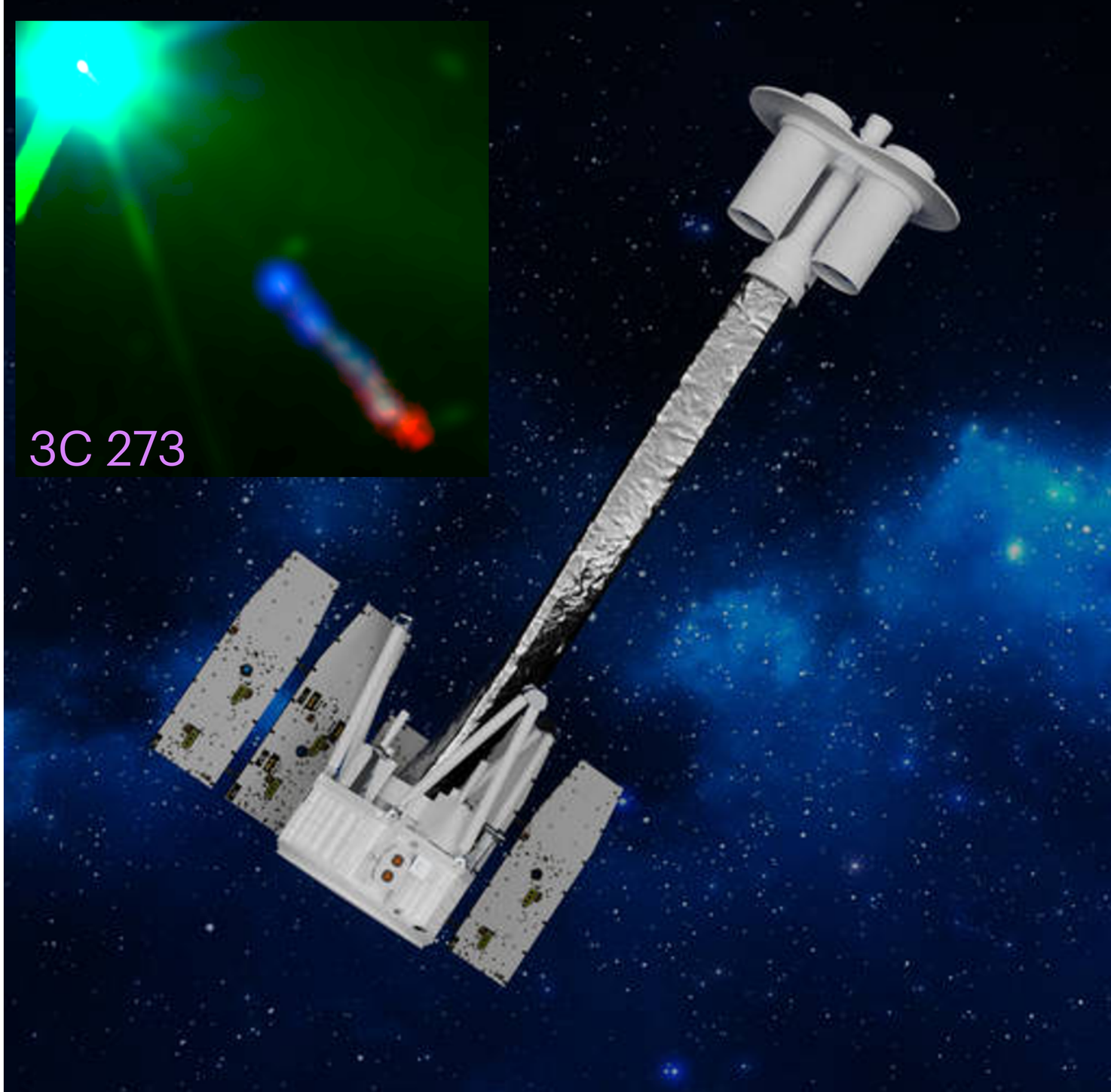
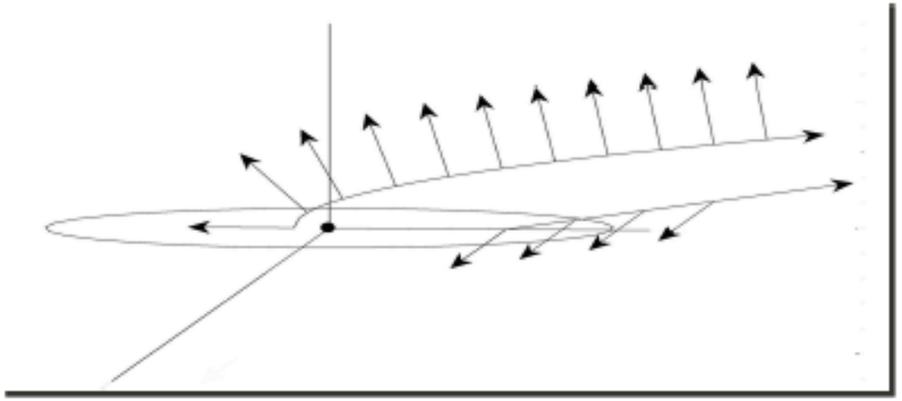
IXPE Overview of Blazars and AGN Results

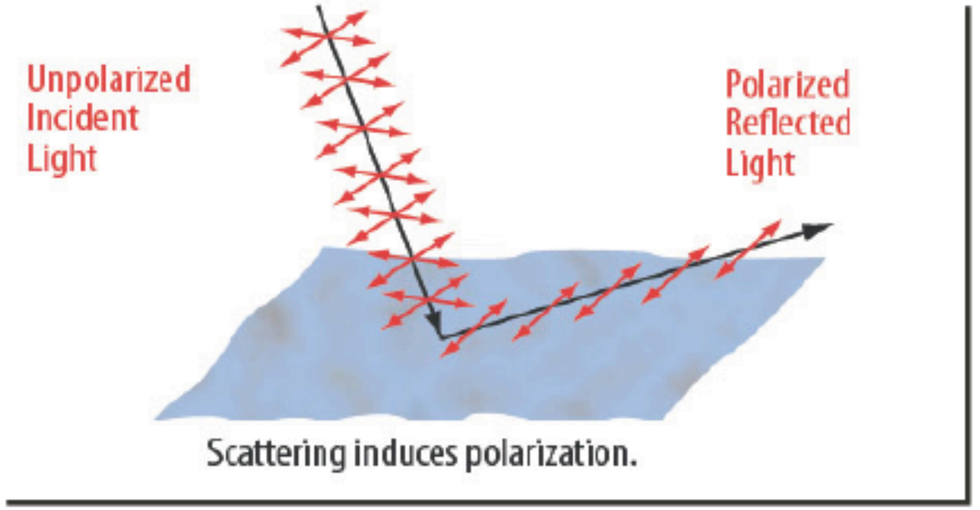
Herman L. Marshall (MIT) and IXPE Team



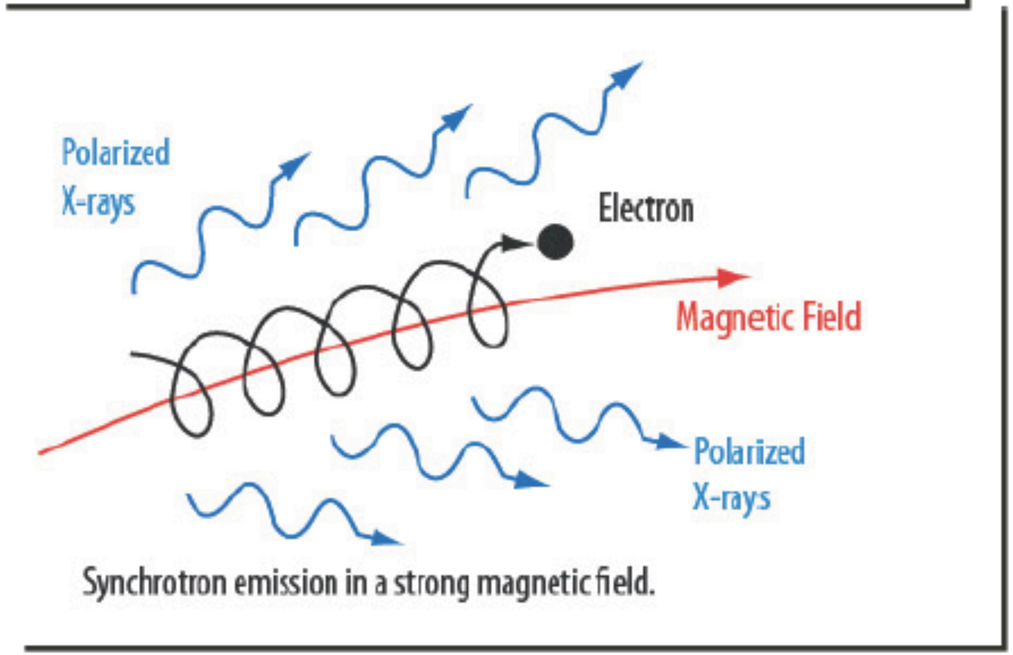
Polarimetry Probes of Physics

- Polarization measurements allow us to study:
  - ✓ Scattering
  - ✓ Magnetic fields
  - ✓ Strong gravity





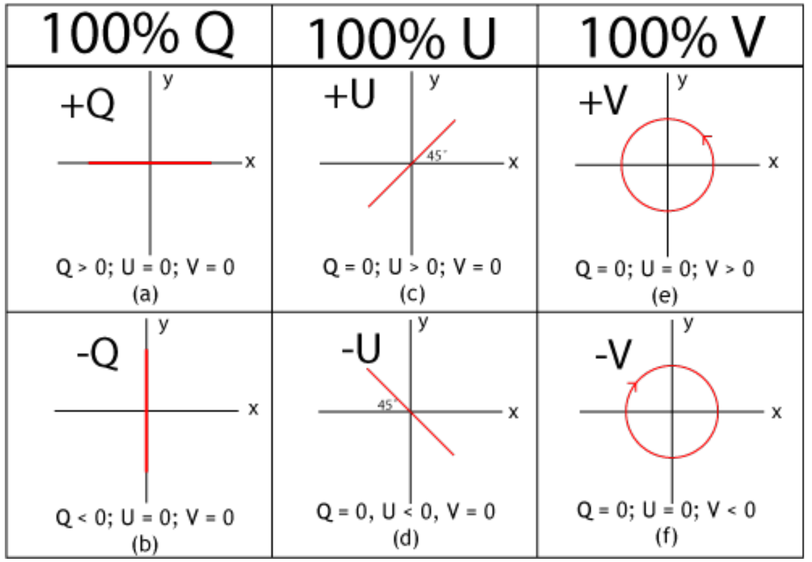
Scattering induces polarization.



Synchrotron emission in a strong magnetic field.

A Few Basics

- Stokes parameters are handy:
  - I = total intensity
  - Q, U are orthogonal linearly polarized parts
  - V is circular (+ or -) polarized intensity
- Common alternative: Π, ϕ
  - $\Pi = (Q^2 + U^2)^{1/2} / I$
  - $\phi = \tan^{-1}(U/Q) = 2 \times \text{EVPA}$



- A beam is “unpolarized” if the photon **set** is randomly polarized (Π = V = 0)
- MDP = ‘Minimum Detectable Polarization’ (at 99% conf.) = $\dfrac{4.292\sqrt{N_S + N_B}}{\mu N_S}$

$$4.292 = 2(-\log[0.01])^{1/2}$$

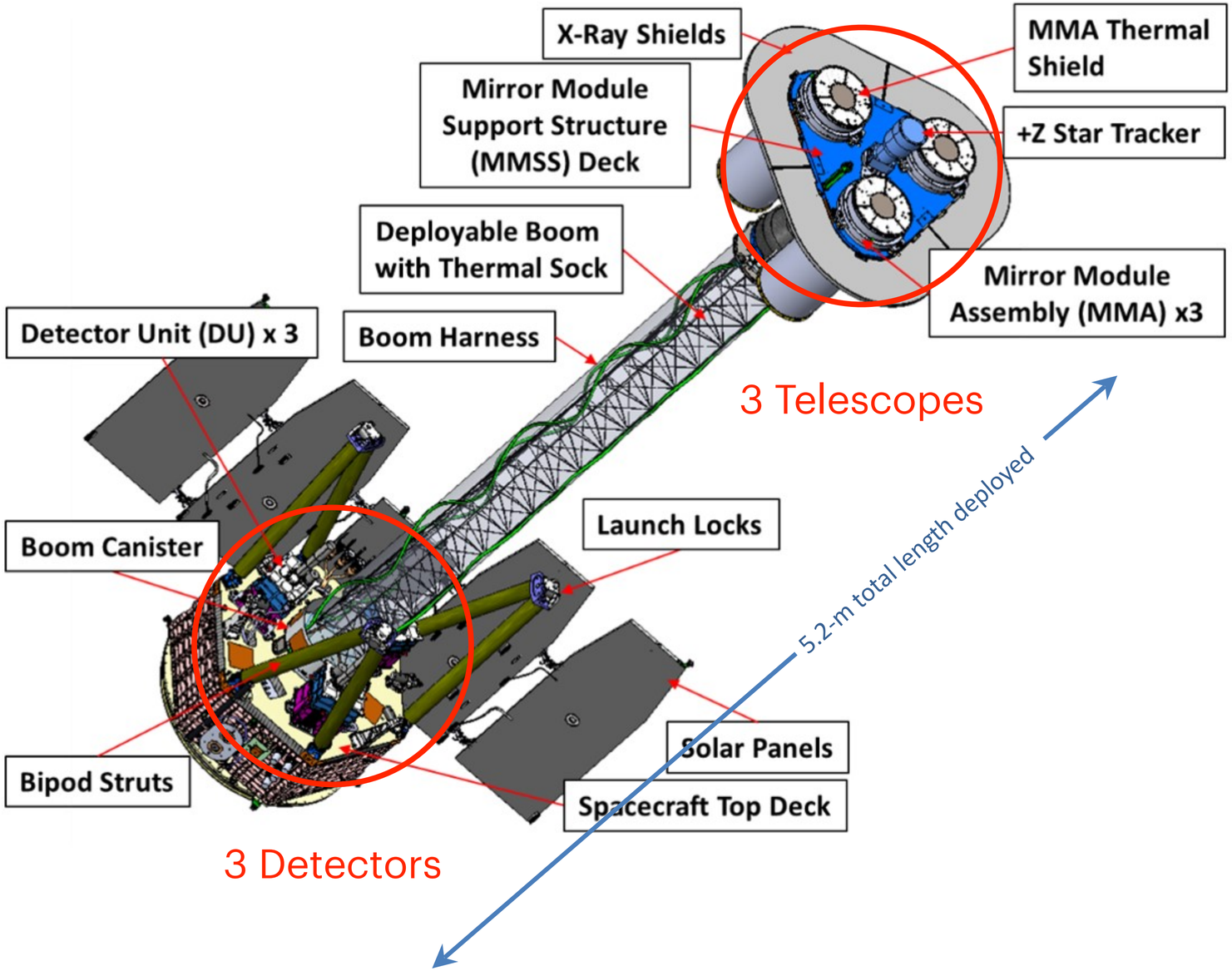
IXPE Mission Overview

Launched Dec. 9, 2021

Principal Investigator: Phil Kaaret (originally Martin C. Weisskopf) (MSFC)
Co-Investigators: Luca Baldini, Ronaldo Bellazzini, Enrico Costa, Ronald Elsner, Victoria Kaspi, Jeffery Kolodziejczak, Luca Latronico, Herman L. Marshall, Giorgio Matt, Fabio Muleri, Stephen L. O'Dell, Brian D. Ramsey, Roger W. Romani, Paolo Soffitta, Allyn Tennant

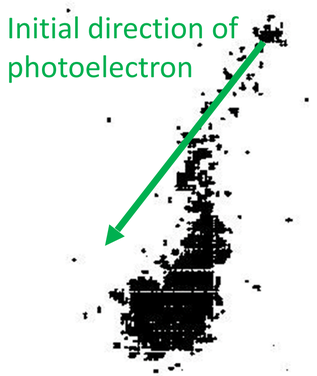
- Bandpass: 2-8 keV
- Imaging: 28" HPD (average)
- Low Earth Orbit, 2+ yr mission
- No proprietary data
- No consumables; only orbit limits mission lifetime
- Detectors (ASI) are working well!
- Over 80 papers, 10+ in press/submitted
- Observing plan is dynamic
- GO program started in February, 2024

The Imaging X-ray Polarimetry Explorer (IXPE)

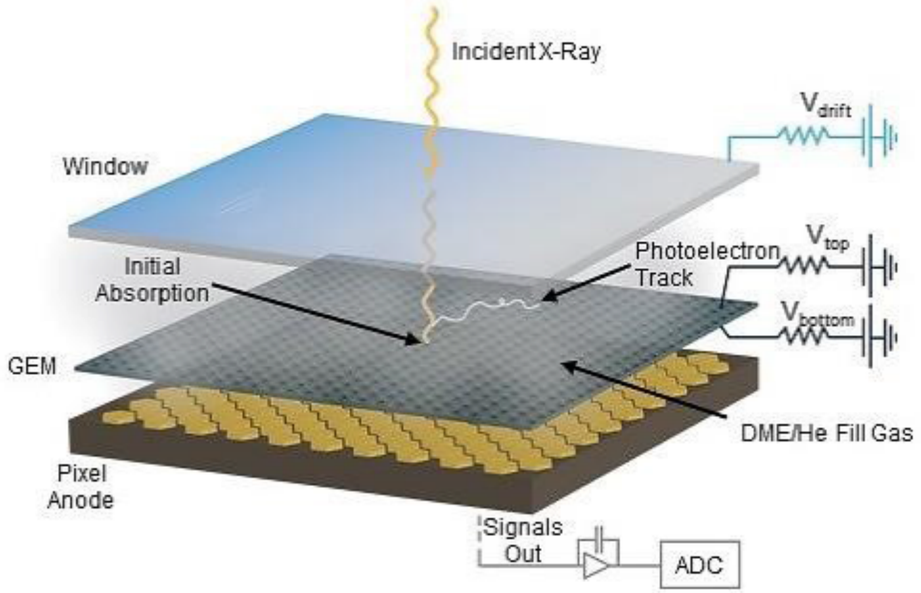


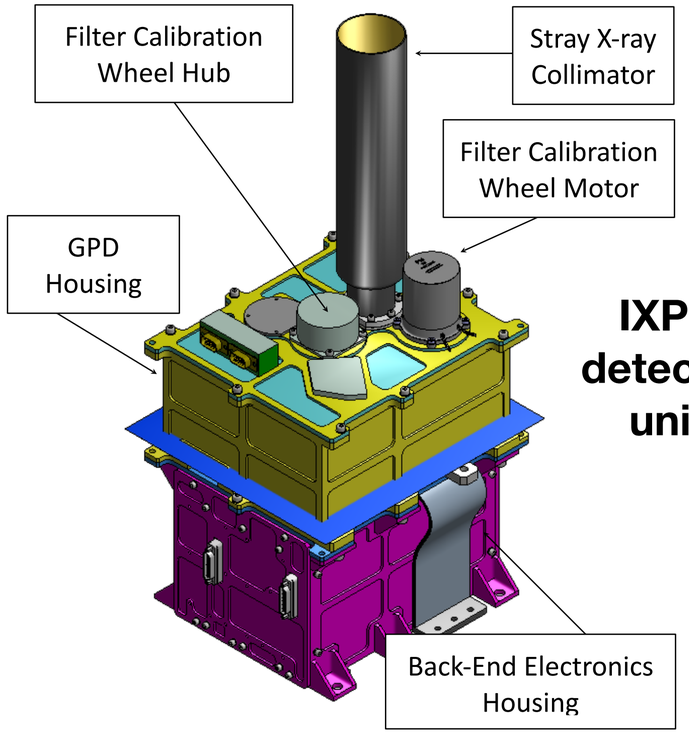
Imaging Polarimetry Detector
(an Italian contribution to IXPE)

- Photons eject K shell electrons from detector gas atoms
- Photoelectron direction is related to the photon's polarization angle
- Photoelectron loses energy via L shell ionizations; total charge is proportional to E
- Charge is amplified by GEM, drifts to fine pixel anode



Gas Pixel Detector (GPD)

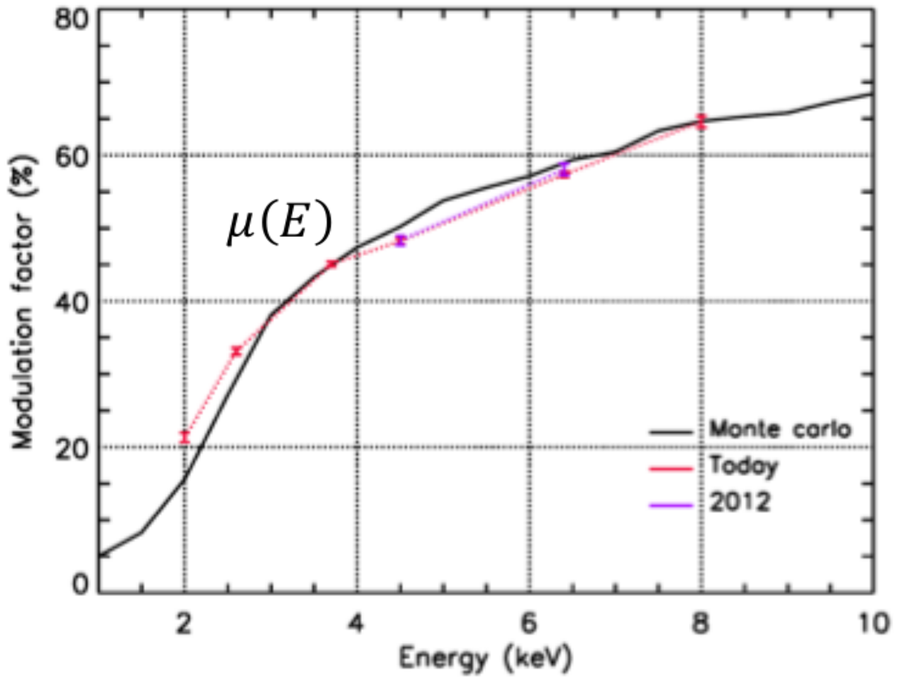


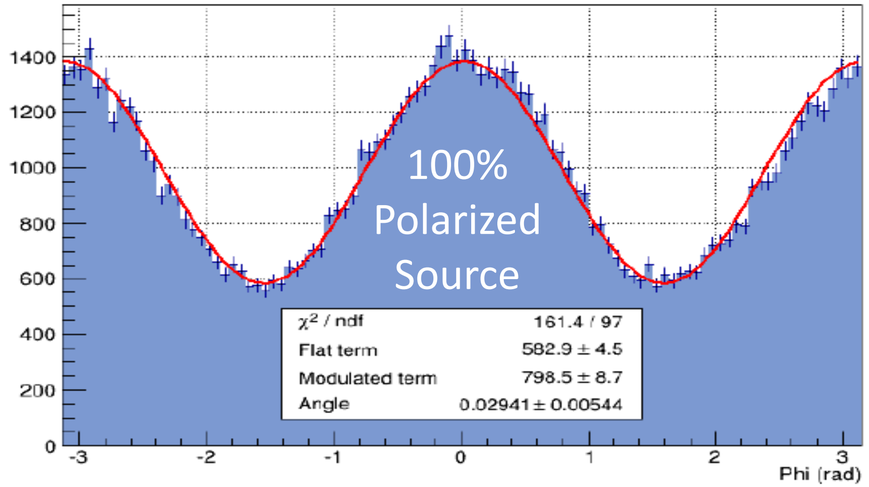


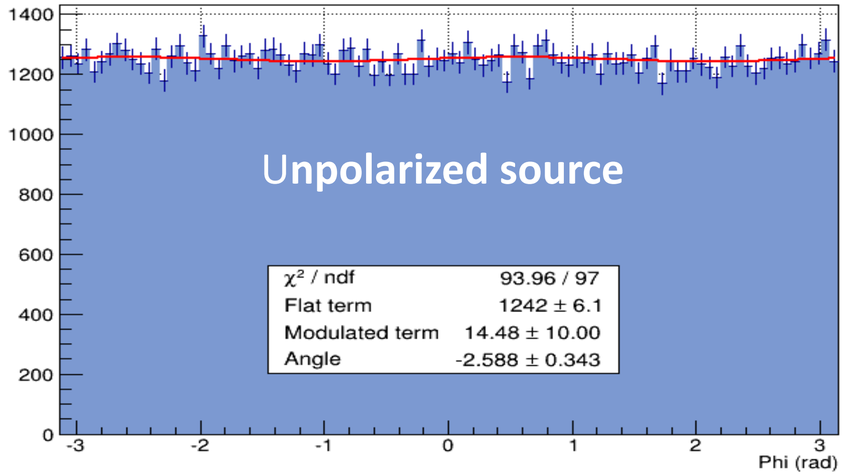
IXPE detector unit

Measuring Polarization

- Energy range depends on gas mixture — IXPE: 2-8 keV
- Tracks are longer, easier to measure at high energy
- Angle is probabilistically related to Q, U
  - Need models in I, Q, U
  - Need statistics, spectral fitting in I, Q, U

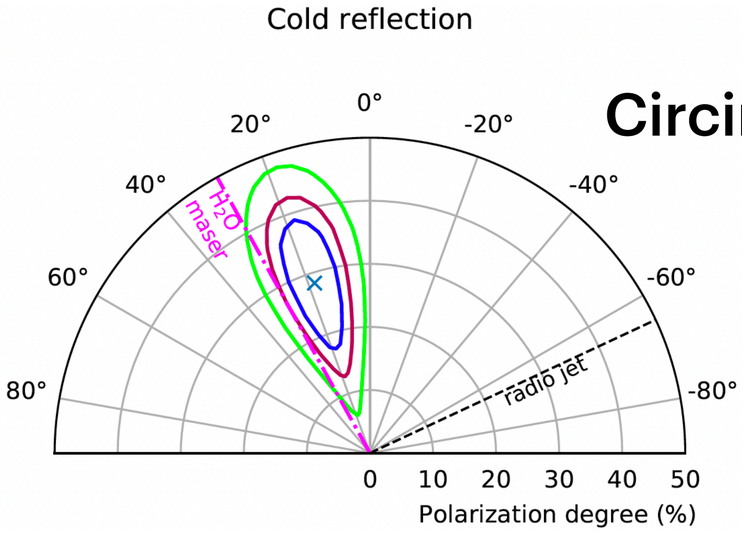


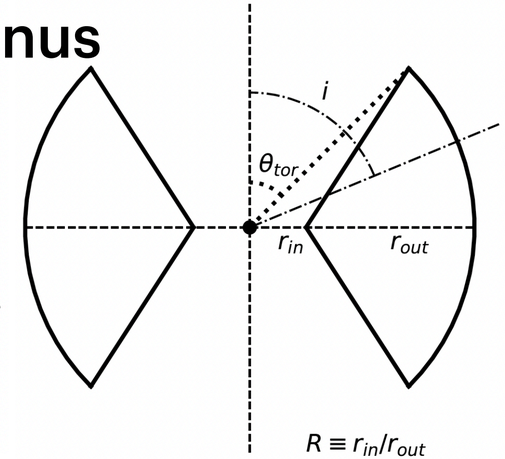


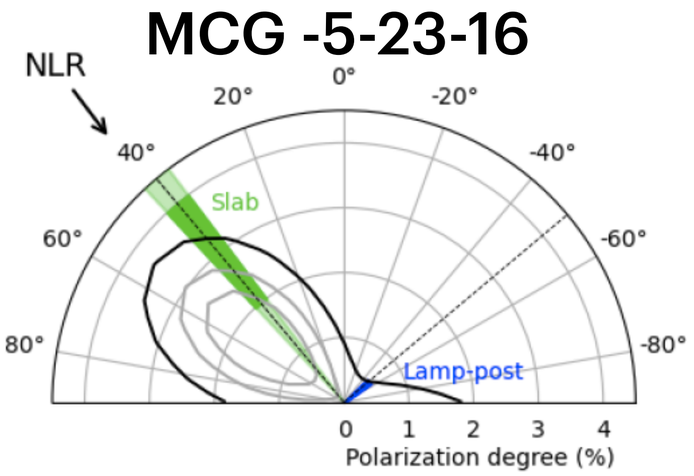


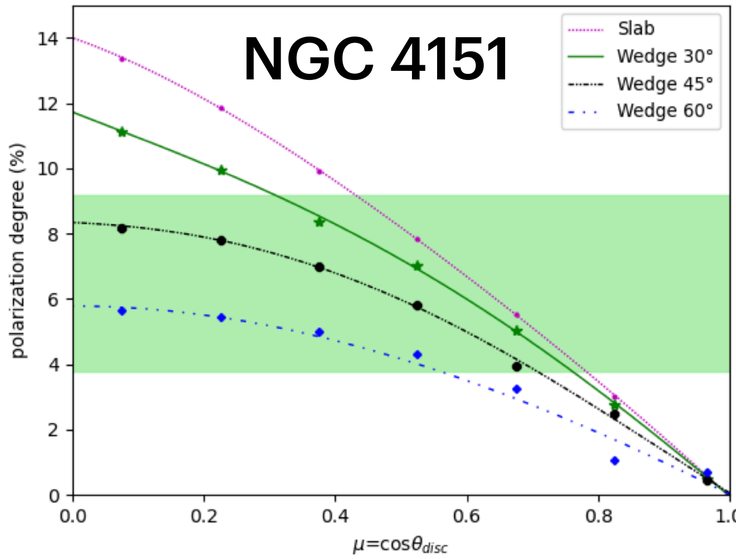
Radio Quiet AGN — Summary

- Detections:
  - Circinus Galaxy (Ursini+): 28 ± 7% for neutral reflector (perp. to jet)
  - NGC 4151 (Gianolli+): 4.1 ± 1.1% from disk corona (perp. to jet)
  - NGC 1068 (Marin+): 12.4 ± 3.6%, like Circinus (perp. to jet)
- Upper Limits or Marginal:
  - MCG-5-23-16 (Tagliacozzo, submitted): 1.6 ±0.7%
  - IC 4329A (Ingram+): 3.3 ±1.1% from disk corona (perp. to jet)



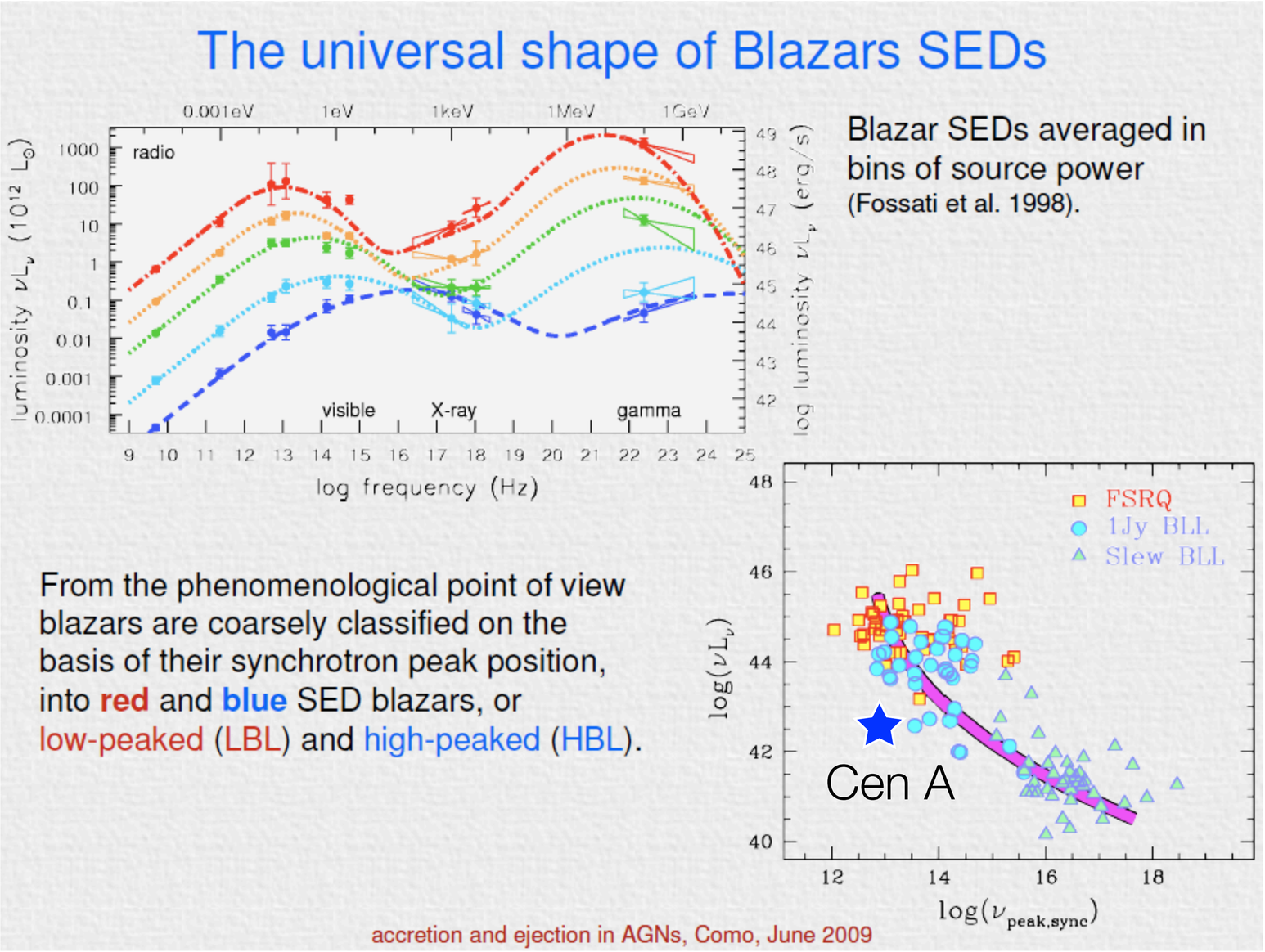






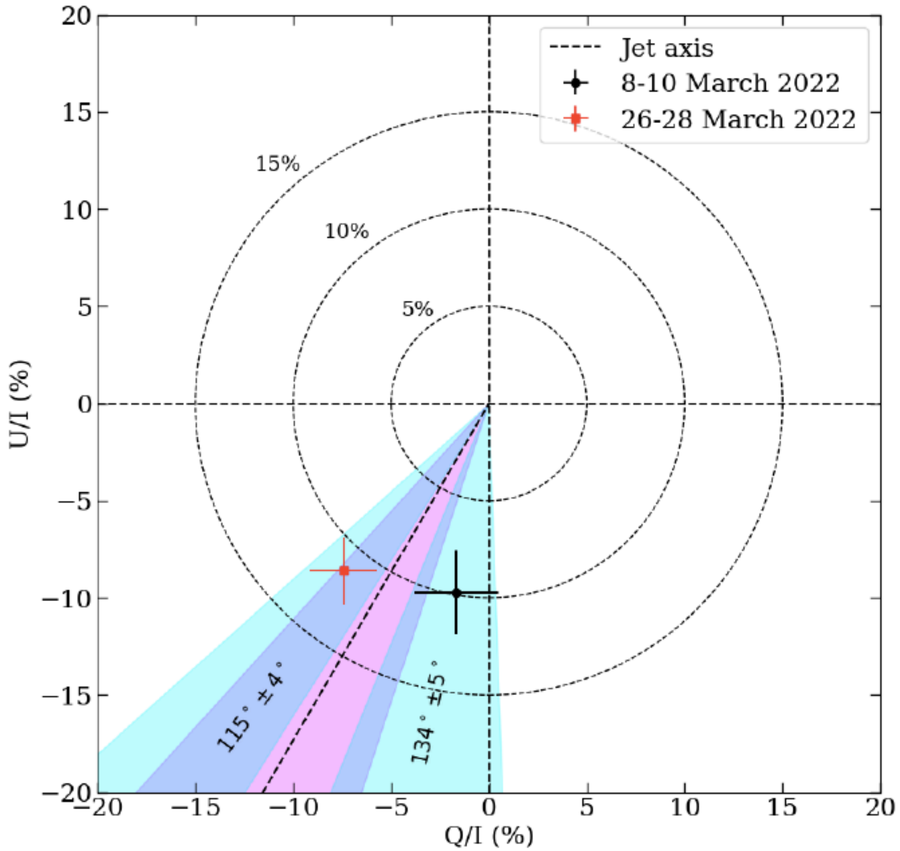
Blazars in General

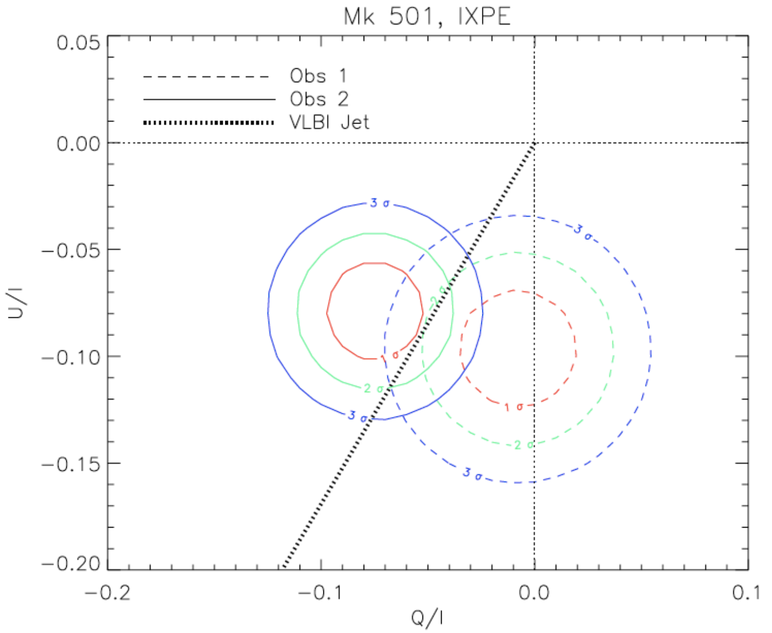
- Jet dominated SED
- High Spectral Peak (HSP): SED peak above optical band
  - Lower luminosity than others
  - Synchrotron extends to X-rays
  - Examples: Mk 421, Mk 501
  - IXPE: 10-15% polarized
- Low Spectral Peak (LSP): SED peak above optical band
  - Higher L than HSPs
  - X-ray band: Compton scattered
  - Polarization depends on seed photons (disk? jet? BLR?)



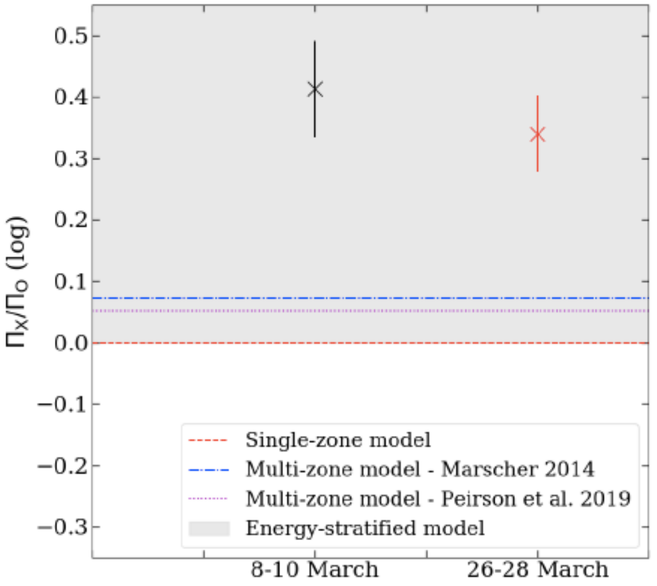
Mk 501 (HSP Blazar) (Liodakis+, '22)

- Two observations
- Consistent EVPA
- EVPA = jet direction
- Shock model favored
- $\Pi_X = 2.5\Pi_O$ –> stratified shocks

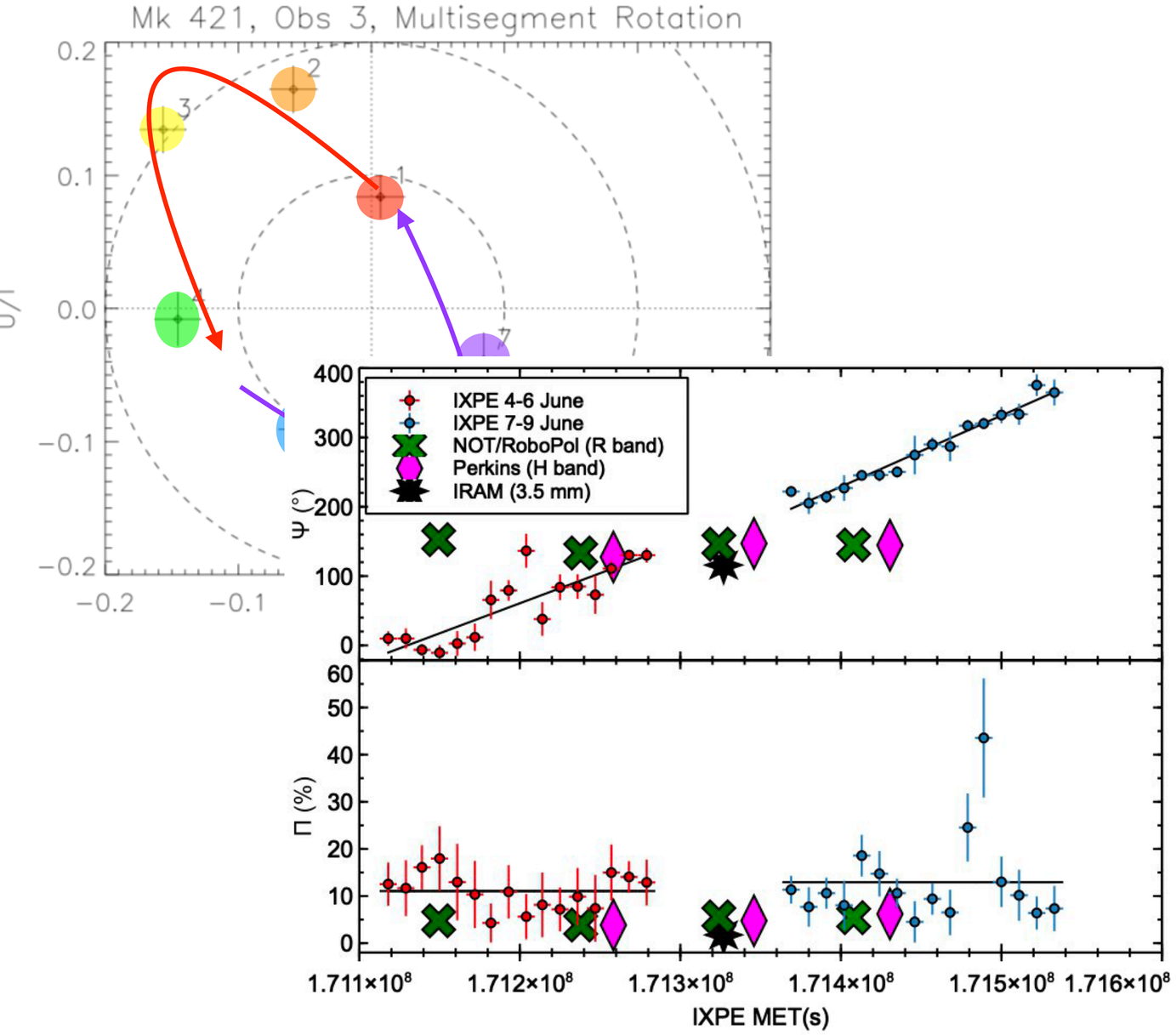




Model	Multiwavelength polarization	Variability†	Polarization angle
Single zone	constant*	moderate	any
Multizone	mildly chromatic	high	any
Energy stratified (shock)	strongly chromatic	slow	along the jet axis
Energy stratified (magnetic reconnection)	constant	moderate	perpendicular to jet axis
Observed	strongly chromatic	slow	along the jet axis



Mrk 421 Observations



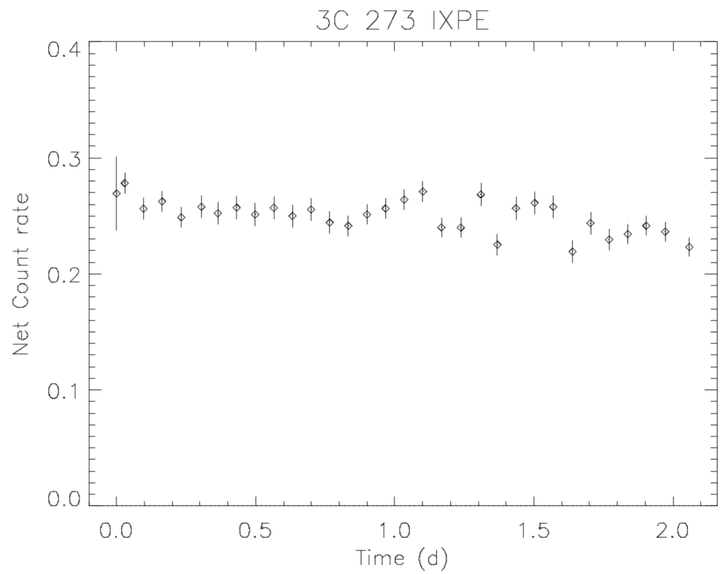
Mk 421, 4-5/24
Segment 1

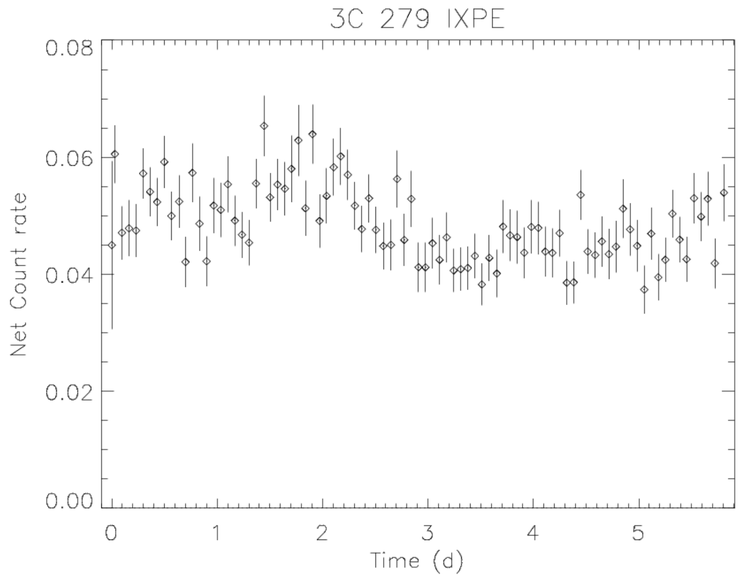
Mk 421, 4-5/24
Segment 2

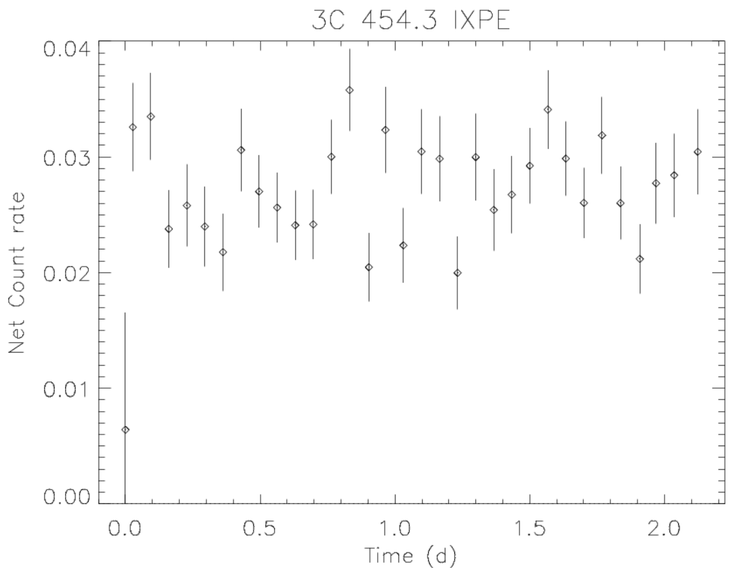
Marscher, PI

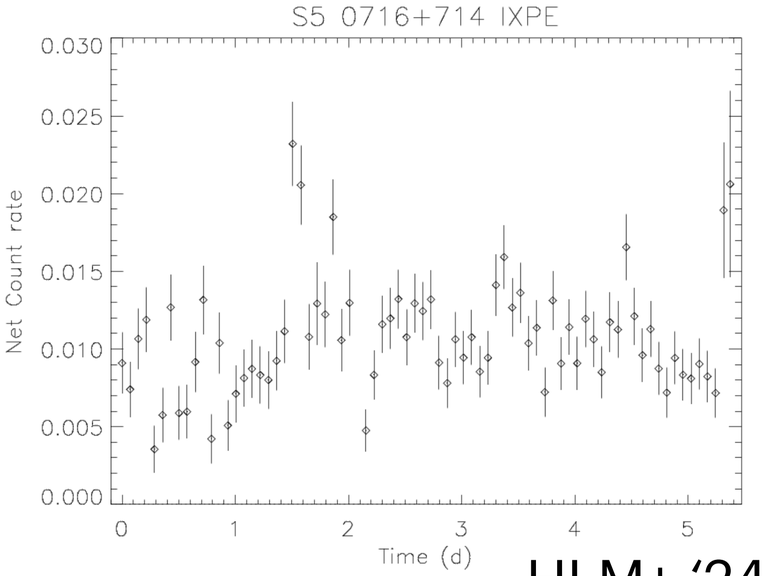
LSP & ISP Blazars

- 3C 273
  - Classic quasar, z=0.158
  - Brightest AGN after Cen A
  - kpc scale jet extends to >20”
- 3C 279
  - Superluminal, PA = -153°
- 3C 454.3
  - Showed gamma-ray flares
- S5 0716+714
  - Brightest of the ISP blazars
- High L, slow variability









HLM+ ‘24

Observation Summary

- Exposures of 1-4 days
- X-ray spectra: Swift, XMM
- Optical/IR polarimetry: Skinakas/RoboPol, NOT/ALFOSC, Palomar/WIRC+Pol, St Petersburg, T60/DIPOL-2, Kanata/HONIR, Perkins/MIMIR
- Radio band: IRAM (1.3, 3.5 mm; POLAMI project)

Table 1. Summary of IXPE Observations HLM+ '24

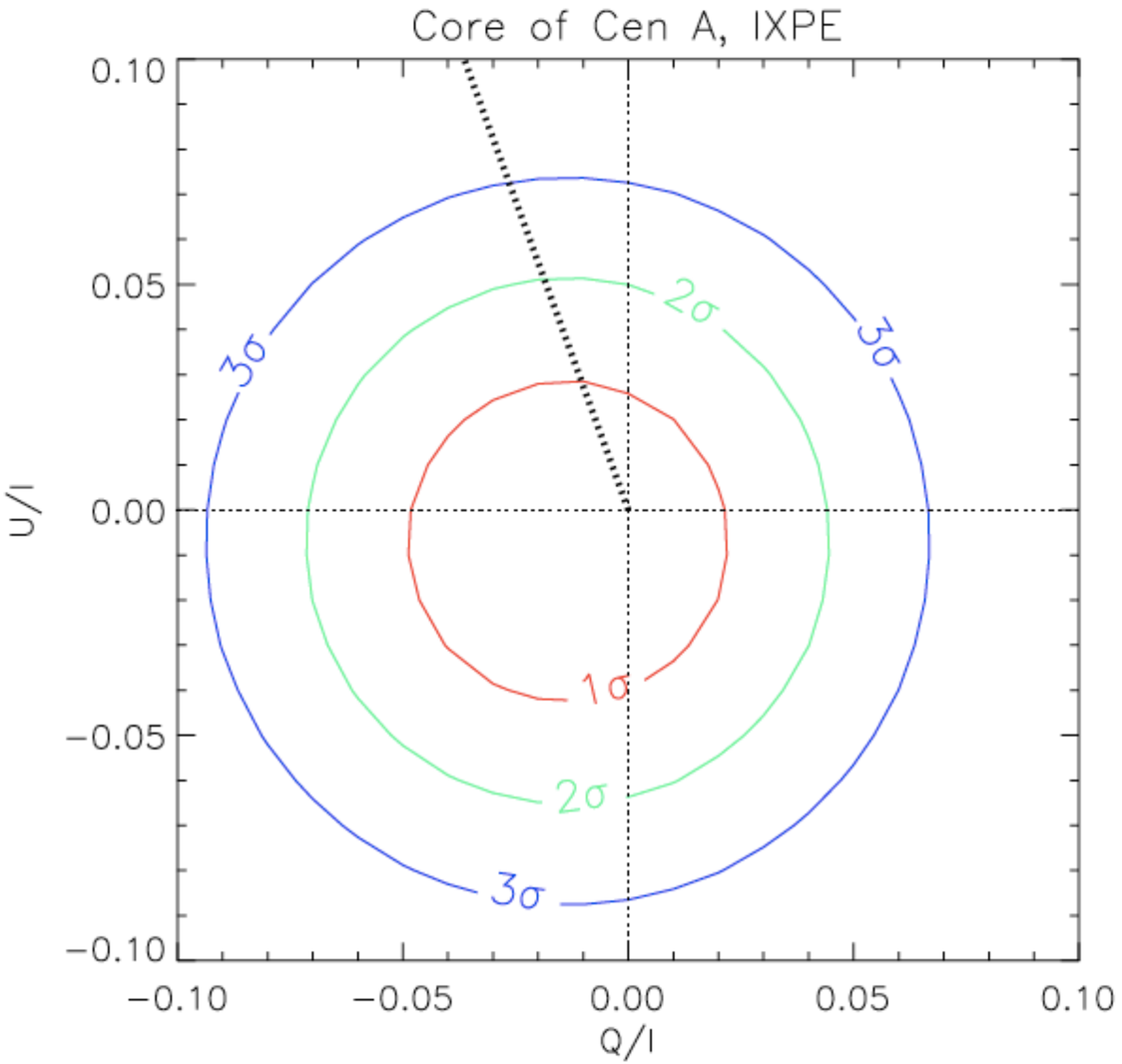
Source	Instrument	Observation ID	MJD range	Exposure (ks)[a]	Π_X[b]
3C 273	IXPE	01005901	59732.37 - 59734.45	95.28	$< 9.0\%$
3C 279	IXPE	01005701	59743.02 - 59748.85	264.42	$< 12.7\%$
3C 454.3	IXPE	01005401	59730.19 - 59732.34	98.12	$< 28\%$
3C 454.3 (Obs 2)	IXPE	02008901	60115.92 - 60121.89	274.92	$< 10.1\%$
S5 0716+714	IXPE	01005301	59669.43 - 59674.80	358.68	$< 26\%$

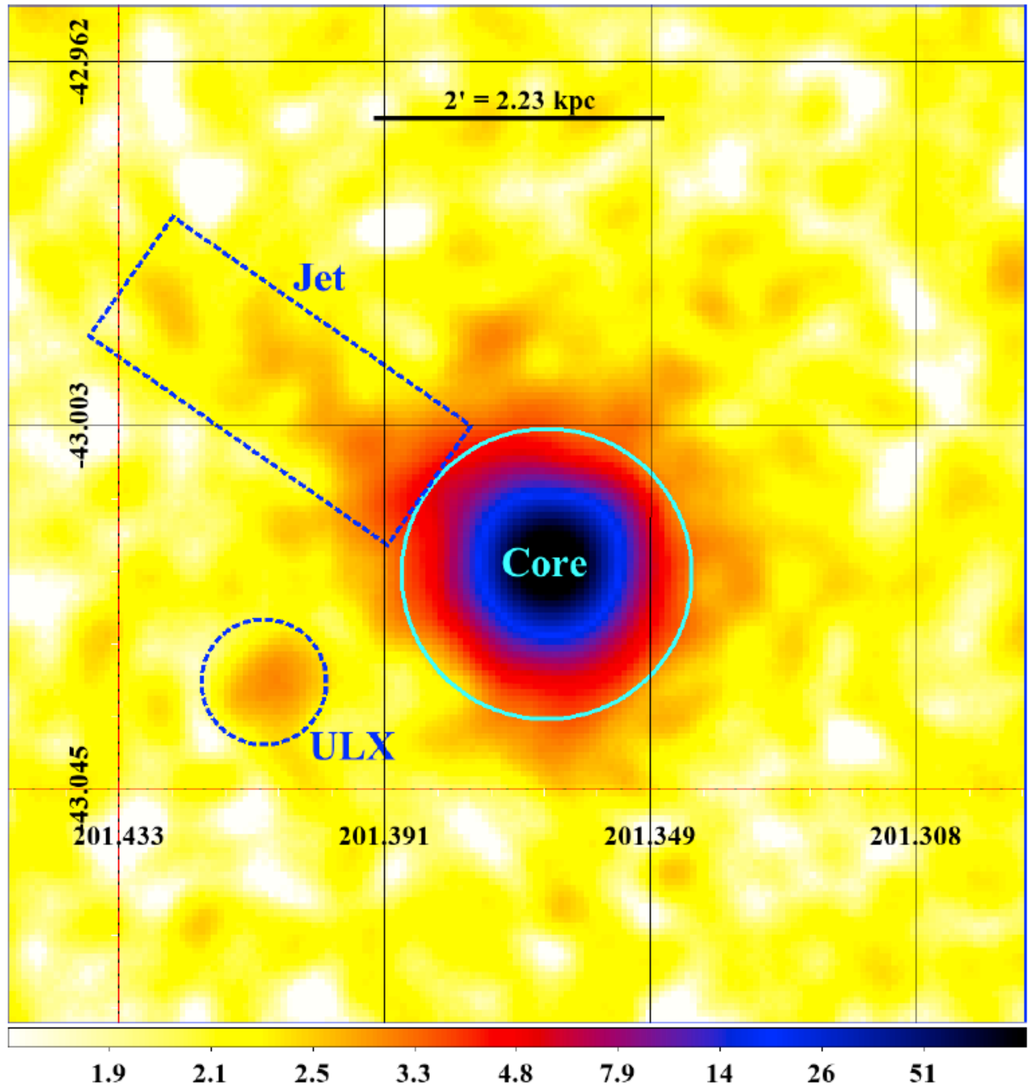
[a] Average of exposures for the three detector units.

[b] 99% confidence limits using the unbinned, event-based likelihood method (§ 2.1).

Cen A (Ehlert+ ’22)

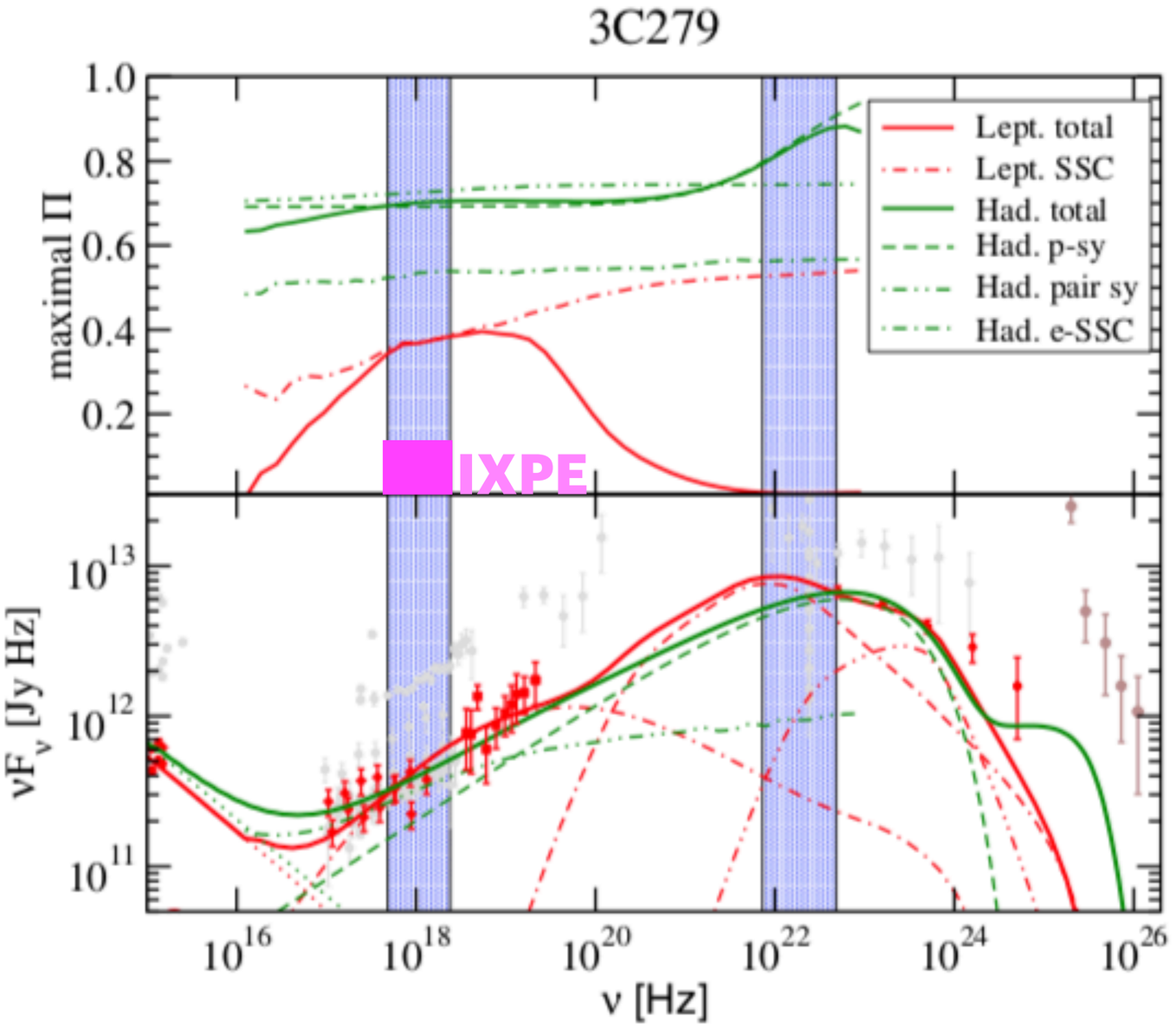
Core: PD < 6.5%; no good limit on jet or ULX





Summary of LSP Blazar Results

- No significant detections — except **NEW** marginal detection of Pic A
- Limits are higher or comparable to optical polarization limits
- Hadronic models predicting high polarization are ruled out
  - Zhang & Boettcher ’13: up to 70%
  - Observed: < 13%
- Synchrotron self-Compton models are not favored
- Seed photons for Comptonization are likely unpolarized (stars, BLR)



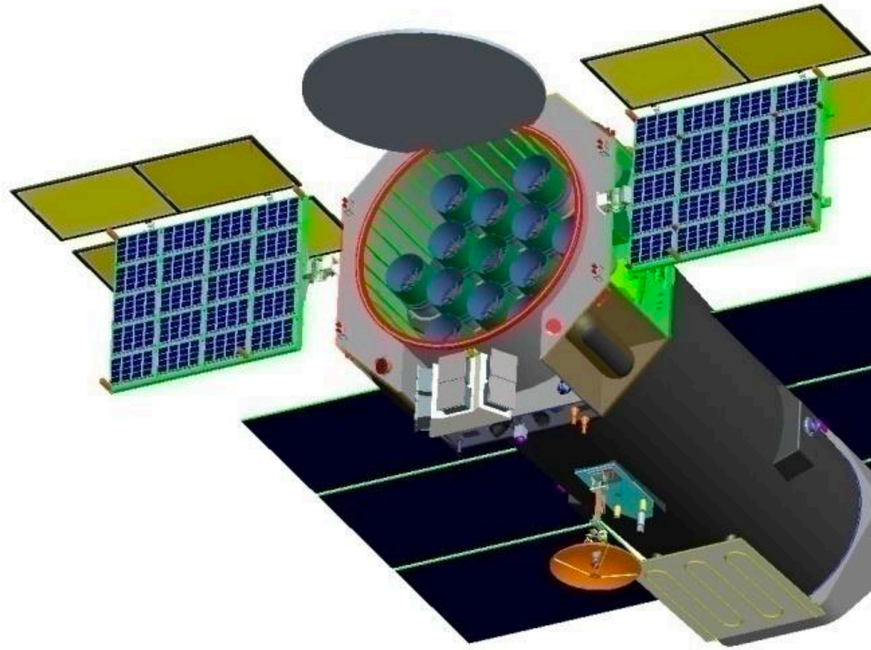
Zhang & Boettcher ’13

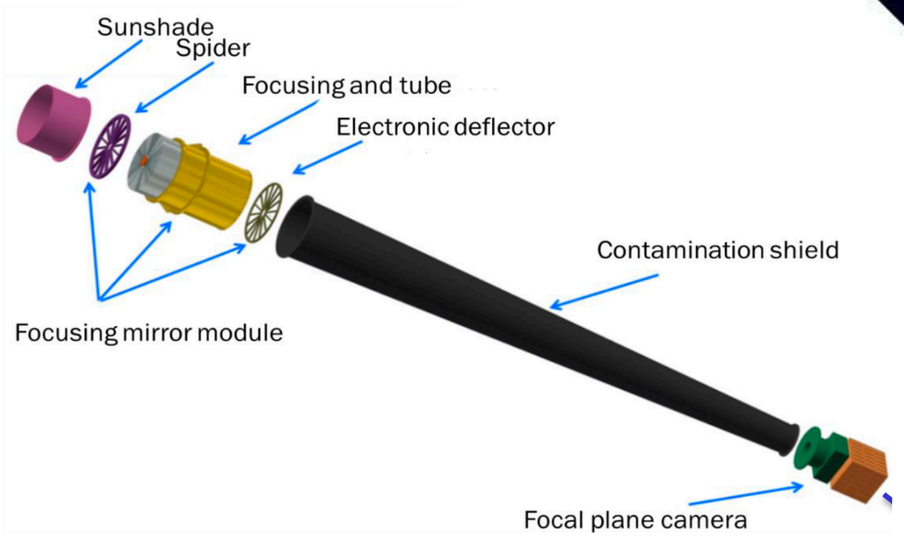
Possible Futures

- Extending existing missions: IXPE (2022), XPoSAT (2024)
  - non-secular EVPA rotations?, jet knot/hotspot polarimetry, P(E) or PA(E)?, Outburst tracking
- Increase sensitivity: e.g. eXTP (2028)
- Broadening the bandpass
  - COSI (2027) — up to 500 keV
  - REDSoX (2027) & GOSoX (SmallSat concept: 2032?) — < 1 keV
  - XPP (Probe concept; 2040?) — 0.1 to 50 keV
- R&D (5+ yr before a mission proposal)
  - Increase resolving power: e.g., Si-based photoelectron tracker
  - Increase spatial resolution (1” and better!): better optics & detectors
  - Circular polarization?

eXTP (CSA and ESA)

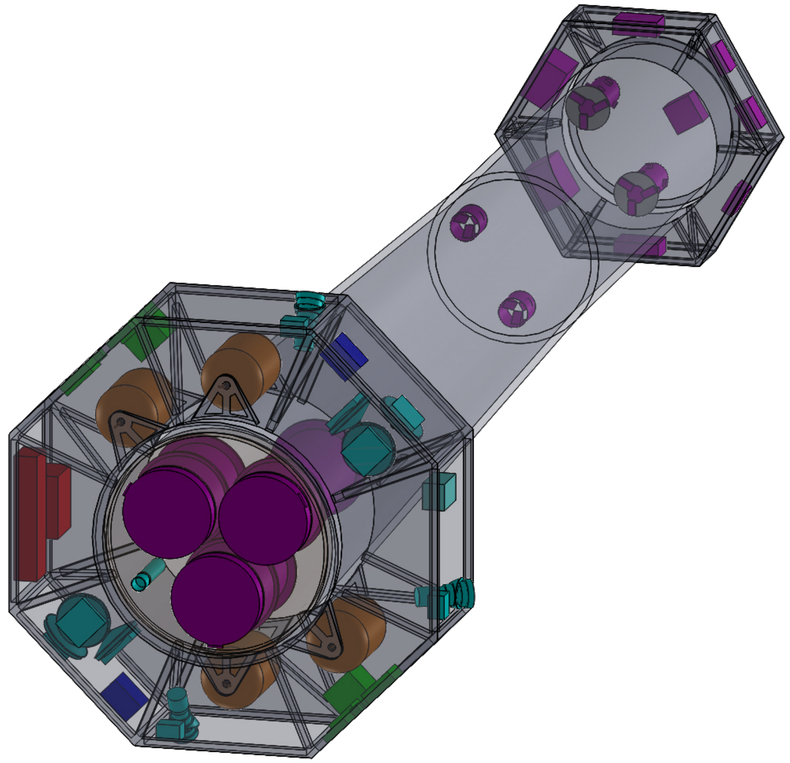
- Four experiments
  - Wide Field Monitor
  - Large Area Detector
  - Spectroscopic Focussing Array
- 4 x Polarimetry Focussing Array
  - IXPE-based gas pixel detectors, 15” optics, 5.5 m focal length
  - 4 x 100 cm^2, 2-10 keV
- Due for formal approval
- Launch by 2028



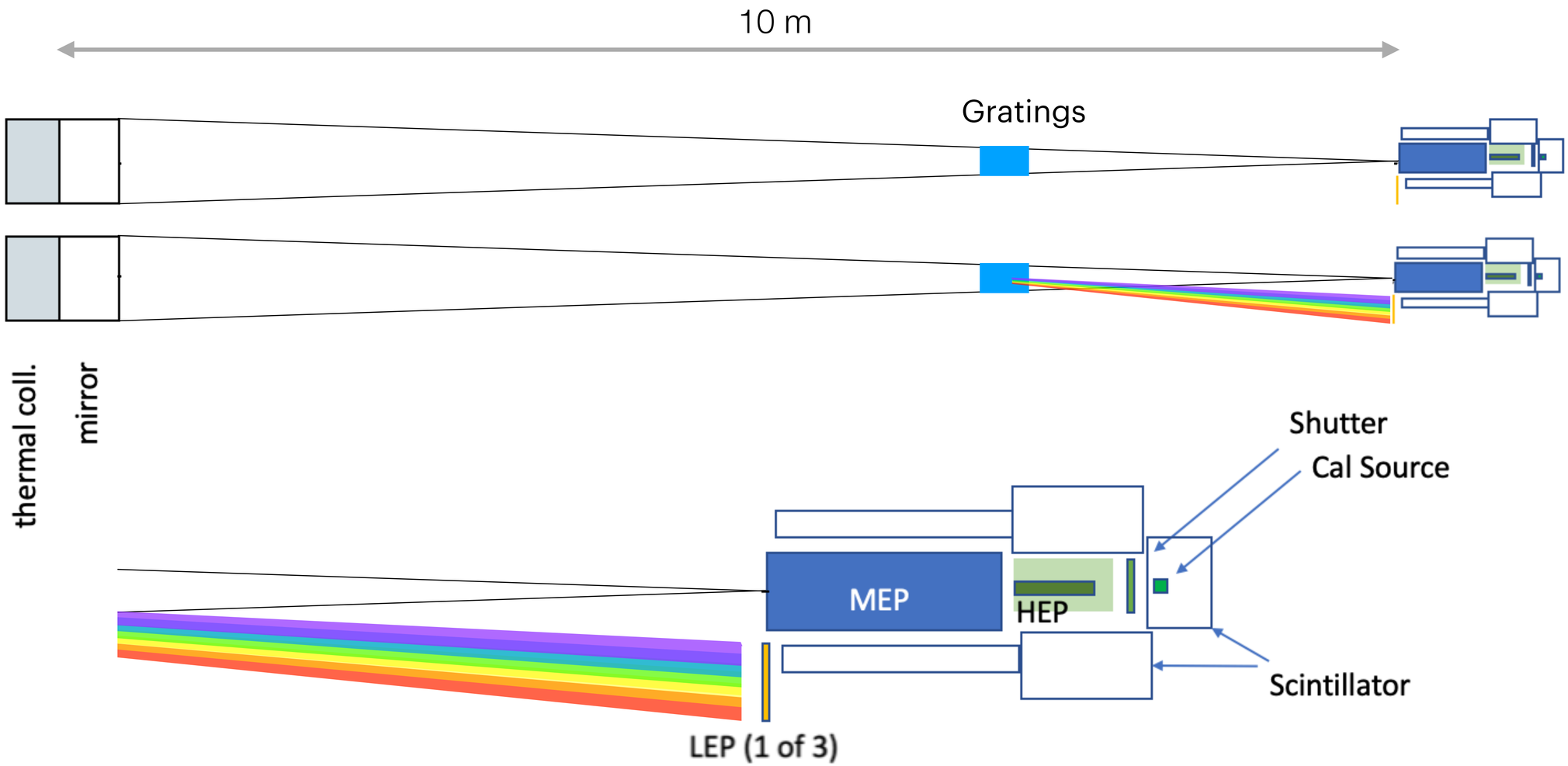


X-ray Polarimetry Probe (XPP)

- Combines four types of polarimeters
  - A bigger IXPE with a Gas Pixel Detector (2-10 keV)
  - Common optics polarimeter:
    - MIT's REDSoX design (0.15-1.0 keV)
    - GSFC's Time Projection Chamber (photoelectron tracker, 2-8 keV)
    - U. Washington's CZT & LiH scatterer (5-50 keV)
- One spacecraft, 3 mirror assemblies with 10 m focal length
- Spinning, body mounted solar panels
- 5-50 year lifetime
- White paper written for 2020 Astrophysics Decadal review



Broad Band X-ray Polarimeter



IXPE Mission Overview

Launched Dec. 9, 2021

Principal Investigator: Martin C. Weisskopf (MSFC)
Co-Investigators: Luca Baldini, Ronaldo Bellazzini, Enrico Costa, Ronald Elsner, Victoria Kaspi, Jeffery Kolodziejczak, Luca Latronico, Herman L. Marshall, Giorgio Matt, Fabio Muleri, Stephen L. O'Dell, Brian D. Ramsey, Roger W. Romani, Paolo Soffitta, Allyn Tennant

- Bandpass: 2-8 keV
- Imaging: 28" HPD (average)
- Low Earth Orbit, 2+ yr mission
- No proprietary data
- No consumables; only orbit limits mission lifetime
- Detectors (ASI) are working well!
- Over 80 papers, 10+ in press/submitted
- Observing plan is dynamic
- GO program started in February, 2024