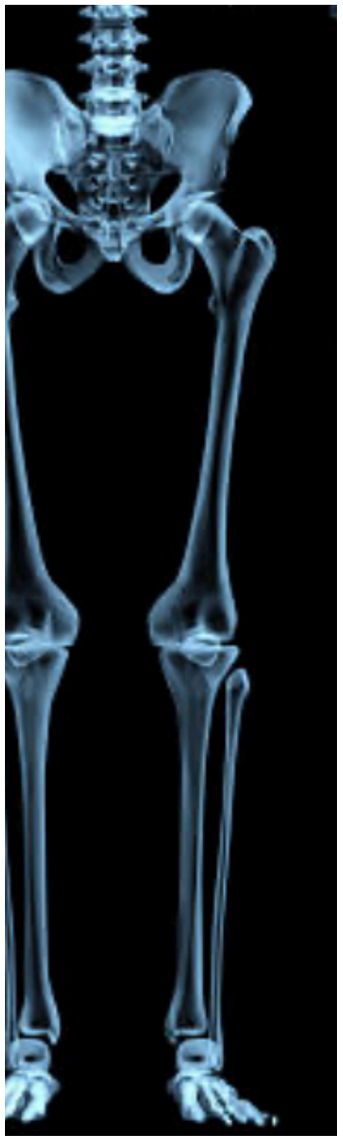
Mapping the blazar radiation zone with X-ray polarization and TeV gamma-ray observations

Manel Errando

Washington University in St Louis

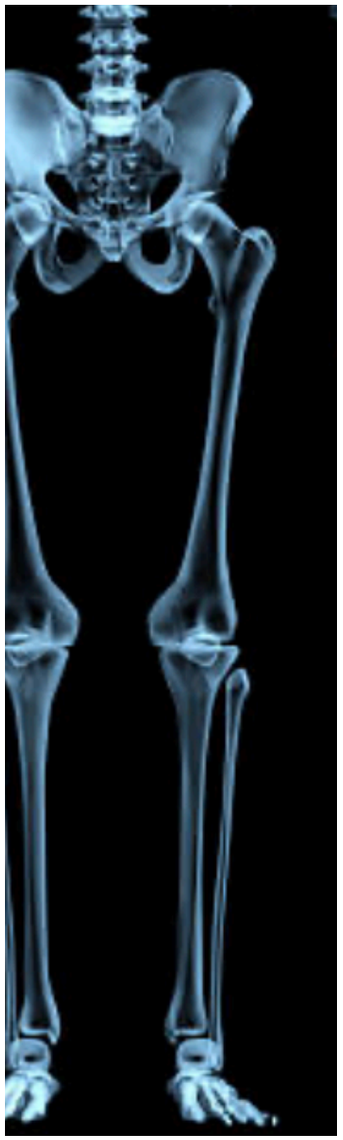
on behalf of the VERITAS Collaboration

Polarization measures B field geometry



X-rays
Reveal skeleton

Polarization measures B field geometry



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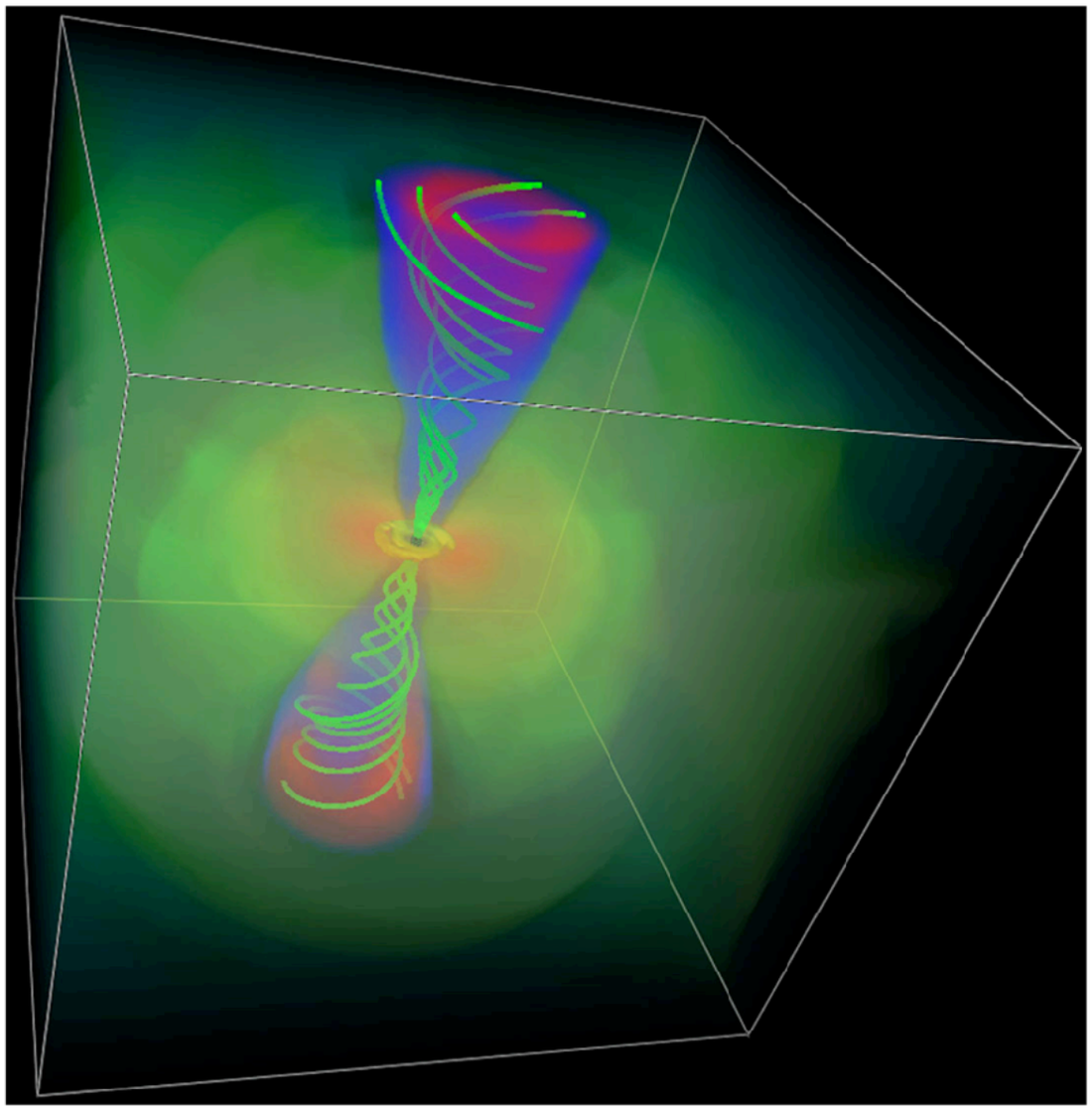
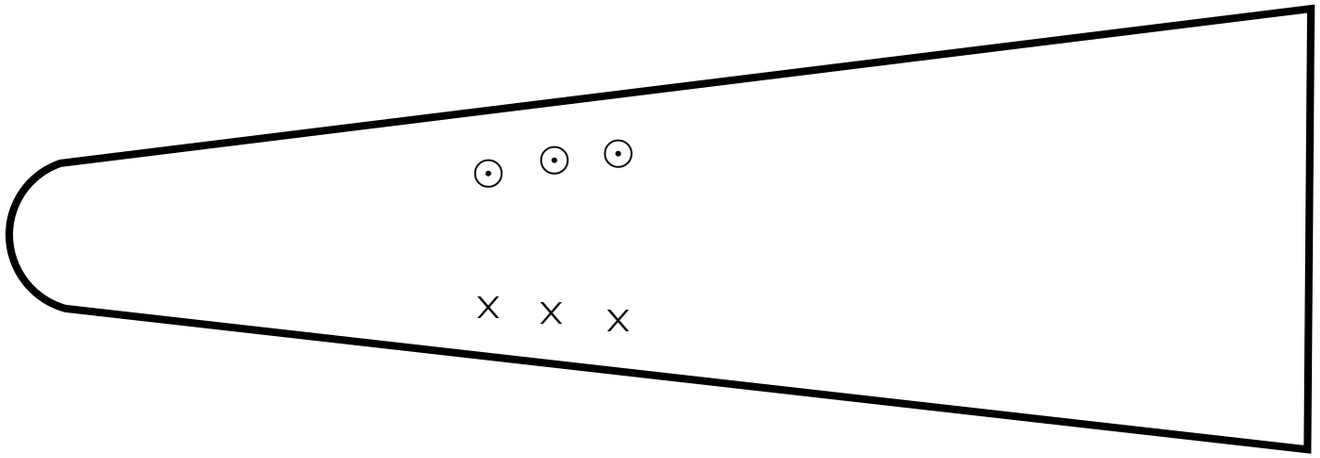


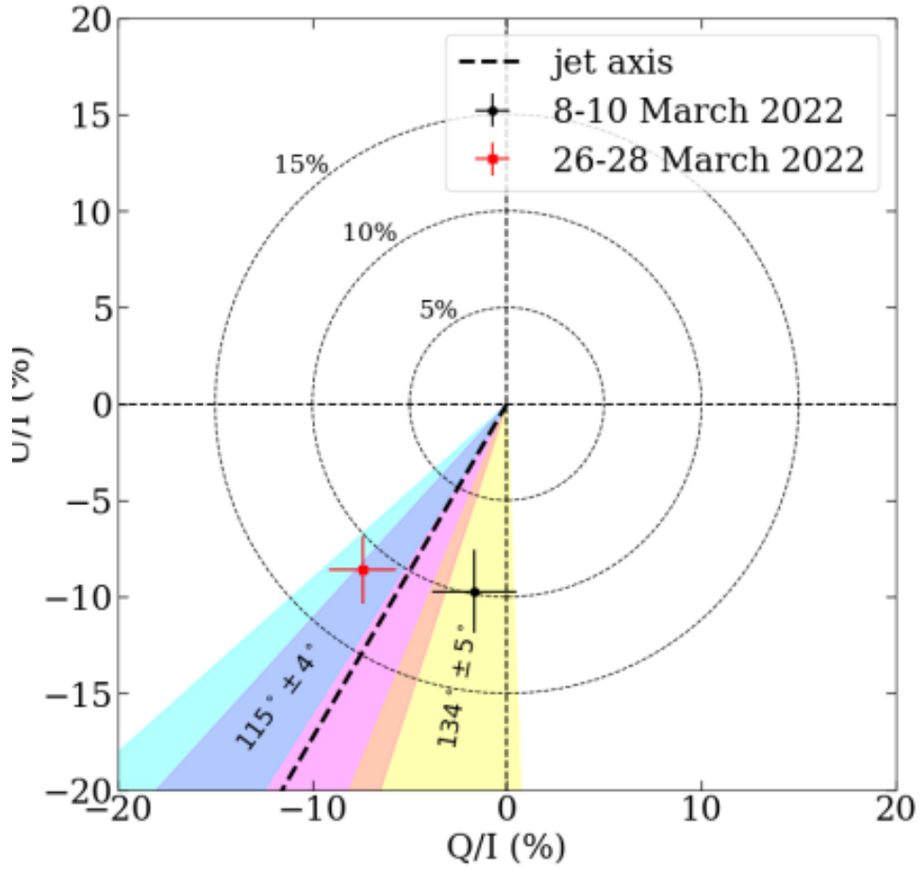
McKinney + Blandford 2009

X-ray polarization
Reveals magnetic field structure in astrophysical objects

First blazar observation: Mrk 501

- X-ray polarization 11% ± 2%
- Optical polarization 4% ± 1%





Liodakis, et al. (2022) Nature, 611, 677

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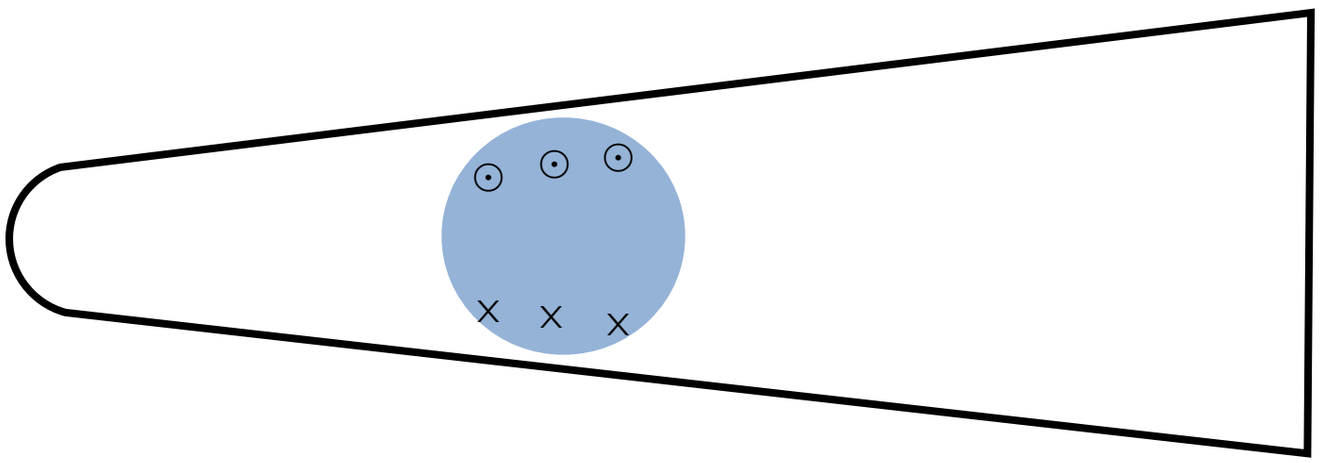
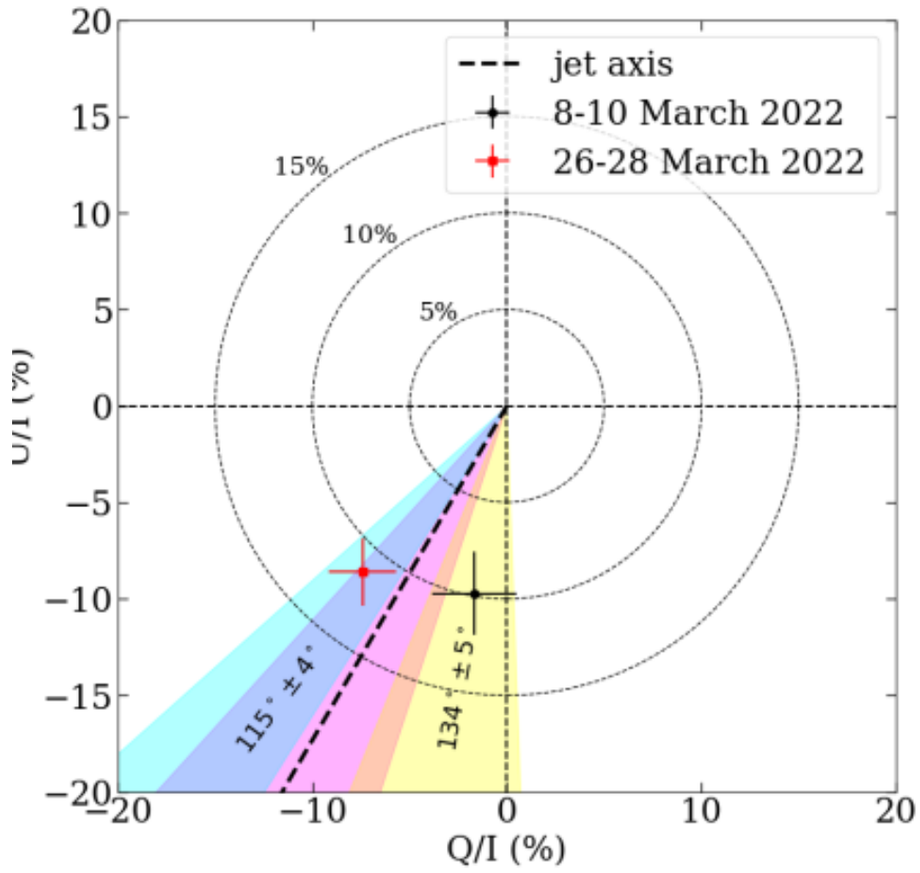


Optical region



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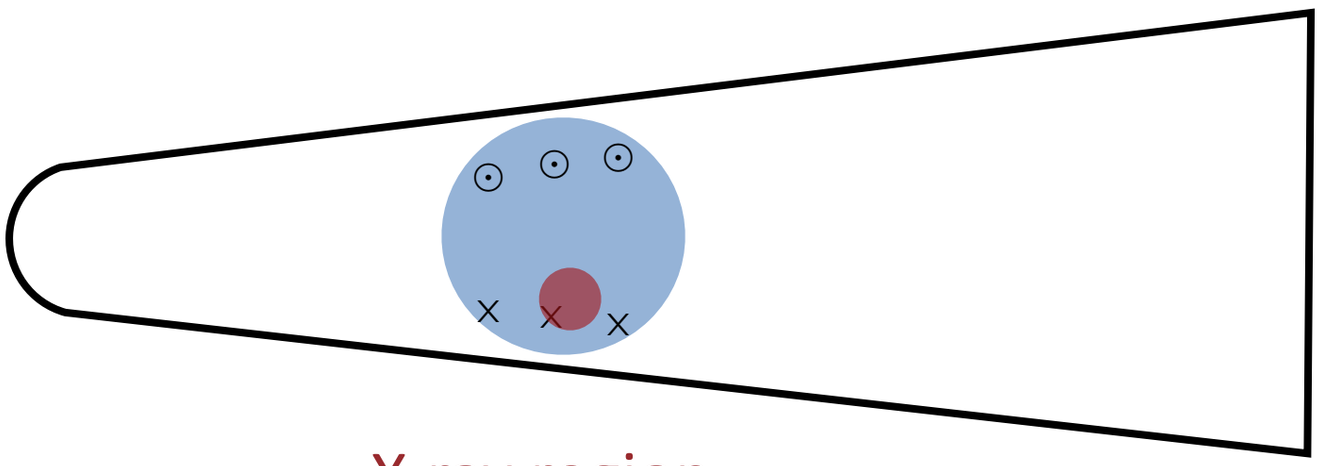
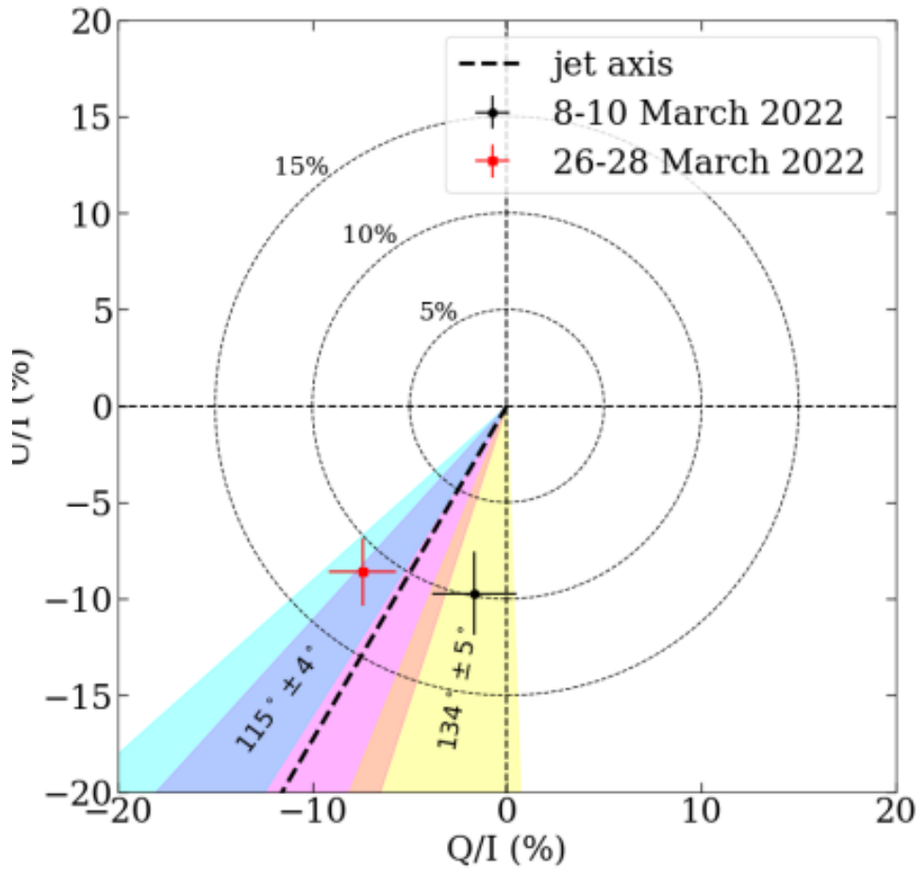


X-ray region

Optical region



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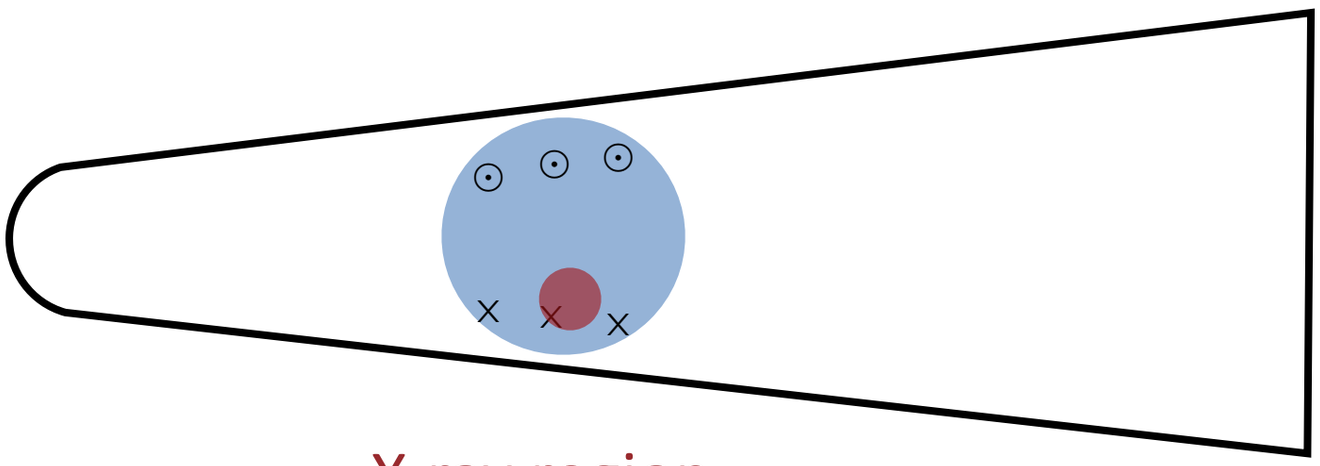
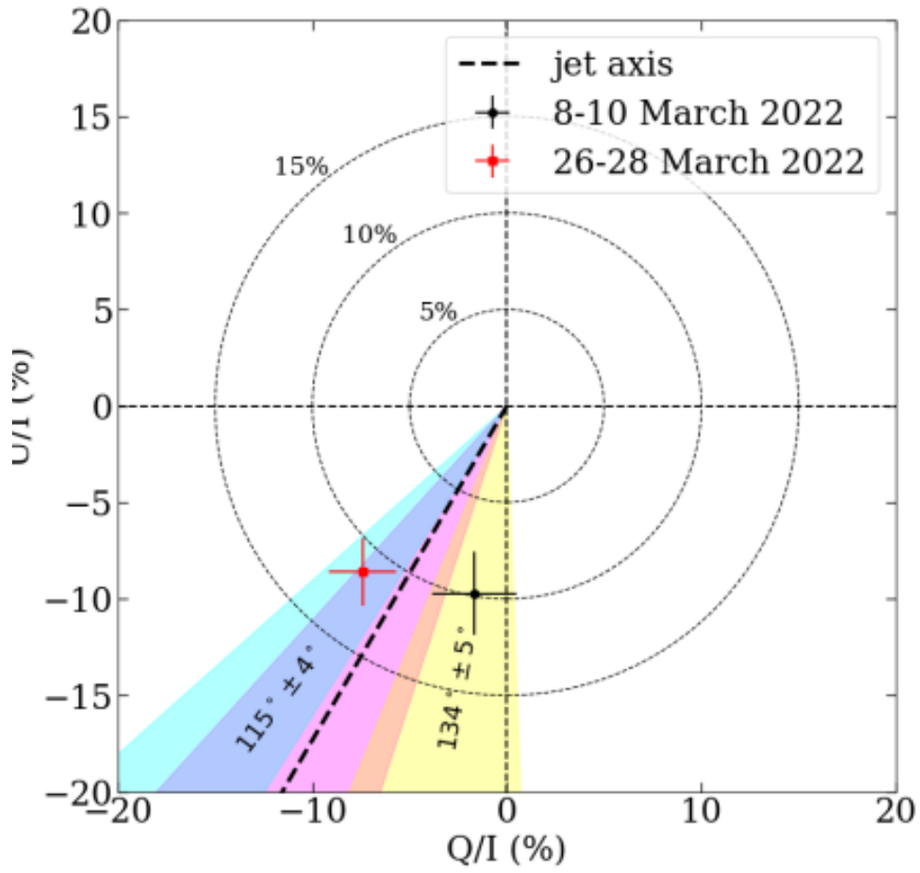


X-ray region

Optical region



Liodakis, et al. (2022) Nature, 611, 677

The X-ray emitting region in relativistic jets is more compact than the that at longer wavelengths. The highest-energy particles occupy a small volume and radiate quickly.

Summary of X-ray polarization results

Source	Reference	X-ray polarization
Mrk 421	Di Gesu+ 2022	~15%
Mrk 501	Liodakis+ 2022	~10%
BL Lac	Middei+ 2023	< 12.6% (UL)
BL Lac flare	Peirson+ 2023	~22%
PG 1553+113	Middei+ 2023	~10%
Mrk 421	Di Gesu+ 2023	~10%, rotation
1ES 0229+200	Ehlert+ 2023	~18%
Mrk 421	Kim+ 2024	~14%
1ES 1959+650	Errando+ 2024	~8%, <5% (UL)
PKS 2155-304	Kouch+, 2024	~30%, ~15%
Mrk 501	Chen+ 2024	~9%, ~6%, ~18%
3C 273, 3C 279, 3C 454.3, S5 0716+714	Marshall+ 2024	<10-30% (UL)

Summary of X-ray polarization results

Source	Reference	X-ray polarization	TeV (VERITAS)
Mrk 421	Di Gesu+ 2022	~15%	✔
Mrk 501	Liodakis+ 2022	~10%	✔
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PG 1553+113	Middei+ 2023	~10%	
Mrk 421	Di Gesu+ 2023	~10%, rotation	✔ (not rotation)
1ES 0229+200	Ehlert+ 2023	~18%	UL
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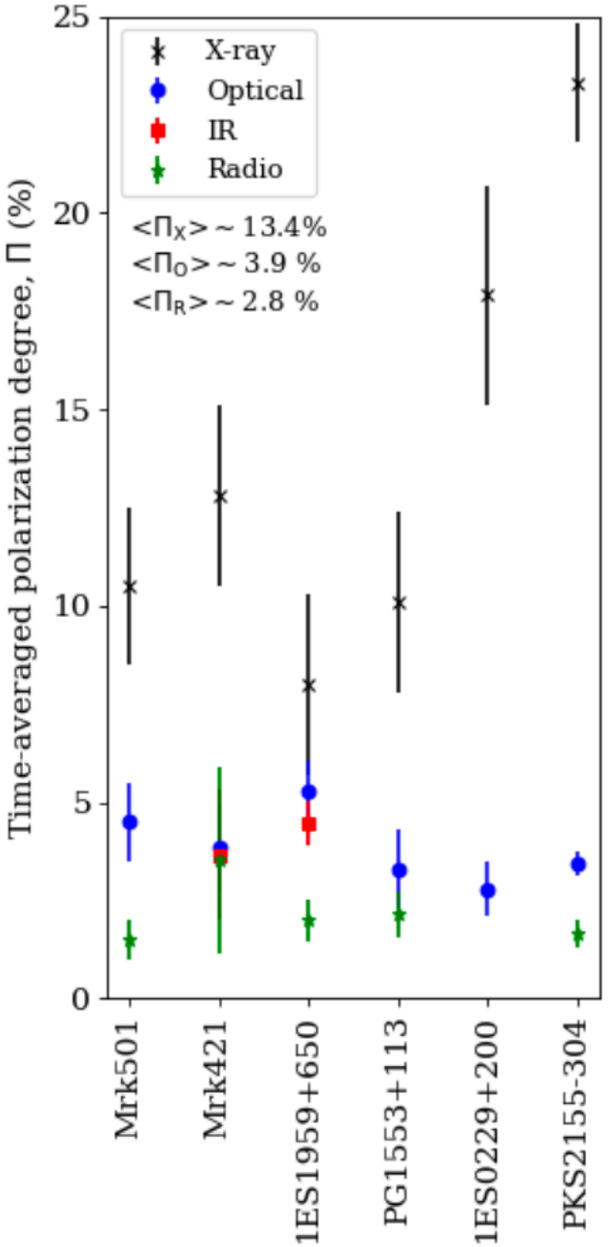
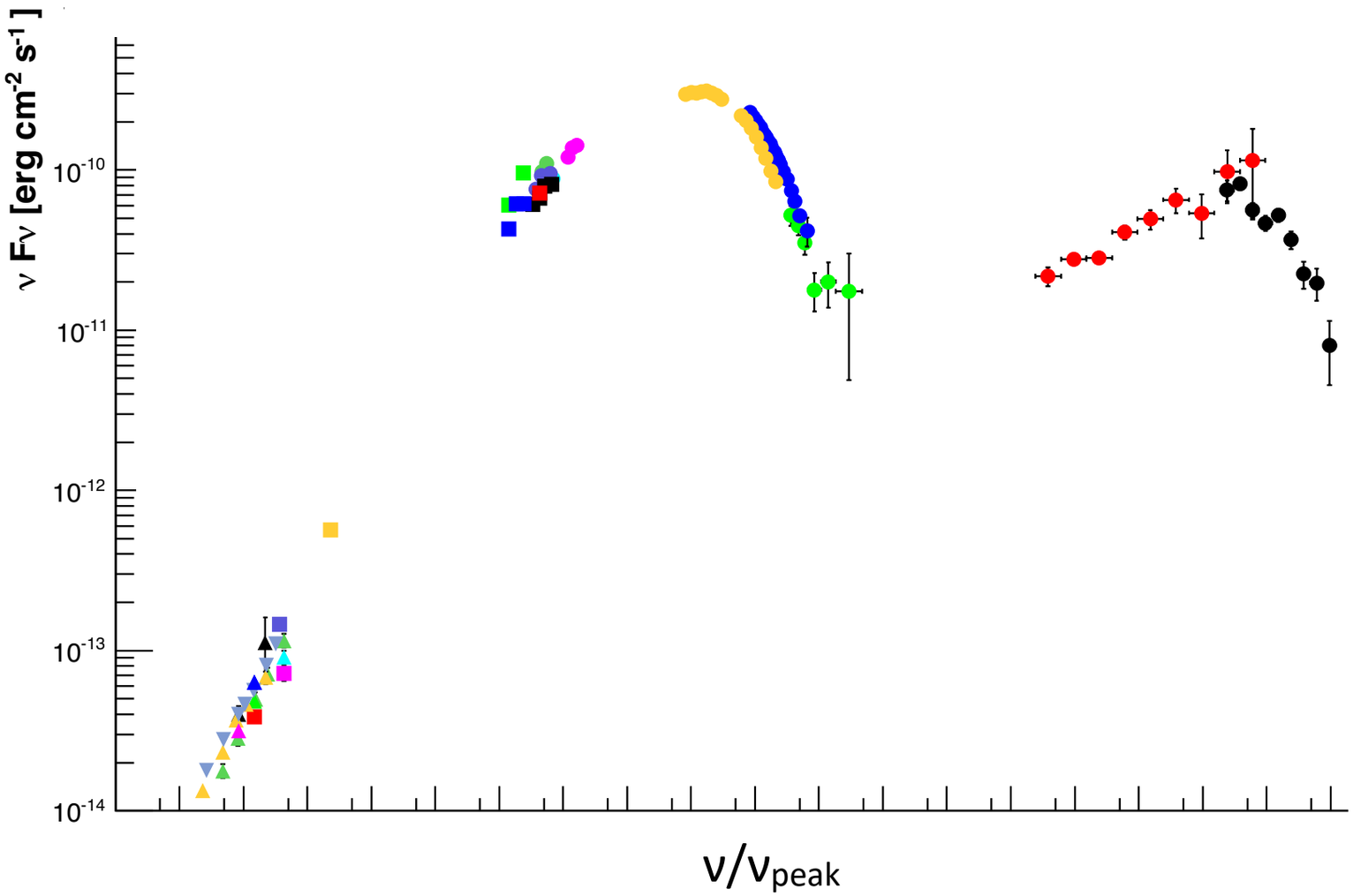
Polarization, blazar jets



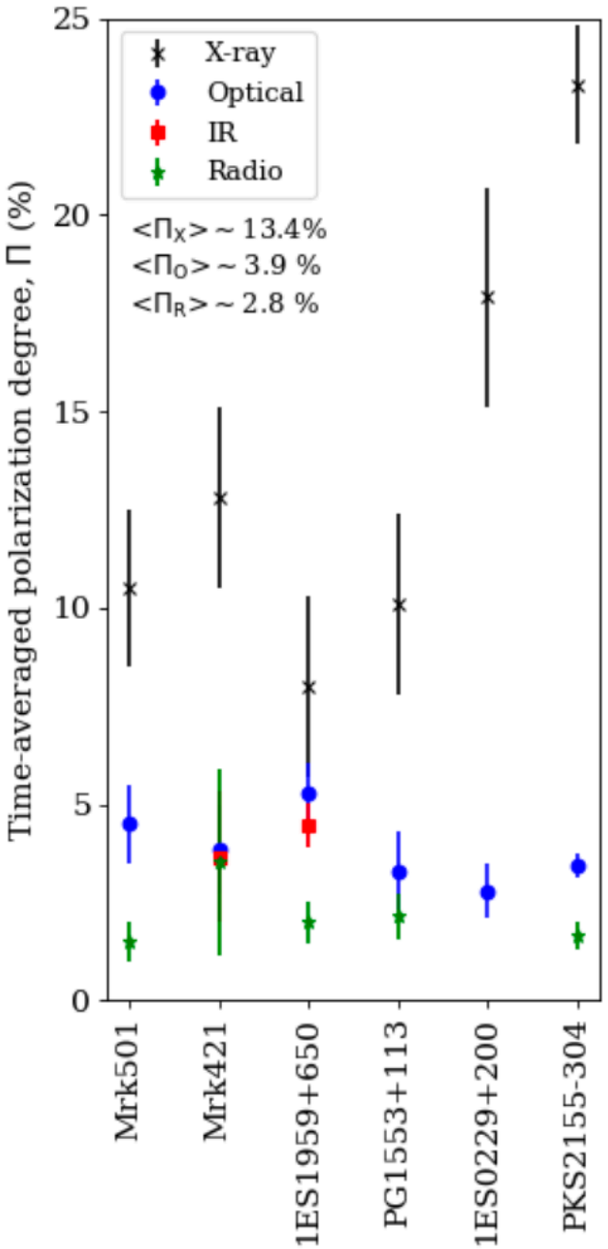
Kouch+ 2024



More often than not:
EVPA is aligned with the jet direction
X-ray polarization is higher than optical polarization

Polarization, blazar jets

Increasing polarization → Ordered B → More compact region



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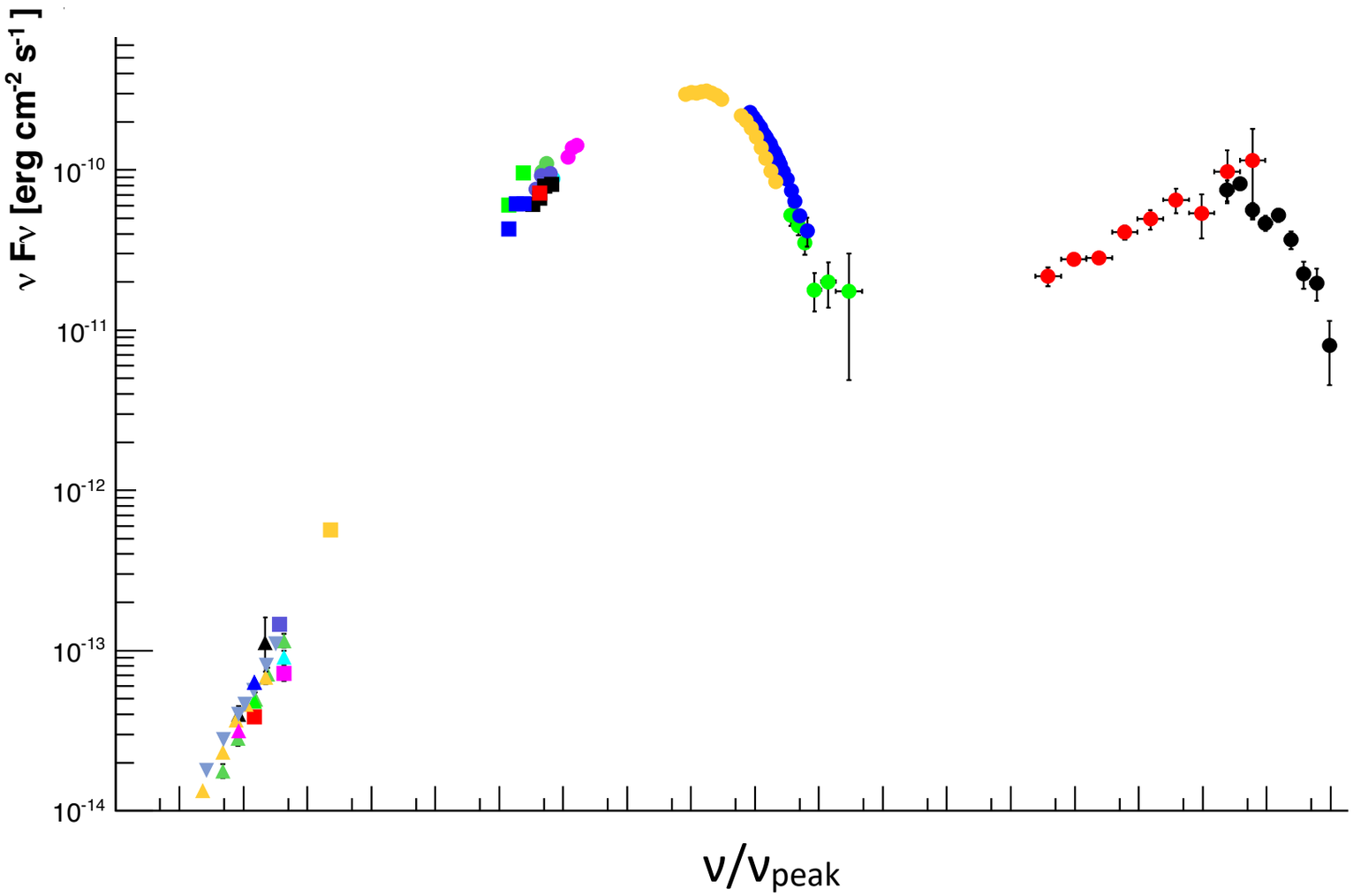

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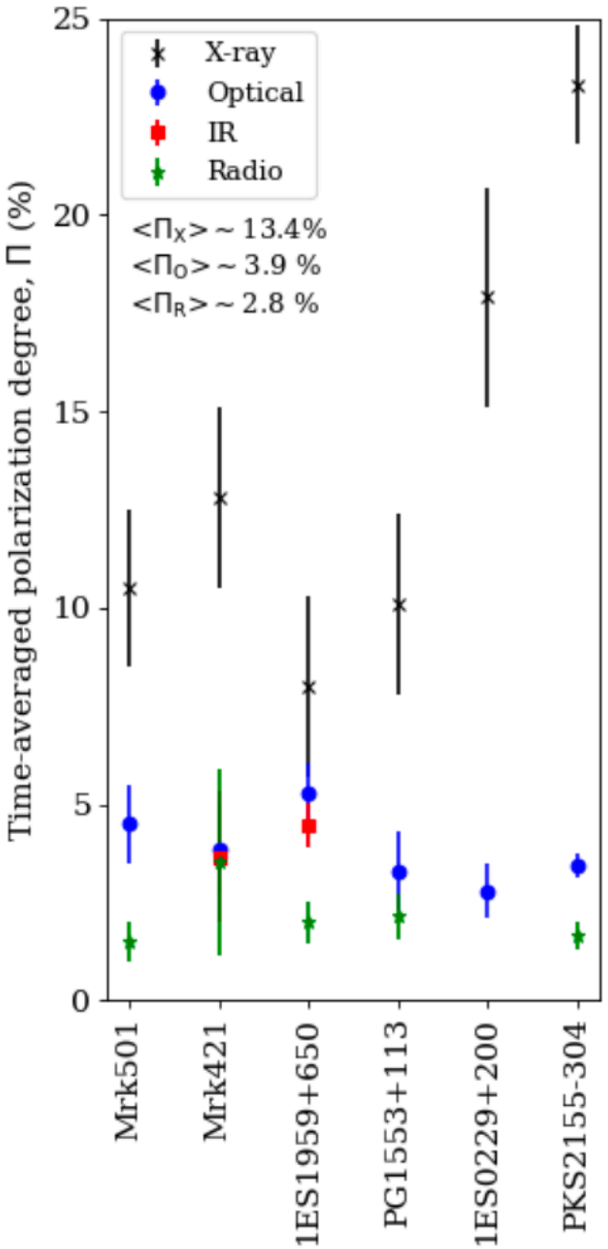

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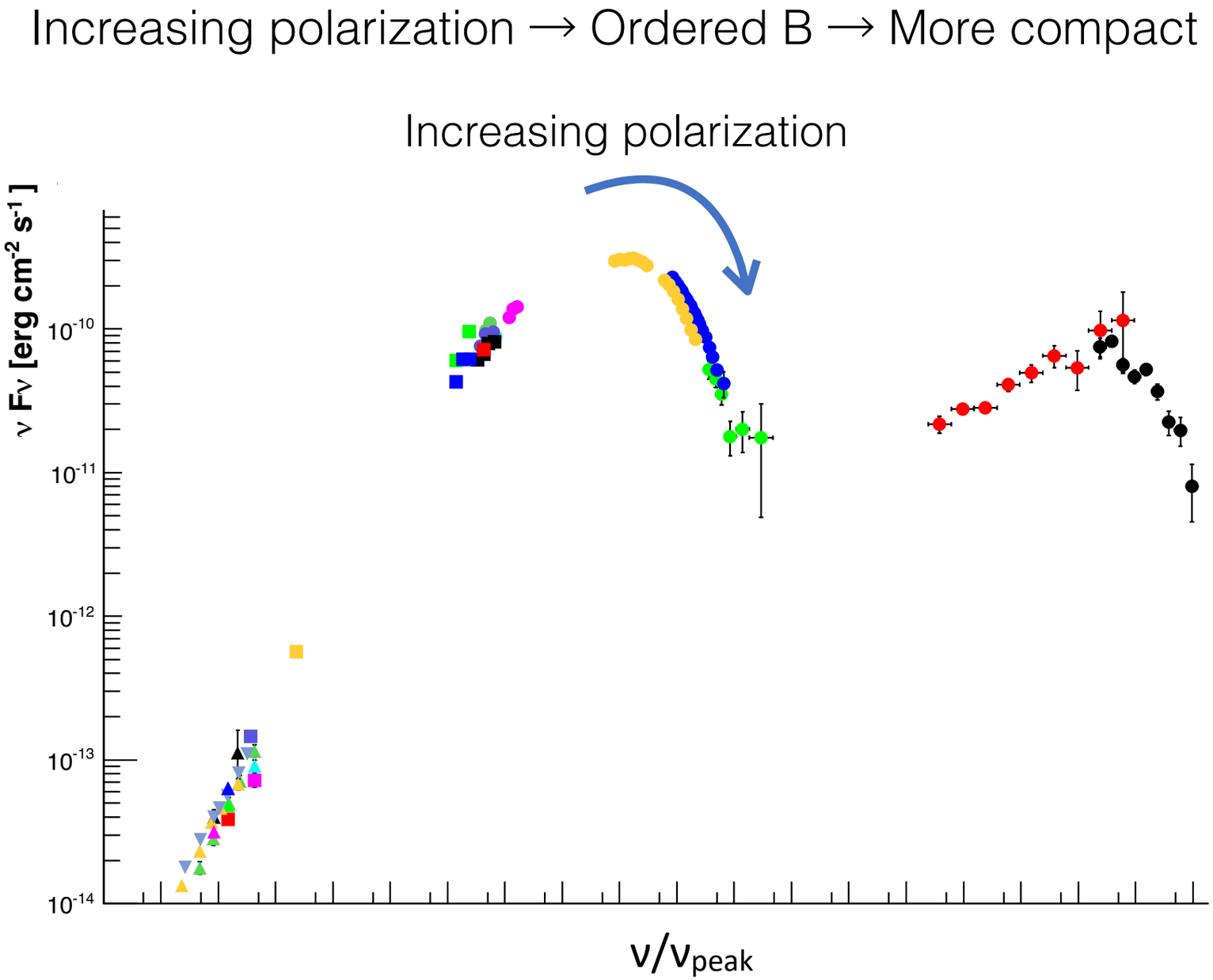

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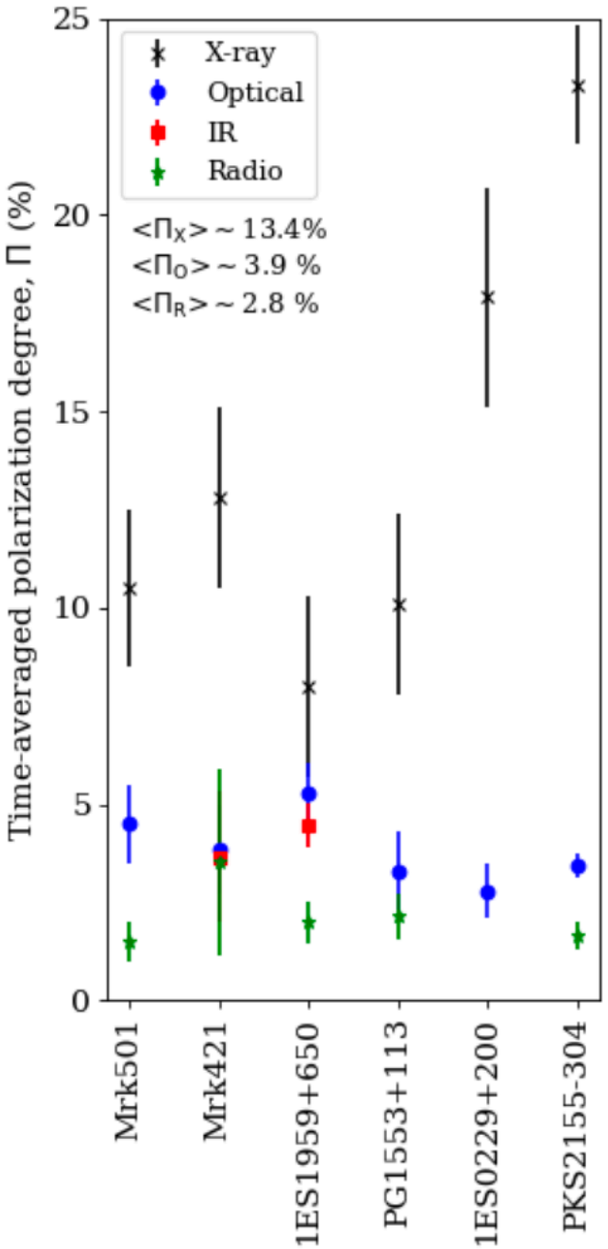

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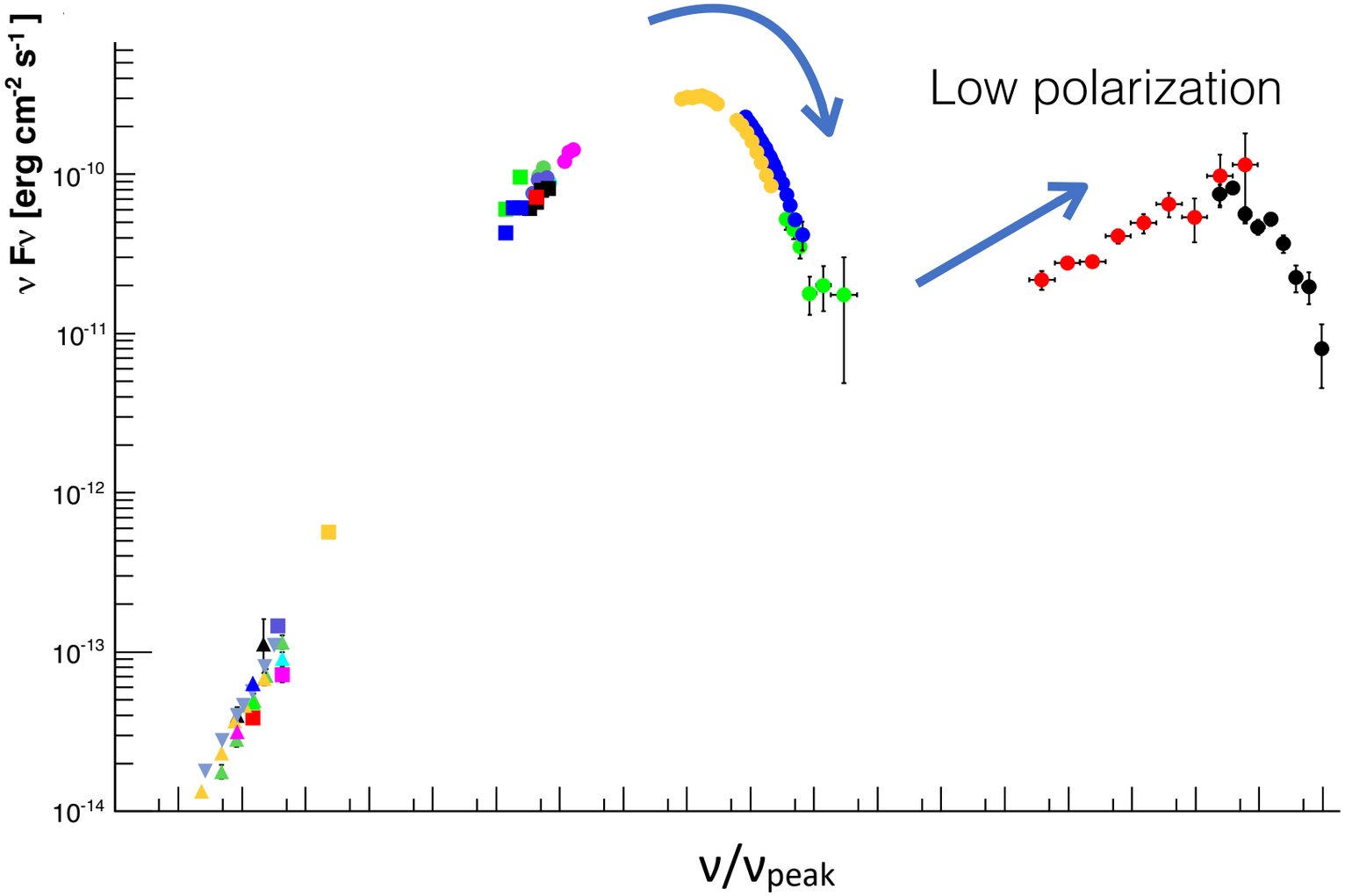

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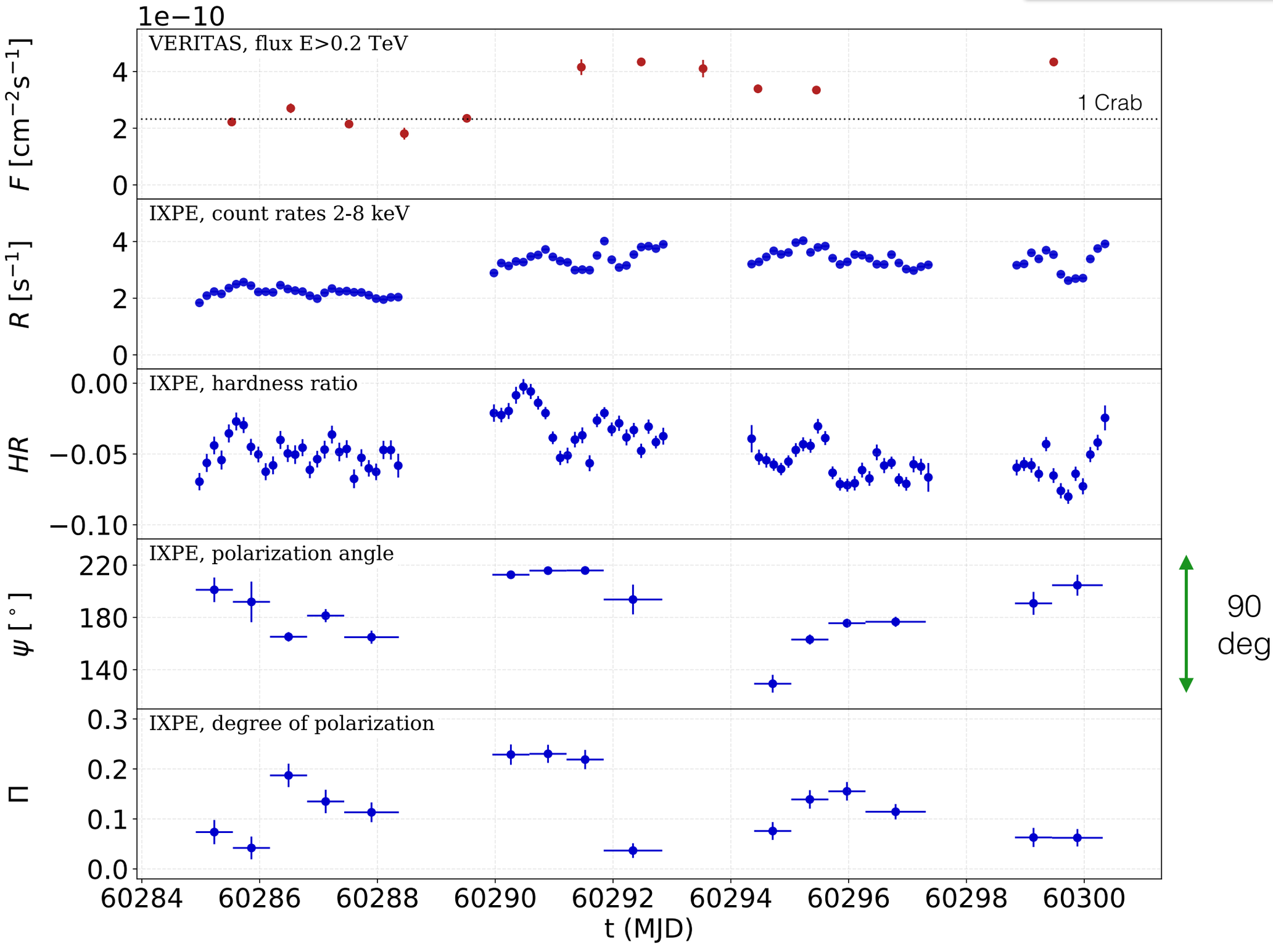
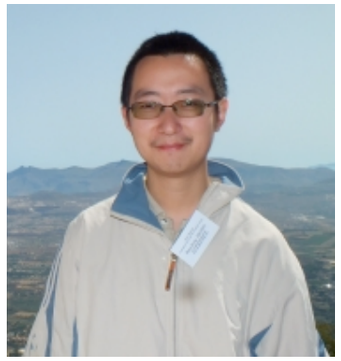
Jet dynamics: Mrk 421 with VERITAS

VERITAS coll., in prep

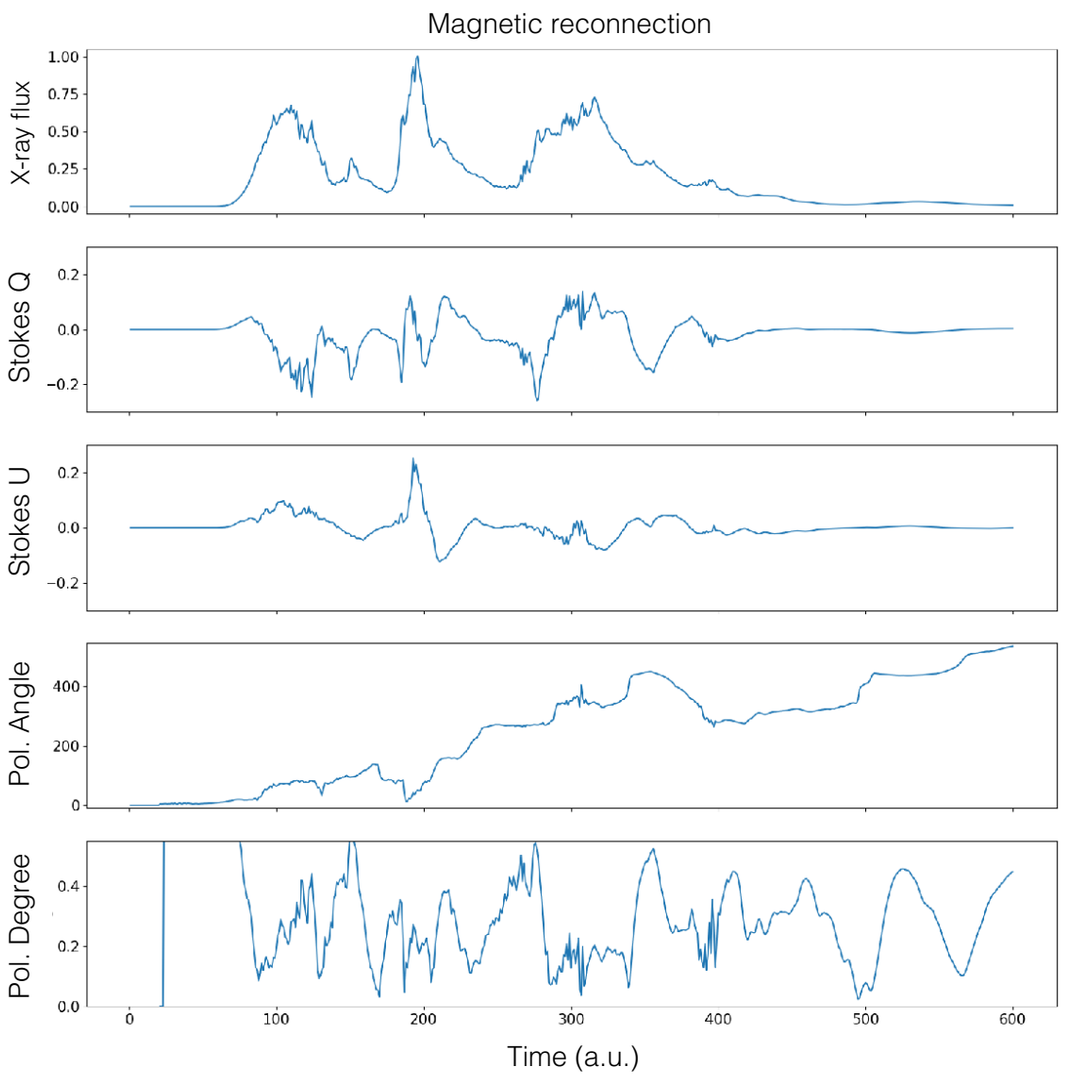


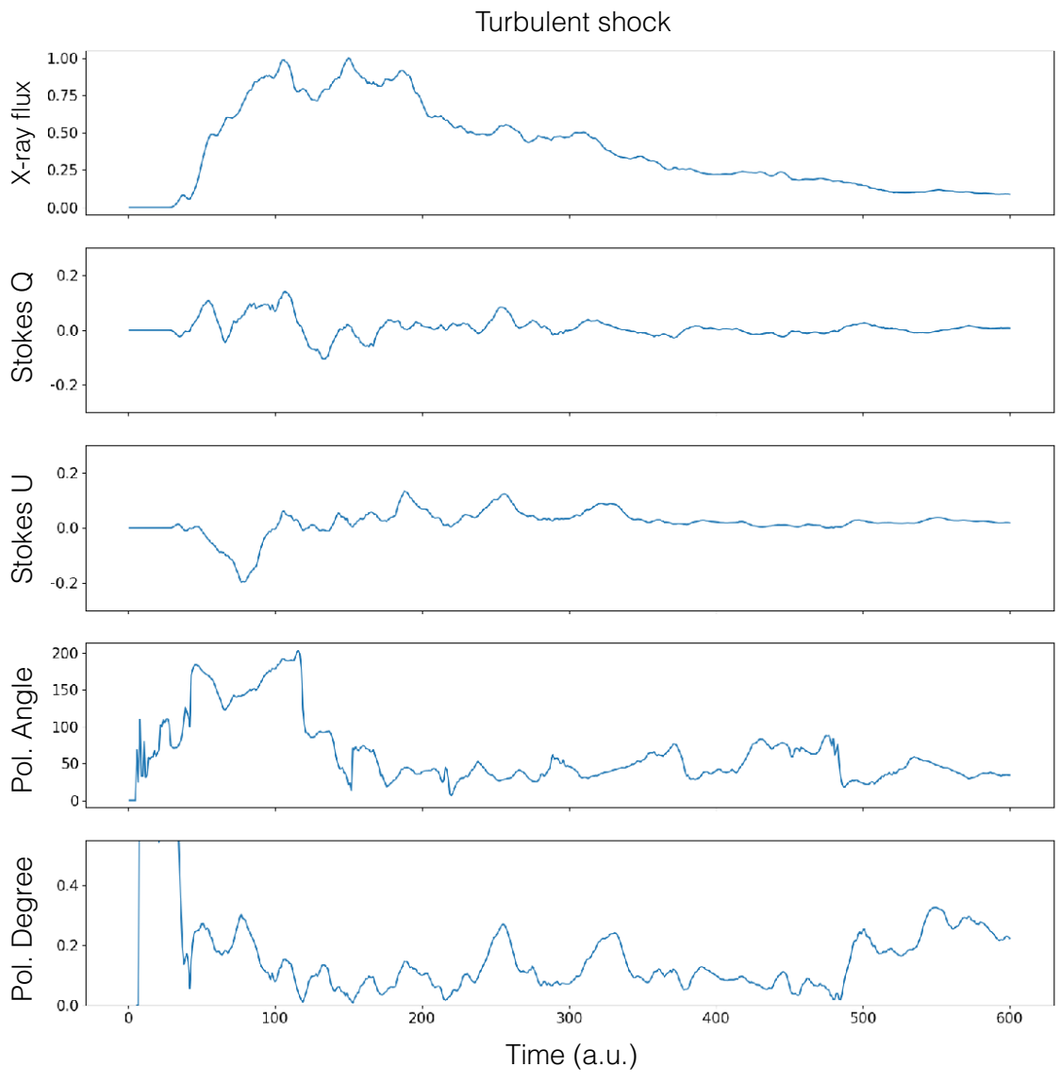
Particle-in-cell simulations



In collaboration with Haocheng Zhang
(NASA Goddard)

Zhang+ 2018





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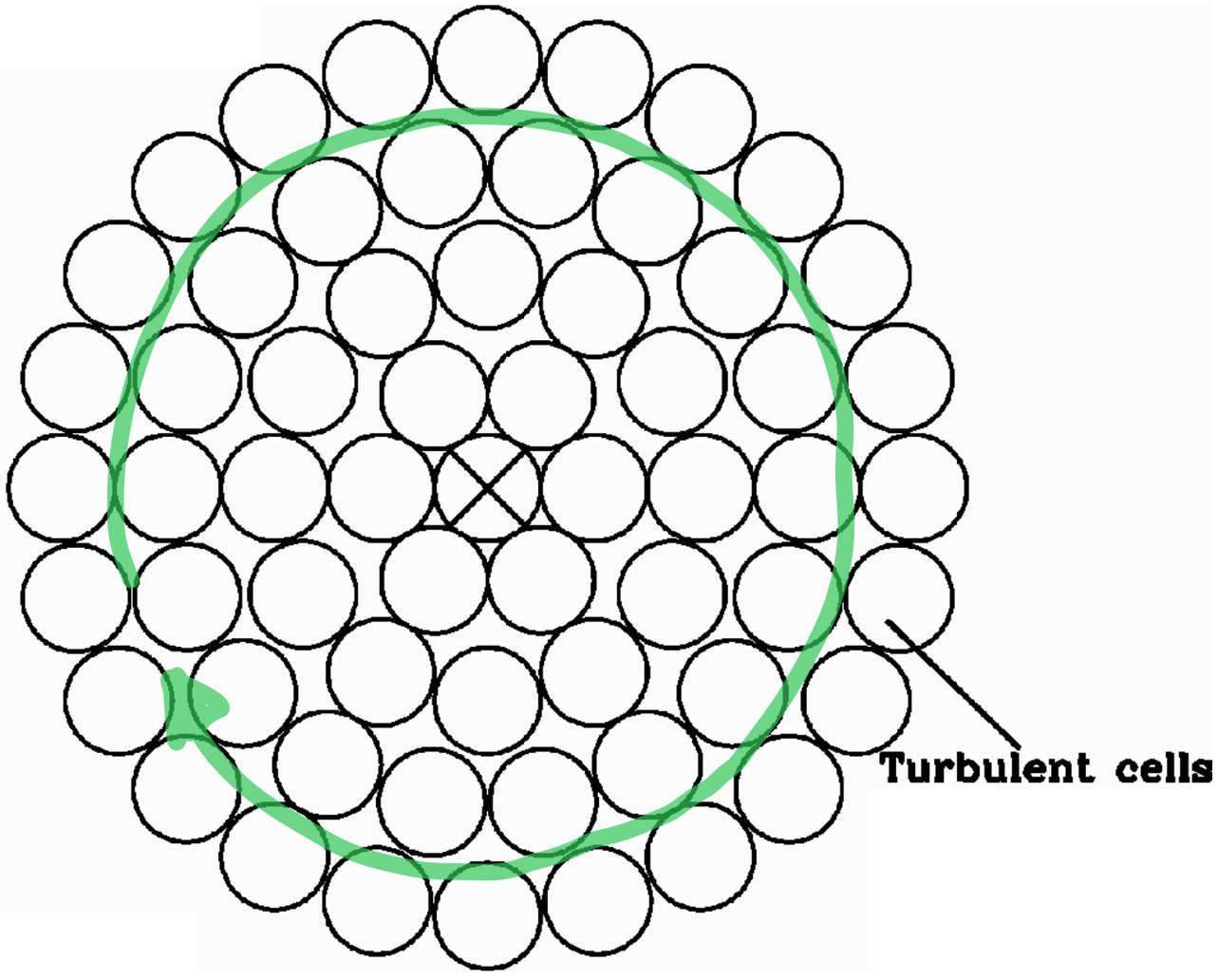

Toroidal B field

- Match simulation cooling time to observed flux variability timescale.
- Add emission from multiple cells.
- Explore parameter space:
  - Shocks vs mag. reconnection
  - Number of cells
  - Compactness of cell cluster
  - Cell brightness distribution: equal, power law.
- Calculate metrics: Polarization degree, pol. angle, variability timescales and range

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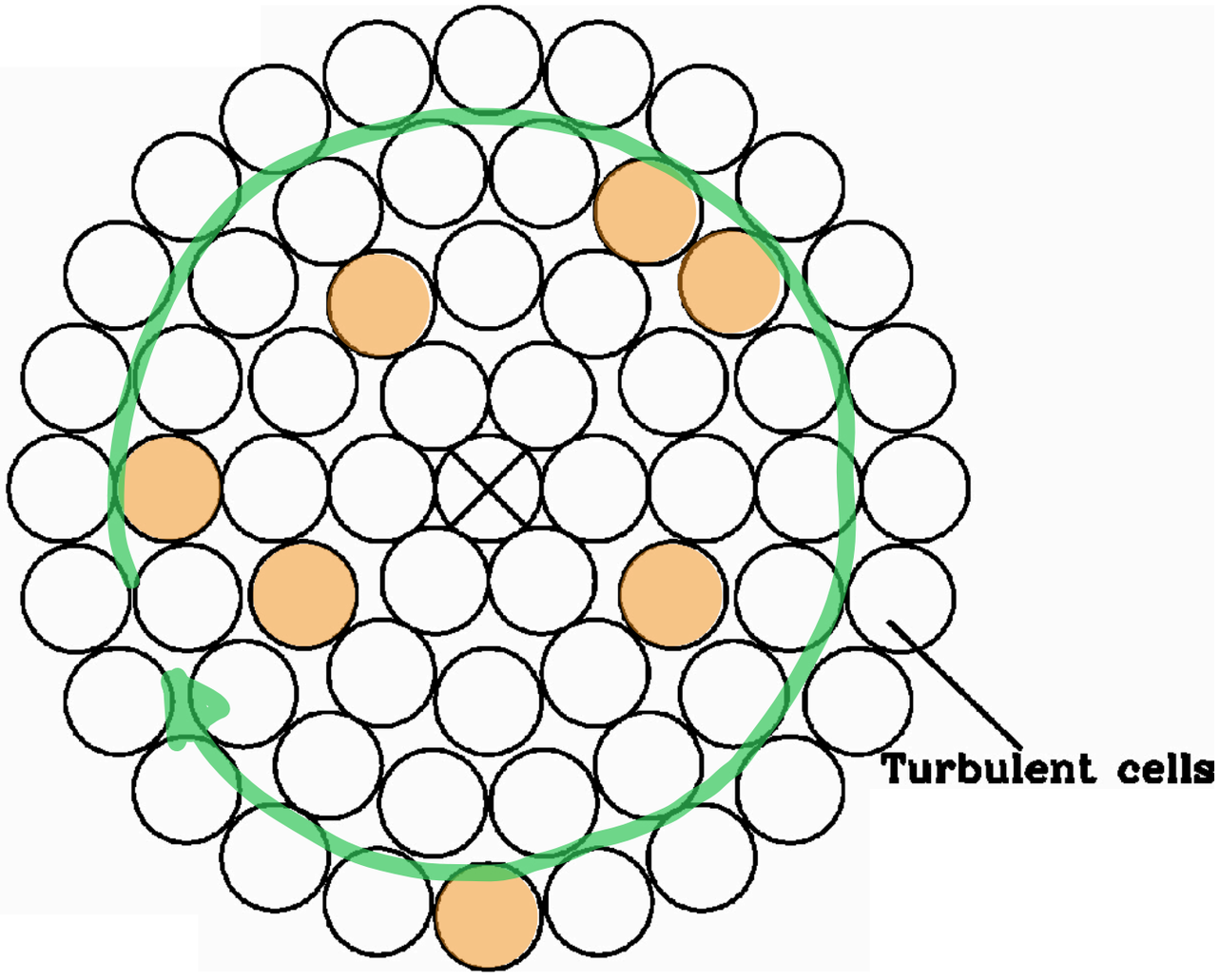

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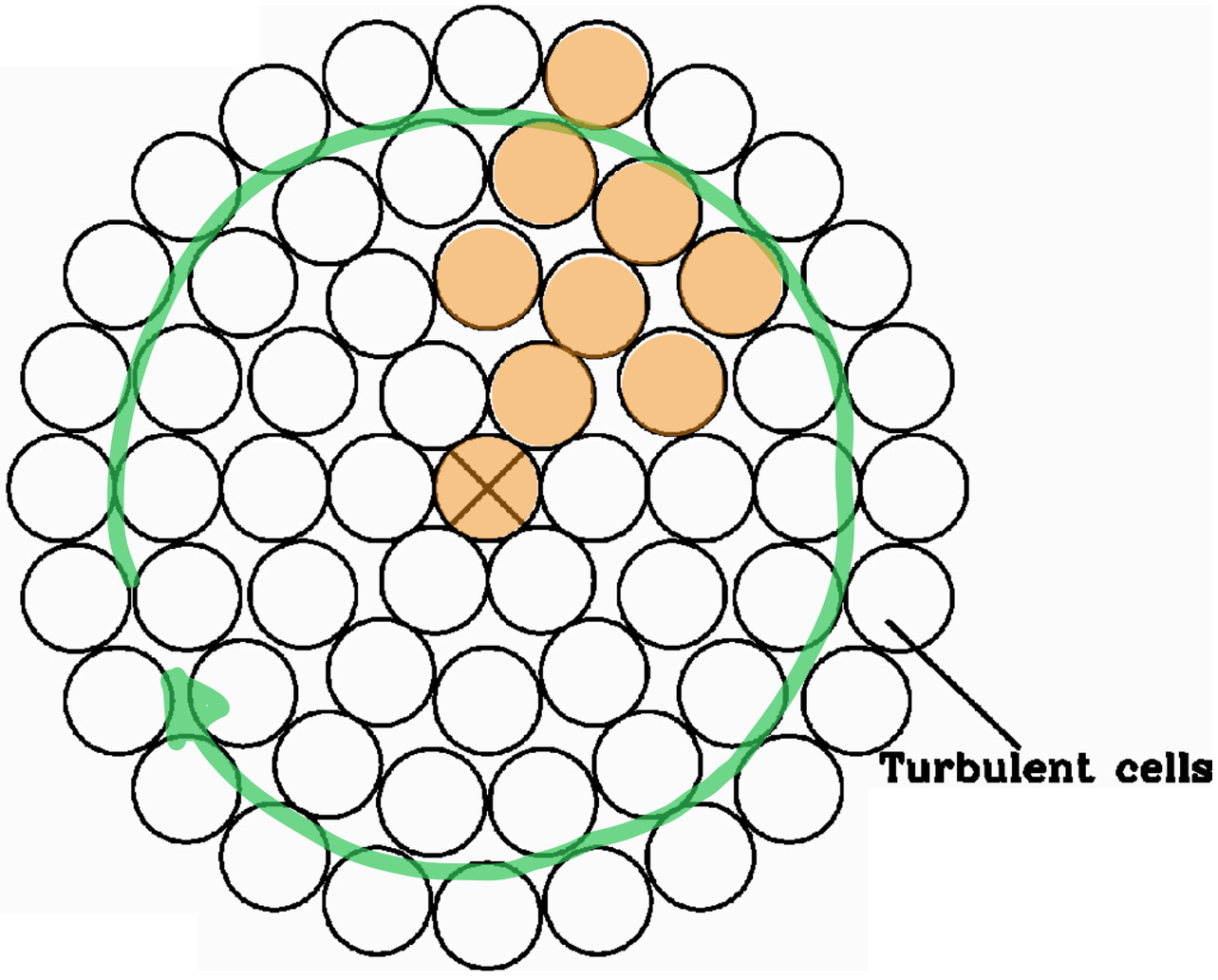

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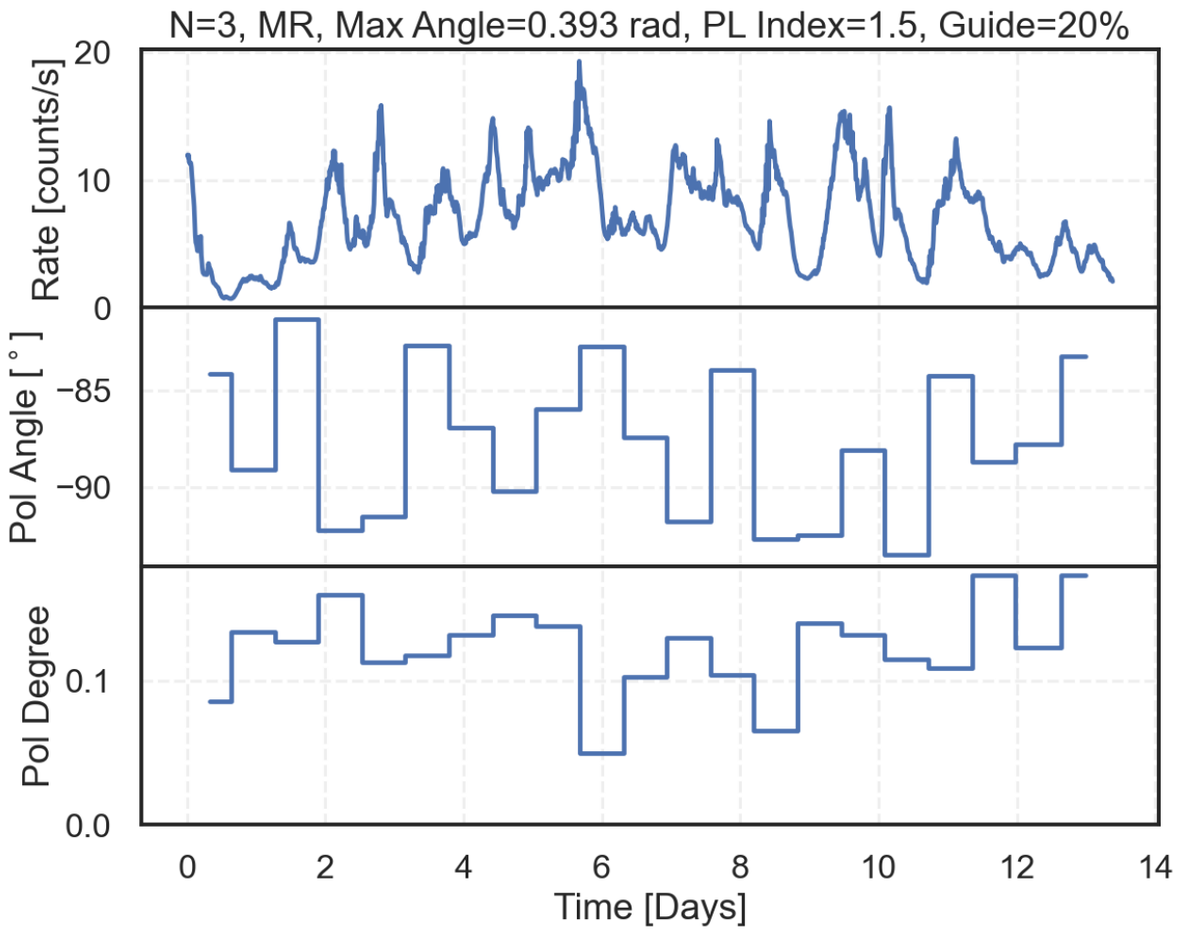
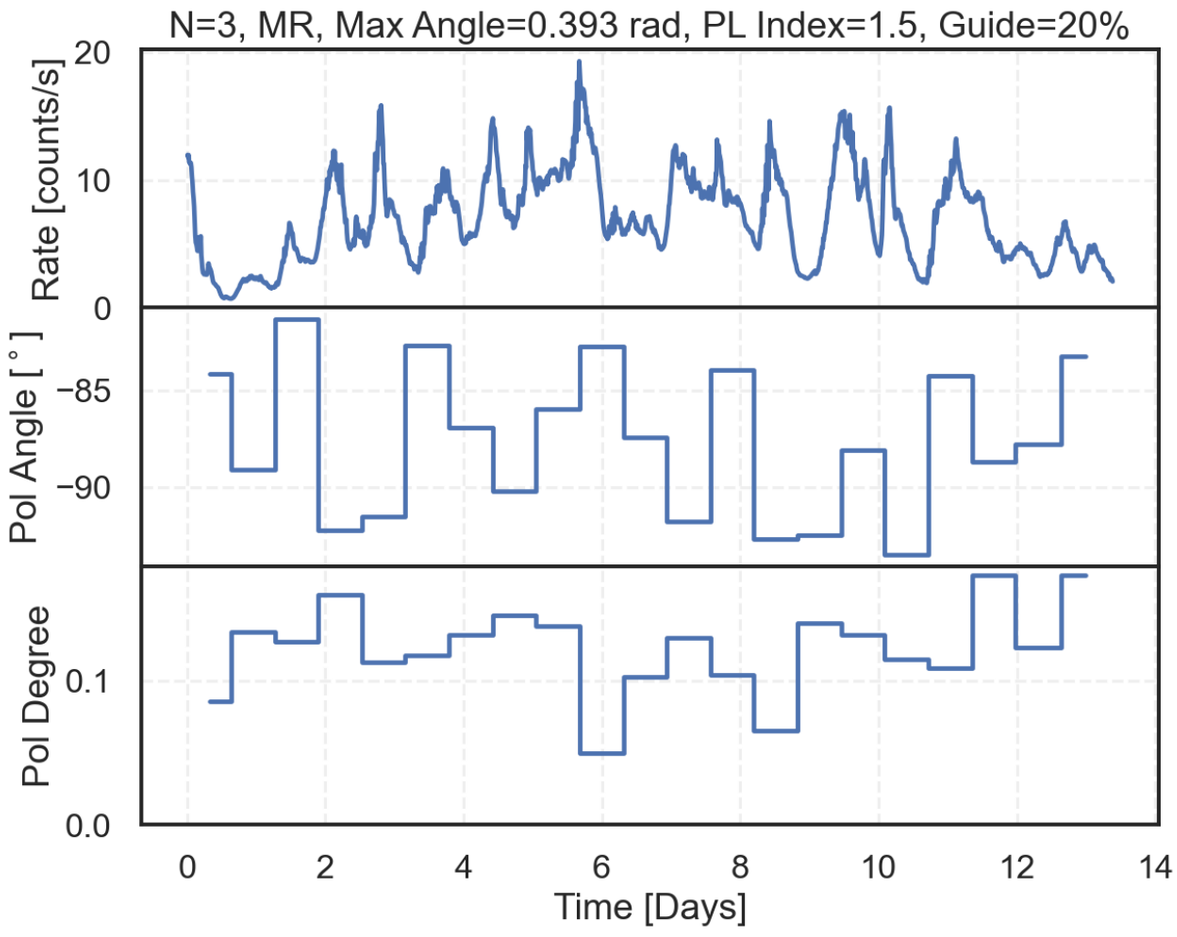
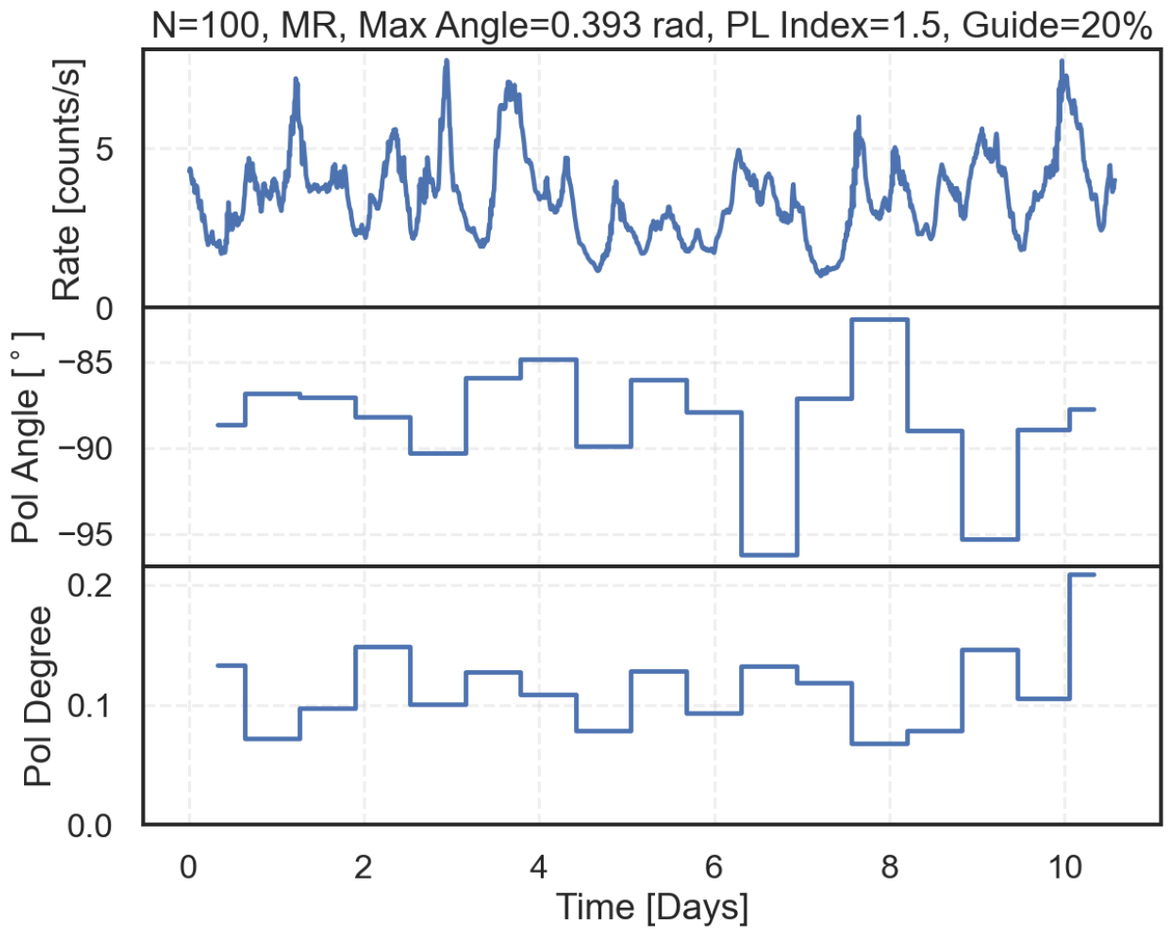
Mag. reconnection multi-cell simulation



- Small number of cells, compact
- Can produce 10% polarization
- Too much flux variability

Mag. reconnection multi-cell simulation

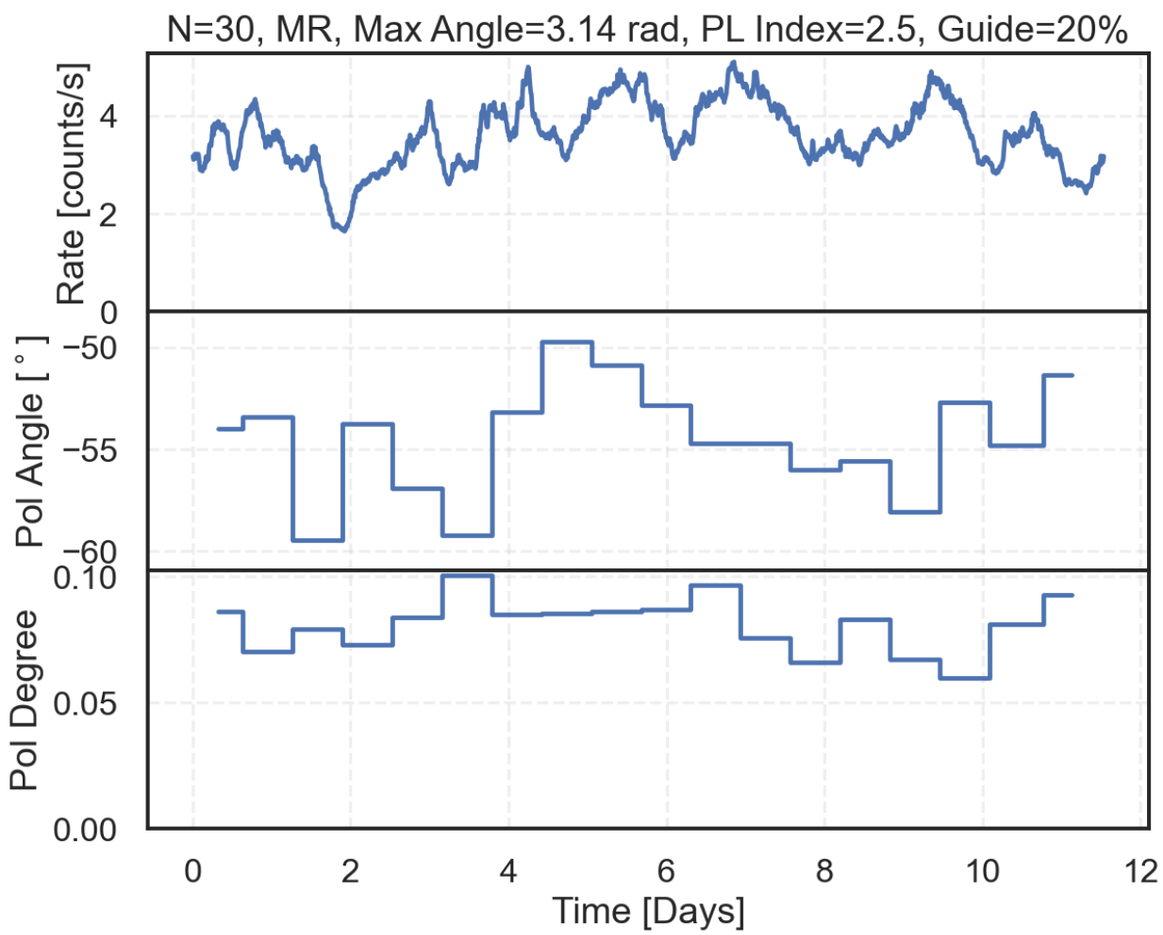




- Small number of cells, compact
- Can produce 10% polarization
- Too much flux variability

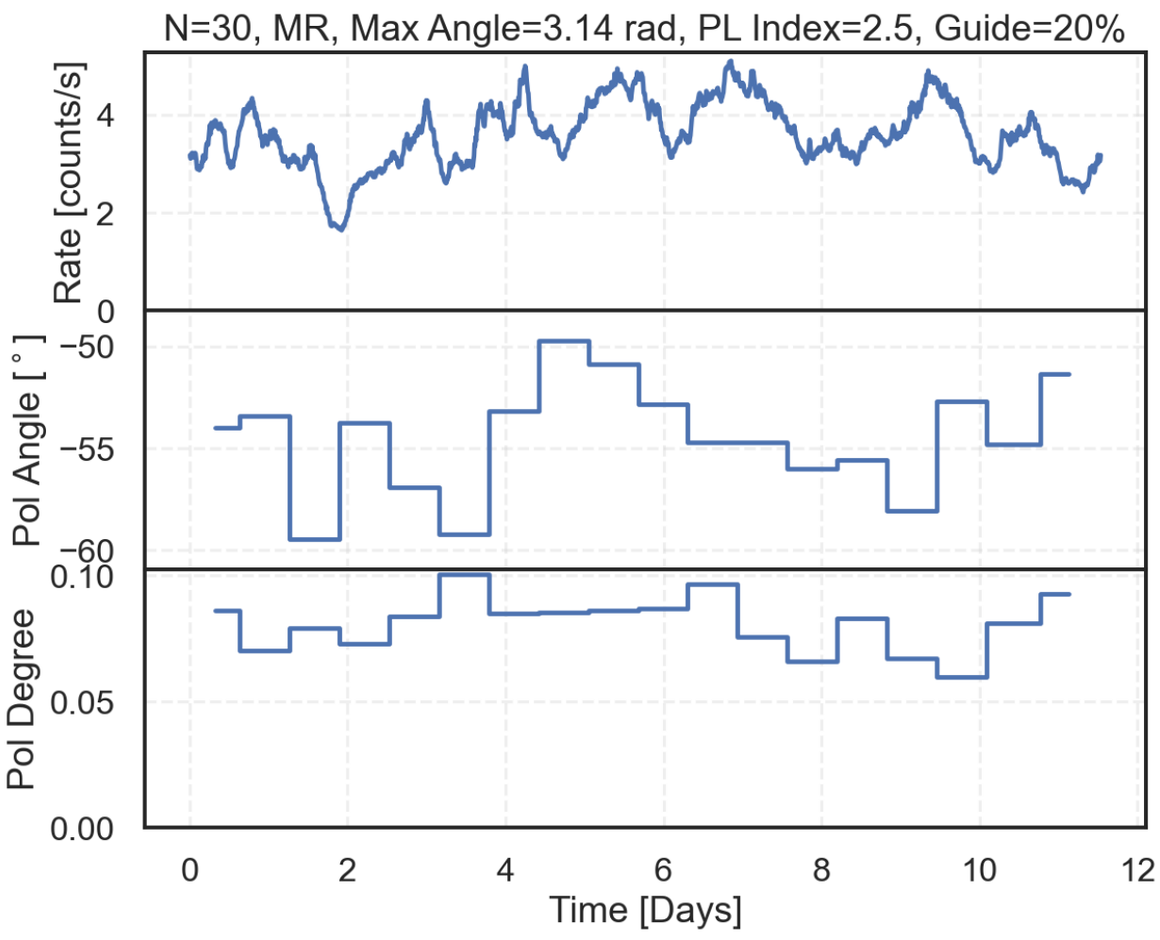
- Increase number of cells
- Flux variability closer to data
- Pol. deg and angle too steady

Mag. reconnection multi-cell simulation



- Less compact cluster, 1/4 jet
- Reproduces light curve and pol. deg
- Pol. Angle still too steady

Mag. reconnection multi-cell simulation



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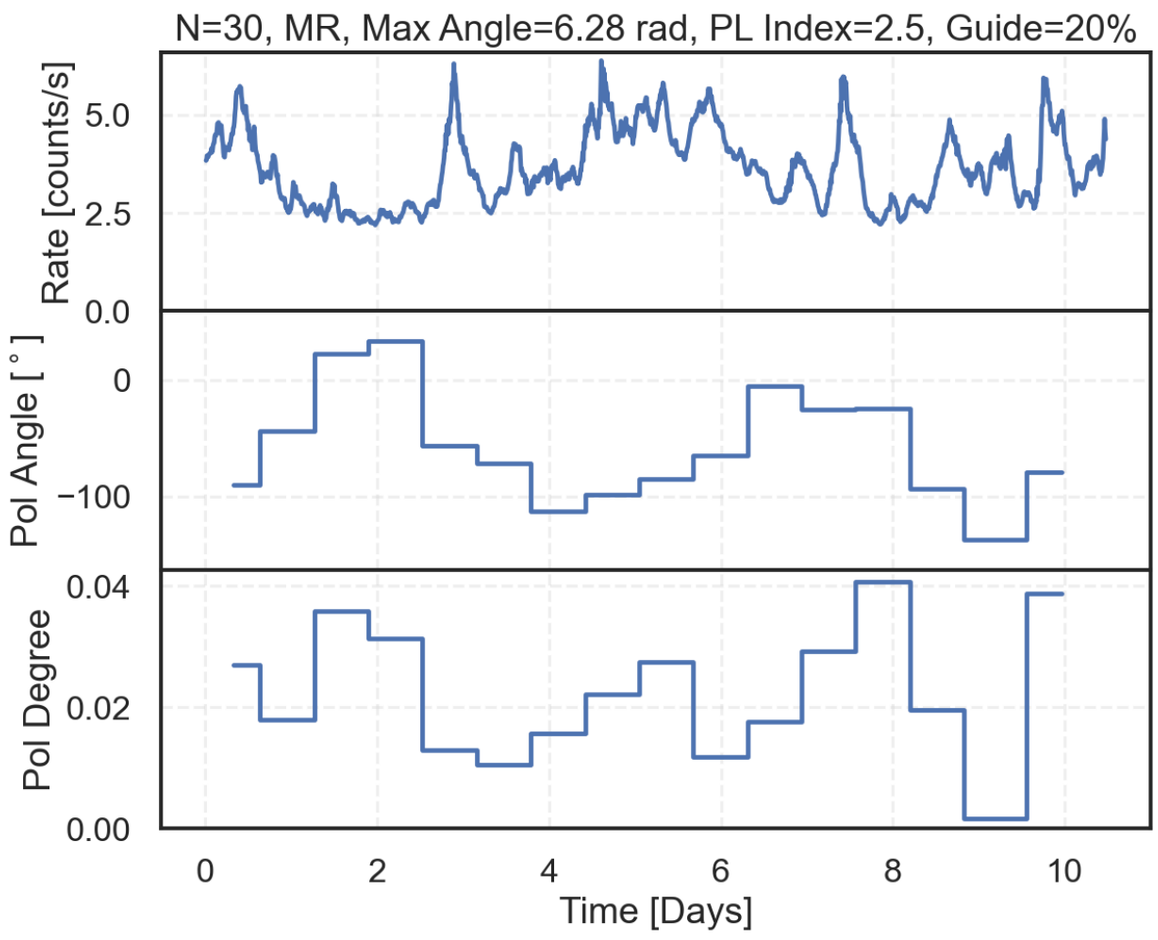
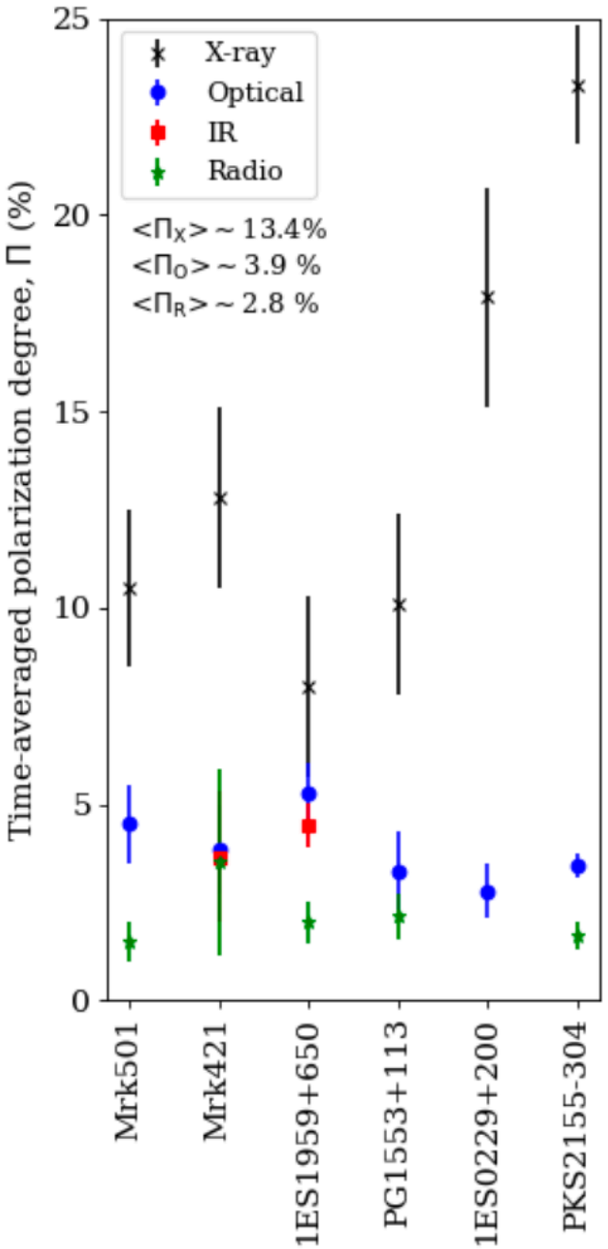


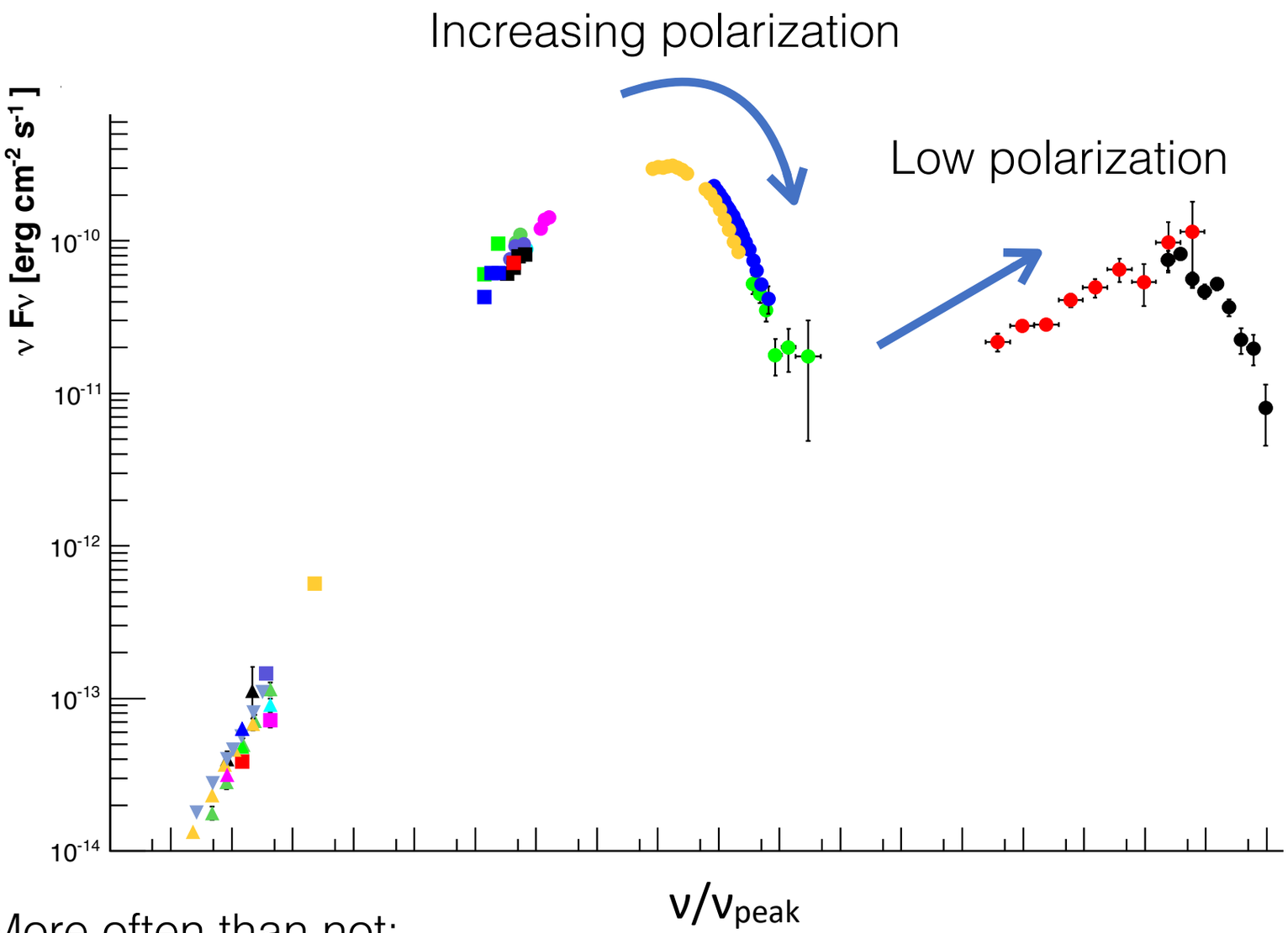
- Even less compact, 1/2 jet
- Pol. angle swings similar to data
- But pol. degree is too small

Summary



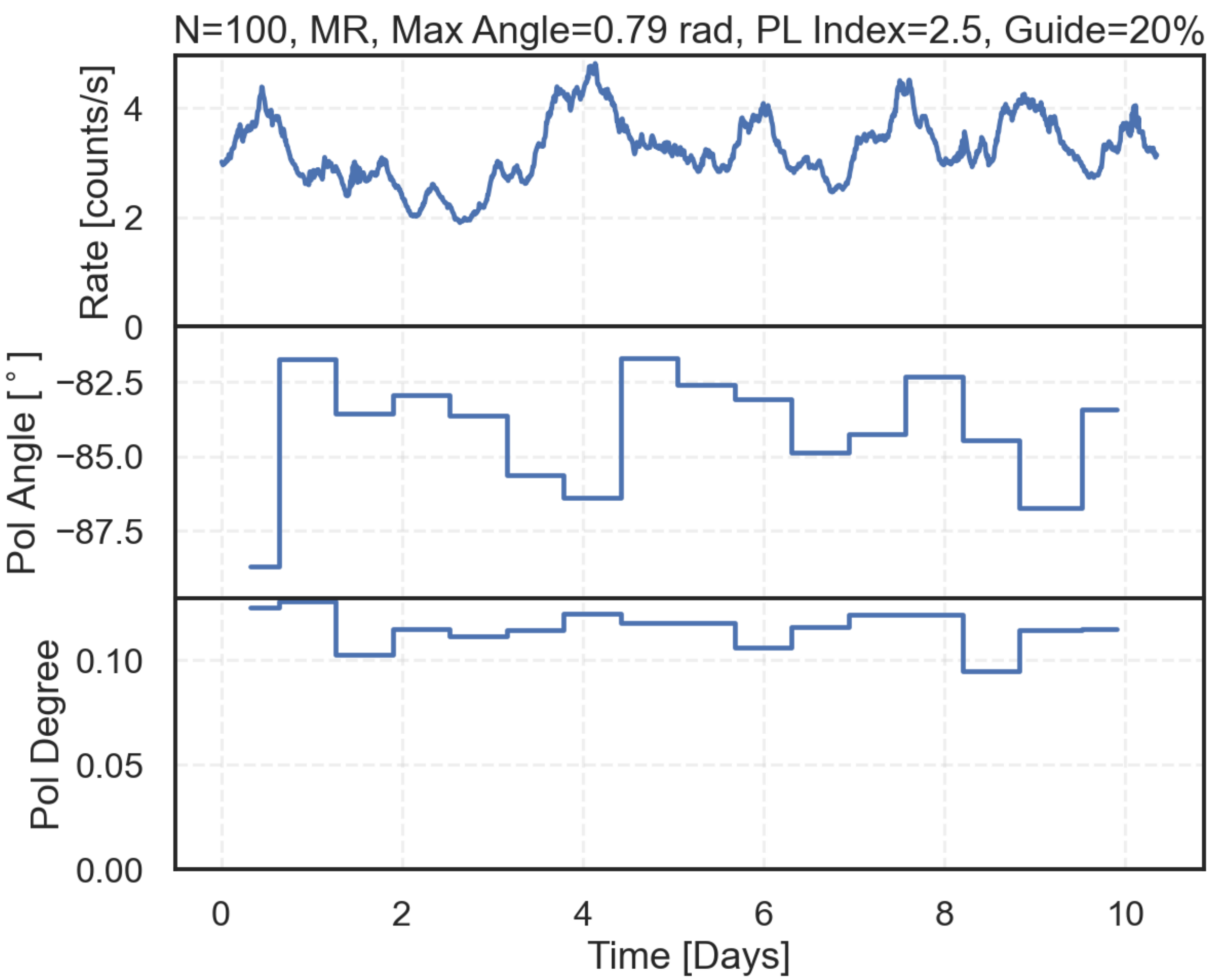
Kouch+ 2024

Increasing polarization → Ordered B → More compact region



More often than not:
EVPA is aligned with the jet direction
X-ray polarization is higher than optical polarization
Emission likely to originate from a localized region in the jet
Complexity of pol. dynamics favor multi-zone emission region

Backup slides


N=100, MR, Max Angle=0.79 rad, PL Index=2.5, Guide=20%
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4
2
0
Pol Angle [°]
−82.5
−85.0
−87.5
Pol Degree
0.10
0.05
0.00
0
2
4
6
8
10
Time [Days]

N=10, MR, Max Angle=0.393 rad, PL Index=1.5, Guide=20%

Rate [counts/s]

10

5

0

Pol Angle [°]

−80

−90

−100

Pol Degree

0.1

0.0

0

2

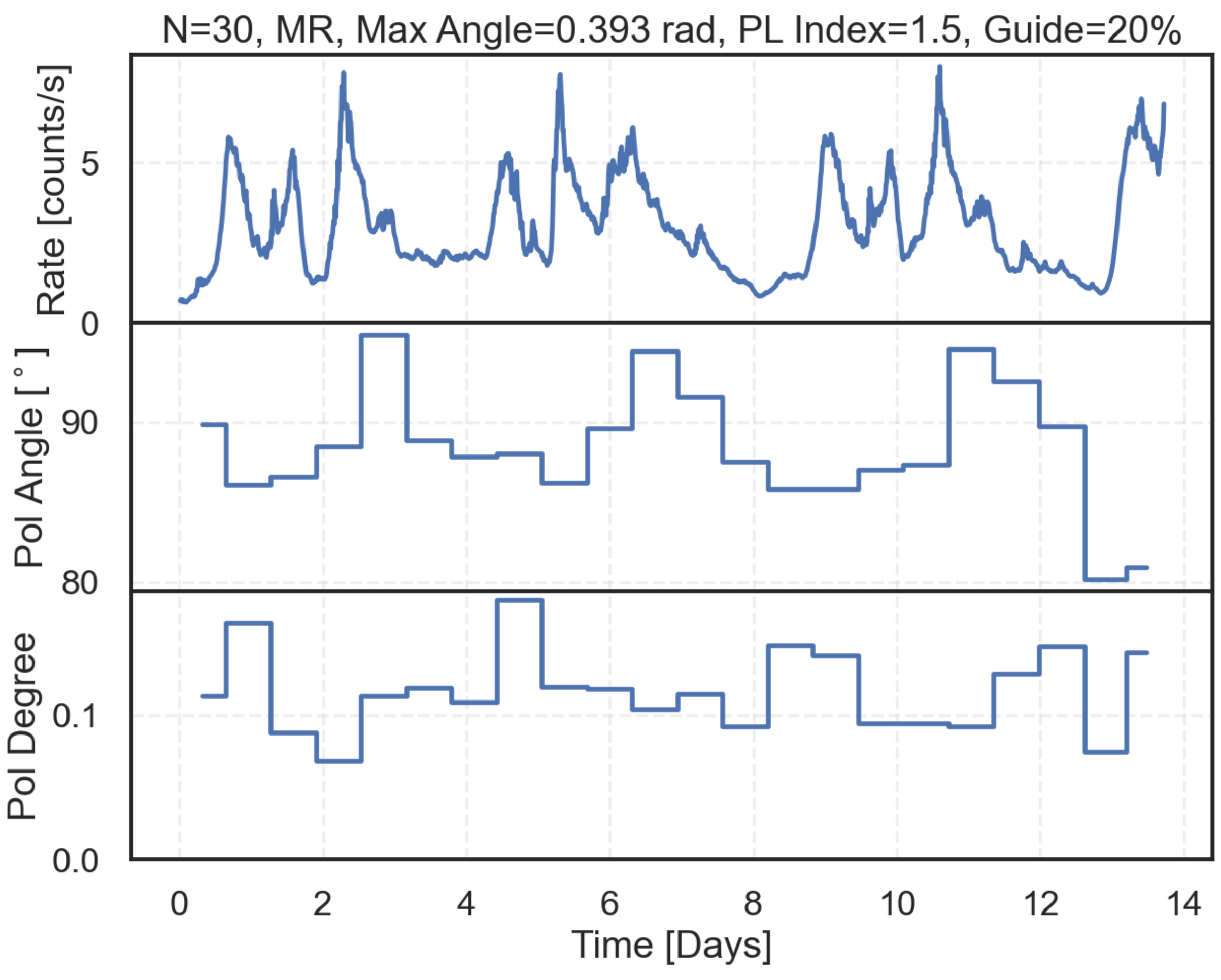
4

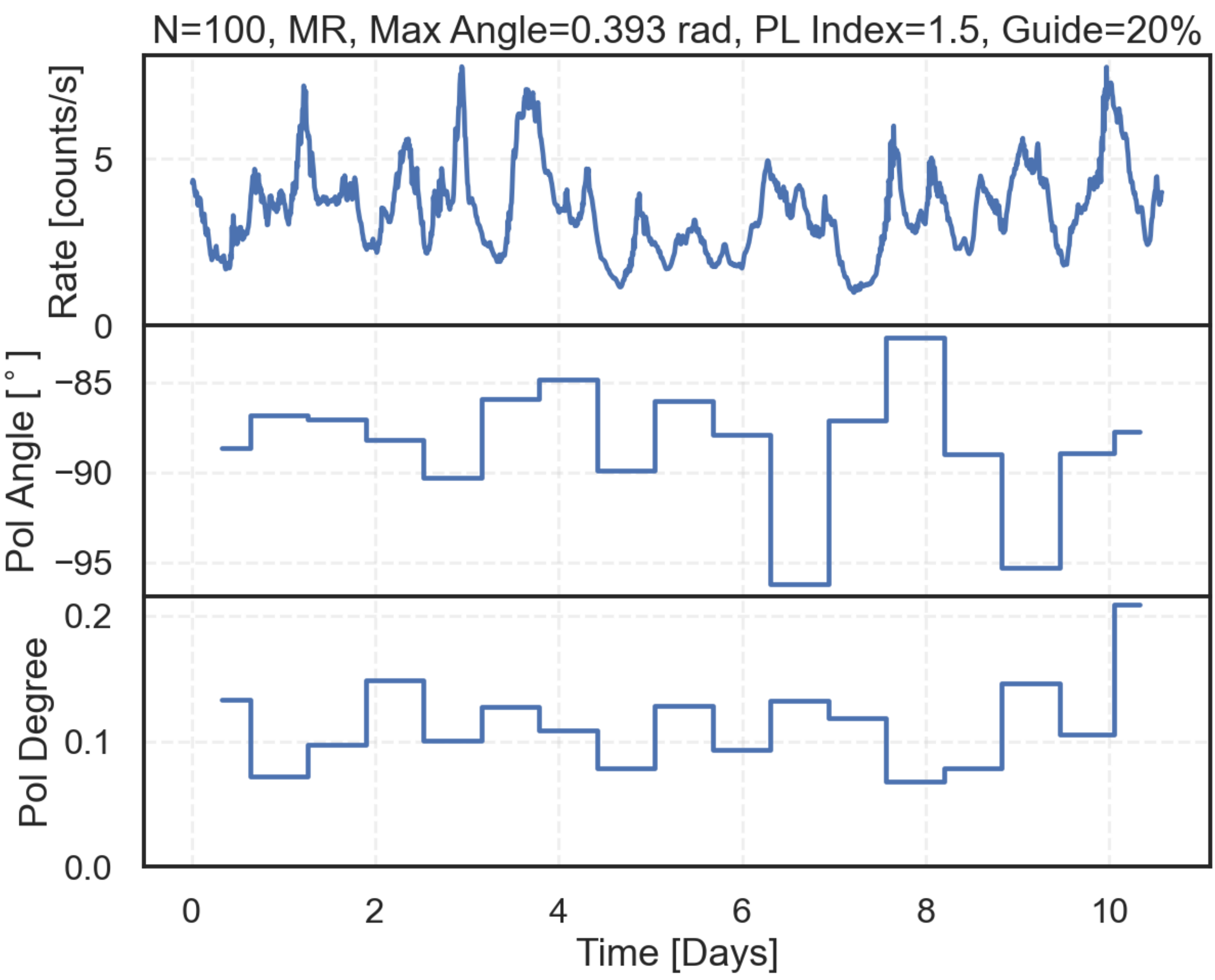
6

8

10

Time [Days]


N=30, MR, Max Angle=0.393 rad, PL Index=1.5, Guide=20%
Rate [counts/s]
5
0
Pol Angle [°]
90
80
Pol Degree
0.1
0.0
0
2
4
6
8
10
12
14
Time [Days]


N=100, MR, Max Angle=0.393 rad, PL Index=1.5, Guide=20%
Rate [counts/s]
5
0
Pol Angle [°]
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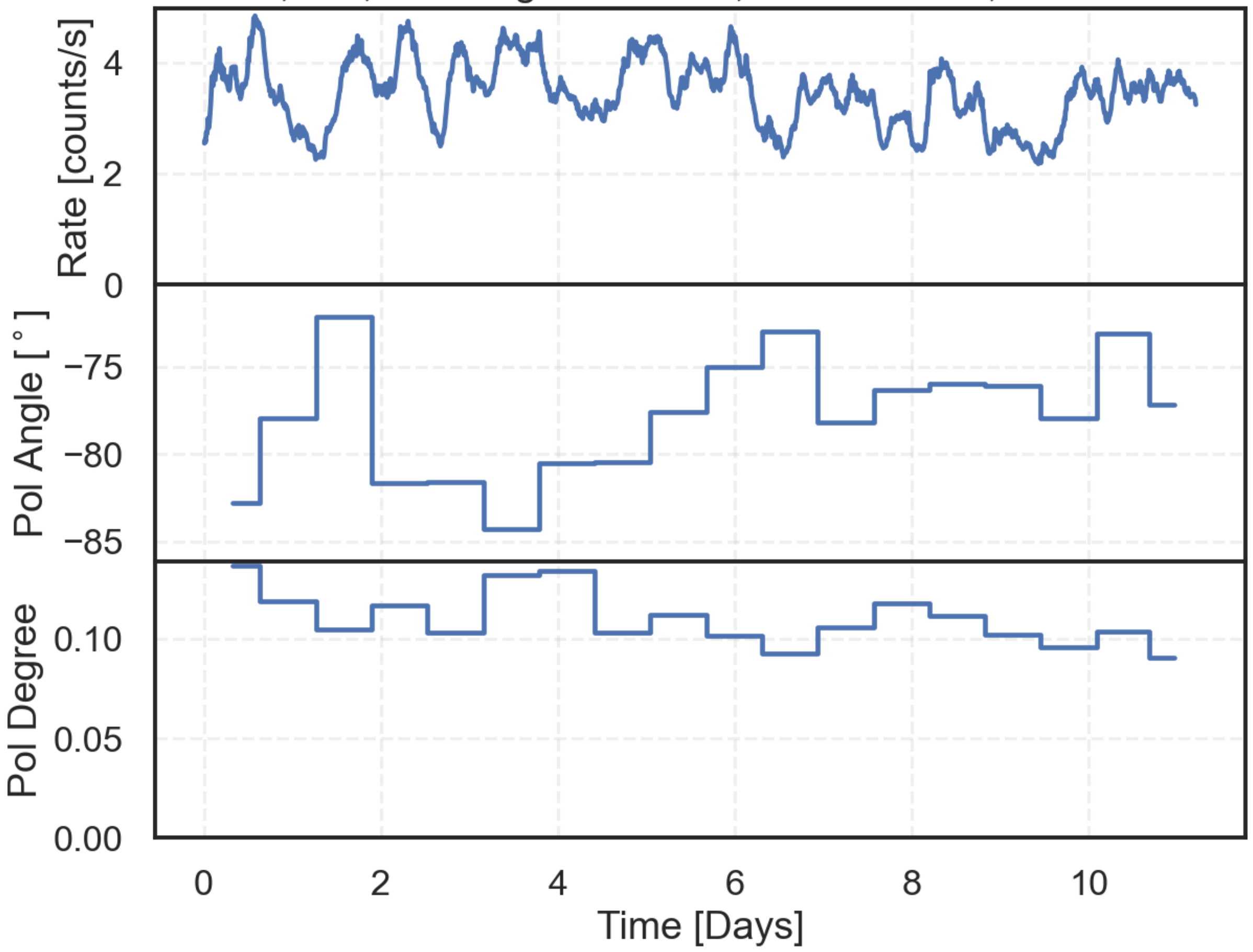
−90
−95
Pol Degree
0.2
0.1
0.0
0
2
4
6
8
10
Time [Days]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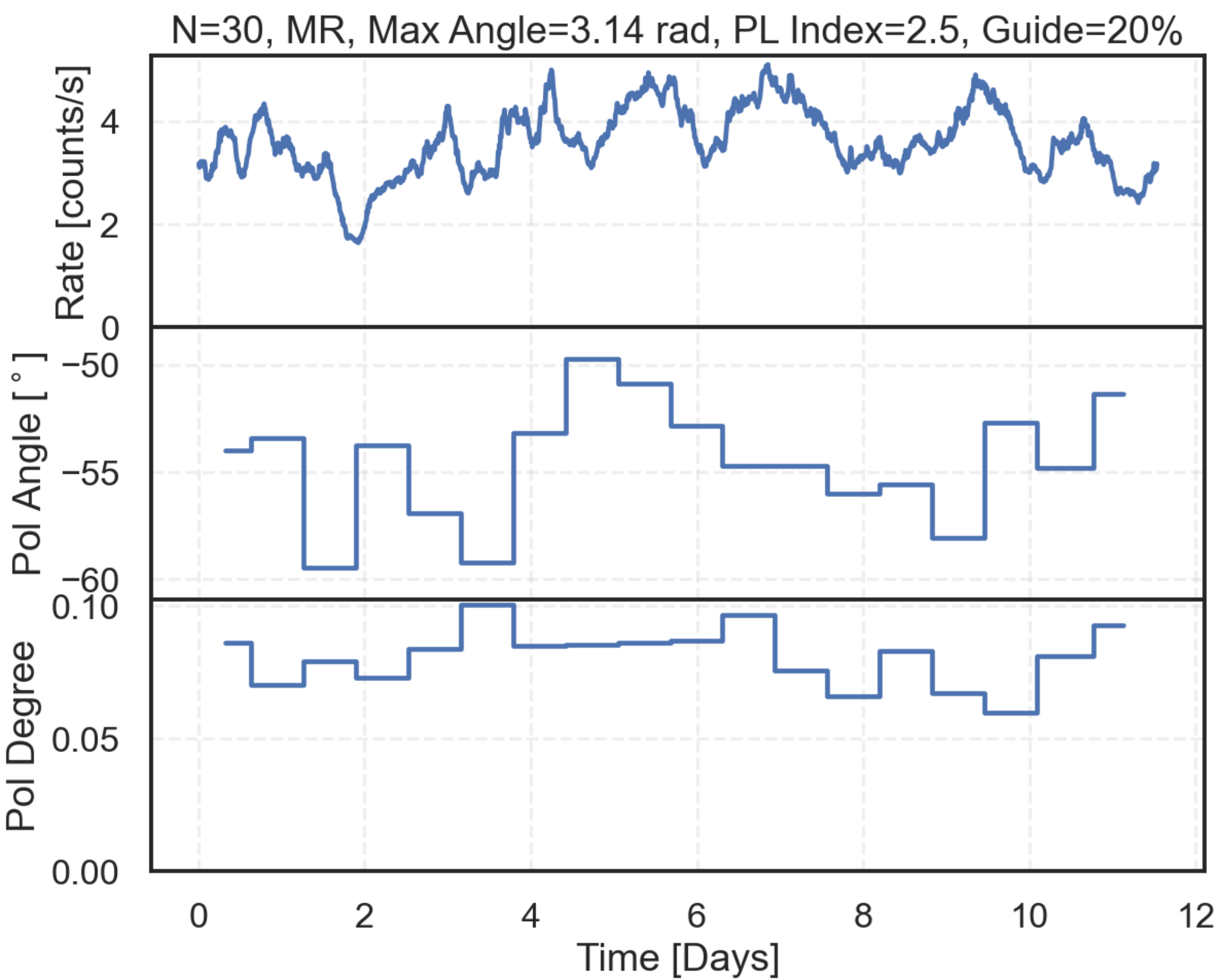
2
0
Pol Angle [°]
−75
−80
−85
Pol Degree
0.10
0.05
0.00
0
2
4
6
8
10
Time [Days]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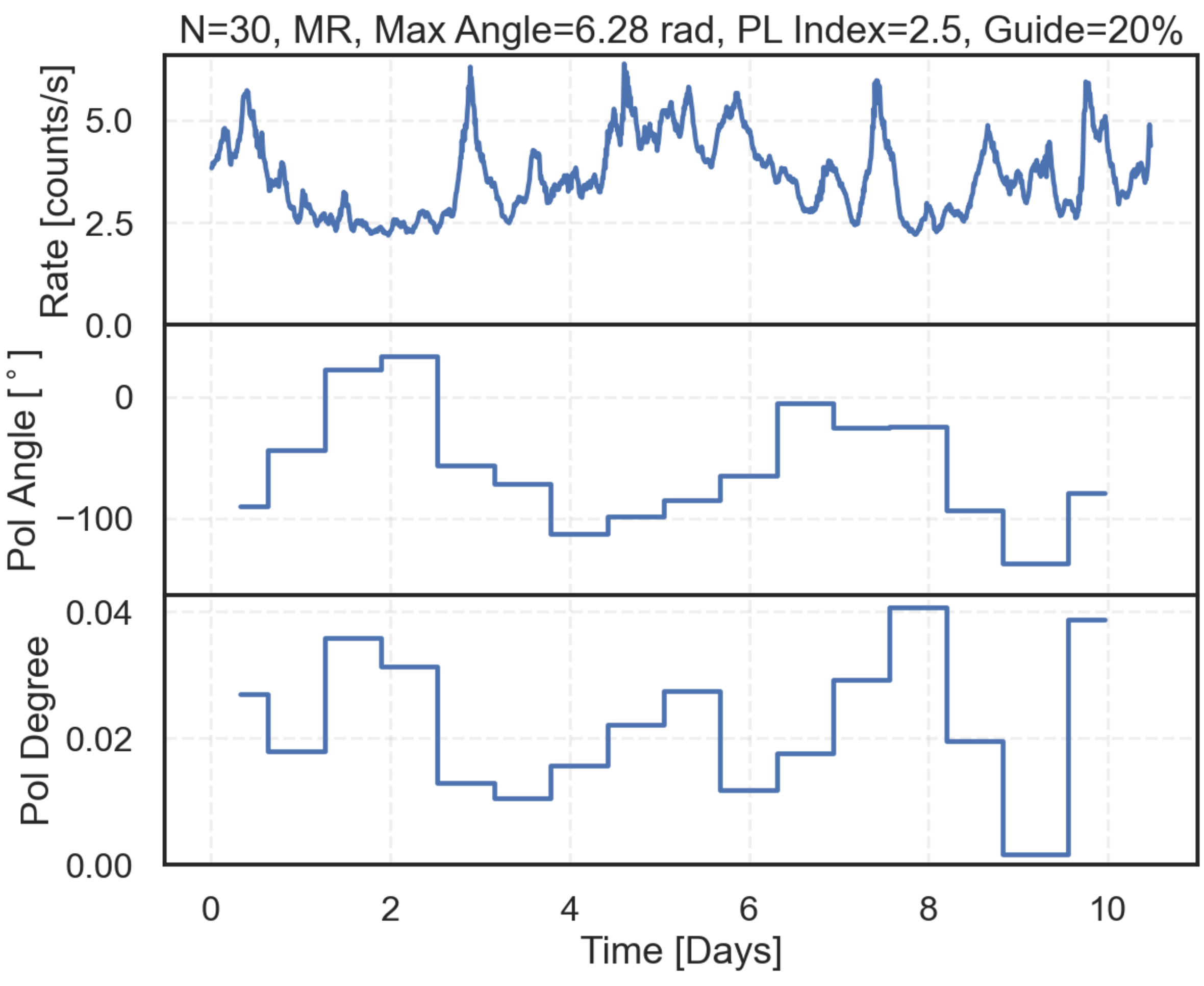
Rate [counts/s]
0
2
4
Pol Angle [°]
−50
−55
−60
Pol Degree
0.00
0.05
0.10
0
2
4
6
8
10
12
Time [Days]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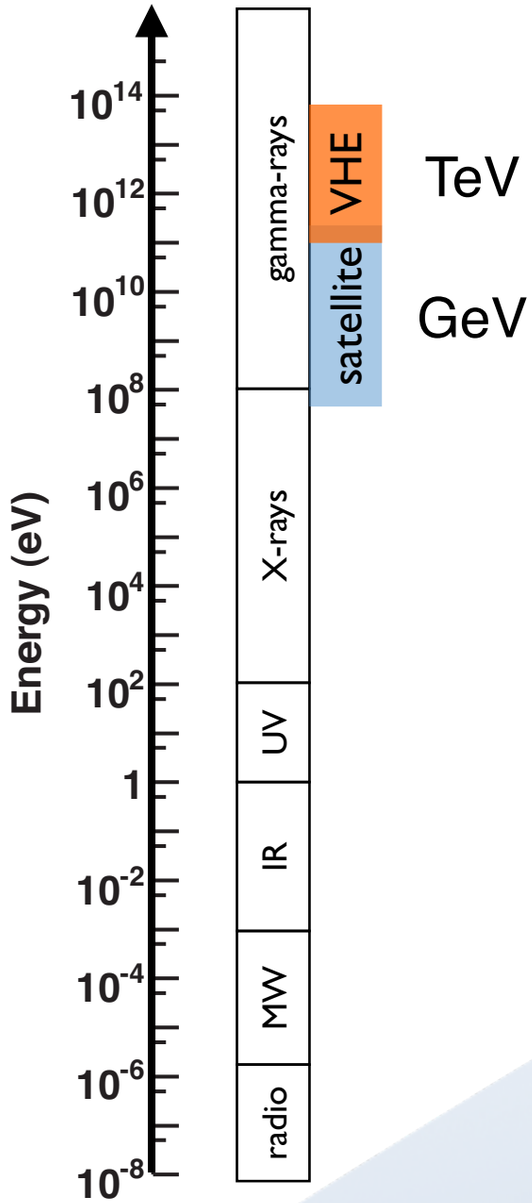
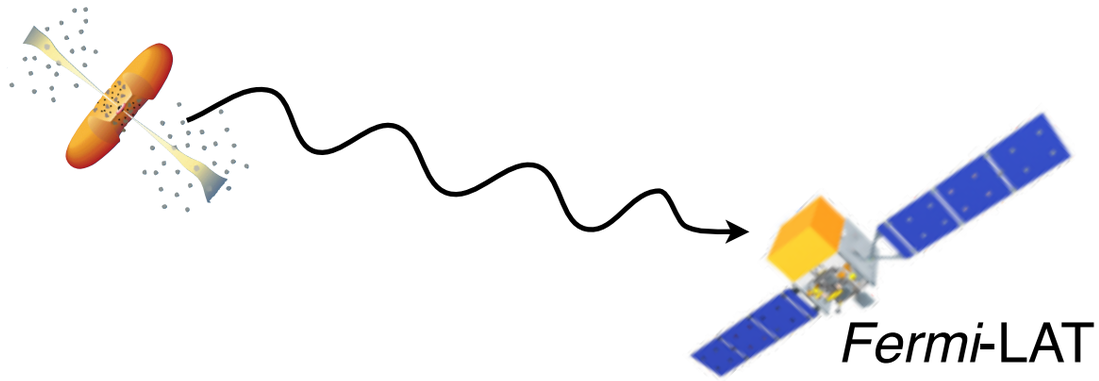
2.5
0.0
Pol Angle [°]
0
−100
Pol Degree
0.04
0.02
0.00
0
2
4
6
8
10
Time [Days]

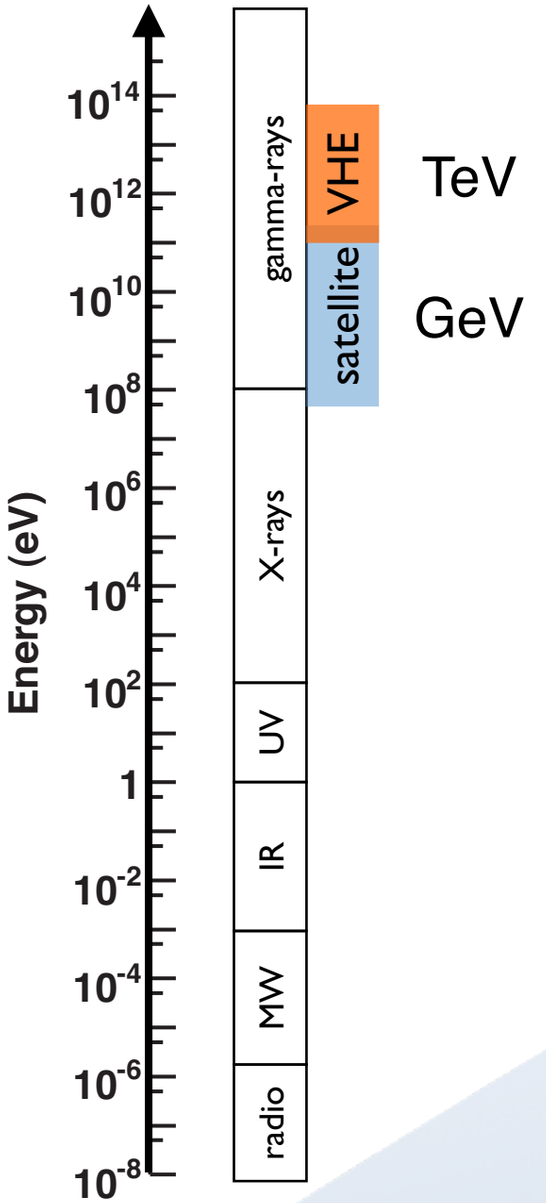


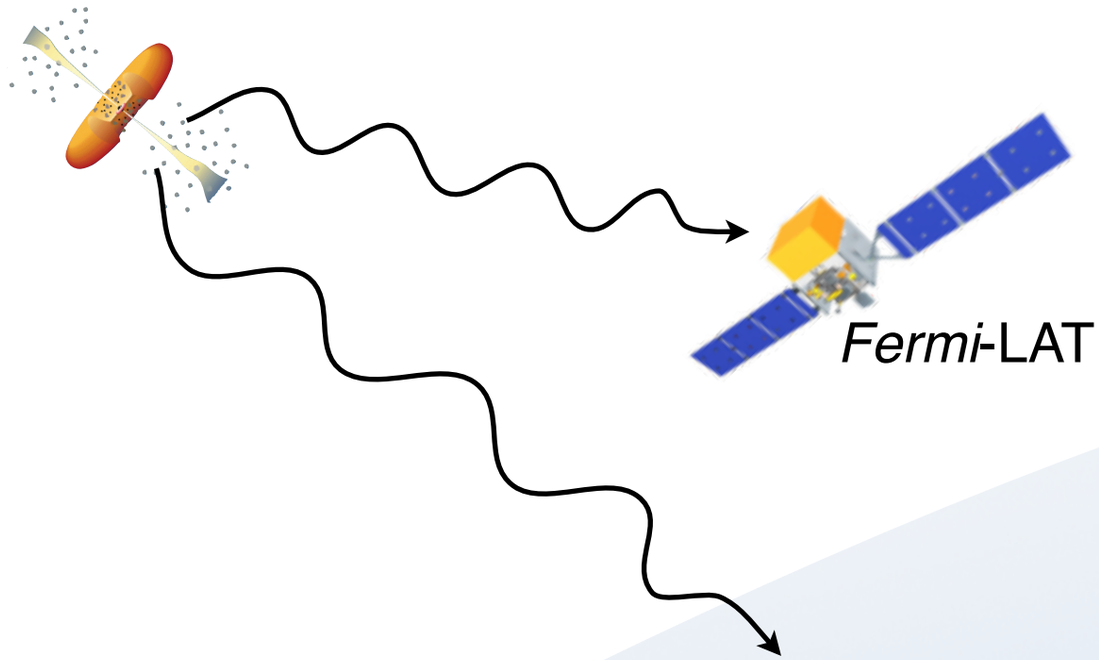


Gamma-ray satellites

100 MeV - 300 GeV

Fermi-LAT, AGILE





Gamma-ray satellites

100 MeV - 300 GeV

Fermi-LAT, AGILE

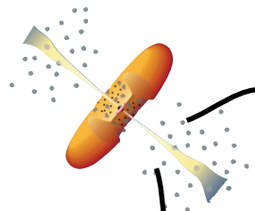
Energy (eV)

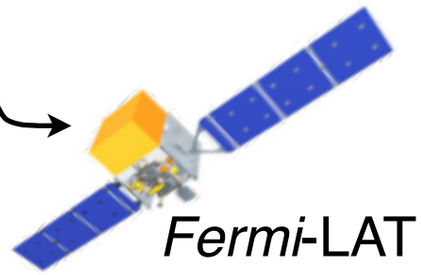
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}

gamma-rays
VHE
satellite
X-rays
UV
IR
MW
radio

TeV

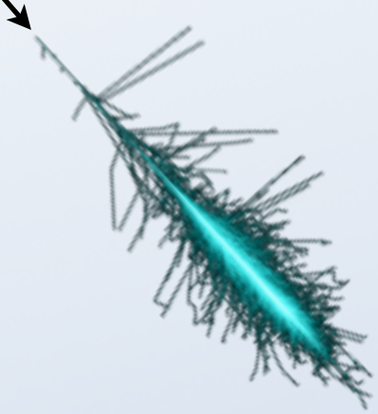
GeV





Fermi-LAT

Gamma-ray satellites
100 MeV - 300 GeV
Fermi-LAT, AGILE



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Gamma-ray satellites
100 MeV - 300 GeV
Fermi-LAT, AGILE

Fermi-LAT

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Gamma-ray satellites
100 MeV - 300 GeV
Fermi-LAT, AGILE

Fermi-LAT

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Gamma-ray satellites
100 MeV - 300 GeV
Fermi-LAT, AGILE

Fermi-LAT

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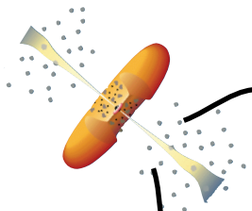
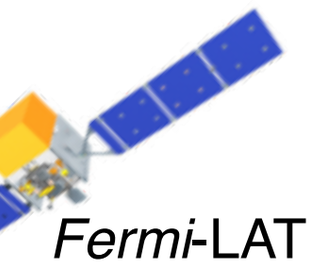
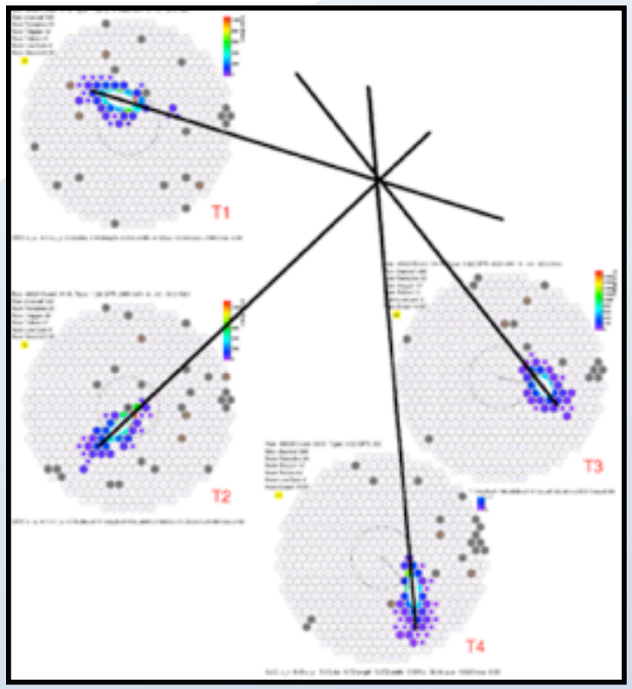
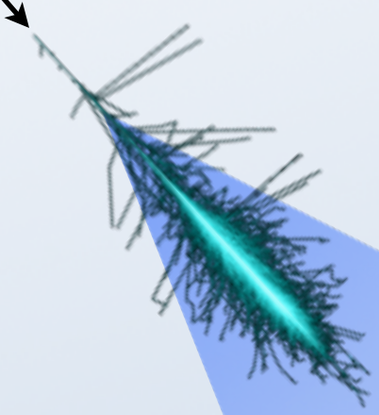




Fermi-LAT

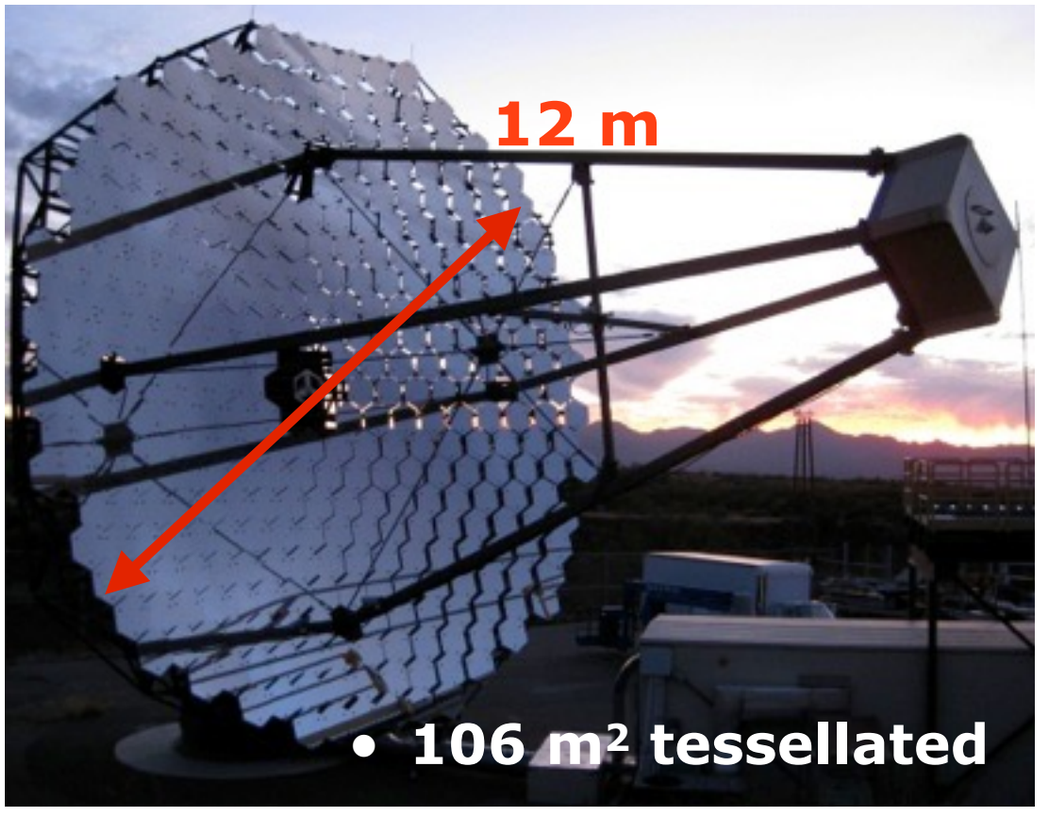
Gamma-ray satellites
100 MeV - 300 GeV
Fermi-LAT, AGILE

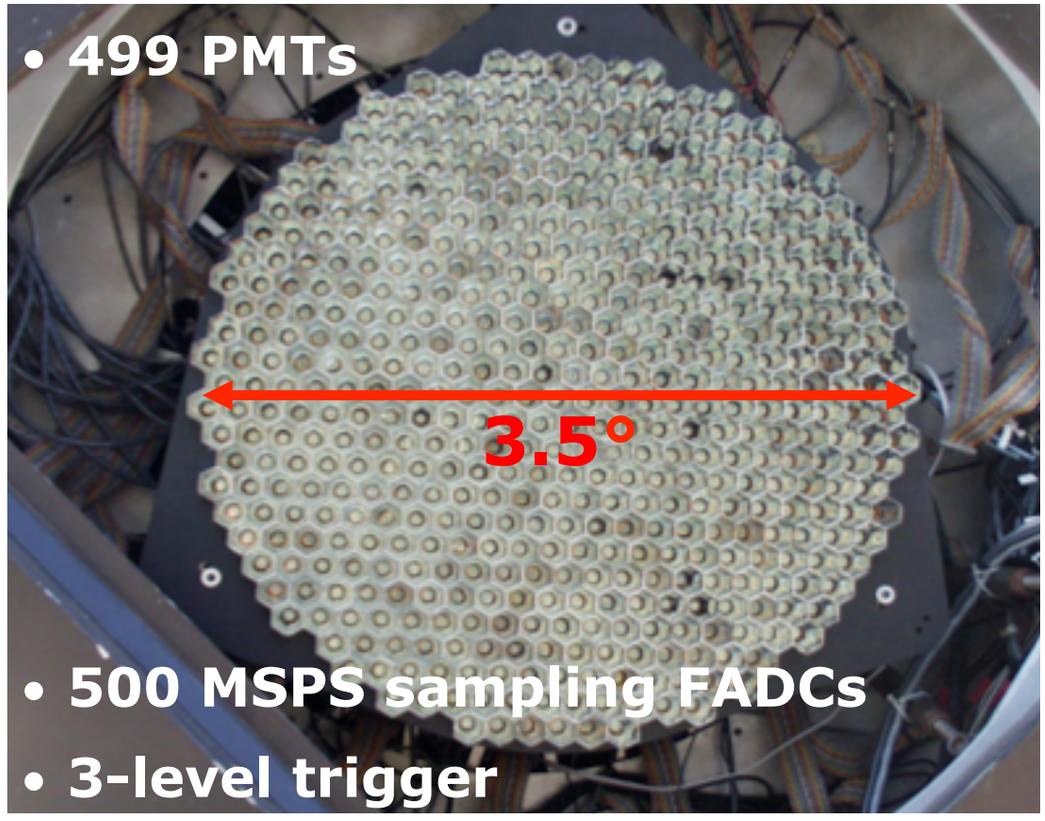




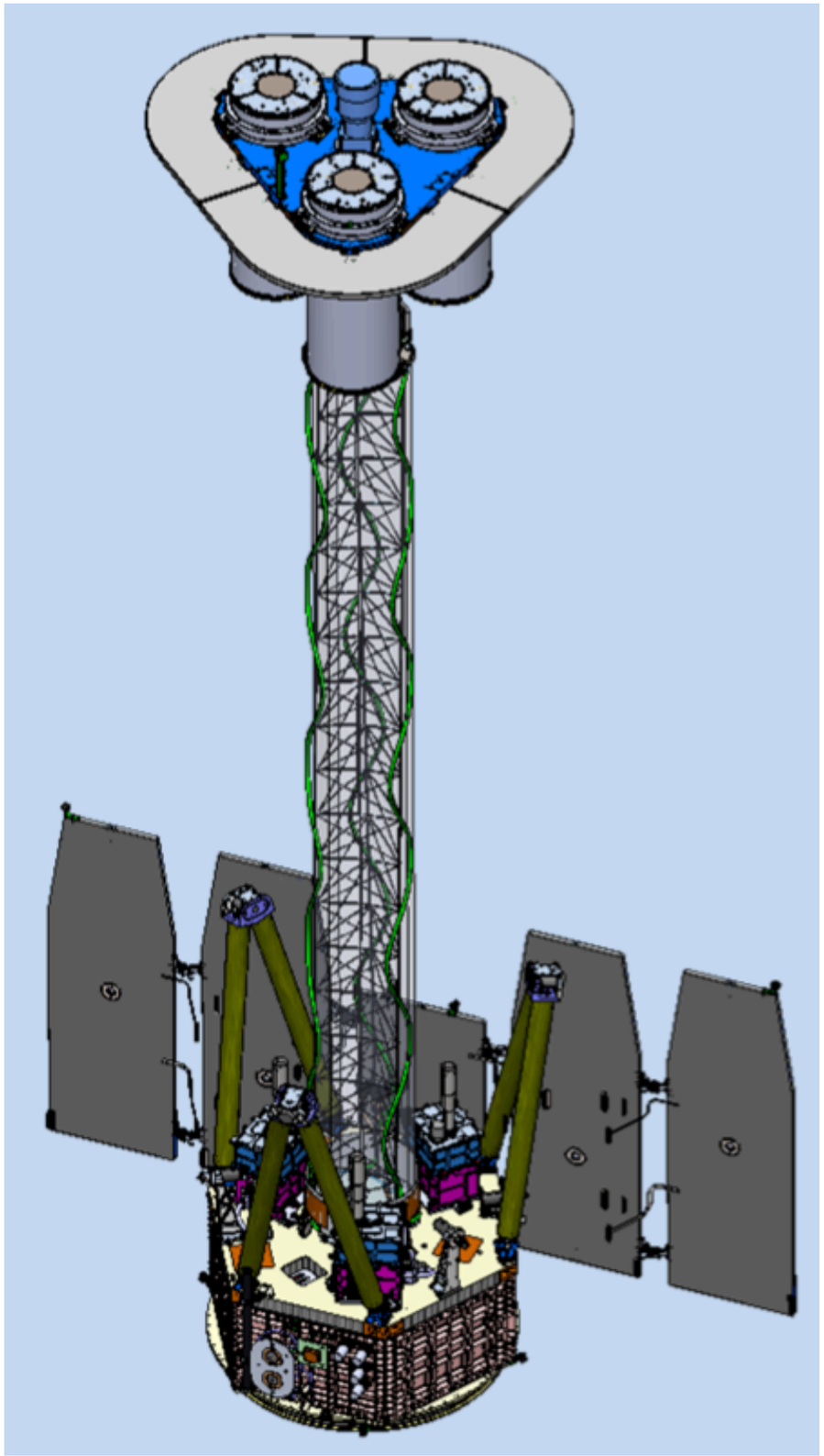
Imaging Cherenkov telescopes
100 GeV - 50 TeV
H.E.S.S., VERITAS, MAGIC

- **Situated at 1280m altitude at Whipple Observatory in Arizona**



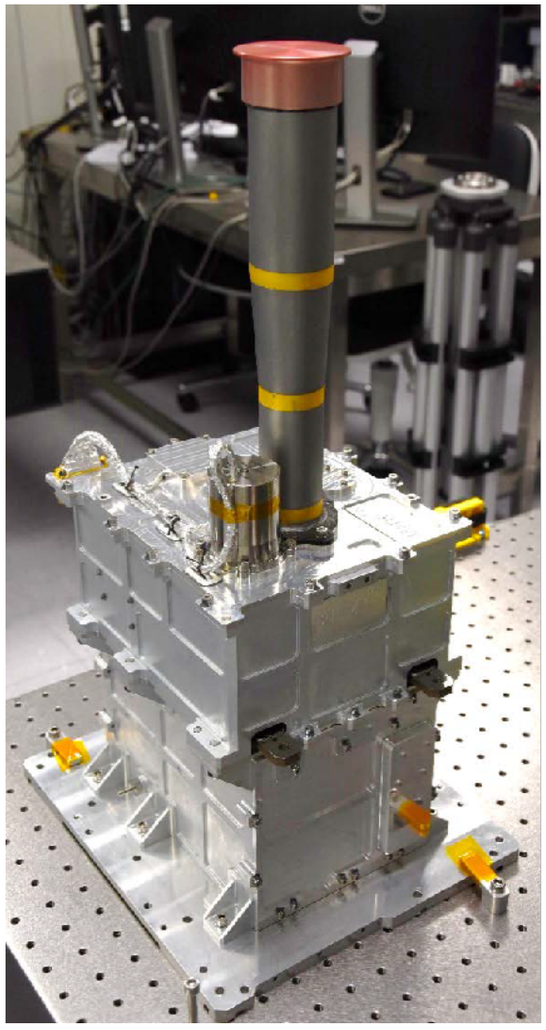


IXPE status and operations

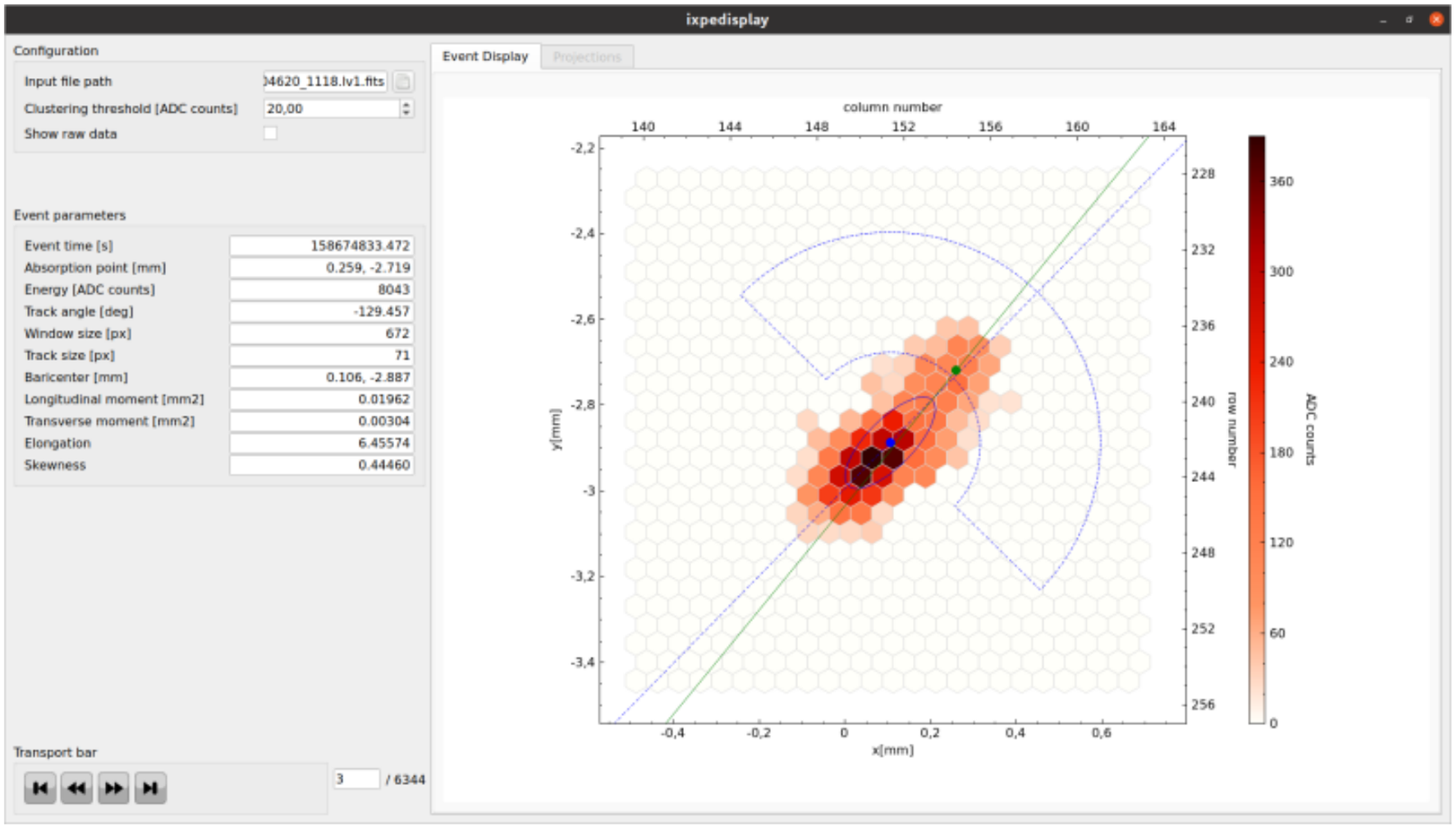


- Launched on Dec 9th 2021.
- Boom deployed on Dec 15.
- Commissioning and calibration finished successfully.
- Science operations started Jan 11 2022.
- Sensitive to X-ray polarization in the 2-8 keV band.
- First X-ray polarimeter in space in 40 years.

X-ray polarization via the photoelectric effect



Detector Unit (DU) INAF/IAPS, INFN-PI



First photo-electron track obtained during IXPE science operations

SNR Cas A, 2022 January 11, initiated by 2.7-keV photon in DU1.

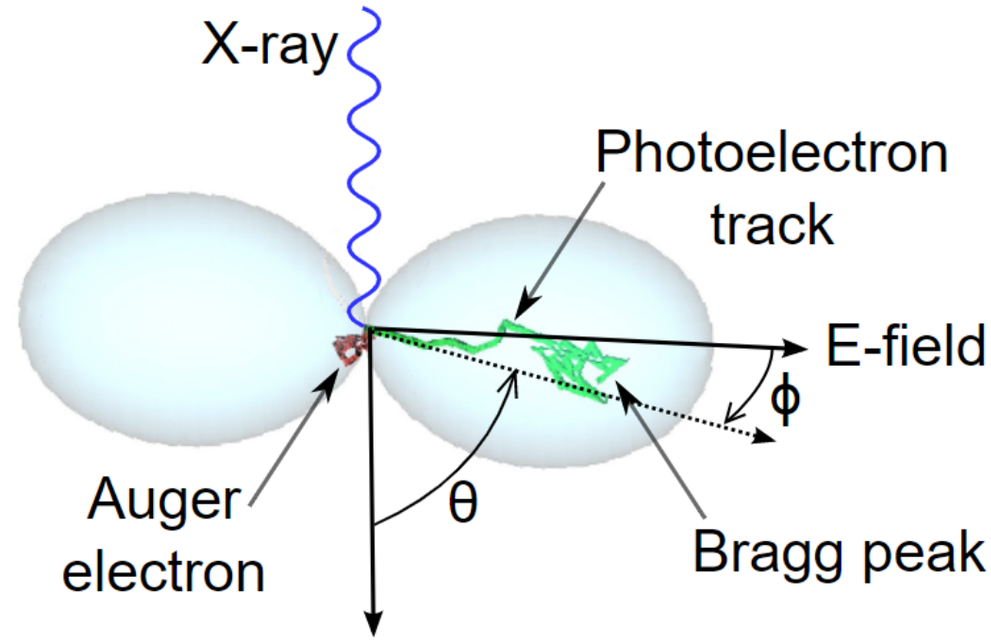
Key is to find photoelectron direction at interaction point.

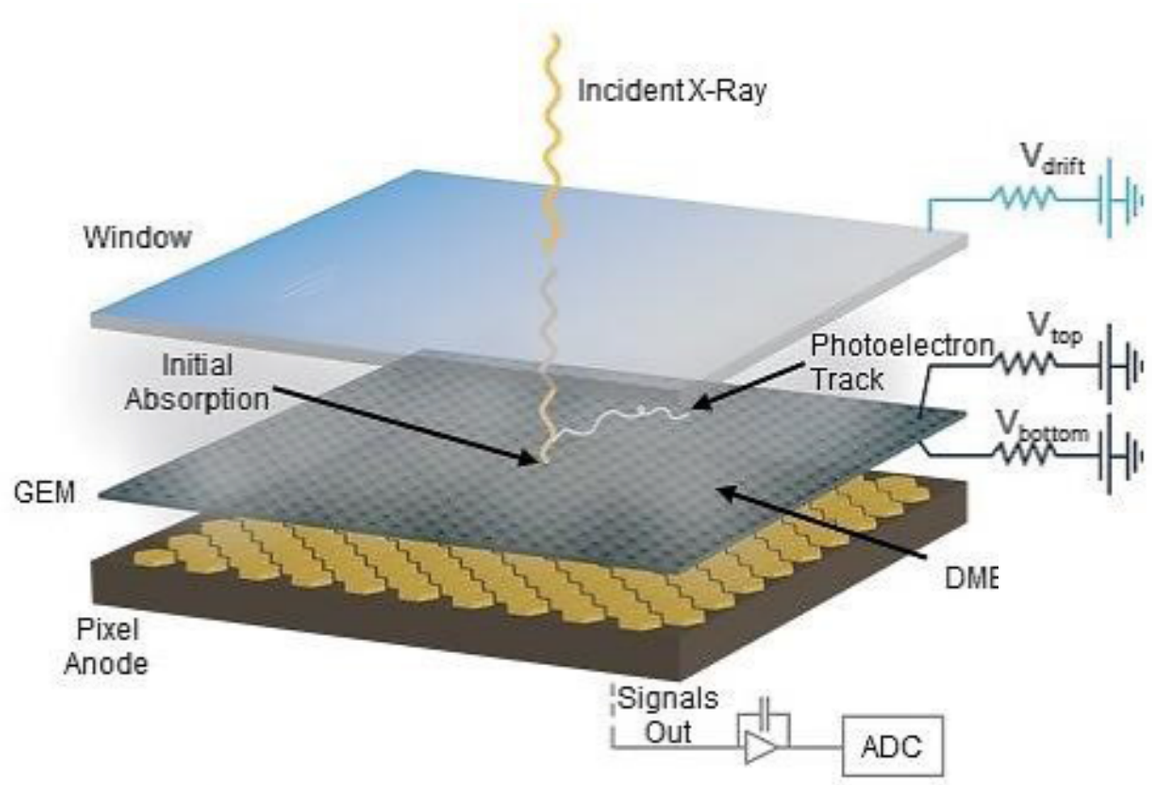
X-ray polarization via the photoelectric effect

IXPE uses the photoelectric effect.

•Photoelectron ejected along photon E field.

$\sin^2\theta \cos^2\phi$ distribution





INAF/IAPS, INFN-PI

IXPE uses ‘gas pixel detector’ (GPD).

•Photoelectron liberates electrons in gas (DME),

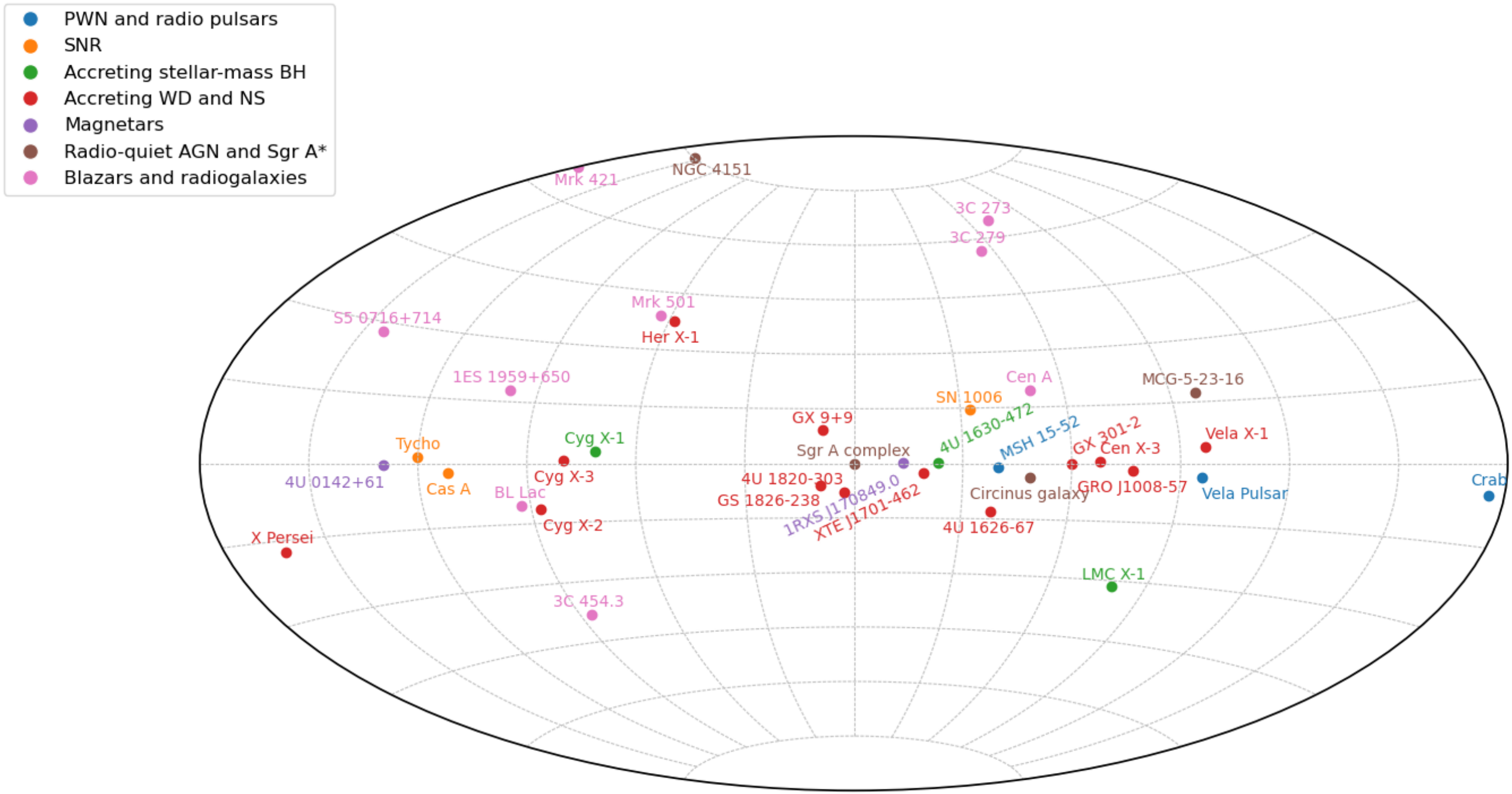
•multiplied in gas electron multiplier (GEM),

•imaged with 105k hexagonal pixels 50µm.

•Concept from Costa et al. (2001)

•Extensive development of readout in Italy.

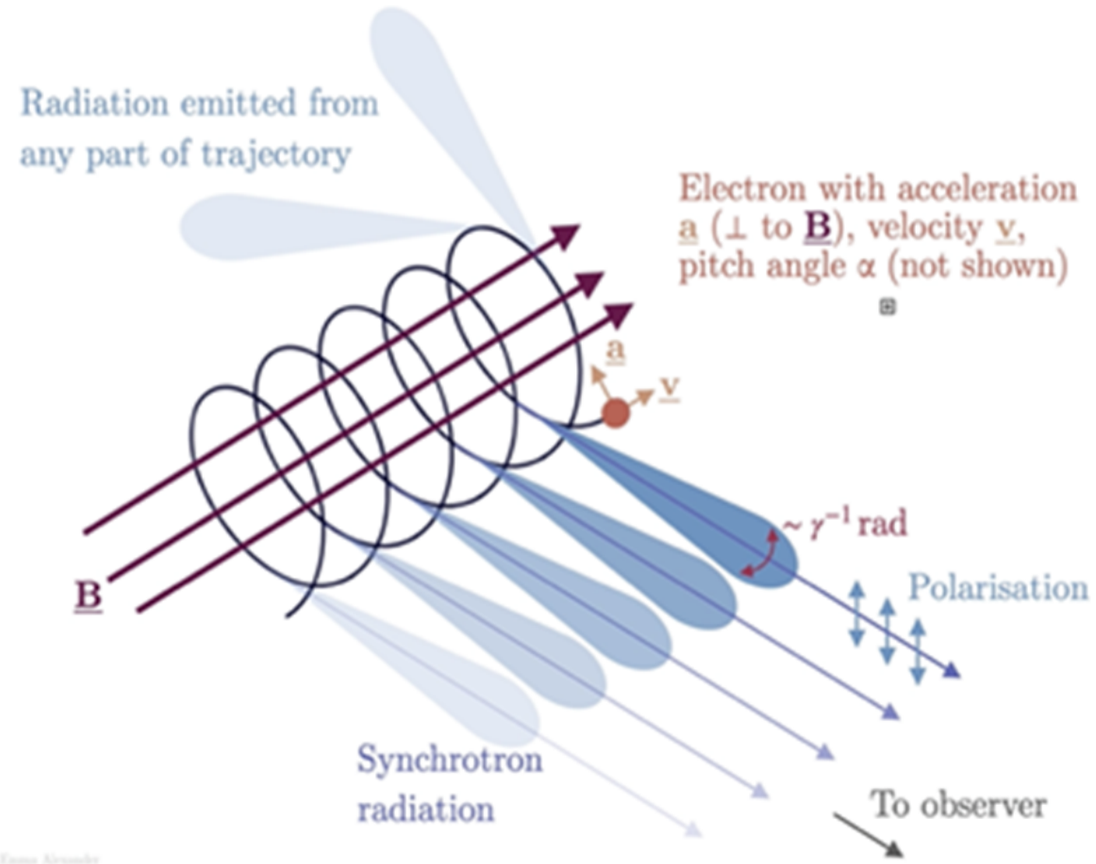
First IXPE targets



Selected IXPE science results

- Blazar jets
- Pulsar wind nebulae
- Supernova remnants

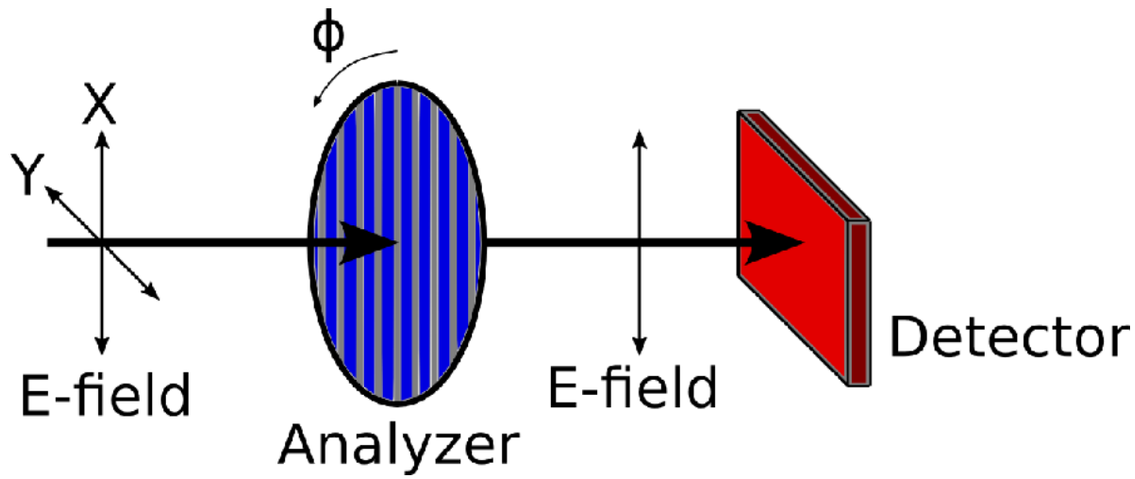
Emission in first group is via synchrotron radiation

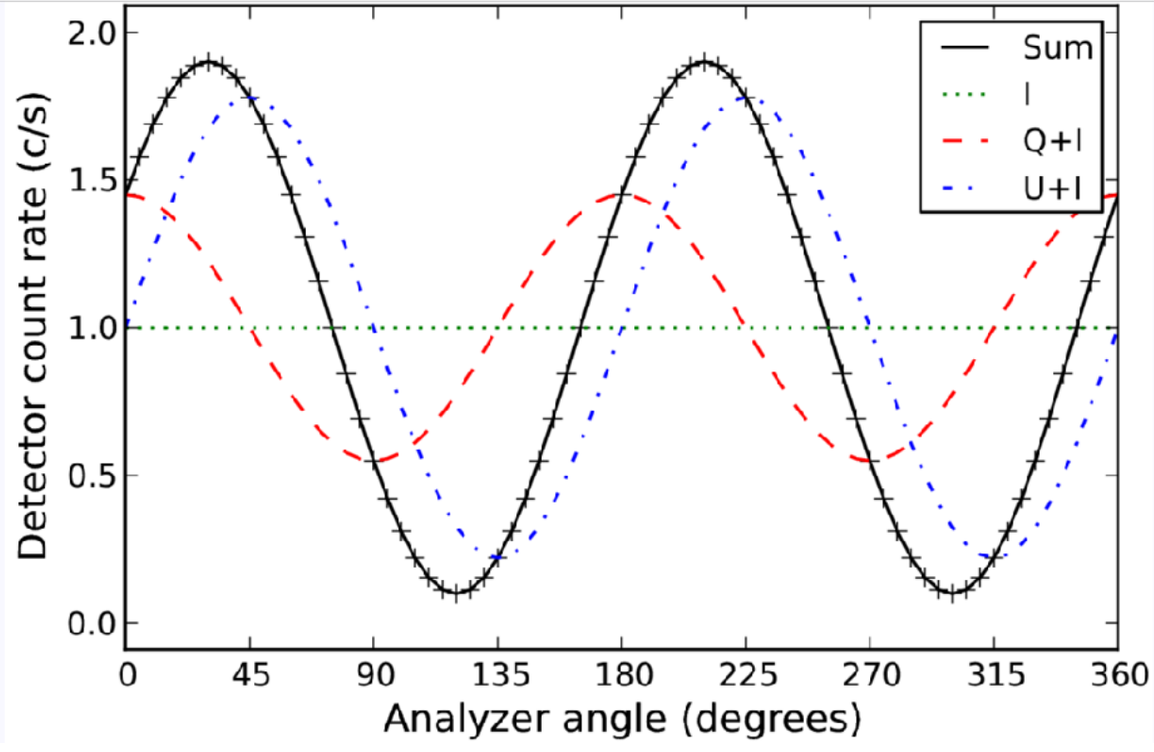


- Radio-quiet active galactic nuclei
- Echoes of Sgr A*
- Accreting stellar-mass black holes
- Accreting neutron stars (low B)
- Magnetars
- Accretion powered pulsars

Stokes parameters and MDP

- Work in Stokes parameters
  - Independent, gaussian errors
  - Simply additive
  - No coordinate singularity at $\Pi = 0$
- Compute Stokes parameters (q_i, u_i) for each X-ray from initial direction of photoelectron
- Do spectropolarimetry (in Xspec) using spectra in Stokes I, Q, and U and 'modulation response'.





•Minimum Detectable Polarization (MDP)

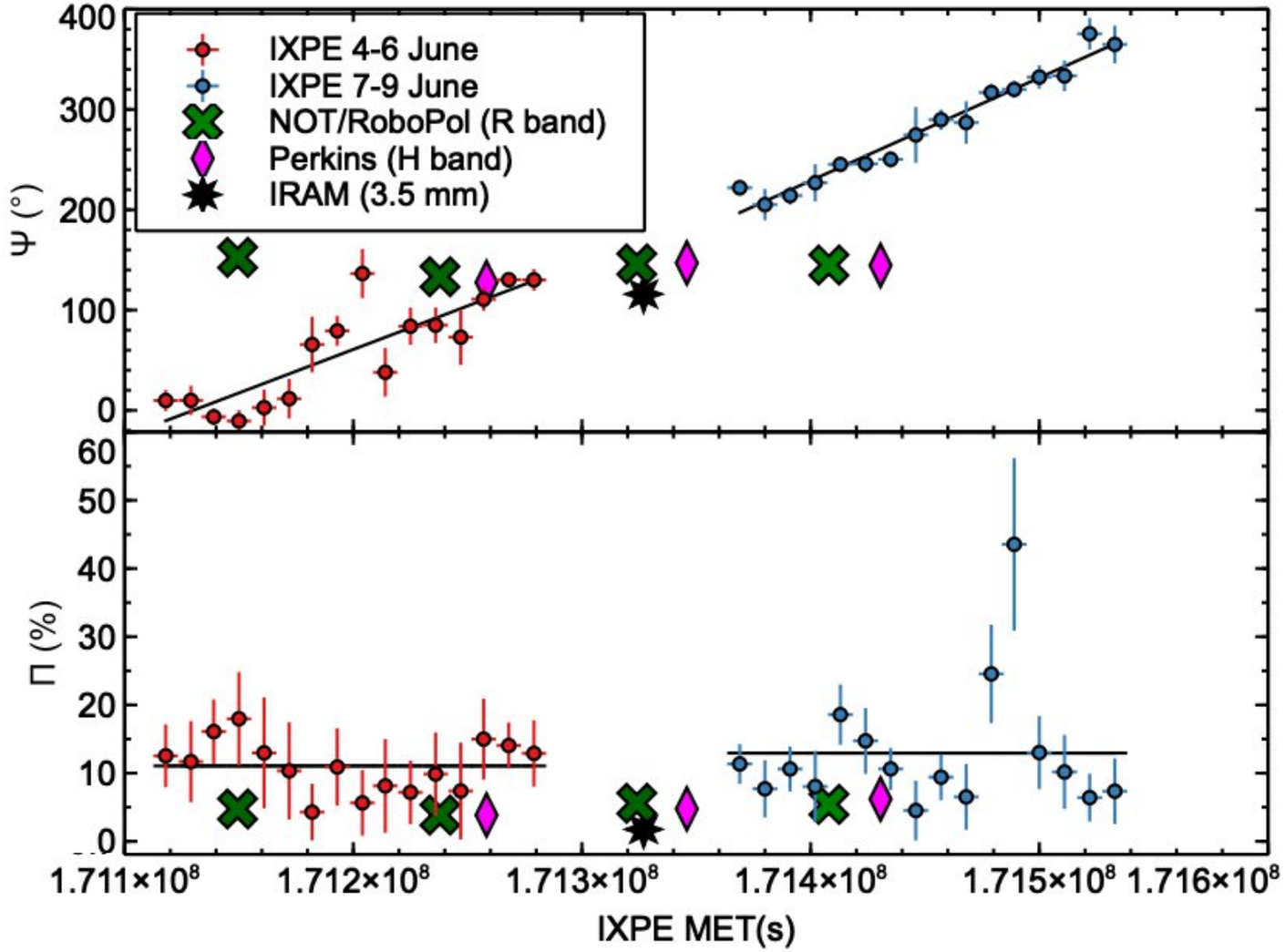
$$MDP99 = \frac{4.29}{\mu\, s}\sqrt{\frac{s+b}{T}}$$

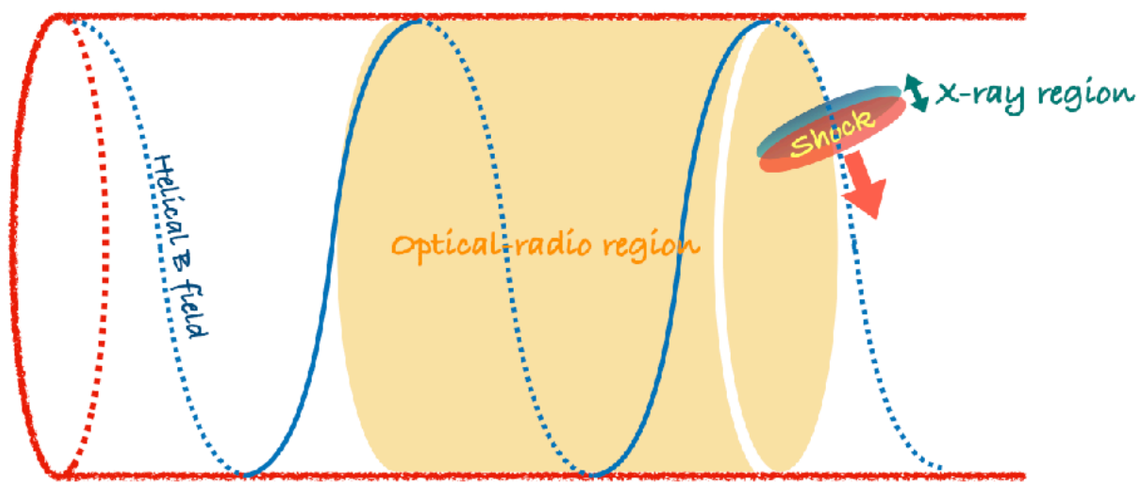
where μ = modulation factor, *s* = source rate, *b* = background rate, *T* = exposure time.

For MDP = 2% with μ = 0.4 and *b* = 0, need 3×10^5 X-rays.

Polarization angle rotation: Mrk 421

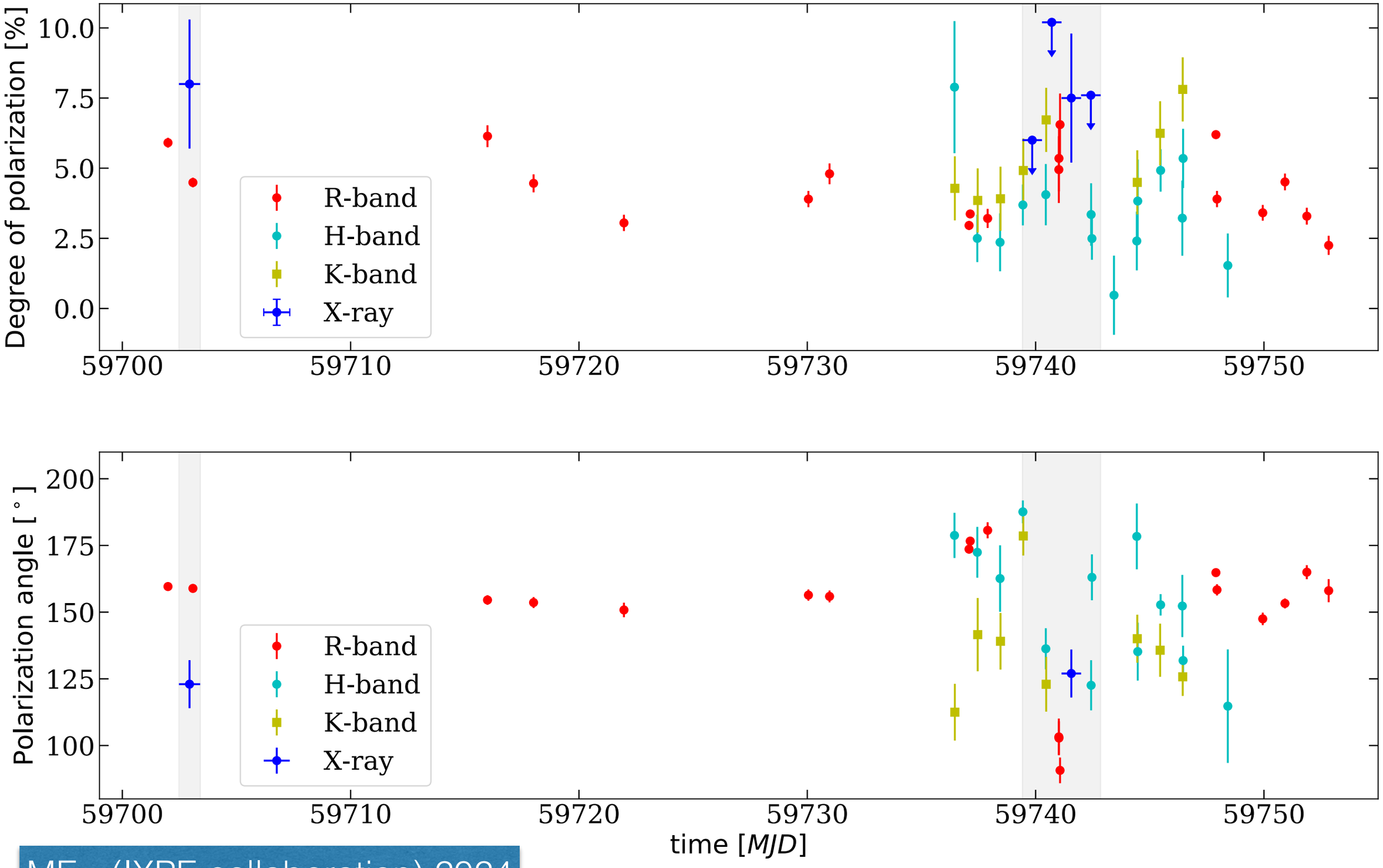
- Rotation of the X-ray polarization angle of ~85°/day.
- Compatible with compact X-ray emitting region in helical motion around the jet spine.





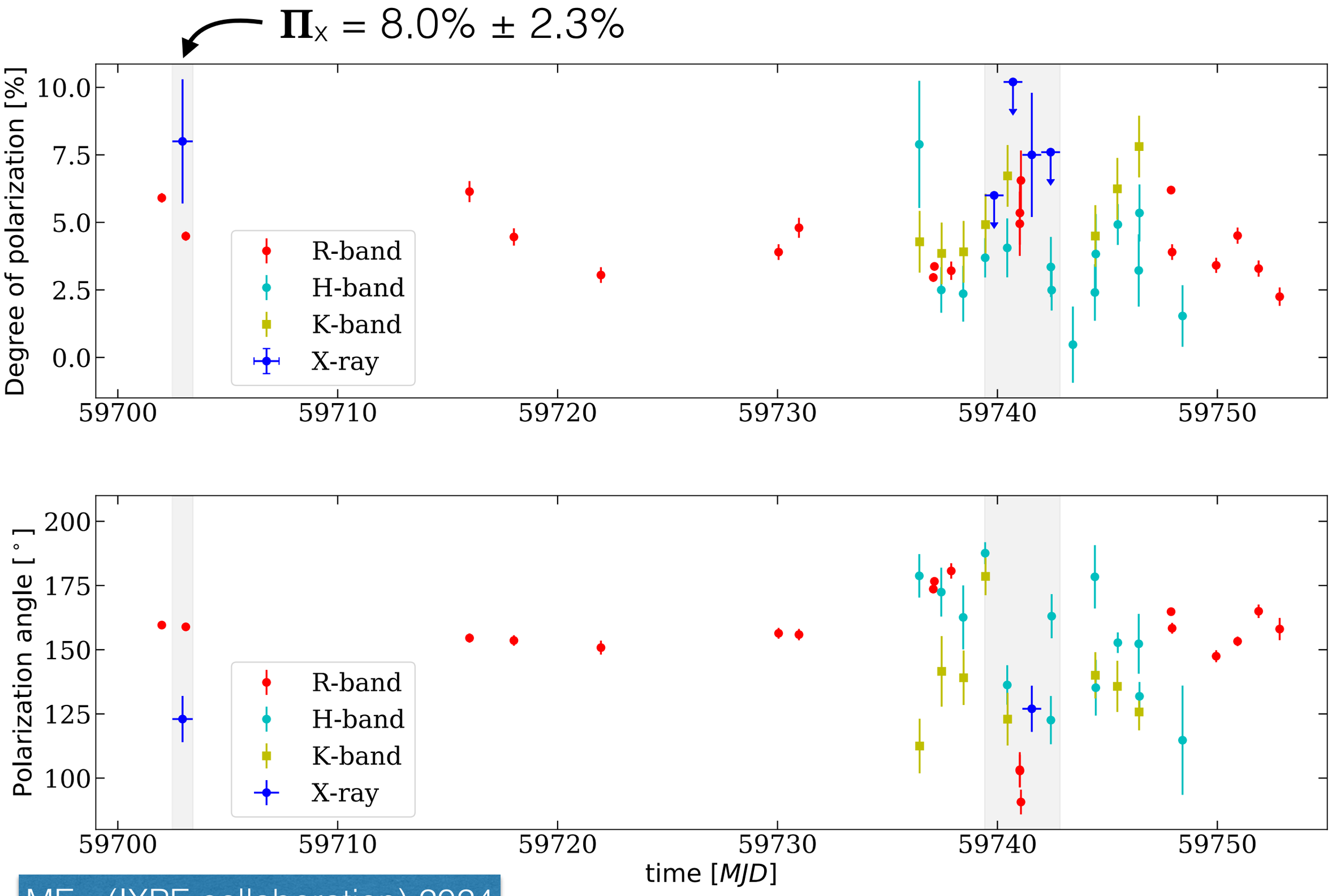
Di Gesu+ 2023, Nat. Astron.

Turbulence in the jet: 1ES 1959+650



ME+ (IXPE collaboration) 2024

Turbulence in the jet: 1ES 1959+650



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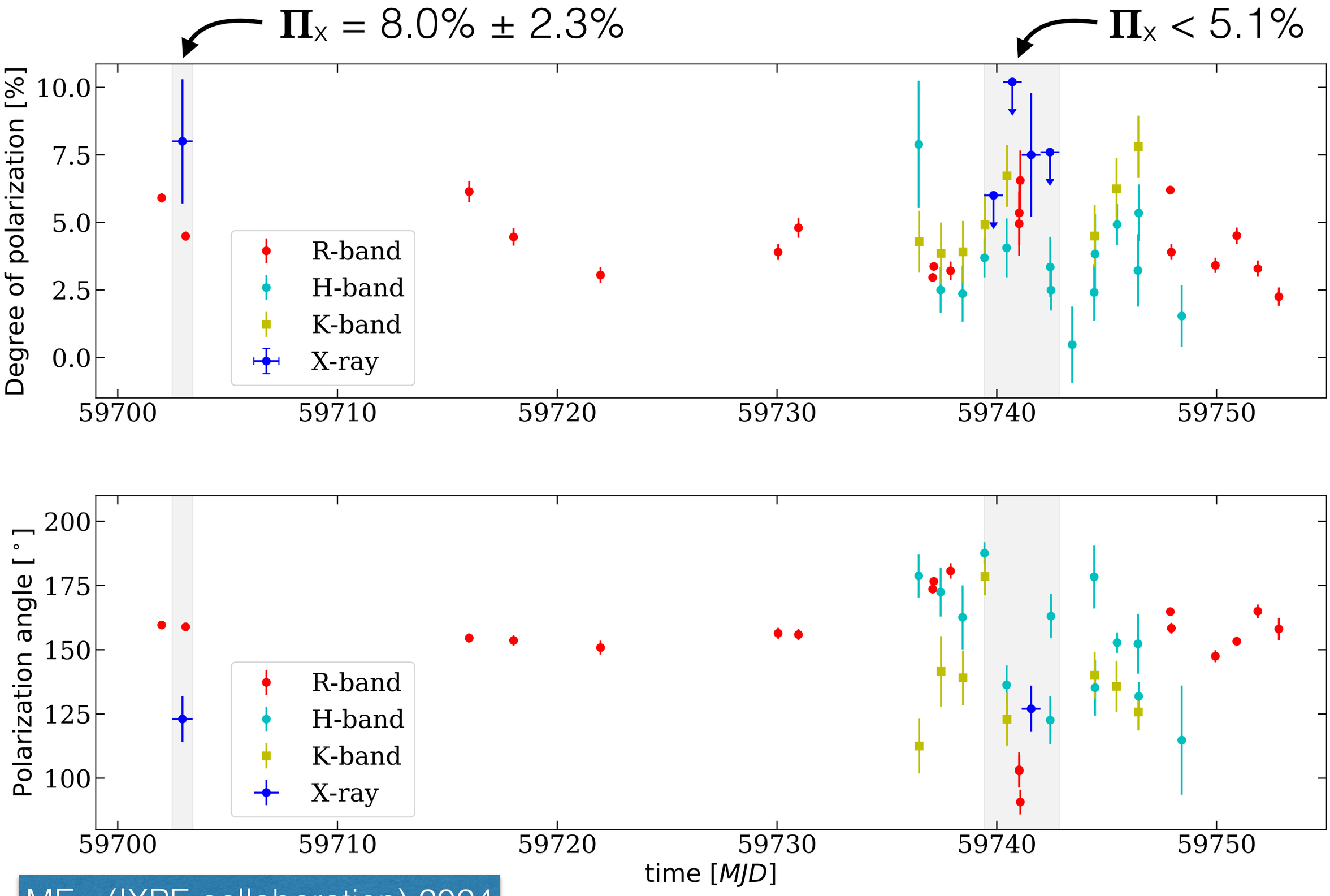
Turbulence in the jet: 1ES 1959+650



ME+ (IXPE collaboration) 2024

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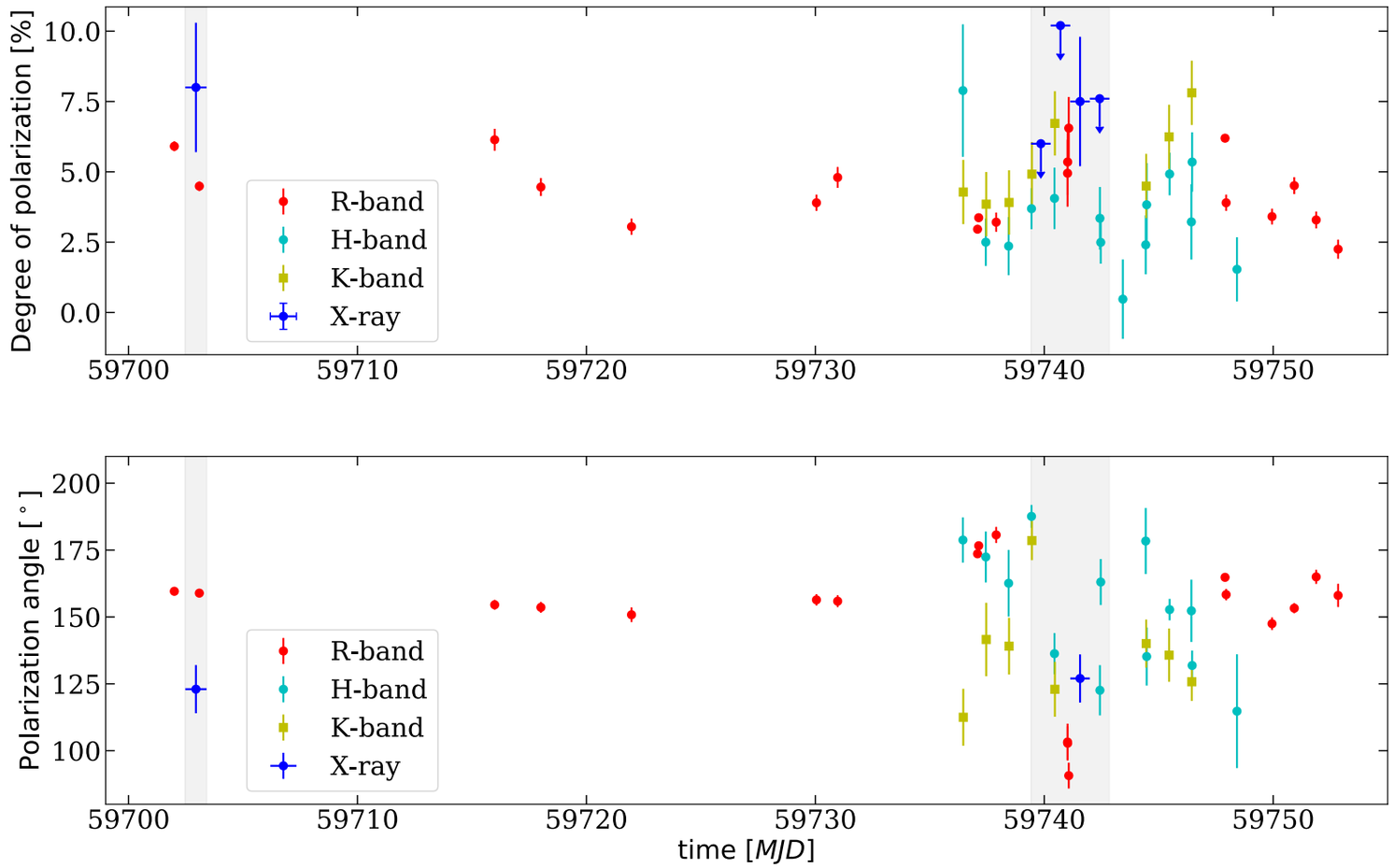
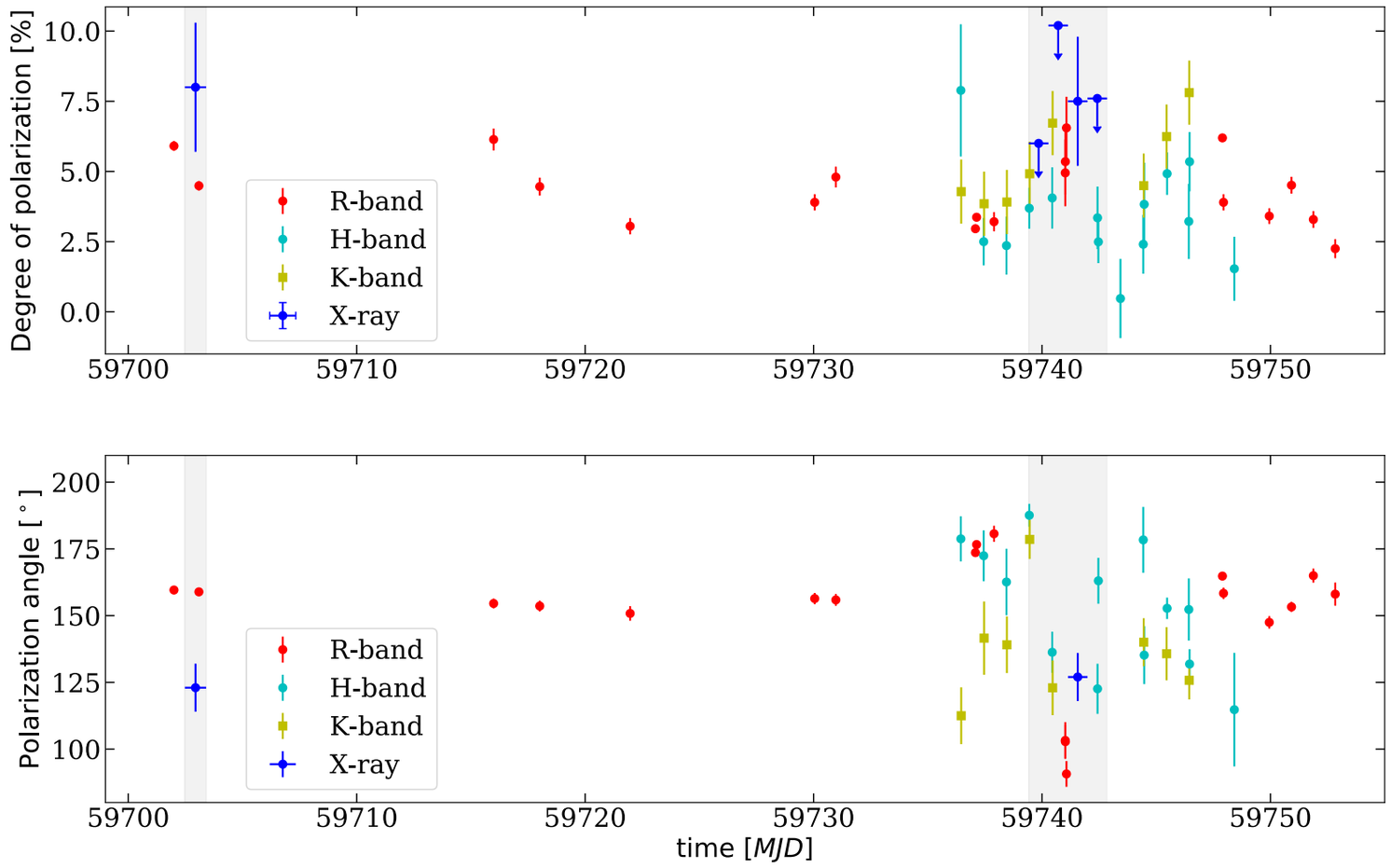


- IXPE makes a time-averaged measurement of X-ray polarization. Depending on flux level and polarization state, it takes IXPE 30-100 ksec or longer to measure the polarization state.
- Changes of X-ray polarization in timescales shorter than the IXPE integration time lead to depolarization.

ME+ (IXPE collaboration) 2024

Turbulence in the jet: 1ES 1959+650

The low X-ray polarization during the second observation of 1ES 1959+650 may be attributed to turbulence in the jet flow with dynamical timescales shorter than 1 day.



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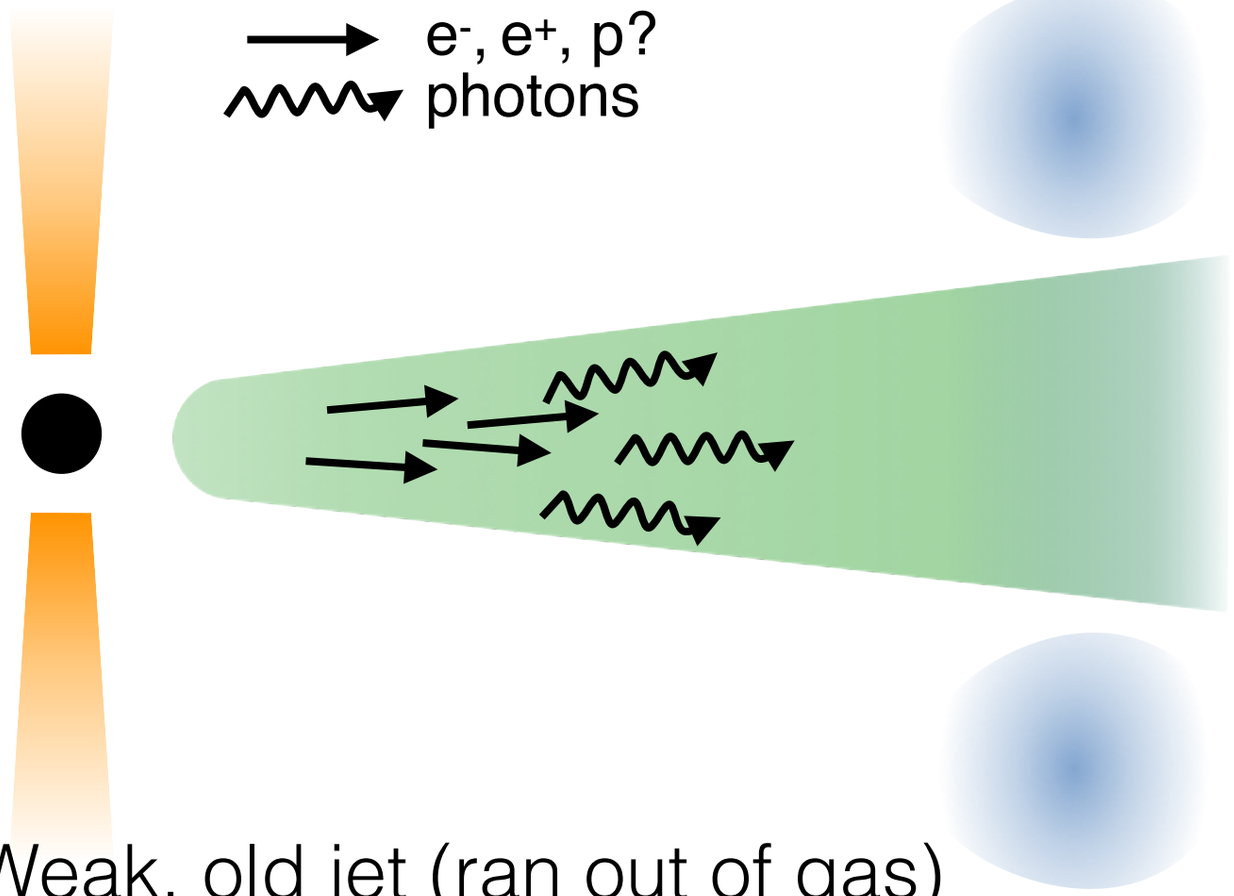
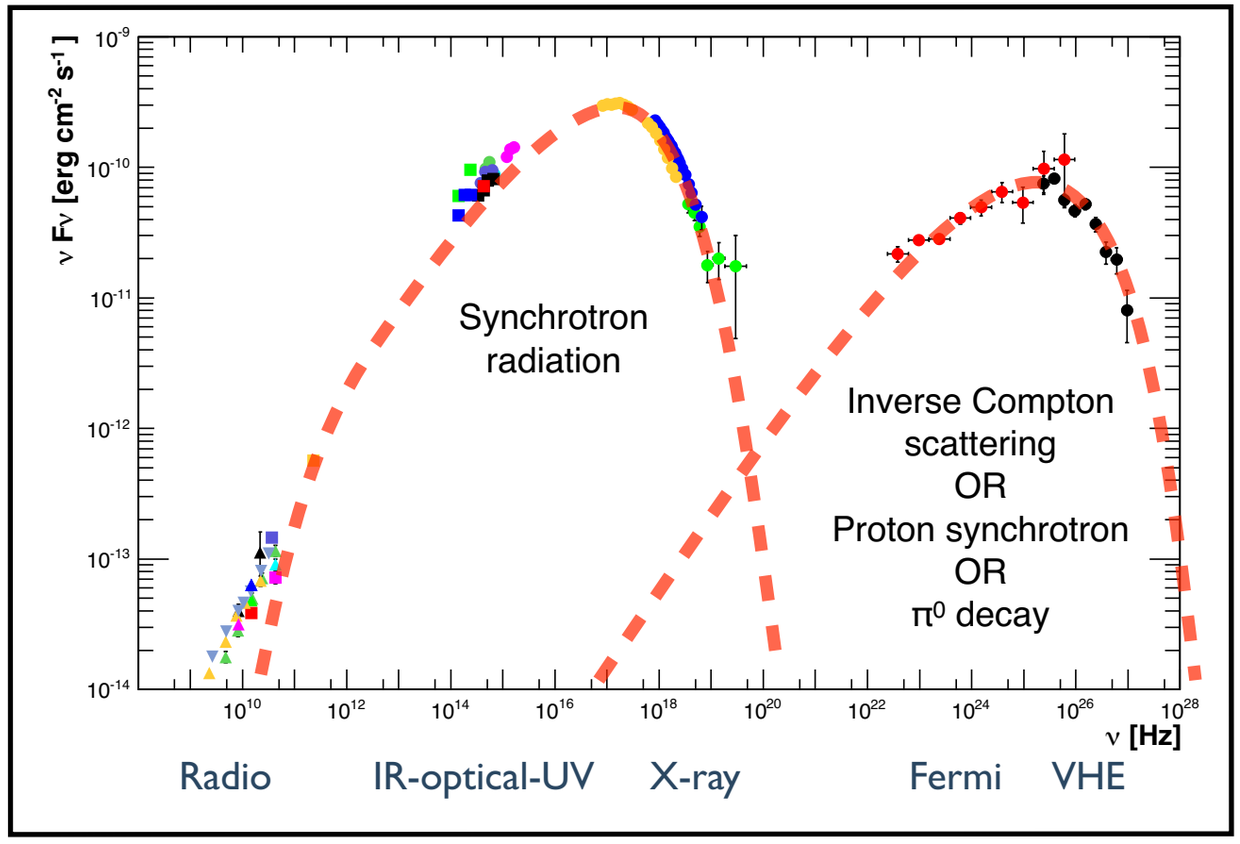
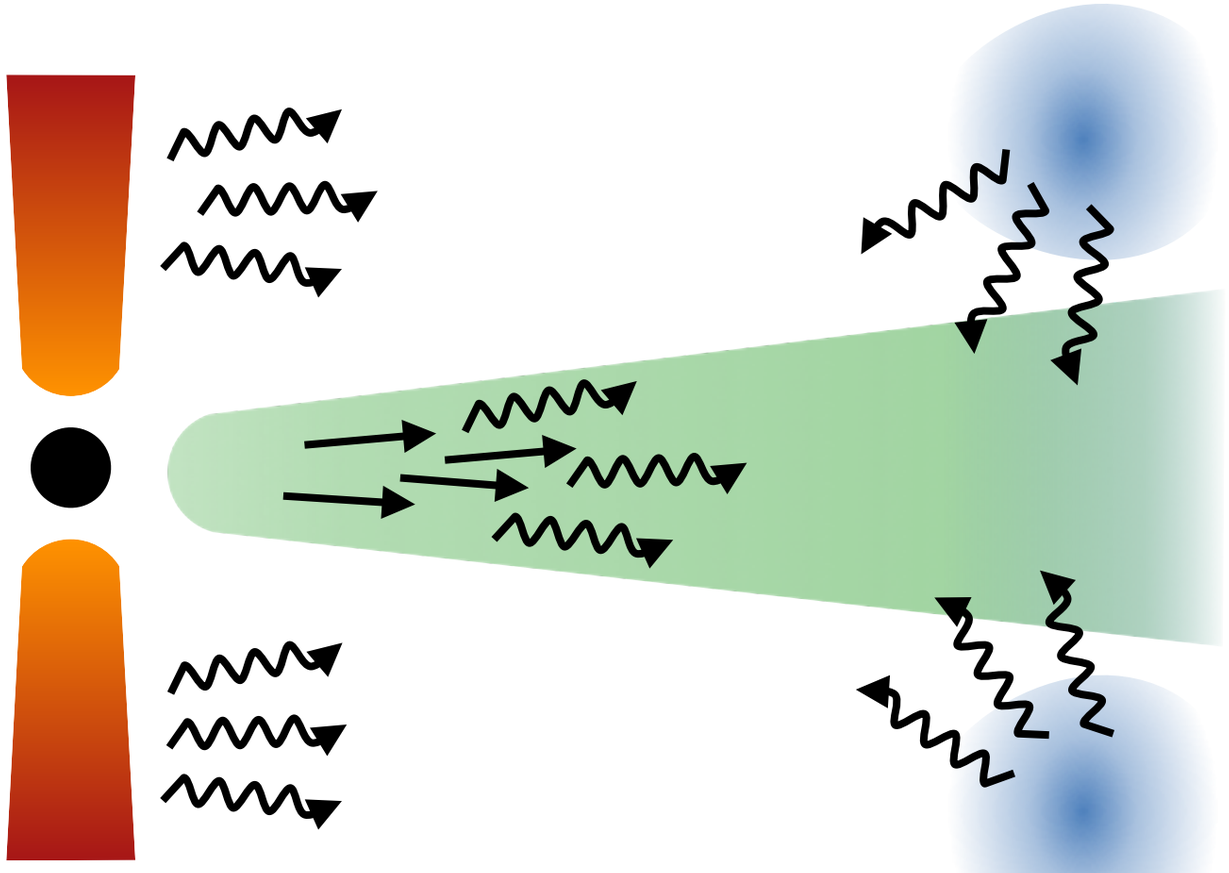
ME+ (IXPE collaboration) 2024

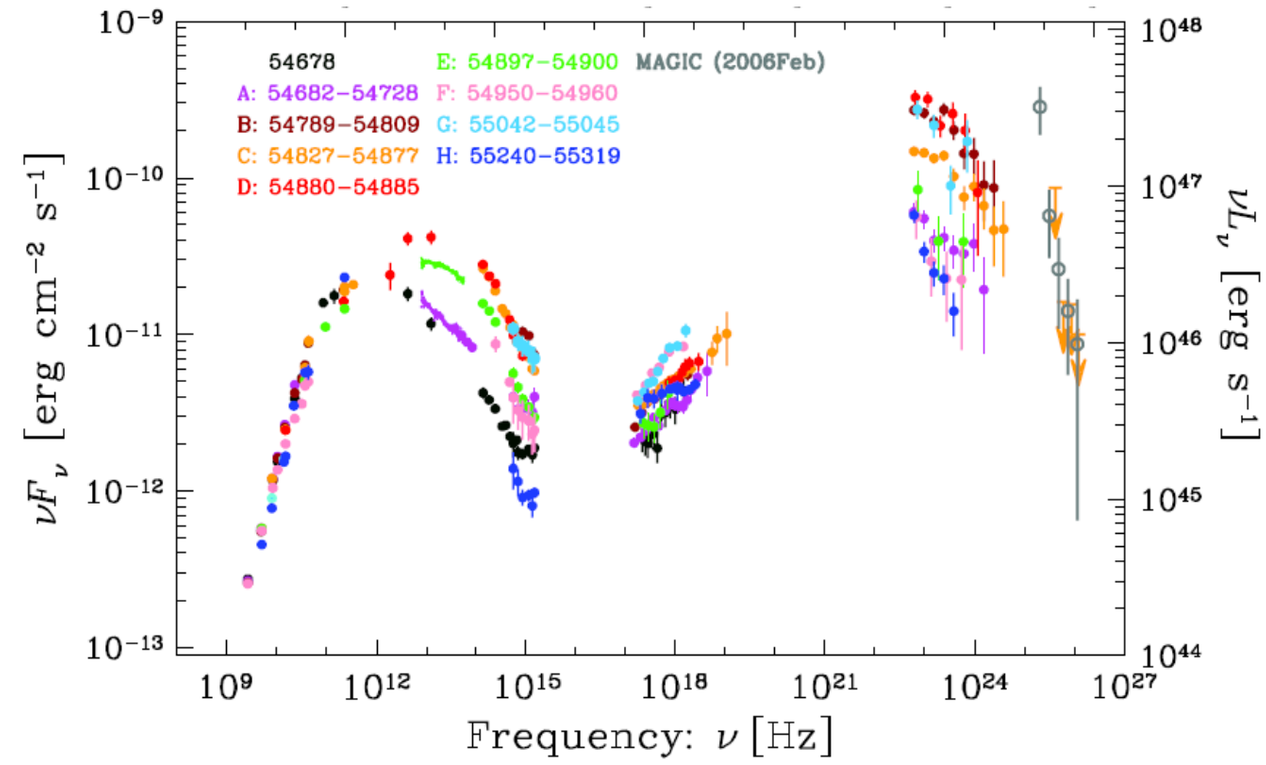


Weak, old jet (ran out of gas)

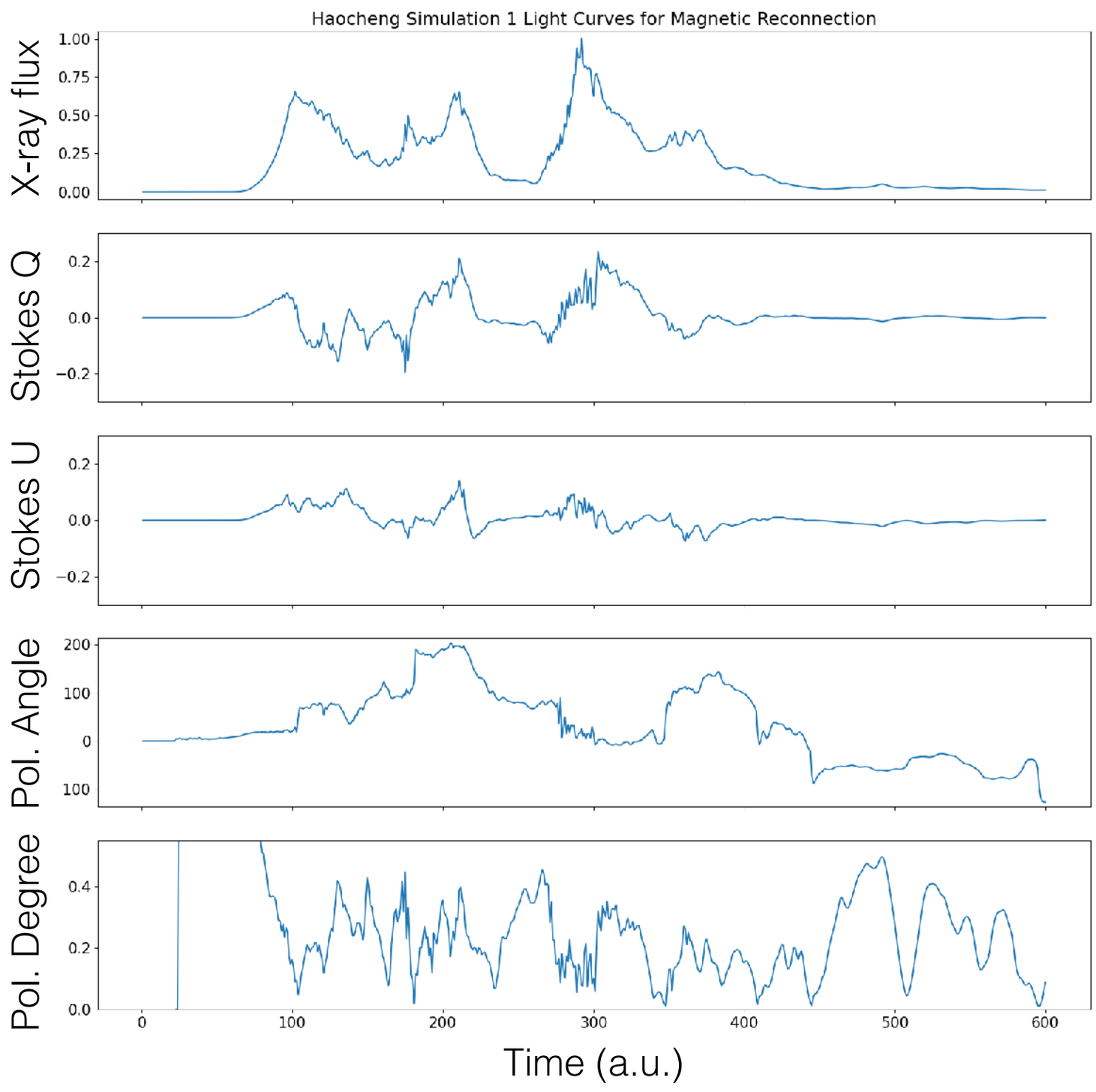




Strong, young jet (gas is available)



Magnetic reconnection



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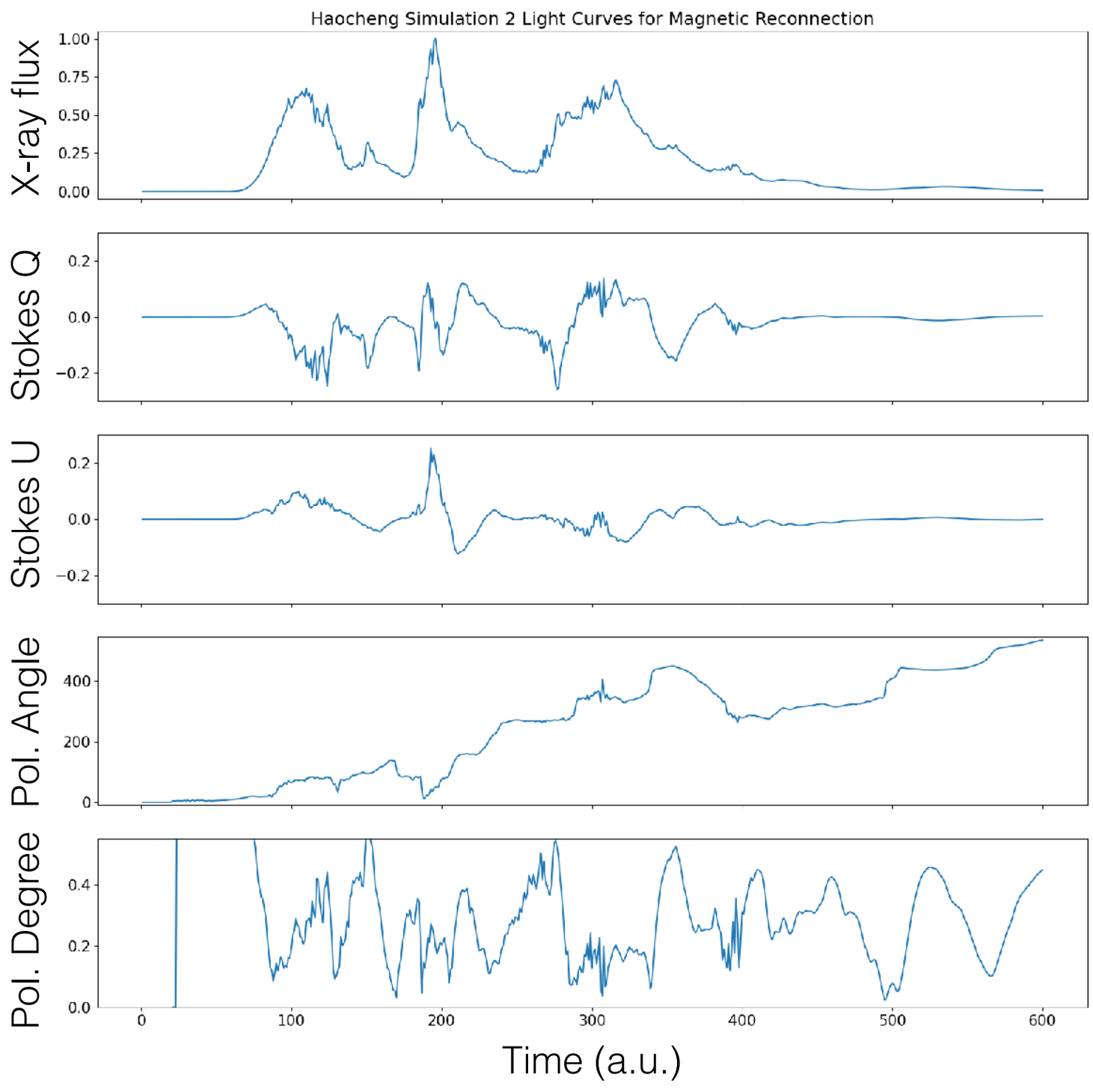

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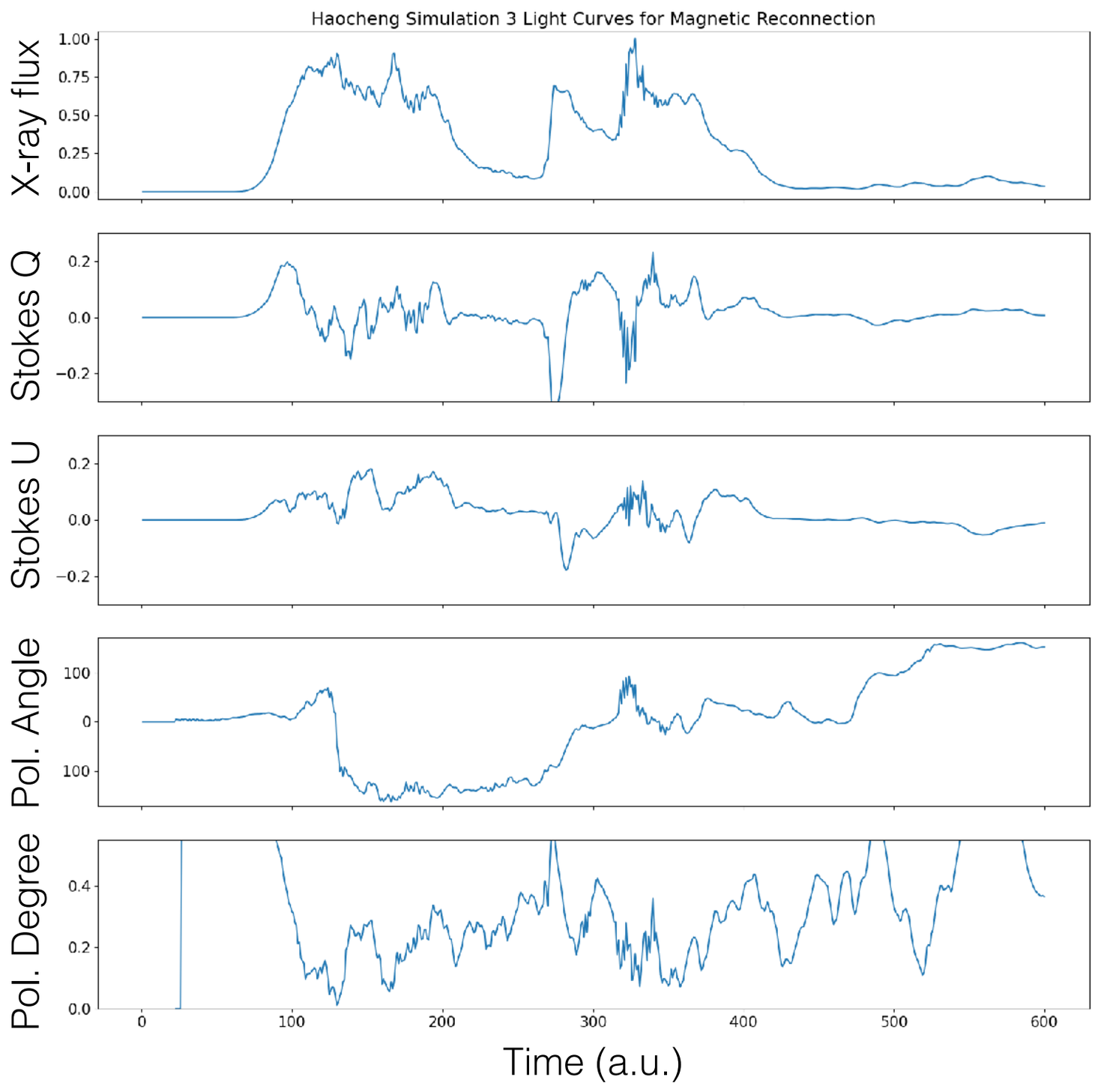
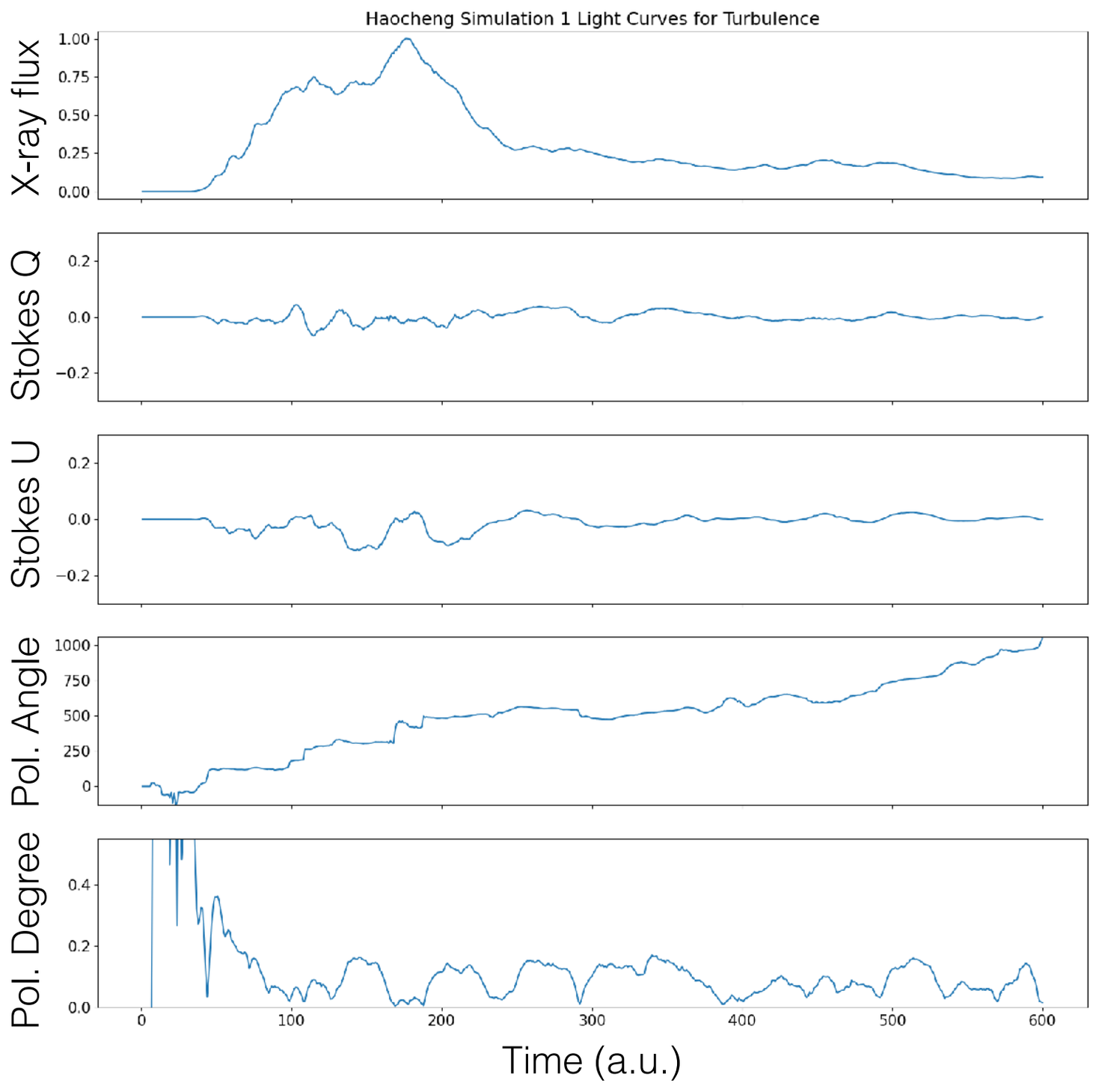


Turbulent shock acceleration



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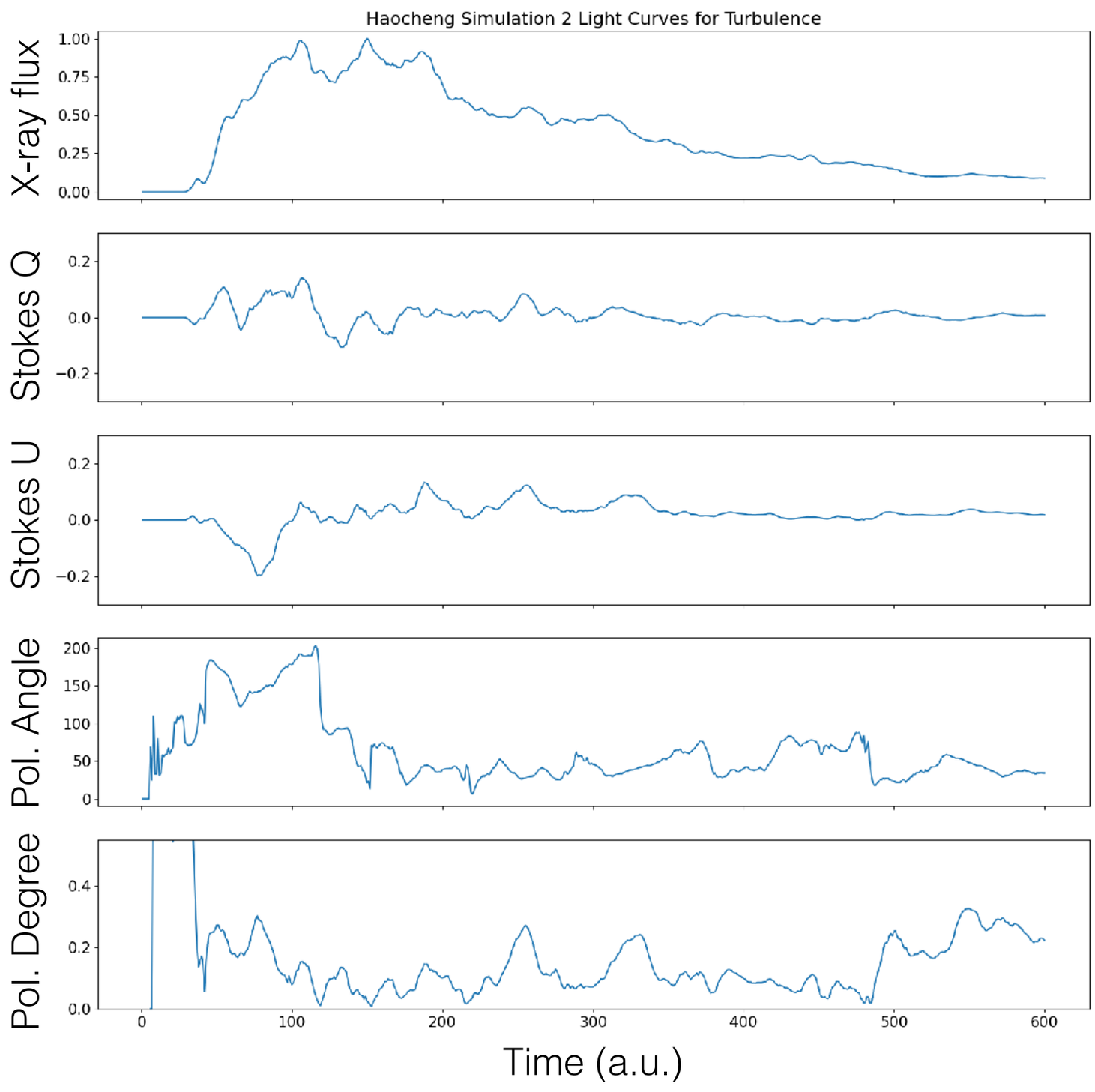

Turbulent shock acceleration