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

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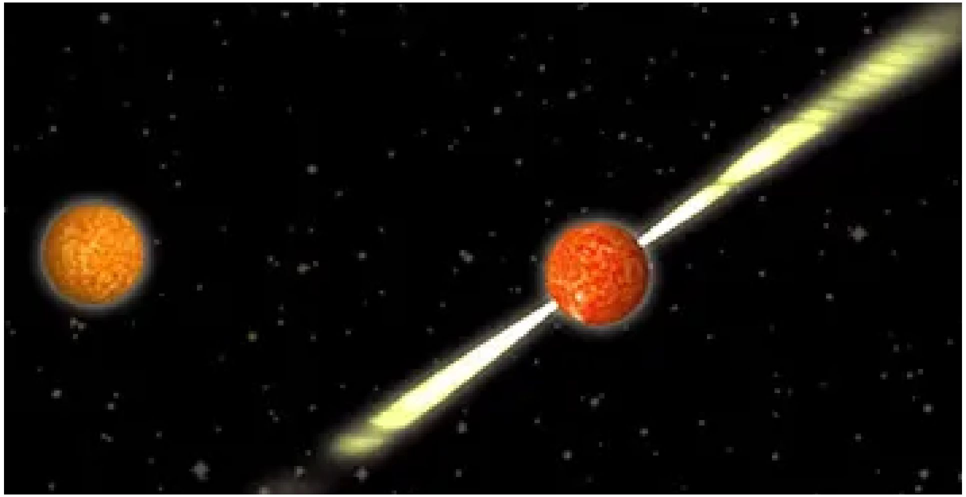

Astronomy & Astrophysics manuscript no. aa50605-24
August 16, 2024

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Received 3 May 2024 / Accepted 16 June 2024

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

Pulsar

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

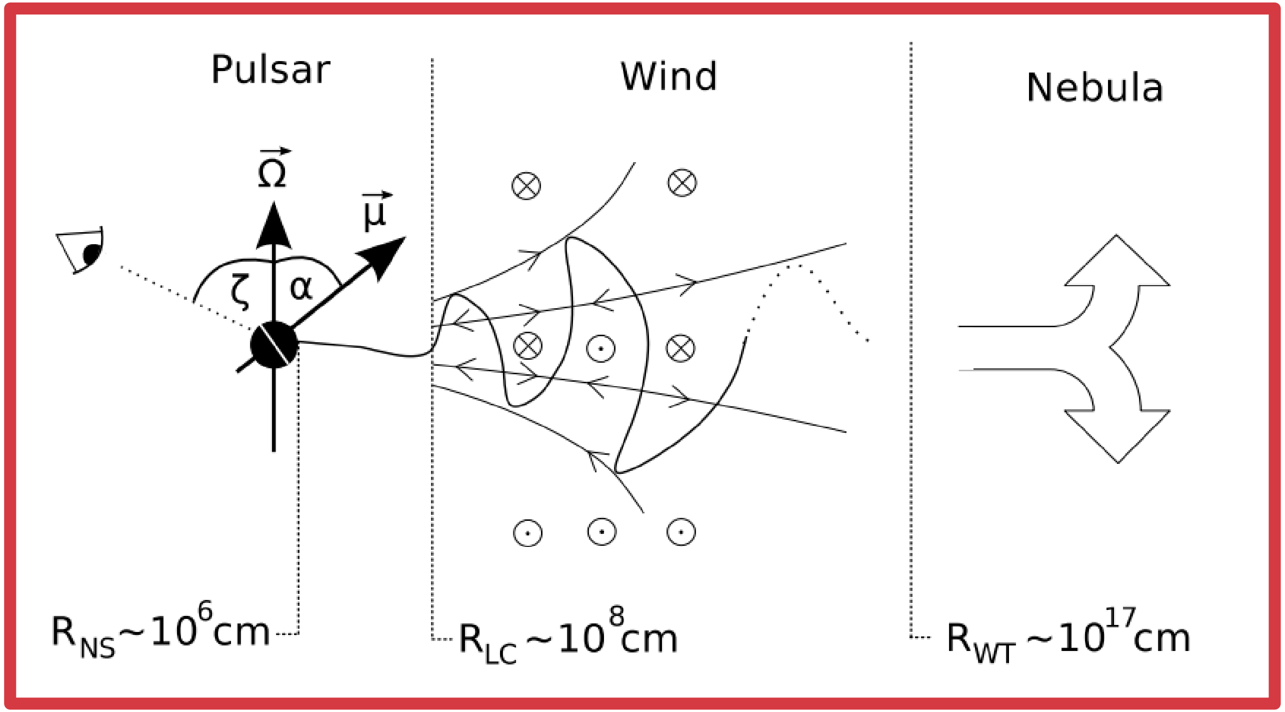
PULSAR

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



Bühler & Blandford (2014)

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 ?

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Choice of companion characteristics

Settled in the pulsar wind

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

Unmagnetized companion

Perfectly conducting companion

Pulsar-companion interaction

Many opened questions: Rearrangement of the magnetosphere ?
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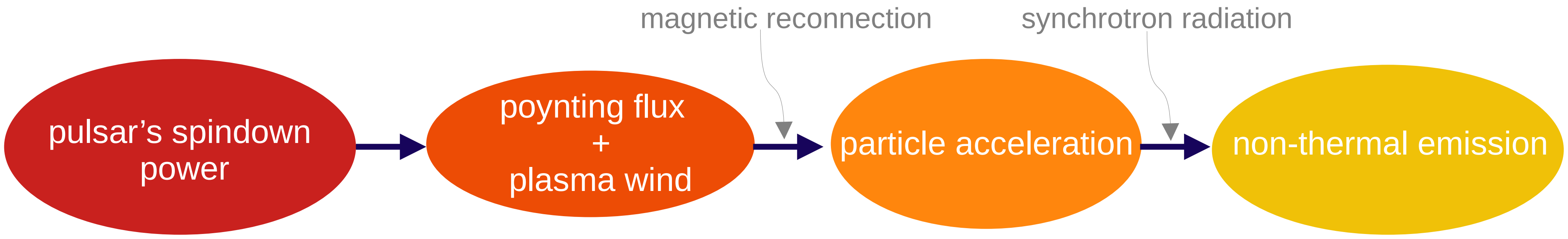
Energy transfer sequence



In order to explain the electromagnetic emissions:

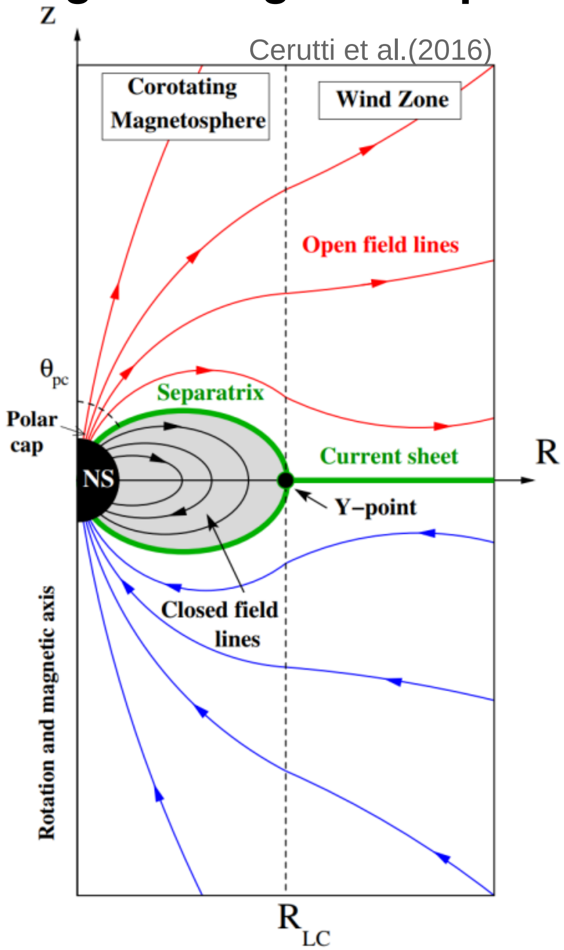
- need of global magnetospheric simulations
- need of kinetic scales for relativistic plasma

} **Global PIC simulations**

2D equatorial view

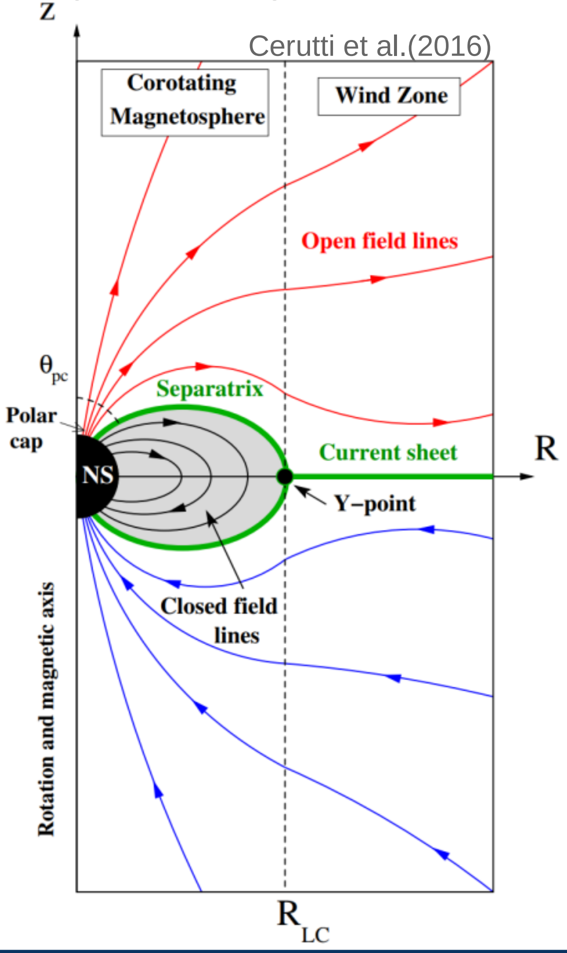
Aligned magnetic dipole

Cerutti et al.(2016)

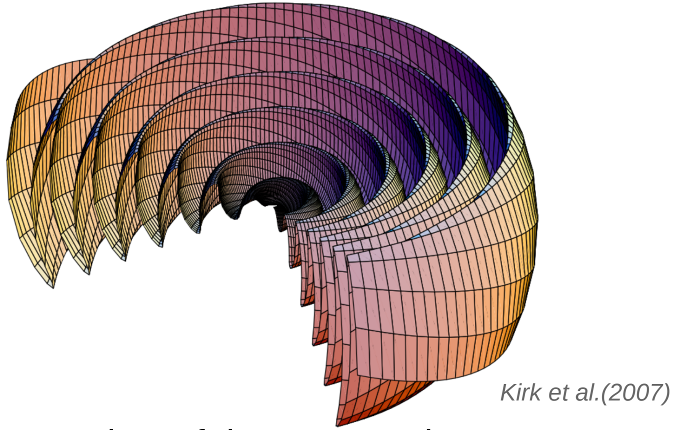


2D equatorial view

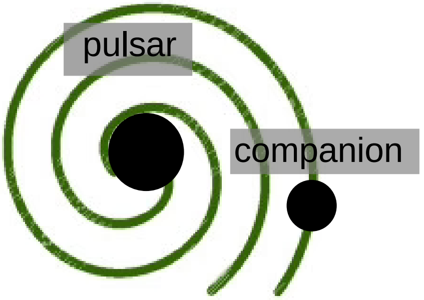
Aligned magnetic dipole



Inclined magnetic dipole



3D view of the current sheet



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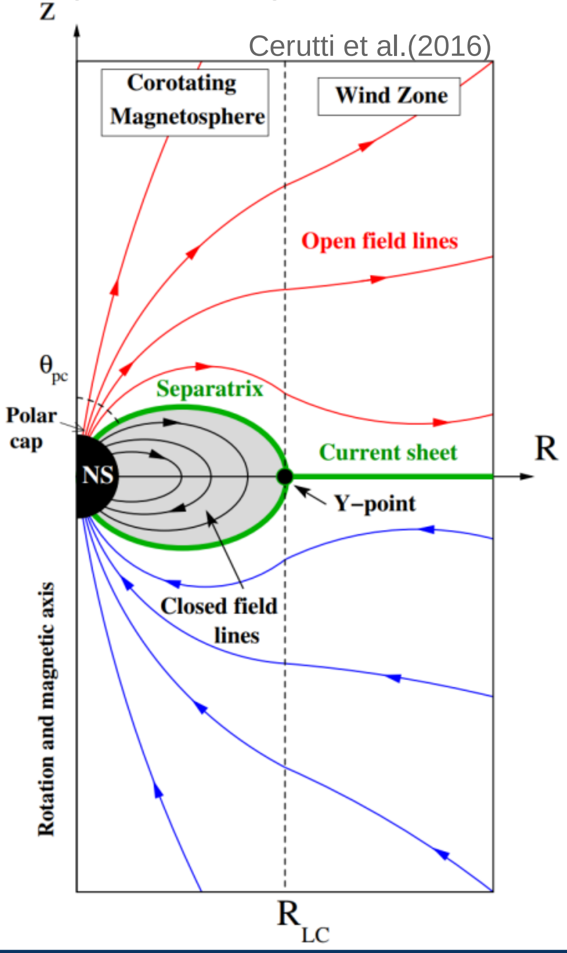

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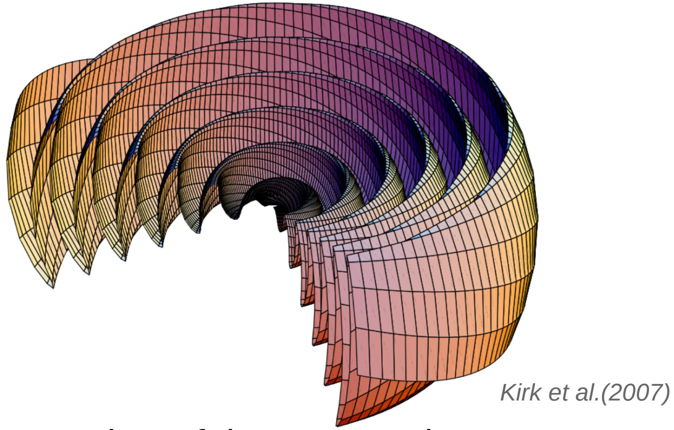
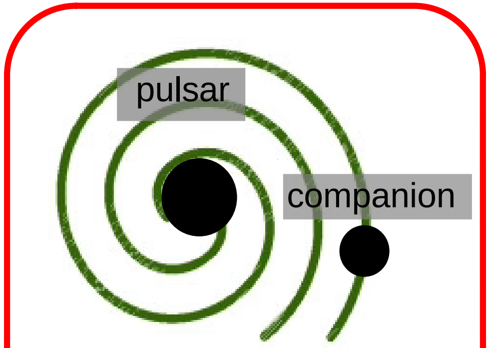
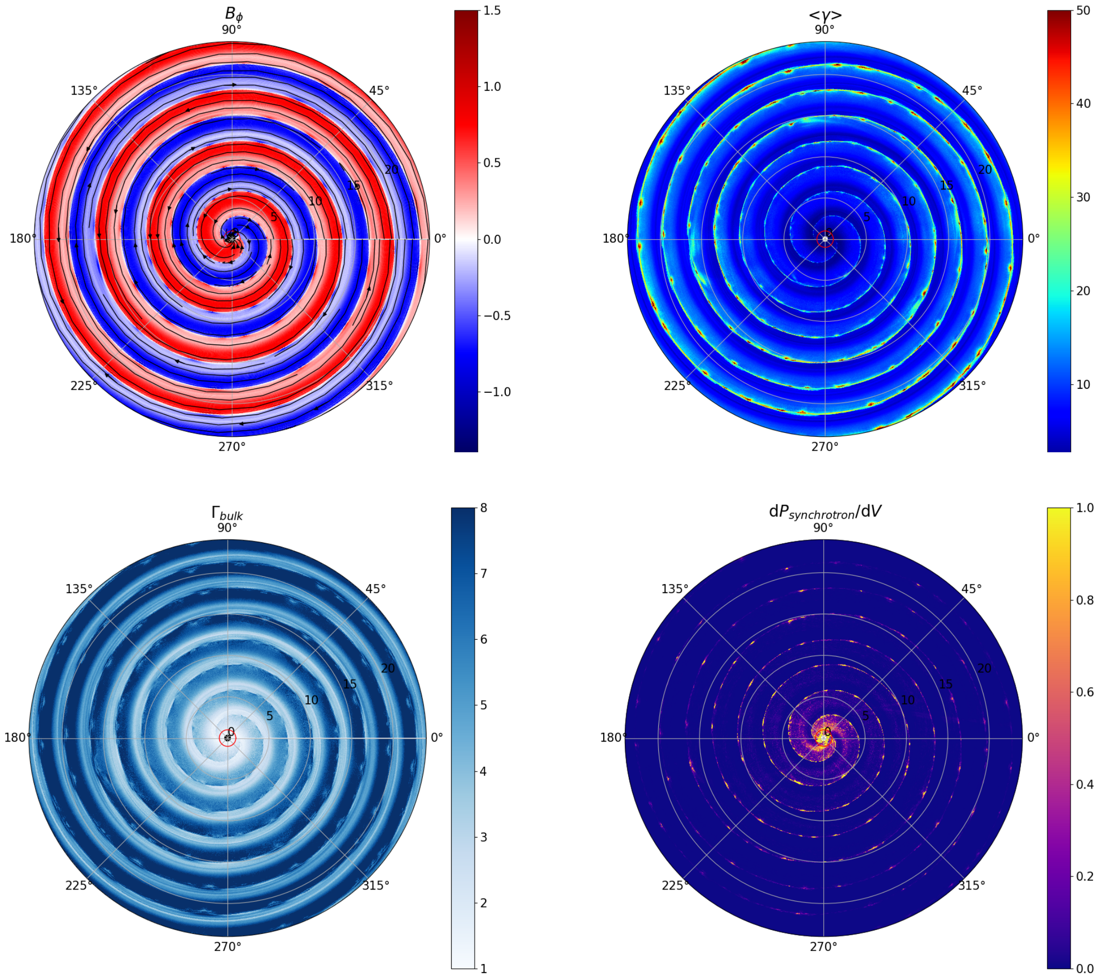


3D view of the current sheet



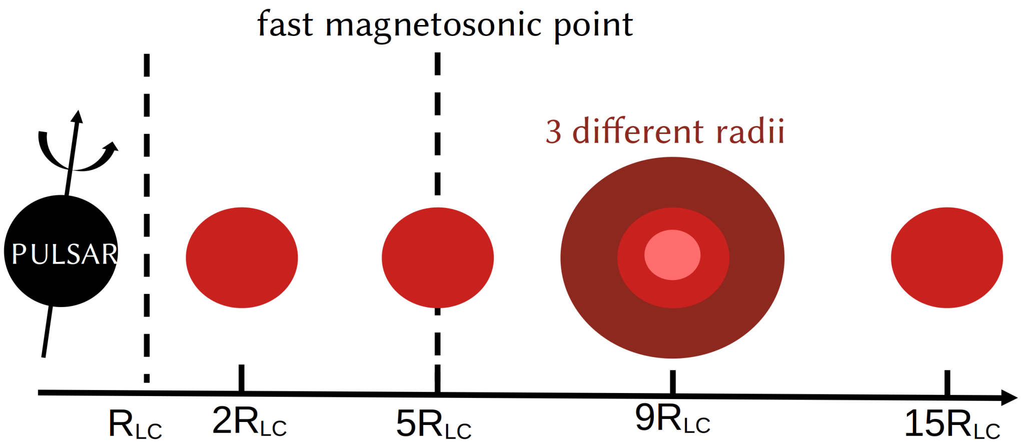
2D equatorial view

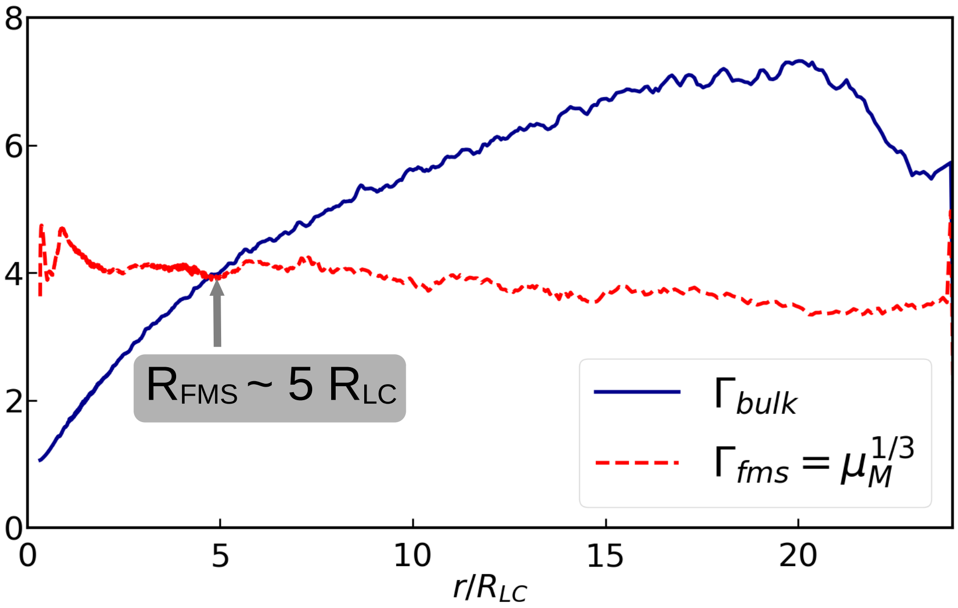
Reference case: the isolated pulsar magnetosphere



- ‘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

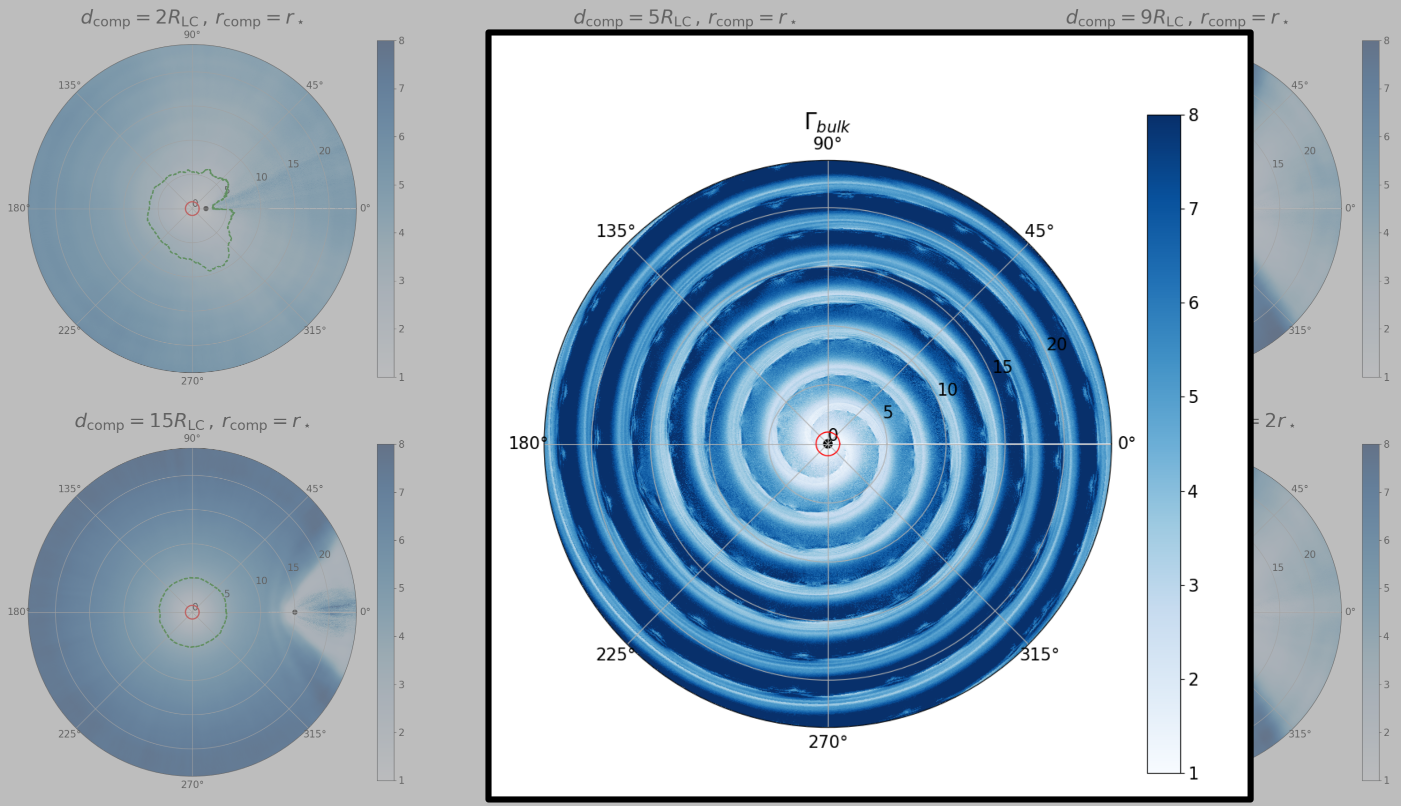




- Companion in the wind zone: $P_{orb,companion} >> P_{spin,pulsar}$
  ⟶ **companion at rest** in the simulation

- **2 different regimes** depending on the location with respect to the fast magnetosonic point

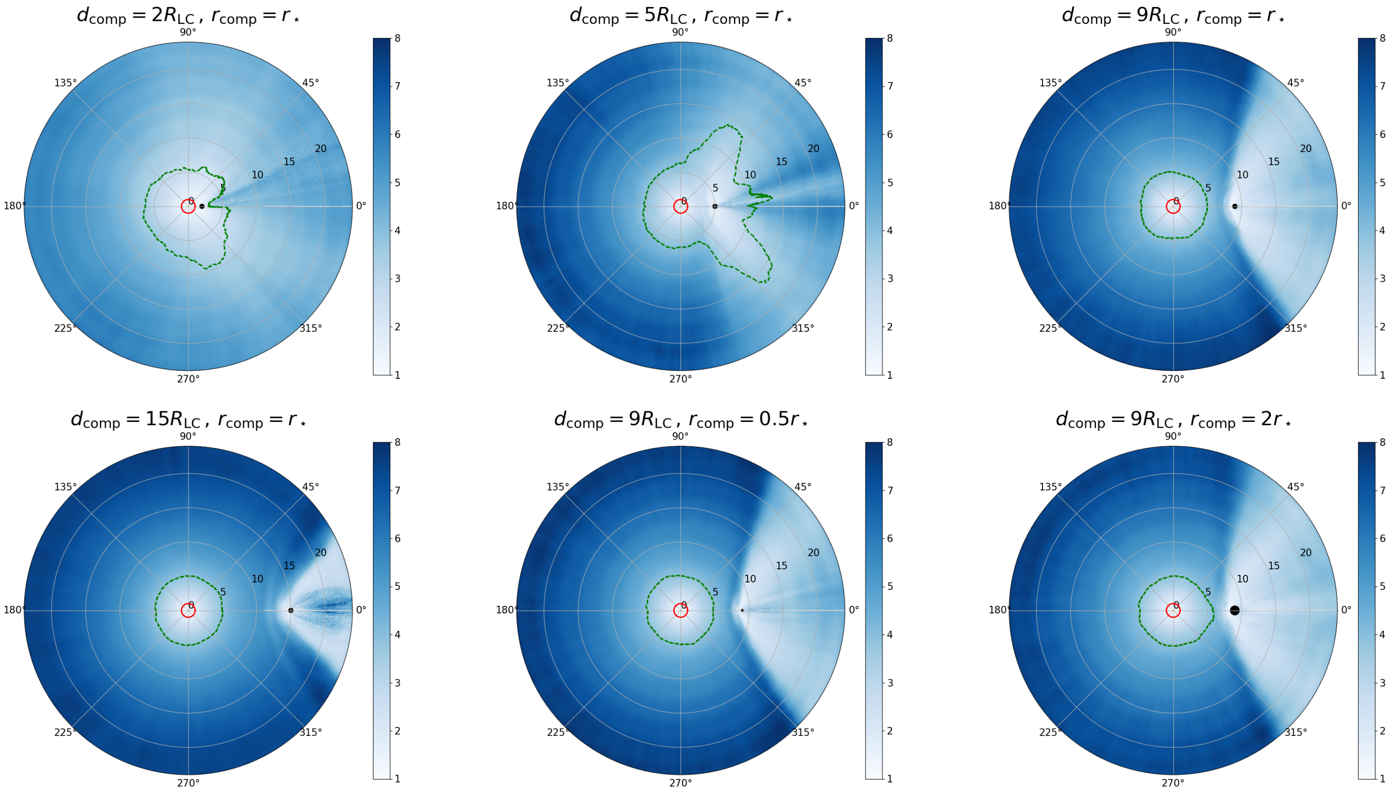
Bulk Lorentz factor averaged over several P_{spin}



- 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

Bulk Lorentz factor averaged over several P_{spin}



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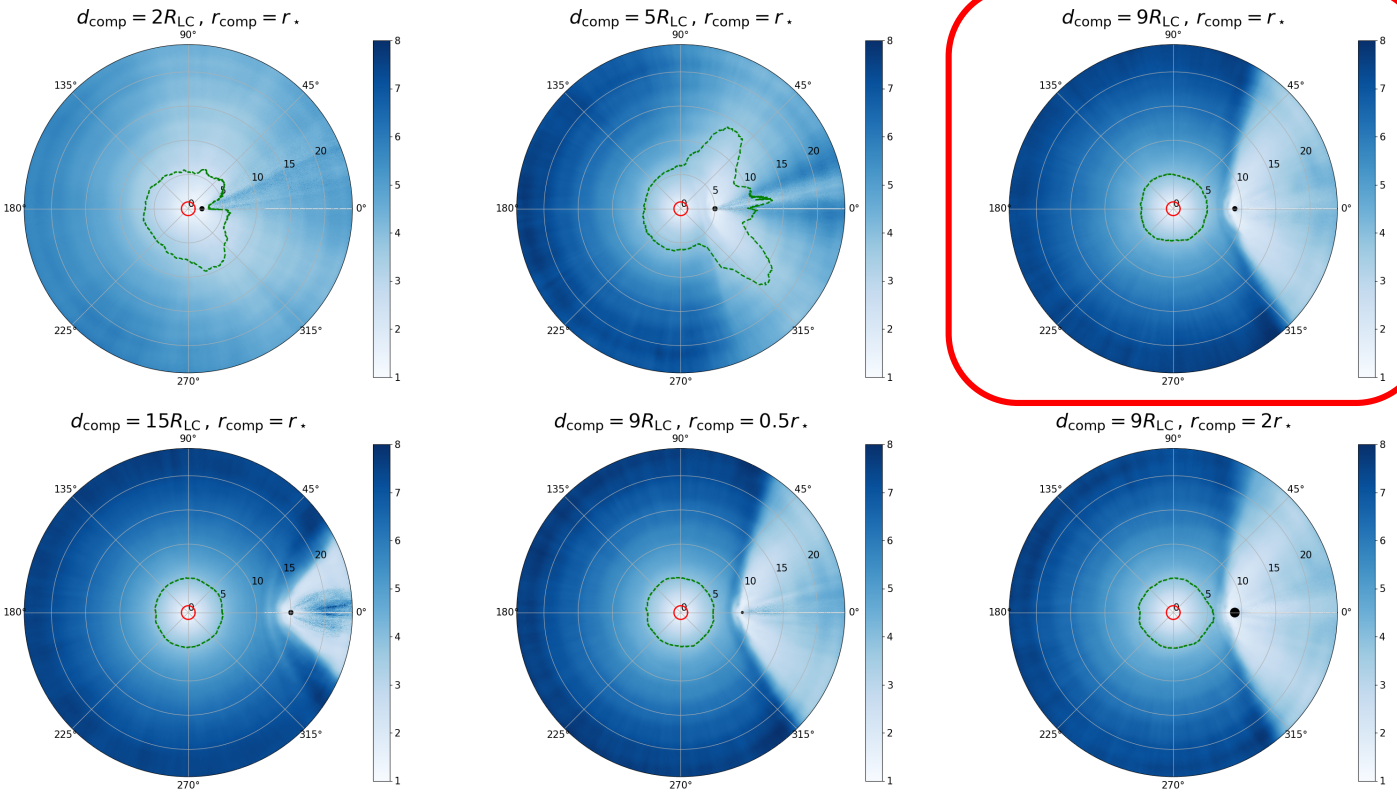

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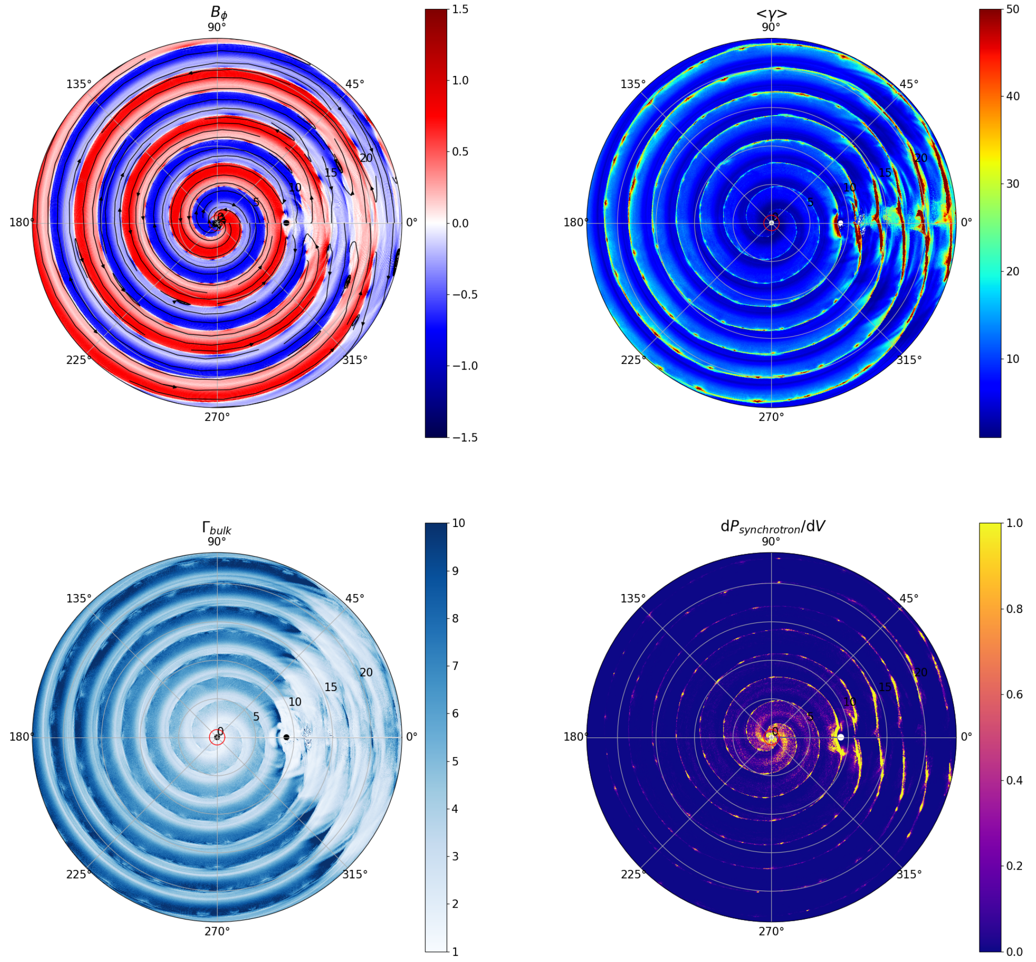
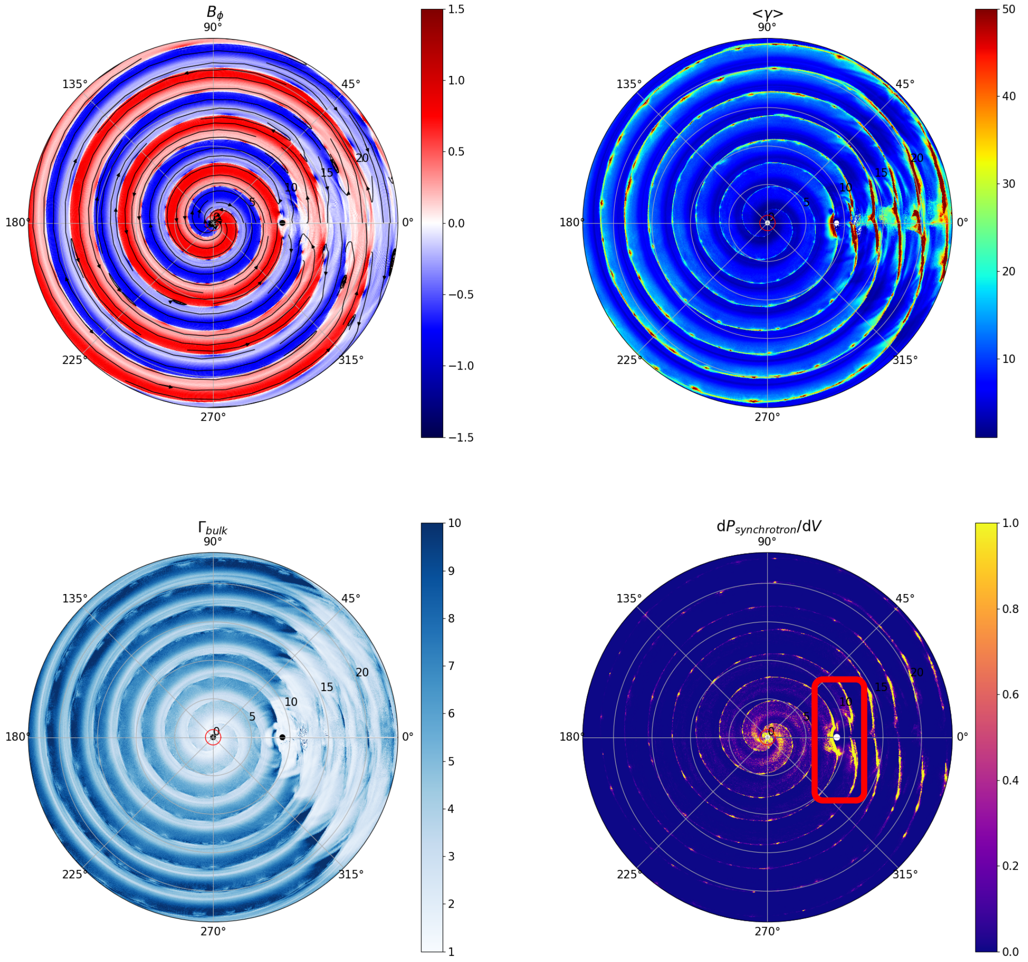
Interaction with a companion (d_{comp} = 9 R_{LC}, r_{comp} = r_{pulsar})



- **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

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



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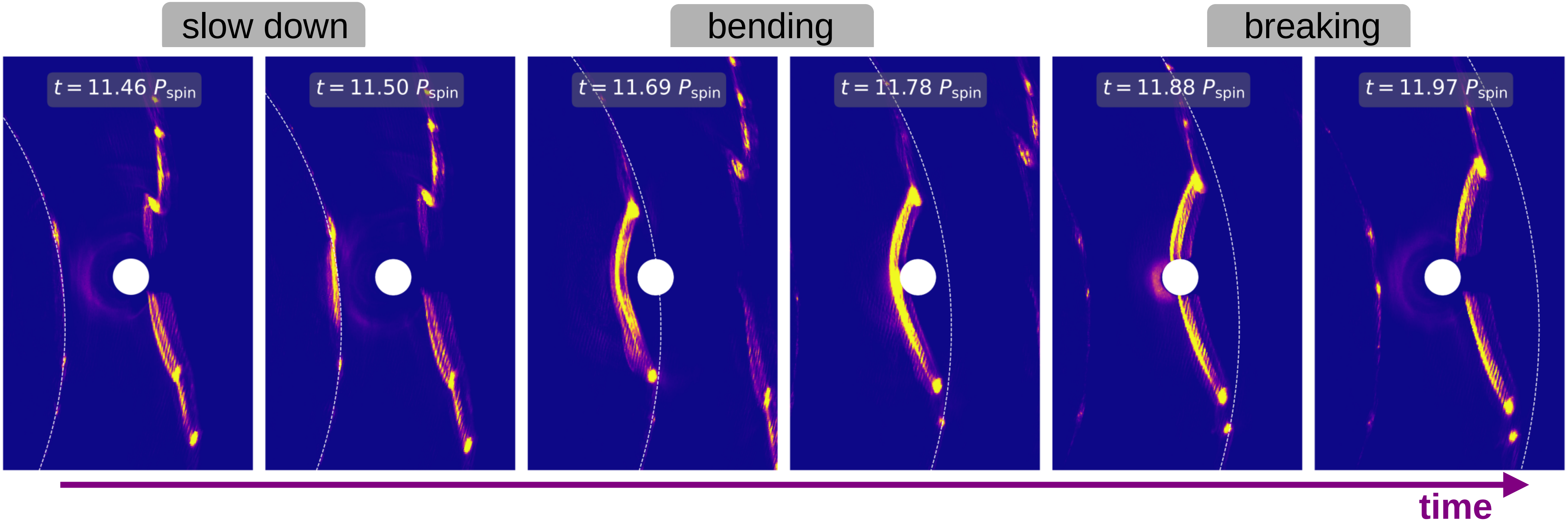
Zoom on the current sheet at the companion surface



→ magnetic field lines pile up in front of the companion

→ **forced reconnection**

→ enhanced particle acceleration

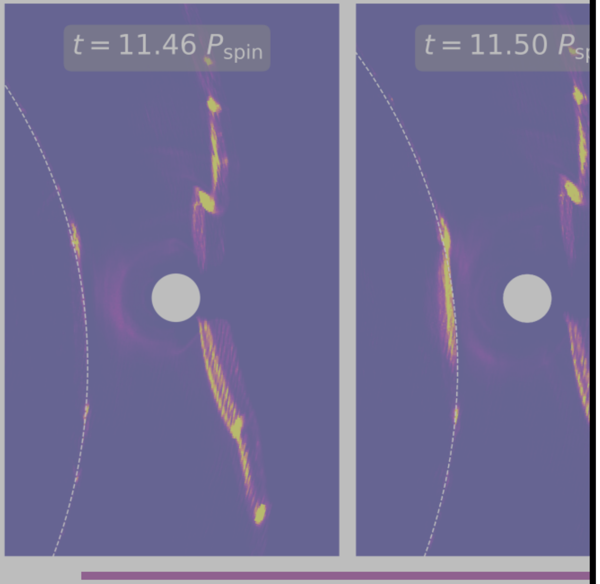
→ enhanced non-thermal radiation

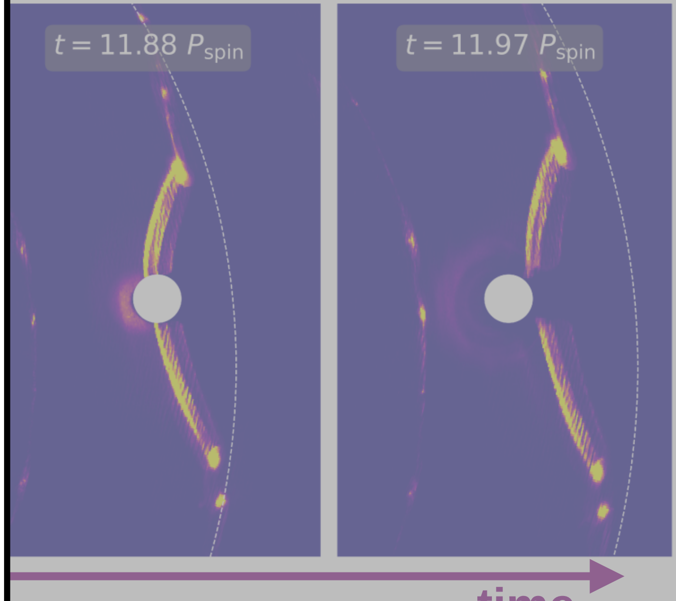
Zoom on the current sheet at the companion surface

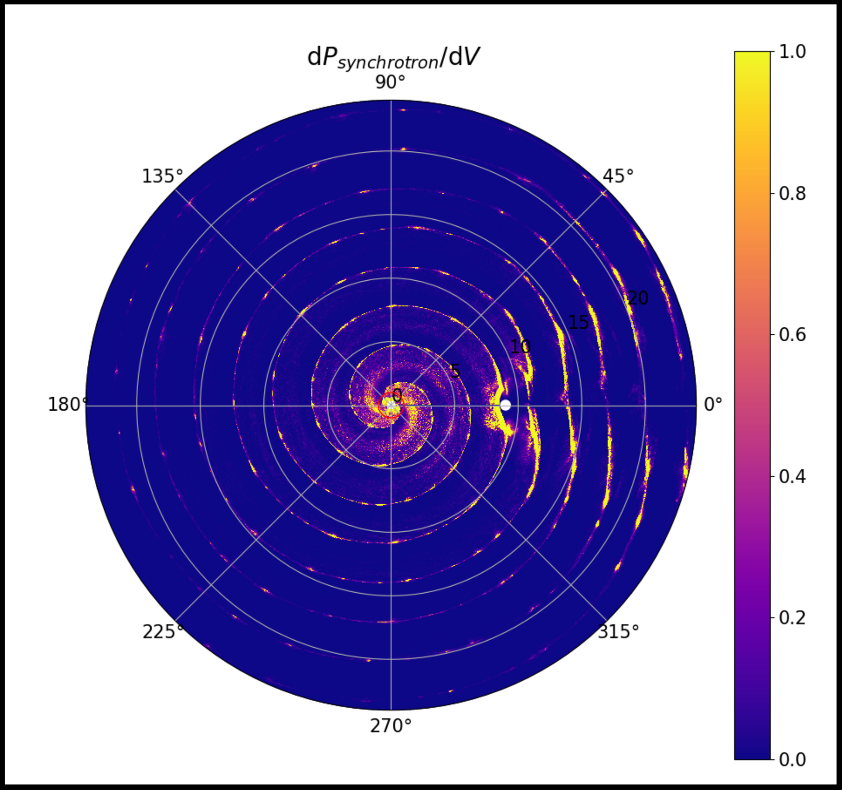
slow down

bending

breaking



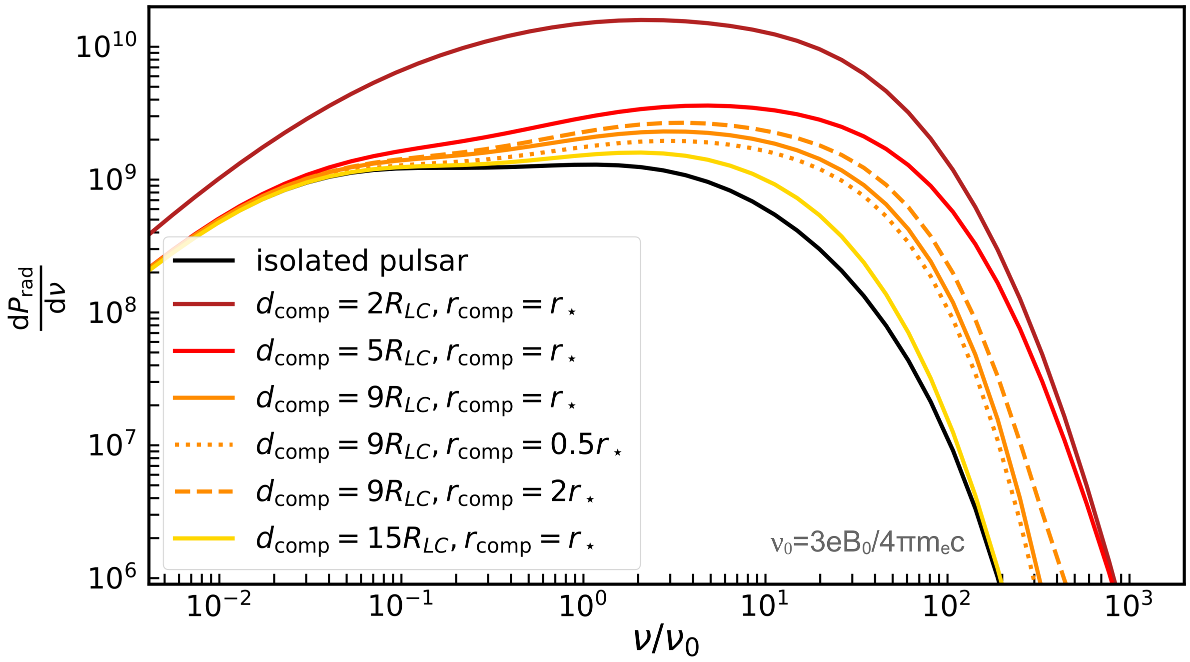




time

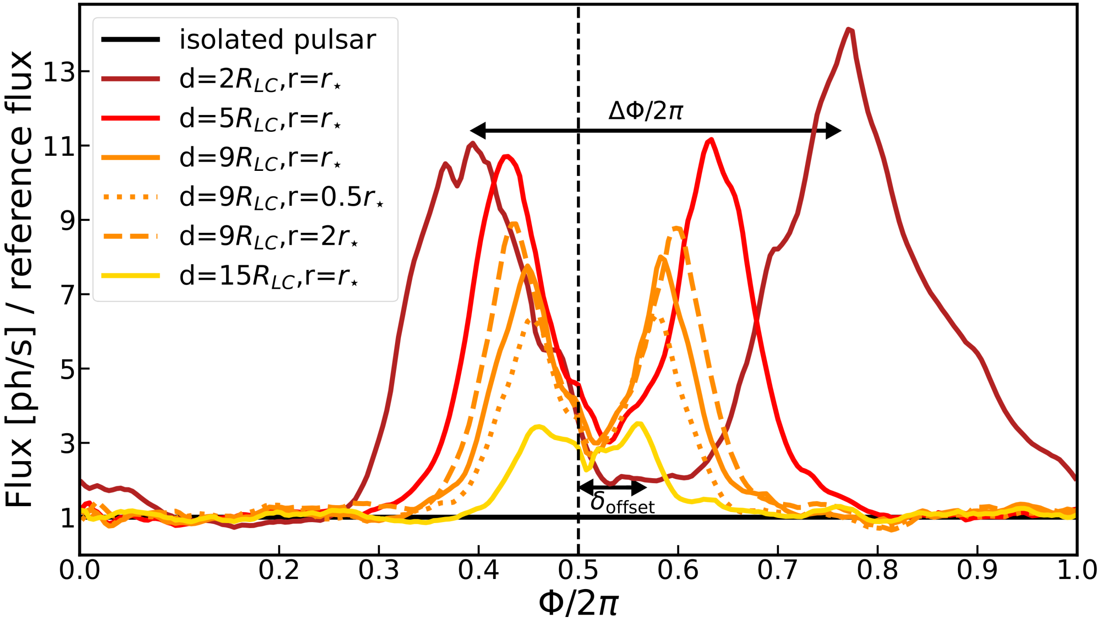
- ⟶ magneti… …nion
- ⟶ **forced r…**
- ⟶ enhanced particle acceleration
- ⟶ enhanced non-thermal radiation

High-energy spectra



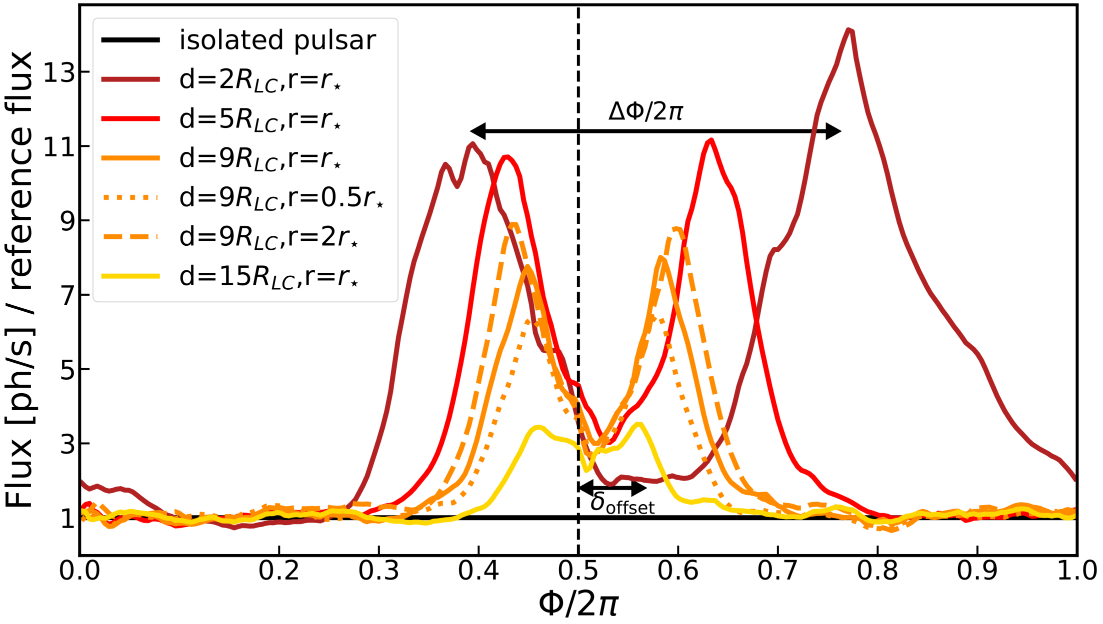
- **Significant enhancement** of the high-energy radiation compared to the isolated pulsar
- Emission **decreases with d_{comp}** and **increases with r_{comp}**

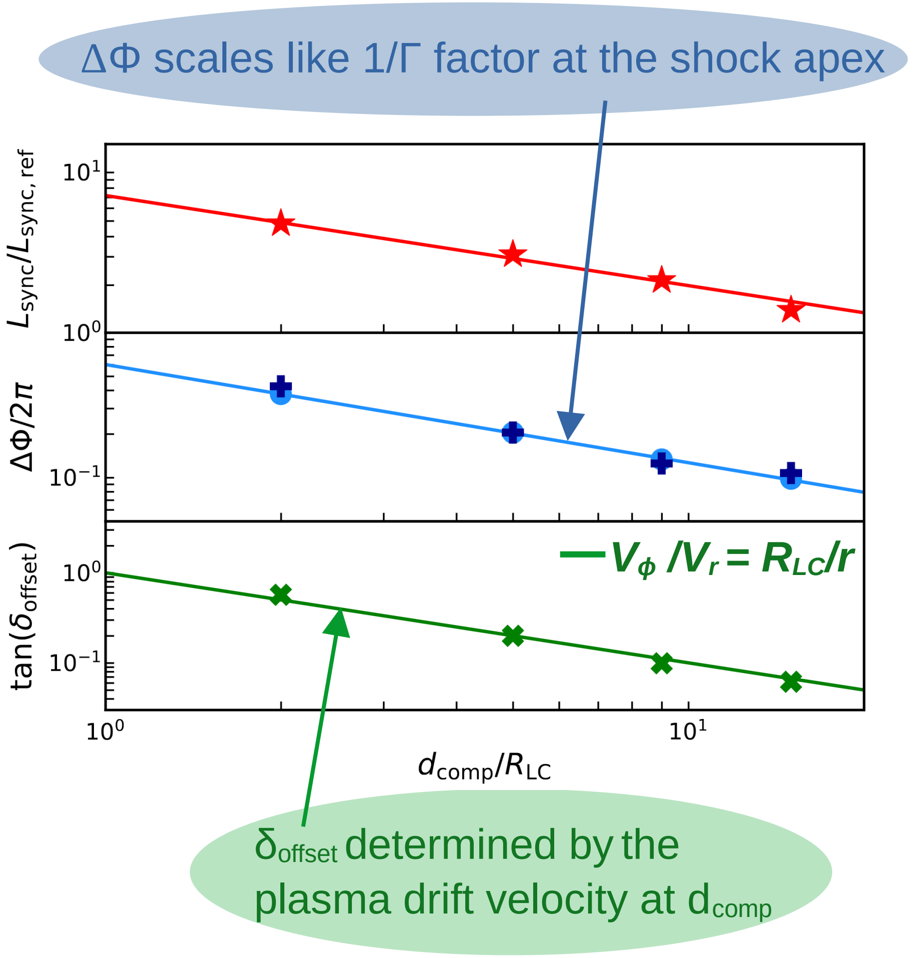
High-energy light curves



- **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 $\Delta\Phi$

High-energy light curves





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

Conclusion

When adding a companion in the pulsar wind:

- Significant alteration of the dynamical and energetic properties of the pulsar wind
- Forced reconnection → enhanced particle acceleration → enhanced non-thermal radiation
  → orbital-modulated hollow cone of light
- Transients should be observable on galactic distances (soft γ-ray band)

What about radio counterparts ?

- from plasmoid mergers (Lyubarsky, 2019; Philippov et al., 2019)
- fast radio bursts (Mottez, Zarka, Voisin, 2020; Decoene, 2021)

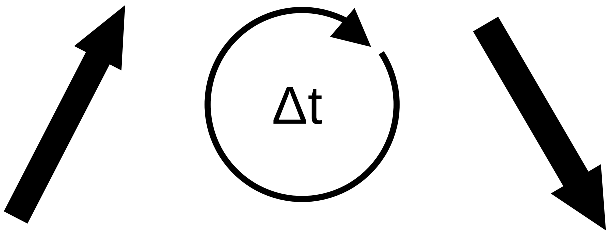
➡ **Recently discovered galactic long-period radio transients**
(Hurley-Walker et al. 2022,2023; Rea et al, 2022,2024)

Backup slides

Particle-in-cell (PIC) simulations

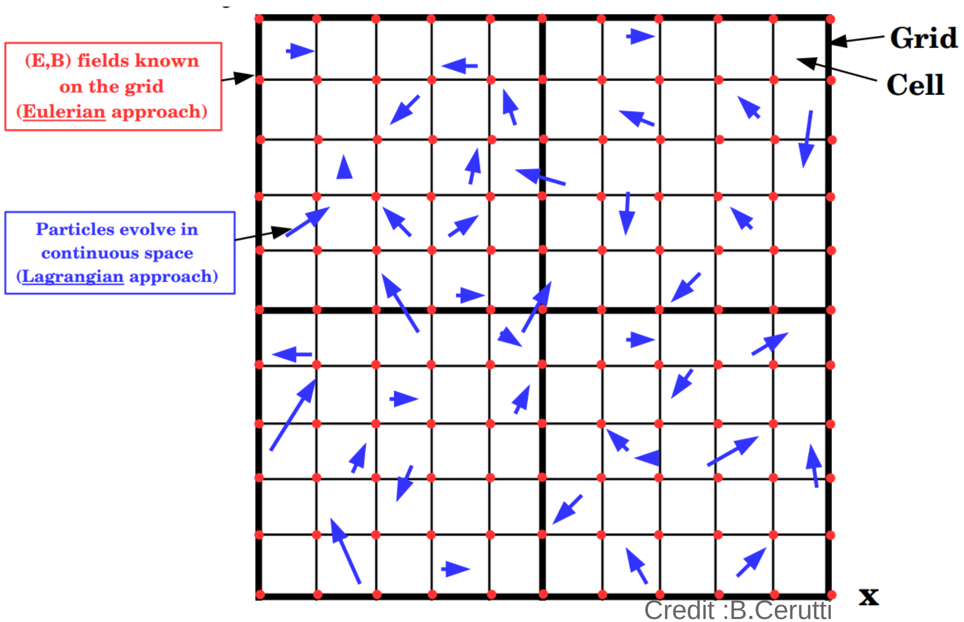
Solve Abraham-Lorentz-Dirac equation

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



Solve Maxwell equations

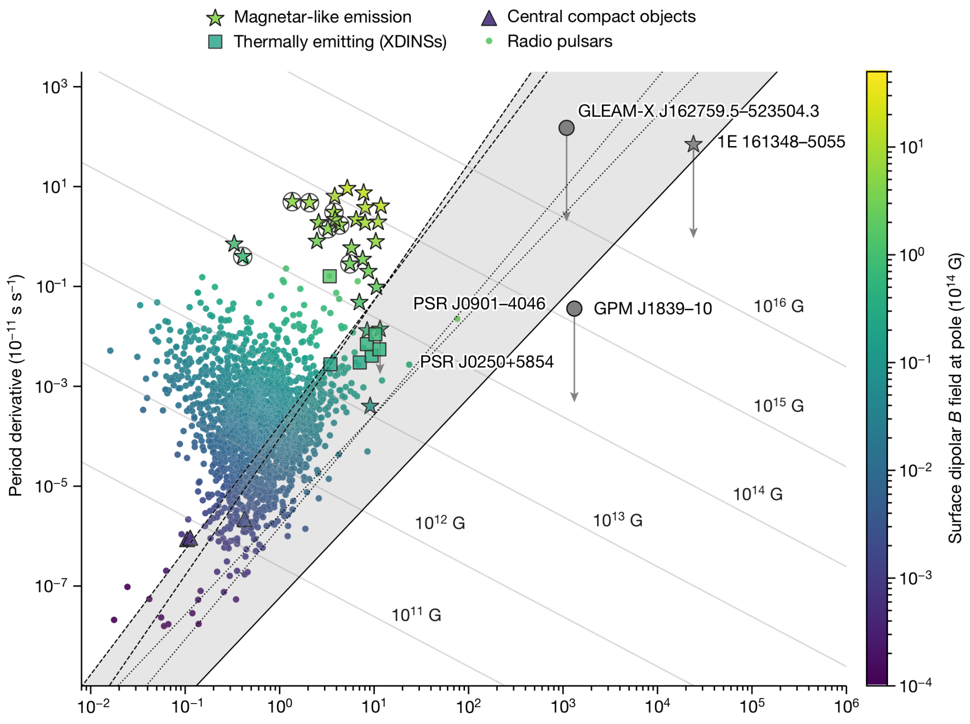
Deposit charge and current densities



Credit :B.Cerutti

Long-period radio transients

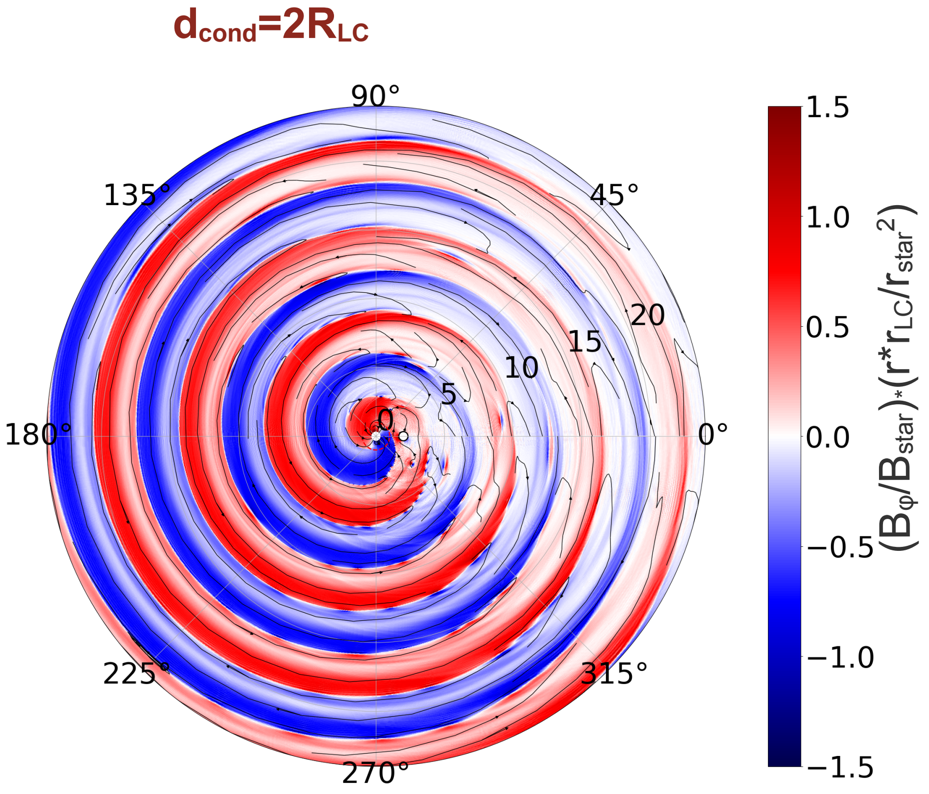
Several discoveries of long-period (10-1000s) radio transients → which phenomenon ? / which object ?



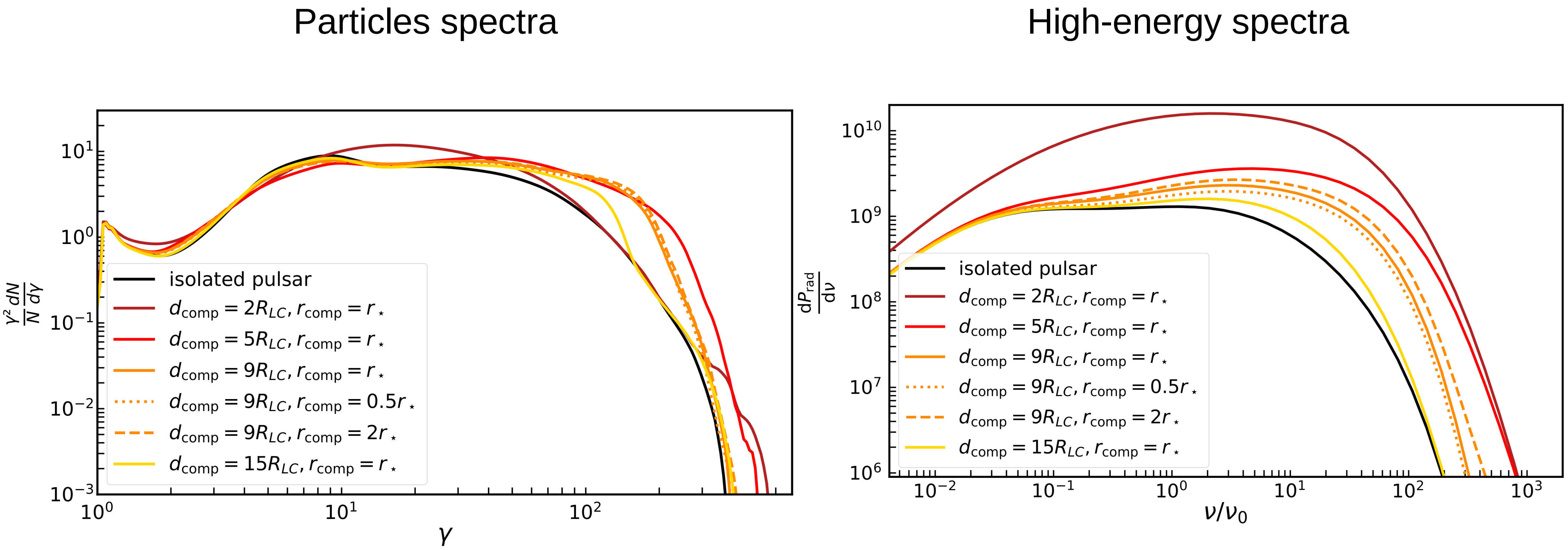
Hurley-Walker et al.(2023)

Considered interpretations:

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



d_{cond}=2R_{LC}
d_{cond}=9R_{LC}
90°
45°
0°
315°
270°
225°
180°
135°
0
5
10
15
20
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
$(B_\varphi/B_{star})*(r*r_{LC}/r_{star}^2)$


Particles spectra
High-energy spectra
$\frac{\gamma^2}{N}\frac{dN}{d\gamma}$
γ
$\frac{dP_{\rm rad}}{d\nu}$
ν/ν_0
isolated pulsar
$d_{\rm comp} = 2R_{LC}, r_{\rm comp} = r_\star$
$d_{\rm comp} = 5R_{LC}, r_{\rm comp} = r_\star$
$d_{\rm comp} = 9R_{LC}, r_{\rm comp} = r_\star$
$d_{\rm comp} = 9R_{LC}, r_{\rm comp} = 0.5r_\star$
$d_{\rm comp} = 9R_{LC}, r_{\rm comp} = 2r_\star$
$d_{\rm comp} = 15R_{LC}, r_{\rm comp} = r_\star$

Simulation parameters

$\delta_{cs} < r_{comp} < \pi R_{LC}$

$\delta_{cs} / r_{comp} \sim 0.15$ (run D2R1) to 0.9 (run D9R05)

$\sigma_{star} = 250$, $\sigma_{LC} \sim 60$

$\kappa_{star} = n_{star} / n_{GJ} = 10$, where n_{star} is the density injected at the surface of the star

$(d_e / \Delta r)_{LC} \sim 10$ at $r = R_{LC}$

r_L at $r_{LC} \sim 1$ cell in the wind and ~70 cells inside the current sheet

Parameter	Value
Number of cells	$4096\,(r) \times 4096\,(\phi)$
Inner boundary	$r_\star$
R_{LC}	$3\ r_\star$
r_{absorb}	$24\ R_{LC}$
$(d_e/\Delta r)_{LC}$	16.2
σ_{LC}	60
$P_{spin}/\Delta t$	4.3×10^4
r_{fms}	$5.1\ R_{LC}$
Γ_{fms}	3.9
$d_e^\star / r_\star$	1.8×10^{-3}
Plasma composition	Electrons and positrons
Injection model	from the star surface