Simulations de coalescences d'étoiles à neutrons

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Séminaire Dautreppe

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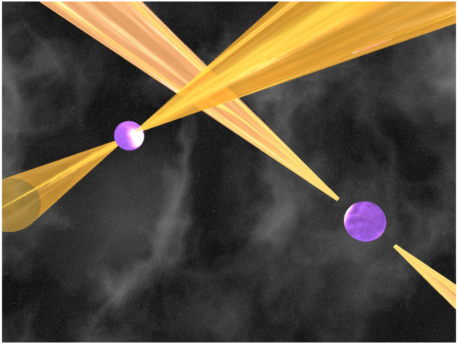
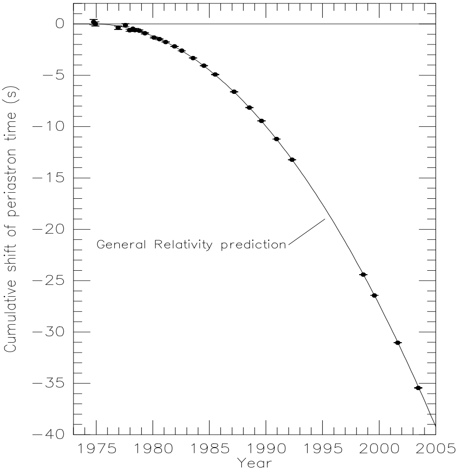


Artist's impression of a binary pulsar

- Binary pulsar: pulsar with a binary companion, a white dwarf or a neutron star
- Companion often invisible: discovered thanks to Doppler effect
- Allows precise tests of pulsar physics and general relativity

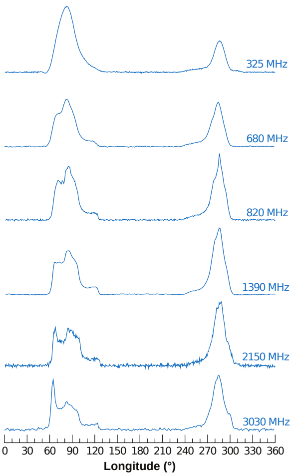
Example: PSR B1913+16



Taylor et al. (1982)

- First binary pulsar, discovered by Hulse & Taylor (1974)
- Allowed the first indirect detection of gravitational waves, through decay of orbital period for instance (Nobel prize in 1993)
- First accurate determination of neutron star masses + check consistency of general relativity

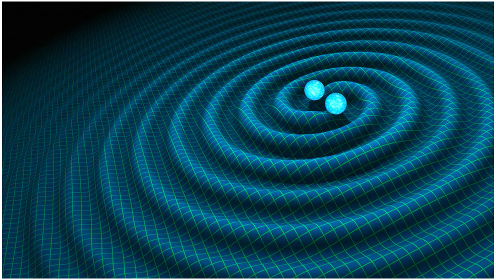
Example: The "double" pulsar J0737-3039A,B



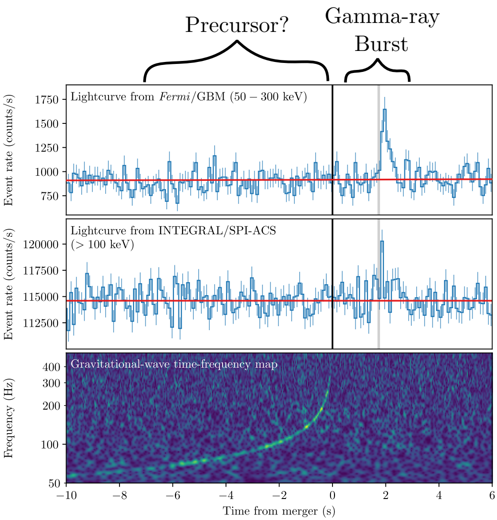
Kramer et al. (2006)

- Both pulsars are detected in this system, one of the closest to Earth
- New constraints on General Relativity, in a few years of observation
- New insights in pulsar astrophysics: pulse modulation, eclipses,...

- Two orbiting masses lose energy through gravitational waves
- Similar to electromagnetic radiation of accelerated charges
- Come back tomorrow for more information!

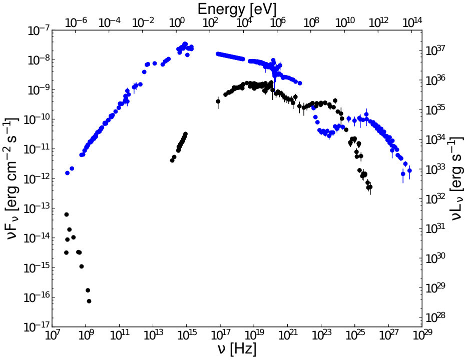


Artist's impression of a binary close to merger



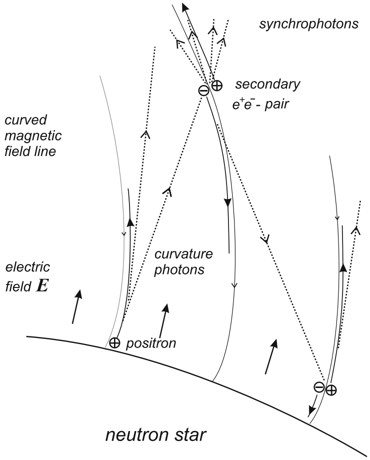
Abbott et al. (2017)

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



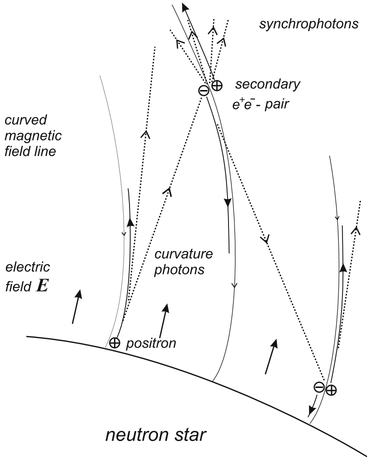
Spectral energy distribution of the Crab pulsar (black) and the Crab nebula (blue). Bülher et al. (2014)

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



Secondary plasma generation. Taken from Beskin (2010).

1. Electric fields induced (similarly to a Faraday disk)



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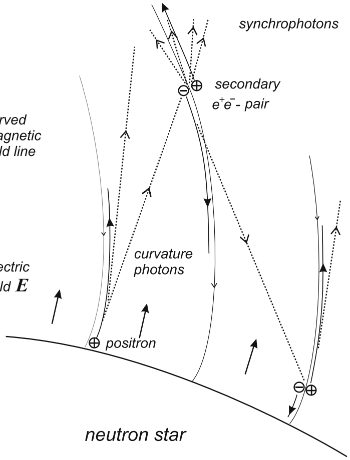
2. Primary charges extracted from stellar surface



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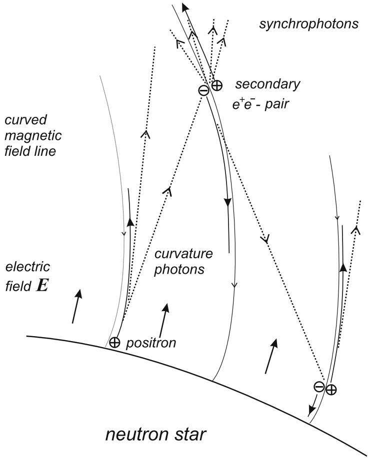
3. Radiated energetic photons in magnetic fields



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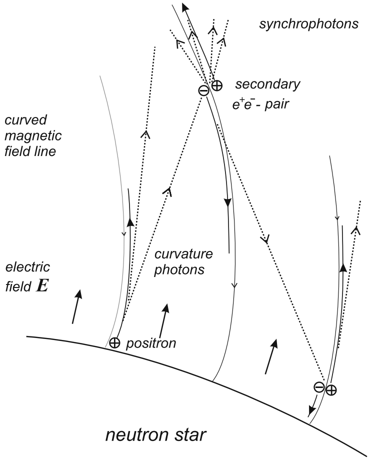

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$\Rightarrow$ Magnetosphere filled with $e^{\pm}$ plasma

Plasma simulations

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

Plasma simulations	*State of the art*

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  ↳ Isolated pulsar case well understood

- Unfit to model a binary pulsar

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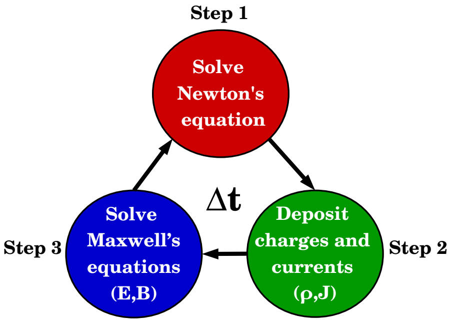
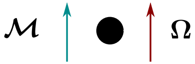
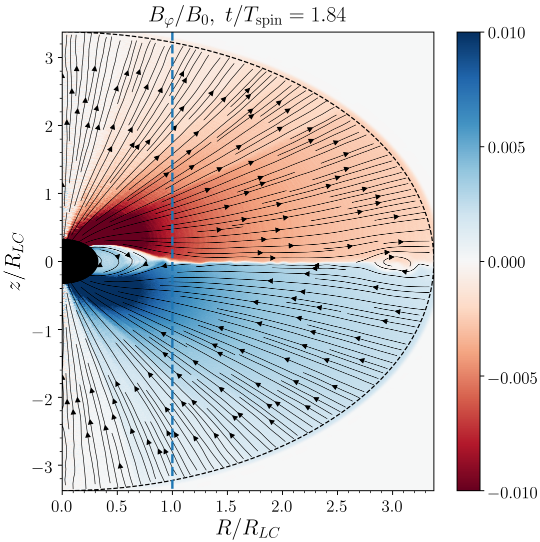
⇒ We developed a 2D PIC cylindrical code to simulate a binary merger in an axisymmetrical setup



- Relativistic particle motion and EM fields are self-consitently evolved
- Fields are computed on a grid to save computation time
- Computationally expensive: from microphysics to macrophysics


$\mathcal{M}$
Ω


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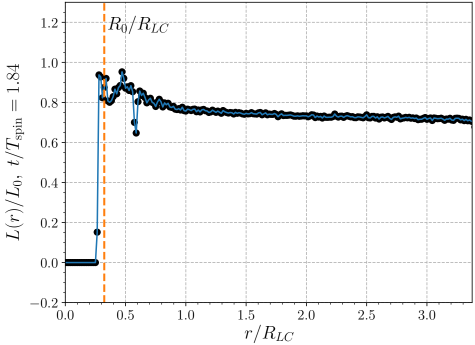


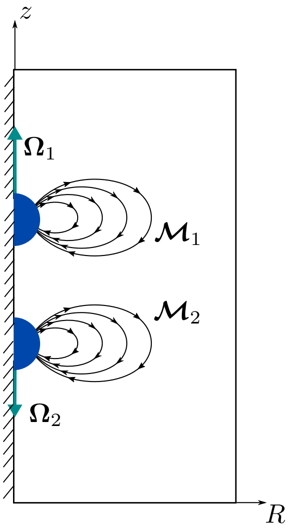
Normalized Poynting flux through a sphere of radius r around the pulsar.

Force-free spindown

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

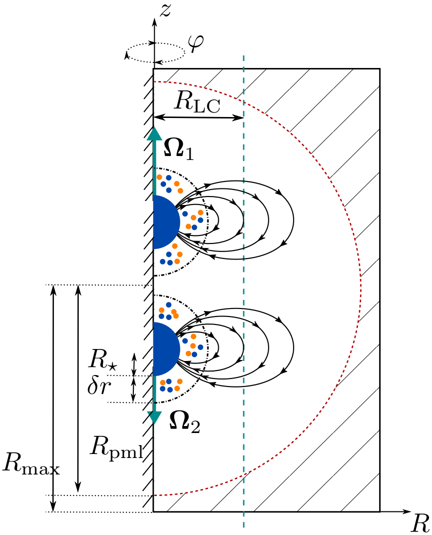
Dissipation: energy transferred to the particles through **magnetic reconnection** in the current sheet

↳ Radiative efficiency of a few %



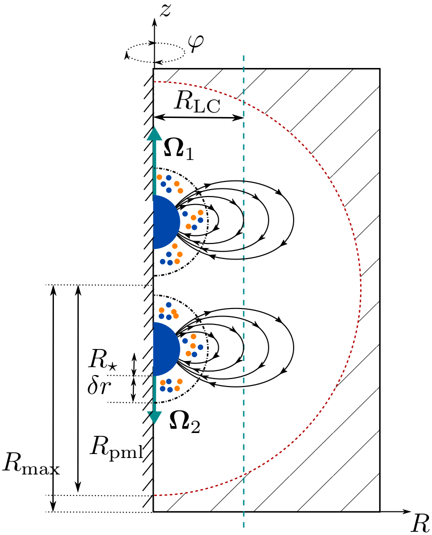
Geometry

- Magnetic 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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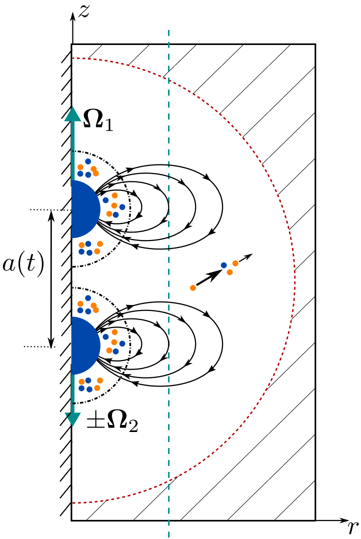
Boundary conditions

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

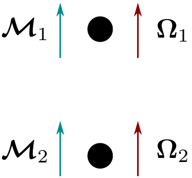


- Pair creation if a particle gets too energetic → Secondary pair generation in real pulsars
- Simulation stops when the stars touch

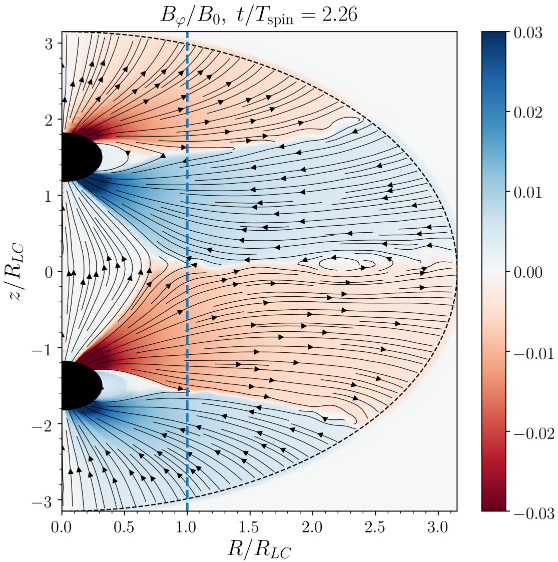
Variable separation

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

Inspiral due to the emission of gravitational waves



$\mathcal{M}_1$
$\mathbf{\Omega}_1$
$\mathcal{M}_2$
$\mathbf{\Omega}_2$



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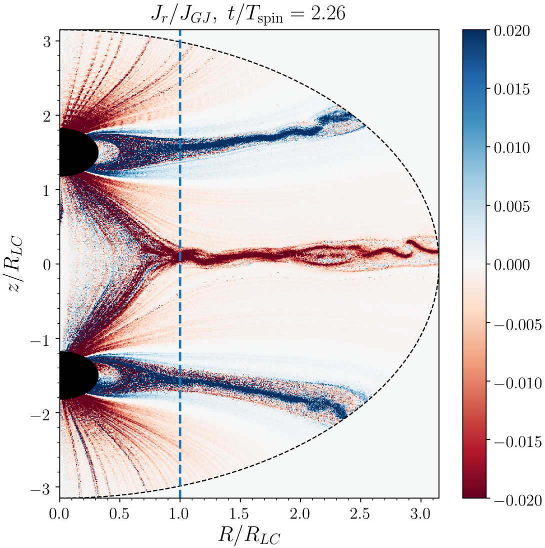
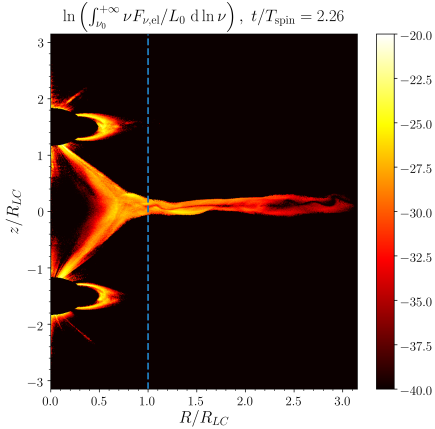
2.5
3.0
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03

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

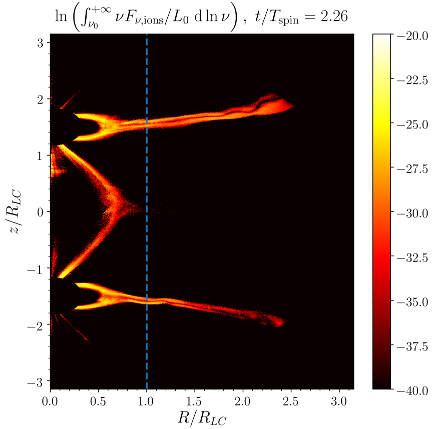


Parallel configuration

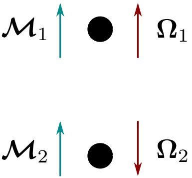
Electrons



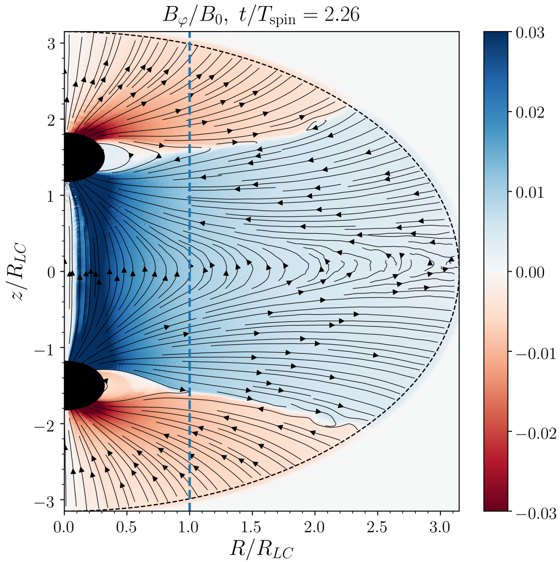
Positrons



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



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



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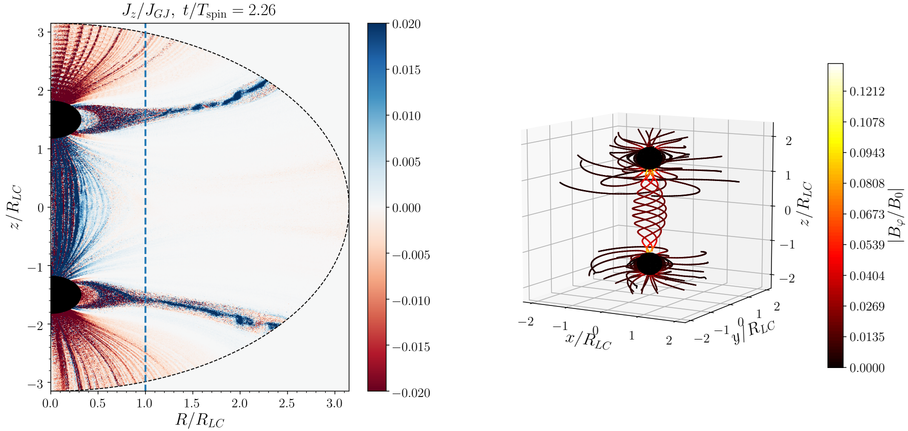
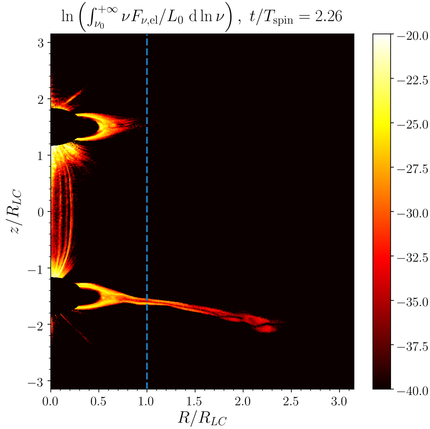


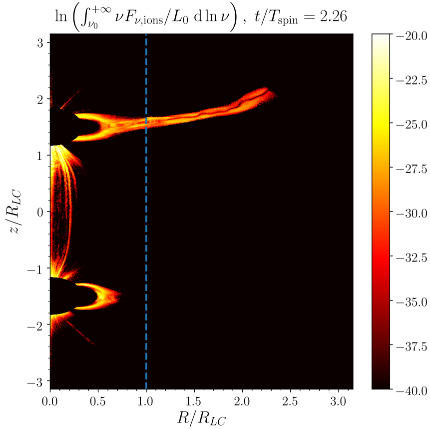
Main feature: Twisted field lines $\Rightarrow$ Pair creation and dissipation

Anti-parallel configuration

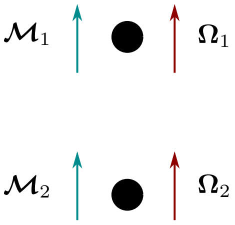
Electrons

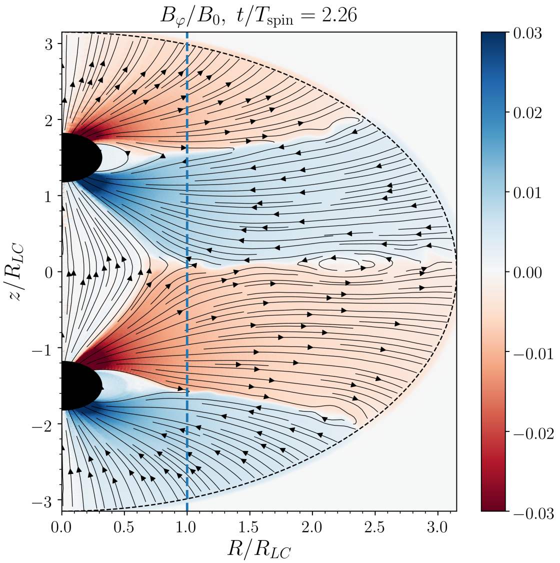


Positrons

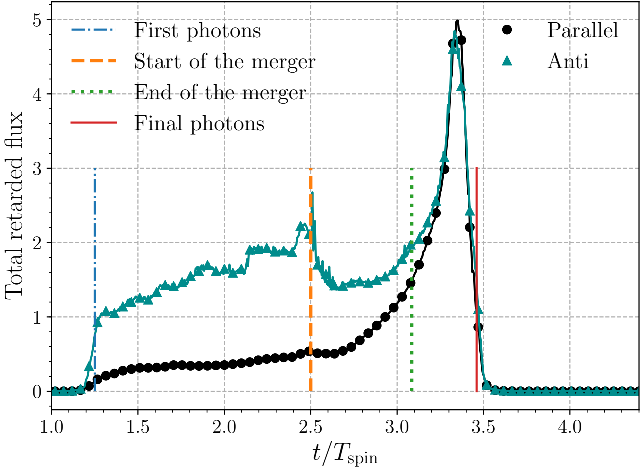


$\eta_{\not\parallel} = 22.5\% \rightarrow$ Enhanced radiation at inner poles

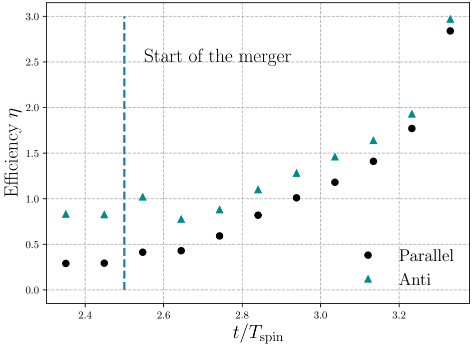




Lightcurve constructed by collecting photons according to the observation angle and their time delay



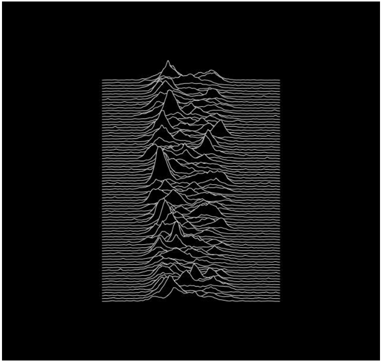
- **Before merger**: Parallel and anti-parallel configurations different
- **After merger**: Similar lightcurves → Common mechanism



- 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. More pessimistic expectations than theoretical works
2. 3D simulations with orbital motion would probably yield a more powerful outburst
3. Relation to Fast Radio Bursts?



Artwork of the album Unknown Pleasures by Joy Division.

Thank you for your attention!