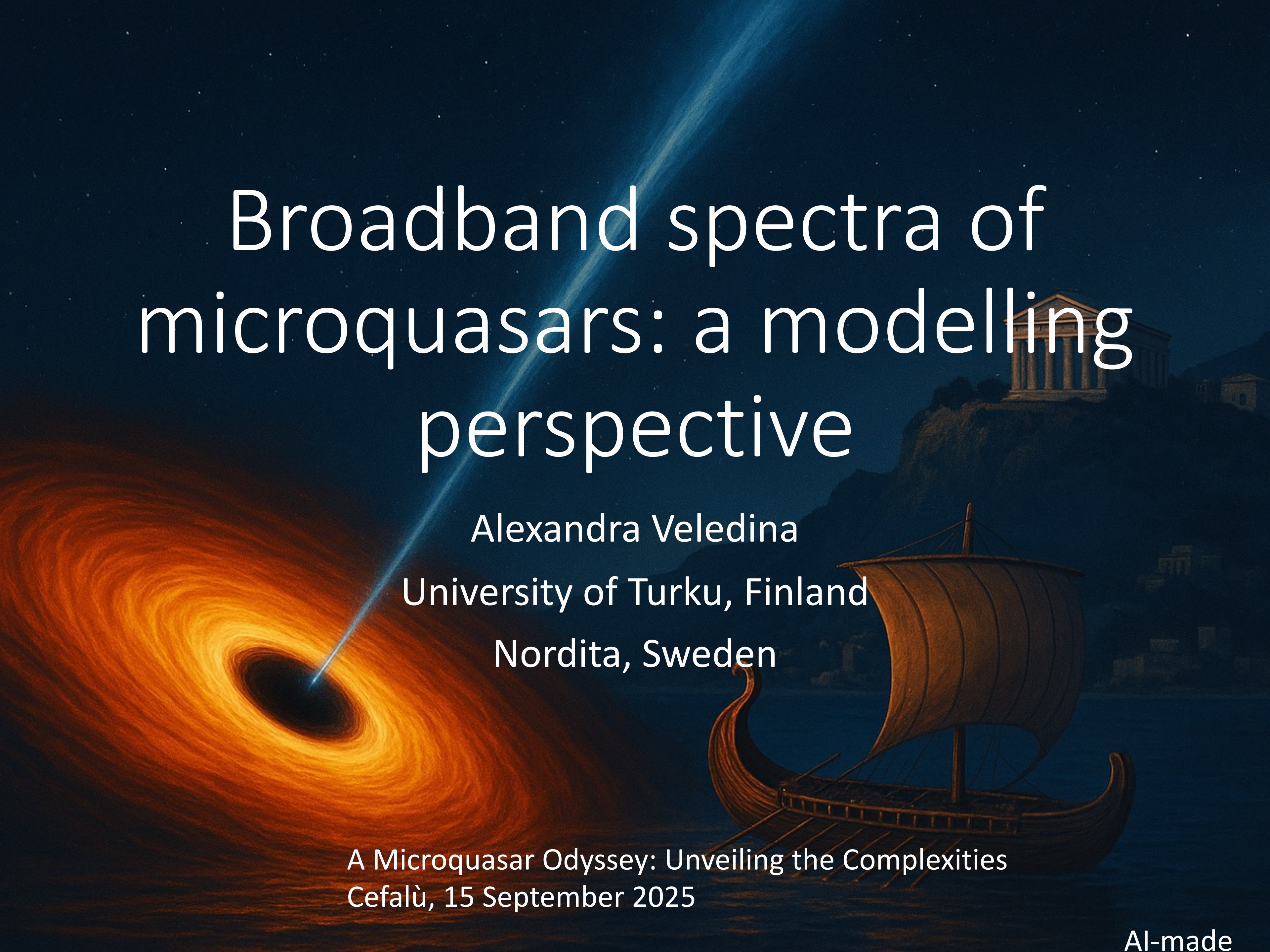


Broadband spectra of microquasars: a modelling perspective

Alexandra Veledina

University of Turku, Finland

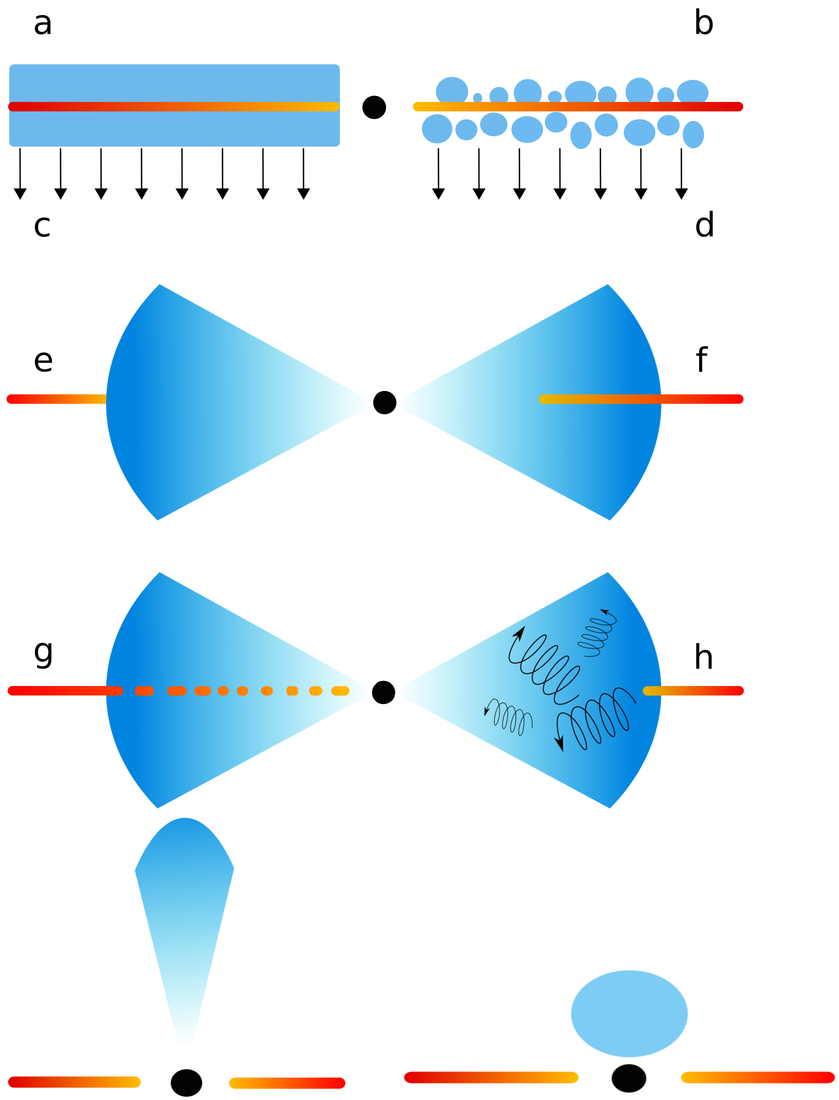
Nordita, Sweden

A Microquasar Odyssey: Unveiling the Complexities

Cefalù, 15 September 2025

AI-made

Proposed geometries



Poutanen, AV, Zdziarski 2018

Sandwich corona

(Haardt & Maraschi 1991, 1993; Stern et al. 1995; Poutanen & Svensson 1996; Zdziarski et al. 1998; Malzac et al. 2001)

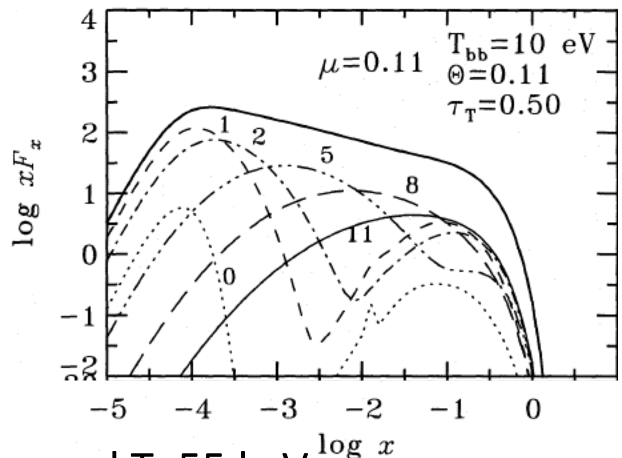
Too soft spectra $\Gamma>2$

Hot flow models

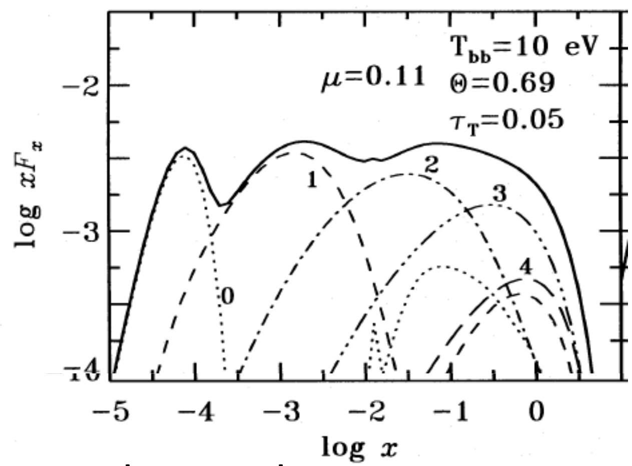
(Eardley & Lightman 1975; Ichimaru 1976; Narayan & Yi 1994, 1995; Poutanen et al. 1997; Esin et al. 1997; Ferreira et al. 2006; Yuan et al. 2007; Veledina et al. 2013)

Seed photons?

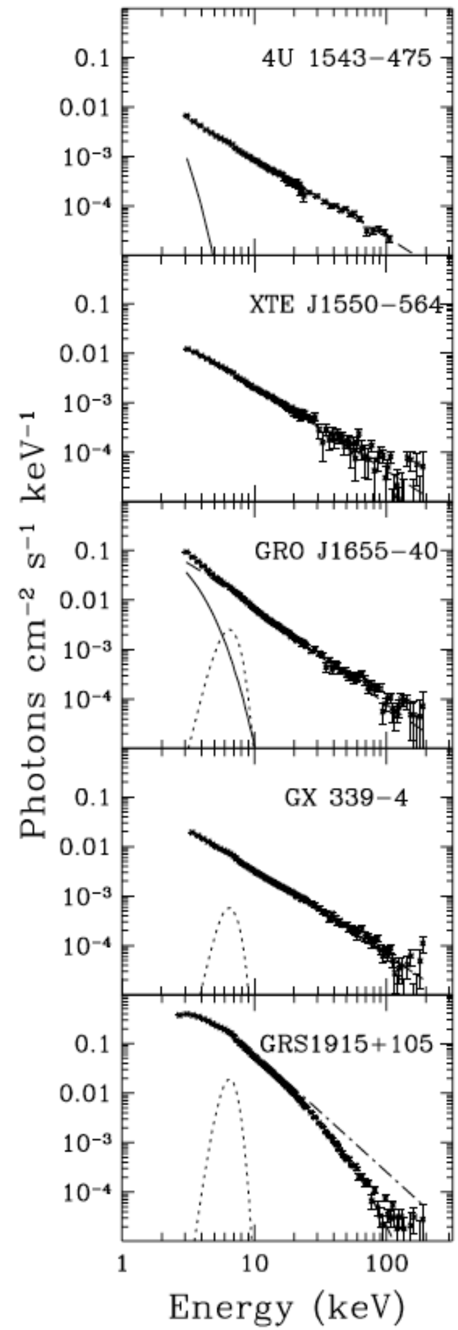
Comptonization in hot plasma



kT=55 keV

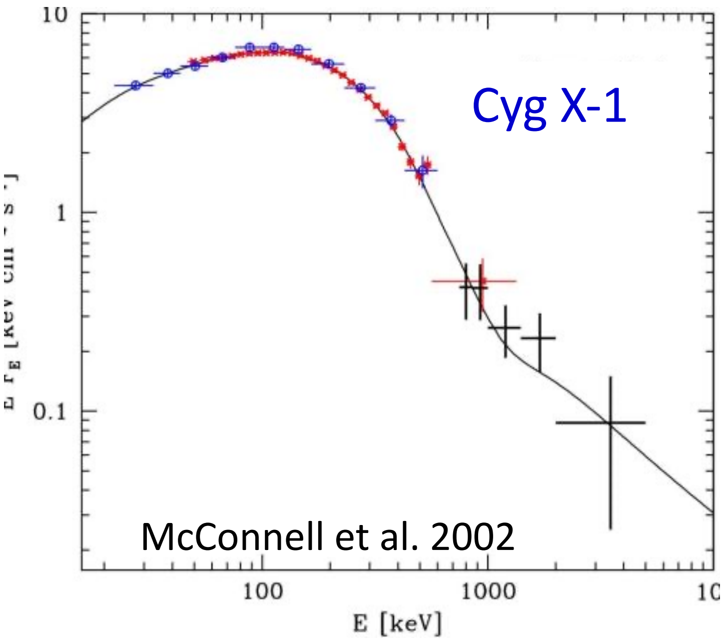


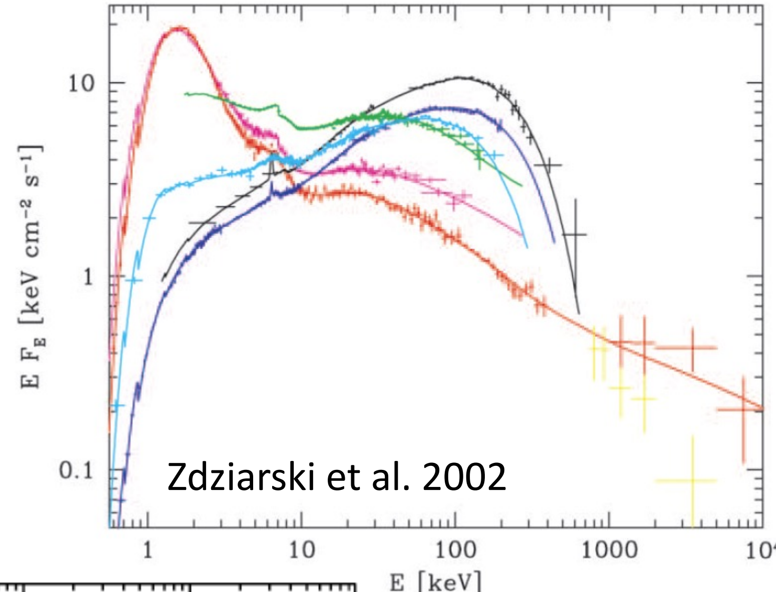
kT=350 keV

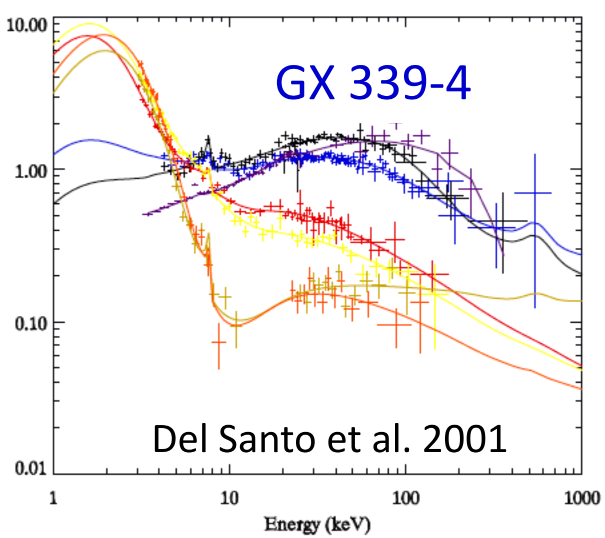


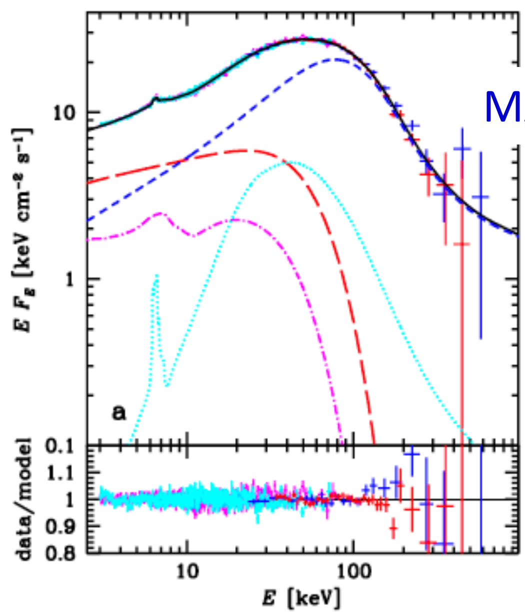
McClintock & Remillard 2006
Poutanen & Svensson 1996

High-energy emission: gamma-ray tails





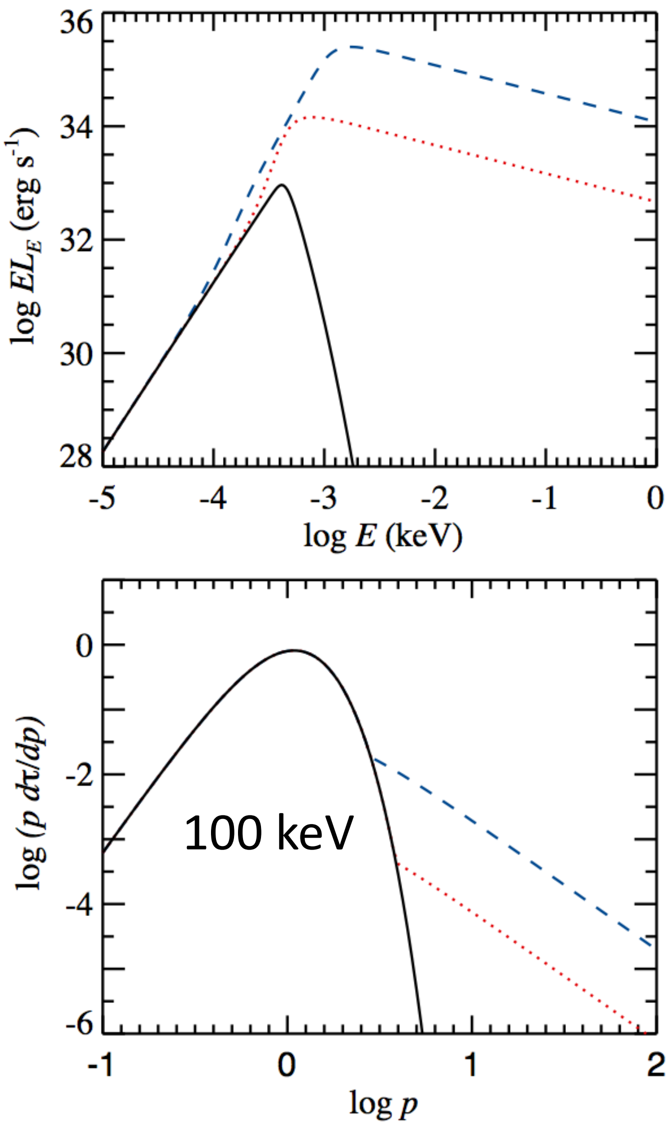




MAXI J1820+070

Zdziarski+AV+2021

Synchrotron in hybrid plasma



Hybrid electrons, 1% energy in the non-thermal component

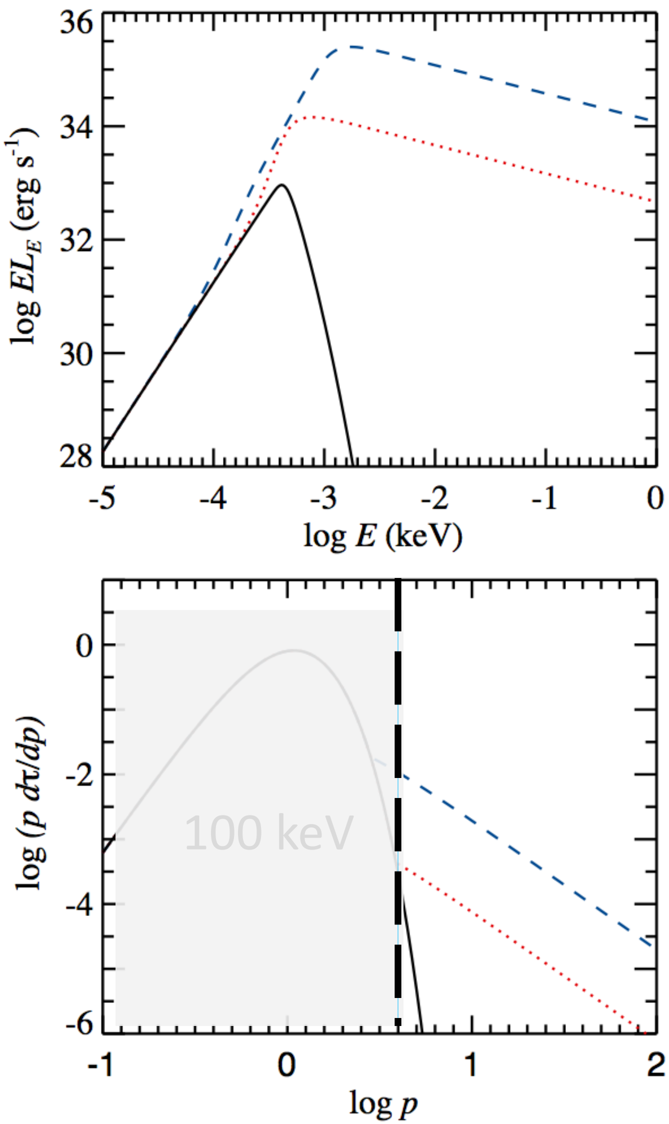
Hybrid electrons, 0.01% energy in the non-thermal component

Thermal electrons, 100 keV

$$R = 9\times10^7\,\mathrm{cm} \quad \tau = 1.0 \quad B = 3\times10^5\,\mathrm{G}$$

Synchrotron can be the main source of seed photons for Comptonization

Synchrotron in hybrid plasma



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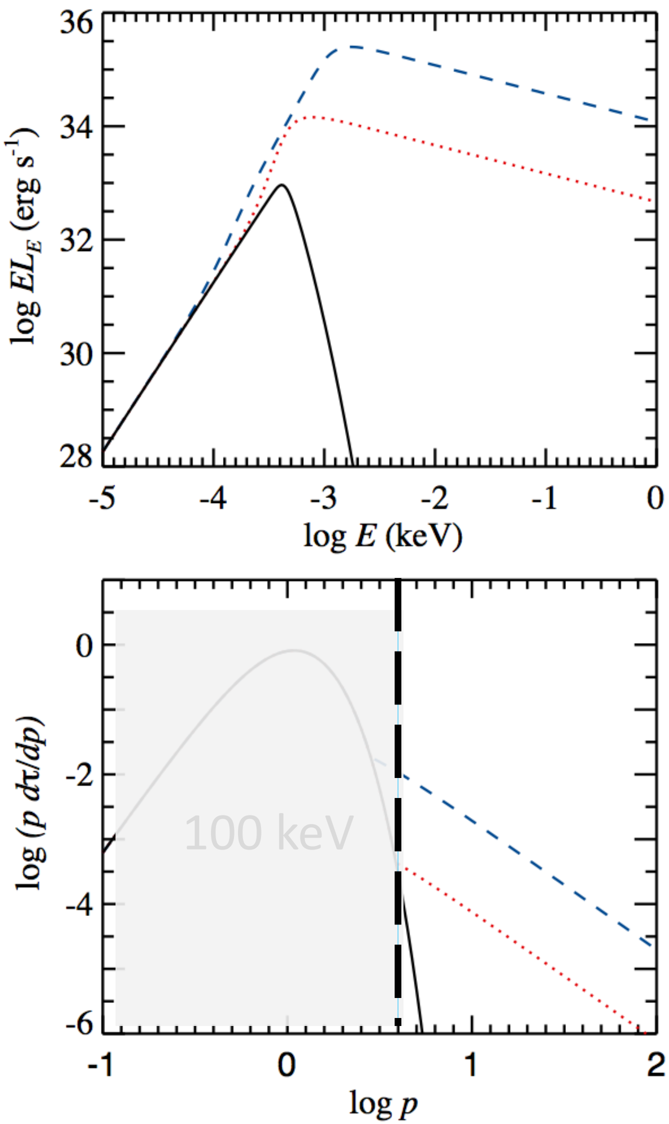
Synchrotron can be the main source of seed photons for Comptonization

First noted by Wardzinski & Zdziarski, 2001

Synchrotron in hybrid plasma



Hybrid electrons, 1% energy
in the non-thermal component

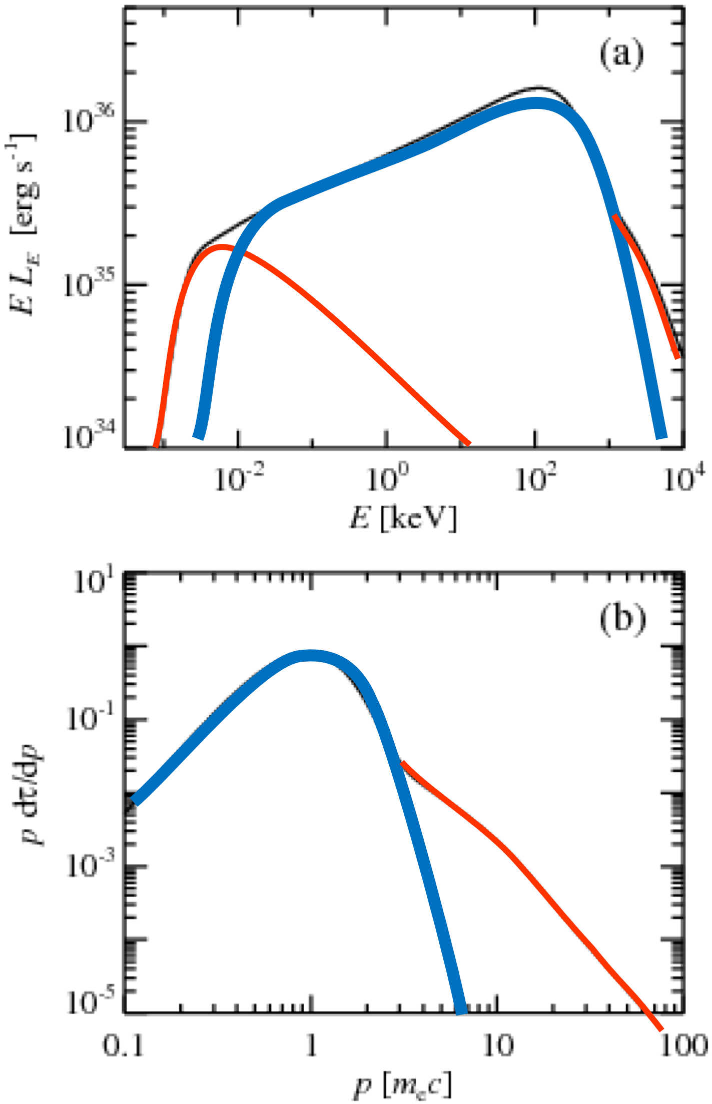
Hybrid electrons in accretion models:

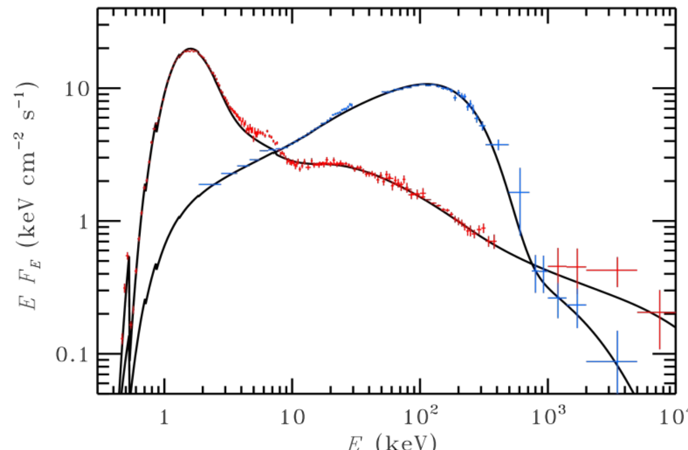
- black hole binaries (Poutanen & Vurm 2009, Malzac & Belmont 2009, AV et al. 2013)
- supermassive black holes (Ozel et al. 2001, Yuan et al. 2003, AV et al. 2011, Niedzwiecki et al. 2015)

Comptonization

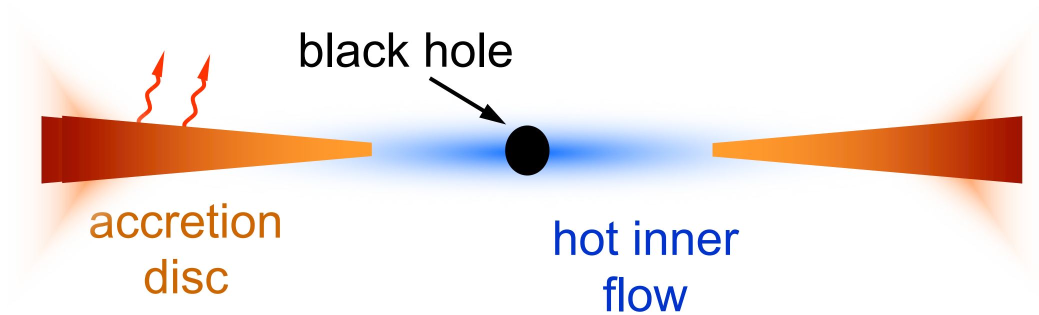
First noted by Wardzinski & Zdziarski, 2001

Synchrotron Self-Compton (SSC) mechanism in hybrid plasma





Poutanen & Vurm 2009

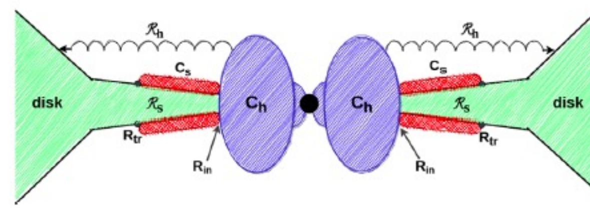


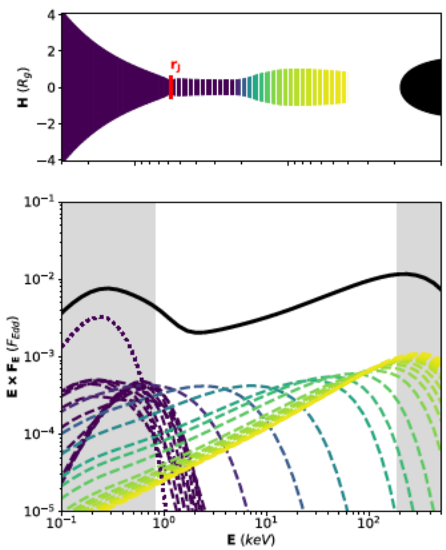
$R = 9 \times 10^7\,\mathrm{cm}$ $\quad \tau = 1.0 \quad$ $B = 3 \times 10^5\,\mathrm{G}$

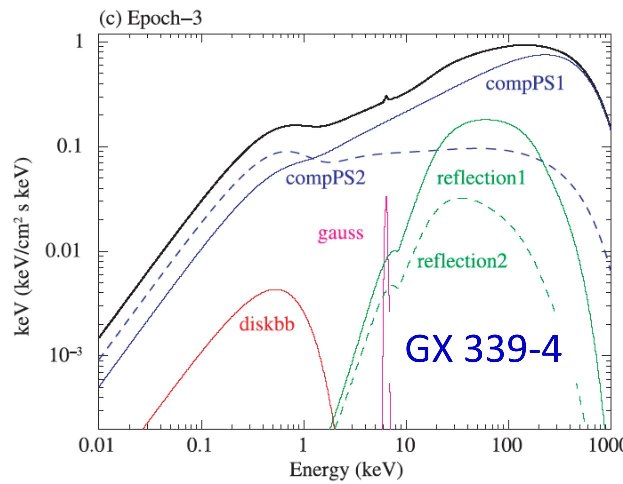
$L = 10^{37}\,\mathrm{erg\,s^{-1}}$

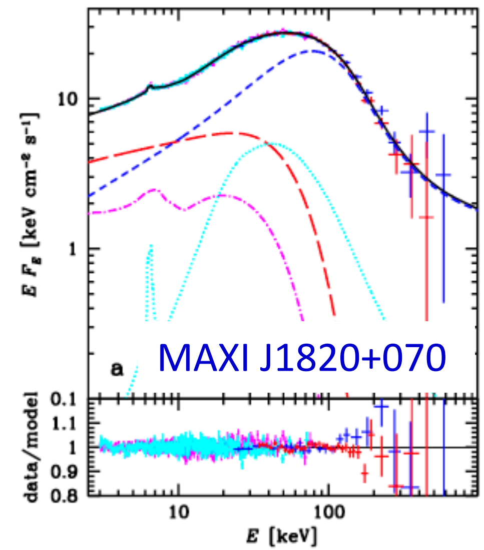
Spectral decomposition: DC vs SSC

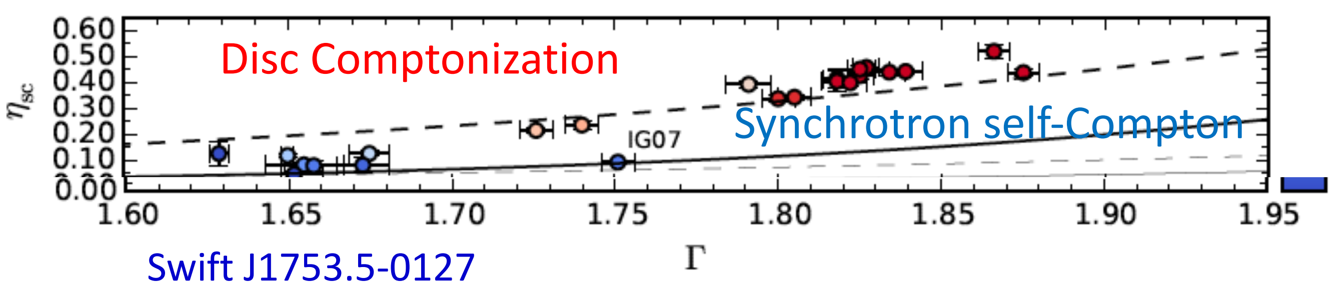
- Spectra deviate from power-law: two-components
- Change of the sources of seed photons
- Multiwavelength timing: SSC+DC





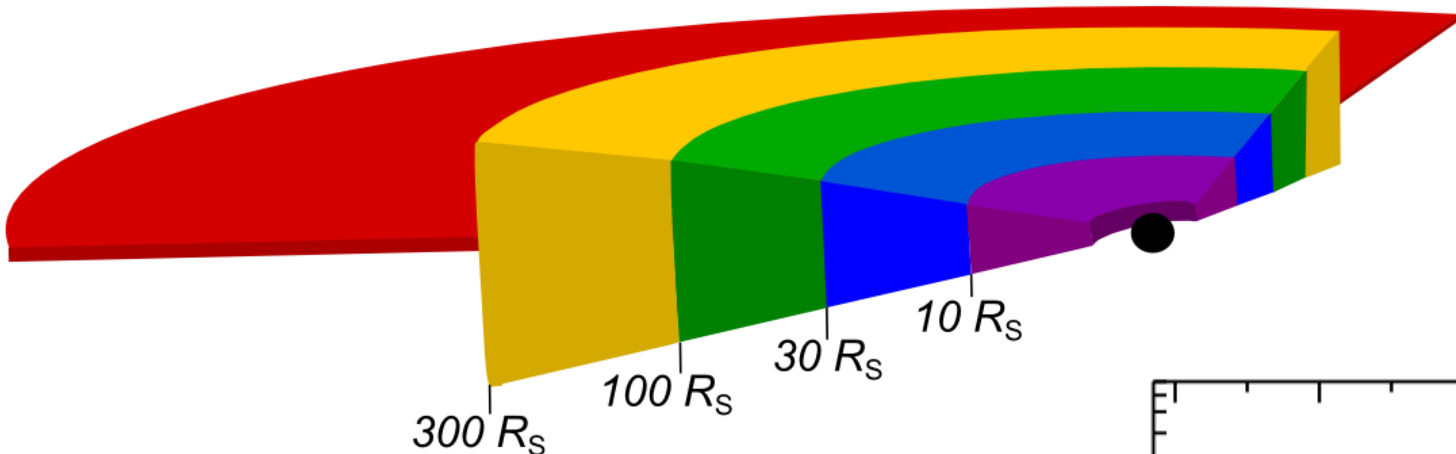






Shidatsu+2010
AV 2016, 2018
Kajava+AV+2016
Marino+2021
Zdziarski+AV+2021

Extended inhomogeneous accretion flow

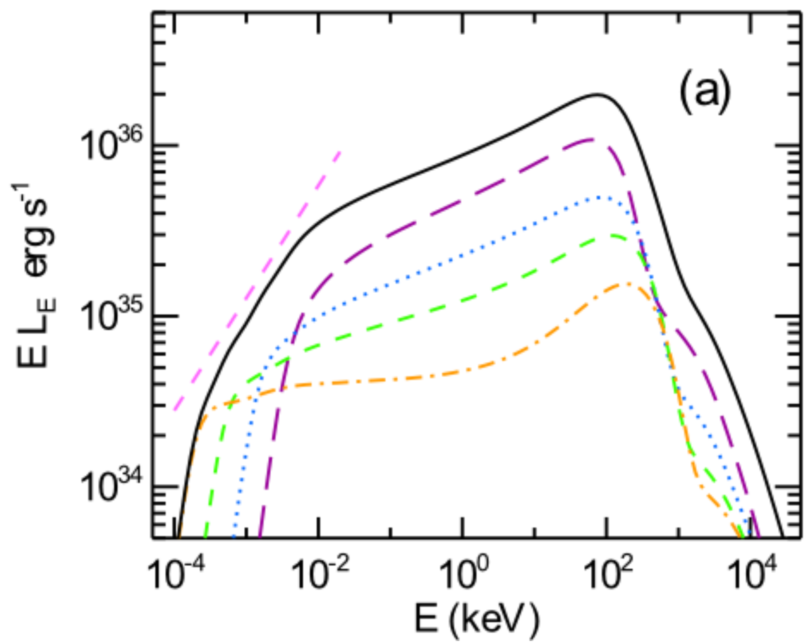


$$\nu_t \approx 3 \times 10^{15} B_6^{\frac{p+2}{p+4}} (\sigma_T n_0 R)^{\frac{2}{p+4}} \text{ Hz}$$

$$\nu L_\nu = 4\pi^2 R^2 \nu I_\nu \approx 2 \times 10^{36} R_8^2 \ B_6^{-1/2} \ \nu_{15}^{7/2} \text{ erg s}^{-1}$$

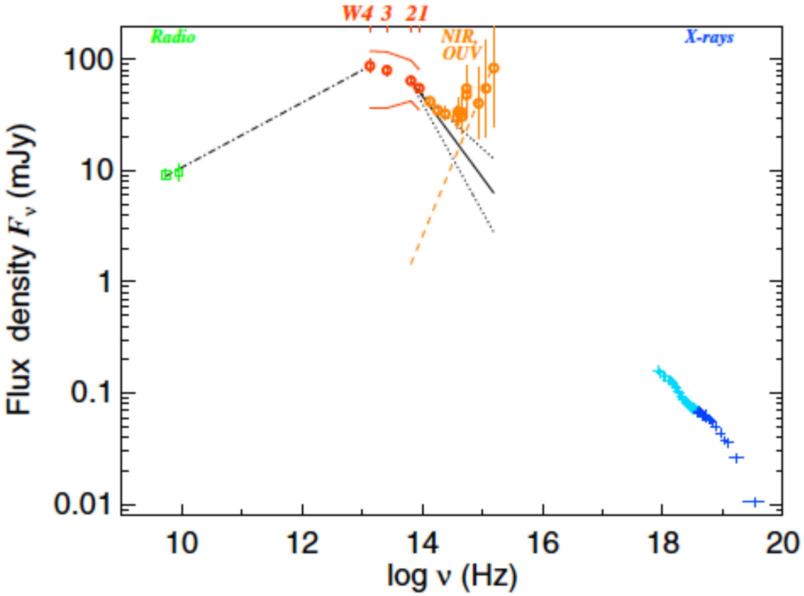
$$\alpha_{\rm OIR} = \frac{5\theta + \beta(2p+3) - 2p - 8}{\beta(p+2) + 2\theta}$$

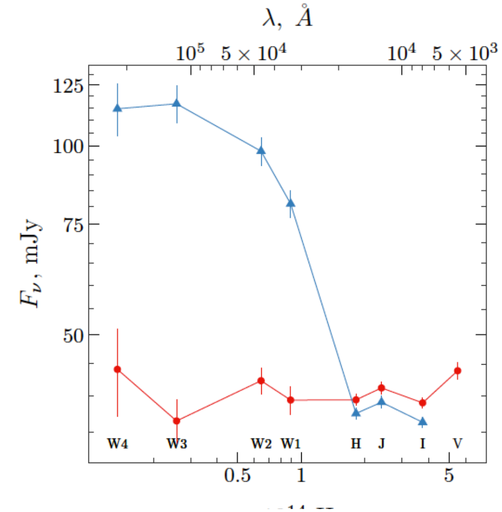
between -0.5 and 0.5



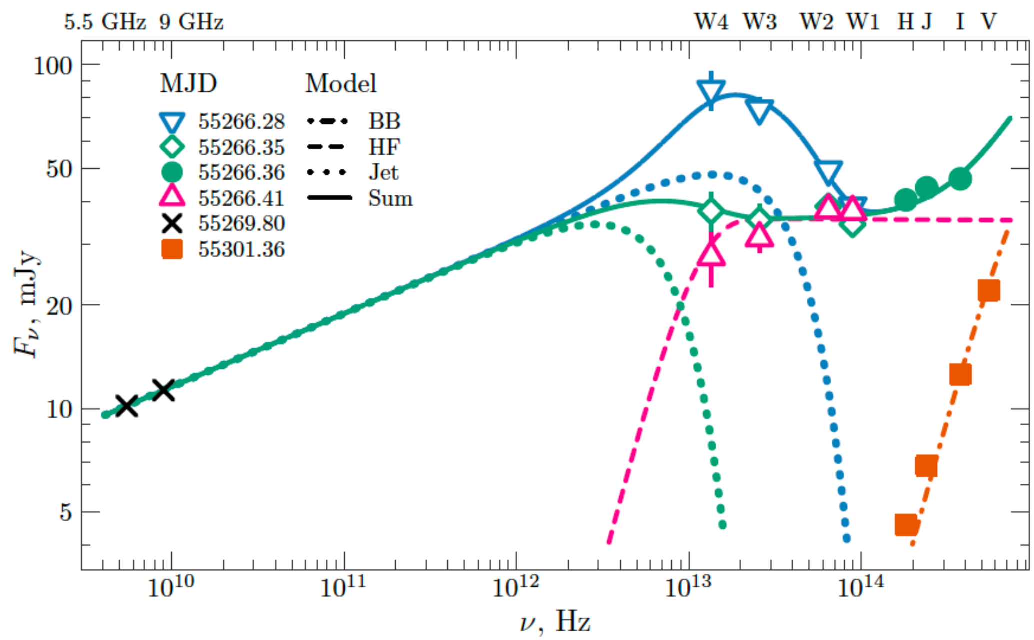
AV+2013

Broadband spectral modelling: counting components





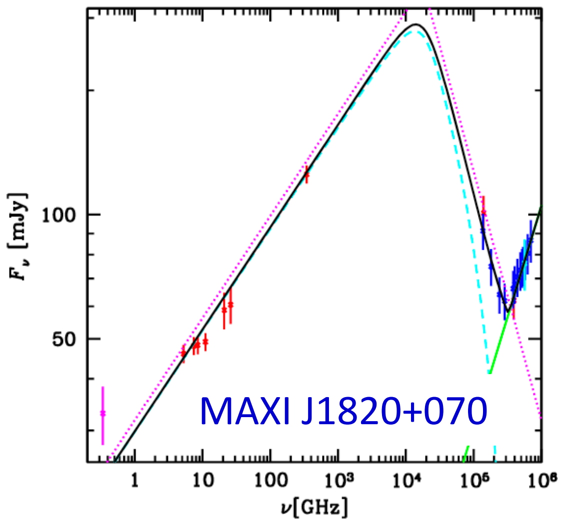
Gandhi+2011
Kosenkov+AV+2020

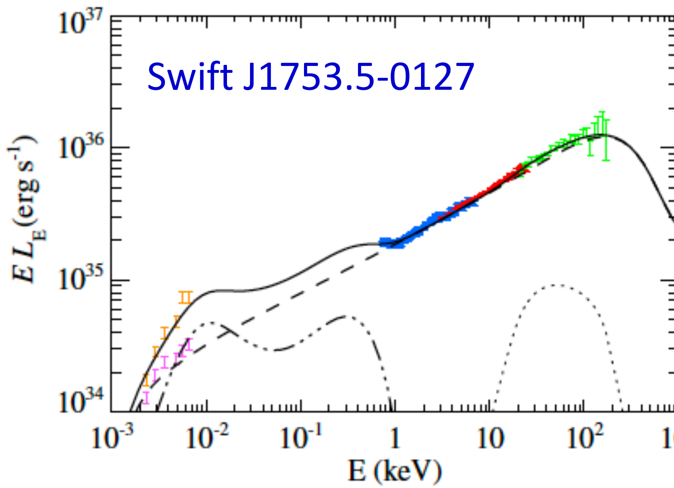


Timing is important to distinguish among different scenarios

Broadband spectral modelling: counting components

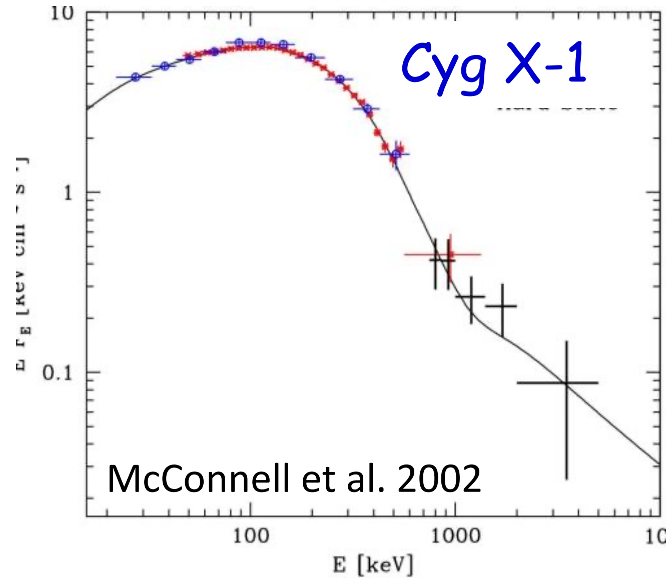
- Some sources have dominant hot flow component, some other jet emission
- Search for the spectral components continues (together with timing)

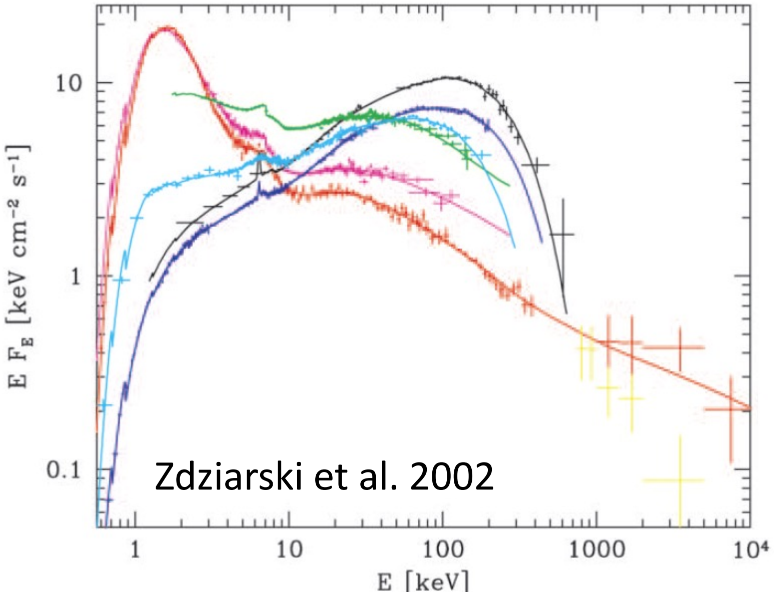


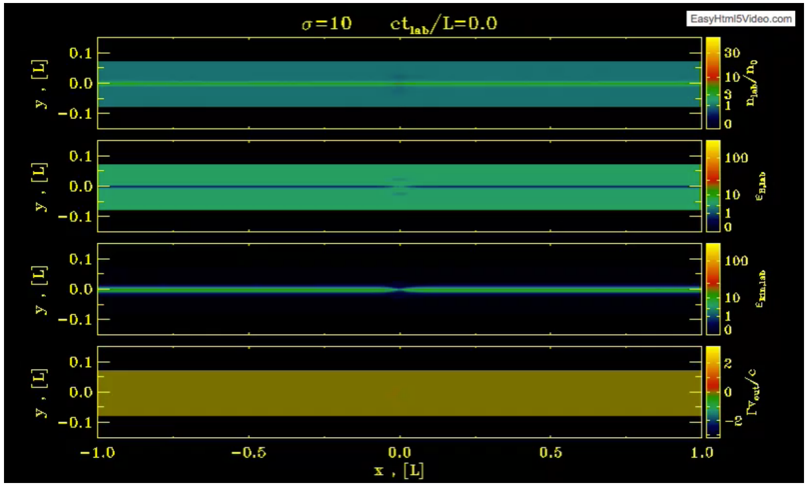


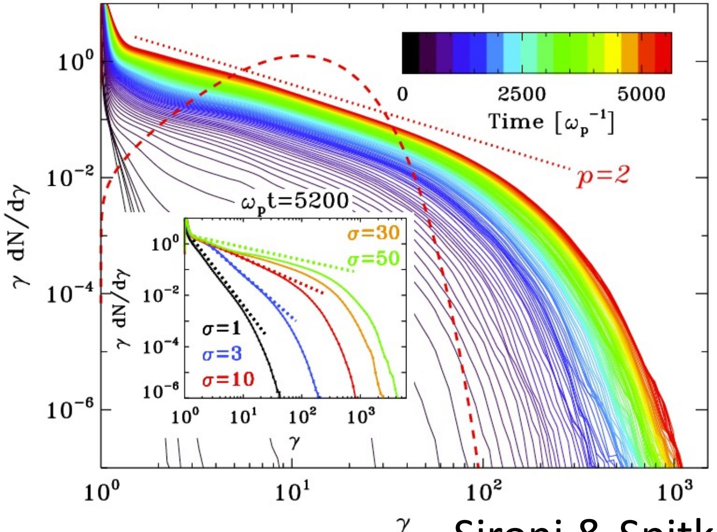
Kajava+AV+2016
Zdziarski+2022

Origin of non-thermal particles: simulations



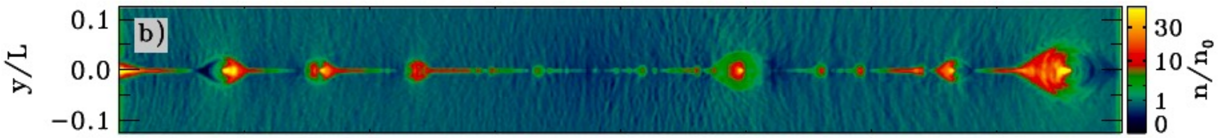


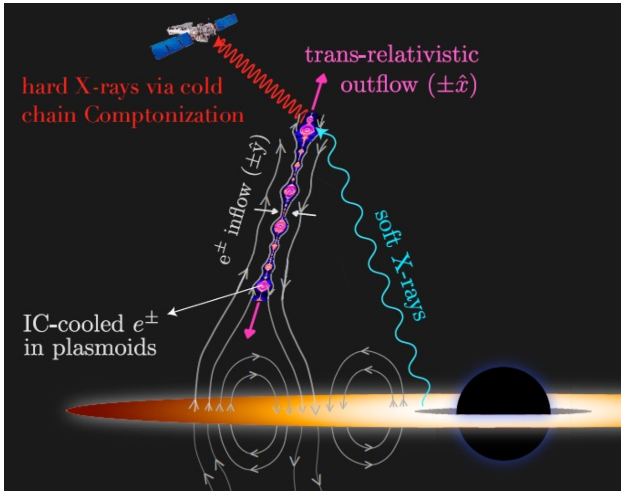




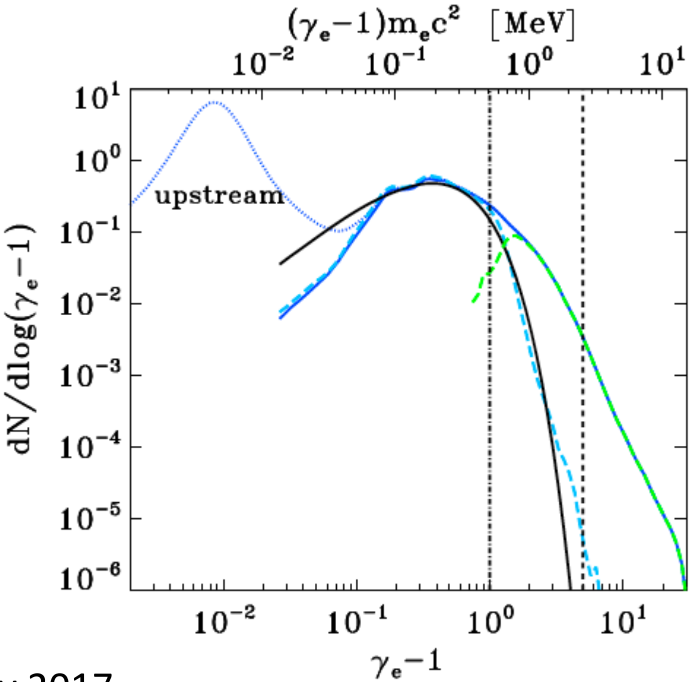
Sironi & Spitkovsky 2014

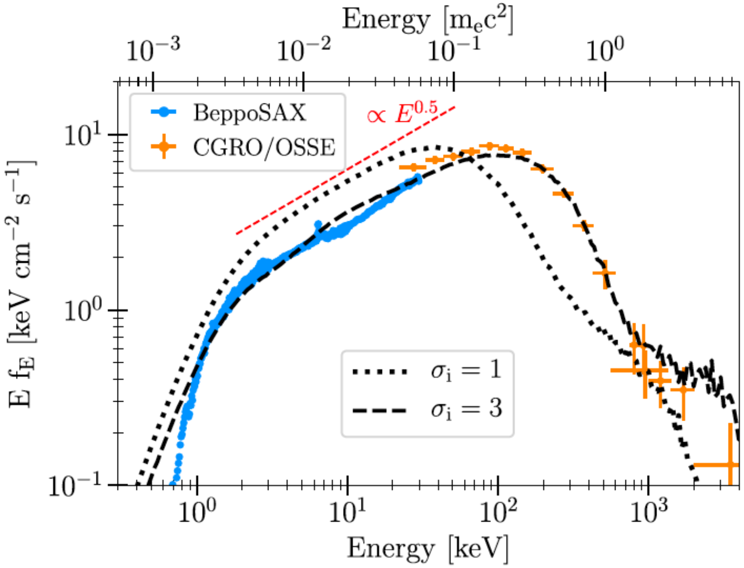
Option 1: magnetic reconnection





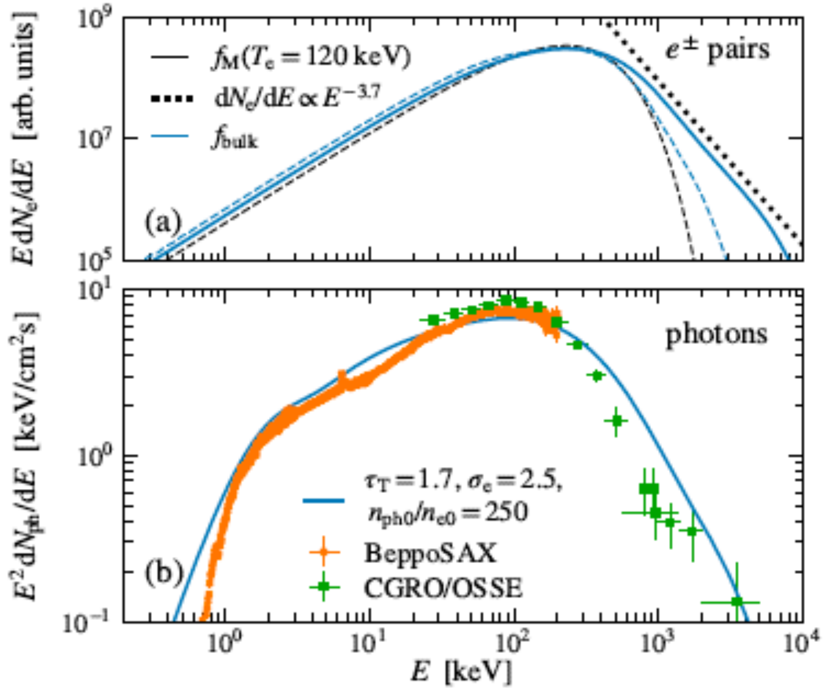
- Particles are cold and reside in plasmoids
- Difficulties with thermalization of particles
- Comptonization: thermal vs bulk motions

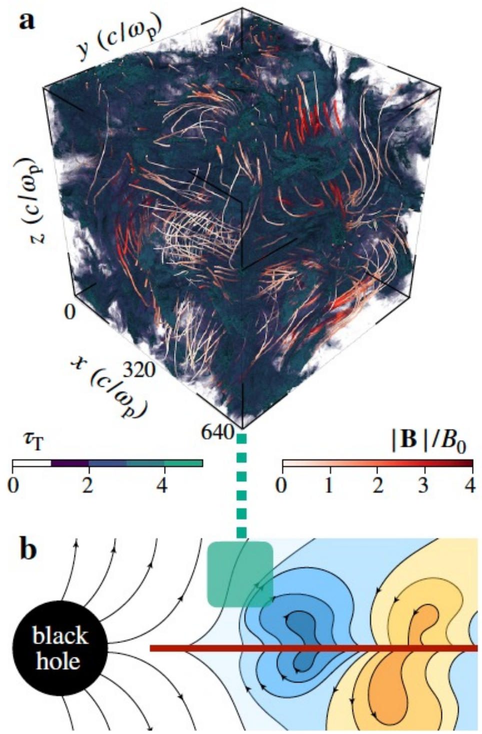


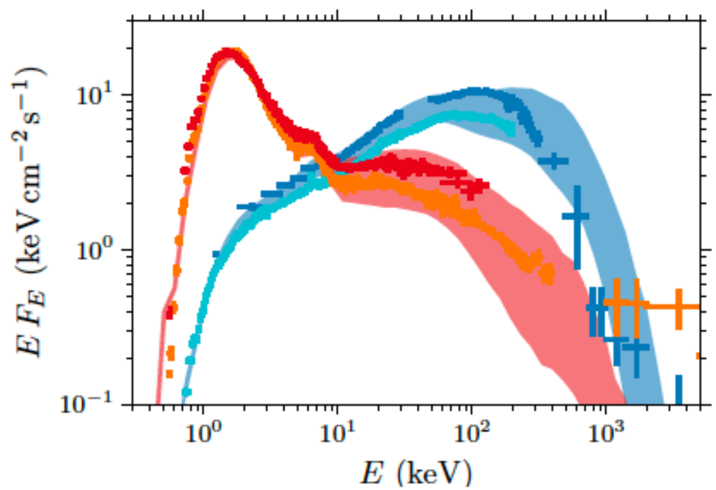


Beloborodov 2017
Sironi & Beloborodov 2020
Sridhar+2021, 2023

Option 2: turbulence



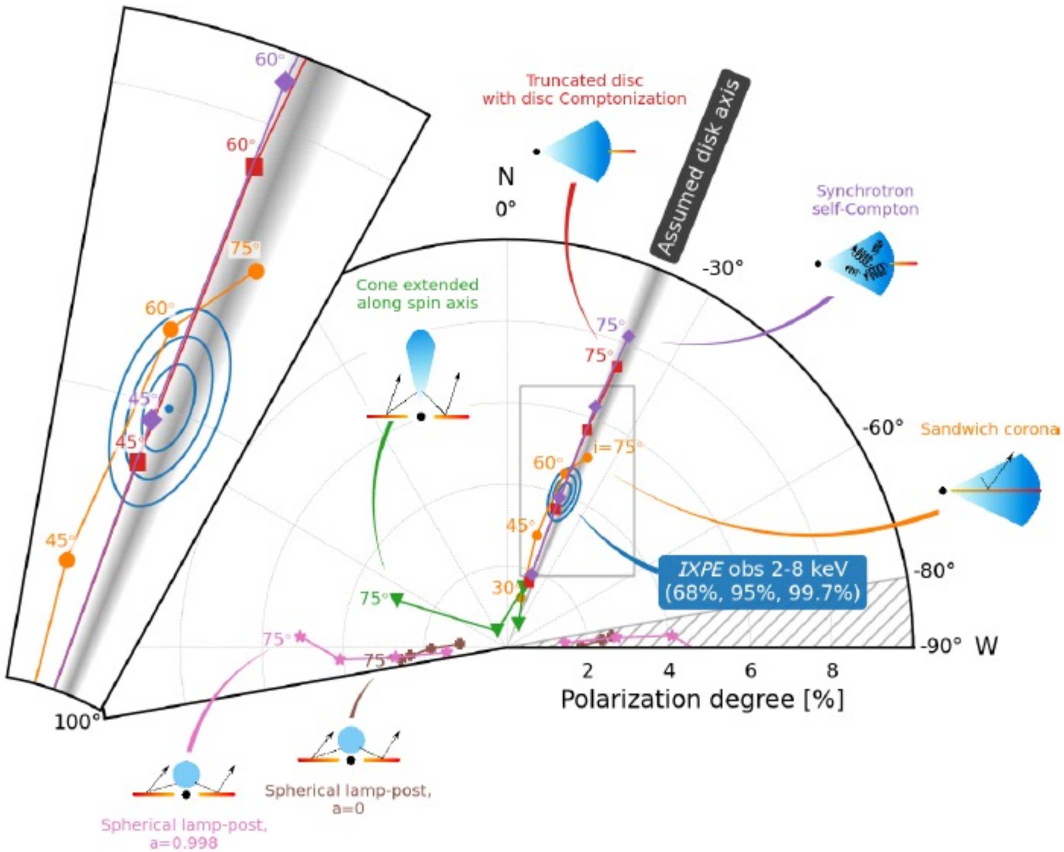




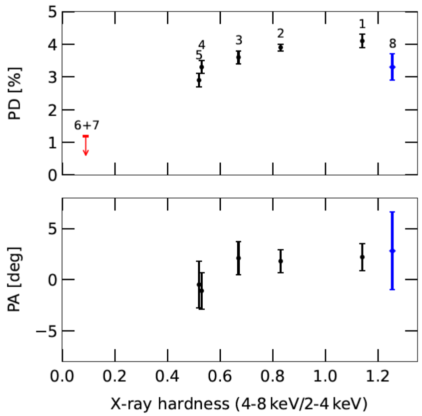
Grošelj+2024 (isotropic blackbody Comptonization)
Nättilä 2024 (synchrotron self-Compton)

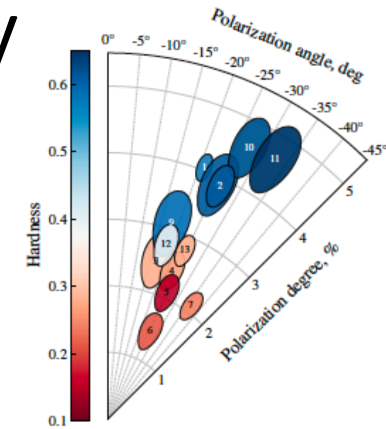
Shape and location of hot medium: insights from X-ray polarimetry

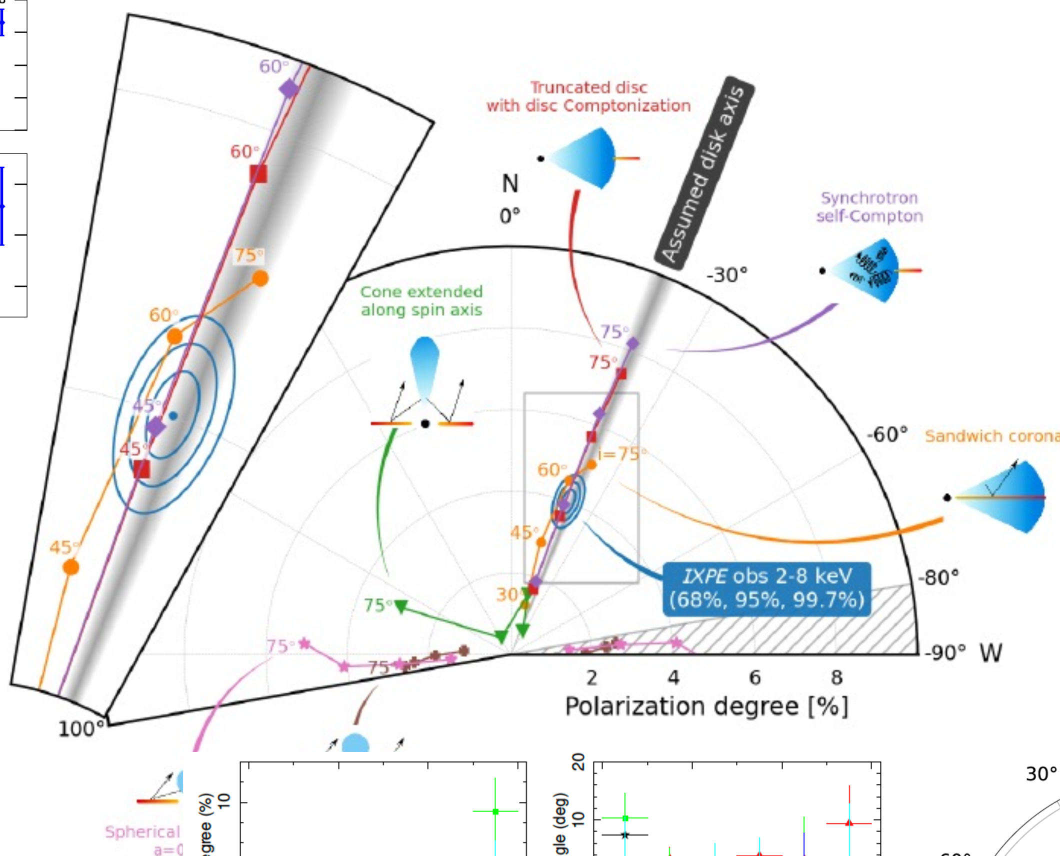
Krawczynski+AV+2022

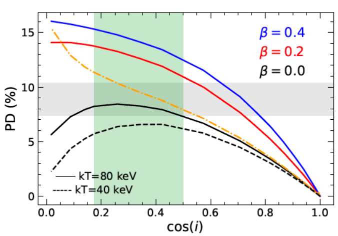


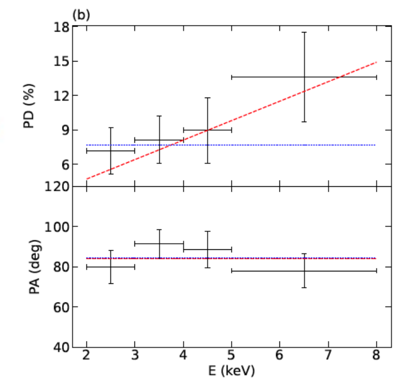
Shape and location of hot medium: insights from X-ray polarimetry



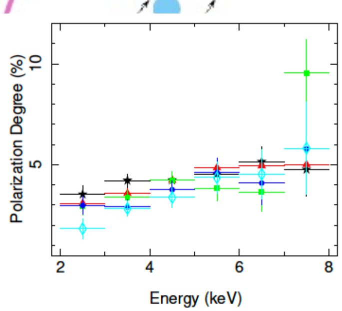


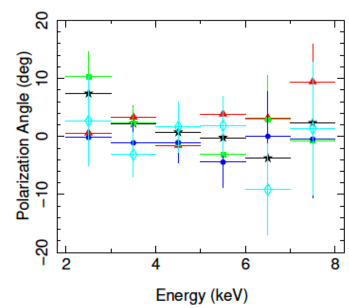


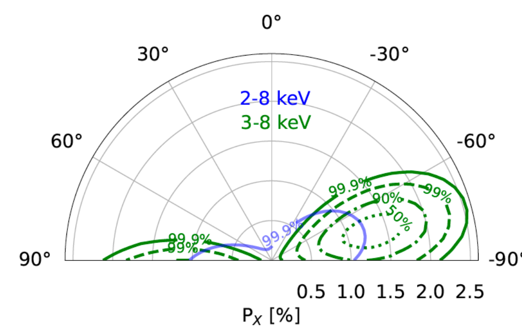




Krawczynski+AV+2022
AV+2023
Ingram+2024
Podgorny+2024
Mastroserio+2024
Kravtsov+2025
Ewing+2025

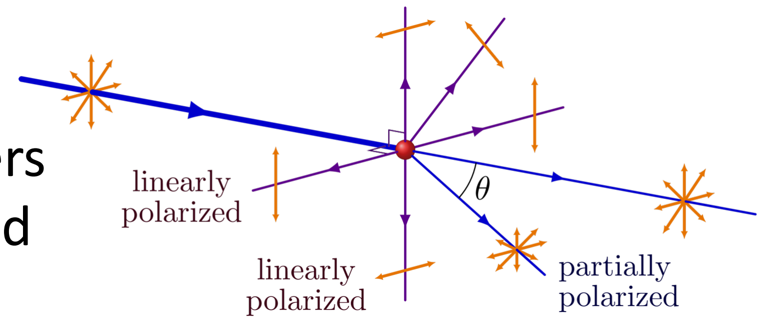




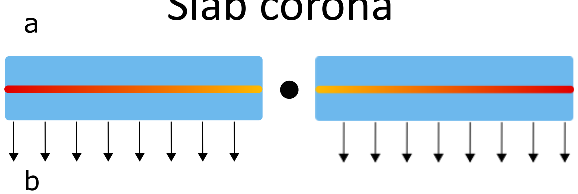


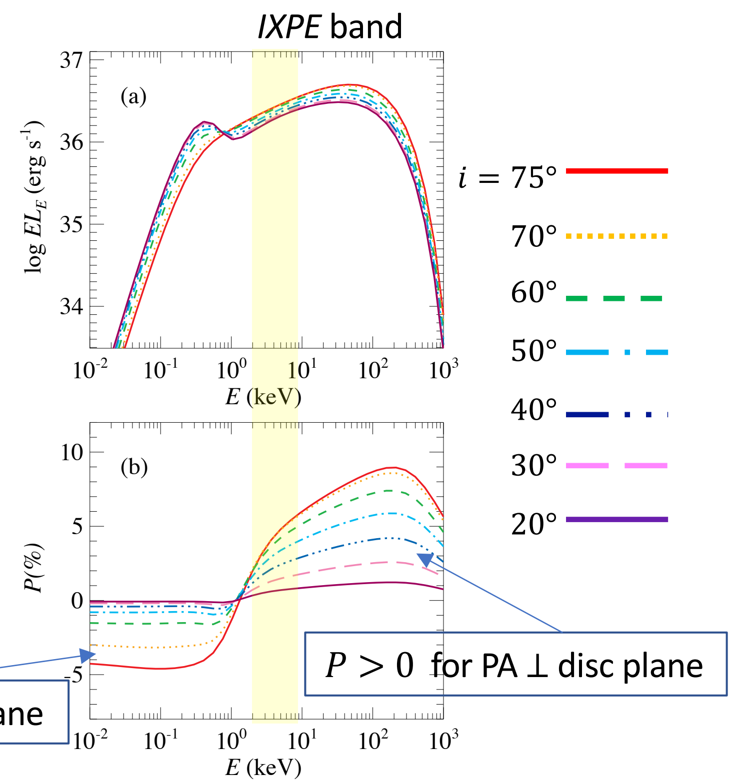
Spectro-polarimetric modelling

- PA ∥ disc plane for first scattering and
  ⊥ disc plane for higher scattering orders
- Polarization increases in the 2–8 keV band



Slab corona



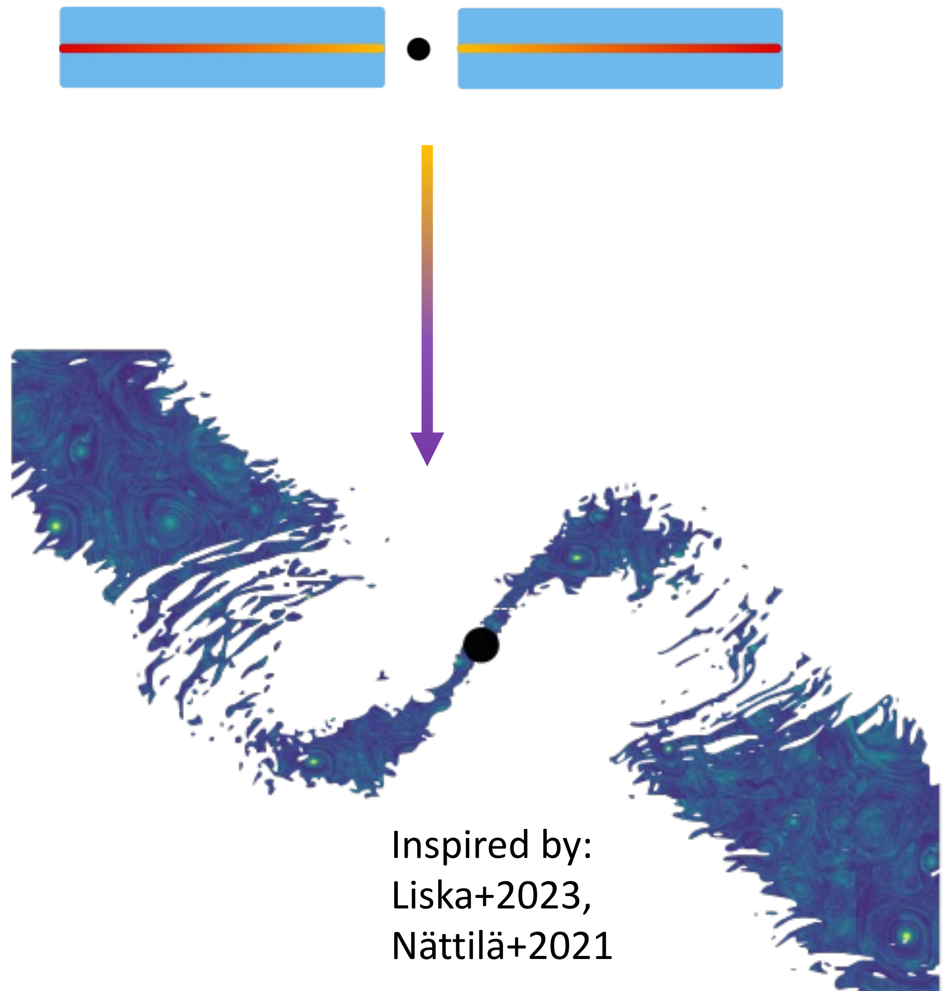


Monte-Carlo (MONK: Zhang+2019,
KerrC: Krawczynski & Beheshtipour, 2022)

Analytical (compps+artpol): Poutanen & Svensson 1996, Loktev+AV+2022,2024, AV+in prep.

Current problems and future directions of spectral modelling

- Hard state: same spectral shape for many orders of magnitude
- Angular distribution of particle distribution and emission
- Spectropolarimetry: hight PD
- Results from simulations into phenomenological description
- eXTP: variability of polarization?



Inspired by:
Liska+2023,
Nättilä+2021

Summary

- Spectral modelling enables determination of useful parameters
- Non-thermal particles put constraints on the mechanisms of energy transformation
- Non-thermal particles & broadband spectra
- Thermal Comptonization vs bulk motion of plasmoids
- Polarimetric data and spectral modelling