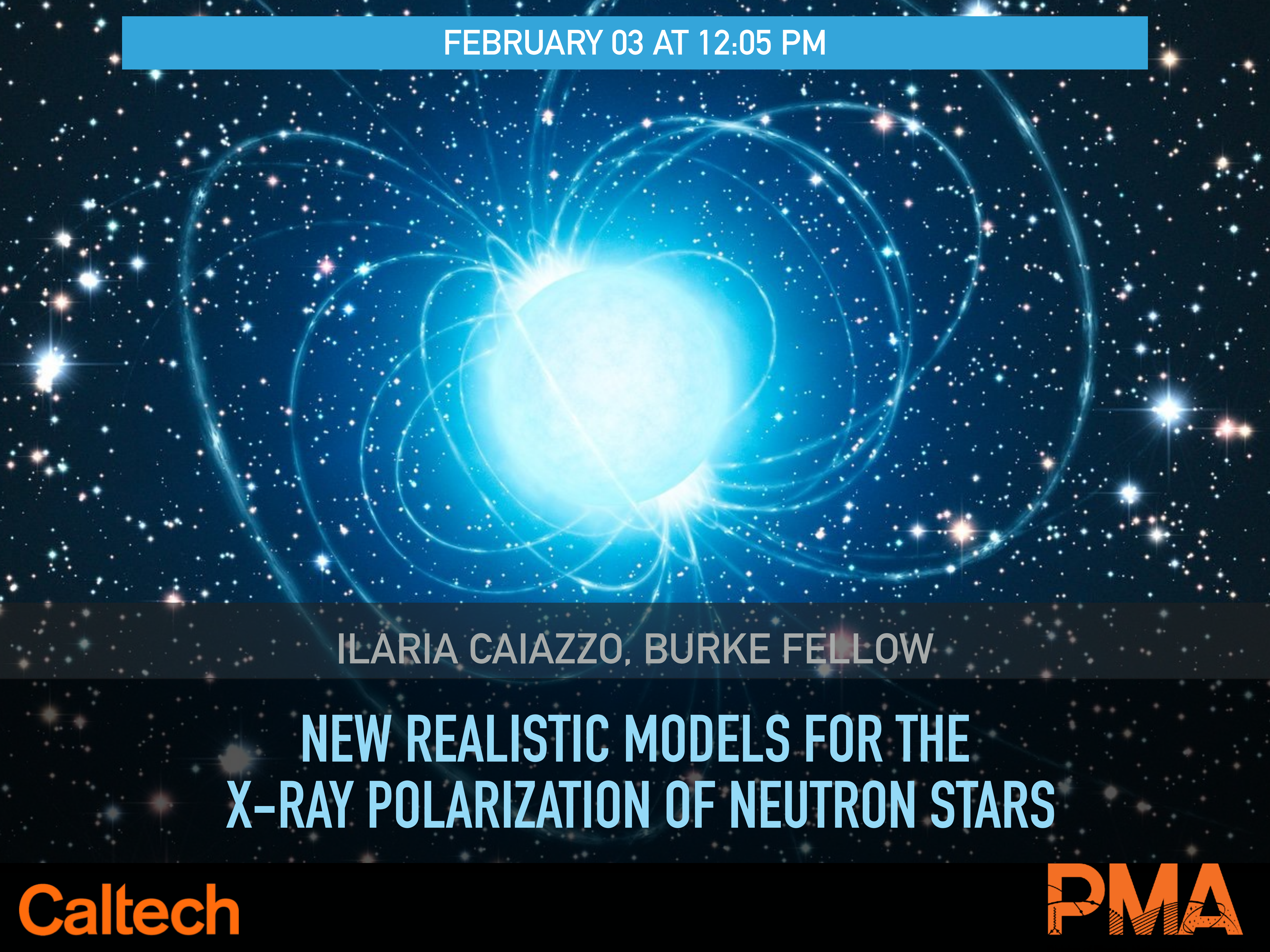
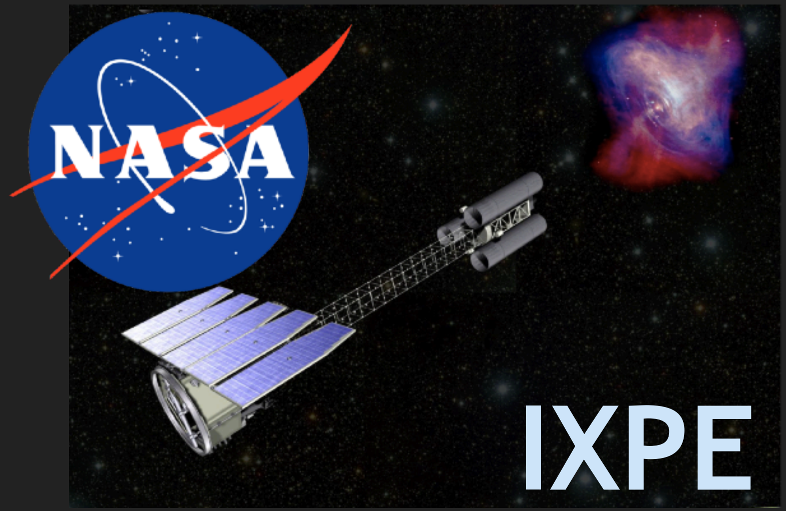

FEBRUARY 03 AT 12:05 PM
ILARIA CAIAZZO, BURKE FELLOW
NEW REALISTIC MODELS FOR THE
X-RAY POLARIZATION OF NEUTRON STARS
Caltech
PMA

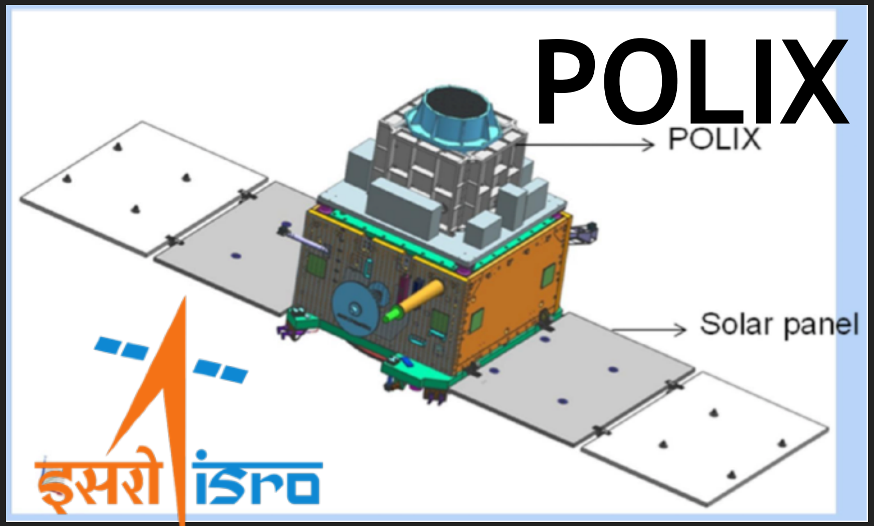
X-RAY POLARIMETRY – HAPPENING NOW!

Several X-ray missions that will have an X-ray polarimeter on board will be launched in the near future.

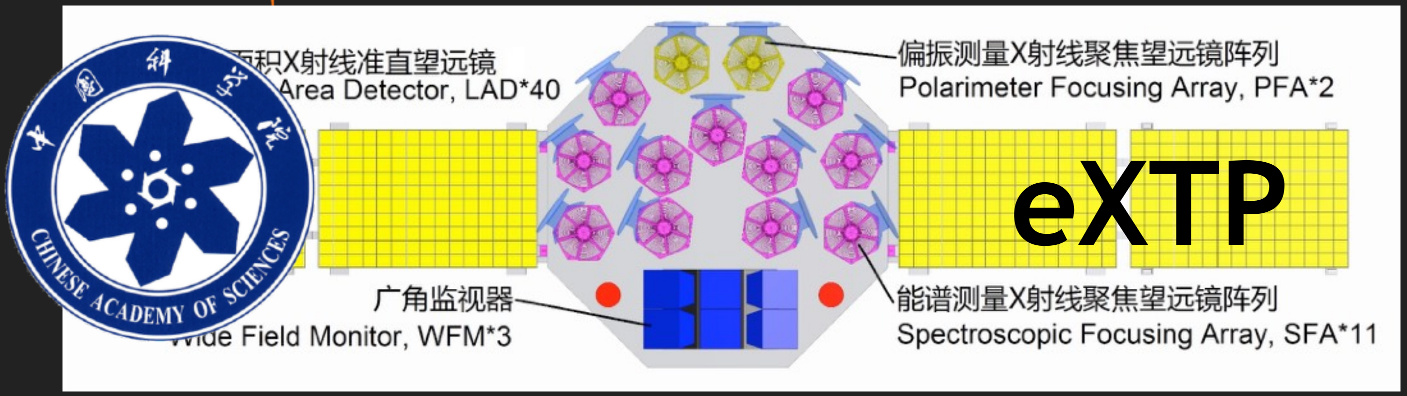
- **IXPE**, 2021



- **POLIX** ,2021



- **eXTP** 2027

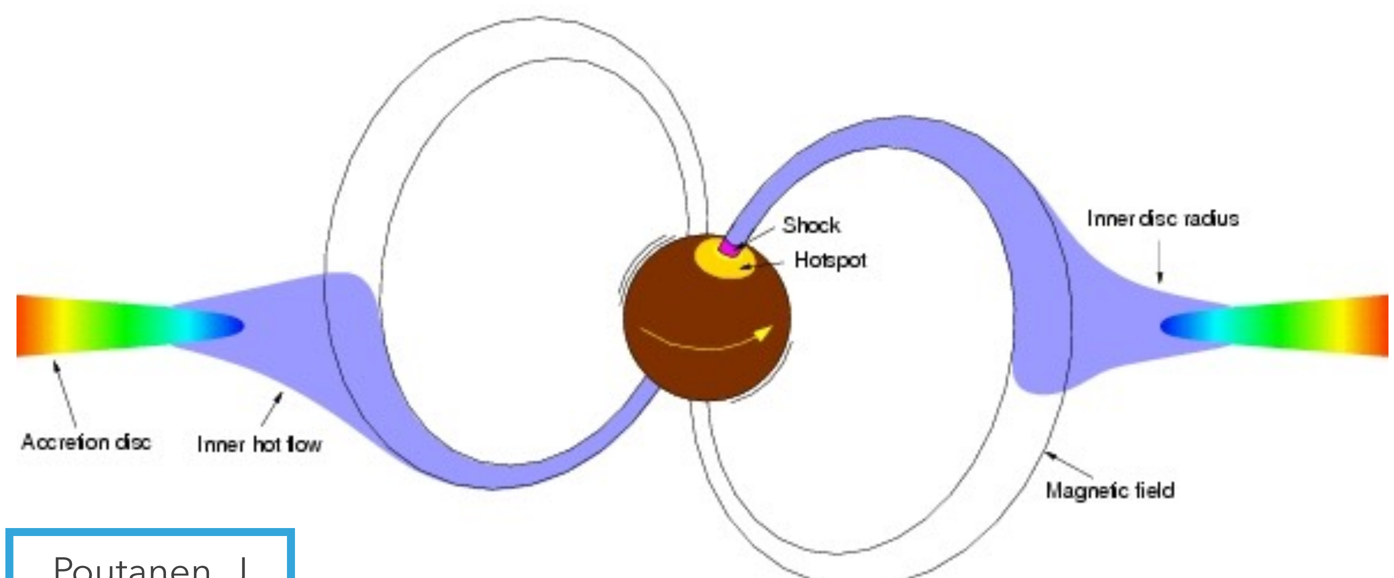


A few small missions are already getting exciting results:

- Ballon-born **X-Calibur**: quasi-detection X-ray pulsar GX 301-2
- CubeSat **Polarlight**: phase-resolved Crab

And others under development: XPP, PiSox, Lamp…

ACCRETING X-RAY PULSARS

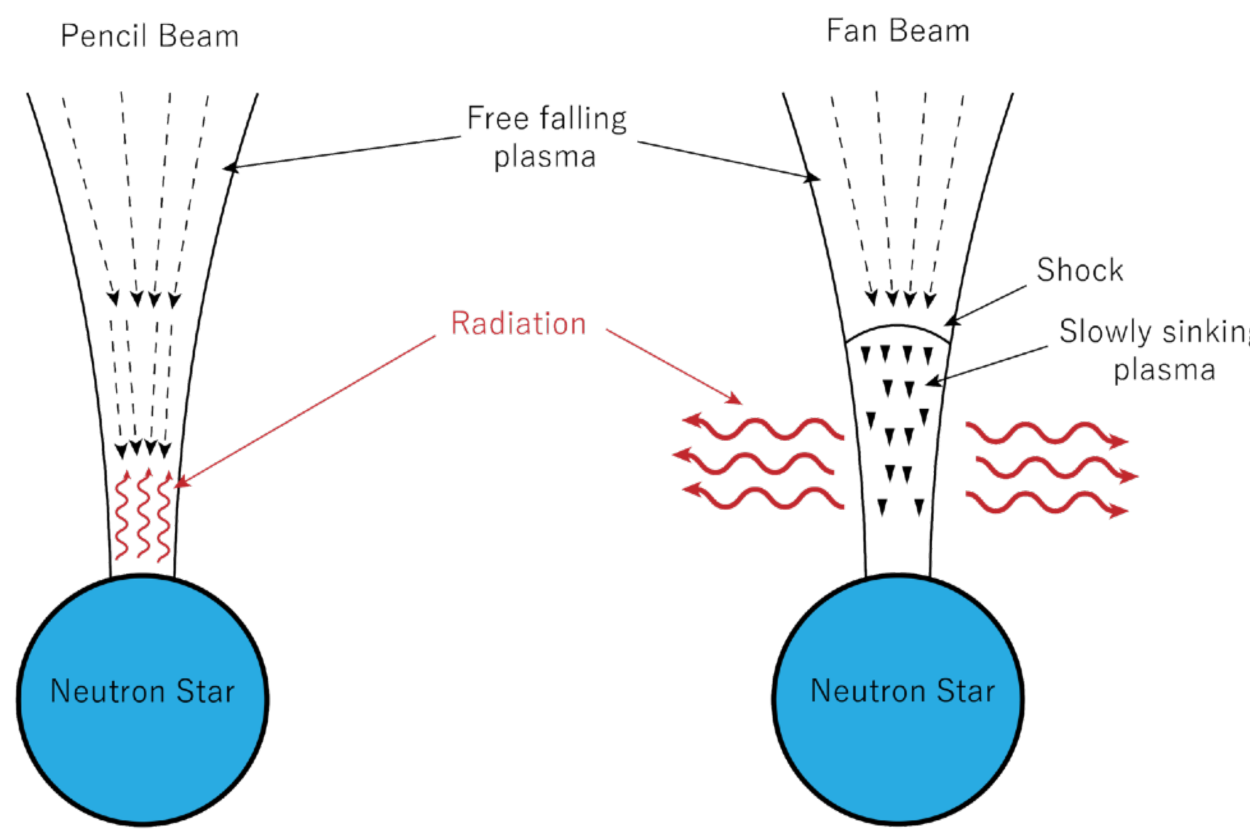


Poutanen, J

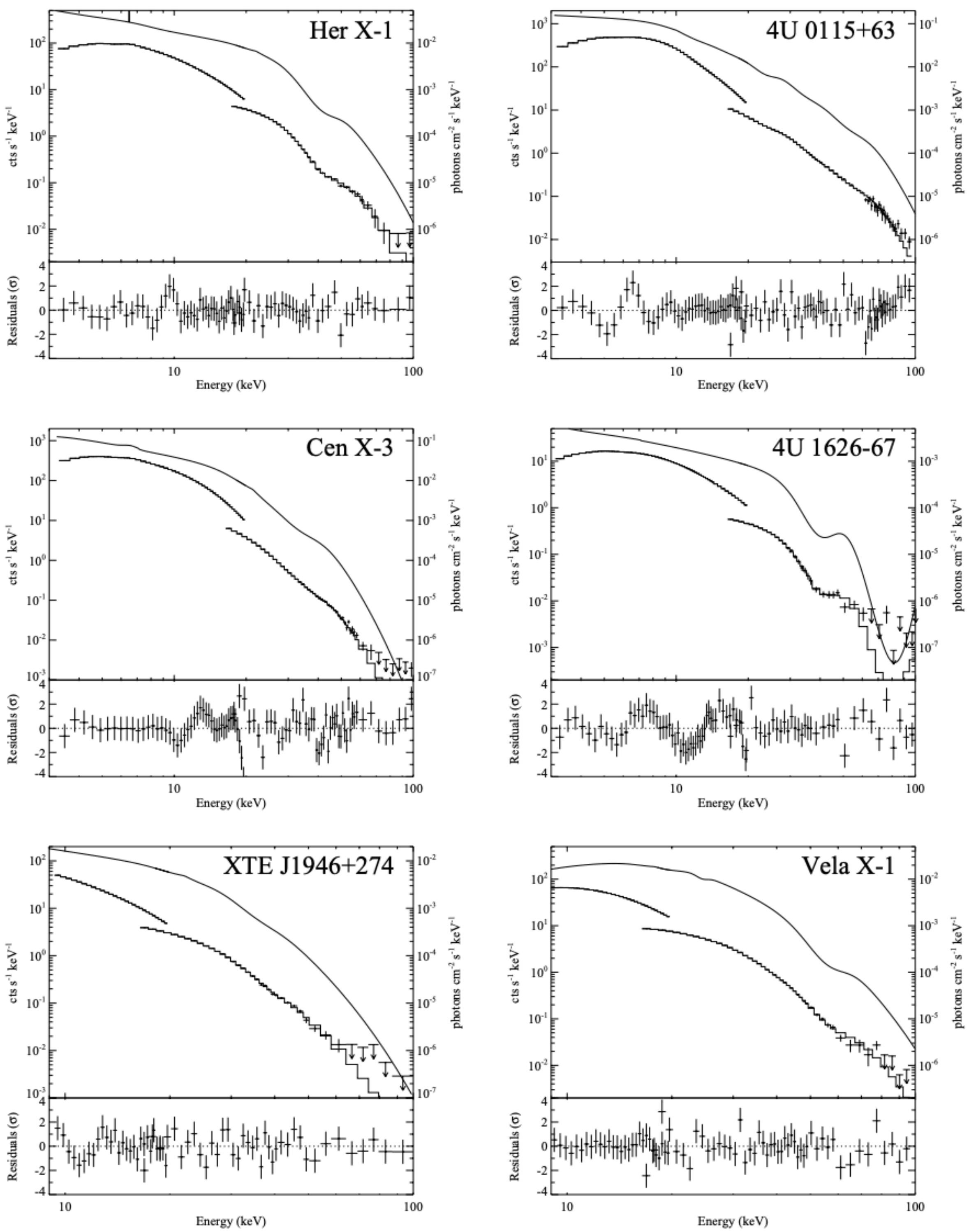
- Strongly magnetized: $B \sim 10^{12}\,\mathrm{G}$
- Accretion disk disrupted at the Alfvén radius, where the ram and magnetic pressure become comparable

$$R_A \sim 10^9\,\mathrm{cm} \sim 1{,}000\,\mathrm{R}_*$$

- At low L_X heat released deep in the atmosphere → hot spot
- At $L_X > L_{\rm crit} \sim 4 \times 10^{36}\,\mathrm{erg\,s^{-1}} \sim 0.03\,\mathrm{L_{Edd}}$ radiation dominated shock above the surface → accretion column



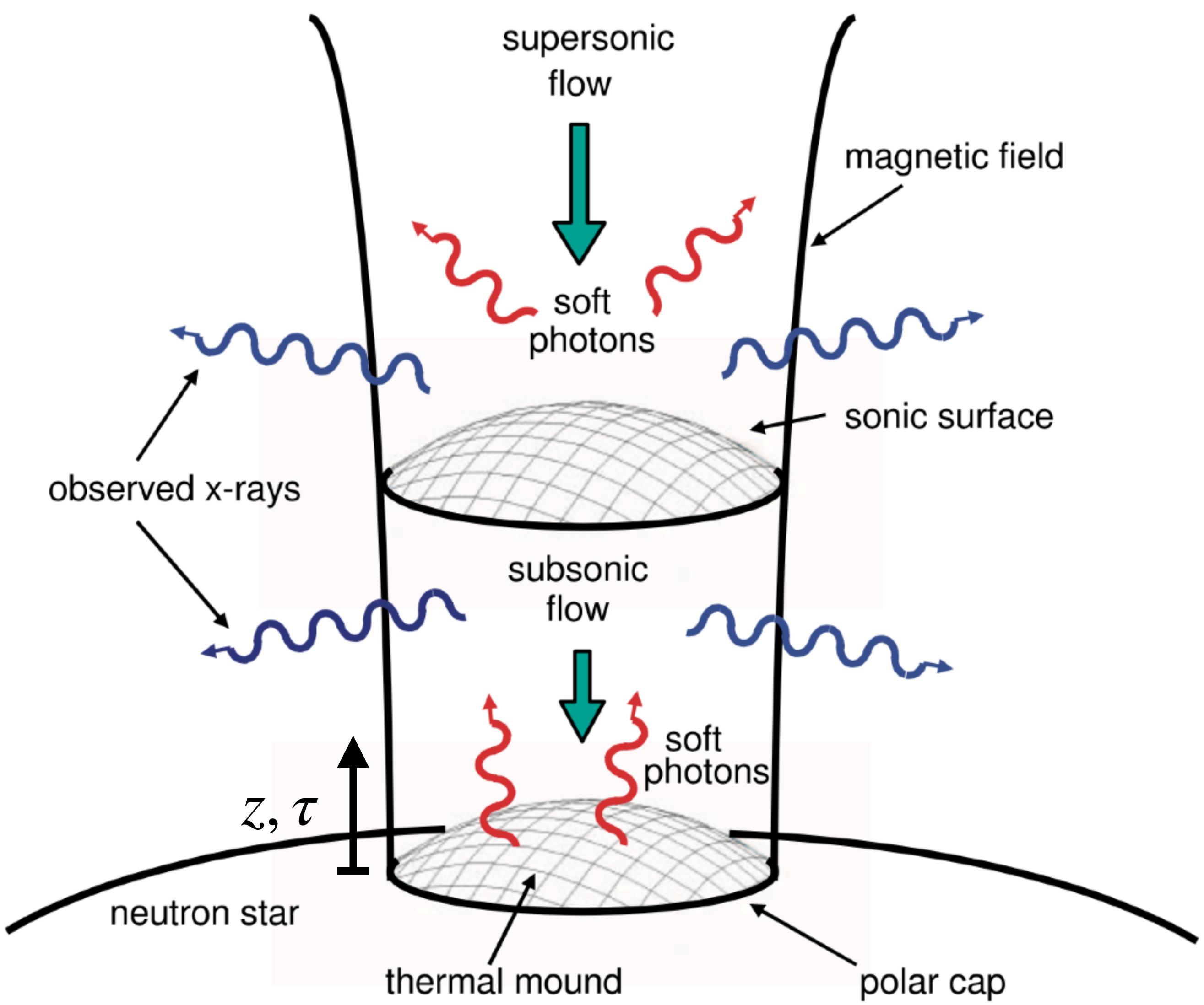
ACCRETING X-RAY PULSARS SPECTRA



- Very hard to find a physical model that explains the broad band X-ray emission of X-ray pulsars:
  - accretion regions are radiation-dominated → radiation transfer is coupled with the hydrodynamics of the flow
  - relativistic bulk motion in the infalling gas → hard to model Compton scattering
  - strong magnetic field → complicated cross sections for scattering and absorption

Coburn et al 2002

THE BECKER AND WOLFF MODEL



Becker and Wolff 2007

- Supersonic flow slowed down inside the column due to radiation pressure
- Seed photons: blackbody, bremsstrahlung and cyclotron
- Thermal mound: photosphere for BB photons
- Compton scattering: *bulk* and *thermal* Comptonization
  - *bulk*: photons gain energy interacting with electrons that are part of a converging flow (first order Fermi energization, Blanford & Payne, 1981)
  - *thermal*: stochastic motion (Kompaneets equations)

THE BECKER AND WOLFF MODEL

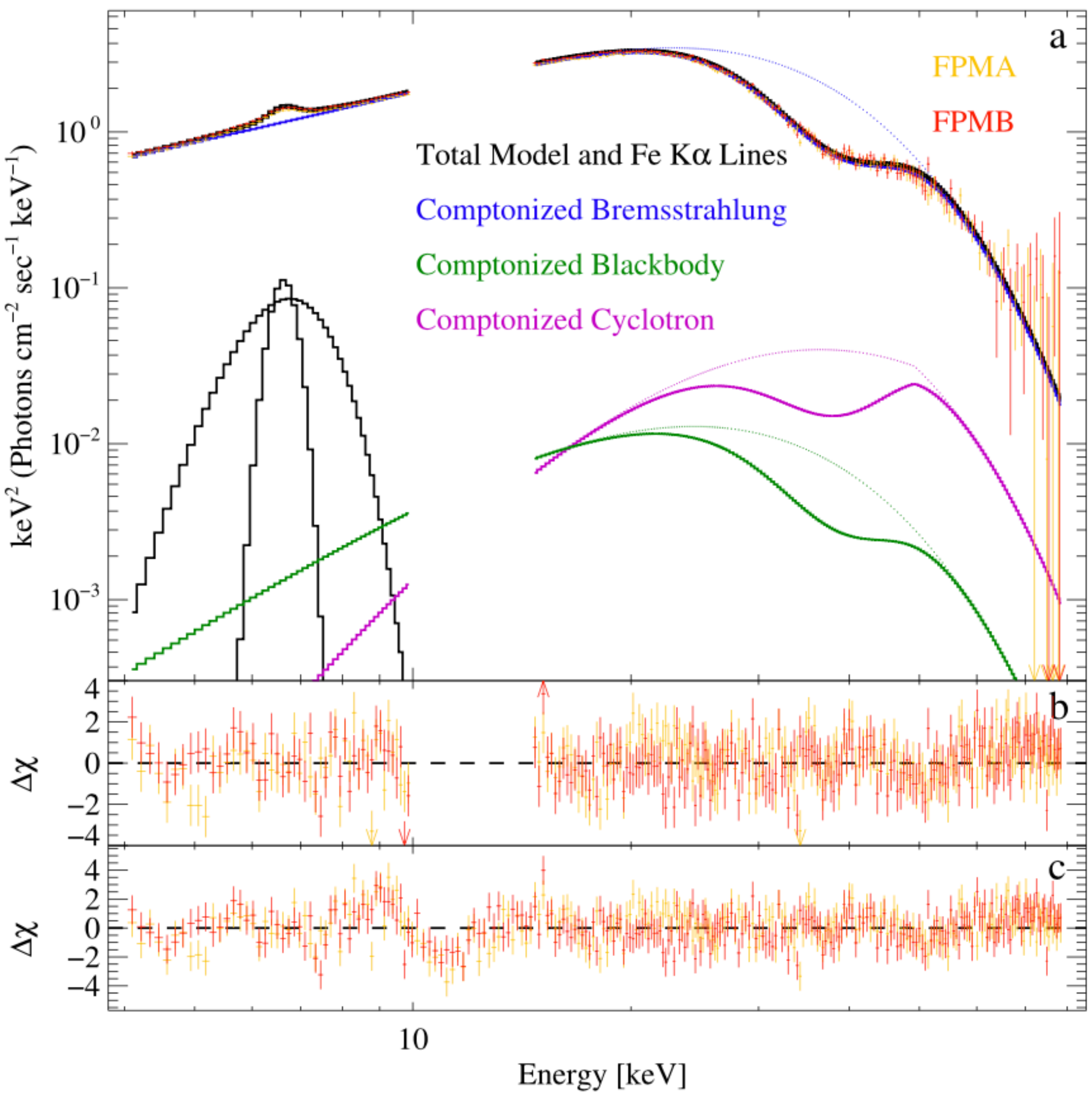


Table 1
Her X-1 XSPEC Model Parameters

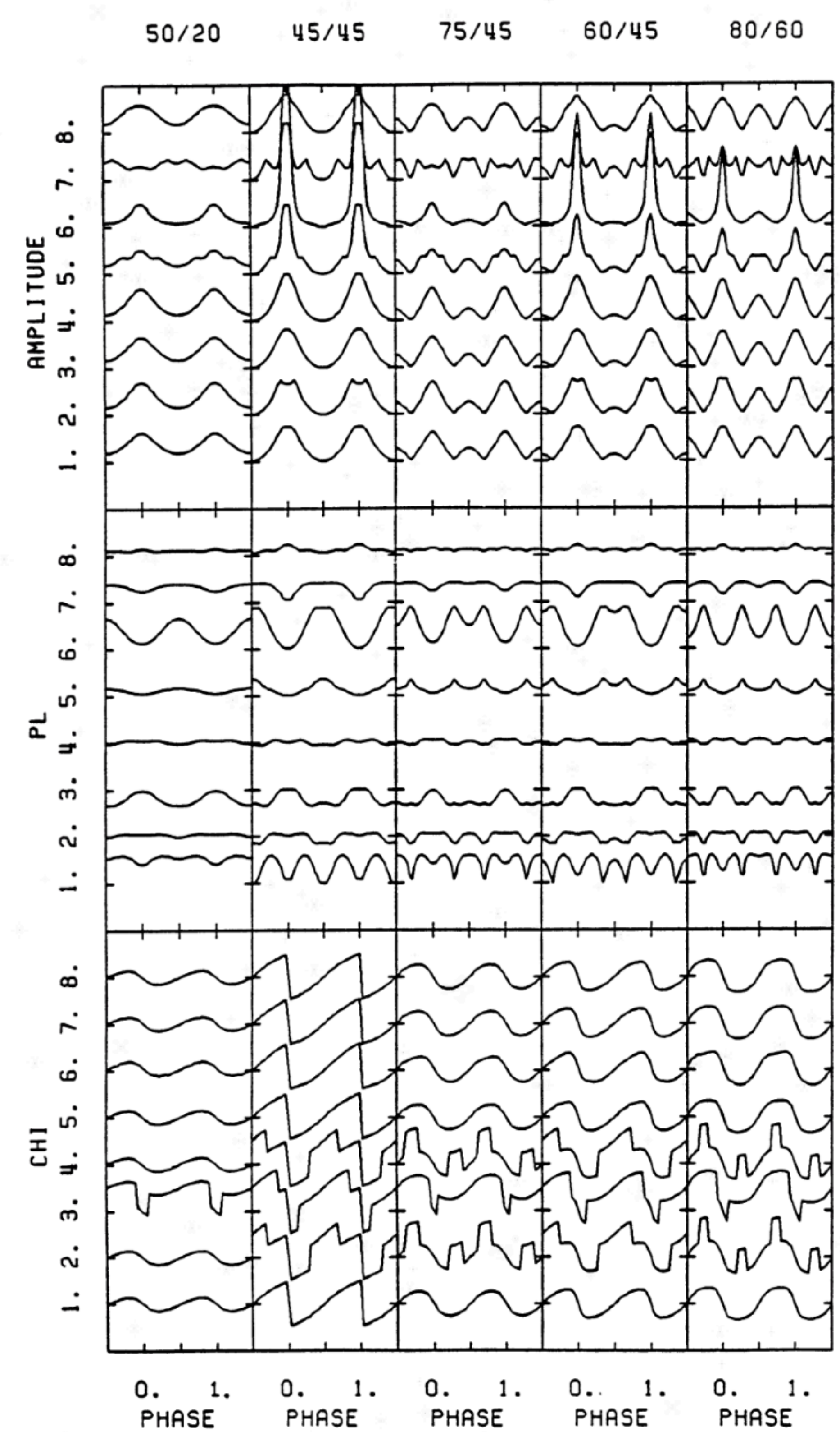
Parameter	Value
N_H (cm^{-2})	1.7×10^{20} (Fixed)
Distance (kpc)	6.6 (Fixed)
$\dot{M}$ (g s^{-1})	2.5935×10^{17} (Fixed)
kT_e (keV)	$4.58^{+0.07}_{-0.07}$
r_0 (m)	$107.0^{+1.7}_{-1.8}$
B (Gauss)	4.25×10^{12} (Tied to E_{CRSF})
$\sigma_\perp$ (σ_T)	1.0 (Fixed)
$\sigma_\parallel$ (σ_T)	$5.20^{+0.08}_{-0.07} \times 10^{-5}$
$\bar{\sigma}$ (σ_T)	$3.5^{+0.2}_{-0.2} \times 10^{-4}$
E_{CRSF} (keV)	$37.7^{+0.2}_{-0.2}$
σ_{CRSF} (keV)	$7.1^{+0.2}_{-0.2}$
τ_{CRSF}	$0.98^{+0.06}_{-0.06}$
E (FeKα_n) (keV)	$6.61^{+0.02}_{-0.02}$
σ (FeKα_n) (keV)	$0.26^{+0.03}_{-0.04}$
A(FeKα_n)[a]	$0.0029^{+0.0006}_{-0.0006}$
E (FeKα_b) (keV)	$6.53^{+0.07}_{-0.08}$
σ (FeKα_b) (keV)	$0.90^{+0.21}_{-0.14}$
A(FeKα_b)[a]	$0.0043^{+0.0005}_{-0.0005}$
C_{FPM}	$1.037^{+0.002}_{-0.002}$
χ^2/dof	545.55/450
Flux (5–60 keV) (erg cm^{-2} s^{-1})	$6.96^{+0.01}_{-0.01} \times 10^{-9}$

Note.
[a] Normalization units: photons cm^{-2} s^{-1} in the line.

Wolff et al 2016

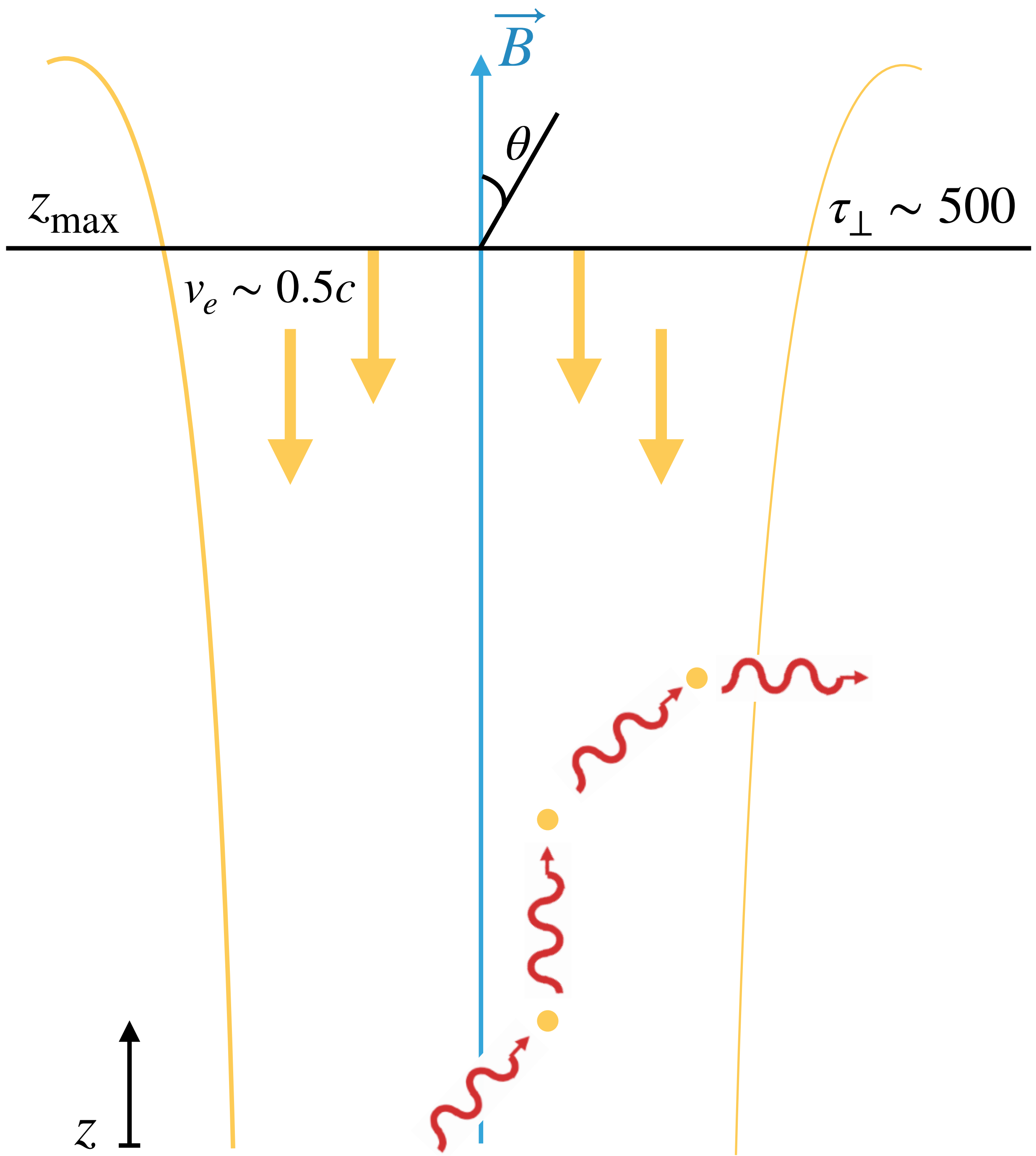
X-RAY PULSARS POLARIZATION MODELS

- Only available models are from 1985: Meszaros and Negel 1985
- Solve radiative transfer for each polarization mode
- Slab or cylinder of static, homogeneous atmosphere: constant ρ, T, B; v=0
- No relativistic effect (plasma impacting at ~0.5 c)
- Derived spectra do not fit recent observation of X-ray pulsars



NEW POLARIZATION MODELS: CAIAZZO & HEYL 2020

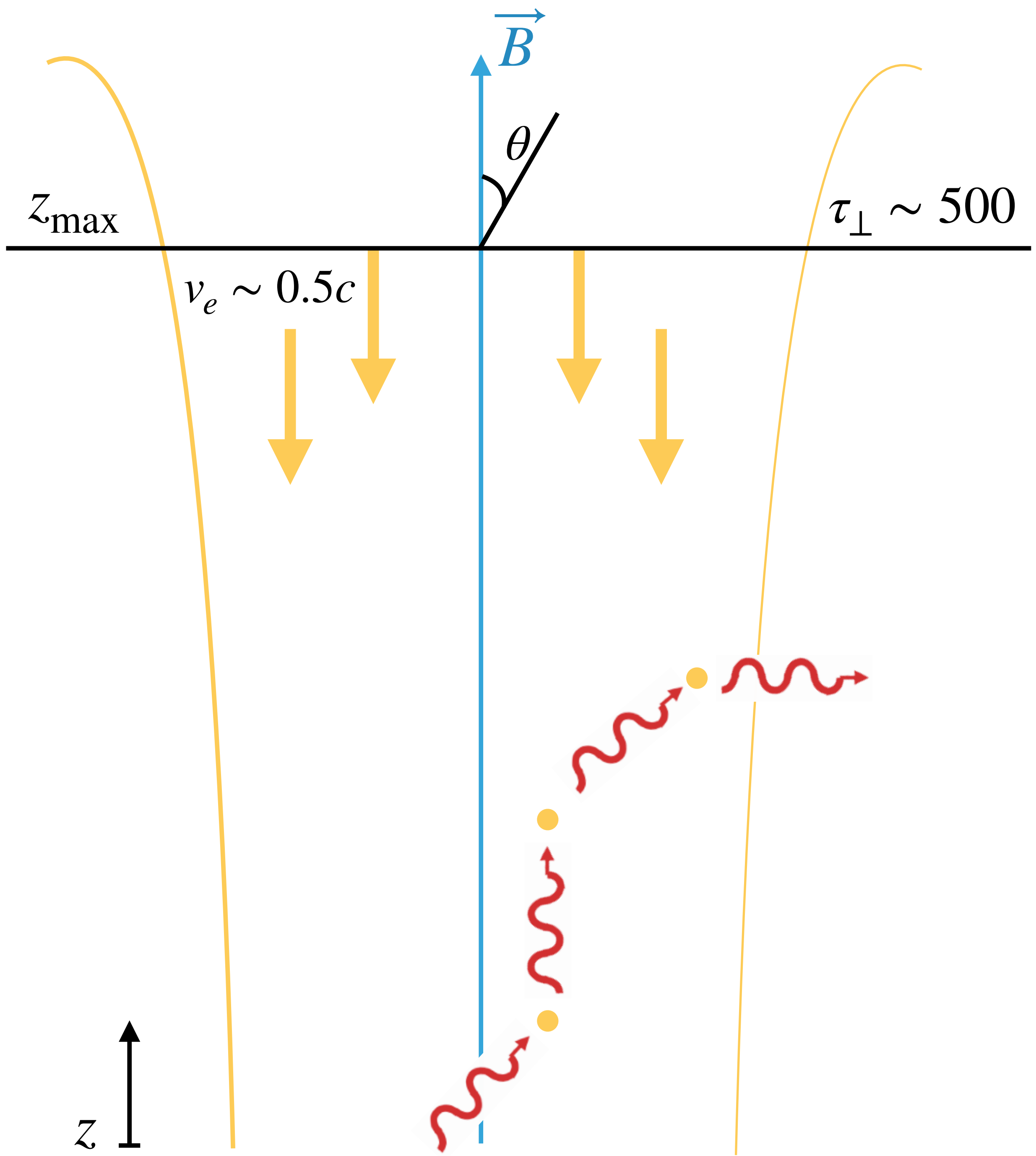
- Based on the Becker and Wolff spectral formation model: same assumptions on the column

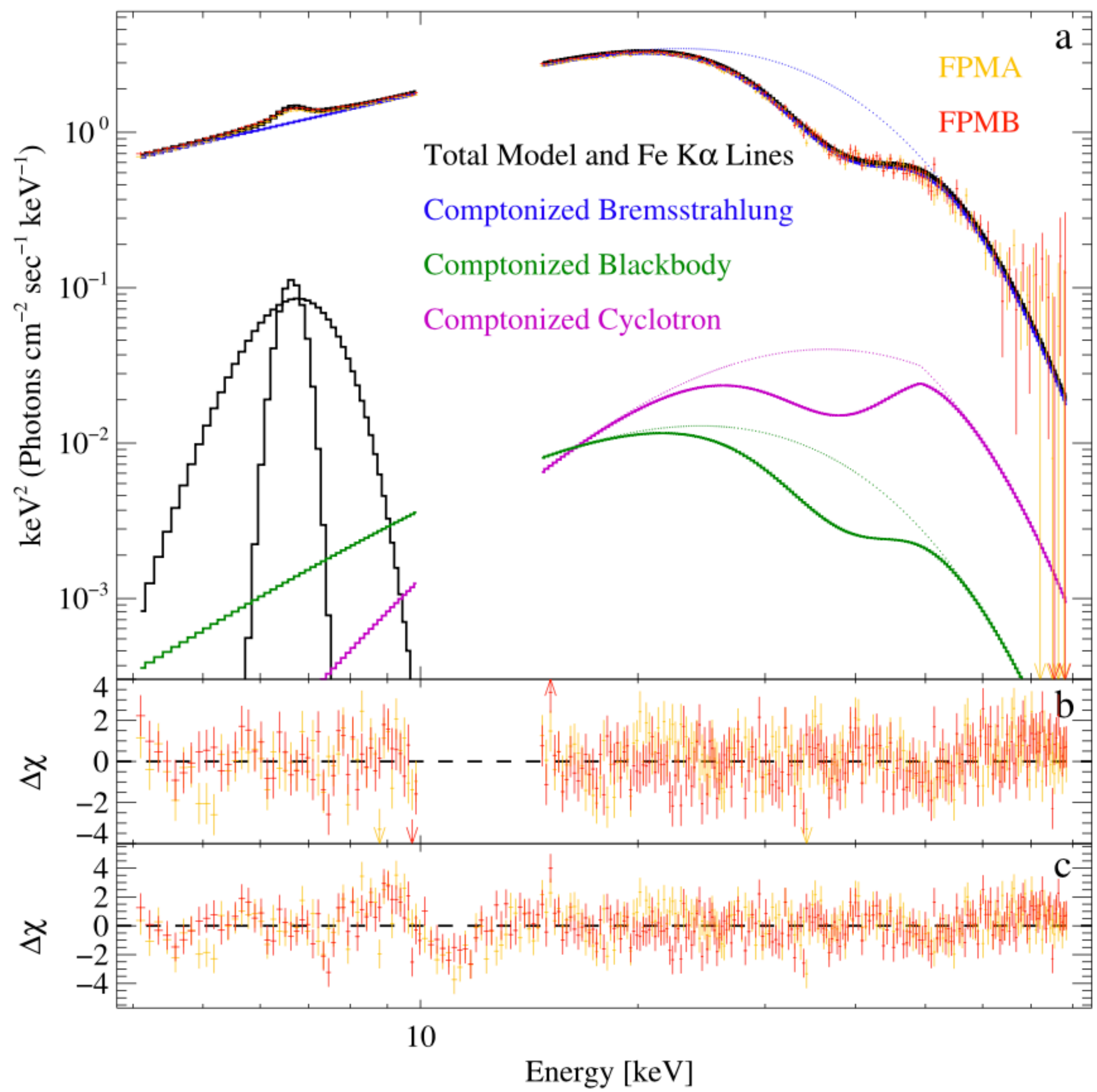


- Polarization calculated independently of radiation transfer
- Take into account **macroscopic structure** and **dynamics** of the accretion column
- Calculate the changes that happen during the propagation of the radiation toward the observer, including the effects of **relativistic beaming**, **gravitational lensing** and **quantum electrodynamic**
- Calculations are exact and fully analytical, therefore easy fit to data

POLARIZATION INSIDE THE COLUMN

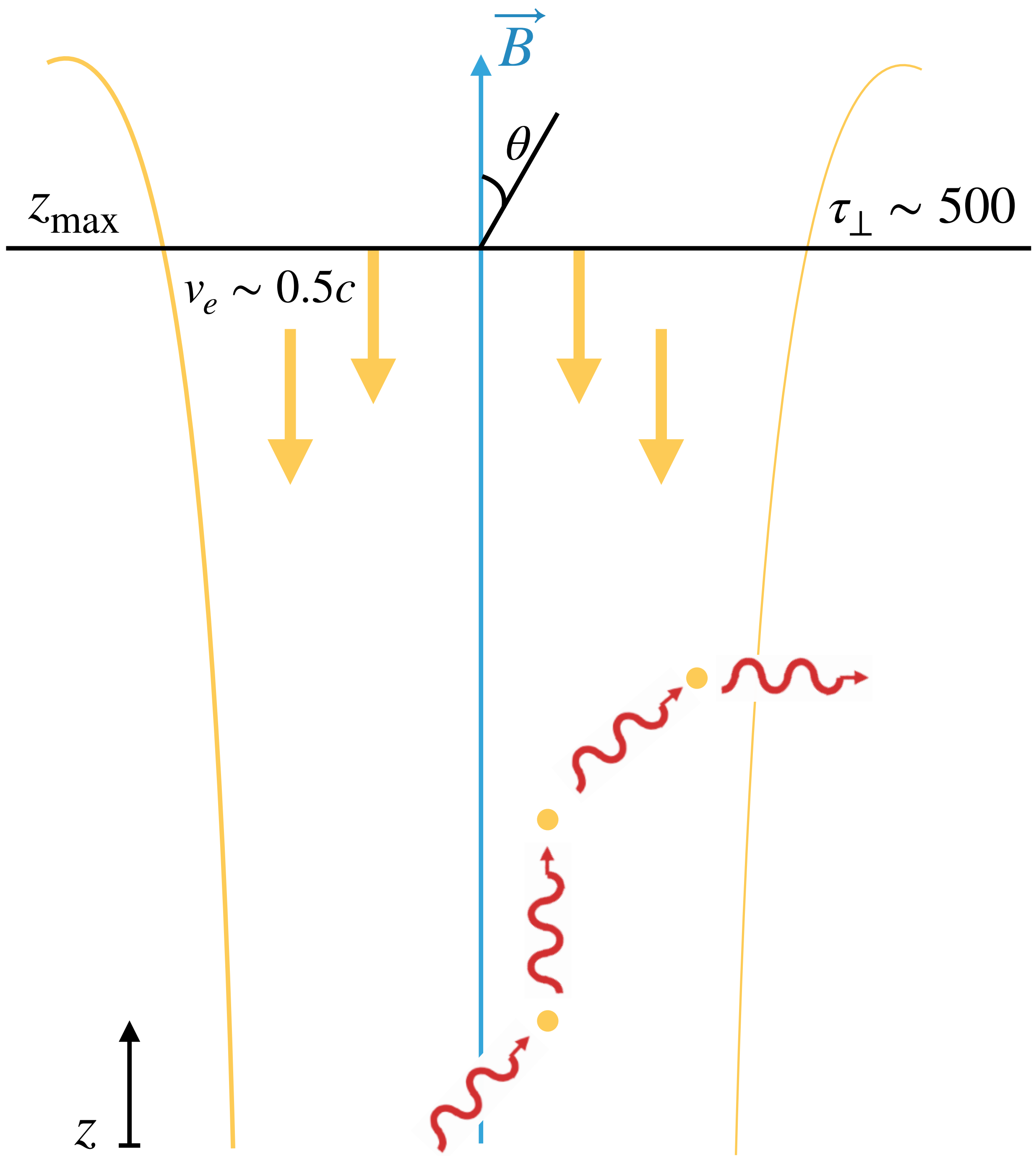
- Seed photons inside the column are scattered by the infalling electrons

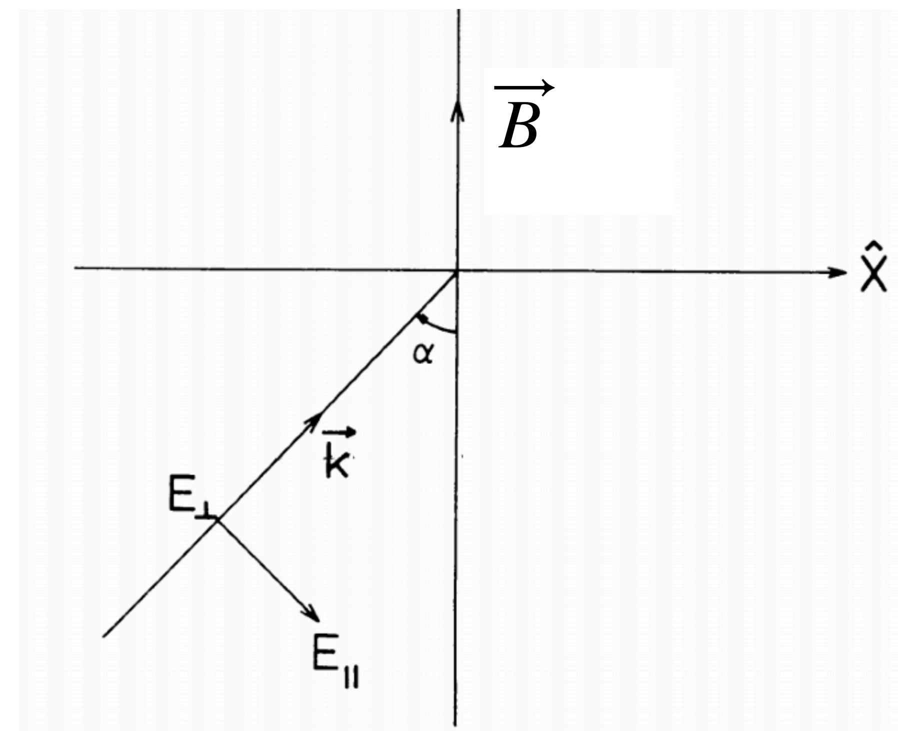




POLARIZATION INSIDE THE COLUMN

- Scattering dominated by the strong magnetic field: electrons forced to move parallel to the field





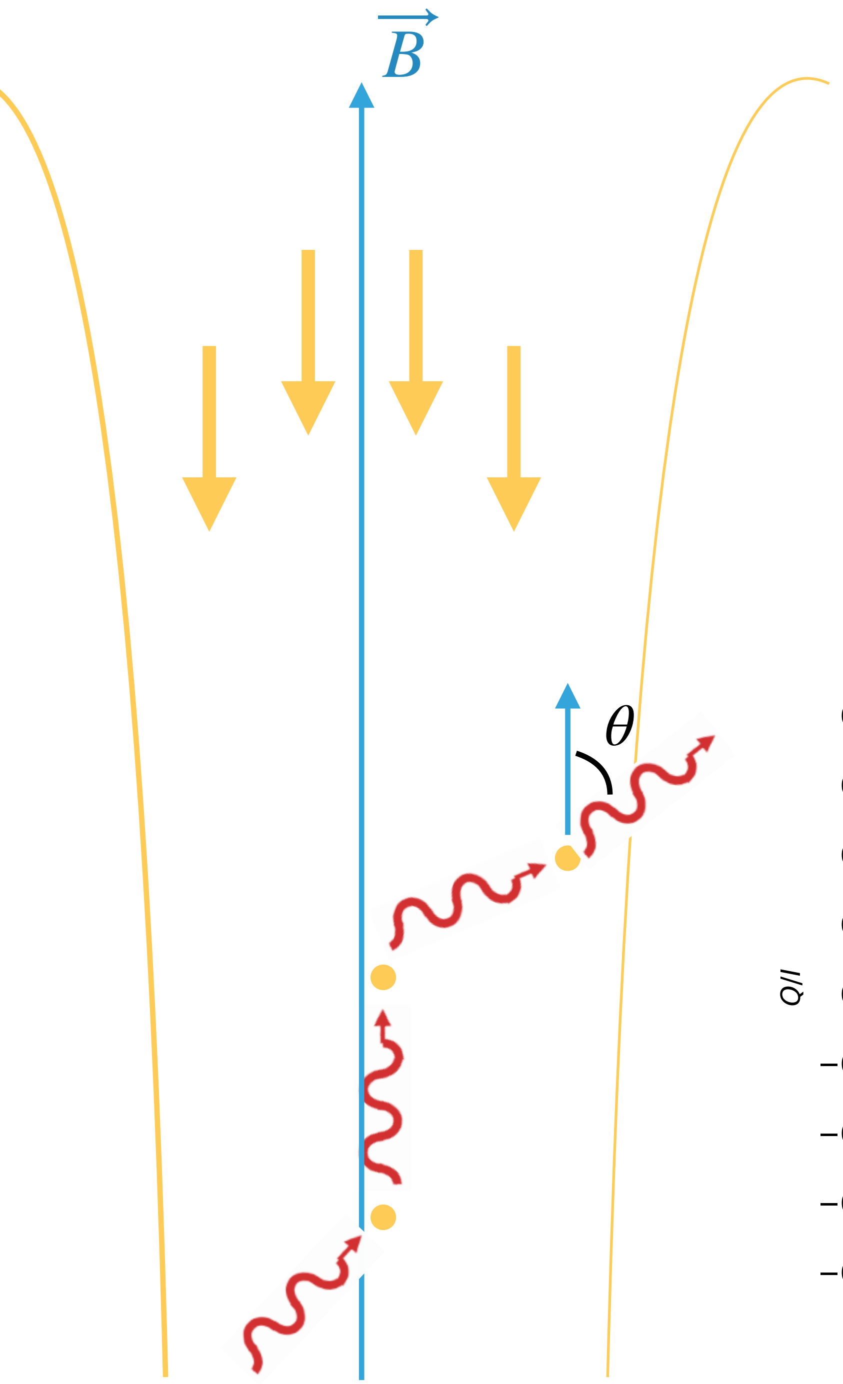
- For each scattering, the average change in Stokes parameters can be expressed by:

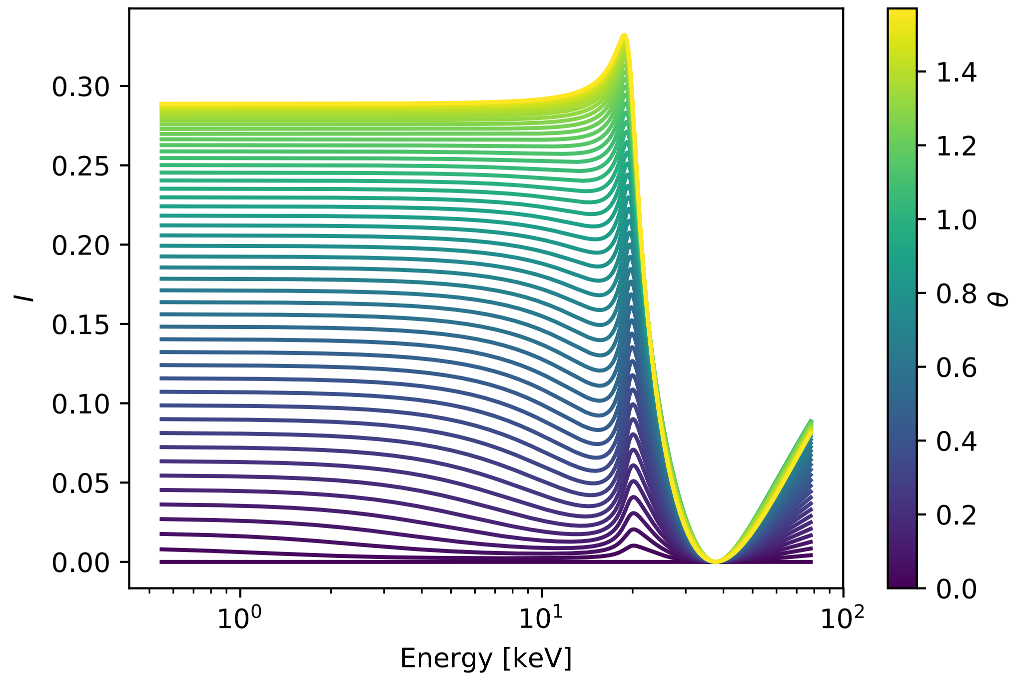
$$\mathbf{S}' = \mathbf{M} \cdot \mathbf{S}$$

where $\mathbf{S} = (I, Q, U, V)$ and

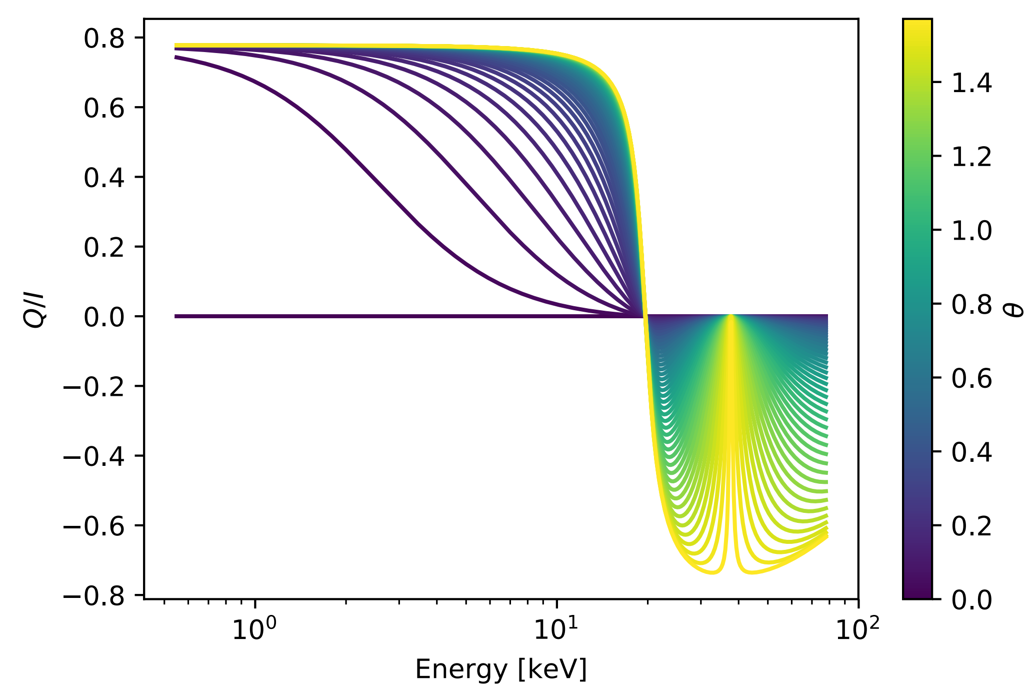
$\mathbf{M} = \mathbf{M}(\alpha, \theta, E_p, B)$ is a 4x4 matrix

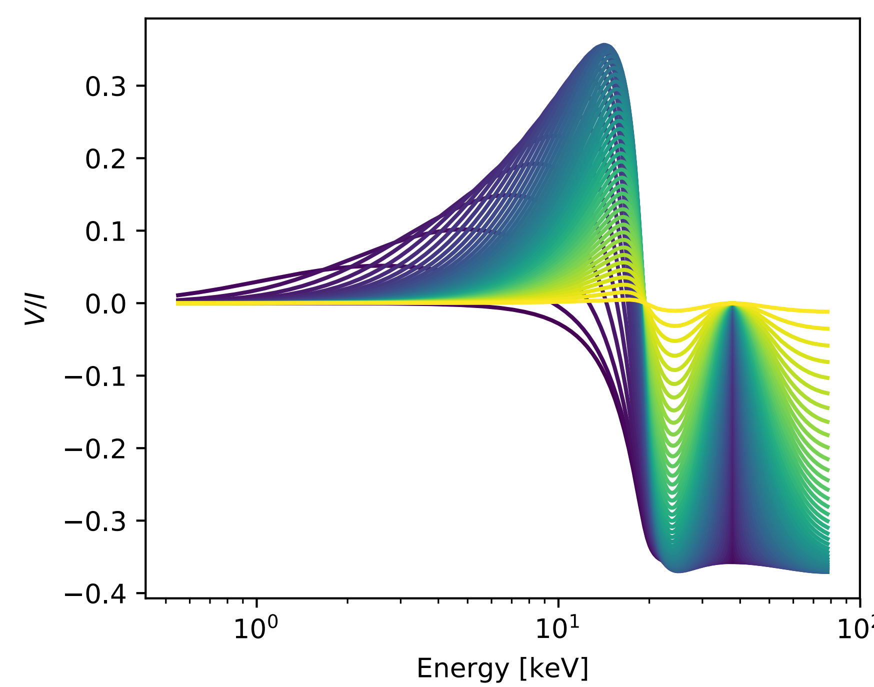
POLARIZATION INSIDE THE COLUMN





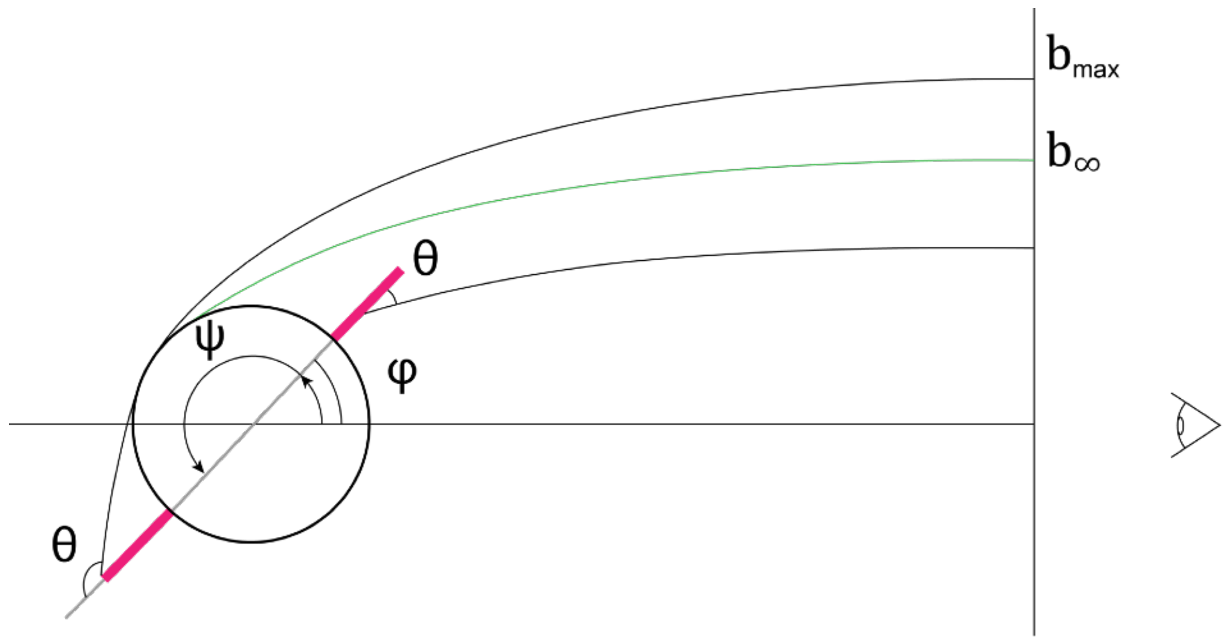
- This is just to show the beaming pattern, the total phase-averaged flux is the one from the B&W model

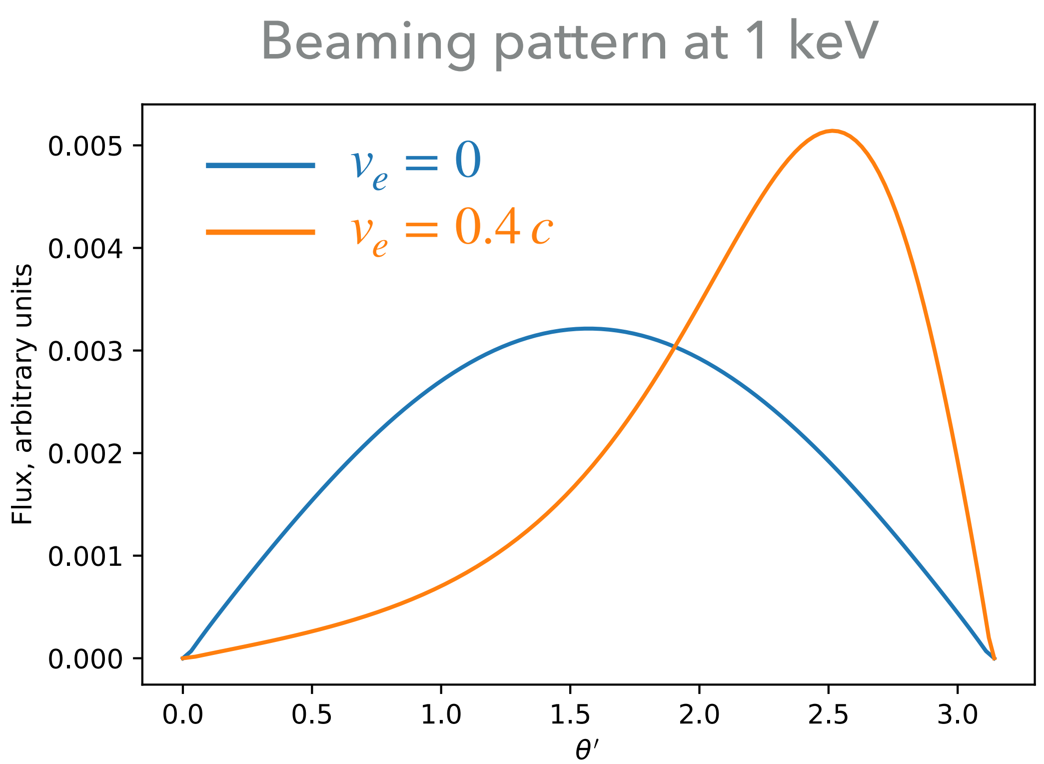


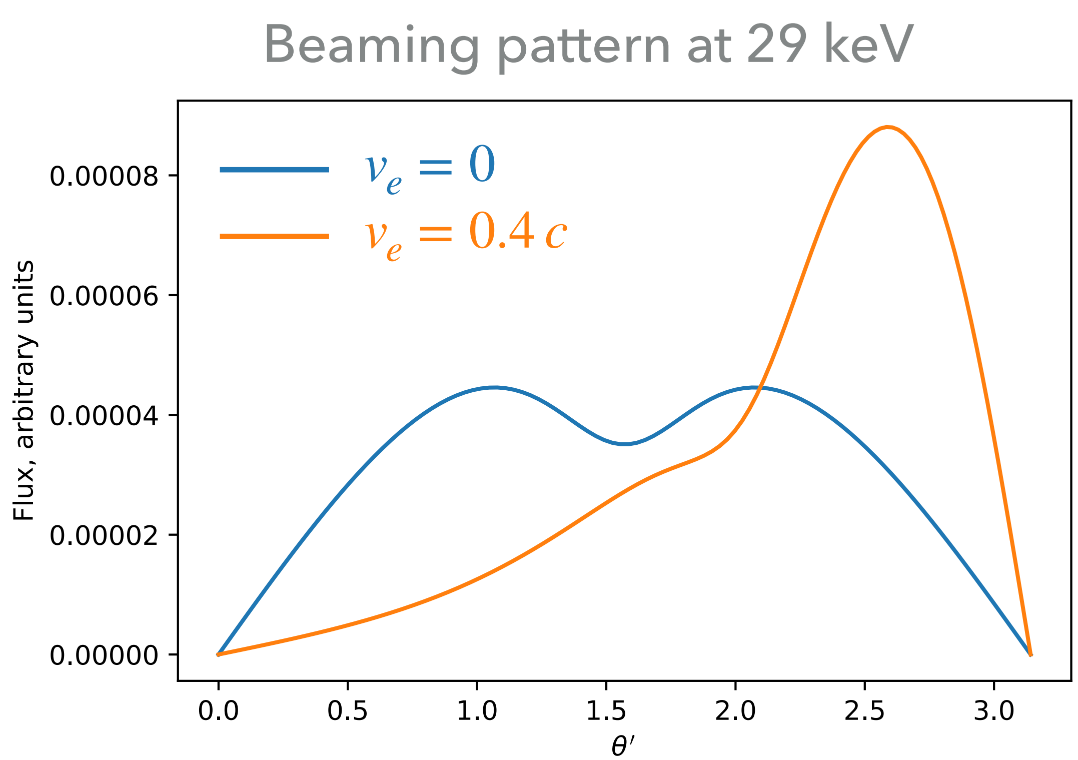


RELATIVISTIC EFFECTS

- Relativistic beaming and aberration: depends on the speed of the electrons and therefore on the height along the column
- Gravitational lensing: we see the columns from the front and from the back, magnification of the back column



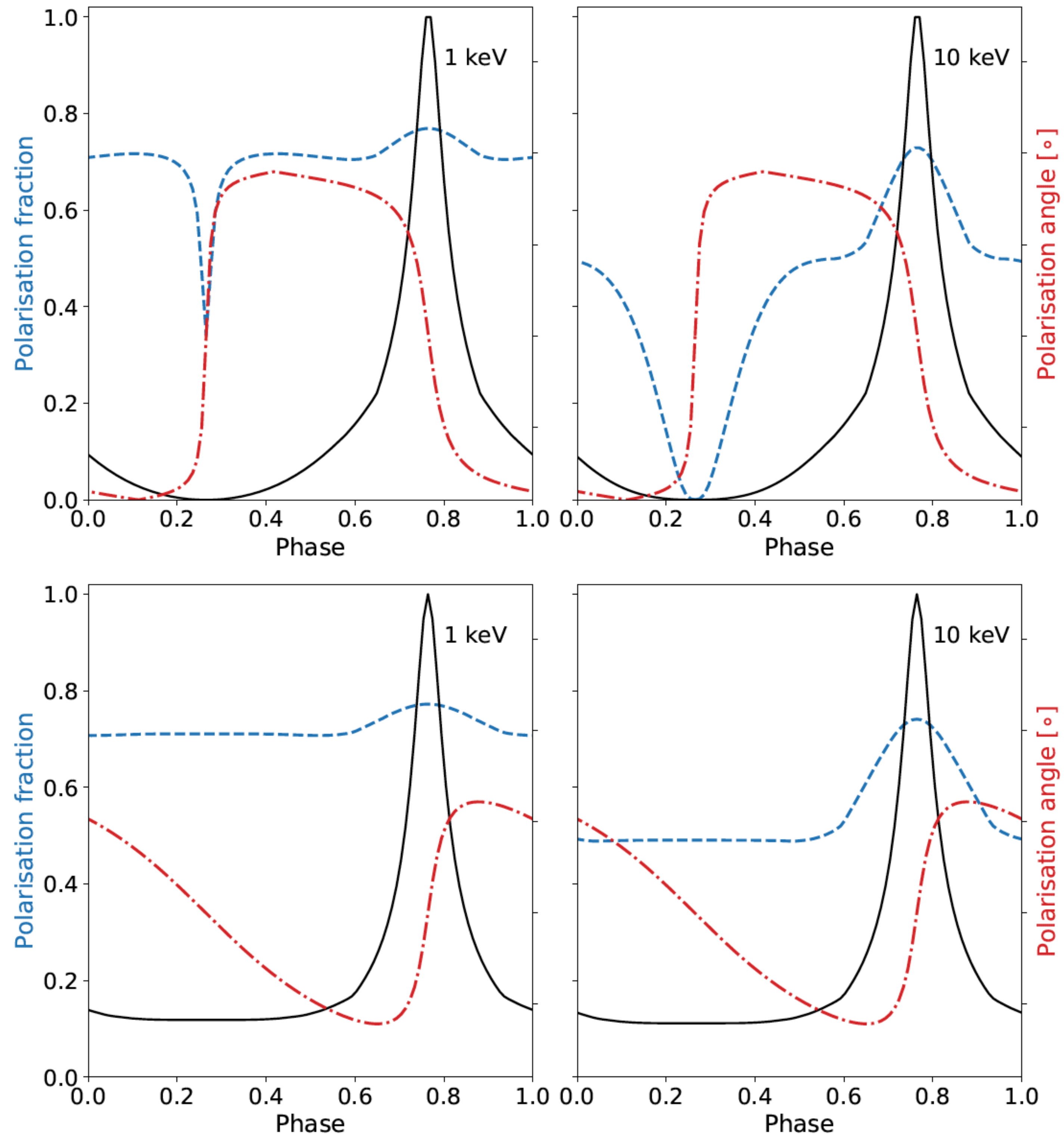




+ QED EFFECT : VACUUM BIREFRINGENCE

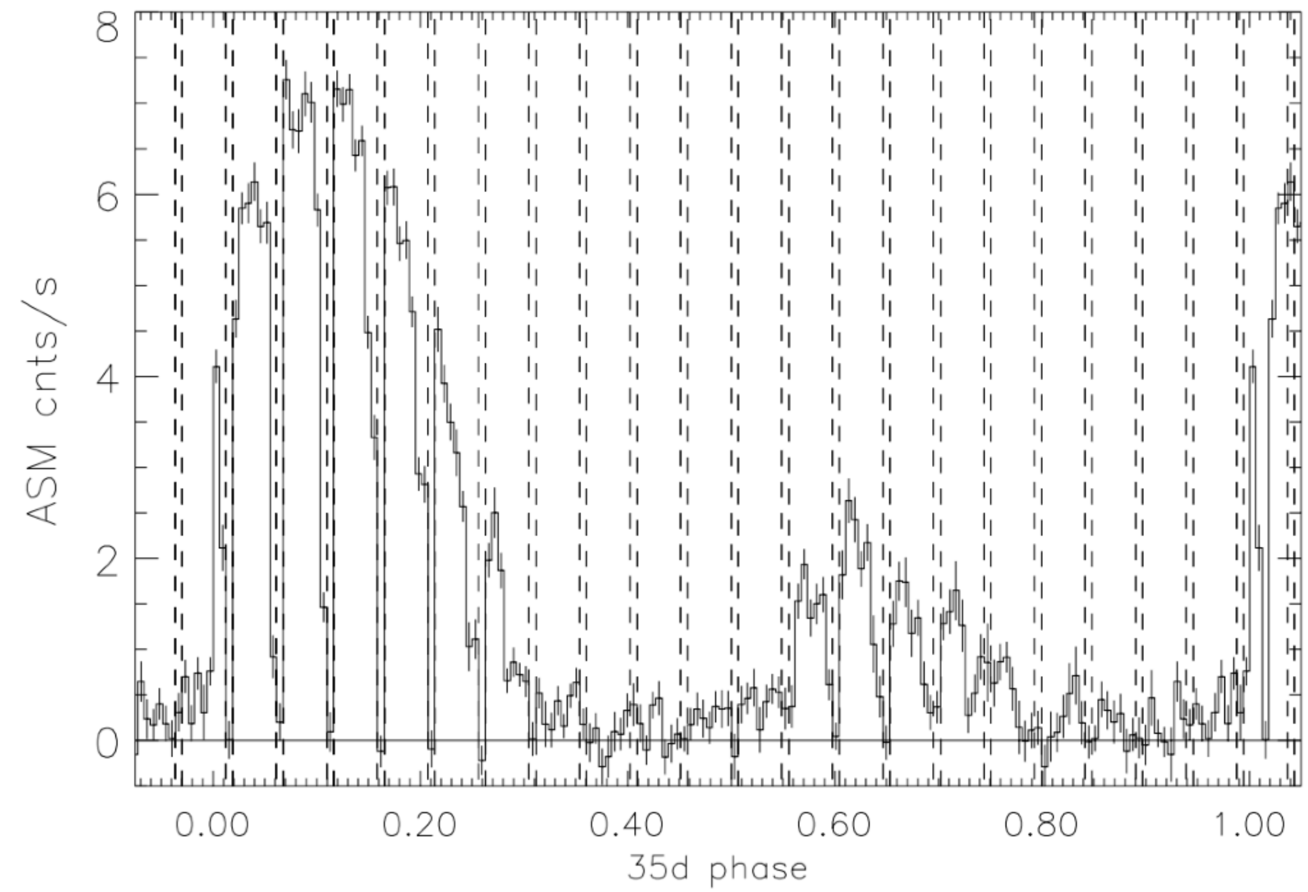
POLARIZATION SIGNAL AT THE OBSERVER

- Prediction of the polarization signal: linear polarization fraction and angle with phase
- Prediction of the beaming pattern and cyclotron energy variation with phase
- For different geometries and different parameters can be fitted to observed data as: strength of the field, radius of the column, height of the column, accretion rate…

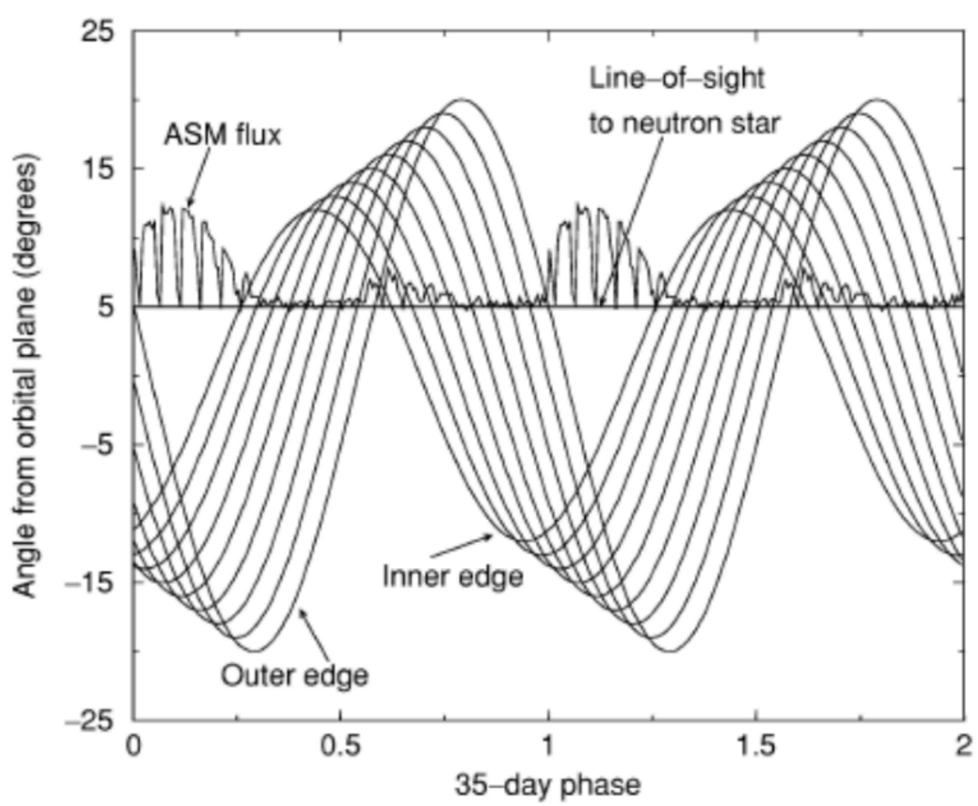


HERCULES X-1

- Accreting X-ray pulsar with a ~2 $M_\odot$ A-type companion, HZ Her
- Neutron star pulsations: 1.24 s period
- Eclipses: 1.7 d period
- Additional 35 d X-ray flux cycle
    - Disk precession



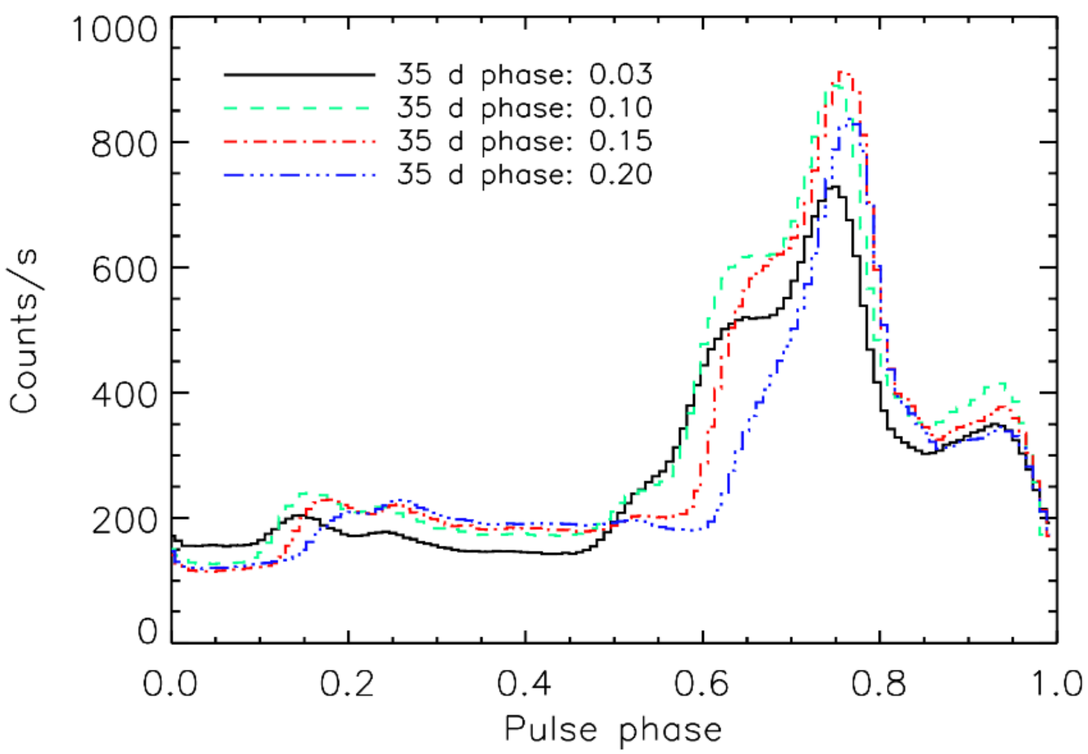
RXTE, Scott & Leahy 1999



Leahy 2002

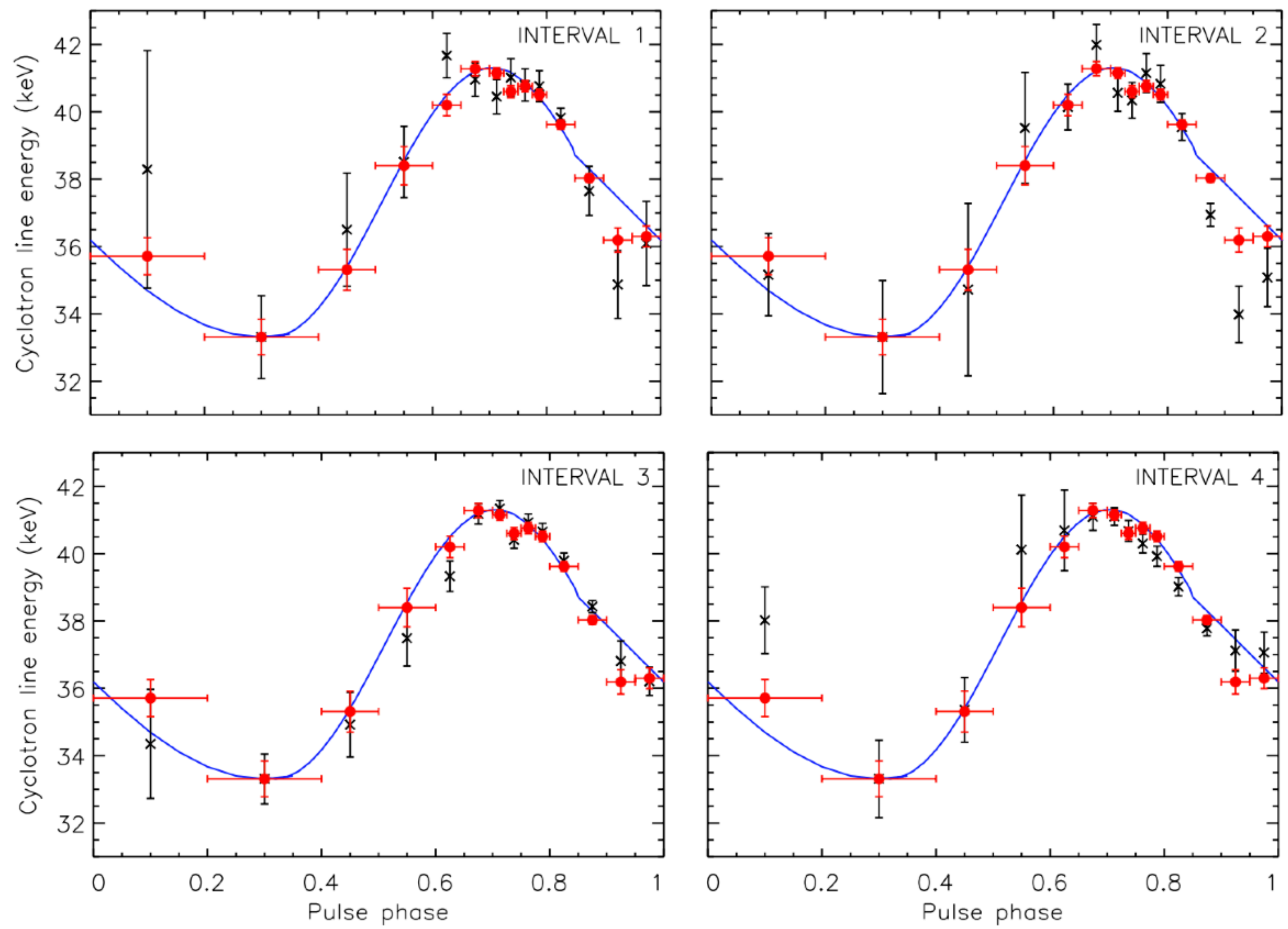
HERCULES X-1

- Pulse profile



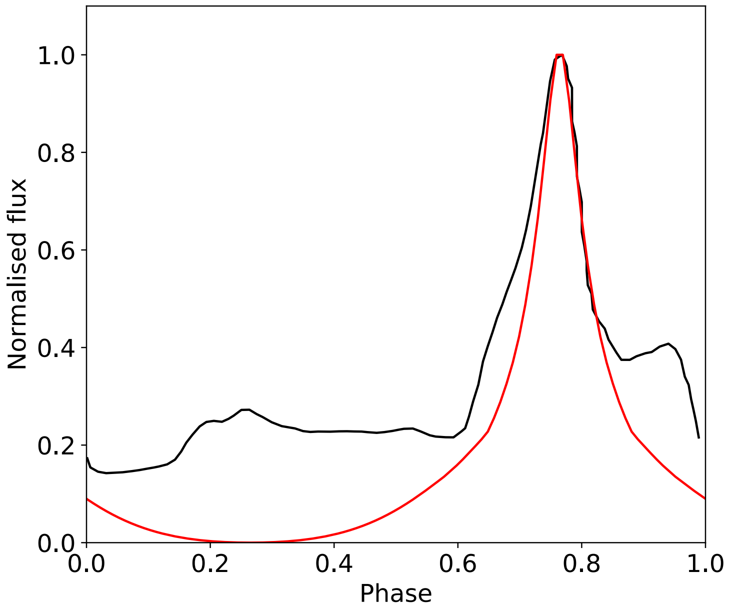
Vasco et al 2013

- Cyclotron line energy modulation

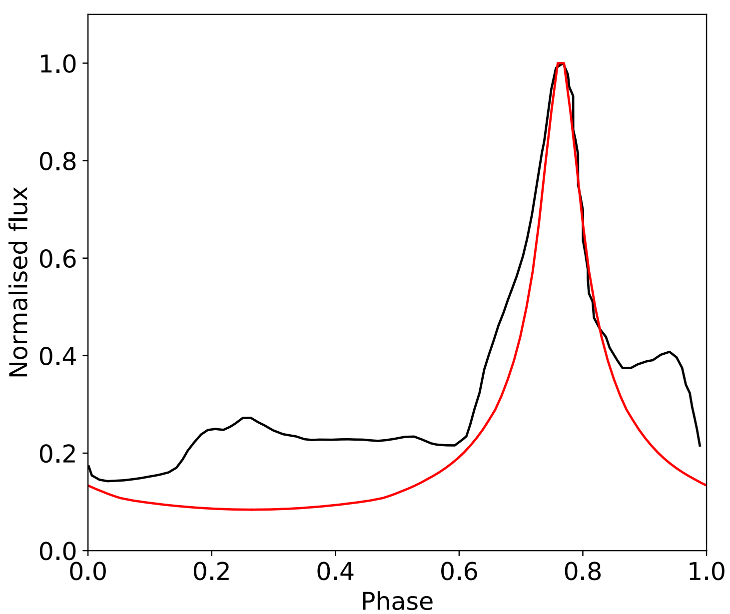


CAIAZZO & HEYL MODEL - PULSE PROFILE

- One column

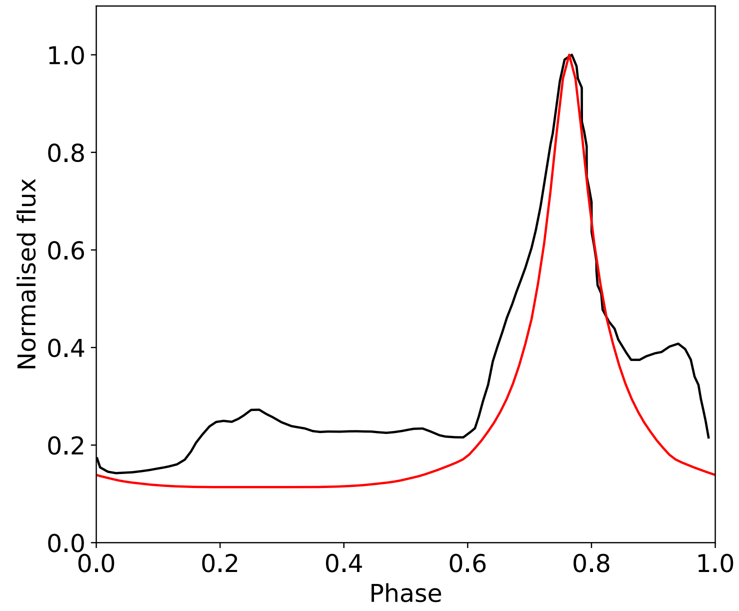


$\alpha = 83^\circ \ \beta = 86^\circ$

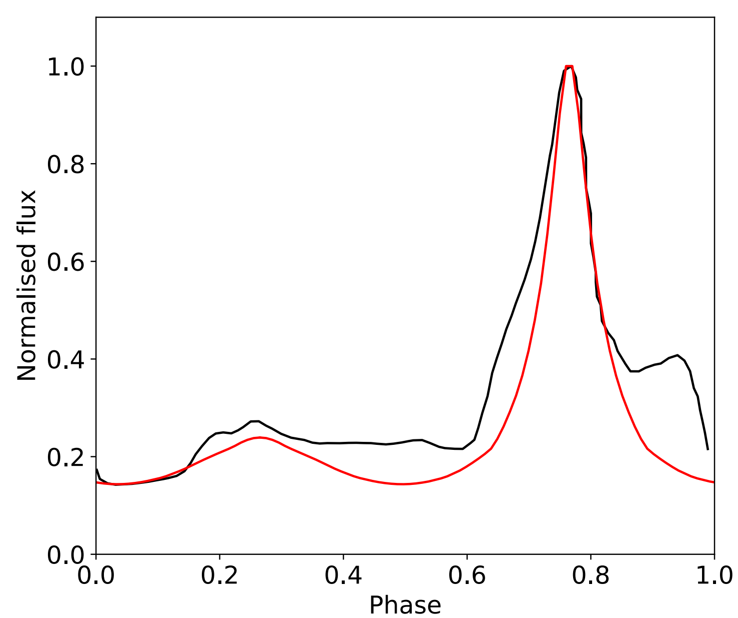


$\alpha = 30^\circ \ \beta = 155^\circ$

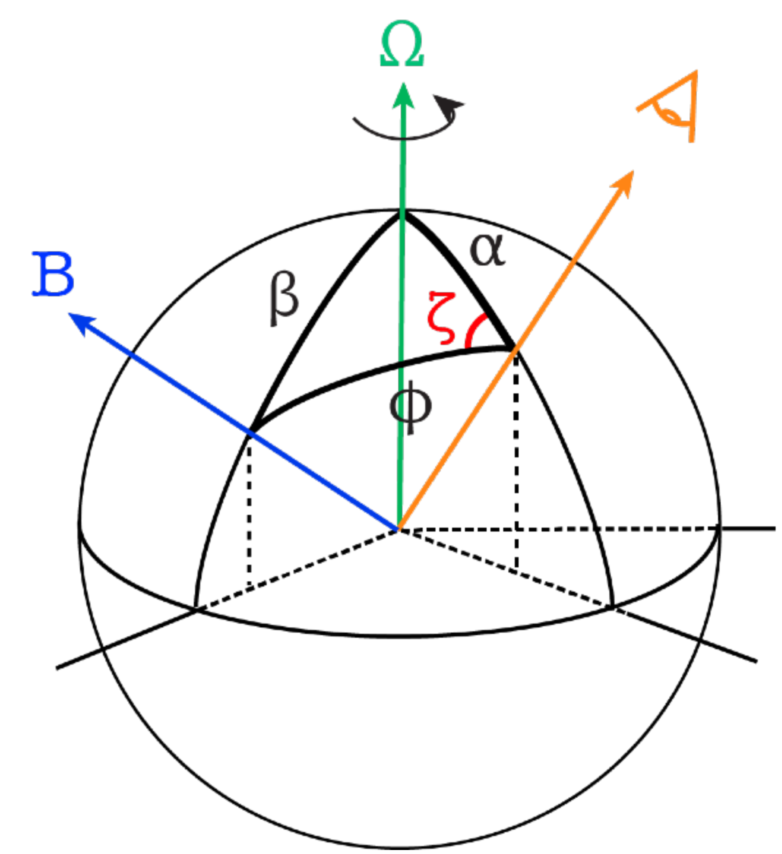
- Two columns



$\alpha = 50^\circ \ \beta = 42^\circ$



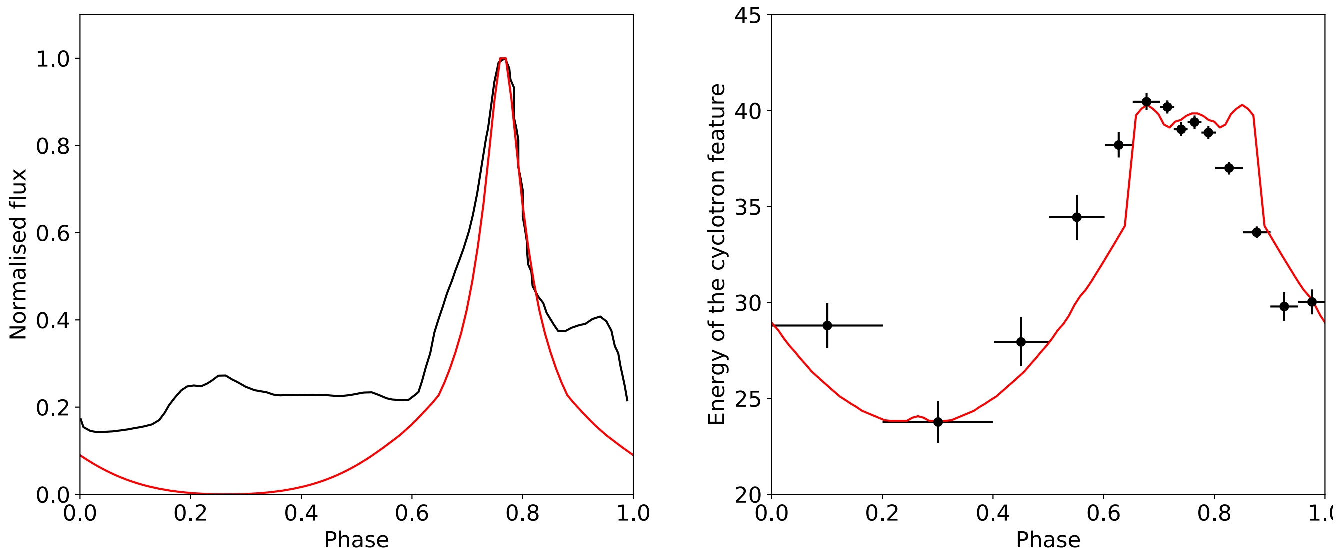
$\alpha = 75^\circ \ \beta = 115^\circ$



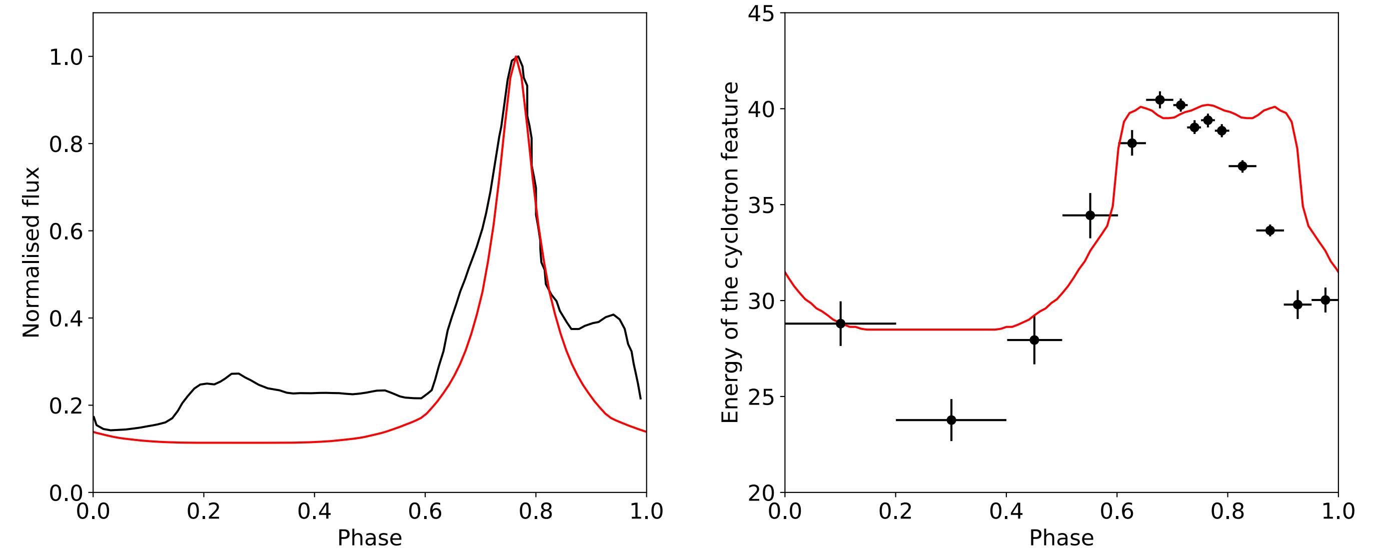
Geometry

CAIAZZO & HEYL MODEL – PULSE PROFILE

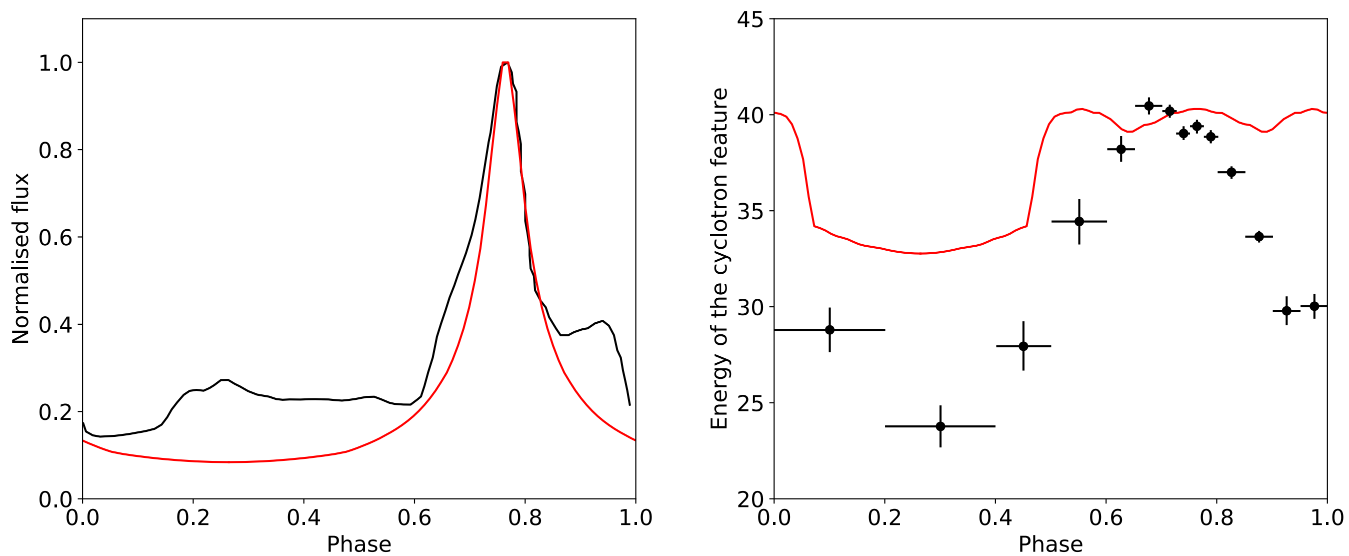
- One column
- Two columns



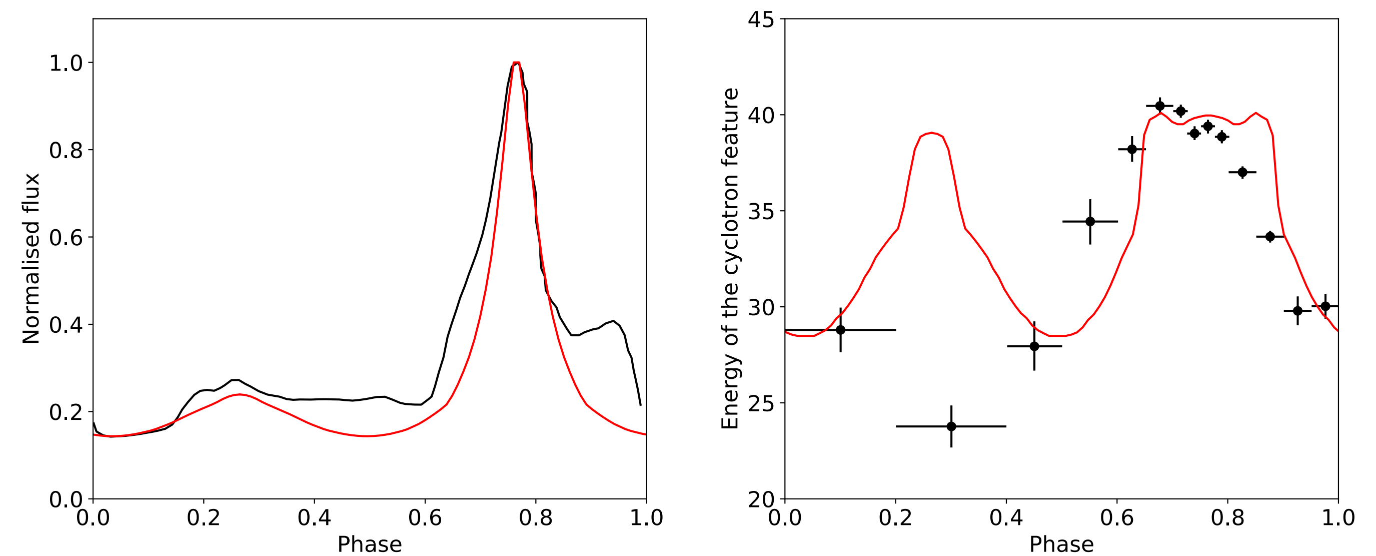
$\alpha = 83^\circ \ \beta = 86^\circ$



$\alpha = 50^\circ \ \beta = 42^\circ$



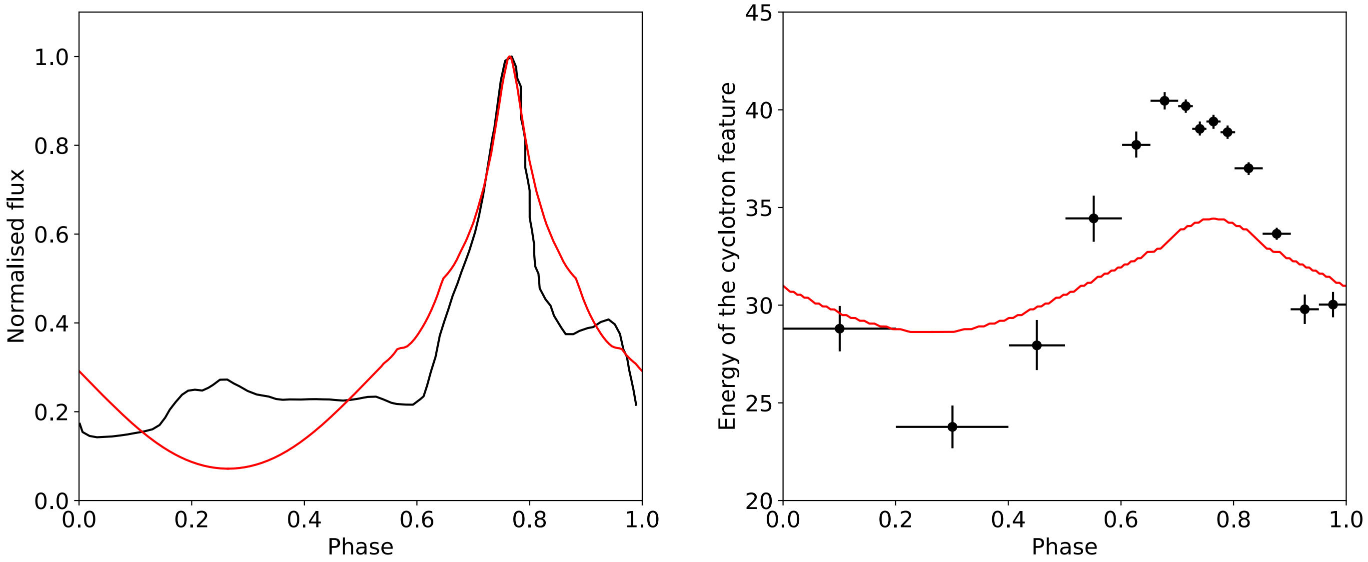
$\alpha = 30^\circ \ \beta = 155^\circ$



$\alpha = 75^\circ \ \beta = 115^\circ$

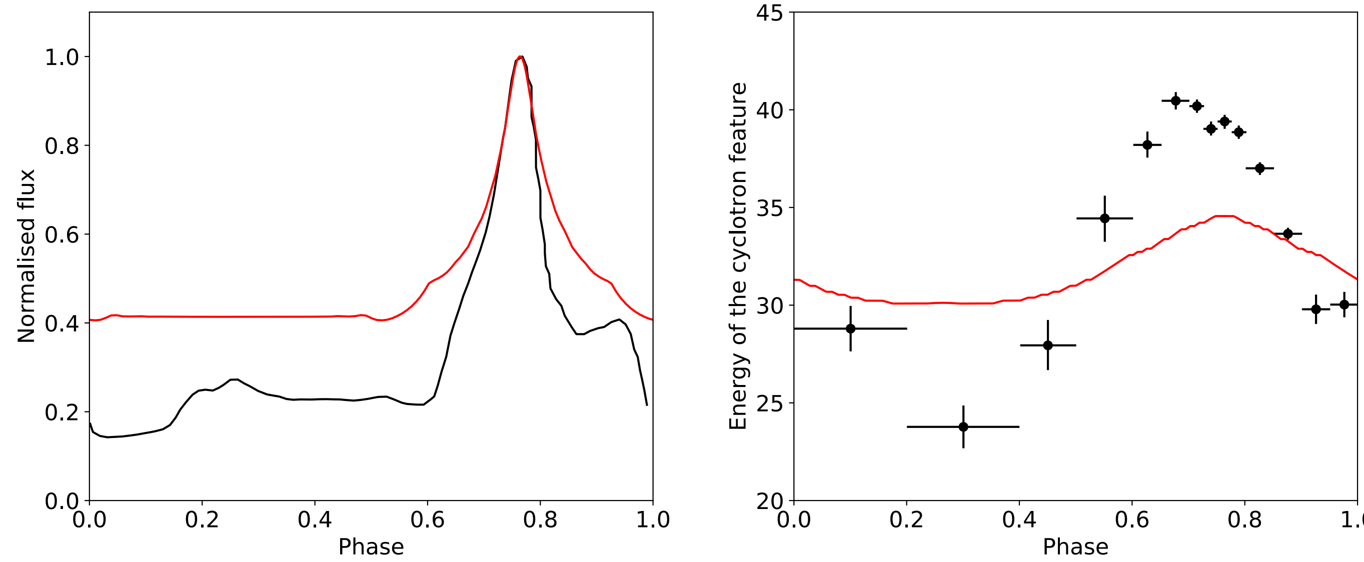
CAIAZZO & HEYL MODEL – PULSE PROFILE

- Shorter one-column



$\alpha = 67^{\circ}\ \beta = 120^{\circ}$

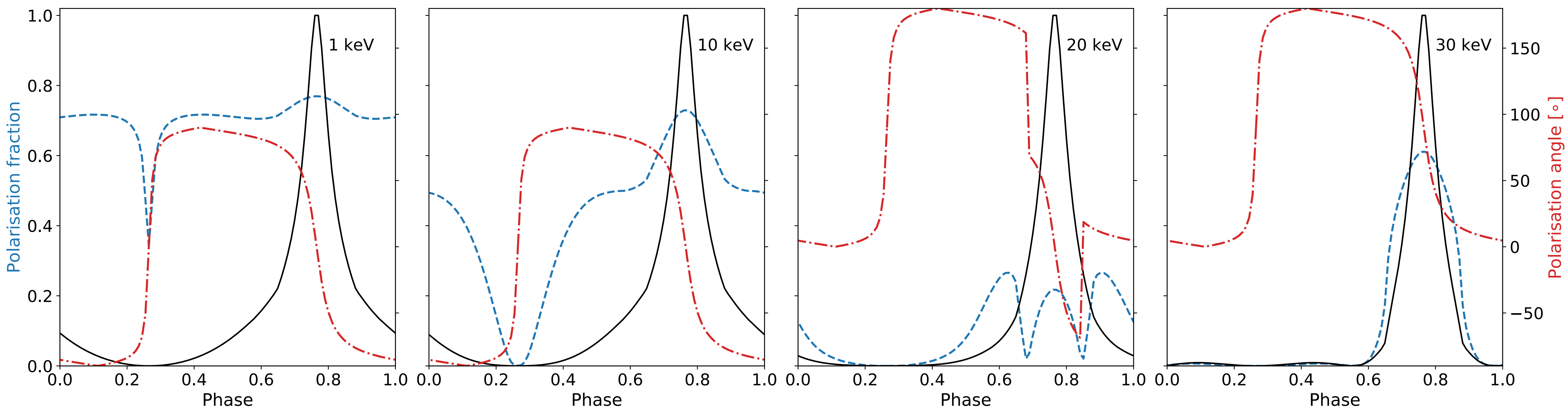
- Shorter two-columns



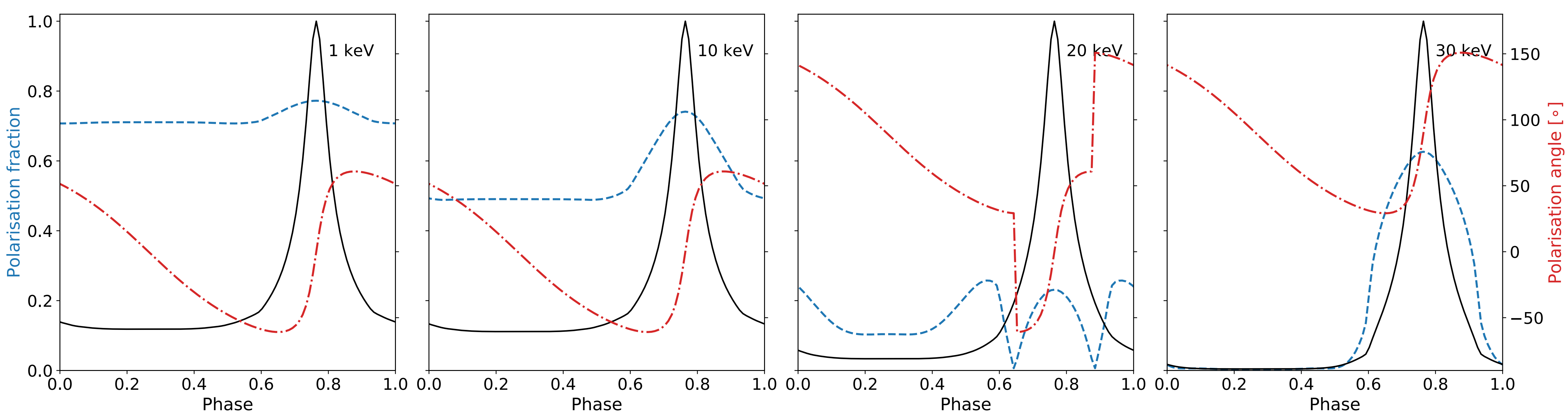
$\alpha = 46^{\circ}\ \beta = 40^{\circ}$

- In the Becker and Wolff model the height of the column is determined by the velocity profile of the electrons inside the column. If electrons are slowed down in an adiabatic shock at the top of the column, the predicted height is reduced

CAIAZZO & HEYL MODEL – POLARIZATION SIGNAL FROM THE COLUMN(S)



- One column $\alpha = 83^{\circ}$ $\beta = 86^{\circ}$



- Two columns $\alpha = 50^{\circ}$ $\beta = 42^{\circ}$

SUMMARY

- X-ray polarization observations can help constrain the accretion processes and accretion geometry in X-ray pulsars like Hercules X-1.
- In order to get the most of the upcoming observations, we need a model that treats consistently the spectral formation and polarization signal, which agrees with current observations and that can be easily fitted to the new polarization data.
- Our model is a step in the right direction, even if still presents some simplifications. The next step will be to extend it to the case of low-luminosity X-ray pulsars where the column might not be present.
- Check out our papers on the arXiv!

Caiazzo & Heyl 2020a
https://ui.adsabs.harvard.edu/abs/2021MNRAS.501..109C/abstract
Caiazzo & Heyl 2020b
https://ui.adsabs.harvard.edu/abs/2021MNRAS.501..129C/abstract

THANK YOU!