Broadband spectral analysis of the most extreme gamma-ray blazars

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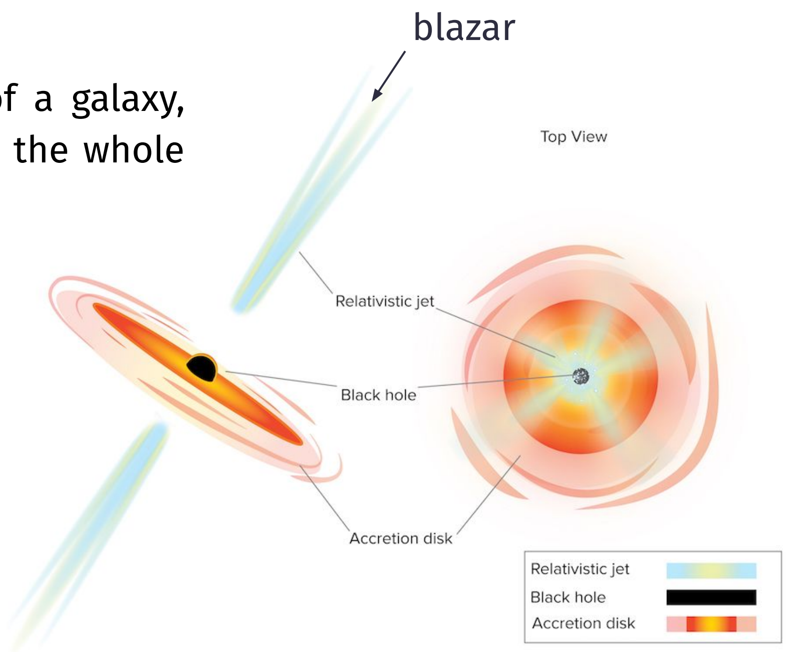
Outline

- Introduction to blazars
- Motivation of the project
- Blazar sample selection and reconstruction of the broadband SEDs
- Broadband SED modelling
  - Host galaxy emission
  - Synchrotron and Inverse Compton emission
- Results
- Detectability predictions with CTAO
- Summary and conclusions

Introduction to blazars

- **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

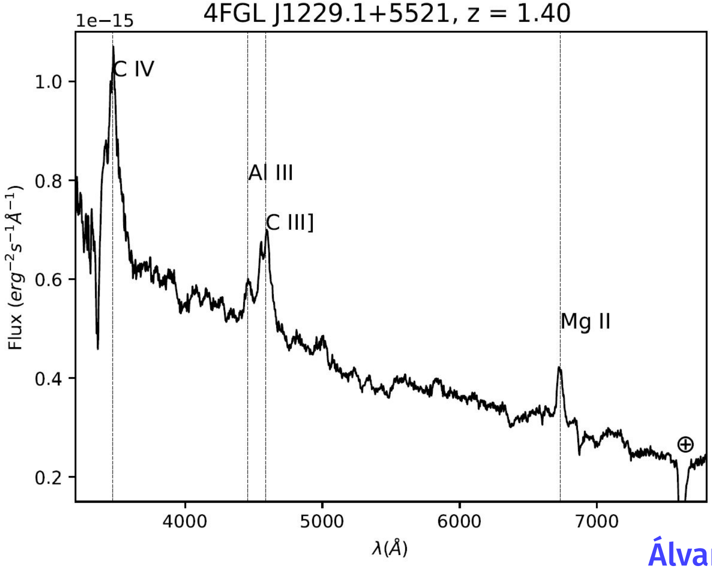
⇨ **blazars:** AGNs with their jets pointing towards the Earth (most dominant source type in the extragalactic γ-ray sky)



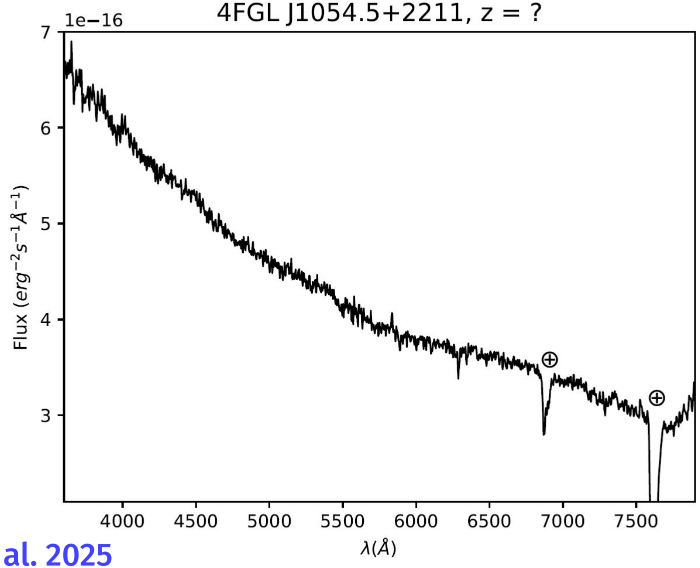
Introduction to blazars

Classification of blazars based on their optical spectra:

FSRQs: broad emission lines (EW > 5 Å)



BL Lacs: almost featureless continuum

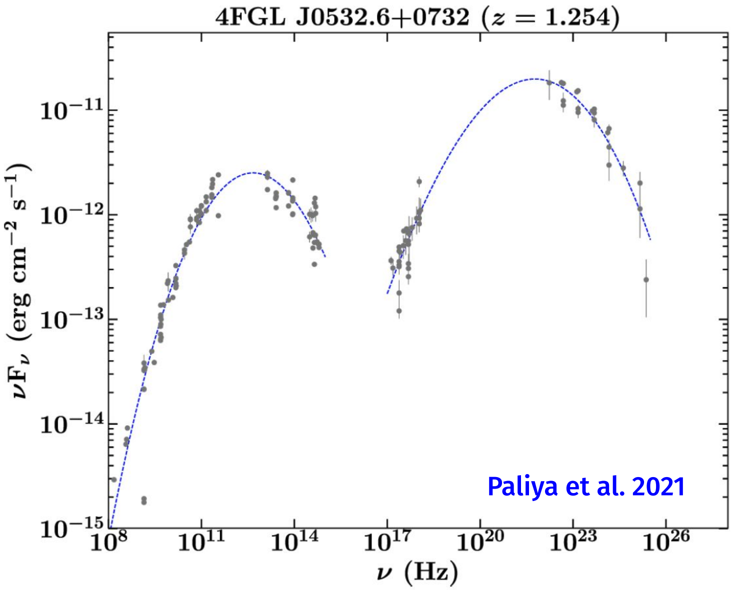


Álvarez Crespo et al. 2025

Introduction to blazars: broadband SED

Broadband spectral energy distribution (SED):

- dominated by **non-thermal** emission from radio to γ rays
- **double-peaked structure**:
  - lower energy peak (IR to X-rays) attributed to **synchrotron emission** from relativistic electrons
  - higher energy peak: debated origin (both hadronic and leptonic processes proposed)

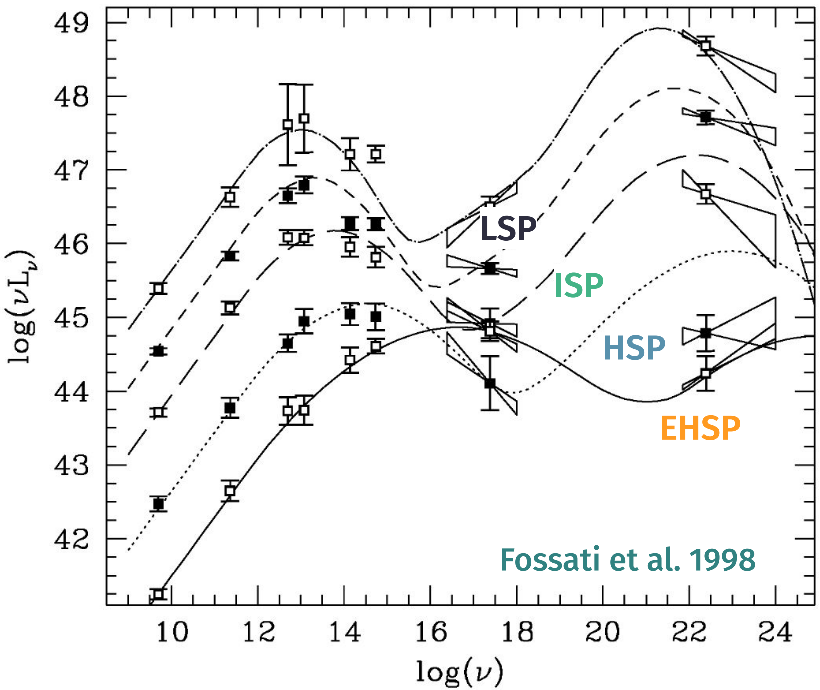


→ **synchrotron-self-Compton (SSC) model** attributes the peak to **inverse Compton (IC) scattering** of the electron population with photons produced by the synchrotron process

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)**: $10^{14} \leq \nu_{SP} < 10^{15}$ 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} ≥ 0.4 keV)



EHSPs: the most extreme blazars

Extremely high synchrotron-peaked (EHSP) blazars:

- the least luminous but most energetic blazars (end of the blazar sequence)
- essential to understand non-thermal emission and acceleration processes in jets
- very high energies reached → cosmological studies (EBL, blazar evolution, EGB, IGMF)
- very heterogeneous group (EHSPs with very hard VHE spectra, blazars becoming EHSPs only when flaring, EHSPs with energetic synchrotron peaks but moderate TeV spectra,...)
- potential very-high-energy (VHE, E > 100 GeV) emitters → targets for IACTs
- a few dozens of sources of this class known

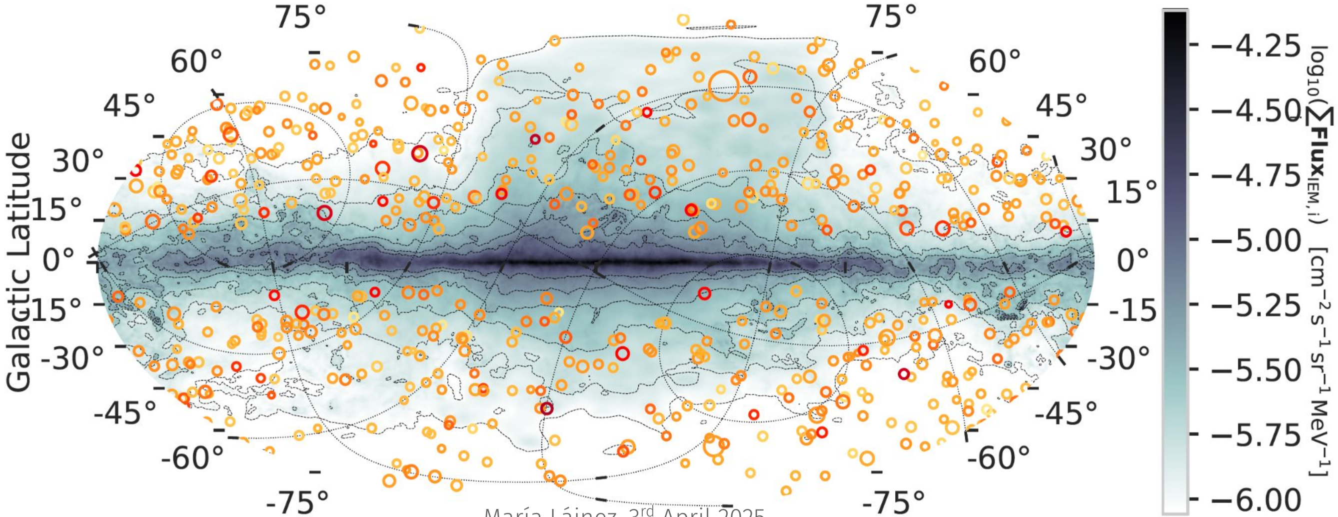
Aim: **search for EHSPs** within a wide selection of blazars and blazar candidates by studying their broadband SED + **examine the multi-wavelength properties of EHSPs** by considering a large sample with a broad spectral coverage

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**

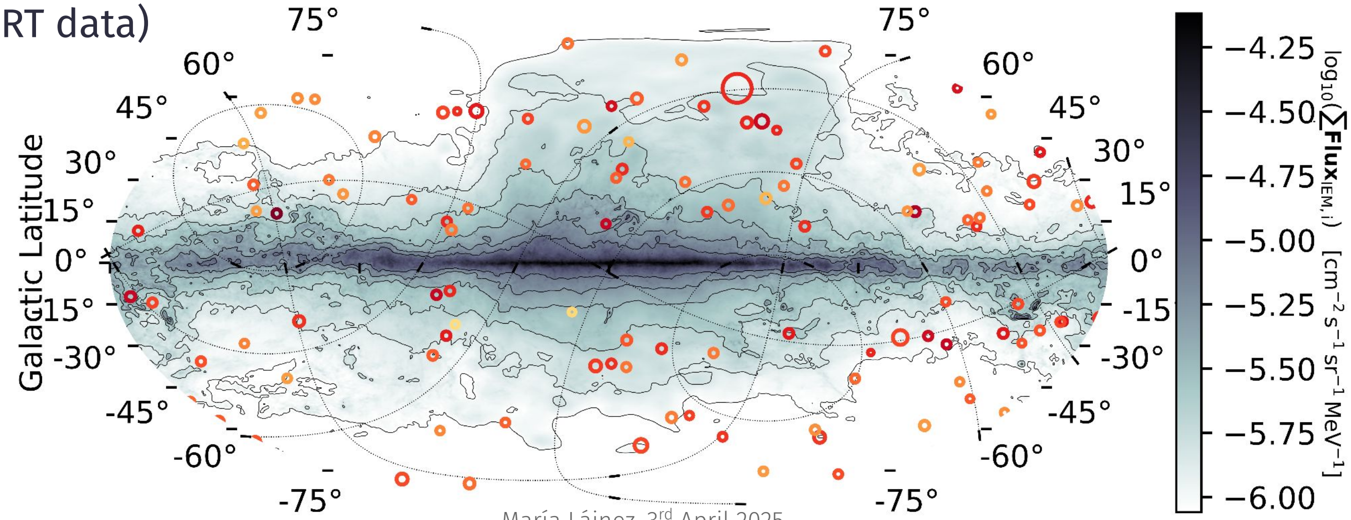


Blazar sample selection

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**



Blazar sample: 4FGL-DR4 classification

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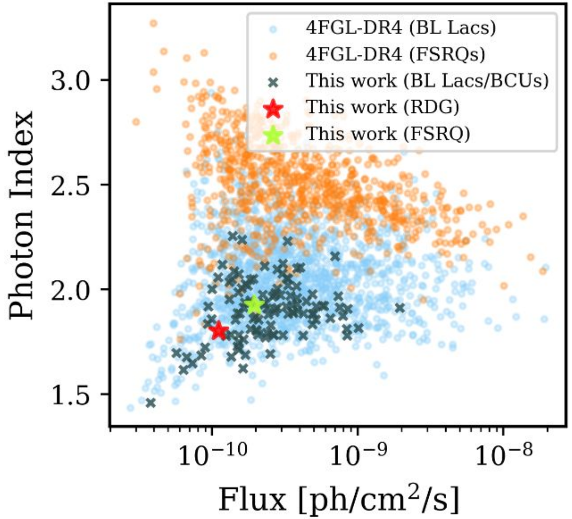
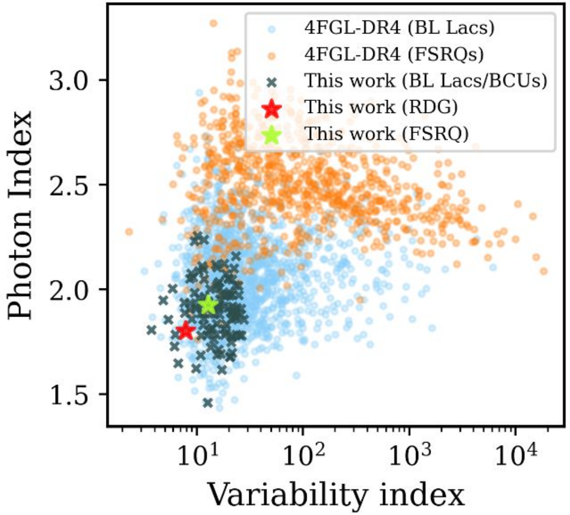
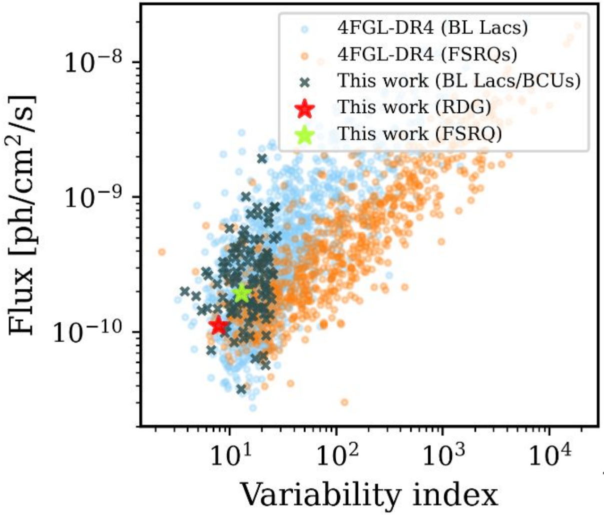
- **124 sources** in the final sample
  - 93 BL Lacs
  - 29 blazar candidates of uncertain type (BCUs)
  - 1 FSRQ (4FGL J0132.7-0804), 1 radiogalaxy (4FGL J1518.6+0614)
- The selected sources (mostly BL Lacs) have harder spectra than FSRQs





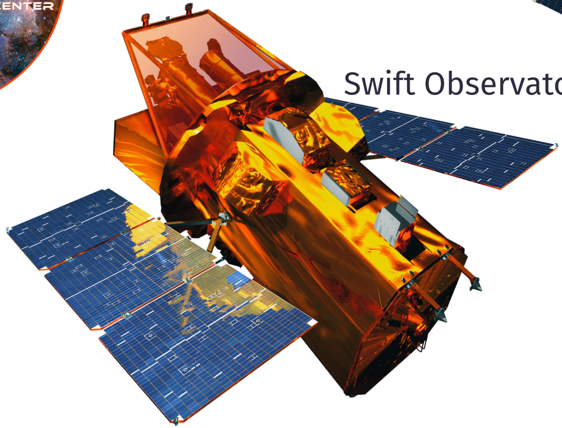


Multi-wavelength data

- *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

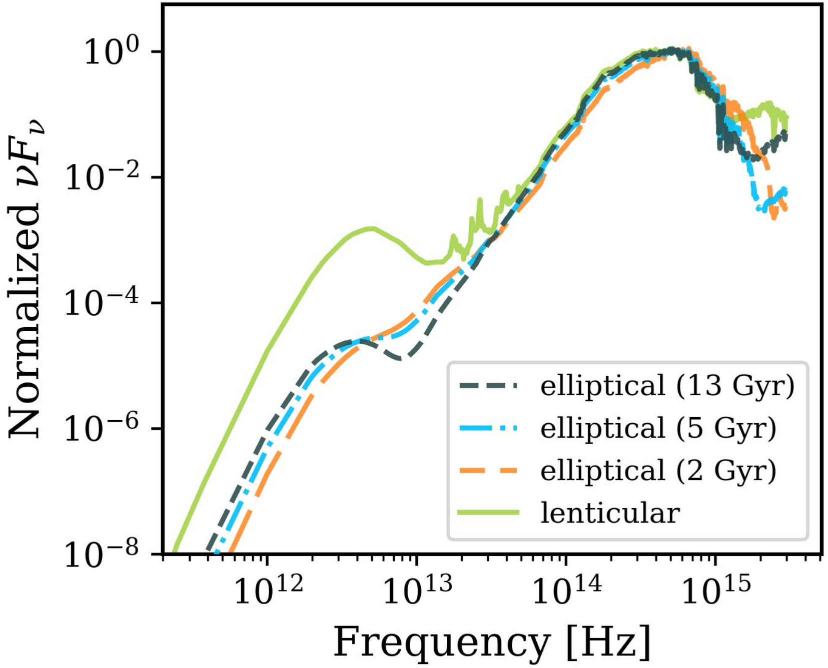
*https://tools.ssdc.asi.it/SED/

Broadband SED modeling: 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

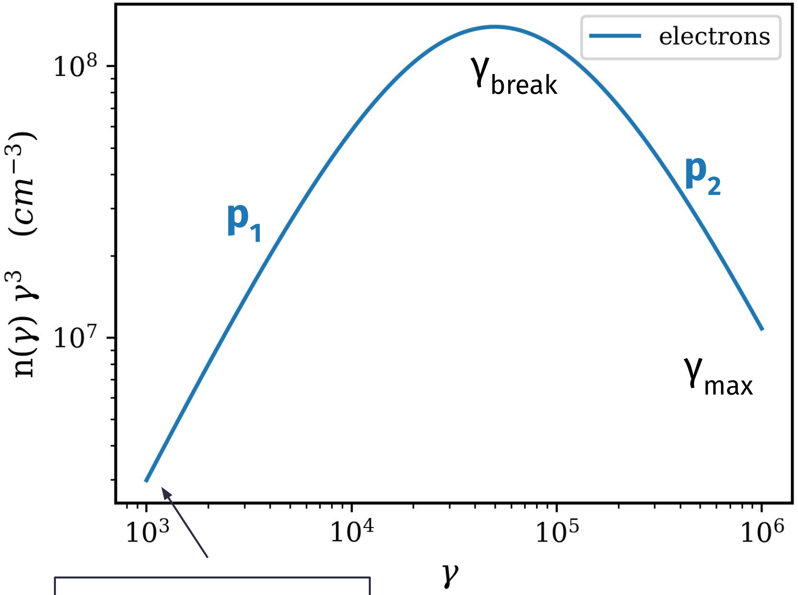
- **Negligible contribution to the EC emission at high energies** (not a significant source of seed photons for the EC process) →not included in the broadband SED modelling



*SWIRE Template Library (Polletta et al. 2007)

Broadband SED modeling

- **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



γ_{min} fixed at 10^3

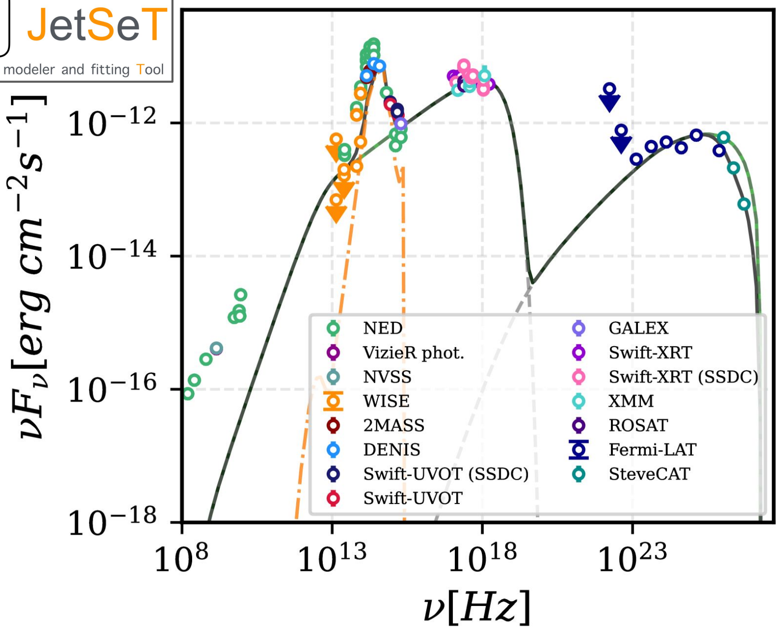
Broadband SED modeling

- Some parameters fixed to typical EHSP values: $R=10^{16}$cm, $R_H=2\times10^{18}$cm (distance blob - BH), Γ=20
- 7 free parameters: B, N, p_1, p_2, γ_{max}, γ_{break}, θ
- Data fitted in the range [5×10^{10} Hz, 10^{27} Hz], excluding radio emission (believed to originate from a region much larger than the compact region responsible for the rest of the SED + significant synchrotron self-absorption)
- Applied EBL attenuation using model from Saldana-Lopez et al. 2021, Domínguez et al. 2024a.
- Modeling done using **JetSeT** (Tramacere A. 2020)

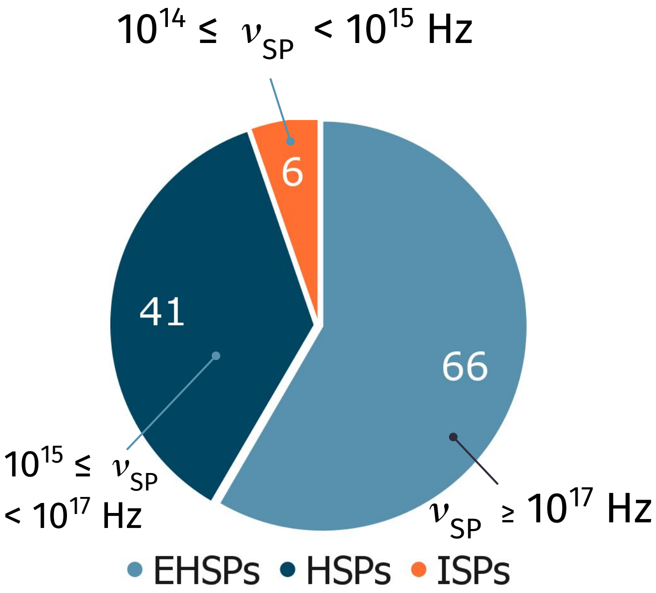
We exclude sources with poor fitting results (χ^2/dof > 1.5) ⇨ **113 surviving sources**

*All MWL SEDs of the 124 sources + best-fit models in the Appendix (https://arxiv.org/abs/2502.11888)

JetSeT
Jets SED modeler and fitting Tool

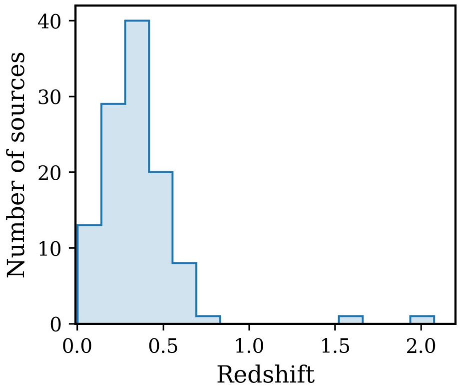


Broadband SED modeling results

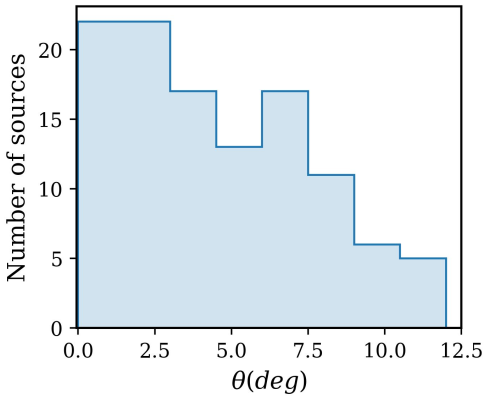


113 sources

No significant differences in the redshift distribution of EHSPs and HSPs/ISPs ⇨ **no clear evidence of an evolutionary connection**

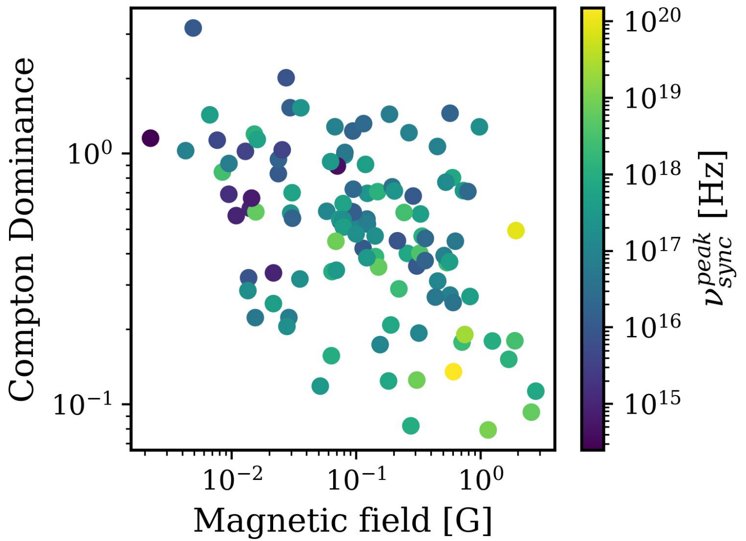


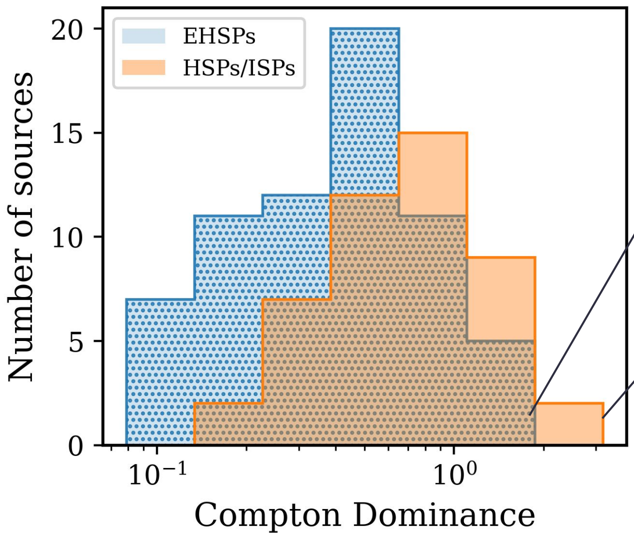
Jet viewing angle: **θ<12°**, 85% of the sources with θ<8° ⇨ Doppler factors between ~2 and 40, typical for blazars (**jets closely aligned with our line of sight**)



Broadband SED modelling results

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





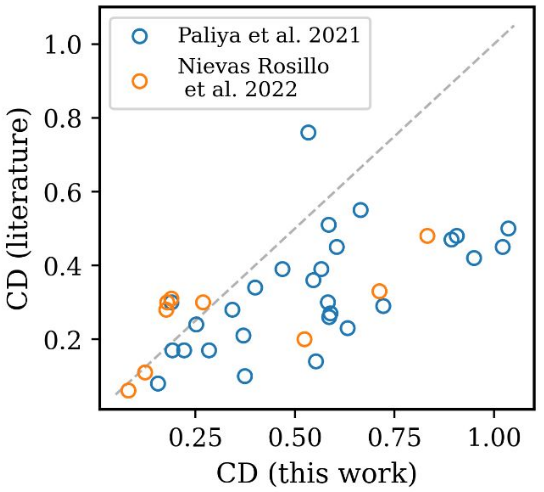
lower ν_{SP} →lower B → higher CD

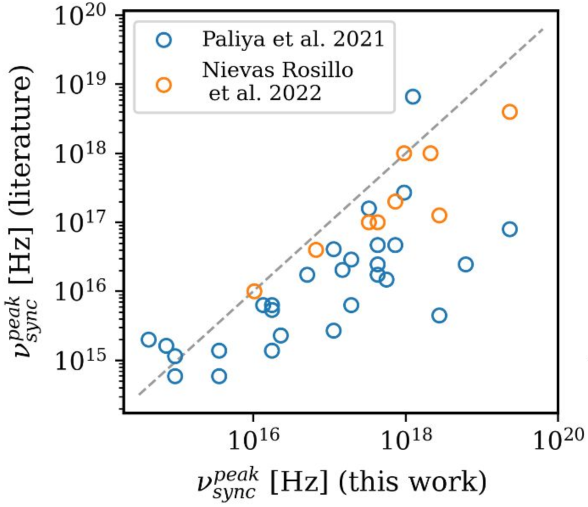
EHSP candidates have lower CD than HSPs/ISPs

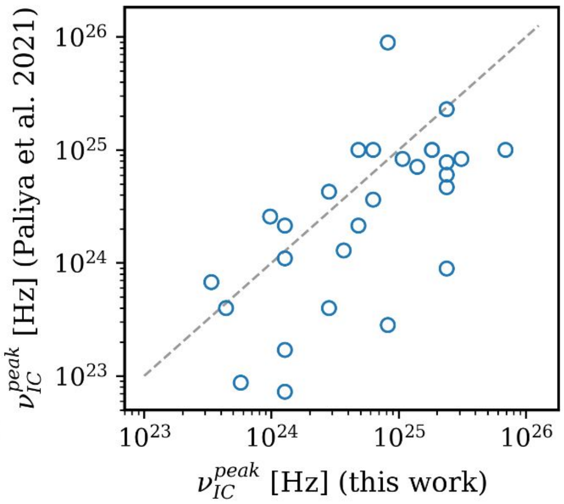
Results comparison with other works

28 overlapping sources with **Paliya et al. (2021)**, which catalogues 1077 γ-ray blazars/BCUs detected by *Fermi*-LAT

- our ν_{SP} values are systematically higher by a factor ~ 6 → impact on CD (no host galaxy component in their model, potentially increasing their synchrotron component)
- less deviation in ν_{ICpeak} → less sensitive to modelling assumptions



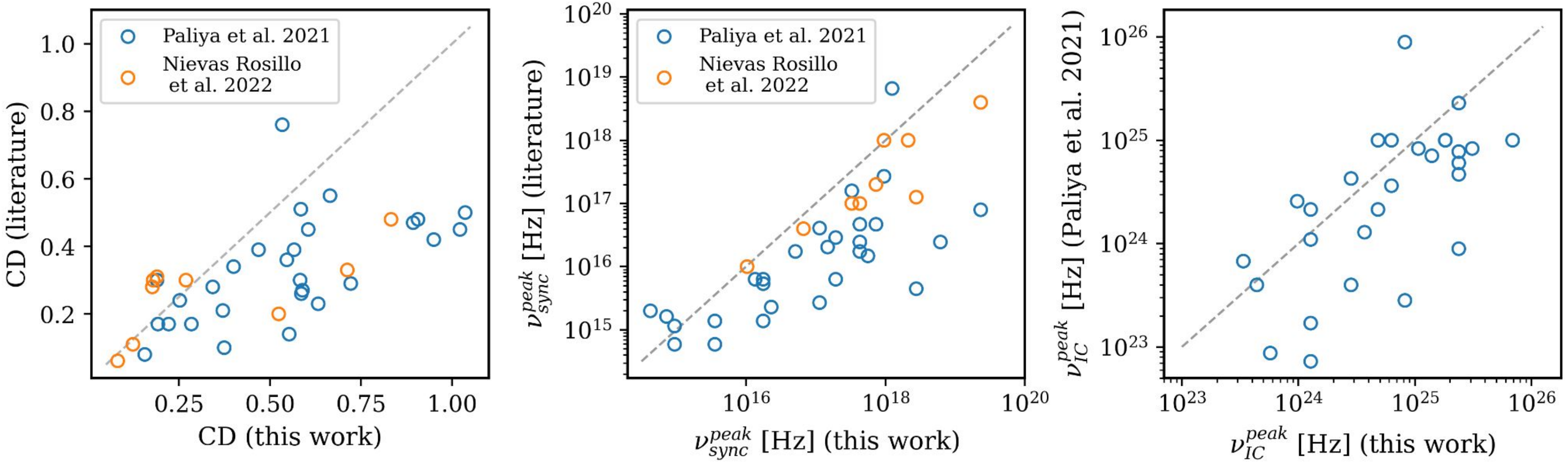




Results comparison with other works

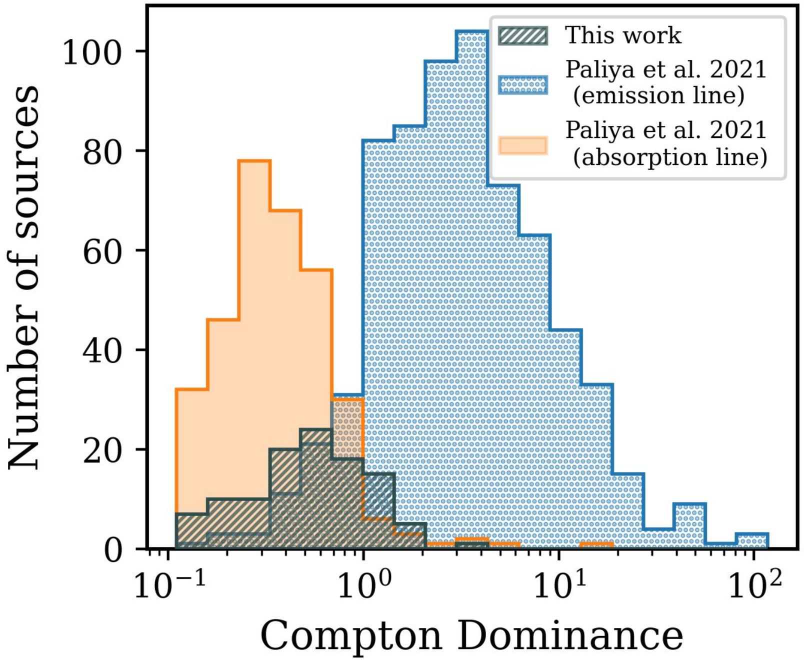
9 overlapping sources with **Nievas Rosillo et al. (2022)**, whose sample contains 22 2BIGB catalogue sources classified as BCU in 4FGL

- better agreement than with Paliya et al. (2021), likely due to Nievas Rosillo et al. (2022) including a blackbody component to account for host galaxy emission
- our ν_{SP} values remain systematically a factor of 3 higher



Compton Dominance

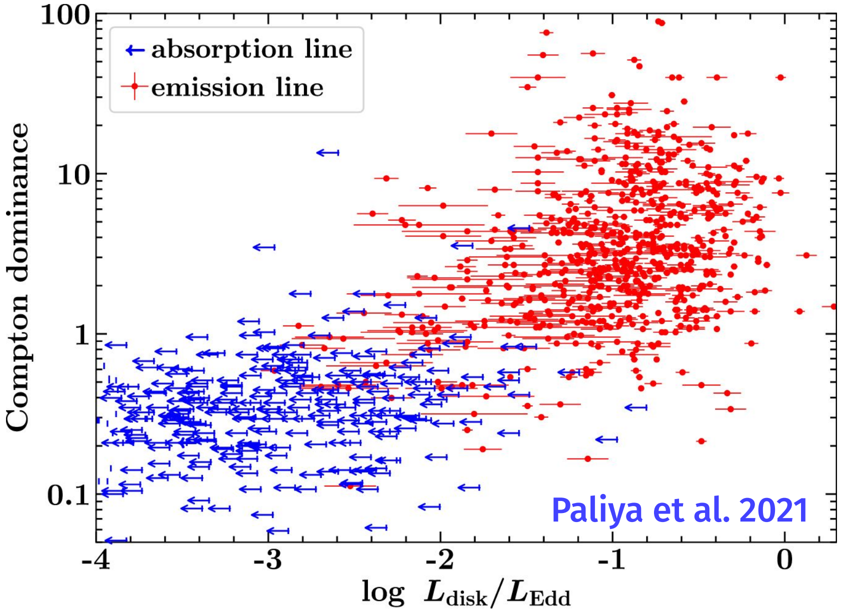
- Paliya et al. 2021:
  - **absorption-line blazars**: primarily **BL Lacs**, whose spectra show absorption lines attributed to the stellar population of the host galaxy
  - **emission-line blazars**: typically **FSRQs**
- Sources selected for this work are at the **high end of the absorption-line blazar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



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

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

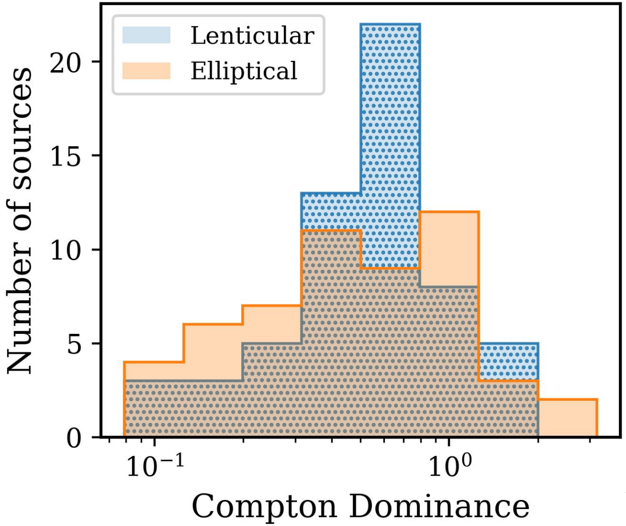
  → **CD < 1** → low accretion activity or emission site located far from the core (i.e., the strong radiation fields weakened by the time they reach the emitting region)

- **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)

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**

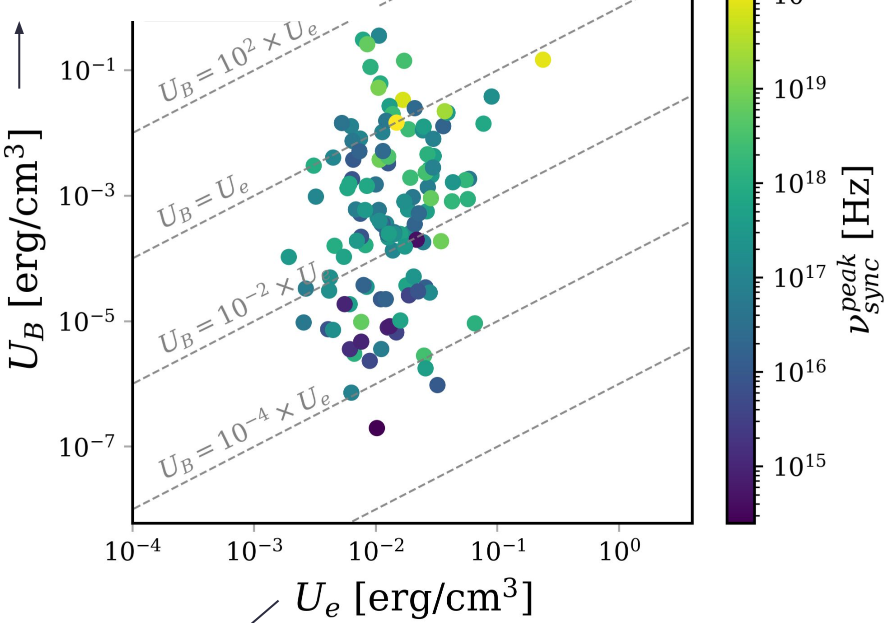
  → host galaxy generally **not a significant source of seed photons for EC** (even in galaxies with high star formation rates, unlikely to impact the high-energy regime)
- Host galaxy temperatures: from 3200 to 6400 K



Energy budget

- **Ratio U_B/U_e**: energy density of the magnetic field to that of the relativistic electrons
  - critical parameter to understand the physical conditions and energy balance in blazar jets
  - reveals jet's magnetisation + balance between magnetic fields and particle energies in producing the observed radiation
  - crucial to understand the interplay between synchrotron and IC processes + energy budget of the system
- **Jet close to equipartition (U_B/U_e ~ 1)**: energetically efficient (minimizes energy losses during the acceleration/transport of particles)

magnetic energy density

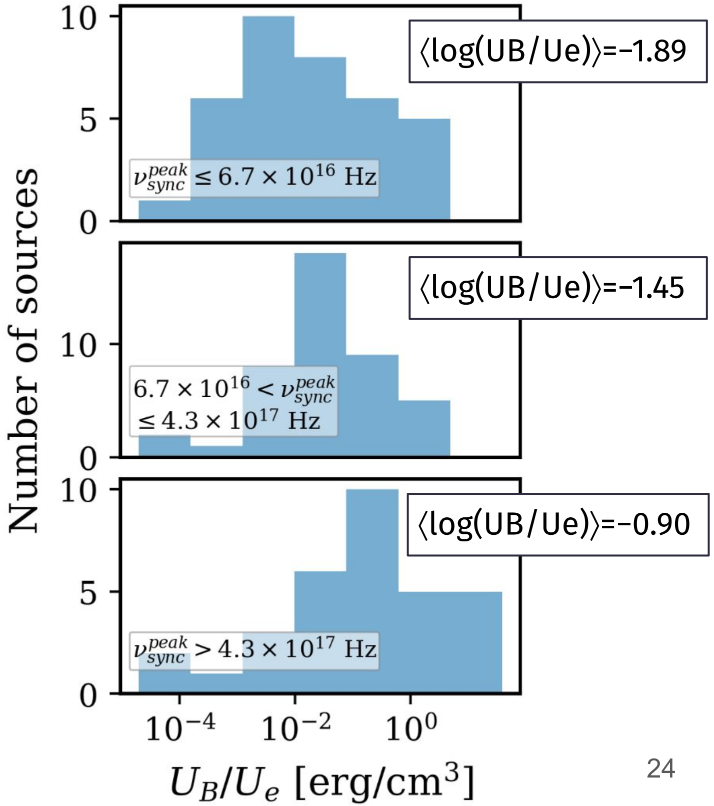


kinetic energy density (energy carried by the population of relativistic electrons)

Energy budget

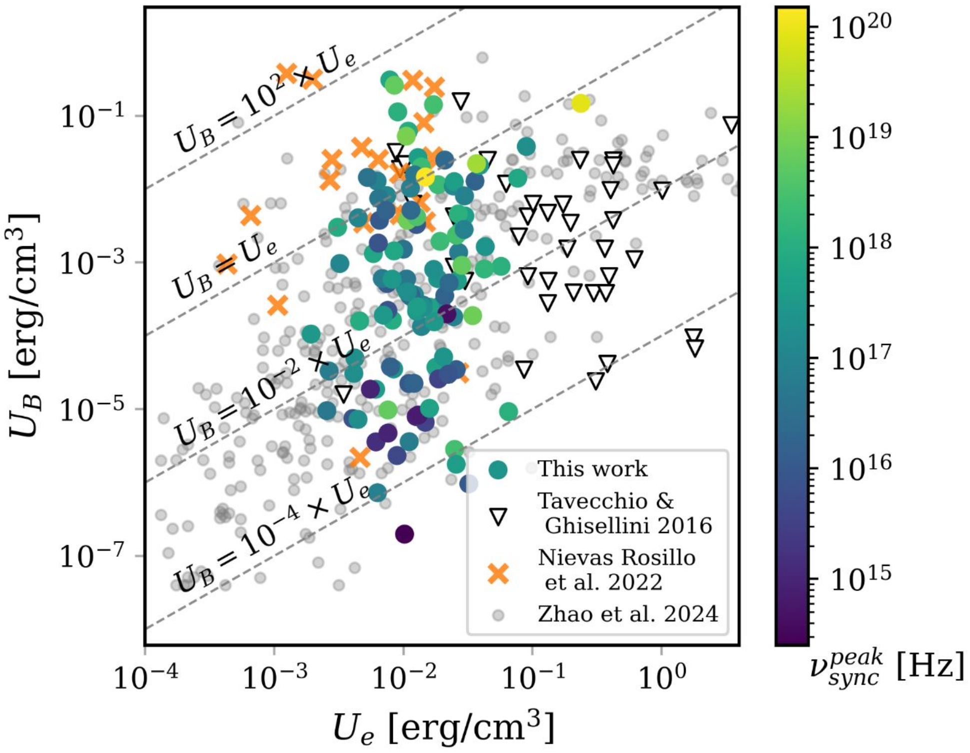
- Our results suggest a **relation between the U_B/U_e ratio and the synchrotron peak frequency** → most extreme sources closer to the line $U_B \approx U_e$
- To verify if there is a dependence of U_B/U_e on the synchrotron peak frequency, we divide our sample into three subsamples with different ranges of ν_{SP} + fit each distribution of U_B/U_e to a Gaussian function

⇨ the most extreme sources are generally closer to equipartition than the sources with lower synchrotron peak frequencies



Energy budget: comparison with other works

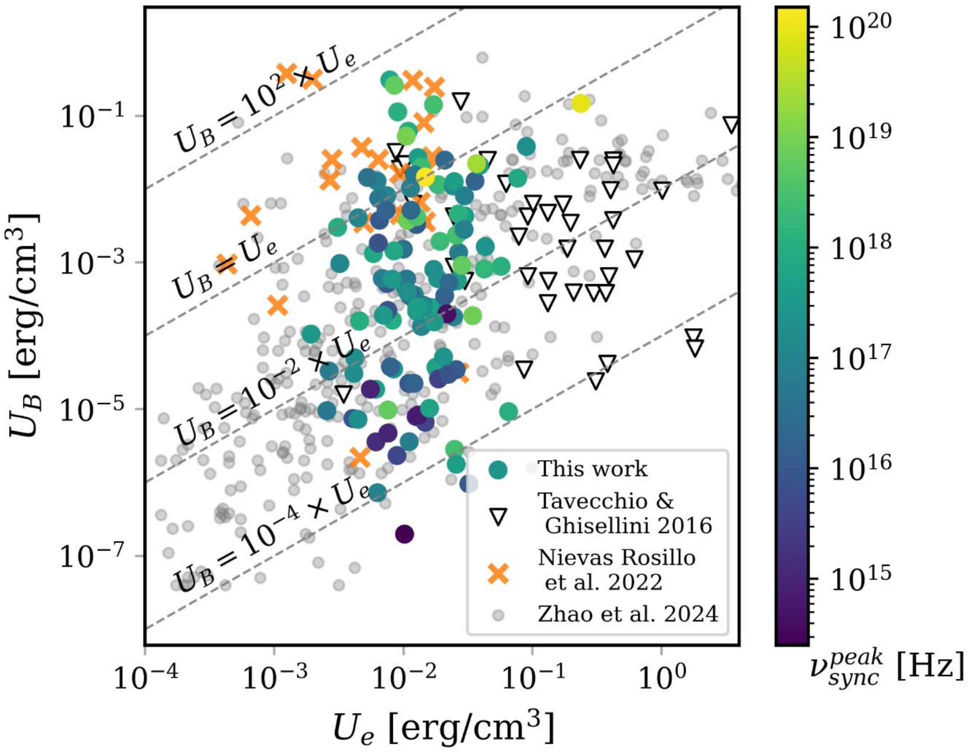
- Agreement with the results obtained by **Nievas Rosillo et al. (2022)** → most sources in their sample **close to equipartition** (the two potential VHE emitters in their sample have the smallest U_B/U_e ratios)
- Differences with **Zhao et al. (2024)** and **Tavecchio & Ghisellini (2016)** → most sources from their samples far from equipartition, with $U_B << U_e$, clustering mainly around the line $\mathbf{U_B = 10^{-2} \times U_e}$



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)



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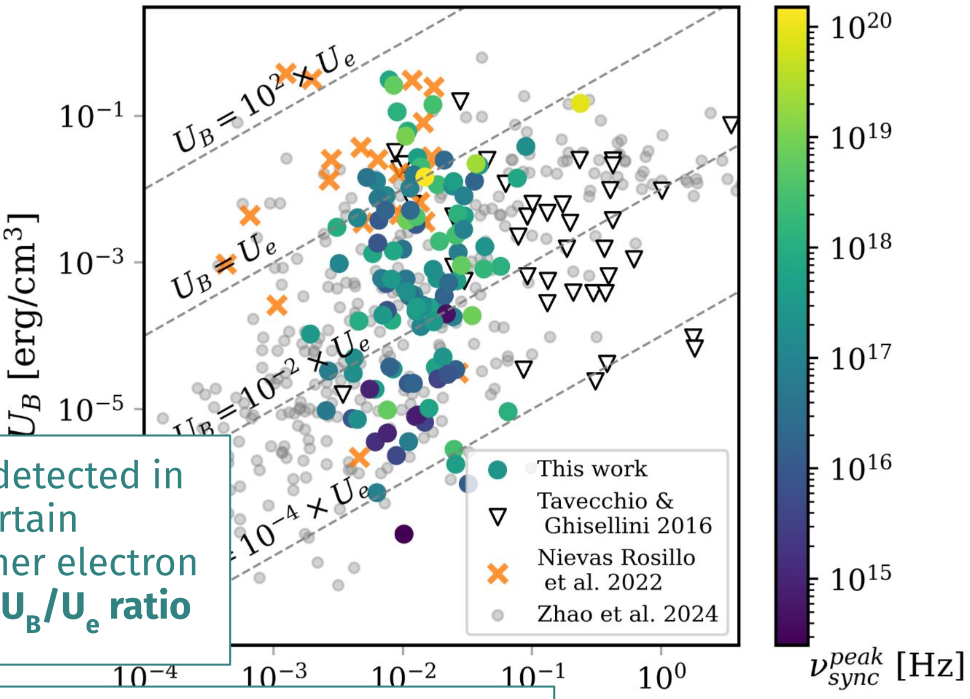
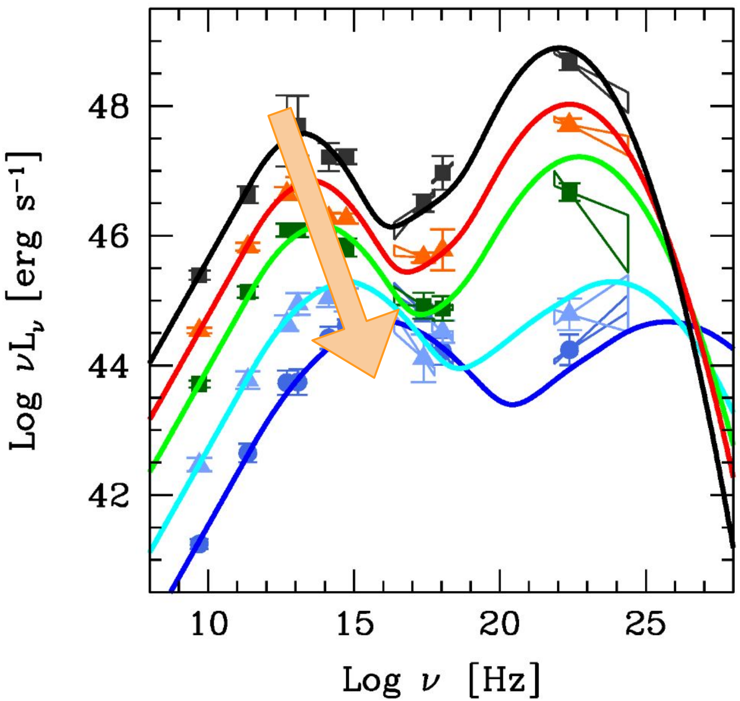


TG16 and Z24 include **variable sources** + sources detected in TeV (typically detected during flares) → during certain observations, may be **far from equilibrium** → higher electron energy injection → lower magnetisation → **lower U_B/U_e ratio**

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

The blazar sequence and the role of EHSPs

Blazar sequence: anti-correlation between luminosity and ν_{SP} (EHSPs at the lower-luminosity, high-peak regime)



- **low CD among EHSPs** → synchrotron/SSC processes dominant + absence of strong external photon fields
- **large number of EHSPs identified** (66/113): challenge their presumed rarity and suggest many were missed due to instrumental limitations and selection biases

  → EHSPs more common than previously thought?
- Most extreme EHSPs, with the highest ν_{SP} and CD $\gtrsim$1, challenge traditional models → **revised model**?

The blazar sequence and the role of EHSPs

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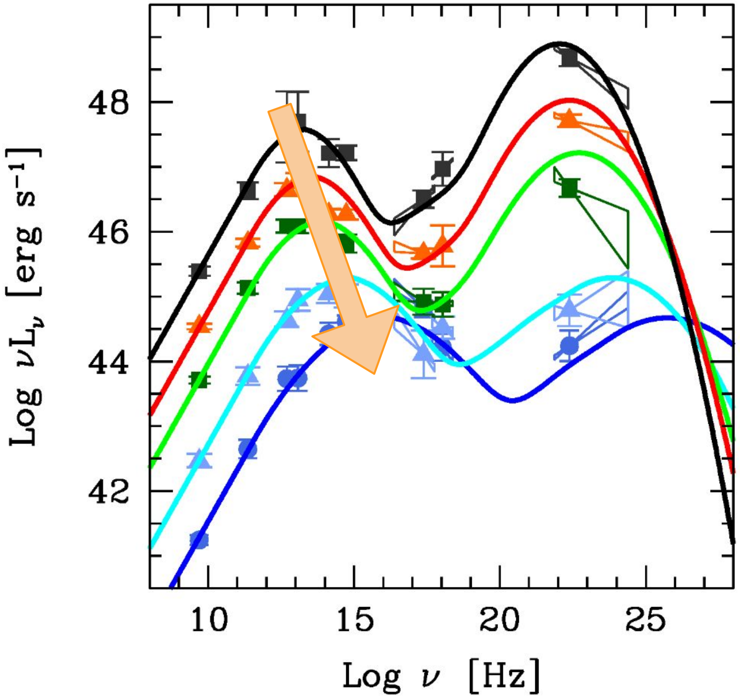

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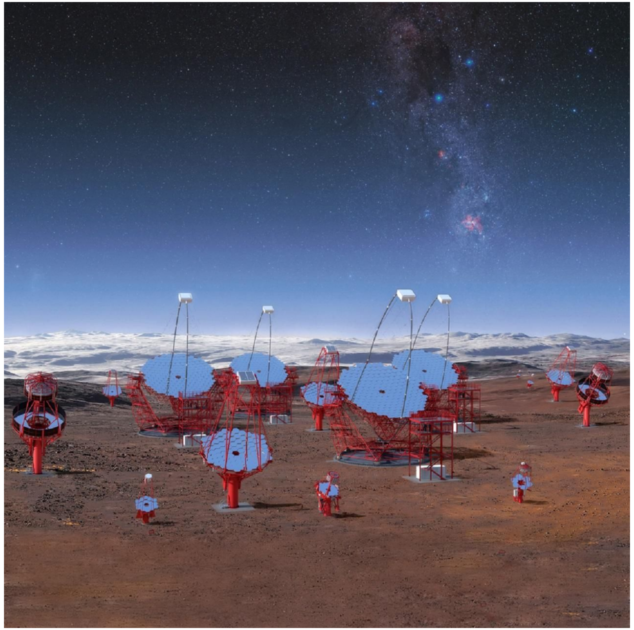
⇨ **observations of EHSPs with CTAO can test these ideas, observations of EHSPs at high redshifts or with unexpected luminosities could further refine the blazar sequence**

Detectability predictions with CTAO

- **EHSPs** regarded as **promising VHE emitters** (spectra extending to extremely high frequencies), but **very few detected at VHE**, < 20 detected by IACTs (low fluxes + relatively steady emission + EBL attenuation)

- Higher-energy peak of the SED in VHE for many EHSPs → **essential to study these sources at VHE to understand the acceleration processes in their jets**

- **Cherenkov Telescope Array Observatory (CTAO)**: next generation of IACTs, which detect the Cherenkov light produced by the interaction of γ rays with the atmosphere (low duty cycles) → **selection of promising targets** to optimise the observation time

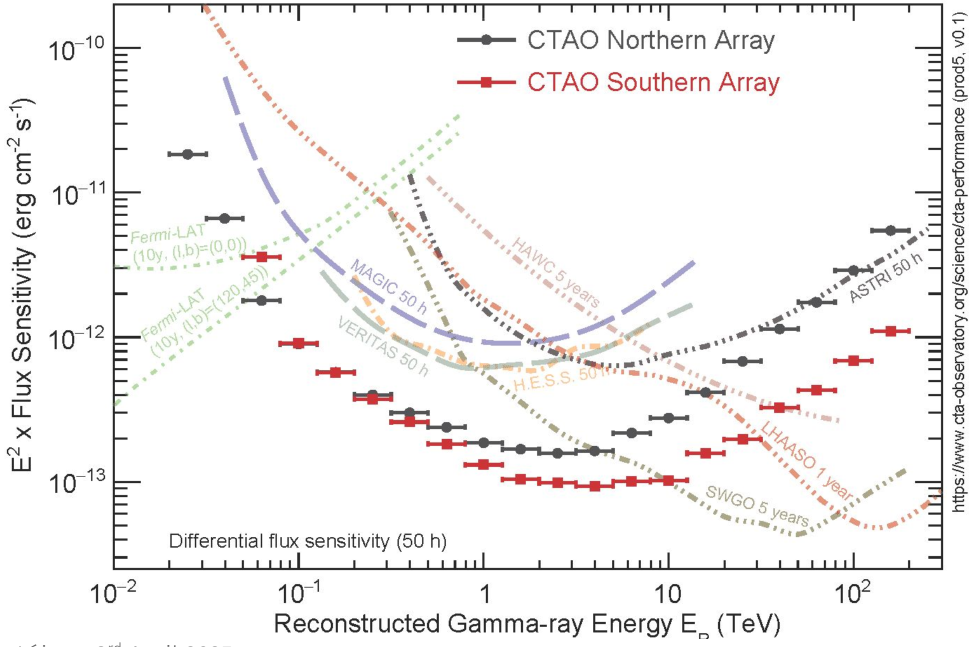


CTAO

Detectability predictions with CTAO

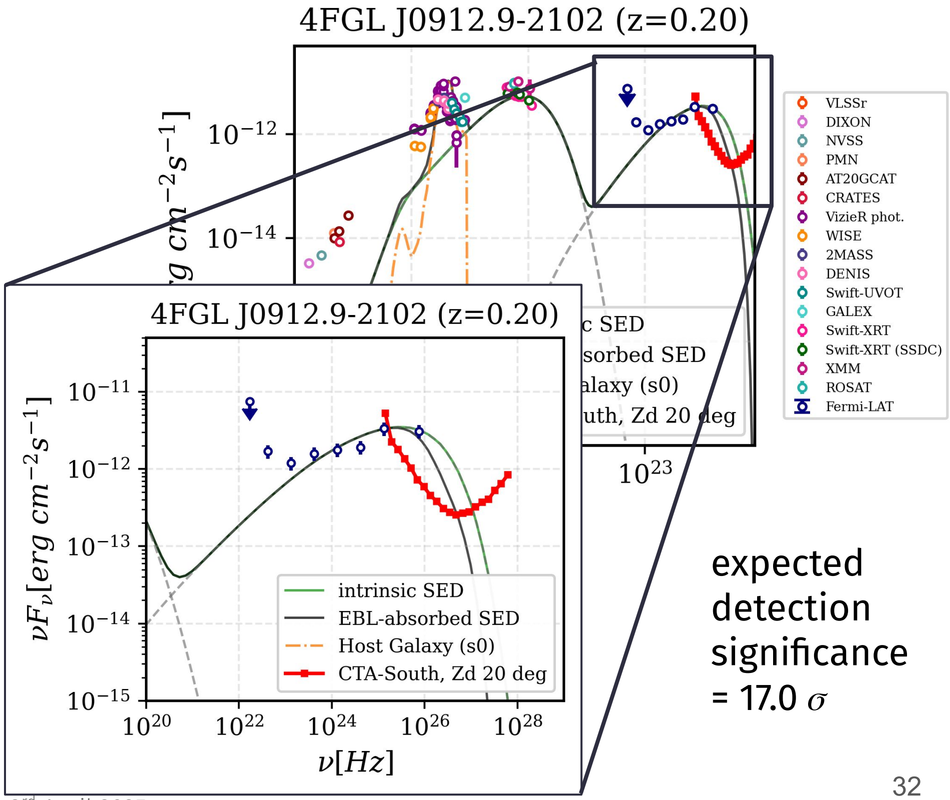
Using the spectral shape resulting from the SED modelling, we estimate the **expected detection significance with CTAO assuming 20-hour observations** (same procedure as in Domínguez et al. 2024b)

- Significance estimation done using the **CTAO instrument response functions (IRFs)** for the *Alpha Configuration* (13 telescopes in the north, 51 in the south) → produced for 3 different ZD (20, 40, 60 deg) for the north and south arrays
- CTAO-North/South IRFs for sources with positive/negative declination
- IRF configuration corresponding to the closest ZD used for the significance estimation → ZD determined by assuming **observations around culmination time**



Detectability predictions with CTAO

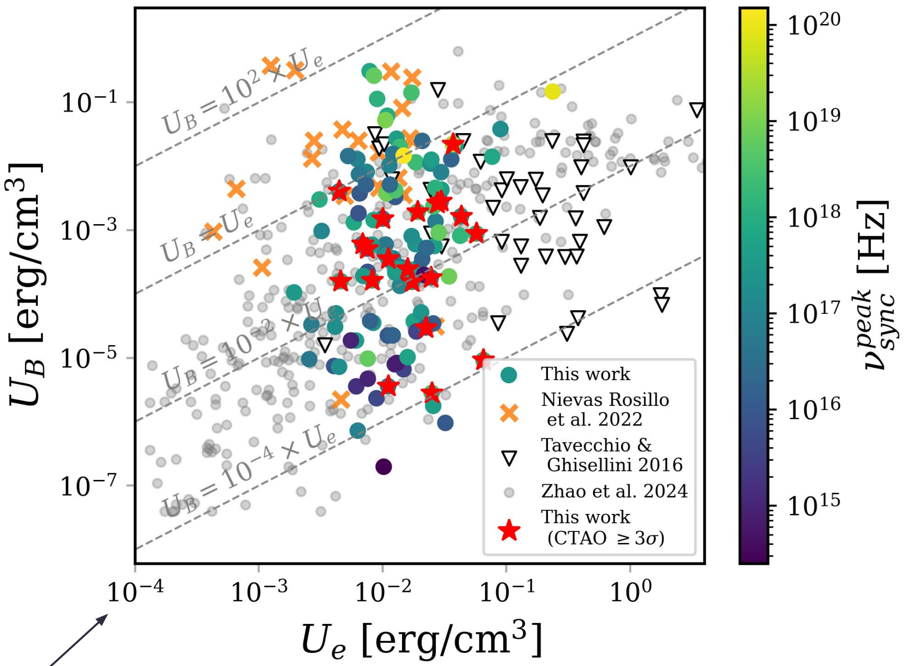
- Best-fit model extrapolated to TeV energies + EBL absorption → **assumed spectral shape**
- From the sensitivity curves, we derive the differential flux, and the number of excess and background events required to generate a 5σ signal in each energy bin: f5, n_exc5, n_off5
- Number of excess events 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

Detectability predictions with CTAO: results

- **9 potential VHE emitters** (out of 113): **expected CTAO detection significance ≥ 5σ** after 20 hours of exposure with CTAO
- **11 additional sources with expected detection significance ≥ 3σ** that could be detected with a longer exposure
- 20 sources detectable above 3σ:
  - 12 sources have **ν_{SP}≥ 10^{17} Hz**
  - all characterised by **low magnetisation**: B ranging from 0.0084 to 0.74 G
- No clear relation between the U_B/U_e ratio and their detectability predictions with CTAO



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 ~ 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 shaping 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 slightly longer exposures
- Catalog with our results to be published soon!

Thanks for your attention!

Acknowledgements

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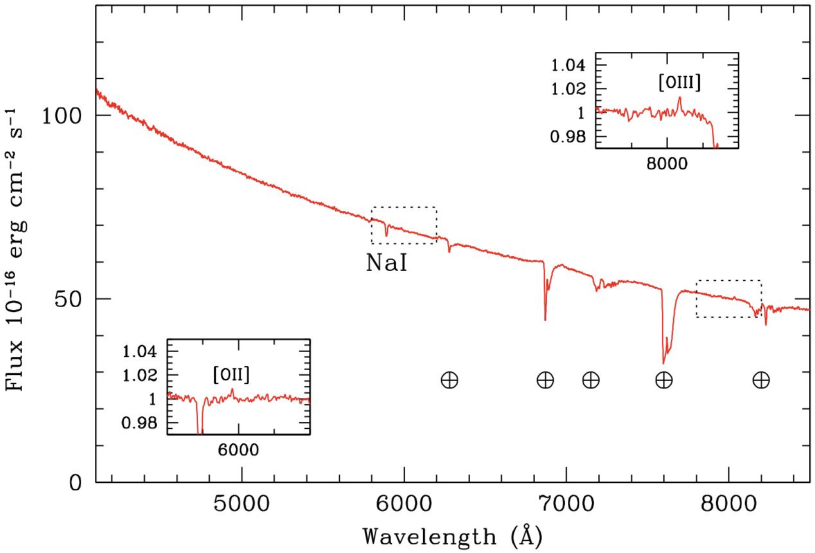
Masquerading BL Lacs

- FSRQ-like behaviour but no emission lines in their optical spectra

  → intrinsical FSRQs with an efficient accretion disk and prominent optical emission lines which appear very faint due to a a very bright, Doppler-boosted jet; in contrast, *real* BL Lacs are instead intrinsically weak-lined

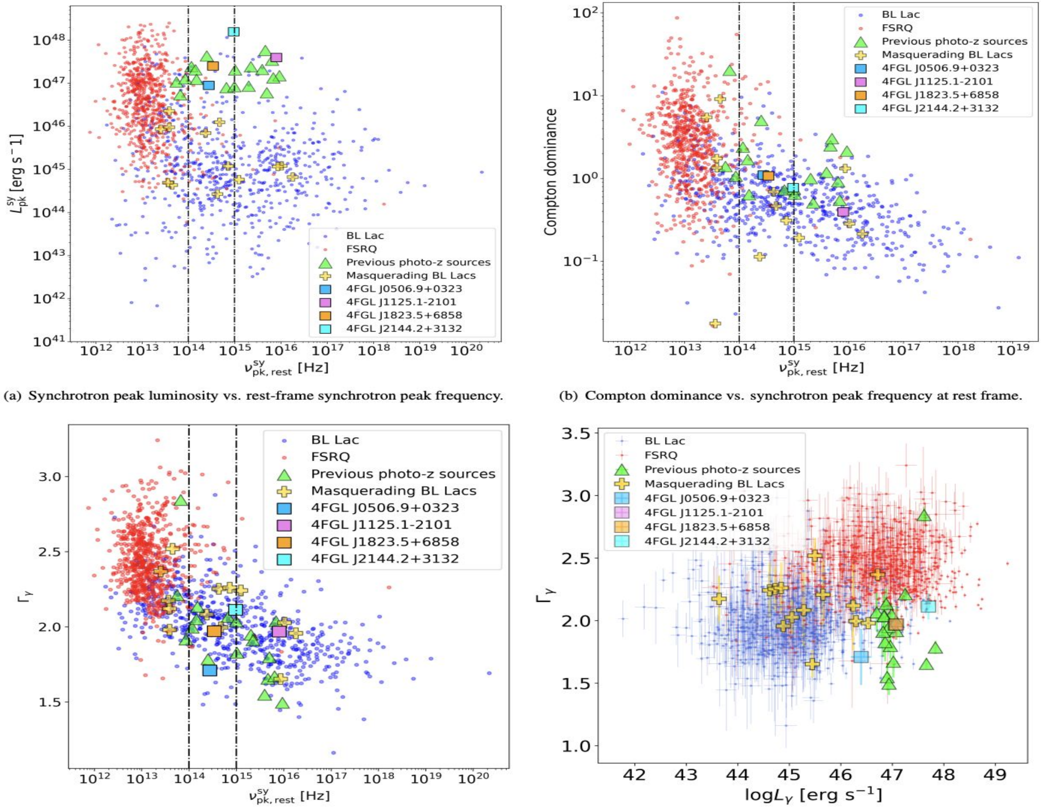
- This is the case for many FSRQs while flaring, and also might be the case with other weaker sources but with hidden (for some not-so-clear reasons) gas structures.

Optical spectrum of PKS 1424+240 (masquerading BL Lac object):



Padovani et al. 2022

Masquerading BL Lacs



(a) Synchrotron peak luminosity vs. rest-frame synchrotron peak frequency.

(b) Compton dominance vs. synchrotron peak frequency at rest frame.

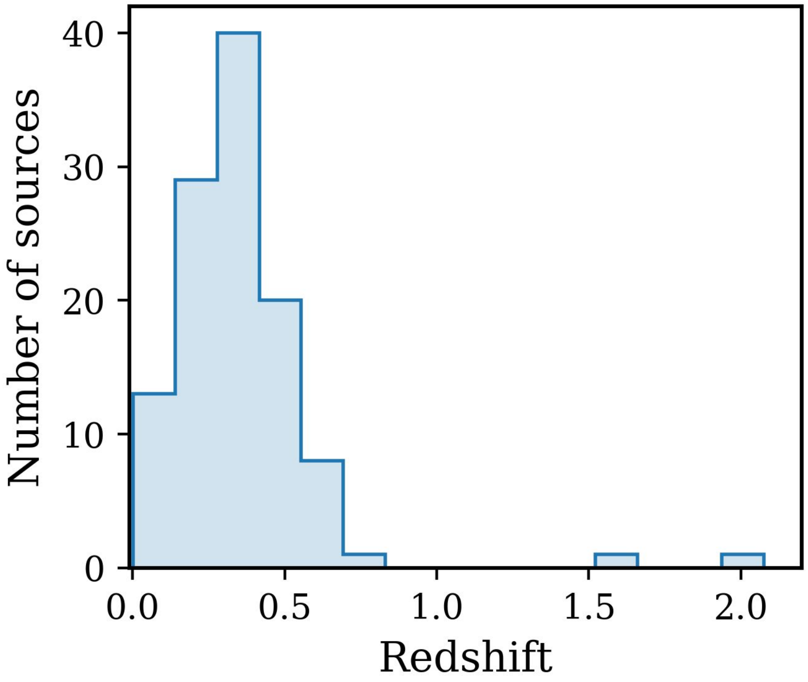
(c) Gamma-ray index vs. synchrotron peak frequency at rest frame.

(d) Gamma-ray index vs. gamma-ray luminosity (0.1-100 GeV).

Sheng et al. 2024

Blazar sample: redshift distribution

- Sources:
  - 44 (35.5%) are from 4LAC: **spectroscopic/photometric**
  - 38 (30.6%) from 2BIGB: all **photometric**
  - 33 (26.6%) from Paliya et al. (2021): all **spectroscopic**
  - 9 (7.3%) from Goldoni (2021): all **spectroscopic**
- Most of the sources in our sample (~86%) have a redshift of **z < 0.5**
- Farthest blazar in the sample located at z = 2.075 (1RXS J032342.6−011131) → uncertain



Host galaxy templates

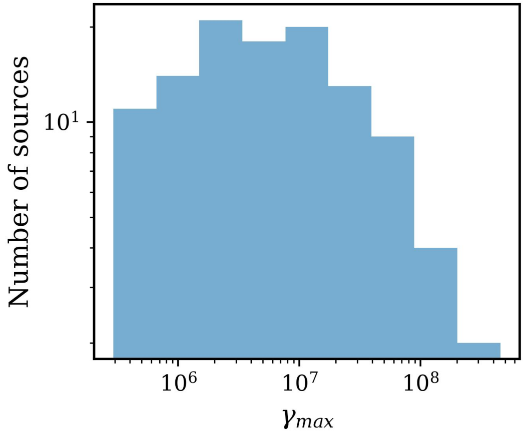
- We are considering 4 different templates*:
    - **lenticular galaxy**
    - **elliptical galaxy of 13 Gyrs**
    - **elliptical galaxy of 5 Gyrs**
    - **elliptical galaxy of 2 Gyrs**
- We get nu and nuFnu from the templates, and we apply a frequency correction to the nu values which depends on the redshift of the source:

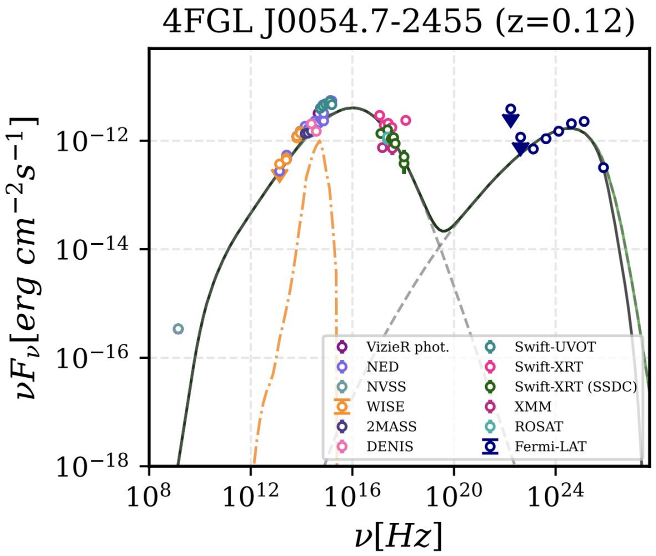
  nu*1/(1+z)

http://www.iasf-milano.inaf.it/~polletta/templates/swire_templates.html

Broadband SED modeling results

MAXIMUM LORENTZ FACTOR γ_{max}: values ranging from 2.9×10^5 to 4.6×10^8





highest γ_{max}

Determining γ_{max} is challenging due to the lack of measurements between 10^{18} Hz and ~ 10^{20} Hz (gap between NuSTAR and *Fermi*-LAT energy ranges) which may result in γ_{max} values larger than expected.

CTAO: 3 main telescope types

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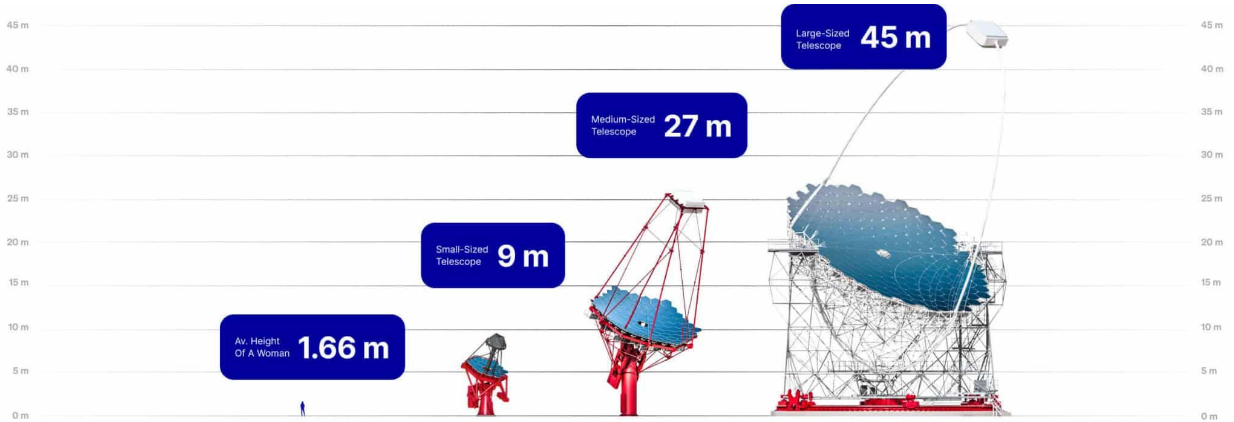
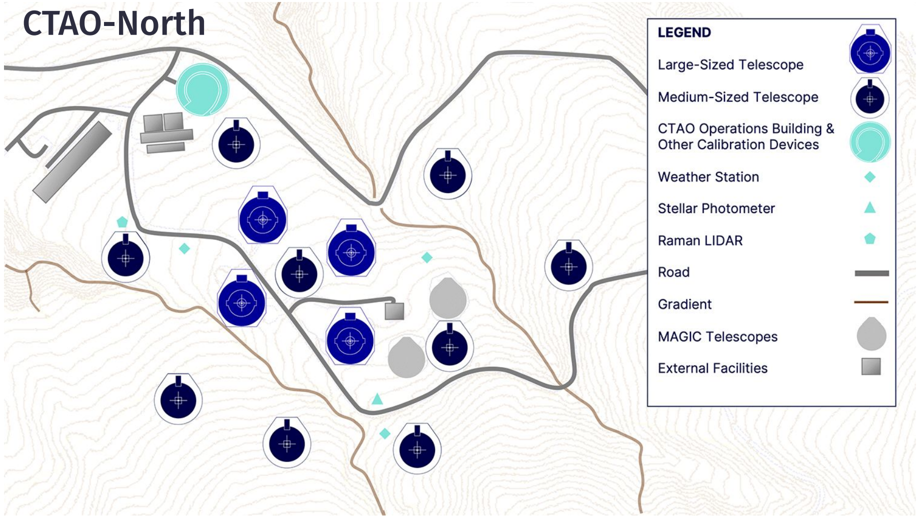
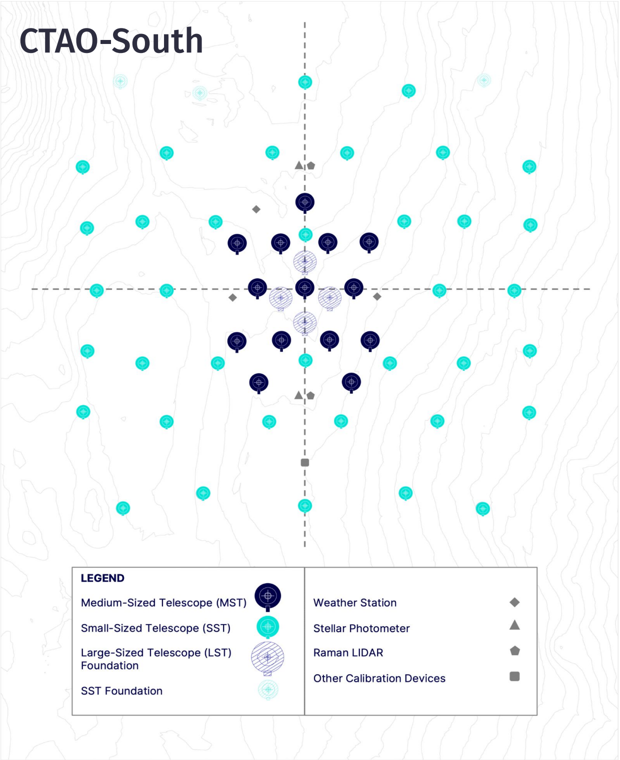
- **Larged-Sized Telescopes (LSTs)**: reflector of 23 m of diameter and a field of view (FOV) of ~ 4.3°, designed to detect the lowest-energy gamma rays.
- **Medium-Sized Telescopes (MSTs)**: diameter of 12 m and a FOV of ~ 8°, will cover the mid-energy range (gamma rays with energies from ~ 150 GeV to 5 TeV)
- **Small-Sized Telescopes (SSTs)**: diameter of 1.8 m and a FOV of ~ 9°, will be able to detect the highest energy gamma rays (above 5 TeV)



CTAO *Alpha Configuration*

- **CTAO Northern array:** 13 telescopes (4 LSTs + 9 MSTs) distributed over an area of about 0.5 km^2
- **CTAO Southern array:** 51 telescopes (14 MSTs + 37 SSTs) distributed over a ~3 km^2 area





Source detected at VHE

Only source in our blazar sample already detected by an IACT: 4FGL J0013.9−1854/SHBL J001355.9−185406

- expected detection significance: 3.9σ, calculated for 20 hours of CTAO observations
- previous detection by H.E.S.S., which required 41.5 hours of exposure (observations performed at a medium ZD of 12.9 deg)
- The source's steady emission across all wavelengths and the possibility of it undergoing a mild γ-ray flare during the H.E.S.S. observations further highlight its potential as a **strong candidate for VHE detection with CTAO**