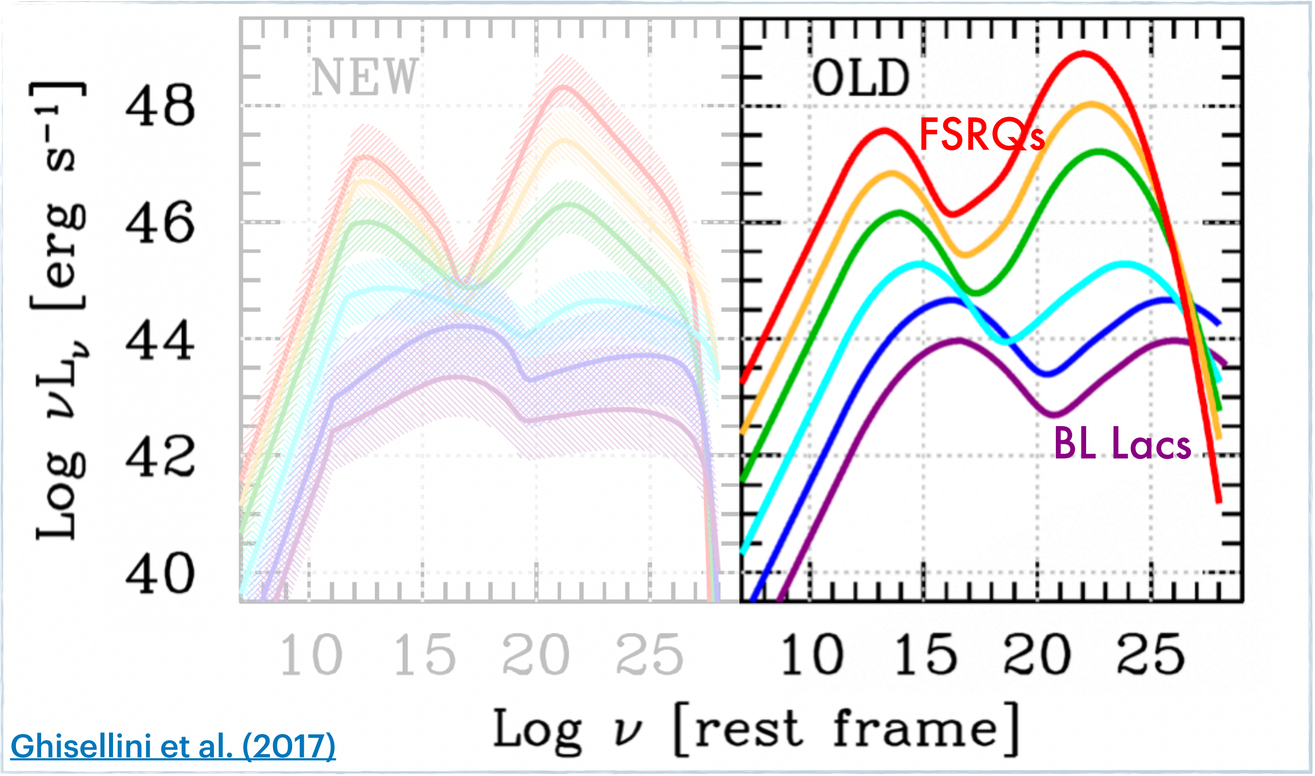
The blazar sequence and its TeV extension: towards a physical interpretation

I. Viale, E. Prandini, C. Righi, F. Bovolon

The blazar sequence

Original sequence: Fossati et al. (1998)

- 126 sources from X-ray and radio samples
- Radio luminosity bins



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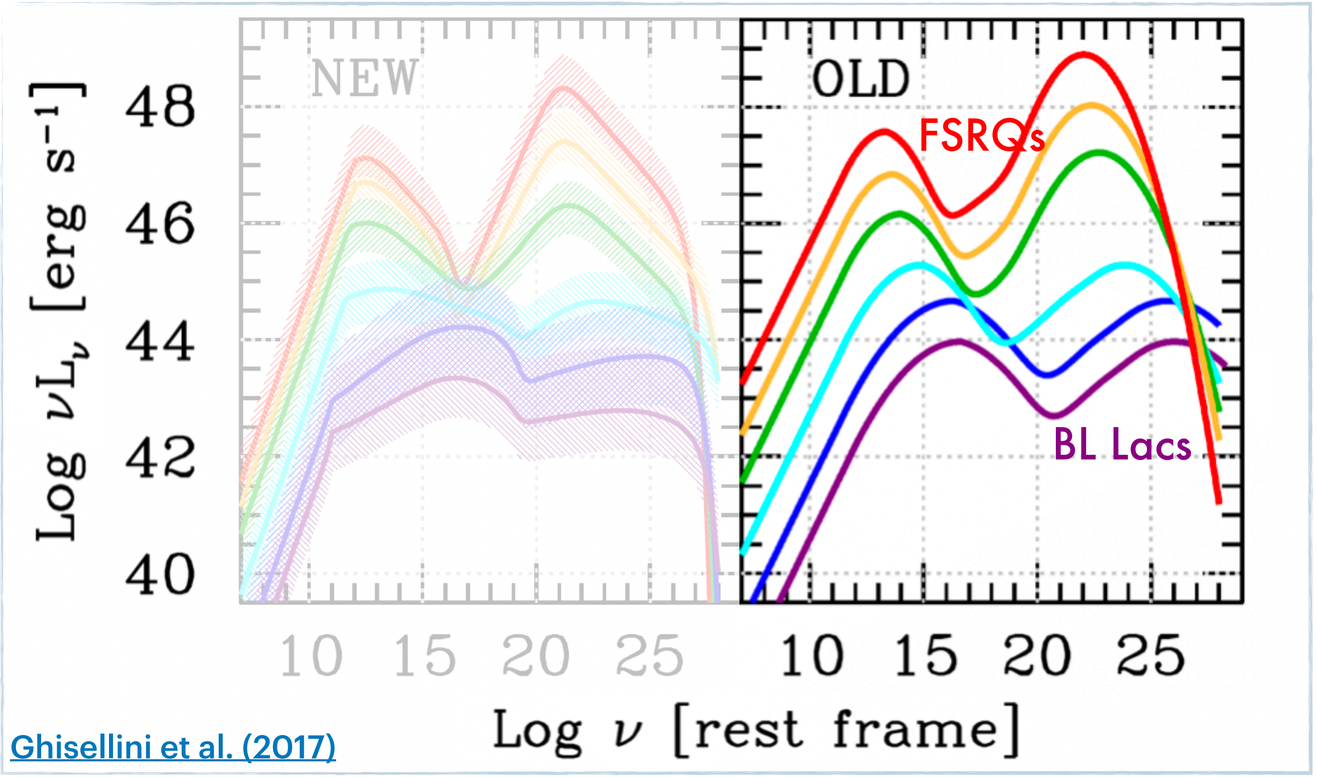

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Main results:

- Anti-correlation between total luminosity and peak frequencies
- Correlation between peak frequencies of bumps
- Increase of Compton dominance with total luminosity

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- 747 sources from 3LAC Fermi catalog
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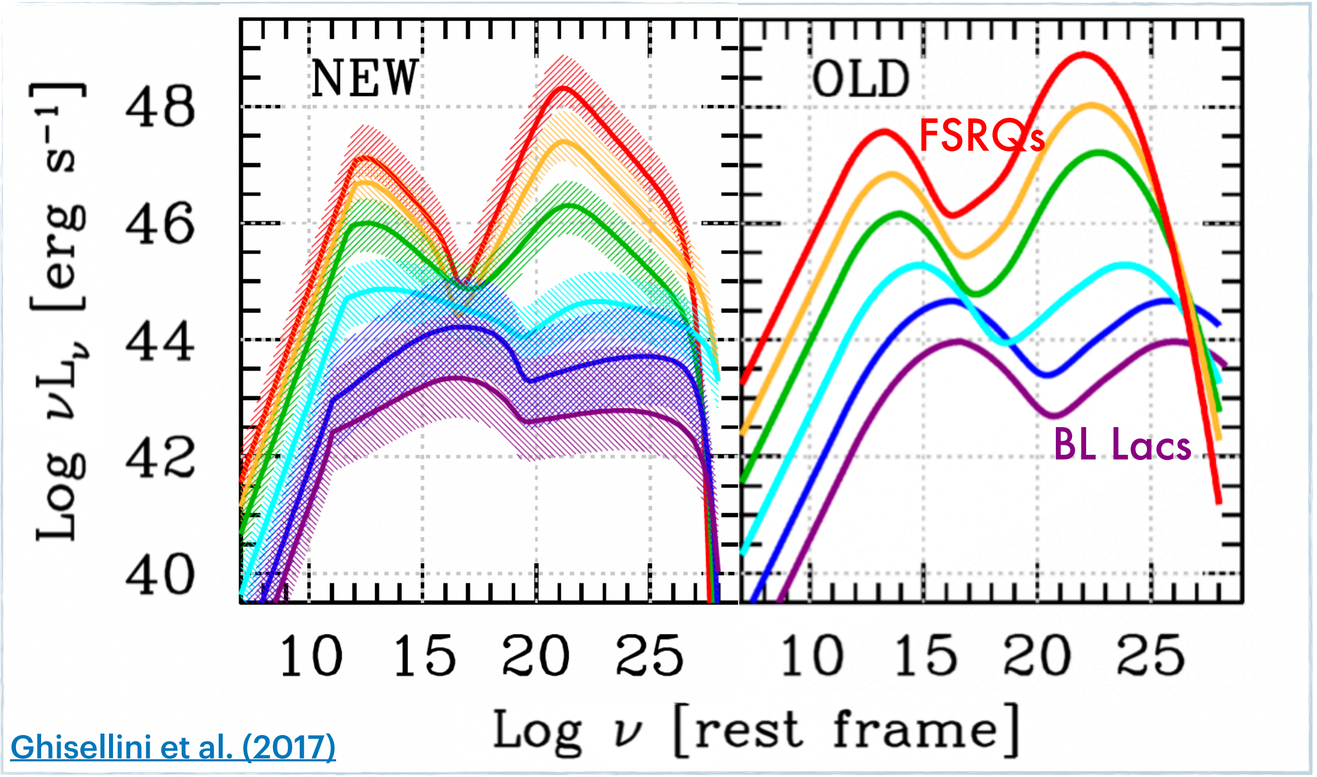

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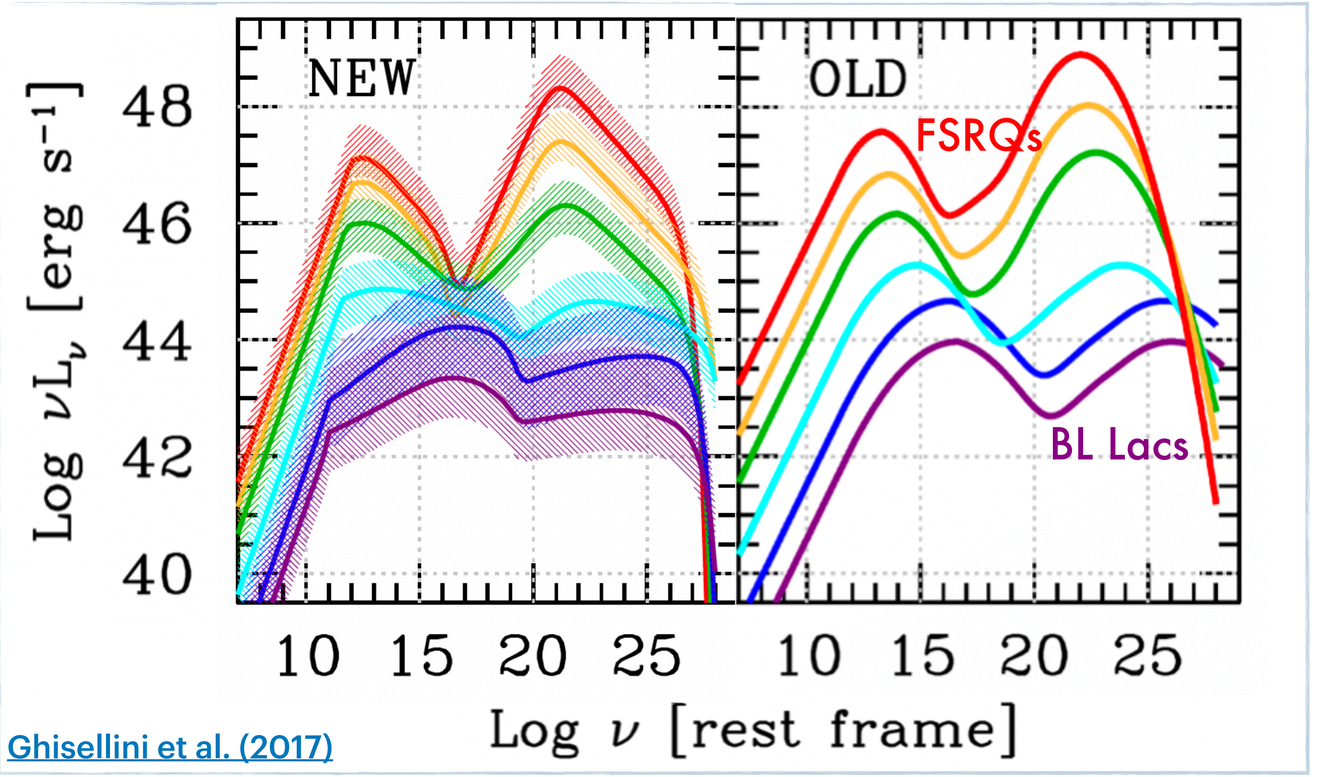

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Main results:

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- FSRQs: stable synchrotron peak frequency
- BL Lacs: peaks correlate with luminosity

This work

Goals

Is the blazar sequence physically driven?

Provide a starting point for sources modeling

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Provide a starting point for sources modeling

To do it we …

Concentrated only on TeV BL Lac sources

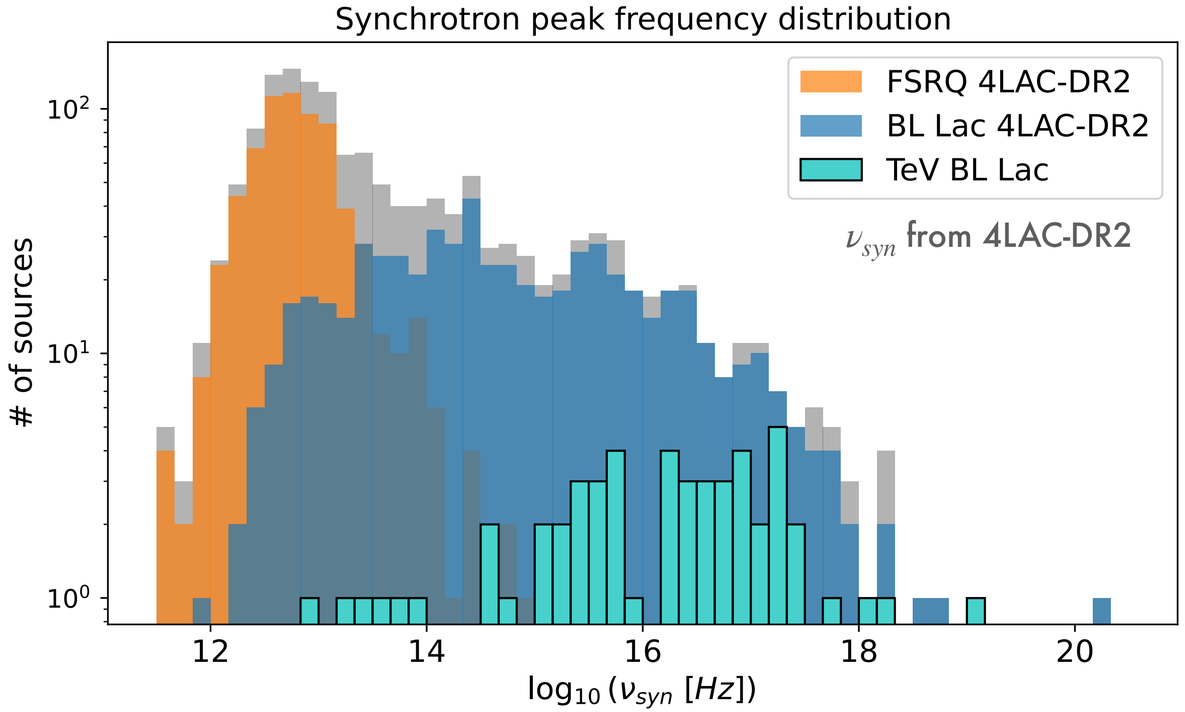
Include TeV data in their SEDs

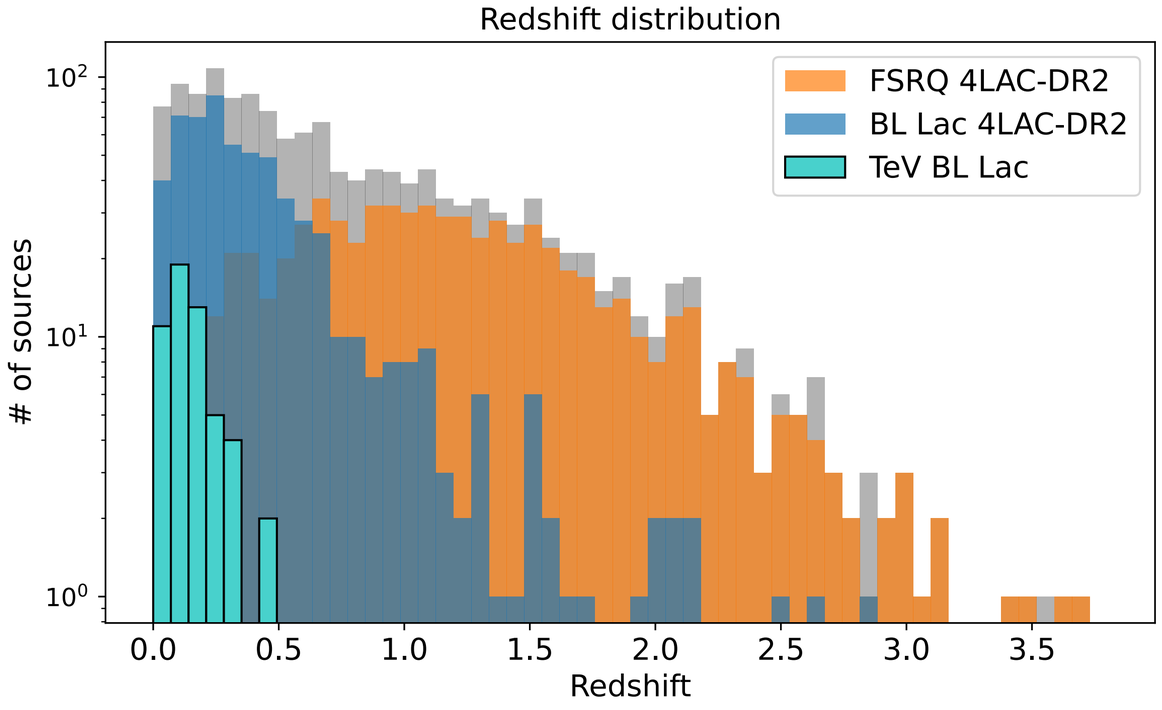
Modeled their emission in framework of Synchrotron Self Compton model

Is there a trend in the model parameters?

Our sample

- 84 TeV-detected blazars at TeVCat, data from 4LAC-DR2
- Concentrate only on BL Lacs with known redshift → total of 56 sources
- ν_{syn} bins used instead of luminosity bins → ν_{syn} values based on BlaST T. Glauch et al. (2022)
- Selection of one representative source per bin + additional objects for better sampling





Selected sources

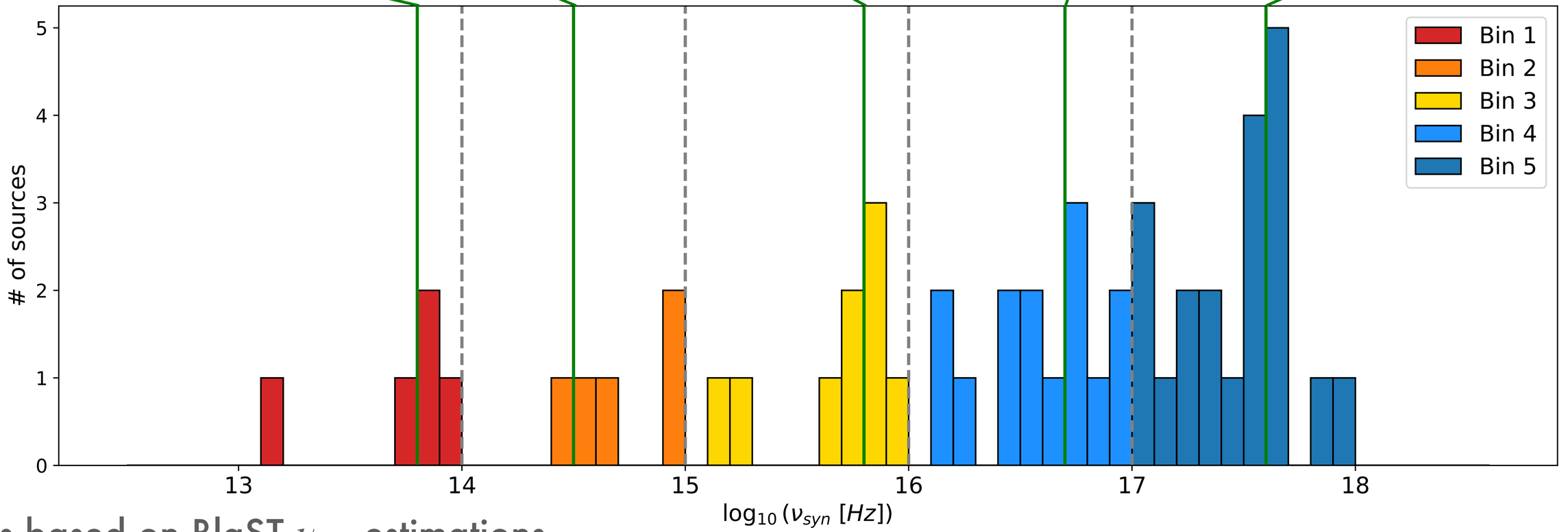
6 sources
BL Lac

3 sources
TXS 0506+056

9 sources
PKS 2155-304

14 sources
PG 1218+304

20 sources
PKS 0548-322



Bins based on BlaST ν_{syn} estimations

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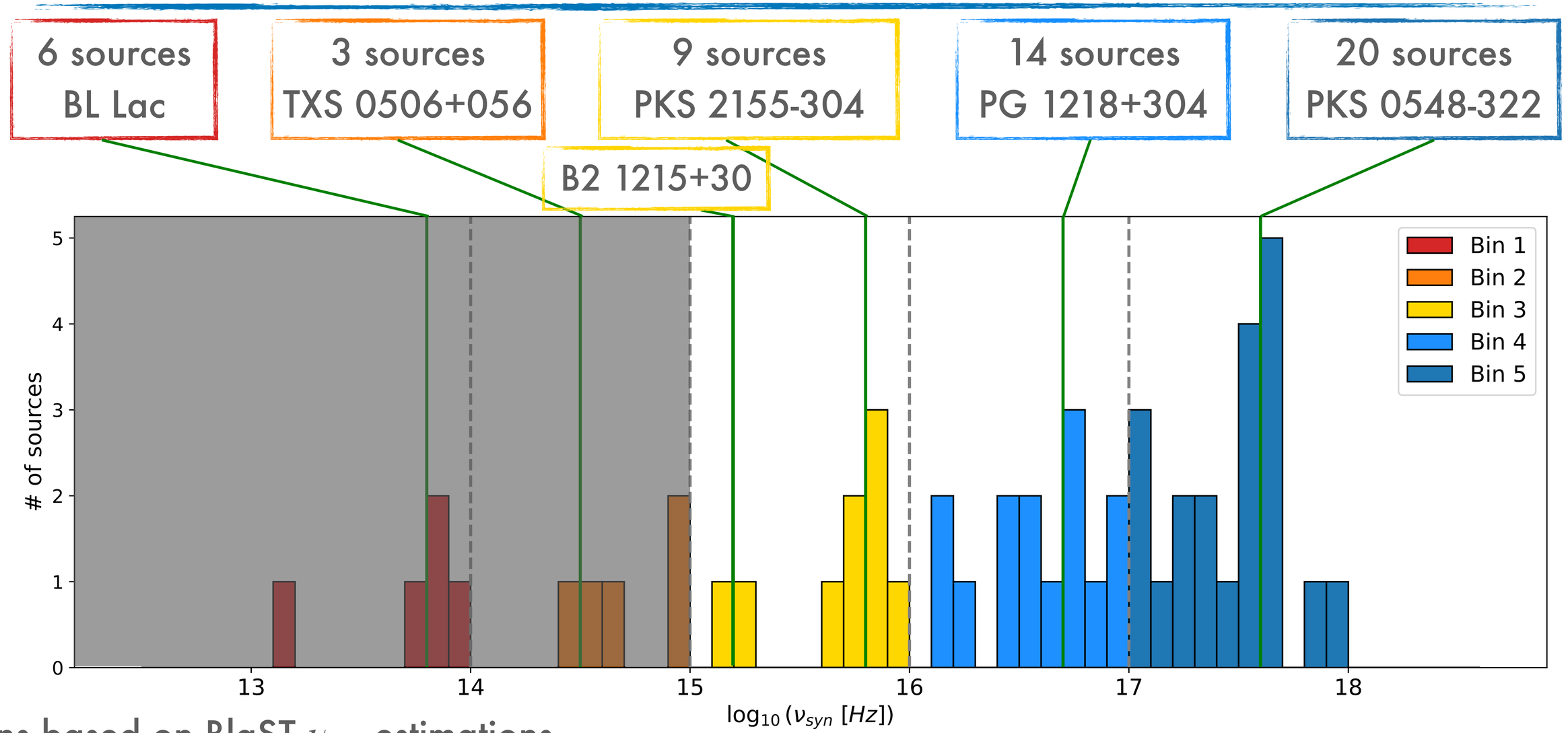

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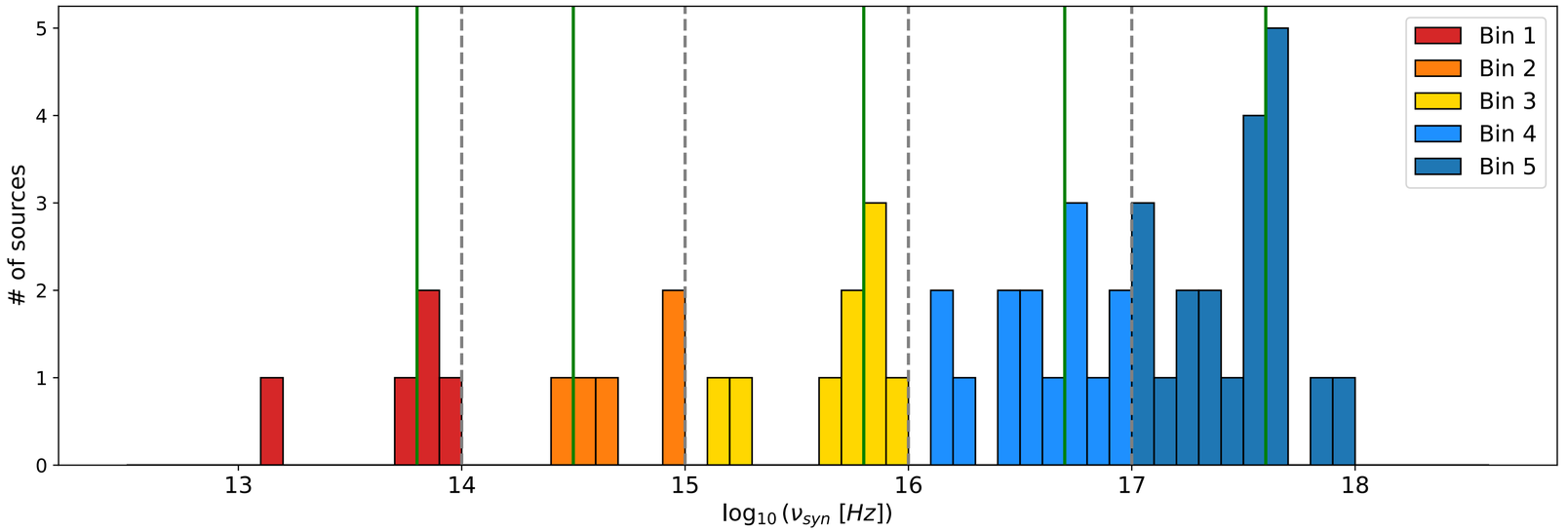
Sources selection based on:

- Good ν_{syn} coverage
- Availability of VHE data



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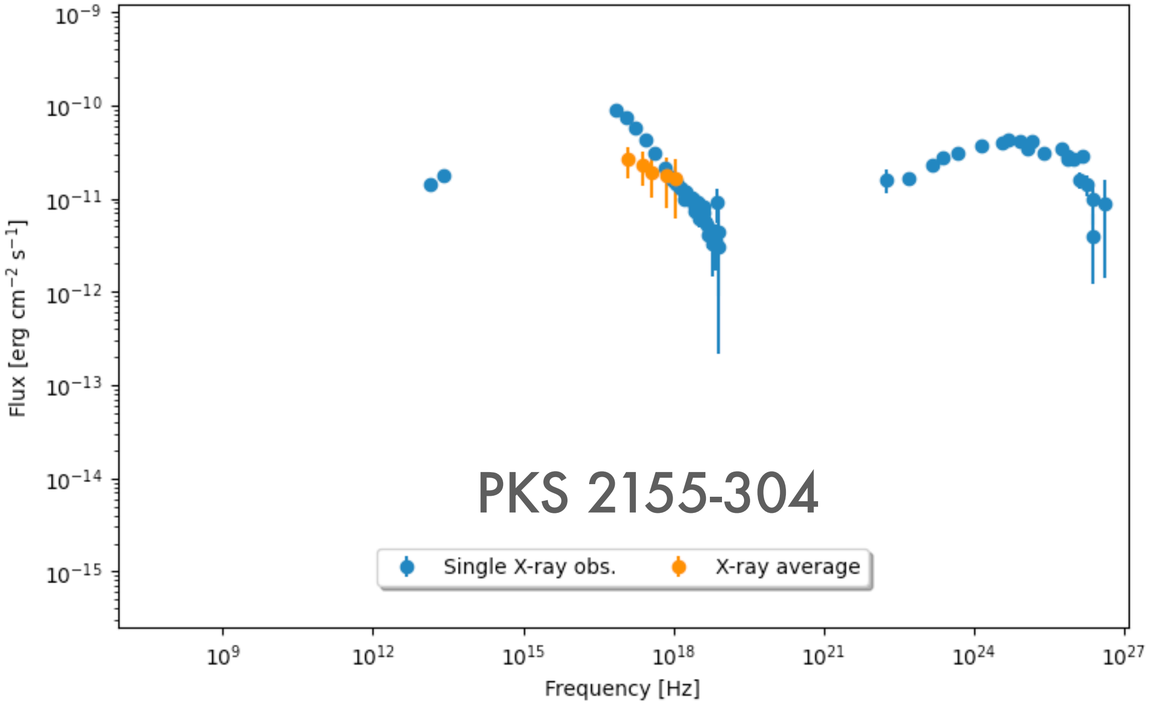
- However, averages may be biased on instrument duty cycle and source state of activity



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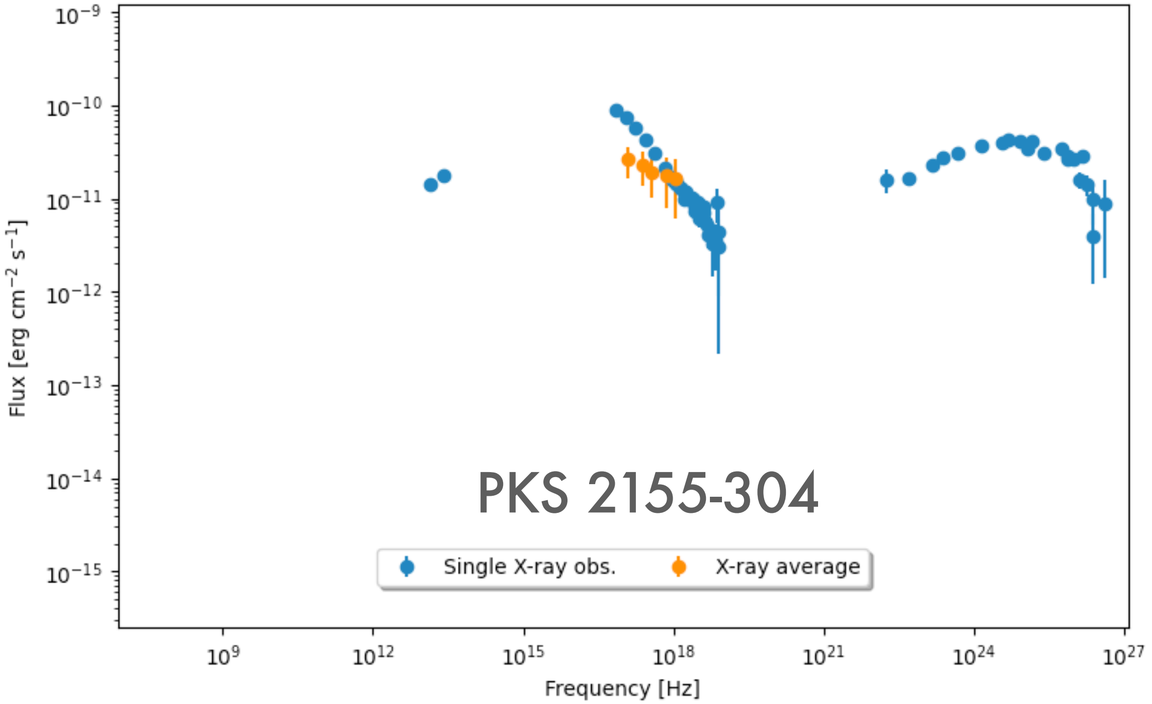

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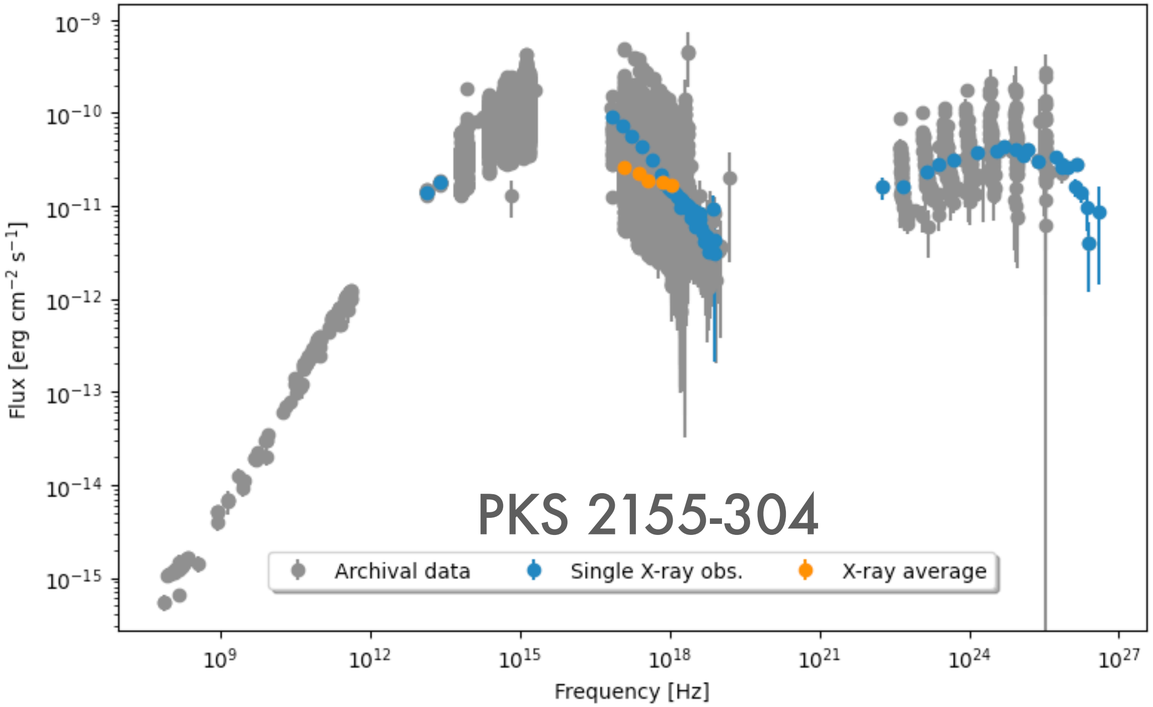

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- Select data in quiescent state of activity

Data retrieved from MMDC + Fermi + STeVECat

Sahakyan et al. (2024) Abdollahi et al. (2022) Gréaux et al. (2023)

- Main difficulties:
  - Very large variability in X-rays
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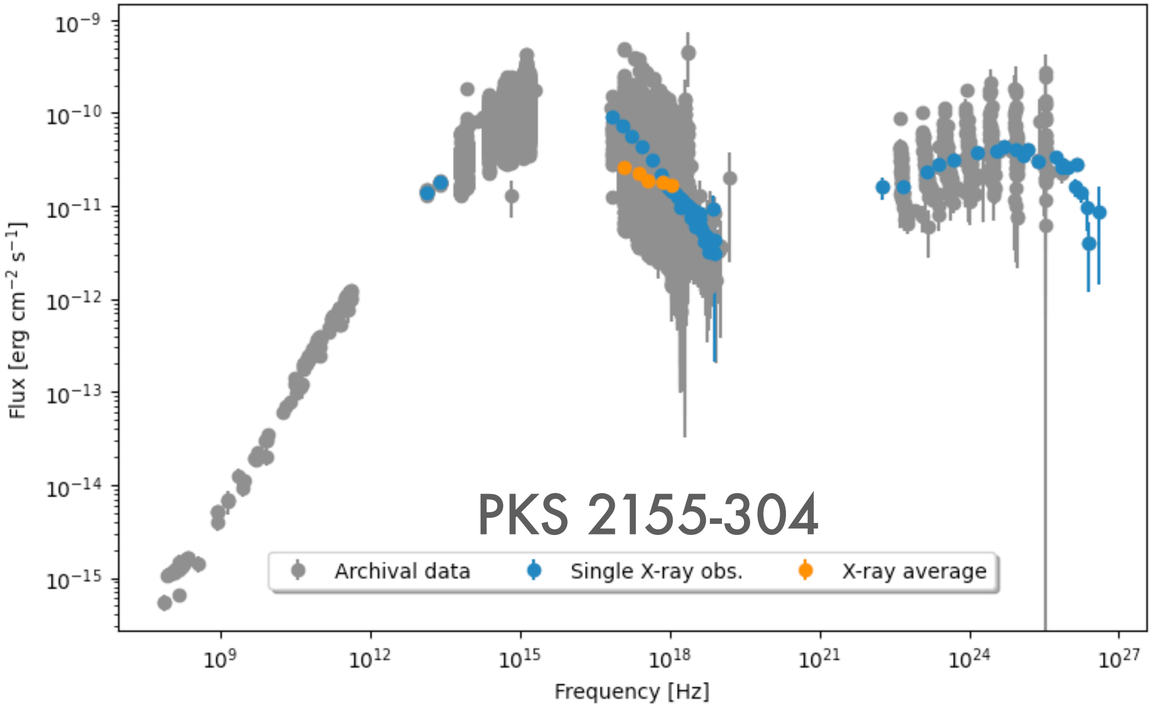

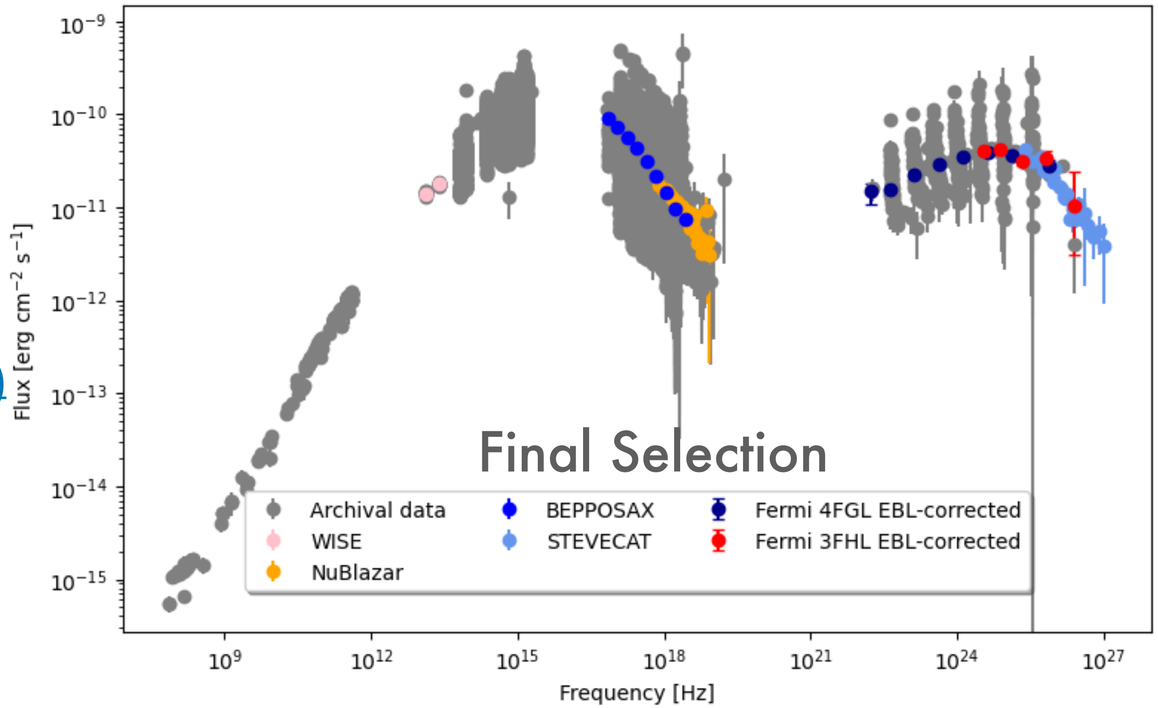

Modeling

All selected sources modeled with 1-zone Synchrotron Self Compton model

- Aim: is there trend in model parameters describing the sequence?

Concentrated only on HBL as starting point, $\nu_{syn} > 1 \times 10^{15}$ Hz

- Difficult to describe sources with lower ν_{syn} with pure SSC

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Modeling performed with agnpy C. Nigro et al. (2022)

- Open-source python package for time-independent blazar modeling
- Assumed broken power-law electron distribution
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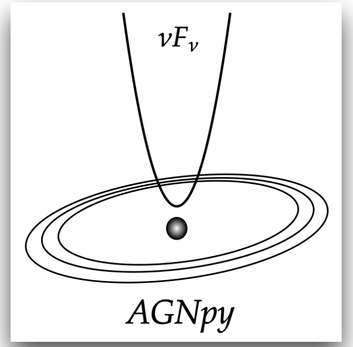

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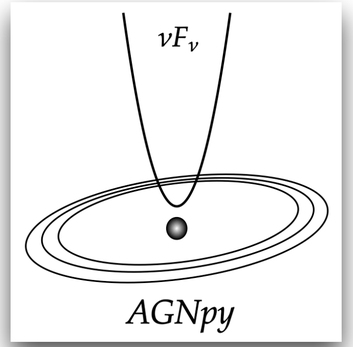


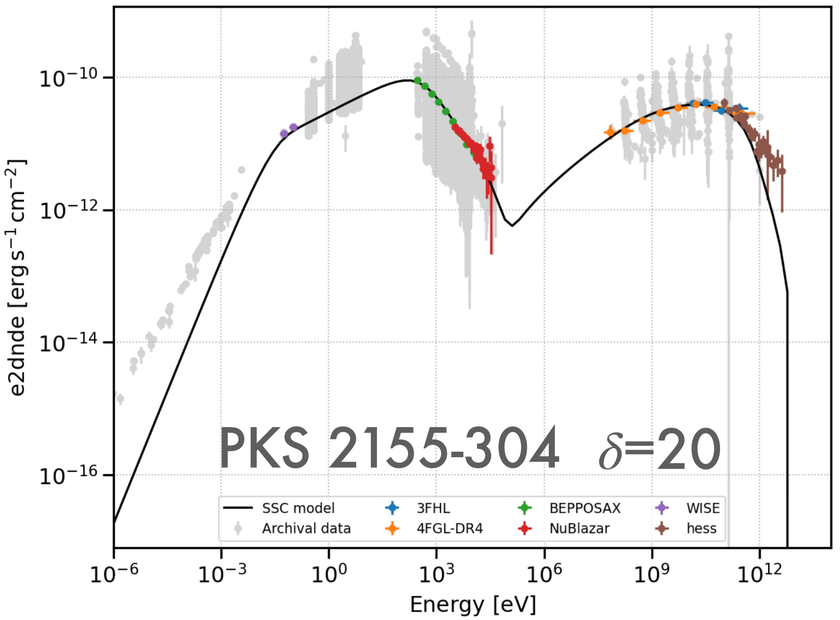
Our approach:

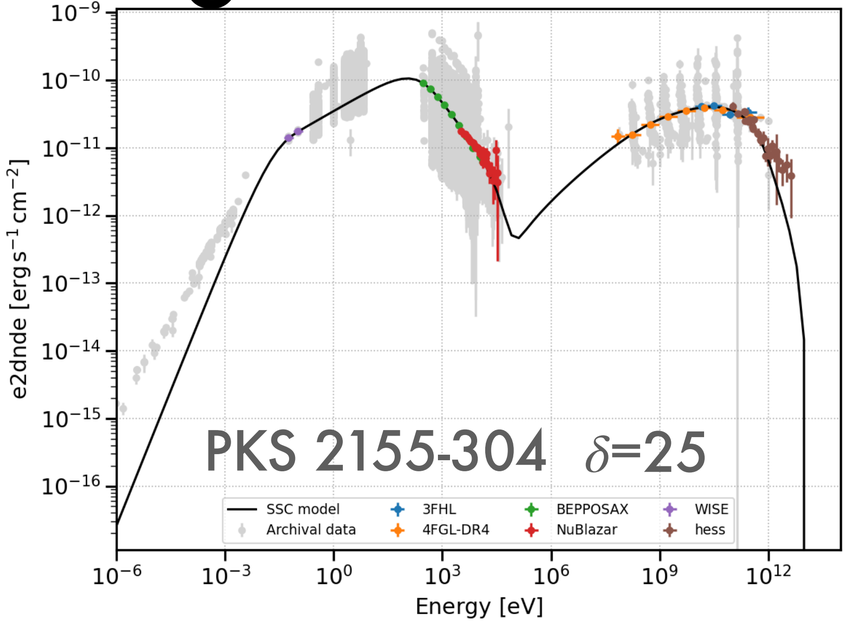
- In order to look for a trend we need to reduce free parameters

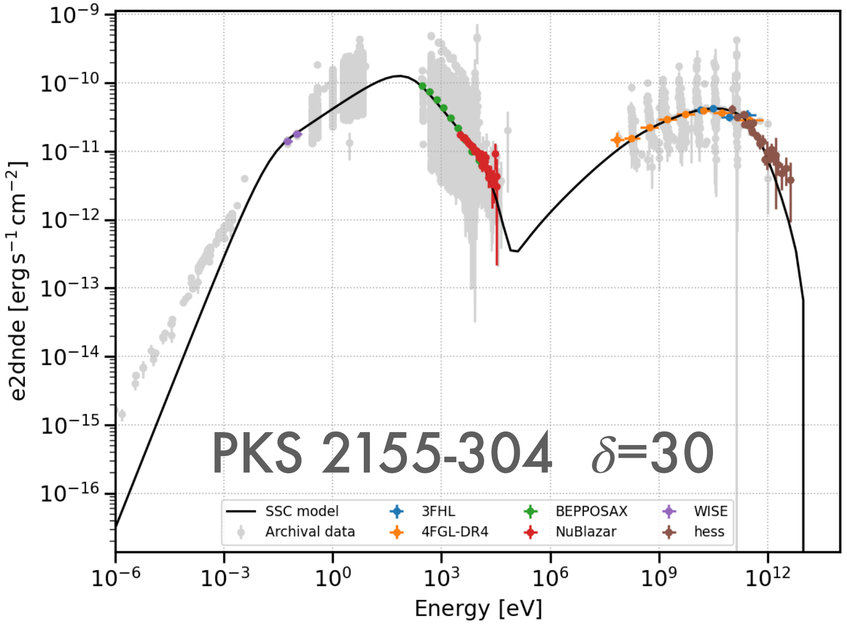
→

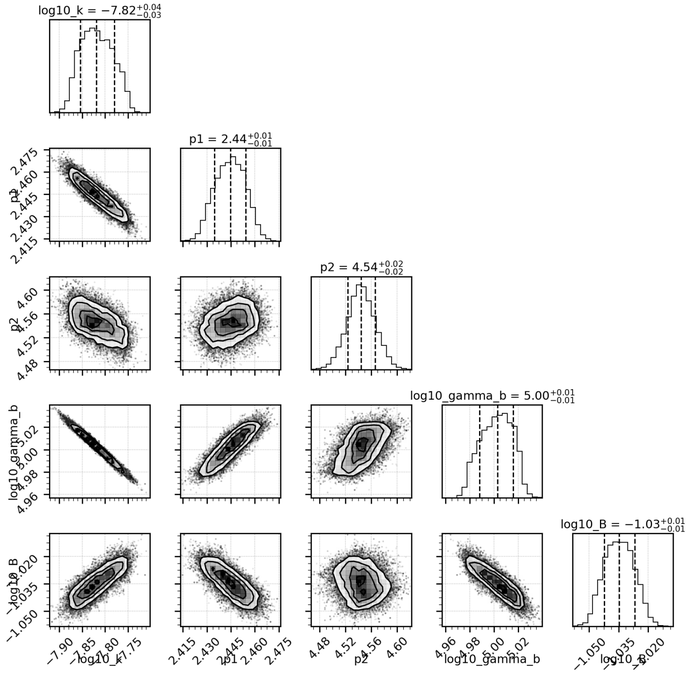
- Fixed:
  - γ_{min}=~~100~~, 10^3 N. Sahakyan (2020)
  - γ_{max}=1x10^6 (1x10^7 for last bin), V. A. Acciari et al. (2020) X. Z. Zhao et al. (2024)
  - t_{var}=1 day
- Scanning of δ=10, 15, 20, 25, 30, 40

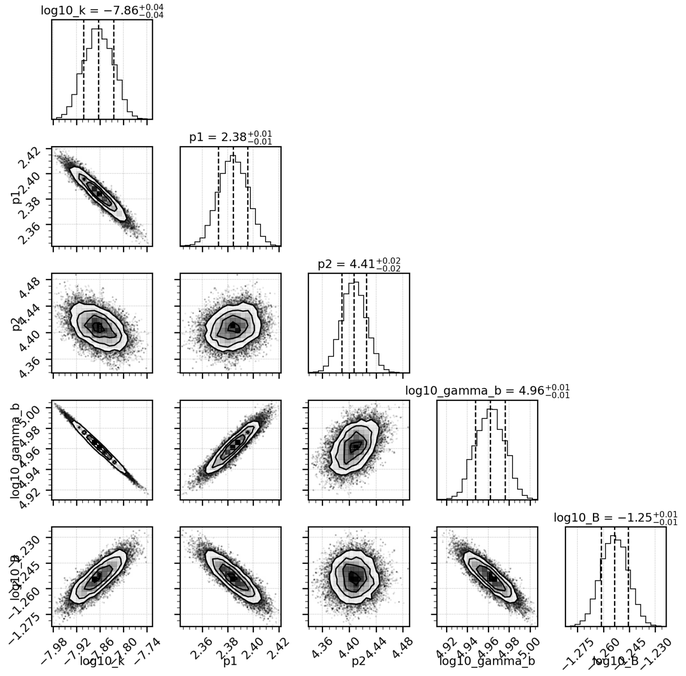
Modeling results - Effect of δ

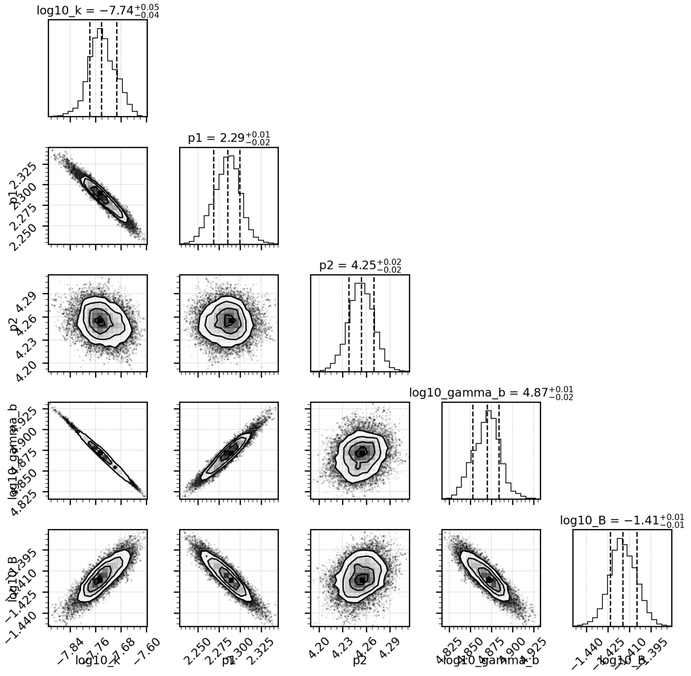












Modeling results - Best fit

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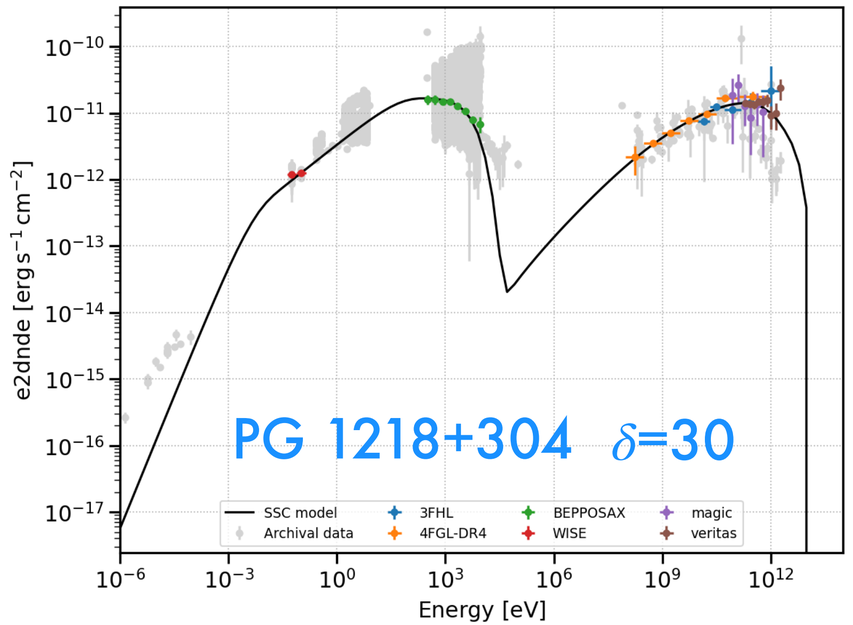

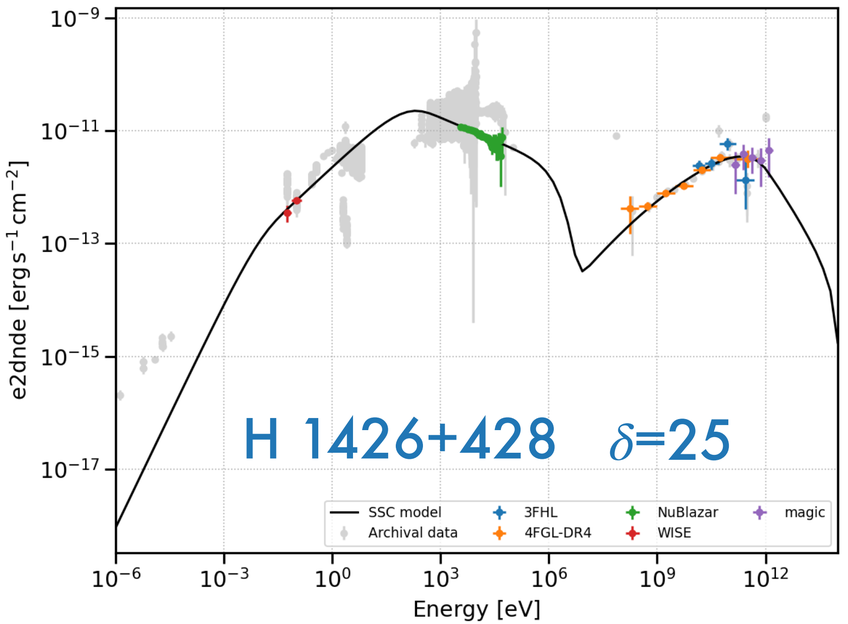

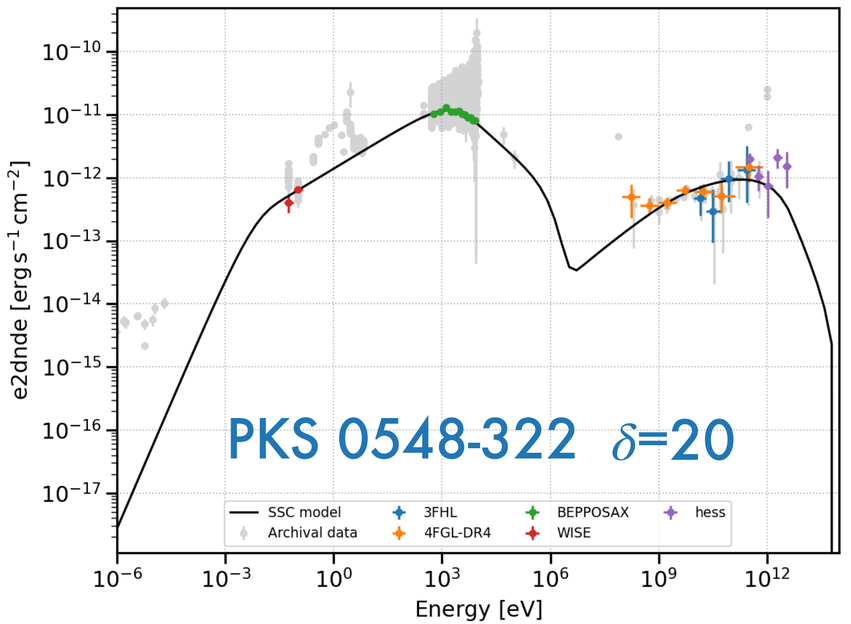

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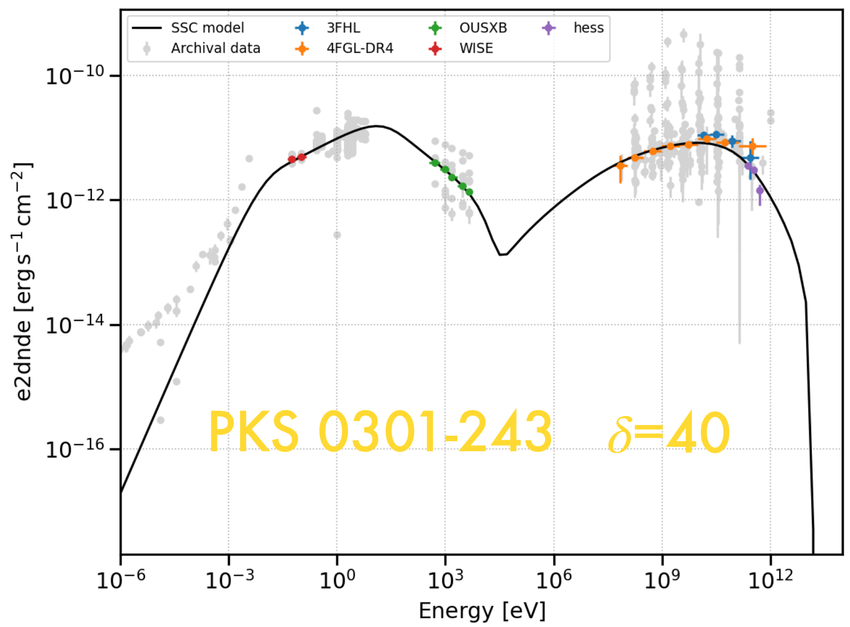
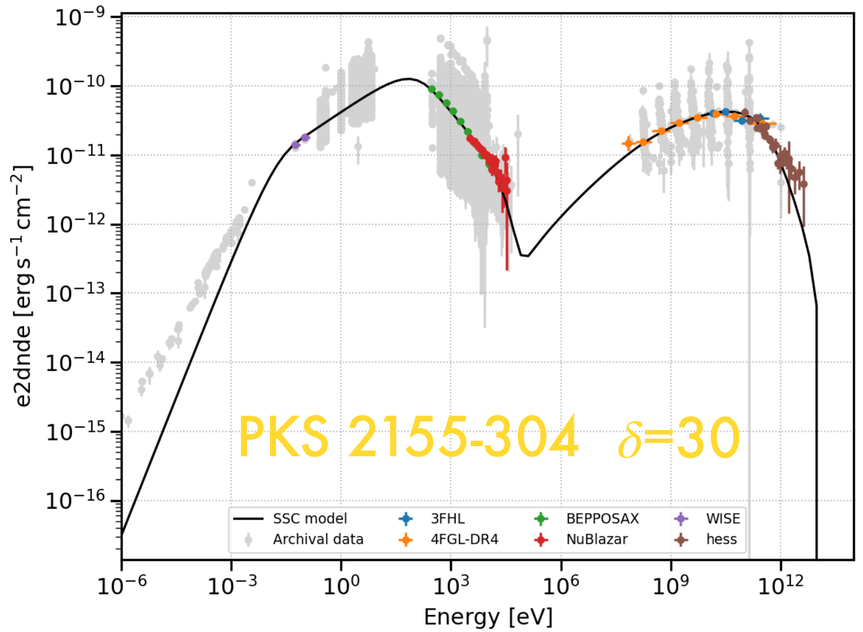
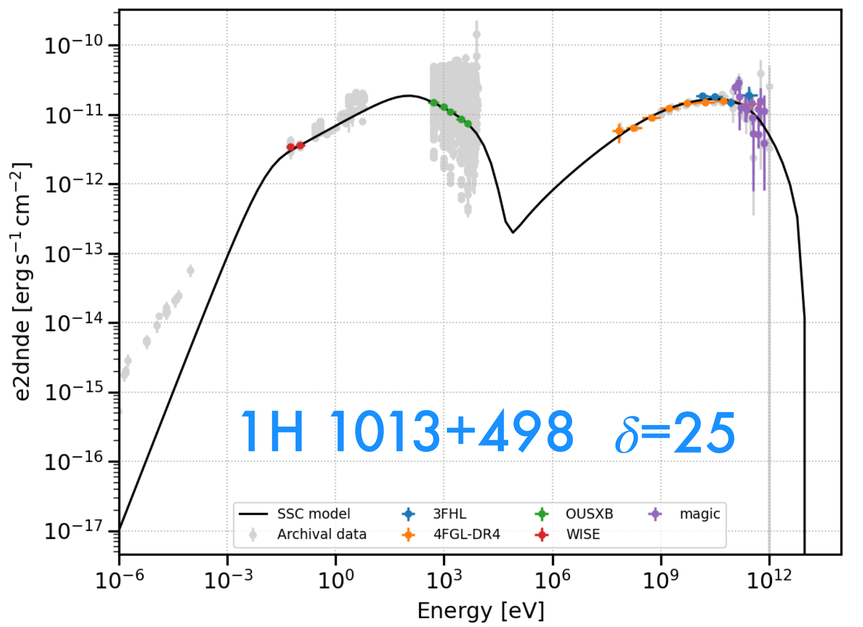
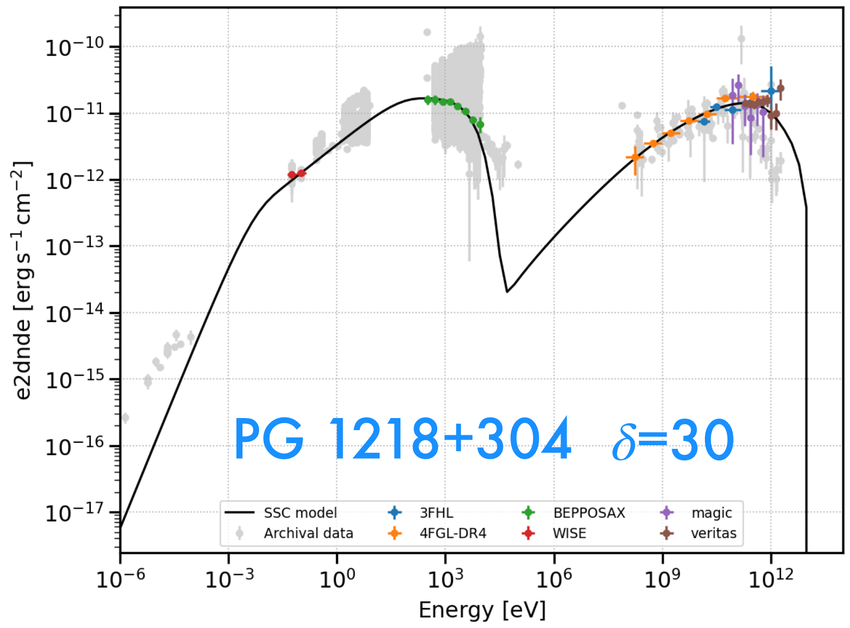
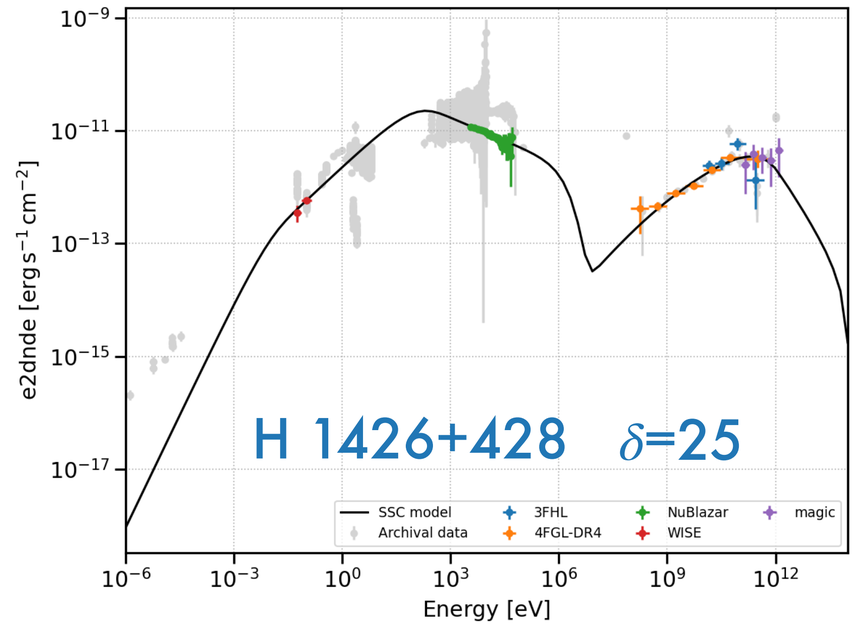
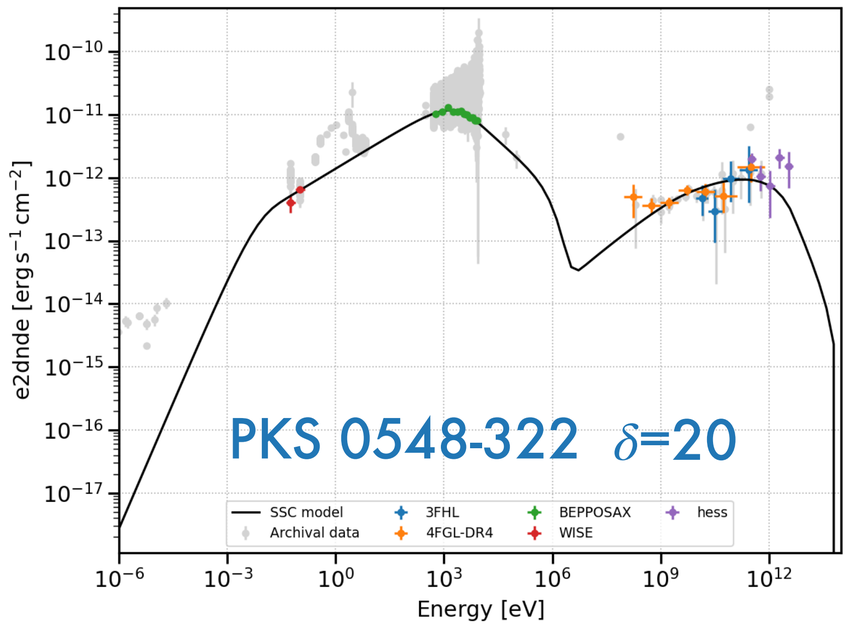






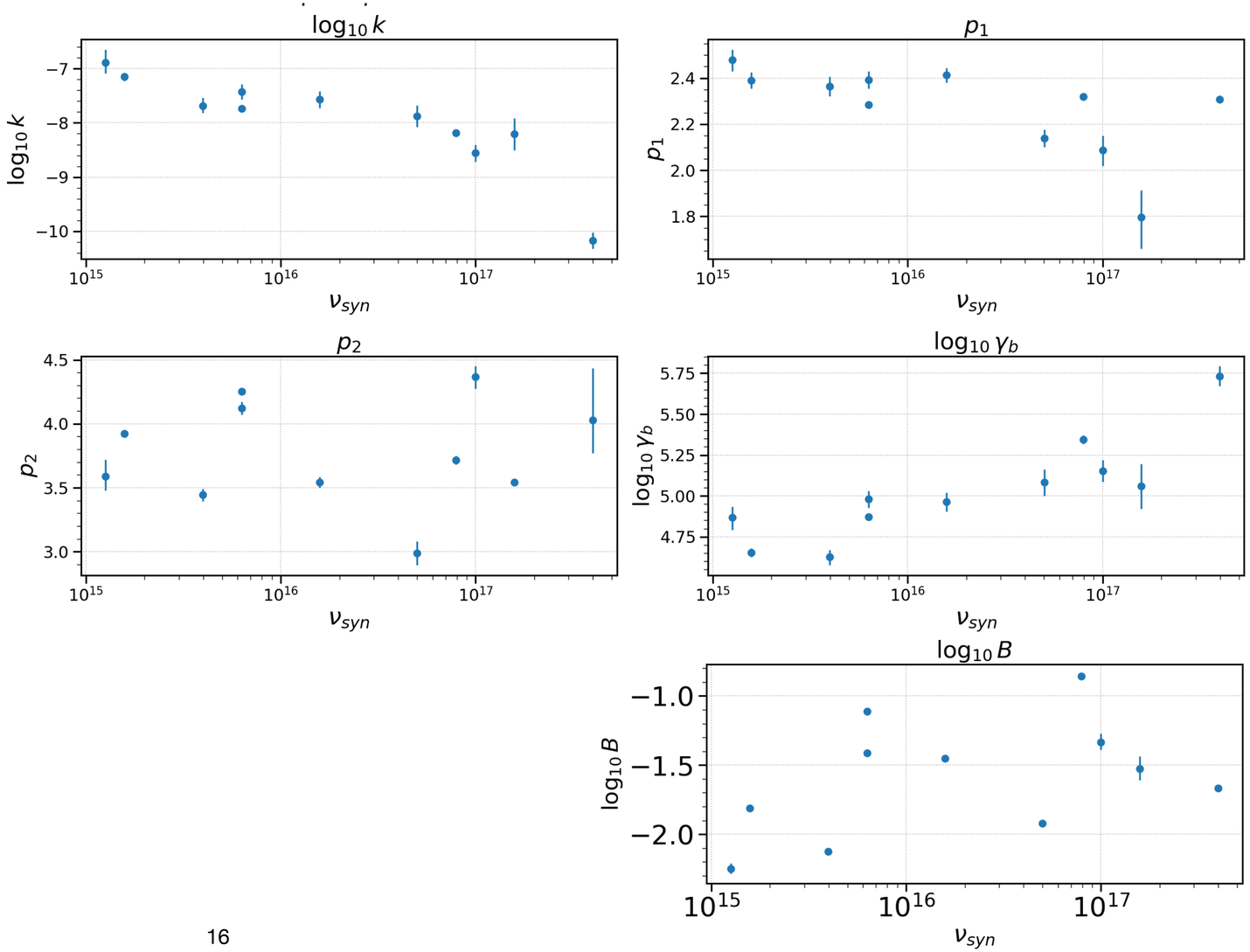






Modeling results - Comparison

Spearman coefficient	
Parameter	Value
k [cm-3]	-0.934
p_1	-0.706
p_2	0.132
γ_{break}	0.884
B [G]	0.428



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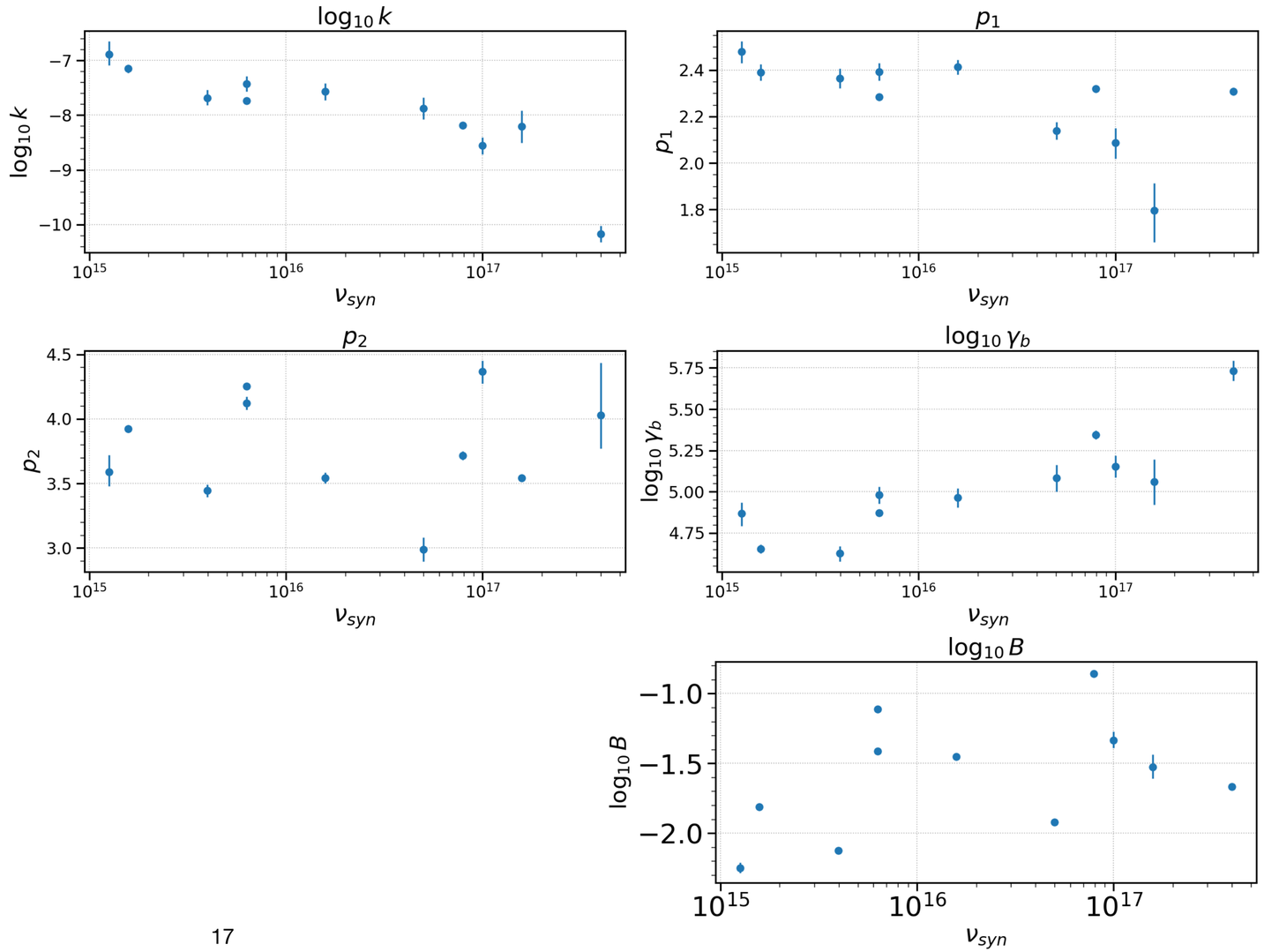

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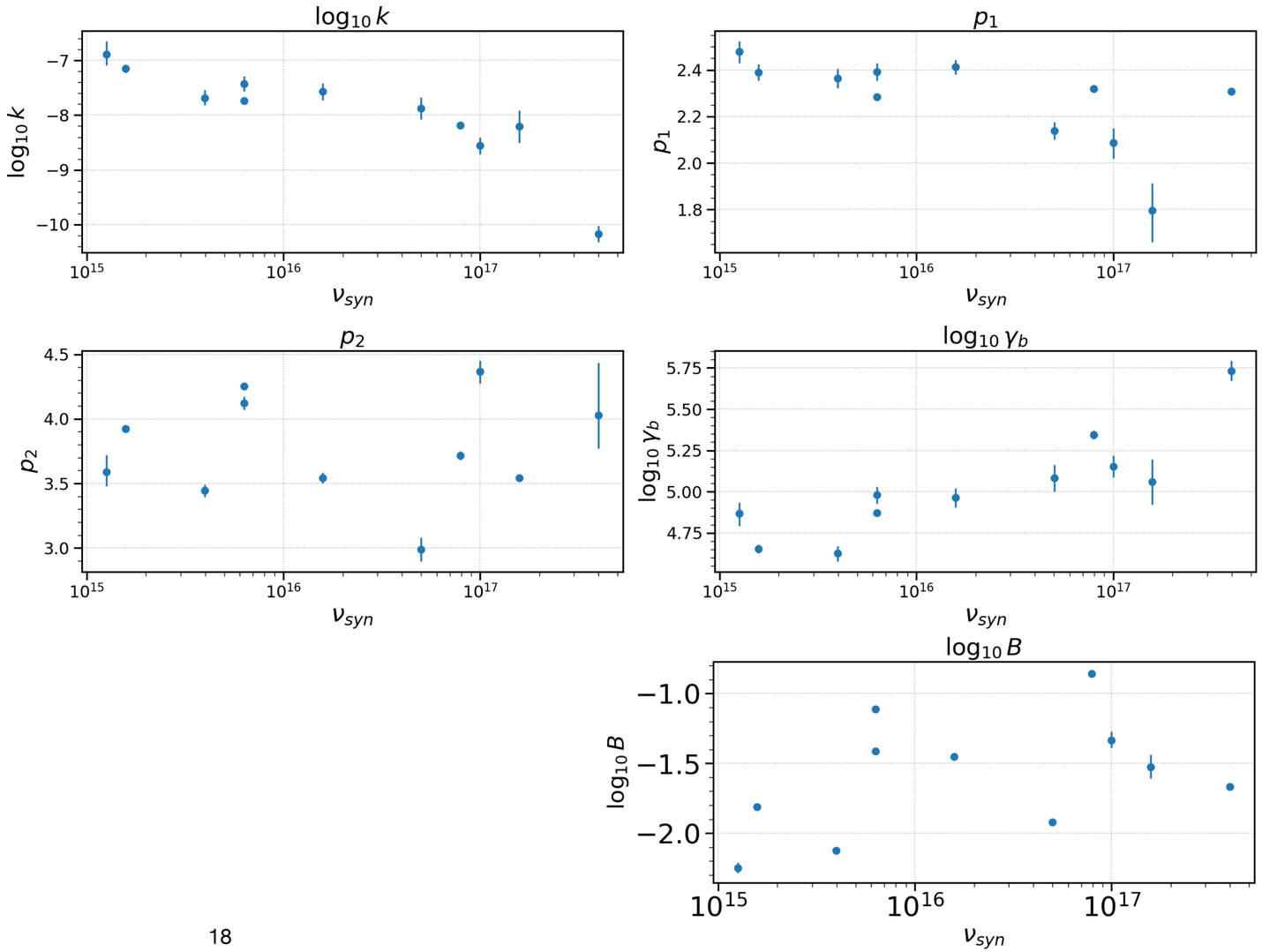

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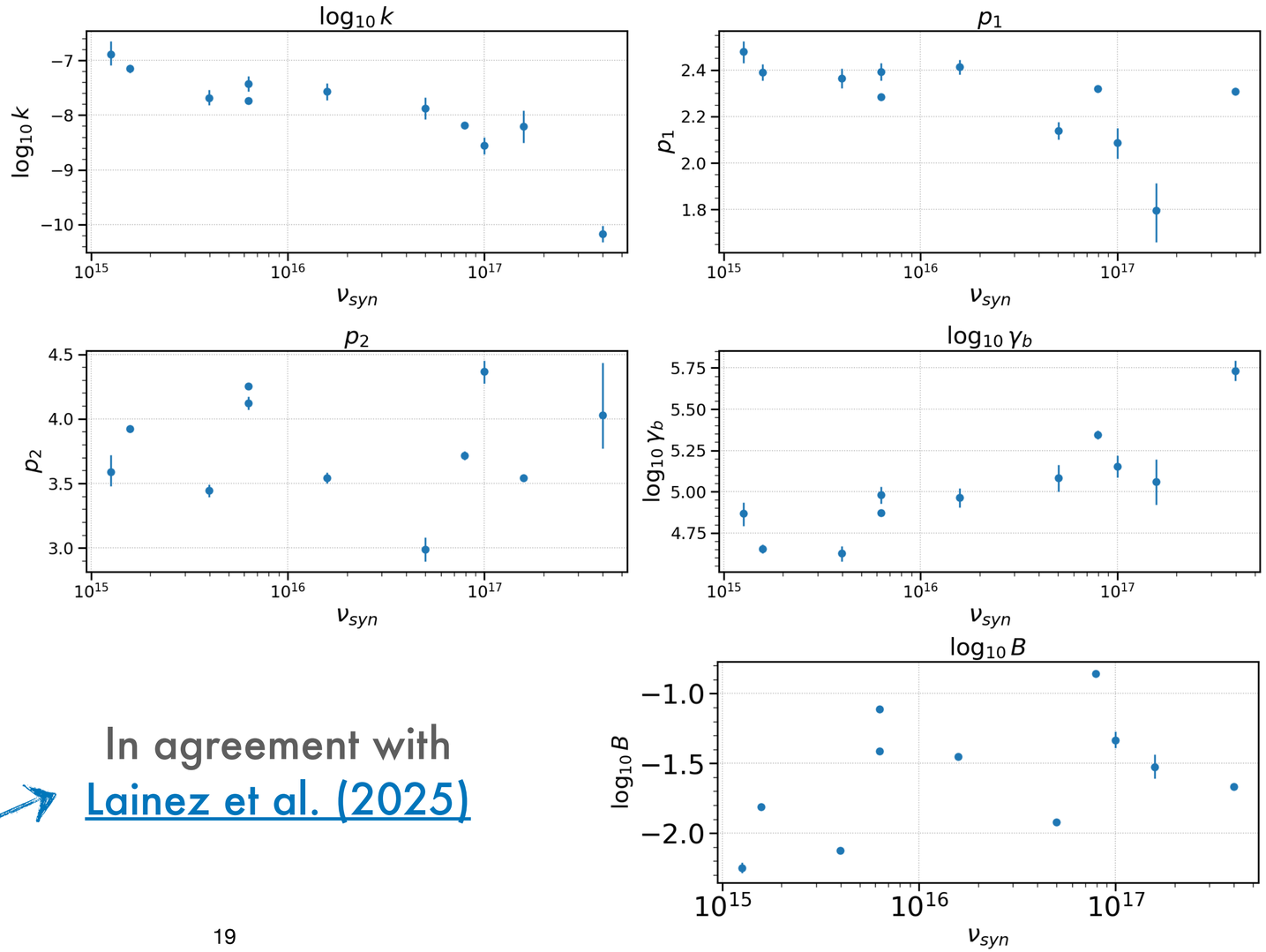

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Strong correlation found for break Lorentz factor γ_{break}

Hint of correlation found for magnetic field B

In agreement with Lainez et al. (2025)

Take home messages and outlook

- Investigation of TeV sources in the blazar sequence
- Non-trivial data selection
  - Flux averages not representative of source emission → Need of single observations
  - Large variability in X-rays
  - Lack of simultaneous data in quiescent state
- Synchrotron Self Compton model
  - Reduce number of free parameters in order to look for trends
  - Sample of 11 sources analyzed, HBLs considered
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  - Obs. strategy of simultaneous X-ray and γ-ray data
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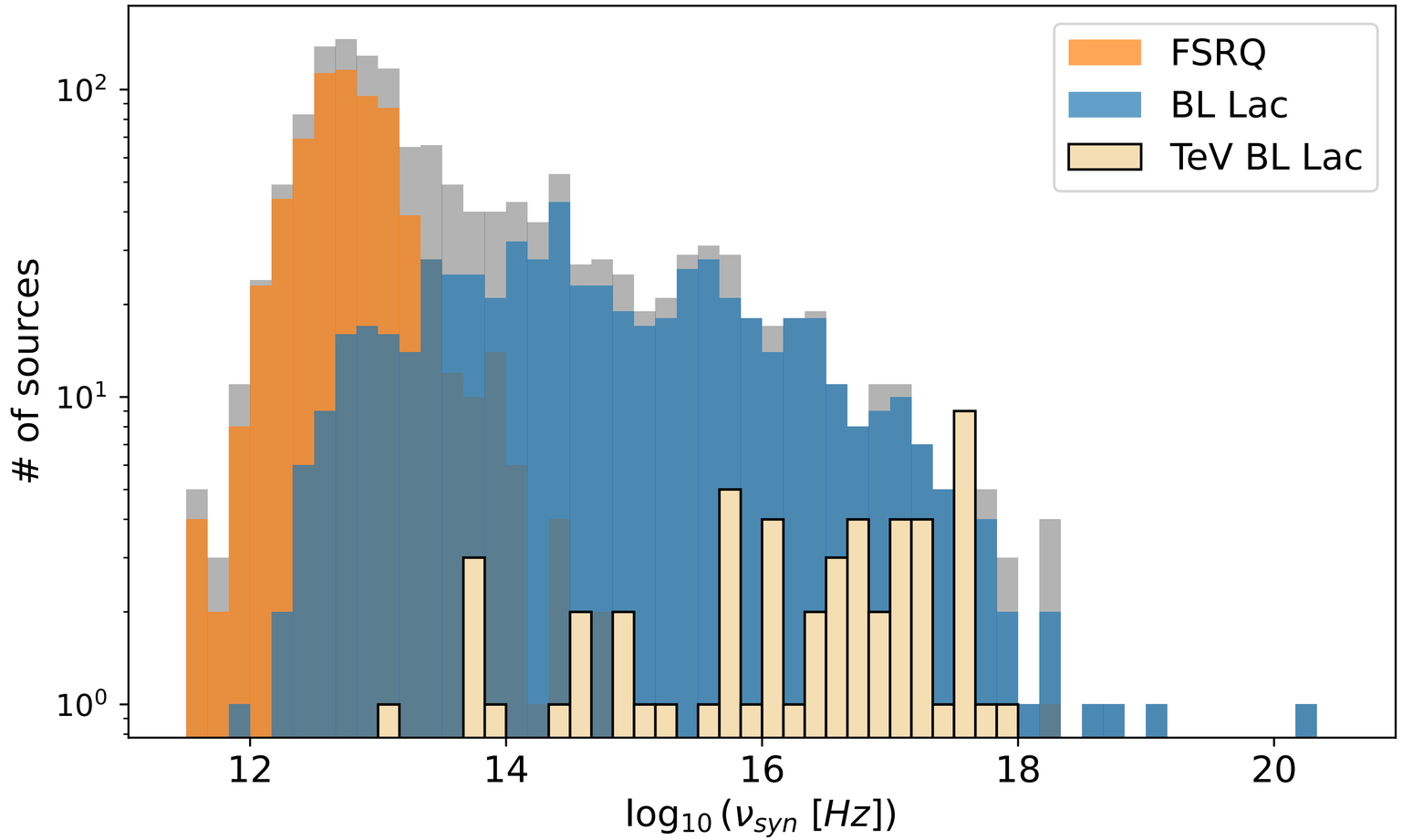
Thank you!

Backup

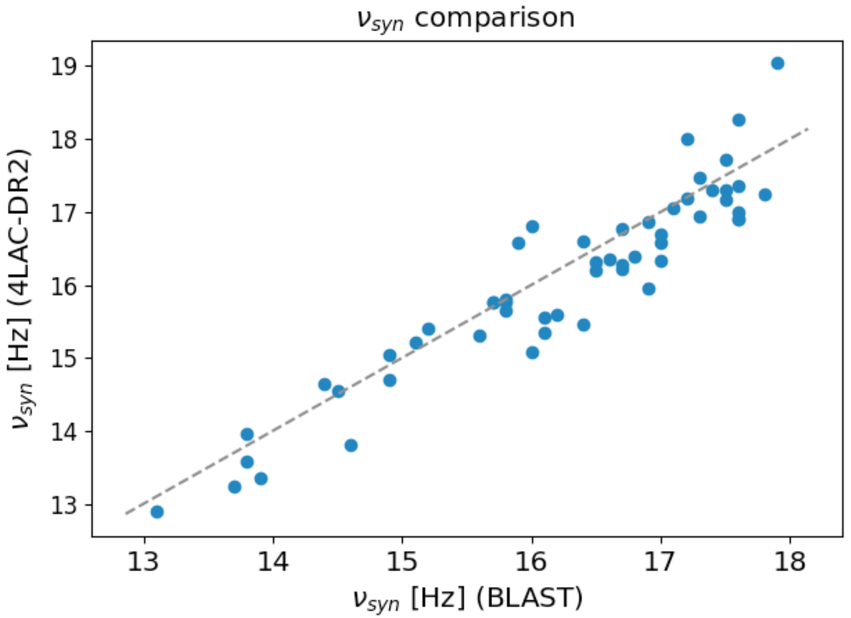
Synchrotron peak frequency distribution for BlaST

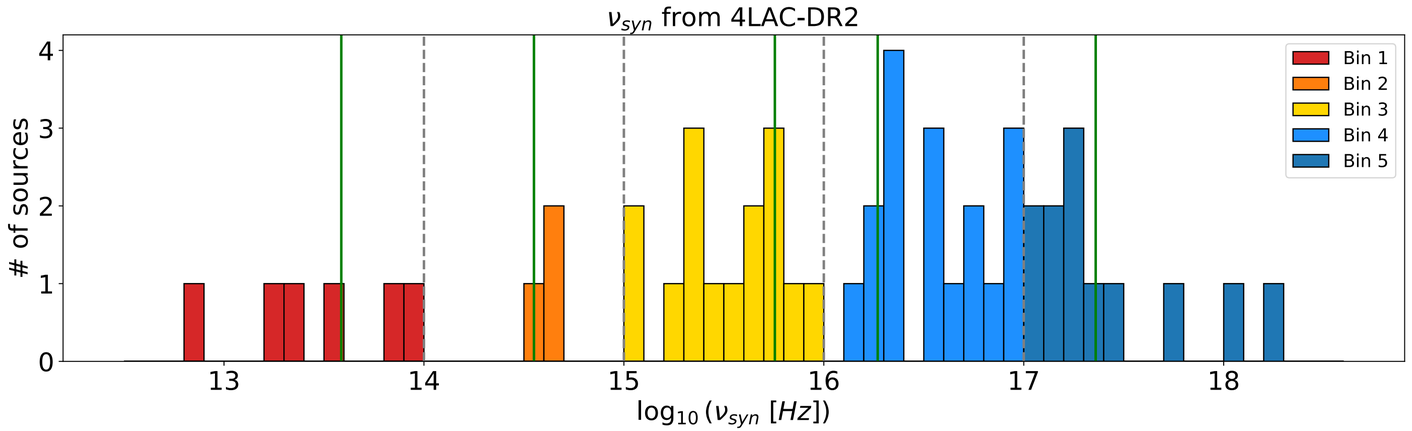
BlaST distribution of ν_{syn} compared to 4LAC-DR2

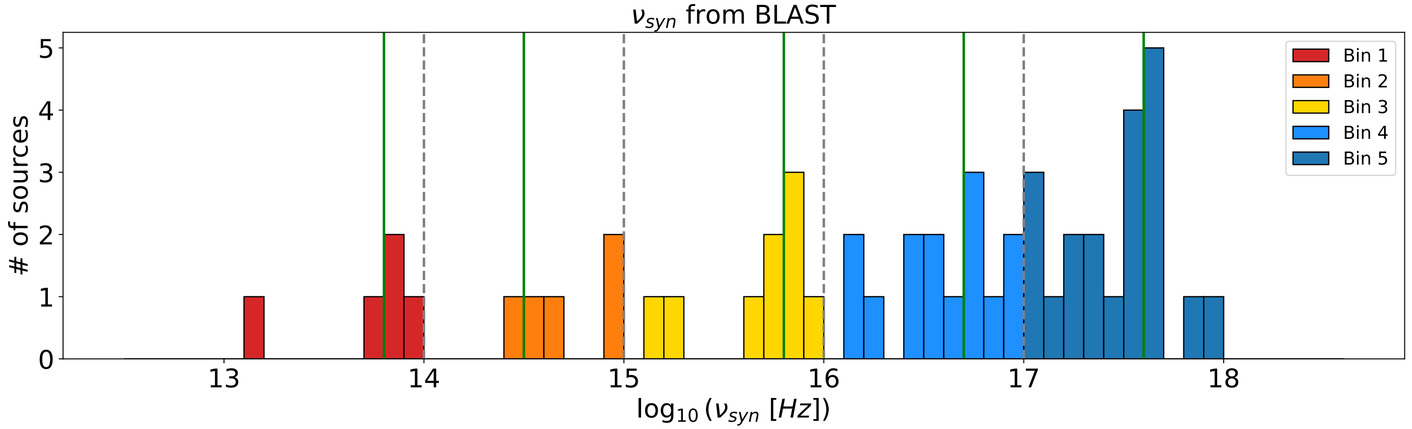


Synchrotron peak frequency bins

- Comparison of ν_{syn} between 4LAC-DR2 and BlaST T. Glauch et al. (2022)
  - Machine learning-based tool
  - More precise as it takes into account host galaxy and disk emission







- BlaST results more consistent with Lainez et al. (2025) and Biteau et al. (2020) for EHSPs

Bins based on BlaST values for ν_{syn}

Data selection