A DAY-SCALE TEV HARD LAG

1ES 1959+650

LHAASO-WCDA monitoring of the 2024 active state

GeV leads | TeV follows

LHAASO-WCDA observed a ~5-day TeV-delayed flaring event in blazar 1ES 1959+650

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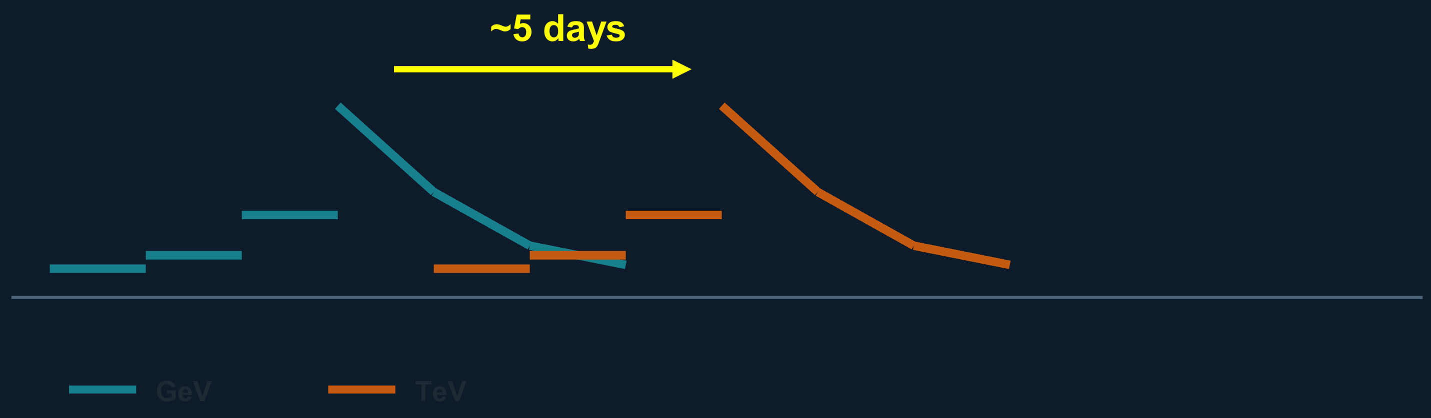
and the LHAASO Collaboration



Long-term, uniform TeV sampling exposes a temporal behavior that pointed observations can easily miss.

The result in one slide

TeV after GeV

$$\Delta t = 5.0^{+2.1}_{-2.1}\ \mathrm{d}$$

3.4 sigma

against uncorrelated red-noise simulations

Flare f2

Softest observed TeV state

$$\Gamma_{\mathrm{obs}} = 3.50 \pm 0.14$$

01

Three TeV flares

Bayesian Blocks resolve f1, f2, and f3 in the 2024 active phase.

02

A distinct timing mode

The full-period DCF contains both near-zero and +5-day components.

03

Physics

Particle acceleration can explain the ordering; alternatives remain

LHAASO (on AGN)

Large FoV, almost full sky survey

to find new (type) sources

the NGC 4278

Long-term and uniform time sampling

to find new temporal behavior

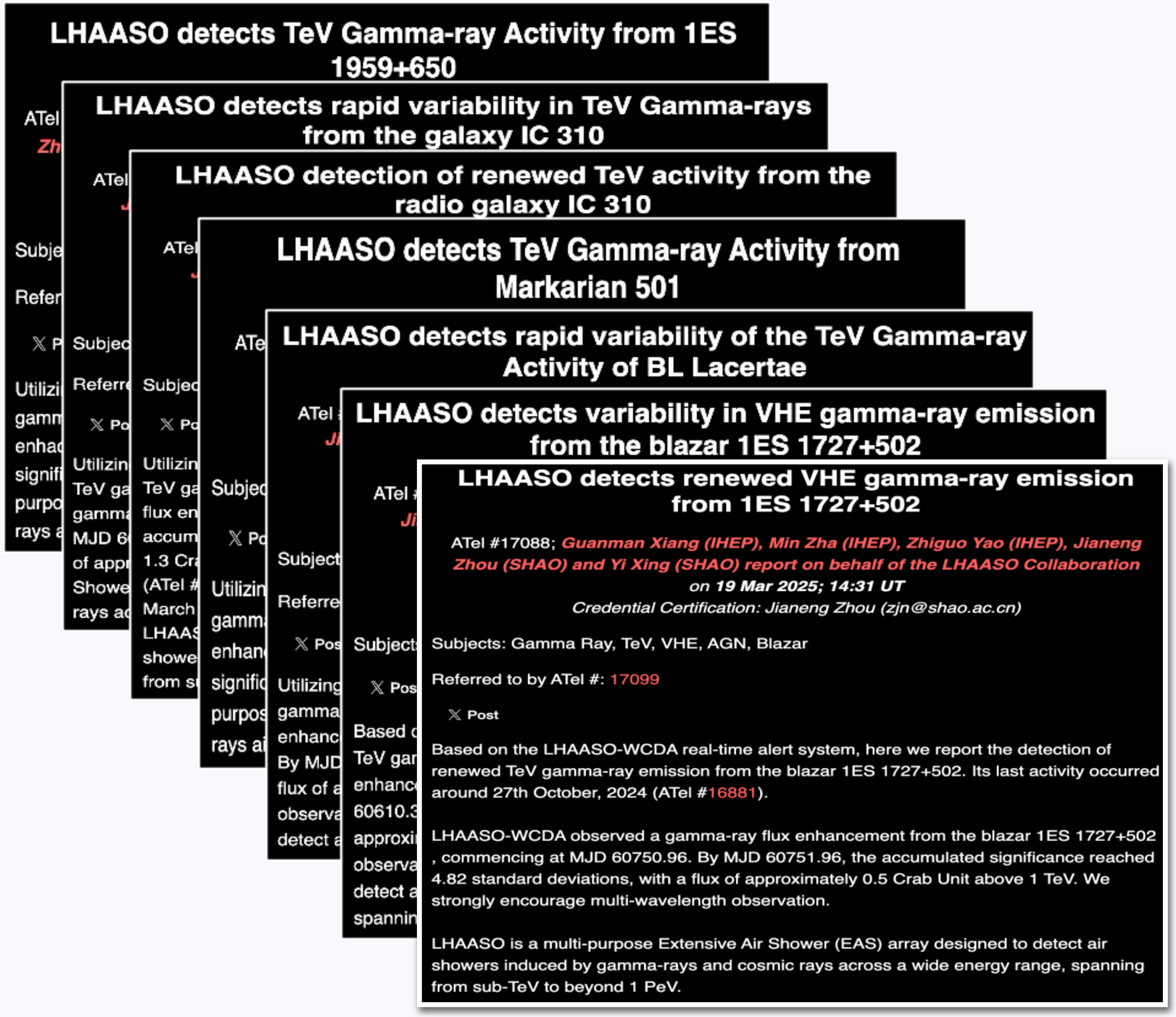
the 1ES 1959+650

The hard lag @ TeV/GeV

The monitoring system based on LHAASO-WCDA

- The LHAASO-WCDA real-time flare monitor was fully established at the end of 2023.
- Started to share the alerts to MAGIC Collaboration from 2024.
- First 7 alerts from 5 sources:

- ATel#16437
- ATel#16513
- ATel#16540
- ATel#16625
- ATel#16850
- ATel#16881
- ATel#17088



The monitoring system based on LHAASO-WCDA

- The system issued an alert for the first trigger event from blazar 1ES 1959+650

  (except the known & frequently flaring source Mrk 421)

- It was triggered at the eve of the year of Dragon.

AGN Flare Alert!!!

发起会议

gmxiang 发送给 zham@ihep.ac.cn , gmxiang , Jianeng Zhou , yixing

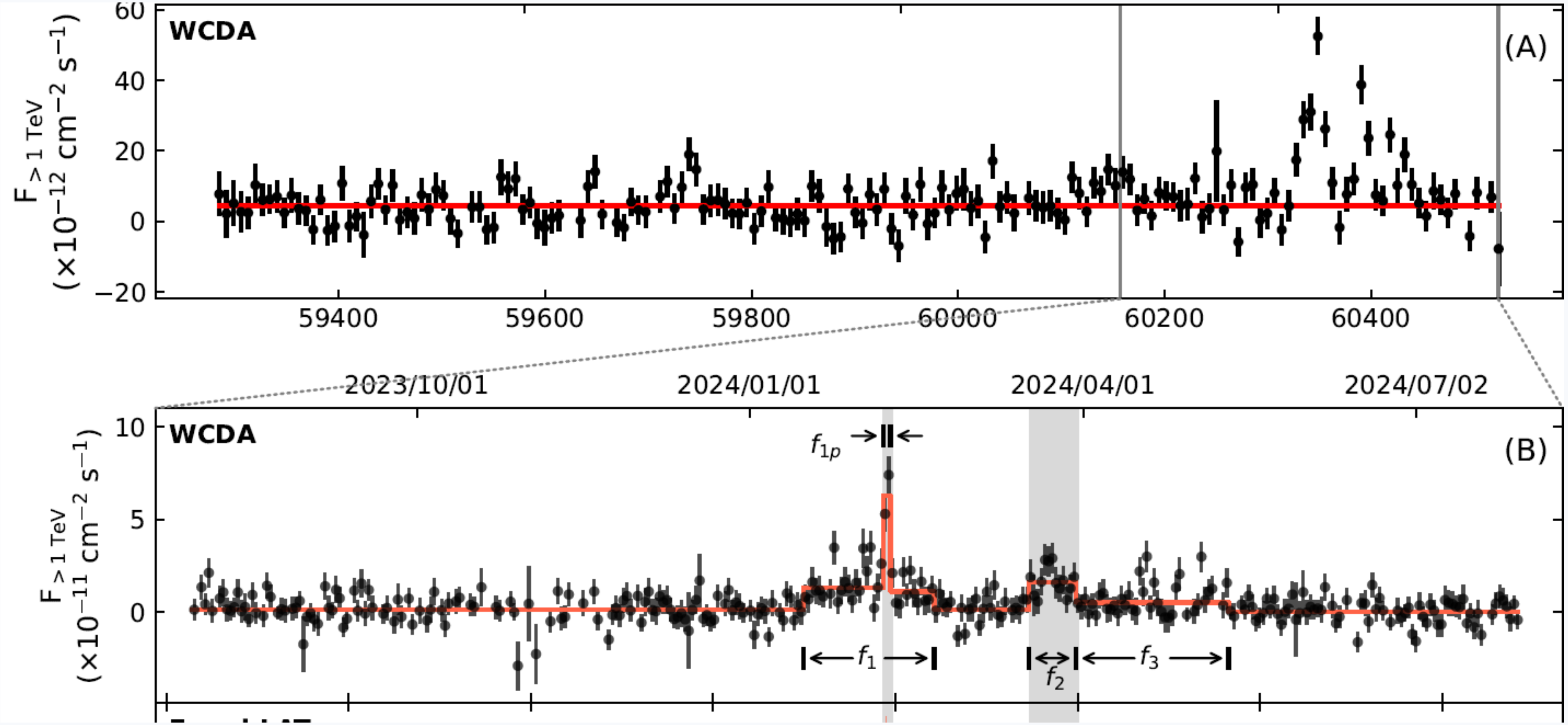
2024-02-08 22:48:26

Detected 1 flare(s).

From 1ES1959+650 .

Continue Flaring	Name	Position(R.A,Dec,J2000)	Sig_max(in sigma)	Duration	MJD	Flux(Crab Units > 1 TeV)	ON	BK
✗	1ES1959+650	299.86,65.09	5.34	2.0	60346.02 - 60347.33	0.5	89.0	46.92

Bayesian Blocks isolate three TeV flares

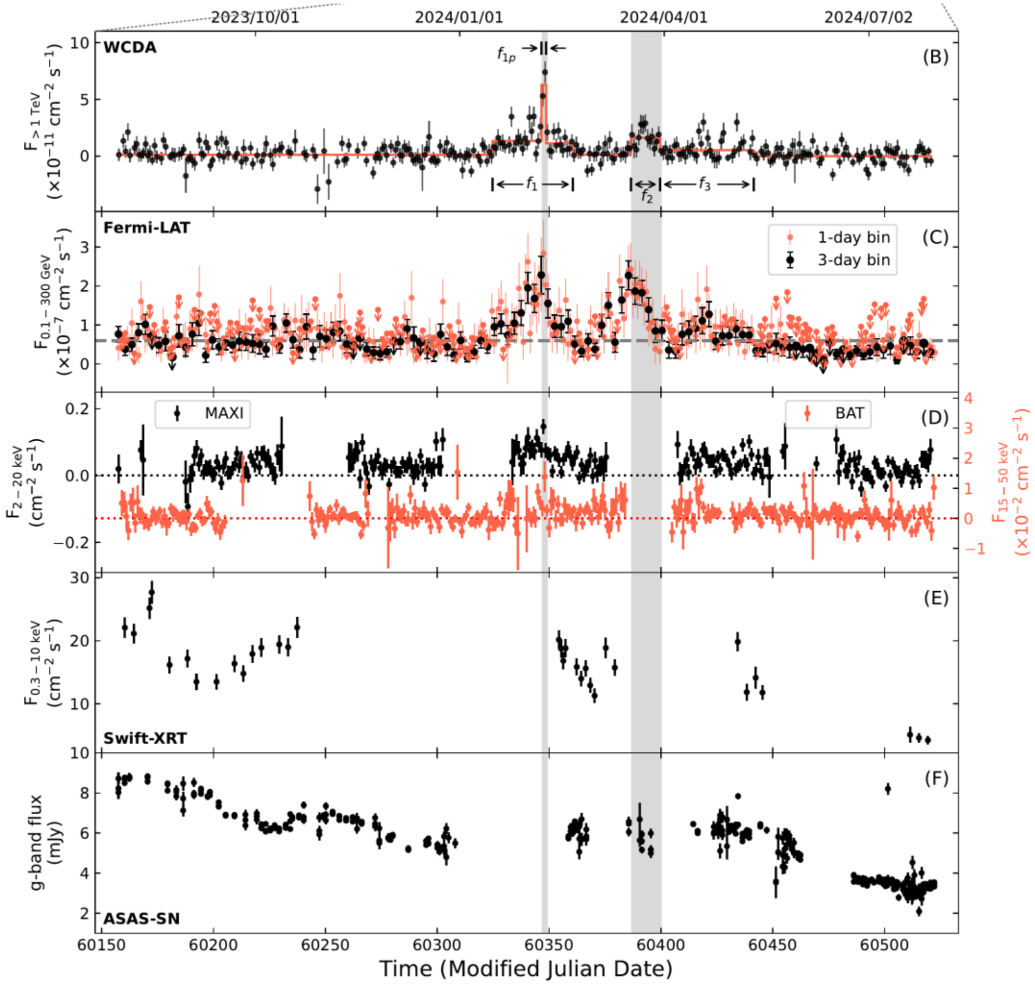


Flare f1
MJD 60324.7-60360.6
strongest peak: f1p

Flare f2
MJD 60386.6-60399.5
GeV -> TeV hard lag

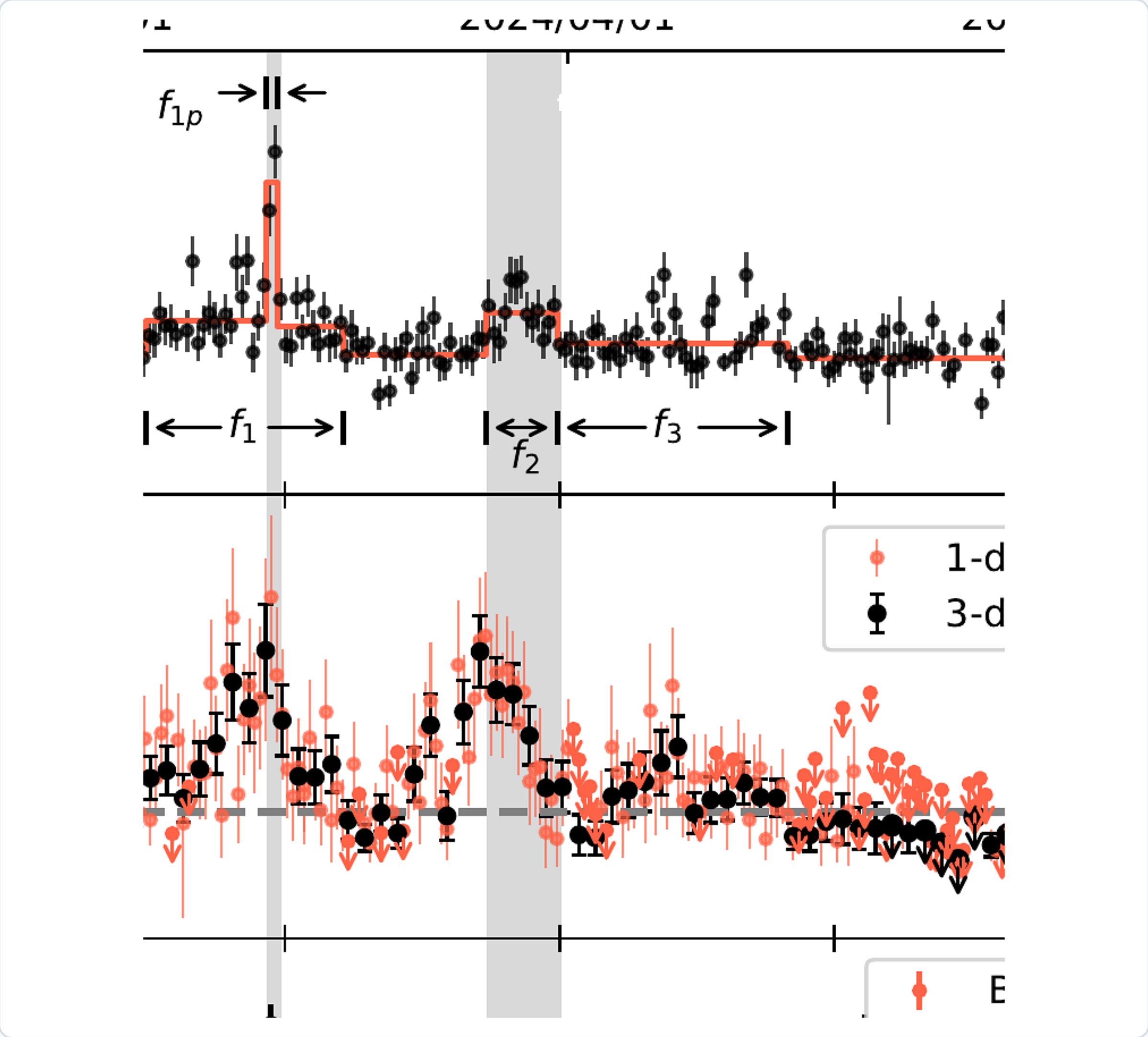
Flare f3
MJD 60399.5-60441.4
extended lower-flux state

Multiwavelength of the 2024 activity



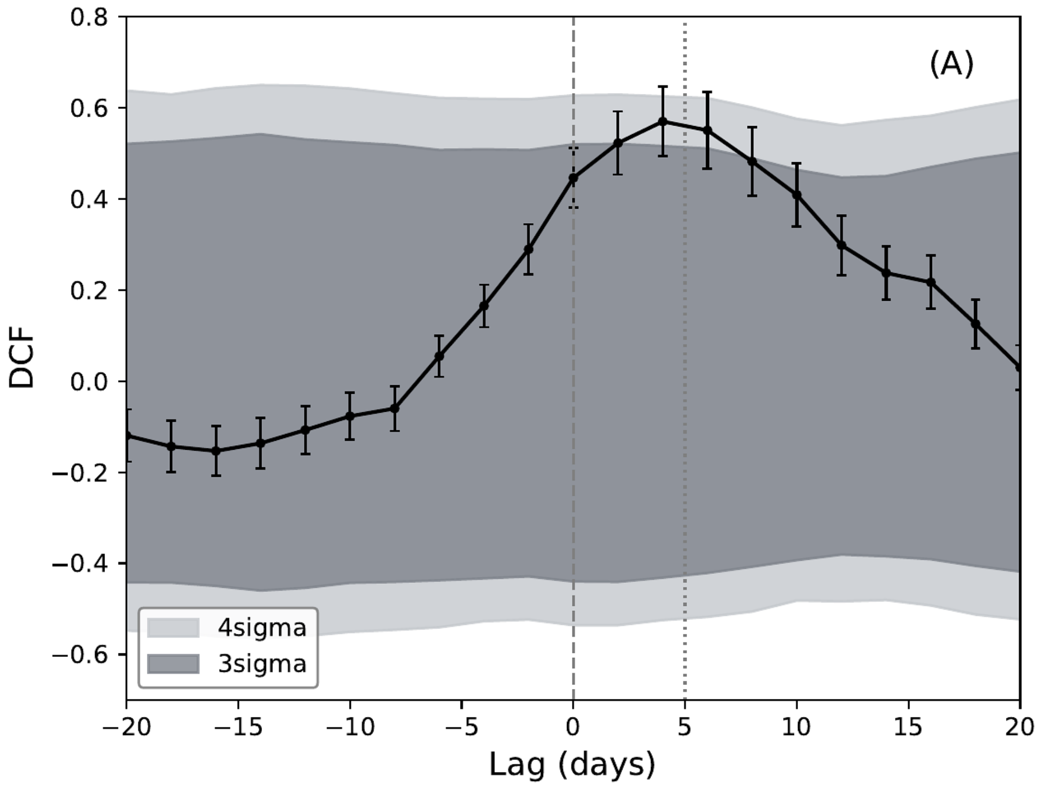
- Broad GeV activity accompanies the TeV active phase.
- Flare f1 has X-ray enhancement; f2 lacks MAXI/BAT/ Swift-XRT coverage.
- Optical g band shows no clear f2 flare structure.

Flare f2: GeV rises first, TeV follows



The eye suggests a delay.

DCF: A day-scale TeV hard lag in flare f2



- FR/RSS Monte Carlo: 10,000 paired realizations
- Centroid from bins above 80% of the DCF peak
- Median and 16th/84th percentiles -> lag and 1 sigma

Flare f2 only

$$\Delta t = 5.0^{+2.1}_{-2.1}\ \mathrm{d}$$

TeV lags GeV

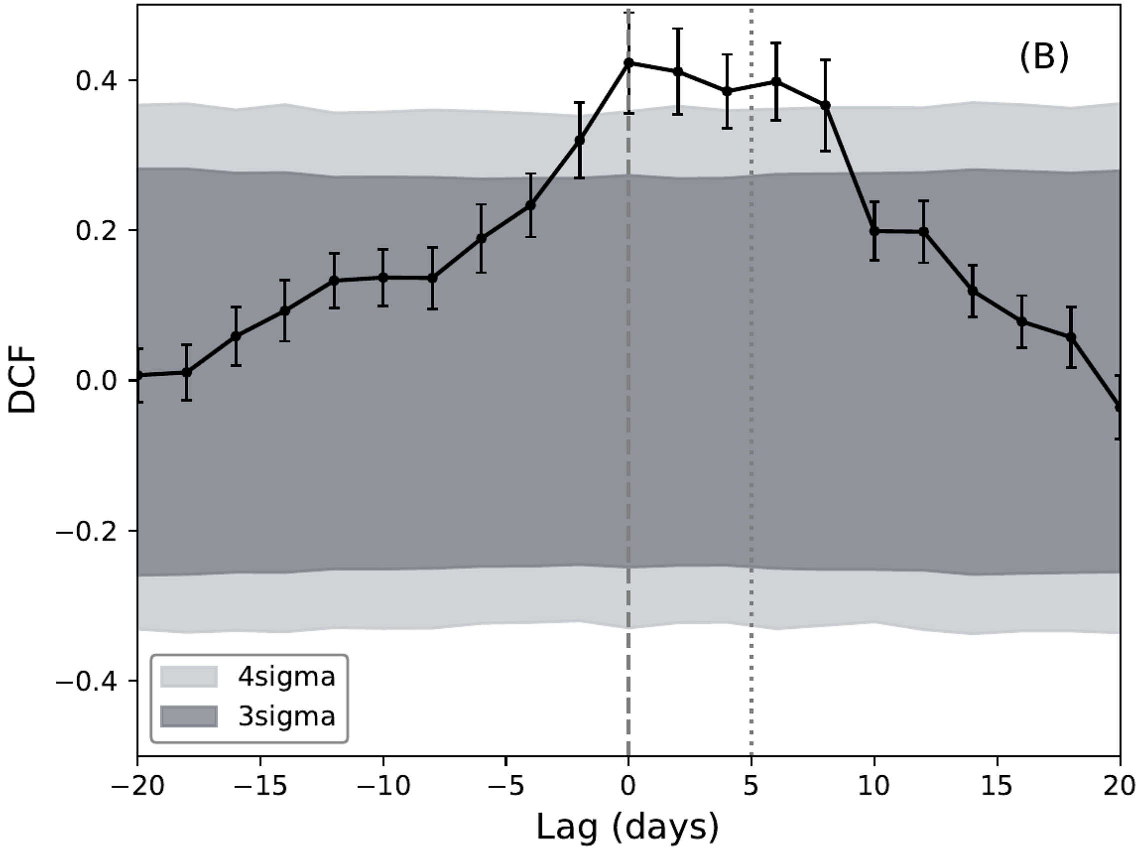
3.4 sigma

relative to uncorrelated red-noise simulations

p = 0.009

chance temporal-coincidence test

The full data set contains two timing modes



A broad peak/bump

~0 days **Simultaneous component**

quiescent / f1 dominated

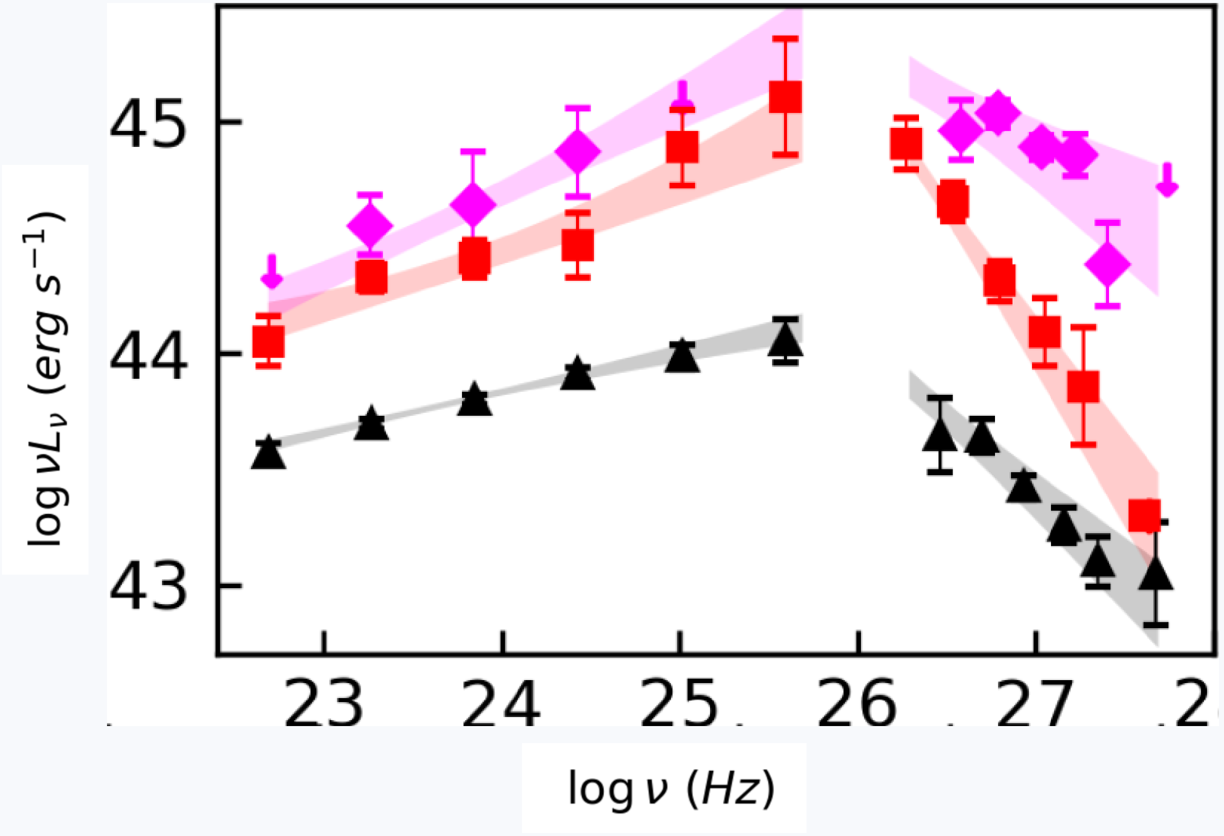
+5 days **hard-lag component**

flare f2 dominated

Both components exceed 4 sigma in the full-period DCF.

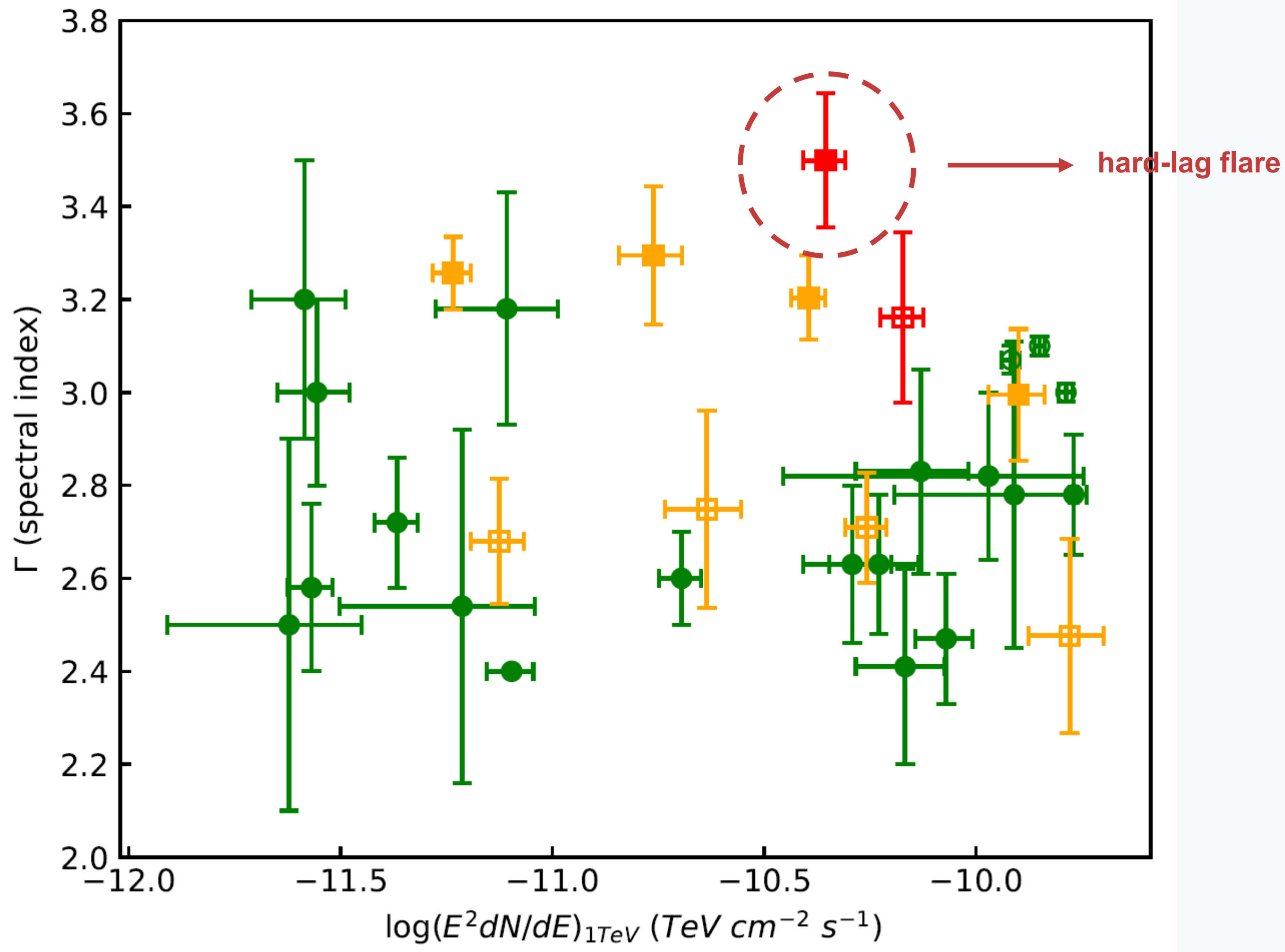
Spectra

Period	WCDA Norm. F_0 (10^{-12} TeV^{-1} cm^{-2} s^{-1})	WCDA Spectral Index (Γ)	WCDA TS	LAT Norm. N_0 (10^{-12} MeV^{-1} cm^{-2} s^{-1})	LAT Index (α)
Flare f_1	55.22 ± 6.02	2.71 ± 0.12	245.79	7.17 ± 0.18	1.73 ± 0.02
Flare f_{1p}	166.39 ± 33.72	2.48 ± 0.21	152.16	12.90 ± 1.53	1.64 ± 0.07
Flare f_2	67.16 ± 7.81	3.16 ± 0.18	93.25	7.93 ± 0.99	1.75 ± 0.06
Flare f_3	23.15 ± 4.68	2.75 ± 0.21	55.13	4.58 ± 0.11	1.73 ± 0.02
Quiescent	7.49 ± 1.07	2.68 ± 0.13	170.57	2.10 ± 0.06	1.83 ± 0.02



f2: softest TeV
f1p: hardest TeV

Historical TeV spectra



Flare f2

Observed TeV index

$$\Gamma_{obs} = 3.50 \pm 0.14$$

EBL-corrected intrinsic

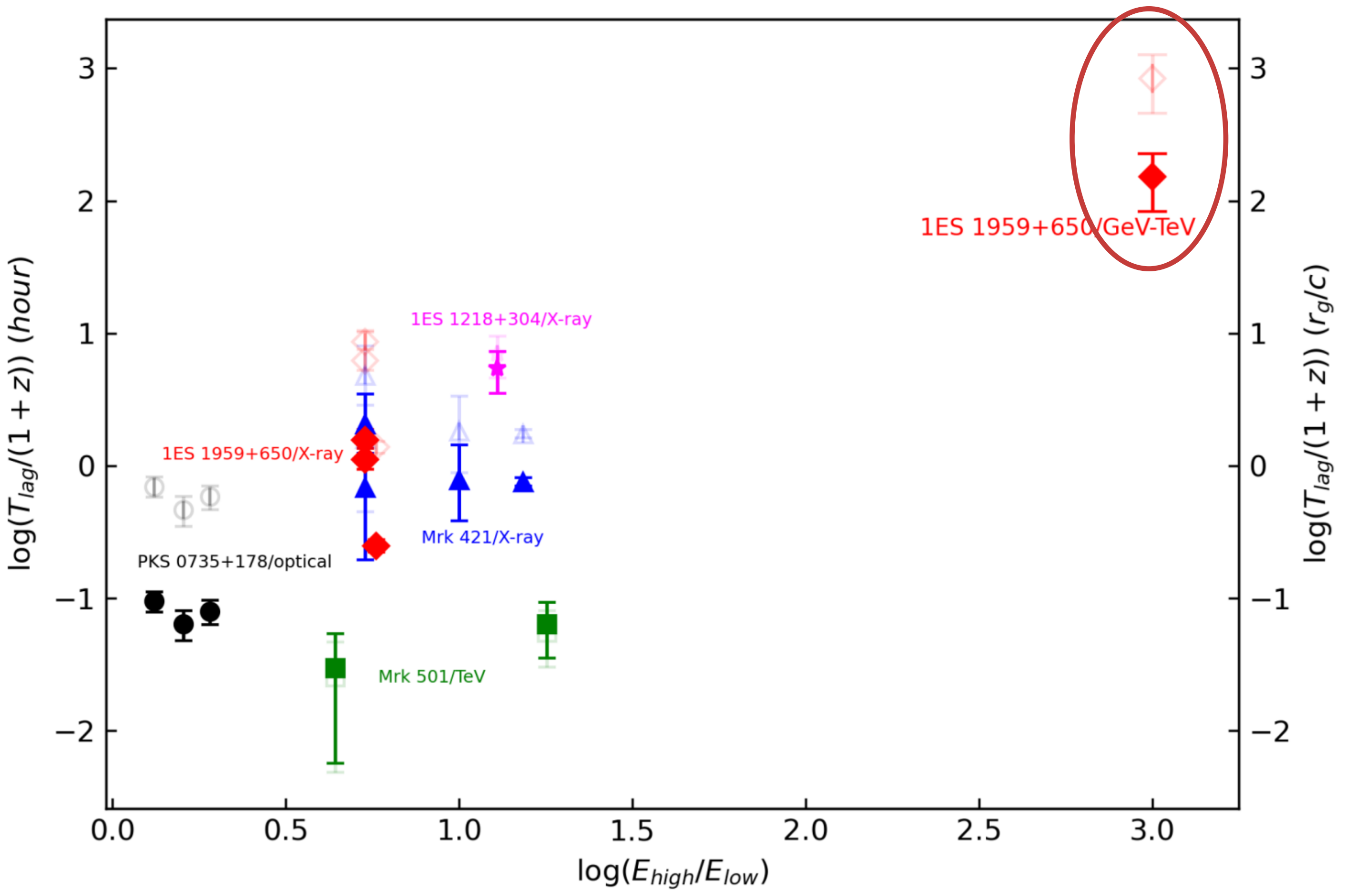
$$\Gamma_{int} = 3.16 \pm 0.18$$

It lies toward the soft end of historical TeV states.

Hard lags in blazars: previously on minute-hour

ENERGY BANDS	SOURCE	REPRESENTATIVE LAG	NOTE
TeV intra-band	Mrk 501	**~4 min**	lag increases with energy separation
X-ray	Mrk 421	**minutes-hours**	repeated hard-lag episodes
X-ray	1ES 1218+304	**~hours**	high-energy X-rays lag
X-ray	1ES 1959+650	**~ks-hours**	reported before the 2024 gamma-ray event
Optical	PKS 0735+178	**<10 min**	g-r-i-zs chromatic lag
GeV -> TeV	**1ES 1959+650**	**5.0 d**	**this work: a different timing-energy regime**

Timing-energy regime



largest energy separation

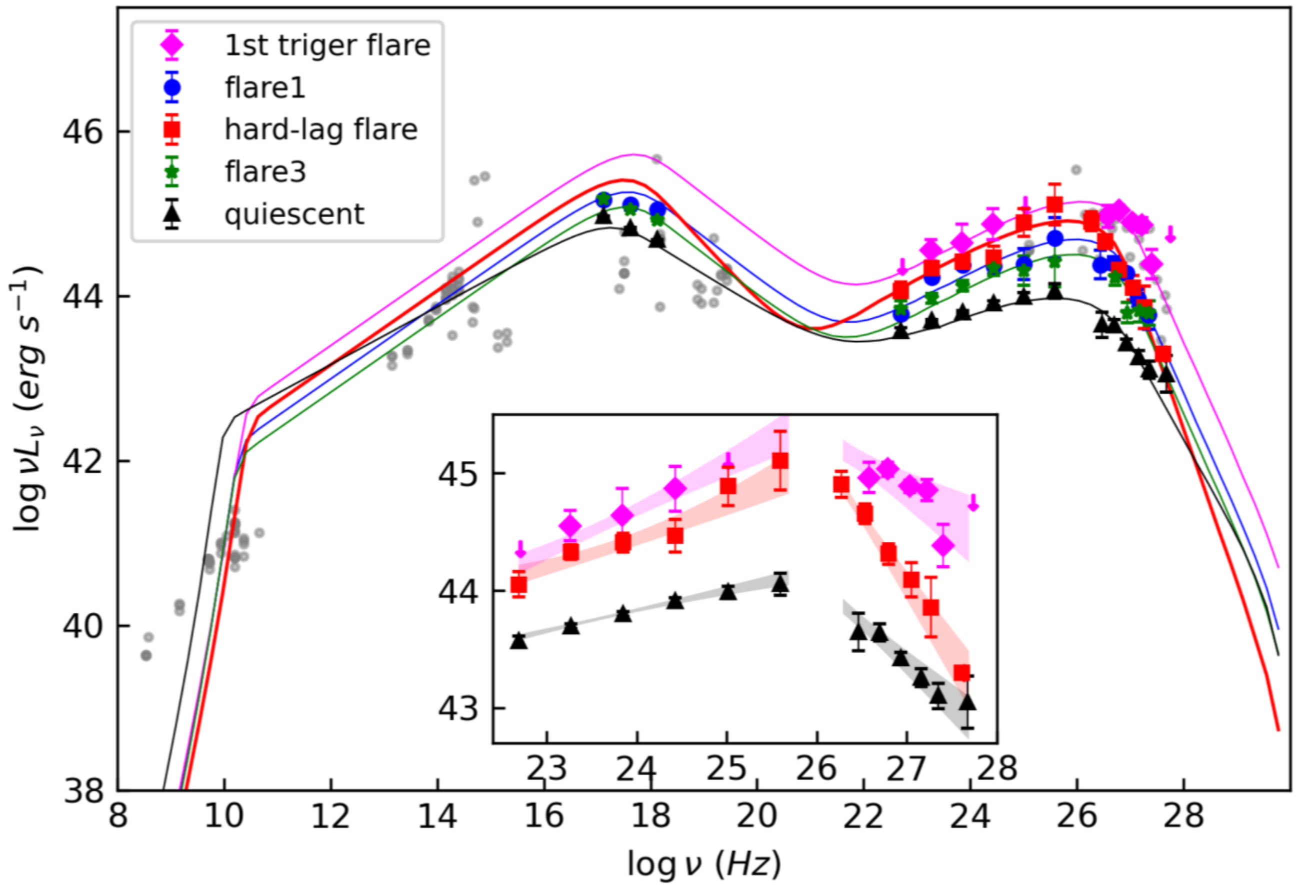
+

longest lag

maybe different mechanism

Possible origins of the hard lag

Broadband SEDs: representative jet parameters



- Opacity constrain

$$\tau_{\gamma\gamma} = \frac{(\nu L_\nu)\sigma_T E}{20\pi m_e^2 c^6 \delta^6 \Delta t_{obs}} < 1$$

$$\delta \gtrsim 10$$

- not all simultaneous.
- Stationary one-zone SSC: not time lag.

States	δ	B (Gs)	R (cm)	γ_0	p_1	p_2	N_0
Flare f_1	15	0.015	9.6×10^{16}	6.3×10^5	2.1	4.0	185
Flare f_{1p}	20	0.015	9.6×10^{16}	6.3×10^5	2.1	4.0	185
Flare f_2	15	0.023	9.6×10^{16}	5.0×10^5	2.1	4.4	329
Flare f_3	14	0.015	9.6×10^{16}	6.3×10^5	2.1	4.0	185
Quiescent	11.5	0.008	4.9×10^{17}	6.7×10^5	2.3	3.8	153

Standard Fermi-I acceleration too fast

Relativistic shock acceleration

$$t_{\mathrm{acc,I}} \simeq \frac{\eta\,\gamma m_e c}{eB}$$

For B ~ 0.02 G, acceleration is much faster than days.

Stochastic acceleration can reach day-scale lags

Hard-sphere diffusion

$$D_{\gamma\gamma} \propto \gamma^2 \quad t_{\mathrm{acc,II}} \simeq \frac{\gamma^2}{2D_{\gamma\gamma}} \approx \mathrm{const.}$$

$$\Delta t_{1\to 2} = t_{\mathrm{acc}} \ln\left(\frac{\gamma_2}{\gamma_1}\right)$$

Representative jet conditions

B = 0.02 G | delta = 15 | vA = 0.1c

t'acc ~ 50 d | **t'cool ~ 75 d**

$\gamma_{\mathrm{G}} \sim 3 \times 10^4$ | $\gamma_{\mathrm{T}} \sim 3 \times 10^5$

Observer-frame

$$\tau_{\mathrm{lag}} \sim \frac{1+z}{\delta}\, t'_{\mathrm{acc}} \ln\left(\frac{\gamma_{\mathrm{T}}}{\gamma_{\mathrm{G}}}\right)$$

~7-8 days

same order as the measured 5-day lag

Acceleration and losses become comparable near γ_T - a soft TeV spectrum is qualitatively plausible.

Alternatives

FS / RS

forward / reverse shocks

One collision can create two shocked regions (for TeV and GeV respectively).

ZONE

stratified or multi-zone jet

GeV and TeV emission may be produced at different positions or in different dynamical layers.

tau

opacity / escape

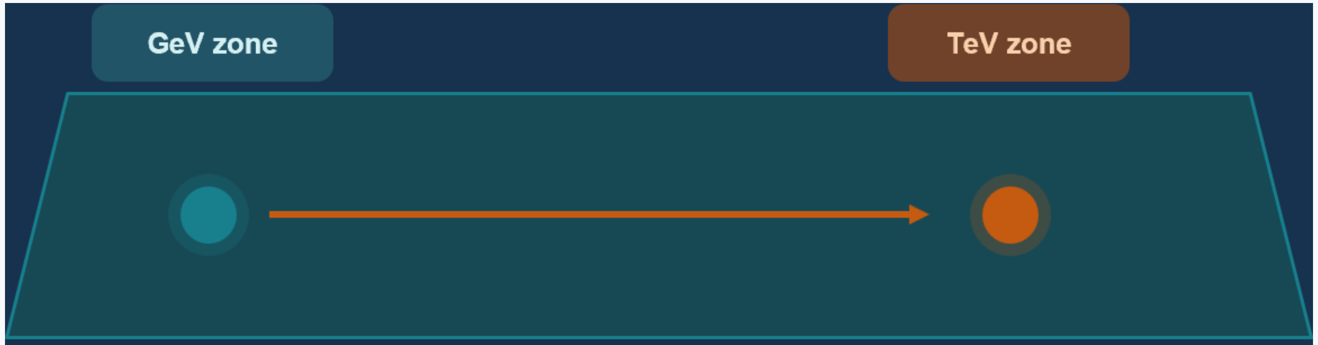
Delayed transparency or energy-dependent escape.

distinct events

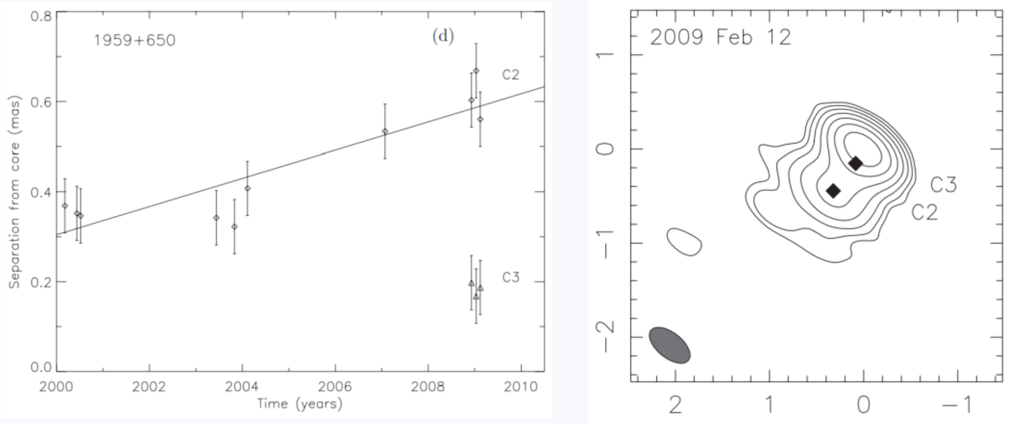
central-engine activity

Two shell pairs ejected at different times could collide at different radii.

The jet propagation

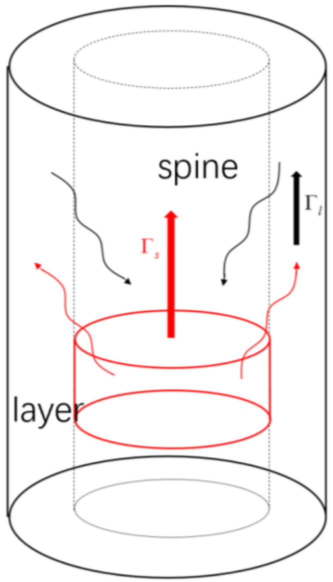


$$\Delta r \sim 1 \left(\frac{\Gamma}{15} \right)^2 \left(\frac{\Delta t}{5\,\mathrm{d}} \right) \mathrm{pc}$$



Jet proper motion: v_app ~ 0.1 c

- VLBI pattern speeds are subluminal or stationary on parsec scales.
- Maybe a fast gamma-ray spine inside a slow radio sheath



Summary

01 Three TeV flares

Bayesian Blocks identify f1, f2, and f3 during the 2024 active phase.

02 A TeV delay

Flare f2: $\Delta t = 5.0 \pm 2.1$ d, with TeV after GeV and a 3.4σ DCF significance.

03 A rare spectral–timing state

Flare f2 has the softest TeV spectrum among the WCDA flares: Γ_{obs}= 3.50 ± 0.14.

04 Physical implication

Particle acceleration is plausible, alternatives remain

Long-term, uniform time monitoring of LHAASO reveal
a new timing behavior in 1ES 1959+650
the hard TeV/GeV lag

Thank you!