Enhanced high-energy emission in a pulsar wind interacting with a companion

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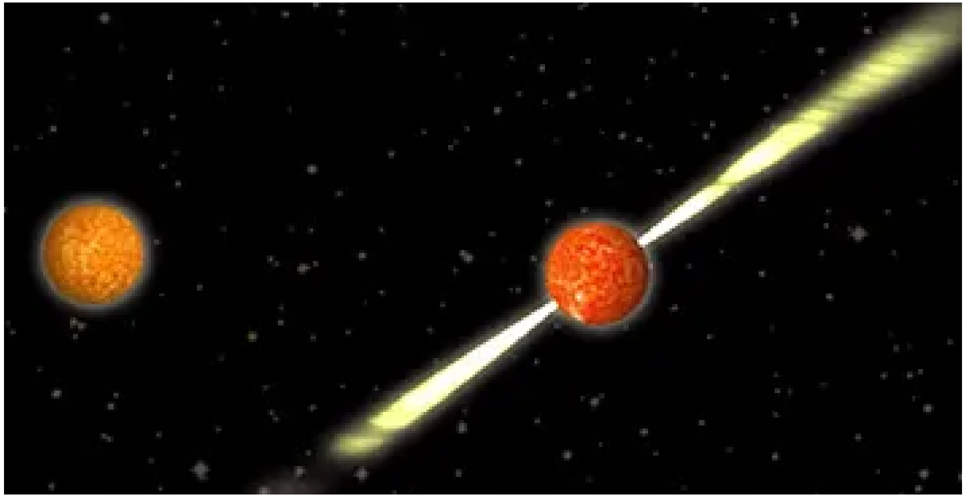

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Enhanced particle acceleration in a pulsar wind interacting with a companion

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ABSTRACT

Context. Pulsar winds have been shown to be preferred sites of particle acceleration and high-energy radiation. Numerous studies have been conducted to better characterize the general structure of such relativistic plasmas in isolated systems. However, many pulsars are found in binary systems and there are currently no ab initio models available that would include both the pulsar magnetosphere and the wind of the pulsar in interaction with a spherical companion.
Aims. We investigate the interaction between a pulsar wind and a companion to probe the rearrangement of the pulsar wind, assess whether it leads to an enhancement of particle acceleration, and predict the high-energy radiative signature that stems from this interaction. We consider the regime where the companion is small enough to hold between two successive stripes of the wind.
Methods. We performed two-dimensional (2D) equatorial particle-in-cell simulations of an inclined pulsar surrounded by a spherical, unmagnetized, perfectly conducting companion settled in its wind. Different runs correspond to different distances and sizes of the companion.
Results. We find that the presence of the companion significantly alters the structure of the wind. When the companion lies beyond the fast magnetosonic point, a shock is established and the perturbations are advected in a cone behind the companion. We observe an enhancement of particle acceleration due to forced reconnection as the current sheet reaches the companion surface. Hence, high-energy synchrotron radiation is also amplified. The orbital light curves display two broad peaks reaching up to 14 times the high-energy pulsed flux emitted by an isolated pulsar magnetosphere. These effects increase with the growth of the companion size and with the decrease of the pulsar-companion separation.
Conclusions. The present study suggests that a pulsar wind interacting with a companion induces a significant enhancement of high-energy radiation that takes the form of an orbital-modulated hollow cone of emission, which should be detectable by galactic-plane surveys, possibly with long-period radio transient counterparts.

Key words. acceleration of particles – magnetic reconnection – radiation mechanisms: non-thermal – methods: numerical – pulsars: general – stars: winds, outflows

1. Introduction

A few percent of galactic pulsars are found in binary systems (Lorimer 2008; Breton 2009). While tight binary systems involving magnetically coupled neutron stars have been studied in the past (e.g., Hansen & Lyutikov 2001; Palenzuela et al. 2013; Crinquand et al. 2019; Most & Philippov 2020), fewer class of relevant applications from which we expect characteristic signatures, as suggested by Mishra et al. (2023), analogously to the Solar system planets and moons (e.g., Neubauer 1980 for the Jupiter-Io interaction). We should also consider the case of asteroids interacting with a pulsar wind, which have been proposed to trigger repeating fast radio bursts (Dai et al.

➡ see *Richard-Romei & Cerutti, 2024* in A&A

arXiv:2406.18663

Pulsar

PULSAR

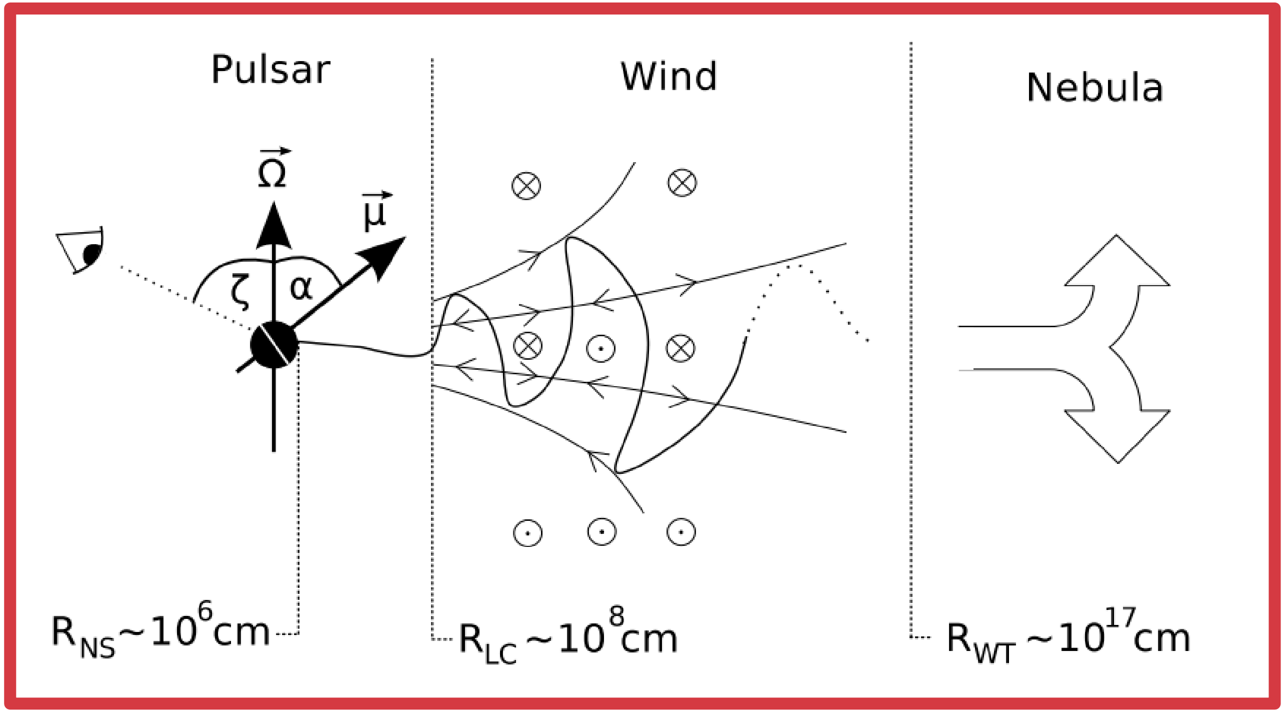
Fast spinning & magnetised neutron star

- R = 10 – 15 km
- M = 1.4 – 2 M_{sun}
- B_{field} = 10^9 G – 10^{14} G
- P_{spin} = ms – seconds
- Spindown = 10^{-15} s/s

MAGNETOSPHERE

- E,B fields + plasma
- 3 main zones: - light cylinder $R_{LC} = c/\Omega$
  - pulsar wind
  - nebula

$\vec{\mu}$: magnetic moment
$\vec{\Omega}$: angular speed



Bühler & Blandford (2014)

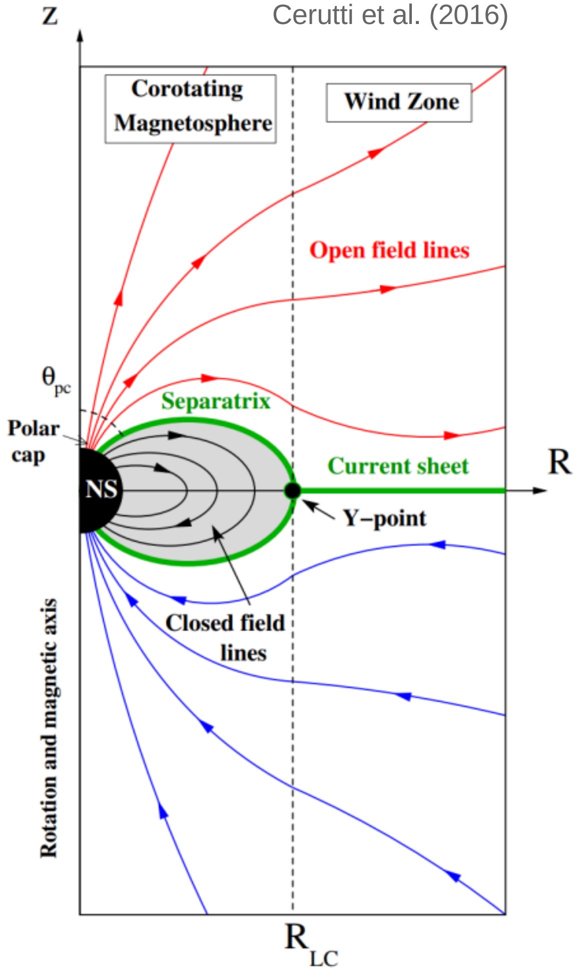
Pulsar magnetosphere

Closed zone: Inactive zone
Closed field lines in corotation with pulsar
Plasma confined in closed field loops
Null poloidal current

Opened zone: Active zone
Field lines opened by pulsar rotation
Outgoing Poynting flux
Relativistic wind
Non-zero poloidal current

Separatrix + current sheet:
Interface zone between opposite B fields
Non- zero returning poloidal current
Energy dissipation zone

Cerutti et al. (2016)



Pulsar-companion interaction

Many opened questions: Rearrangement of the magnetosphere ?
Strength and location of particle acceleration ?
Strength of high-energy radiation ?
New class of long-period high-energy transients ?

Choice of companion characteristics

Settled in the pulsar wind

Intermediate size ($r_{comp} < \lambda_{stripe}$)

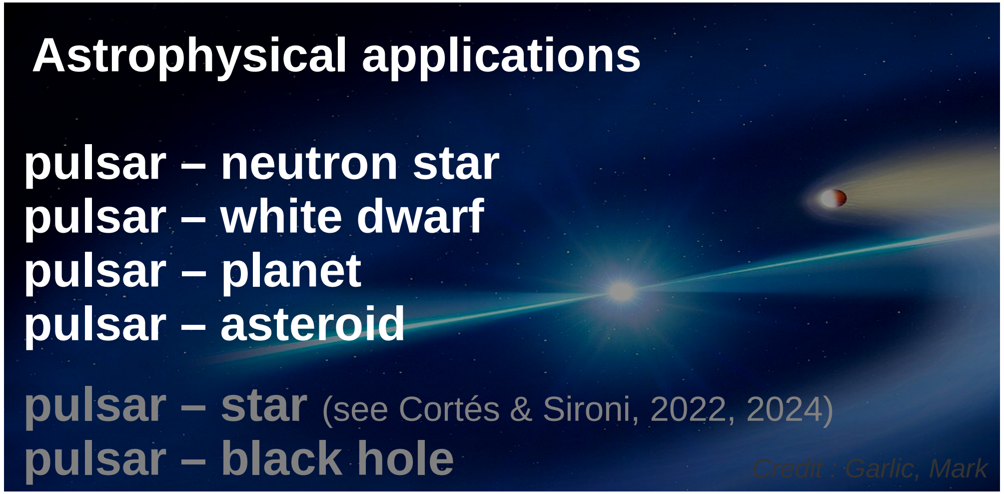
Unmagnetized companion

Perfectly conducting companion

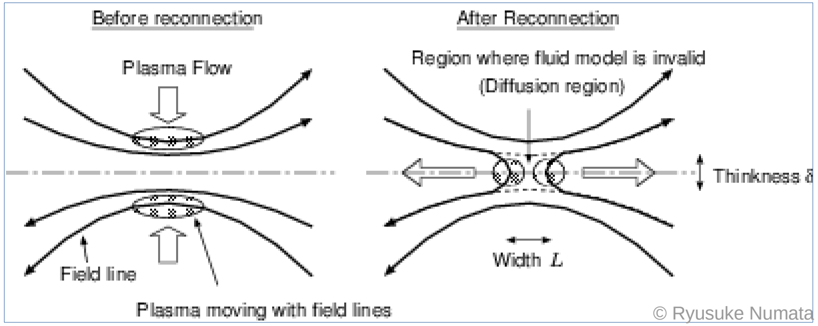
Astrophysical applications

pulsar – neutron star
pulsar – white dwarf
pulsar – planet
pulsar – asteroid

pulsar – star (see Cortés & Sironi, 2022, 2024)
pulsar – black hole



Energy transfer sequence



magnetic reconnection

synchrotron radiation

pulsar's spindown power → poynting flux + plasma wind → particle acceleration → non-thermal emission

In order to explain the electromagnetic emissions:

- need of global magnetospheric simulations
- need of kinetic scales for relativistic plasma

} Global PIC simulations

Particle-in-cell (PIC) simulations

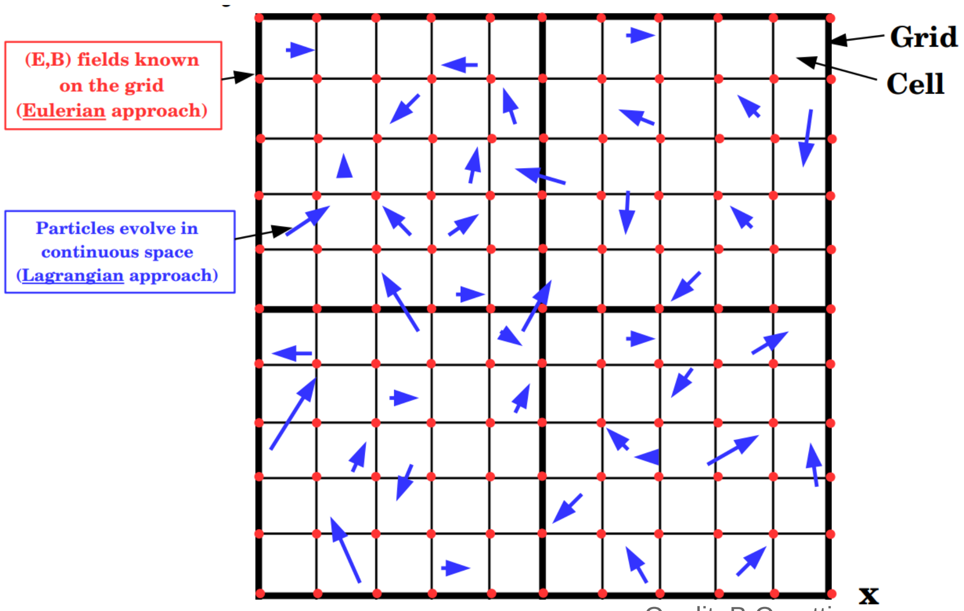
Solve Abraham-Lorentz-Dirac equation

$$\frac{\mathrm{d}(\gamma m_e \mathbf{v})}{\mathrm{d}t} = q(\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B}) + \mathbf{f}_{\mathrm{rad}}$$

Δt

Deposit charge and current densities

Solve Maxwell equations

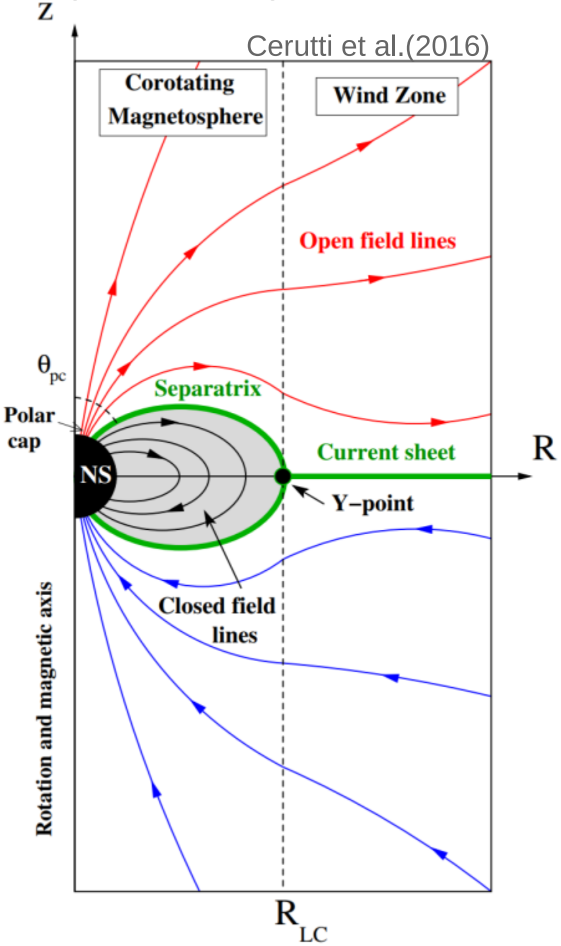


Credit :B.Cerutti

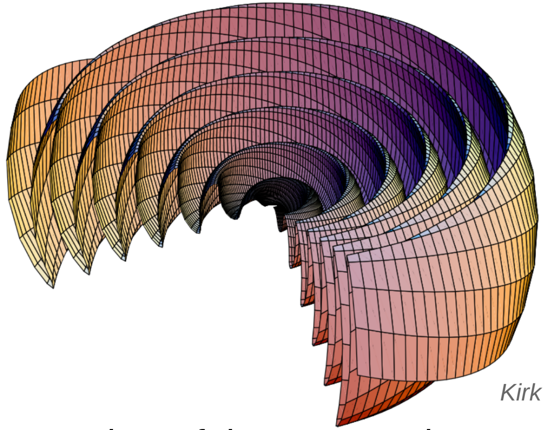
2D equatorial view

Aligned magnetic dipole

Cerutti et al.(2016)

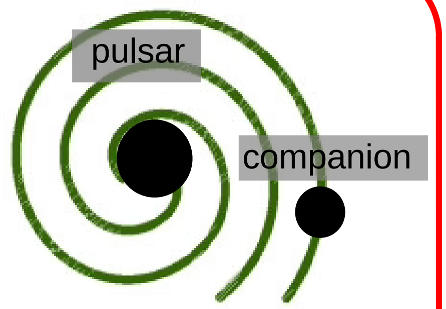


Inclined magnetic dipole



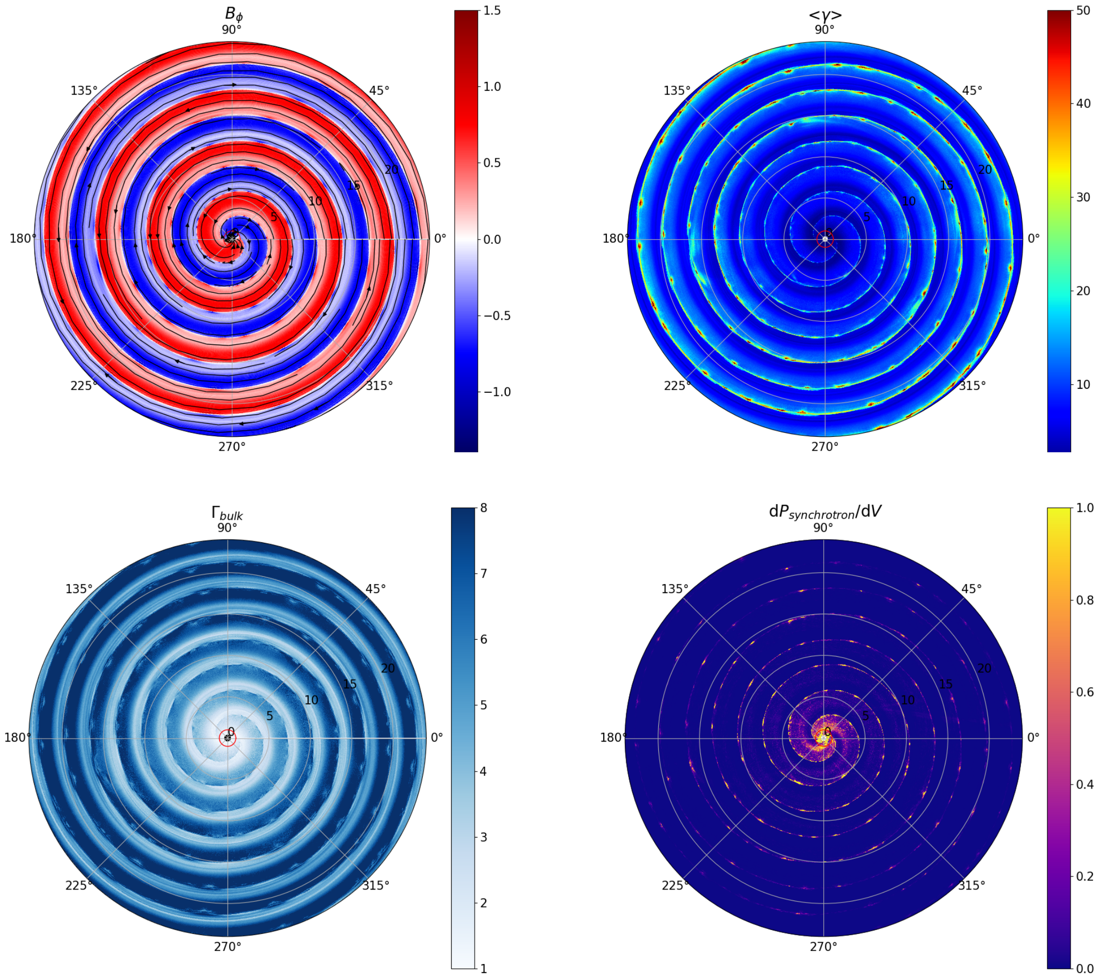
Kirk et al.(2007)

3D view of the current sheet



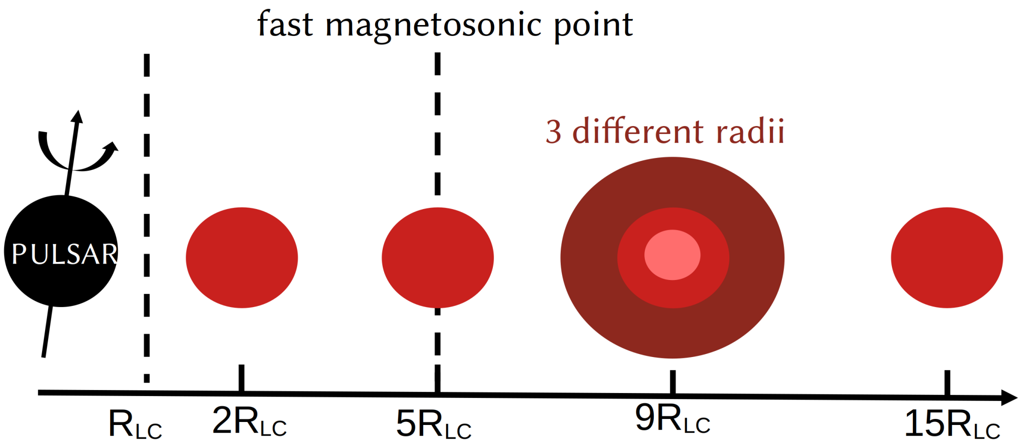
2D equatorial view

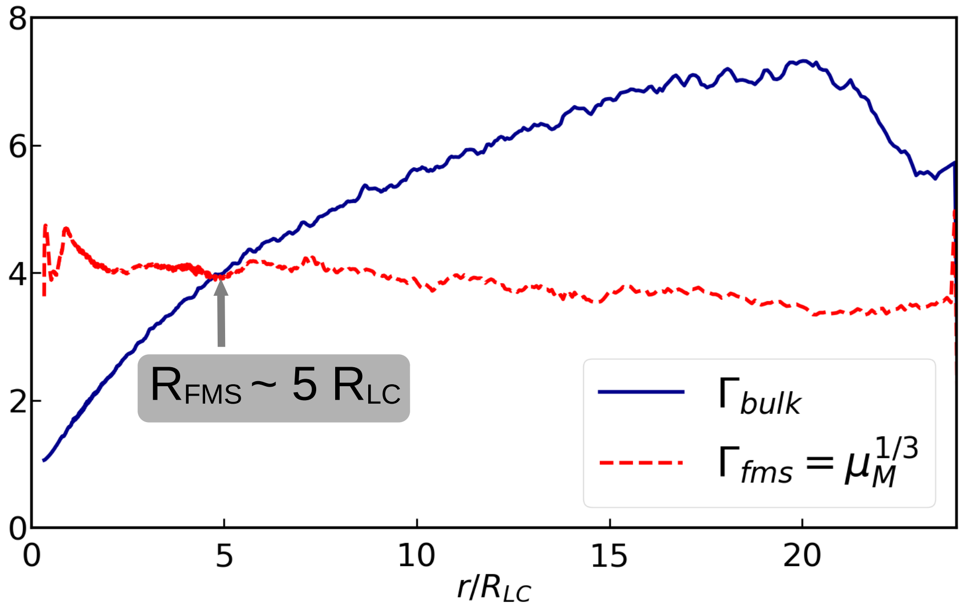
Reference case: the isolated pulsar magnetosphere



- ‘stripped wind’: magnetic field stripes of alterning polarity
- bulk Lorentz factor globally increases with radius
- highest mean Lorentz factor in the current sheets due to magnetic reconnection
- high-energy synchrotron radiation emitted from plasmoids

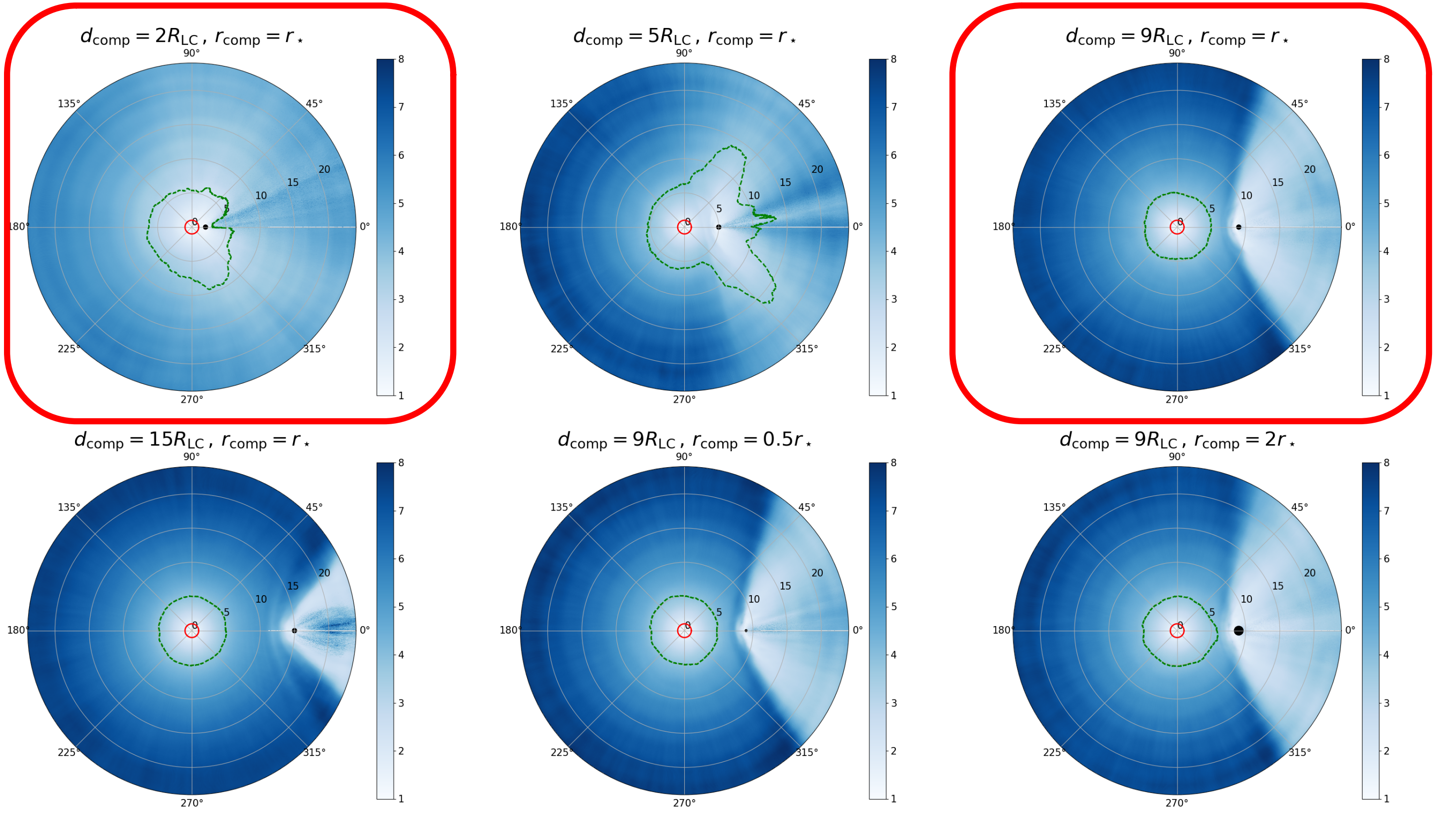
Parametric study





- Companion in the wind zone: $P_{orb,companion} >> P_{spin,pulsar}$
  ⟶ **companion at rest** in the simulation
- **2 different regimes** depending on the location with respect to the fast magnetosonic point

Bulk Lorentz factor averaged over several P_{spin}

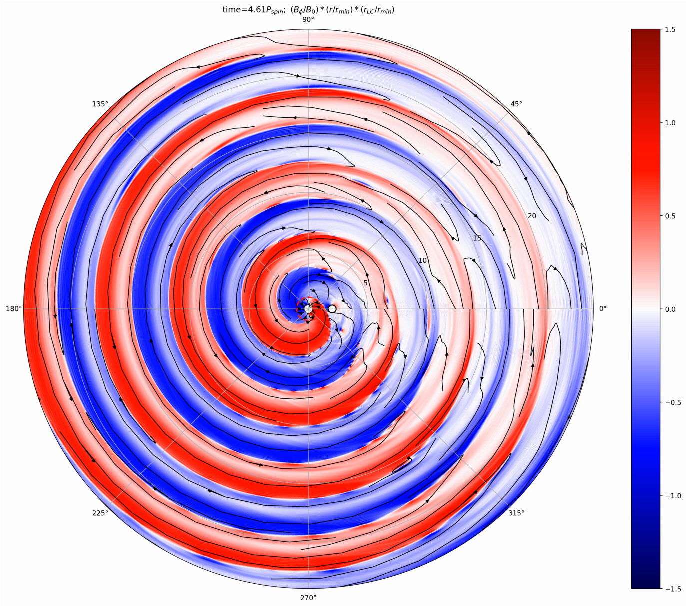


- if $r_{comp} > r_{fms}$, shock
- higher r_{comp} implies broader shocked cone
- higher binary separation implies narrower shocked cone

red circle = light cylinder radius
green contour line = fast magnetosonic surface

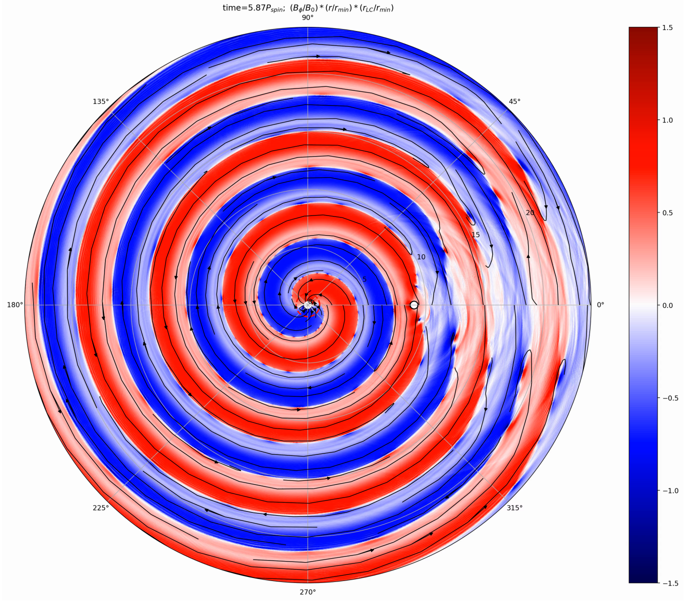
Two different regimes

$d_{comp} = 2\ R_{LC} < r_{FMS}$



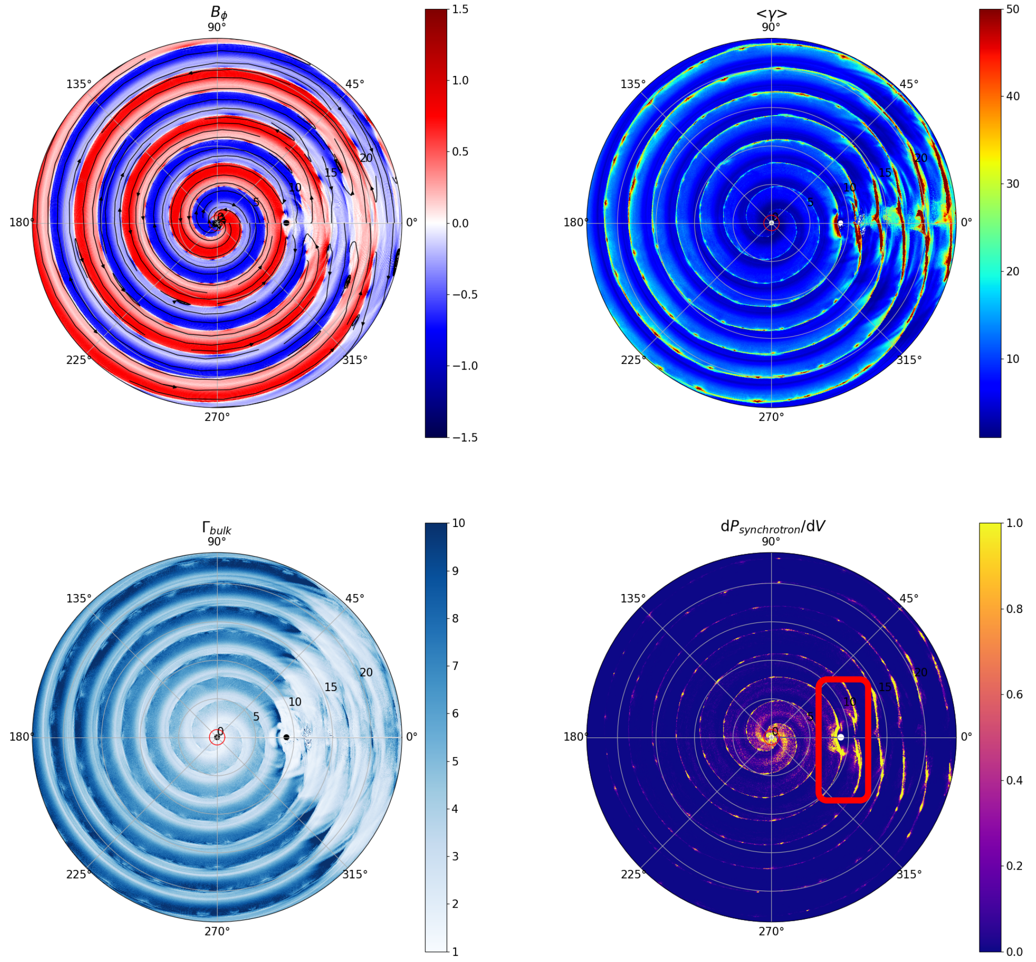
$(B_\varphi/B_{star})*(r*r_{LC}/r_{star}^2)$

$d_{comp} = 9\ R_{LC} > r_{FMS}$



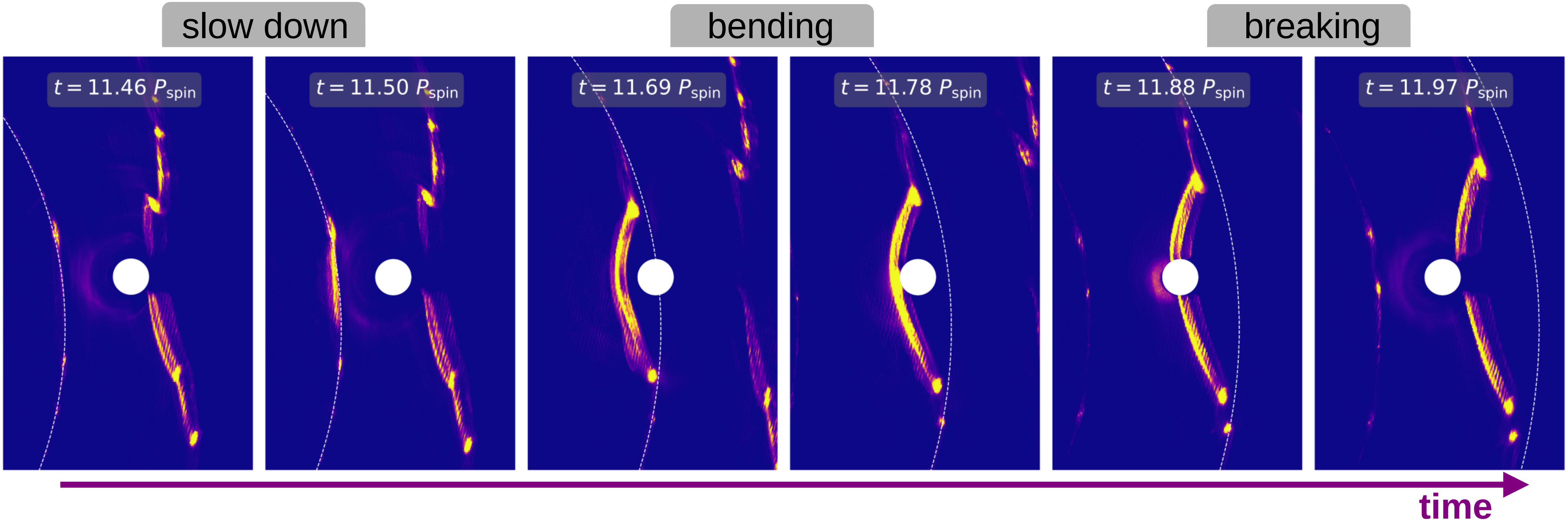
$(B_\varphi/B_{star})*(r*r_{LC}/r_{star}^2)$

Interaction with a companion (d_{comp} = 9 R_{LC}, r_{comp} = r_{pulsar})



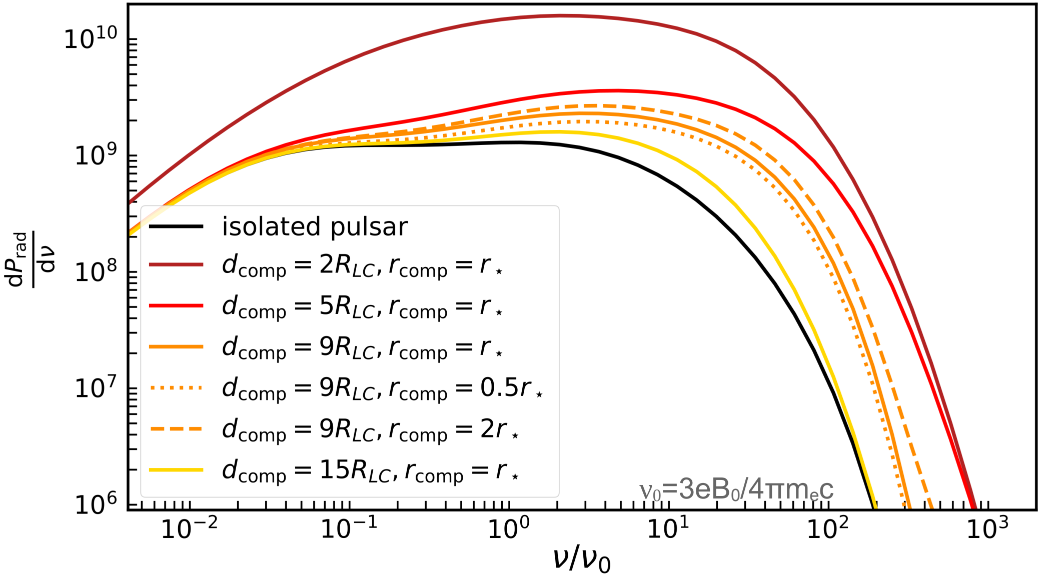
- **perturbations advected** in a cone behind the companion
- increased magnetic islands on the cone surface
- **favorable zone for particle acceleration** behind the companion
- very low density inside the cone
  ⟶ **highest synchrotron power** at its borders

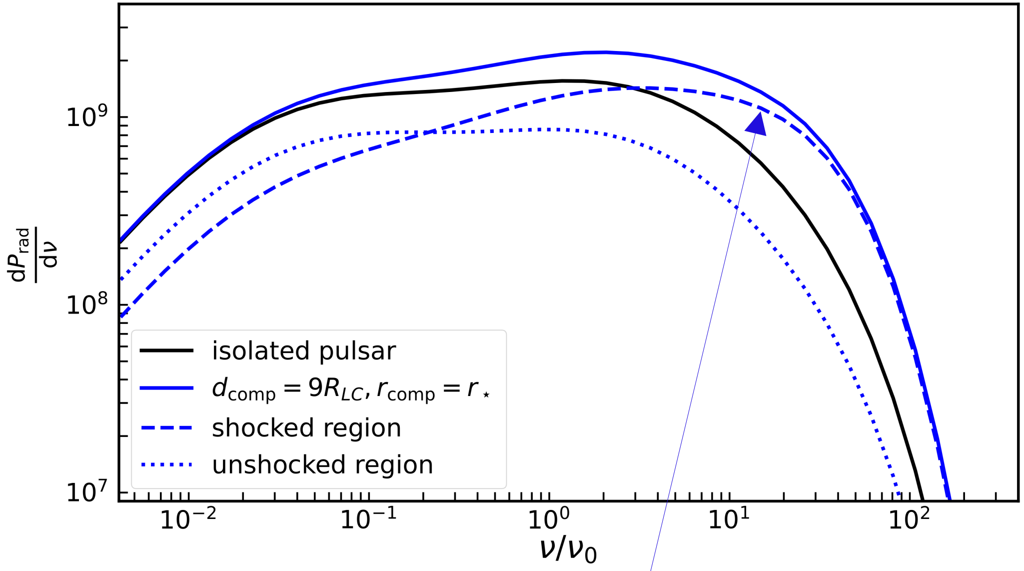
Zoom on the current sheet at the companion surface



→ magnetic field lines pile up in front of the companion
→ **forced reconnection**
→ enhanced particle acceleration
→ enhanced non-thermal radiation

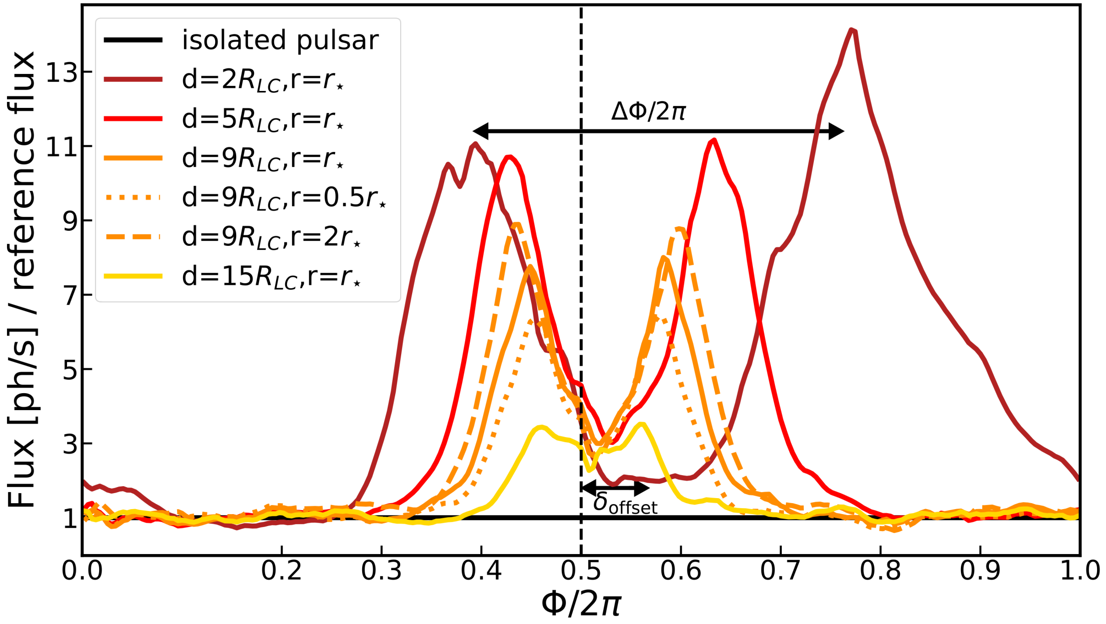
High-energy spectra

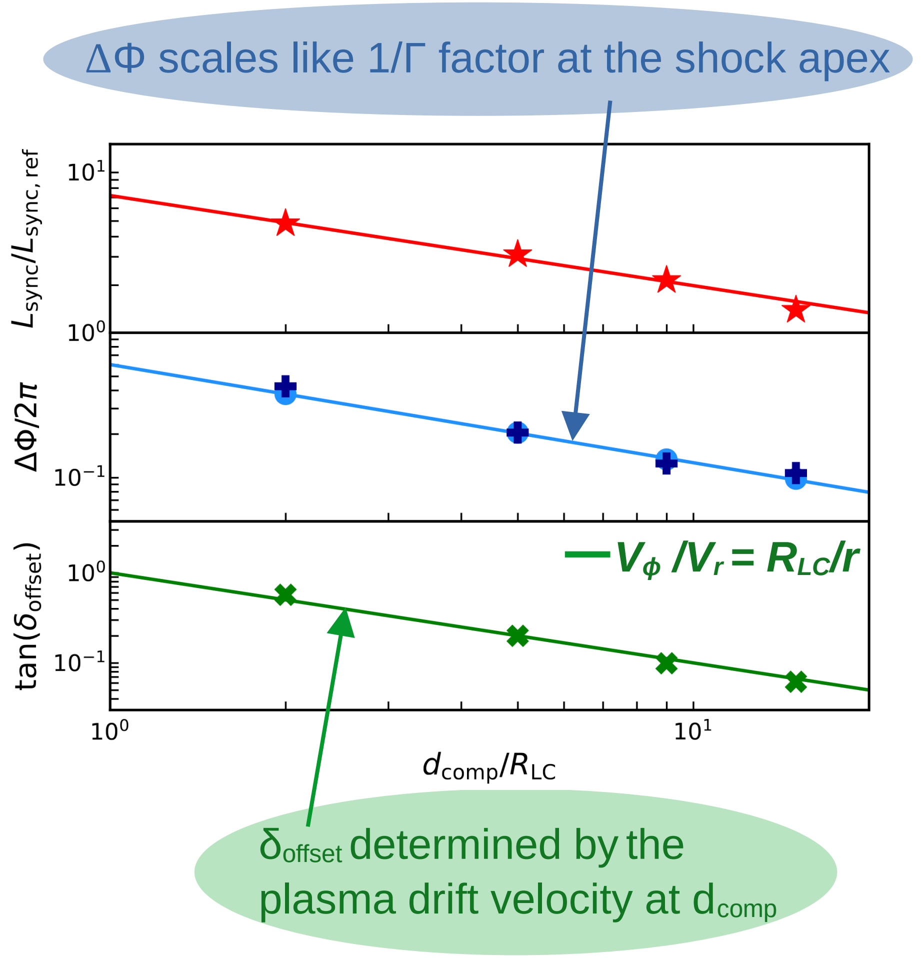




- **Significant enhancement** of the high-energy radiation compared to the isolated pulsar
- Emission **decreases with d_{comp}** and **increases with r_{comp}**

additional contribution **exclusively due to the shocked part**





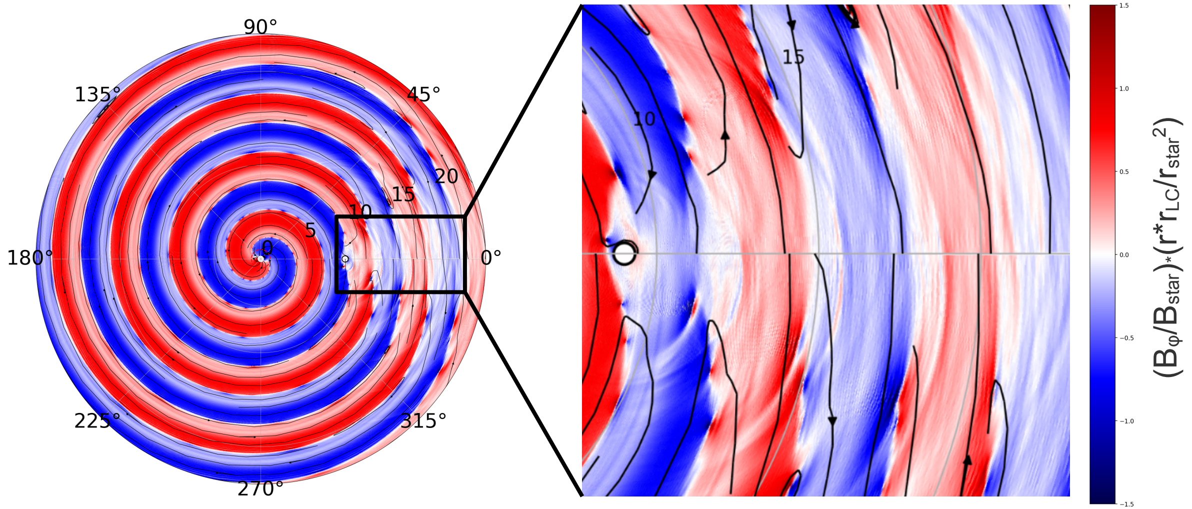
- **Enhancement of the radiation flux up to ~ x10**
- **2 broad peaks per orbit:** hollow cone of emission
- Higher r_{comp} ➡ higher peaks and higher $\Delta\Phi$
- Higher d_{comp} ➡ lower peaks and lower $\Delta\Phi$

What about radio counterparts?

- Coherent radio emission as a low frequency counterpart of relativistic magnetic reconnection

→ *Lyubarsky (2018), Philippov et al. (2019)*

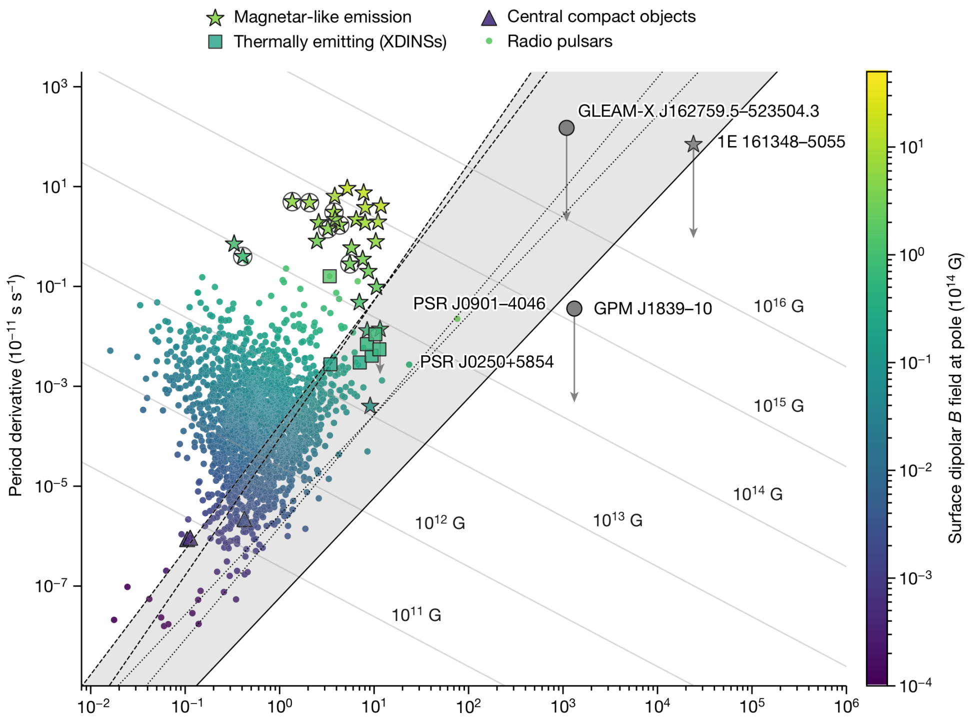
- collision of plasmoids with each other and with B field
- perturbation of B field
- short fast magnetosonic pulse
- pulse escapes the plasma as a radio wave



- See also the predictions of Fast Radio Bursts in the presence of a companion (Mottez, Zarka, Voisin, 2020; Decoene, 2021)

Recently discovered galactic long-period radio transients

Several discoveries of long-period (10-1000s) radio transients → which phenomenon ? → which object ?



Hurley-Walker et al.(2023)

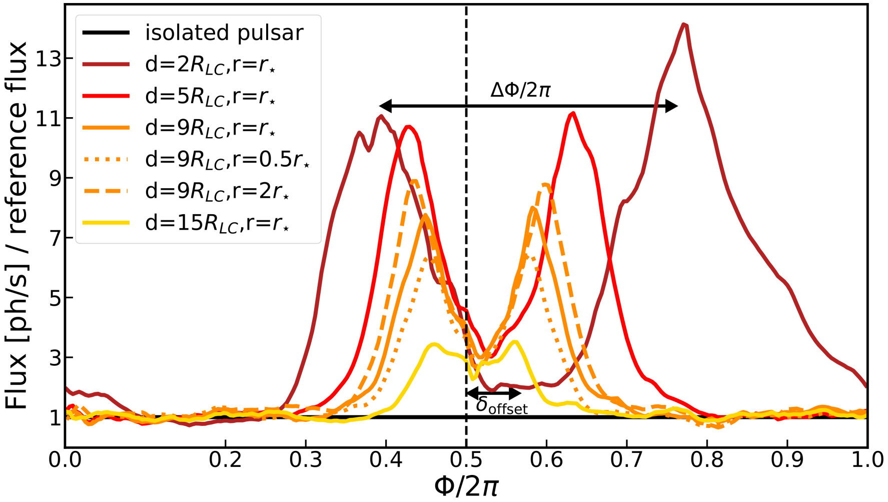
Considered interpretations:

- isolated pulsar
- isolated magnetar
- white dwarf
- proto-white dwarf
- white dwarf + companion
- neutron star + companion
- star + exoplanet
- brown dwarf binaries
- new objects ?

Conclusion

When adding a companion in the pulsar wind:

- **Significant alteration** of the dynamical and energetic properties of the pulsar wind
- **Two different regimes** depending on the companion location with respect to the fms point
- Forced reconnection
  → enhanced particle acceleration
  → enhanced non-thermal radiation as an **orbital-modulated hollow cone of light**
- Transients should be observable on **galactic distances** (soft γ-ray band)



Optical and X-ray pulses from the transitional millisecond pulsar J1023+0038

Collaborators: Benoît Cerutti[1], Riccardo La Placa[2], Alessandro Papitto[2]

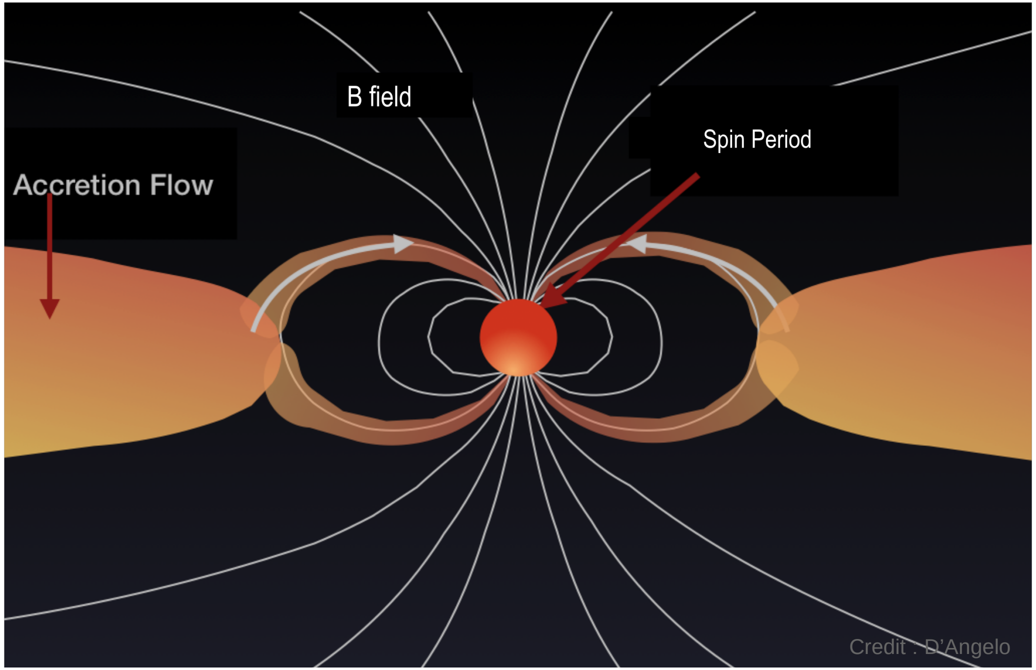
[1]IPAG, Grenoble
[2]INAF, Rome

Transition millisecond pulsars

Definition:

- millisecond pulsar
  + low-mass companion star
  → accretion disk

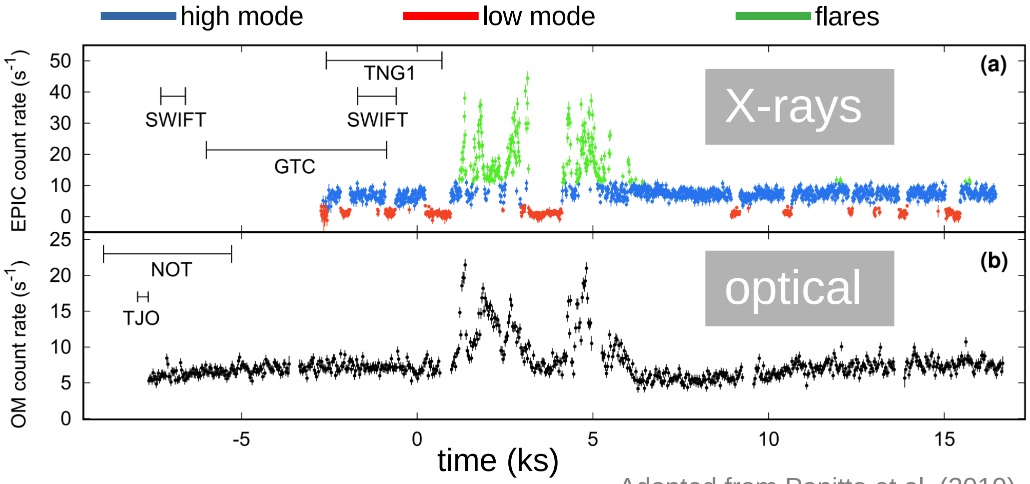
- transitions between **rotation-powered** and **accretion-powered** states
  → $\tau_{transition}$ ~ few weeks



Optical and X-ray pulses from the transitional millisecond pulsar J1023+0038

J1023+0038 characteristics (see *Papitto et al., 2019*):

- **first detection of optical pulses from a ms pulsar**
- detection in the presence of an accretion disc
- simultaneous detection of X-ray pulsations
- 2 X-ray intensity modes: **high** and **low**
- no γ-ray pulses



Adapted from Papitto et al. (2019)

Main question: where do these optical and X-ray pulses come from?

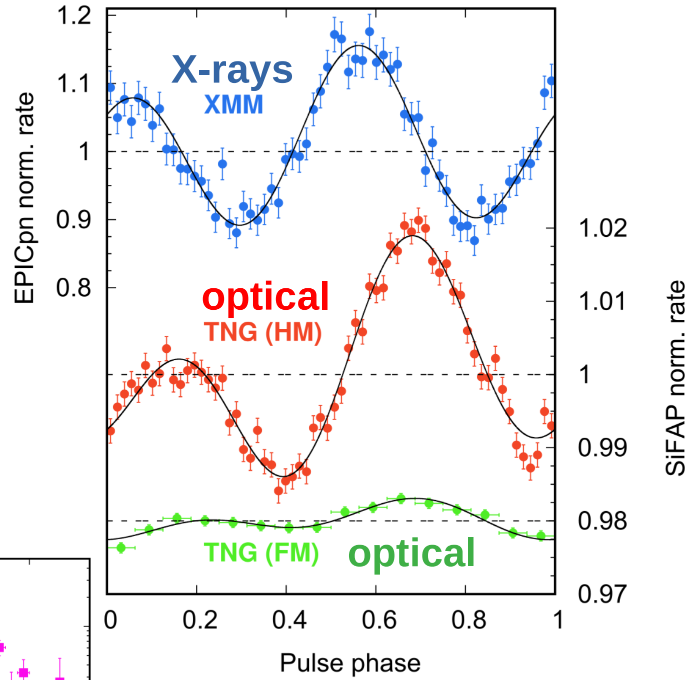
- ✗ accretion? pulsed optical luminosity is too high
- ✗ activity of a rotation-powered pulsar? pulsed optical and X-ray emission is too high

Pulse characteristics

High mode (~70 % of the time):

- coherent quasi-simultaneous optical and X-ray pulsations
- two broad peaks 180° apart
- modulation by P_{spin}
- similar pulse profiles
- same emitting region (~kms apart)
- both compatible with the same power-law spectrum $F_\nu \propto \nu^{-0.7}$

Strong indication that optical and X-ray pulses originate from the **same phenomenon**

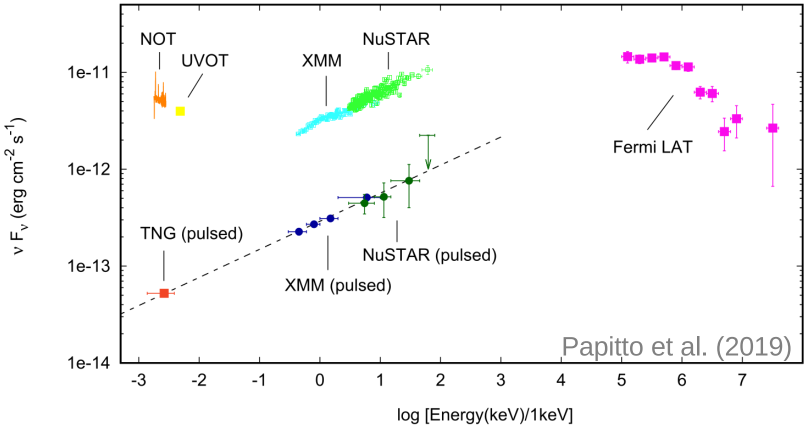


Adapted from Papitto et al. (2019)

Low mode: no pulsations

Flares:

- optical pulses
- no corresponding X-ray pulses but likely due to low photon statistics



Papitto et al. (2019)

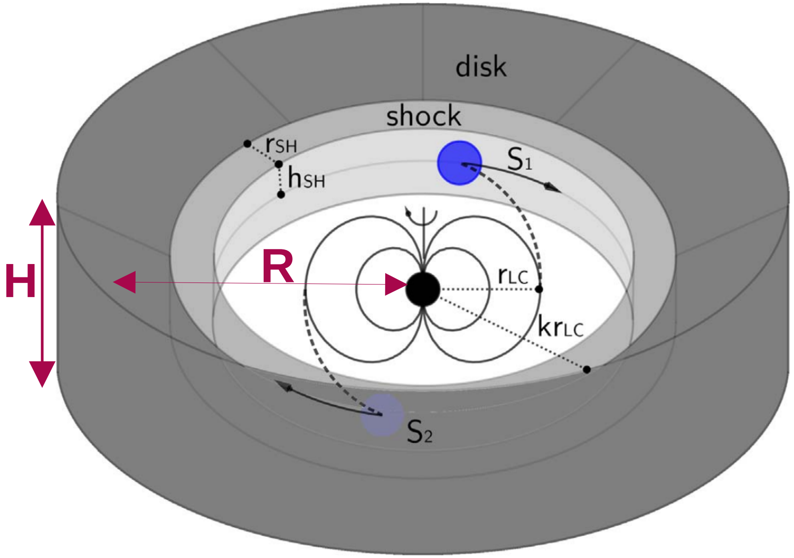
Possible models

Model proposed by *Papitto et al.(2019)*:

- **intrabinary shock** between striped pulsar wind and accretion disc, at ~ few R_{LC}
- **Fermi acceleration**
- pulses due to **synchrotron emission**

What we think may happen:

- **no shock** (high magnetization and before r_{FMS})
- disc → rearrangement of the magnetosphere
- **forced reconnection** in the current sheet at the disc surface
- enhanced particle acceleration and **synchrotron radiation**

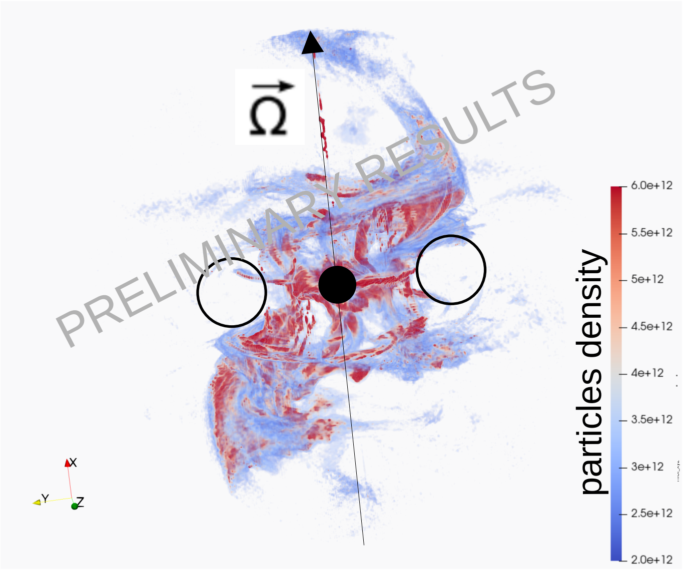


Adapted from Papitto et al. (2019)

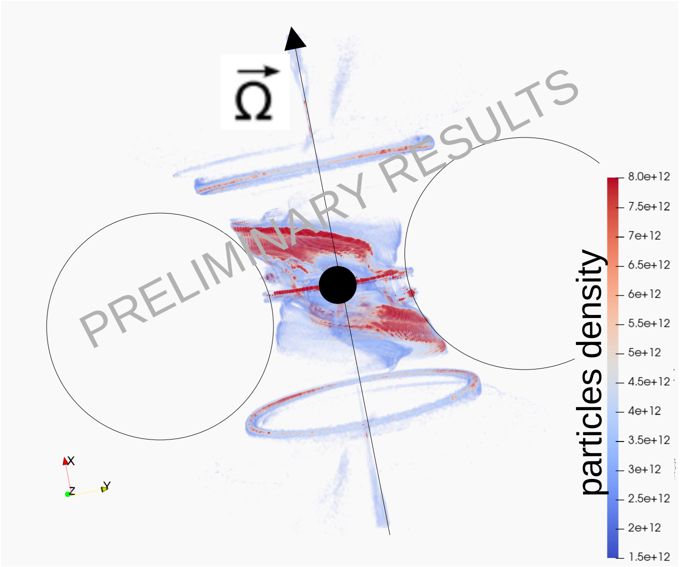
3D PIC simulations of a ms pulsar surrounded by a torus (no accretion, perfect conductor)
Run of 3 simulations for different inclinations and H/R ratios and for ~ 3 P_{spin}

First numerical experiments: 3D structure of the magnetosphere

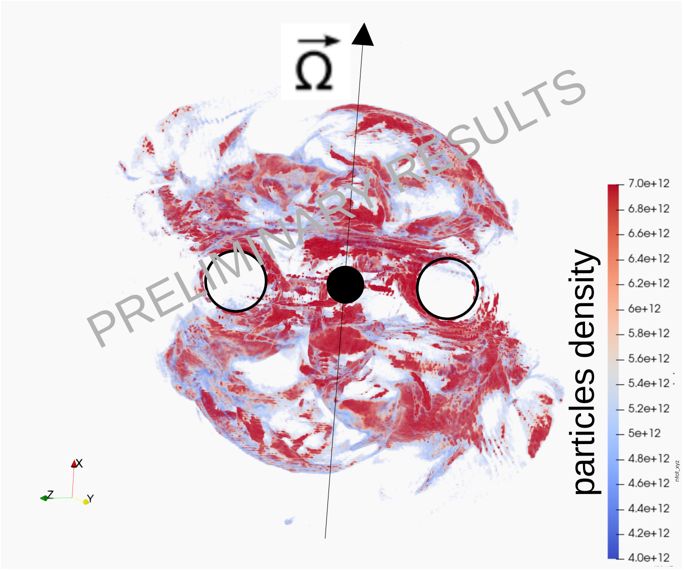
χ=15°, H/R=0.3



χ=15°, H/R=0.7



χ=75°, H/R=0.3



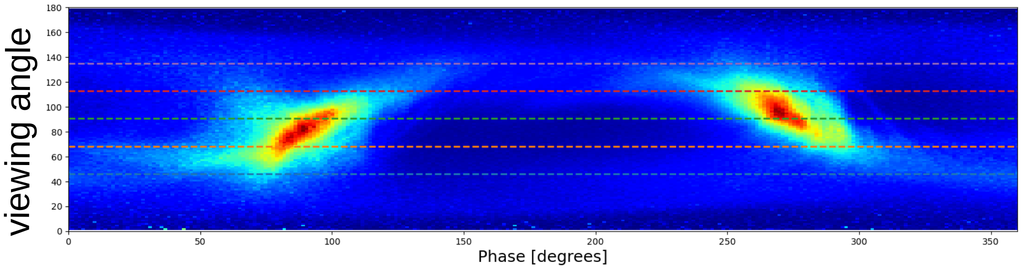
- Isotropization of the plasma
- Difficult to reach a stationary state → the solutions are still evolving

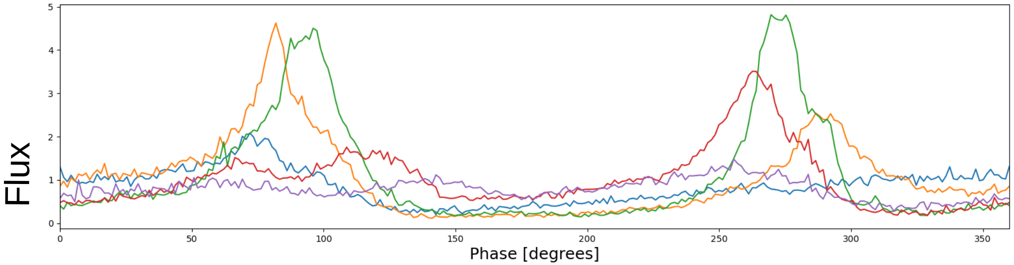
To be continued

First numerical experiments: light curves

Isolated pulsar

skymap

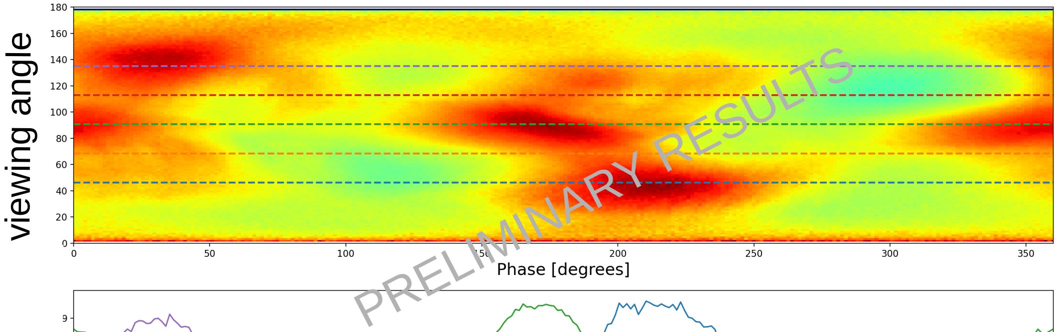


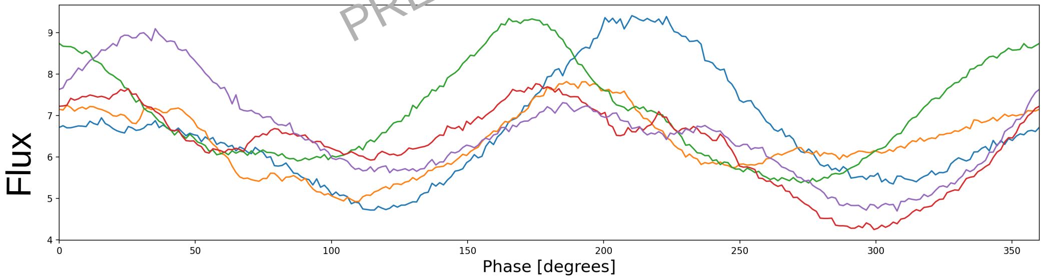


lightcurves for different viewing angles

Transition pulsar χ=15°, h/R=0.7

skymap





lightcurves for different viewing angles

- Global increase of the emitted flux
- Orbital modulation with 2 broad pulses

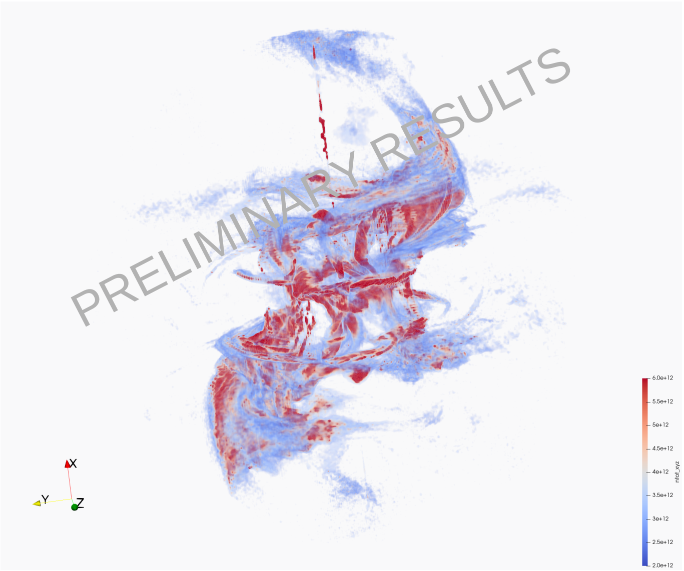
To be continued

Conclusion

Impact of the accretion disc:

- reconfiguration of the magnetosphere
- isotropization of the plasma
- increase of the synchrotron emission and broadening of the pulses

➡ promising preliminary results given the observations



⚠ The simulations are still evolving:
to be confirmed after reaching the stationary solutions

Thank you !