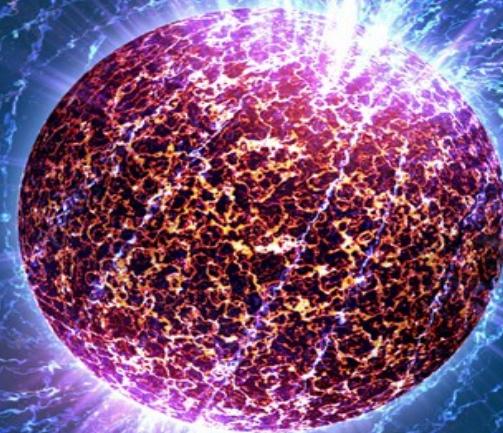


Radiative PIC simulations and their applications to pulsars



Benoît Cerutti

CNRS & Université Grenoble Alpes, Grenoble, France.

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
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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.

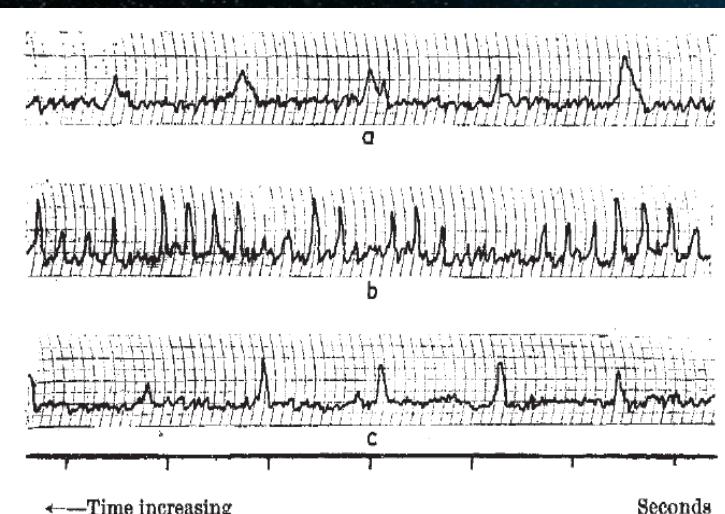
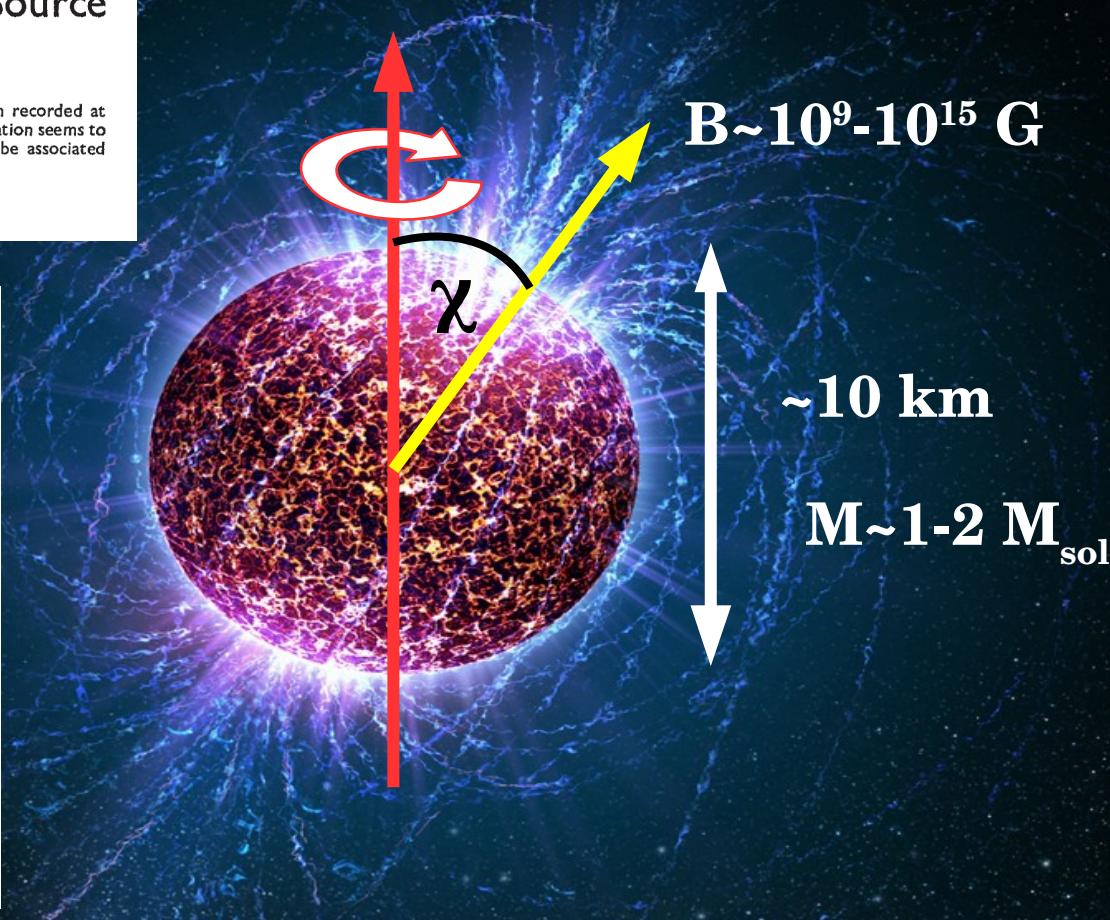


Fig. 1. Pulses observed with a recording time constant of about 0.03 s on March 21, 1968. (a) CP.0834. (b) CP.0950, during a period of intense activity. (c) CP.1138.

Spin period P : 1 ms – few seconds

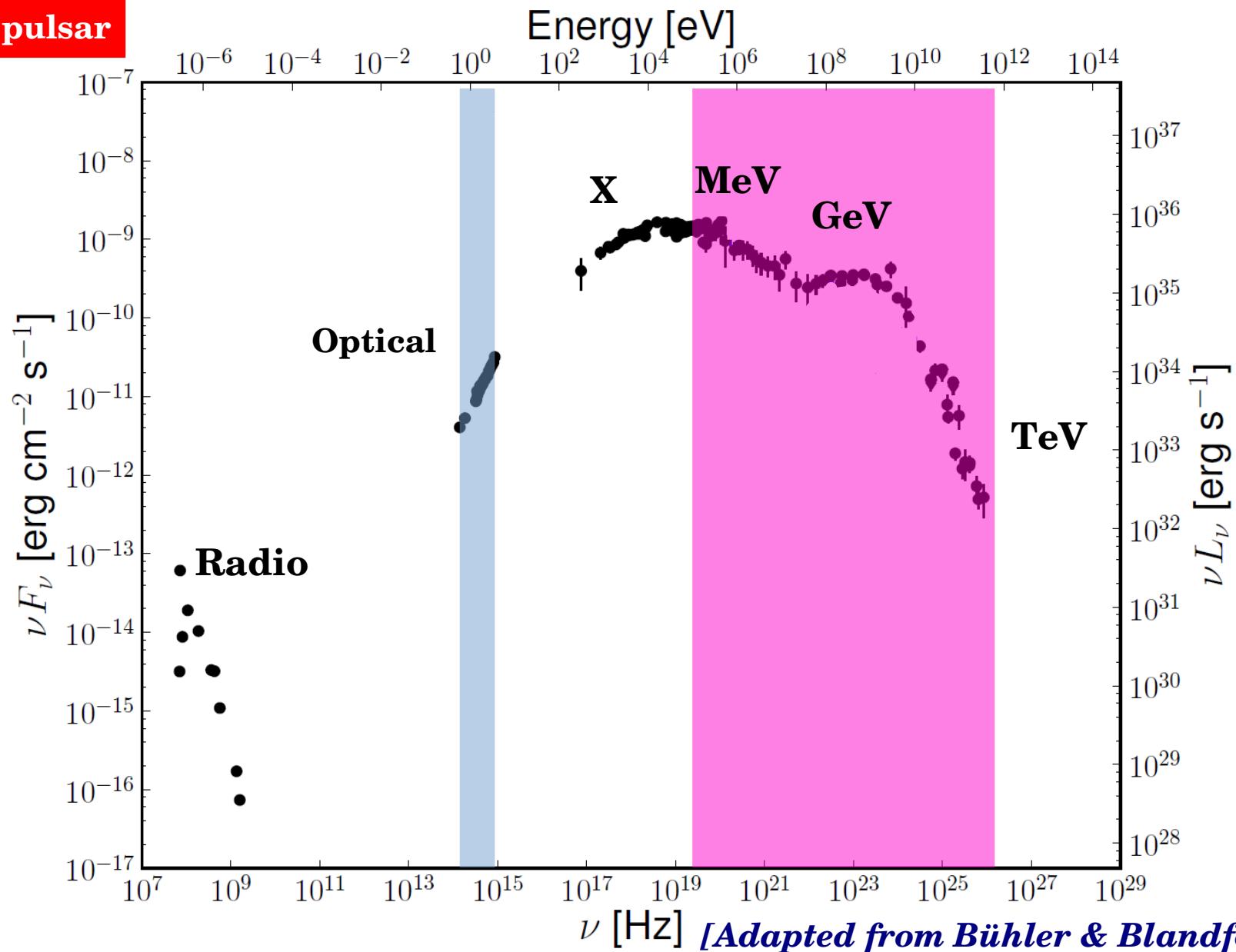


Pulsars represent great laboratories to explore extreme physical conditions :

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

Pulsars shine throughout the electromagnetic spectrum

The Crab pulsar



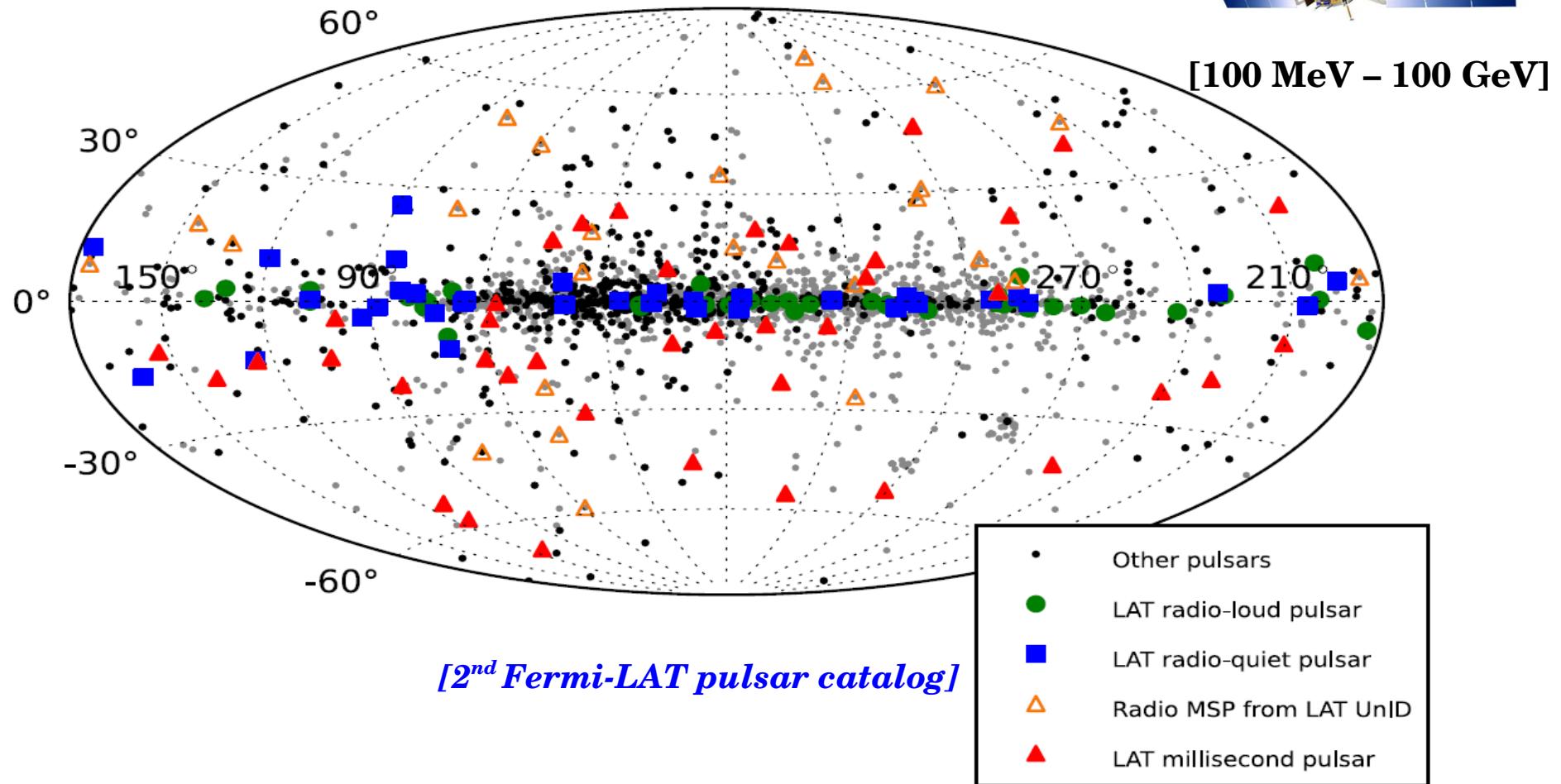
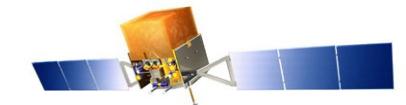
A large fraction of the pulsar spindown is released in light,
in particular in the gamma-ray band => Efficient particle acceleration !

Most Galactic accelerators are pulsars

Fermi-LAT

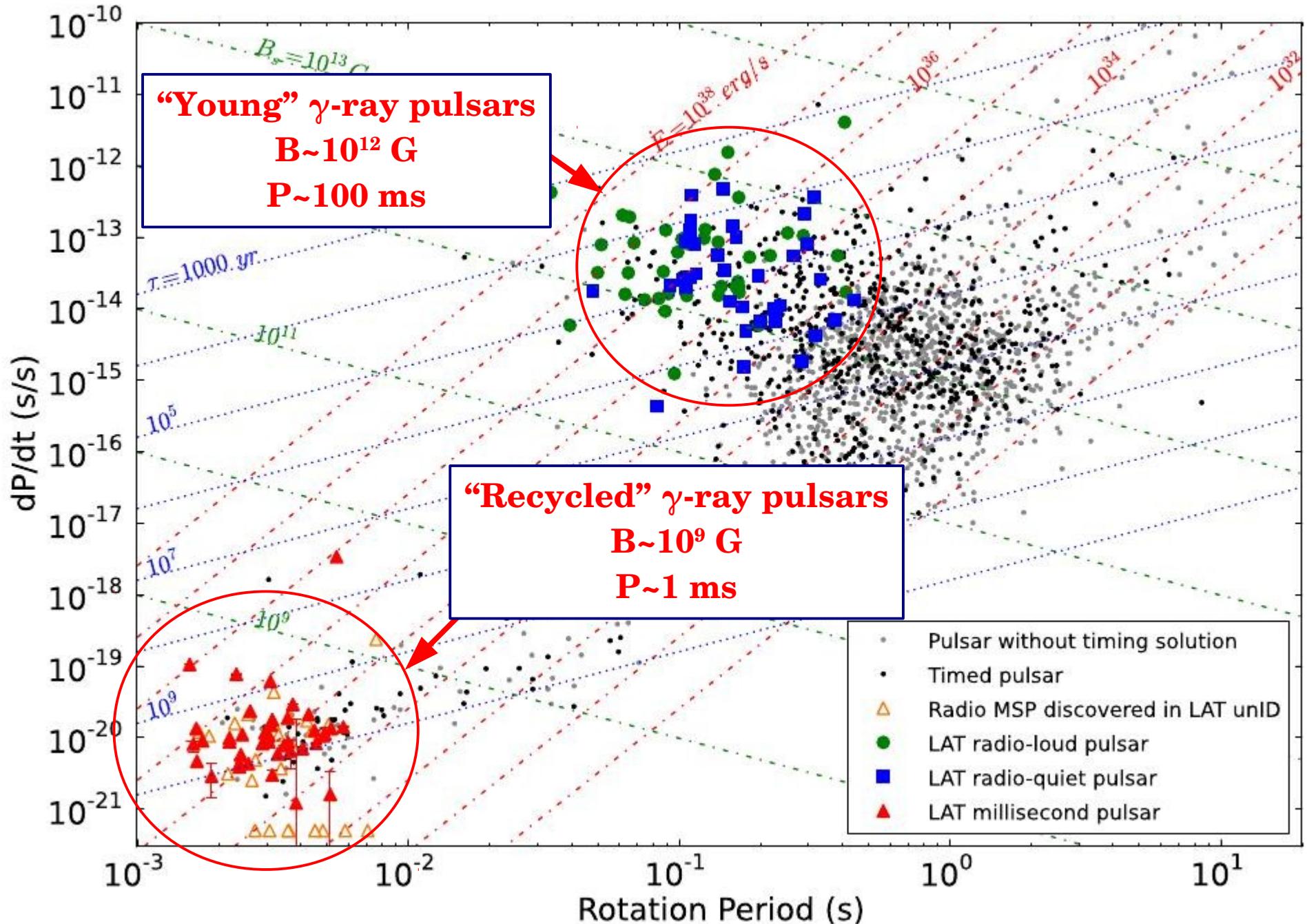
~ >100 gamma-ray pulsars

Galactic coordinates



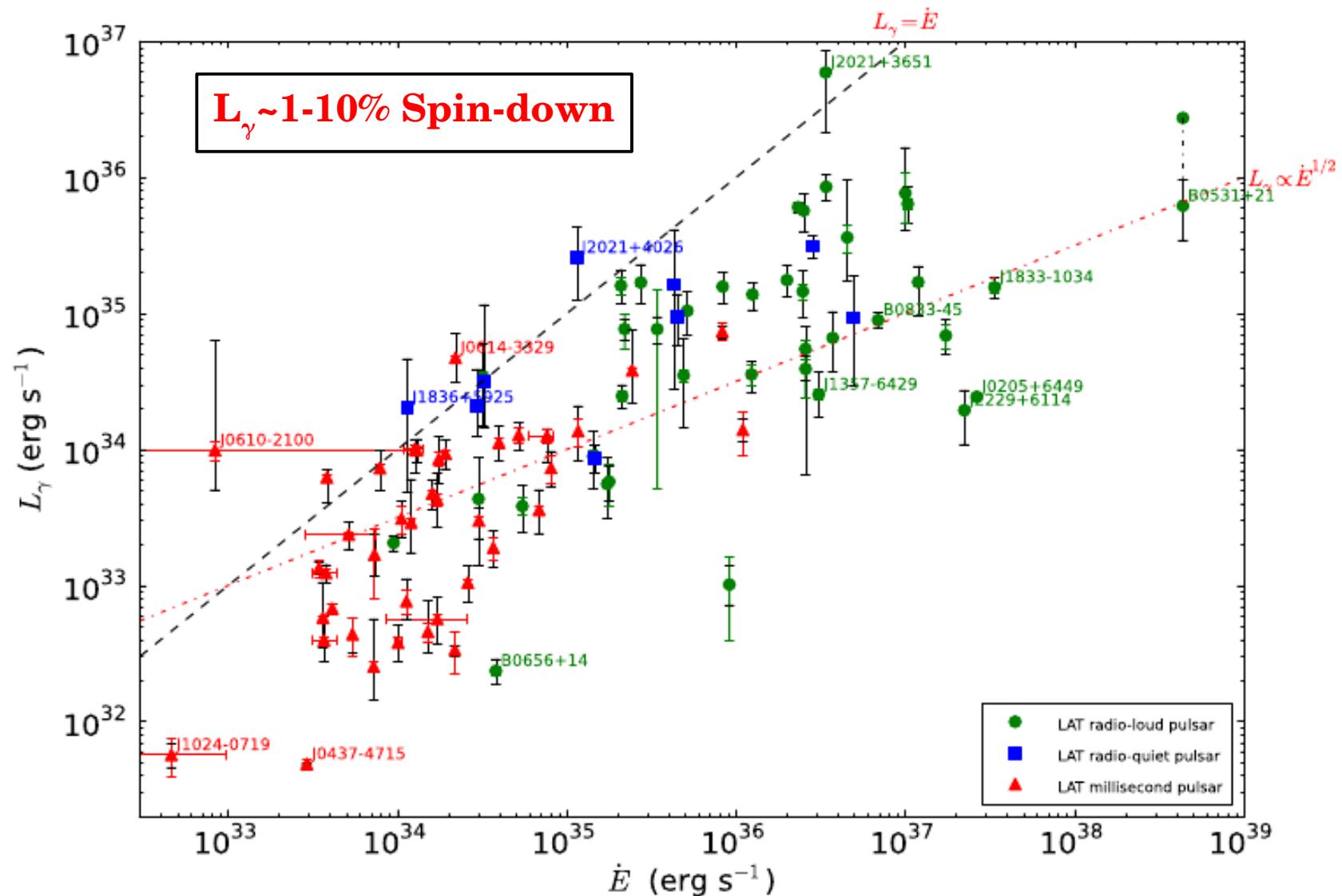
Exquisite gamma-ray data put tight constraints on particle acceleration models

Pulsars emitting gamma rays: Rotation-powered



[2nd Fermi-LAT pulsar catalog]

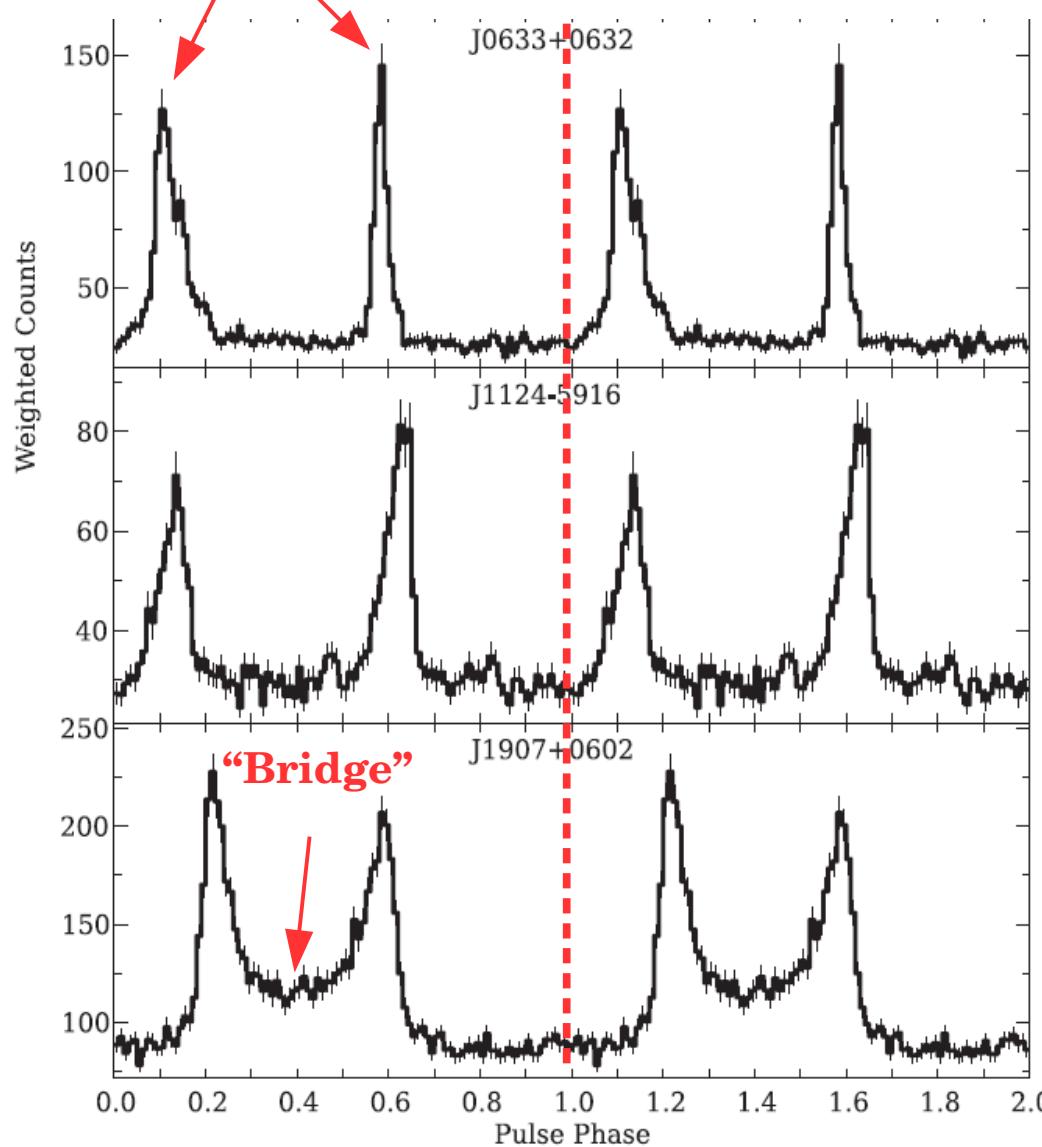
Pulsars are efficient particle accelerators



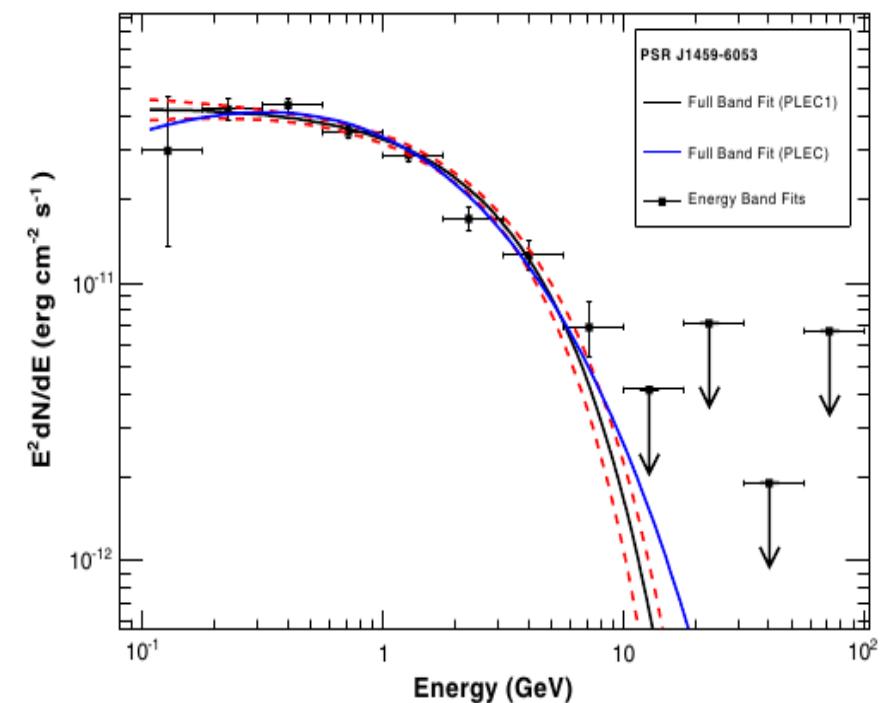
[2nd Fermi-LAT pulsar catalog]

Typical gamma-ray pulsar signal

Two peaks lightcurves



Hard power-law + exponential cut-off



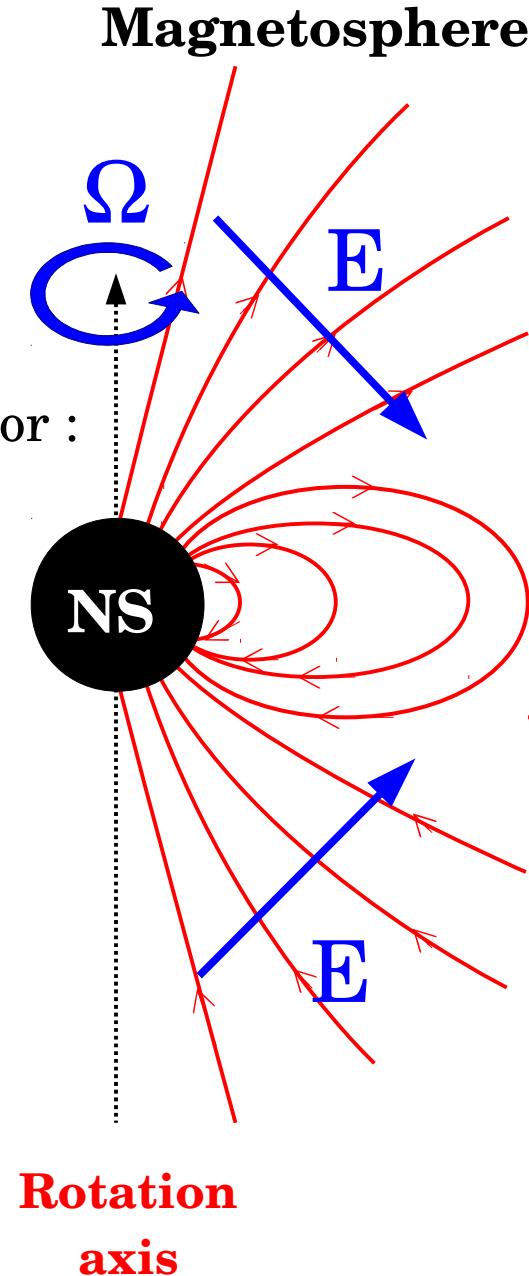
[2nd Fermi-LAT pulsar catalog]

How/Where are particles accelerated?
How/Where do they radiate?

Pulsar electrodynamics

Elements of a pulsar magnetosphere: vacuum

(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 :

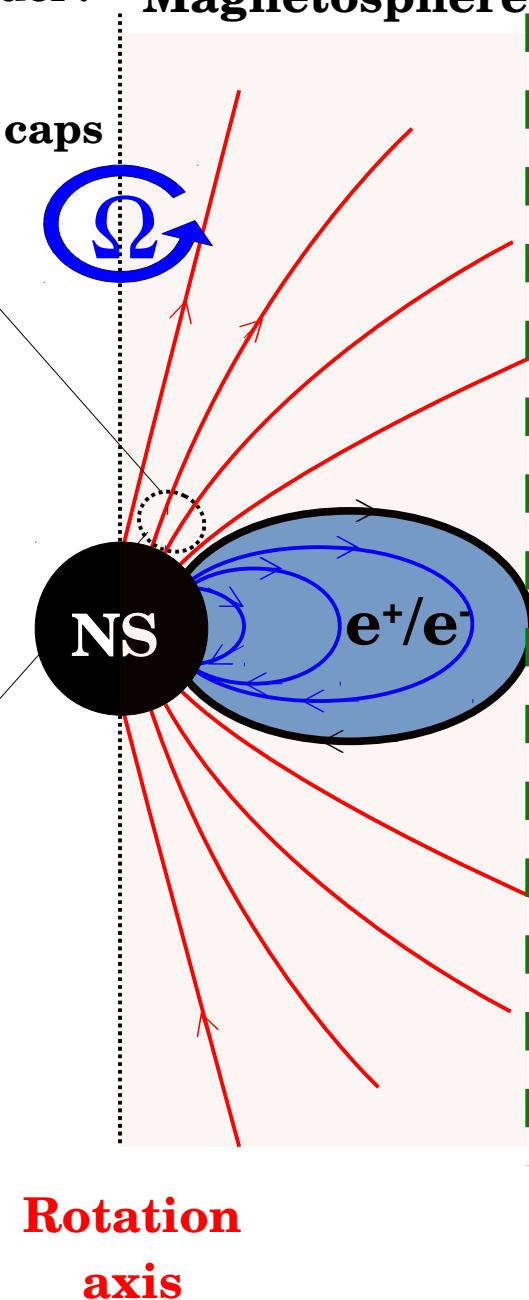
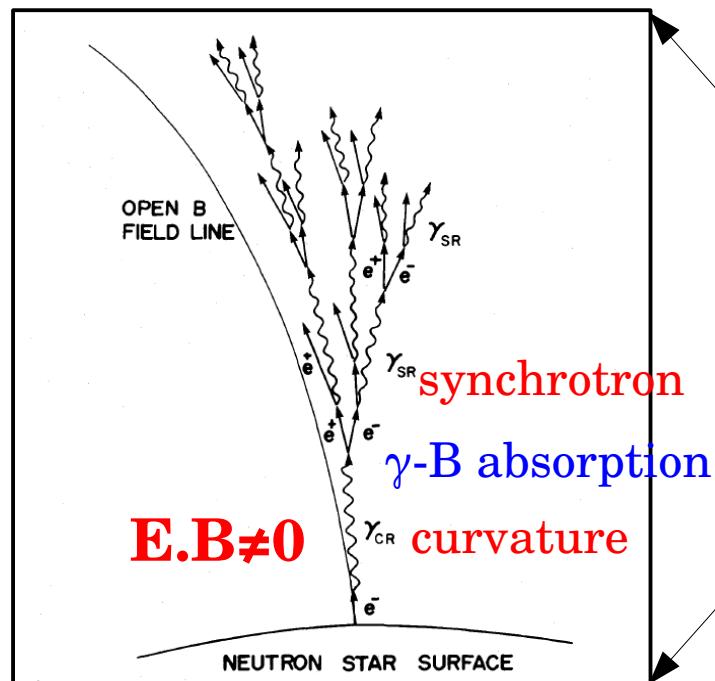
$$\Delta \Phi = \frac{R^2 \Omega B}{c} \approx 10^{18} V$$

(for a Crab-like pulsar)

Elements of a pulsar magnetosphere: plasma filled

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

Copious pair creation in the polar caps

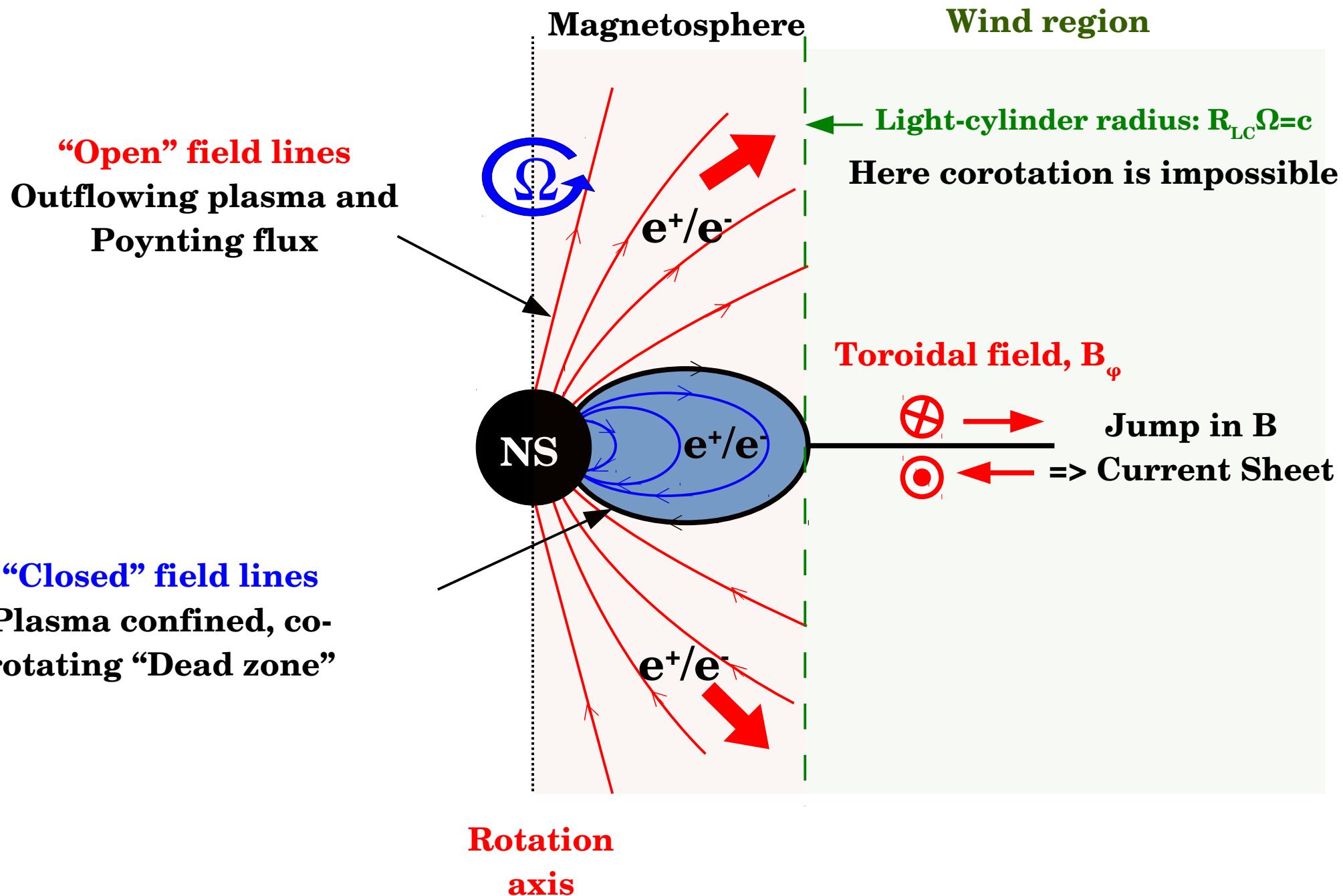


Daugherty & Harding 1982 ; Timokhin
& Arons 2013 ; Chen & Beloborodov
2014 ; Philippov et al., 2015

Potential polar cap (Crab):

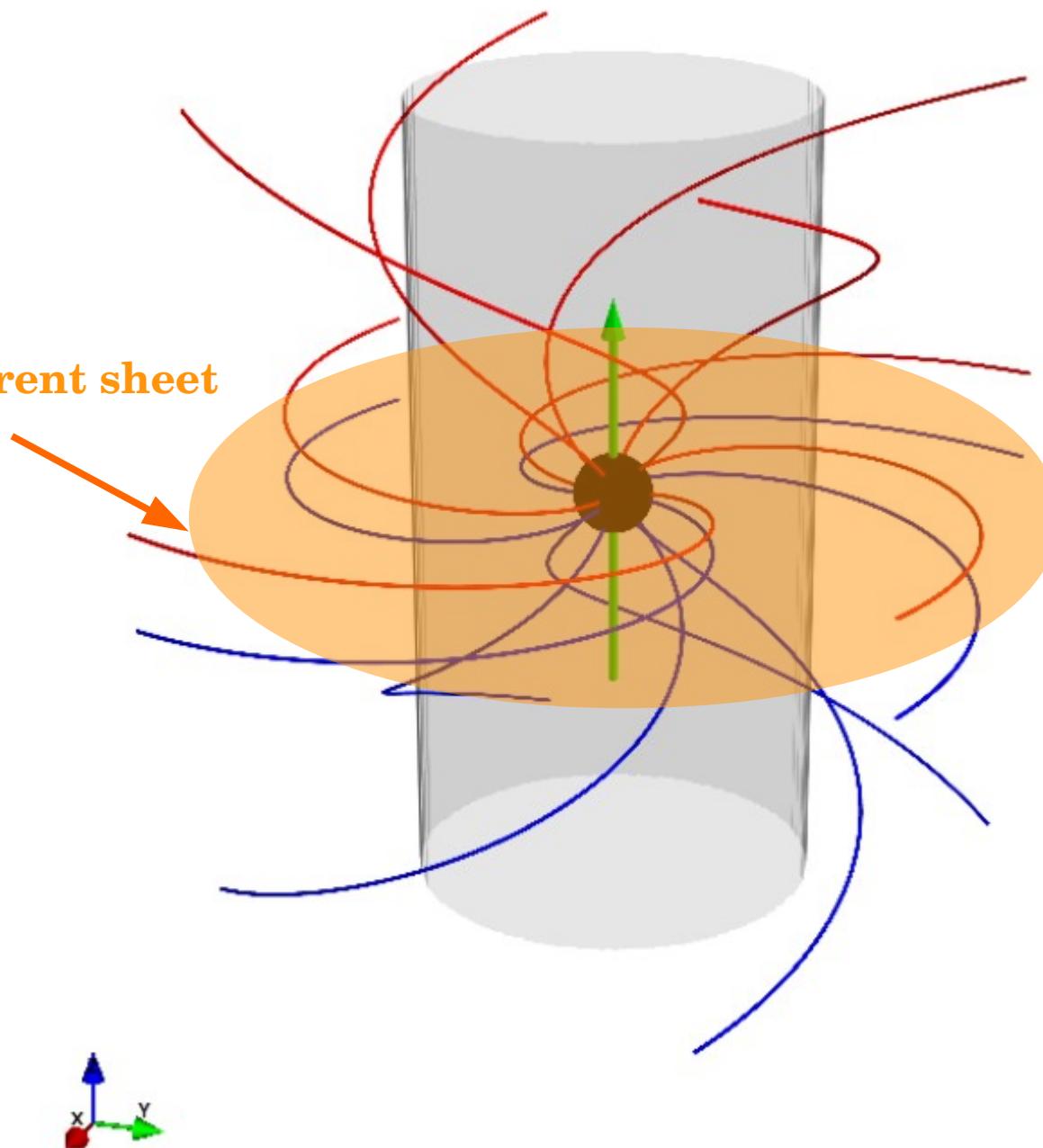
$$\Delta \Phi_{pc} = \frac{R^3 \Omega^2 B}{c^2} \approx 10^{16} V$$

Elements of a pulsar magnetosphere: plasma filled

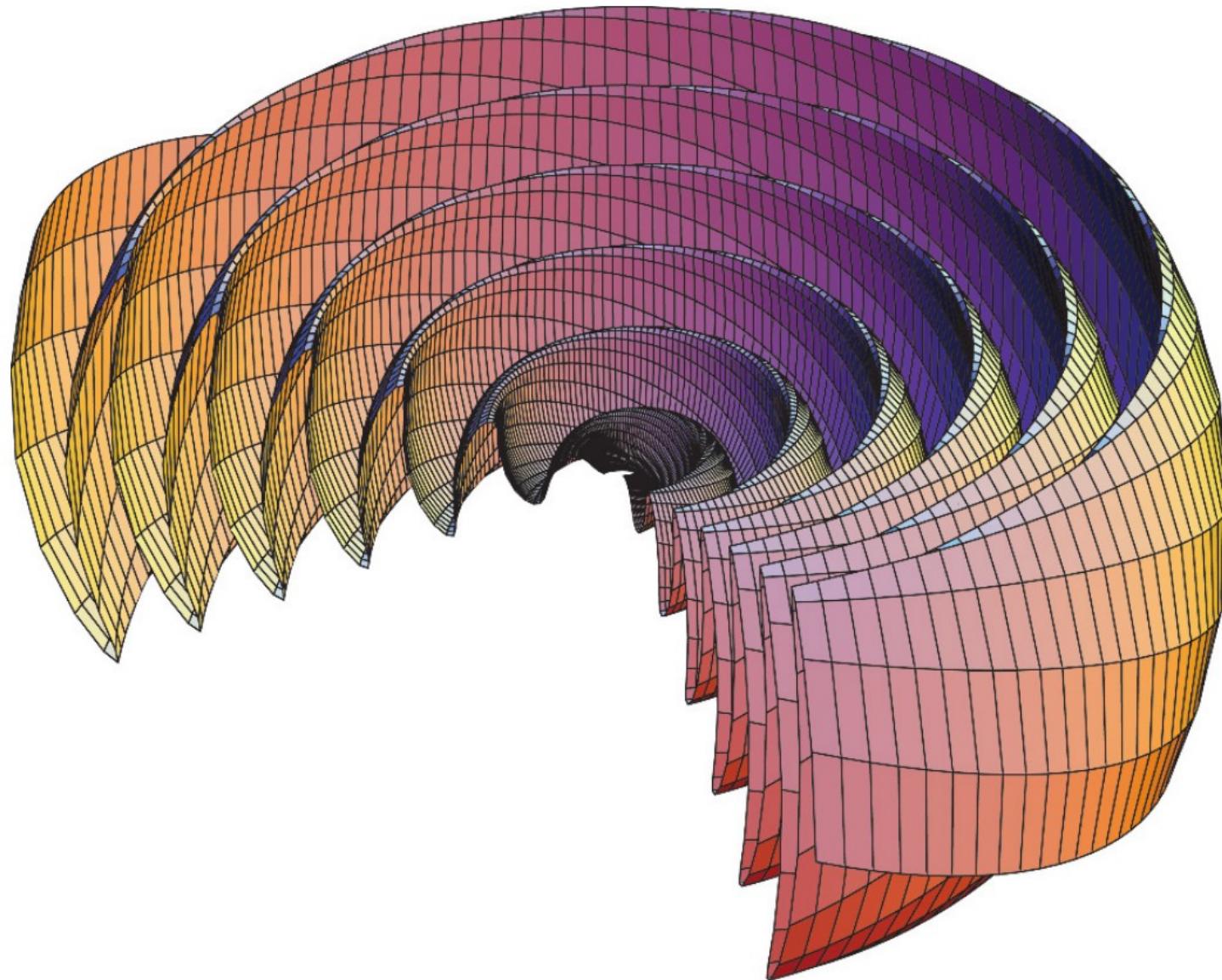


A 3D view at the aligned pulsar field lines

Equatorial current sheet



Ballerina skirt: oblique rotator current sheet



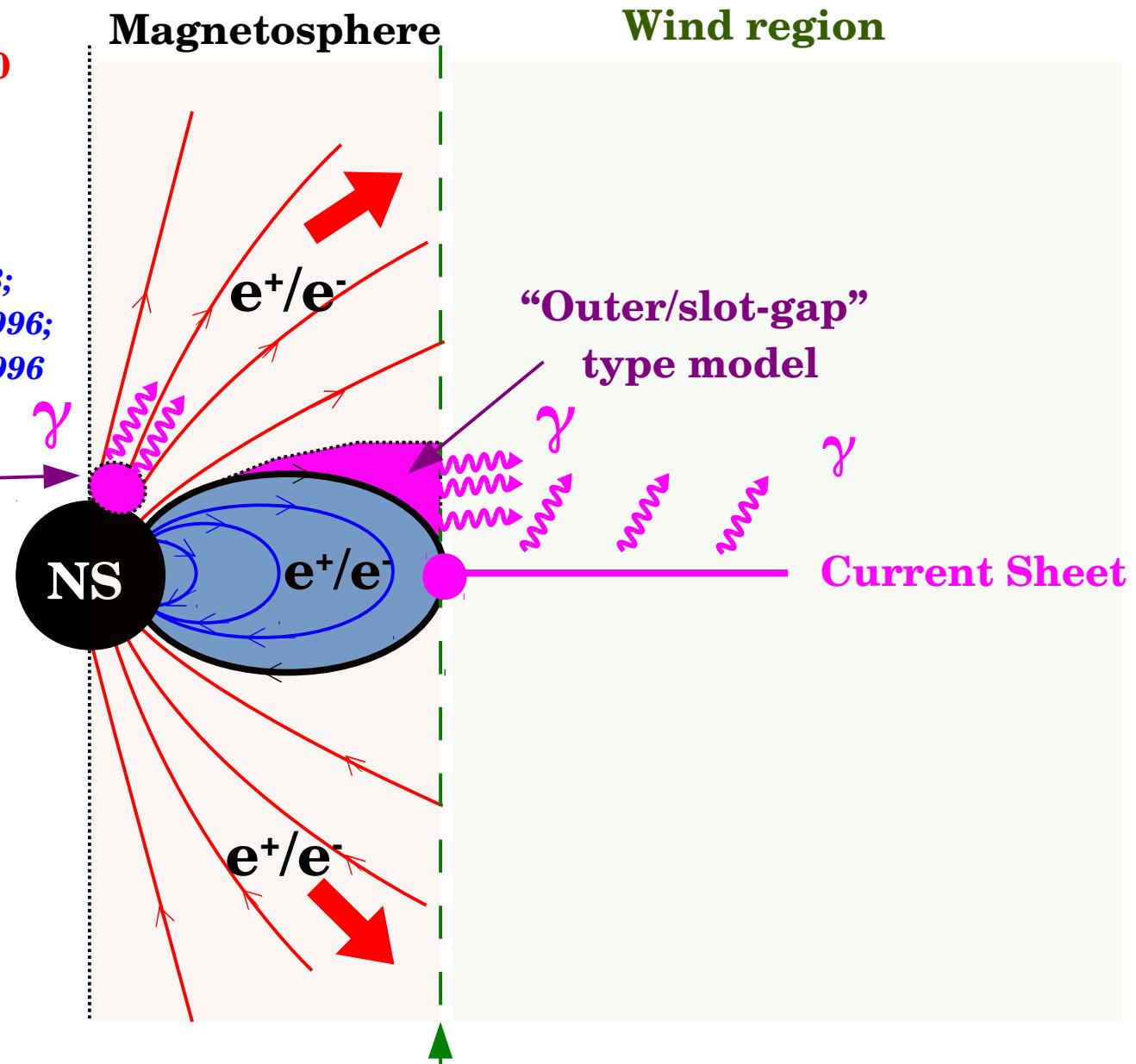
Proposed sites for particle acceleration

Acceleration where $E \cdot B \neq 0$

γ -ray : **curvature** or
synchrotron radiation

e.g. Arons 1983;
Muslimov & Harding 2003;
Cheng et al. 1986; Romani 1996;
Coroniti 1990 ; Lyubarskii 1996

“Polar-cap”
type model



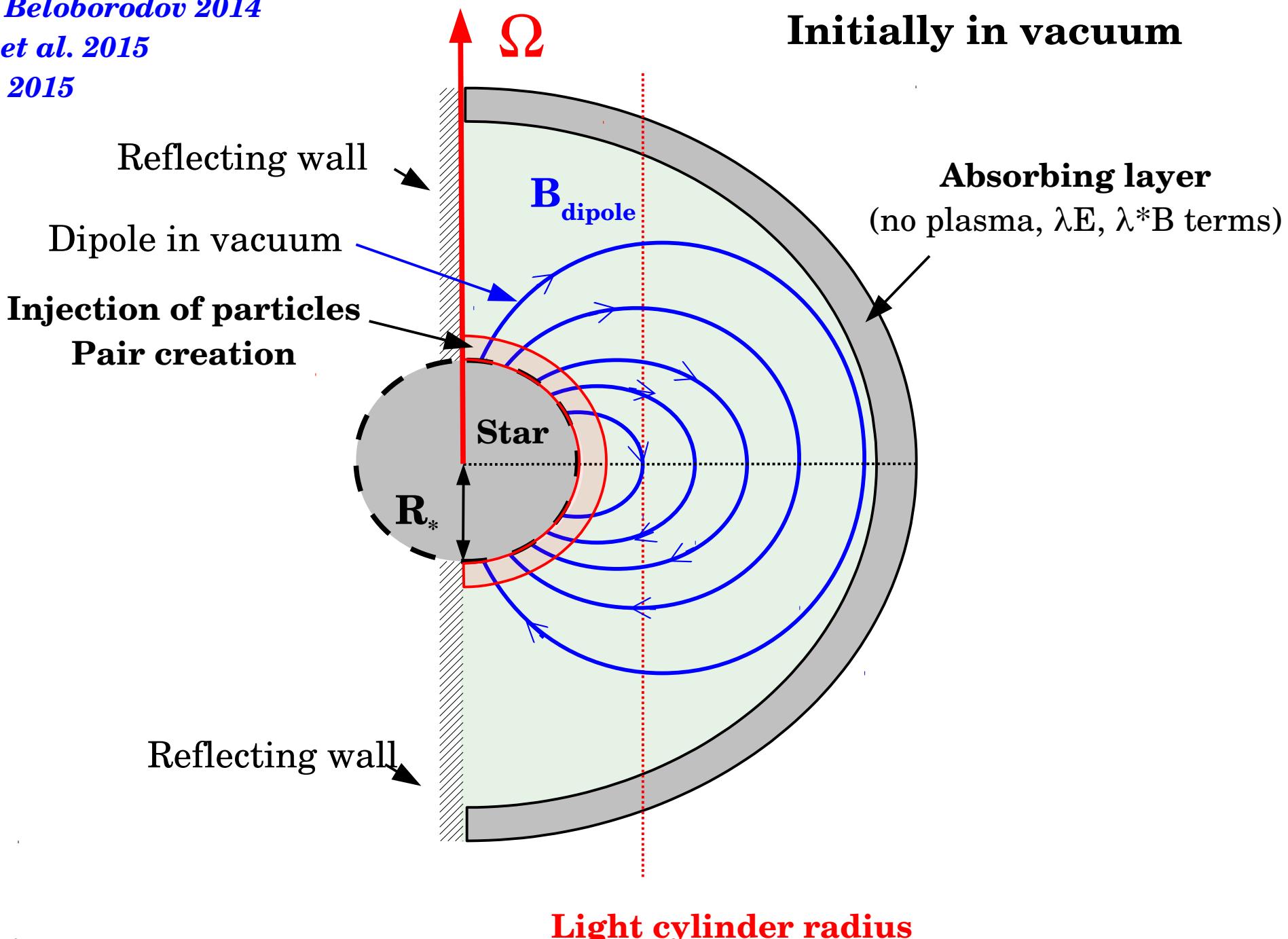
=> Need for global PIC simulations!

The numerical setup: an aligned rotator (2D)

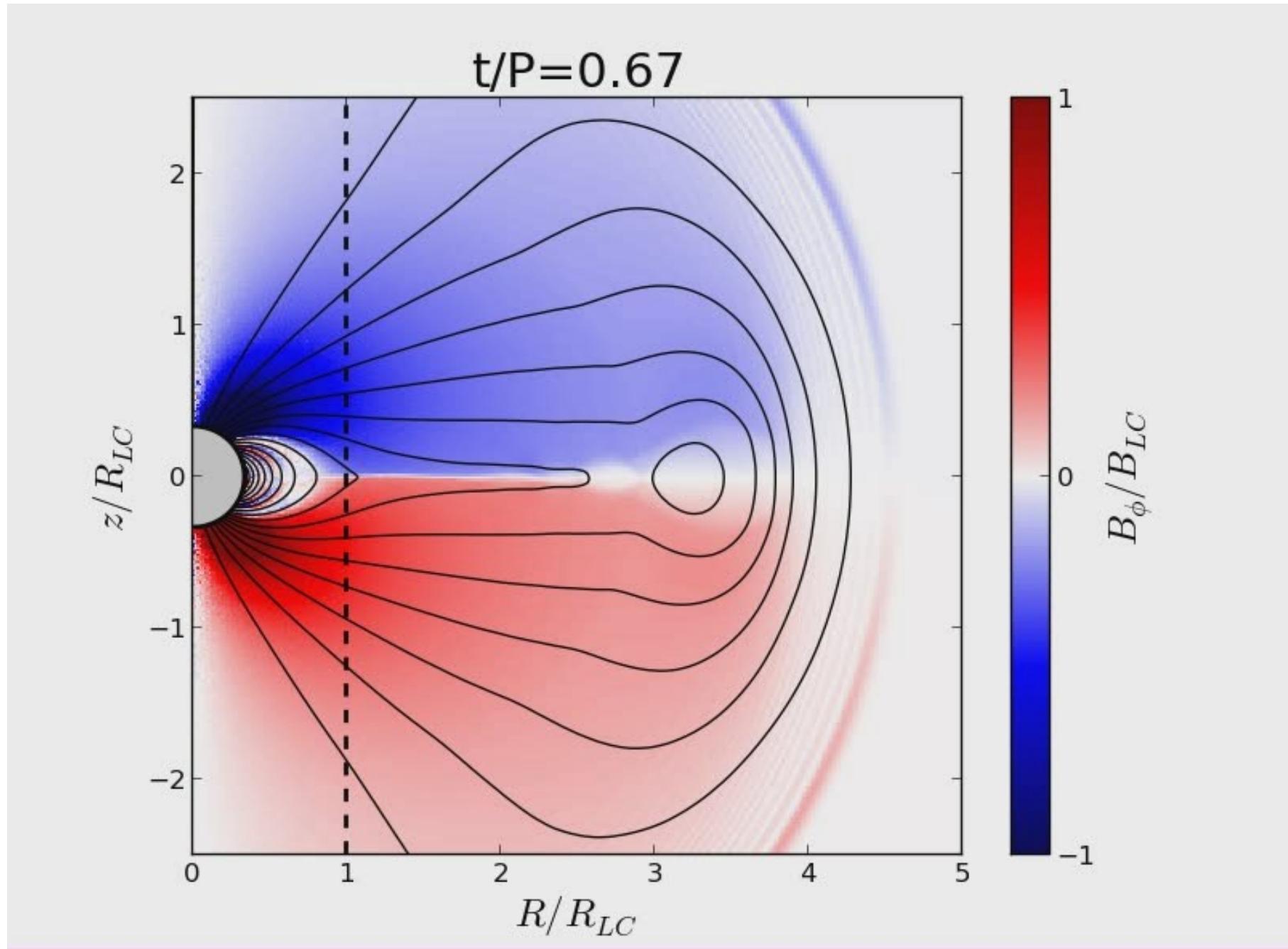
Chen & Beloborodov 2014

Cerutti et al. 2015

Belyaev 2015



Toroidal magnetic field

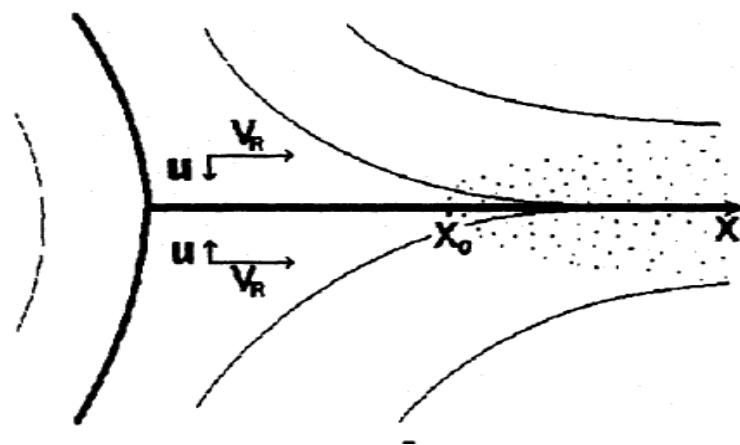
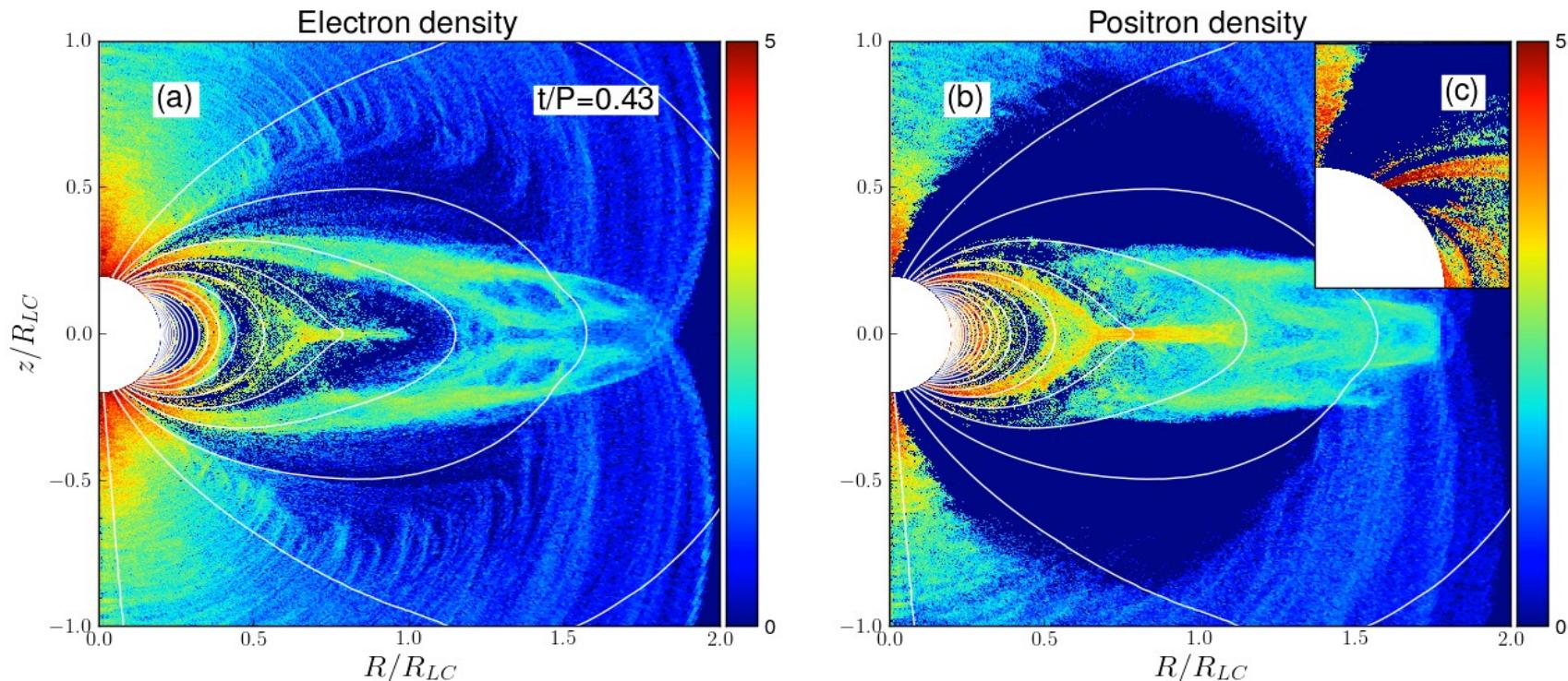


Pair creation and filling of the magnetosphere

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

Chen & Beloborodov 2014; Philippov+2015a,b

Includes Lense-Thirring

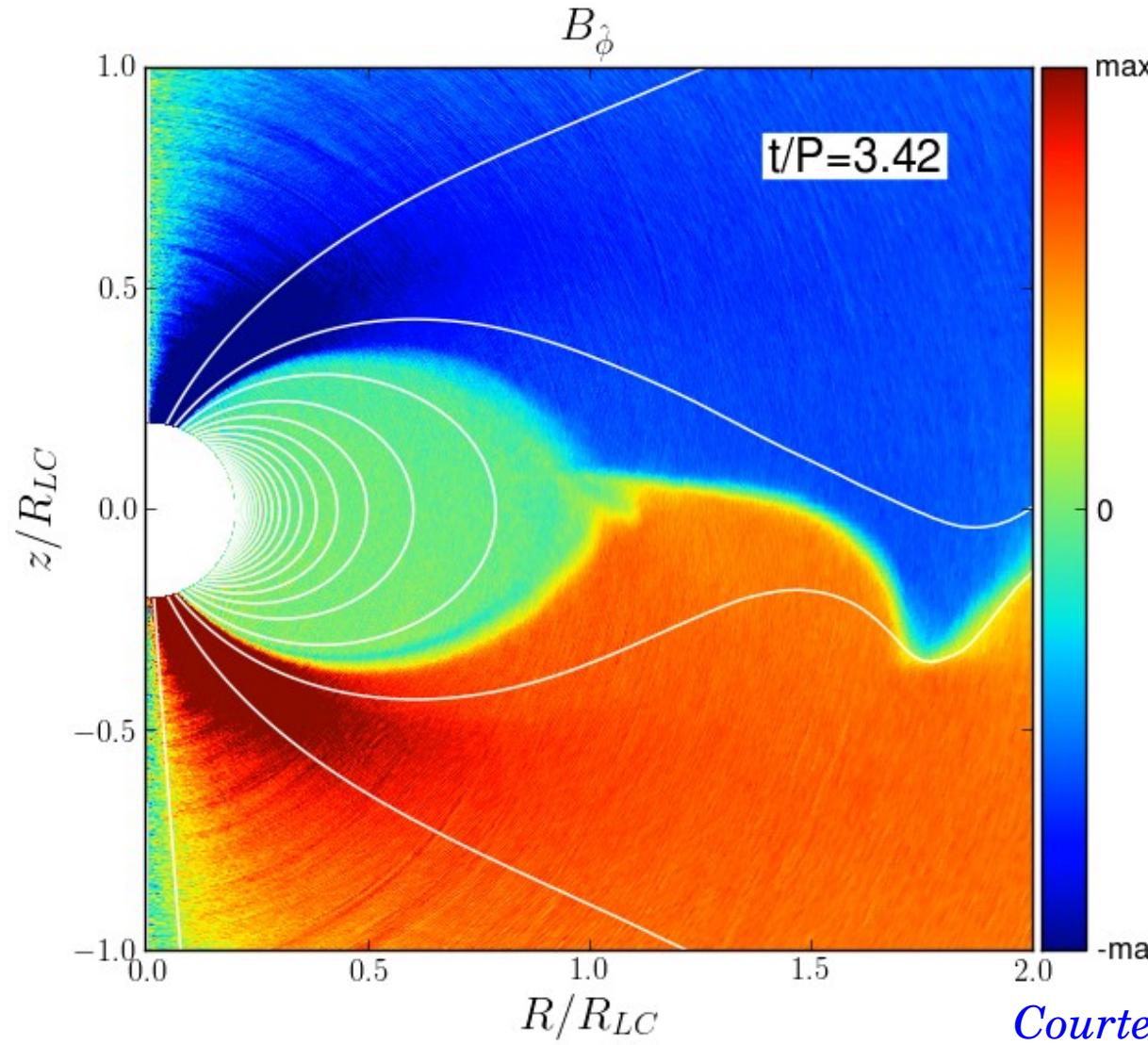


Courtesy of Sasha Philippov

Pair creation in the **sheet** anticipated
by *Y. Lyubarsky in 1996*

Imprints on the fields

Time-dependent discharge of the polar-cap : **Origin of the radio emission ?**

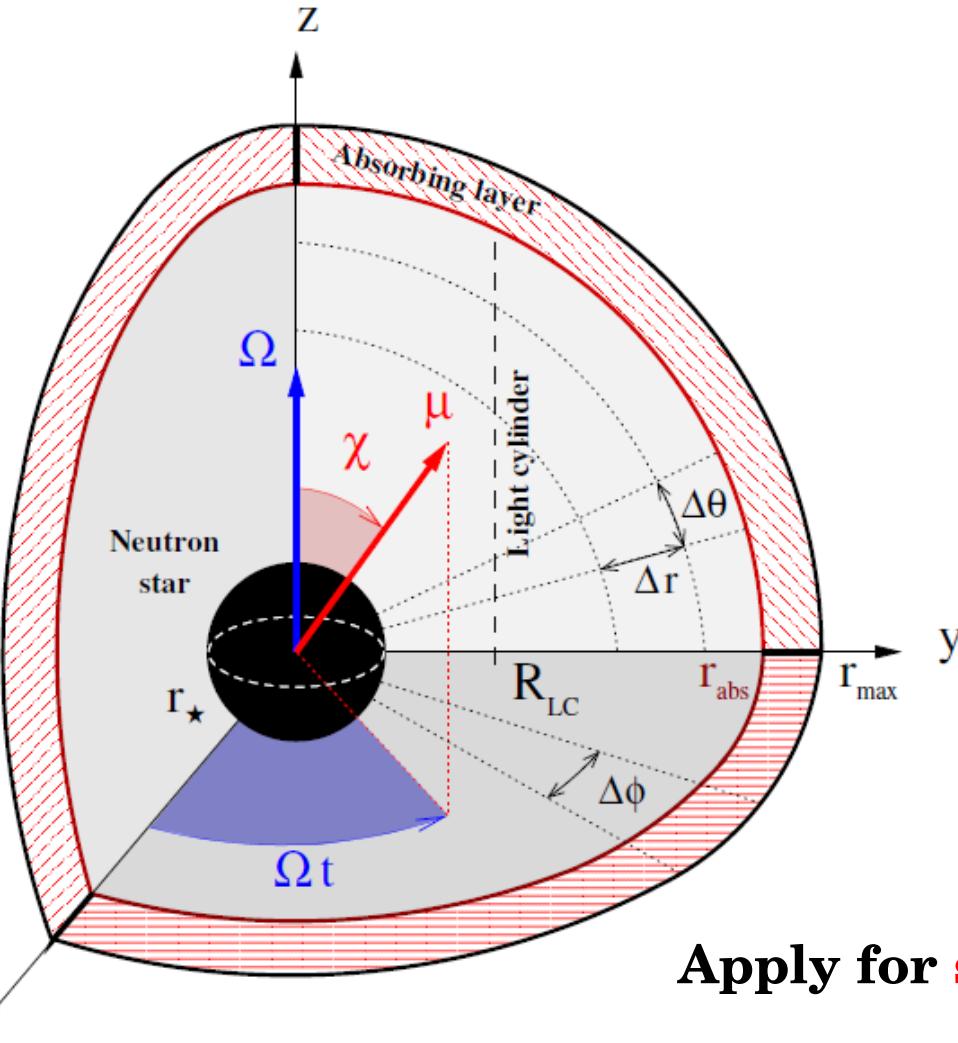


Power in the stripes $W \sim 10^{-2} L_0$, enough to power the radio emission

Global 3D PIC with radiation reaction force

Zeltron code : <http://benoit.cerutti.free.fr/Zeltron/>

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



Radiation reaction force

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

Emitted radiation spectra :

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

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

Apply for **synchrotron** and **curvature** radiation

($\log(r) \times \theta \times \varphi$) : 1024 × 256 × 256

A digression about modeling curvature radiation

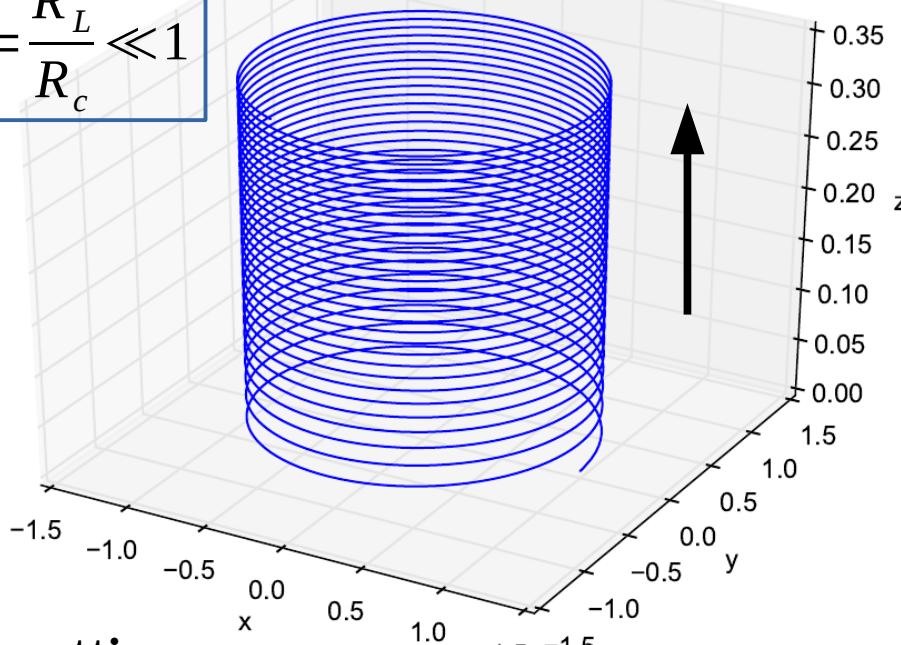
Radiation reaction force (Landau-Lifschitz):

$$\mathbf{g} = \frac{2}{3} r_e^2 [(\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B}) \times \mathbf{B} + (\boldsymbol{\beta} \cdot \mathbf{E}) \mathbf{E}] \quad \left. \begin{array}{l} \text{"Non-relativistic" term,} \\ \text{Must be included even if } \gamma \gg 1 \end{array} \right\}$$
$$- \frac{2}{3} r_e^2 \gamma^2 [(\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B})^2 - (\boldsymbol{\beta} \cdot \mathbf{E})^2] \boldsymbol{\beta}, \quad \left. \begin{array}{l} \text{"Relativistic" term} \end{array} \right\}$$

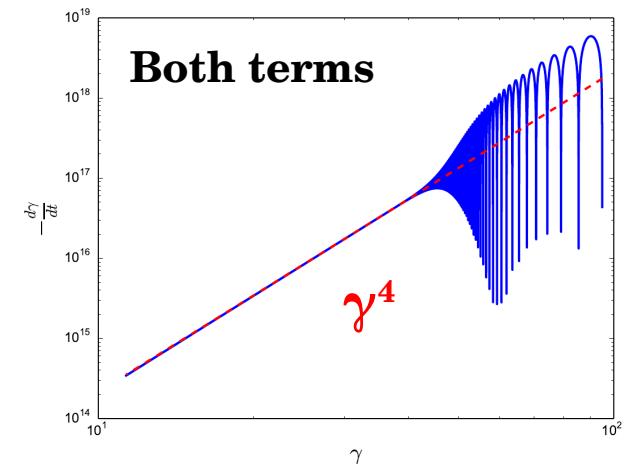
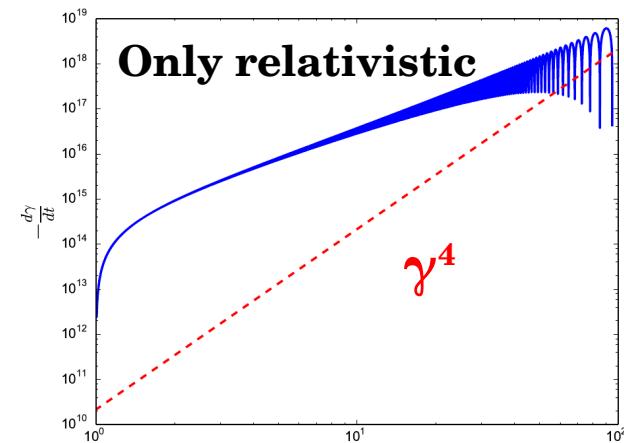
Consider a particle moving along a magnetic loop with zero pitch angle

Curvature drift velocity :

$$\beta_d = \frac{R_L}{R_c} \ll 1$$



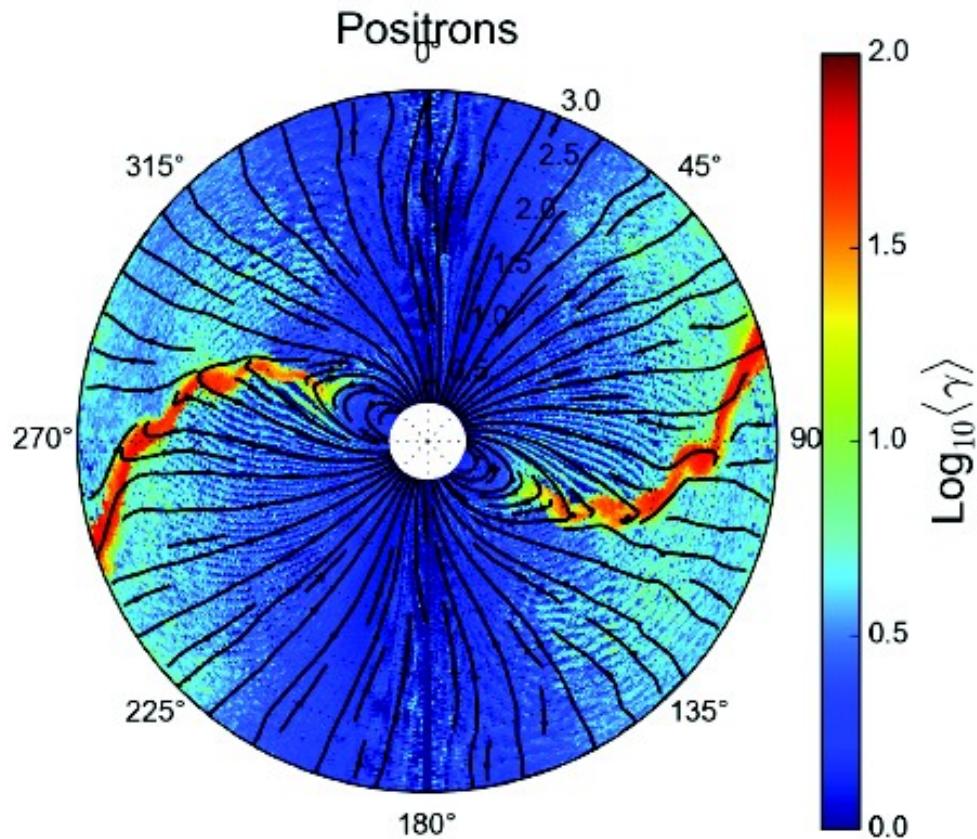
B. Cerutti



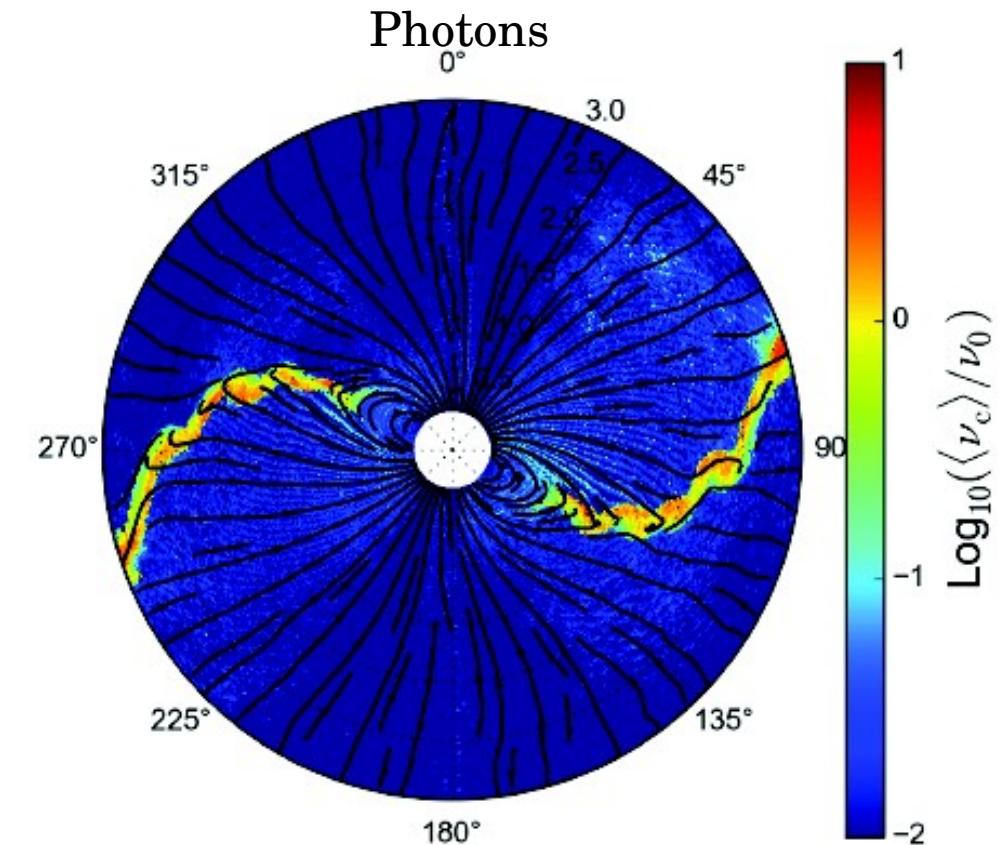
Particle acceleration

Particle / radiation mean energy ($\chi=30^\circ$)

Cerutti et al. 2016



Relativistic reconnection



Mostly synchrotron radiation

Particle energy in the sheet given by :

$$\sigma_{LC} \approx \frac{\Phi_{PC}}{\Gamma_{LC} \kappa_{LC}} \approx 50$$

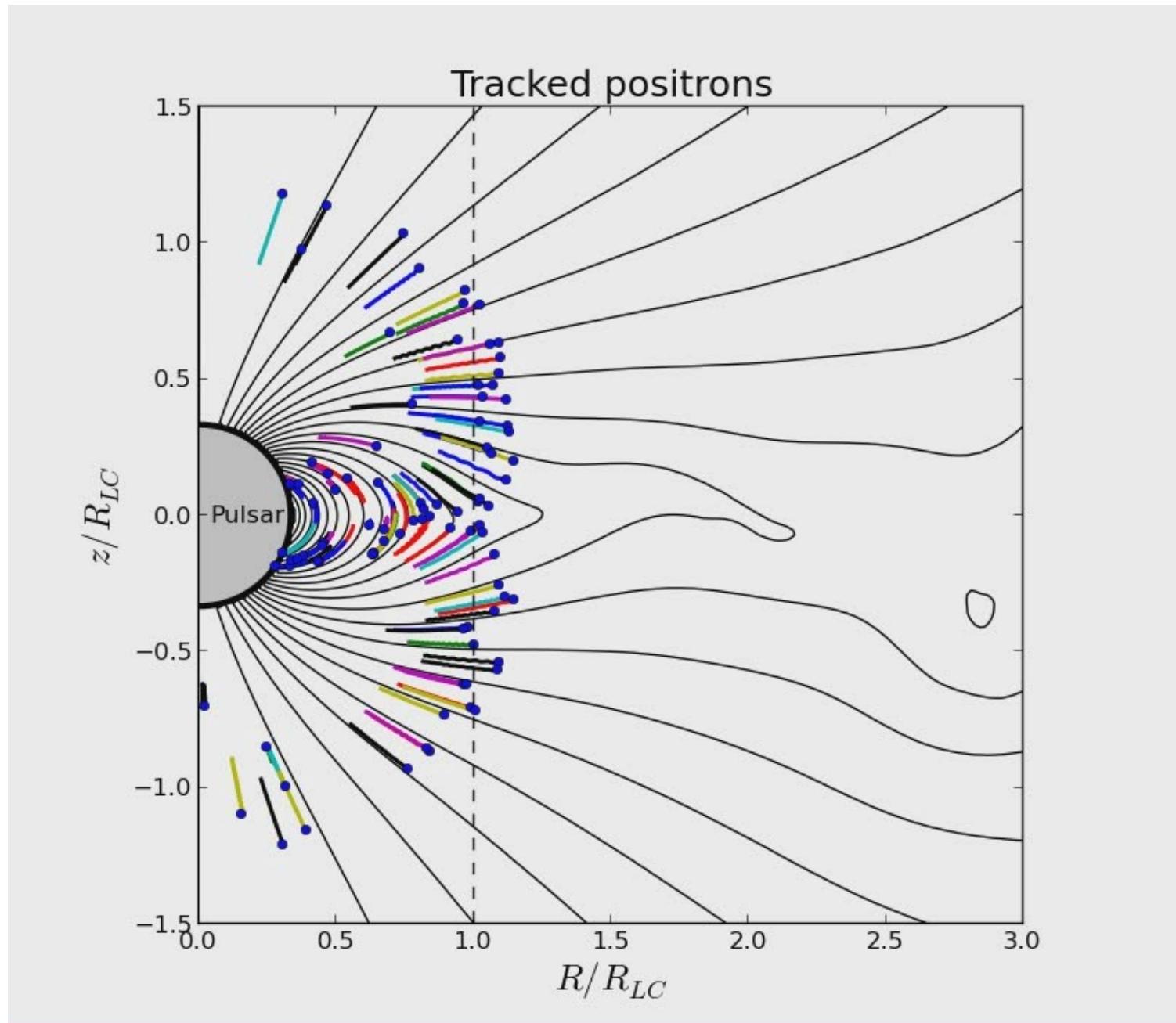
(here)

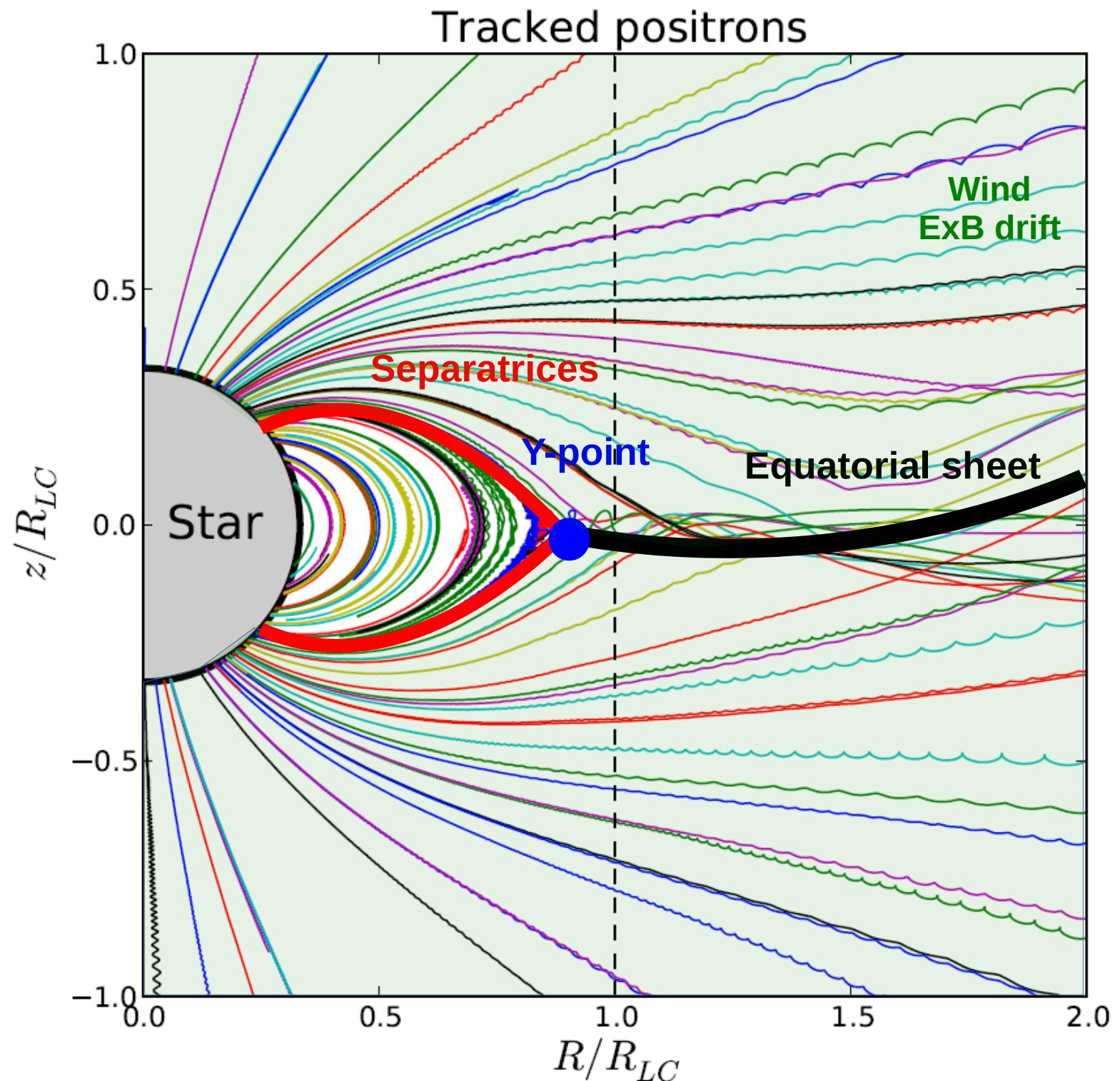
Plasma multiplicity, depends on microphysics !

Cerutti et al. 2015; Philippov & Spitkovsky 2014, 2017

Particle acceleration and e^+/e^- asymmetry

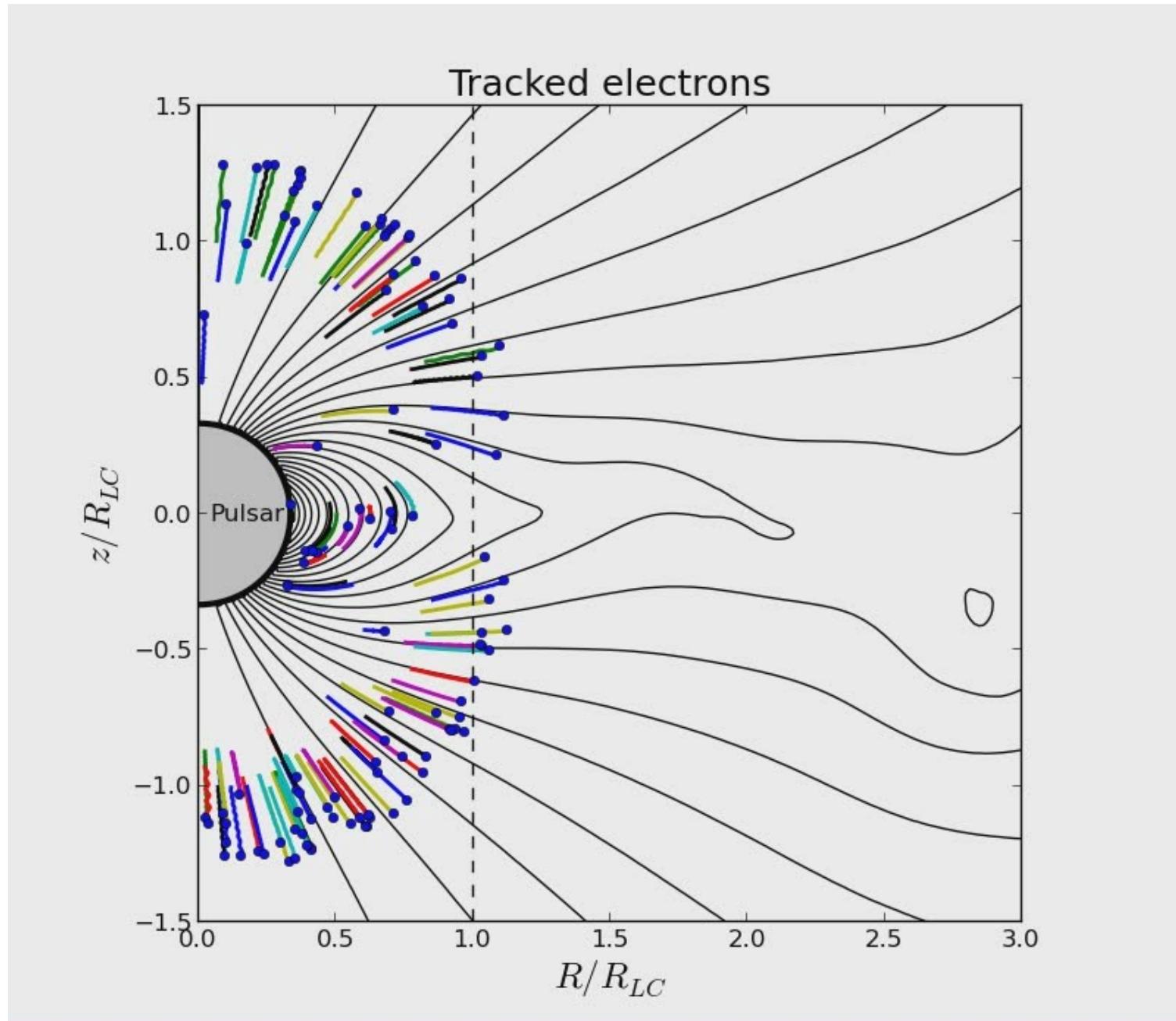
2D





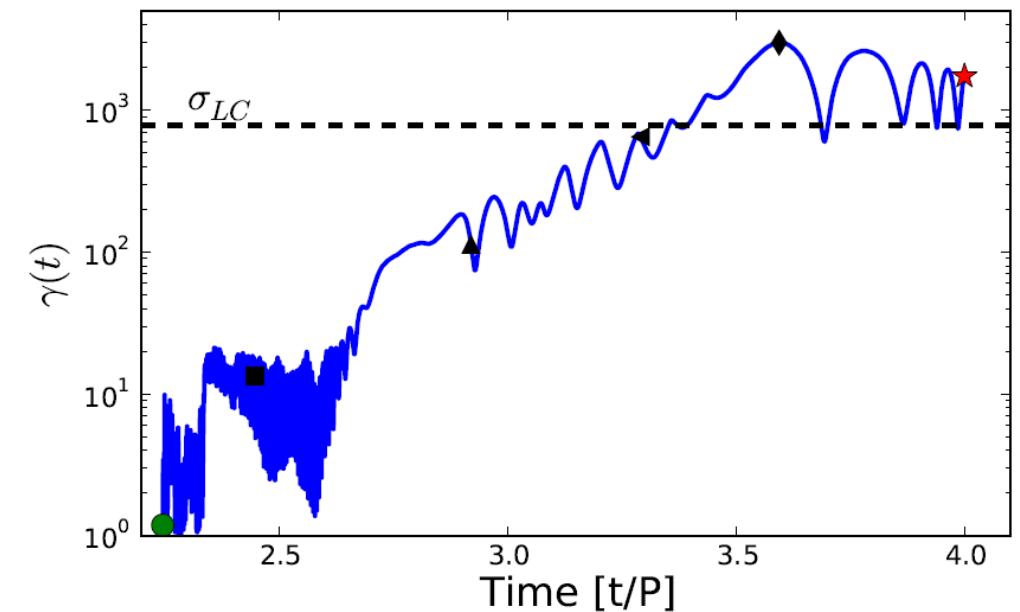
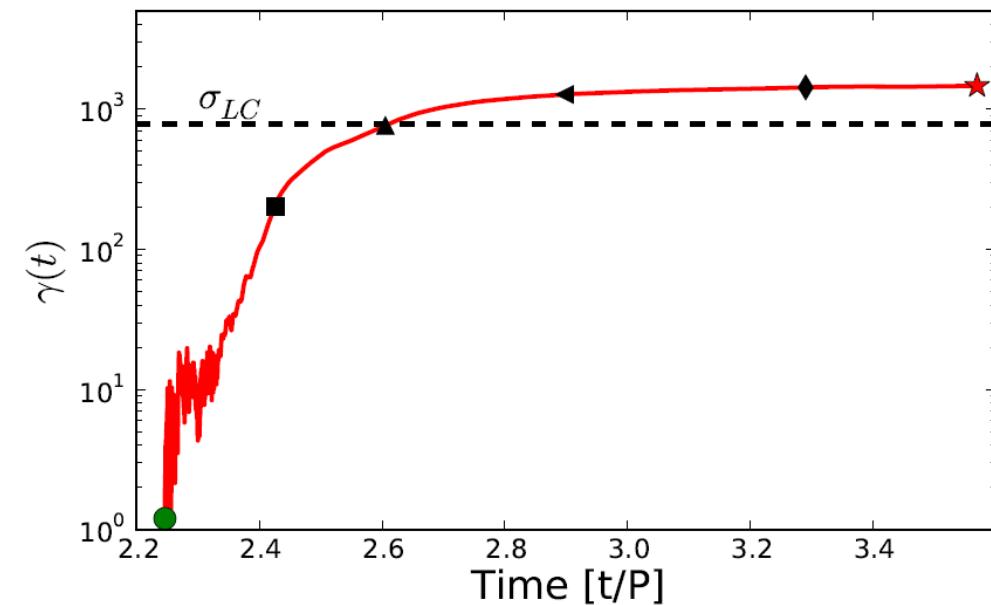
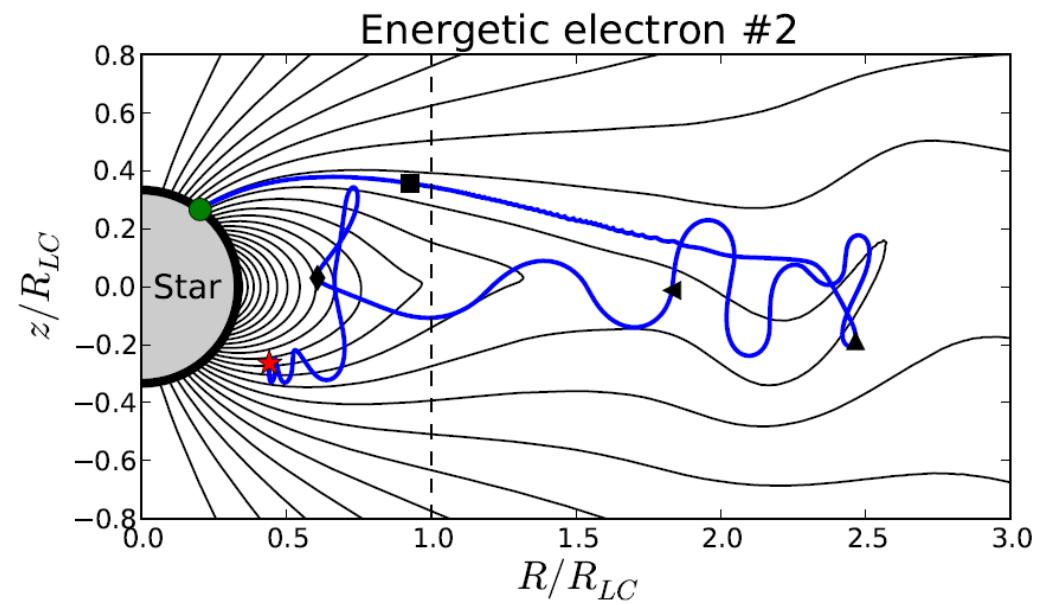
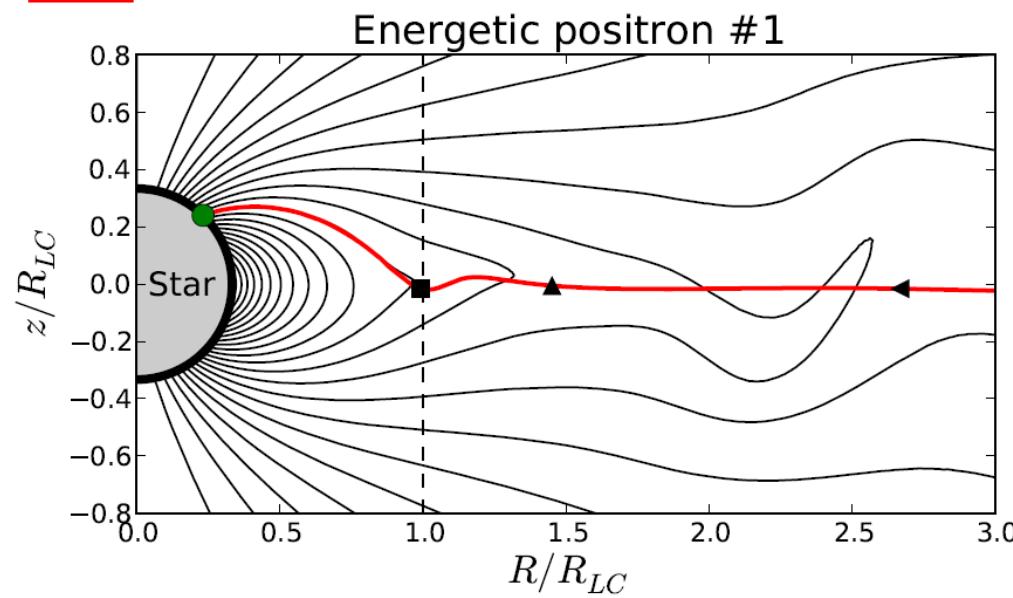
Particle acceleration and e^+/e^- asymmetry

2D



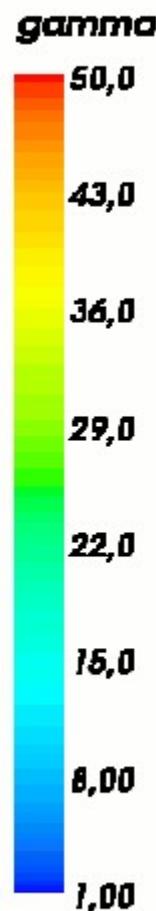
Particle acceleration and e^+/e^- asymmetry

2D

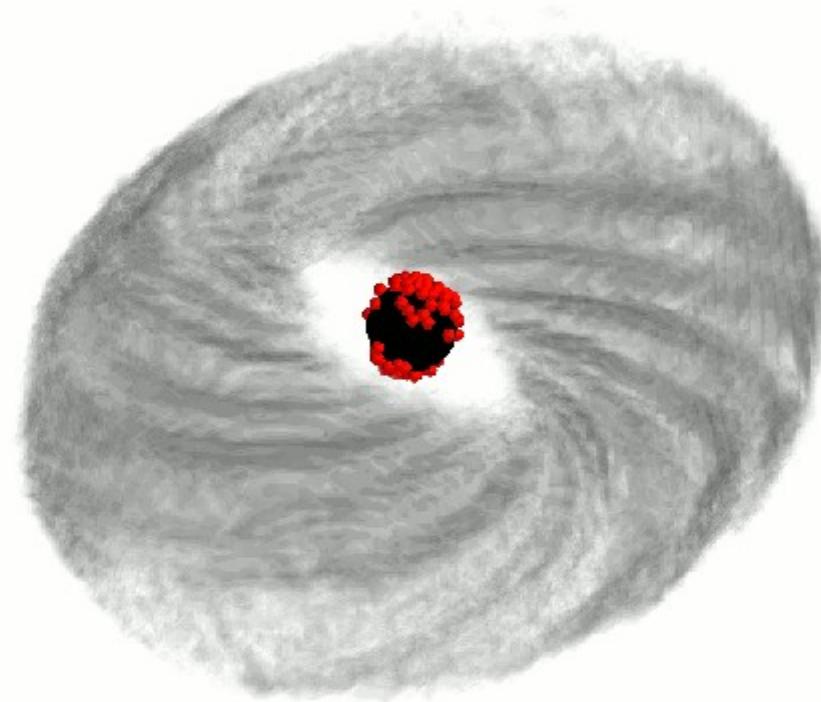


Positron orbits in oblique pulsar (30°)

In the co-rotating frame



Tracked positrons



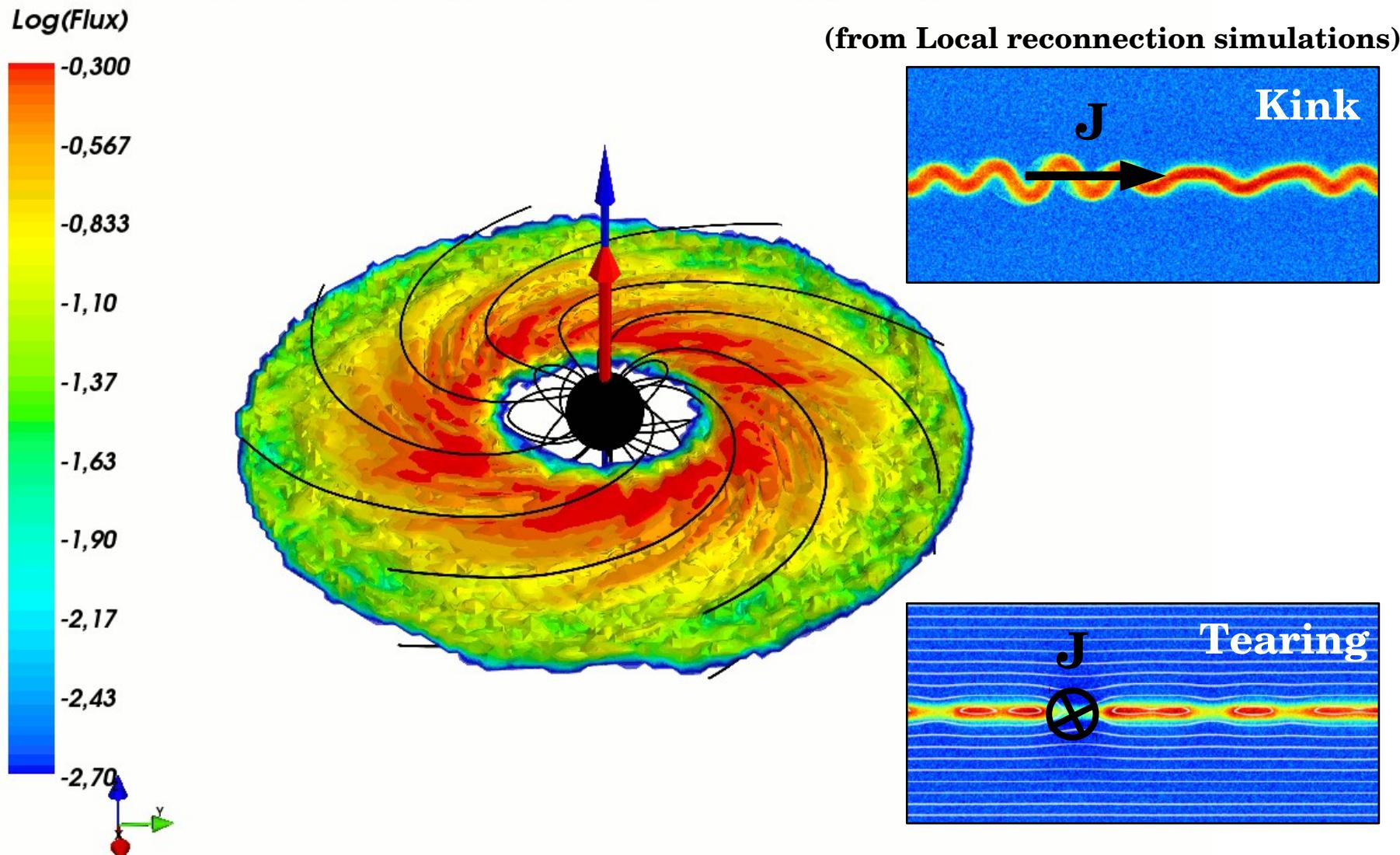
Rotating sprinkler



High-energy radiation

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

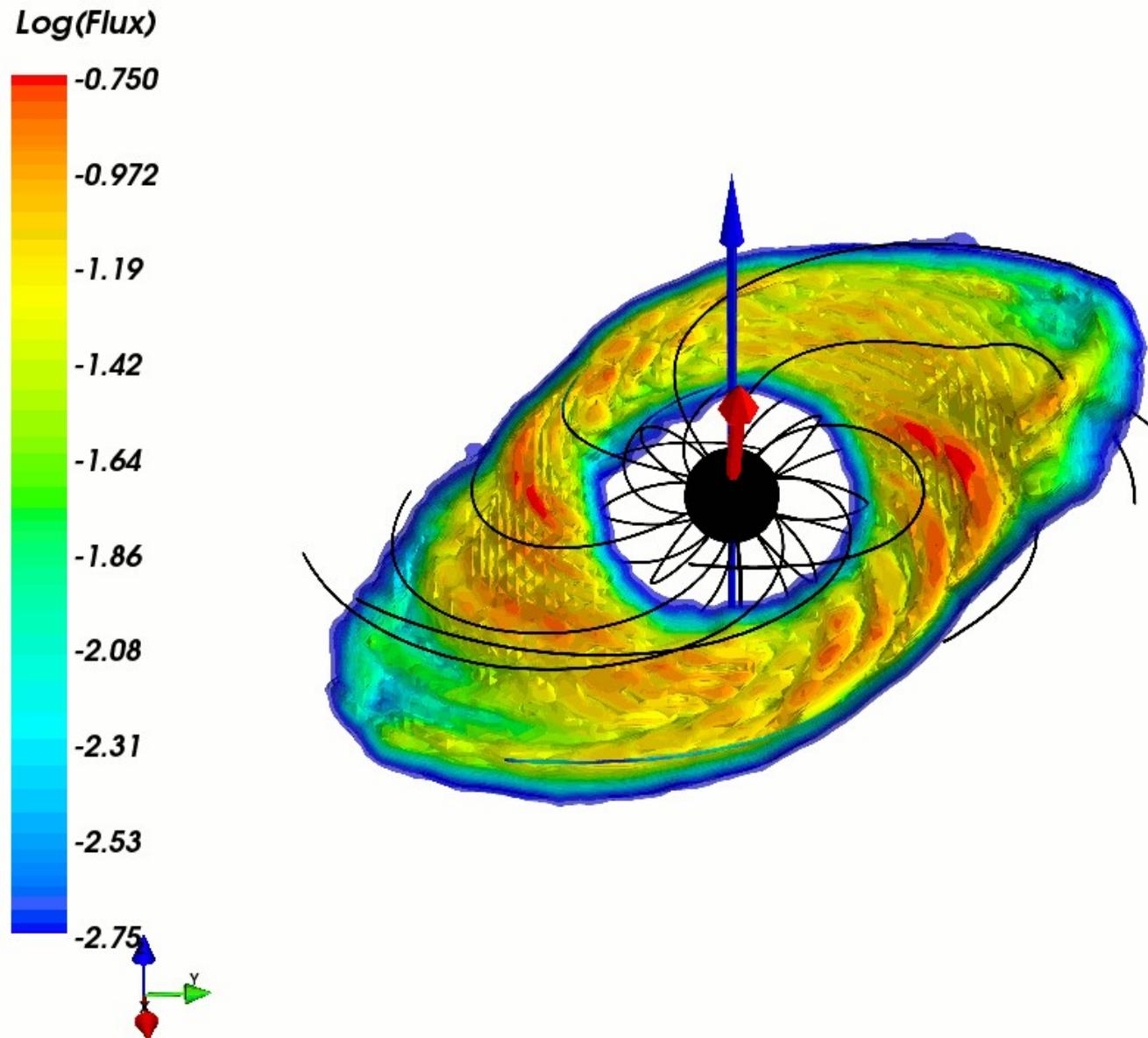
i=0 - Phase=0.00 - Positrons -



Presence of spatial irregularities due to **kinetic instabilities** in the sheet
(e.g., kink and tearing modes)

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

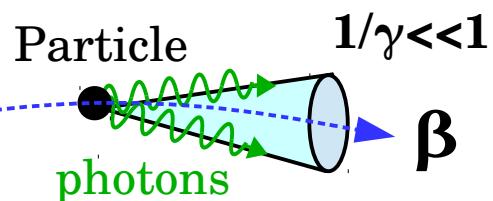
i=30 - Phase=0.00 - Positrons -



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

$i=0$ - Phase=0.00 - Positrons -

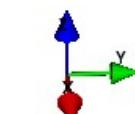
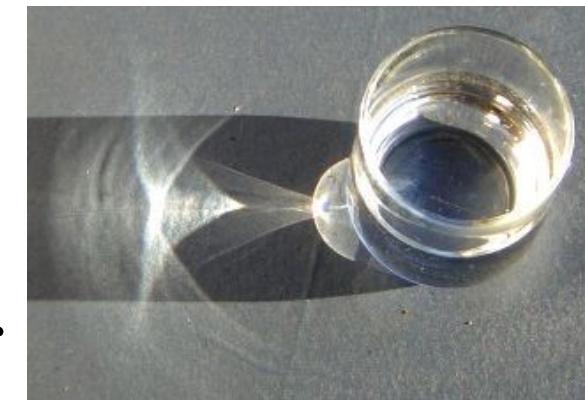
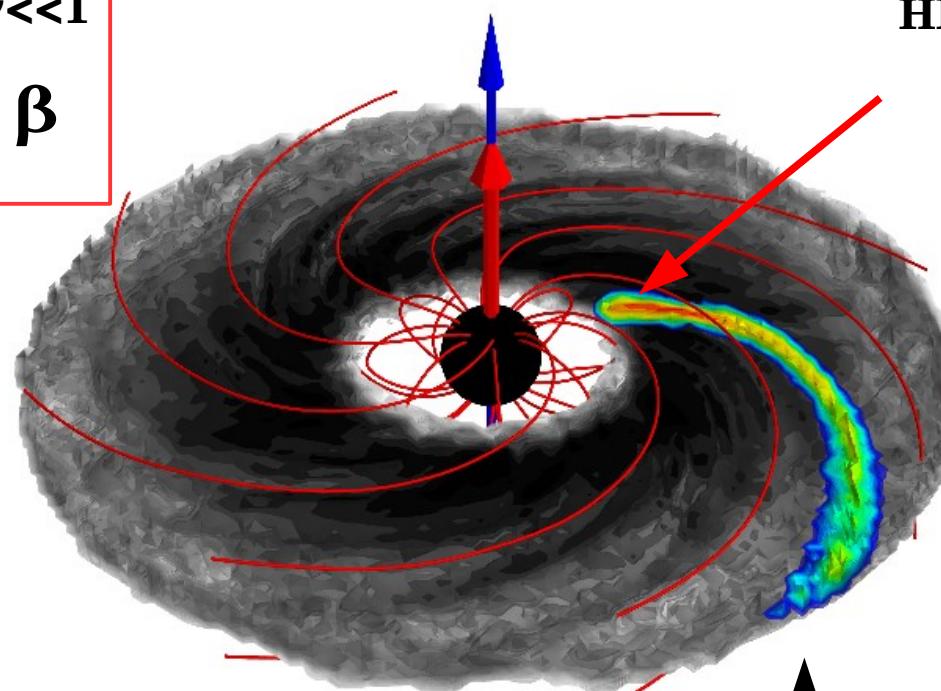
Relativistic beaming



Gray : Total flux (all directions)

Color : Observed flux

HE flux concentrated close to the light-cylinder



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

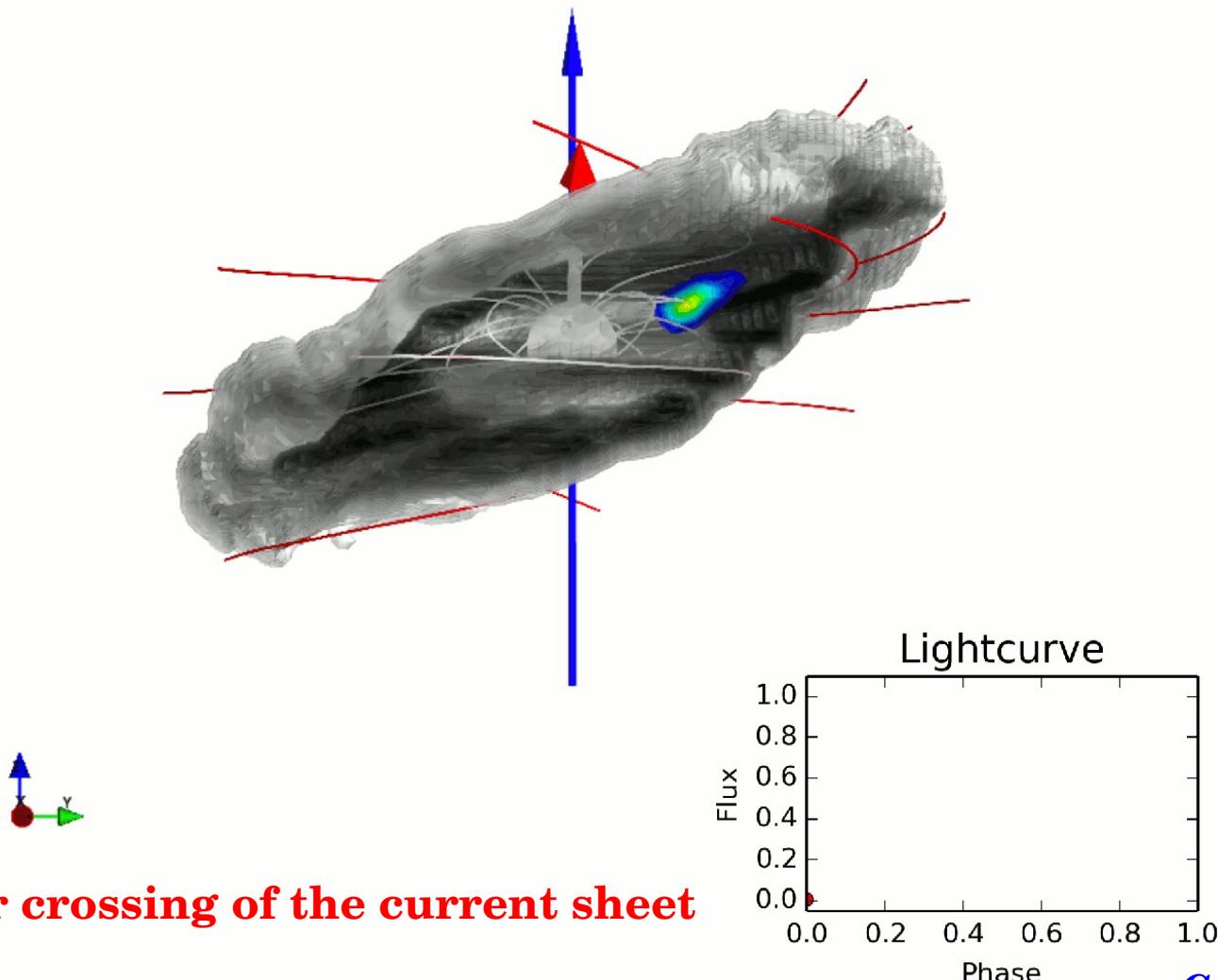
Observed high-energy radiation flux ($\nu > \nu_0$, $\chi = 30^\circ$)

Gray : Total flux (all directions)

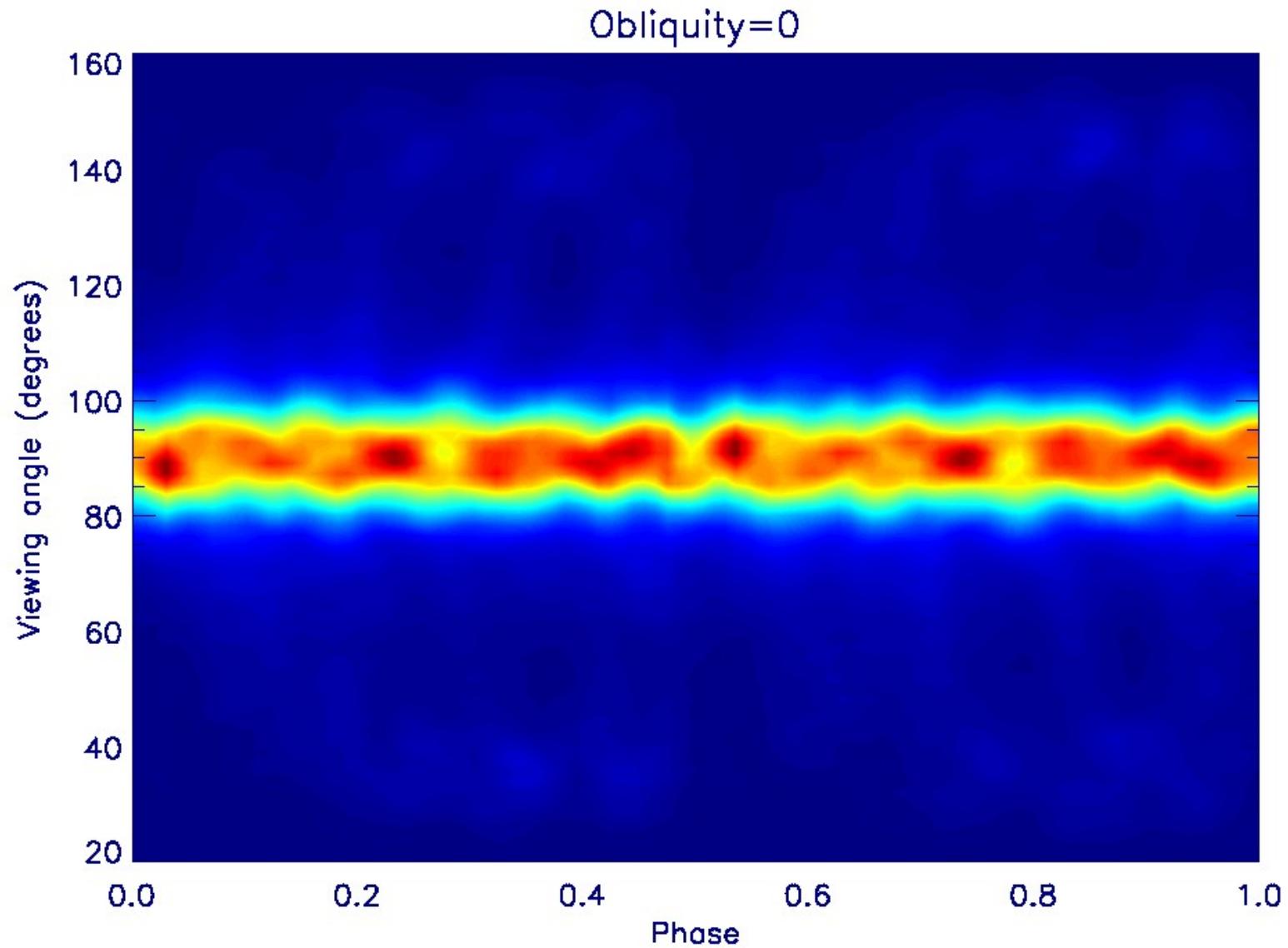
Light curve shaped by the geometry of the current sheet

Color : Observed flux

$i=30$ - Phase=0.00 - Positrons -

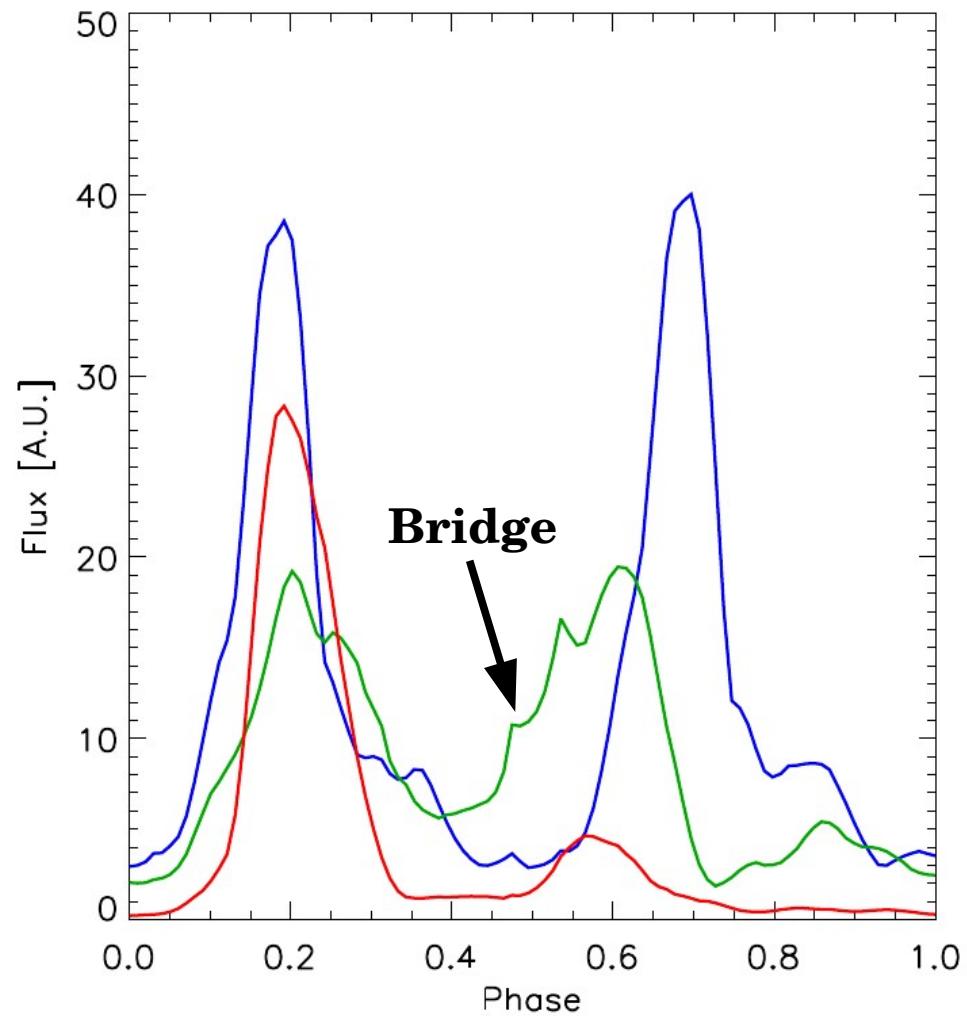
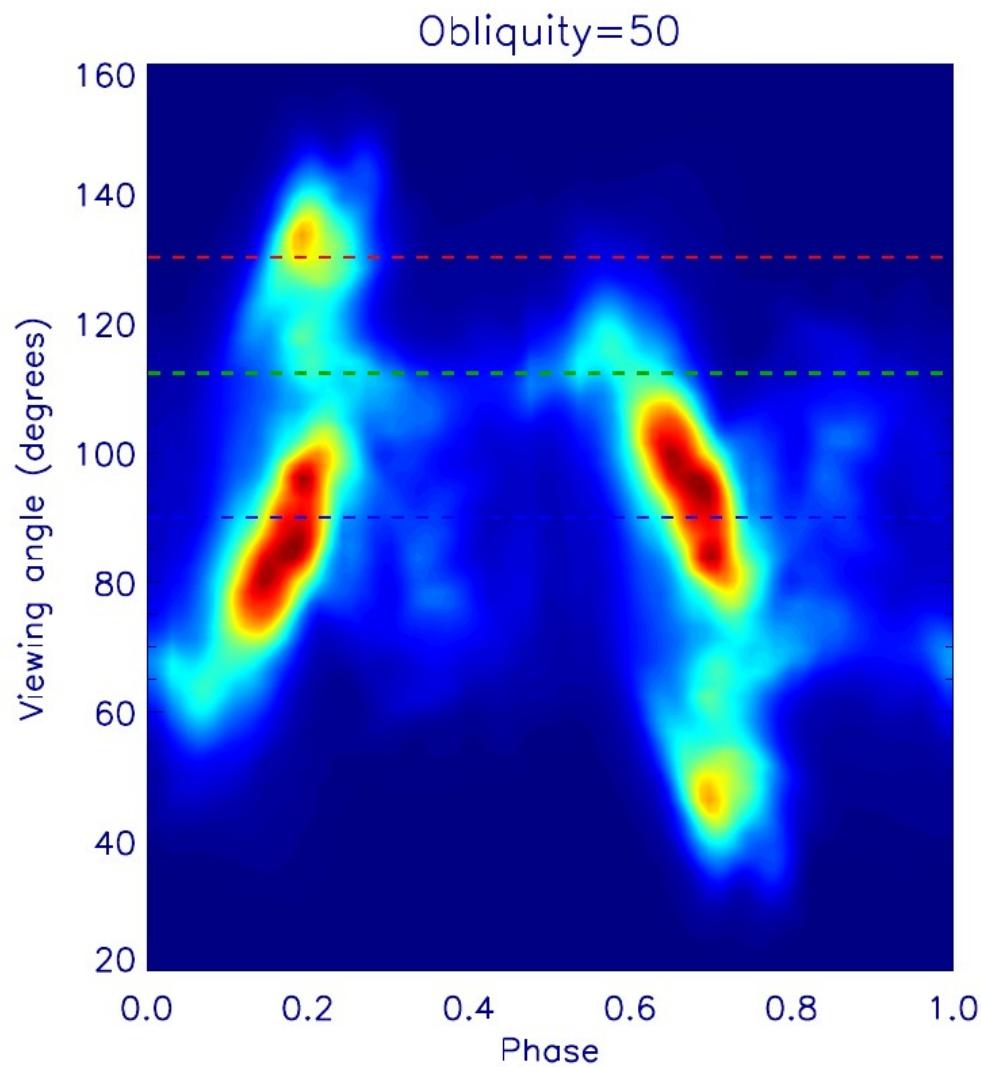


Skymaps



High-energy photons are **concentrated within the equatorial regions where most of the spin-down is dissipated.**

A few typical lightcurves

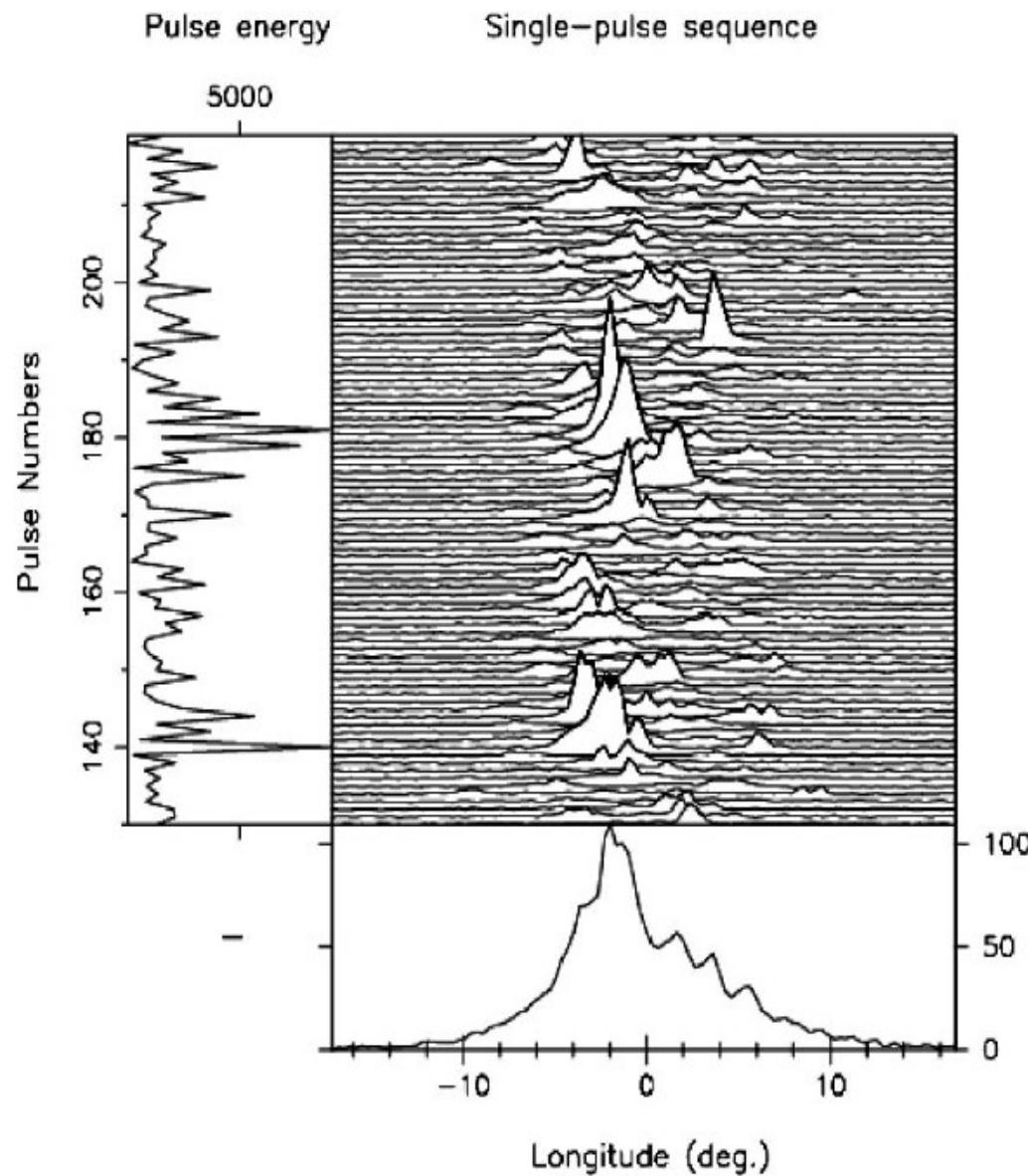


Cerutti et al. 2016

See also Philippov & Spitkovsky 2017

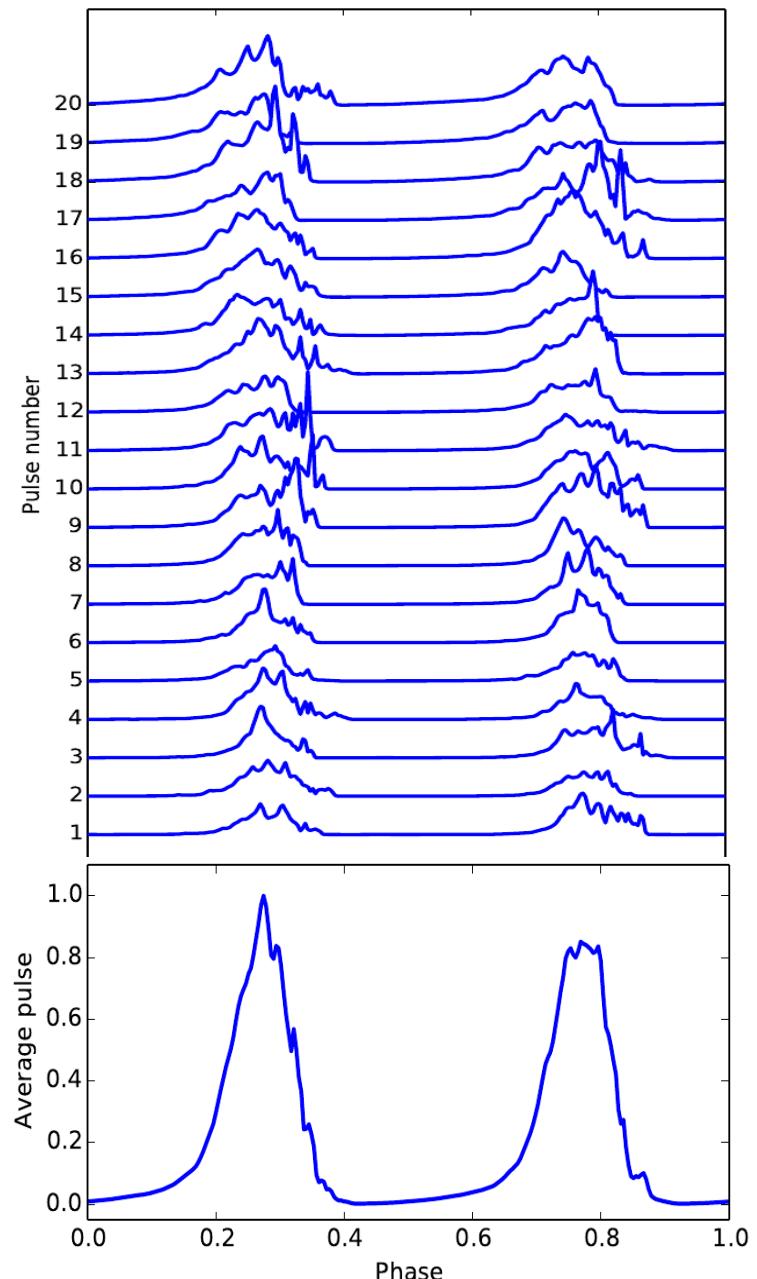
Pulse-to-pulse variability

Radio (observations)



Deshpande & Rankin 1999

Gamma (PIC simulations)



Cerutti & Philippov, submitted, 2017

B. Cerutti

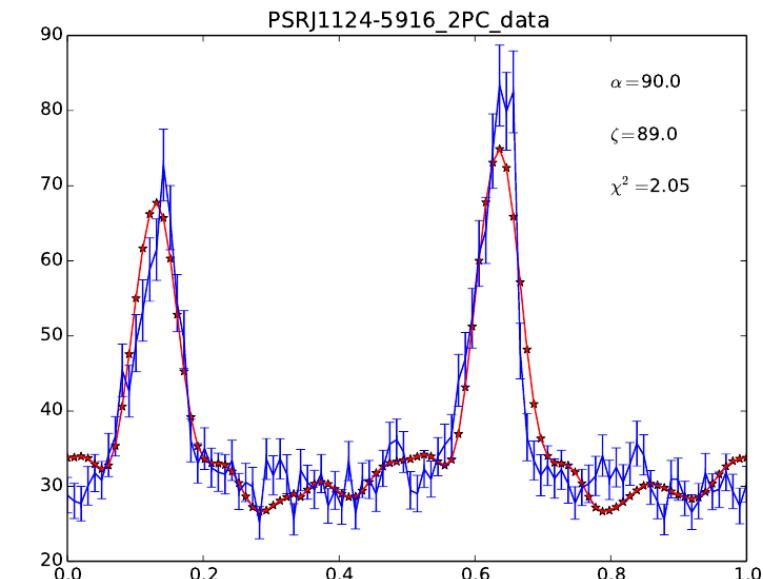
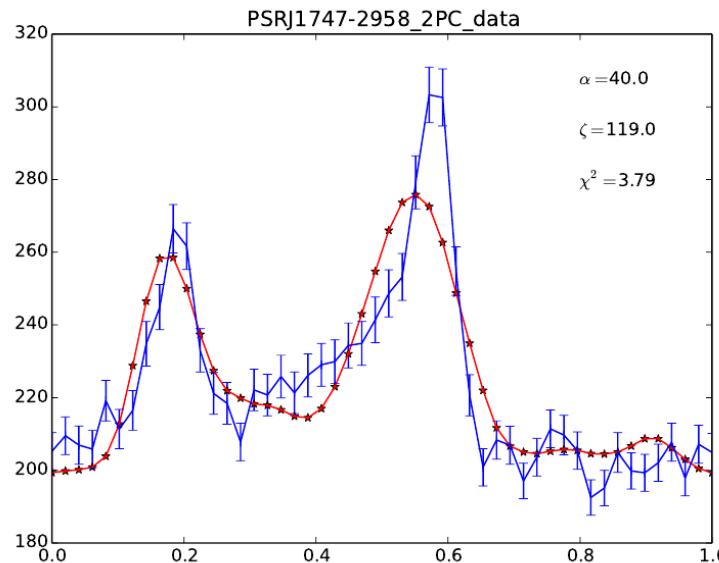
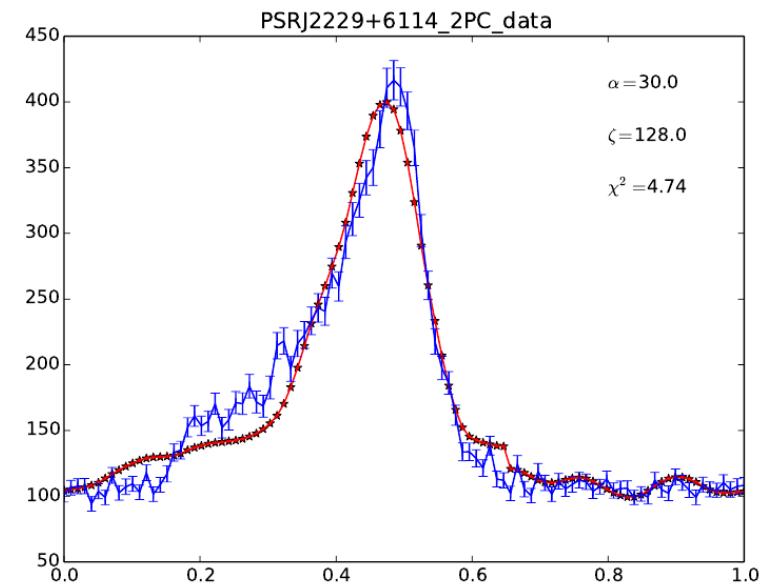
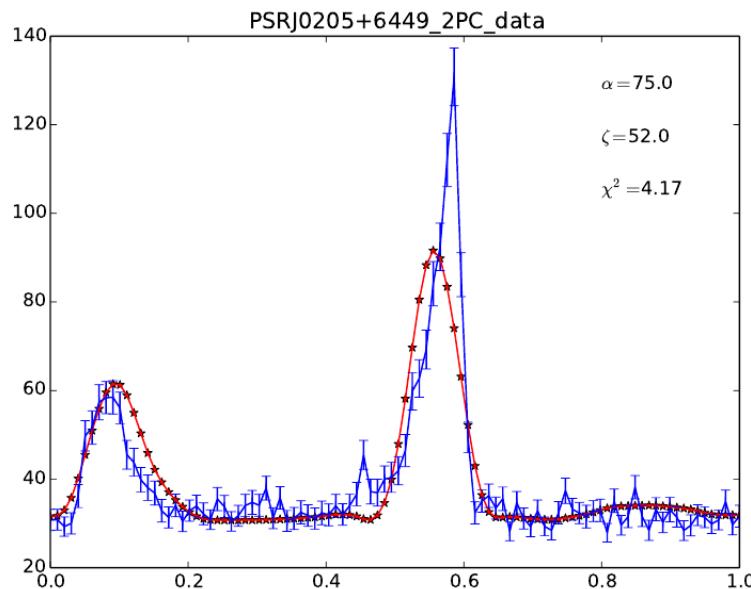
From PIC to observations

Fitting Fermi-LAT pulsar lightcurves

PRELIMINARY

Second catalog (*Abdo+2013*) : 117 pulsars

Observations
PIC model



Courtesy of **Aloïs de Valon** (Univ. Grenoble Alpes), Master thesis project

B. Cerutti

Fitting Fermi-LAT pulsar lightcurves

PRELIMINARY

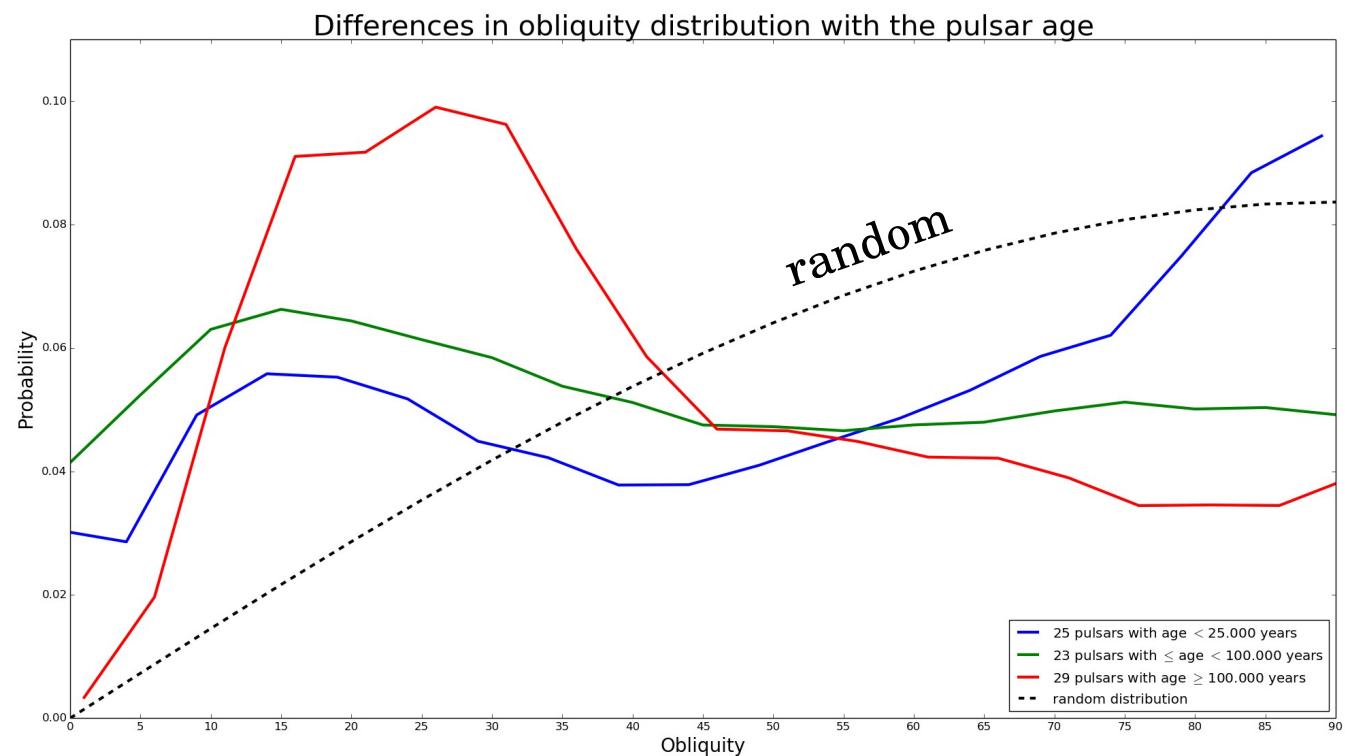
Key findings :

- Pulsar **viewing angles** are consistent with a **random distribution** (>90 % chance)
- Millisecond pulsars are **closer to alignment** ($\chi < \sim 45^\circ$) than young isolated pulsars.
- Evidence for alignment with age, **alignment timescale 10^5 - 10^6 years**.
- **Magnetic axis** of very young pulsars nearly randomly distributed
=> **Random distribution at birth ?**

Age < 25 000 yrs

25 000 yrs < Age < 10^5 yrs

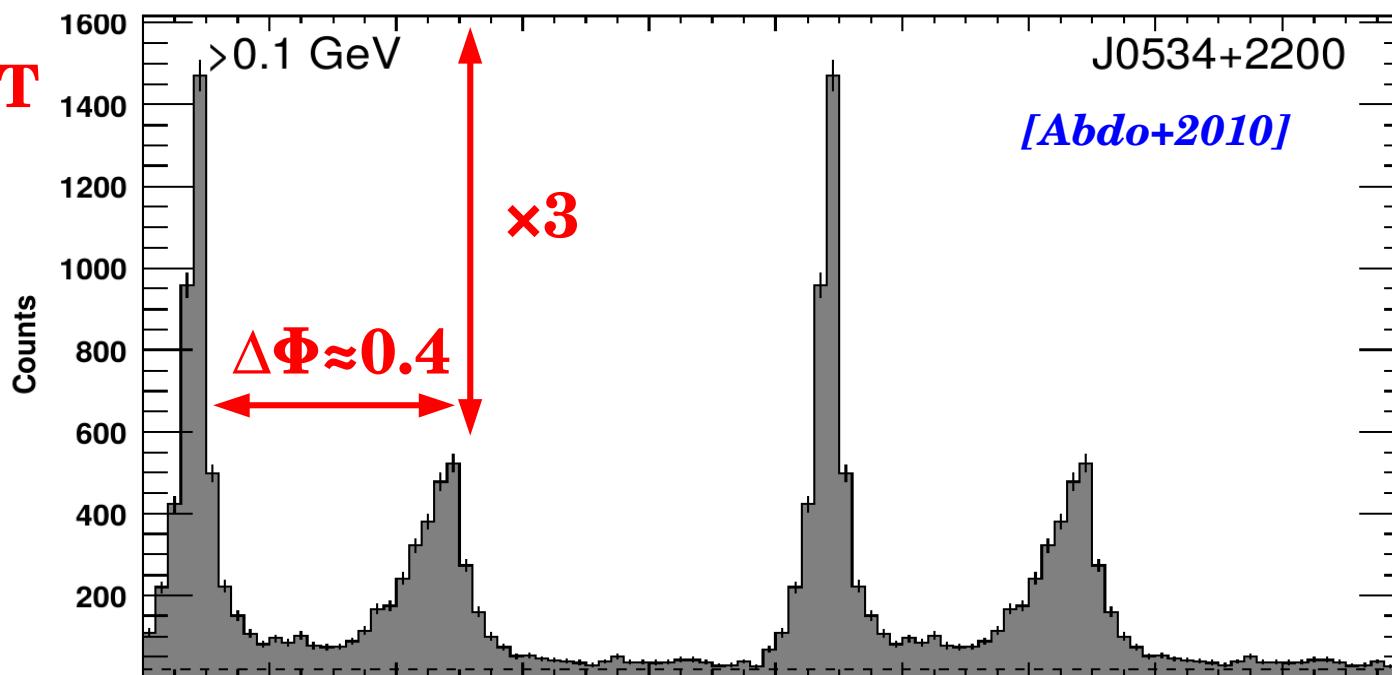
Age > 10^5 yrs



Modeling the phase-resolved polarization

Jérémie Mortier (Univ. Grenoble Alpes), Master thesis project

Fermi-LAT

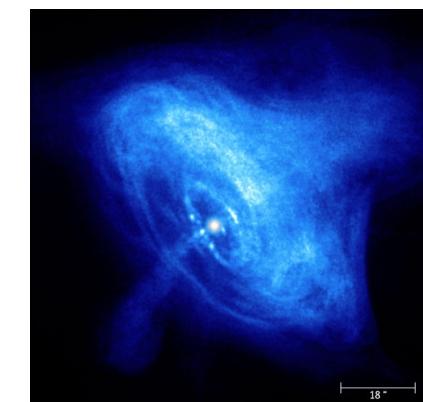
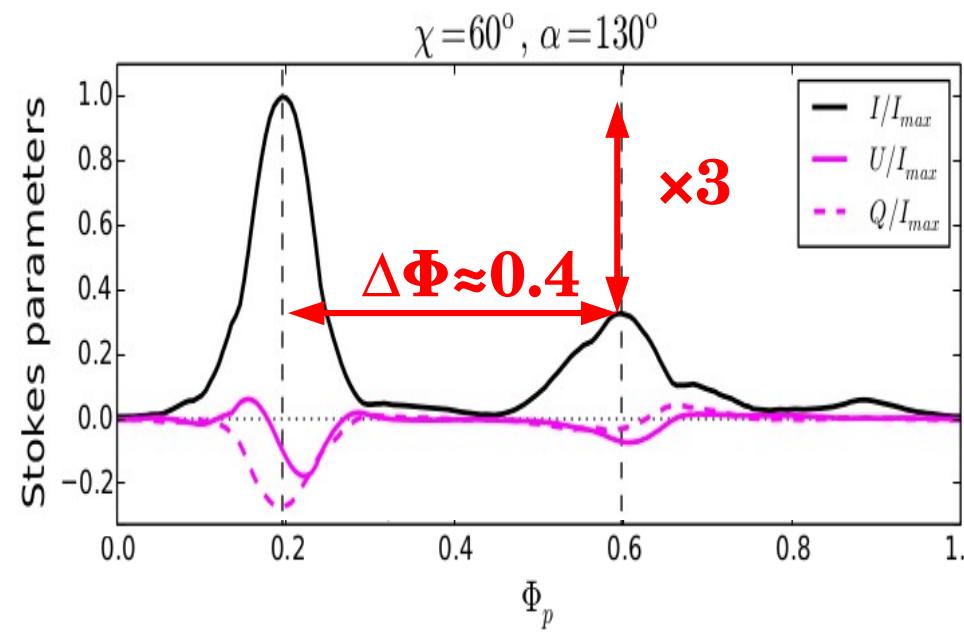


PIC model

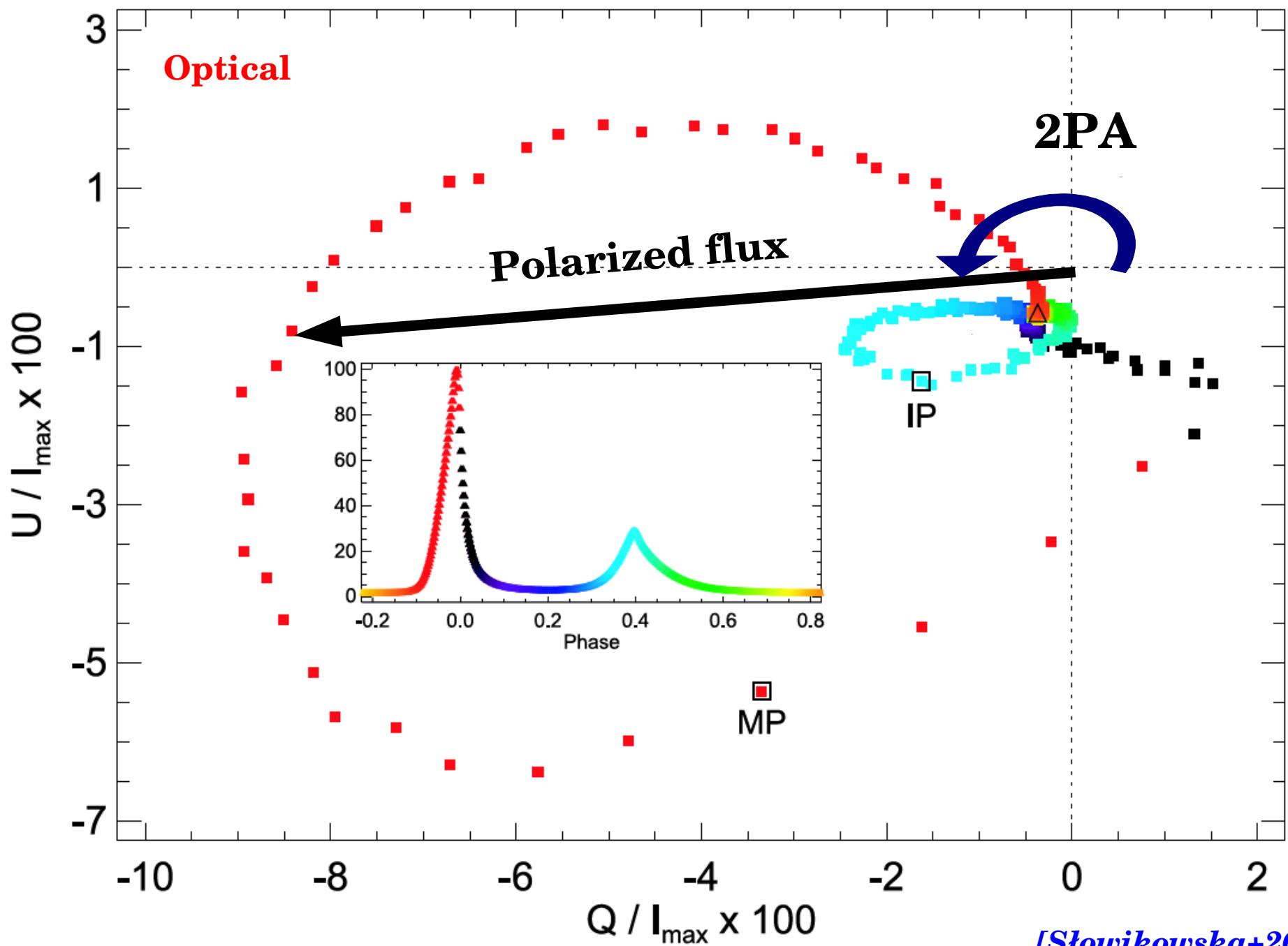
$\chi=60^\circ, \alpha=130^\circ$

Consistent with the nebula morphology in X-rays

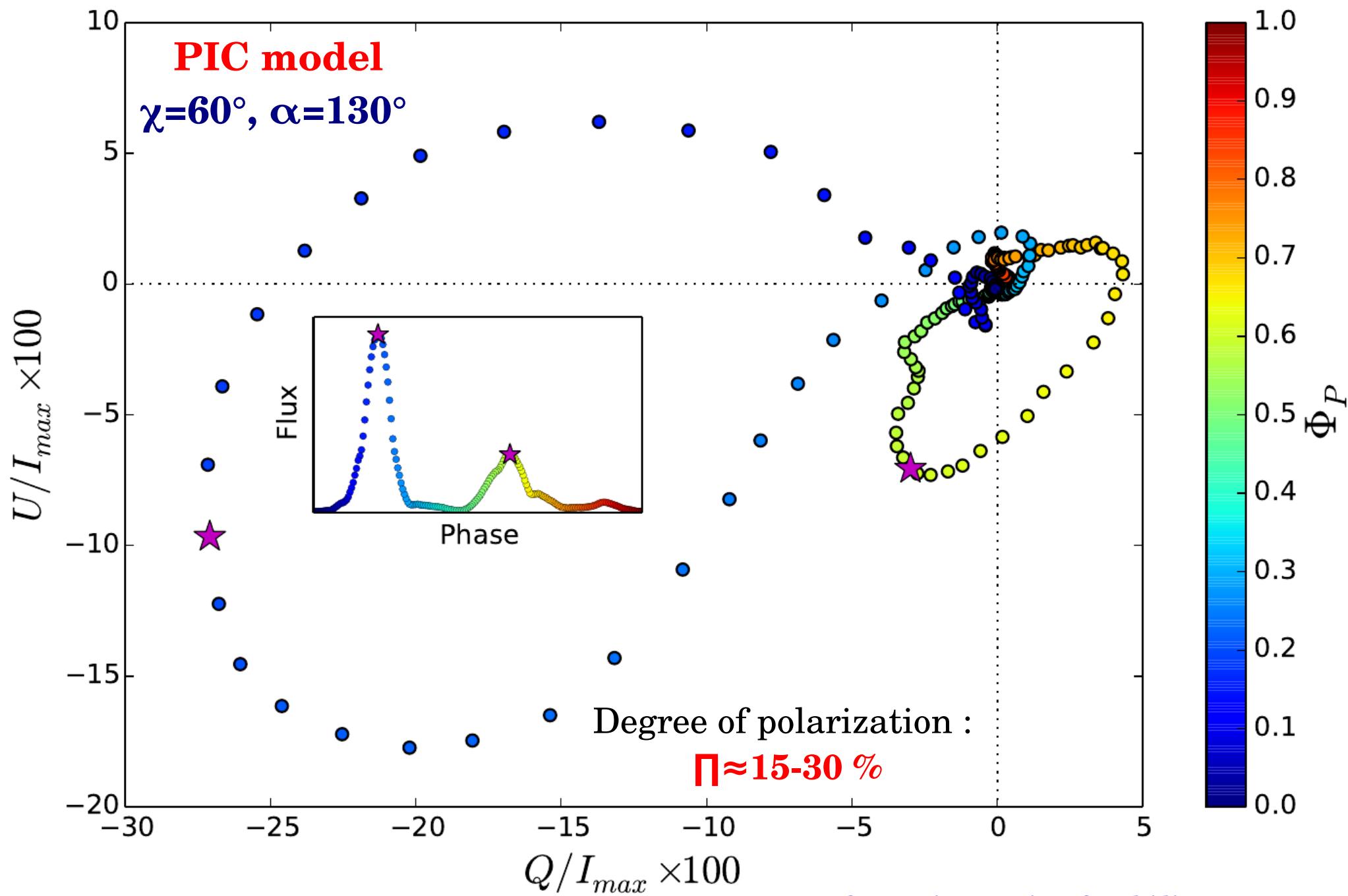
[e.g. Weisskopf+2012]



(Incoherent) Polarization signature : Observations



(Incoherent) Polarization signature : PIC

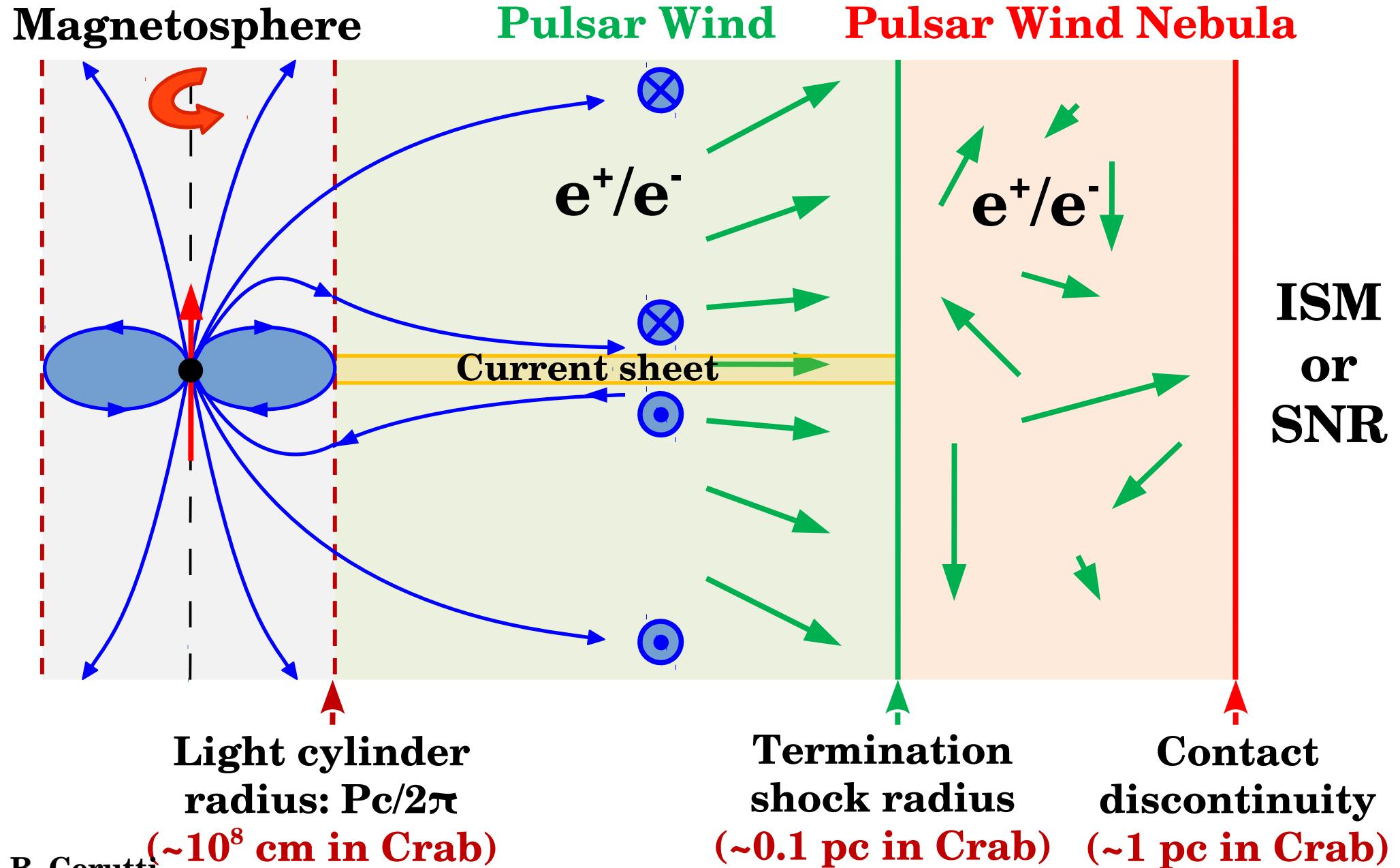


Conclusions (1)

- **Global radiative PIC simulations** is the way to go to solve particle acceleration in pulsars.
- Simulations demonstrate the major role of **relativistic reconnection** in particle acceleration
- High-energy emission could be **synchrotron radiation from the current sheet $>\sim R_{LC}$**
- **Pulse profile and polarization** provide robust constraints on **Crab pulsar** inclination and viewing angles.
- Origin of the **radio** emission still unclear, **more physics in PIC** to capture in the polar-cap discharge?

The classical picture of pulsar wind nebulae

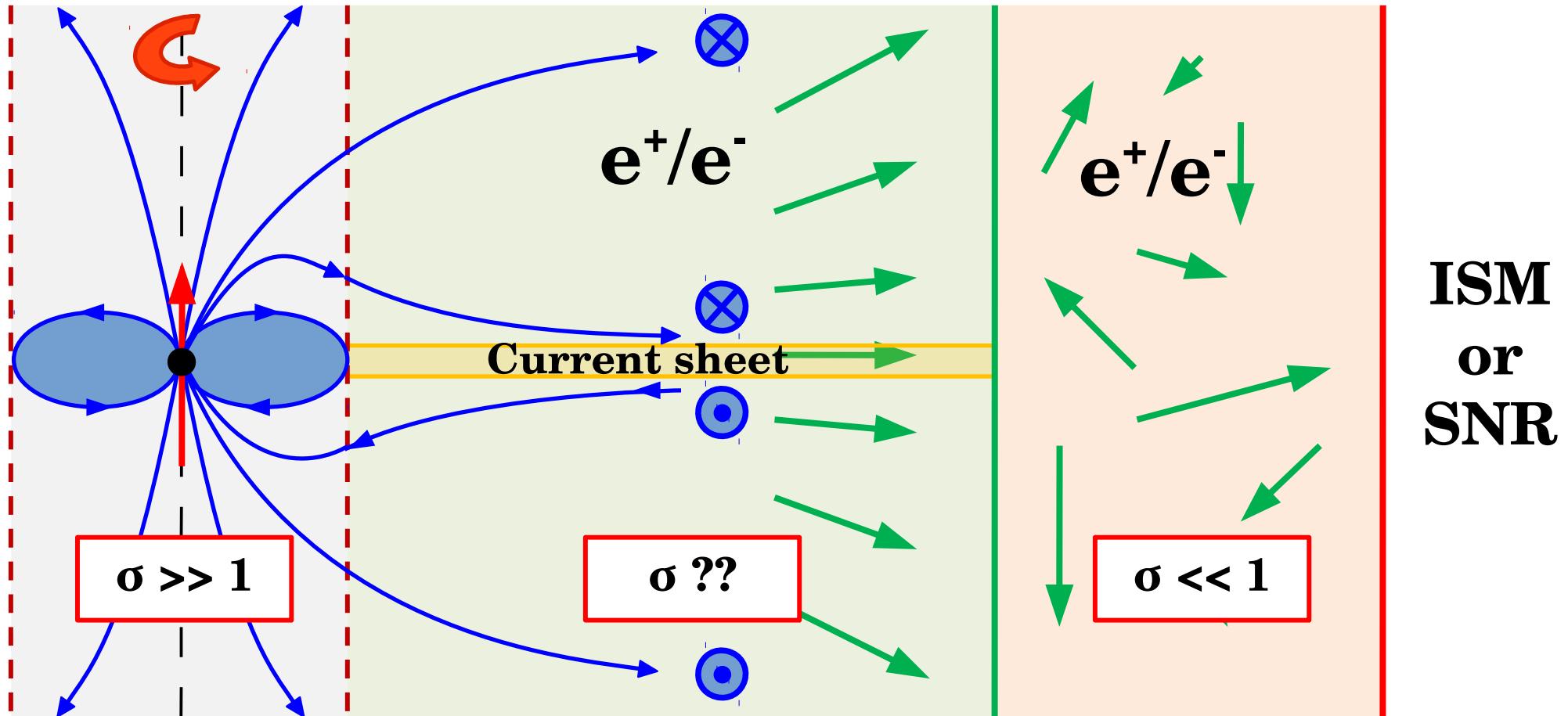
[See review by Kirk et al. 2009]



The σ -problem

[See review by Kirk et al. 2009]

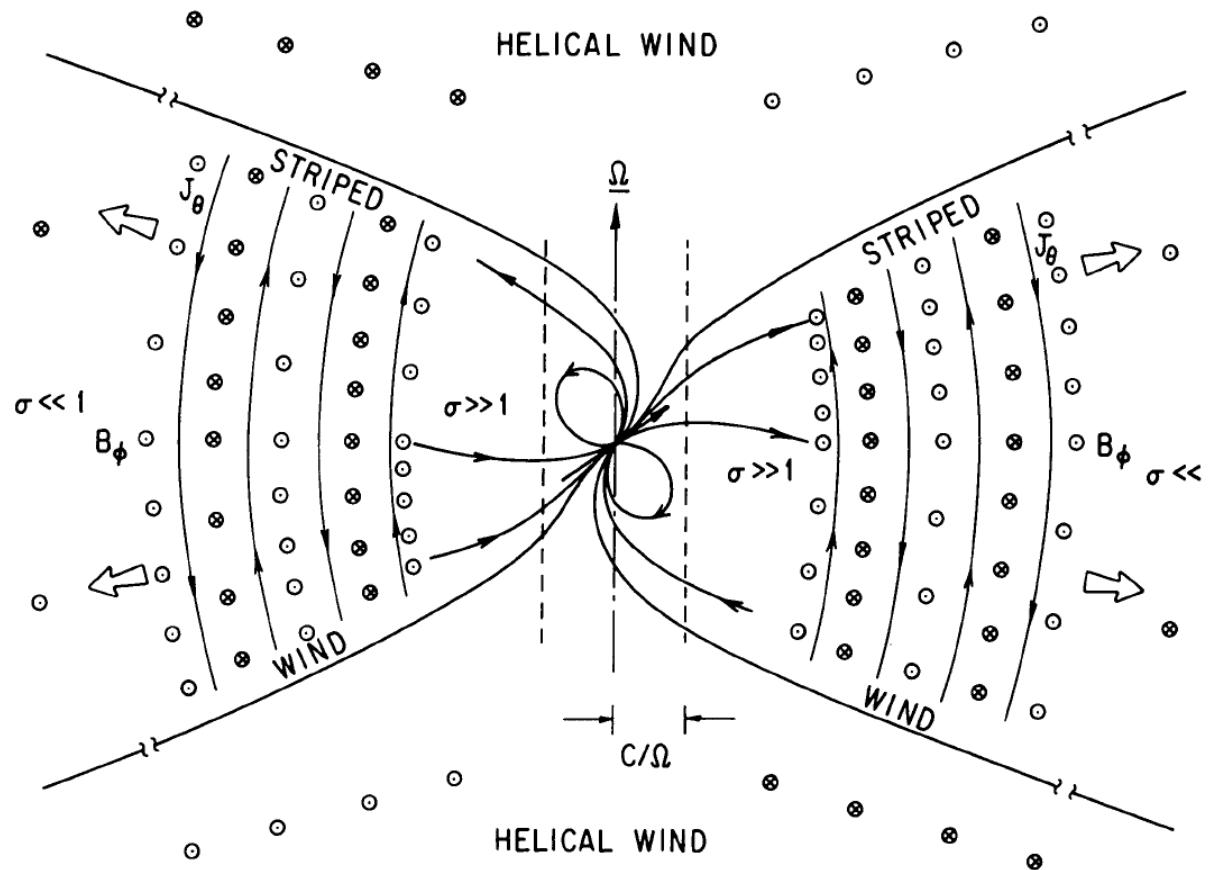
Magnetosphere Pulsar Wind Pulsar Wind Nebula



Transition $\sigma \gg 1$ to $\sigma \ll 1$ unknown: “sigma” problem
=> Dissipation somewhere in between needed!

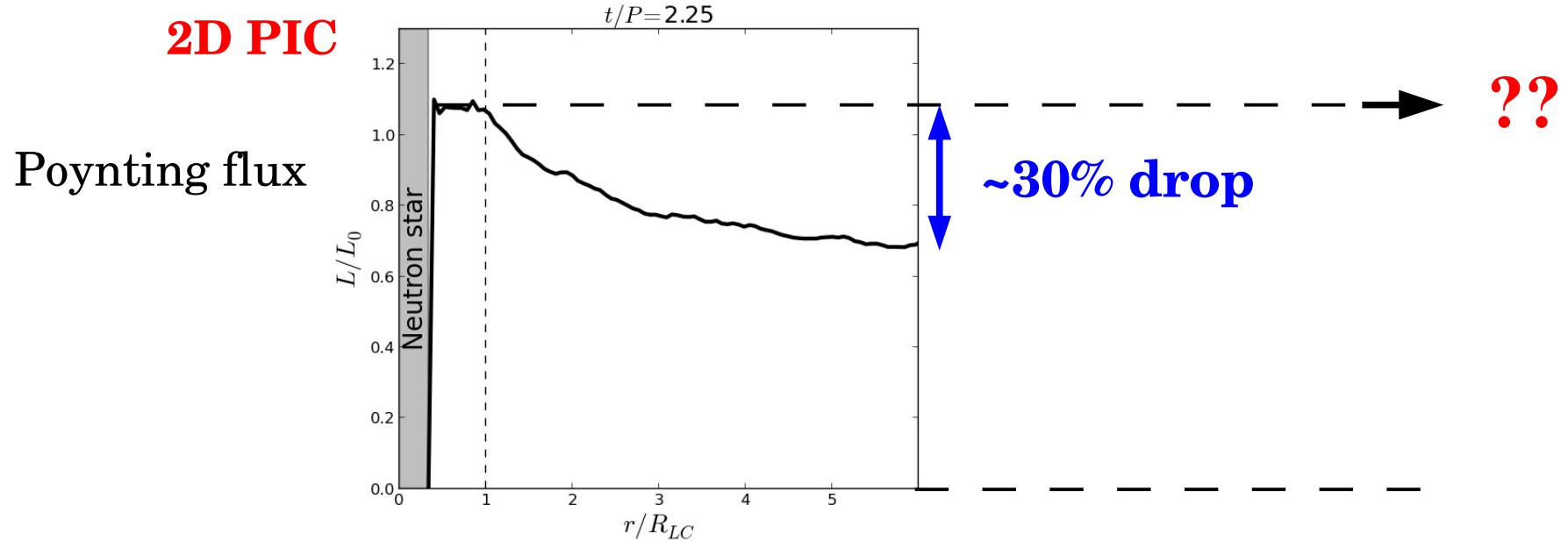
Dissipation in the wind

Coroniti 1990 ; Michel 1994 ; Lyubarsky & Kirk 2001 ; Kirk & Skjæraasen 2003



How far does magnetic reconnection proceeds in the wind?

Close in or at the termination shock ?

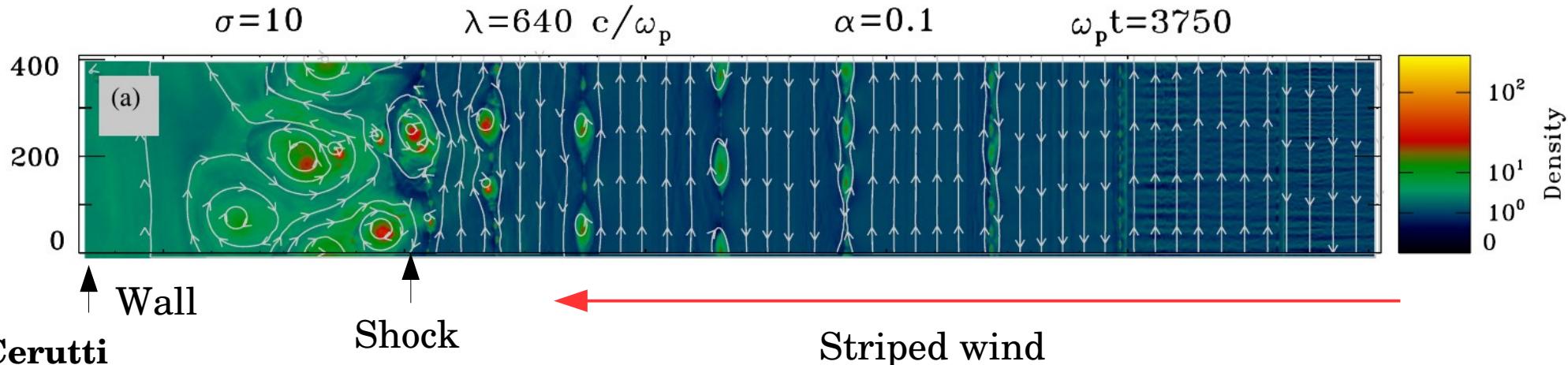


Scenario 1 : Complete dissipation far before the shock

Coroniti 1990 ; Michel 1994 ; Lyubarsky & Kirk 2001 ; Kirk & Skjæraasen 2003

Scenario 2 : Shock-driven reconnection at the termination shock

Lyubarsky 2003 ; Pétri & Lyubarsky 2007 ; Sironi & Spitkovsky 2011



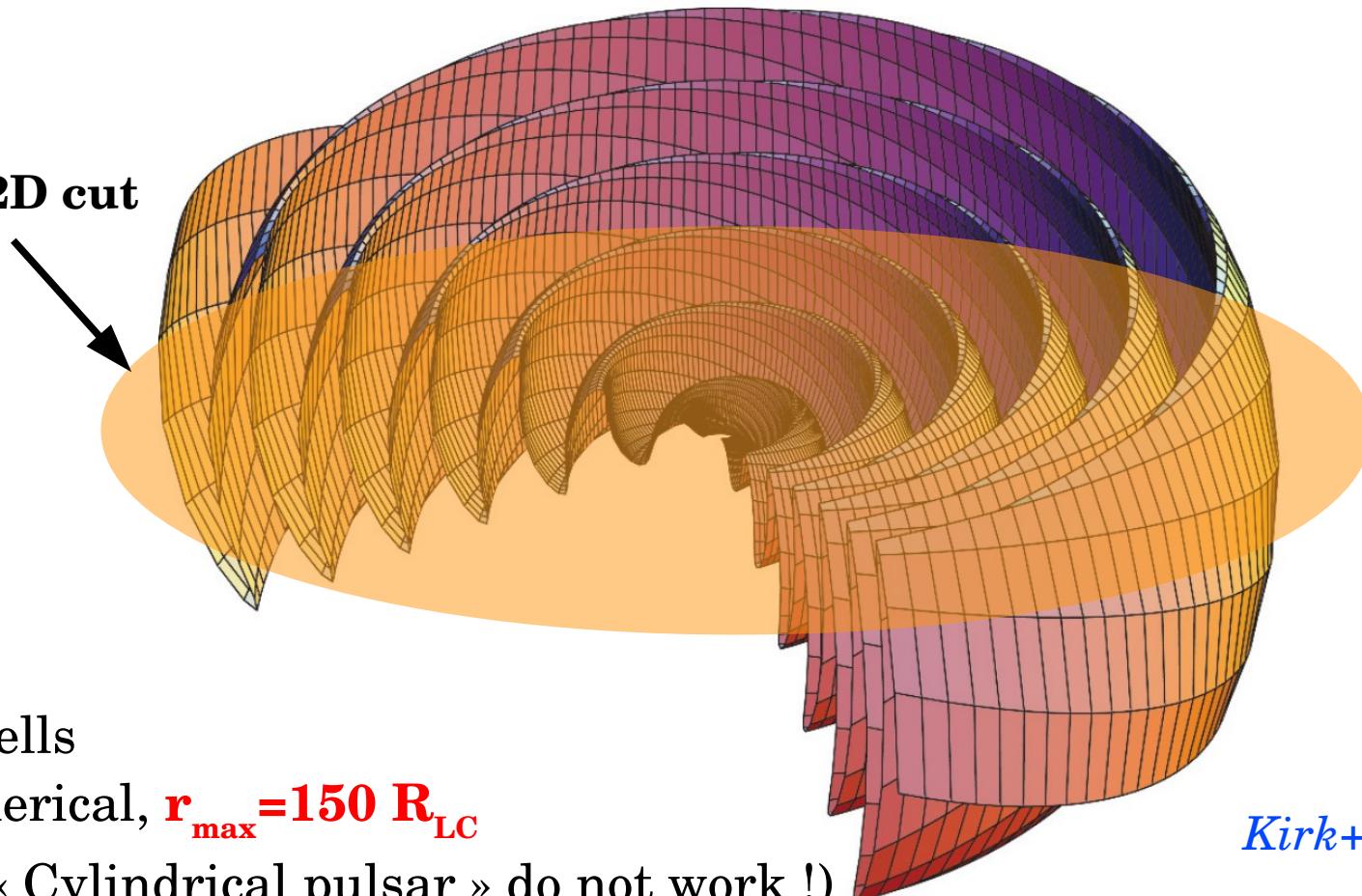
The numerical challenge

We need to probe large radii, very large box!!

3D simulations too expansive!

=> 2D simulations of the oblique rotator!?

Equatorial 2D cut

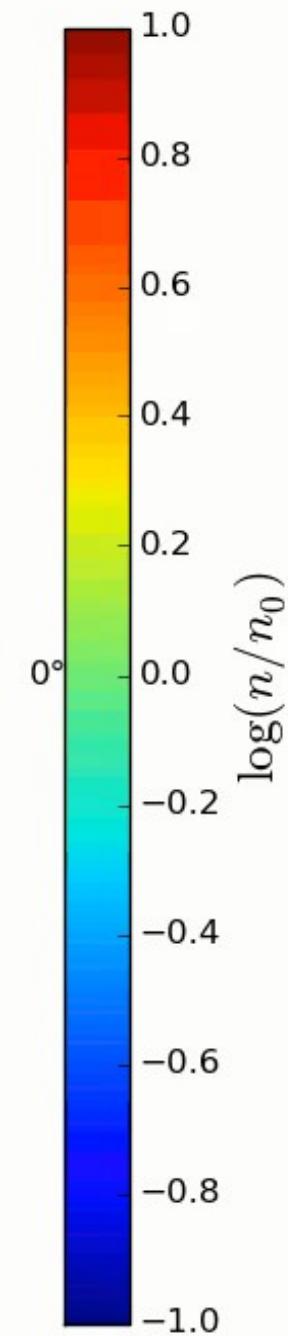
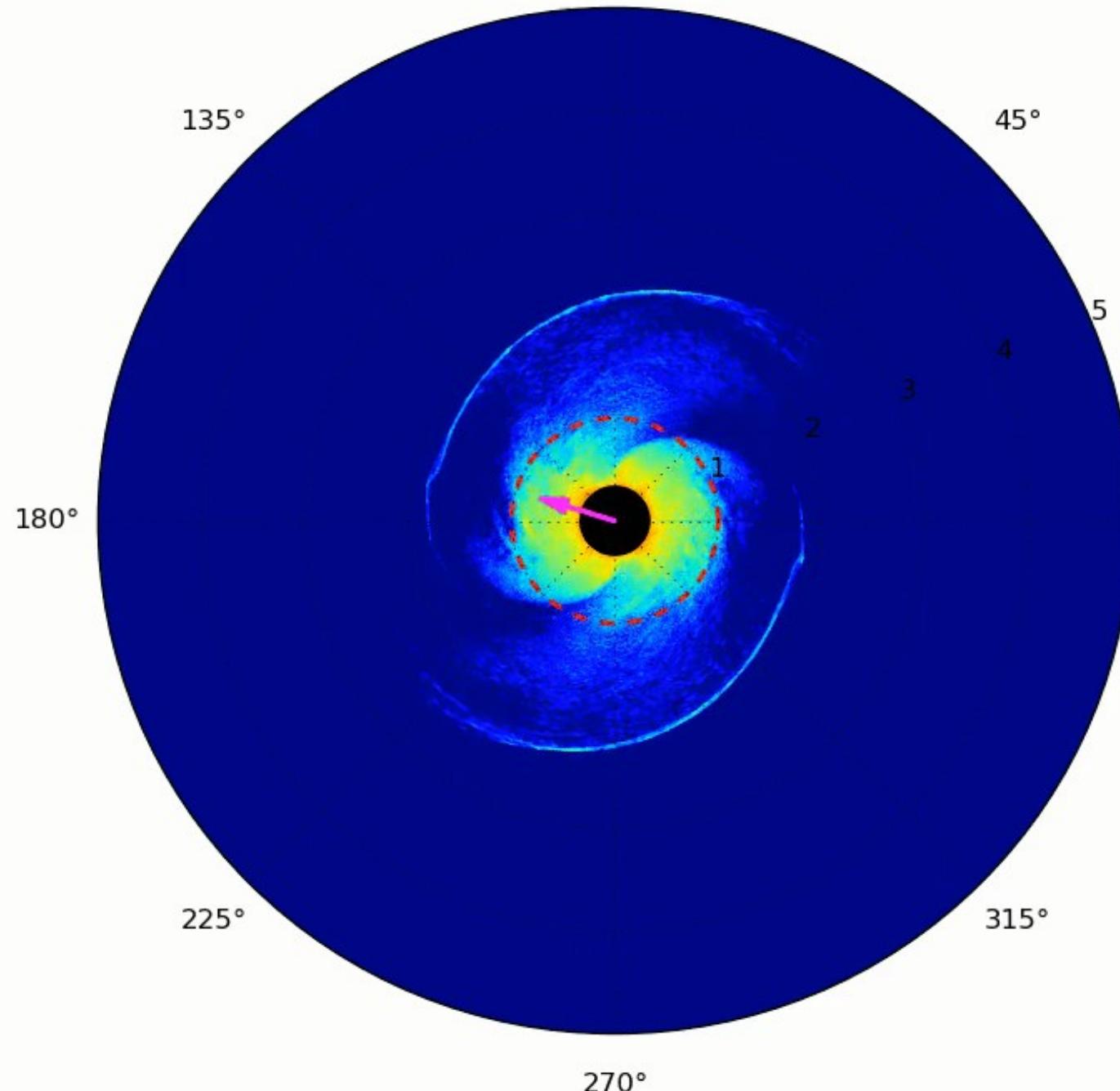


4096×4096 cells

$r\varphi$ -plane spherical, $r_{\max} = 150 R_{LC}$

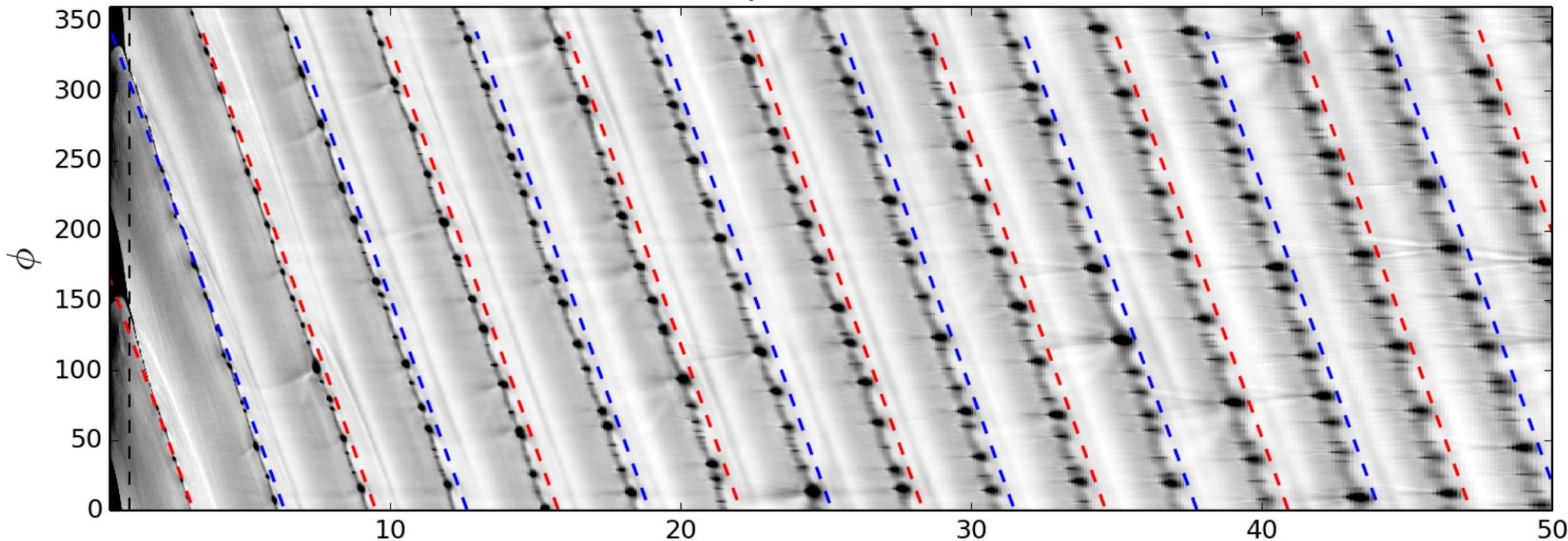
(Warning : « Cylindrical pulsar » do not work !)

Time=0.4532



Dissipation in the wind

$t/P = 25.76$



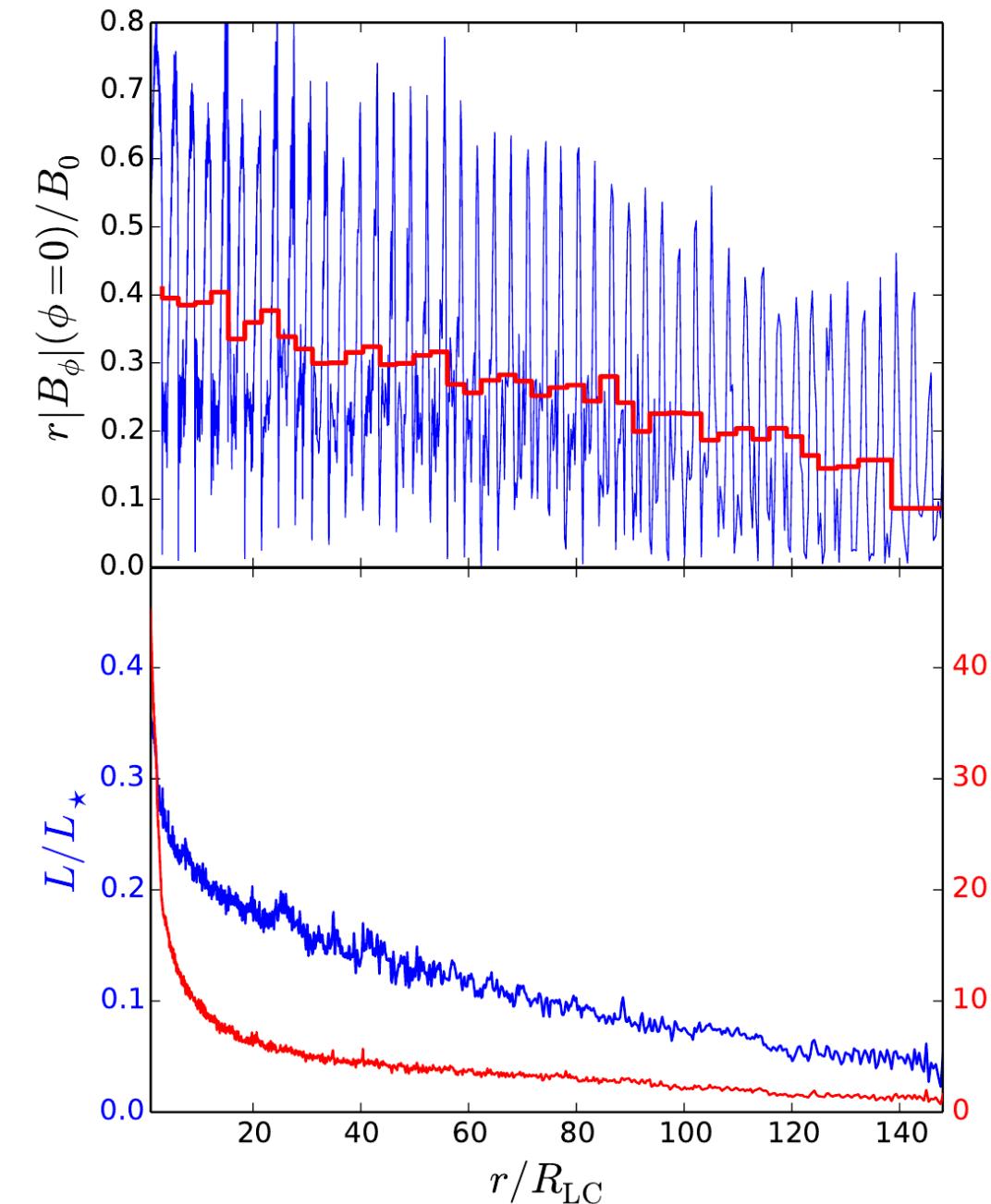
Linear expansion of the sheet : $\Delta(r) \approx \Delta_{LC} \left(\frac{r}{R_{LC}} \right)$

$$\Delta(r) = \frac{1}{\pi \kappa_{LC}} \left(\frac{r}{R_{LC}} \right) = \frac{1}{\pi \kappa}$$

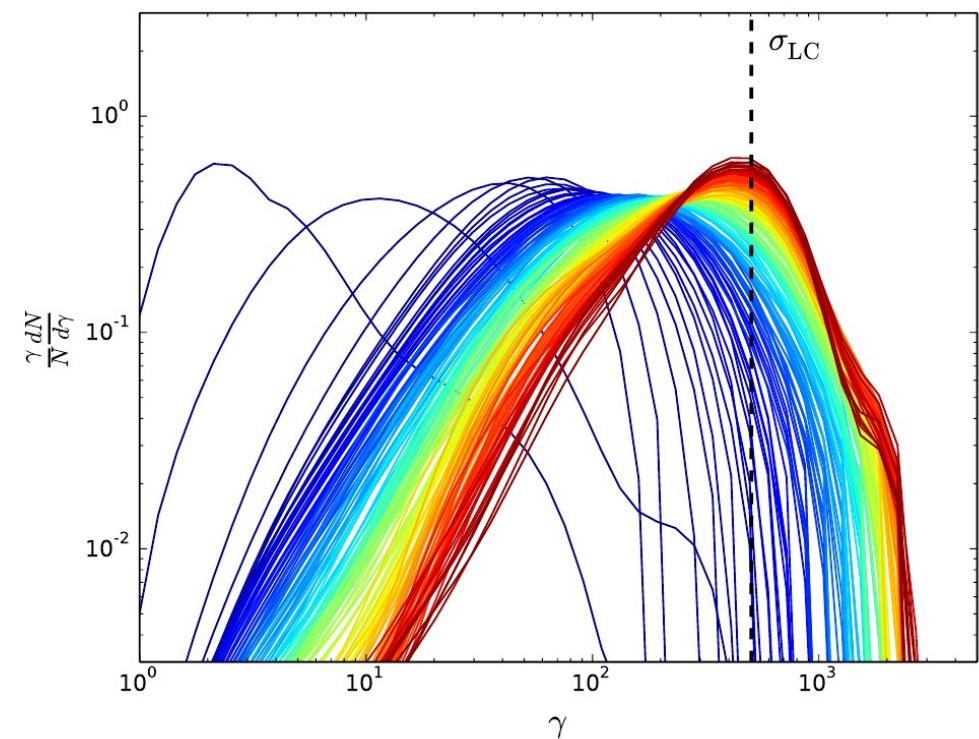
Complete dissipation where $\Delta=1 \Rightarrow r_{diss}/R_{LC} = \pi \kappa_{LC} \sim 10^2 - 10^5 \ll R_{shock}/R_{LC}$

Cerutti & Philippov, submitted

Dissipation in the wind



Particle spectra



Narrow particle energy distribution
set by $\sigma_{\text{LC}} \sim \Phi_{\text{pc}} / \kappa_{\text{LC}}$

Conclusions (2)

- Relativistic reconnection **proceeds in the wind**
- Complete dissipation most likely far before the termination shock radius, $\mathbf{R}_{\text{diss}}/\mathbf{R}_{\text{LC}} \sim \kappa_{\text{LC}} \sim 10^2 - 10^5 \ll \mathbf{R}_{\text{shock}}$
- Particle distribution « thermalize » into a **narrow distribution** centered around Lorentz factor given by $\sigma_{\text{LC}} \sim \Phi_{\text{pc}} / \kappa_{\text{LC}}$
- **Pulsars in binary** systems good targets to probe magnetic dissipation within the wind as $\mathbf{R}_{\text{shock}} \sim \mathbf{R}_{\text{diss}}$