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

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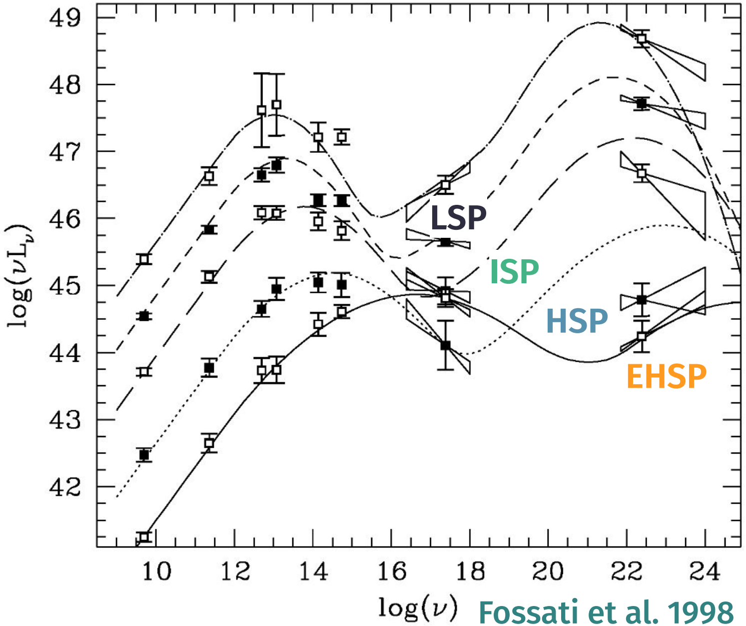
Introduction to blazars: spectral classification

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

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



Fossati et al. 1998

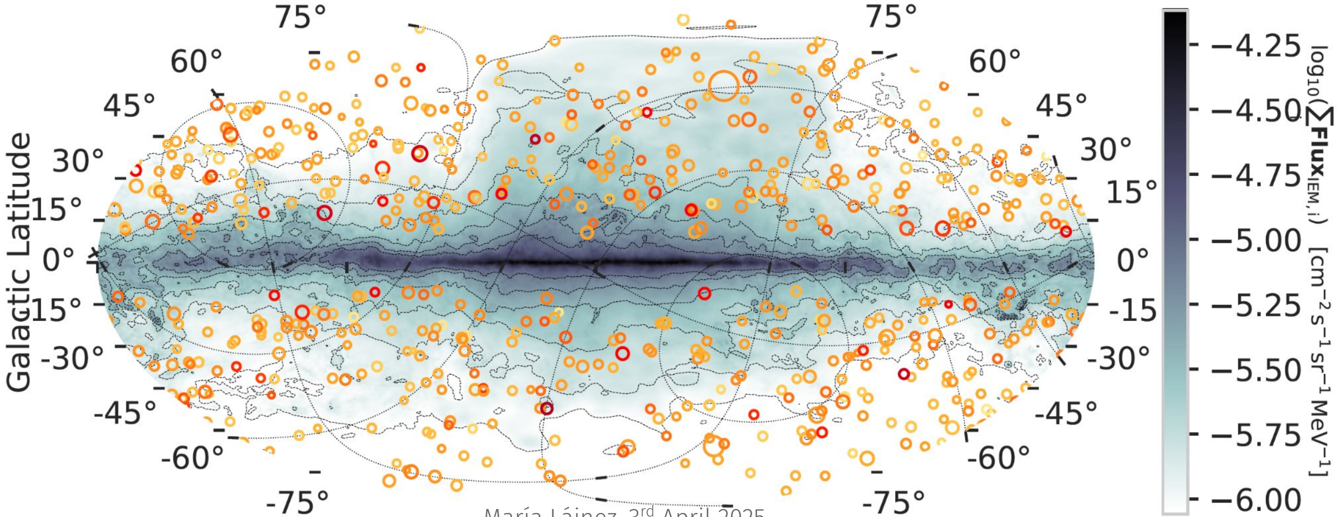
Aim: **search for EHSPs** within a wide selection of blazars/ blazar candidates by studying their broadband SED + **examine the multi-wavelength properties of EHSPs**

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°)

⇨ **657 sources**

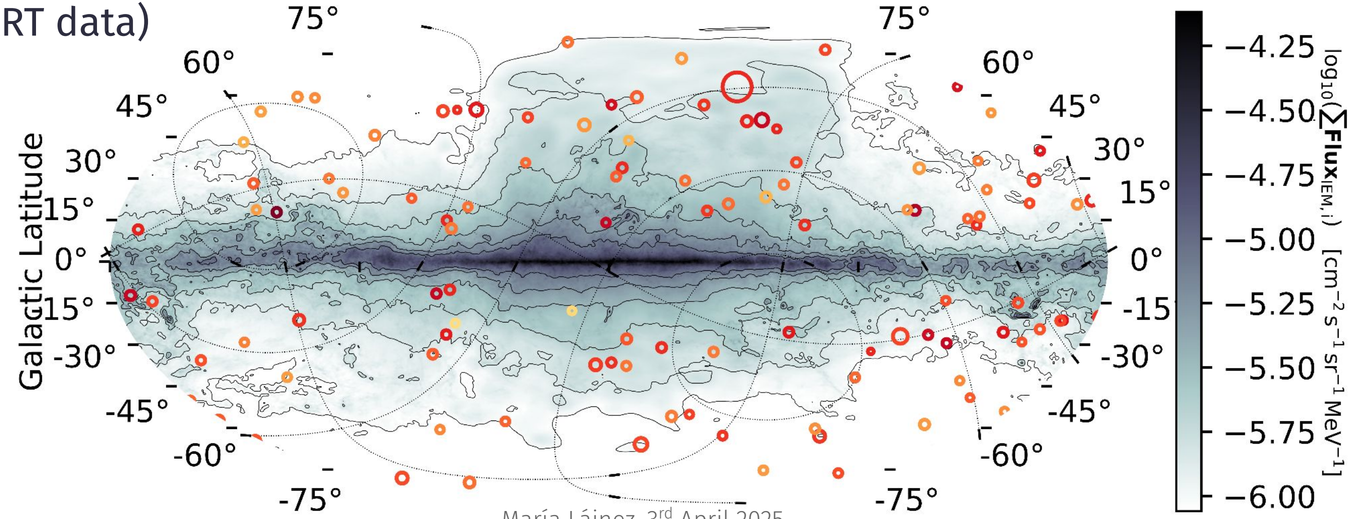


Blazar sample selection

Additional cuts to select sources with low variability across different energy bands:

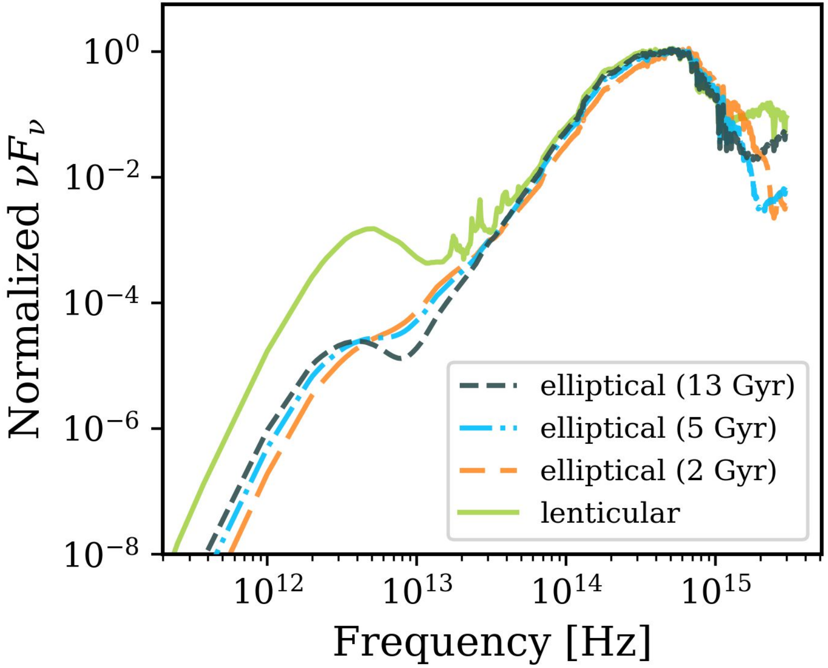
- γ **rays**: variability index (4FGL-DR4) < 27.69 (source with variability index > 27.69 variable at a significance >99%)
- **X-rays**: sources with a single Bayesian block in their light curve (*Swift*-XRT data)

⇨ **124 sources**



Broadband SED modeling: host galaxy emission

- **Host galaxy's thermal emission** often prominent in the optical range of EHSPs' SED (low non-thermal flux at optical/UV + synchrotron peak at high frequencies)
- 4 different host galaxy models*: elliptical galaxies of 2 Gyr, 5 Gyr, and 13 Gyr, and a lenticular galaxy



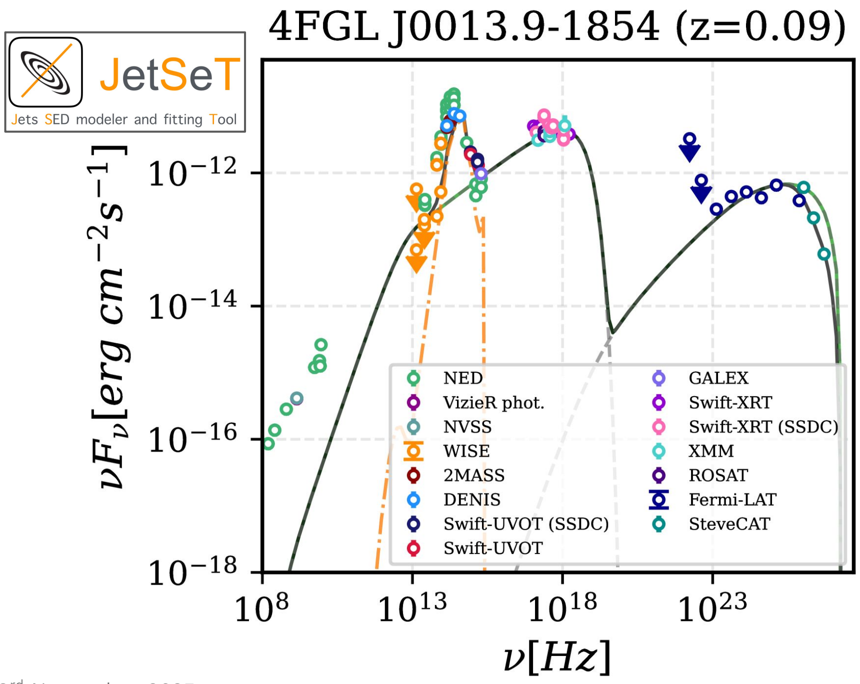
*SWIRE Template Library (Polletta et al. 2007)

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**
- 3 fixed ($R=10^{16}$cm, $R_H=2\times10^{18}$cm, $\Gamma=20$) + 7 free parameters (B, N, p_1, p_2, γ_{max}, γ_{break}, θ)
- Applied EBL attenuation using model from Saldana-Lopez et al. 2021, Domínguez et al. 2024a.
- Modeling done using **JetSeT** (Tramacere A. 2020)

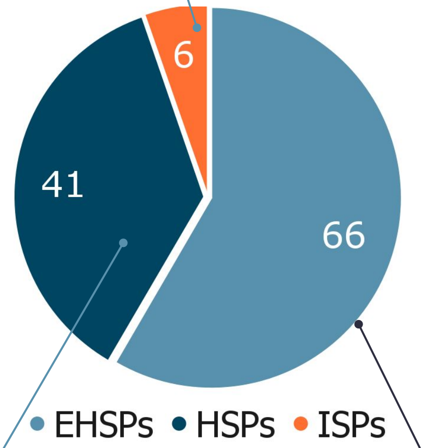
We exclude sources with poor fitting results (χ^2/dof > 1.5) ⇨ **113 surviving sources**

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



Broadband SED modelling results

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

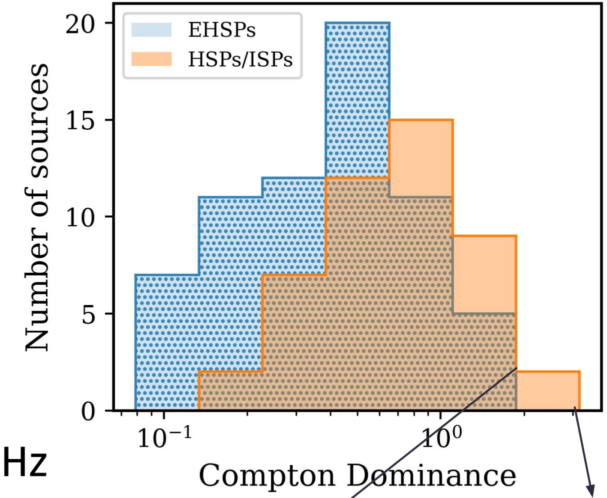


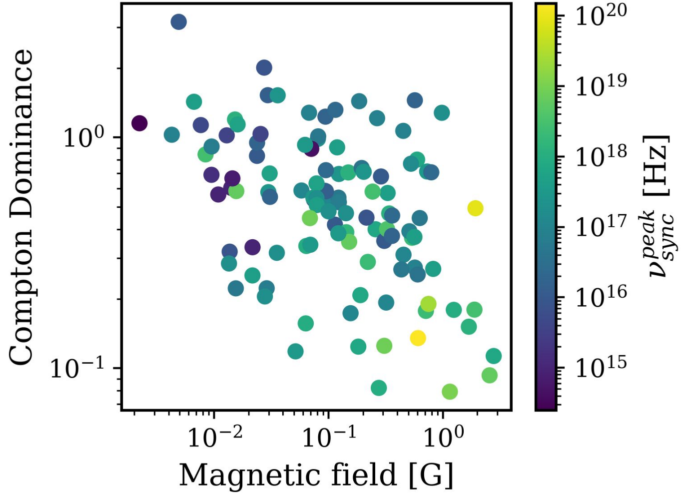
$10^{15} \leq \nu_{SP} < 10^{17}$ Hz

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

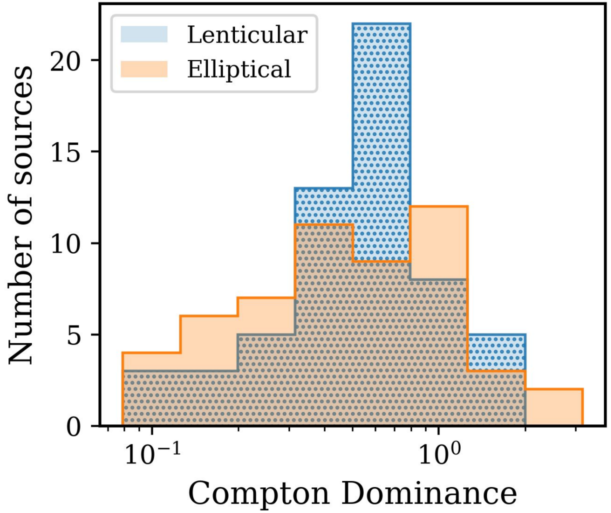
highest CD: CD=3.2 (HSP)

lower ν_{SP} → lower B → higher CD

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

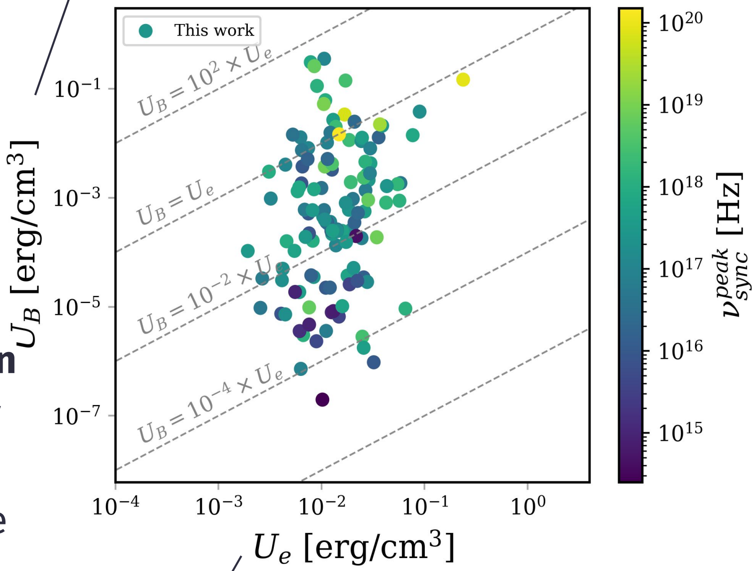
- No significant differences between the two types of galaxies → **negligible impact of the host galaxy emission on the blazar's non-thermal emission**



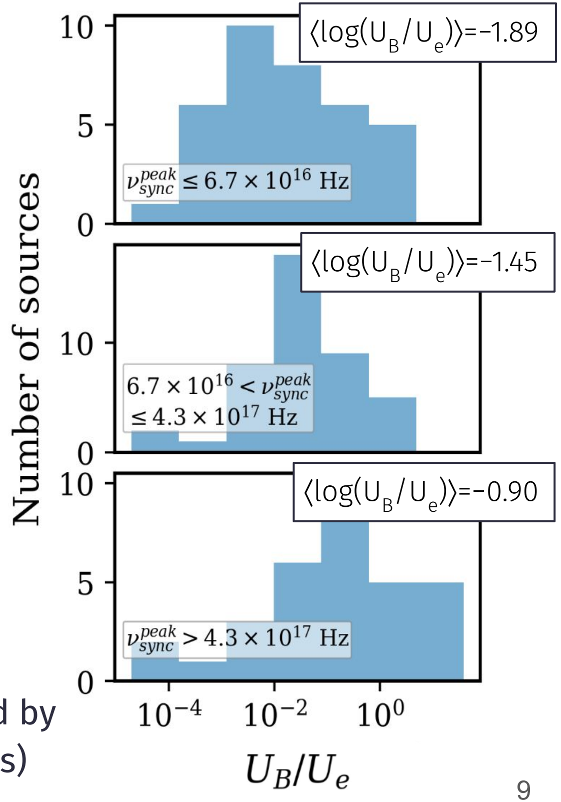
Energy budget

- 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

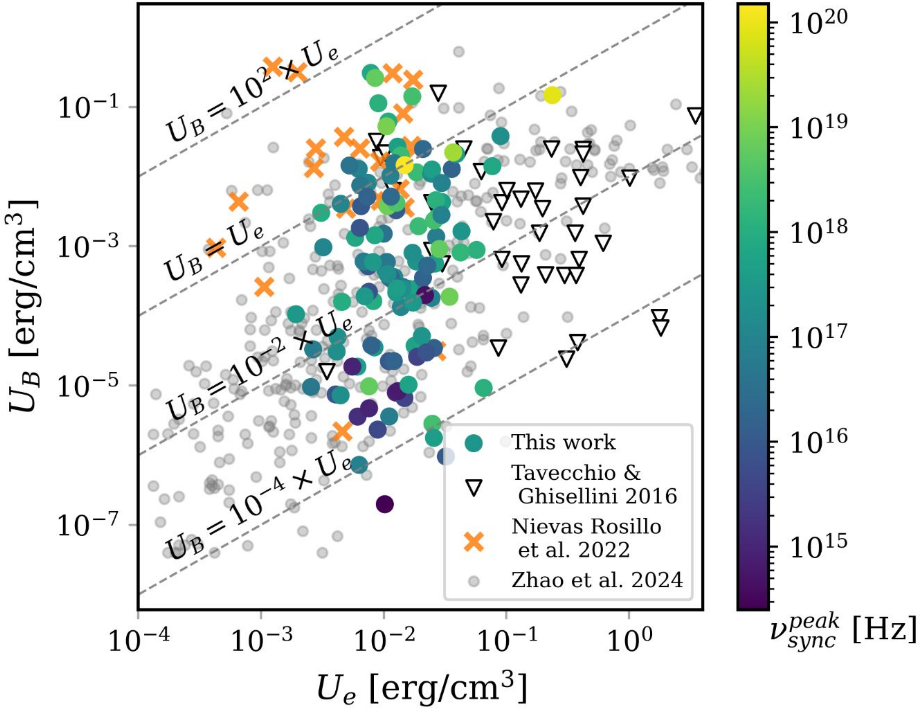


kinetic energy density (energy carried by the population of relativistic electrons)



Energy budget: comparison with other works

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



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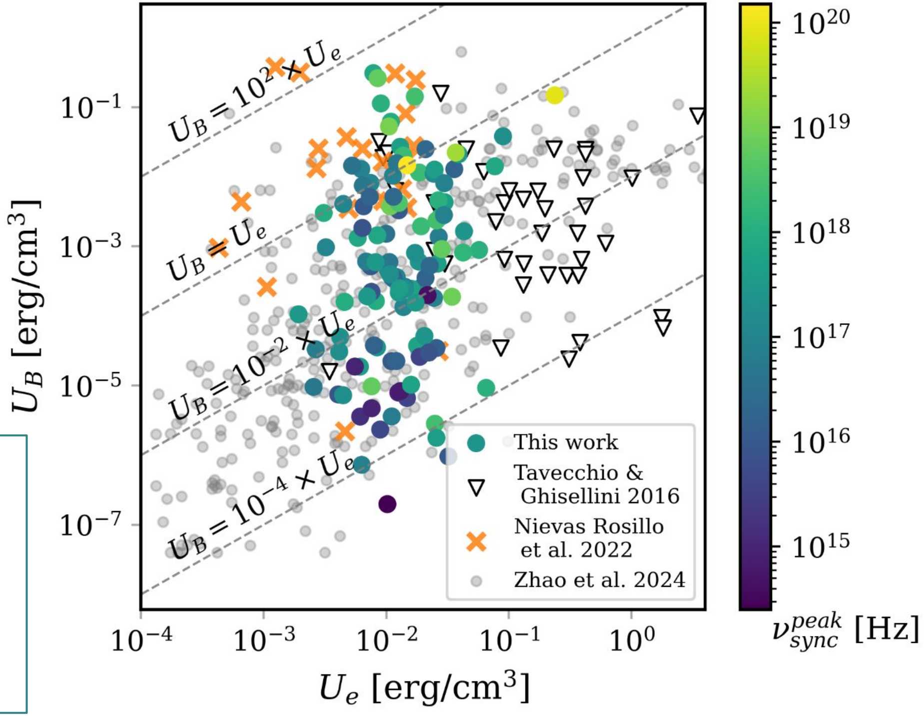
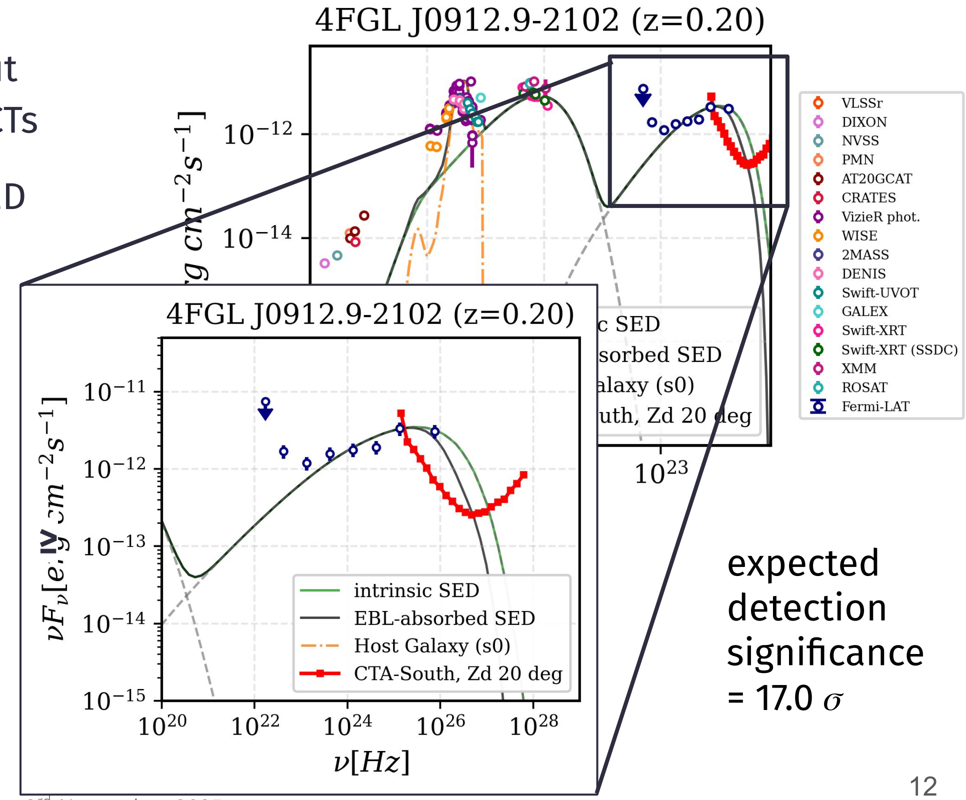
TG16 and Z24 include **variable sources** + sources detected in VHE → during certain observations, may be **far from equilibrium** → higher electron energy injection → lower magnetisation → **lower U_B/U_e ratio**



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)
- No clear relation between the U_B/U_e ratio and their detectability predictions with CTAO



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
- No significant differences in the radiative properties of sources hosted by different galaxy types (S0/ell) → **host galaxy has a negligible impact on the high-energy emission**
- **Higher ν_{SP} sources (EHSPs) closer to energy equilibrium/ equipartition ($U_B/U_e \sim 1$)** 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: **9 strong VHE γ-ray candidates** in 20-hour observations, 11 extra sources detectable at 5σ with longer exposures

Thanks for your attention!

Acknowledgements

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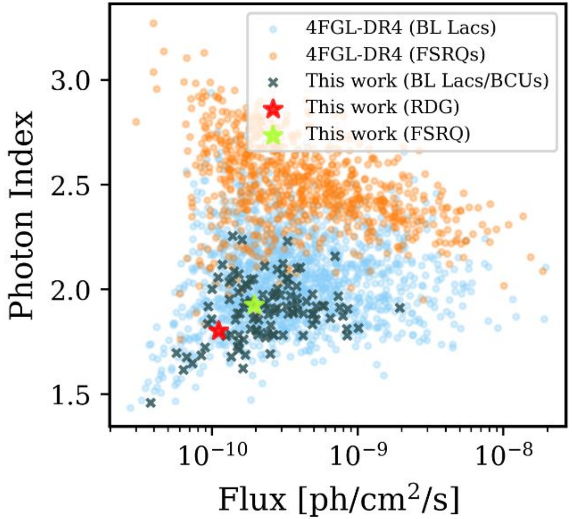
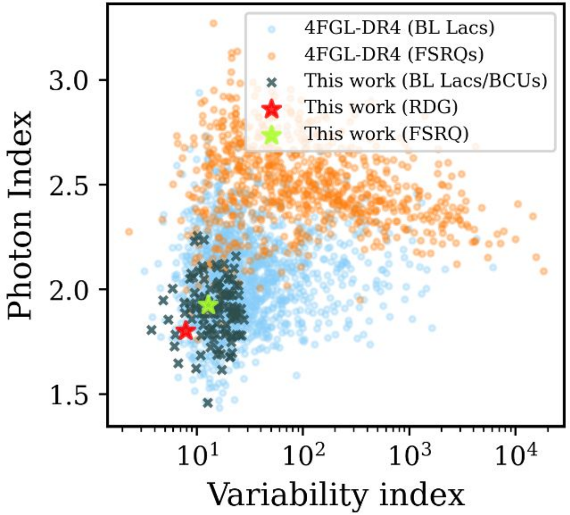
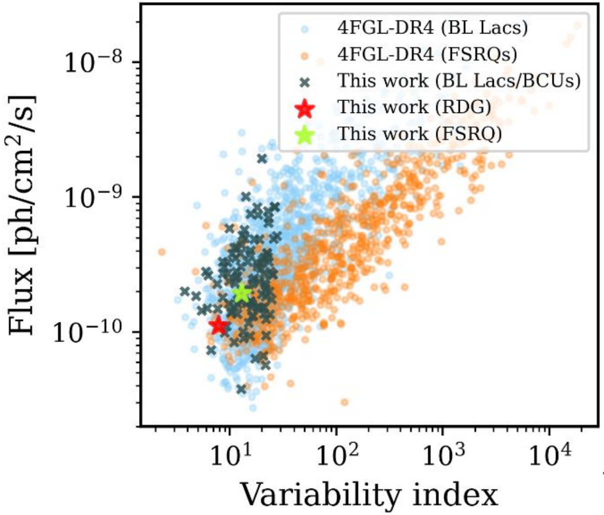
Blazar sample: 4FGL-DR4 classification

- **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





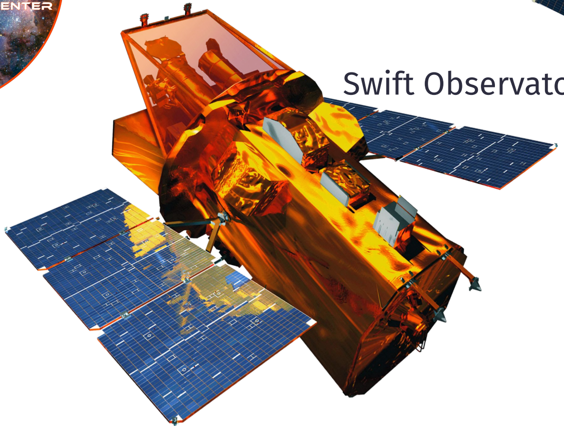


Multi-wavelength data

- *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

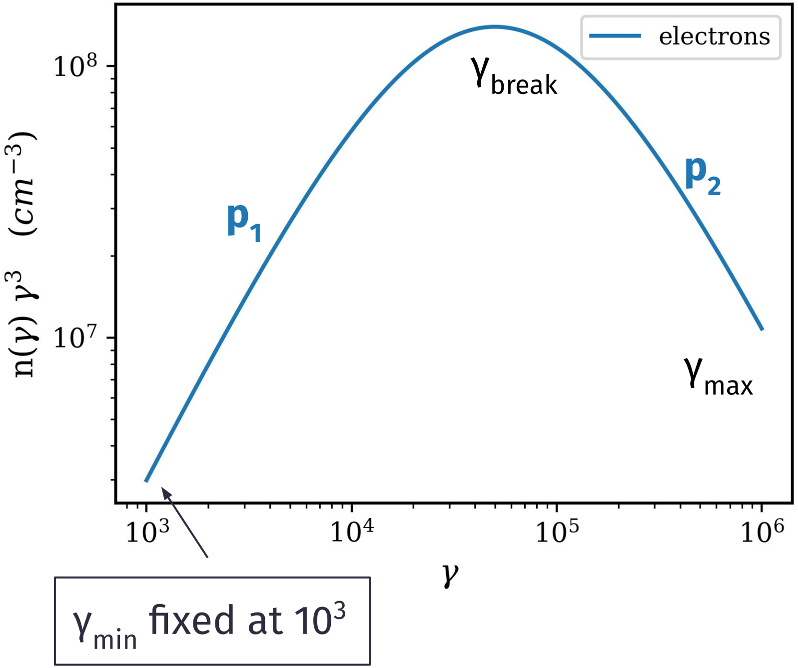


Swift Observatory

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

Broadband SED modeling: details

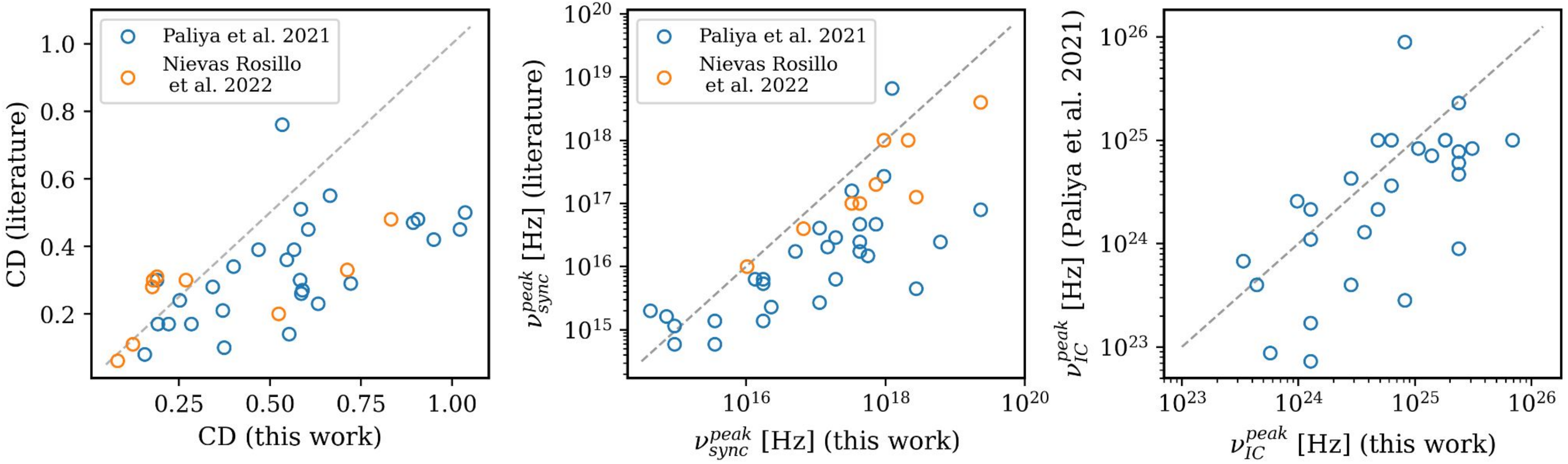
- **One zone SSC model** (higher-energy peak due to IC of electrons with photons produced in the synchrotron process) + **best-fit host galaxy model**
- No EC component (simple environments, no dusty torus/ BLR to supply photons for the EC)
- Emission produced in a **single spherical region or blob** 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



Results comparison with other works

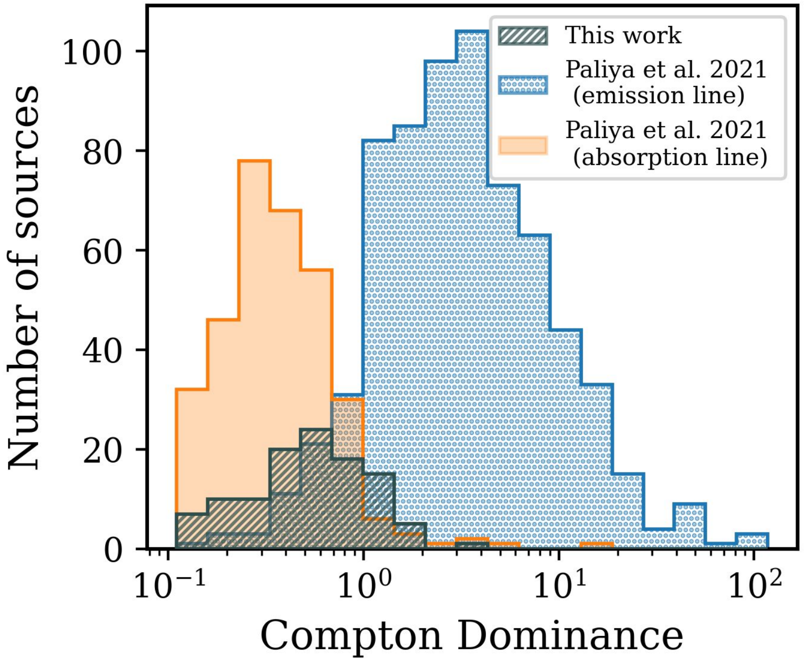
28/**9** overlapping sources with **Paliya et al. (2021)**/**Nievas Rosillo et al. (2022)**

- Our ν_{SP} values systematically higher by a factor ~ 6 (P+21)/~ 3 (N+22) → impact on CD; better agreement with N+22 (includes host galaxy component, no host galaxy component in the model of P+21)
- Less deviation in ν_{ICpeak} → less sensitive to modelling assumptions



Compton Dominance

- Paliya et al. 2021:
  - **Absorption-line blazars**: primarily **BL Lacs**, whose spectra show absorption lines attributed to the stellar population of the host galaxy
  - **Emission-line blazars**: typically **FSRQs**
- Sources selected for this work are at the **high end of the absorption-line blazar sample**
- Our predominantly EHSP sample shows **higher CD than absorption-line blazars**, suggesting greater radiative efficiency (yet high synchrotron peak values)



CD of the BCUs, FSRQ and radiogalaxy

- **FSRQ** (4FGL J0132.7−0804/ PKS 0130−083): CD = 0.27

  *FSRQ blazars typically have CD $\gtrsim$ 1 → 4FGL J0132.7−0804 probably misclassified as FSRQ, but likely a BL Lac (very narrow emission lines)

- **Radiogalaxy** (4FGL J1518.6+0614/ TXS 1516+064): CD = 0.12

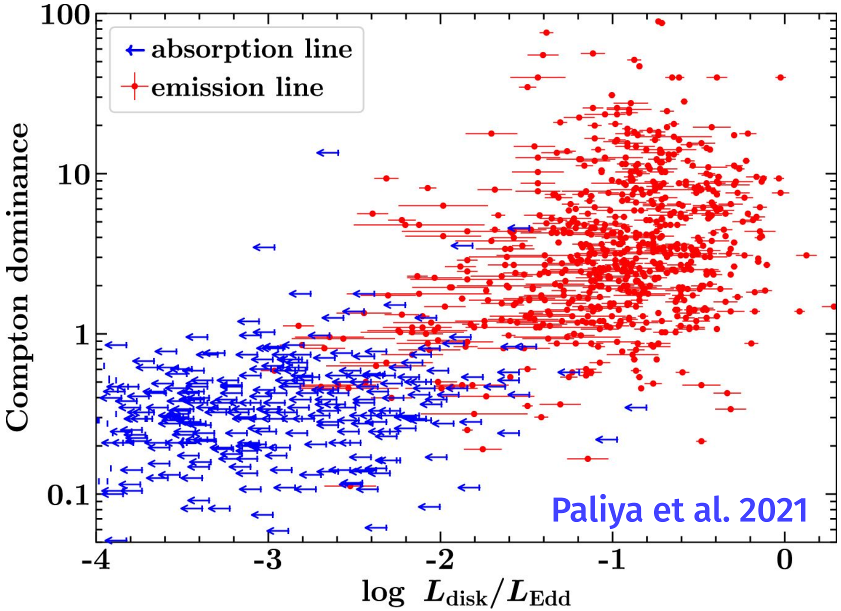
  → **CD < 1** → low accretion activity or emission site located far from the core (i.e., the strong radiation fields weakened by the time they reach the emitting region)

- **29 BCUs** in the sample: all but two have **CD < 1**, showing **similar emission properties to those of BL Lacs** → remaining two BCUs: 4FGL J0611.1+4325 (CD = 1.4) and 4FGL J1719.3+1205 (with CD = 1.5)

Compton Dominance classification

- Paliya et al. (2021) found a correlation between accretion luminosity and CD in blazars:
  - **emission-line blazars**: generally CD > 1 and $L_{disk}/L_{Edd} > 0.01$
  - **absorption-line blazars**: generally CD < 1 and $L_{disk}/L_{Edd} < 0.01$
- Most EHSPs in our sample have CD ≲ 1 → $L_{disk}/L_{Edd} \leq 0.01$ → **low-Compton-dominated (LCD) objects**

  *more Compton-dominated blazars (mainly FSRQs) typically classified as high-Compton-dominated (HCD) objects

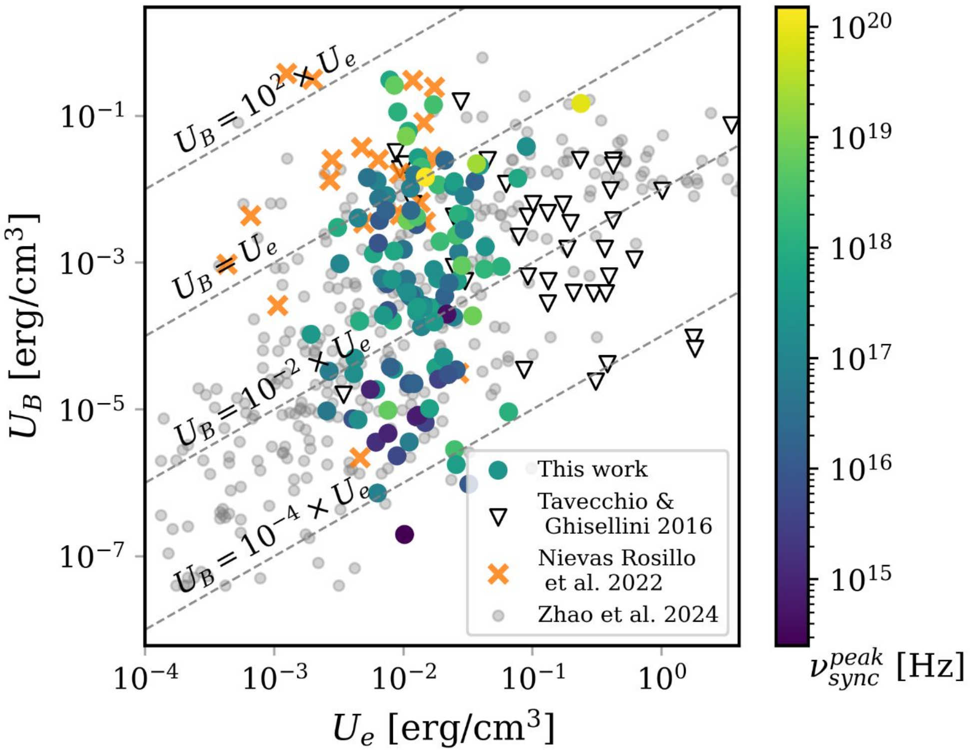


⇨ **our blazar sample mainly consists of LCD objects, with no emission lines and low accretion activity**

Energy budget: comparison with other works

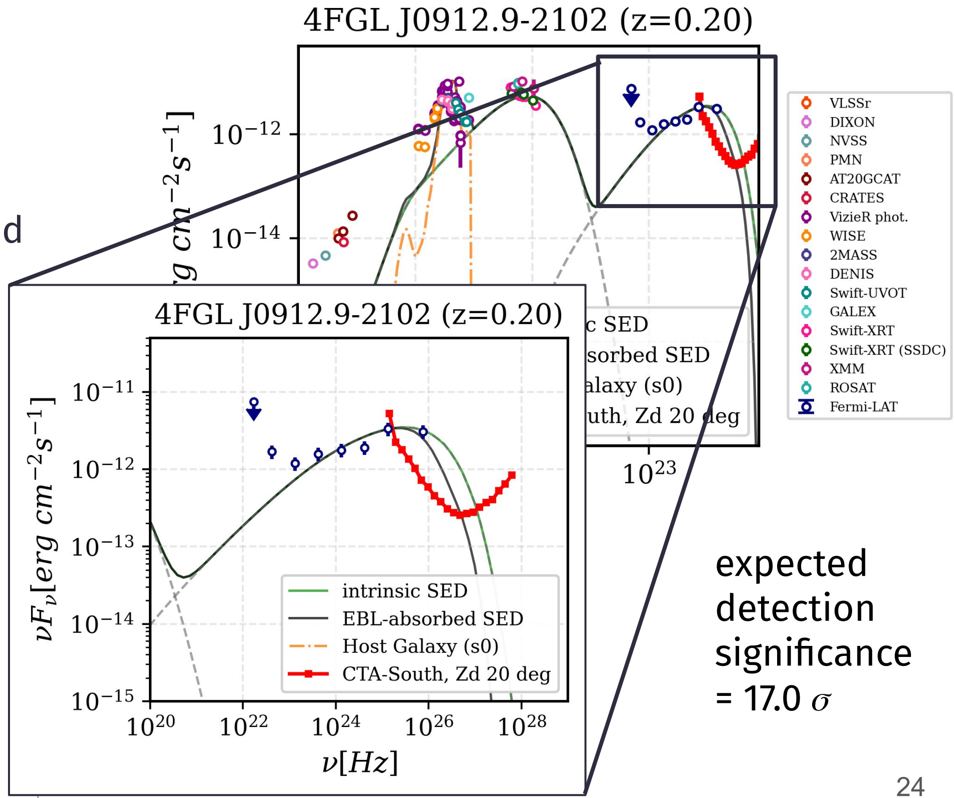
SAMPLE SELECTIONS:

- **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

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No clear relation between the U_B/U_e ratio and their detectability predictions with CTAO