On the physics of the most luminous gamma-ray emitting binaries

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High Energy Phenomena in Relativistic Outflows VIII

Institut d'Astrophysique de Paris, Observatoire de Paris
October 23, 2023

Outline

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1. Introduction
2. Binary scales
3. Beyond binary scales
4. Discussion

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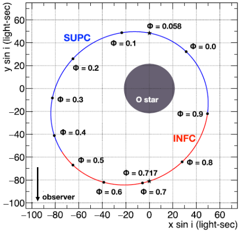

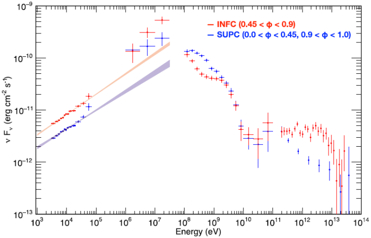

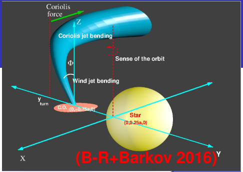

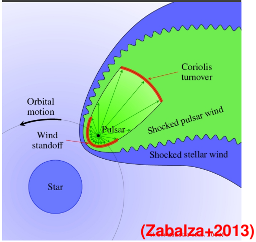

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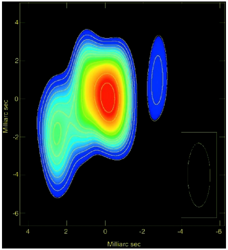

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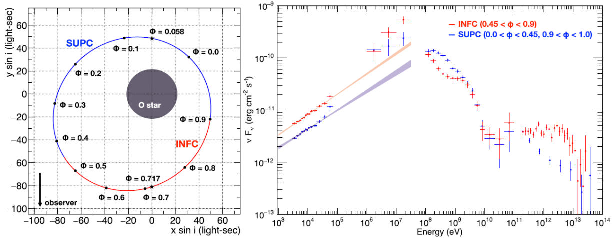

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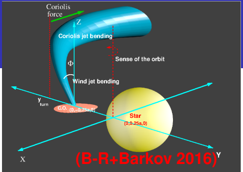

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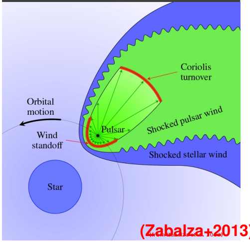

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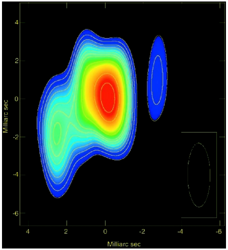

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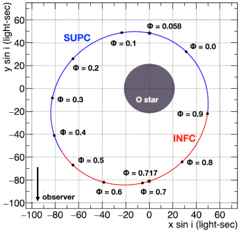

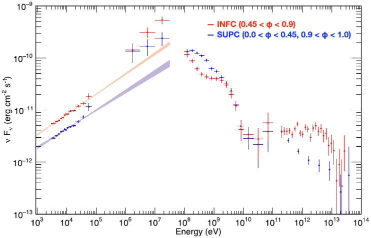

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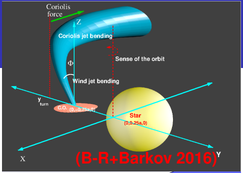

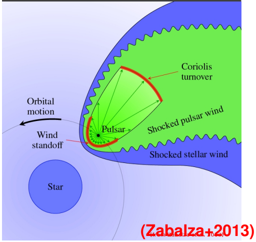

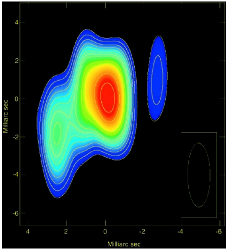

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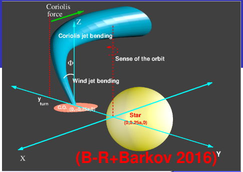

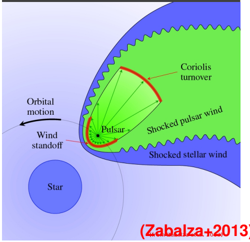

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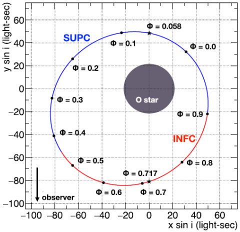

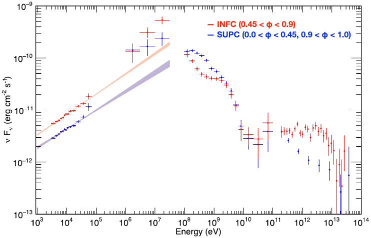

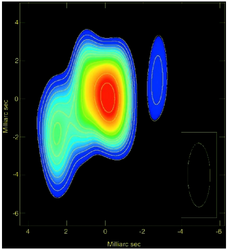

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Motivation

- **Large NT power: at least $\sim 10^{37}$ erg s^{-1} (or more) in most of the sources.**
- Acceleration rates close to $\sim qBR$ for $e^{\pm}$, up to ~ 100 TeV, on binary scales (mostly).
- Interplay of orbit, $v_{\rm ISM}$, outflow/medium interaction leads to rich physics.
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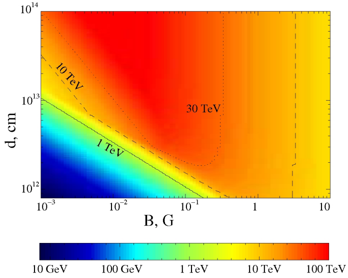
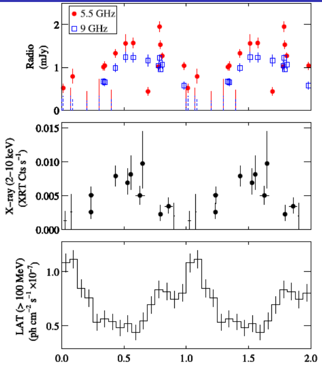
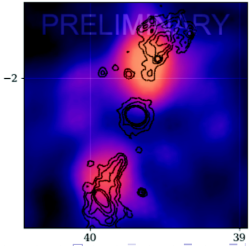
(Koljonen+23 ↑; Khangulyan+08 -LS 5039- ↓; Corbet+16 -LMC P3- →)







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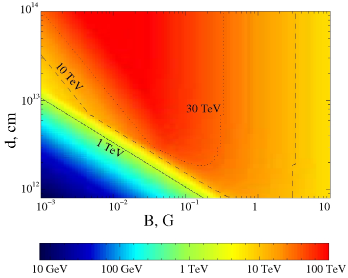

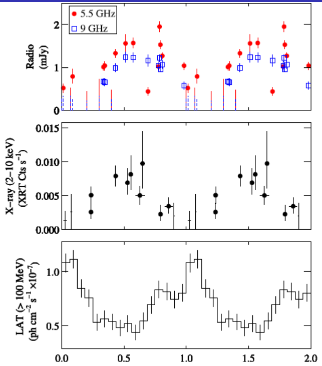

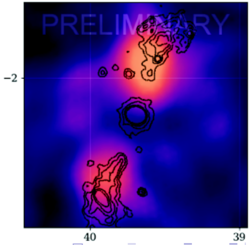

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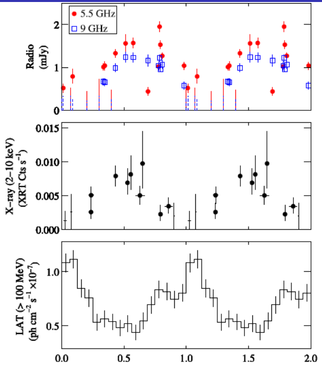

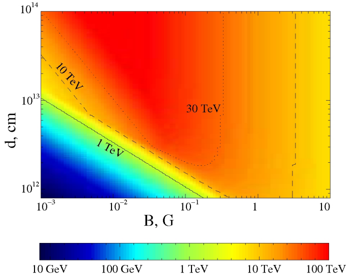

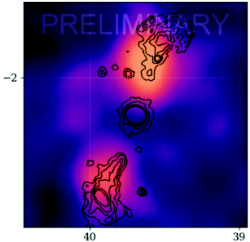

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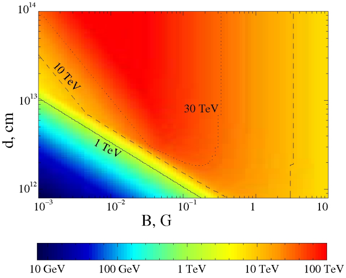

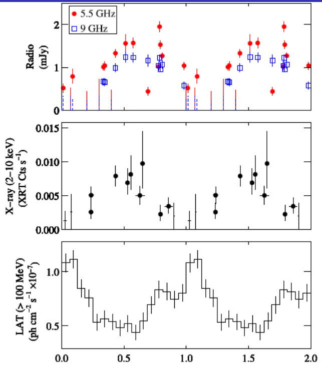

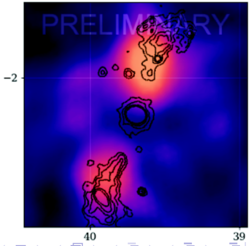

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  - Dense radiation field.
  - Substantial and structured stellar wind.
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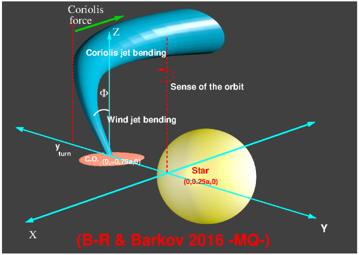

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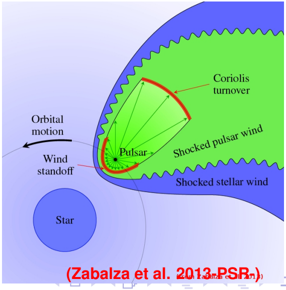

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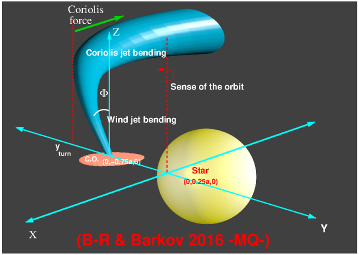

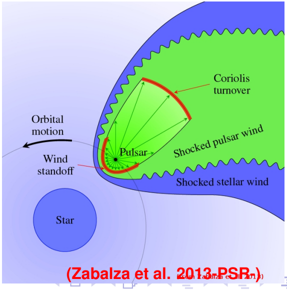

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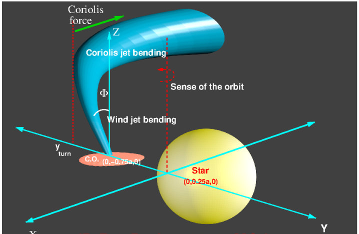

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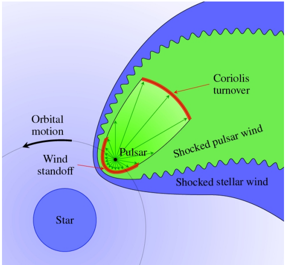

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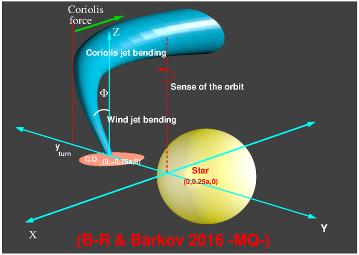

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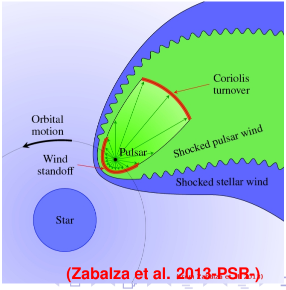

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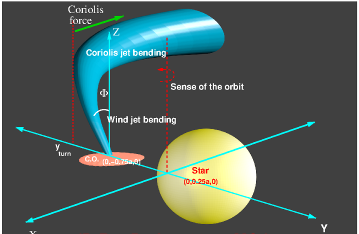

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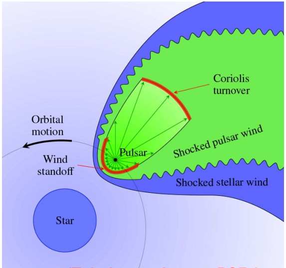

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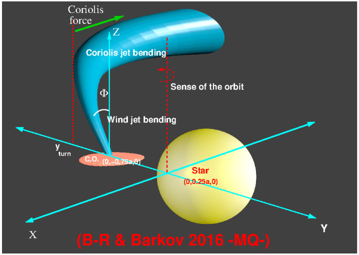

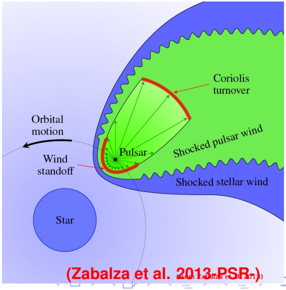

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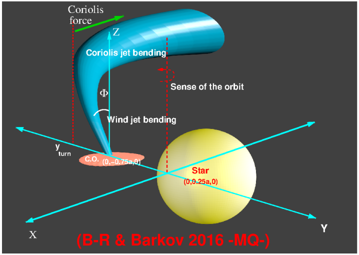

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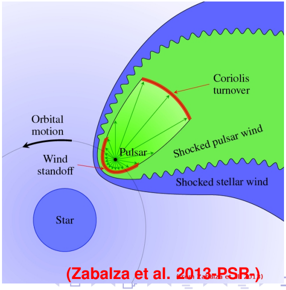

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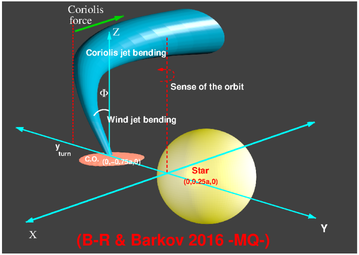

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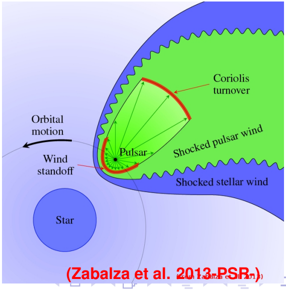

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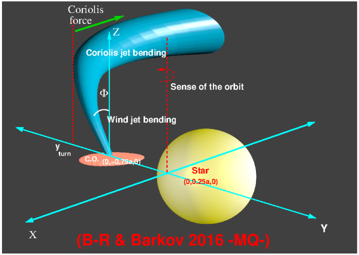

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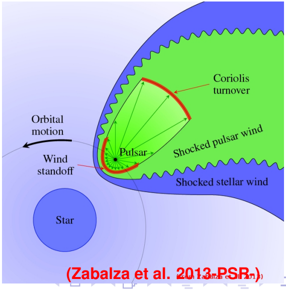

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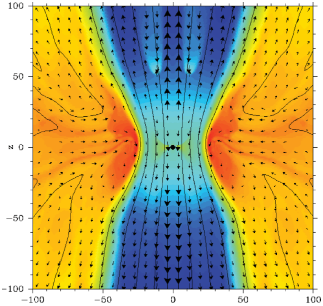
Relativistic outflows: winds and jets

- **In a HMMQ:**
  - A jet can form, protected from the stellar wind by an accretion wind.
  - Magnetization, content and velocity are unclear, possibly structured.
  - The jet can already suffer internal or recollimation shocks, and mass-load.
- In a non-accreting pulsar:
  - Pulsar wind likely magnetized, anisotropic and ultrarelativistic.
  - The pulsar wind is accelerated by B dissipation; how fast is it?
- Highly relativistic unshocked flow in a dense photon field plus $e^{\pm}$-creation:
- IC and 1-shot converter mechanism?

(Derishev&Aharonian12)



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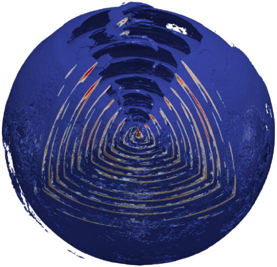

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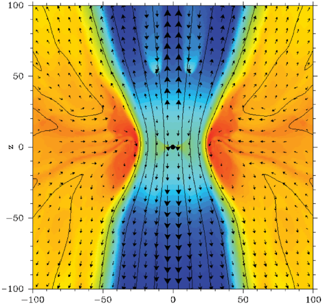

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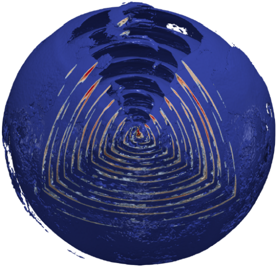

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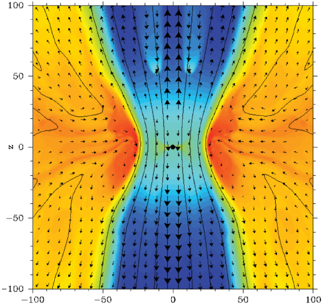

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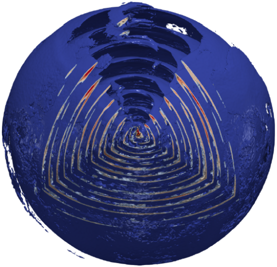

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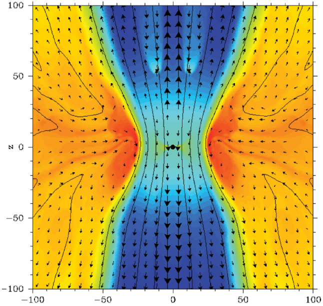

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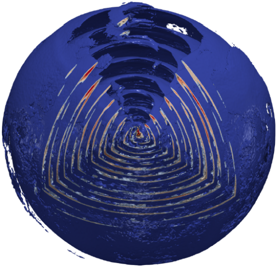

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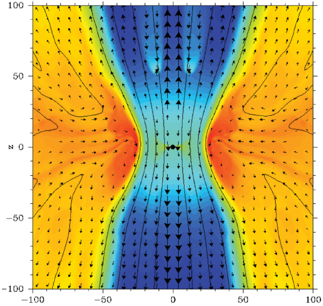

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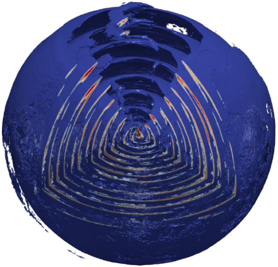

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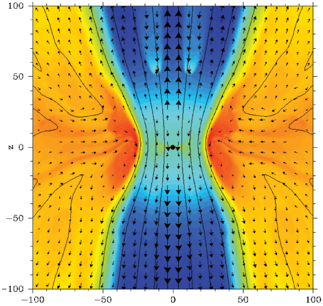

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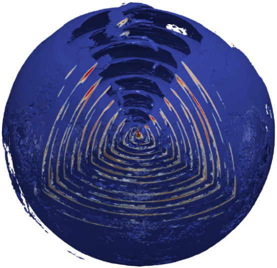

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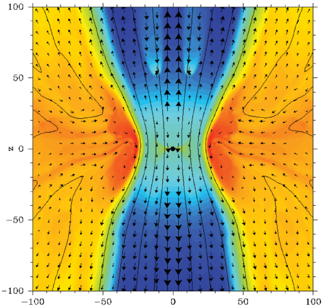

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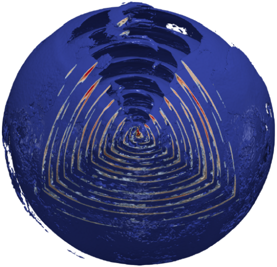

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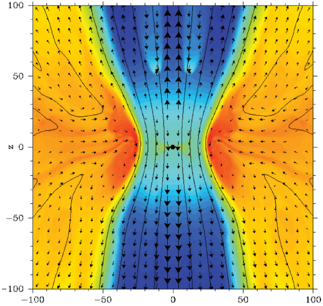

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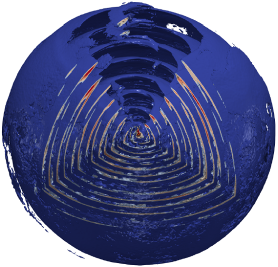

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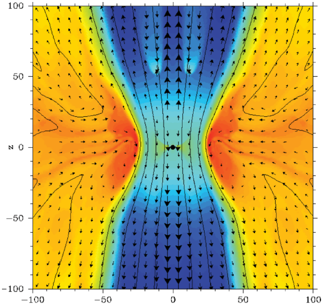

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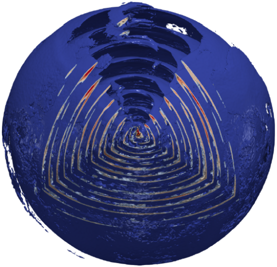

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- ...there is no clear evidence of radiation reprocessing in radio, X-rays, gamma rays.
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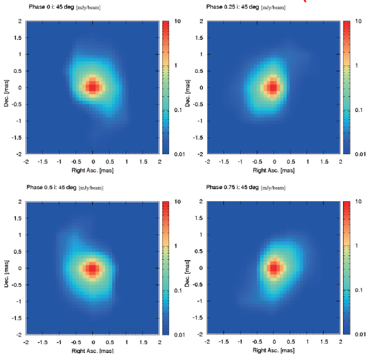

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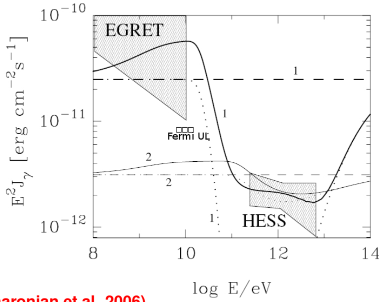

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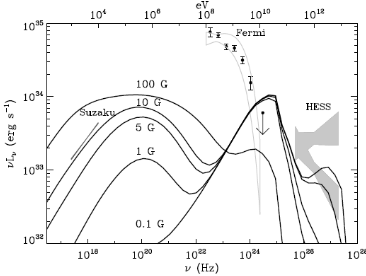

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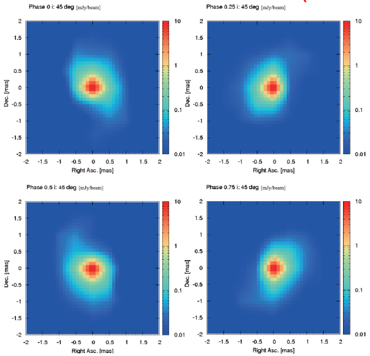

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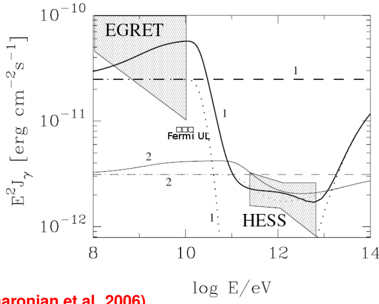

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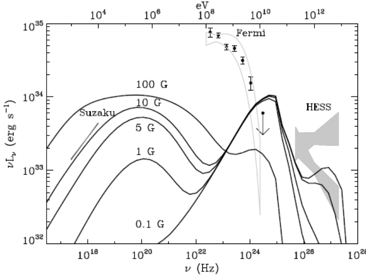

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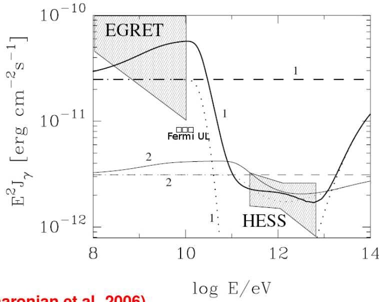

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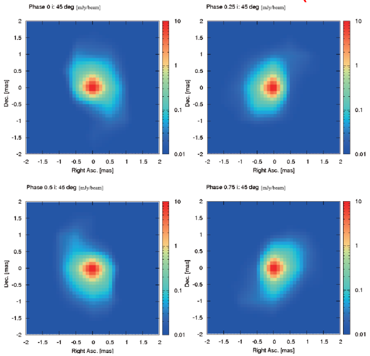

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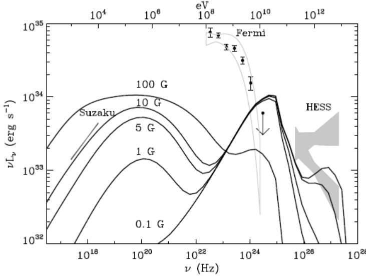

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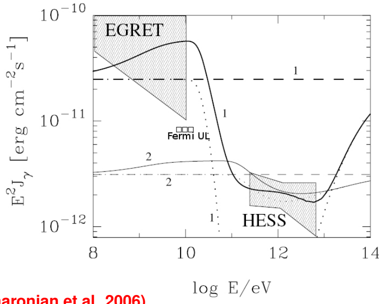

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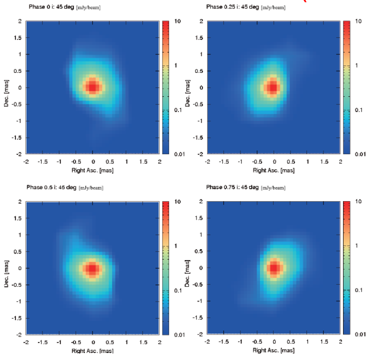

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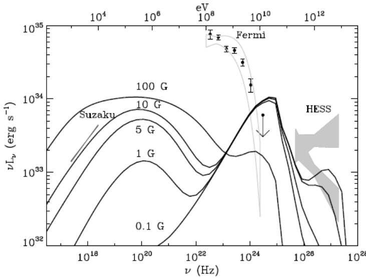

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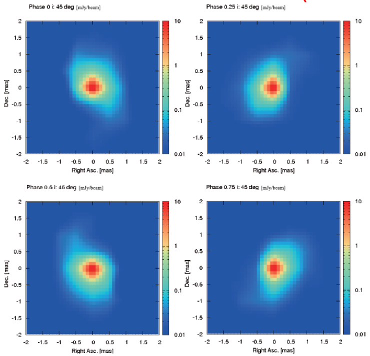

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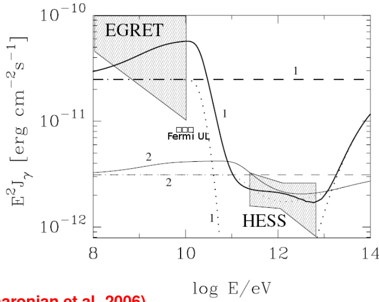

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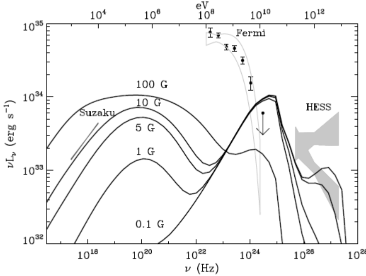

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Substantial and structured stellar wind

- **Massive star wind determines dynamics:**
  - $L_{\rm o}/\dot{M}c \approx 5\times10^7\,(L_{\rm o,36}/\dot{M}_{-7})$ **cm s^{-1},**
  - $\sqrt{2L_{\rm o}/\dot{M}} \approx 5\times10^8\,\sqrt{L_{\rm o,36}/\dot{M}_{-7}}$ **cm s^{-1}.**
- **The winds are complex:**
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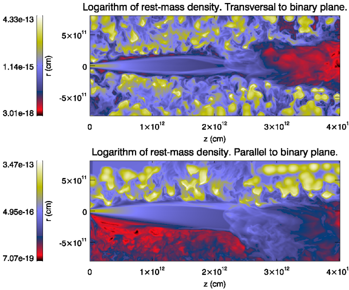

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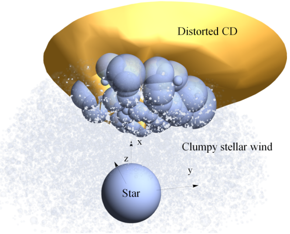

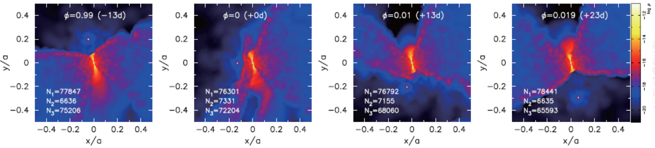

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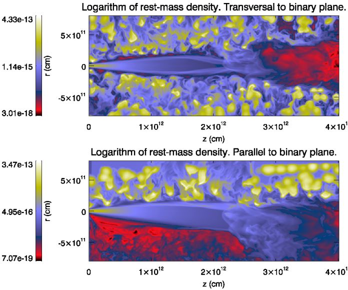

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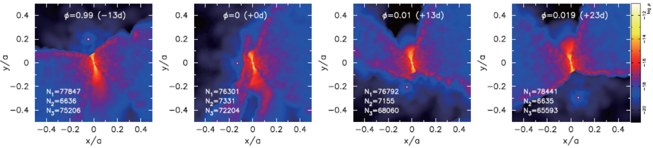

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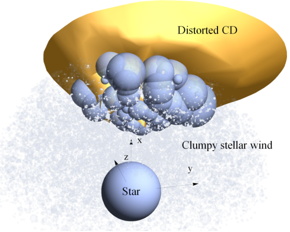

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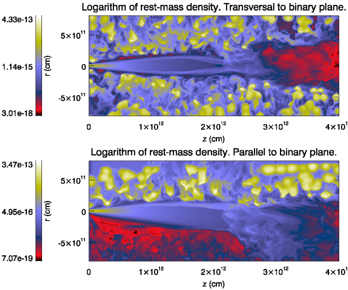

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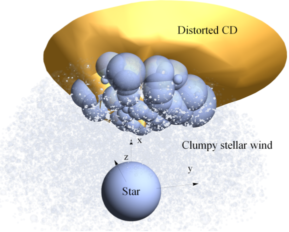

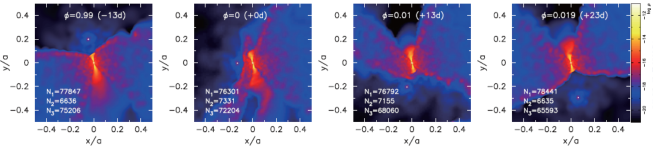

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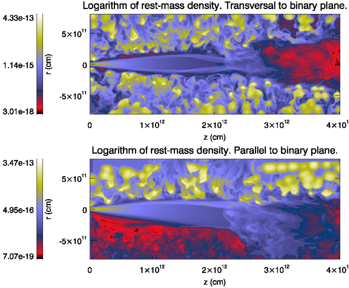

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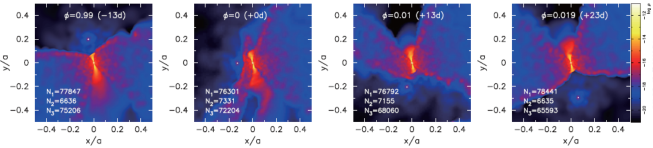

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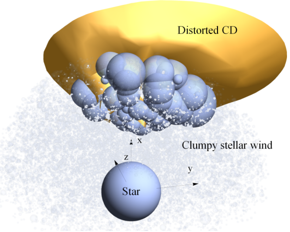

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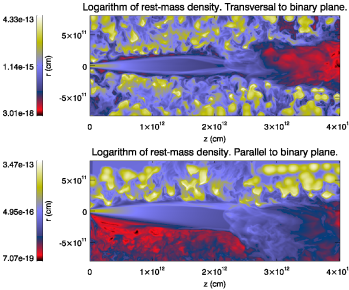

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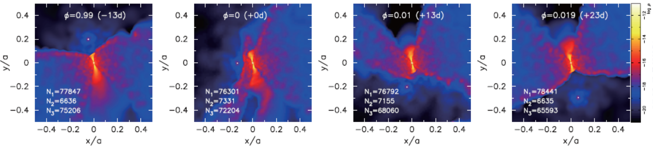

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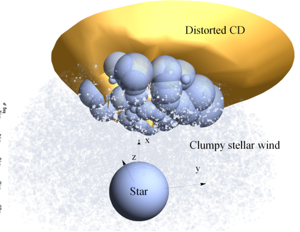

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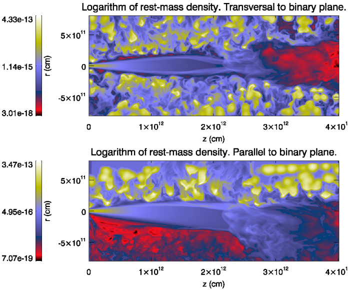

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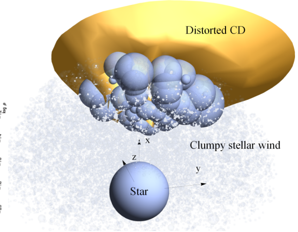

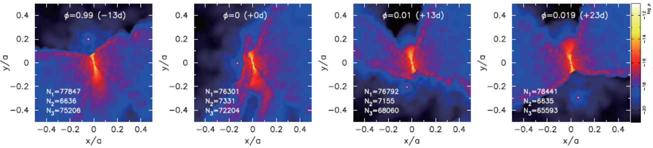

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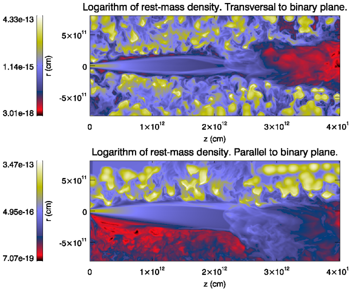

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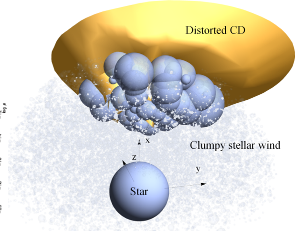

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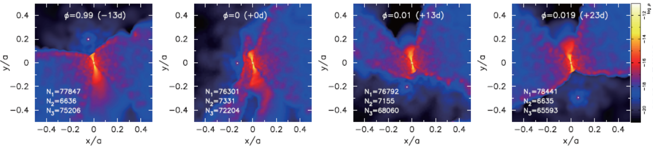

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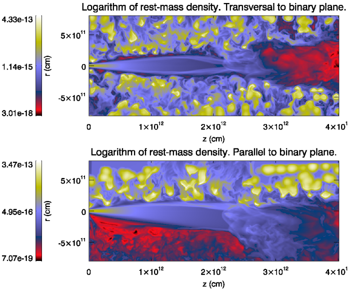

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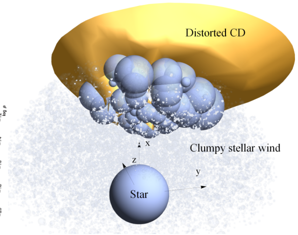

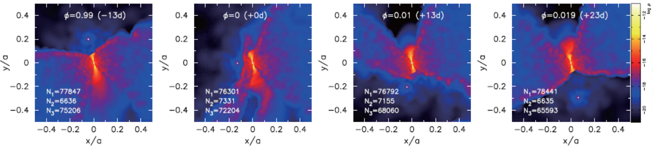

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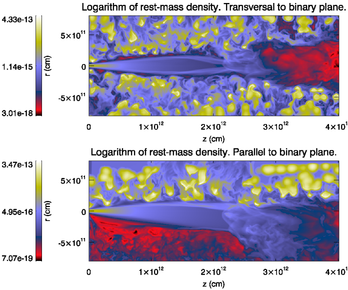

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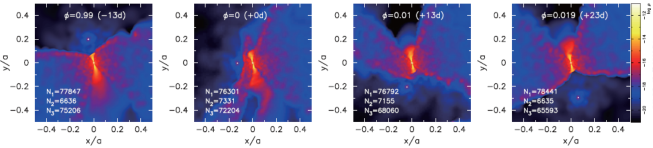

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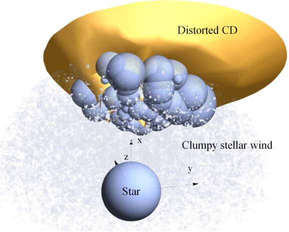

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Relativistic effects and energetics

- **Reduction/enhancement of target fields:** $\epsilon_0' = \delta_* \epsilon_0$, $u' \propto \delta_*^2 u$, $\delta_* = \Gamma(1-\beta\mu)$, $B' \approx B/\Gamma$.
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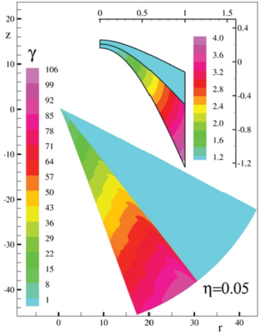

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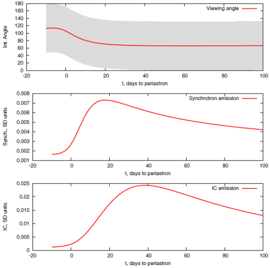

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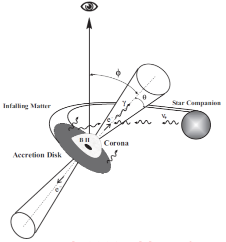

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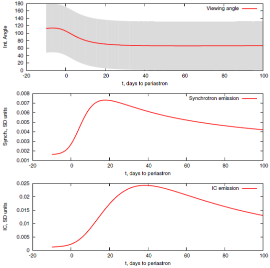

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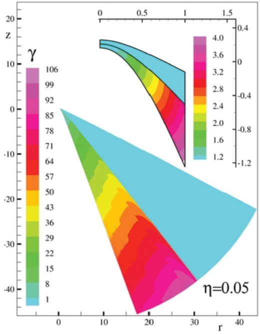

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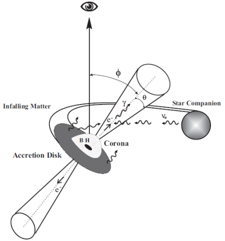

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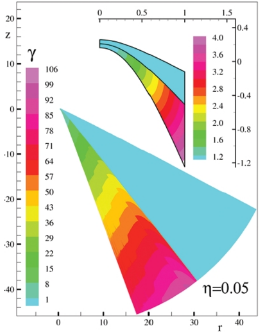

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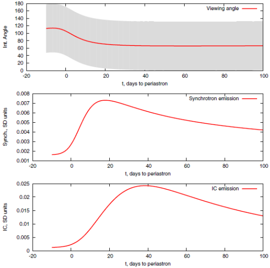

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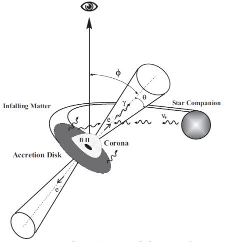

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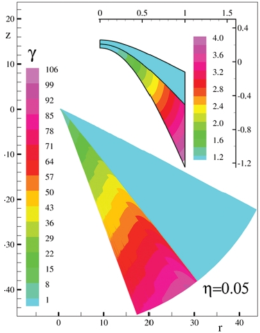

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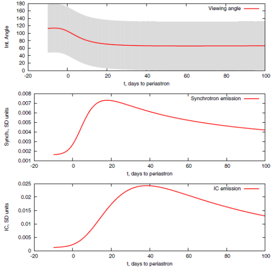

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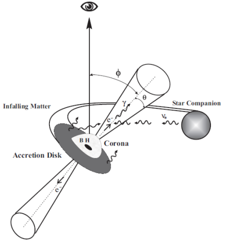

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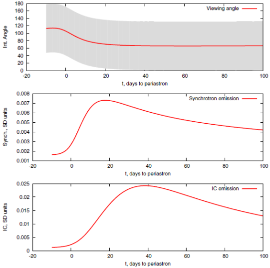

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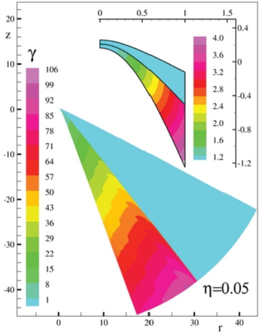

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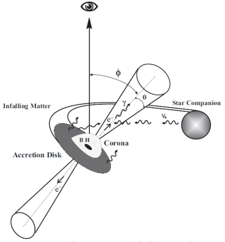

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- Shocked flow soon gets unstable.
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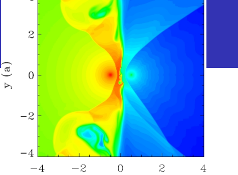
- What is the role of B?

(Lamberts et al. 2013-PSR-→)



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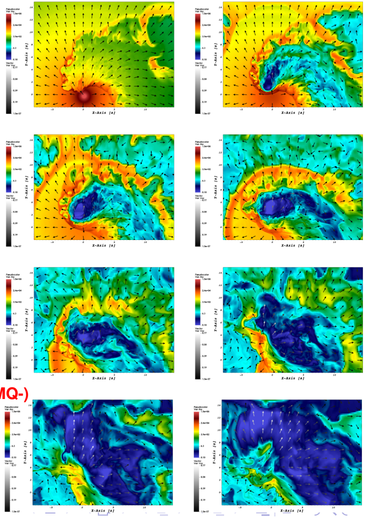

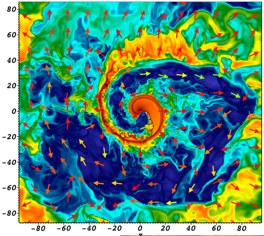

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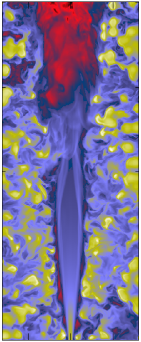
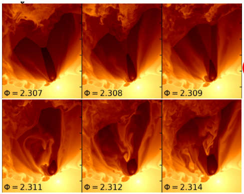


(Perucho&B-R+12-MQ-)



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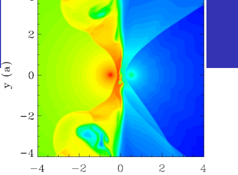

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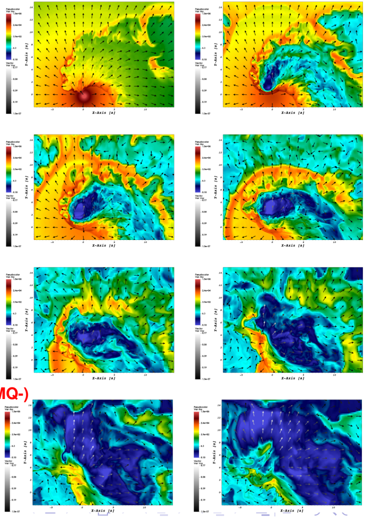

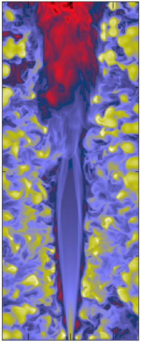

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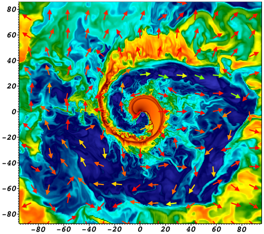

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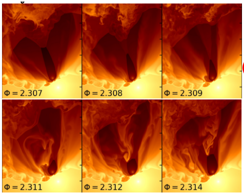

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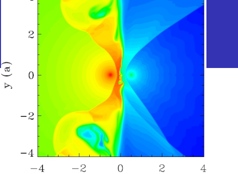

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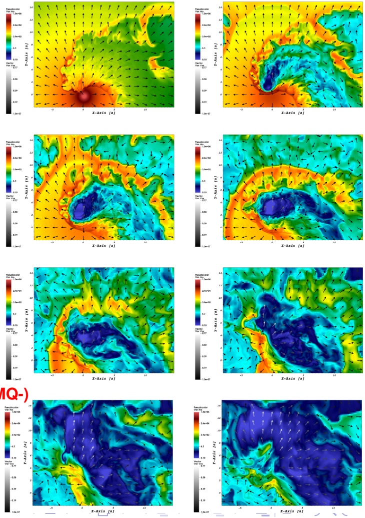

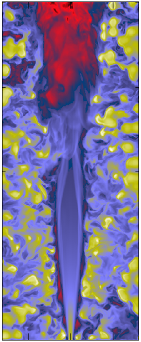

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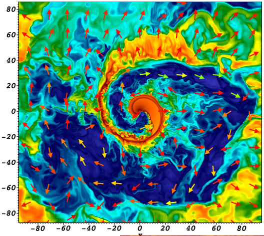

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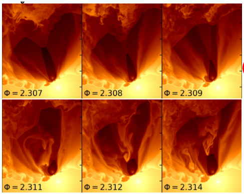

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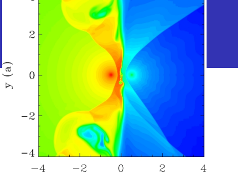
- In pure HD, R.-M., R.-T., and K.-H. instabilities are important.
- Instabilities+mixing on all scales.
- What is the role of *B*?

(Lamberts et al. 2013-PSR-→)



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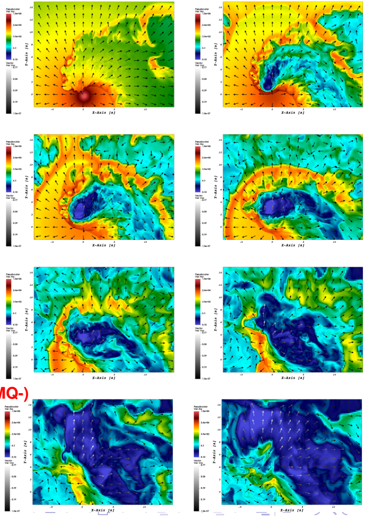
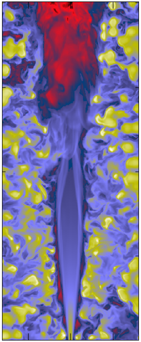
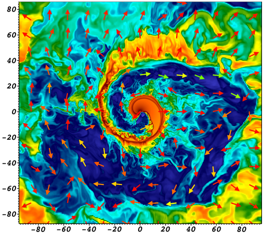




(Perucho&B-R+12-MQ-)



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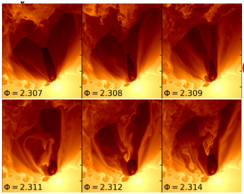

(Kissmann+2023-PSR-)

Shocks, instabilities and mixing

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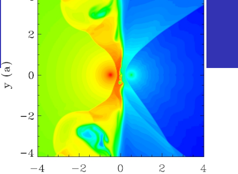

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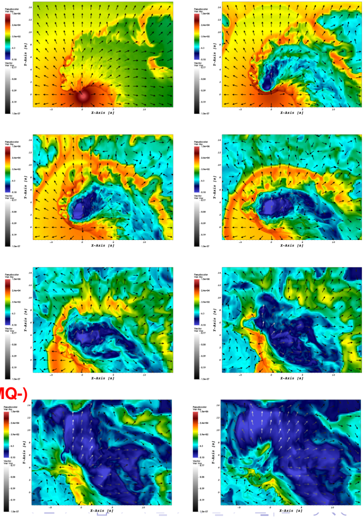

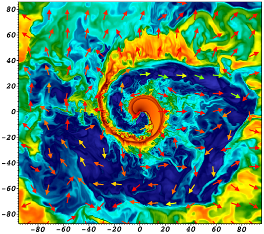

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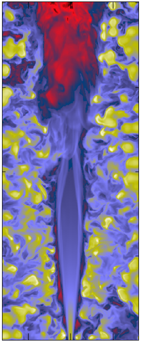

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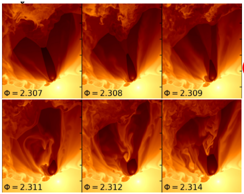
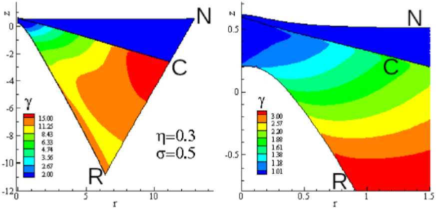


Magnetic fields

- **In winds, as $\sigma \sim 1$, postshock physics is affected:**
  - The anisotropic P_B modifies size and geometry.
  - Flow direction and velocity are strongly modified.
  - Reconnection can occur in shocked flow current sheets.
- In winds and jets, B can both enhance or suppress instability.



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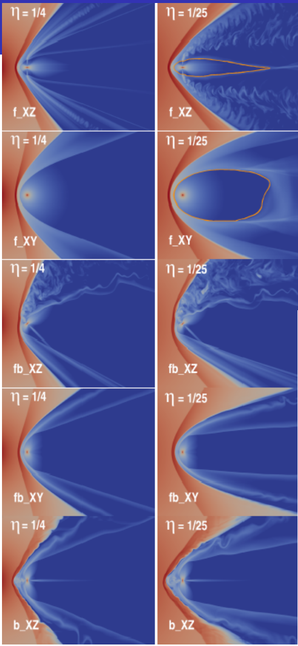

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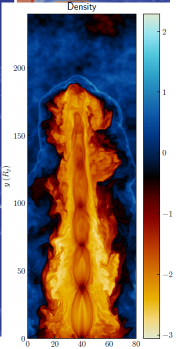

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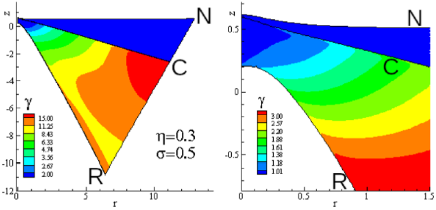

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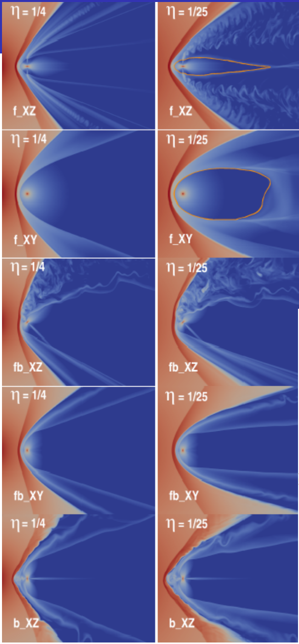

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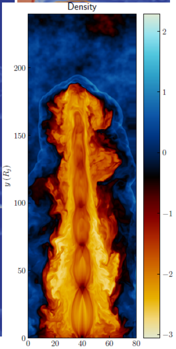

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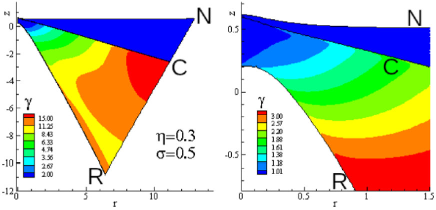

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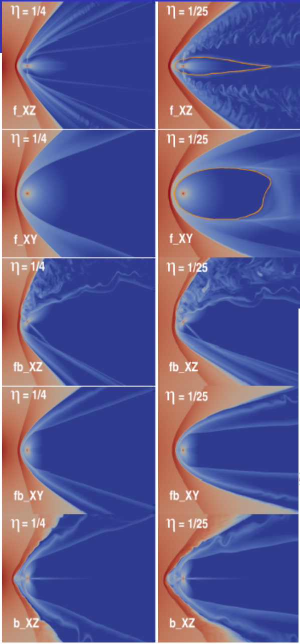

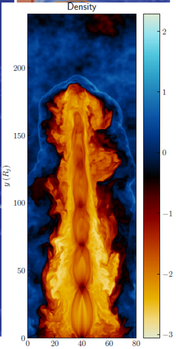

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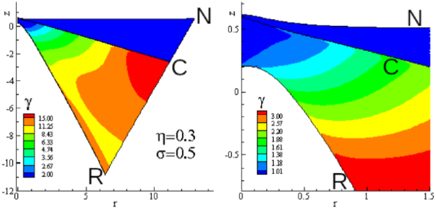

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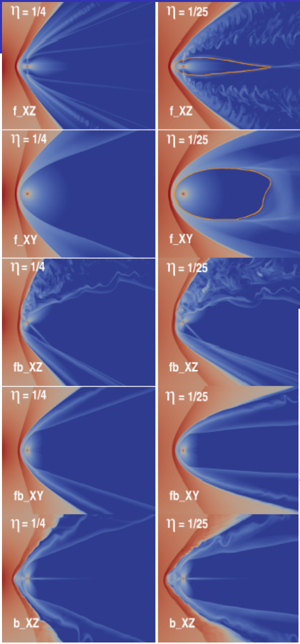

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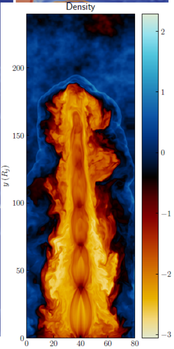

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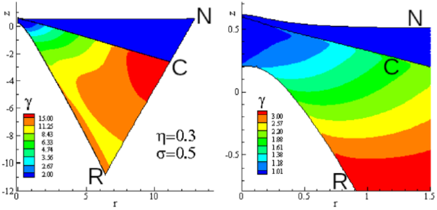

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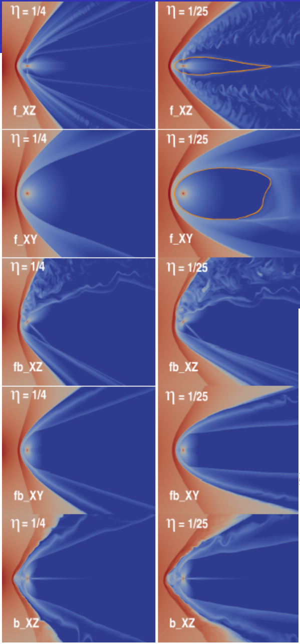

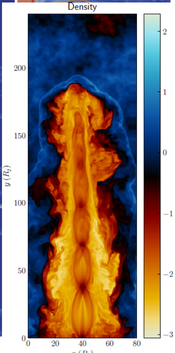

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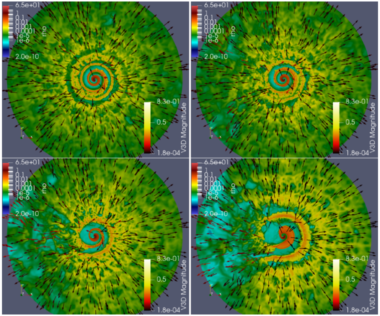
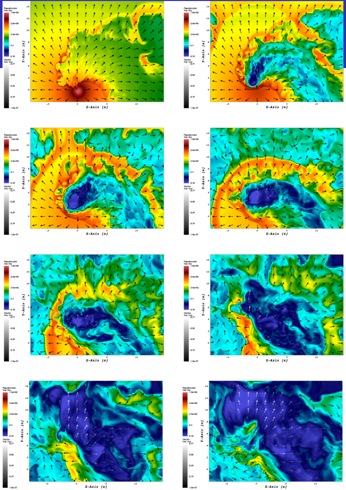
Outline

Orbital motion and eccentricity

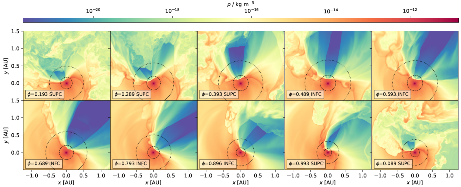
- **Orbit causes a strong Coriolis shock in the pulsar wind and more instability.**
- A spiral structure forms (orbital plane; expanding perpendicularly).
- For high e a mixed fast outflow is produced in the apastron direction.
- HMMQ jets also affected by orbit.



(Barkov & B-R 2021; see observations: e.g. Pavlov+2015)



(Barkov & B-R 2022-MQ-↑)   (Huber et al. 2021-PSR-↓)



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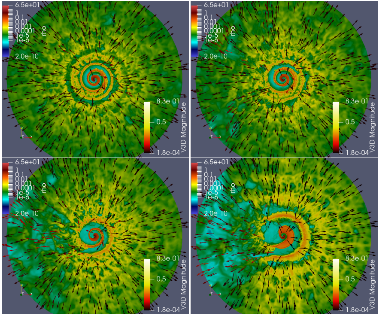

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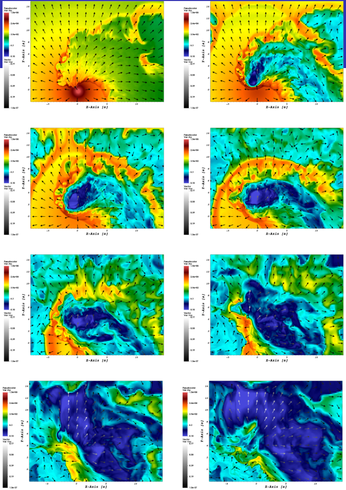

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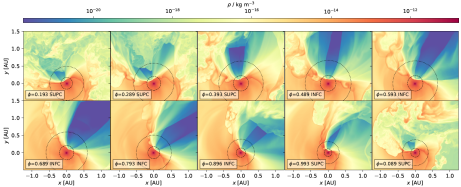

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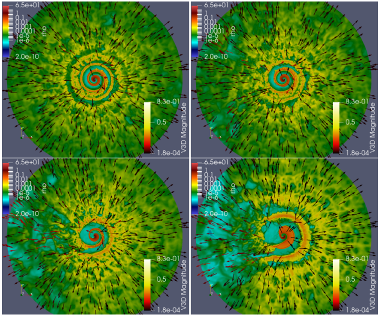

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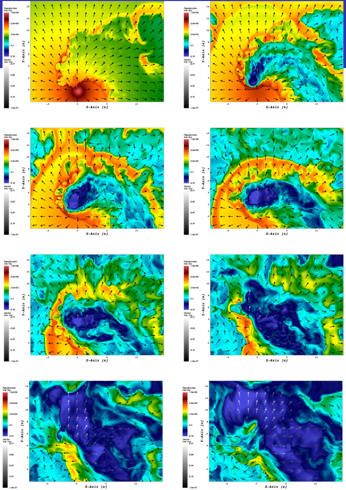

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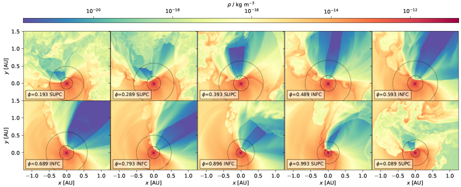

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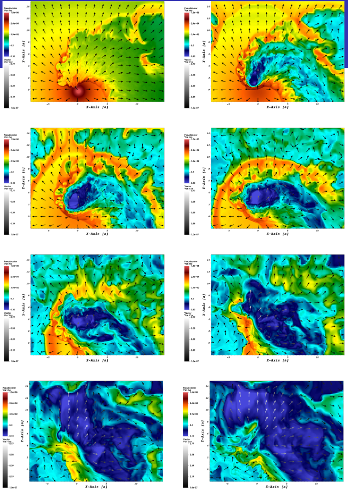

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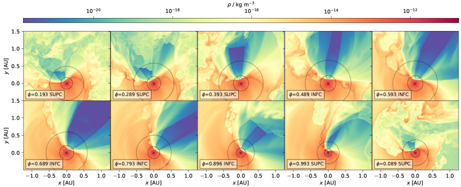

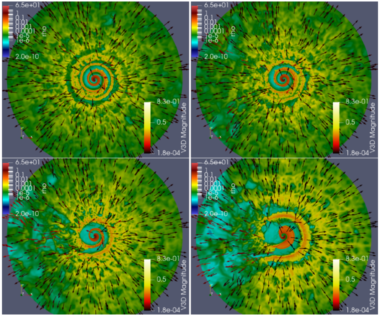

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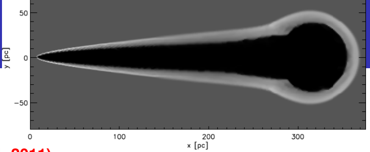
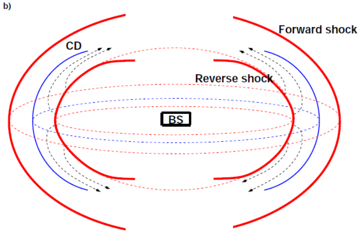
Large scale interactions



(Yoon et al. 2011)

- **Mass-loaded, reaccelerated fast outflow interacts with medium.**
- Evidence of large scale radio, X-ray and gamma rays: local acceleration;

  (e.g. Mirabel+92; Safi-Harb+99; Paredes+07; HAWC; HESS)
- adiabatic losses in expanding outflow prevent binary CR to reach the ISM.
- What is the role of proper motion? Bent jets? sPWN-like?



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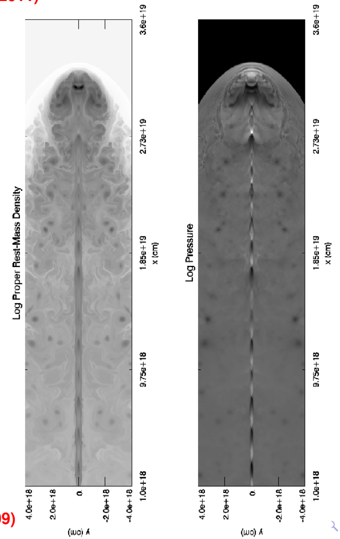

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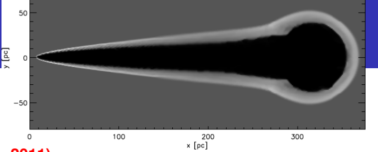

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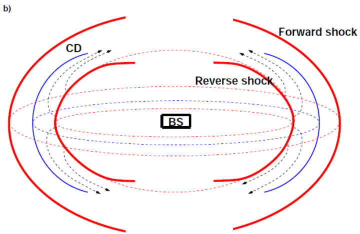

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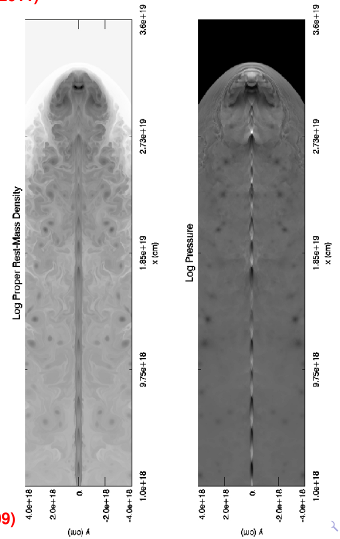

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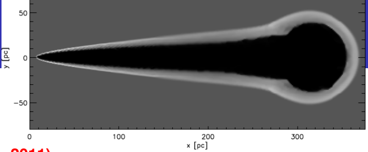

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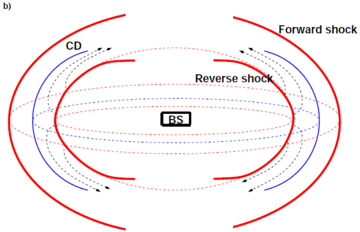

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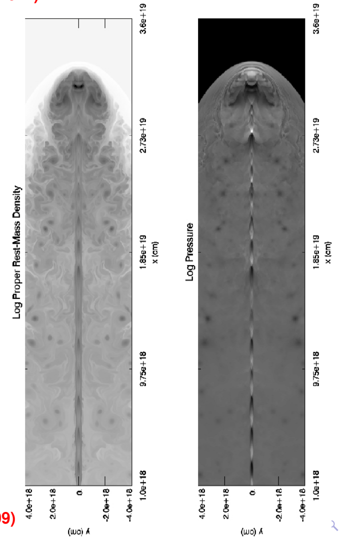

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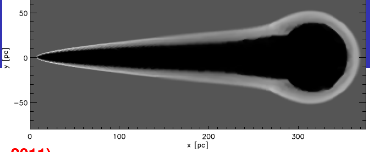

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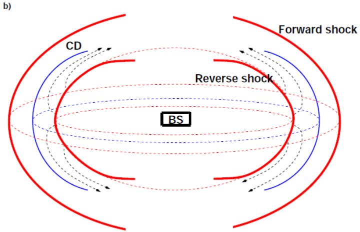

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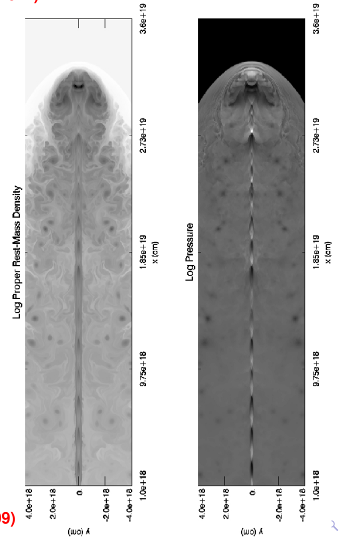

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Outline

Most relevant aspects?

- **The stellar wind and orbital motion shape the HMGB relativistic outflows via shocks, turbulence, mixing...**
- This leads to different regions likely to host non-thermal activity:
  - Efficient acceleration of $e^{\pm}$ and p/nuclei in the strongly dissipative outflow.
  - Dense radiation fields; fast synchrotron, IC and escape.
- On large scales:
  - Extended radio, X-rays and gamma rays are detected.
  - Adiabatic cooling implies efficient acceleration.
- Relativistic HMGB are young powerful (moving) systems that can significantly affect the ISM due to their large luminosity.
- Small galactic population (10s of sources?) with a non-trivial role in the high-energy sky (UHE γ-rays, PeV CR and... perhaps even ν?).

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- **This leads to different regions likely to host non-thermal activity:**
  - **Efficient acceleration of $e^{\pm}$ and p/nuclei in the strongly dissipative outflow.**
  - **Dense radiation fields; fast synchrotron, IC and escape.**
- **On large scales:**
  - **Extended radio, X-rays and gamma rays are detected.**
  - **Adiabatic cooling implies efficient acceleration.**
- **Relativistic HMGB are young powerful (moving) systems that can significantly affect the ISM due to their large luminosity.**
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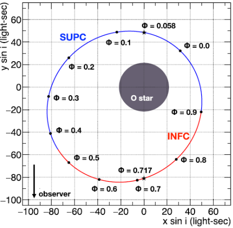
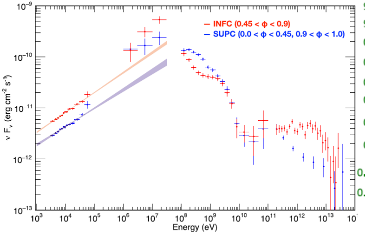
Thank you.

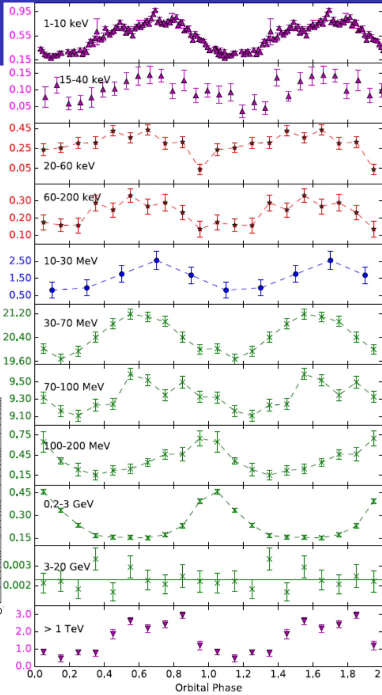
BACKUP SLIDES

LS 5039 at high energies

- **O6.5V(f) + a possible neutron star at** ≈ 2 **kpc**
- $P \approx 3.9$ **days and** $e \approx 0.35$
- **Reaching** $\approx 2 \times 10^{35}$ **(GeV) and** 5×10^{33} **erg s**$^{-1}$ **(TeV).**
- **MeV detection (consistent variability and SED) reaching** $\approx 5 \times 10^{35}$ **erg s**$^{-1}$**.**







(Casares et al. 2005a; Aharonian et al. 2006; Takahashi et al. 2009; Chang et al. 2016; Yoneda et al. 2021)

Moderately eccentric, compact, O+CO? binary

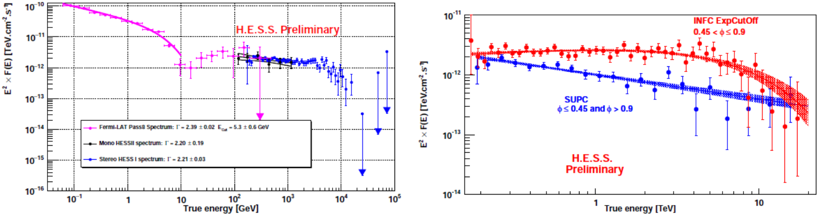


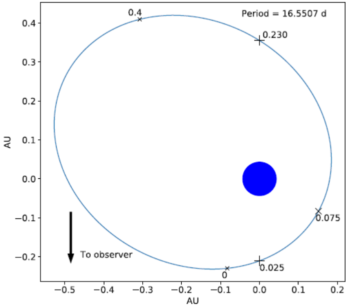
FIGURE 4. *Left*: SEDs obtained from monoscopic and a stereoscopic analyses of the H.E.S.S.-II and H.E.S.S.-I data sets, respectively. Results of fits with power-law functions are given in the inset. Also an SED obtained from a re-analysis of Fermi-LAT data is shown. *Right*: SEDs resulting from H.E.S.S.-I analyses for parts of the orbit corresponding to the inferior or superior conjunction. The corresponding orbital phase ranges are given for reference. Fit results are given in the main text.

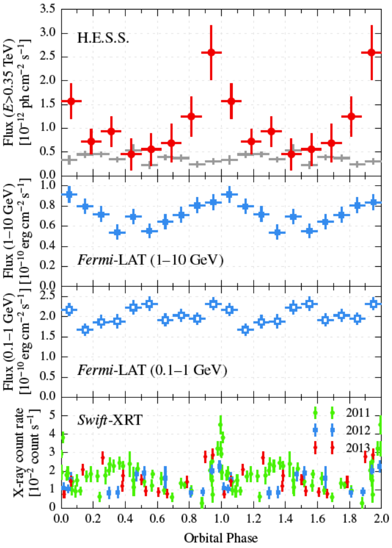
Detected by HAWC up to $\sim$ 100 TeV.

(HESS: Bordas et al. 2015; Goodman, Gamma2022)

1FGL J1018.6−5856 at high energies

- **O6V(f) + a possible neutron star at ≈ 6.4 kpc**
- $P \approx 16.6$ **days and** $e \approx 0.53$
- **Reaching** $\approx 10^{36}$ **(HE) and** 5×10^{33} **erg s^{-1} (VHE)**
- **Possibly detected in MeV**

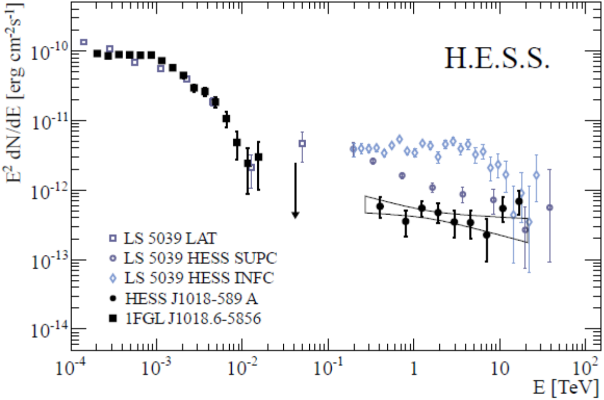




(Ackermann et al. 2012; HESS 2015; Collmar, VGGRS 2017; van Soelen et al. 2022)

1FGL J1018.6−5856 > 10 TeV

Moderately eccentric?, relatively compact, O+CO? binary (10s)

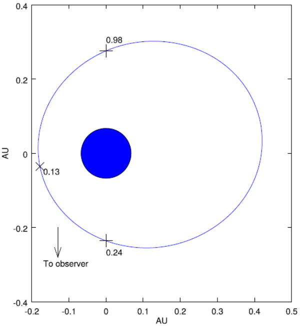


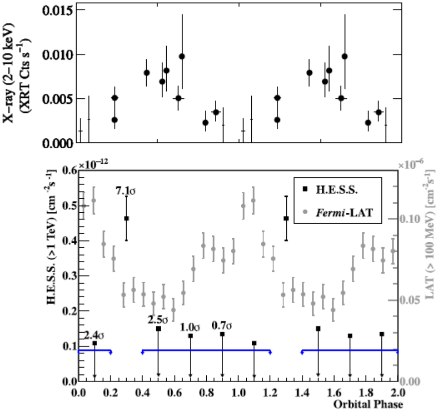
(HESS 2015)

Fig. 1. SED of HESS J1018–589 A/1FGL J1018.6–5856 is shown in black (filled squares and circles for the LAT and HESS detection). For comparison, the SEDs of LS 5039 during superior (SUPC) and inferior conjunction (INFC) are also included (blue points from Hadasch et al. 2012; Aharonian et al. 2005a).

LMC P3 at high energies

- **O5III(f) $+$ a possible neutron star at $\approx$ 50 kpc**
- $P \approx 10.3$ **days and** $e \approx 0.4$
- **Reaching** $\approx 4 \times 10^{36}$ **(HE) and** 5×10^{35} **erg s**$^{-1}$ **(VHE)**

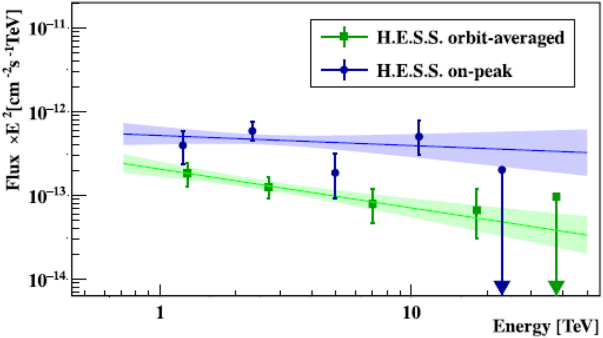




(Corbet et al. 2016; HESS 2018; van Soelen et al. 2019)

LMC P3 $>$ 10 TeV

Moderately eccentric, compact, O+CO? binary

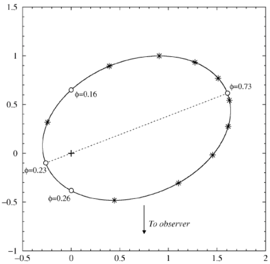


(HESS 2018)

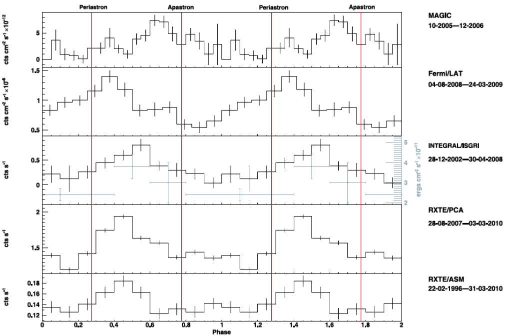
Fig. 3. Spectral energy distribution averaged over the full orbit (green, squares) and for the on-peak orbital phase range (orbital phase from 0.2 to 0.4: blue, circles). The data points have 1 σ statistical error bars, upper limits are for a 95% confidence level. The best fit and its uncertainty are represented by the solid lines and shaded areas, respectively.

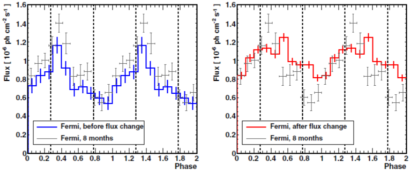
LS I +61 303 at high energies

- **B0V(e) + a neutron star at** ≈ 2 **kpc**
- $P \approx 26.5$ **days and** $e \approx 0.6 - 0.7$
- **Reaching** $\approx 2 \times 10^{35}$ **(HE) and** 5×10^{33} **erg** s^{-1} **(VHE)**
- **Similar MeV SED to LS 5039**



(Casares+2005b; Albert+2006; Zhang+2010; Hadasch+2012; Collmar, VGGRS 2017; Weng+22)





Messy behavior due to superorbital modulation.

LS I +61 303 > 10 TeV

Eccentric, relatively compact, Be+pulsar binary

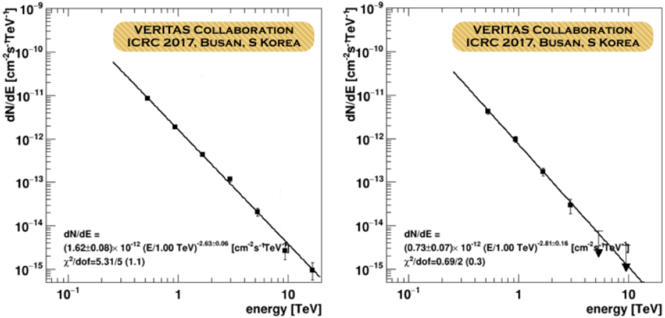
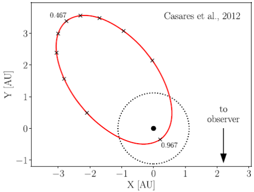


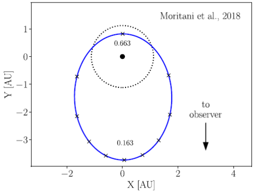
Figure 3: Spectral energy distribution (SED) for LS I +61°303 for two parts of the orbit (parts of the orbit shown on top panels). SED on the *left* is near apastron passage covering $\phi = 0.5 \rightarrow 0.8$ and SED on the *right* is for the rest of the orbit for $\phi = 0.8 \rightarrow 0.5$. The orbital parameters shown on top panel are used from [14]

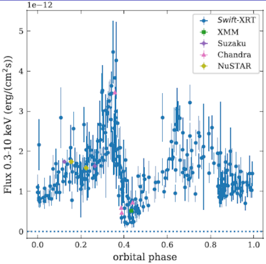
(VERITAS: Kar et al. 2017)

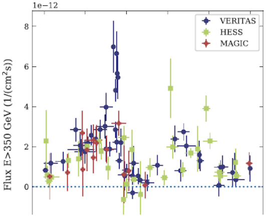
HESS J0632+057 at high energies

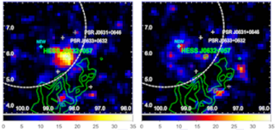
- **B0V(pe) + a possible neutron star at ≈ 2 kpc**
- $P \approx 317$ **days and** $e \approx 0.6 - 0.8$
- **Reaching** $\approx 10^{34}$ **(HE) and** 3×10^{32} **erg s^{-1} (VHE)**











(Casares et al. 2012; Li et al. 2017; Moritani et al. 2018; Adams et al. 2021)