

# A new window to the high-energy Universe with the Imaging X-ray Polarimetry Explorer

I. Liodakis  
Institute of Astrophysics - FORTH

The extreme Universe (CTA-Japan Workshop)  
2025



Funded by  
the European Union



European Research Council  
Established by the European Commission



INSTITUTE OF ASTROPHYSICS  
FOUNDATION FOR RESEARCH AND TECHNOLOGY HELLAS

Where is the polarization coming from?

Magnetic fields

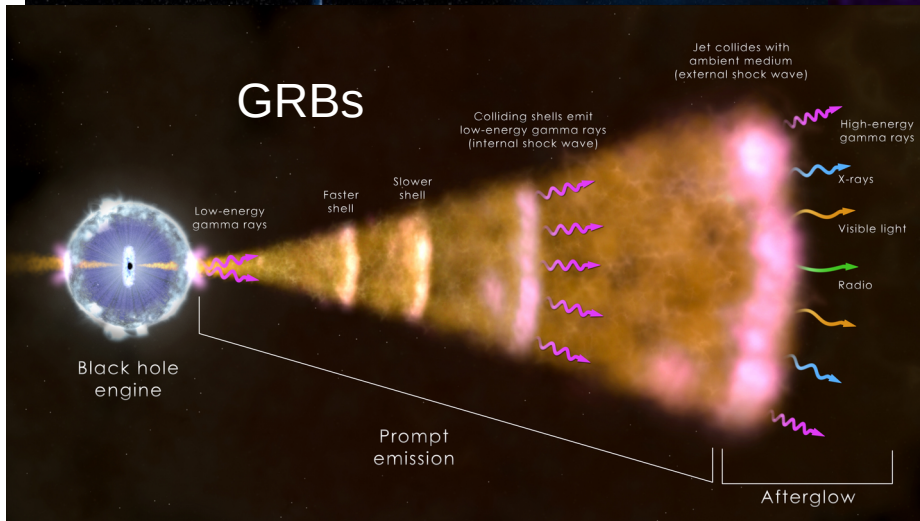
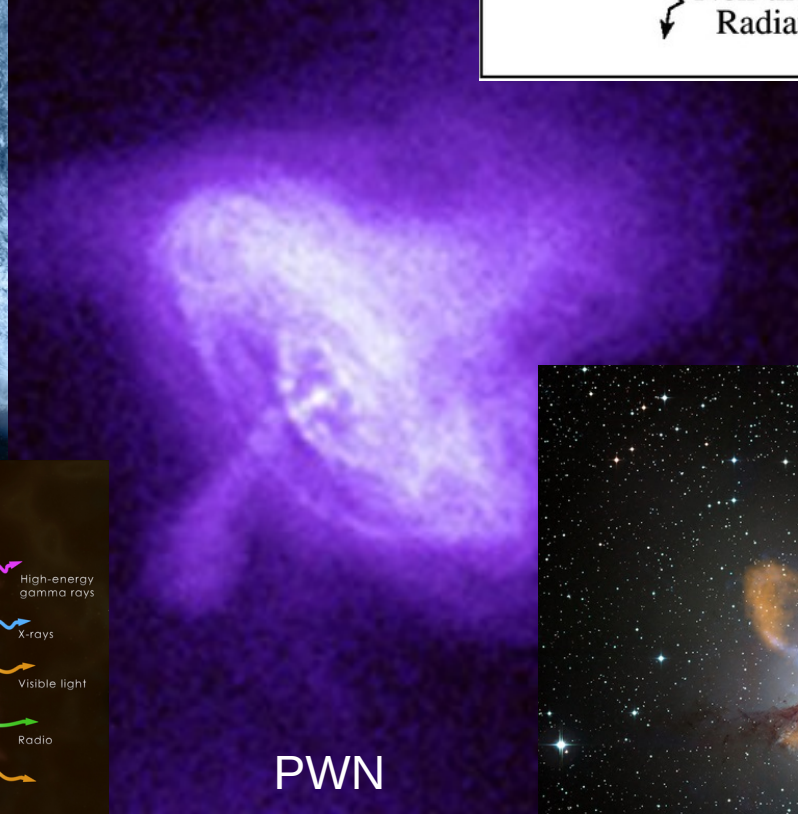
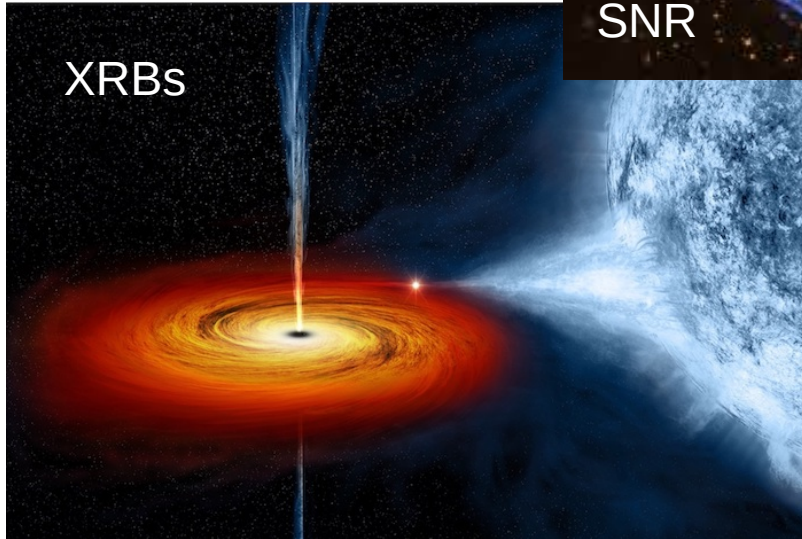
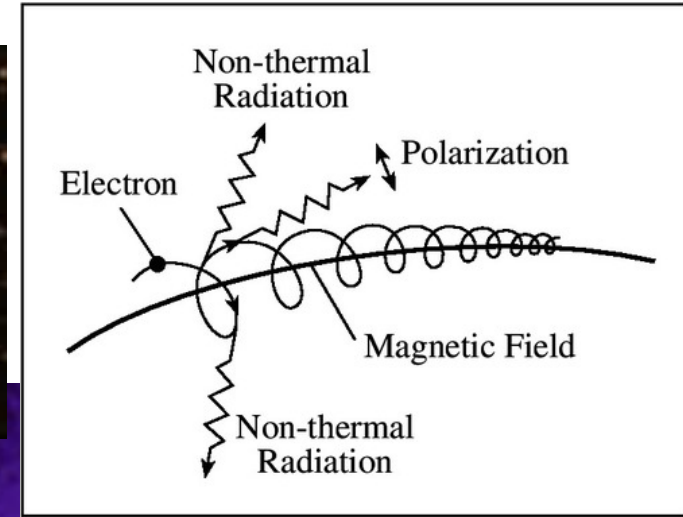
Geometry

# Where is the polarization coming from?

Magnetic fields

Geometry

Synchrotron radiation

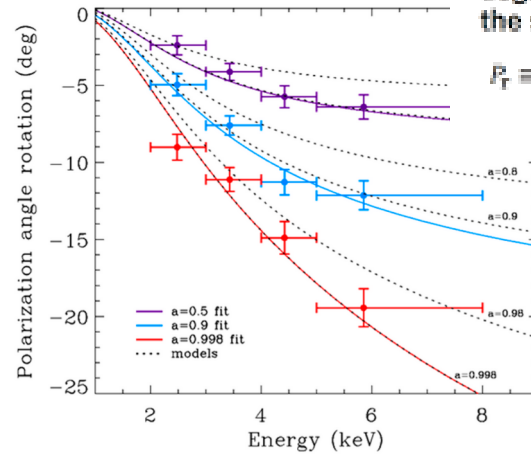
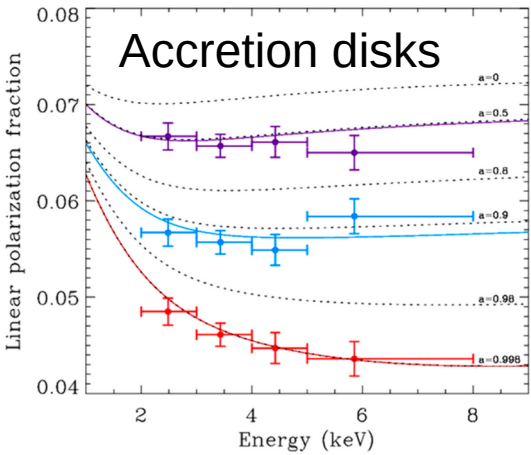
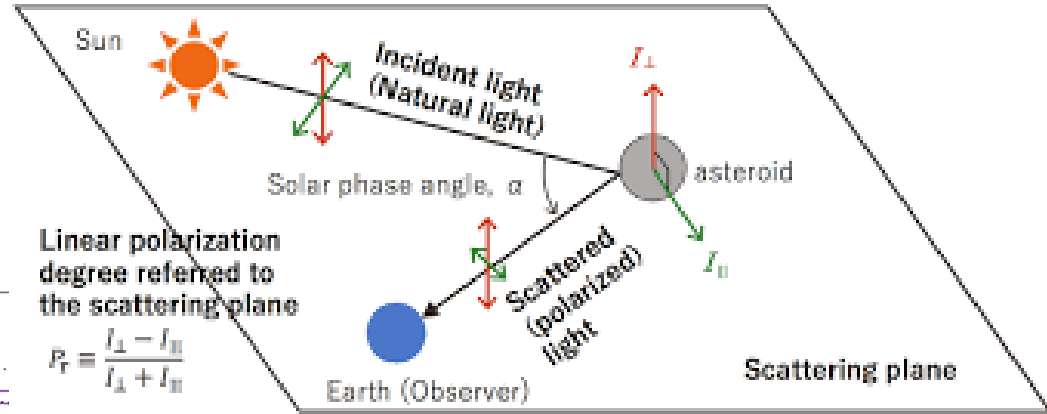


# Where is the polarization coming from?

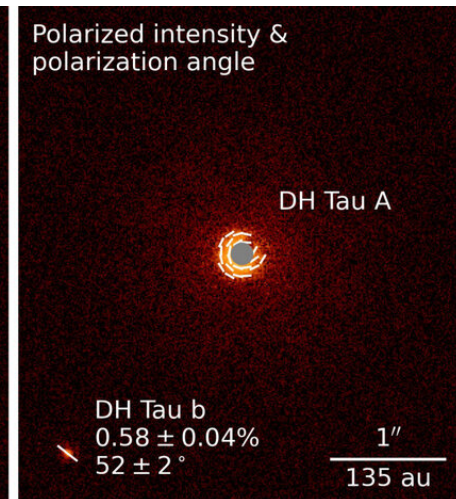
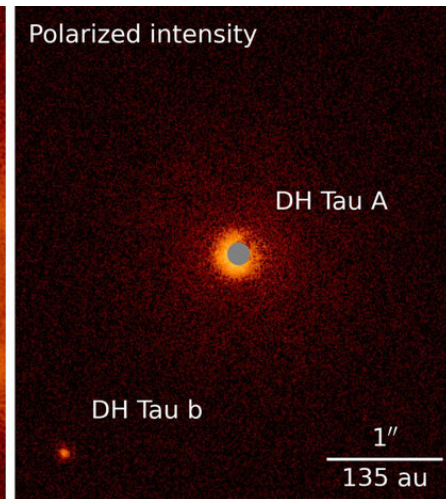
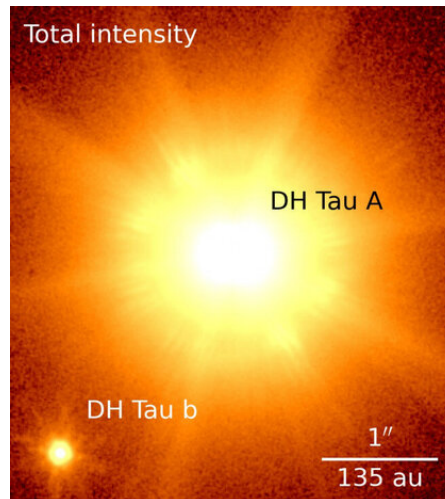
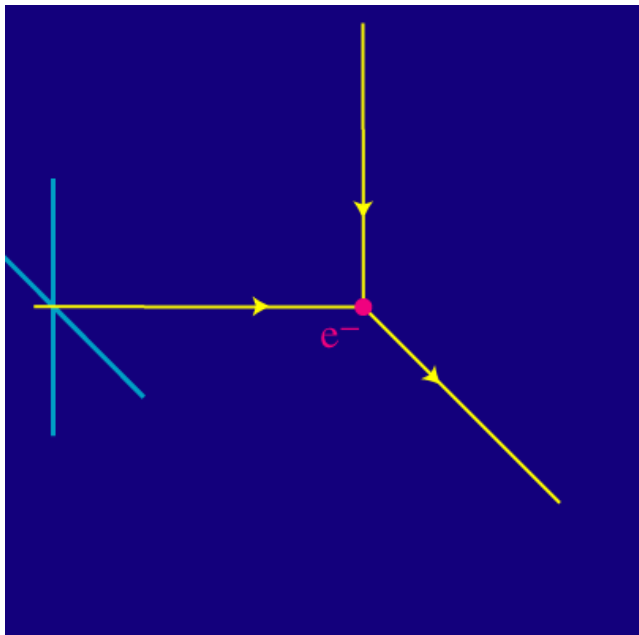
Asteroids

Magnetic fields

Geometry

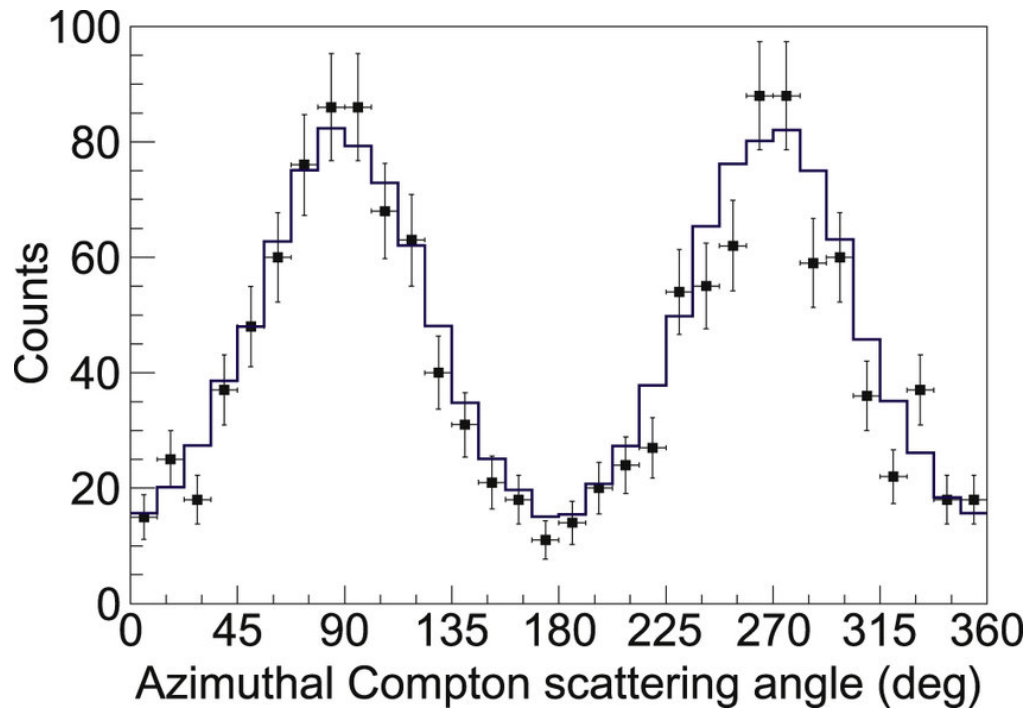
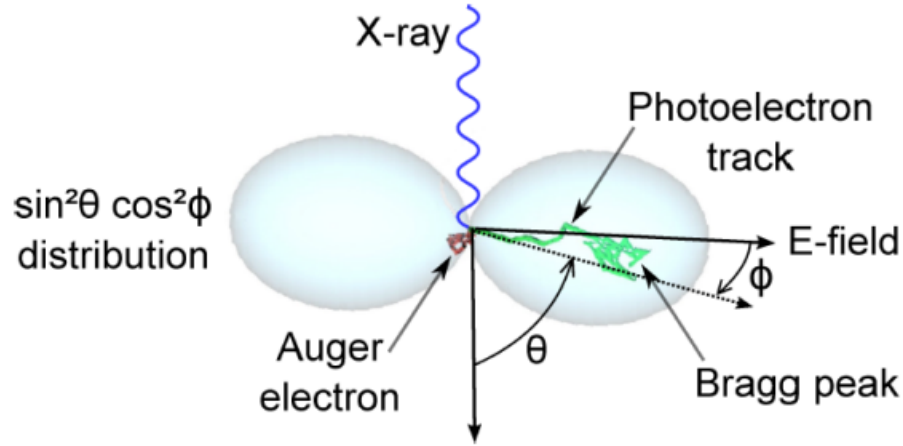


Exoplanets

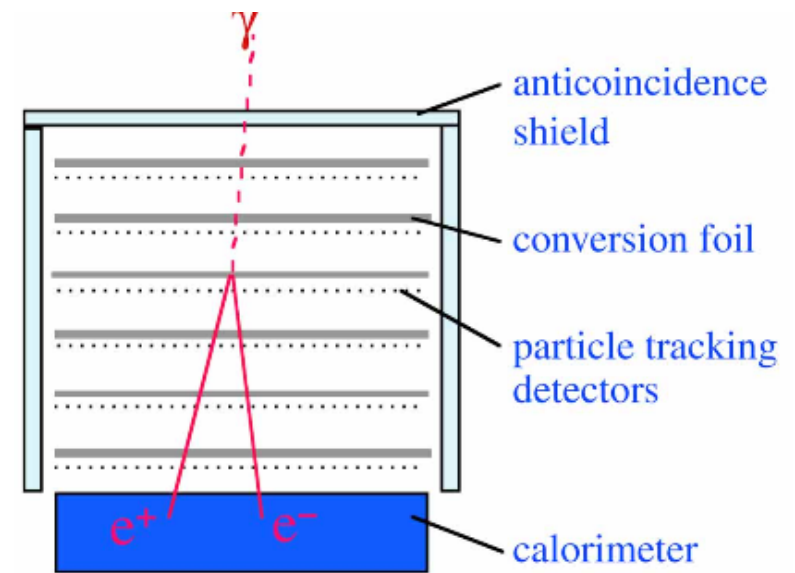
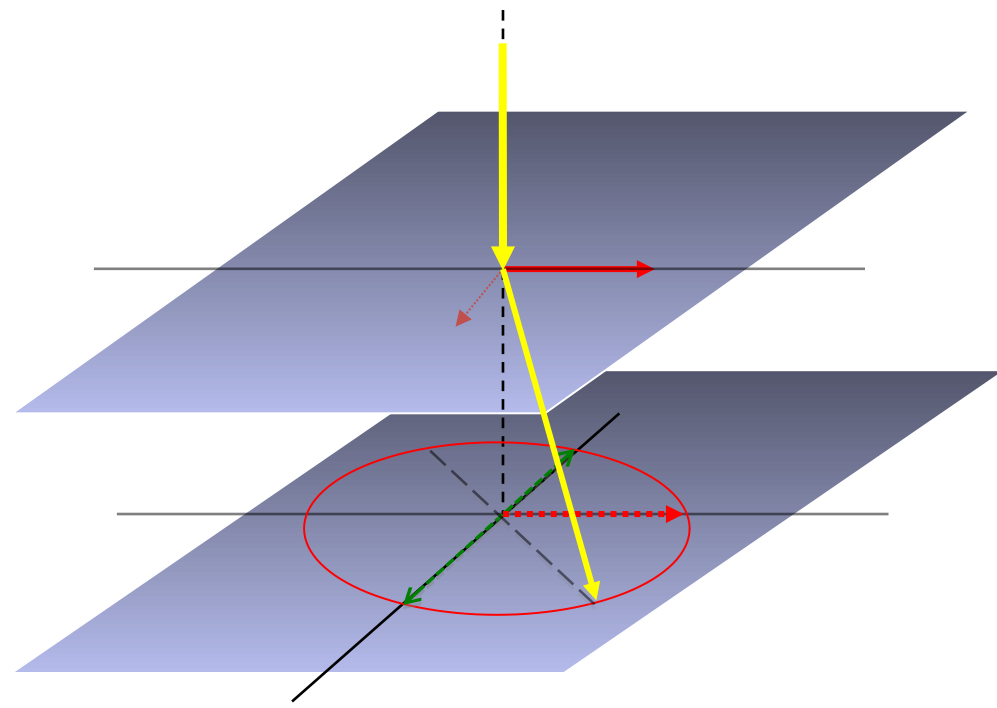


# Polarization at high energies

Photoelectric effect (~1-30 keV)



Compton scattering (~50 keV-30 MeV)



Pair creation (~20 MeV-300 GeV)

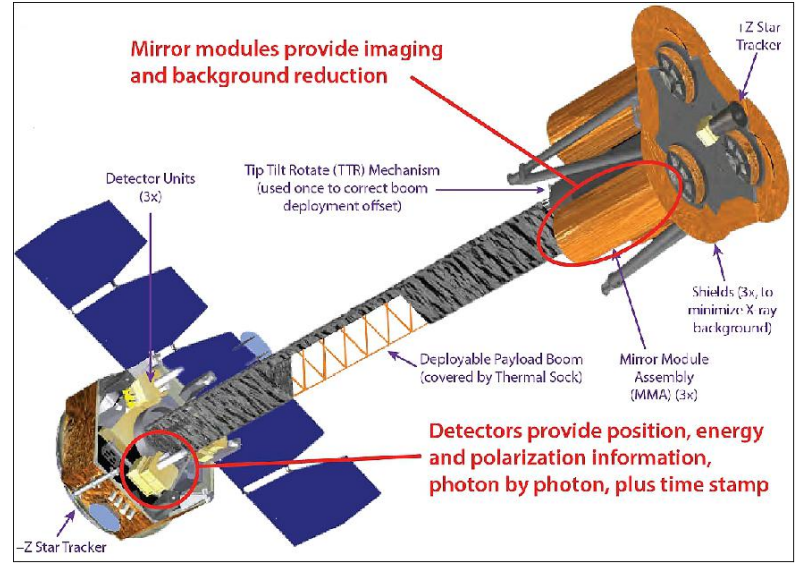
# A new era with the Imaging X-ray Polarimetry Explorer

## IXPE Topical Working Groups

- TWG1 Pulsar Wind Nebulae
- TWG2 Supernova Remnants
- TWG3 Accreting Black Holes
- TWG4 Accreting Neutron Stars
- TWG5 Magnetars
- TWG6 Radio-Quiet AGN & Sgr A
- TWG7 Blazars & Radio Galaxies

**70+ published papers!**  
**More on the way...**  
**+ GO program Cycle 1 on-going!**

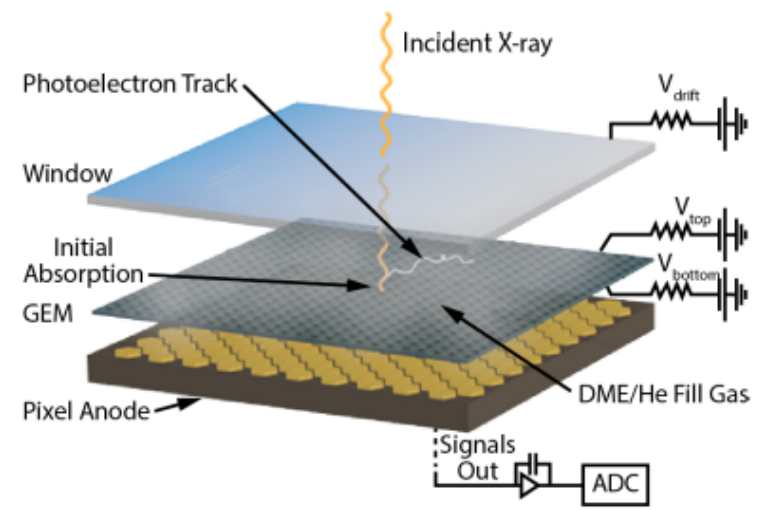
Gas pixel detector



Small NASA mission

Launched Dec 2021

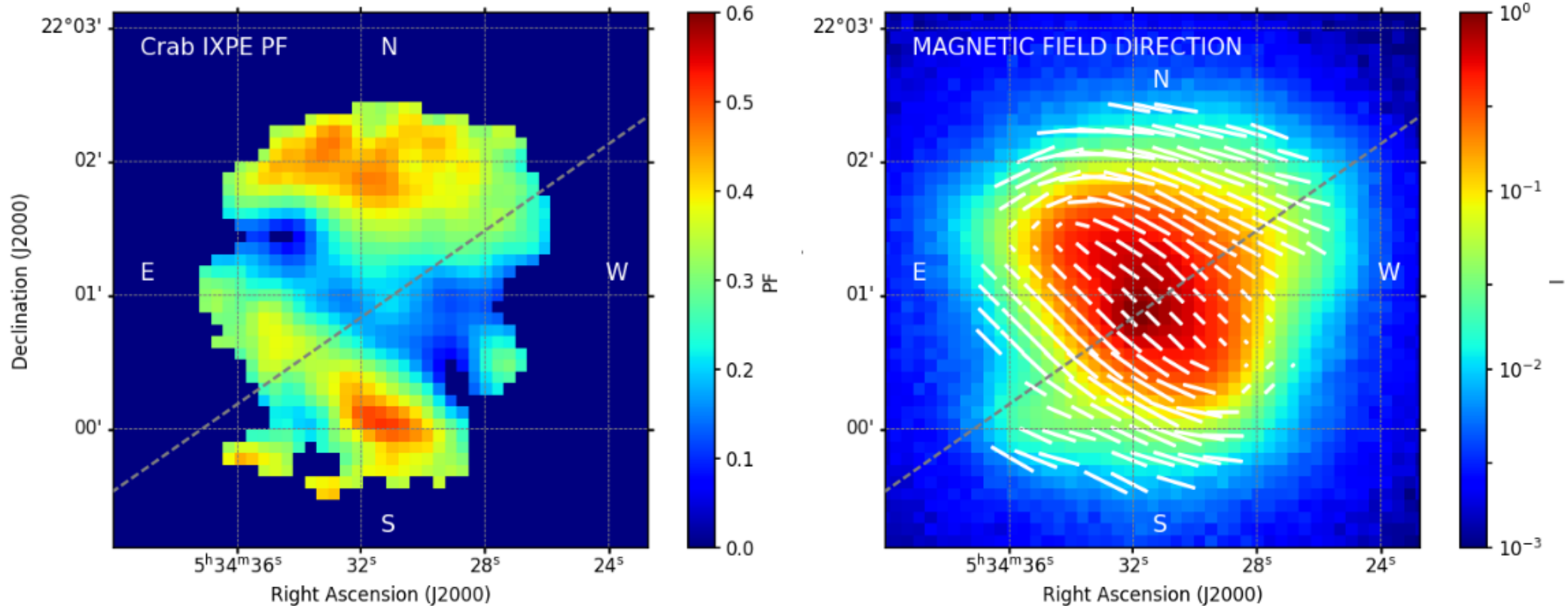
Measuring X-rays in the 2-8 keV energy range



# Crab Nebula & Pulsar

Bucciantini et al.[+IL], (2022)

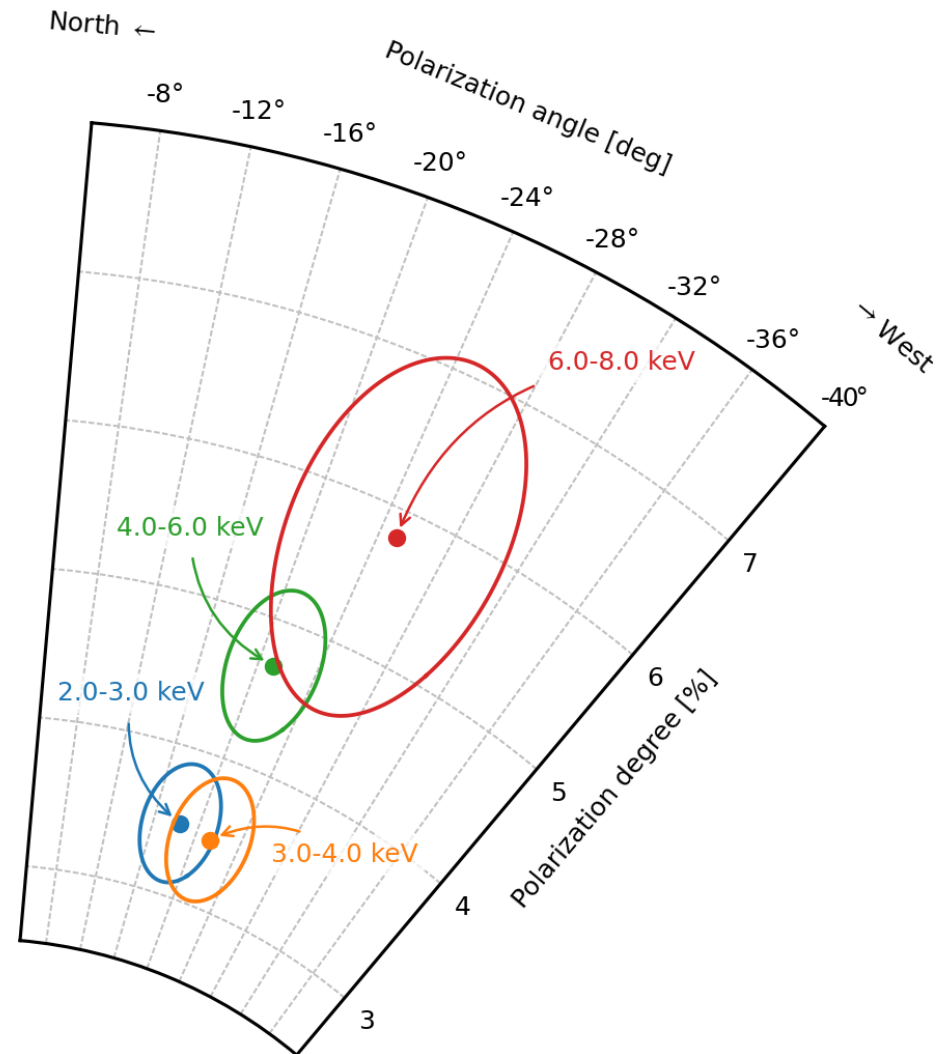
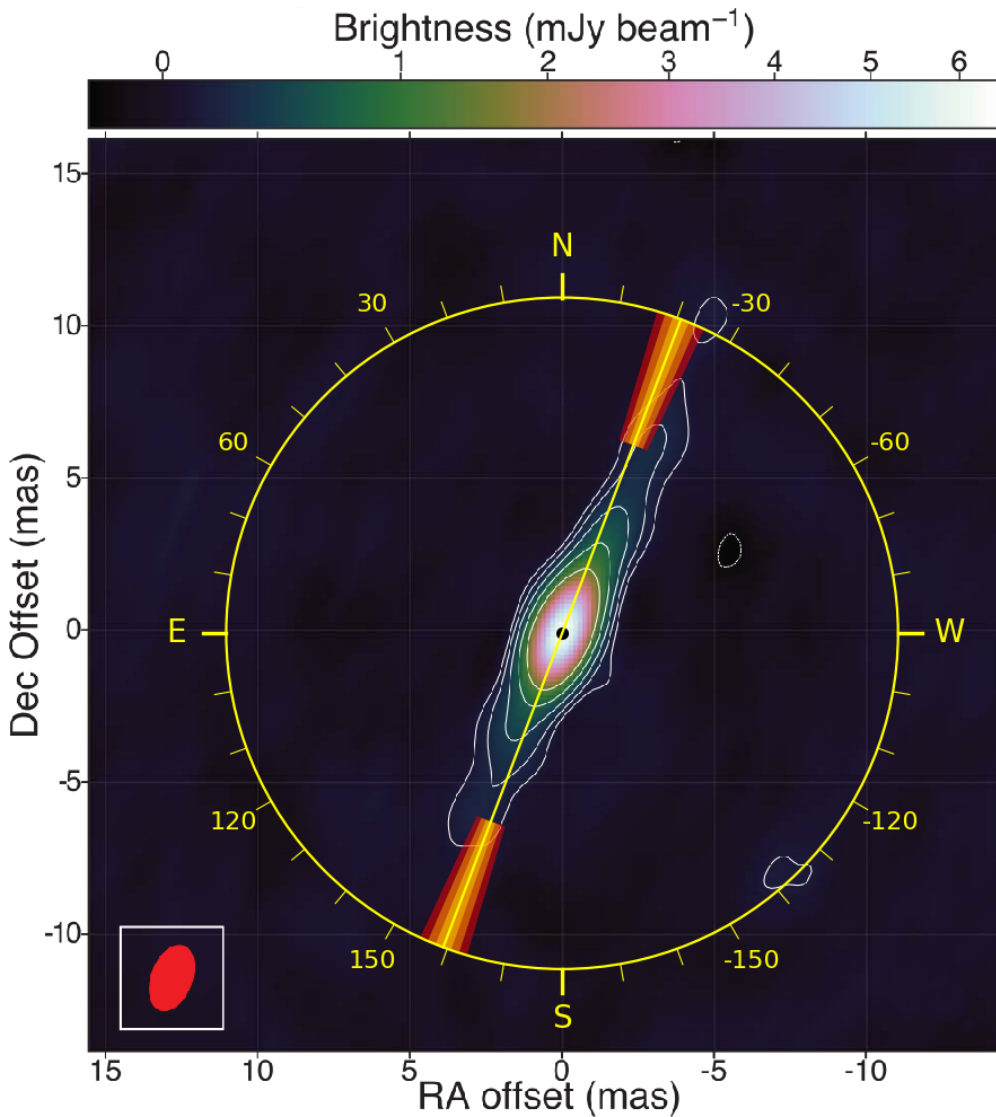
- Integrated polarization consistent with the Weisskopf et al., (1976) measurement
- pulsed emission mostly unpolarized
- large scale toroidal magnetic field



# Cyg X-1

Krawczynski et al.[+IL], (2022)

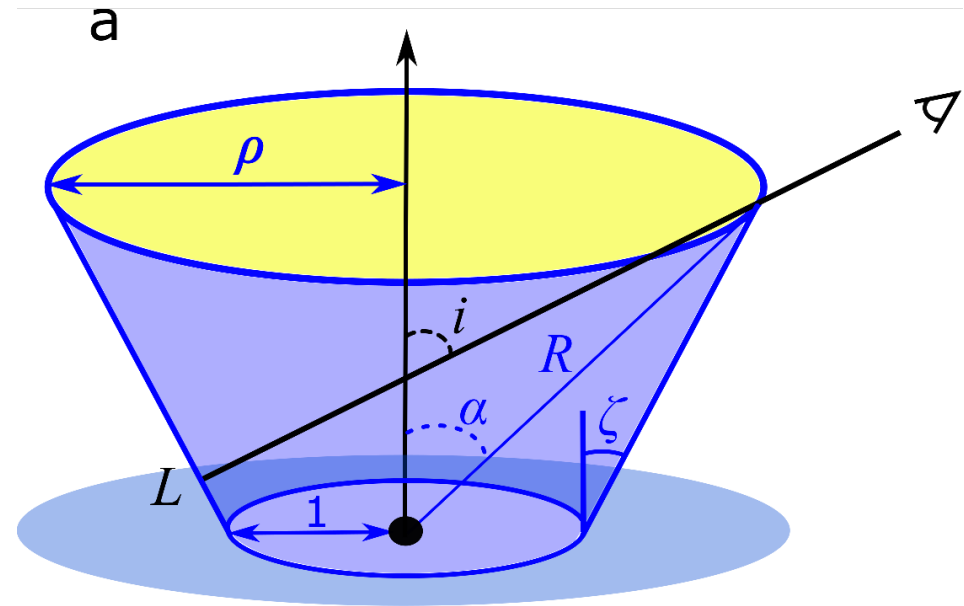
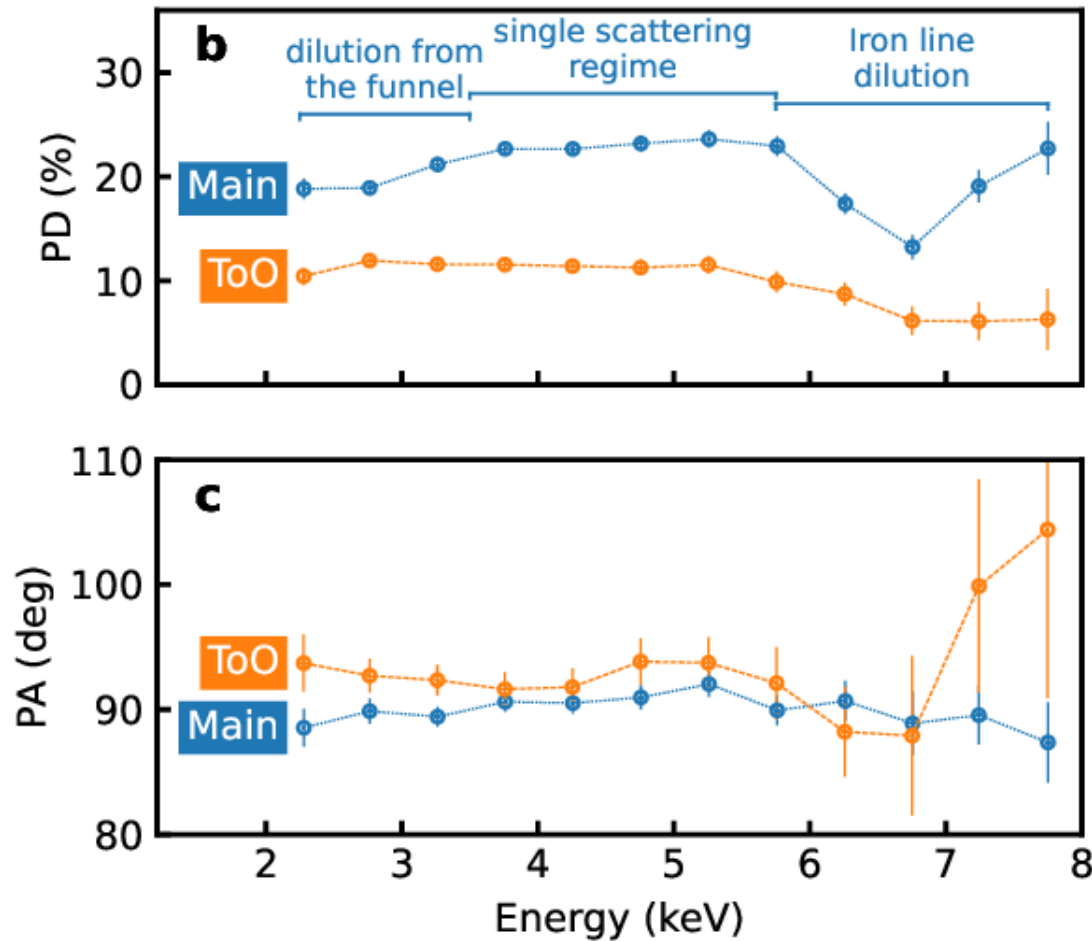
- ~4% polarization in tension with theoretical models
- Polarization angle aligned with the radio jet

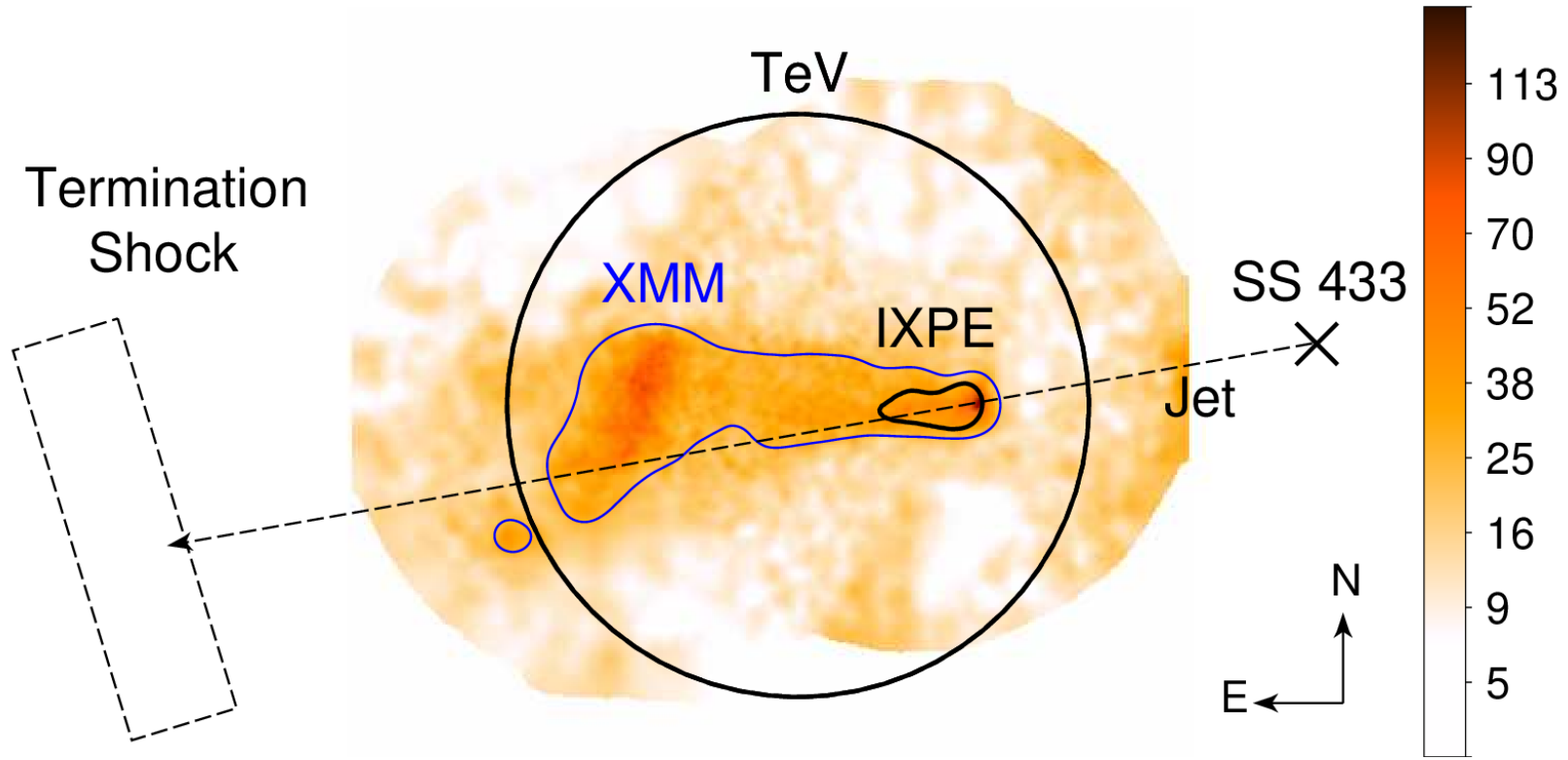




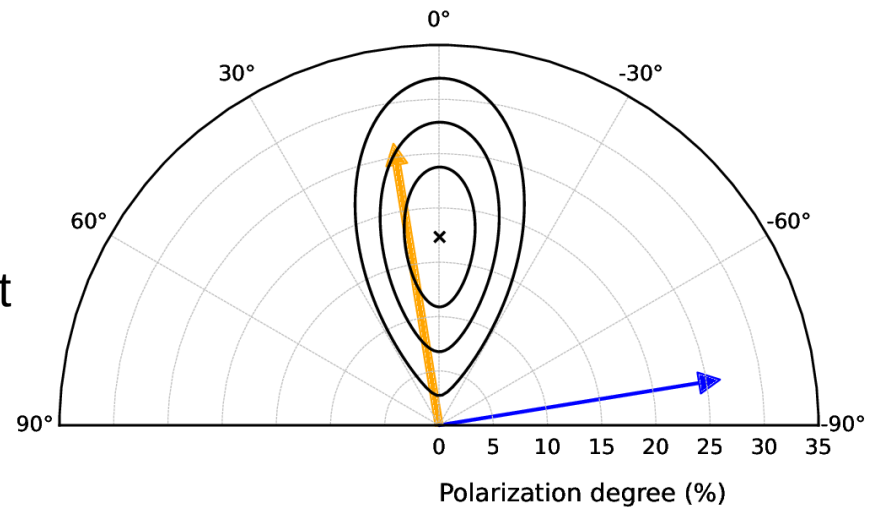
# Cyg X-3

- ~25% energy independent polarization degree
- Polarization angle orthogonal with the radio jet





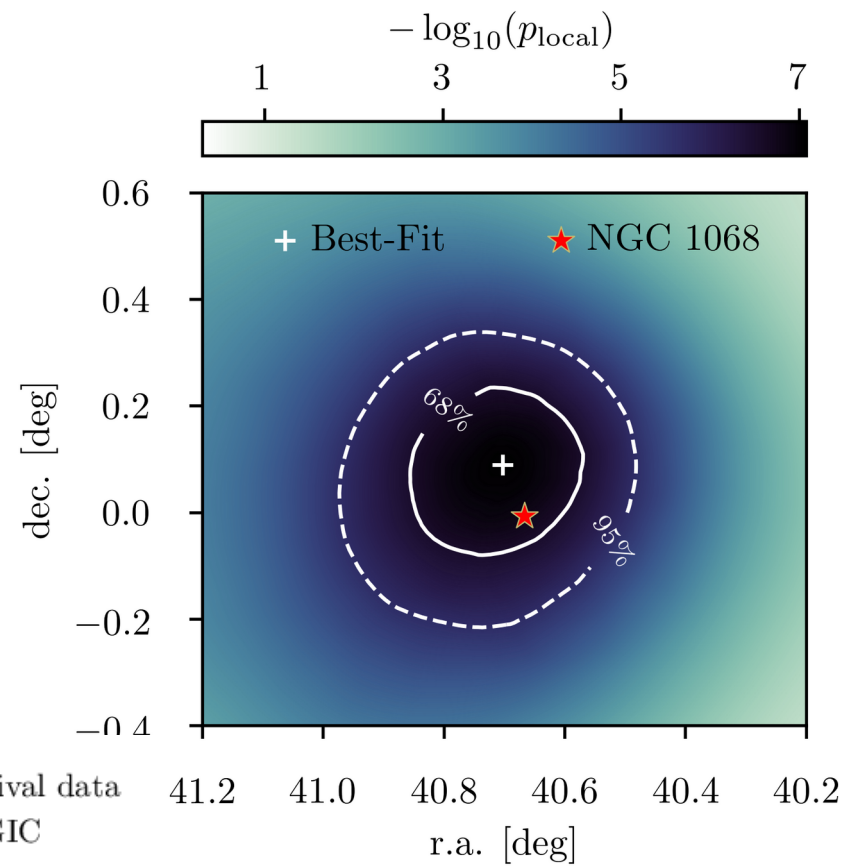
- Highly polarized (38% - 77%)
- Polarization angle orthogonal with the radio jet



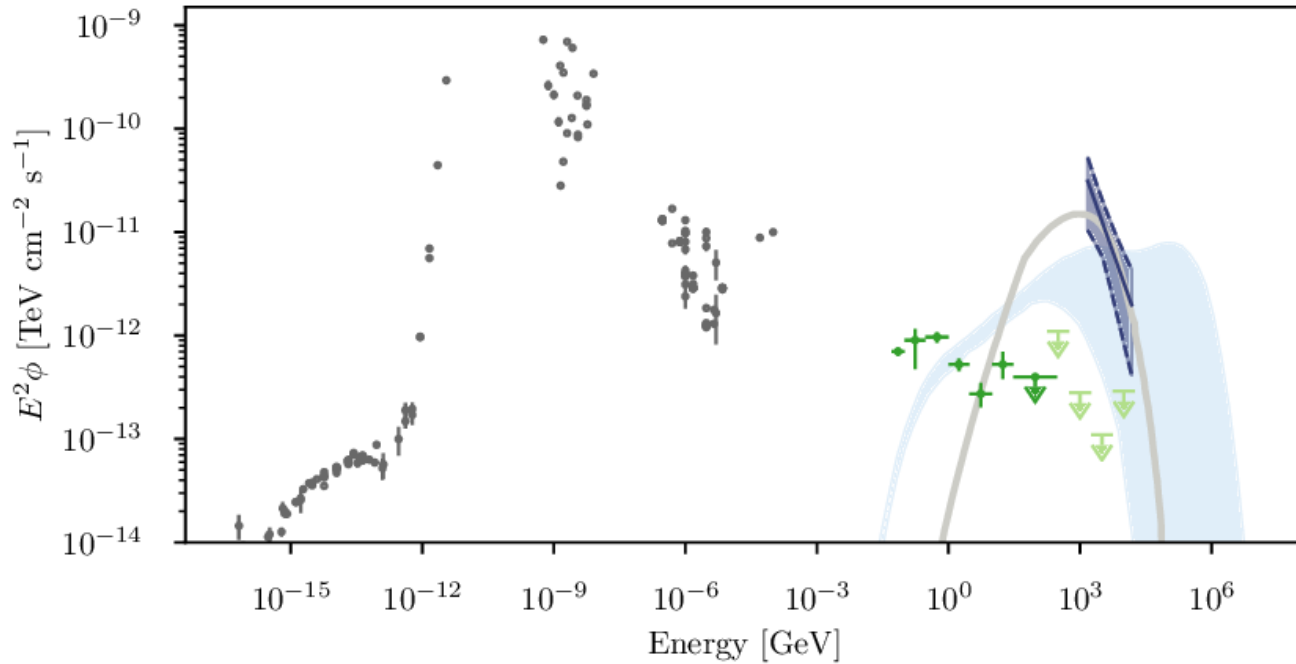
# NGC 1068

~4.2 $\sigma$  post-trial detection (110 source sample)

Coincident with the strongest hotspot on the sky



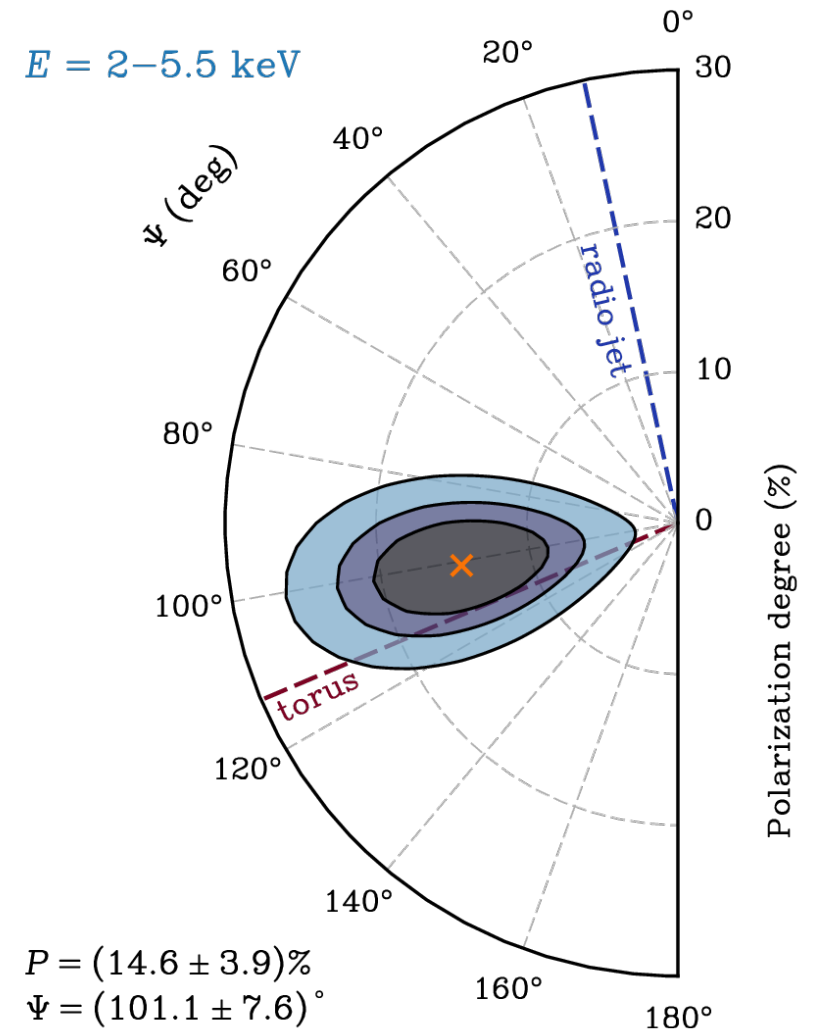
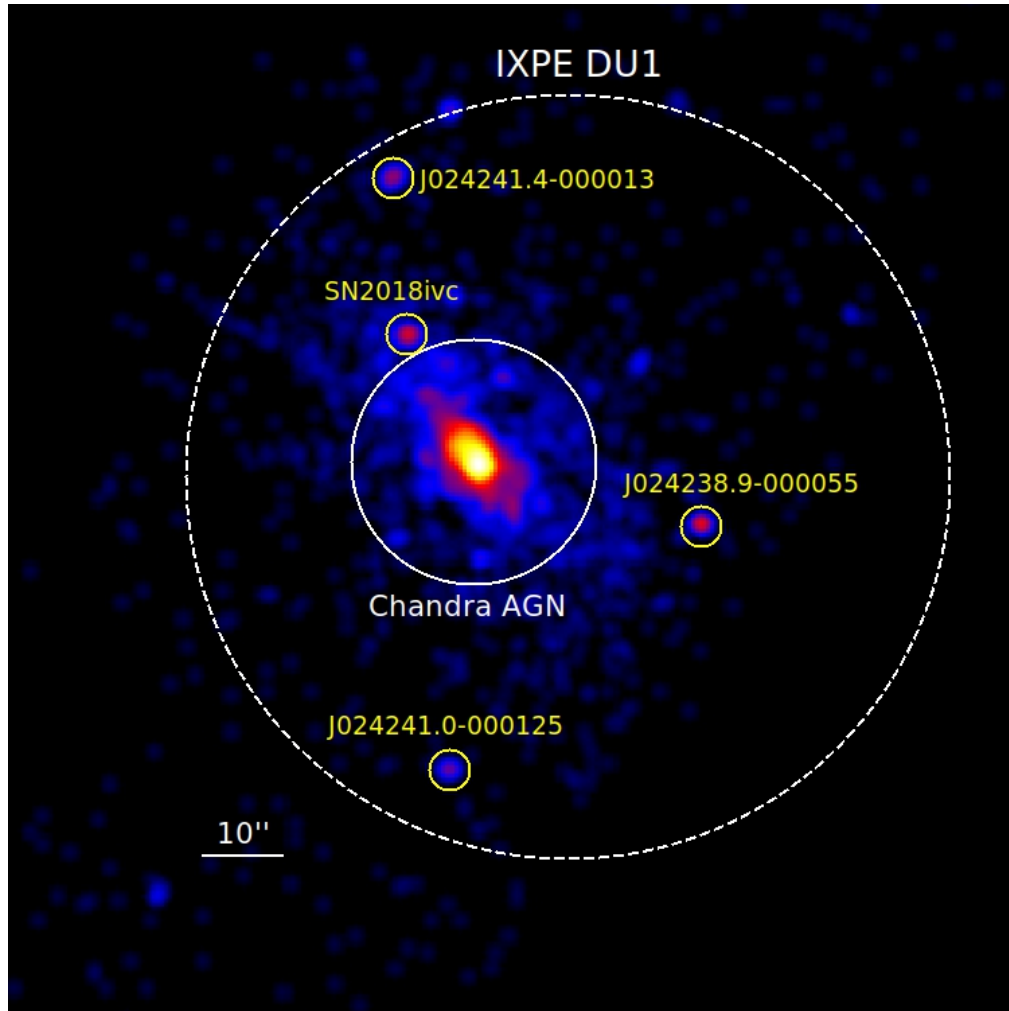
— Murase et al  $\nu_\mu + \bar{\nu}_\mu$     IceCube  $\nu_\mu + \bar{\nu}_\mu$     † Archival data  
— Inoue et al  $\nu_\mu + \bar{\nu}_\mu$     + 4FGL-DR2    + MAGIC



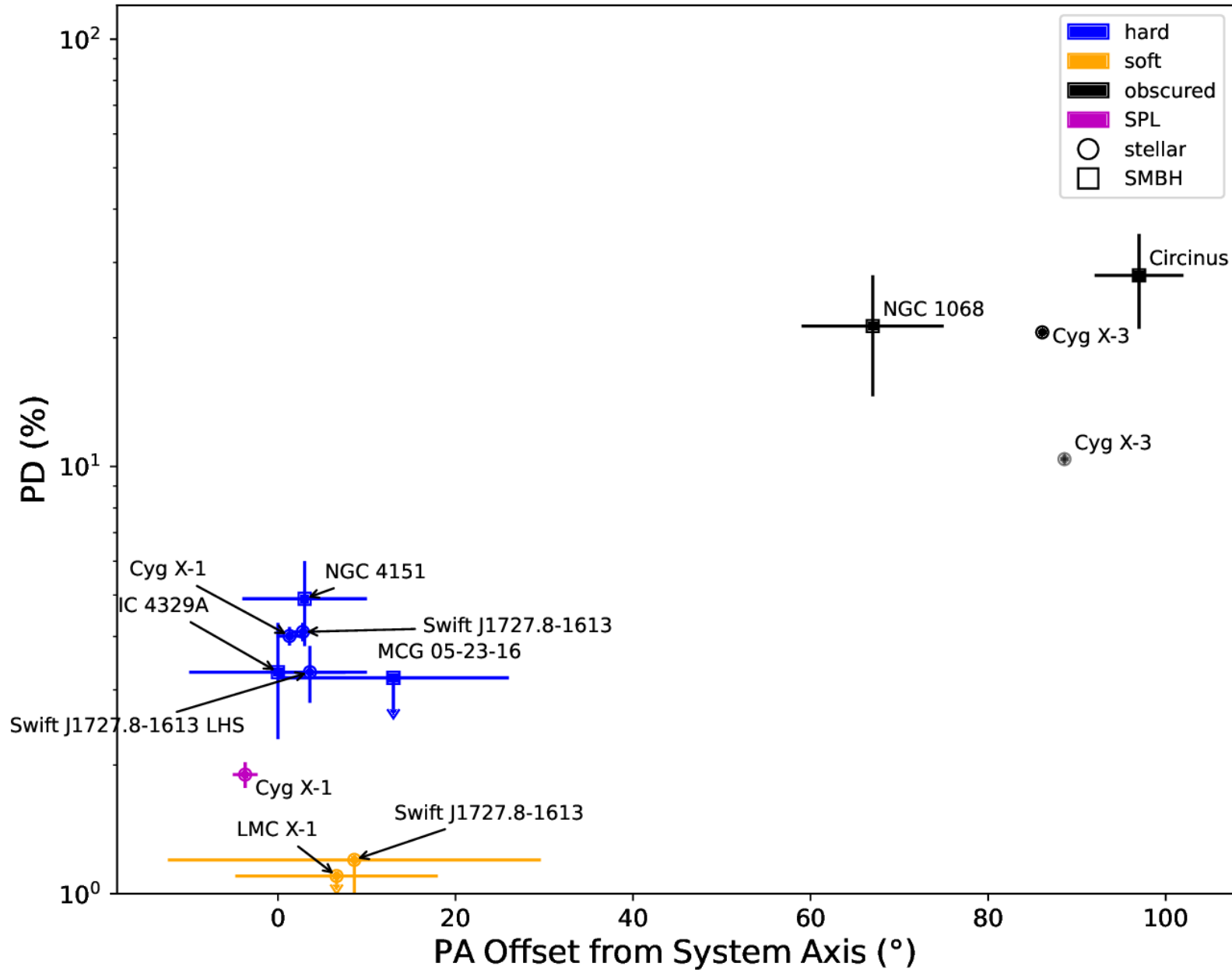
# NGC 1068

Marin et al. [+IL], (2024)

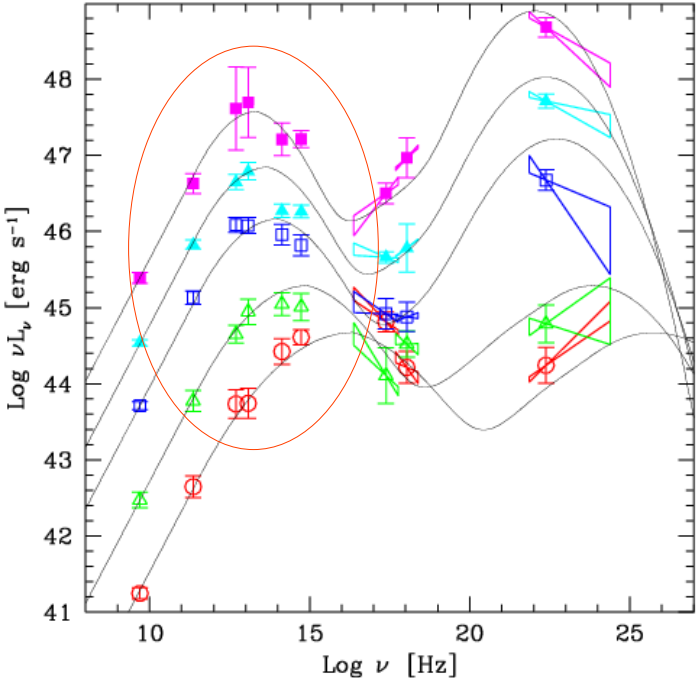
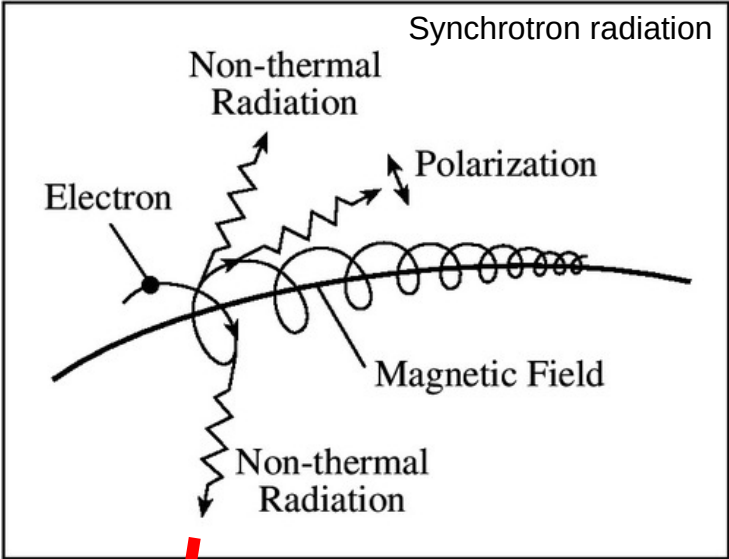
~14% roughly perpendicular to the radio jet  
(~21% at the 3.5-6 keV)



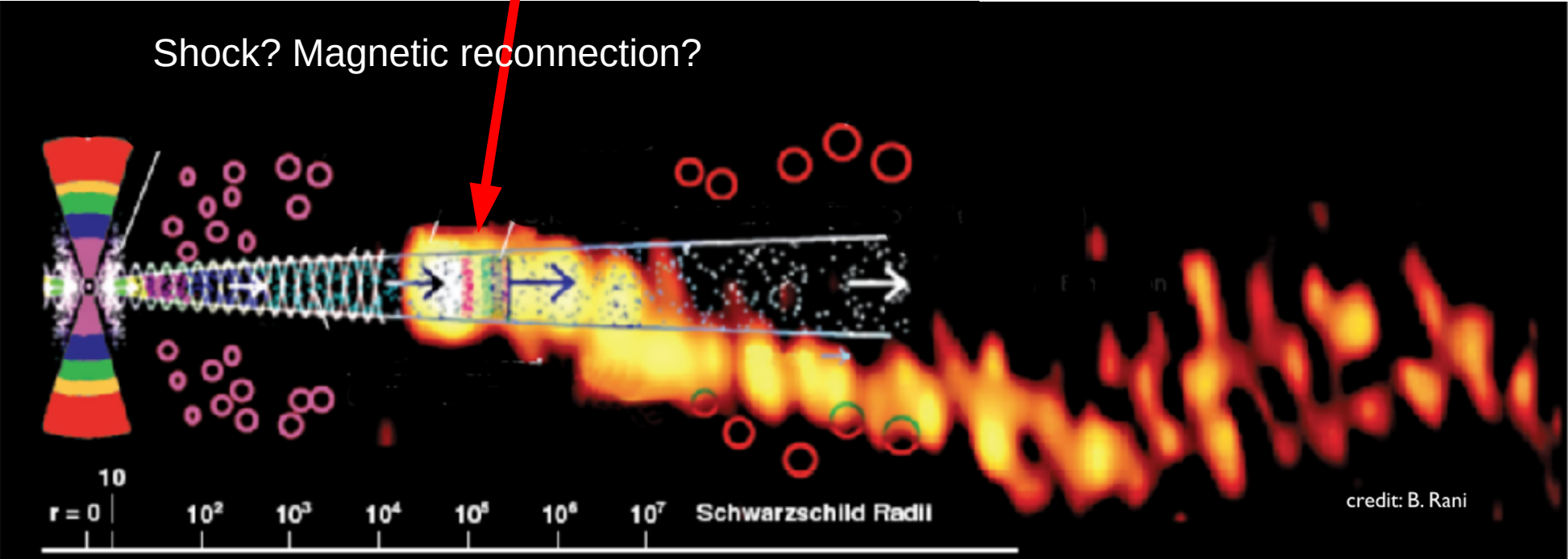
# Unified polarization properties of BHs



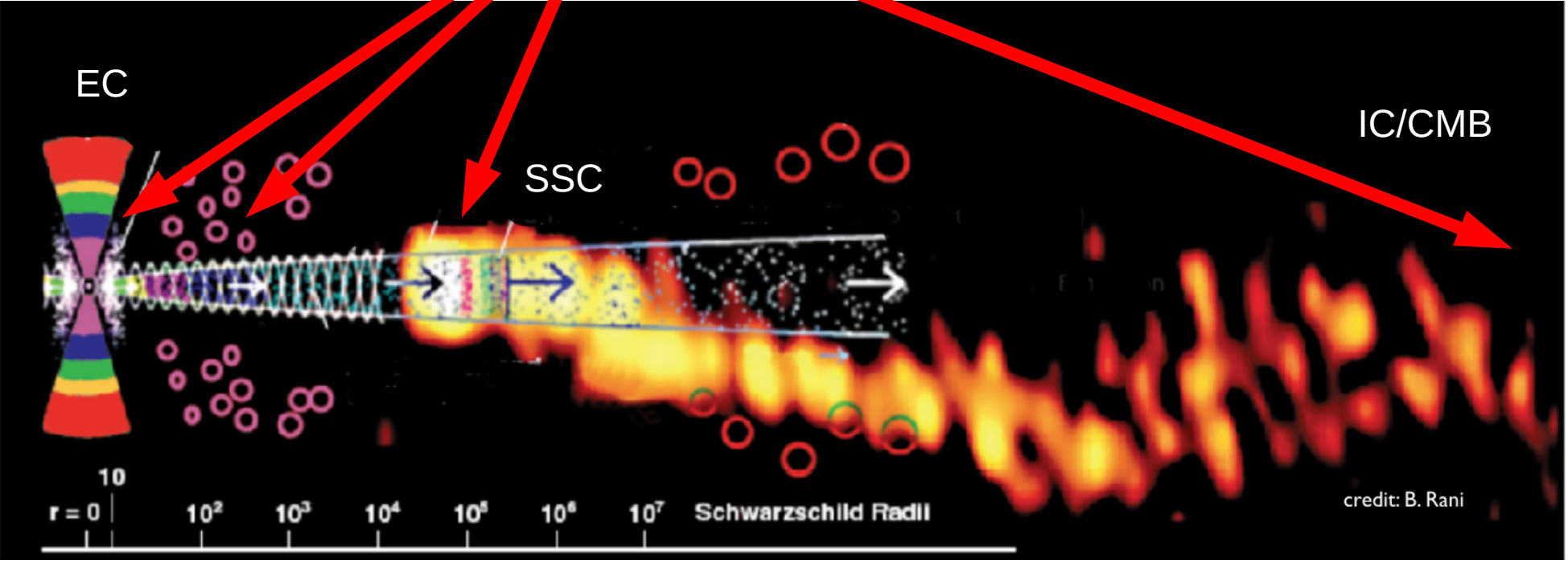
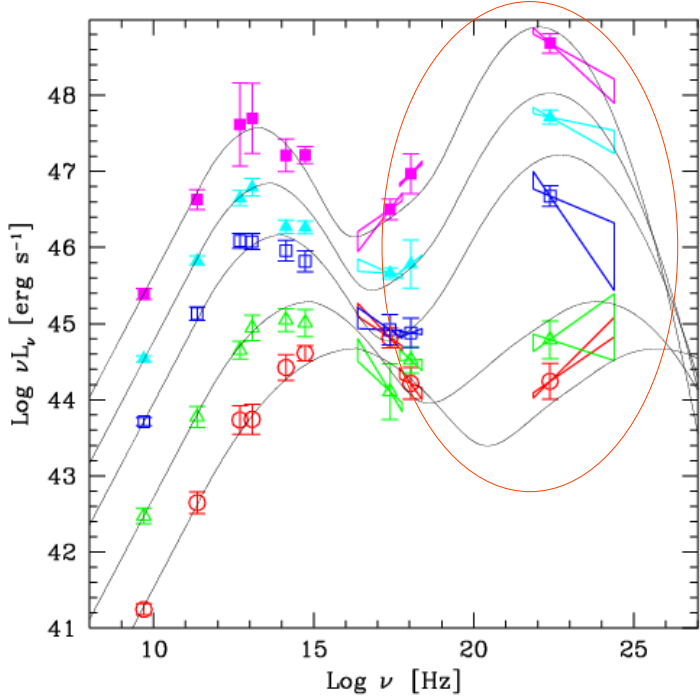
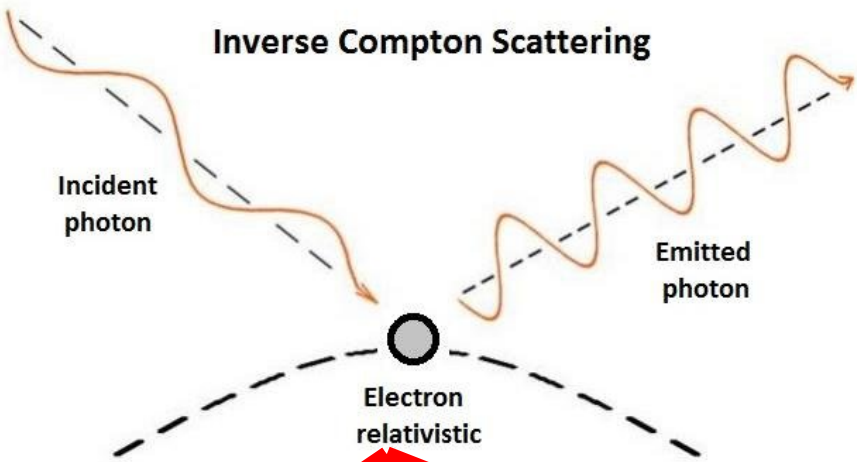
# How do blazars make light?



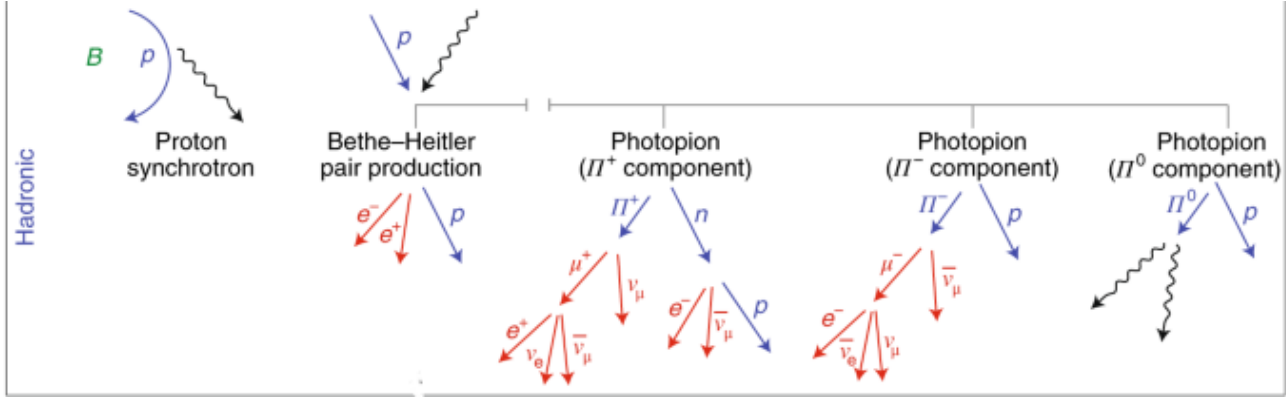
Shock? Magnetic reconnection?



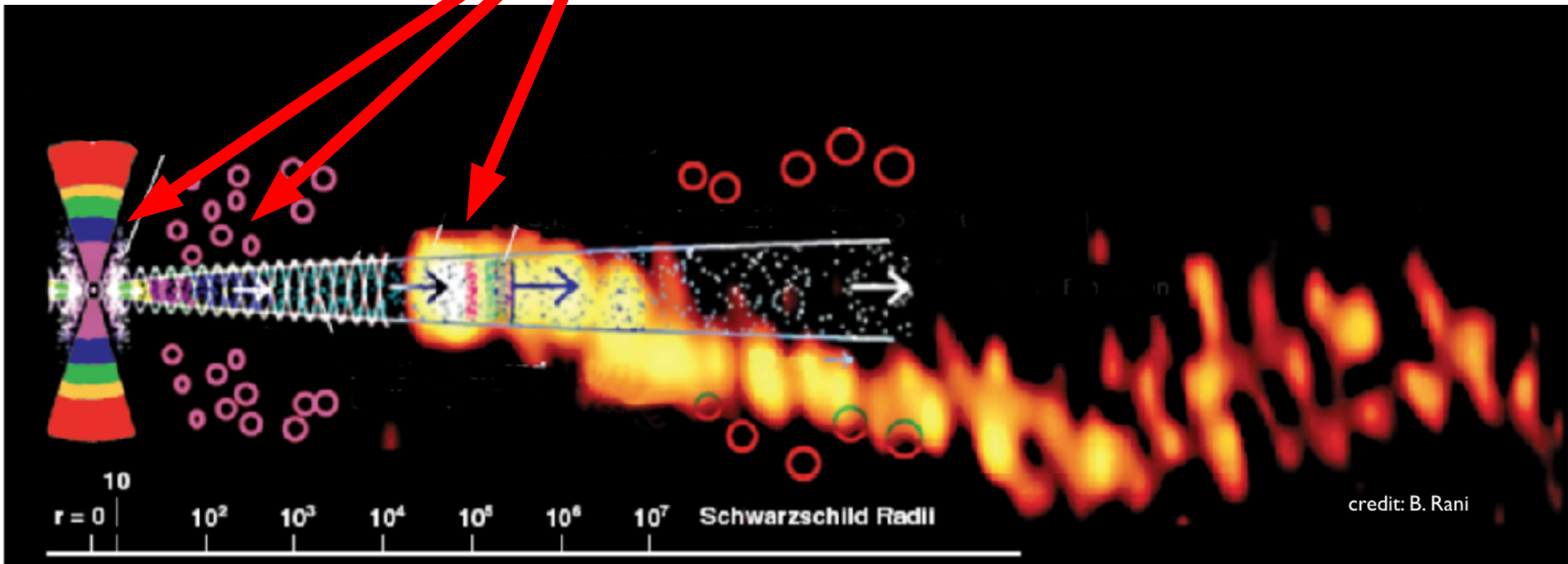
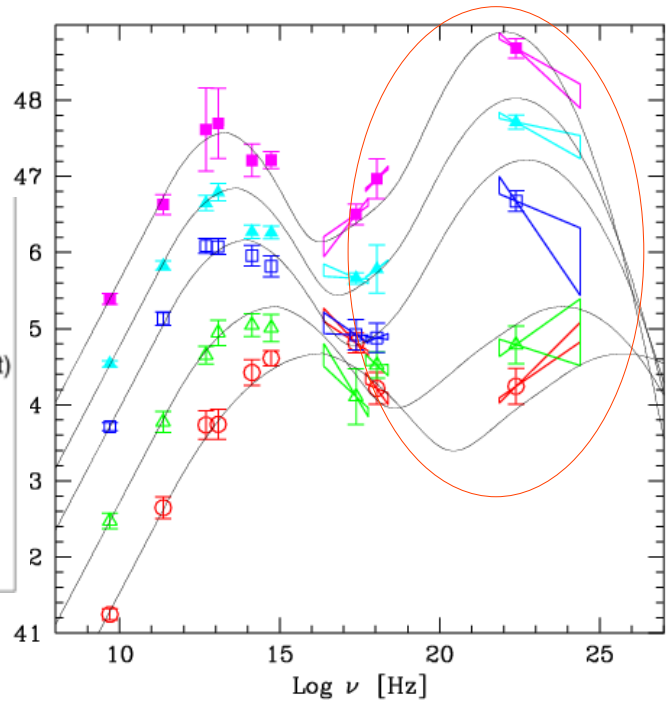
# How do blazars make light?



# How do blazars make light?



???





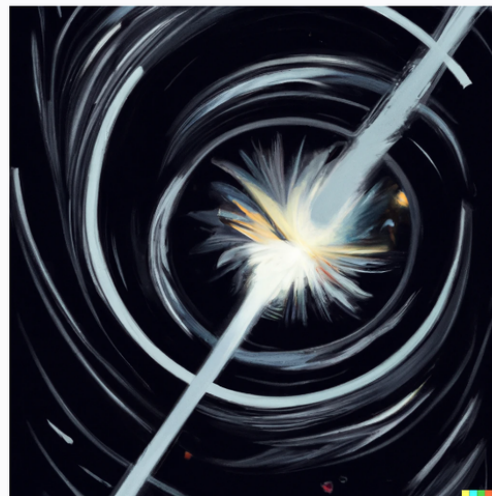
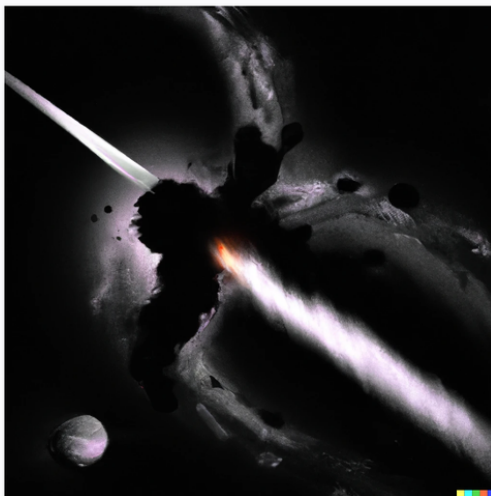
## **Blazar-IXPE key science question v1:**

*How are particles accelerated?*

## **Blazar-IXPE key science question v2:**

*What is the origin of their high-energy emission?*

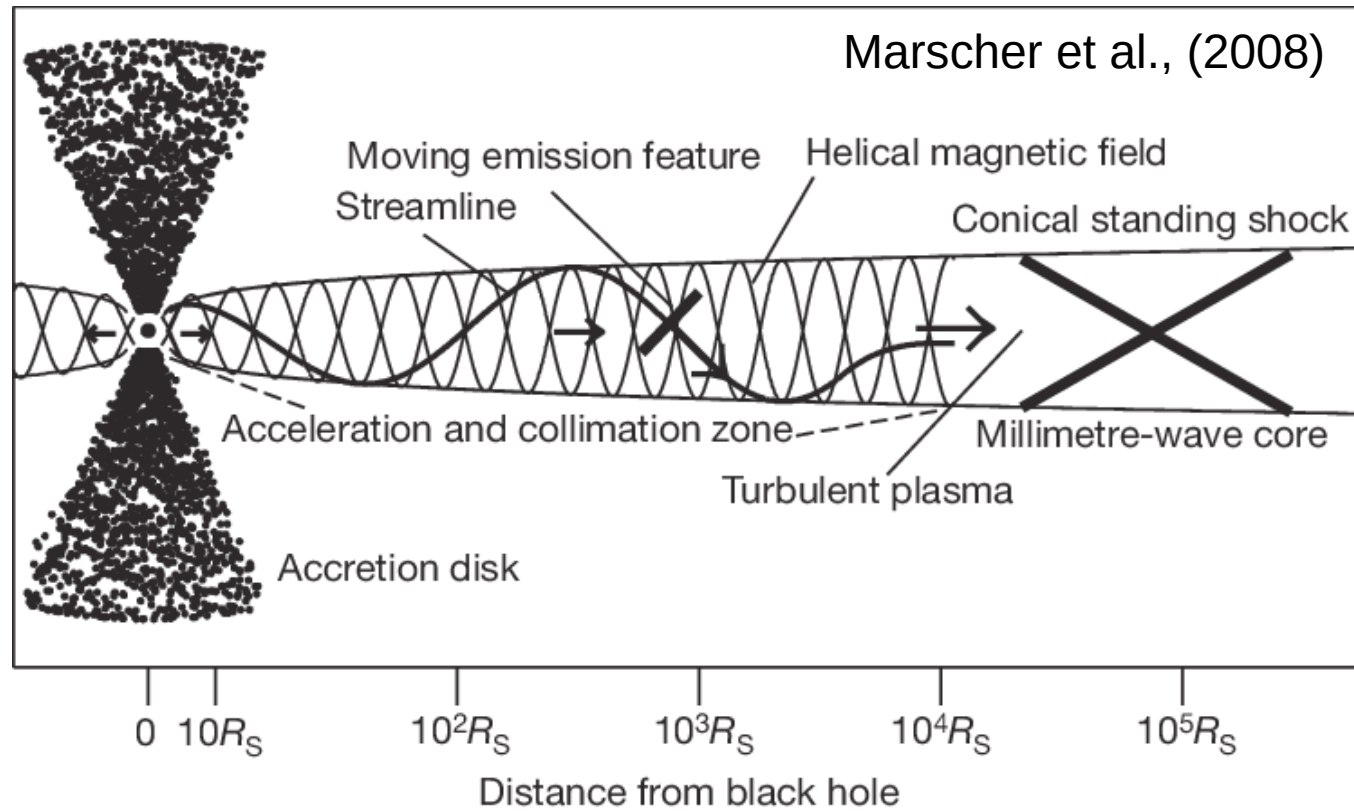
*What is the composition of the jets?*



# How are particles accelerated?

Shocks?

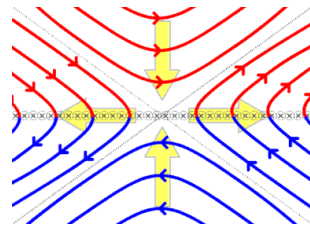
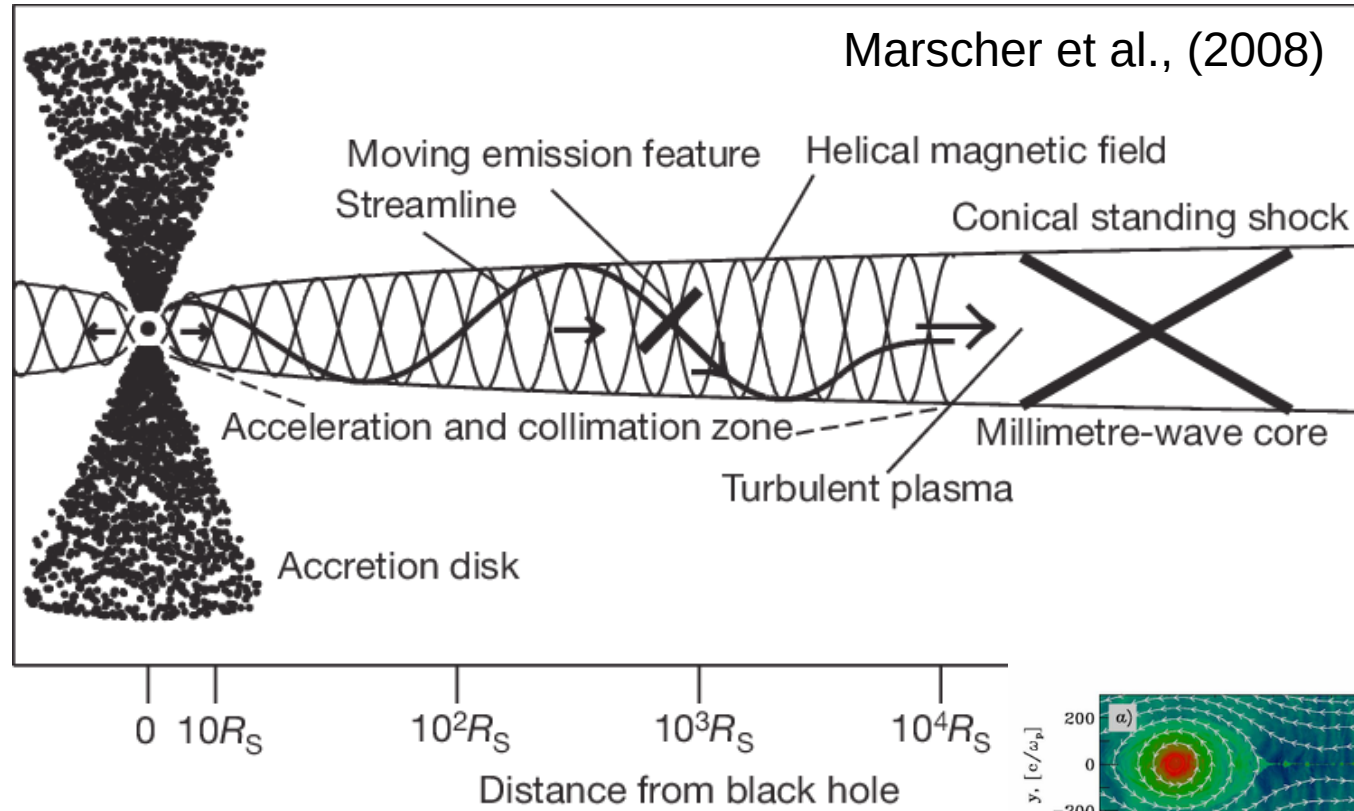
Marscher et al., (2008)



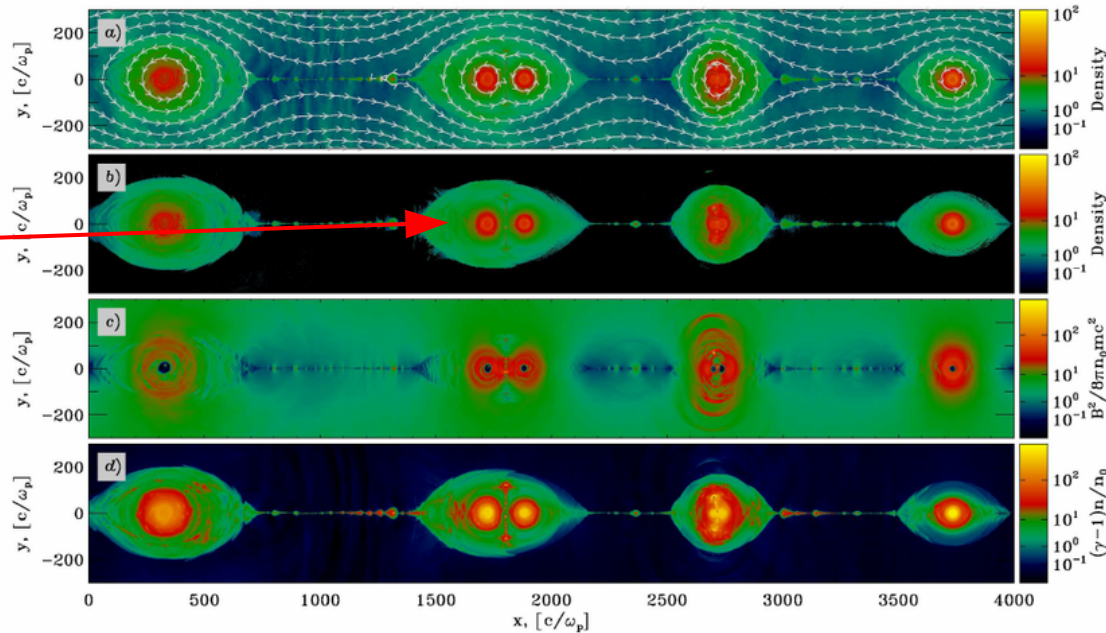
# How are particles accelerated?

Shocks?

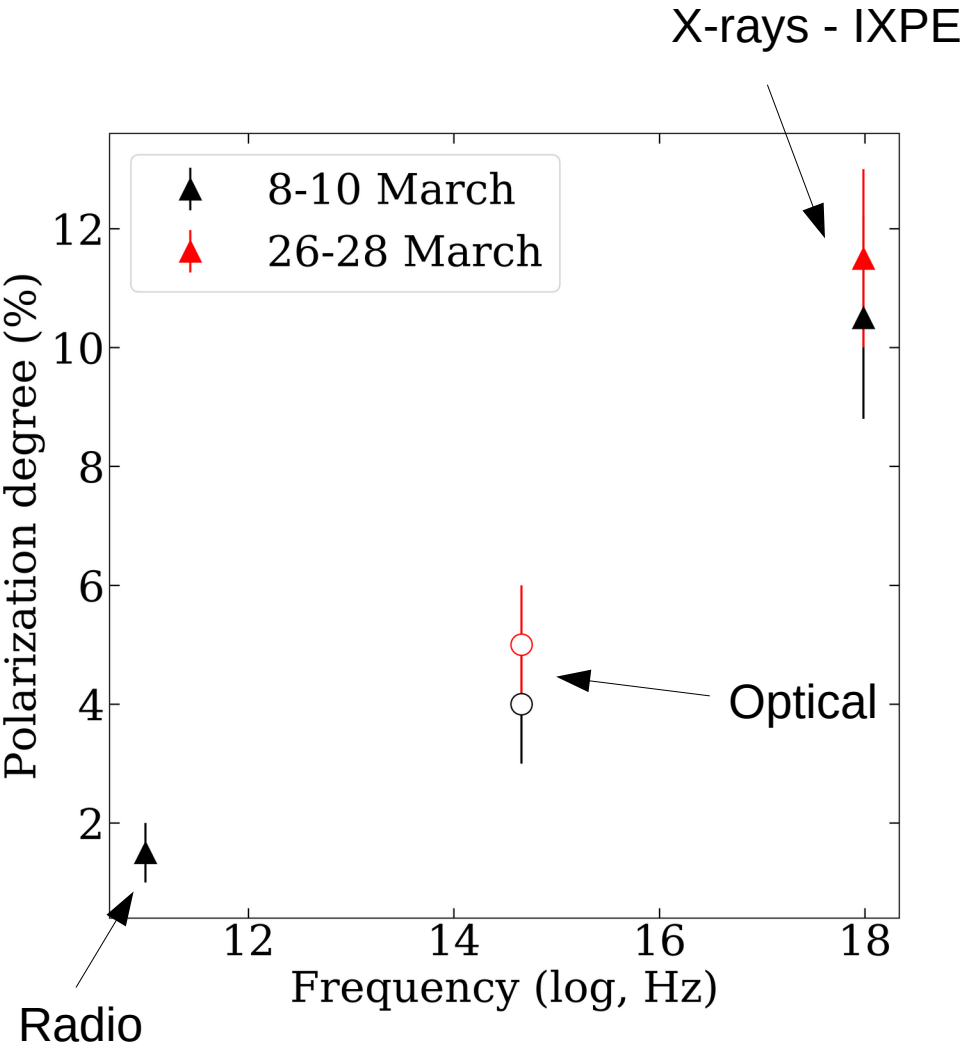
Marscher et al., (2008)



Magnetic reconnection?  
Sironi et al., (2013)



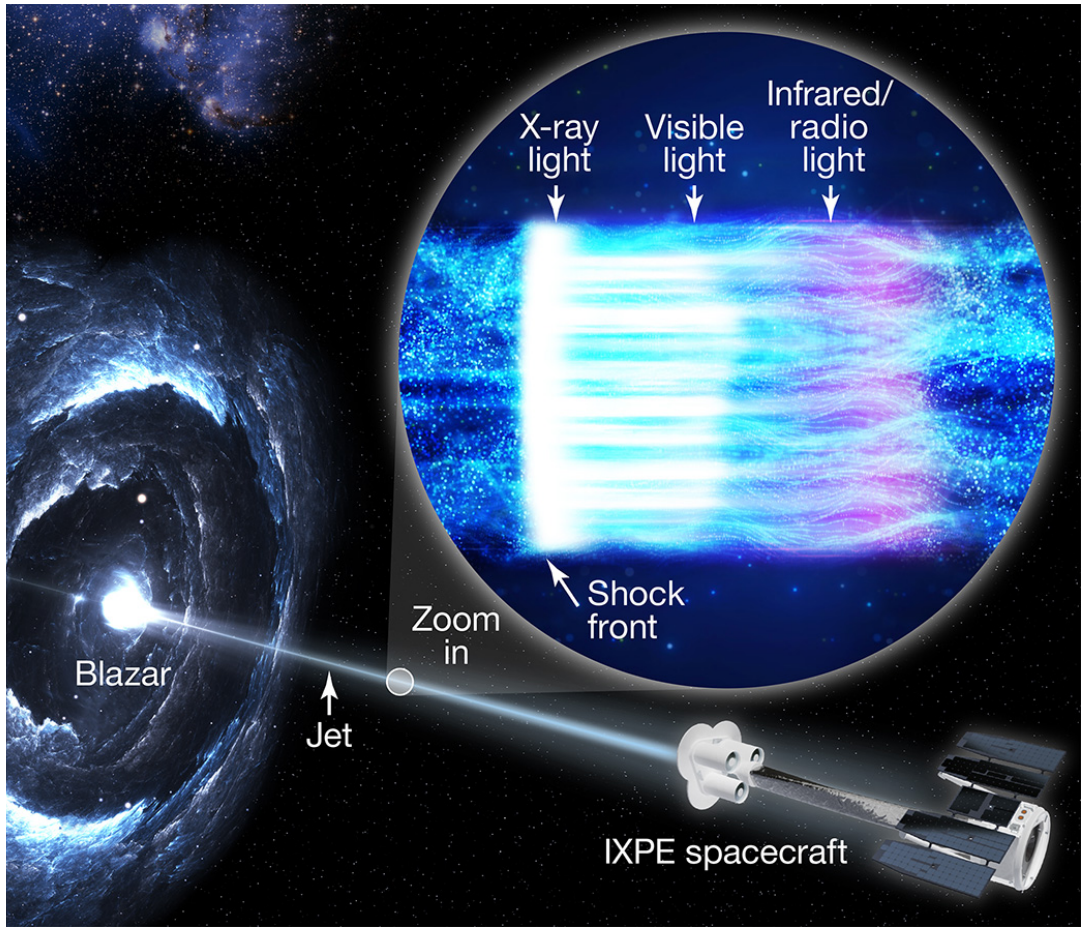
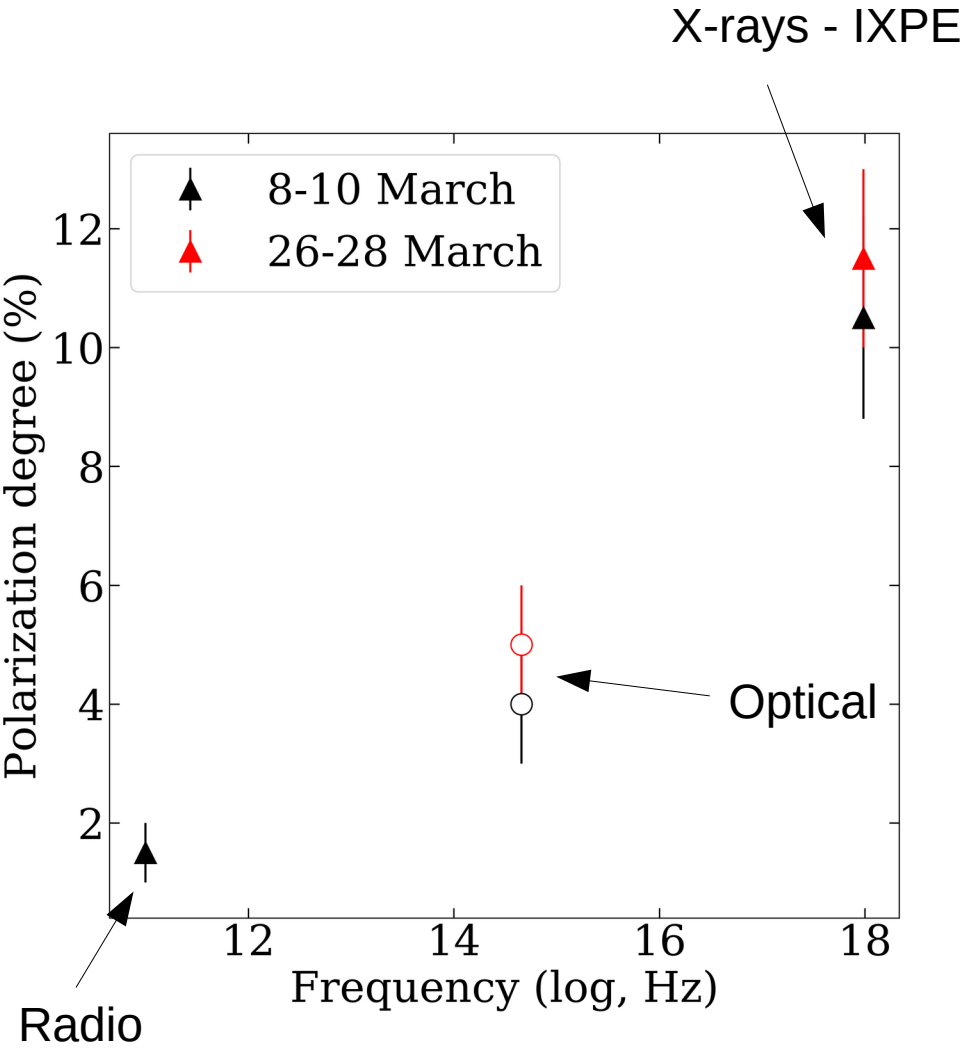
# First detection of X-ray polarization from a supermassive black hole!



*Markarian 501*

Lioudakis et al., 2022, arXiv:2209.06227

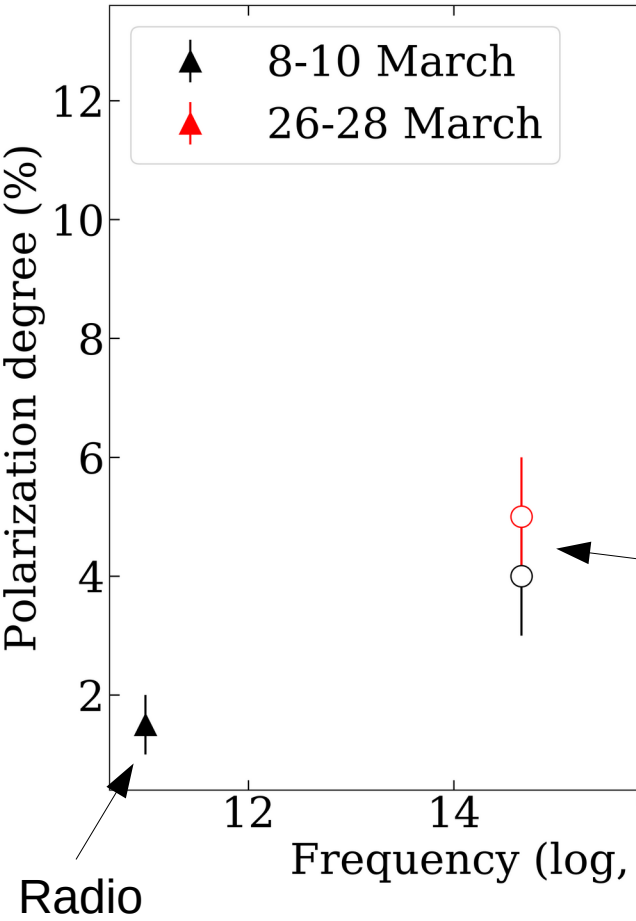
# First detection of X-ray polarization from a supermassive black hole!



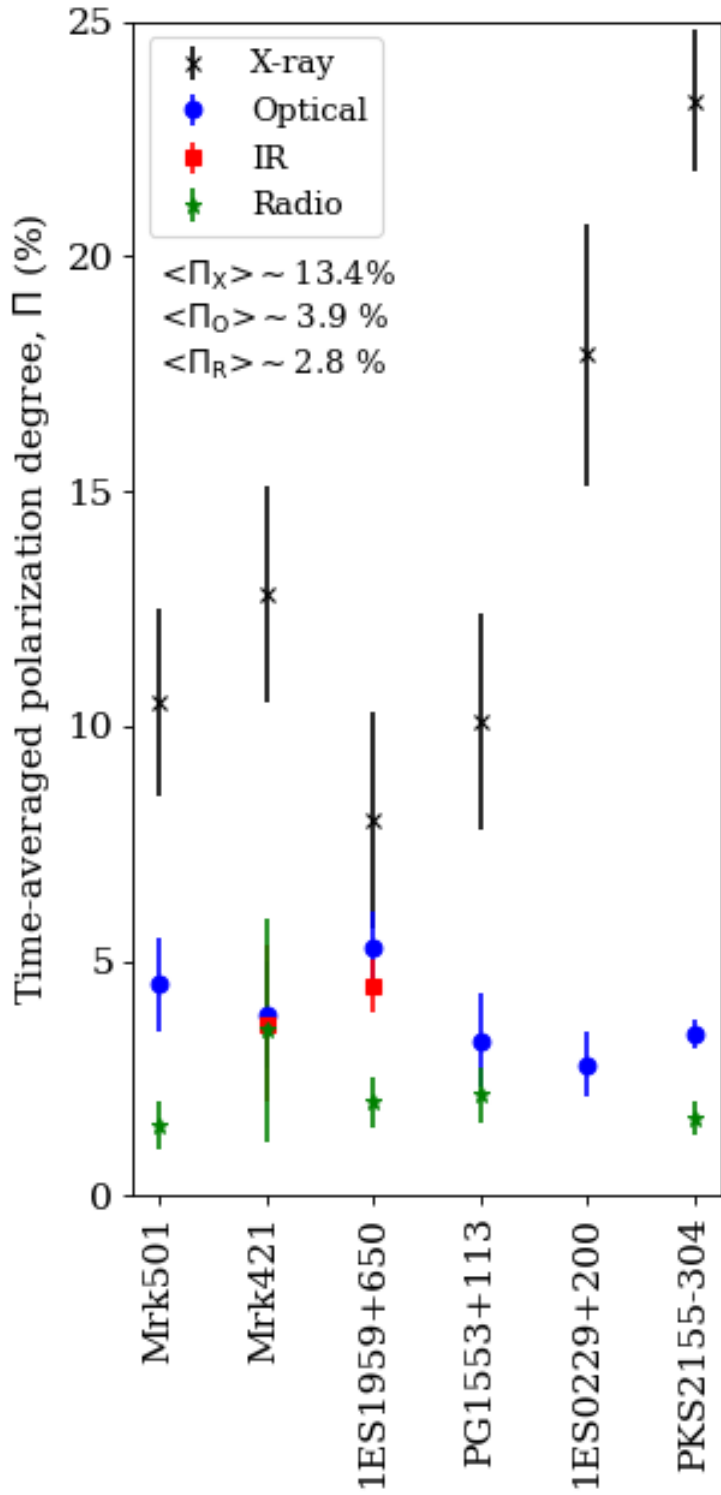
Credit: Pablo Garcia (NASA/MSFC)

Markarian 501  
Lioudakis et al., 2022, arXiv:2209.06227

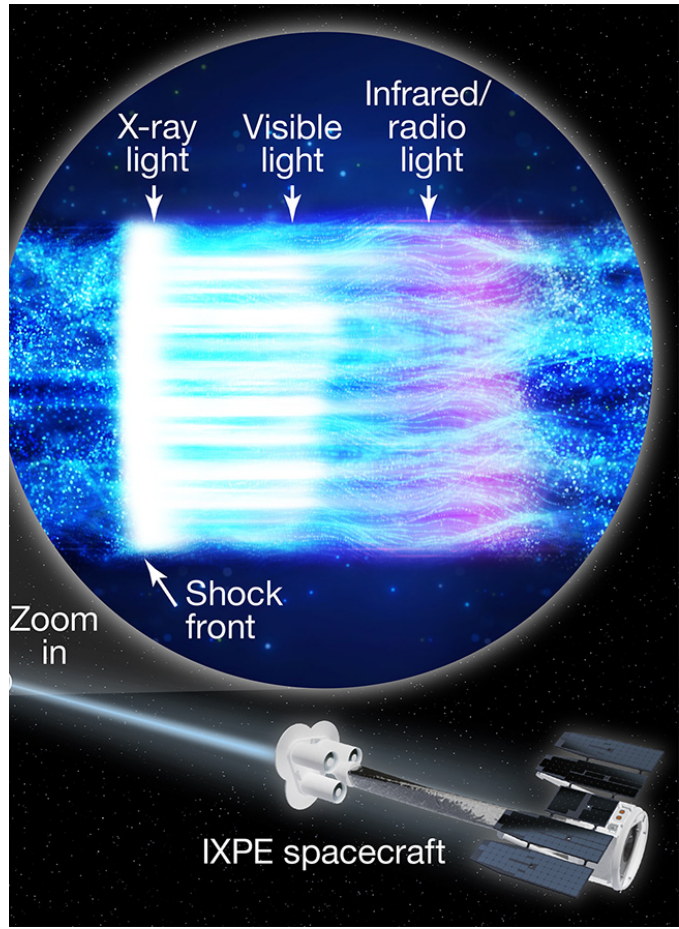
# First detection of X-ray



Markarian 501  
 Lioudakis et al., 2022, arXiv:2203.00001



# Massive black hole!

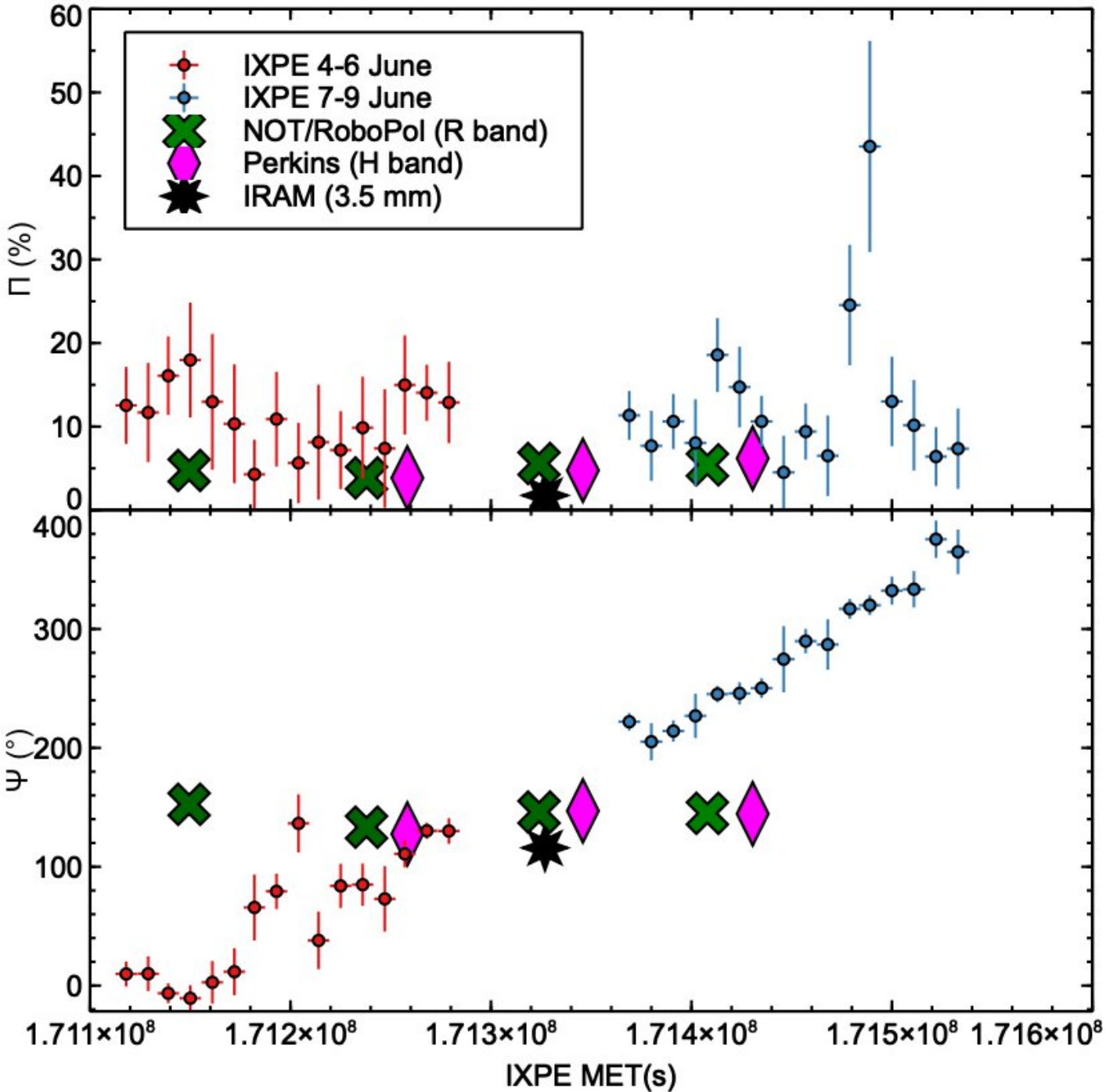


a (NASA/MSFC)

Kouch, Lioudakis et al., 2024  
 arXiv:2406.01693

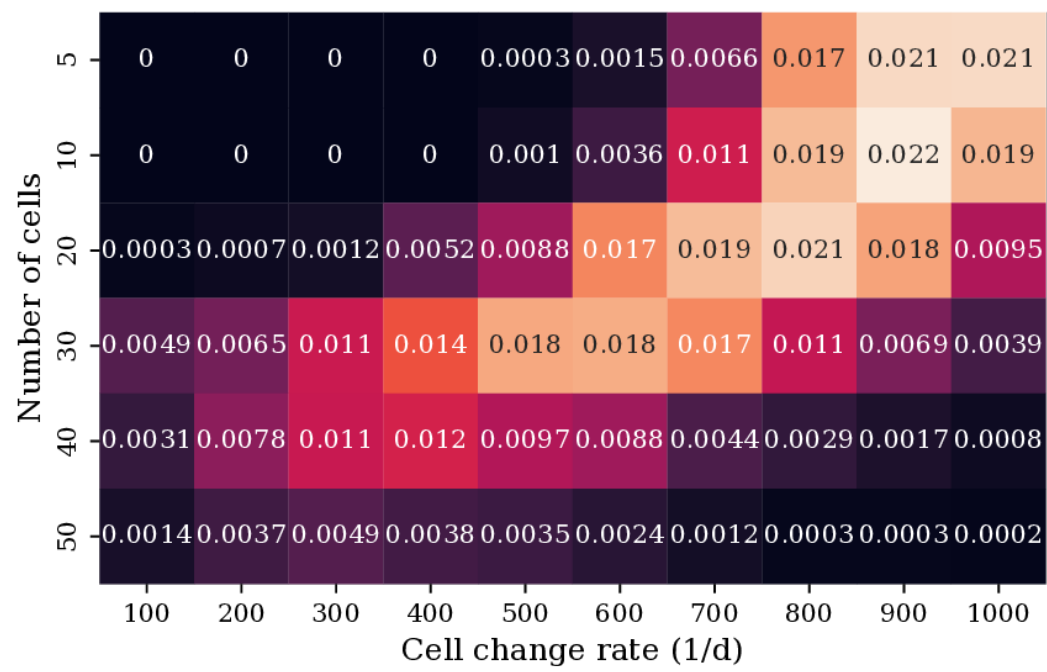
# Mrk 421

First X-ray  
polarization angle  
rotation!



# Mrk 421

Random walk is unlikely!

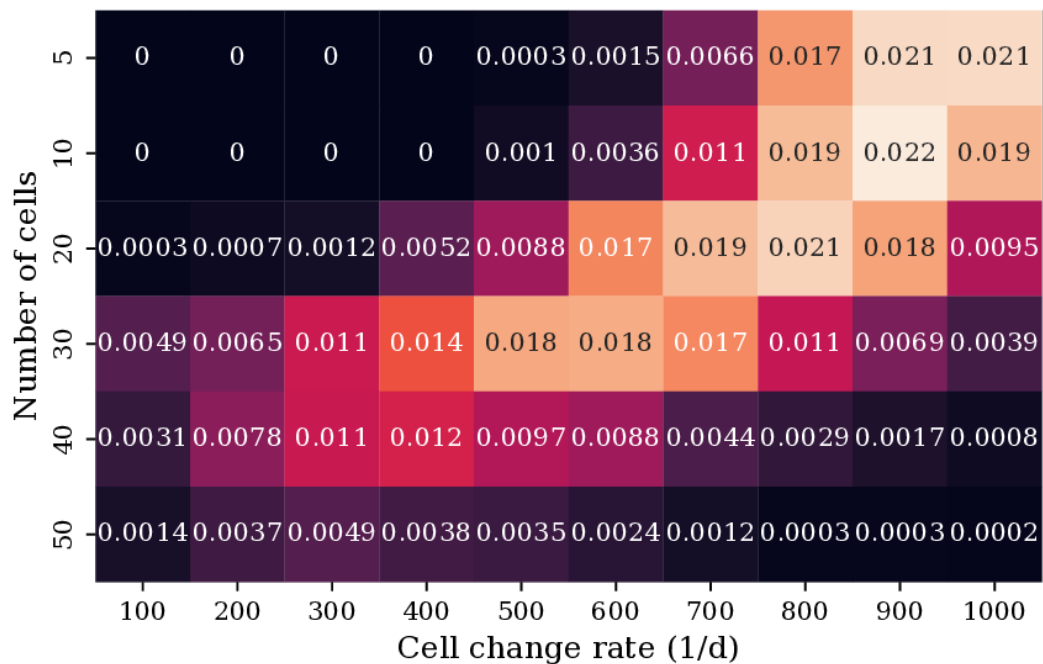
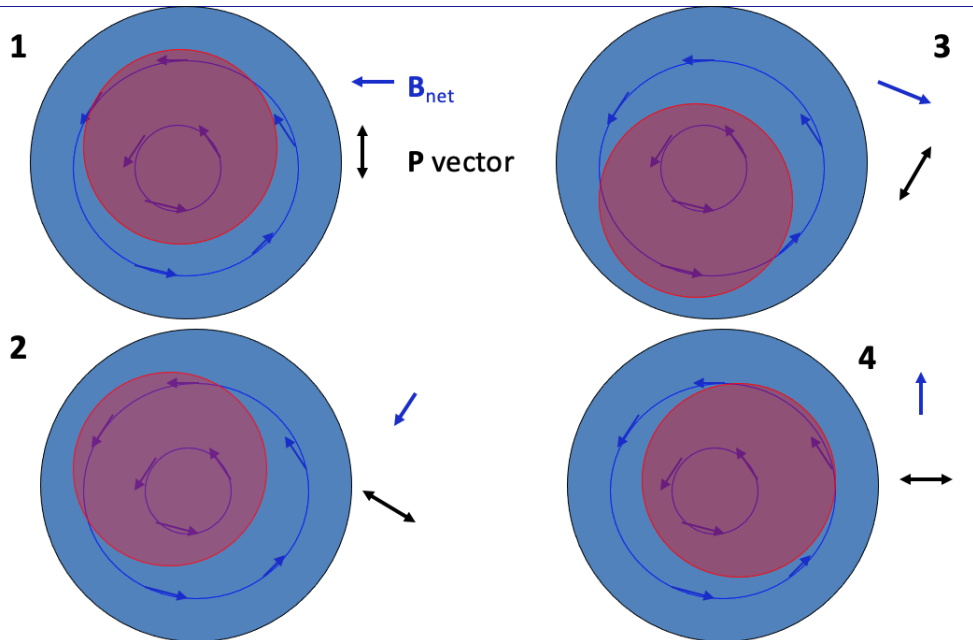




# Mrk 421

Random walk is unlikely!

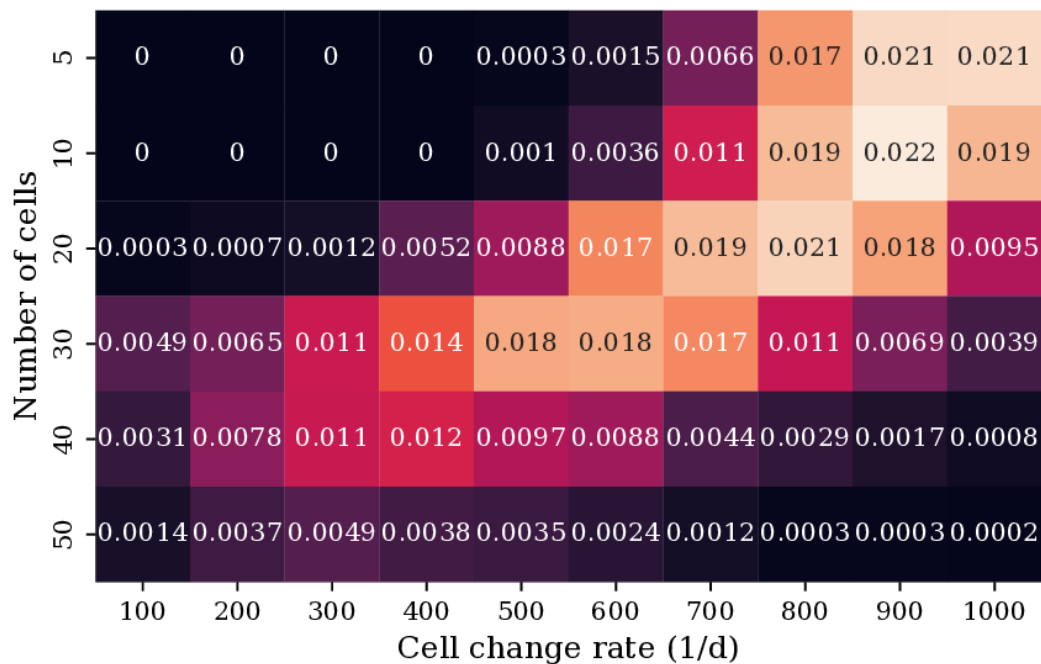
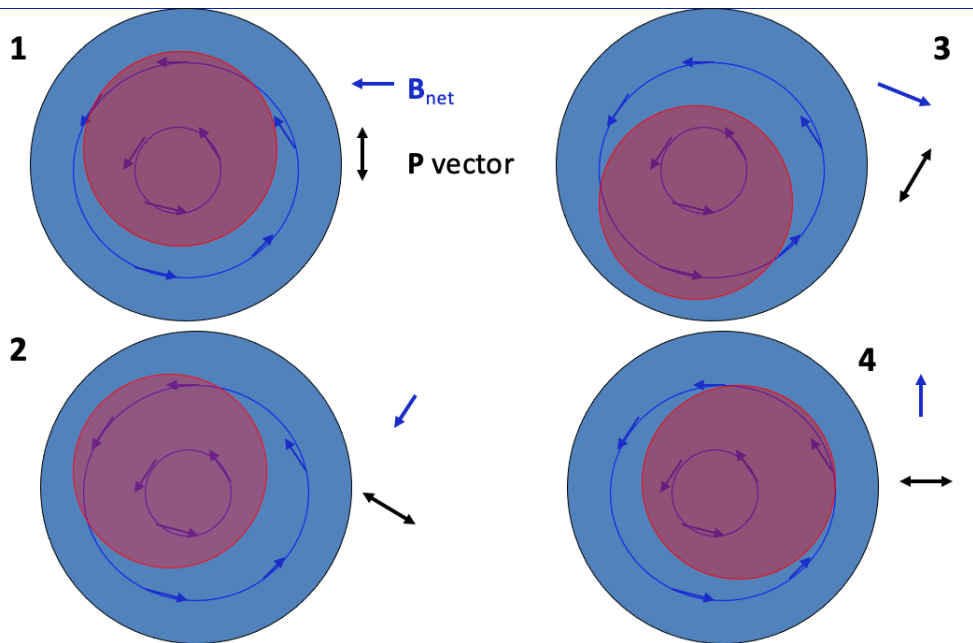
Shock moving in the jet?



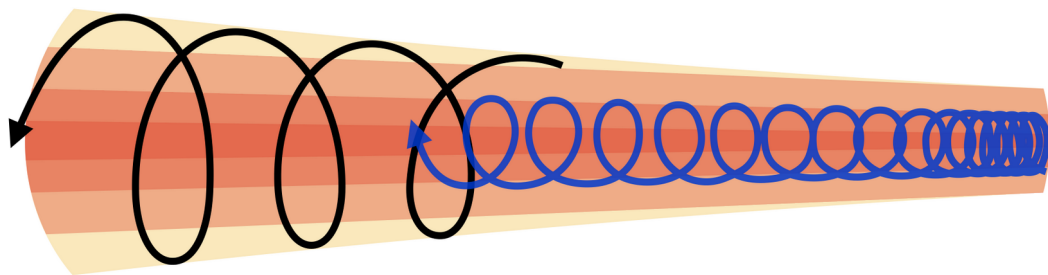
# Mrk 421

Random walk is unlikely!

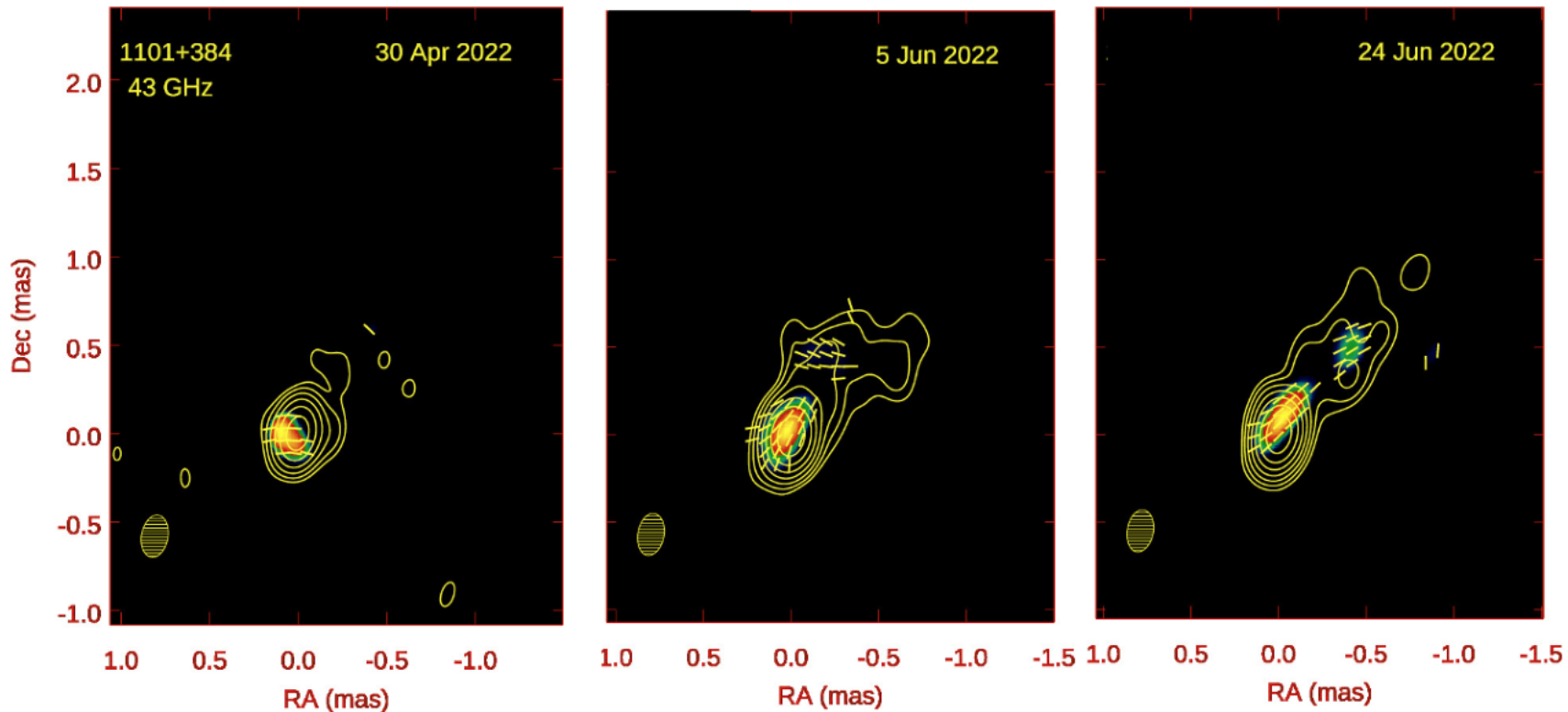
Shock moving in the jet?



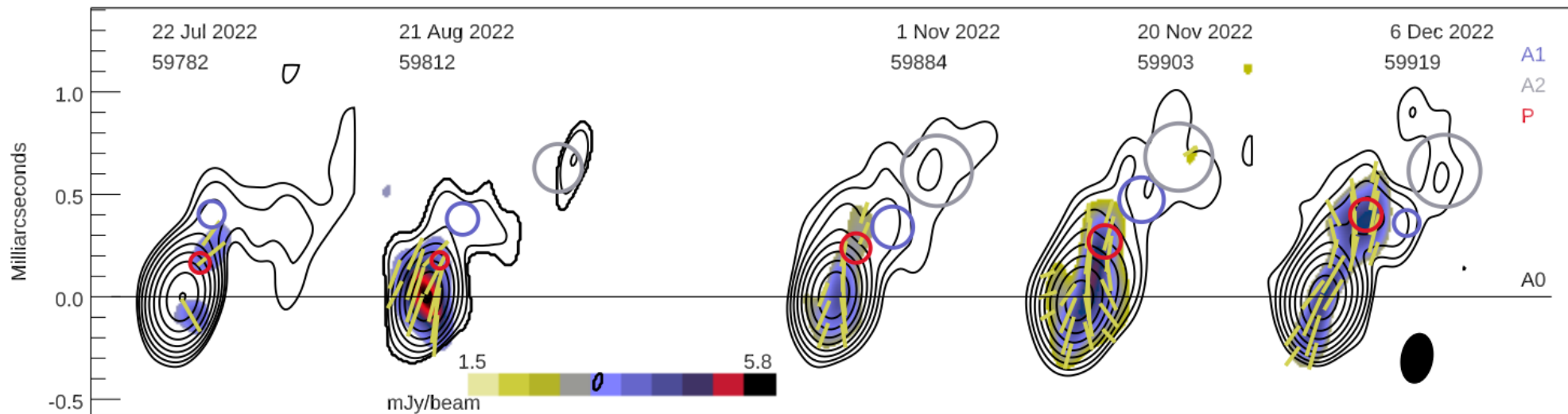
Spine-sheath geometry?



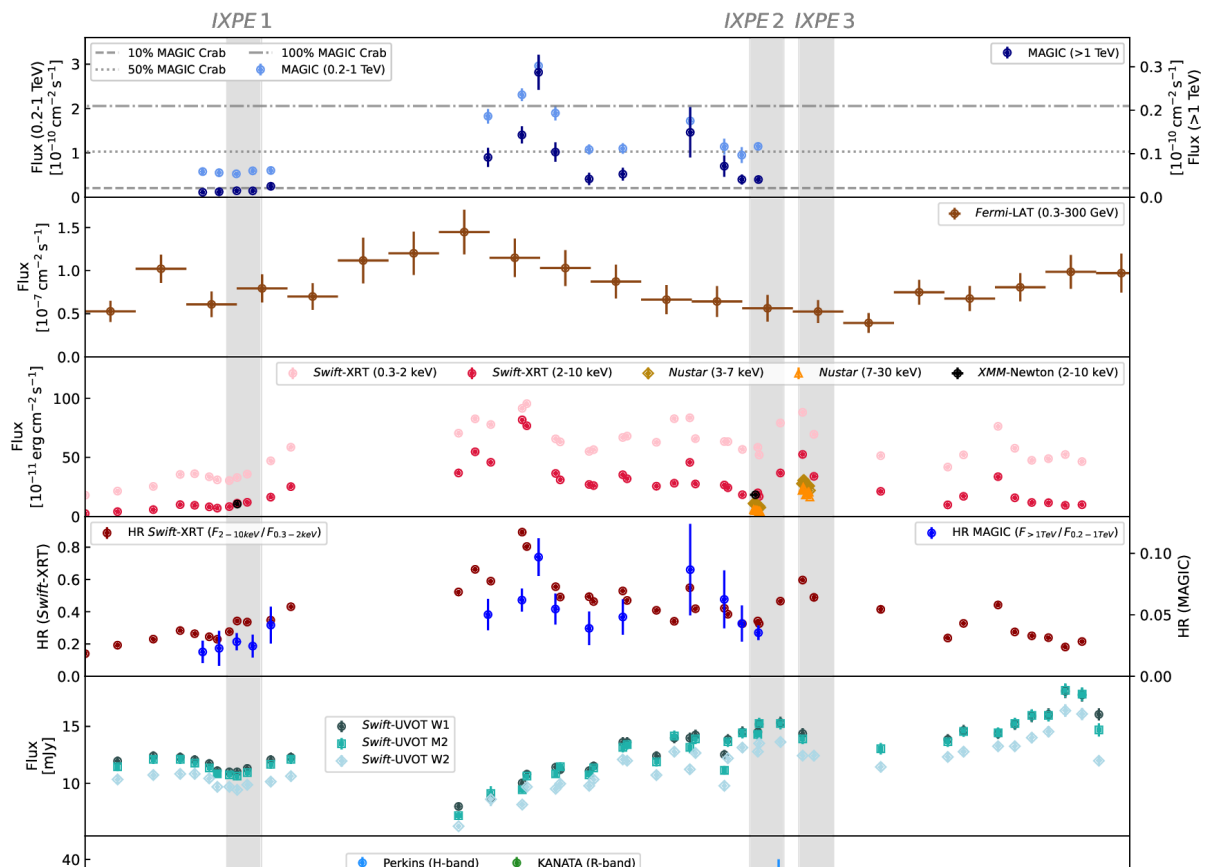
# Mrk 421



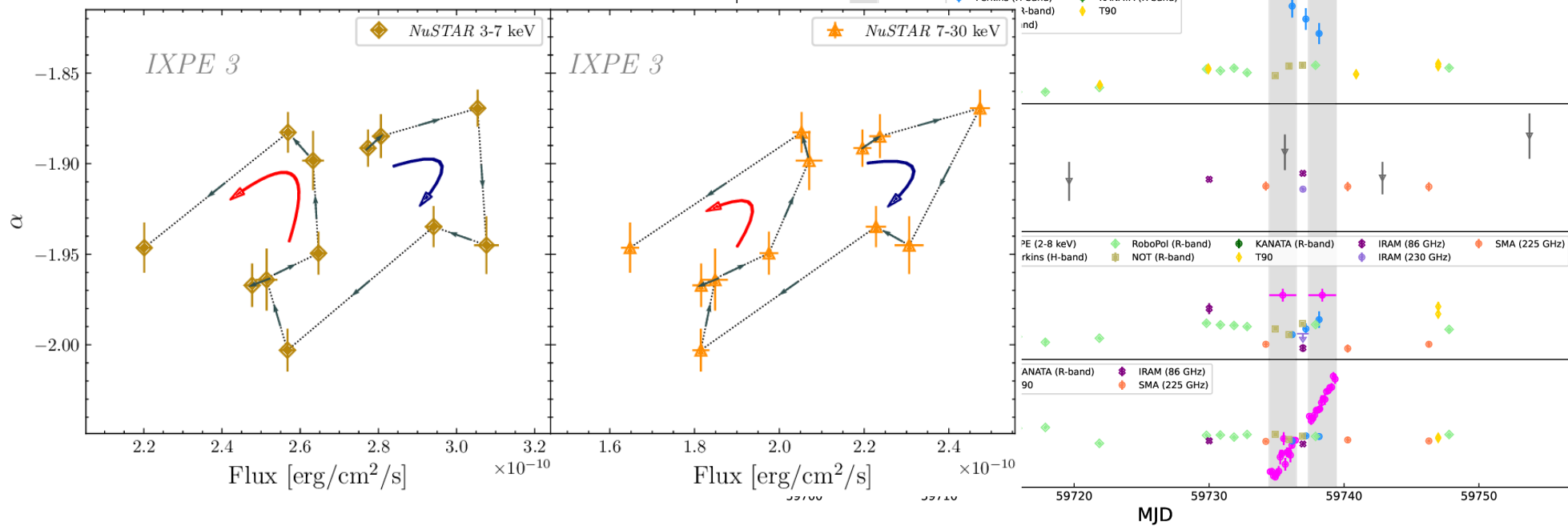
## Mrk 421



# Mrk 421



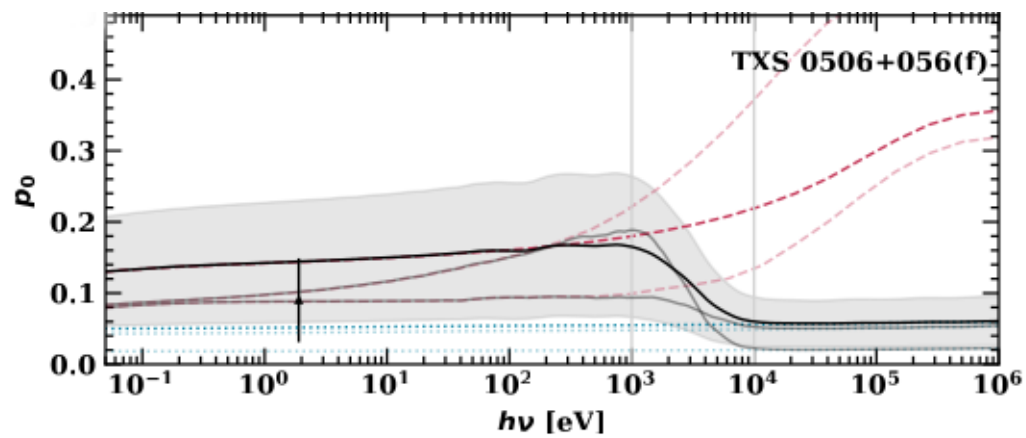
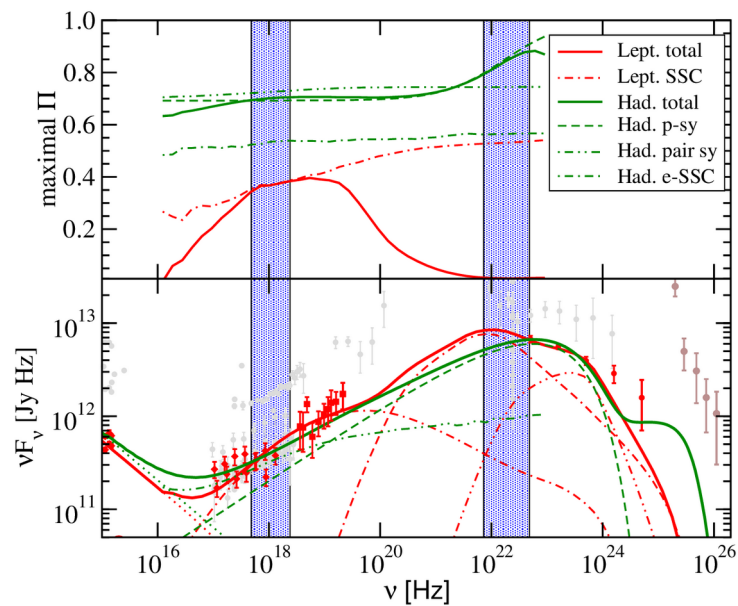
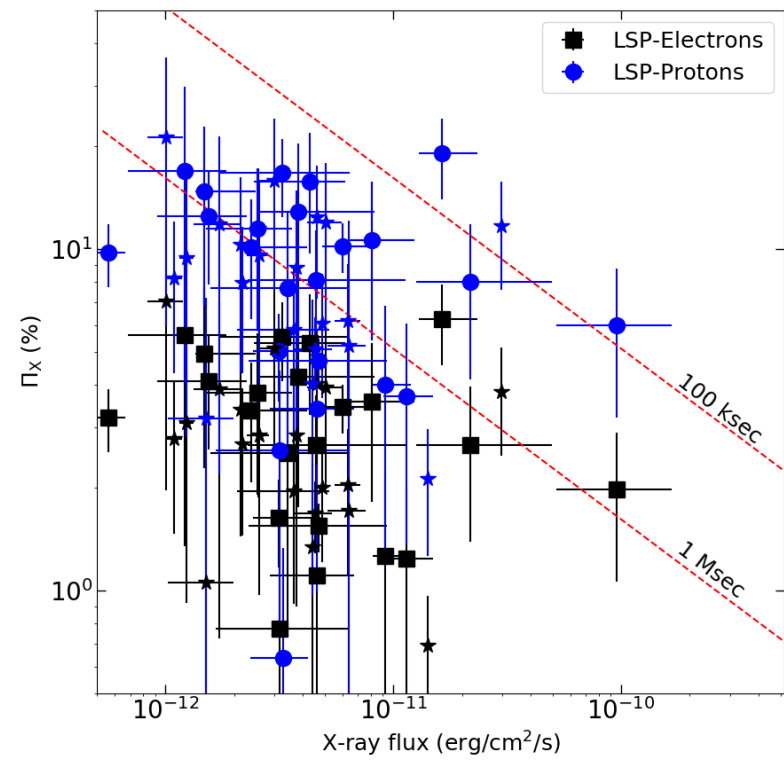
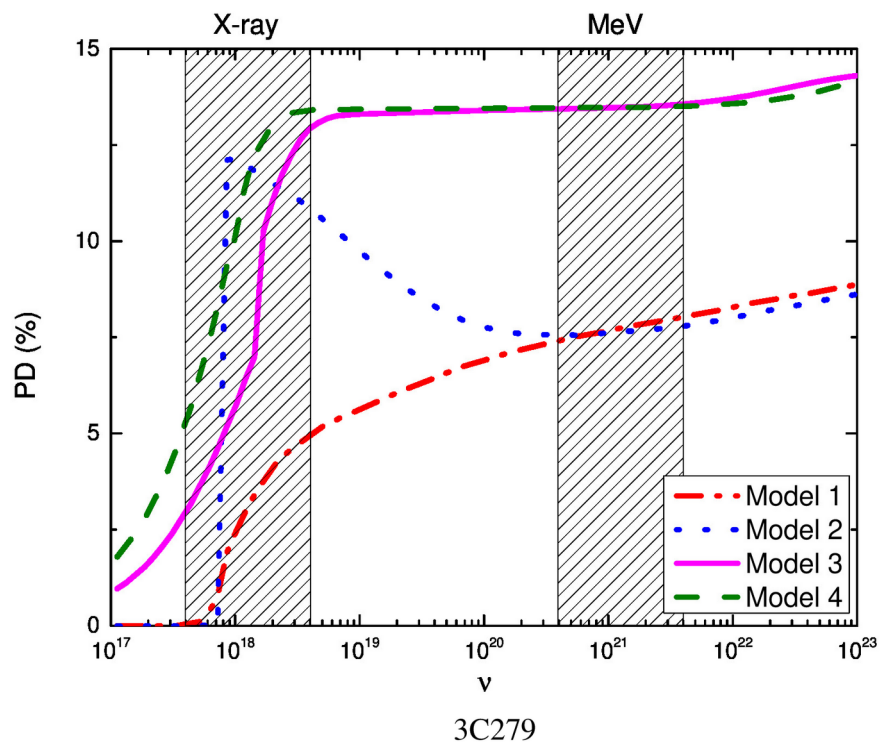
Abe et al., (2023)



# High-energy polarization predictions.

Liodakis et al., 2019

Peirson, Liodakis et al., 2022



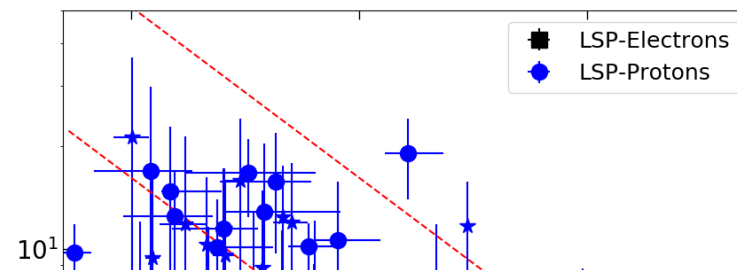
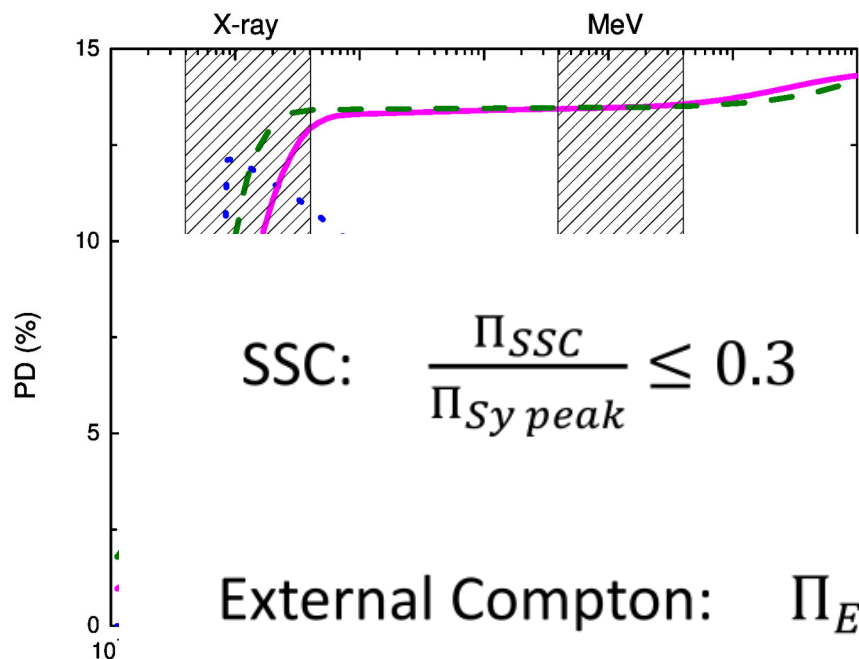
Zhang & Boettcher 2013

Zhang et al., 2019

# High-energy polarization predictions.

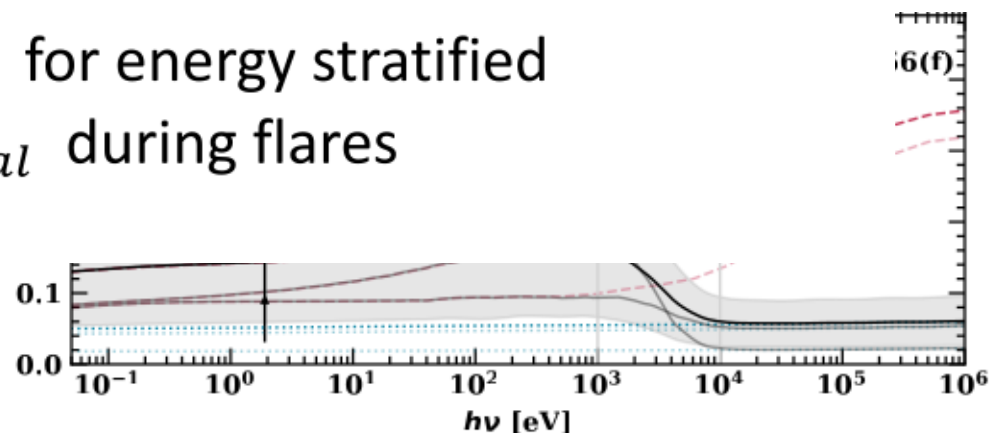
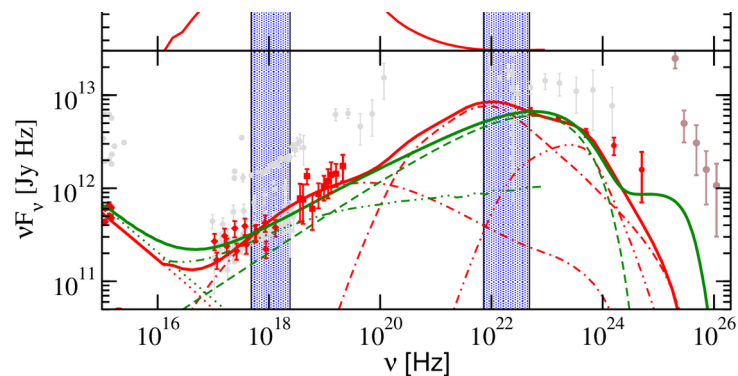
Lioudakis et al., 2019

Peirson, Lioudakis et al., 2022



Zhang, Boettcher, Lioudakis 2024

Hadronic:  $\Pi_{X, had} \approx \Pi_{radio}$  for energy stratified  
 $\Pi_{X, had} \approx \Pi_{optical}$  during flares



Zhang & Boettcher 2013  
 Zhang et al., 2019

BL Lac



BL Lac



**Polarization can give a unique view of high-energy processes in the Universe.**

**The X-ray polarization window is finally open!**

**Many fantastic synergies between CTA and IXPE  
Many more discoveries on the way!**