X-ray polarimetry of accreting black holes: from theory to observations and back

Michal Dovčiak

Astronomical Institute
Academy of Sciences of the Czech Republic
Prague

Compact Objects in 3D – Steps towards X-ray Polarimetric-Spectral-Timing

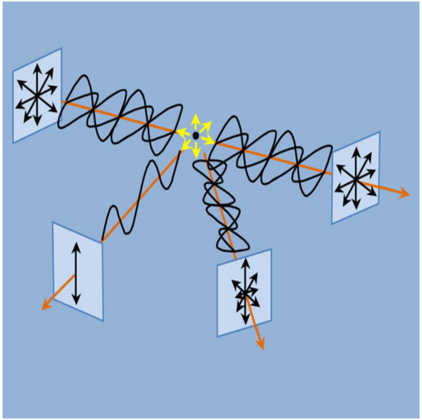
16th – 20th February 2026, Lorenz center, Leiden, The Netherlands

Plan of the talk

- **Processes inducing polarization**
  $\rightarrow$ Compton scattering
  $\rightarrow$ Synchrotron radiation
- **Polarization in BH XRBs**
  $\rightarrow$ outflowing clouds and jets
  $\rightarrow$ winds
  $\rightarrow$ corona
  $\rightarrow$ disc reflection
  $\rightarrow$ thermal radiation
- **IXPE observations of accreting BH**
- **Physical models of polarization for XSPEC**

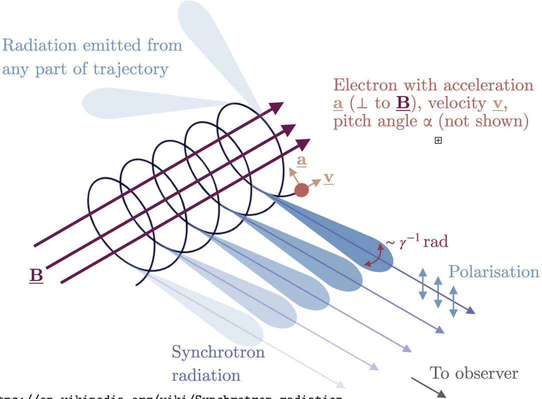
Processes inducing polarization

Scattering



$$P = \frac{\sin^2\theta}{\frac{E_0}{E} + \frac{E}{E_0} - \sin^2\theta}$$

Synchrotron



https://en.wikipedia.org/wiki/Synchrotron_radiation
#/media/File:Emmaalexander_synchrotron.png

$$P = \frac{p+1}{p+7/3}$$ for power-law e^- distribution, γ^{-p}

$P = 69.2\%$ for $p = 2$

Compton scattering and Synchrotron radiation

Scattering

$$P = \frac{\sin^2\theta}{\frac{E_0}{E} + \frac{E}{E_0} - \sin^2\theta}$$

- Polarization induced by scattering depends on
  - energy of electrons and their possible bulk motion
  - seed photon properties
  - number of photon scatterings
  - **geometry of scattering region** (seed photons $\rightarrow$ scattering region $\rightarrow$ $\rightarrow$ observer)
- Thomson scattering has larger polarization degree than Compton Scattering

Synchrotron

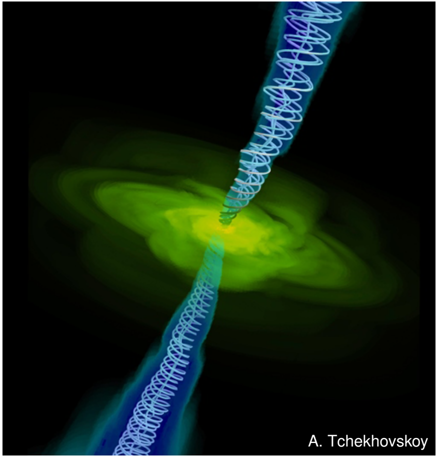
$$P = \frac{p+1}{p+7/3} \text{ for power-law } e^{-} \text{ distribution, } \gamma^{-p}$$

$$P = 69.2\% \text{ for } p = 2$$

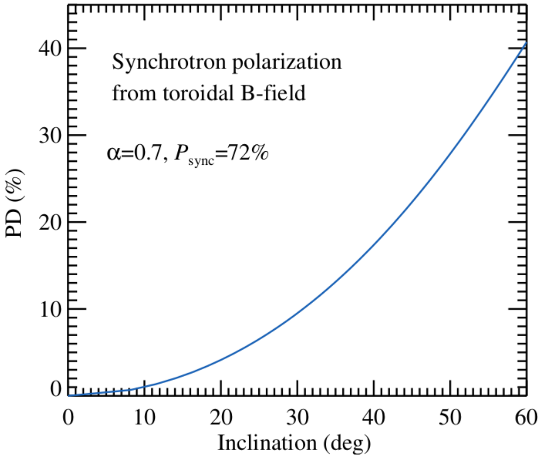
- Polarization of synchrotron radiation depends on
  - energy distribution of electrons
  - **direction of magnetic field**

    $\rightarrow$ e.g. magnetic field parallel with the jet may give high polarization levels in the direction perpendicular to the jet

Example of polarization of synchrotron emission in a jet



https://physics.aps.org/articles/v12/5

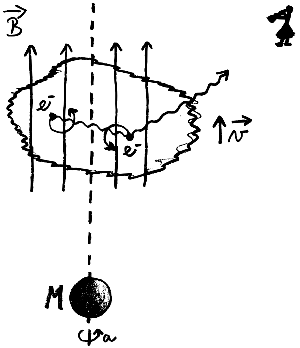


Credit: J. Poutanen

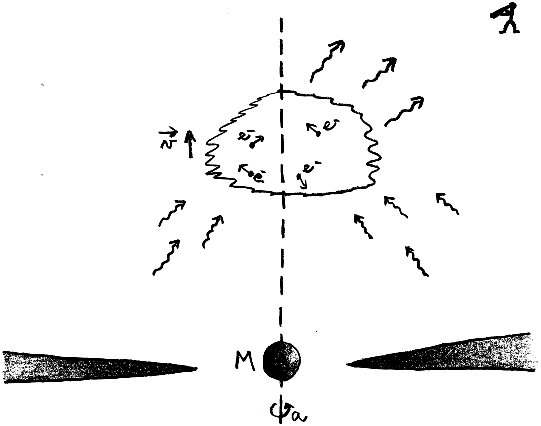
- polarization direction parallel with the jet
- polarization degree increases with the inclination
- the final effect depends on how much this component contributes to the total flux of the object

Compton scattering – seed photon origin

Synchrotron self-Compton



Scattering of disc radiation



Poutanen (1994) *ApJSS*, 92, 607

McNamara, Kuncic & Wu (2009) *MNRAS* 395, 1507 (jet)

Beloborodov (1998) *ApJ*, 496, L105 (plane-parallel optically thin wind)

Clouds – polarization properties

Synchrotron self-Compton

- power-law e^- distribution γ^{-p} with $p = 2$
- optical radius of the cloud $\tau = 0.1$
- aligned magnetic field, edge-on view

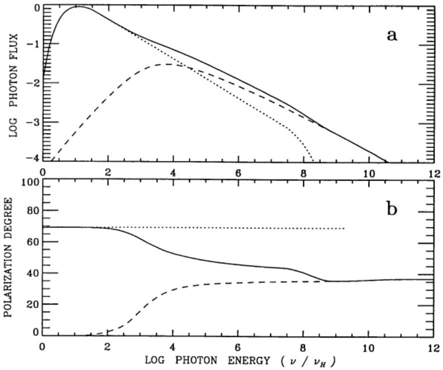


FIG. 1.—(*a*) Intensity and (*b*) polarization of synchrotron self-Compton radiation. *Dotted lines*—initial synchrotron radiation; *dashed lines*—inverse Compton scattered radiation; *solid lines*—intensity and polarization of the total radiation. Here $\tau = 0.1$, $\alpha = 0.5$, $\sin\zeta = 1$, and $\gamma_{min} = 10$.

Scattering of disc radiation

- Maxwell e^- distribution with T_e
- cloud velocity $\Gamma = 5$
- blackbody radiation with $T_{ph} = 0.01\,keV$

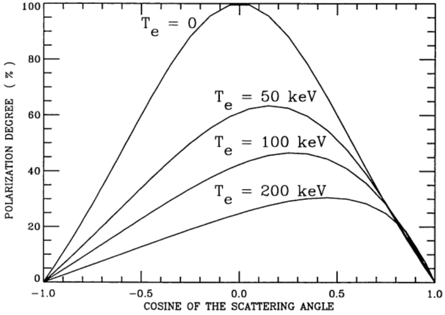
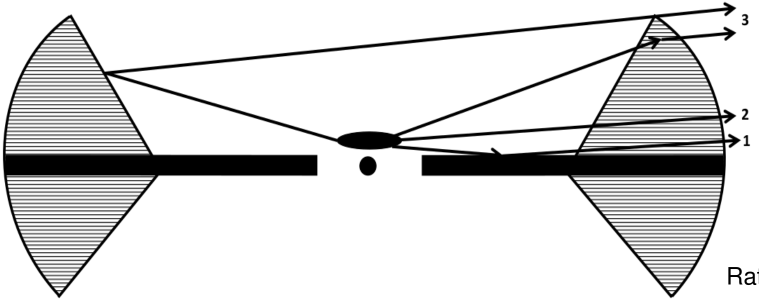


FIG. 2.—Polarization degree of radiation scattered by relativistic jet as a function of the cosine of the scattering angle.

Poutanen (1994) *ApJSS*, 92, 607

Winds



Ratheesh et al. (2021) *A&A*, 655, A96

Tomaru et al. (2024) *MNRAS*, 527, 7047

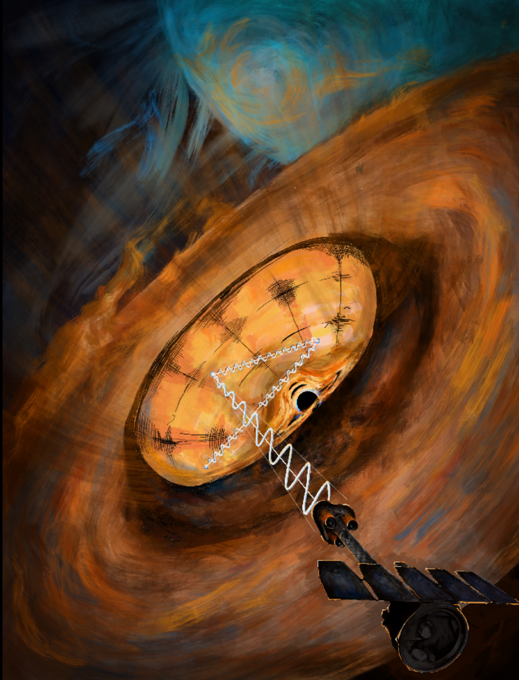
Nitindala et al. (2025) *A&A*, 694, A230

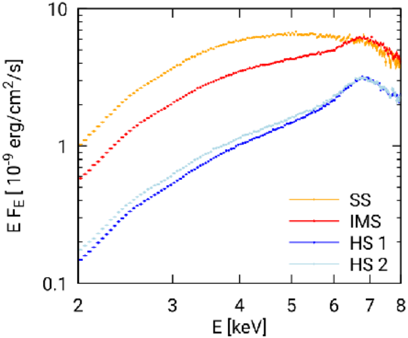
- the primary X-ray radiation reflected by the wind
  → **reflection features** in the spectra (emission lines)
  → reflected component may be highly polarized
- the primary X-ray radiation transmitted through the wind
  → **absorption features** in the spectra (absorption lines)
  → the primary spectra have rather low polarization degree, it de-polarizes the reflected component
- these effects depend on inclination and opening angle of the wind and on its transparency

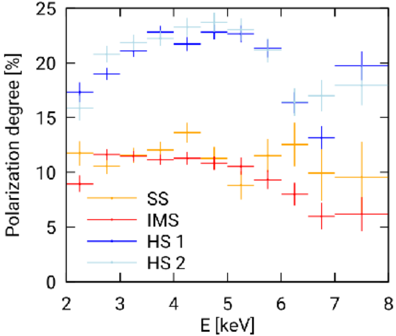
IXPE OBSERVES HIGHLY POLARIZED OBSCURED BLACK HOLE

Cyg X–3

- very high polarization levels in hard state (~21%)
- polarization direction perpendicular
  to the radio ejections
- spectro-polarimetric properties suggest a source
  hidden behind the obscuring accretion disc wind
- high polarization due to reflection off the walls
  of a funnel (opening angle ~15°)
- much lower polarization (~10%) in much brighter
  soft states suggests either change in funnel geometry
  or ionisation
- similarities with Type 2 RQ AGN







Cyg X-3

Observed in 3 different states:

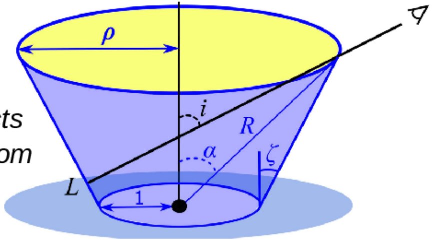
- **Hard state** → **PD ~ 20%**
- **Intermediate state**
- **Soft state**

Intermediate state and Soft state → **PD ~ 10%**

Veledina et al (2024) Nature Astronomy, 8, 1031
Veledina et al (2024) A&A, 688, L27

i = 30°
α = 10°
R = 10

Most of radiation reflects towards the observer from opposite funnel wall



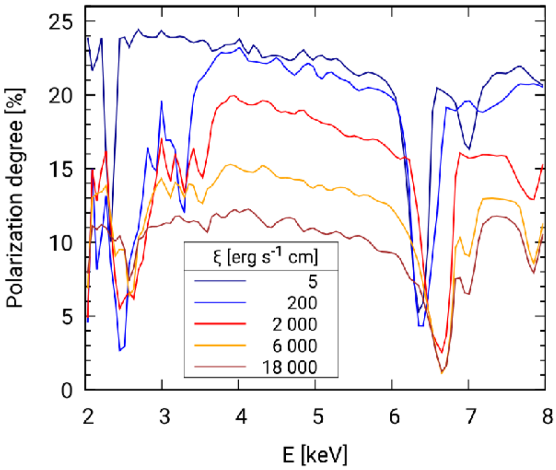
Cyg X-3

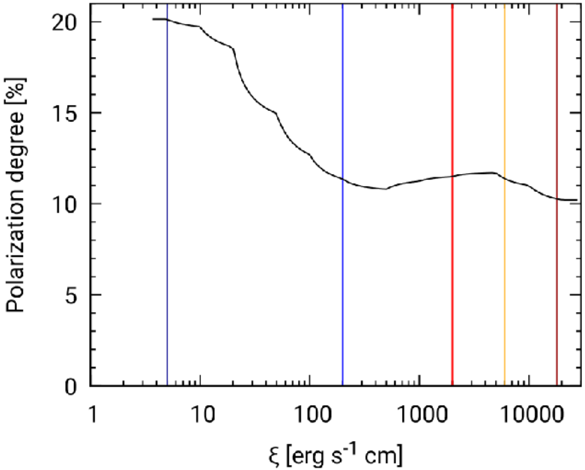
i = 30°
α = 10°
R = 10

→

$\theta_i = 85°$
$\theta_e = 55°$
φ = 0°

PD change due to ionisation for the same scattering geometry





Cyg X-3

Model: `polrot * tbabs ( stokes₁ + stokes₂ )`

`stokes = atable{stokes_unpol-v2.fits}`

ξ_1 = 20 erg/s/cm^{-1}

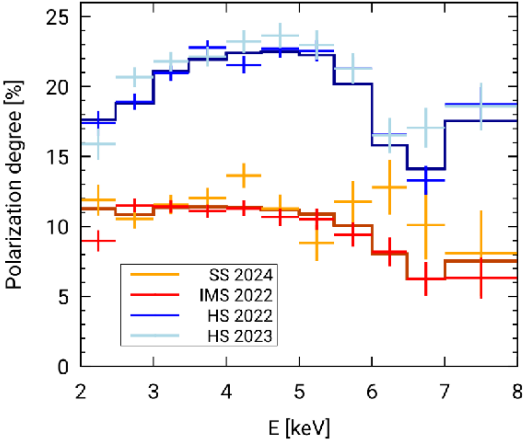
ξ_2 = 6 800 erg/s/cm^{-1}

ratio = 2000:1

θ_i = 85°, **θ_e= 52°** → i = 30°, **α = 13°**, R = 11

ξ = 20 000 erg/s/cm^{-1}

θ_i = 85°, **θ_e= 58°** → i = 30°, **α = 7°**, R = 11



Hard state – scattering in the corona

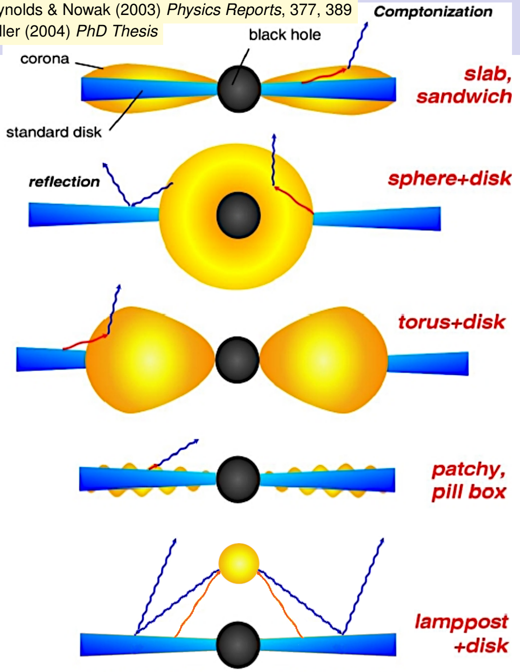
Reynolds & Nowak (2003) *Physics Reports*, 377, 389
Müller (2004) *PhD Thesis*

Corona geometry:

- slab, sandwich corona
- spherical corona
- hot inner accretion flow (truncated disc)
  → possible need for internal synchrotron seed photons
- patchy corona
- lamp-post corona (spherical, cone-shaped)
  → height, speed, disc truncation
  → possible need for internal synchrotron seed photons

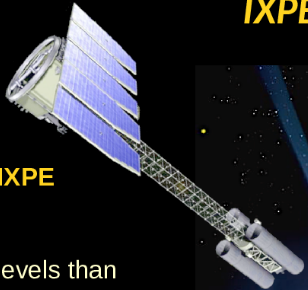
3D Monte Carlo codes with GR:

- PANDURATA – Schnittman & Krolik (2010) *ApJ*, 712, 908
  → sandwich, sphere, patchy
  – Schnittman & Krolik (2013) *ApJ*, 777, 11
- MONK – Zhang, Dovčiak & Bursa (2019) *ApJ*, 875, 148
  – Zhang et al. (2022) *MNRAS*, 515, 2882
  → lamp-post
- KERRC – Krawczynski & Beheshtipour (2022) *ApJ*, 934, 4
  → wedge, cone



IXPE DETERMINES GEOMETRY OF HOT CORONA

IXPE
Imaging
X-Ray
Polarimetry
Explorer



IXPE

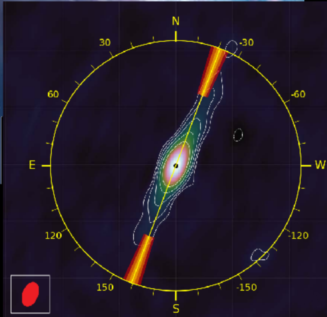
Cyg X–1

- higher polarization levels than expected (~4%)
- polarization direction aligned with radio jets
- hot corona extended along accretion disc

Swift J1727.8–1613 (~4.1%)

GX 339–4 (~1.3%)

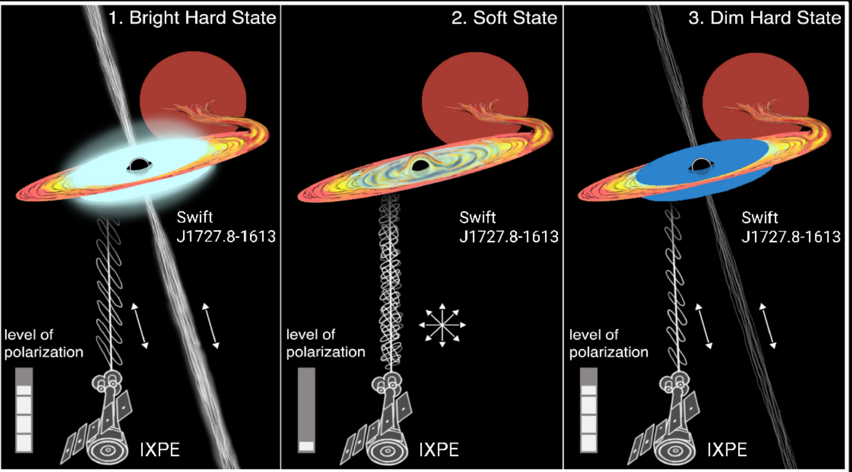
IGR J17091–3624 (~9%)



Cyg X-1 radio jets

UNIQUE *IXPE* OBSERVATIONAL CAMPAIGN OF BH XRB *SWIFT J1727.8–1613*

- five observations in the hard intermediate state: Veledina et al. (2023), Ingram et al. (2024)
- two observations in the soft state (SS): Svoboda et al. (2024)
- one observations In the reverse transition back to the hard state (HS): Podgorný et al. (2024)



- the first and only BH XRB observed at different stages of its outburst
- polarization dramatically drops when the source transits to its soft state
- polarization properties in the reverse transition to the dim HS are recovered to those of the bright HS – this shows that the corona geometry should be very similar at the beginning and end of the outburst!

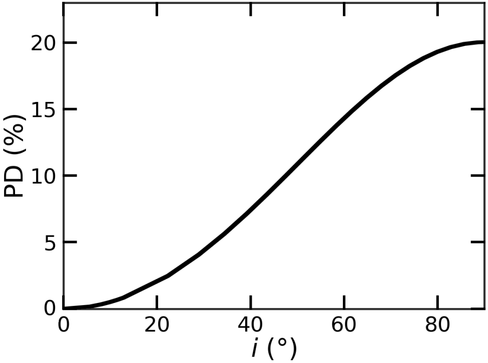
Polarization induced by reflection from the accretion disc

- polarization by reflection from the disc
  - Matt (1993) *MNRAS*, 260, 663
  - Poutanen et al. (1996), *MNRAS*, 283, 892
  - Dovčiak et al. (2011) *ApJ*, 731, 75
  - Podgorný et al. (2022) *MNRAS*, 510, 4723
  - Podgorný et al. (2023) *MNRAS*, submitted
- depolarization due to unpolarized relativistically broadened fluorescent Kα line
  - Chen & Eardley (1991) *ApJ*, 382, 125
  - Ogura, Ohuo & Y. Kojima (2000) *PASJ*, 52, 841

Chandrasekhar single scattering approximation for reflection of unpolarized isotropic illumination

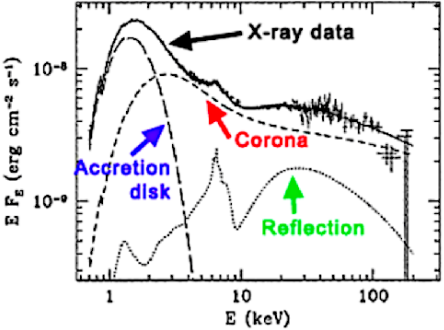
$\rightarrow$ dependence on inclination

$\rightarrow$ PA perpendicular to the axis

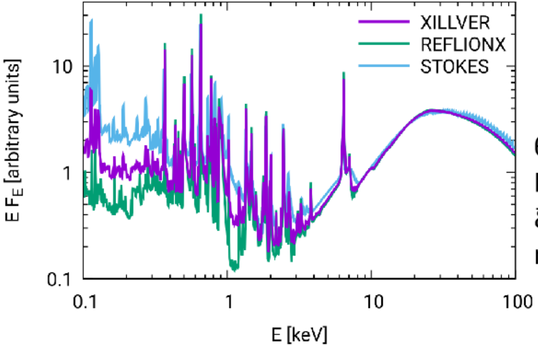


Chandrasekhar (1960) *Radiative Transfer*

Reflection component



Gierlinski et al. (1999)



$\theta = 45°$
$\Gamma = 2$
$\xi = 100$
$n_H = 10^{15}\ cm^{-3}$

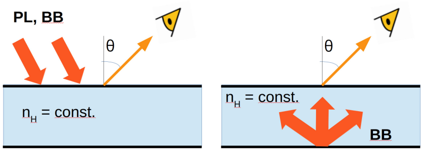
Different flavours of tables exist:

- REFLIONX, REFLIONX_HD
- XILLVER, XILLVERD, XILLVERNS

Main parameters:

- geometry of scattering – μ_i, μ_e, φ
- ionisation of the reflector – ξ
- density of the reflector – n_H
- shape of illuminating spectra – Γ, E_c, T_{BB}
- other: abundance, ...

Radiative transfer in the slab — reflection and transmission



Power-law illumination:

- Podgorný et al. (2022) *MNRAS*, 510, 4723
  - `https://github.com/jpodgorny/stokes_tables`

→ dependent on scattering geometry (defined by 3 angles), power-law index, ionisation and incident polarisation

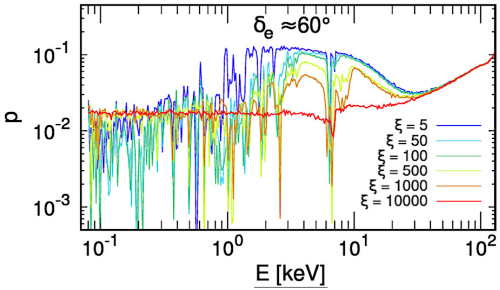
→ available as table models for `XSPEC` in `OGIP FITS` files

Black-body illumination:

- Podgorný et al. (2025) *A&A*, submitted (arXiv: 2507.23687)

Black-body transmission:

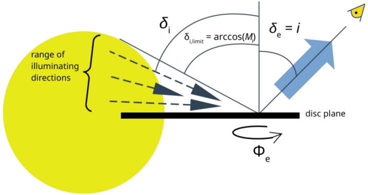
- Taverna et al. (2021) *MNRAS*, 501, 3393
- Ratheesh et al. (2024) *ApJ*, 964, 77
- Marra et al. (2025) *A&A*, 705, A8

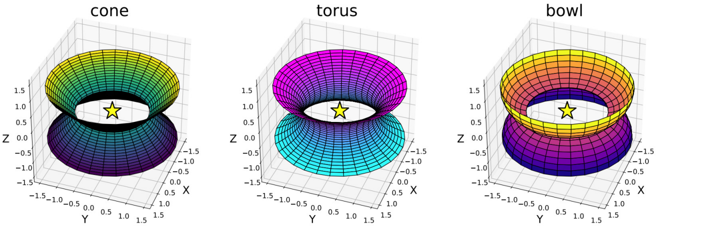


Example figure:

Energy dependent polarisation degree dependence on disc ionisation, ξ, for emission angle of 60° for an isotropic unpolarised illumination by a power-law radiation with photon index $\Gamma = 2$ for a constant density slab with density of $n_{\mathrm{H}} = 10^{15}\,\mathrm{cm}^{-3}$.

Non-relativistic distant reflection





Reflection from a distant disc or torus:

- Podgorný et al. (2024) *MNRAS*, 530, 2608
  - Disc: `https://github.com/jpodgorny/xsstokes_disc`
  - Torus: `https://github.com/jpodgorny/xsstokes_torus`

→ reflection tables are integrated over scattering geometry for a given shape of the distant reflector

Distant reflector — various shapes (cone, torus, bowl)

- Podgorný (2025) *A&A*, 702, A43

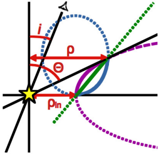
→ includes ionization dependence

STOKES

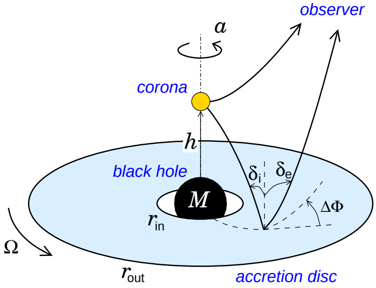
Goosmann & Gaskell (2007) *A&A*, 465, 129

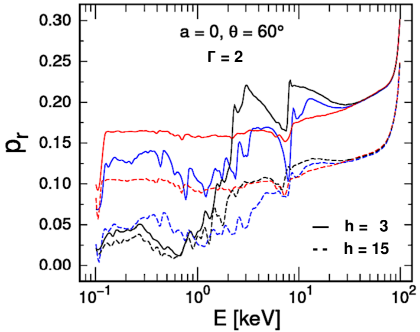
SKIRT

Vander Meulen et al. (2024) *A&A*, 689, A297



Relativistic reflection from accretion disc illuminated by corona





Exmple figure: Energy dependent polarisation degree for disc reflection for low (black), medium (blue) and high (red) disc ionisations and unpolarised illumination

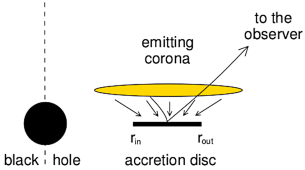
KYNSTOKES:

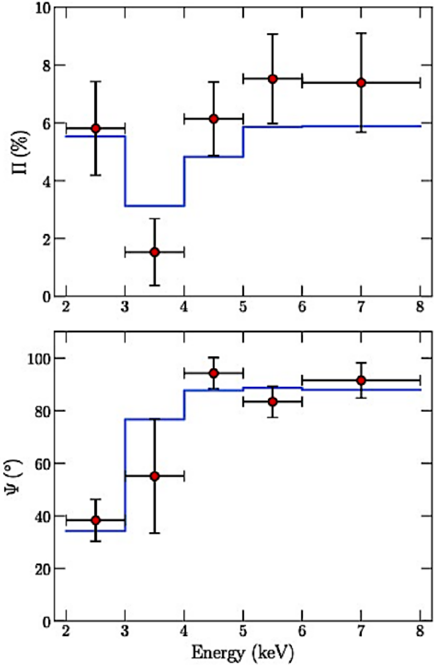
- Podgorný et al. (2023) *MNRAS*, 524, 3853

○ `https://projects.asu.cas.cz/dovciak/kynstokes`

→ lamp-post corona and extended corona just above the disc are included

→ illumination by black-body is being worked on to be used for neutron stars





NGC 4151

Can the polarisation properties be explained within the context of **X-ray disc illumination**?

Absorption * (X-ray continuum + X-ray reflection from the disc)

KYNSTOKES

+ X-ray reflection from the torus

XSSTOKES_TORUS

+ scattering of the X-ray continuum (the “mirrored component”)

POLCONST*POWERLAW

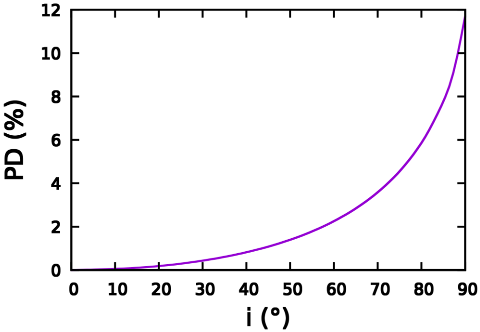
Soft state – polarization of thermal emission

- Connors, Piran & Stark (1980) *ApJ*, 235, 224
- Laor, Netzer & Piran (1990) *MNRAS*, 242, 560
- Dovčiak et al. (2008) *MNRAS*, 391, 32
- Schnittman & Krolik (2009) *ApJ*, 701, 1175
- Krawczynski (2012) *ApJ*, 754, 133
- Taverna et al. (2020) *MNRAS*, 493, 4960
- Taverna et al. (2021) *MNRAS*, 501, 3393
- Mikušincová et al. (2022) *MNRAS*, 519, 6138
- Ratheesh et al. (2023) *Nature Astronomy*, submitted

Pure semi-infinite electron-scattering atmosphere illuminated by unpolarized isotropic black-body radiation

$\rightarrow$ dependence on inclination

$\rightarrow$ PA perpendicular to the axis



Chandrasekhar (1960) *Radiative Transfer*

IXPE MEASURES BLACK HOLE SPINS

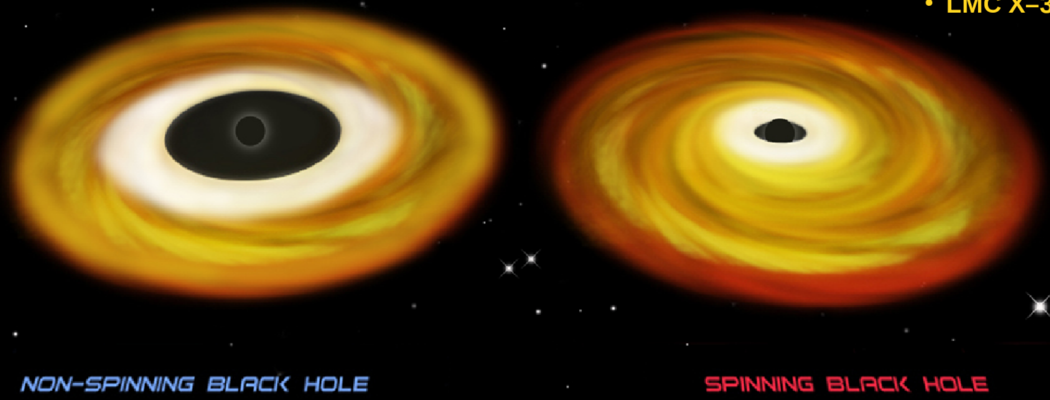
- accretion disc reaches much closer to the highly spinning black hole
- relativistic effects are more pronounced
- polarization degree and angle change with energy
- one can measure spin via polarimetry

Very high spin:

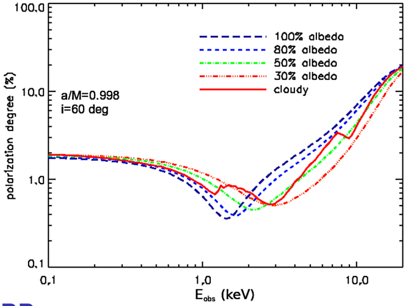
- **Cyg X–1**
- **4U 1957+115**
- **GRS 1739–278**

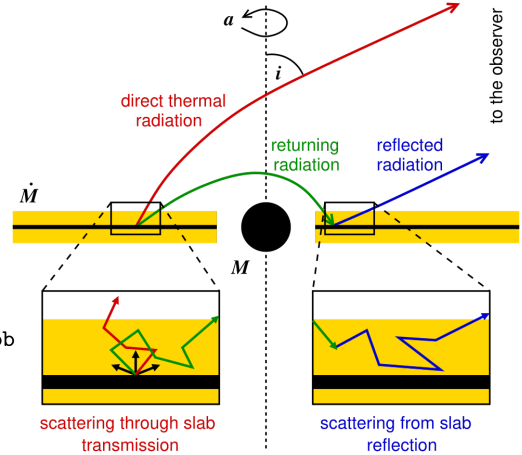
Low spin:

- **LMC X–3**



Thermal radiation from accretion disc





KYNBB:

- Dovčiak et al. (2008) *MNRAS*, 391, 32
- ○ `https://projects.asu.cas.cz/stronggravity/kyn#kynbb`

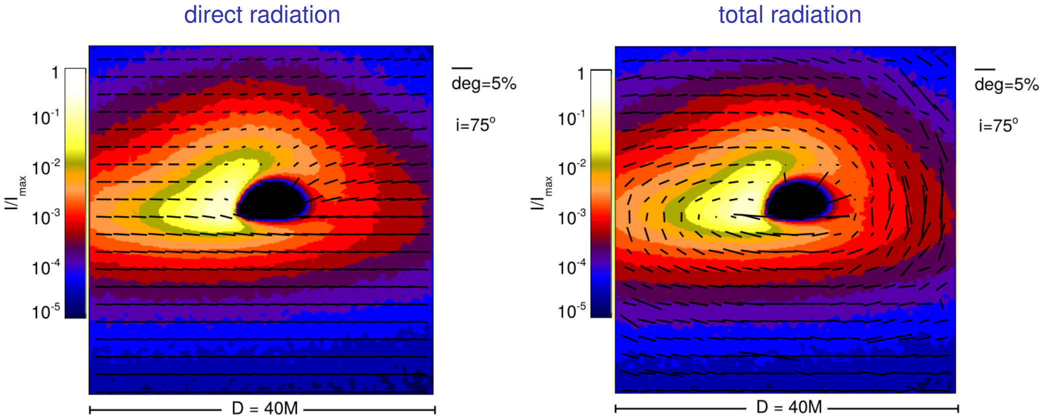
→ different radiative transfer models for scattering being implemented

KYNBBRR (including Returning Radiation):

- Taverna et al. (2020) *MNRAS*, 391, 32
- Mikušincová et al. (2023) *MNRAS*, 519, 6138

→ disc reflection due to self-irradiation is included parametrized by albedo or ξ in XILLVERNS or STOKESBB

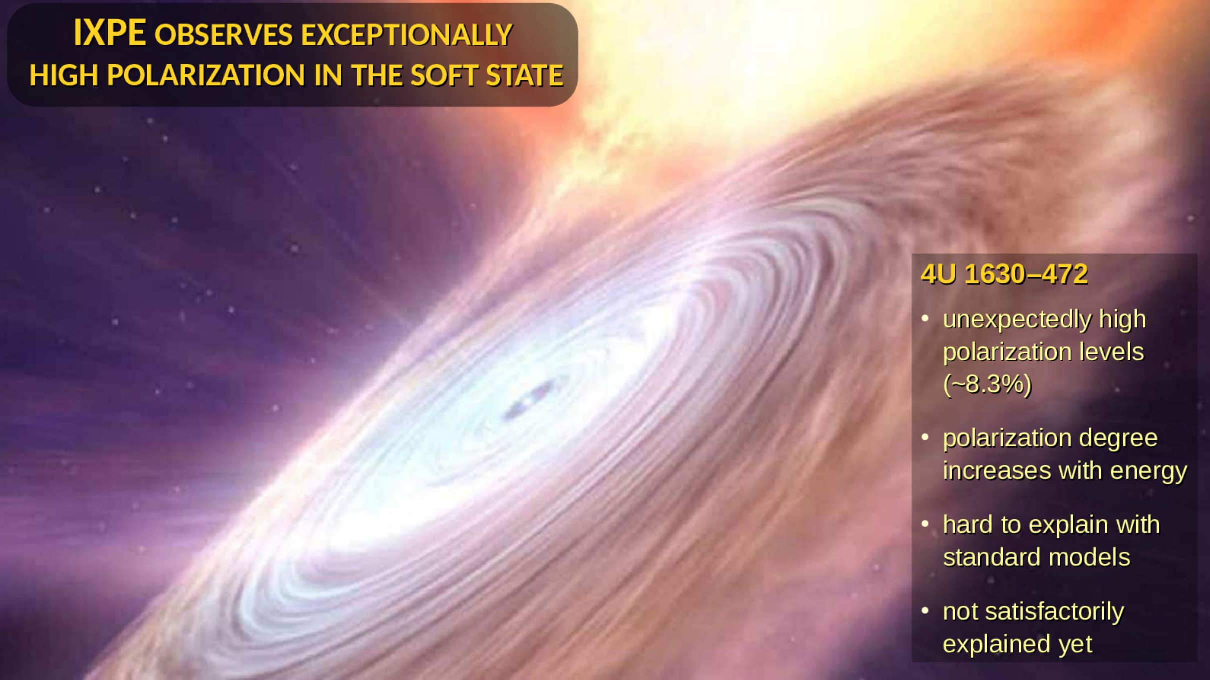
Returning radiation



Schnittman & Krolik (2009) *ApJ*, 701, 1175

- close to BH $\to$ strong light bending $\to$ disc self-irradiation
- direct radiation parallel with the disc $\to$ larger flux, lower PD
- reflected radiation azimuthal direction $\to$ smaller flux, larger PD

IXPE OBSERVES EXCEPTIONALLY HIGH POLARIZATION IN THE SOFT STATE



4U 1630–472

- unexpectedly high polarization levels (~8.3%)
- polarization degree increases with energy
- hard to explain with standard models
- not satisfactorily explained yet

Availability of the models

All public models are available also via HEASARC web page

More models for XSPEC:

◦ `https://heasarc.gsfc.nasa.gov/docs/software/xspec/moremodels.html`