An Introduction to Multi-Wavelength Polarimetry and Applications to (Mostly) Fermi-Detected Blazars

Haocheng Zhang (UMBC/CRESST II/NASA GSFC)

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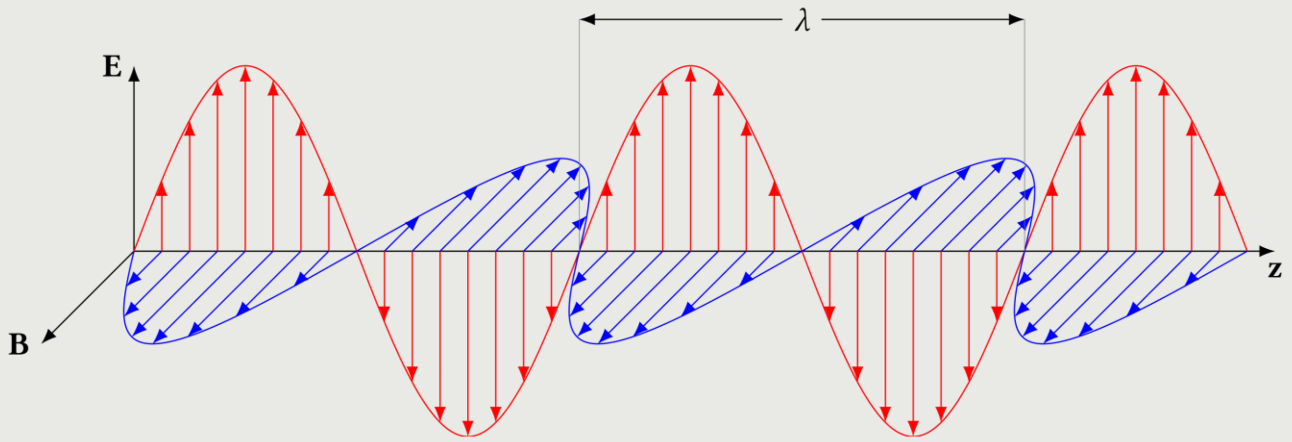
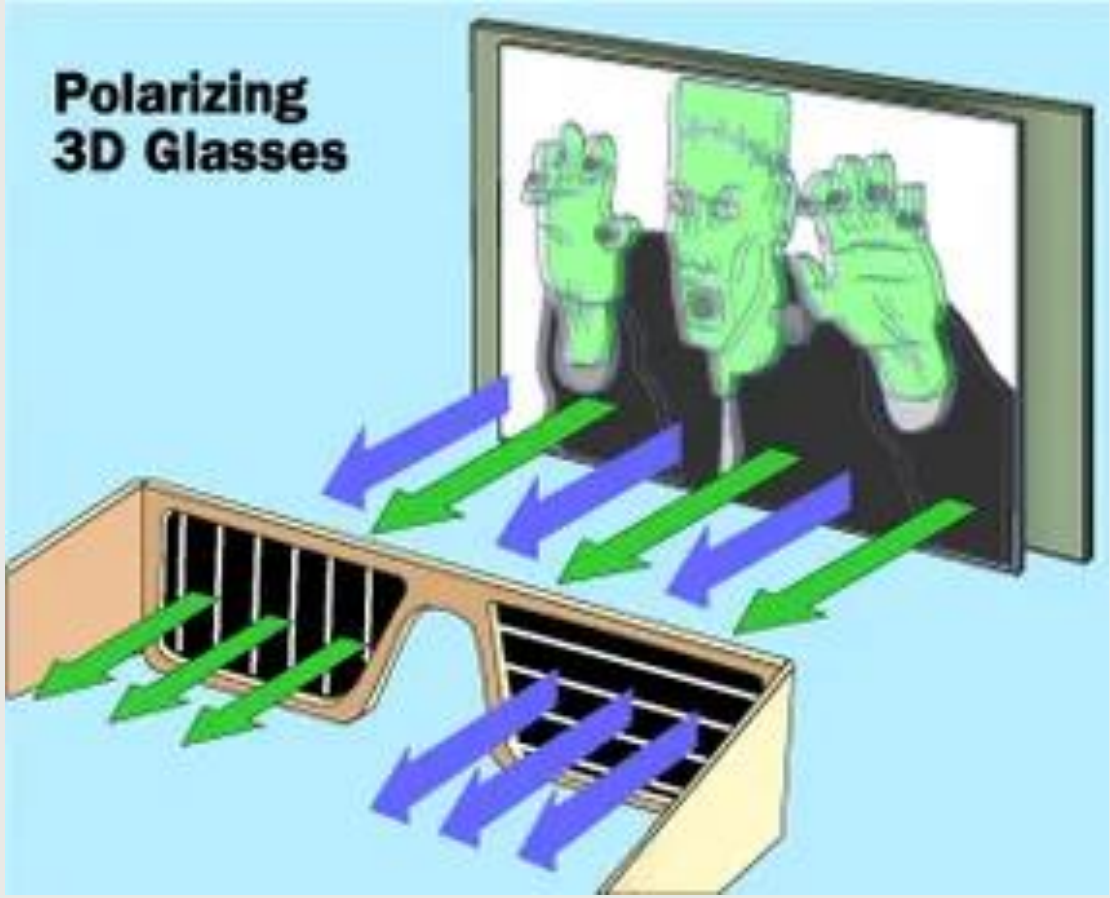
What is Polarization?





- A property of the transverse waves
- Describes if the wave has a preferential plane of oscillation
- EM waves are perfect examples of transverse waves that can be polarized

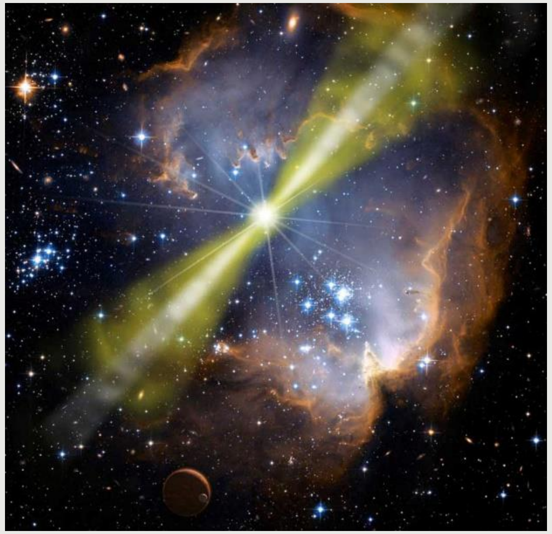
Why is Polarization Relevant to Fermi?

- Fermi actually has polarimetry capability in theory, though the sensitivity is bad.
- Many Fermi-detected sources have strong nonthermal radiation components, such as synchrotron and inverse Compton scattering, which can be polarized.
- Polarization can help to provide important physical information that is not possible with spectrum and light curve.

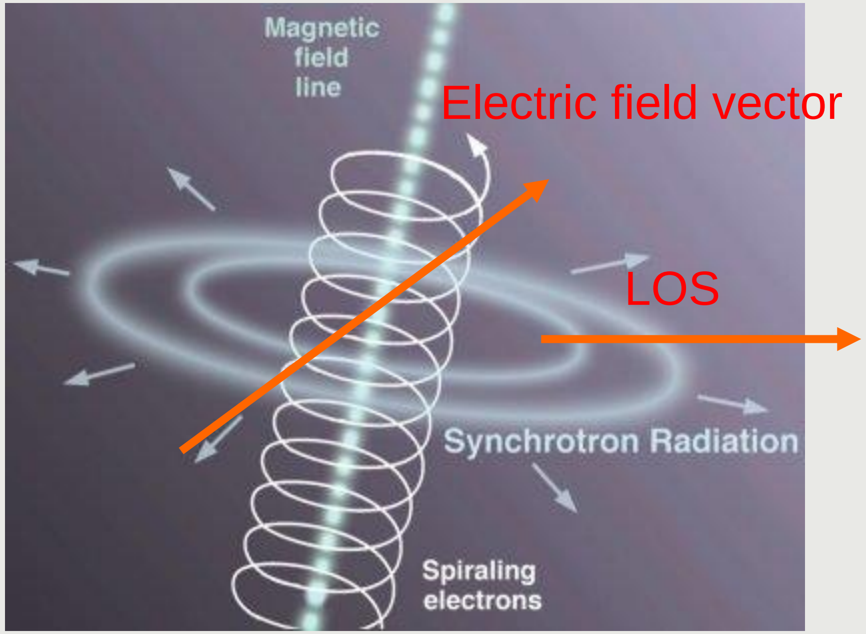
Blazar

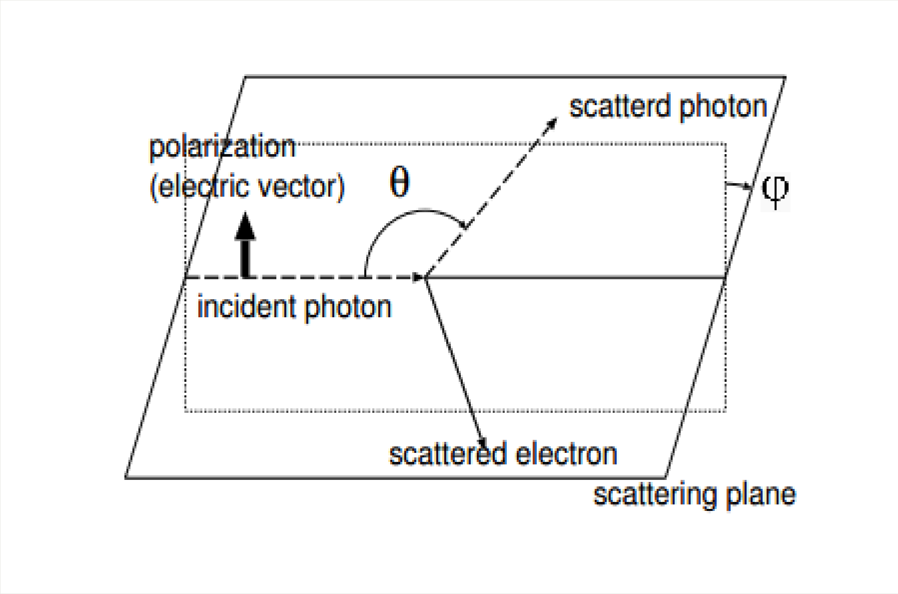
PWN

GRB



Synchrotron & Compton Scattering



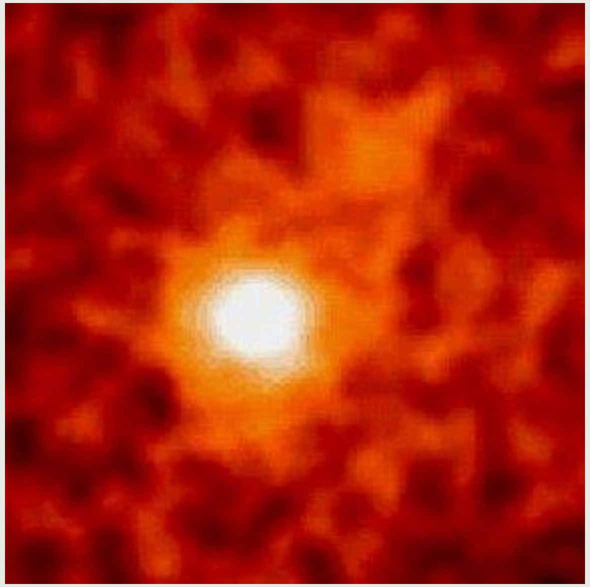


- ❑ Synchrotron polarization degree depends on how ordered the magnetic field is
- ❑ Synchrotron polarization angle depends on the magnetic field morphology
- ❑ Compton scattering polarization degree and angle depend on both the seed photon polarization and scattering angle

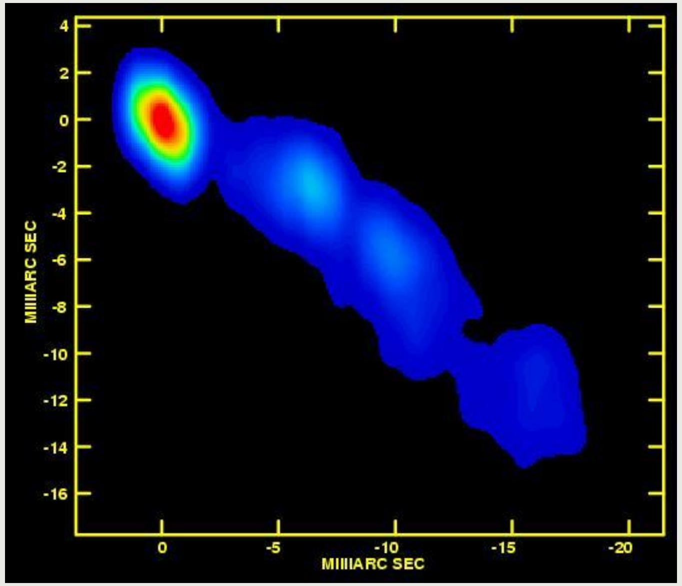
Radiative processes in astrophysics by Rybicki & Lightman, Chapter 6 Synchrotron Radiation

Bonometto, Cazzola & Saggion, 1970 A&A, McMaster, 1961 Reviews of Modern Physics

What Physical Information can Polarization Provide?



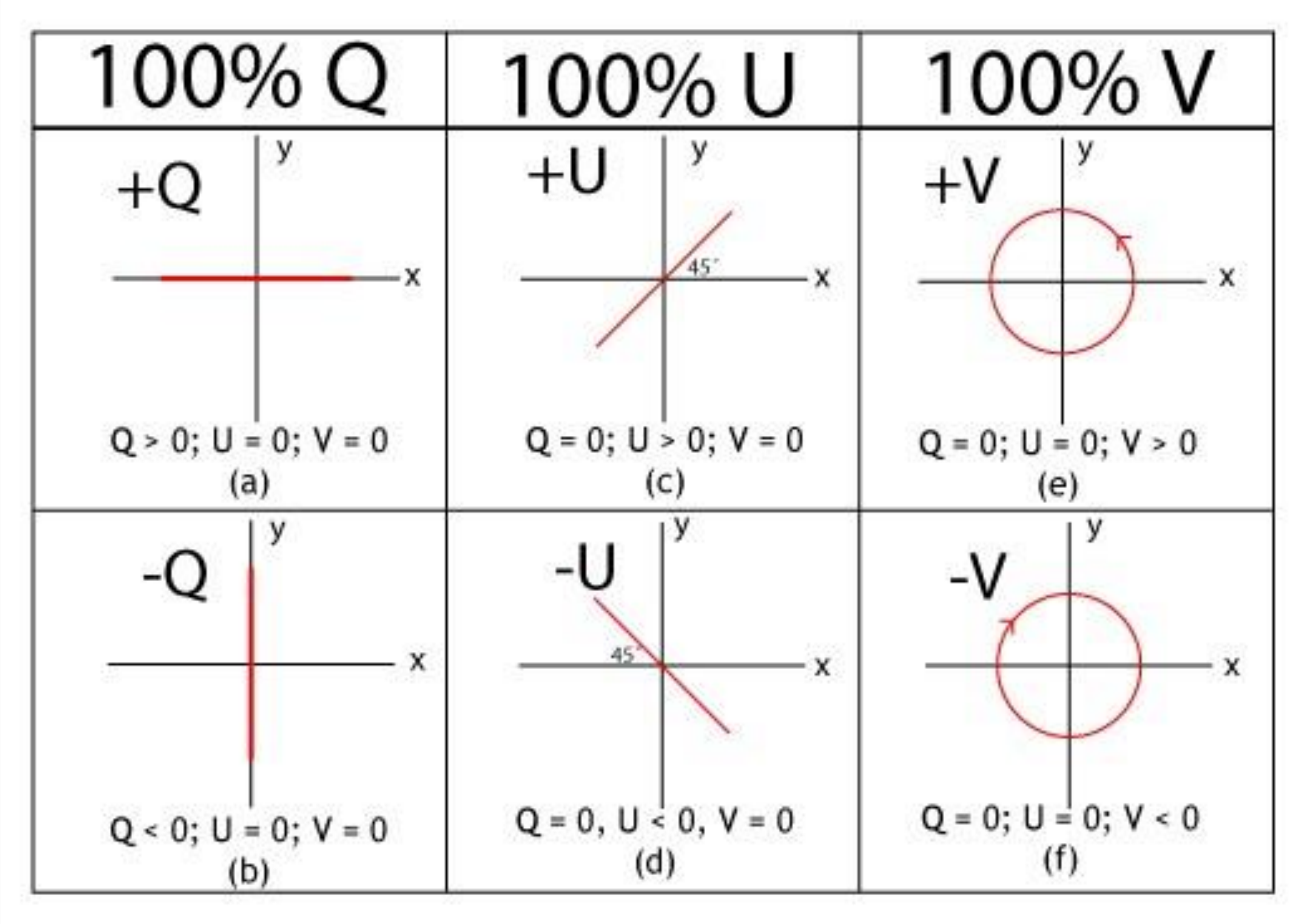
Point (0D)



1D or 2D

Polarization reveals 3D structure

Polarization and Stokes Parameters



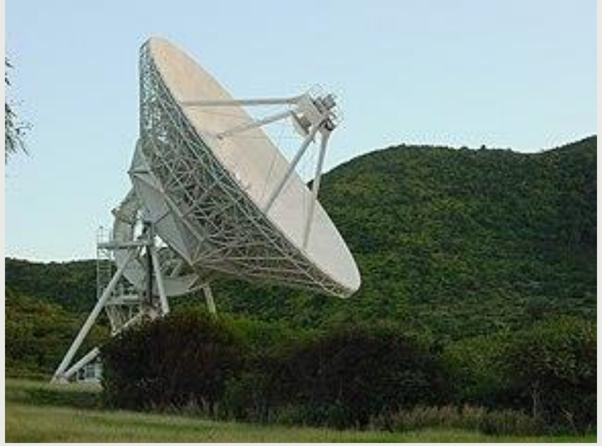
I $S_0 = I$

Q $S_1 = pI \cos 2\psi \cos 2\chi$

U $S_2 = pI \sin 2\psi \cos 2\chi$

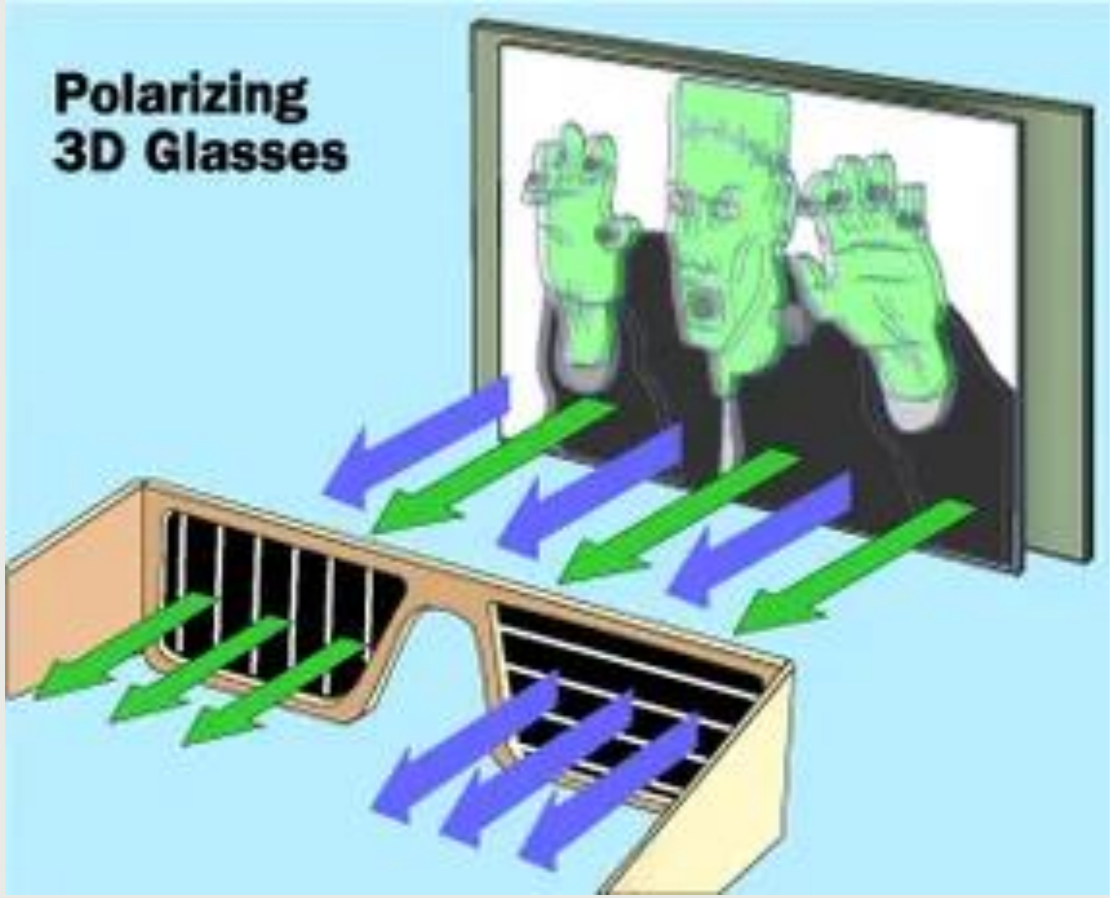
V $S_3 = pI \sin 2\chi$

Why is Polarimetry Not Frequently Considered?



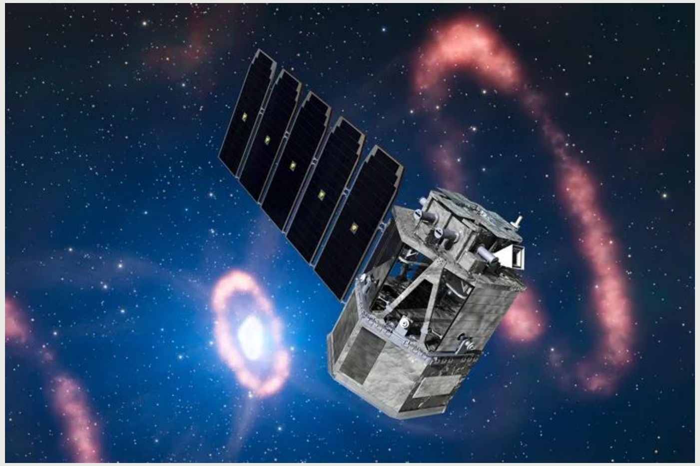
VLBA

RoboPol



We have a limited number of polarizing glasses (for now)!

IXPE



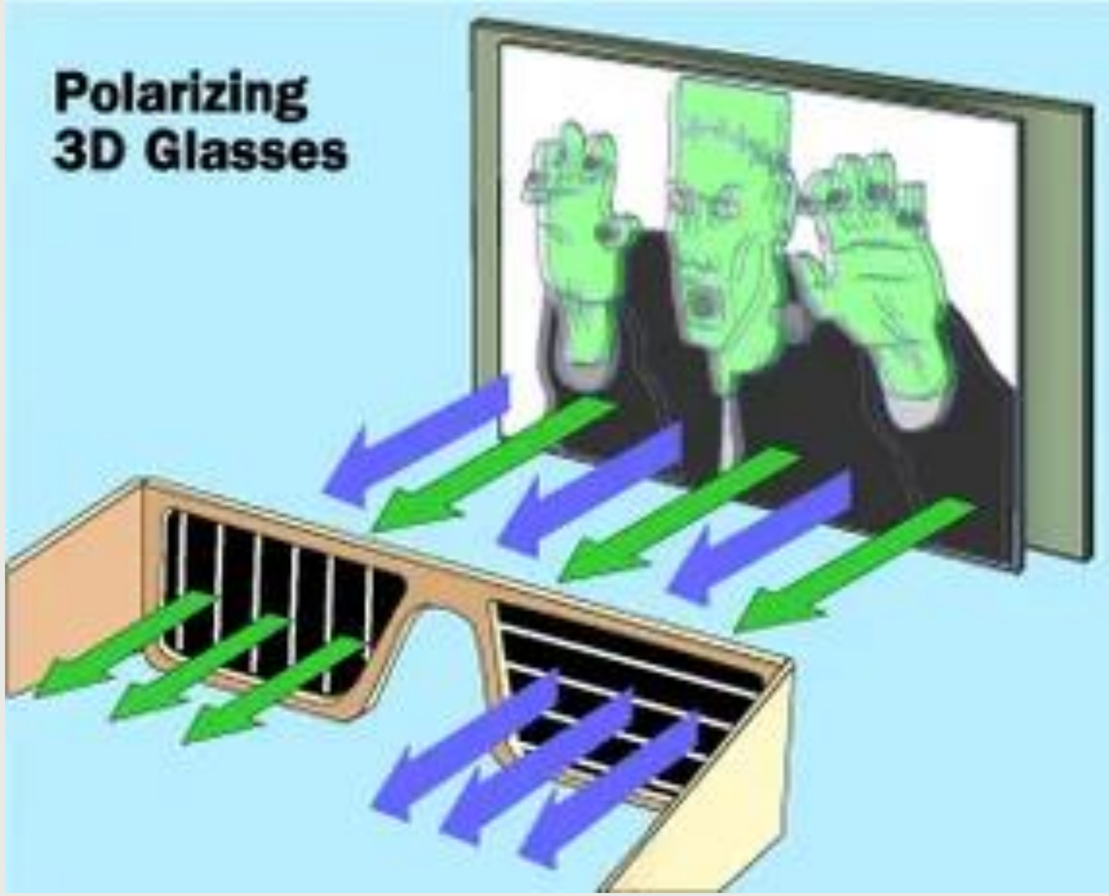
COSI (2027)

Why is Polarimetry Not Frequently Considered?

Polarization modeling requires comprehensive studies of:

- ❑ Fluid dynamics, such as magnetic field and plasma density distribution and evolution.
- ❑ Particle transport, such as acceleration, cooling, spatial transport, and distribution.
- ❑ Radiation transfer, such as absorption, scattering, Faraday rotation, light crossing delays, and relativistic aberration.
  - Toy model → Toy polarization
  - Physical model → Physical polarization

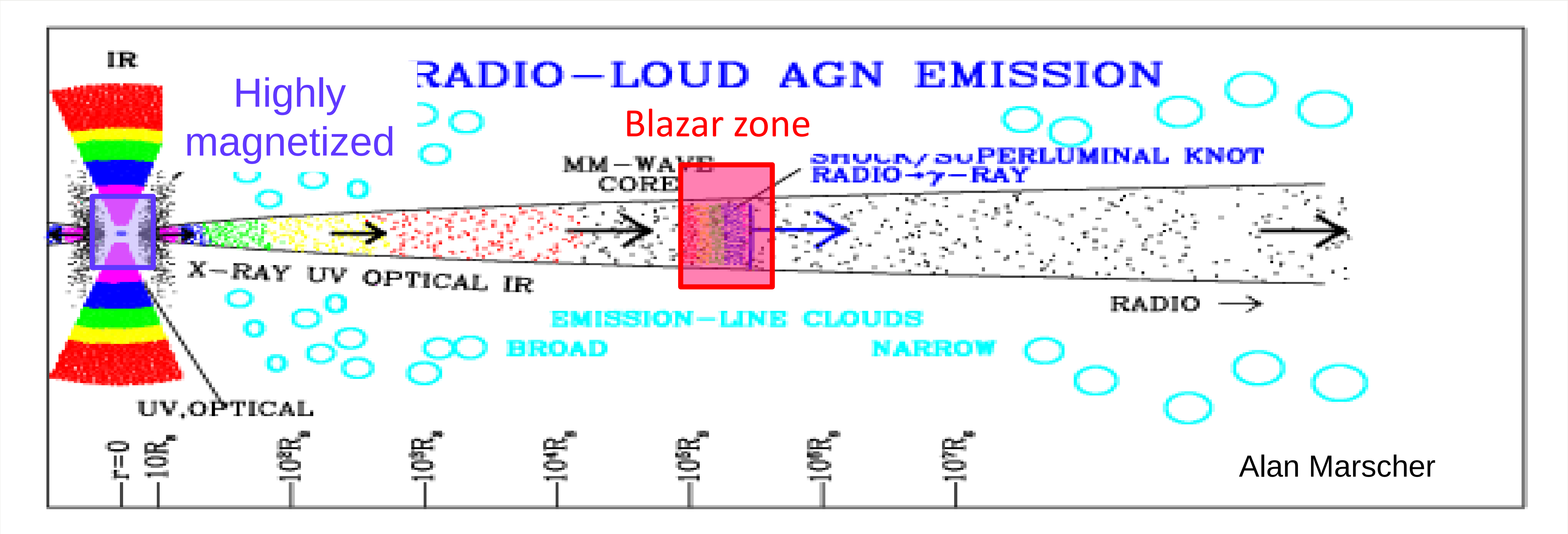
A full treatment of fluid dynamics, particle transport, and radiation transfer that is directly applicable to Fermi-detected sources does not exist.



Polarization models are still developing.

However, good polarization models, even under development, can already provide invaluable physical insights

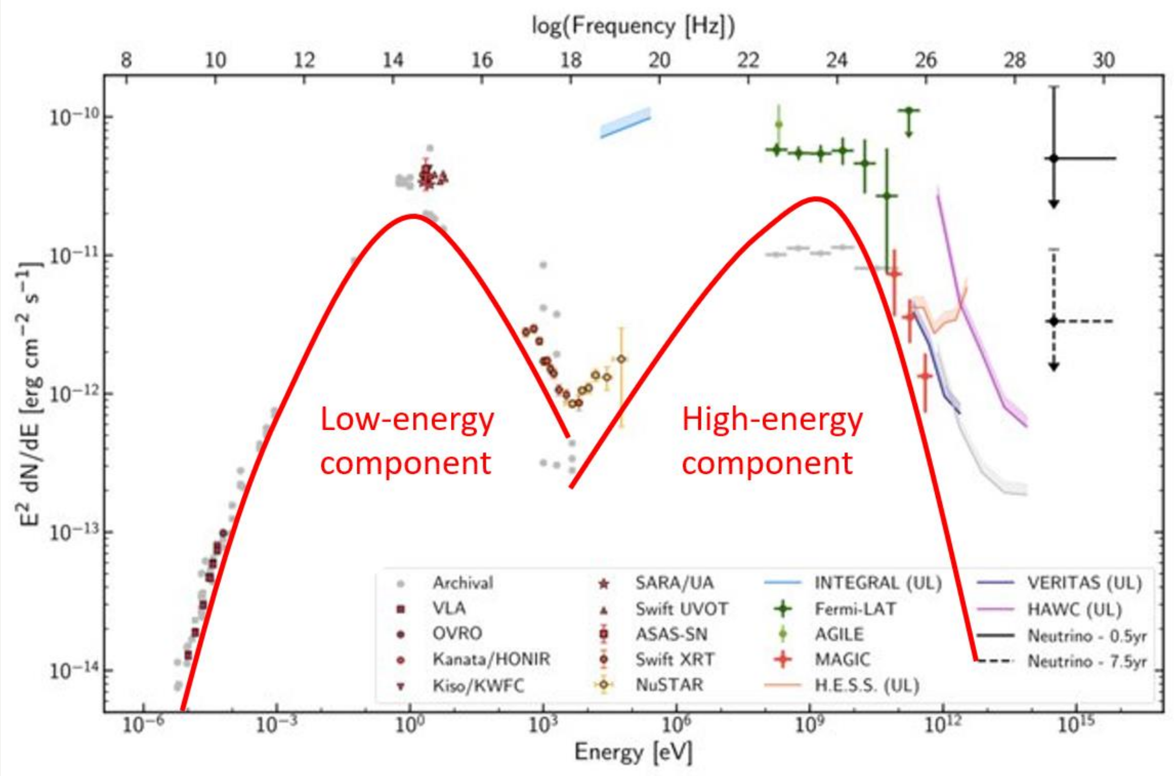
Blazar Jet



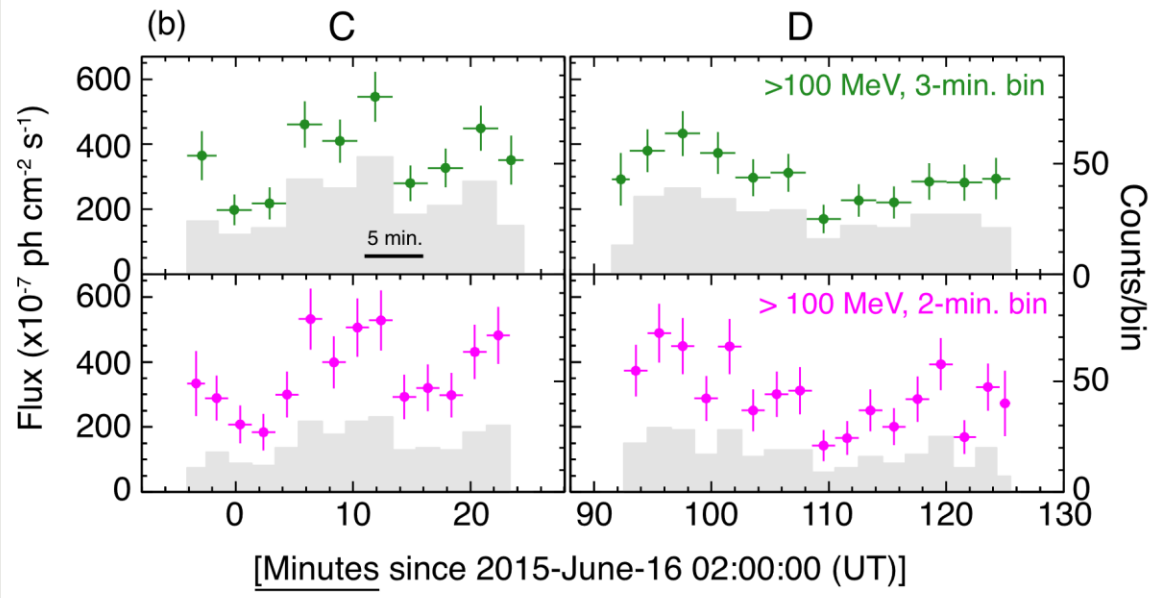
Blazars are relativistic plasma jets from accreting supermassive black holes, pointing very close to our line of sight.

They are the most numerous extragalactic gamma-ray sources due to Doppler boosting.

Time-Domain & Multi-Messenger Source



IceCube+ 2018 Science 361, 1387

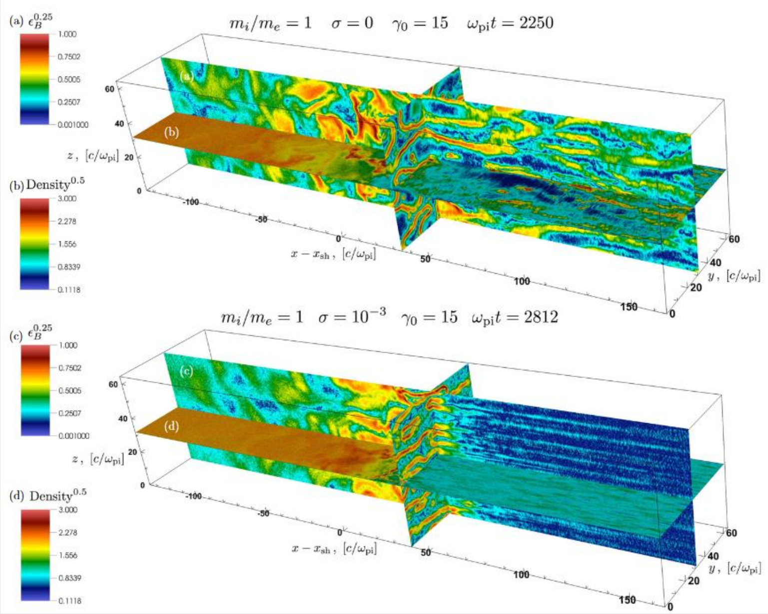


Ackermann+ 2016, ApJL 824, L20

- ❑ Nonthermal-dominated emission
- ❑ Highly variable
- ❑ Connection with cosmic rays and neutrinos

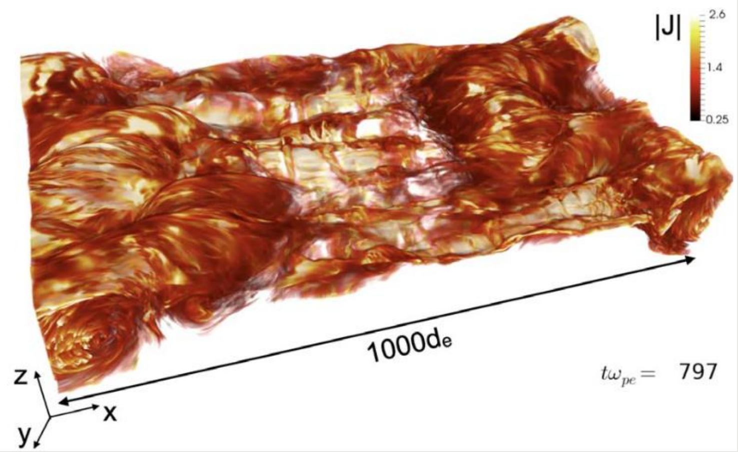
Time-Domain & Multi-Messenger Source

- Blazars can accelerate nonthermal electrons/protons and produce multi-wavelength flares.



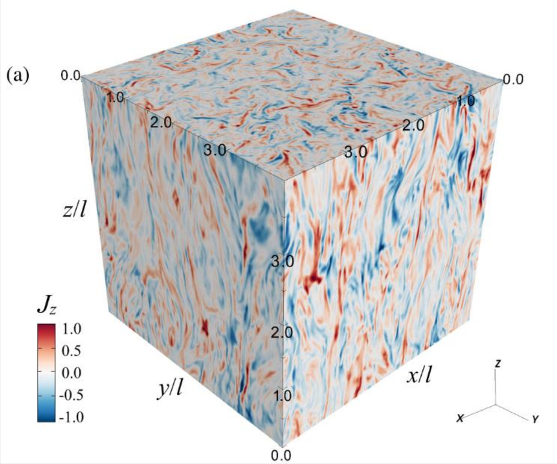
[Sironi+ 2013, ApJ 771,54](#)

Shock



Magnetic Reconection

[Guo+ 2021, ApJ 919, 111](#)



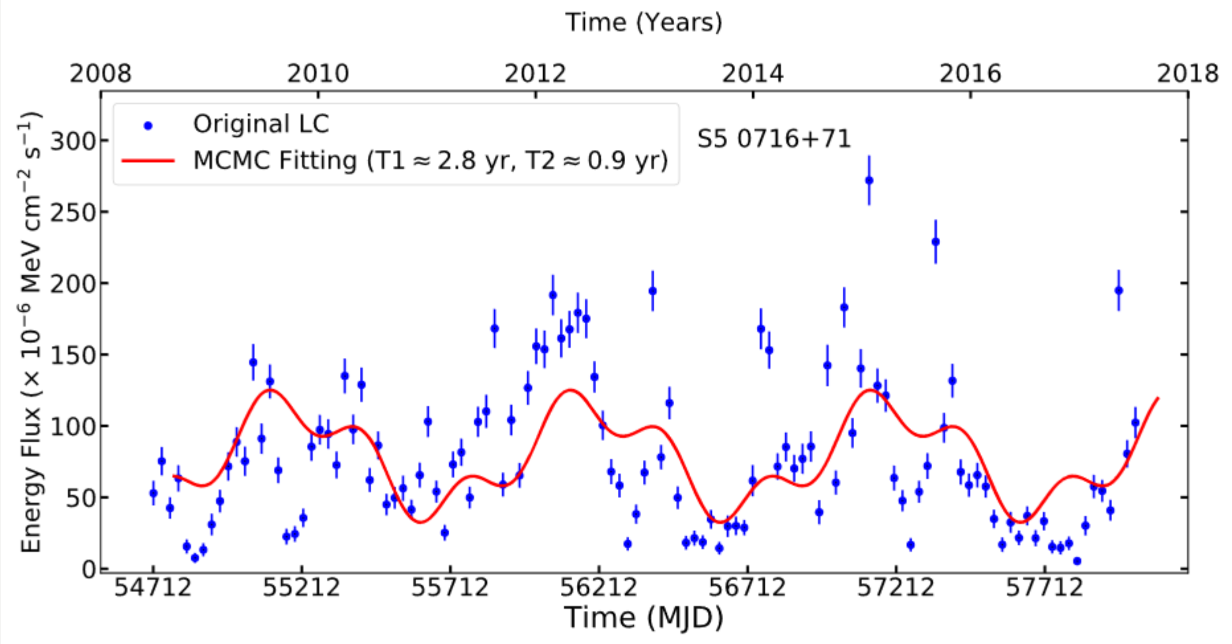
Turbulence

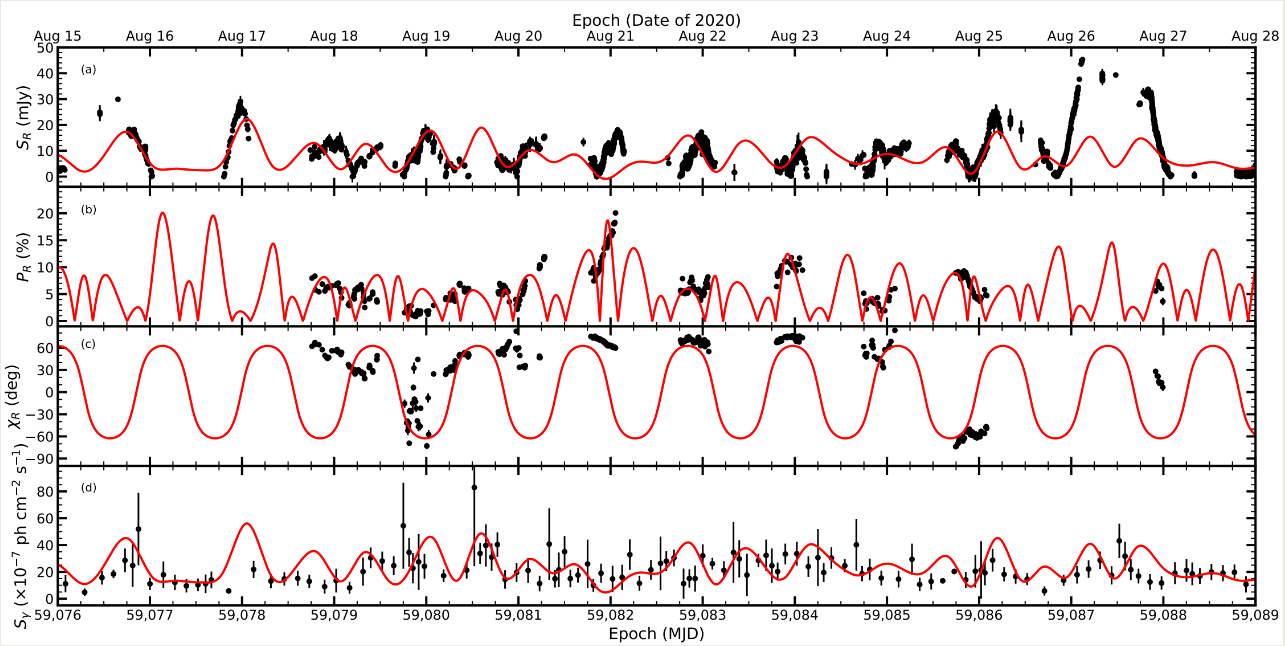
[Comisso & Sironi 2018, PRL 121, 255101](#)

List of unsolved problems in astronomy

- The Oh-My-God particle and other ultra-high-energy cosmic rays: What physical processes create cosmic rays whose energy exceeds the GZK cutoff?[10]

Time-Domain & Multi-Messenger Source





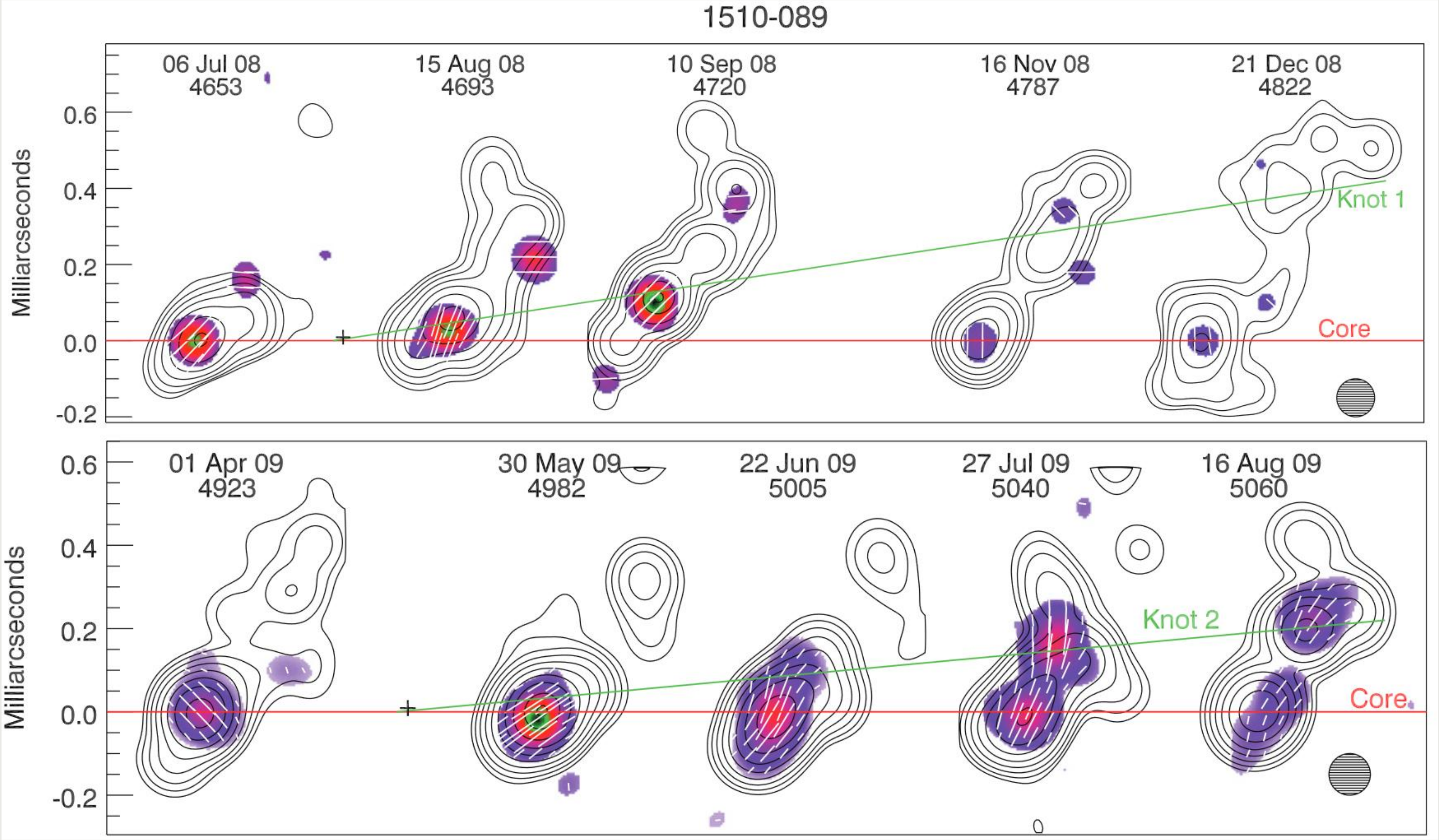
[Penil+ 2020, ApJ 896, 134](#)

[Jorstad+ 2022, Nature 609, 265](#)

- Quasi-periodic oscillation (QPO) indicates binary black holes or internal jet activities.

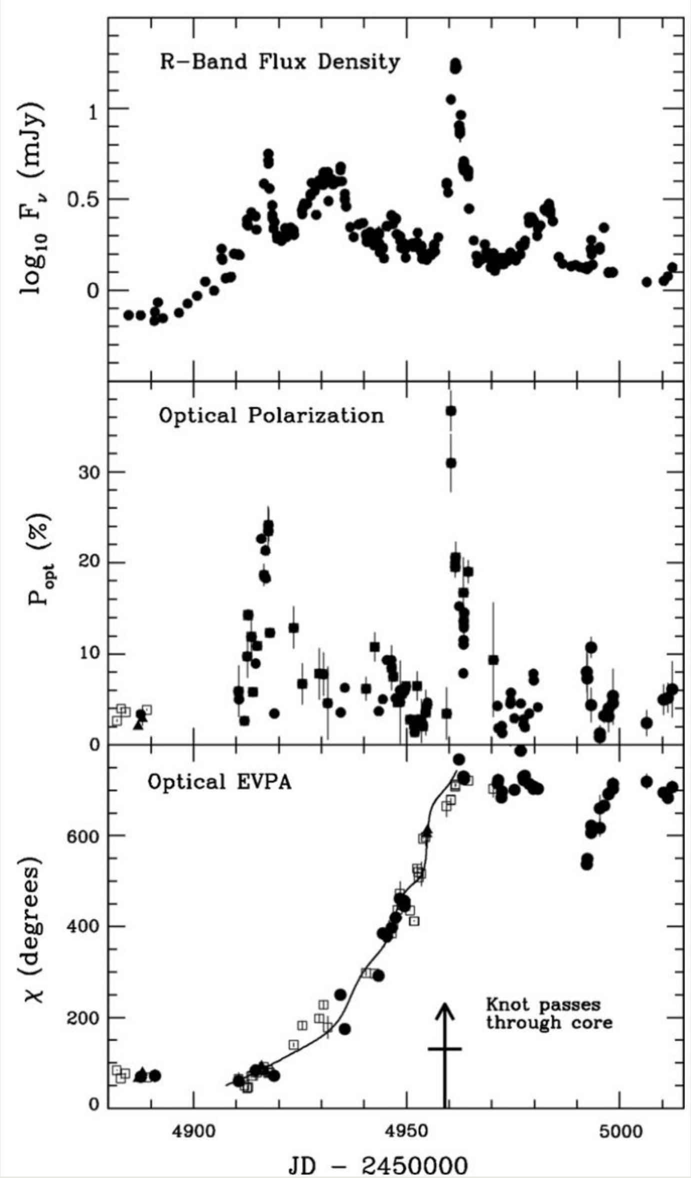
- Final parsec problem: Supermassive black holes appear to have merged, and what appears to be a pair in this intermediate range has been observed, in PKS 1302-102.[22] However, theory predicts that when supermassive black holes reach a separation of about one parsec, it may take billions of years to orbit closely enough to merge—greater than the age of the universe.[23]
- The formation of high-redshift quasars:
  - How do the most distant quasars grow their supermassive black holes up to 10^{10} solar masses so early in the history of the universe (with redshift greater than 6 to 7)?

Polarization Observations

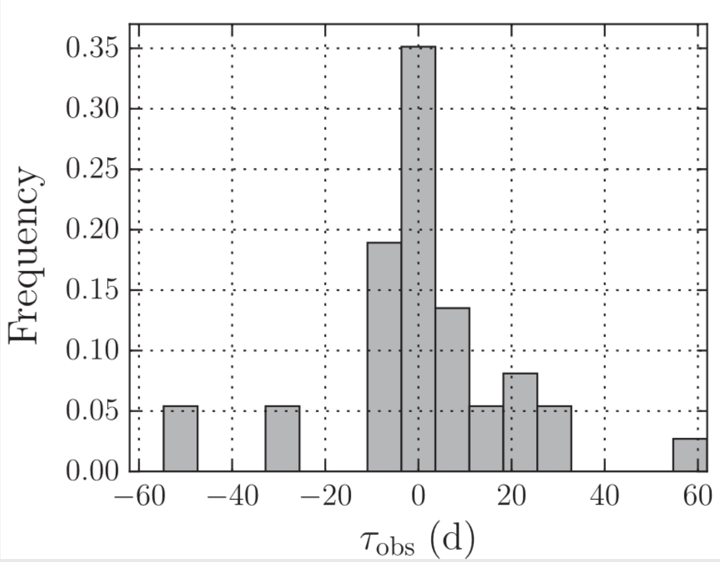


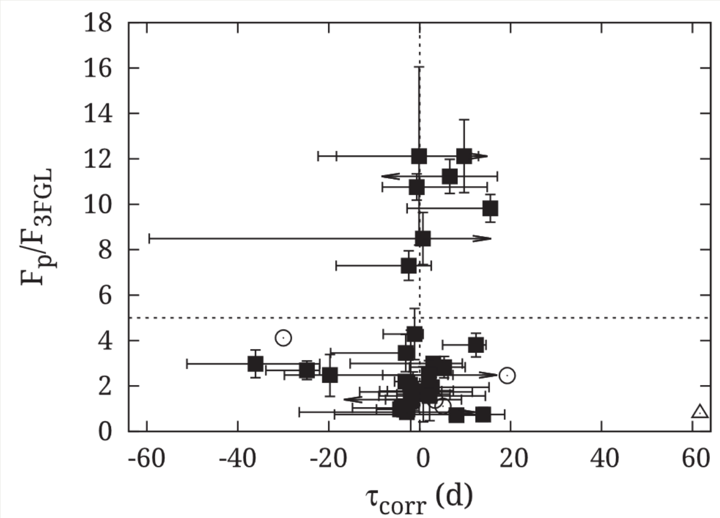
Marscher+ 2010, ApJL 710, L126

Polarization Observations

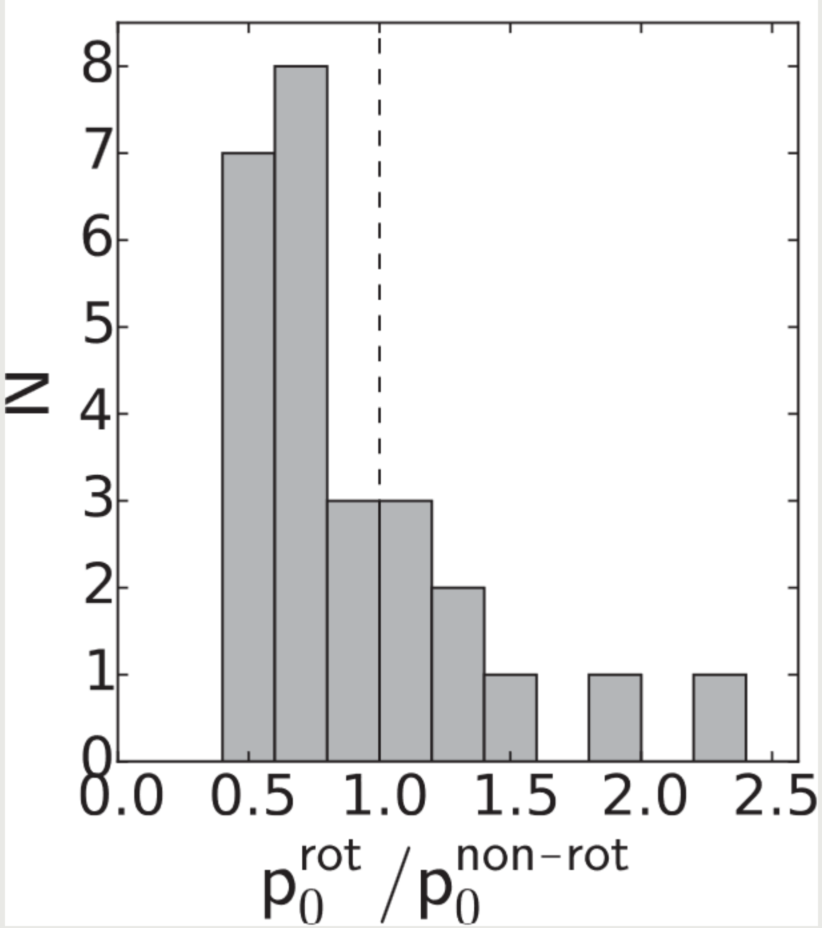


Marscher+ 2010, ApJL 710, L126



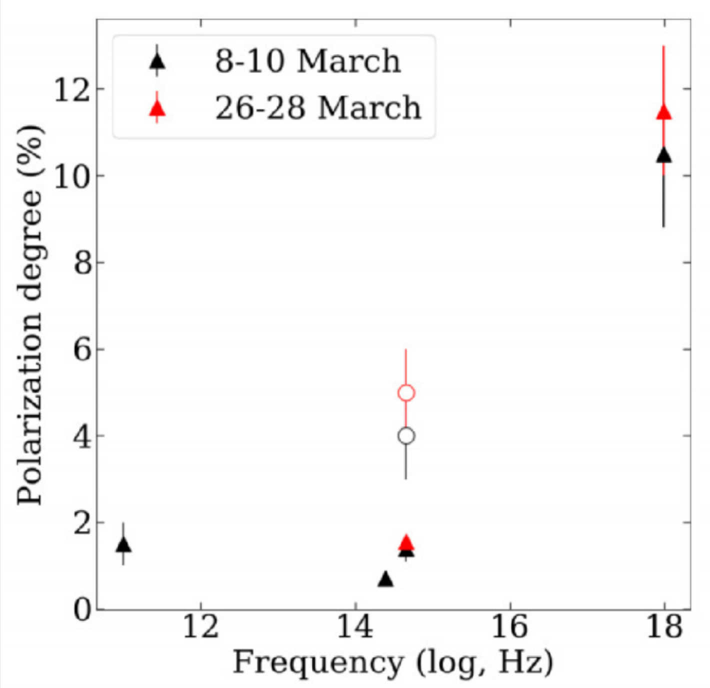


Blinov+ 2018, MNRAS 474, 1296

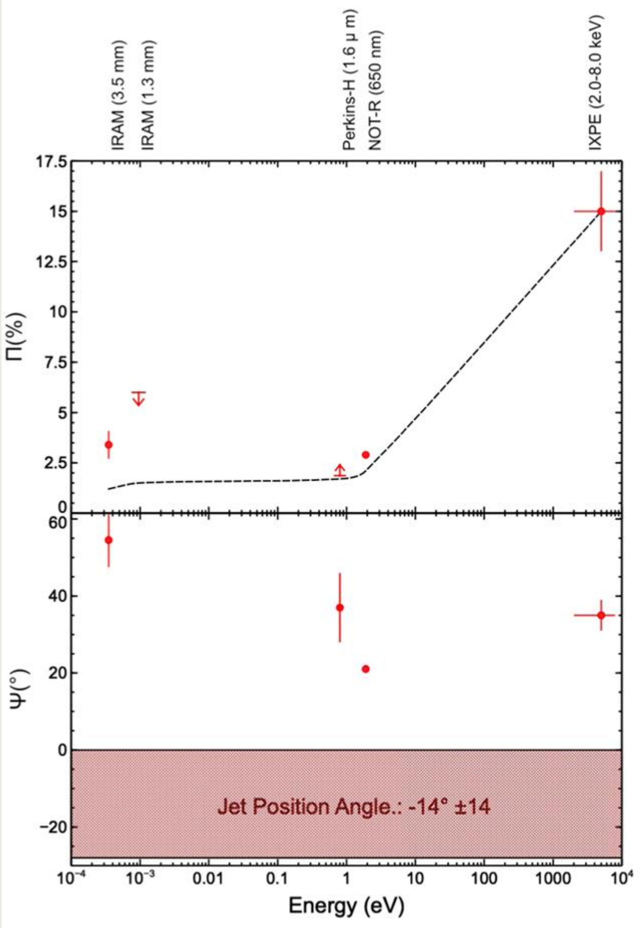


Blinov+ 2016, MNRAS 457, 2252

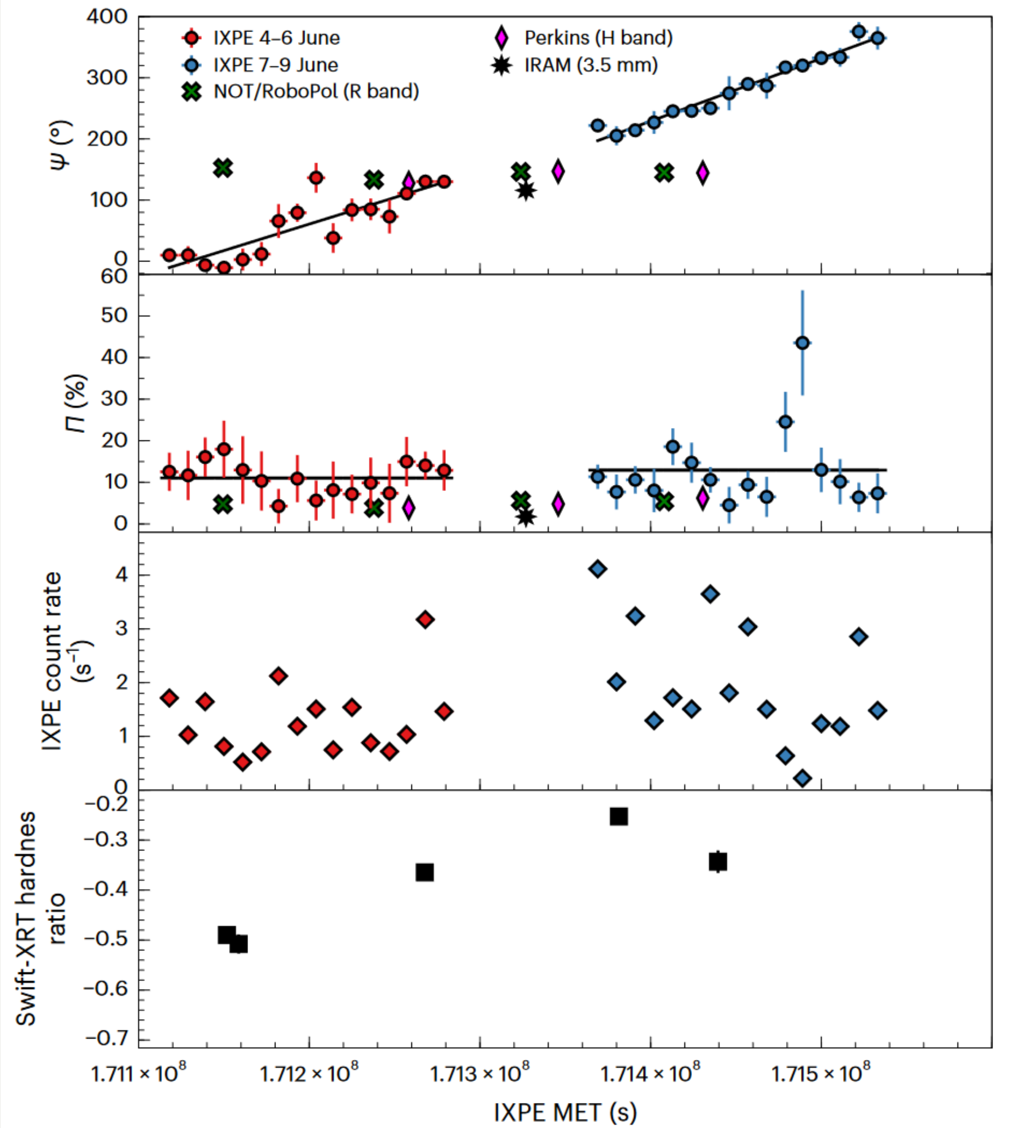
Polarization Observations



Liodakis+ 2022 Nature 611, 677



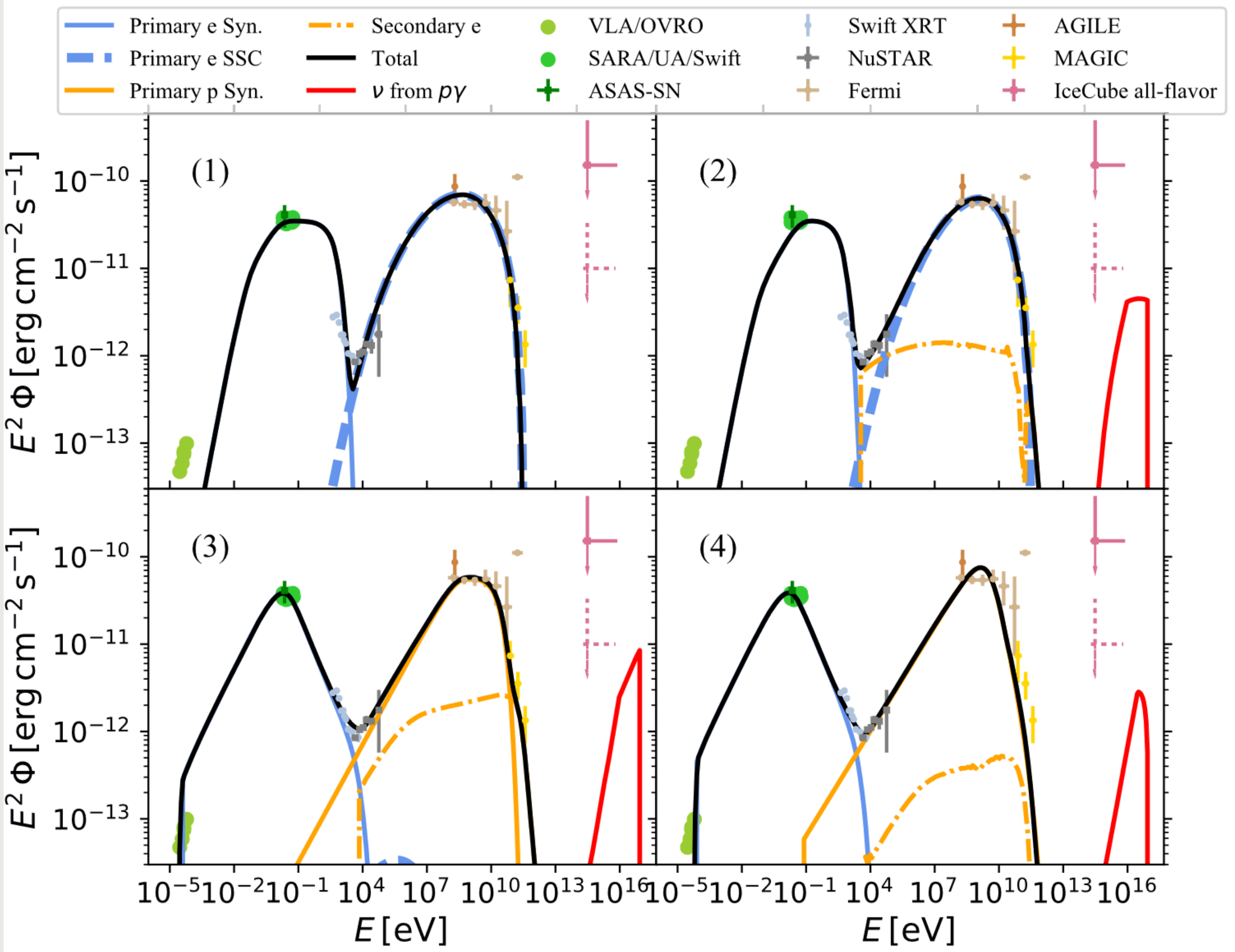
Di Gesu+ 2022, ApJL 938, L7



Di Gesu+ 2023 Nature Astronomy 7, 1245

Case I: Leptonic vs Hadronic Radiation Models

Leptonic vs Hadronic



Zhang+ 2019 ApJ 876, 109

Leptonic and hadronic models cannot be distinguished by spectral fitting only

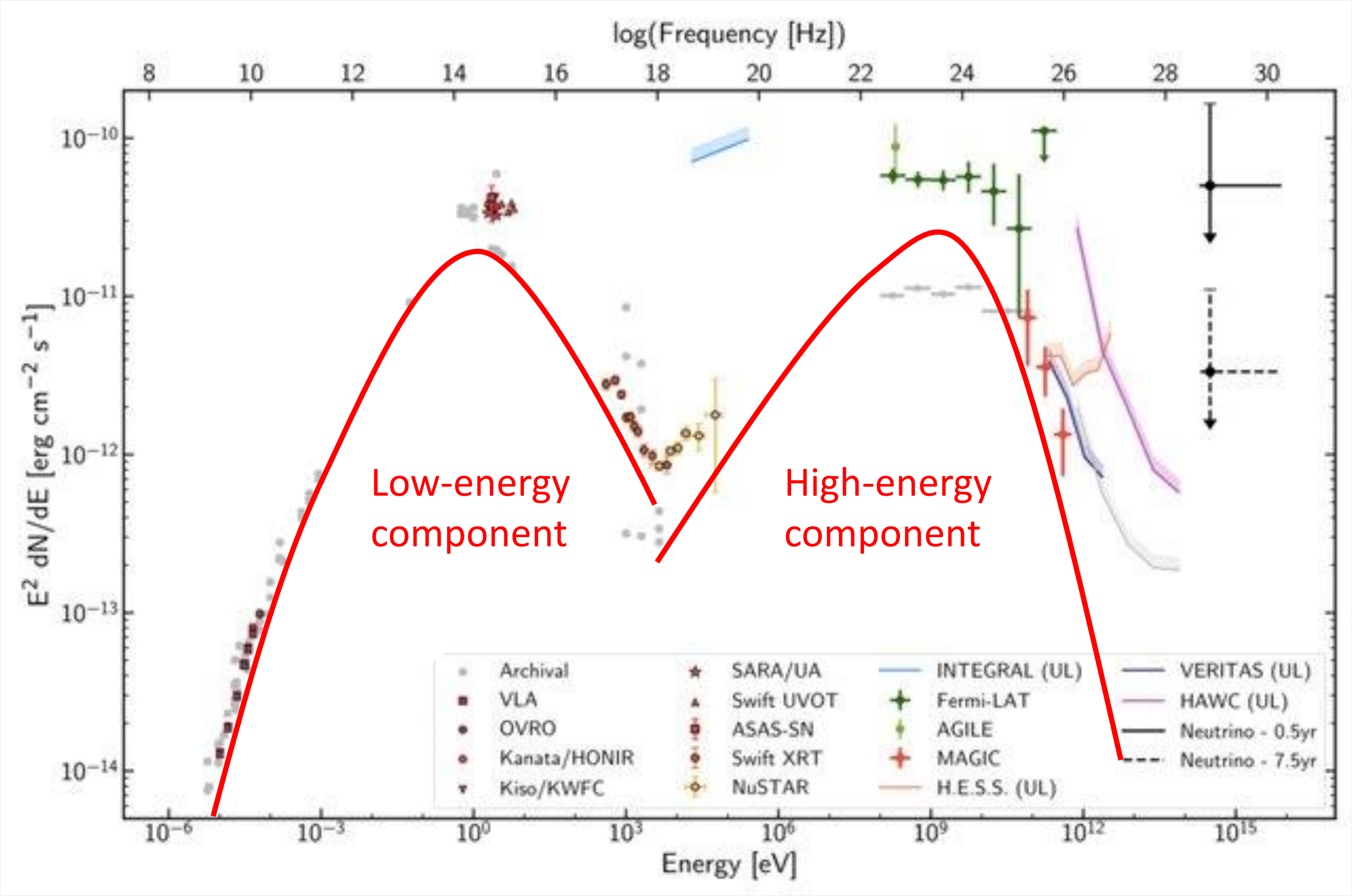
Leptonic Model:

1. High-energy component comes from inverse Compton scattering by electrons.
2. Seed photons may be synchrotron itself (SSC), or external thermal photons (EC).

Hadronic Model:

1. High-energy component comes from proton synchrotron and/or hadronic cascades.
2. Inverse Compton scattering by electrons can contribute as well.
3. Acceleration of cosmic rays and production of neutrinos

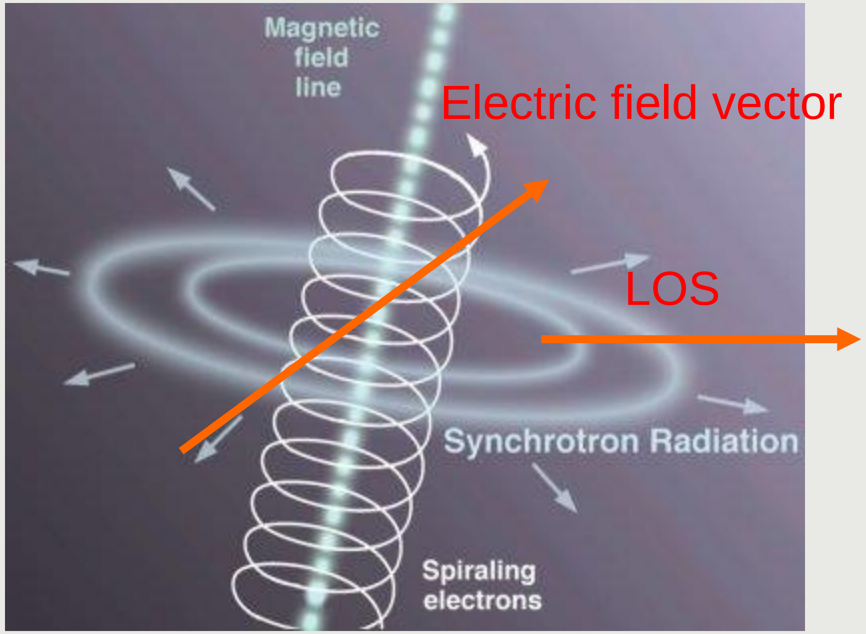
How about Neutrinos?



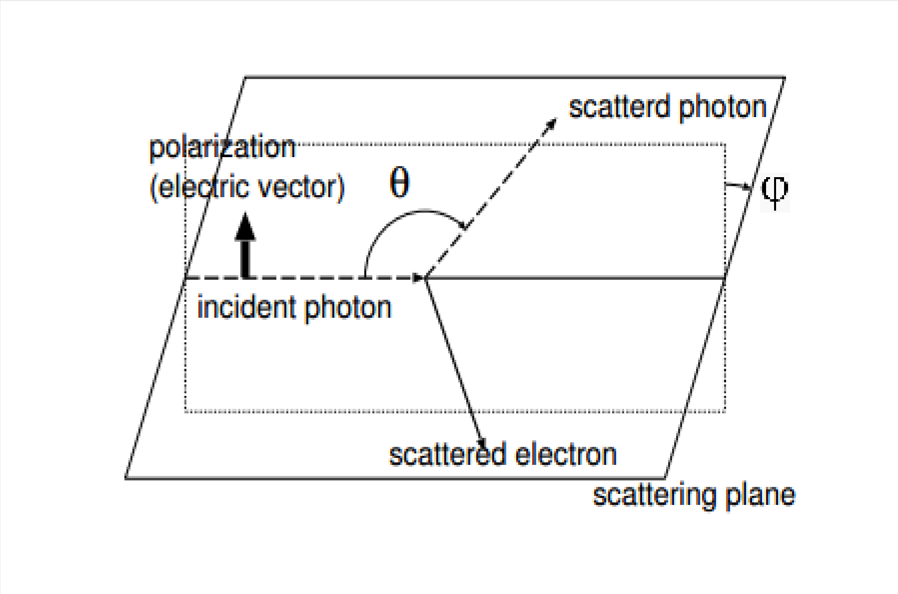
IceCube+ 2018 Science 361, 1387

- ❑ IceCube has limited resolution; it is hard to tell if the neutrinos are coming from the same source.
- ❑ Even if a super-IceCube can confirm the direction, neutrinos do not necessarily correlate with photons.

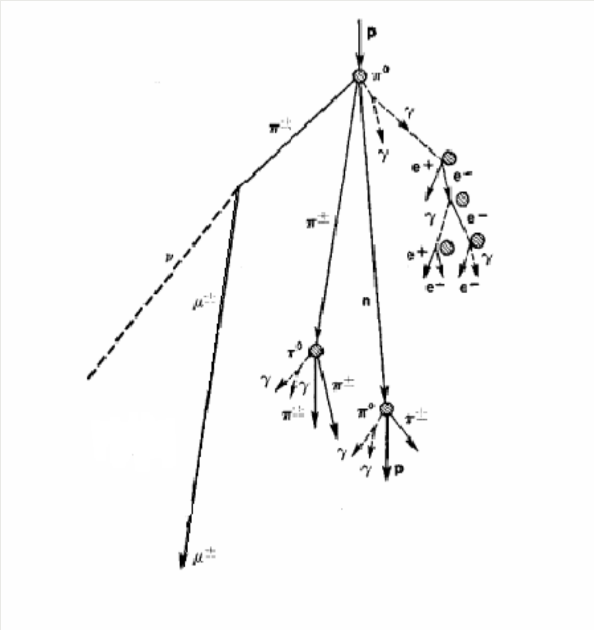
Synchrotron & Compton Scattering



Synchrotron is strongly polarized.



Compton scattering reduces polarization.



Protons and cascading charged particles can emit via synchrotron.

Hadronic Cascade

$p + \gamma \rightarrow p(n) + \pi^0(\pi^+)$

$p + \gamma \rightarrow p + e^+ + e^-$

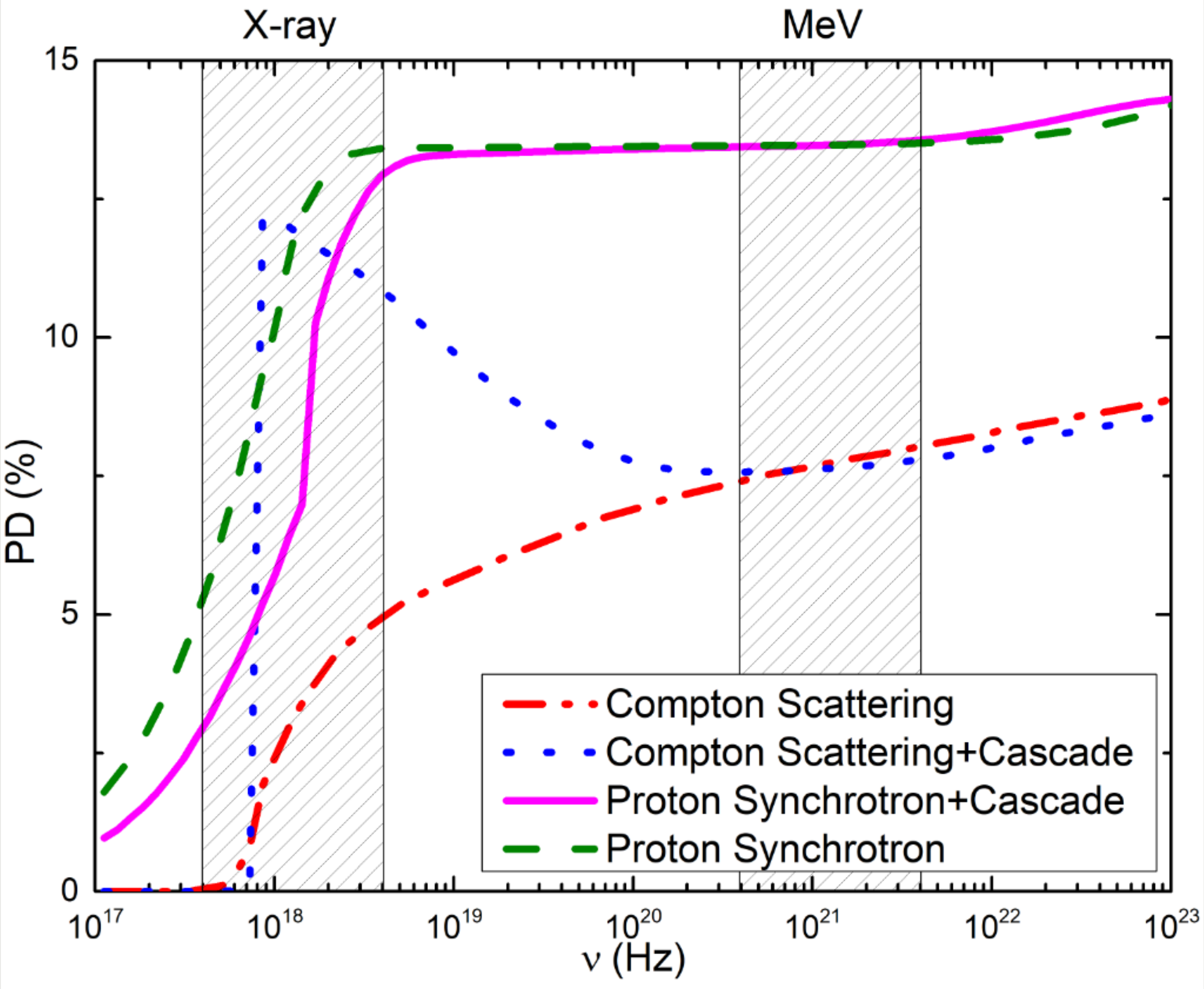
$\pi^0 \rightarrow \gamma + \gamma,\ \pi^+ \rightarrow \mu^+ + \nu_\mu$

$\mu^+ \rightarrow e^+ + \nu_\mu + \nu_e$

1. Pure leptonic: SSC and/or EC
2. Leptonic + hadronic cascades: SSC and/or EC + pair synchrotron
3. Proton synchrotron: SSC + pair/proton synchrotron

- ❑ Polarization is a property of the photons.
- ❑ High-energy polarization degree can distinguish these models.

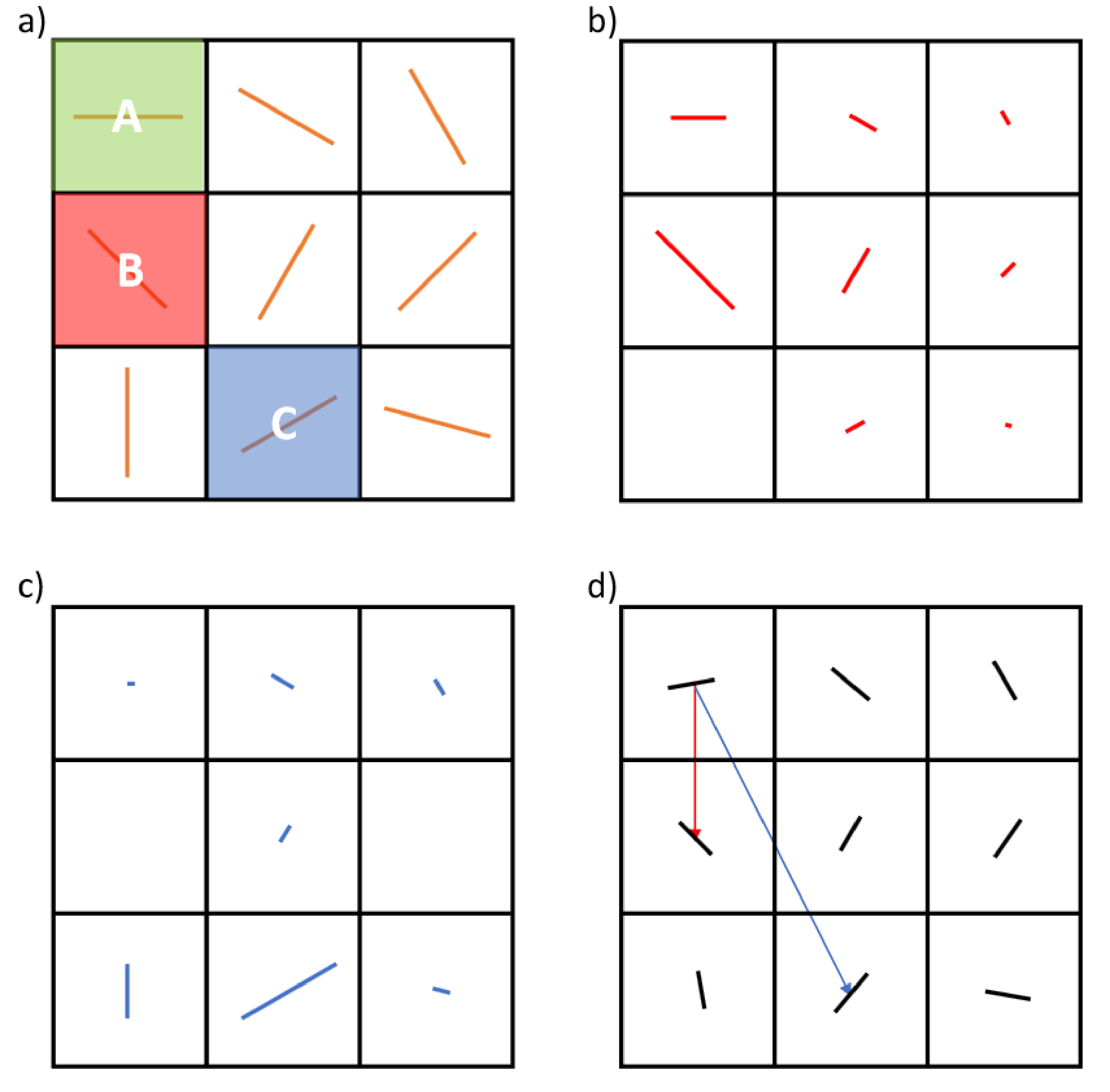
MeV Polarimetry as a Unique Probe



Zhang+ 2019 ApJ 876, 109

1. Hadronic models predict systematically higher polarization in MeV gamma-ray bands.
2. MeV polarization can identify proton synchrotron, which can constrain the maximal proton energy in the blazar zone.

A Multi-Zone Picture



$$\Pi_{syn,tot} = \frac{1}{\sqrt{N}} \Pi_{syn,max}$$

$$\Pi_{ssc,tot}(a) = \frac{1}{\sqrt{N(a)}} \Pi_{ssc} \propto \frac{1}{a} \Pi_{ssc}$$

$$F_{tot} = \sum_{a=1}^{a_{max}} F_0 = a_{max} F_0$$

$$F_{pol} \propto \Pi_{ssc} F_0 \sqrt{\sum_{a=1}^{a_{max}} \frac{1}{a} (\cos^2(2\mathcal{R}(PA)) + \sin^2(2\mathcal{R}(PA)))}$$

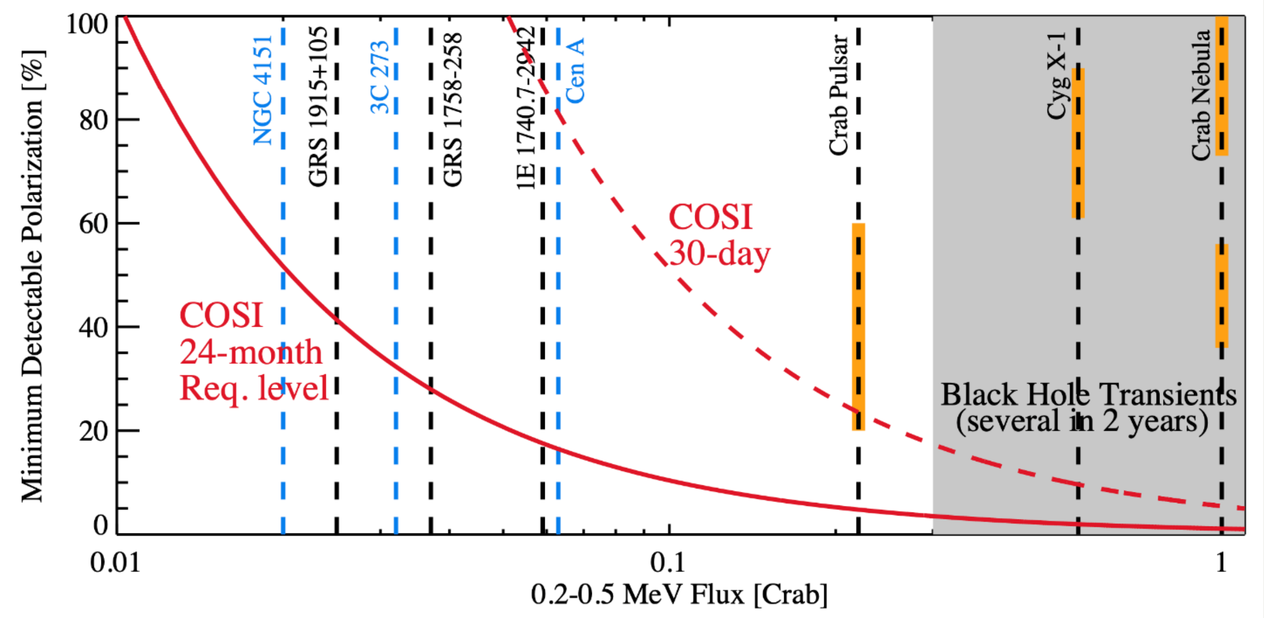
$$\Pi_{ssc,tot} = \frac{1}{\sqrt{N}} \frac{1}{N^{1/3}} \Pi_{ssc,max} \sim 50\% \frac{1}{N^{5/6}} \Pi_{syn,max}$$

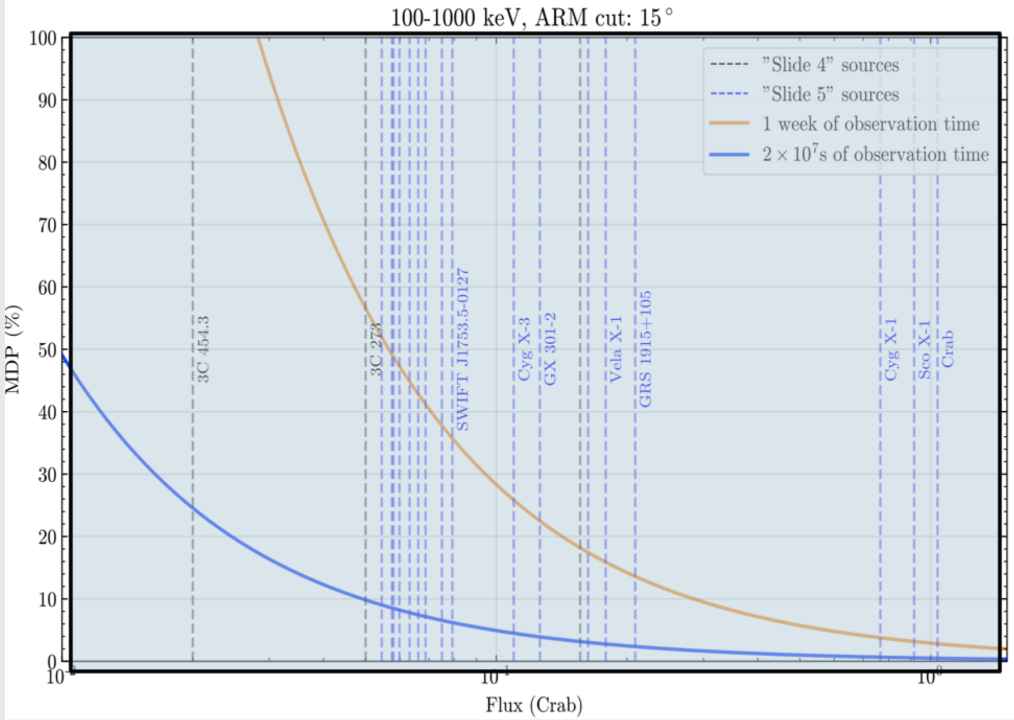
Π_o	5%	10%	15%	20%	25%	40%
Π_{SSC}	0.43%	1.4%	2.7%	4.3%	6.3%	14%

Detectable? Yes!

2FHL Name (1)	Optical Pol. (%) (2)	lep. Pol. (1 keV, %) (4)	had. Pol. (1 keV, %) (5)	lep. Pol. (1 MeV, %) (6)	had. Pol. (1 MeV, %) (7)
J0456.9−2323	9.9*	4.2	9.5	1.0	10.1
J0957.6+5523	5.7†	1.6	6.6	1.0	7.2
J1224.7+2124	5.4*	1.8	50.8	0.0	55.3
J1256.2−0548	15.0*	8.7	14.4	1.6	16.4
J1427.3−4204	…	…	…	…	…
J1512.7−0906	3.8*	2.5	9.7	0.0	9.7
J2000.9−1749	13.0†	6.0	13.4	0.5	15.7
J2254.0+1613	5.8*	1.9	6.2	0.0	6.9
J0456.9−2323	35.3*	15.3	34.7	3.6	38.3
J0957.6+5523	…	…	…	…	…
J1224.7+2124	29.1*	1.8	50.8	0.0	55.3
J1256.2−0548	34.5*	20.1	33.1	3.7	37.9
J1427.3−4204	…	…	…	…	…
J1512.7−0906	25.8*	17.1	66.4	0.1	66.6
J2000.9−1749	…	…	…	…	…
J2254.0+1613	25.0*	8.7	28.0	0.2	28.4

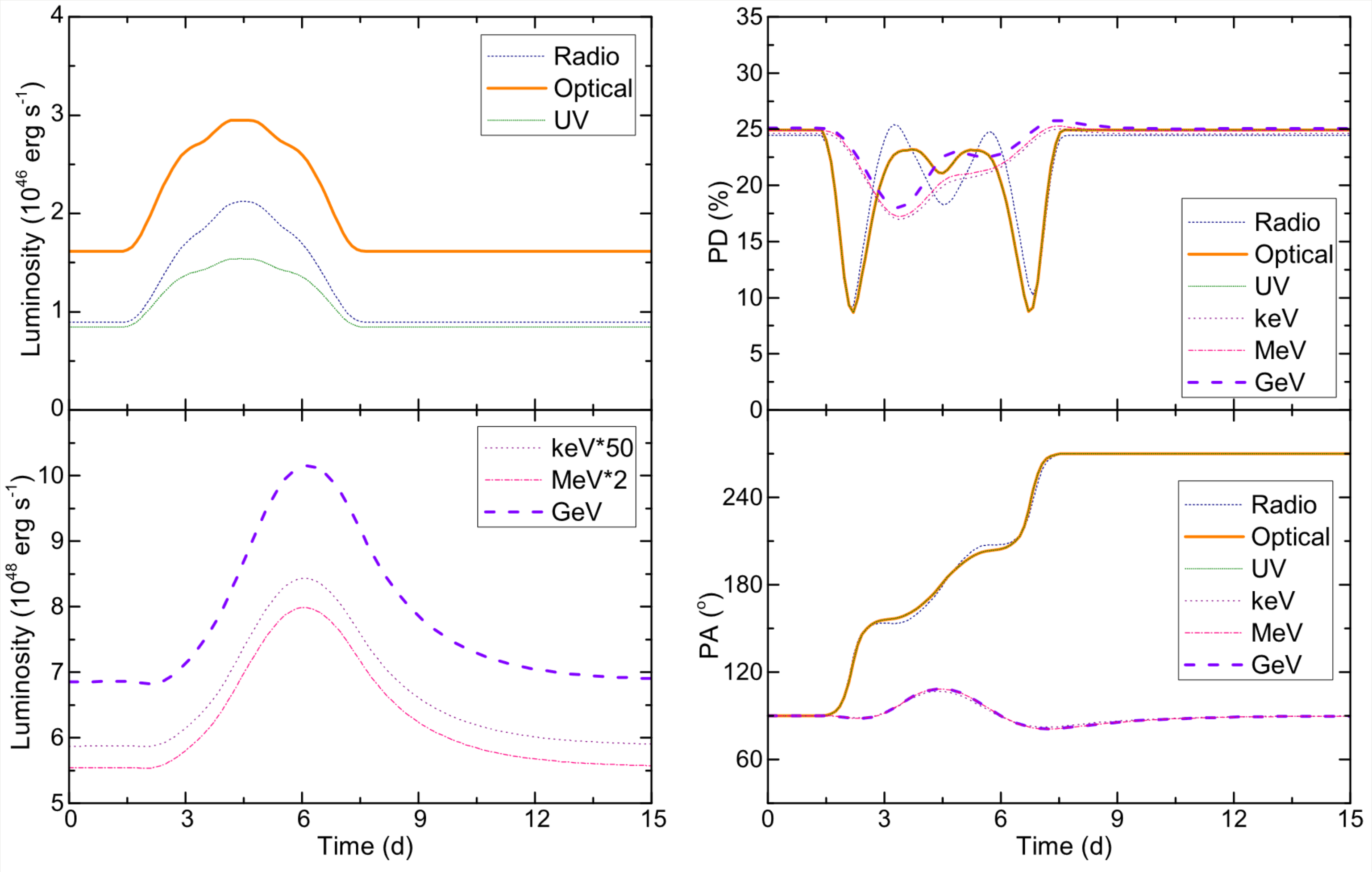
Paliya+ 2018 ApJ 863, 98





1. COSI can detect polarization for the bright blazar 3C 273 as well as a couple of bright blazar flares during its mission span.
2. AMEGO-X can detect 10 blazar flares per year, unambiguously distinguish leptonic and hadronic models.

Flares Actually Help MeV Polarimetry



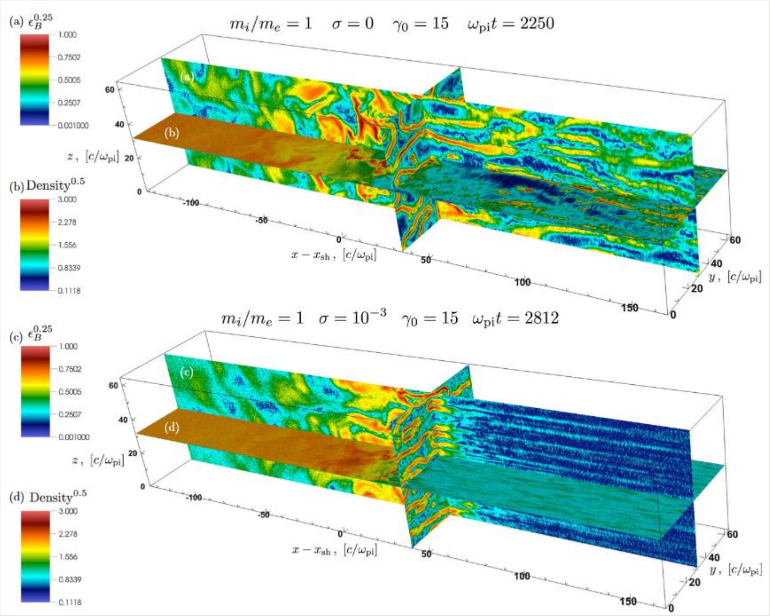
Zhang+ 2016 ApJ 829, 69

1. MeV polarization degree under the hadronic scenario is comparable to the optical counterpart.
2. MeV polarization is much more stable in time than the optical counterpart, due to very slow proton cooling.
3. MeV flare can be as bright as the GeV flare.
4. Ideal for COSI and AMEGO-X to detect polarization during flaring states.

Case II: Polarization Variability in Particle Acceleration

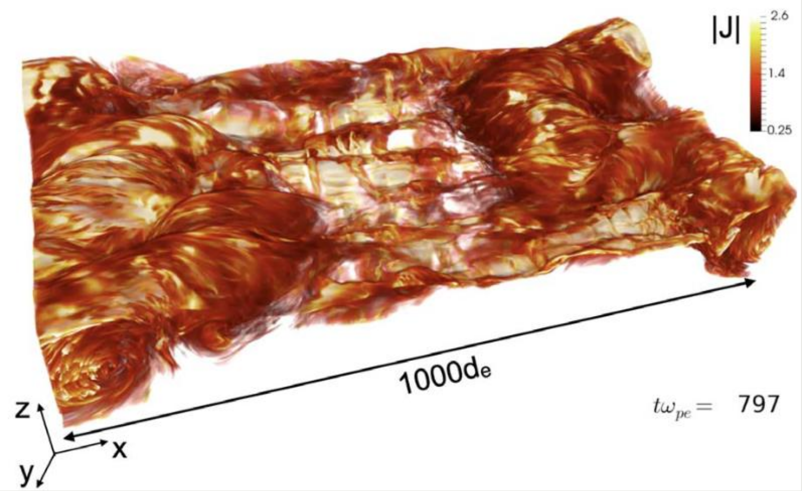
Particle Acceleration in the Blazar Zone

- ❑ Blazars can accelerate nonthermal electrons/protons and produce multi-wavelength flares.
- ❑ Numerical simulations have shown that all three mechanisms can produce typical blazar spectra and light curves.
- ❑ But we need to distinguish them!



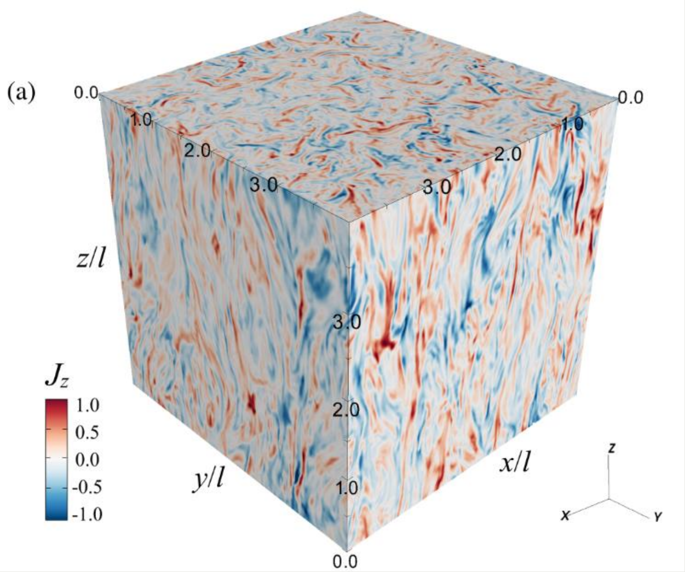
Sironi+ 2013, ApJ 771,54

Shock



Magnetic Recononection

Guo+ 2021, ApJ 919, 111



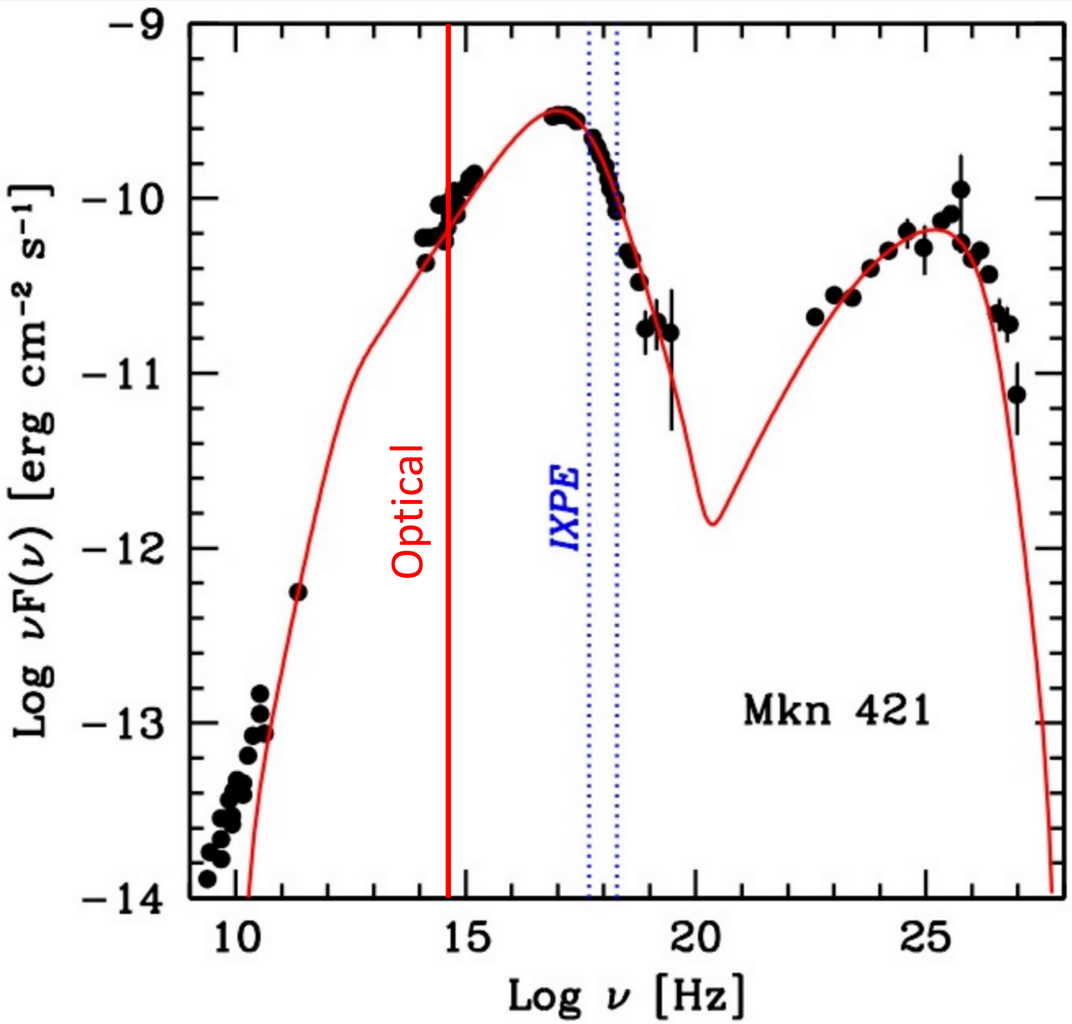
Turbulence

Comisso & Sironi 2018, PRL 121, 255101

Optical and X-ray Polarization can Distinguish them

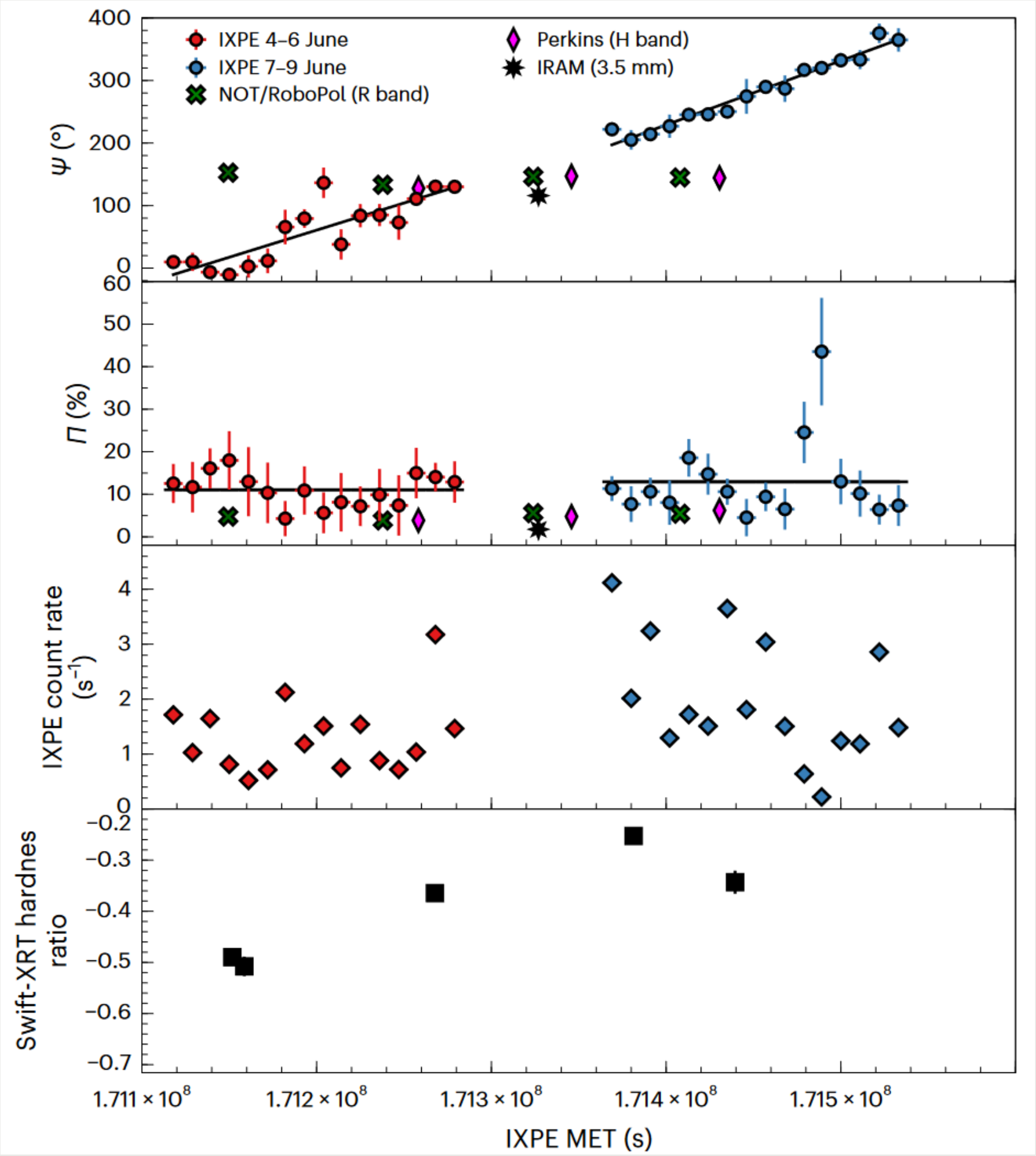
Polarization can directly reveal the magnetic field structure and evolution.

Optical and X-ray polarization together can constrain the particle acceleration mechanisms in high-synchrotron-peaked blazars.



Tavechhio 2021, Galaxies 9, 37

X-ray Polarization Angle Swing



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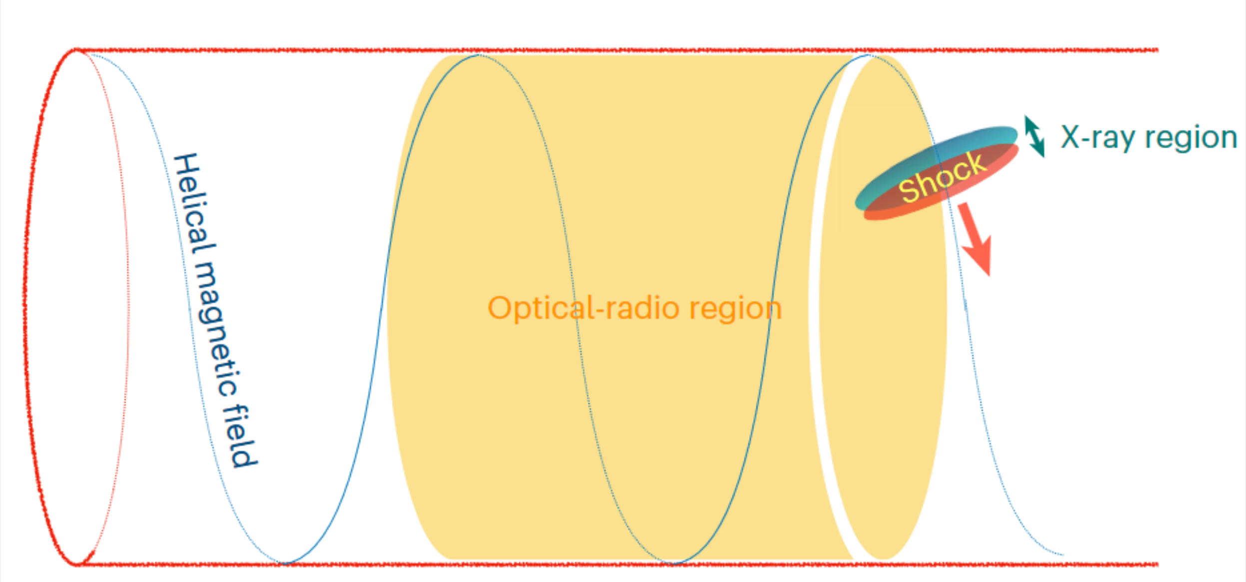
- ❑ Continuous angle swing in one direction
- ❑ Swing amplitude $> 180°$
- ❑ Variability in both flux and polarization degree

Two types of models:

1. Geometric: bending jet, shock in a helical magnetic field, etc.
2. Physical: shock, kink instability, magnetic reconnection, and turbulence

Geometric Models



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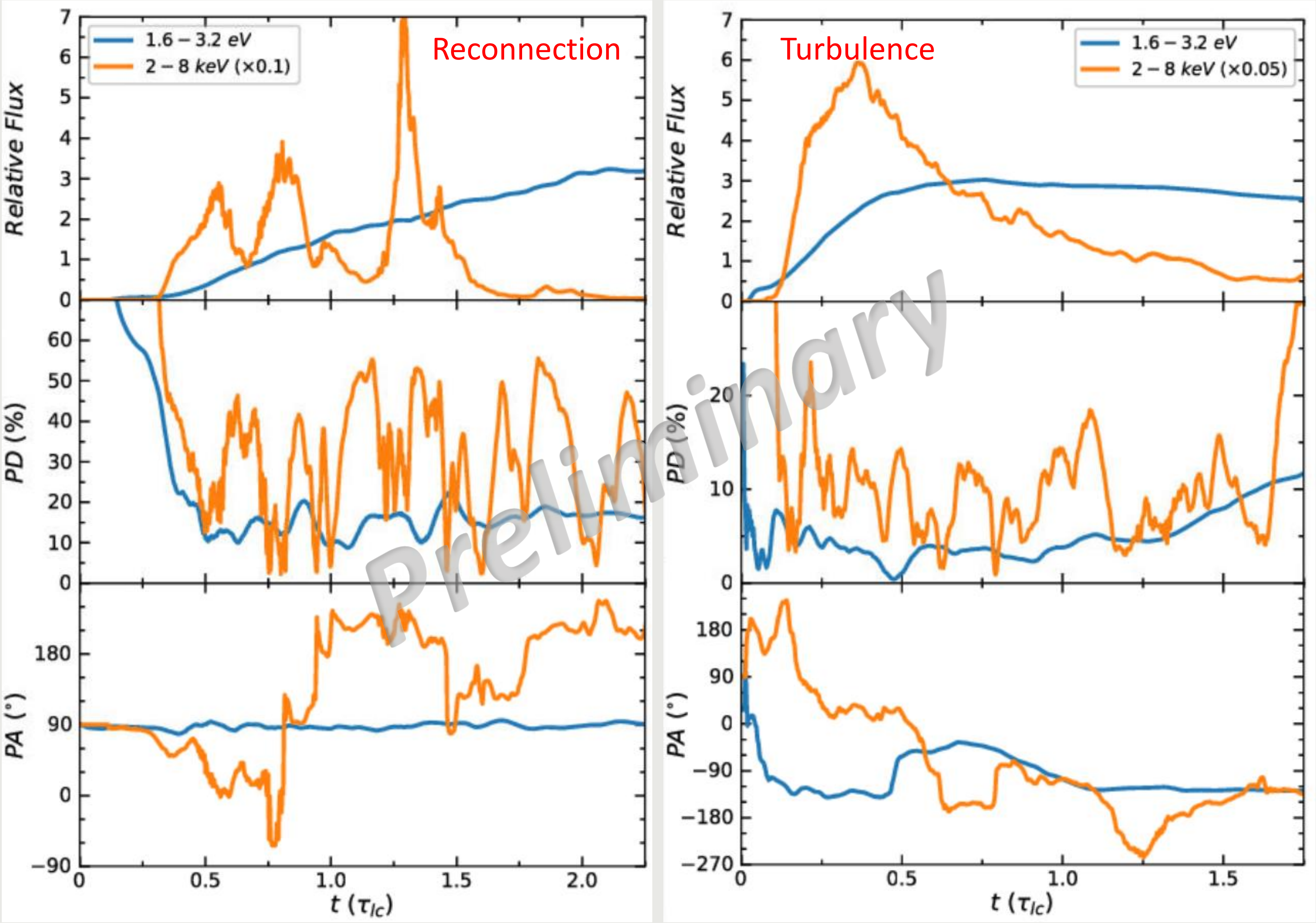
Shocked emission region moving in a helical magnetic field:

- ❑ Continuous angle swing in one direction due to the motion of the emission region
- ❑ Variability in both flux and polarization degree are due to shock acceleration

- ❑ However, most geometric models involving large-scale jet structures, such as bending jet, curved jet trajectory, etc., require any angle rotations $> 90^\circ$ in the same direction.
- ❑ Other geometric models usually have clear correlation between flux, polarization degree, and angle.

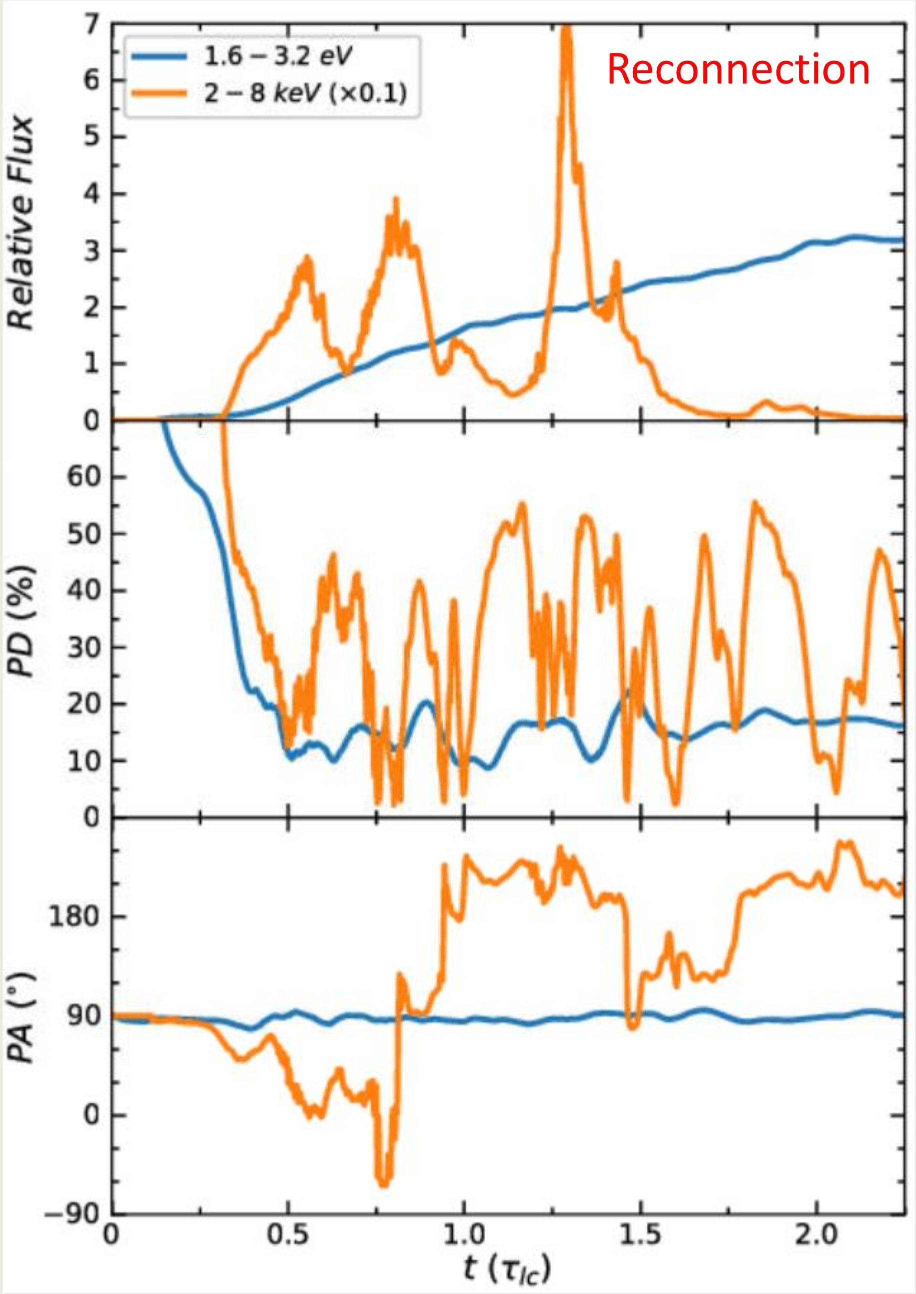
IXPE can easily confirm or reject most geometric models by detecting angle rotation in both directions or confirming correlation between flux and polarization.

Physical Models



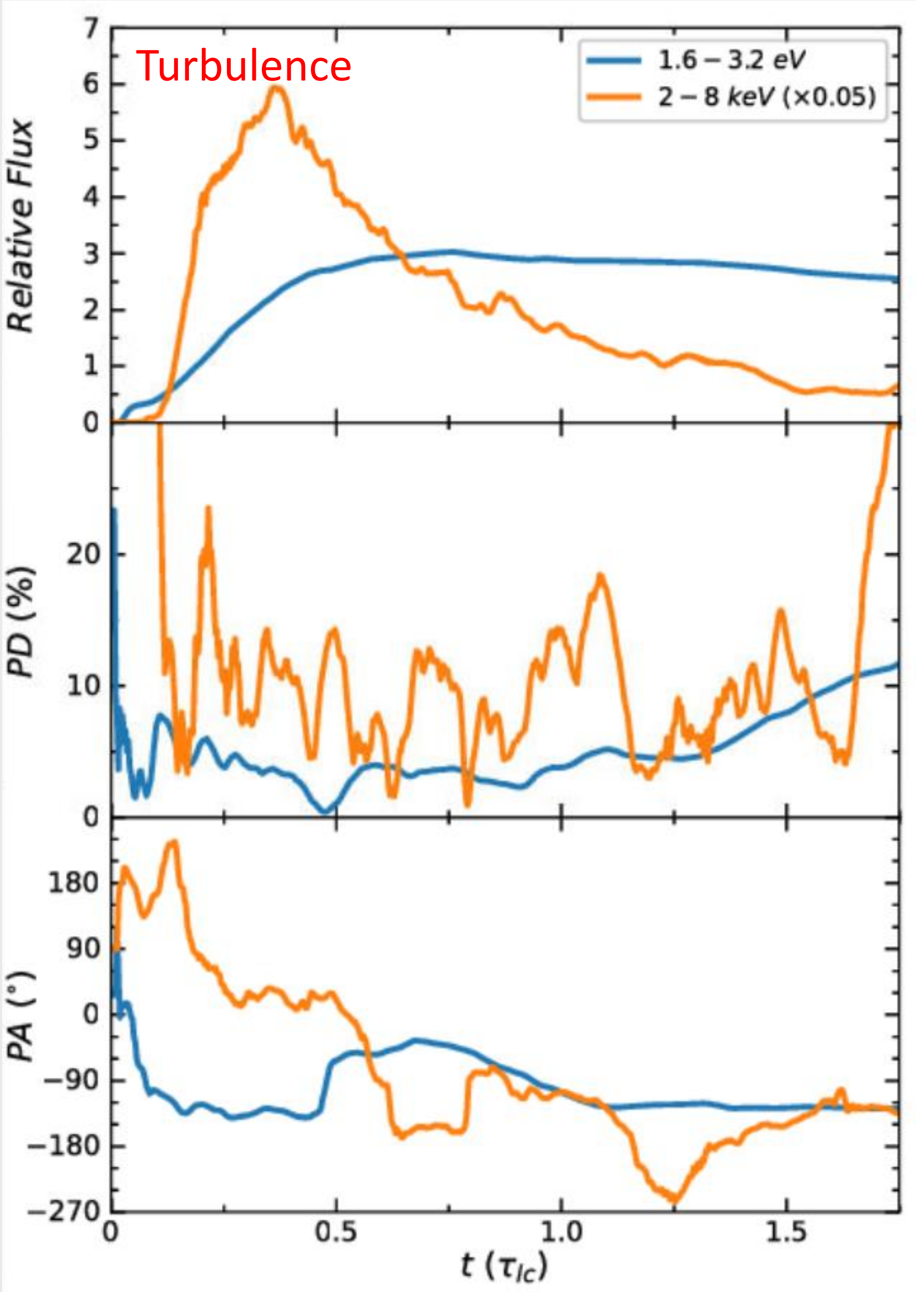
Two cherry-picked particle-in-cell simulations of reconnection and turbulence that show the strongest polarization variability

Magnetic Reconnection



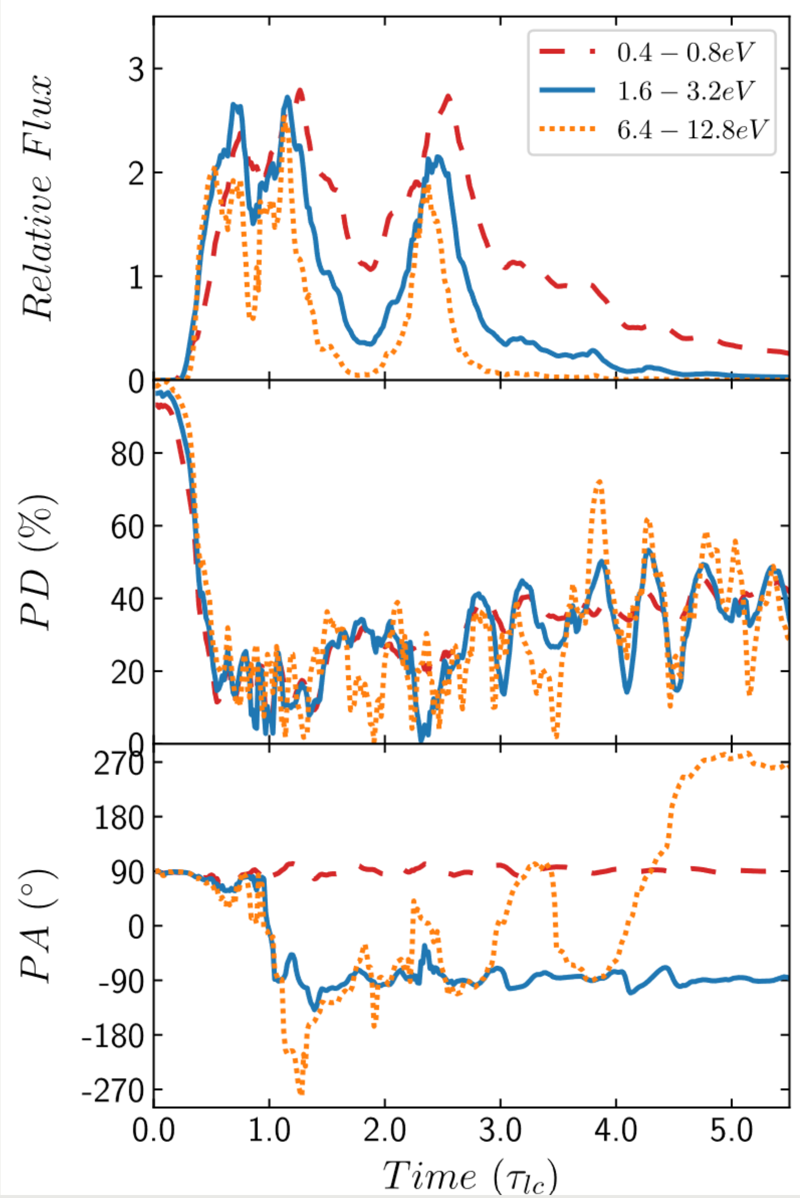
- Much faster flux variability in X-ray than optical
- Flashes of high X-ray polarization degree
- Fast X-ray angle swings that can result in zero X-ray polarization if unresolved
- X-ray angle rotations $> 90°$ are associated to X-ray flares
- Angle rotation in both directions and of arbitrary amplitudes
- Much larger X-ray polarization variability amplitude than optical

Turbulence

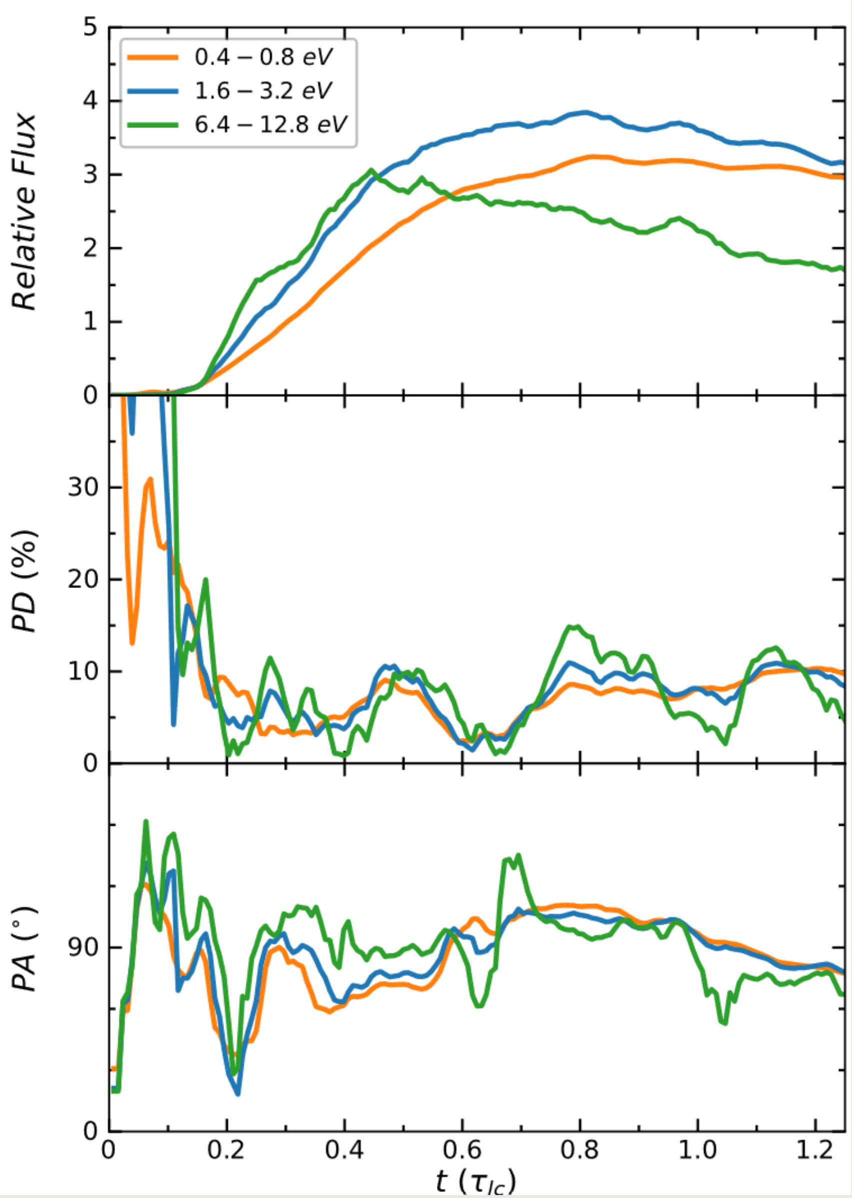


- ❑ X-ray angle rotations > 90° are NOT associated to X-ray flares
- ❑ Angle rotation in both directions and of arbitrary amplitudes
- ❑ Comparable X-ray polarization variability amplitude than optical

Reconnection vs Turbulence



Zhang+ 2020, ApJ 901, 149

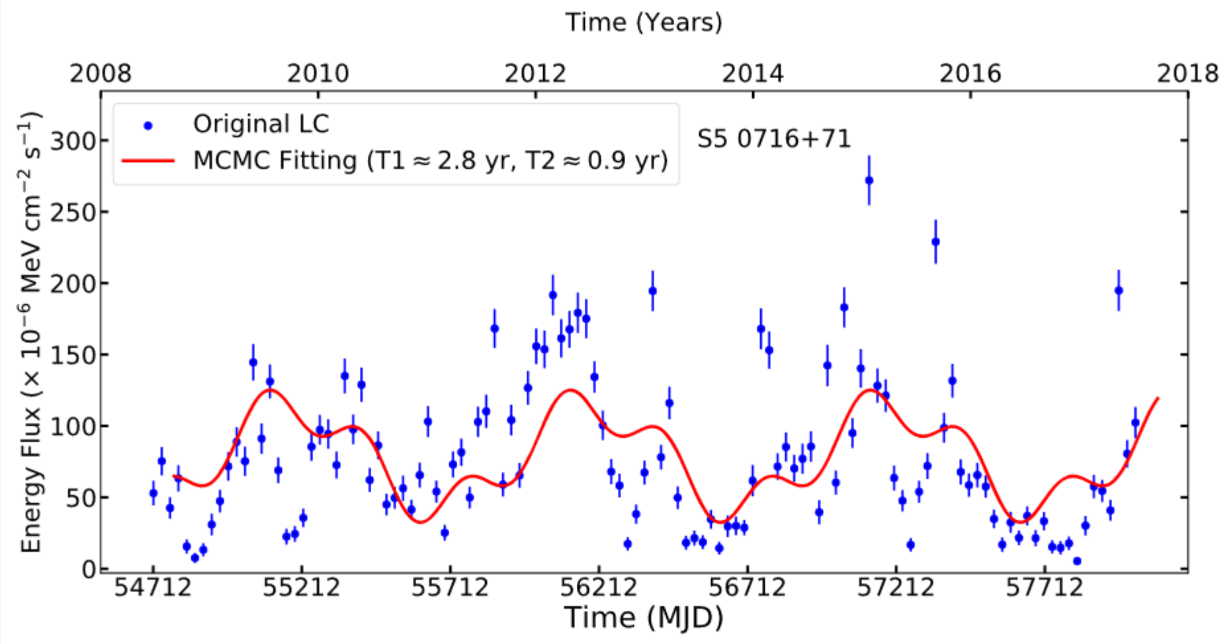


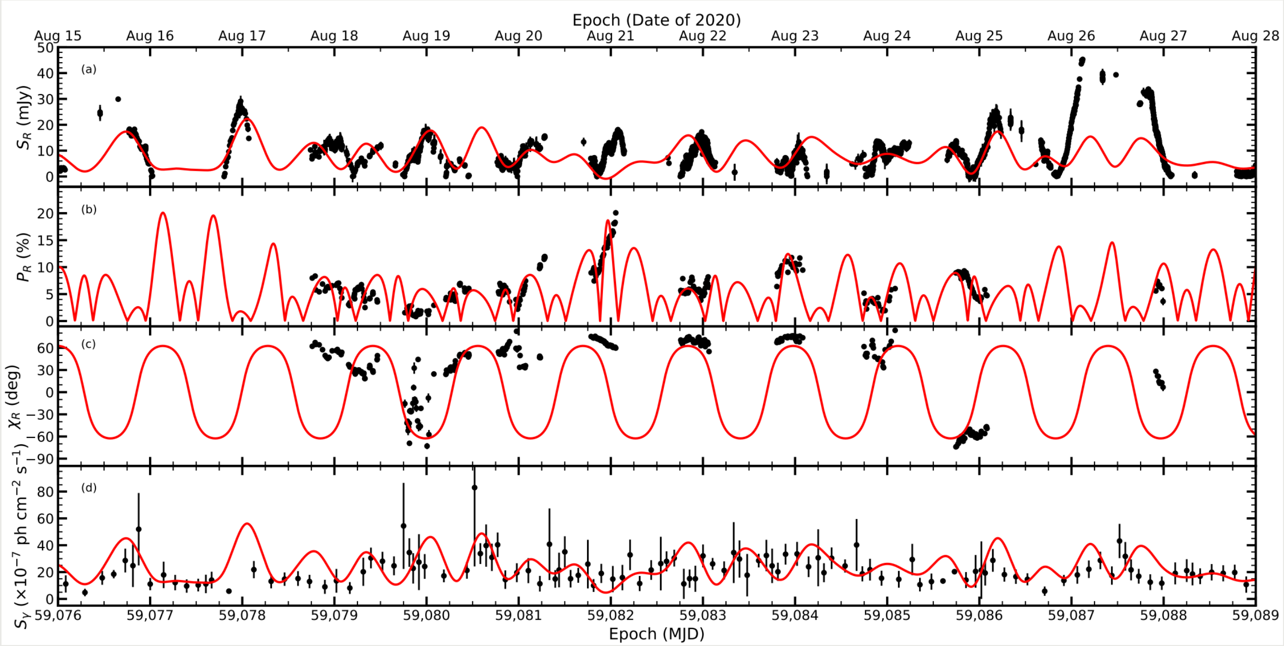
Zhang+ 2023, ApJ 949, 71

- ❑ Non-cherry-picked particle-in-cell simulations of reconnection and turbulence
- ❑ Reconnection shows a larger polarization variation amplitude ratio than turbulence between high- and low-energy bands.

Case III: Kink-Driven Transient QPOs

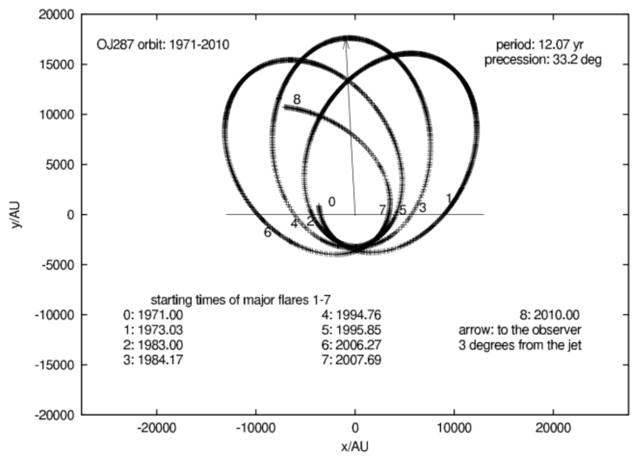
Persistent and Transient QPOs

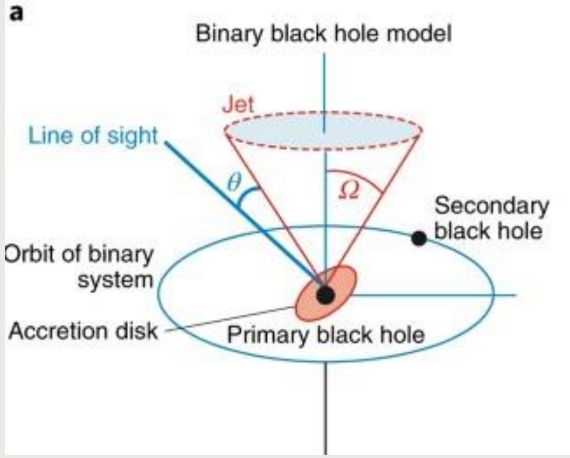




Penil+ 2020, ApJ 896, 134

Jorstad+ 2022, Nature 609, 265

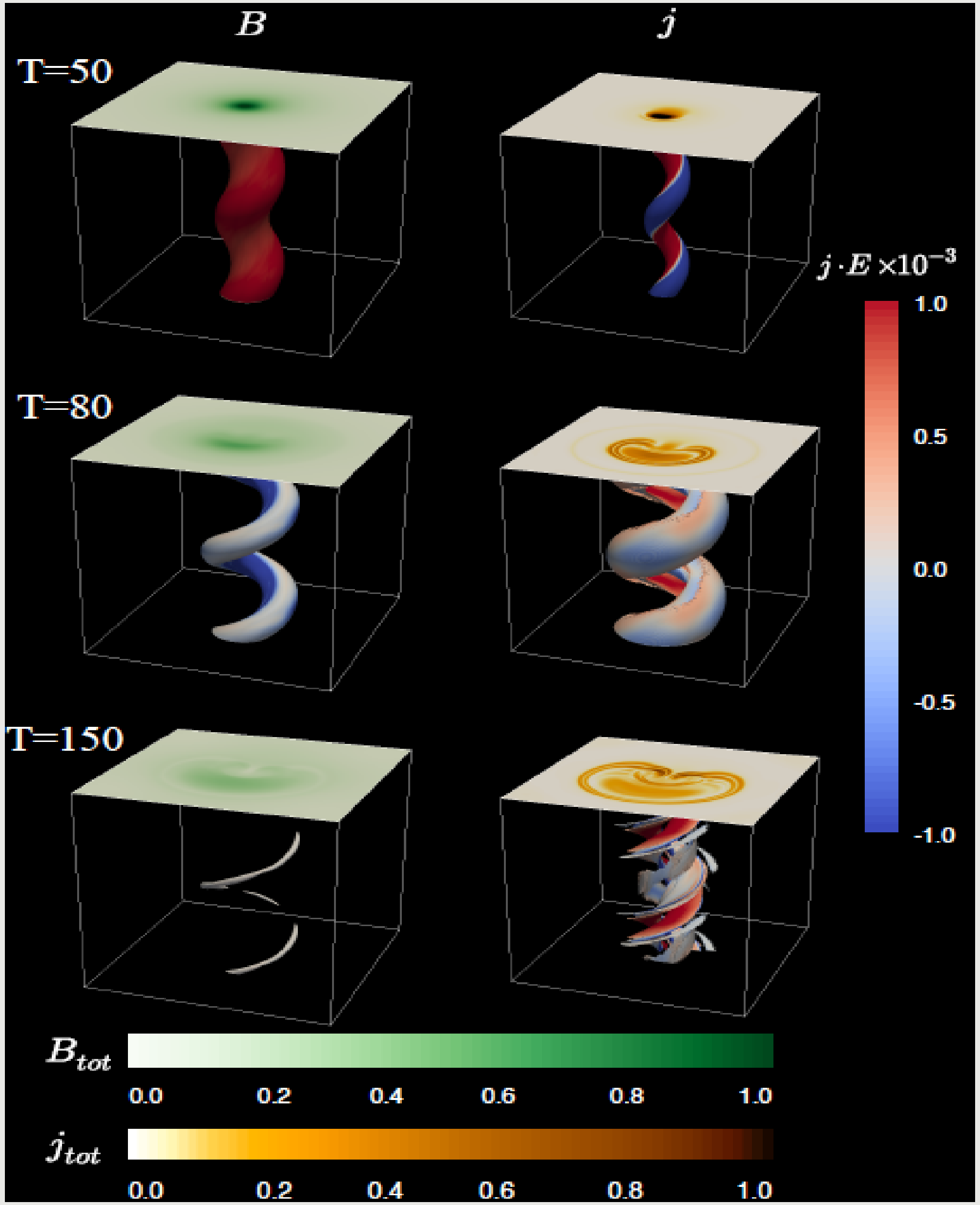




Valtonen+ 2006, ApJ 646, 36

Abraham 2018, NatAstro 2, 443

Kink Instability



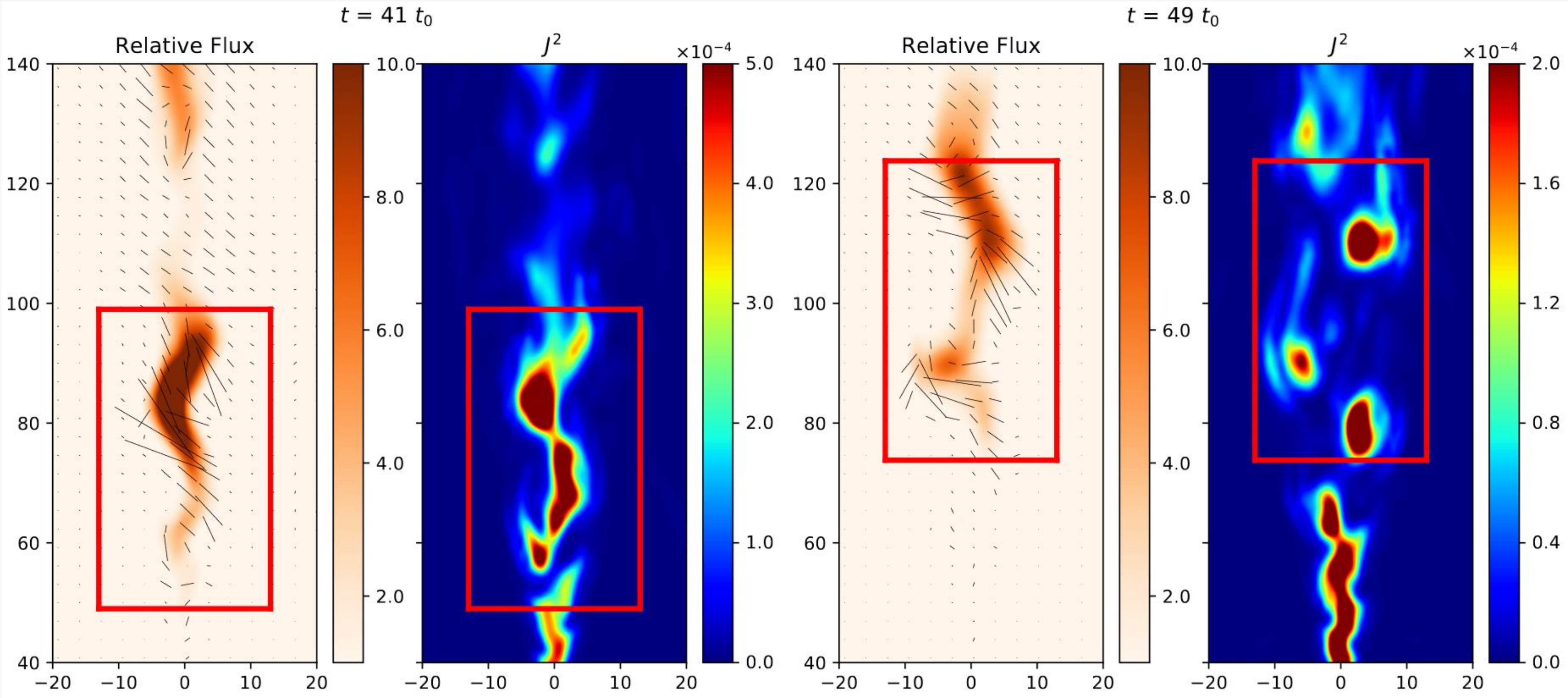
Zhang+ 2017 ApJ 835, 125

1. An MHD fluid effect when the safety factor $q = \frac{r \cdot B_p}{z \cdot B_t} < 1$
2. Strong in a magnetized jet fluid
3. Naturally quasi-periodic structure

Usually strong at $\sim pc$ from the central engine, if the jet is magnetized.

Kink Instability in Global Jet Simulations

[Barniol Duran+ 2017, MNRAS 469, 4957](#)

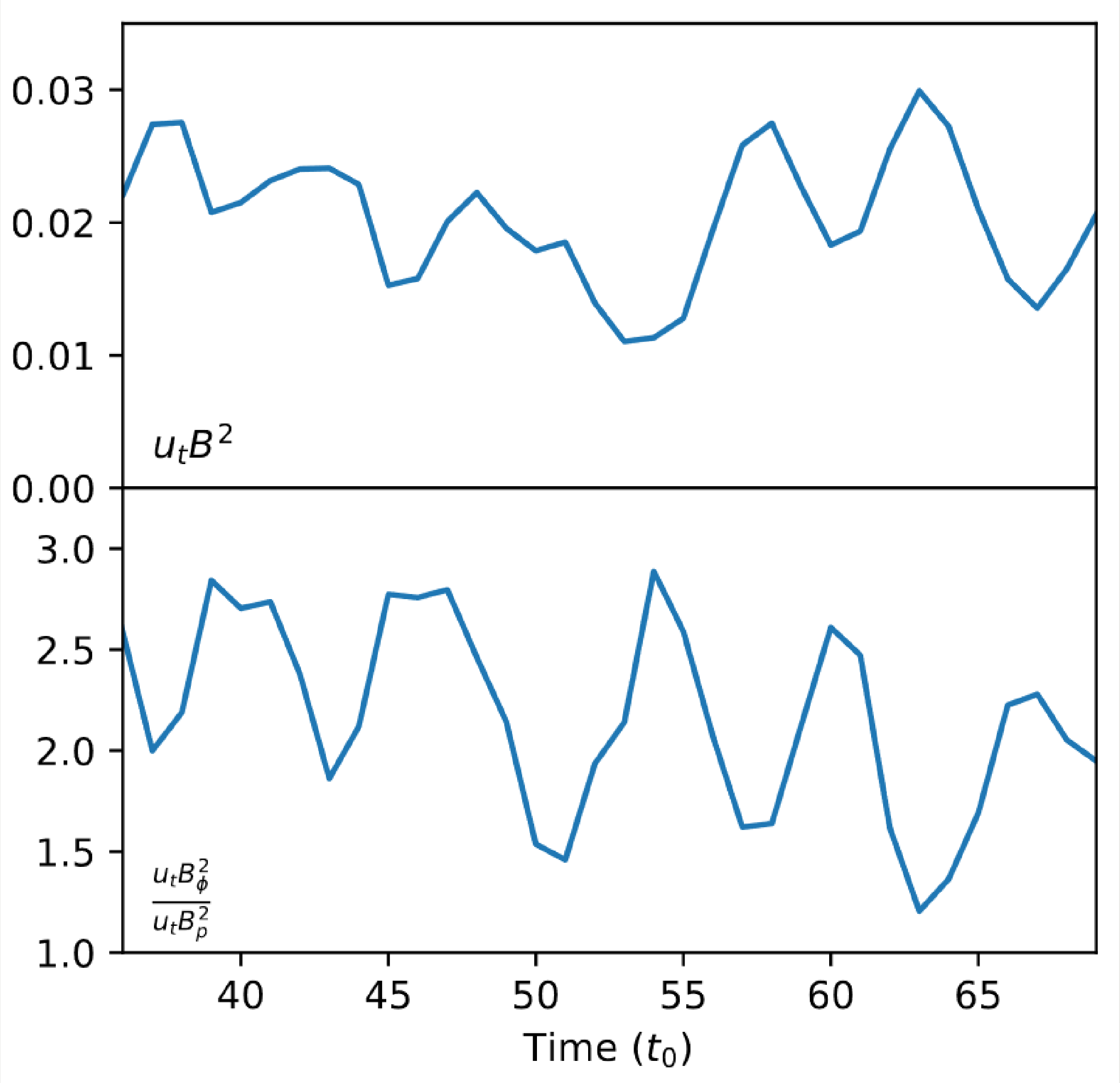


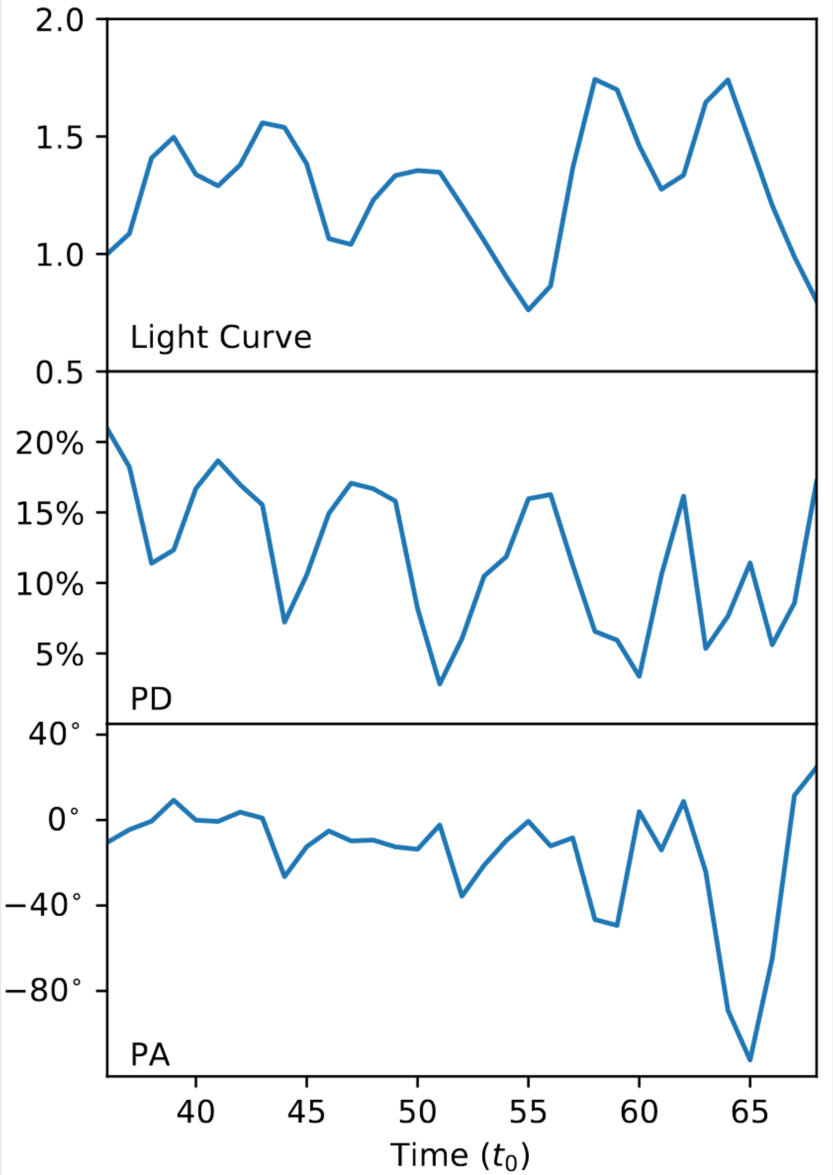
[Dong+ 2020, MNRAS 494, 1817](#)

Kink instabilities can happen in large scales.

One or two kink nodes may become very strong, due to changes in the surrounding medium (recollimation shock, density changes, etc.).

QPO Signatures From Kink Instabilities



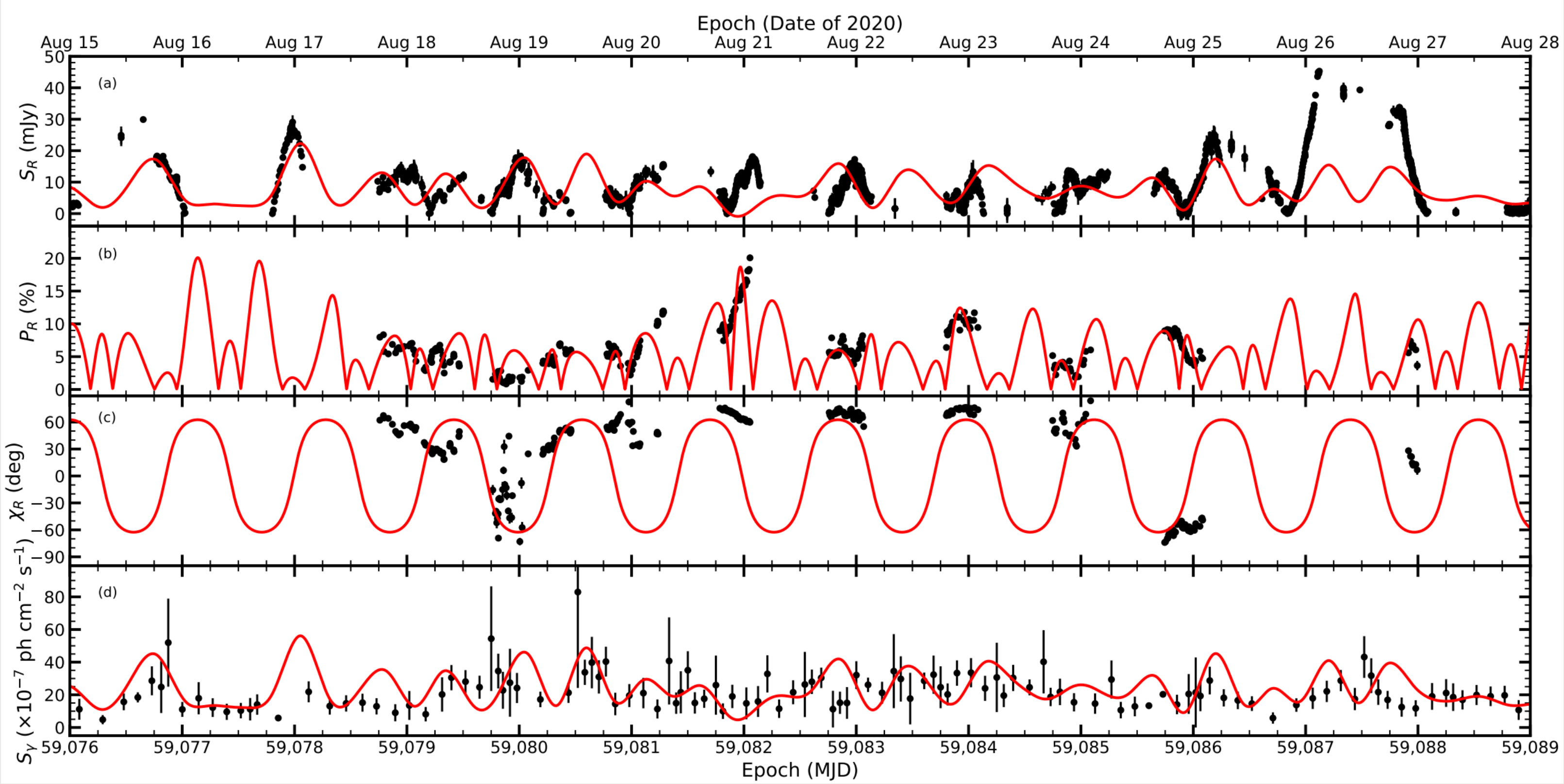


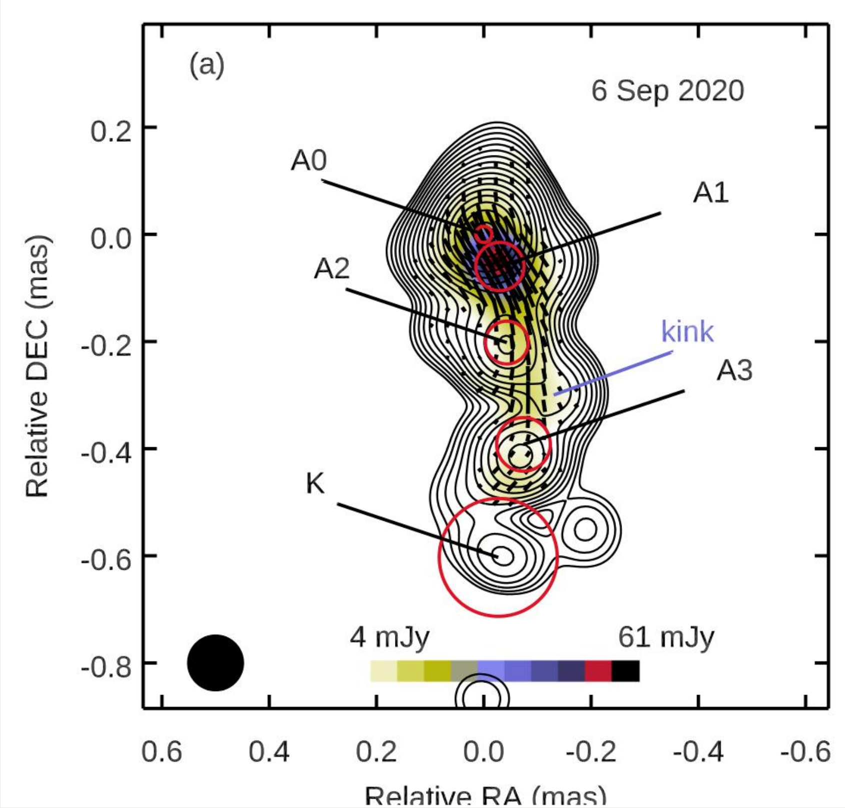
QPO in flux and polarization

Dong+ 2020, MNRAS 494, 1817

QPO injection of particles in central spine!

Now Observed!





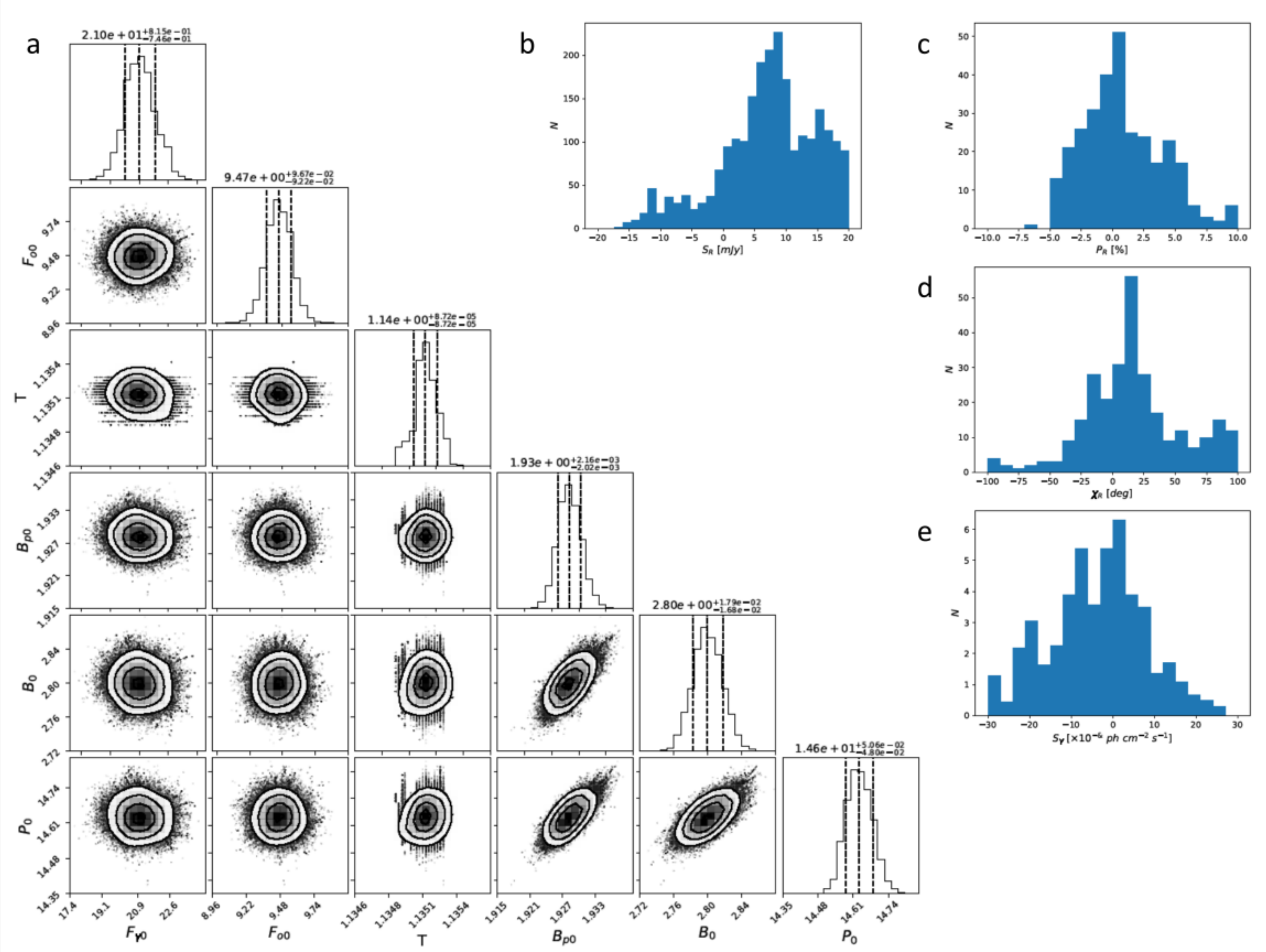
Jorstad+ 2022, Nature 609, 265

QPO from kink is characterized by QPO in polarization, either degree or angle.

Significant turbulence can diminish QPO signatures.

QPO period can range from day to month, and the total duration is limited when kink saturates.

QPO Analysis

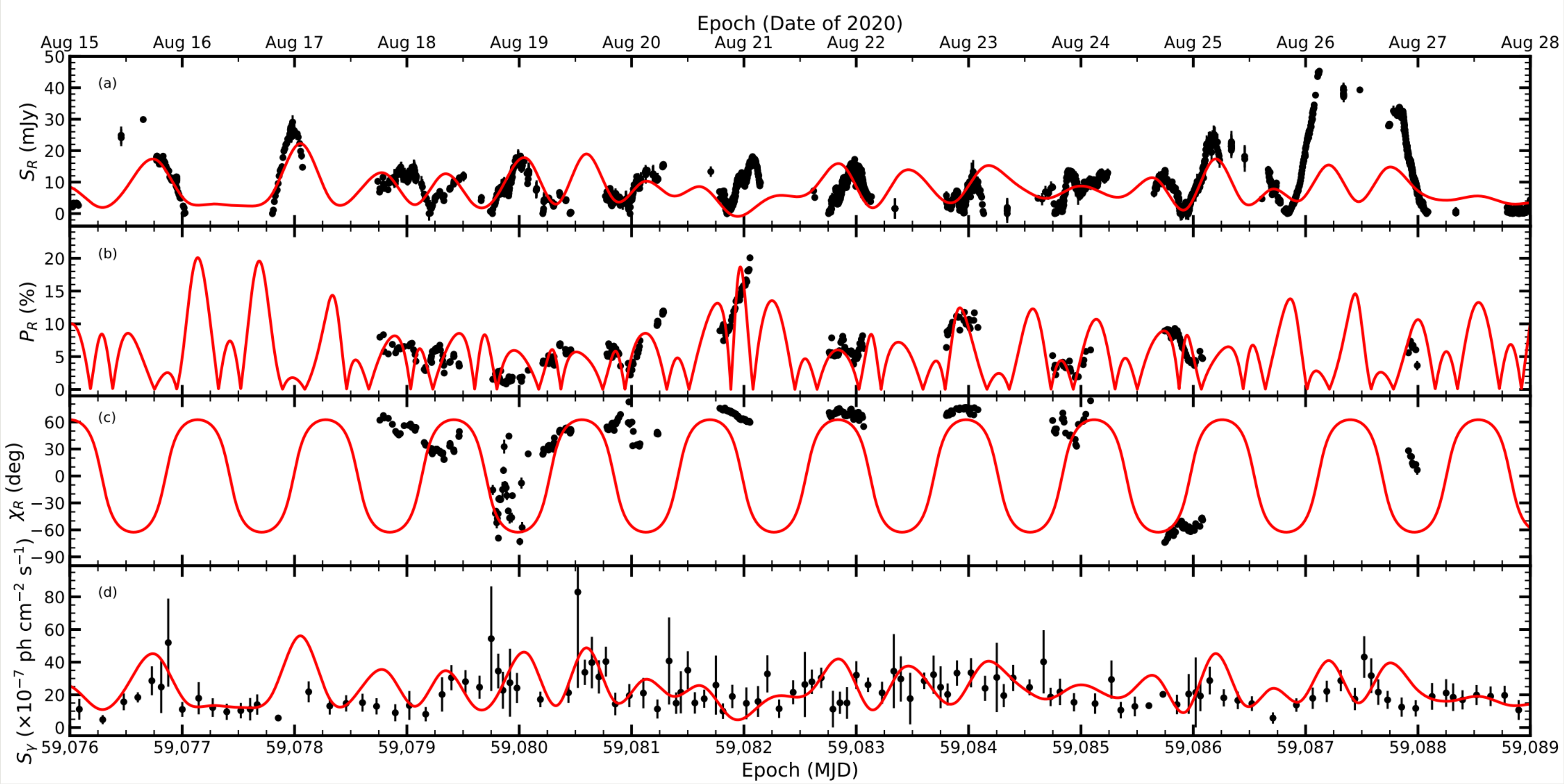


MCMC fitting based on strictly period kink instability model derives a period of the kink structure at $\sim 1.1\ d$, which will lead to $\sim 0.55\ d$ period in flux.

Errors of the fitting curve compared to the data roughly follow Gaussian distributions, indicating a turbulent component.

[Jorstad+ 2022, Nature 609, 265]

Polarization Reveals Kink Instabilities in Blazars



Jorstad+ 2022, Nature 609, 265

- QPOs in both flux and polarization are strong evidence for kink instabilities in blazars.
- If kink instabilities are present, the blazar zone must be magnetized, then only magnetic reconnection and turbulence can efficiently accelerate particles.