Modelling the effect of Be discs on the emission from gamma-ray binaries

(featuring a new orbital solution for HESS J0632+057)

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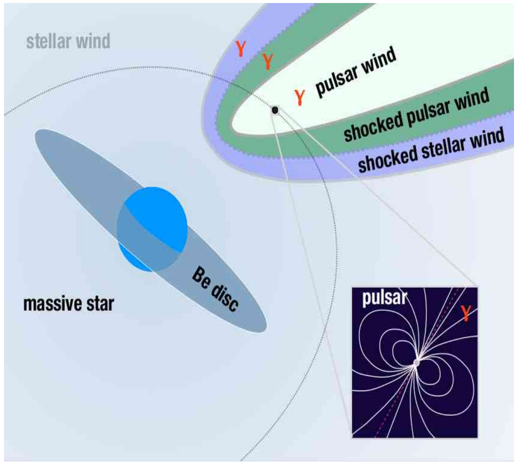
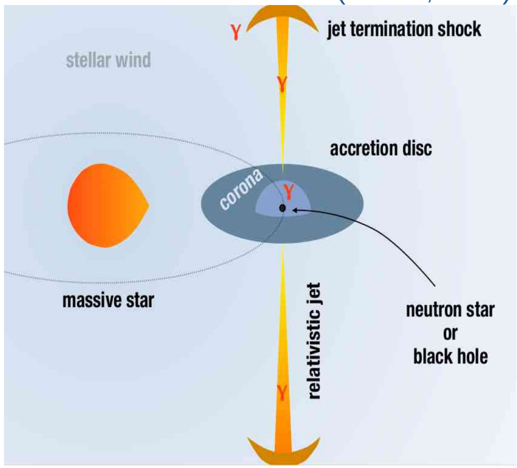
Gamma-ray binaries

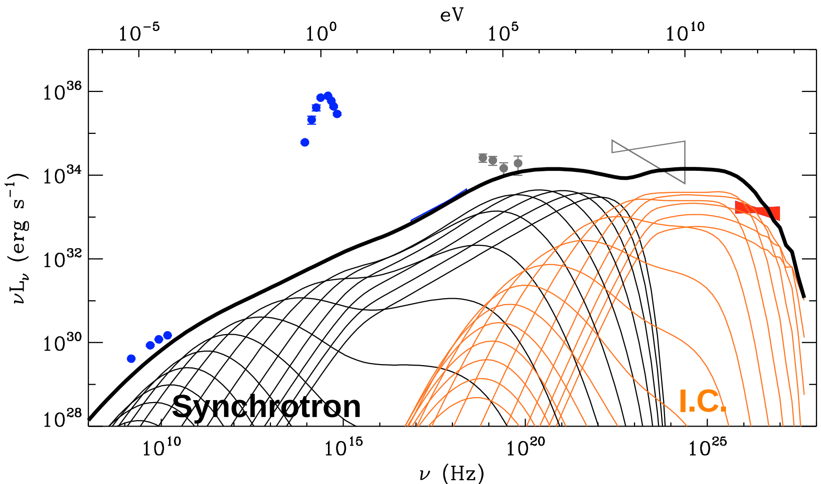
(Dubus, 2006)



Pulsar-wind scenario



Microquasar scenario

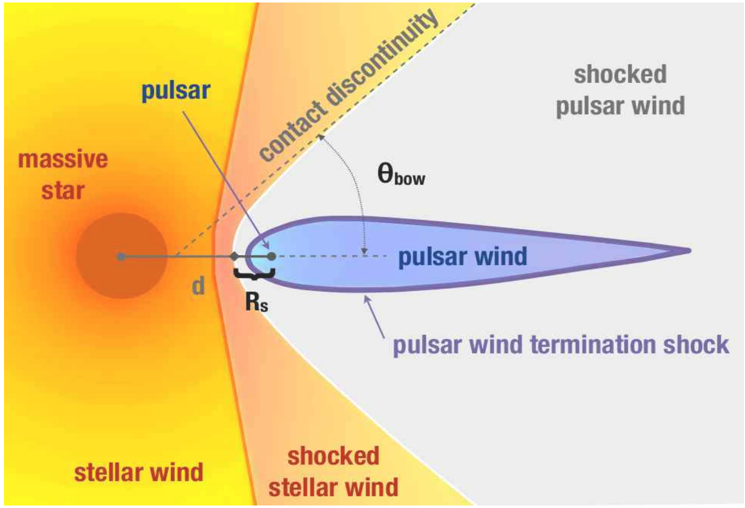


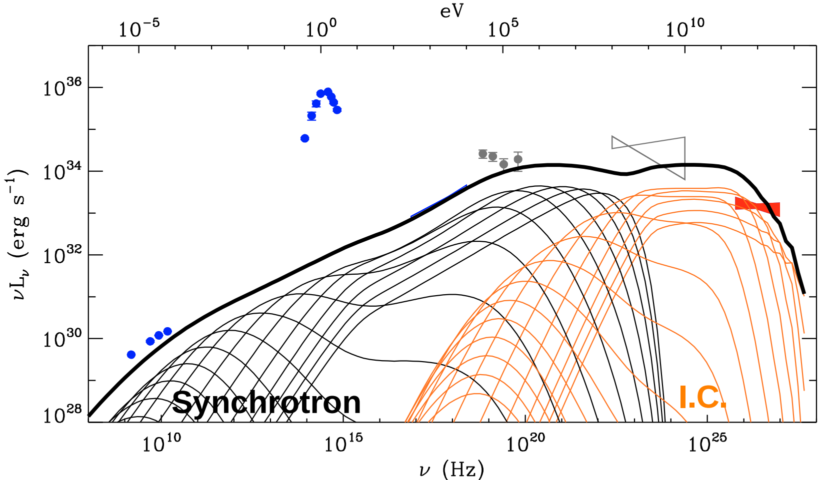
- Very efficient emitters → energy peaks at >1 MeV
- Stellar-wind/circumstellar disc from O/Be star collides with relativistic pulsar wind from NS
  - produces a termination shock
  - particles accelerated to HE & VHE
- **O-type systems** – IBS between stellar wind and pulsar wind
  - Emission usually peaks near periastron (X-ray) / inferior conjunction (IC TeV)
- **Be-type systems** – shock forms between stellar wind and/or circumstellar disc and pulsar wind

Gamma-ray binaries

Pulsar-wind scenario

(Dubus, 2006)





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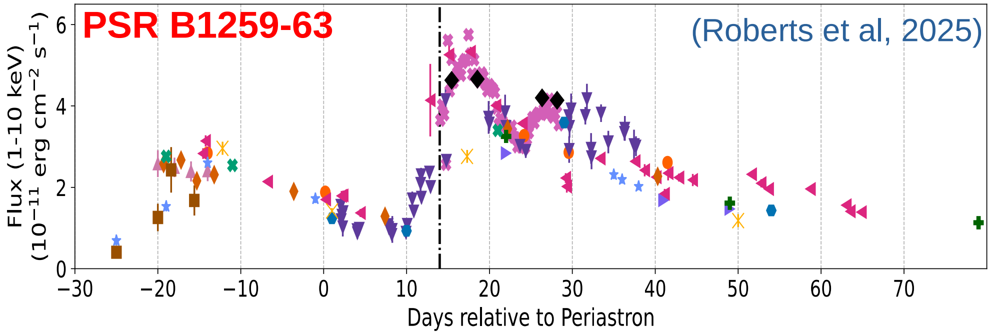
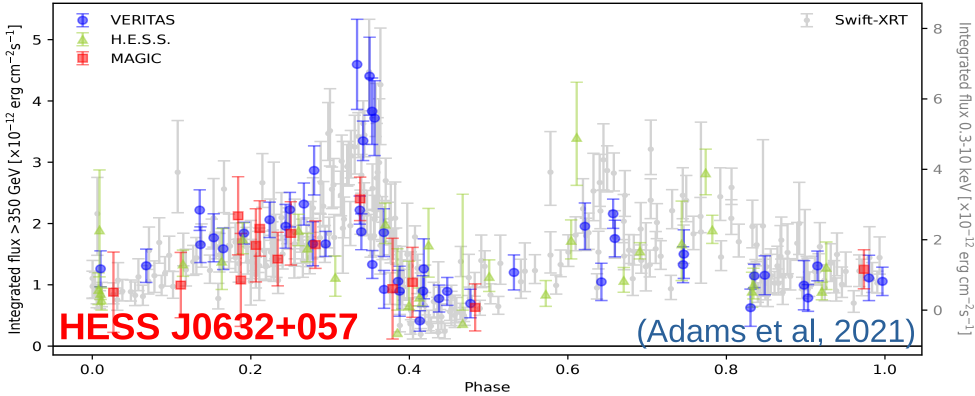
Be gamma-ray binaries

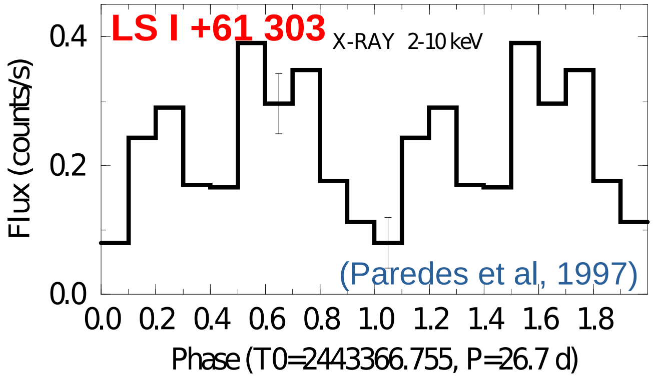
- For the **Be systems** (*PSR B1259-63; HESS J0632+057; LS I +61 303*; *PSR J2032+4127*) we usually see double peaked X-ray/TeV lightcurves

→ connected to the pulsar-disc interaction?

	Orbital Period [d]	Companion	Disc / emission
PSR B1259-63	3.4 yr	O9.5 Ve	Double peaks X-ray & radio
LS I +61°303	26.5	B0 Ve	Precessing disc?
HESS J0632+057	317.3	B0 Vpe	Double peaks X-ray and TeV
PSR J2032+4127	43.8 – 48.8 yr	B0 Vpe	?



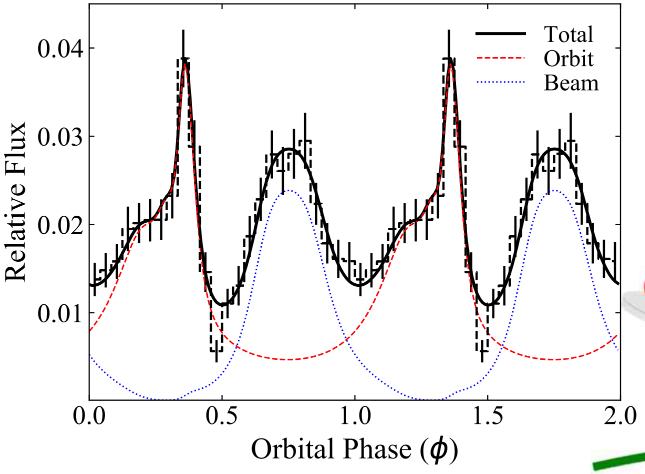




Be gamma-ray binaries

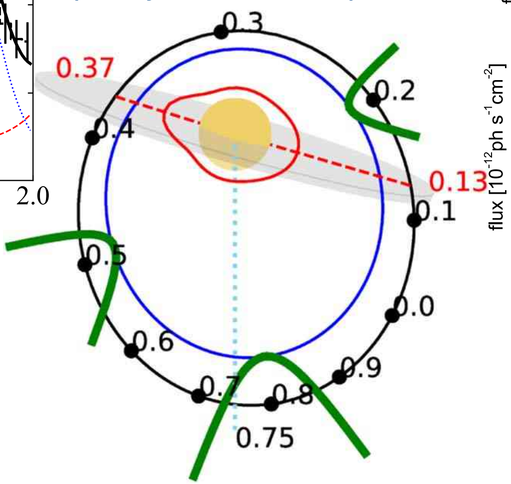
- Several studies looking into modelling the non-thermal emission/re-producing the double-peaked behaviour of the lightcurves
(e.g. Chen & Takata, 2019,2022; Chen et al, 2024; Tokayer et al, 2021)

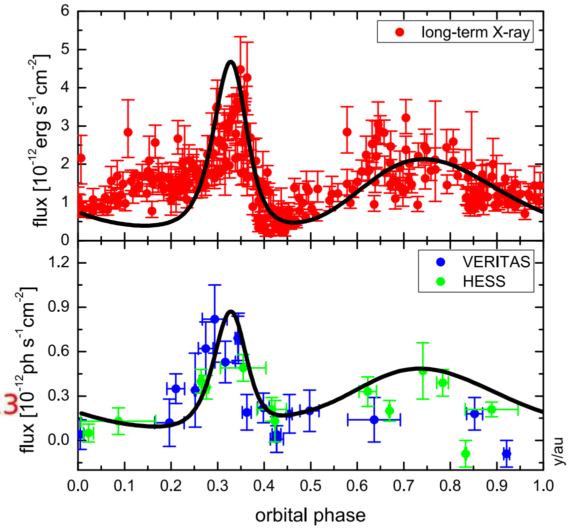
→ **but peak positions not always physically constrained by true disc/orbit geometry**



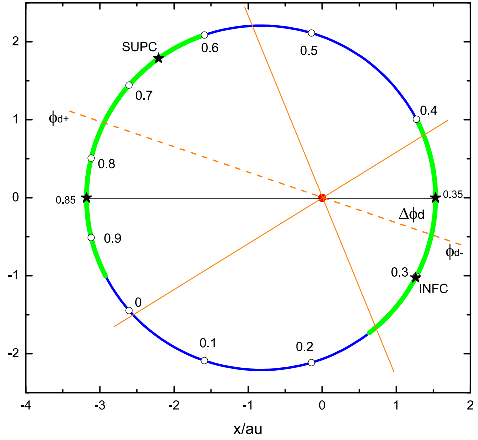
e.g. for HESS J0632+057

(Tokayer et al, 2021)



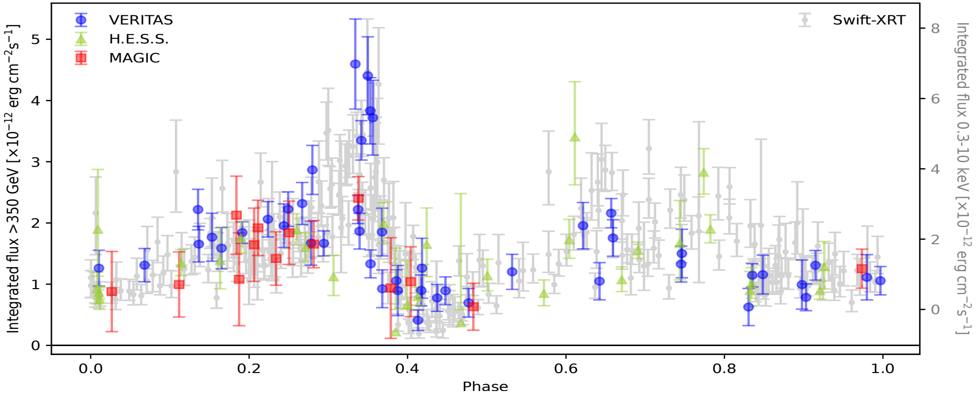


(Chen et al, 2022)



Be gamma-ray binaries

- Can we reproduce the behaviour of the non-thermal emission in the Be γ-ray binaries (i.e. the double-peaked lightcurves) from the interaction with the disc – **physically** confined by disc/orbit geometry



Model the non-thermal emission

Physical model/representation of the **disc** and **system geometry**

constrain orbit

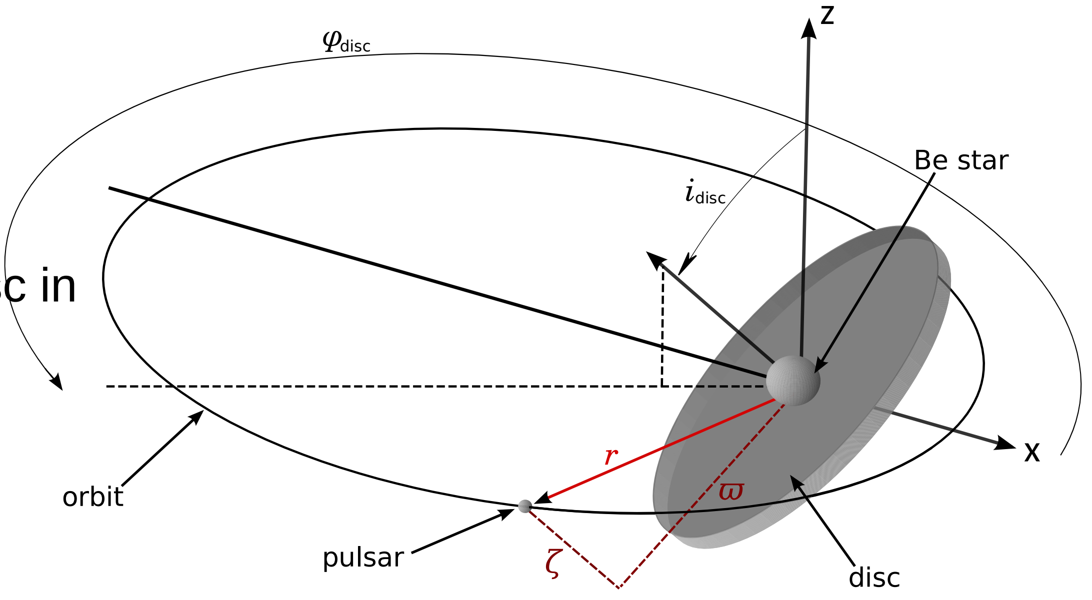
Optical observations

Model optical emission lines (Be-disc)

Physical model of the disc

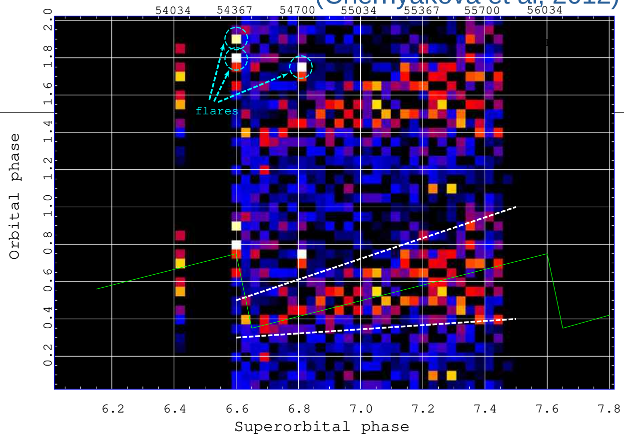
Case I – static disc (no precession)

- 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)



Physical model of the disc: Case II

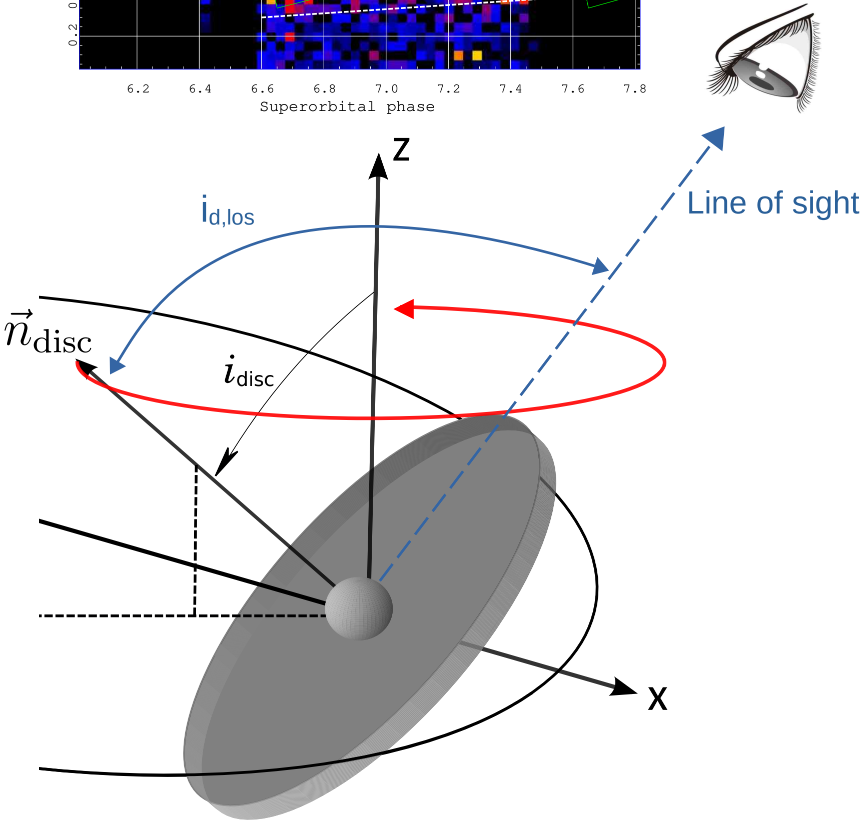
(Chernyakova et al, 2012)



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

Case II – with precession

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



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)

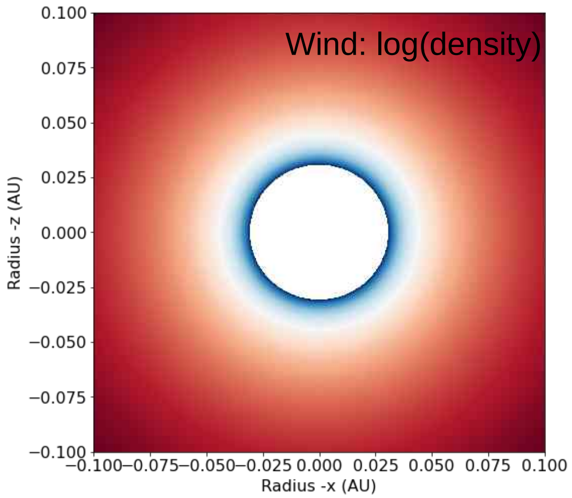
- Ram-pressure of the circumstellar disc:

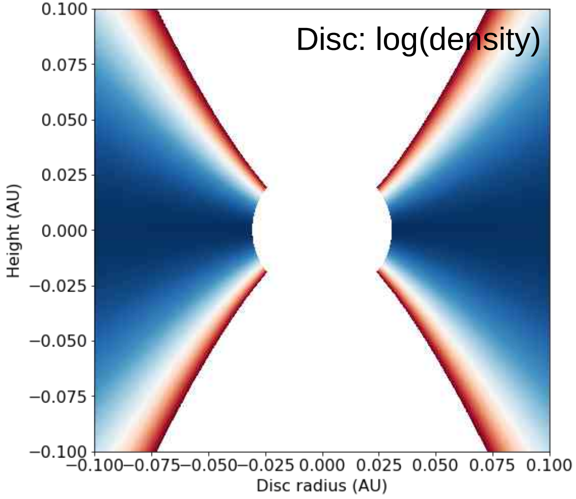
$$p_{\rm disc} = \rho_{\rm disc} v_{\rm disc}^2$$

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

(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,

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

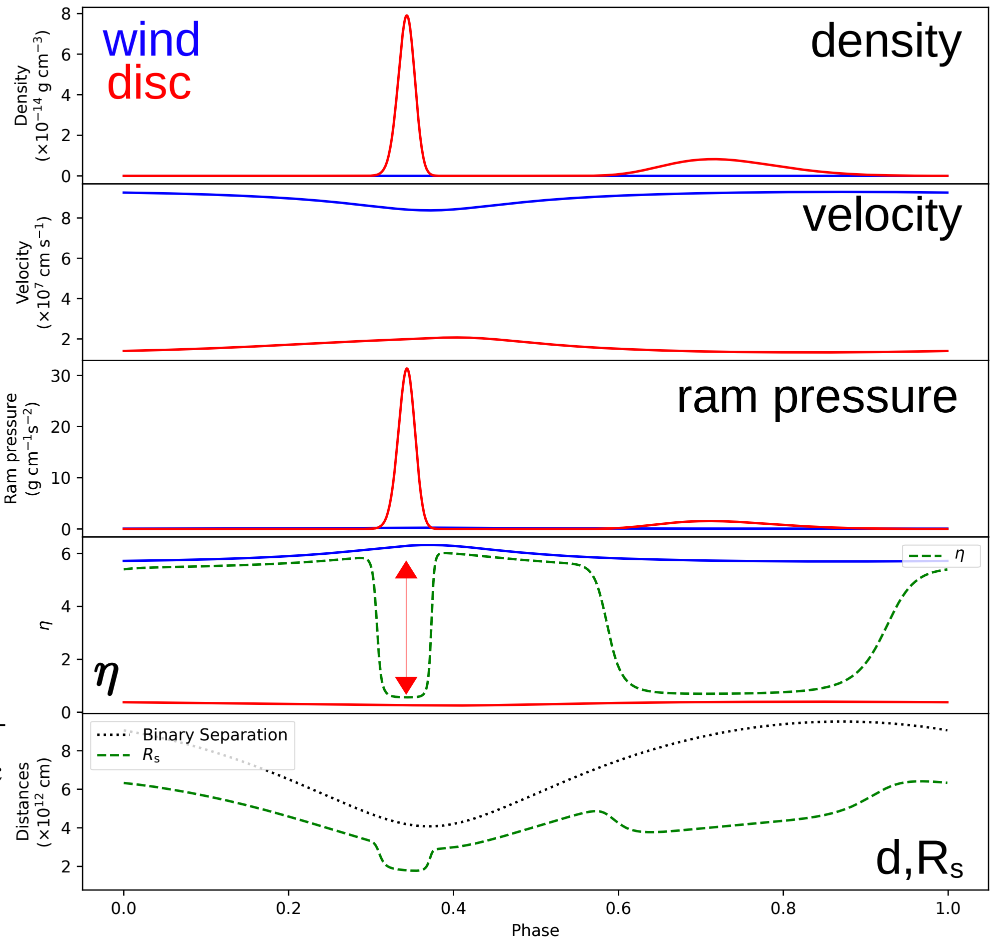
(e.g. Eichler & Usov, 1993; Kennel & Coroniti 1984; Dubus 2006, 2015.)

- **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**

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



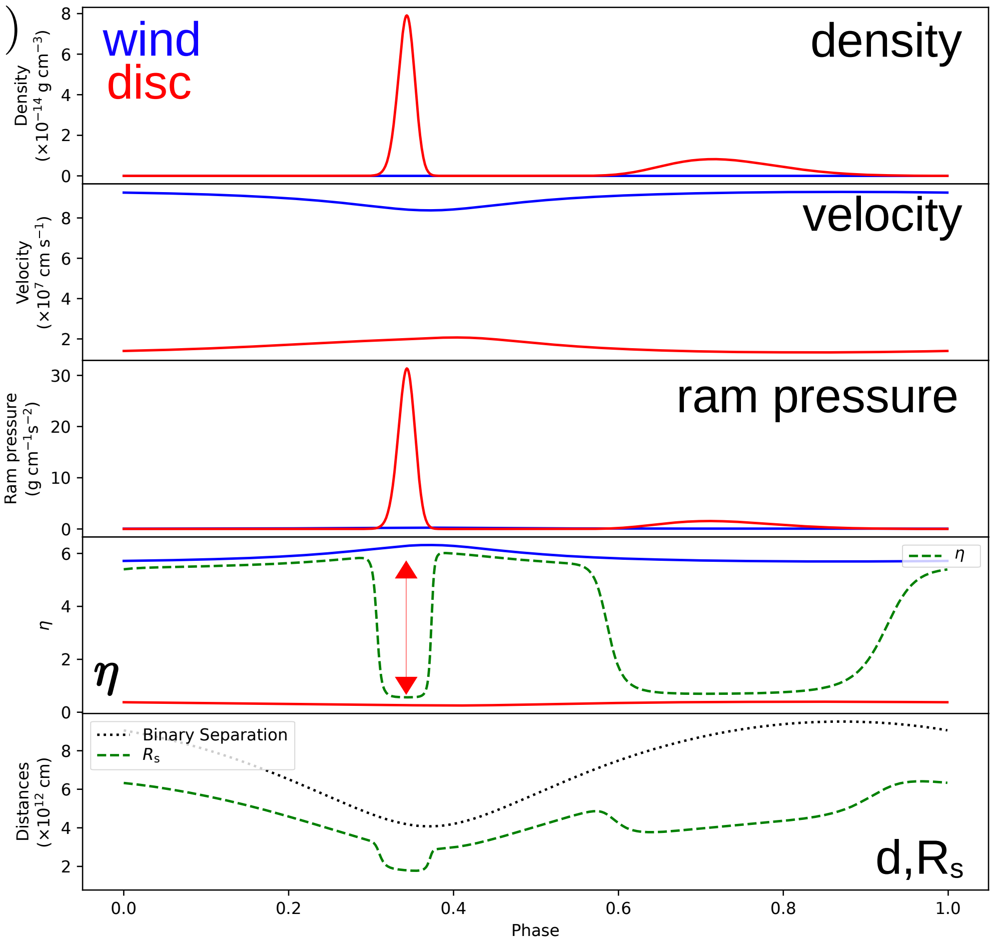
Solving the shock stand-off (III)

- 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 non-thermal emission

- For now, 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:

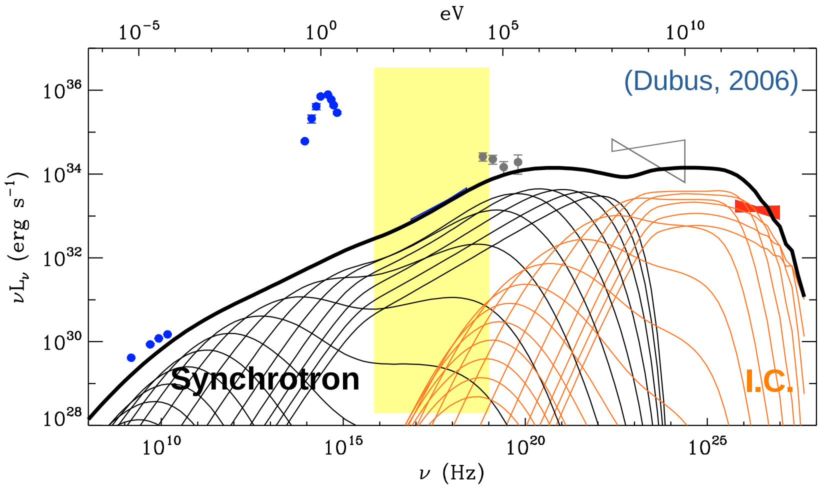
$$B = 3(1-4\sigma)\left(\frac{\dot{E}/c}{R_s^2}\frac{\sigma}{1+\sigma}\right)^{1/2}$$

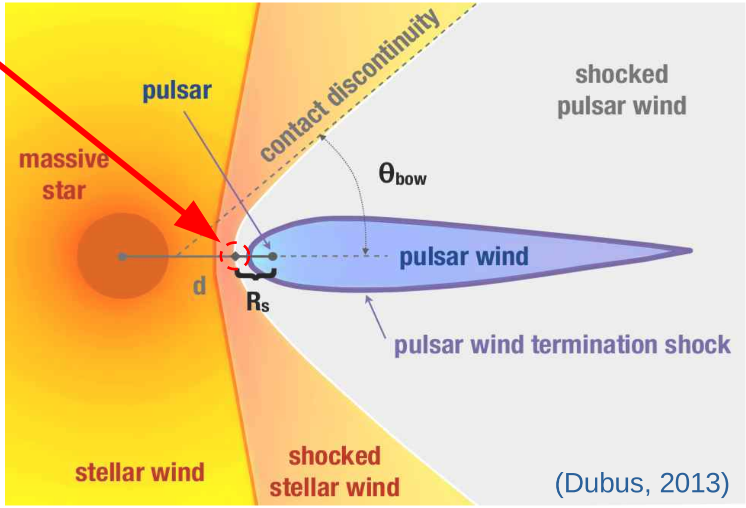
(Kennel & Coroniti, 1984)

- ∴ $B \propto 1/R_s$ → 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 $R_0 = d_{peri}$

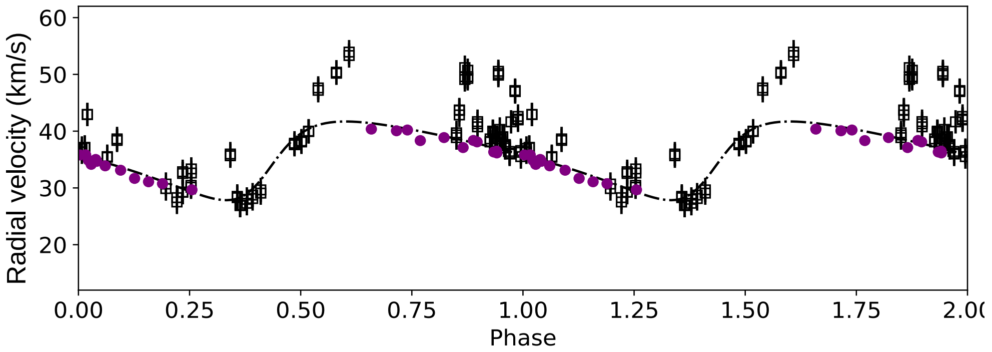


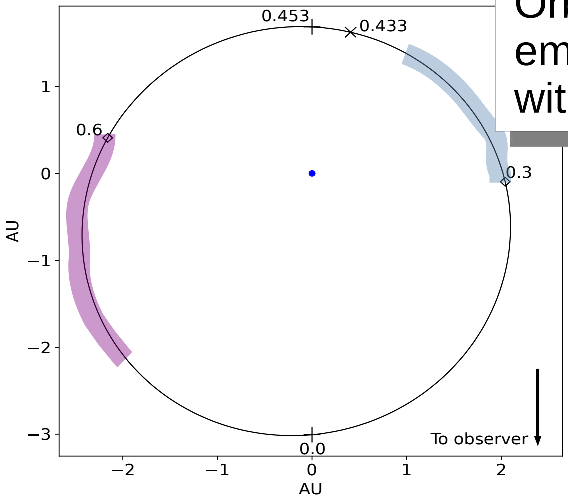


Application with a non-precessing disc

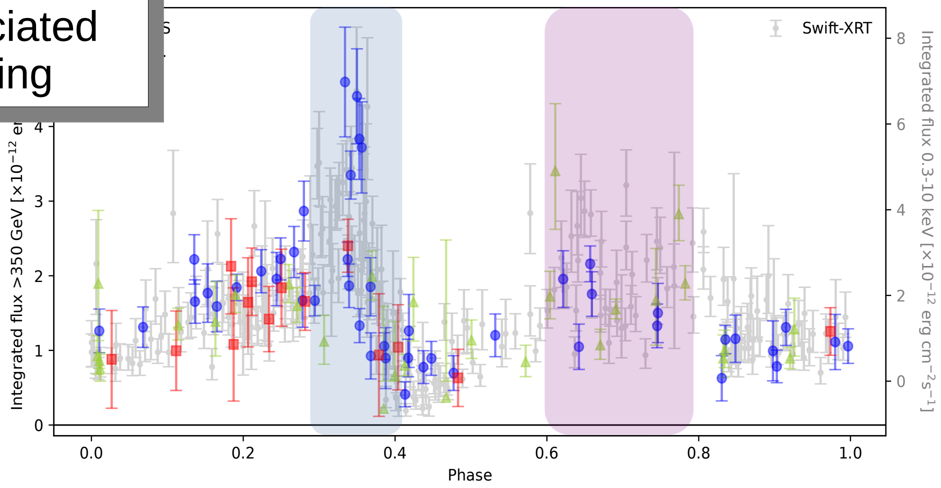
HESS J0632+057:

- **New orbital solution** with SALT data **(Matchett and van Soelen, 2025)** provides an orbit which is more consistent with the X-ray/TeV emission peaks produced by interaction with the disc





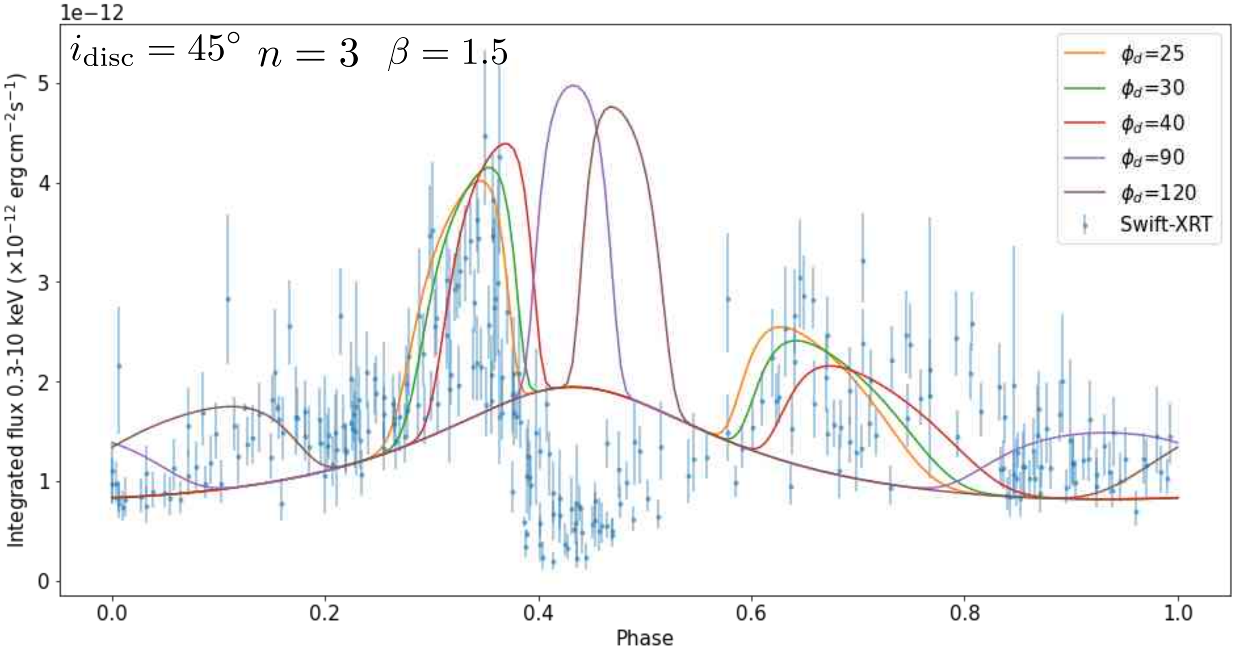
Orbit more consistent with emission peaks associated with pulsar-disc crossing

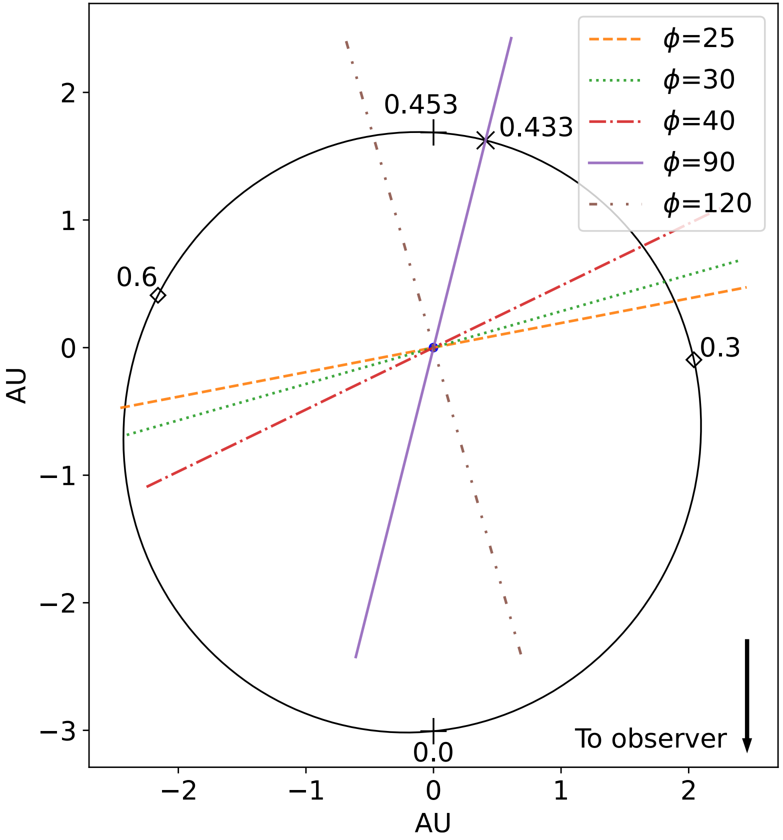


Application with a non-precessing disc

Preliminary

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





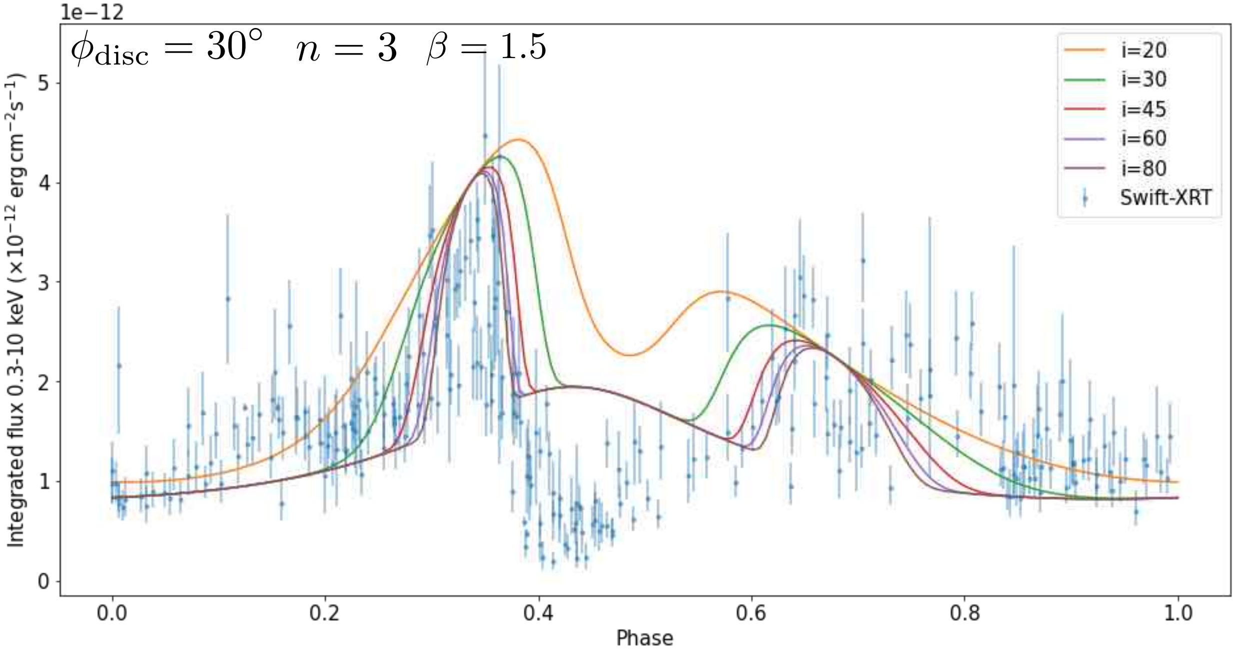
→ affects the positions (orbital phase) of peaks

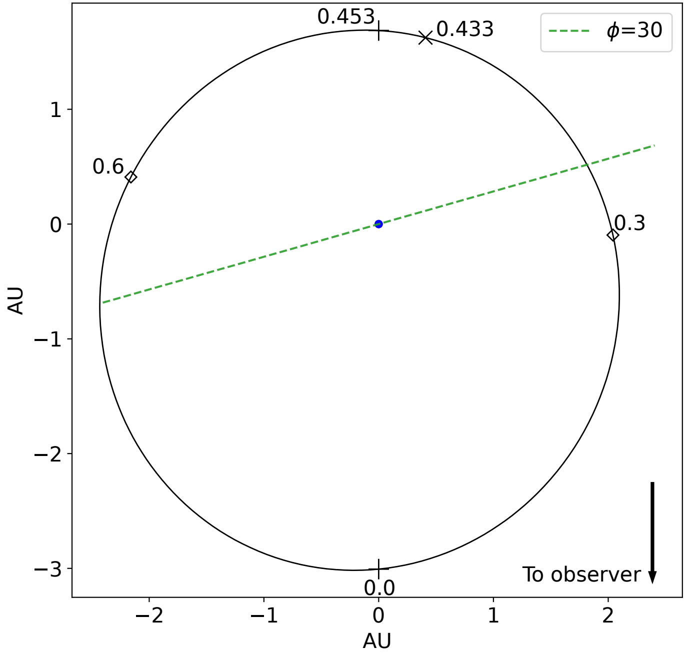
→ best ‘fit’ $\phi_{\rm disc} = 30°$

Application with a non-precessing disc

Preliminary

- Changing the disc inclination (i_{disc})



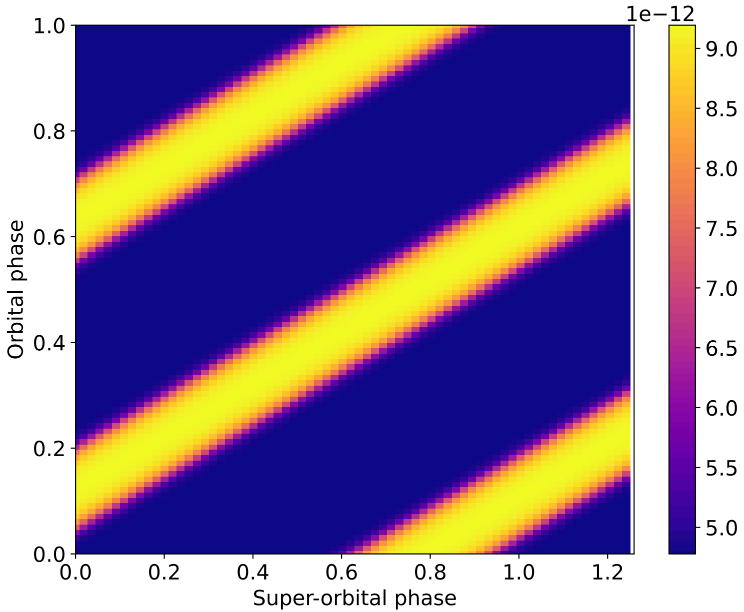


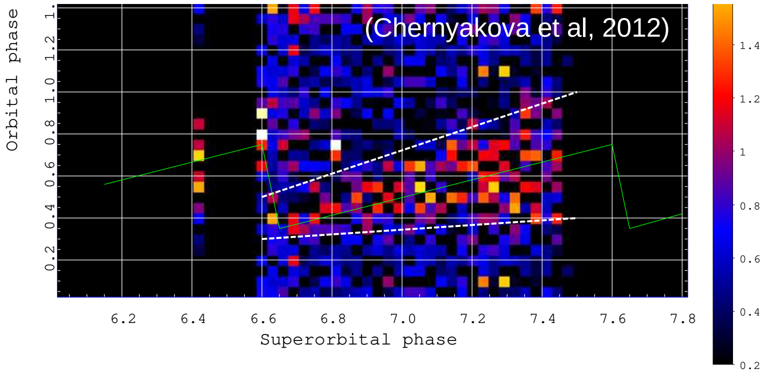
→ 0° disc in plane of orbit
→ The less inclined the disc, the greater the depth that the pulsar must pass through ∴ increasing the width of the peaks

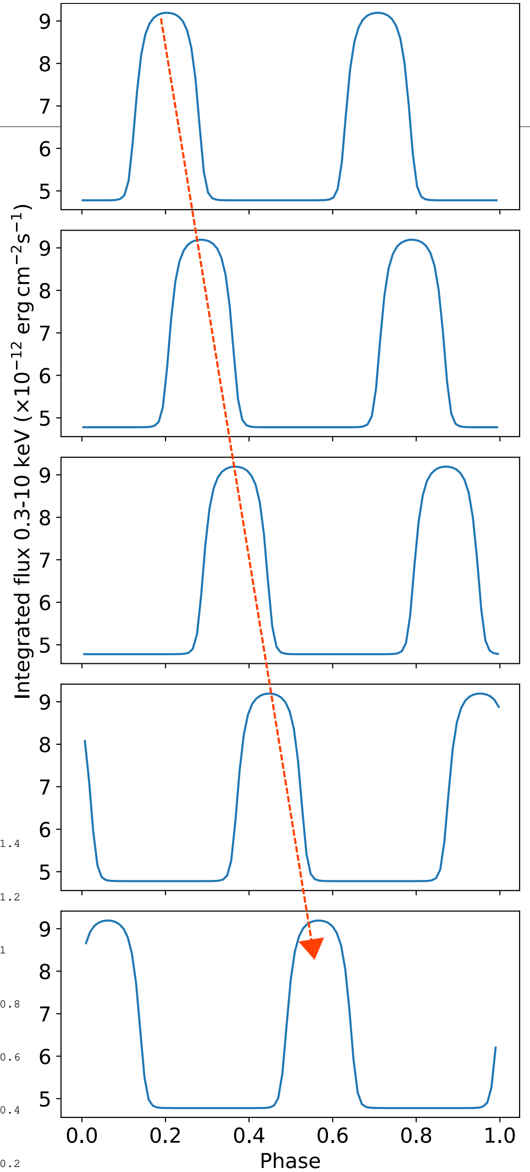
Application with a precessing disc

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:
  $i_{disc}\!=\!30^{\circ},\ P_{Prec}\!=\!2\times1664\,\mathrm{d}$
- Produces phase-shifting X-ray peaks, similar to idea for LS I +61°303 (Chernyakova 2012, 2023)



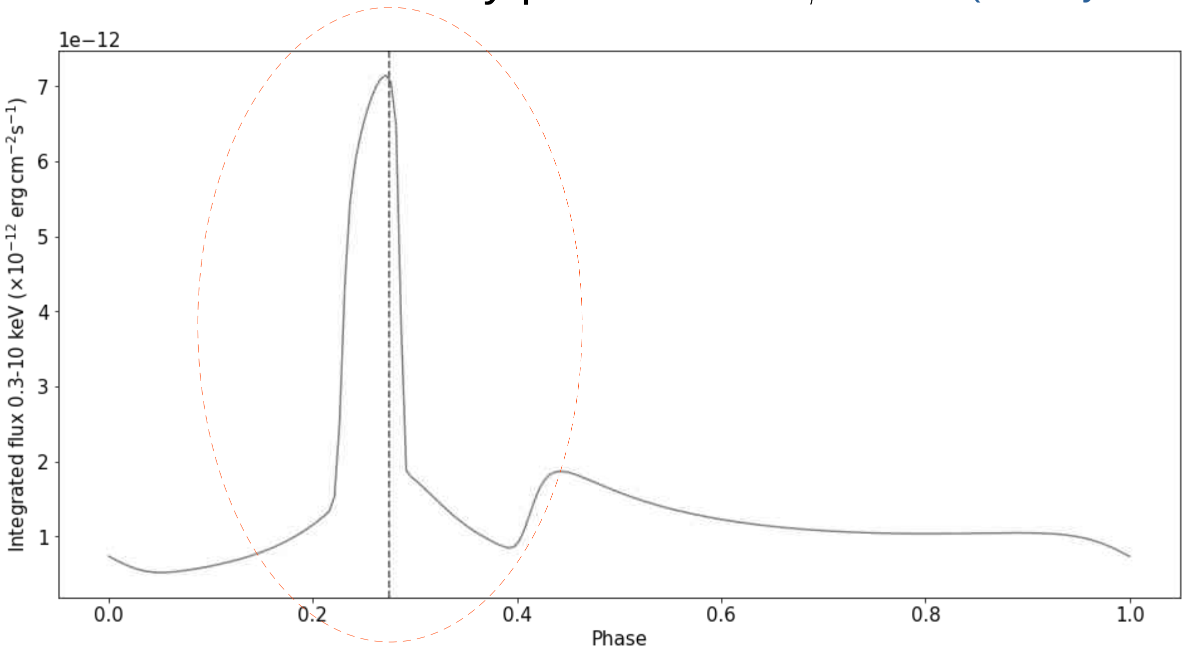


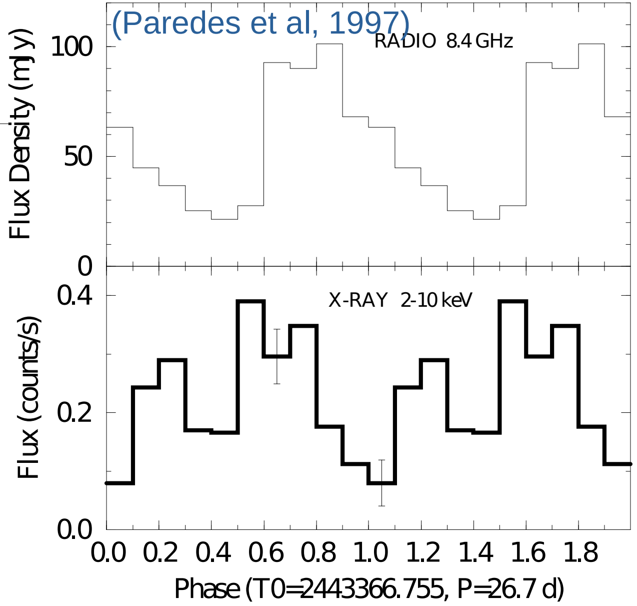


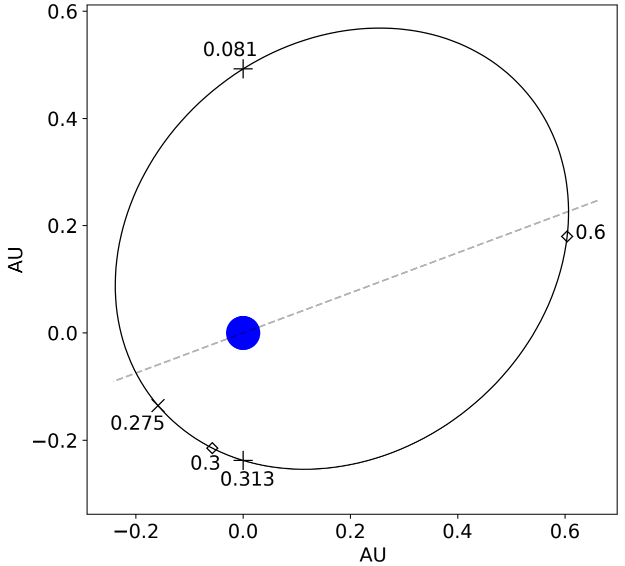
Application with a precessing disc

Preliminary

- **LS I +61°303:**
- Phase drift in the X-ray peak around $\phi \simeq 0.6$ (Chernyakova, 2012)







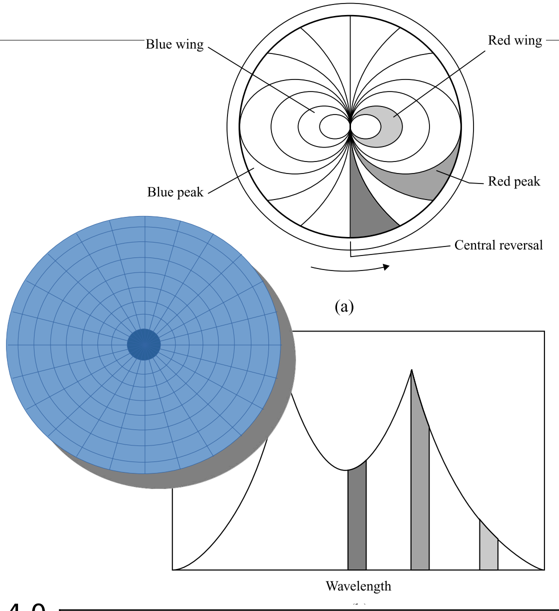
- Cannot reproduce the peak (single or maximum) around $\phi \simeq 0.6$ → problem with the model? Orbit? Something we're not taking into account?

Modelling the optical (Be disc) emission

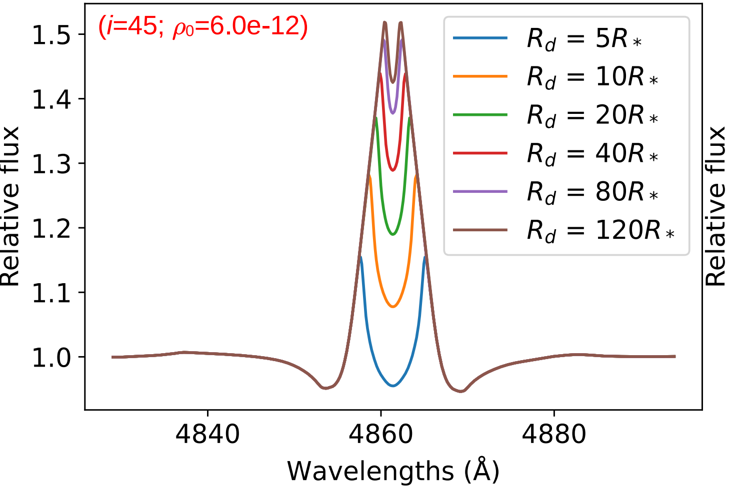
(Robinson, 2007)

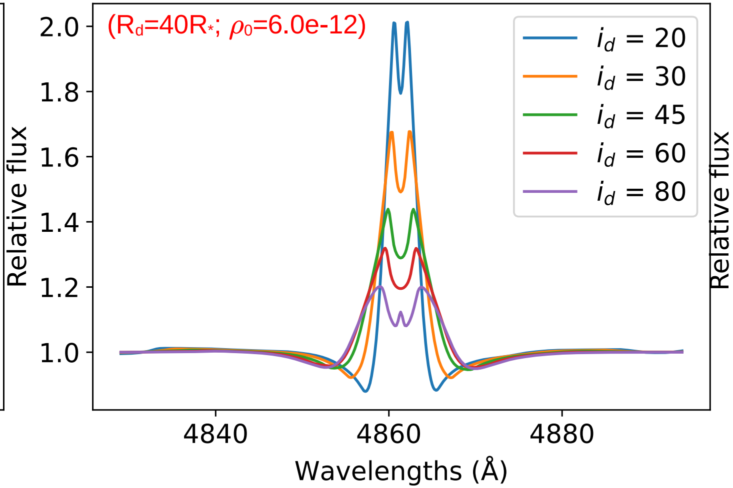
- Building on the `BEDISK` emission line synthesis code (e.g. Gies et al 2006; Sigut & Jones, 2007) we can model the Hα, Hβ and Hγ emission lines:
  → based on the disc density, radius and inclination.

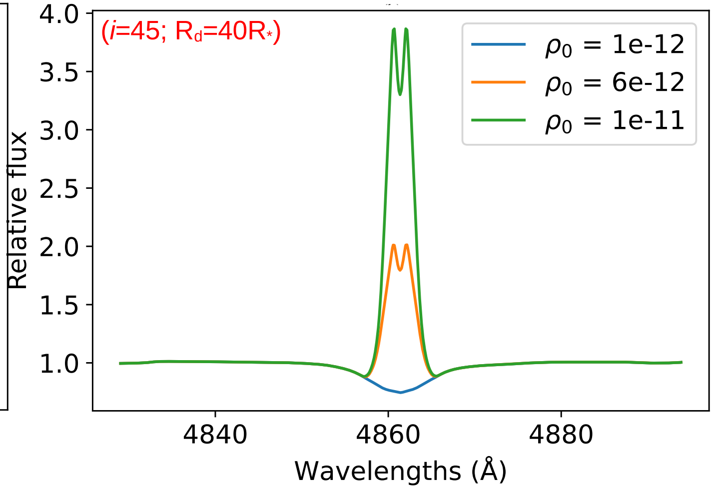
  - Determines the optical depth, thus flux vs. velocity distribution for each cell in a rectilinear disc grid - for a Keplerian disc inclined w.r.t the LoS



e.g. Hβ:

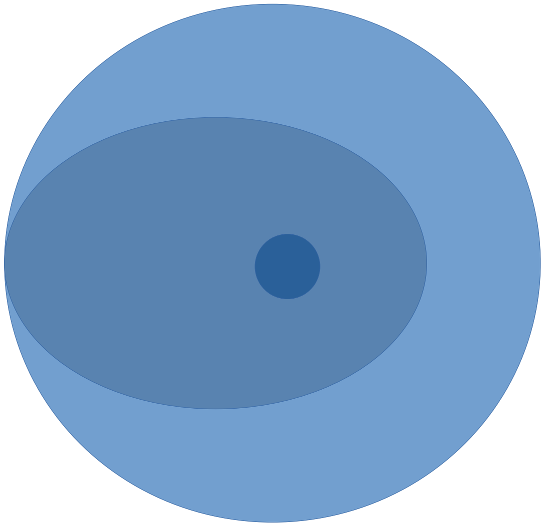


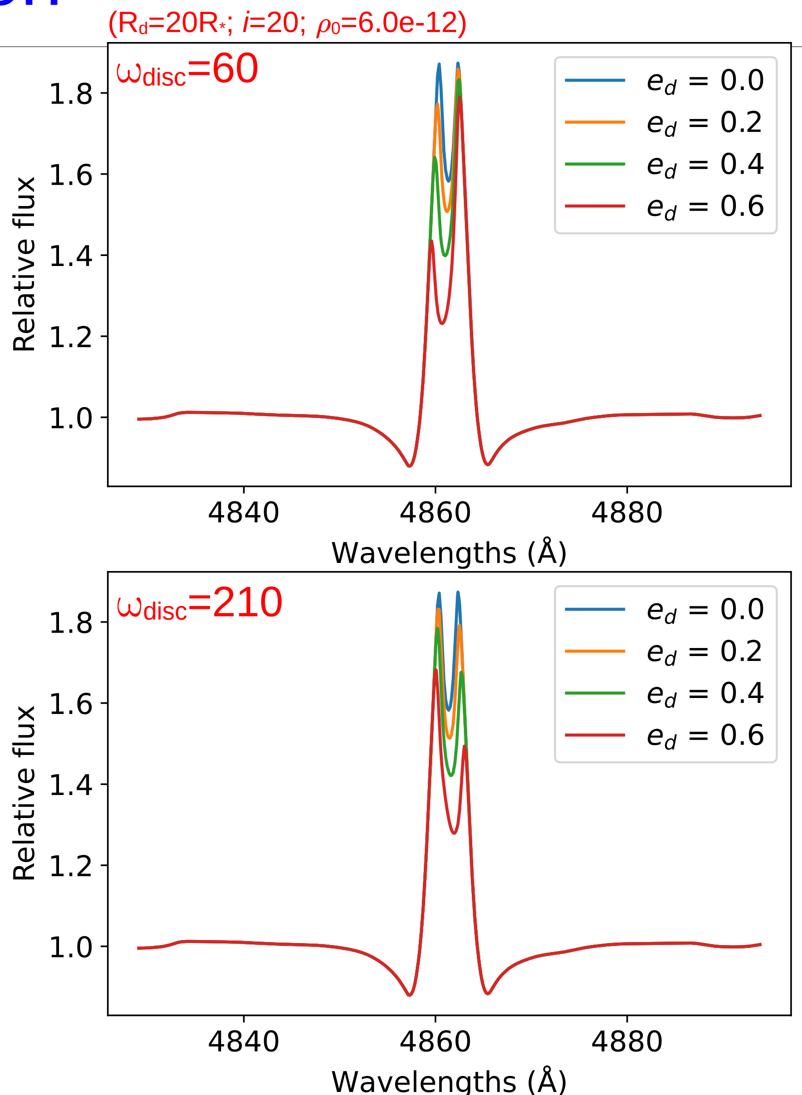




Modelling the optical (Be disc) emission

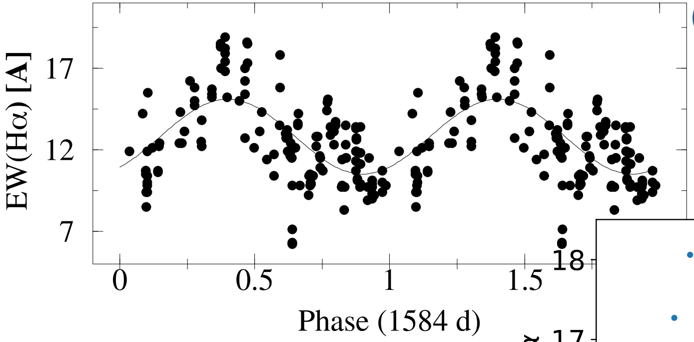
- **Implementation of an ‘elliptical’ disc**:
  - Very simple approximation to force an asymmetric material distribution / “mimic” spiral density structures / truncating of the disc that results in the asymmetric line profiles observed



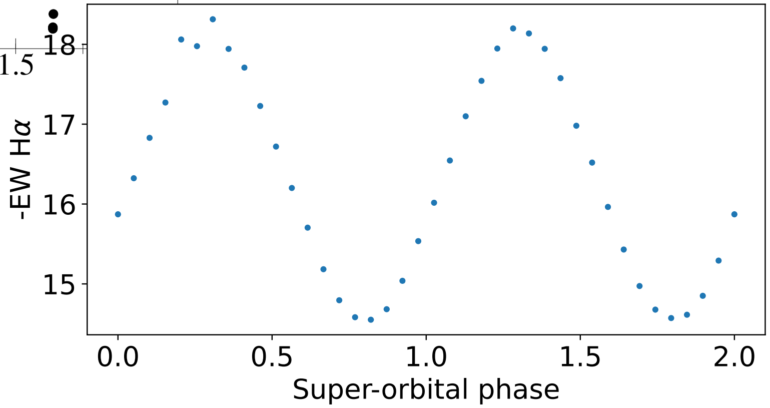


Modelling the optical (Be disc) emission

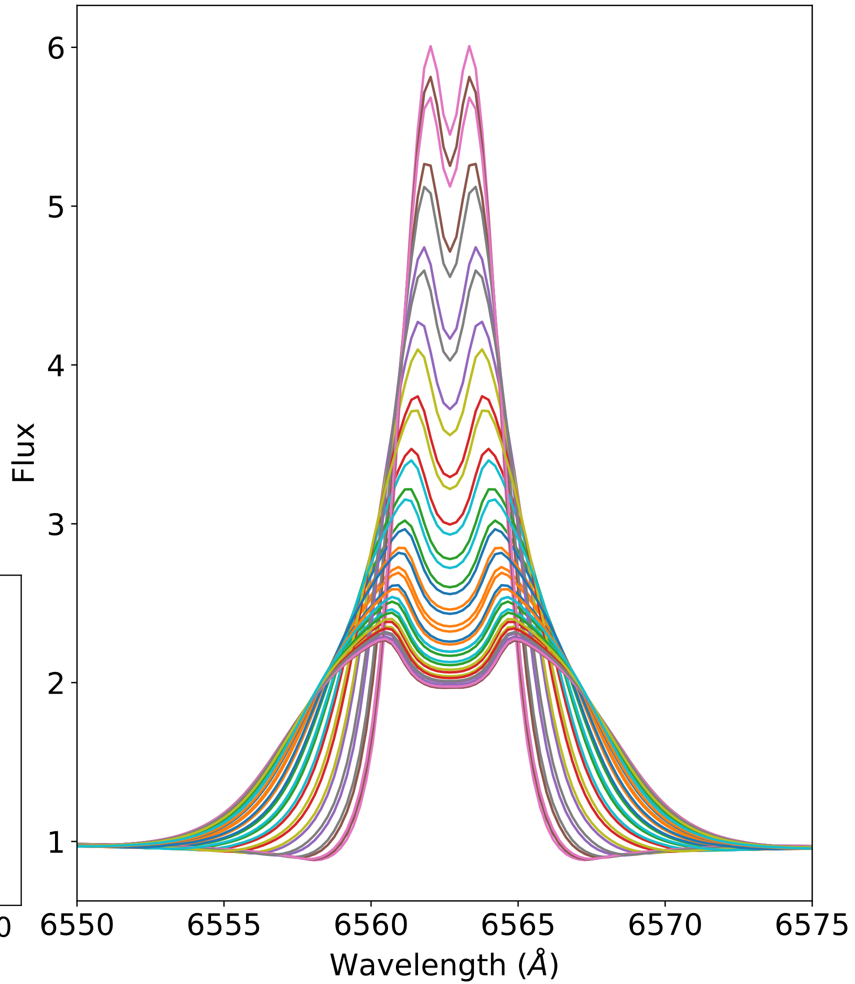
- **Implementation of a precessing disc:**
  - In addition to seeing a shift in the X-ray peaks for LS I +61 303, we also see super-orbital modulation of the EW → consistent with disc inclination (disc normal) changing with precession ∴ line profile changing.



(Zamanov et al, 2000)



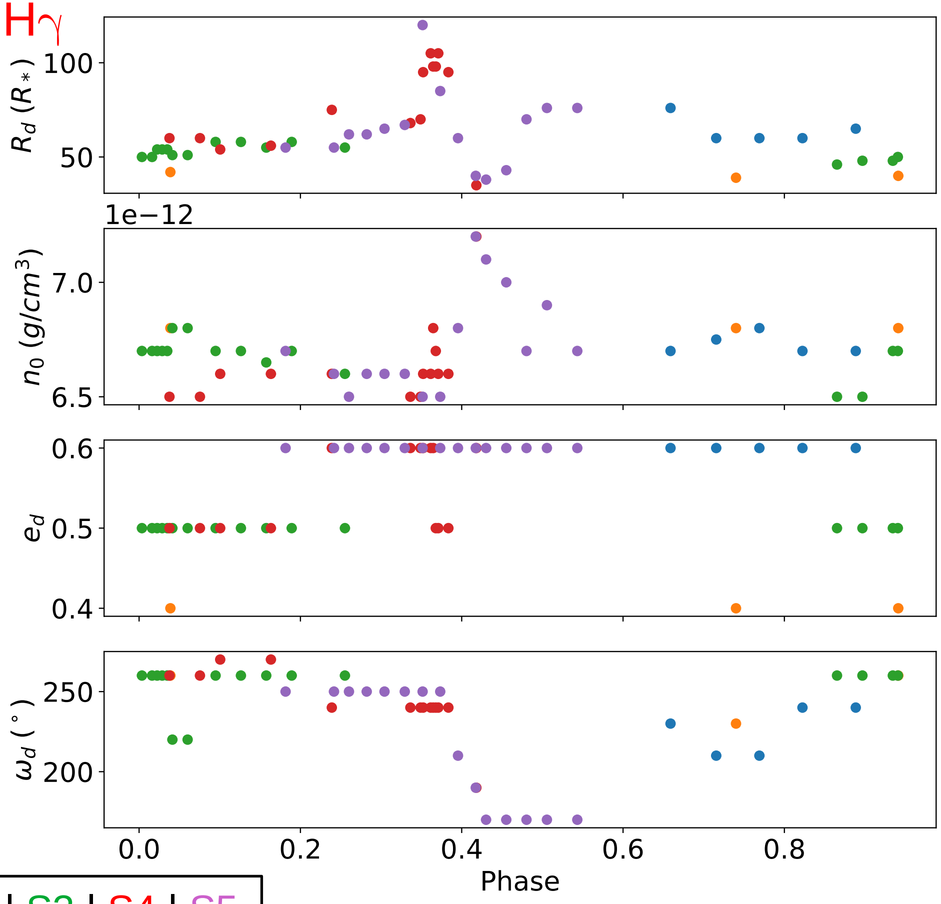
(R_d=60R_*; ρ_0=6.5e-12)

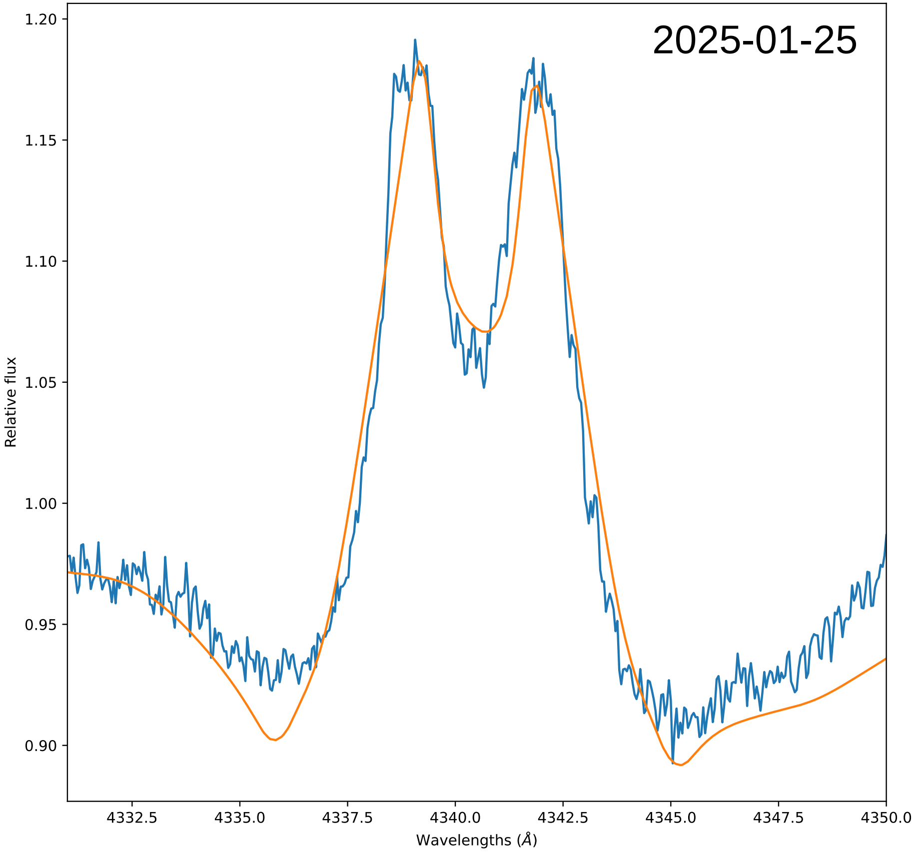


Modelling the optical (Be disc) emission

Preliminary

- Fitting the modelled/synthetic emission lines to SALT HRS data for HESS J0632+057
  - Hγ





S1 | S2 | S3 | S4 | S5

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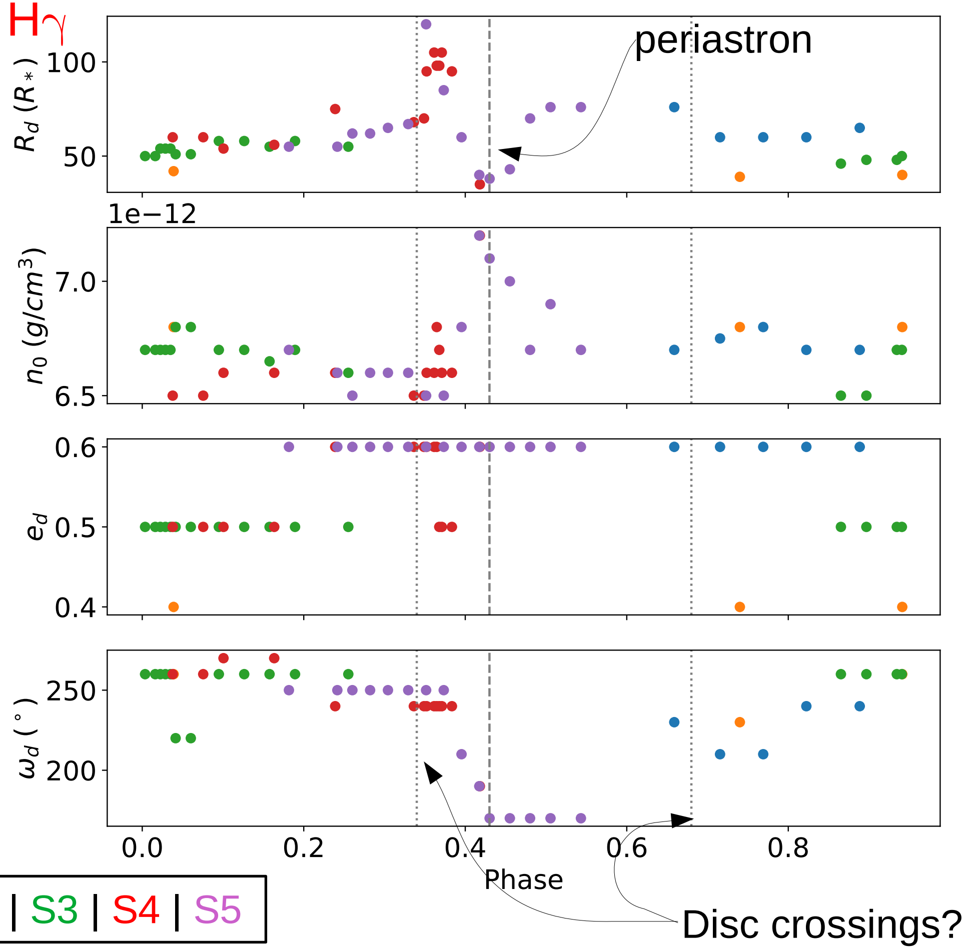

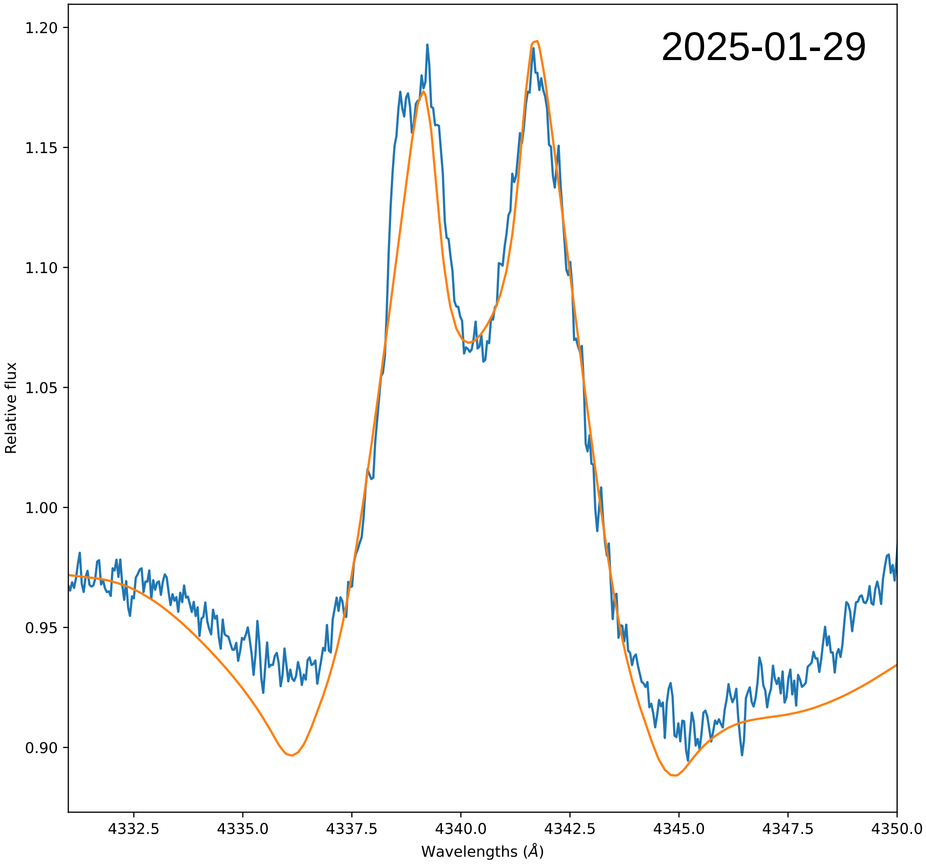

S1 | S2 | S3 | S4 | S5

Summary

- Using a simple, **physical disc model** we **model the shock stand-off parameters** and the **non-thermal emission**
  - Can implement **precession** into the physical disc model, which does reproduce a shifting/migrating emission peak → but exact positions of modeled X-ray peaks still need to be constrained.
  - Include IC emission & incorporate particle cooling for the input particle spectrum.

- Adapted the BEDISK code to **model synthetic Balmer emission lines** to fit to the **optical spectroscopic observations**:
  - Implementation of an **"elliptical disc"/asymmetric disc** to model asymmetric line peak profiles.
  - Implementation of **precession** (from physical disc model) → can mimic super-orbital modulation seen in the EWs of LS I +61 303.
  - Feed BEDISK parameter fits into physical disc model → constrain disc parameters needed for the non-thermal emission modelling.

Thank you