Aspects of X-ray data analysis for accreting compact objects: theory and results

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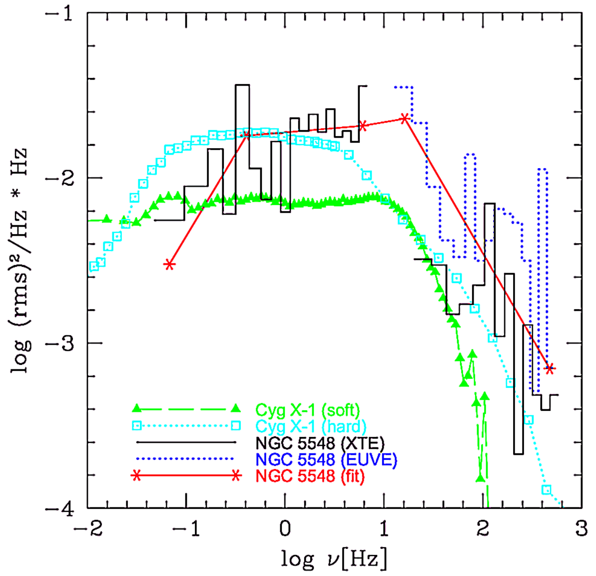
Previous lecture

Seyfert galaxy NGC 5548 used as a reference source, since it's mass is quite well known: $6.8*10^7\ M_{SUN}$

Assuming $10\ M_{SUN}$ BH mass in Cyg X-1, the PSD has to be shifted by 6.83 in log(f).

Location of the break frequency matches well the soft state spectrum of Cyg X-1, but normalization in NGC 5548 is higher



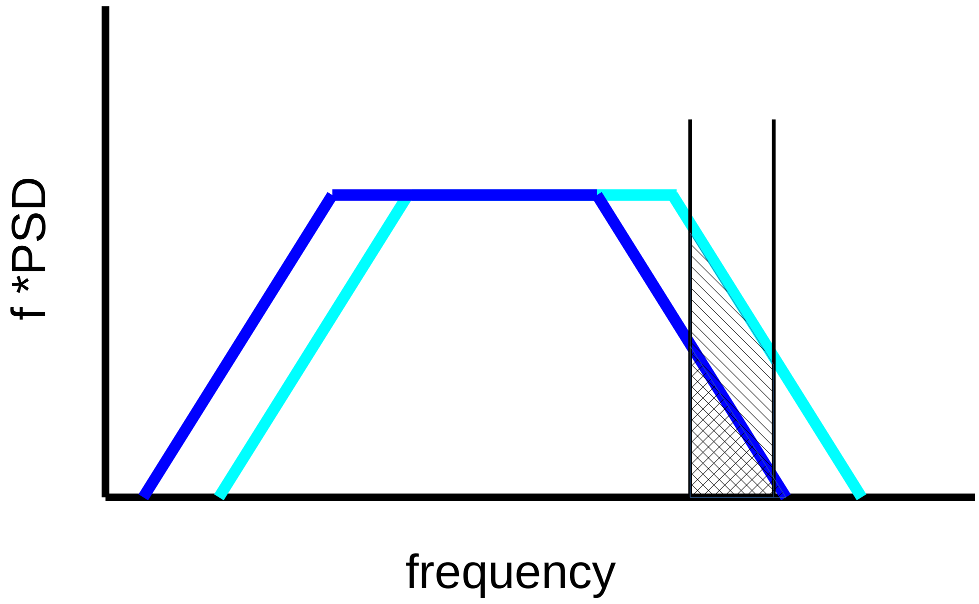
$$T_B = \frac{M_{BH}^{1.12}}{\dot{m}_E^{0.98}}$$

The variance method

The amplitude of variability – the integral of PSD over the marked frequency range – scales with BH mass.

Need to assume:

- Universal shape of power spectrum
- The same frequency range for all sources
- In practice: use σ from lightcurve rather than integrate PSD



$$M_{BH} \propto \frac{1}{\sigma}$$

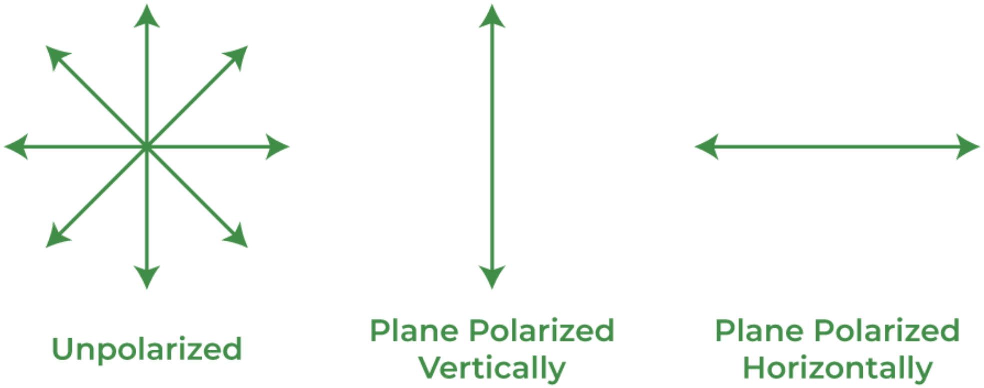
Polarization of X-ray emission from accreting compact objects

Provides additional, independent observable, beyond the spectral and timing properties

Polarization of radiation

A single photon is always in *a* quantum polarisation state

A beam of photons may be unpolarised, if it’s a statistical mixture with no preferred direction



Polarization of radiation

Description of polarization:

- Stokes parameters
- PD (Polarization Degree)
- PA (Polarization Angle)

$$\mathrm{PD} = \frac{\sqrt{Q^2 + U^2}}{I}$$

$$\psi = \frac{1}{2}\arctan\left(\frac{U}{Q}\right)$$

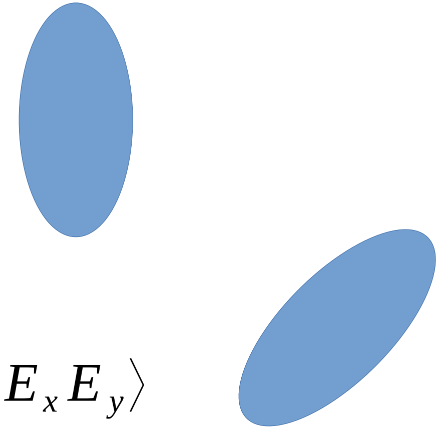
$$(I, Q, U, V)$$

$$I = \langle E_x^2 \rangle + \langle E_y^2 \rangle$$

$$Q = \langle E_x^2 \rangle - \langle E_y^2 \rangle$$

$$U = \langle E_{45}^2 \rangle - \langle E_{135}^2 \rangle = 2\langle E_x E_y \rangle$$

$$V = 2\langle E_x E_y \sin\delta \rangle$$



Polarization of radiation

Example:

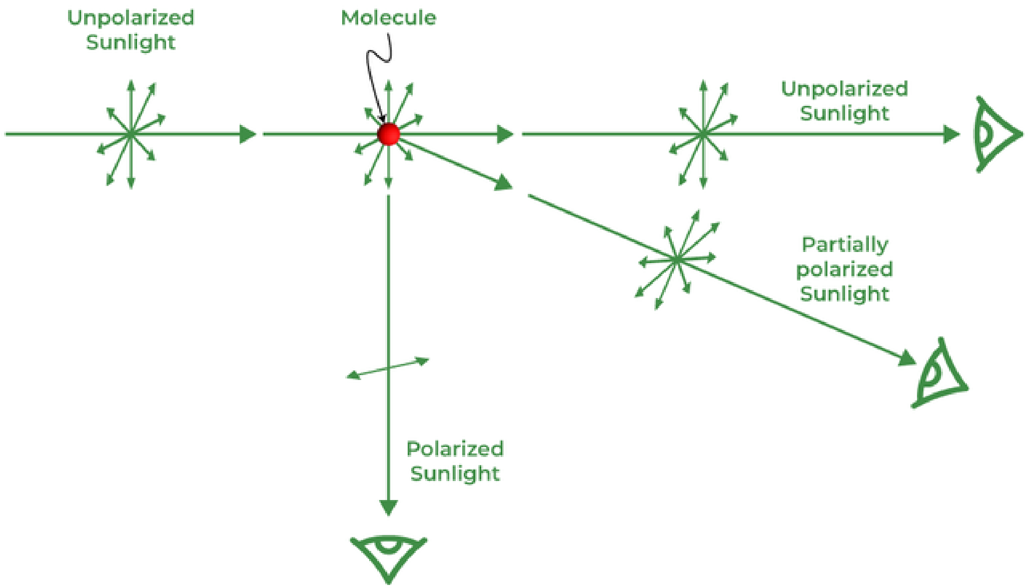
$$E_x = 0 \, ; \qquad E_y = 1$$

$$Q = -1 \, ; \qquad U = 0 \, ; \quad I = 1$$

$$\mathrm{PD} = 1$$

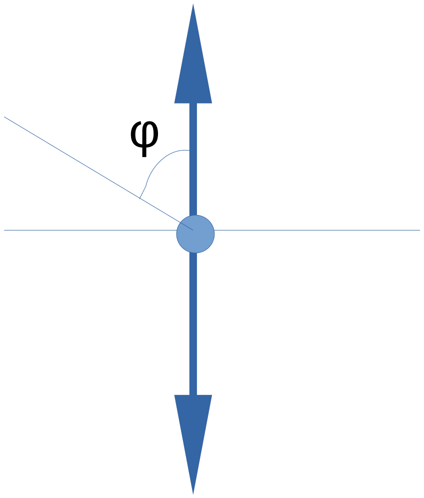
$$\psi = \frac{1}{2} \arctan\left(\frac{U}{Q} \right) = \frac{1}{2} \arctan\left(\frac{0}{-1} \right) = \frac{1}{2} 180^{\circ} = 90^{\circ}$$

Polarization as a result of scattering



Scattered photon is preferentially polarized in the plane perpendicular to the scattering plane

Scattering of a polarized light



$$\frac{d\sigma}{d\Omega} \propto 1 - \sin^2\theta \cos^2\phi$$

Largest for φ = 90º

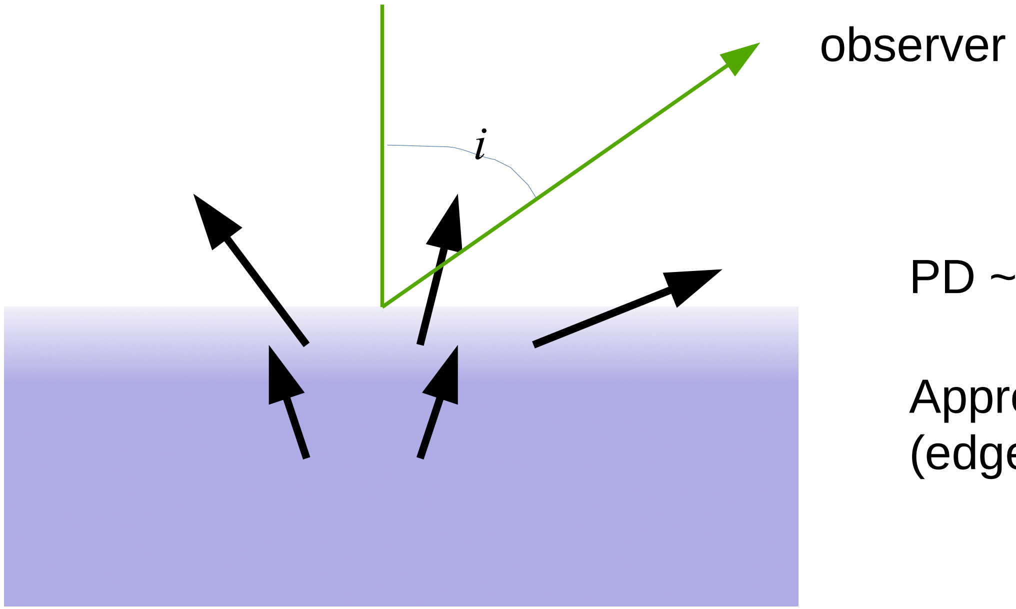
The azimuthal angle of the scattered photon is preferably 90º

Scattering off an energetic electron

Complicated: transform the photon from electron rest frame, do scattering there, transform back to initial frame. Polarization will be changed, both PD and PA

Accretion disk

Emission from an accretion disk is somewhat polarized because of scattering in upper layers of the disk



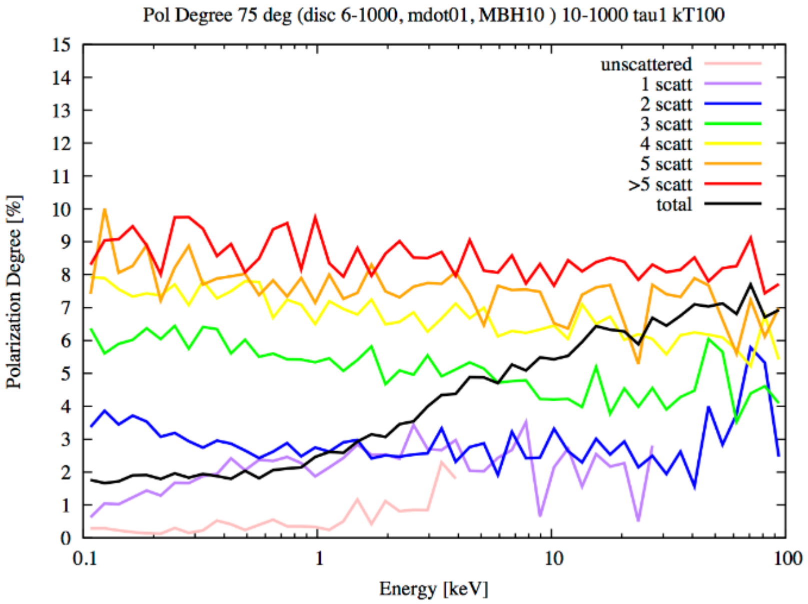
$$PD(i) \propto \sin^2 i$$

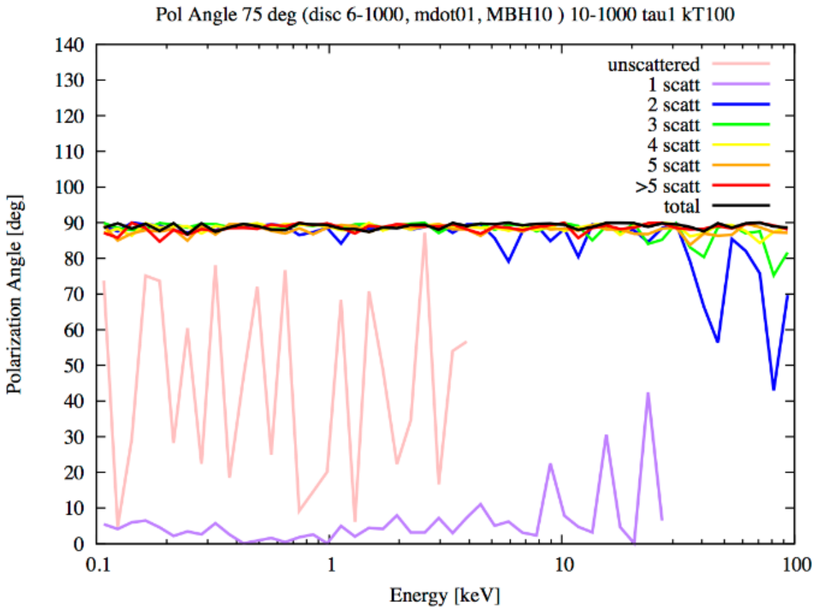
PD ~ 1% for i<30º

Approaching 10% for high i (edge-on view)

Accretion disk with a hot corona

Polarisation of emission from accretion disk is modified by inverse Compton scattering in the corona, as well as relativistic effects in propagation

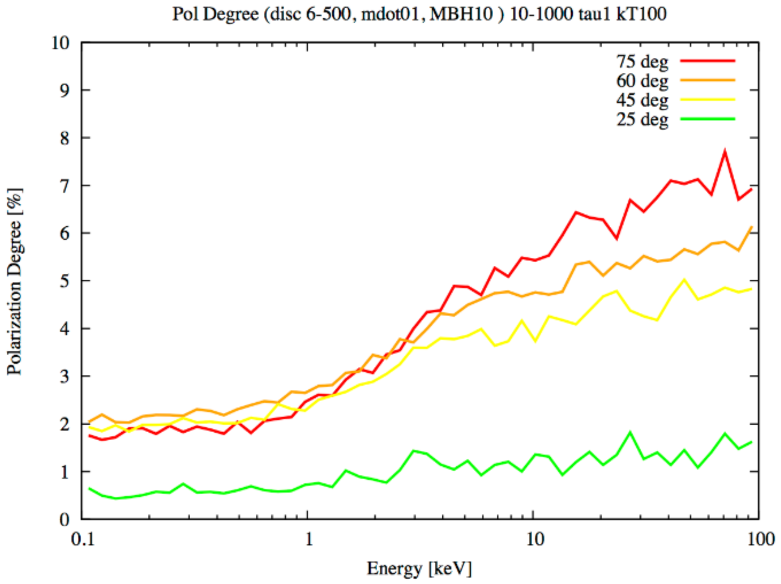


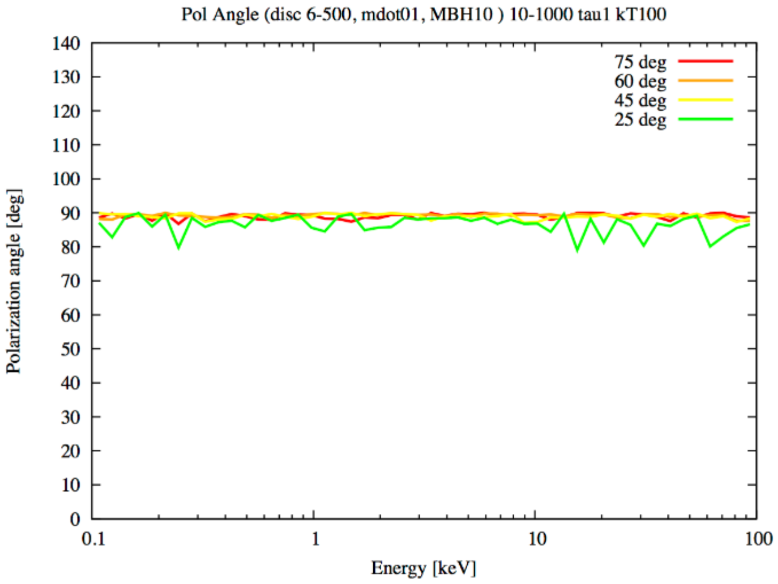


Tamborra et al., 2018, A&A, 619, A105

Accretion disk with a hot corona

Energy dependence for different inclination angles

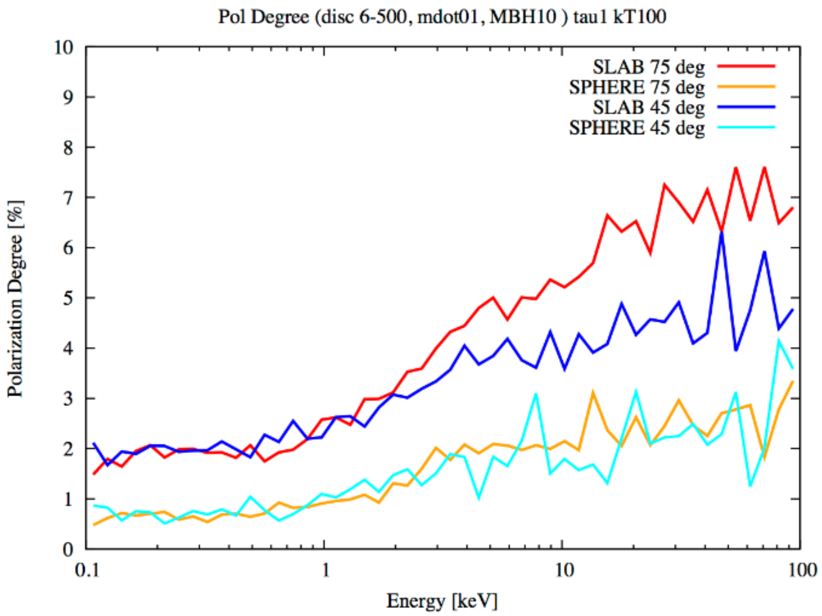


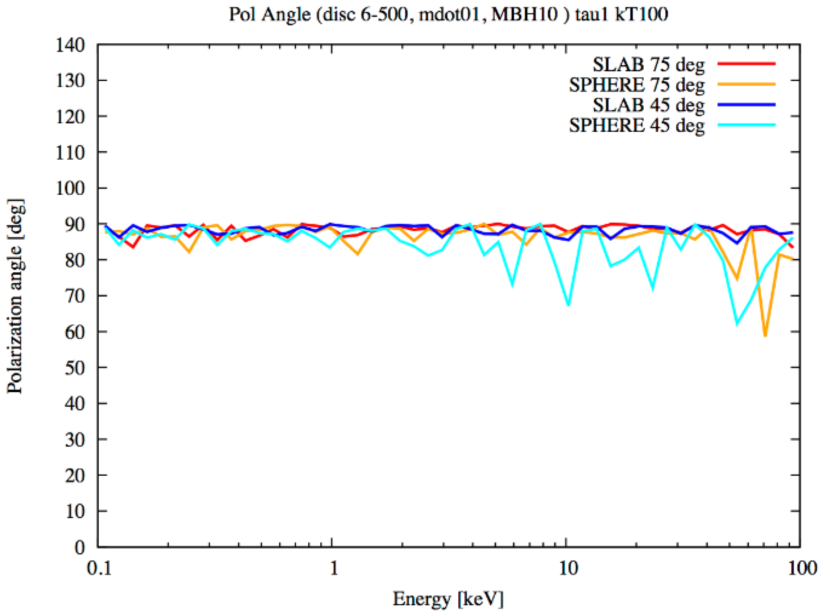


Tamborra et al., 2018, A&A, 619, A105

Accretion disk with a hot corona

Comparison of a slab corona vs spherical corona/flow





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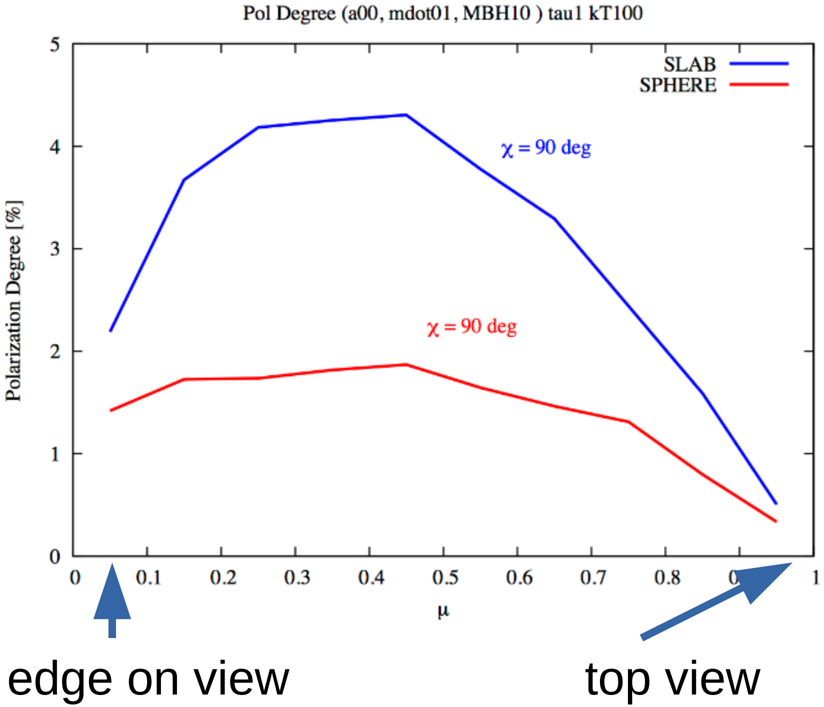
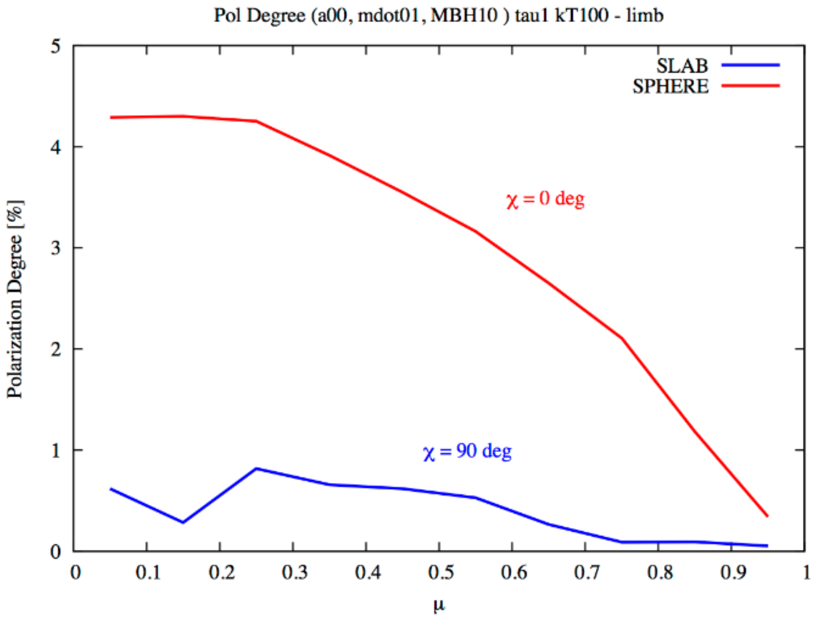
Accretion disk with a hot corona

Energy integrated (2-8 keV) results, function of inclination, for two assumptions about the accretion disk emission





Tamborra et al., 2018, A&A, 619, A105

Observations

Instruments: IXPE - Imaging X-ray Polarimetry Explorer   (NASA)

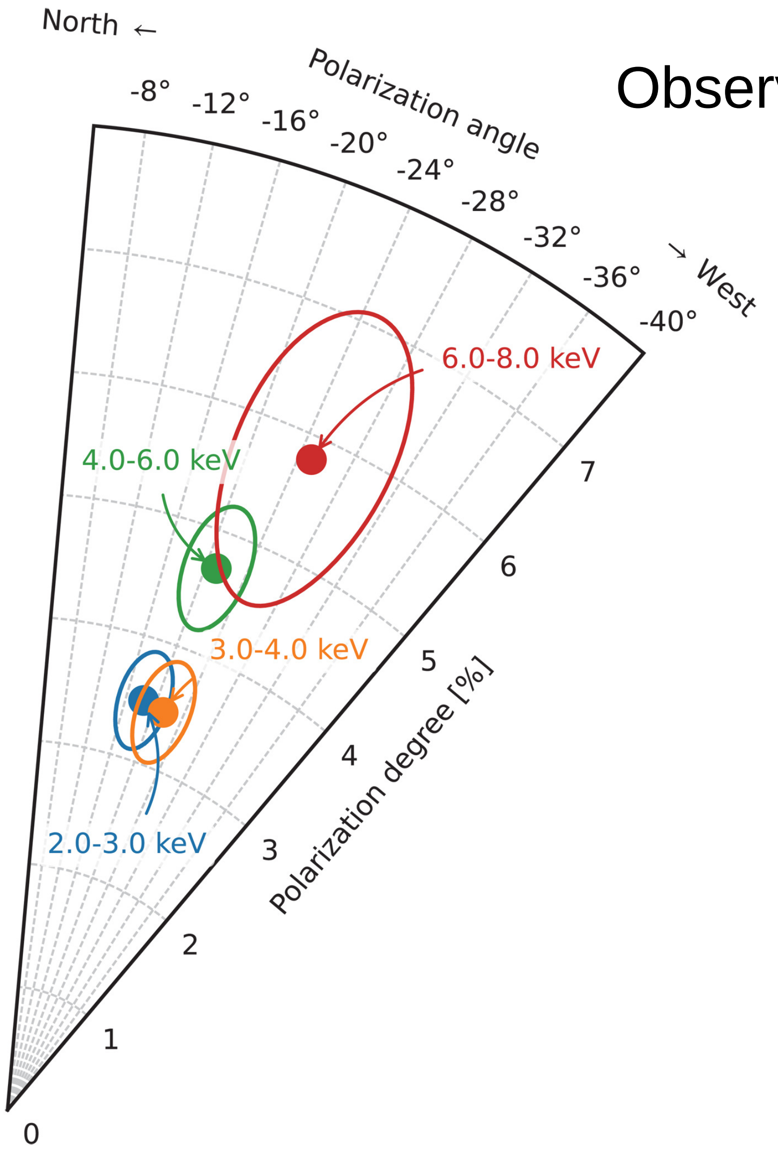
Principle of operation: when an X-ray photon is absorbed in the detector and an electron ejected (photoelectric effect), the direction of motion of the electron depends on polarization of the photon

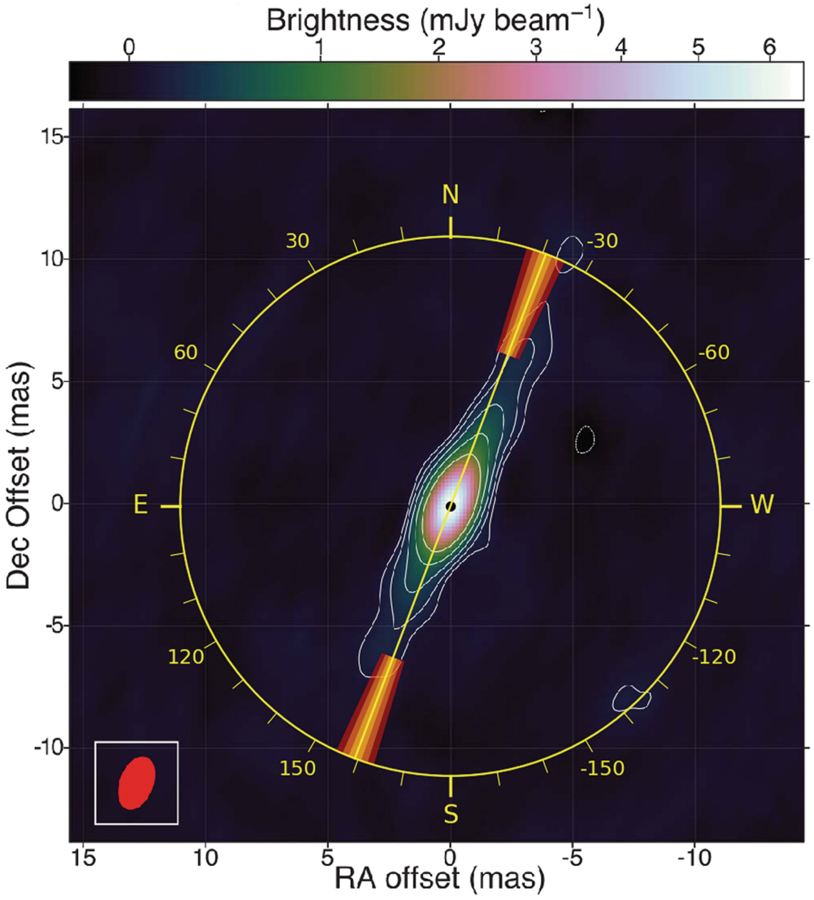
$$\frac{d\sigma}{d\Omega} \propto \cos^2\phi$$

Photoelectrons are preferentially emitted along the direction of polarization

Observations

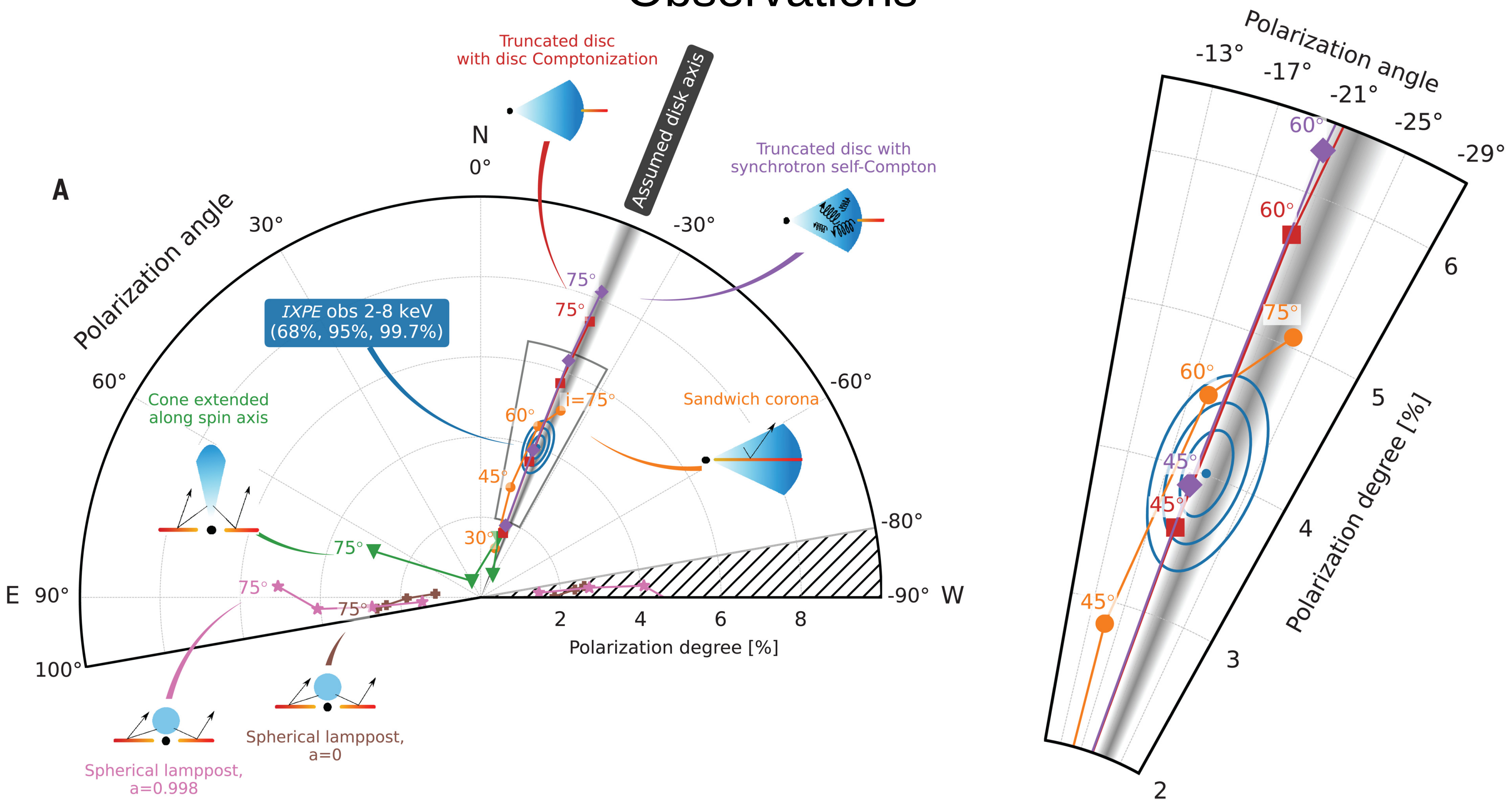
Cyg X-1





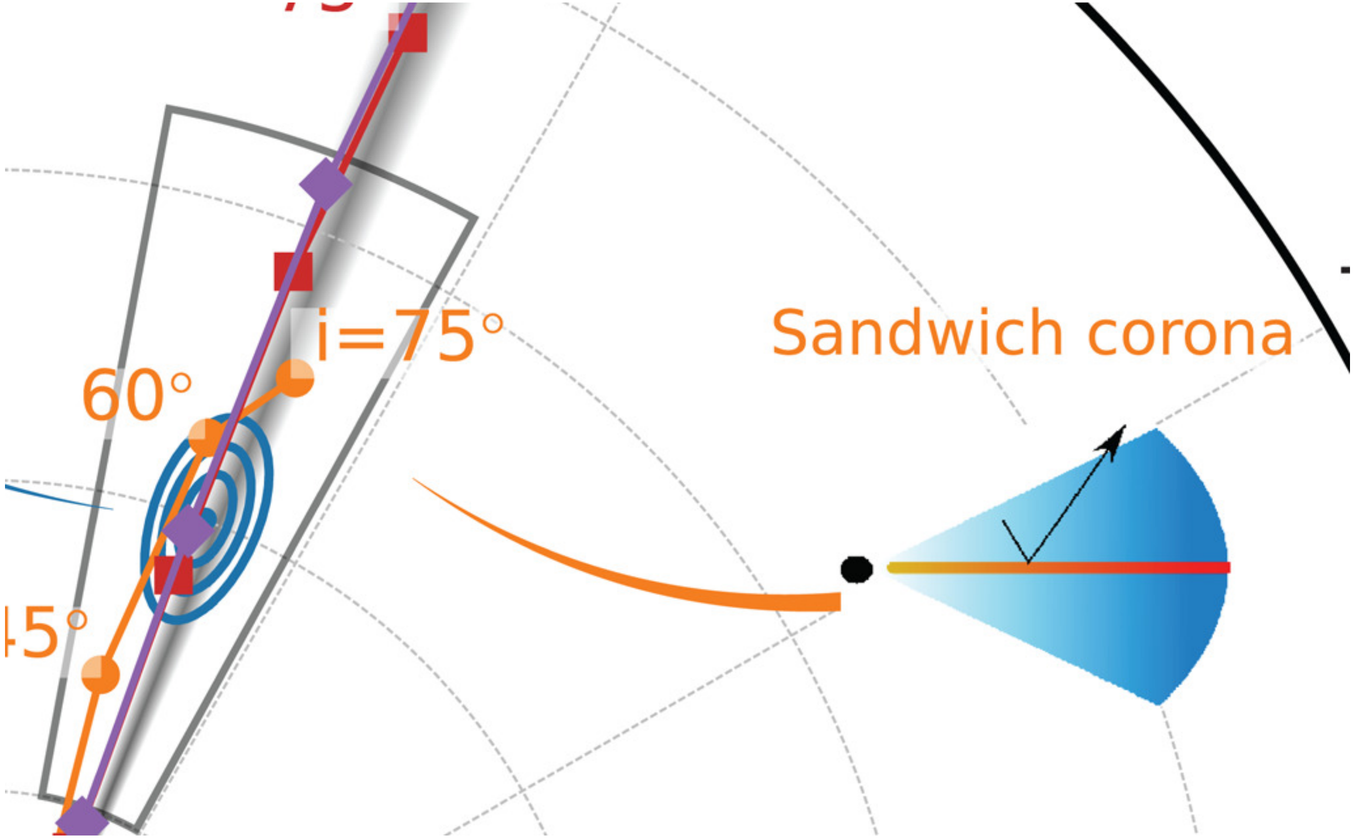
Krawczynski et al., 2022, Science, 378, 650

Observations



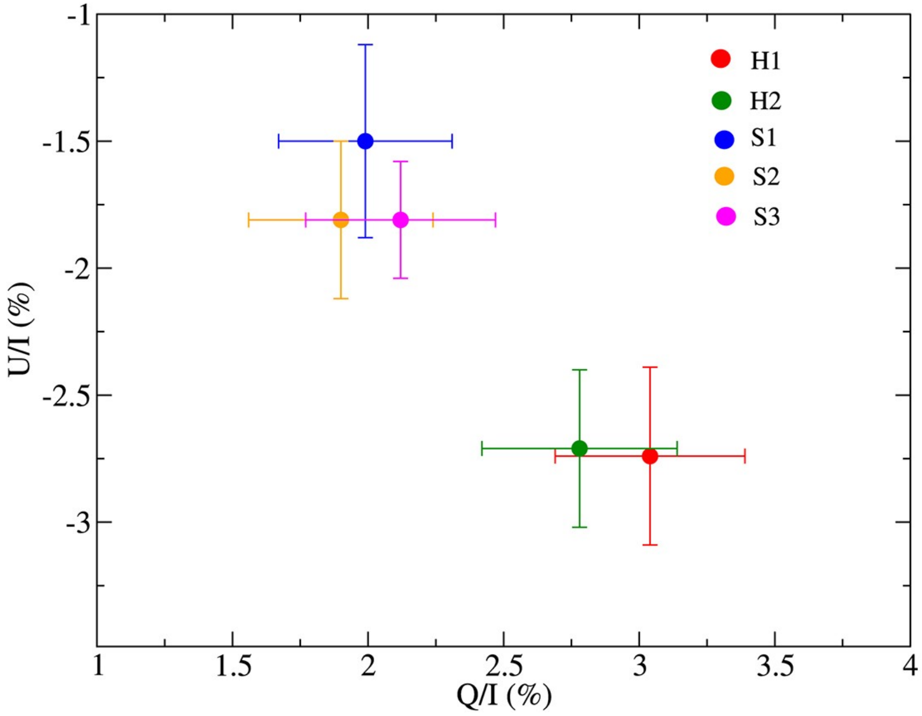
Krawczynski et al., 2022, Science, 378, 650

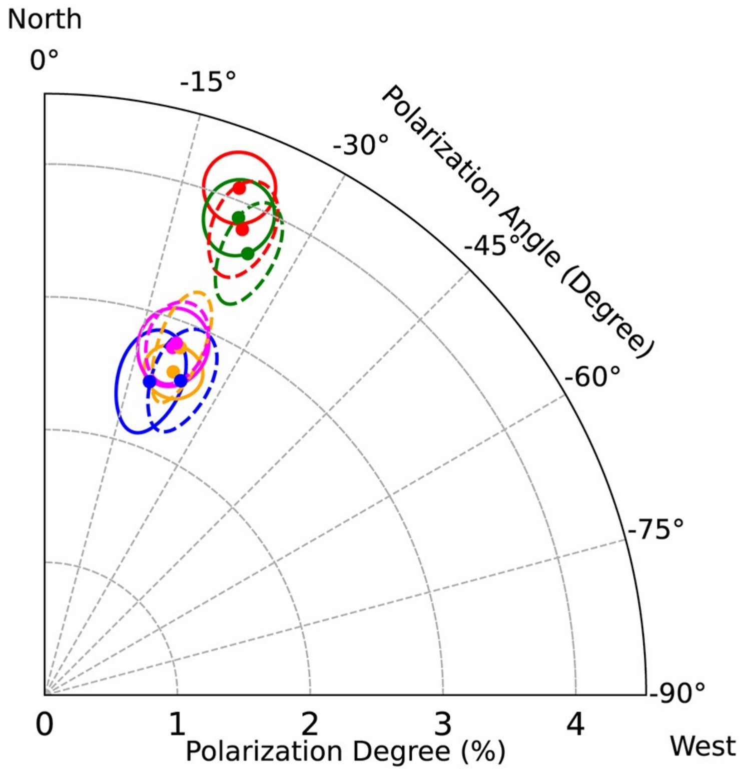
Observations



Krawczynski et al., 2022, Science, 378, 650

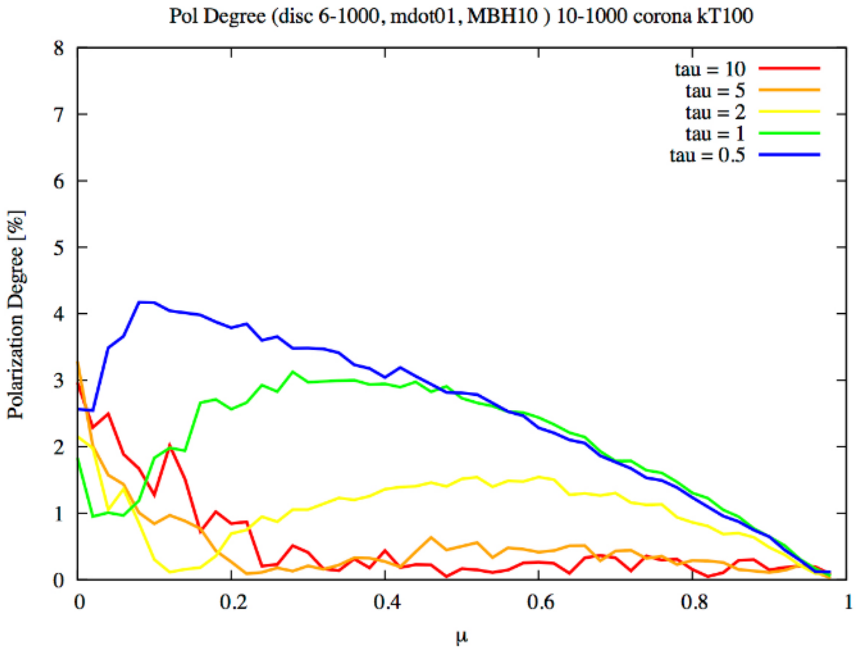
Observations – Cyg X-1, hard vs. soft state

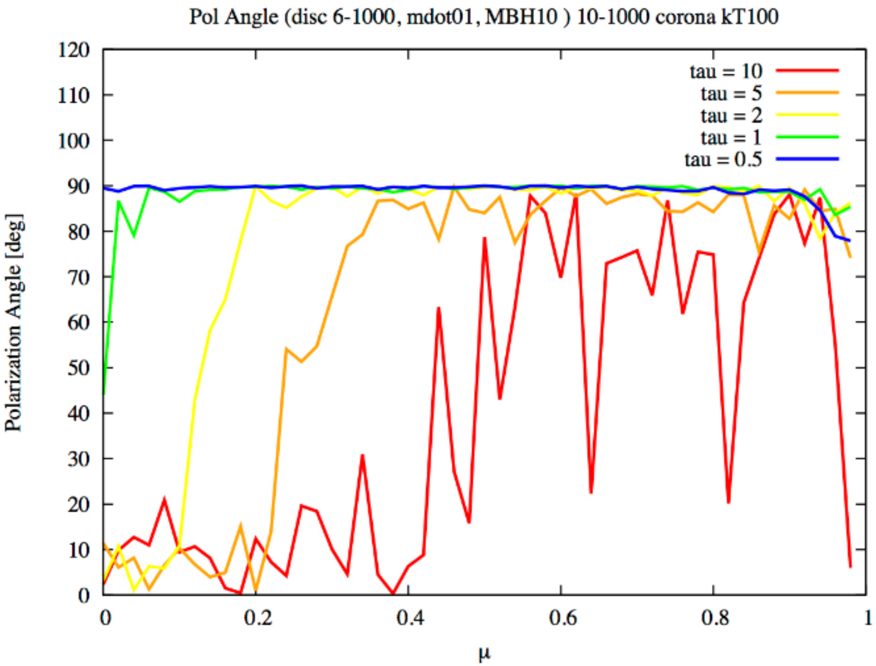




Jana & Chang, 2023, MNRAS, 527, 10837

Models: dependence on optical thickness





Tamborra et al., 2018, A&A, 619, A105

Observations – Cyg X-1, hard vs. soft state

Lower polarization degree in soft state, interpretation uncertain

Geometry: hard state – spherical, soft state – closer to plane parallel would imply

Lower polarization in hard state

Optical depth: hard state – larger, soft state – smaller, would imply

Lower polarization in hard state

Jana & Chang, 2023, MNRAS, 527, 10837

YouTube movies

https://www.youtube.com/watch?v=W1cTpqM9DaU

https://www.youtube.com/watch?v=Fu-aYnRkUgg

Aspects of X-ray data analysis for accreting compact objects: theory and results

1	October 7.	X	4	November 4.	X	7	December 2.	X	10	January 6.	another day	14	February 3.	X (?)
	October 14.	–		November 11.	–	8	December 9.	X	11	January 13.	X	15	February 10.	X
2	October 21.	X	5	November 18.	X	9	December 16.	X	12	January 20.	X			
3	October 28.	X	6	November 25.	X		December 23.	–	13	January 27.	X			
							December 30.	–						