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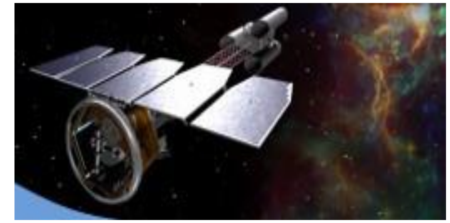

X-ray Polarimetry: Galactic Compact Objects

Giorgio Matt (Univ. Roma Tre, Italy)

Many thanks to:
Andrea Gnarini, Lorenzo Marra, Roberto Taverna, Francesco Ursini, …
the IXPE TWG3 and TWG4

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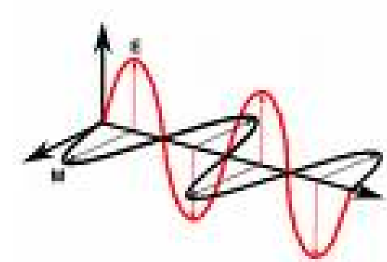
PLAN OF THE LECTURE

Introduction

Accreting Stellar-mass Black Holes

Accreting, Weakly Magnetized Neutron Stars



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General introduction

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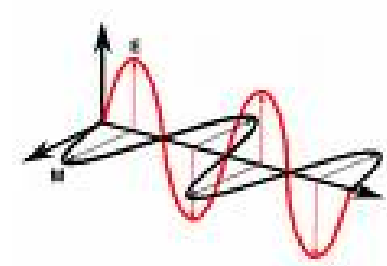
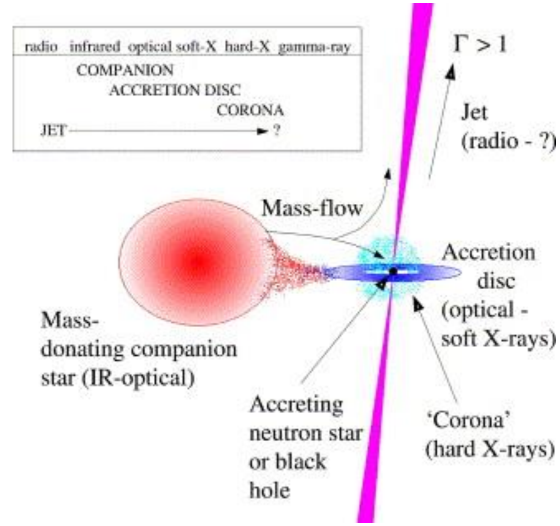


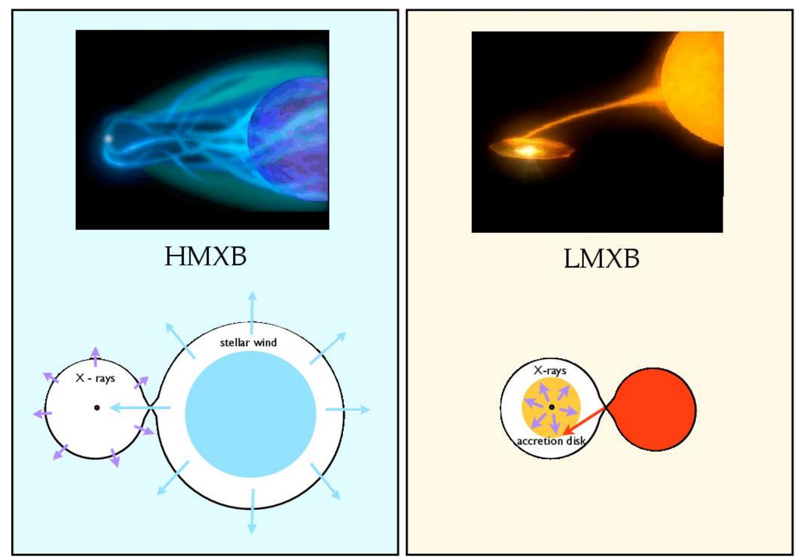
INTRODUCTION



Accreting Compact Objects in binary systems share several common features regardless of the nature of the compact object (BH or NS).

The accretion mode depends on the mass/evolutionary stage of the companion star.

The most important emission mechanism (as far as polarization is concerned) in accreting non magnetized compact objects is Compton scattering. Synchrotron emission may have a role if jet emission is important.

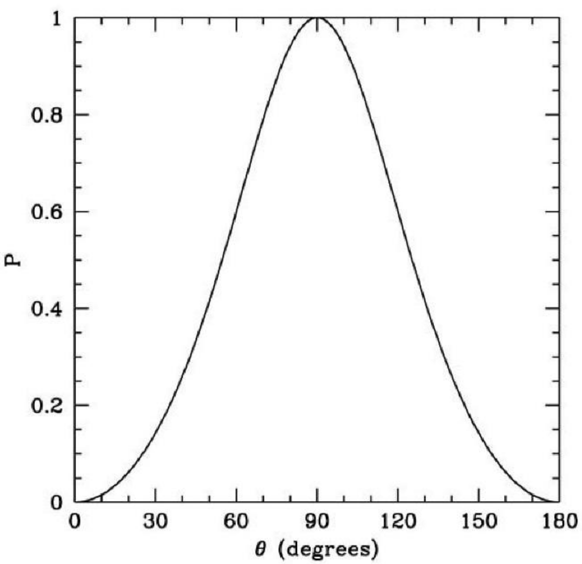


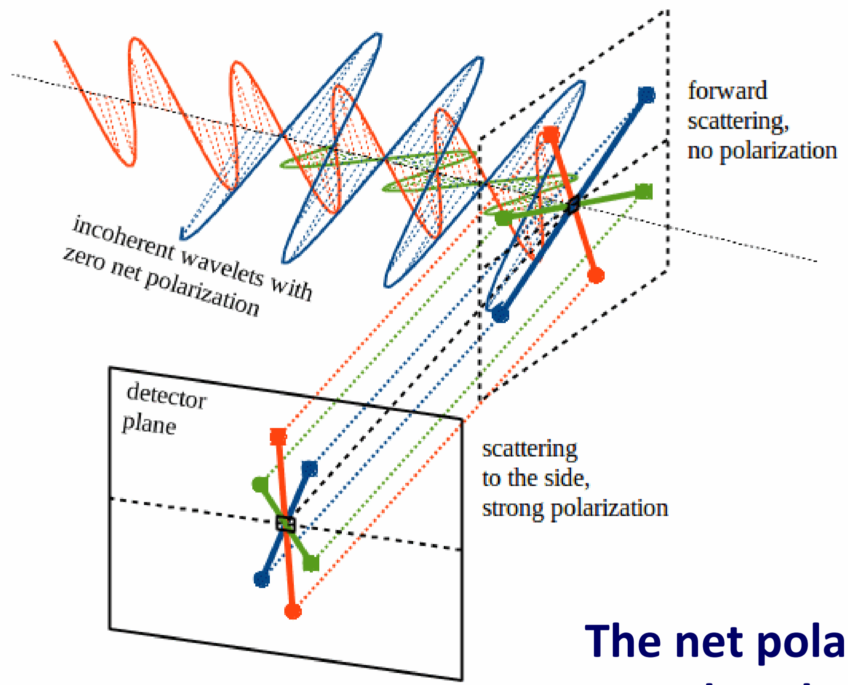
THOMSON SCATTERING

The scattered radiation is polarized. A 100% polarized incident beam gives rise to a 100% polarized scattered beam, independently of the scattering angle.

If the incident beam is unpolarized, the polarization of the scattered radiation is:

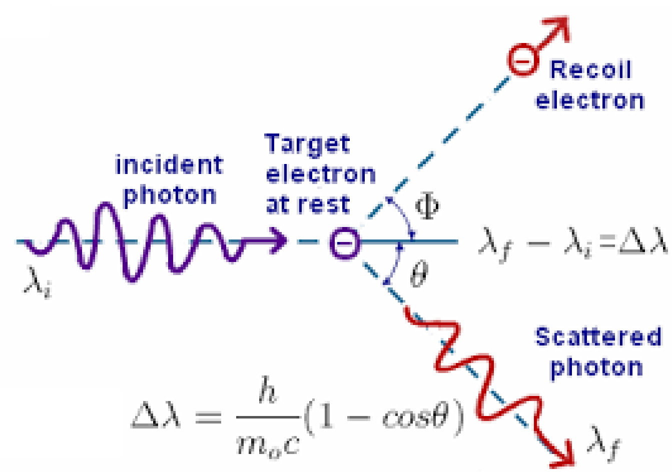
$$P = \frac{1-\cos^2\theta}{1+\cos^2\theta}$$



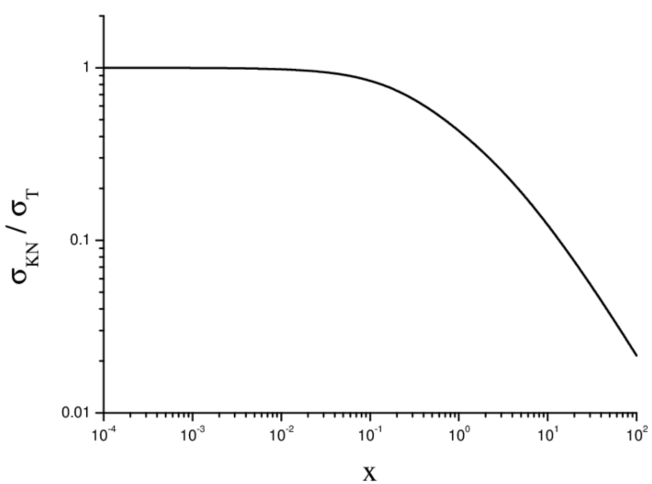


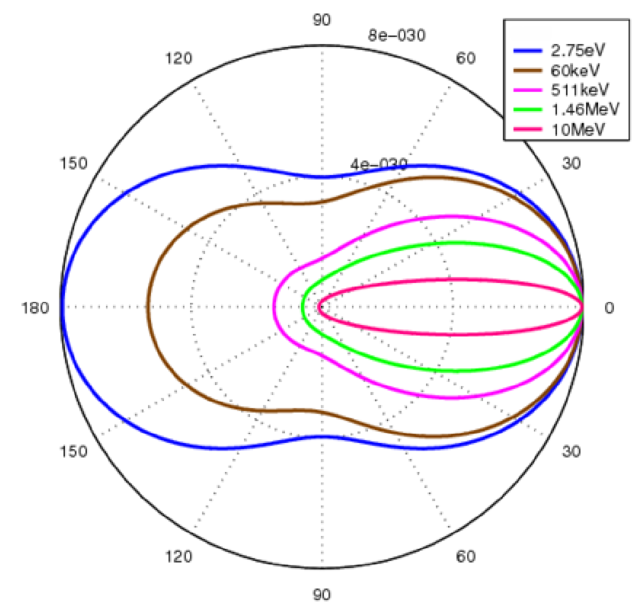
The net polarization vector is normal to the scattering plane.

COMPTON SCATTERING



When *hν* is no longer « *mc²* the scattering is inelastic. The Klein-Nishin cross section decreases with energy, and the emission pattern is more complex.





COMPTON SCATTERING

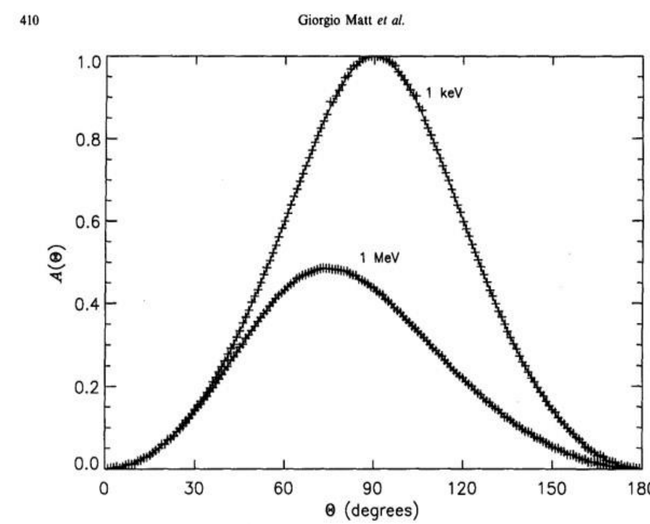
Compton scattering radiation is polarized, but less than Thomson scattering. Polarization degree decreases with $h\nu/mc^2$ in the reference frame of the electron

A 100% polarized beam gives rise to <100% polarized scattered radiation, depending on the scattering angle.

For an unpolarized beam, maximum polarization is less than 100%.

$\beta = E/E_0$
Θ=polar scatt. angle
Φ=azimuthal scatt. angle

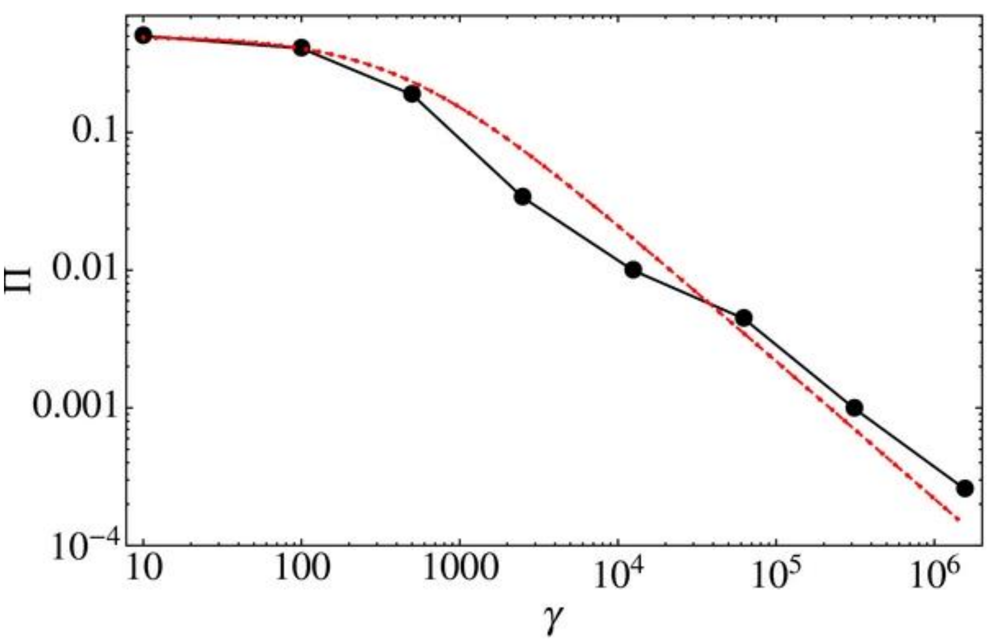
$$\Pi_P = 2\frac{1-\sin^2\Theta\cos^2\Phi}{\beta+\beta^{-1}-2\sin^2\Theta\cos^2\Phi}.$$



$$\Pi_U = \frac{1-\cos^2\Theta}{1+\cos^2\Theta+\beta+\beta^{-1}-2}.$$

INVERSE COMPTON SCATTERING

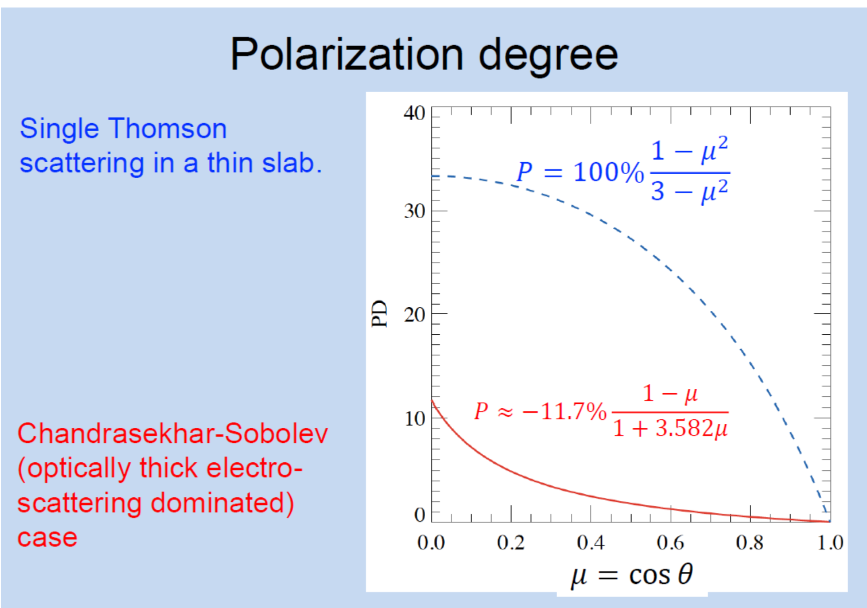
In the observer reference frame, the electron may be moving, and it is also possible that the kinetic energy of the electron is larger than the energy of the photon. In this frame, it is the photon which gains energy (i.e. frequency). The polarization properties are calculated by going to the electron frame, calculating the polarization in the appropriate (Thomson or Compton) regime, and transforming back into the observer frame.

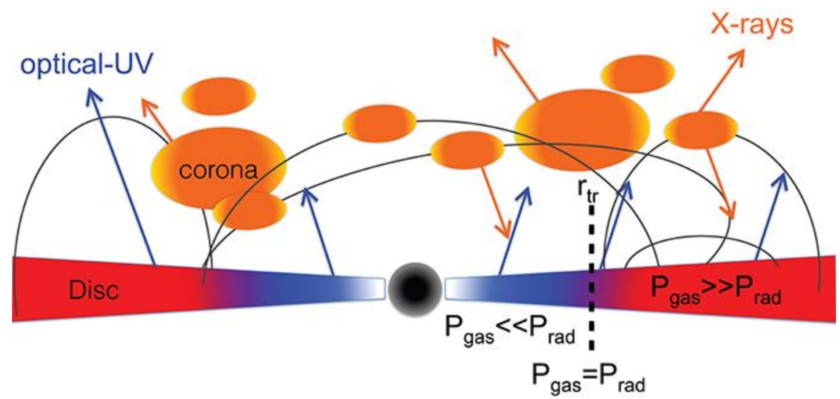


Net polarization degree of all emitted photons as a function of the electron Lorentz factor. Electron distribution is monoenergetic and isotropic, photon distribution is monoenergetic and unidirectional (from Krawczynski 2011)

COMPTONIZATION

An important astrophysical process is the so called Comptonization, i.e. the emission due to repeated scattering by hot electrons off soft seed photons (e.g. the upper layer of the accretion disc or the hot corona).



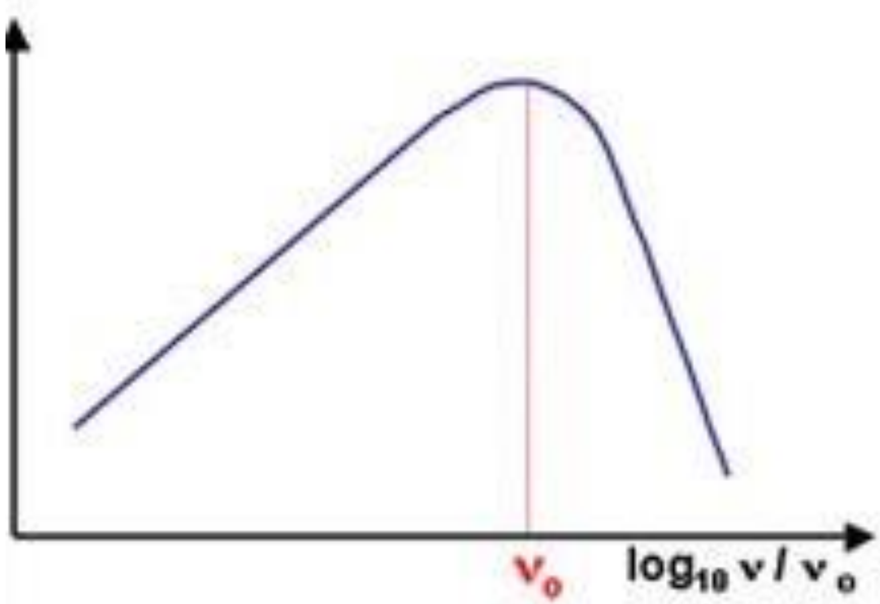


The polarization properties strongly depend on the physical (electron temperature, optical depth) and geometrical parameters of the corona.

Courtesy: J. Poutanen

SYNCHROTRON EMISSION

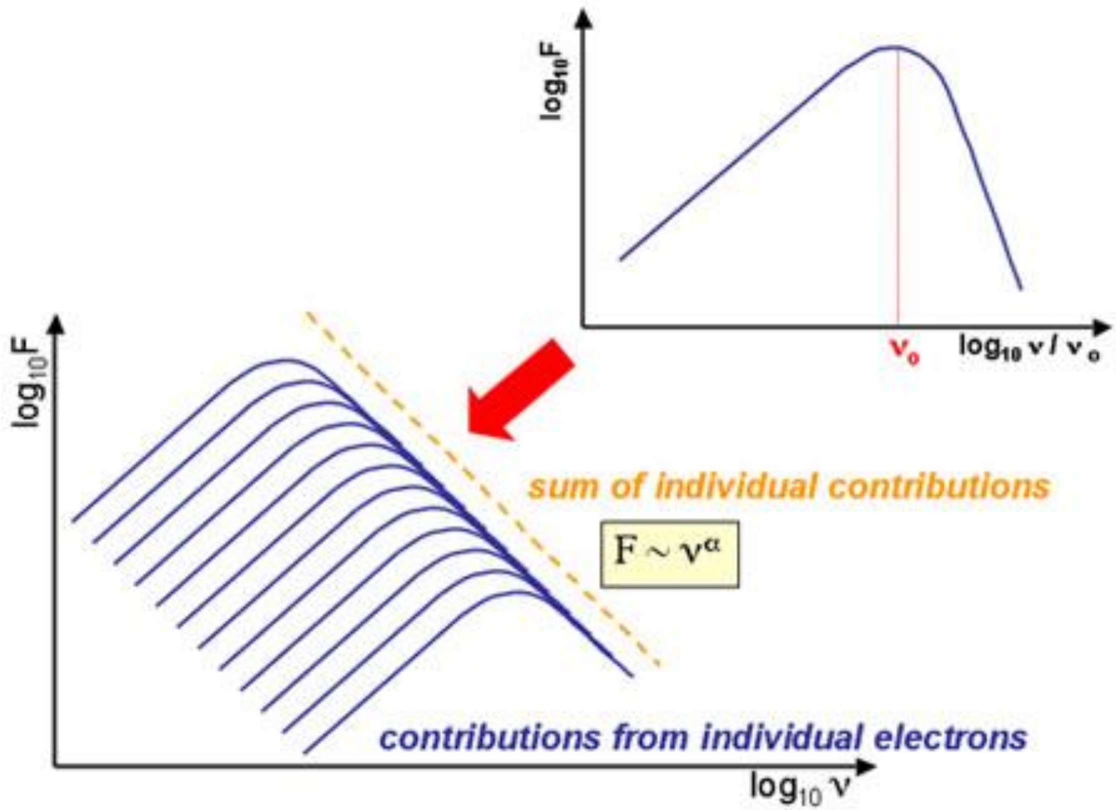
It is produced by the acceleration of a moving charged particle in a magnetic field due to the Lorentz force.



The synchrotron spectrum from a single electron is peaked at:

$$\nu_0 = \frac{3\gamma^2 eB \sin\alpha}{4\pi mc}$$

SYNCHROTRON EMISSION



To get the total spectrum from a population of electrons, we must know their energy distribution. A particularly relevant case is that of a power law distribution, $N(E)=KE^{-p}$.

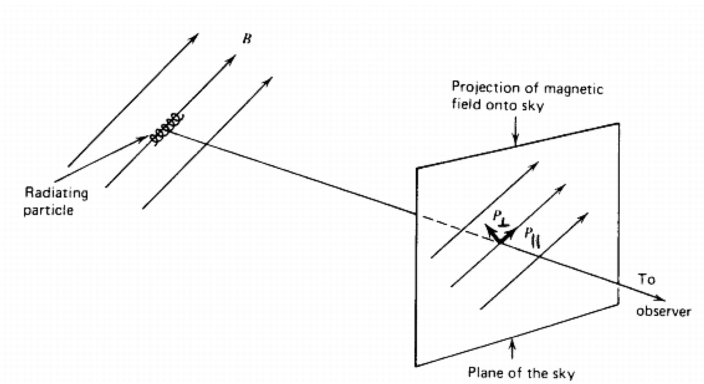
The total spectrum is also a power law, $F(\nu)=C\nu^{-\alpha}$, with $\alpha=(p-1)/2$

SYNCHROTRON EMISSION

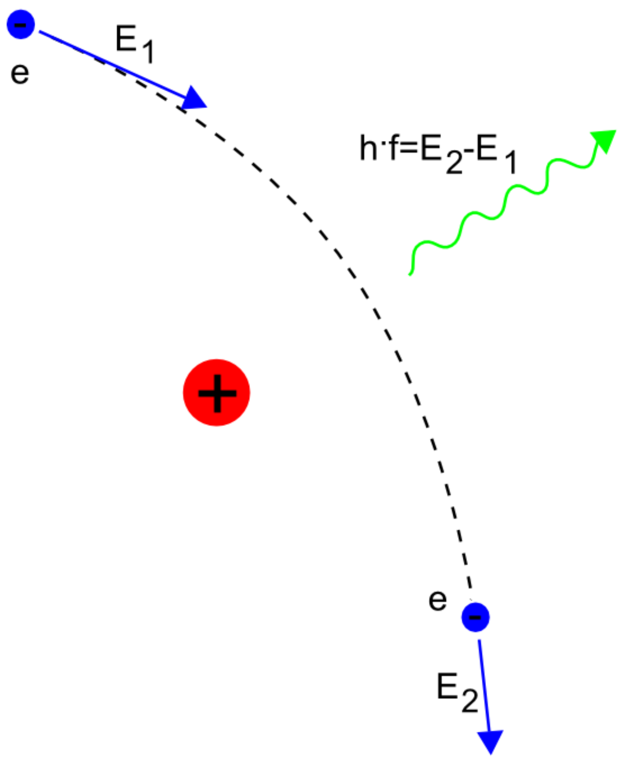
The radiation is polarized perpendicularly to the projection of B onto the sky

For a power law distribution of emitting particles, and a uniform B, the degree of polarization is $\Pi=(p+1)/(p+7/3)$.

This is actually un upper limit, because the magnetic field is never perfectly ordered.



BREMSSTRAHLUNG



It is produced by the deflection of a charged particle (usually an electron in astrophysical situations) in the Coulombian field of another charged particle (usually an atomic nucleus).

Bremsstrahlung photons are polarized with the electric vector perpendicular to the plane of interaction.

In most astrophysical situations, and certainly in case of thermal bremsstrahlung, the planes of interaction are randomly distributed, resulting in null net polarization.

For an anisotropic distribution of electrons, however, bremsstrahlung emission can be polarized.

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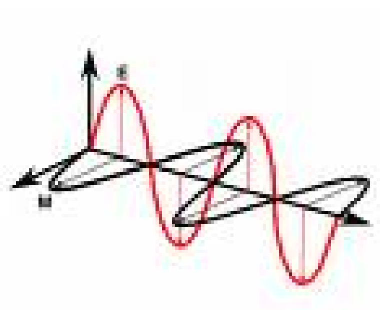
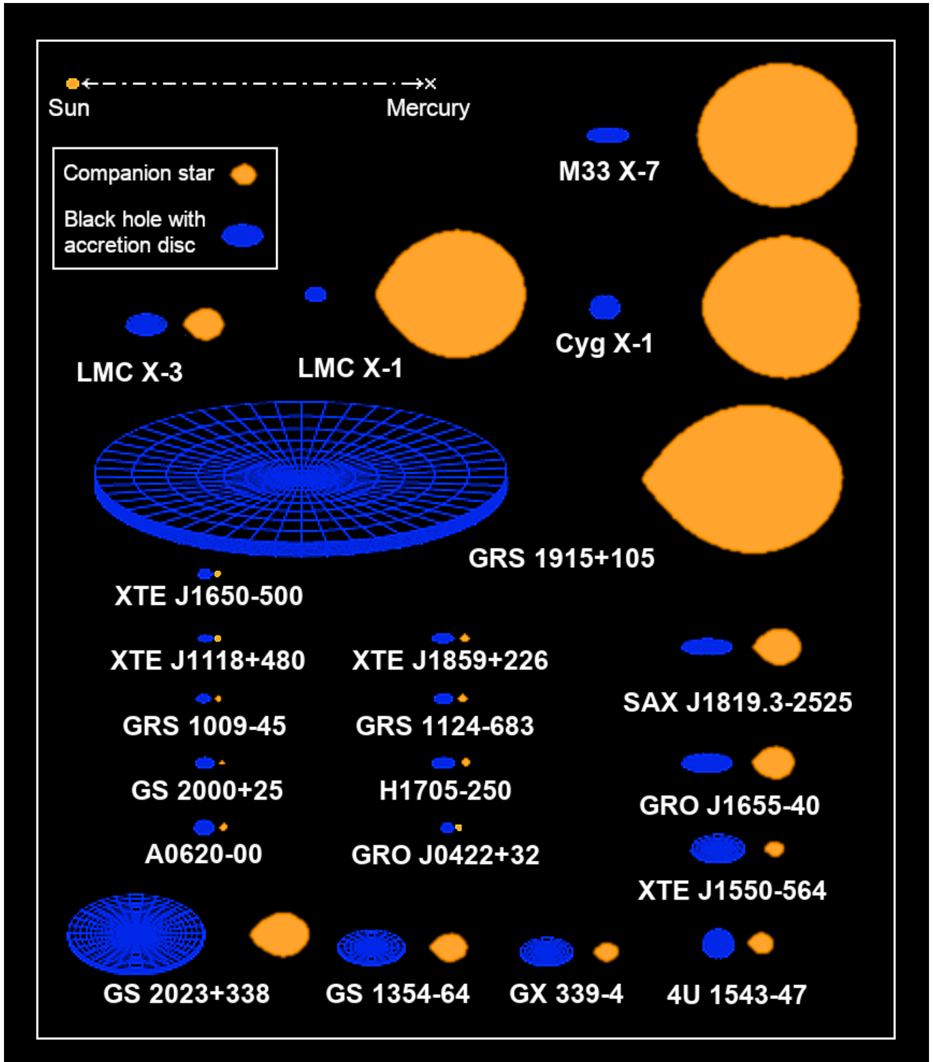


ACCRETING STELLAR-MASS BLACK HOLES

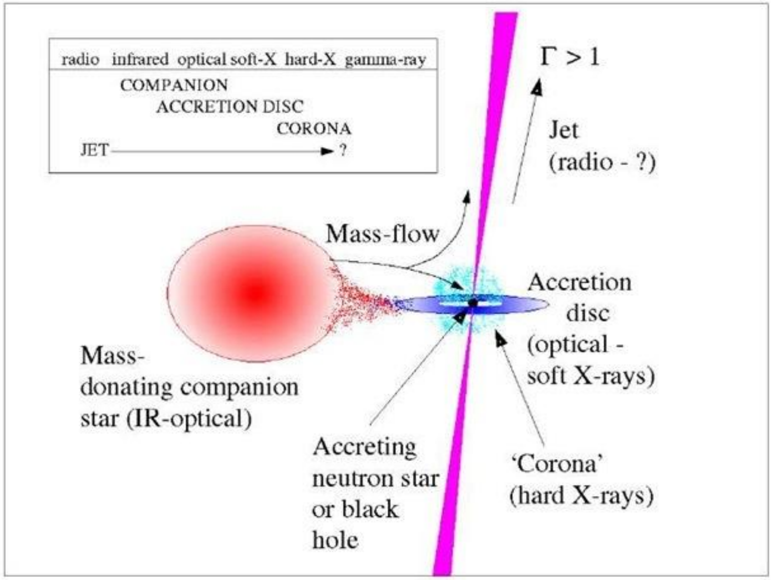


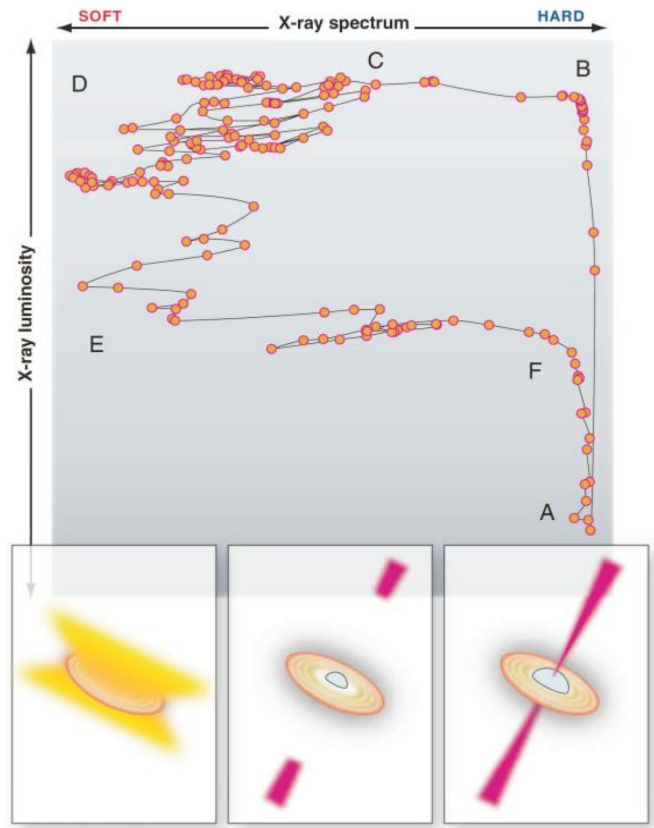
Several dozen accreting stellar-mass BH known. Only 10 of them are persistent. From 77 transients only 14 had at least 2 outbursts.

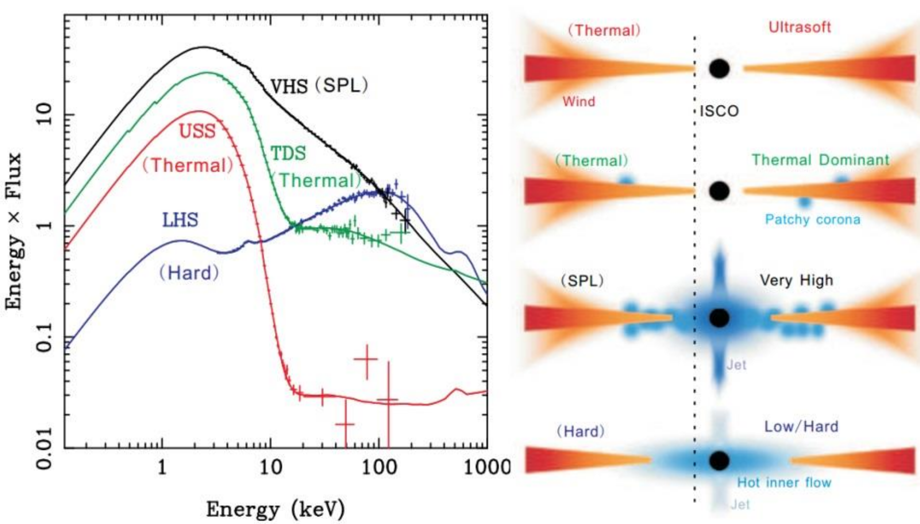
The majority of accreting black hole systems belong to the LMXRB class.

What follows, strictly speaking, apply to LMXRB, even if many characteristics are shared by HMRXB, when an accretion disc is formed

ACCRETING STELLAR-MASS BLACK HOLES







Fender & Belloni 12

Done et al. 07

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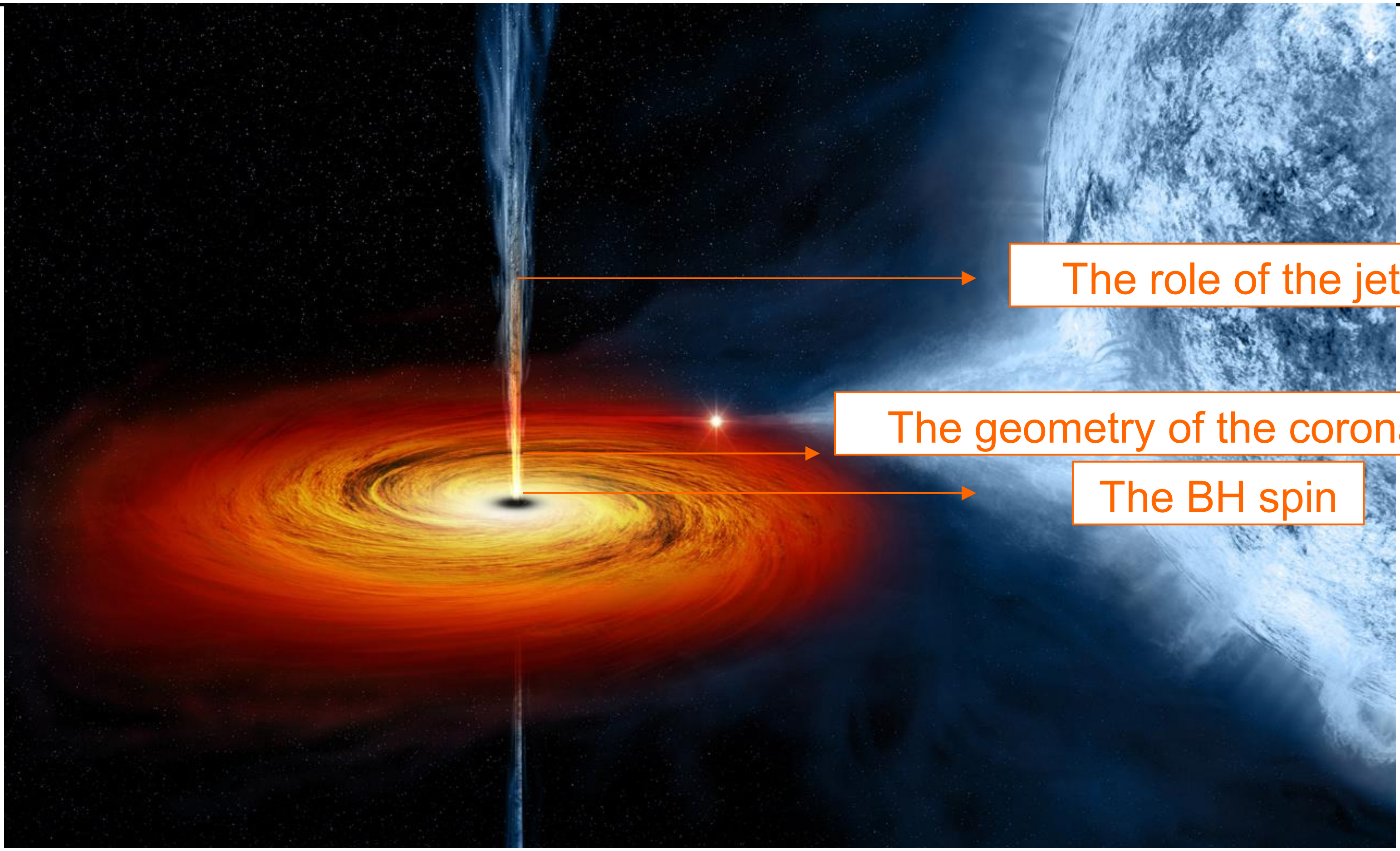
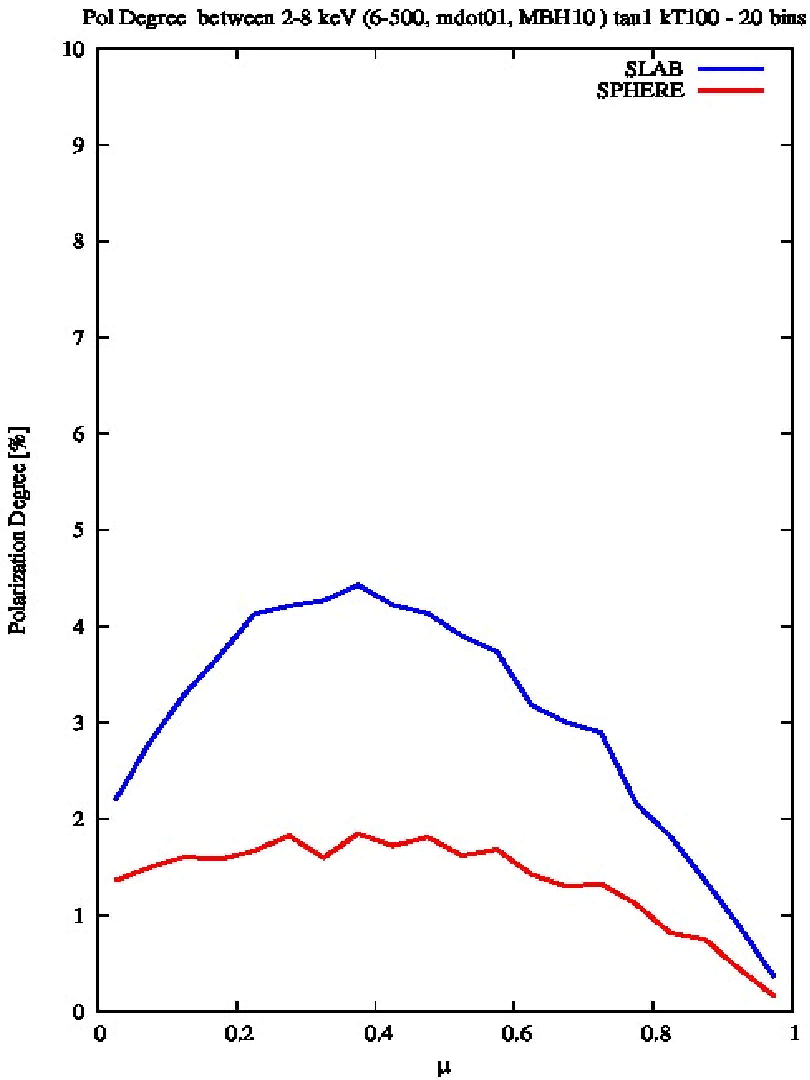
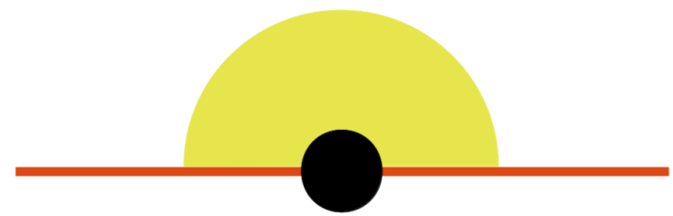
ACCRETING STELLAR-MASS BLACK HOLES



X-ray polarimetry can provide answers to several key problems, foremost among them: ***The geometry of the corona – The spin of the BH***

THE GEOMETRY OF THE HOT CORONA (HARD STATE)



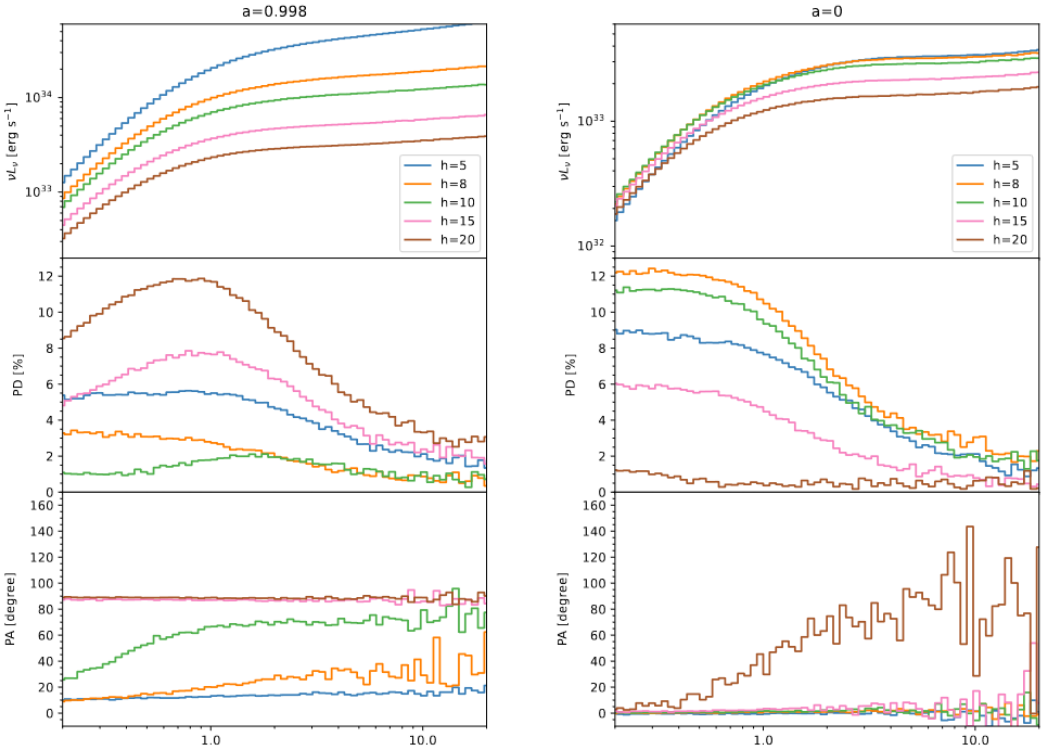


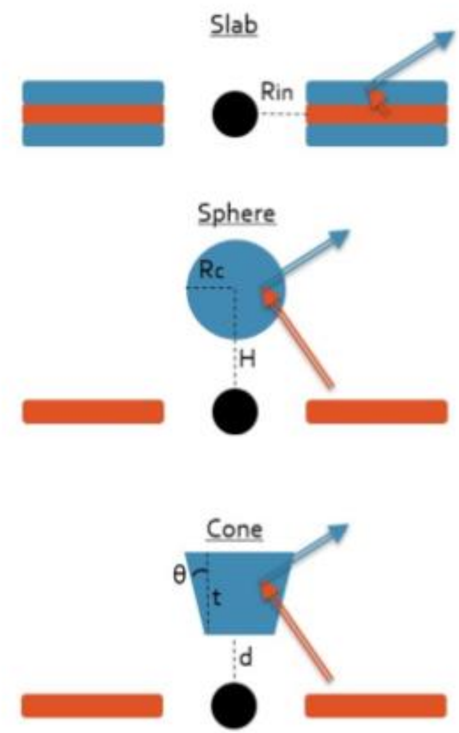
The geometry of the hot corona cannot be derived from spectroscopic of timing observations.

Emission is expected to be polarized if the corona OR the radiation field are not spherical (Schnittman & Krolik 2010, Behestipour et al. 2017, Tamborra et al. 2018, Zhang et al. 2022)

Courtesy: F. Tamborra

THE GEOMETRY OF THE HOT CORONA (HARD STATE)





Lamppost corona, i=75 deg (Zhang et al. 2022).

This is just an example, as the polarization properties strongly depend on the system parameters (BH mass, accretion rate, coronal temperature and optical depth).
Simulations must be "customized", so it is very important to have independent information on these parameters.

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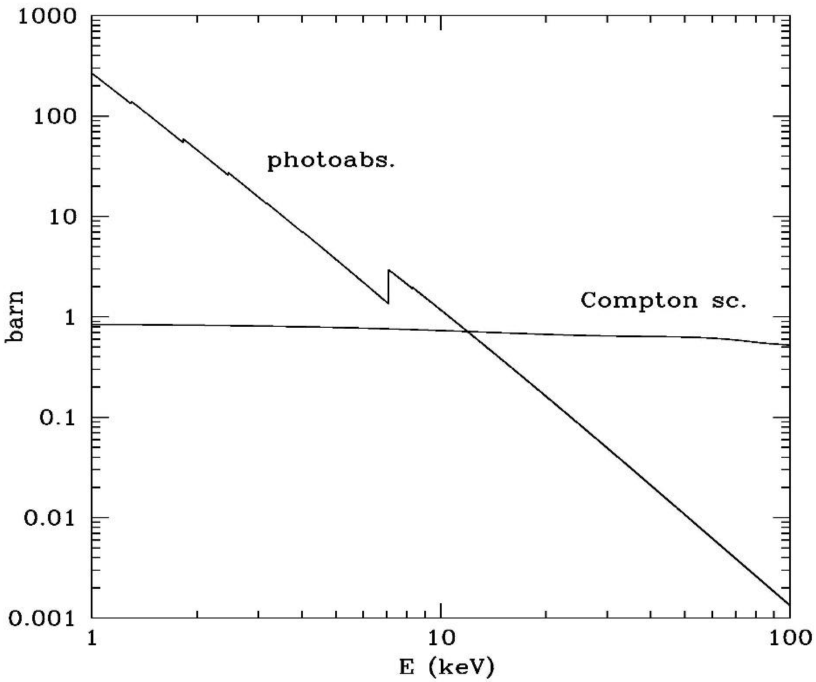
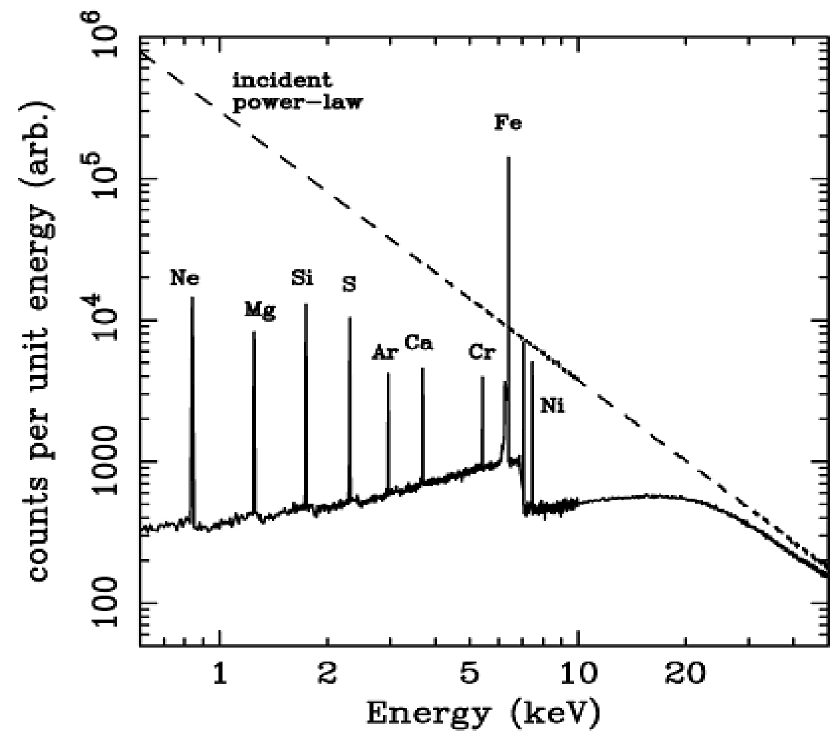
REFLECTION



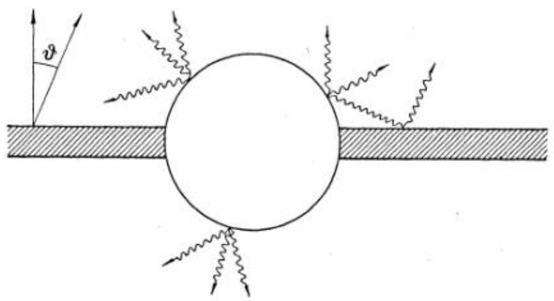
A rather common astrophysical situation is when X-rays illuminates `cold' matter, producing the so called *Compton reflection continuum*



(Reynolds et al. 1995)

The shape of the continuum is due to the competition between photoabsorption and Compton scattering. Fluorescent lines are also produced, Fe Kα being the most prominent

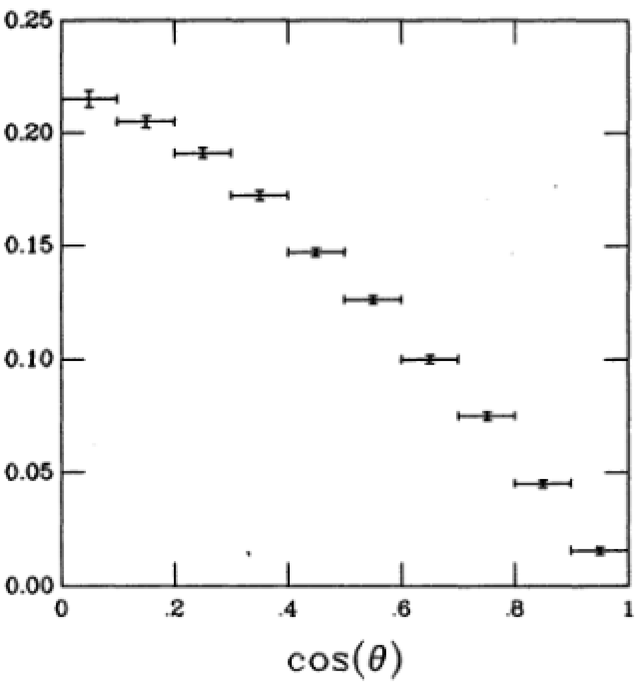
REFLECTION



The continuum is due to Compton scattering, so it is polarized. The polarization degree and angle depends on the geometry of the system and the ionization of the matter.

See e.g. Matt (1993) and Podgorny et al. (2022, 2023) for more general geometrical and physical situations.

See Ratheesh et al. (2021) for reflection from a wind.



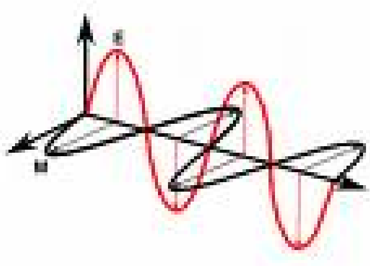
Polarization of reflected emission from a disk (Matt et al. 1989).

IXPE observed three sources in hard state:

Cygnus X-1

Cygnus X-3

Swift J1727.8-1613



CYGNUS X-1

Distance: $2.22^{+0.18}_{-0.17}$ kpc

Orbital Inclination: $27.1^\circ \pm 0.8^\circ$

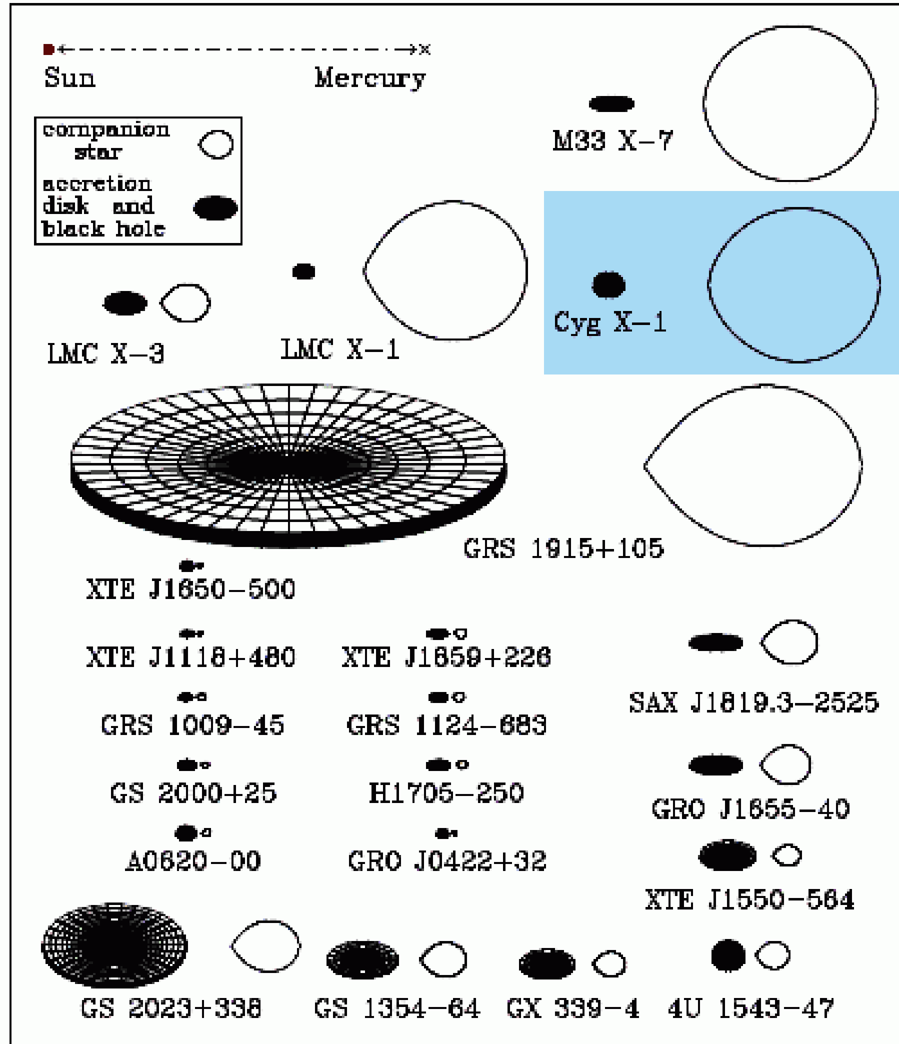
Companion mass: $40.6^{+7.7}_{-7.1}\, M_\odot$

Period: 5.6 day

BH Mass: $21.2 \pm 2.2\, M_\odot$

BH spin: $\gtrsim 0.92$

Arguably the best studied accreting stellar-mass black hole.

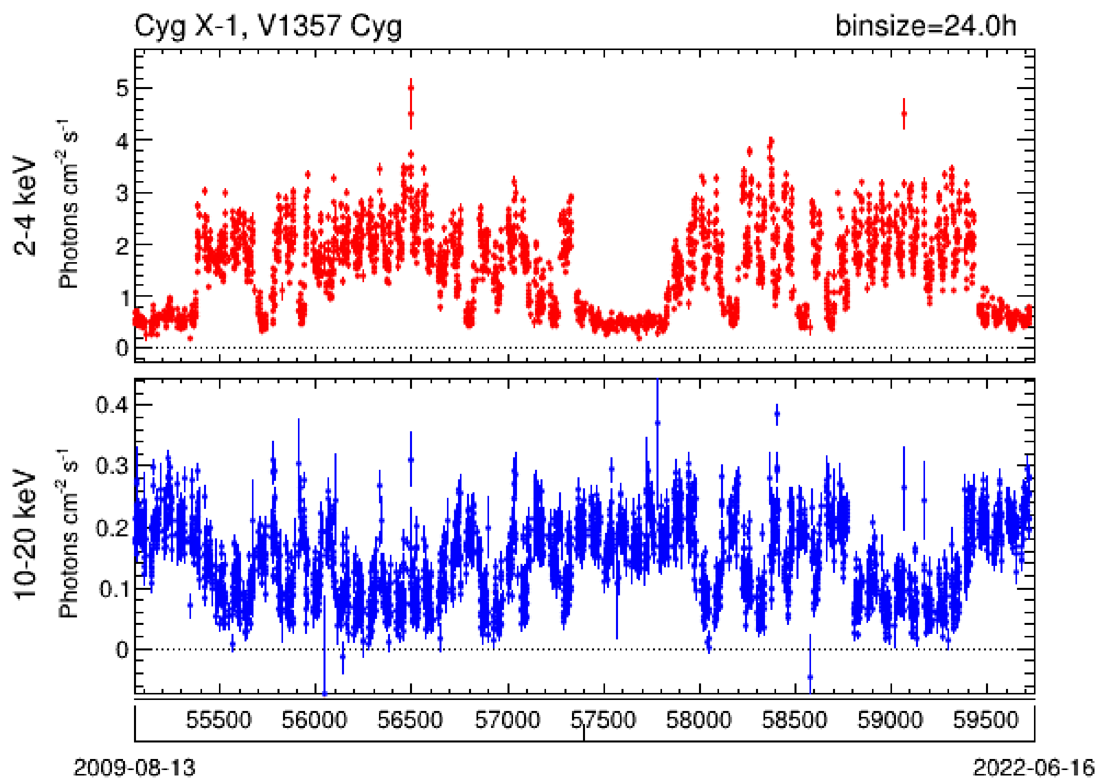


CYGNUS X-1

One of the brightest X-ray sources in the sky

Persistent source, changing from long-term hard state to episodes of (never perfect) soft state

From the orbital inclination, a PD of 1% or less was expected



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CYGNUS X-1

- **Observations:**
  - **IXPE: 242 ksec (15-21/5)**
  - NuSTAR: 42 ksec (18-21/5)
  - NICER: 87 ksec (15-21/5)
  - SWIFT: 54 ksec (15-20/5)
  - INTEGRAL: 196 ksec (15-20/5)
  - ART-XC: 171 ksec (15-19/5)
  - optical telescopes with polarimetry (DIPol-2, RoboPol)

- **Additional ToO**
  - to check variability of polarization
  - IXPE: 100 ksec (20-21/6)
  - NuSTAR: 40 ksec
  - NICER: 40 ksec

Krawczyinski et al. 2022

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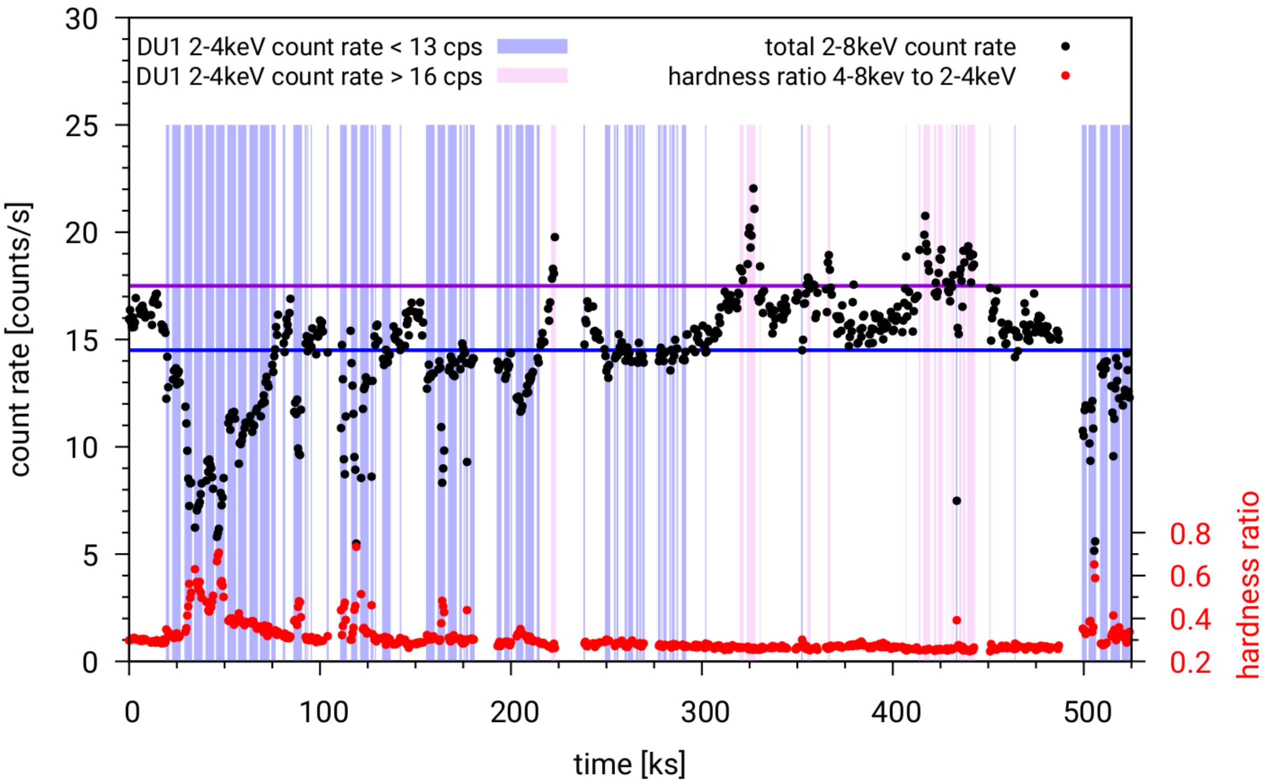
CYGNUS X-1



- High variability
- Mean IXPE Flux:

  5.2×10^{-9} ergs cm^{-2} s^{-1}

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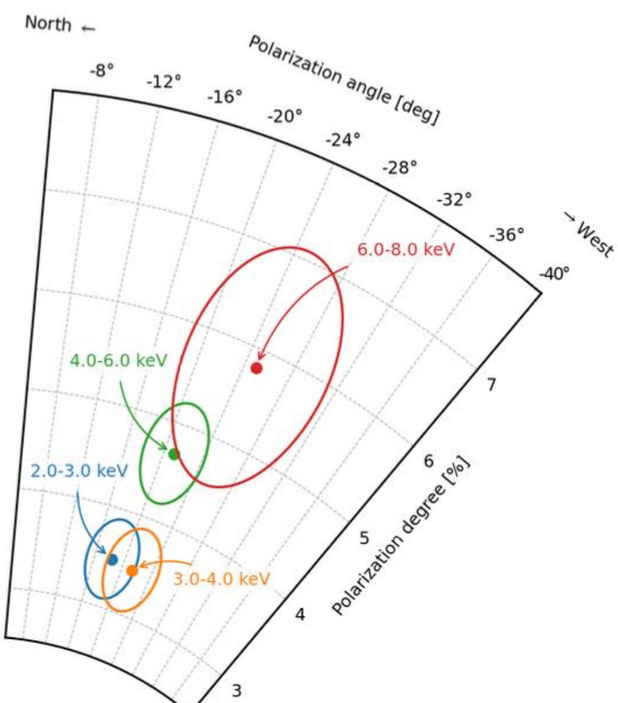
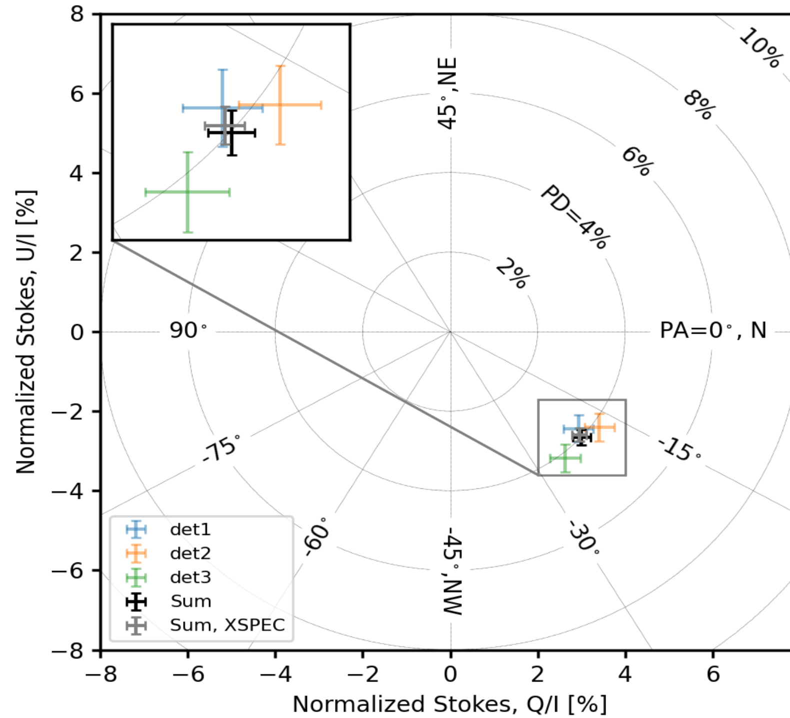
CYGNUS X-1

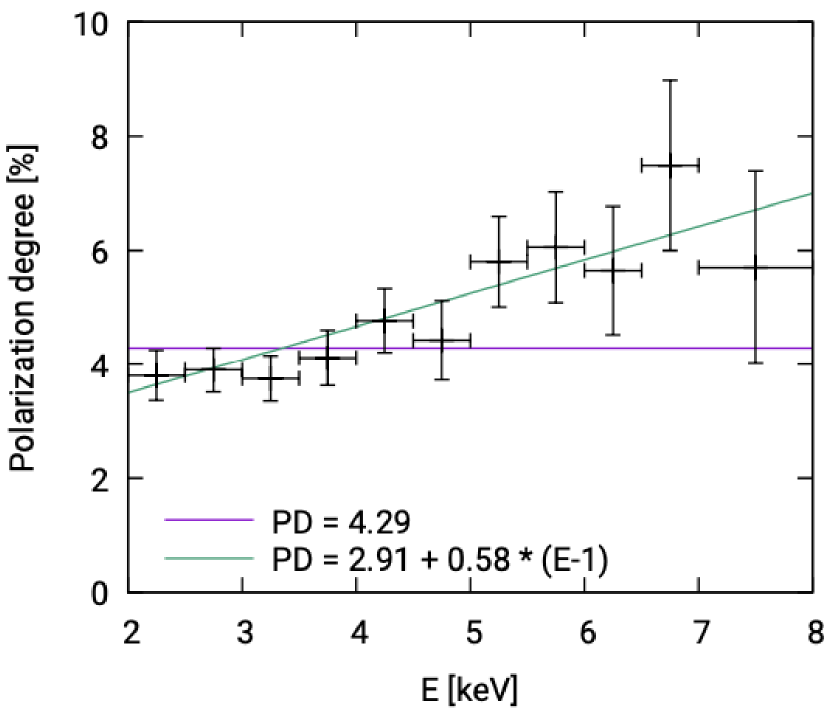
PD = (4.0 ± 0.2) %

PA = (-22 ± 1) deg

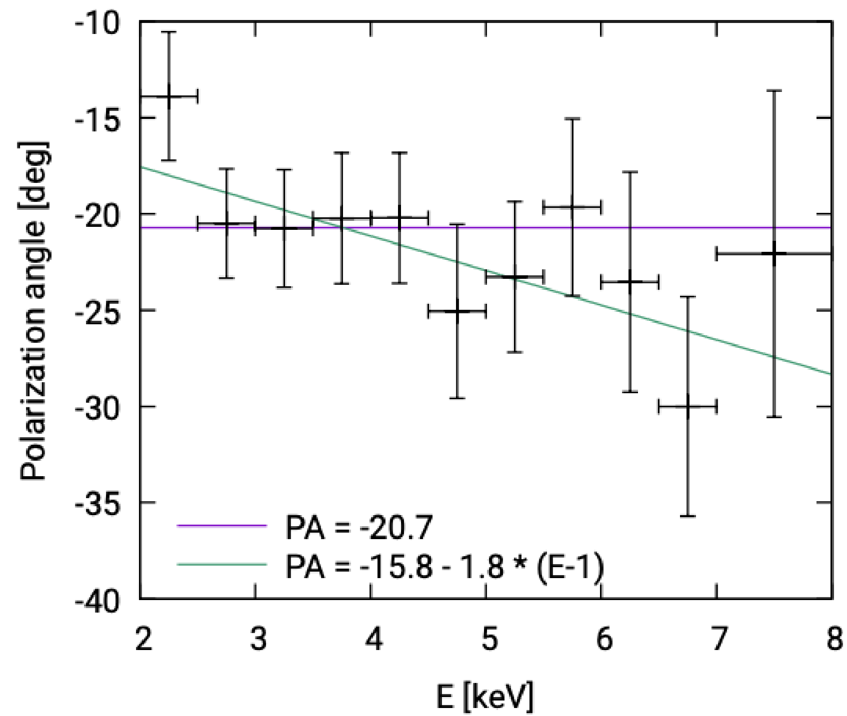




CYGNUS X-1



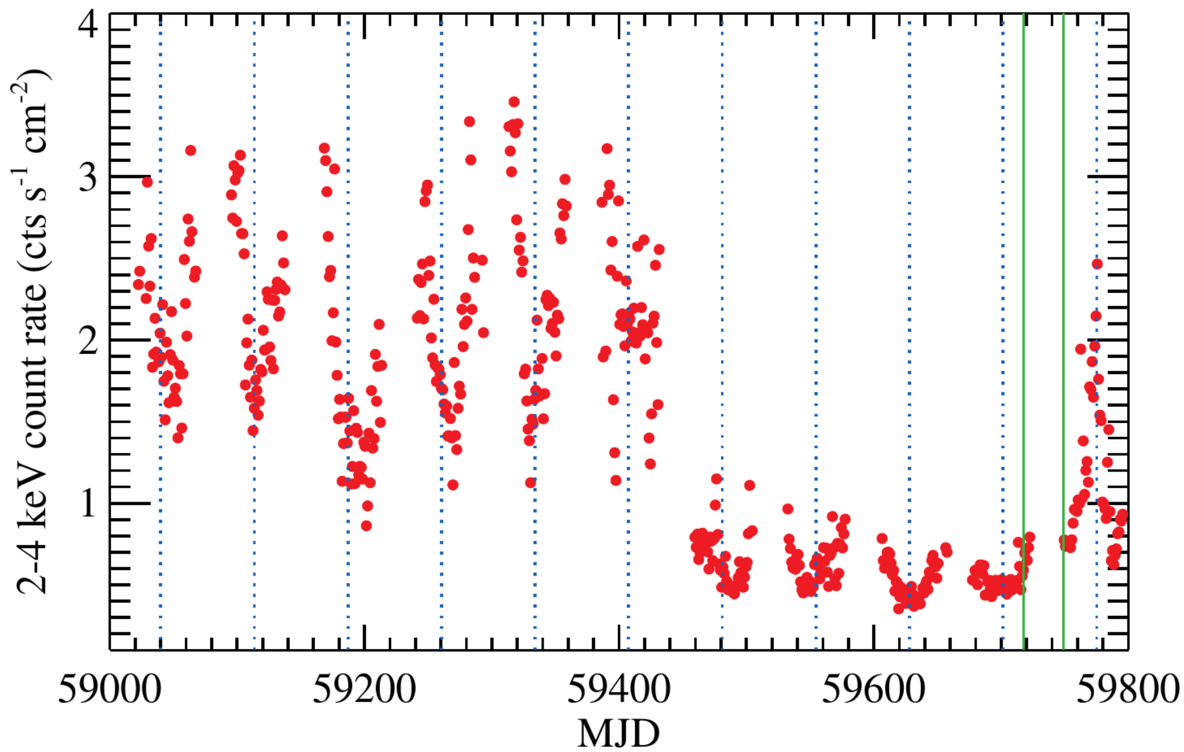
Polarization degree [%]
E [keV]
PD = 4.29
PD = 2.91 + 0.58 * (E-1)



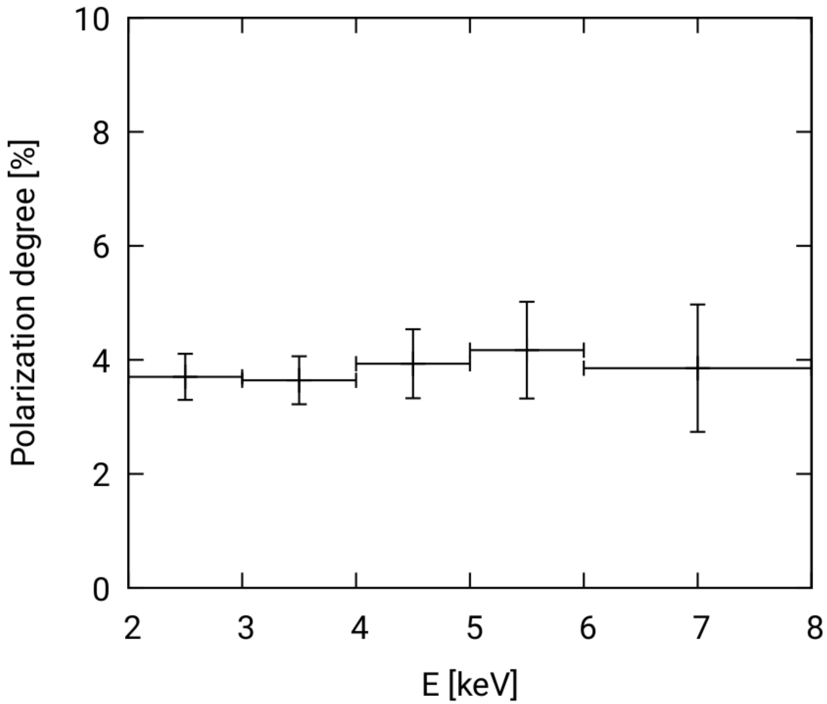
Polarization angle [deg]
E [keV]
PA = -20.7
PA = -15.8 - 1.8 * (E-1)

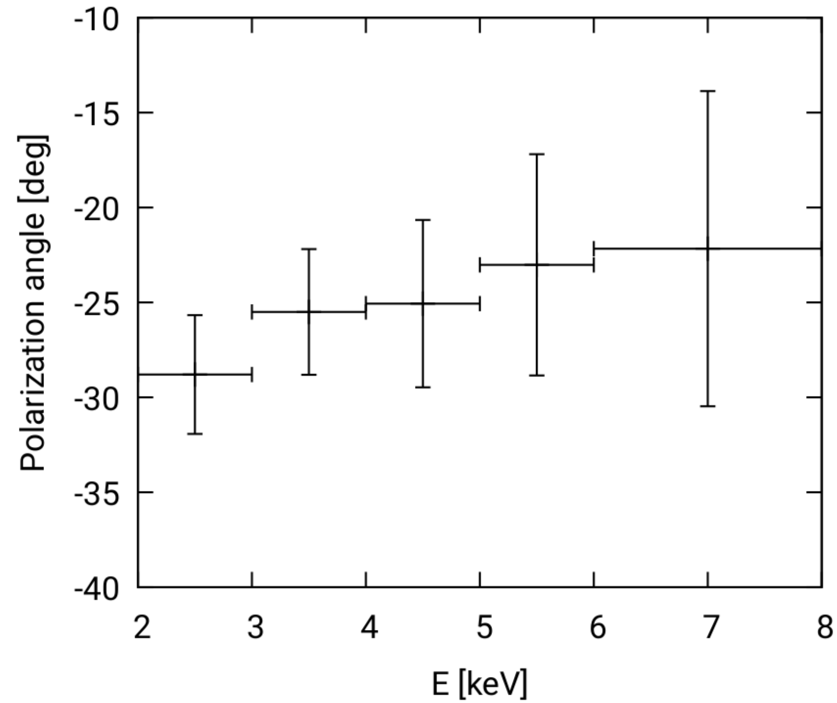
SUPERORBITAL PERIODICITY?

- different X-ray, optical and radio instruments indicate the presence of a superorbital periodicity (Poutanen, Zdziarski & Ibragimov 2008) – **73.5 days**
- precession of the accretion disc?
- a second observation was performed about one month later



SUPERORBITAL PERIODICITY?





Polarization properties of 2nd obs: nothing changed (within the errors)

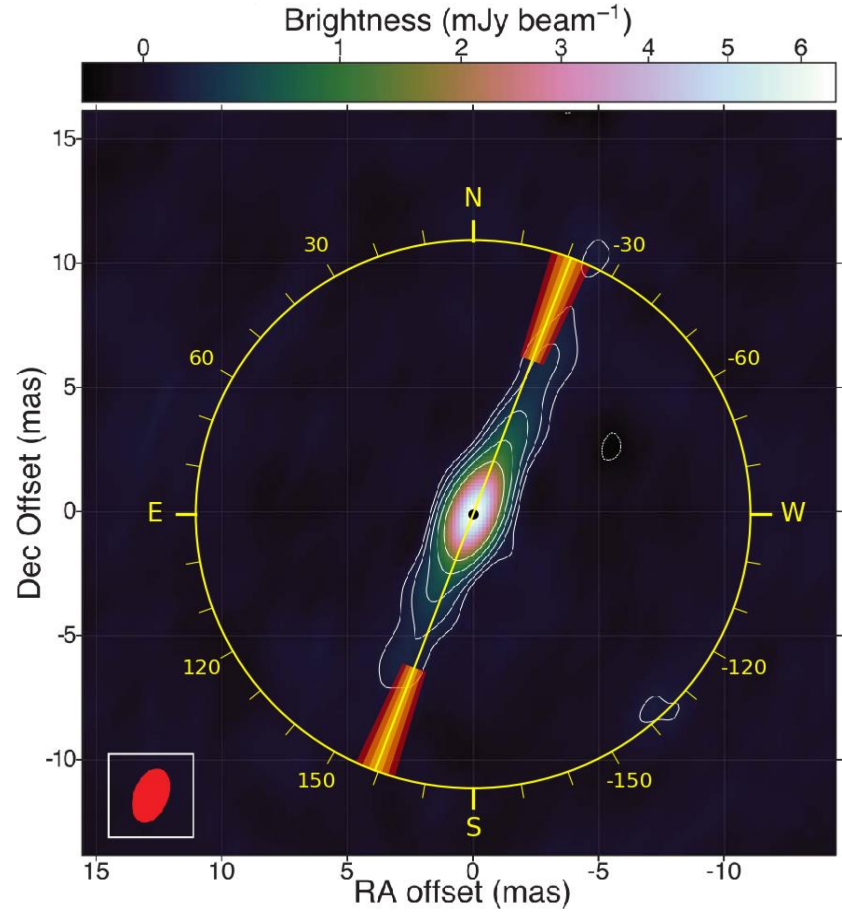
ALIGNMENT WITH THE RADIO JET

The X-ray polarization angle is well aligned ($<5^0$) with the radio jet.

Clear evidence of a relation between the jet and inner accretion flow!!

Polarization angle either parallel or perpendicular to inner flow for symmetry reasons.

Assuming that the jet is not parallel to the disc
→ Perpendicular polarization!

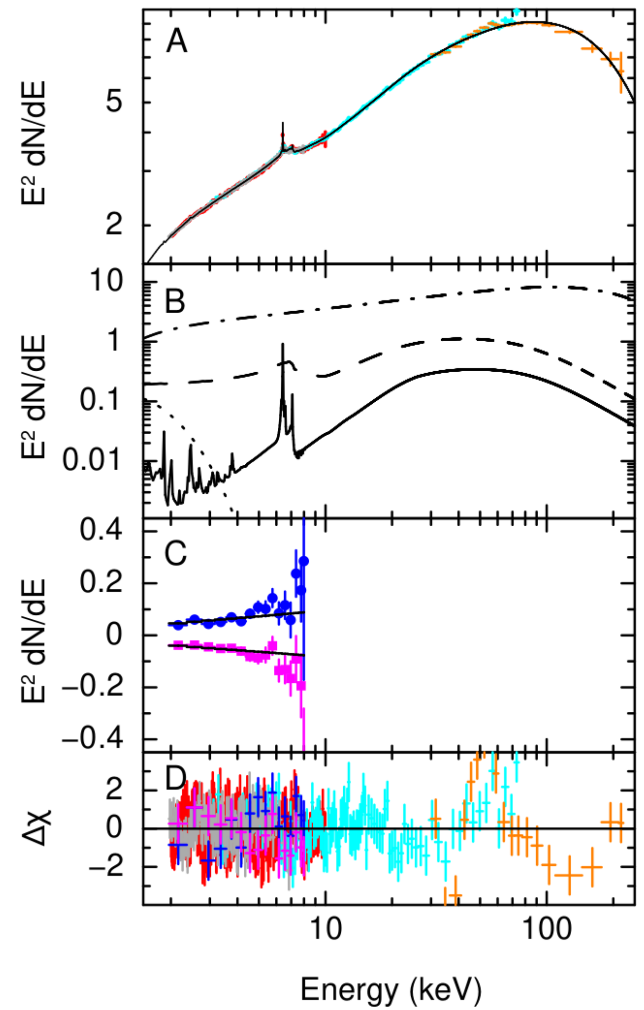


SPECTRAL FITS

IXPE + NuSTAR + NICER + INTEGRAL in 2-250 keV

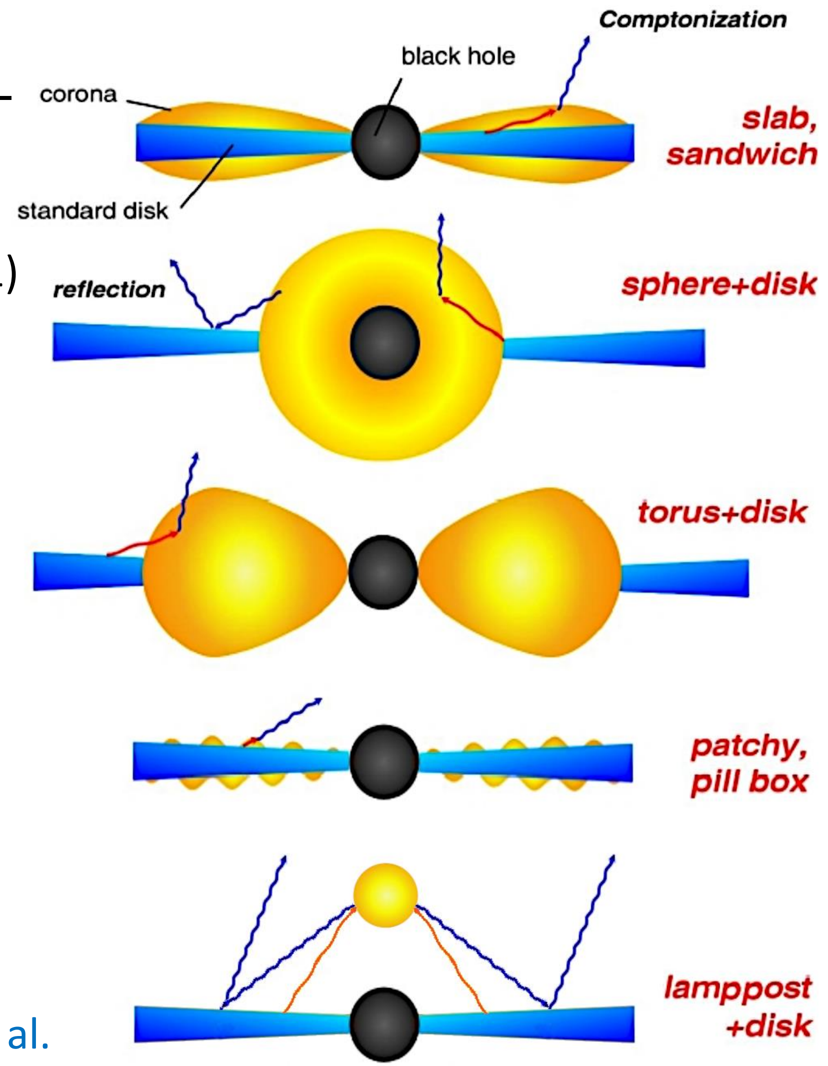
Spectral components:

- cross-calibration (mbpo)
- Galactic absorption (tbabs)
- thermal emission (diskbb, < 1%)
- Comptonization (nthcomp, 90%)
- relativistic reflection (relxillcp, 10%)
-



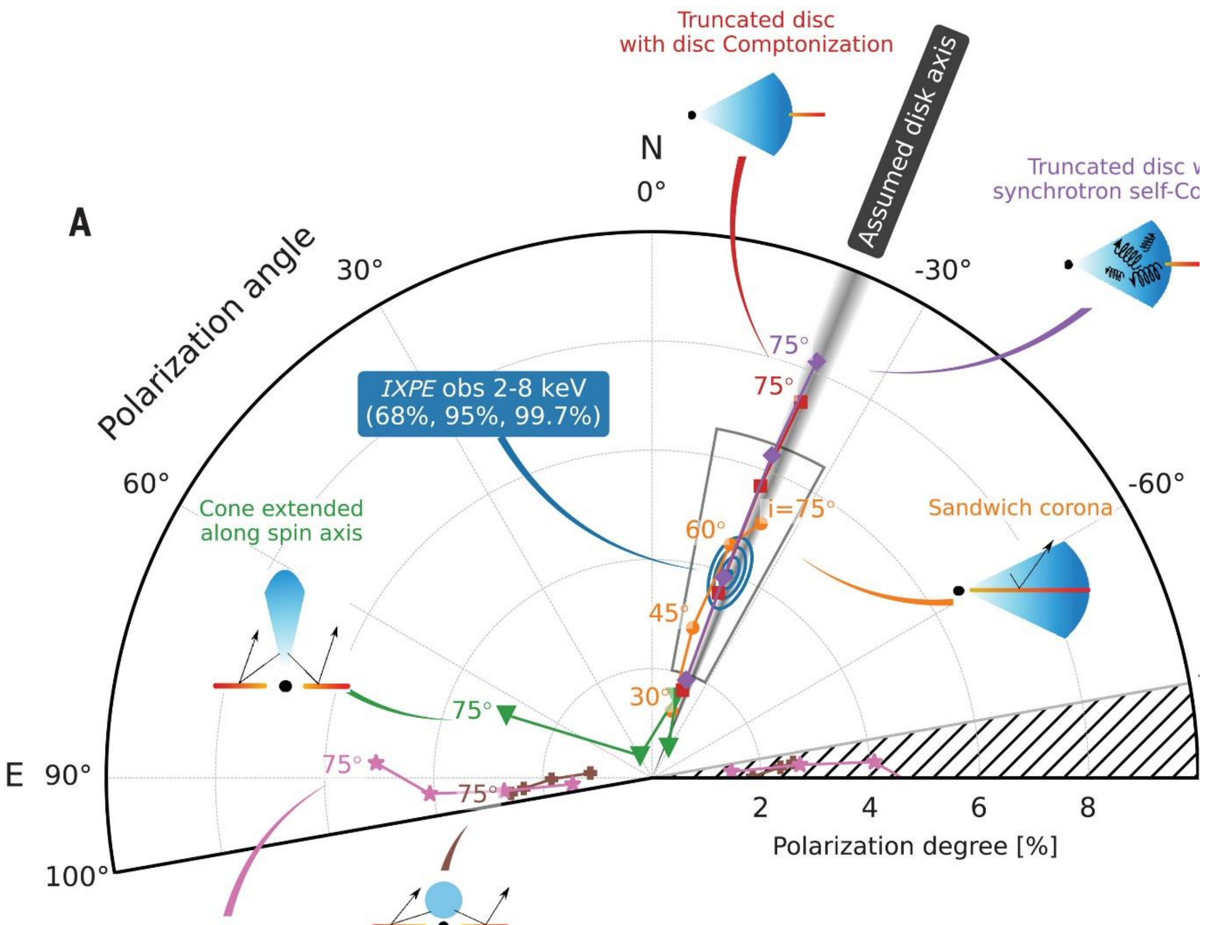
The geometry of the corona

- **Slab sandwich corona**
  Consistent with PD and PA but for i>65 deg
  Steeper spectrum expected (Haardt & Maraschi 1991)
- **Spherical corona**
  low polarization degree (Schnittman & Krolik 2010)
- **Hot inner accretion flow (truncated disc)**
  Consistent with PD and PA but for I > 45 deg
  Disc photons or internal synchrotron seed photons
- **Patchy corona**
  Again requiring high inclinations (Schnittman & Krolik 2010)
- **Lamp-post corona (spherical, cone-shaped)**
  low PD or perpendicular PA (Zhang et al. 2022)
- **Relativistic (v≈0.4 c) outflowing corona** (Poutanen et al. 2023, Dexter & Begelman 2024)



THE GEOMETRY OF THE CORONA

Either the inner flow is misaligned with the orbital plane, or the corona is outflowing at mildly relativistic velocities



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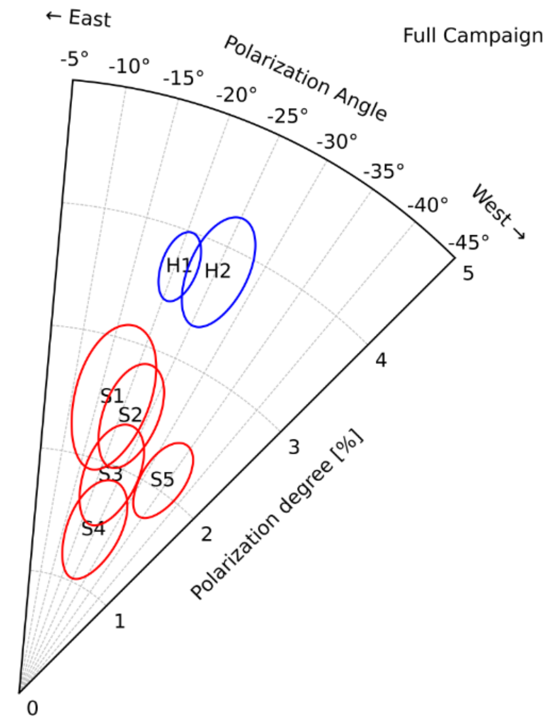
MORE OBSERVATIONS….

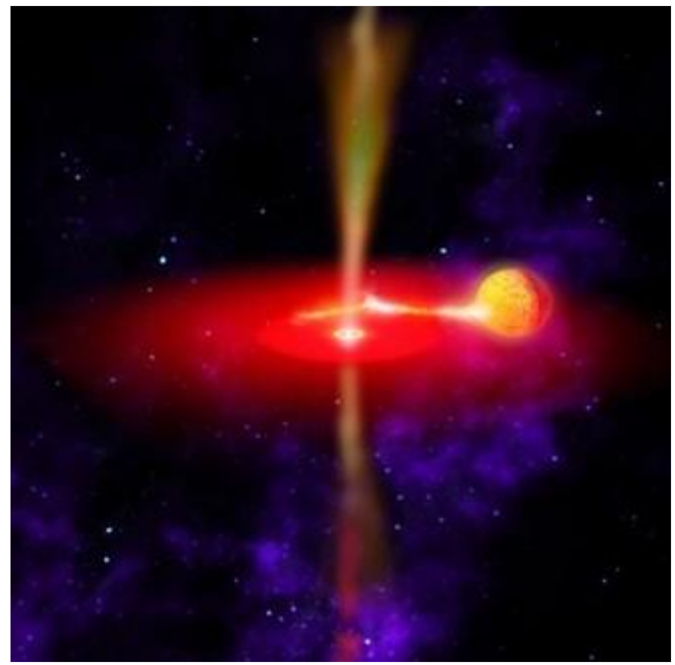
- **Five more observations in May-June 2023 after a transition to a softer state**
- **Still a significant comptonization component (plus reflection) present**
- **Polarization is about half that in hard state, with the same PA**
- **Evidence for increase with energy → Comptonization and/or reflection**



Steiner et al. 2024

CYGNUS X-3

- A bright, persistent but very variable source
- Brightest radio source of its class, but no optical counterpart due to large optical extinction
- Flaring gamma-ray emission
- A HMXB, with a Wolf-Rayet companion star
- Estimated distance of about 10 kpc
- Estimated orbital inclination of about 30 deg.



- Observed by IXPE twice on Oct-Nov 2022

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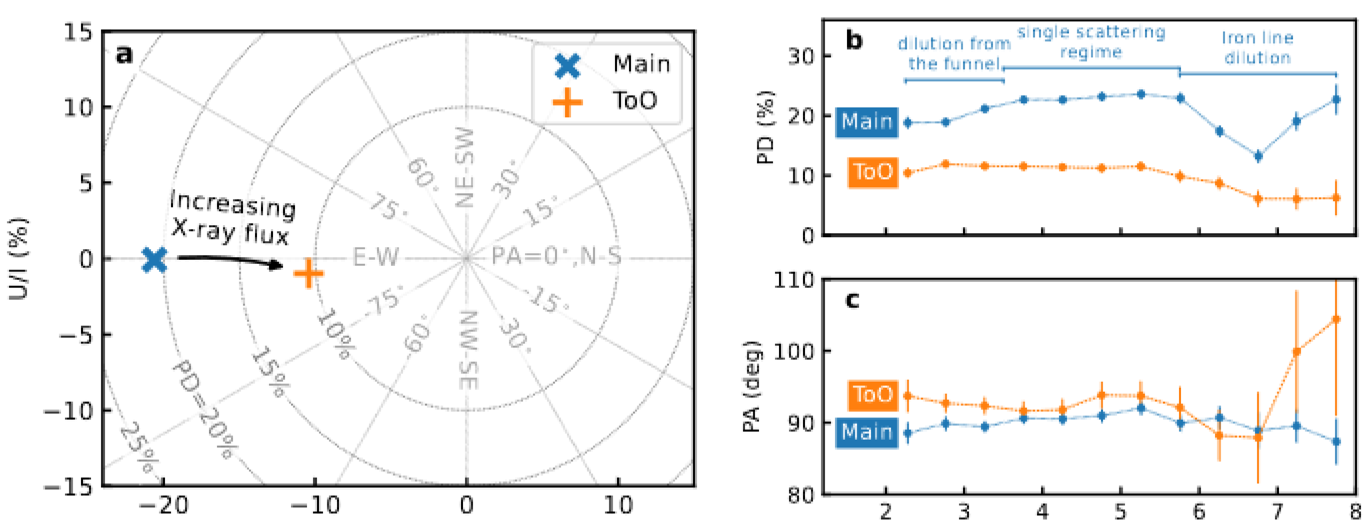
CYGNUS X-3

- Very large polarization degree detected

  (20% in the first obs., 10% in the second)

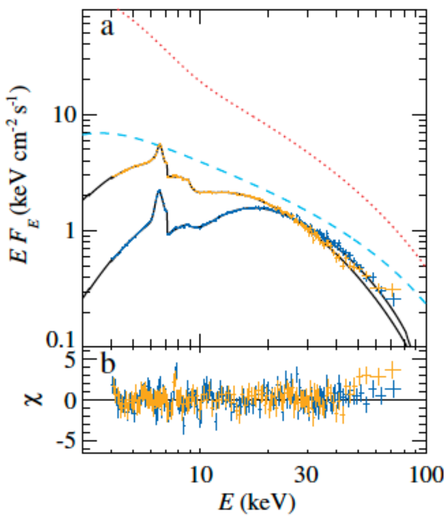
- PA orthogonal to the radio jet
- Observed again in Nov. 2023, results very similar to the first obs.

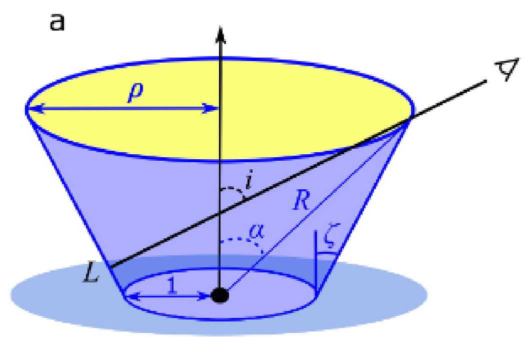


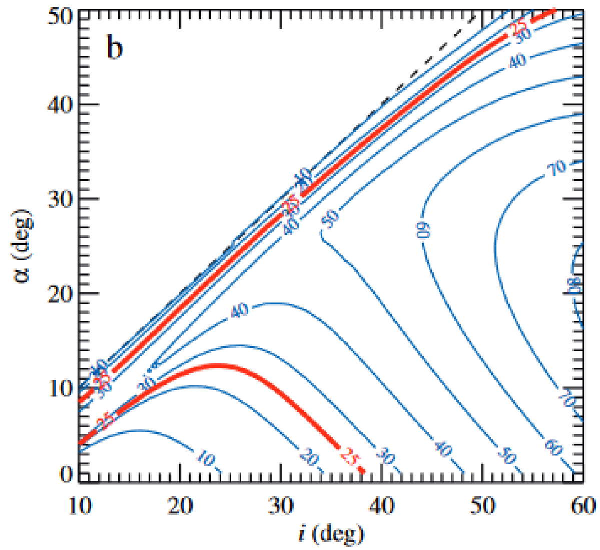
Veledina et al. 2024

CYGNUS X-3

- The spectra is reflection dominated, especially in the first obs.
- Results well explained by reflection in a narrow funnel (likely a thick wind)
- Some primary emission likely piercing through the absorber in the second obs.



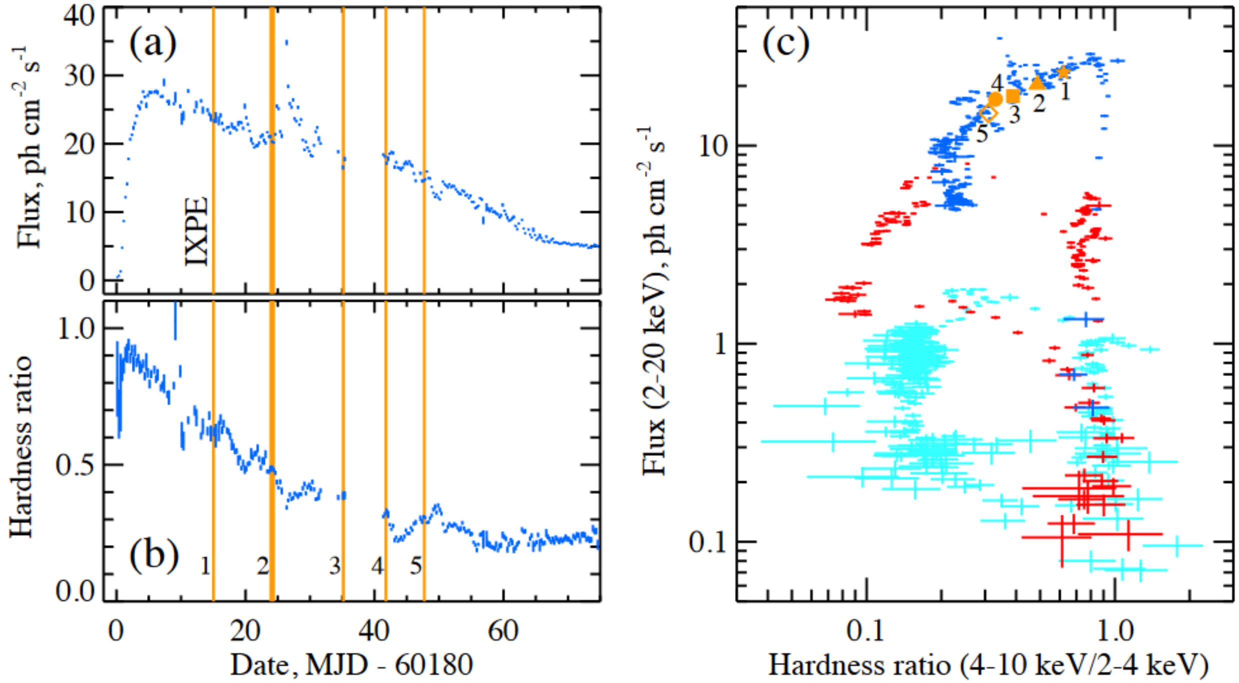




Veledina et al. 2024

SWIFT J1727.8-1613

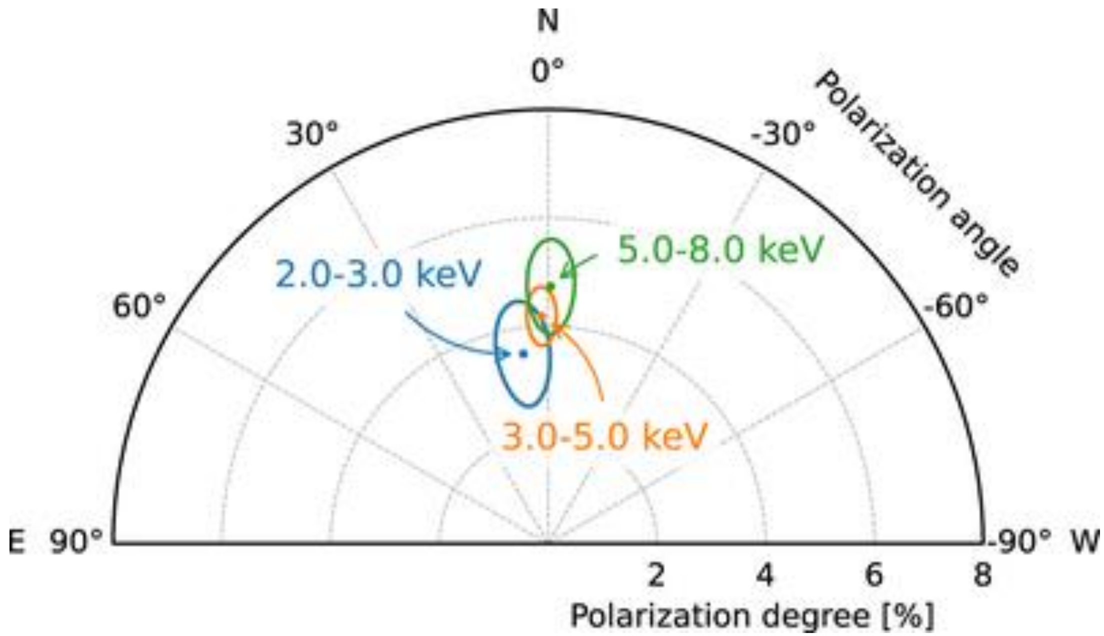
- A new, exceptionally bright transient source
- Observed by IXPE five times in Sep-Oct 2023
- First in hard state, than transitioning to a soft state (but not quite reached)



Veledina et al. 2023, Ingram et al. 2024

SWIFT J1727.8-1613

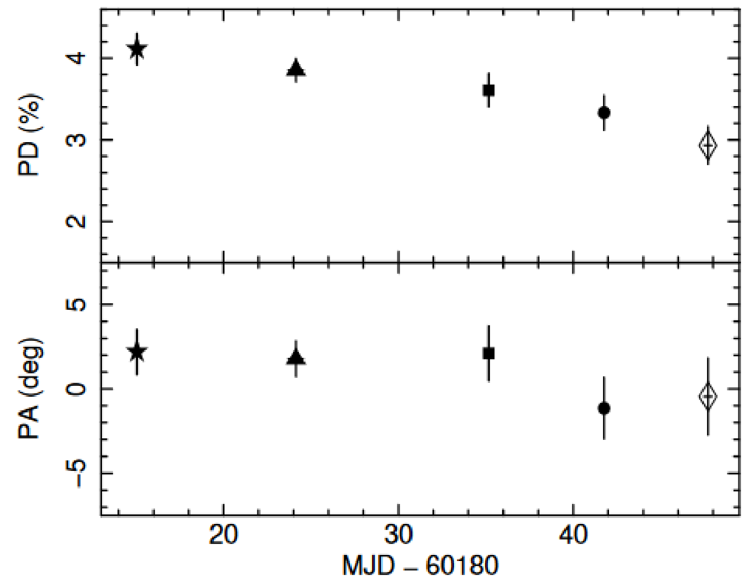
- First observation (the hardest one): PD≈4%
- PA aligned with sub-mm polarization, which is usually found aligned with the radio jet
- Similar corona as in Cyg X-1 ?

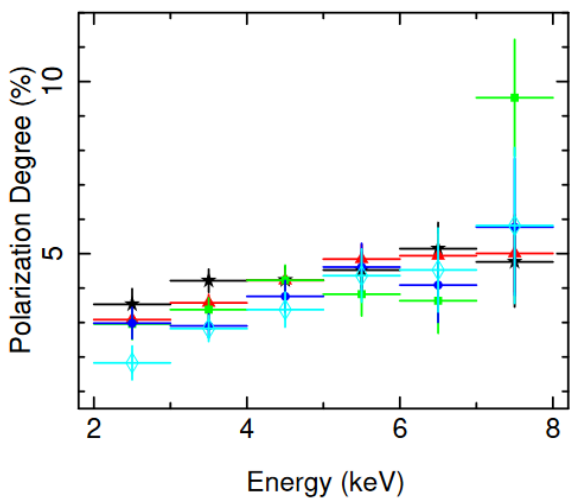


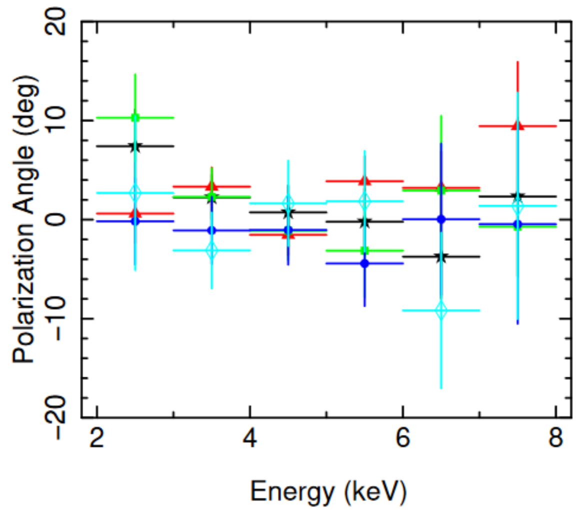
Veledina et al. 2023

SWIFT J1727.8-1613

- Polarization decreasing in time (especially in the soft band), but increasing in energy
- An increasing contribution by a less (or differently) polarized thermal emission?

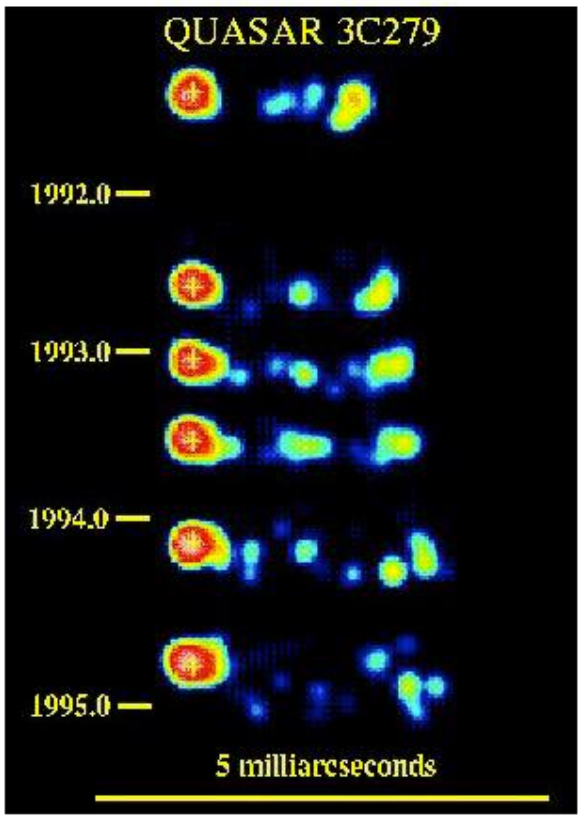


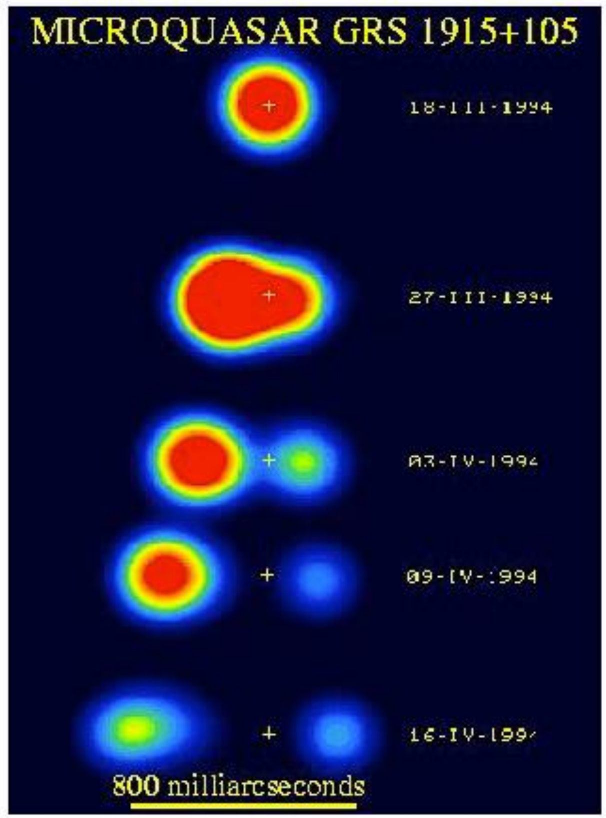




Ingram et al. 2024

THE ROLE OF THE JET (HARD STATE)



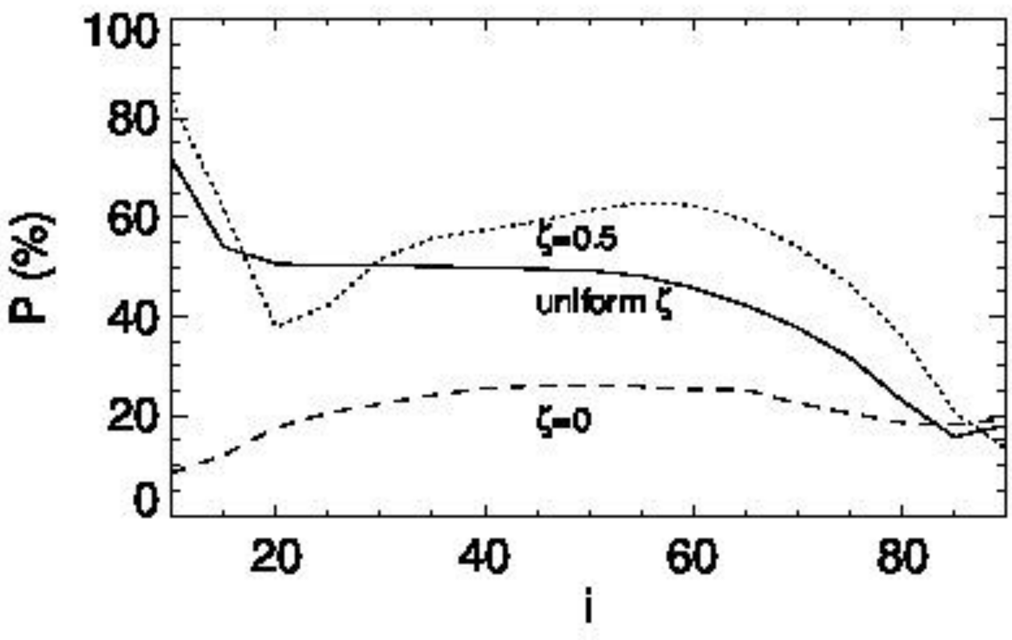


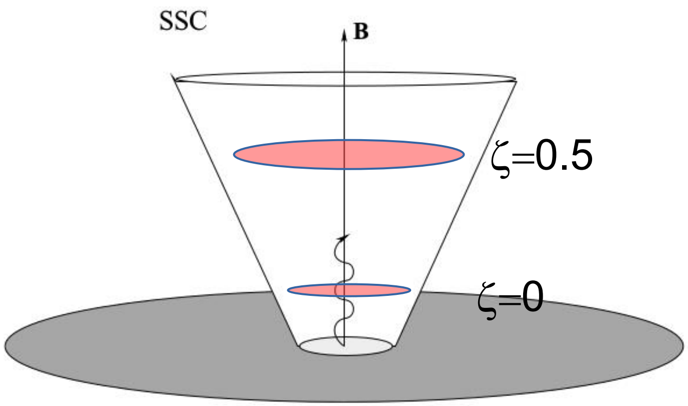
These sources are emitting jets (which may even be superluminal).

Jets are launched only in hard states.

They are probably weak emitter in X-rays, at least when the source is luminous

THE ROLE OF THE JET (HARD STATE)





McNamara et al. 2009

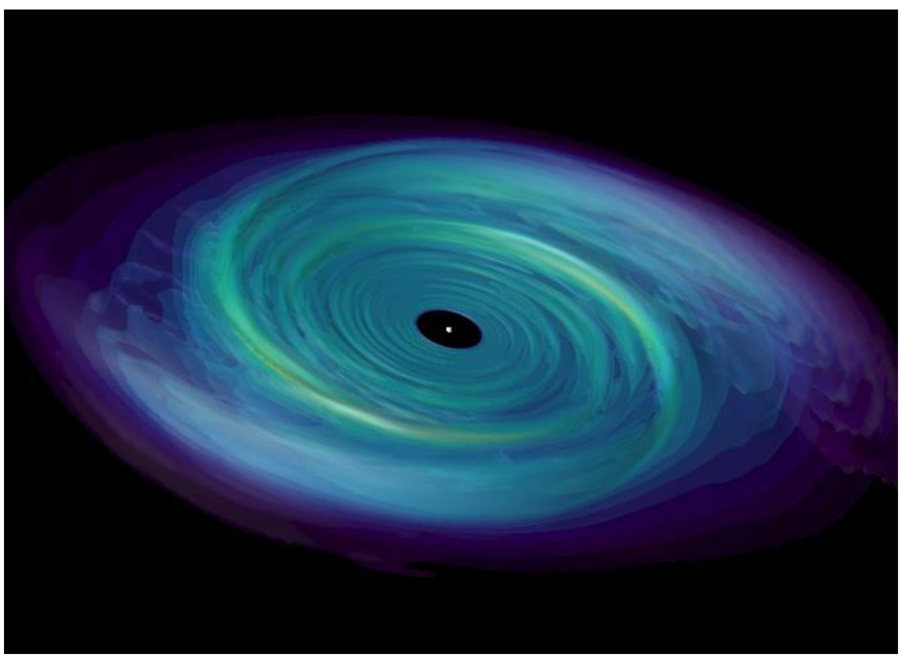
Corona emission is predicted to be less than 10%.

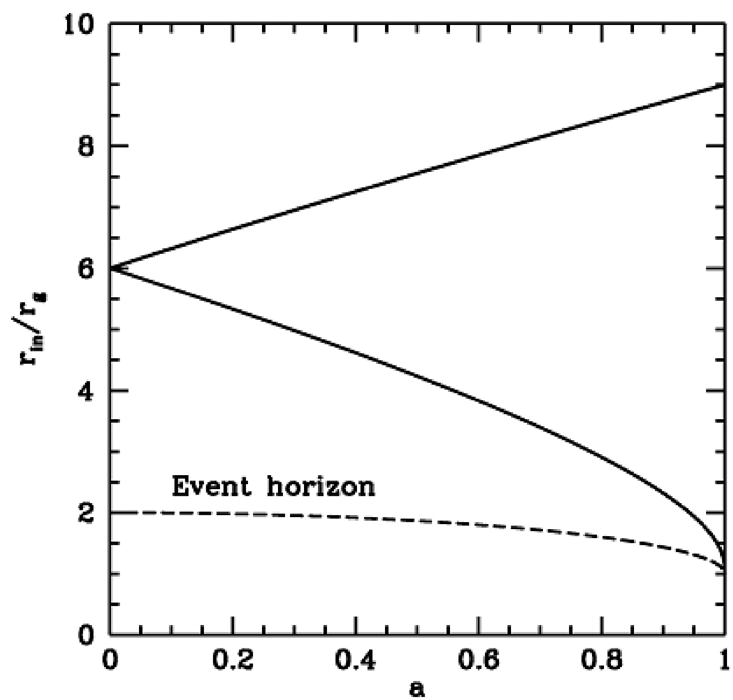
Much larger polarization degrees are expected for jet emission

THE SPIN OF THE BLACK HOLE (SOFT STATE)

In accreting Galactic black hole systems, X-ray polarimetry can provide a technique to measure the spin of the black hole, in addition to the three methods employed so far.

This technique actually measures the inner disc of the radius, which in turn is assumed to be coincident with the Innermost Stable Circular Orbit (ISCO), a rather safe assumption in the soft state. Then, the relation between the ISCO and the black hole spin is used.

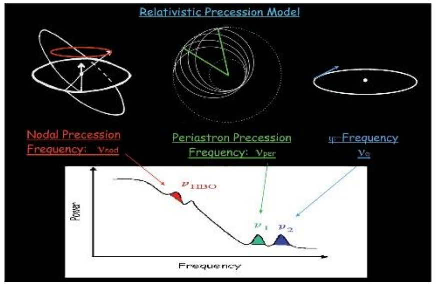




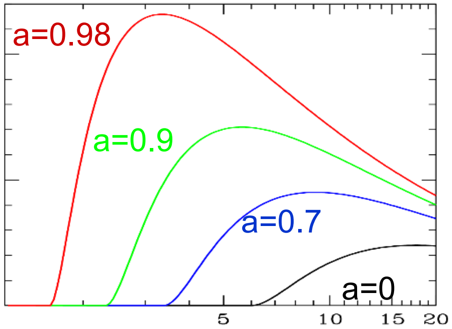
THE SPIN OF THE BLACK HOLE (SOFT STATE)

In accreting Galactic black hole systems, X-ray polarimetry can provide a technique to measure the spin of the black hole, in addition to the three methods employed so far.

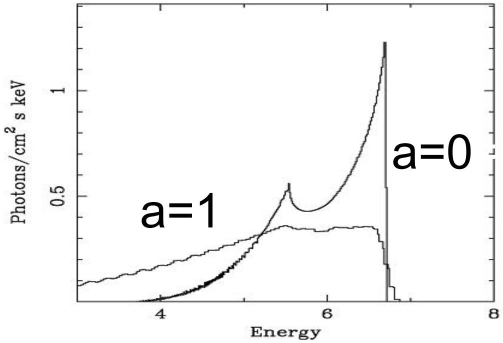
QPO **Based on the broad features in the power spectrum explained in terms of relativistic precession**



Continuum **Based on the fitting of the thermal disc emission, whose shape depends on the inner radius (assumed to coincide with the ISCO), and then on the spin**



Iron line **Based on the profile of the iron line emitted in the accretion disc, which depends on the inner radius (assumed to coincide with the ISCO), and then on the spin**



THE SPIN OF THE BLACK HOLE (SOFT STATE)

In accreting Galactic black hole systems, X-ray polarimetry can provide a technique to measure the spin of the black hole, in addition to the three methods employed so far.

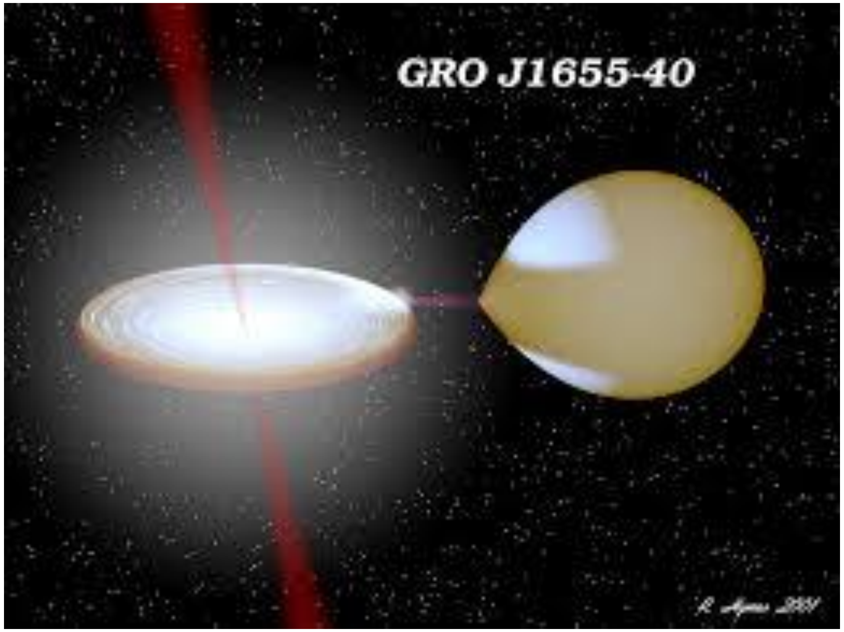
Why another method, besides the three ones already in use?

J1655-40:

QPO a = J/Jmax= 0.290±0.003

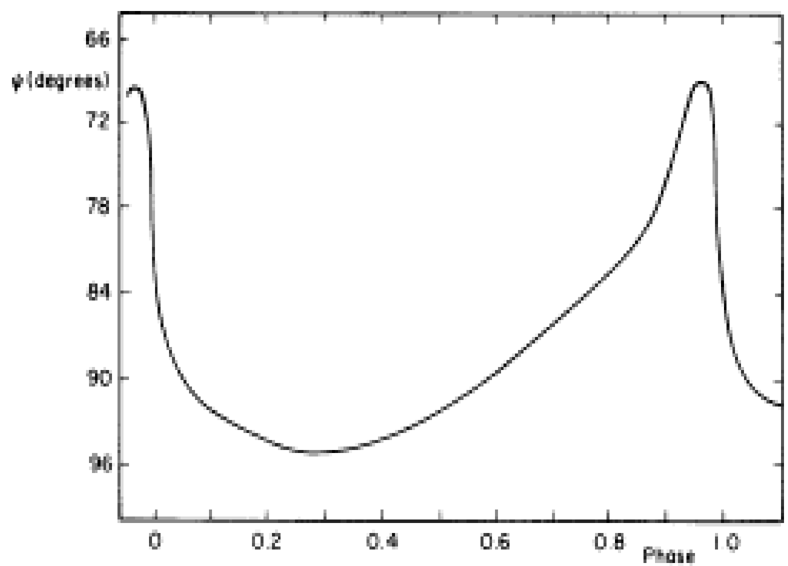
Continuum: a = J/Jmax 0.7±0.1

Iron line a = J/Jmax 0.95

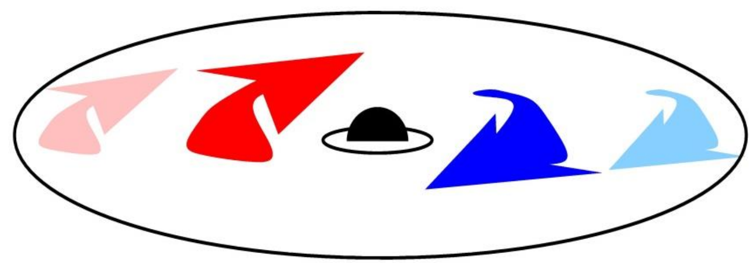


THE SPIN OF THE BLACK HOLE (SOFT STATE)

- **For an accreting Galactic BH in the soft state**
  - Scattering polarizes the thermal disk emission (e.g. Chandrasekhar 1960)
  - Polarization angle rotates due to GR effects
    - Polarization rotation is greatest for emission from inner disk
    - Inner disk is hotter, producing higher energy X-rays



Connors & Stark 1977



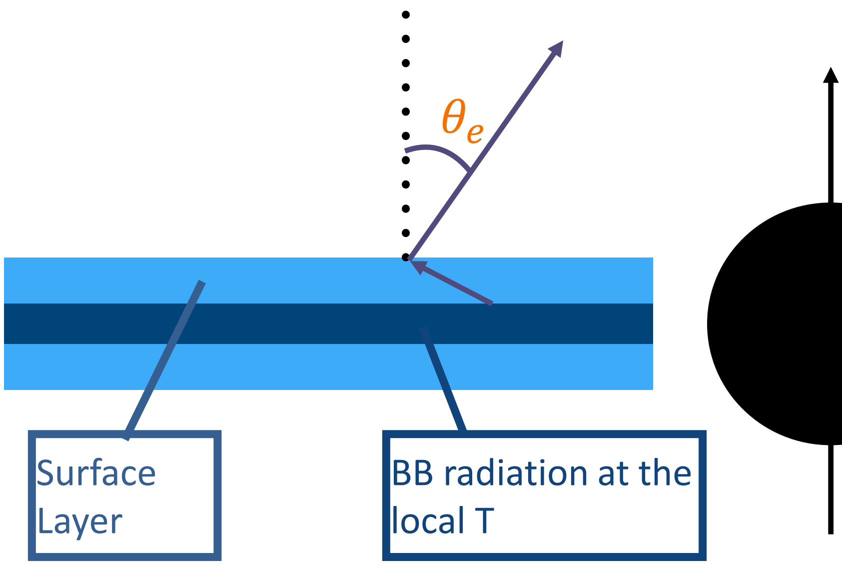
Orbiting spot with:
a=0.998; R=11.1 Rg; i=75.5 deg

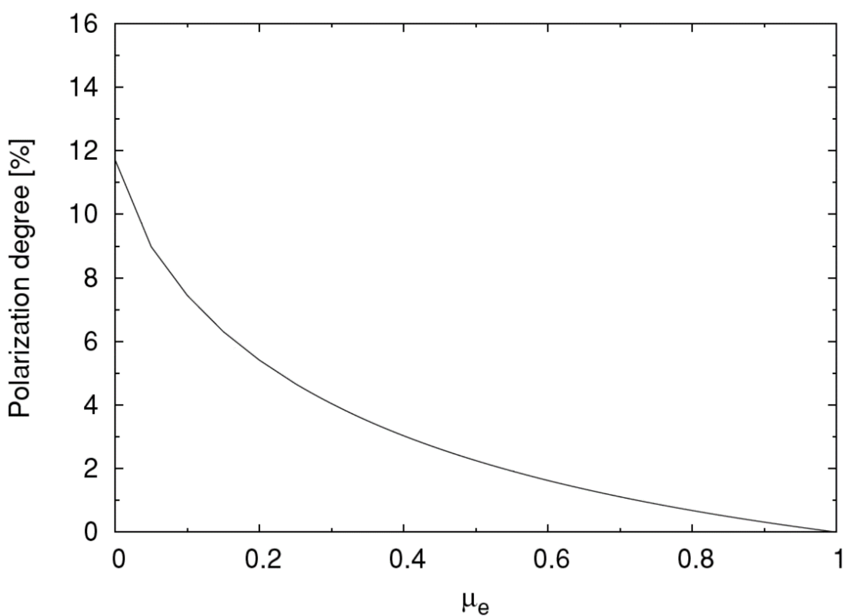
(Phase=0 when the spot is behind the BH)

The PA of the net
(i.e. phase-averaged) radiation is also rotated!

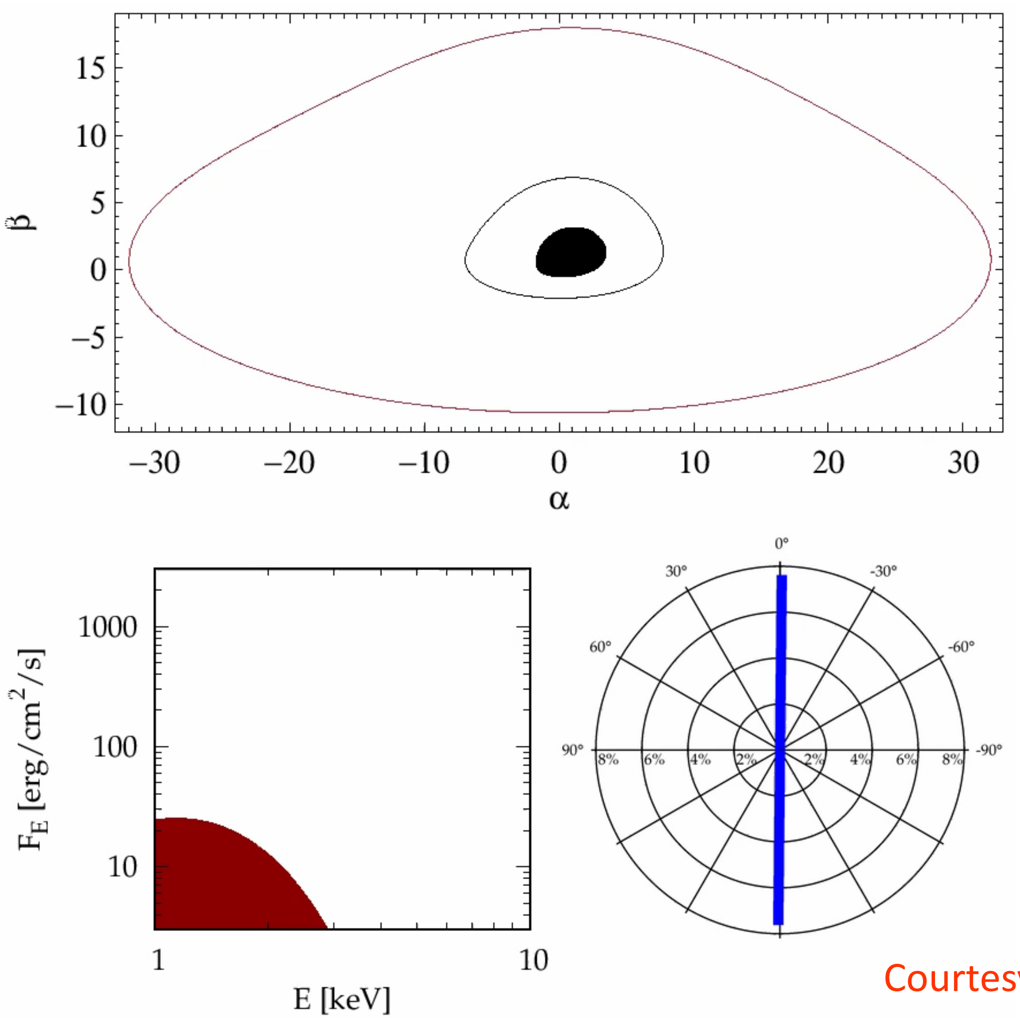
THE SPIN OF THE BLACK HOLE (SOFT STATE)

Thermal disc radiation is polarized if there is an upper layer where scattering dominates. Because the density diminishes in the outer layers of the disc, this is possible. In case of a pure, semi-infinite plane-parallel scattering atmosphere, the Chandrasekhar (1960) results applies.

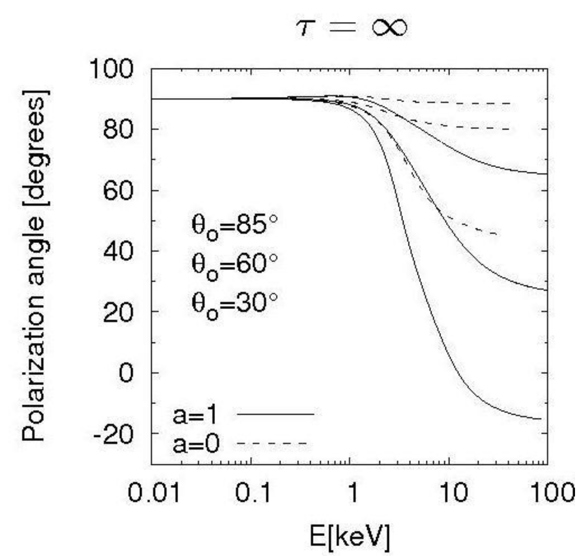




THE SPIN OF THE BLACK HOLE (SOFT STATE)

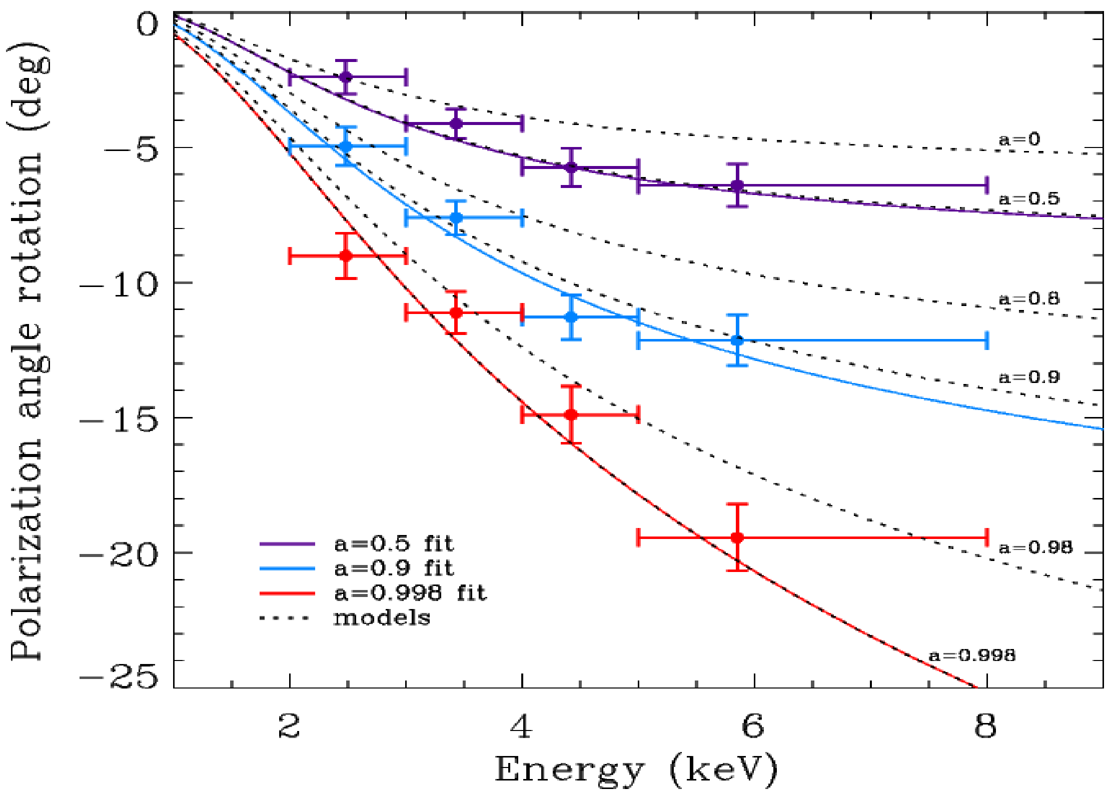


Rotation of the polarization angle with energy



Courtesy: Michal Dovciak

THE SPIN OF THE BLACK HOLE (SOFT STATE)



Rotation of the polarization angle with energy

200 ks IXPE observation of GRS1915+105

Marshall Space Flight Center
agenzia spaziale italiana

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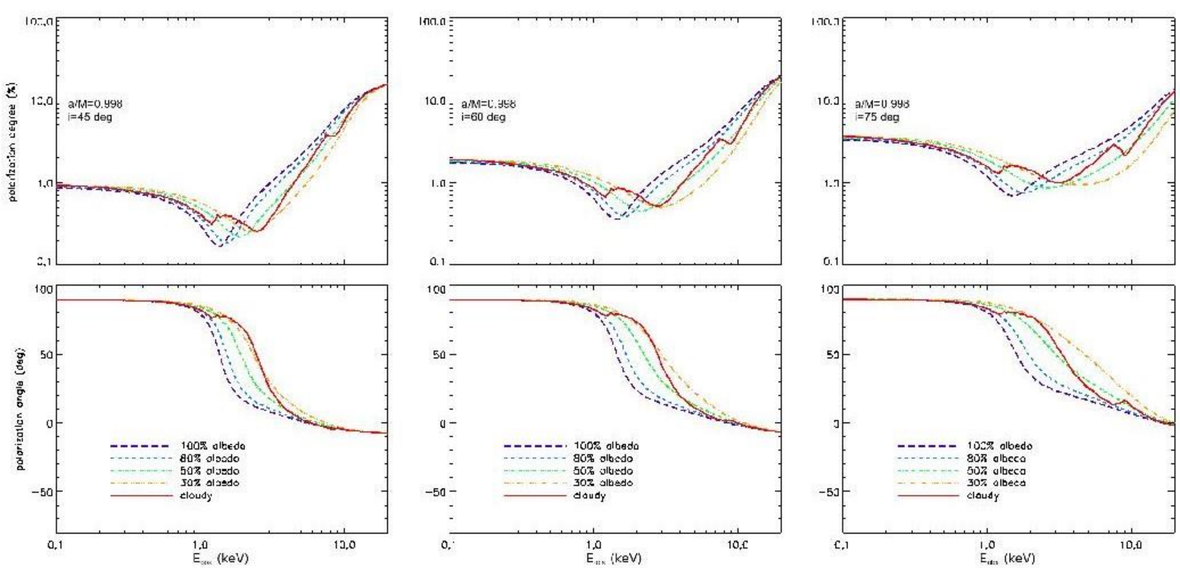
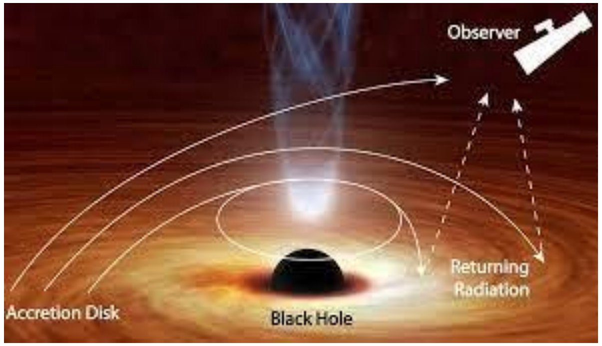
THE SPIN OF THE BLACK HOLE (SOFT STATE) – COMPLICATION #1

Previous results do not include the so-called "returning radiation" (Cunningham 1976), i.e. disc photons which illuminate the disc itself.

It may be significant, however, especially for high spin. Schnittman & Krolik 2009 included this effect in their calculations, assuming a perfect disc reflectivity (100% albedo, i.e. no absorption). We re-calculated the effect with a more realistic albedo.





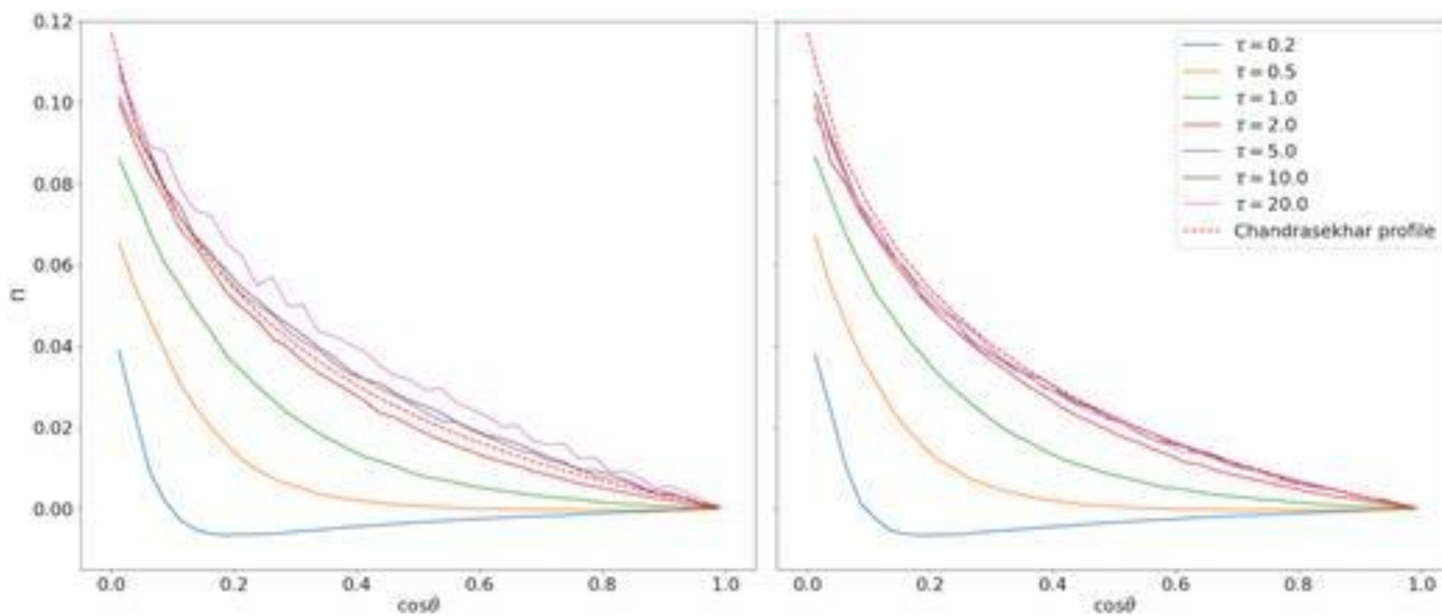
Taverna et al. 2020

THE SPIN OF THE BLACK HOLE (SOFT STATE) – COMPLICATION #2

Is the thermal emission really polarized *à la* Chandrasekhar?

The assumption is that the thermal black body emission pass through a pure scattering (e.g. fully ionized) atmosphere.

Given the temperature and density conditions in the disc surface, however, significant (mostly photoelectric) absorption is likely to occur (e.g. the disc in not fully ionized).



Taverna et al. 2021

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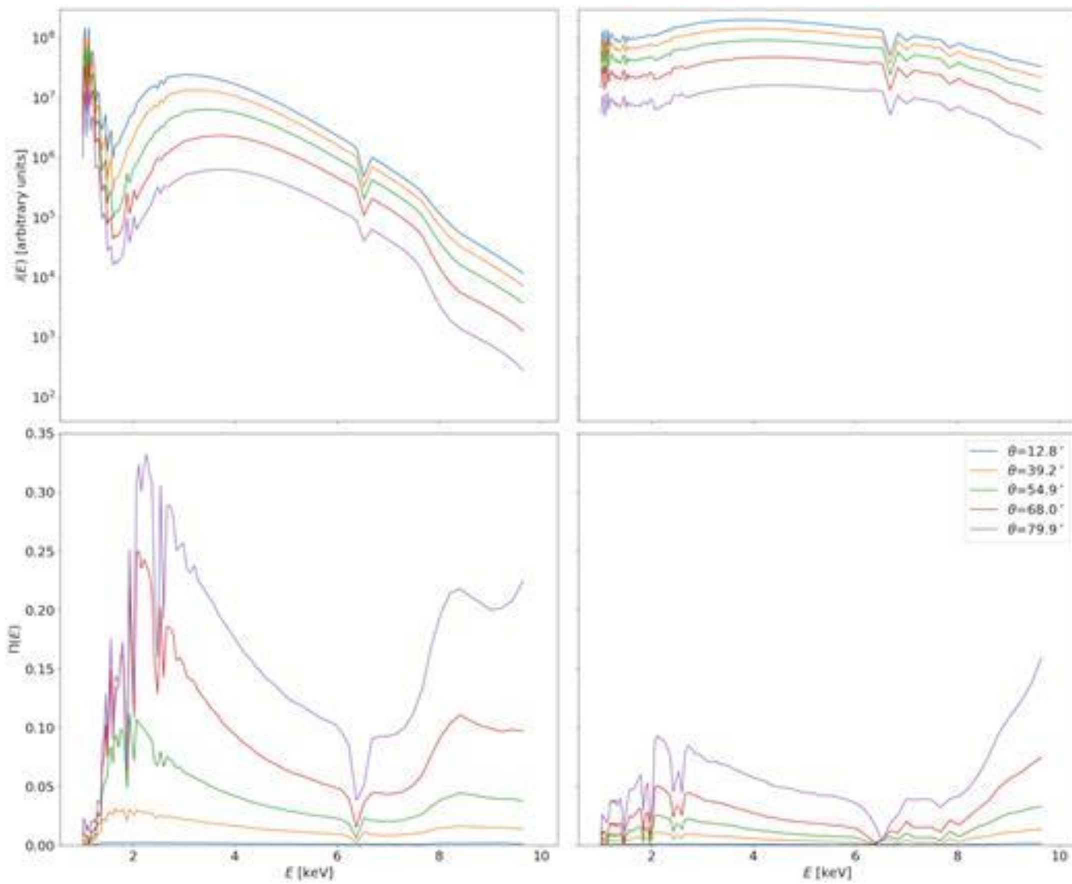
THE SPIN OF THE BLACK HOLE (SOFT STATE) – COMPLICATION #2

When absorption is included, the polarization changes significantly.

In particular, the PD increases at those energies when absorption is relevant.

This is due to the fact that in this case photons before the last scattering come preferentially from the vertical direction.



Taverna et al. 2021

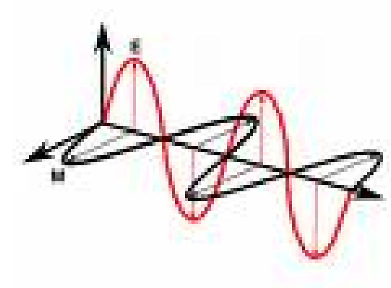
IXPE observed four accreting BHs in soft state:

4U 1630-47

LMC X-1

4U 1957+11

LMC X-3



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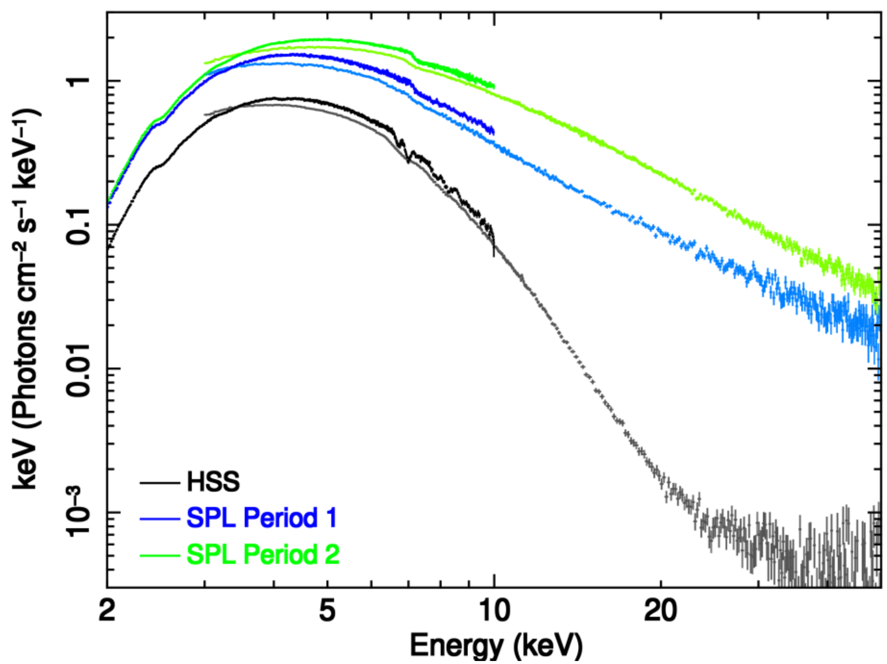
4U 1630-47

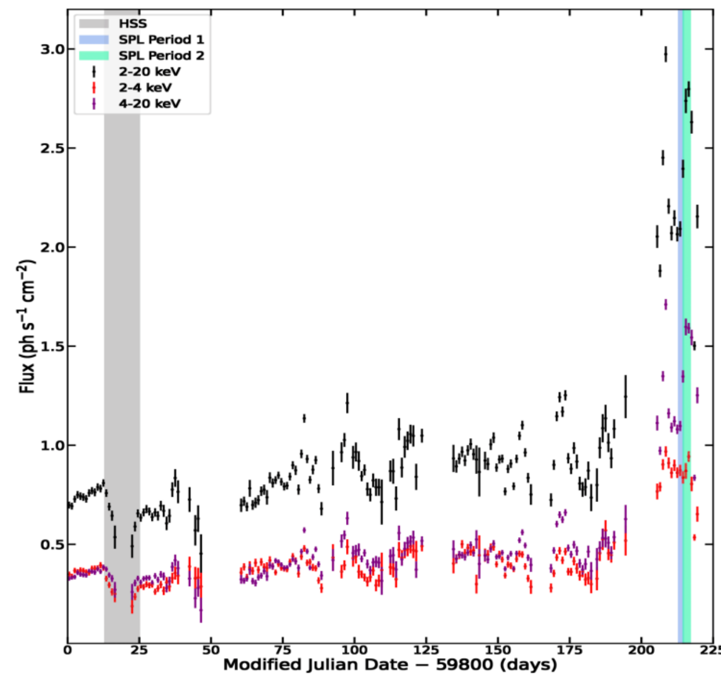
Transient LMXB (?) observed twice by IXPE (in soft and SPL state)

Distance ~ 11.5 kpc; Mass ~ $10M_{\odot}$

No resolved radio jet, no detected companion

Inclination likely high (dips, disc wind) but not extreme (no eclipses)





Observed by IXPE on:

Aug 2022 (Rawat et al. 2023, Ratheesh et al. 2024)

March 2023 (Rodriguez Cravero et al. 2023, Rawat et al. 2023)

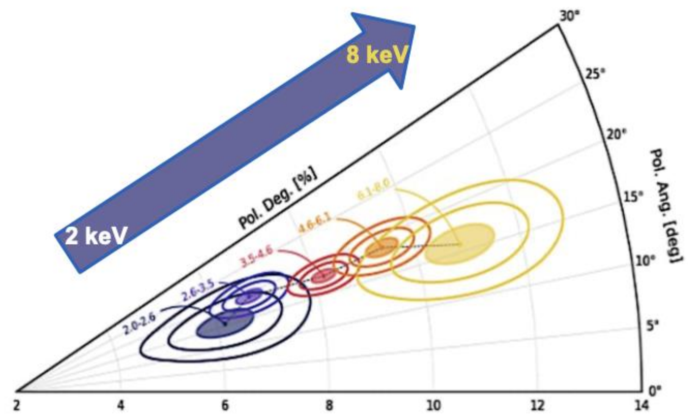
4U 1630-47

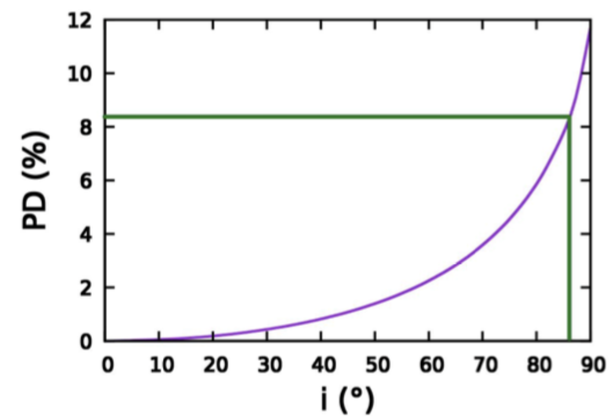
Soft state: PD=8.32 ± 0.17 % (energy averaged), strongly increasing with energy

→ No standard disc ?

Significant absorption in the disc plus mildly relativistic outflow of the upper layer required to fit the data

PA constant with energy, so likely not very high BH spin





Proposed alternative: reflection from the wind. But:

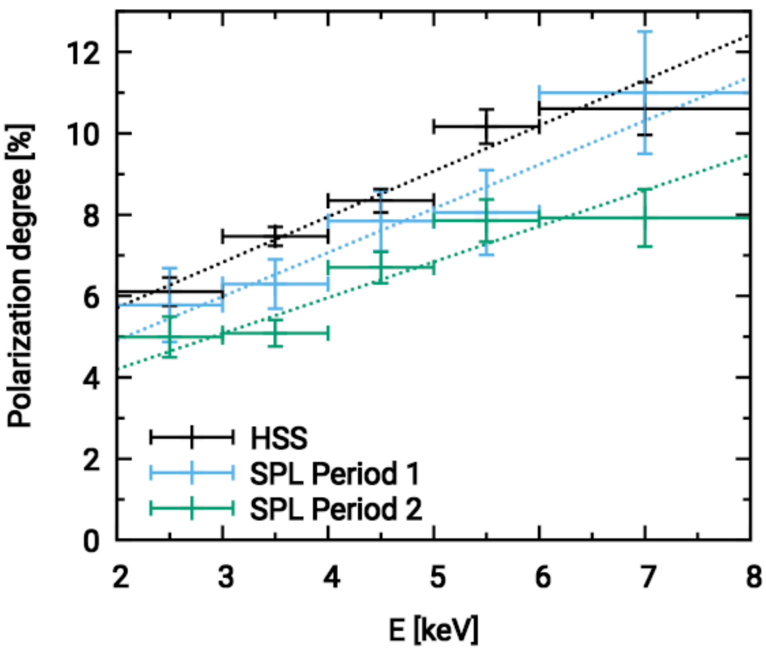
PD increase with energy not explained

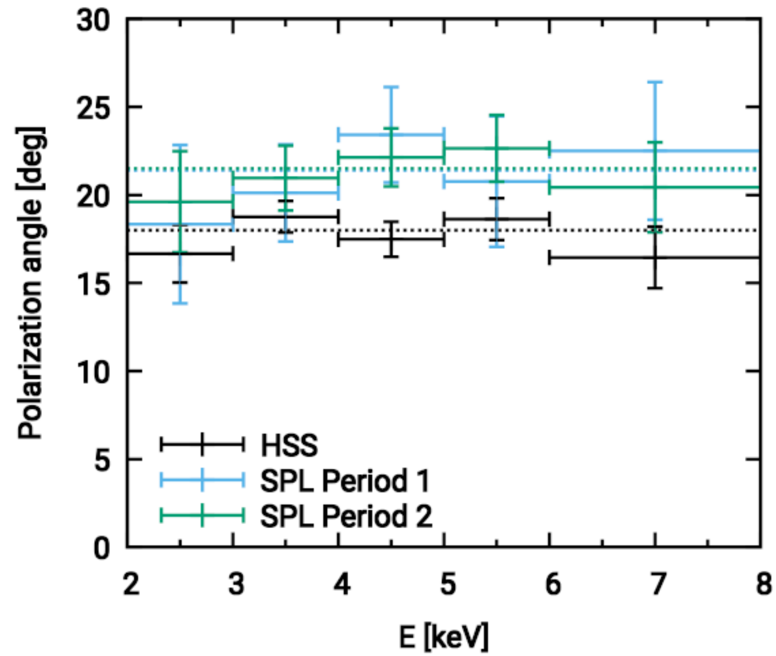
Requires large covering factor, but no emission lines are observed

IXPE
Imaging X-Ray Polarimetry Explorer

4U 1630-47

Soft Power Law state: PD=6.75 ± 0.21 % (energy averaged), again strongly increasing with energy. Same PA as in the soft state





Geometry of the corona similar to that of the accretion disc?

LMC X-1

A persistent, HMXRB always in the soft state. Much of this system is known:

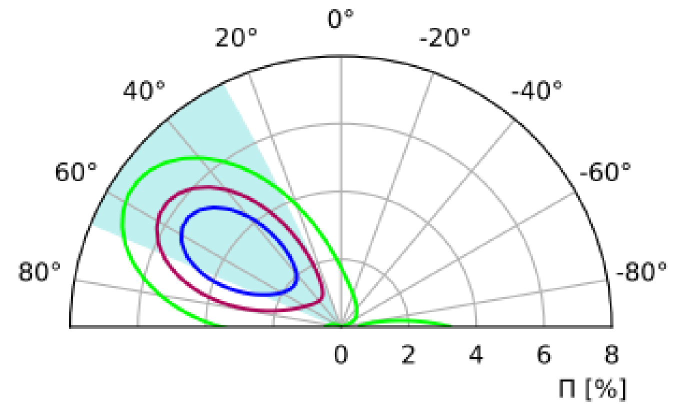
BH mass: 10.91±1.41 solar masses

Orbital inclination: 36.38 ± 2.02 deg

Companion star: ~3.6 solar masses

Distance: 48.10 ± 2.02 kpc

No jet detected, but ionization cone



Observed by IXPE on Oct 2022

No clear detection (PD: 1.0 ± 0.4 %) (Podgorny et al. 2023)

→ consistent with standard accretion disc at low inclination

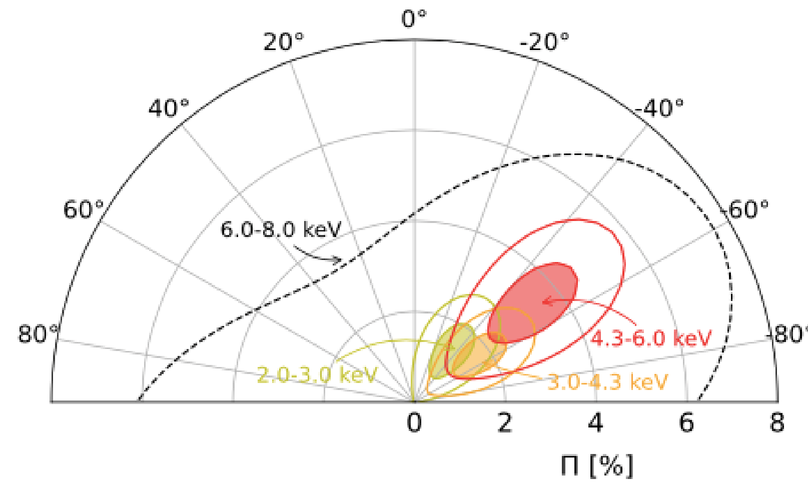
(but hint of a PA alignment with the ionization cone)

IXPE
Imaging X-Ray Polarimetry Explorer

4U 1957+115

A persistent, LMXRB always in the soft state. Almost nothing of this system is known.

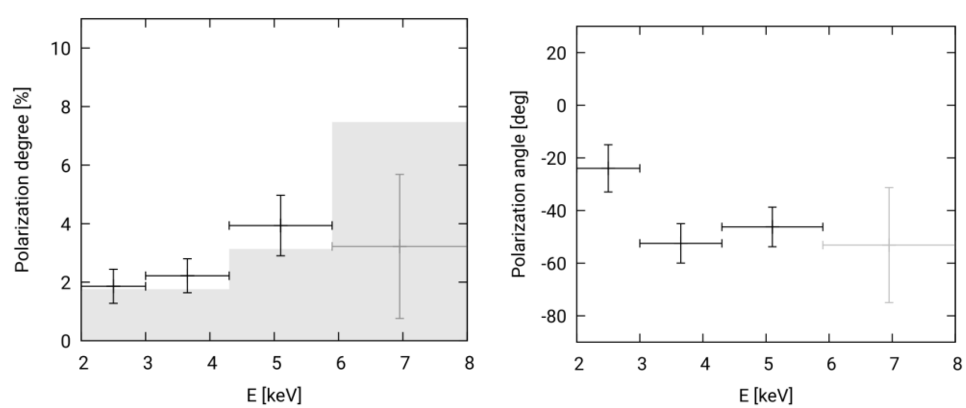
Observed by IXPE on May 2023



Significant detection: PD=1.9±0.6 %

Evidence for an increase of PD with energy

Standard disc, but large amount of returning radiation required by the fit → high spin, high albedo



(Marra et al. 2024, Kushwaha et al. 2024)

LMC X-3

A persistent, LMXRB always in the soft state. Much of this system is known:

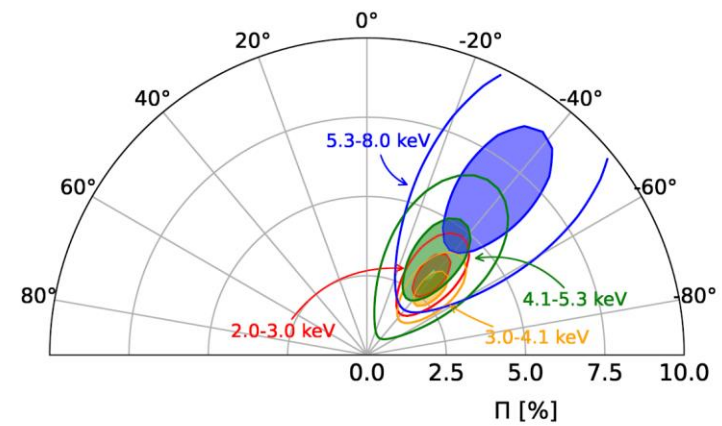
BH mass: 6.98±0.56 solar masses

Orbital inclination: ~70 degrees

Companion star with a mass of ~3 solar masses

Distance: 43.1 kpc

But unknown orientation



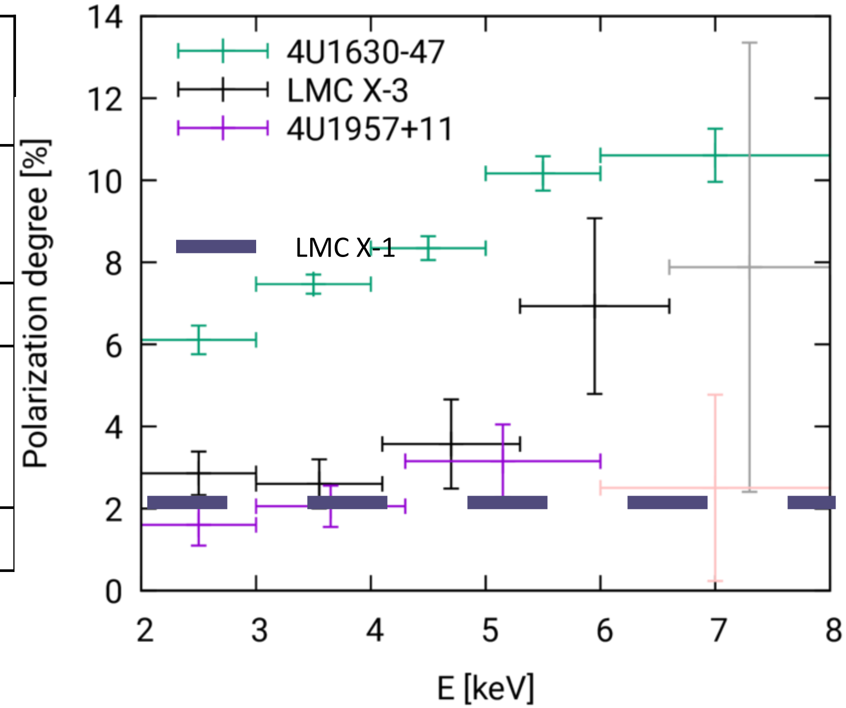
Observed by IXPE on July 2023

Significant detection (PD: 3.07 ± 0.40 %) (Svoboda et al. 2024, Majumder et al. 2024)

→ consistent with standard or slim accretion disc at relatively high inclination, low spin and absorption effects

ACCRETING BH IN SOFT STATE

Source	Class	State	Average 2-8 keV PD
4U1630-47	LMXB	Soft SPL	**~ 8%** **~ 6%**
LMC X-1	HMXB	Soft	**< 2.2 %**
4U1957+115	LMXB	Soft Steep power-law state	**~ 1.9 %** **~ 6%**
LMC X-3	HMXB	Soft	**~ 3 %**



Less information on the BH spin than hoped… (but let's wait for GX 339-4!)

But extremely interesting (and surprising) results!!

No really satisfactory explanation for 4U 1630-47. Need for a change of paradigm?

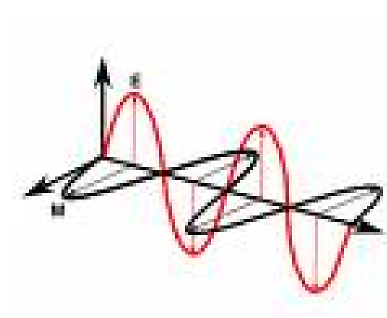
Imaging X-Ray Polarimetry Explorer

PLAN OF THE LECTURE

General introduction

Accreting Stellar-mass Black Holes

Accreting, Weakly Magnetized Neutron Stars



WEAKLY MAGNETIZED NS - LMXRB

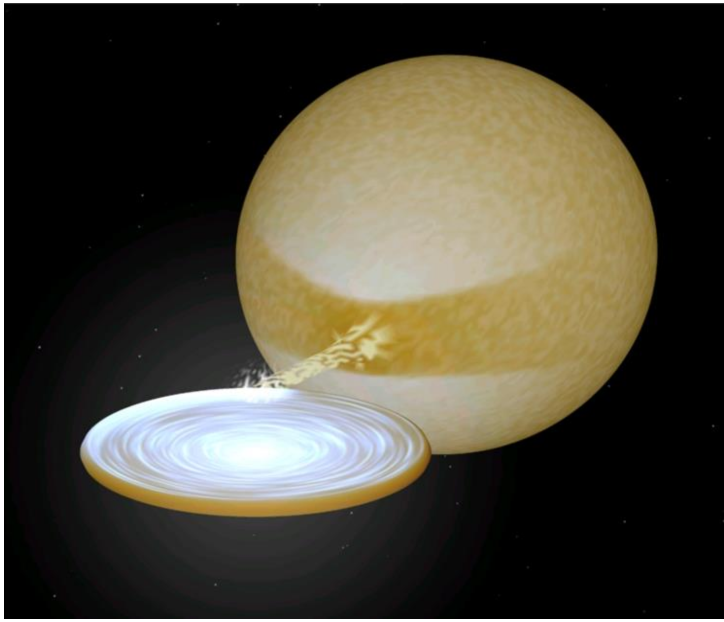
In these sources, matter accretes via Roche-lobe overflow. The NS magnetic field is not strong enough to govern the accretion pattern. An accretion disc is formed.

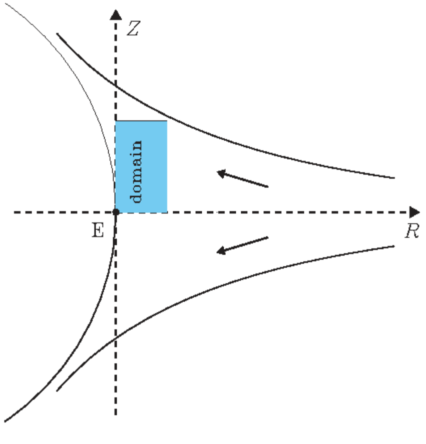
They are X-ray bright systems – 0.01-1 the Eddington luminosity.

Often persistent, but always very variable sources, with possible X-ray bursts.

The presence of the NS instead of a BH results in two main differences:

- the NS itself emits soft X-rays
- the accretion flow is stopped at the neutron star surface and a boundary/spreading layer can form





WEAKLY MAGNETIZED NS - LMXRB

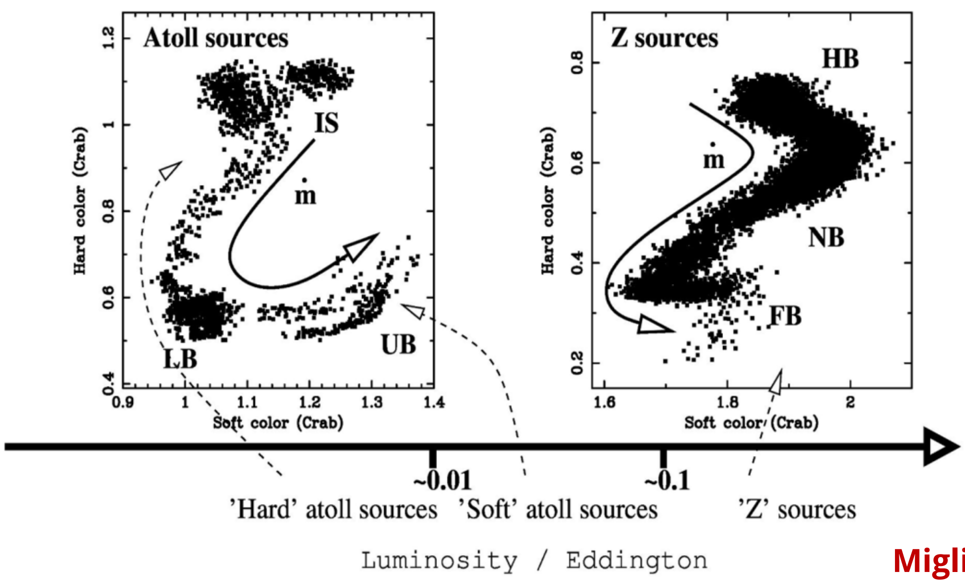
Traditionally classified by their **joint timing** and **spectral properties**, i.e. according to their tracks in the **Hard color-Soft color Diagram:**

Atoll sources:

Persistent or transient sources

Normally fainter (but can reach also Eddington luminosities)

L ≈ 10^{36} erg/s



Z-sources:

Mostly persistent sources

Always above 10% Eddington luminosity (higher accretion rates)

L ≳ 10^{38} erg/s

Migliari et al. 2006

Hard color: (6-20/4.5-6) keV
Soft color: (3-4.5/1-3) keV

Hard color vs intensity is often also used

IXPE Imaging X-Ray Polarimetry Explorer

WEAKLY MAGNETIZED NS - LMXRB

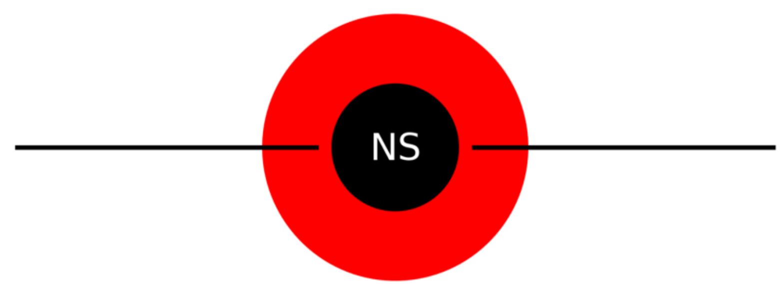
X-ray radiation coming from NS-LMXBs is generally modelled with a **thermal emission** (either from the NS or the disc) and a **Comptonised one** by a corona of hot electrons

Western Model
(White et al. 1988)

- NS pure blackbody
- Disc photons Comptonised

Eastern Model
(Mitsuda et al. 1984)

- Multicolour disc blackbody
- NS photons Comptonised



Likely a too rigid scheme! And there is also reflection...

NS – LMXRB WITH IXPE (only published results)

Atoll Sources:

GS 1826–238: Atoll in high soft state, with extremely regular X-ray burst (*Capitanio et al. 2023*)

GX 9+9: Atoll consistently observed in bright soft state, in the banana branch of the CCD (*Ursini et al. 2023, Chatterjee et al. 2023*)

4U 1820–303: Ultra-compact NS-LMXB accreting from He white dwarf. Peculiar behaviour of intrinsic luminosity along superorbital ~170 days period (*Di Marco et al. 2023*)

4U 1624–49: Bright Atoll in the banana state showing periodic 6–8 hours dips in the light curve (i.e. highly inclined system) (*Saade et al. 2024*)

Z-Sources:

Cyg X–2: Typical bright Z-source, displaying the full Z-track, with weak FB (*Farinelli et al. 2023*)

XTE J1701–462: Transient NS-LMXB in outburst after ~ 16 yrs. Only known source to show all the different states during its outburst evolution (from Z- to Atoll-state) (*Cocchi et al. 2023, Jayasurya et al. 2023*)

GX 5–1: Bright Z-sources observed twice during its motion along the Z-track (*Fabiani et al. 2024*)

Sco X–1: Brightest source in the X-ray sky (nearby system). Characterized by a strong and frequent FB and less evident HB (*La Monaca et al. 2024*)

Cir X-1: Peculiar source in a highly eccentric orbit, passing through all atoll and Z states. Likely highly inclined, as a dip is observed in every orbit. Both radio and X-ray jets observed (*Rankin et al. 2024*).

ATOLL SOURCES

Source	PD(2–4 keV)	PD(4–8 keV)	PD(2–8 keV)
GS 1826–238	< 1.1%	< 1.6%	< 1.1%
GX 9+9	0.8% ± 0.6%	3.1% ± 1.2%	1.6% ± 0.6%
4U 1820–303*	< 1.2%	2.9% ± 0.9%	< 1.1%
4U 1624–49	2.4% ± 1.4%	4.3% ± 1.6%	3.5% ± 1.2%

* PD(7–8 keV) = 9.6% ± 3.9%. **Notes**: The errors are at the 90% confidence level.

Observed PD generally rather weak in the 2–8 keV (≲1.5–2%), except for 4U 1624–49 which is observed at very high inclination (> 70°)

Increasing trend of the PD with energy observed for most of Atoll sources, in particular a strong energy dependence is found for 4U

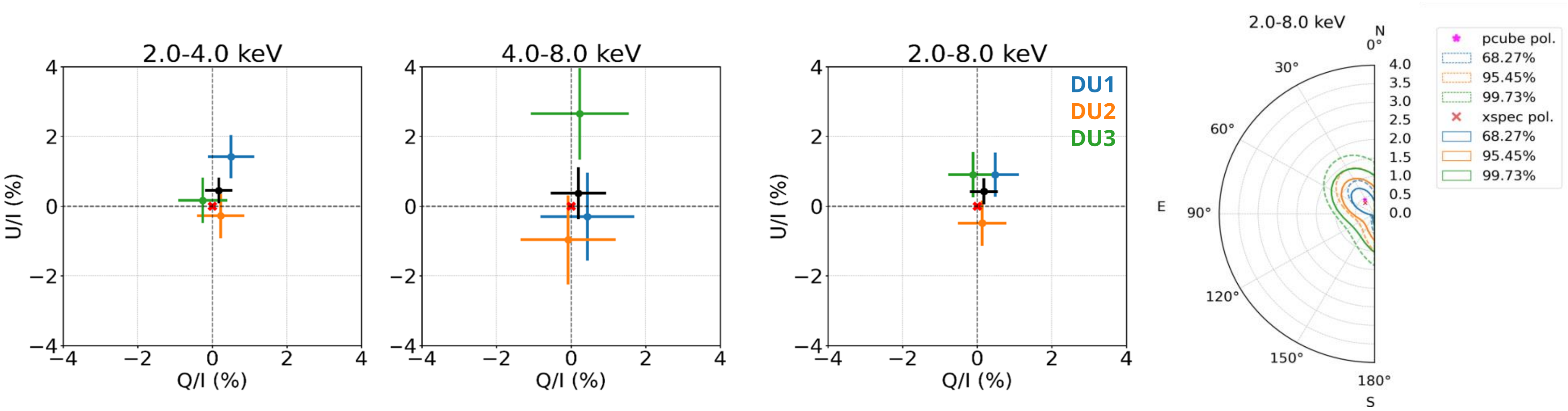
The combination of Comptonization in the spreading layer plus reflection can reproduce the polarization detected for most sources; an additional contribution (e.g. winds) or a particular shape of the Comptonizing region (e.g. outflowing corona) is required for 4U 1820–303 high PD

GS 1826-238

First NS LMXB observed by IXPE.

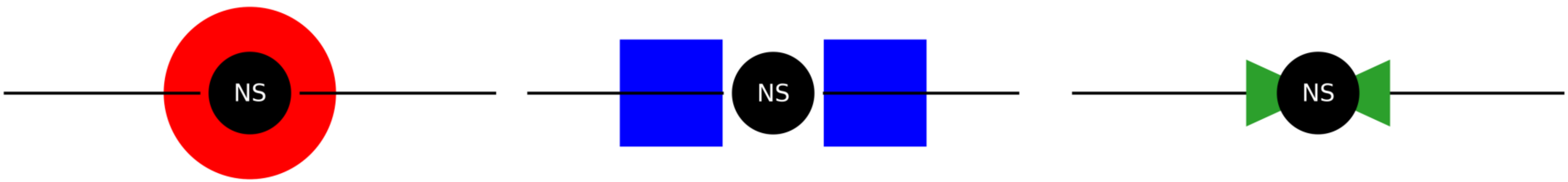
No polarization detected:
PD(2-4 keV) ≲ 1.6%, PD(4-8 keV) ≲ 2.4%, PD(2-8 keV) ≲ 1.3%

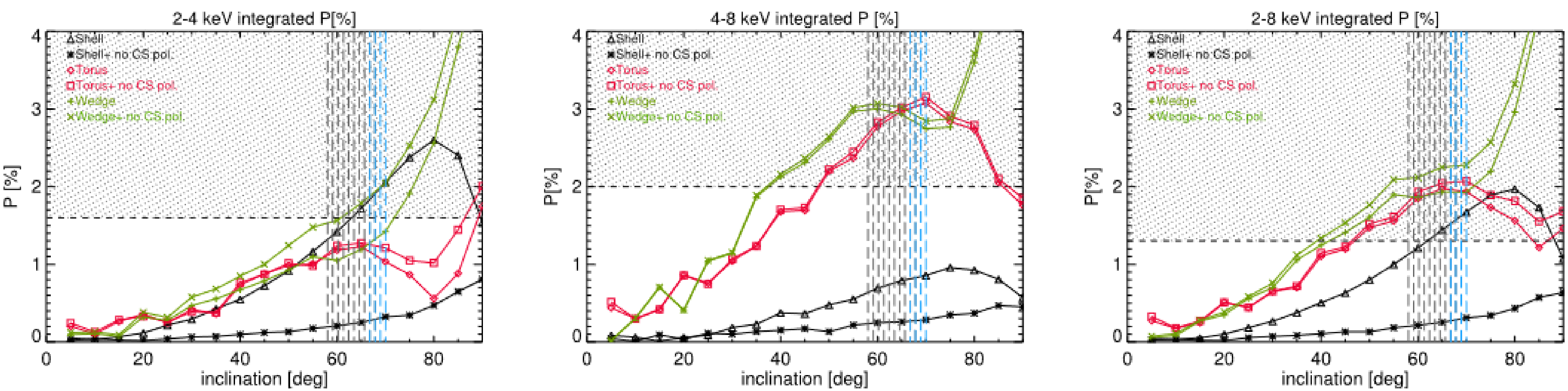
Capitanio et al. 2023



GS 1826-238

Best-fit spectral parameters used as input parameters for the GR Monte Carlo radiative transfer MONK simulations (Zhang et al. 2019, Gnarini et al. 2022)





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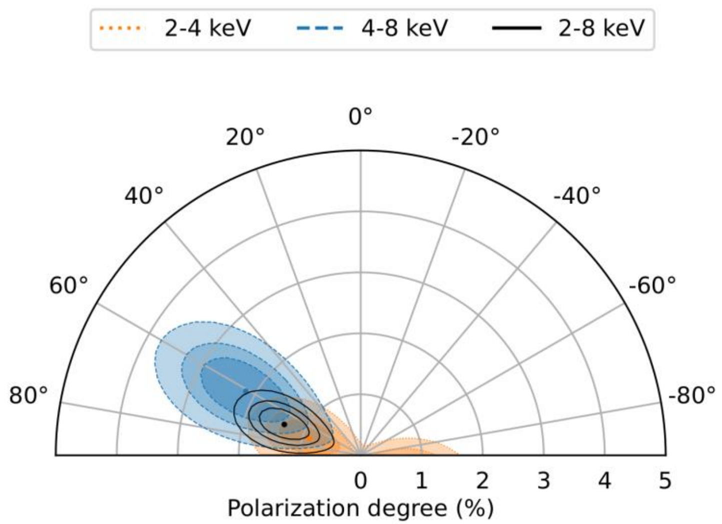
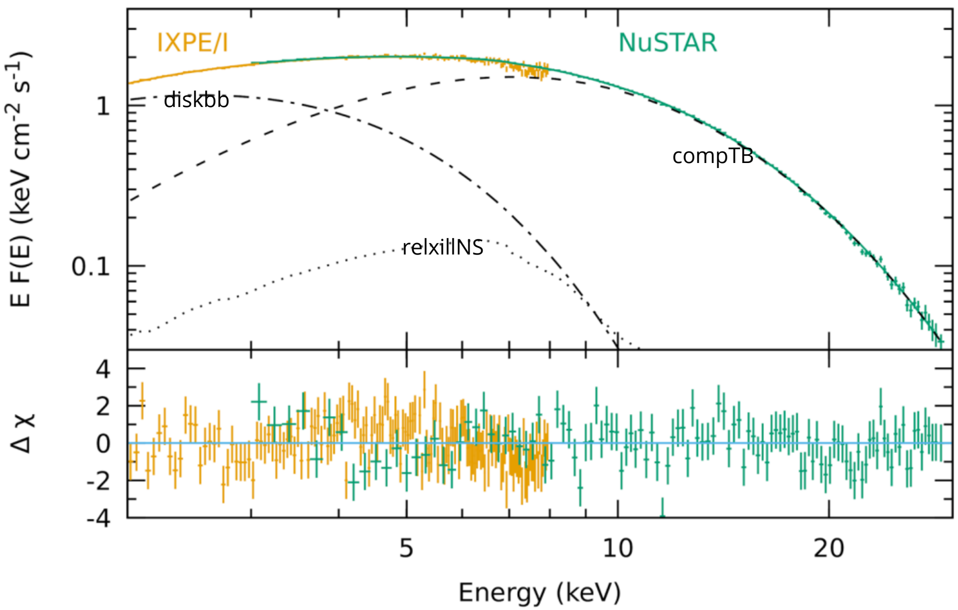
GX 9+9

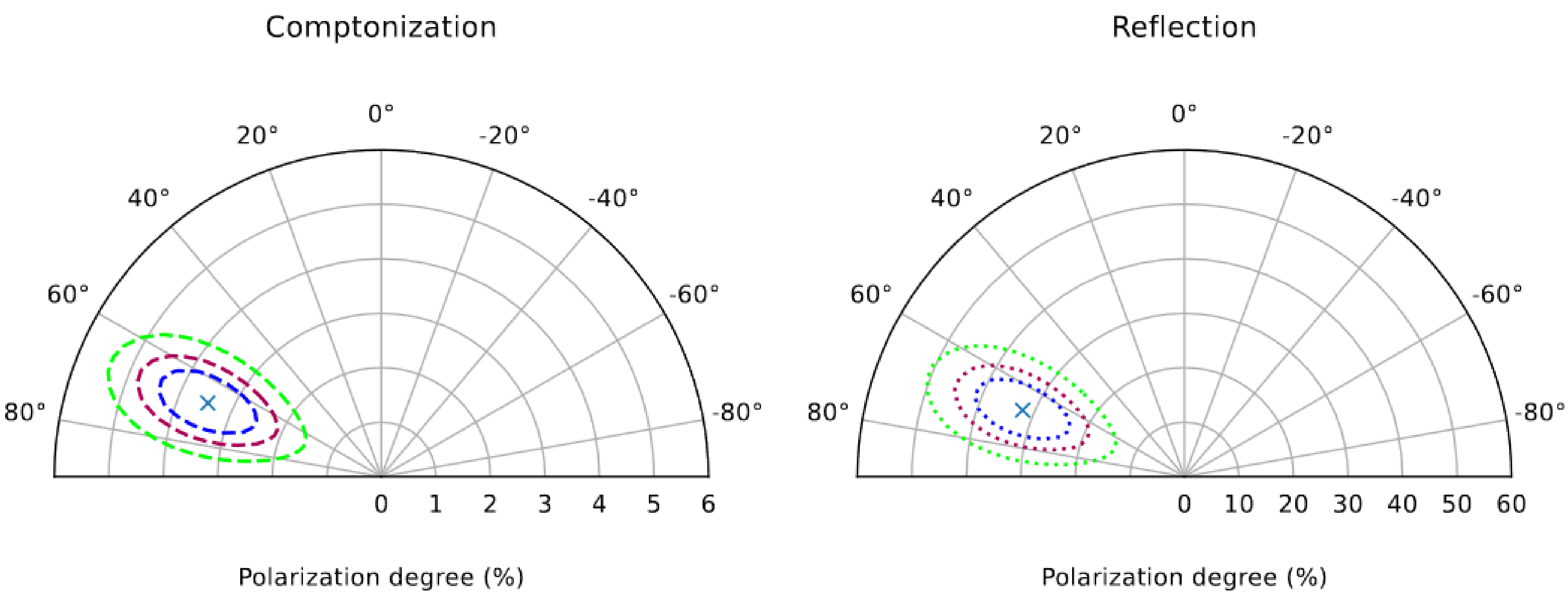
Significantly polarization detected in the 2–8 keV band (1.4% ± 0.3%) and in the 4–8 keV band (2.2% ± 0.5%)





GX 9+9

From the spectropolarimetric analysis, only an upper limit is found for the PD of the disc emission. Polarization due to the Comptonization component or the reflection component, or both.



Z SOURCES

Source	PD(2–4 keV)	PD(4–8 keV)	PD(2–8 keV)
Cyg X–2	1.0% ± 0.4%	2.4% ± 0.8%	1.5% ± 0.4%
XTE J1701–462 (Obs. I)	3.9% ± 0.6%	5.3% ± 1.0%	4.4% ± 0.6%
XTE J1701–462 (Obs. II)	< 1.0%	1.5% ± 0.9%	0.8% ± 0.5%
GX 5–1 (Obs. I)	3.8% ± 0.5%	4.9% ± 0.8%	4.3% ± 0.5%
GX 5–1 (Obs. II)	1.8% ± 0.5%	2.6% ± 0.8%	2.0% ± 0.5%
Cir X–1 (Obs. I)	1.5% ± 0.4%	1.8% ± 0.7%	1.6% ± 0.4%
Cir X–1 (Obs. II)	0.8% ± 0.5%	2.2% ± 0.8%	1.4% ± 0.5%
Sco X–1*	0.9% ± 0.4%	1.2% ± 0.4%	1.1% ± 0.3%

* PD(3–4 keV), PD(4–8 keV), PD(3–8 keV).

Notes: The errors are at the 90% confidence level.

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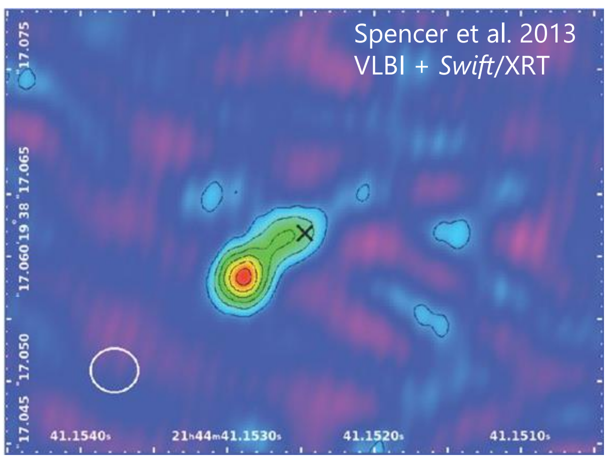
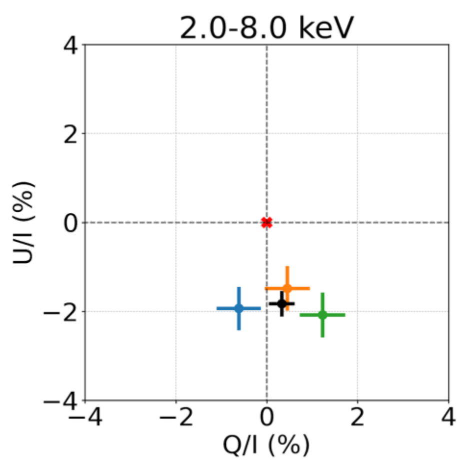
Polarimetry
Explorer

CYGNUS X-2

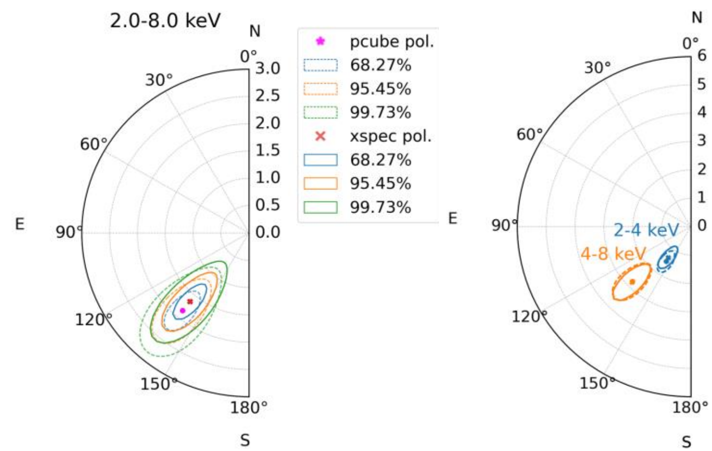
Polarization detected in the 2–8 keV band PD = 1.85 ± 0.29 %, with marginal evidence of PD increasing with energy

Polarizaton angle consistent with the radio jet direction PA = 140°± 4°

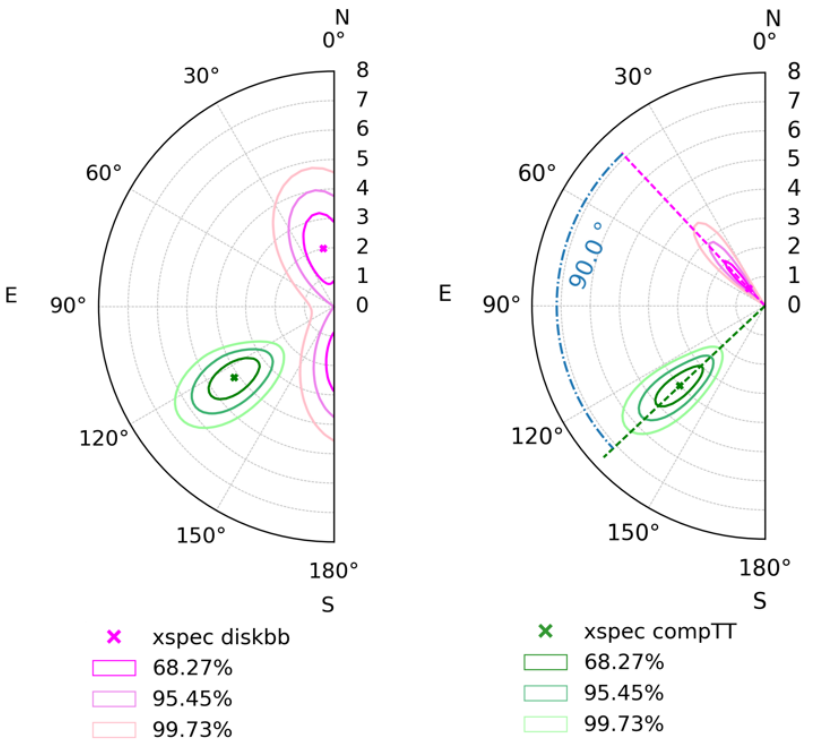




Farinelli et al. 2023



CYGNUS X-2



Spectro-Polarimetric fit with free polarization angle for both comptonization and disc emission:

`diskbb`	$\mathrm{PD} < 4.4\%$	$\mathrm{PA} = \mathrm{unconstrained}$
`compTT`	$\mathrm{PD} = 4.2\% \pm 1.8\%$	$\mathrm{PA} = 126^\circ \pm 14^\circ$

Spectro-Polarimetric fit with disc polarization angle perpendicular to the comptonization one:

`diskbb`	$\mathrm{PD} < 3.3\%$	$\mathrm{PA} = \mathrm{PA}_{\mathtt{compTT}} - 90^\circ$
`compTT`	$\mathrm{PD} = 4.0\% \pm 1.8\%$	$\mathrm{PA} = 133^\circ \pm 11^\circ$

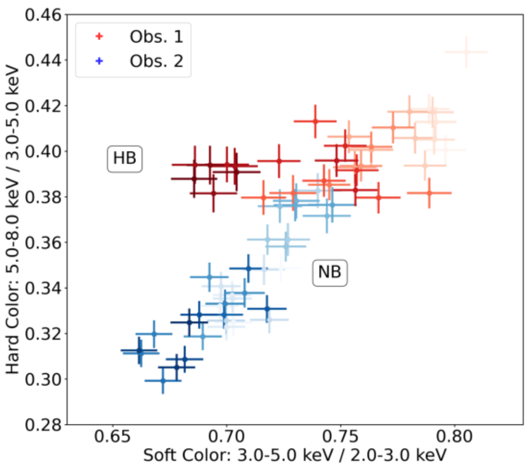
The spreading layer emission can produce PA perpendicular to the disk but it is not so easy to reproduce the PD

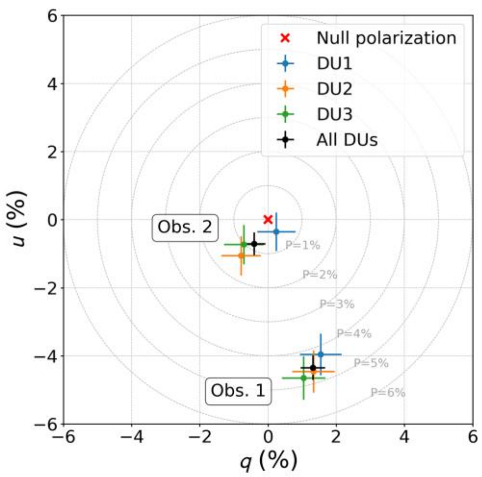
→ Reflection could provide an important contribution

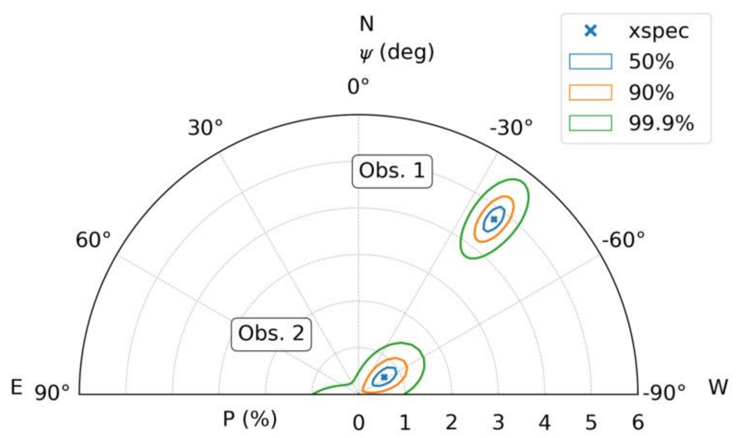
XTE J1701-462

- Only known transient Z-type, observed in outburst after 16 years
- Showed all the known spectral states: Z, Bright Atoll and Island state

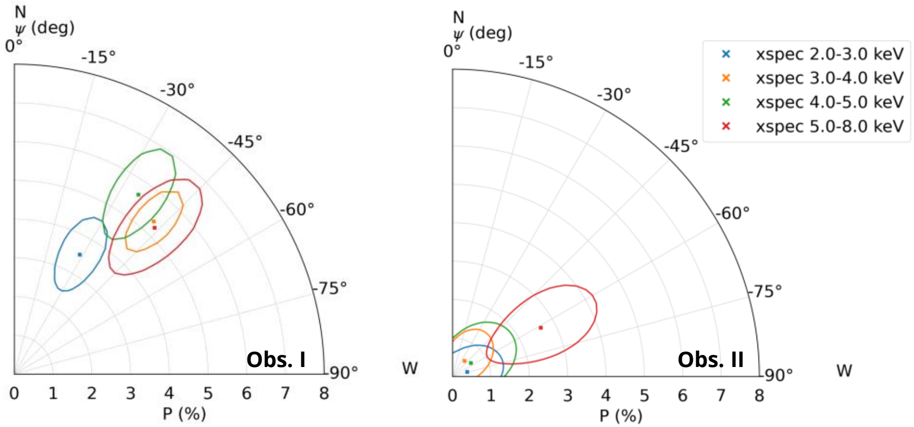
Strong polarization (4.6 ± 0.4% in 2-8 keV) detected during the first pointing, while only a ~ 1% upper limit (at 90% CL) during the second







XTE J1701-462



Evidence of increase of polarization degree with energy in Obs. II (similar to Cyg X-2 and GX 9+9)

How to explain the strong variation of PD between the two observations?

The position on the CCD seems to be correlated with the PD variation

Changes in the accretion geometry and coronal properties?

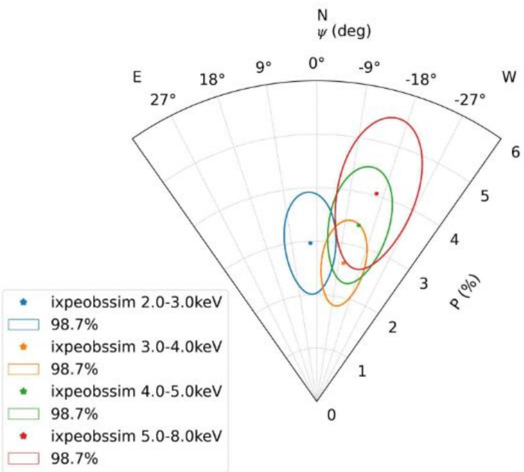
Different contribution of reflection along the Z-branches?

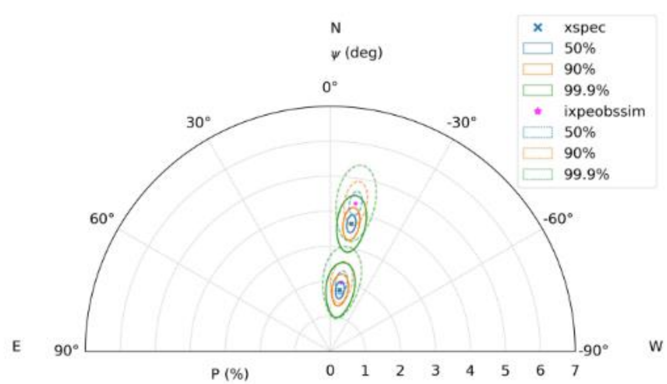
GX 5-1

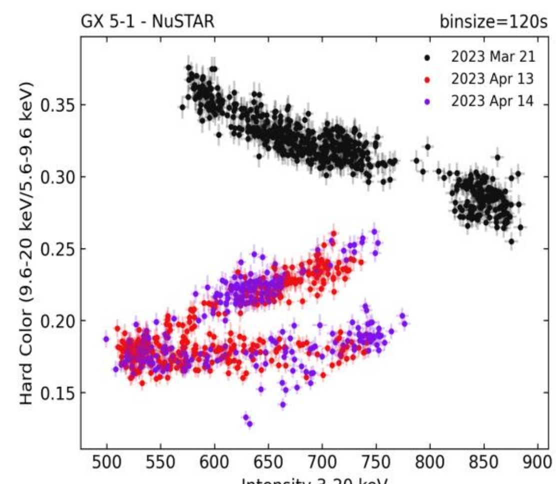
Significant Polarization detected in both observations but variable with the position of the source along the Z-track (PD Obs 1 = HB > PD Obs 2 = NB/FB)

Disk polarization is consistent with the classical results for a high optical depth scattering atmosphere above the accretion disc (Chandrasekhar 1960)

High PD (≈ 4%) is difficult to explain only with Comptonization, reflection of soft photons may be significant





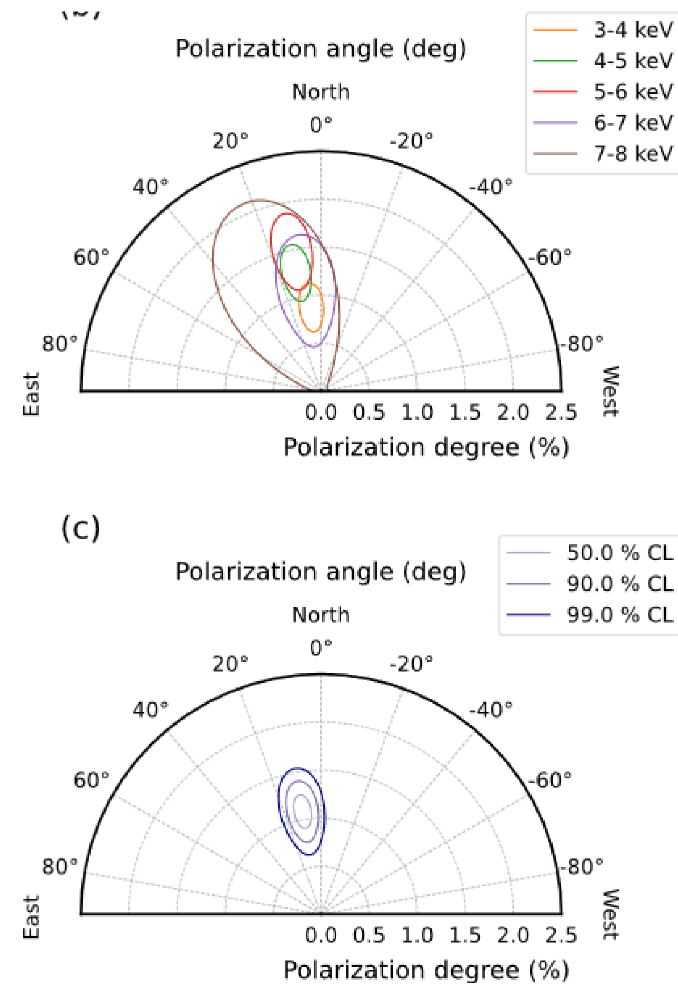


SCO X-1

By far the brightest extrasolar X-ray source in the sky (observable by IXPE only with a filter). Not very much studied in the past just because it is too bright!!

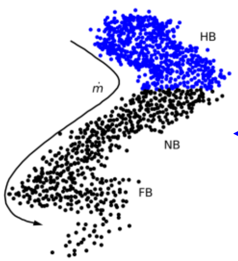
PD=1.0 ± 0.2%, less than observed by PolarLight. PA rotated by ~50 deg. with respect to radio jet (and PolarLight).

Spectropolarimetric analysis indicates that the dominant contribution to the PD comes from the Comptonization component



Z SOURCES

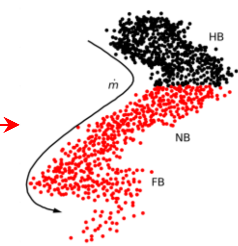
HB



Source	PD(2–4 keV)	PD(4–8 keV)	PD(2–8 keV)
Cyg X–2	1.0% ± 0.4%	2.4% ± 0.8%	1.5% ± 0.4%
XTE J1701–462 (Obs. I)	3.9% ± 0.6%	5.3% ± 1.0%	4.4% ± 0.6%
XTE J1701–462 (Obs. II)	< 1.0%	1.5% ± 0.9%	0.8% ± 0.5%
GX 5–1 (Obs. I)	3.8% ± 0.5%	4.9% ± 0.8%	4.3% ± 0.5%
GX 5–1 (Obs. II)	1.8% ± 0.5%	2.6% ± 0.8%	2.0% ± 0.5%

Notes: The errors are at the 90% confidence level.

NB/FB



The observed polarization seems to be related to the position along the Z-track:

- On the Horizontal Branch, the X-ray radiation is more polarized (up to 4–5%)
- Moving towards the Normal and Flaring branches, the PD decreases (~1–2%)

The PA direction of Cyg X–2 is consistent with that of the radio-jet (frequently observed in the HB)

The Comptonization alone cannot easily explain the high PD detected and reflection probably provides an important contribution, even if the reflection fraction to the total flux is relatively small

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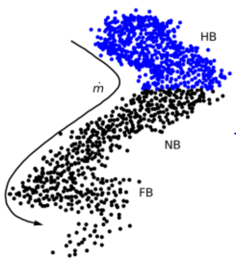
Z SOURCES

HB



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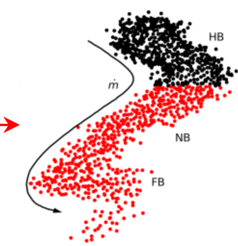
GX 5–1 (Obs. II)	1.8% ± 0.5%	2.6% ± 0.8%	2.0% ± 0.5%

Notes: The errors are at the 90% confidence level.

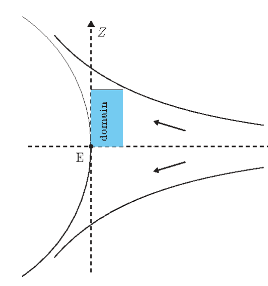
NB/FB



The observed polarization seems to be related to the position along the Z-track:

- On the Horizontal Branch, the X-ray radiation is more polarized (up to 4–5%)
- Moving towards the Normal and Flaring branches, the PD decreases (~1–2%)

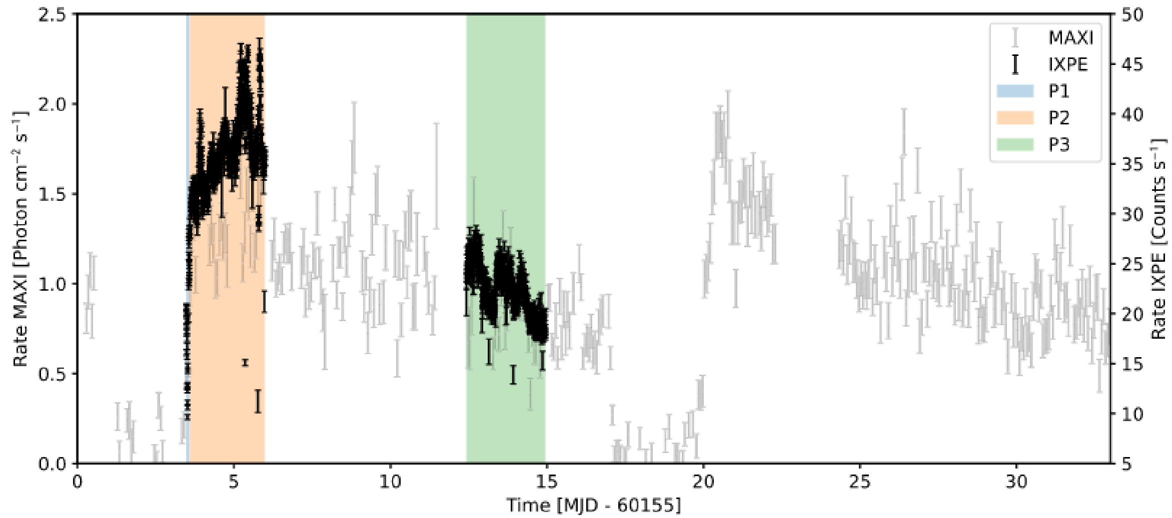
As the accretion rate increases moving from HB to NB (and FB), it is well possible that the spreading layer becomes more isotropic, and then less polarized

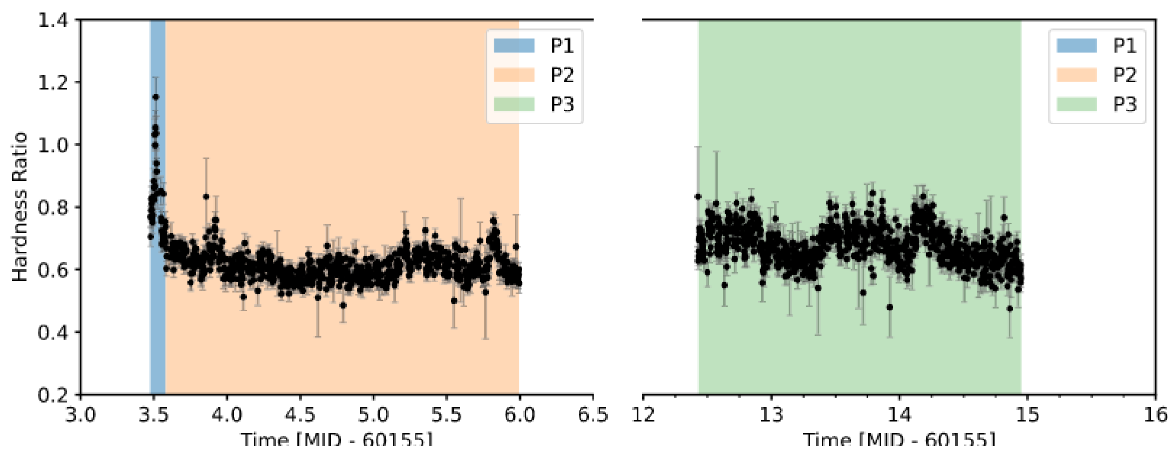


Circinus X-1

Observed by IXPE at two different phases in the 16.6 day orbital period.

Flux and spectrum change significantly along the highly eccentric orbit, possibly due to variations in the mass accretion rate.

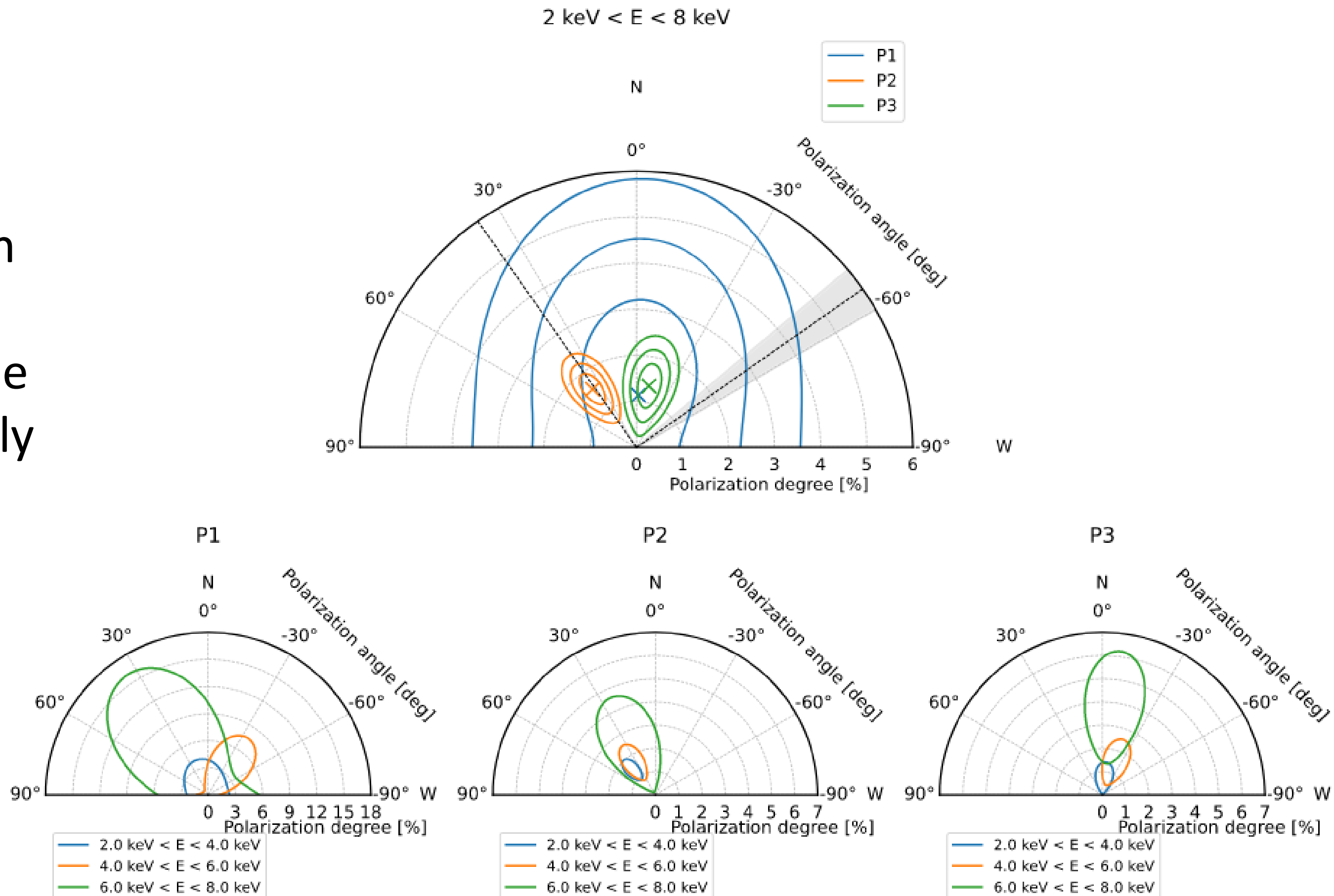




Circinus X-1

Significant variation of the polarization angle with time.

Oddily, this variation is different from 90 degrees, as would be expected in an axially simmetric system.



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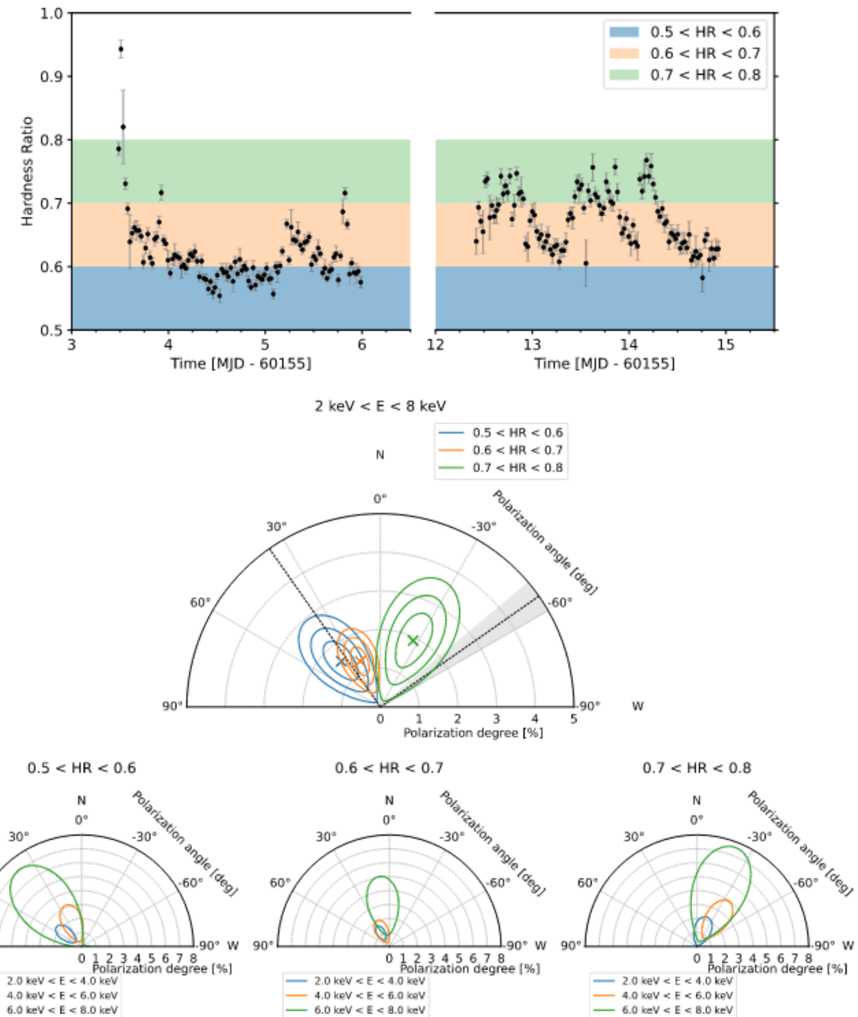
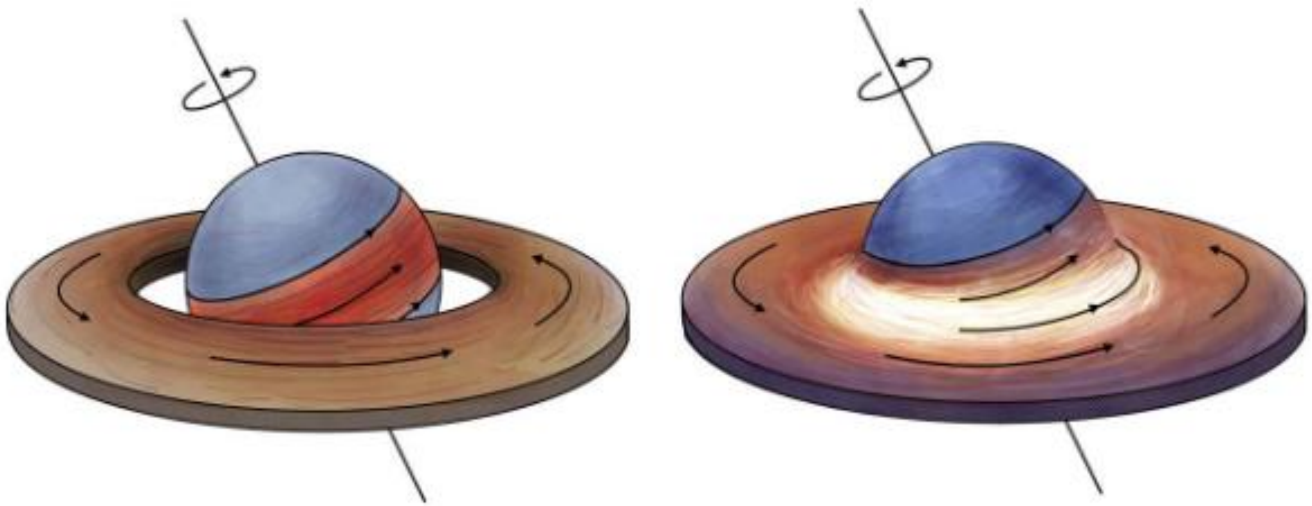
Circinus X-1

Significant variation of the polarization with the hardness ratio.

What is the basic parameter?



Circinus X-1



One possible explanation: depending on phase (HR), a different component dominates. If the NS axis is not aligned with the disc axis, the rotation of PA can be explained

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SUMMARY ON NS-LMXBs

- **Atolls are generally low-polarized** (< 1.5–2%) but with **strong energy dependence** (in 4U 1820–303, PD can reach up to 9–10% in 7–8 kev)
- **Z-sources are more polarized and exhibit strong variations of PD as they move along the CCD**:
  - In the Horizontal Branch more polarized (≈ 4% in 2-8 keV)
  - In the Normal or Flaring branch less polarized (< 2% in 2-8 keV)
- **Observed polarization is consistent with a boundary/spreading layer polarized emission** illuminating the ionized surface of the accretion disc, producing **polarized reflection**

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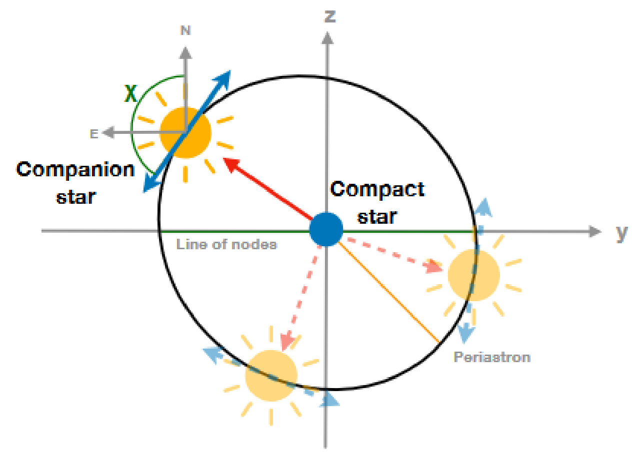
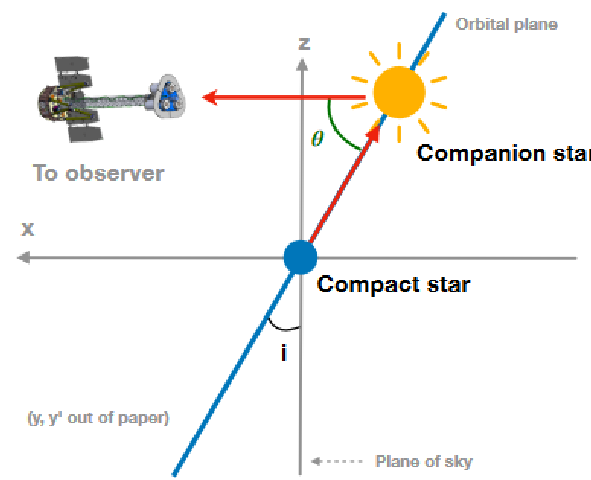
REFLECTION FROM THE COMPANION STAR

X-rays from the the accreting compact object are reflected – and polarized – by the companion star. A phase-dependent polarization is therefore expected (Rankin et al. 2024b).

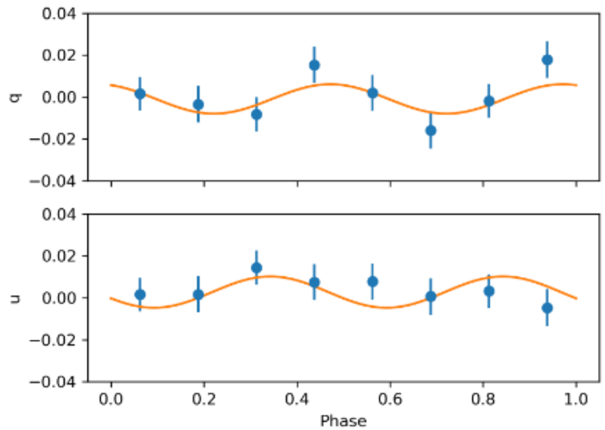
The measurability of this effect depends on the solid angle subtended by the companion star to the X-ray source.



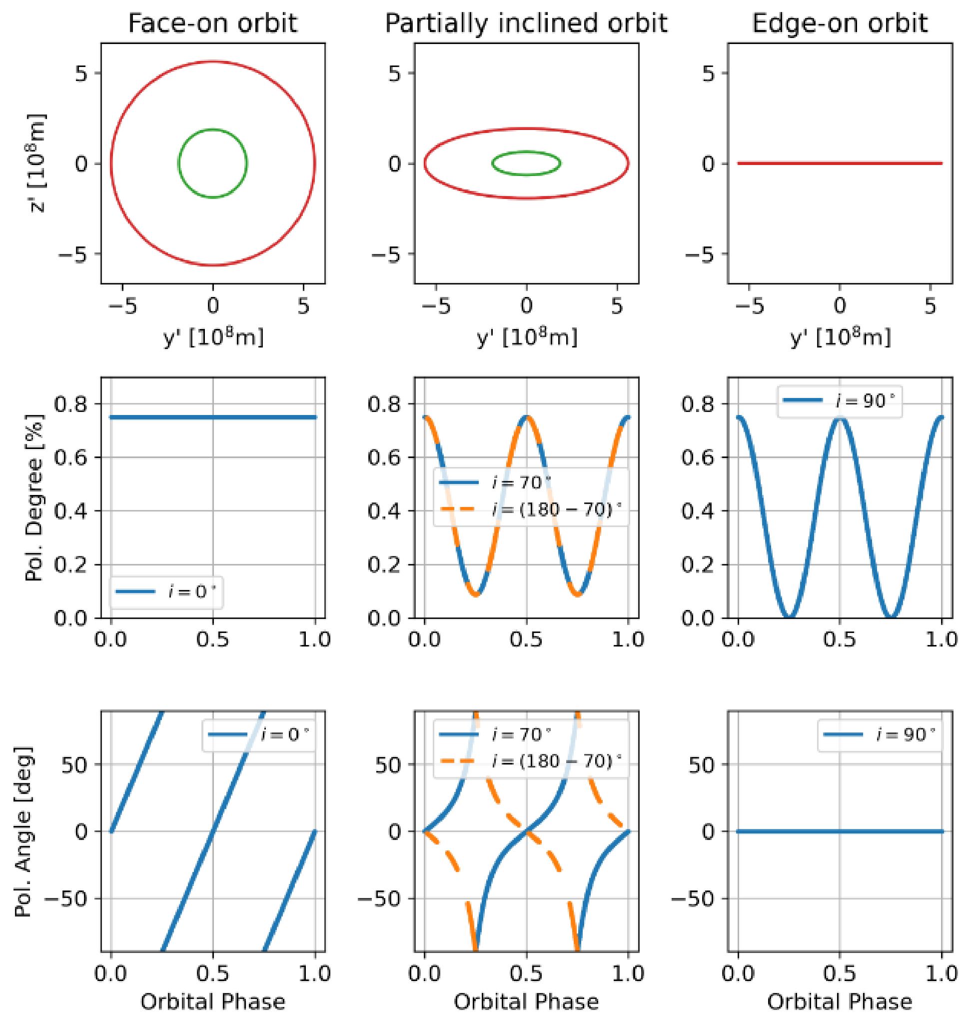


REFLECTION FROM THE COMPANION STAR

The phase-dependent polarization depends on the orbital inclination, which can therefore be measured.



When applied to the IXPE data of GS 1826-238, a high inclination angle is suggested, in broad agreement with independent estimates.



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CONCLUSIONS

IXPE results on both Accreting Stellar-mass Black Holes and Accreting, Weakly Magnetized Neutron Stars are providing some confirmation of theoretical expectations but also many surprises.

A large diversity of behaviours is found, even among sources of the same subclass.

IXPE results are adding important pieces of information which must be considered in any future modeling of these sources.

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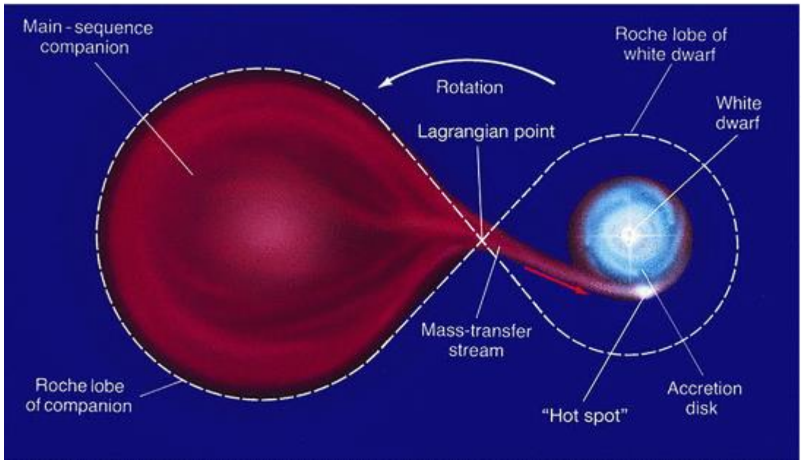
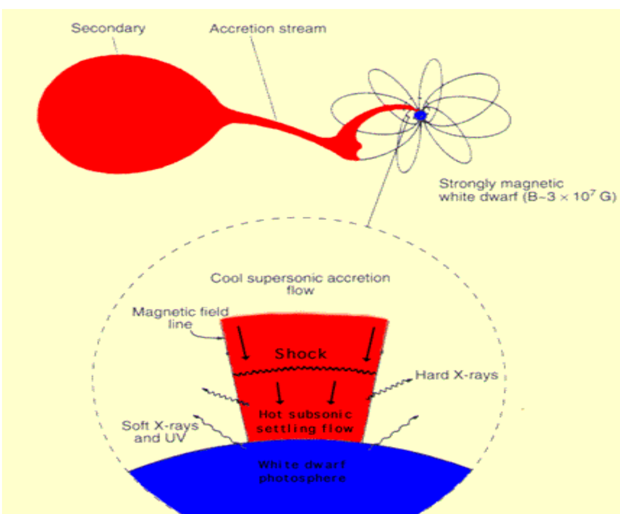
ACCRETING MAGNETIZED WHITE DWARFS

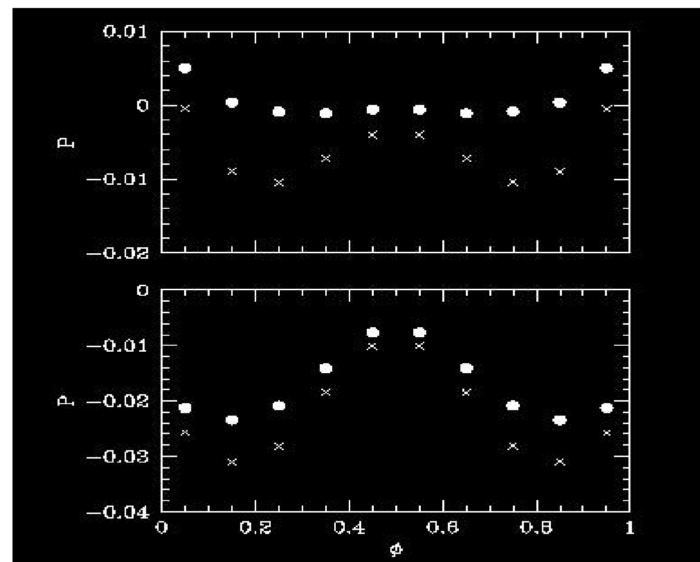


Matter is transferred via Lobe Roche overflow to the White Dwarf. In Magnetic (10^7-10^8 G) Cataclysmic Variables accretion occurs in columns over the magnetic poles. Main emission process is thermal bremsstrahlung, but scattering may be relevant. Polarization gives information on the accretion mode (Matt 2004; McNamara et al, 2008).



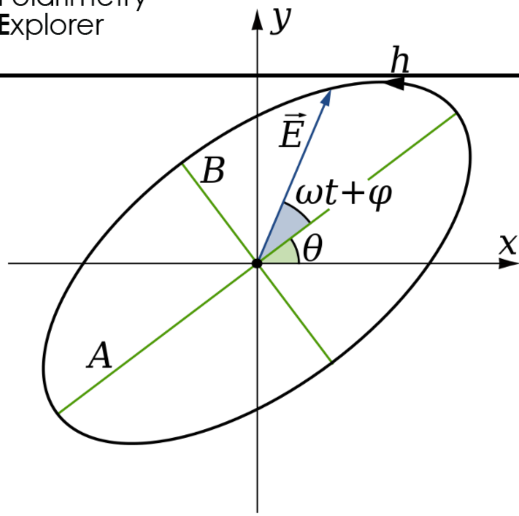
Filled circles:
5-10 keV

Crosses:
10-15 keV



Matt 2004

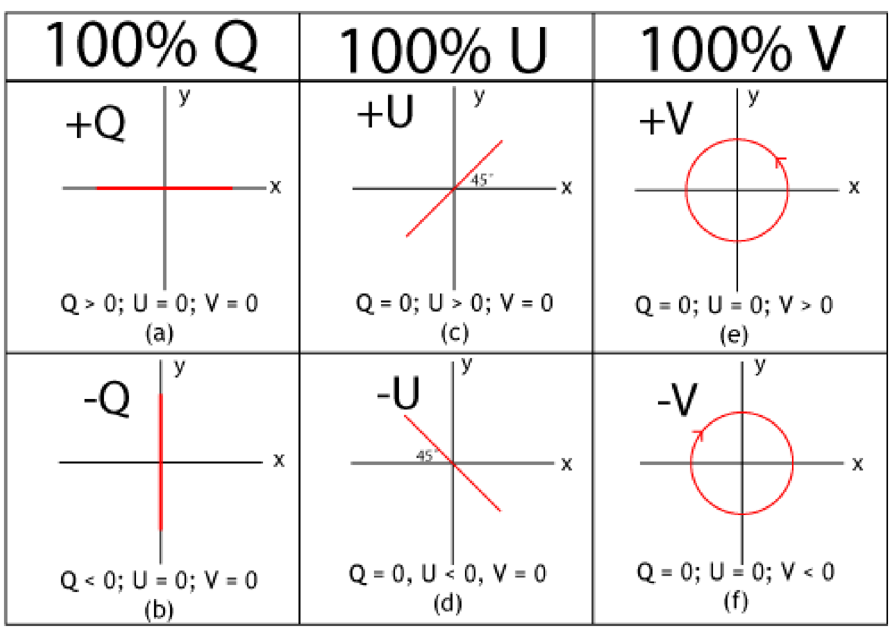
POLARIZATION



The polarization vector (which is a *pseudovector*, i.e. modulus π) rotates forming an ellipse. For a monochromatic, coherent wave, polarization is described by the *Stokes parameters*:

If B=0, radiation is linearly polarized → V=0

$$
\begin{aligned}
I &= A^2 \\
Q &= A^2 \cos 2\,\theta \\
U &= A^2 \sin 2\,\theta \\
V &= \mathbf{0} \\
I &= \sqrt{Q^2 + U^2}
\end{aligned}
$$



Stokes parameters are fluxes, and can be treated as such (just remember they can be negative!)

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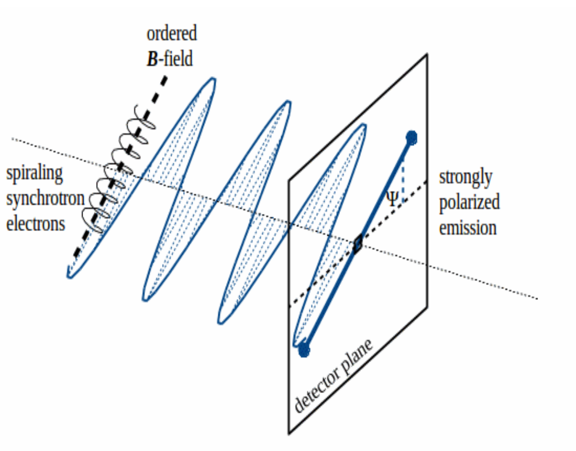
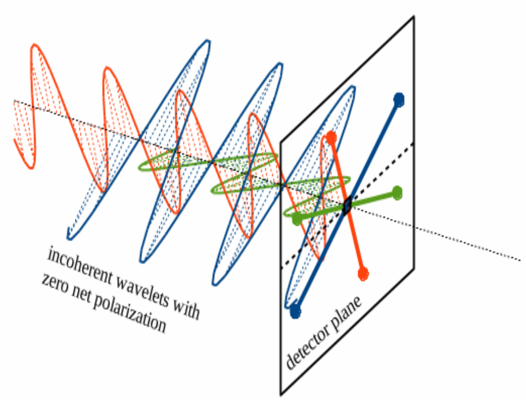
POLARIZATION





If the radiation is incoherent, when summing up the contributions of all photons I increases, while this is not necessarily true for the other Stokes parameters. Therefore:

$$I_T \geq \sqrt{Q_T^{\ 2} + U_T^{\ 2} + V_T^{\ 2}}$$

The net polarization degree and angle are given by:

$$\Pi = \frac{\sqrt{Q_T^{\ 2} + U_T^{\ 2} + V_T^{\ 2}}}{I_T}$$

$$\chi = \frac{1}{2}\arctan\frac{U_T}{Q_T}$$