Investigating the puzzling radio structures of the gamma-ray binary LS 5039

E. Molina and V. Bosch-Ramon
Universitat de Barcelona - ICCUB

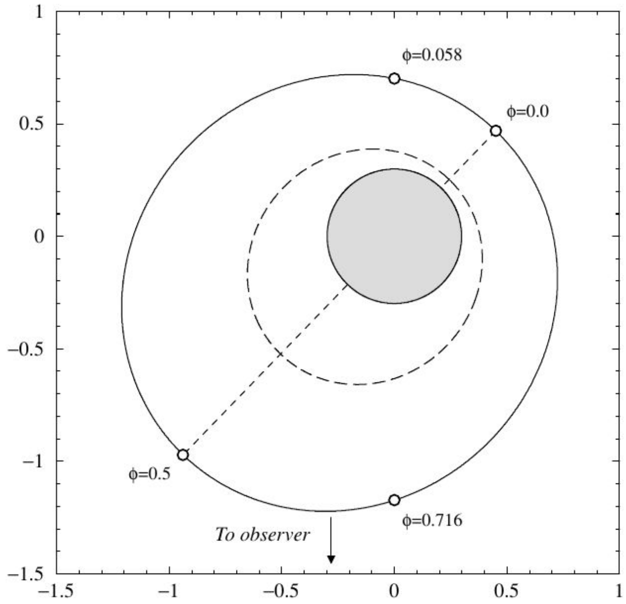
Gamma 2022 Symposium
Barcelona, 6 July 2022

Outline

- Introduction
- Wind interaction in pulsar-wind binaries
- Observations of LS 5039
- Our model
- Final remarks

Introduction: LS 5039

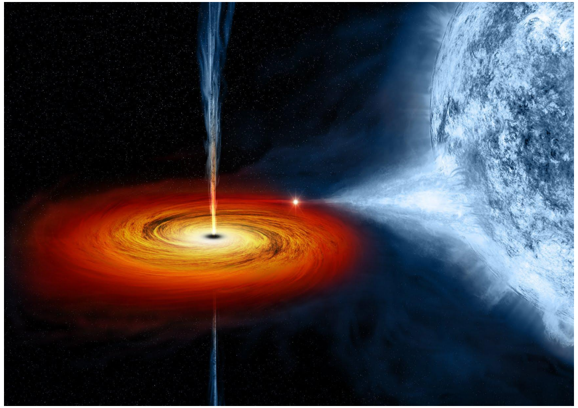
- LS 5039 is a high-mass gamma-ray binary with an unknown compact object.
  - Distance: 2.04 ± 0.06 kpc Bailer-Jones+21
  - Orbital period: 3.9 days
  - Eccentricity: 0.35 ± 0.04 Casares+05
  - Neutron star (black hole) favoured for high (low) inclinations.



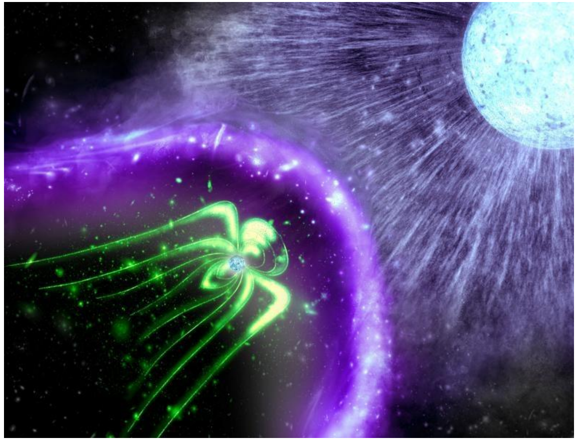
Casares+05

Introduction: LS 5039

- LS 5039 is a high-mass gamma-ray binary with an unknown compact object.
    - Distance: 2.04 ± 0.06 kpc Bailer-Jones+21
    - Orbital period: 3.9 days
    - Eccentricity: 0.35 ± 0.04 Casares+05
    - Neutron star (black hole) favoured for high (low) inclinations.
- Two main possible physical scenarios:
    - Microquasar e.g. McSwain&Gies02, Bosch-Ramon&Paredes04, Dermer&Böttcher06
    - Pulsar-wind e.g. Zabalza+13, Dubus+15, Yoneda+20, Molina&Bosch-Ramon20, Huber+21



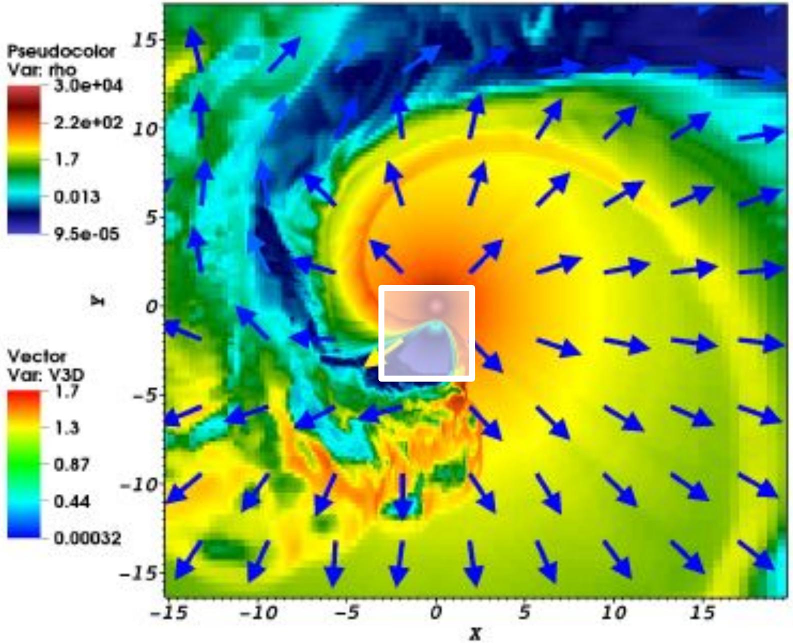
Credit: NASA/CXC/M.Weiss



Credit: Kavli IPMU

Wind-wind interaction in pulsar-wind binaries

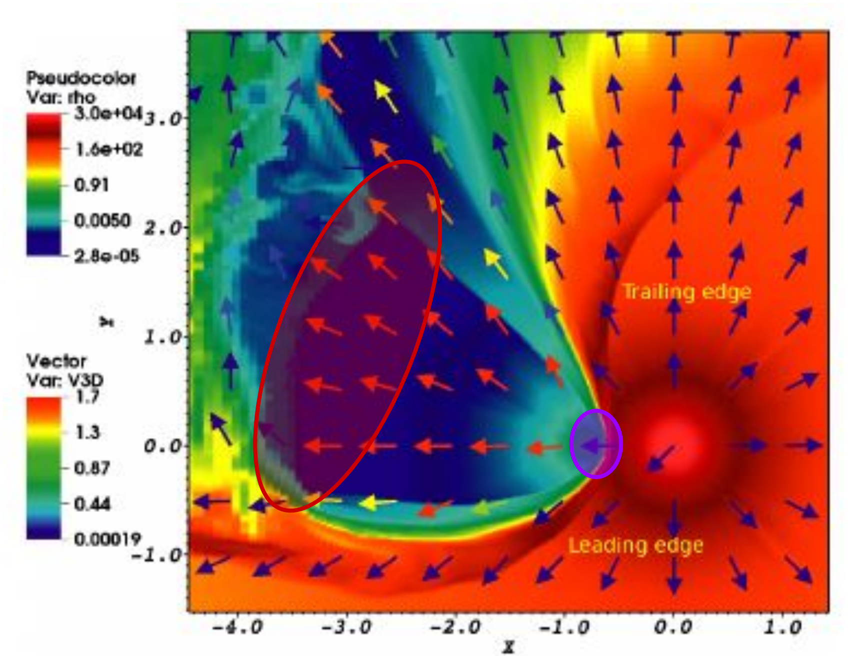
- Orbital motion makes the shocked pulsar wind follow a spiral-like path.



Bosch-Ramon+15

Wind-wind interaction in pulsar-wind binaries

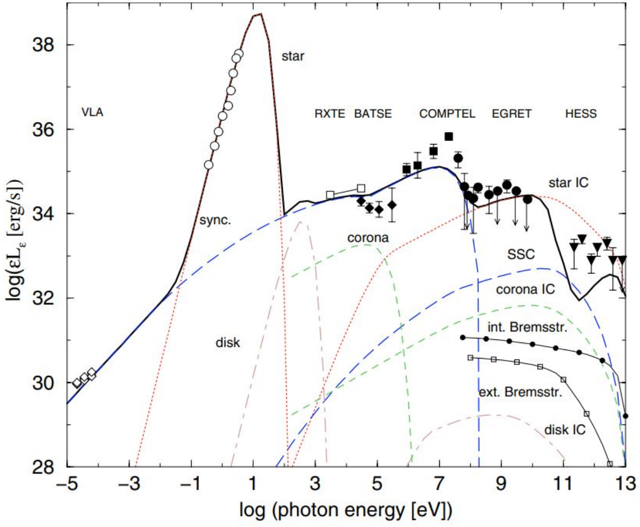
- Orbital motion makes the shocked pulsar wind follow a spiral-like path.
- Initially, the contact discontinuity (CD) takes an approximately conical shape, until the stellar wind becomes dynamically dominant.
- Two main sites for particle acceleration: the **wind standoff** and the **Coriolis turnover**.



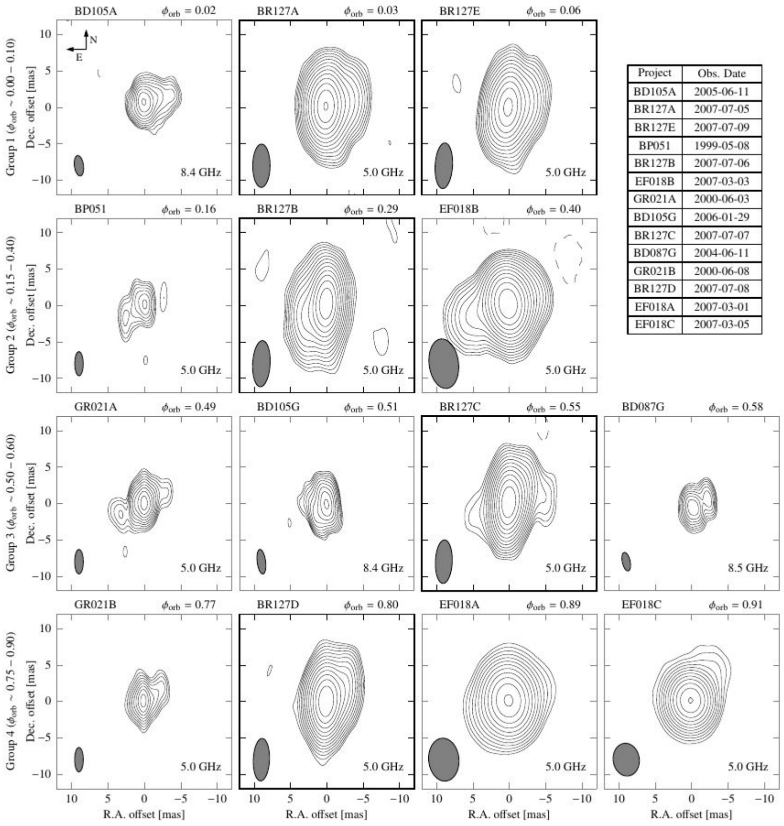
Bosch-Ramon+15

Observations of LS 5039

- Emission from radio to very-high-energy (VHE; > 100 GeV) gamma rays.
    - **Varying morphology** of the radio emission.



Paredes+06



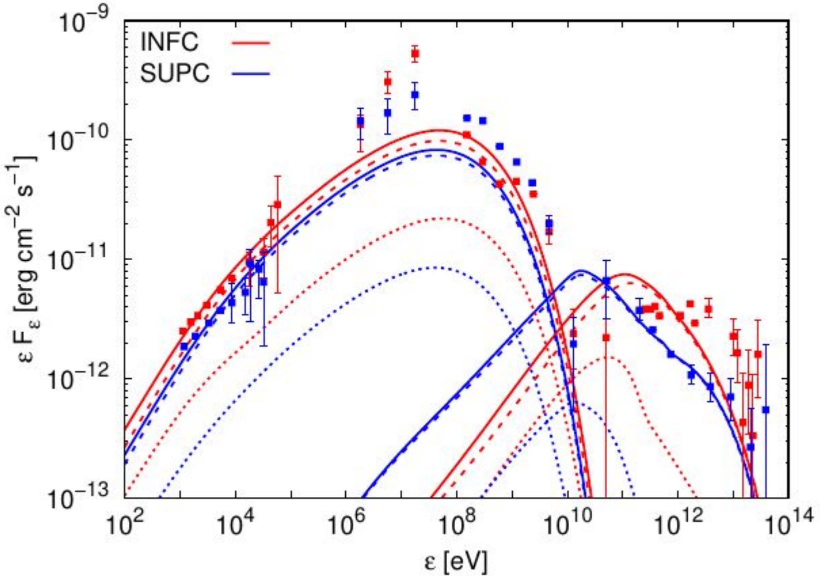
Moldón+12

Our model

- System with a massive O/B star with an **isotropic and homogeneous** wind and a non-accreting pulsar.
- We compute the trajectory of the **1D axis** of a conical CD from momentum transfer by the stellar wind, accounting for orbital motion.
  - Accelerating shocked flow up to the **Coriolis turnover**. Bogovalov+08
  - Constant flow speed beyond the **Coriolis turnover** to account for wind mixing.
- Non-thermal electrons are injected at the **two-wind standoff** and **Coriolis turnover** locations.

Our model

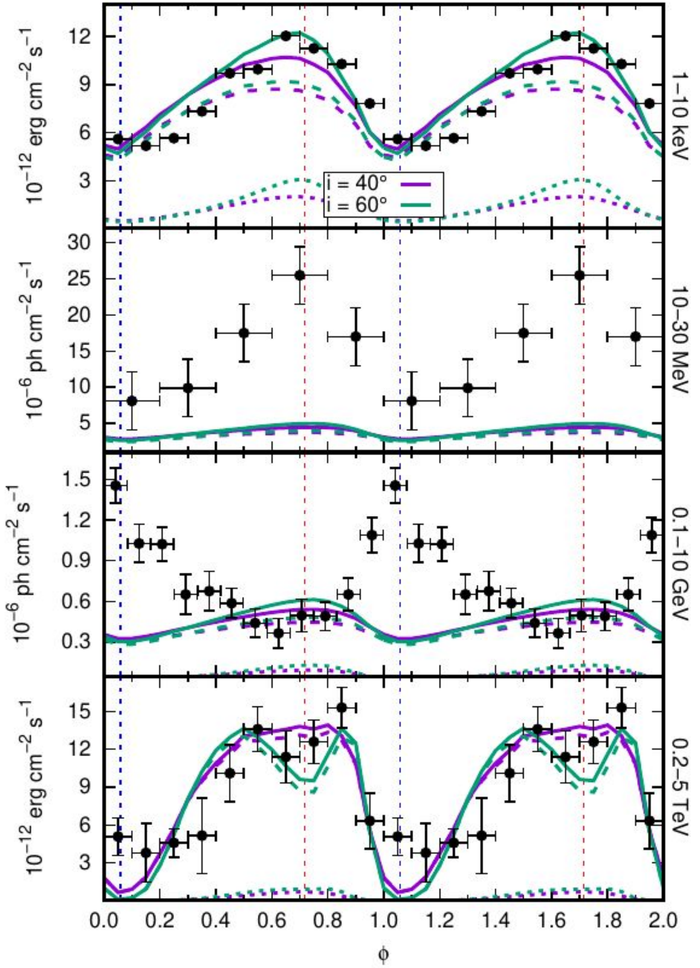
- X-ray and VHE emission and modulation well reproduced.
- Average high-energy emission is approximately good, but not its modulation.
- The ~ 10 MeV emission is underestimated by a factor of 5.
    - Need to account for additional sources, like secondary emission and the unshocked pulsar wind. Derishev+12, Bosch-Ramon21



Molina&Bosch-Ramon20

Our model

- X-ray and VHE emission and modulation well reproduced.
- Average high-energy emission is approximately good, but not its modulation.
- The ~ 10 MeV emission is underestimated by a factor of 5.
    - Need to account for additional sources, like secondary emission and the unshocked pulsar wind. Derishev+12, Bosch-Ramon21

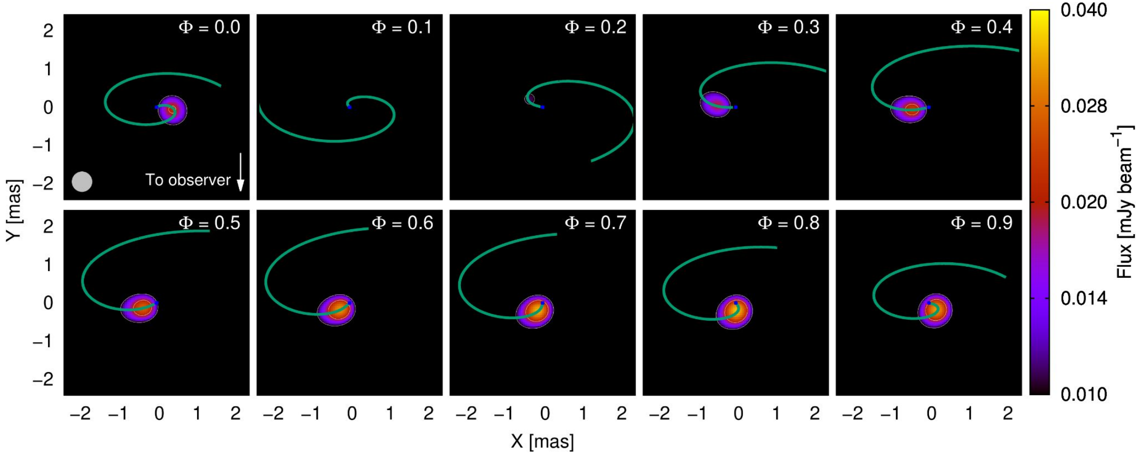


Molina&Bosch-Ramon20

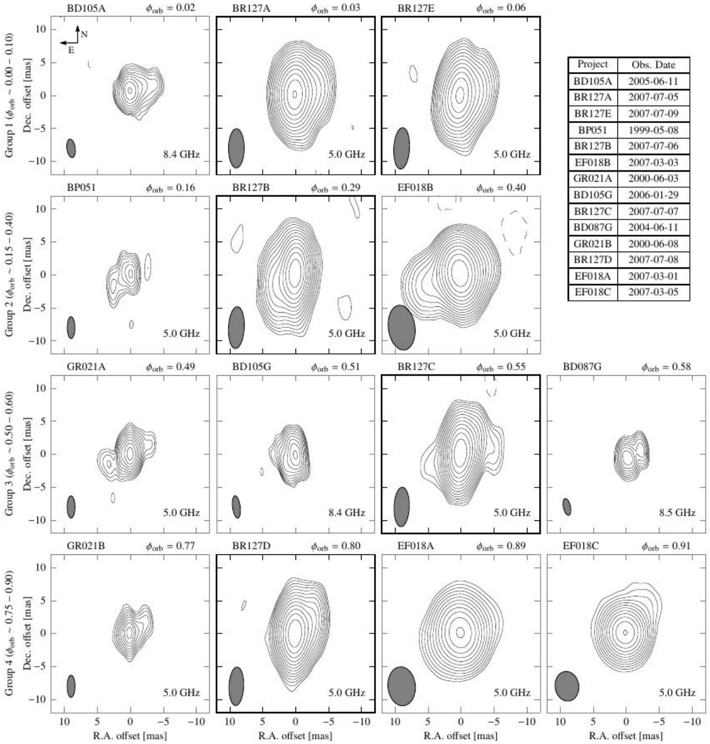
Our model

- Reacceleration is needed for a proper comparison with the radio observations.

5 GHz



Molina&Bosch-Ramon20



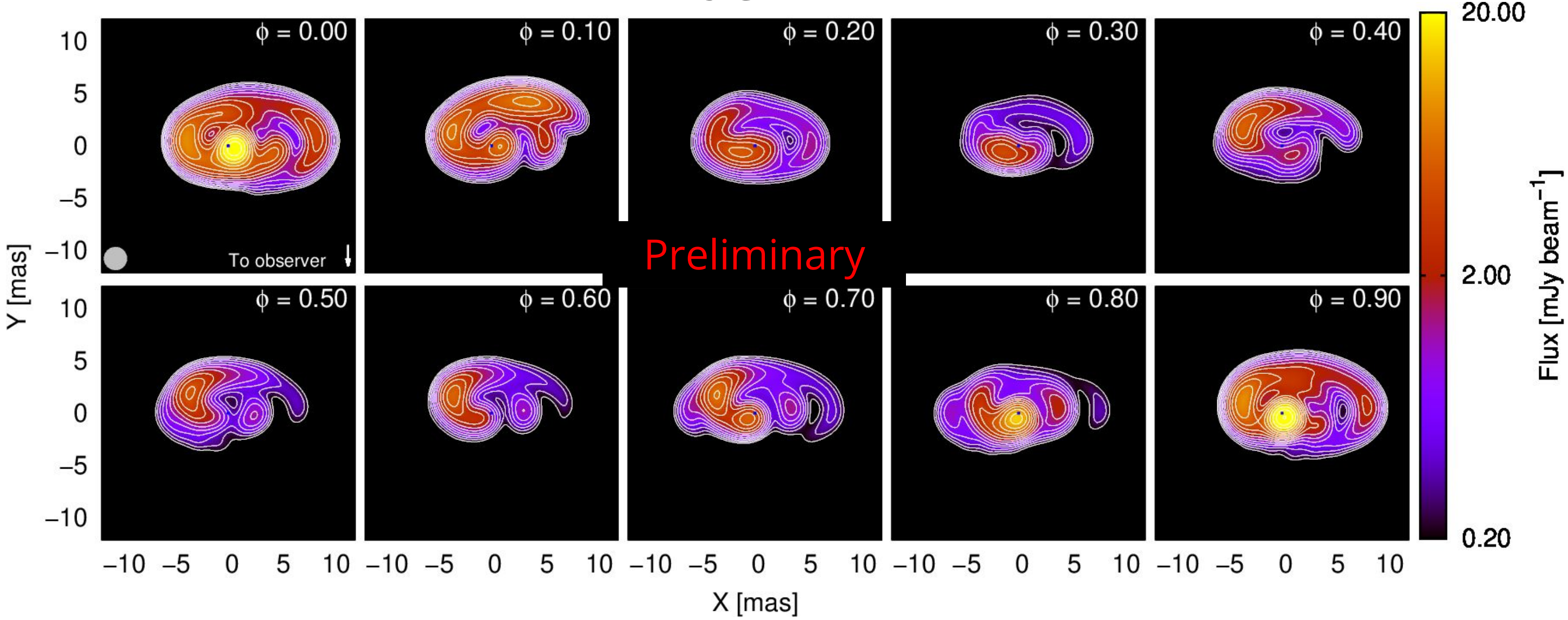
Project	Obs. Date
BD105A	2005-06-11
BR127A	2007-07-05
BR127E	2007-07-09
BP051	1999-05-08
BR127B	2007-07-06
EF018B	2007-03-03
GR021A	2000-06-03
BD105G	2006-01-29
BR127C	2007-07-07
BD087G	2004-06-11
GR021B	2000-06-08
BR127D	2007-07-08
EF018A	2007-03-01
EF018C	2007-03-05

Moldón+12

Our model

- Study of the extended radio emission through an updated particle distribution computation, based on the evolution of the dynamical properties of the outflow.

5 GHz



Final remarks

Summary

- Overall spectral shape from X-rays to VHE gamma rays well reproduced, except for the 10 MeV range.
- X-ray and VHE modulation also reproduced by the model.
- A modified model accounting for reacceleration is needed for a comparison with radio data.

Future work

- Include mass-loading into the outflow.
- Produce radio maps for many parameter combinations and compare with observations.
- Implement the microquasar scenario.
    - Favor one scenario over the other?

Backup

Our model

	Parameter	Value
Star	Temperature $T_\star$	4×10^4 K
	Luminosity $L_\star$	7×10^{38} erg s^{-1}
	Mass-loss rate $\dot{M}_{\rm w}$	$1.5 \times 10^{-7}\ M_\odot$ yr^{-1}
	Wind speed $v_{\rm w}$	3×10^8 cm s^{-1}
Pulsar	Luminosity $L_{\rm p}$	3×10^{36} erg s^{-1}
	Wind Lorentz factor $\Gamma_{\rm p}$	10^5
System	Orbit semi-major axis a	2.4×10^{12} cm
	Orbital period T	3.9 days
	Orbital eccentricity e	0.35
	Distance to the observer d	2.1 kpc
	CD apex NT fraction $\eta_{\rm NT}^A$	0.03
	Cor. shock NT fraction $\eta_{\rm NT}^B$	0.18
	Acceleration efficiency $\eta_{\rm acc}$	0.8
	Injection power-law index p	−1.3
	Coriolis turnover speed $v_{\rm Cor}$	3×10^9 cm s^{-1}
	Magnetic fraction η_B	0.02
	System inclination i	40°, 60°

Molina+20

Model limitations

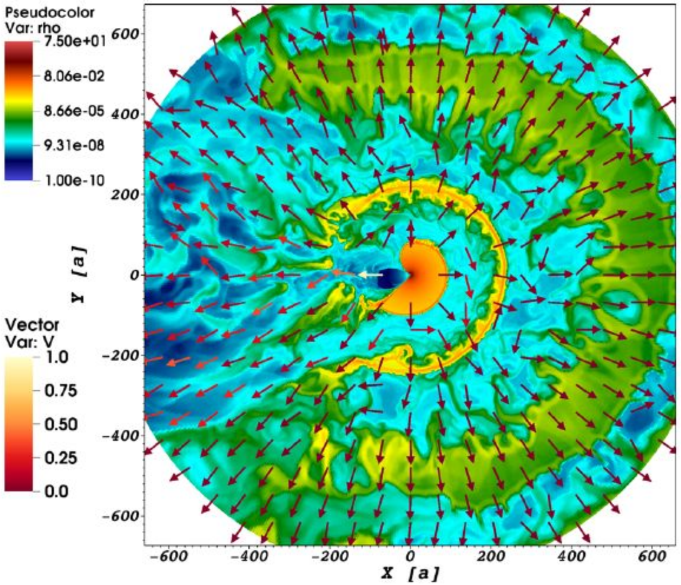
- No particle reacceleration is assumed beyond the 1 or 2 considered sites.
  - Most of the emission concentrated close to the injection sites.
- The computed trajectories are only valid for about the first turn of the helix/spiral.
  - Radiative outputs not significantly affected.
- Large uncertainties in some model parameters:
  - Acceleration efficiency
  - Non-thermal energy budget
  - Magnetic field
  - Flow Lorentz factor

(Magnetic field and Flow Lorentz factor:) Different values explored

Model limitations

- Highly eccentric orbits break the spiral pattern of the outflow.
- If a decretion disk is present, the geometry of the wind interaction radically changes.
    - All the angle-dependent processes are significantly affected.
- Wind clumpiness also has significant dynamical and radiative effects on the outflows.

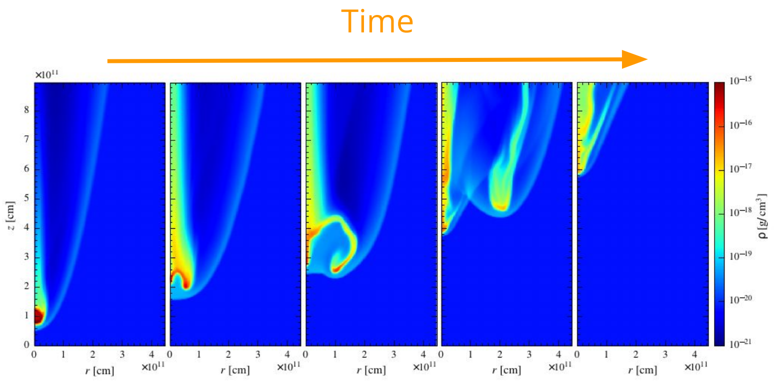
Perucho&Bosch-Ramon12, de la Cita+17



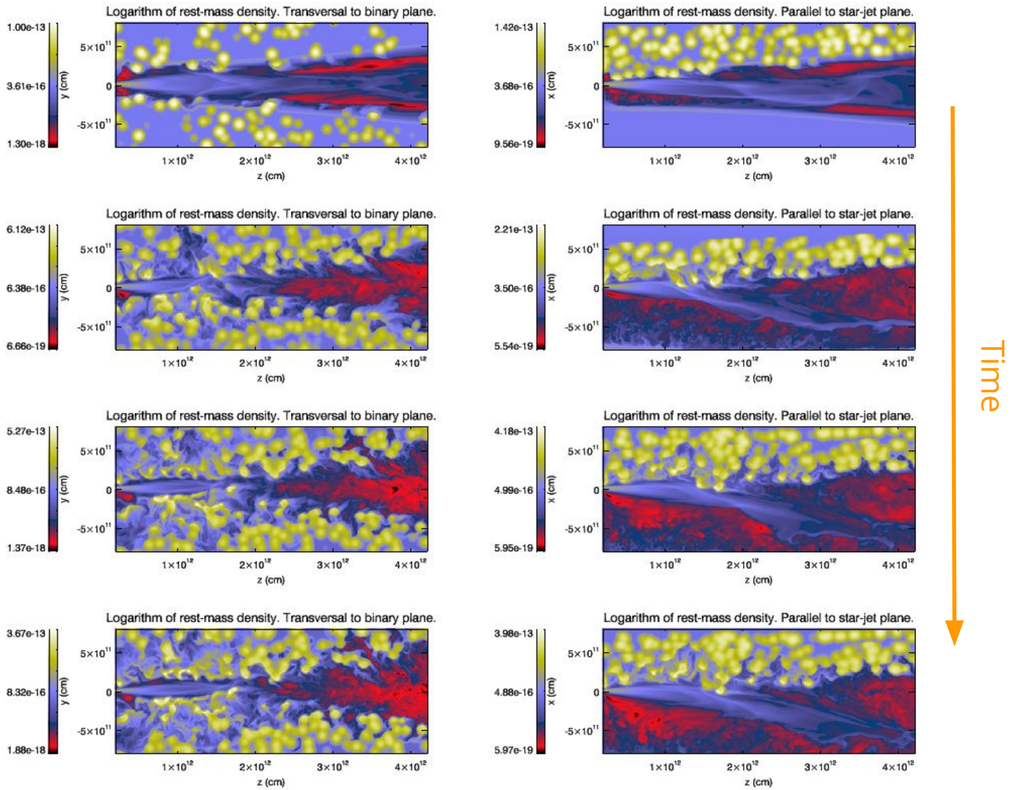
Bosch-Ramon+17

Model limitations

- The stellar wind is taken as homogeneous, but wind clumpiness has significant dynamical and radiative effects on the outflow.



de la Cita+17



Perucho&Bosch-Ramon12