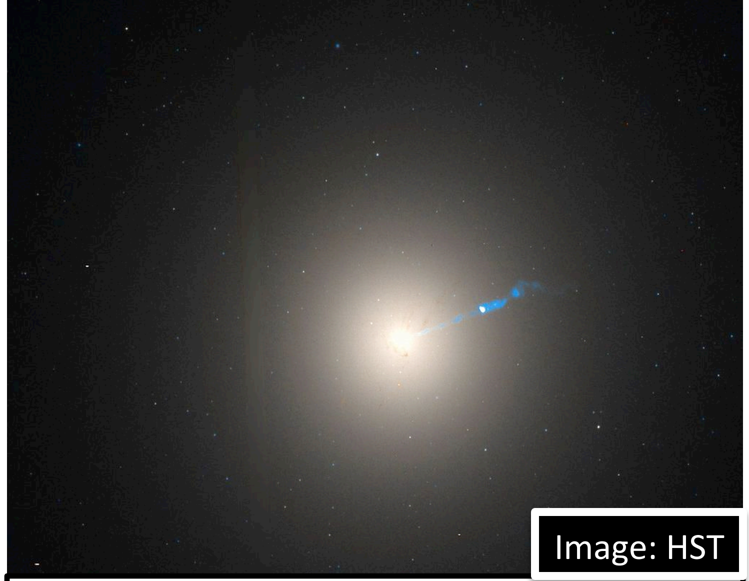


Image: HST

A "curious straight ray ...
apparently connected with the
nucleus by a thin line of matter."
-- Heber Curtis (1918), Lick
Observatory

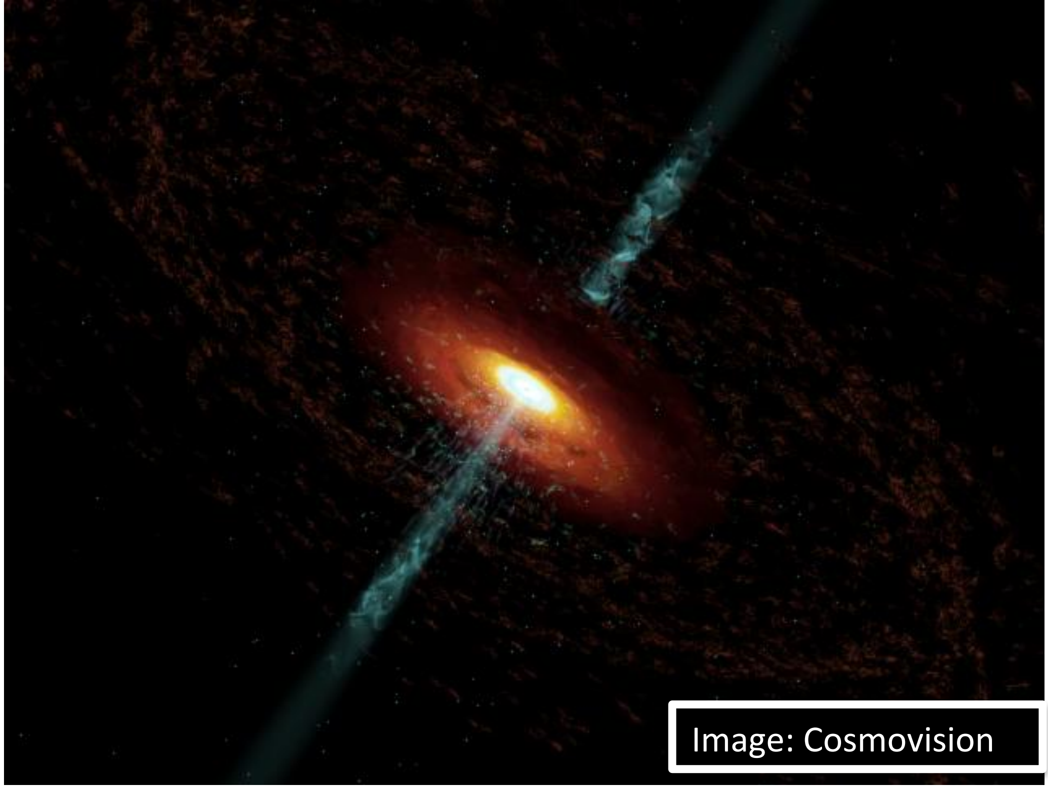


Image: Cosmovision

Physics of Jets from Multi-Wavelength Monitoring of Blazars

Ritaban Chatterjee, School of Astrophysics, Presidency University Kolkata

AAPCOS, Jan 23- 27, 2023.

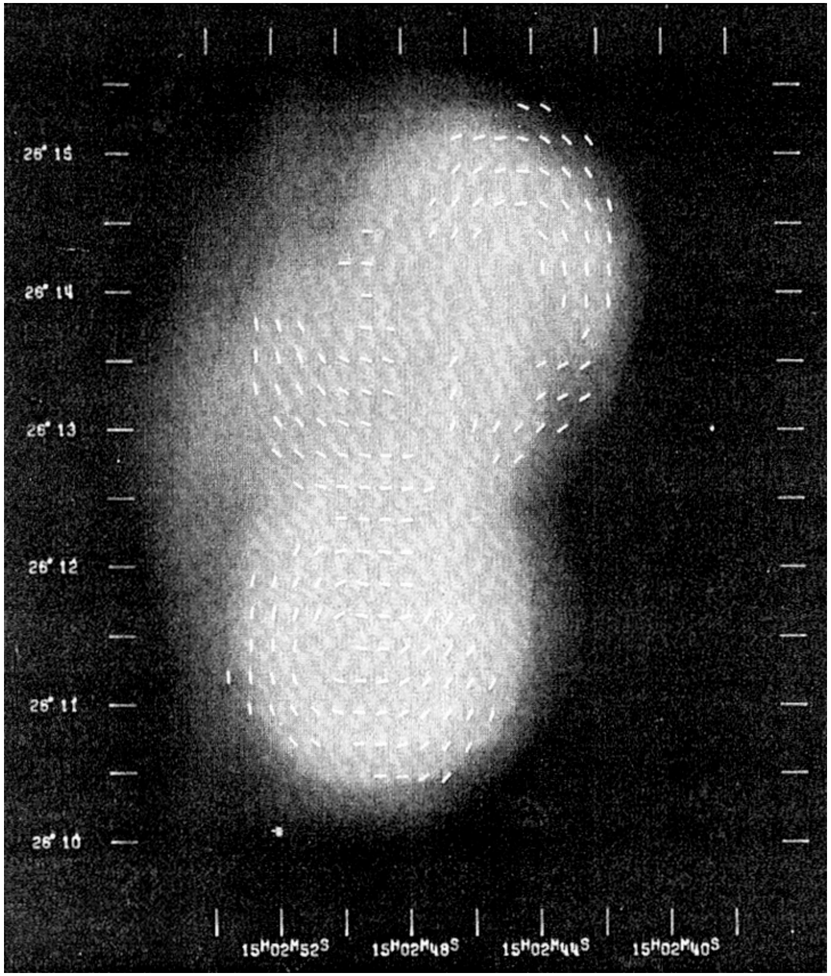
Collaborators

- **Ms. Susmita Das, PhD Student, Presidency U., Kolkata.**
- Dr. Sunil Chandra, North-West U., Potchefstroom, South Africa (Formerly at TIFR)
- Dr. Ritesh Ghosh, GSFC, USA (formerly at IUCAA, Pune, India).
- Dr. Atreyee Sinha, Université de Montpellier, CNRS/IN2P3, France (formerly at IUCAA, Pune, India).

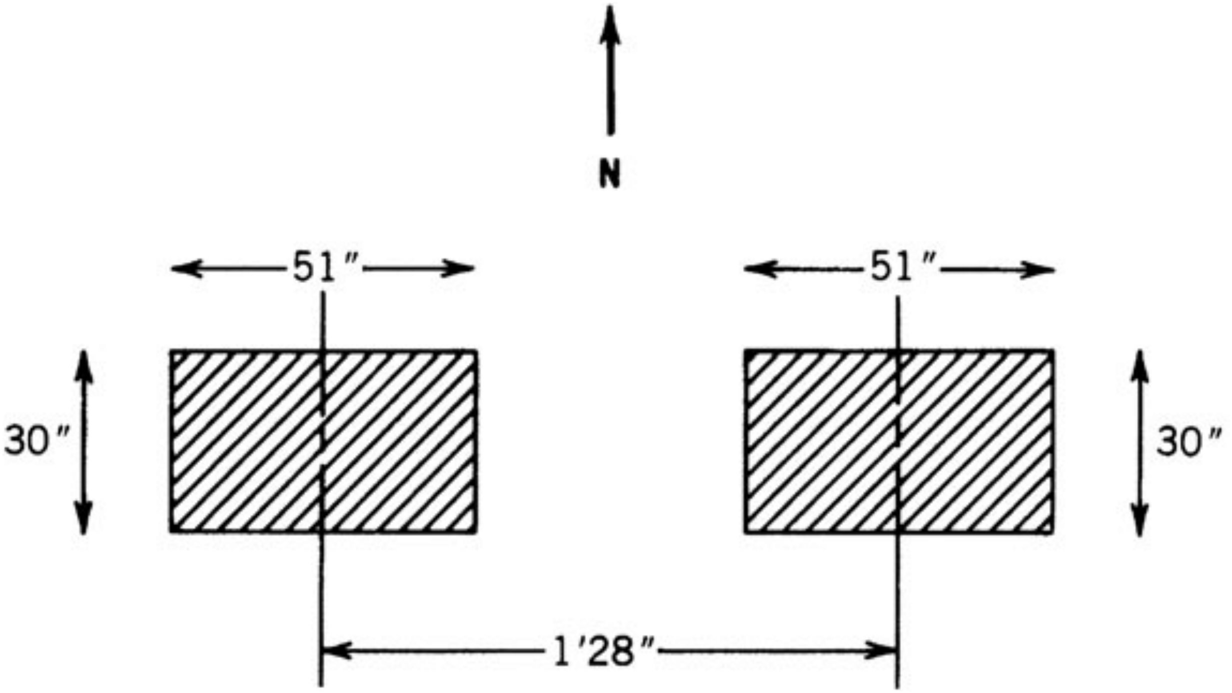
<u>Former BSc-MSc Students, Presidency U. Kolkata</u>

- Mr. Souradip Bhattacharya, Ohio State U., USA
- **Mr. Saugata Barat, U. Amsterdam, Netherlands**
- Ms. Nabanita Das, Georgia State U., USA
- Mr. Archisman Khasnovis, NCRA, Pune, India
- Mr. Kaustav Mitra, Yale. U., USA
- Mr. Sripan Mondal, IIT BHU, India
- Mr. Sagnick Mukherjee, UCSC, USA
- Mr. Agniva Roychowdhury, U. Maryland Baltimore County, USA
- Mr. Aritra Kundu, U. Pennsylvania, USA
- **Ms. Garima Rajguru, Clemson University, USA.**

Extragalactic Radio Sources: Looked like one blob



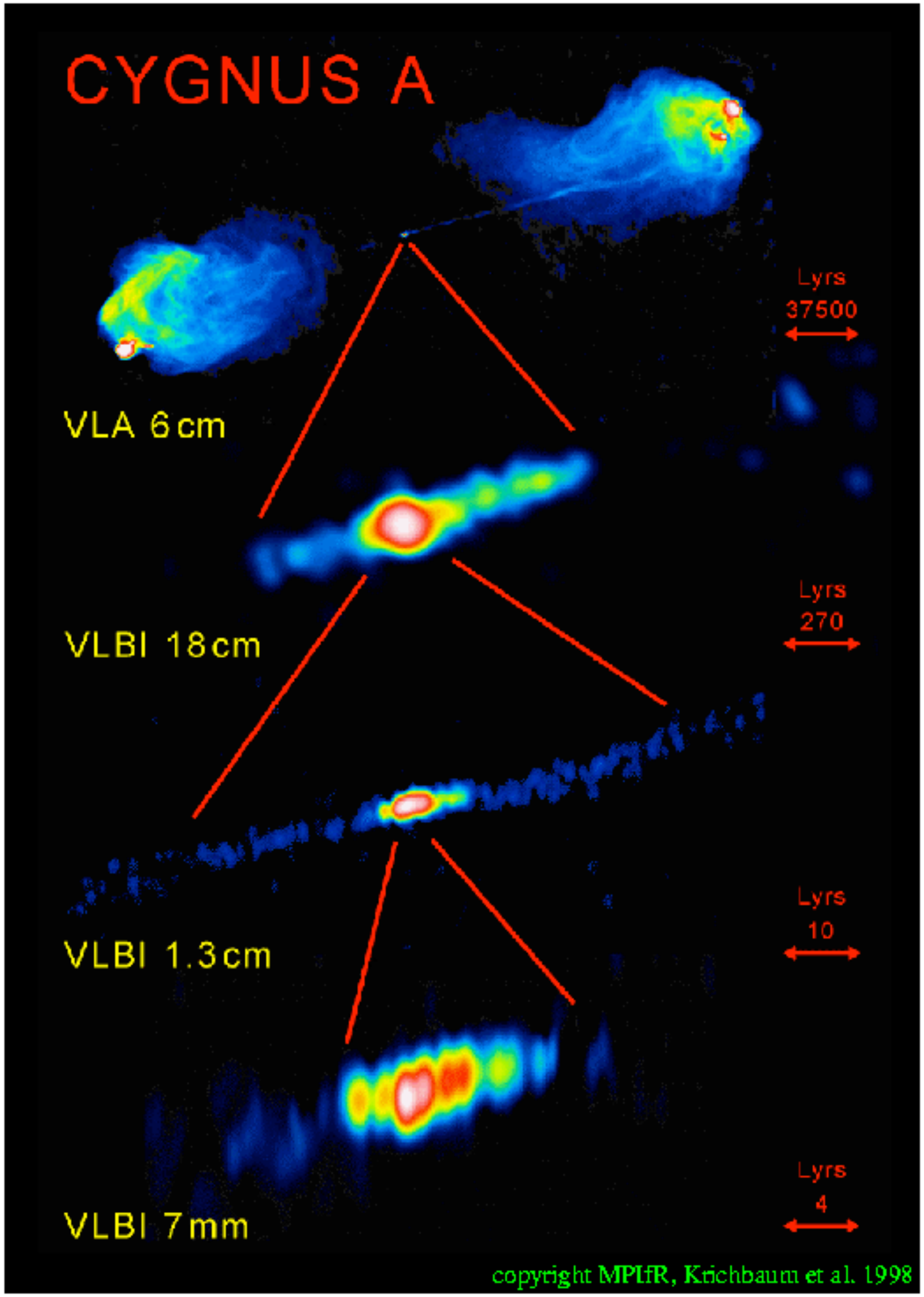
Better Resolution through Radio Interferometry



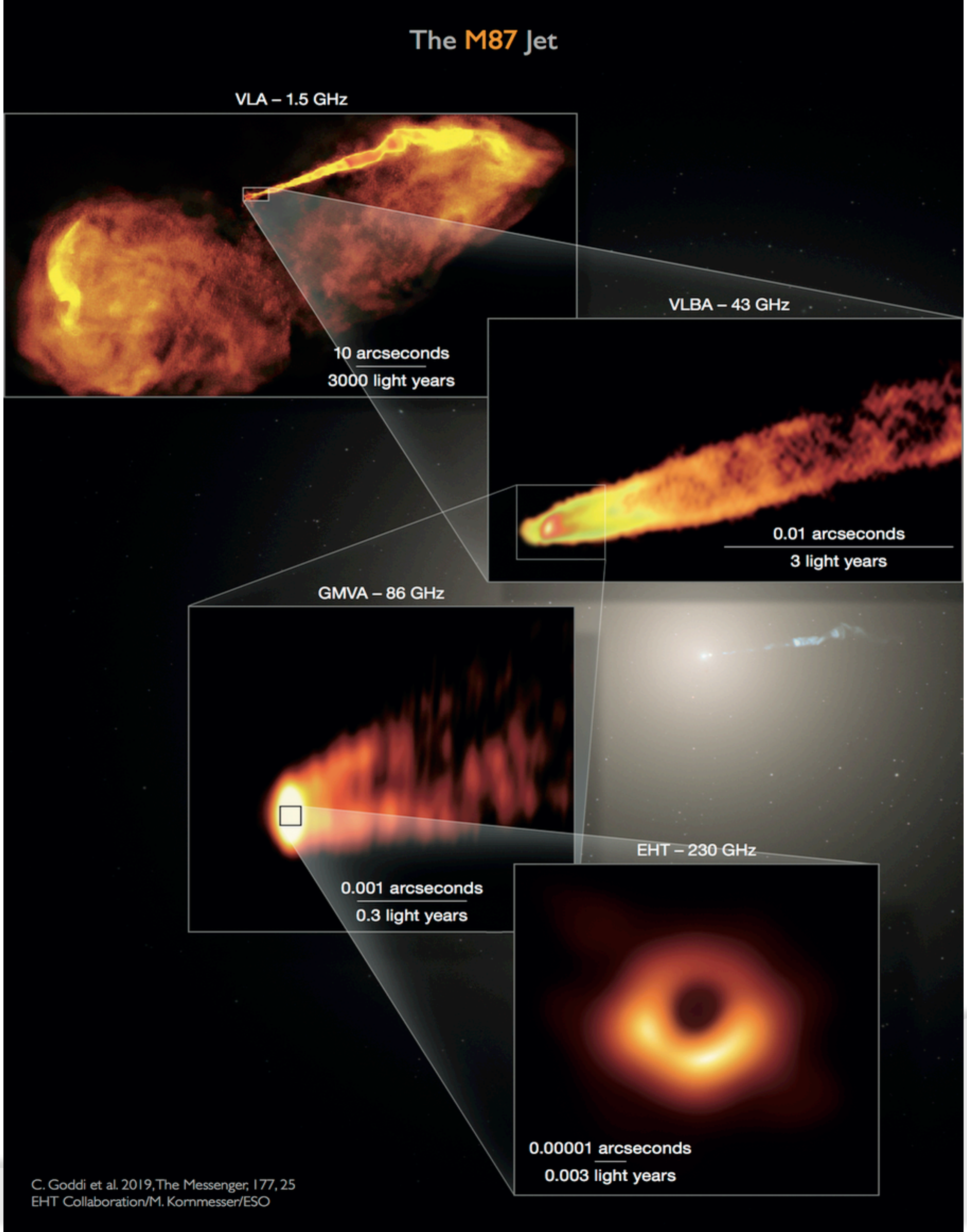
Mrinal Kumar Dasgupta, Jodrell Bank Observatory (later at Science College Calcutta, Radiophysics & Electronics Dept.)

R.C. Jennison and M.K. Das Gupta, Nature 172, 996 (1953); R. Hanbury Brown, R.C. Jennison and M.K. Das Gupta, Nature 170, 1061 (1952).

Discovery of Double-Lobed Radio Source Cygnus A



copyright MPIfR, Krichbaum et al. 1998



The M87 Jet

VLA – 1.5 GHz

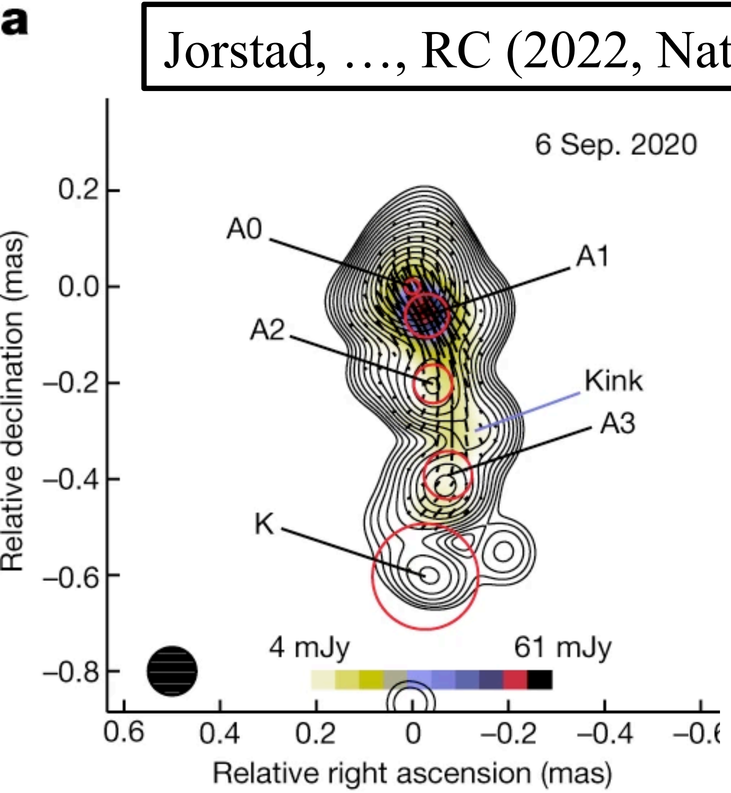
VLBA – 43 GHz

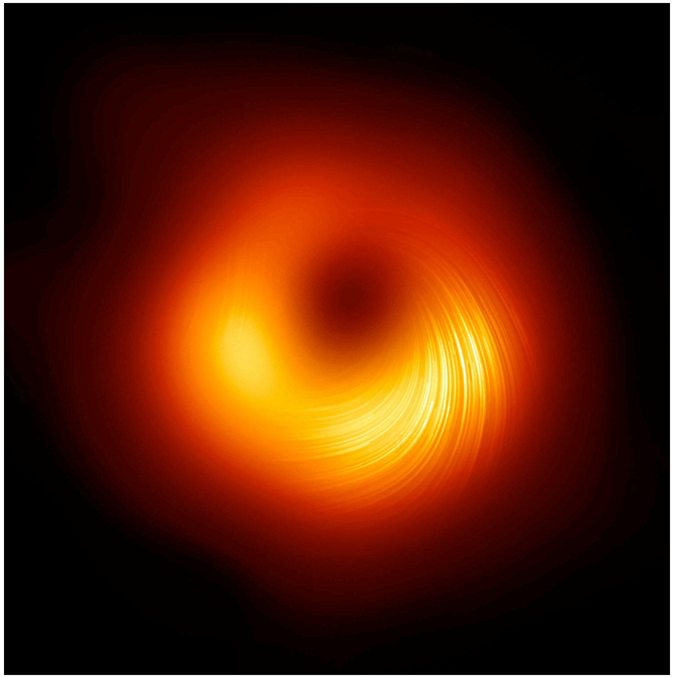
GMVA – 86 GHz

EHT – 230 GHz

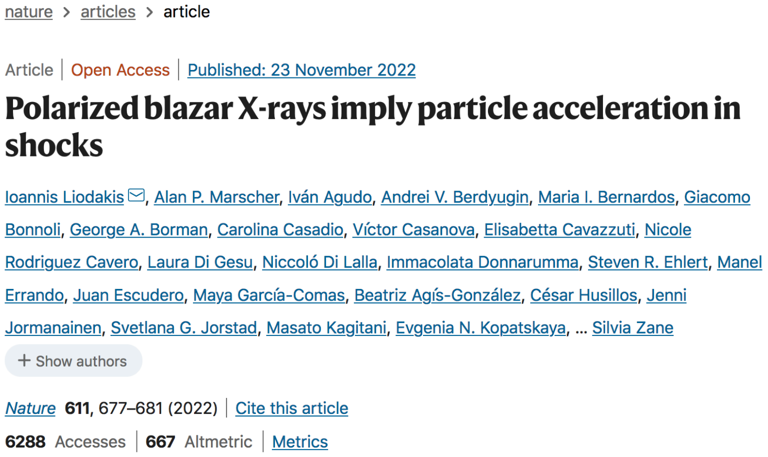
C. Goddi et al. 2019, The Messenger, 177, 25
EHT Collaboration/M. Kornmesser/ESO

Jorstad, …, RC (2022, Nature)





- Kink Instability in Jet.
- Disordered magnetic field driven by kink instability may facilitate magnetic reconnection: Particle acceleration.
- Dissipation of magnetic energy: Large scale jets are kinetic energy driven. Jet launching is driven by magnetic field.



nature > articles > article

Article | Open Access | Published: 23 November 2022

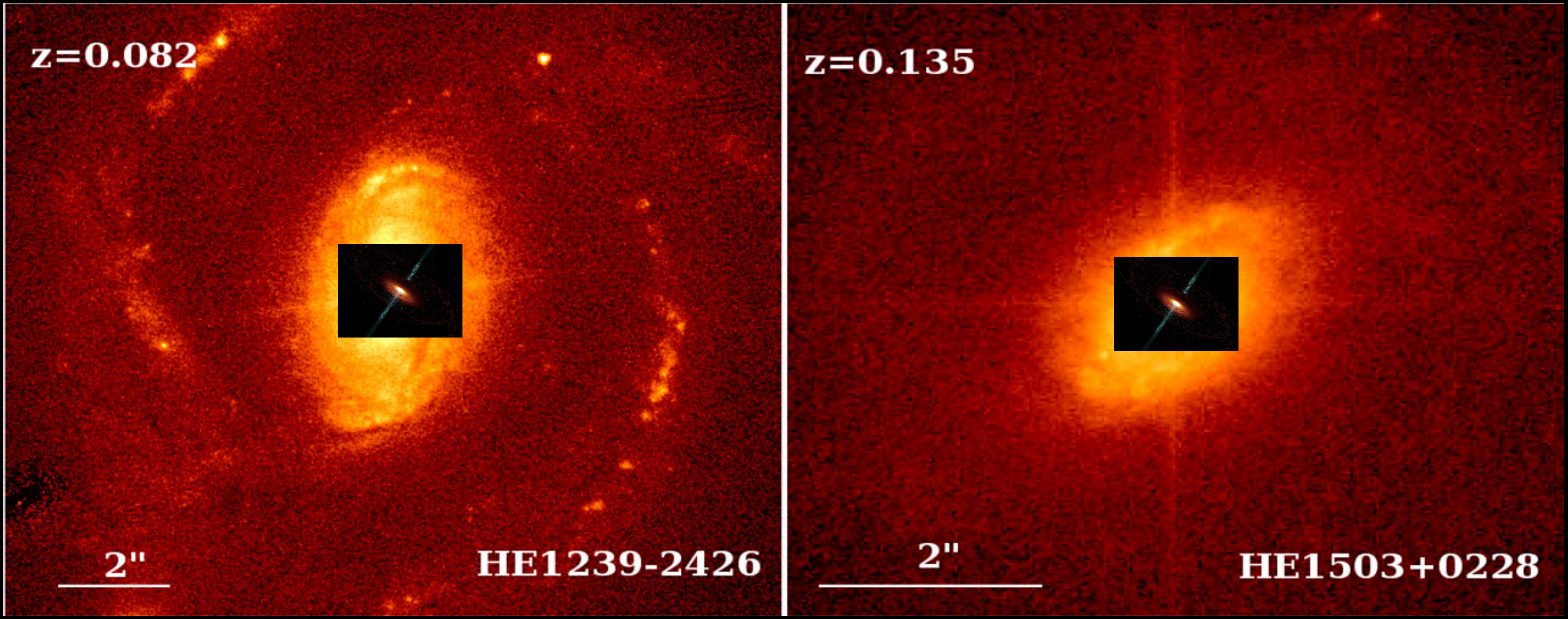
Polarized blazar X-rays imply particle acceleration in shocks

Ioannis Liodakis, Alan P. Marscher, Iván Agudo, Andrei V. Berdyugin, Maria I. Bernardos, Giacomo Bonnoli, George A. Borman, Carolina Casadio, Víctor Casanova, Elisabetta Cavazzuti, Nicole Rodriguez Cavero, Laura Di Gesu, Niccoló Di Lalla, Immacolata Donnarumma, Steven R. Ehlert, Manel Errando, Juan Escudero, Maya García-Comas, Beatriz Agís-González, César Husillos, Jenni Jormanainen, Svetlana G. Jorstad, Masato Kagitani, Evgenia N. Kopatskaya, ... Silvia Zane

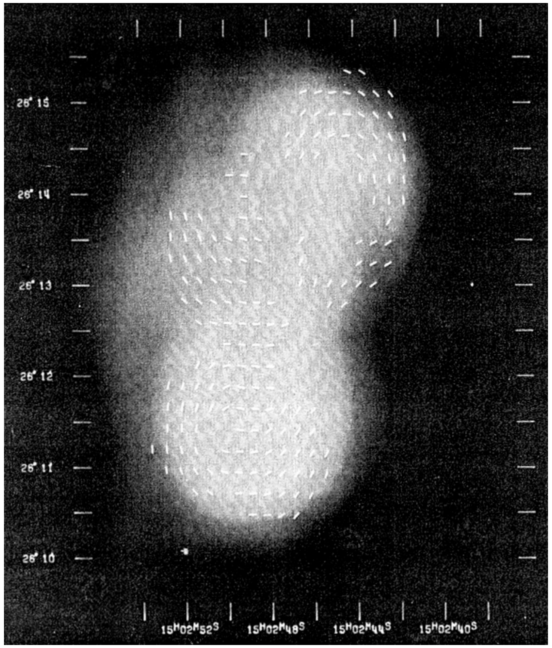
+ Show authors

Nature **611**, 677–681 (2022) | Cite this article

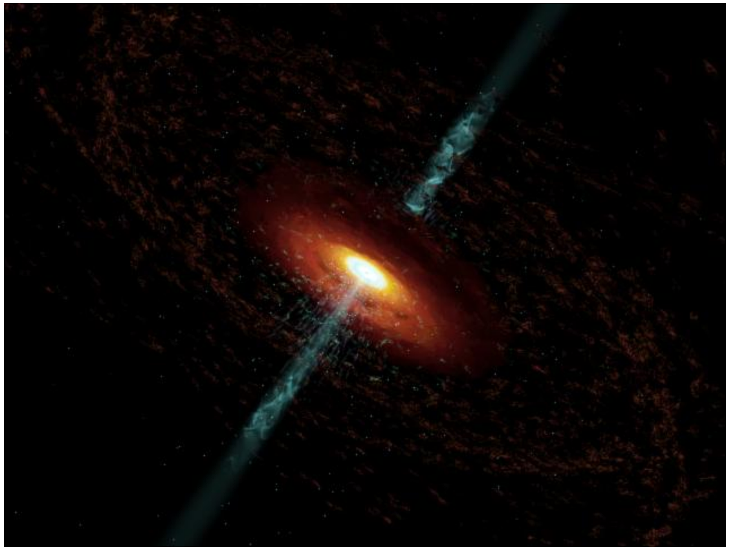
6288 Accesses | **667** Altmetric | Metrics


z=0.082
2"
HE1239-2426
z=0.135
2"
HE1503+0228

Resolution is worse at higher energies



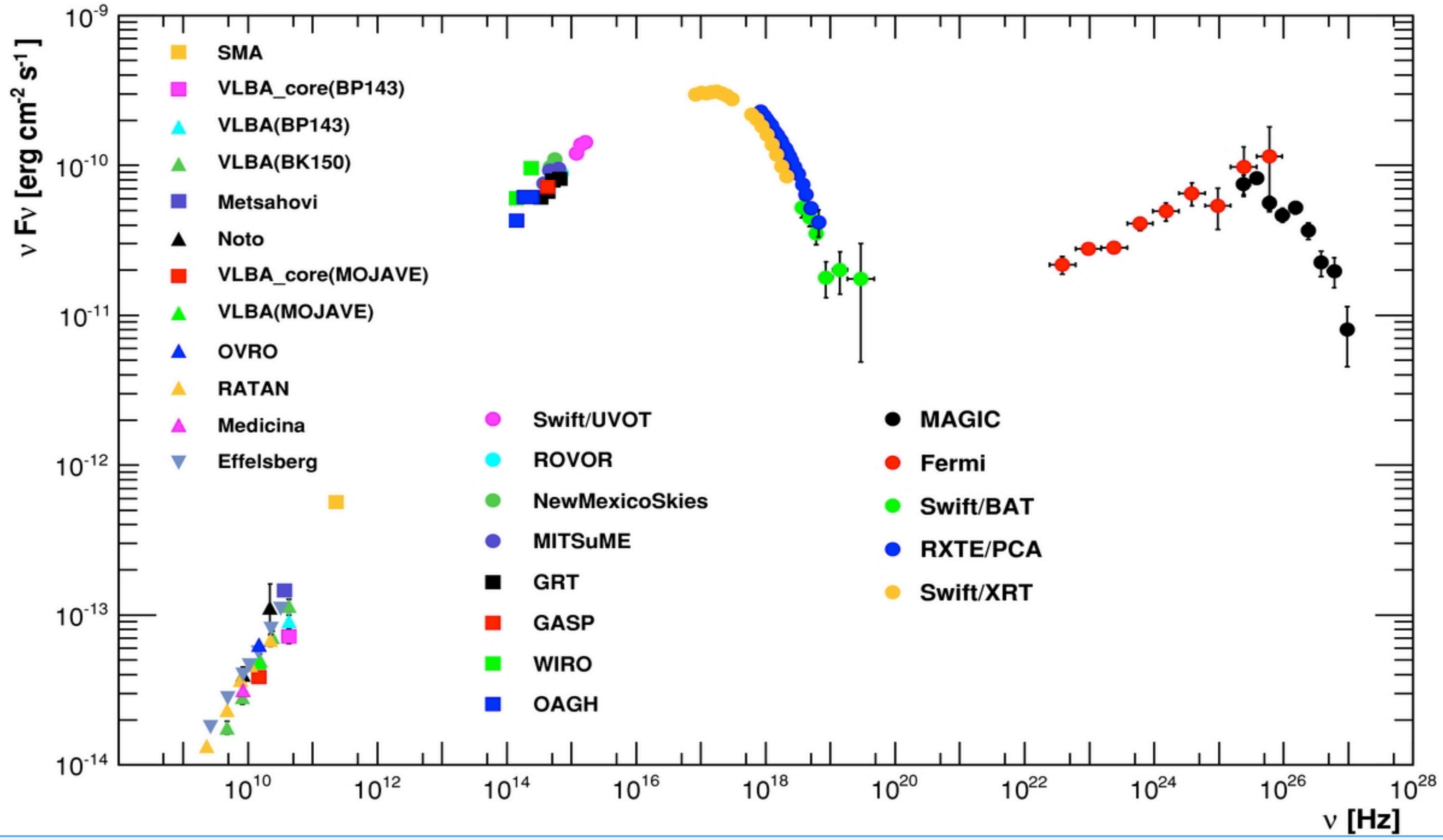
- Multi-wavelength variability, spectra, polarization



- Location of high energy emission region.
- Emission mechanism and particle acceleration
- Relation between accretion disk and jet

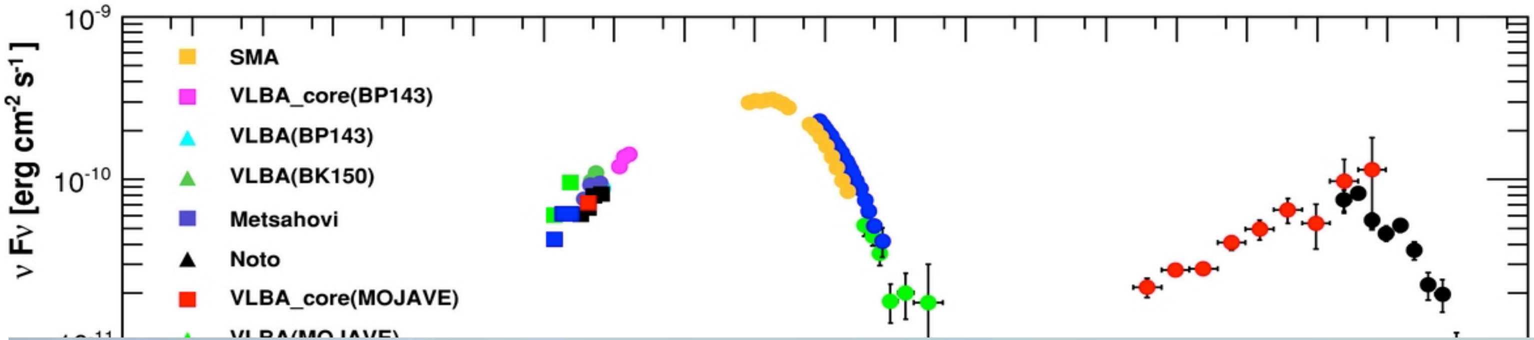
Emission Mechanism and Particle Acceleration in the Jets

SED of Mrk 421



Spectral energy distribution of Mrk 421 averaged over all the observations taken during the multi-frequency campaign from 2009 January 19 (MJD 54850) to 2009 June 1 (MJD 54983). The legends denote the observing facilities used. The host galaxy has been subtracted, and the optical/X-ray data were corrected for the Galactic extinction (Abdo et al., 2011).

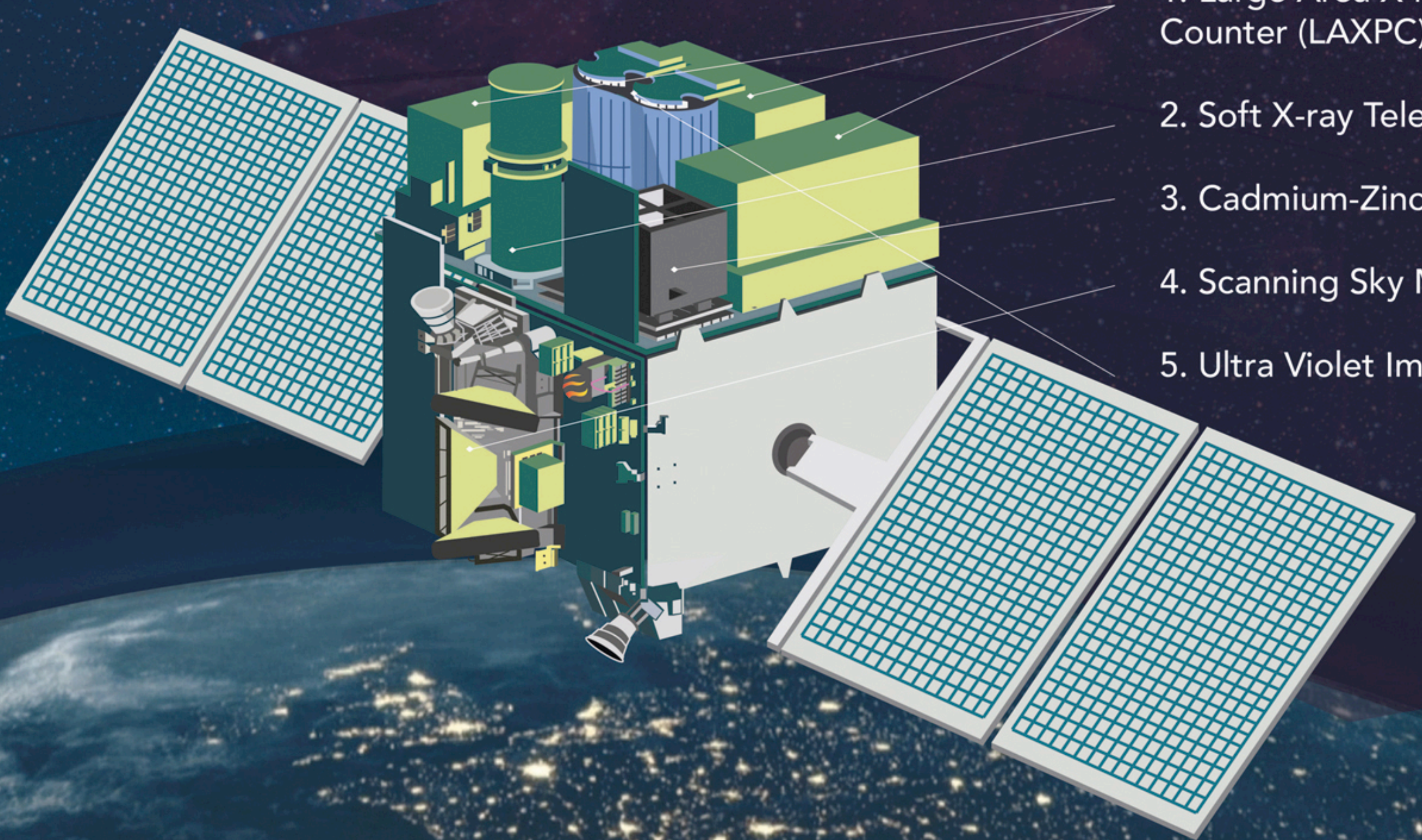
SED of Mrk 421



Spectral en ng the
multi-frequ 983). The
legend den The host
galaxy has extinction
(Abdo et al

India's first Multiwavelength Space Observatory

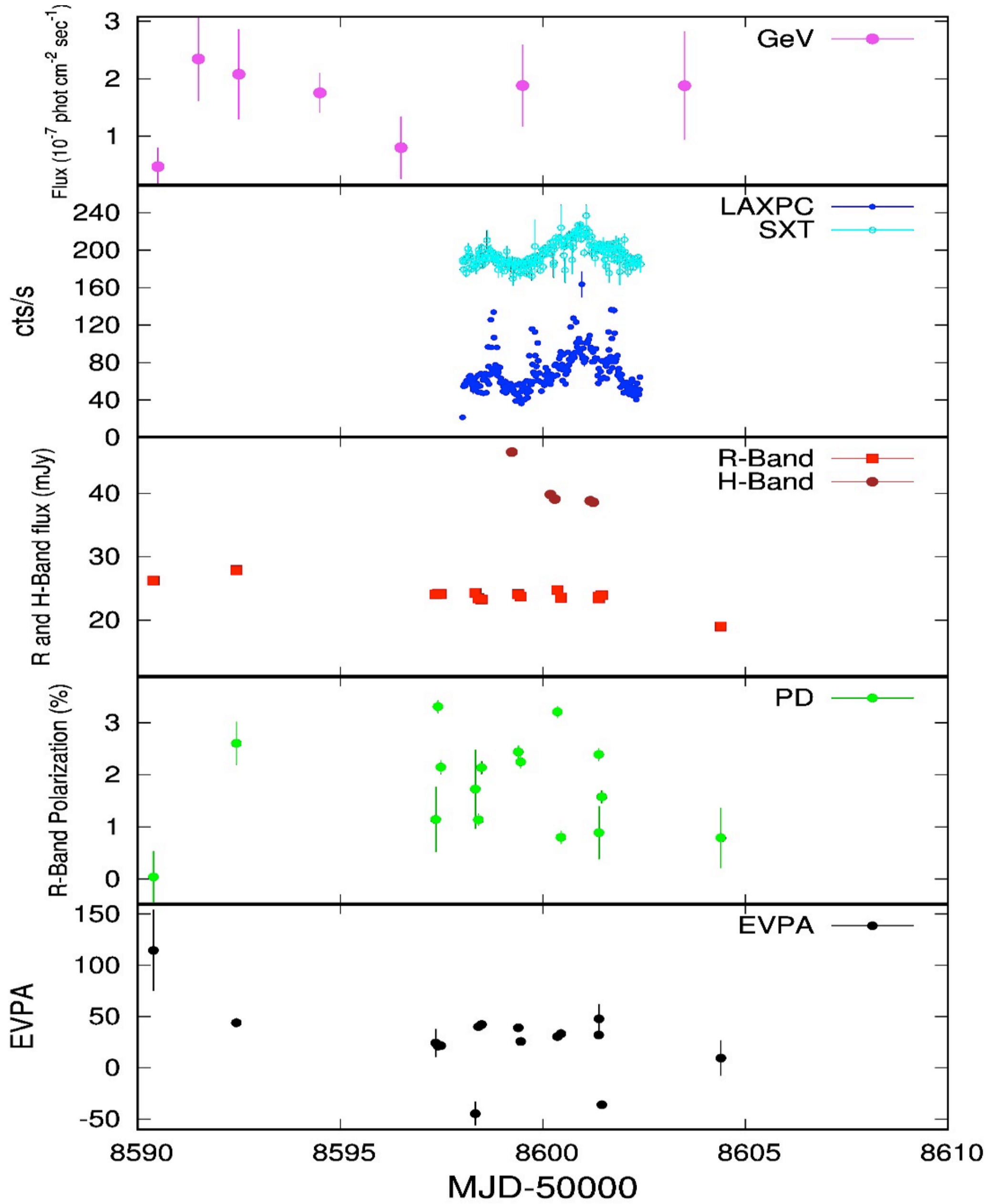
ASTROSAT



The 5 telescopes of the Astrosat

1. Large Area X-ray Proportional Counter (LAXPC)
2. Soft X-ray Telecope (SXT)
3. Cadmium-Zinc-Telluride Imager (CZTI)
4. Scanning Sky Monitor (SSM)
5. Ultra Violet Imaging Telescope (UVIT)

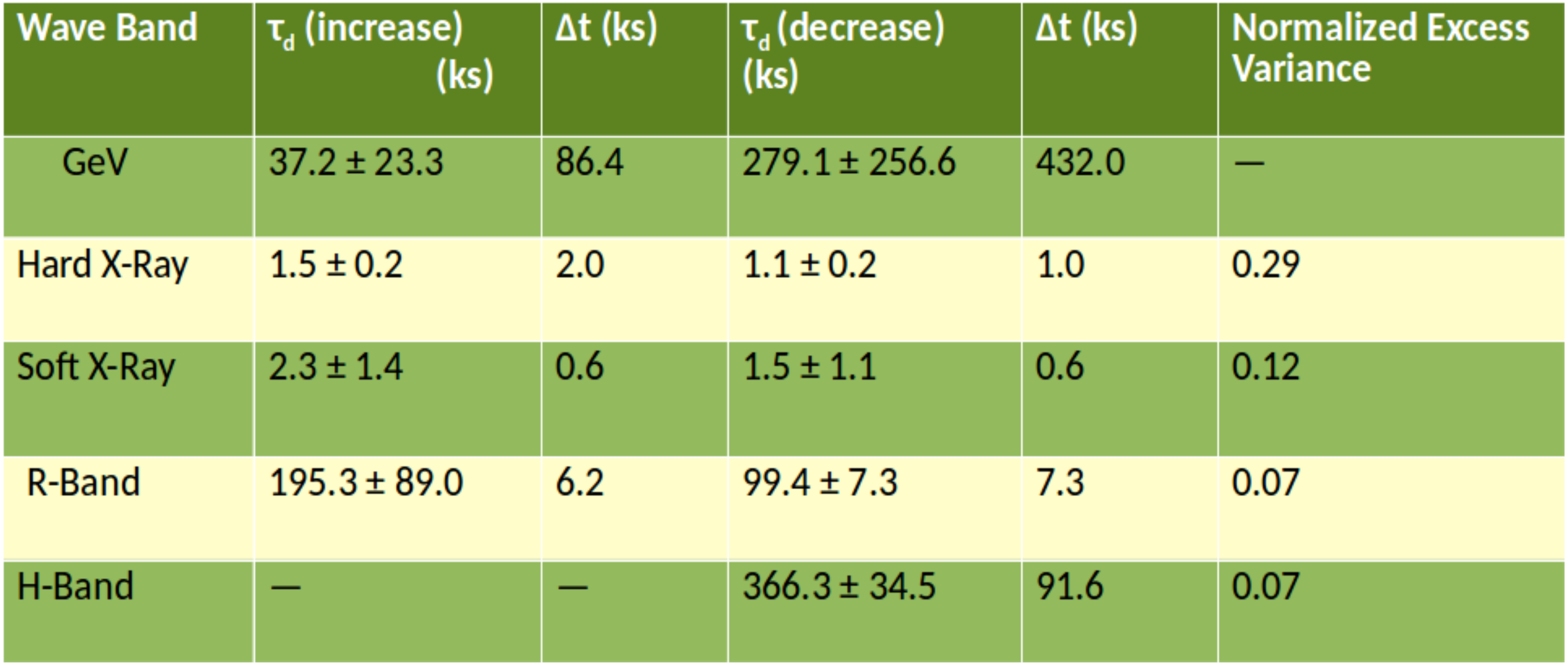
Multi-wavelength Variability of Mrk 421



- Simultaneous multi-wavelength observation from April 16 – May 6, 2019.
- γ-rays flux (0.1-300 GeV): Fermi-LAT
- Hard X-ray (4-20 keV) and soft X-ray (0.7-8 keV): AstroSat's LAXPC and SXT instruments.
- The optical flux and polarimetric data: St. Petersburg University 40 cm LX-200 telescope and the Crimean observatory 70 cm AZT-8 telescope.
- The near-infrared H-band flux density: Mount Abu Infrared observatory using Near-Infrared Camera and Spectrograph (NICS) instrument.

RC, Das, Khasnovis, et al. (2021), JApA

Variability timescale and excess variance at different bands



Wave Band	τ_d (increase) (ks)	Δt (ks)	τ_d (decrease) (ks)	Δt (ks)	Normalized Excess Variance
GeV	37.2 ± 23.3	86.4	279.1 ± 256.6	432.0	—
Hard X-Ray	1.5 ± 0.2	2.0	1.1 ± 0.2	1.0	0.29
Soft X-Ray	2.3 ± 1.4	0.6	1.5 ± 1.1	0.6	0.12
R-Band	195.3 ± 89.0	6.2	99.4 ± 7.3	7.3	0.07
H-Band	—	—	366.3 ± 34.5	91.6	0.07

The increasing variability timescale and decreasing normalized excess variance from X-ray to optical-NIR band agree with the model in which emission of those wave bands in Mrk 421 is generated via the synchrotron process by the relativistic electrons in the jet.

RC, Das, Khasnovis, et al. (2021), JApA

Calculation of magnetic field and Lorentz factor

Synchrotron cooling timescale,

$$t_{cool} \simeq 7.7 \times 10^{8} (1 + z)\delta^{-1} B^{-2} \gamma_{eff}^{-1} \text{ s}$$

Characteristic frequency of the electron distribution responsible for the emission at the synchrotron peak of the SED,

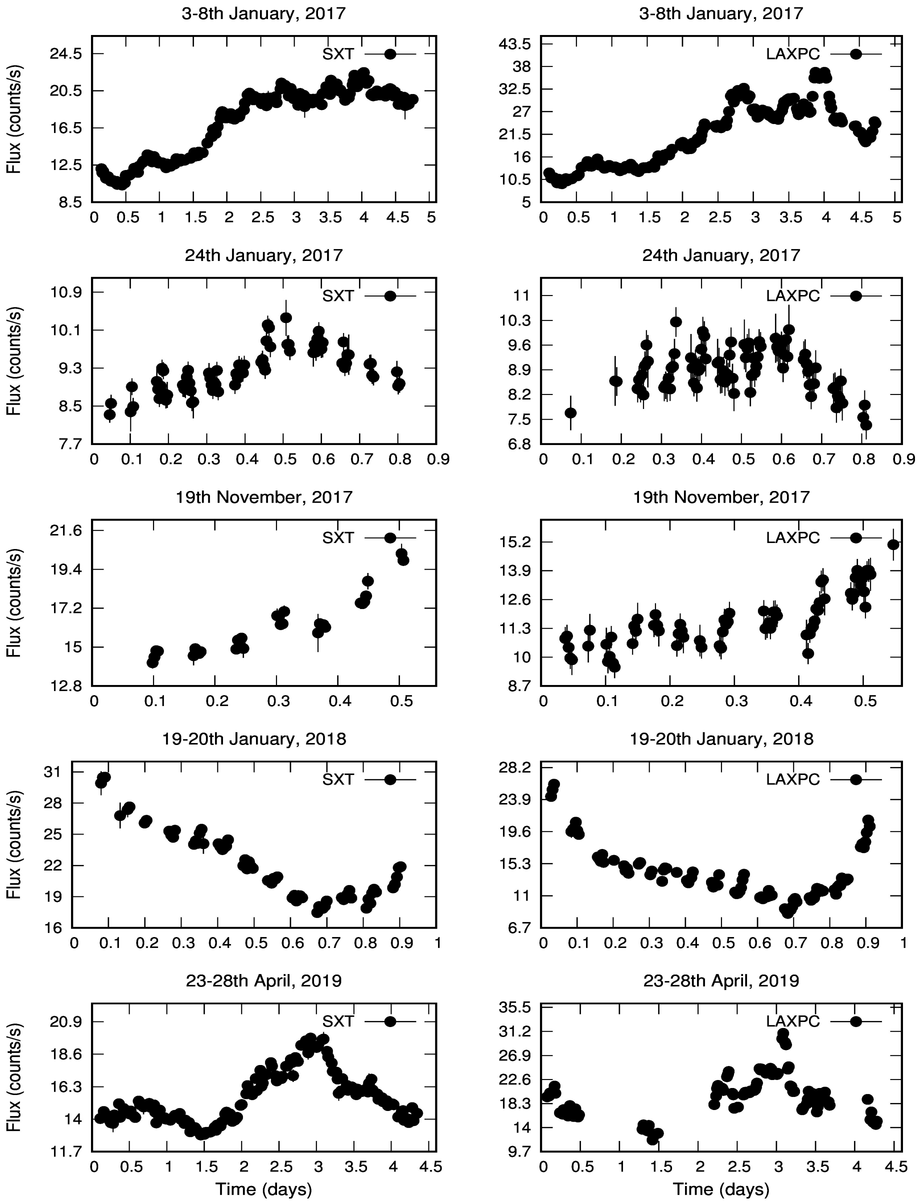
$$\nu_{ch} = 4.2 \times 10^{6} \gamma_{eff}^{2} B \text{ Hz}$$

By choosing $z = 0.031$, $\delta = 20$, $\nu_{ch} = 10^{18}$ Hz and $t_{cool} = 1.1$ ks from the above, we obtain,

$$\boxed{B = 0.5 \text{ Gauss}, \ \gamma_{eff} = 1.6 \times 10^{5}}$$

- The estimated values are consistent with those obtained from SED modeling (e.g., Abdo et al., 2011).

Soft and Hard X-ray light curves of 1ES 1959+650 and Mrk 421 at Multiple Epochs During 2016-19


3-8th January, 2017

3-8th January, 2017

24th January, 2017

24th January, 2017

19th November, 2017

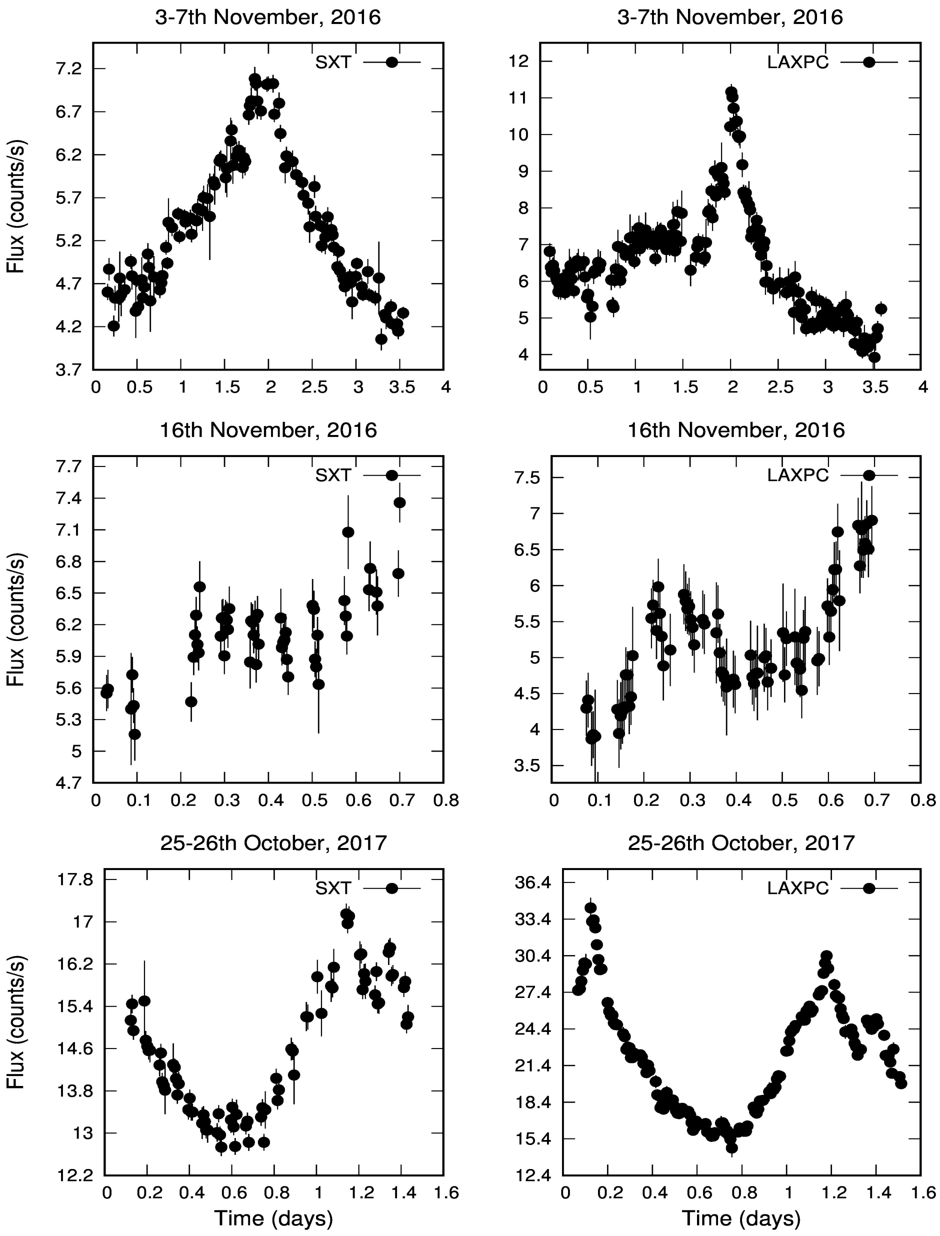
19th November, 2017

19-20th January, 2018

19-20th January, 2018

23-28th April, 2019

23-28th April, 2019


3-7th November, 2016

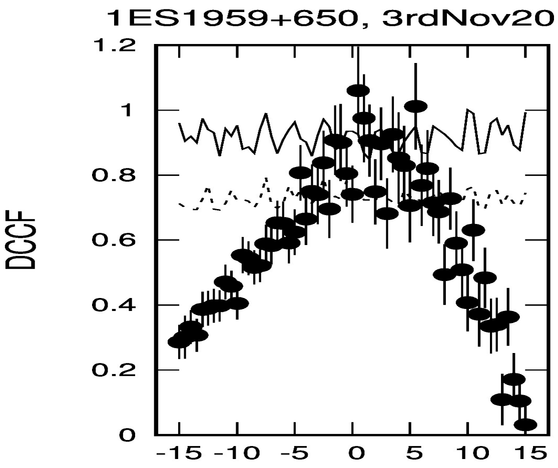
3-7th November, 2016

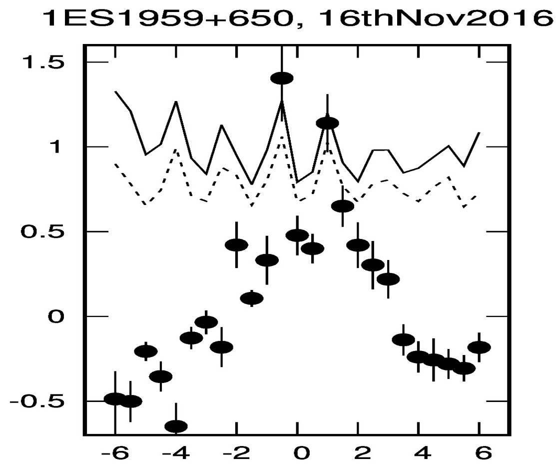
16th November, 2016

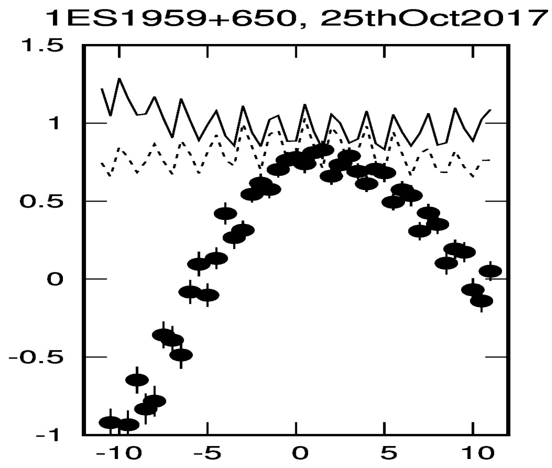
16th November, 2016

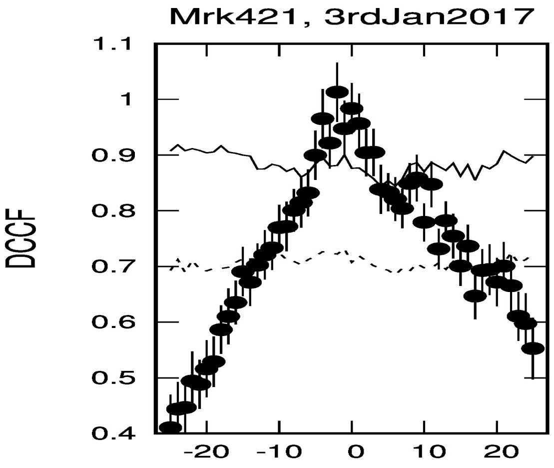
25-26th October, 2017

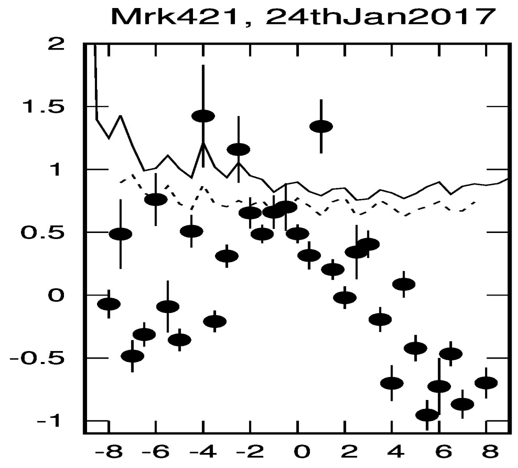
25-26th October, 2017

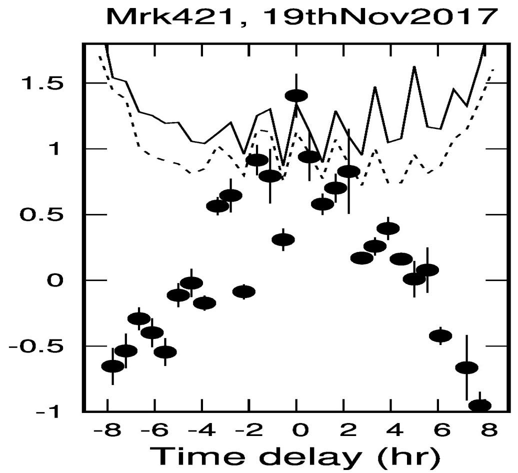


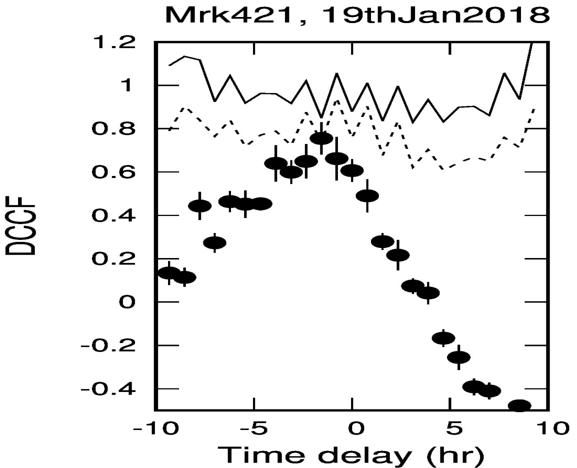


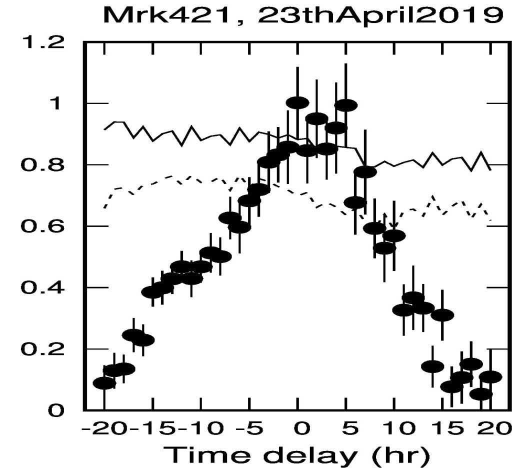












Soft-Hard X-ray Cross-Correlation Functions: Shows zero, positive, and negative time delays

Das & RC (2022), Submitted to ApJ

What Causes the Lags?

☐ Radiative Cooling: Faster for particles emitting higher energies

⇒ Happens earlier at hard X-rays

⇒ Soft lag

☐ Gradual Acceleration: Earlier for particles emitting lower energies

⇒ Happens earlier at soft X-rays

⇒ Hard lag

Observation date	Time lag (hr)
2017 January 3-8	3.90 (+0.74, -0.95)
2017 January 24	−1.42 (+1.21, -1.15
2017 November 19	0.57 (+0.54, -0.29)
2018 January 19-20	−3.07 (+1.07, -1.70
2019 April 23-28	1.24 (+0.50, -0.56

Das & RC (2022), Submitted to ApJ

Acceleration and Cooling Timescale

- Acceleration and Cooling timescsle in observer's frame (Zhang et al. 2002),
-

$$t_{acc}(E) = 9.65 \times 10^{-2} (1 + z)^{3/2} \xi B^{-3/2} \delta^{-3/2} E^{1/2}$$

$$t_{cool}(E) = 3.04 \times 10^{3} (1 + z)^{1/2} B^{-3/2} \delta^{-1/2} E^{-1/2}$$

ξ = Acceleration parameter

= λ / r_g = Mean free path /Gyroradius (Inoue & Takahara 1996)

Physical Parameters from Time Lag

- **In Mrk 421**, (from hard and soft lag)

If $\delta \sim (10 - 20)$ then, $B = (0.06 - 0.14)$ Gauss, $\xi \sim 10^4$

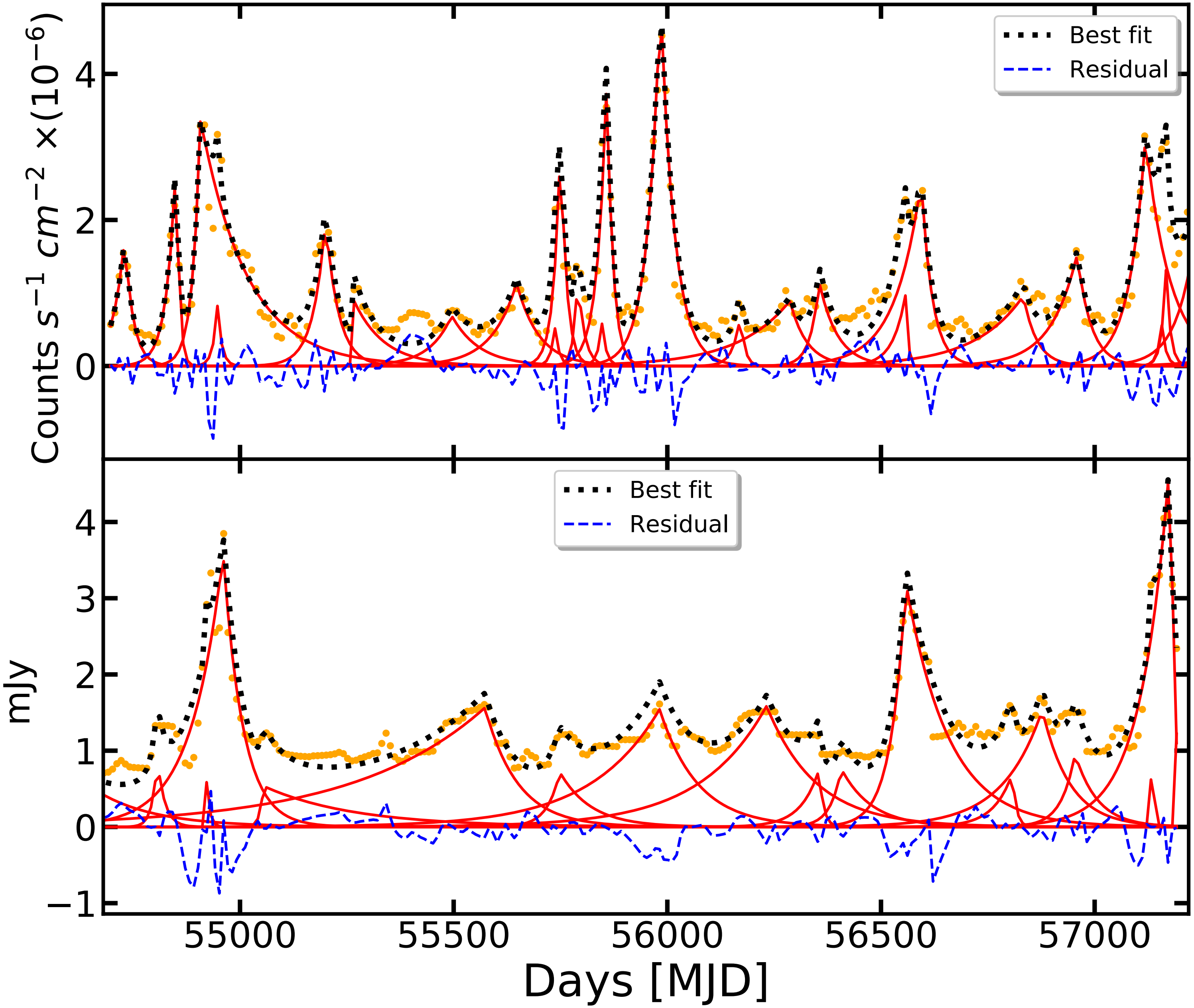
- **In 1ES 1959+650**, (from hard lag)

$B \delta \xi^{-2/3} = 1.05 \times 10^{-3}$

If $B = 0.1$ G and $\delta = 10$, $\xi \sim 10^4$

- $\xi = \lambda / r_g \sim 10^4$ => Amplification in each scattering ~ 0.007% - 0.23%

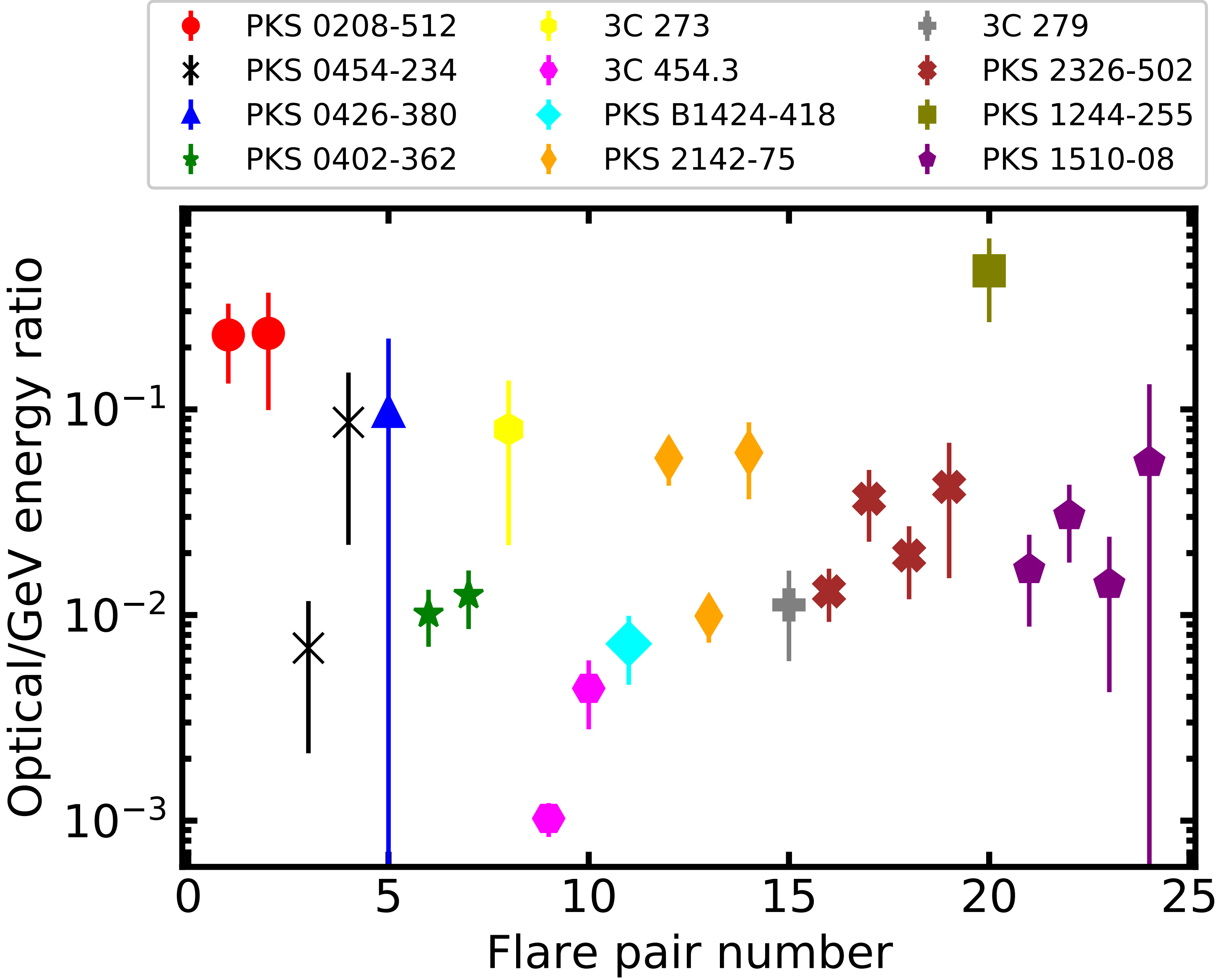
Locating the Gamma-Ray Emission Region in the Jets



GeV and Optical R-band light curves of the blazar PKS 1510-089 During 2008-2016.

“Flare Pairs” are simultaneous outbursts at both bands.

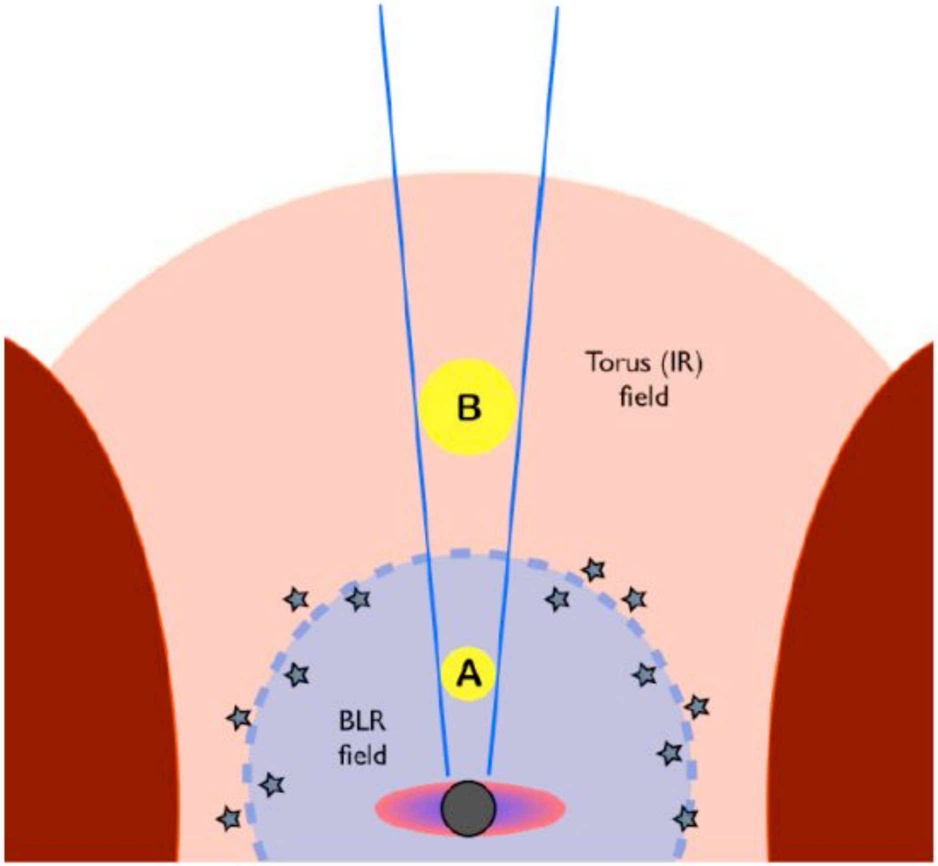
Barat, RC & Mitra (2022, MNRAS)



Optical/GeV Energy Dissipation Ratio of Flare Pairs in Several Blazars

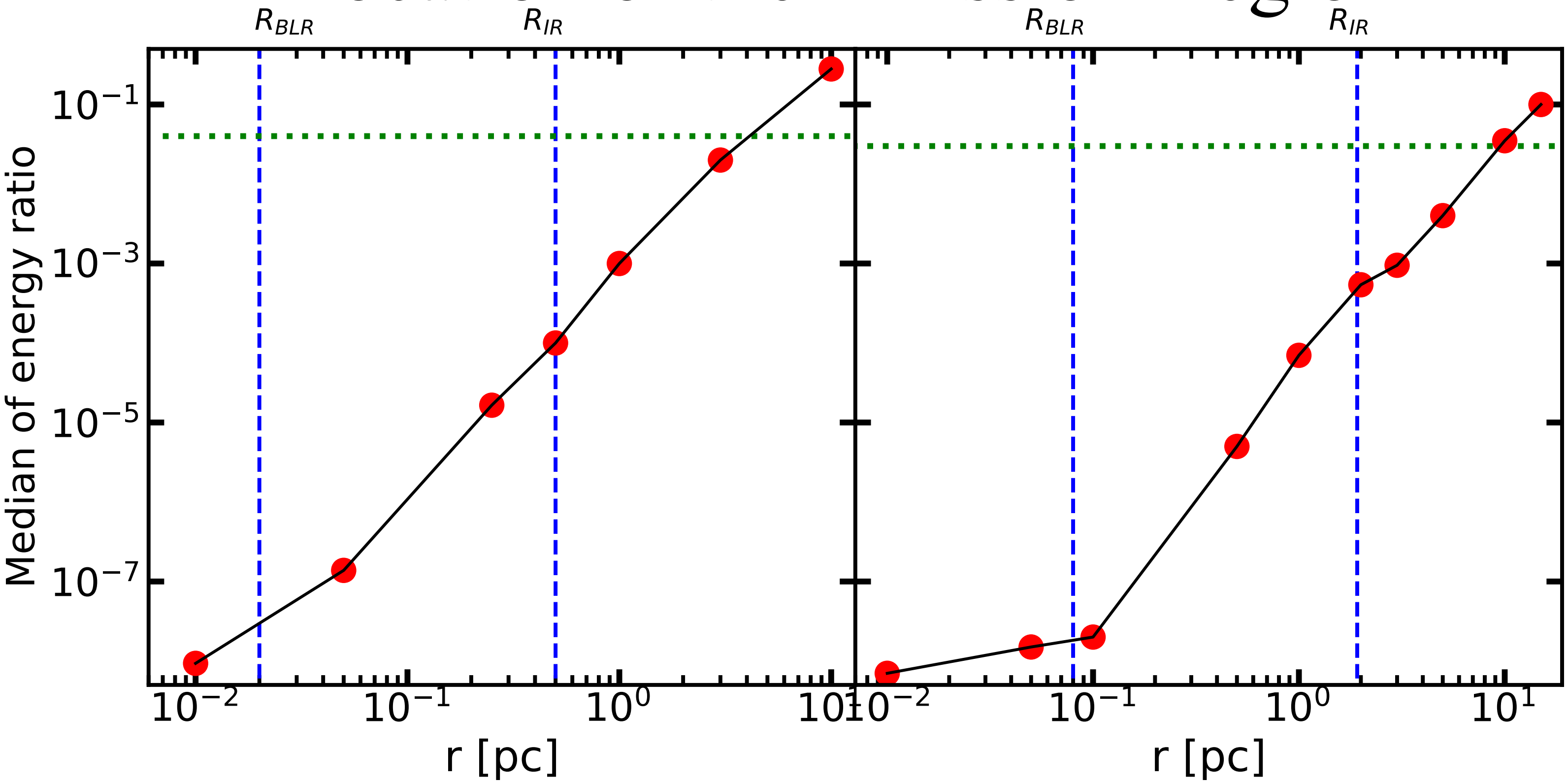
Barat, RC & Mitra (2022, MNRAS)

Source of External Photons in the Jet: BLR (0.1-1 pc) and Torus (10-100 pc)



Credit: Fabrizio Tavecchio

Theoretical Optical/GeV Energy Dissipation Ratio vs Location of the Emission Region



$$t_{cool}^{sync} \simeq 7.7 \times 10^{8} \, (1+z) \delta^{-1} B^{-2} \gamma_{eff}^{-1} \text{ s}$$

$$t_{cool}^{IC} \simeq 3.0 \times 10^{7} \, U_{rad}^{-1} \gamma_{IC}^{-1} \text{ s}$$

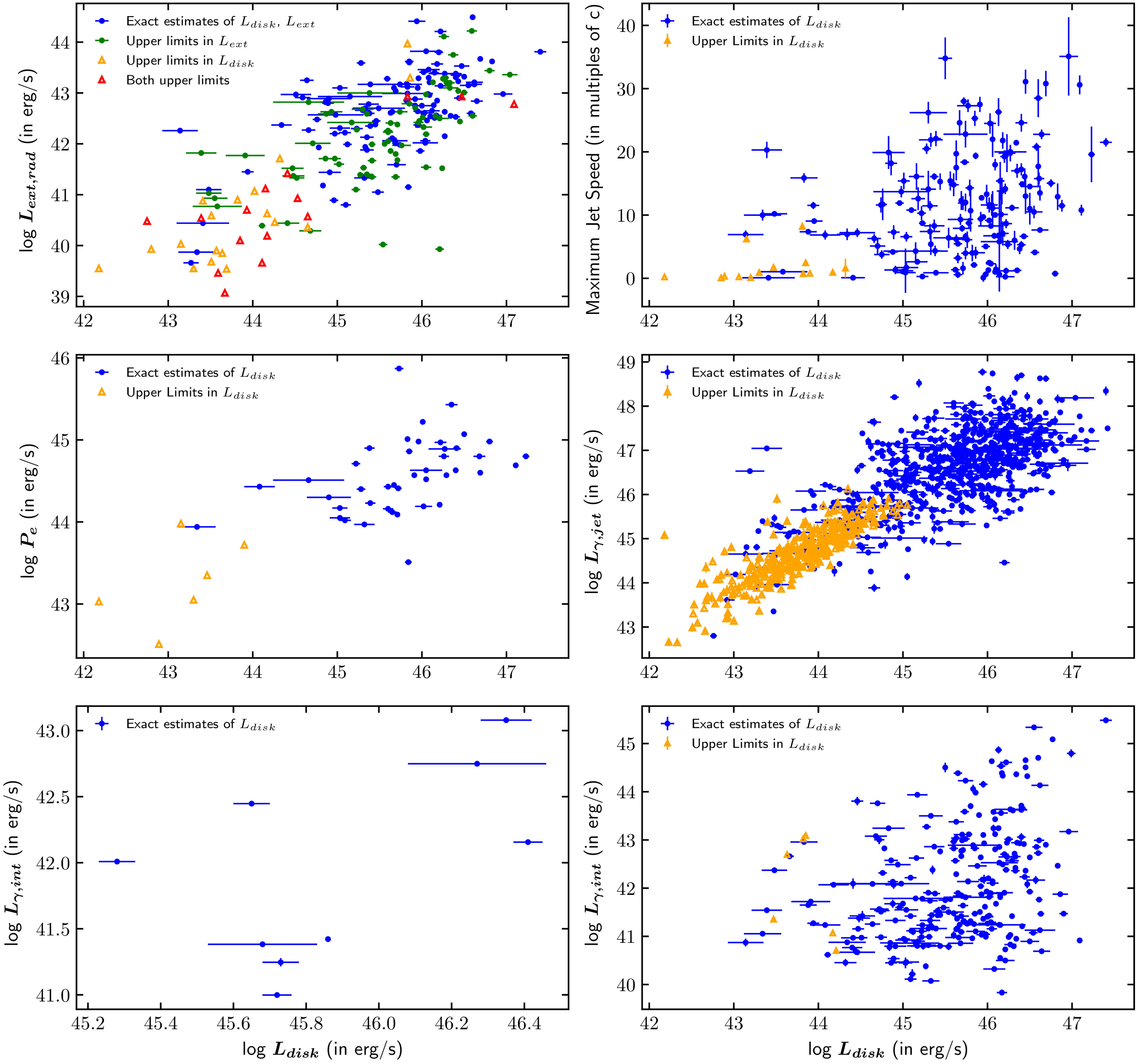
Barat, RC & Mitra
(2022, MNRAS)

Accretion Disk-Jet Connection in a Large Sample of AGN

No Universally Accepted Proxy of Jet Power

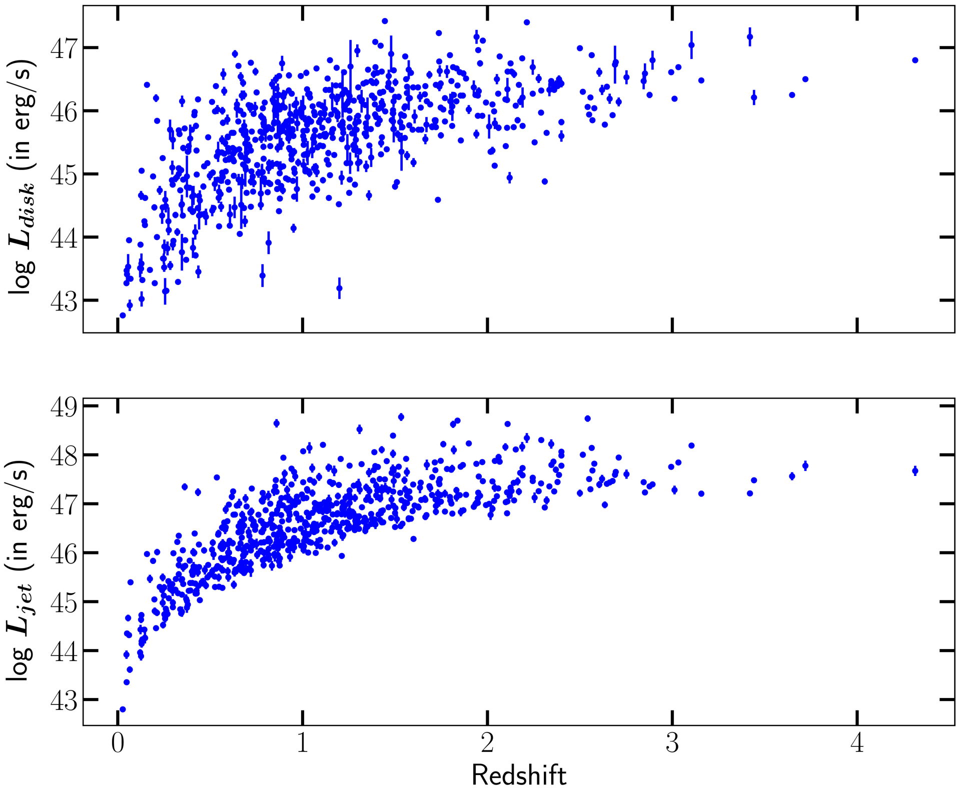
- Gamma-ray luminosity: Beamed
- Beaming correction: Precise value available for only a handful of blazars
- Superluminal speeds of radio knots: Not clear if apparent speed is suitable
- Electron kinetic power obtained from SED fitting: Model dependent
- Low-frequency radio emission: Not affected by beaming and not variable. Kpc scale

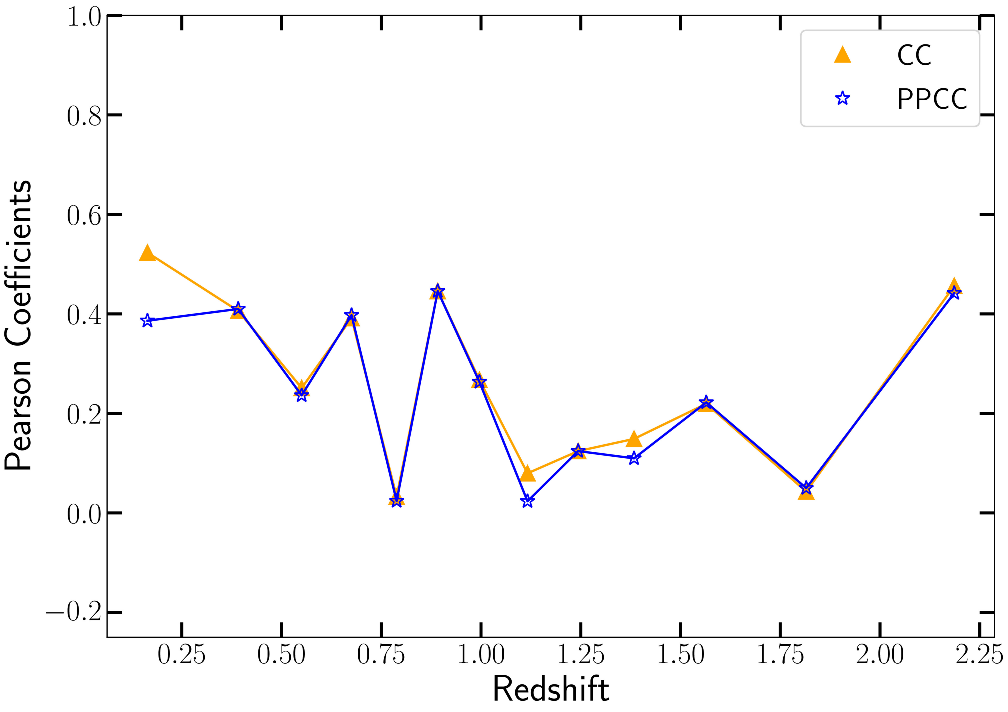
Different Measures of Jet Power vs Disk Power: Strong Correlation Observed



Rajguru & RC (2022, Phys Rev D)

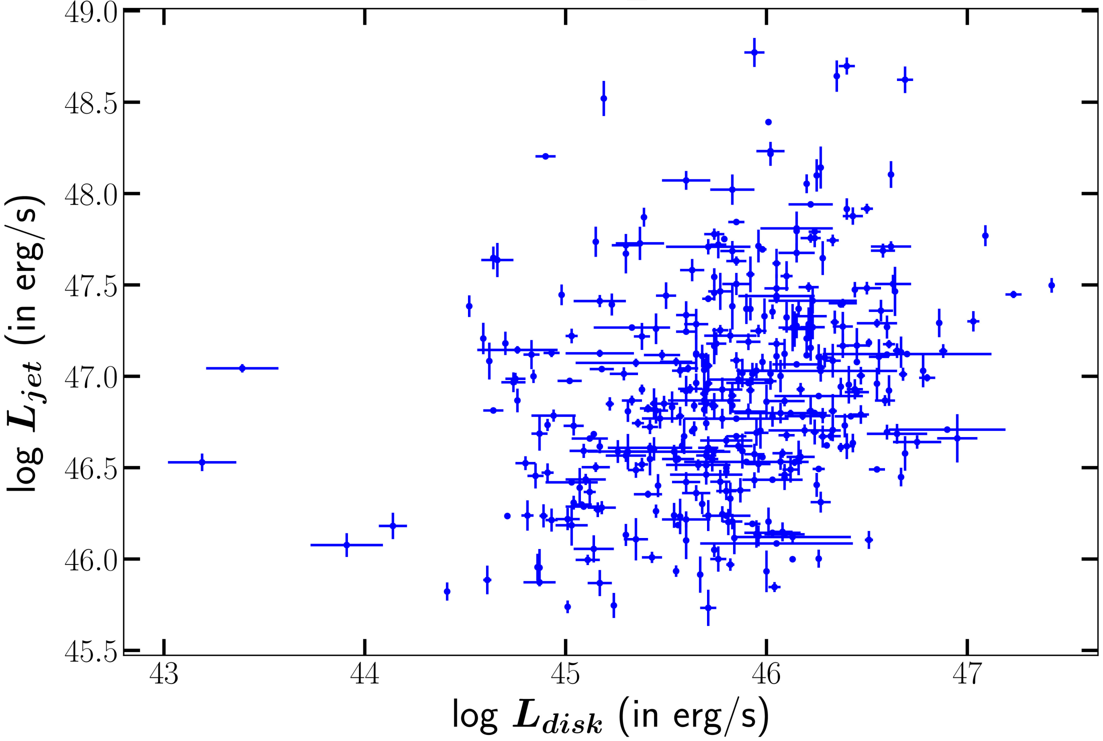
Common Redshift (Distance) Dependence of Various Measures of Jet Power: Intrinsic Correlation is Weaker





Rajguru & RC (2022, Phys Rev D)

Correlation is Weaker after Correction for Common Redshift Dependence



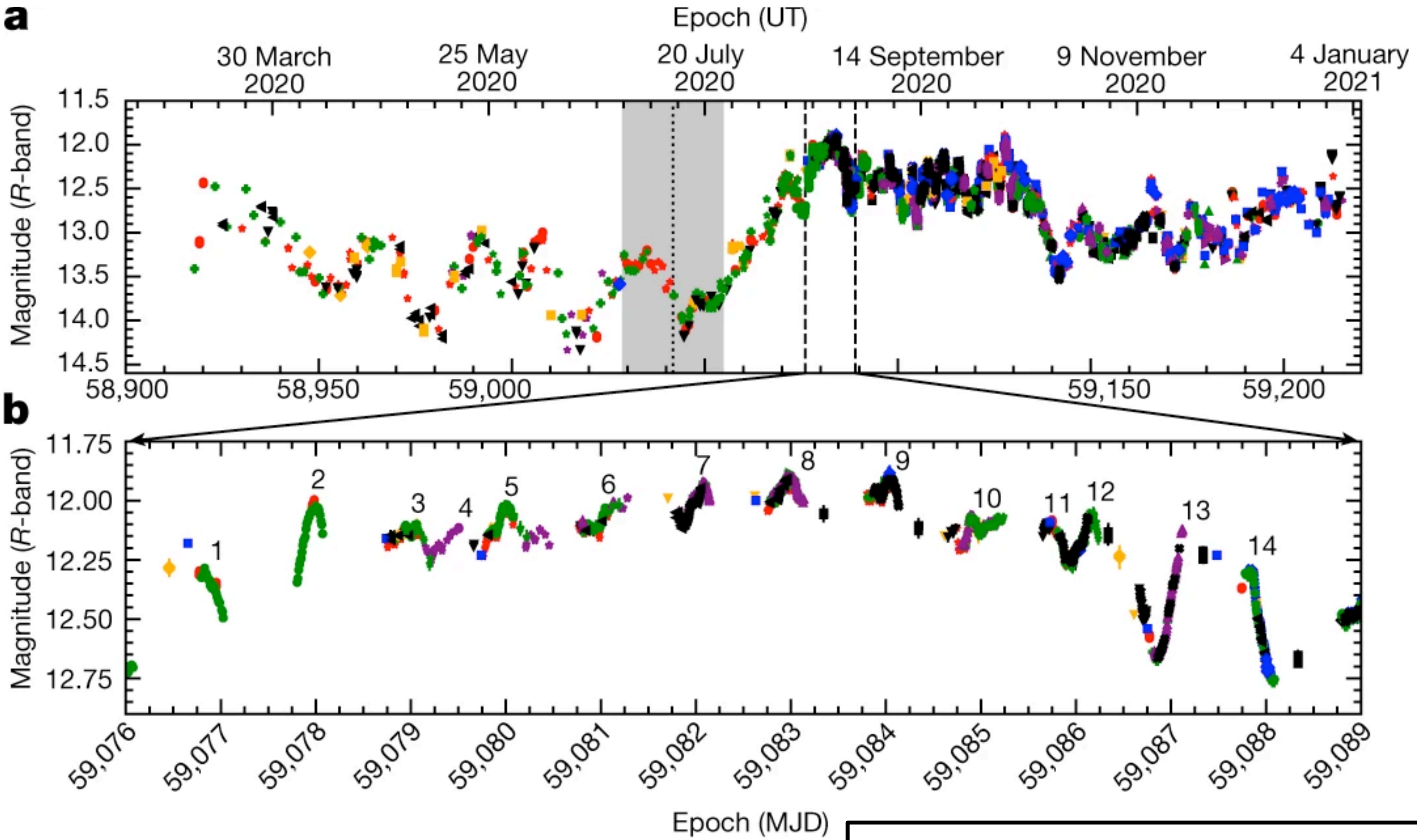
High Disk Power is a Necessary but not Sufficient Condition for High Jet Power

Rajguru & RC (2022, Phys Rev D)

THE END

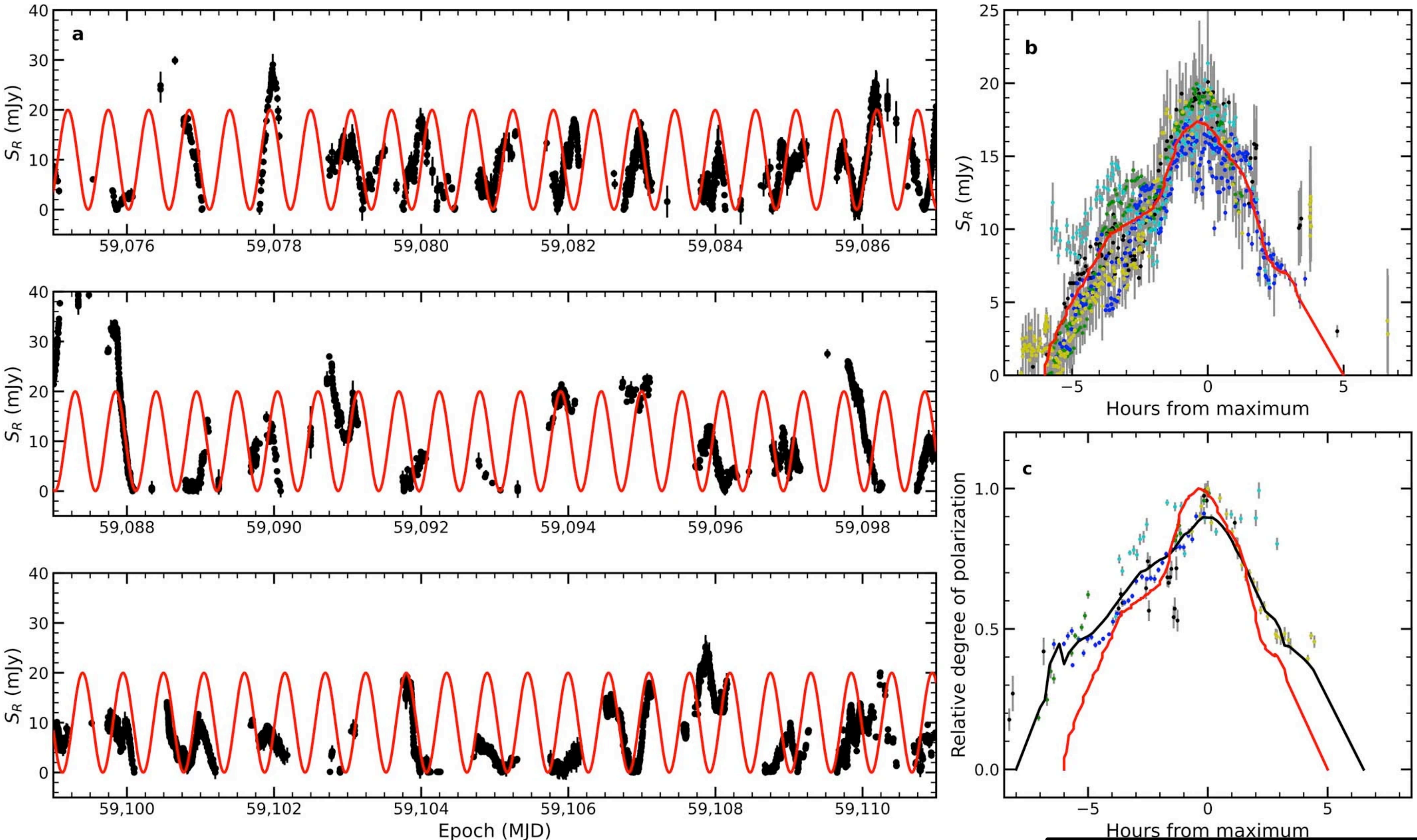
Magnetic field and Fluid Properties in the Jets

R-Band Flux Variation in the Blazar BL Lac



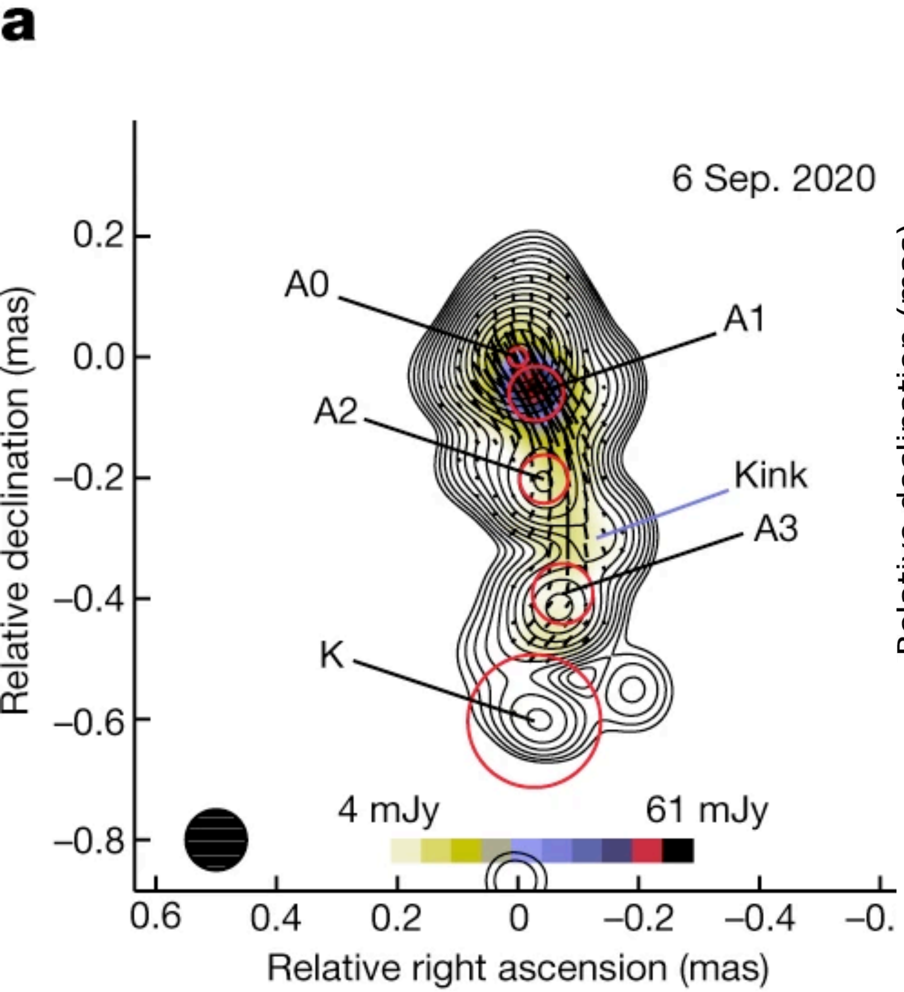
Jorstad, …, RC (2022, Nature)

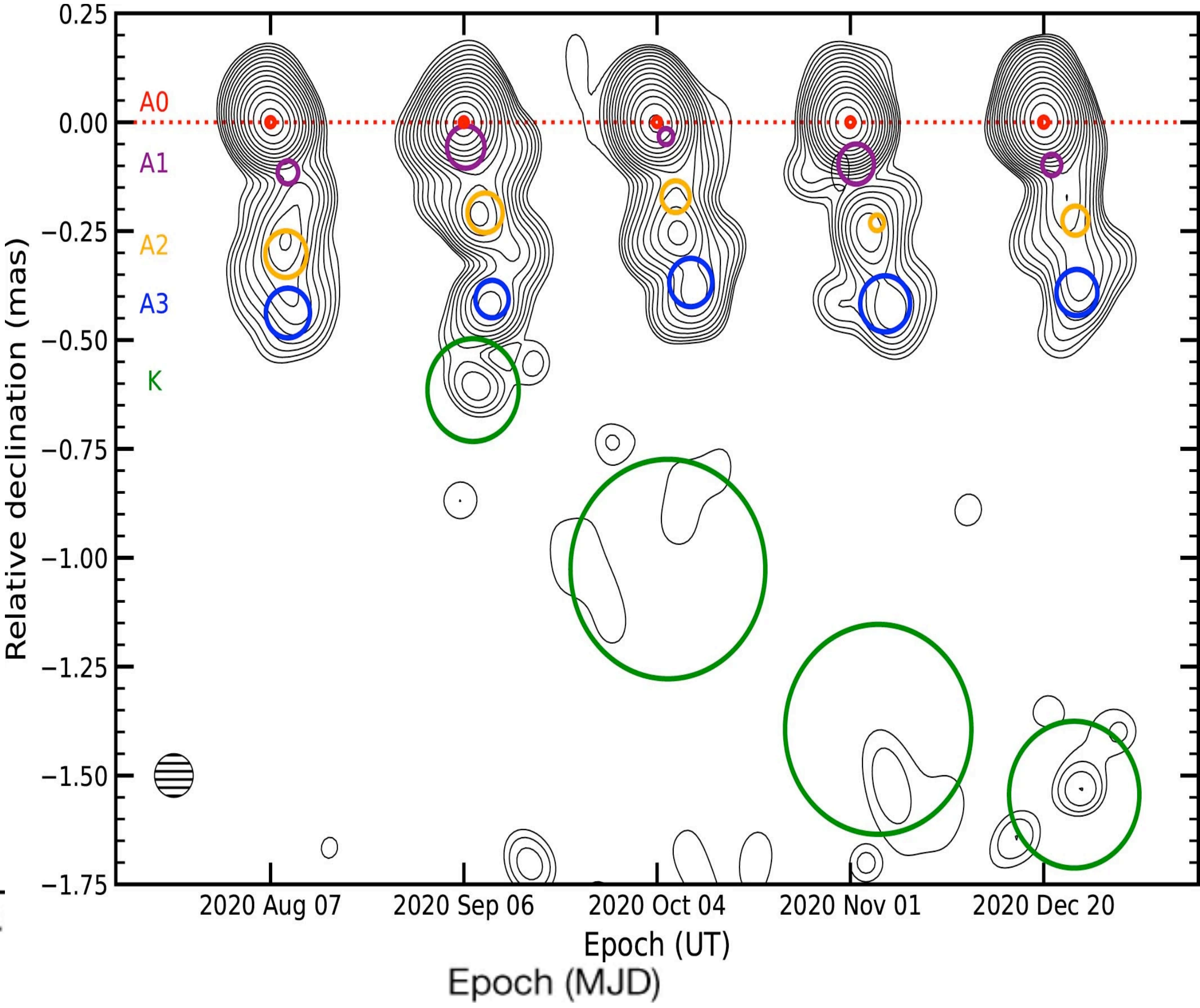
Quasi-Periodic Oscillation in Optical Flux and Polarization



Jorstad, …, RC (2022, Nature)

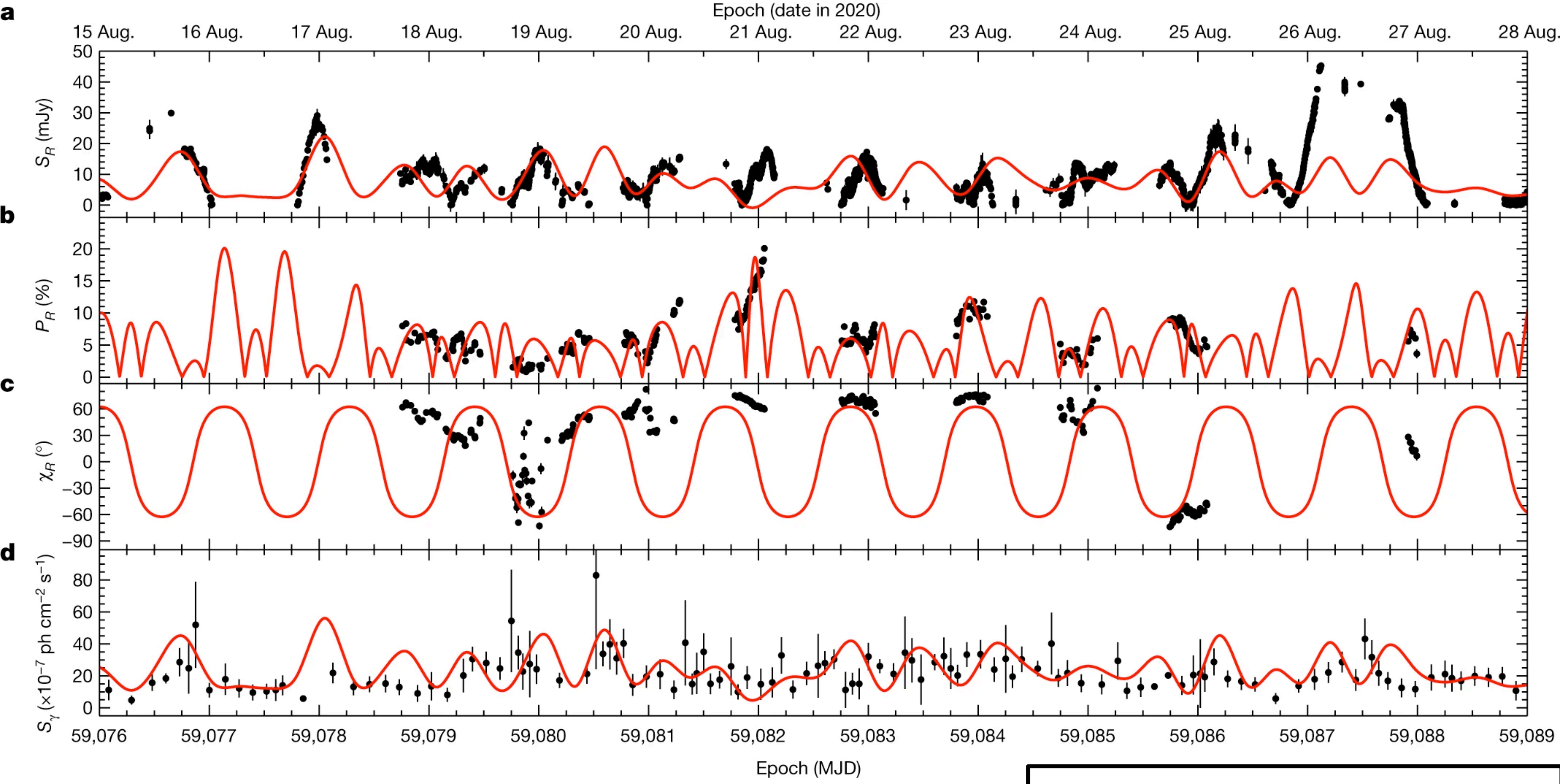
Sub-pc Scale Radio Image of the Jet





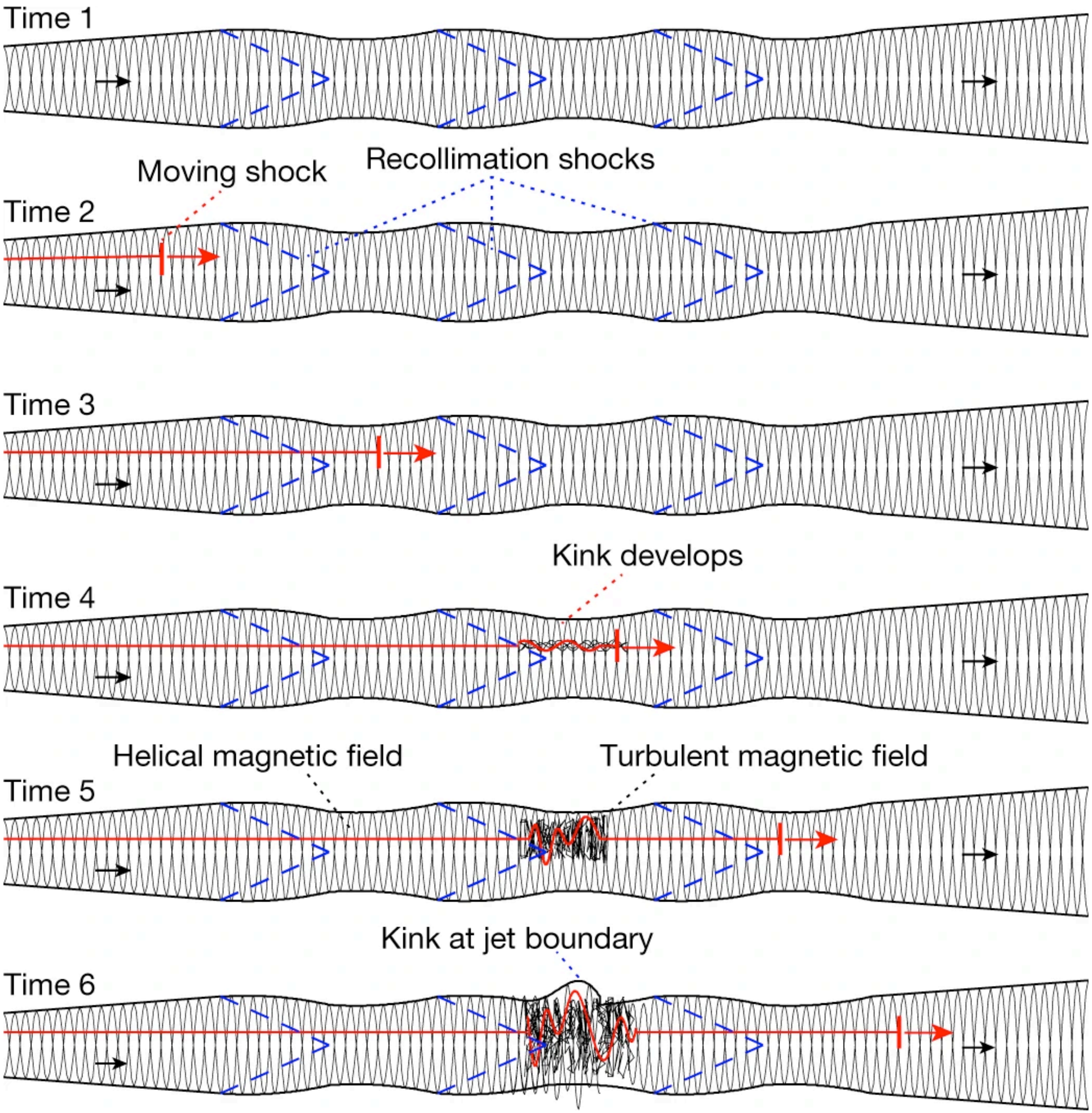
Jorstad, …, RC (2022, Nature)

Fitting of a kink instability model to the data: Many free parameters (uses an MCMC code to optimize)



Jorstad, …, RC (2022, Nature)

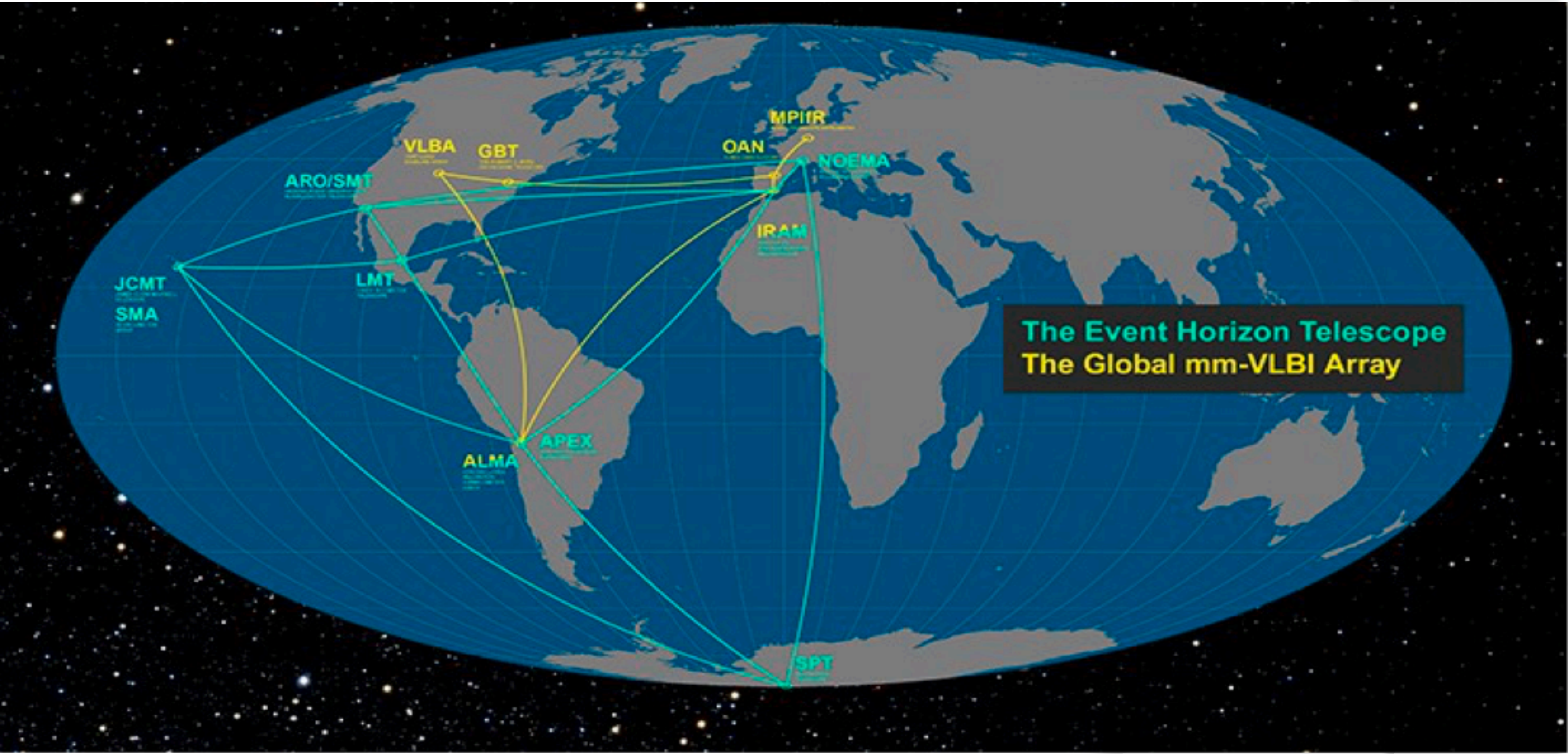
Schematic Picture of the Supposed Mechanism

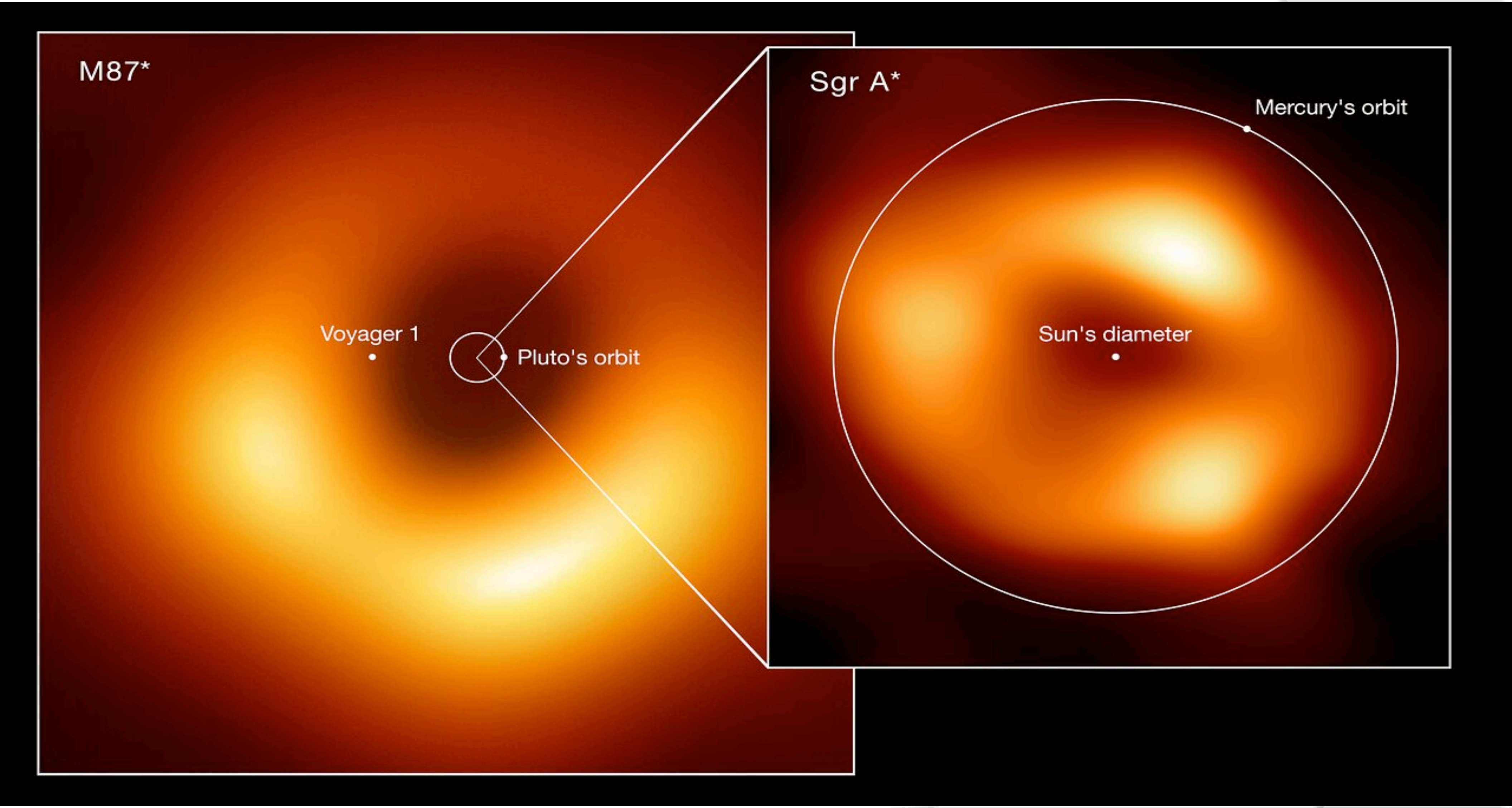


Jorstad, …, RC (2022, Nature)

Literature on Kink Instability in Jets

- **Dong, L., Zhang, H. & Giannios**, **D.** Kink instabilities in relativistic jets can drive quasi-periodic radiation signatures. Mon. Not. R. Astron. Soc. 494, 1817–1825 (2020).
- **Barniol, D. R., Tchekhovskoy, A. & Giannios, D.** Simulations of AGN jets: magnetic kink instability versus conical shocks. Mon. Not. R. Astron. Soc. 469, 4957–4978 (2017).
- **Zhang, H. et al.** Polarization signatures of kink instabilities in the blazar emission region from relativistic magnetohydrodynamic simulations. Astrophys. J. 835, 125 (2017).
- **Bodo, G., Tavecchio, F. & Sironi, L.** Kink-driven magnetic reconnection in relativistic jets: consequences for X-ray polarimetry of BL Lacs. Mon. Not. R. Astron. Soc. 501, 2836–2847 (2021).
- **Acharya, S., Borse, N. S. & Vaidya, B**. Numerical analysis of long-term variability of AGN jets through RMHD simulations. Mon. Not. R. Astron. Soc. 506, 1862–1878 (2021).


MPIfR
VLBA
GBT
OAN
NOEMA
ARO/SMT
IRAM
JCMT
SMA
LMT
APEX
ALMA
SPT
The Event Horizon Telescope
The Global mm-VLBI Array


M87*
Voyager 1
Pluto's orbit
Sgr A*
Mercury's orbit
Sun's diameter