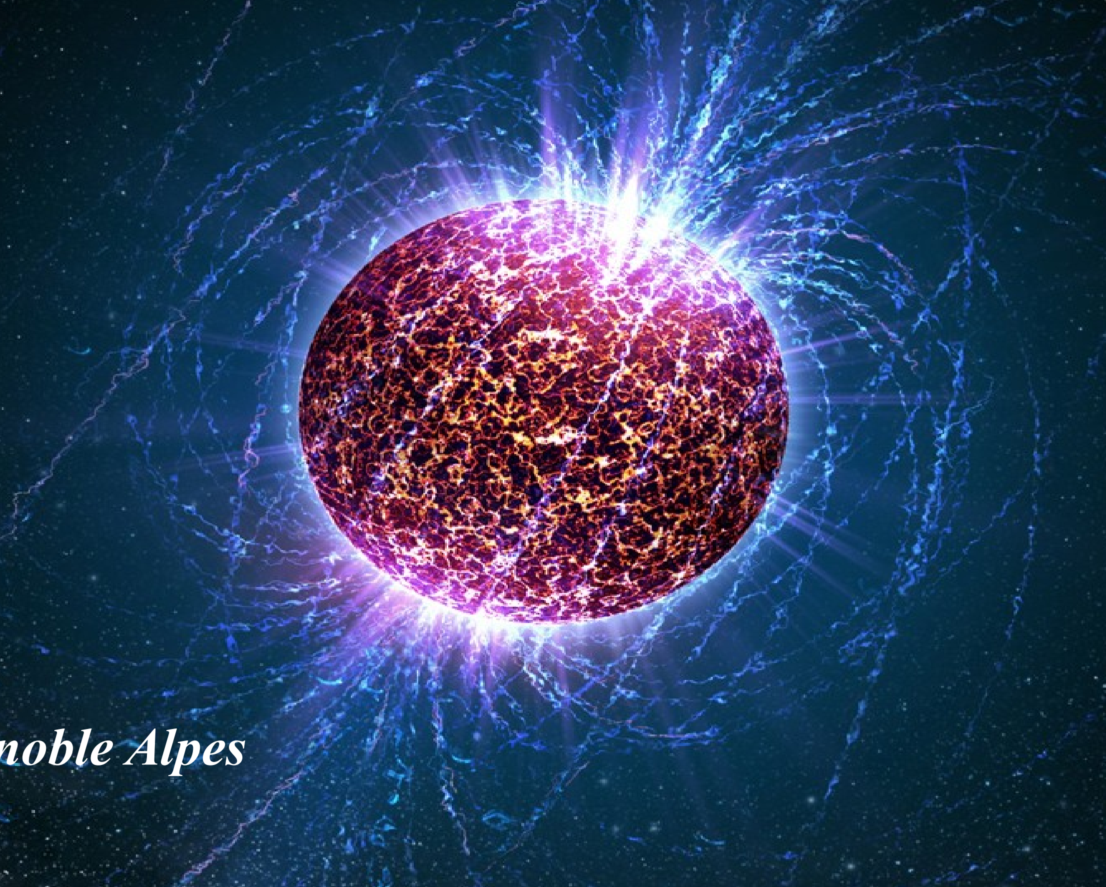
PIC modeling of particle acceleration and high-energy radiation in pulsars



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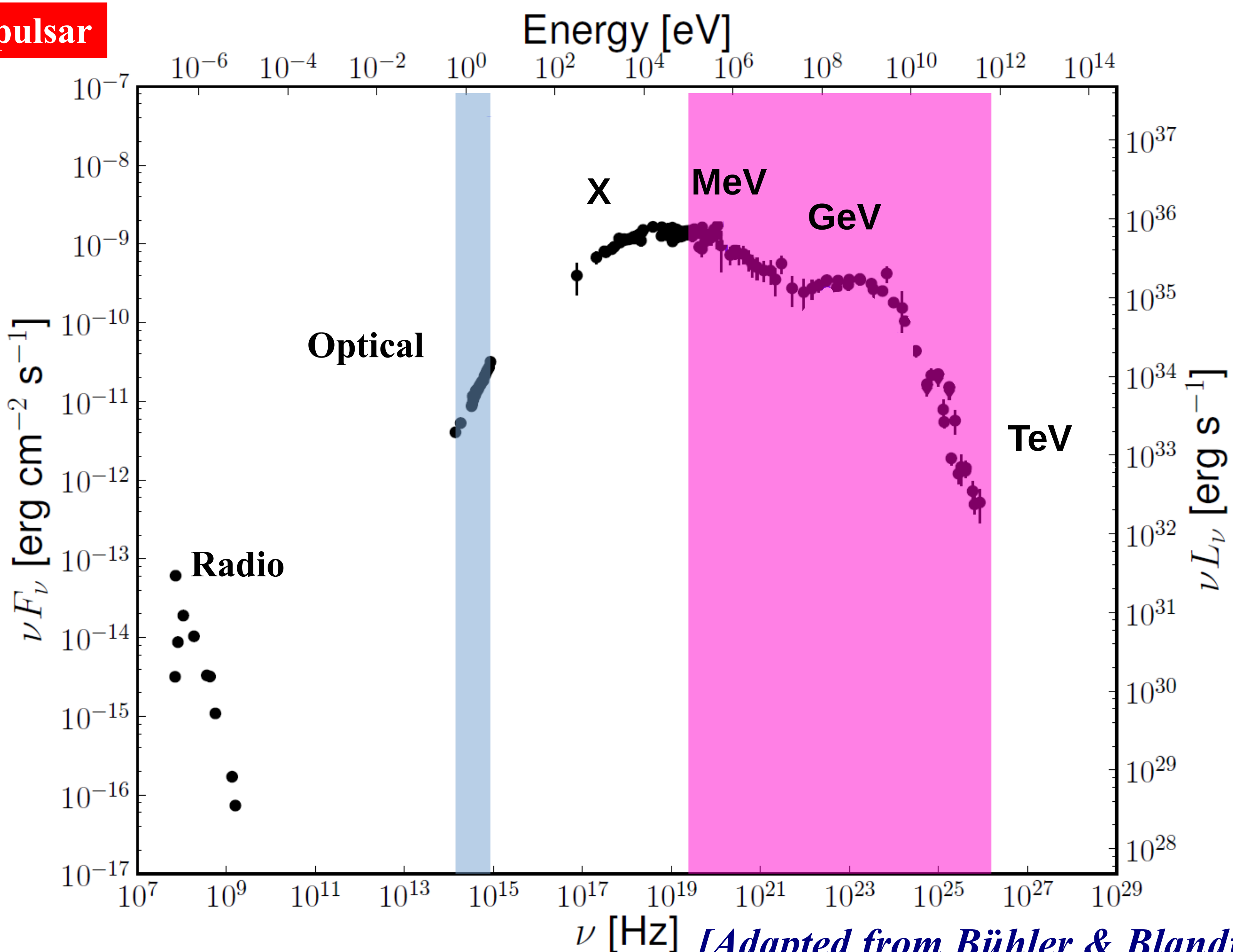
Beyond a PeV, Sept. 13-16, 2016, Paris.

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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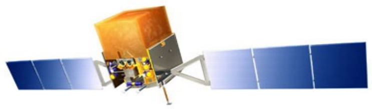
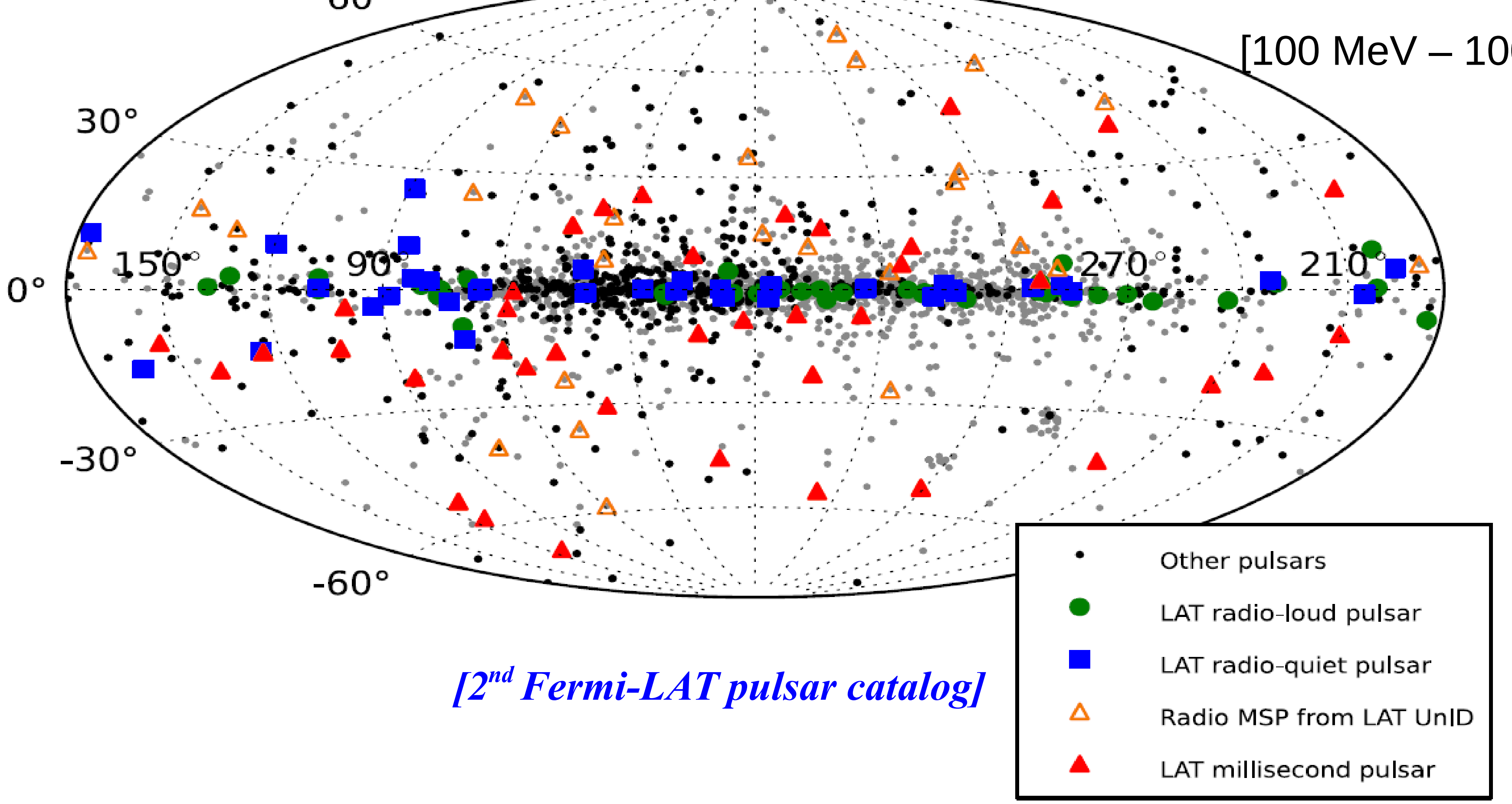
Most Galactic accelerators are pulsars

~ 100 gamma-ray pulsars

Fermi-LAT



[100 MeV – 100 GeV]



[2nd Fermi-LAT pulsar catalog]

Pulsars emitting gamma rays young and ms, i.e., rotation-powered

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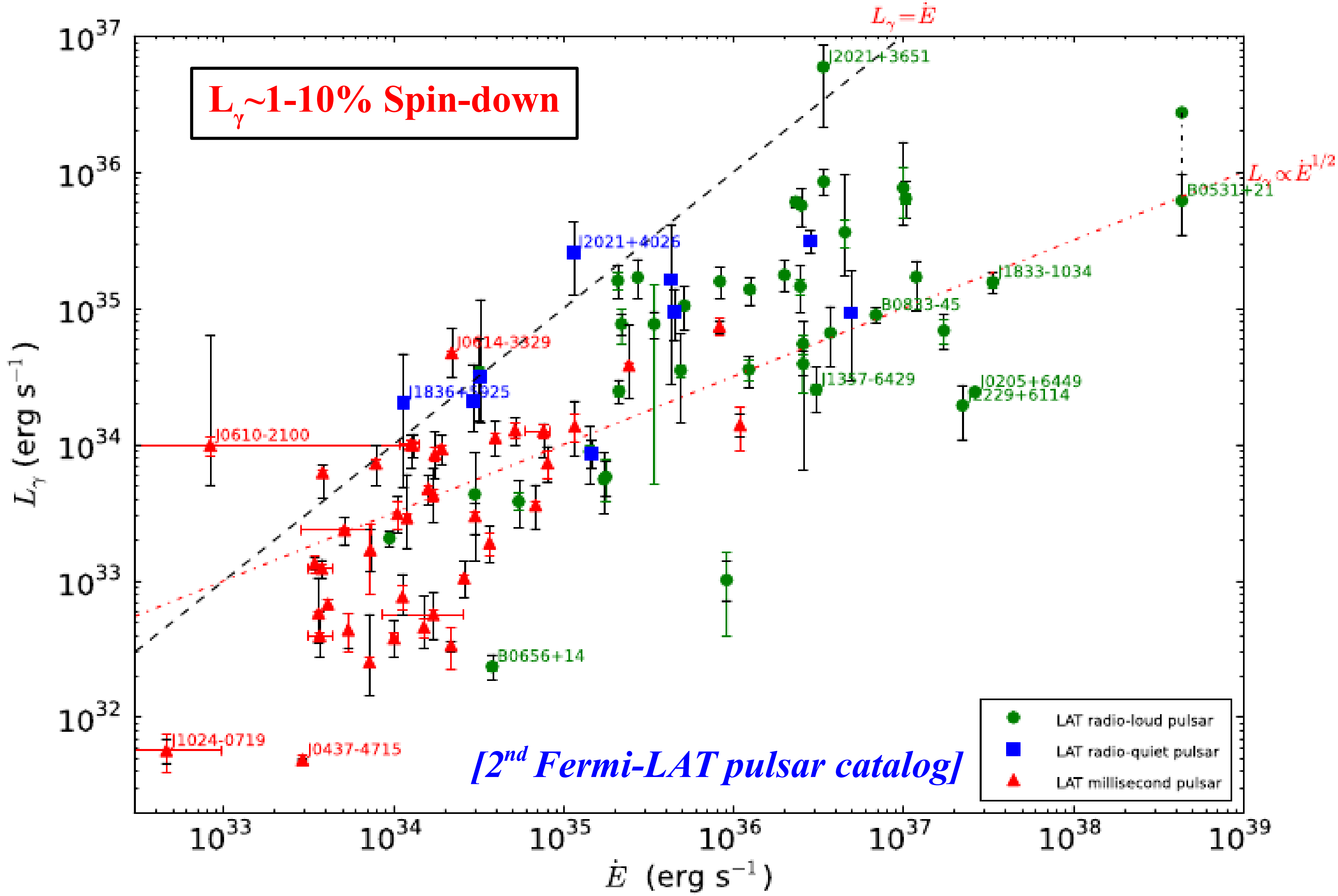
Pulsars are efficient particle accelerators



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

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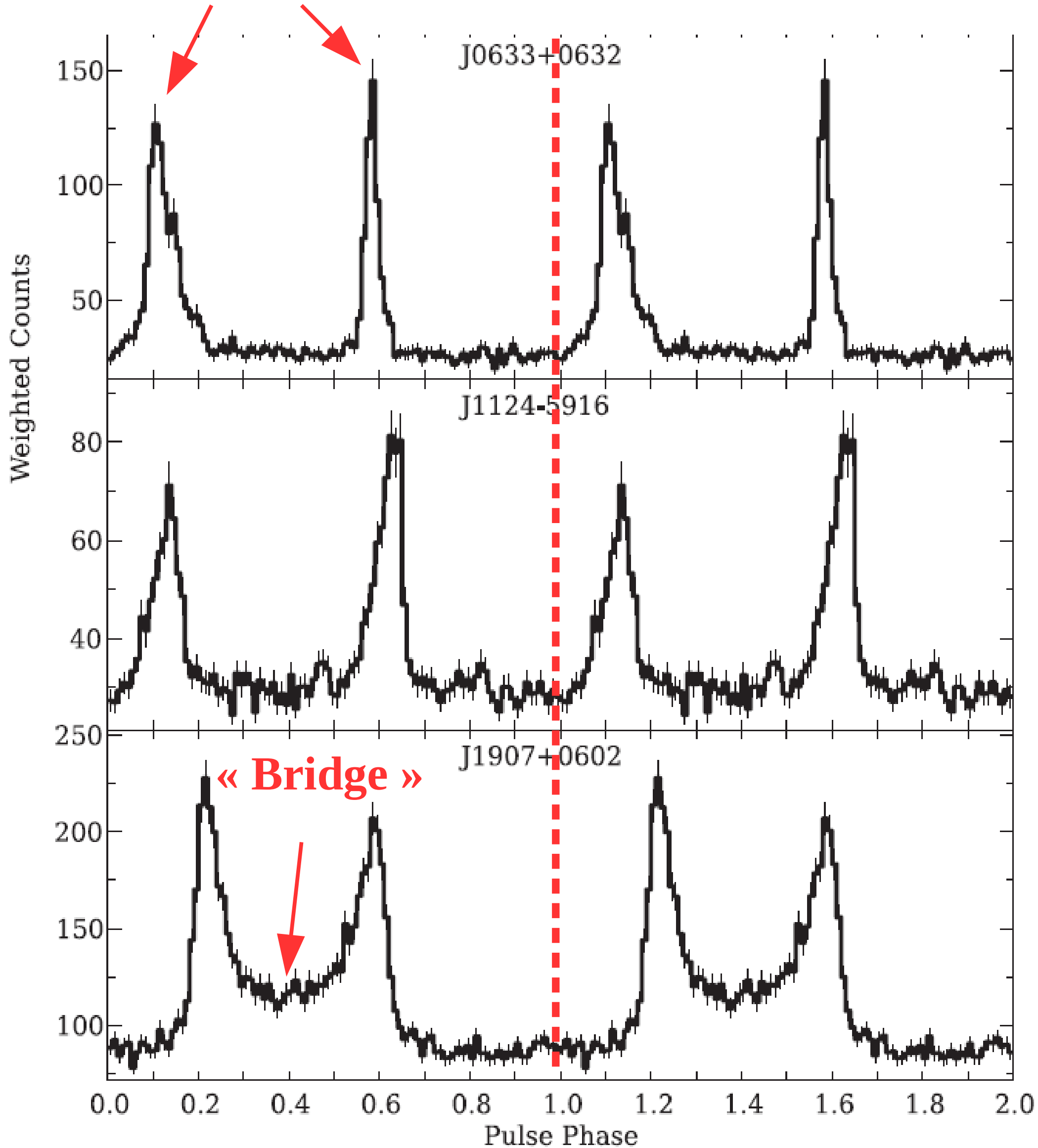
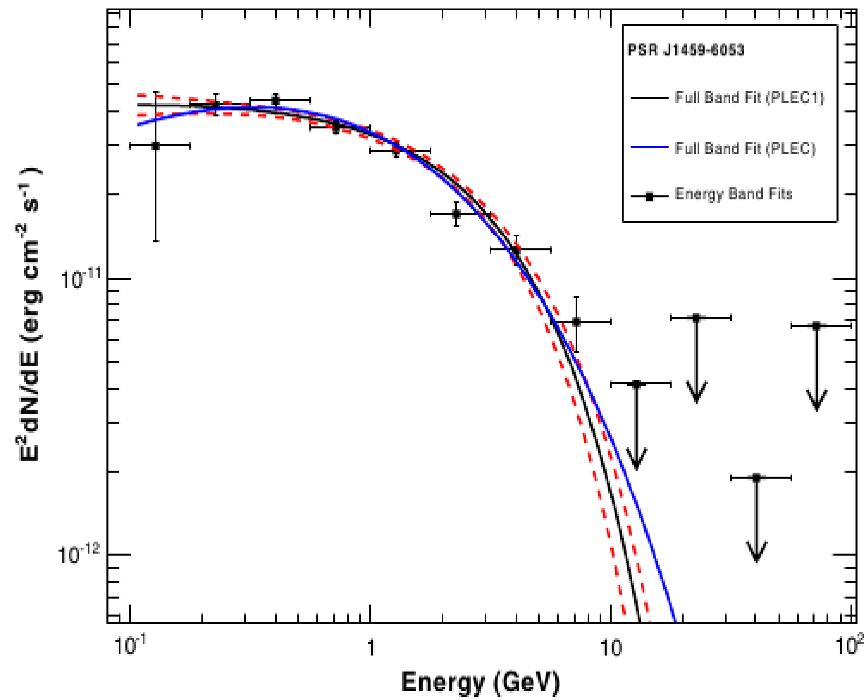
Typical gamma-ray pulsar signal

Two peaks lightcurves



Hard power-law + exponential cut-off



[2nd Fermi-LAT pulsar catalog]

How and where are particle accelerated and radiate?

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Elements of a pulsar magnetosphere: vacuum

Rotation of the field lines induce electric field :

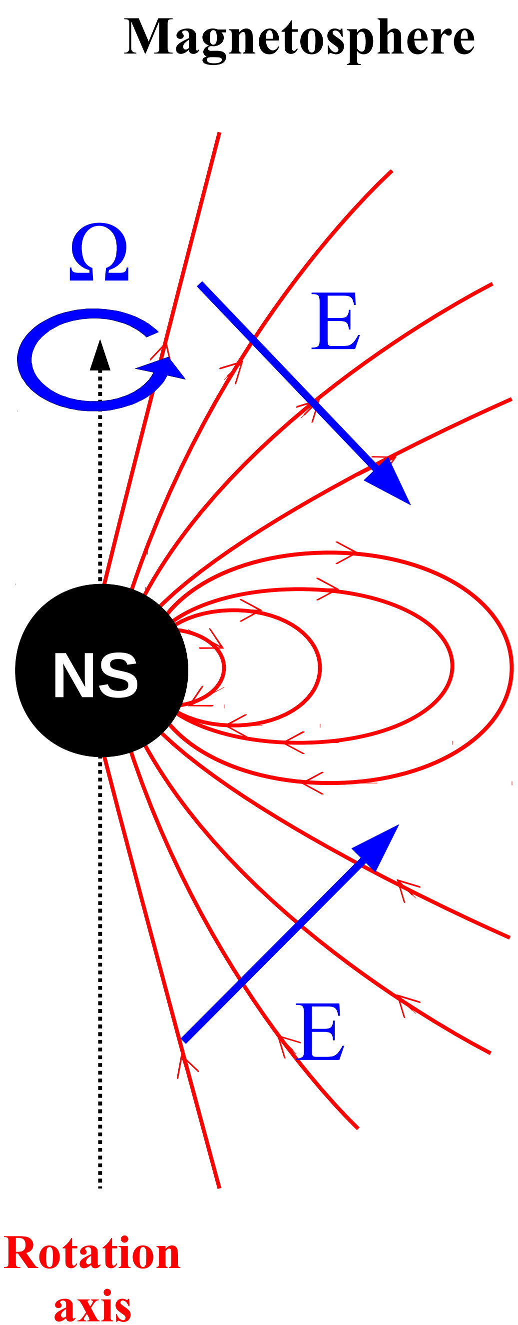
$$E = \frac{R\,\Omega\,B}{c}$$

Potential difference pole/equator :

$$\Delta\Phi = \frac{R^2\,\Omega\,B}{c} \approx 10^{16}\,V$$

(for a Crab-like pulsar)

Beyond a PeV!



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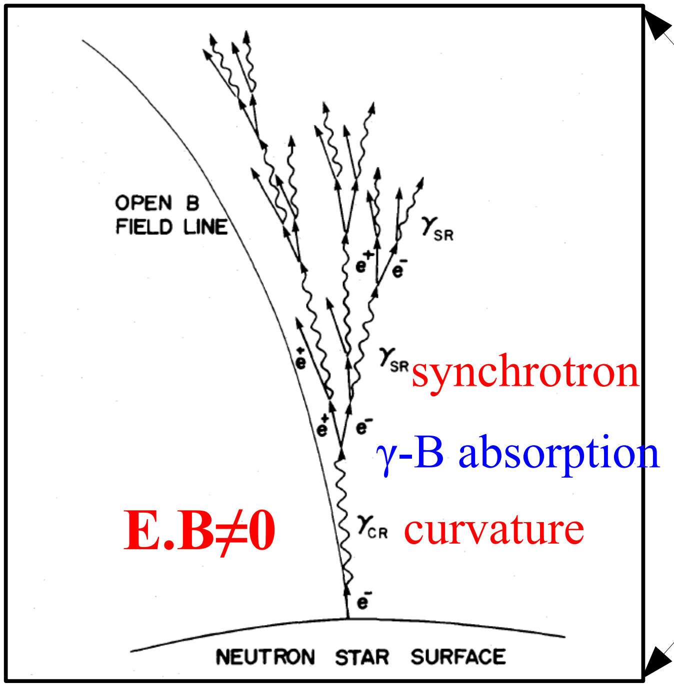
Elements of a pulsar magnetosphere: plasma filled

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

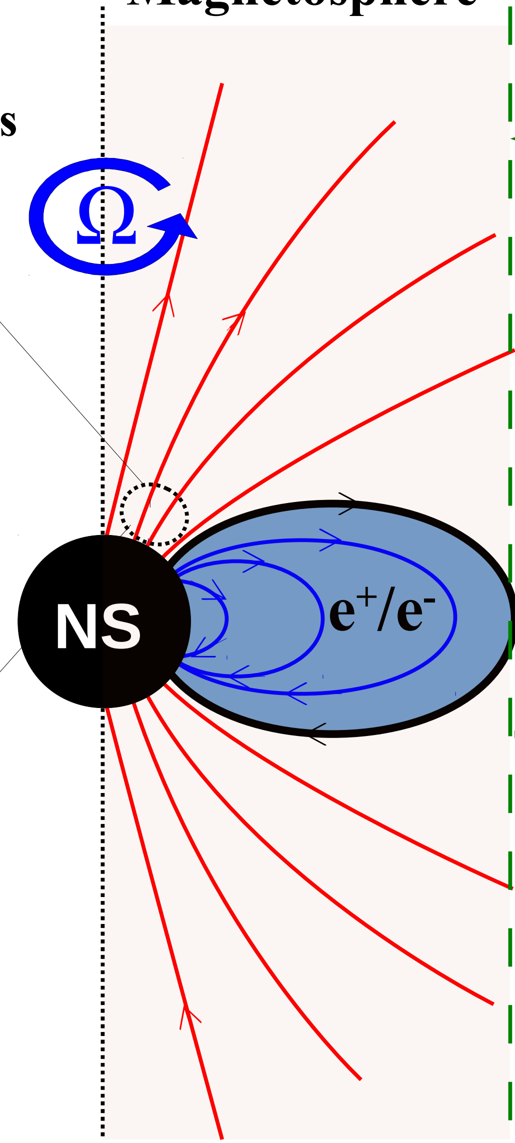
Potential polar cap (Crab):

$$\Delta\Phi_{pc} = \frac{R^3\,\Omega^2\,B}{c^2} \approx 10^{14}\,V$$

Below a PeV ... :(

Magnetosphere

Wind region



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

Here corotation is impossible !

Rotation axis

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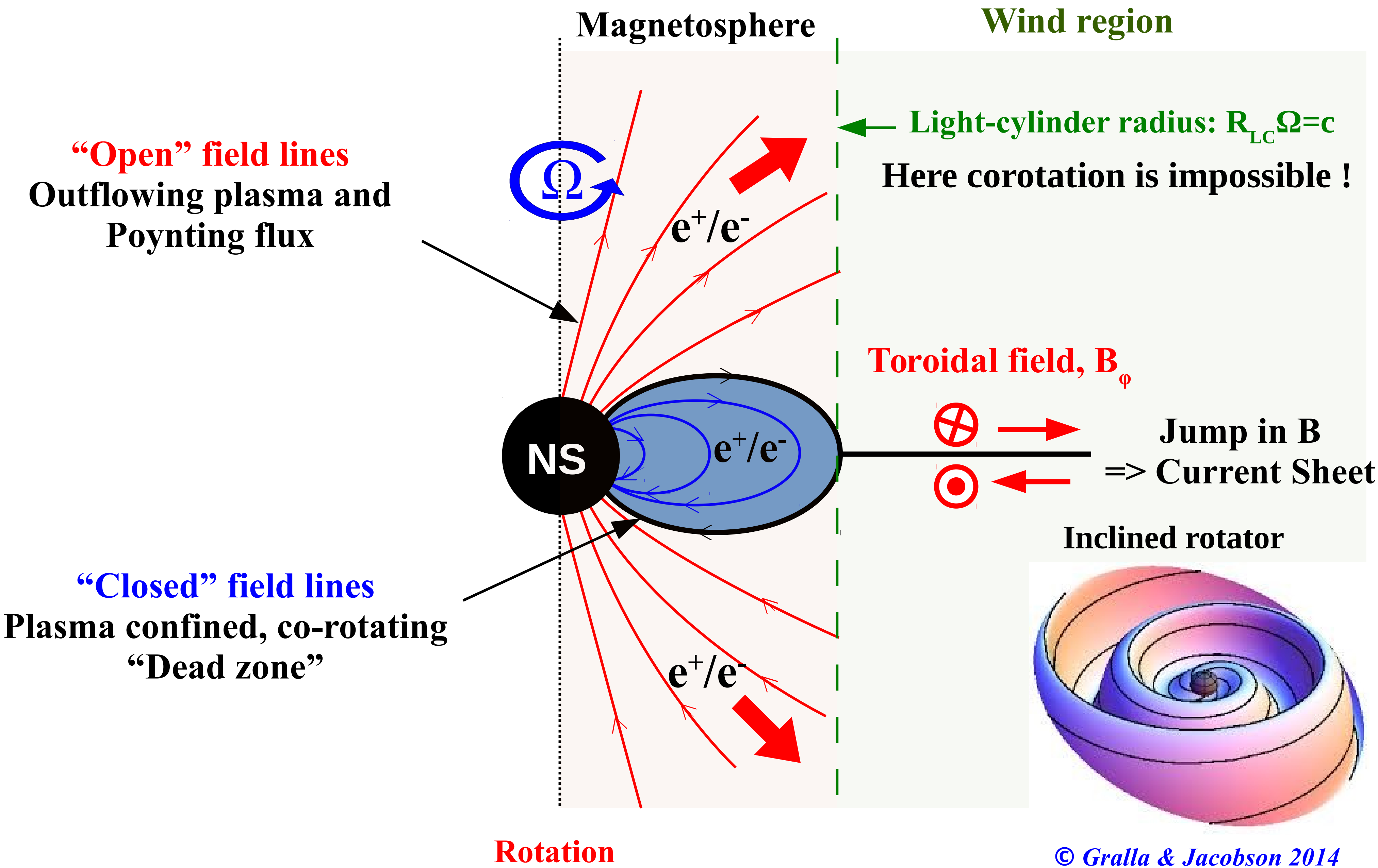
Elements of a pulsar magnetosphere: plasma filled



Similar to the heliospheric current sheet.

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Proposed sites for particle acceleration

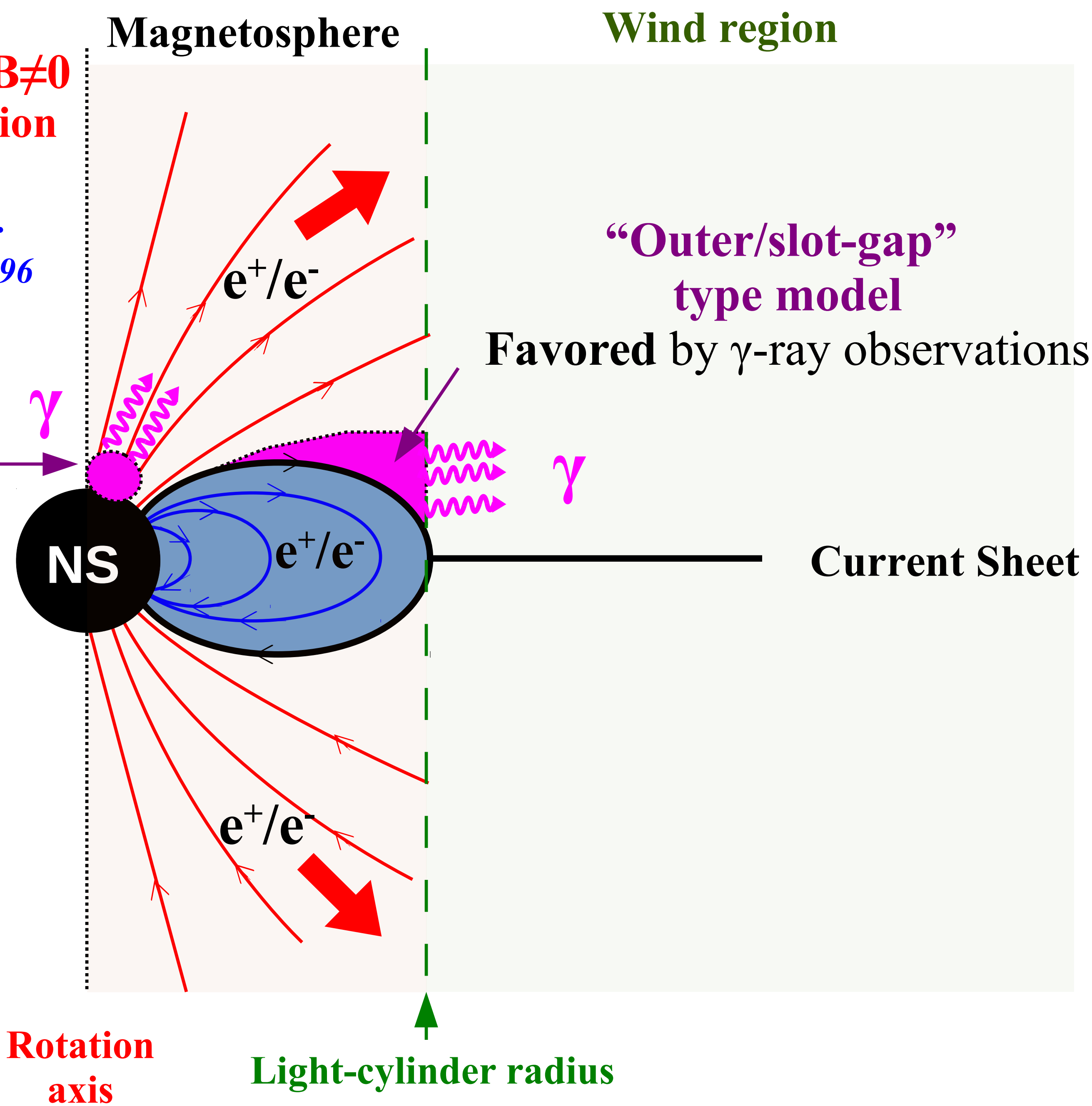
Acceleration in gaps, E.B≠0
γ-ray : curvature radiation

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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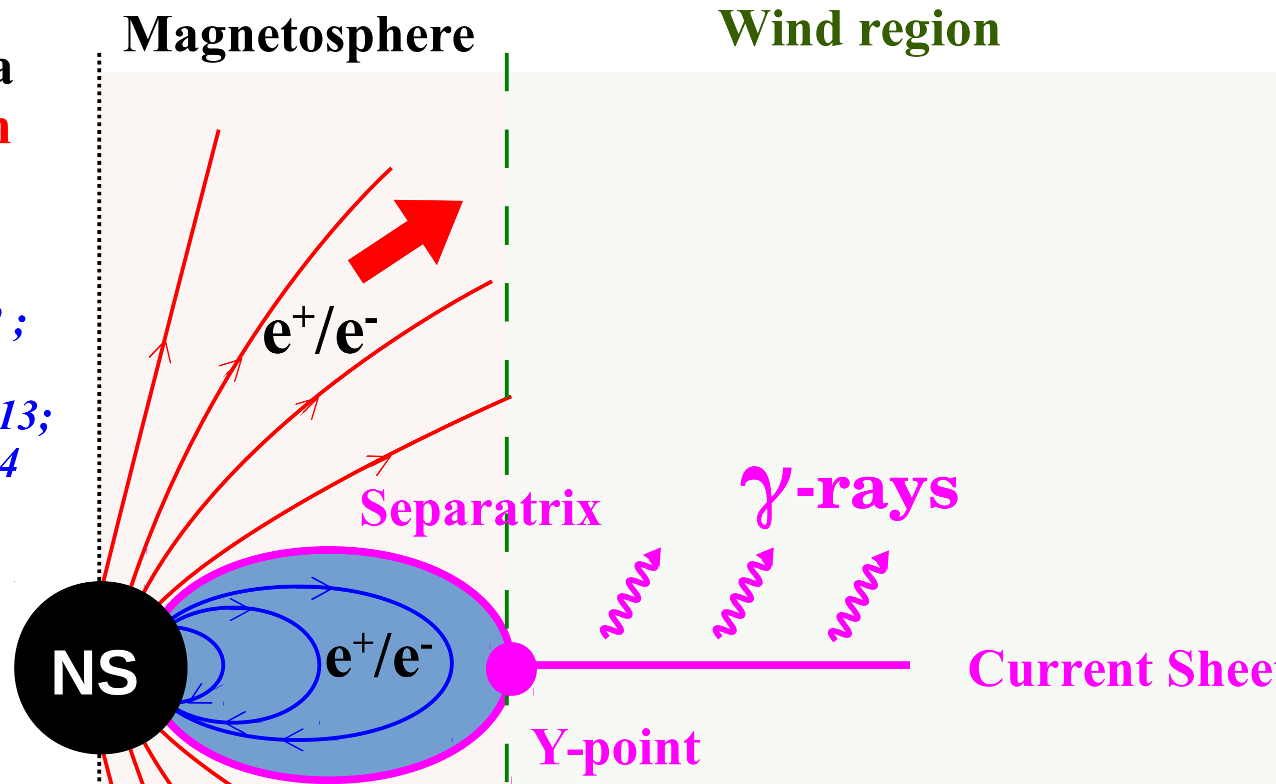
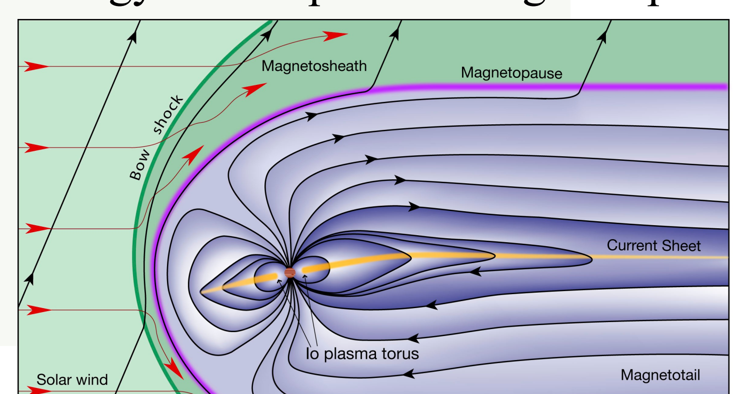
Proposed sites for particle acceleration

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



Analogy with Jupiter-Io magnetosphere



Models dependent on the geometry of the magnetosphere

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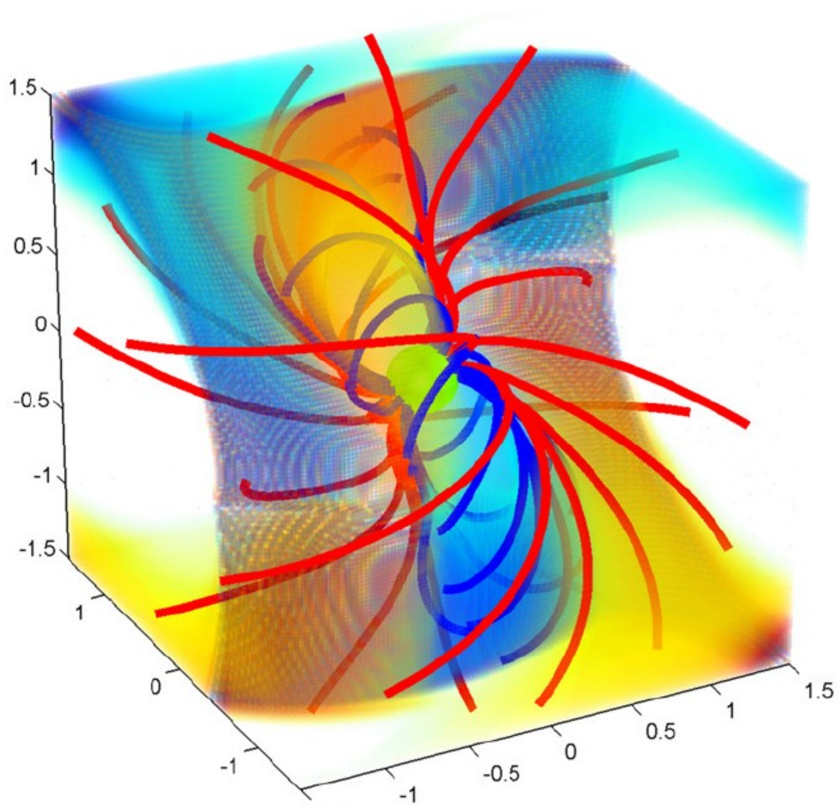
Insight from the MHD approach

(Force Free / Resistive Force Free / Full MHD)

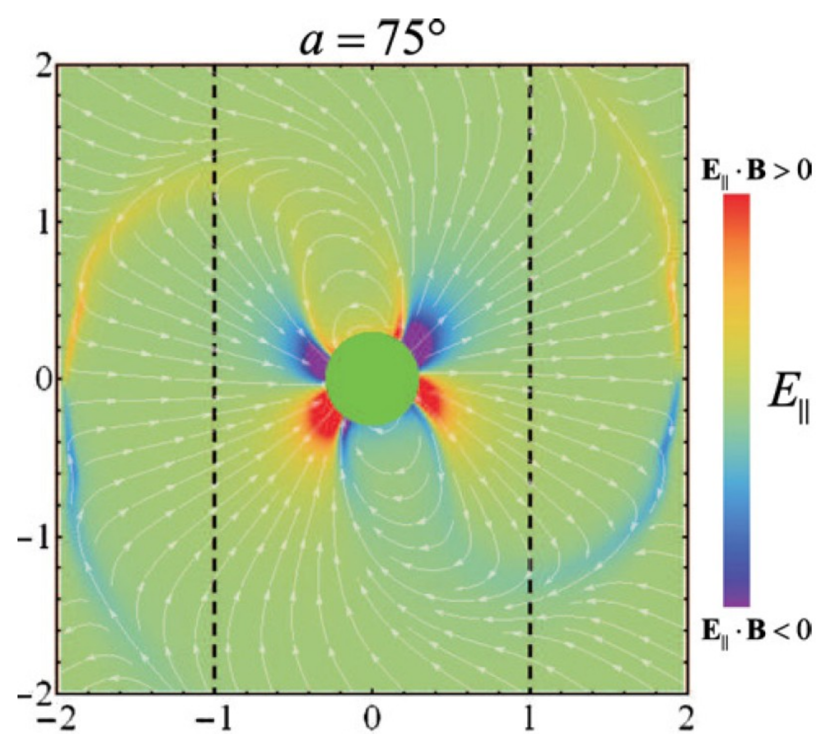
Ideal Force-Free field geometry with prescribed emitting field lines

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

PIC simulations !

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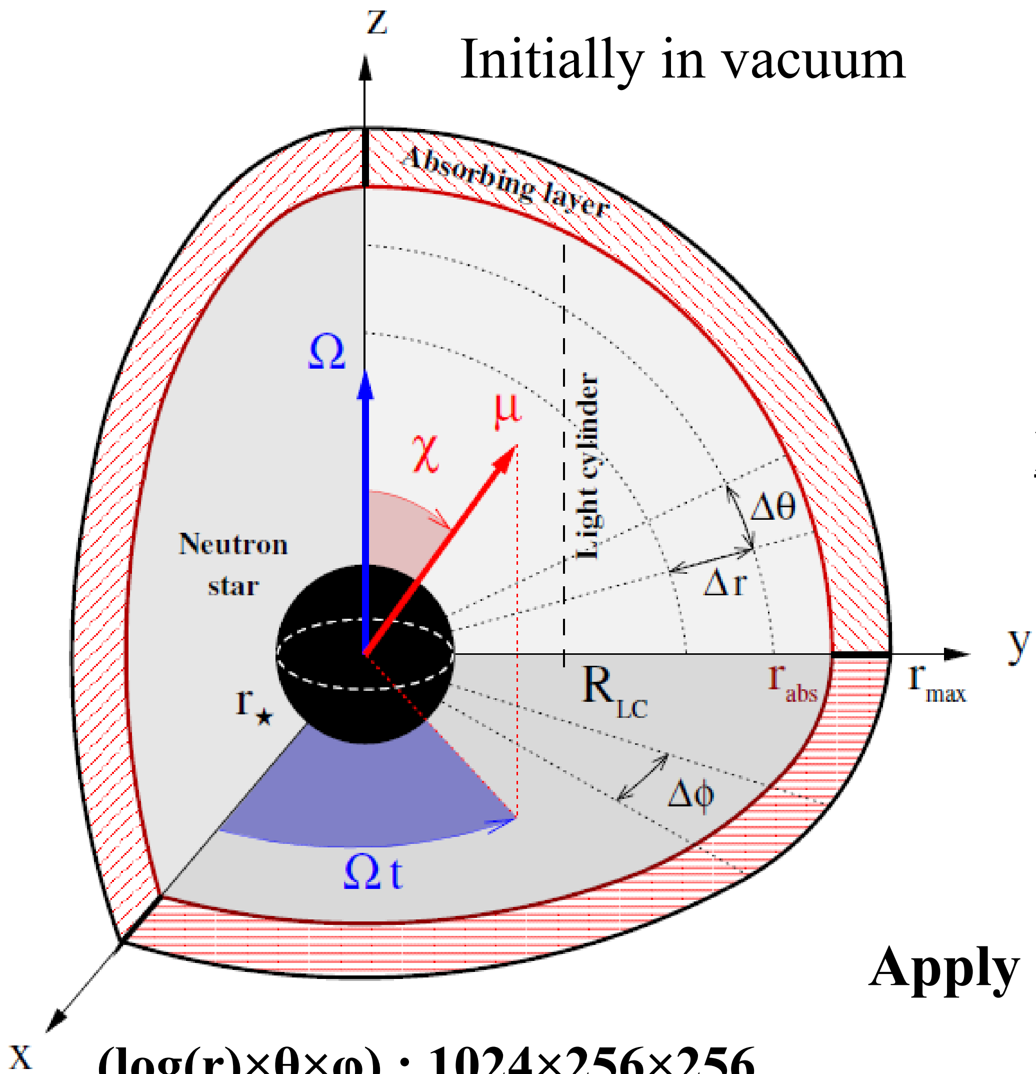
Global 3D spherical PIC with radiation reaction force

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

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



(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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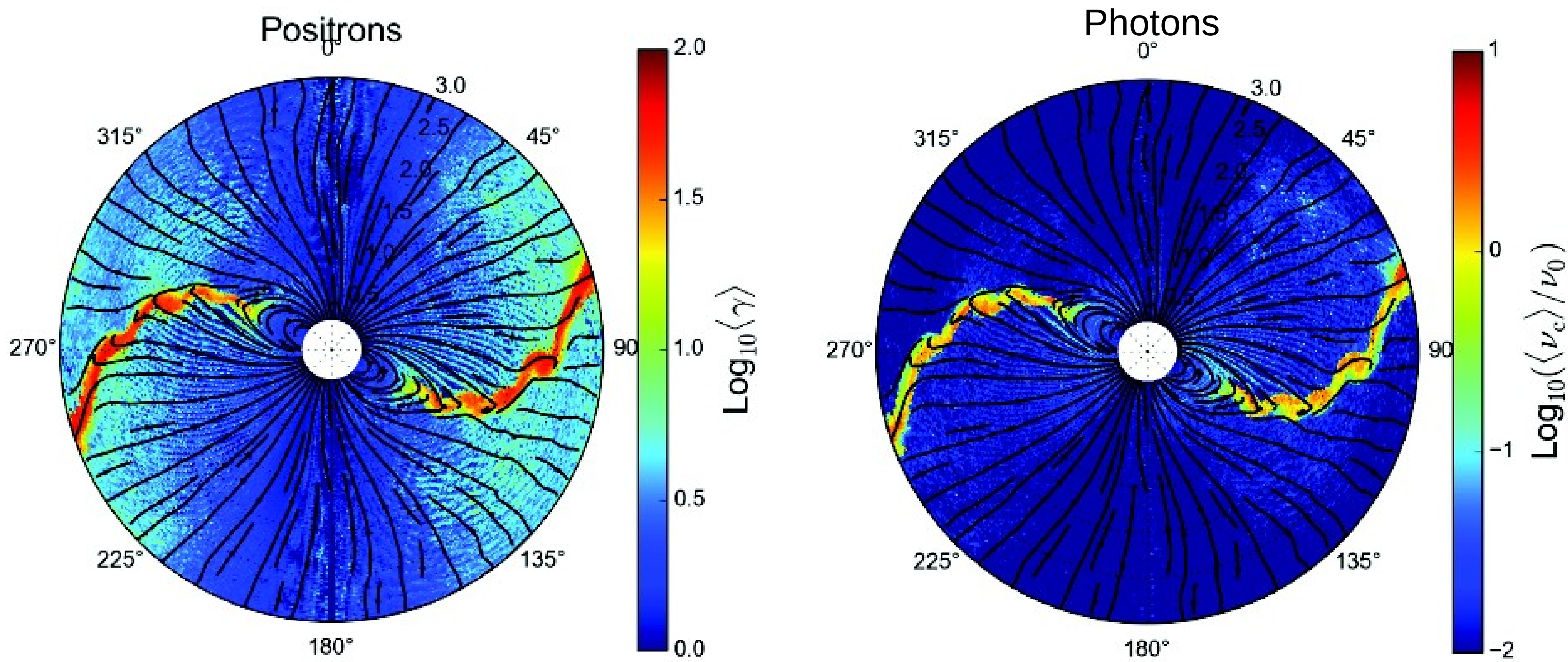
Particle / radiation mean energy (χ=30°)

Cerutti et al. 2015b



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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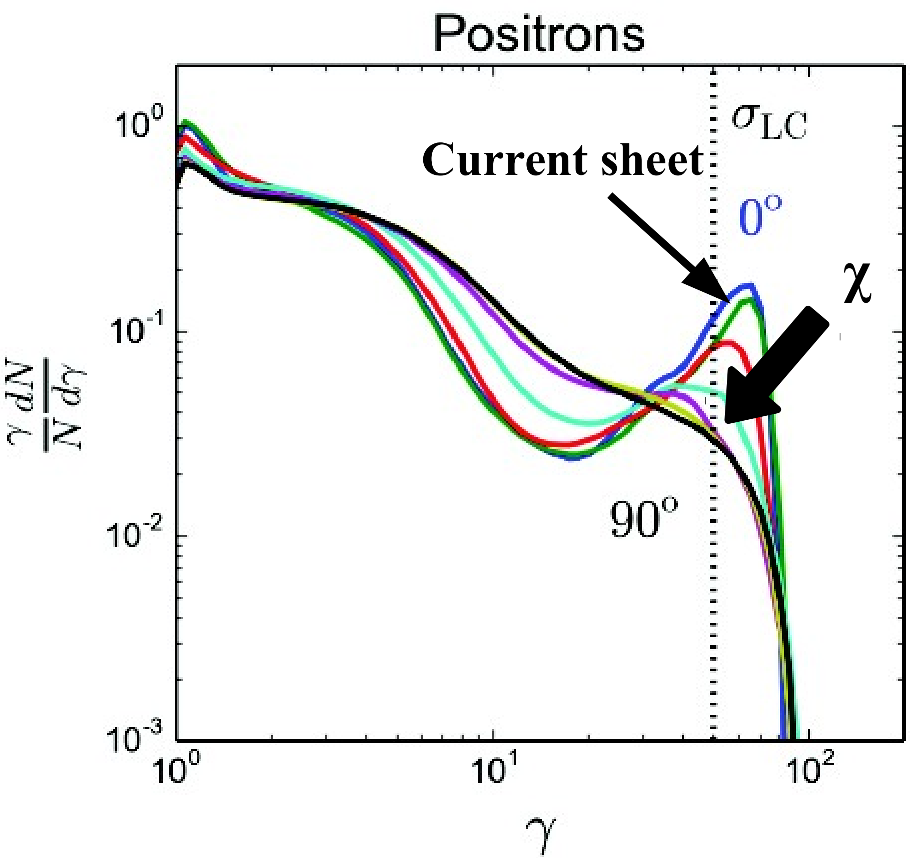
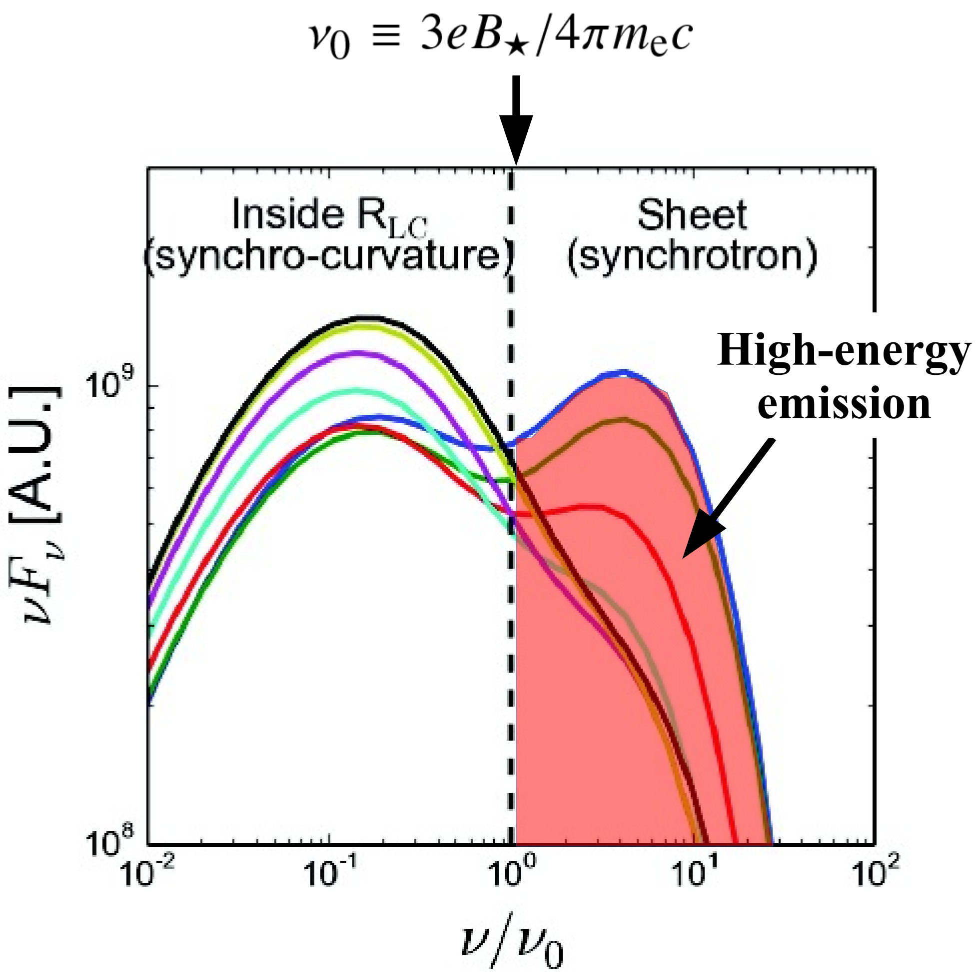
See also in 2D axisymmetric Cerutti et al. 2015

Particle / radiation spectra





Particle acceleration and emission of energetic radiation decreases with pulsar inclination

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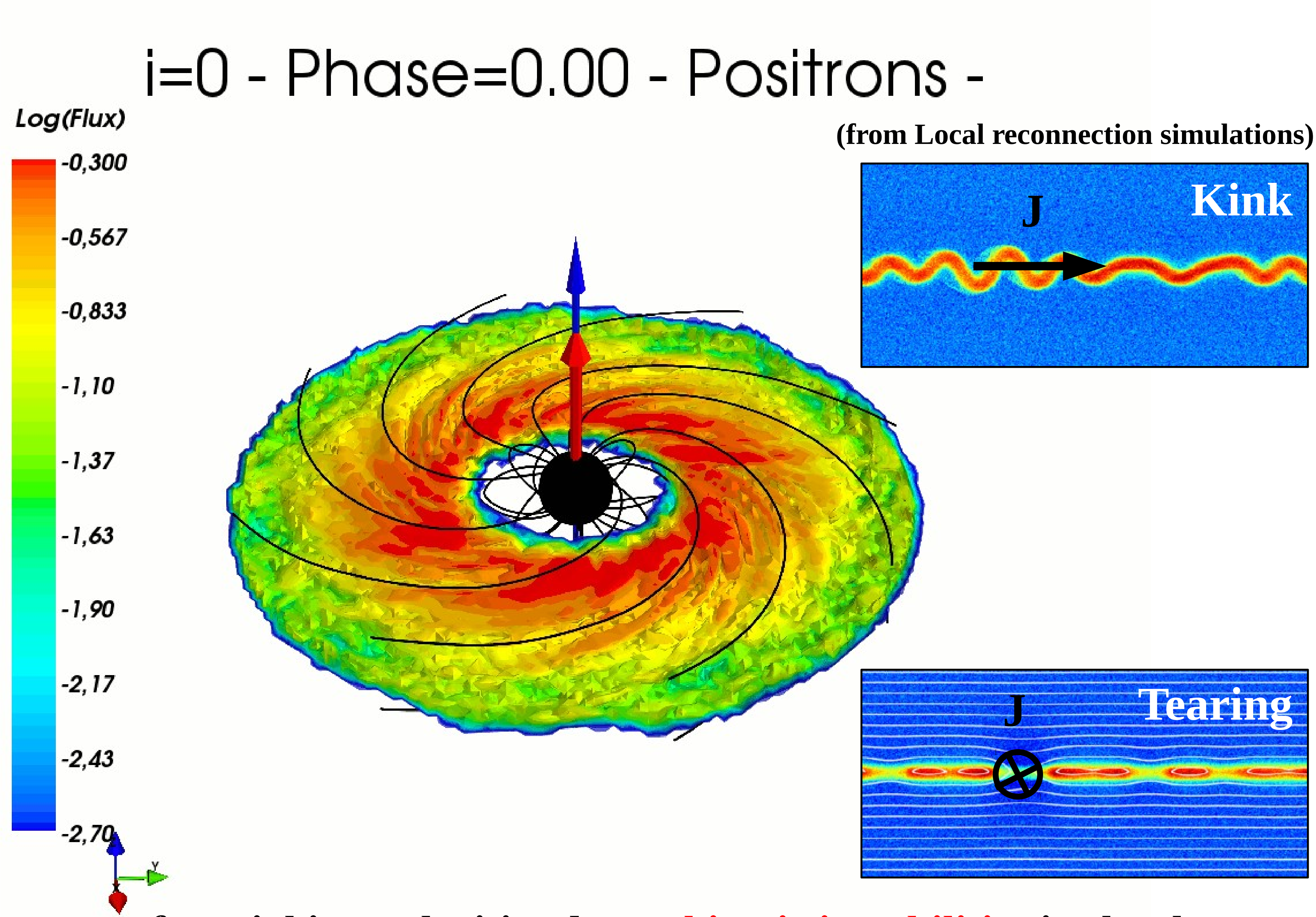
Cerutti et al. 2016a

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

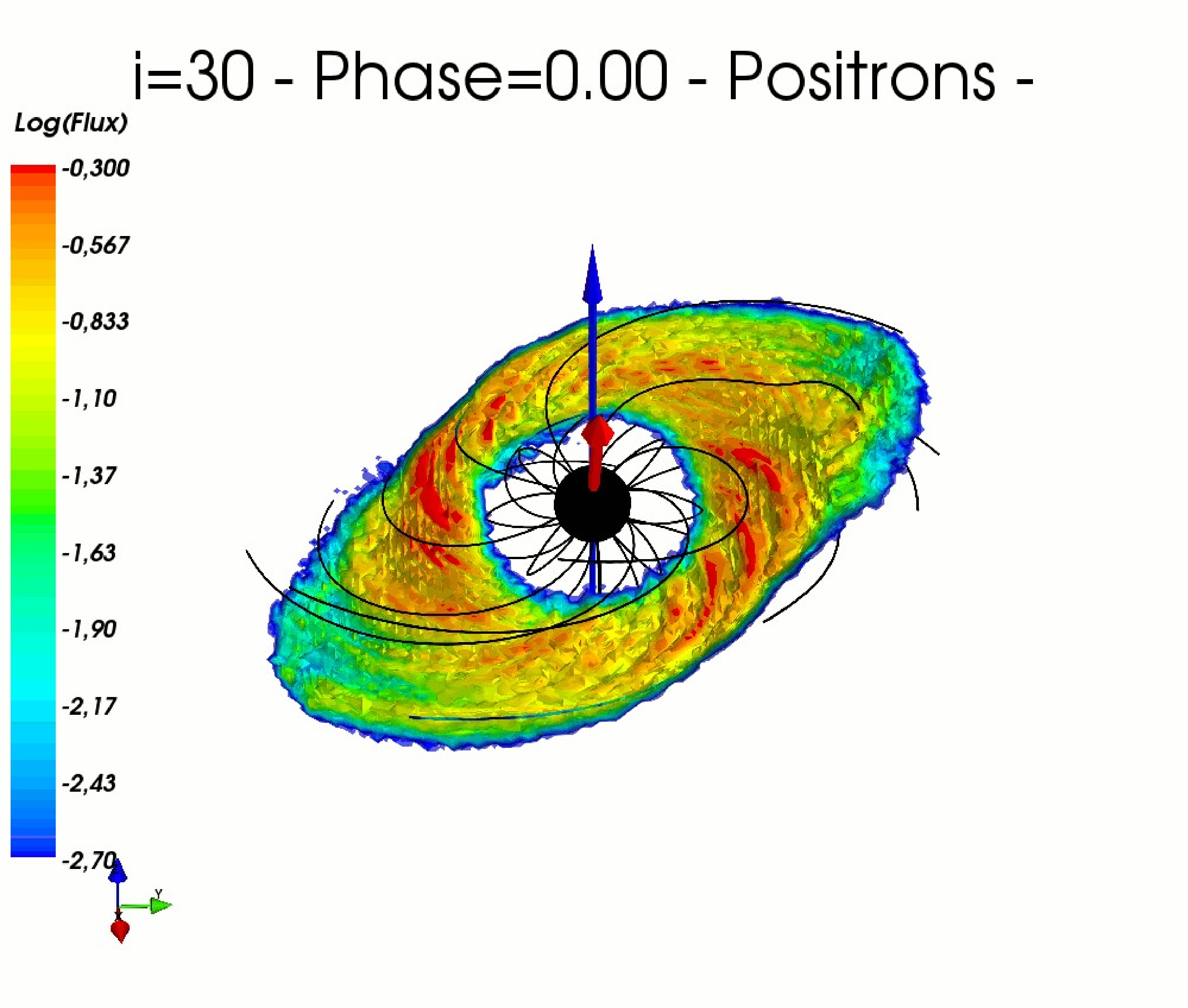


Presence of spatial irregularities due to kinetic instabilities in the sheet

(e.g., kink and tearing modes, see also Philippov et al. 2015a)

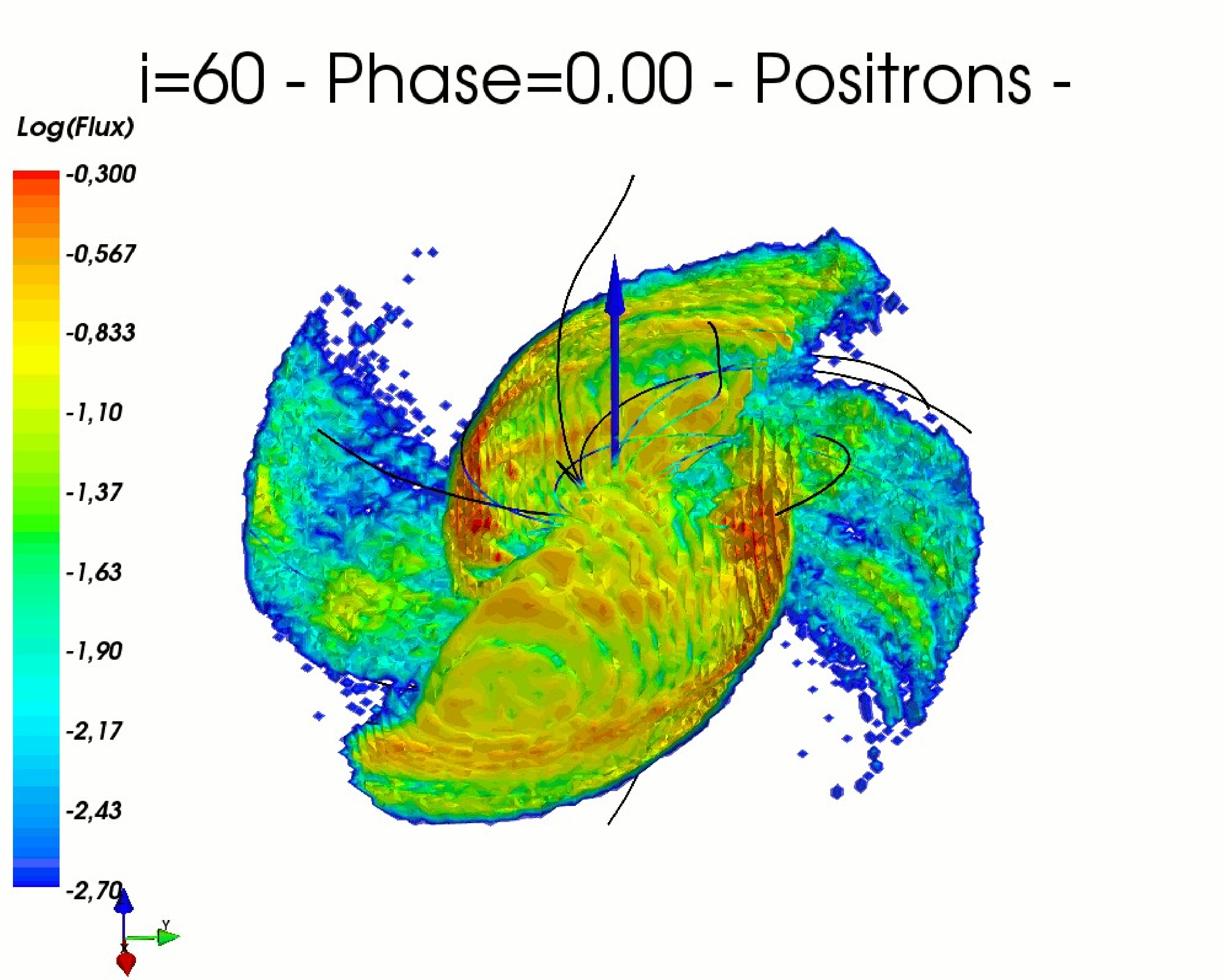
Cerutti et al. 2016a

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



Cerutti et al. 2016a

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



Small contribution from the wind regions : Could be due to reconnection induced inflow towards the sheet (Tchekhovskoy et al. 2013)

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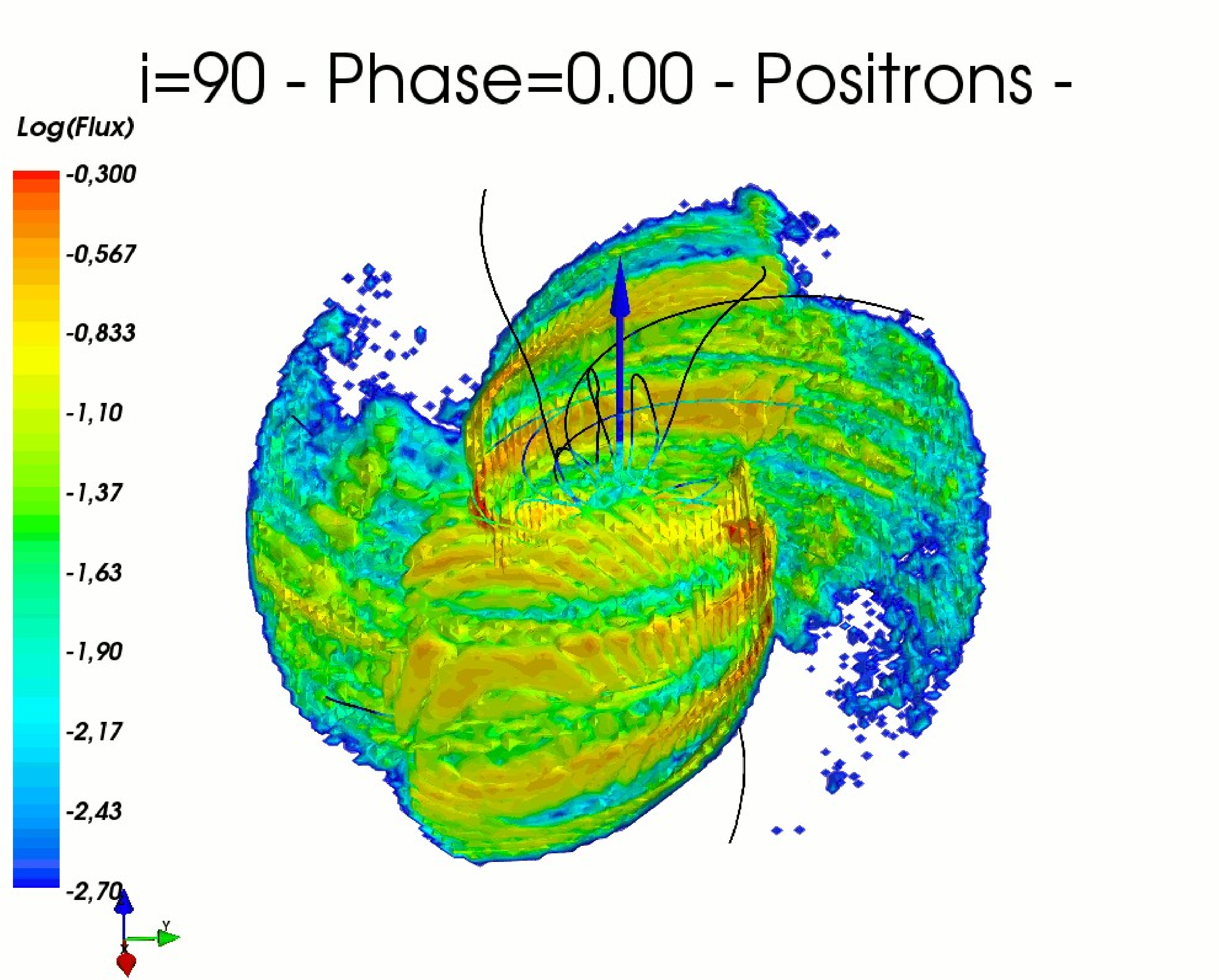
Cerutti et al. 2016a

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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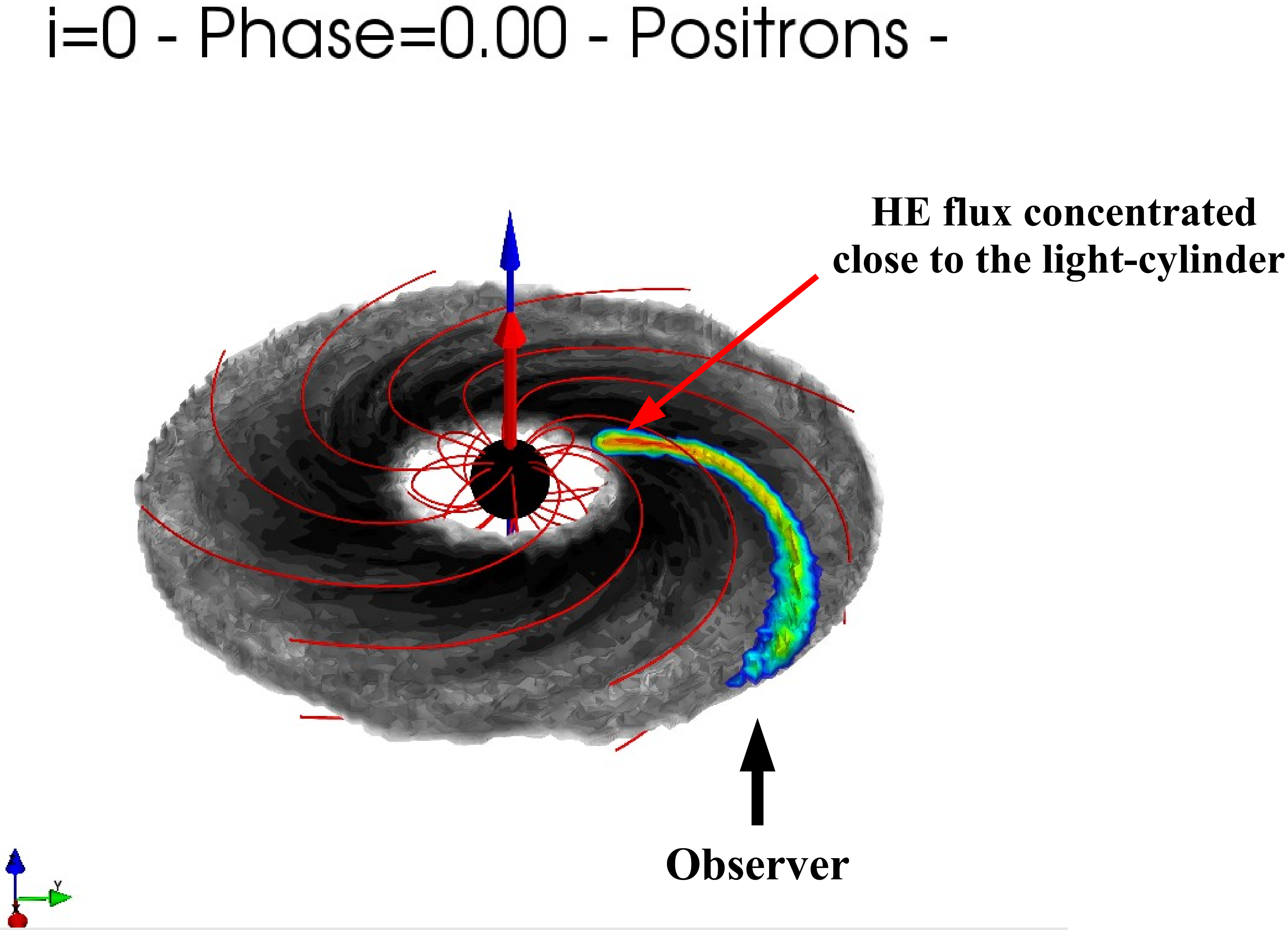
Cerutti et al. 2016a

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

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



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

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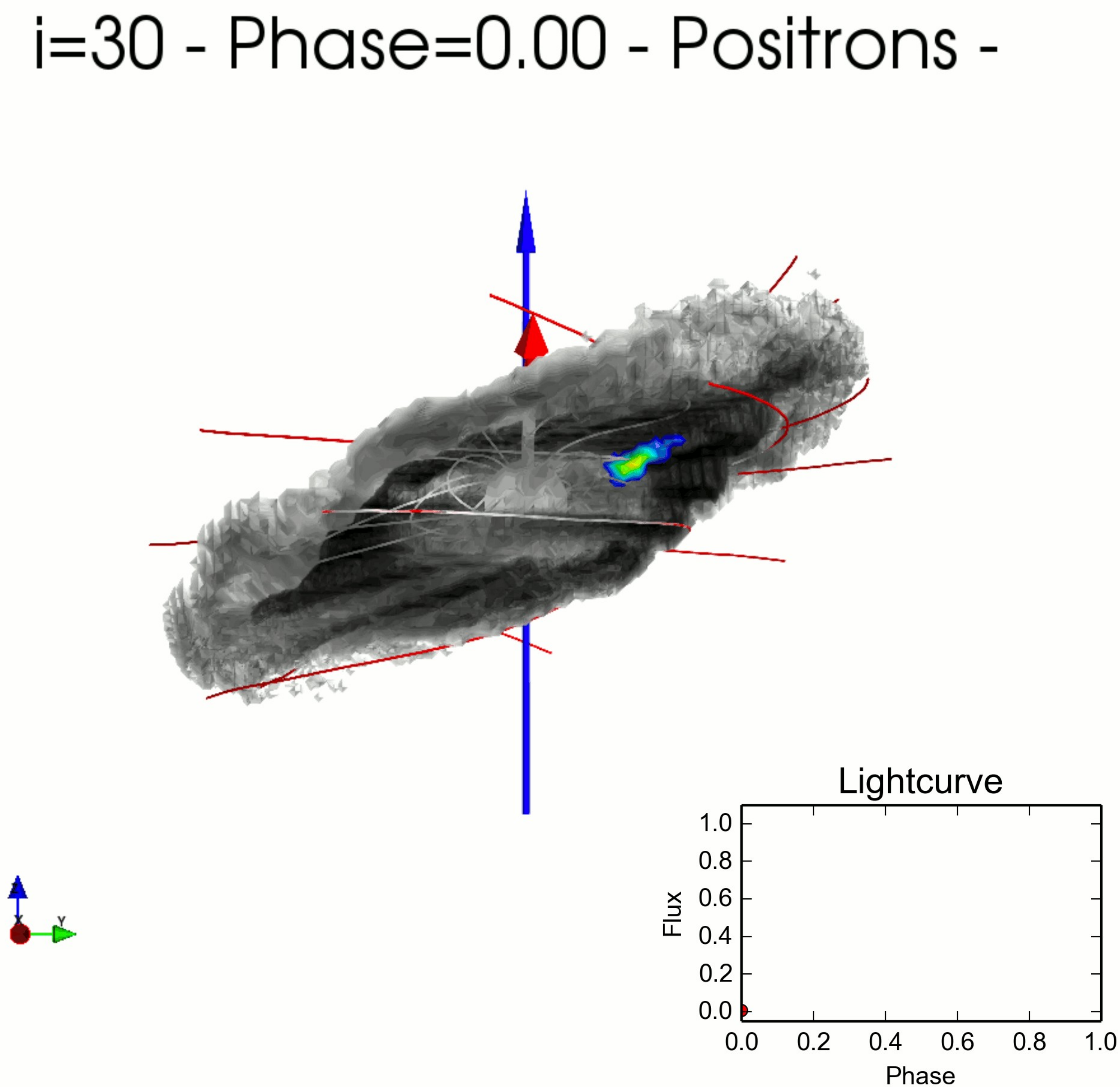
Observed high-energy radiation flux ($\nu > \nu_0$, $\chi = 30°$)

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

Light curve shaped by the geometry of the current sheet



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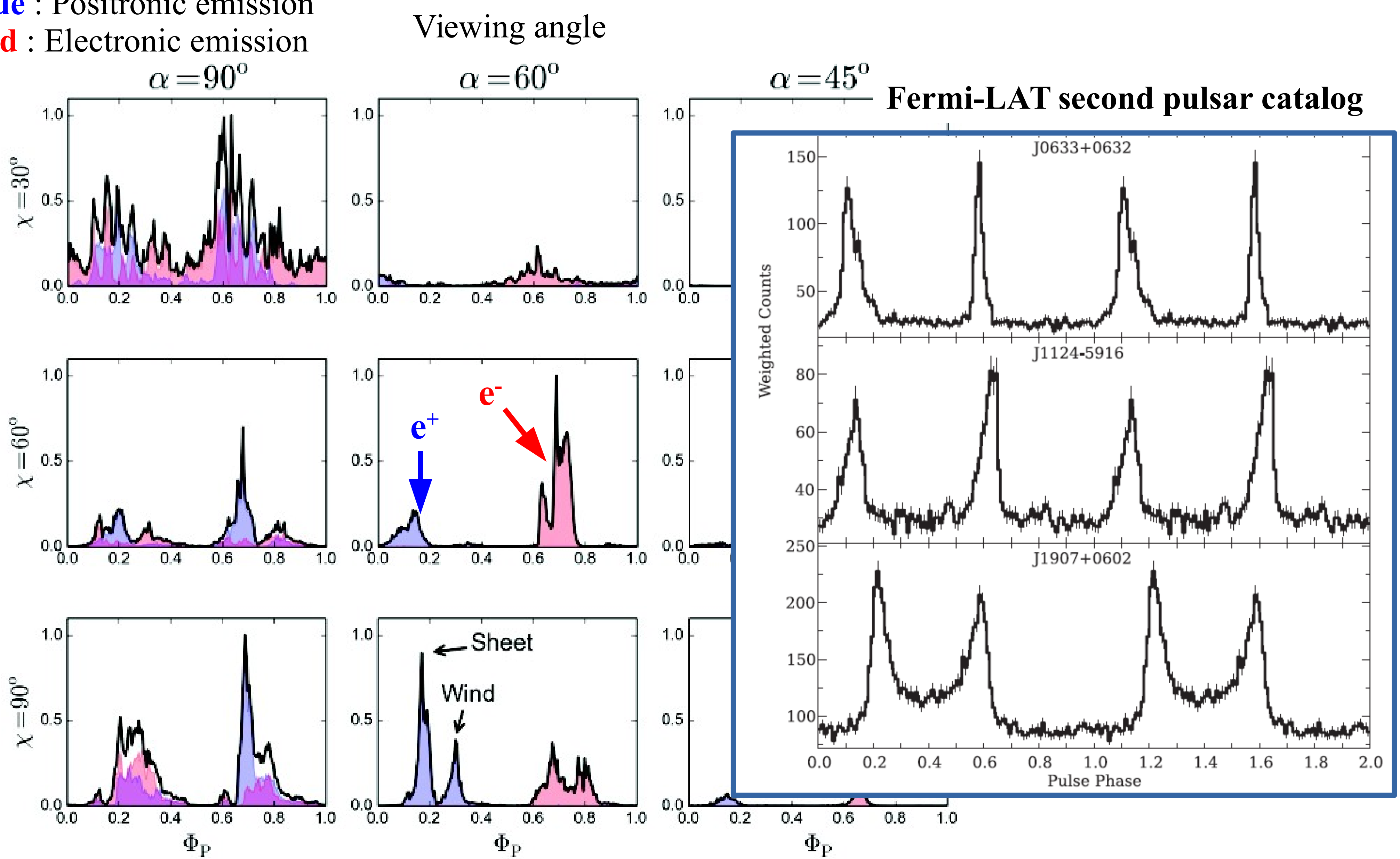
Cerutti et al. 2016a

Two-peaked lightcurves are very generic

One peak per crossing of the current sheet

Blue : Positronic emission
Red : Electronic emission



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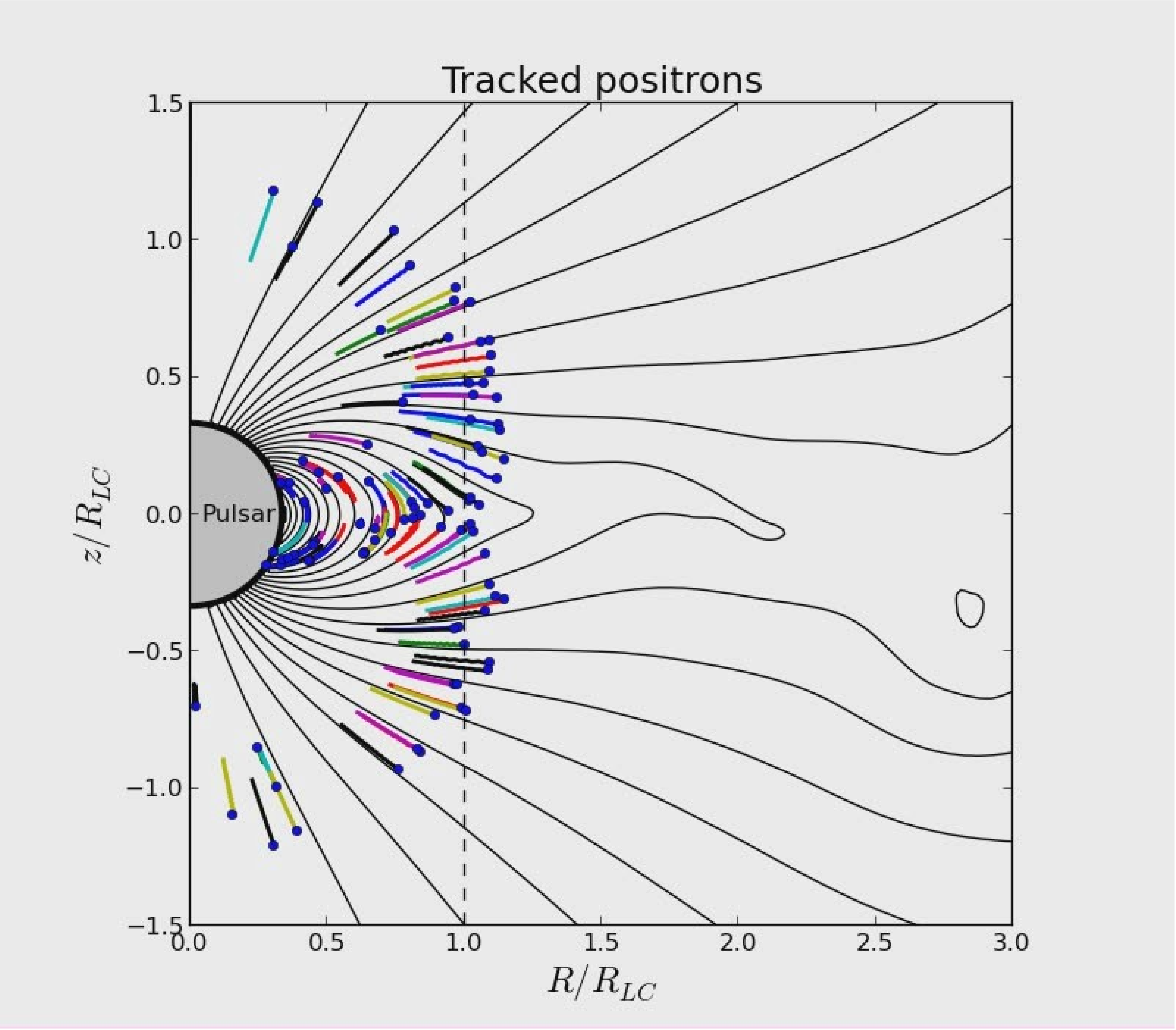
Cerutti et al. 2016a

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

2D



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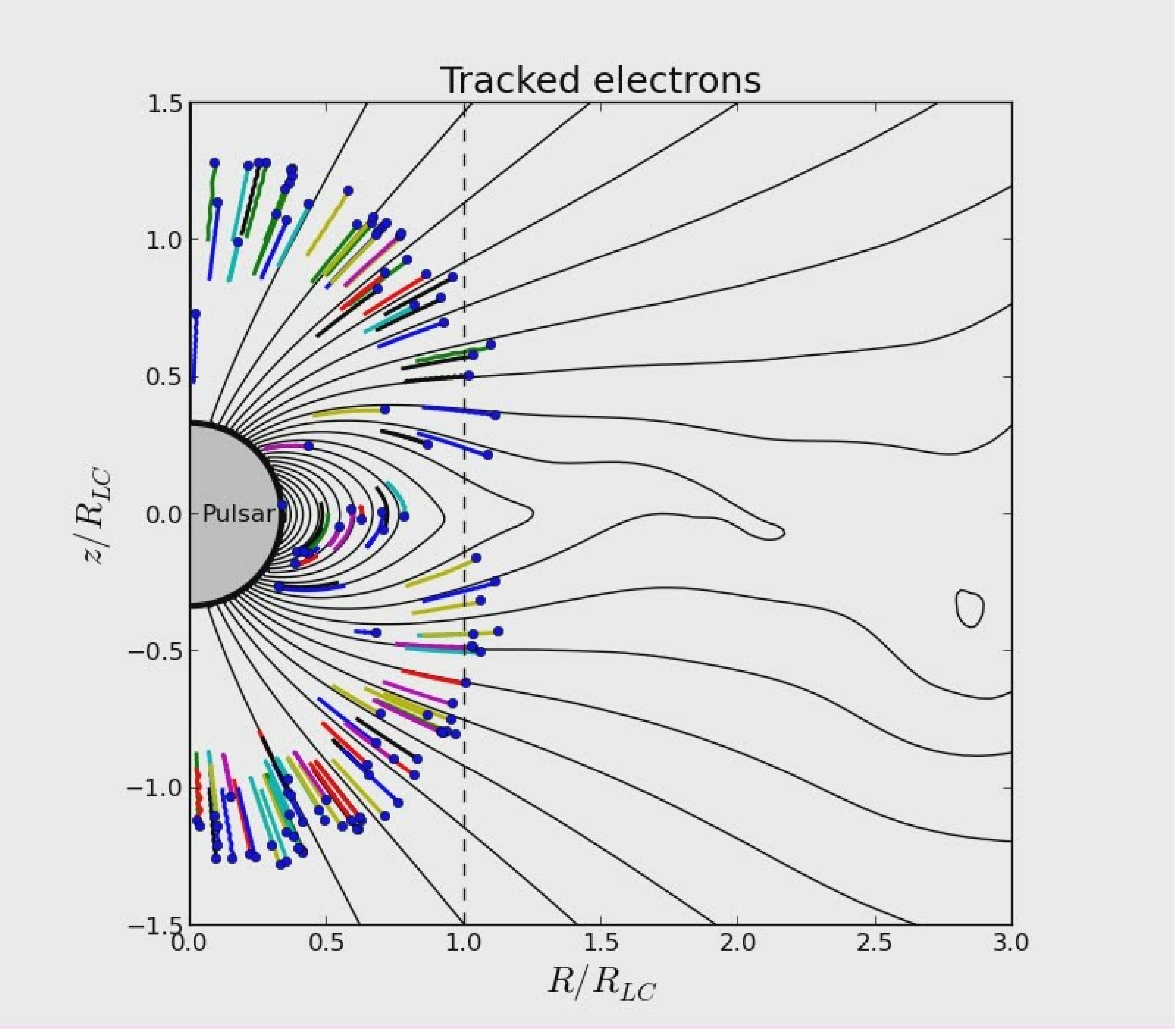
Particle acceleration and origin of the e^+/e^- asymmetry

2D



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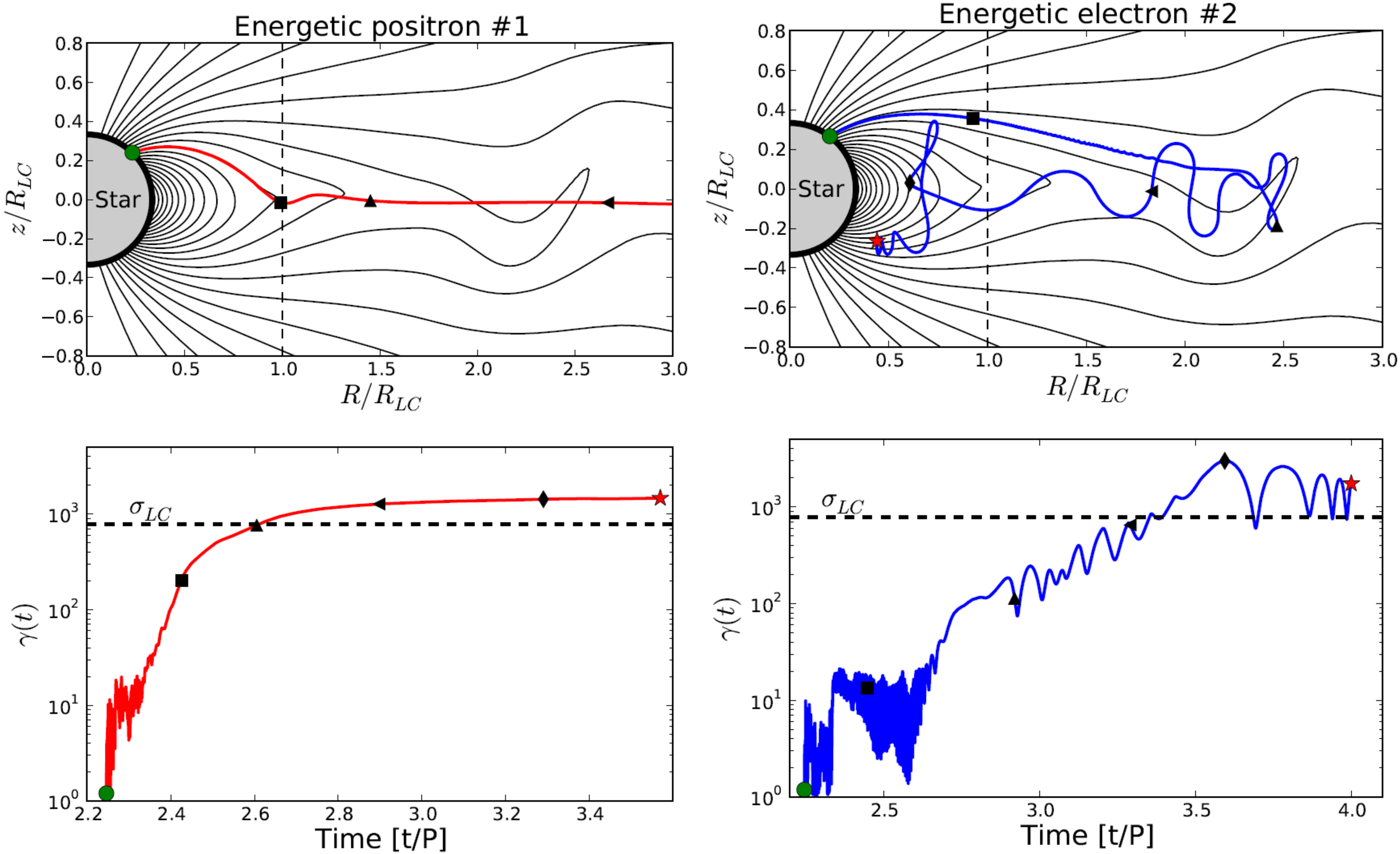
Particle acceleration and origin of the e^+/e^- asymmetry

2D (aligned pulsar)



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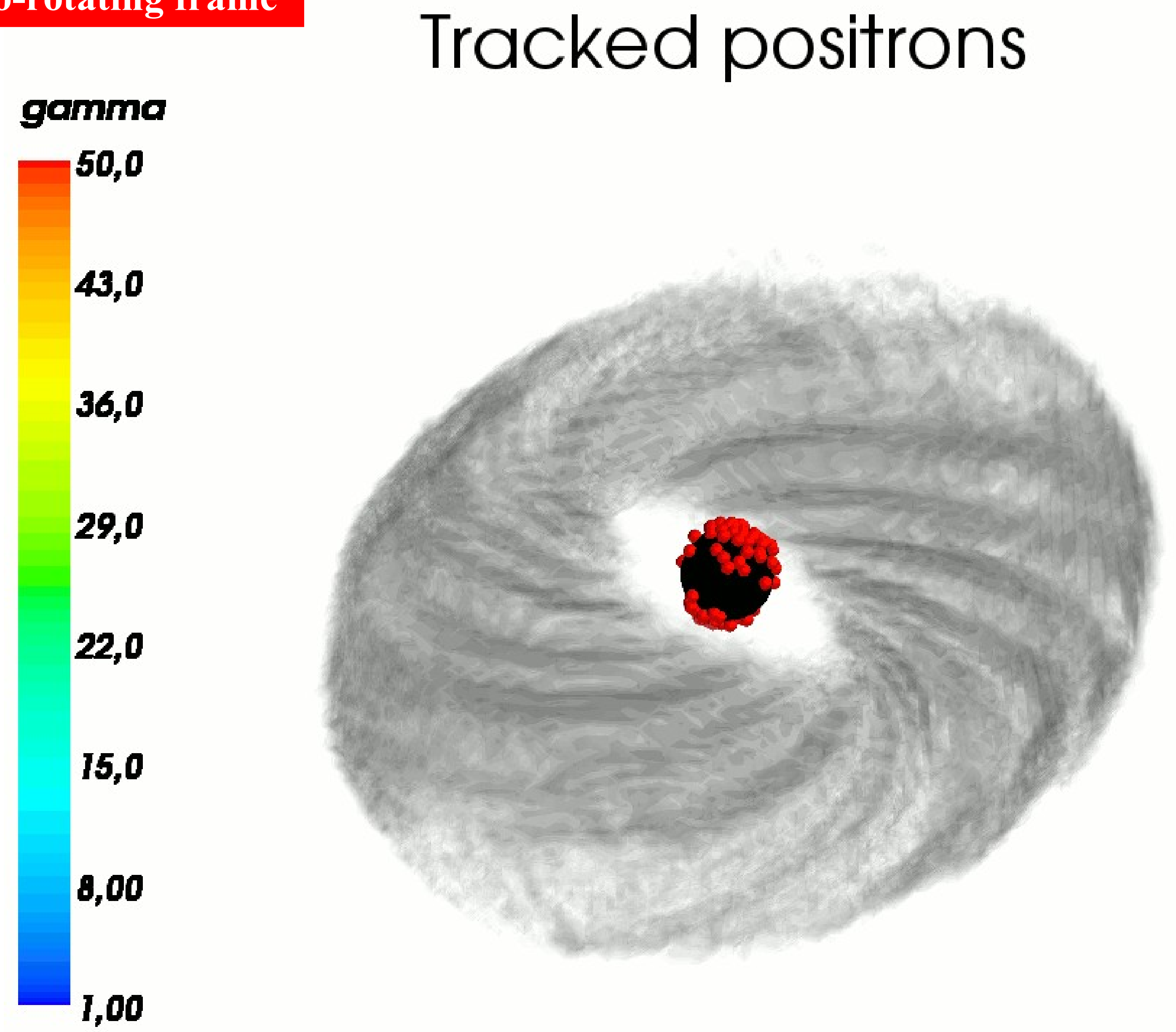
Cerutti et al. 2015

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

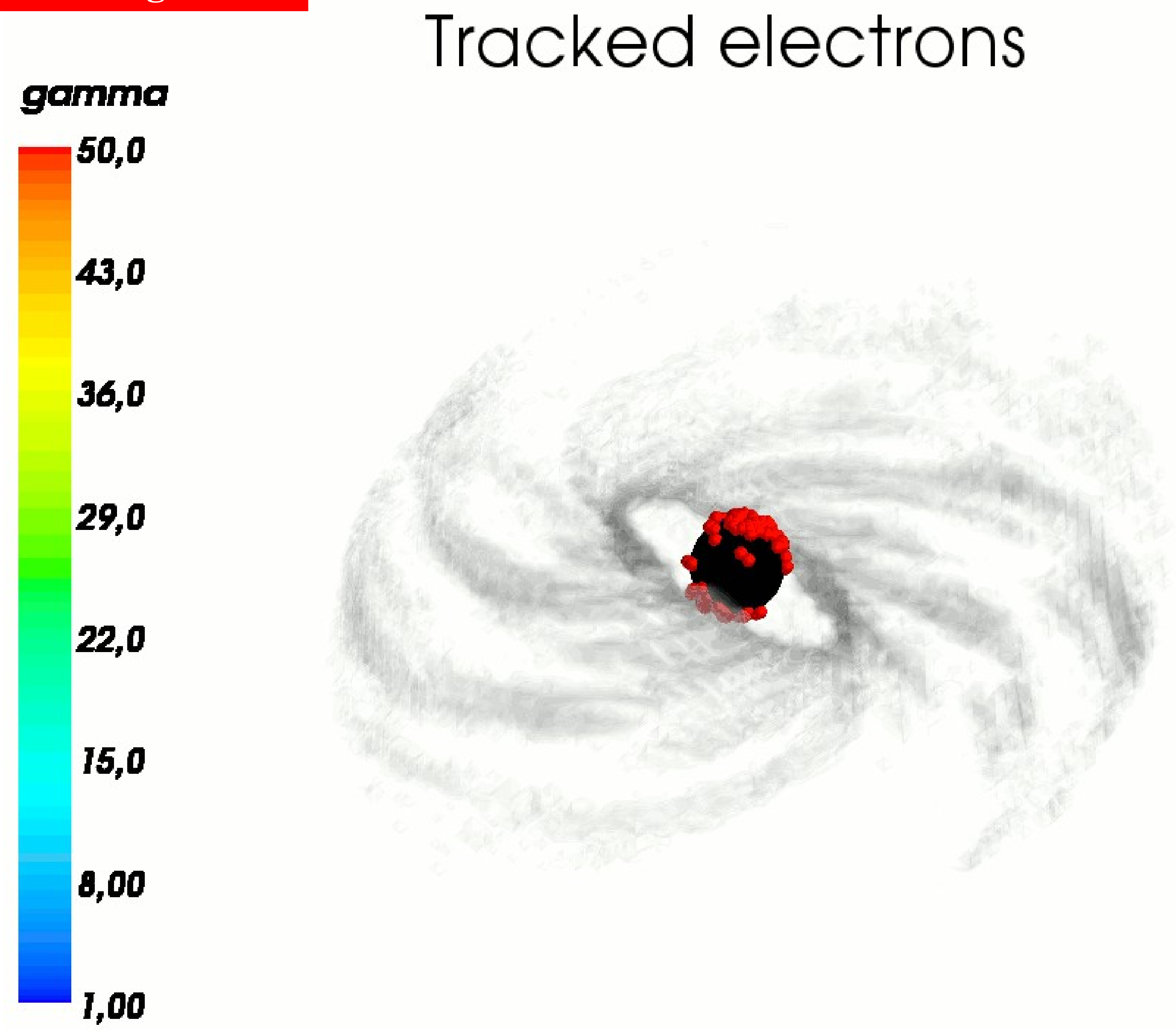
In the co-rotating frame



Cerutti et al. 2016a

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

In the co-rotating frame



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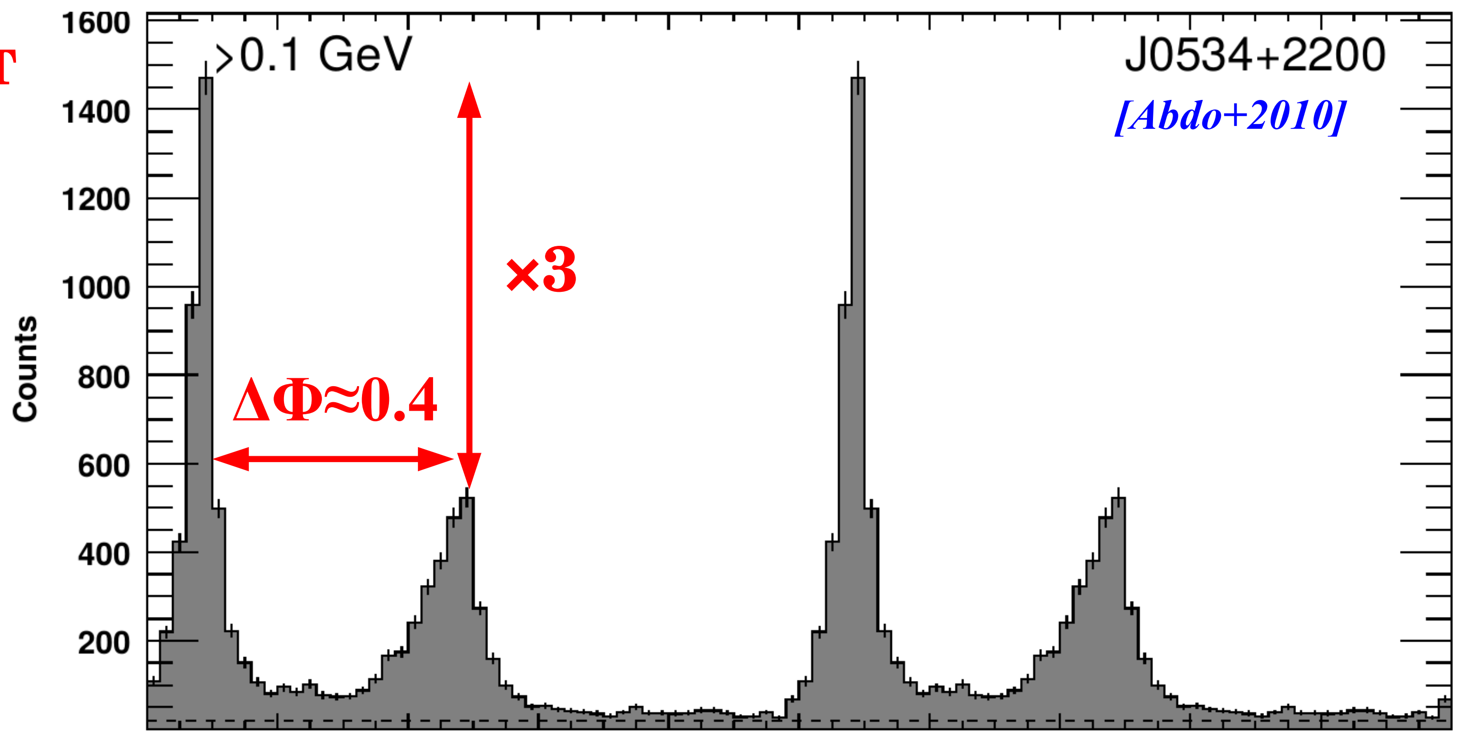
Cerutti et al. 2016a

Application to the Crab pulsar

***Fermi*-LAT**

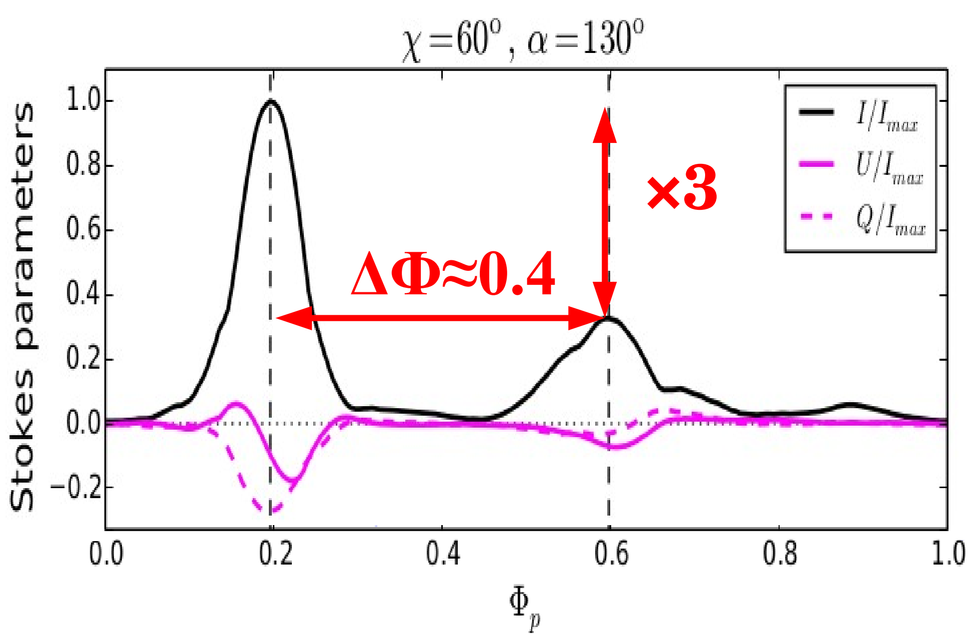


PIC model

χ=60°, α=130°

Consistent with the nebula morphology in X-rays

[e.g. Weisskopf+2012]



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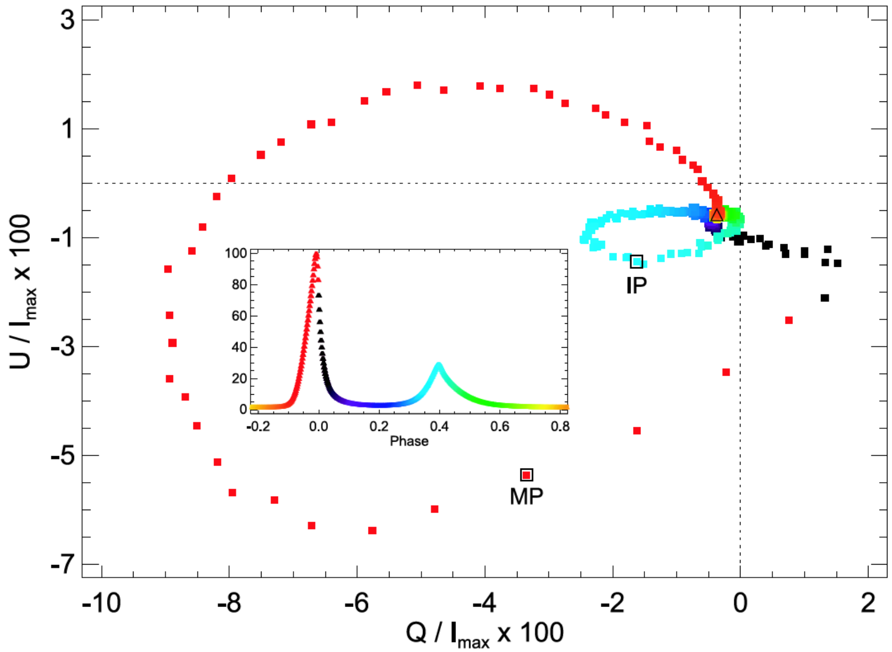
(Incoherent) Polarization signature

Optical



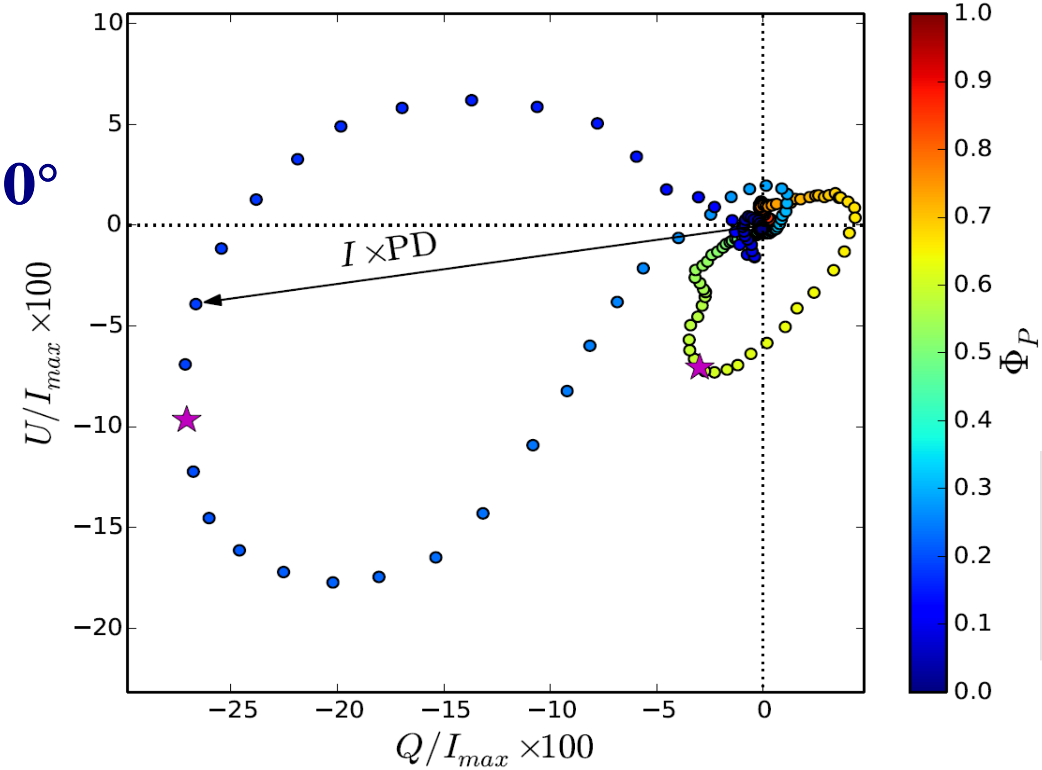
Polarization sensitive to **magnetic geometry**

Each pulse is accompanied by **rapid swing** of the polarization angle

[Słowikowska+2009]

PIC model

χ=60°, α=130°



Degree of polarization :
∏≈15-30 %

Morphology consistent with observations
Robust solution !

Swing associated with the **crossing of the sheet**
(See also Pétri & Kirk 2005)

[Cerutti+2016b]

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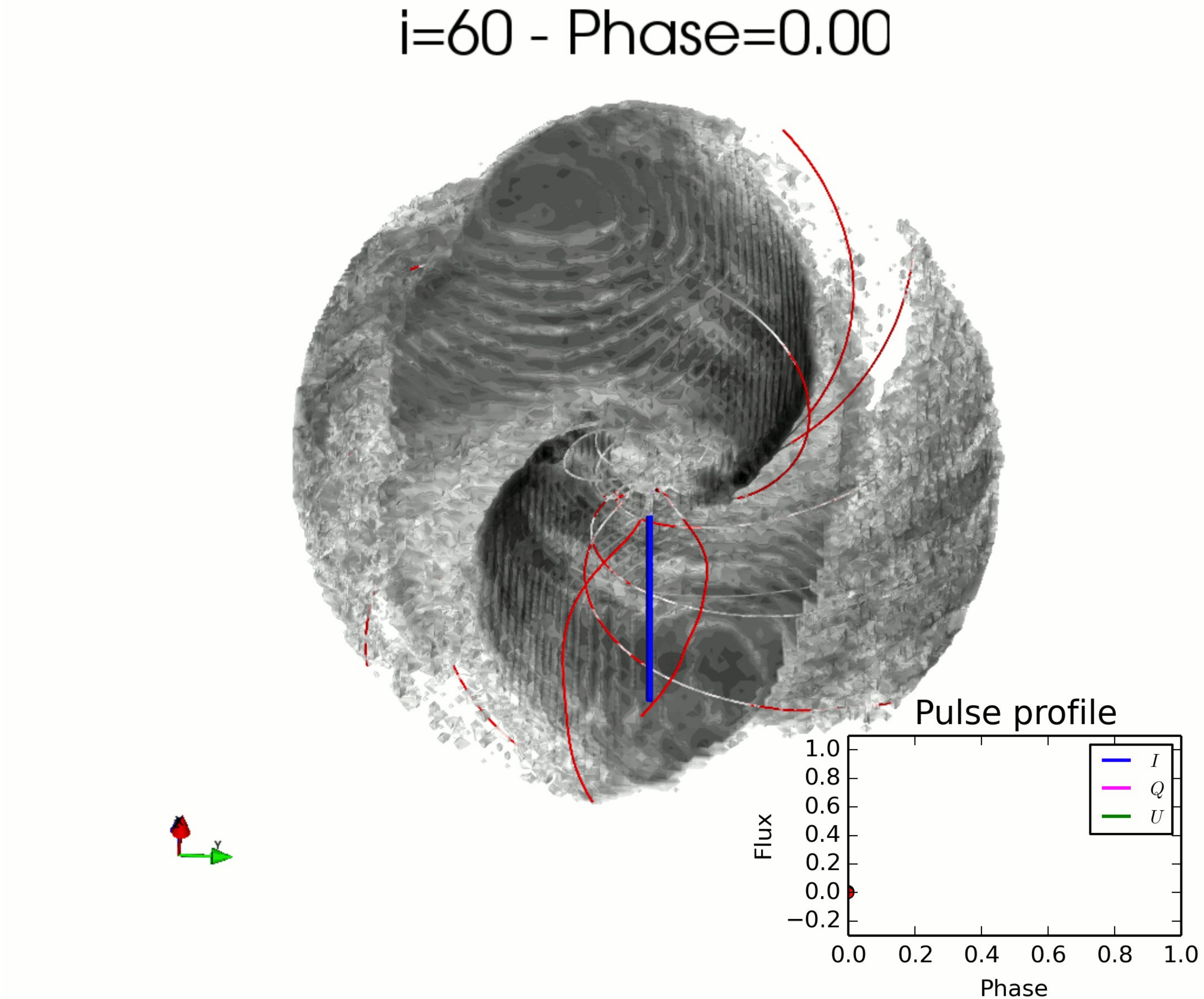
The Crab pulsar as we may see it !

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

- 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.**