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X-ray polarization from hybrid electrons in coronae of accreting black holes

Juri Poutanen
(University of Turku, Finland)

Imaging X-ray Polarimetry Explorer
IXPE
NASA • MSFC • ASI • INAF • INFN • Ball • OHB-I • LASP • MIT • Stanford • Roma Tre • Nagoya

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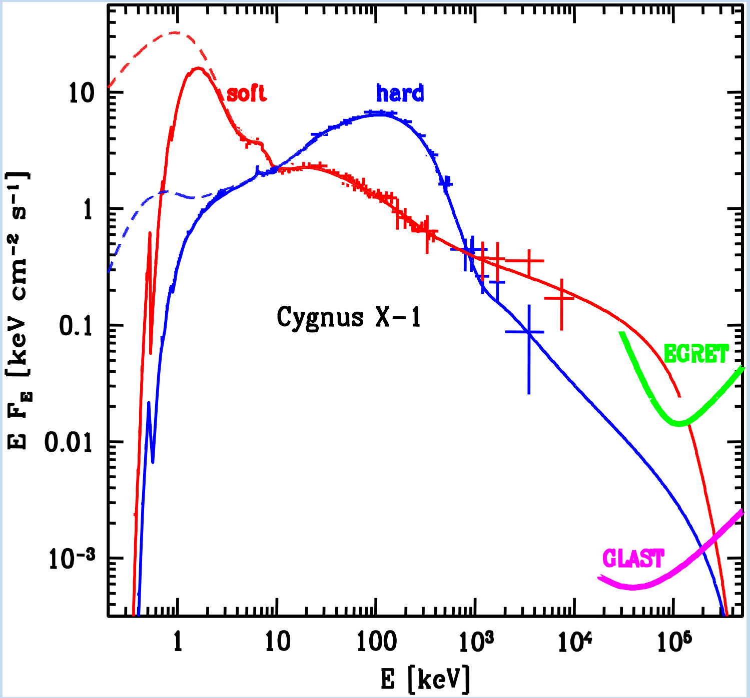
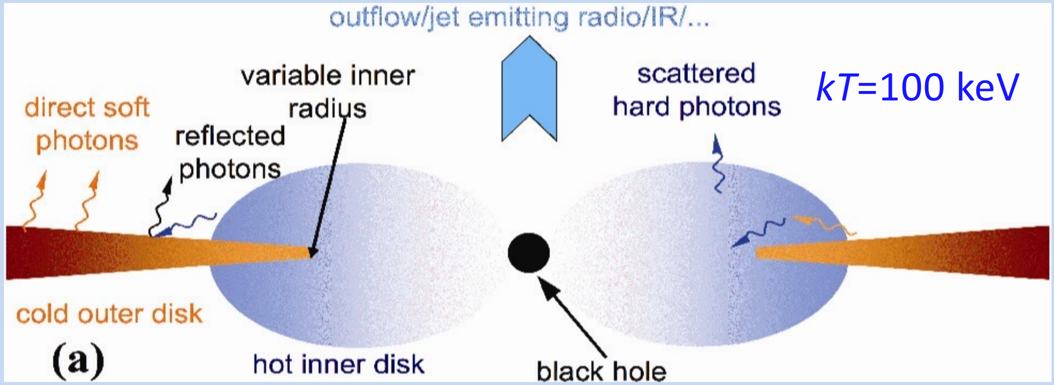
Cefalu, Tomaso Belloni memorial meeting

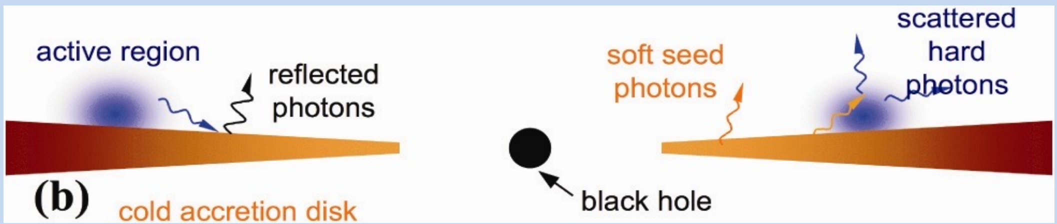
A standard paradigm:
hot accretion flow and cold disc



hard state



soft state



Hard state - standard cold outer disc + hot inner flow

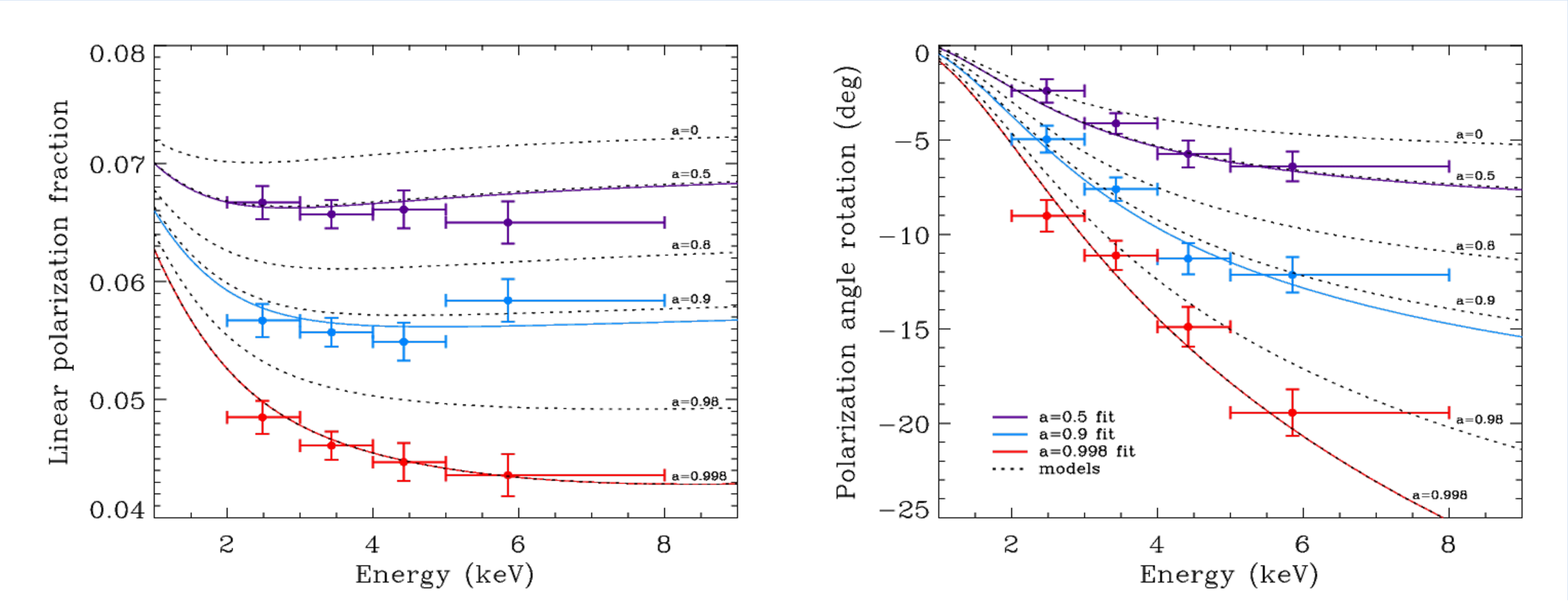
Soft state - standard accretion disc plus nonthermal corona

Poutanen et al. 1997, Esin et al. 1997, Zdziarski & Gierlinski 2004, Done et al. 2007

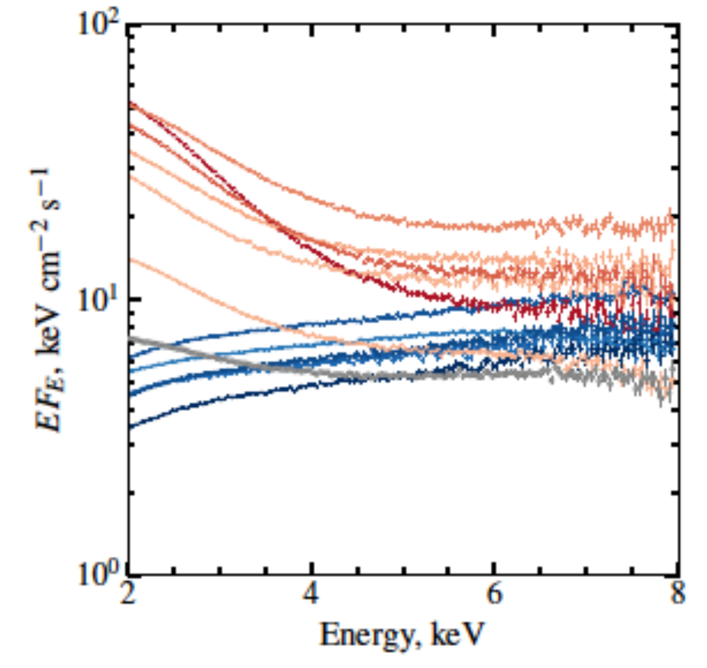
Soft state

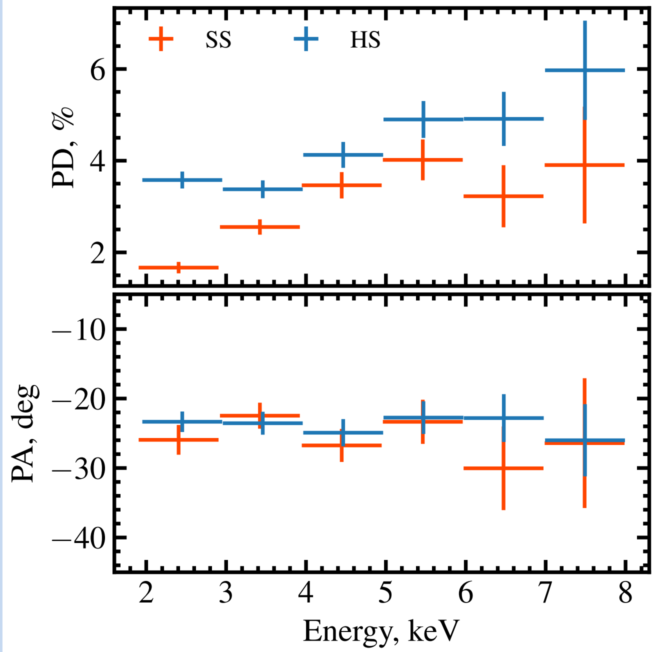
- **Polarization angle was predicted (Connors et al. 1980, Dovciak et al. 2008) to show strong energy dependence.**
- **The amplitude depends on the black-hole spin**
  - Scattering polarizes the thermal disk emission
  - Polarization rotation is greatest for emission from inner disk
    - Inner disk is hotter, producing higher energy X-rays
  - Priors on disk orientation constrain the black hole spin
    - a = 0.50±0.04; 0.900±0.008; 0.99800±0.00003 (200-ks observation)

Polarization angle along the disk surface!



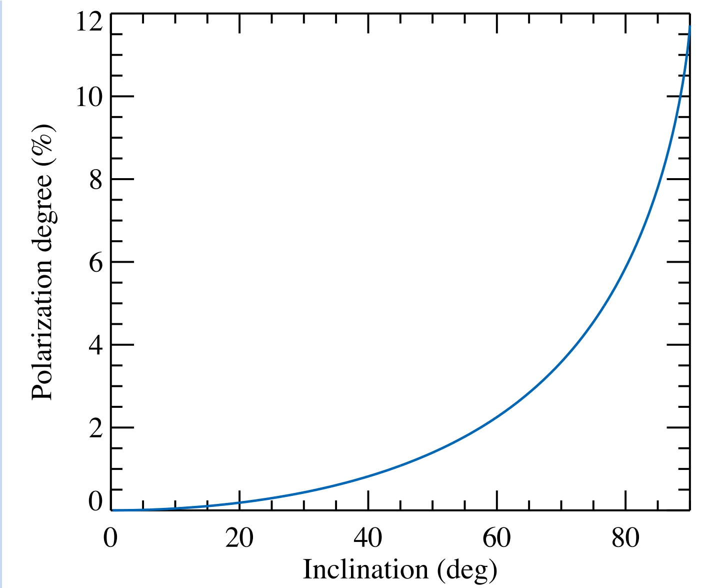
Hard - soft state comparison: Cyg X-1



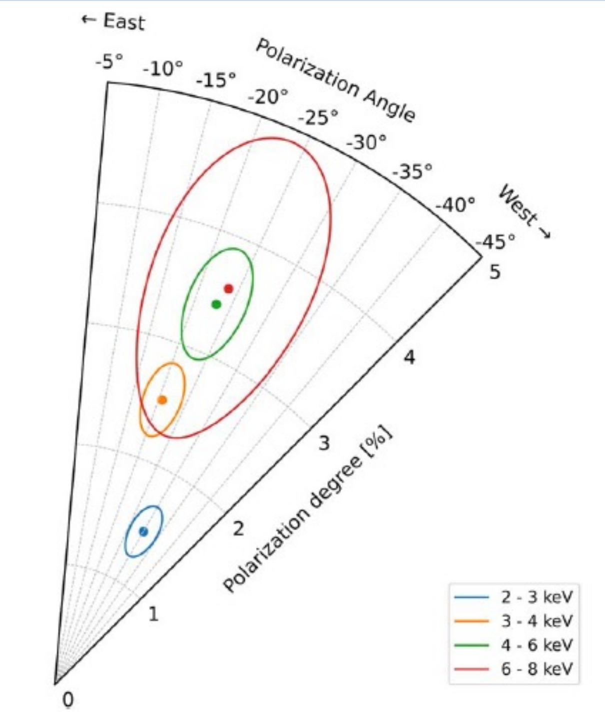


Kravtsov et al. (2025)

- **In the soft state polarization degree drops.**
- **It is not surprising: the PD is the electron-scattering dominated atmosphere is very low at small inclinations ----------->>>>>>>>>>>>>>**
- **However, polarization angle is the same as in the hard state, i.e. parallel to the jet.**
- **And no energy dependence is observed.**

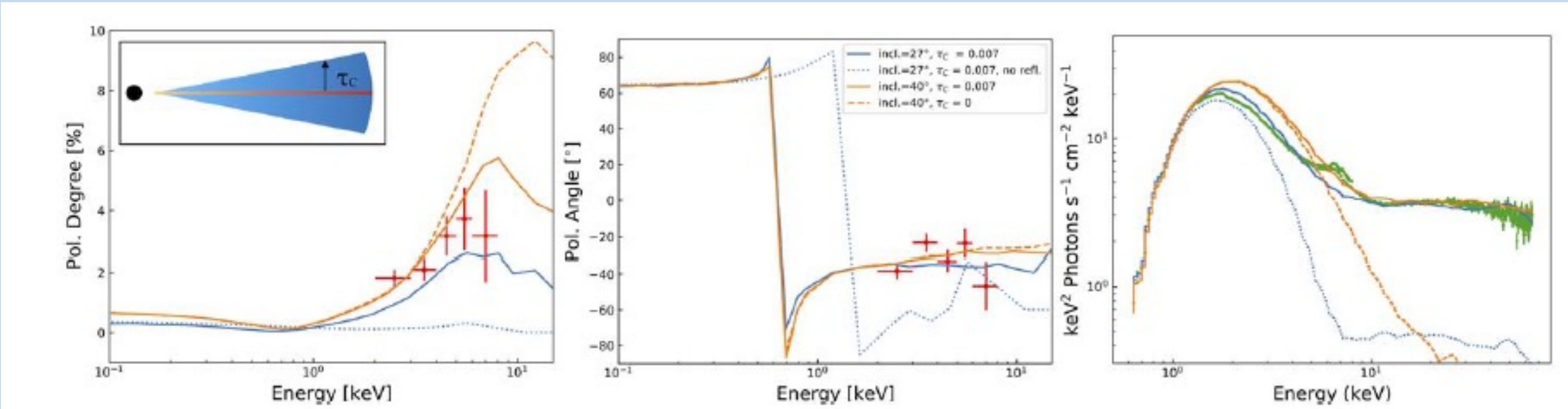


Soft state: Cygnus X-1

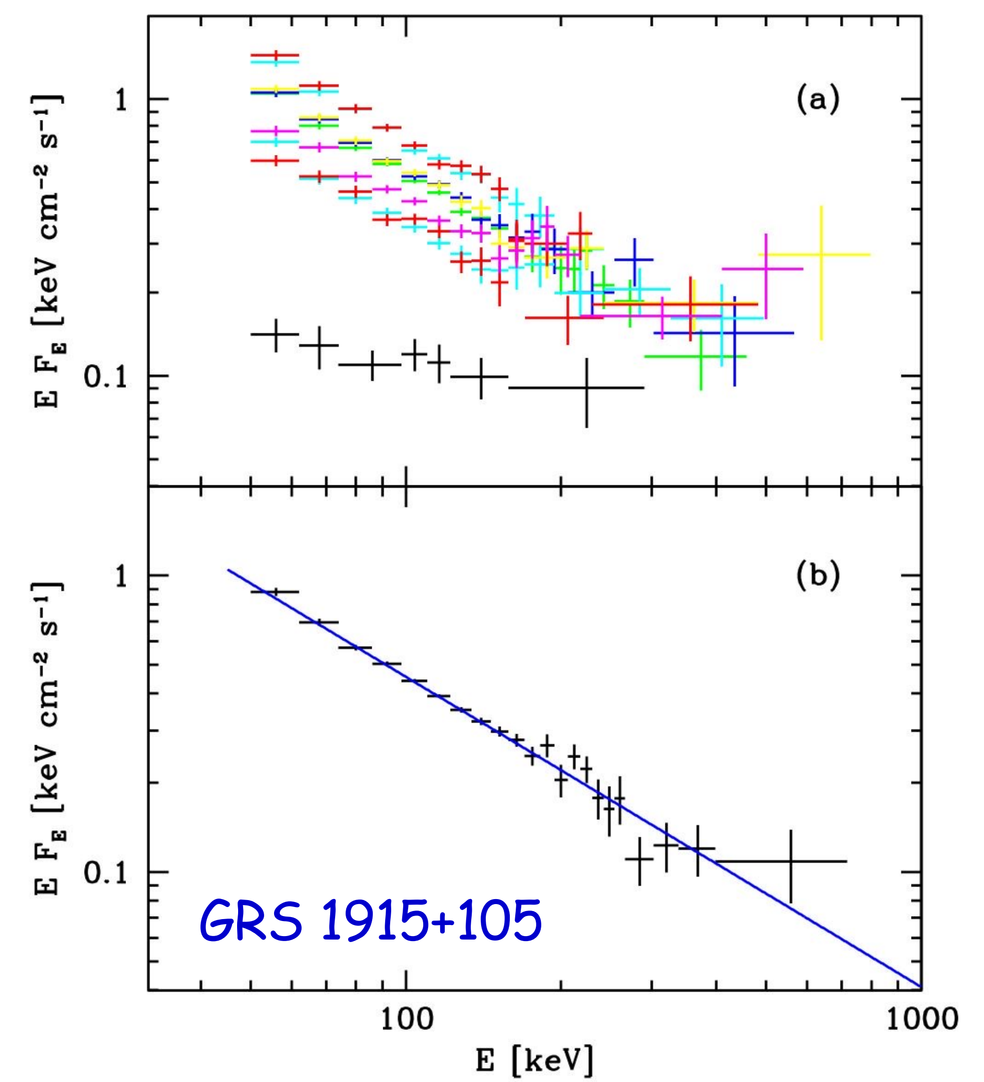


- **PD grows with energy.**
- **Steiner et al. 2024 modeled the SED and polarization using kerrC model assuming spin a=0.998, disk albedo =1.**
- **Returning radiation was found to dominate the polarization signal.**
- **Or rather reflection of Comptonized radiation (kT_e=250 keV) from a fully ionized disc.**

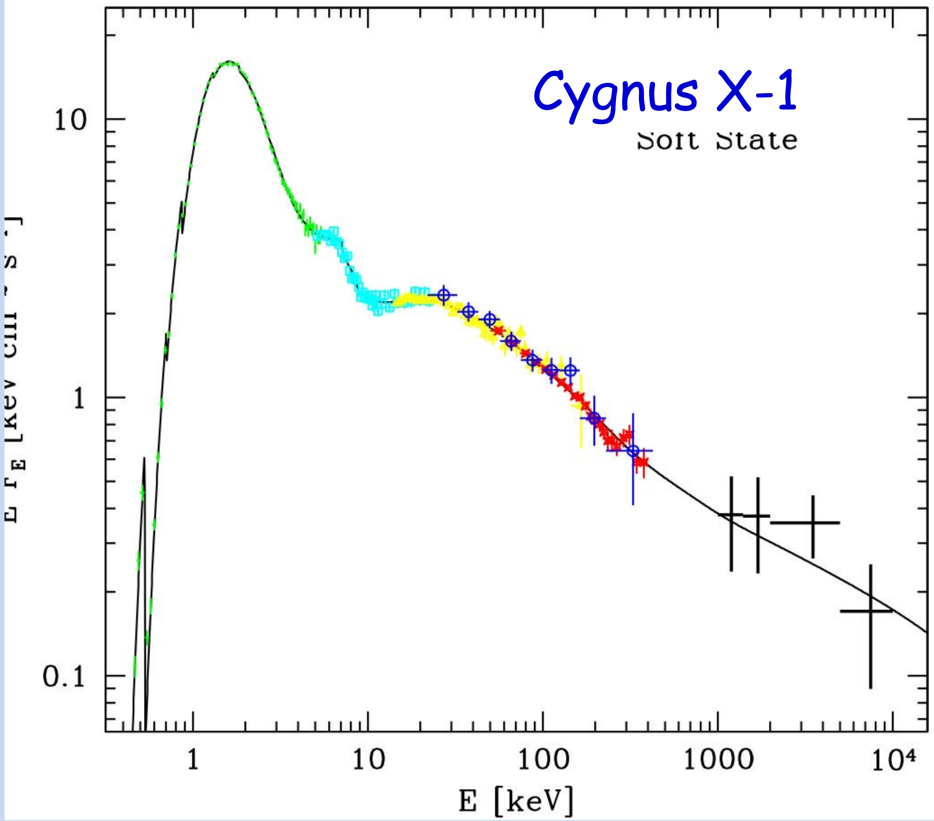
- **A reasonable fit was obtained for an inclination i=40^o.**



Non-thermal tails in soft states



Zdziarski et al. 2001



McConnell et al. 2002

Electron distribution

- **Around accreting bright black holes, accelerated (by shocks, turbulence, magnetic reconnection) electrons should cool down rapidly.**
- **What would be their steady-state distribution?**
- **Power-law with index larger by 1 than the injection index? Yes, at high-energies…**
- **But what happens when electrons cool down to $\gamma \sim 1$. Will the power-law continue there?**
- **Other processes start to interfere: Coulomb collisions, synchrotron self-absorption.**

Electron cooling

- **Escape time is larger than light-crossing time**

$$t_{esc} > R/c$$

- **Cooling is determined by synchrotron and Compton:**

$$t_{cool} \approx \frac{R}{c}\frac{1}{\gamma}\frac{1}{(l + l_B)} << \frac{R}{c} < t_{esc}$$

$l_B \equiv U_B R \dfrac{\sigma_T}{m_e c^2}$ - magnetic compactness parameter

$l \equiv \dfrac{L}{R}\dfrac{\sigma_T}{m_e c^3}$ - radiation compactness parameter

$$\boxed{l = 10 \frac{L}{0.03 L_{Edd}} \frac{30 R_S}{R}}$$

Cooling is faster than escape for any Lorentz factor γ at $l > 1$ or $l_B > 1$

Thermalization by Coulomb collisions

- **Cooling** $\dot{\gamma}_{Compton} \propto (\gamma\beta)^2, \quad \dot{\gamma}_{synchrotron} \propto (\gamma\beta)^2$

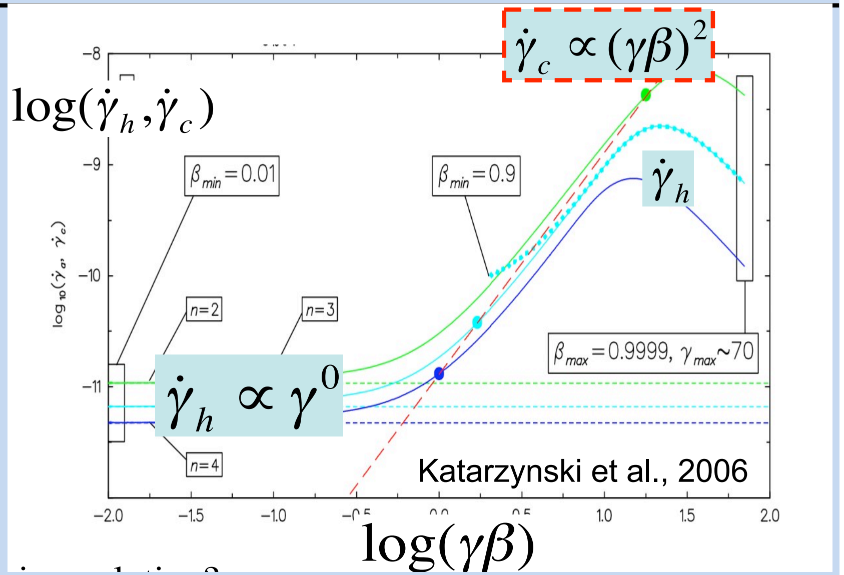
- **Rate of energy exchange with low-energy thermal pool of electrons** $\dot{\gamma}_{Coulomb} \propto \gamma^0 n_e \ln\Lambda$

- **Thermalization happens at low energies**

$$\dot{\gamma}_{Compton} + \dot{\gamma}_{synchrotron} < \dot{\gamma}_{Coulomb} \Rightarrow (\gamma\beta)_{th} < \left[\ln\Lambda \frac{\tau_T}{l_B + l_{rad}}\right]^{1/2} \approx 1$$

- **Anything else? We forgot about magnetic fields…**

Thermalization by synchrotron self-absorption



- **Assume power-law distribution**

$$N_e(\gamma) \propto \gamma^{-n}$$

- **Electron heating in self-absorption regime at $\gamma \gg 1$**

$$\dot\gamma_h \propto (\gamma\beta)^2$$

- **Electron cooling**

$$\dot\gamma_c \propto (\gamma\beta)^2$$

- **Ratio of heating to cooling**

$$\boxed{\frac{\dot\gamma_h}{\dot\gamma_c} = \frac{5}{n+2}}$$

γ^{-3} is a solution?

"Turbulent plasma reactor"- Kaplan, Tsytovich
It is not a solution! Rees 1967, McCray 1969, Ghisellini et al. 1988

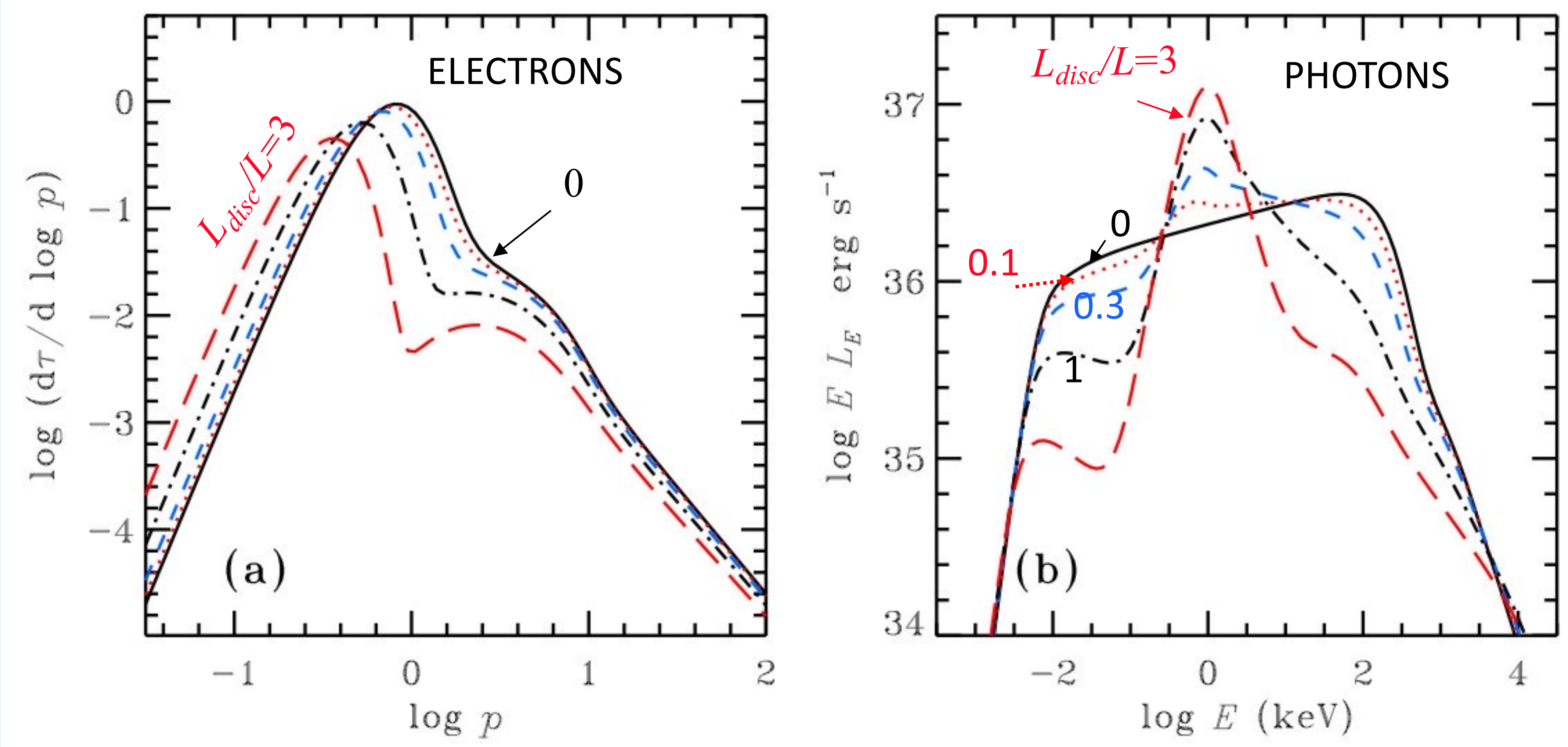
- **In non-relativistic regime**

$$\dot\gamma_h \propto \gamma^0 = \text{const}$$

- **Thus, at low energies heating always dominates**

Ghisellini et al. 1988, 1998, Poutanen & Vurm 2009, Malzac & Belmont 2009

Photon and electron distributions at state transitions



$L = 10^{37}$ erg/s, $\Gamma_{inj} = 3.0$, $\tau_T = 1.5$, $l_B / l = 1$

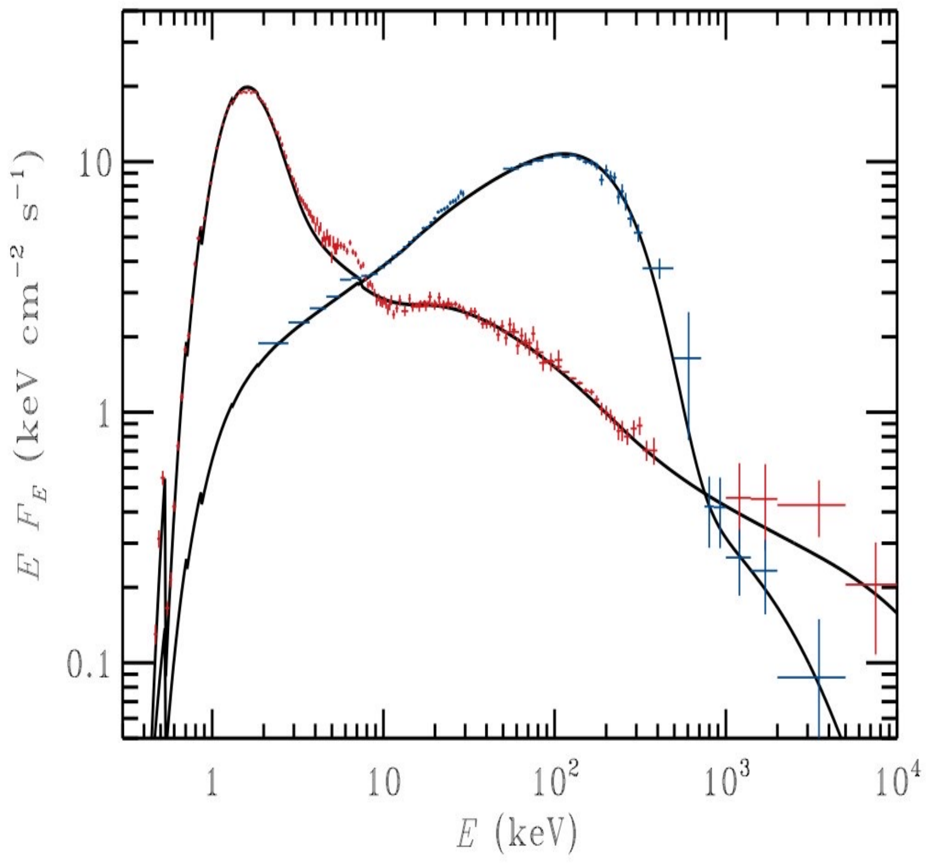
$L_{disc} / L = 0, \quad 0.1, \quad 0.3, \quad 1, \quad 3$

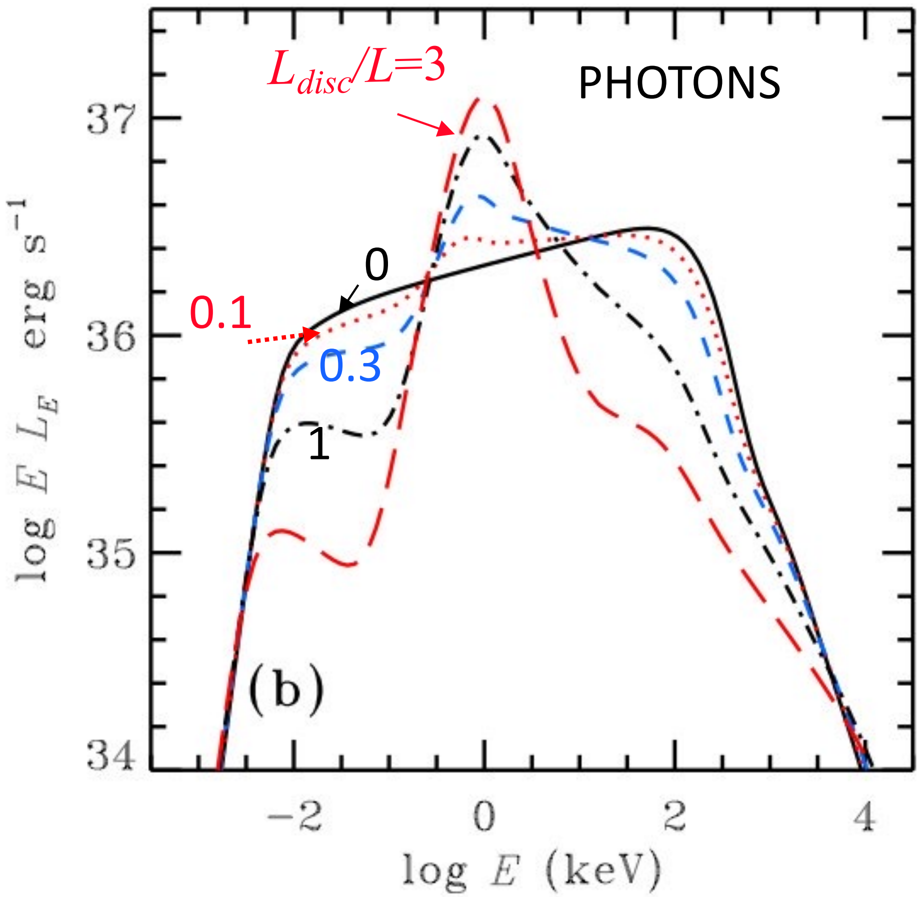
$\alpha = \quad 0.89, 0.97, 1.13, 1.61, 2.46$

$kT_e = \quad 66, \quad 61, \quad 49, \quad 31, \quad 16$ keV

Poutanen & Vurm 2009,
Malzac & Belmont 2009

Photon and electron distributions at state transitions





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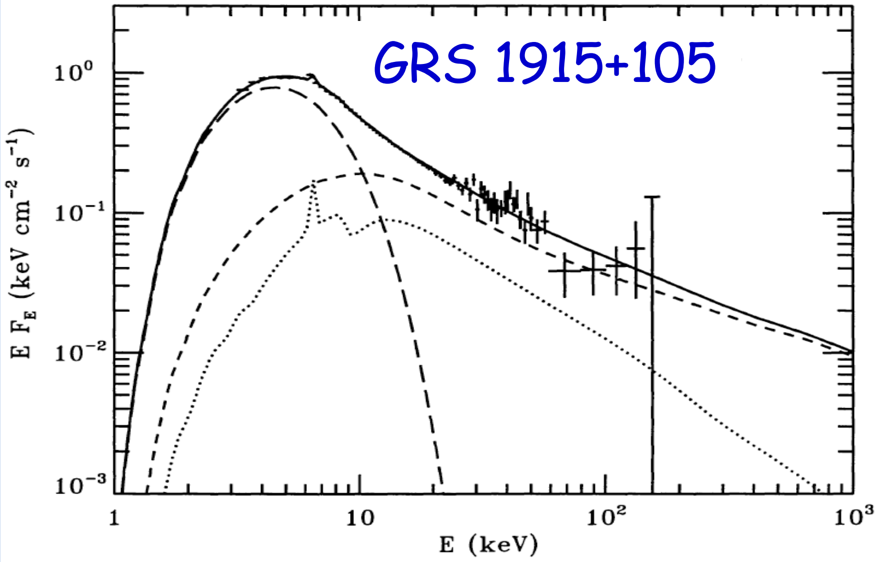
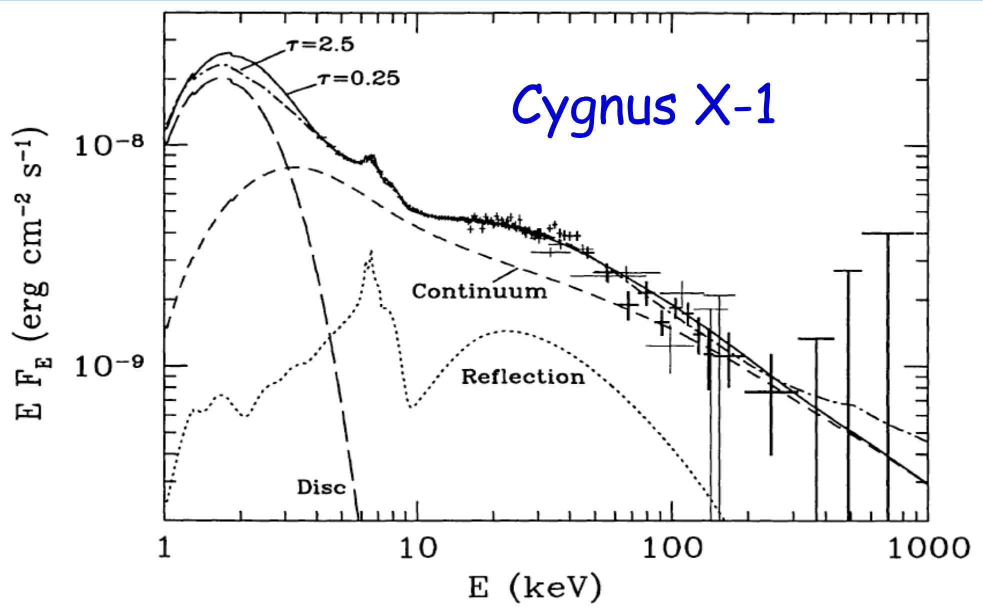
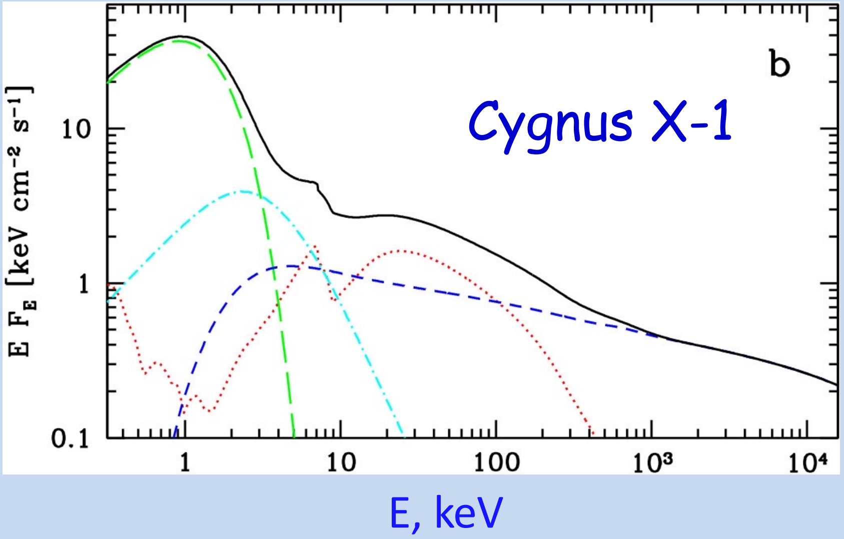
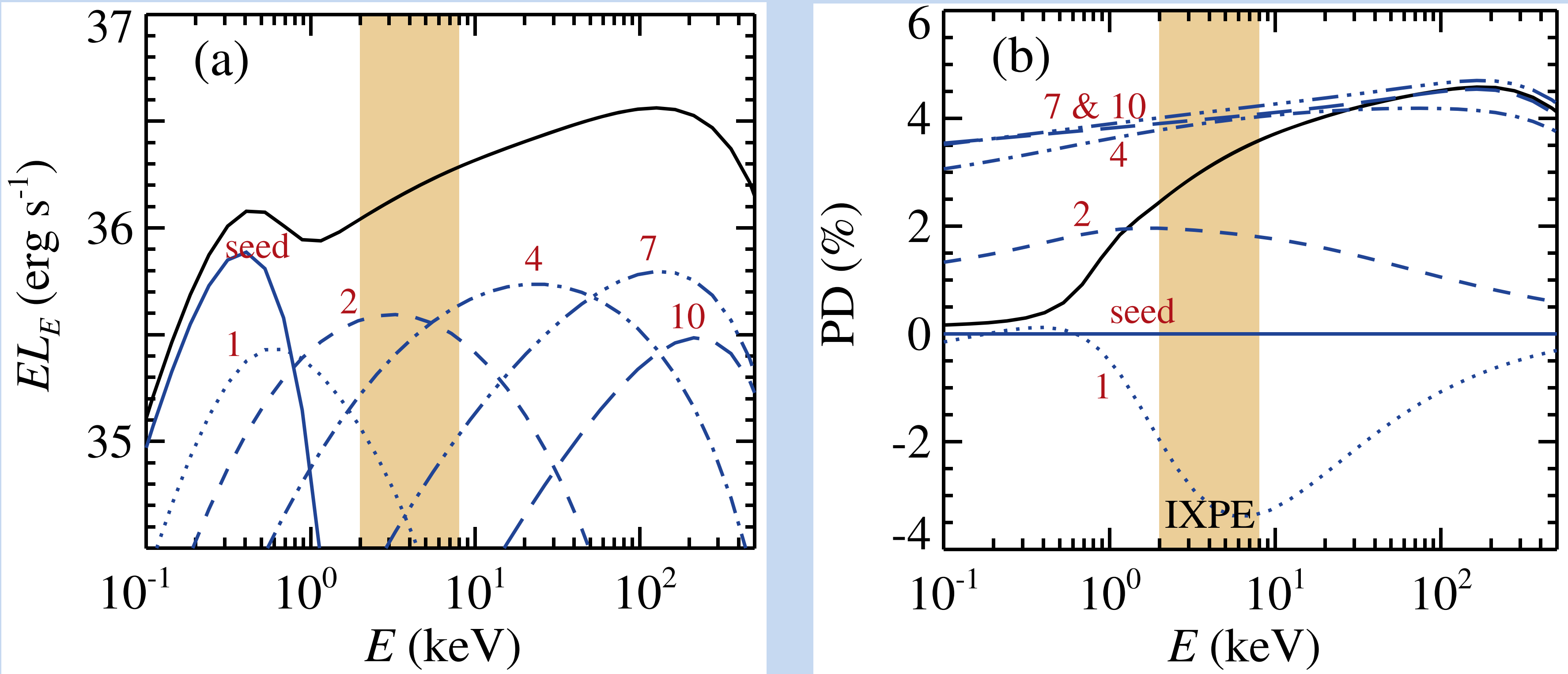
Soft state electron distribution is hybrid







Polarization from a Comptonizing slab (application to the hard state)

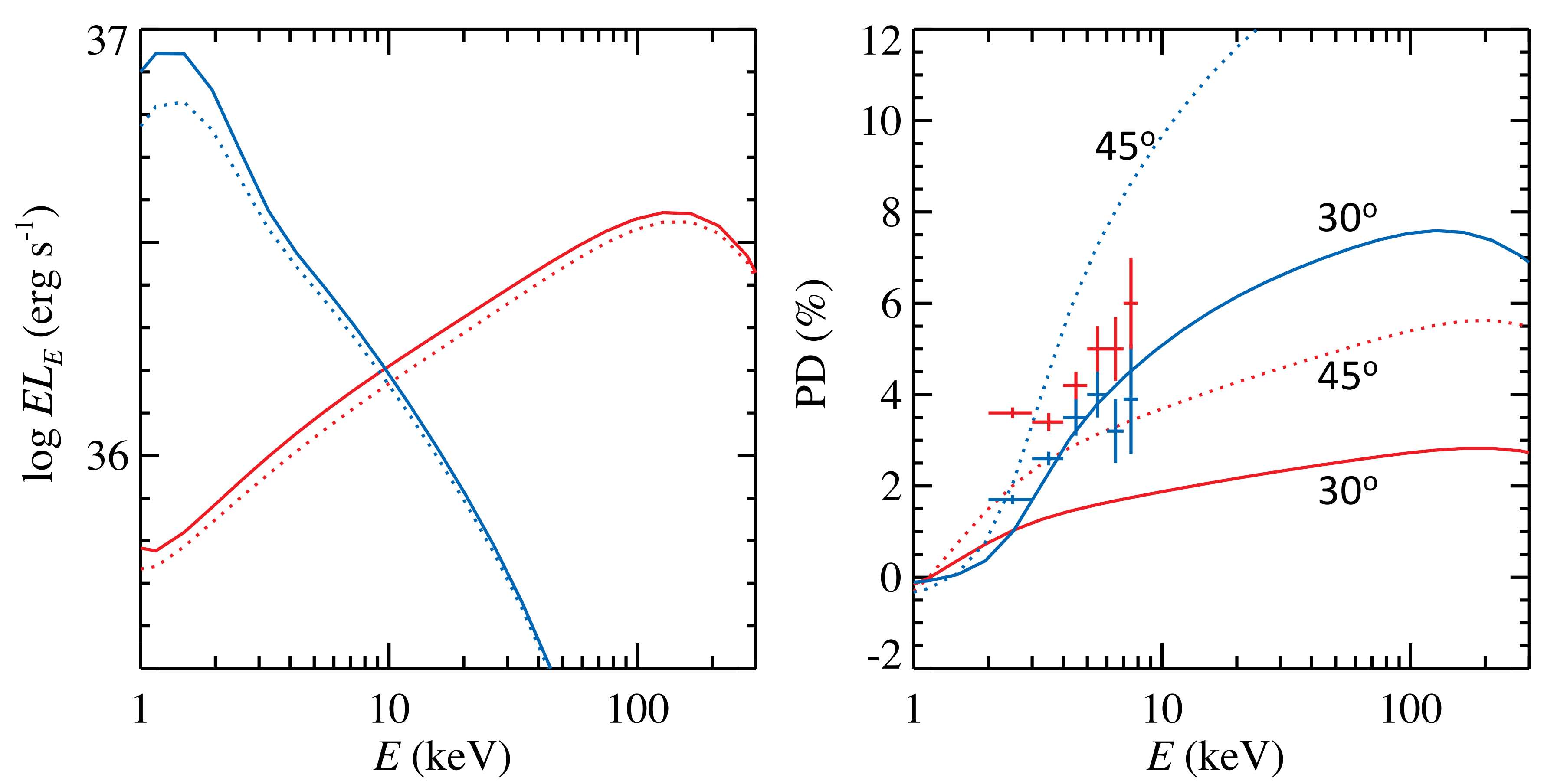


Thermal Comptonization in an outflowing corona

kT_e=100 keV, kT_{bb}=0.1 keV, β_0=v/c=0.4

Poutanen, Veledina, Beloborodov 2023

Varying electron temperature (hard-soft state transition)

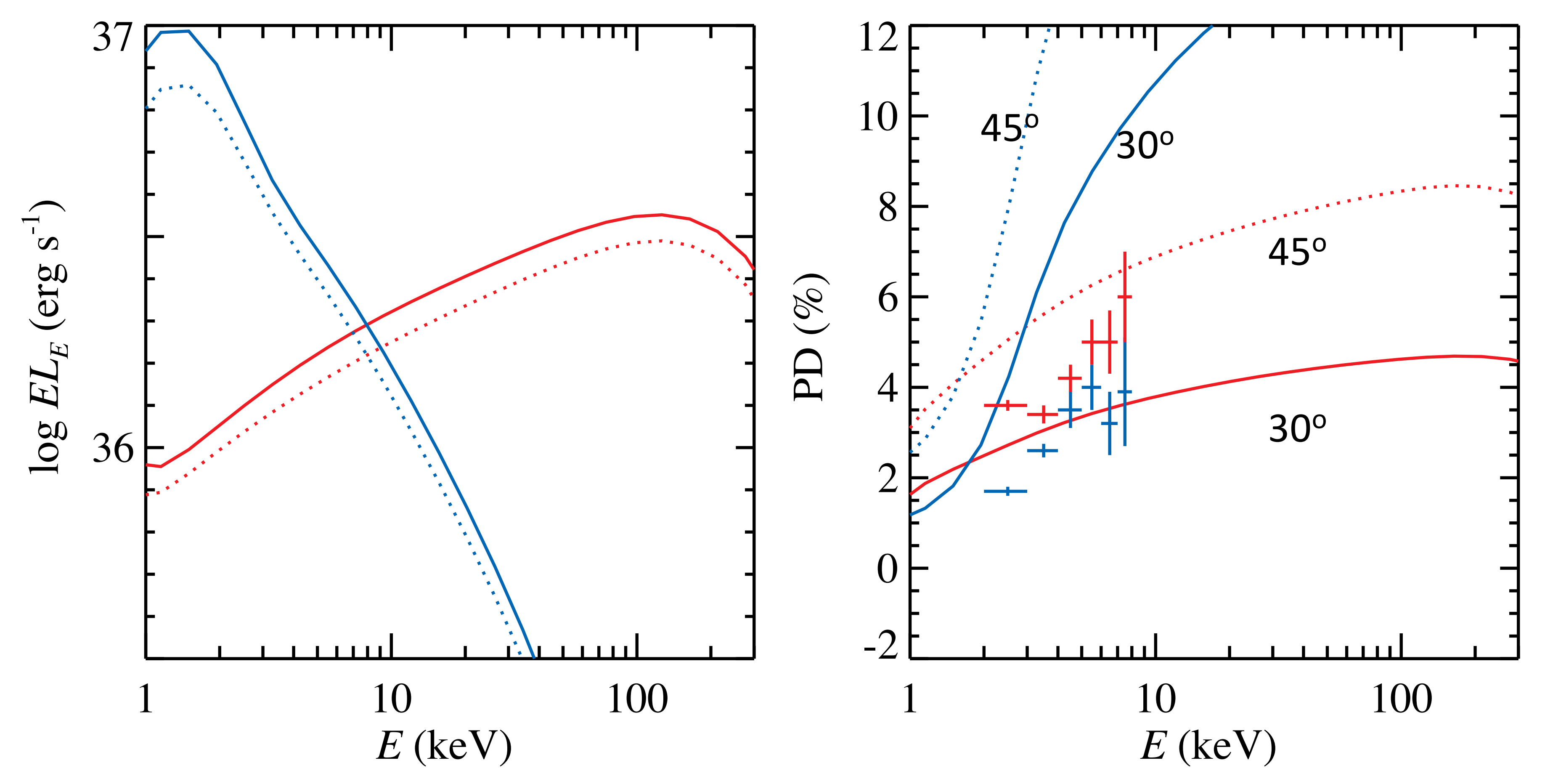


Thermal Comptonization in a static corona

kT_e=100 keV, kT_{bb}=0.1 keV, τ=1, β_0=v/c=0

kT_e=25 keV, kT_{bb}=0.3 keV, τ=1, β_0=v/c=0

Varying electron temperature (hard-soft state transition)



Thermal Comptonization in an outflowing corona

kT_e=100 keV, kT_{bb}=0.1 keV, τ=1, β_0=v/c=0.4

kT_e=25 keV, kT_{bb}=0.3 keV, τ=1, β_0=v/c=0.4

Conclusion

- It is rather natural to expect hybrid= thermal+nonthermal electron distribution.

- Variations in the role of the disc soft photons may nearly completely explain the difference in the X/gamma-ray spectra of hard vs soft states.

- In the soft state, Compton scattering in a hybrid (static) slab-corona is consistent with the observed X-ray spectrum of Cyg X-1 and thermal Comptonization at low kT_e produces X-ray polarization.

- No high spin, returning radiation or reflection is needed.