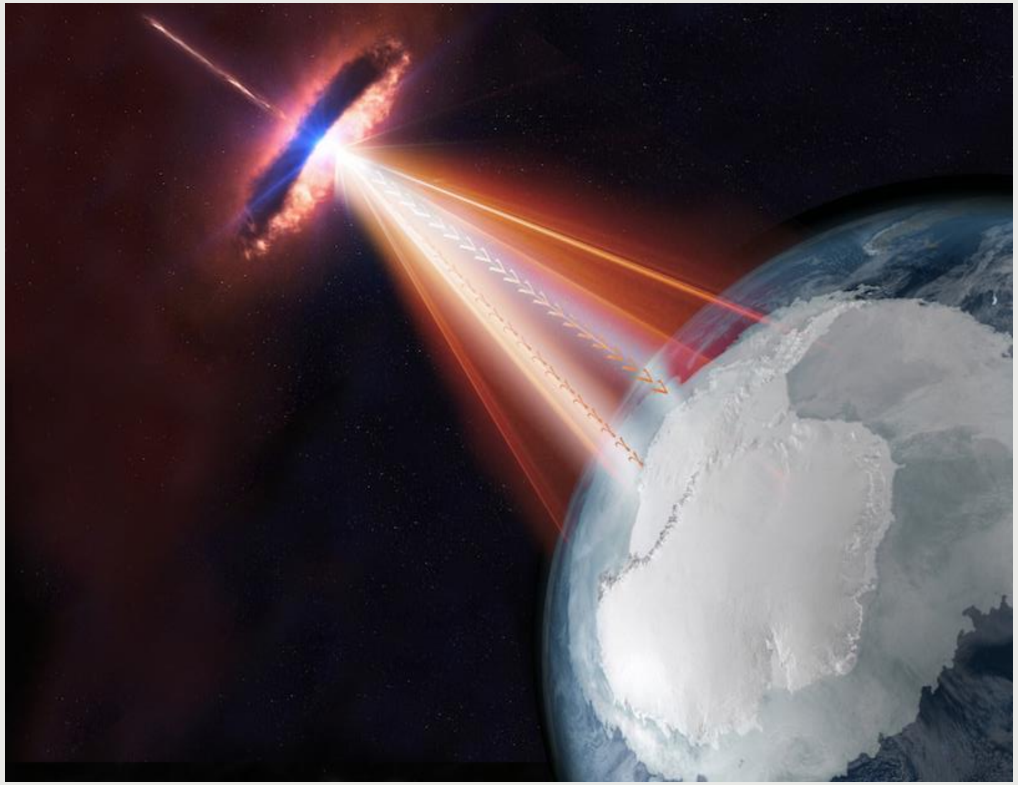
Multi-Wavelength Polarization in Blazars

Haocheng Zhang (UMBC/NASA GSFC/CRESST II)



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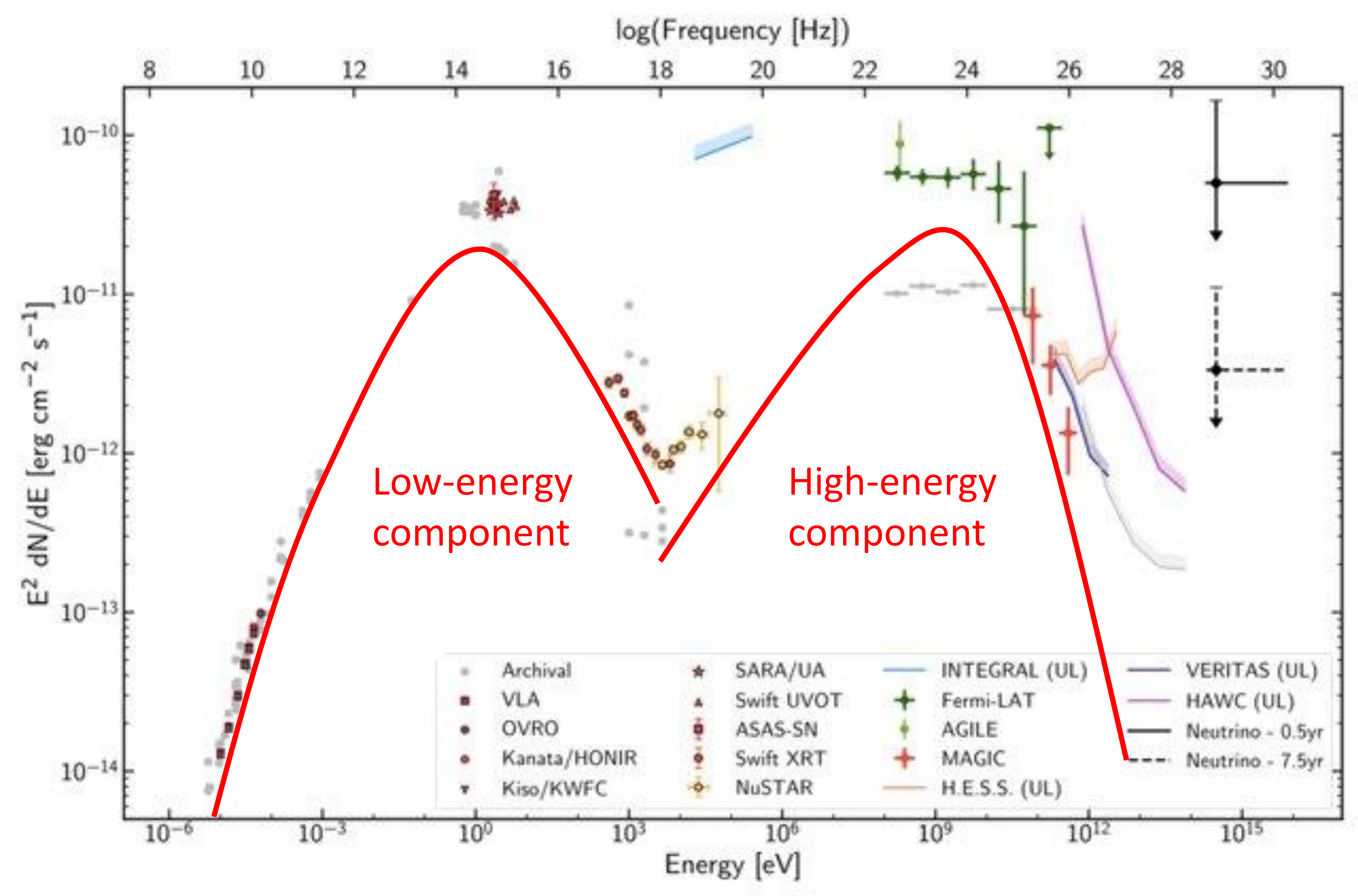
Hui Li
Fan Guo

Feb 22, 2024

A Multi-Messenger View of Blazars



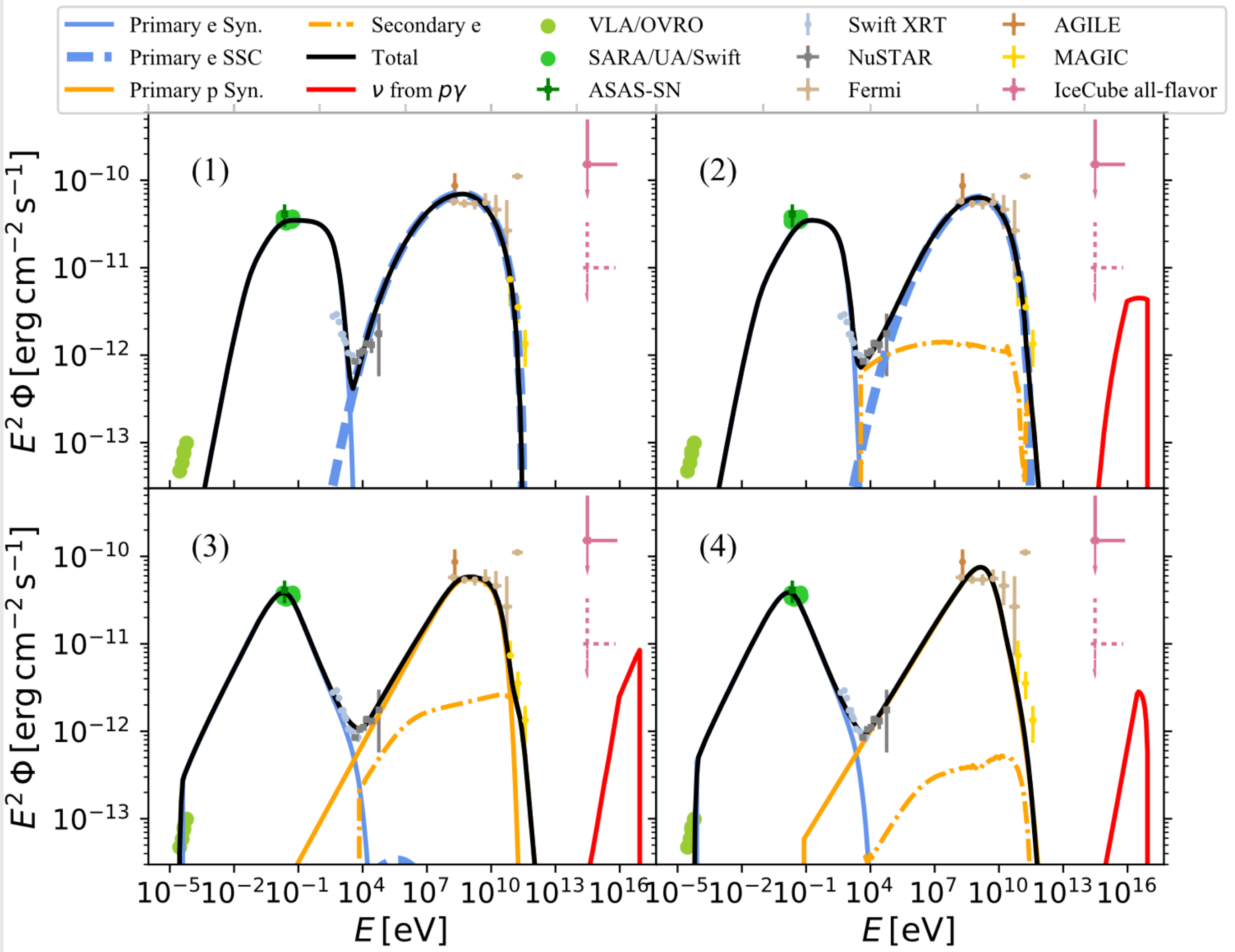
IceCube+ 2018 Science 361, 1387

- ☐ What is the physical connection between neutrinos and multi-wavelength flares?
- ☐ How do blazar jets accelerate cosmic rays?
- ☐ Can blazars produce ultra-high-energy cosmic rays?

Key unknowns:

1. Leptonic vs hadronic
2. Particle acceleration mechanism
3. Physical conditions in the blazar zone

Leptonic vs Hadronic



Zhang+ 2019 ApJ 876, 109

Leptonic and hadronic models cannot be distinguished by spectral fitting only

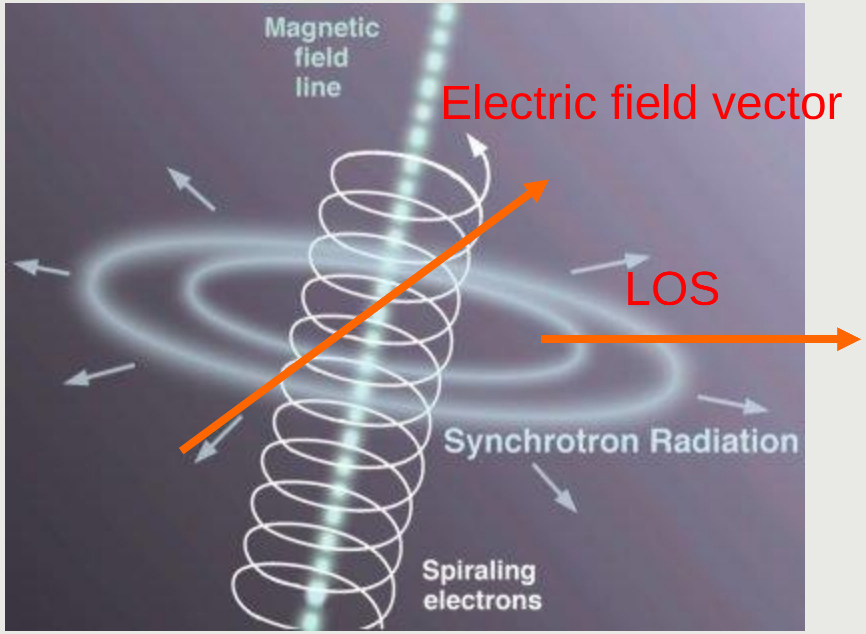
Leptonic Model:

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

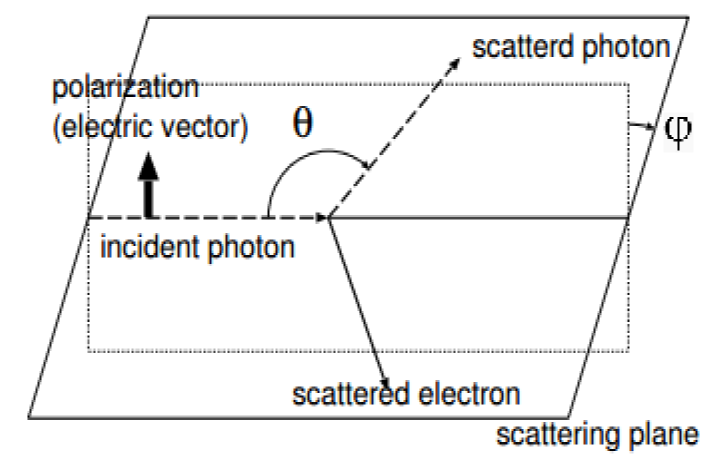
Hadronic Model:

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

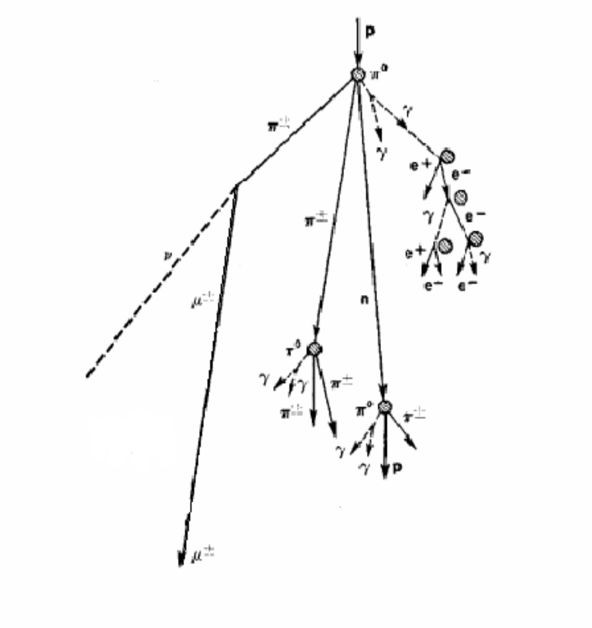
Synchrotron & Compton Scattering



Synchrotron is strongly polarized.



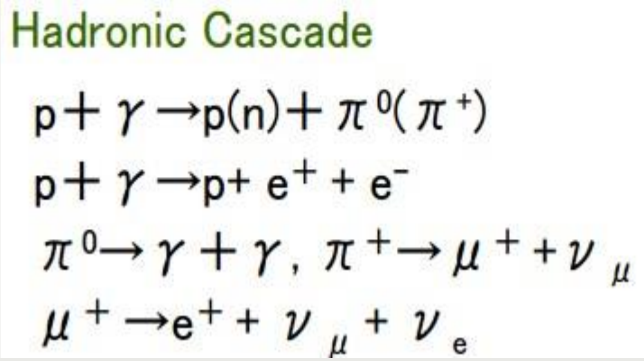
Compton scattering reduces polarization.



Protons and cascading charged particles can emit via synchrotron.

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

High-energy polarization degree can distinguish these models!



Hadronic Cascade

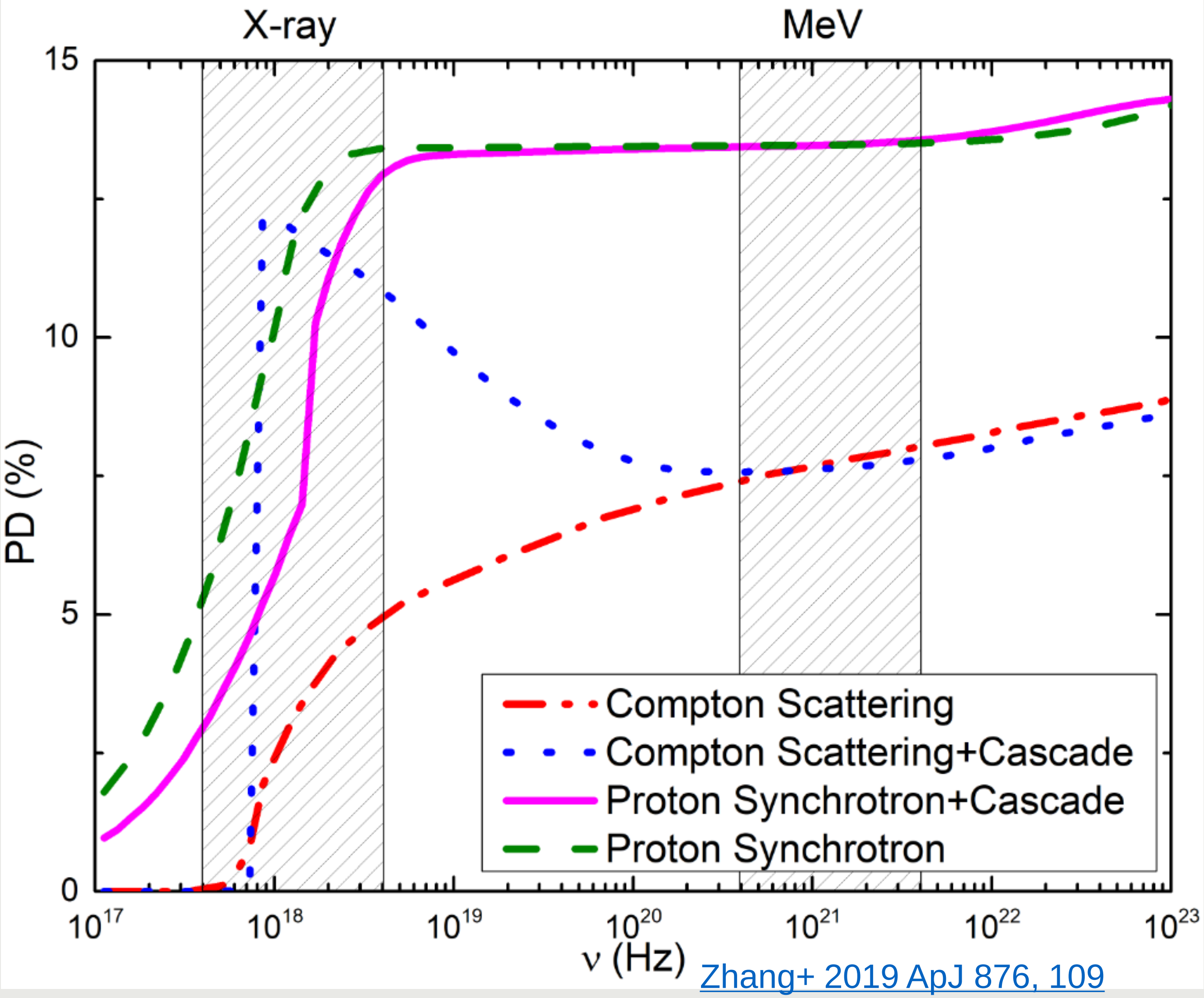
$p+\gamma \rightarrow p(n)+\pi^0(\pi^+)$

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

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

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

MeV Polarimetry as a Unique Probe

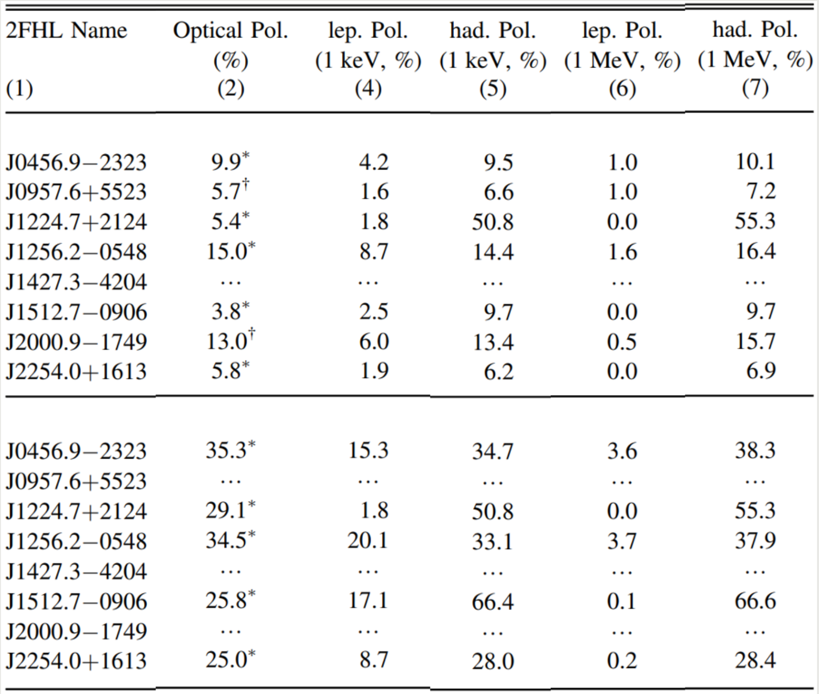


Zhang+ 2019 ApJ 876, 109

1. Hadronic models predict systematically higher polarization in X-ray and MeV gamma-ray bands.
2. High MeV polarization unambiguously points to proton acceleration and neutrino production.
3. MeV polarization can identify proton synchrotron, which can constrain the maximal proton energy in the blazar zone.

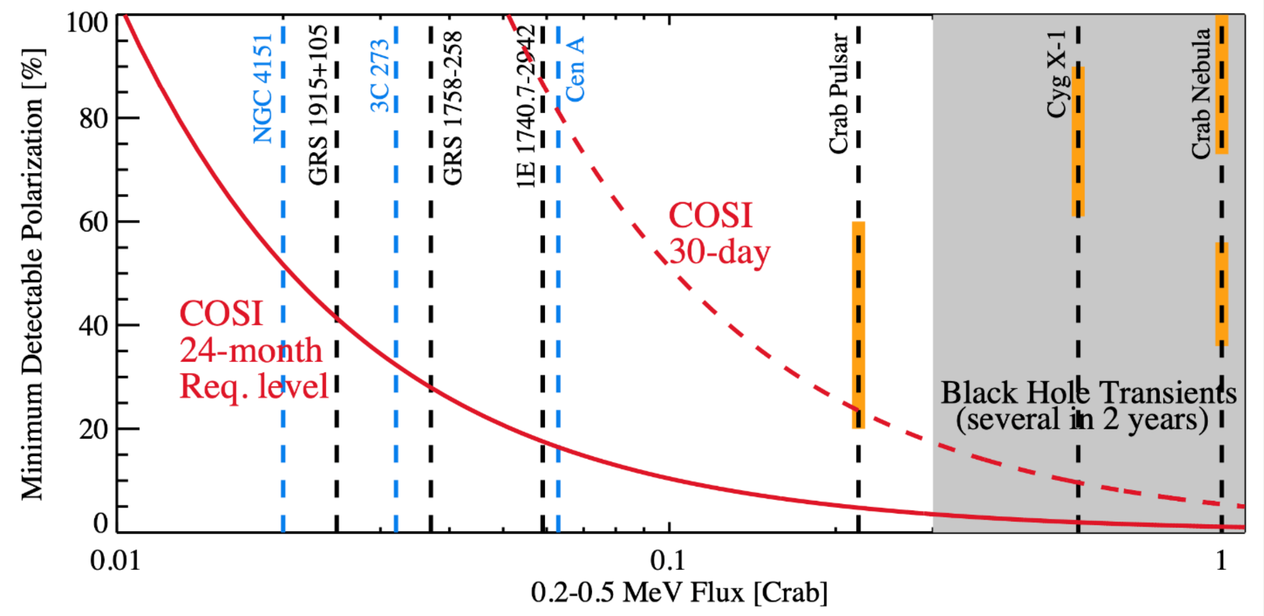
MeV polarimetry can probe cosmic ray acceleration and neutrino production for blazars of all classes.

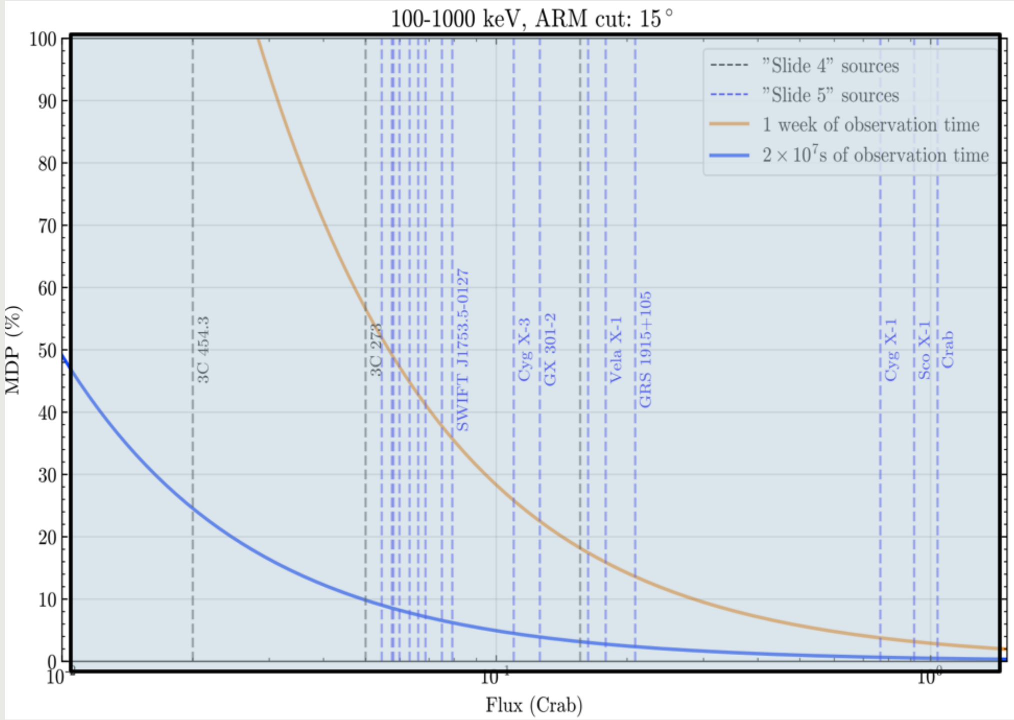
Detectable? Yes!



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

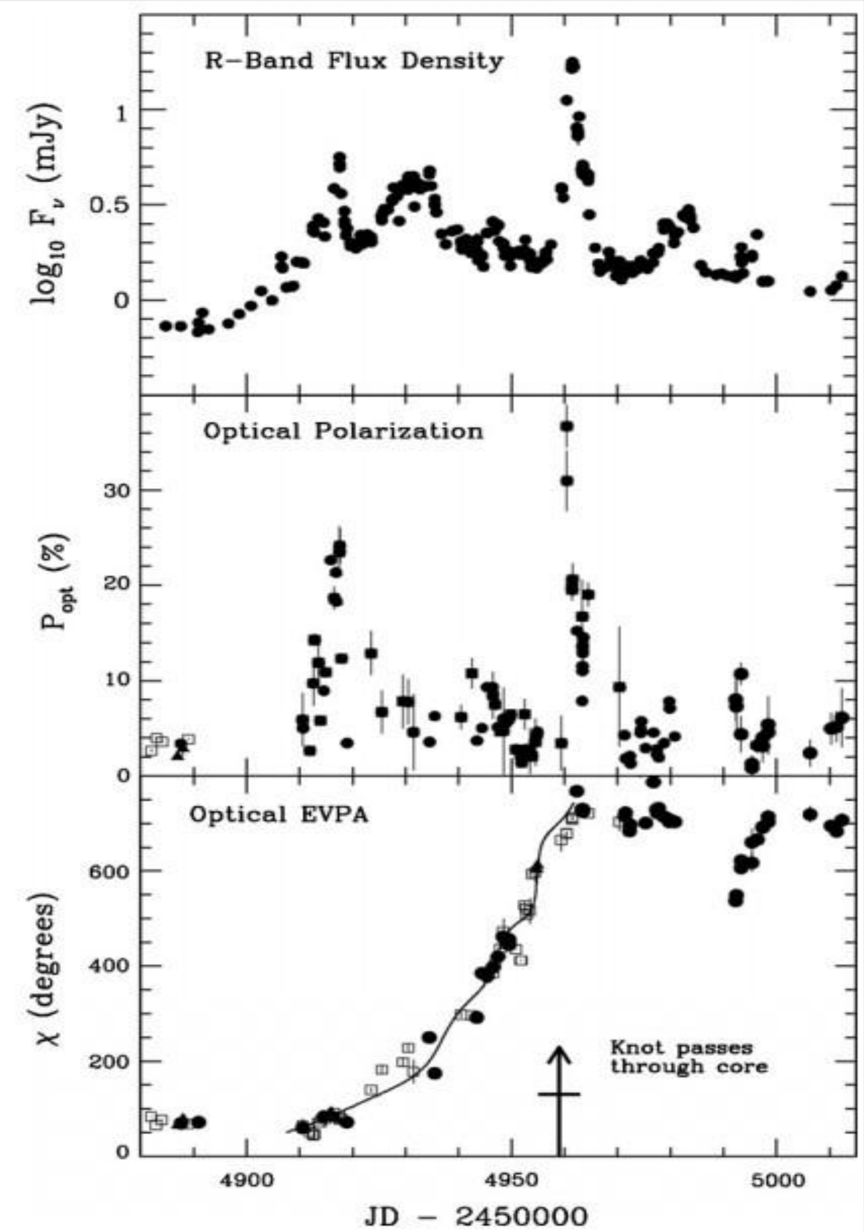
Paliya+ 2018 ApJ 863, 98



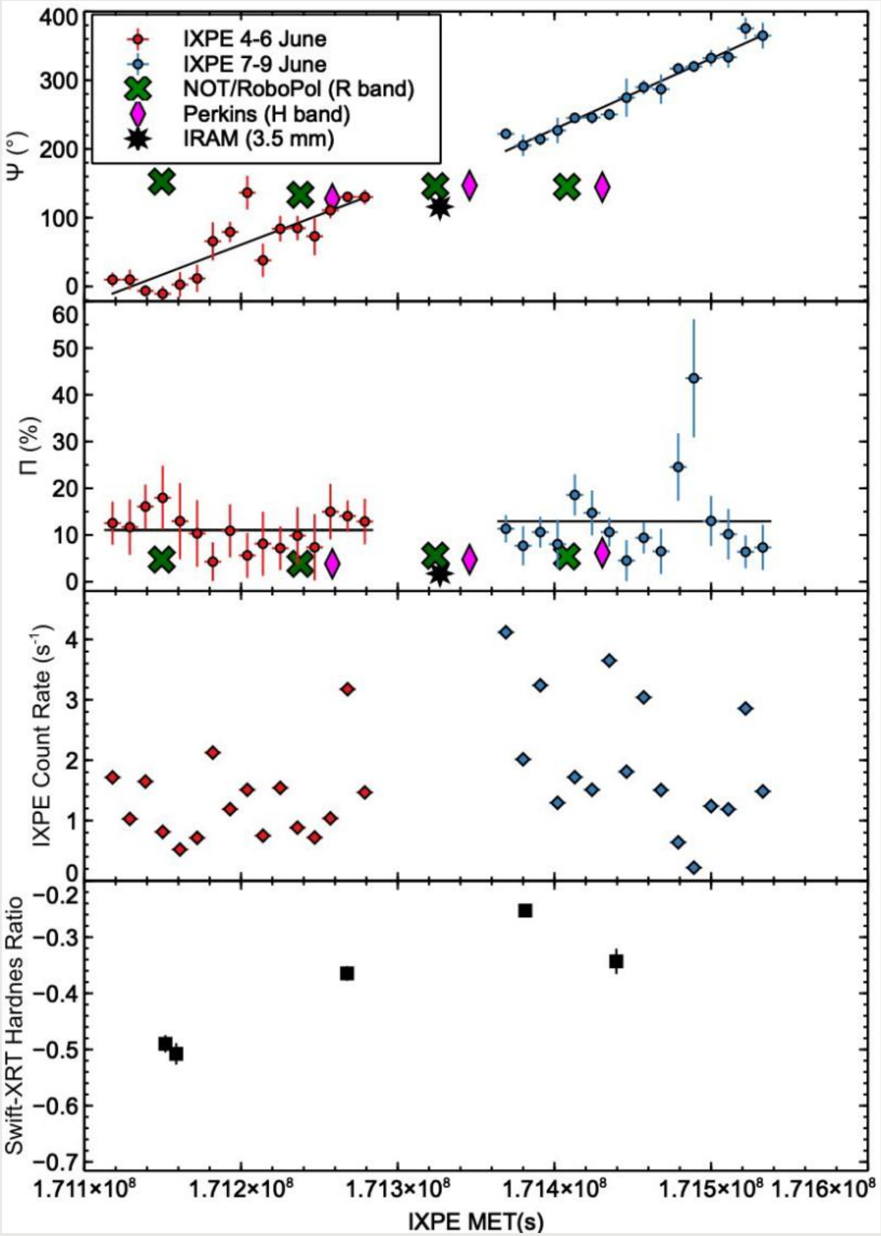


1. COSI can detect polarization for the bright blazar 3C 273 as well as a couple of bright blazar flares during its mission span.
2. AMEGO-X can detect 10 blazar flares per year, unambiguously distinguish leptonic and hadronic models.

However, Blazars are Variable …



[Marscher+ 2010 ApJL 710 L126](#)



[Di Gesu+ 2023 Nature Astronomy 7, 1245](#)

Co-evolution of particles and magnetic field leads to polarization variability.

Geometric effects can also lead to polarization variability.

If unresolved in time, variations in polarization angle can cancel out polarization.

Multi-wavelength Radiation and Polarization

Previous approach:

1. Use a power-law distribution of particles for steady state.
2. Solve a Fokker-Planck equation for particle evolution.
3. Assume a chaotic magnetic field structure.
4. Magnetic strength changes in time put in by hand.

Multi-wavelength Radiation and Polarization

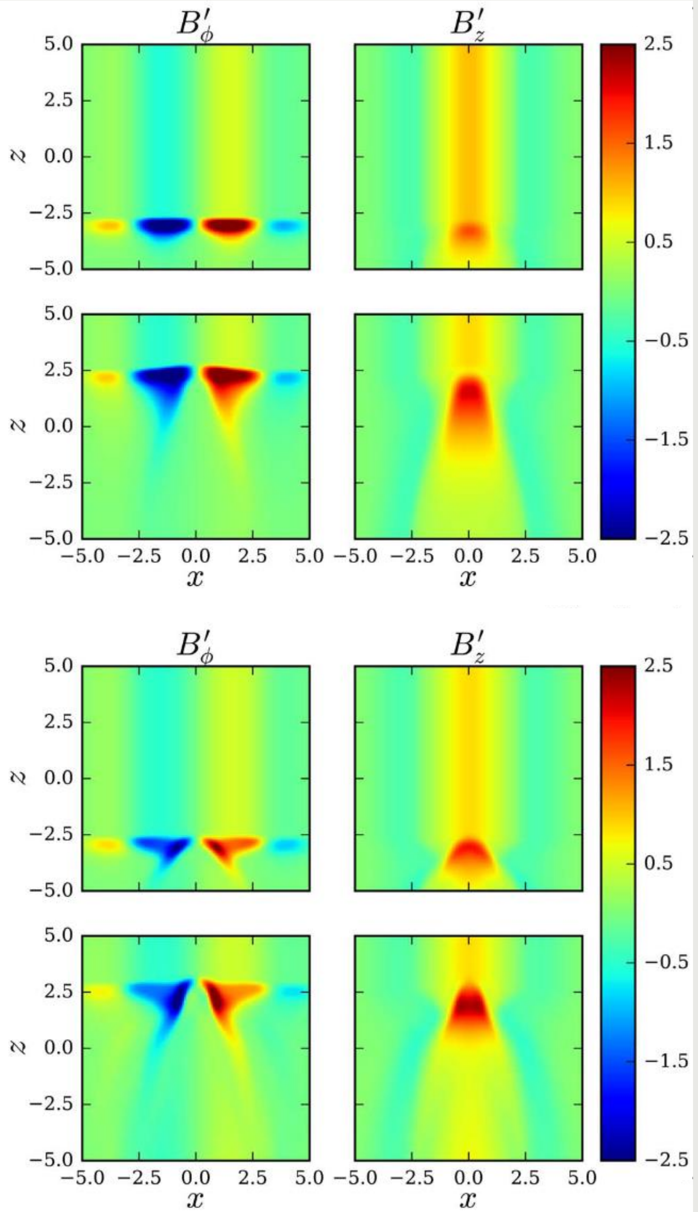
Previous approach:

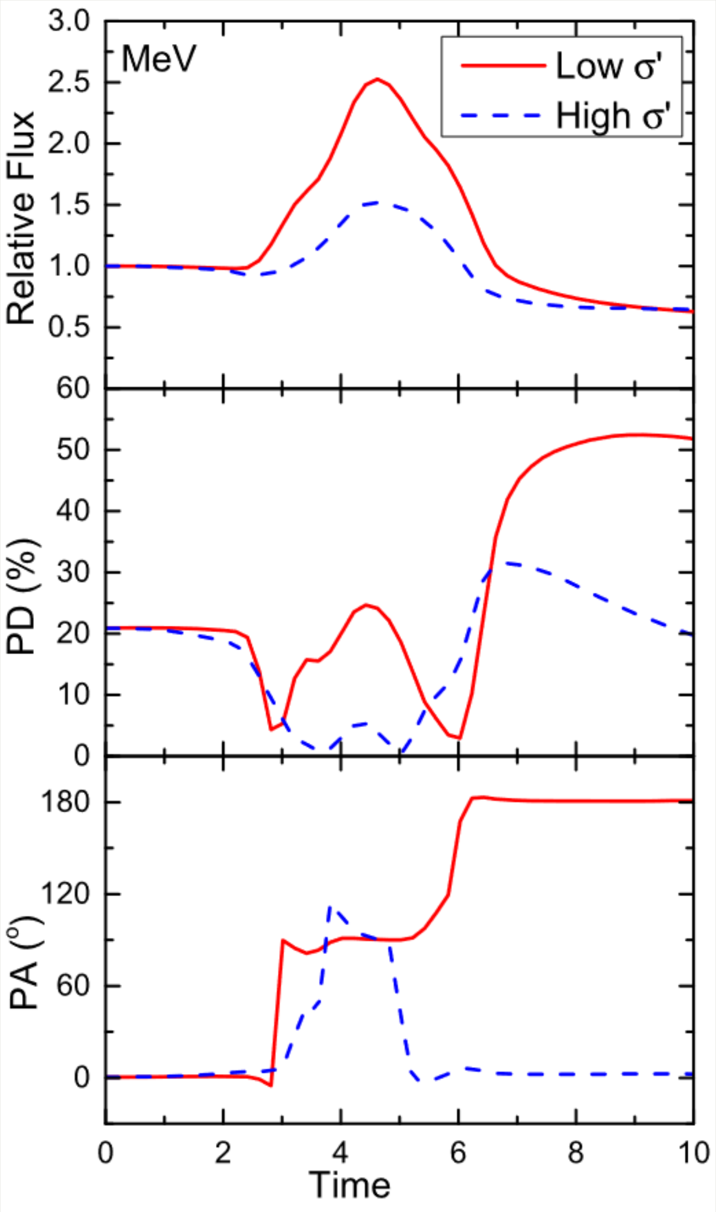
1. ~~Use a power-law distri[illegible] of p[illegible]es for steady state.~~
2. ~~Solve a Fokker-Planck equa[illegible] particle evolution.~~
3. ~~Assume a chaotic magn[illegible]cture.~~
4. ~~Magnetic strength cha[illegible]es in time p[illegible]n by hand.~~

Previous approach is only good for spectra and light curves studies, but not polarization.

We need self-consistent magnetic field and particle evolution!

Fluid Dynamical Time >> Proton Dynamical Time

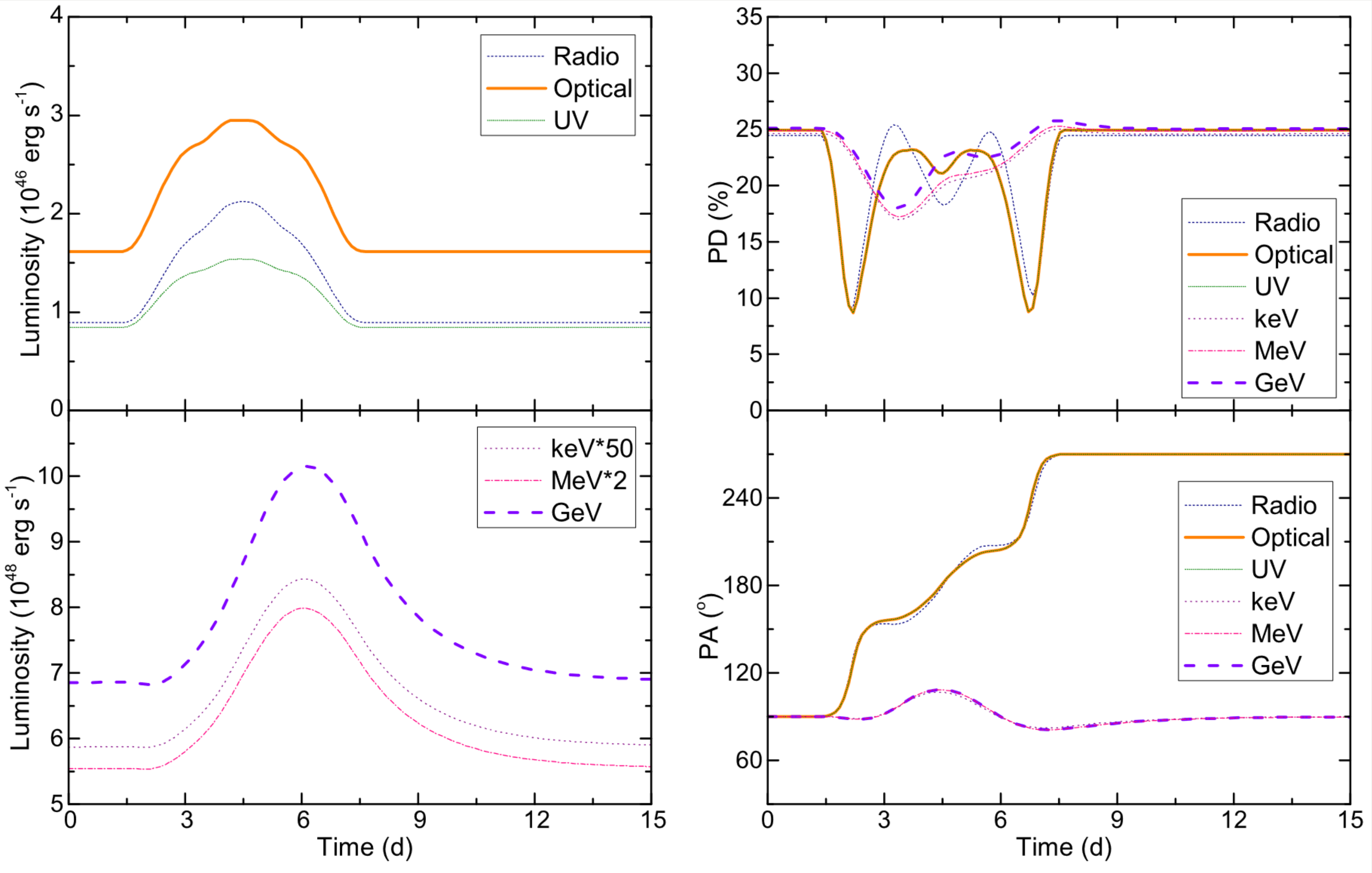




1. Polarization evolution is dominated by the magnetic field structure and evolution.
2. Hadronic polarization can vary in time.
3. Polarization angle swings may happen. If unresolved, hadronic emission may appear unpolarized.

Zhang+ 2019 ApJ 876, 109

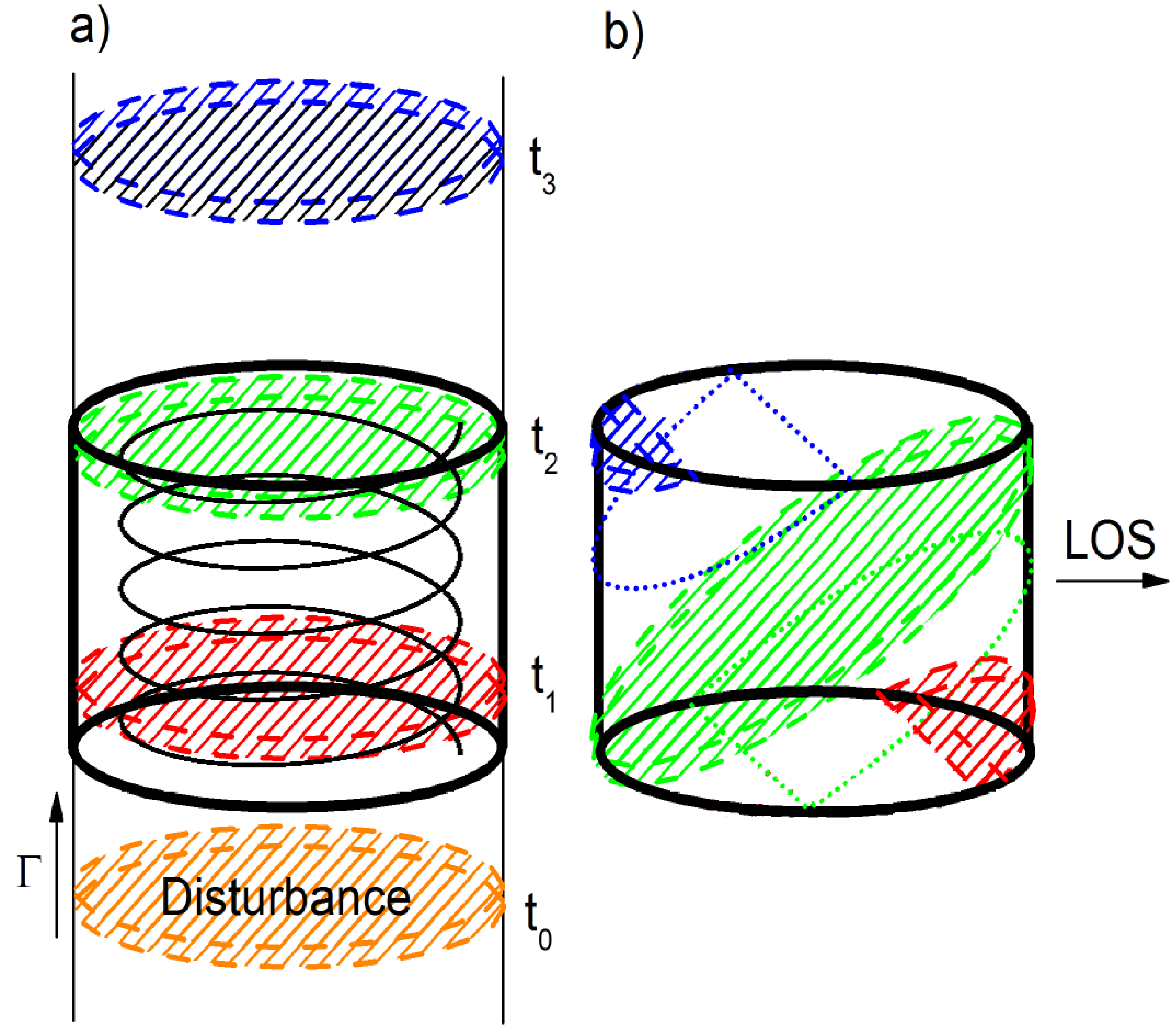
Proton Dynamical Time >> Fluid Dynamical Time



Zhang+ 2016 ApJ 829, 69

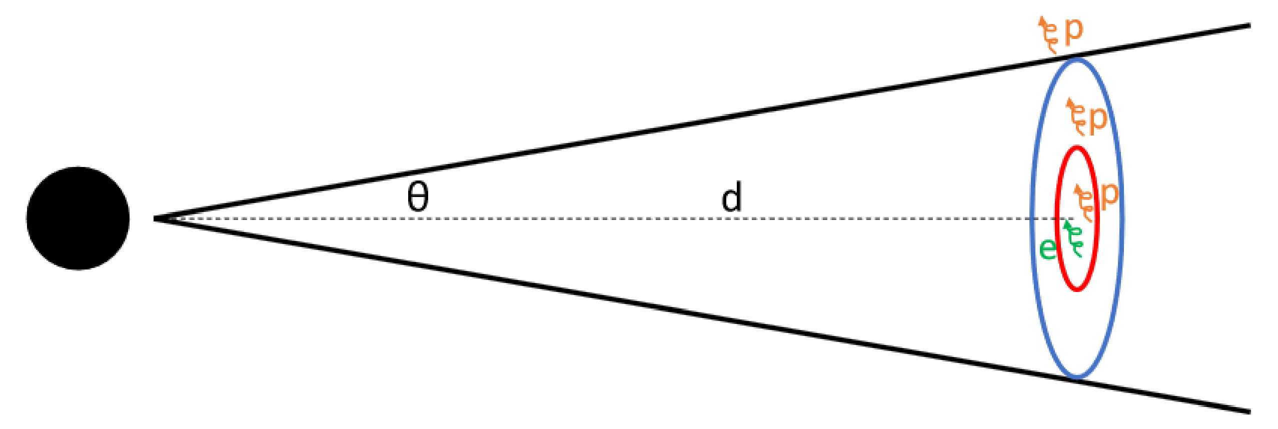
1. Hadronic polarization degree is comparable to the optical counterpart.
2. Hadronic polarization is much more stable in time than the optical counterpart, due to very slow proton cooling.
3. Ideal for COSI and AMEGO-X to detect polarization during flaring states.

Light Crossing Delay



Zhang+ 2016 ApJ 829, 69

Energy Stratification Effects

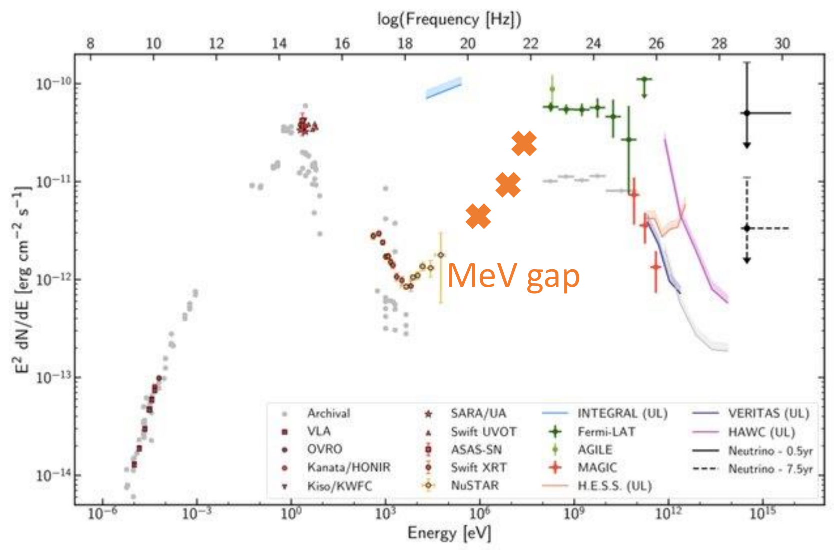


Protons cool much slower than electrons, they may occupy a much larger region than electrons or even escape from the jet, due to diffusion and advection.

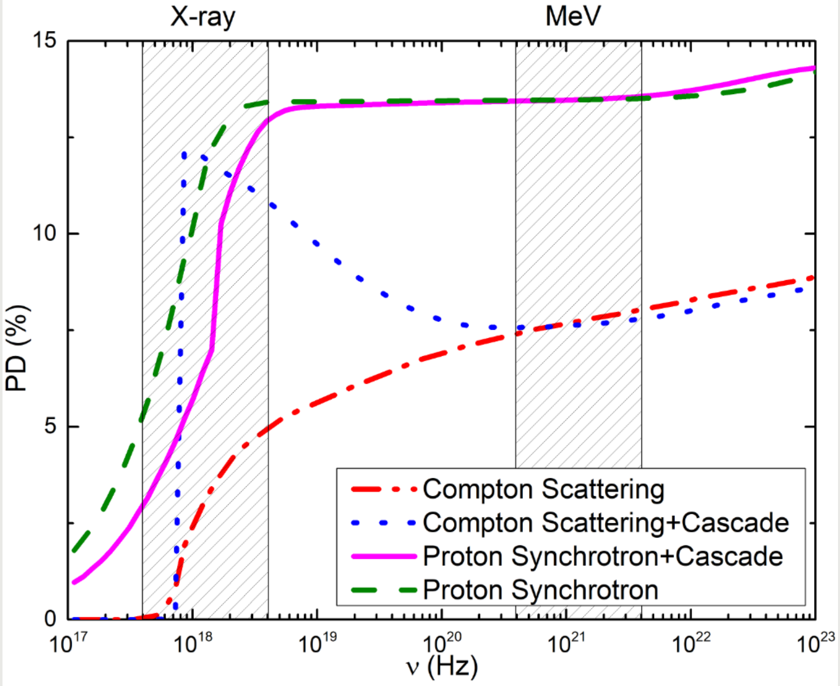
During flares, if the variability time scale of the hadronic emission is comparable to the primary synchrotron, protons and electrons are likely co-spatial, then the hadronic polarization is comparable to the primary synchrotron.

In the quiescent state, hadronic polarization is unconstrained. However, if protons occupy similarly large parts of jet as the electrons that synchrotron emit radio, a net long-term hadronic polarization may appear.

Multi-Wavelength Spectropolarimetry & Neutrino Detection

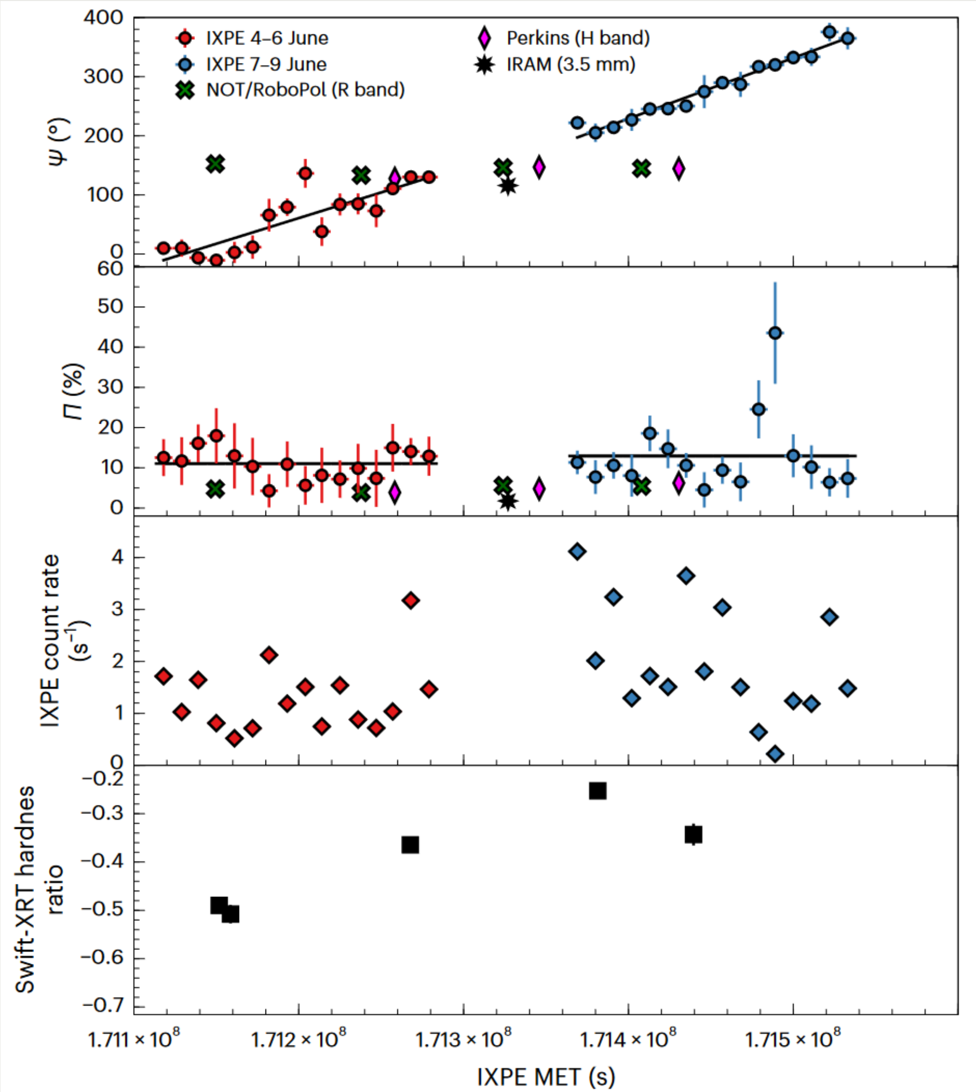


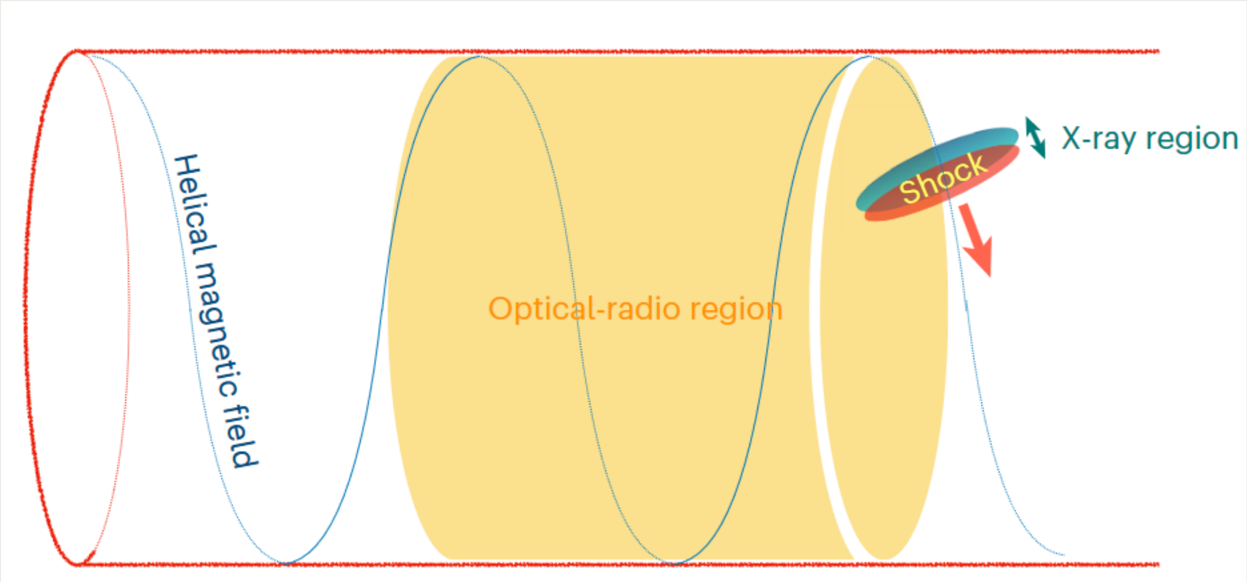
keV	MeV	ν	Conclusion
Y	Y	Y	Proton synchrotron, ν, UHECR (?)
N	Y	Y	Proton synchrotron, ν, UHECR (?)
Y	N	Y	Leptonic+hadronic cascades, ν, CR
Y/N	Y/N	N	Unknown mechanism (unlikely) or we need a better IceCube
N	N	Y	ν is not from the blazar zone
N	N	N	Pure leptonic



Takeaway message:
Significant polarization in the high-energy spectral component is clear evidence for hadronic processes.
Polarization can probe the connection between neutrinos and radiations.
If the proton synchrotron is confirmed by polarization, blazars may accelerate ultra-high-energy cosmic rays.
Multi-zone model is a must!

X-Ray Polarization Angle Swing





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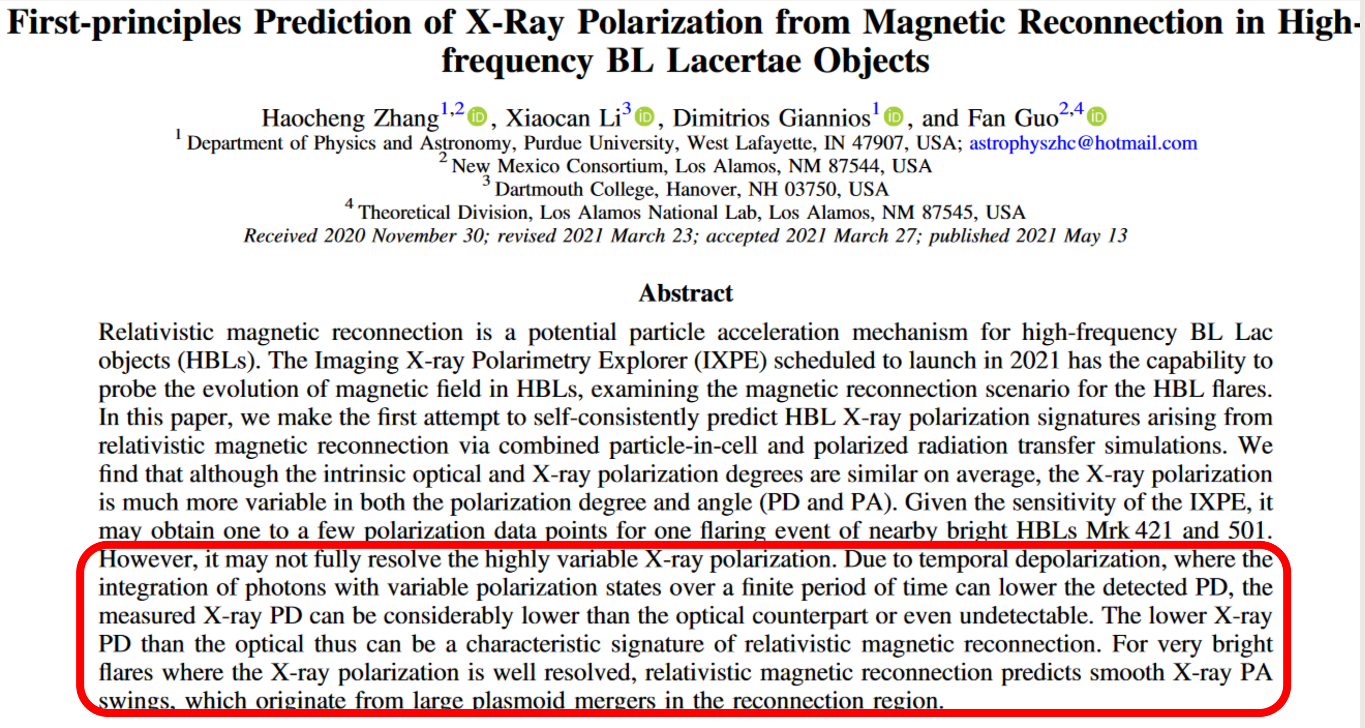
1. Shocked region moving in a helical magnetic field.
2. Angle swings result from geometric effects.
3. Angle rotations can be arbitrarily large, but stay in the same direction

Magnetic Reconnection as An Alternative



First-principles Prediction of X-Ray Polarization from Magnetic Reconnection in High-frequency BL Lacertae Objects

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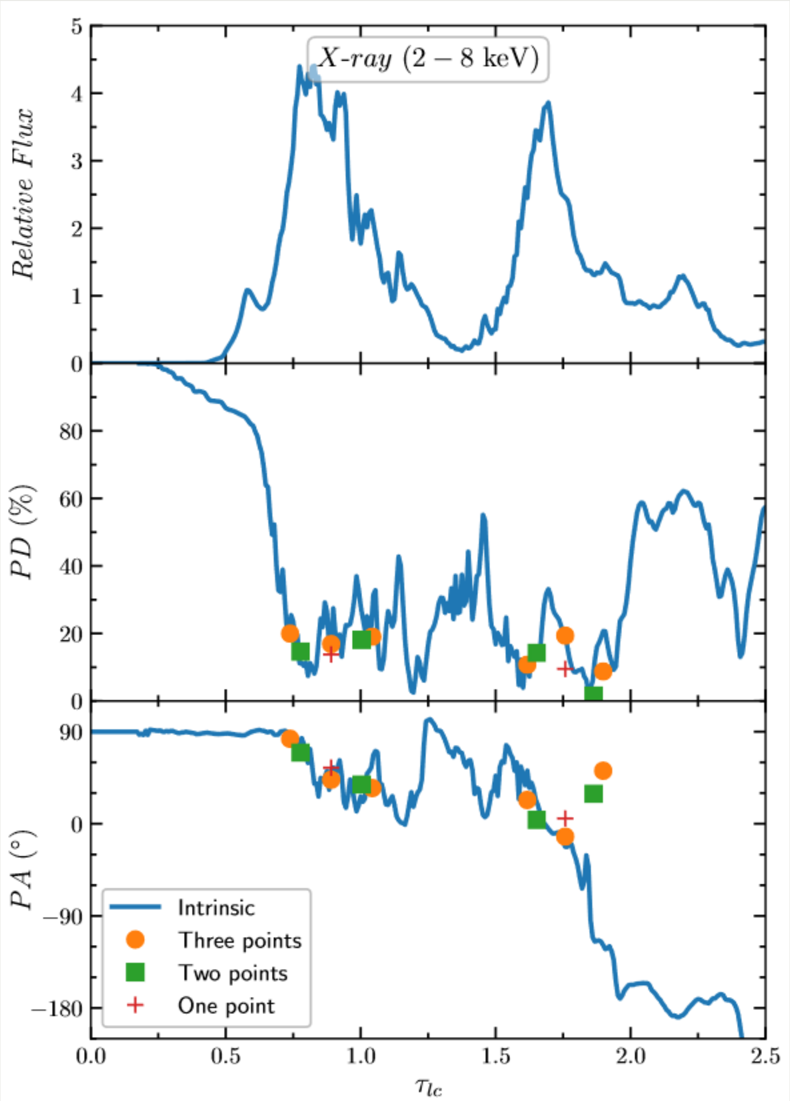
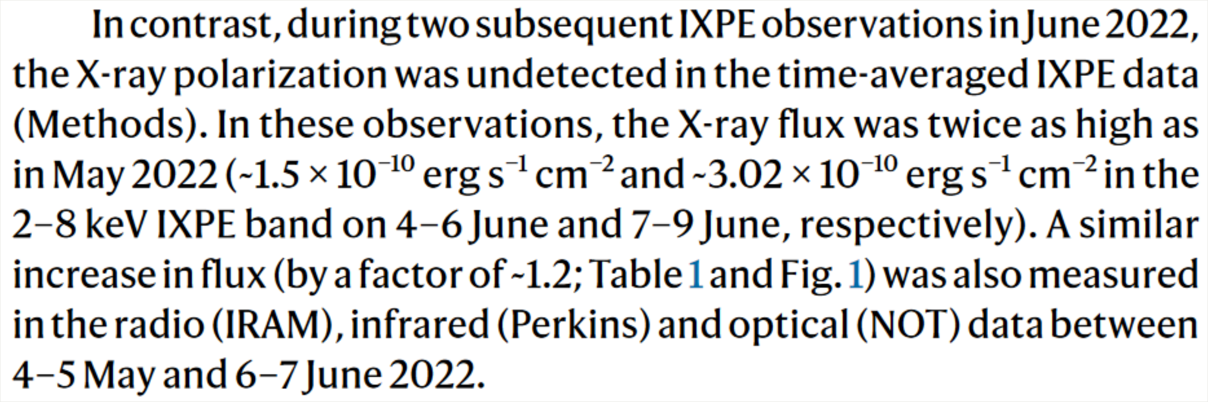
Abstract

Relativistic magnetic reconnection is a potential particle acceleration mechanism for high-frequency BL Lac objects (HBLs). The Imaging X-ray Polarimetry Explorer (IXPE) scheduled to launch in 2021 has the capability to probe the evolution of magnetic field in HBLs, examining the magnetic reconnection scenario for the HBL flares. In this paper, we make the first attempt to self-consistently predict HBL X-ray polarization signatures arising from relativistic magnetic reconnection via combined particle-in-cell and polarized radiation transfer simulations. We find that although the intrinsic optical and X-ray polarization degrees are similar on average, the X-ray polarization is much more variable in both the polarization degree and angle (PD and PA). Given the sensitivity of the IXPE, it may obtain one to a few polarization data points for one flaring event of nearby bright HBLs Mrk 421 and 501. However, it may not fully resolve the highly variable X-ray polarization. Due to temporal depolarization, where the integration of photons with variable polarization states over a finite period of time can lower the detected PD, the measured X-ray PD can be considerably lower than the optical counterpart or even undetectable. The lower X-ray PD than the optical thus can be a characteristic signature of relativistic magnetic reconnection. For very bright flares where the X-ray polarization is well resolved, relativistic magnetic reconnection predicts smooth X-ray PA swings, which originate from large plasmoid mergers in the reconnection region.



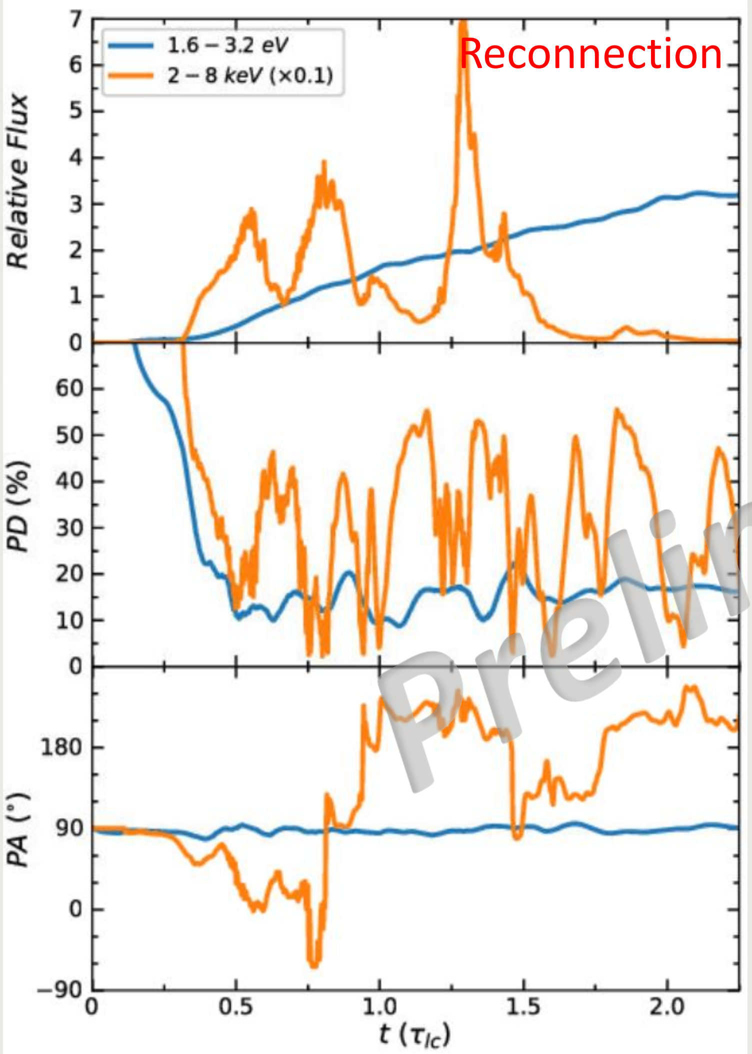
[Zhang+ 2021 ApJ 912, 129](#)

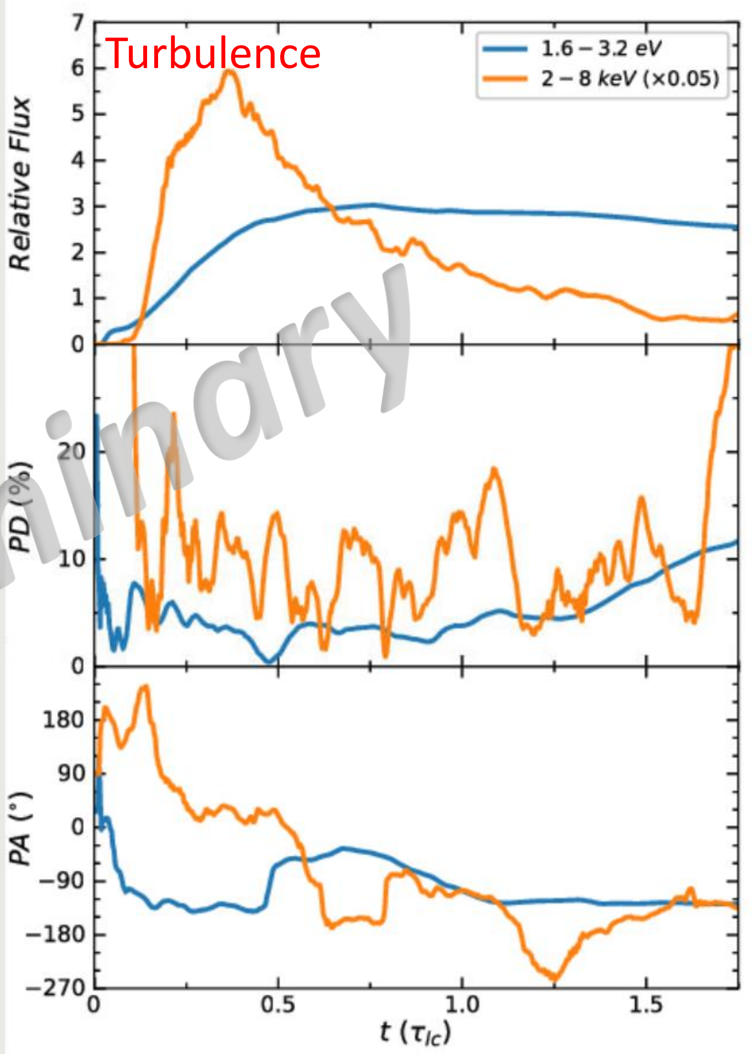


In contrast, during two subsequent IXPE observations in June 2022, the X-ray polarization was undetected in the time-averaged IXPE data (Methods). In these observations, the X-ray flux was twice as high as in May 2022 (~1.5×10^{-10} erg s^{-1} cm^{-2} and ~3.02×10^{-10} erg s^{-1} cm^{-2} in the 2–8 keV IXPE band on 4–6 June and 7–9 June, respectively). A similar increase in flux (by a factor of ~1.2; Table 1 and Fig. 1) was also measured in the radio (IRAM), infrared (Perkins) and optical (NOT) data between 4–5 May and 6–7 June 2022.

[Di Gesu+ 2023 Nature Astronomy 7, 1245](#)

Reconnection vs Turbulence





Reconnection

- ☐ Flashes of high X-ray polarization ~40-50%
- ☐ Fast X-ray angle swings
- ☐ Swings with arbitrary amplitude and in both directions

Turbulence

- ☐ Swings in both directions
- ☐ Swings not associated to flare or PD changes
- ☐ Smooth swings have limited amplitudes

Angle Swings can Probe Particle Acceleration

1. Shock in a helical magnetic field expects angle swing in the same direction.

2. Turbulence does not expect many angle swings, and most of the swings should have small amplitudes.

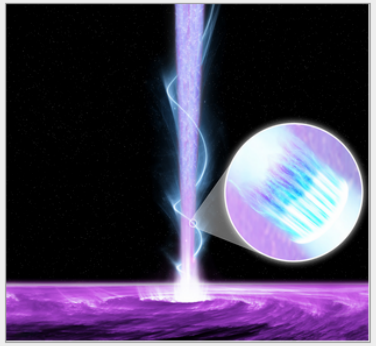
3. Reconnection expects large swings in both directions.

Summary

1. Significant polarization in the high-energy spectral component is clear evidence for hadronic processes.
2. Polarization can probe the connection between neutrinos and radiations.
3. If the proton synchrotron is confirmed by polarization, blazars may accelerate ultra-high-energy cosmic rays.
4. Multi-wavelength polarization variations can distinguish different particle acceleration mechanisms.
5. Future X-ray and gamma-ray polarimeters can have much better sensitivity on polarization.

Relativistic jets from AGN in the era of high energy polarimetry

Aims and scope



Relativistic jets from active galactic nuclei (AGN) are among the most powerful and luminous phenomena in our universe. Blazars and radio-loud active galactic nuclei (RLAGN) contain relativistic jets, propelled from the vicinity of a supermassive black hole out to hundreds of kiloparsecs. How they appear to an observer (i.e., their AGN subclass) depends on the inclination of the jet to the line of sight. In particular, in blazars the emission from the jet is relativistically boosted toward us, dominating the spectral energy distribution (SED), which extends into high-energy bands - X-rays and gamma-rays - and displays a high level of linear polarization from radio to optical wavelengths. In this context, multi-wavelength polarimetry has been proposed as a valuable diagnostic tool for investigating particle acceleration processes and the geometrical characteristics of the magnetic field inside the jet. Moreover, X-ray and gamma-ray polarimetry are currently in the limelight as they allow us to explore more extreme particle acceleration and cosmic ray acceleration. However, due to inherent characteristics and instrumental challenges to measure X-ray and gamma-ray photons, high-energy polarization has remained a much more veiled field of polarization compared to other wavelengths. The successful launch of the Imaging X-ray Polarimetry Explorer (IXPE) on December 9, 2021, marked a significant advance in our polarimetry capabilities by extending the technique into the X-ray range. Over a year and a half of operation, IXPE has detected X-ray polarization from blazars and RLAGN, helping to resolve uncertainties in particle acceleration processes and revealing new features of the magnetic field geometry inside the jet.

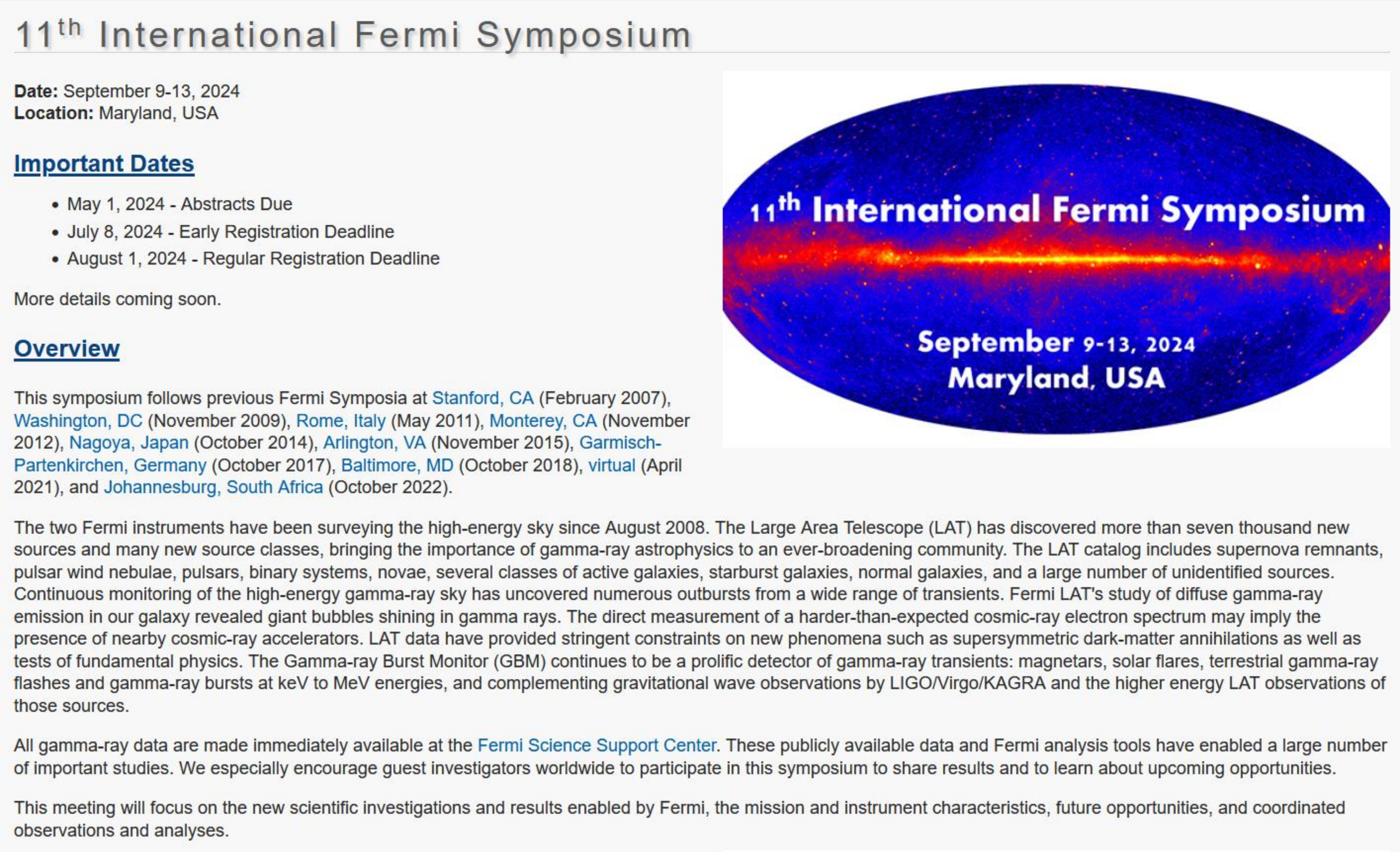
This journey of discovering the previously hidden features of jets will continue with further polarization measurements, more advanced theoretical models, and more precise measurements in the future. The field of gamma-ray polarimetry is expected to experience growth thanks to future missions such as the Compton Spectrometer and Imager (COSI, planned for launch in 2027), the All-sky Medium Energy Gamma-ray Observatory (AMEGO, planned for launch in 2029), and enhanced ASTROGAM (eASTROGAM, planned for launch in 2029). In the realm of X-ray polarimetry, next-generation missions such as the enhanced X-ray Timing and Polarimetry mission (eXTP, planned for launch in 2027) are already under development. These new projects combined with the development of theoretical models can answer pressing questions on black hole and jet physics, and provide invaluable insights into the high-energy processes in the Universe.

The aim of this session is to discuss high-energy polarimetry in the science of relativistic jets, presenting the latest polarization measurements and advances in theoretical modeling. Additionally, the session will offer a comprehensive view of the future of high-energy polarimetry by examining upcoming facilities that can provide novel data to the field and exploring how this data can best be utilized to advance our understanding of the inner physics of relativistic jets.

(Image credit : NASA/Pablo Garcia)

Programme

- New Polarization Measurements of Relativistic Jets of AGN in the High-Energy Band
- Novel Theories and Modeling of Relativistic Jets of AGN Involving High-Energy Polarimetry
- The Future of High-Energy Polarimetry: Upcoming Developments and Trends



11th International Fermi Symposium

Date: September 9-13, 2024
Location: Maryland, USA

Important Dates

- May 1, 2024 - Abstracts Due
- July 8, 2024 - Early Registration Deadline
- August 1, 2024 - Regular Registration Deadline

More details coming soon.

Overview

This symposium follows previous Fermi Symposia at Stanford, CA (February 2007), Washington, DC (November 2009), Rome, Italy (May 2011), Monterey, CA (November 2012), Nagoya, Japan (October 2014), Arlington, VA (November 2015), Garmisch-Partenkirchen, Germany (October 2017), Baltimore, MD (October 2018), virtual (April 2021), and Johannesburg, South Africa (October 2022).

The two Fermi instruments have been surveying the high-energy sky since August 2008. The Large Area Telescope (LAT) has discovered more than seven thousand new sources and many new source classes, bringing the importance of gamma-ray astrophysics to an ever-broadening community. The LAT catalog includes supernova remnants, pulsar wind nebulae, pulsars, binary systems, novae, several classes of active galaxies, starburst galaxies, normal galaxies, and a large number of unidentified sources. Continuous monitoring of the high-energy gamma-ray sky has uncovered numerous outbursts from a wide range of transients. Fermi LAT's study of diffuse gamma-ray emission in our galaxy revealed giant bubbles shining in gamma rays. The direct measurement of a harder-than-expected cosmic-ray electron spectrum may imply the presence of nearby cosmic-ray accelerators. LAT data have provided stringent constraints on new phenomena such as supersymmetric dark-matter annihilations as well as tests of fundamental physics. The Gamma-ray Burst Monitor (GBM) continues to be a prolific detector of gamma-ray transients: magnetars, solar flares, terrestrial gamma-ray flashes and gamma-ray bursts at keV to MeV energies, and complementing gravitational wave observations by LIGO/Virgo/KAGRA and the higher energy LAT observations of those sources.

All gamma-ray data are made immediately available at the Fermi Science Support Center. These publicly available data and Fermi analysis tools have enabled a large number of important studies. We especially encourage guest investigators worldwide to participate in this symposium to share results and to learn about upcoming opportunities.

This meeting will focus on the new scientific investigations and results enabled by Fermi, the mission and instrument characteristics, future opportunities, and coordinated observations and analyses.

Backup Slides

IXPE polarization should be 4~6 times of optical for HSPs

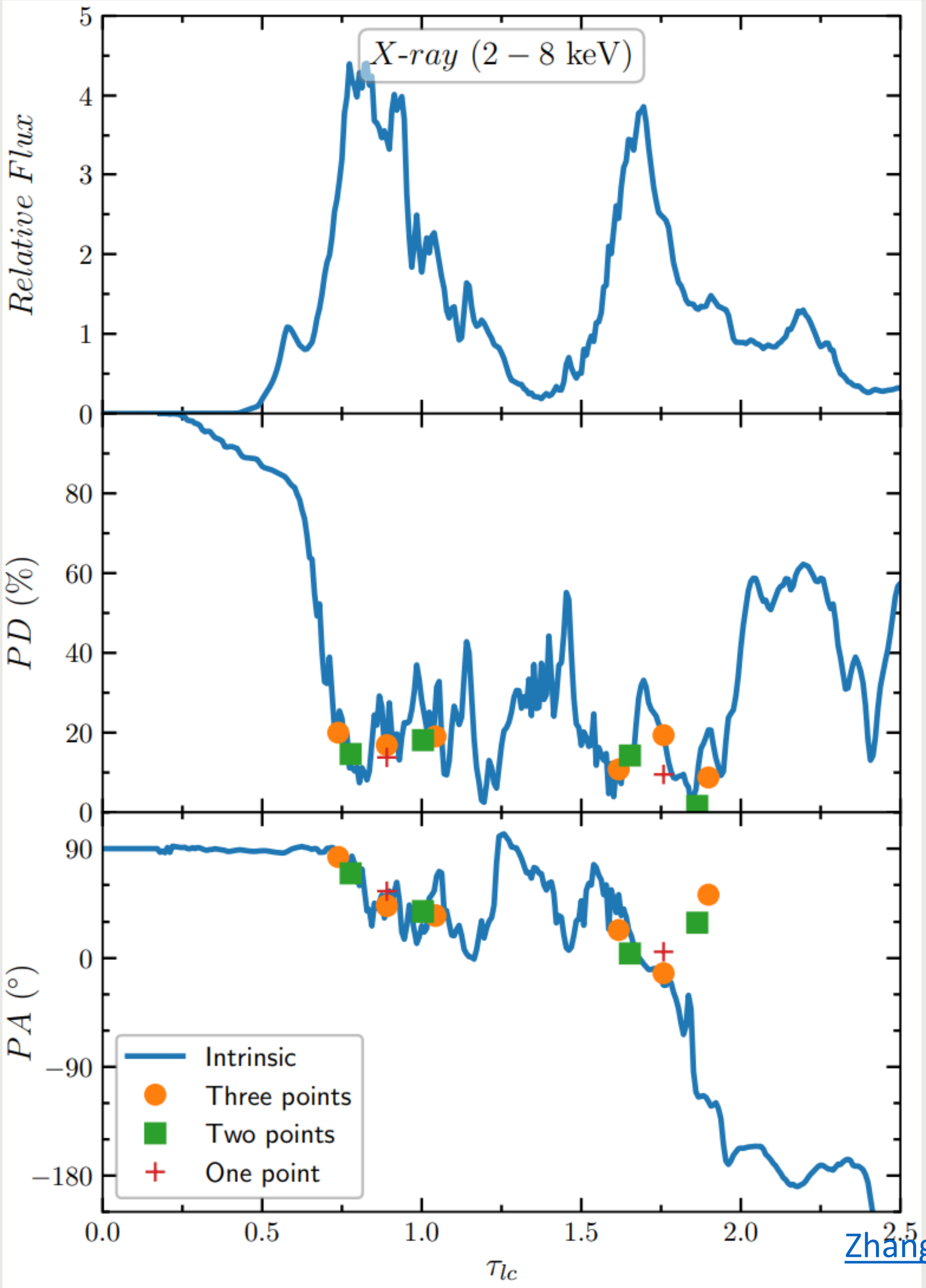
Since $\nu_{syn} \propto \gamma^2$, X-ray electrons should have $\gamma_X \sim 30\gamma_O$.

And since $\tau_{cool} \sim \gamma^{-1}$, X-ray electrons can survive 30 times shorter times than optical electrons.

This means they occupy 30 times less space than optical electrons.

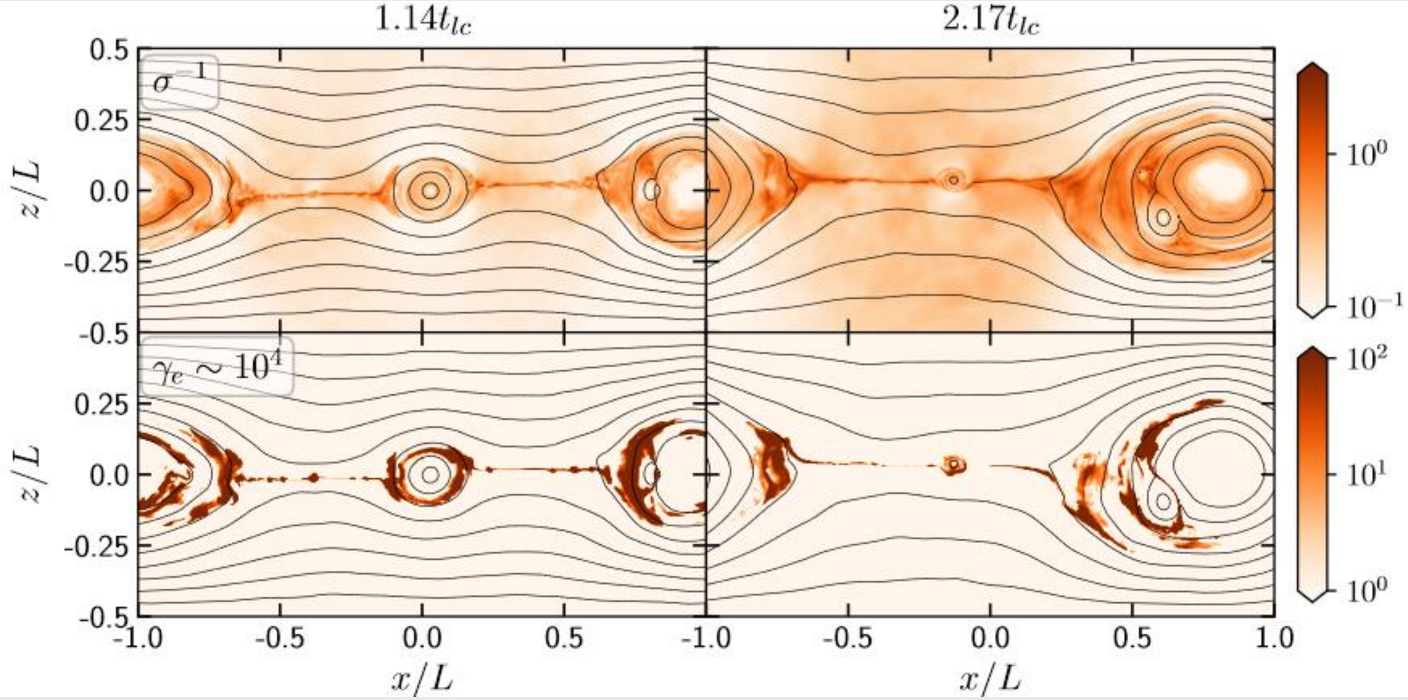
Assuming a completely chaotic magnetic field, polarization degree $\Pi \propto 1/\sqrt{N}$.

So $\Pi_X \sim \sqrt{30} \sim 5\Pi_O$.



Zhang+ 2021, ApJ 912, 129

Ways to save proton synchrotron model



Zhang+ 2022 ApJ 924, 90

Emission region may be highly inhomogeneous.

Emission region may have additional Doppler boosting due to anisotropy.