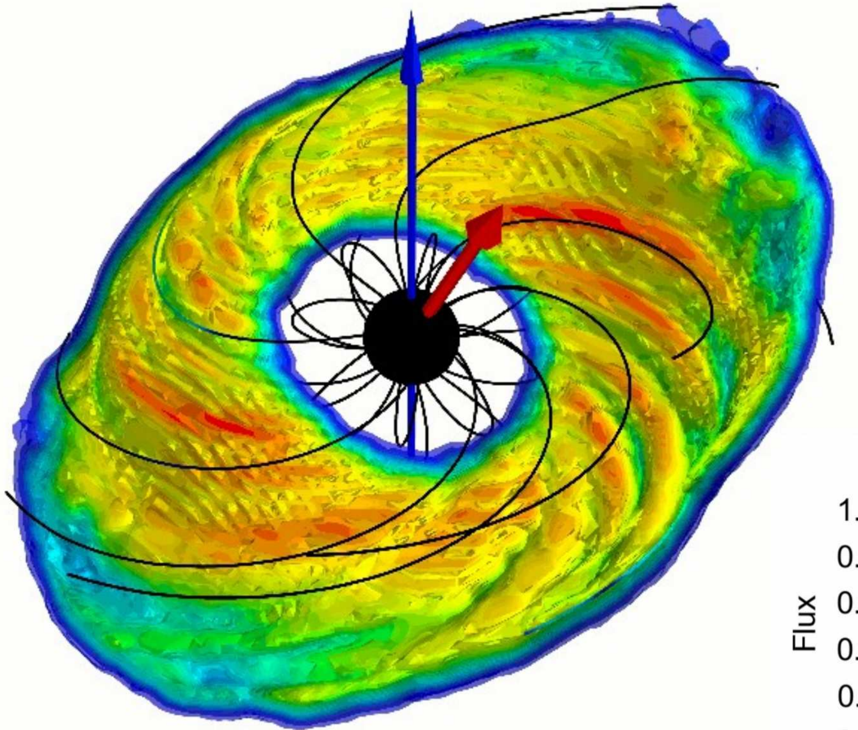
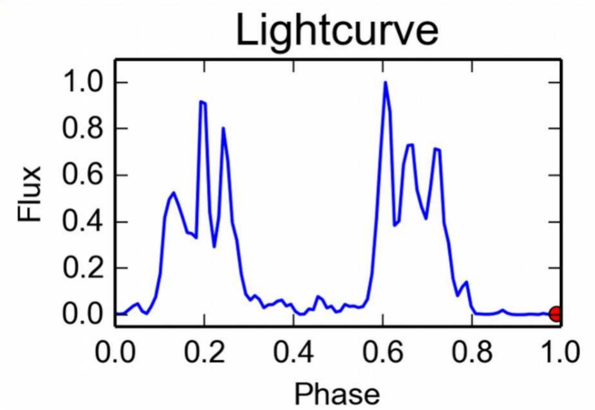
A global PIC view at pulsar magnetospheres





Benoît Cerutti

CNRS & Université Grenoble Alpes (France)

Collaborators: S. Philippov (*CCA*), A. Spitkovsky (*Princeton*), K. Parfrey (*Princeton*), B. Crinquand (Grenoble), C. Guépin (JSI fellow), J. Mortier (*Grenoble*), A. de Valon (*Grenoble*), G. Dubus (*Grenoble*)

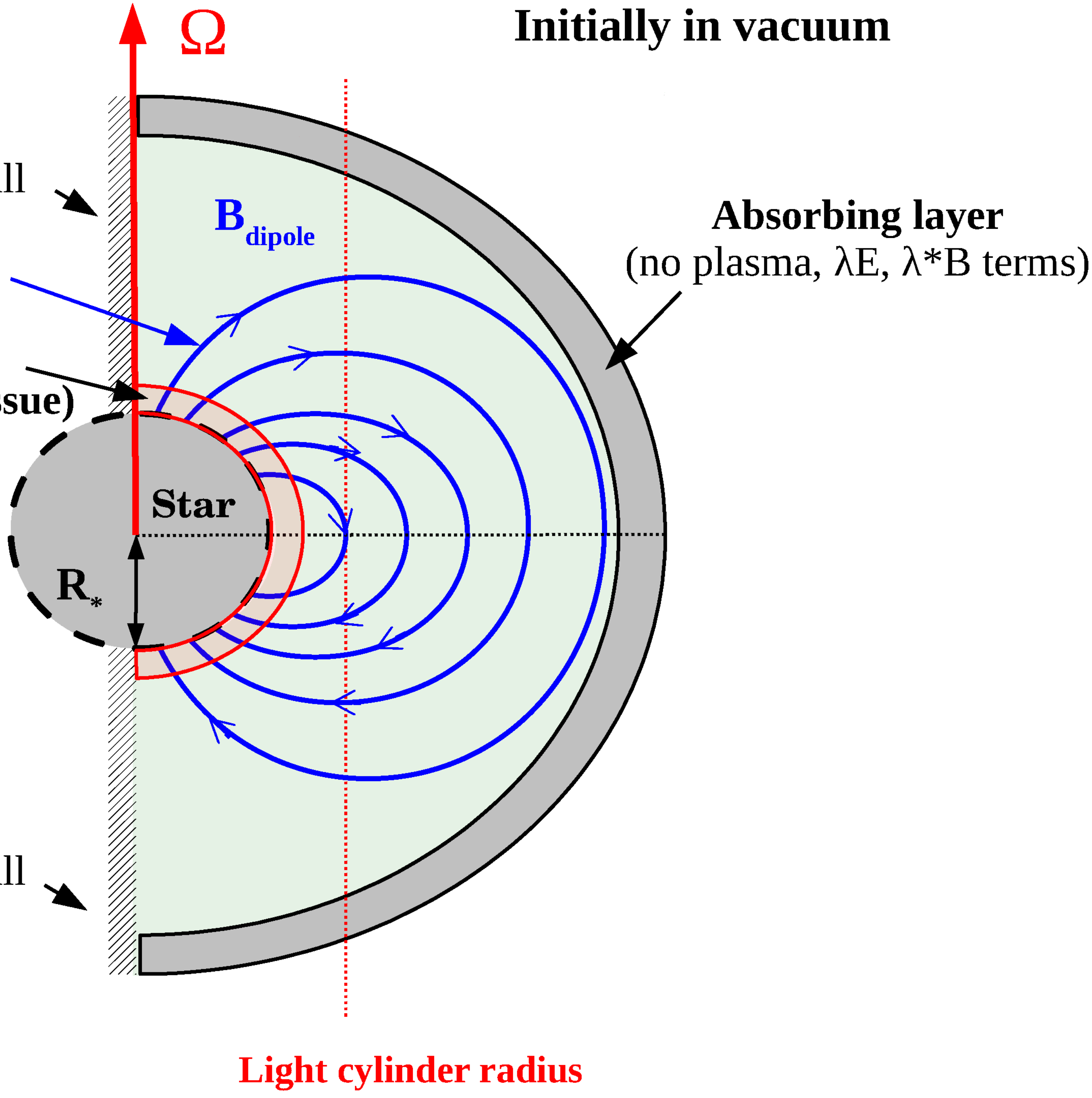
ISSI pulsar magnetosphere working group meeting, Bern, Dec. 9-13, 2019

PIC simulations of pulsar magnetosphere: An overview

References	Aligned/ Oblique	Particle injection	Extra physics
Philippov & Spitkovsky (2014)	**Aligned**	Volume injection	
Chen & Beloborodov (2014)	**Aligned**	Pair creation	
Cerutti et al. (2015)	**Aligned**	Stellar surface	
Belyaev (2015)	**Aligned**	Injection E.B≠0	
Philippov et al. (2015a)	**Oblique**	Pair creation	
Philippov et al. (2015b)	**Aligned**	Pair creation	**GR corrections**
Cerutti et al. (2016a,b)	**Oblique**	Stellar surface	**Radiation & Polarization**
Cerutti & Philippov (2017)	**Oblique (2D)**	Stellar surface	
Philippov & Spitkovsky (2018)	**Oblique**	Pair creation	**GR & radiation & ions**
Kalapotharakos et al. (2018)	**Oblique**	Volume/surface injection	**Radiation (curvature)**
Brambilla et al. (2018)	**Oblique**	Volume/surface injection	
Crinquand et al. (2019)	**Aligned**	Pair creation	**Merging binary pulsar**
Guépin et al. (2019)	**Aligned**	Pair creation	**ions**
Chen et al. (2019)	**Aligned**	Pair creation (surface only)	

The numerical setup: an aligned rotator (2D)

Philippov & Spitkovsky 2014
Chen & Beloborodov 2014
Cerutti et al. 2015
Belyaev 2015



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A digression about modeling curvature radiation

Radiation reaction force (Landau-Lifschitz):

$$\mathbf{g} = \frac{2}{3} r_e^2 \left[(\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B}) \times \mathbf{B} + (\boldsymbol{\beta} \cdot \mathbf{E})\mathbf{E} \right]$$

"Non-relativistic" term, Must be included even if $\gamma >> 1$

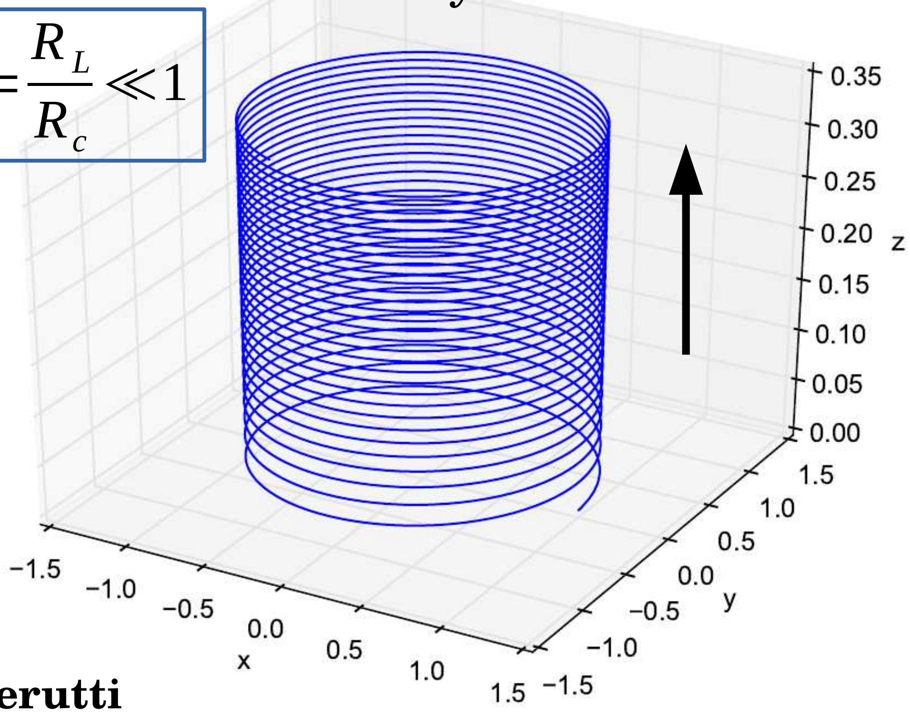
$$- \frac{2}{3} r_e^2 \gamma^2 \left[(\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B})^2 - (\boldsymbol{\beta} \cdot \mathbf{E})^2 \right] \boldsymbol{\beta},$$

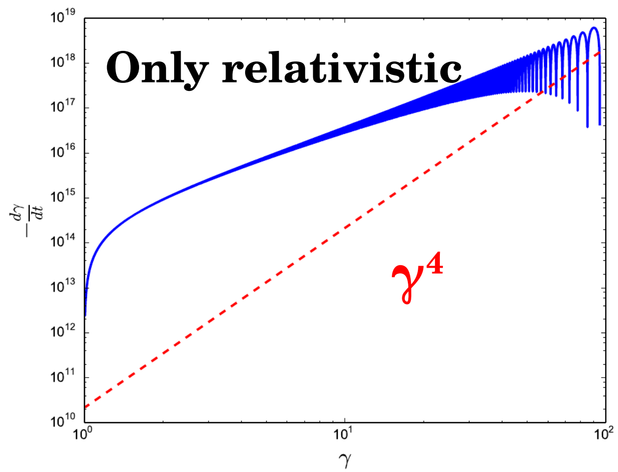
"Relativistic" term

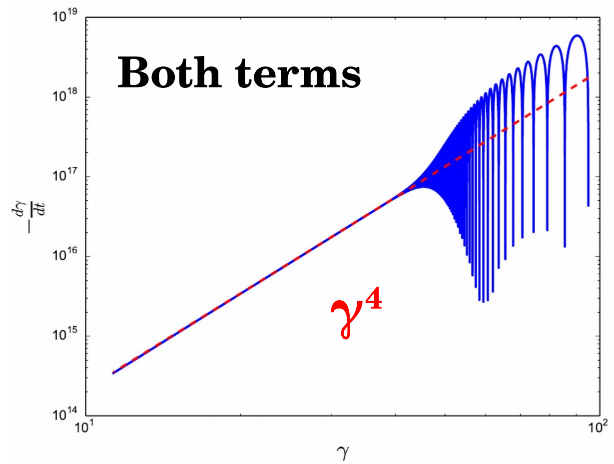
Consider a particle moving along a magnetic loop with zero pitch angle

Curvature drift velocity :

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







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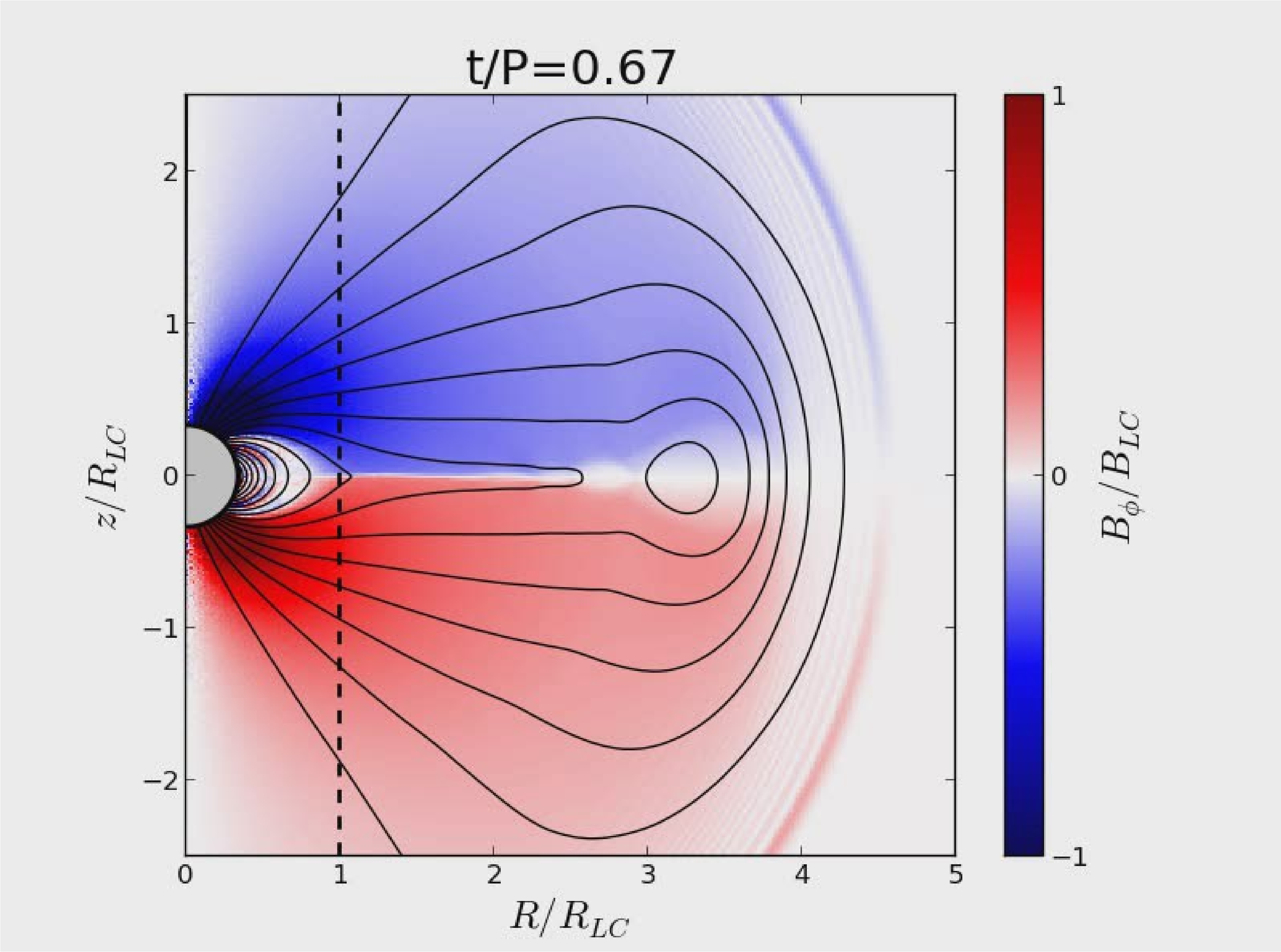
Toroidal magnetic field



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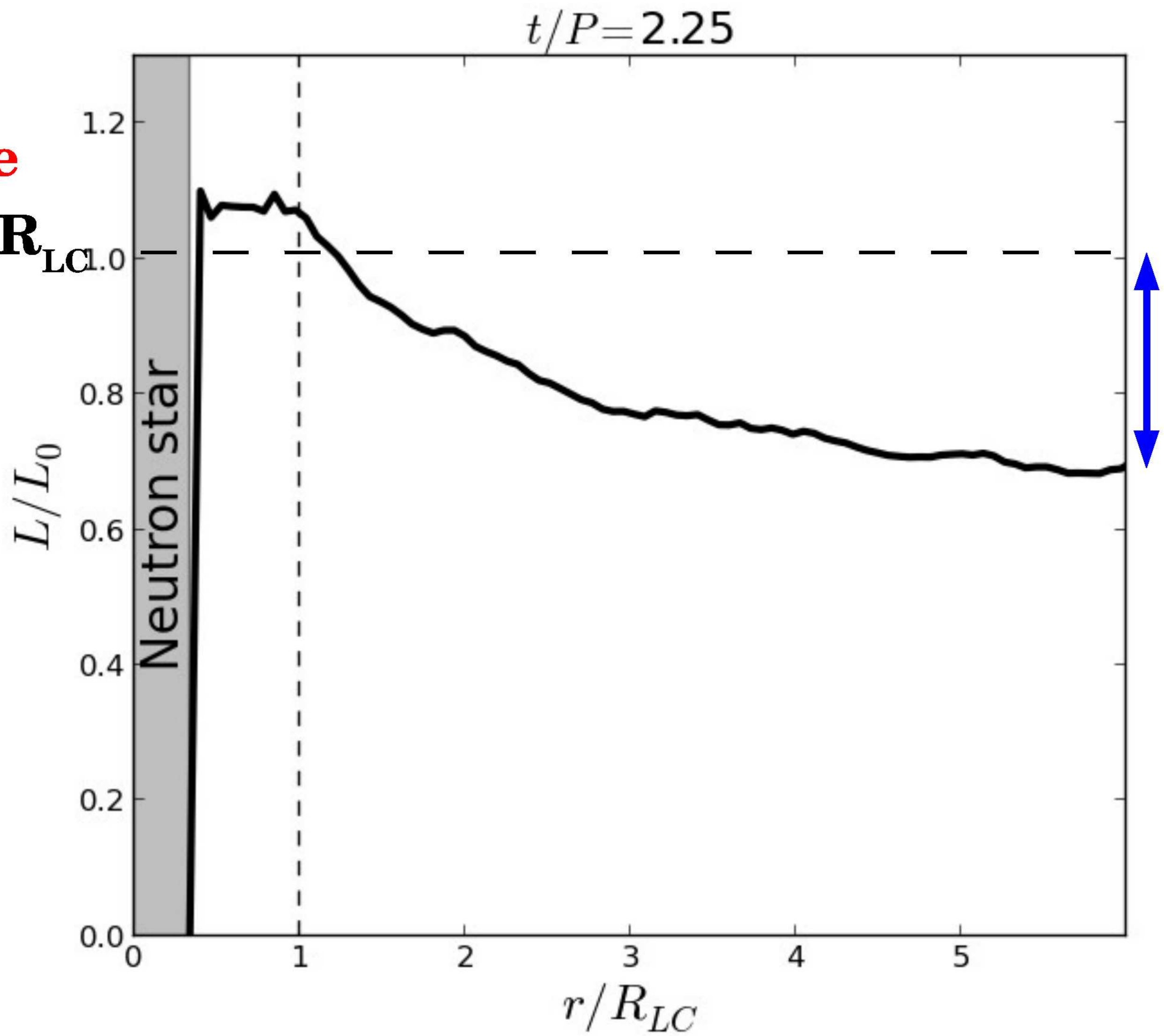
Cerutti et al. 2015

Pulsar spin down and dissipation

Force-free

$L_0 = cB_*^2 R_*^6 / 4R_{LC}$



~30% drop

Significant dissipation within a few R_{LC}!

=> Energy transferred to energetic particles and radiation!

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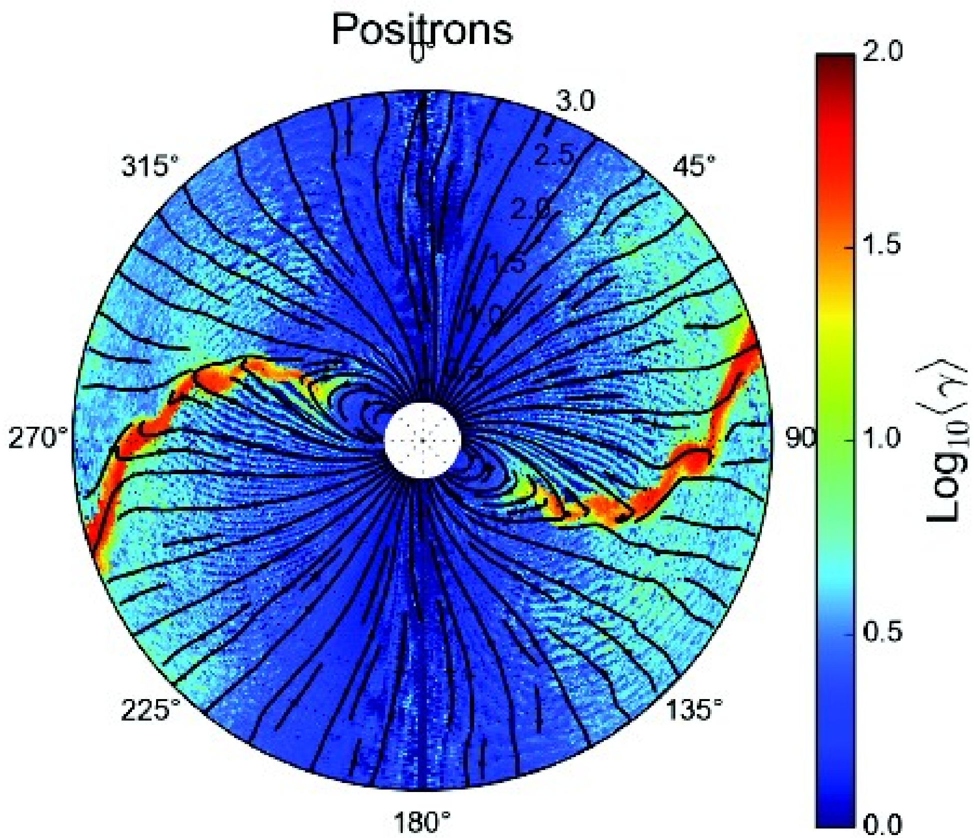
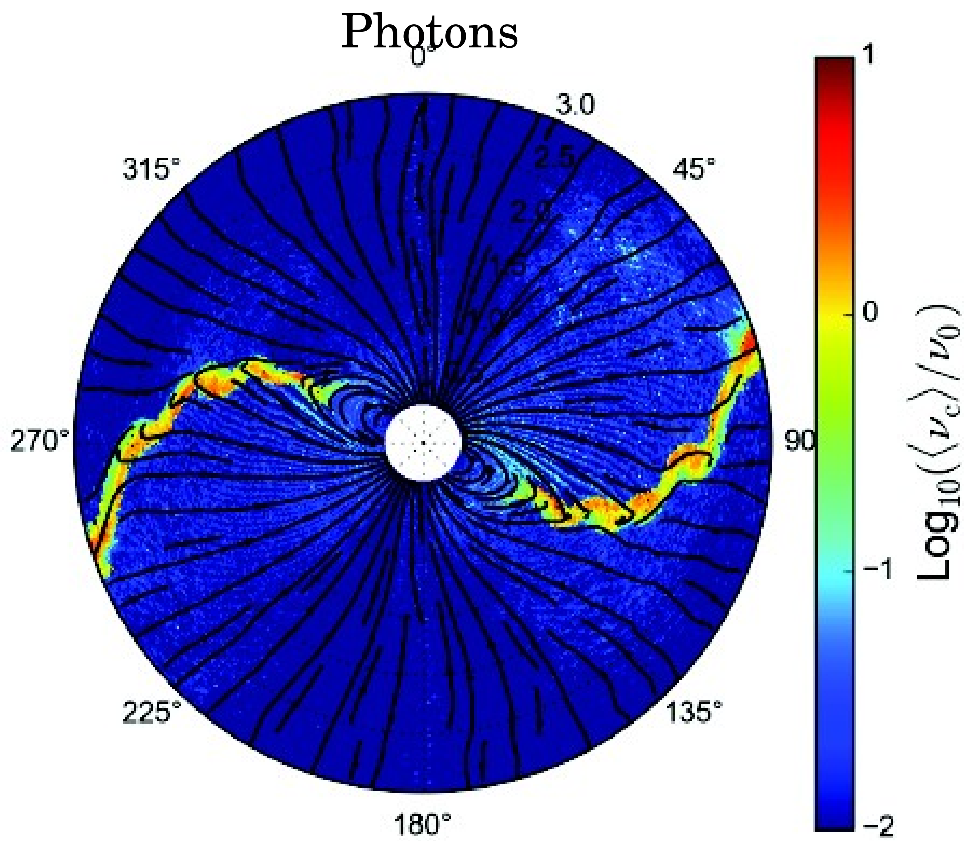
Particle / radiation mean energy (χ=30°)

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 !

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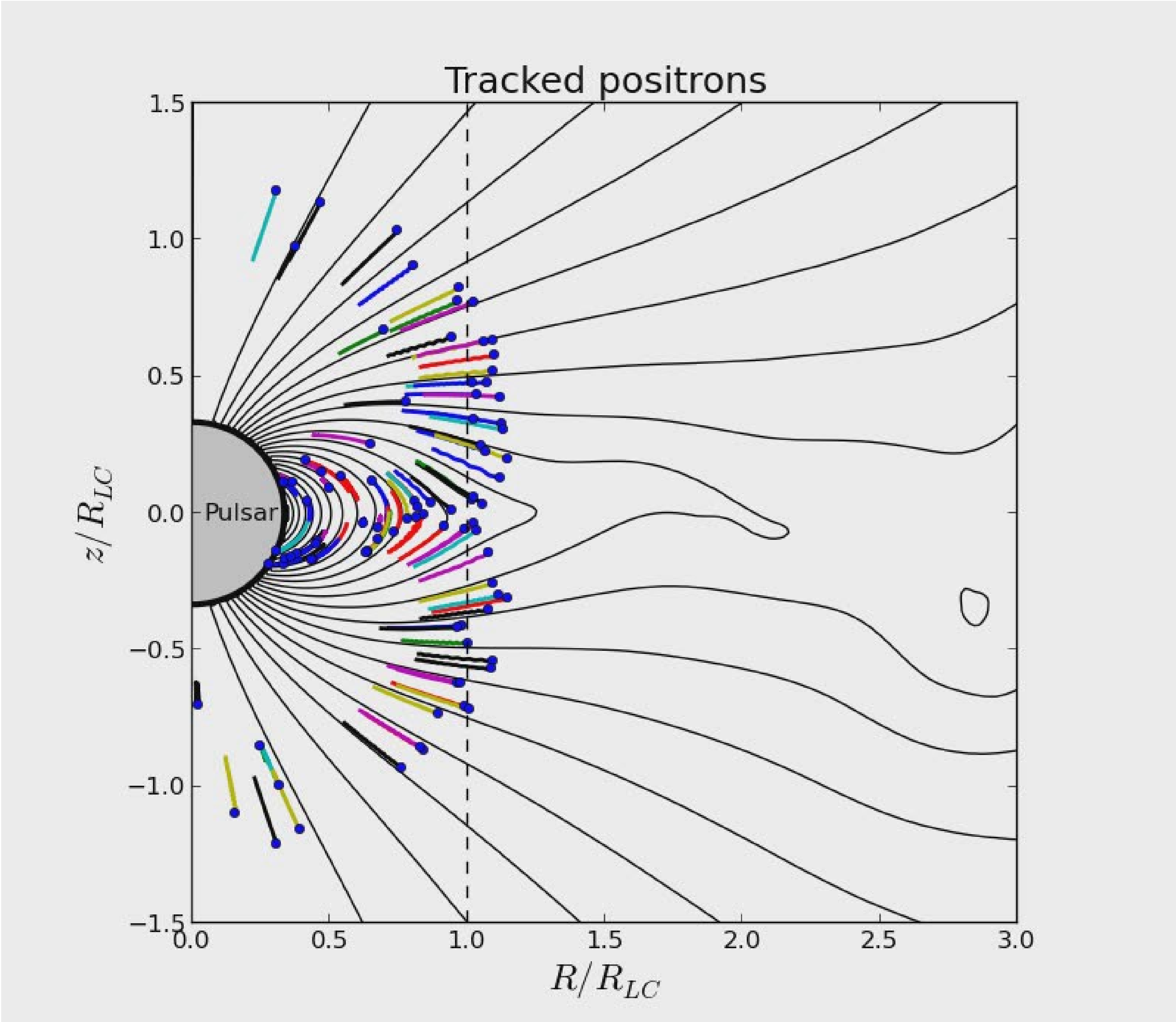
Cerutti et al. 2015; Philippov & Spitkovsky 2014; 2017

Particle acceleration and e+/e- asymmetry

2D



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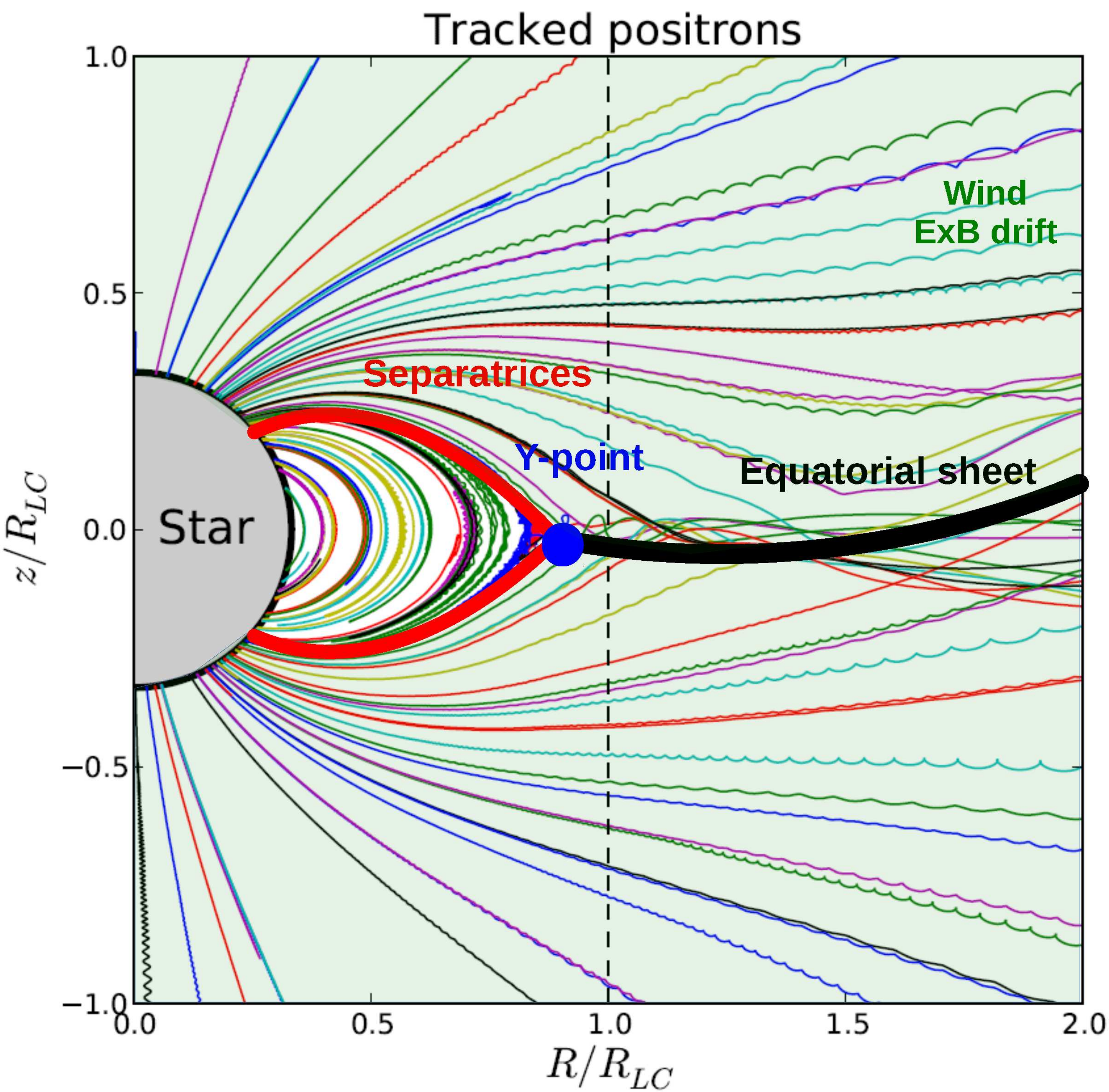
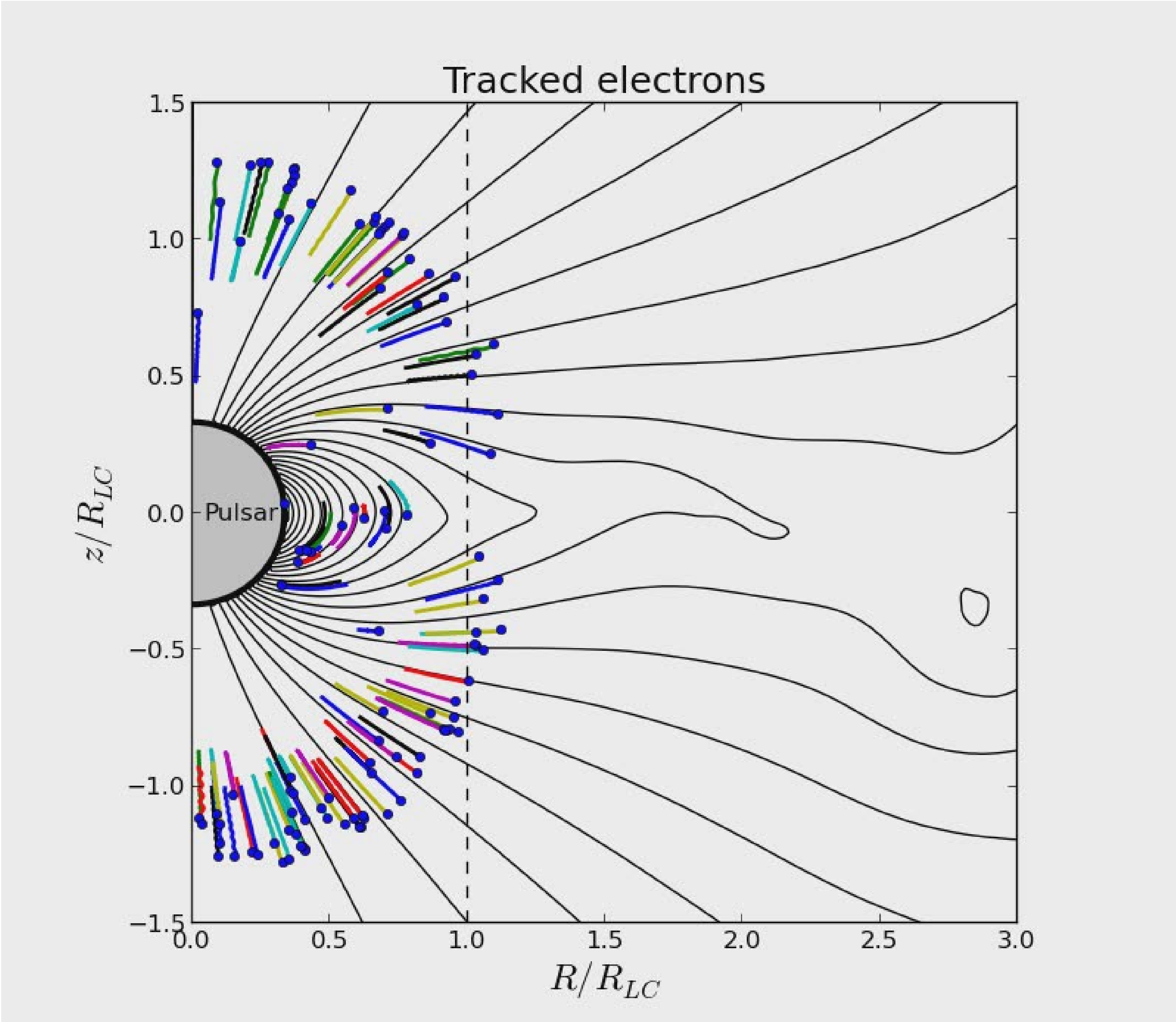

Tracked positrons
Wind
ExB drift
Separatrices
Y-point
Equatorial sheet
Star
1.0
0.5
0.0
−0.5
−1.0
0.0
0.5
1.0
1.5
2.0
z/R_{LC}
R/R_{LC}

Particle acceleration and e^+/e^- asymmetry

2D



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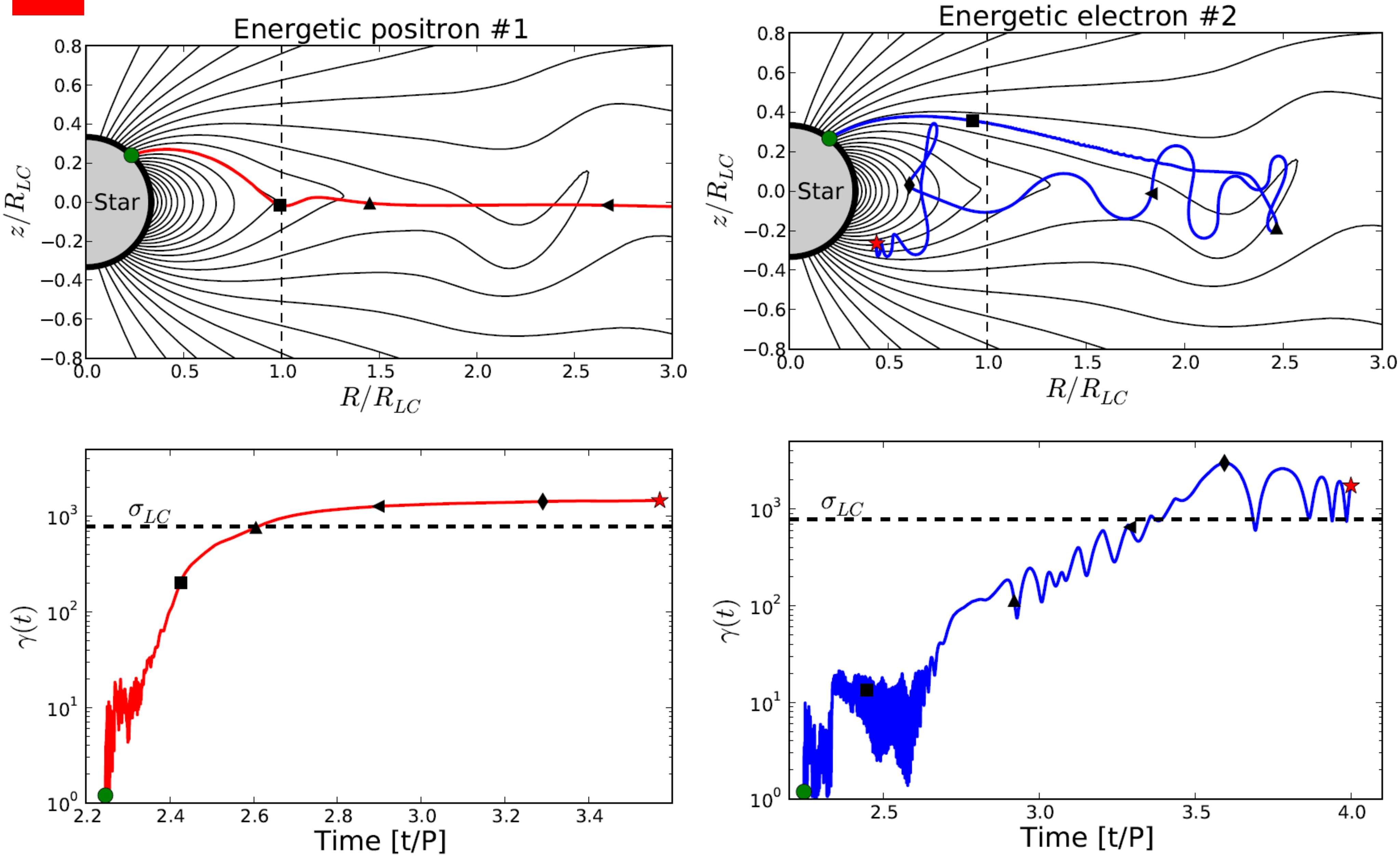
Particle acceleration and e^+/e^- asymmetry

2D



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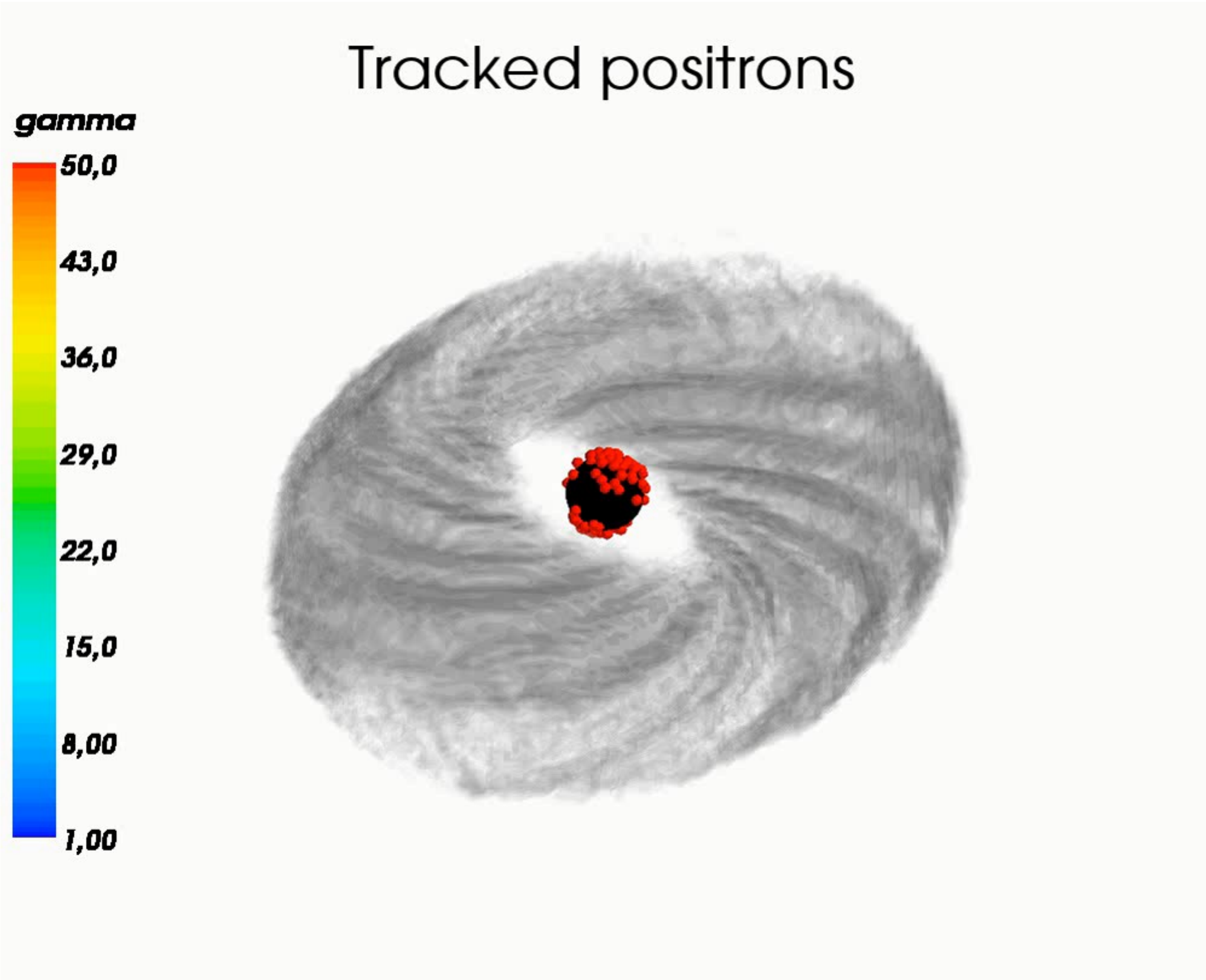
Cerutti et al. 2015

Positron orbits in oblique pulsar (30°)

In the co-rotating frame



From Cerutti et al. 2016

See also Philippov & Spitkovsky 2018 and Brambilla et al. 2018

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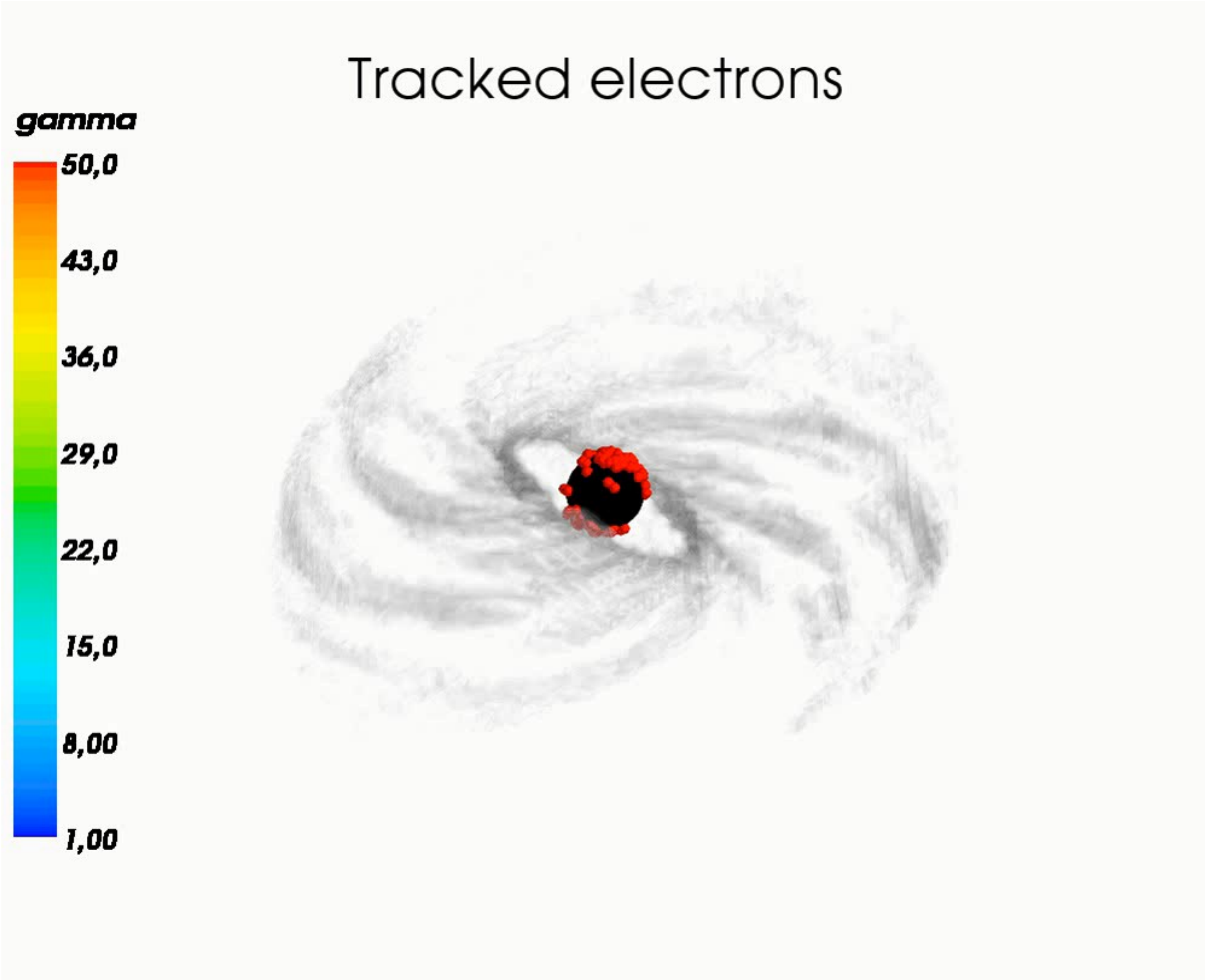
Electron orbits in oblique pulsar (30°)

In the co-rotating frame



From Cerutti et al. 2016

See also Philippov & Spitkovsky 2018 and Brambilla et al. 2018

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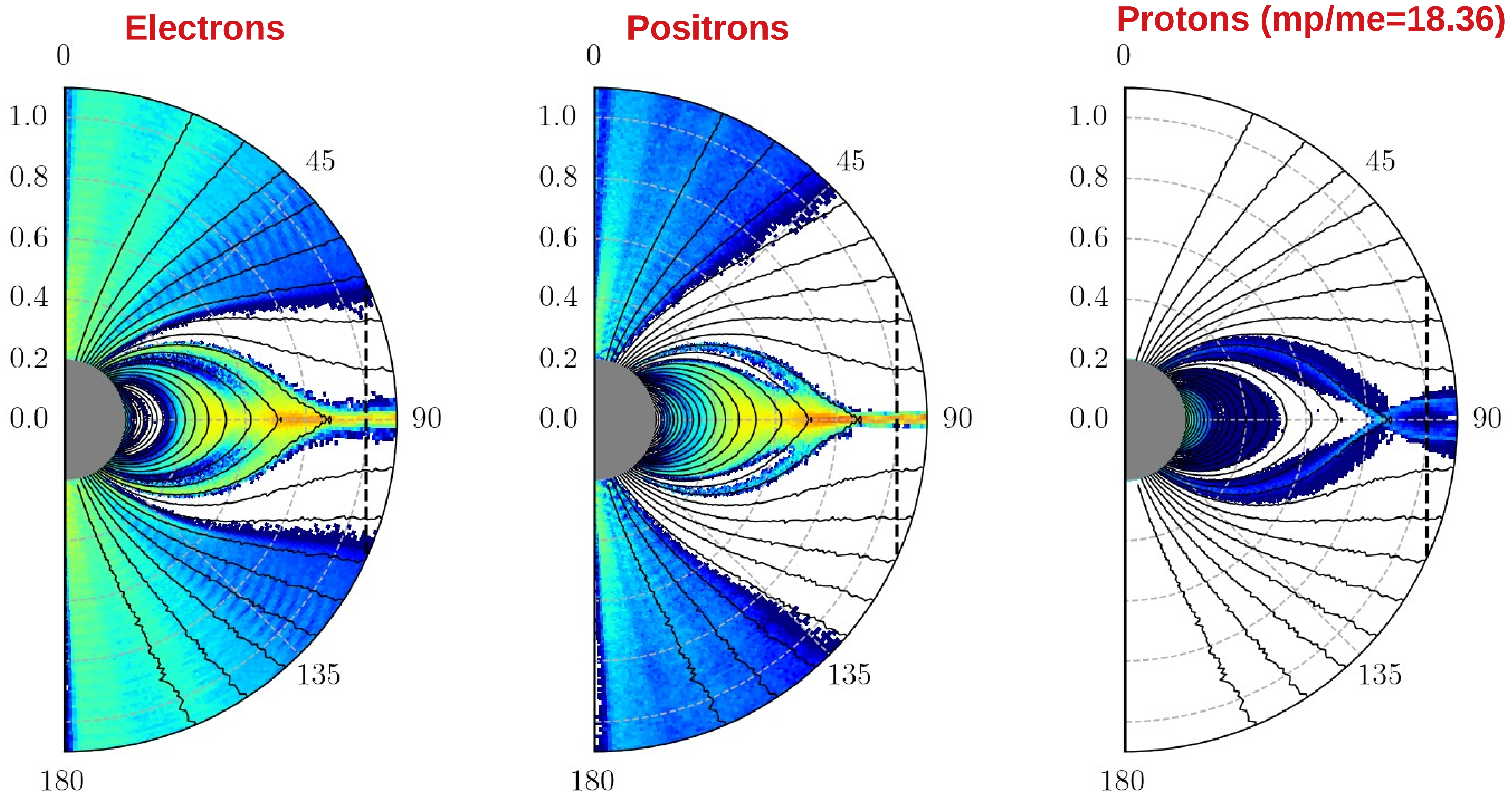
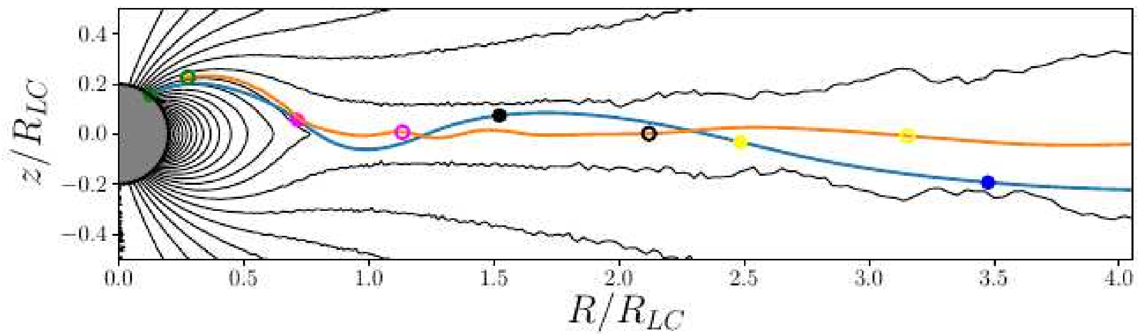
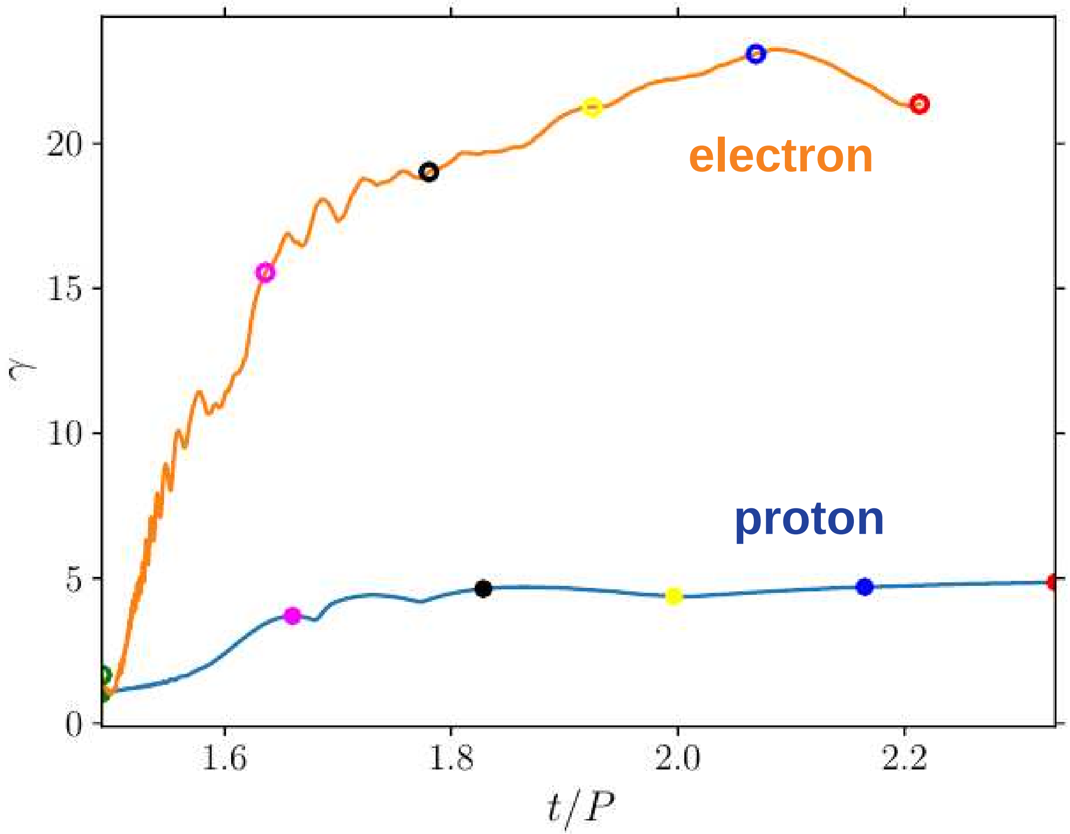
Proton acceleration

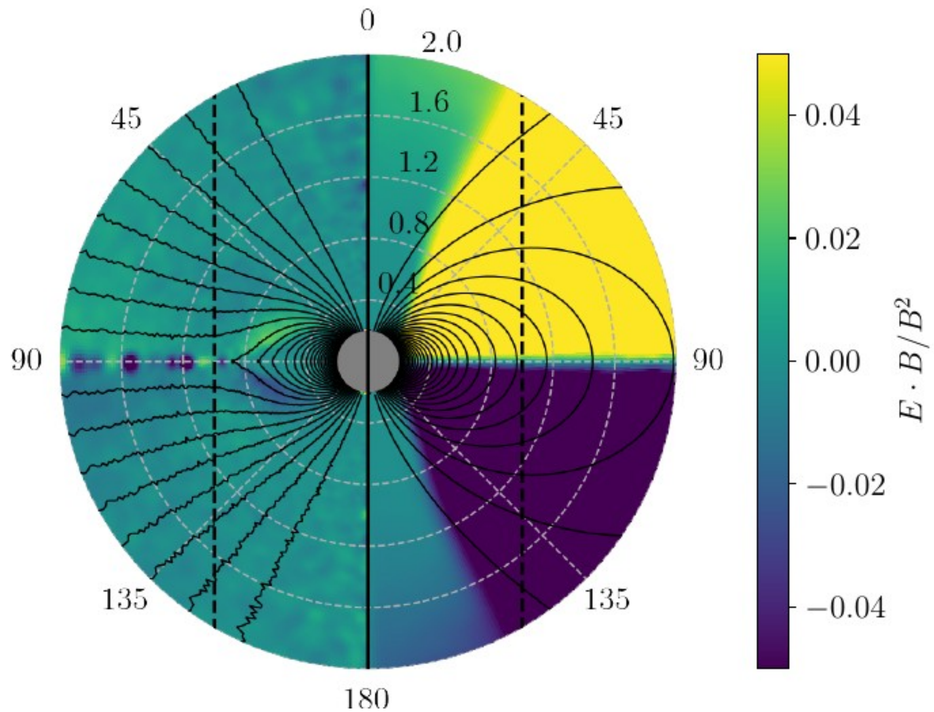


From Guépin, Cerutti & Kotera (2019)

Proton acceleration

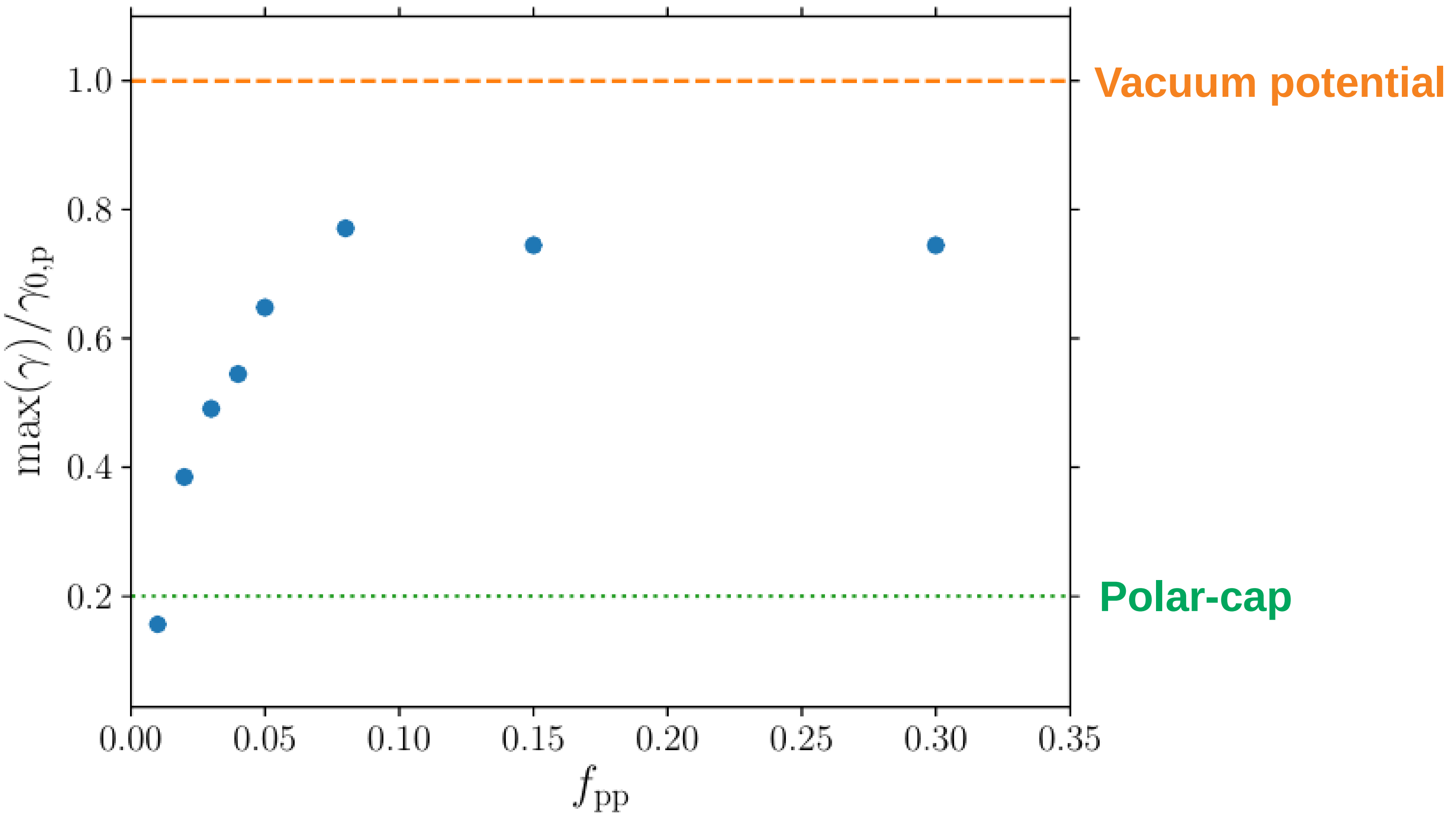






From Guépin, Cerutti & Kotera (2019)

Proton acceleration

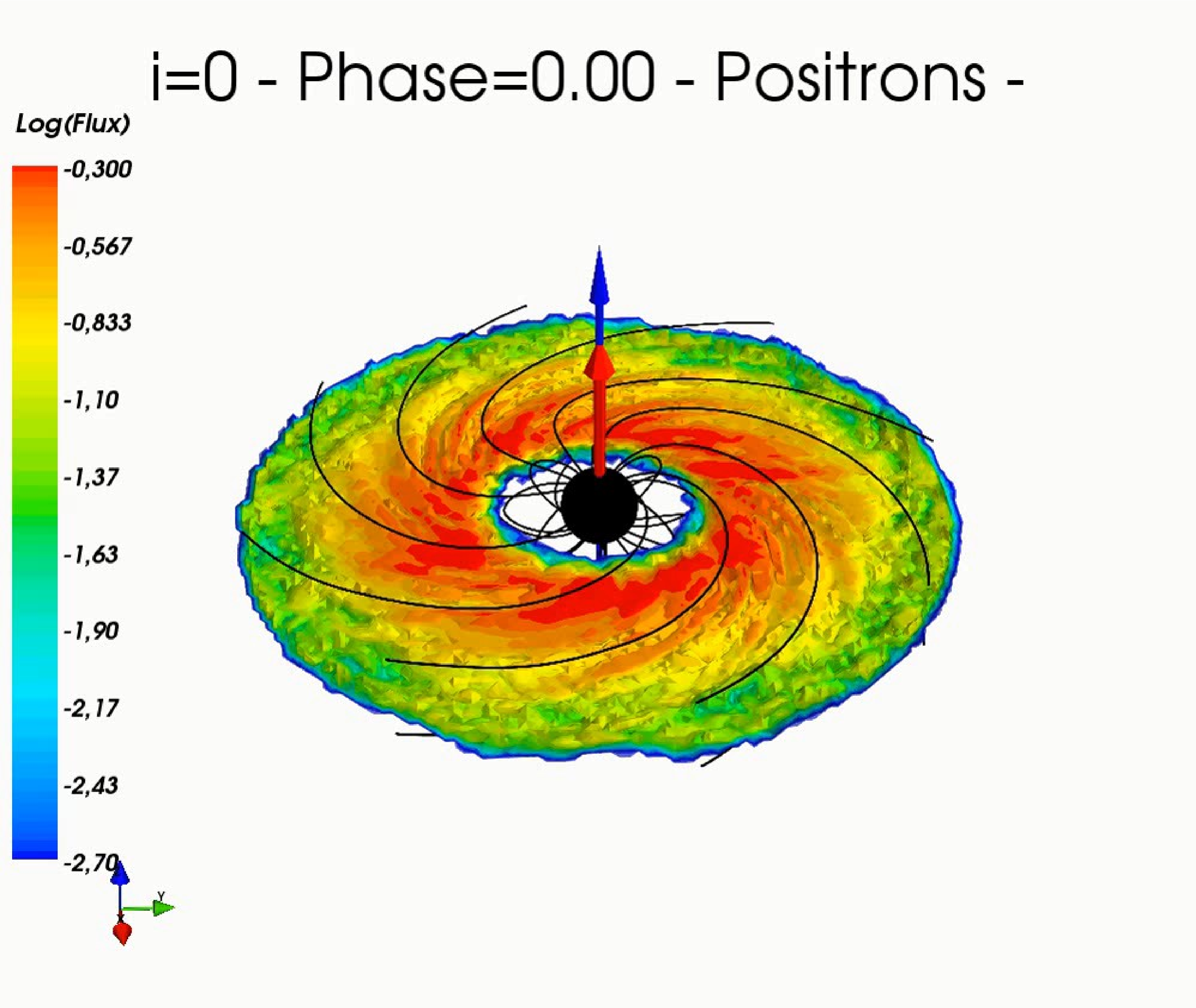


High pair production rate → **Low pair production rate**

~ 1 % of the spindown goes into particles

From Guépin, Cerutti & Kotera (2019), see also Philippov & Spitkovsky 2018

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



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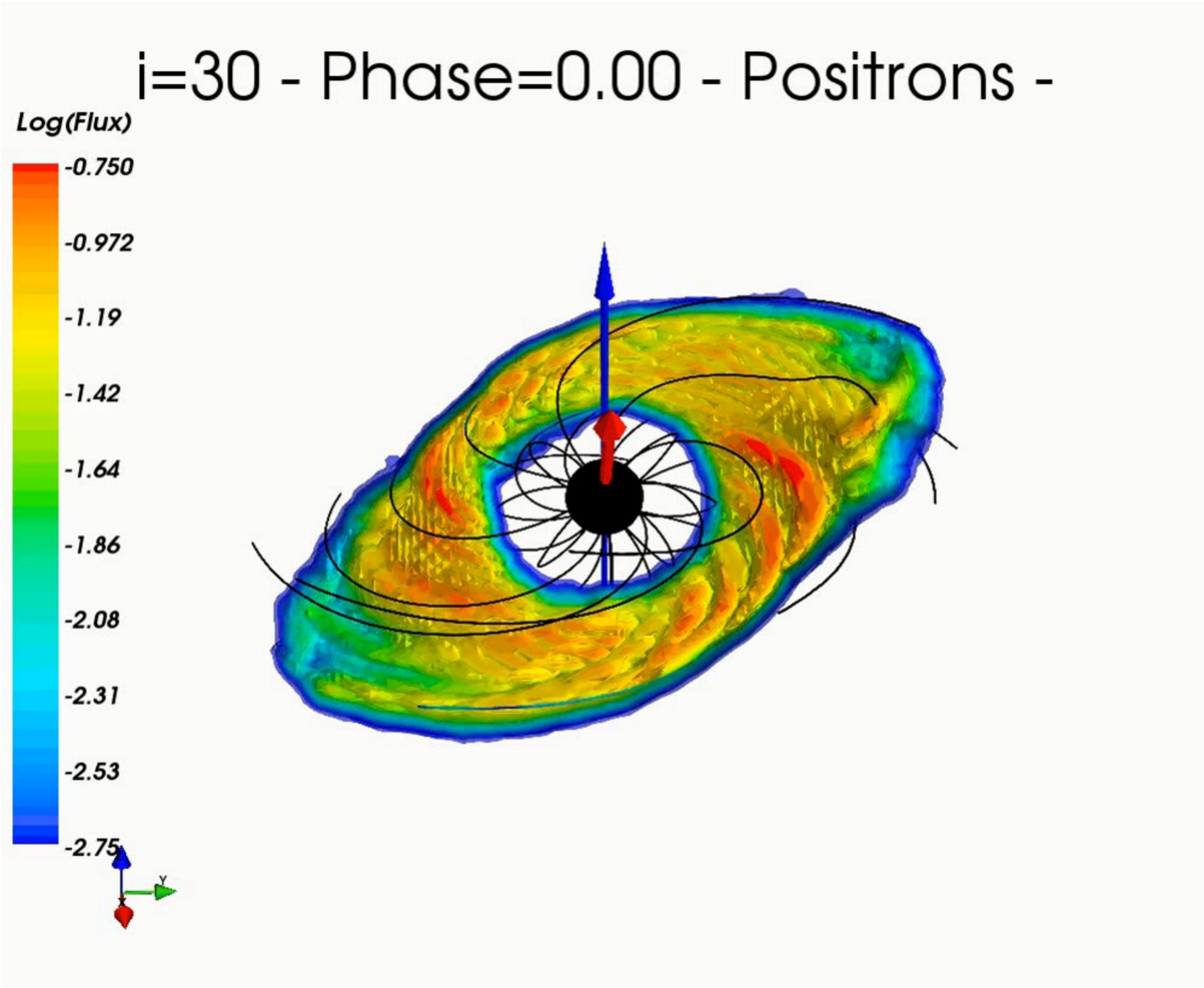
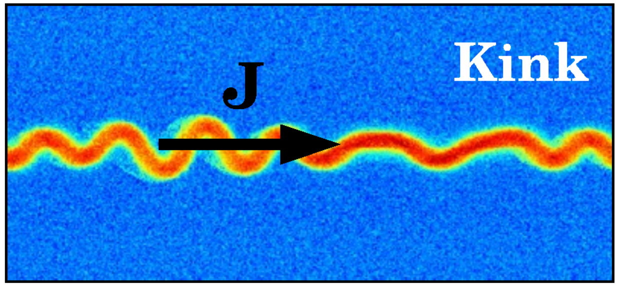
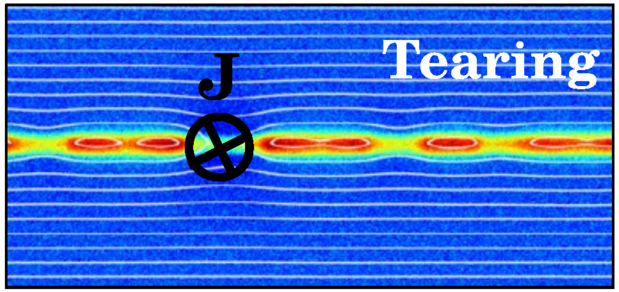
Cerutti et al. 2016

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



(Local reconnection simulations)





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

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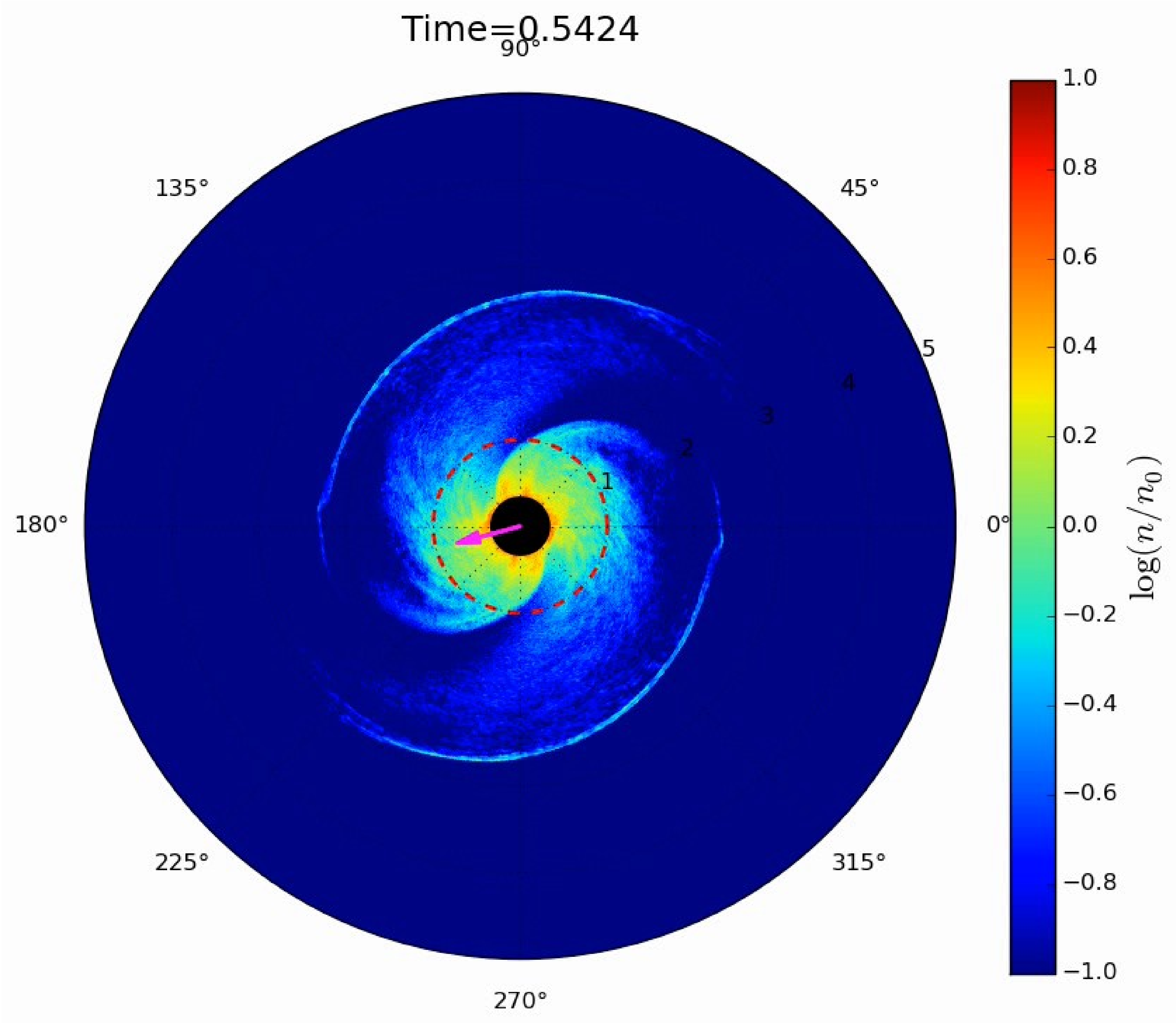
Cerutti et al. 2016

The tearing mode in action (mid-plane)



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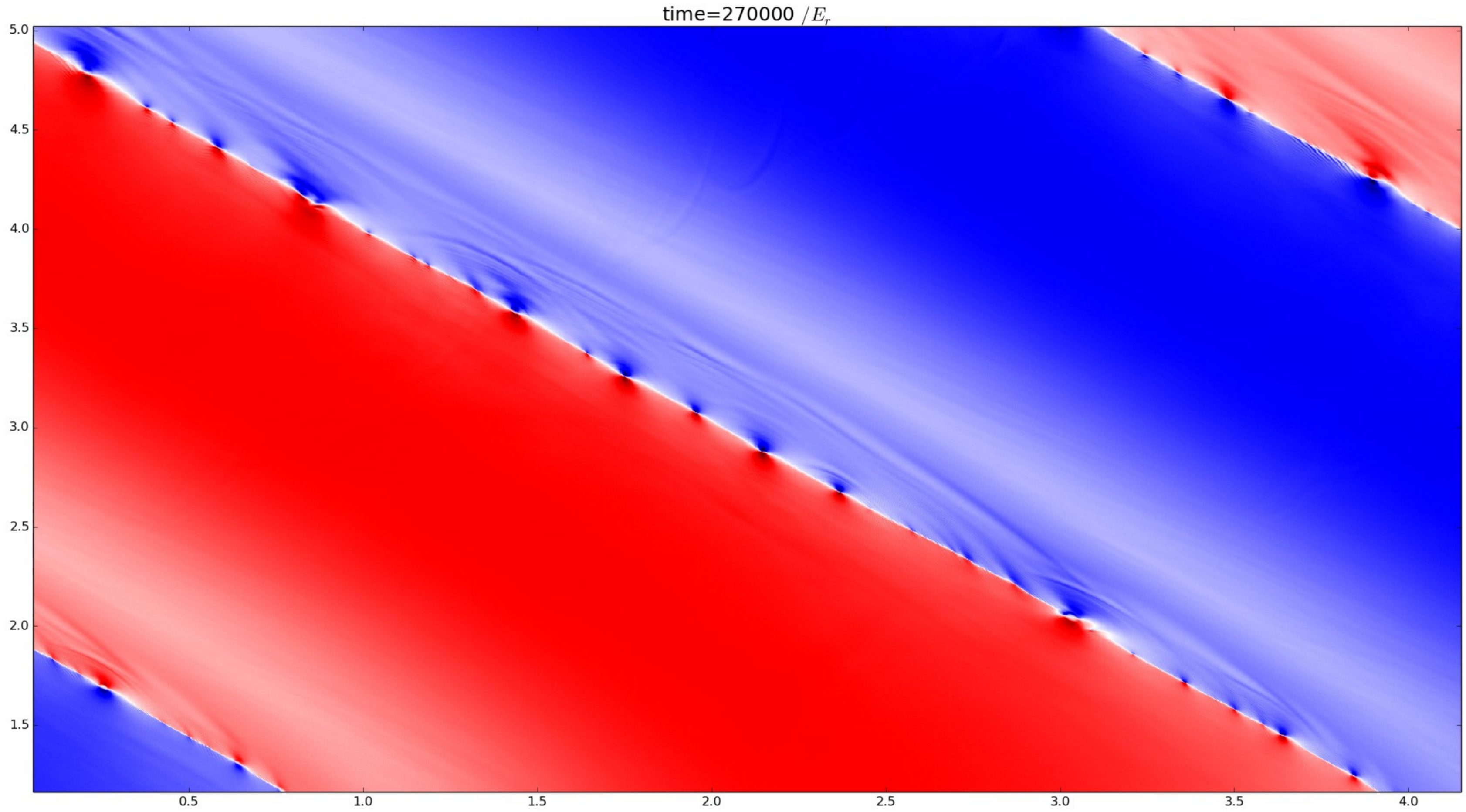
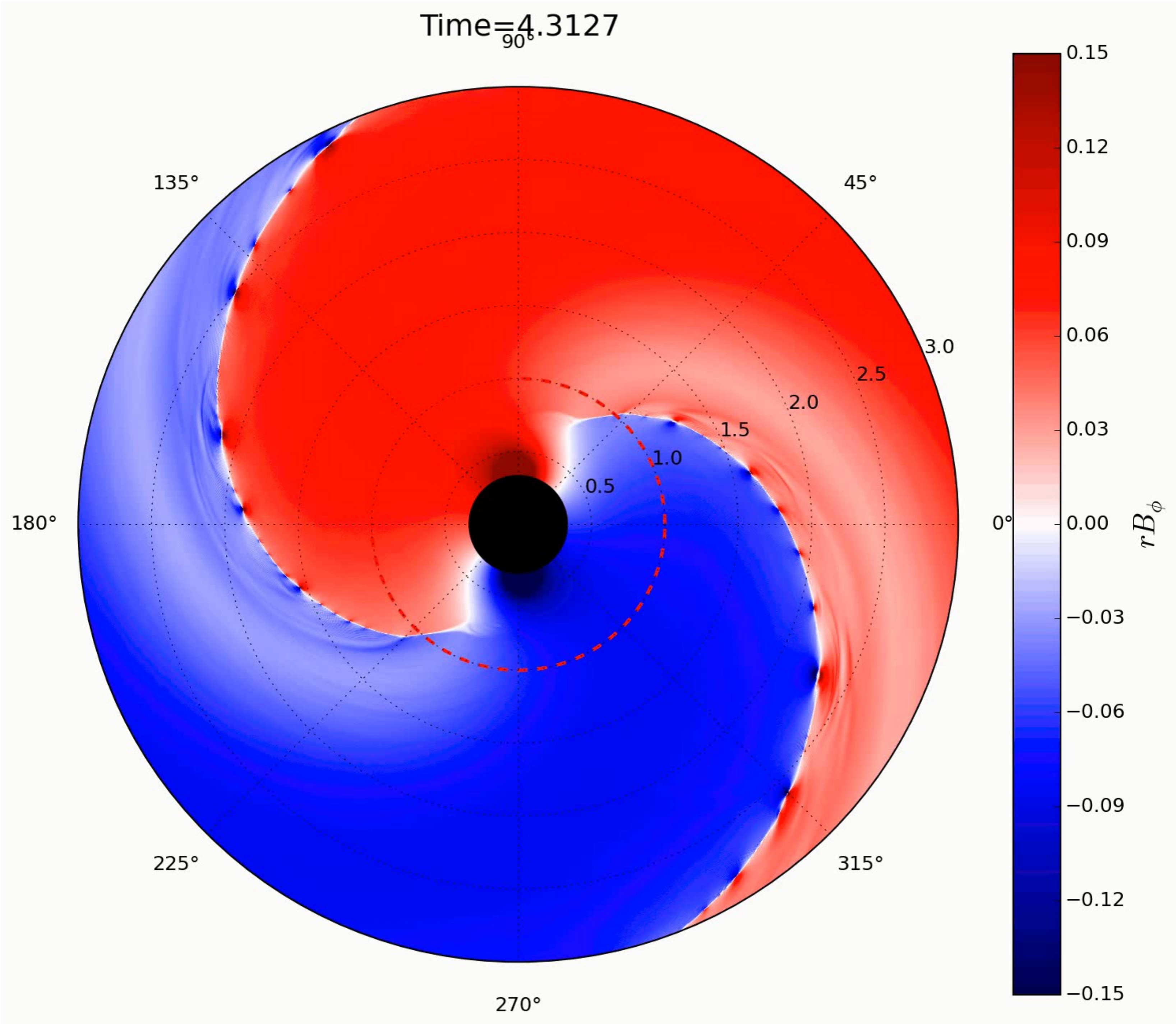
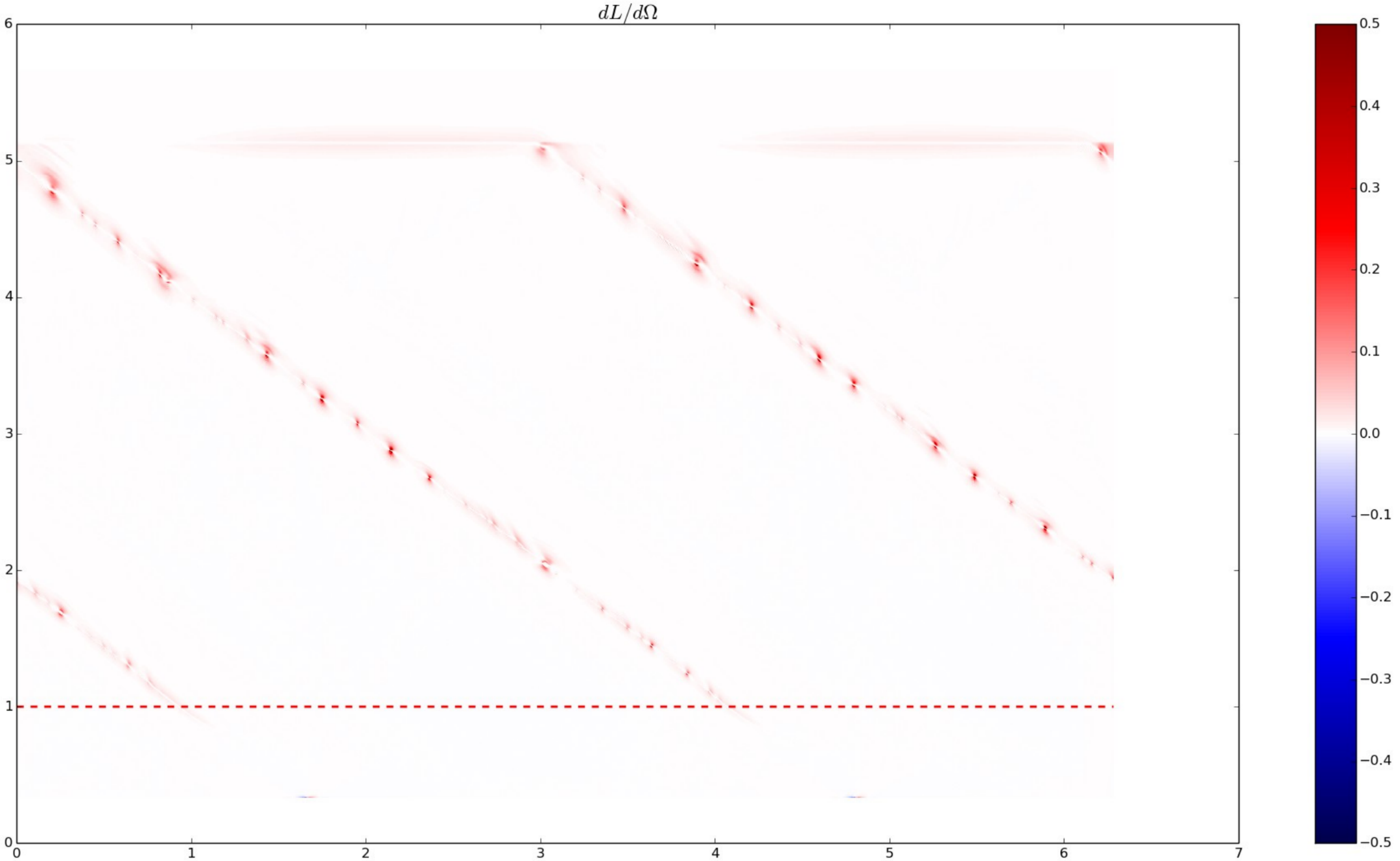
Island mergers create Poynting flux fluctuations



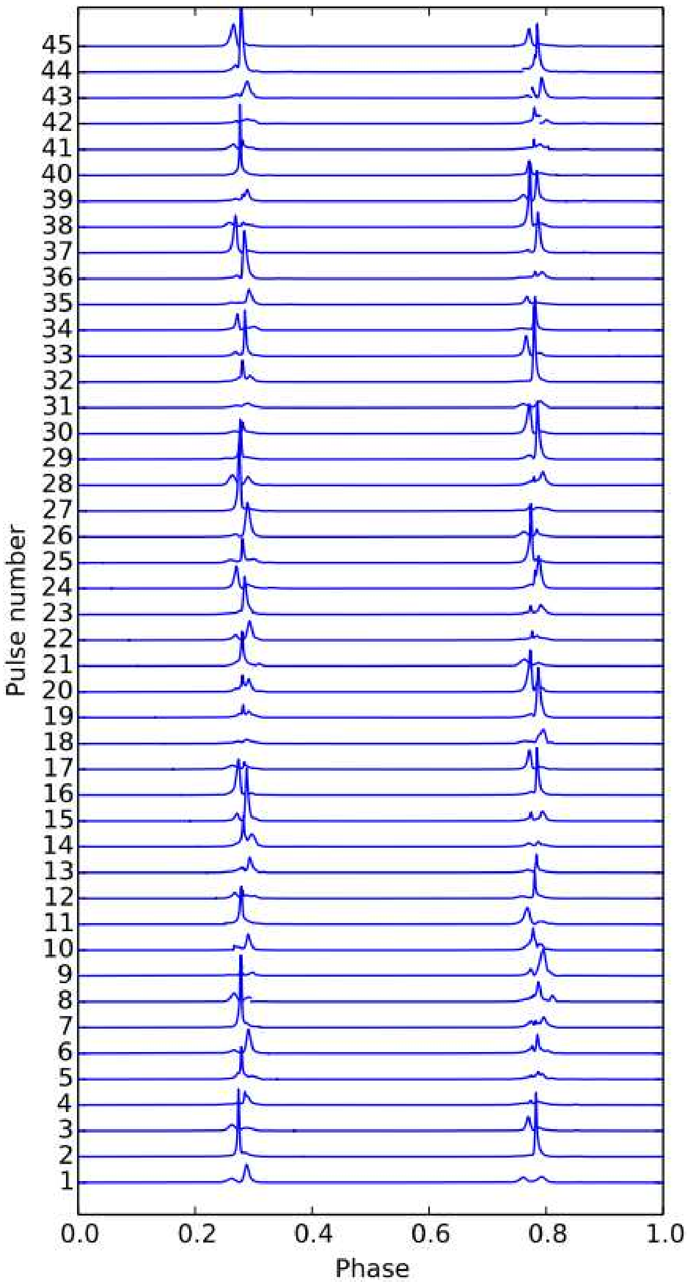


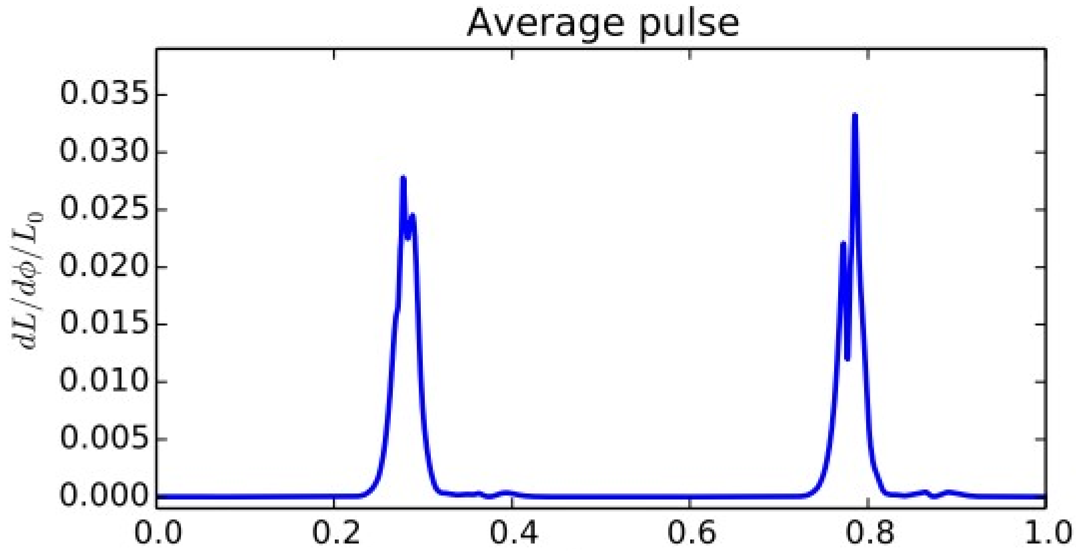
Time=4.3127
90°
45°
135°
180°
0°
225°
270°
315°
0.5
1.0
1.5
2.0
2.5
3.0
0.15
0.12
0.09
0.06
0.03
0.00
−0.03
−0.06
−0.09
−0.12
−0.15
rB_ϕ

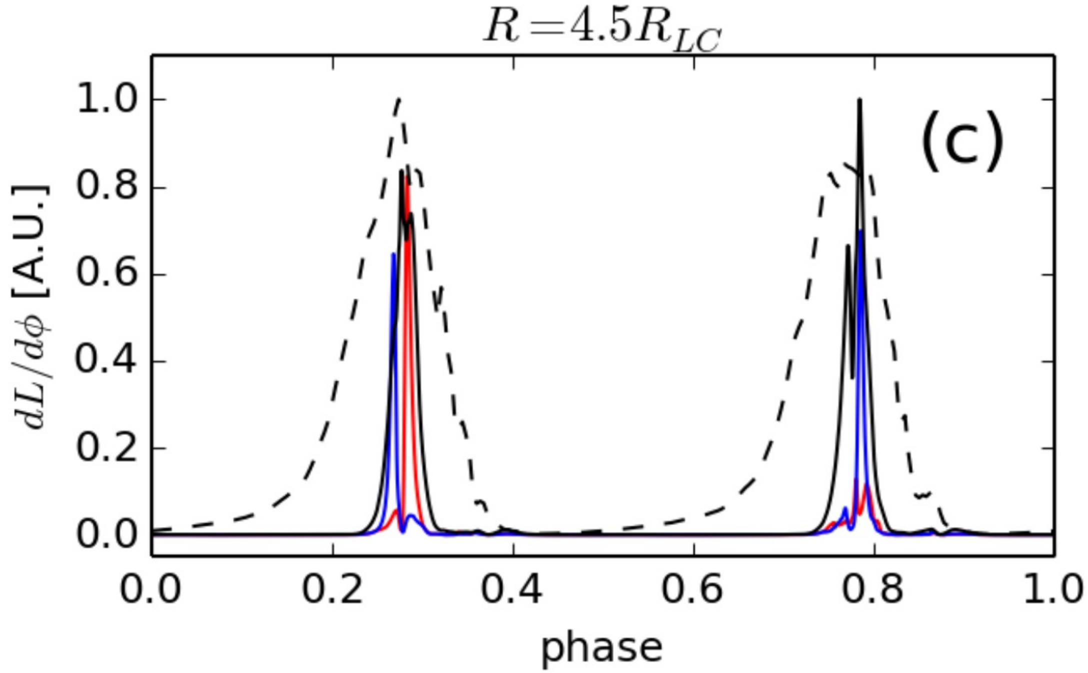
After substracting the DC wind component



Pulse-to-pulse variability : radio profile from the sheet



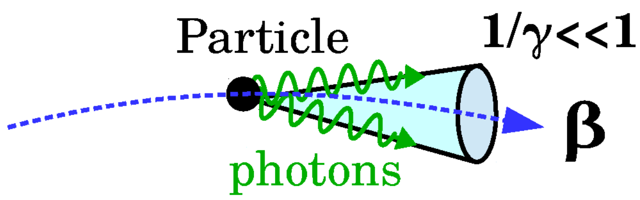




Observed high-energy radiation flux ($\nu>\nu_0$, $\chi=0°$)

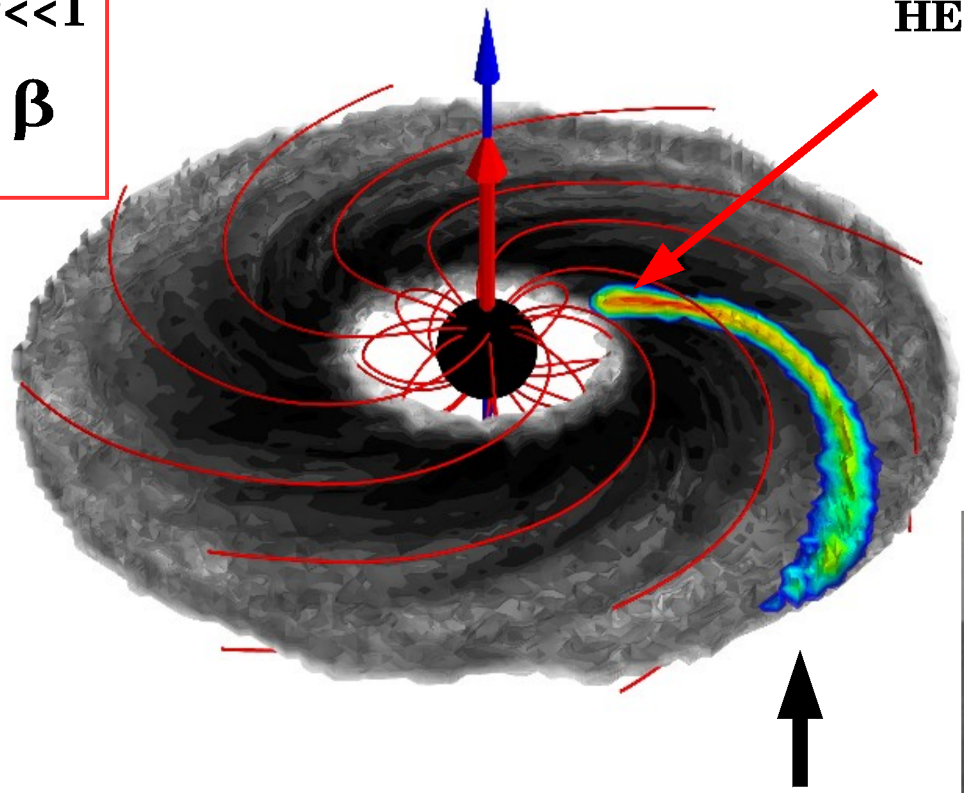
i=0 - Phase=0.00 - Positrons -

Relativistic beaming



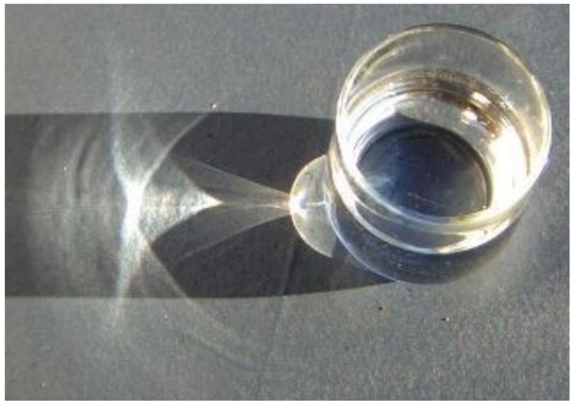
Gray : **Total** flux (all directions)

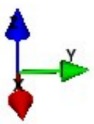
Color : **Observed** flux



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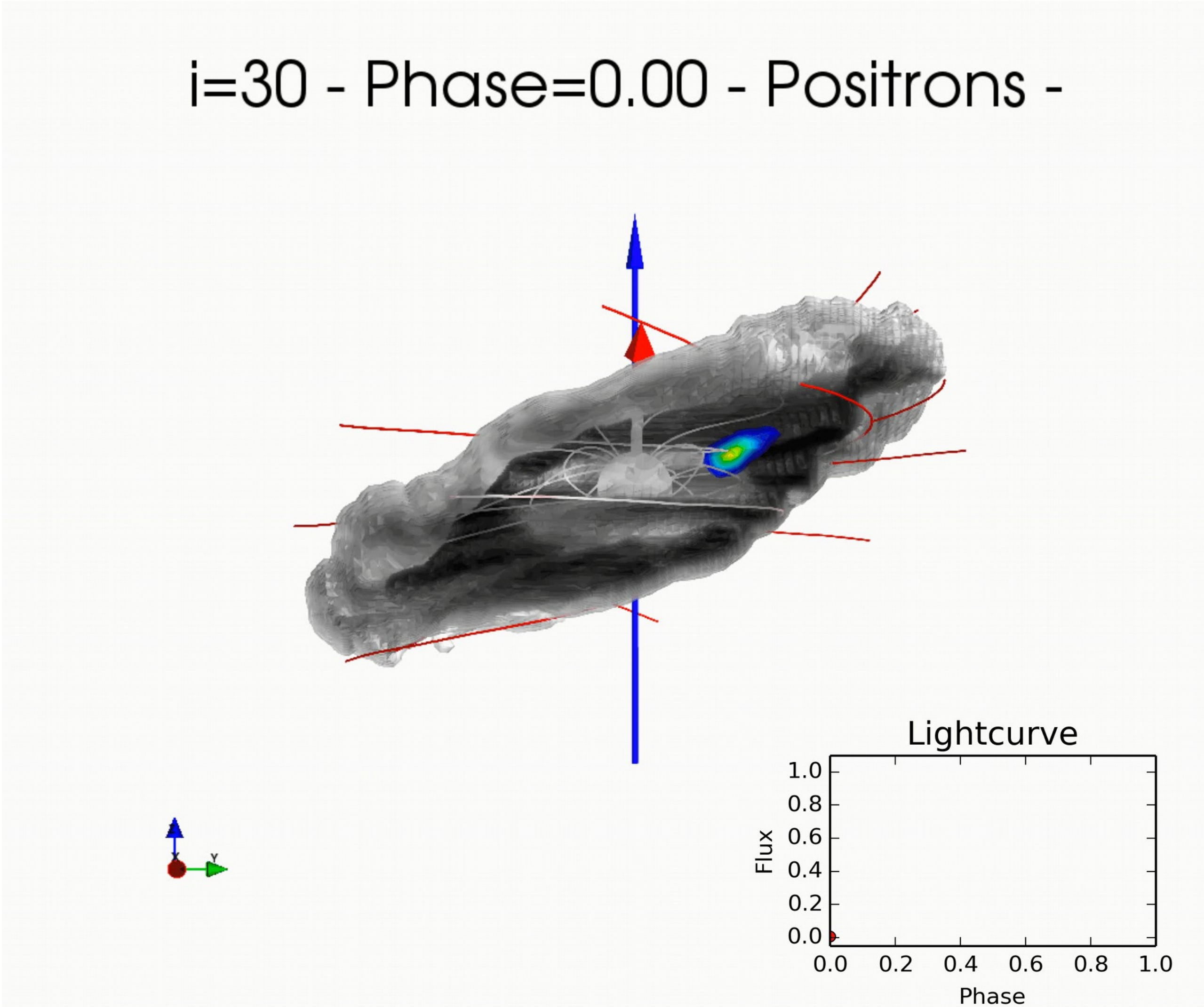
Observed high-energy radiation flux ($\nu>\nu_0$, χ=30°)

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

Color : **Observed** flux

Light curve shaped by the geometry of the current sheet



One pulse per crossing of the current sheet

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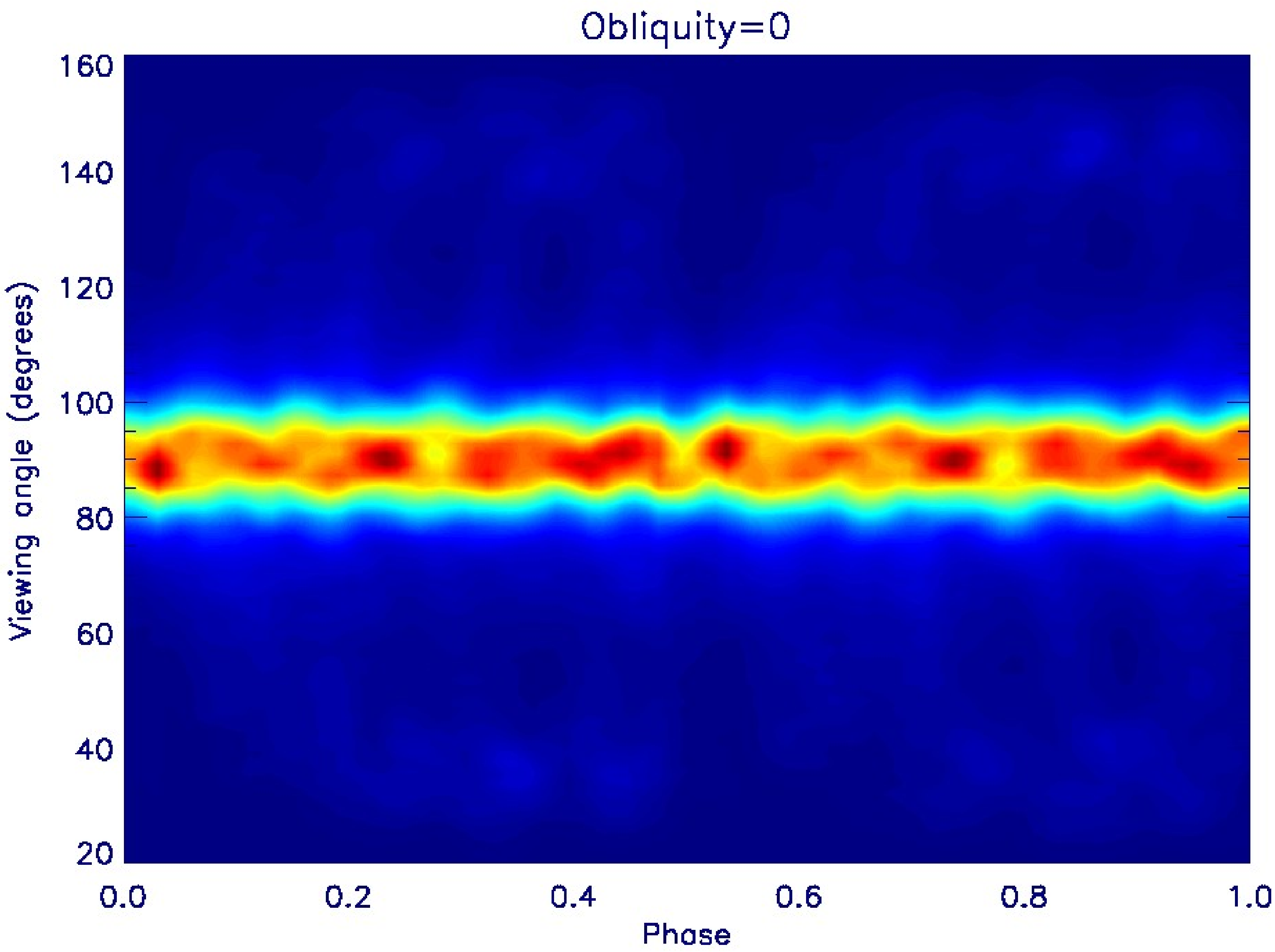
Cerutti et al. 2016

Skymaps



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

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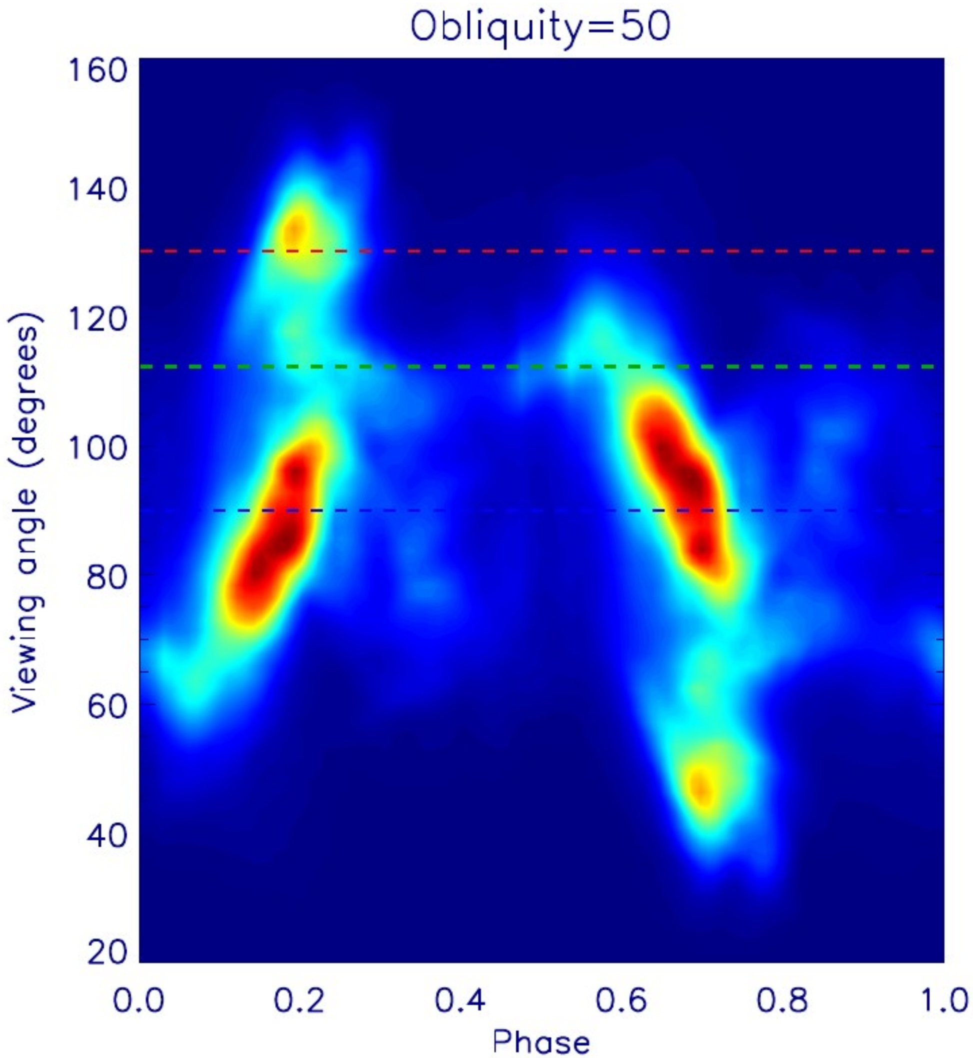
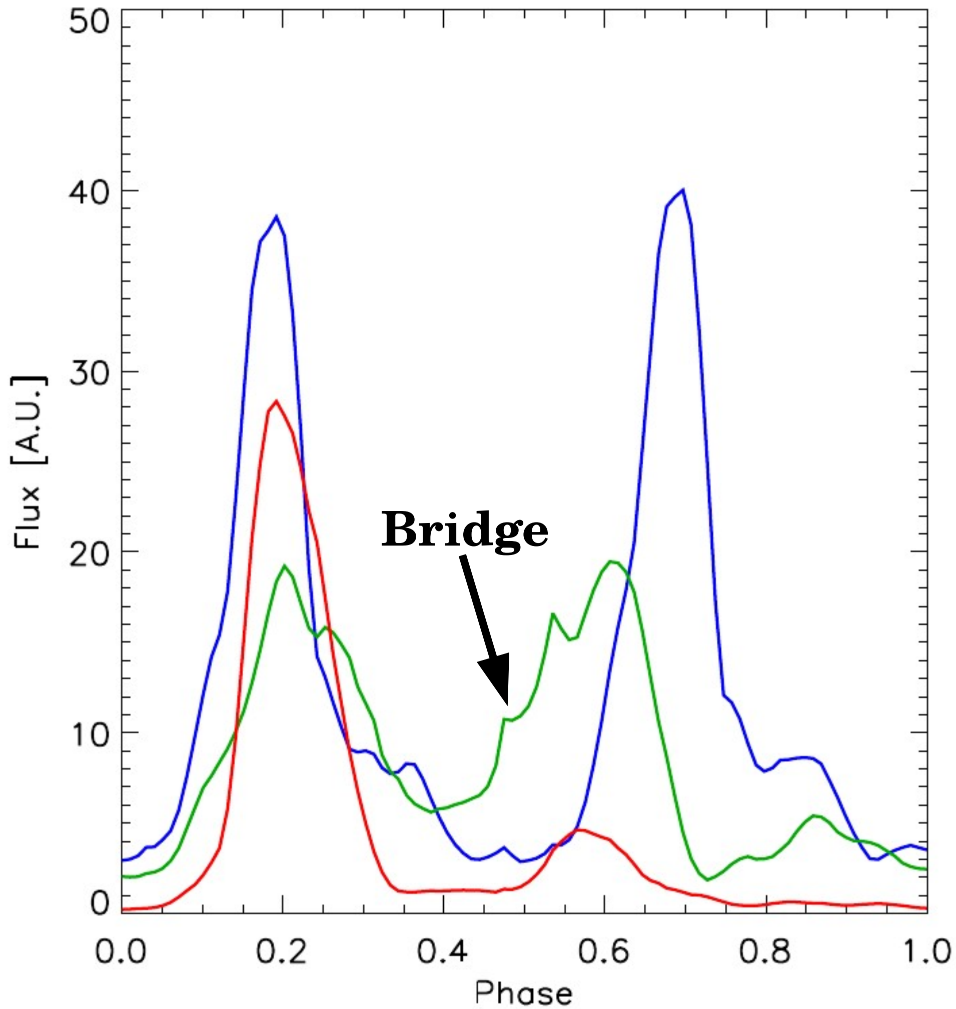
A few typical lightcurves





Cerutti et al. 2016

See also Philippov & Spitkovsky 2018

Kalapotharakos+2018

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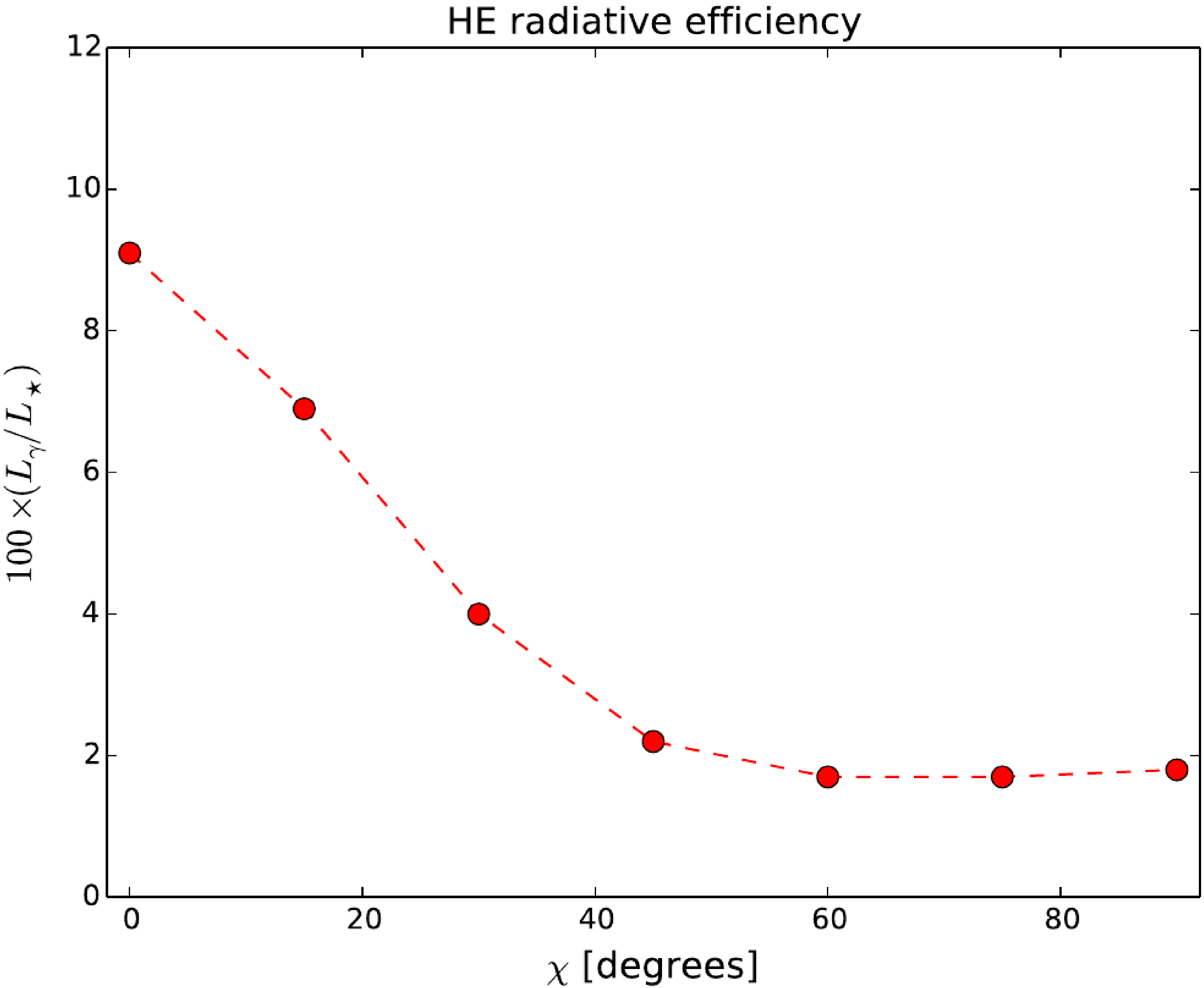
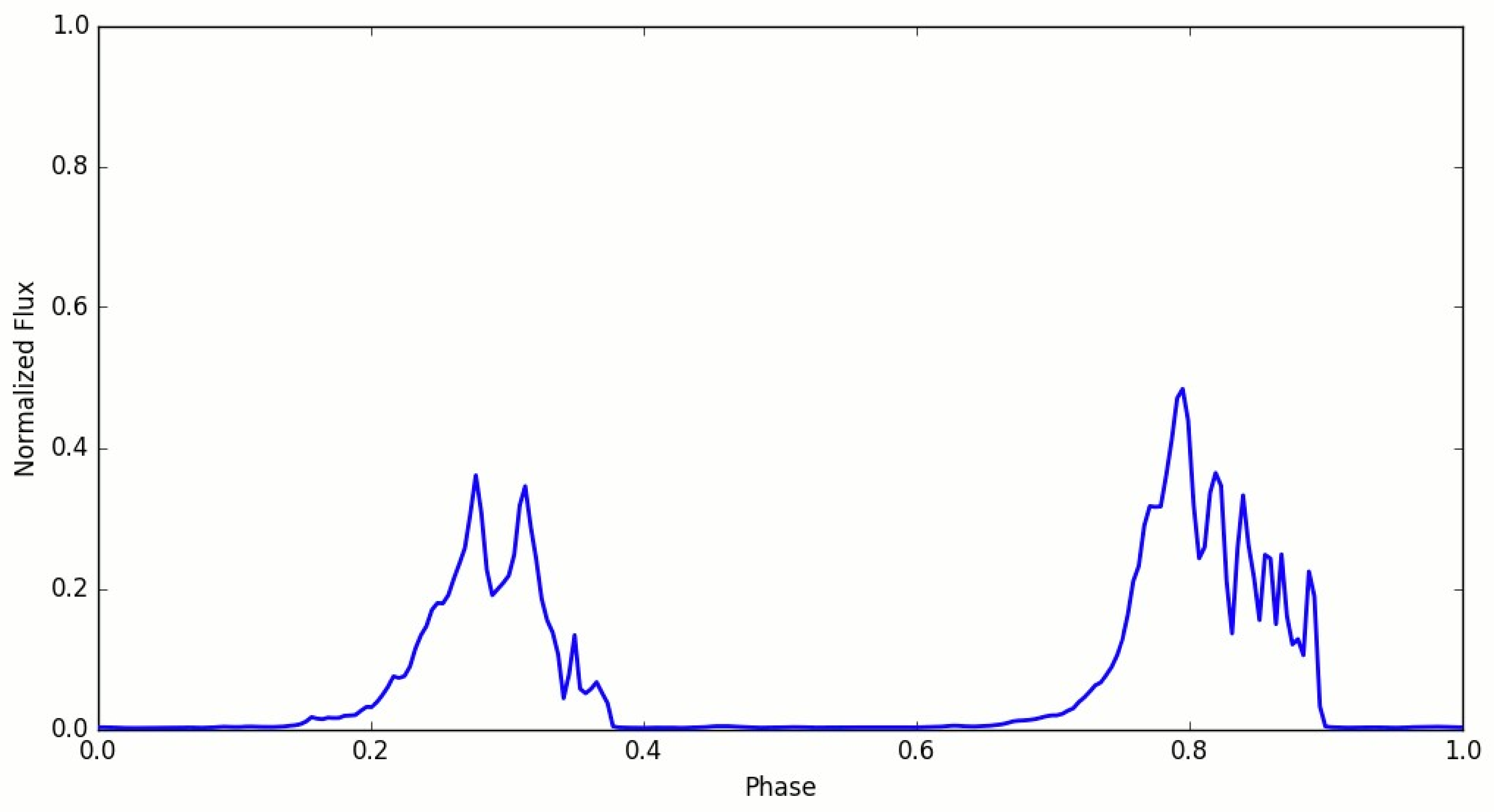

HE radiative efficiency
$100 \times (L_\gamma / L_\star)$
χ [degrees]
0
2
4
6
8
10
12
0
20
40
60
80

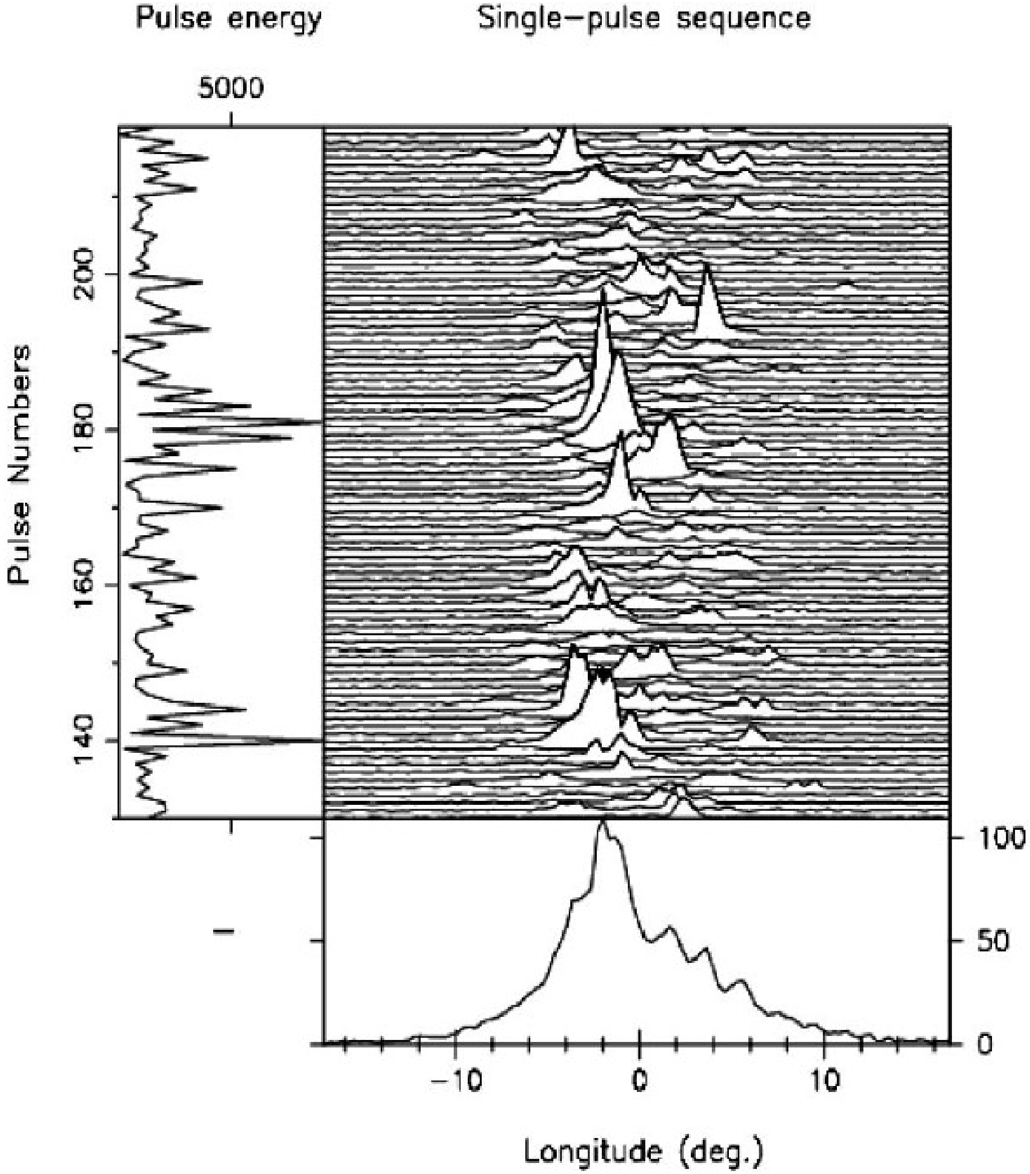
Pulse-to-pulse variability



Cerutti & Philippov 2017

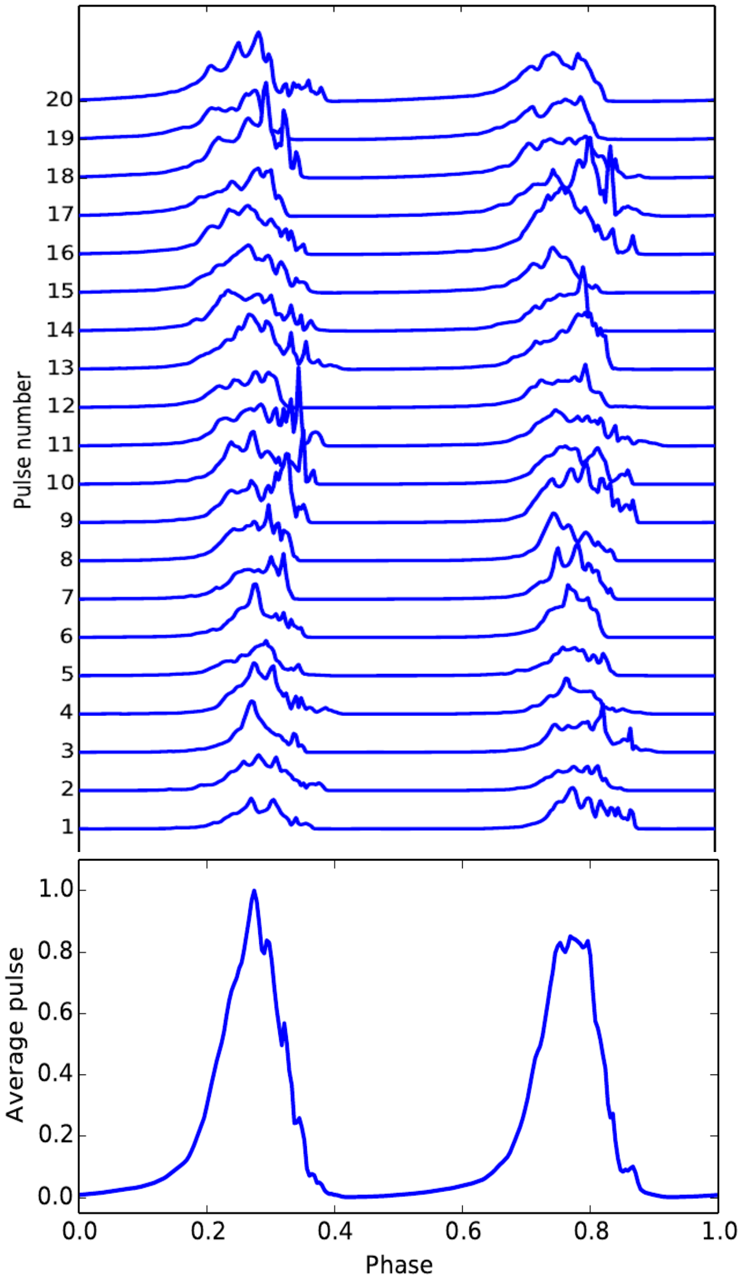
Pulse-to-pulse variability

Radio (observations)



Deshpande & Rankin 1999

Gamma (PIC simulations)



Cerutti & Philippov, submitted, 2017

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Fitting Fermi-LAT pulsar lightcurves

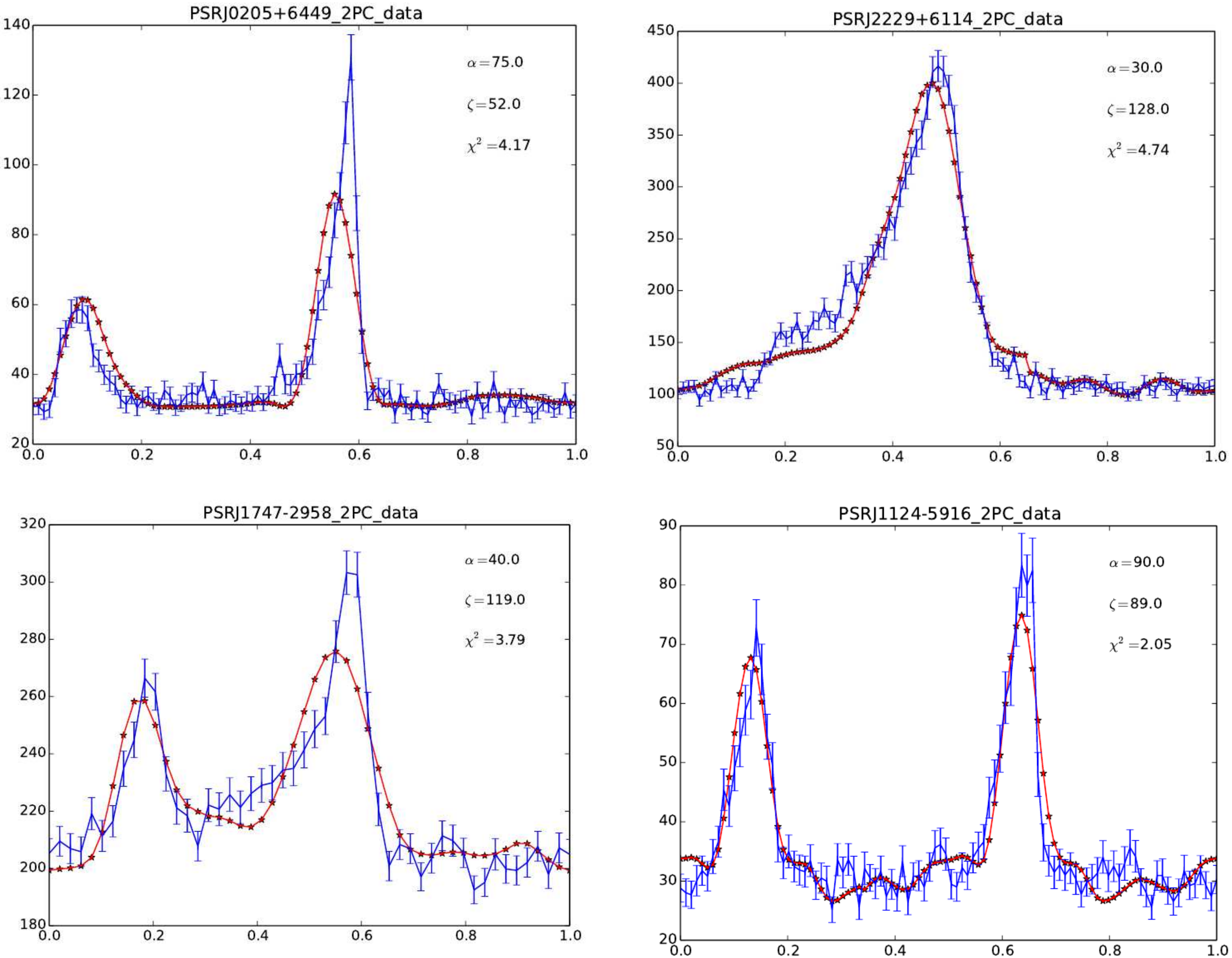
PRELIMINARY

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

Observations

PIC model

χ^2 method



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

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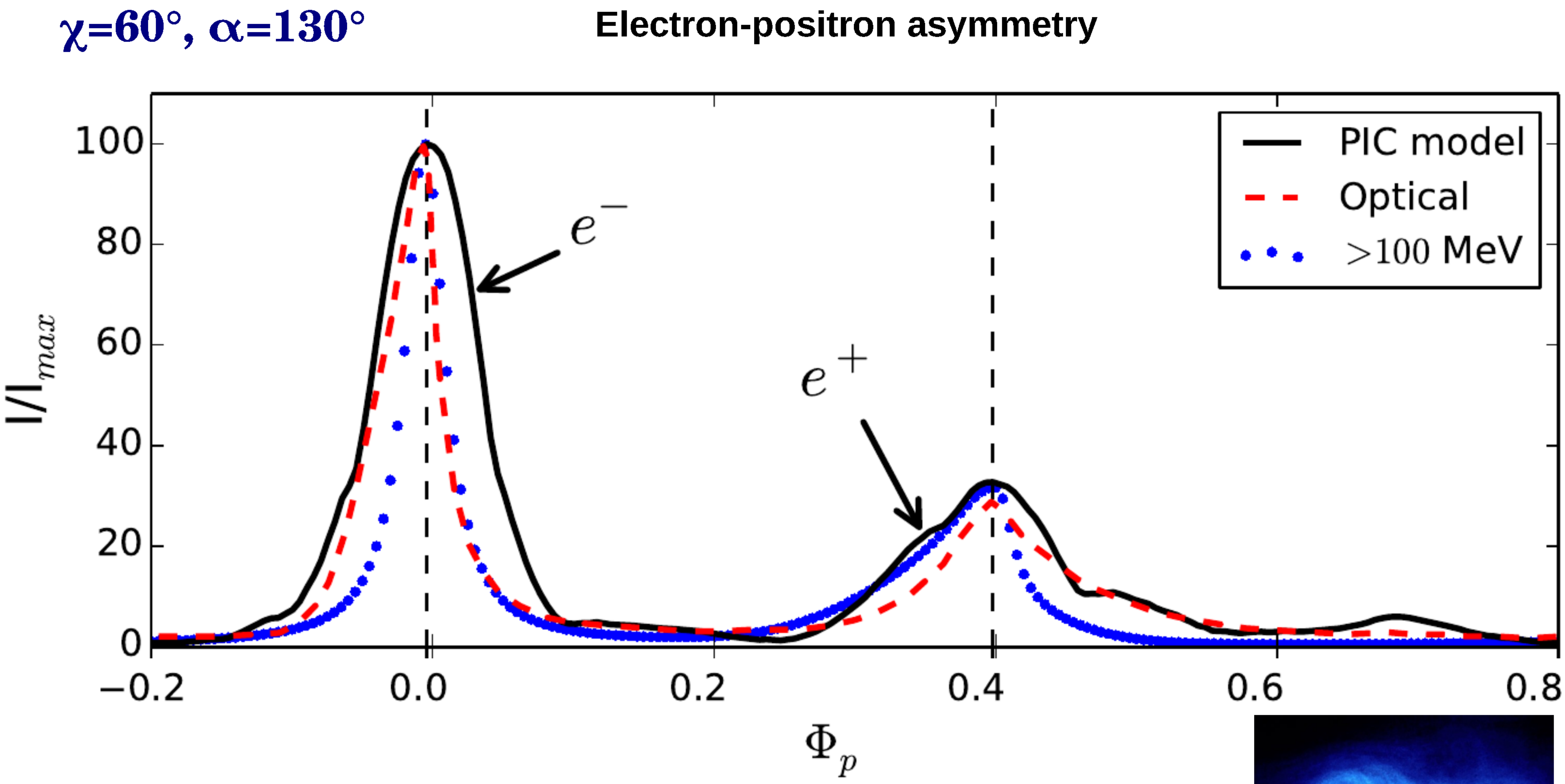
Crab pulse profile

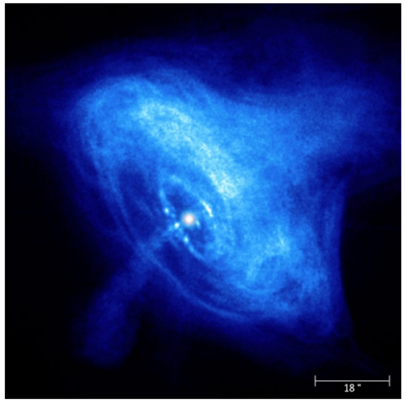
PIC model

χ=60°, α=130°

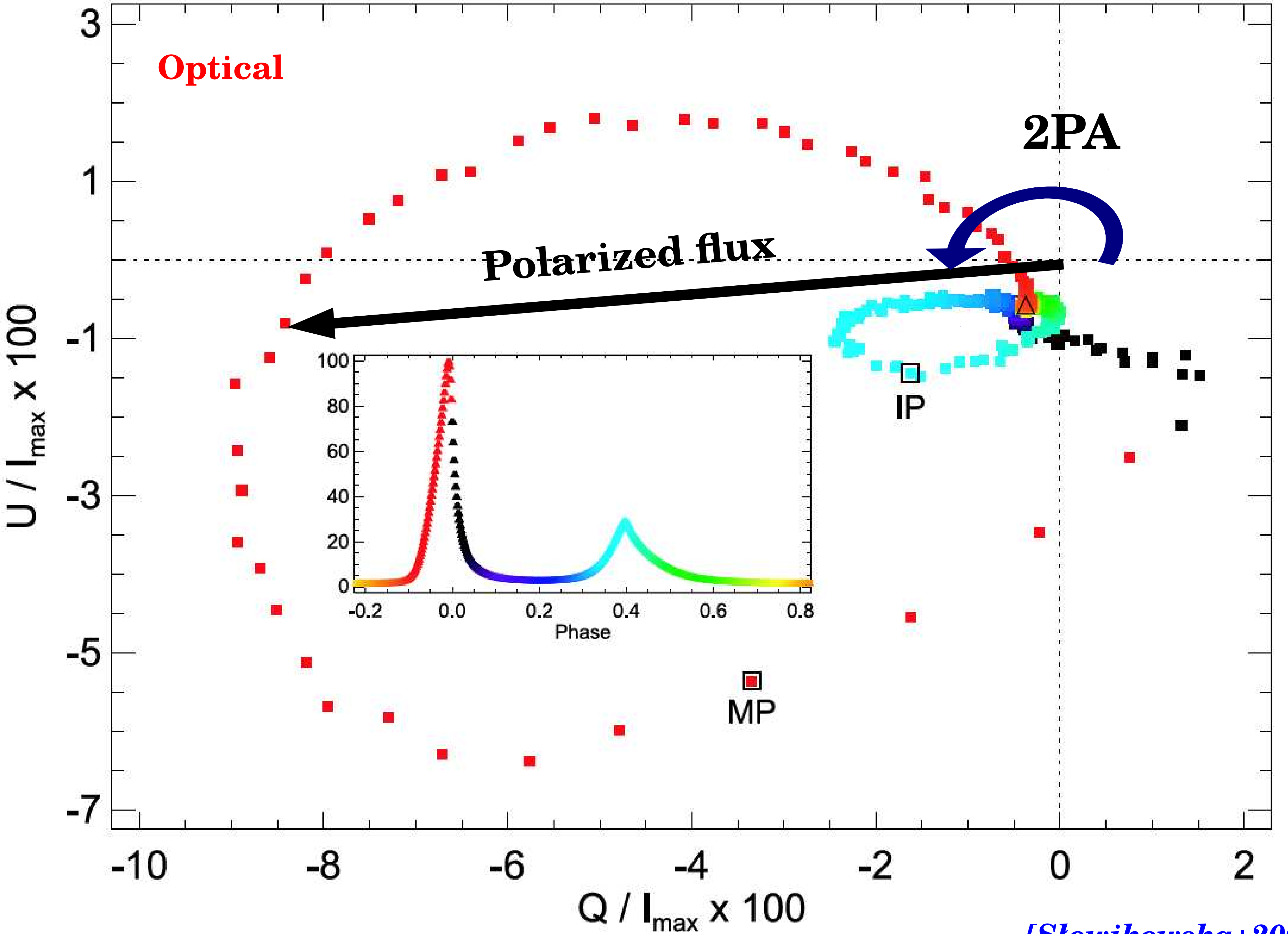


Consistent with the nebula morphology in **X-rays**

[e.g. Weisskopf+2012]



(Incoherent) Polarization signature : Observations



[Słowikowska+2009]

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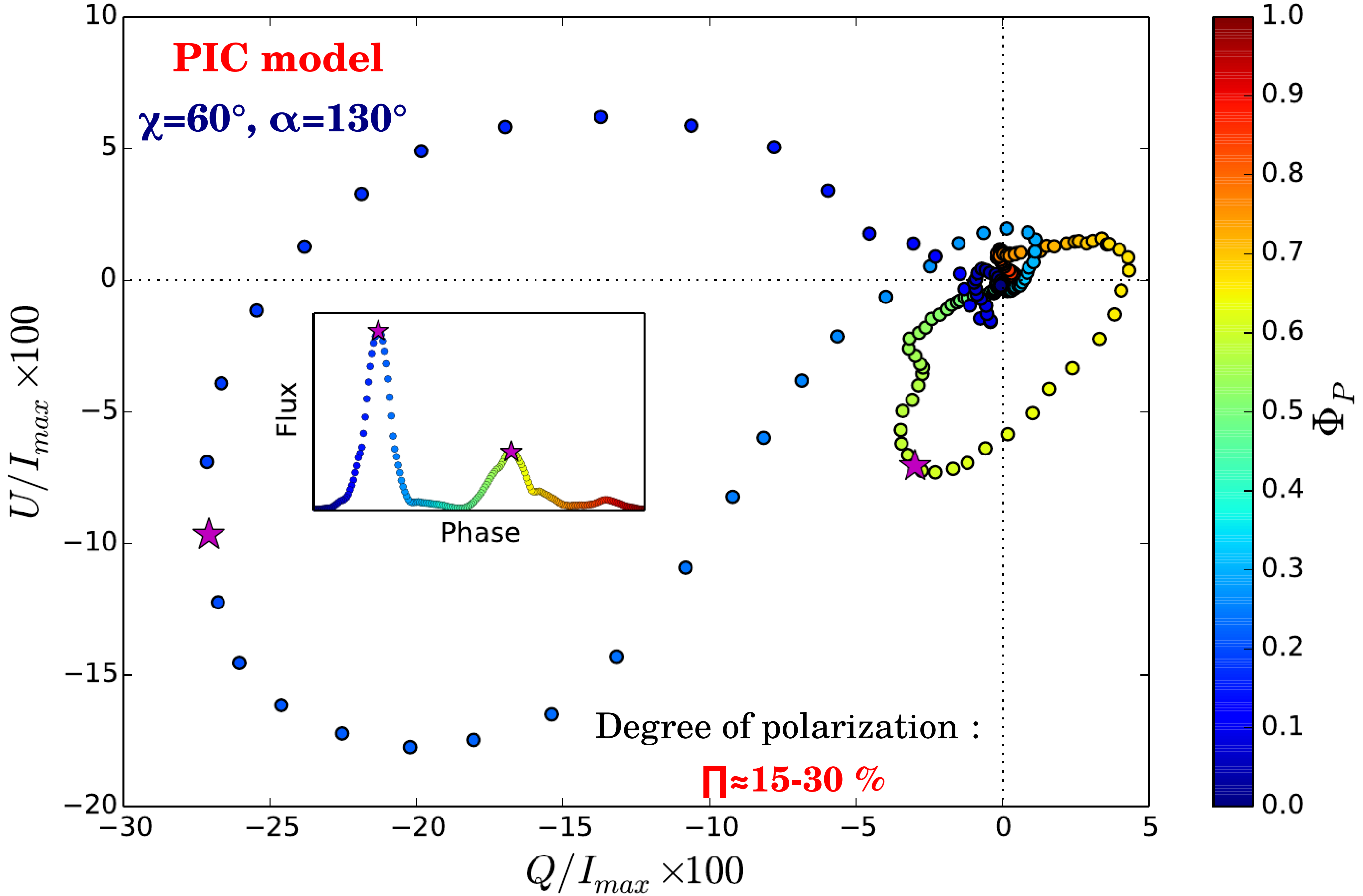
(Incoherent) Polarization signature : PIC

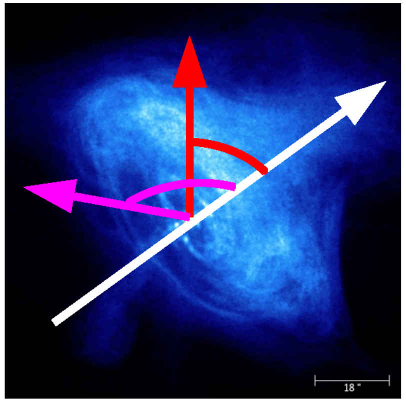


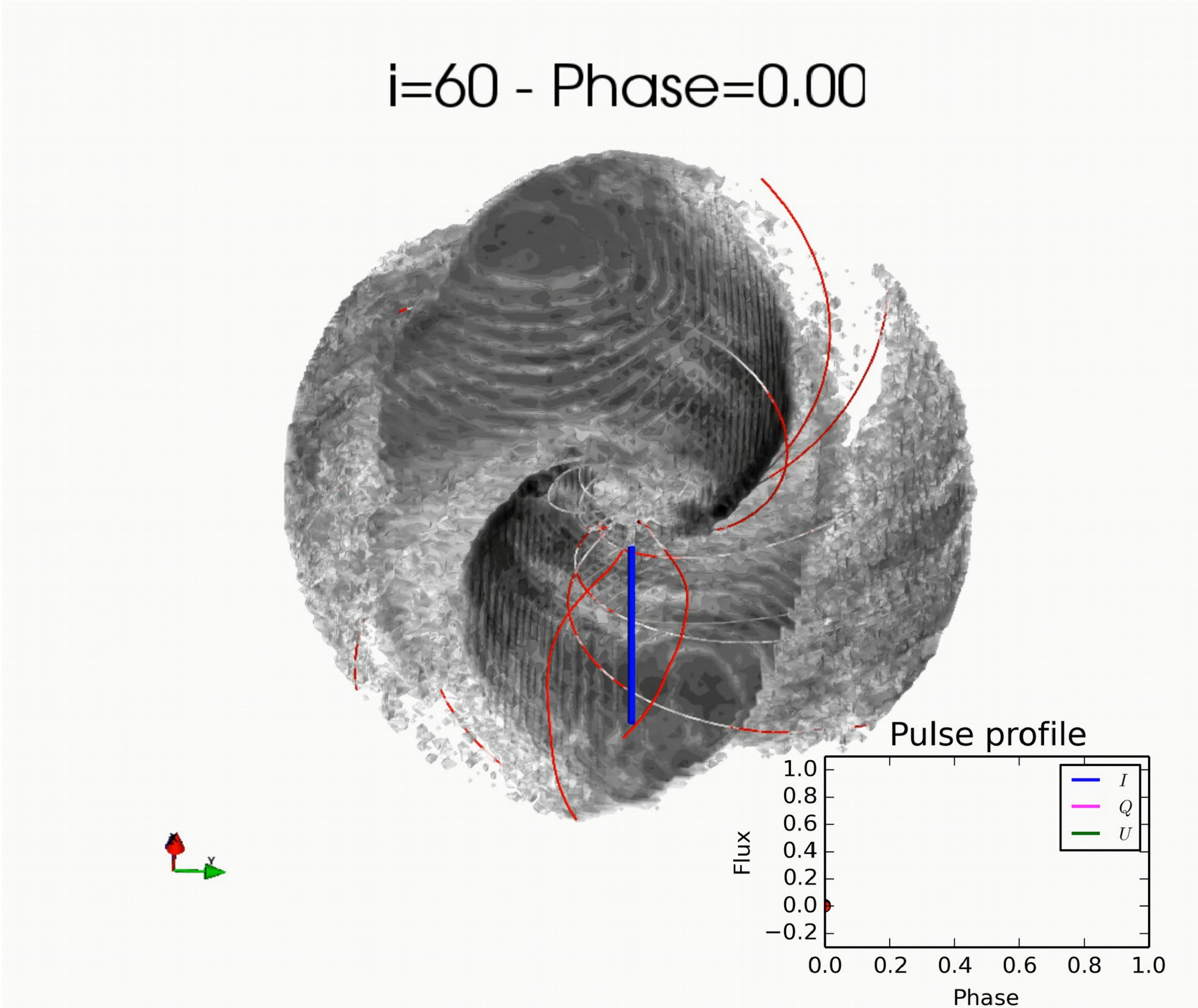
[Cerutti, Mortier & Philippov 2016]

The Crab pulsar as we may see it !

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

Obs





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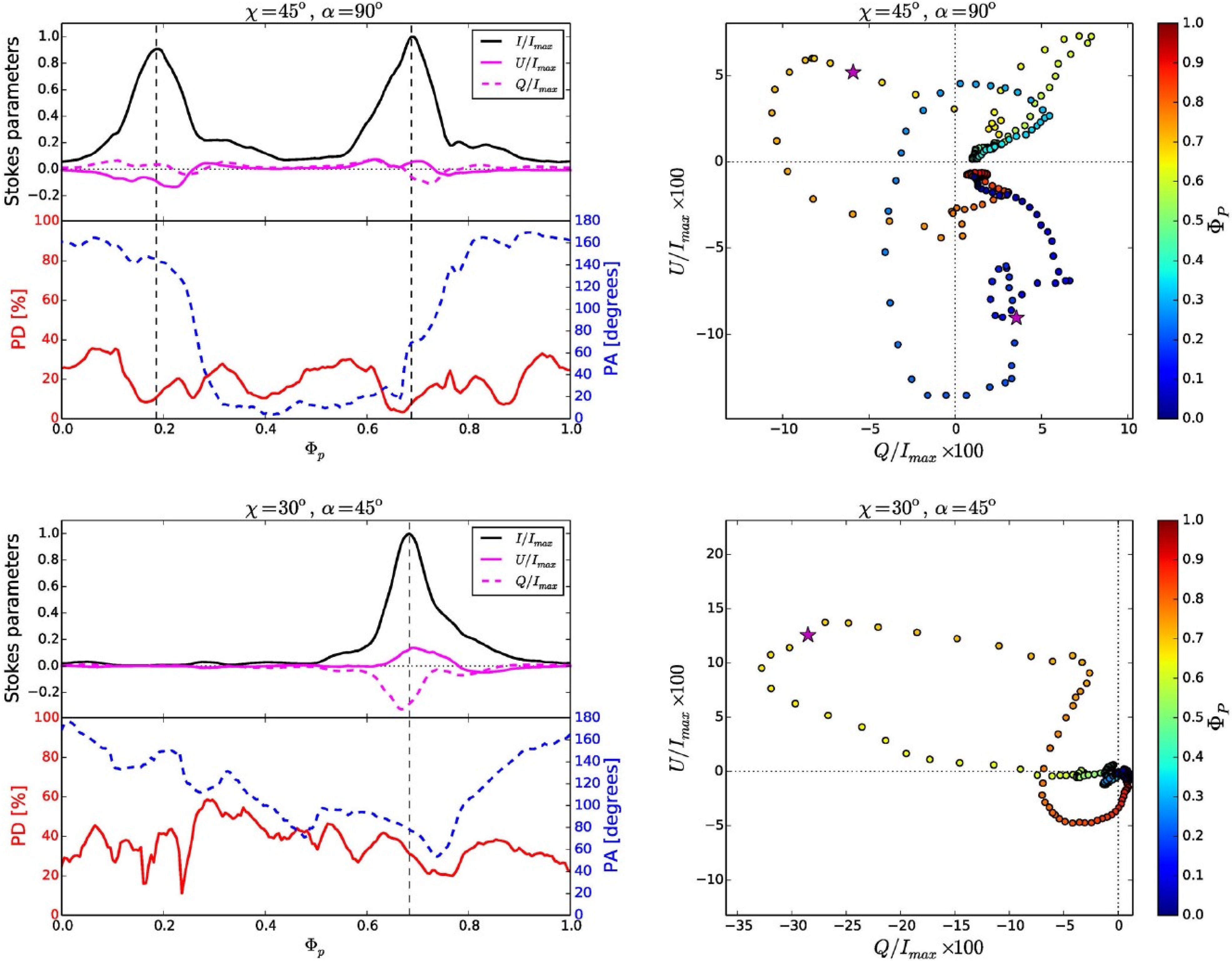
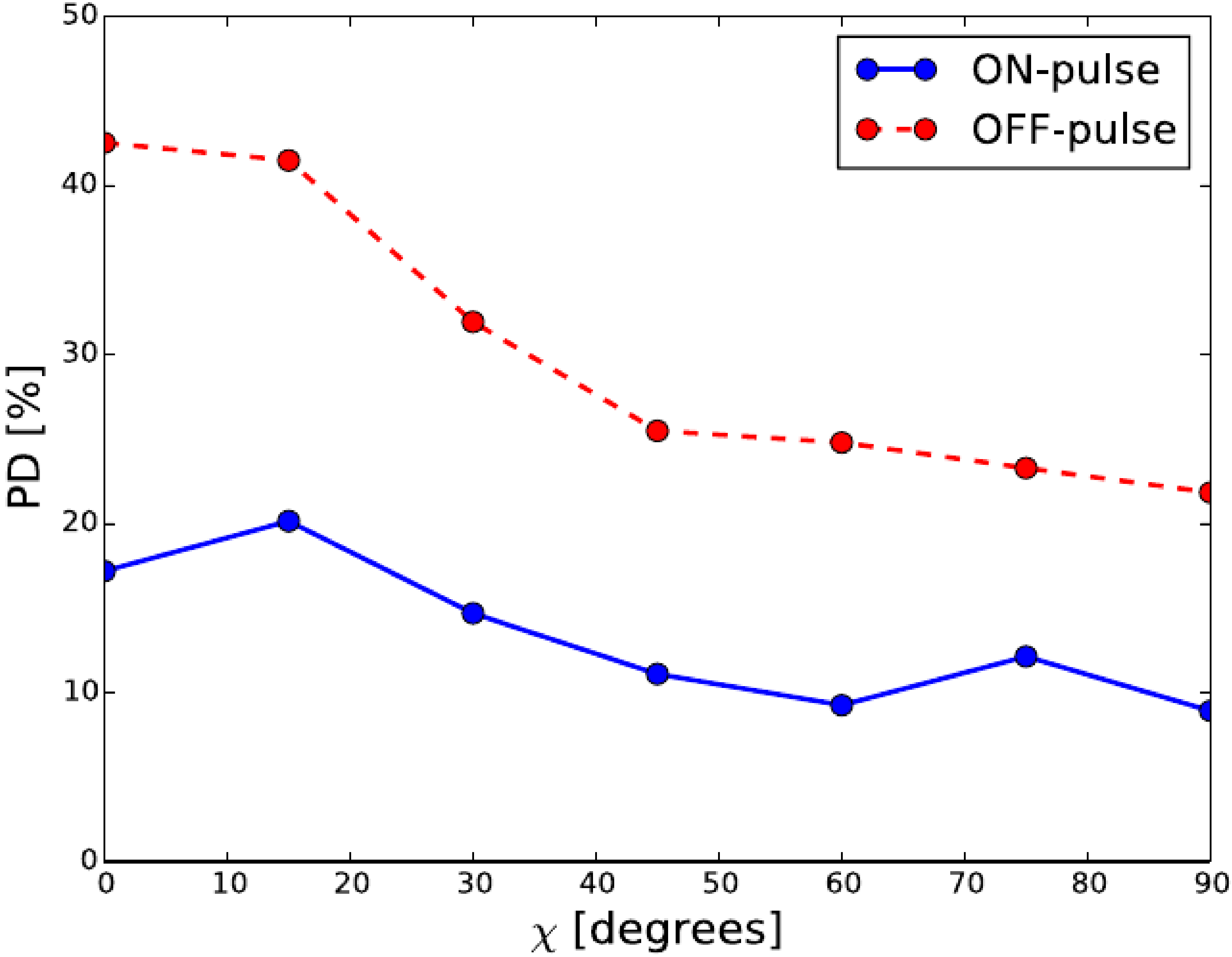


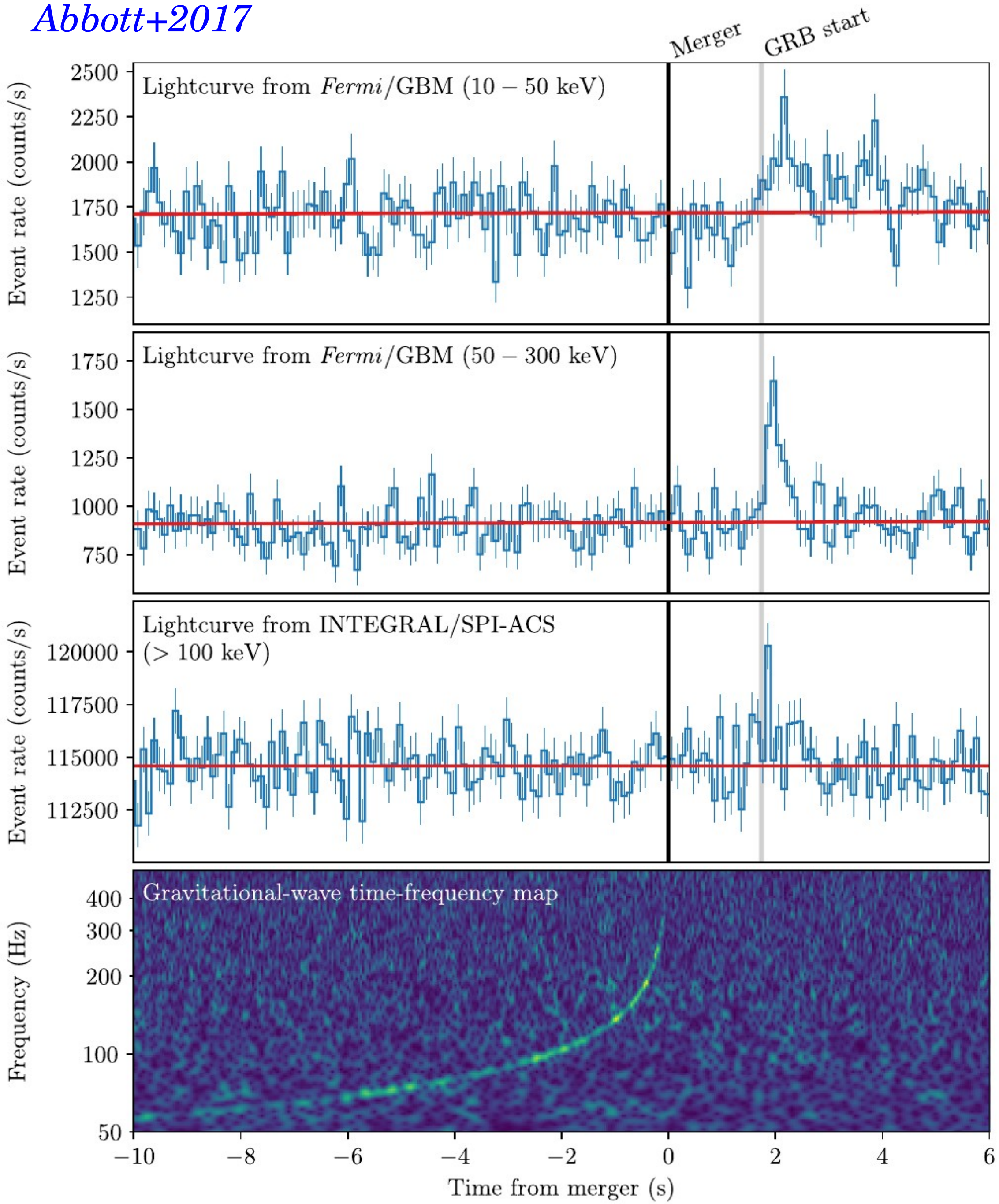
$\chi = 45^{o}$, $\alpha = 90^{o}$
Stokes parameters
I/I_{max}
U/I_{max}
Q/I_{max}
PD [%]
PA [degrees]
Φ_p
$U/I_{max} \times 100$
$Q/I_{max} \times 100$
Φ_P
$\chi = 30^{o}$, $\alpha = 45^{o}$
Stokes parameters
I/I_{max}
U/I_{max}
Q/I_{max}
PD [%]
PA [degrees]
Φ_p
$U/I_{max} \times 100$
$Q/I_{max} \times 100$
Φ_P

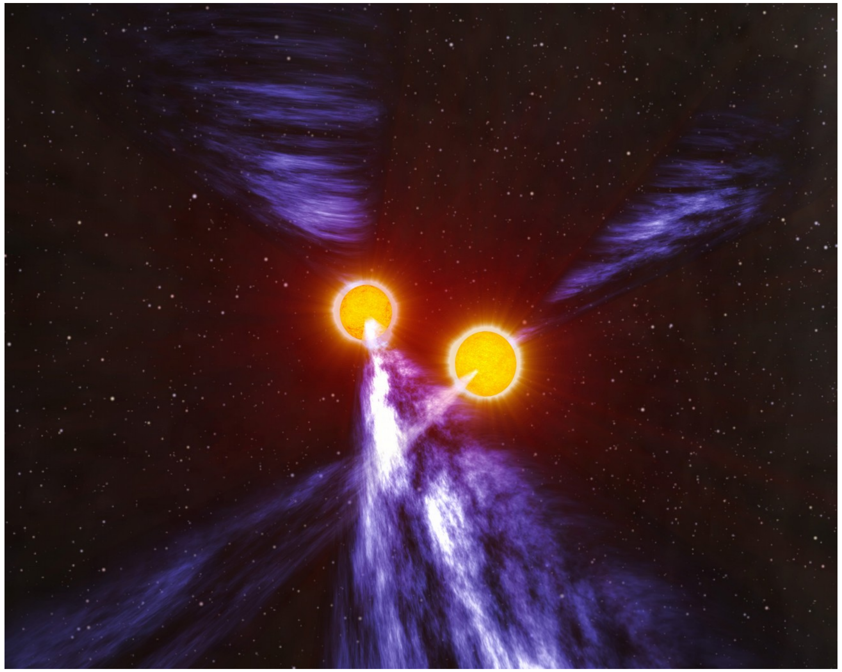
ON versus OFF pulse polarization



Merging binary pulsar

Abbott+2017

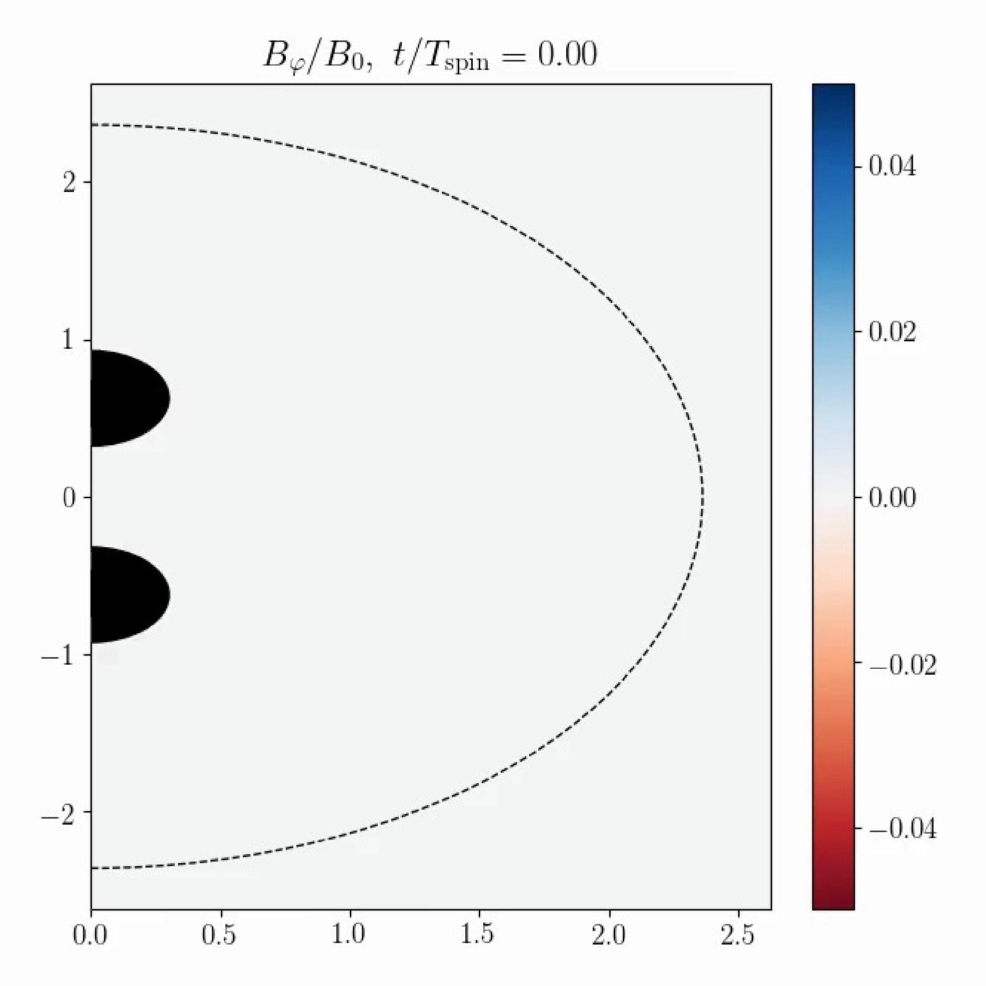




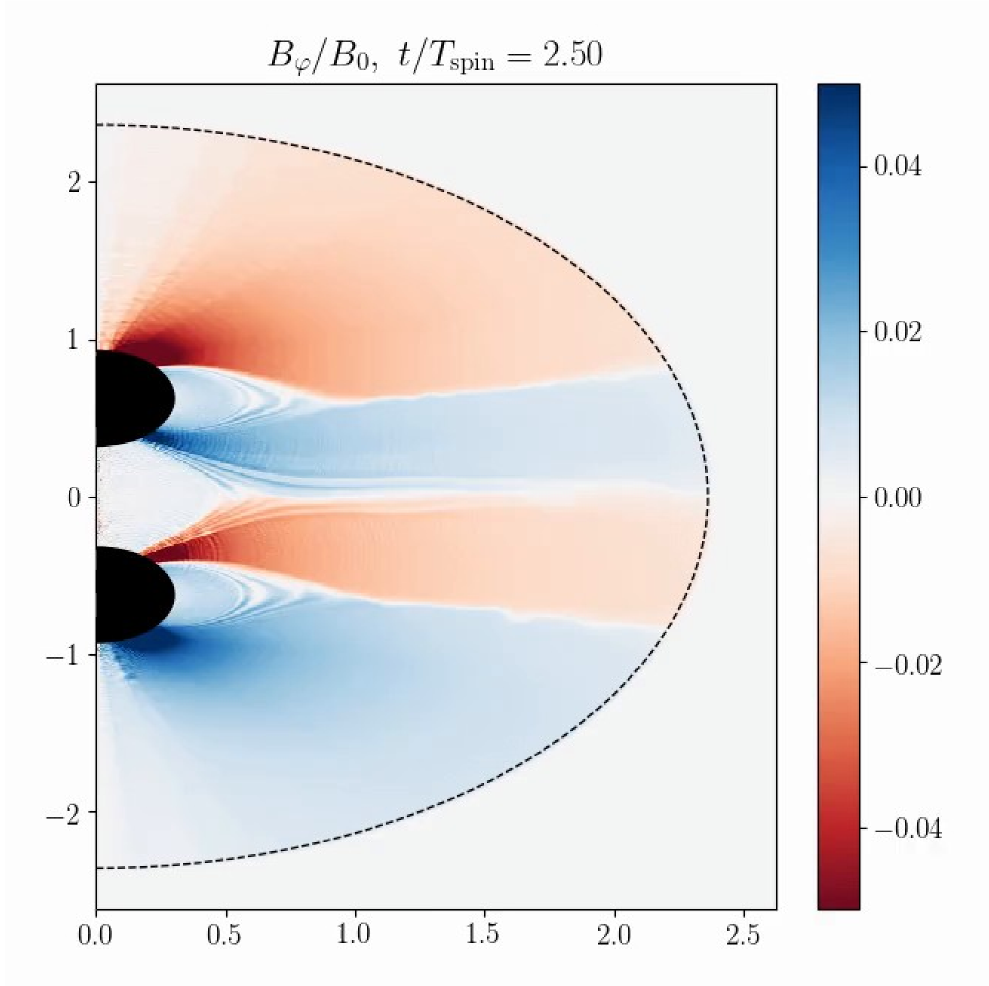
Interacting magnetospheres: an electromagnetic precursor to merging neutron star?

Merging binary pulsar: PIC simulations

Establishement of the magnetospheres



Inspiral begins

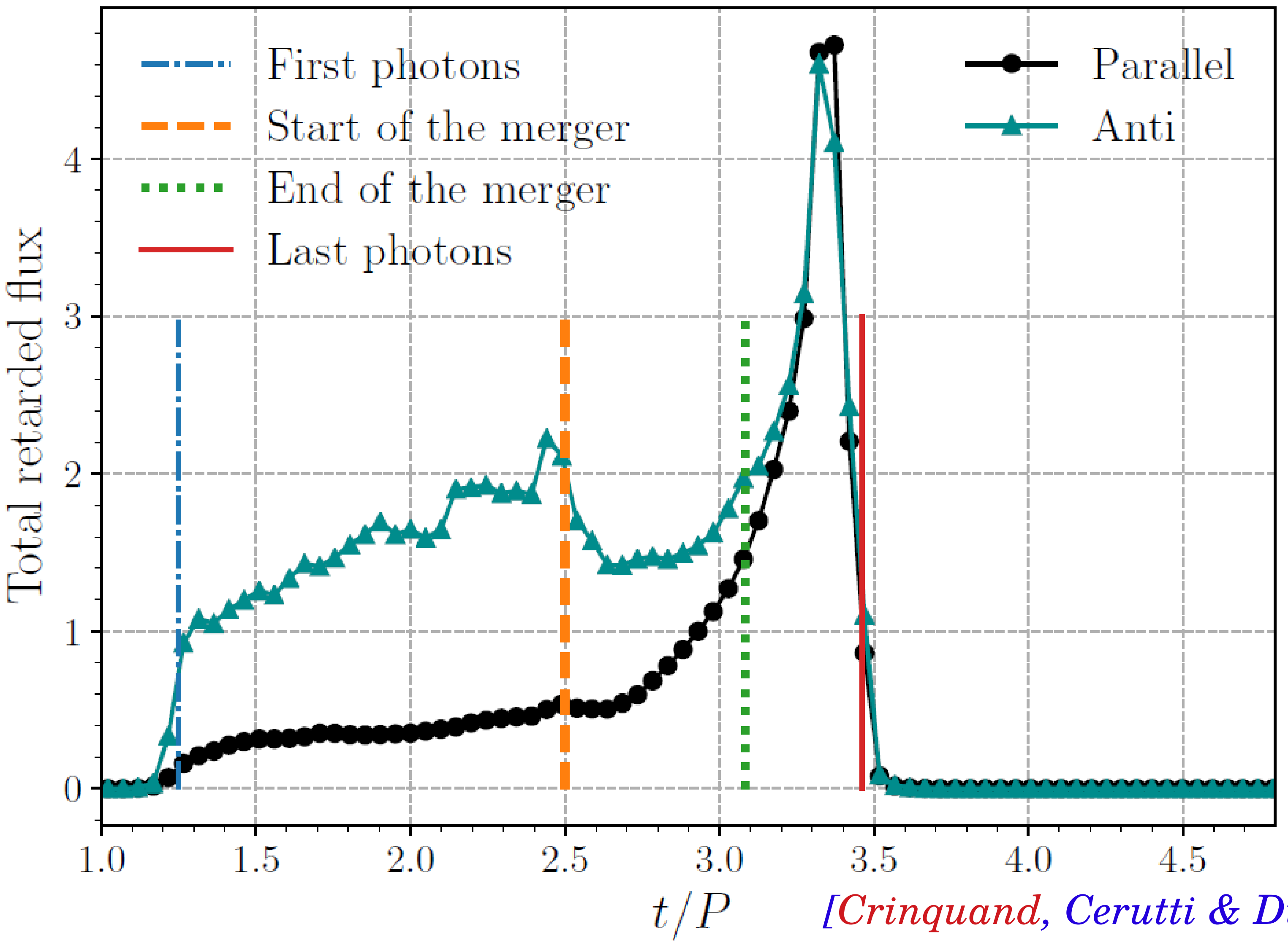


[Crinquand, Cerutti & Dubus 2018]

Driven reconnection in the inspiral phase. Reconnection of the poloidal field

=> Strong magnification of dissipation

A detectable precursor?



[Crinquand, Cerutti & Dubus 2018]

2 orders of magnitude gamma-ray luminosity increase during the inspiral !
Still **too weak to be detected.** Go to 3D + orbital motion !

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.

- **Open questions :**
  - How to scale simulations up to realistic pulsars ?
  - How to refine pair creation modeling ?
  - What is origin of the radio emission ?
  - ...