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Different dissipation mechanisms of Blazar jet underlying variability

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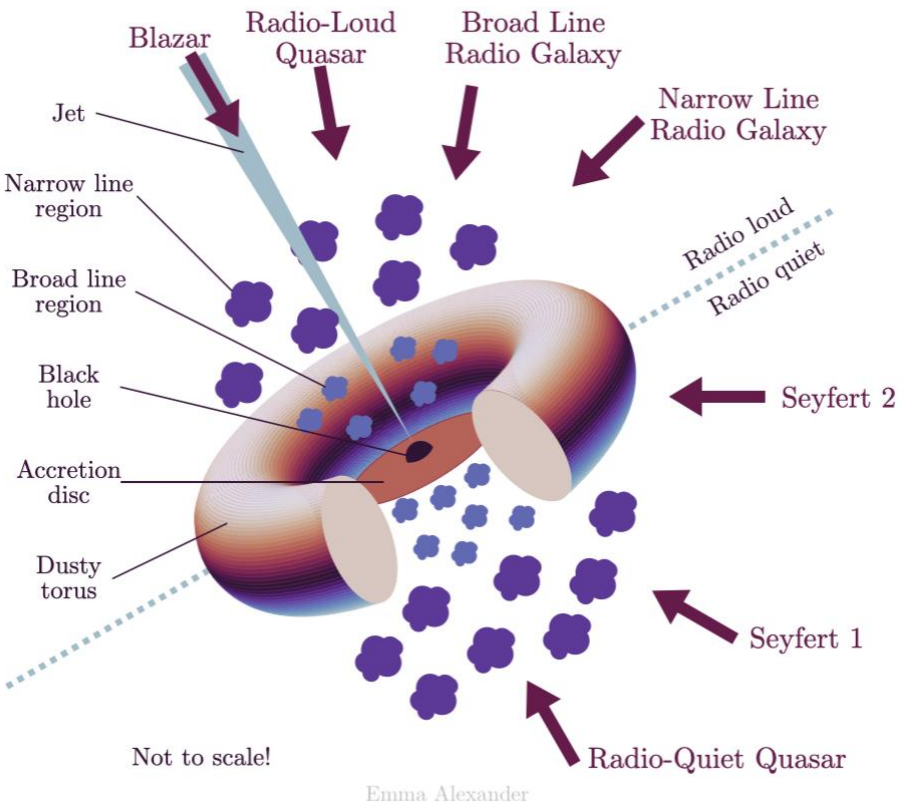
Blazar

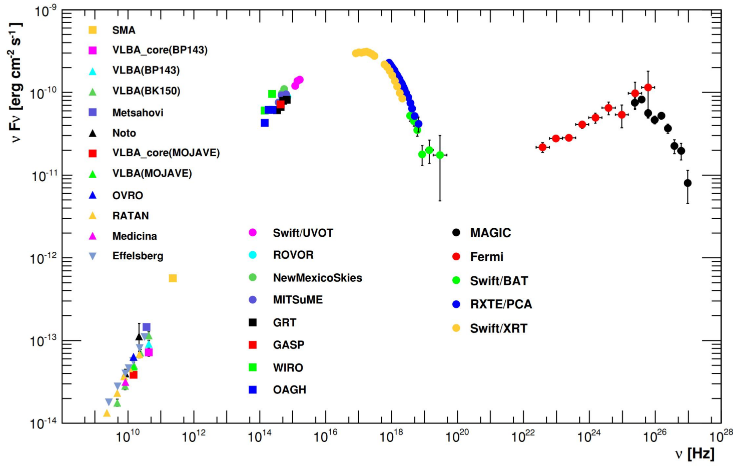
A ***Blazar*** is a subclass of *active galactic nuclei* (**AGN**) whose relativistic jet is closely aligned with our line of sight.

- Double-humped spectral energy distribution
- Multi-timescale (mins~yrs) and strong variability

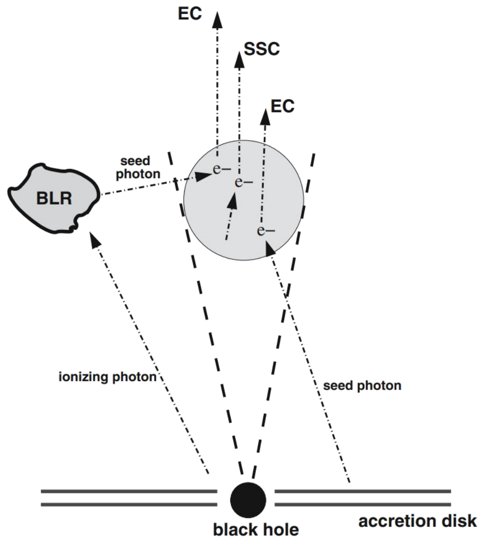
- One-zone model and its challenges



Schematic illustration of the AGN unified model.
Credit: ***Emma Alexander***, adapted from ***Urry & Padovani (1995)***, licensed under CC BY 4.0.

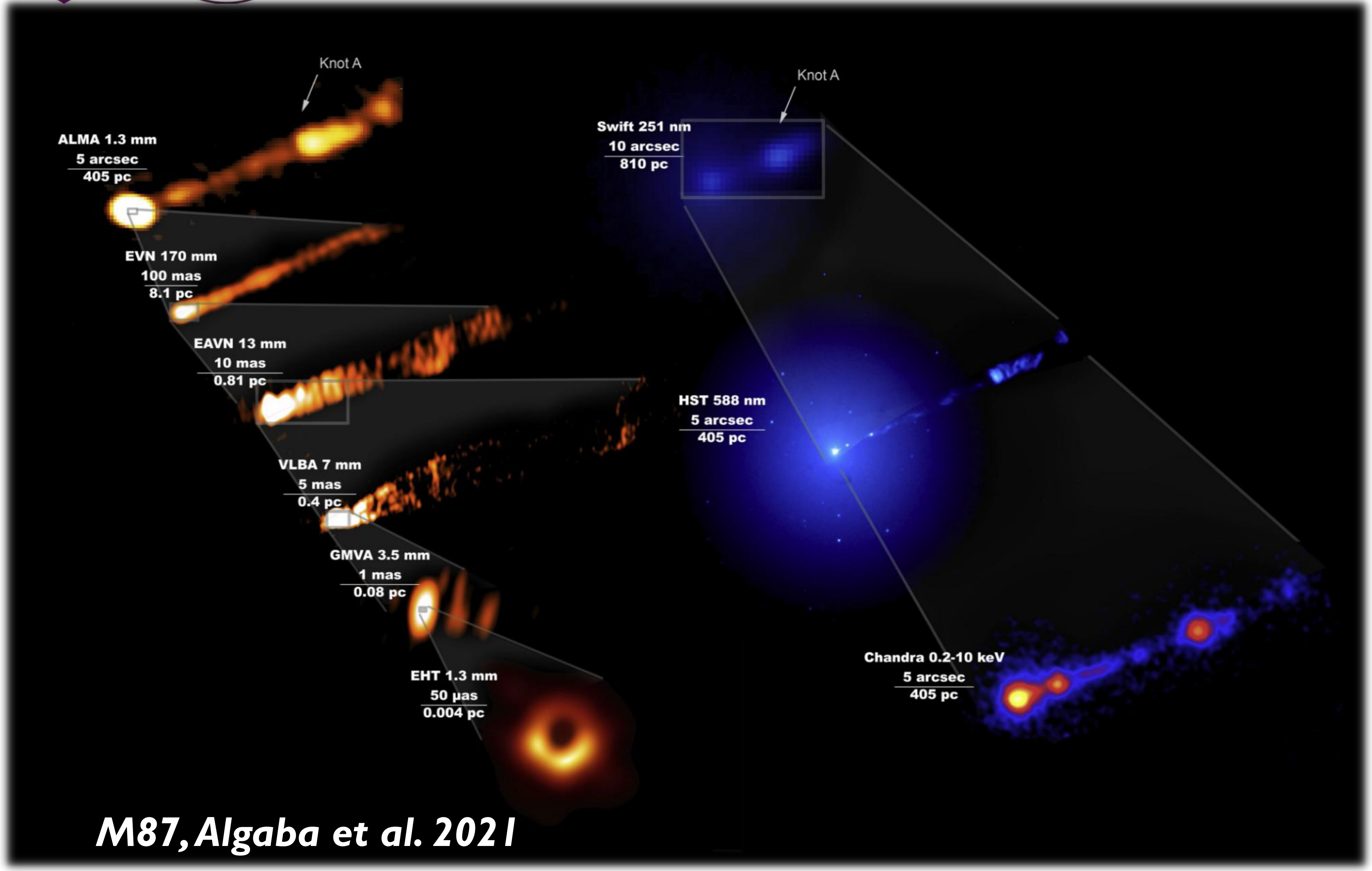


Mrk 421, Abdo et al. 2011



Beckmann & Shrader 2012

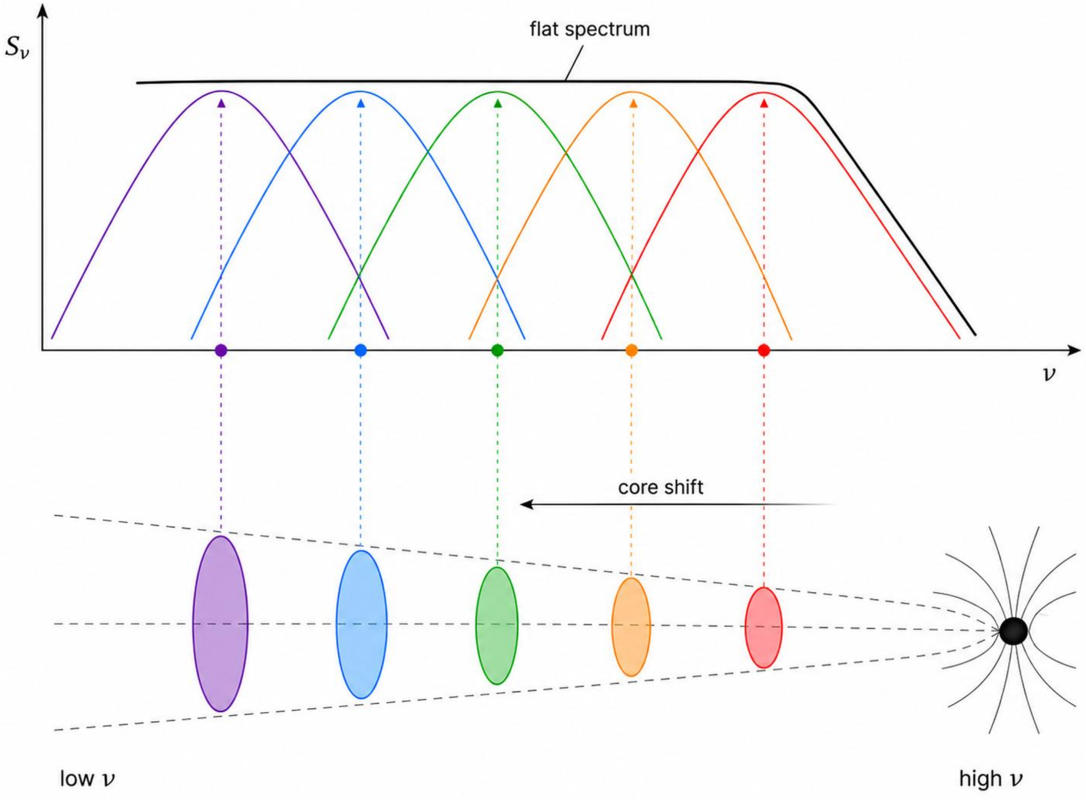
Blazar



M87, Algaba et al. 2021

Extended Multi-wavelength Jet

- Multi-scale jet structures, from black hole vincity to kiloparsec
- Localized particle acceleration repeated energy dissipation
- An **extended multi-scale jets** rather than a single emitting region



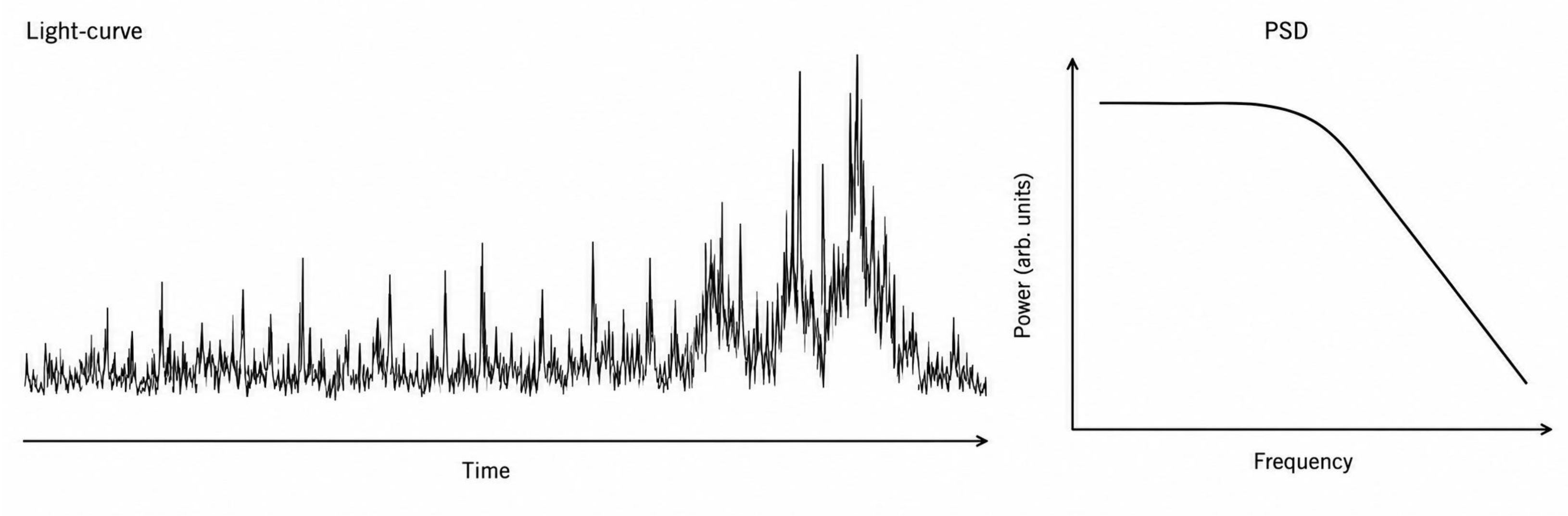
Schematic illustration of flat radio spectrum & core-shift.

Flat Radio Spectrum & Core Shift

- ***Flat radio spectrum***: the superposition of synchrotron emission from multiple jet regions.
- ***Core-shift effect***: the location of radio cores changes with the observed frequency.

- Provide constraints on the jet's physics (e.g., *Blandford & Königl 1979, Königl 1981*...)

Blazar



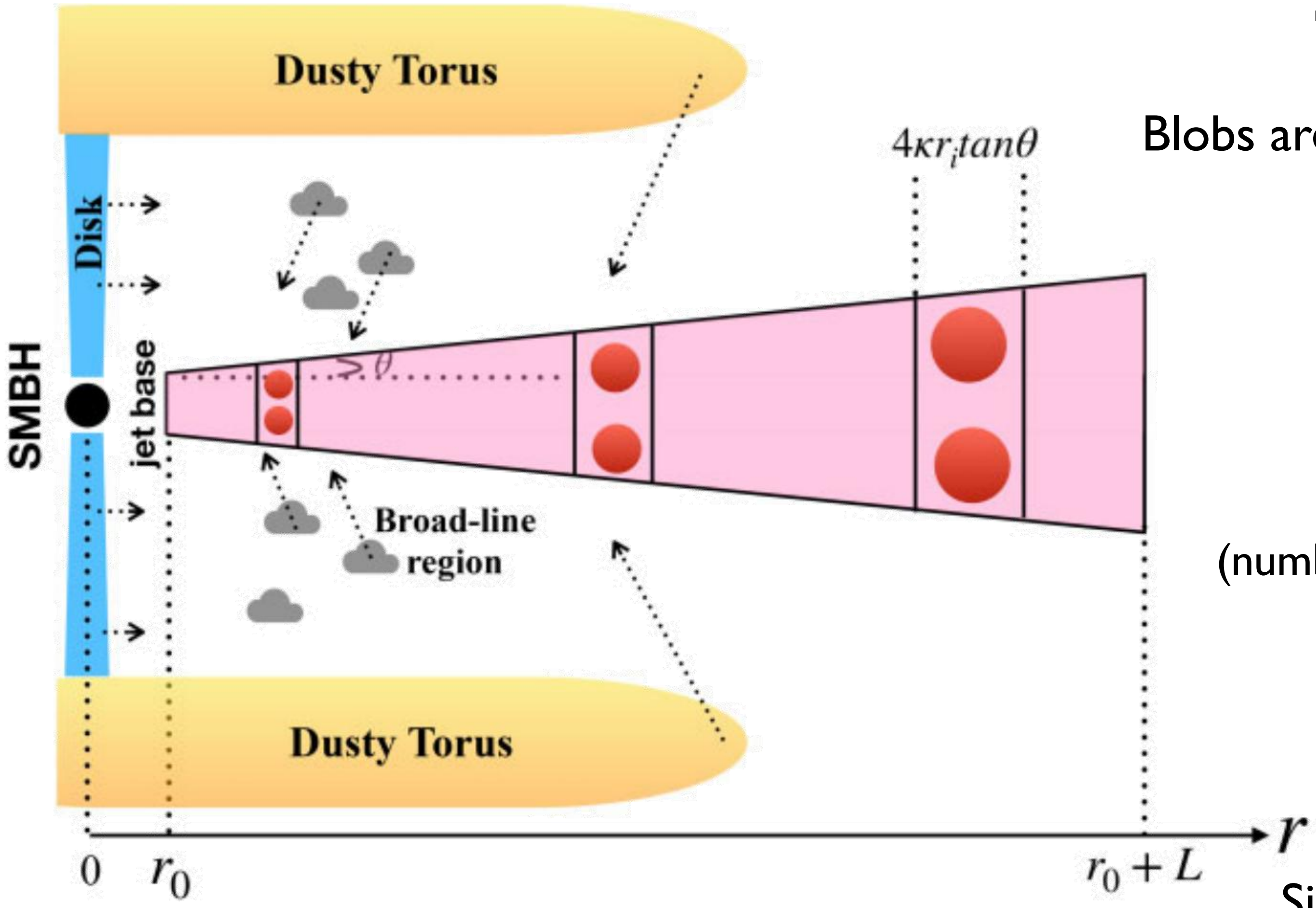
Variability & Joint Analysis

- ***Variability***: time-dependent dissipation
- ***Power spectral density*** (**PSD**): how variability power is distributed over different timescales & characteristic timescale.

- **Core-shift** locates the emission region
- **SEDs** reveal the physical propertites
- **LCs** record the dynamical dissipation

Constraining jet physics by jointly combining spectral, spatial, and temporal information.

Model



Schematic illustration of stochastic dissipation model.
Liu et al. 2023 MNRAS

Stochastic Dissipation Model

Blobs are generated independently, continuously and randomly.

Low-state: numerous weak blobs

Flare-state: several powerful blobs

Dissipation probability:

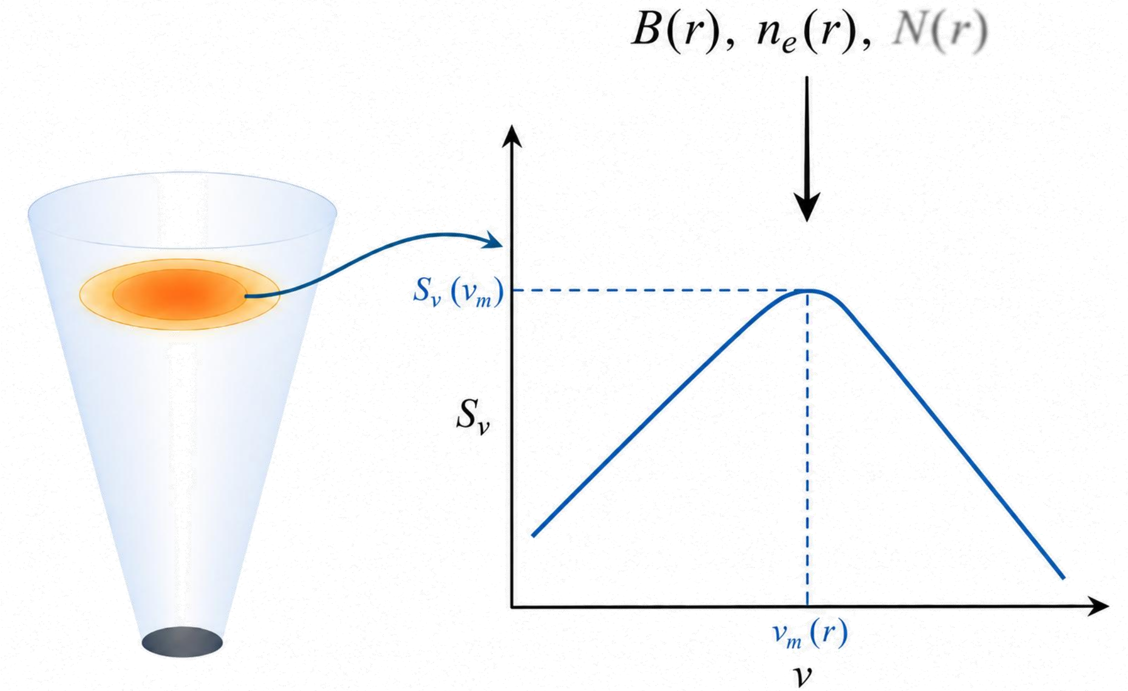
(number of radiating blob per unit time and per unit distance)

$$p(r)\,[\mathrm{pc}^{-1}\,\mathrm{s}^{-1}] \sim r^{-\alpha_{\mathrm{blob}}}$$

Calculating the radiative evolution of all blobs

Simulating MW **LCs**, **SEDs** and globe **core-shift**

Model

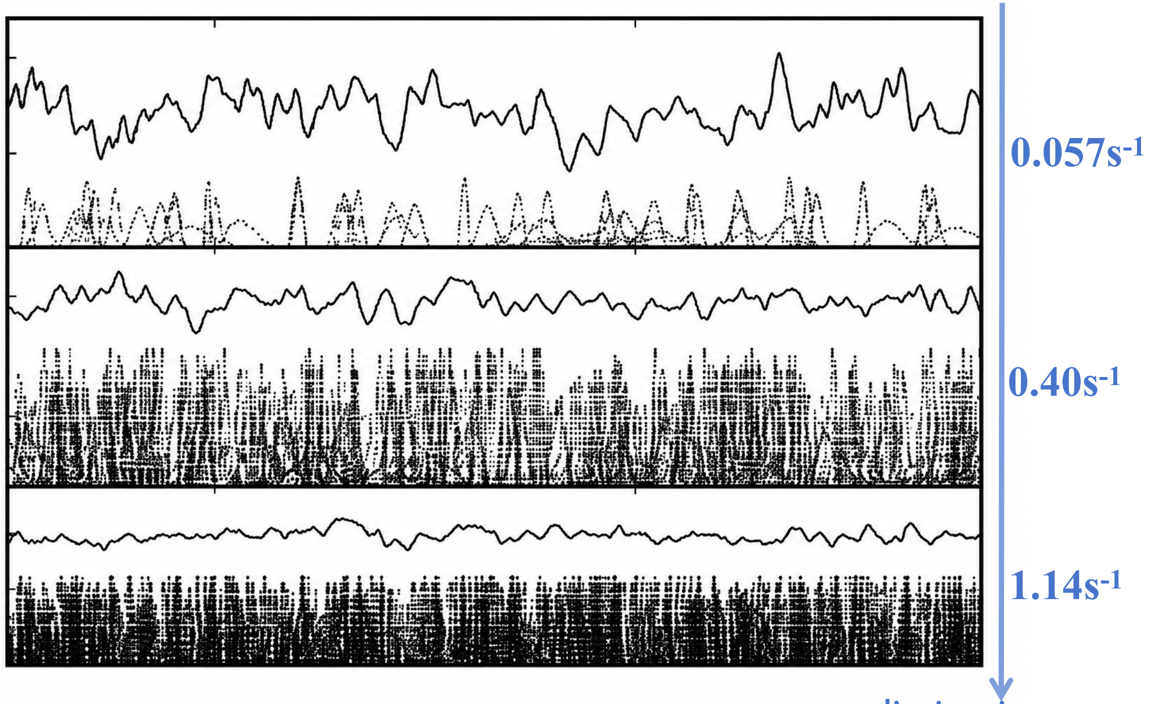


Spectral & Spatial

- **Magnetic field** and **electron density** <u>frequency-dependent core position</u>
- Distribution of **magnetic field, electron density blob number** → <u>total radio spectrum</u>.
- Constraints on parameter distributions.

Model

Temporal



LCs with different blob numbers (adopted from ***Liu et al. 2023***)

The rms PSD amplitude depends on **the dissipation rate**. More blobs — lower PSD level; Fewer blobs — higher PSD level

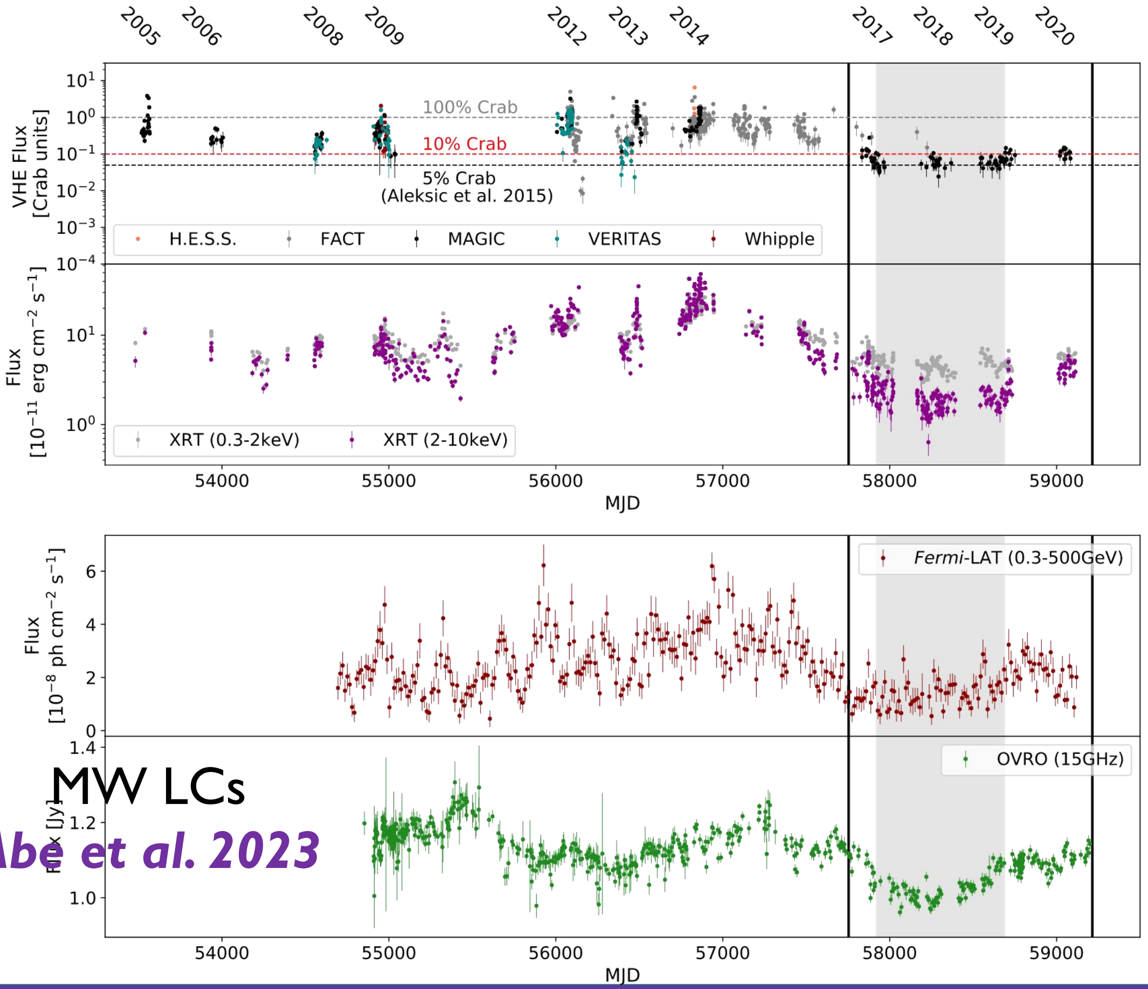
$$\mathbb{E}[P_{\rm seg}](r,\nu,f) \propto \frac{1}{\dot{N}_{\rm blob}(r)}, \quad \dot{N}_{\rm blob}(r) \approx p(r)\Delta r$$

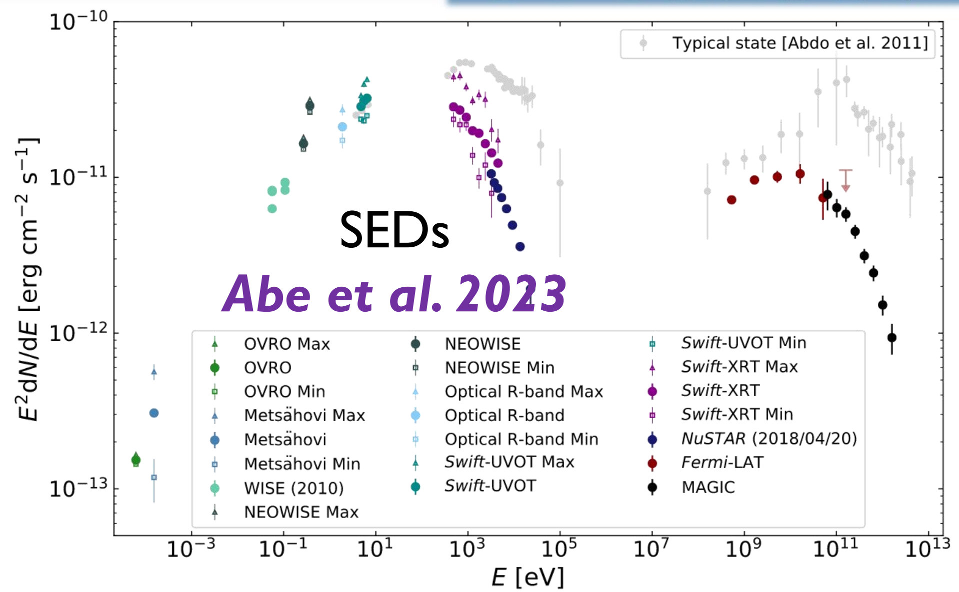
Radio variabilities provide insights of the distribution of **dissipation rate** along the jet

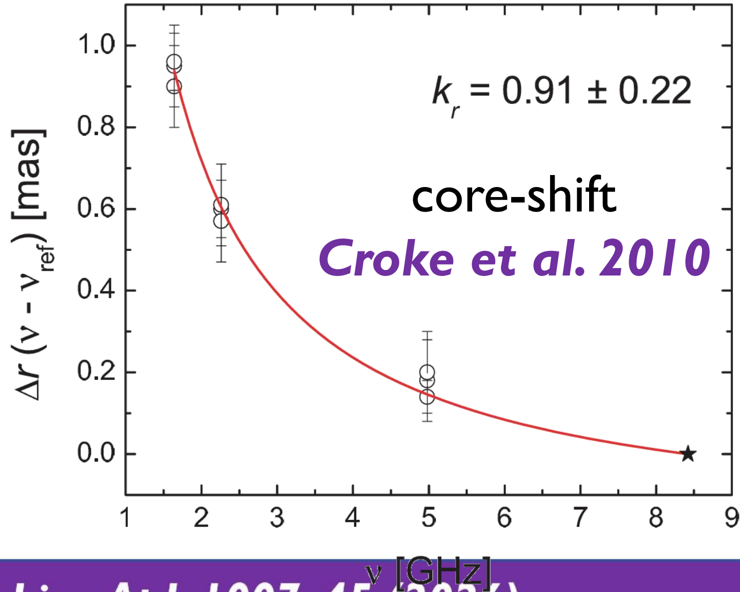
Mrk 501

very-low-activity state of *Mrk 501*

suited for a joint **spectro-timing-astrometric** analysis.

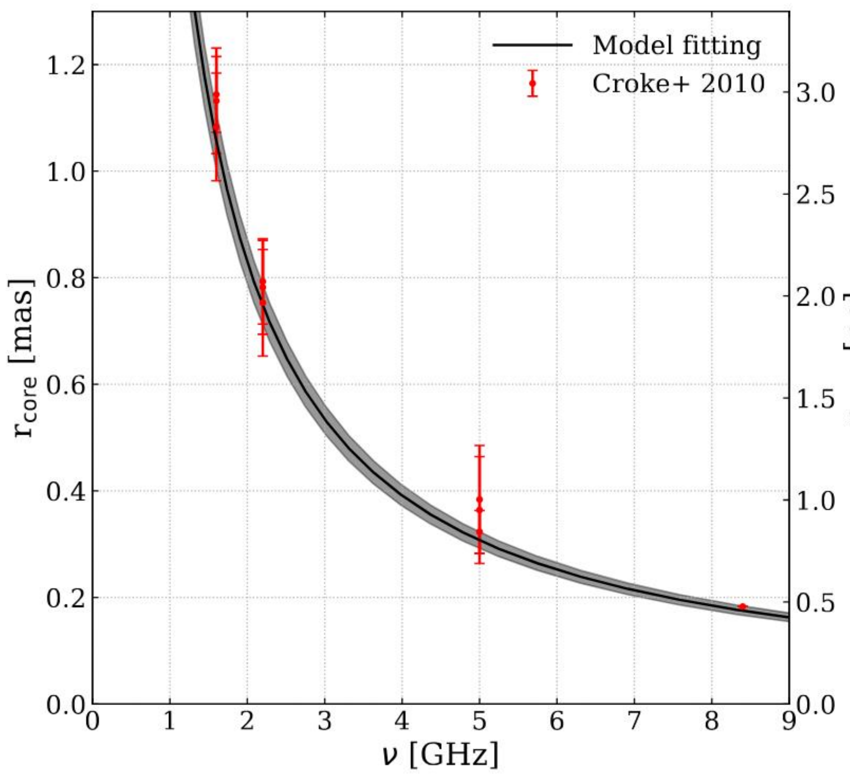


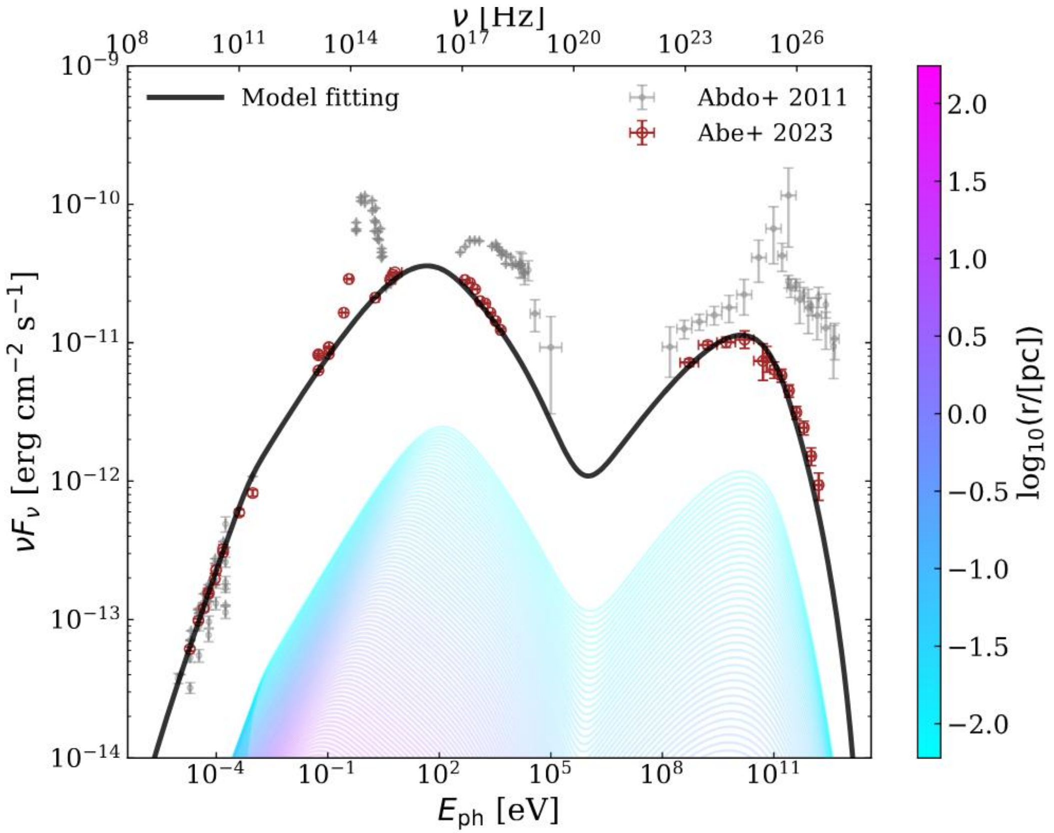




Model Results for Mrk 501

Core-shift & SEDs





Parameters	Values
r_0 (pc)	0.006
B'_0 (G)	0.53
$L'_{e,0}$ (erg s^{-1})	7.6×10^{40}
κ	0.16
$\dot{N}$ (s^{-1})	0.025
$\delta_{\rm D}$	15
$\gamma'_{\rm min}$	1.0
$\gamma'_{\rm max,1}$	4.0×10^4
$\gamma'_{\rm max,2}$	5.0×10^6
s	2.1
$\alpha_{\rm blob}$	2.0
α_B	1.0
α_L	0.3
α_γ	2.3

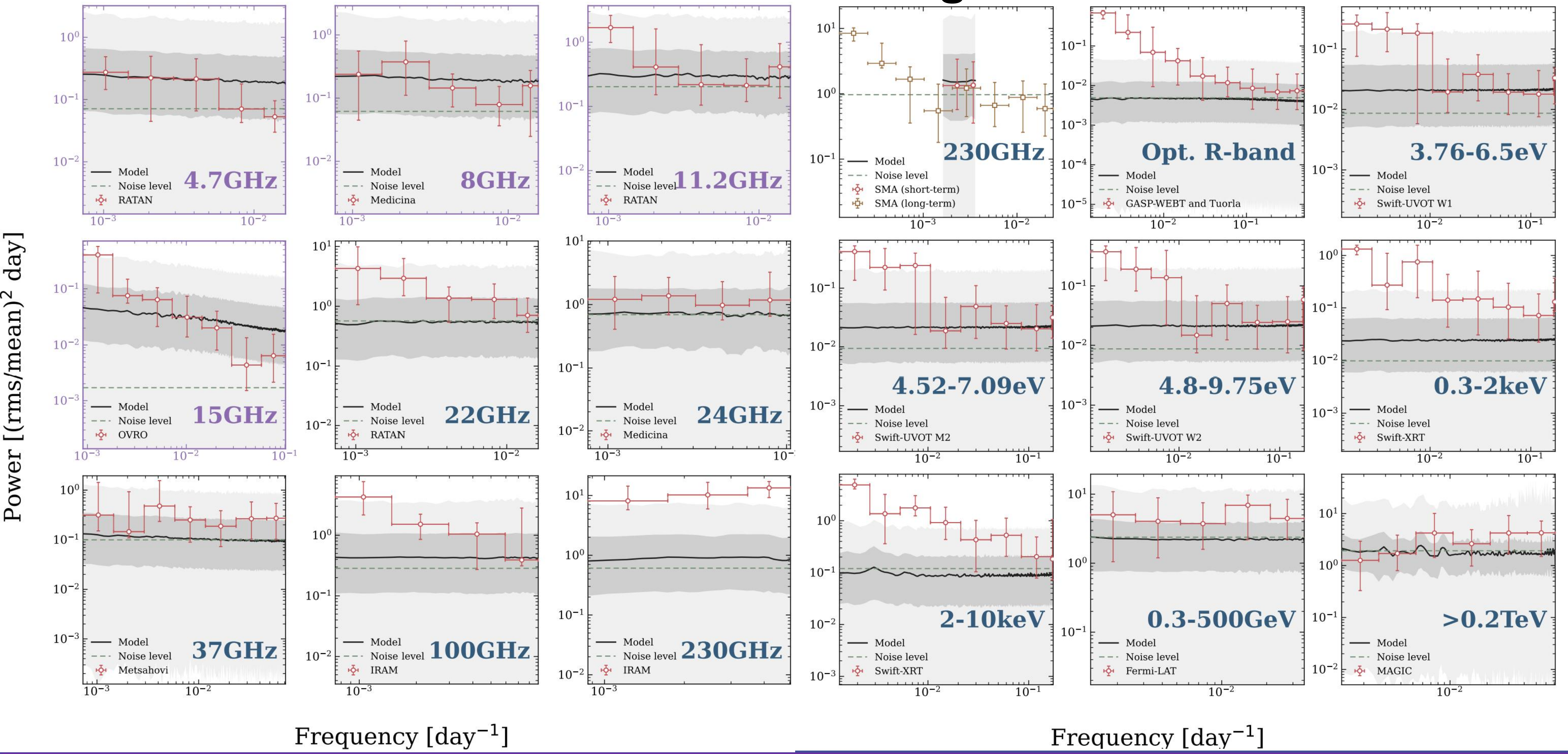
Baseline Model

$$\dot{N}_{\rm blob}(r) \sim r^{-1.0},\ n_e(r) \sim r^{-1.7}$$

- Dissipation becomes stronger toward the black hole.
- The electron density decreases with distance.

Model Results for Mrk 501

Multi-wavelength PSDs



- **≤15GHz**
  Model provides a good fit to the observed PSD amplitude.

- **>15GHz**
  The intrinsic model PSD is lower than the observed PSD.

Model Results for Mrk 501

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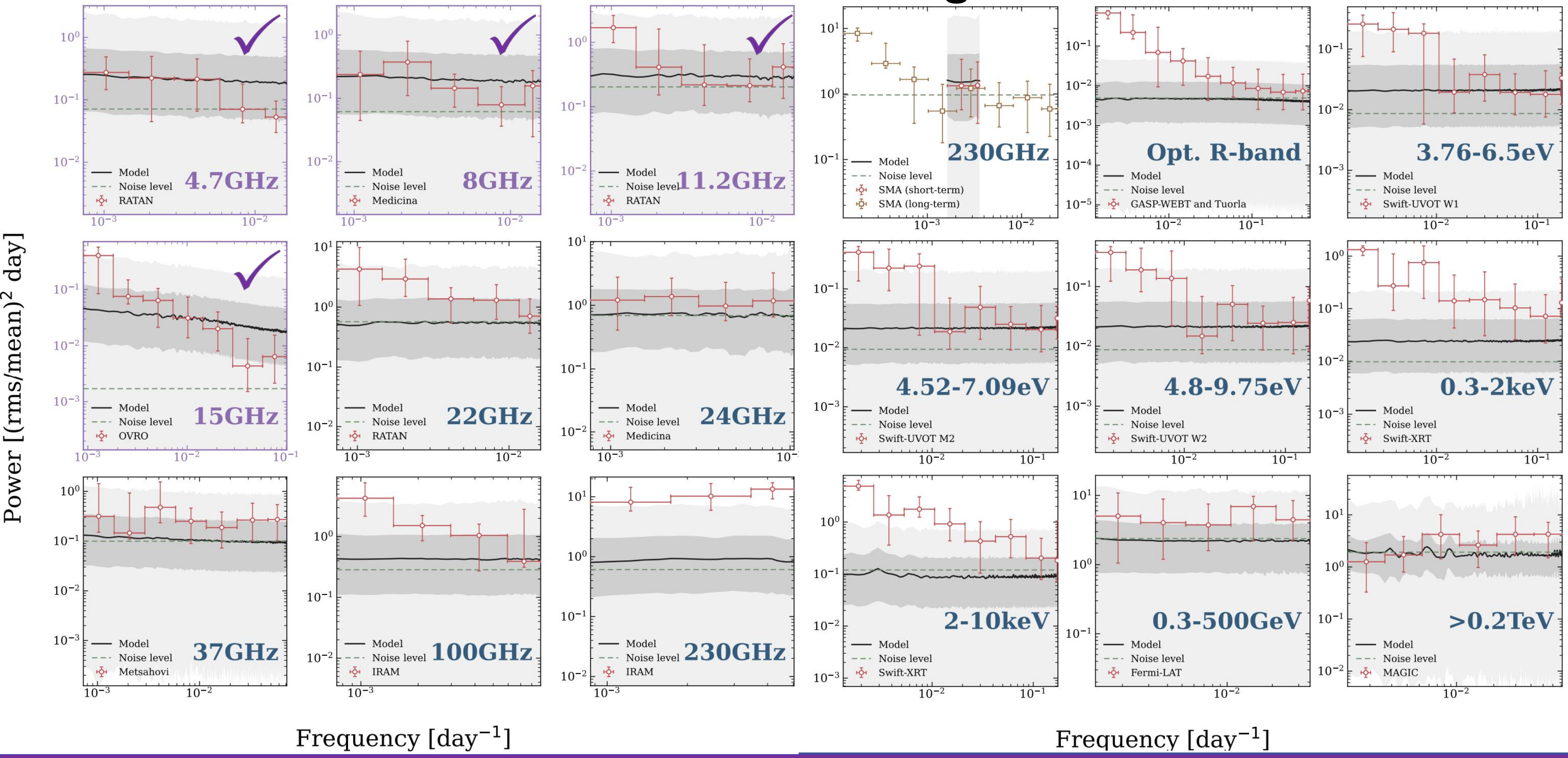
Multi-wavelength PSDs



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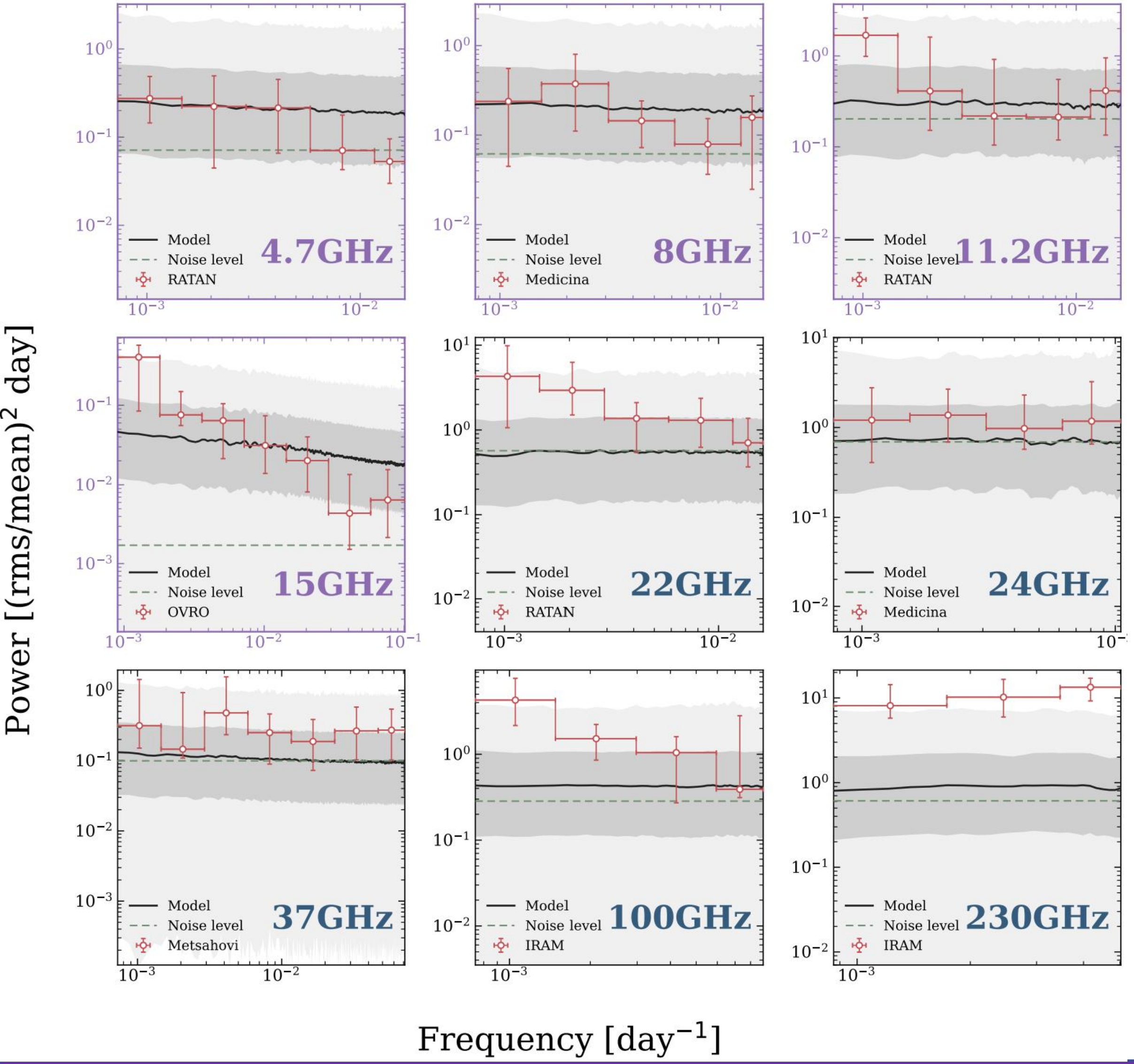
Model Results for Mrk 501



PSD Discepancies

radio spectrum + core-shift (**1.6-8.4GHz**)
→ parameter distributions (**0.5-3pc**)

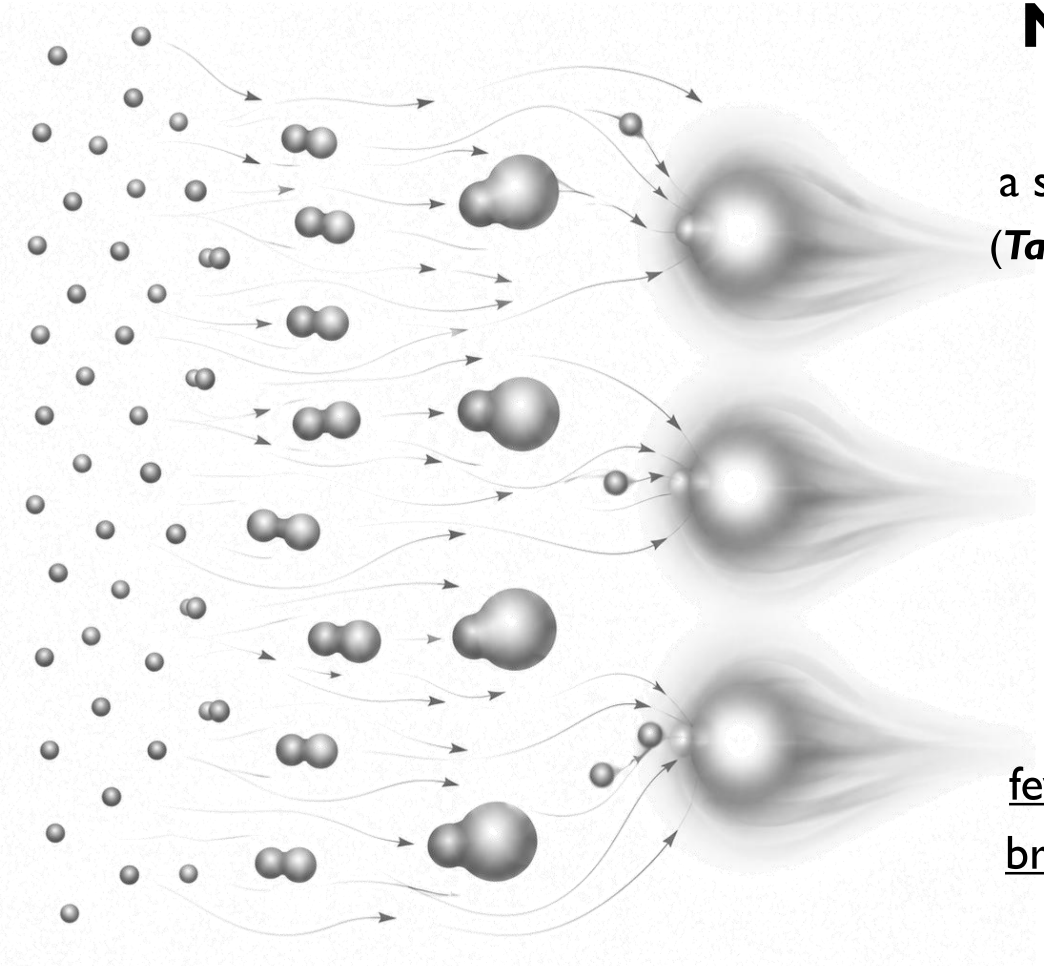
Good fit in the outer jet region (**4.7-15GHz, ≥0.25pc**)
Larger discrepancies in the inner jet (**>15GHz, <0.25pc**)
(**fewer** effective **radiating blobs** in inner region)

Different parameter distribubtion

Changing **dissipation mechanism** from inner to outer jet?

Model Results for Mrk 501

Model Modification



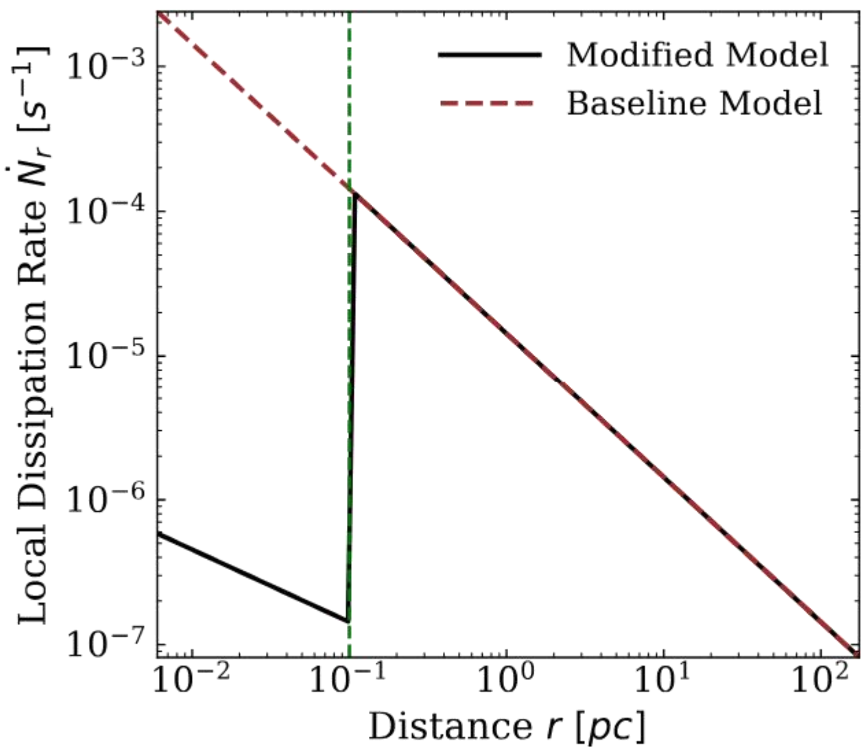
Schematic illustration of blob-mergering scenario.

a simple **blob-merging** picture (***Takamoto 2013, Sironi et al. 2016, Petropoulou et al. 2018...***)

a large number of small primary blobs

↓ **merge**

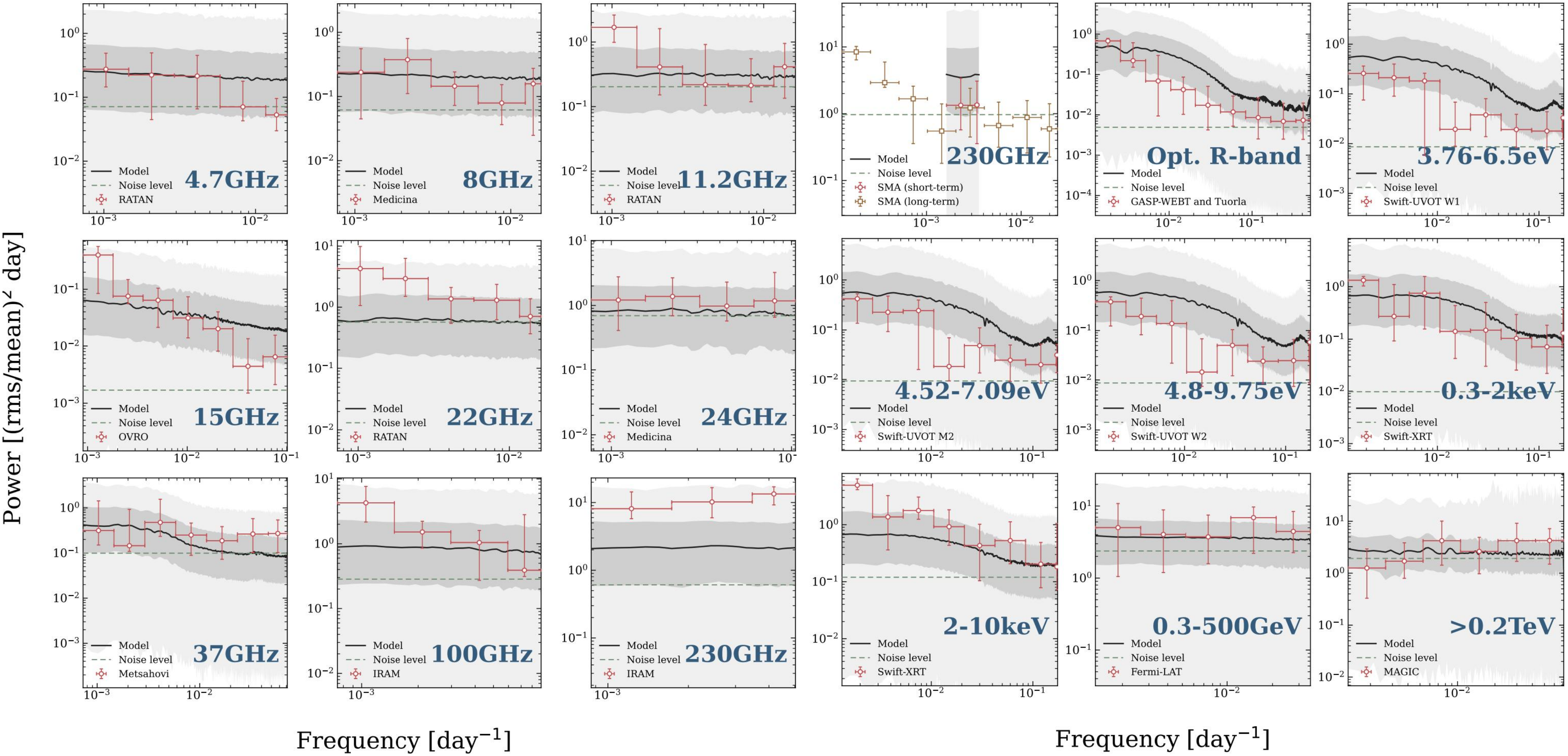
fewer radiating blobs. larger, brighter, and/or longer-lived.



Distribution of **blob dissipation rate**

Model Results for Mrk 501

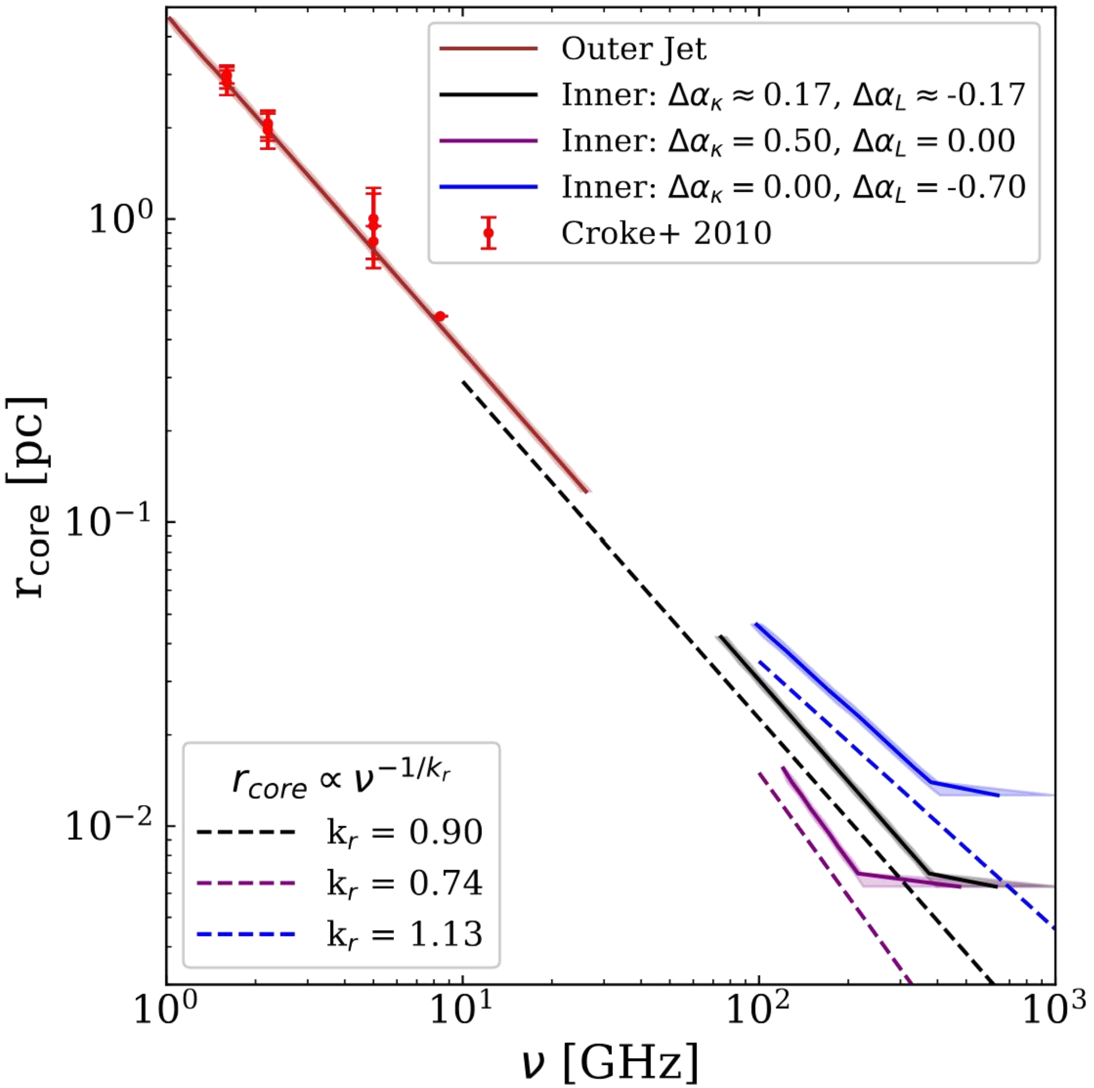
Modified Multi-wavelength PSDs



Most of the results are consistent within **1σ**.

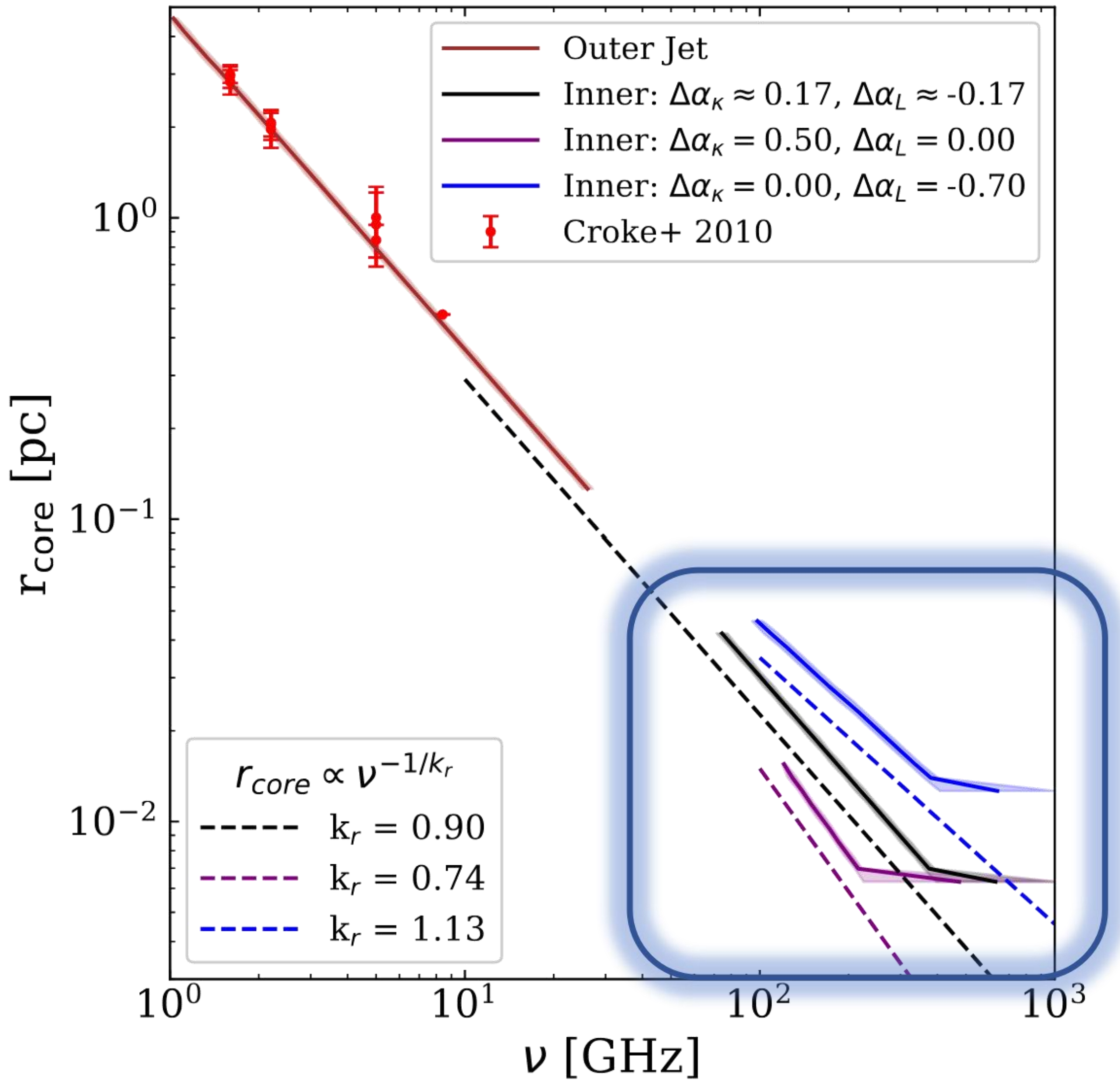
All results are consistent within **3σ**

Prospects for the inner jet



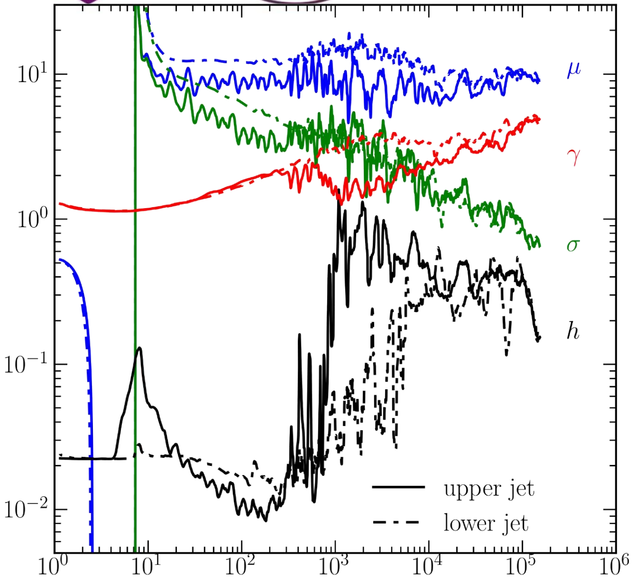
Different features between inner and outer jets.

Prospects for the inner jet



Millimeter/sub-millimeter VLBI observations in the future will be important for understanding this scale-dependent dissipation picture.

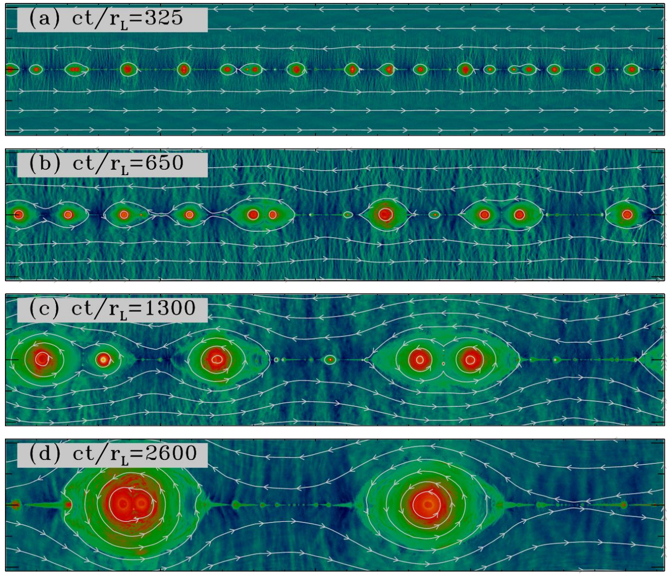
Discussion



Chatterjee et al. 2019

Evolution of Magnetized Jets

Coalescence Instability
(Sironi et al. 2025)



Petropoulou & Sironi 2018

Reconnection Interpretation of the Changing Dissipation Mechanism

- Inner jet: high magnetization enables efficient plasmoid formation and coalescence.
  - Rapid merging → fewer but larger and longer-lived radiating blobs.
- Outer jet: lower magnetization suppresses merging, and primary plasmoids radiate independently.

(***Daughton et al. 2007, Loureiro et al. 2007, Takamoto 2013, Sironi et al. 2016, Petropoulou et al. 2018...***)

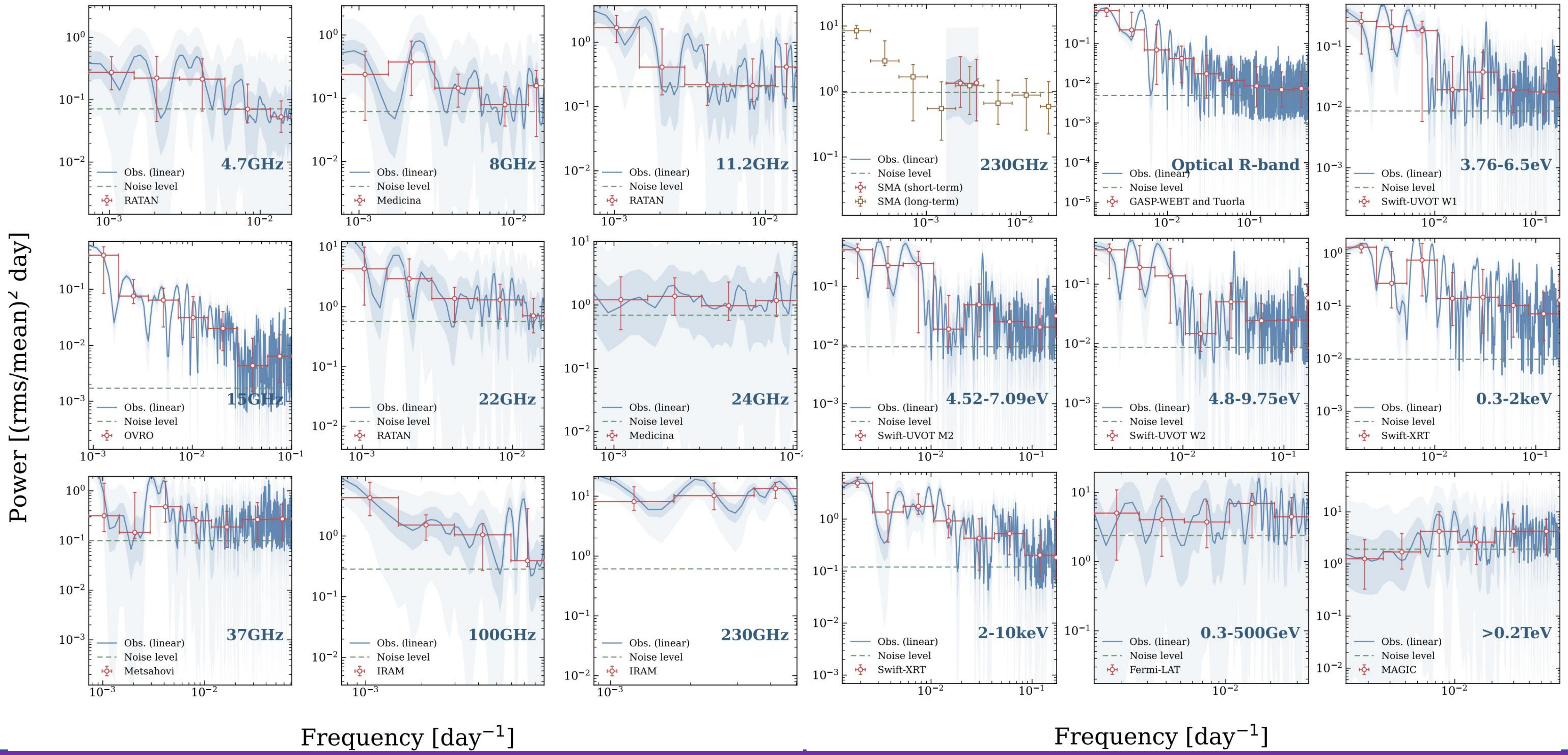
Summary

- A **spectro-timing-astrometric** model, providing a more comprehensive understandings of blazar jets.
- Jointly fits the SED, radio core shift, and multiwavelength PSDs of Mrk 501.
  - The baseline model underpredict higher-frequency variability (>15GHz).
  - Inner/Outer jets follow different parameter distributions.
- A simple **blob-merging scenario**, the inner and outer jets having different effective parameter distributions.
  - Inner: fewer, larger, more energetic, and longer-lived blob; Outer: baseline distribution.
  - Transition on sub-parsec scales around $0.1\mathrm{pc}(M_{BH}/10^9 M_{sun})\sim 10^3 R_g$.
- Possible magnetic reconnection origin with efficient plasmoid coalescence...
- Future high-cadence monitoring and mm/sub-mm VLBI can test this scale-dependent dissipation scenario.

诚耀百廿 雄创一流

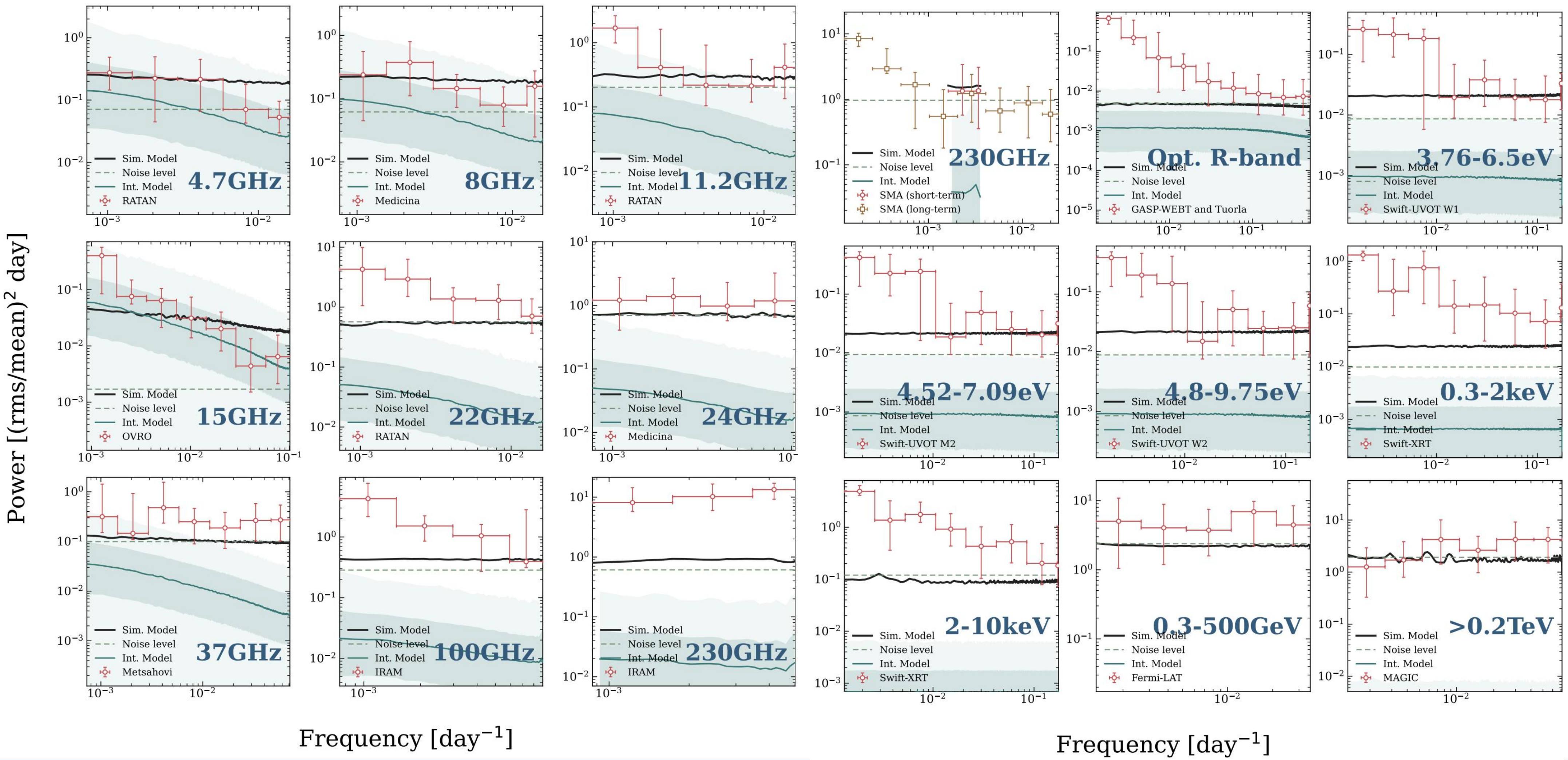
Backup

linear PSDs of observations

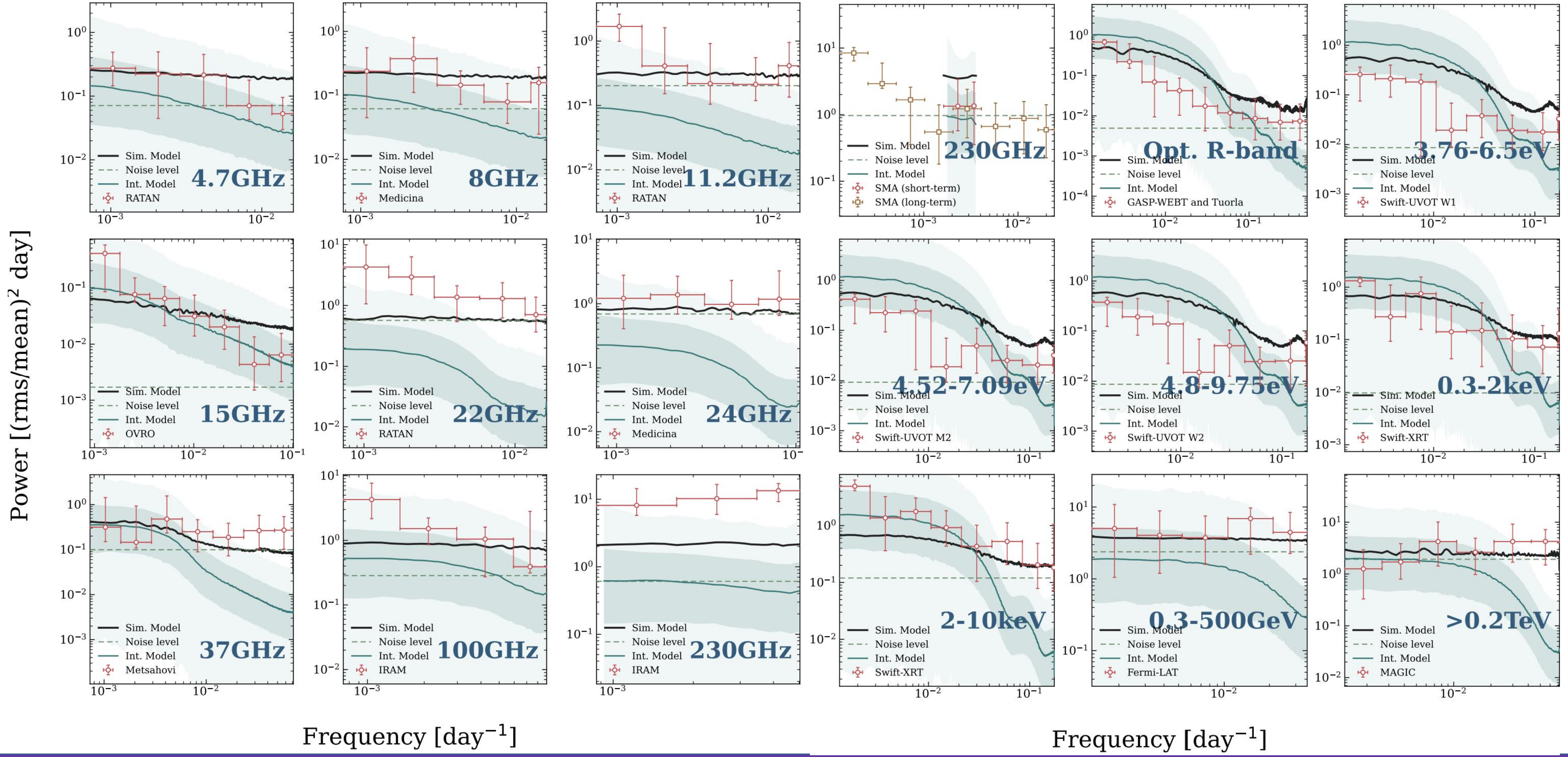


Backup

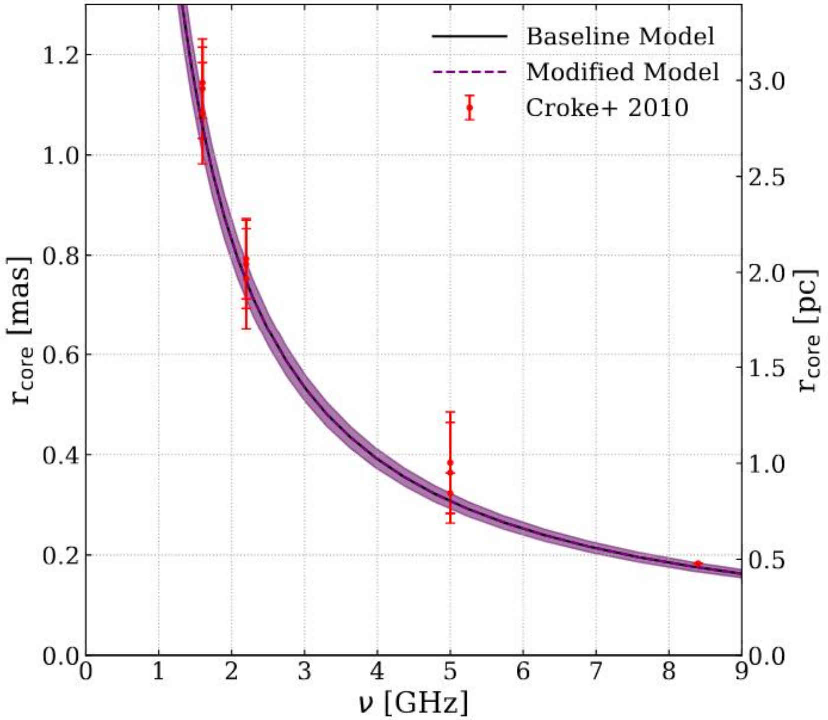
Intrinsic PSDs of baseline model

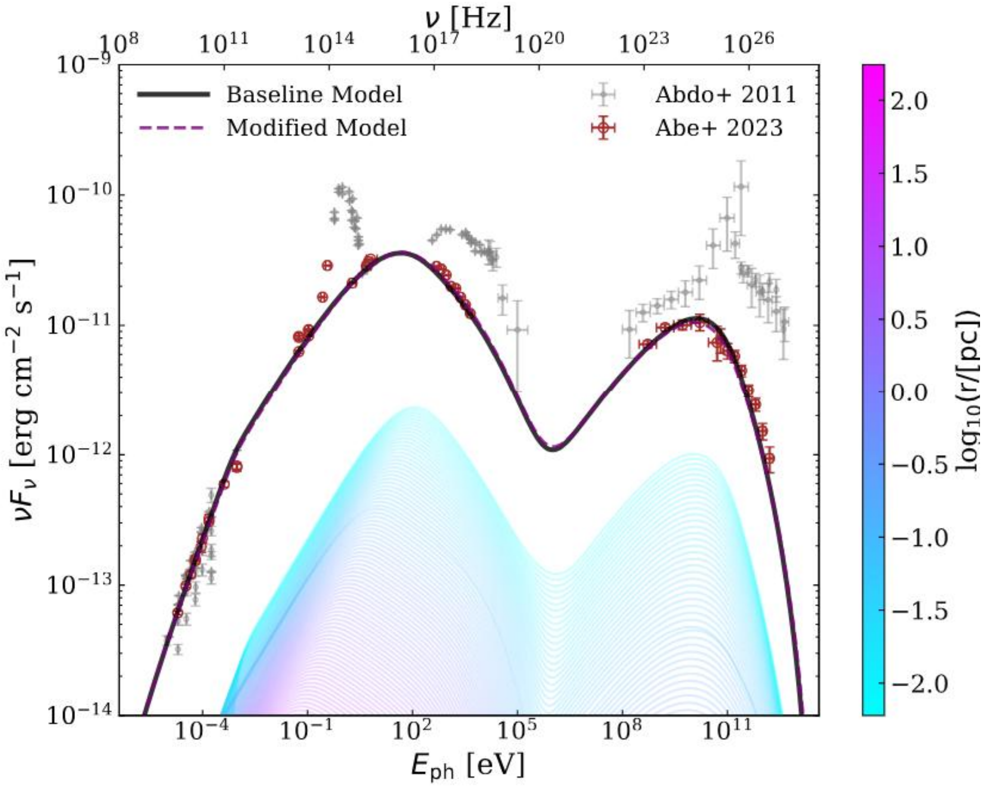


Intrinsic PSDs of modified model



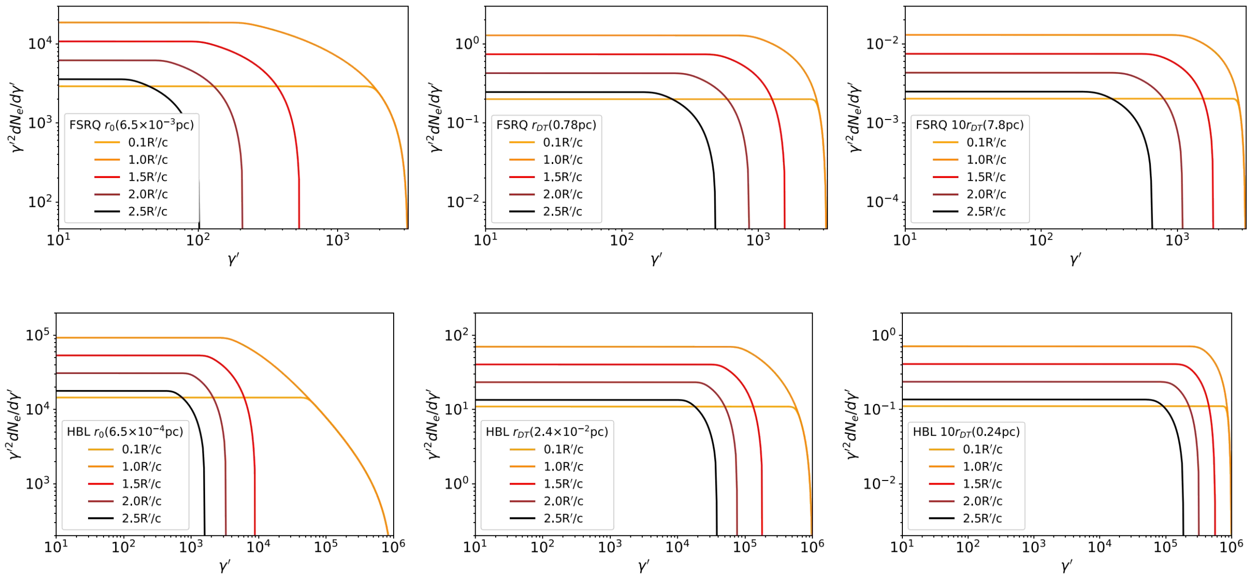
Modified Core-shift & SEDs



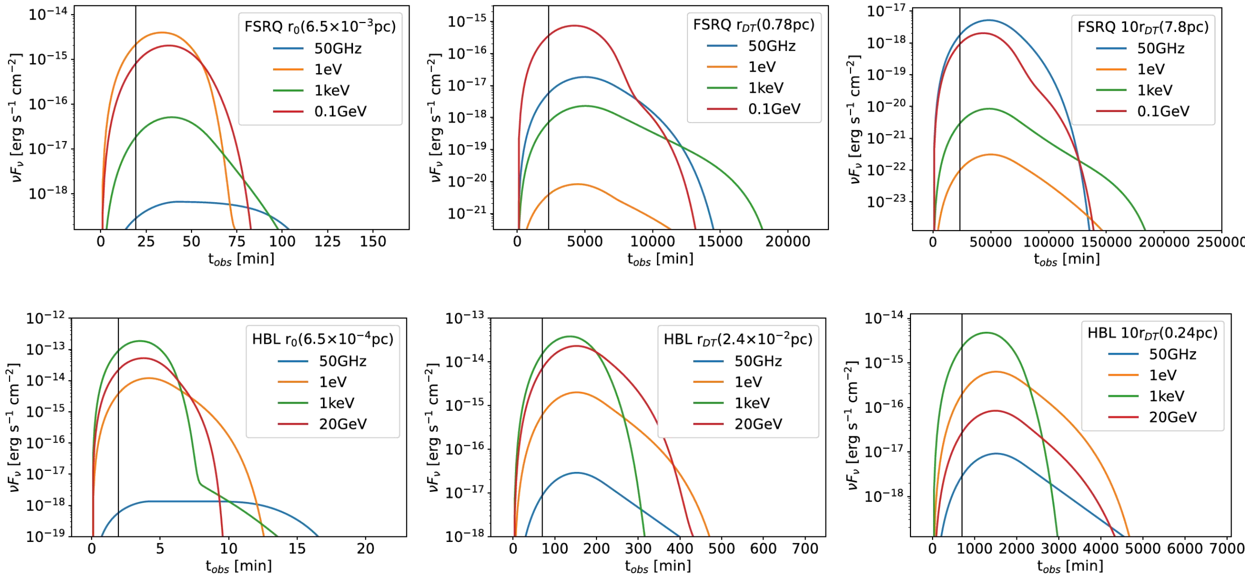


Radiative evolution of blobs

electron energy distribution



m.w. light curves

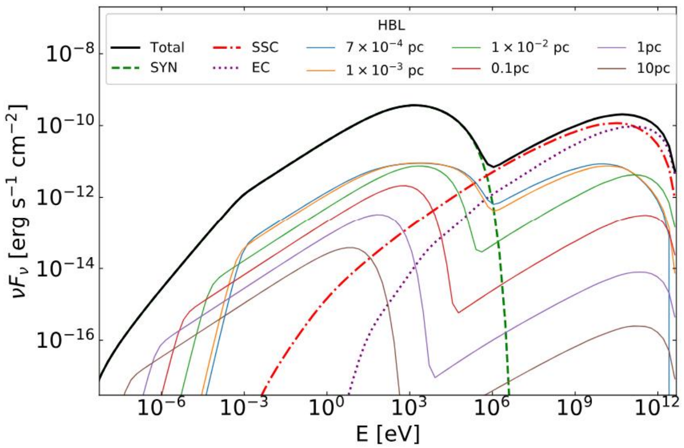


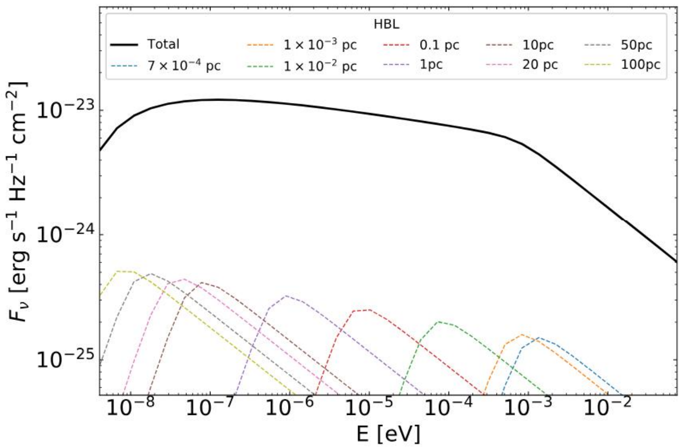
Liu et al. 2023 MNRAS

Backup

Radiation of the jet

spectral energy distribution





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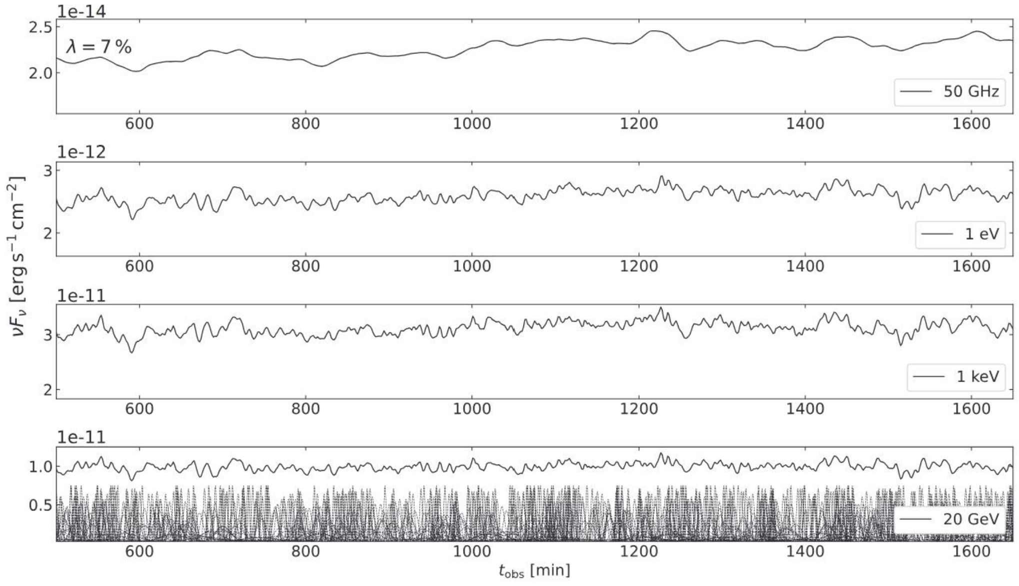

Liu et al. 2023 MNRAS