

# Time-Dependent Studies of Blazar Emission:

Insights from PKS 2155-304

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# Outline

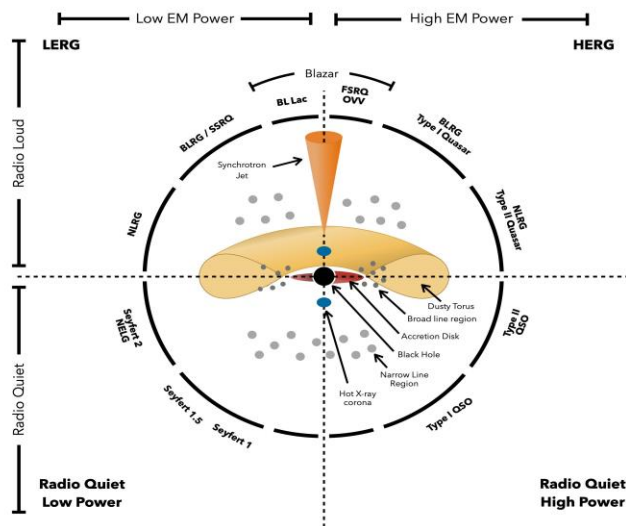
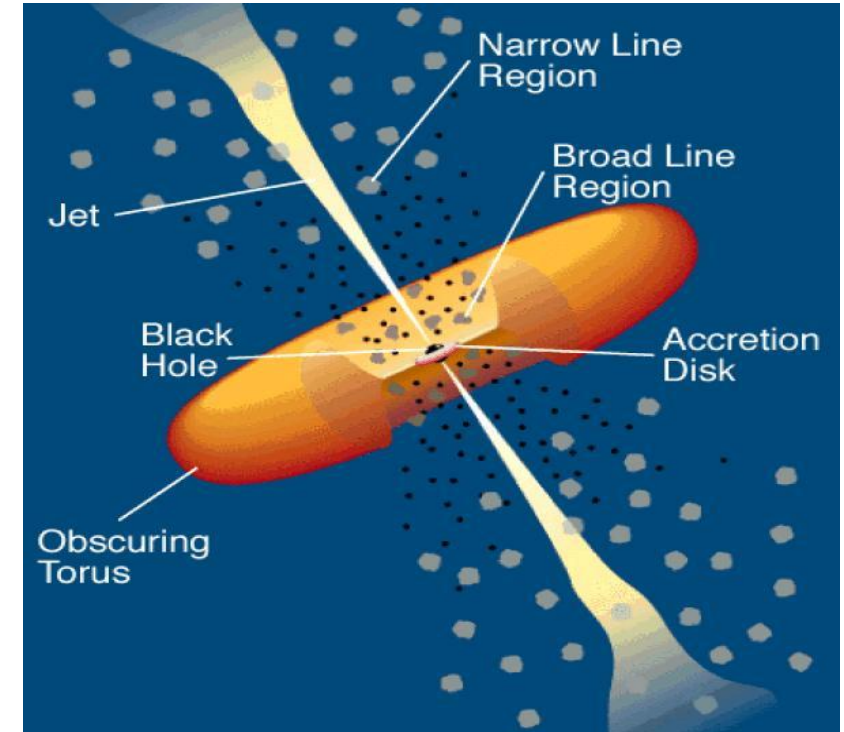
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- AGNs and Blazars
- Scientific Motivation & Workflow
- PKS 2155 – 304 : Multiwavelength analysis, state identification, projected modeling
- Comparative view of flaring states and the quiescent state
- Current Progress
- Future Direction & Conclusions



# Active Galactic Nuclei (AGN)

- Supermassive black hole (SMBH) + accretion disk
- Broad Line Region (BLR)
- Narrow Line Region (NLR)
- Dusty Torus
- Relativistic jets (radio-loud subset)

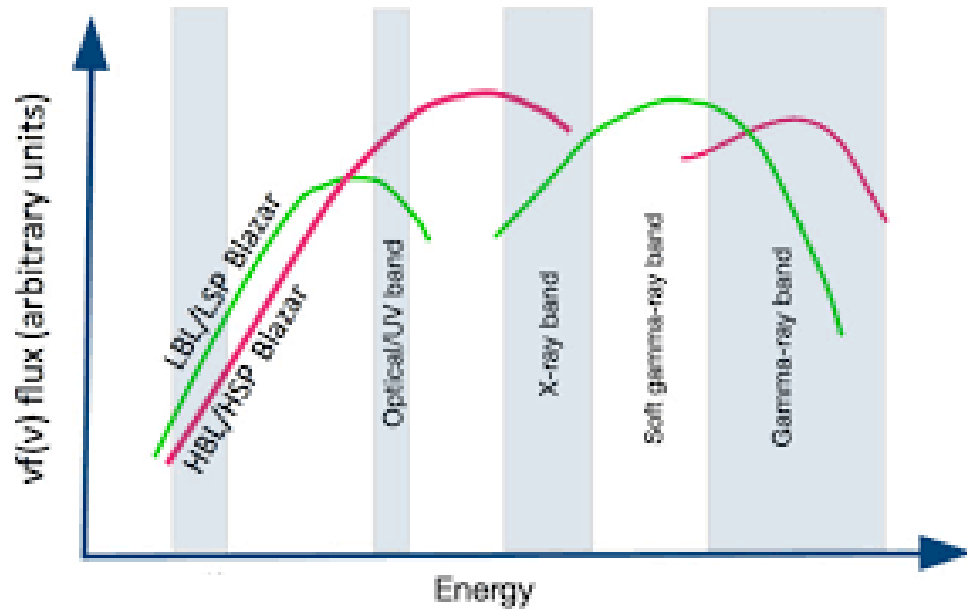


J. E. Thorne

**Blazars: jets closely aligned with the line of sight**  
Extreme flux variability across the electromagnetic spectrum  
**This work: PKS 2155-304 (BL Lac, HBL)**



# Broadband SEDs of BL Lacs & FSRQs

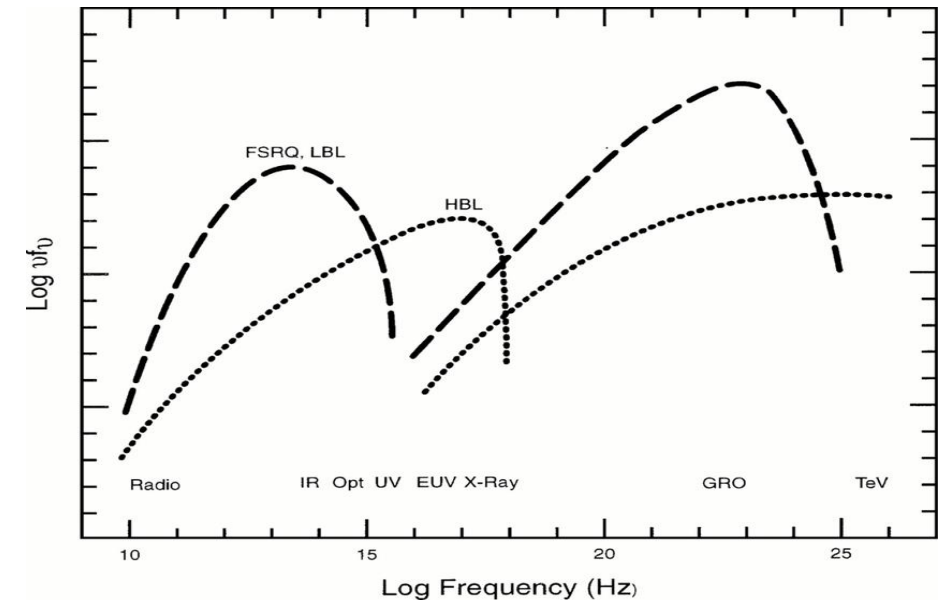


**Synchrotron hump** Radio to UV/X-ray - relativistic electrons in the jet B-field

**Inverse Compton hump** X-ray to  $\gamma$ -ray - up-scattered photons

**BL Lac (HBL):** Synchrotron peaks at UV/X-ray; IC dominated by SSC

**FSRQ:** Synchrotron peaks at radio/IR; IC dominated by EC from BLR and dust torus; broad emission lines visible



# Why Variability Matters ?

**Emission regions:** Variability timescale constrains the size of the emitting region via causality:  
 $R \lesssim c\Delta t \delta/(1+z)$

**Particle acceleration:** Flux rise times probe acceleration mechanisms: diffusive shock acceleration, magnetic reconnection

**Radiative cooling:** Decay timescales measure synchrotron and IC cooling rates, constraining B-field and particle energy

**Jet dynamics:** Correlated variability between wavebands tests the co-spatiality of emitting zones and jet structure

**Multi-wavelength approach:** Simultaneous coverage from  $\gamma$ -ray to optical breaks model degeneracies and yields unique physical parameters



# Scientific Workflow



**Data:** Fermi-LAT ( $\gamma$ -ray), Swift-XRT (X-ray), Swift-UVOT (UV/optical), Steward Observatory (optical), SMARTS

**Bayesian Blocks:** Change-point algorithm (Scargle et al. 2013) — objectively identifies flux transitions

**HOP algorithm:** Groups Bayesian Block states into discrete flaring and quiescent episodes by local flux topology

**Time-dep. model:** Kinetic equation for  $N(\gamma, t)$  — self-consistent SEDs and model light curves at each timestep



# PKS 2155-304 – Source Overview

**Classification:** High-frequency peaked BL Lac (HBL)

**Redshift:**  $z = 0.116$  (~500 Mpc)

**Synchrotron peak:** UV – soft X-ray

**HE mechanism:** Synchrotron self-Compton (SSC)

**Significance:** Among brightest and most variable blazars in the sky; benchmark TeV source

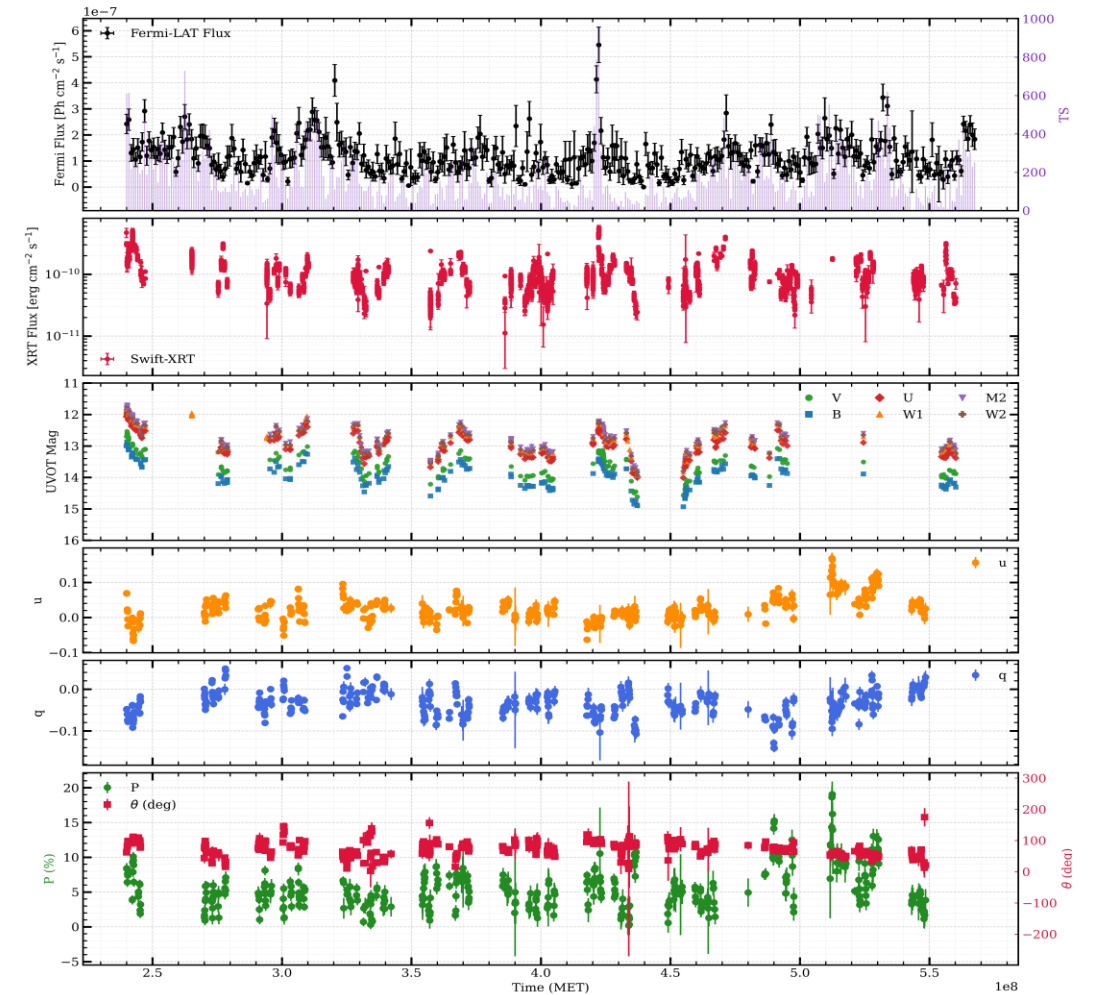
**Dataset:** Fermi-LAT, Swift-XRT, UVOT, SMARTS, Steward Observatory

**Coverage:** 2008 – 2018 (10 years)

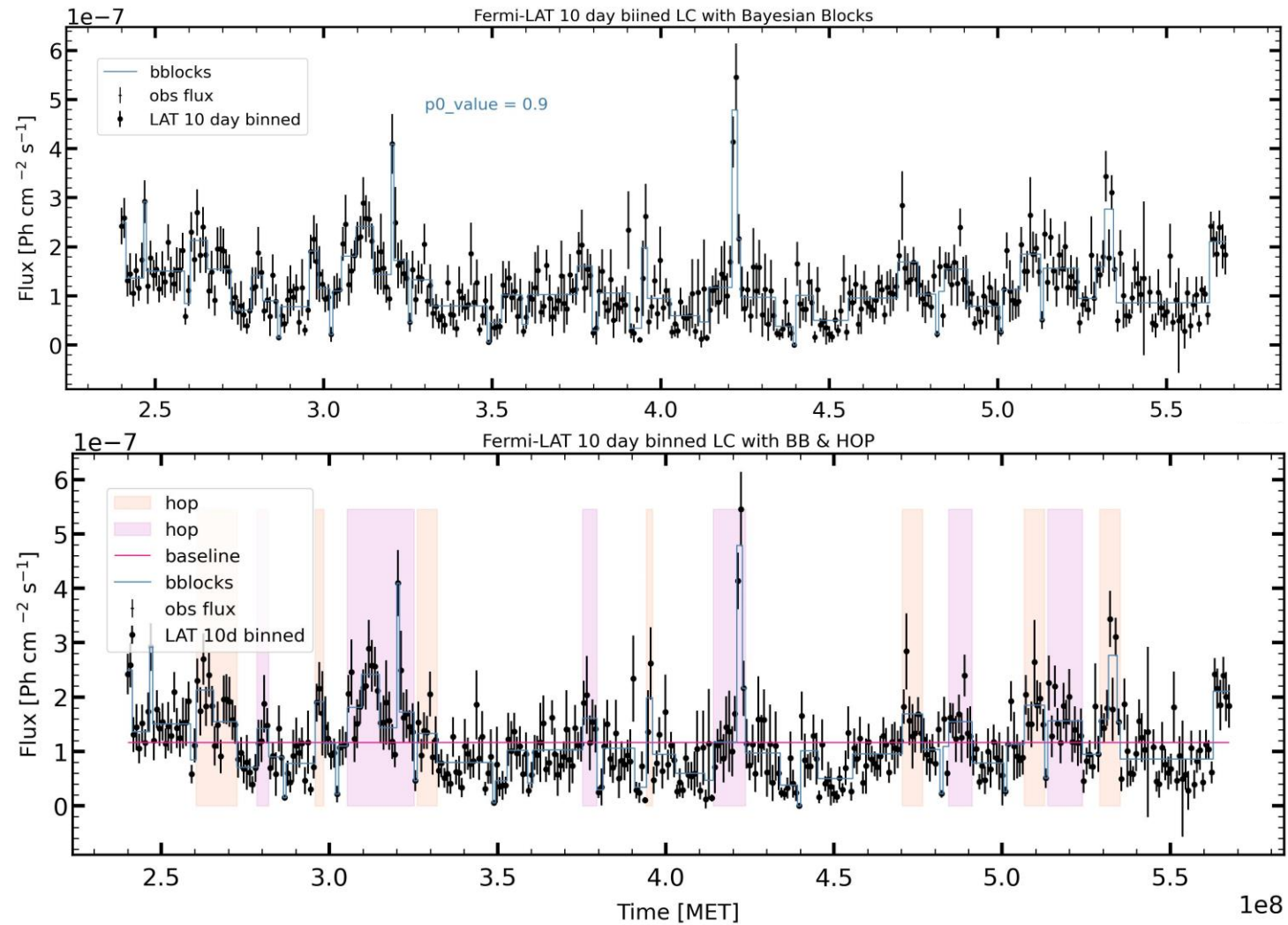


# PKS 2155-304 – MWL Lightcurves (2008-2018)

- Fermi-LAT light curve of 10 days binning within the energy range of 0.1 – 300 GeV.
- Swift-XRT light curve of 1000 sec binning within the energy range 0.1 – 10.0 keV.

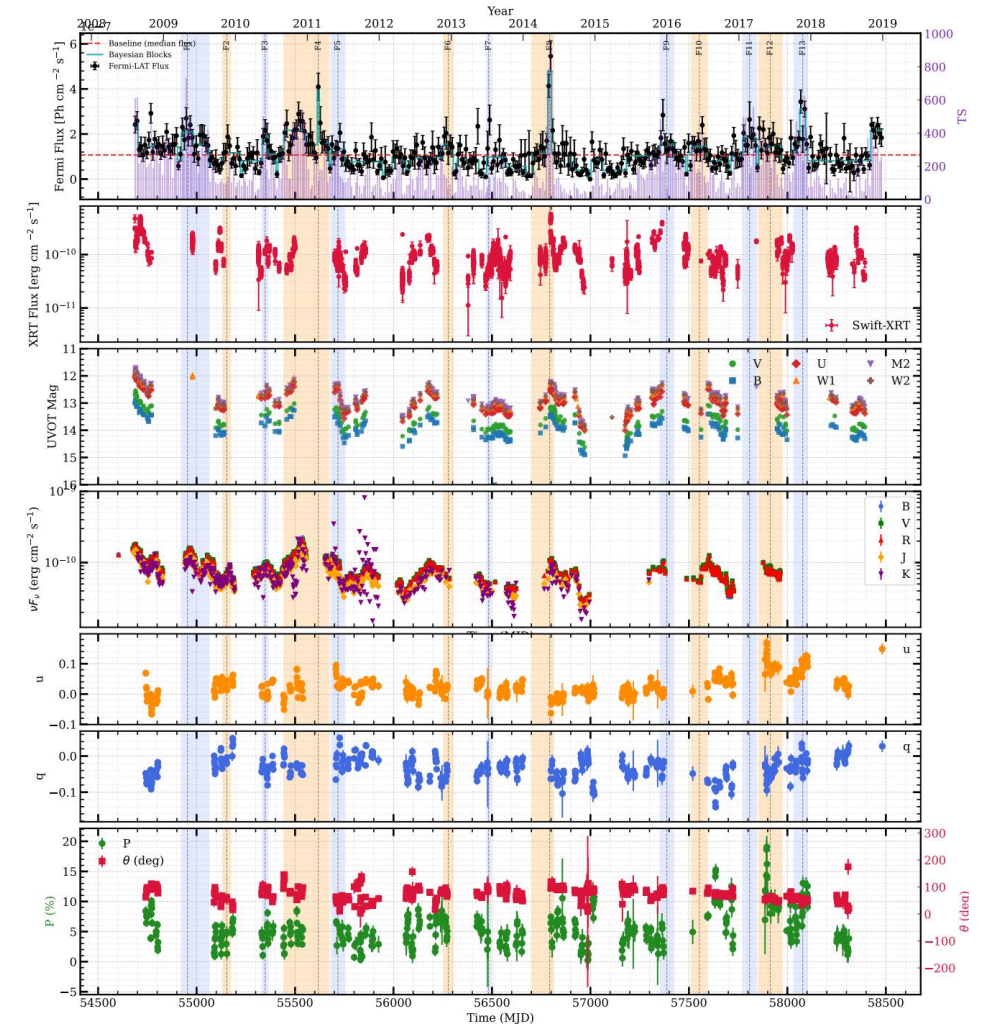


# Bayesian Block & HOP Application – PKS 2155-304



# HOP Flare Identification – PKS 2155-304

- HOP algorithm groups Bayesian Block segments by local flux topology: identifies peaks and associates surrounding blocks into discrete flaring episodes.
- Output: catalogue of flaring and quiescent epochs, each with start/end MJD, peak flux, and mean flux — used to select steady-state & time-resolved SED epochs.

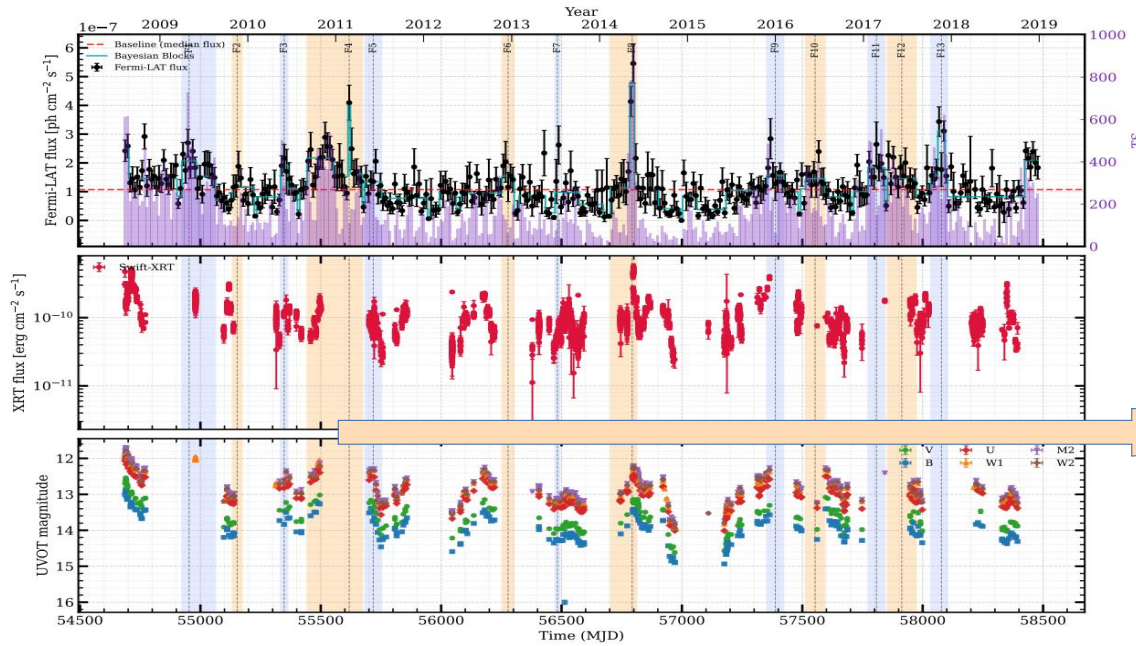


# One zone Hadro-Leptonic Code (OneHaLe) ?

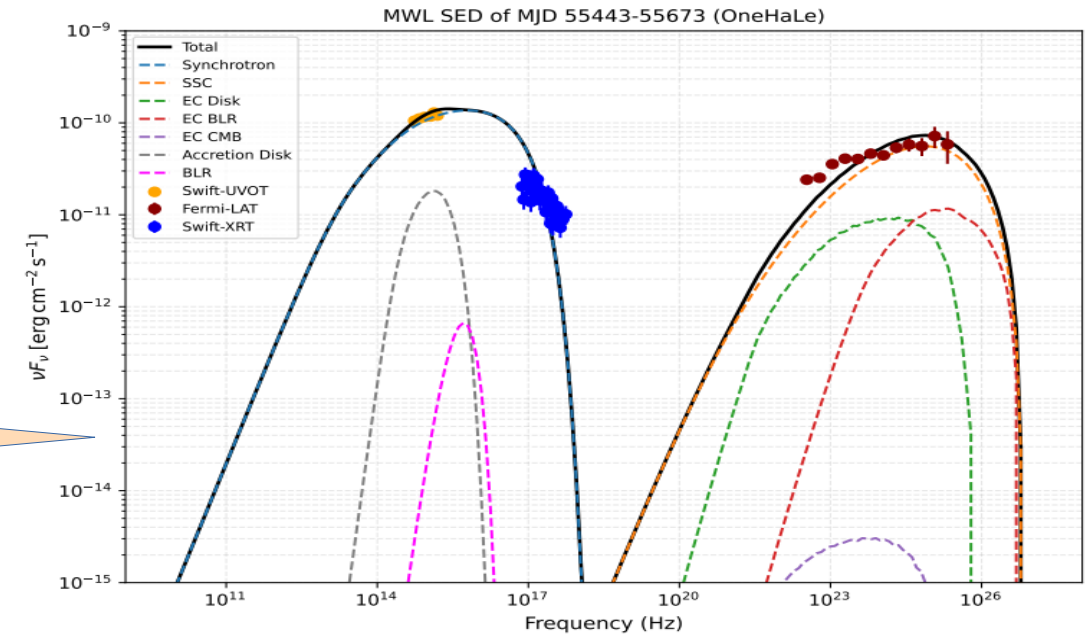
- OneHaLe is a time-dependent, one-zone code for blazar emission; here we use its leptonic option.
- A spherical emitting region contains relativistic electrons in a magnetic field and moves with bulk Lorentz factor  $\Gamma$ .
- Electrons produce synchrotron radiation and upscatter those photons through synchrotron self-Compton (SSC) emission.
- Electron inputs:  $\gamma_{e,\min}$ ,  $\gamma_{e,\max}$ , injection index  $p$ , injection power  $L_{e,\text{inj}}$ , and acceleration/escape timescales.
- Emission-region inputs: radius  $R$ , magnetic field  $B$ ,  $\Gamma$ , and viewing angle  $\theta_{\text{obs}}$ ; these set the spectrum and Doppler boosting.
- Variability limits the region size:  $R \lesssim c \Delta t \delta / (1 + z)$ .



# PKS 2155-304 – Steady-State SED (55443-55673)



$$\begin{aligned}
 B &= 0.014 \text{ G}; R = 4.80 \times 10^{17} \text{ cm} \\
 \Gamma &= 19.0; z = 0.116 \\
 \theta_{\text{obs}} &= 0.053 \text{ rad } (3.01^\circ) \\
 \gamma_{\text{e,min}} &= 3.00 \times 10^3 \\
 \gamma_{\text{e,max}} &= 3.00 \times 10^5
 \end{aligned}$$

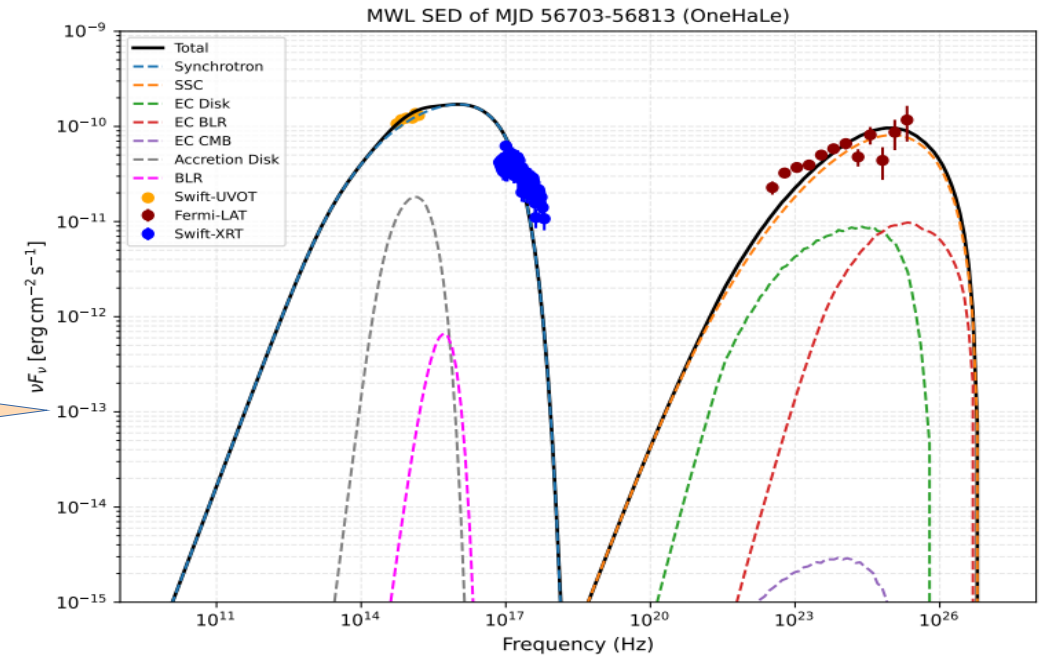
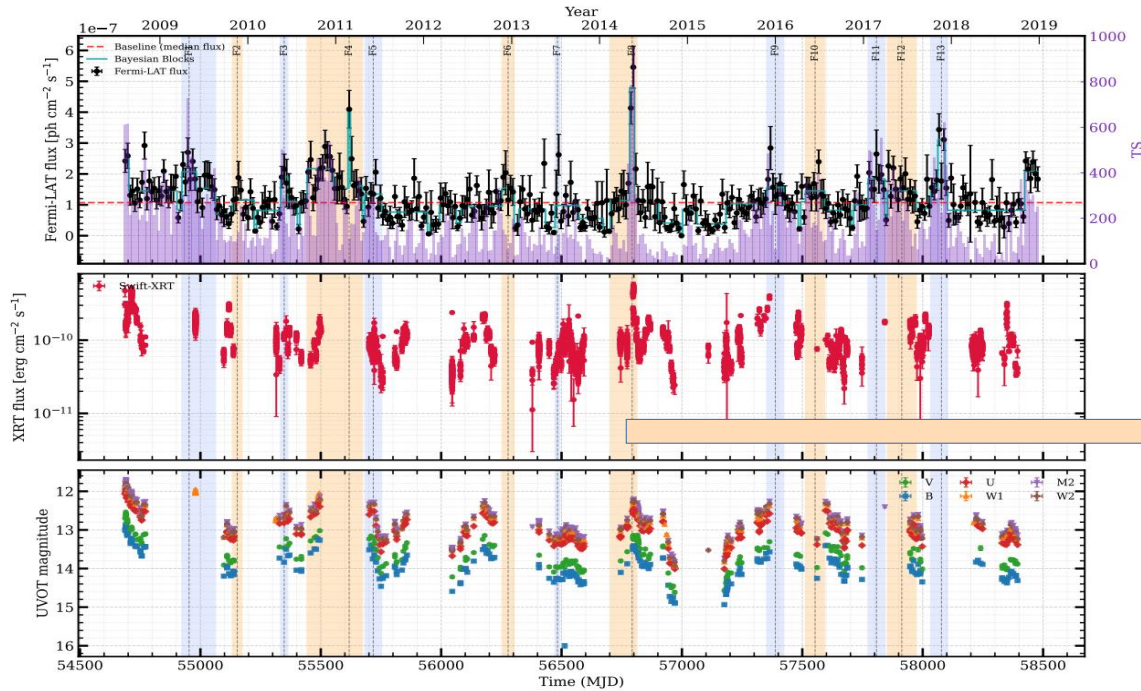


$$\begin{aligned}
 P &= 1.55; L_{\text{e,inj}} = 3.00 \times 10^{41} \text{ erg s}^{-1} \\
 t_{\text{acc}}/t_{\text{esc}} &= 0.80; t_{\text{esc}} = 15 R/c \\
 M_{\text{BH}} &= 4.0 \times 10^9 M_{\odot} \\
 L_{\text{disk}}/L_{\text{Edd}} &= 1.0 \times 10^{-3}
 \end{aligned}$$

$$t_{\text{var}} \approx 10.9 \text{ days}$$



# PKS 2155-304 – Steady-State SED (56703-56813)



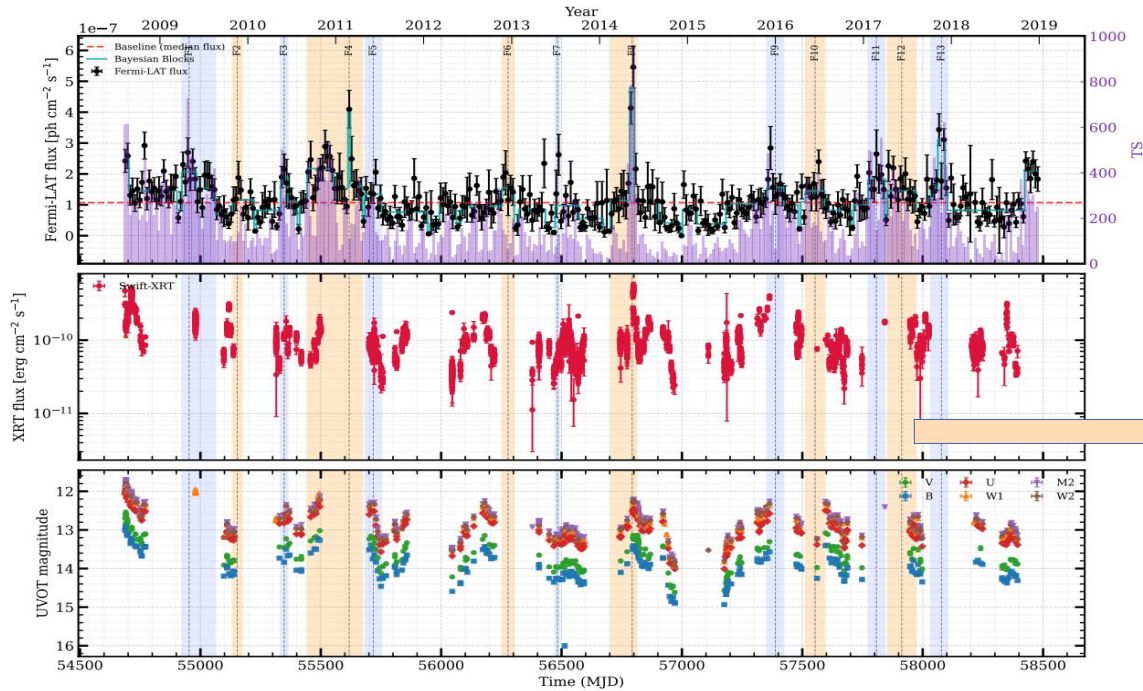
$$\begin{aligned}
 B &= 0.016 \text{ G}; R = 4.00 \times 10^{17} \text{ cm} \\
 \Gamma &= 19.0; z = 0.116 \\
 \theta_{\text{obs}} &= 0.053 \text{ rad } (3.01^\circ) \\
 \gamma_{\text{e,min}} &= 3.00 \times 10^3 \\
 \gamma_{\text{e,max}} &= 3.15 \times 10^5
 \end{aligned}$$

$$\begin{aligned}
 P &= 1.35; L_{\text{e,inj}} = 3.65 \times 10^{41} \text{ erg s}^{-1} \\
 t_{\text{acc}}/t_{\text{esc}} &= 0.90; t_{\text{esc}} = 15 R/c \\
 M_{\text{BH}} &= 4.0 \times 10^9 M_{\odot} \\
 L_{\text{disk}}/L_{\text{Edd}} &= 1.0 \times 10^{-3}
 \end{aligned}$$

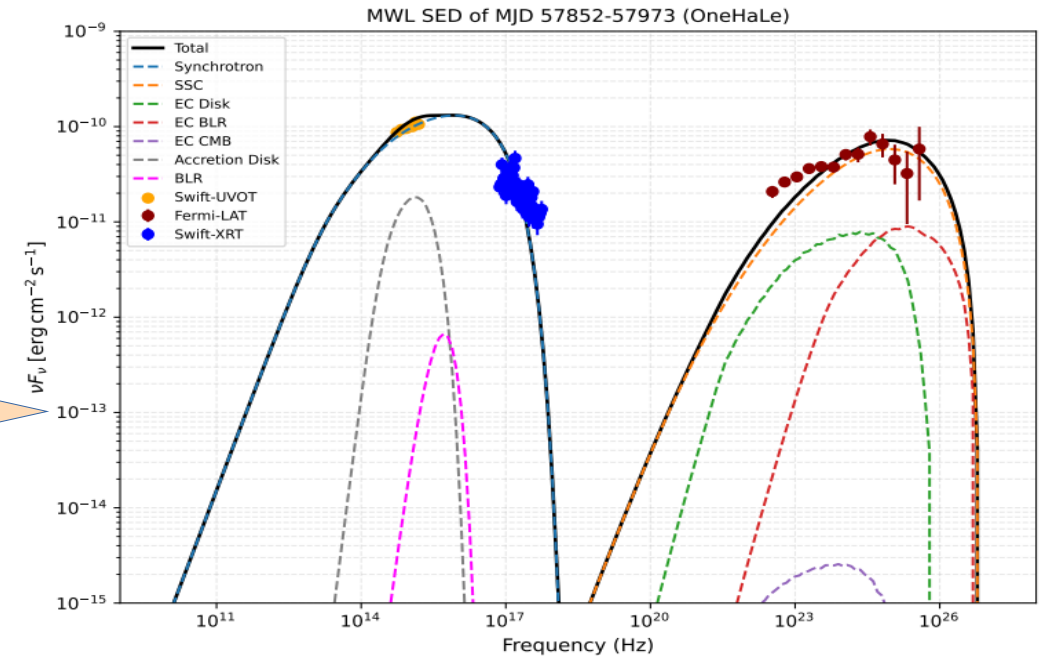
$$t_{\text{var}} \approx 9.07 \text{ days}$$



# PKS 2155-304 – Steady-State SED (57852-57973)



$$\begin{aligned}
 B &= 0.015 \text{ G}; R = 4.00 \times 10^{17} \text{ cm} \\
 \Gamma &= 19.0; z = 0.116 \\
 \theta_{\text{obs}} &= 0.053 \text{ rad } (3.01^\circ) \\
 \gamma_{\text{e,min}} &= 3.00 \times 10^3 \\
 \gamma_{\text{e,max}} &= 3.00 \times 10^5
 \end{aligned}$$

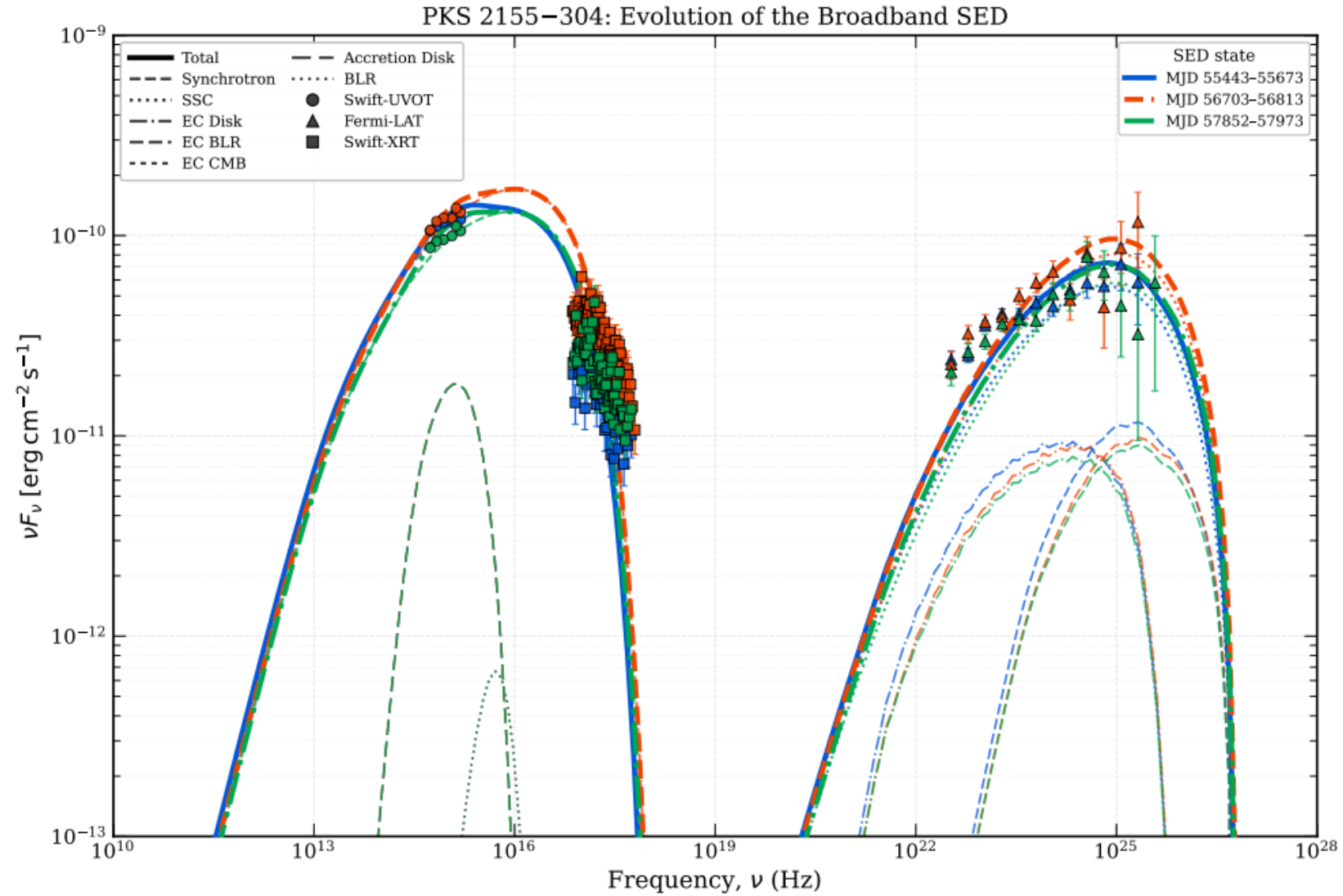


$$\begin{aligned}
 P &= 1.45; L_{\text{e,inj}} = 2.85 \times 10^{41} \text{ erg s}^{-1} \\
 t_{\text{acc}}/t_{\text{esc}} &= 0.92; t_{\text{esc}} = 15 R/c \\
 M_{\text{BH}} &= 4.0 \times 10^9 M_{\odot} \\
 L_{\text{disk}}/L_{\text{Edd}} &= 1.0 \times 10^{-3}
 \end{aligned}$$

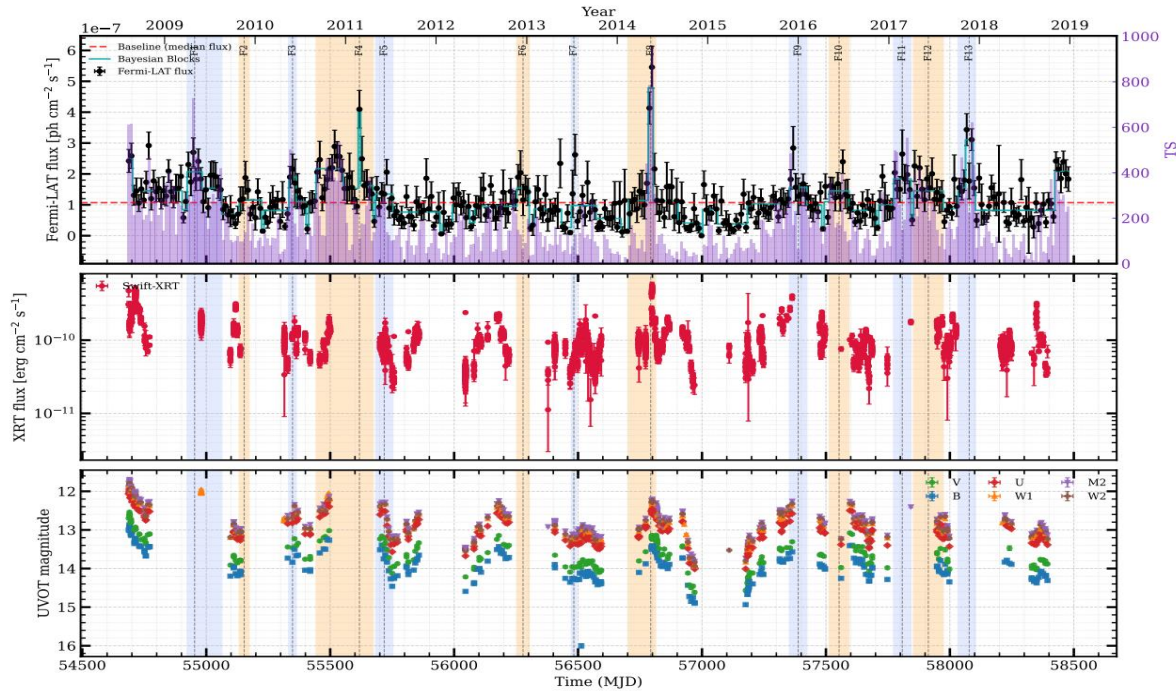
$$t_{\text{var}} \approx 9.07 \text{ days}$$



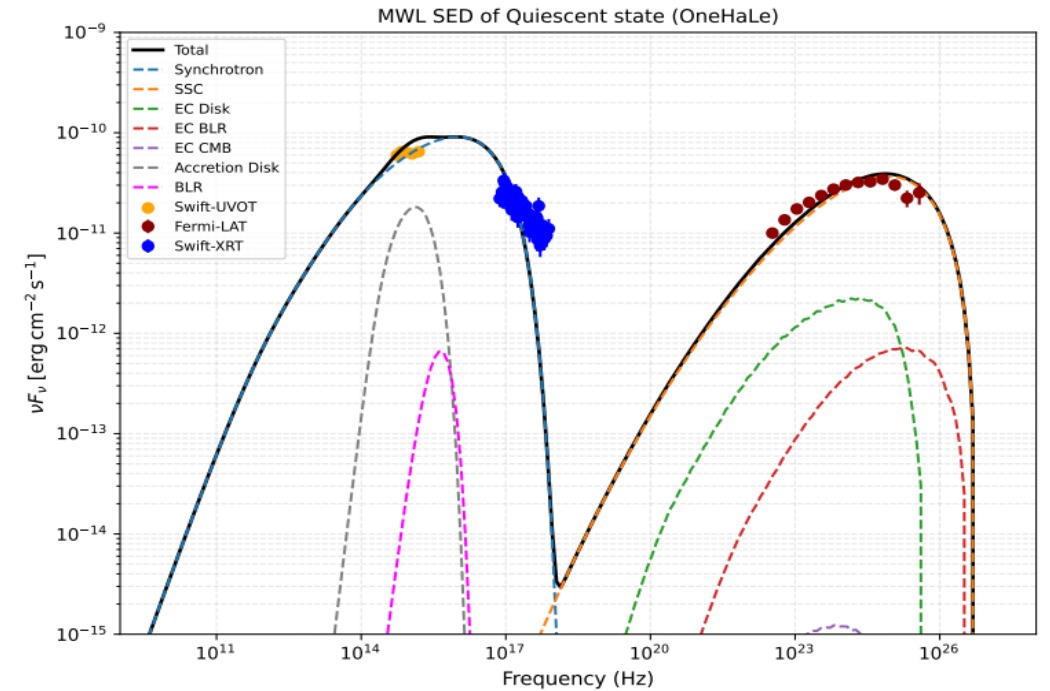
# PKS 2155-304 – Steady-State SED (evolution of Fstate)



# PKS 2155-304 – Steady-State SED (Q-state)



$$\begin{aligned}
 B &= 0.018 \text{ G}; R = 2.50 \times 10^{17} \text{ cm} \\
 \Gamma &= 20.0; z = 0.116 \\
 \theta_{\text{obs}} &= 0.05 \text{ rad} (2.86^\circ) \\
 \gamma_{\text{e,min}} &= 8.70 \times 10^2 \\
 \gamma_{\text{e,max}} &= 2.90 \times 10^5
 \end{aligned}$$

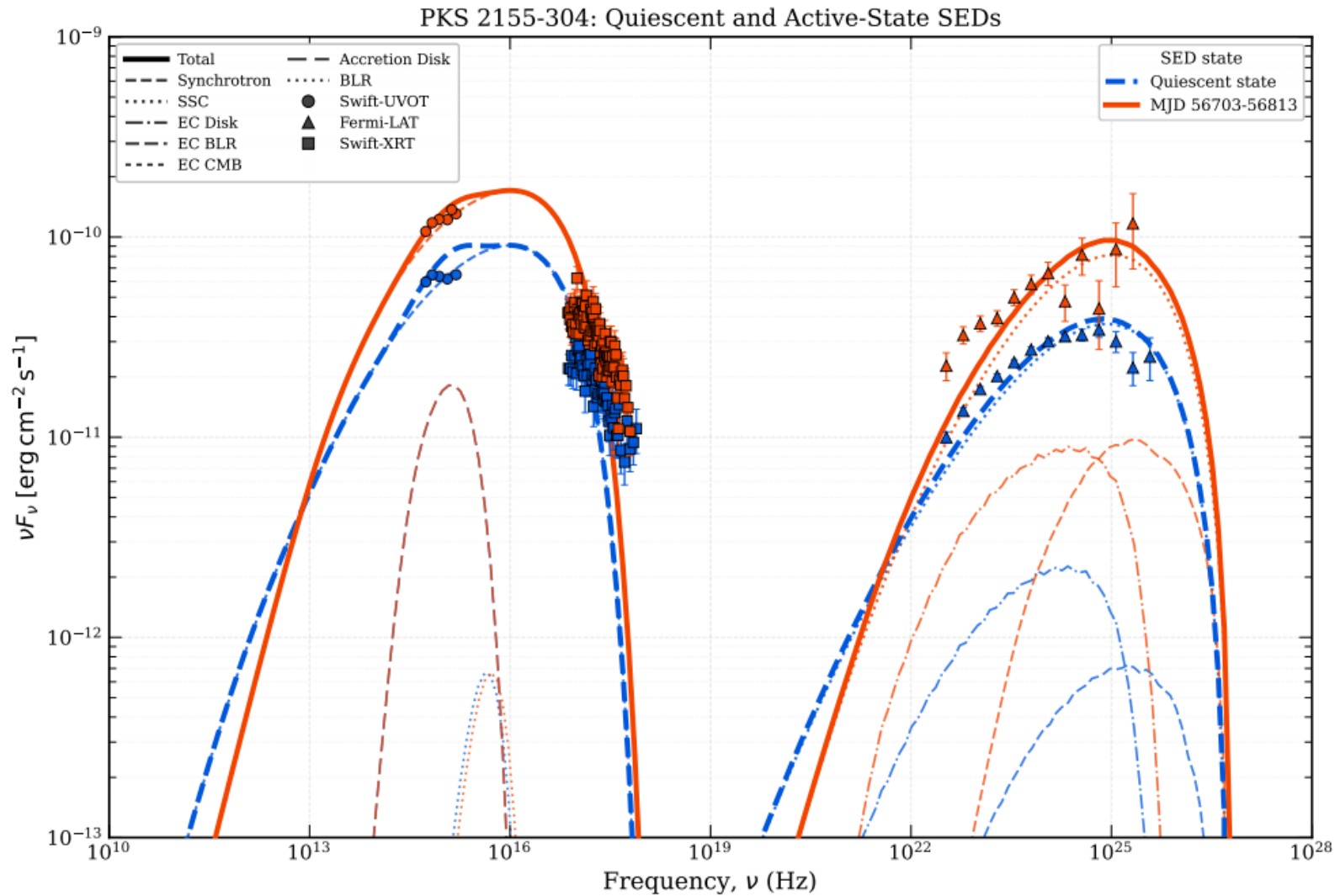


$$\begin{aligned}
 P &= 1.35; L_{\text{e,inj}} = 1.85 \times 10^{41} \text{ erg s}^{-1} \\
 t_{\text{acc}}/t_{\text{esc}} &= 1.5; t_{\text{esc}} = 50 R/c \\
 M_{\text{BH}} &= 4.0 \times 10^9 M_{\odot} \\
 L_{\text{disk}}/L_{\text{Edd}} &= 1.0 \times 10^{-3}
 \end{aligned}$$

$$t_{\text{var}} \approx 5.39 \text{ days}$$



# PKS 2155-304 – Steady-State SED (Fstate & Q-state)



# PKS 2155-304 – Current Progress

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- ✓ Multi-wavelength light curves (2008–2018)
- ✓ Bayesian Block analysis
- ✓ HOP flare identification
- ✓ Equilibrium SED modeled in F & Q states
- 🔄 Time-dependent SED + light curves modeling



# Future Directions

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**CTA era:** The Cherenkov Telescope Array will extend multiwavelength campaigns into the TeV band and help constrain electron cooling through rapid variability.

**Population studies:** Apply Bayesian Blocks, HOP, and time-dependent modeling to a blazar sample to compare the drivers of flux variability across sources.

**Extending to VHE:** Combine Fermi-LAT and archival H.E.S.S., MAGIC, and VERITAS data for PKS 2155-304 to constrain optical-to-TeV SEDs during flares.

**Beyond one zone:** Use H.E.S.S. VHE data to test a time-dependent leptonic code that couples diffusive shock acceleration with radiative transfer, especially where a one-zone SSC model cannot reproduce the TeV spectrum.



# Conclusions

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- 1. Multi-wavelength campaign:** Ten-year (PKS 2155-304) datasets constructed from Fermi-LAT, Swift-XRT, Swift-UVOT, and Steward Observatory.
- 2. State identification:** Bayesian Block analysis and HOP algorithm provide objective, statistically robust separation of flaring and quiescent epochs in both sources.
- 3. Steady-state modeling:** PKS 2155-304: leptonic SED modeling across all identified states completed — EC/BLR dominates the  $\gamma$ -ray emission; physical parameters vary systematically between states.
- 4. Time-dependent modeling:** Kinetic modeling (self-consistent SEDs + model light curves) underway for both sources — probing particle injection, cooling, and escape on flare timescales.



# References

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# Thank You

Questions & Discussion

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*Fermi-LAT · Swift-XRT/UVOT · Steward Observatory Monitoring Program · SMARTS*

