POLARIMETRY OF BLAZAR JETS: FROM RADIO TO X-RAYS

Resolving structure, tracking dynamics, probing particle acceleration

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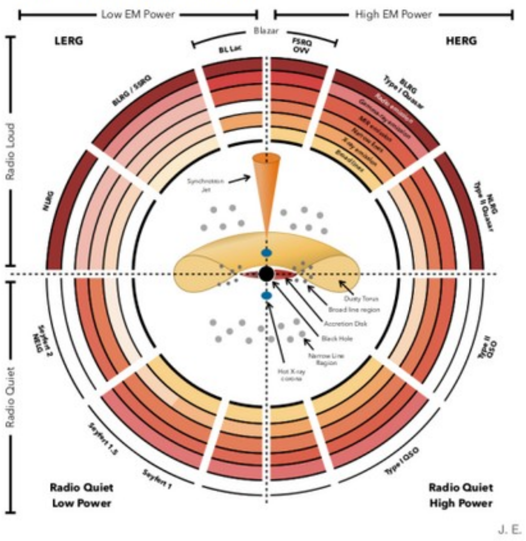
Blazars: short introduction

Source: Thome J. E., et al., 2022



Blazars are AGNs with relativistic jet oriented close to our line of sight

Two major observational consequences

- Observed flux is Doppler boosted

  $F_{obs} \propto \delta^p F_{rest}$, $p \simeq 3-4$ $\delta \approx 15 \Rightarrow F_{obs} \approx 3000\text{-}50000\, F_{rest}$

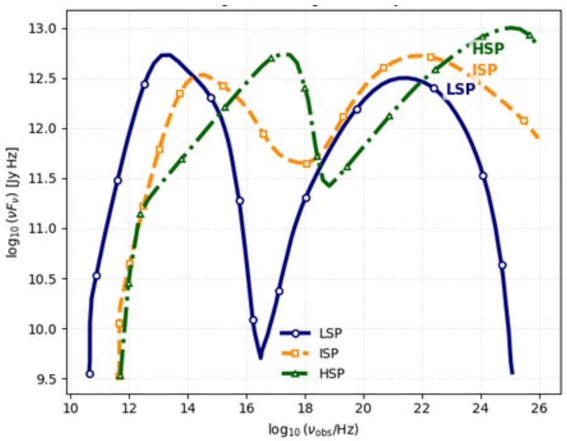
- Variability is fastened

  $\Delta t_{obs} = \Delta t_{rest}\,(1+z) / \delta$: $\delta \approx 15$, $z=1 \Rightarrow$ 15-day event observed as 2-day event

Classification based on presence of emmision lines in the spectrum:

1) FSRQs have strong emission lines
2) BL Lacs have weak or apsent lines

- Both are radio-loud, jet-dominated AGN



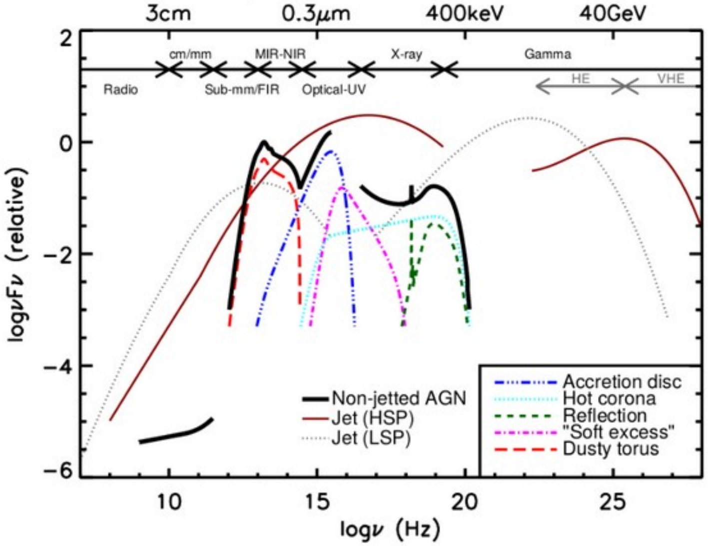
Independent classification by synchrotron-peak frequency: :

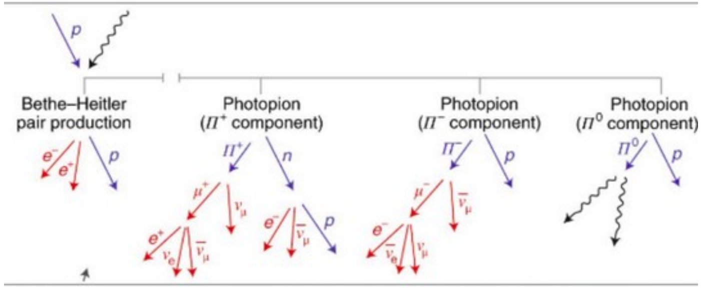
- **LSP**: peak is $\nu_{syn} < 10^{14}$ Hz
- **ISP**: peak is 10^{14} Hz $< \nu_{syn} < 10^{15}$ Hz
- **HSP**: peak is $\nu_{syn} > 10^{15}$ Hz

BL Lacs can be **LSP**, **ISP** and **HSP**
FSRQs are mostly **LSPs**

Blazar SEDs and emission mechanisms

Source: Padovani et al. (2017)





A blazar SED contains two broad humps.

LOW-ENERGY HUMP:

Originate from e- synchrotron emission from the jet

HIGH-ENERGY HUMP:

Its origin is still debated

1) LEPTONIC MODELS:

IC scattering of ambient photons

SSC: ambient photons are jet sinhrotron photons

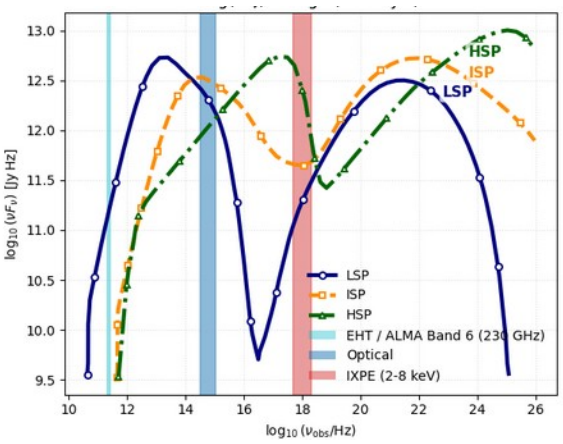
EC: ambient photons are from AD, BLR, torus

2) HADRONIC MODELS

Proton synchrotron emission and/or

Radiation from secondary particles in hadronic cascades

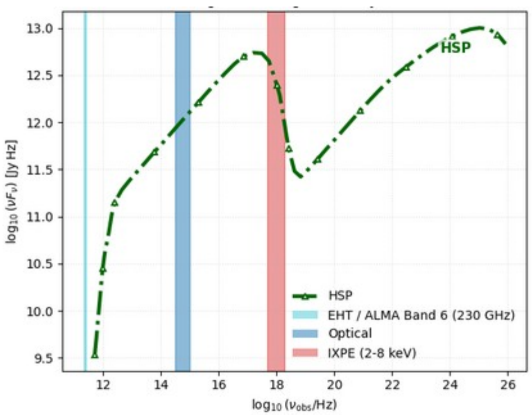
Which emission mechanisms dominate the radio, optical, and X-ray bands?



Radio and **optical**: predominantly e- synchrotron emission from the jet

X-rays: the dominant mechanism depends on the <u>blazar class</u> and <u>emission model</u>

	LSP/FSRQ	ISP	HSP
Leptonic:	IC: SSC and/or EC	e- synch. and/or IC	e- syn.
Hadronic:	p+ syn and/or casc.	e- syn and/or hadronic	e- syn.



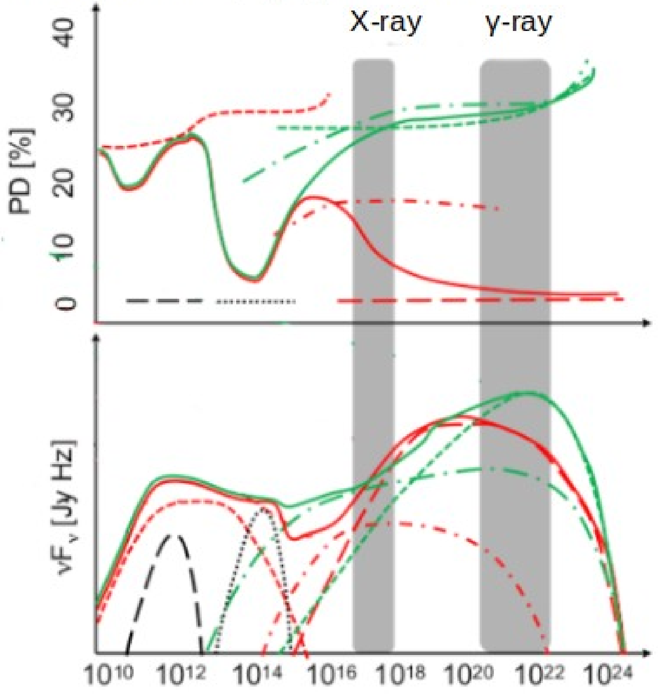
HSP: in the energy-stratified synchrotron picture

RADIO	**OPTICAL**	**X-RAY**
Low energy e-	Higher energy e-	Highest-energy e-
Long cooling time	Shorter cooling time	Shortest cooling time
=>probe larger region	=>Smaller emitting region	=> probe acceleration site

Why can polarization break the SED degeneracy?

Illustrative one-zone predictions for an LSP/FSRQ

Source: Bottcher, ppt presentation



RED — leptonic model

GREEN — hadronic model

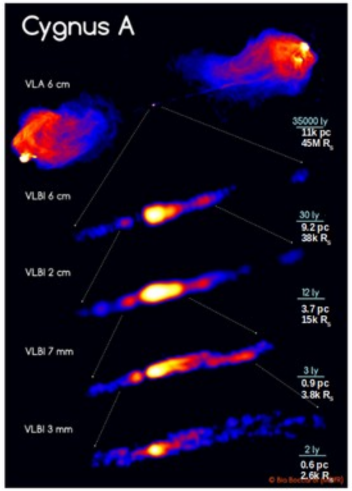
Solid lines — total emission

Indicative values: strongly dependent on magnetic-field order, geometry and time averaging.

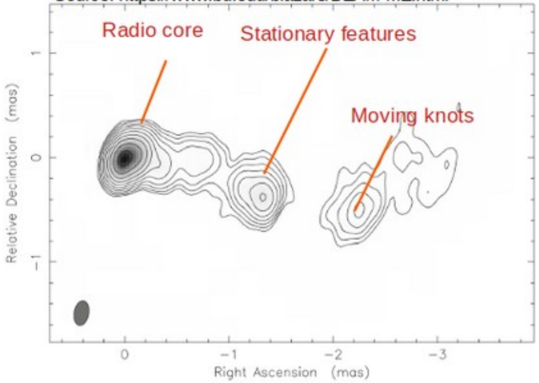
Legend	Radiation mechanism	Indicative linear polarisation	Origin of polarization
··············	**Accretion disk**	Low	Electron scattering in the disk atmosphere
— — — —	**Dust torus**	Very low	Weakly polarized thermal dust emission
– – – –	**e- synchrotron**	High (up to ~70%)	Intrinsic synchrotron polarization
— • —	**SSC**	Moderate ($< P_{syn}$; $\sim½\ P_{syn}$)	IC scattering of polarized synchrotron photons
— —	**EC**	Very low	IC scattering of nearly unpolarized external photons
– – – –	**p+ synchrotron**	High (up to ~70%)	Intrinsic synchrotron polarization
— • —	**pγ cascades**	Moderate–High	Synchrotron emission from secondary e± pairs

SED can't distinguish between emmision models but polarisation can

Radio VLBI - two properties worth noting



FSRQ 3C345, VLBA @ 43 GHz.
Source: https://www.bu.edu/blazars/BEAM-ME.html



Angular resolution

$\Theta \sim \lambda / b$ [rad]

1) increase the baseline (VLBI / space-VLBI)
(e.g. space-VLBI RadioAstron; **b ≈ 300000 km**, $\lambda \approx 1.3$ cm, $\Theta \approx$ 9-10 uas ang.res.)

2) decrease λ or increase ν:
(e.g. EHT; b ≈ 10000 km, **$\lambda \approx 1.3$ mm**, $\Theta \approx$ 20-25 uas ang.res.)

Sinchrotron self absorption (SSA)

SSA decreases steeply with frequency (e.g. $\tau^{SSA}_{\nu} \propto \nu^{-3}$)

=> with higher ν we observe regions progressively closer to the black hole.

What is the radio core?

cm-VLBI: radio core is often $\tau_{\gamma} \approx 1$ surface set mainly by SSA

mm/submm-VLBI: we may observe a physical feature (e.g. recollimation shock)

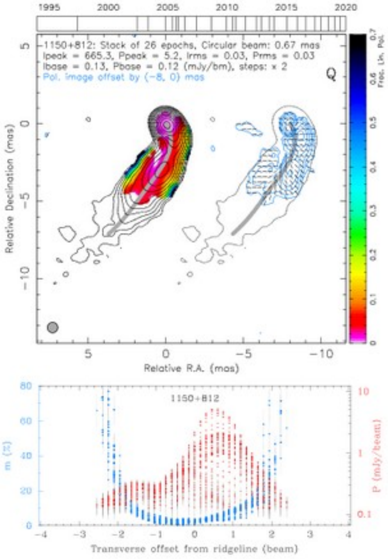
Observed **core-shift** relation ($r_{core} \propto \nu^{-1}$) support the SSA interpretation

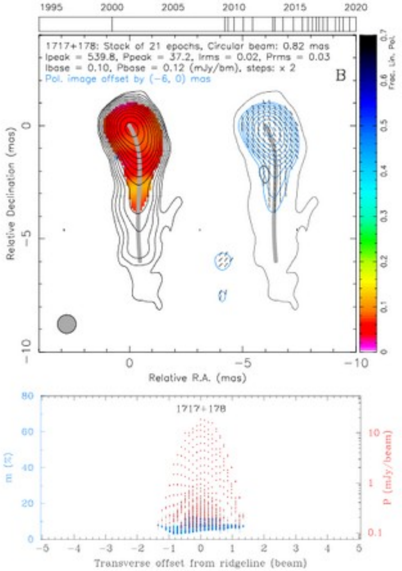
=> If the core shifts upstream at higher frequencies, this supports the SSA interpretation.

Persistent polarization structure beneath jet variability

Pushkarev et al. (2023): MOJAVE: stacked 15-GHz VLBA observations of 436 AGN jets

Top: colour bar = m_L, sticks = EVPA
bottom: **blue** = m_L, **red** = P intensity





Stacked polarisation maps

QUASAR 1150+812
U-shaped mL profile
Fountain-like EVPA

BL LAC 1717+178
Nearly flat mL profile
EVPA aligned with the jet

Goal:
Does a persistent polarization structure remain beneath the strong variability of AGN jets?

Data and method:
- Sample: 436 AGN jets observed with the VLBA at 15 GHz
- Align radio maps using VLBI core and stack Stokes I,Q,U maps
  => Variable **Q,U components average out** and **stable patterns remain**

Fractional polarization m_L:
- generally increases downstream and toward the jet edges
- often produces U- or W-shaped transverse profiles
- quasi-constant profiles occur in some jets, mainly BL Lacs

EVPA orientation:
- quasars: EVPA tends to have “fountain-like” orientaion
- BL Lacs: EVPA tends to align with the local jet direction

Interpretation:
- BL Lac-type: aligned EVPA + nearly flat mL
  => a persistent ordered field, but not a unique signature of a helical field
- Quasar-type: fountain-like EVPA + U-shaped mL
  => polarization cancellation near the jet axis, consistent with a helical field

Differences between blazar types:
- mL(BLLac, core) > mL(quasar, core) up to hectopc scales
- m_L(HSP) < m_L(LSP/ISP)

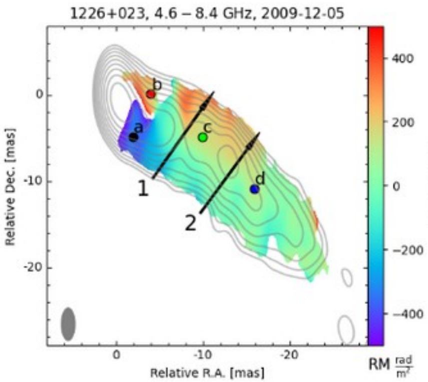
Faraday rotation: probing the magnetized jet environment

Low-energy electrons in a magnetized plasma rotate the EVPA by an amount proportional to λ^2

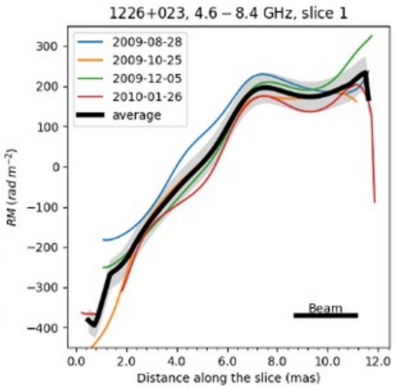
$$\chi = RM\lambda^2 + \chi_0$$

$$RM \propto \int n_e B_\parallel \mathrm{d}l$$

Source: Lisakov et al. (2021)
FSRQ 3C 273 — VLBA, 4.6–8.4 GHz



RM map:
Color - RM,
Contour – Stokes I



Transverse RM gradient:
Multiple epoch

What the $\chi(\lambda^2)$ fit provides:
- χ_0: Faraday-corrected EVPA
- $|RM|$: the line-of-sight integral of n_e $B_\parallel$ (not B alone)
- sign(RM): direction of the density-weighted $B_\parallel$
- a sign-changing transverse RM gradient:
  evidence for an ordered toroidal/helical field component

Depolarisation:
- A uniform external screen rotates EVPA but leaves m_L unchanged.
- Depolarization occurs when different EVPA average:
  - within the observing beam
  - across the receiver bandwidth
  - along the line of sight when emitting and rotating plasma are mixed

Data:
- 3C 273, four VLBA epochs in 2009–2010
- multifrequency polarimetry at 4.6–15.4 GHz
- pixel-by-pixel fits of $\chi(\lambda^2)$

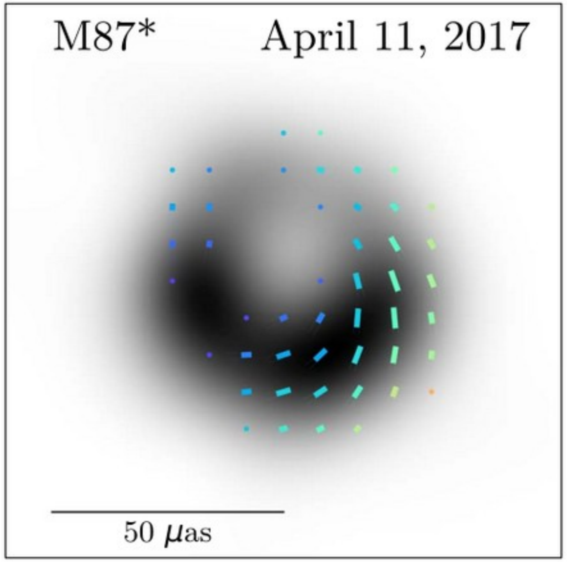
Results:
- smooth transverse RM gradient
- RM changes from about −400 to +200 rad m^{-2}
- the pattern remained stable over five months

Interpretation:
- The sign-changing transverse RM gradient indicates an ordered toroidal/helical magnetic field in an external Faraday-rotating sheath.

mm-VLBI probes horizon-scale polarized emission

mm-VLBI: higher angular reslolution + lower opacity + reduced λ^2 sensitivity to FR
=> we can probe horizon-scale regions

Akiyama et al. (2021)
EHT Collaboration 2021, Paper VIII



Grayscale: total intensity I
Ticks: orientation = EVPA
length = polarized intensity P
color = fractional polarization

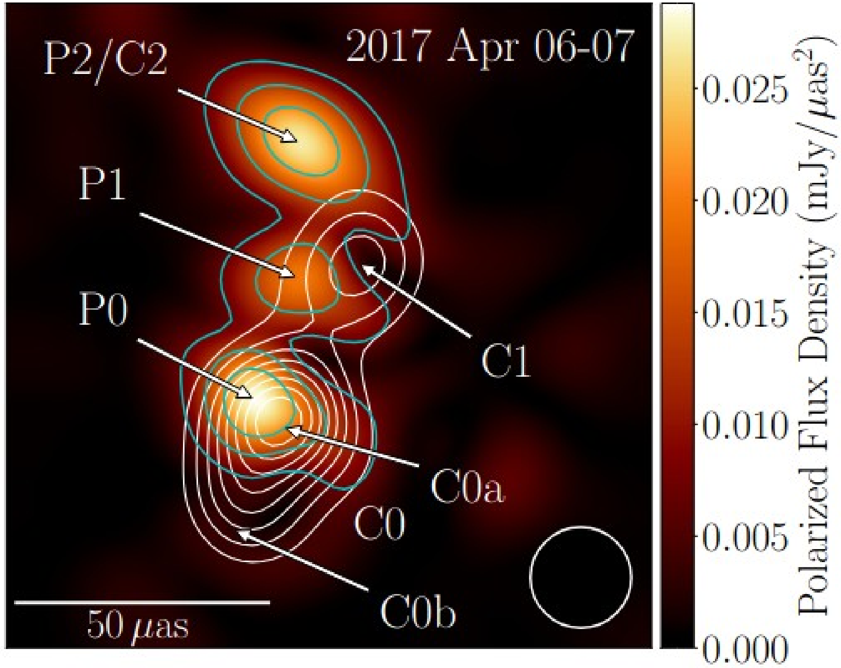
Akiyama et al. (2021):
- The first resolved linear-polarization image on event-horizon scales

M87: horizon-scale polarimetry:
- resolved LP on event-horizon scales, close to launching region
- nearby radio galaxy; benchmark for jet-launching physics
- EHT at 230 GHz; simultaneous unresolved ALMA data
- low net polarization: mainly internal Faraday depolarization

GRMHD interpretation:
- generated a library of GRMHD models
- azimuthal EVPA is consistent with organized poloidal magnetic flux
- MAD model can explaines the observation

EHT resolves the innermost blazar jet: NRAO 530

Jorstad et al. (2023)



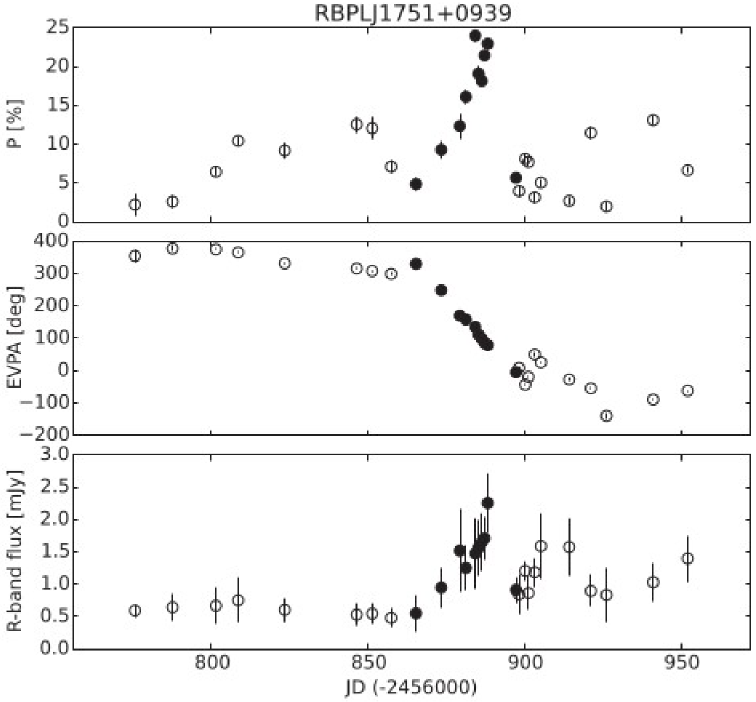
White contours: total intensity I
Color scale and cyan contours: polarized intensity P

NRAO 530 — FSRQ, z=0.902:

- EHT at 230 GHz, ~20μas;
- C0, C1, C2: total intensity components
  P0, P1, P2: polarized components
- C0: 1.3-mm core, modeled as C0a + C0b
- P0/C0: m_L~5–8%
- C2 average: m_L~20%, P2 local region up to ~60%
  (High m_L at P2: ordered B; possible shear)
- EVPA downstream: oblique (P0) → ∥ jet (P1) → ⊥ jet (P2)
- EVPA pattern: consistent with a helical field

Optical polarimetry: unresolved, but densely sampled

Blinov et al. (2016)
LBL OT 081 EVPA rotation ~335° in 32 d



Why optical?
- Dense sampling; time-scales from years to intranight
- Integrated I,Q,U: no spatial information
- FR negligible in optical: measured EVPA closer to intrinsic EVPA

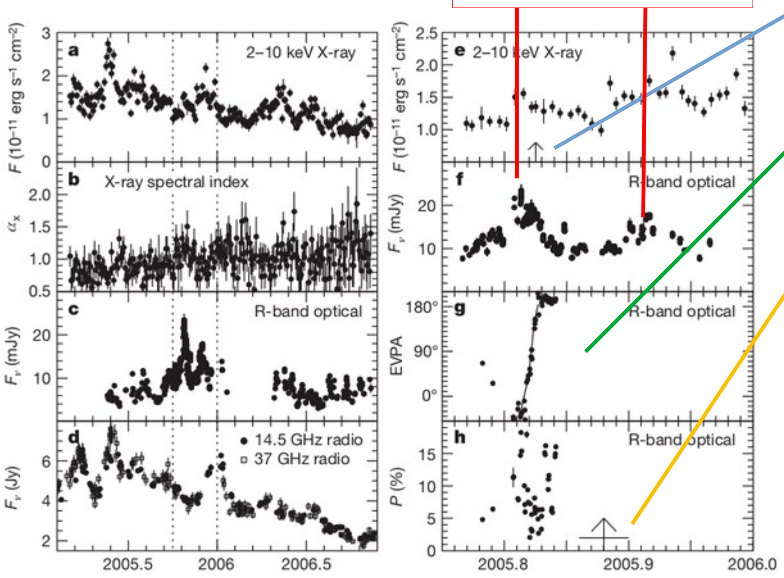
Observed behaviour:
- Flux, p, and EVPA are usually <u>erratic</u>
- Occasionally we observe large-amplitude <u>EVPA rotations</u>

RoboPol project: population results
- monitored ~40 γ-ray–loud and a γ-ray–quiet (i.e. Fermi-detected vs. Fermi-undetected)
- γ-ray–loud blazars are ∼3× more polarised (mean p: 9.2% versus 3.1%)
- Detected 40 EVPA rotations in 24 blazars
- Rotations cluster near γ-ray flares

Multiwavelength timing + VLBA constrain the flare site

A classic case: BL Lacertae - Marscher et al. (2008)

Flare 1 Flare 2

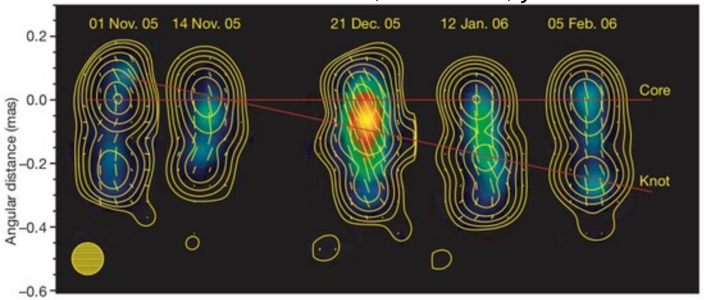


TeV detection with MAGIC

EVPA rotation

Estimated epoch of knot–core crossing

43-GHz VLBA: contours = I, colour = P, yellow ticks = EVPA



Observed:

- Flare 1: optical/X-ray flare and >0.2 TeV detection with MAGIC
- $\sim 240^\circ$ optical EVPA rotation in five days; p reaches a minimum
- Flare 2 coincides with the estimated knot–core crossing

Proposed interpretation:

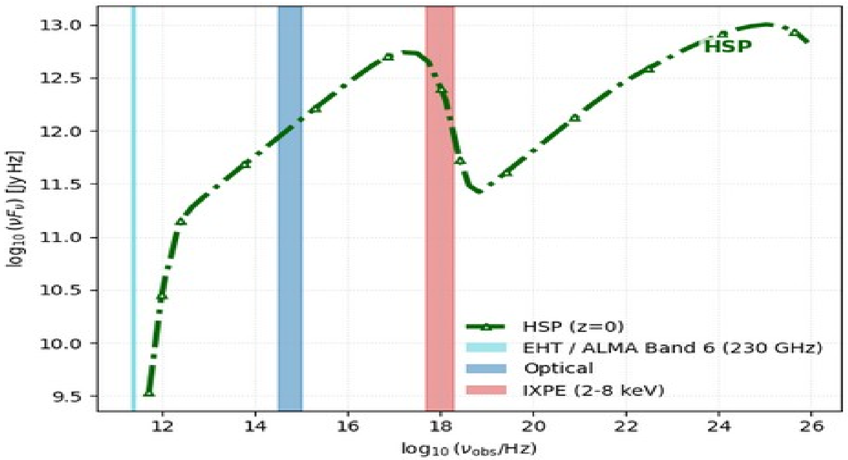
- one moving disturbance produces both flares
- Flare 1: upstream of the core, in a helical-field ACZ
- Flare 2: at a standing shock identified with the 43-GHz core

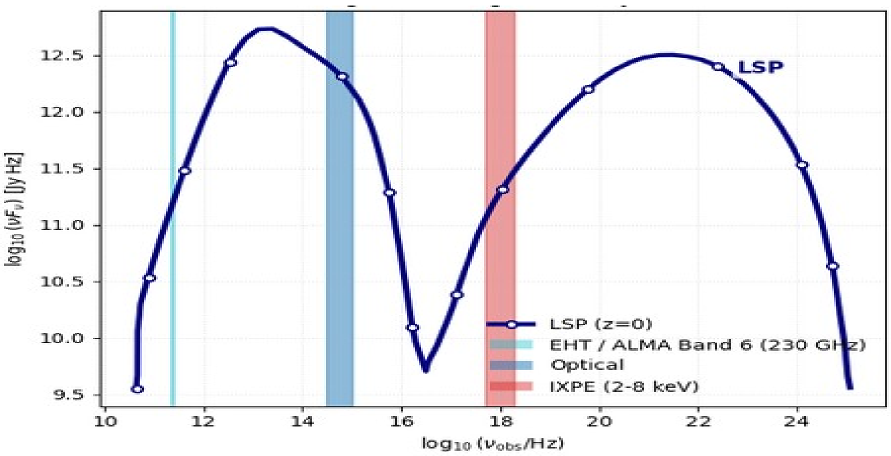
Takeaway:

-Optical polarization traces the disturbance before it becomes radio-v
- VLBA follows it downstream to the 43-GHz core

IXPE probes different physics in HSP and LSP blazars

Linear polarization in the 2–8 keV band





HSP blazars:
- X-rays probe the first hump: e- syn. emmision
- Highest-energy electrons; shortest cooling time
- Compact region close to the acceleration site

Energy-stratified shock model:
- Shock compress the B
- X-rays probe a smaller region near the shock
- optical and radio probe a larger region further away
- we expect: $p_X > p_{opt} > p_{radio}$

LSP blazars:
- X-rays usually sample the low-energy side of the high-energy hump
- SSC, EC, or hadronic emission may contribute

Expectations:

EC: very low p_X

SSC: low–moderate p_X

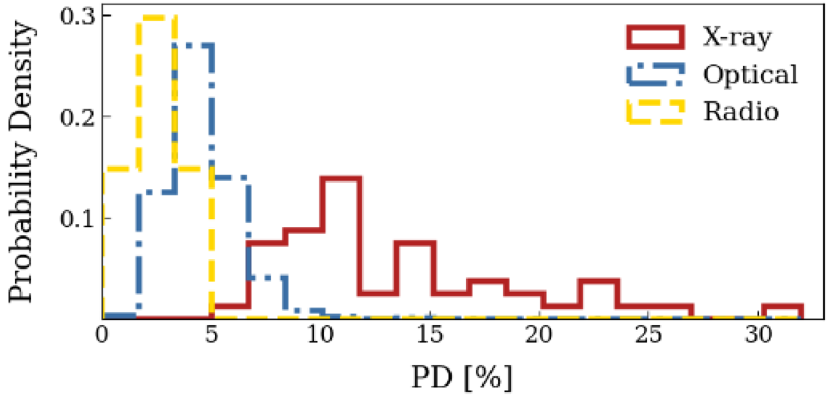
Hadronic scenario: potentially high p_X

IXPE averages Q and U over time and energy => reduce the measured p_X

A population test of energy stratification in HSP jets

Capecchiacci et al. (2025): example of HSP blazars observed with IXPE

Capecchiacci et al. 2025



median(p_X/p_{opt}) = 2.5
median(p_X/p_{mm}) = 6.0
median(p_{opt}/p_{mm}) = 1.7

Sample and data:

- Six HSP blazars in multiple IXPE epochs
- Simultaneously, the observed in optical
- Occasianally observed in mm-radio (~225 GHz)

Results:

- Population trend: $p_X > p_{opt} > p_{mm}$
- X-ray EVPA cluster around the jet axis (median $|\mathrm{EVPA}_X - \mathrm{PA}_{jet}| \simeq 2.5^o$)

Interpretation:

- Support the energy-stratified model

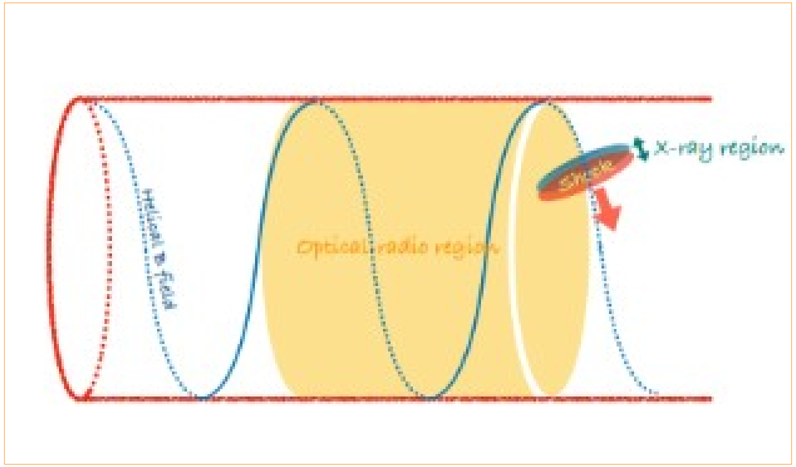
Interpretation:

– Short X-ray cooling length → compact region close to the acceleration site
– Cooling + downstream advection → larger optical/mm regions and more field averaging
– Supports energy stratification; shocks are favored, but not uniquely established

Mrk 421: stable p_X, rapidly rotating EVPA

Di Gesu et al. (2023): the first >360° X-ray EVPA rotation

Source: Di Gesu et al. 2023



Data:
- Two IXPE pointings: 4–6 and 7–9 June 2022
- X-ray polarimetry in ~3-hour time bins
- Quasi-simultaneous optical, IR and mm polarimetry

Results:
- They measured low frac. pol: p_X = 10%±1%
- EVPA rotation ≥360° over five days (~80–90° day−1)
- Didn’t find corresponding EVPA rot. in optical/IR/mm
- Random-walk simulations: stochastic origin unlikely

Interpretation:
- EVPA rotation cancels Q and U in the time-integrated signal
- X-ray and longer-wavelength regions are not fully co-spatial
- Proposed model: a localized shock propagating through a helical magnetic field

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Time averaging can hide a polarized but rotating signal.
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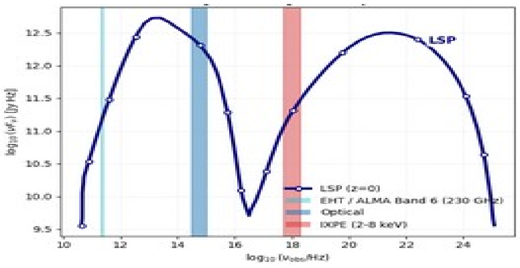
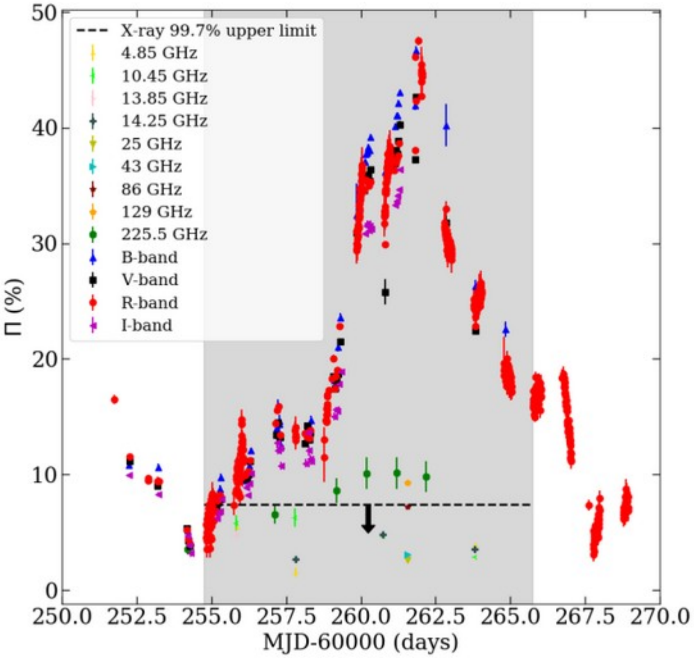
BL Lac: polarization favors Compton-dominated X-rays

Agudo et al. (2025): example of LSP/ISP blazar measured with IXPE



For LSP blazars, IXPE probe the second hump in the SED
It is often photon-limited, so IXPE provide onli upper limits



Data:
- BL Lacertae: usually an LSP; can shift to an ISP state during flares
- IXPE: ~500 ks, 7–17 November 2023
- Simultaneously observed in optical and radio/mm

Results:
- In optical average p_{opt}~25%; peak 47.5%±0.4%
- In mm it is p_{mm} is variable and increased up to ~10%
- IXPE measured $p_X < 7.4\%$ at 3σ
- No compelling >3σ evidence for X-ray EVPA rotation

Interpretation:
- Low frac. pol. In X-ray excudes the hadronic scenario
- The observed optical–X-ray contrast favors Compton scattering
- Broadband spectral modeling favors SSC

Summary: one jet, three complementary polarimetric views

RADIO — Resolving structure
- VLBI resolves the jet from parsec to horizon scales
- Persistent m, EVPA and RM patterns constrain ordered B and the jet environment
- mm-VLBI approaches the polarized jet base

OPTICAL — Tracking dynamics
- Unresolved, but densely sampled
- Flux, p(t) and EVPA rotations trace evolving disturbances
- Multiwavelength timing + VLBA constrain the flare location

X-RAYS — Isolating the physics
- HSPs: freshest electrons; pX>popt>pmm supports energy stratification
- Rapid EVPA rotations reveal a compact but dynamic region
- LSPs/ISPs: pX constrains Compton versus hadronic emission