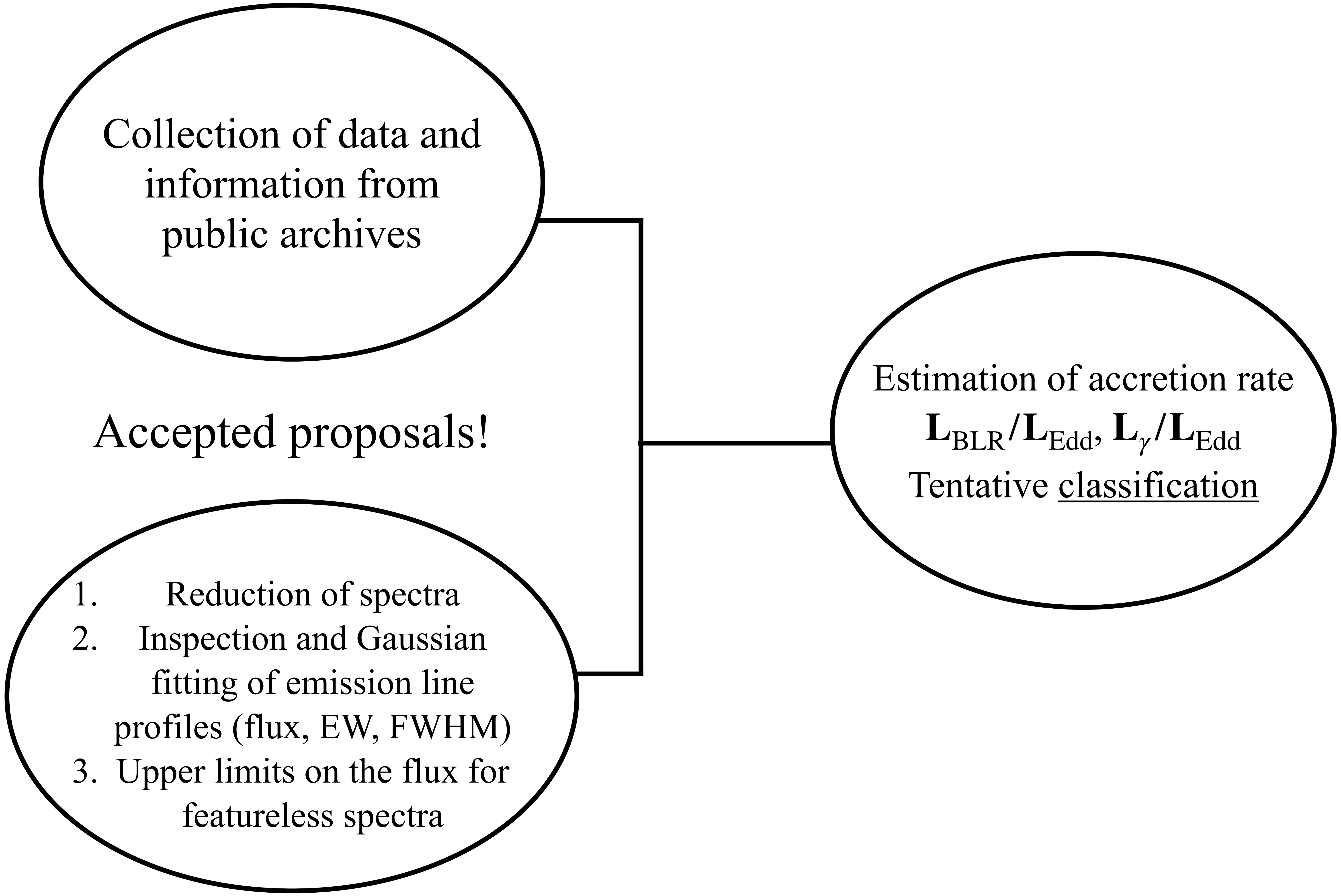
# Adopted approach for the data analysis of our work

Collection of data and information from public archives

Accepted proposals!

1. Reduction of spectra
2. Inspection and **Gaussian fitting** of emission line profiles (flux, EW, FWHM)
3. **Upper limits** on the flux for *featureless* spectra

# Adopted approach for the data analysis of our work



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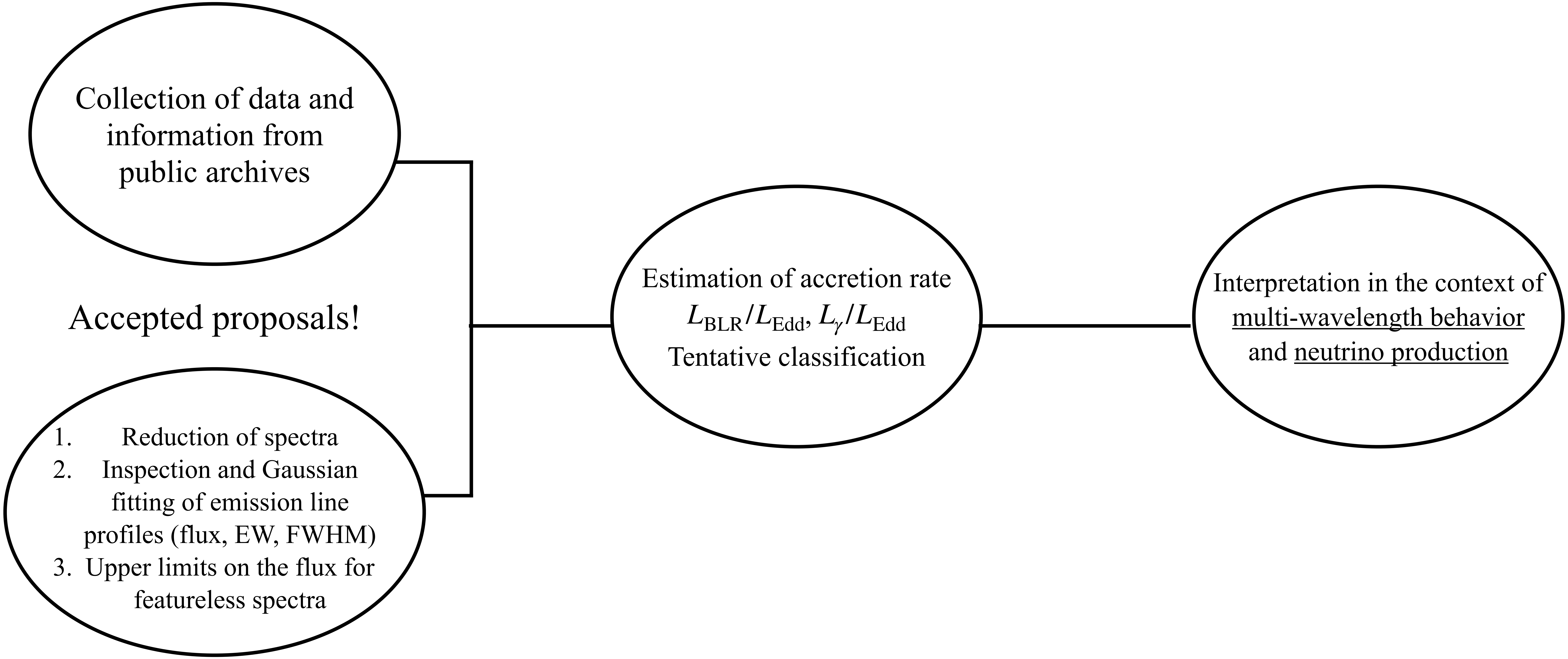

# Summary

- High-energy astrophysical **neutrinos**: important messengers, still unclear origin.
- **Active Galactic Nuclei**: good candidates.
- Work in progress: study of selected sample of blazars candidately associated with IceCube neutrinos.
    - Multi-wavelength approach: *proprietary* and *archival* data.
    - Optical spectroscopy: key tool to study the intrinsic physical properties.

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  - Multi-wavelength approach: *proprietary* and *archival* data.

  - Optical spectroscopy: key tool to study the intrinsic physical properties.

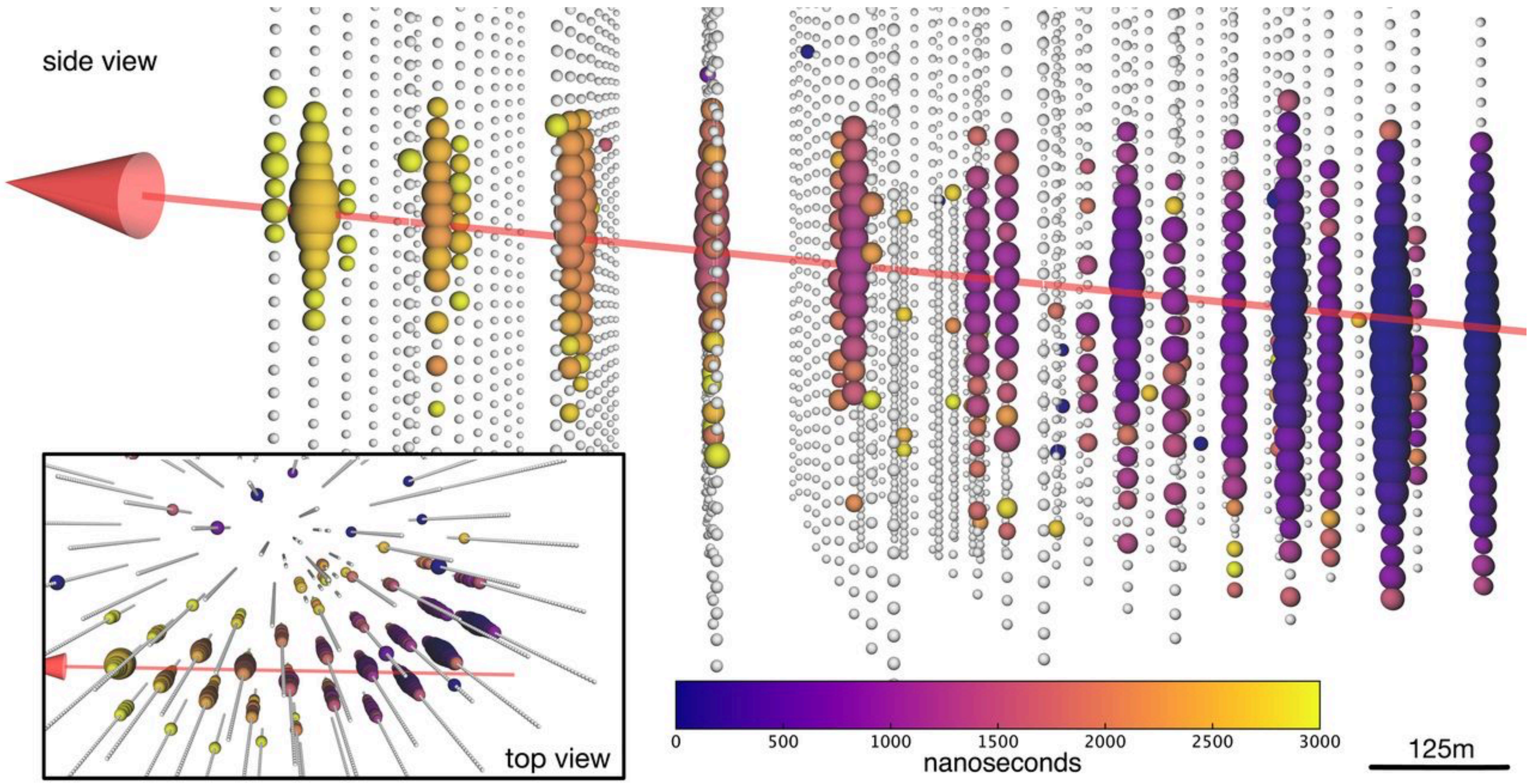
Thank you for the attention!

# Back-up slides

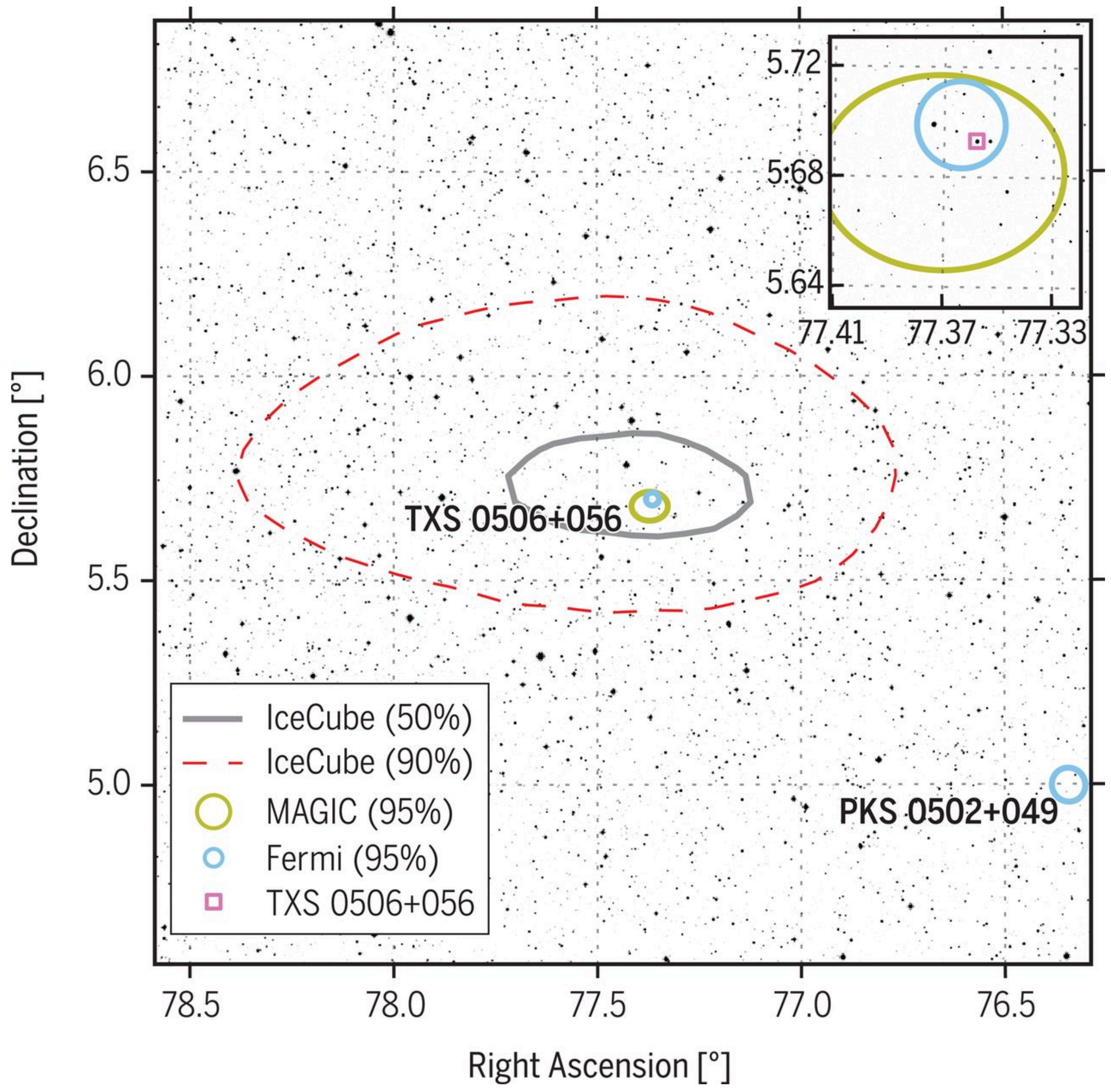
# IceCube-170922A and TXS 0506+056

On 22 September 2017, the IceCube Neutrino Observatory detected a $\sim 290\,\mathrm{TeV}$ neutrino.

The direction was consistent with the $\gamma$-ray blazar **TXS 0506+056**, which was in a *flaring state* at that time

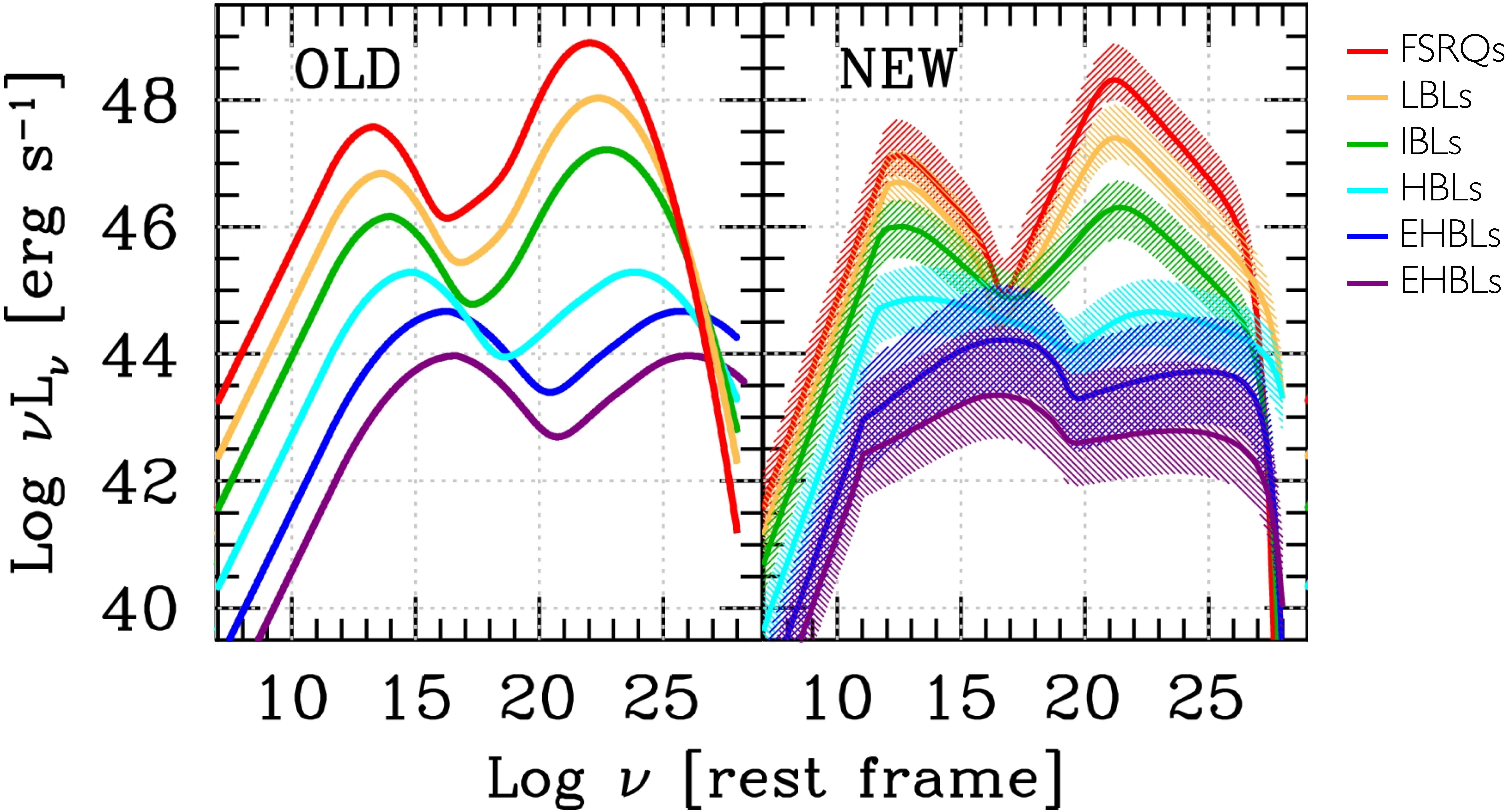



IceCube Collaboration (2018), Science, v. 361, I6398, id. eaat1378




Multi-messenger observations of the region around the blazar's position

# The blazars sequence




Ghisellini et al. (2017), Monthly Notices of the Royal Astronomical Society, Vol. 469, I1, p.255-266
Fossati et al. (1998), MNRAS Vol. 299, I2, pp. 433–448

# The production of neutrinos in blazars

**p-$\gamma$** interaction

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

**p-p** interaction

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

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

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

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

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

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

Blazars' relativistic *jets* are able to
**accelerate** electrons and hadrons

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

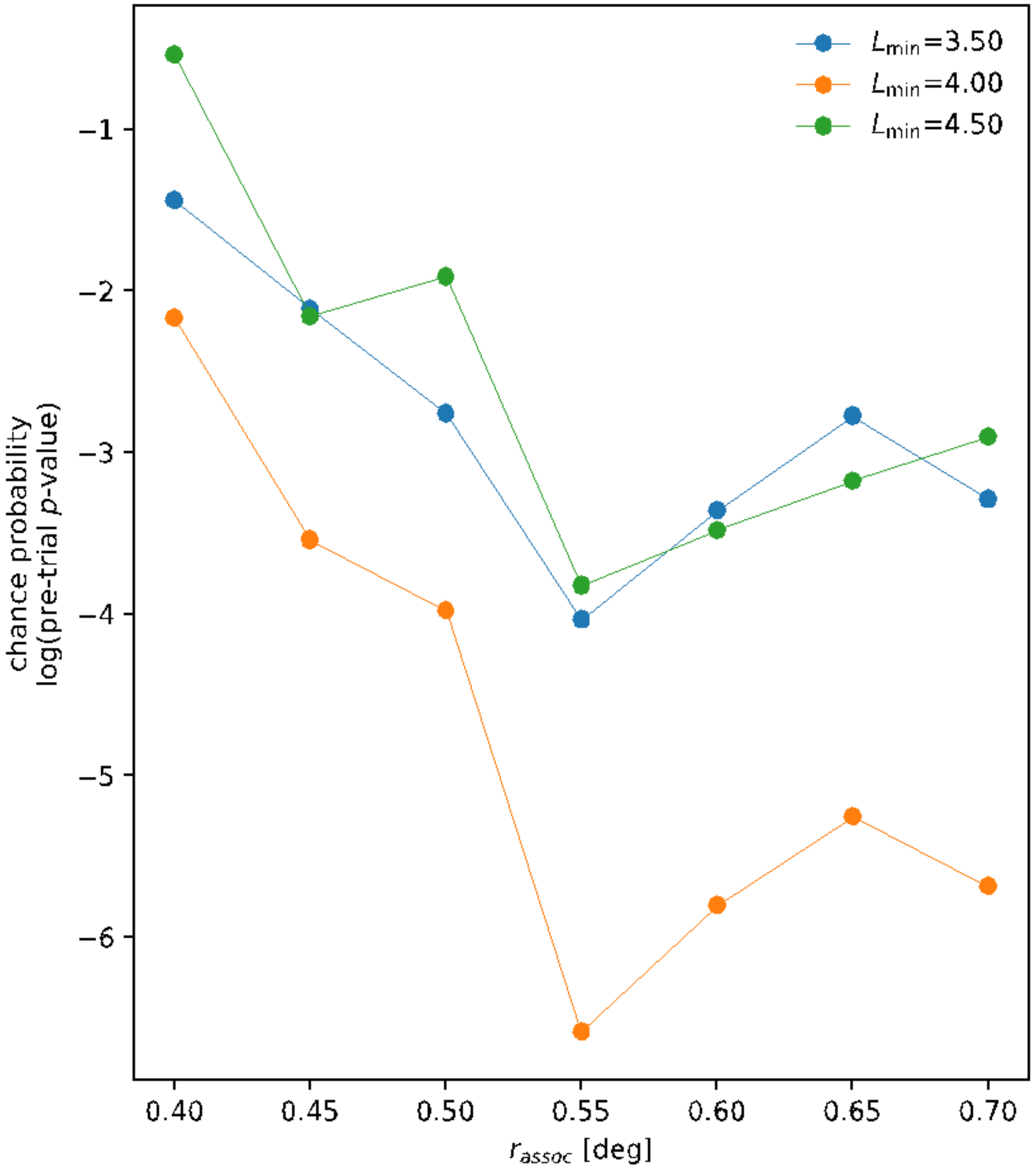
# The selection of PeVatron blazars

Positional cross-matching strategy

- Discrepancy from background
  - $L_{min} = [3.5, 4.0, 4.5]$
    - 44, 19, 9 neutrino spots
- Optimal association radius = median angular resolution for energy proxy 1 TeV
  - $[0.4^\circ, 0.7^\circ]$ with step $0.05^\circ$

minimum pre-trial p-value ↔ strongest potential correlation analysis

| Sky region | 5BZCat | Hotspots | Matches | pre-trial p-value | post-trial p-value |
|---|---|---|---|---|---|
| Southern sky ($L \geq 4$) | 1177 | 19 | 10 | $3 \times 10^{-7}$ | $2 \times 10^{-6}$ |




Buson et al. (2022), Astrophysical Journal Letters, Vol. 933, I2, L43

# Derivation of physical properties from optical spectral line profiles

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

$$L_{\rm BLR} = L_{\rm line} \cdot \frac{< L_{\rm BLR} >}{L_{\rm rel.\,frac.}} \sim 10\,\%\, L_{\rm disk} \qquad \text{where} \qquad \mathrm{L}_{\rm rel.frac.} = \begin{cases} 77 & \text{for H}\alpha\,, \\ 22 & \text{for H}\beta\,, \\ 34 & \text{for Mg II}\,, \\ 63 & \text{for C IV}\,, \end{cases}$$

$$\log\left(\frac{M_{\rm BH}}{M_\odot}\right) = \mathrm{a} + \mathrm{b} \cdot \log\left(\frac{\lambda \cdot \mathrm{L}}{10^{44}\ \mathrm{erg} \cdot \mathrm{s}^{-1}}\right) + \mathrm{c} \cdot \log\left(\frac{\mathrm{FWHM}}{\mathrm{km} \cdot \mathrm{s}^{-1}}\right) \qquad \text{with} \qquad (\mathrm{a,b,c}) = \begin{cases} (0.379,0.43,2.1) & \text{for H}\alpha\,, \\ (0.672,0.61,2.0) & \text{for H}\beta\,, \\ (0.740,0.62,2.0) & \text{for Mg II}\,, \\ (0.660,0.53,2.0) & \text{for C IV}\,, \end{cases}$$

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

$$r_{\rm BLR} = 10^{17} \cdot \left(\frac{L_{\rm disk}}{10^{45}\,\mathrm{erg} \cdot \mathrm{s}^{-1}}\right)^{1/2} \mathrm{cm} \qquad r_{\rm DT} = 2 \times 10^{18} \cdot \left(\frac{L_{\rm disk}}{10^{45}\,\mathrm{erg} \cdot \mathrm{s}^{-1}}\right)^{1/2} \mathrm{cm}$$

Francis et al. (1991), ApJ 373, p.465; Celotti et al. (1997), MNRAS 286, I2, pp. 415-424; Sbarrato et al. (2012), MNRAS 421, I2, pp. 1764-1778; Ghisellini et al. (2014), Nature 515, I7527, pp. 376-378; Shen et al. (2011), ApJSS 194, I2, 45, 21 pp. McLure & Dunlop (2004), MNRAS 352, I4, pp. 1390-1404; Vestergaard & Osmer (2009), ApJ 699, I1, pp. 800-816; Ghisellini & Tavecchio (2008), MNRAS 387, I4, pp. 1669-1680; Ghisellini et al. (2017), MNRAS 469, I1, p.255-266

# Estimation of the upper limits on the flux of not-detected lines

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

↓

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

↓

Flux uncertainty = 10%
$F_{\text{max}}$= 1% continuum

↓

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