X-ray polarization from Comptonizing inflows and outflows

Juri Poutanen
(University of Turku)

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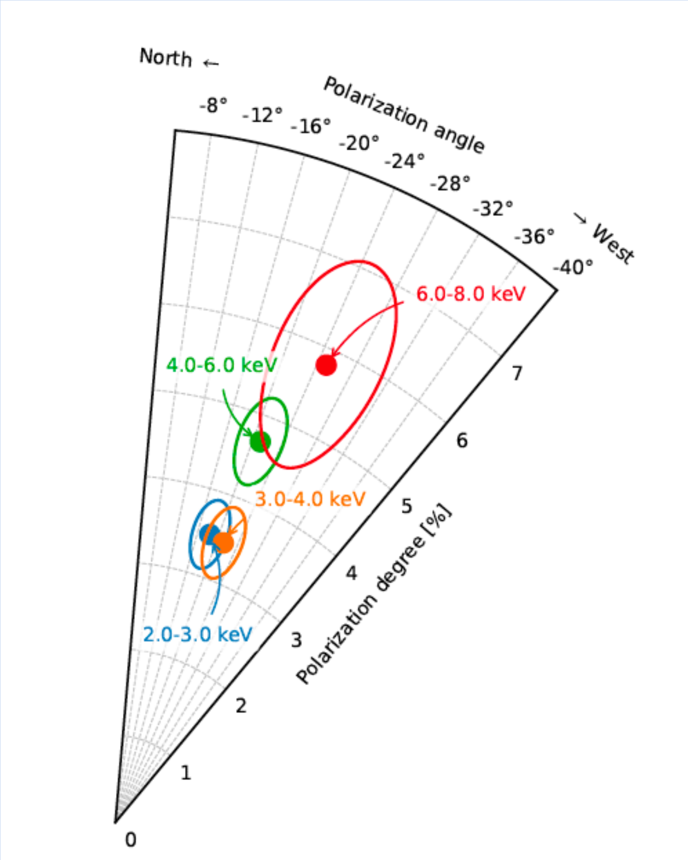
Sesto

Plan

1. Motivation: X-ray polarimetry of Cyg X-1 and Swift J1727.8−1613
2. Polarization from scattering in a static slab
3. Polarization from scattering in an outflow
4. Conclusions

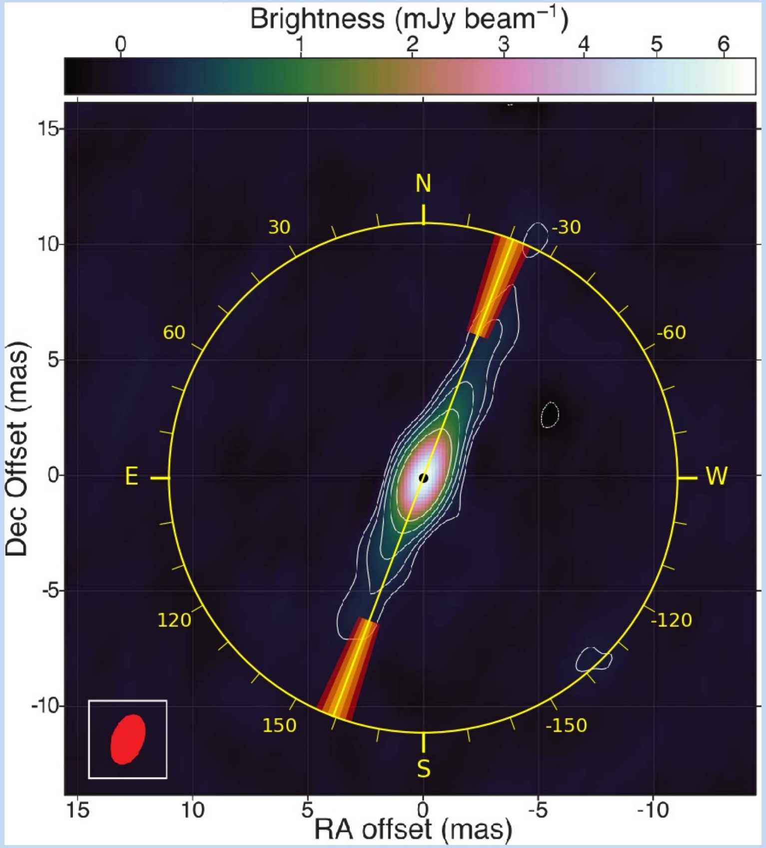
Cygnus X-1

IXPE observed Cyg X-1 in the hard state in May and June 2022.



PD = 4.0 ± 0.2 %
PA = −20.7 ± 1.4 deg

Krawczynski et al. 2022, Science

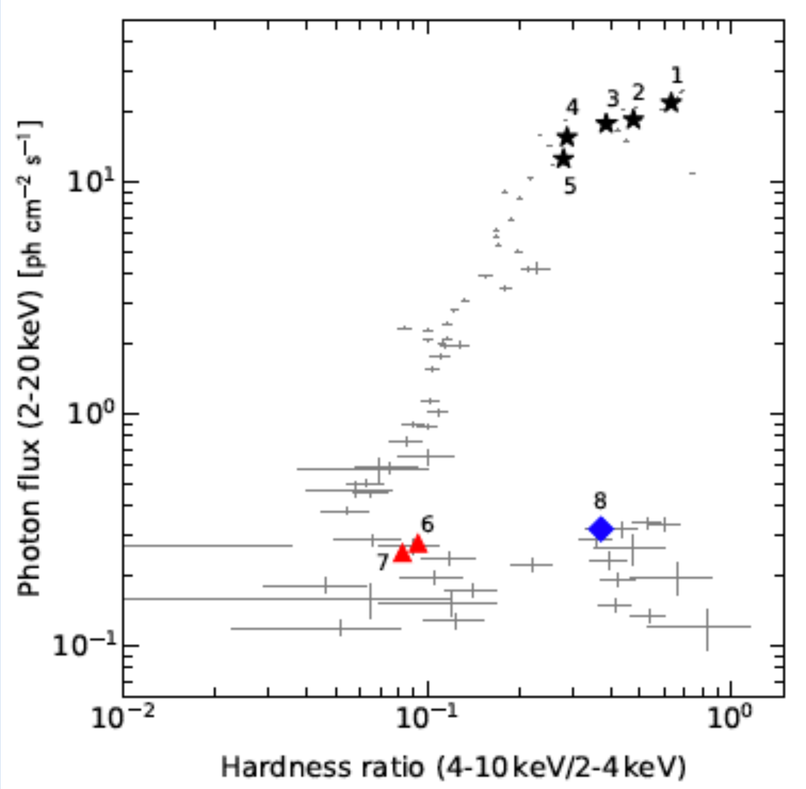


X-ray polarization
parallel to the jet

Inclination is 27.5 ±0.8 deg
(Miller-Jones et al. 2021).

Swift J1727.8−1613

IXPE observed Swift J1727.8−1613 in the rising and decaying hard state in September 2023 and April 2024, respectively.



1: PD = 4.1 ± 0.2 %

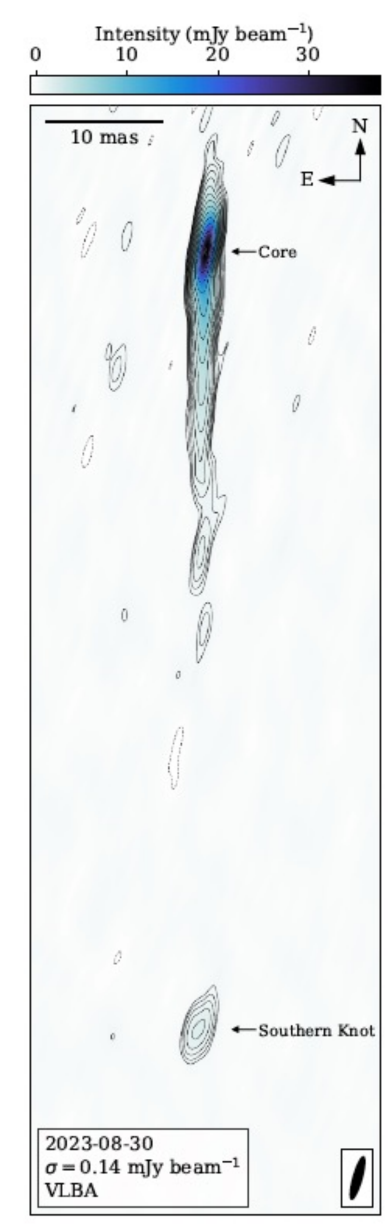
PA = 2.2 ± 1.3 deg

(Veledina et al. 2023)

8: PD = 3.3 ± 0.4 %

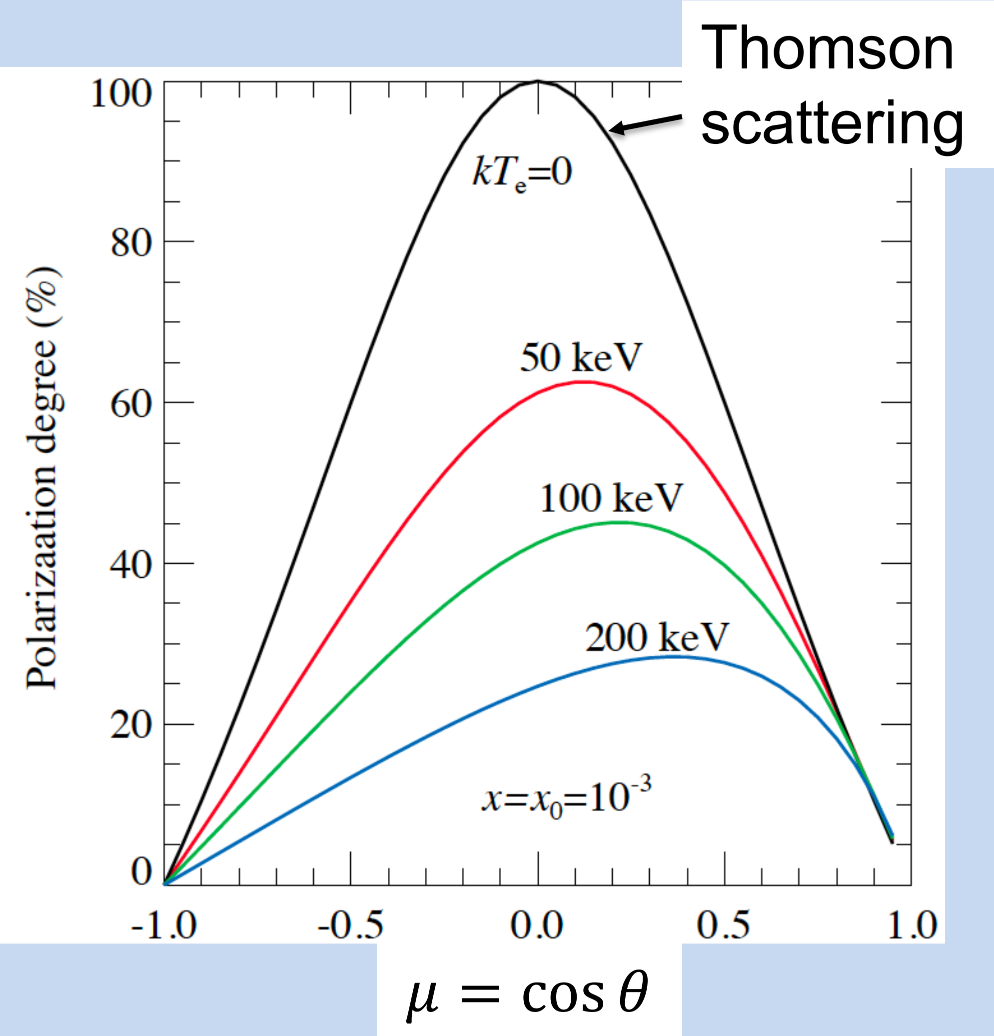
PA = 3 ± 4 deg

(Podgorny et al. 2024)



X-ray polarization parallel to the jet of position angle −0.60 ± 0.07 deg. Inclination is $27 < i < 37$ deg (Wood et al. 2024).

Compton scattering off hot electrons



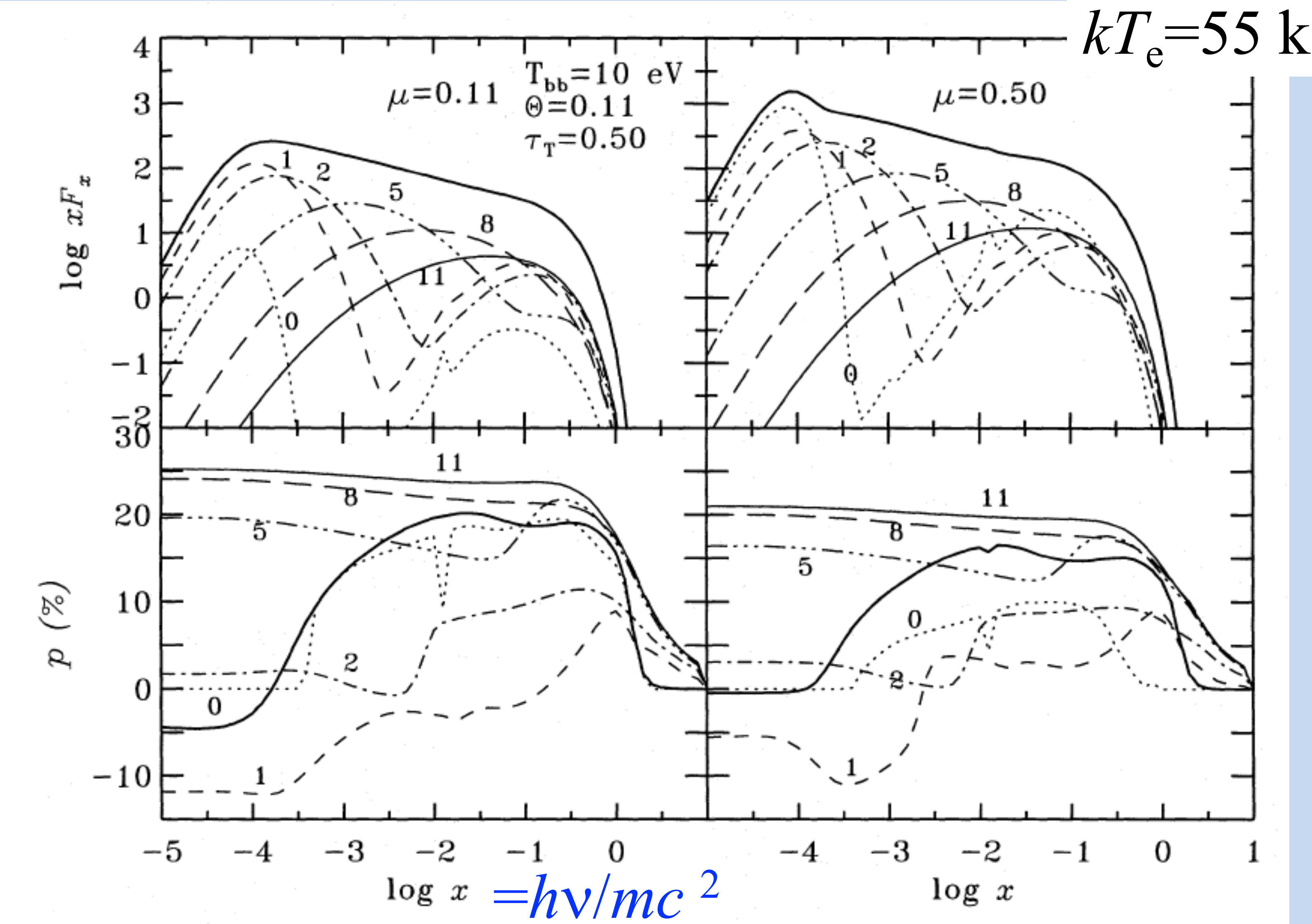
Thomson scattering

$\mu = \cos\theta$

Poutanen 1994

Comptonization in a slab (compps)

(Poutanen & Svensson 1996)



kT_e=55 keV

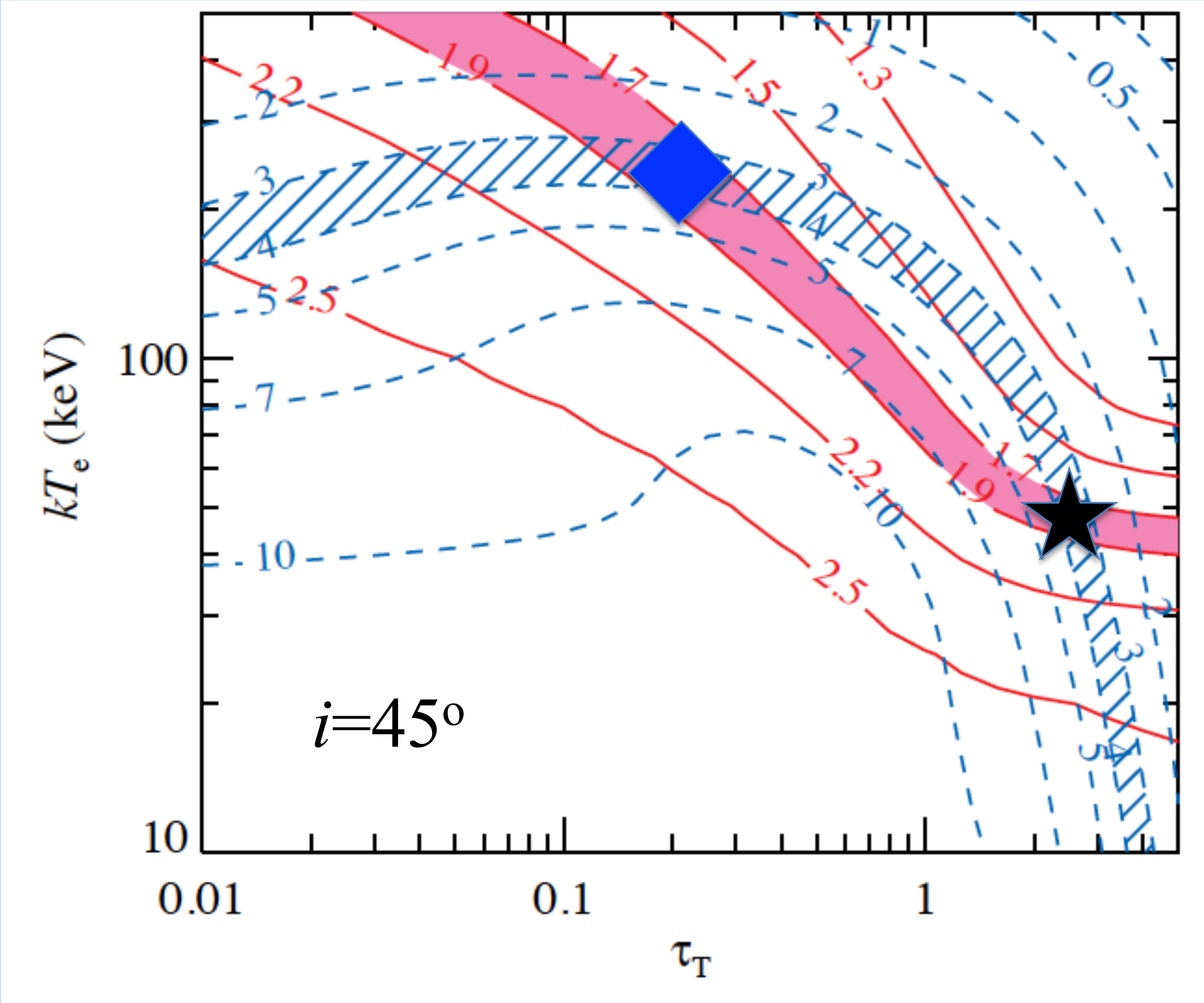
$=h\nu/mc^2$

Comptonization in a slab (compps)

Two solutions with the optical depth varying by factor of 10 when the flux varied by a factor of 100. Evidence for advective flow?

$$L \propto \dot{M}^2$$

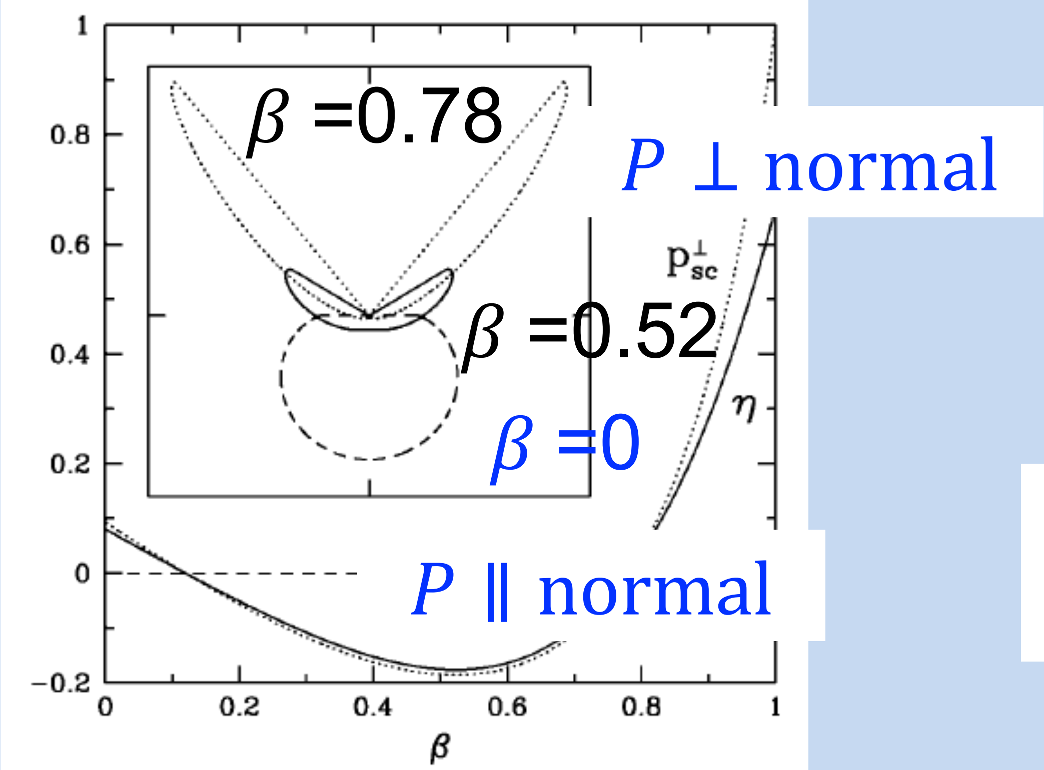
At smaller inclination, such a high PD cannot be achieved.



Polarizations from a dynamic corona

(Beloborodov 1998)

- Consider Thomson scattering in an optically thin outflow.
- Lower boundary condition: electron-scattering dominated disk.



$$p_{sc}(\mu) = \frac{3\,(1-\mu_c^2)\,\eta}{(8/3)+(3\mu_c^2-1)\,\eta},$$

$$\eta = \frac{I_2^c - (I_0^c/3) + Q_0 - Q_2}{I_0^c} \approx \frac{I_2^c}{I_0^c} - \frac{1}{3}$$

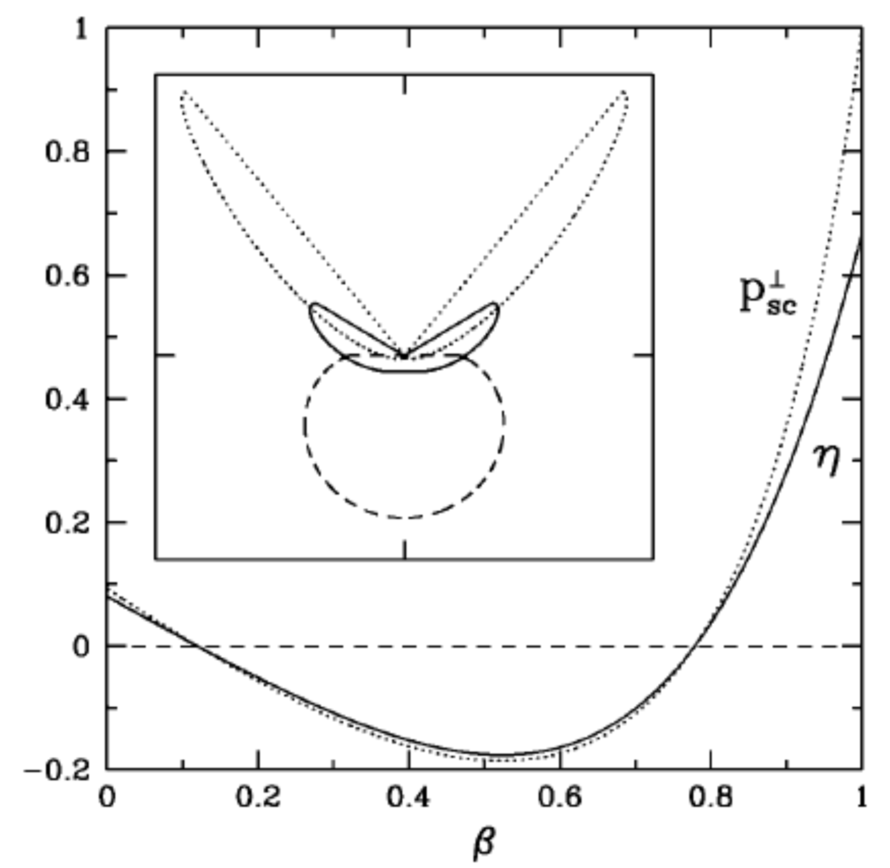
$$I_0^c = \gamma^2\,(I_0 - 2\beta I_1 + \beta^2 I_2)\,,\quad I_2^c = \gamma^2\,(\beta^2 I_0 - 2\beta I_1 + I_2)\,,$$

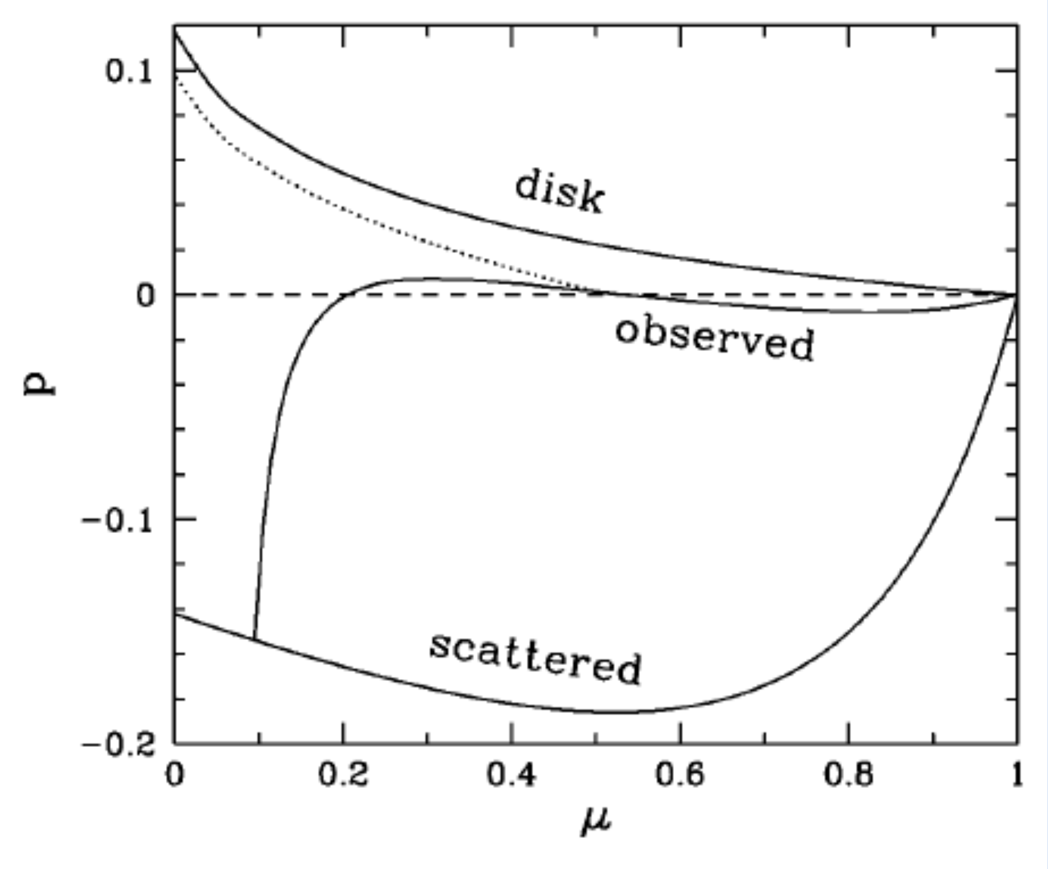
$$I_1^c = \gamma^2\,[-\beta\,(I_0 + I_2) + (1+\beta^2)\,I_1]\,.$$

Polarizations from a dynamic corona

(Beloborodov 1998)

- Consider Thomson scattering in an optically thin outflow.
- Polarization changes sign but the PD is low.

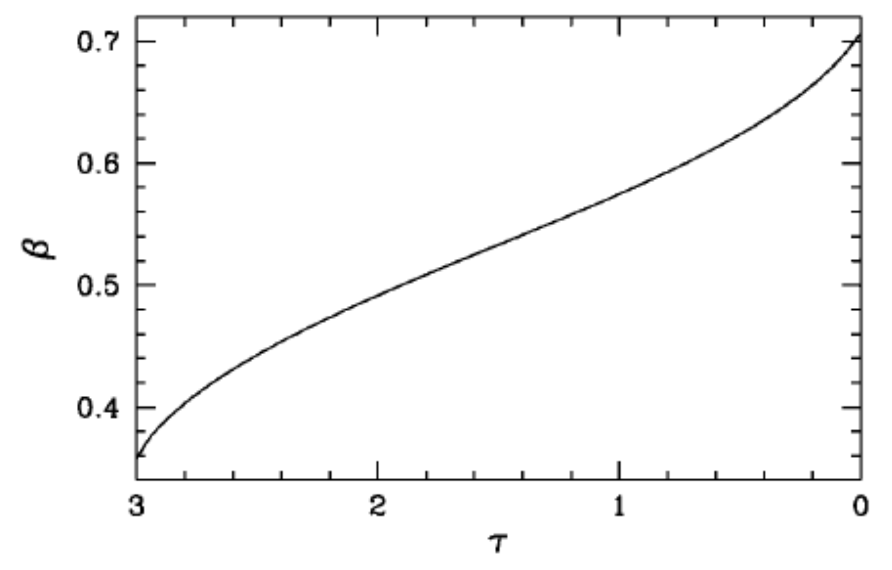


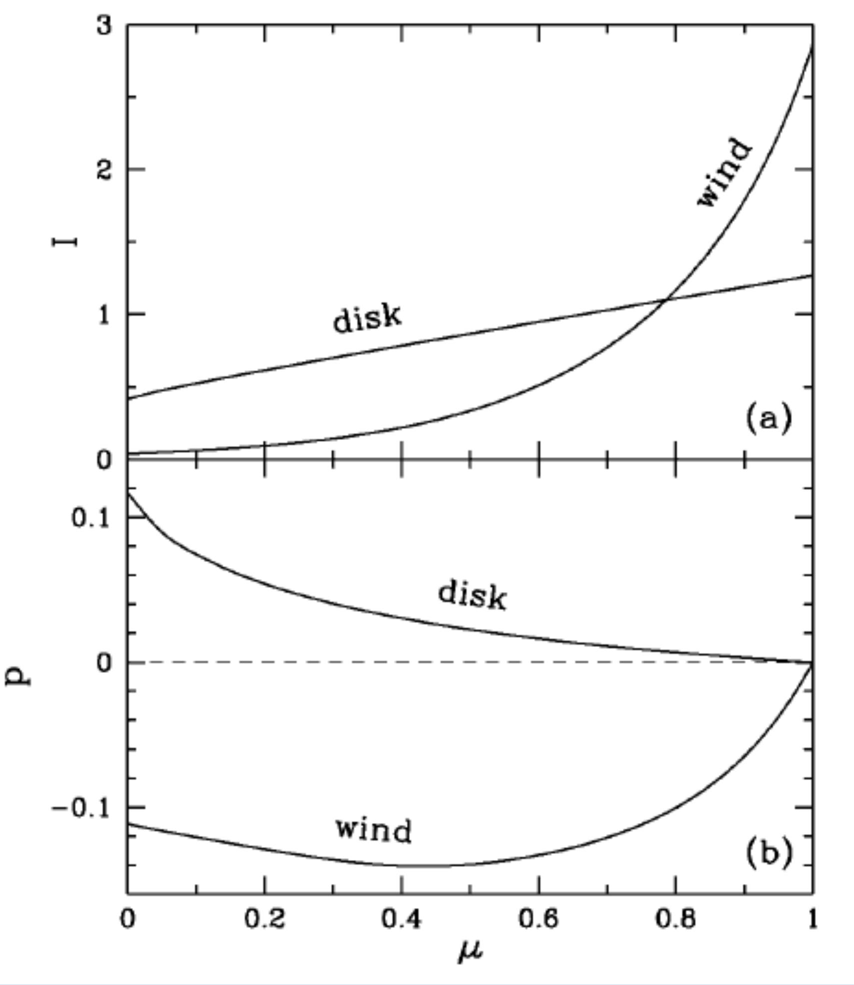


Polarizations from a dynamic corona

(Beloborodov 1998)

- Consider Thomson scattering in an optically thick outflow.





- Outflow of $e^{\pm}$ pairs in equilibrium with the radiation field.
- Polarization is perpendicular to the standard Chandrasekhar-Sobolev result.

Comptonization in a dynamic corona

(Poutanen, Veledina, Beloborodov 2023)

- We need to take into account motion of the gas. RTE:

$$\mu\frac{d\boldsymbol{I}^{\rm l}(\tau, x, \mu)}{d\tau} = [1-\beta(\tau)\mu][-\sigma(x_{\rm c})\boldsymbol{I}^{\rm l}(\tau, x, \mu) + \boldsymbol{S}^{\rm l}(\tau, x, \mu)]$$

- Source function in the lab frame $\boldsymbol{S}^{\rm l}(\tau, x, \mu) = \mathcal{D}^3\, \boldsymbol{S}^{\rm c}(\tau, x_{\rm c}, \mu_{\rm c})$.
- Doppler factor $\mathcal{D} = 1/[\gamma(1-\beta\mu)]$
- Aberration formula $\mu_{\rm c} = \frac{\mu-\beta}{1-\beta\mu}, \qquad \mu = \frac{\mu_{\rm c}+\beta}{1+\beta\mu_{\rm c}}$.
- Source function in comoving frame

$$\boldsymbol{S}^{\rm c}(\tau, x_{\rm c}, \mu_{\rm c}) = x_{\rm c}^2 \int_0^\infty \frac{dx'_{\rm c}}{x'^2_{\rm c}} \int_{-1}^{1} d\mu'_{\rm c} \times \boldsymbol{R}(x, \mu; x'_{\rm c}, \mu'_{\rm c})\boldsymbol{I}^{\rm c}(\tau, x'_{\rm c}, \mu'_{\rm c}) = \mathcal{R}\boldsymbol{I}^{\rm c}$$

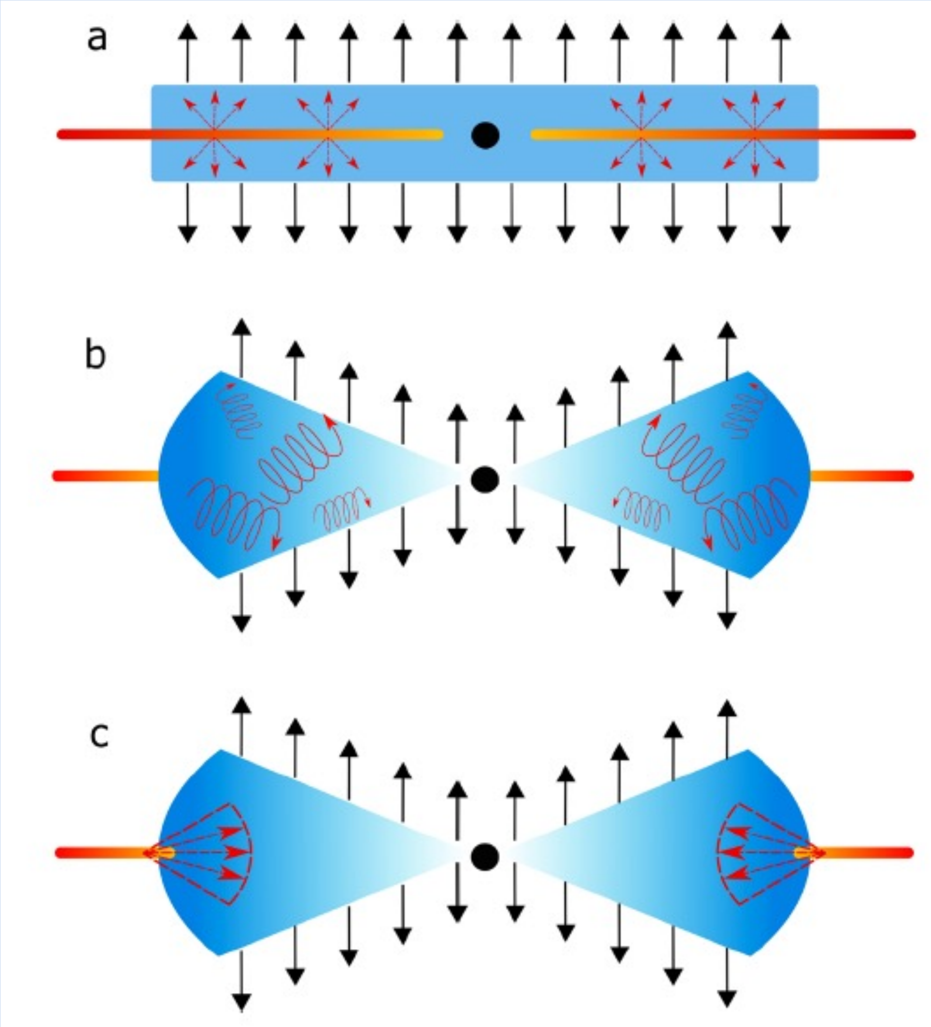
- Intensity in comoving frame $\boldsymbol{I}^{\rm c}(\tau, x_{\rm c}, \mu_{\rm c}) = \mathcal{D}^{-3}\, \boldsymbol{I}^{\rm l}(\tau, x, \mu)$.

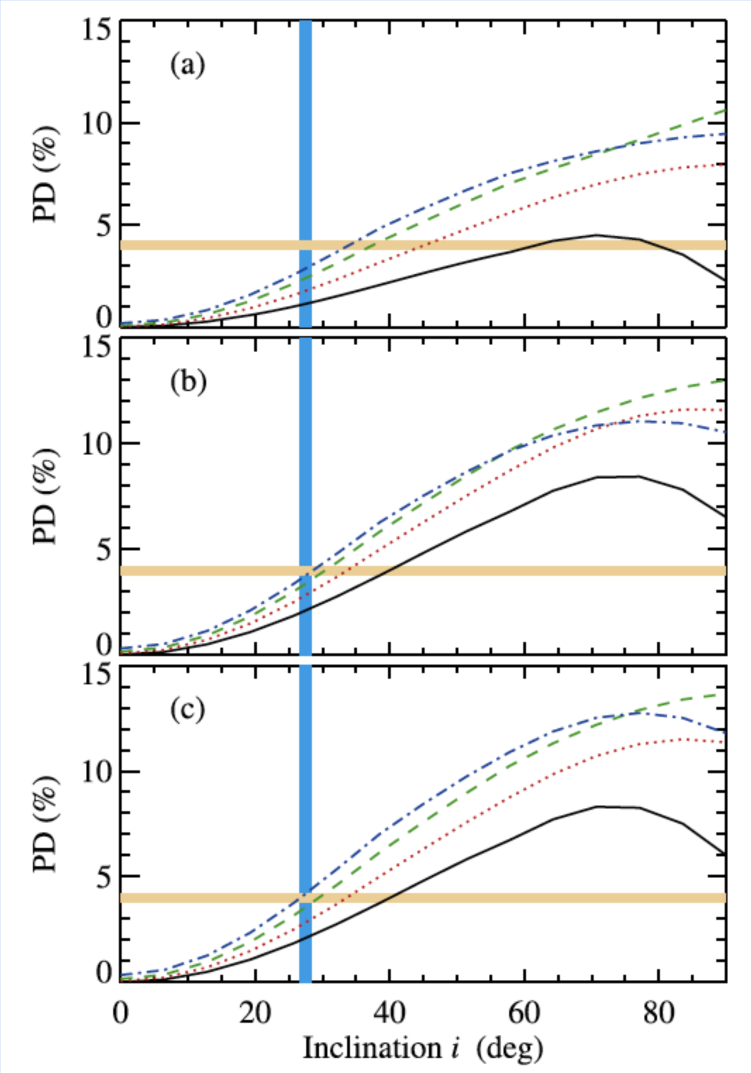
Comptonization in a dynamic corona

(Poutanen, Veledina, Beloborodov 2023)

$\beta(\tau) = \beta_0(\tau/\tau_0)$

Three geometries:





β_0	
0	——
0.2	········
0.4	- - - -
0.6	-·-·-·-

Comptonization in a dynamic corona

(Poutanen, Veledina, Beloborodov 2023)

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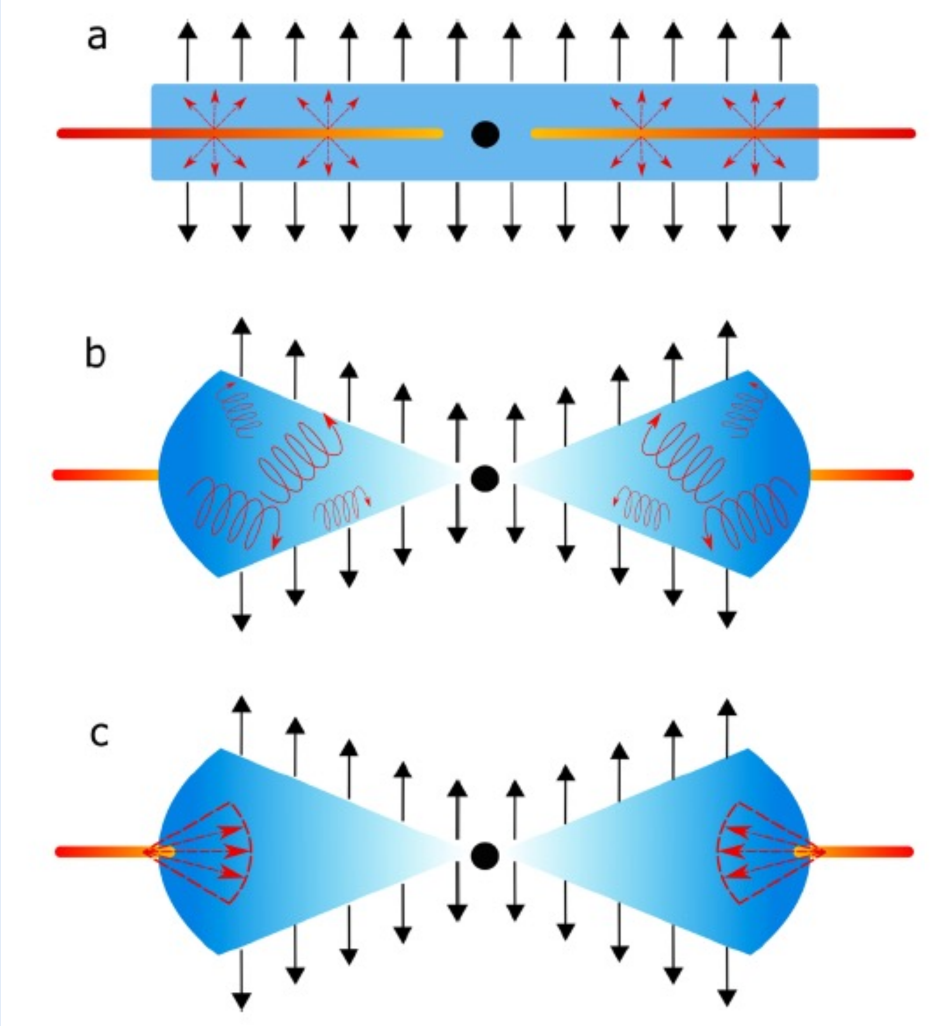

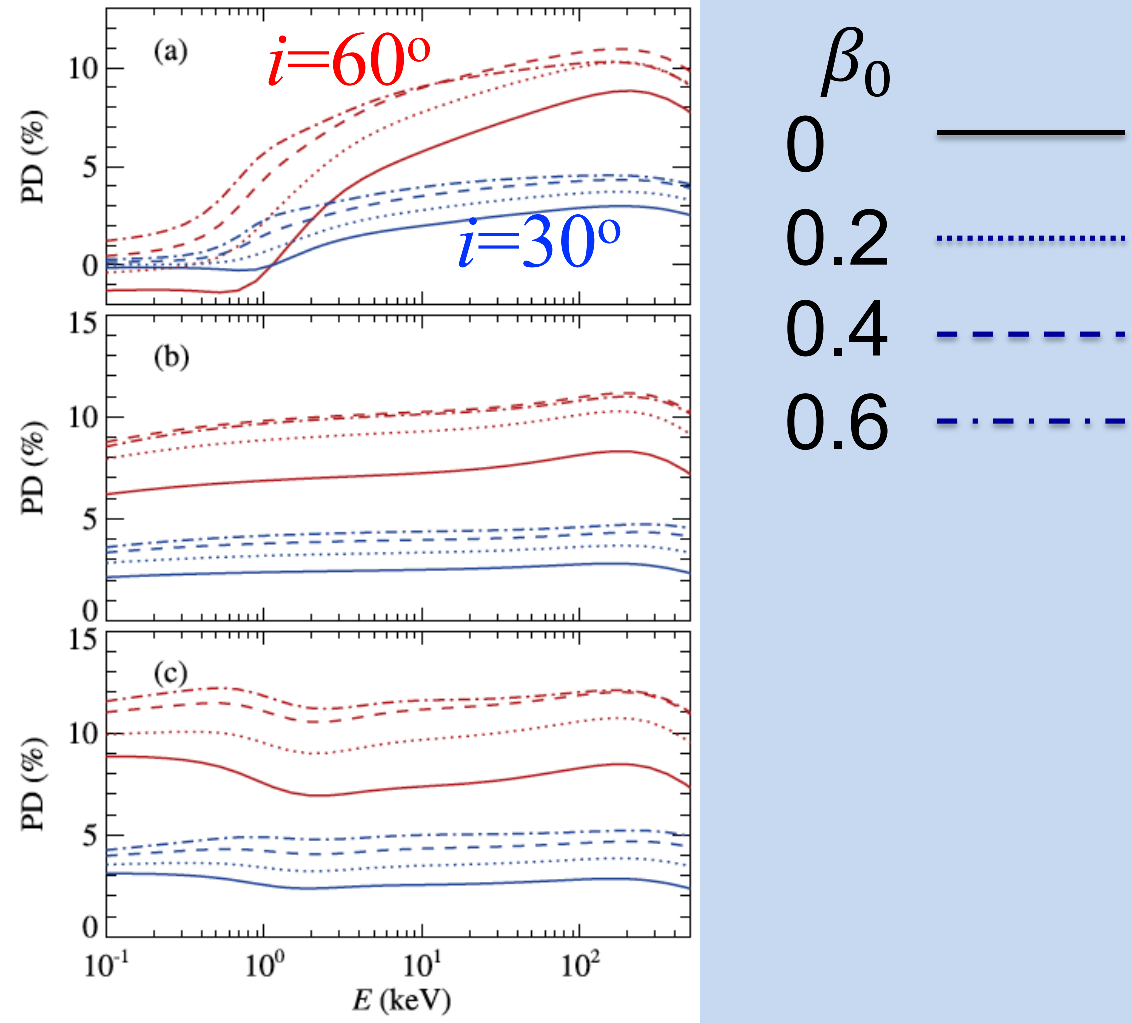

Conclusions

- 4% PD from accreting black holes observed at 30 deg inclination cannot be achieved in a static corona.
- Mildly relativistic outflow affects the angular distribution of seed photons in the gas frame producing polarization of scattered radiation parallel to the flow.
- Relativistic aberration leads to a higher PD at lower inclination.