Electromagnetic precursor of a binary neutron star coalescence

Benjamin Crinquand

Institut de Planétologie et d'Astrophysique de Grenoble

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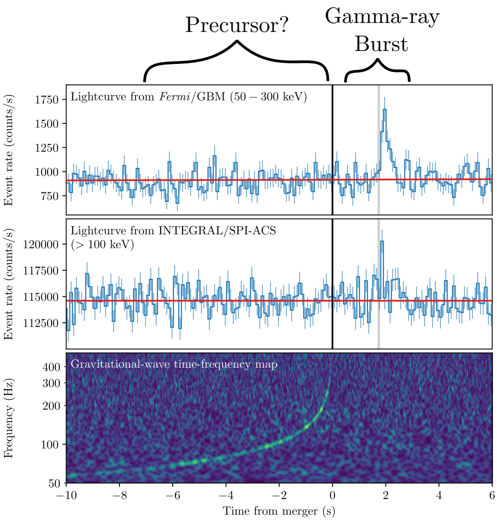
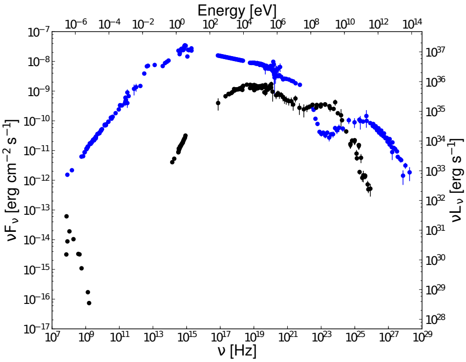


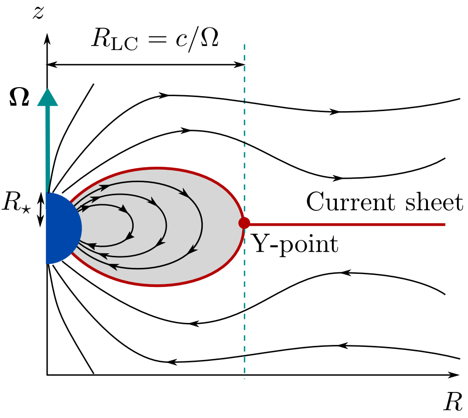
Abbott et al. (2017)

- Recent joint detection of EM and GW waves ⇒ Signature of a binary neutron star merger
- Multi-messenger astronomy
- Electromagnetic precursor signal?



Spectral energy distribution of the Crab pulsar (black) and the Crab nebula (blue). Bülher et al. (2014)

- Wealth of observation from pulsars, from radio to γ ray
- Non-thermal emission $\Rightarrow$ Particle acceleration from pulsars
- Mostly synchrotron radiation (+ Inverse Compton)



Force-free regime

Dense, magnetized plasma:

$$\rho \boldsymbol{E} + \boldsymbol{j} \times \boldsymbol{B}/c = \boldsymbol{0}$$

Main features

- Open magnetic field lines
- Growth of a toroidal component B_φ
- Outgoing Poynting flux

w

Plasma simulations

1. **MHD fluid simulations**
   Drawback: cannot capture microphysics
2. **Kinetic simulations**
   Drawback: greater computational cost

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State of the art

- 2D particle-in-cell *spherical* simulations performed by Cerutti *et al.*

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- Unfit to model a binary pulsar

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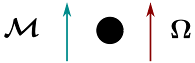
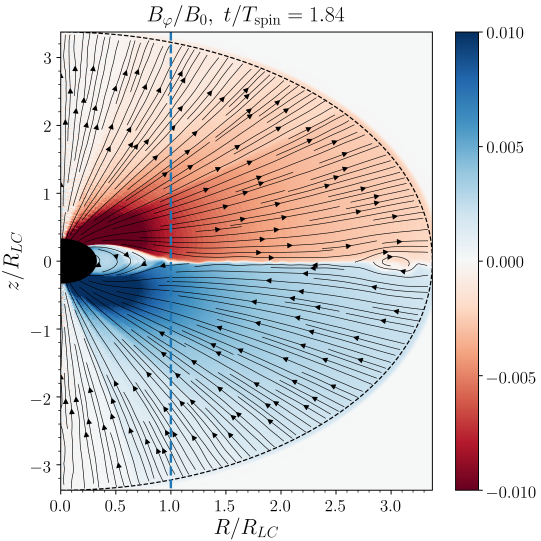
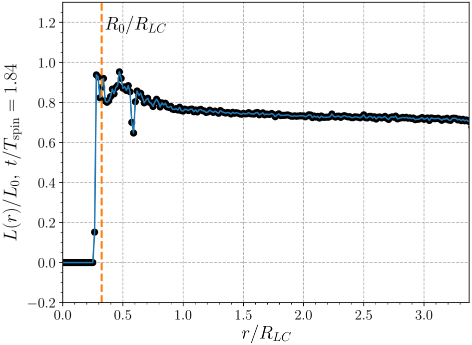
⇒ We developed a 2D PIC cylindrical code to simulate a binary merger in an axisymmetrical setup



$\mathcal{M}$
Ω



$B_\varphi/B_0,\ t/T_{\rm spin} = 1.84$
z/R_{LC}
R/R_{LC}
3
2
1
0
−1
−2
−3
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0.010
0.005
0.000
−0.005
−0.010



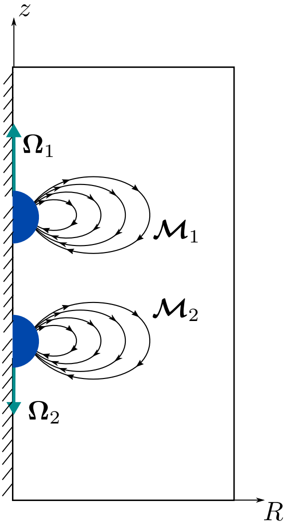
Normalized Poynting flux through a sphere of radius r around the pulsar.

Force-free spindown

$$L_0 \sim \frac{B_0^2 R_0^6 \Omega^4}{4\mu_0 c^3} \quad (1)$$

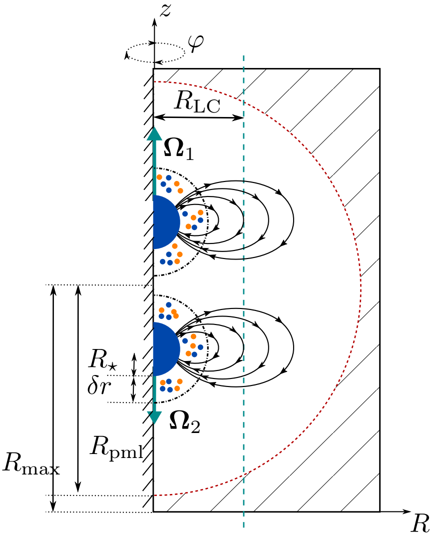
Dissipation: energy transferred to the particles through **magnetic reconnection** in the current sheet

↳ Radiative efficiency of a few %



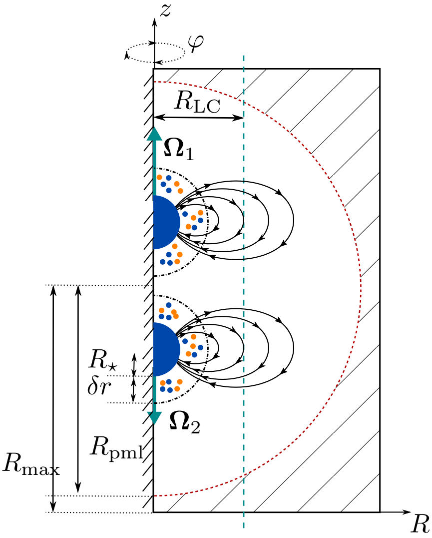
Geometry

- Magnetix and spin axes all aligned with the symmetry axis
- $\rightarrow$ Orbital motion neglected
- Two configurations of interest: *Parallel* and *Anti-parallel* spin axes, with parallel magnetic moments



Initial conditions

- Rotation of a perfect conductor induces an electric field: $\boldsymbol{E} + (\boldsymbol{\Omega} \times \boldsymbol{r}) \times \boldsymbol{B}/c = \boldsymbol{0}$ inside a star
- Particles are launched from the stellar surface with corotation



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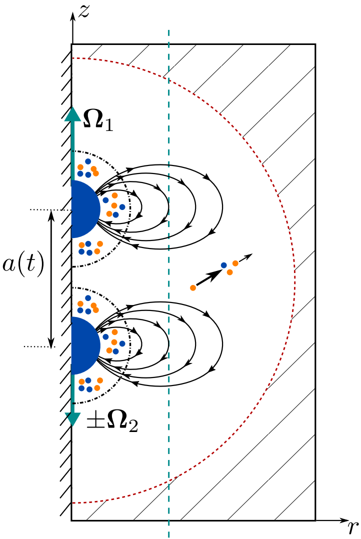
Boundary conditions

- Cylindrical symmetry on the axis
- Outer boundary: fields are damped through numerical resistivity $\Rightarrow$ No reflection

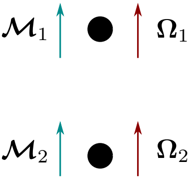


- Pair creation if a particle gets too energetic → Secondary pair generation in real pulsars
- Simulation stops when the stars touch

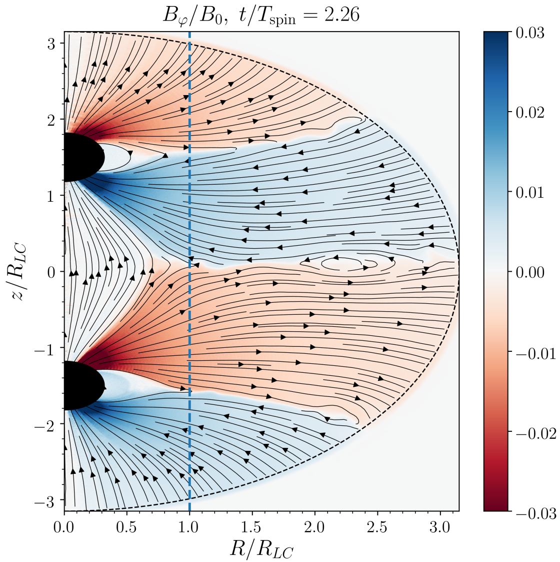
Variable separation

$$a(t) = a_0(1 - 4t/\tau)^{1/4} \qquad (2)$$

Inspiral due to the emission of gravitational waves

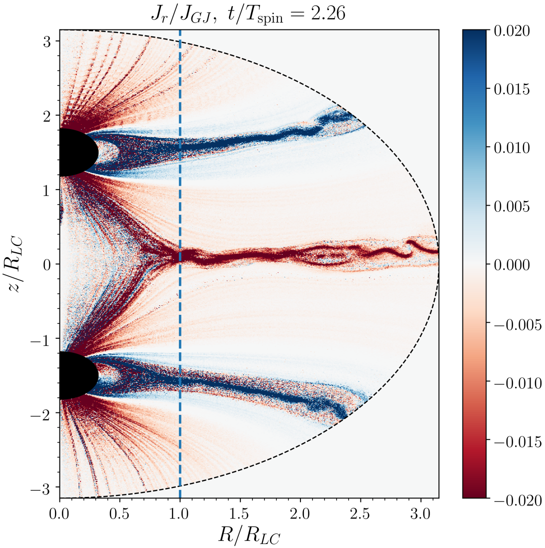


$\mathcal{M}_1$
Ω_1
$\mathcal{M}_2$
Ω_2

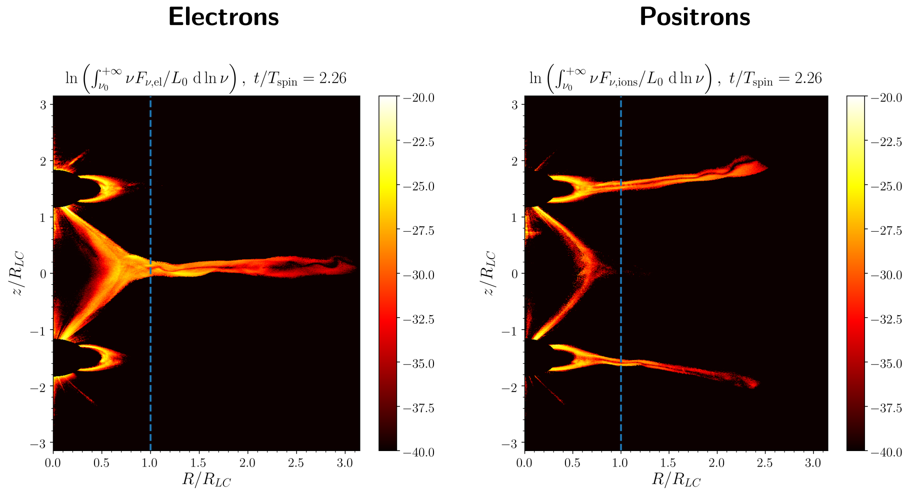


$B_\varphi/B_0,\ t/T_{\rm spin} = 2.26$
z/R_{LC}
R/R_{LC}
3
2
1
0
−1
−2
−3
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03

Main feature: “Midway” current sheet → Prominent site for reconnection

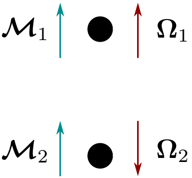


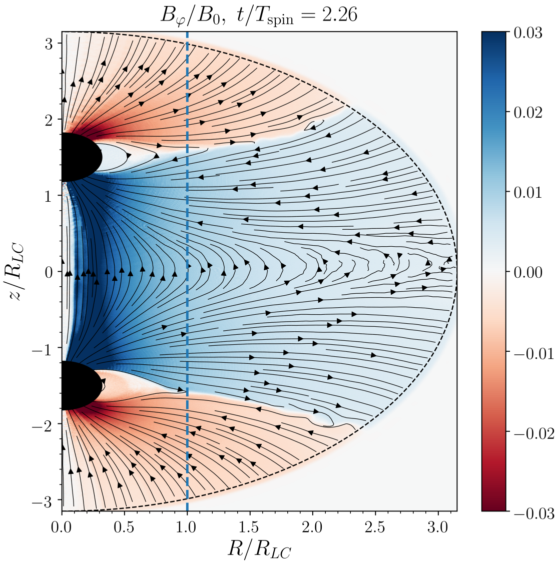
Parallel configuration

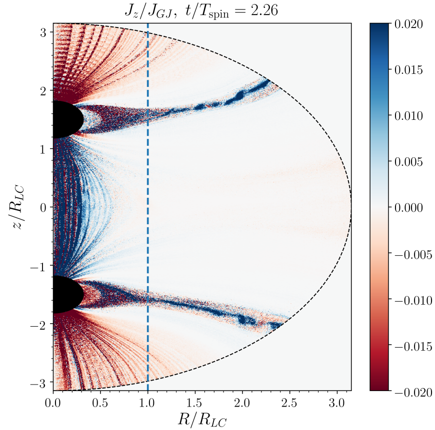


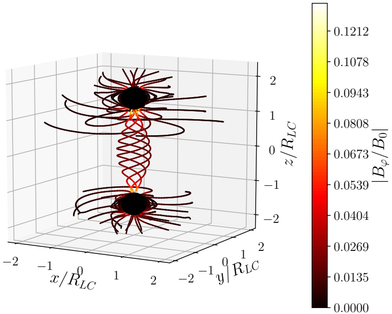
$\eta_{\parallel} = 21.3\% \rightarrow$ Reconnection layer inside the light cylinder

Results
Anti-parallel configuration







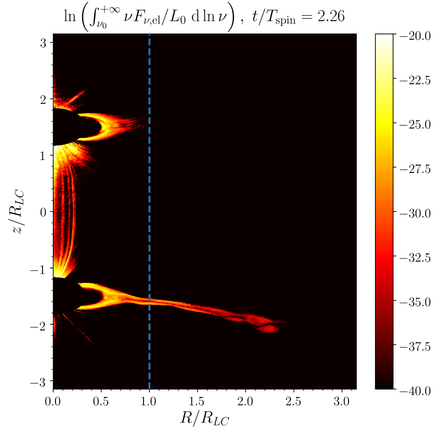


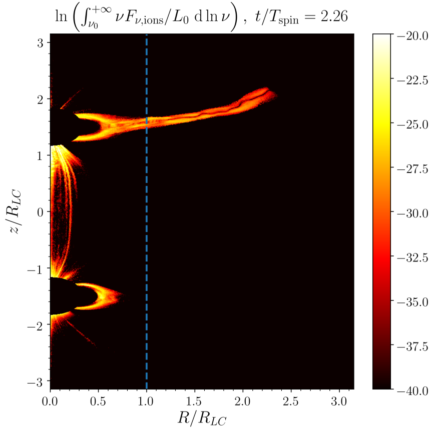
Main feature: Twisted field lines

⇒ Emf between the stars ⇒ Poloidal currents and pair creation

Anti-parallel configuration

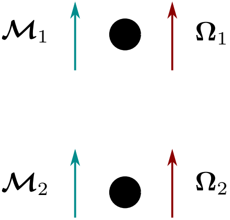
Electrons | **Positrons**

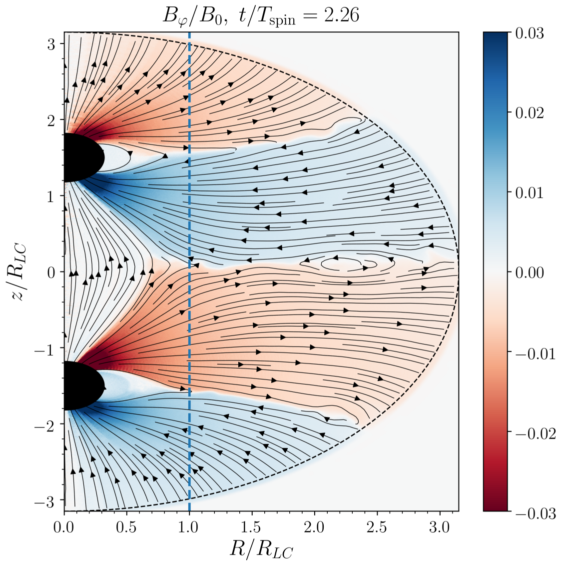




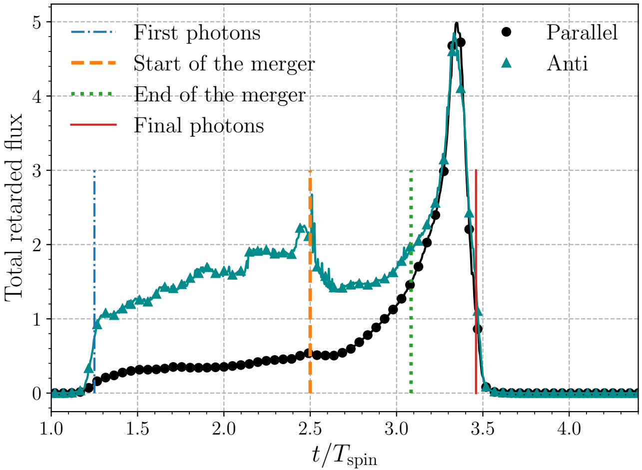
$\eta_{\not\chi} = 22.5\%$ → Enhanced radiation at inner poles

Binary merger: an observable signature?

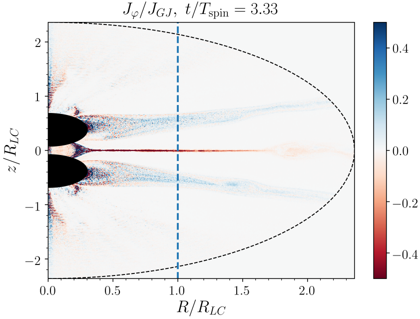




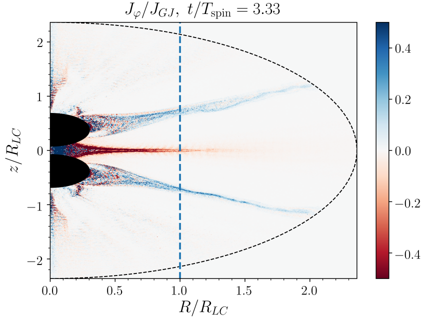
Lightcurve constructed by collecting photons according to the observation angle and their time delay



- **Before merger**: Parallel and anti-parallel configurations different
- **After merger**: Similar lightcurves → Common mechanism



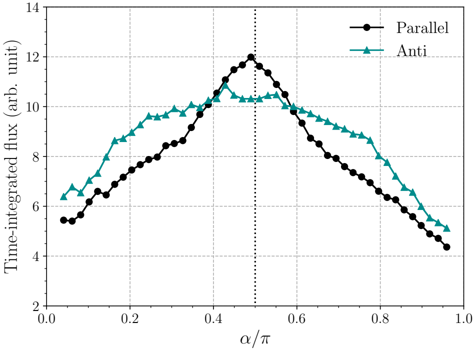
Parallel



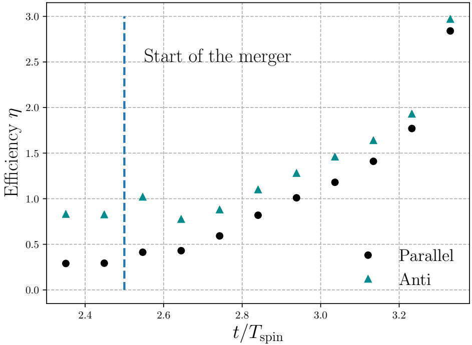
Anti-parallel

Poloidal field discontinuity at $z = 0$ that dominates the toroidal discontinuity in both configurations

$\Rightarrow$ Current sheet, magnetic reconnection site



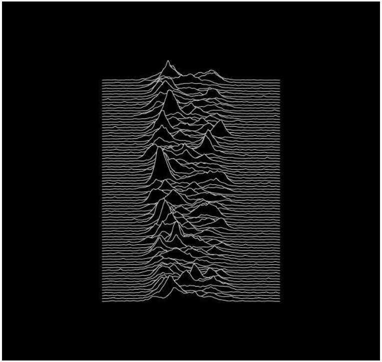
- Radiation mainly emitted in the equatorial plane
- Signal not strongly anisotropic



- Great increase in bolometric luminosity: Total radiated power increases by one to two orders

  ↳ Energy flux $\sim 10^{38}$ erg/s
- Merger event GW170817: output power $\sim 10^{46}$ erg/s, just above Fermi-GBM sensitivity
- Hope for radio detection (better sensitivity)

1. Asymetric simulations ($B_{0,\mathrm{up}}/B_{0,\mathrm{down}} = 4$, $\Omega_{\mathrm{up}}/\Omega_{\mathrm{down}} \sim 0.25$): more realistic setup
2. More pessimistic expectations than theoretical works
3. 3D simulations with orbital motion would probably yield a more powerful outburst
4. Relation to Fast Radio Bursts?



Artwork of the album Unknown Pleasures by Joy Division.

Thank you for your attention!