Hybrid numerical simulation to model pulsar magnetospheres

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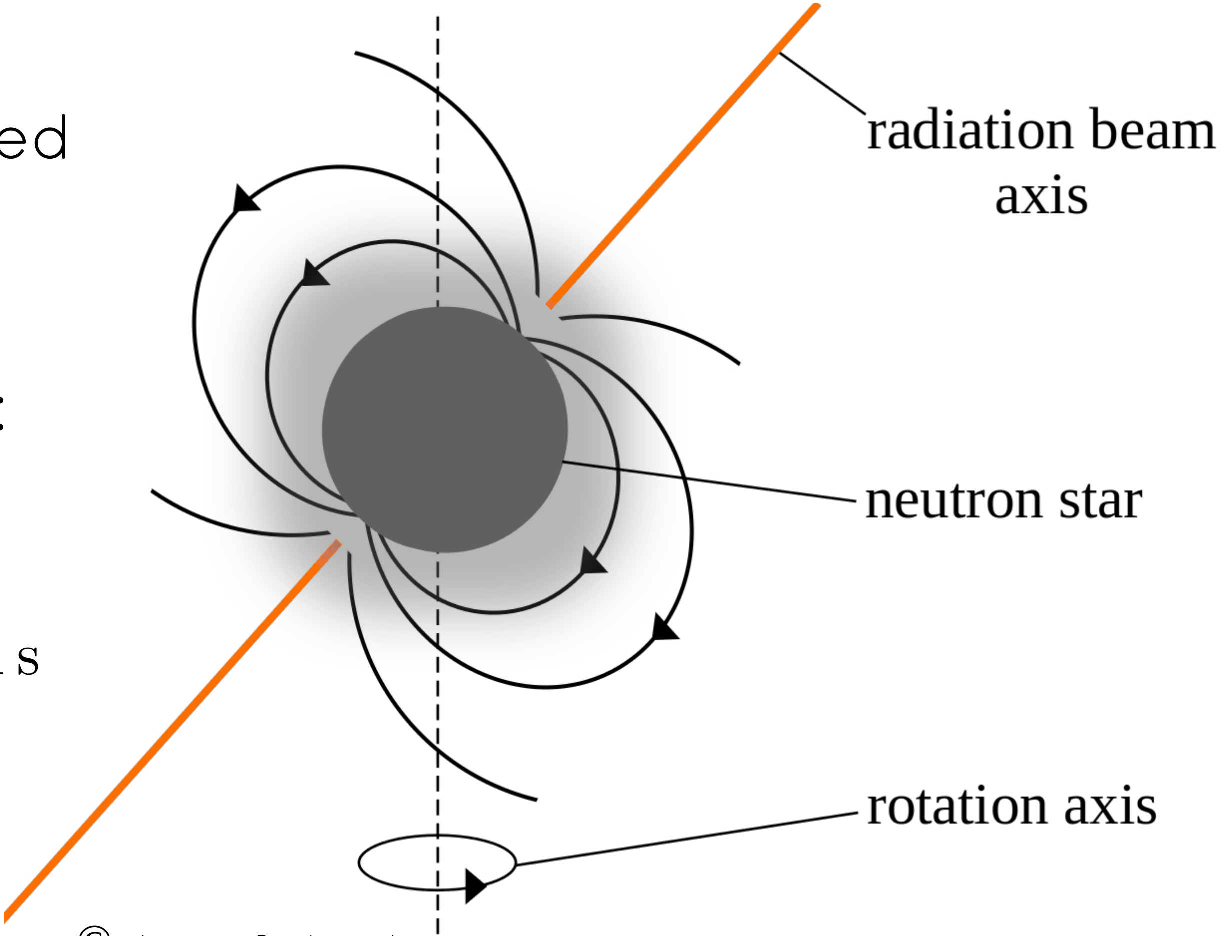
Canonical pulsar

Rotating, highly magnetized neutron star

Canonical radio pulsar:

- Surface magnetic field:
$$B_* = 10^9 - 10^{14}\,G$$
- Pulsed emission
- Spin period: $P = 1\,\mathrm{ms} - 1\,\mathrm{s}$



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Pulsar magnetosphere

Aligned pulsar

2D **axisymmetric**

Force free: magnetic field + conductive plasma

Perfectly conducting NS and magnetosphere

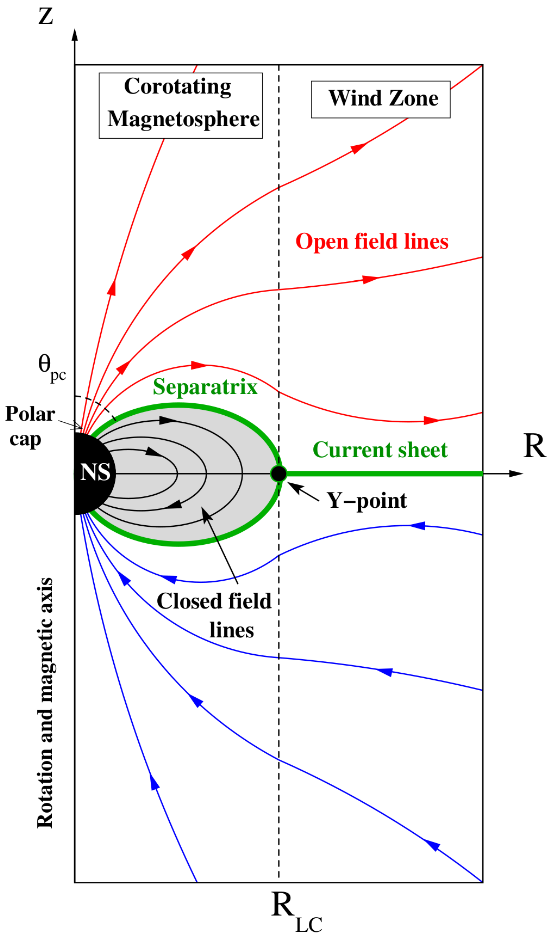
Fast rotator → electric field

Current sheet: relativistic reconnection, particle acceleration, pulsed emission

Light cylinder $R_{LC} = \frac{c}{\Omega}$

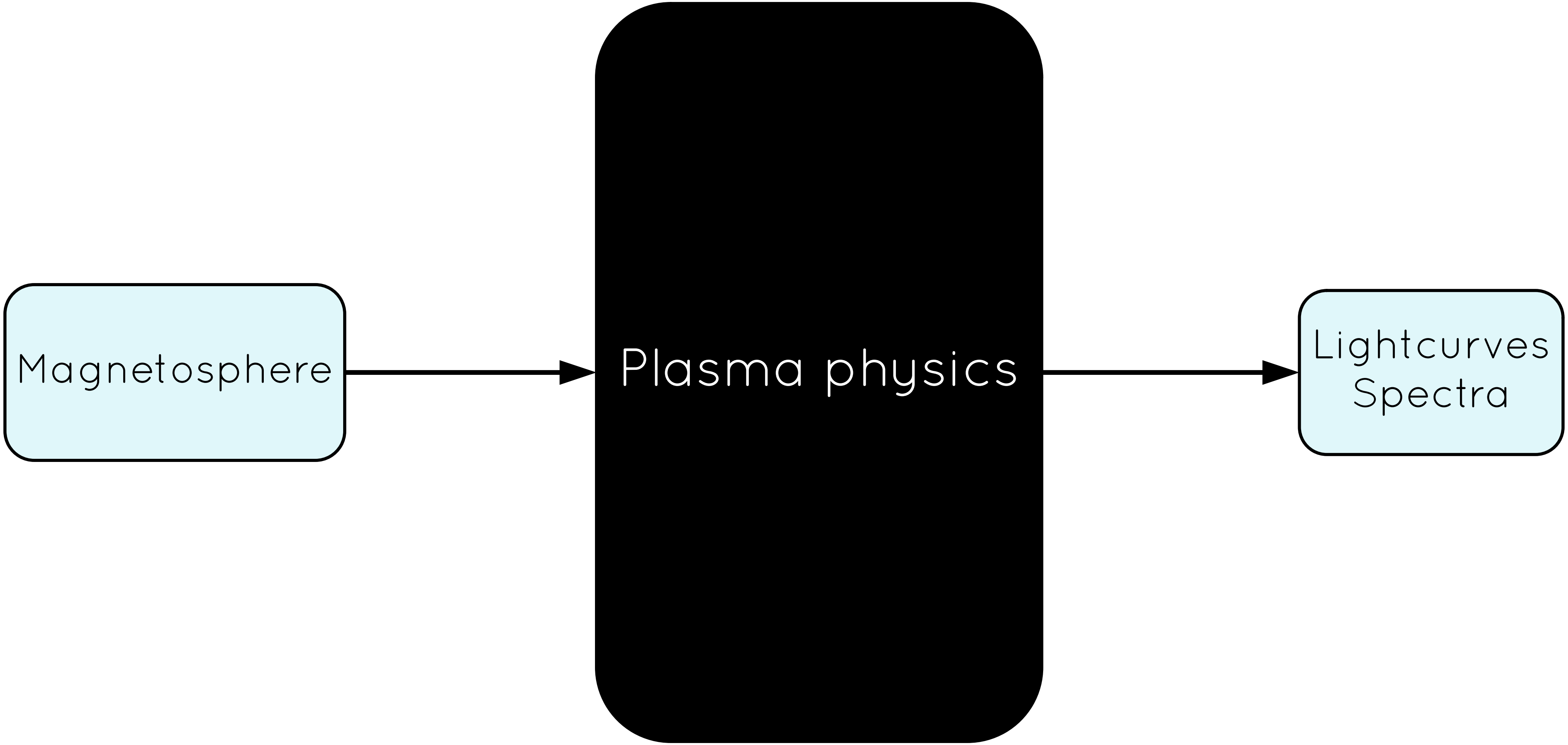
Closed field lines = corotating magnetosphere

Open field lines = wind zone

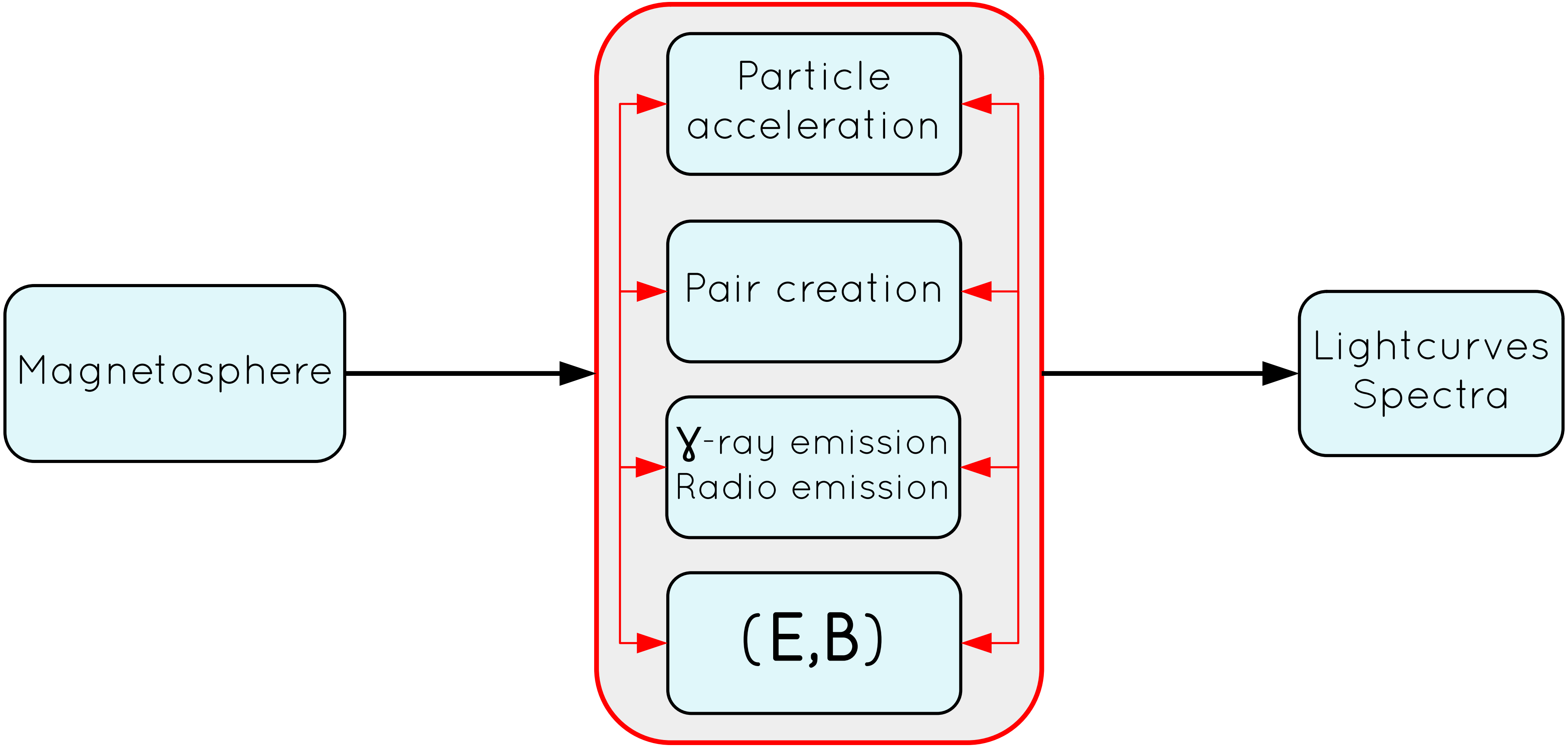


[Cerutti, B., & Beloborodov, A. M. (2017).]

Particle acceleration



Particle acceleration



Numerical approaches

Force-Free Electrodynamics vs Particle-in-Cell

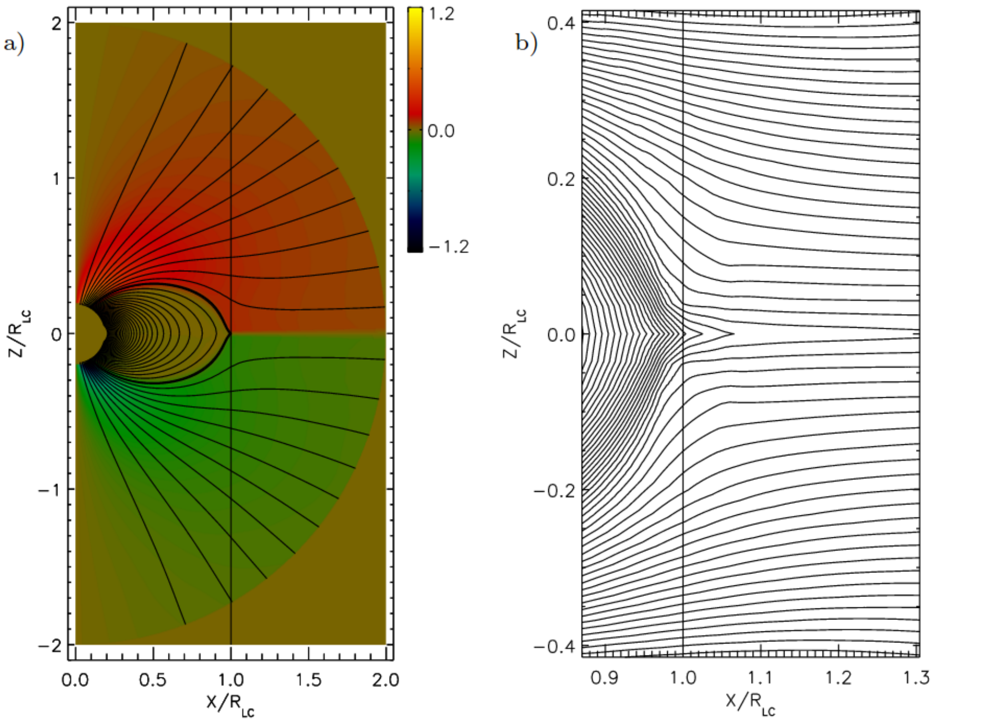


Fig: Aligned dipole magnetosphere. a) Poloidal fieldlines of steady state solution. b) Zoom in near the Y-point. [Spitkovsky, A. (2006)]

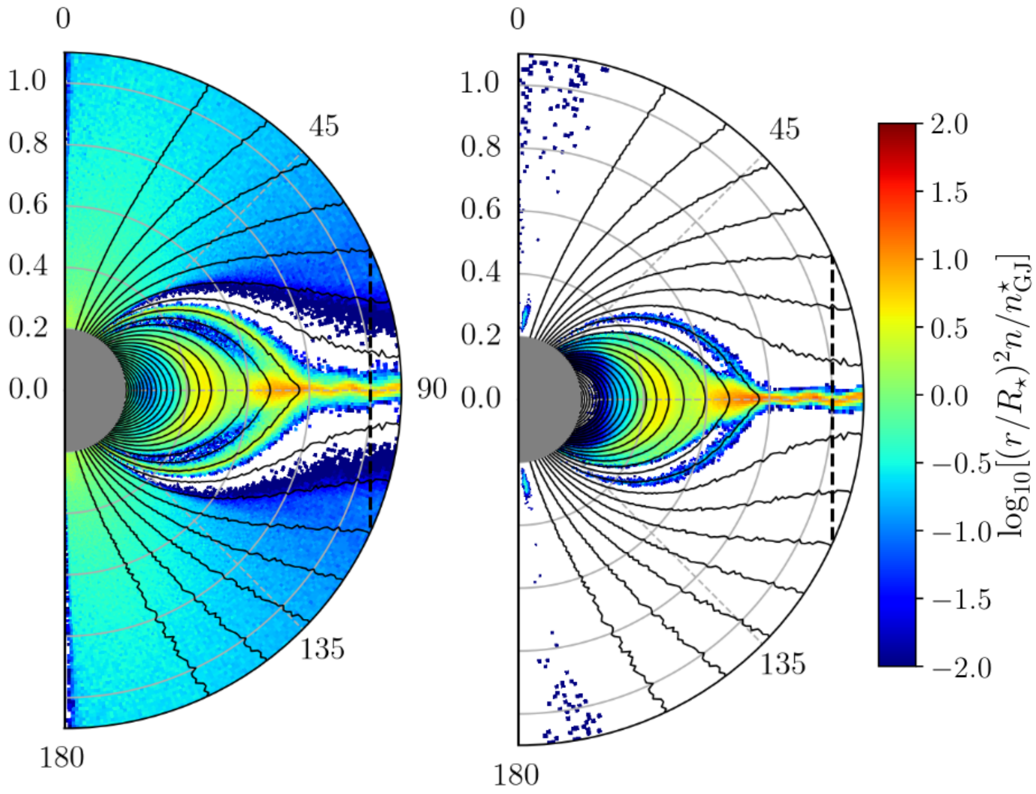


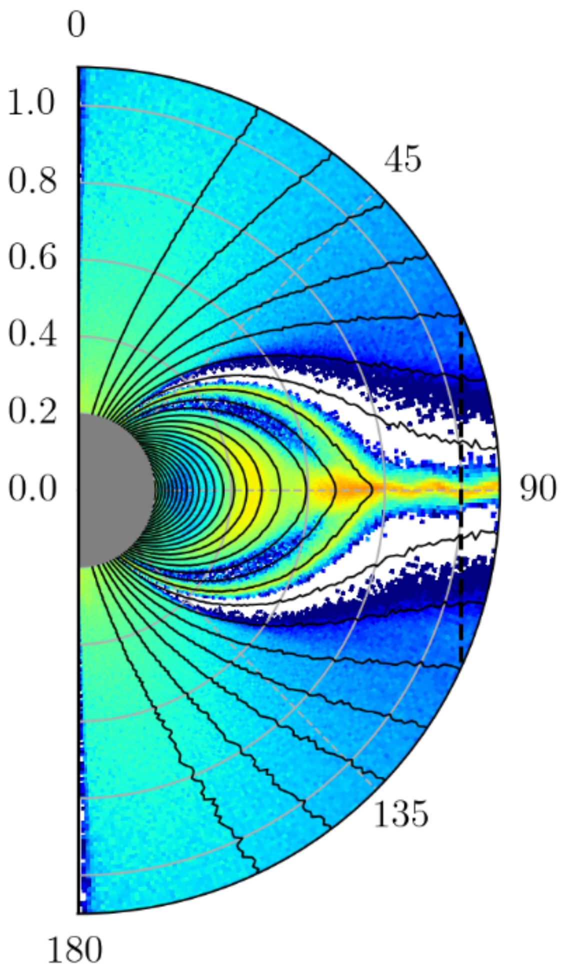
Fig: Density maps of electrons and positrons (left and right) with a zoom in near the Y-point [Guépin, C. et al (2017)]

Scale separation problem

- **Global** PIC simulations **must resolve plasma scales:**

$$r_L \ll R_{LC}$$

- Scale separation issue:
  - Skin depth: $\delta_E = 1\text{cm} - 1\text{m}$
  - Star radius: $r_* = 10\text{km}$
  - Light cylinder radius: $R_{LC} = 50 - 5000\text{km}$
- Realistic scale separation: 10^{5-7}
- PIC simulations are rescaled
  - Scale separation: 10^3
- Are results of PIC simulations still **valid** for larger scale separations?



Comparison

Method	PIC	FFE
Particle acceleration		
Large scales		
Microphysics		
Energy dissipation		
Computational time		

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Method	PIC	FFE
Particle acceleration	✓	✗
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Particle acceleration	✓	✗
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Microphysics	✓	✗
Energy dissipation	✓	✗
Computational time	✗	✓

Motivations

Complementarity between PIC and FFE!

↓

Build a HYBRID method combining both in the same numerical framework to bridge the scale separation gap

Method	PIC	FFE
Particle acceleration	✓	✗
Large scales	✗	✓
Microphysics	✓	✗
Energy dissipation	✓	✗
Computational time	✗	✓

Hybrid method

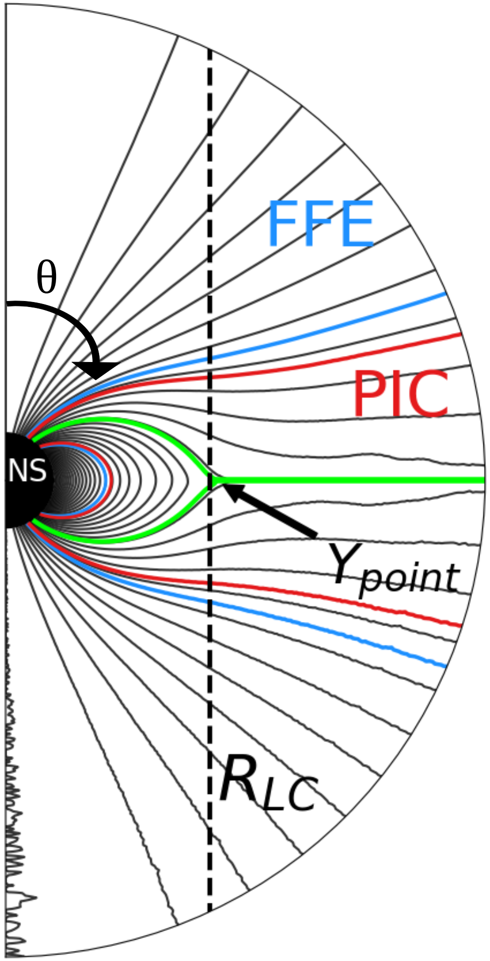
Hybrid criterion

- Domain separation criterion:

  Magnetic flux function $\Psi = \iint \mathbf{B} \cdot \mathrm{d}\mathbf{S}$

- Isocontours of Ψ = magnetic field lines
- Transition zone
- Separatrix inside the PIC domain
- Computing power focused on the current sheet

[Cerutti, B. et al. (2013)]



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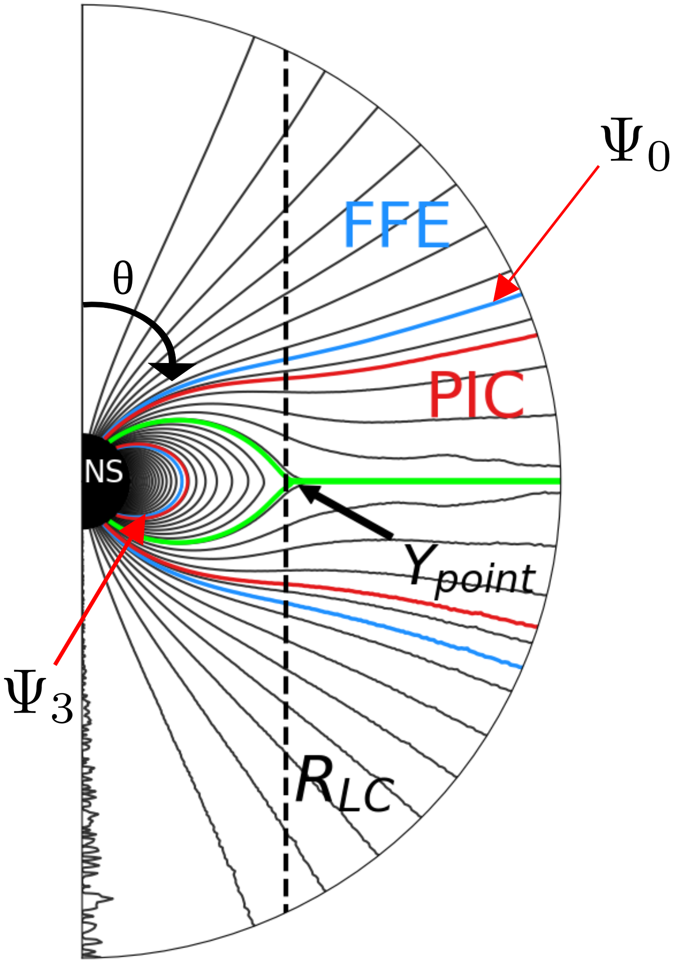
If $\Psi \in [\Psi_0, \Psi_3]$:

↳ PIC

Else:

↳ FFE

[Cerutti, B. et al. (2013)]



Coupling

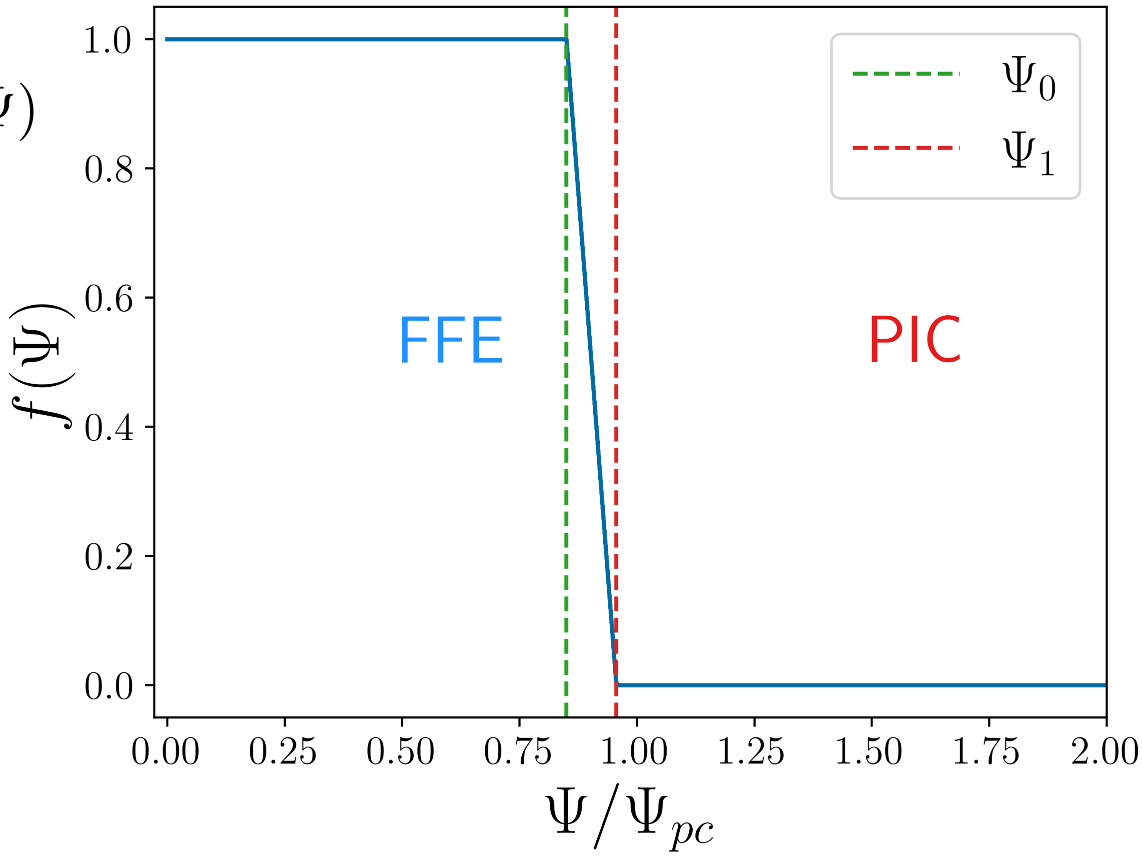
Current density:

$$\mathbf{J} = \mathbf{J}_{\text{PIC}} \cdot (1 - f(\Psi)) + \mathbf{J}_{\text{FFE}} \cdot f(\Psi)$$

Linear interpolation on Ψ

Thickness: $\Psi_1 - \Psi_0 = 0,1\Psi_{PC}$

$$\Psi_{PC} = \frac{B_* r_*^3}{R_{LC}}$$



Aligned dipole

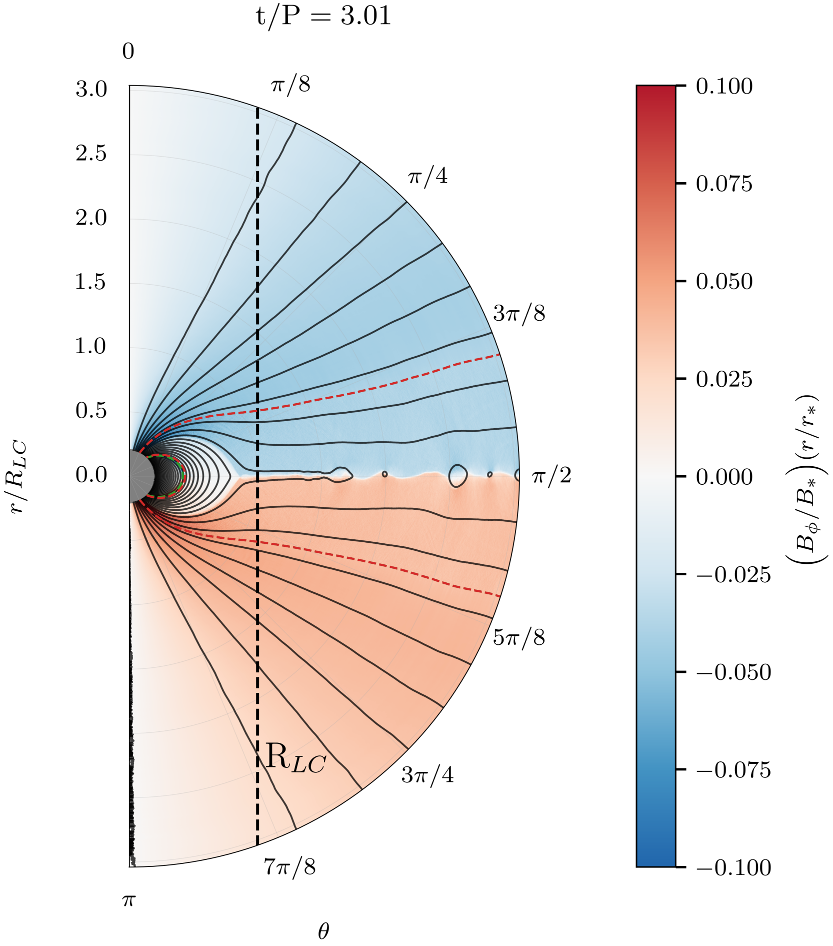
Simulation parameters

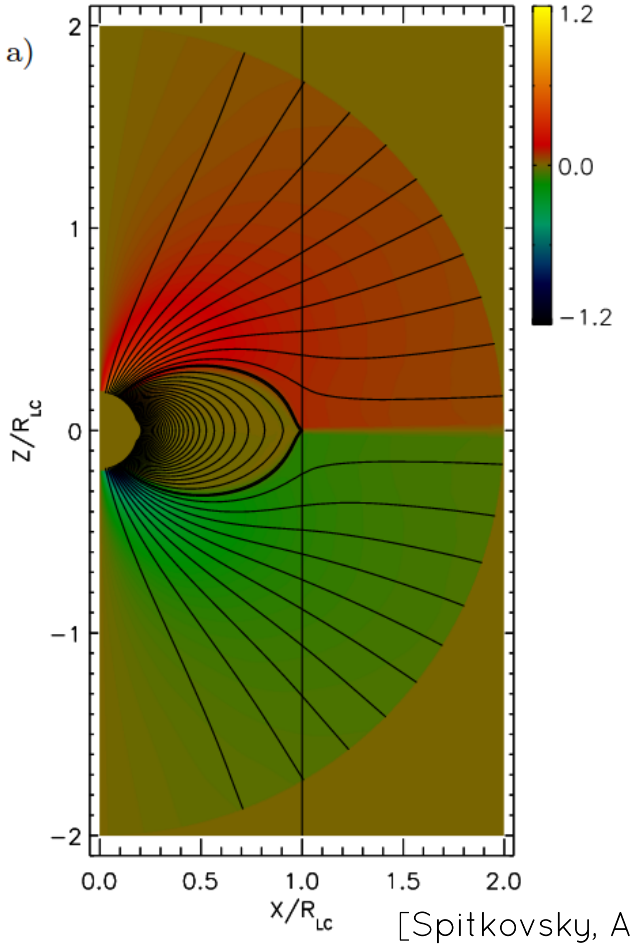
Resolution	(r,θ)=(4096,4096)
Star radius	$\mathrm{r}_* = 10\,\mathrm{km}$
Inner edge	$r_{min} = r_*$
Light cylinder	$R_{LC} = 5r_* \quad (\mathrm{P} = 1\mathrm{ms})$
Outer edge	$r_{Max} = 3R_{LC}$
Field amplitude	$B_0 = 10^6\mathrm{G}$
Particle injection	Extracted from the NS by **E**
Radiative losses	ON

Simulation parameters

Scale separation	$\mathrm{d}_e/r_* = 2 \times 10^{-5}$
Plasma composition	Pairs (+ creation) & protons
Mass ratio	$\mathrm{m}_i/m_e = 1836$
Polar cap Lorentz factor	$\gamma_{pc} = 1,33 \times 10^7$
Threshold	$\gamma_{thr} = 0,05\gamma_{pc}$
Secondary Lorentz factor	$\gamma_s = 0,1\gamma_{thr}$

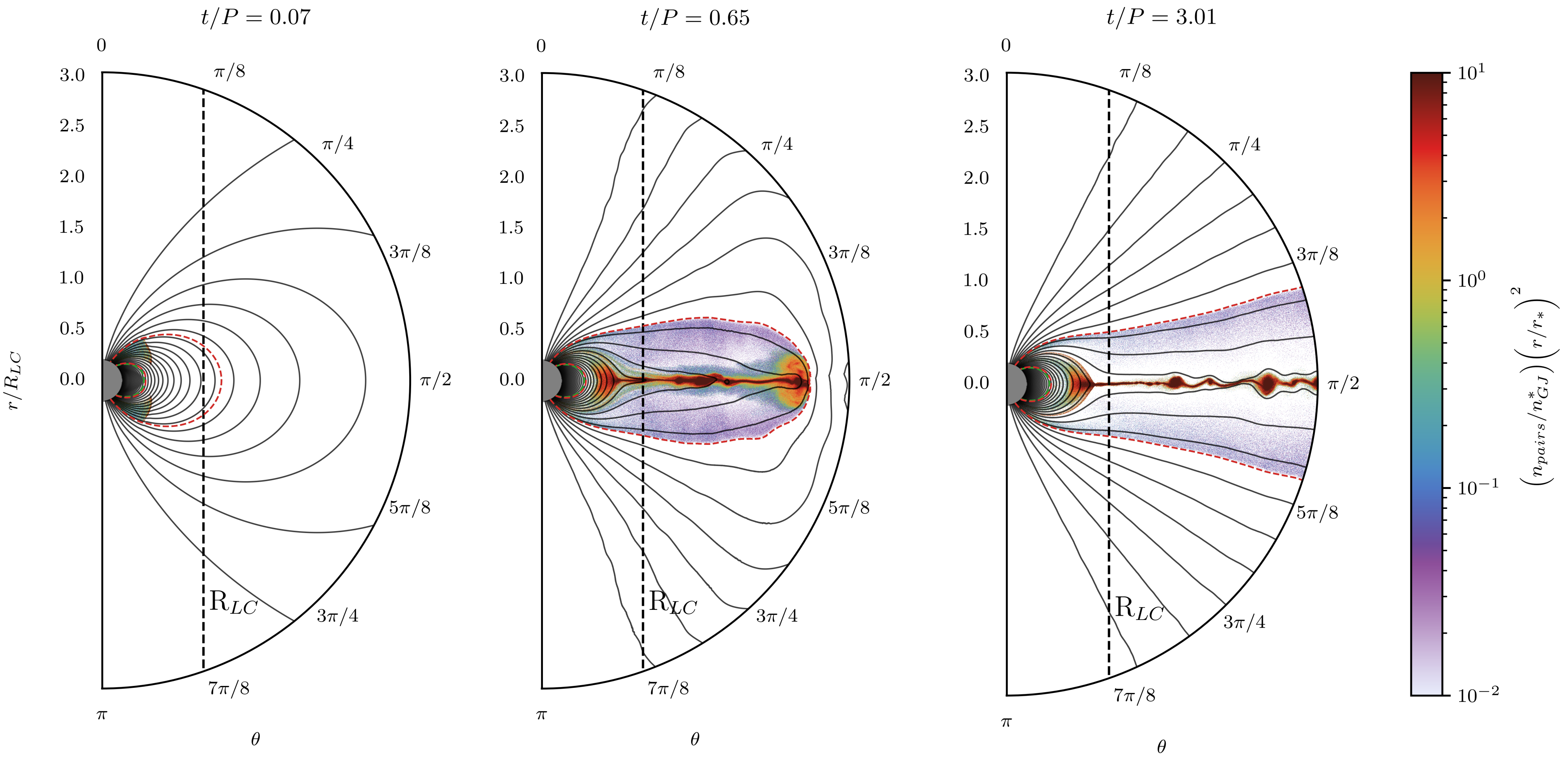
Magnetosphere



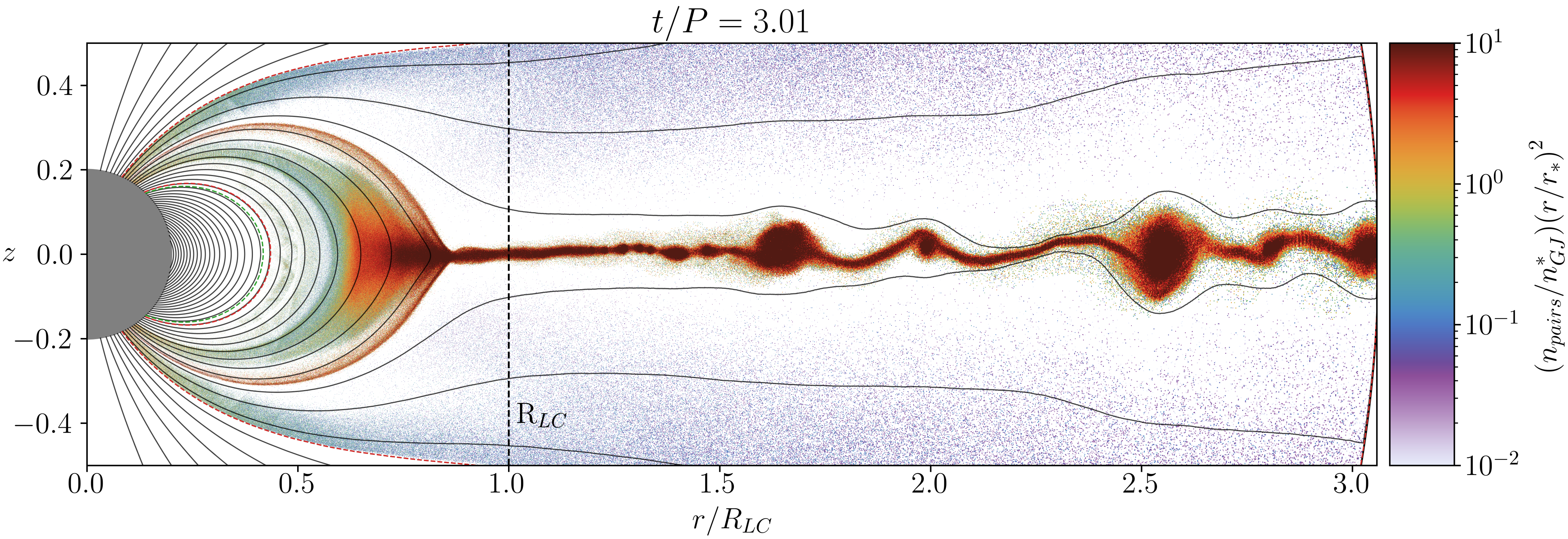


[Spitkovsky, A. (2006)]

Pairs density

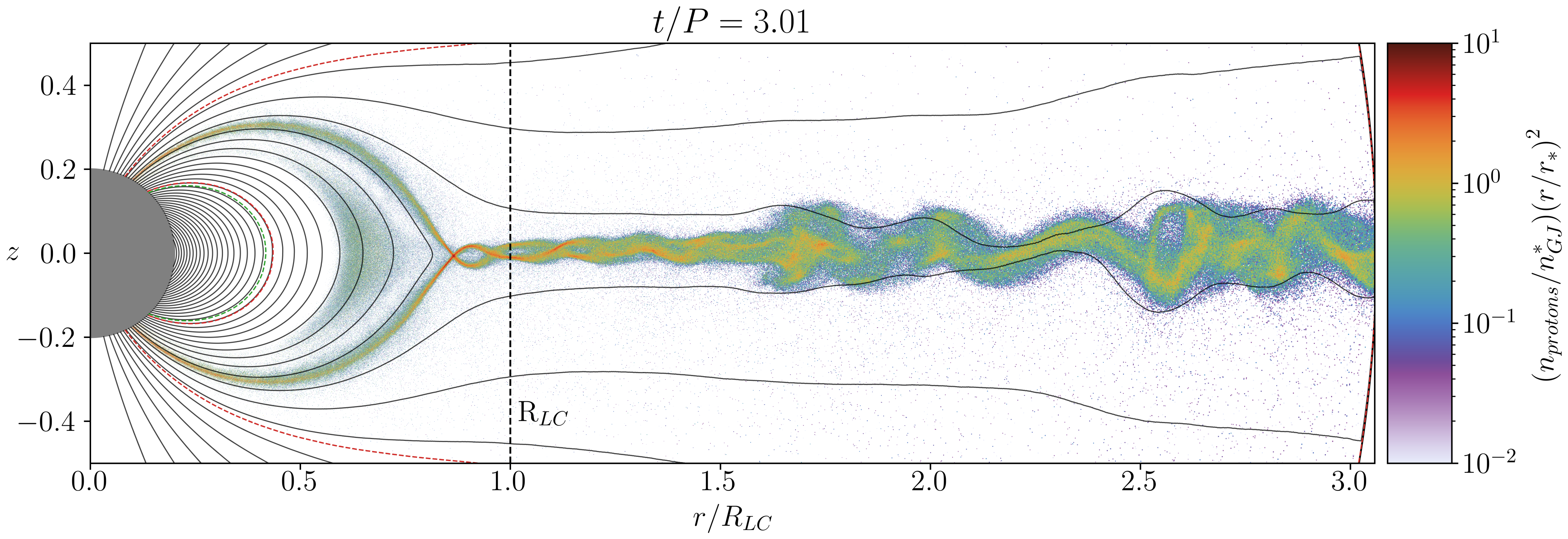


Pairs density



[Soudais, A. & Cerutti, B., (in prep.)]

Protons density



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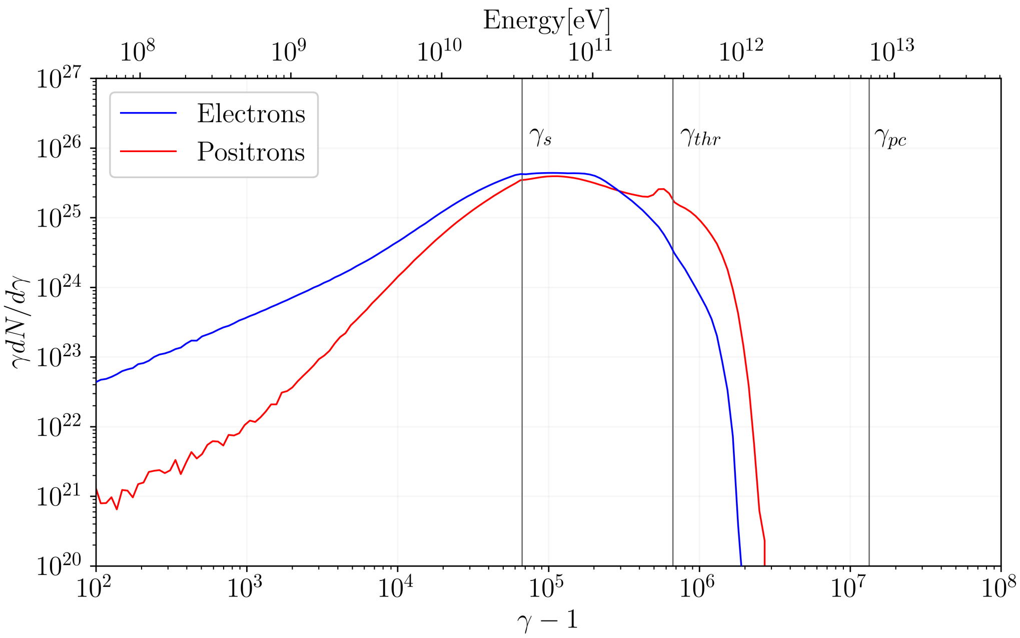
Spectra



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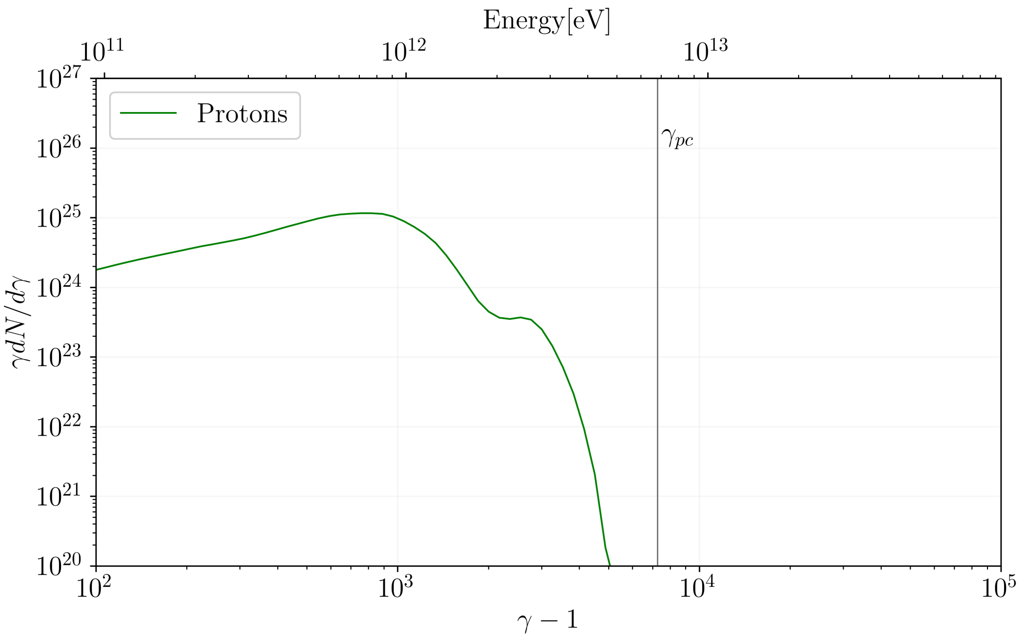
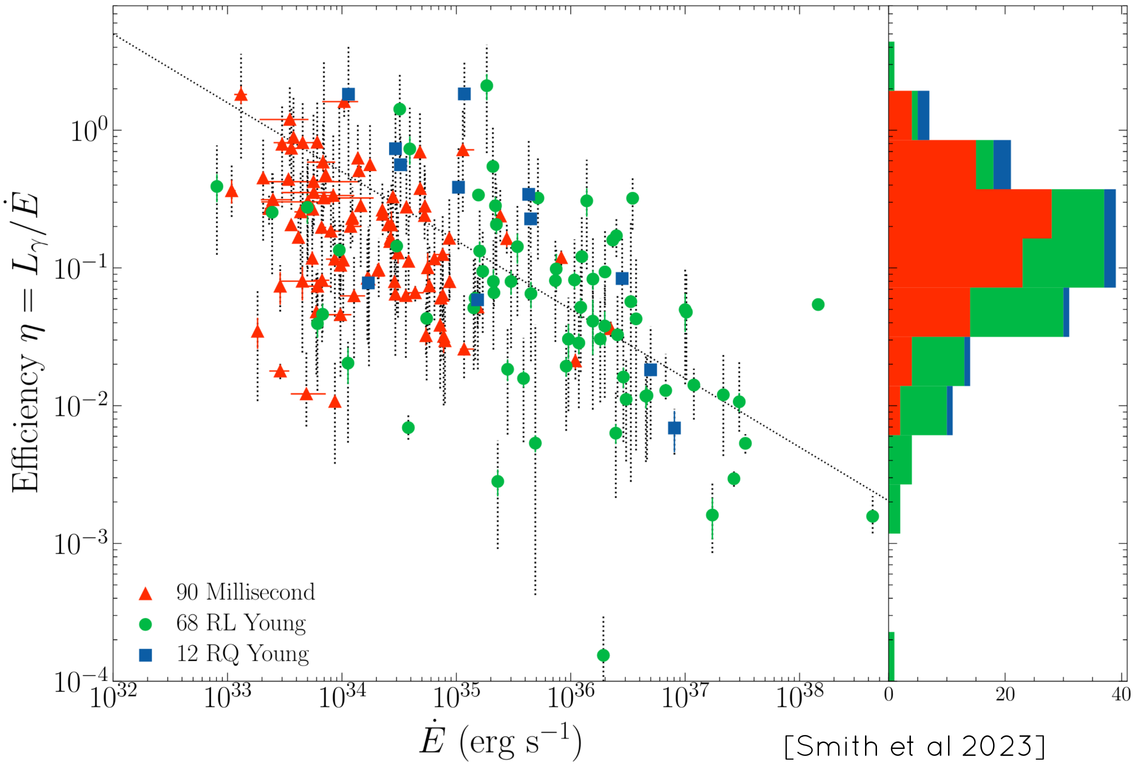


$$\gamma_{max} \approx 0.1\gamma_{pc}$$

[Guépin, C. et al (2017)]

Fermi pulsars (3PC)



[Smith et al 2023]

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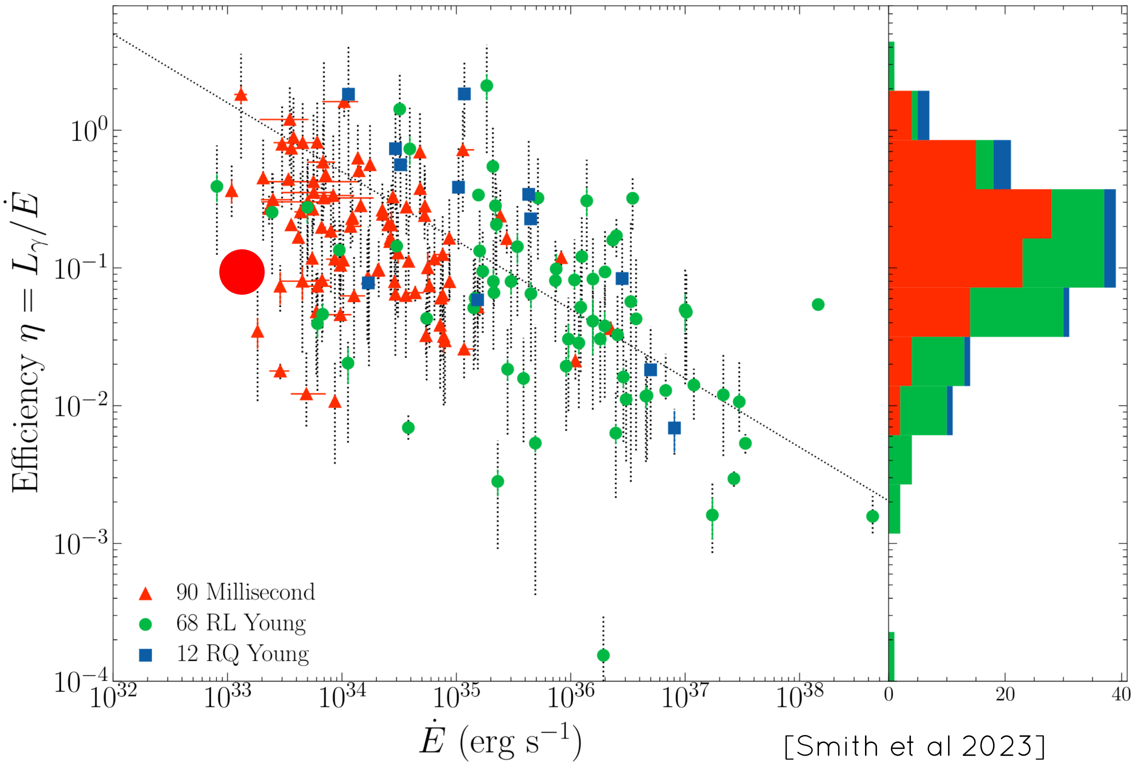

[Smith et al 2023]

On going run: 10^7G
Weak millisecond pulsar in the Fermi-LAT range

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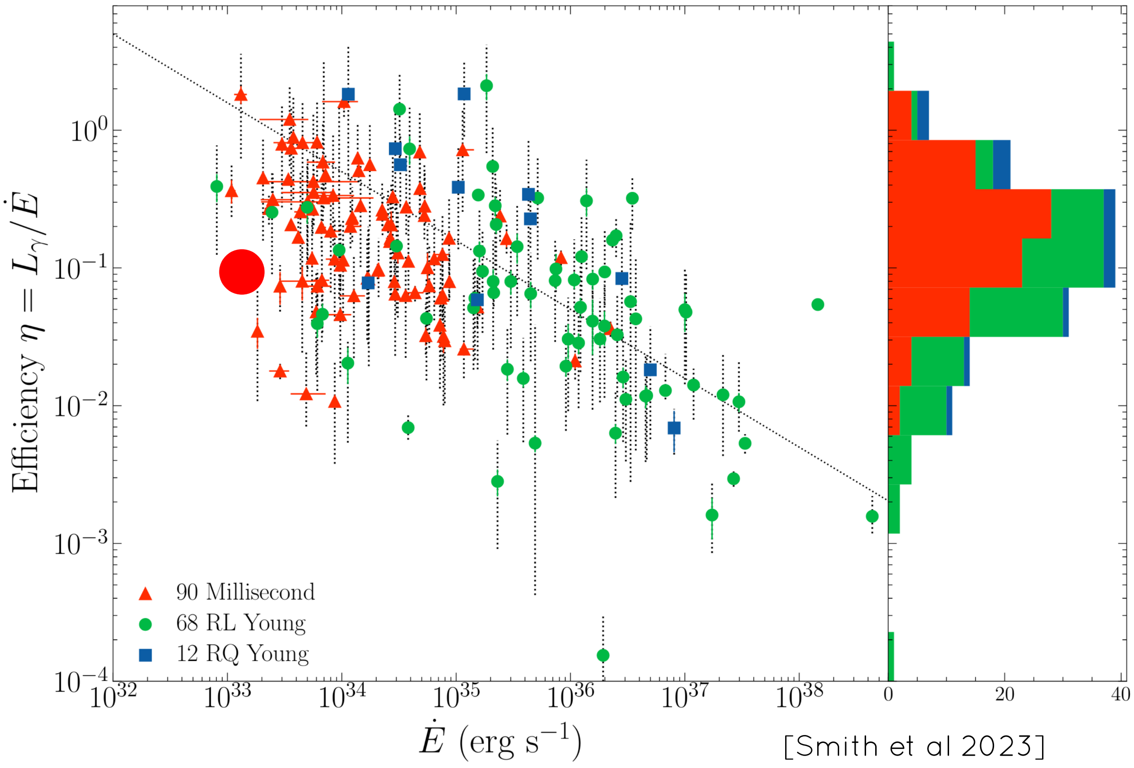

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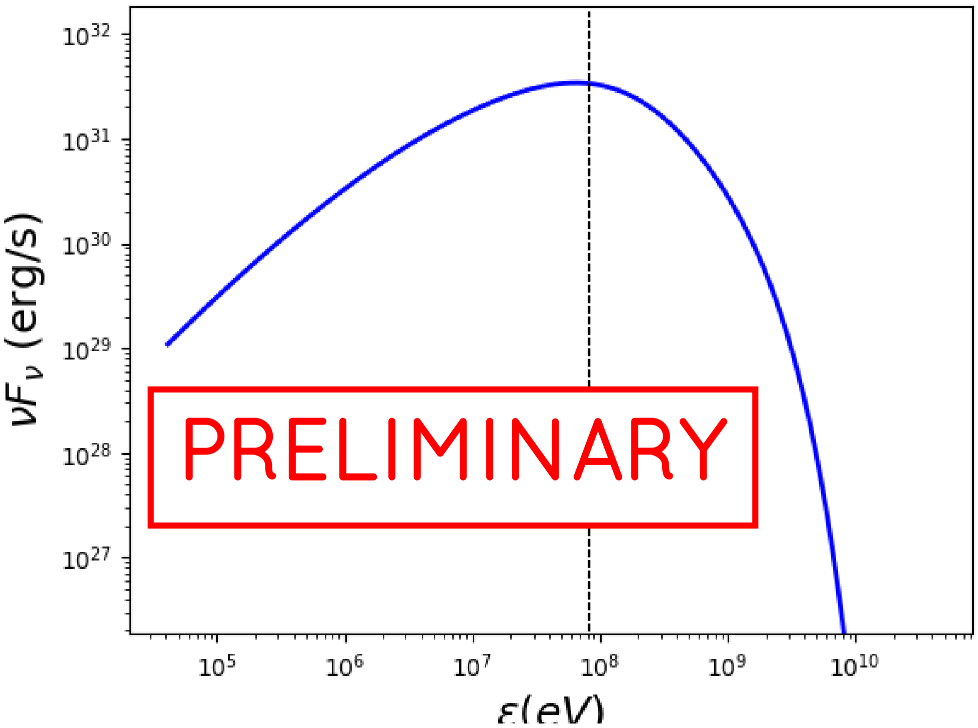

Conclusion & Perspectives

- Recover magnetosphere, plasmoids, separatrix, spectra
- One ms pulsar with 10^7 G simulation to scale
- Direct evidence of synchrotron and gamma emissions (Fermi 3PC)
- On going developments : black hole magnetospheres (GRPIC+GRFFE)