Probing extreme particle acceleration in blazars: a new population of EHSP candidates and their TeV prospects

M. Láinez et al. (2025), Astronomy & Astrophysics, 700, A229

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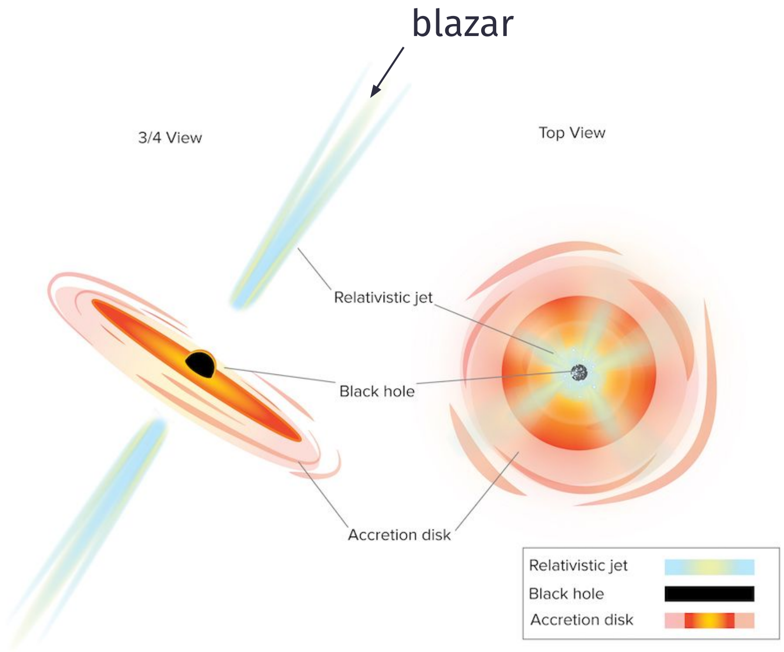
Introduction to blazars: general properties

- **Active galactic nucleus (AGN):**
  - active supermassive black hole at the center of a galaxy, accreting material and emitting radiation across the whole electromagnetic spectrum
  - so bright emission that it can outshine the rest of the galaxy
  - variable at different flux- and time- scales
- **Unified model**: jetted radio-loud AGNs classified in different types based on their jet viewing angle

  ⇨ **blazars**: AGNs with their jets pointing towards the Earth (most dominant source type in the extragalactic γ-ray sky)

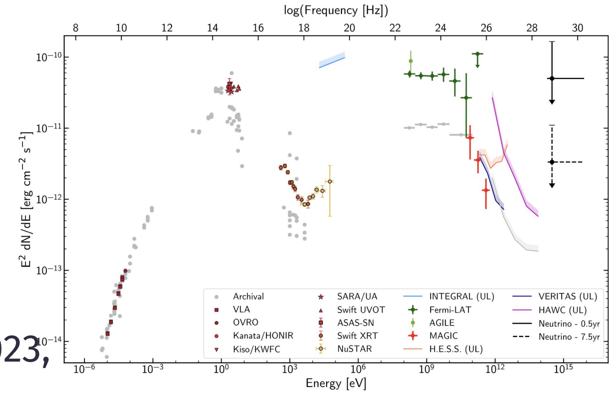


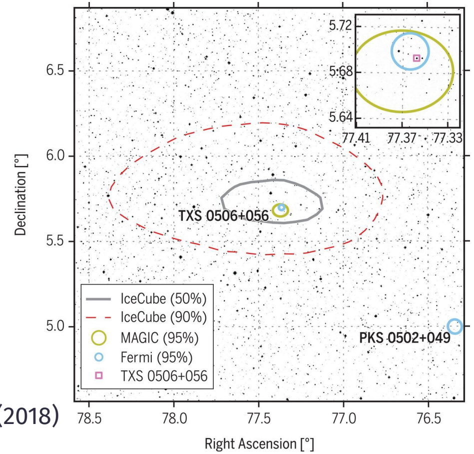
Blazars in the multi-messenger context

- 2017: **first neutrino–blazar association** (TXS 0506+056), confirming **blazars** as candidate neutrino sources → opened the multi-messenger era for blazars

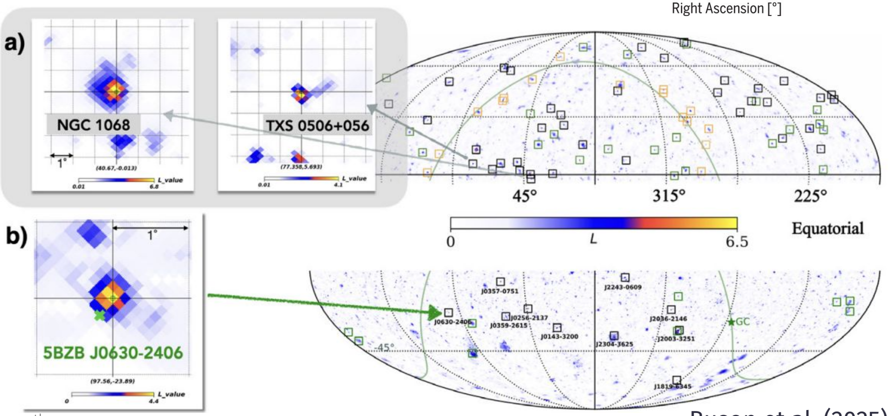
- Recent studies (Buson et al. 2022, 2023, 2025) report **correlations between blazars and neutrino data**, supporting blazars as promising high-energy neutrino source candidates.

- **Gravitational-wave emission scenarios associated with blazars** (binary SMBH systems) have also been proposed (e.g. Rico et al. 2025).





IceCube Collaboration et al. (2018)

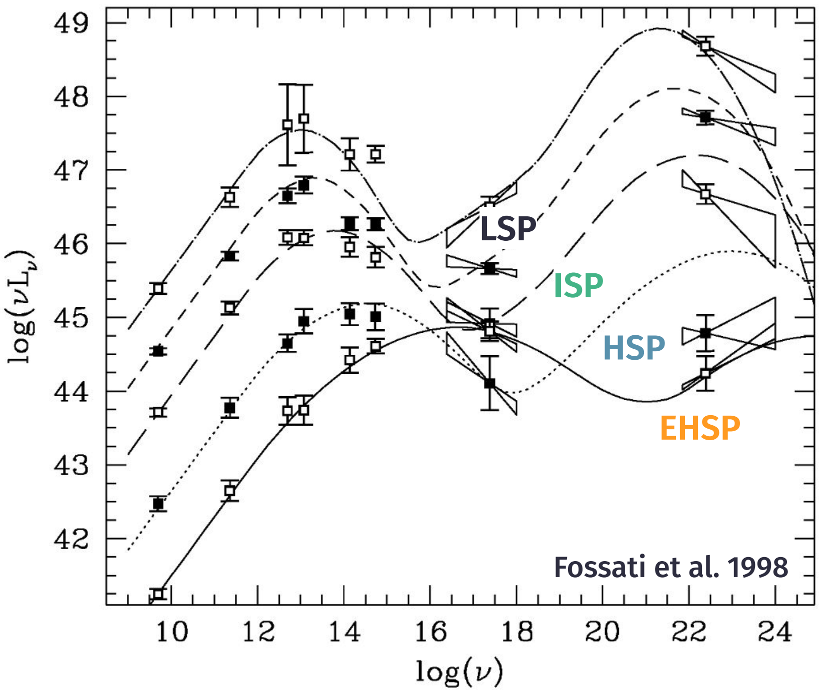


Buson et al. (2025)

Introduction to blazars: broadband SED classification

Blazars classification based on their synchrotron peak frequency (ν_{SP}):

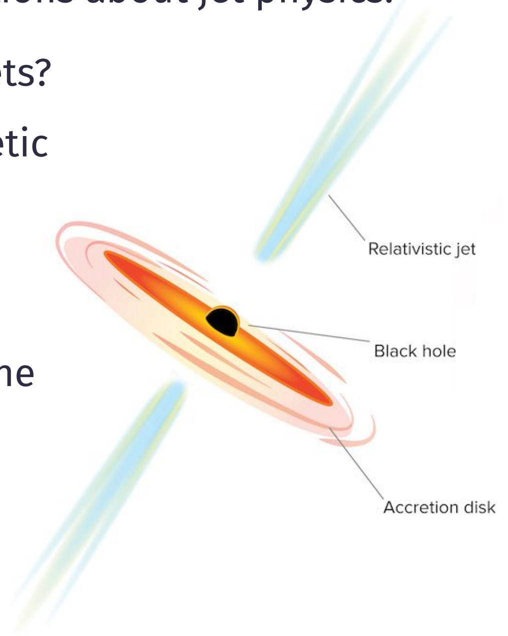
- **LSPs (low-synchrotron peaked)**: $\nu_{SP} < 10^{14}$ **Hz** ($E_{SP} < 0.4$ eV)
- **ISPs (intermediate-synchrotron peaked)**: $10^{14} \leq \nu_{SP} < 10^{15}$ **Hz** (0.4 eV ≤ $E_{SP} < 4.0$ eV)
- **HSPs (high-synchrotron peaked)**: $10^{15} \leq \nu_{SP} < 10^{17}$ **Hz** (4.0 eV ≤ $E_{SP} < 0.4$ keV)
- **EHSPs (extremely high-synchrotron peaked)**: $\nu_{SP} \geq 10^{17}$ **Hz** ($E_{SP} \geq 0.4$ keV)



Blazar jets: key open questions

Blazars entered the multi-messenger era, highlighting many open questions about jet physics:

- Where and how are high-energy gamma-rays produced in blazar jets?
- What is the nature of the emitting particles? How do electromagnetic and neutrino emissions connect?
- Which processes accelerate particles to the highest energies, particularly in EHSPs?
- What drives the diversity of blazar SEDs and their position along the blazar sequence?
- How do blazars evolve? What subclass of blazars are closer to equipartition, and what does this imply for their evolution?



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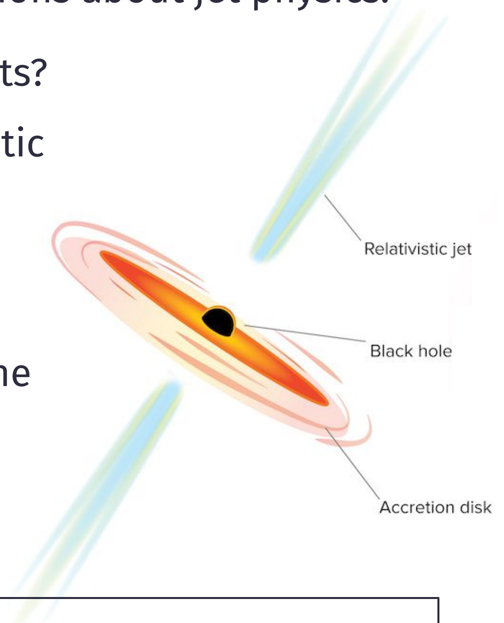


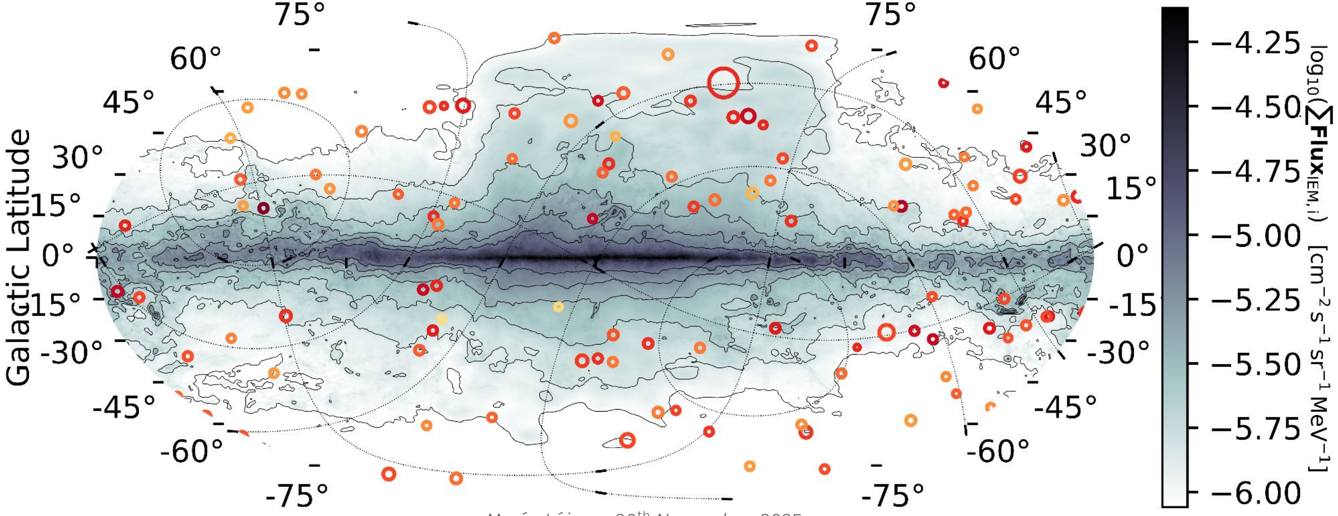
Aim: **search for EHSPs** within a wide selection of blazars/ blazar candidates by studying their broadband SED + **examine the multi-wavelength properties of EHSPs**

Blazar sample selection

Base catalog: **2BIGB catalog** (Arsioli et al. 2022), a catalog of 1160 γ-ray emitting blazars from the 3HSP catalogue (largest collection of HSPs, EHSPs). Cuts:

- have redshift estimate
- flux measurements in all bands
- outside the galactic plane ($|b|$ > 10°)
- additional cuts to select sources with low variability (γ rays, X-rays)

⇨ **124 sources**



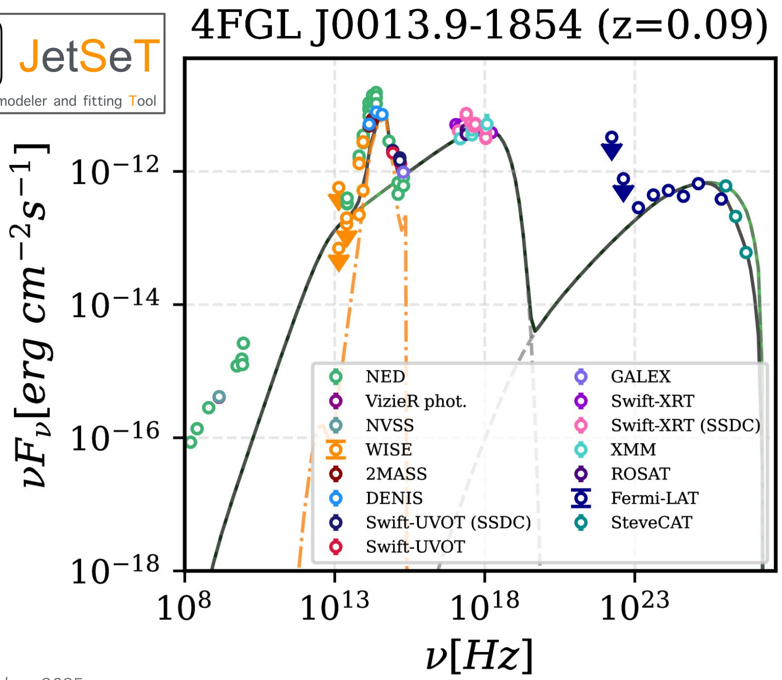
Broadband SED modelling

- **One-zone SSC model** (higher-energy peak due to IC of electrons with photons produced in the synchrotron process) + **best-fit host galaxy model**
- 7 free parameters: B, θ, N, p_1, p_2, γ_{max}, γ_{break}
- Applied EBL attenuation using model from Saldana-Lopez et al. 2021, Domínguez et al. 2024a.
- Modeling done using **JetSeT** (Tramacere A. 2020)

We exclude sources with poor fitting results (χ^2/dof > 1.5) ⇨ **113 surviving sources**

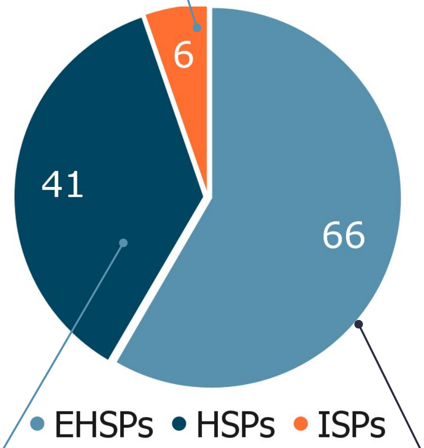
*All MWL SEDs of the 124 sources + best-fit models available in https://zenodo.org/records/15882910

JetSeT
Jets SED modeler and fitting Tool



Broadband SED modelling results

$10^{14} \leq \nu_{SP} < 10^{15}$ Hz

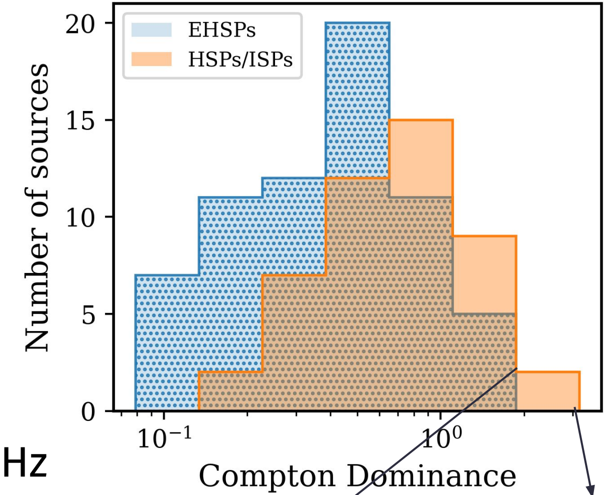


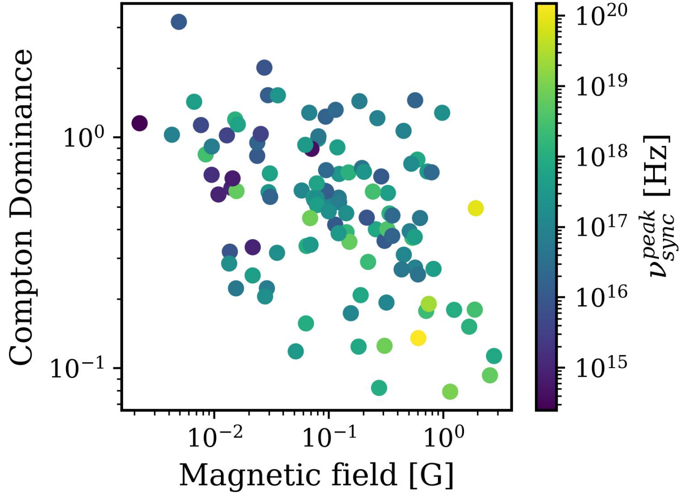
$10^{15} \leq \nu_{SP} < 10^{17}$ Hz

$\nu_{SP} \geq 10^{17}$ Hz

113 sources

Compton dominance (CD): relative strength of inverse Compton emission compared to synchrotron emission in the SED ($CD = L_{IC} / L_{sync}$)





EHSP with highest CD: CD=1.5

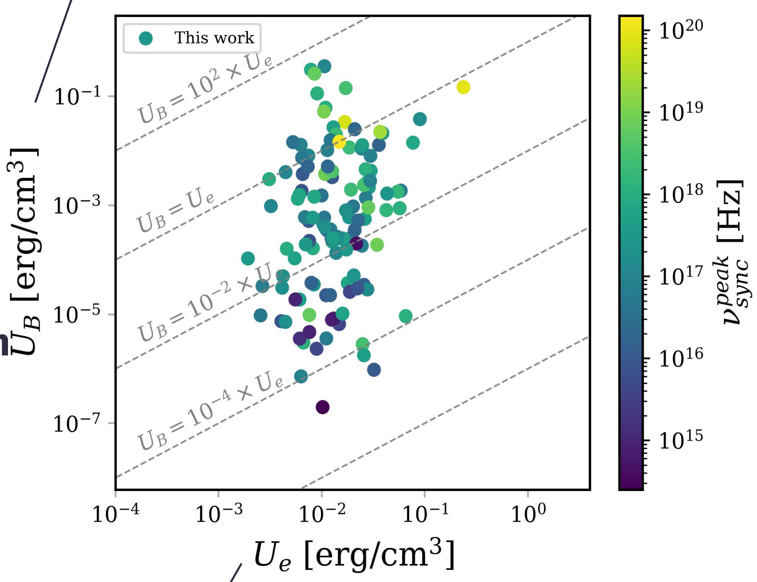
highest CD: CD=3.2 (HSP)

lower ν_{SP} → lower B → higher CD

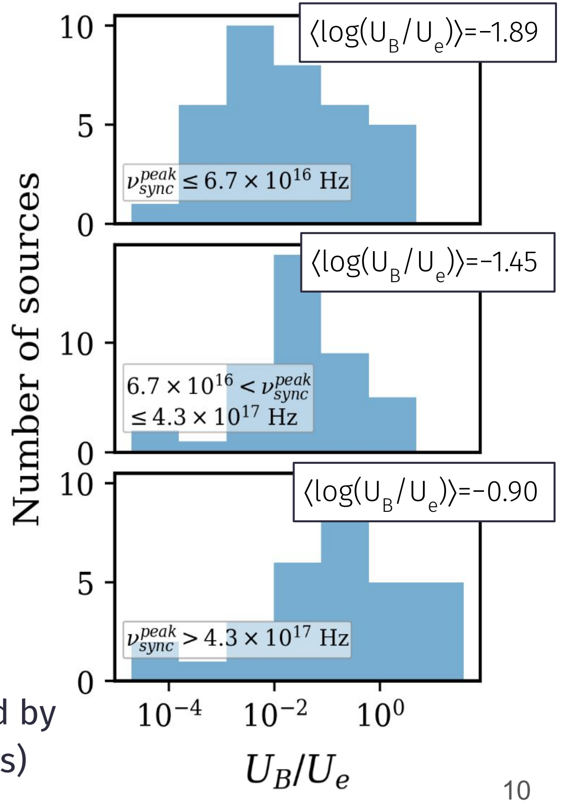
Energy budget

- Our results suggest a **relation between the U_B/U_e ratio and the synchrotron peak frequency** → most extreme sources closer to the line $U_B \approx U_e$
- **Jet close to equipartition (U_B/U_e ~ 1)**: energetically efficient (minimizes energy losses during the acceleration/transport of particles)

magnetic energy density

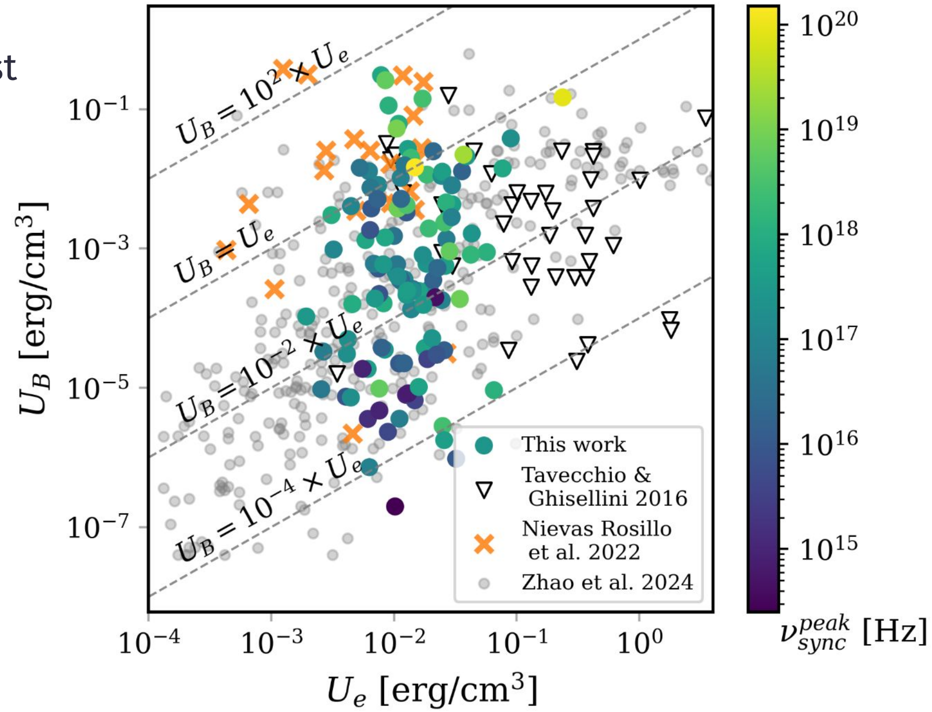


kinetic energy density (energy carried by the population of relativistic electrons)



Energy budget: comparison with other works

- Agreement with **Nievas Rosillo et al. (2022)**: most sources **close to equipartition**
- Differences with **Zhao et al. (2024)** and **Tavecchio & Ghisellini (2016)**: most sources far from equipartition (U_B << U_e) clustering around **$U_B = 10^{-2} \times U_e$**



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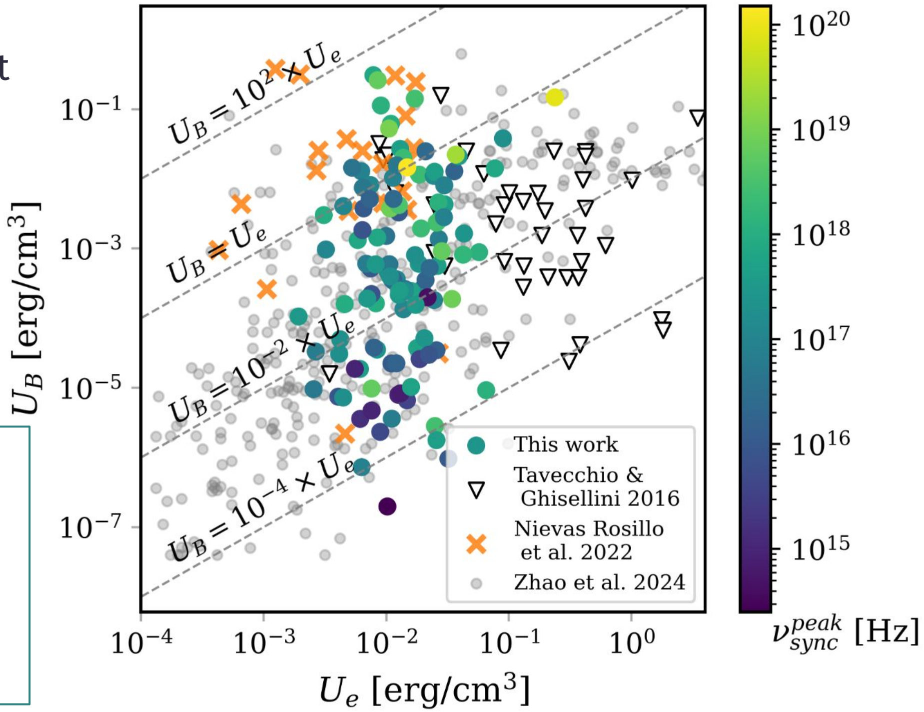
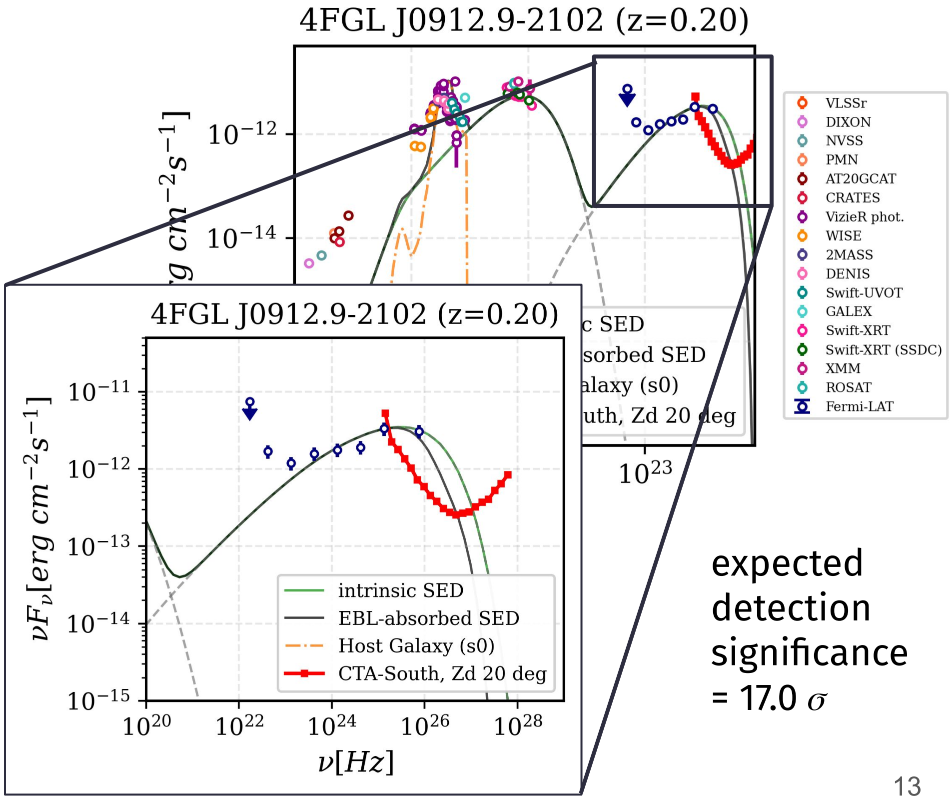


TG16 and Z24 include **variable sources** + sources detected in VHE → during certain observations, may be **far from equilibrium** → higher electron energy injection → lower magnetisation → **lower U_B/U_e ratio**

Sources in our sample characterised by **low variability** → **closer to equipartition**

Detectability predictions with CTAO

- **EHSPs** regarded as **promising VHE emitters**, but **very few detected at VHE**, < 20 detected by IACTs
- Using the spectral shape resulting from the SED modelling (+ applying EBL absorption), we estimate the **expected detection significance with CTAO (Alpha configuration) assuming 20-hour observations**
- RESULT: **9 sources** (out of 113) with **expected CTAO detection significance ≥ 5σ + 11 additional sources with expected significance ≥ 3σ** (detectable with longer exposure)



expected detection significance = 17.0 σ

Summary and conclusions

- Systematic **search for EHSPs** by **modelling broadband SEDs of 124 blazars** using a one-zone SSC model + host galaxy model → **66 EHSP candidates**
- Low CD values (CD < 1) in EHSPs → **SSC-dominated emission** with few external photon fields
- **Higher ν_{SP} sources (EHSPs) closer to energy equilibrium/ equipartition (U_B/U_e ~ 1)** than less extreme blazars, possibly due to finely balanced particle acceleration and magnetic fields
- Differences in the U_B/U_e distribution with other works highlight the **importance of sample selection and variability criteria** in studying the physical properties of EHSPs
- CTAO detectability predictions using the modelled SEDs: several EHSPs are **strong candidates for VHE γ-ray detection**, providing useful targets for future **multi-messenger follow-up**

Thanks for your attention!

Acknowledgements

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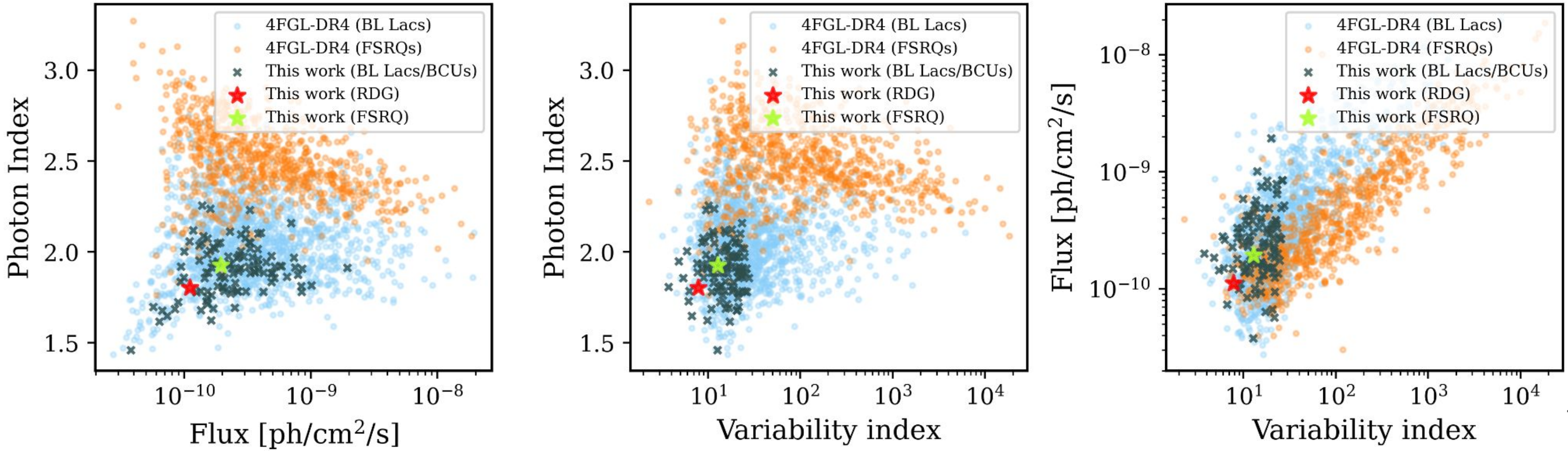
Blazar sample: 4FGL-DR4 classification

- **124 sources** in the final sample
  - 93 BL Lacs
  - 29 blazar candidates of uncertain type (BCUs)
  - 1 FSRQ (4FGL J0132.7-0804), 1 radiogalaxy (4FGL J1518.6+0614)

- The selected sources (mostly BL Lacs) have harder spectra than typical FSRQs

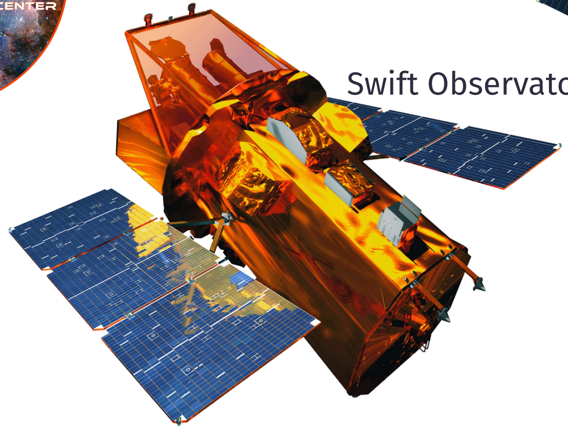


Multi-wavelength data

- *Swift*-XRT and *Swift*-UVOT data (data analysis)
- 4FGL-DR3 catalog (*Fermi*-LAT 12-year Source Catalog)
- STeVECat: the Spectral TeV Extragalactic Catalog (Gréaux et al. 2023)
- Space Science Data Center - ASI SED builder* (archival data)

Only **non-variable sources** selected for our study
→ we can combine **non-contemporaneous datasets**

Fermi Gamma-ray Space Telescope

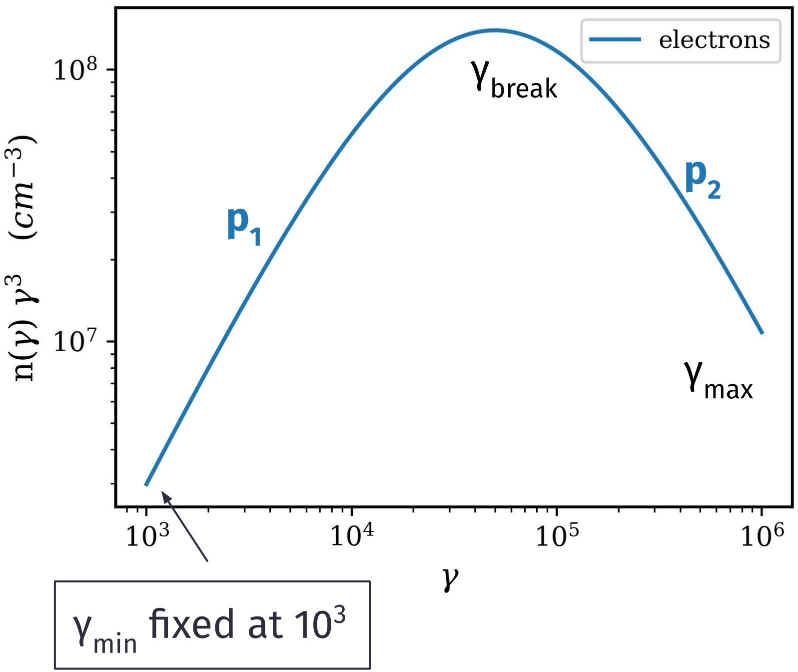


Swift Observatory

*https://tools.ssdc.asi.it/SED/

Broadband SED modeling: details

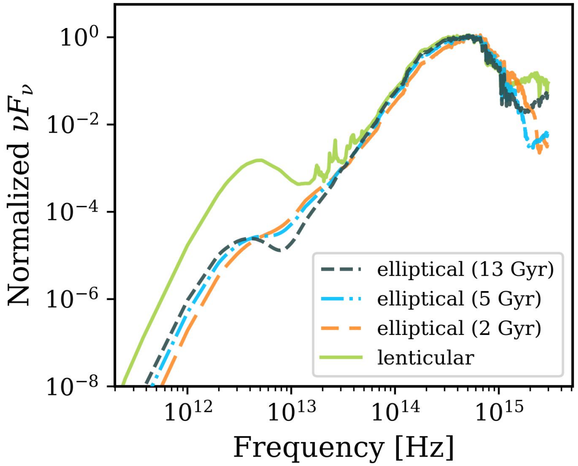
- **One zone SSC model** (higher-energy peak due to IC of electrons with photons produced in the synchrotron process) + **best-fit host galaxy model**
- No EC component (simple environments, no dusty torus/ BLR to supply photons for the EC)
- Emission produced in a **single spherical region or blob** of radius R located within the jet filled with ultra-relativistic electrons moving with bulk Lorentz factor Γ (both synchrotron and IC originate from the same region)
- **Electron population** modelled with a **broken power-law** distribution: a lower energy population with spectral slope p_1 and a higher energy population with spectral slope p_2

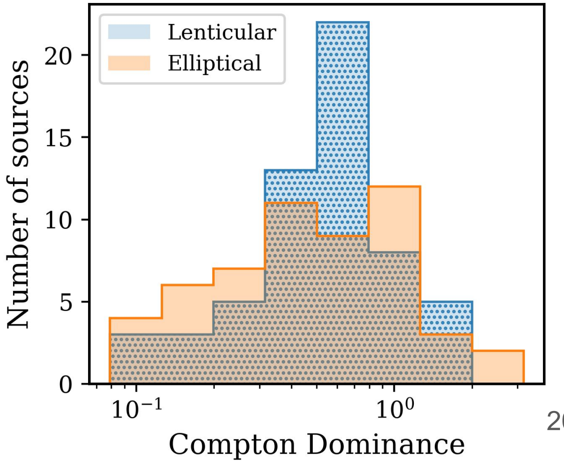


Host galaxy results

- Best-fit host galaxy model (host galaxy template with lowest χ^2 value):
  - elliptical galaxy: 54 sources
    - elliptical galaxy of 13 Gyr: 27 sources
    - elliptical galaxy of 5 Gyr: 10 sources
    - elliptical galaxy of 2 Gyr: 17 sources
  - lenticular galaxy: 59 sources

- No significant differences between the two types of galaxies → **negligible impact of the host galaxy emission on the blazar's non-thermal emission**

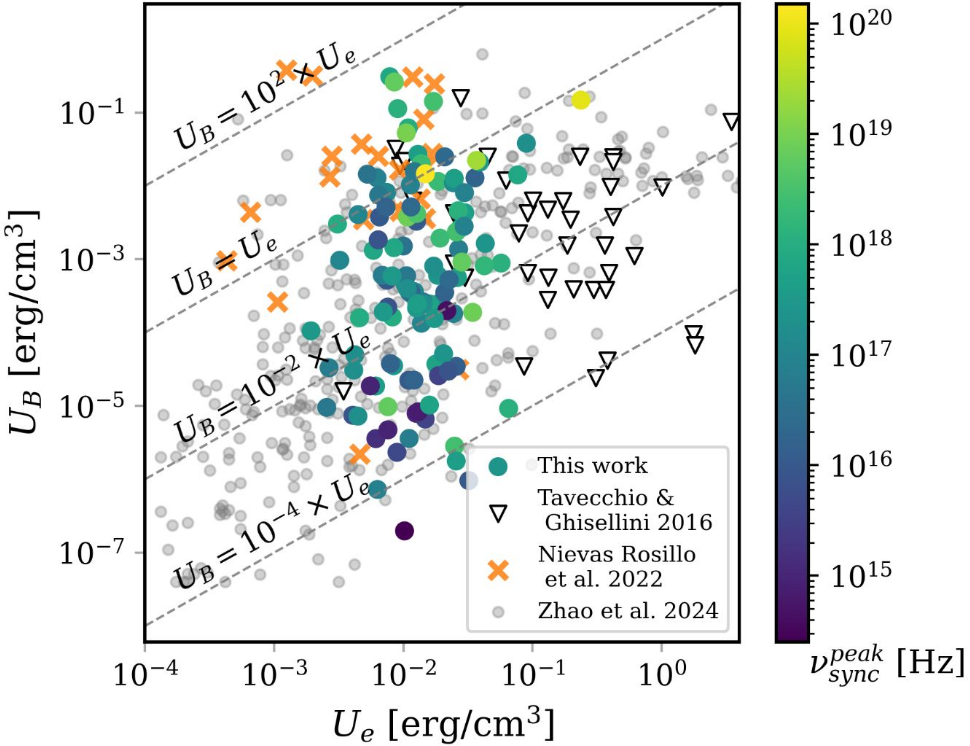




Energy budget: comparison with other works

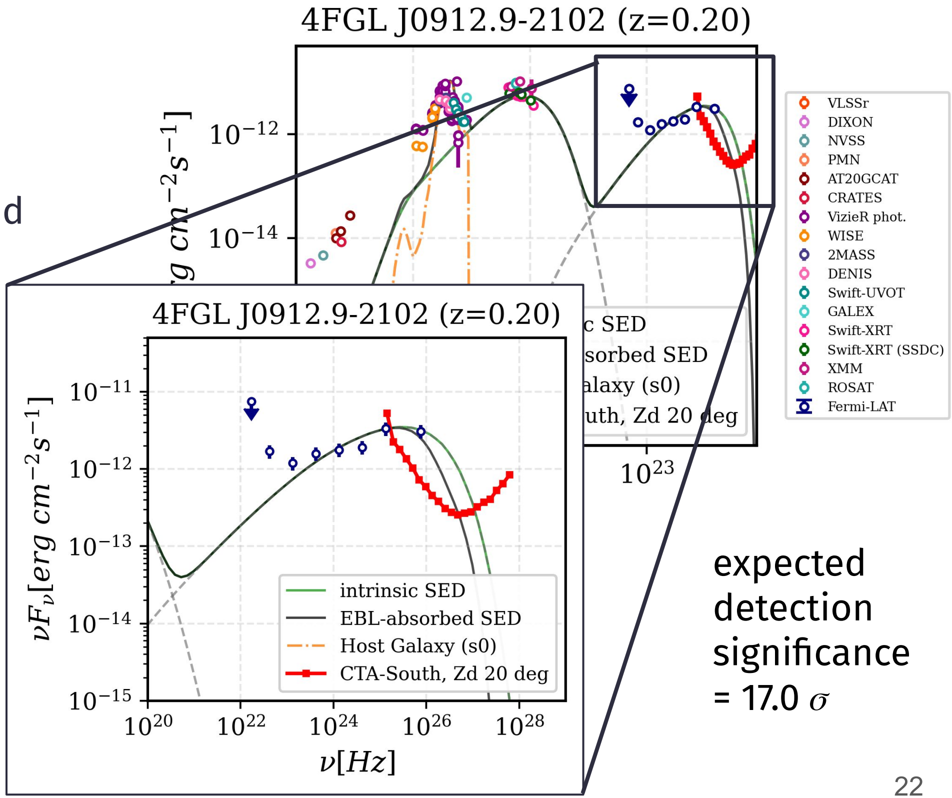
SAMPLE SELECTIONS:

- **Tavecchio & Ghisellini 2016**: 45 BL Lac objects, 12 detected in the TeV γ-ray band
- **Nievas Rosillo et al. 2022**: 22 2BIGB sources classified as BCU in 4FGL → 17 EHSP candidates
- **Zhao et al. 2024**: 348 HSP blazars (all 4FGL HBL blazars with $\nu_{SP} \geq 10^{15}$ Hz in their modelling)



Detectability predictions with CTAO

- Best-fit model extrapolated to TeV energies + EBL absorption → **assumed spectral shape**
- From the sensitivity curves, we derive the differential flux, and the number of excess and background events required to generate a 5σ signal in each energy bin: f5, n_exc5, n_off5
- Number of excess events obtained by scaling linearly the ratio of the differential fluxes in each bin: **n_exc = sum(n_exc5*f/f5)**,
  f differential flux in each energy bin for the assumed spectral shape
- **Expected detection significance**: estimated using **Li & Ma (1983) (eq. 17)**



expected detection significance = 17.0 σ