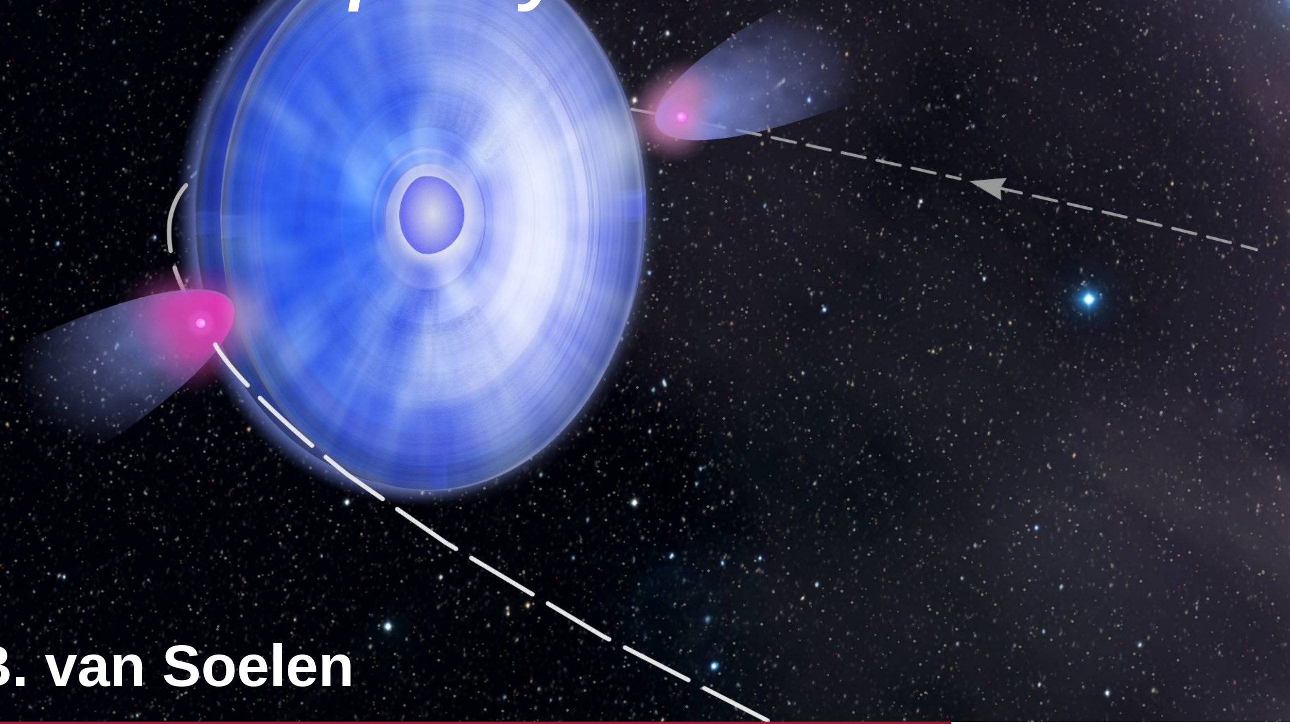
Investigating the effect of Be-discs on the emission from γ-ray binaries



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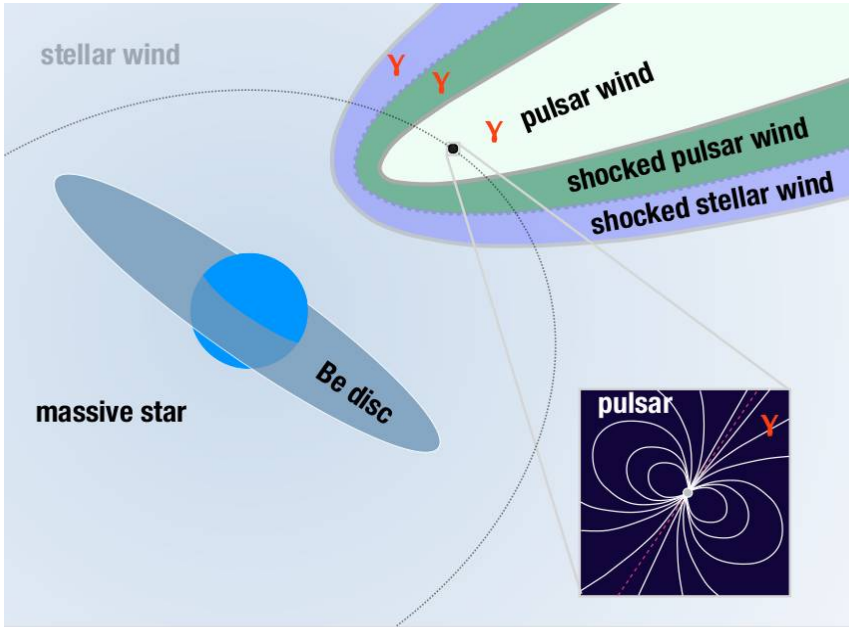
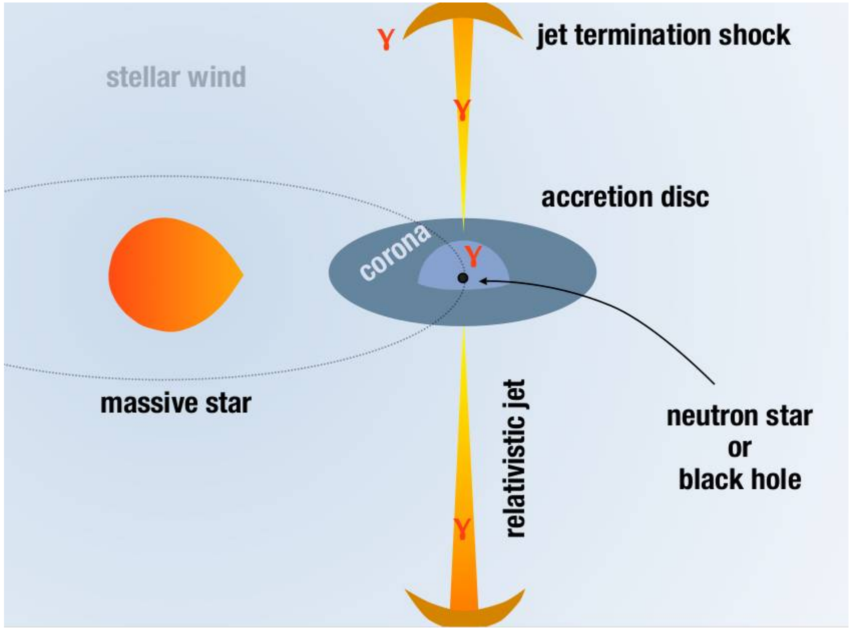
Gamma-ray binaries



Pulsar-wind scenario



Microquasar scenario

Be gamma-ray binaries

- O-type systems – IBS between stellar wind and pulsar wind
  - <O6.5 → need a strong wind to produce γ-ray emission? (van Soelen et al. 2024)

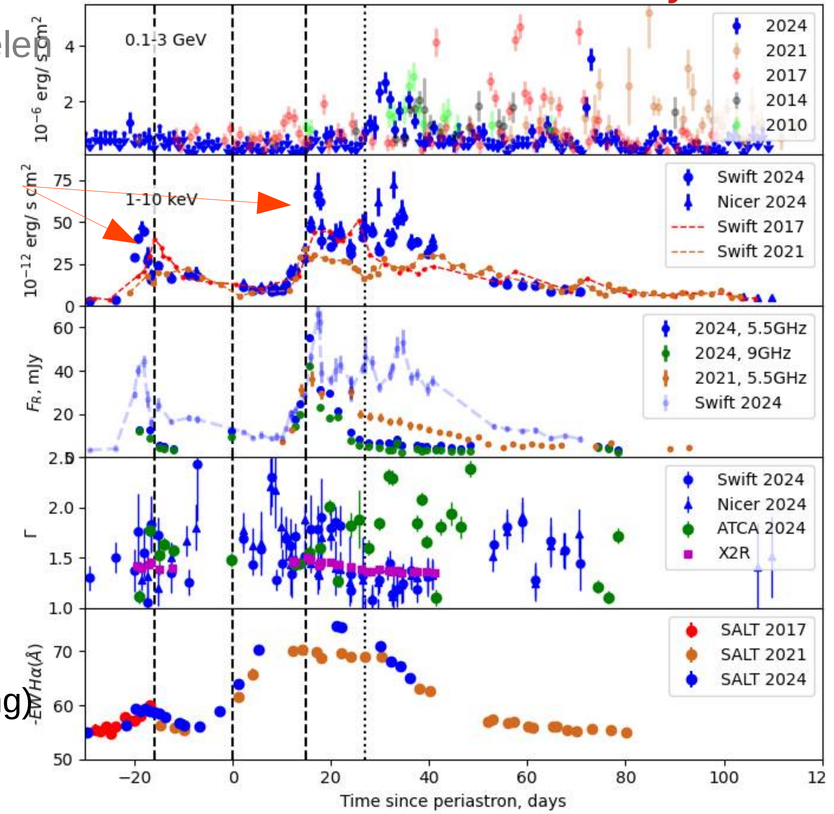
- For the Be systems we (usually) see double peaked lightcurve's → attributed to the pulsar-disc interaction (e.g. PSR B1259-63)
  - Need a disc to produce the (γ-ray) emission?
  - Several studies looking into modelling the emission/ re-producing the double-peaked behaviour

    (e.g. Chen & Takata, 2019,2022; Chen et al, 2024; Tokayer et al, 2021)

    → peak positions not always physically constrained by disc geometry?
  - Can we formally connect the observed optical emission to the disc interaction through modelling?
  - Can we produce a **physical** disc model (static/precessing)
    1) Reproduce the non-thermal emission
    2) Model the optical emission ↔ constrain the disc model

(Chernyakova, 2025)

Denys' Talk



Set-up: physical representation of the system

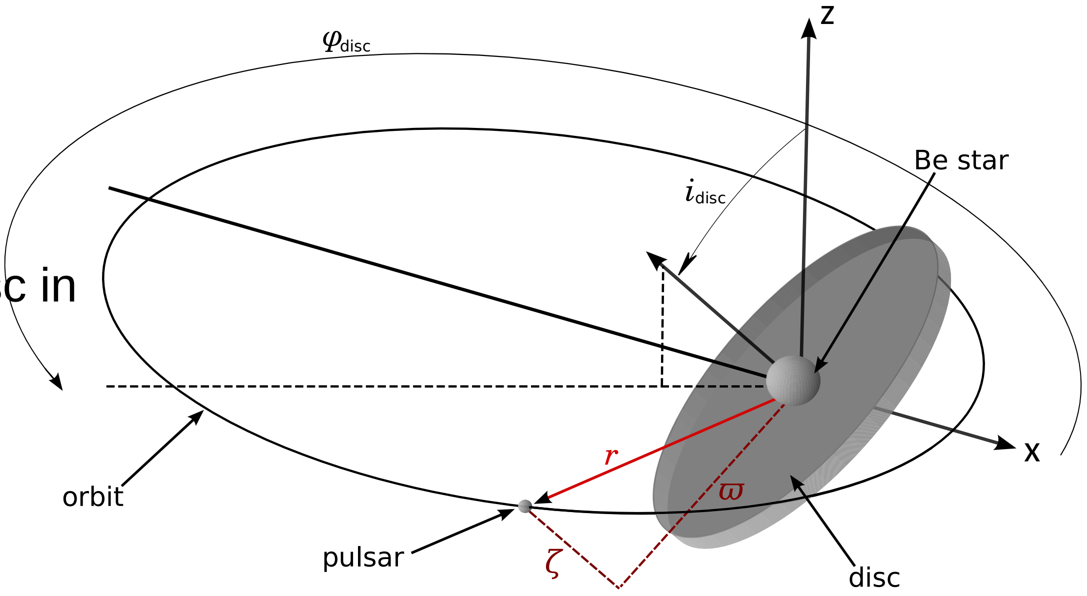
Case I – static disc (no precession)

- Orbit:
  $a, e, P, (T_{\mathrm{per}}, T_0)$

- Assuming a Keplerian, axis-symmetric disc in vertical hydrostatic equilibrium
  $$\rho(\varpi, \zeta) = \rho_0 \left(\frac{R_\star}{\varpi}\right)^n \exp\left[-\frac{1}{2}\left(\frac{\zeta}{H(\varpi)}\right)^2\right]$$
  (Carciofi & Bjorkman, 2006)

- Disc orientation parameters:
  $i_{\mathrm{disc}}, \varphi_{\mathrm{disc}}$

- Based off of physical position of pulsar in orbit (r, θ) and w.r.t. the disc height (ζ) and radius (ϖ) we can then determine the disc density (ρ_{disc}) & velocity (v_{disc}) and/or the stellar wind density (ρ_w) & velocity (v_w)



Solving the shock stand-off (I)

- Determine the ram pressures of stellar wind (p_w) and disc (p_{disc}) along the orbit
- Ram-pressure of stellar wind:

$$p_{\rm w,polar} = \rho_{\rm w,polar} v_{\rm w,polar}^2$$

$$\dot{M}_\star = 4\pi r^2 \rho_{\rm w} v_{\rm w,polar}$$

$$v_{\rm w,polar}(r) = v_{0,\rm polar} + (v_\infty - v_{0,\rm polar})\left(1 - \frac{R_\star}{r}\right)^\beta$$

(Waters et al, 1988; Kong et al, 2011)

(For now, density distribution is still ~spherical $\therefore$ not a proper polar wind)

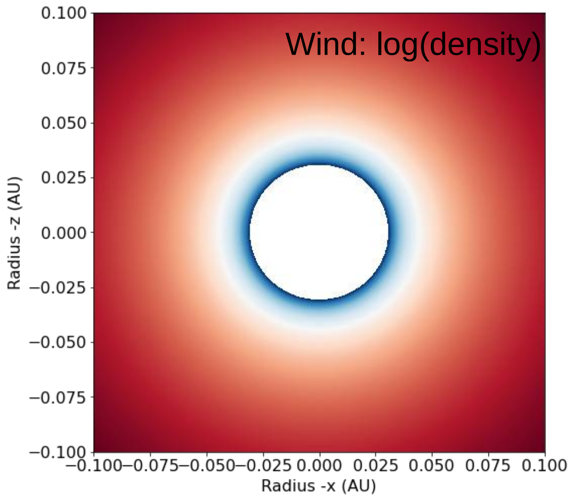
- Ram-pressure of the circumstellar disc:

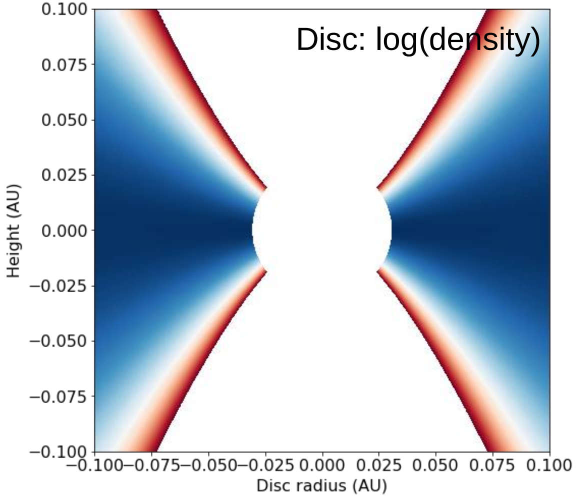
$$p_{\rm disc} = \rho_{\rm disc} v_{\rm disc}^2$$

$$\rho(\varpi, \zeta) = \rho_0 \left(\frac{R_\star}{\varpi}\right)^n \exp\left[-\frac{1}{2}\left(\frac{\zeta}{H(\varpi)}\right)^2\right]$$

(Carciofi & Bjorkman, 2006)

- Shock stand-off distance (R_s) depends on the momentum pressure ratio between the flow upstream (stellar wind) and downstream (pulsar wind) of the shock $(p_{\rm w,polar}/p_{\rm disc} = p_{\rm pw})$





Solving the shock stand-off (II)

- Generally,

$$R_s = \frac{\eta^{1/2}}{1+\eta^{1/2}} d \qquad\qquad \eta = \frac{\dot{E}/c}{\dot{M}_\star v_\star}$$

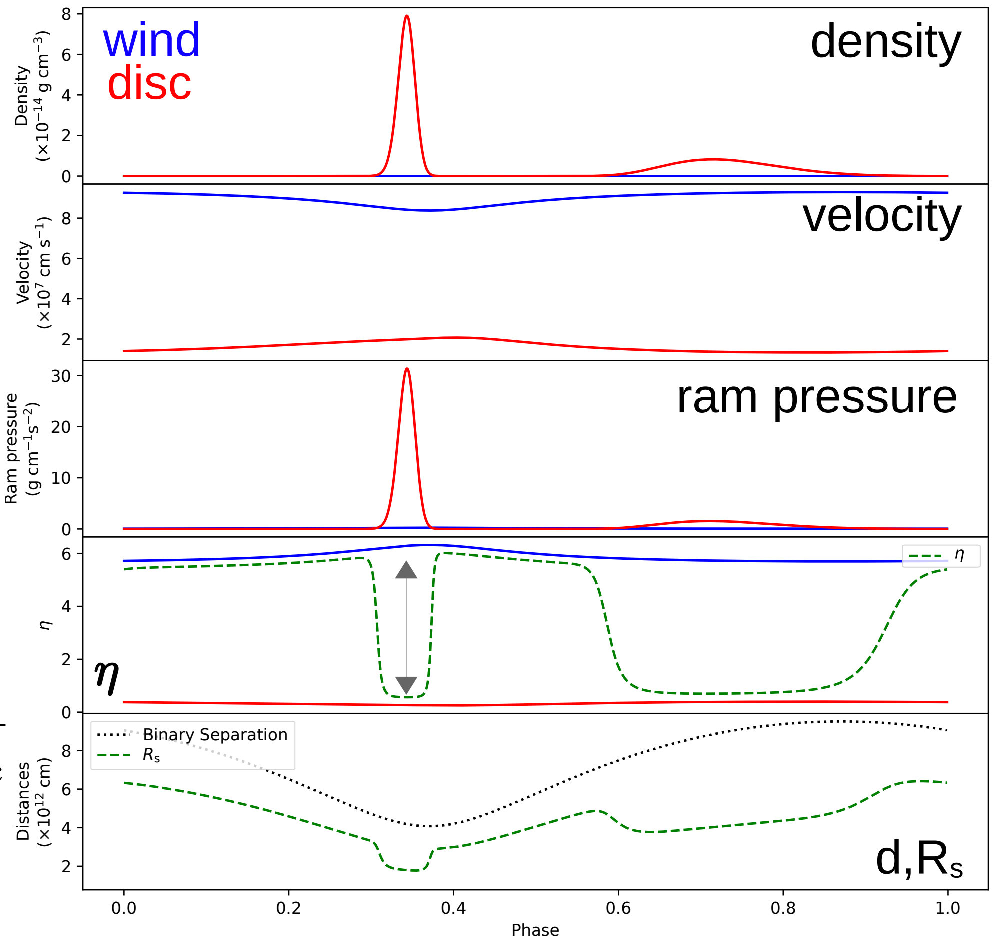
(e.g. Eichler & Usov, 1993; Kennel & Coroniti 1984; Dubus 2006, 2015.)

- **For Be-systems to consider disc:**
- solve for momentum pressure ratio, η, along orbit (equilibrium between ram-pressures) with a 'realistic' representation of the circumstellar disc

transition between wind/disc

Stellar-pulsar wind ⟷ **Disc-pulsar wind**

$$\eta_{\rm w} = \frac{\dot{E}/c}{\dot{M}_{\rm w} v_{\rm w}} \qquad\qquad \eta_{\rm disc} = \frac{\dot{E}/c}{\dot{M}_{\rm disc} v_{\rm disc}}$$



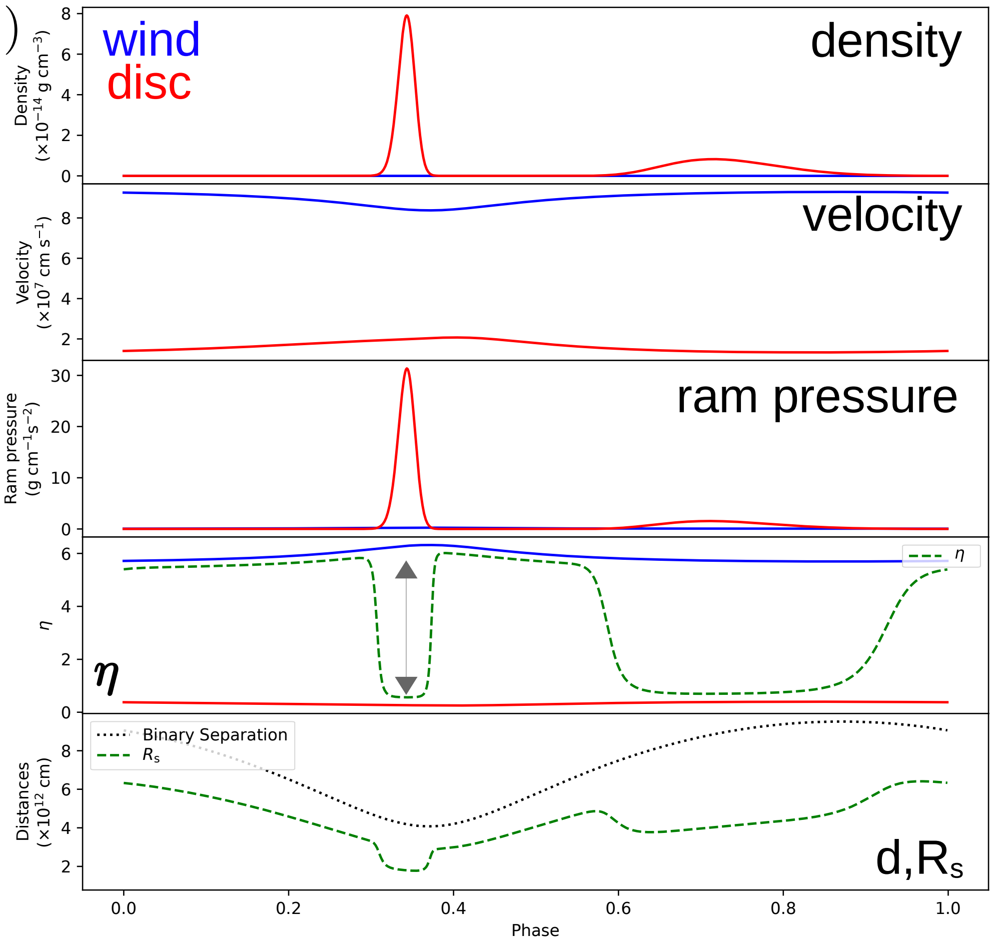
Solving the shock stand-off (III)

- Based off the dominant ram pressure $(p_{\mathrm{w}}/p_{\mathrm{disc}})$ we scale (α) the momentum pressure between the wind → smoothly transition between the shock being formed between the pulsar and stellar-wind/ disc

$$\eta = \eta_{\mathrm{w}} + (\eta_{\mathrm{disc}} - \eta_{\mathrm{w}})\alpha$$

$$R_s = \frac{\eta^{1/2}}{1+\eta^{1/2}} d$$

- From the shock stand-off distance we then model the non-thermal emission → physically **constrained by the geometry** of the disc



Modelling the (synchrotron) emission

- We consider only the **X-ray** emission
- Assume one-zone model → majority of the emission produced at the apex of the shock
- Assume a *fixed* Power-Law electron distribution:

$$N(\gamma) \propto \gamma^{-p} \qquad p = 1.9$$

- $P_{synch} \propto B$ → synchrotron emission will scale with the magnetic field strength at emission region (i.e. apex of the shock)
- B depends on the shock stand-off distance from the pulsar:

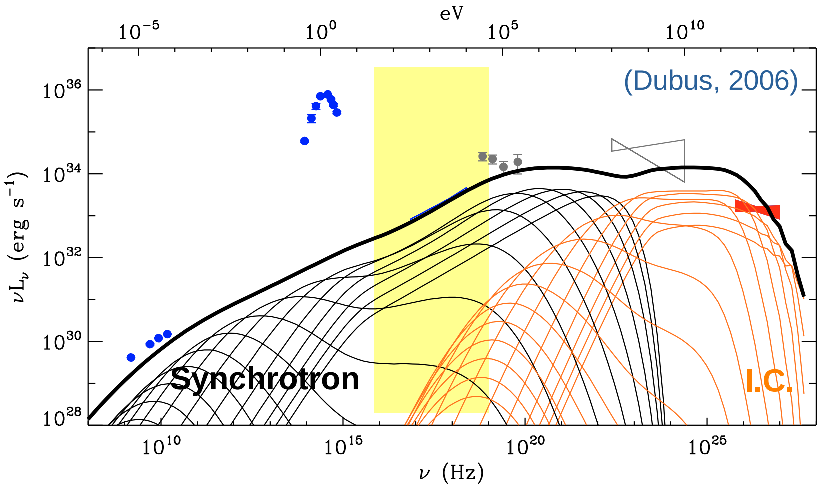
$$B = 3(1-4\sigma)\left(\frac{\dot{E}/c}{R_s^2}\frac{\sigma}{1+\sigma}\right)^{1/2}$$

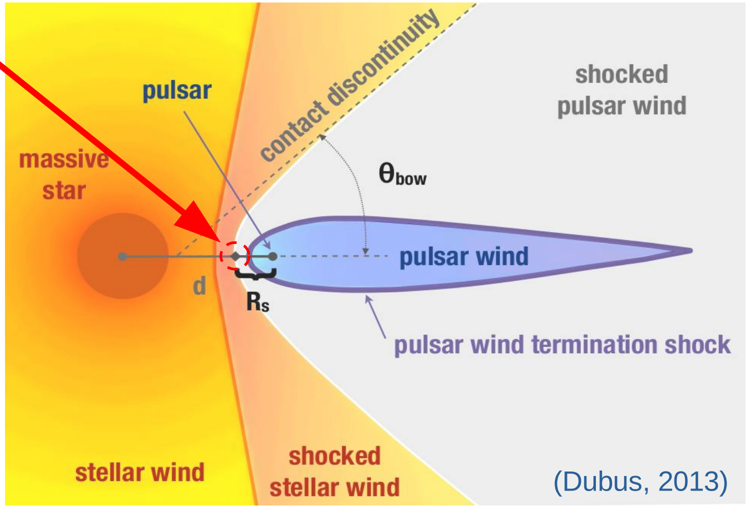
(Kennel & Coroniti, 1984)

- ∴ $B \propto 1/R_s$ → we scale B as:

$$B = B_0\left(\frac{R_s}{R_0}\right)^{-1}$$

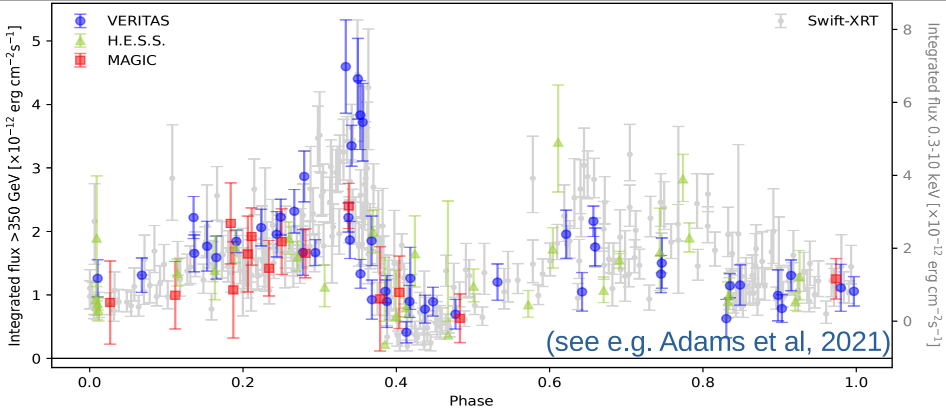
for a magnetic field strength $B_0 = 1G$ at an arbitrary shock distance $R_0 = d_{peri}$



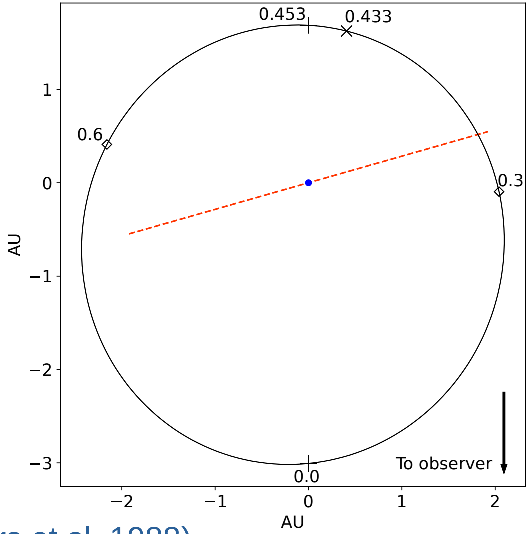


Application with a non-precessing disc

- **e.g. HESS J0632+057:**
  - X-ray and TeV lightcurves display a sharp primary maximum at $\phi \simeq 0.3$, and broad secondary bump at $\phi \simeq 0.6-0.8$.
  - Still some confusion on the orbital solution? **Multiple** orbital solutions for this system (see talks by Brian and J. Casares)
  - Assume new SALT orbit from cross-correlation data $e=0.3,\ \omega=255,\ \phi_{Per}=0.43,\ (P=317.3\,\mathrm{d})$
  - Assume disc orientations of $i_{disc} = 20°, 30°, 45°, 60°, 80°$ and $\phi_{disc} = 25°, 30°, 40°, 90°, 120°$
  - Disc flaring exponent $\beta = 1$-3, radial density fall off exponent $n=2$-4
  - Other model parameters based off of similar works (Carciofi & Bjorkman, 2006; Carciofi, 2011; Kong et al, 2011; Waters et al, 1988)



(see e.g. Adams et al, 2021)

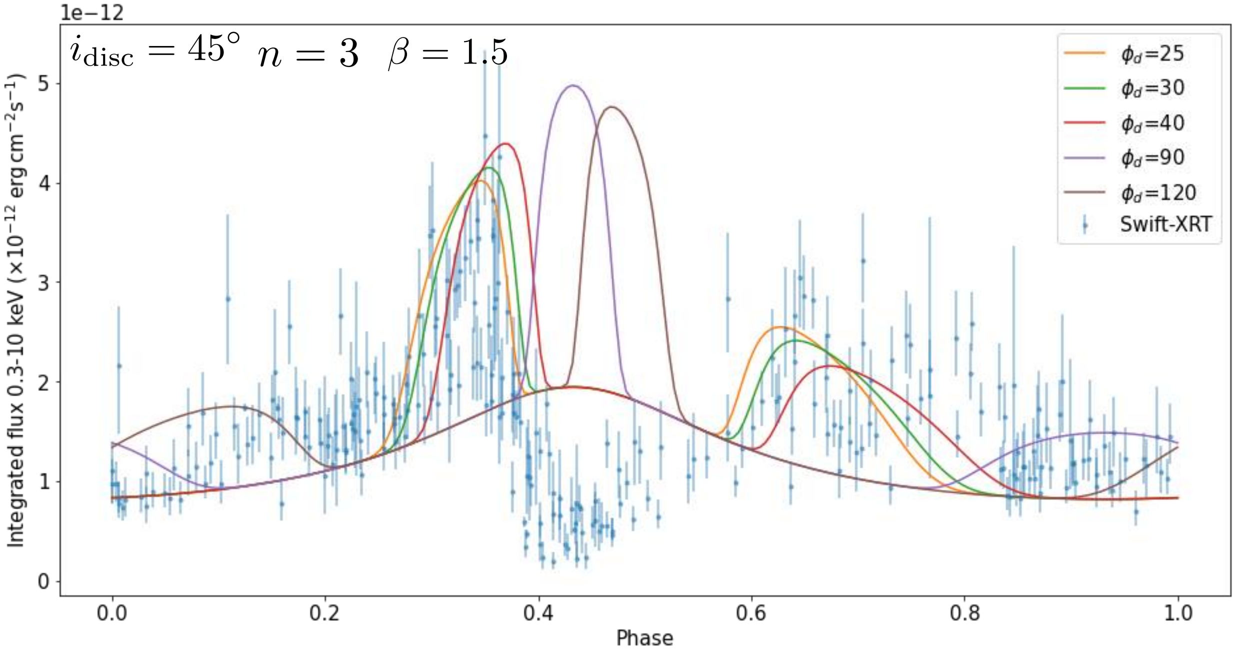


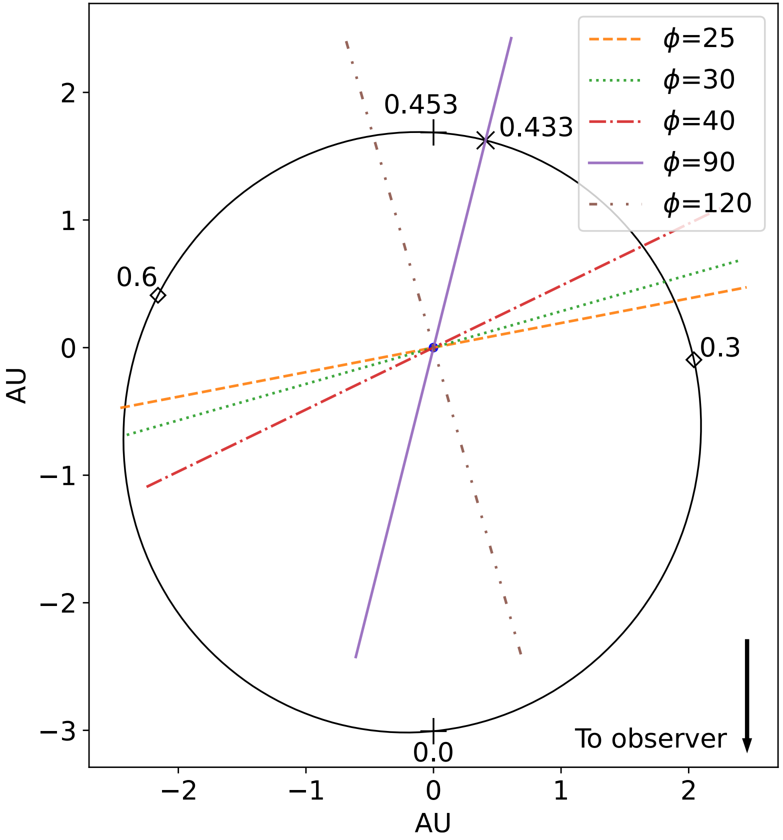
Brian's Talk

Application with a non-precessing disc

Preliminary

- Changing the disc rotation ($\phi_{\rm disc}$)





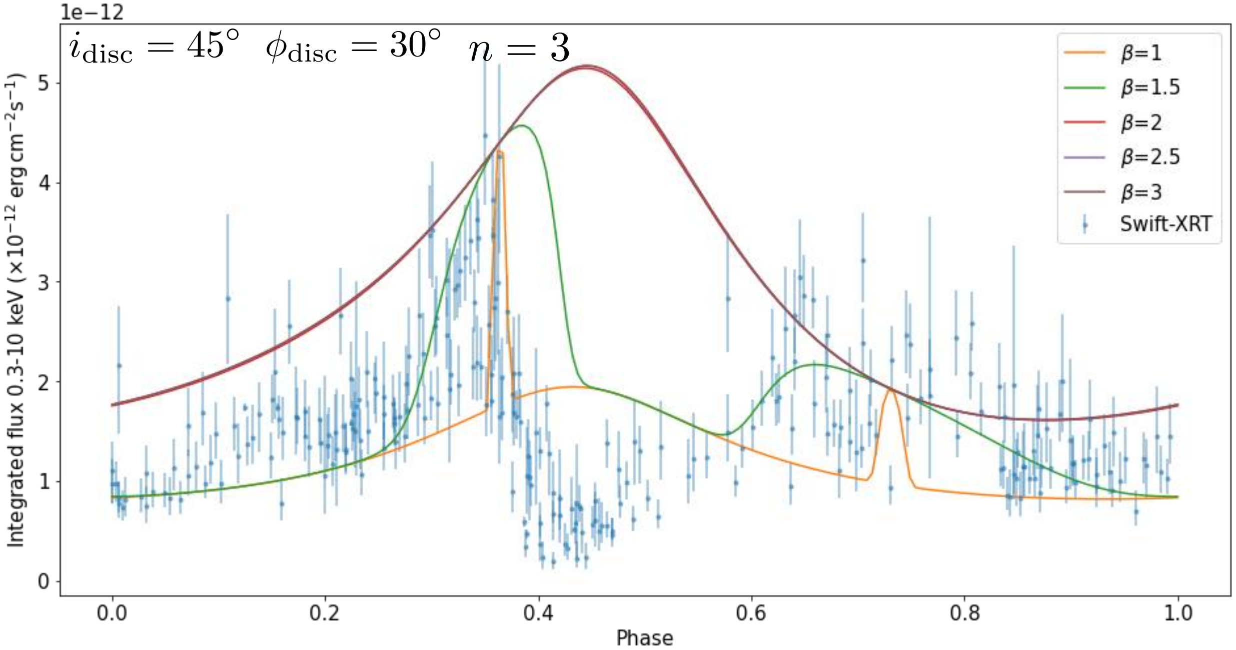
→ affects the positions (orbital phase) of peaks

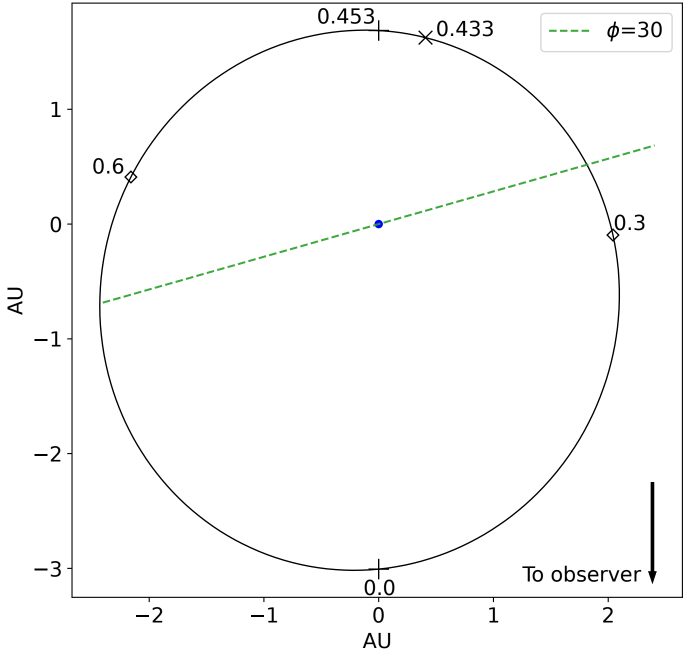
→ best ‘fit’ $\phi_{\rm disc} = 30^\circ$

Application with a non-precessing disc

Preliminary

- Changing the disc flaring exponent (β)





→ affects how flared the disc is:
- for small β, thin, flat disc ~thin emission peak
- for large β, pulsar never passes out of disc ~single peak

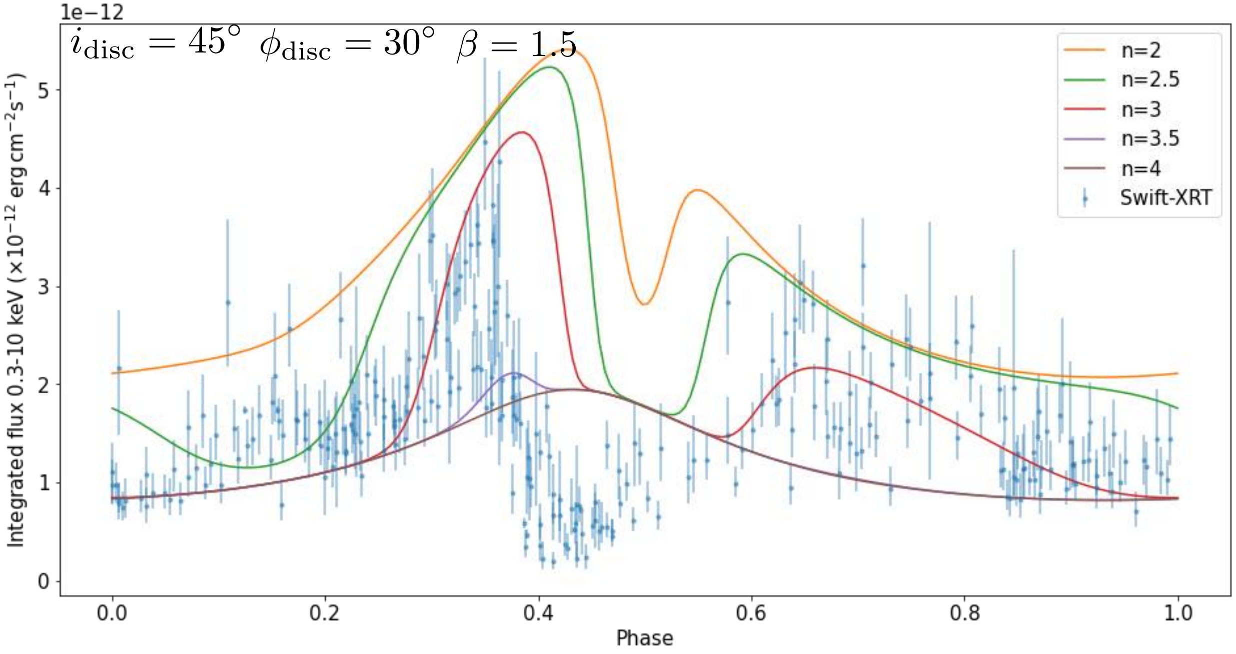
$$\rho(\varpi, \zeta) = \rho_0 \left(\frac{R_\star}{\varpi}\right)^n \exp\left[-\frac{1}{2}\left(\frac{\zeta}{H(\varpi)}\right)^2\right]$$

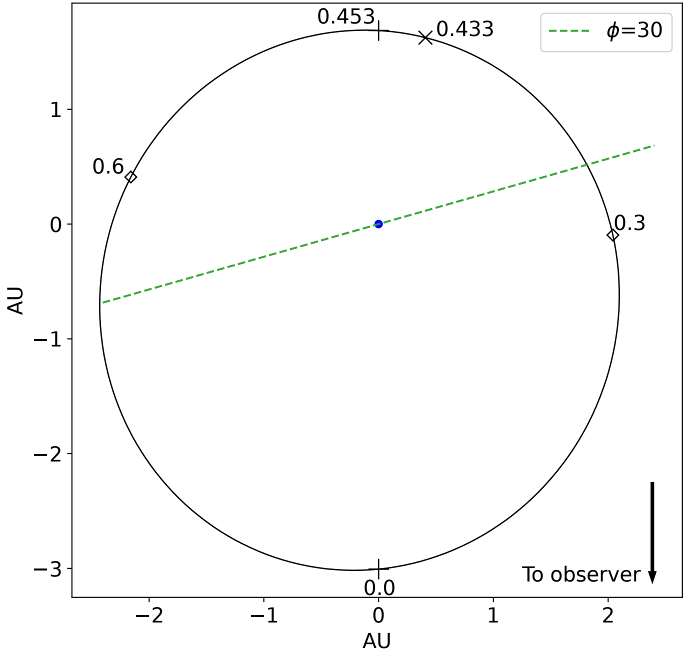
$$H(\varpi) = H_0 \left(\frac{\varpi}{R_\star}\right)^{\beta}$$

Application with a non-precessing disc

Preliminary

- Changing the disc radial density fall-off exponent (n)





$$\rho(\varpi, \zeta) = \rho_0 \left(\frac{R_\star}{\varpi}\right)^n \exp\left[-\frac{1}{2}\left(\frac{\zeta}{H(\varpi)}\right)^2\right]$$

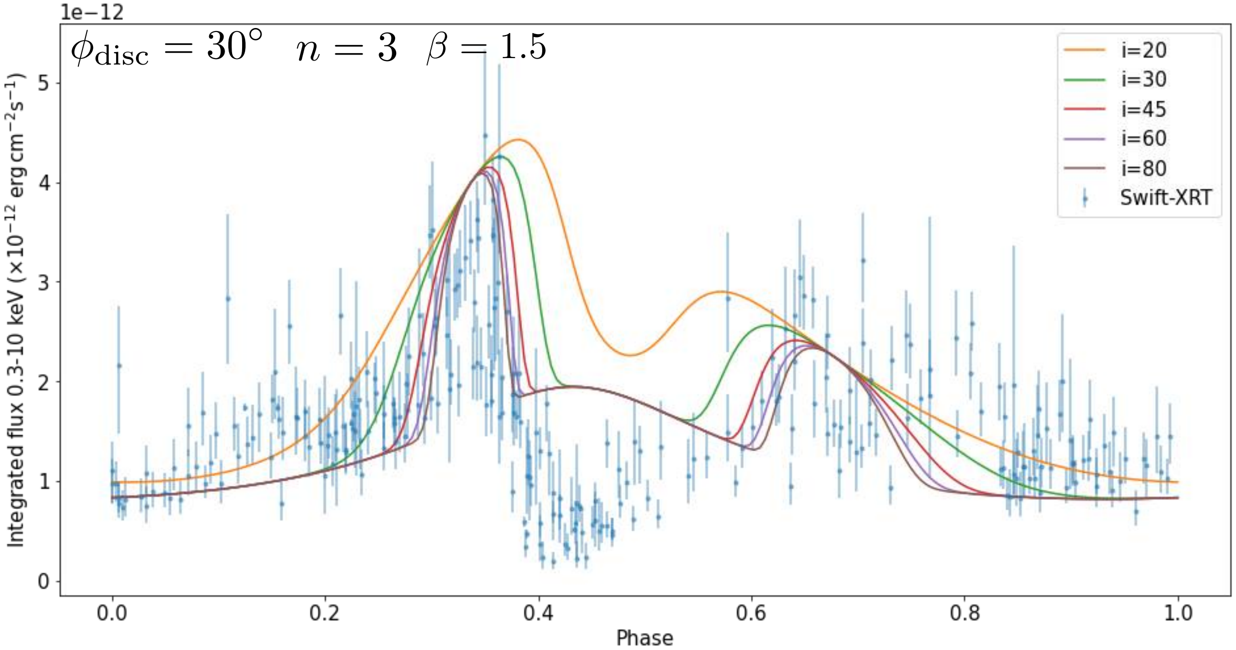
→ affects how quickly the density falls off radially

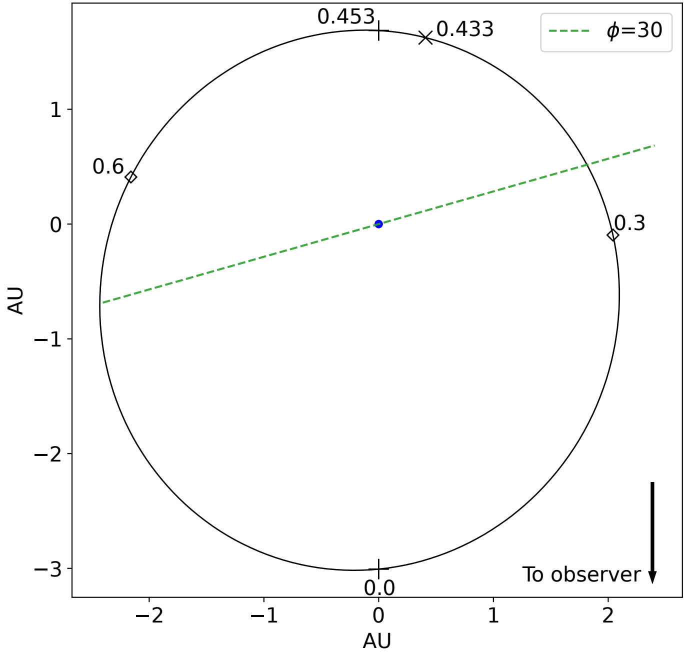
- for large n, disc is sufficiently dense at further radii, enhancing the emission & broadening peaks towards phases further from star/towards edge of disc

Application with a non-precessing disc

Preliminary

- Changing the disc inclination (i_{disc})





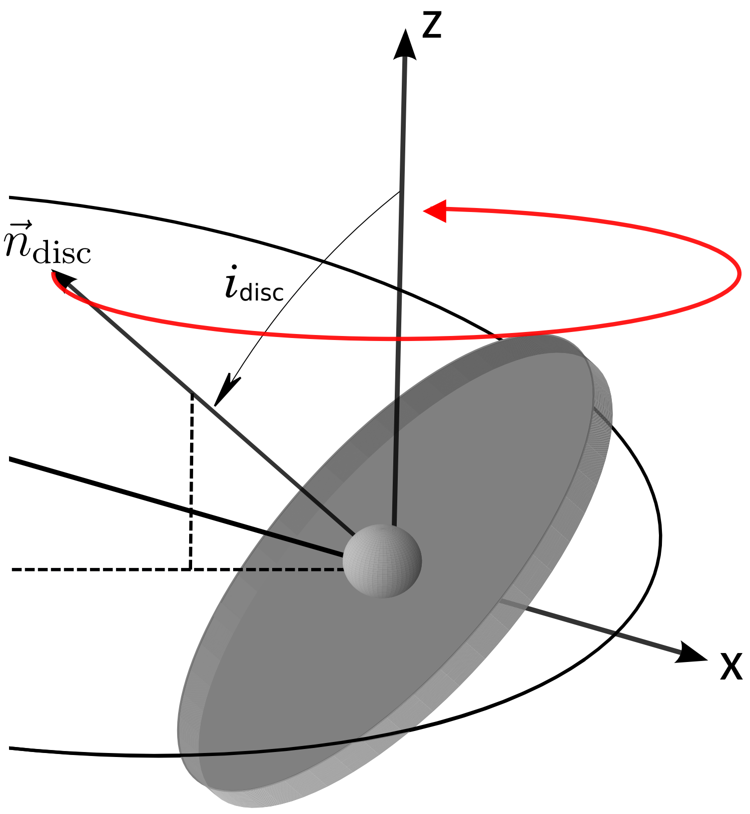
→ 0° disc in plane of orbit
→ The less inclined the disc, the greater the depth that the pulsar must pass through ∴ increasing the width of the peaks

Set-up: physical representation of the system (II)

- For LS I +61°303, we have a super-orbital period and observe emission peaks shifting – precessing disc?

Case II – with precession

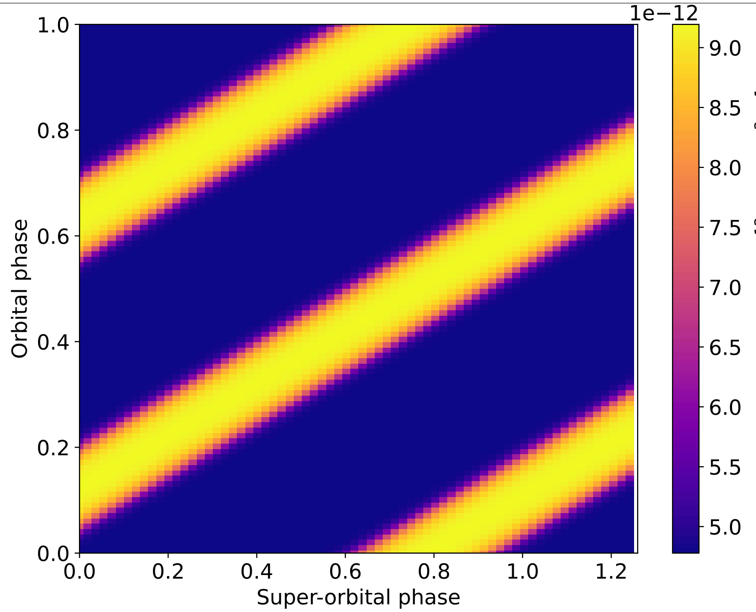
- Orbit parameters:
  $a, e, P, (T_{\mathrm{per}}, T_0)$
- Disc orientation parameters:
  $i_{\mathrm{disc}}, \varphi_{0,\mathrm{disc}}, P_{\mathrm{prec}}$
- $\varphi_{\mathrm{disc}}(t) = \varphi_{0,\mathrm{disc}} + \left(\frac{t - T_{\varphi_{0,\mathrm{disc}}}}{P_{\mathrm{prec}}}\right) 2\pi$
- For each time (t) across several orbits ($\sim P_{\mathrm{super}}$), the orientation of the disc is re-calculated ($\vec{n}_{\mathrm{disc}}$)
  → proceed then to determine pulsar position and disc height and radius components
  → solve shock parameters

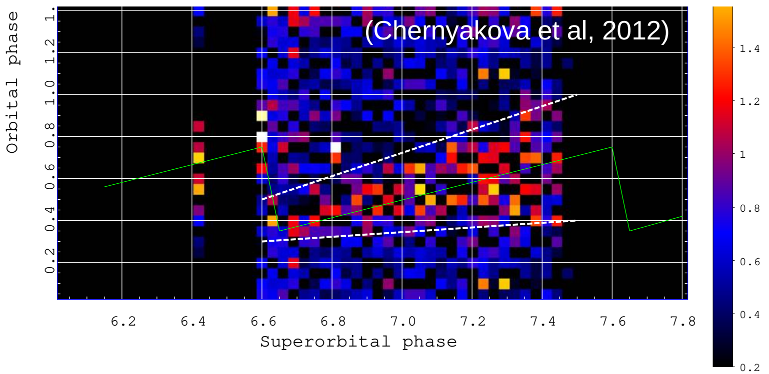


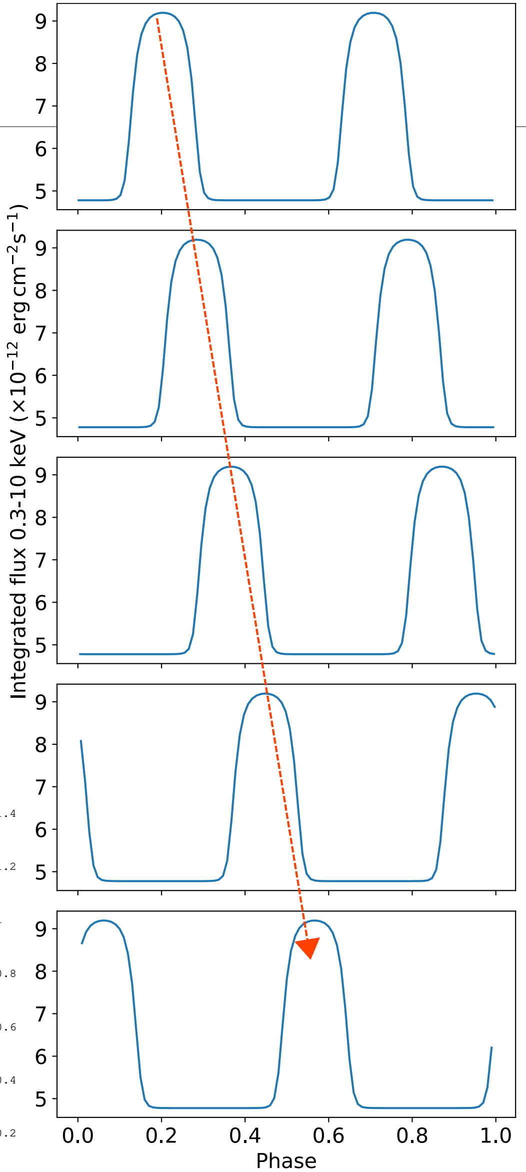
Application with a precessing disc

Preliminary

- **Test case e=0.0 (LS I +61°303-like):**
- Orbit:
  $e\!=\!0.0, \omega\!=\!40.3^{\circ}, P\!=\!30\,\mathrm{d},$
  $T_{Per}\!=\!2451057.89$
- Disc parameters:
  $i_{disc}\!=\!30^{\circ},\ P_{Prec}\!=\!2\times 1664\,\mathrm{d}$
- Produces phase-shifting X-ray peaks, similar to idea for LS I +61°303 (Chernyakova 2012, 2023)
- Can we now build on this by modelling the optical emission?







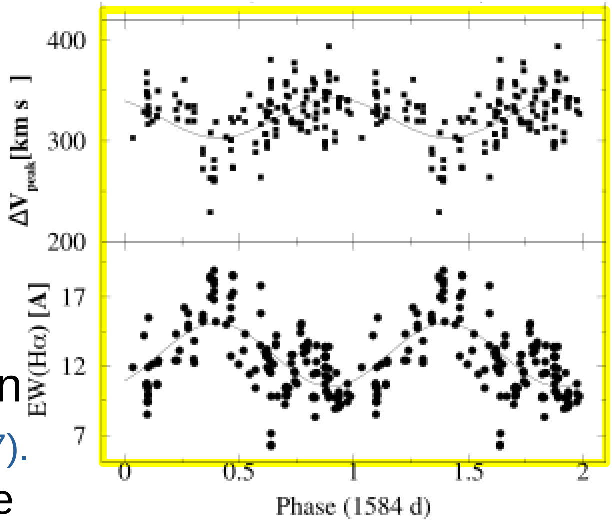
Towards constraining the model with (optical) observations

- We see super-orbital variation in the optical data (e.g. LS I +61°303 Hα emission line, VR peak separation and EWs) (Zamanov et al, 2000)

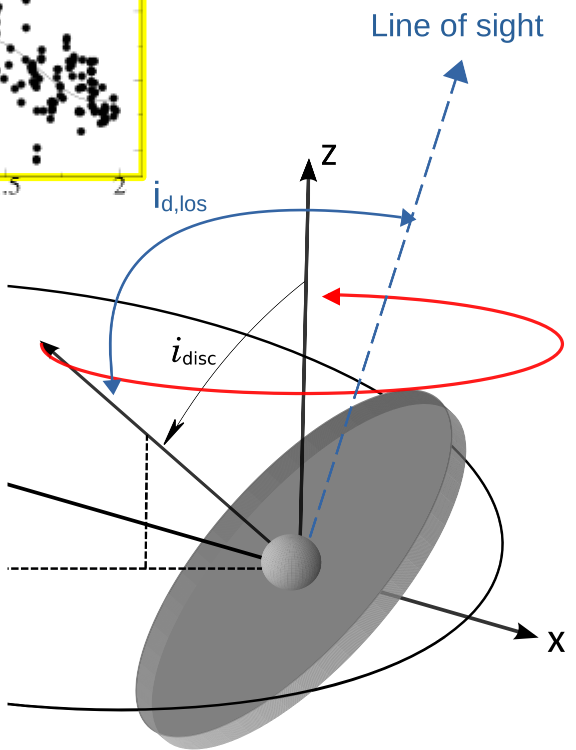
- Model the behaviour of the Hα emission line over the super-orbital period based on a reworked `BEDISK` code (Sigut & Jones, 2007).
  - Takes in parameters of the disc size, and the inclination angle between the disc normal and the observers line of sight to produce a synthetic spectrum of the Hα emission line

    → Determine EWs (and peak separation etc.)

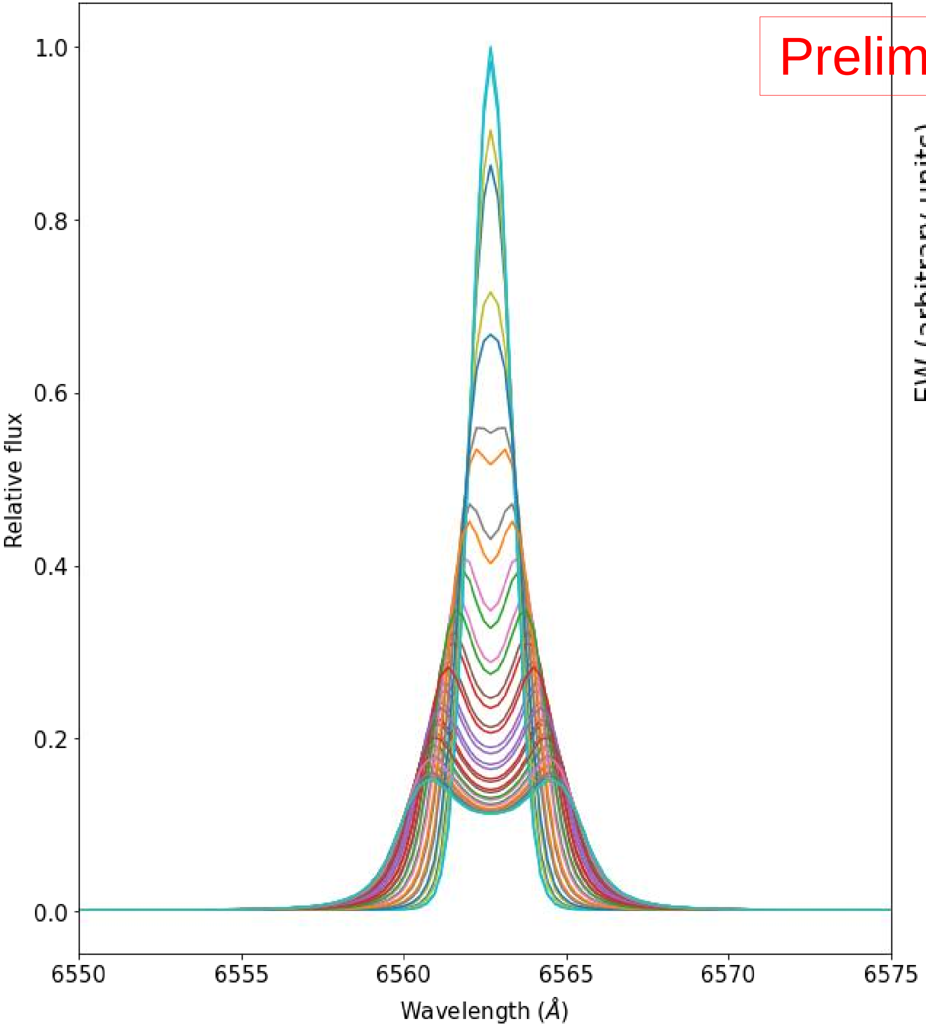
  - Need observations/look at archival data to use the modeled emission lines to constrain the disc geometry



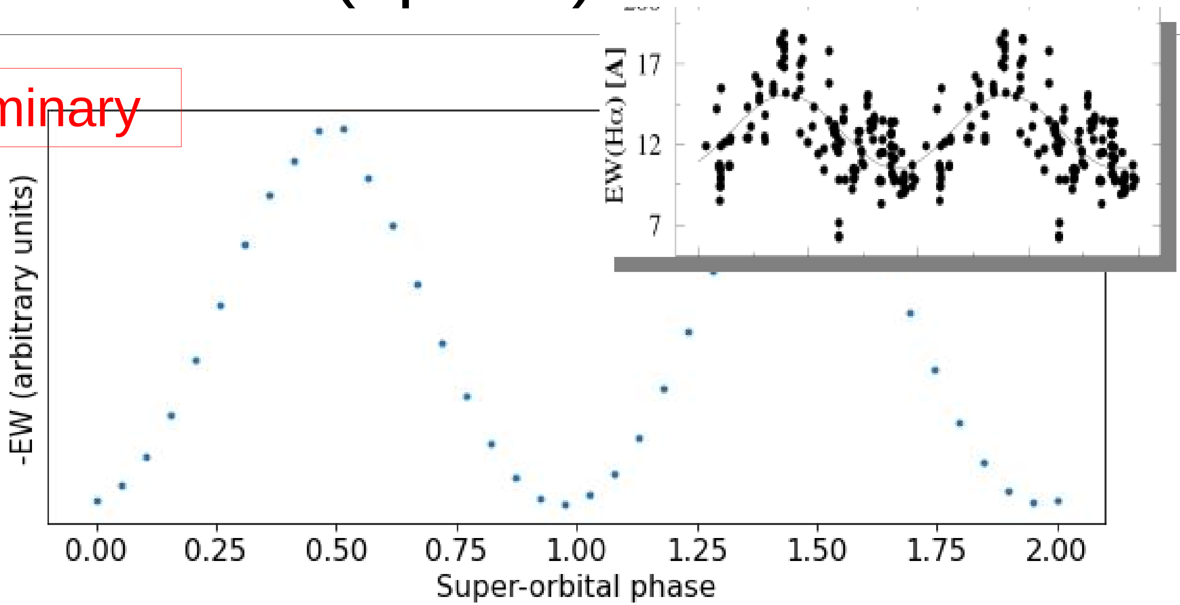
(Zamanov et al, 2000)



Towards constraining the model with (optical) observations



Preliminary

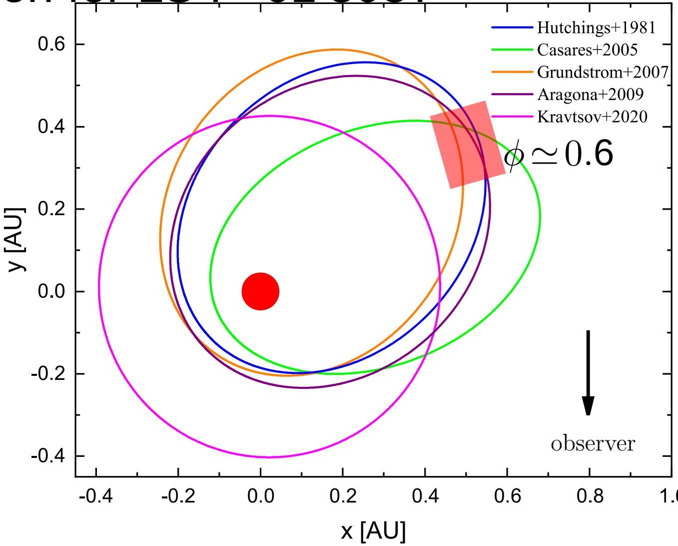


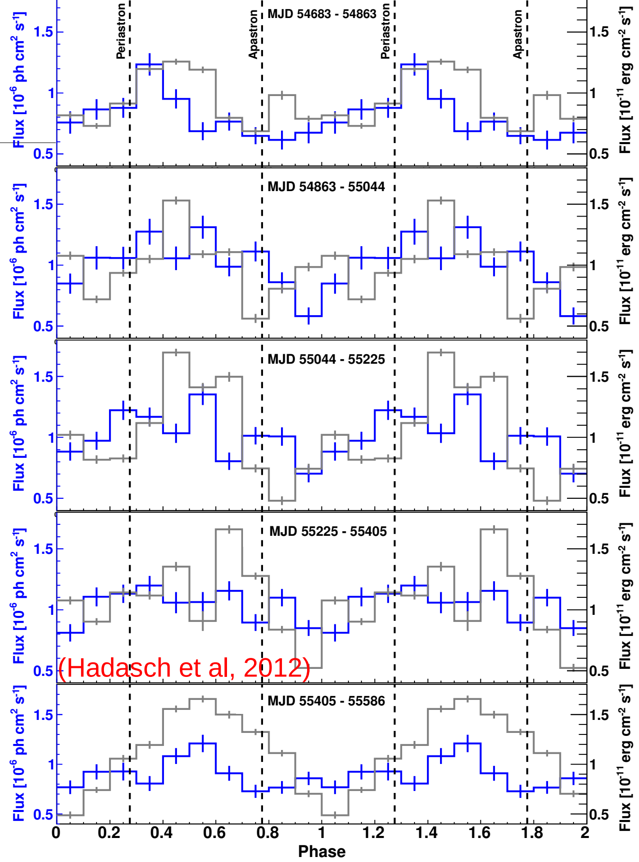
With the precession of the disc, the line profile shape evolves from a double peaked line to a narrow, wine-bottle profile.

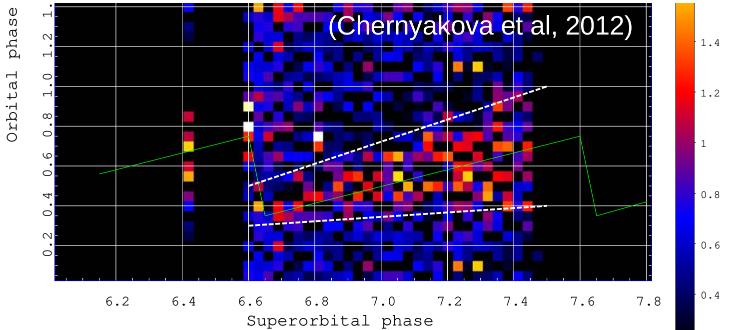
- Based off of the line-profiles and their EWs constrain the disc model?
- Further incorporate asymmetric disc? Asymmetric density distribution / elliptical disc? Growing/shrinking?

Application with a precessing disc

- **LS I +61°303:**
- $P = 26.496$ d, $P_{Super} = 1667$ d
- Phase drift in the X-ray peak around $\phi \simeq 0.6$ (Chernyakova, 2012), similar phase-drift behaviour in the Radio (Gregory 2002)
- Various suggested orbital solutions (Casares et al, 2005; Aragona, 2009)
- What is the orbital solution for LS I +61°303?
- $\phi \simeq 0.6$ towards apastron?
- Chen et al, 2024, used e~0.0 orbit to model the emission







Application with a precessing disc

Preliminary

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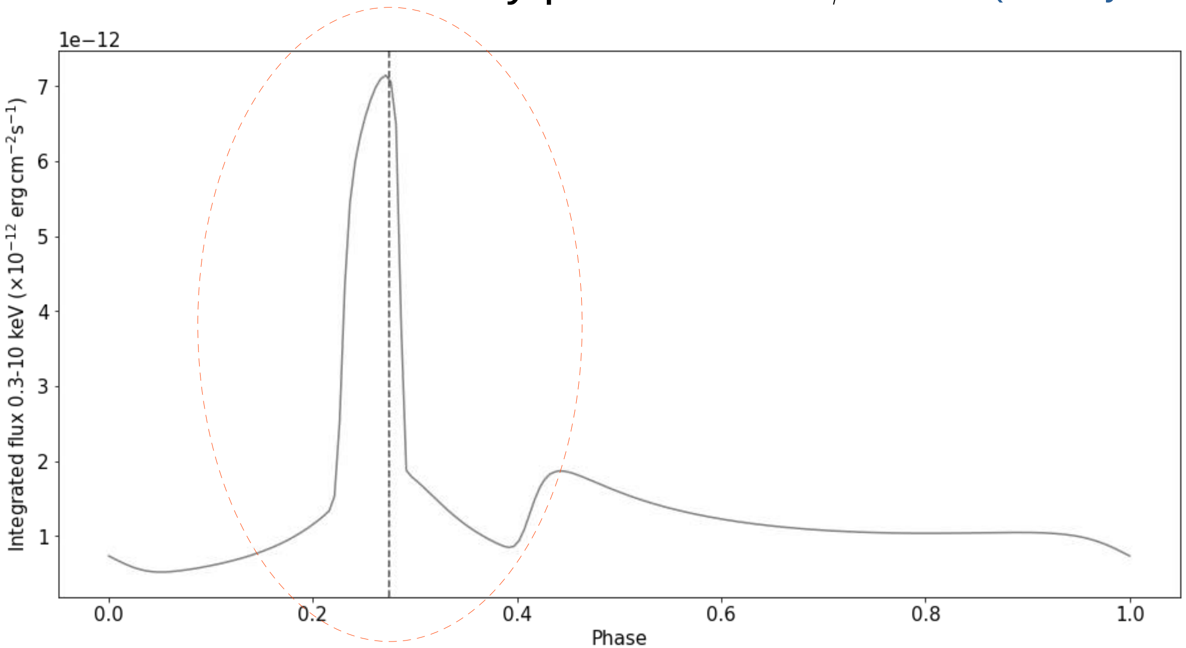
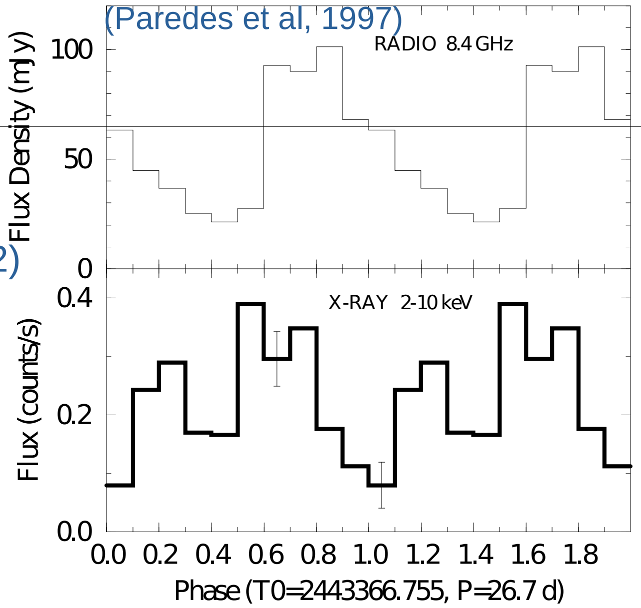
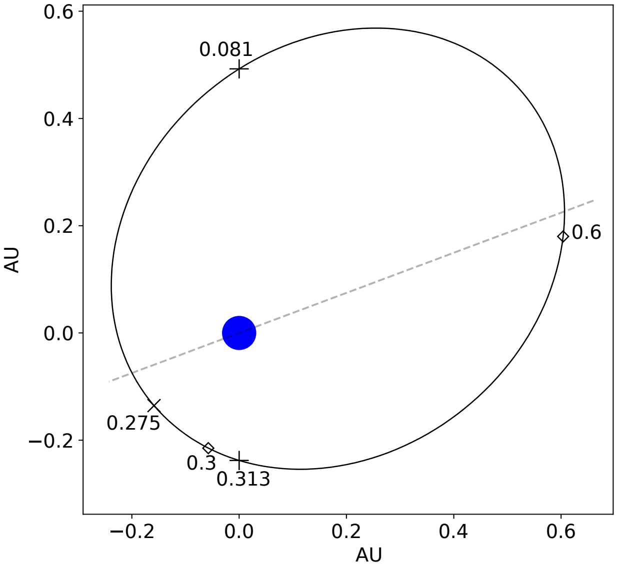
- Phase drift in the X-ray peak around $\phi \simeq 0.6$ (Chernyakova, 2012)







- Cannot reproduce the peak (single or maximum) around $\phi \simeq 0.6$ $\rightarrow$ problem with the model? Orbit? Something we're not taking into account?

Summary

- (Toy) disc model:
  - Physical representation of disc and geometry → physically constrain the (relative) position of the emission peaks
  - Model the non-thermal emission from shock stand-off (synchrotron, include I.C.) - assuming a fixed Power-Law → (evolve particle distribution along the orbit)
  - Can produce double peak for HESS J0632+057 → dip after primary peak?
    - Underlying stellar wind – polar wind?
  - Disc precession – produces a phase shift in the peaks
    - Geometry constrains disc peaks towards periastron – LS I +61°303 X-ray peaks occur near apastron
    - Model the optical emission from the disc, EWs, ΔV_{peaks} (BEDISK code, synthetic spectra) → compare with optical observations and constrain disc model (geometry)
  - Incorporate elliptical / asymmetric disc shape and/or density profile

Thank you