Polarization properties of direct radiation in stellar-mass black hole accretion disks

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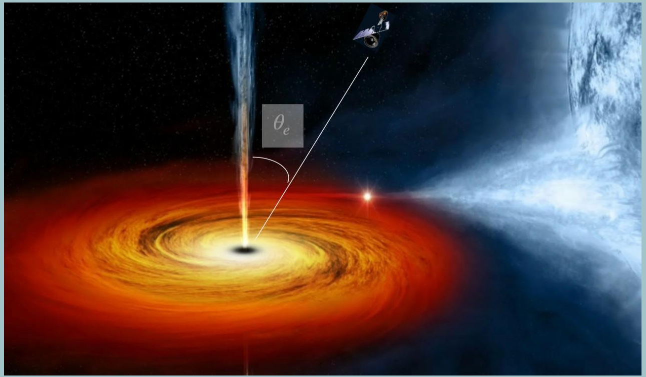
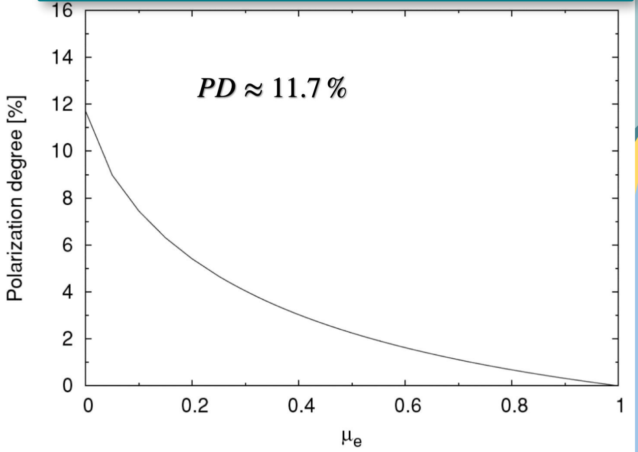
Introduction - Accretion disk emission polarization properties

- Accretion disk emission is polarized because of the **scattering processes** occurring within the disk atmosphere
- **Symmetry arguments**: polarization vector can be either parallel or perpendicular to the disk symmetry axis

- Chandrasekar (1960) and Sobolev (1963) computations for radiation emerging from **a plane-parallel, semi-infinite, pure electron-scattering atmosphere (τ >>1).**
- **PD only depends on the inclination angle**

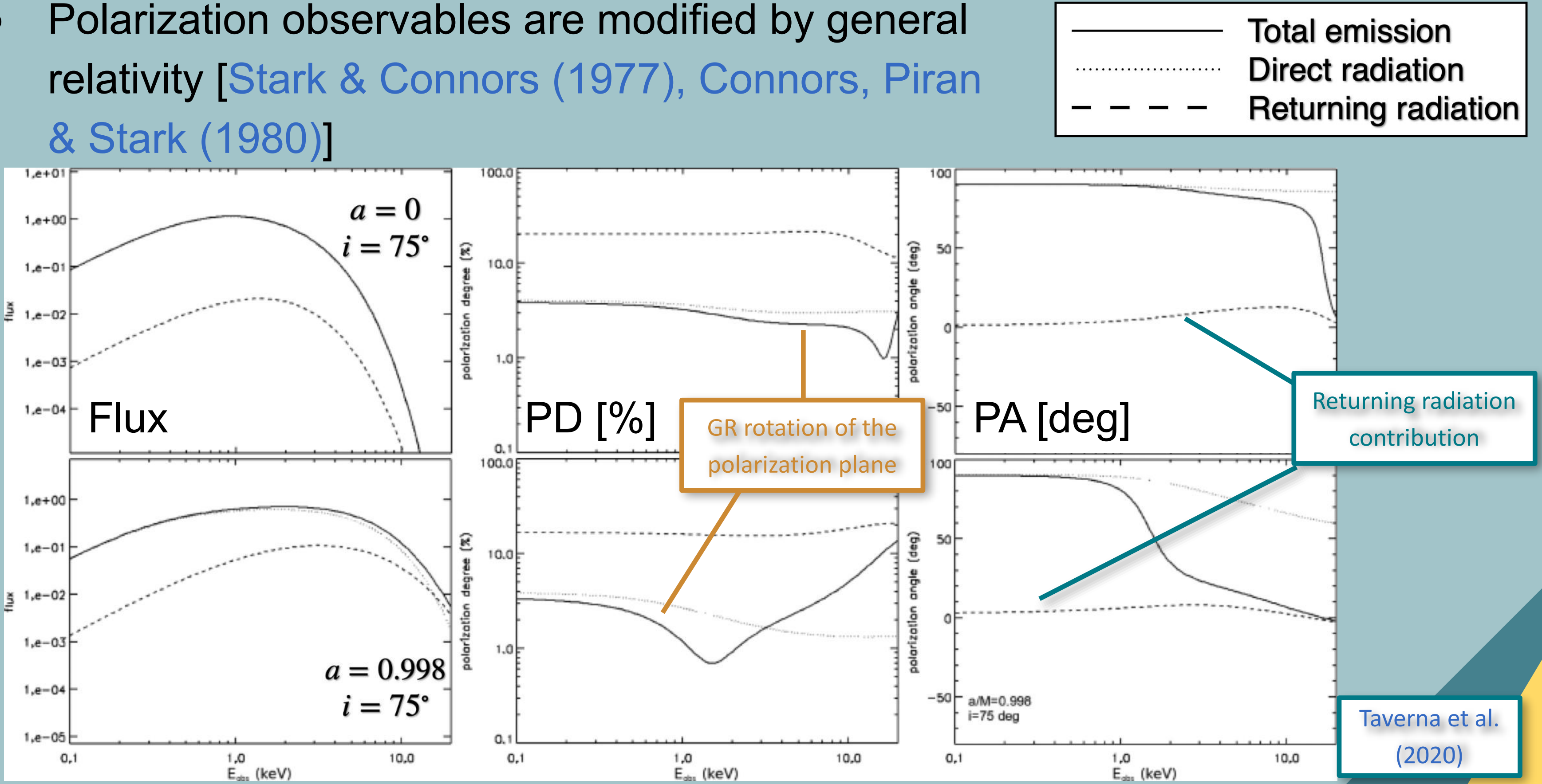


Data from Table XXIV in Chandrasekhar (1960)



Introduction - General relativity effects

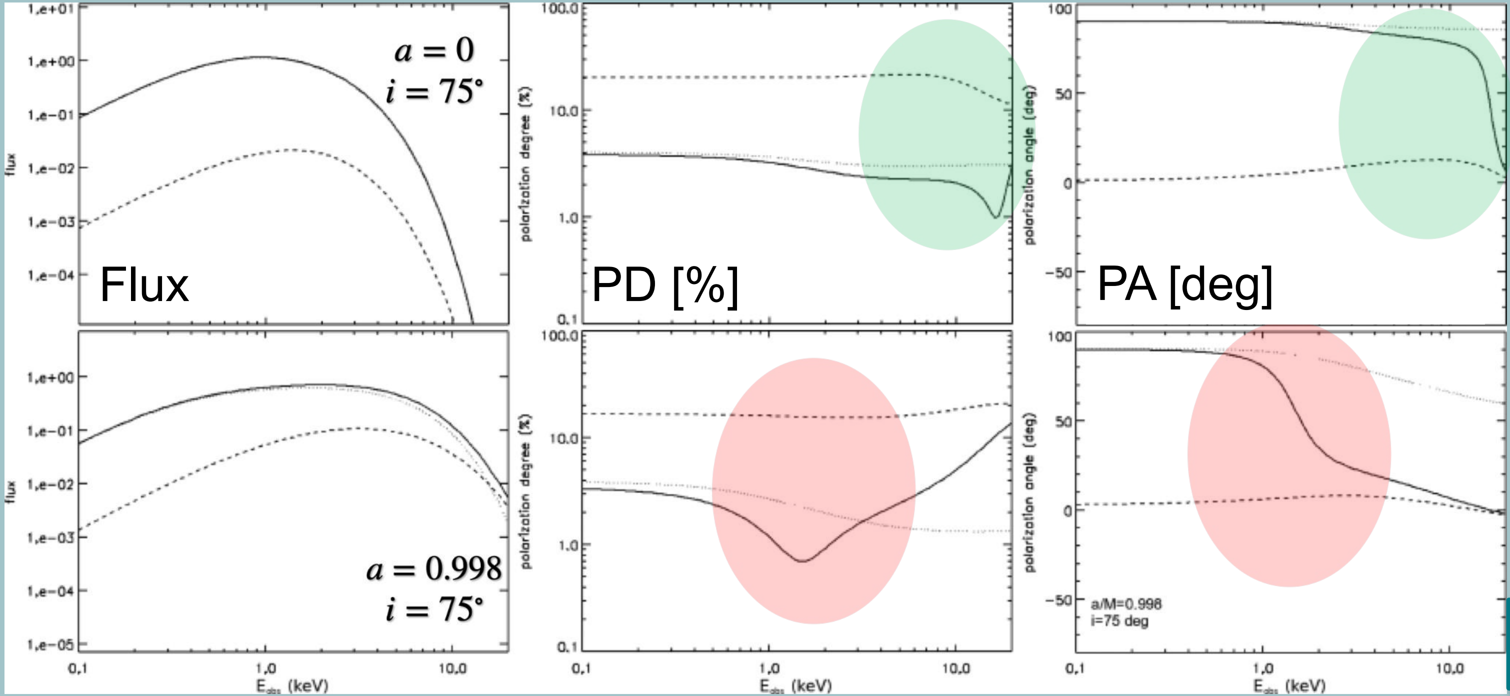
- Polarization observables are modified by general relativity [Stark & Connors (1977), Connors, Piran & Stark (1980)]



Taverna et al. (2020)

Introduction - General relativity effects

- Since **for rotating BHs the ISCO is located closer to the BH**, the **general relativity effects**, along with the contribution of returning radiation, **are expected to be stronger for BHs with larger spin**.



Taverna et al. (2020)

IXPE - First X-ray polarimetric observations of stellar mass BHs

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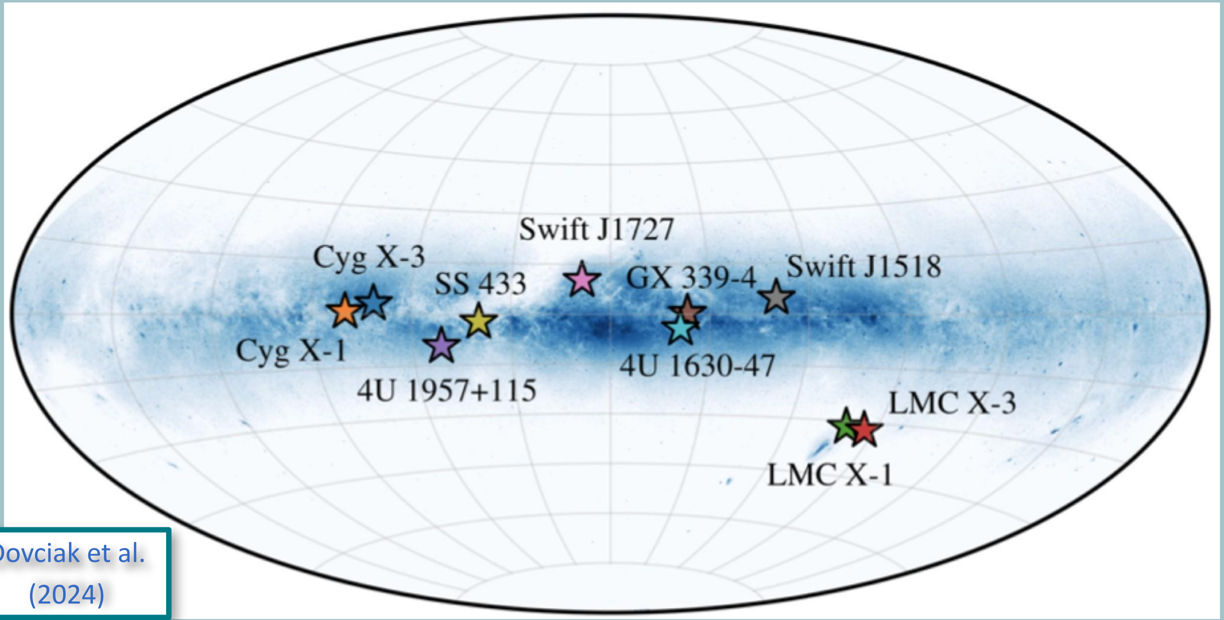
- **IXPE** (launched in December 2021) observed **10+ Stellar mass BH in different spectral states [Dovciak et al. (2024)]**



Dovciak et al. (2024)

+
- IGR J17091–3624 [Ewing et al. (2025)]
- MAXI J1744-295 [Marra et al. submitted to ApJ]

See Shifra Mandel Talk

IXPE - Does the standard model work?

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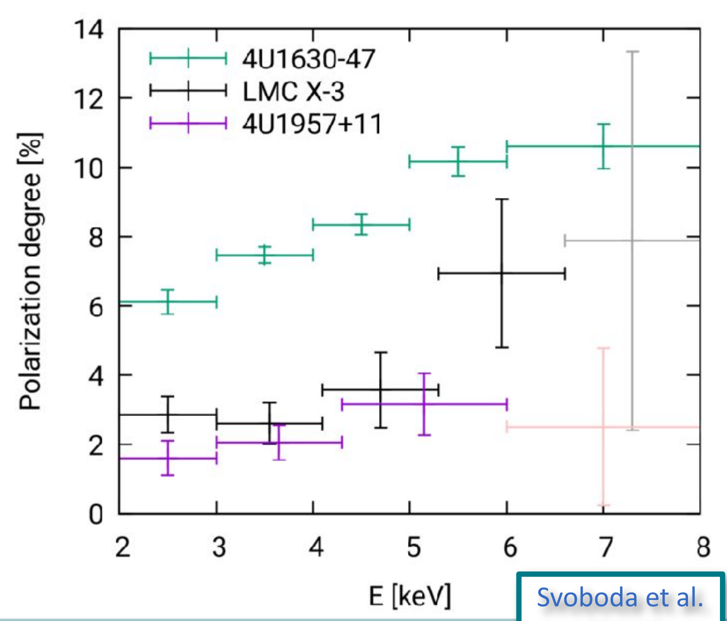
- An **increasing PD behavior with energy was observed**
  - Can be explained in the standard model **assuming a substantial returning radiation contribution**
  - **Only viable for rapidly rotating sources**, e.g. 4U 1957+11
- Never observed the **GR rotation of the polarization angle**
- **4U 1630-47** observation
  - $PD = (8.32 \pm 0.17)\ \%$
  - Substantial PD increase with energy

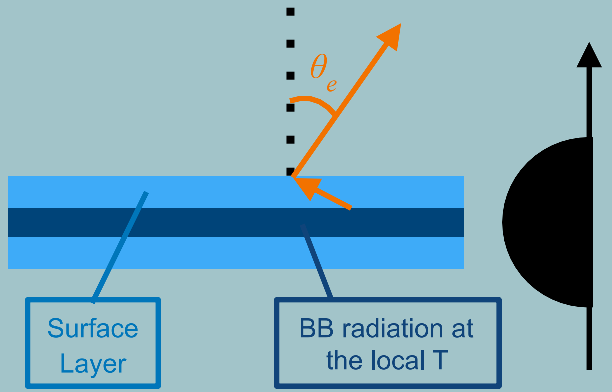


Svoboda et al. (2023)

Much larger than the standard thin disk prediction!

Numerical setup

- Study the **radiative transfer within the disk atmosphere** (Absorption and Compton scattering effects) [Taverna et al. (2021), Marra et al. submitted to A&A]
  - Chandrasekhar's computations consider a pure electron-scattering atmosphere
  - Completely ionized disk medium



Numerical setup

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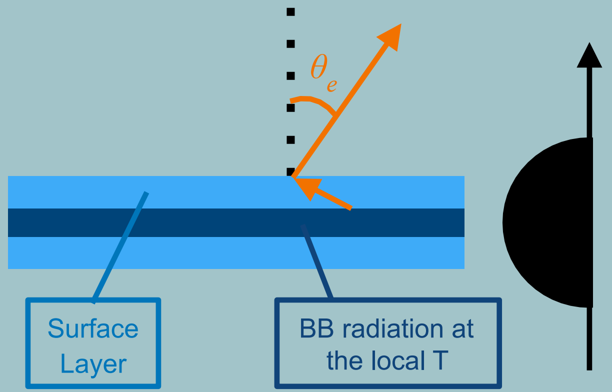
- Study the **radiative transfer within the disk atmosphere** (Absorption and Compton scattering effects) [Taverna et al. (2021), Marra et al. submitted to A&A]

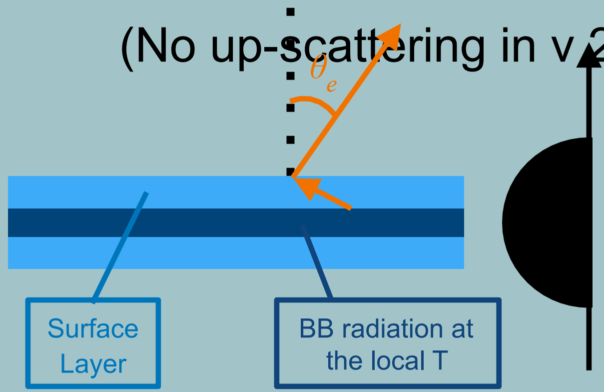
1. Modeling the **ionization structure of an optically-thick, surface layer**
   - **CLOUDY** [Ferland et al. (2017)]
   - Temperature, density (constant) and optical depth
   - Two ionization regimes: Collisional Ionization Equilibrium (**CIE**) and Photo Ionization Equilibrium (**PIE**).



Numerical setup

- Study the **radiative transfer within the disk atmosphere** (Absorption and Compton scattering effects) [Taverna et al. (2021), Marra et al. submitted to A&A]

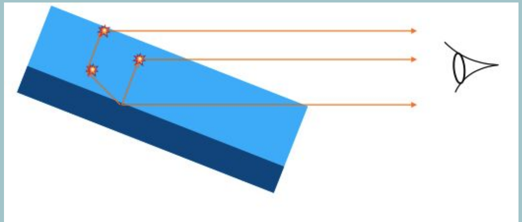
1. Modeling the **ionization structure of an optically-thick, surface layer**
2. Use a Monte Carlo code (**STOKES,** Marin et al. (2018)) to solve the **radiative transfer** for photons propagating **within the surface layer**
   - Seed radiation: unpolarized blackbody emitted from the bottom of the surface slab
   - Includes **Line emission, photoelectric absorption, Compton down-scattering** (No up-scattering in v 2.33)



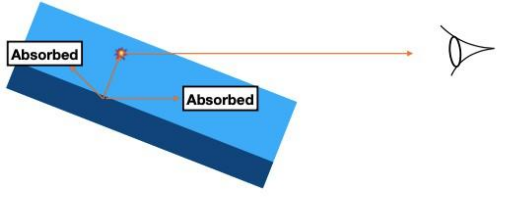
Slab - Including absorption effects

Marra et al.
Submitted to A&A

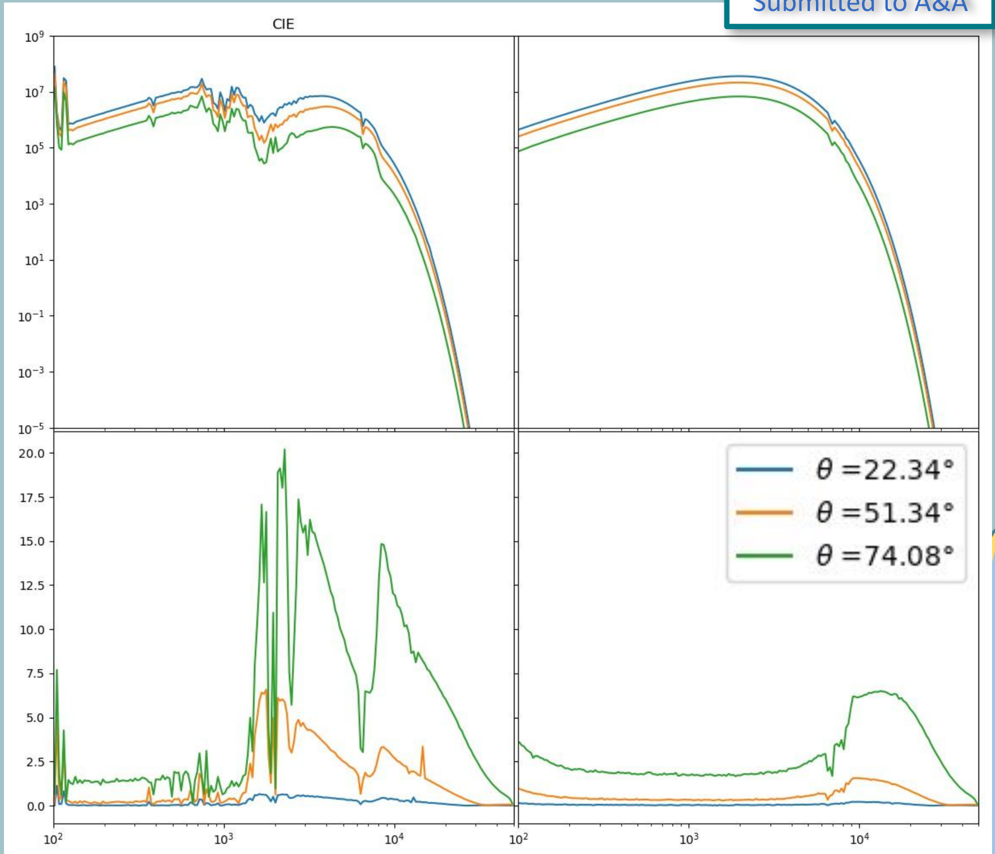
- Slab with **T=0.7 keV**; **d=**$10_{19}\,\mathrm{cm}_{-3}$; $\tau \sim 1$
- **PA perpendicular** to the slab normal
- **Low ionization**:
  - **Polarization degree is higher when the absorption effects are more relevant**



- **No absorption**



- **With absorption**



Slab - Including absorption effects

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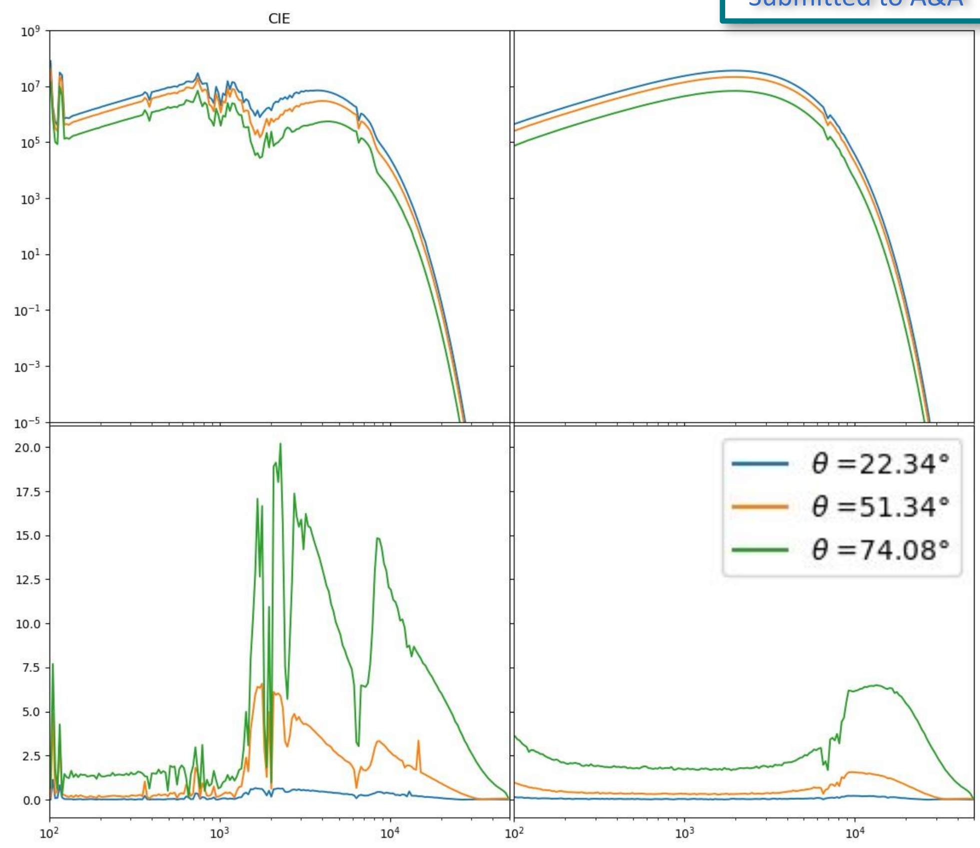
- Slab with **T=0.7 keV**; **d=**$10^{19}\ \mathrm{cm}^{-3}$; $\tau \sim 1$
- **PA perpendicular** to the slab normal
- **Low ionization**
- **High ionization**:
    - **PD increase observed at high energies**, likely caused by Compton down-scattering (BUT no Compton up-scattering in the computations)

Marra et al.
Submitted to A&A



Numerical setup

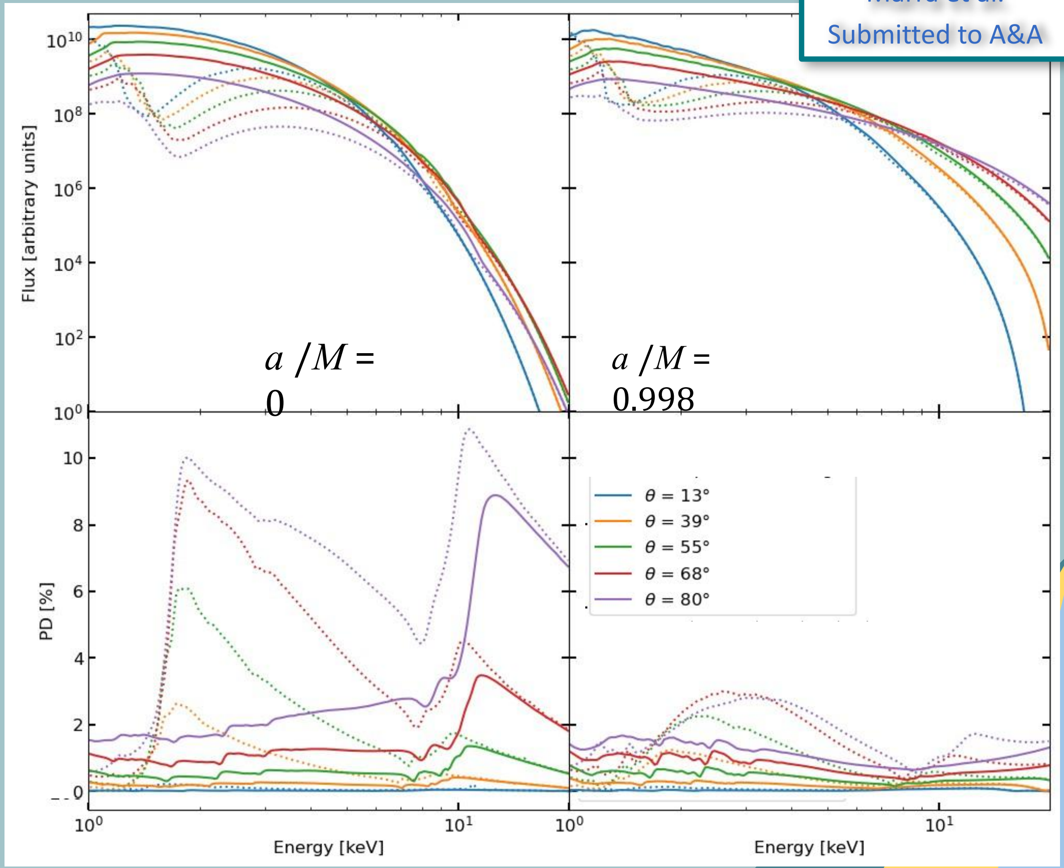
- Study the **radiative transfer within the disk atmosphere** (Absorption and Compton scattering effects) [Taverna (2021), Marra et al. submitted to A&A]

1. Modeling the **ionization structure of an optically-thick, surface layer**
2. Use a Monte Carlo code (**STOKES**, Marin et al. (2018)) to solve the **radiative transfer** for photons propagating **within the surface layer**
3. Include GR effects using the fully relativistic ray tracing package KYN [Dovciak et al. (2008)]
    - $M = 10\ M_{\odot}$; $a = 0 - 0.998$
    - Only **direct radiation** (Returning radiation is still a work in progress)

Polarization properties of disk emission

- Observed radiation is found to be generally **more polarized for** $a/M = 0$ **than for** $a/M = 0.998$;

- **CIE** (dotted lines):
  - **Decreasing PD behavior with energy in the IXPE energy band**



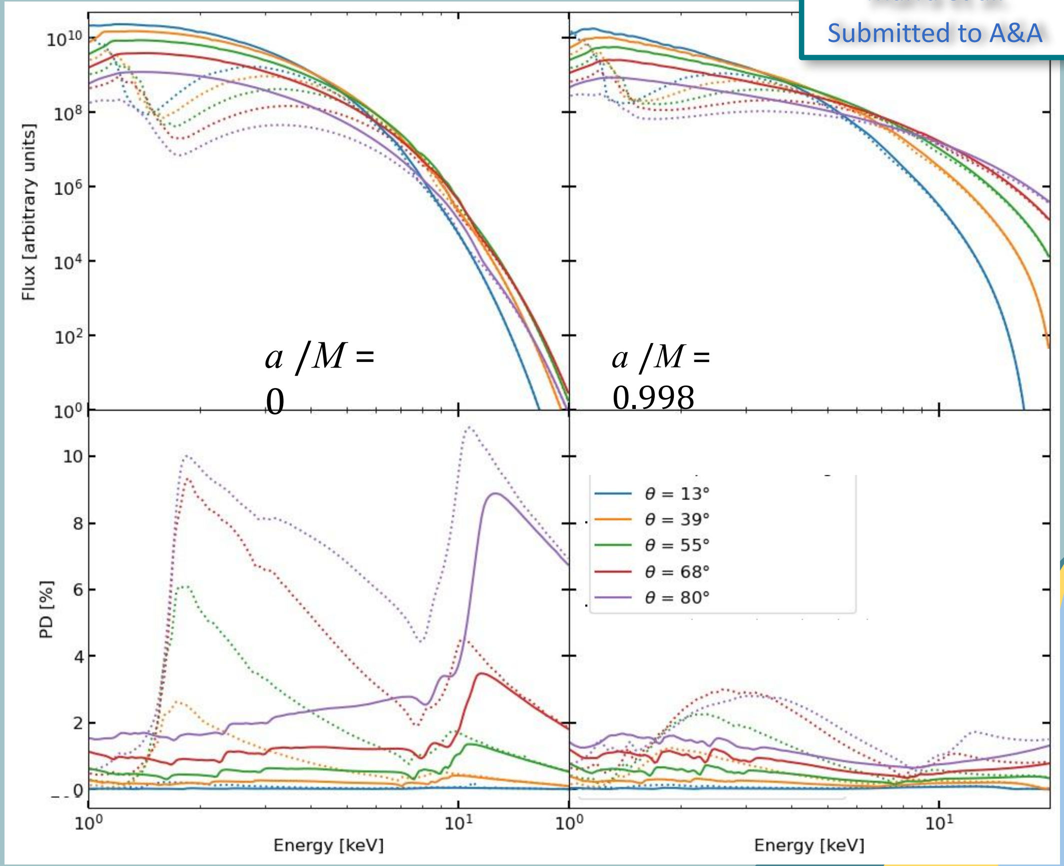
Marra et al.
Submitted to A&A

Polarization properties of disk emission - Including absorption effects

- Observed radiation is found to be generally **more polarized for $a/M = 0$ than for $a/M = 0.998$;**

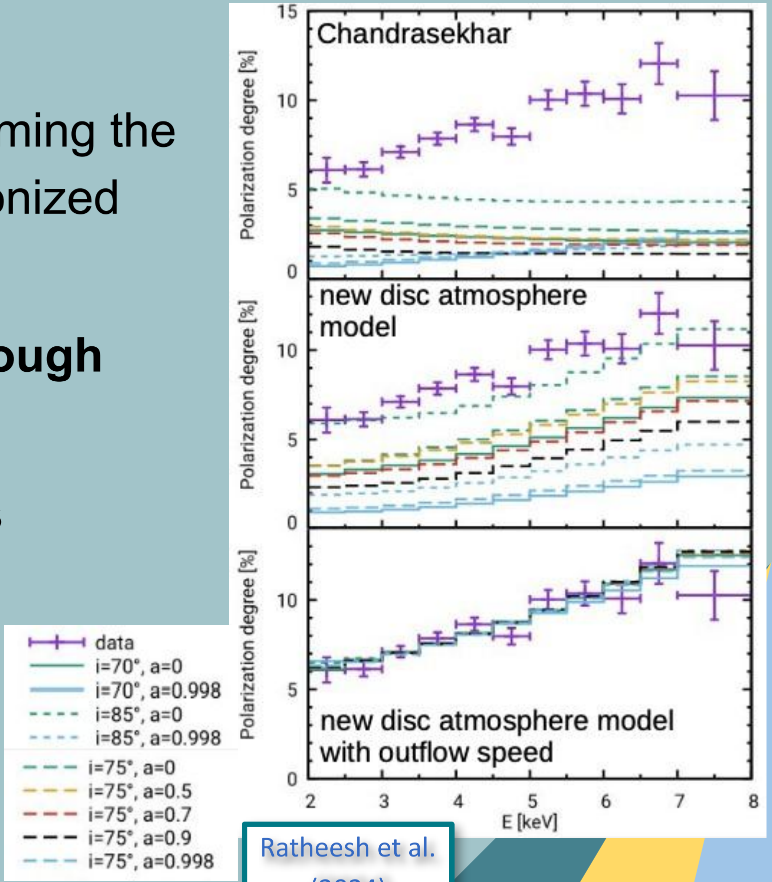
- **CIE** (dotted lines)**:**
  - **Decreasing PD behavior with energy in the IXPE energy band**
- **PIE** (solid lines):
  - Generally lower PD observed with respect to the CIE configuration
  - **Increasing PD behavior with**

Marra et al.
Submitted to A&A



Application to 4U 1630-47 data

- **PD increasing behavior can be described** assuming the thermal emission to be reprocessed in an highly ionized atmosphere;
- However the **PD predicted in this way is not enough** when accounting for GR effects
- Observed PD can be increased including upwards relativistic velocities ($\beta \sim 0.5c; \quad \tau \sim 7$)
- **No scenario** explains all the details of the polarization behavior in a satisfactory manner [but see Nitindala (2025)]



Ratheesh et al. (2024)

Conclusions - THANK YOU FOR YOUR ATTENTION!

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- **Including absorption effects increases the PD of the radiation emerging from an optically thick, plane-parallel atmosphere.**
- **Radiation tends to be basically more polarized for $a/M = 0$ than for $a/M = 0.998$.**
- **When absorption effects are prominent (e.g. CIE) a decreasing PD behavior is expected in the IXPE energy range.**
- **The reprocessing of radiation in an highly ionized atmosphere (e.g. PIE) can give rise to an increasing PD trend with energy.**
- **A detailed interpretation of the interactions between the emerging radiation and the disk atmosphere is crucial for interpreting the IXPE observations of stellar mass BHs in soft state**