Dynamics and emission of interacting pulsar-stellar winds in a high-mass γ-ray binary

Elina Kefala
Valentí Bosch-Ramon

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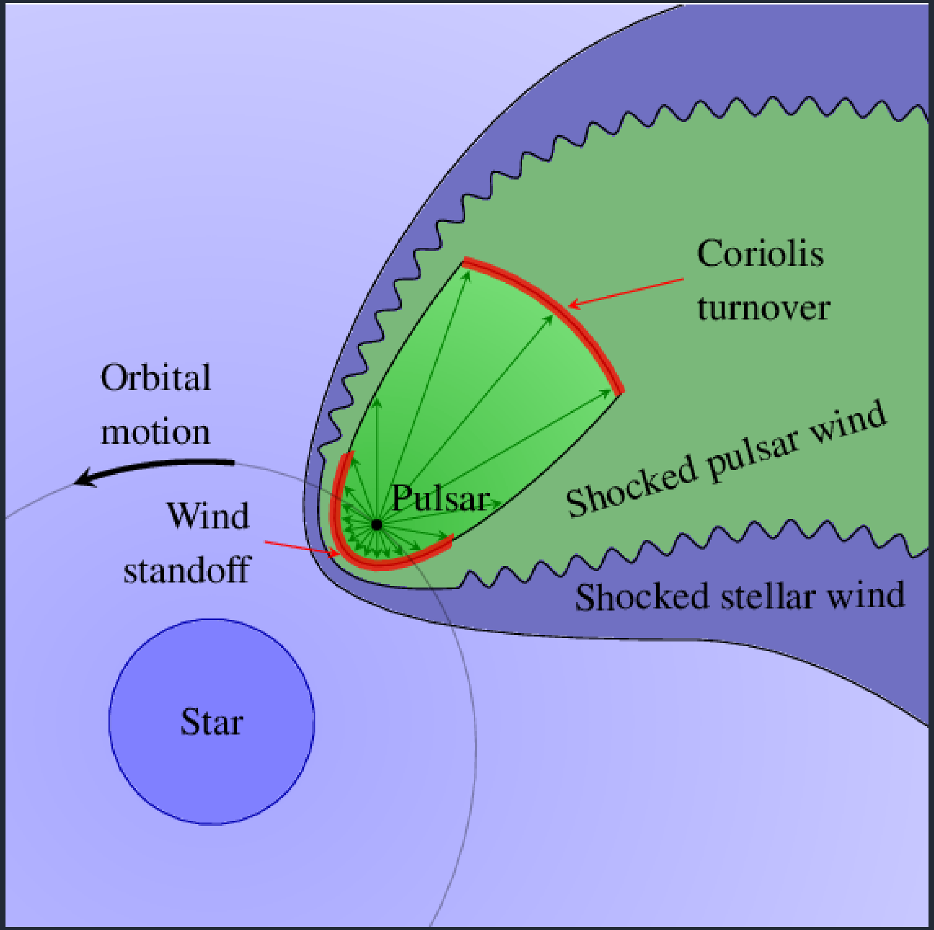
Intro

Gamma-ray binary pulsar scenario

Standard pulsar-wind-powered scenario
Two emitting regions:
Wind standoff + Coriolis turnover



(Zabalza et al. 2013)

- HD/MHD simulations (Bucciantini et al. 2005; 2008, 2012 Romero et al. 2007; van der Swaluw 2003; Vigelius et al. 2006; Romero et al. 2007; Bogovalov et al. 2008; Barkov et al. 2022)
- Collision of the two winds & formation of two terminating shock fronts and a contact discontinuity (CD)
- Coriolis shock formation in the direction opposite to the star due to orbit-induced mixing and spiraling of the stellar and pulsar winds (Bosch-Ramon et al. 2012, 2015; Dubus et al. 2015)

- Gamma-ray emission from the two interaction regions (e.g., Zabalza et al. 2013; Molina & Bosch-Ramon 2020, for a model of LS 5039
- Focus on leptonic scenarios (Bosch-Ramon & Khangulyan 2009)

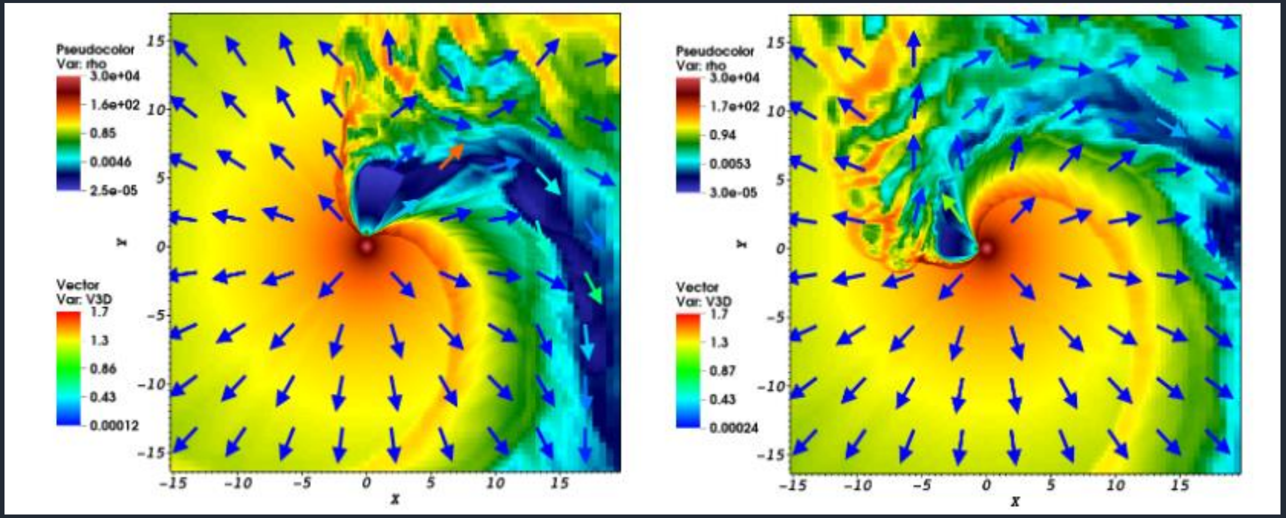
Intro

Location & orbital scaling of shocks

Dependence of the region size/shape and of the processes related to the two-wind interaction (particle acceleration, emission) on the orbital phase

Two different locations contributing to particle acceleration and theHE/VHE emission

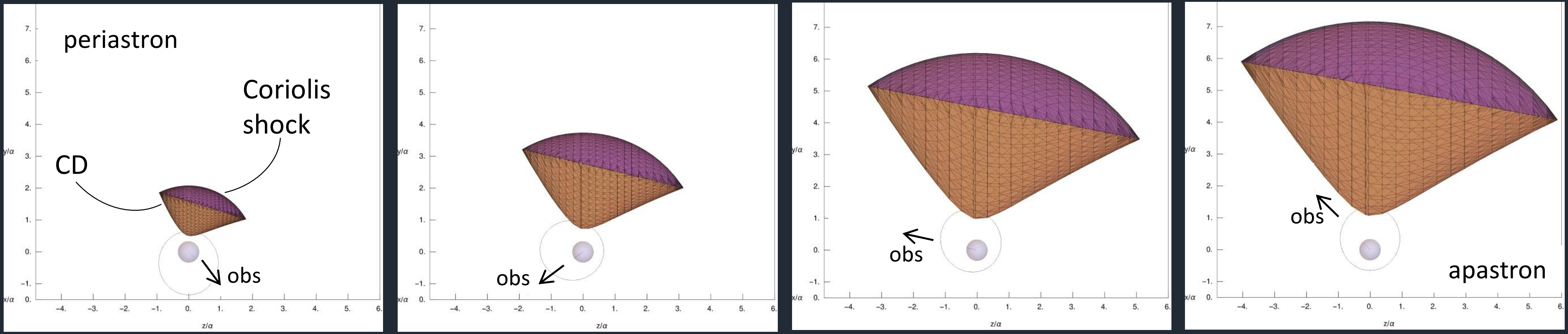
(Bosch-Ramon et al. 2015)



<u>LS 5039:</u> O6.5V(f) star, mildly eccentric orbit (~3.9 d; Casares et al., 2005; Sarty et al., 2011)

Larger scaling for highly eccentric systems

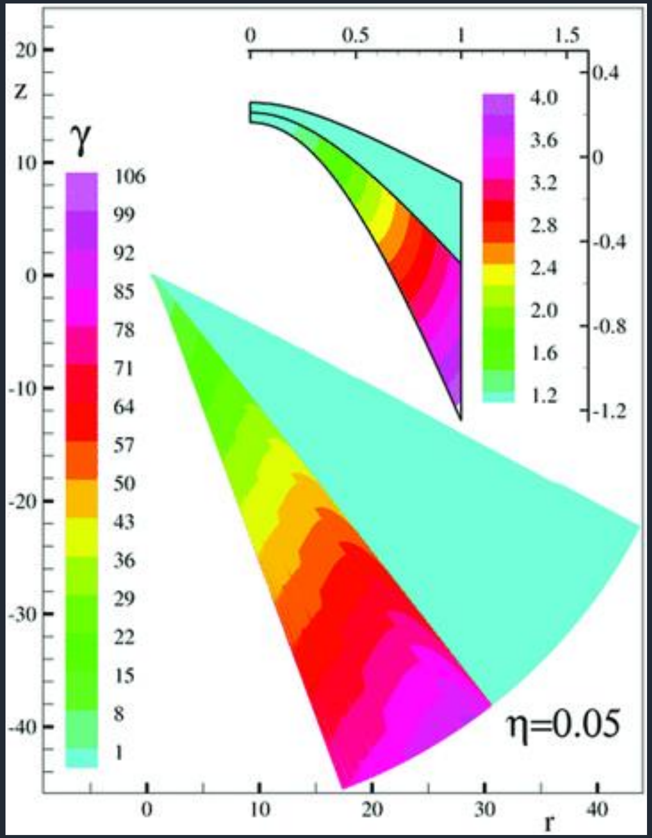
(Kefala & Bosch-Ramon in prep.)



Intro

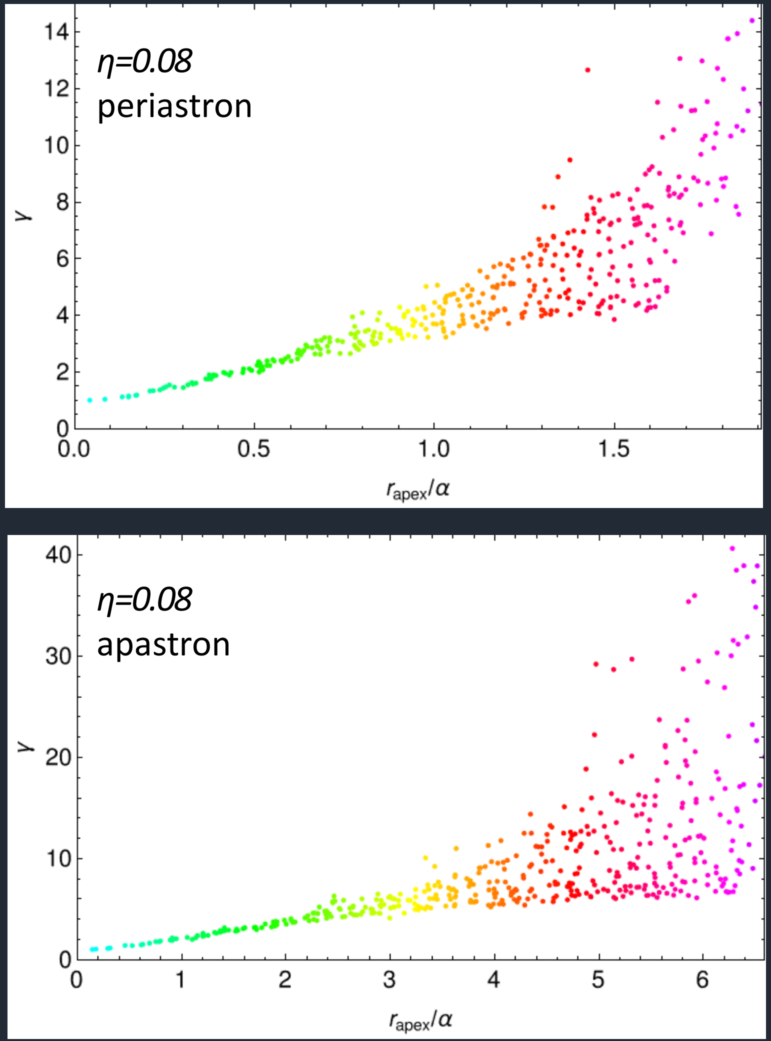
Relativistic
effects &
reacceleration

Boosting particularly relevant for emitters at the rarefaction of the shock and for phases at which the Coriolis shock is the farthest



(Bogovalov et al. 2008)

- Reacceleration of the flow to large Lorentz factors due to adiabatic losses (Bogovalov et al. 2008)
- Significant changes in the Doppler factor ➡ enhancement of the modulation of non-thermal radiation along the orbit



(Kefala & Bosch-Ramon in prep.)

Intro

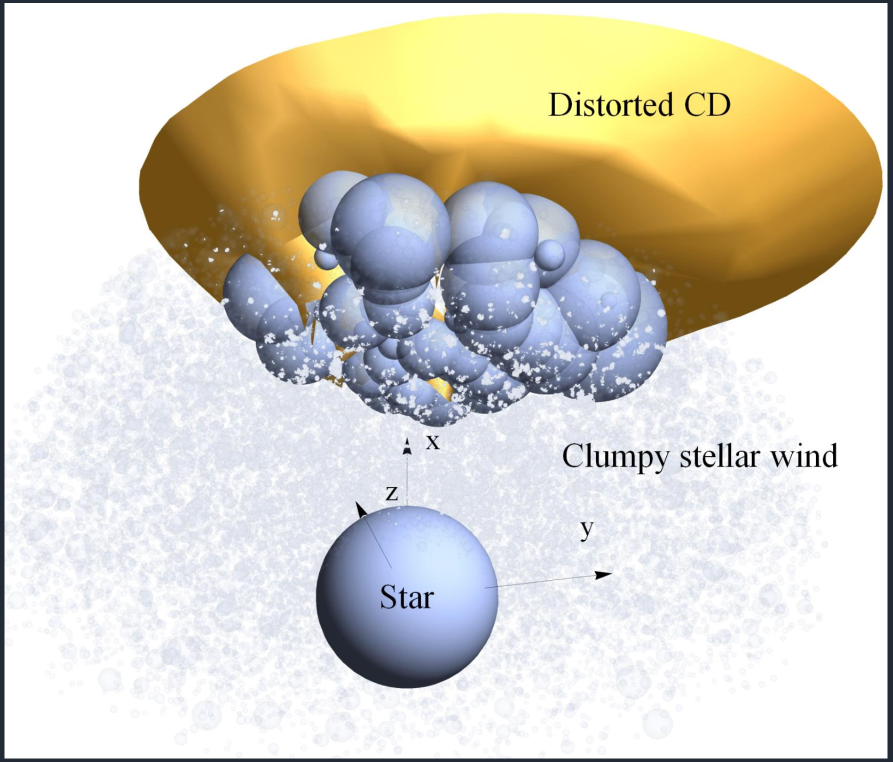
Inhomogeneity
of stellar winds

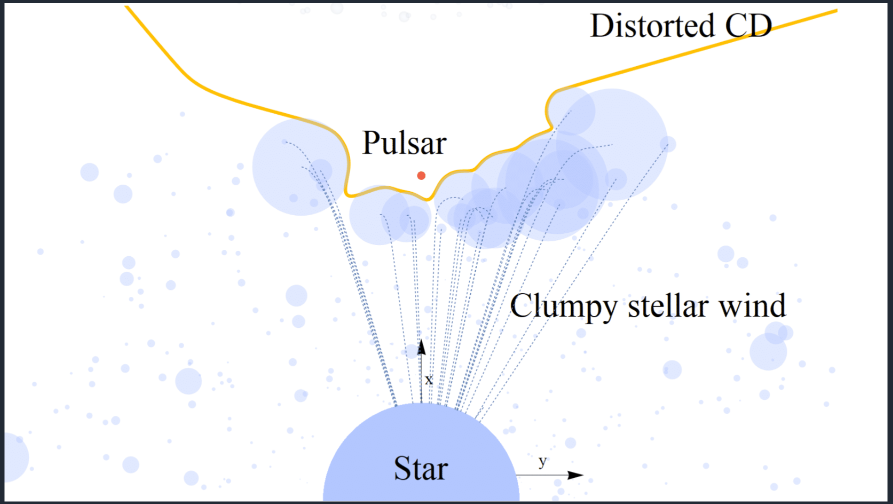
Inhomogeneities in winds of massive stars:

- Radiative instabilities
  (Lucy & Solomon 1970; Runacres & Owocki 2002; Puls et al. 2006, 2008)
- Fragmentation of circumstellar disks
  (Okazaki et al. 2011; Chernyakova et al.2014)

Effect on CD and non-thermal emission:
(e.g., Bosch-Ramon 2013; Paredes-Fortuny et al. 2015; de la Cita 2017a)

Plots drawn from actual HD simulations ➡
(Kefala & Bosch-Ramon 2022)





Similar treatment:

- Massive star binaries (Pittard 2007)
- Accreting X-ray sources (e.g., Oskinova et al. 2012)
- Microquasars (e.g., Araudo et al. 2009; Owocki et al. 2009; Perucho & Bosch-Ramon 2012; de la Cita et al. 2017b; López-Miralles et al. 2022)

Smooth Wind

CD only
Nonrelativistic

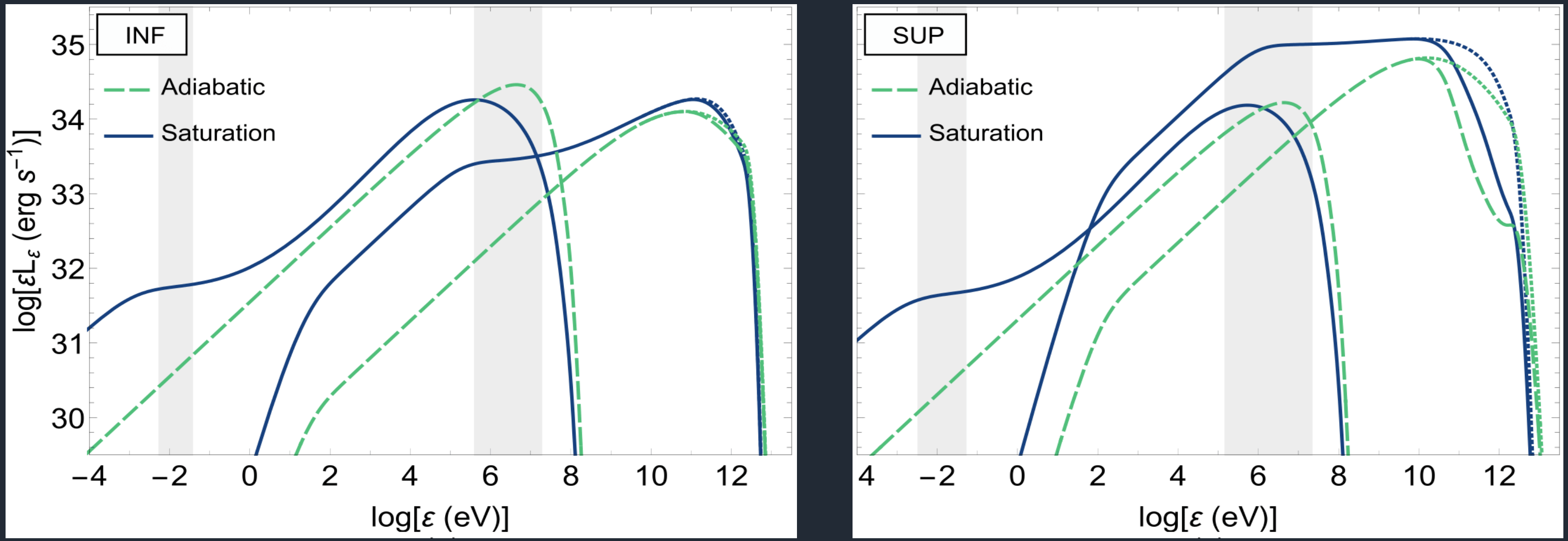
- Multi-zone emitter extending to ~1.7*a*

  Two regimes: *adiabatic* or *radiative*

- No Doppler boosting – no Coriolis shock

Emission in the region of interest mainly produced in the radiative regime

INF: inferior conjunction; SUP: superior conjunction



(Kefala & Bosch-Ramon 2022)

Adiabatic regime:

- hard synchrotron peaking at soft γ rays
- hard IC softening above $\sim$ 1–10 GeV peaking around $\sim$ 10–100 GeV

Radiative regime:

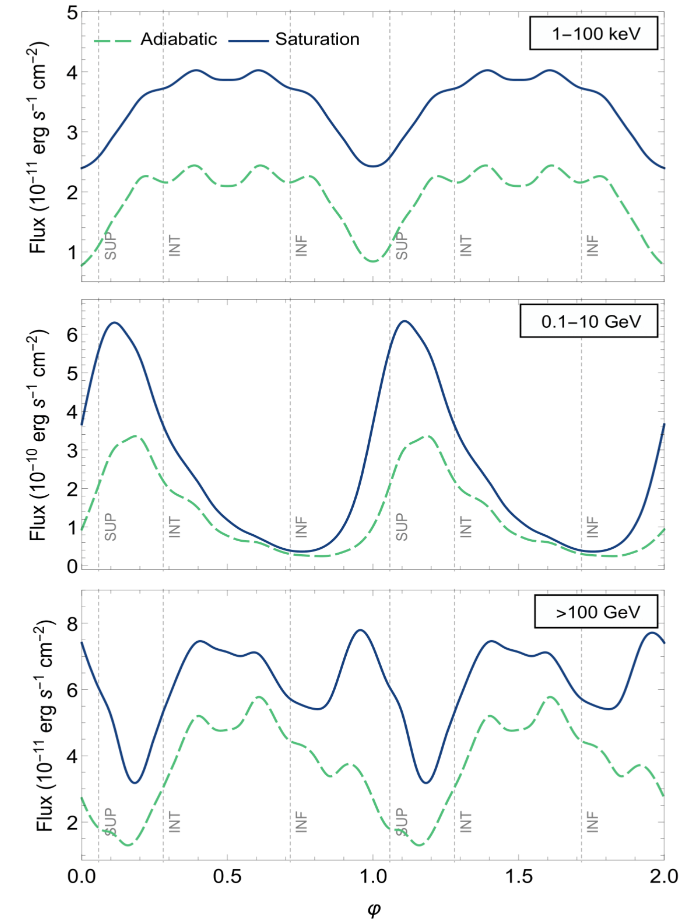
- hard synchrotron down to $\sim$ 10 eV / broader peak
- moderately hard IC around $\sim$ 0.1 – 100 GeV (KN) softening above and below (Thomson losses) hard again below $\sim$ 1 MeV (cooled electrons <Emin)

Smooth Wind

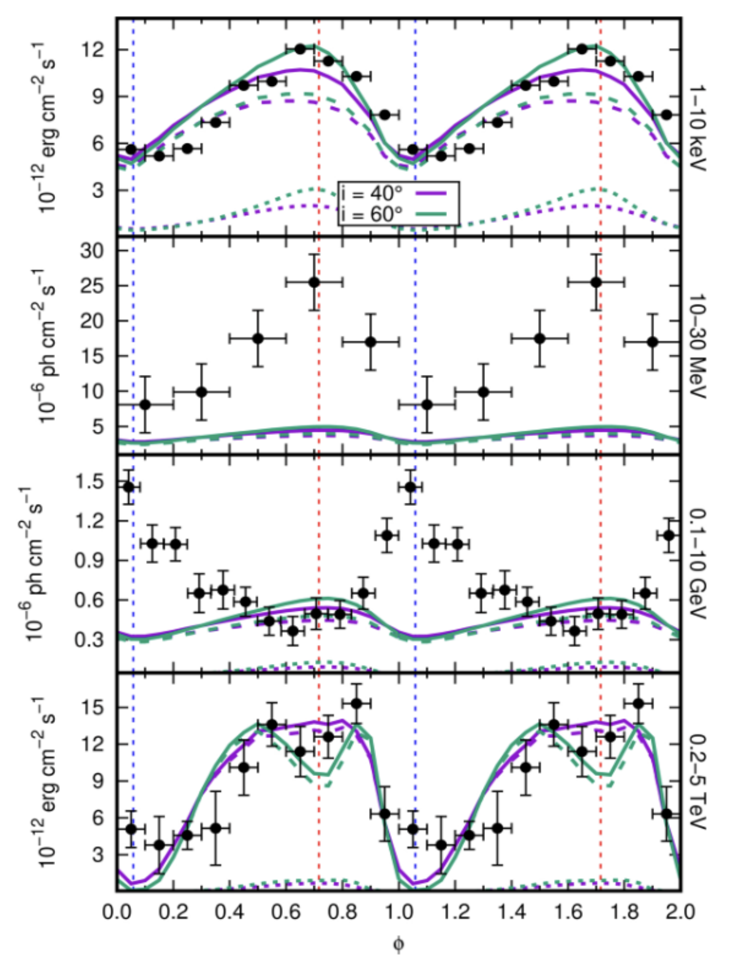
CD only
Nonrelativistic

Effect of:

- spatial volume/angular size on normalization
- emitter-pulsar distance on B and on synchrotron X-rays
- emitter-star distance on IC target photons
- angular effects on HE/VHE IC and on VHE γ-ray absorption



(Kefala & Bosch-Ramon 2022)



(Molina & Bosch-Ramon 2020)

Smooth stellar wind results consistent with literature:

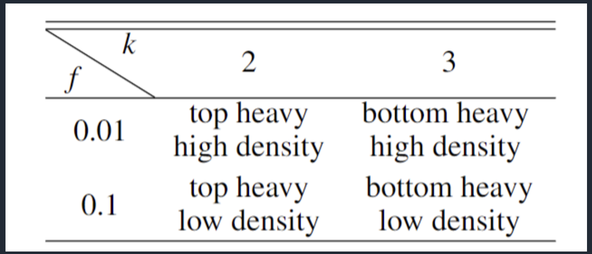
- X-rays peaking at apastron
- HE/VHE peaking at superior/inferior conjunction
- VHE present a secondary peak before periastron (e.g., Khangulyan et al. 2008; Dubus et al. 2008; Takahashi et al. 2009; Molina & Bosch-Ramon 2020)

Clumpy Wind

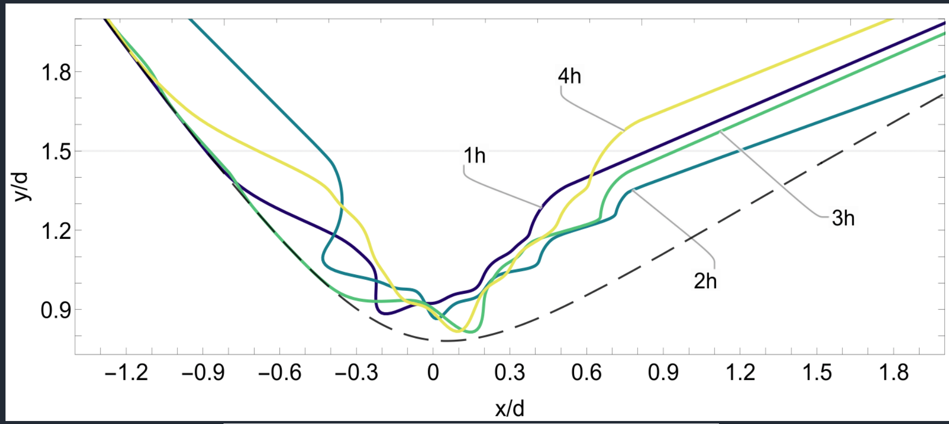
CD only
Nonrelativistic

Effect of size of the emitting region:
Emitting regions extending closer (1.4a) or farther from the star (2a)
Larger sizes of the emitting region do not smooth out the relative changes in the flux

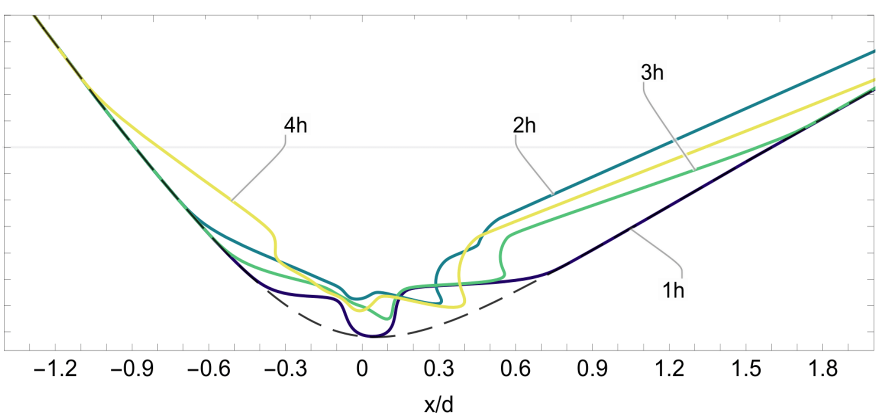
Pulsar-to-stellar wind momentum rate ratio: *η=0.08*



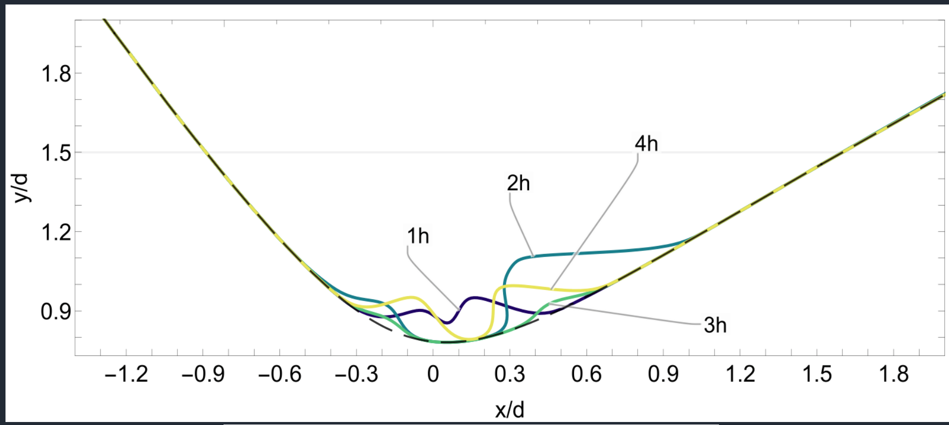
k f	2	3
0.01	top heavy high density	bottom heavy high density
0.1	top heavy low density	bottom heavy low density



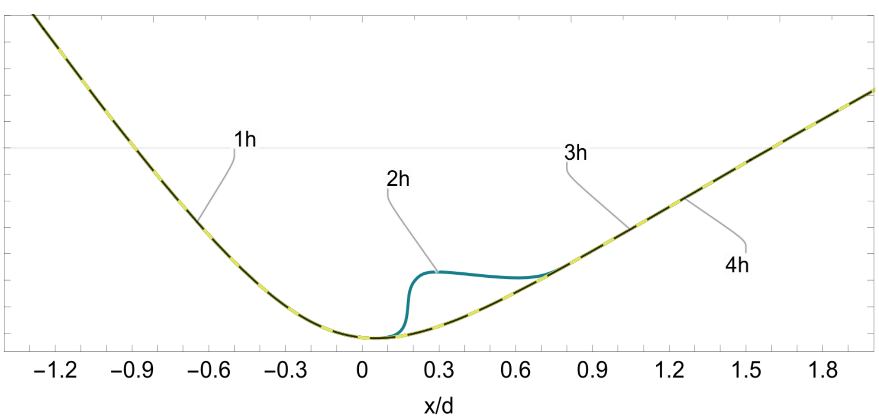
top heavy, high density



bottom heavy, high density



top heavy, low density



bottom heavy, low density

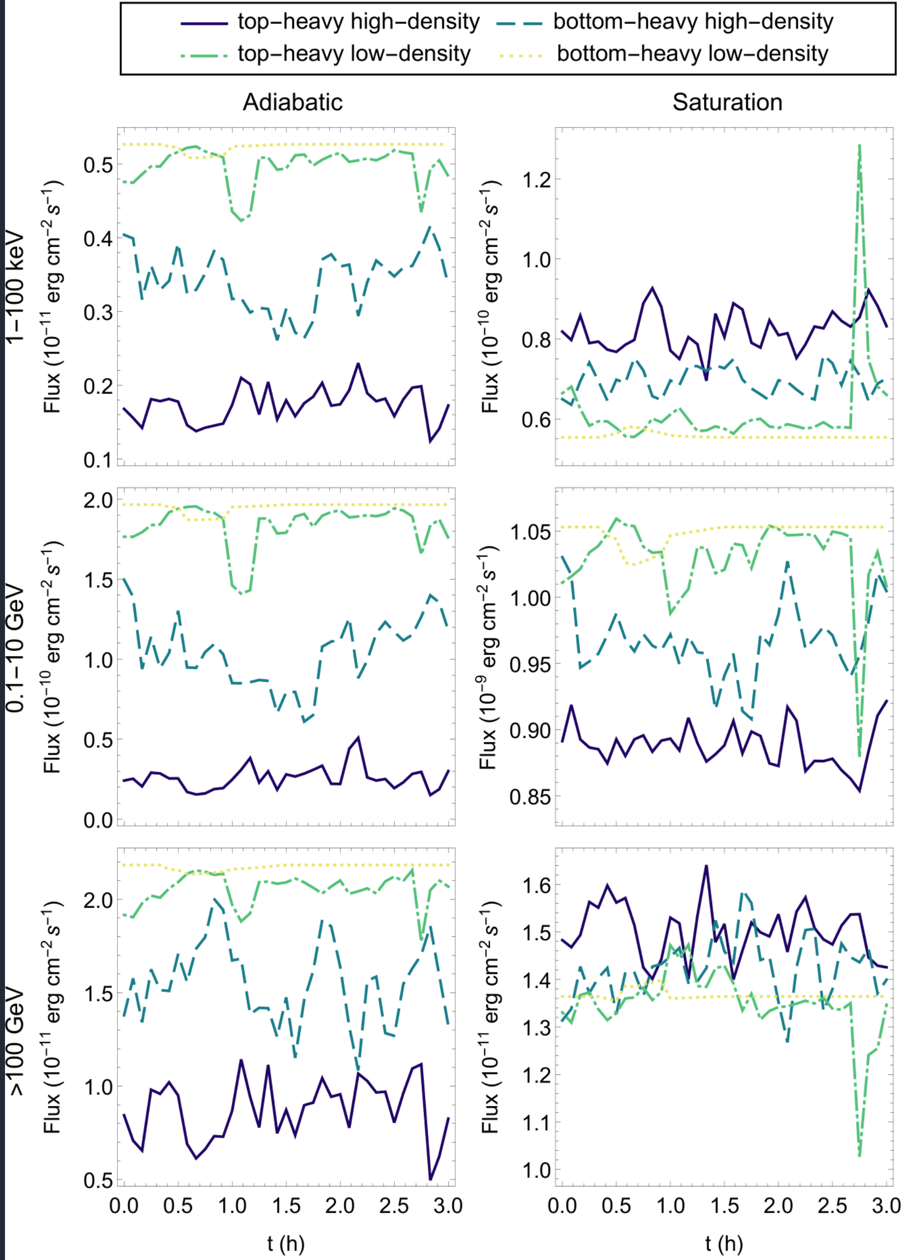
Clumpy Wind

CD only
Nonrelativistic

- Very clumpy ➡ large and rapid variability
  Less clumpy ➡ more sparse large flares
  Least clumpy ➡ identical to smooth wind
- *Moderate flux changes:*
  ~20% (dense clumps)
  10–100% (top-heavy light clumps)
  <10% (bottom-heavy light clumps)

  Variability timescales of ~0.1 – 1 h.
- The adiabatic light curves present significantly higher variability in the dense clump cases.

- <u>Clump interaction rate:</u> 21 large clumps per orbit
  Time between interactions ~1.6 × 10^4 s
  Duration of interaction ~6 × 10^3 s
  Single large-clump interaction ➡ 40% of the time
  Simultaneous interactions ➡ ≈ 14% of the time



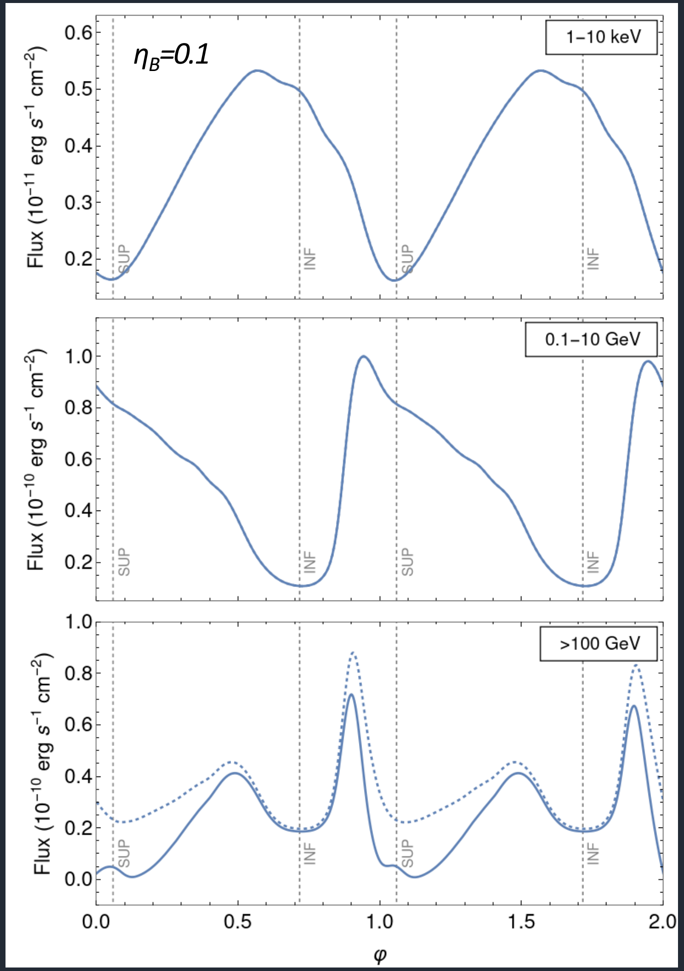
VERY PRELIMINARY RESULTS

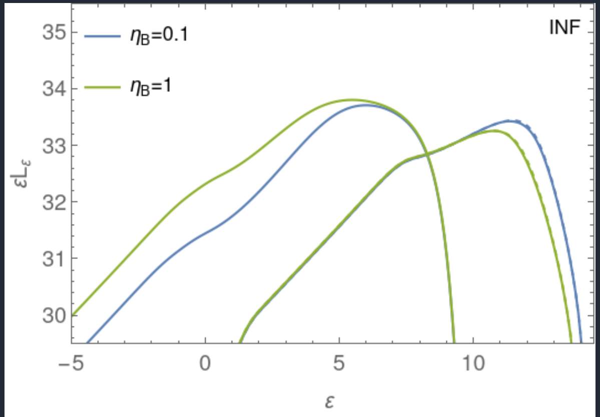
Smooth Wind

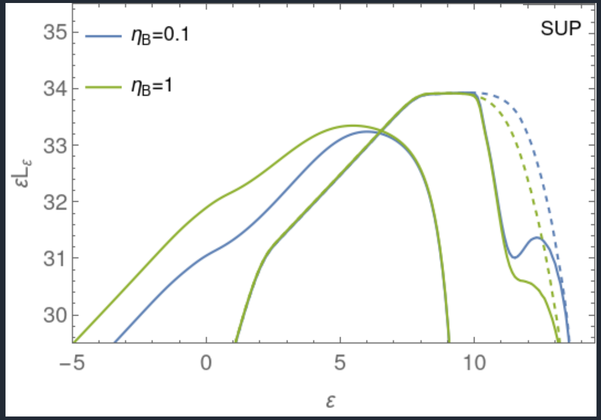
CD+Coriolis shocks
Relativistic case

- Multi-zone emitter including the CD and Coriolis shocks
  Accounting for relativistic effects
  Radiative regime
- Probing for different parameters (particle acceleration, magnetization, etc.) to explain the observed features
- GeV from the bow shock
  TeV from the Coriolis shock
  (Zabalza et al. 2013; Takata et al. 2014; Chen et al. 2017)
- Overall patterns similar to non-relativistic results but certain features enhanced by Doppler boosting

(Kefala & Bosch-Ramon in prep.)







Key Points

CLUMPS

- Smooth stellar wind models are sufficient most of the times
- Clear clump-induced variability in X-rays and HE−VHE gamma-rays
- Wind-clump interactions consistent with variability features; e.g., short-term X-ray variability in LS 5039 (Yoneda et al. 2023) and gamma-ray flare activity from PSR B1259-63 (Chernyakova et al. 2014)
- Current and future instrumentation (e.g., Cherenkov Array Telescope) could detect relative short-term variability in X-rays and VHE gamma rays potentially induced by clumps

CORIOLIS

- Adequate treatment of relativistic effects is necessary
- Boosting is important for extended emitting regions and emitters at the outer parts of interacting regions (e.g., rarefaction of the bow shock)

OVERALL

- Predicted luminosities are similar to those of LS 5039
- Flexibility of the approach allows us to quickly probe the parameter space, include non-trivial physical effects, and evaluate the veracity of the model