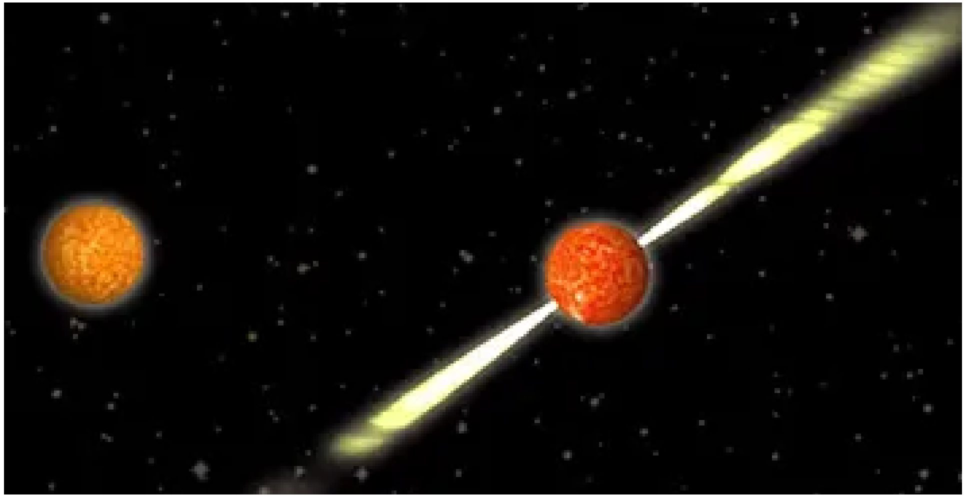
Enhanced high-energy emission in a pulsar wind interacting with a companion

Valentina Richard-Romei, Benoît Cerutti

IPAG, Université Grenoble Alpes, France
valentina.richard-romei@univ-grenoble-alpes.fr



*Richard-Romei & Cerutti,2024,*A&A
arXiv:2406.18663

Pulsar

PULSAR

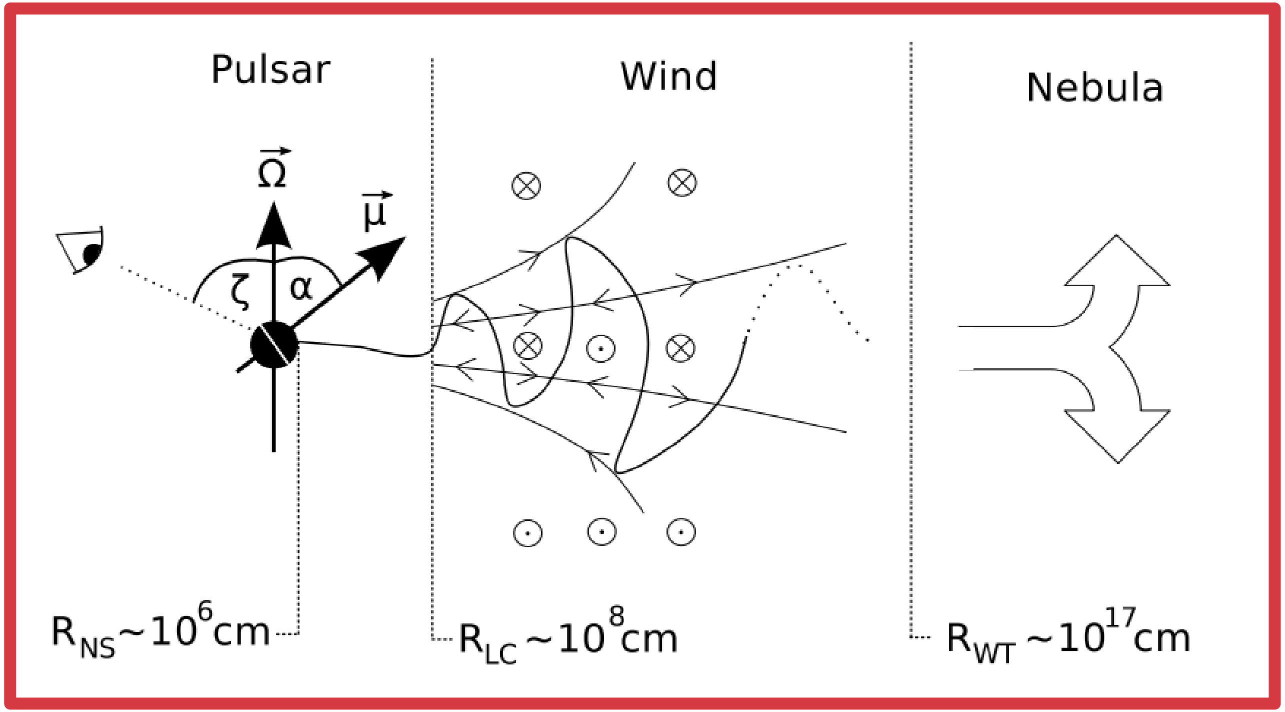
Fast spinning & magnetised neutron star

- 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-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 ?

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

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

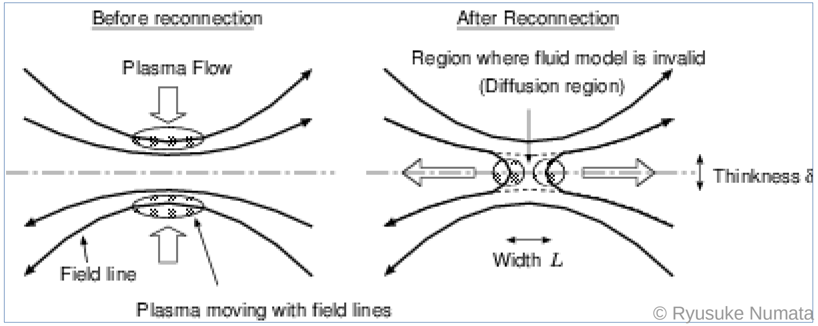
Settled in the pulsar wind

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

Unmagnetized companion

Perfectly conducting companion

Energy transfer sequence



magnetic reconnection

synchrotron radiation

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

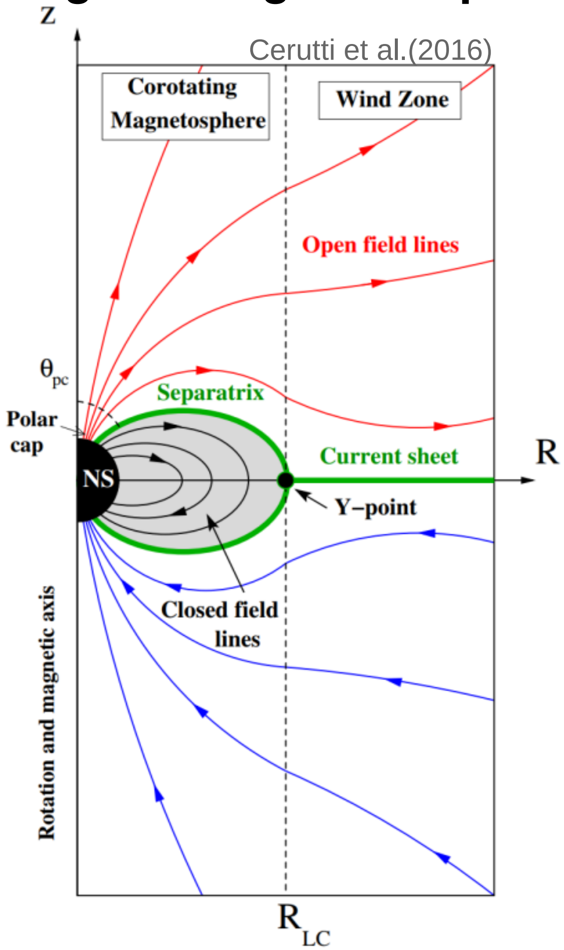
In order to explain the electromagnetic emissions:

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

} Global PIC simulations

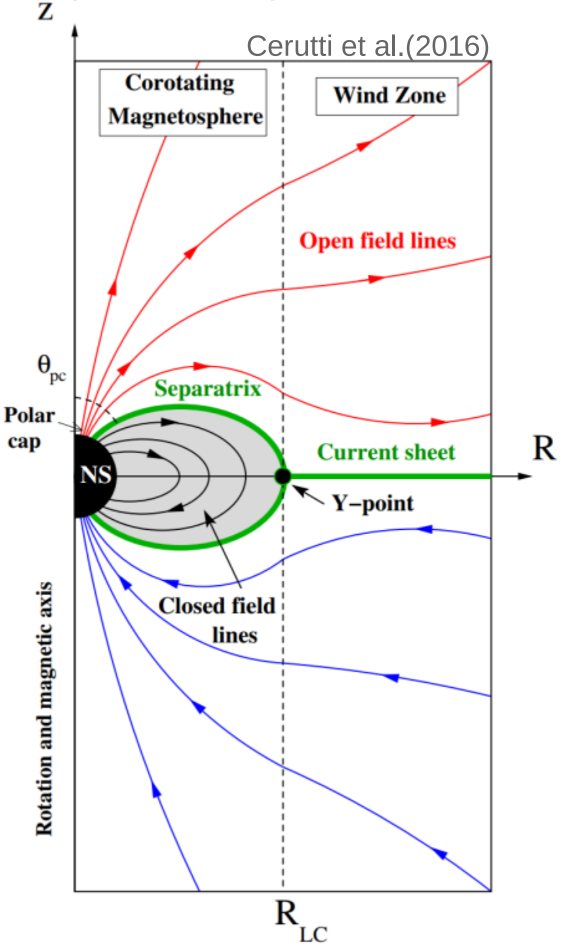
2D equatorial view

Aligned magnetic dipole

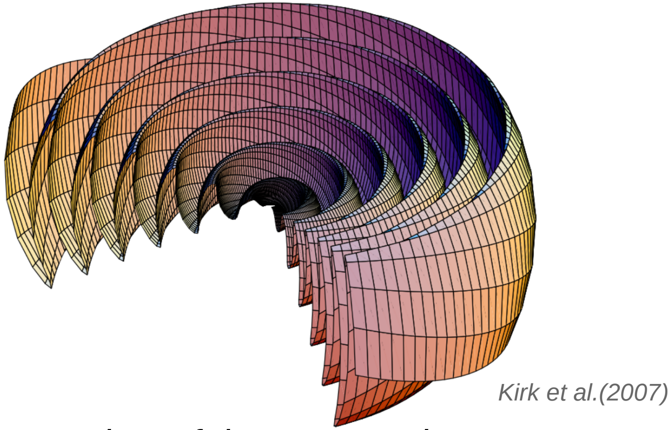


2D equatorial view

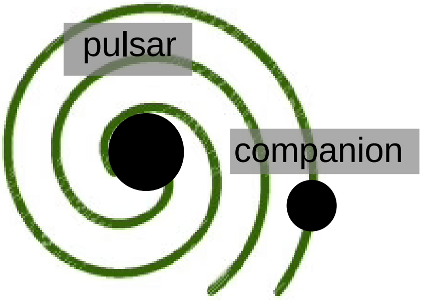
Aligned magnetic dipole



Inclined magnetic dipole



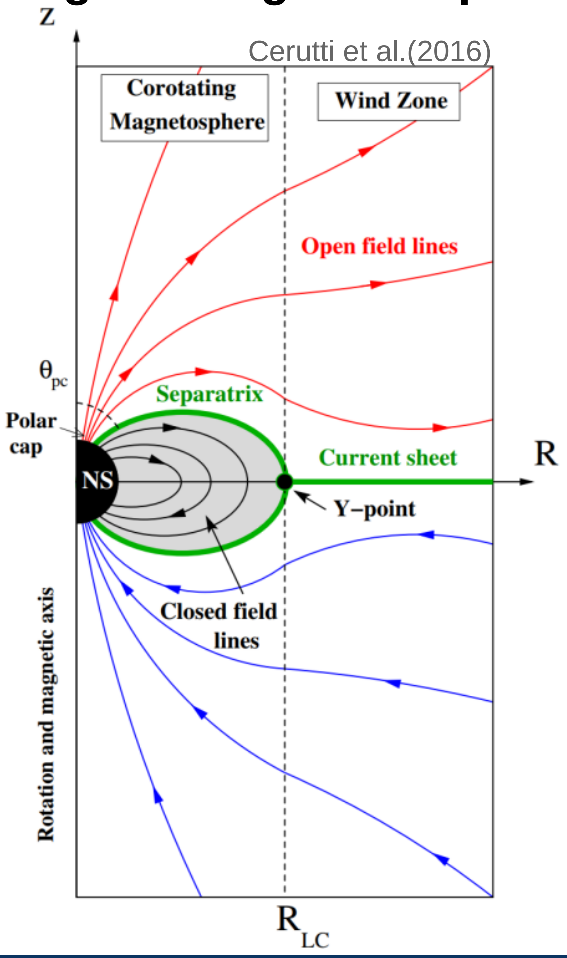
3D view of the current sheet



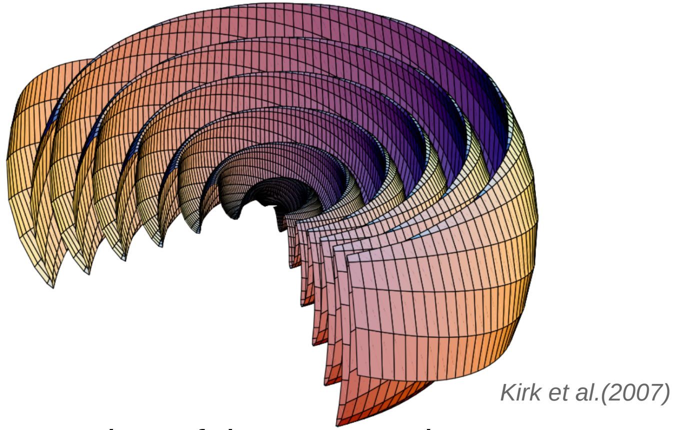
2D equatorial view

2D equatorial view

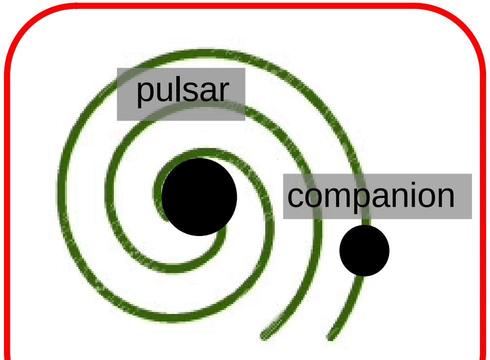
Aligned magnetic dipole



Inclined magnetic dipole

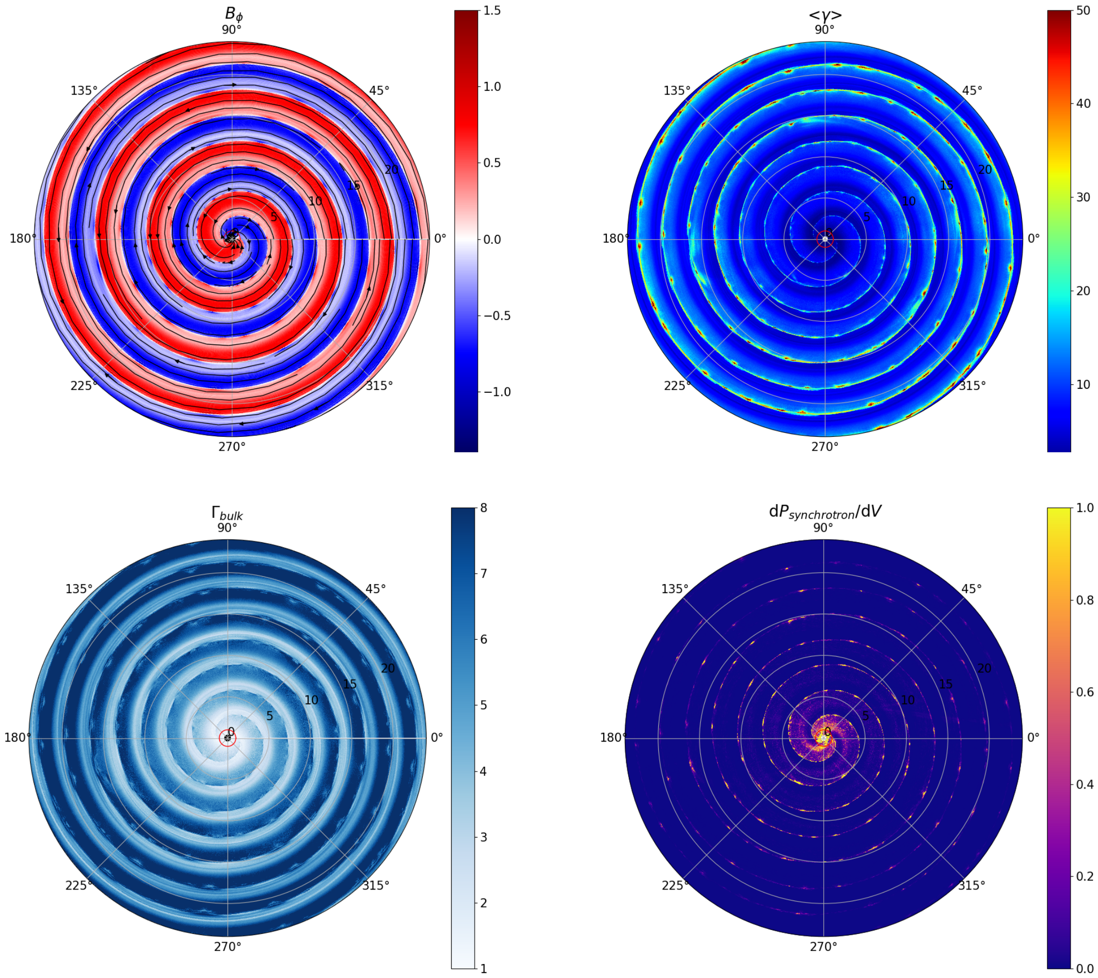


3D view of the current sheet



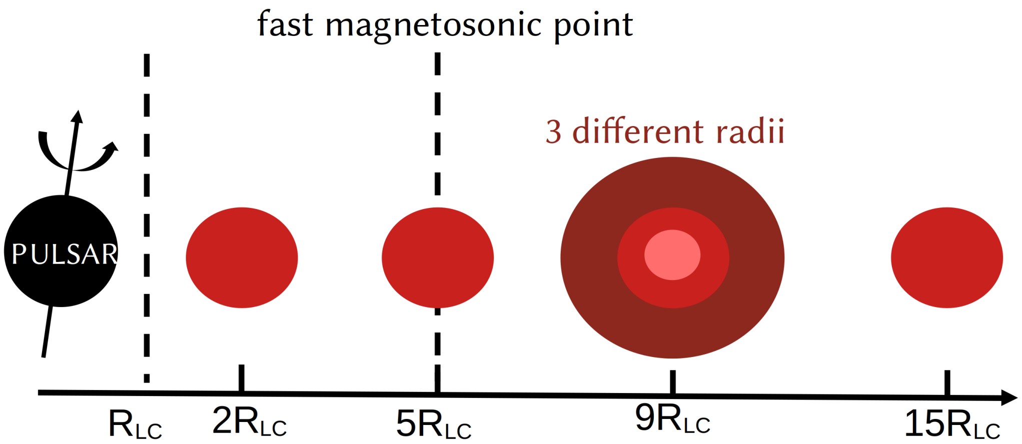
2D equatorial view

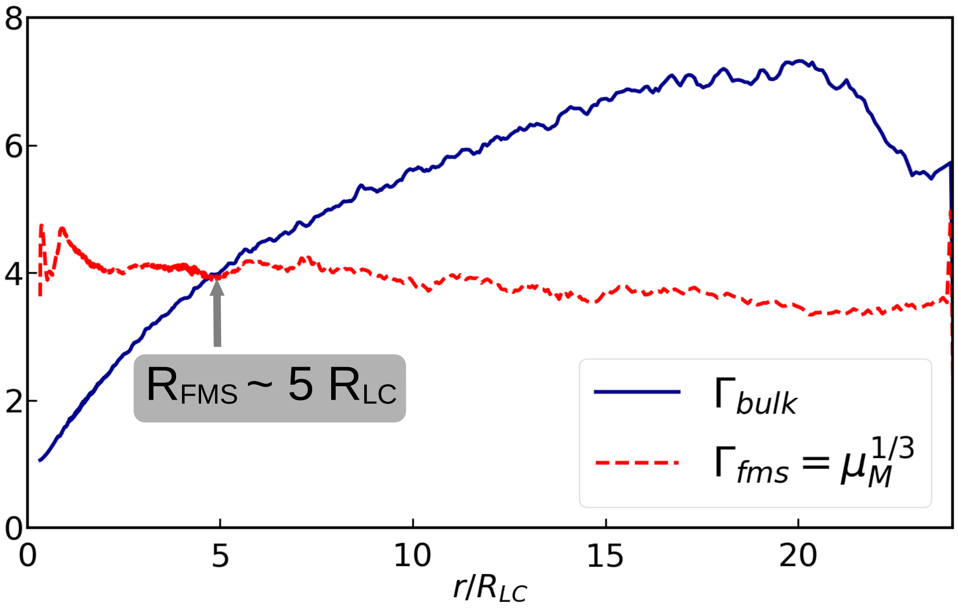
Reference case: the isolated pulsar magnetosphere



- ‘striped 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

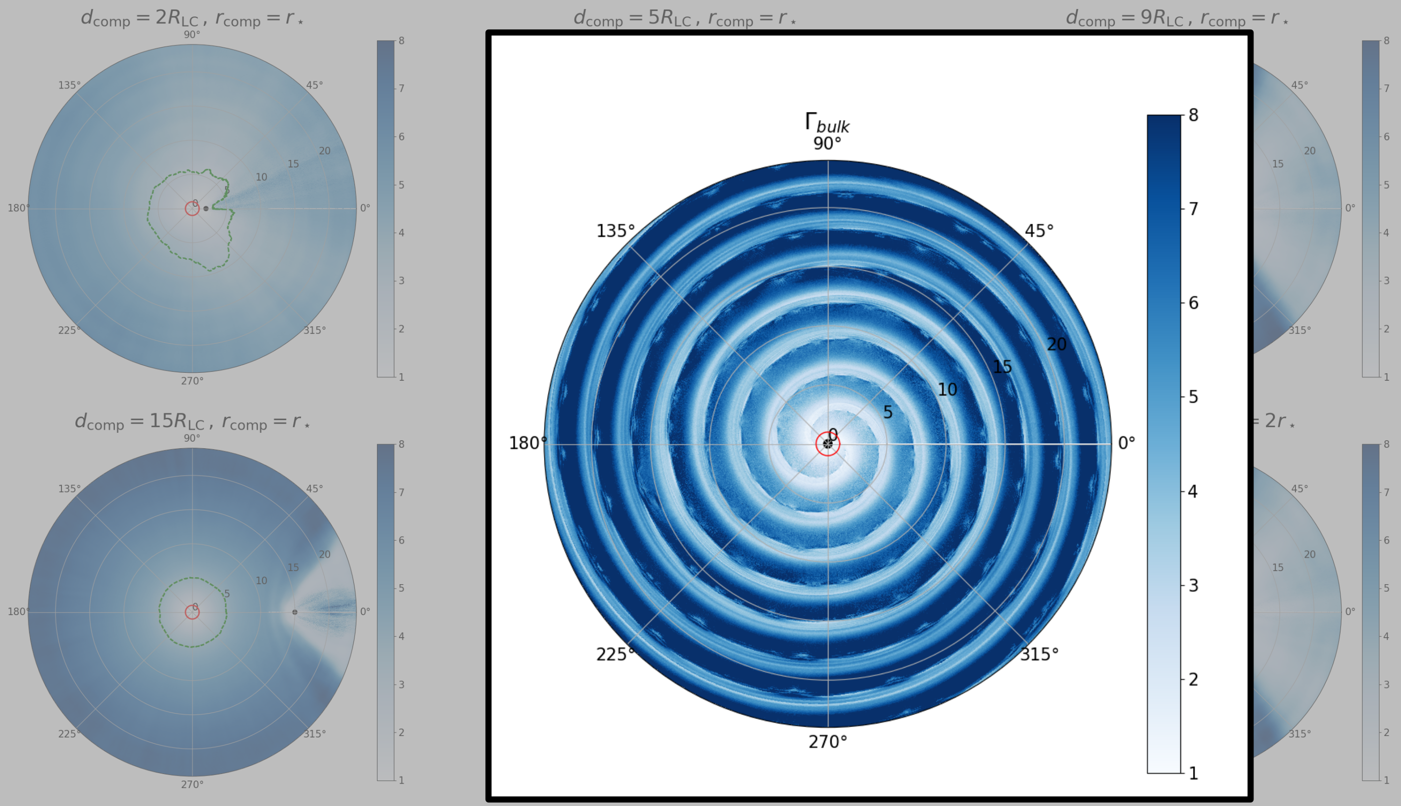




- Companion in the wind zone: $P_{orb,companion} >> P_{spin,pulsar}$
  ⟶ **companion at rest** in the simulation

- **2 different regimes** depending on the companion location with respect to the fms point

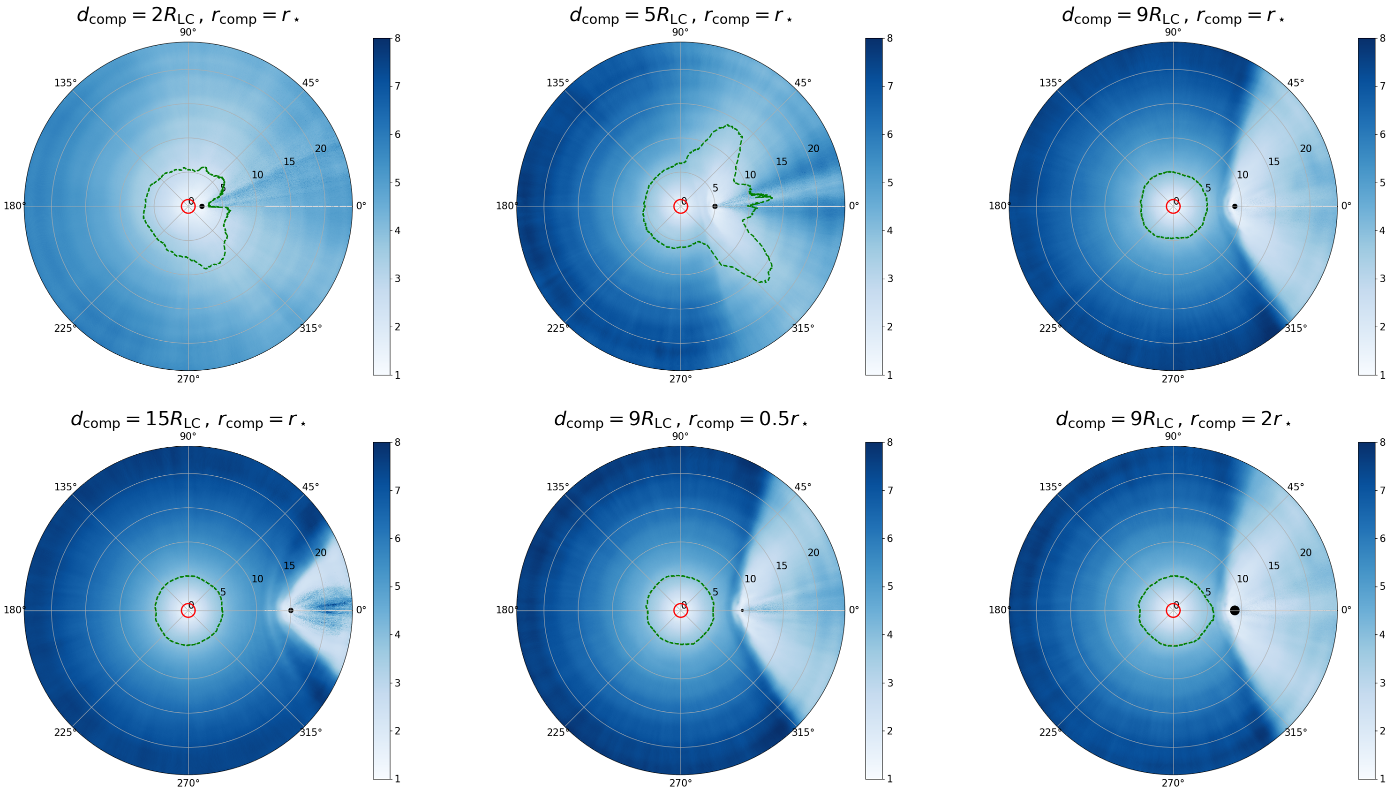
Bulk Lorentz factor averaged over several P_{spin}



- 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

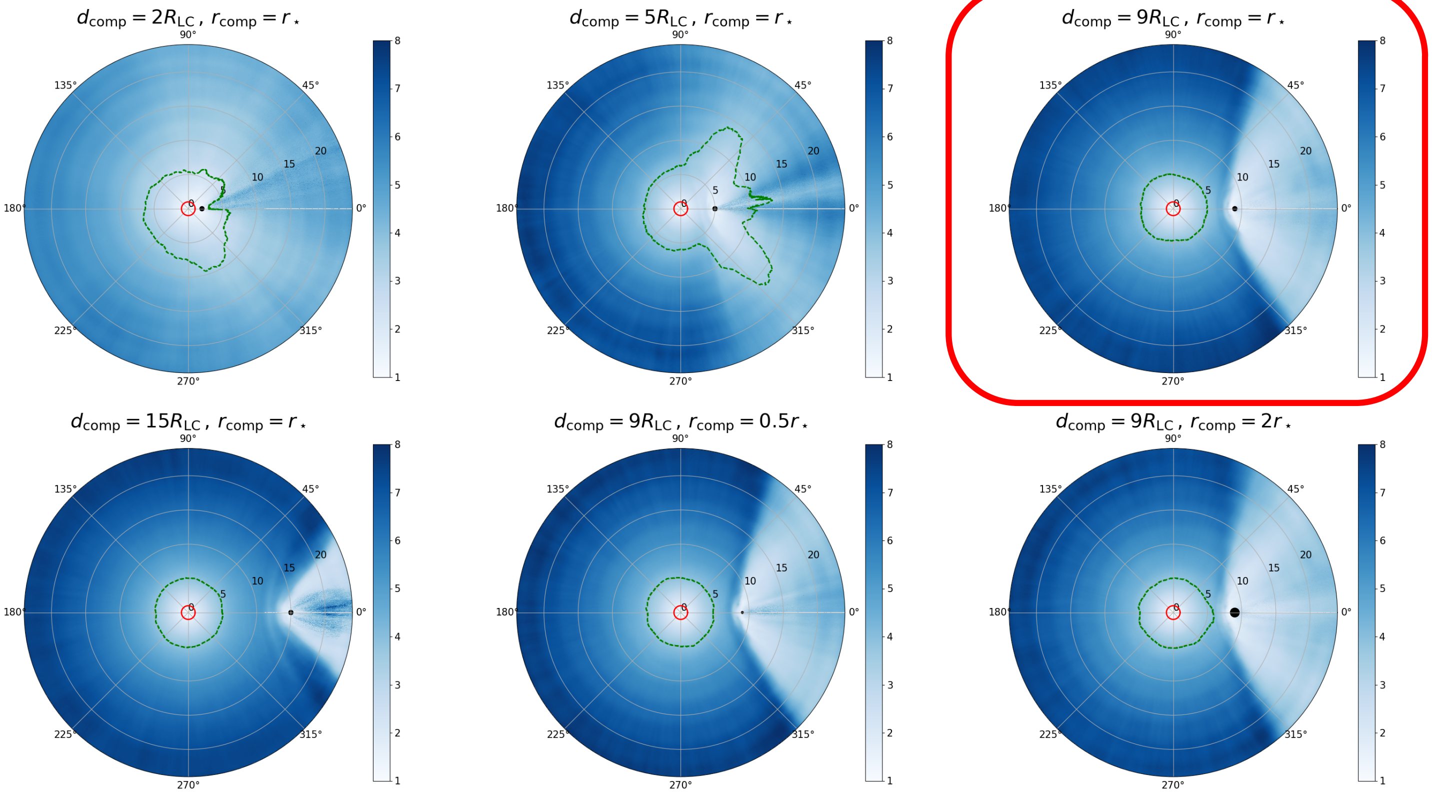
Bulk Lorentz factor averaged over several P_{spin}



- 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

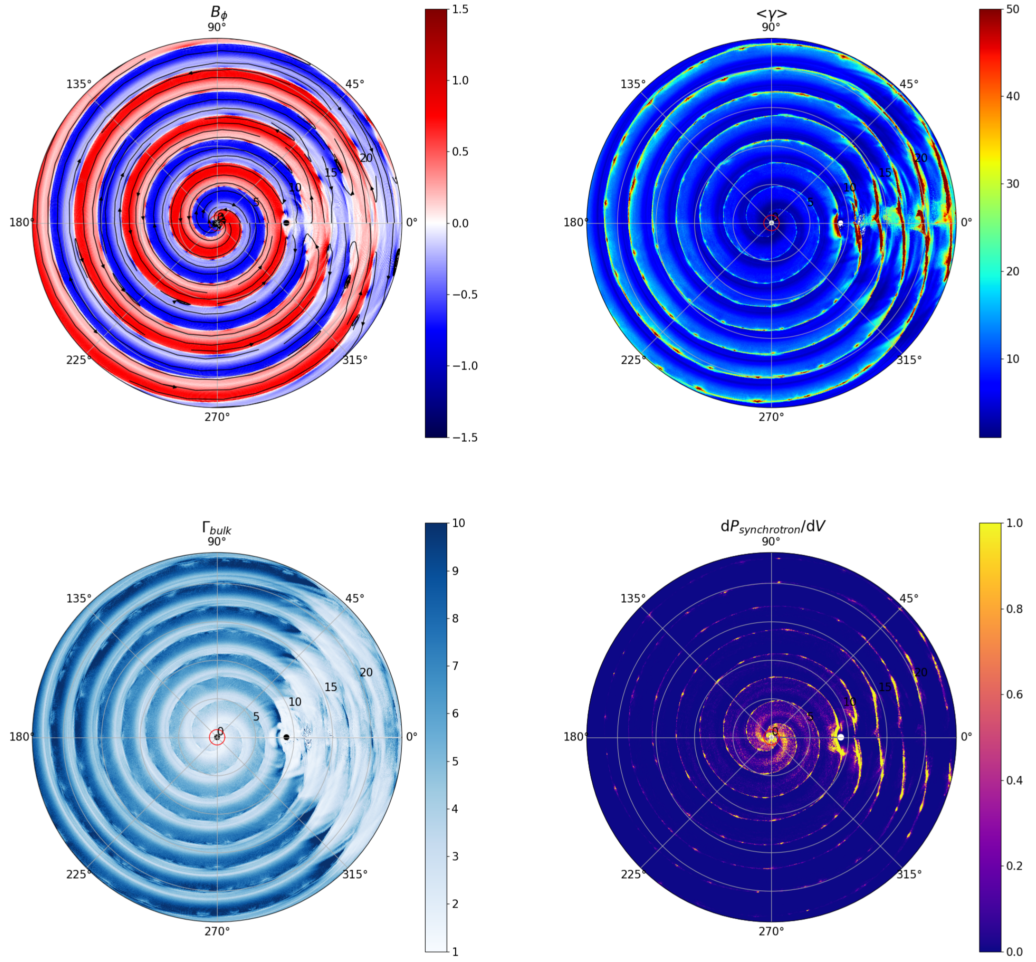
Bulk Lorentz factor averaged over several P_{spin}



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

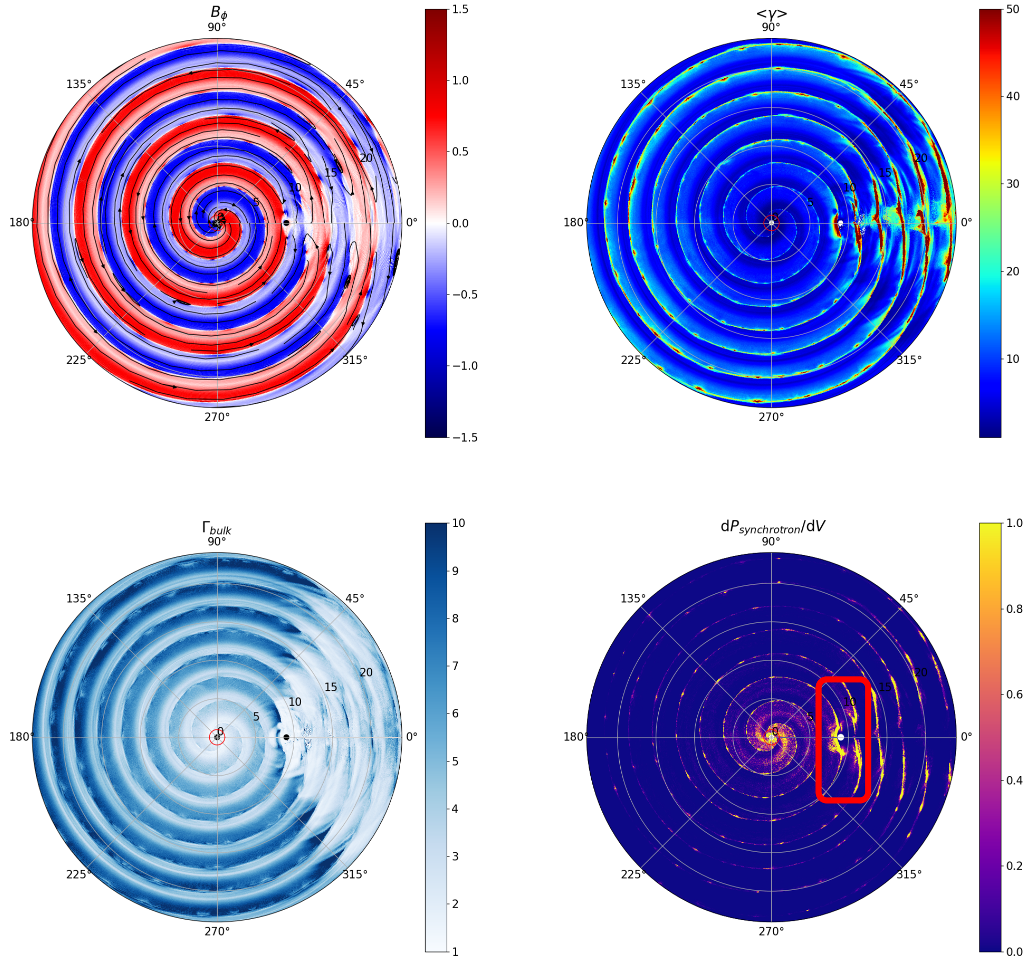
red circle = light cylinder radius
green contour line = fast magnetosonic surface

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



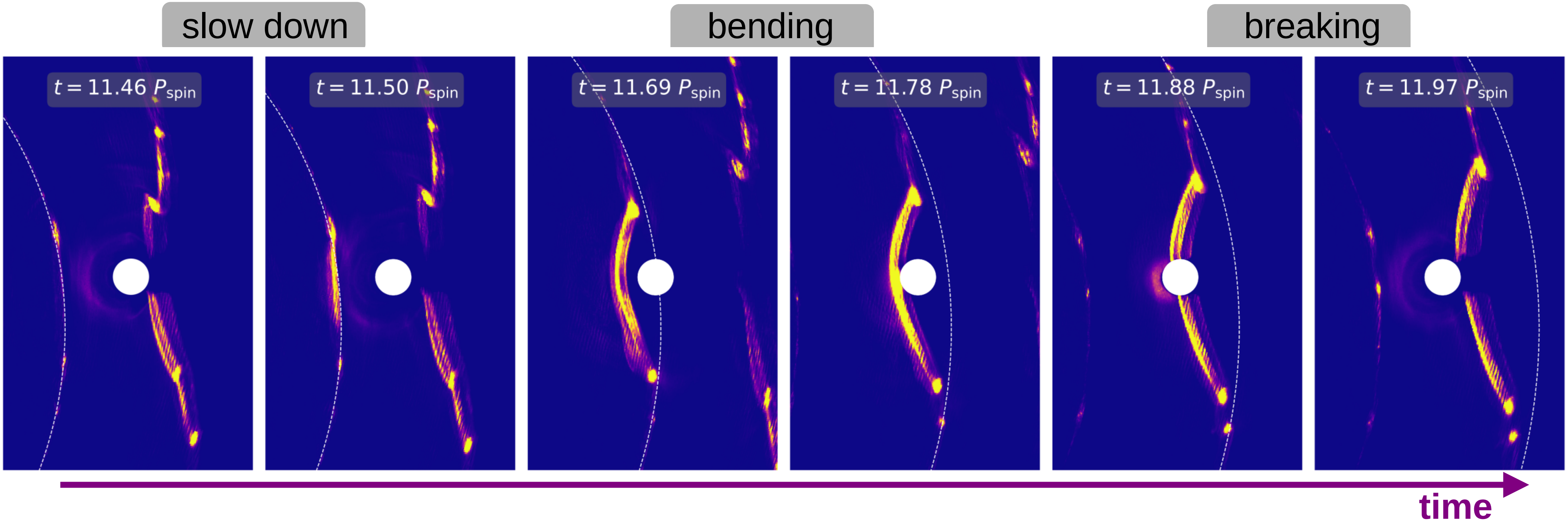
- **perturbations advected** in a cone behind the companion
- increased magnetic islands on the cone surface
- **favorable zone for particle acceleration** behind the companion
- very low density inside the cone
  ⟶ **highest synchrotron power** at its borders

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



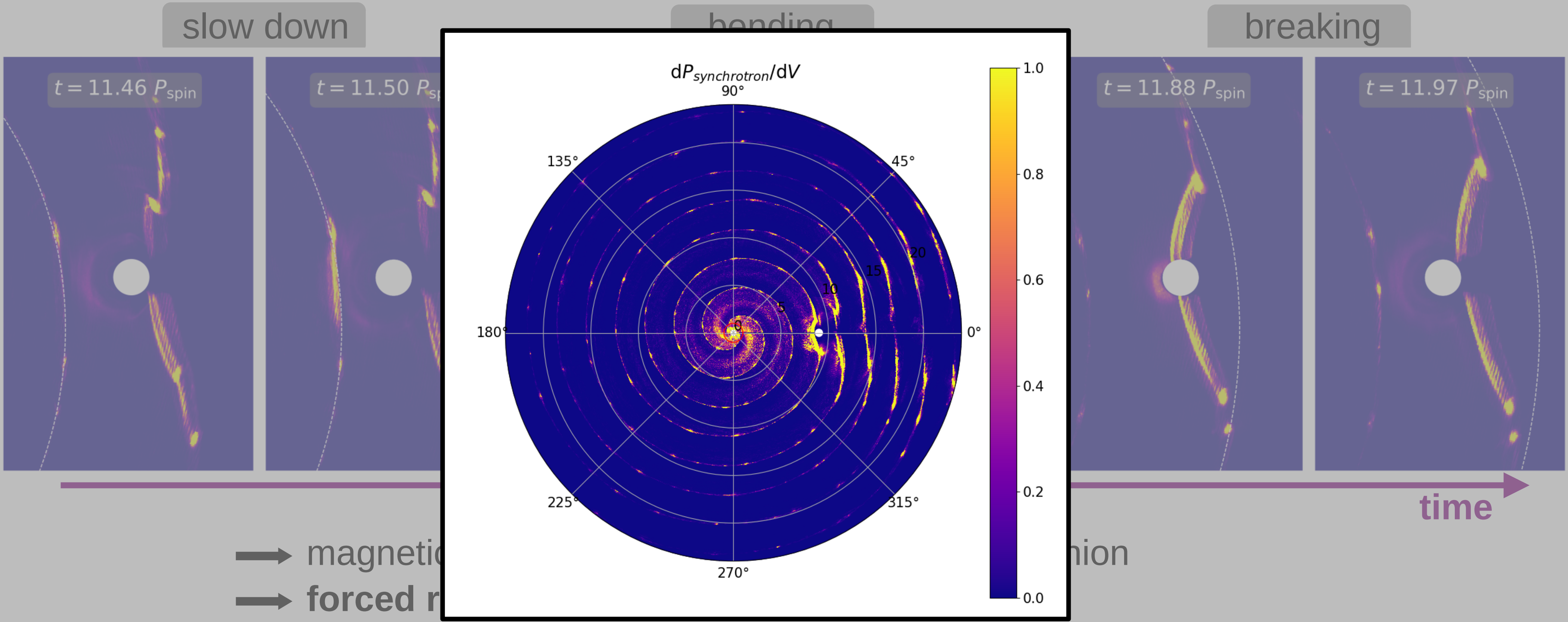
- **perturbations advected** in a cone behind the companion
- increased magnetic islands on the cone surface
- **favorable zone for particle acceleration** behind the companion
- very low density inside the cone ⟶ **highest synchrotron power** at its borders

Zoom on the current sheet at the companion surface



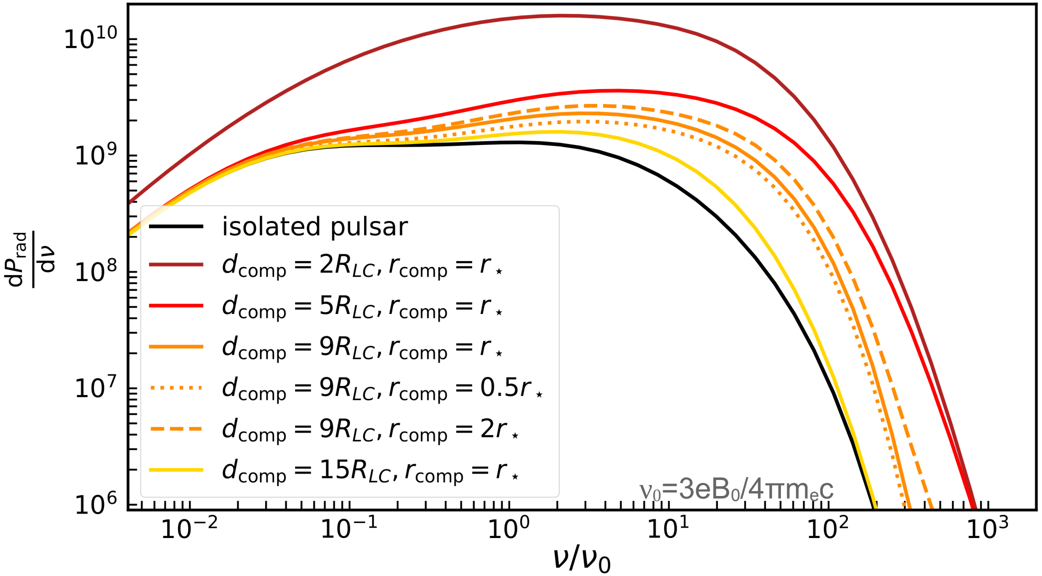
- → magnetic field lines pile up in front of the companion
- → **forced reconnection**
- → enhanced particle acceleration
- → enhanced non-thermal radiation

Zoom on the current sheet at the companion surface

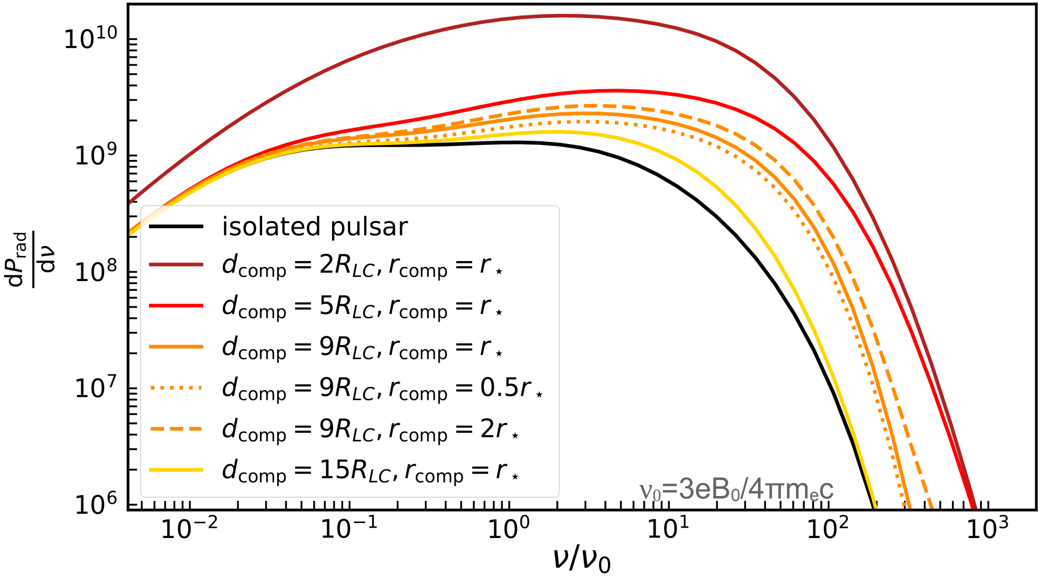


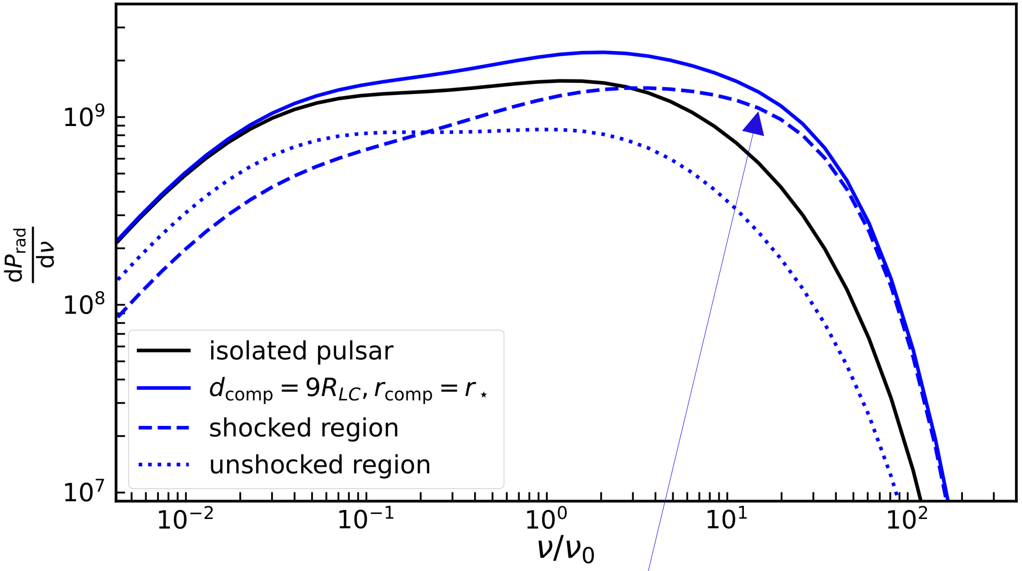
- magneti… …nion
- **forced r…**
- enhanced particle acceleration
- enhanced non-thermal radiation

High-energy synchrotron spectra



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

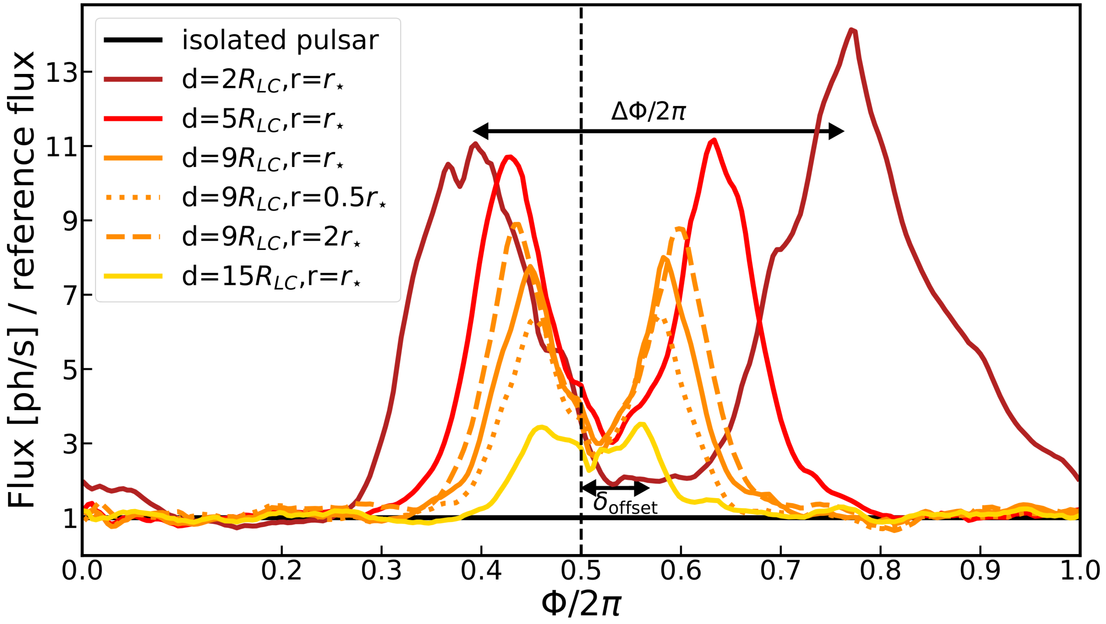




additional contribution **exclusively due to the shocked part**

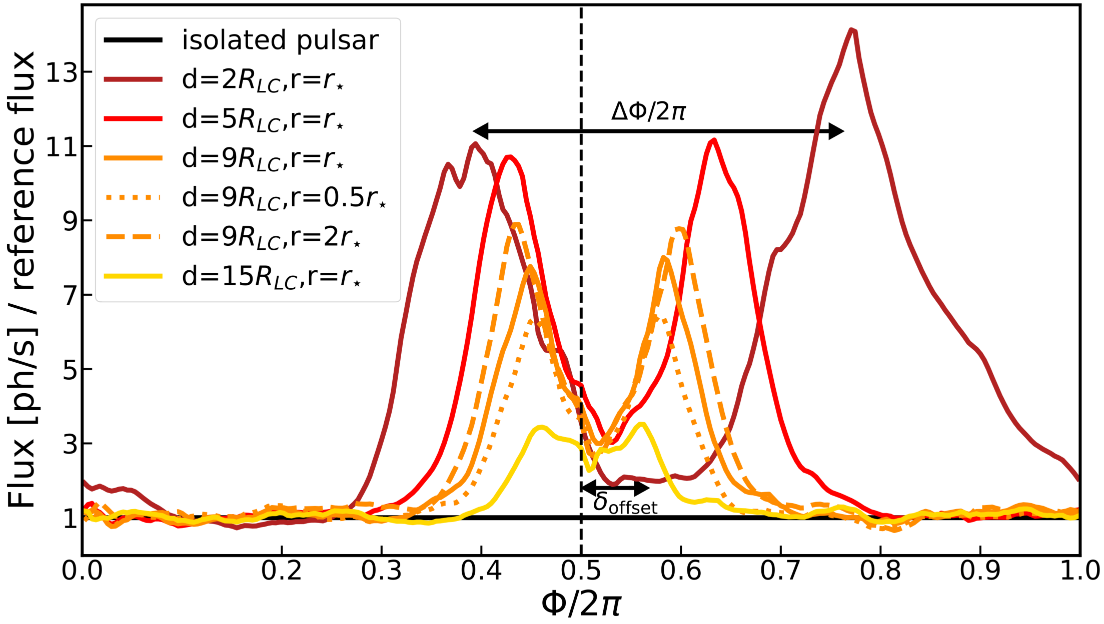
- **Significant enhancement** of the high-energy radiation compared to the isolated pulsar
- Emission **decreases with d_{comp}** and **increases with r_{comp}**

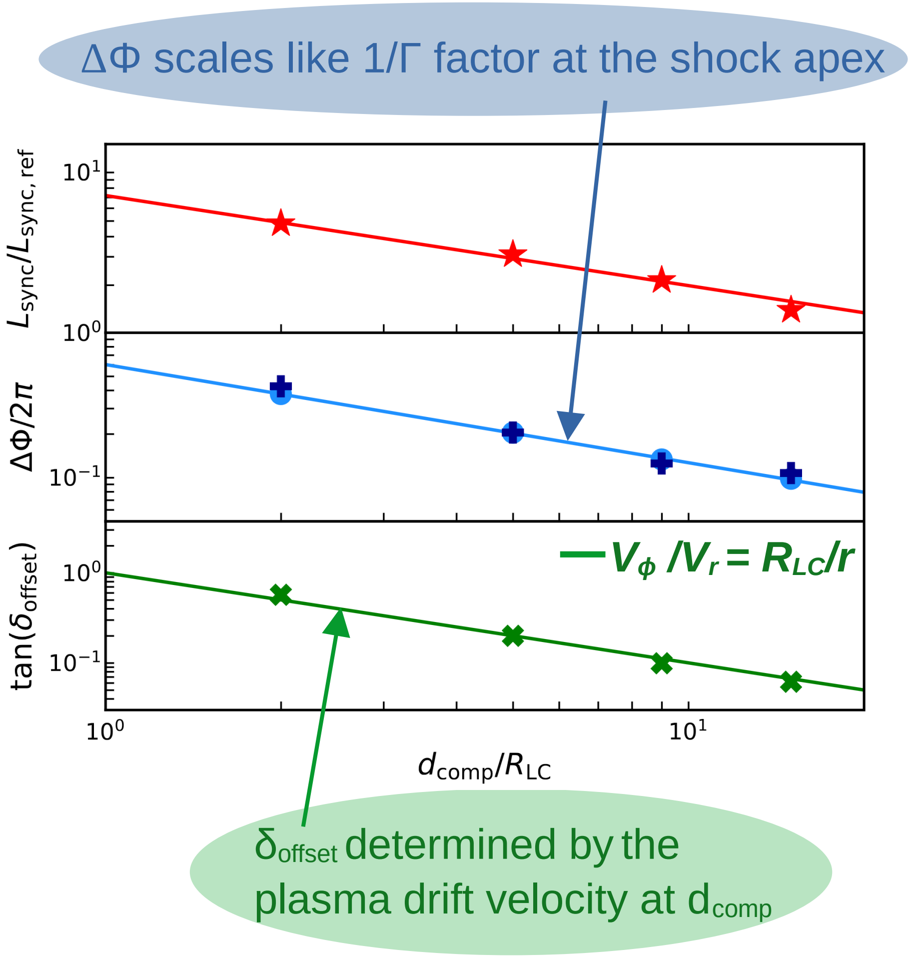
High-energy light curves



- **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

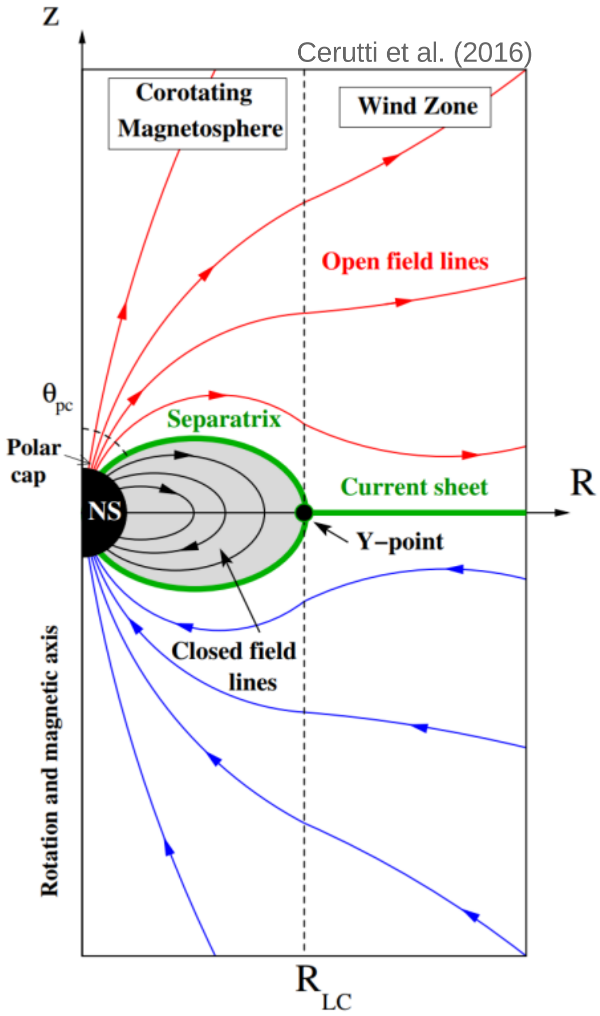
Pulsar magnetosphere

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)



Particle-in-cell (PIC) simulations

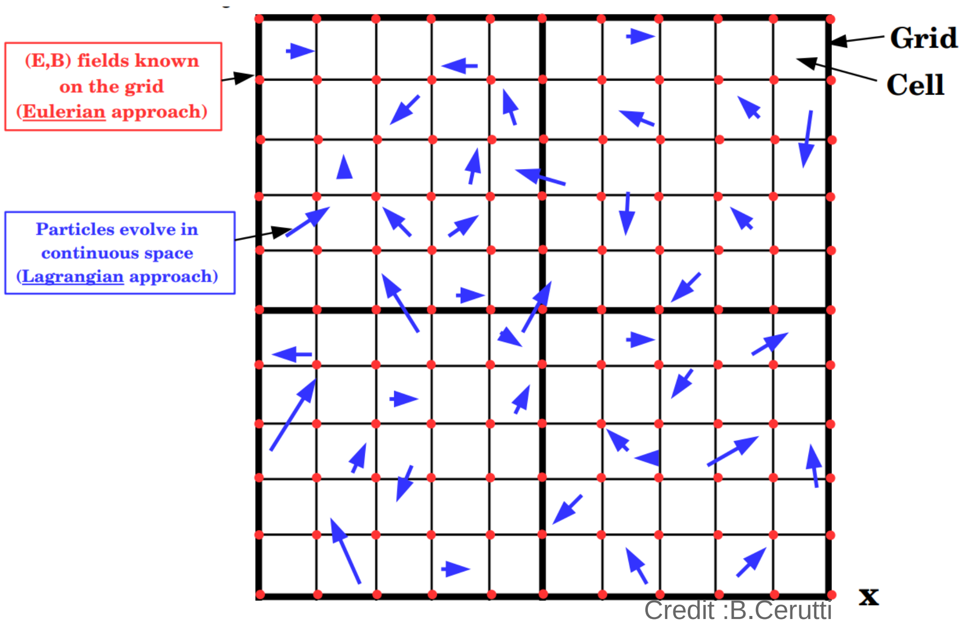
Solve Abraham-Lorentz-Dirac equation

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

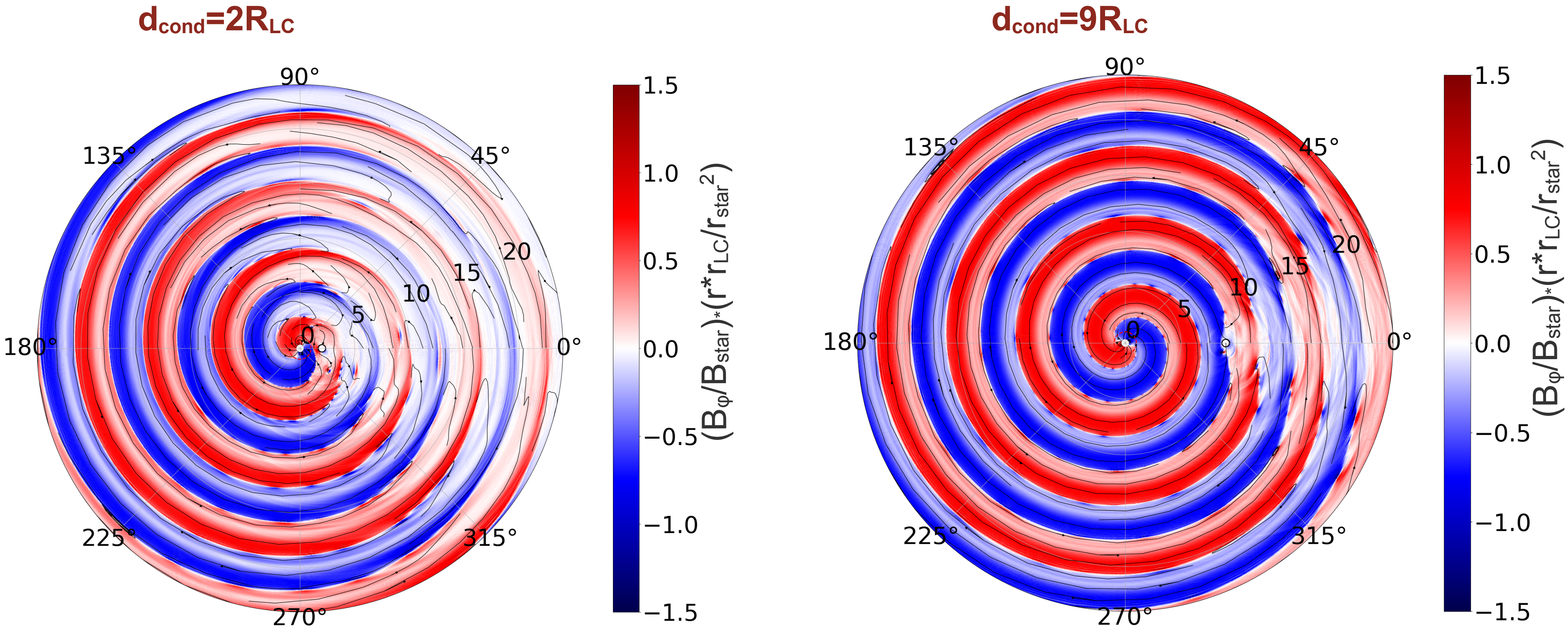
Δt

Deposit charge and current densities

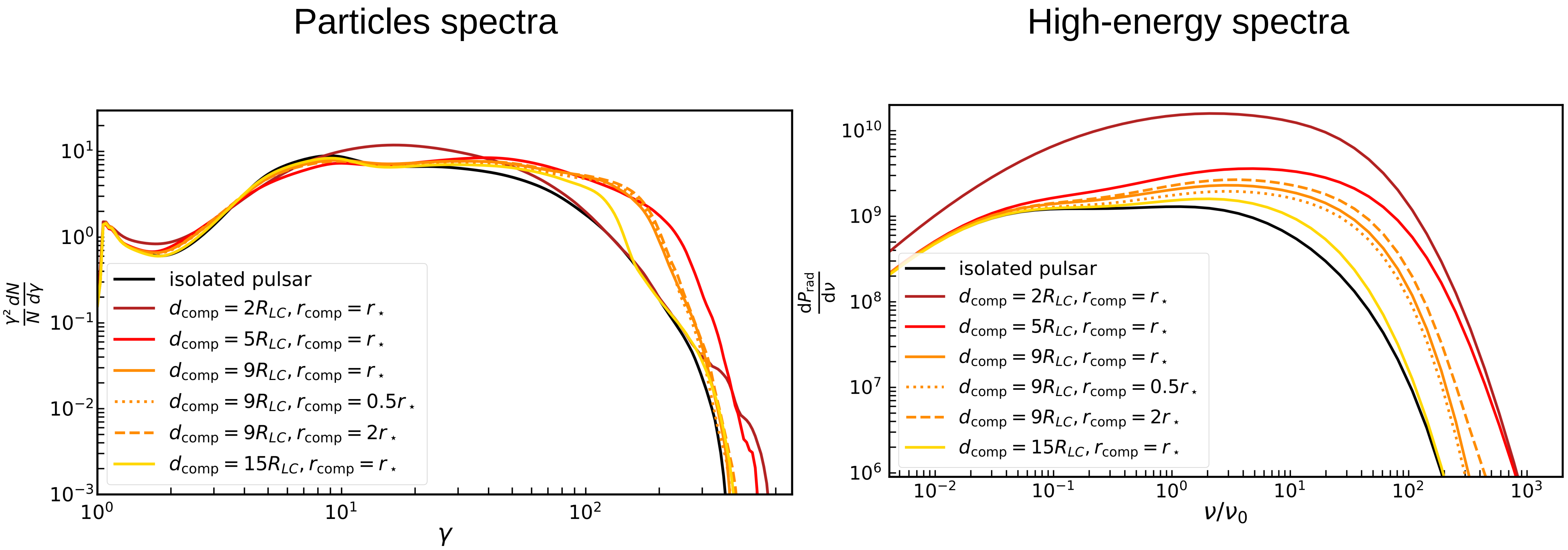
Solve Maxwell equations



Credit :B.Cerutti



d_cond=2R_LC
d_cond=9R_LC
90°
135°
45°
180°
0°
225°
315°
270°
0
5
10
15
20
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
(Bφ/Bstar)*(r*rLC/rstar^2)



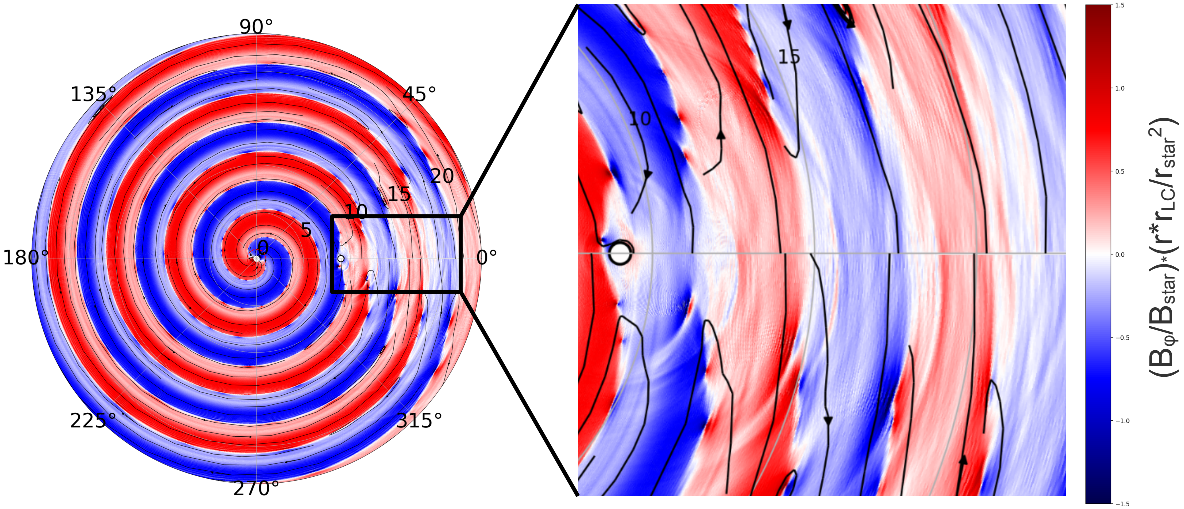
Particles spectra
High-energy spectra
$\frac{\gamma^2}{N}\frac{dN}{d\gamma}$
γ
$\frac{dP_{rad}}{d\nu}$
ν/ν_0
isolated pulsar
$d_{comp} = 2R_{LC}, r_{comp} = r_\star$
$d_{comp} = 5R_{LC}, r_{comp} = r_\star$
$d_{comp} = 9R_{LC}, r_{comp} = r_\star$
$d_{comp} = 9R_{LC}, r_{comp} = 0.5r_\star$
$d_{comp}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

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



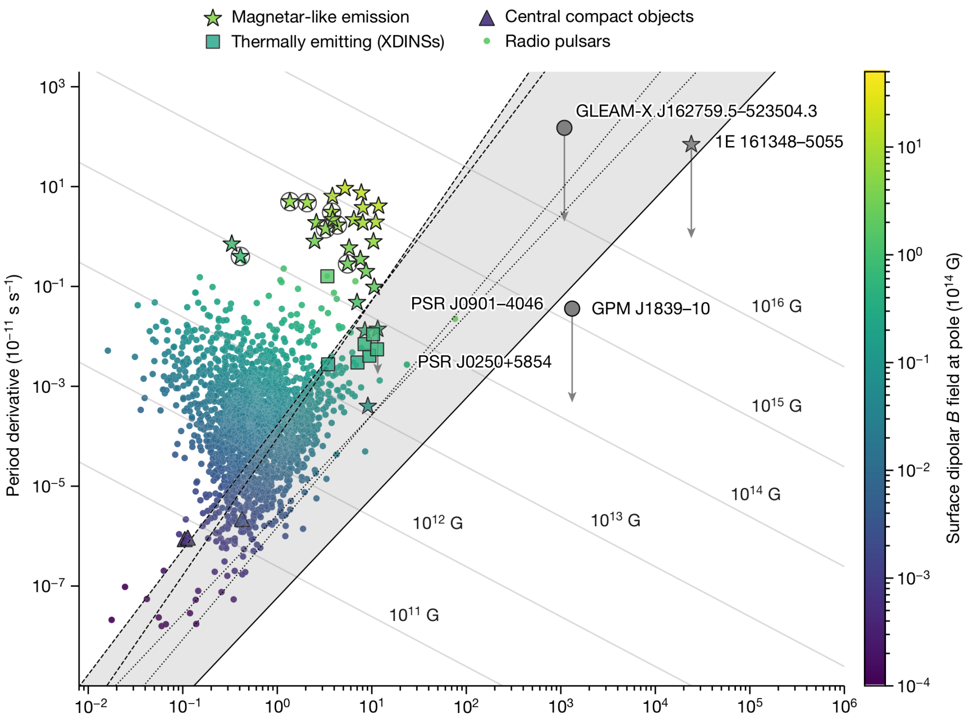
- See also the predictions of Fast Radio Bursts in the presence of a companion (Mottez, Zarka, Voisin, 2020; Decoene, 2021)

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 ?

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