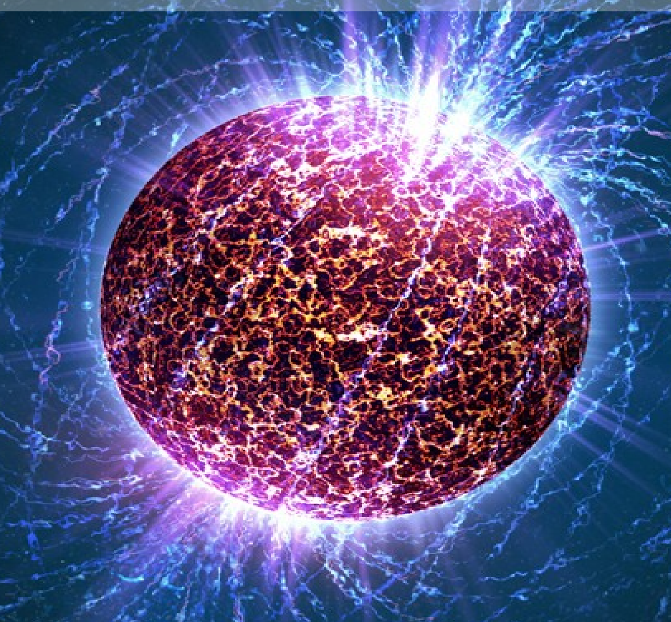
# Particle acceleration and radiation in pulsars

## New insights from PIC simulations



**Benoît Cerutti**

*CNRS & Université Grenoble Alpes, Grenoble, France.*

UNIVERSITÉ Grenoble Alpes

cnrs dépasser les frontières

IPAG Institut de Planétologie et d'Astrophysique de Grenoble

Astrosim seminar, Lyon, June 27, 2017

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# Pulsars are rapidly-rotating, high-magnetized neutron stars

NATURE, VOL. 217, FEBRUARY 24, 1968 709

## Observation of a Rapidly Pulsating Radio Source

by

A. HEWISH
S. J. BELL
J. D. H. PILKINGTON
P. F. SCOTT
R. A. COLLINS

Mullard Radio Astronomy Observatory,
Cavendish Laboratory,
University of Cambridge

Unusual signals from pulsating radio sources have been recorded at the Mullard Radio Astronomy Observatory. The radiation seems to come from local objects within the galaxy, and may be associated with oscillations of white dwarf or neutron stars.

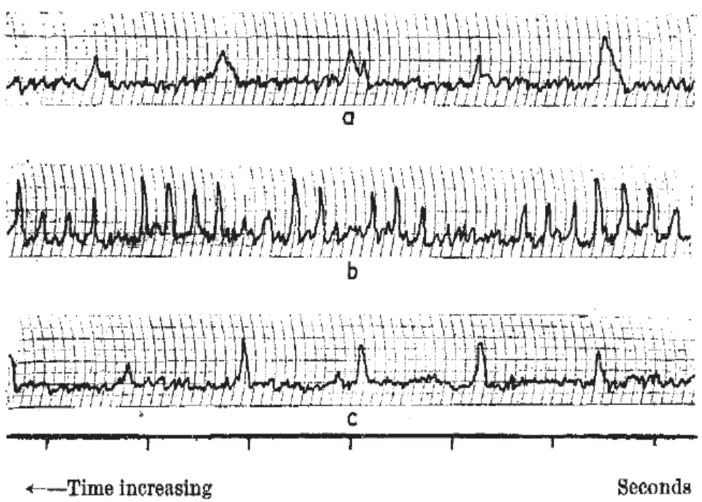
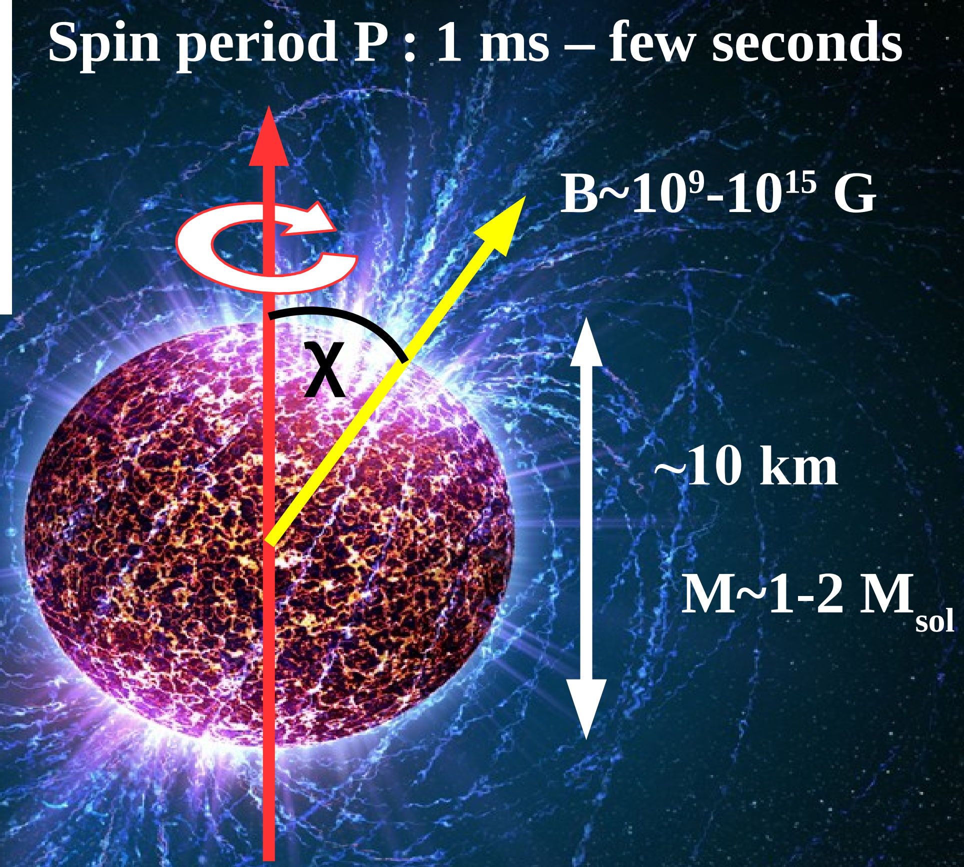



Fig. 1. Pulses observed with a recording time constant of about 0·03 s on March 21, 1968. (a) CP.0834. (b) CP.0950, during a period of intense activity. (c) CP.1133.




**Pulsars represent great laboratories to explore extreme physical conditions :**

Extreme **electromagnetic** fields, test for **General Relativity**, **ultra-dense** matter (equation of state), **pair creation** , **particle acceleration** **and** **radiation**, **relativistic** outflows.

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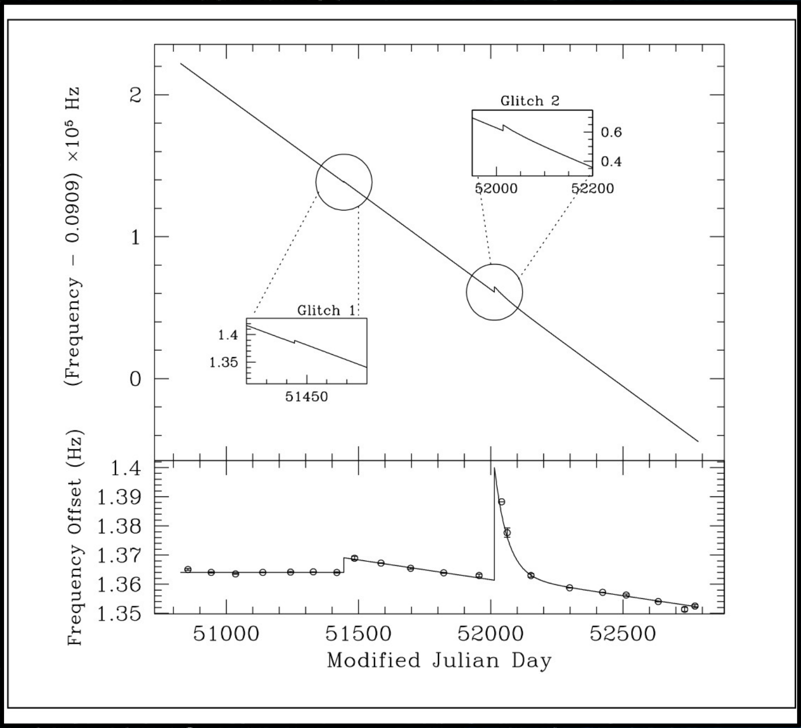
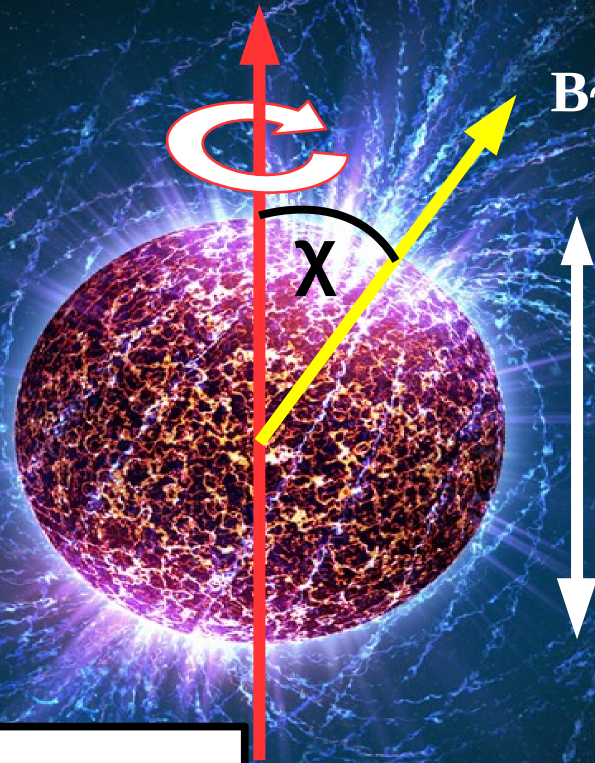
# Pulsars slowdown




*Kaspi & Gavrill (2003)*




<u>Measured with high-accuracy :</u>

**P :** rotation period
Gives the total **rotational energy** available

**dP/dt** : period slowdown (increase)
Gives the total **power release** (**seen** and **unseen** !)

<u>**For a magnetic dipole in vacuum :**</u>

- Age : $T \propto P/\dot{P}$
- Magnetic field : $B \sin\chi \propto \sqrt{P\dot{P}}$

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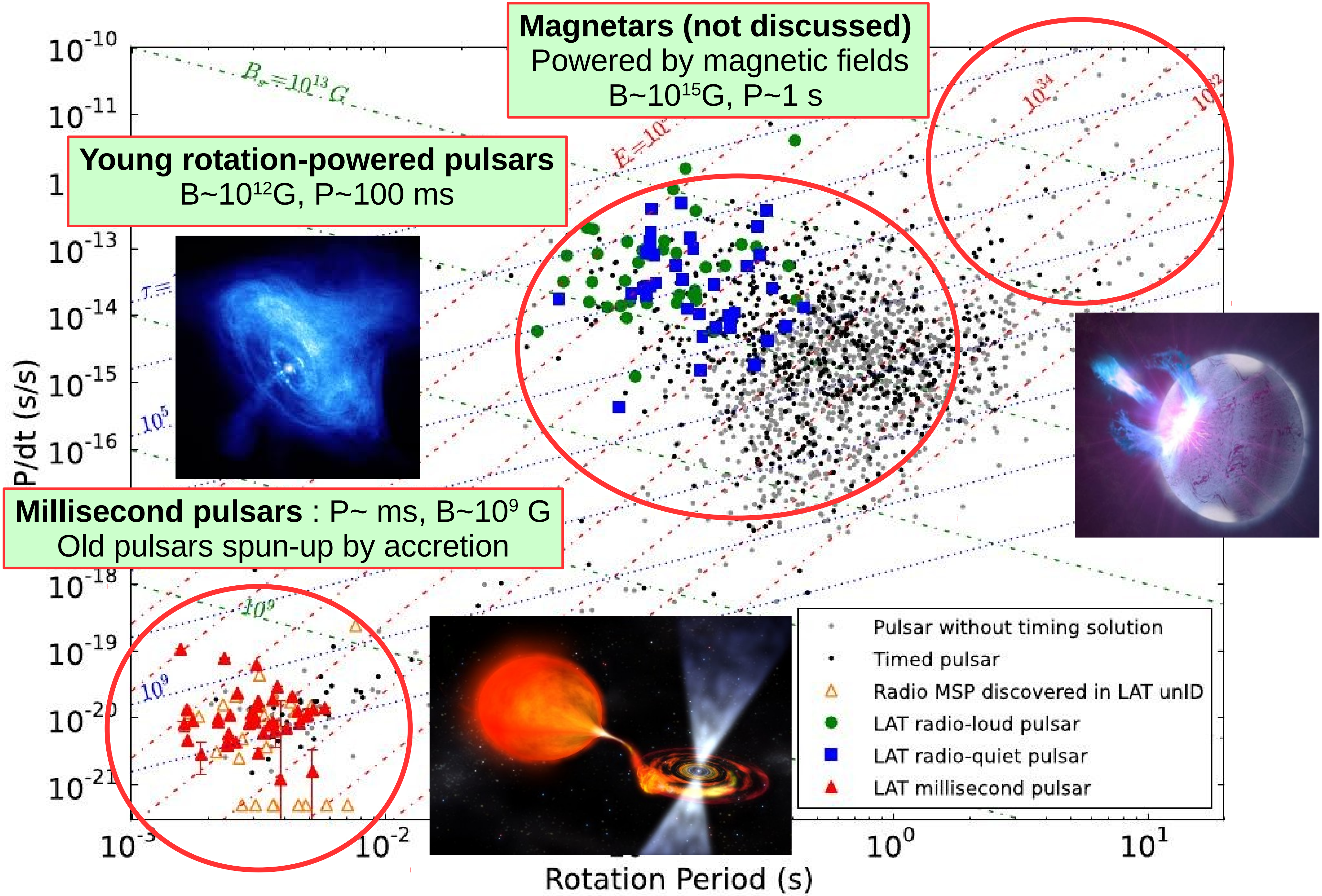
# The P-Pdot diagram : The HR diagram for pulsars

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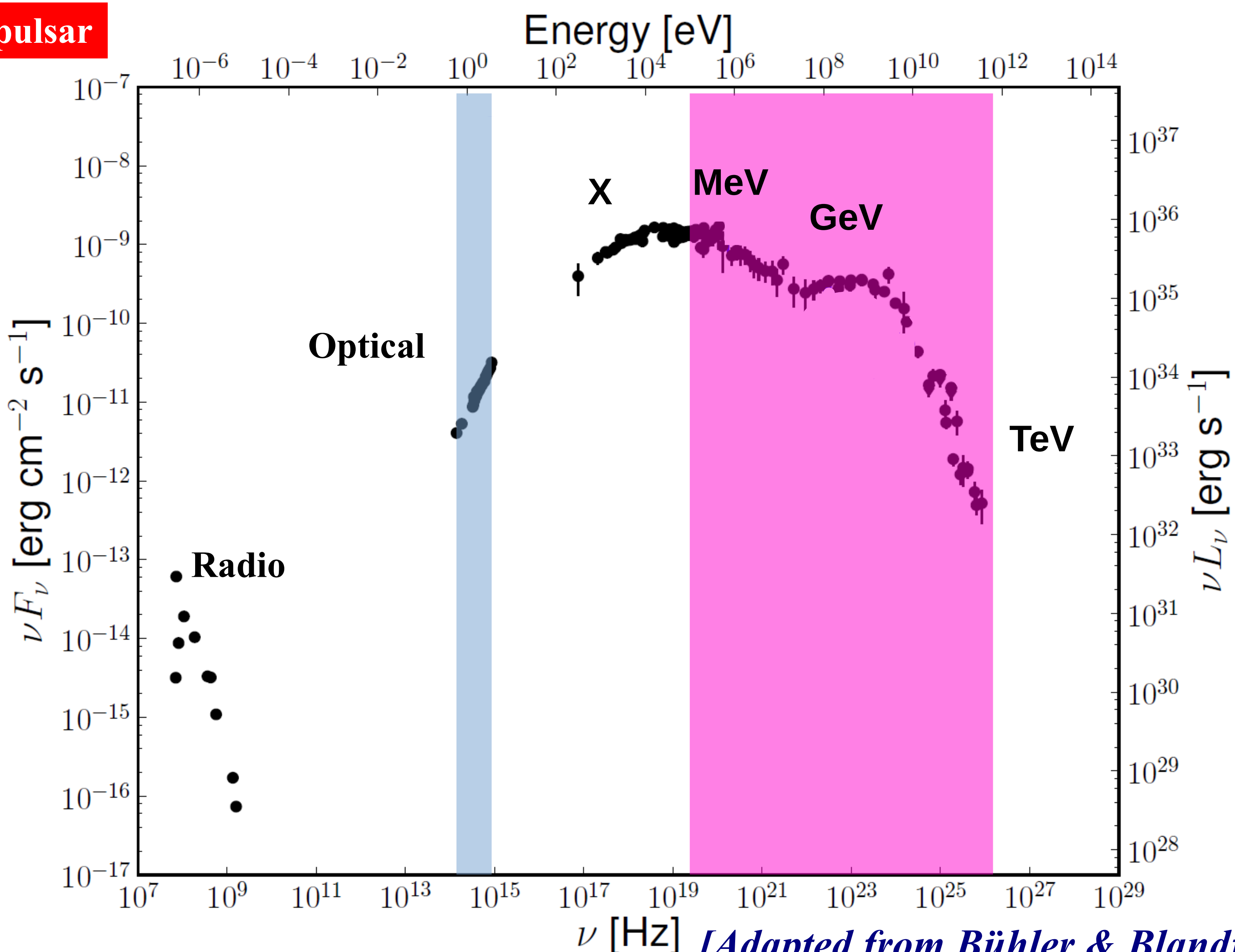
*[2nd Fermi-LAT pulsar catalog]*

# Pulsars shine throughout the electromagnetic spectrum

The Crab pulsar




*[Adapted from Bühler & Blandford 2014]*

**A large fraction of the pulsar spindown is released in light, in particular in the gamma-ray band. => Efficient particle acceleration !**

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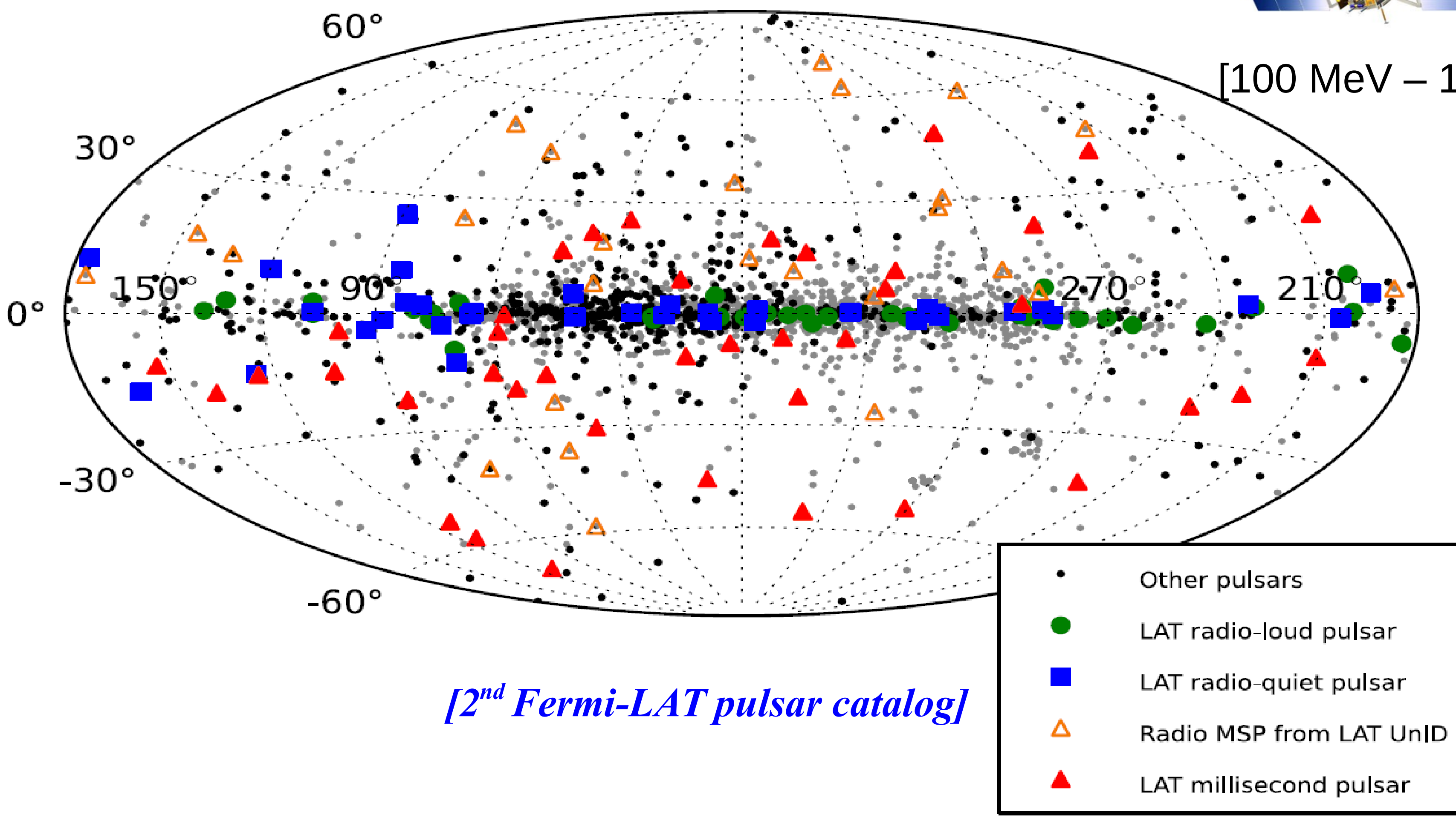
# Most Galactic accelerators are pulsars

**~ 100 gamma-ray pulsars**

***Fermi*-LAT**

[100 MeV – 100 GeV]

**Galactic coordinates**




*[2nd Fermi-LAT pulsar catalog]*

**Exquisite gamma-ray data put tight constraints on particle acceleration models**

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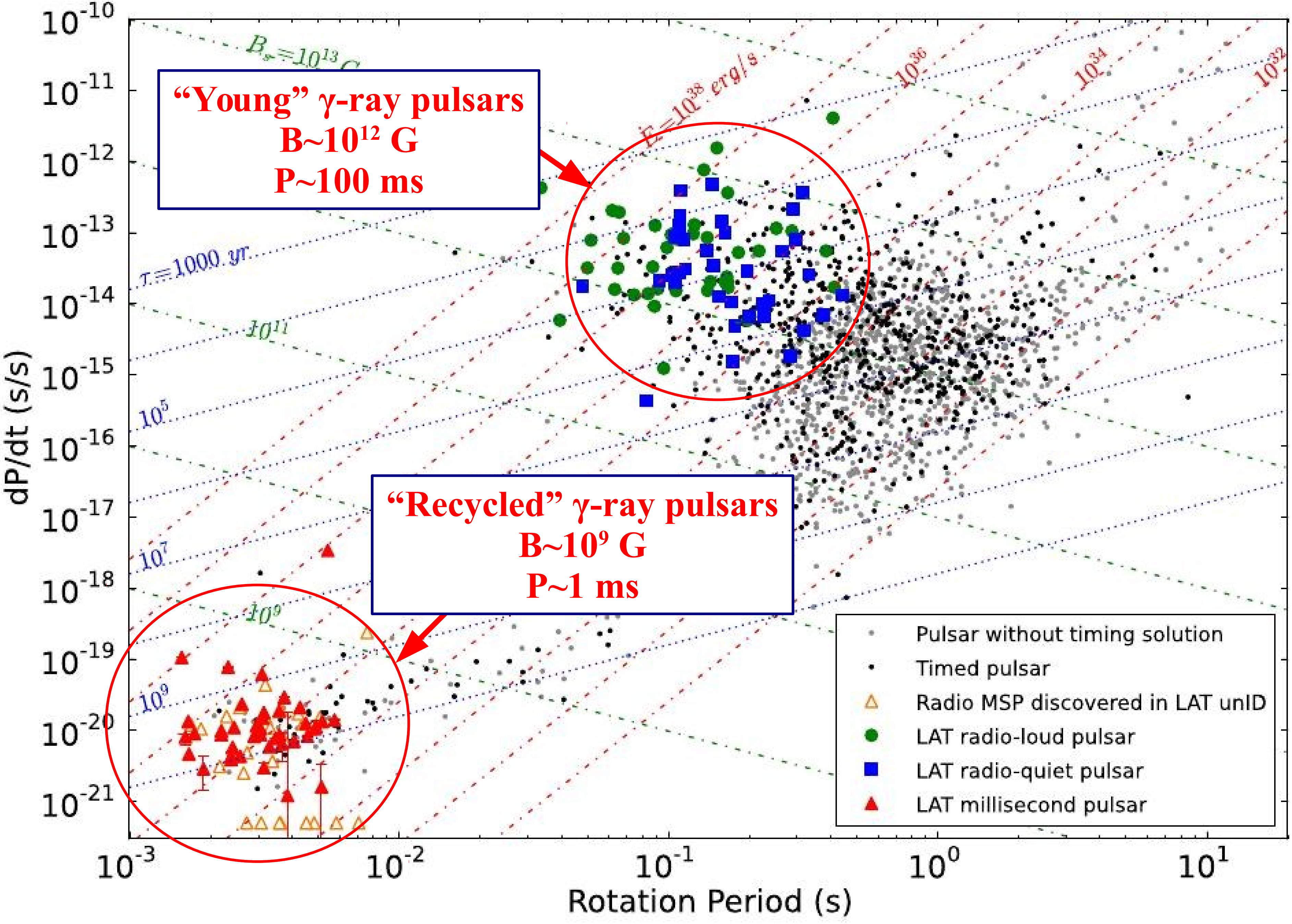
# Pulsars emitting gamma rays: Rotation-powered

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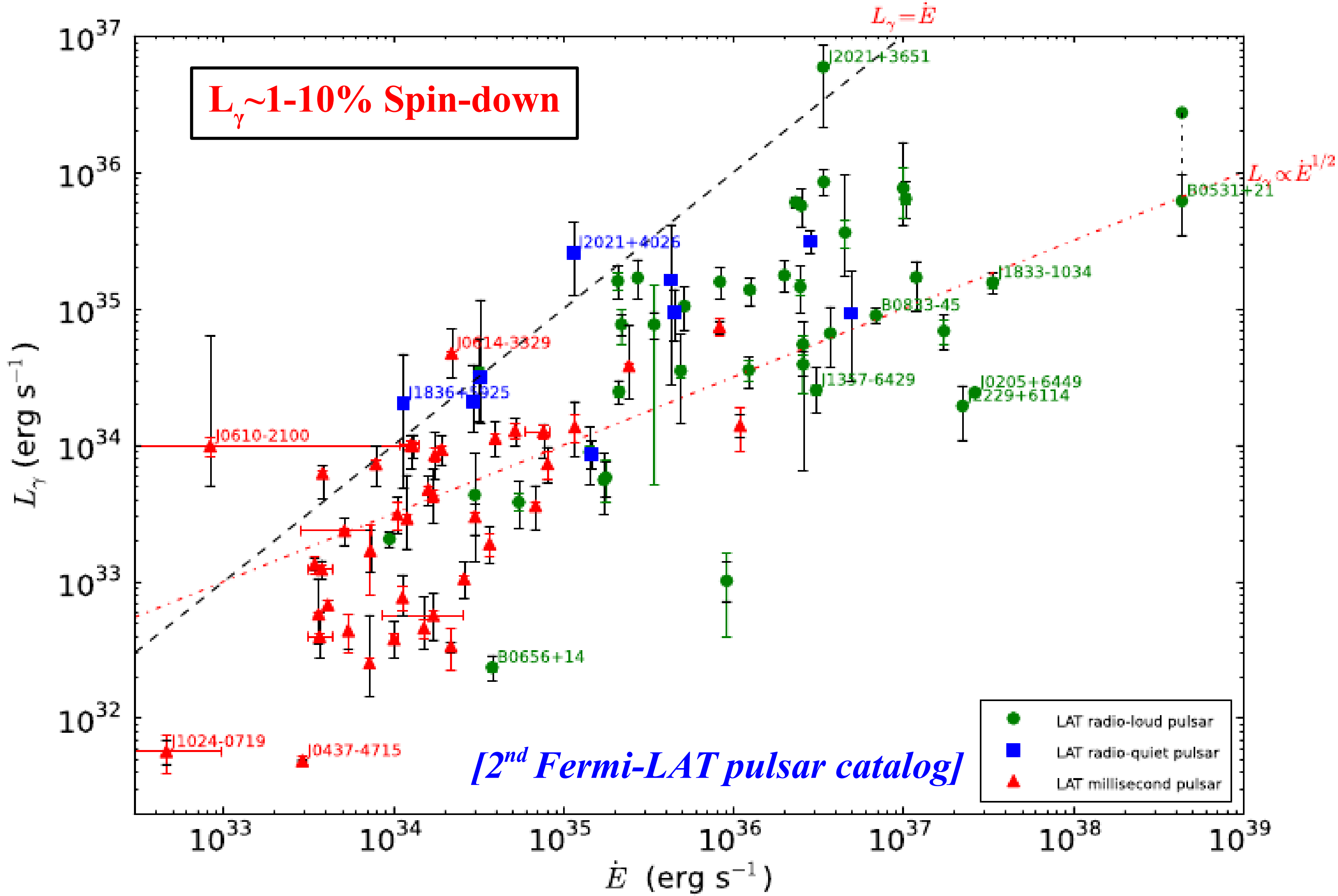
*[2nd Fermi-LAT pulsar catalog]*

# Pulsars are efficient particle accelerators




**How does the star spin-down?**
**How is this energy transferred to particles and radiation?**

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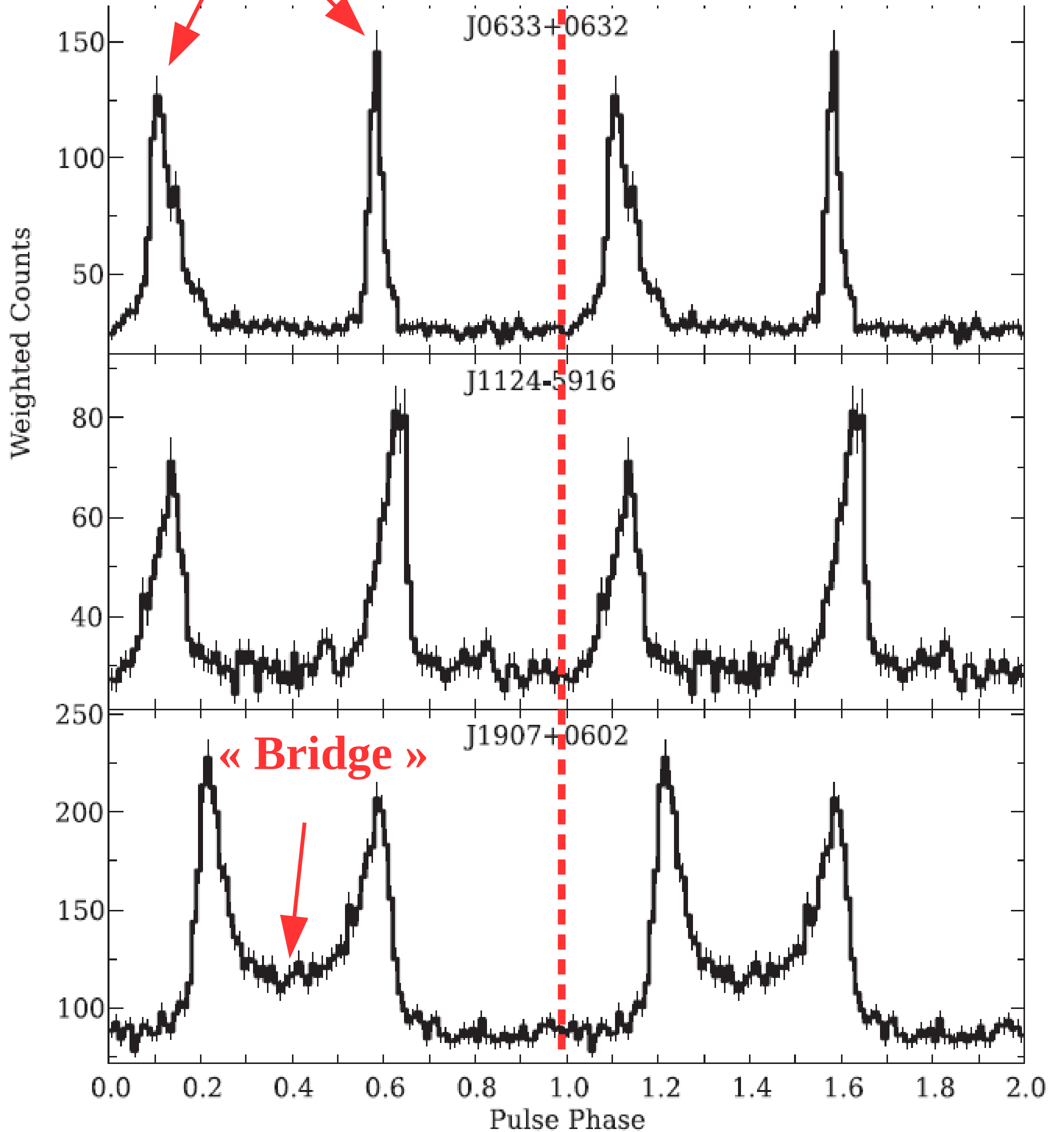
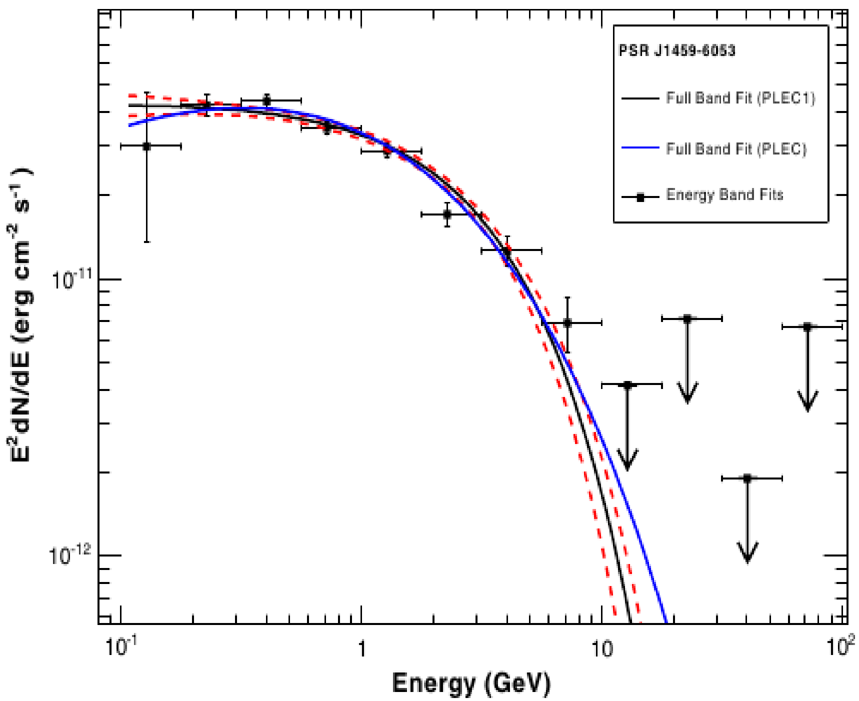
# Typical gamma-ray pulsar signal

Two peaks lightcurves




Hard power-law + exponential cut-off




*[2nd Fermi-LAT pulsar catalog]*

**How are particle accelerated and radiate? Origin particle/photon spectra, cut-off?**

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# Some of the big questions

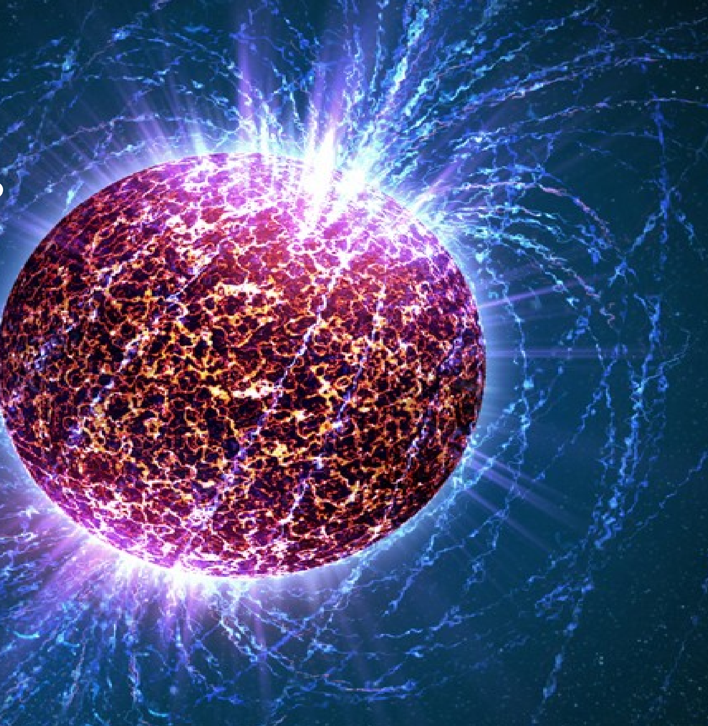
**How does the star spin-down?**

**How is this energy channeled to particles and radiation?**

**How is the plasma generated?**

**How are particle accelerated and radiate?**

**Where is the emission coming from ?**



**=> To address these questions, we need a model of the magnetosphere!**



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# Elements of a pulsar magnetosphere: vaccum

(See review, e.g., **Cerutti & Beloborodov 2016**)

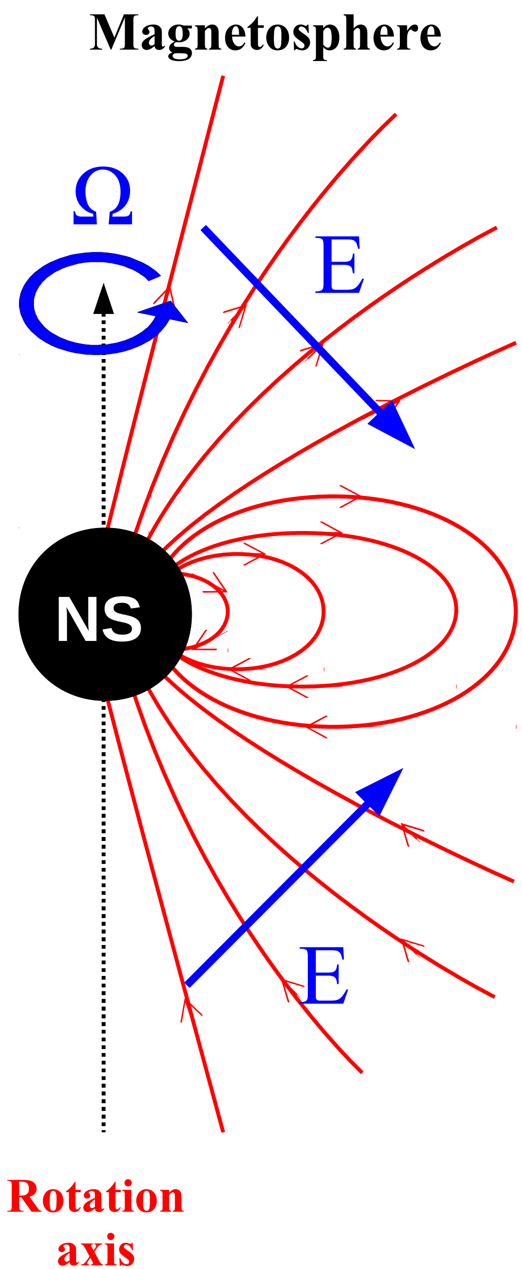
Rotation of the field lines induce electric field :

$$E = \frac{R\,\Omega\,B}{c}$$

Potential difference pole/equator :

$$\Delta\Phi = \frac{R^2\,\Omega\,B}{c} \approx 10^{18}\,V$$

(for a Crab-like pulsar)

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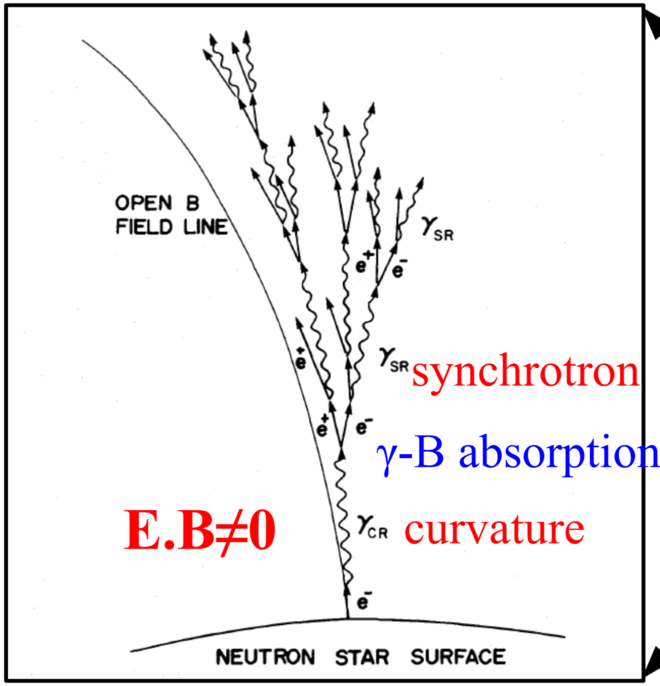
# Elements of a pulsar magnetosphere: plasma filled

**Dipole in vacuum is not a good model !**

**Copious pair creation in the polar caps**



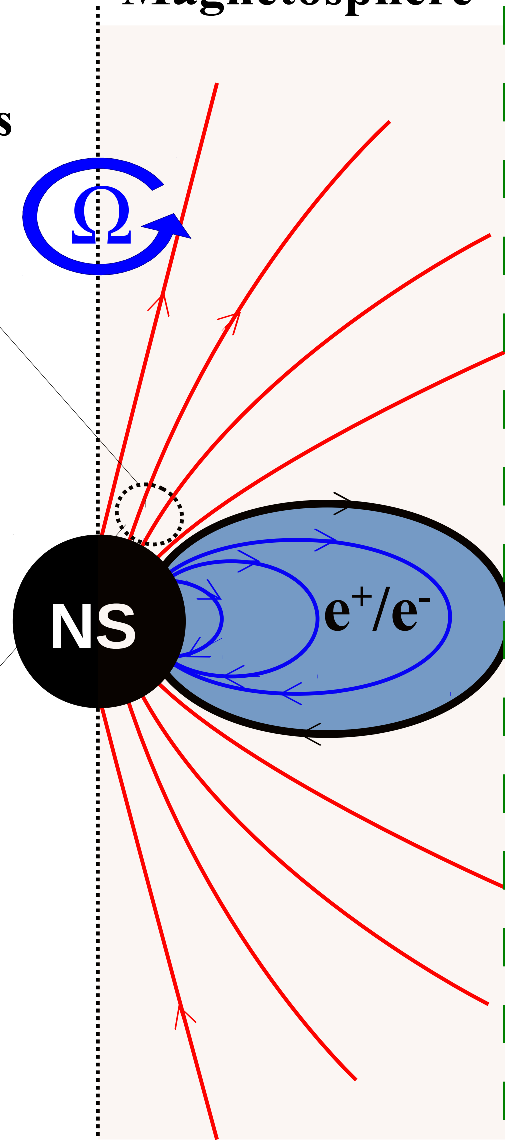

*Daugherty & Harding 1982 ; Timokhin & Arons 2013 ; Chen & Beloborodov 2014 ; Philippov et al., 2015*

Potential polar cap (Crab):

$$\Delta\Phi_{pc} = \frac{R^3\Omega^2 B}{c^2} \approx 10^{16} V$$

**Magnetosphere**

**Wind region**




**Light-cylinder radius: $R_{LC}\Omega=c$**

**Here corotation is impossible !**

**Rotation axis**

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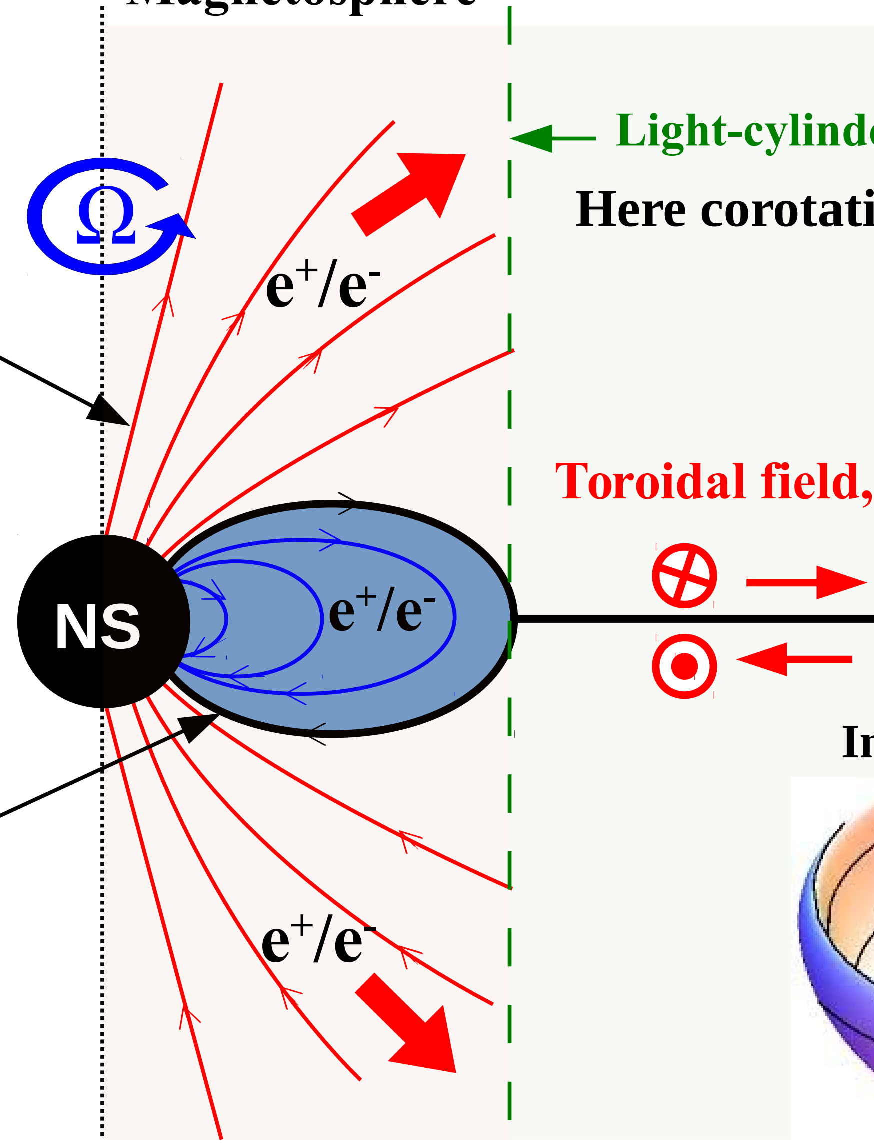
# Elements of a pulsar magnetosphere: plasma filled

**Magnetosphere** **Wind region**

**"Open" field lines**
**Outflowing plasma and Poynting flux**



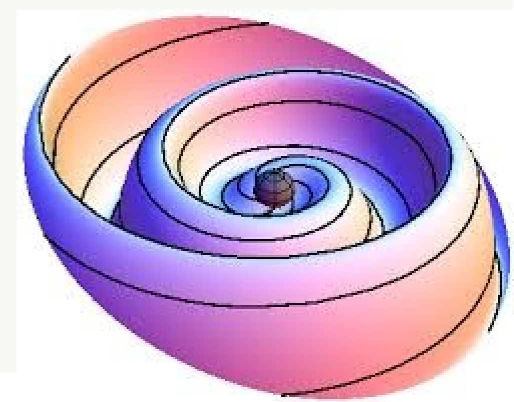

**Light-cylinder radius: $R_{LC}\Omega=c$**
**Here corotation is impossible !**

**Toroidal field, $B_\varphi$**

**Jump in B**
**=> Current Sheet**

**"Closed" field lines**
**Plasma confined, co-rotating**
**"Dead zone"**

**Inclined rotator**



**Rotation axis**

*© Gralla & Jacobson 2014*

**Similar to the heliospheric current sheet.**

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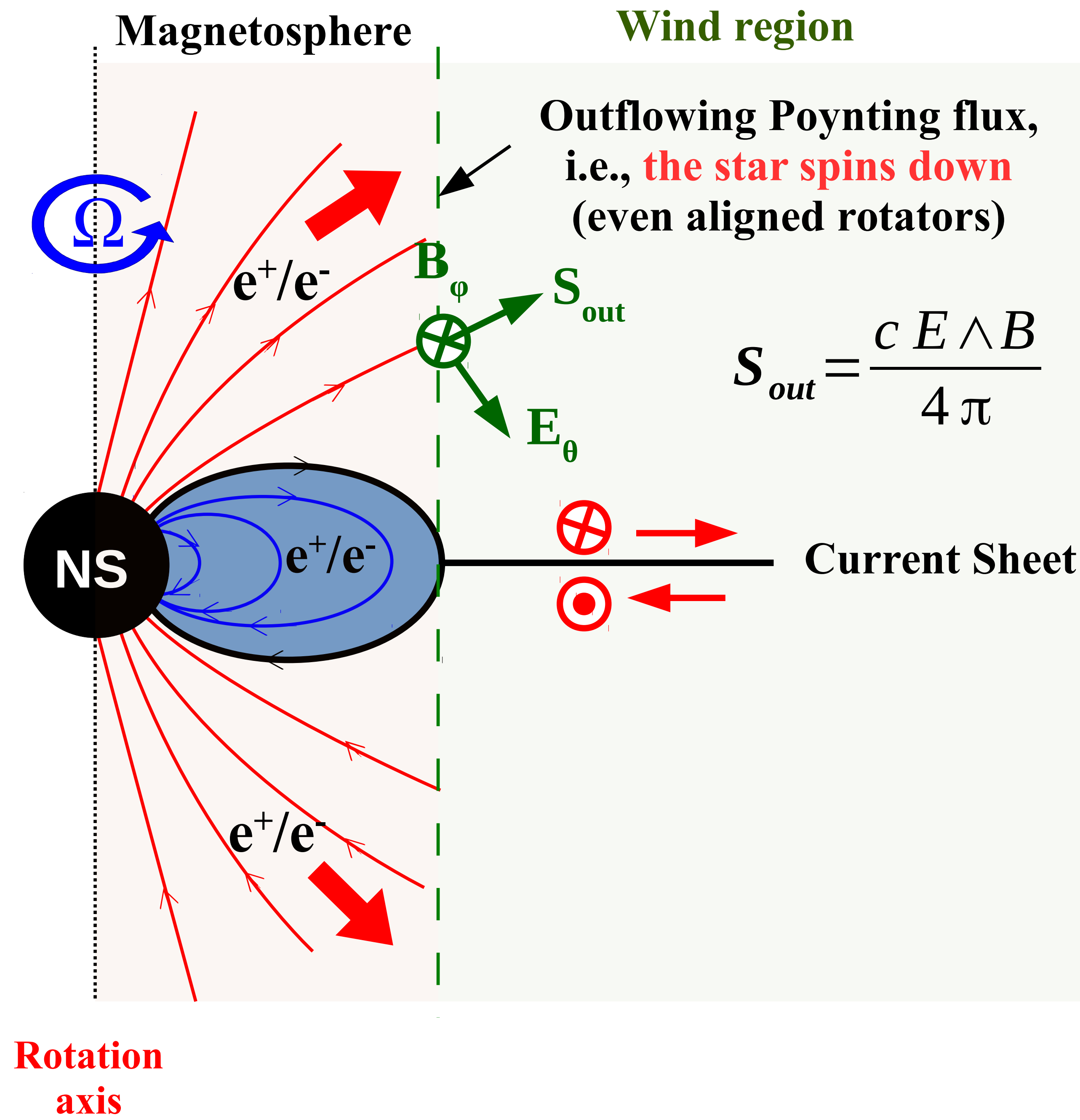
# Elements of a pulsar magnetosphere: plasma filled

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# Proposed sites for particle acceleration

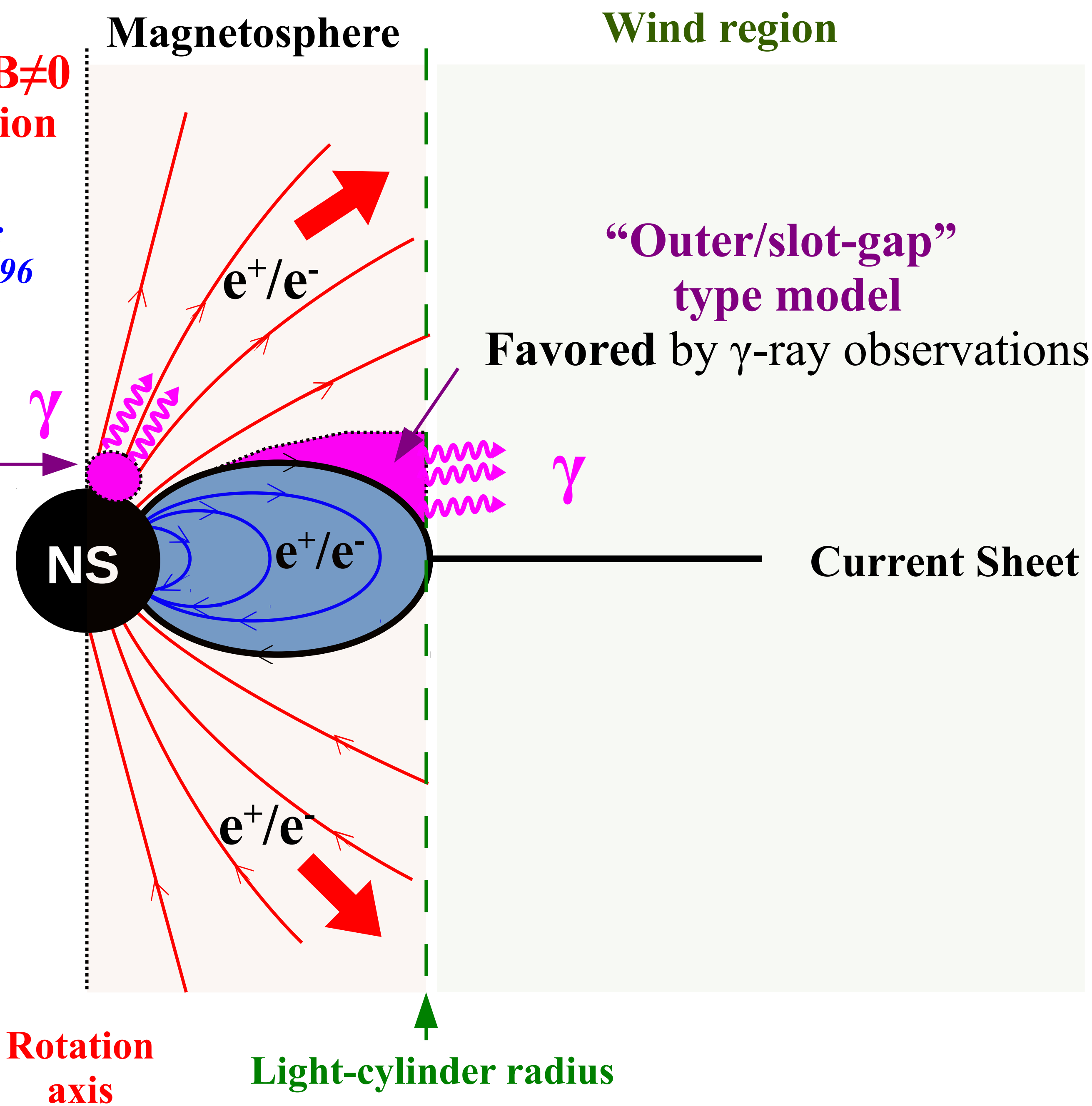
**Acceleration in gaps, E.B≠0**
**γ-ray : curvature radiation**

*e.g. Arons 1983; Muslimov & Harding 2003; Cheng et al. 1986; Romani 1996*

**"Polar-cap" type model**

- Radio emission ?
- γ-rays ?

**Unlikely because absorbed by B**

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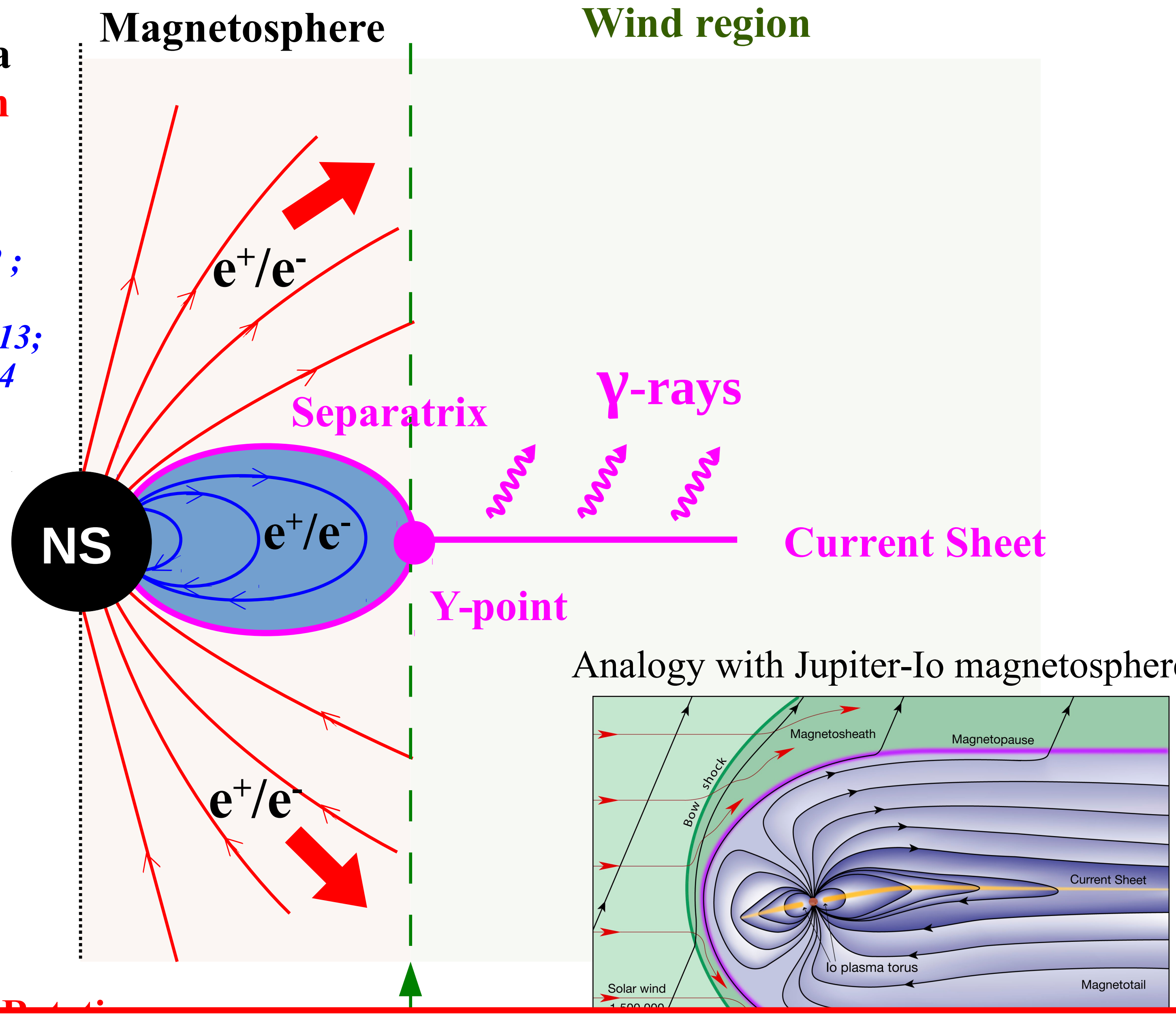
# Proposed sites for particle acceleration

**Particle acceleration via**
**relativistic reconnection**
**γ-ray: Synchrotron**

*Coroniti 1990 ;*
*Lyubarskii 1996 ; Kirk+2002 ;*
*Bai & Spitkovsky 2010 ;*
*Pétri 2012 ; Arka & Dubus 2013;*
*Uzdensky & Spitkovsky 2014*
*Mochol & Pétri 2015*




**Models dependent on the geometry of the magnetosphere**

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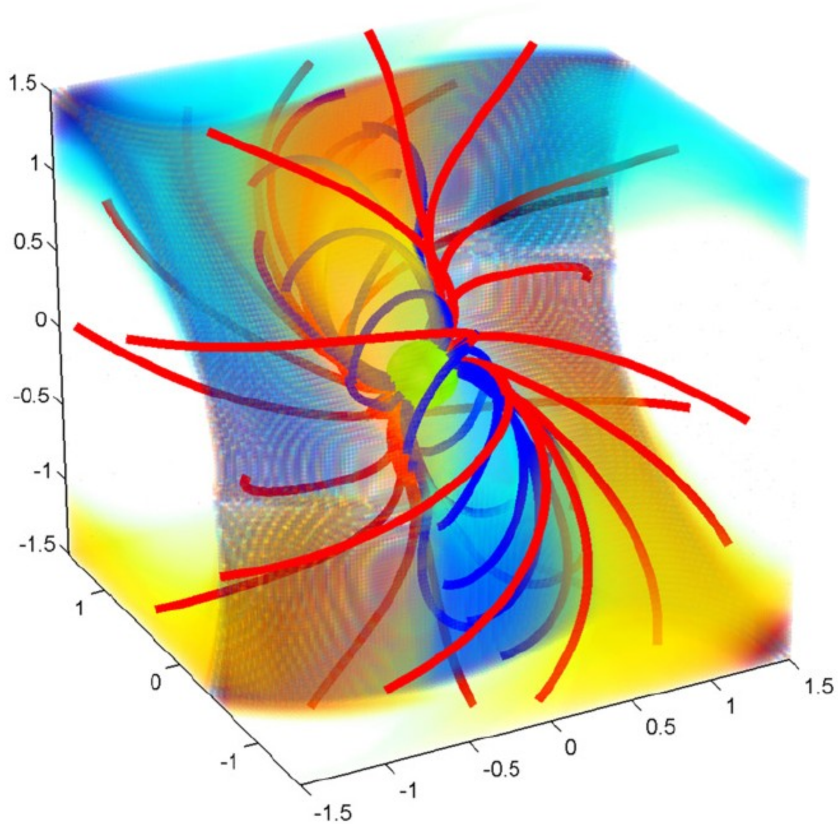
# Insight from the MHD approach

**(Force Free / Resistive Force Free / Full MHD)**

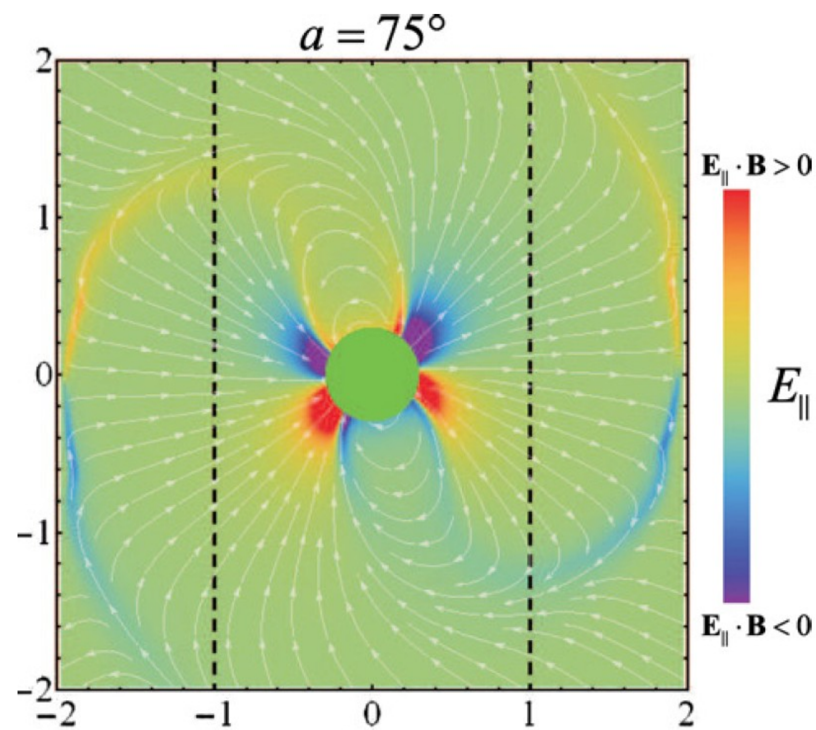
**Ideal Force-Free field geometry with prescribed emitting field lines**

*Bai & Spitkovsky 2010a,b*




**Non-ideal Force-Free with prescribed resistivity**

*Li et al. 2012; Kalapotharakos et al. 2012, 2014*




**Favor high-energy emission from the outer magnetosphere + current sheet**

**Ad-hoc accelerating/radiating zones, large uncertainties ➡ Need for self-consistent approach**
**Particle-in-Cell simulations!**

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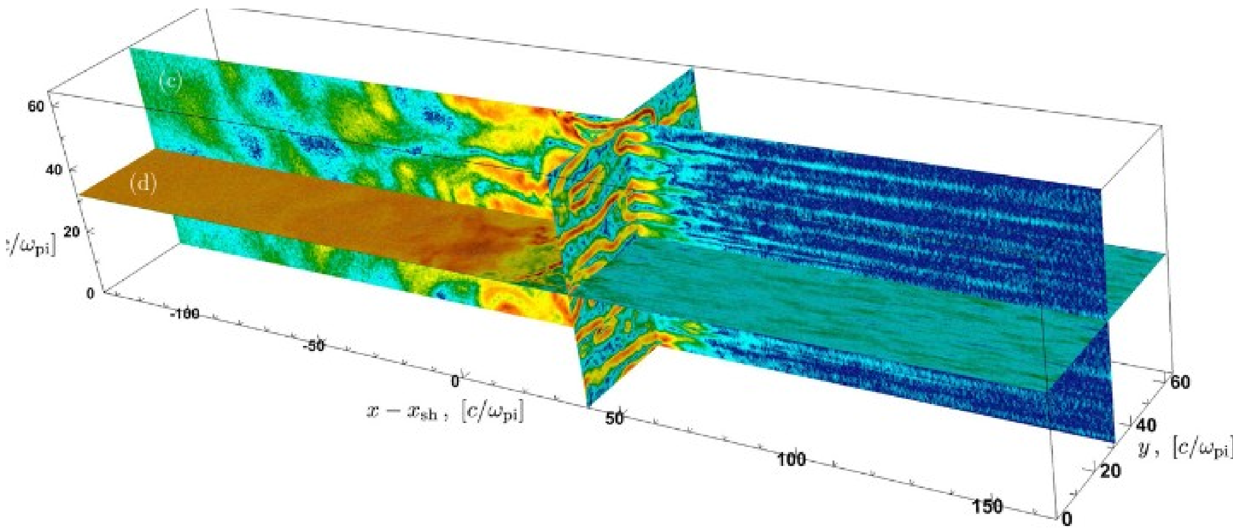
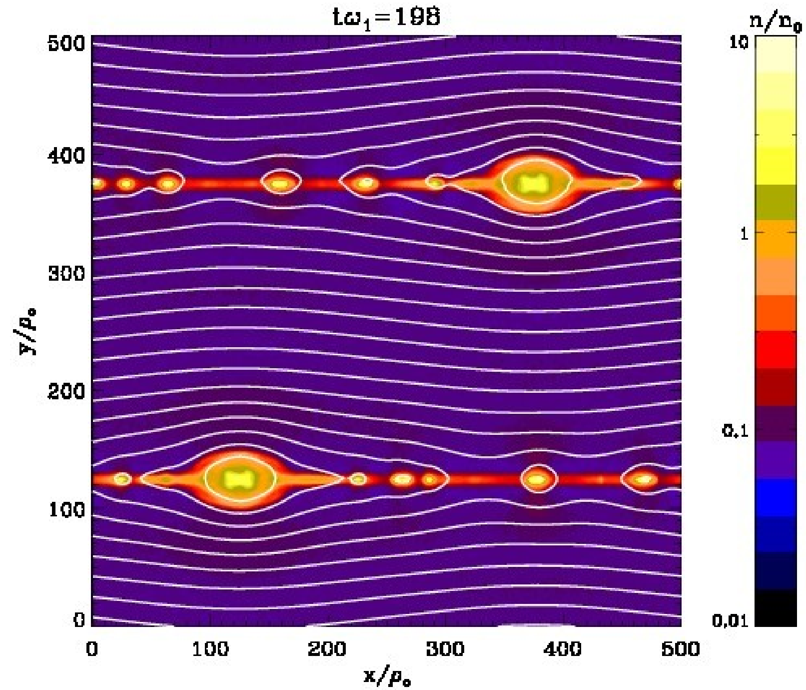
# Astrophysical applications of the PIC methods

Particle acceleration in **collisionless shocks** and **reconnection**




*[Sironi et al. 2013]*




*[Cerutti et al. 2013]*

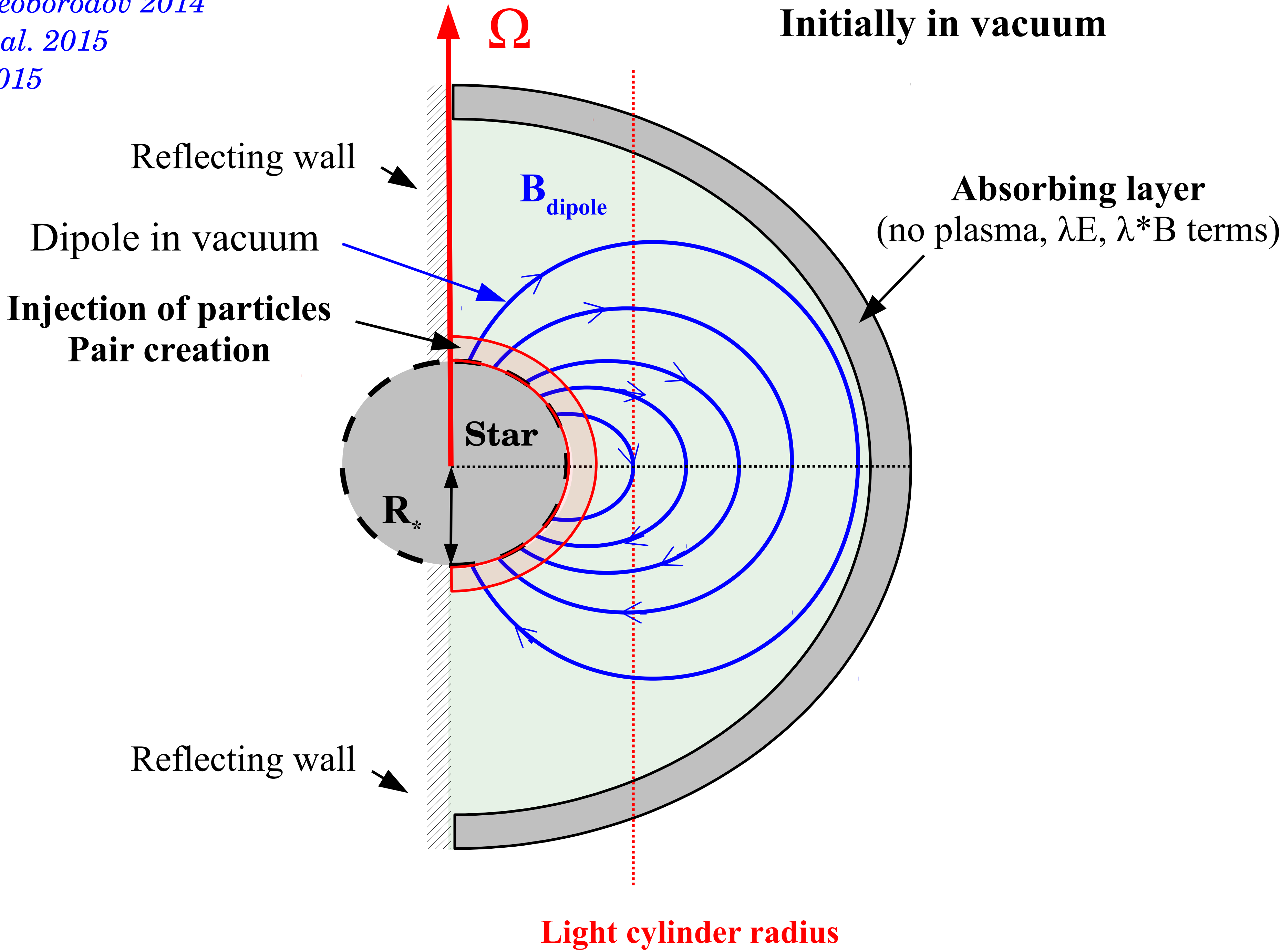
This method is always applied to a microscopic part of an astrophysical system due to the huge scale separation.

In pulsars, we need to solve the problem **globally**! Such simulations were already performed by:

*Philippov et al. 2014, 2015, Chen & Beloborodov 2014, Cerutti et al. 2015 & 2016, Belyaev 2015*

# The numerical setup: an aligned rotator (2D)

*Chen & Beoborodov 2014*
*Cerutti et al. 2015*
*Belyaev 2015*

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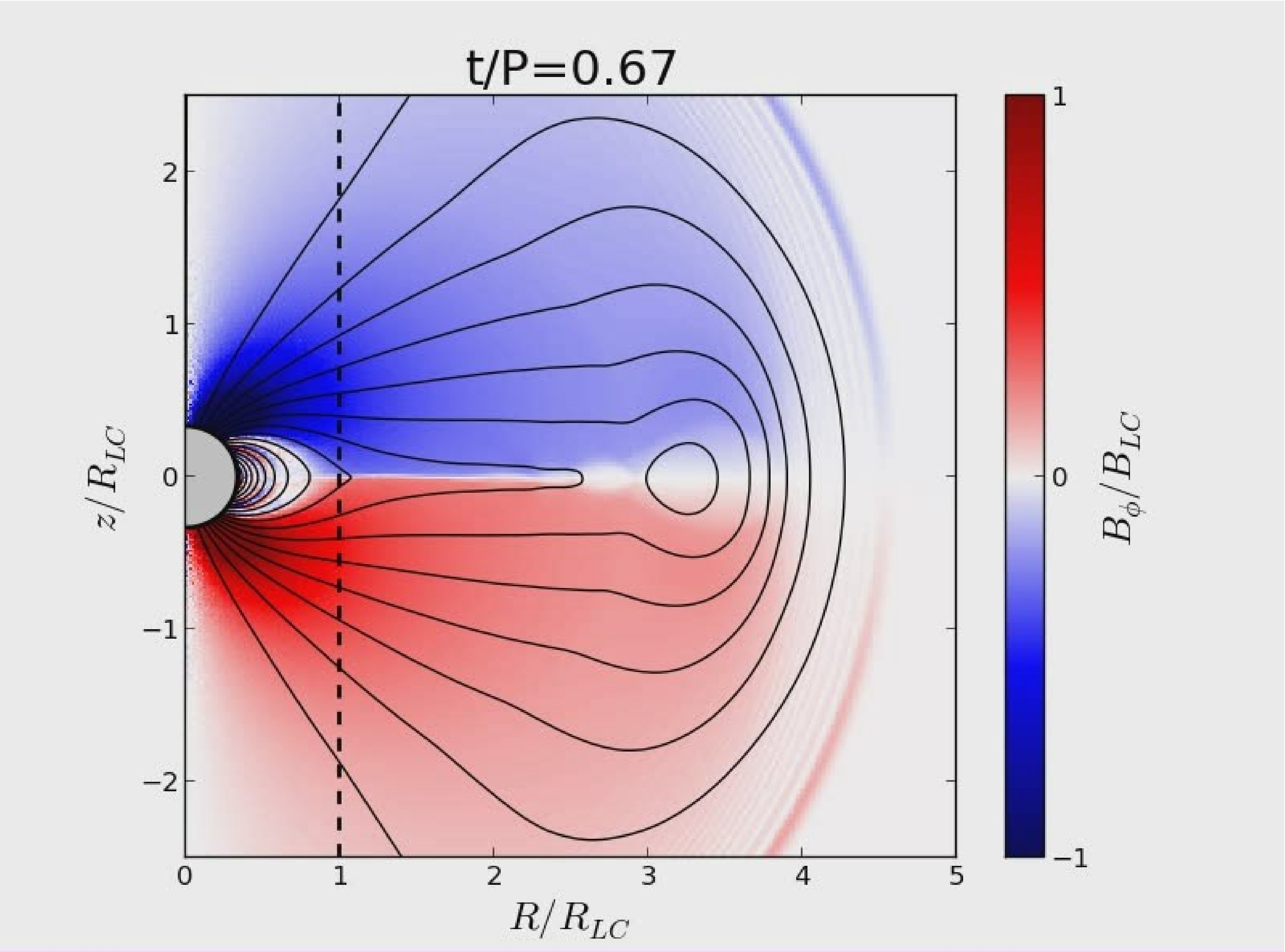
# Toroidal magnetic field

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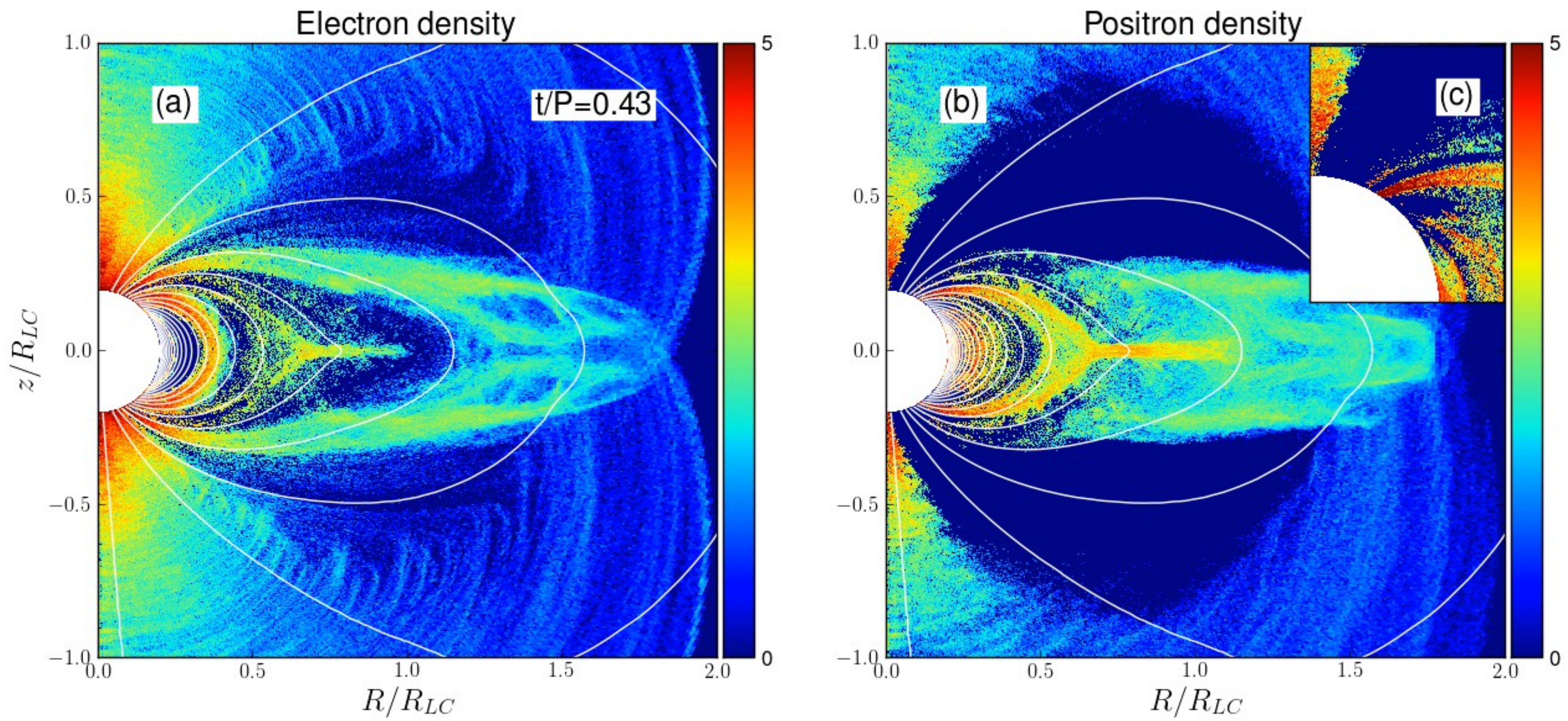
Cerutti et al. 2015

# Pair creation and filling of the magnetosphere

Pair creation at the **polar caps** (**$\gamma$B**) and within the **current sheet** (**$\gamma\gamma$**)




*Courtesy of Sasha Philippov*

*[Philippov et al. 2015b]*

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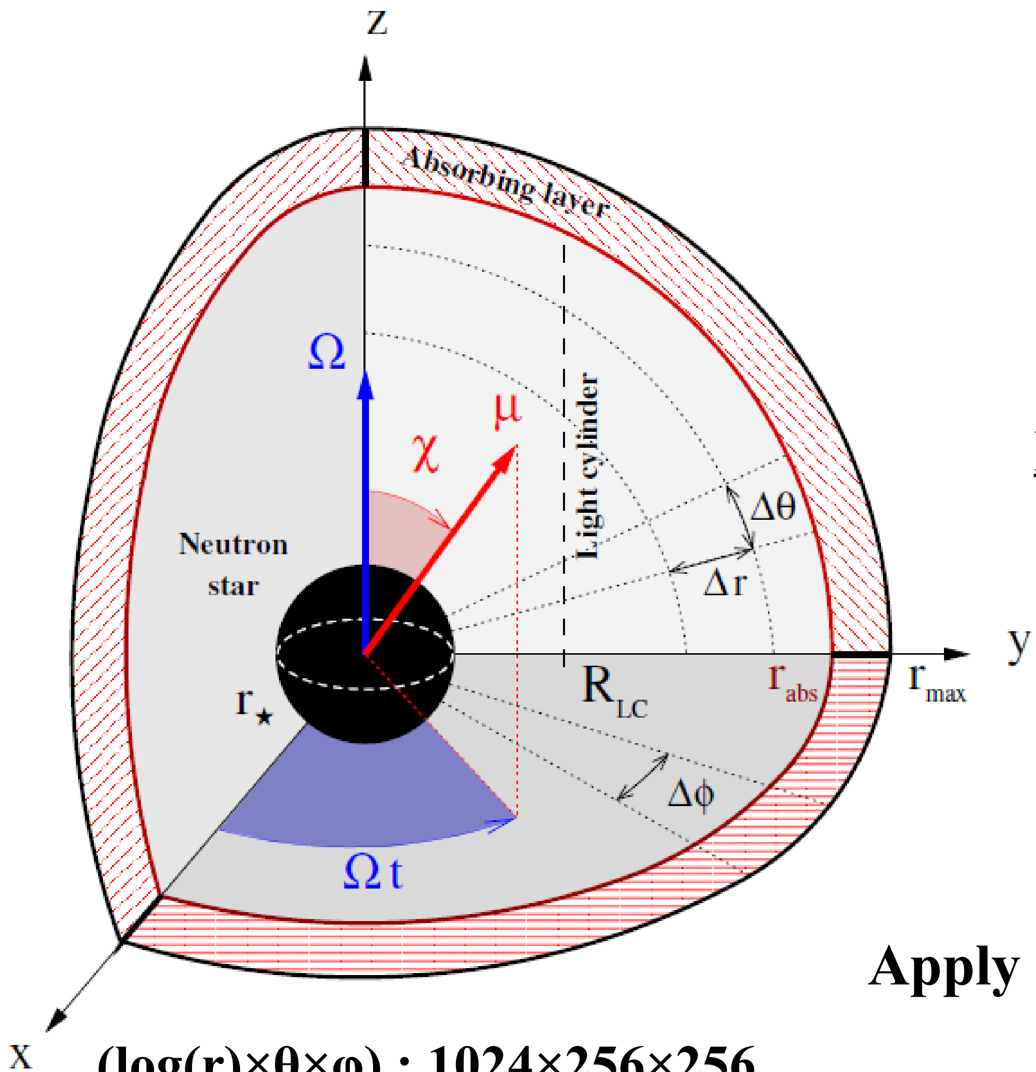
# Global 3D spherical PIC with radiation reaction force

**Zeltron** code : [http://benoit.cerutti.free.fr/Zeltron/](http://benoit.cerutti.free.fr/Zeltron/)

**Assumption** : Large plasma supply provided by the star surface = **Efficient pair creation**




**(log(r)×θ×φ) : 1024×256×256**

**Radiation reaction force**

$$\frac{d(\gamma m_e \mathbf{v})}{dt} = q\left(\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B}\right) + \mathbf{g},$$

**Emitted radiation spectra :**

$$F_\nu(\nu) = \frac{\sqrt{3} e^3 \tilde{B}_\perp}{m_e c^2} \left(\frac{\nu}{\nu_c}\right) \int_{\nu/\nu_c}^{+\infty} K_{5/3}(x)\,dx,$$

$$\tilde{B}_\perp = \sqrt{(\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B})^2 - (\boldsymbol{\beta} \cdot \mathbf{E})^2},$$

**Apply for synchrotron and curvature radiation**

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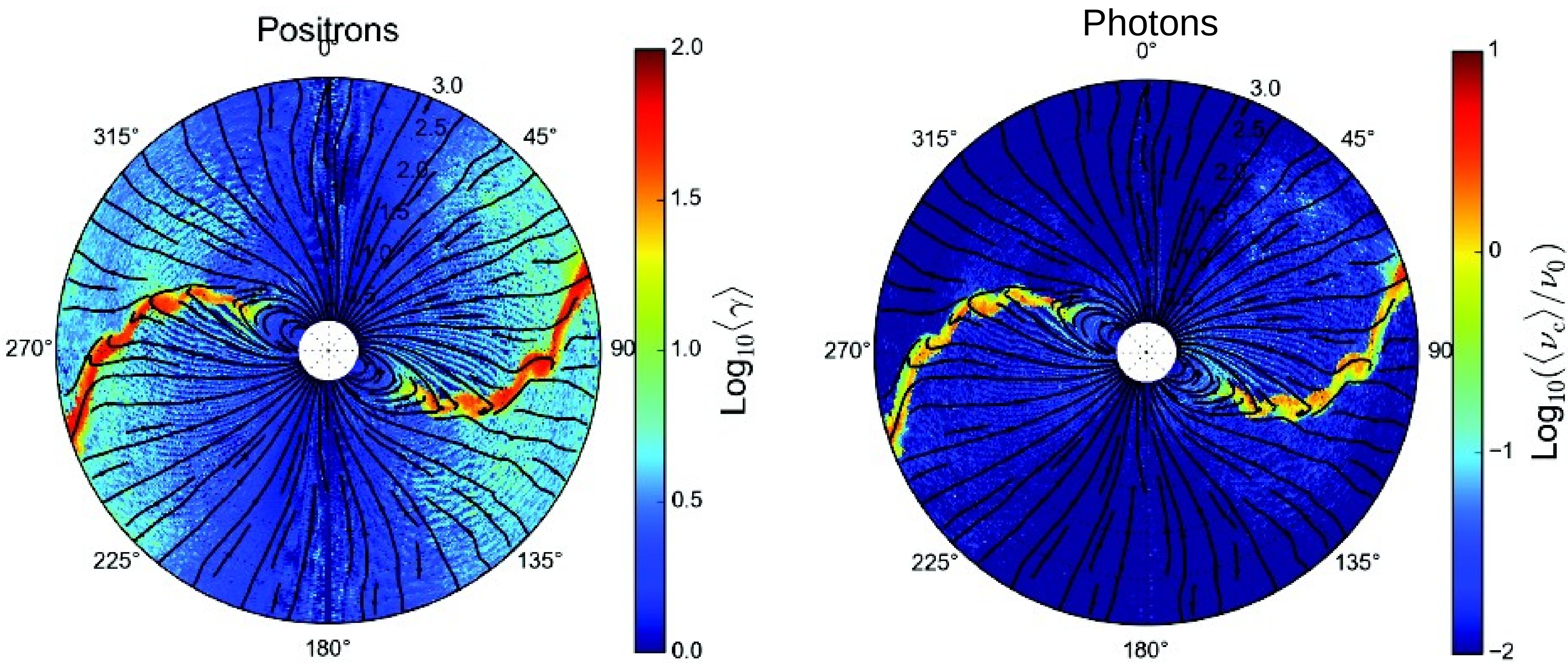
# Particle / radiation mean energy ($\chi$=30°)

*Cerutti et al. 2016*




**Particle acceleration via relativistic reconnection in the current sheet**
**High-energy radiation is synchrotron radiation**

**Particle energy in the sheet given by :** $$\sigma_{LC} = \frac{B_{LC}^2}{4\pi\Gamma n_{LC} m_e c^2} \approx 50$$ **(here)**

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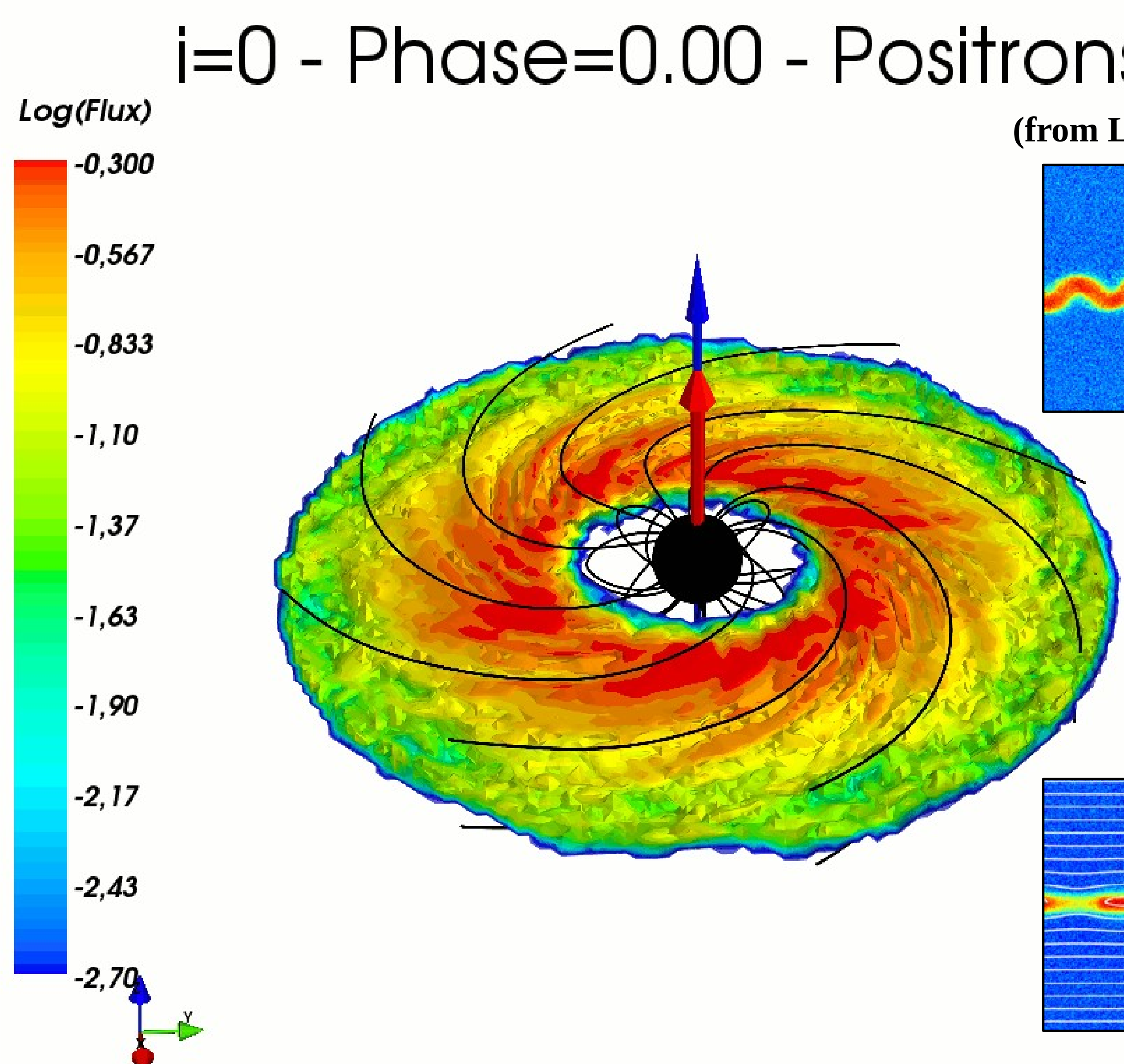
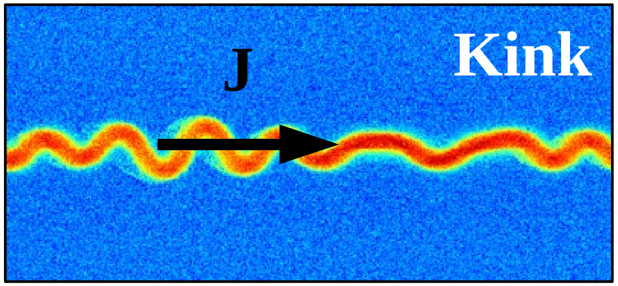
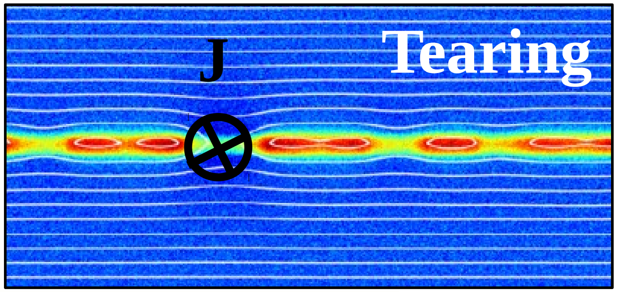
*See also in 2D axisymmetric Cerutti et al. 2015*

# High-energy radiation flux ($\nu>\nu_0$, $\chi=0°$)




(from Local reconnection simulations)




**Presence of spatial irregularities due to kinetic instabilities in the sheet**

**(e.g., kink and tearing modes)**

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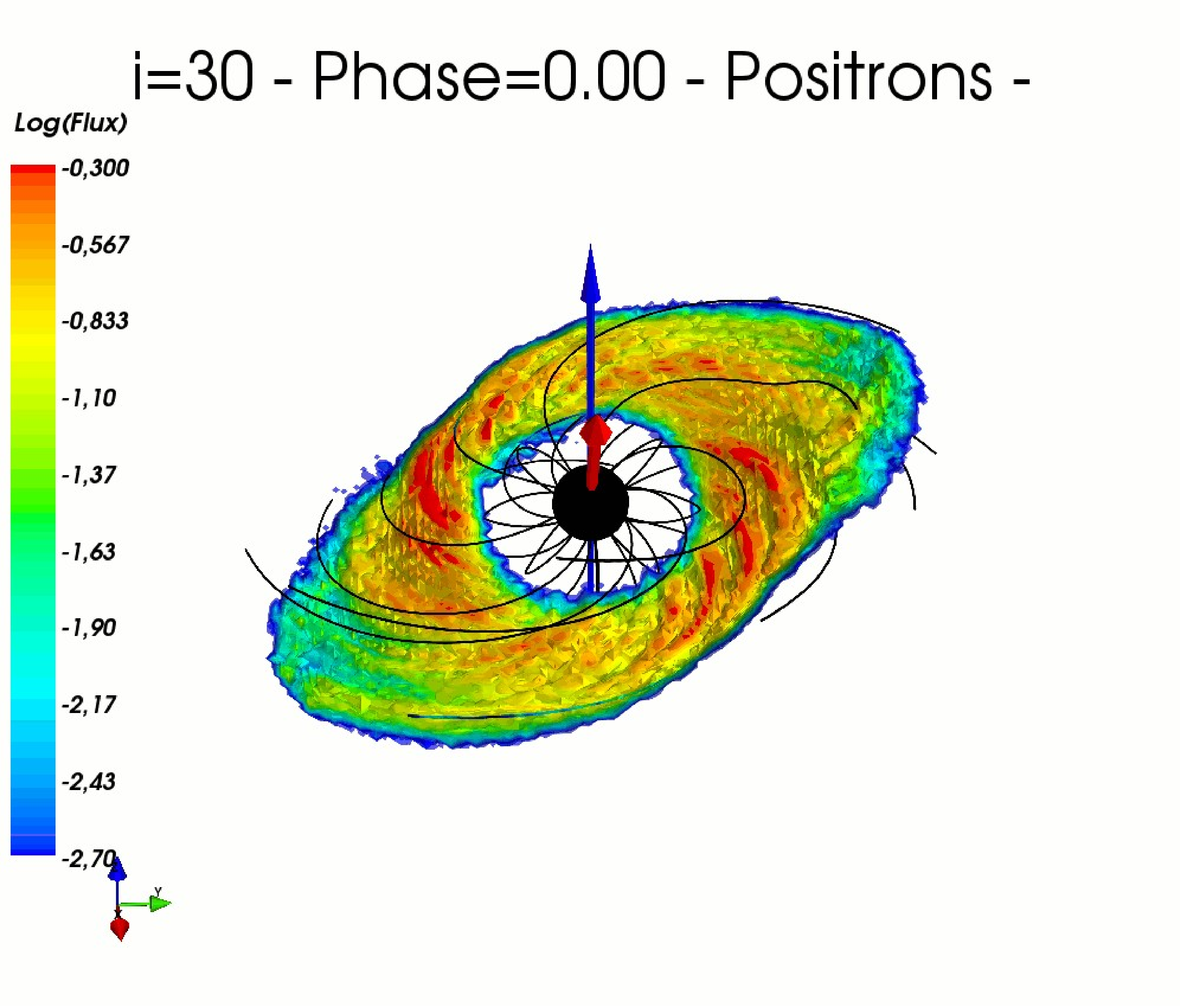
*Cerutti et al. 2016*

# High-energy radiation flux ($\nu>\nu_0$, $\chi$=30°)

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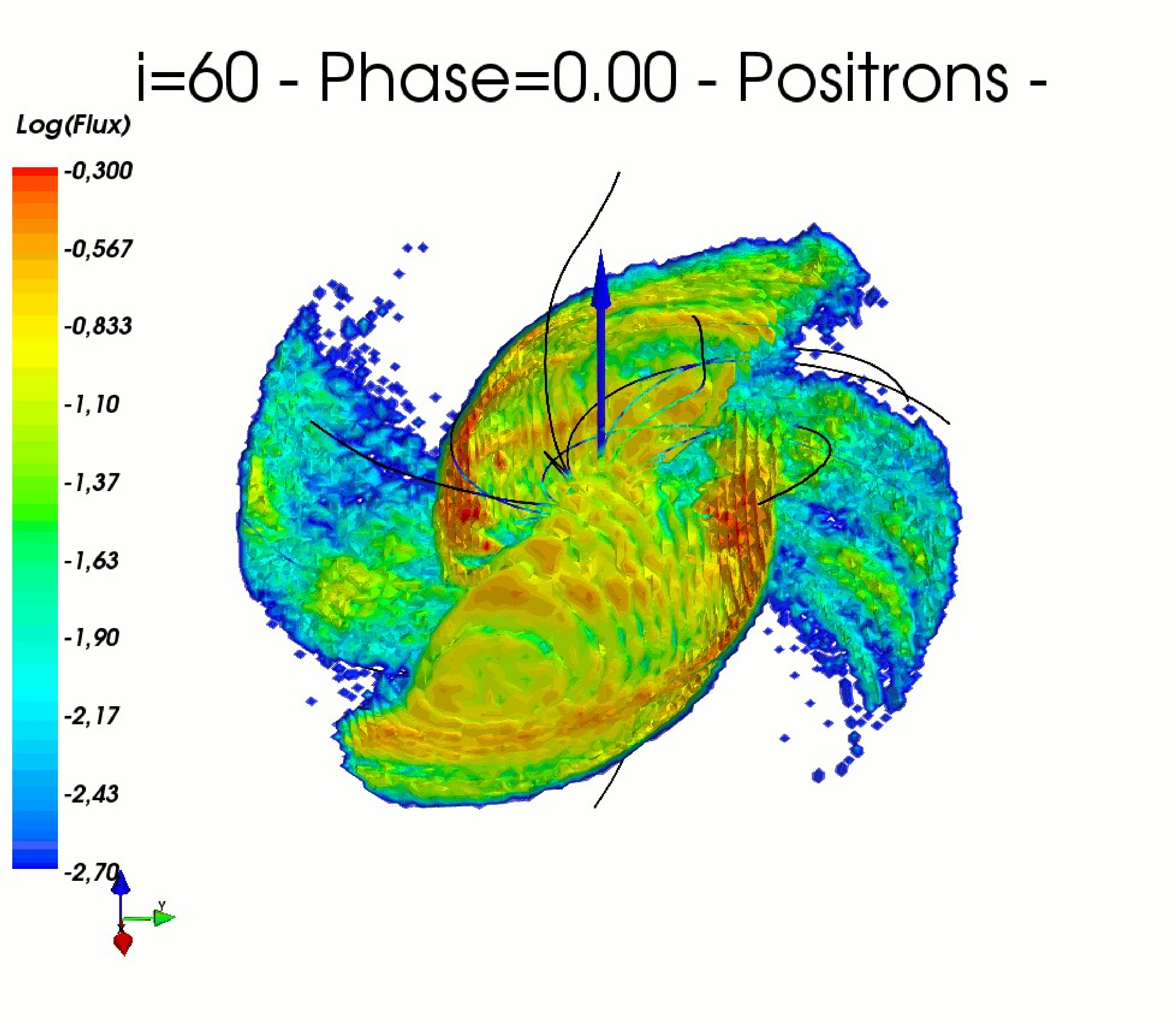
*Cerutti et al. 2016*

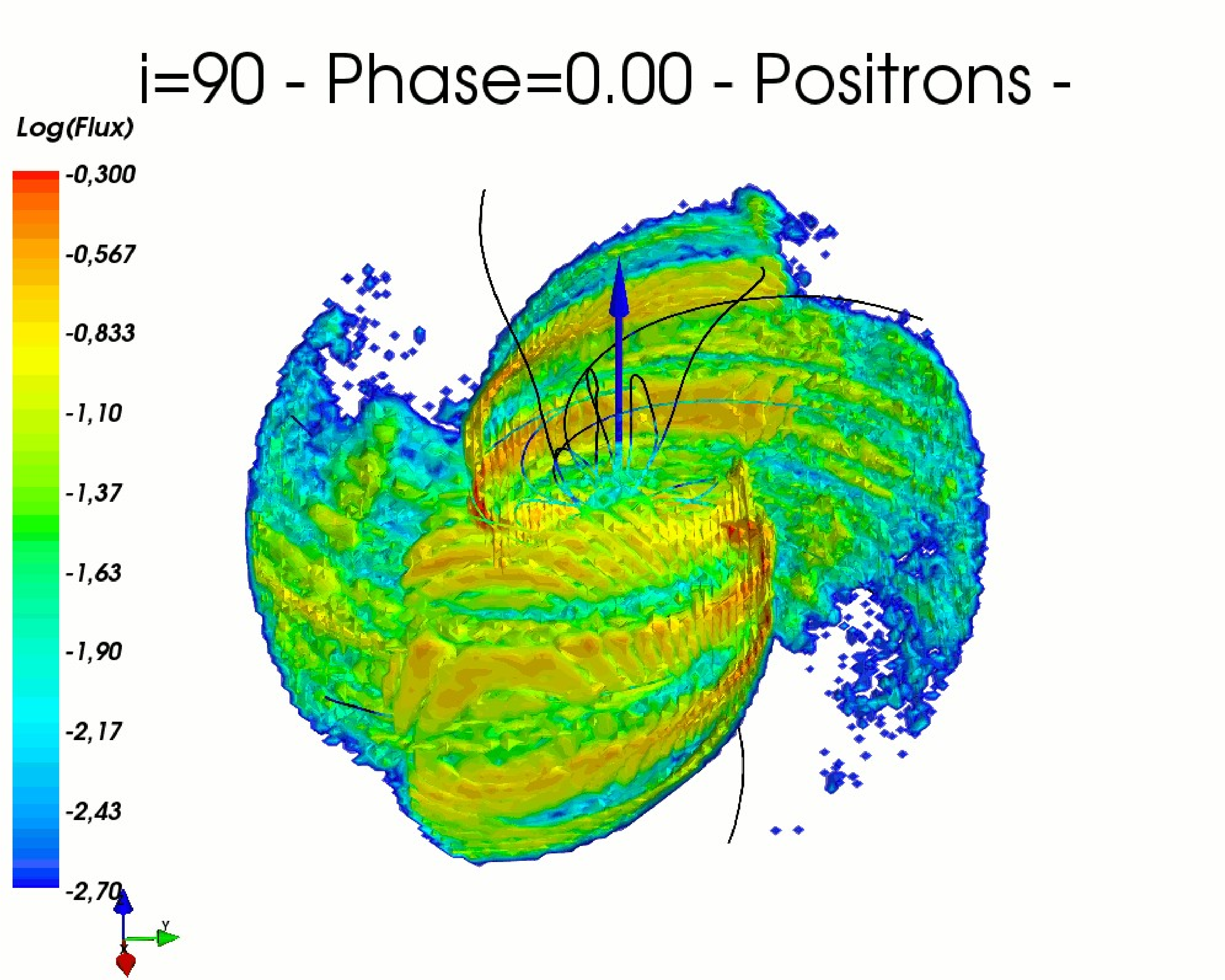
# High-energy radiation flux ($\nu > \nu_0$, $\chi = 60°$)






*Cerutti et al. 2016*

# High-energy radiation flux ($\nu > \nu_0$, $\chi = 90°$)




**Even for the orthogonal rotator, high-energy photons are concentrated within the equatorial regions where most of the spin-down is dissipated.**

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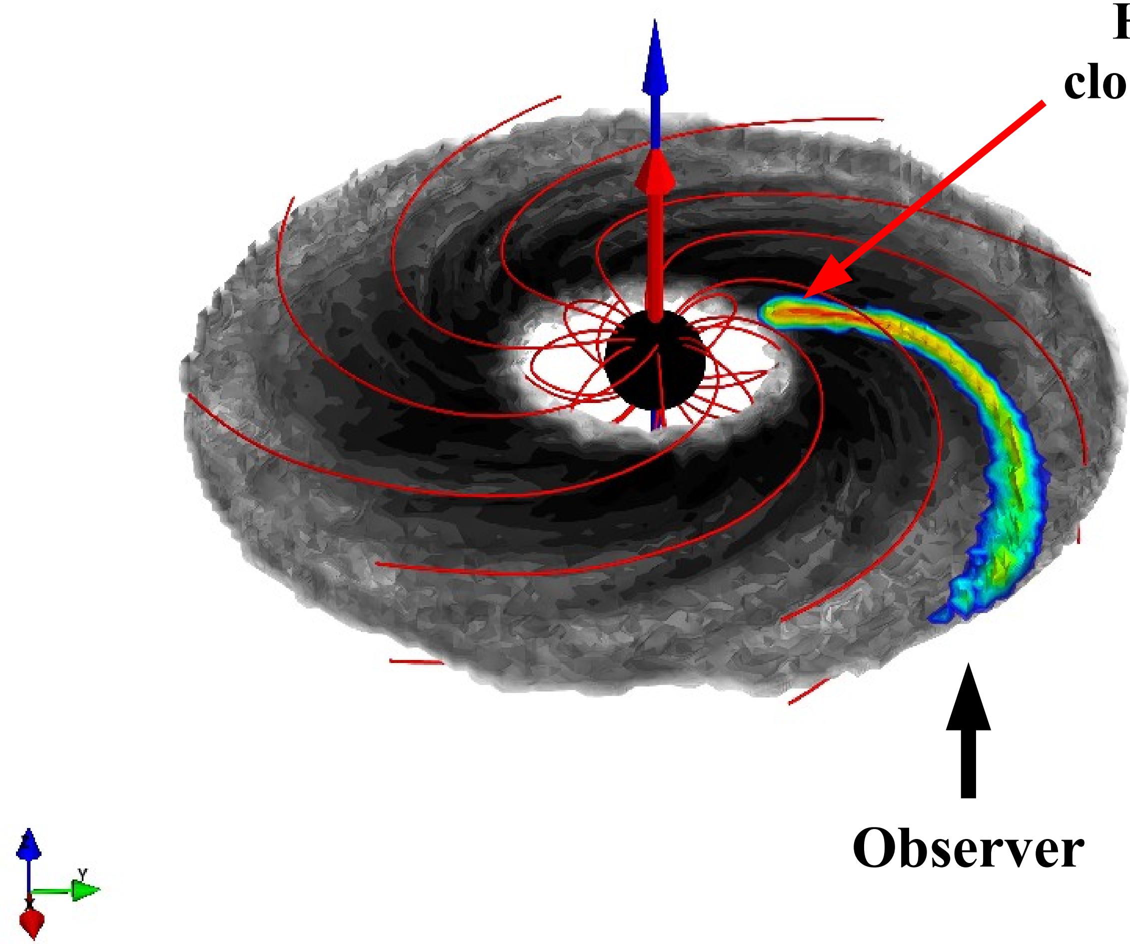
*Cerutti et al. 2016*

# Observed high-energy radiation flux ($\nu > \nu_0$, $\chi = 0°$)

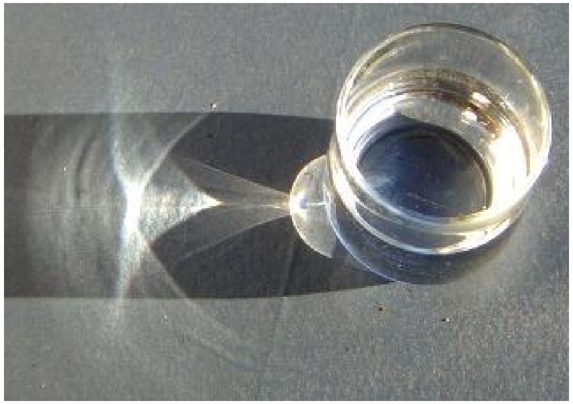
**Gray** : **Total** flux (all directions)
**Color** : **Observed** flux

i=0 - Phase=0.00 - Positrons -



**HE flux concentrated close to the light-cylinder**

**Observer**



**Spatial extension of the observed emission in the sheet**
**=> Formation of a caustic**

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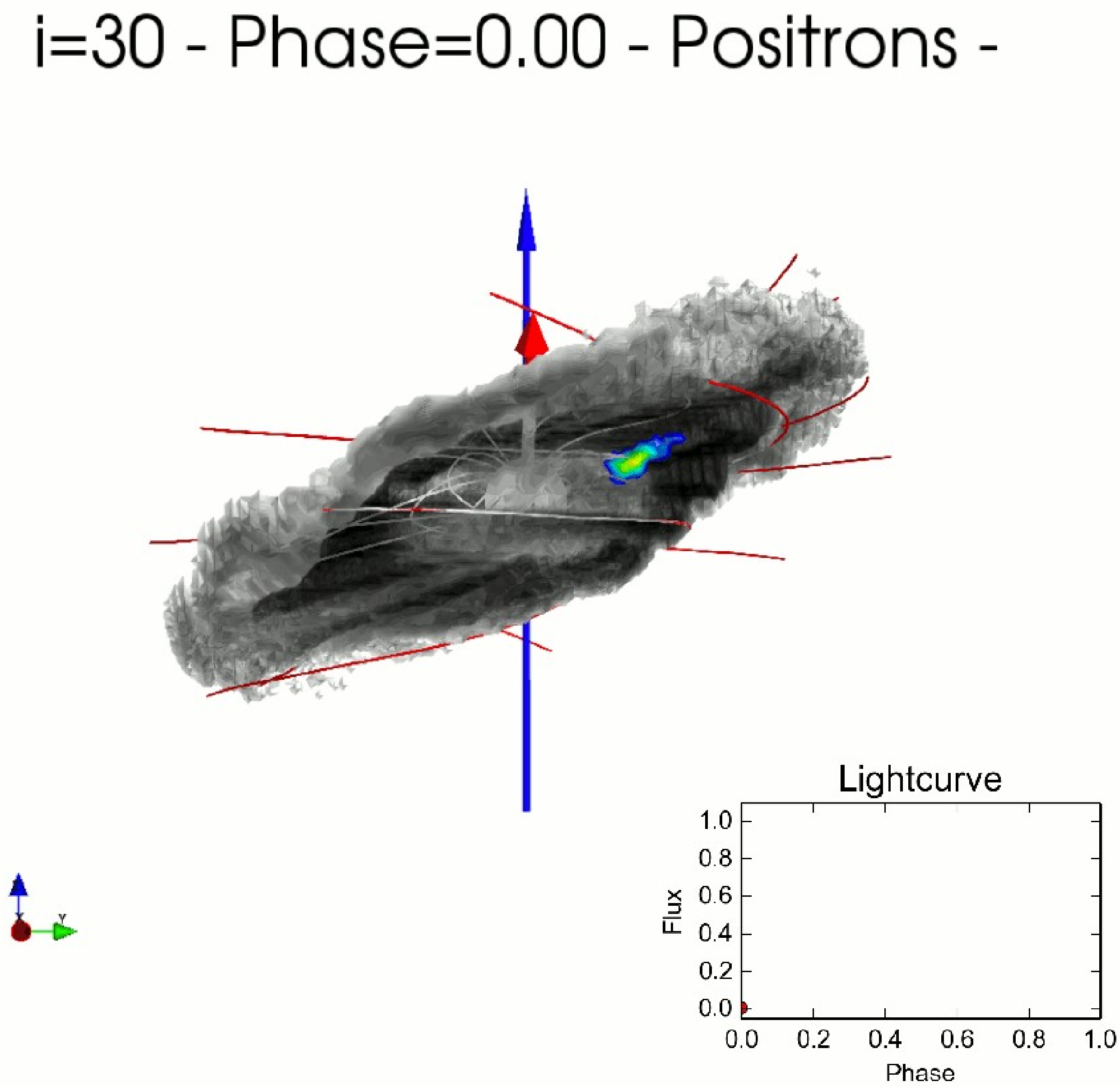
# Observed high-energy radiation flux ($\nu > \nu_0$, $\chi = 30°$)

Gray : **Total** flux (all directions)
Color : **Observed** flux

**Light curve shaped by the geometry of the current sheet**

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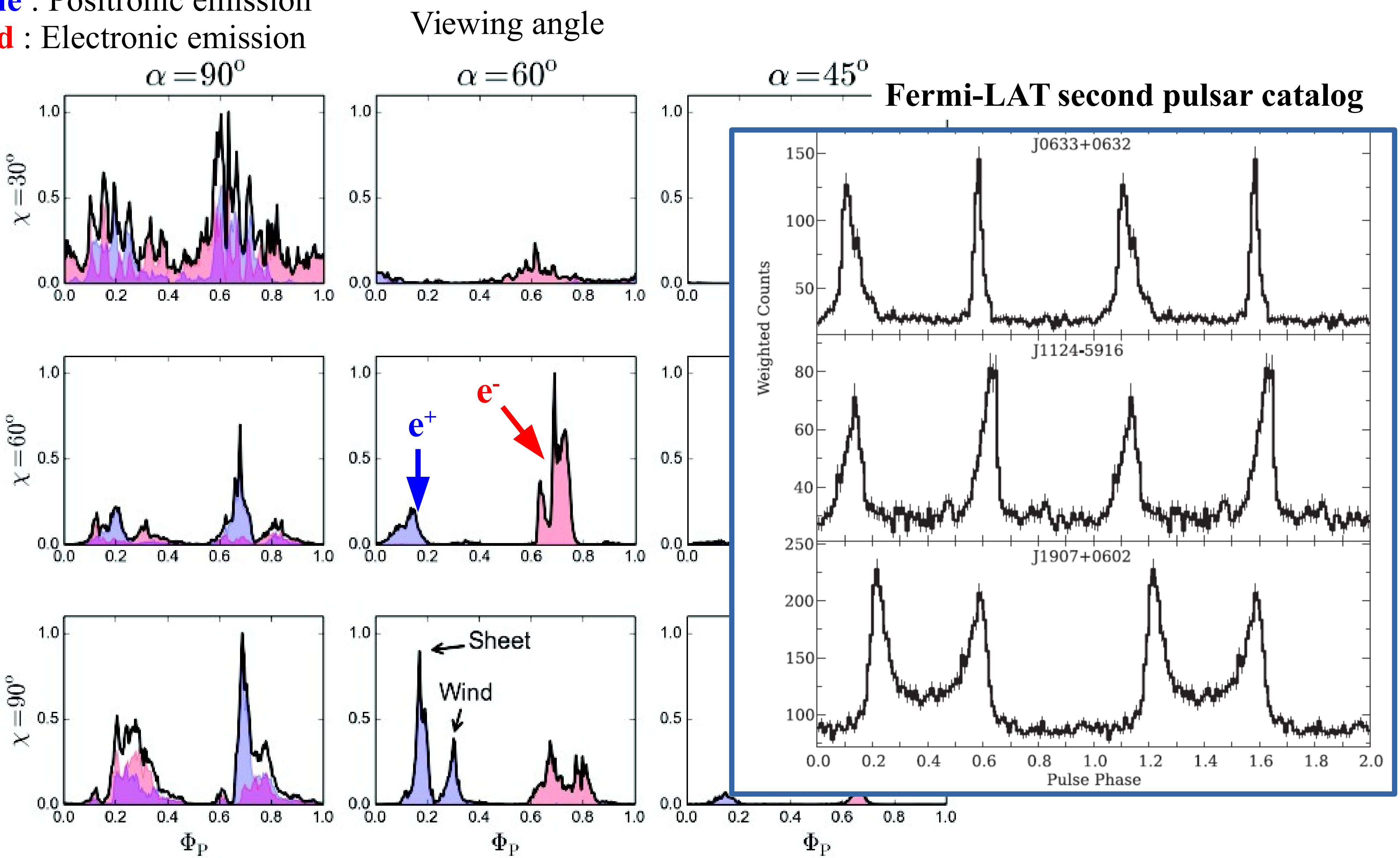
*Cerutti et al. 2016*

# Two-peaked lightcurves are very generic

## One peak per crossing of the current sheet

**Blue** : Positronic emission
**Red** : Electronic emission

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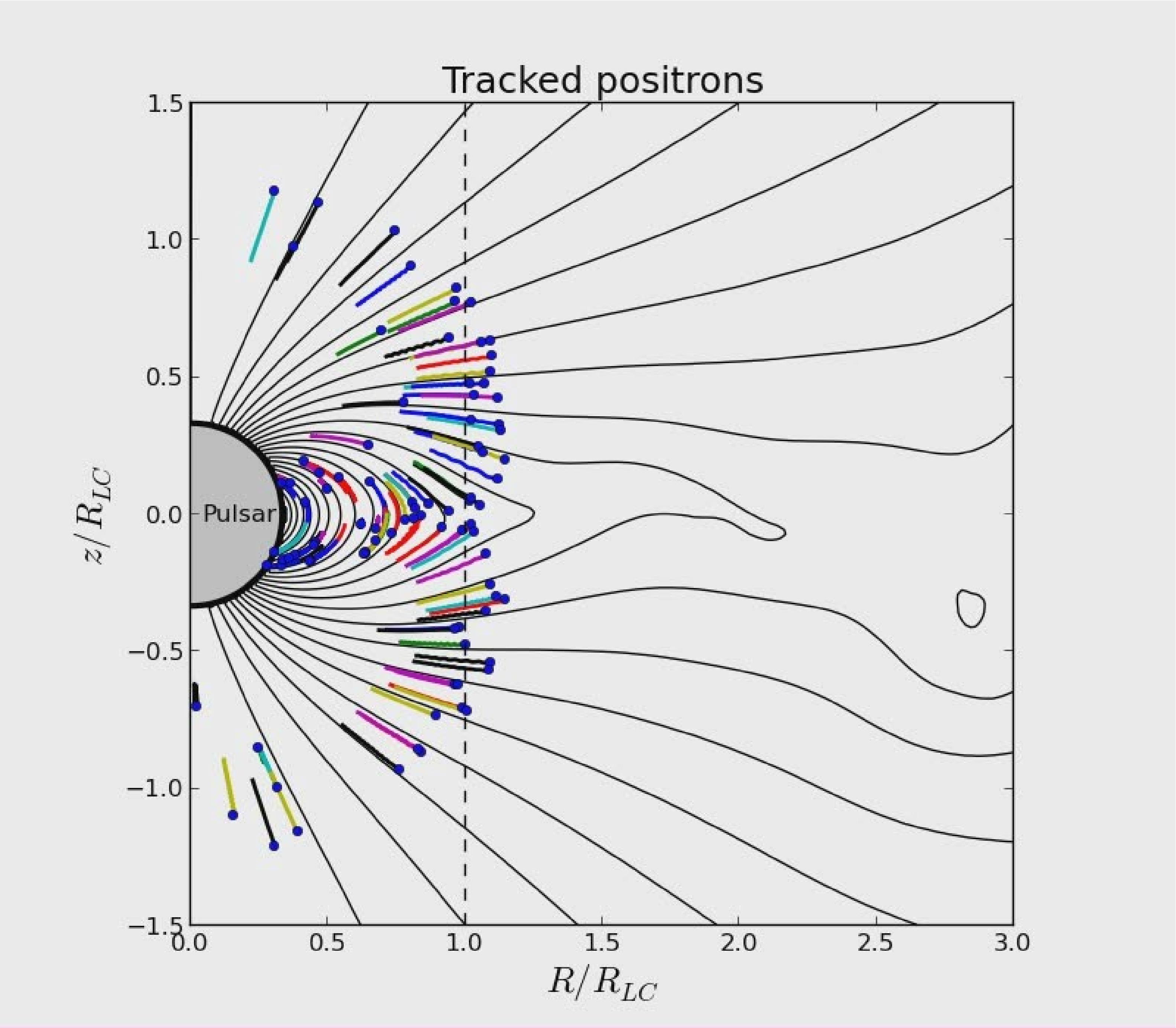
*Cerutti et al. 2016*

# Particle acceleration and origin of the $e^+/e^-$ asymmetry

**2D**

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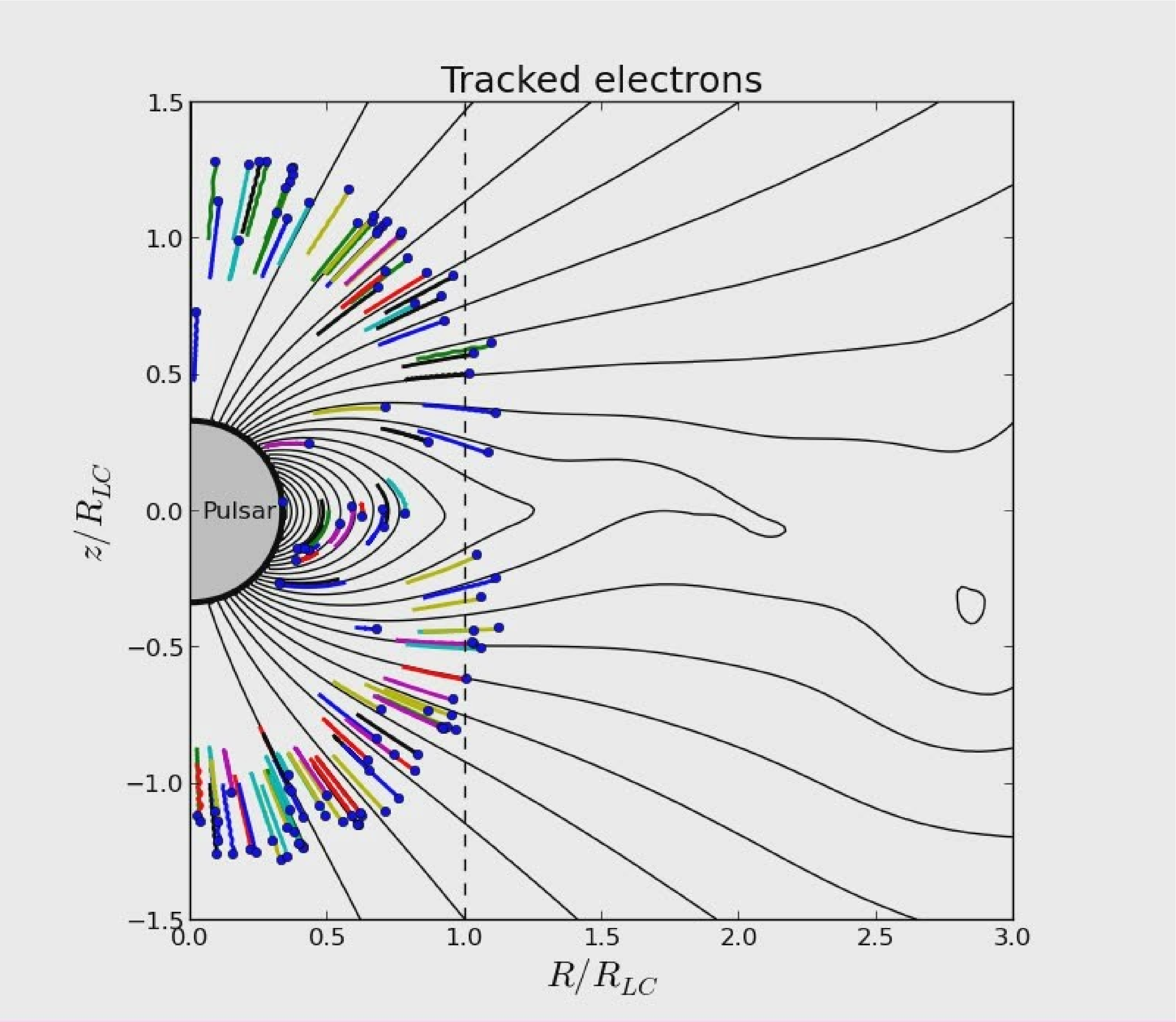
# Particle acceleration and origin of the $e^+/e^-$ asymmetry

**2D**

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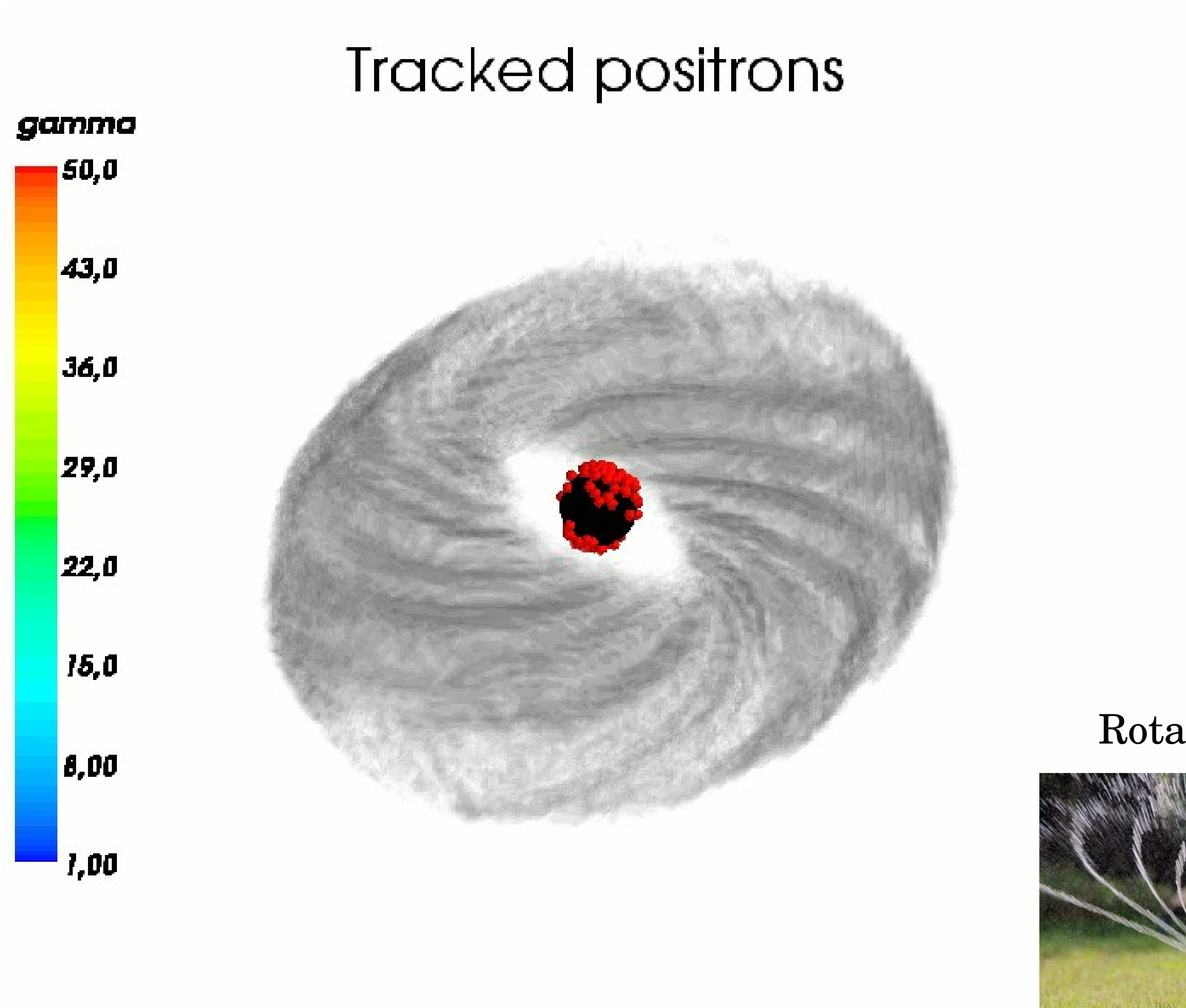
# Particle acceleration and origin of the $e^+/e^-$ asymmetry

**In the co-rotating frame**




Rotating sprinkler

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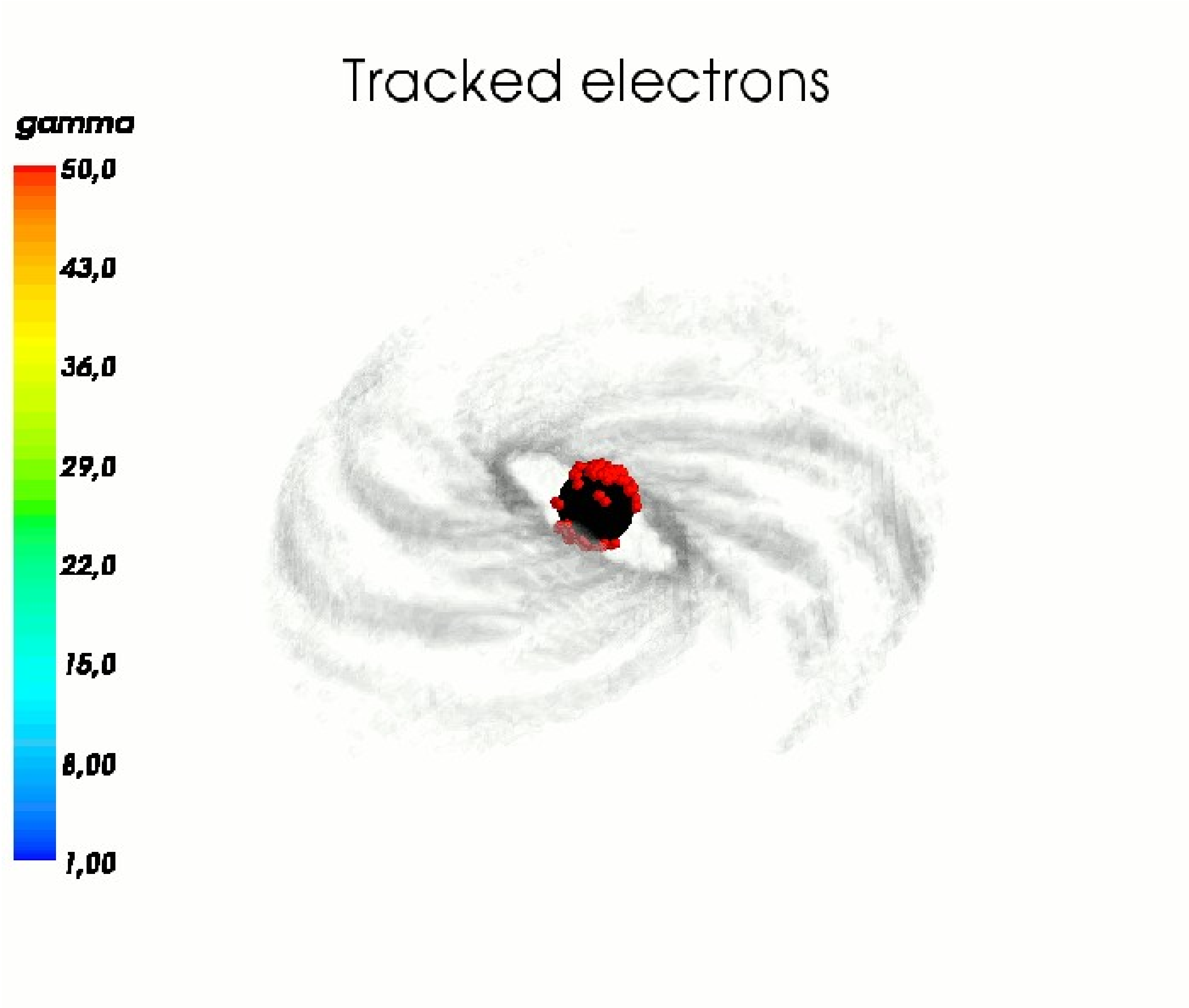
*Cerutti et al. 2016*

# Particle acceleration and origin of the $e^+/e^-$ asymmetry

**In the co-rotating frame**

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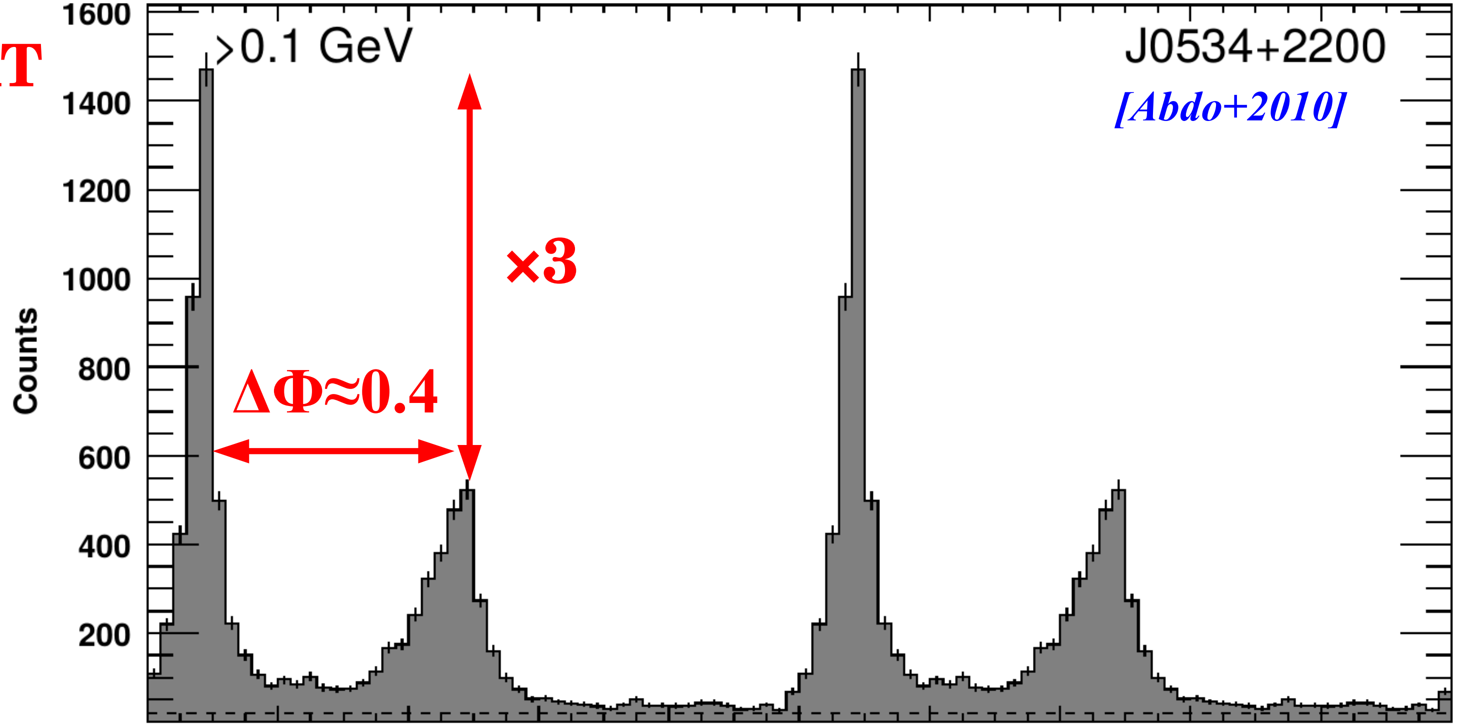
*Cerutti et al. 2016*

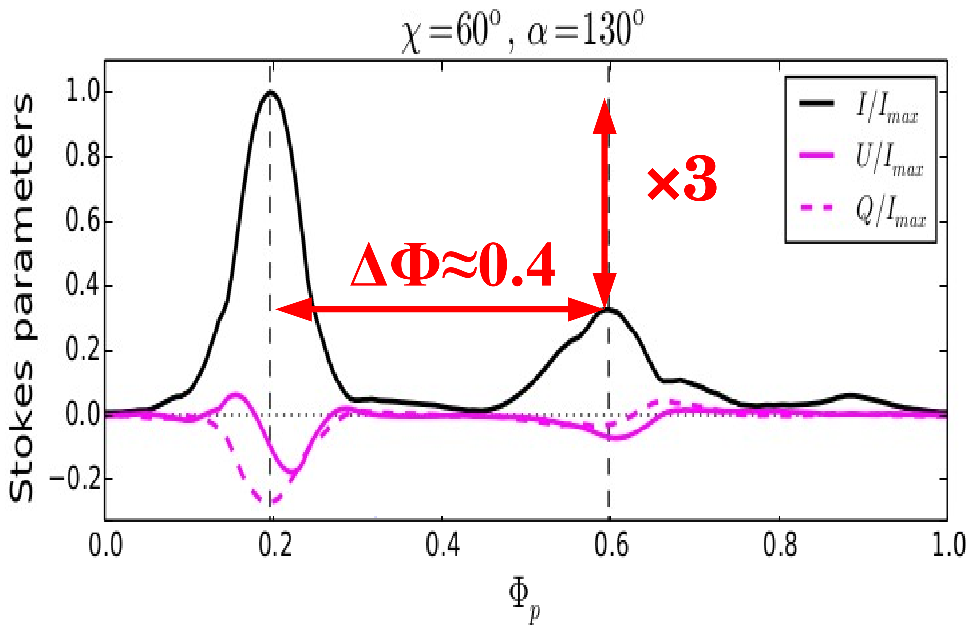
# Application to the Crab pulsar

***Fermi*-LAT**



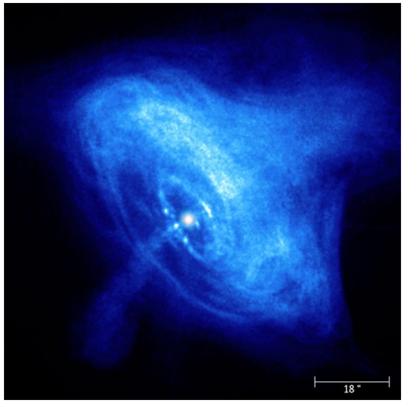

**PIC model**

**χ=60°, α=130°**



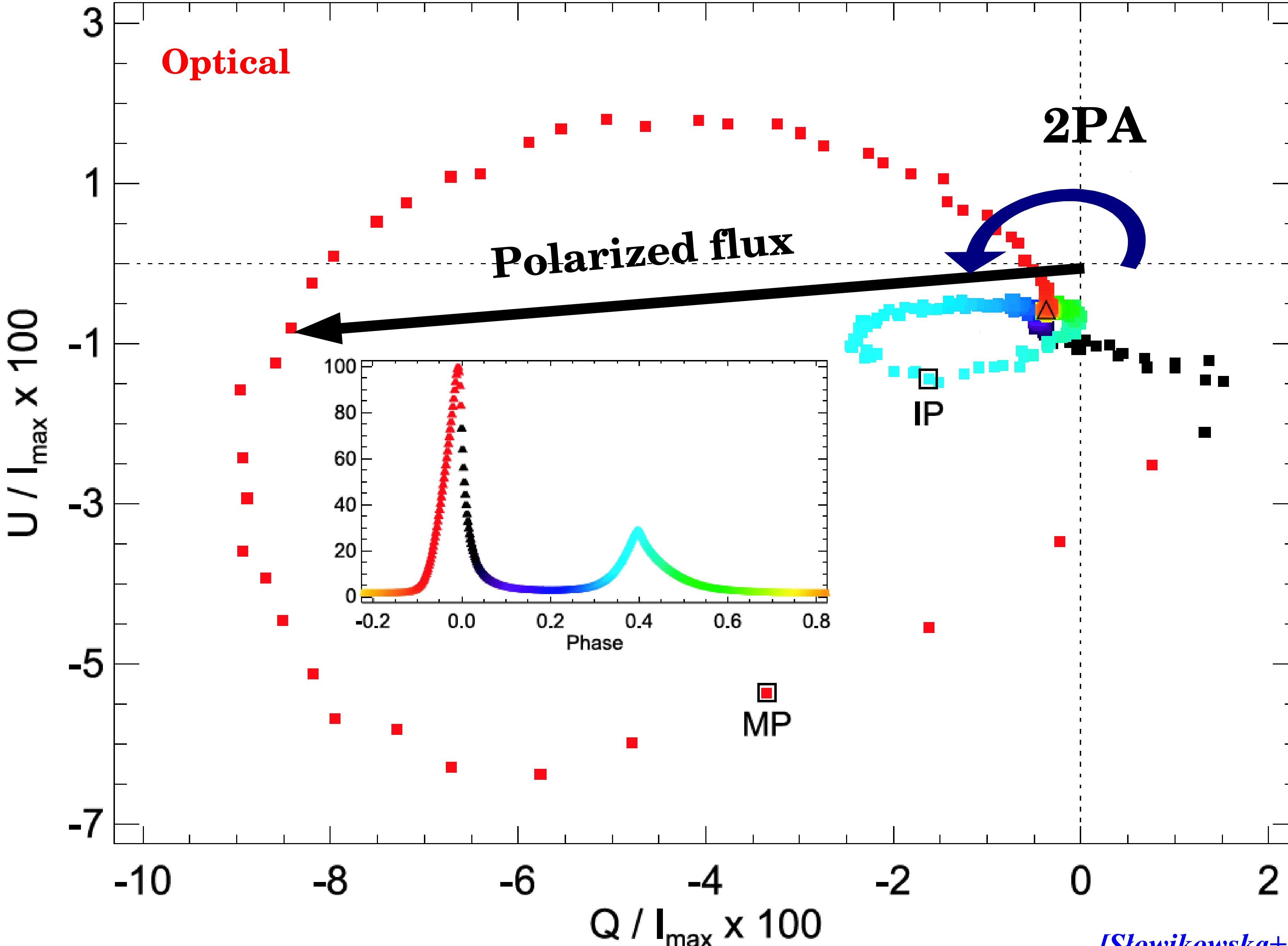

Consistent with the nebula morphology in **X-rays**

*[e.g. Weisskopf+2012]*



**B. Cerutti**

# (Incoherent) Polarization signature : Observations




*[Słowikowska+2009]*

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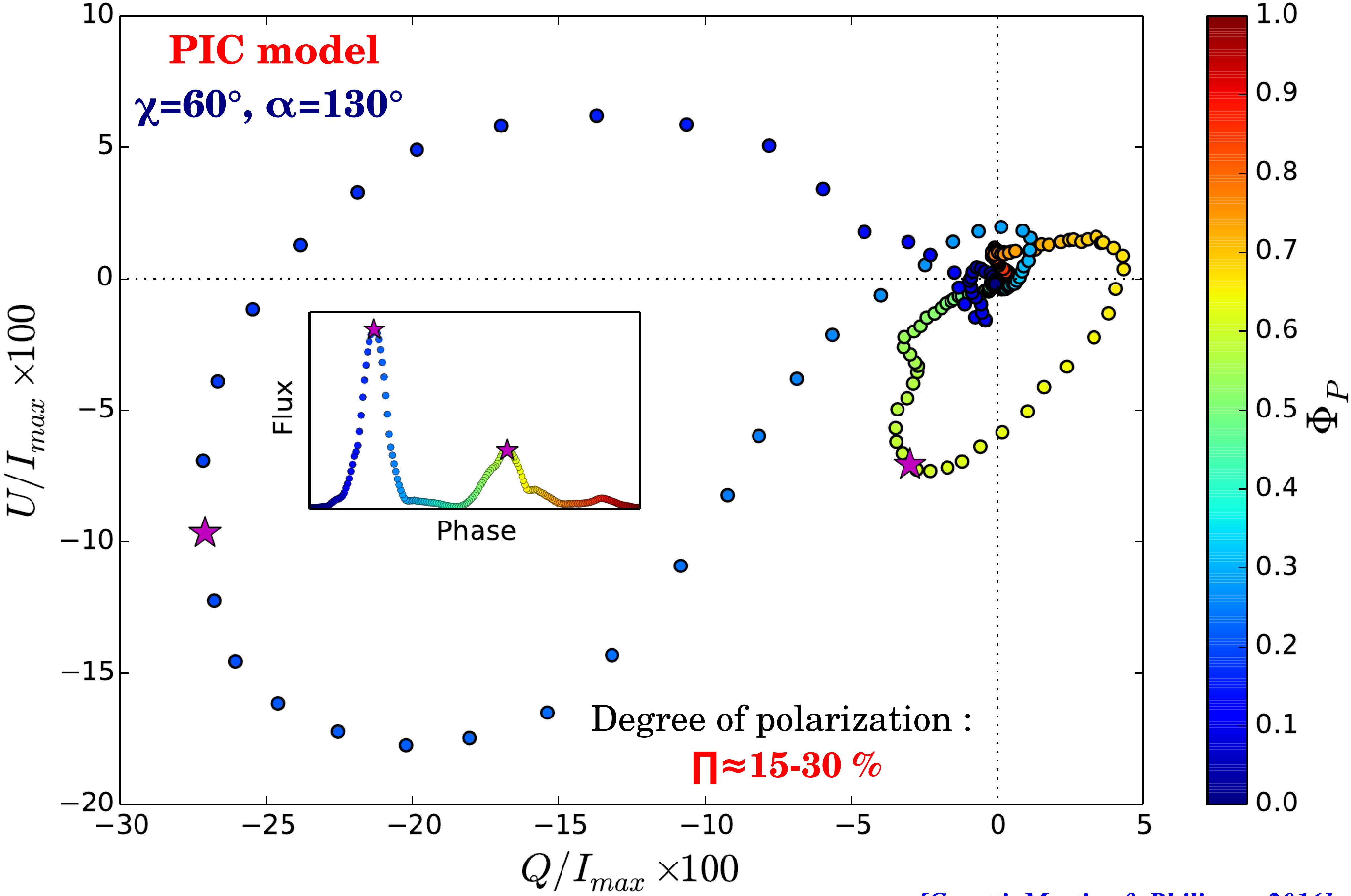
# (Incoherent) Polarization signature : PIC

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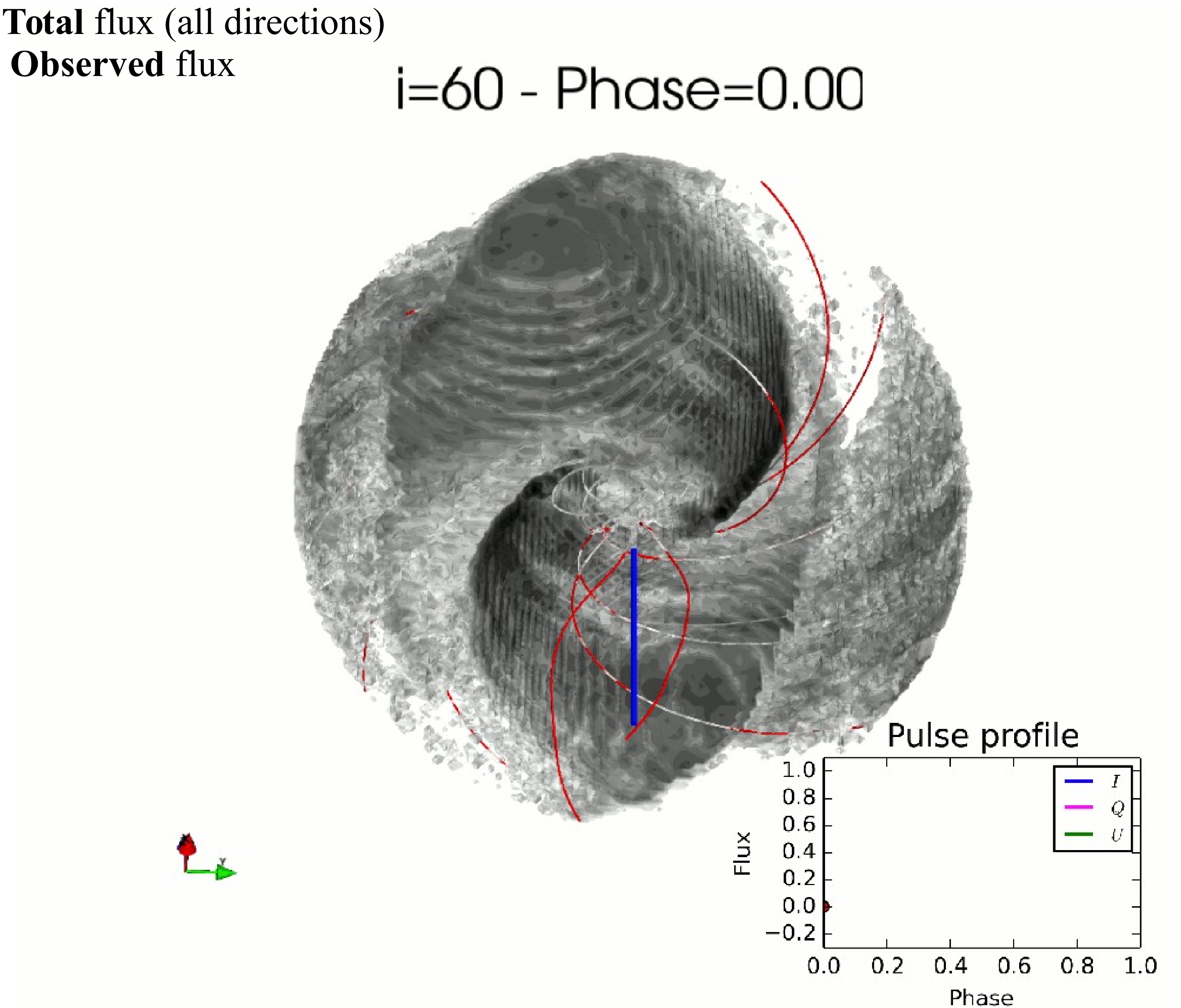
*[Cerutti, Mortier & Philippov 2016]*

# The Crab pulsar as we may see it !

**Gray** : **Total** flux (all directions)
**Color** : **Observed** flux

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# Conclusions

- **Global PIC simulations is the way to go** to solve particle acceleration in **pulsars**, and soon around **black holes**.

- Simulations demonstrate the major role of **relativistic reconnection** in particle acceleration

- High-energy emission could be **synchrotron radiation from the current sheet >~ $R_{LC}$**

- **Pulse profile and polarization** provide robust constraints on **Crab pulsar** inclination and viewing angles.

- More work needed to **compare simulations to observations.**

- Origin of the **radio** emission **still unclear,** more physics to capture in the polar-cap discharge ?