Multiwavelength variability of radio-loud AGN/blazars

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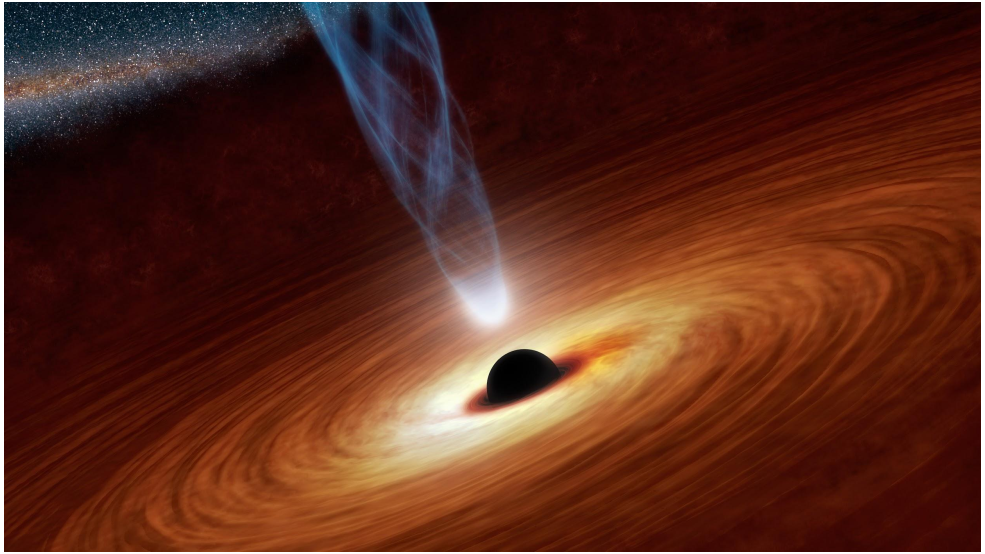


BLAZAR= AGN with one jet pointing toward us

Jet emission affected by relativistic

effects that depend on the

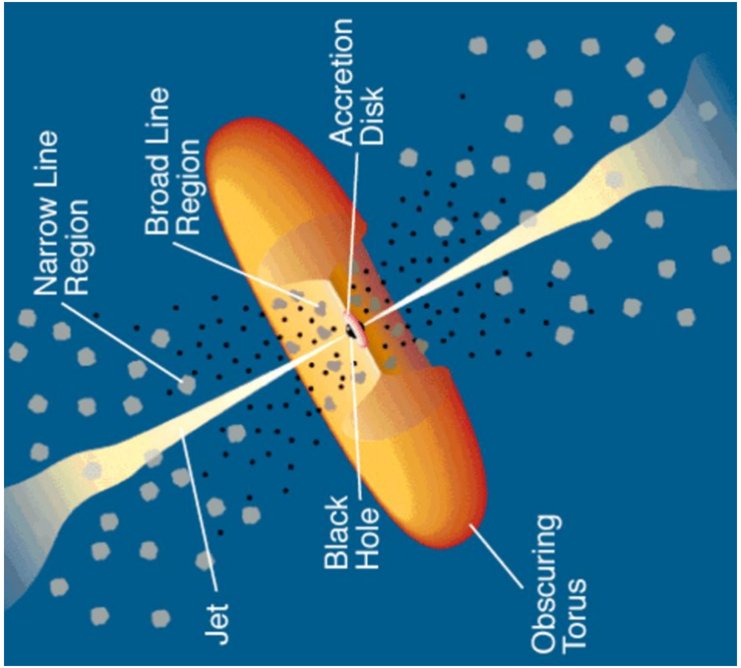
Doppler factor δ

δ=[Γ(1-βcosθ)]$^{-1}$

θ viewing angle

Γ=(1-β^2)$^{-1/2}$ bulk Lorentz factor

β=v/c plasma velocity



Urry & Padovani 1995, PASP, 107, 803

Consequences of Doppler beaming:

- flux relativistically enhanced $F_\nu(\nu) = \delta^{n+\alpha} F'_{\nu'}(\nu)$
- blue-shift of emitted frequencies $\nu = \delta\,\nu'$ prevailing over cosmological redshift
- shortening of variability time-scales $\Delta t = \Delta t'/\delta$

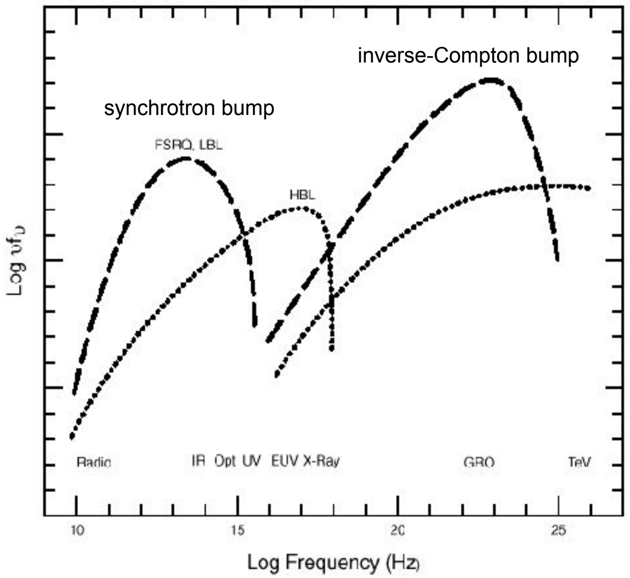
Two types of blazars:

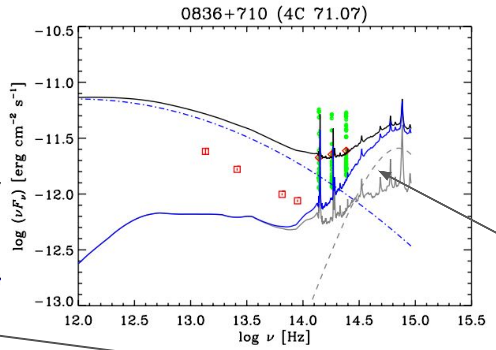
FSRQs (flat-spectrum radio quasars) - strong emission lines

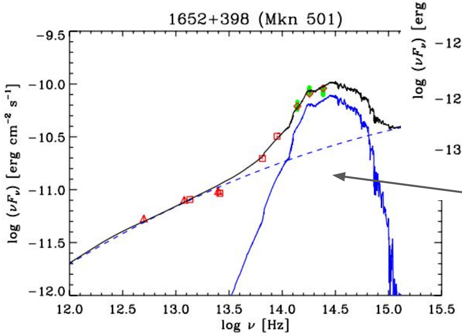
BL Lacs (BL-Lacertae-type objects) - weak or no emission lines

- Low-energy peaked BL Lacs (LBL)
- High-energy peaked BL Lacs (HBL)

Their spectral energy distribution (SED) is dominated by non-thermal radiation from the jet







Raiteri et al. 2014, MNRAS, 442, 629

But in the NIR-optical-UV band:

1. synchrotron from the jet - very variable and polarised
2. accretion disc and broad line region (big blue bump) - less variable and not polarised - can dominate in FSRQs
3. host galaxy (red) - not variable and not polarised - can dominate in low-redshift BL Lacs

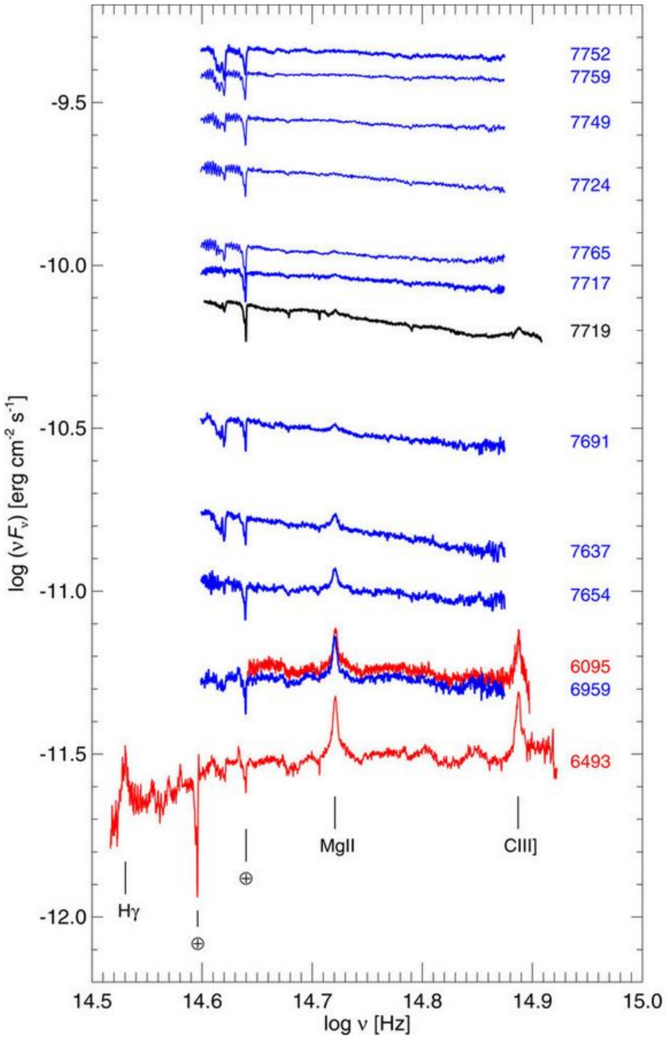
Changing type blazars

FSRQs can look like BL Lacs when the jet emission becomes stronger

BL Lacs can look like FSRQs when the jet emission becomes weaker
(even BL Lacertae itself!)

NOT A CHANGING LOOK PHENOMENON!

CTA 102, Raiteri et al. 2017, Nature, 552, 374

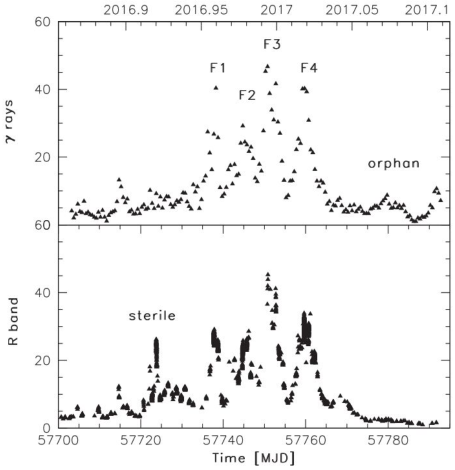


Blazar MW variability

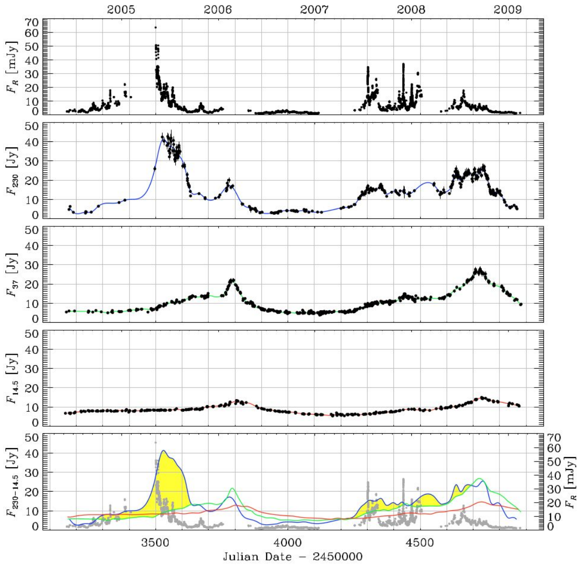
Unpredictable variability at all frequencies on all time-scales

Important information can be derived from the comparison between light curves at different frequencies

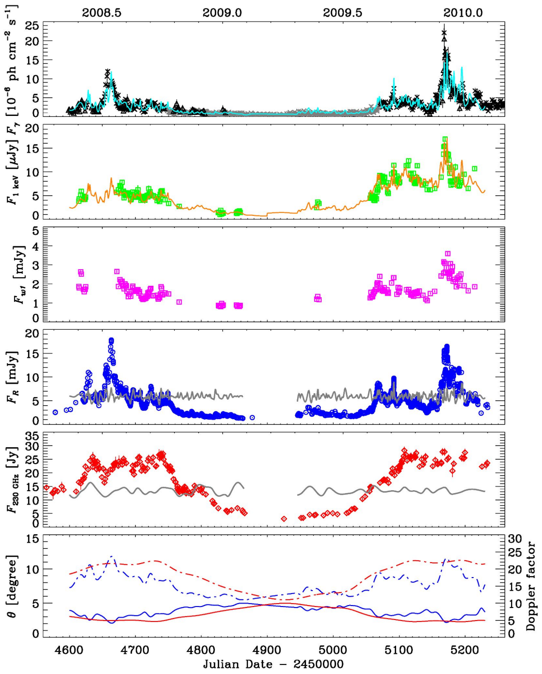
Often observed:
-optical-radio correlation with radio delay increasing with λ ➪ **inhomogeneous jet**
-optical-γ ~simultaneous correlation
BUT exceptions!



CTA 102, D'Ammando et al. 2019, MNRAS, 490, 5300



3C 454.3, Villata et al. 2009, A&A, 504, L9



3C 454.3, Raiteri et al. 2011, A&A, 534, A87

Very well-sampled light curves needed!

https://www.oato.inaf.it/blazars/webt/

Blazar MW variability: causes

Particle acceleration

shock waves (*Marscher & Gear 1985, ApJ, 298, 114*)

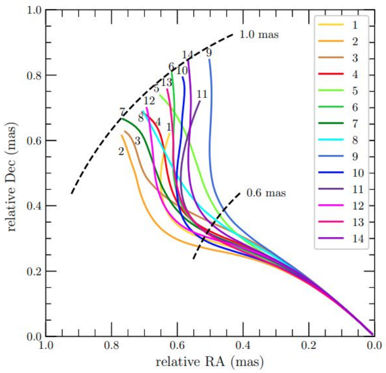
magnetic reconnection (*Sironi & Spitkovsky, 2015, ApJL, 783, L21*)

Orientation changes

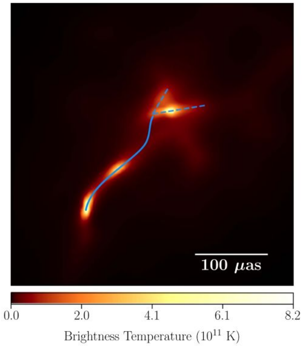
jet precession

jet rotation in supermassive black hole binary systems

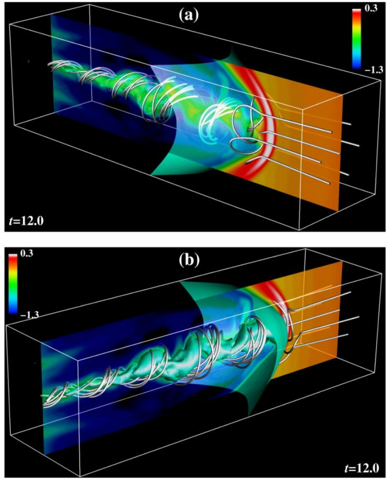
jet twisting (kink instabilities)



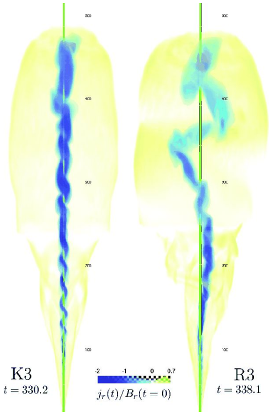
Lico et al. (2020, A&A, 634, A87)
"A parsec-scale wobbling jet in the high-synchrotron peaked blazar PG 1553+113"



Zhao et al. (2022, ApJ, 932, 72)
"Unraveling the Innermost Jet Structure of OJ 287 with the First GMVA + ALMA Observations"



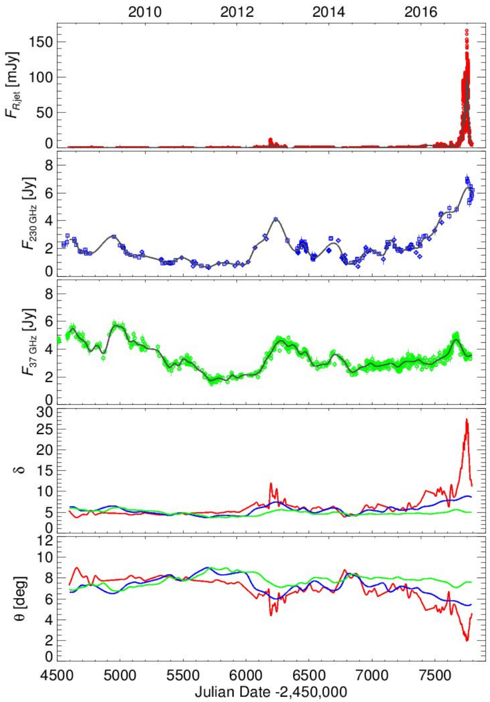
Nakamura et al. (2001, New Astronomy, 6, 61)
"Production of wiggled structure of AGN radio jets in the sweeping magnetic twist mechanism"

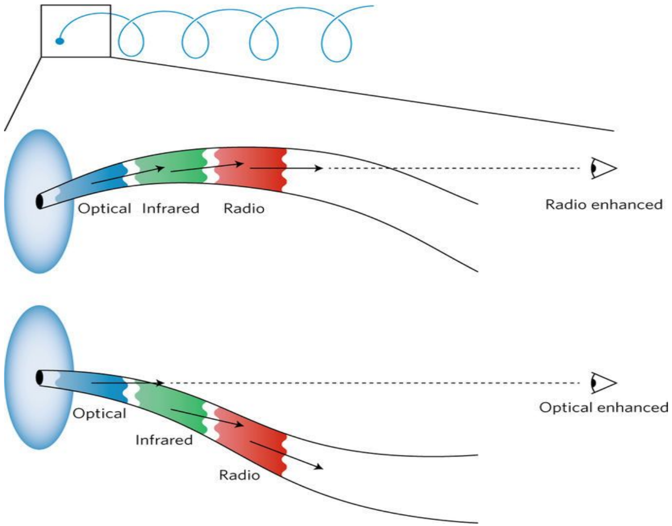


Moll et al. (2008, A&A, 492, 621)
" Kink instabilities in jets from rotating magnetic fields"

Blazar MW variability: geometric interpretation of the long-term trend

CTA 102, Raiteri et al. 2017, Nature 552,374





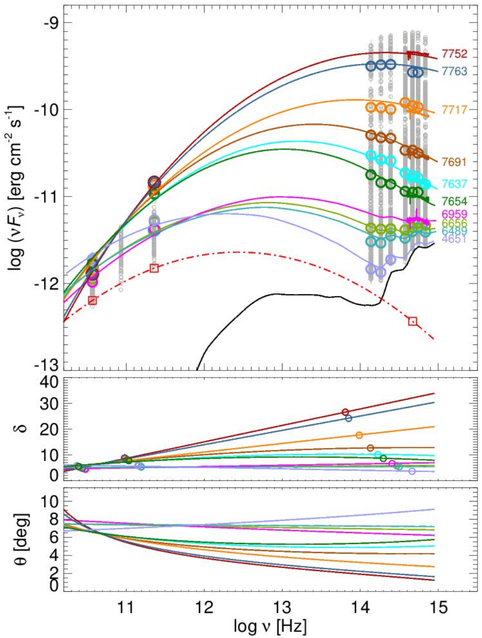
The *jet* is:

inhomogeneous: radiation at different frequencies emitted from different regions

curved: different emitting regions have different viewing angles

twisting: the viewing angle varies in time because of internal (instabilities) and/or external (orbital motion, precession) reasons

Whole Earth Blazar Telescope



Blazar MW variability: analysis of blazar SEDs in different brightness states

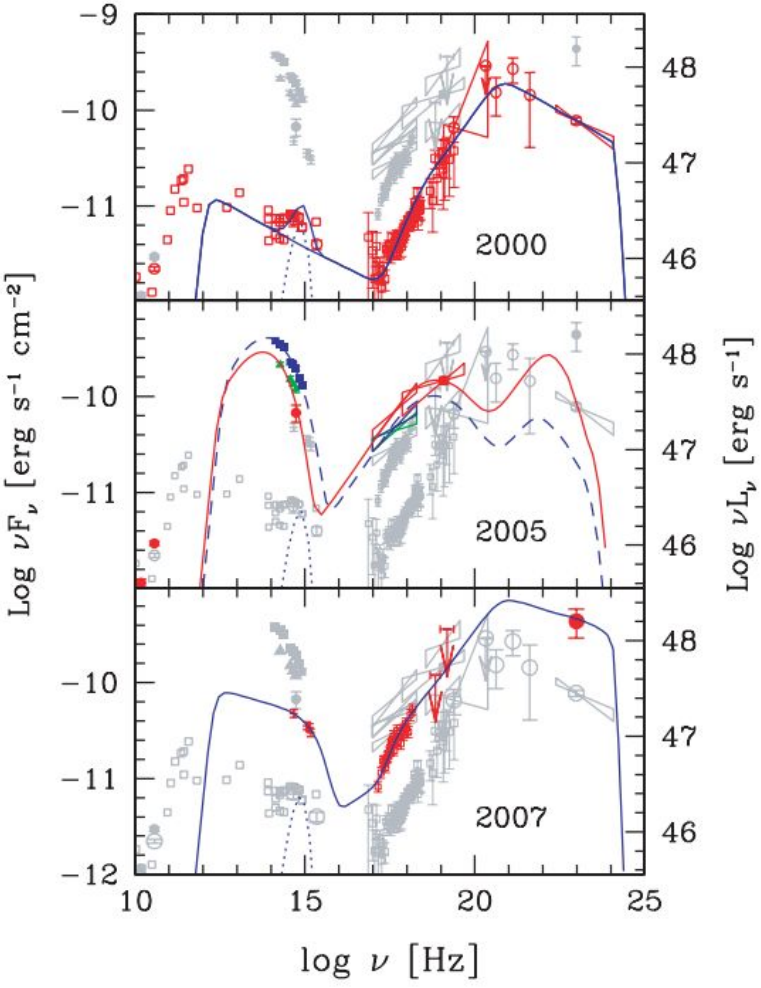
3C 454.3, Ghisellini et al. 2007, MNRAS, 382, L82:

Simple, one-zone, homogeneous synchrotron and inverse Compton model

All the observed radiation comes from this zone, BUT the radio emission

Viewing angle fixed to θ = 3.5 deg

	2000	2005 blue	2005 red	2007	Units
Γ	16	7	8	16	
R	25	15	17	25	10^{15} cm
$\Delta R'$	10	5	9	13	10^{15} cm
B	7	35	15	9	G
γ_{peak}	50	300	400	50	
γ_{max}	40	1	1	2.7	10^3
p	3.4	4.0	4.0	3.2	
L'_{inj}	0.07	0.5	0.4	0.3	10^{45} erg s^{-1}
δ	16.4	11.8	12.9	16.4	
t_{var}	14	11.8	12.2	14	h
L_B	29.3	50.1	15.5	48.5	10^{45} erg s^{-1}
L_p	444.4	180	227	1549	10^{45} erg s^{-1}
L_e	1.55	0.75	1.13	4.7	10^{45} erg s^{-1}
L_{rad}	17.4	22.2	24.8	77.5	10^{45} erg s^{-1}



IntraDayVariability (IDV) and Microvariability

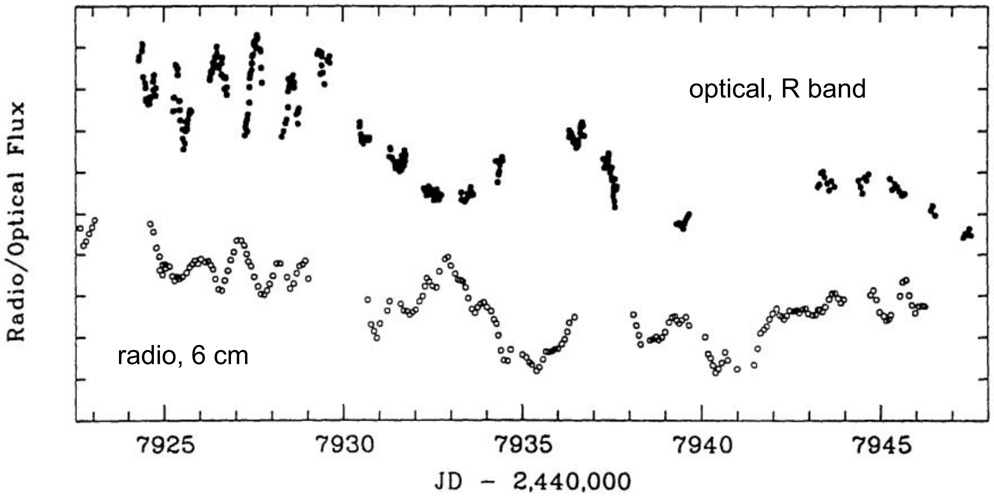
IDV has been known for several decades

Dimension of the emitting region from causality arguments:

$$R < c\, \Delta t_{obs}\, \delta / (1+z)$$

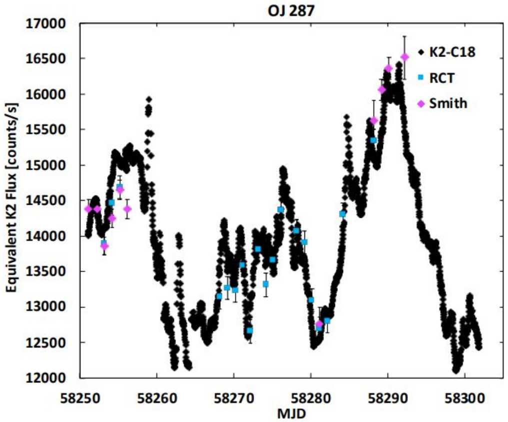
➪ microvariability implies either (unrealistic?) very high δ values (δ >> 50) or R much smaller than typical jet dimensions inferred from SED modelling

➪ emission from jet substructures?

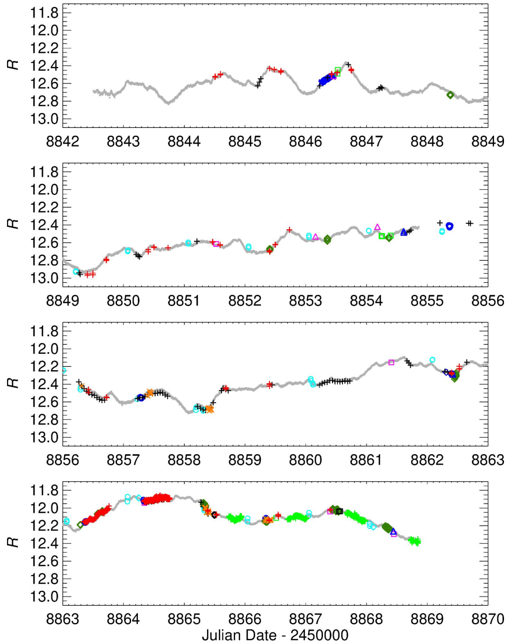


S5 0716+714, Wagner & Witzel 1995, ARAA, 33, 163

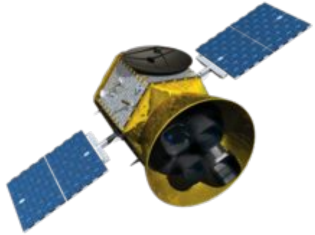
Optical microvariability from space: Kepler and TESS

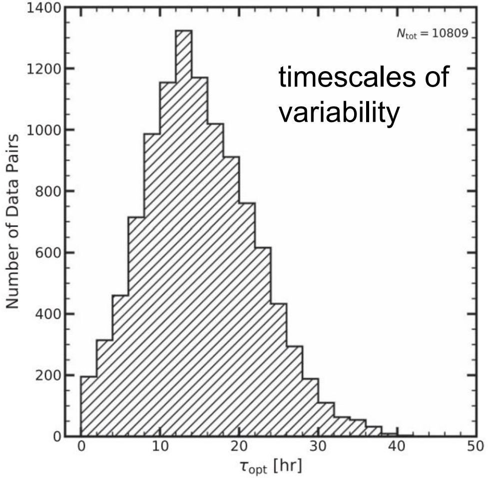


OJ 287, Wehrle et al. 2023, arXiv:2305.17060
K2 observations with cadence of 29.4 min over ~ 80 d in 2018



S5 0716+714, Raiteri et al. 2021, MNRAS, 501, 1100
TESS 2 min cadence
Δt_{obs}~0.2 d ⇨ **R< 4 10^{14} cm x δ**

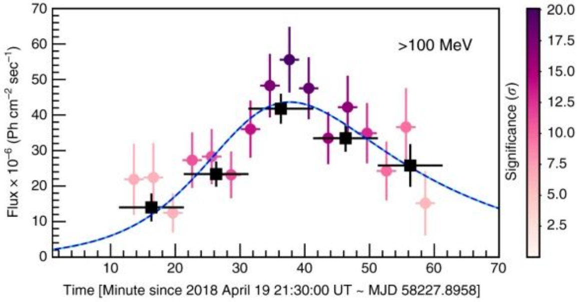




BL Lacertae, Weaver et al. 2020
TESS 2 min cadence
Δt_{obs}~0.5 h ⇨ **R< 5 10^{13} cm x δ**

Microvariability @ high energies

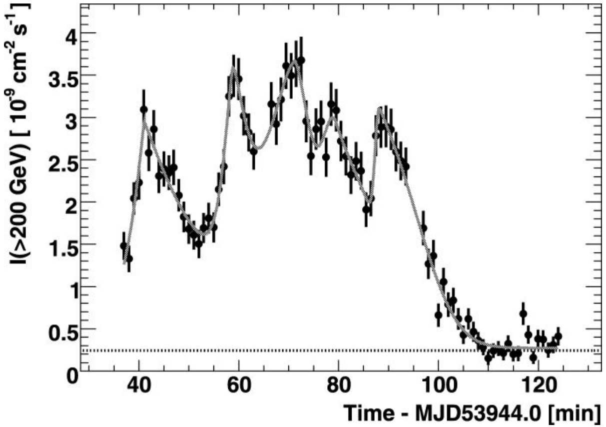
BL Lacs showing **variations at GeV and TeV energies on min time scales**

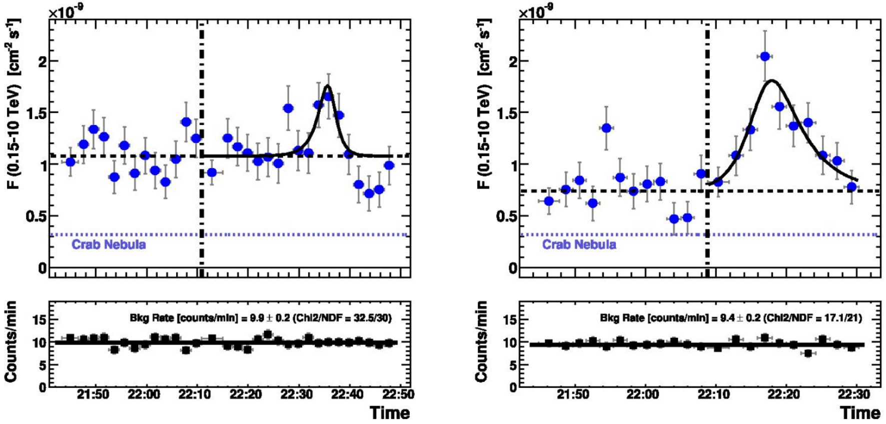


3C 279 with Fermi, Shukla & Mannheim, 2020, Nature Comm, 11, 4176
Magnetic reconnection in a small jet region (plasmoid) **R~8 10^{14} cm**

PKS 2155-304 with HESS, Aharonian et al., 2007, ApJ, 664, L71

R< 5 10^{12} cm x δ

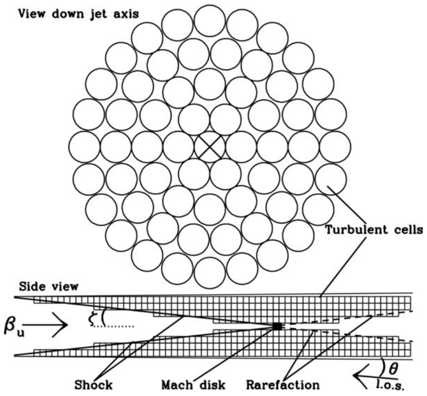




Mkn 501 with MAGIC, Albert et al. 2007, ApJ, 669, 862

Blazar variability: turbulence

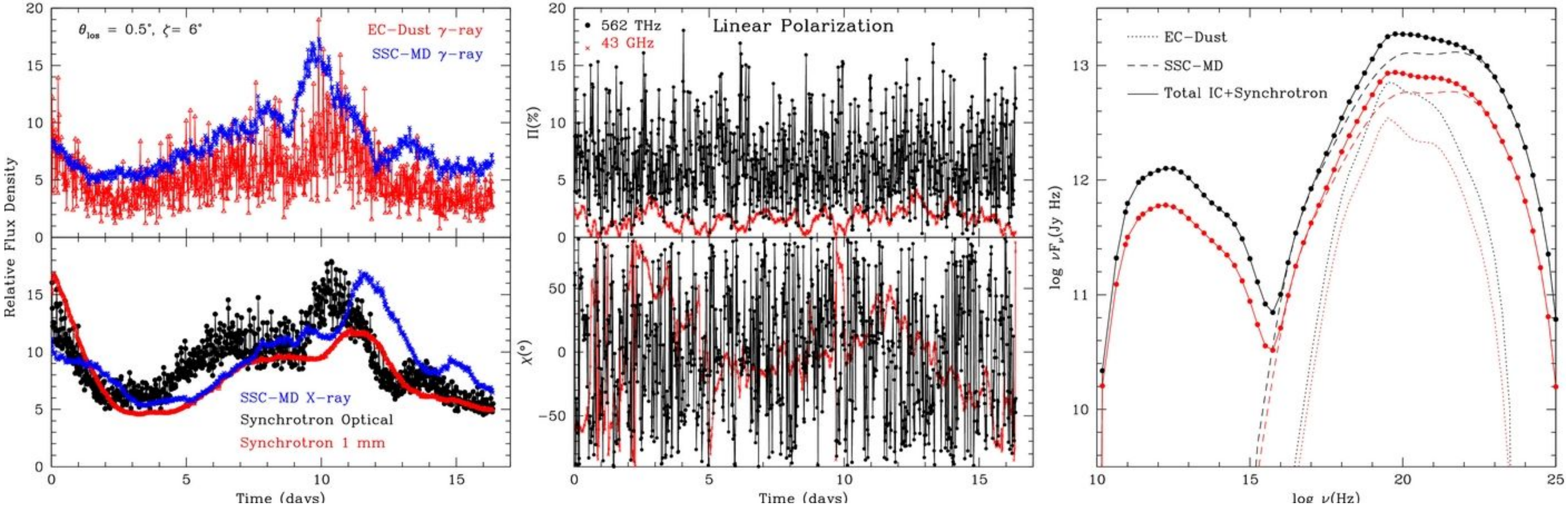
Marscher 2014, ApJ, 780, 87



Turbulent plasma + Shocks

Superposition of ordered and turbulent magnetic field components

Main features of MW light curves (correlations and delays), polarization behaviour (higher P at higher frequencies, EVPA rotations), and SEDs reproduced



Blazar polarimetric behaviour

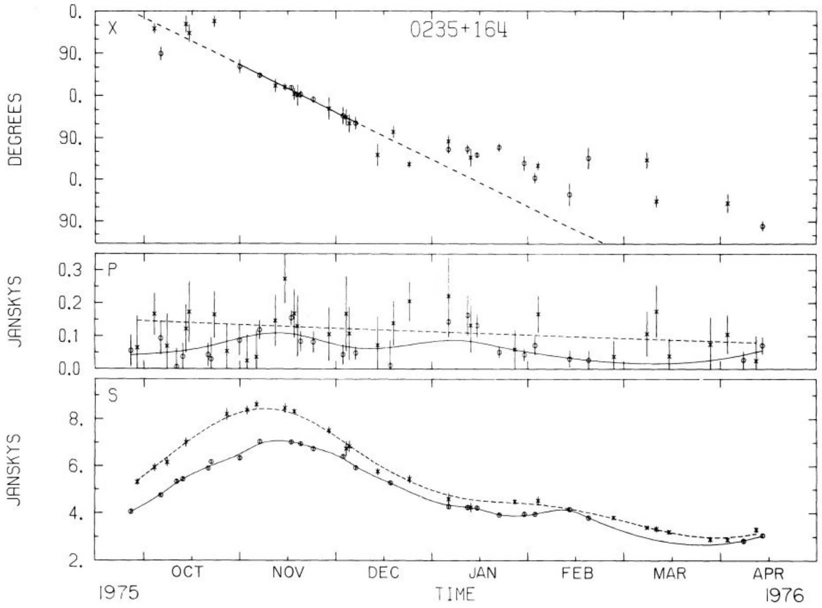
Jets physics governed by magnetic field, which can be studied through polarisation

High P= well-ordered **B**

Both polarization degree (P) and angle (EVPA) very variable

Correlation/anticorrelation of P_{jet} with F_{jet}

Wide rotations of EVPA (but 180 deg ambiguity requires high cadence)



deterministic or stochastic?

Ledden & Aller 1979, ApJ, 229, L1
Radio monitoring at 8 and 14.5 GHs @ UMRAO
Rotating magnetic field structure?

Blazar polarimetric behaviour

3C 279, Abdo et al. 2010, Nature

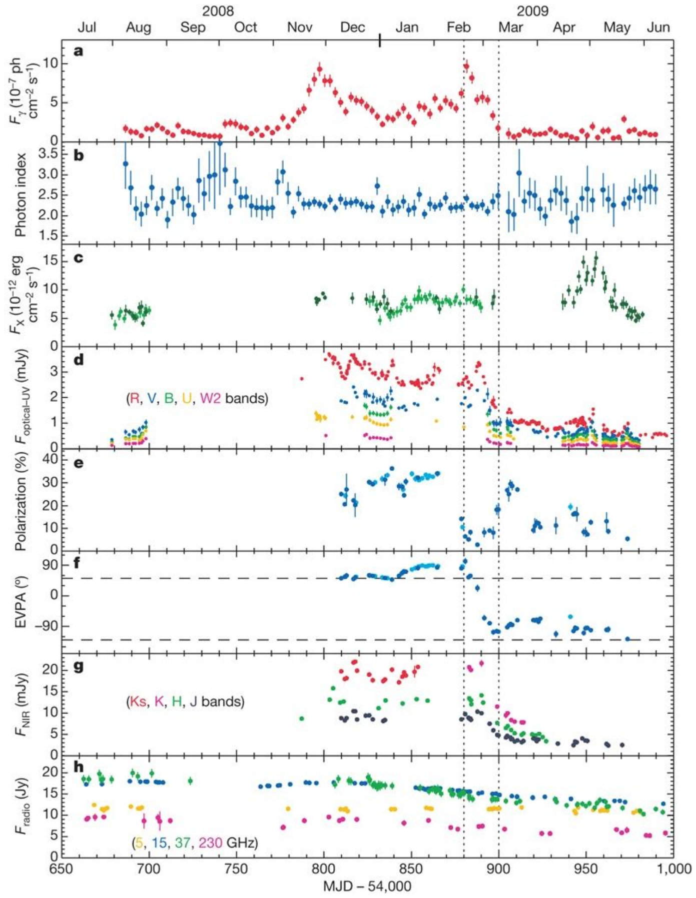
Coincidence of a γ-ray flare with a wide EVPA rotation

RoboPol project @ Skinakas telescope (Greece): statistical properties

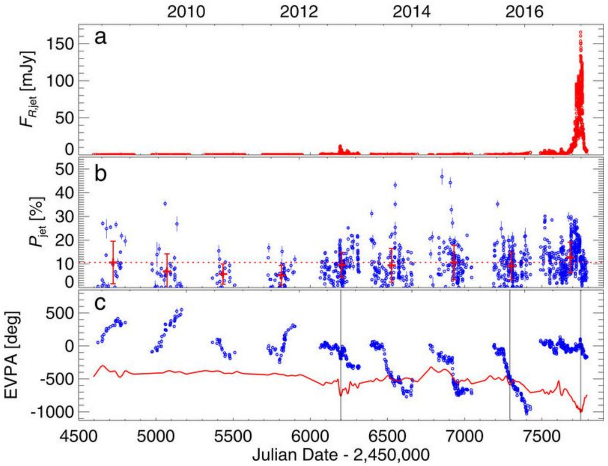
Blinov et al. 2018, MNRAS, 474, 1296;

EVPA rotations often correlated with γ-ray flares

➪ deterministic nature favoured



BUT

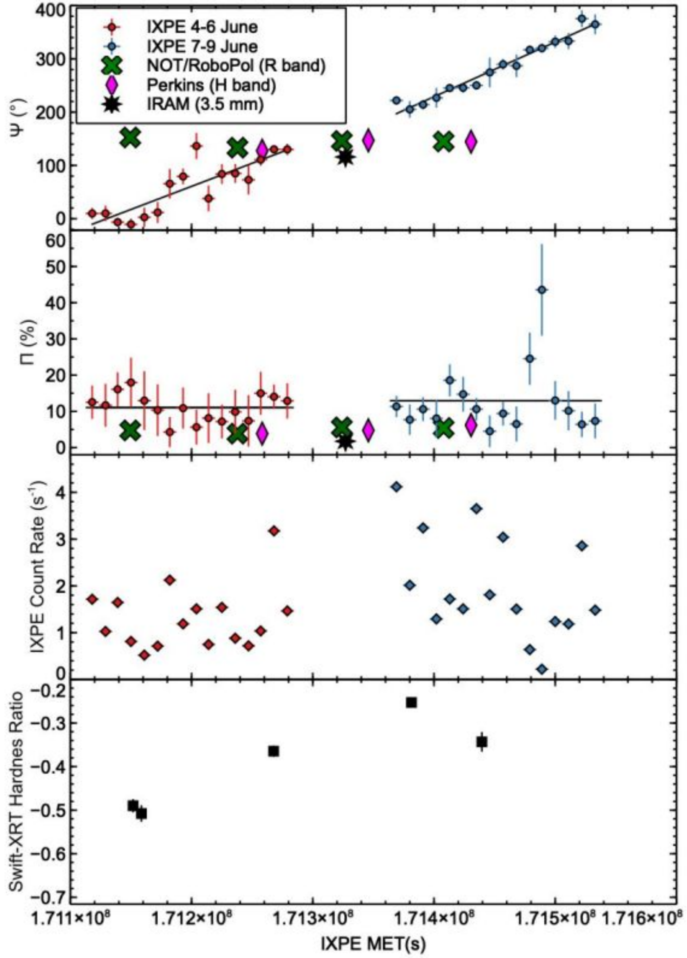


CTA 102, Raiteri et al. 2017, Nature, 552, 374

wide EVPA rotations in both directions not correlated with optical (and γ-ray) flux

➪ turbulence?

Polarization in X-rays: the Imaging X-ray Polarimetry Explorer (IXPE)



Mrk 421, Di Gesu et al. 2023, arXiv:2305.13497

X-ray EVPA rotation ≥ 360◦ with ~ constant rotation rate (80-90 deg/d)
Optical/NIR EVPA constant and consistent with radio EVPA

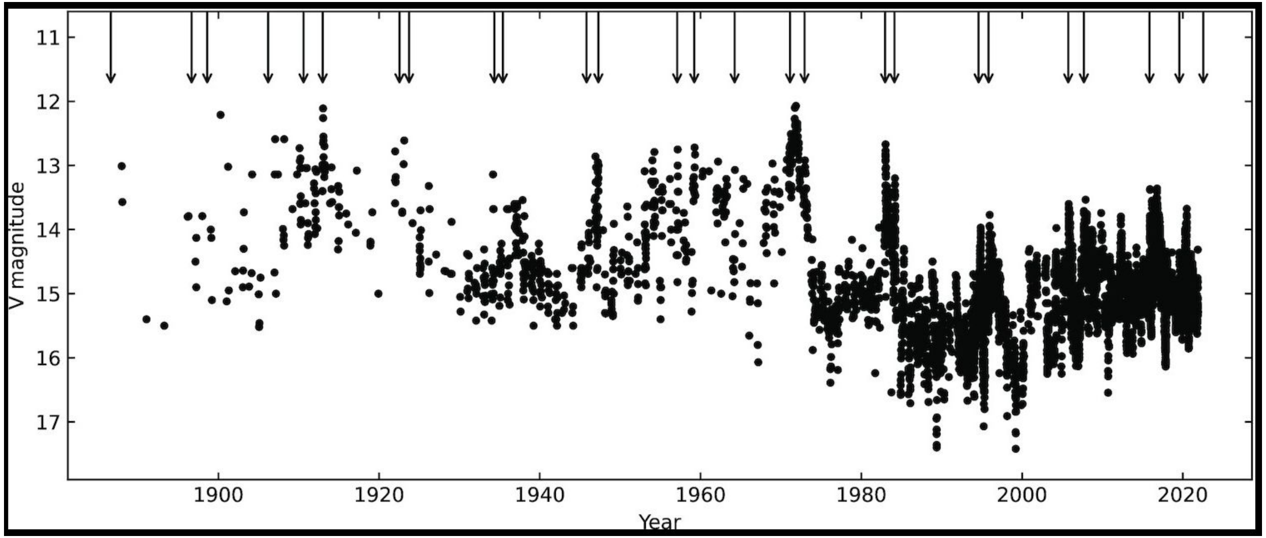
➪ X-rays from an inner spine, optical from a sheath surrounding it

➪ Observed rotation caused by a localized shock propagating along the helical magnetic structure of the jet

Periodicity: OJ 287

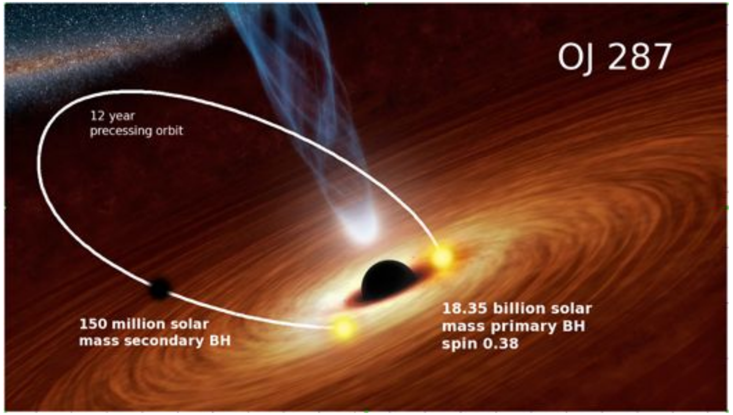
Sillanpaa et al. 1988, ApJ, 325, 628:
~12 yr periodicity of outbursts based on ~ 100 yr of data ➪ binary pair of supermassive black holes

Actually the outbursts are not exactly periodic and they are **double-peaked** (separation of 1-2 yr)



Valtonen et al 2023, MNRAS, 521, 6143

Periodicity of OJ 287 outbursts due to true luminosity changes



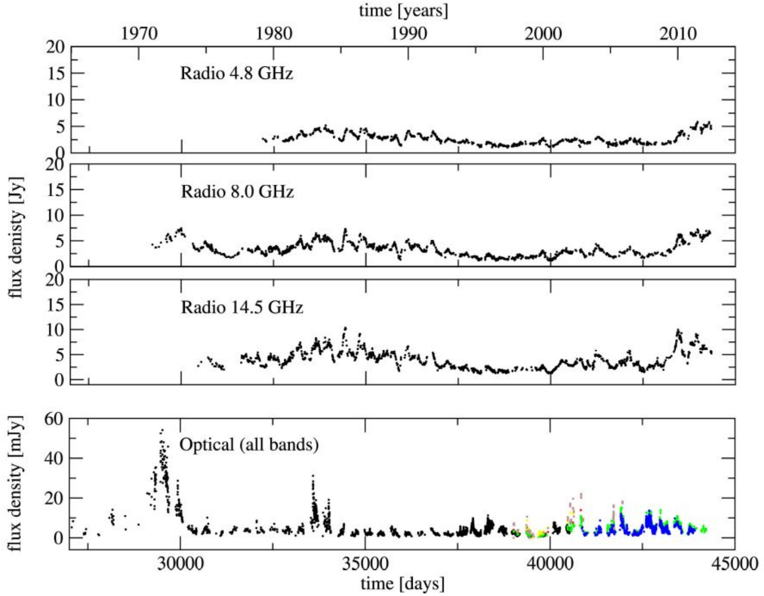
Dey et al. 2018, ApJ, 866, 11

Valtonen et al 2023, MNRAS, 521, 6143

double peak outburst = 2 thermal flares

The secondary SMBH impacts with the accretion disc of the primary twice every orbit

➩ pairs of thermal flares with no counterpart in radio or X rays



Britzen et al. 2018, MNRAS, 478, 3199:

Valtaoja et al. 2000, ApJ, 531, 744

double peak outburst =

1 thermal + 1 synchrotron flare

The secondary SMBH penetrates the accretion disk of the primary during the pericenter passage

➩ thermal flare visible only in the optical regime

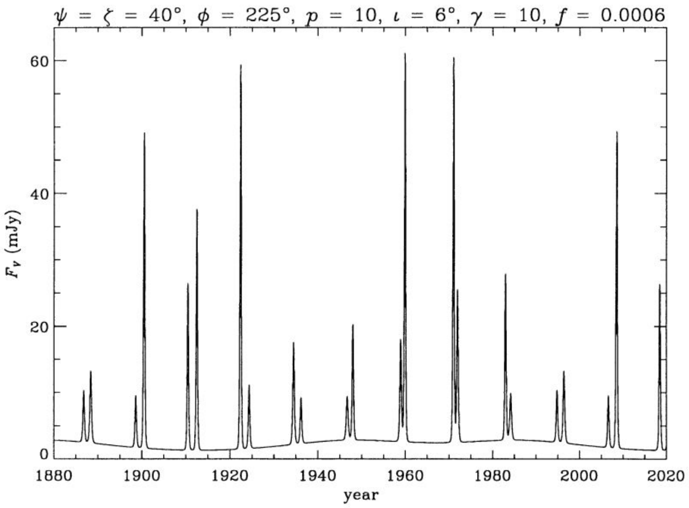
➩ enhanced accretion into the primary BH

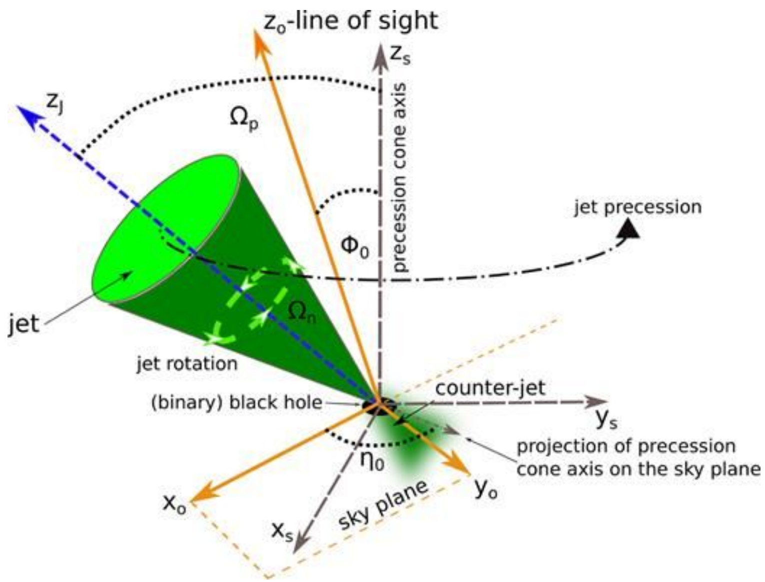
➩ increased jet flow and formation of shocks down the jet

➩ radio and optical synchrotron flares ~a year after

Periodicity of OJ 287 outbursts due to relativistic beaming

Britzen et al. 2018, MNRAS, 478, 3199:
jet precession and rotation (and nutation) to explain both the radio and optical variability with P~24 yr

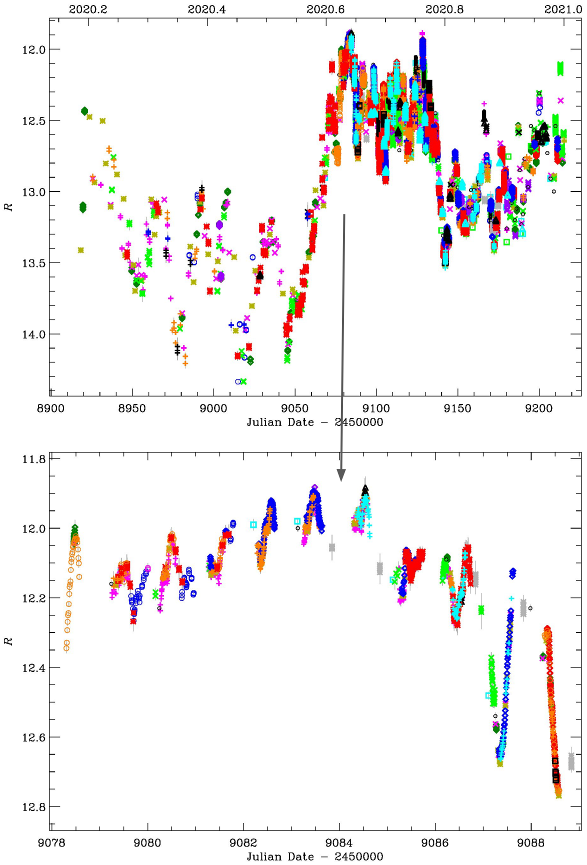




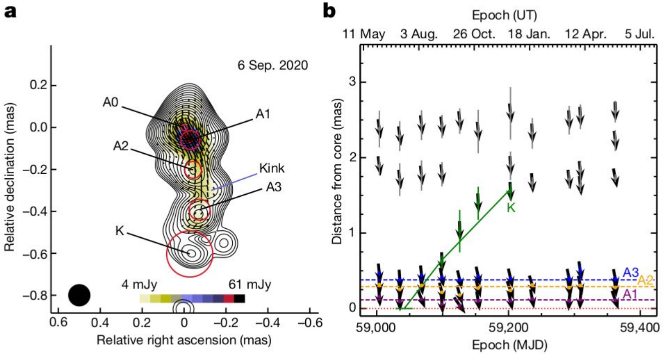
Villata et al. 1998, MNRAS, 293, L13:
binary system with both SMBHs launching a jet (bent and precessing) which periodically aligns with the line of sight

Rapid quasi-periodic oscillations in the relativistic jet of BL Lacertae

Jorstad et al. 2022, Nature, 609, 265

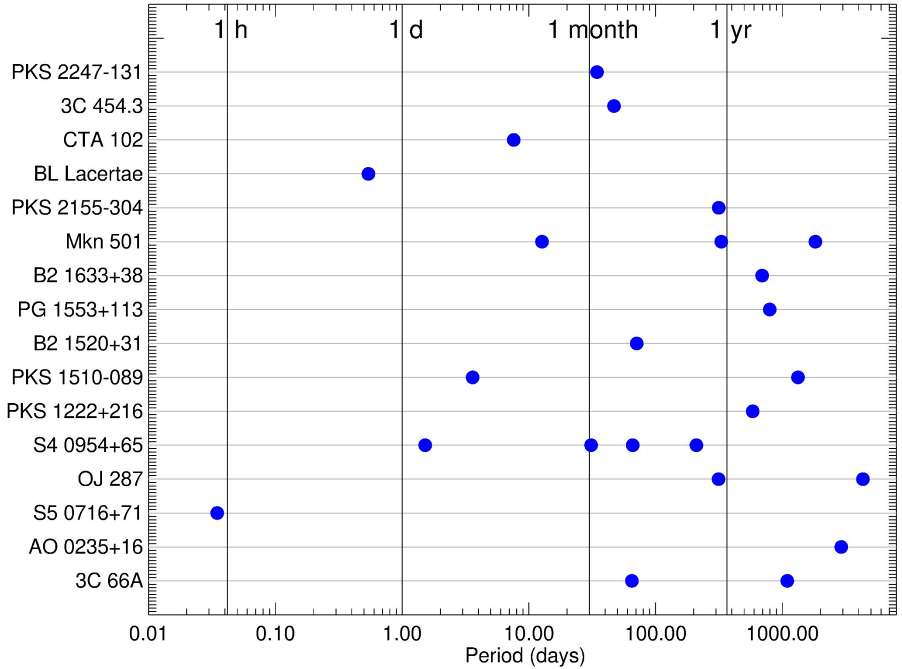


Transient quasi-periodic oscillations (QPOs) with P~13 hr detected in optical flux, optical polarization degree, and gamma-ray flux



QPOs triggered by a ***kink instability*** in the jet, when an off-axis perturbation (shock) met a standing shock

Periodicities: detected (transient) QPOs in blazar MW light curves



3C 66A: Lainela et al. 1999, Otero-Santos et al. 2020

AO 0235+16: Raiteri et al. 2006

S5 0716+71: Hong et al. 2018

OJ 287: Sillanpaa et al. 1988, Kushwaha et al. 2020

S4 0954+65: Raiteri et al. 2021, Kishore et al. 2023, Gong et al. 2023

PKS 1222+216: Otero-Santos et al. 2023

PKS 1510-089: Li et al. 2023

B2 1520+31: Gupta et al. 2019

PG 1553+113: Ackermann et al. 2015

B2 1633+38: Otero-Santos et al. 2020

Mkn 501: Hayashida et al. 1998, Bhatta 2019, Otero-Santos et al. 2023

PKS 2155-304: Sandrinelli et al. 2014

BL Lacertae: Jorstad et al. 2022

CTA 102: Sarkar et al. 2020

3C 454.3: Sarkar et al. 2021

PKS 2247-131: Zhou et al. 2018

Vaughan et al. 2016, MNRAS 461, 3145: stochastic processes can produce false periodicities ➪ importance of calibrating the false positive rate

Covino et al. 2019, MNRAS 482, 1270: analysis of Fermi light curves to check for claimed periodicities ➪ no strong case found!

Studying blazar variability means looking inside the jet, to the heart of the active galactic nucleus to

- understand what are the emission and variability processes
- figure out how the jet is made both from a structural and physical point of view
- obtain information about the black hole(s) which acts as the central engine

Many issues are still to be clarified and need further observational and theoretical effort!

MANY THANKS FOR YOUR ATTENTION

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