The role of general relativity and reconnection in pulsar radiation

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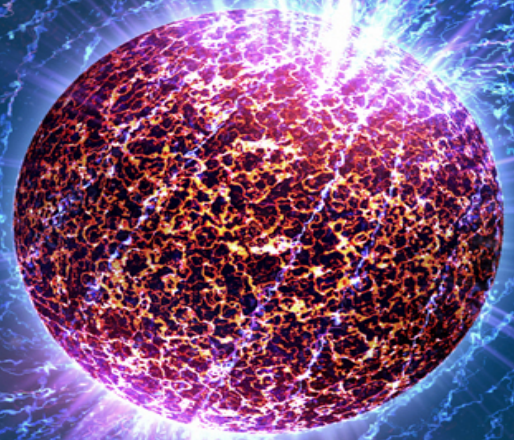
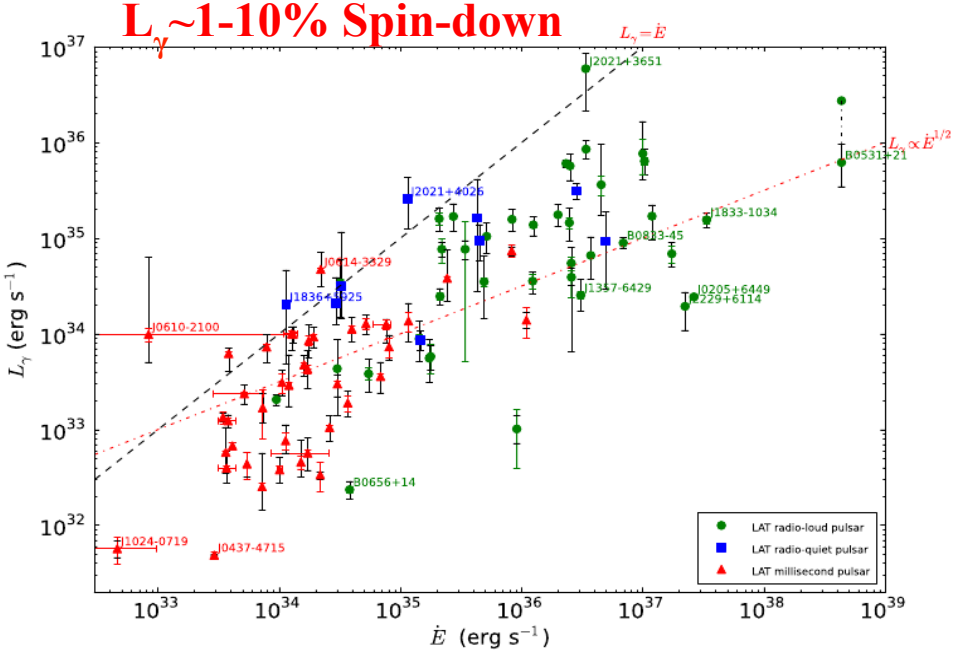


In collaboration with :
Sasha Philippov (Princeton), Anatoly Spitkovsky (Princeton), Sasha Tchekhovskoy (Berkeley)

Atelier PNHE « Accélération de particules en astrophysique des hautes énergies», IPAG, 2 - 4 décembre 2015

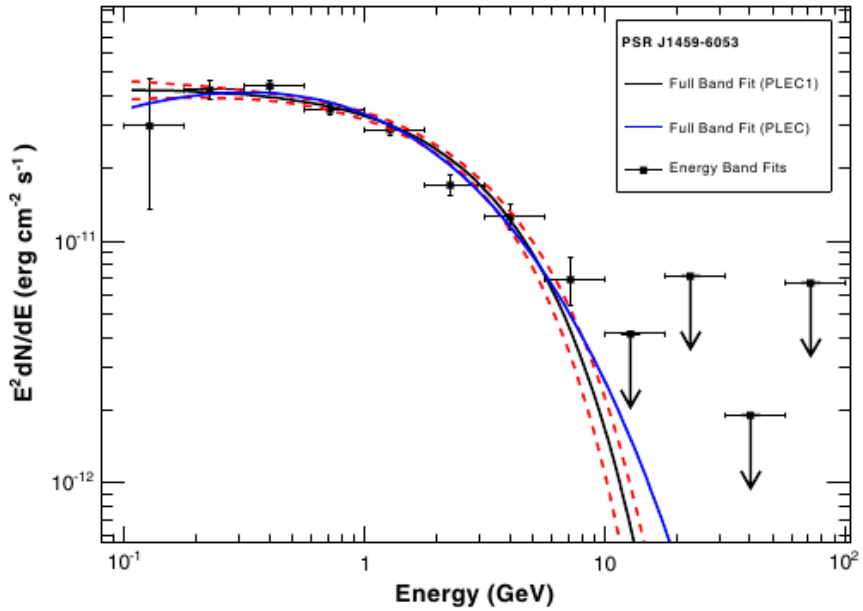
Some big questions about pulsars

L_γ~1-10% Spin-down



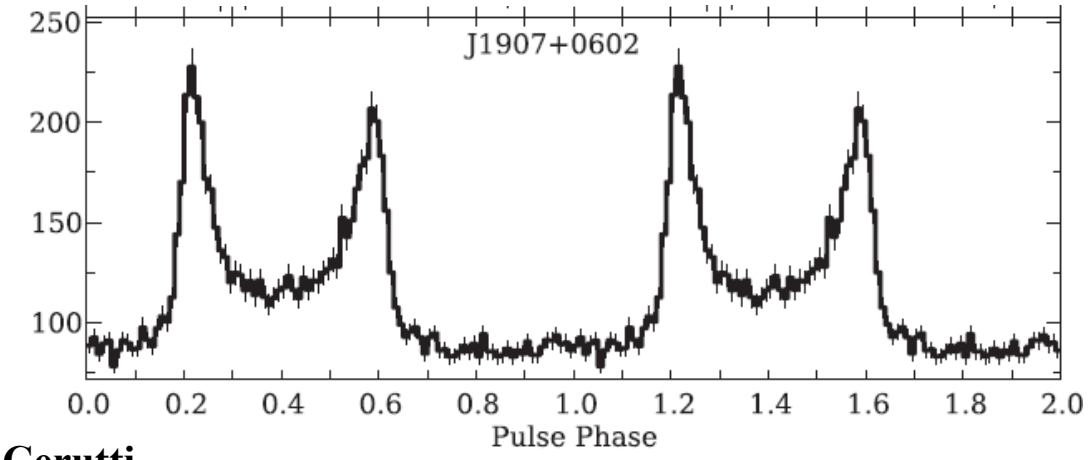
How does the star spin-down?
How is this energy channeled to gamma rays?
How is the plasma generated?

Power-law+cut off ~ few GeV

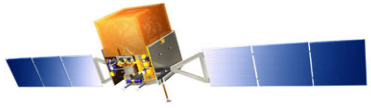


How are particle accelerated and radiate?
Origin particle/photon spectra, cut-off?

2-peak lightcurve

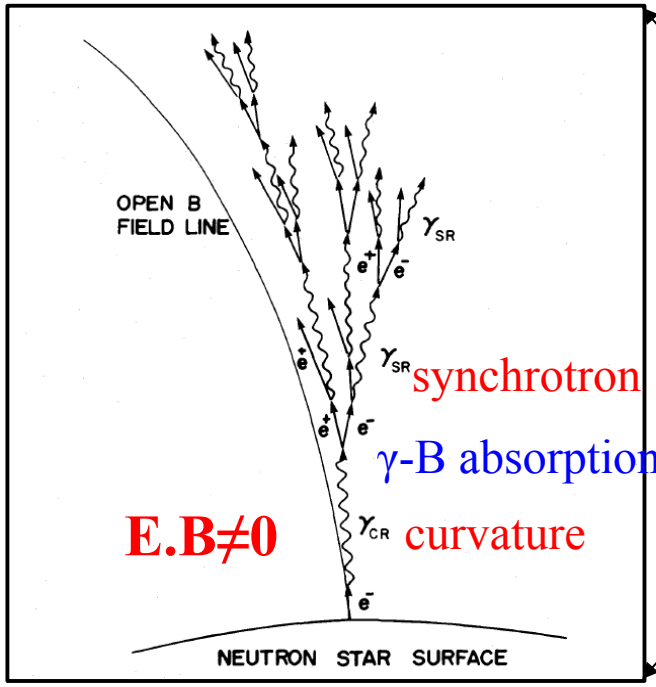


What is the origin of the pulsed emission ?
Where is the emission coming from ?



[2nd Fermi-LAT pulsar catalog]

Elements of a pulsar magnetosphere



Copious pair creation in the polar caps

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

Magnetosphere

Wind region

Ω

e^+/e^-

NS

e^+/e^-

e^+/e^-

Open field lines
Outflowing plasma and Poynting flux

Toroidal field, B_φ

Current Sheet

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

Rotation axis

Light-cylinder radius

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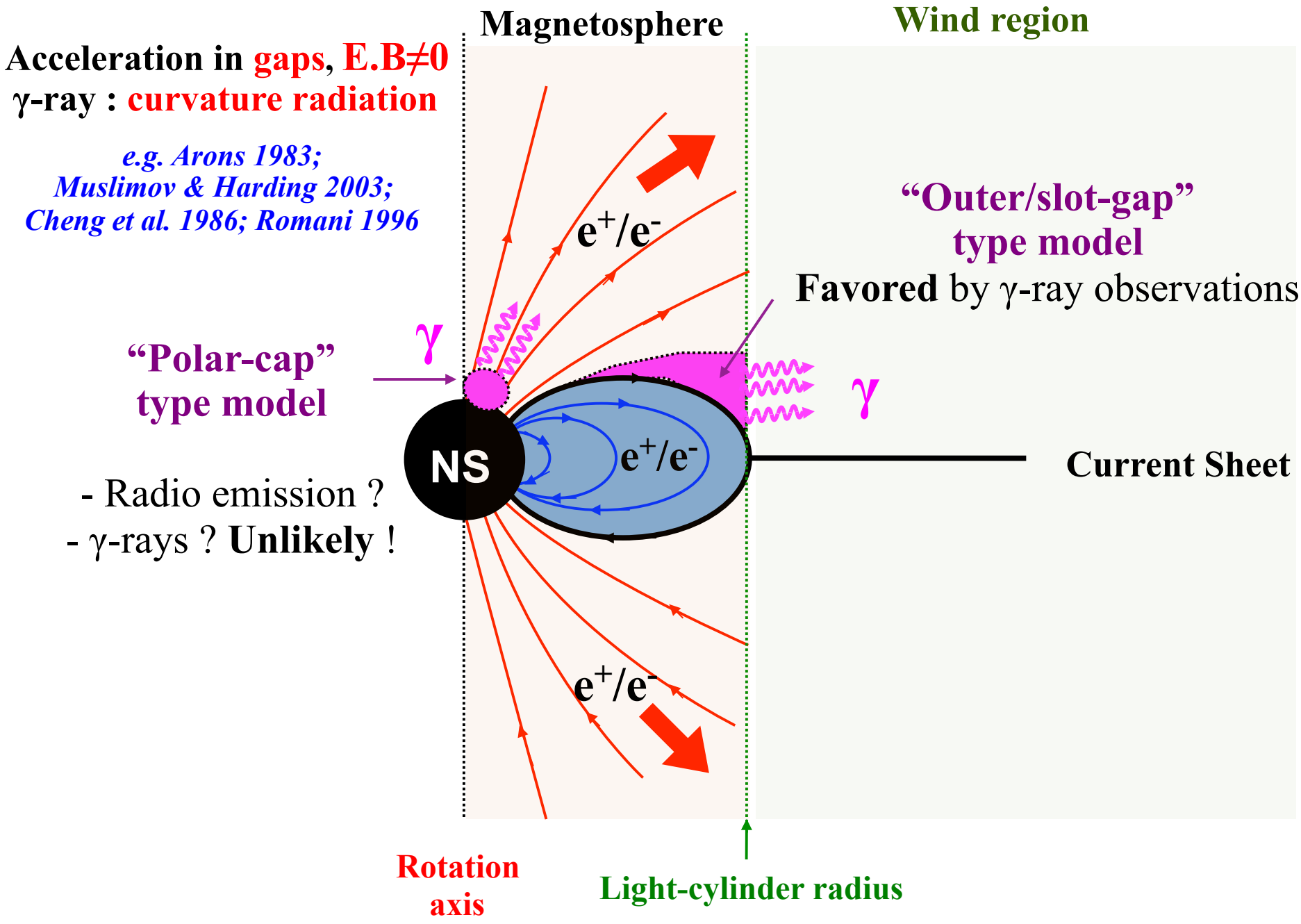
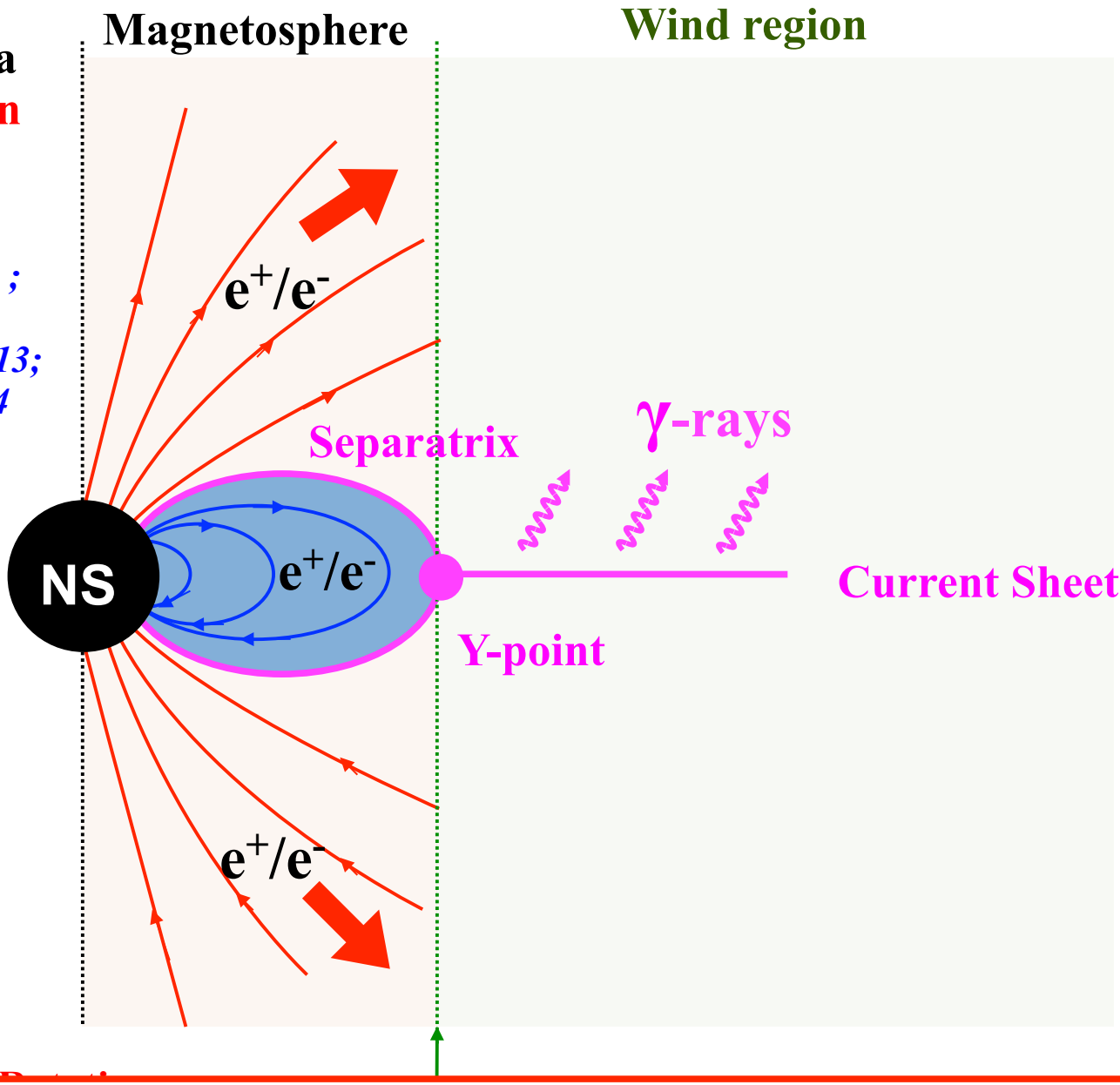
Proposed sites for particle acceleration



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



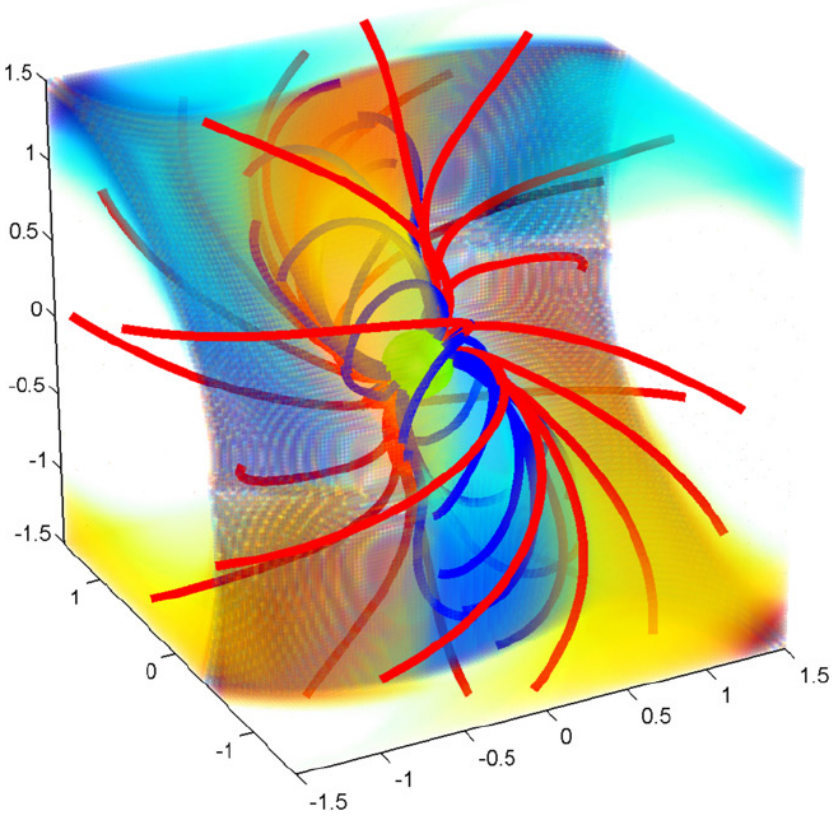
Models dependent on the geometry of the magnetosphere

Insight from the MHD approach

(Force Free / Resistive Force Free / Full MHD)

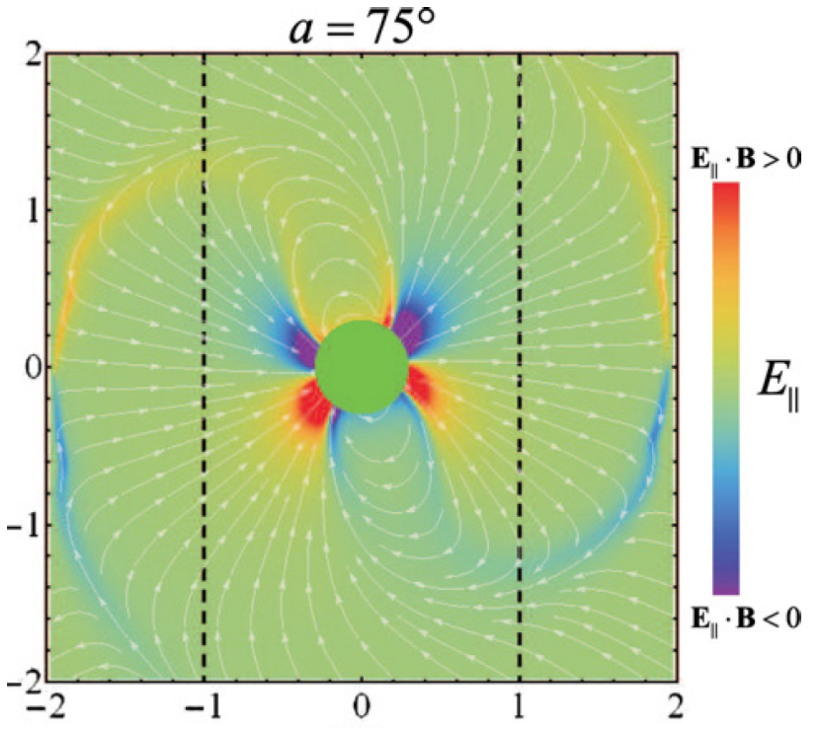
Ideal Force-Free field geometry with prescribed emitting field lines

Bai & Spitkovsky 2010a,b



Non-ideal Force-Free with prescribed resistivity

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



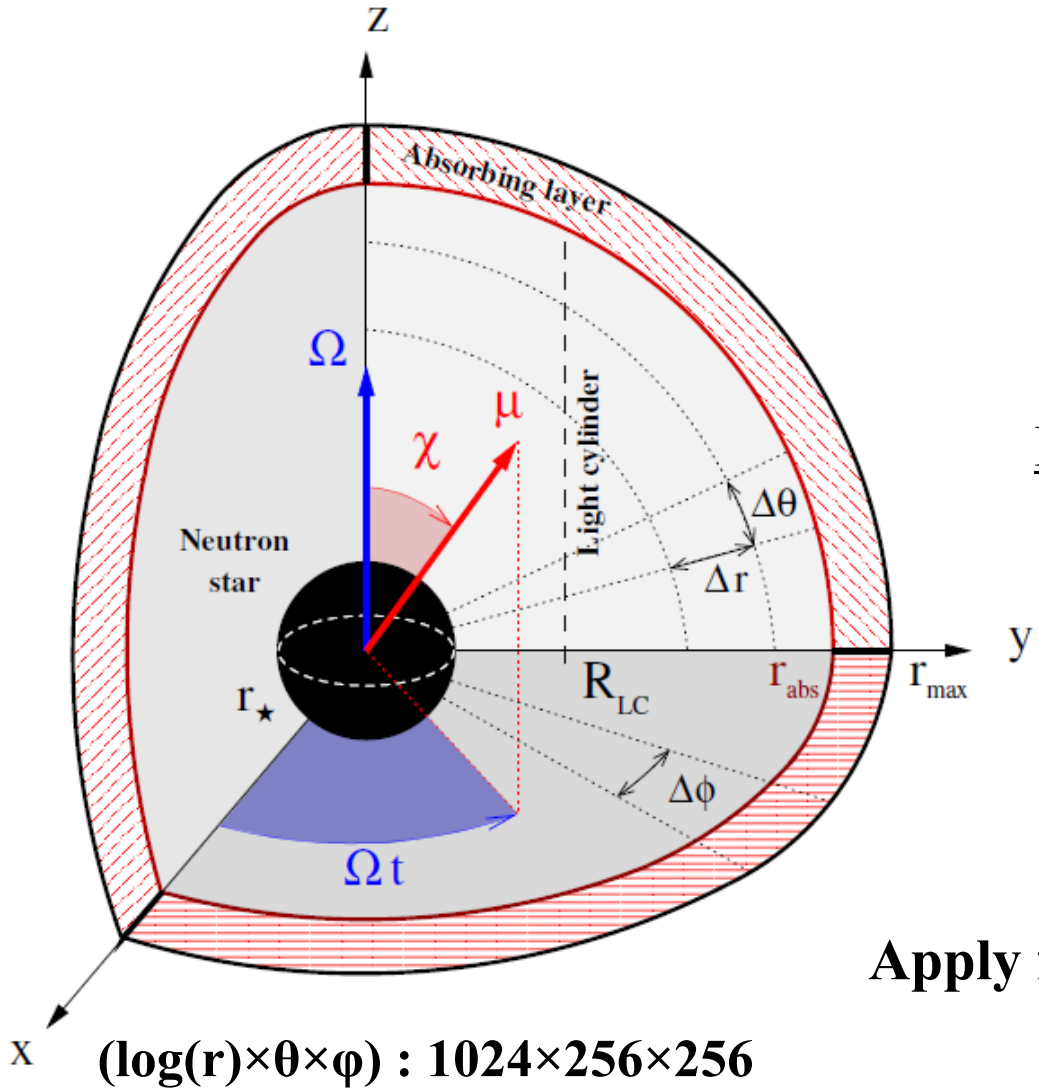
Favor high-energy emission from the outer magnetosphere + current sheet

Ad-hoc accelerating/radiating zones, large uncertainties ➡ Need for self-consistent approach

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



(log(r)×θ×φ) : 1024×256×256

Radiation reaction force

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

Emitted radiation spectra :

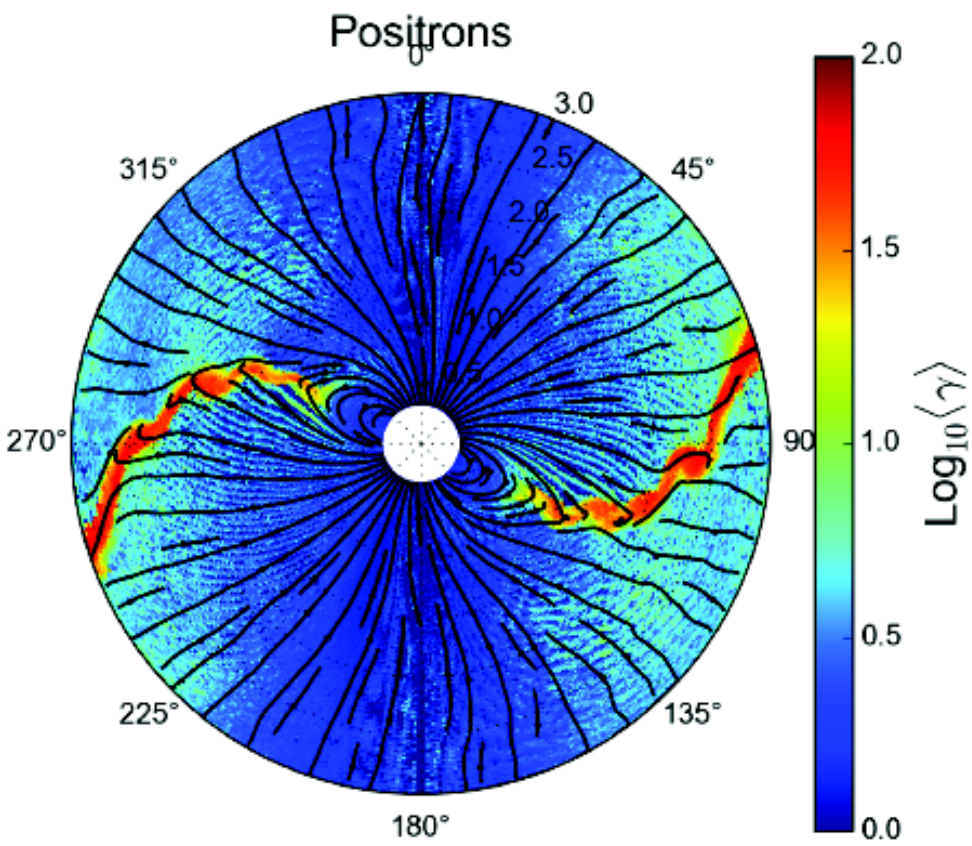
$$F_\nu(\nu) = \frac{\sqrt{3} e^3 \tilde{B}_\perp}{m_e c^2} \left(\frac{\nu}{\nu_c}\right) \int_{\nu/\nu_c}^{+\infty} K_{5/3}(x)\,dx,$$

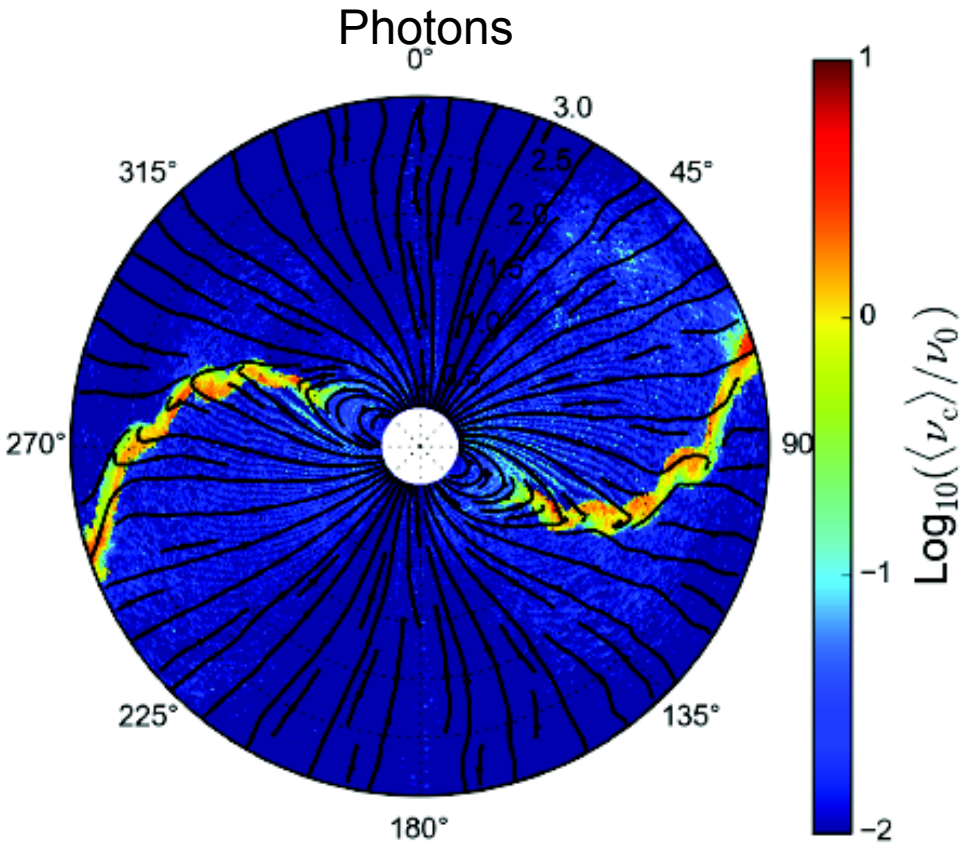
$$\tilde{B}_\perp = \sqrt{(\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B})^2 - (\boldsymbol{\beta} \cdot \mathbf{E})^2},$$

Apply for synchrotron and curvature radiation

Particle / radiation mean energy (χ=30°)

Cerutti et al. 2015b



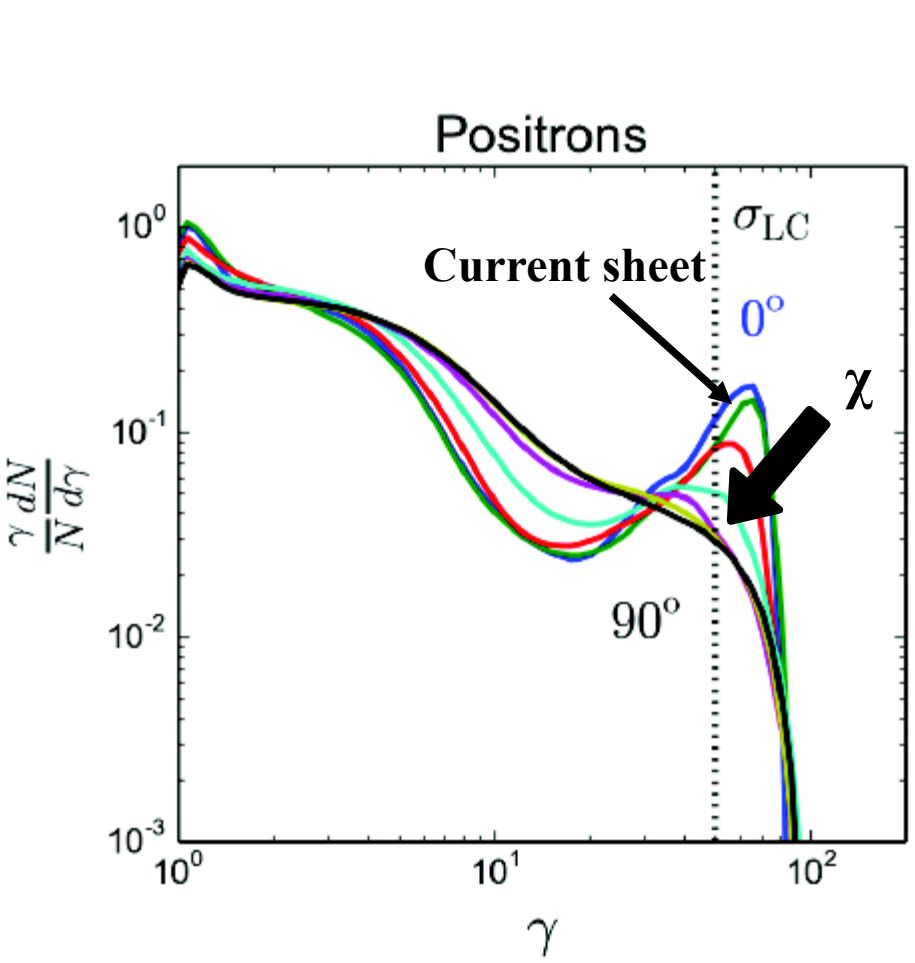


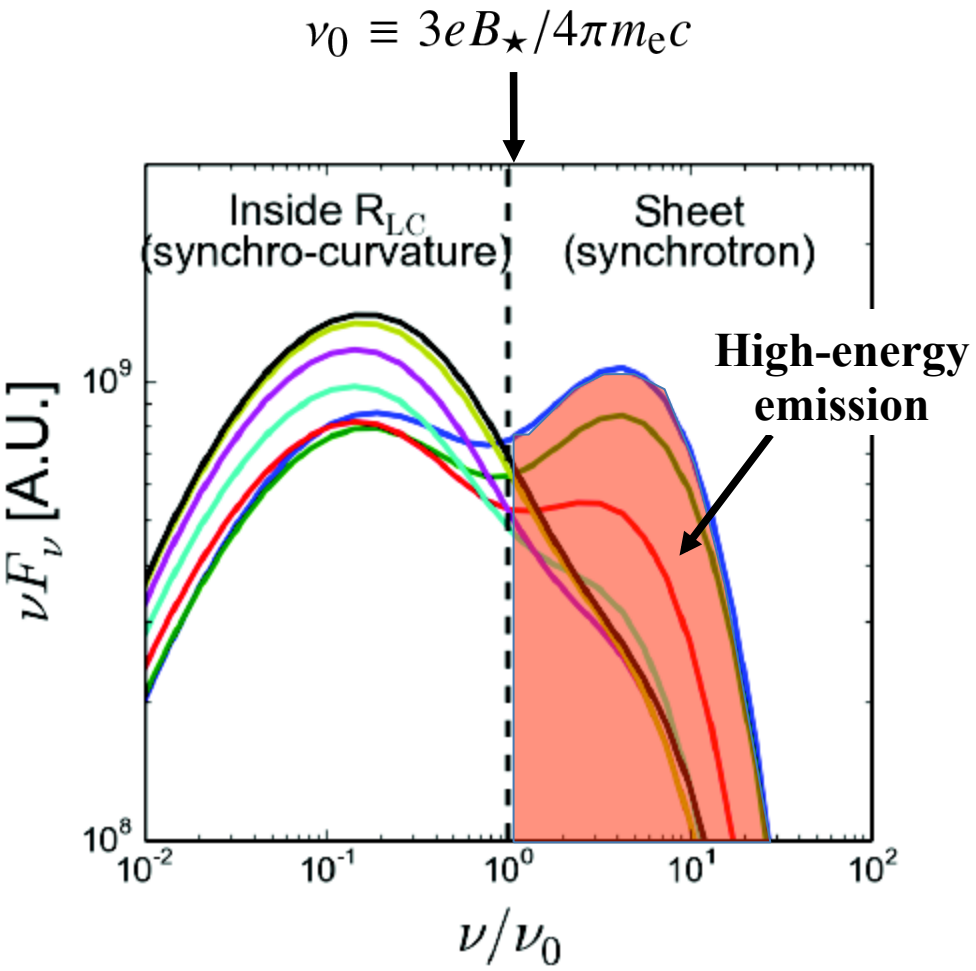
Particle acceleration via relativistic reconnection in the current sheet
High-energy radiation is synchrotron radiation

Particle energy in the sheet given by : **(here)**

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

Particle / radiation spectra





Particle acceleration and emission of energetic radiation decreases with pulsar inclination

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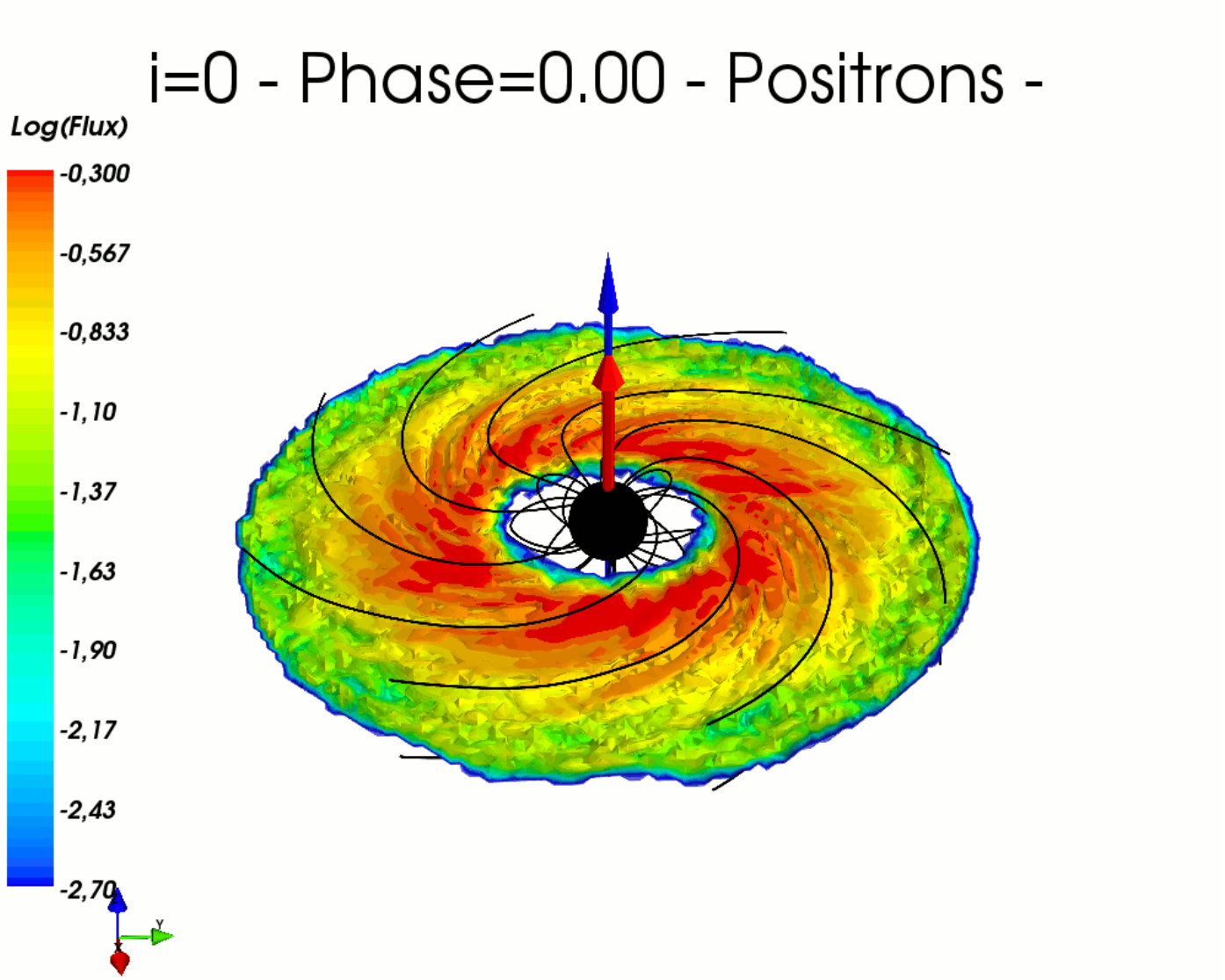
Cerutti et al. 2015b

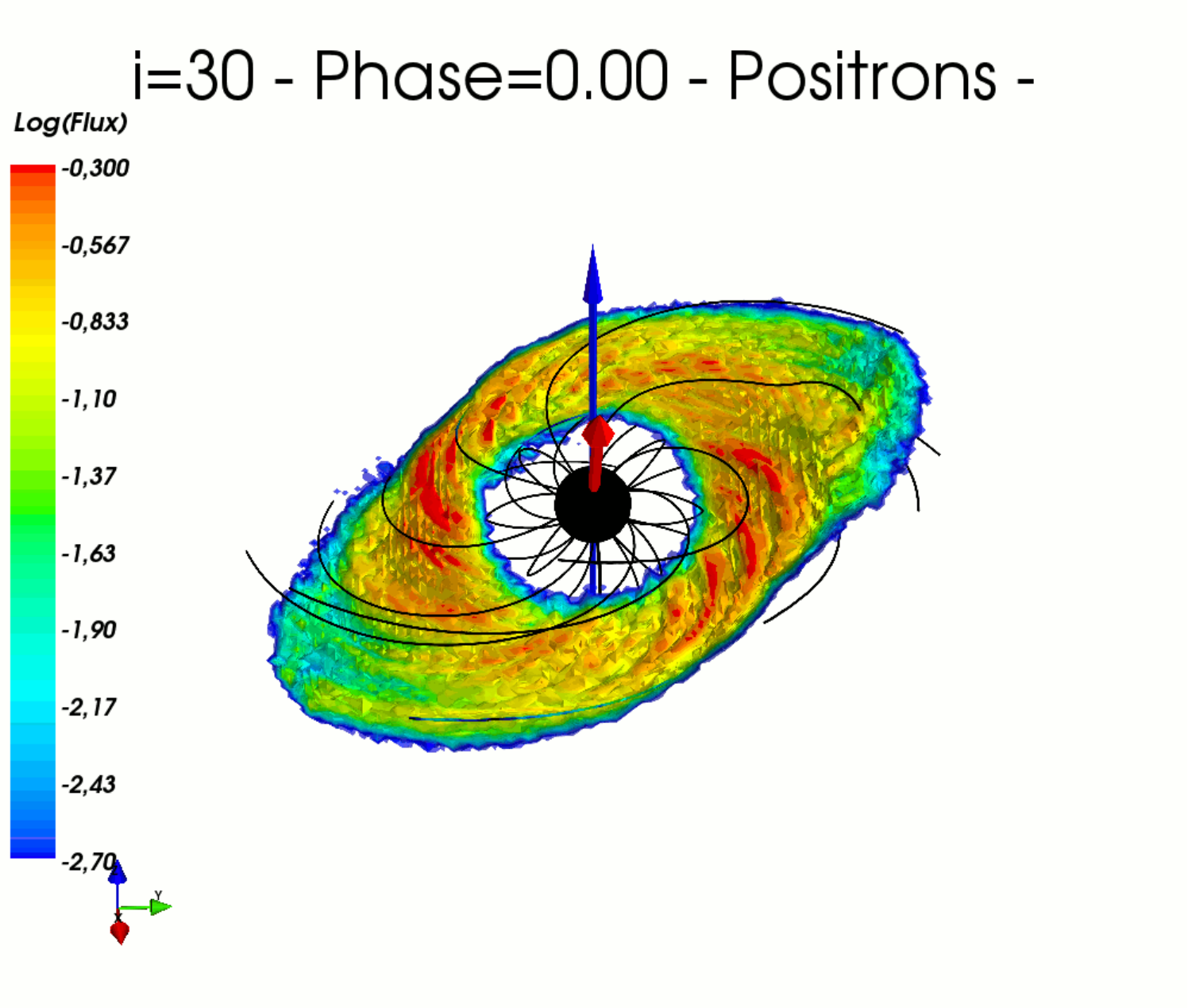
High-energy radiation flux ($v>v_0$, $\chi=0°$)



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. 2015b

High-energy radiation flux ($v>v_0$, $\chi=30°$)



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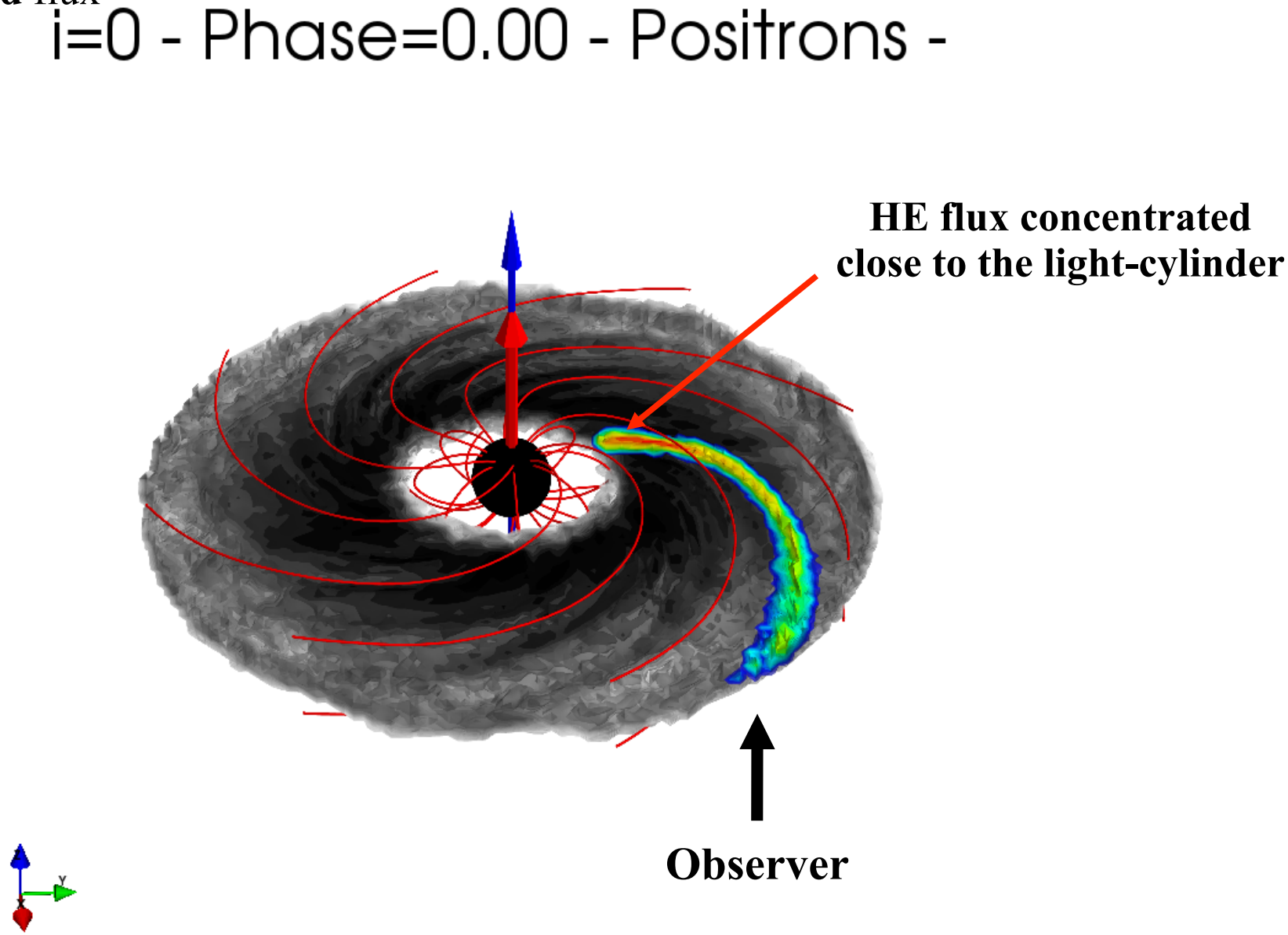
Cerutti et al. 2015b

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

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

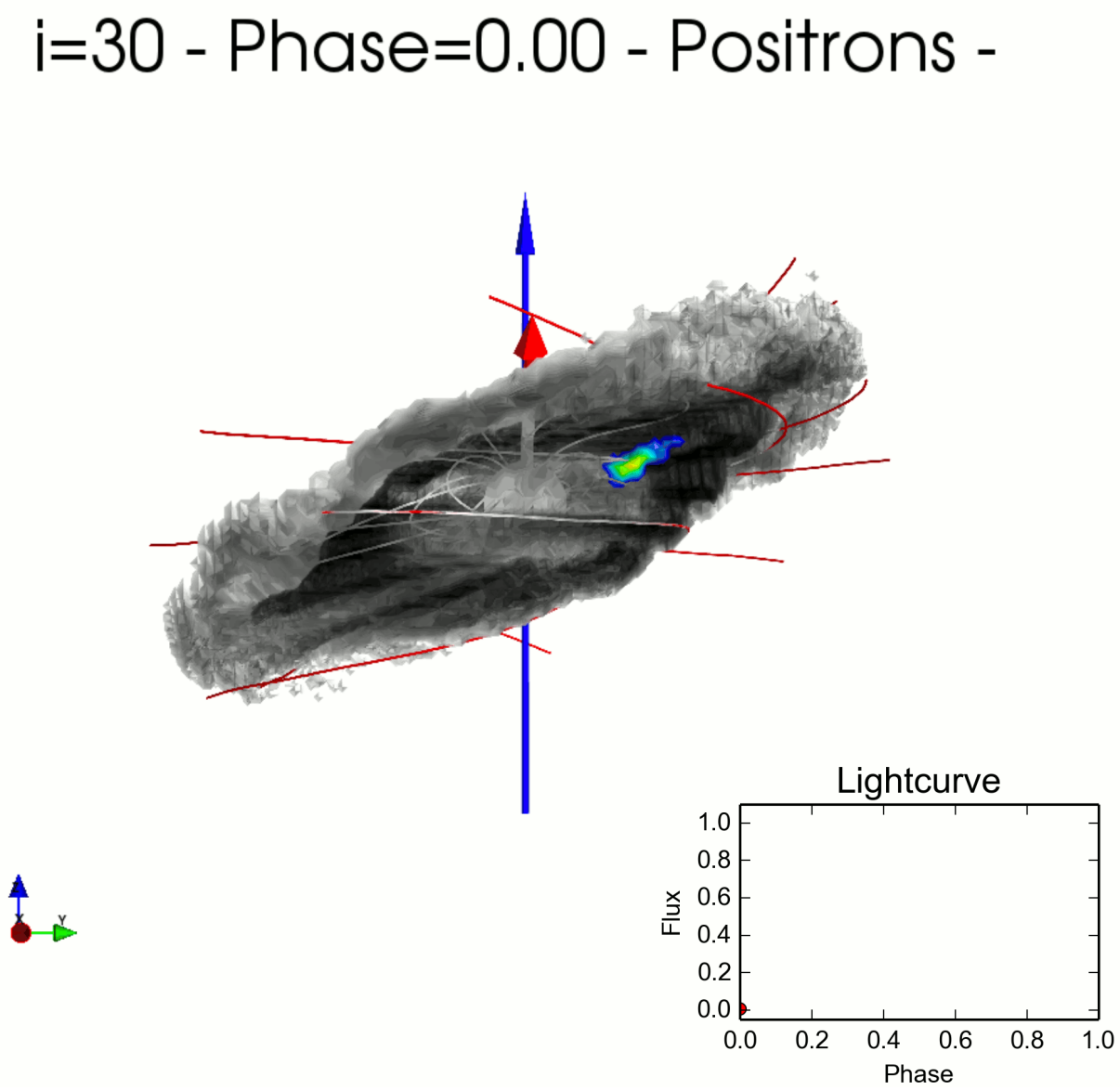


Spatial extension of the observed emission in the sheet
=> Formation of a caustic

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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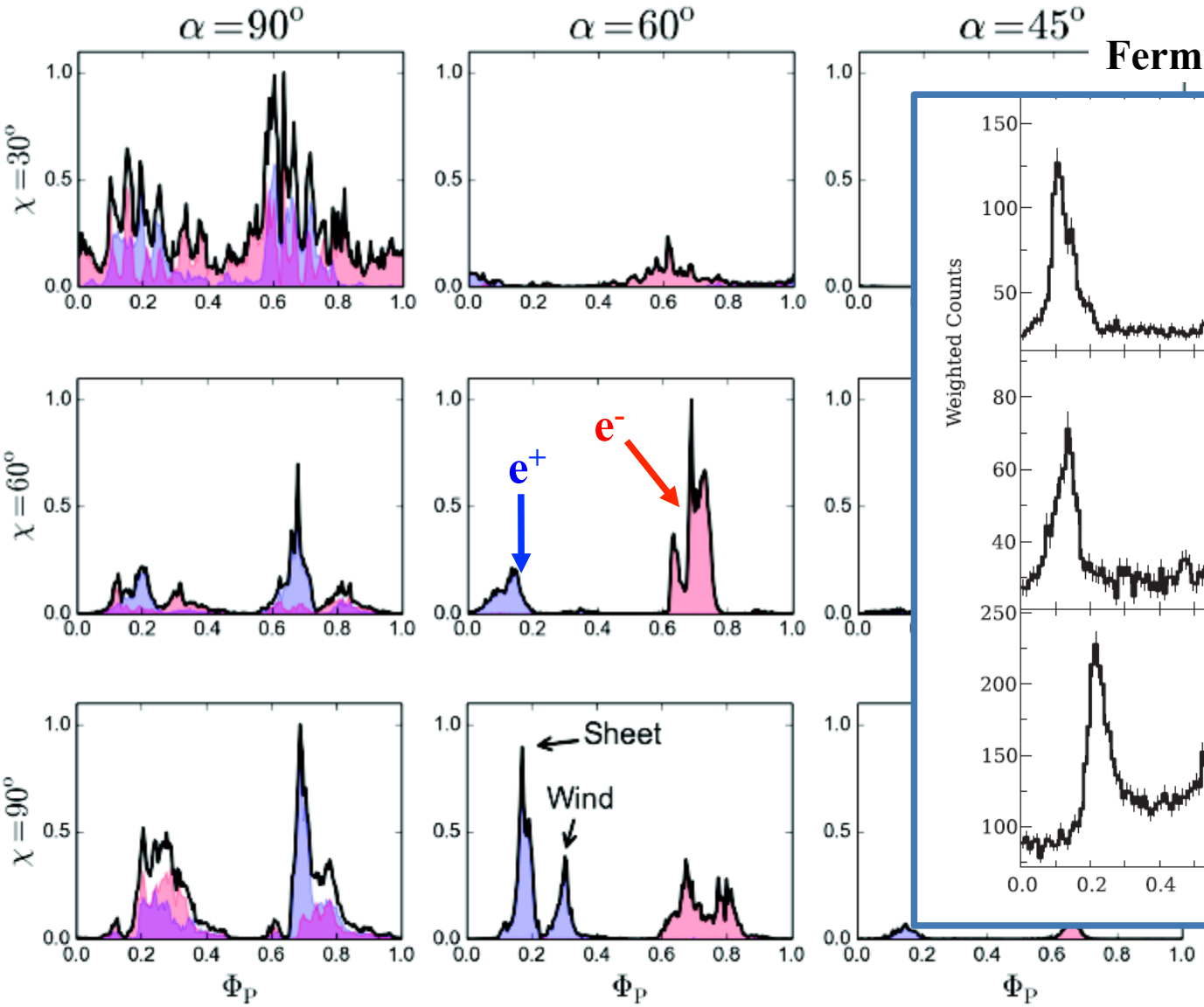
Two-peaked lightcurves are very generic

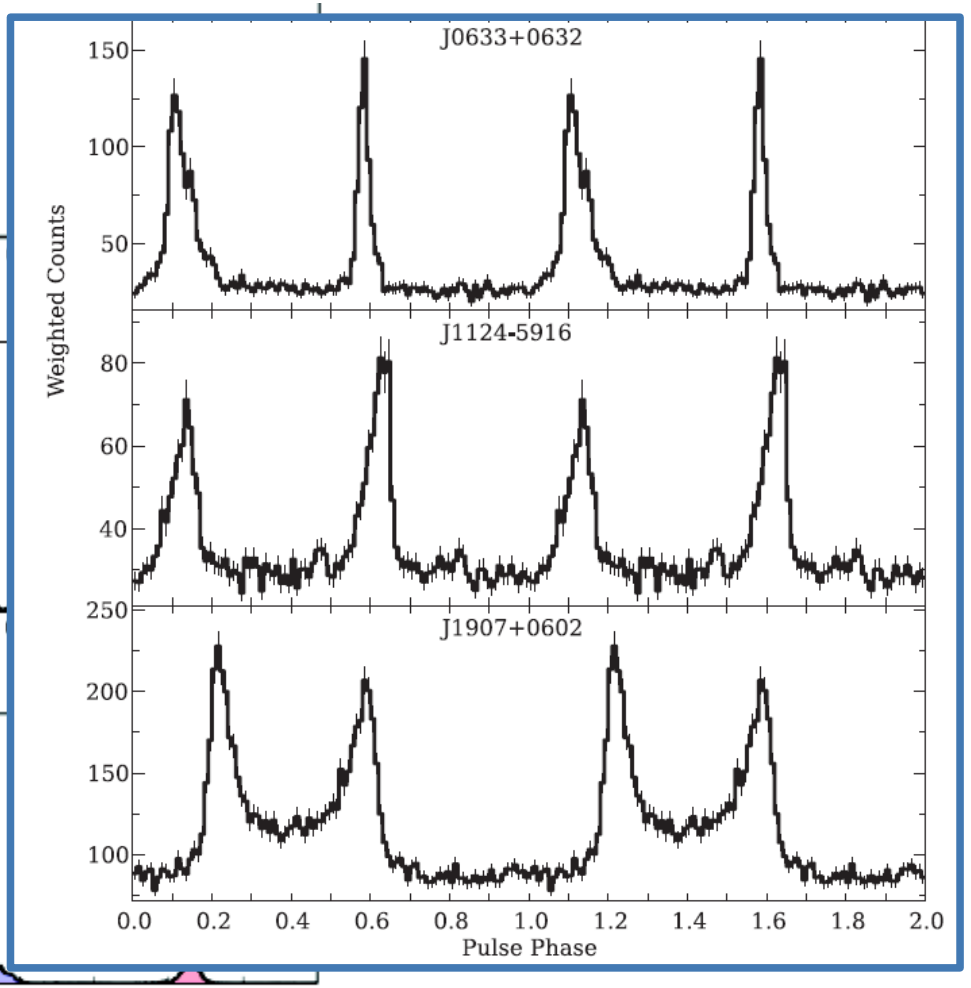
One peak per crossing of the current sheet

Blue : Positronic emission
Red : Electronic emission

Viewing angle



Fermi-LAT second pulsar catalog



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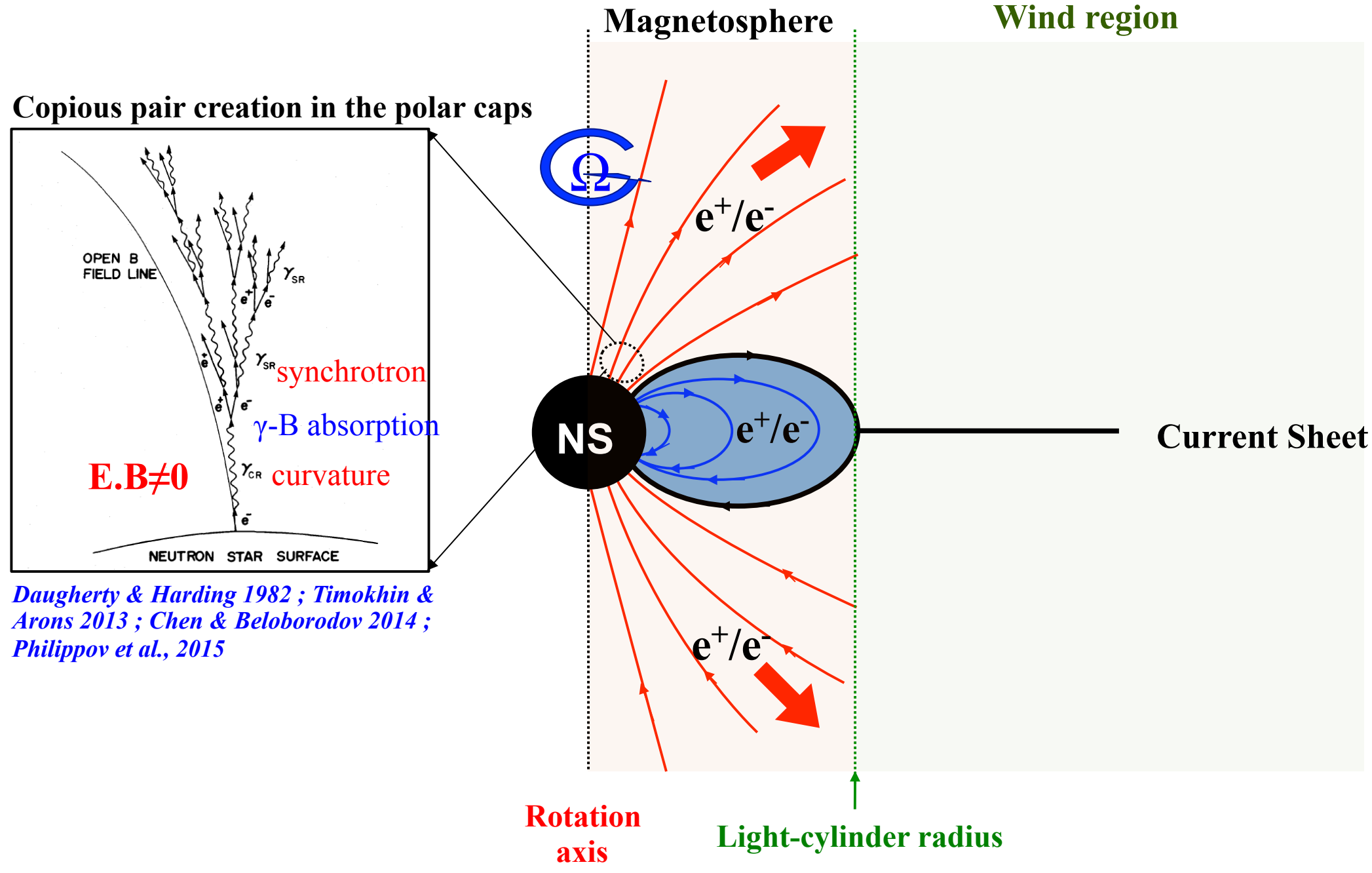
Cerutti et al. 2015b

Is pair creation vigorous in the magnetosphere ?



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

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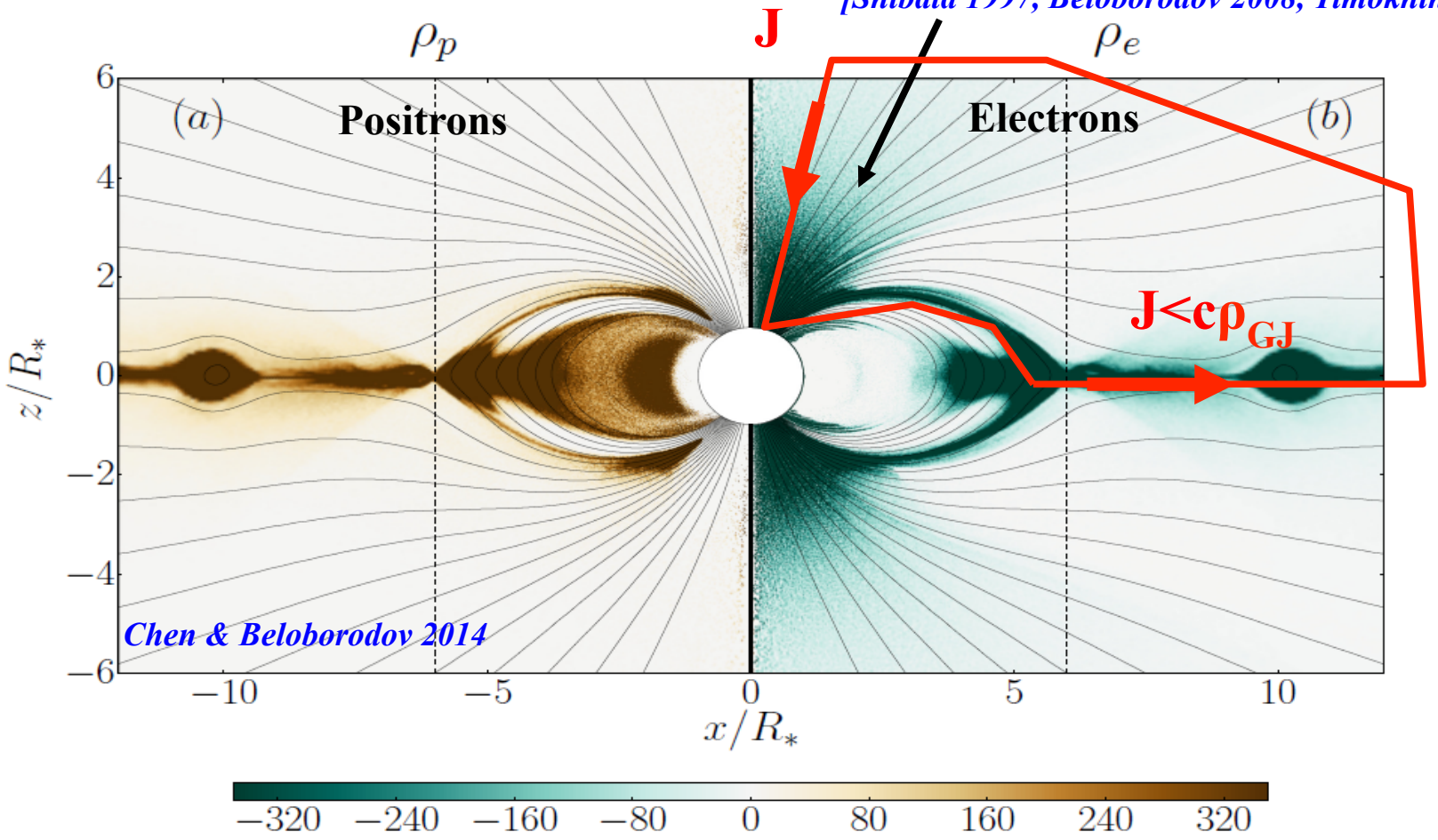
Global PIC simulations with discharge

Ref : Chen & Beloborodov 2014 ; Philippov et al., 2015

The stellar rotation impose a twist on the field lines, hence a current outside the light-cylinder. This current must be matched at the polar cap.

Electrons alone carry enough current
=> No dicharge needed, no acceleration !
[Shibata 1997, Beloborodov 2008, Timokhin & Arons 2013]



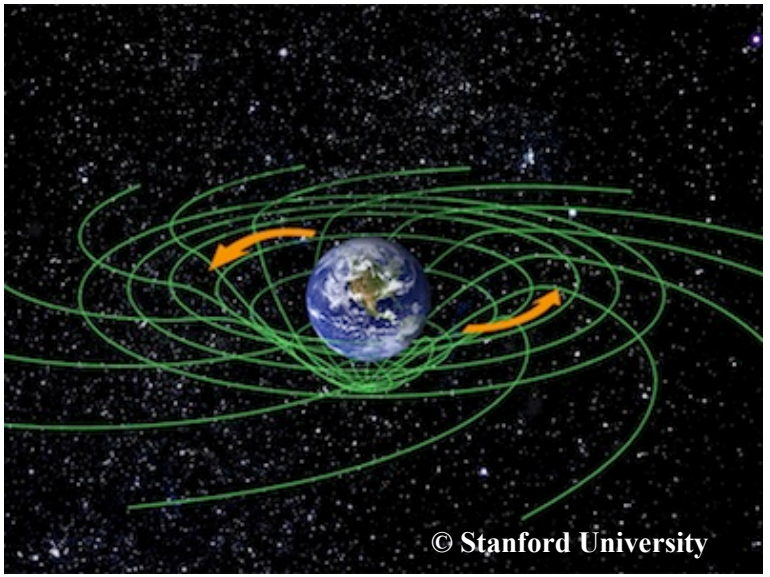
=> Low-multiplicity plasma (κ~1) are in contradictions with observations where κ>>1

General relativistic effects may be a way out !

Ref : Beskin 1990 ; Muslimov &Tsygan 1992 ; Sakai & Shibata 2003

Lense-Thirring frequency :

$$\omega_{LT} = \frac{2}{5}\Omega_* \frac{r_s}{R_*}\left(\frac{R_*}{r}\right)^3$$



Frame-dragging effect reduces the stellar rotation

$$\frac{J_{\hat{r}}}{\rho_{GJ}c} \approx \left(\frac{J_{\hat{r}}}{\rho_{GJ}c}\right)_{\text{flat}} \frac{1}{1-\omega_{LT}/\Omega_*}.$$

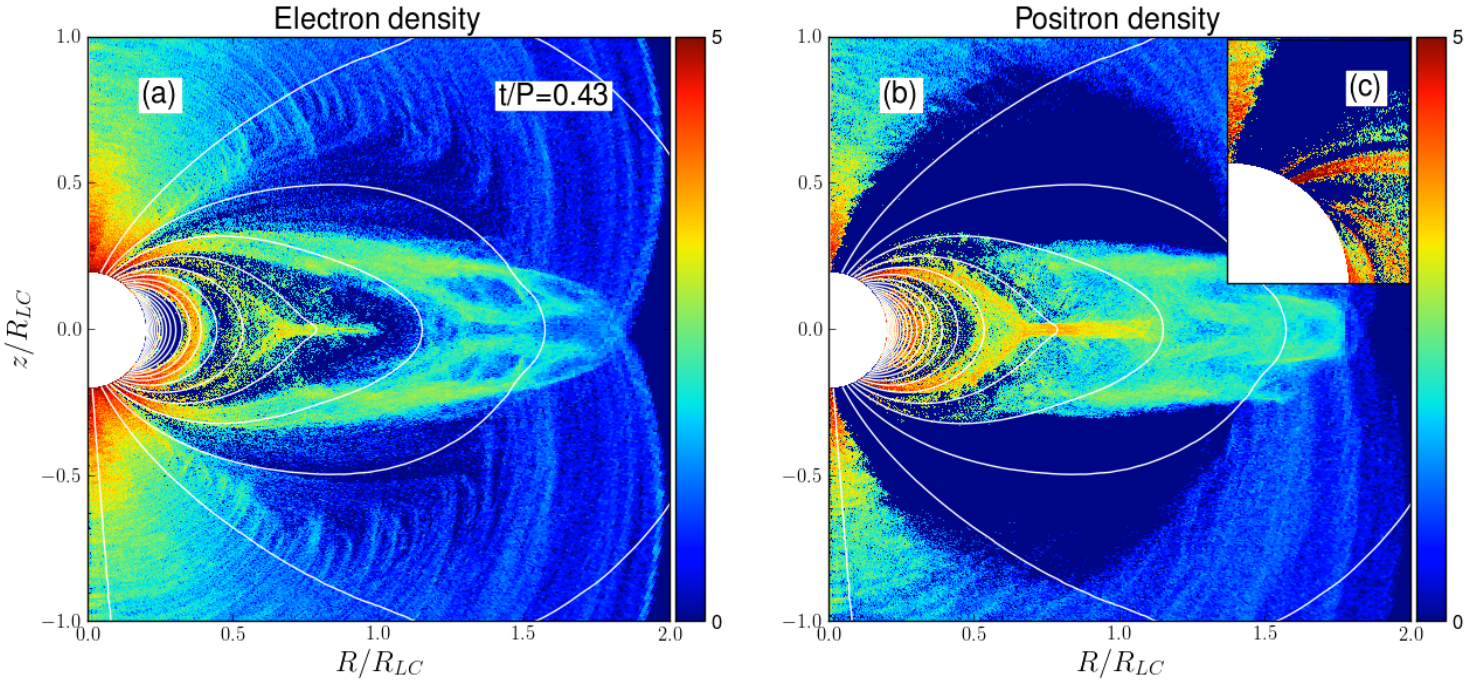
Significant only at the star surface, no changes at the light-cylinder !

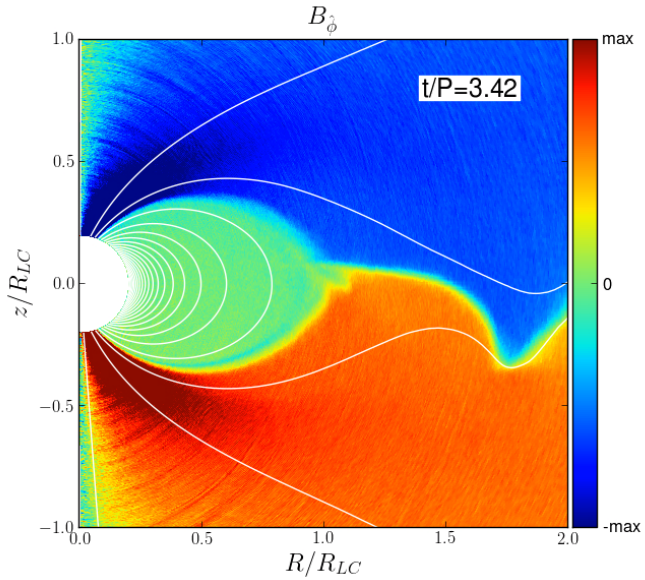
=> Less particles are extracted from the polar cap
=> But the same current is needed

Need a discharge
=> Particle acceleration !

2D GR PIC simulations

Developpment of **EZeltron** *[Philippov et al. 2015b]* **: Zeltron** 3+1 GR electrodynamics





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

Movies by Sasha Philippov

Conclusions

- New **global PIC simulations is the way to go** to solve particle acceleration in pulsars (and more !)
- Simulations demonstrate the major role of **relativistic reconnection** in particle acceleration
- High-energy emission could be **synchrotron radiation from the current sheet**
- More work needed to **compare simulations to observations**
- **Frame-dragging** effect helps pulsars produce plasma, and shine radio waves !