PKS 1424-418: A Best Case of the Blazar Radio/Gamma-Ray Connection

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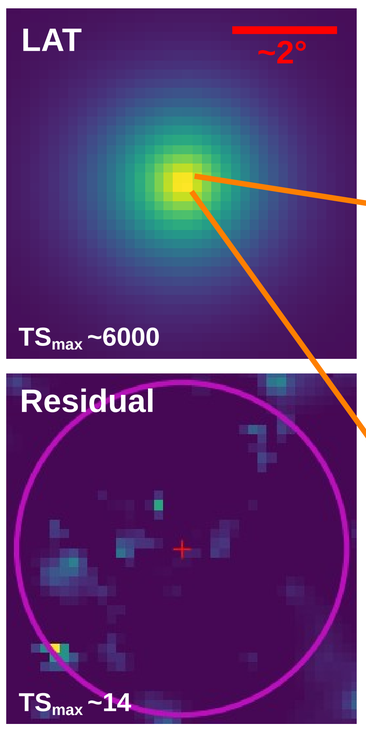
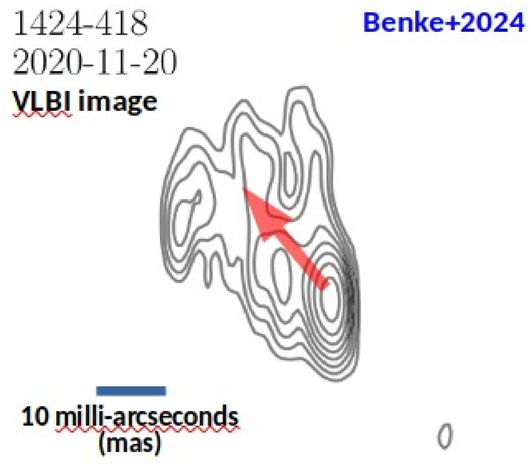
ABSTRACT

Blazars, a subclass of radio-loud AGNs are among the best laboratories for high-energy astrophysics in the Universe. The relativistic jets in blazars are prominent gamma-ray emitters with rapid variablity down to minute scales. The underlying physical mechanisms and origin of the gamma-ray emission, however, are not yet fully understood. One of the key diagnoses for the relevant studies is to explore statistically significant correlations between gamma-ray and lower-energy band (e.g., radio-to-optical) light curves in the sources. In this work, we analyzed the correlation with millimeter (> 90GHz) radio light curves in the blazar PKS 1424-418 and found a long-term, tight radio/gamma-ray connection which is atypical compared to the cases of other blazars. The correlation spans ~8.5 years with a very small amount of time lags (i.e., less than three days). Given the well-known blazar jet model with the core-shift theory, the results indicate that the gamma-ray production site is spatially connected to the location of the millimeter radio core at e.g., (sub)parsec scales in the jet of PKS 1424-418. Additional analysis of the evolution of radio spectral index (95GHz vs. 345GHz) clearly shows us the coincidence between spectral hardenings and the gamma-ray flares. This further implies that a small displacement between the gamma-ray origin and the radio core may occurs when the source flares at gamma-rays, perhaps due to the passage of a strong moving shock/blob. We suggest that this particular blazar might be a persistent source of the radio/gamma-ray connection.

(1) The Blazar PKS 1424-418



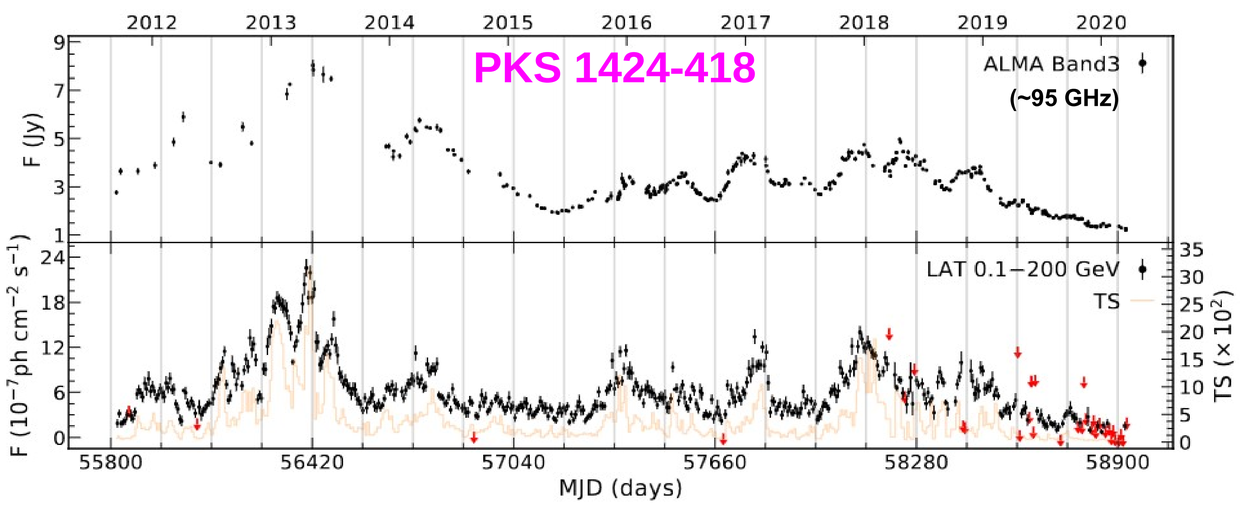
→ This Flat-Spectrum Radio Quasar (FSRQ) is: **[1]** high-redshift (z ~ 1.52; White+1988), **[2]** southern-sky (DEC ~ –42), **[3]** neutrino-detected (Kadler+2016) source with **[4]** the parsec-scale radio jet (Benke+2024, see below).



Very-Bright at both Radio & γ-ray!

(2) Why this particular source?

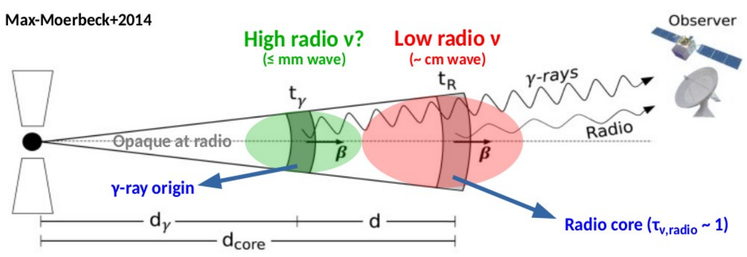
→ Very simple. Because we noticed that its 8.5yrs of radio & γ-ray light curves look surprisingly ``**SIMILAR**`` **to each other**!



*NOTE: After this period, the source became quiescent at **both** radio/γ-ray for **~1.5 yrs**.

(3) Why is that interesting?

→ Such a radio/γ-ray connection in blazar jets is actually not a new discovery and it had already been reported in the past. **BUT** they were...



: Schematic picture of the radio/γ-ray emitting regions in the jets.

In the past, the significant radio/γ-ray correlations in blazars were detected "intermittently" and they lasted just a few years during some flaring events.

→ *This is thought to be due to a long distance between the γ-ray and low-Freq. radio emission sites.*

<The Old Results>

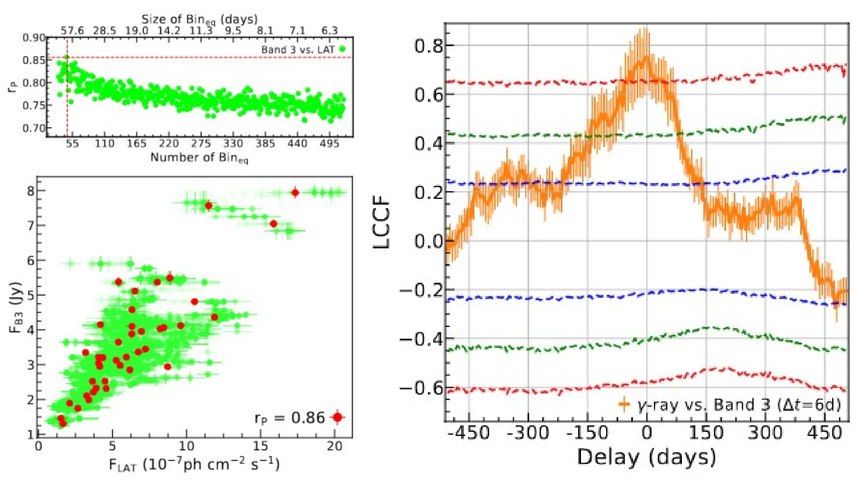
- Used low Freq. radio light curves (i.e., < 40GHz)
- Found only a handful of blazars (e.g., 3 out of 41 sources[1])
- On a short period of time (i.e., ~3 years)
- Large amount of the time delays (e.g., month scales)

<References>

– [1]Max-Moerbeck+2014
– Fuhrmann+2014
– Ramakrishnan+2016

(4) Detailed investigation of the Radio/γ-ray correlation

→ ALMA Band 3/6/7 (**95/235/345 GHz**, respectively) & Fermi-LAT light curves were used to estimate Linear relationship & Cross-correlation.



- *Left*: Pearson correlation (r_P). The average r_P ~ 0.76 with 1σ ~ 0.02 from the 488 calculations of r_P.
- *Right*: Local Cross-Correlation Function (LCCF; Welsh 1999). The 68% (blue), 95% (green), 99.9% (red) confidence levels are shown. The LCCF curve peaks at the delay = 0 with LCCF ~ 0.75 above the 99.9% confidence level.

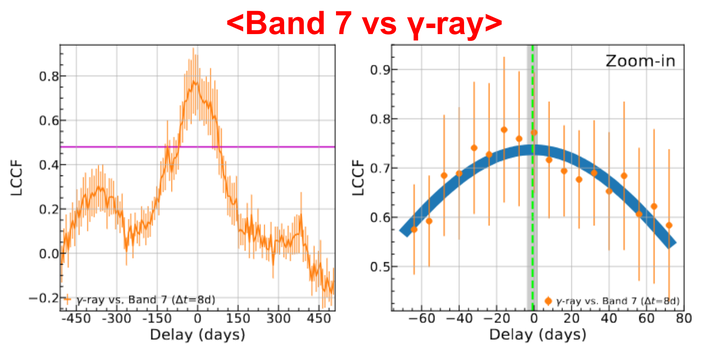
: *Indeed, our visual inspection was correct. There is a **highly significant radio/γ-ray correlation** in PKS 1424-418 **over 8.5 years**!*

- The **data sampling** of Band 3 was the Best, thus we focused on the Band 3 data.
- For the Pearson test, both the data were unevenly sampled. To be conservative, thus we calculated the r_P values in a special binning scheme: many Equal-sized bins (Bin$_{eq}$).

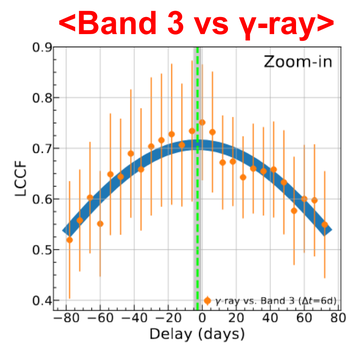
(5) The co-spatiality of the Radio/γ-ray sites in the Jet

→ A Gaussian fit to the LCCF curves of the Band 3 & 7 data

<Band 7 vs γ-ray>



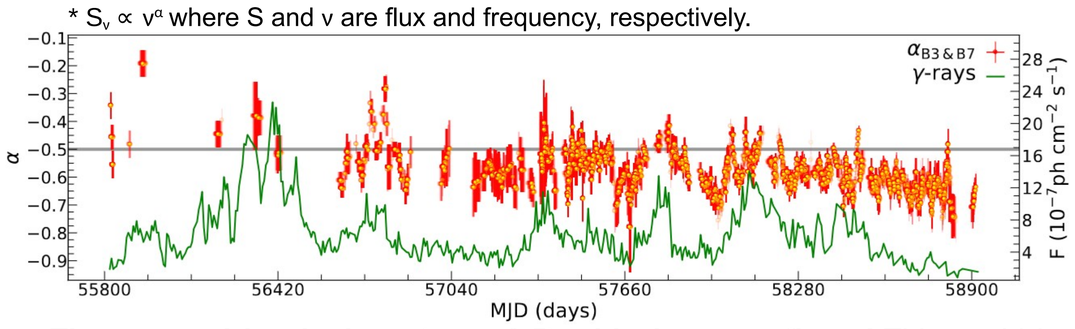
<Band 3 vs γ-ray>



: –0.8±2.6 days (*Left*) and –2.8±2.0 days (*Right*). This suggests the presence of a small amount of time lag between Bands 3 & 7, that could be caused by the core shift effect (see e.g., Figure 1 of Kudryavtseva+2011).

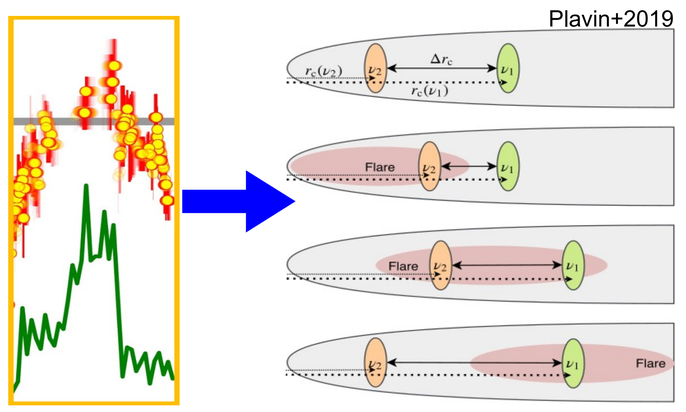
(6) The evolution of the Radio spectral index (α)

* $S_\nu \propto \nu^\alpha$ where S and ν are flux and frequency, respectively.



: ***The spectral hardenings (α > –0.5) with the γ-ray flares!*** This could be the cause of the small delay in the Band 3 LCCF (i.e., optically thin → thick).

(7) Probable physical scenario



- A scenario of the core-shift variability suggested by Plavin+2019.
- The passage of moving shocks through the radio core region.
- An increase in opacity leads to a displacement in the core position.
- Afterwards, the core restores its initial position and the opacity condition.

(8) Summary

In this study, we find,

- The significant radio/γ-ray correlation ***over >8.5 yrs*** with ***almost zero-lag***.
- Typical diagnostic of leptonic models in the scenario of *moving shocks*.
- PKS 1424-418 might be a *persistent* source of such a radio/γ-ray connection.

(9) References

Benke+2024, A&A, 681, A69; **Fuhrmann**+2014, MNRAS, 441, 1899; **Kadler**+2016, NatPh, 12, 807; **Kudryavtseva**+2011, MNRAS, 415, 1631; **Max-Moerbeck**+2014, MNRAS, 445, 428; **Plavin**+2019, MNRAS, 485, 1822; **Ramakrishnan**+2016, MNRAS, 456, 171; **Welsh** 1999, PASP, 111, 1347; **White**+1988, ApJ, 327, 561

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