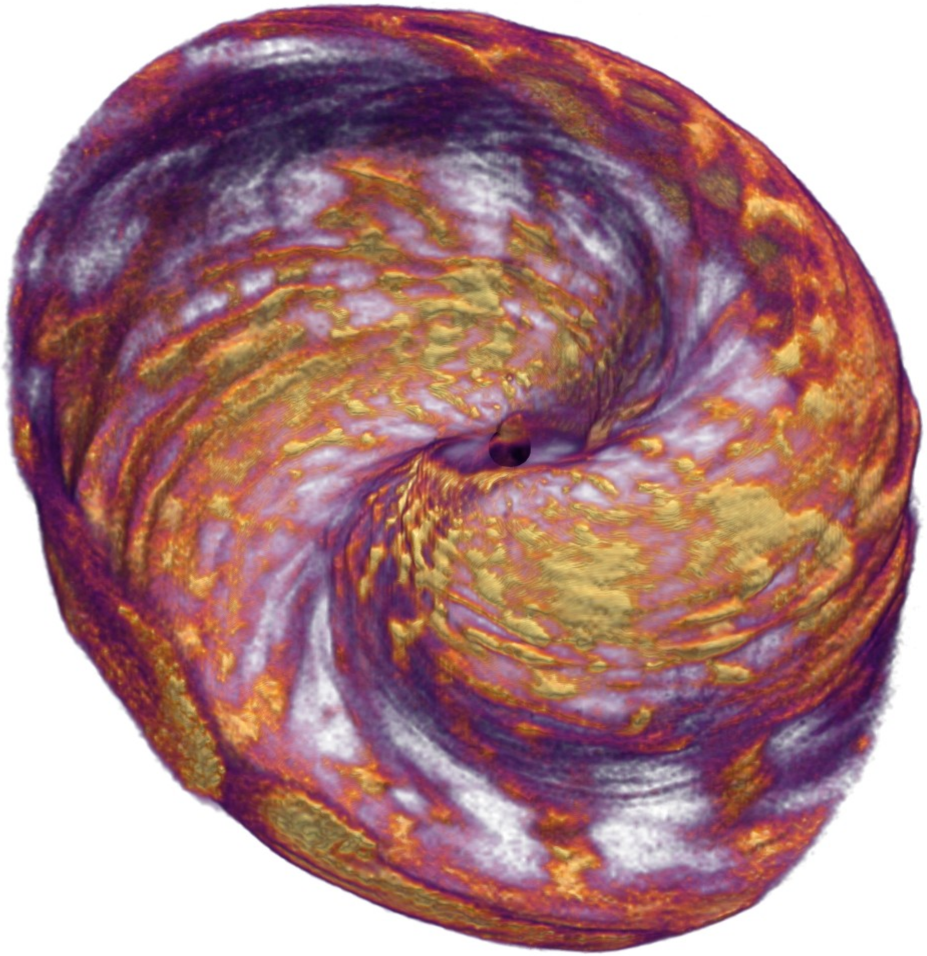
An update of what we have been up to in Grenoble since the last ISSI meeting



Benoît Cerutti, Guillaume Dubus, Enzo Figuereido, Sasha Philippov, Adrien Soudais, Ceyhun Andaç, Yavuz Eksi

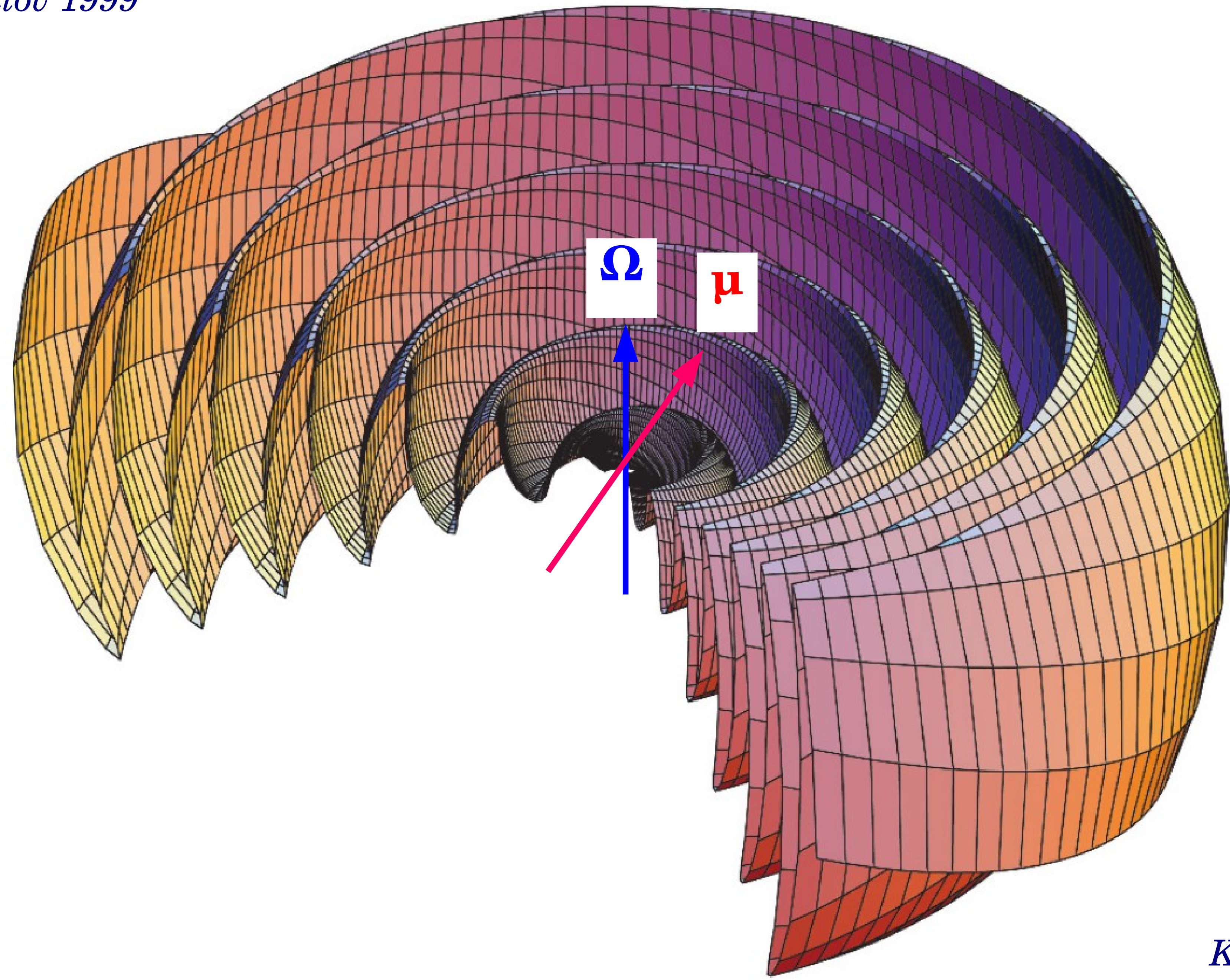
ISSI meeting 2022, Bern, Sept 12, 2022

Part 1: Dissipation

BC + Sasha Philippov + Guillaume Dubus

Inclined rotator: Striped current sheet

Bogovalov 1999

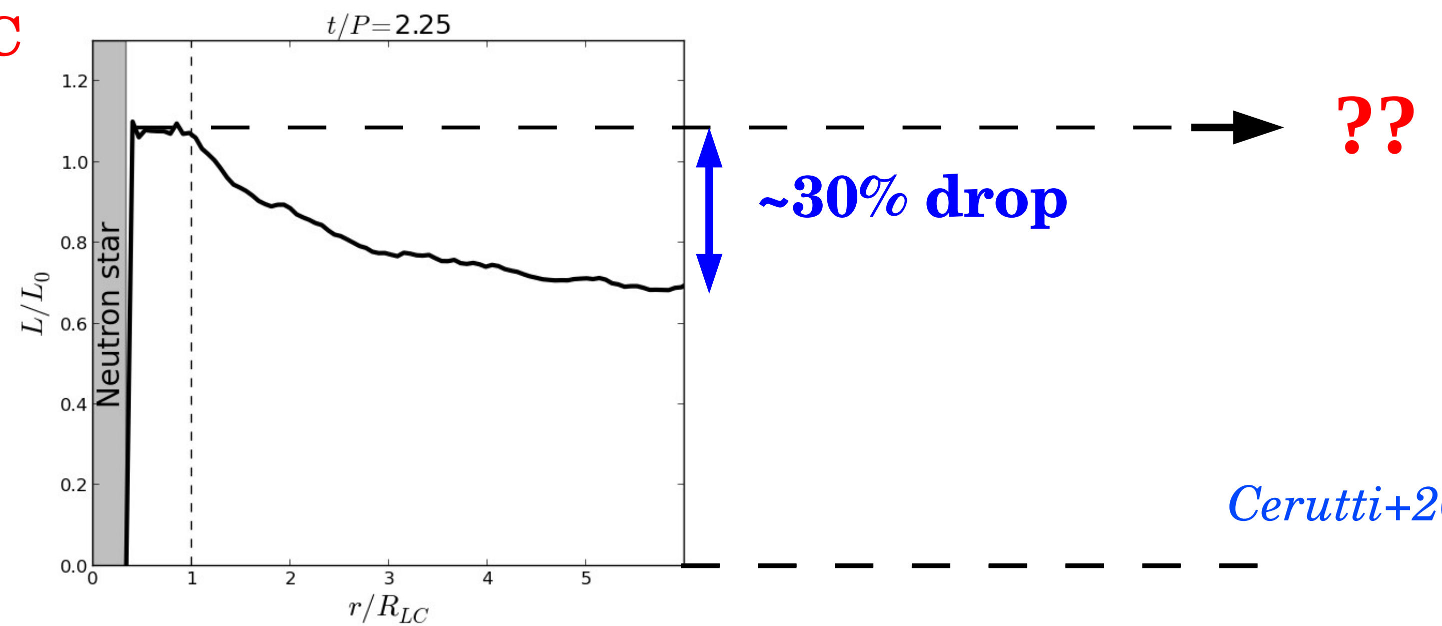


Kirk+2009

Magnetic dissipation and particle acceleration

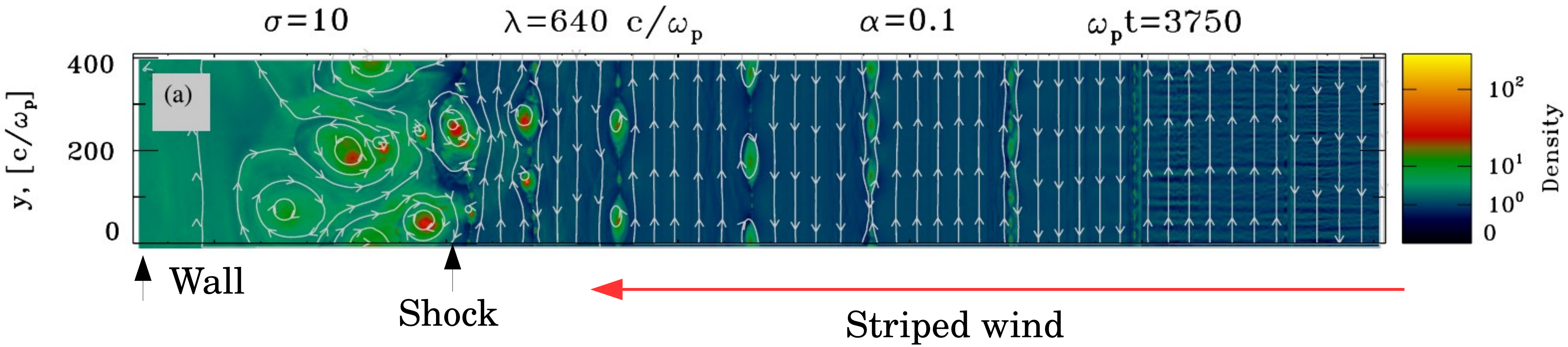
2D PIC

Poynting flux



Cerutti+2015

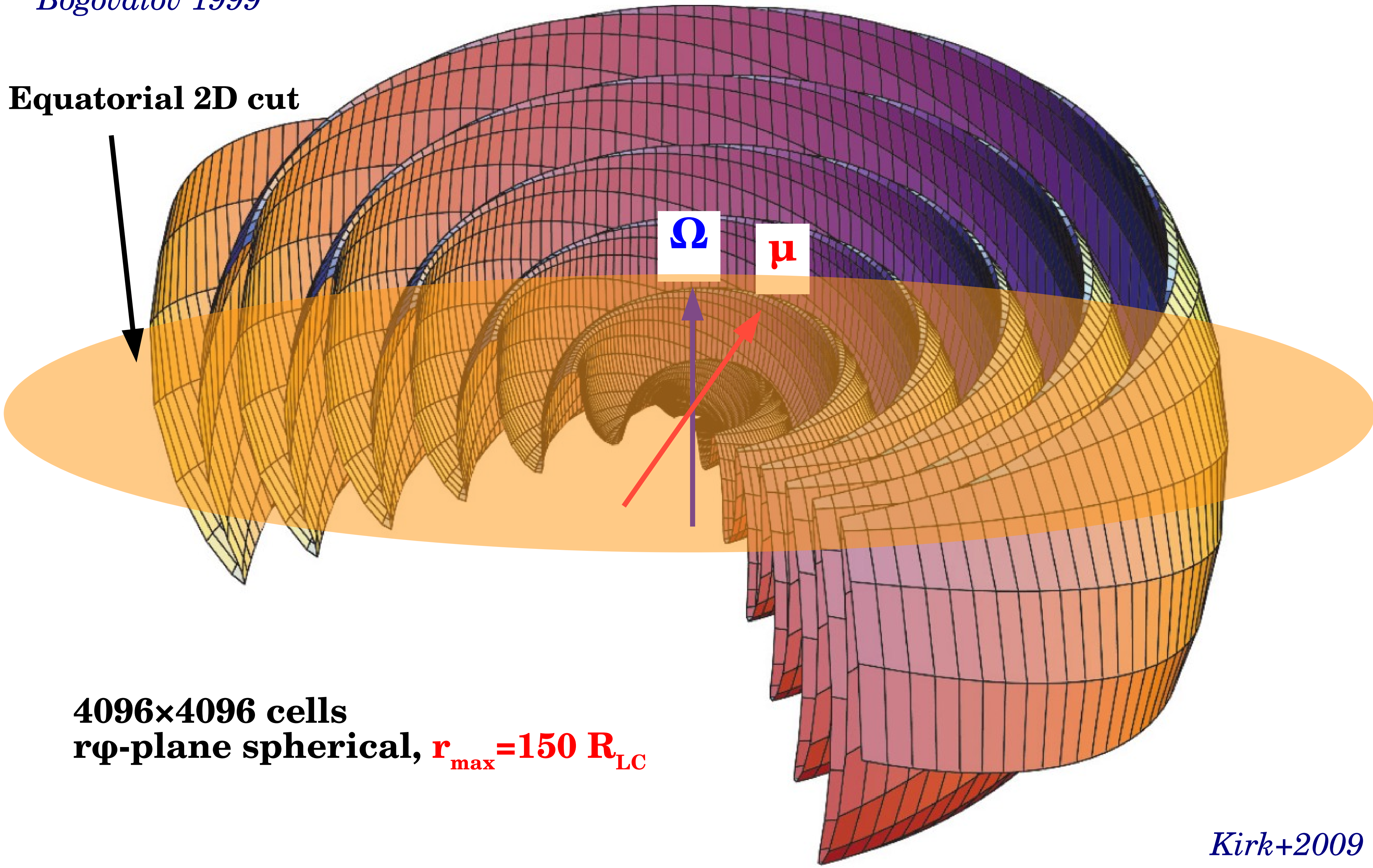
Scenario 1 : Complete dissipation far before the shock
Coroniti 1990 ; Michel 1994 ; Lyubarsky & Kirk 2001 ; Kirk & Skjæraasen 2003
Scenario 2 *:* Shock-driven reconnection at the termination shock
Lyubarsky 2003 ; Pétri & Lyubarsky 2007 ; Sironi & Spitkovsky 2011



First attempt with 2D PIC simulations in 2017

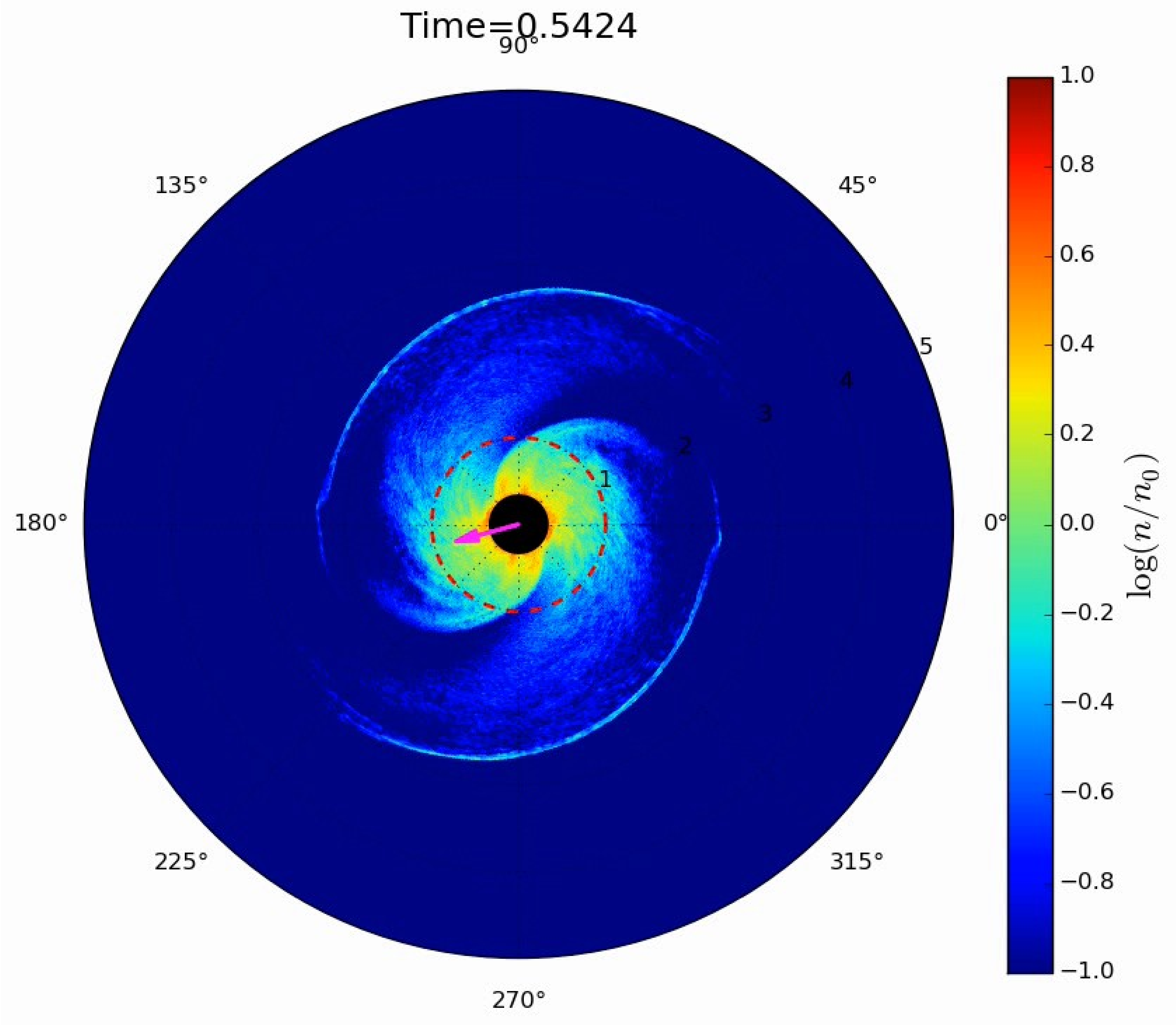
Bogovalov 1999

Equatorial 2D cut



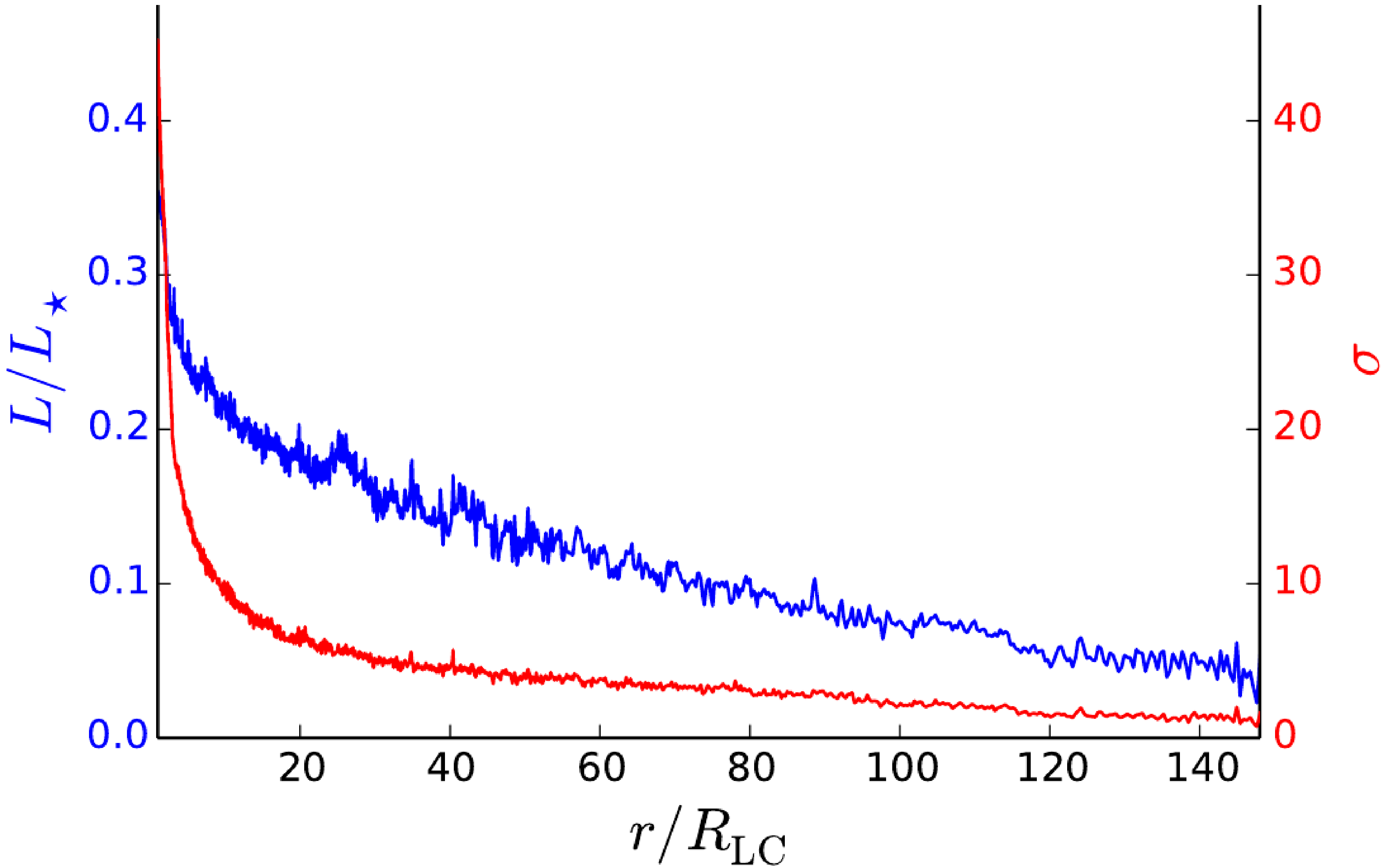
4096×4096 cells
rφ-plane spherical, r_{max}=150 R_{LC}

Kirk+2009



Time=0.5424
90°
45°
0°
315°
270°
225°
180°
135°
1
2
3
4
5
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
$\log(n/n_0)$

Our conclusion was: full dissipation of the stripes



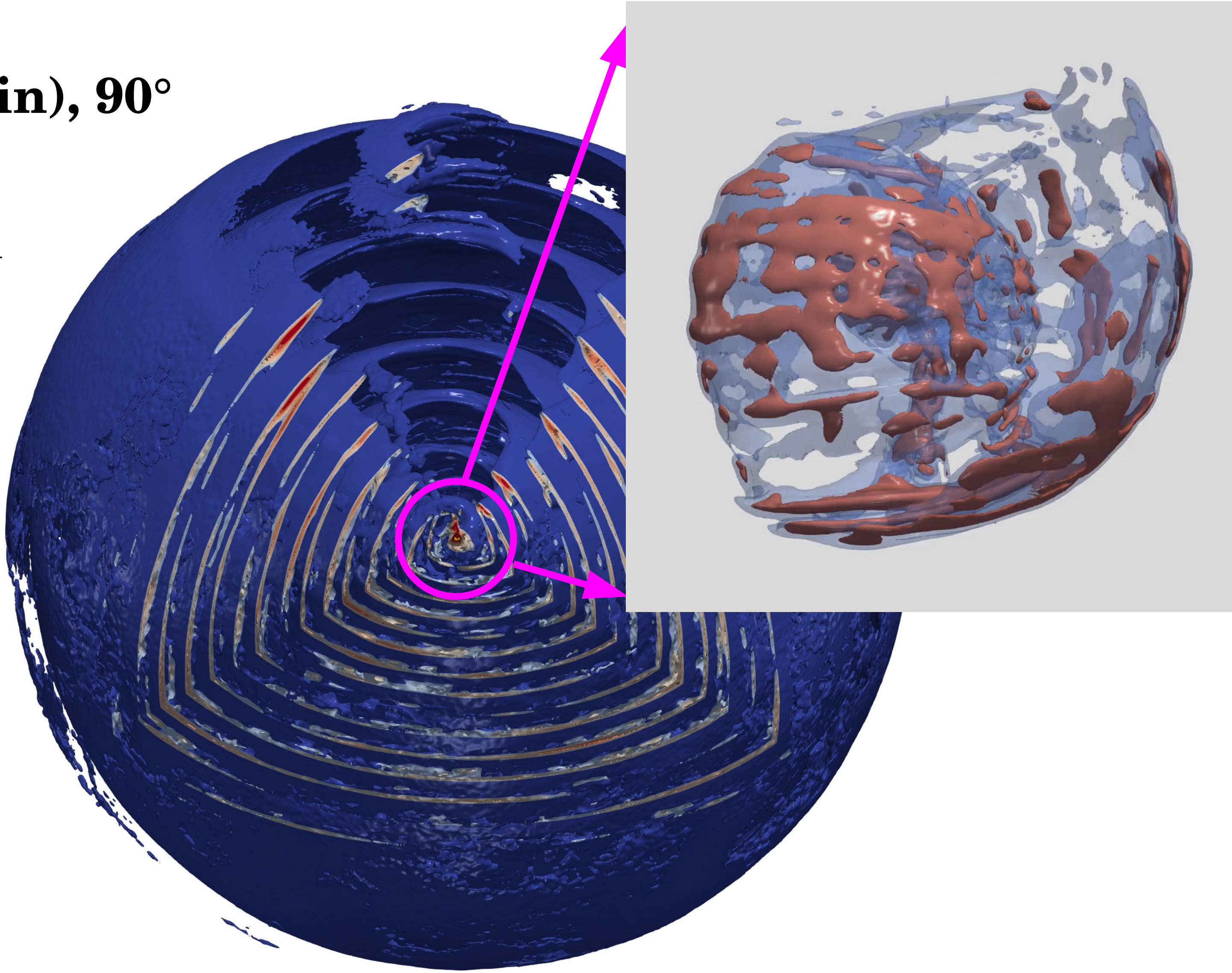
Is it still true in full 3D?
What is the latitudinal dependence of dissipation?

The FROMTON project

PRACE PROJECT: FROM the Magnetosphere TO the Nebula (FROMTON)
26.7 million CPU-hours allocated on Irene-SKL (TGCC)

χ=30°, 60°(r-log & r-lin), 90°

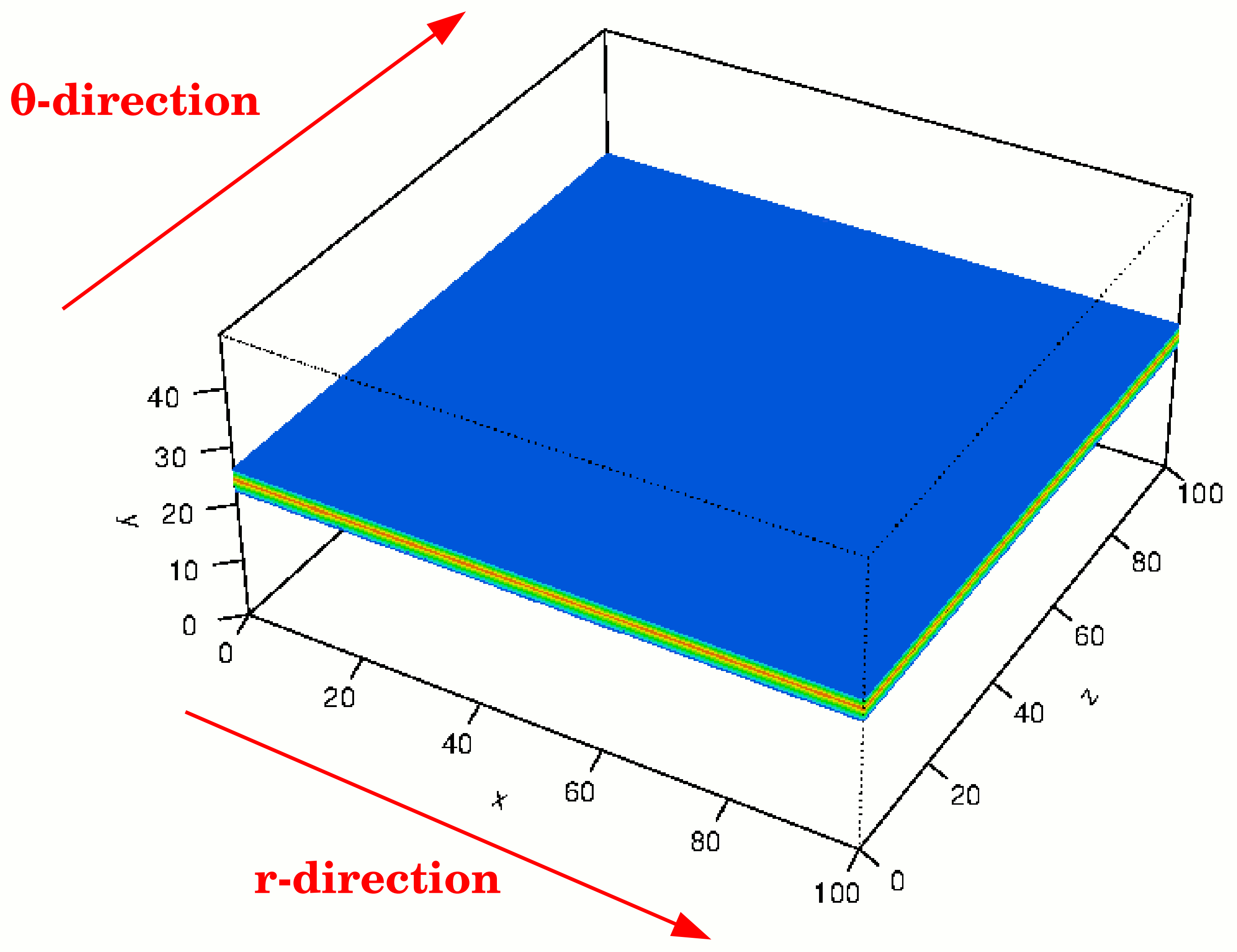
R_{max}=100 R_{LC}
~5 million CPU-hrs per run
(2016×1024×512) cells
(r×θ×φ)
10^{10} particles (~10 per cell)

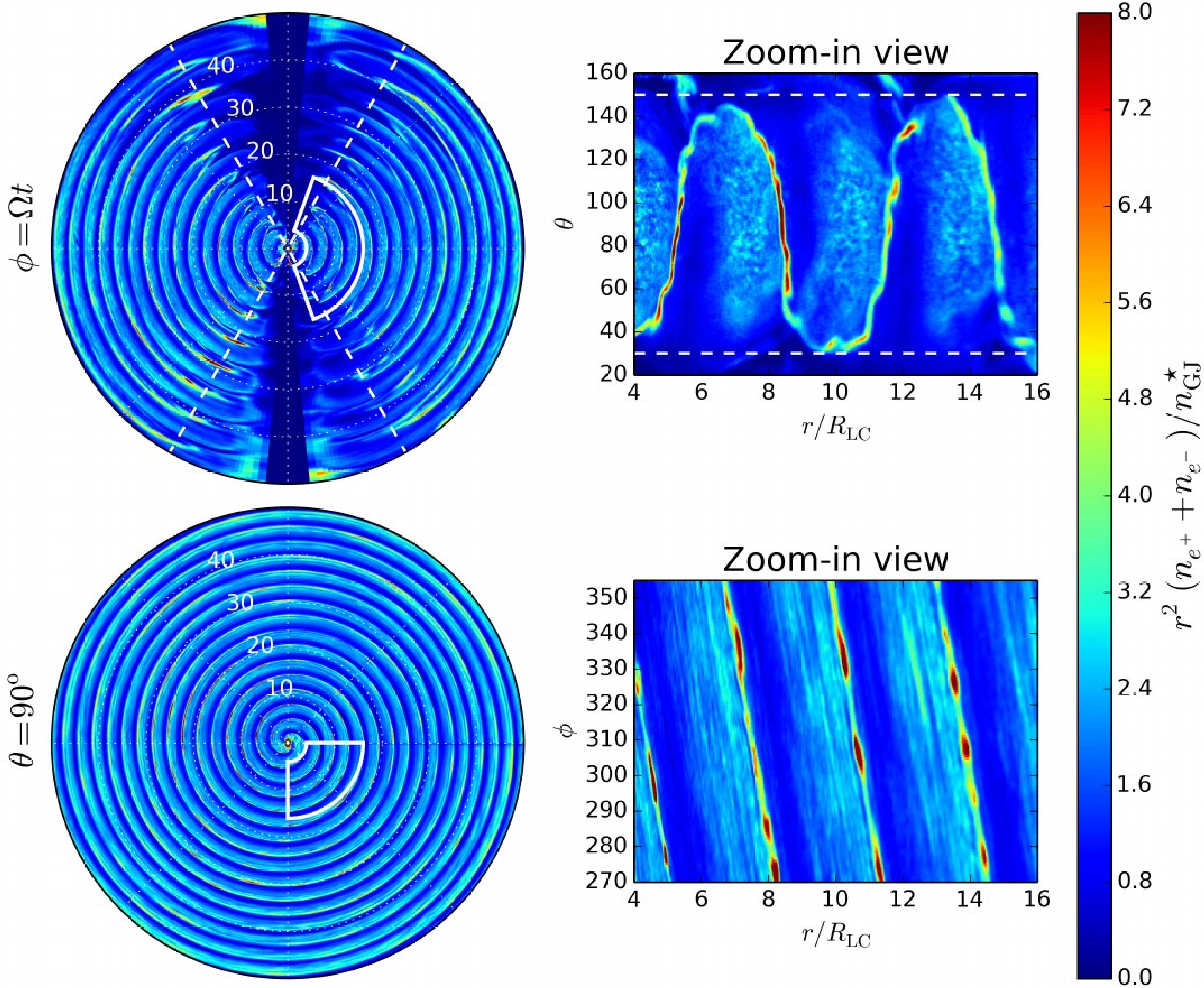


Plasmoid-dominated reconnection: dynamical chain of merging flux ropes

Plasmoid-dominated reconnection: dynamical chain of merging flux ropes

Local 3D Cartesian plane-parallel reconnection





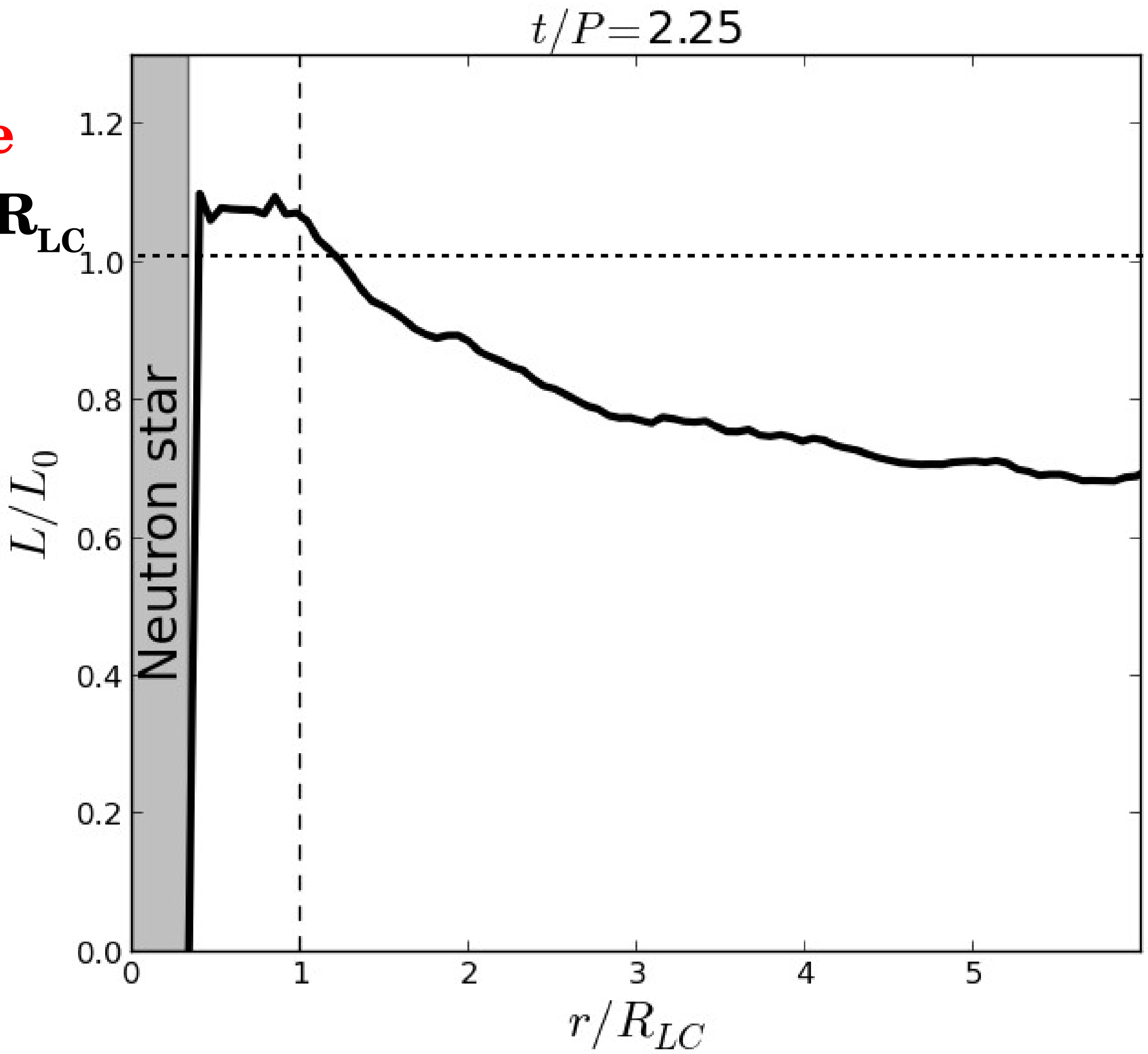
$\phi = \Omega t$
$\theta = 90^{o}$
10
20
30
40
Zoom-in view
θ
ϕ
$r/R_{\rm LC}$
4
6
8
10
12
14
16
20
40
60
80
100
120
140
160
270
280
290
300
310
320
330
340
350
$r^2\,(n_{e^+}+n_{e^-})/n^{\star}_{\rm GJ}$
0.0
0.8
1.6
2.4
3.2
4.0
4.8
5.6
6.4
7.2
8.0

Pulsar spin down and dissipation

e.g., Philippov & Spikovsky 2014; Cerutti et al. 2015; Belyaev 2015; Brambilla et al. 2018

Force-free

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



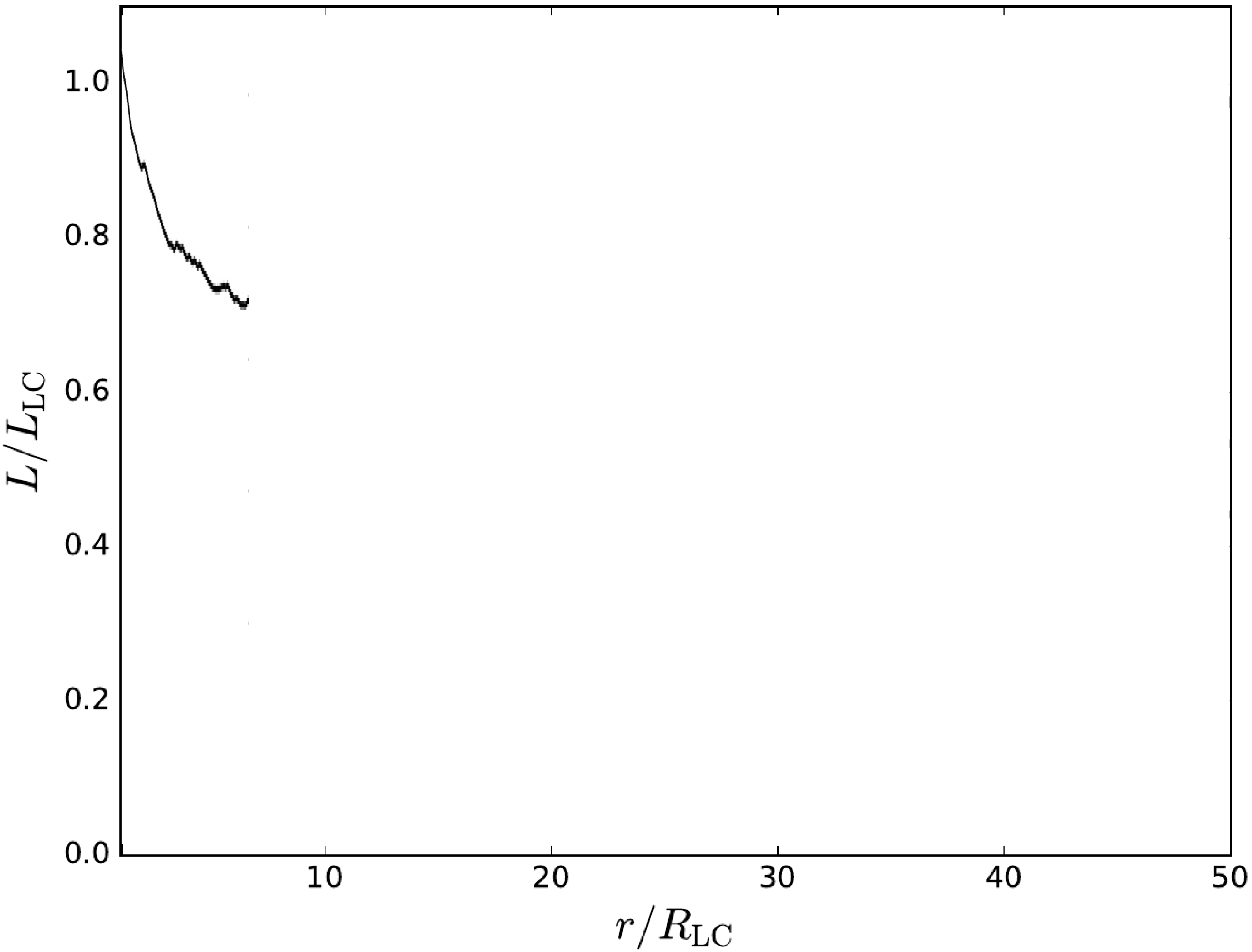
~30% drop

Significant dissipation within a few R_{LC}!

=> Energy transferred to energetic particles and radiation!

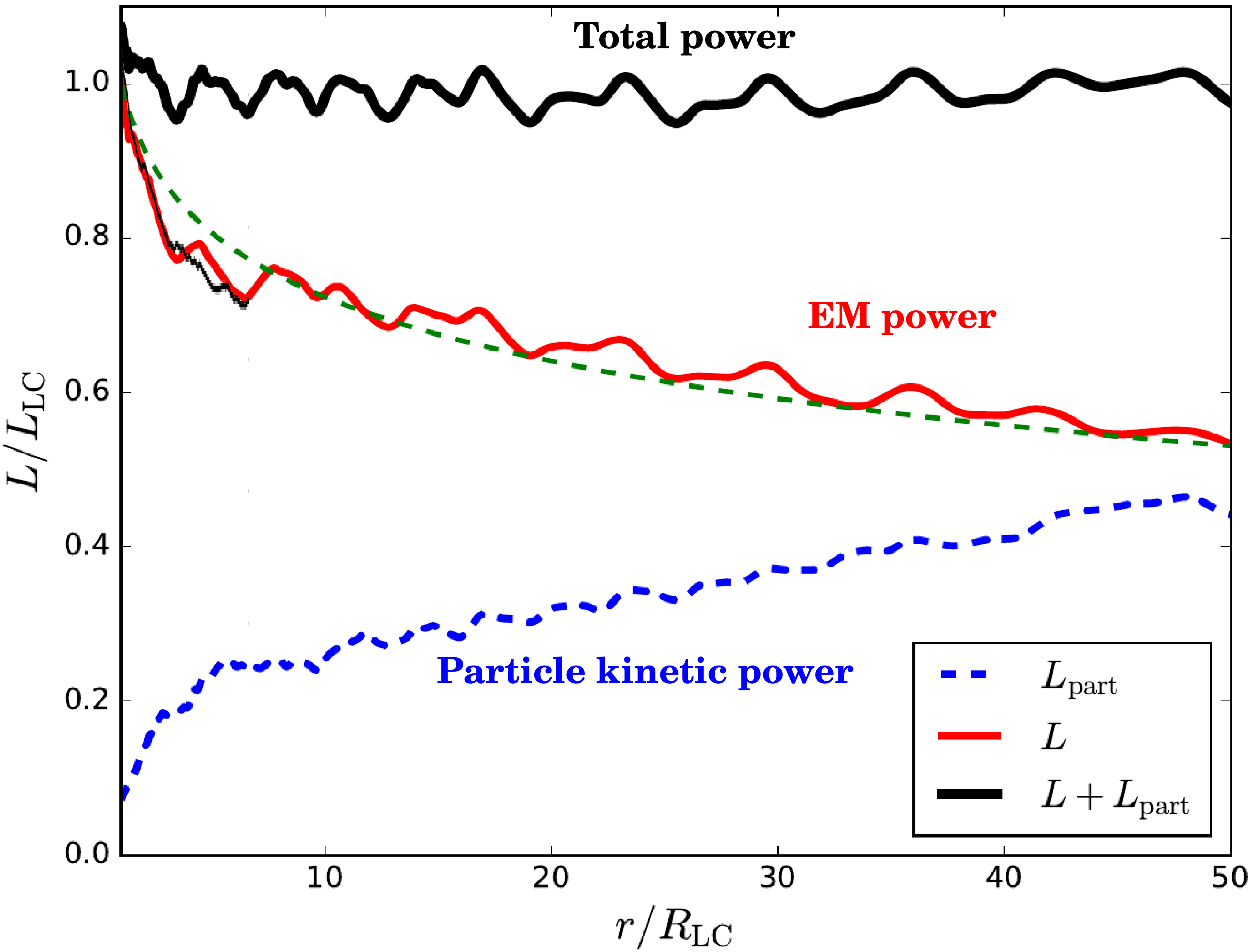
Dissipation proceeds without any sign of saturation

Cerutti et al. 2020



Dissipation proceeds without any sign of saturation

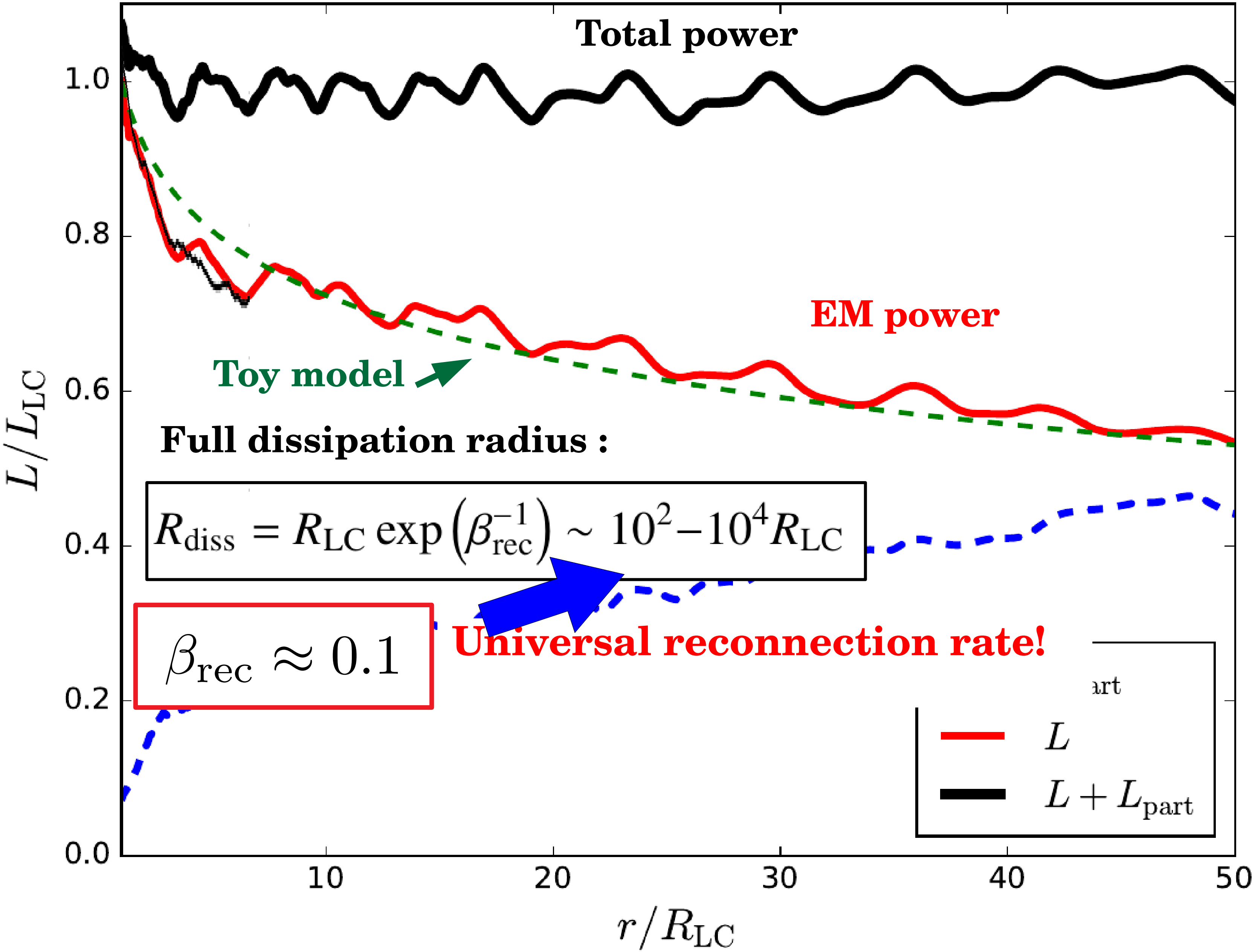
Cerutti et al. 2020



Conclusion: <u>full dissipation</u> of the wind far upstream in isolated pulsars
In contrast with *Kirk+ 2003* and *Lyubarsky & Kirk 2001* conclusions

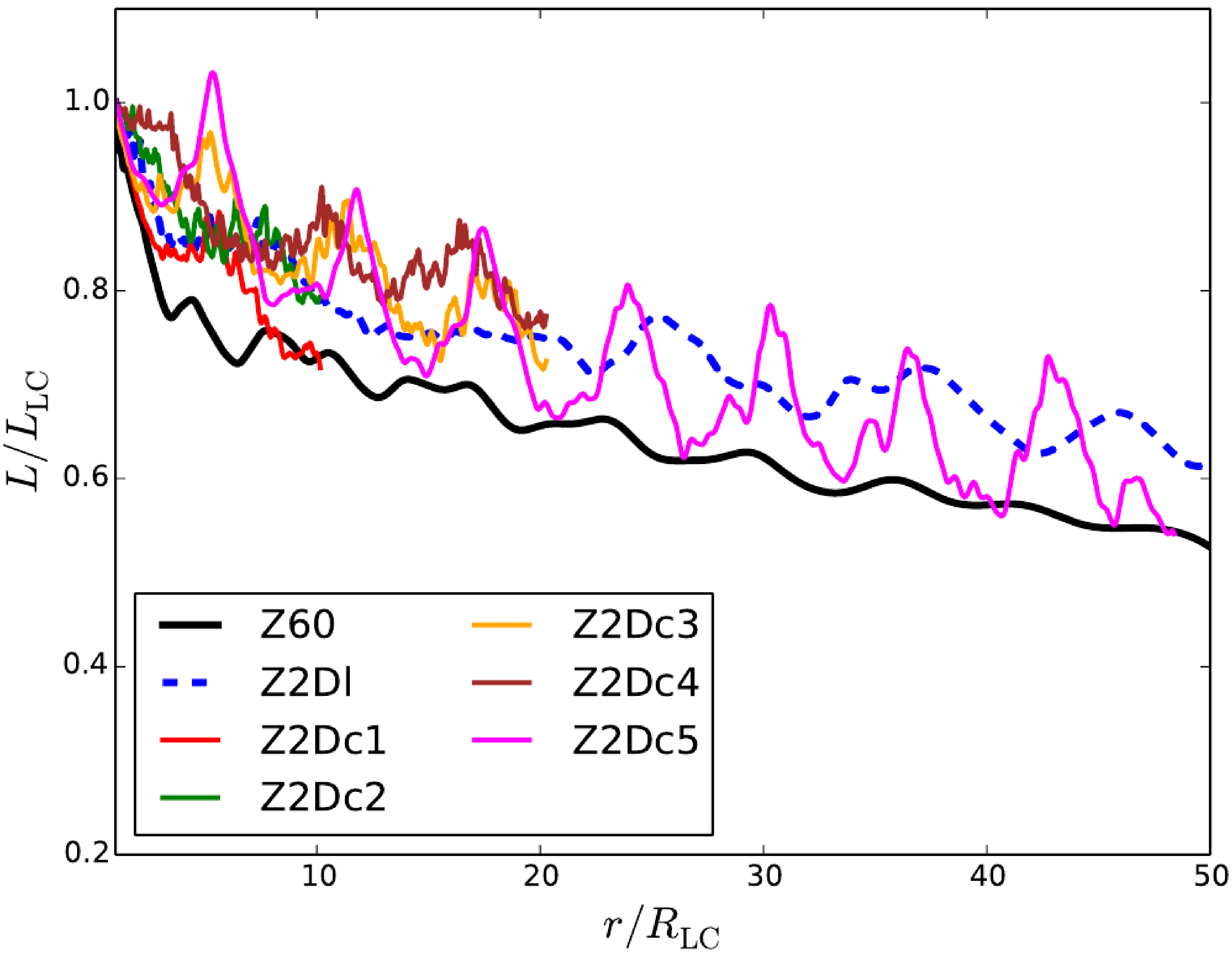
Dissipation proceeds without any sign of saturation

Cerutti et al. 2020

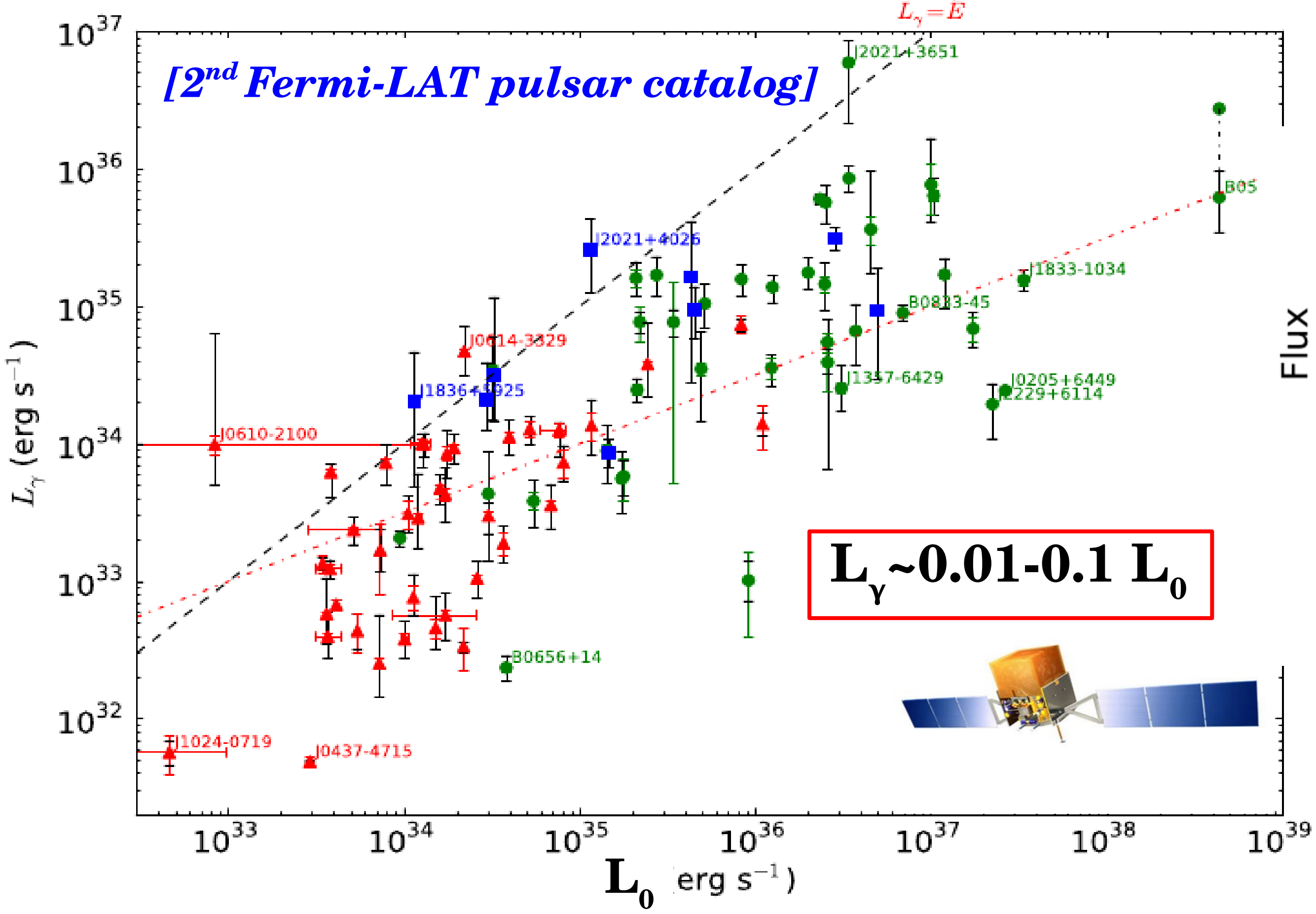


Conclusion: full dissipation of the wind far upstream in isolated pulsars
In contrast with *Kirk+ 2003* and *Lyubarsky & Kirk 2001* conclusions

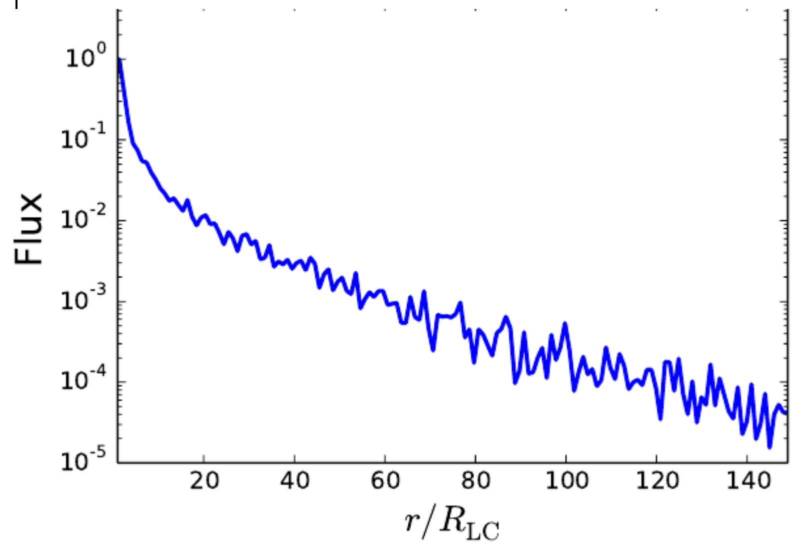
Dissipation rate robust against resolution & grid spacing



Dissipation and the gamma-ray luminosity



PIC simulations



Synchrotron Flux peaked ~ few R_{LC}

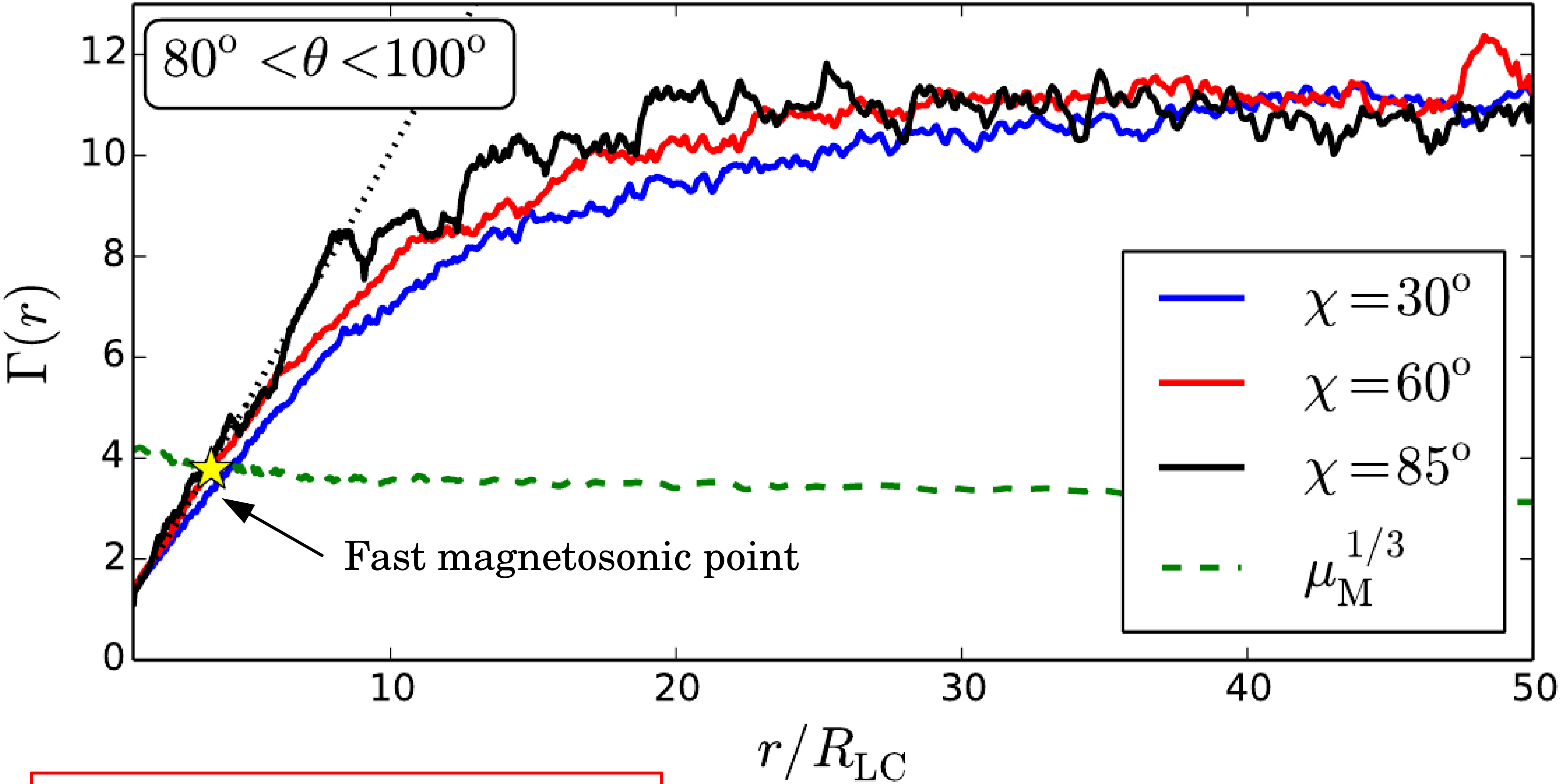
Toy model predicts:

$$\frac{L(r)}{L_0} = 1 - \beta_{rec} \ln\left(\frac{r}{R_{LC}}\right)$$

$$\frac{L_\gamma}{L_0} \approx 1 - \frac{L(r = eR_{LC})}{L_0} = \beta_{rec}$$

The γ-ray luminosity may be a measure of the reconnection rate!

Saturation of the bulk Lorentz factor

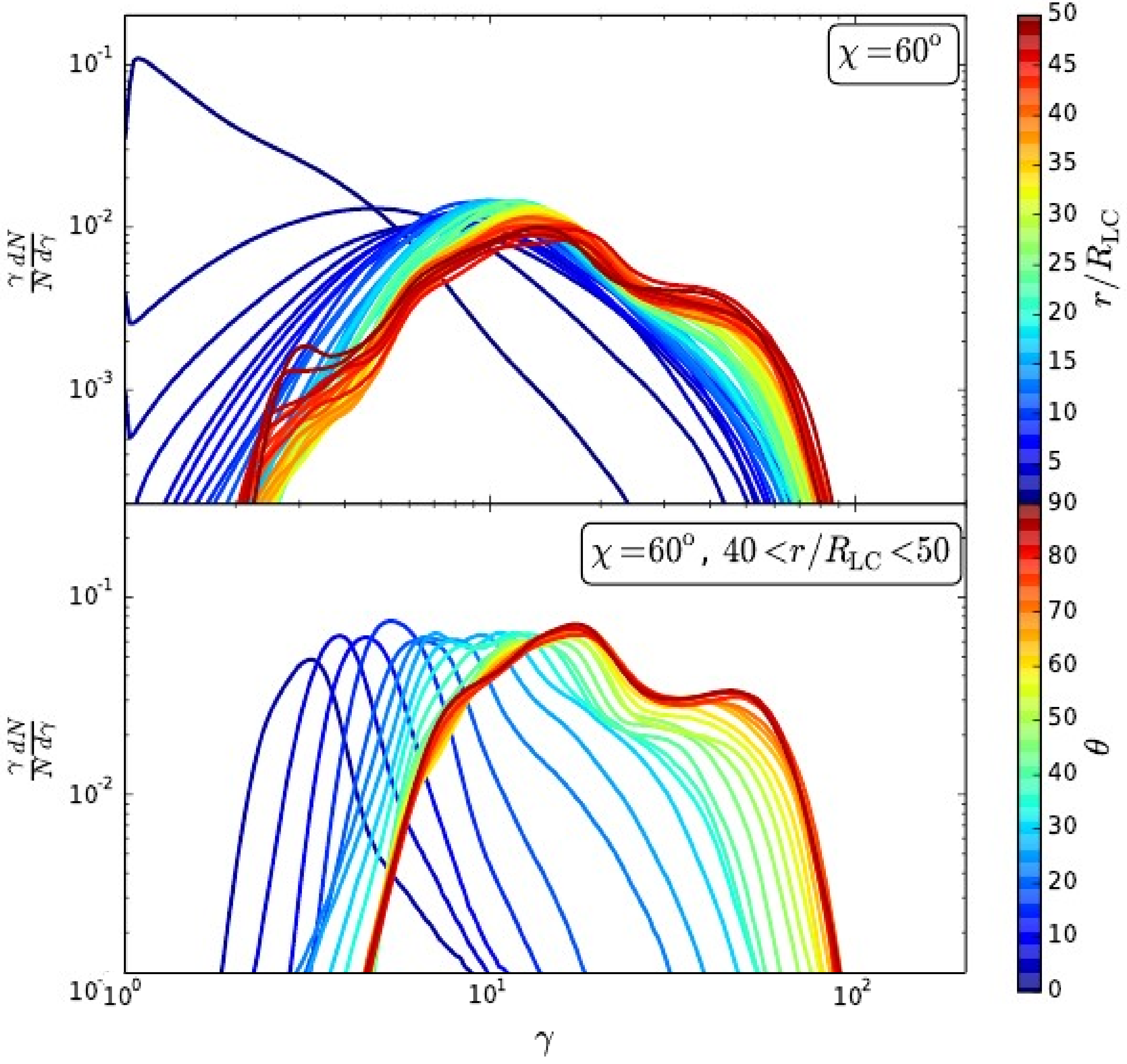


$$\boxed{\mu_{\rm M} \equiv \frac{B^2}{4\pi n m_{\rm e} c^2} = \Gamma\sigma}$$

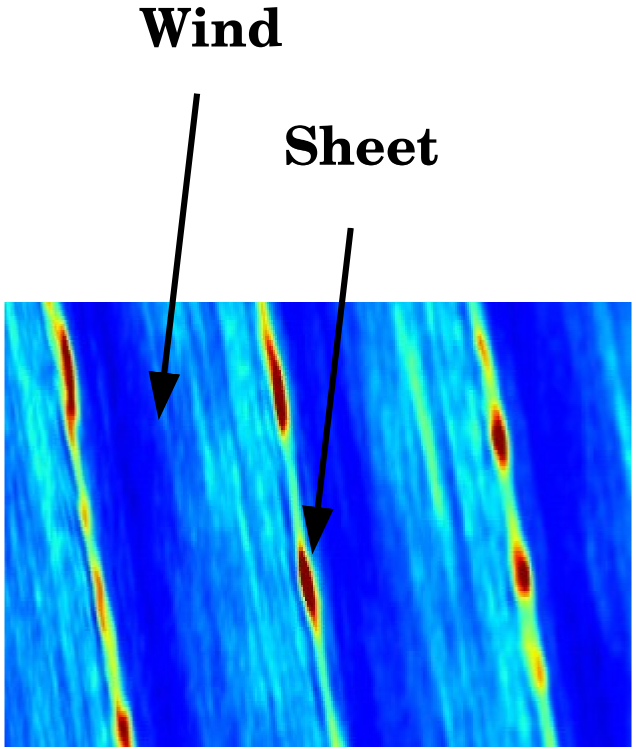
Realistic ~10^2-10^6

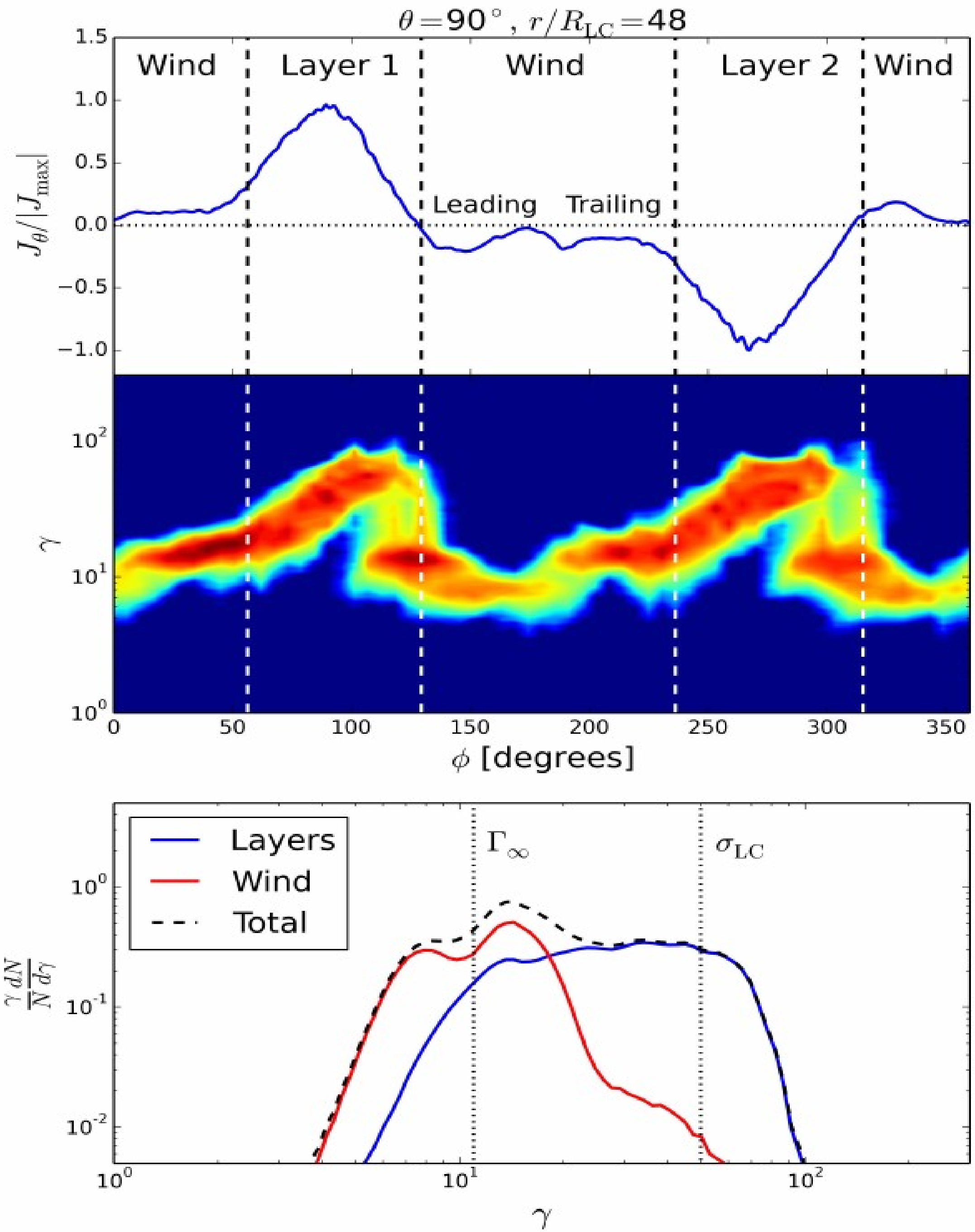
Γ_∞ ~<100 <<< standard model

Particle acceleration



Particle acceleration

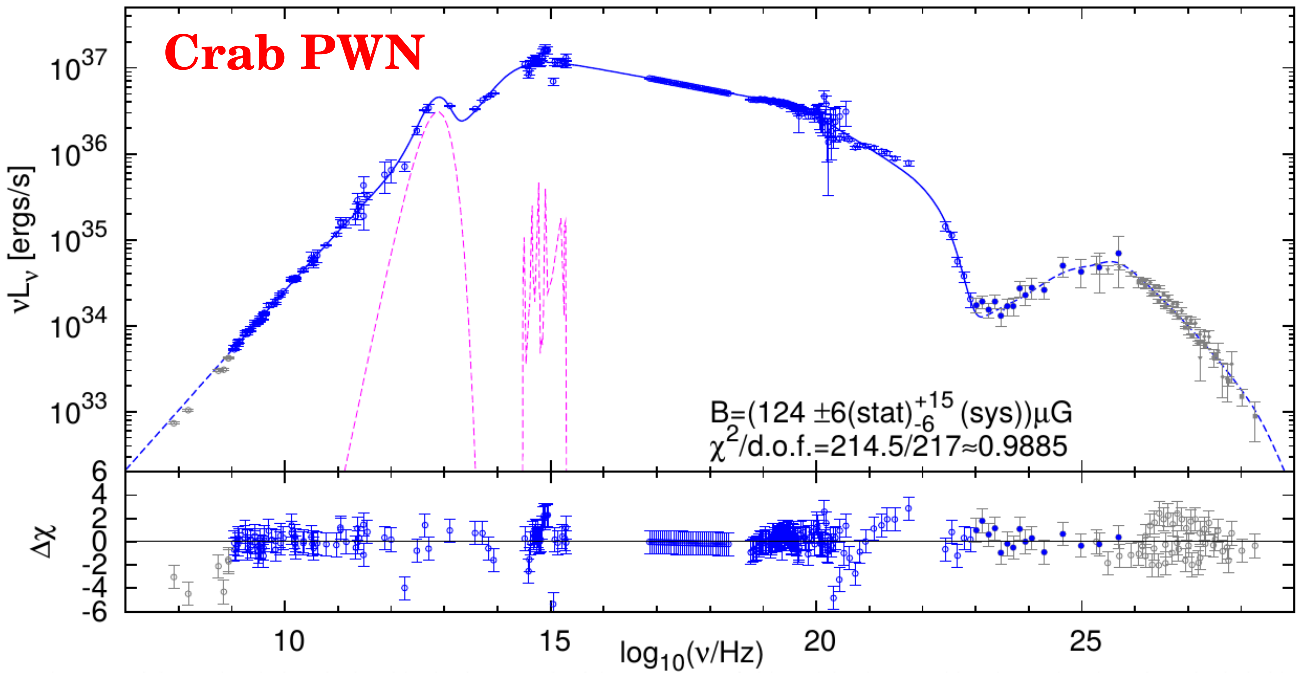




A good model:

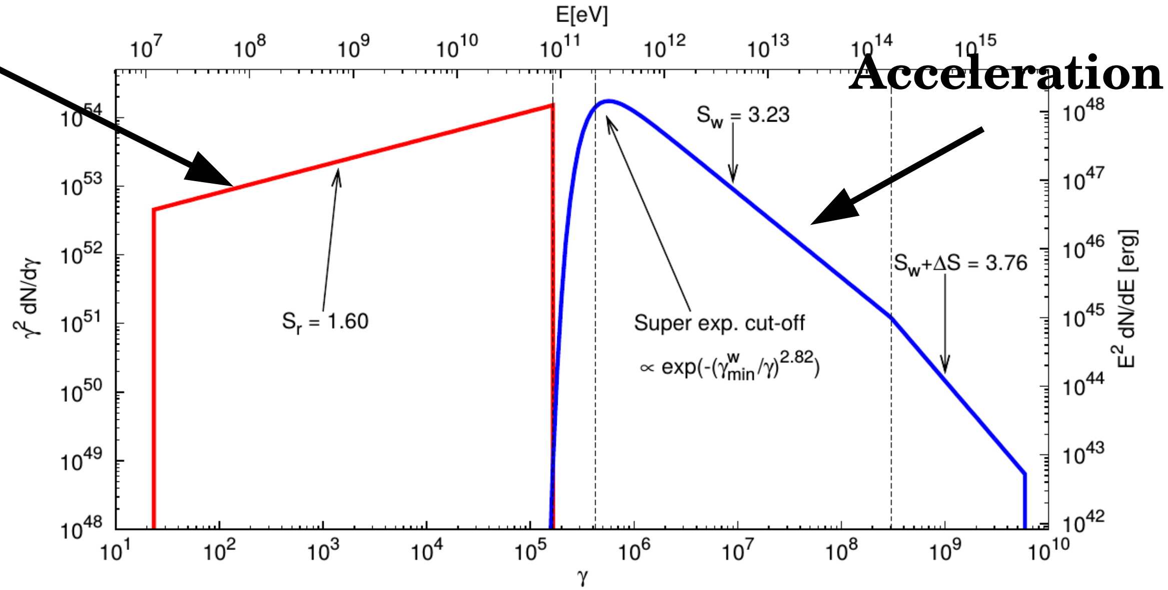
$$\boxed{\frac{dN}{d\gamma} \propto \gamma^{-1},\ \Gamma_\infty < \gamma < \sigma_{\rm LC}}$$

On the origin of the radio electrons in pulsar wind nebulae?



Meyer+2010

??
=>
reconnection in the wind!!



Acceleration at the shock front

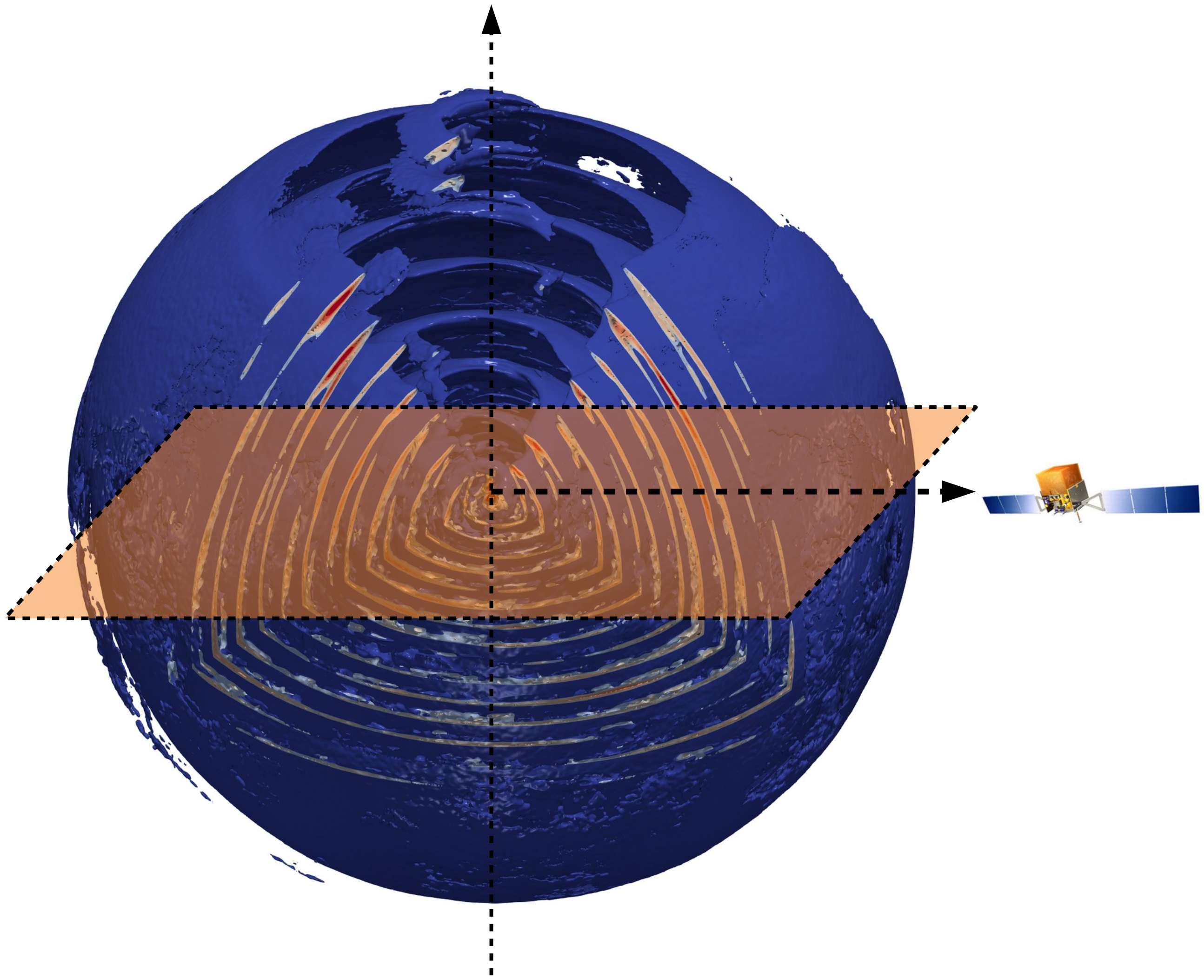
Part 2: Lightcurves & subpulses

Subpulses: BC + Ceyhun Andaç + Yavuz Eski + Guillaume Dubus

Geometric origin of pulses

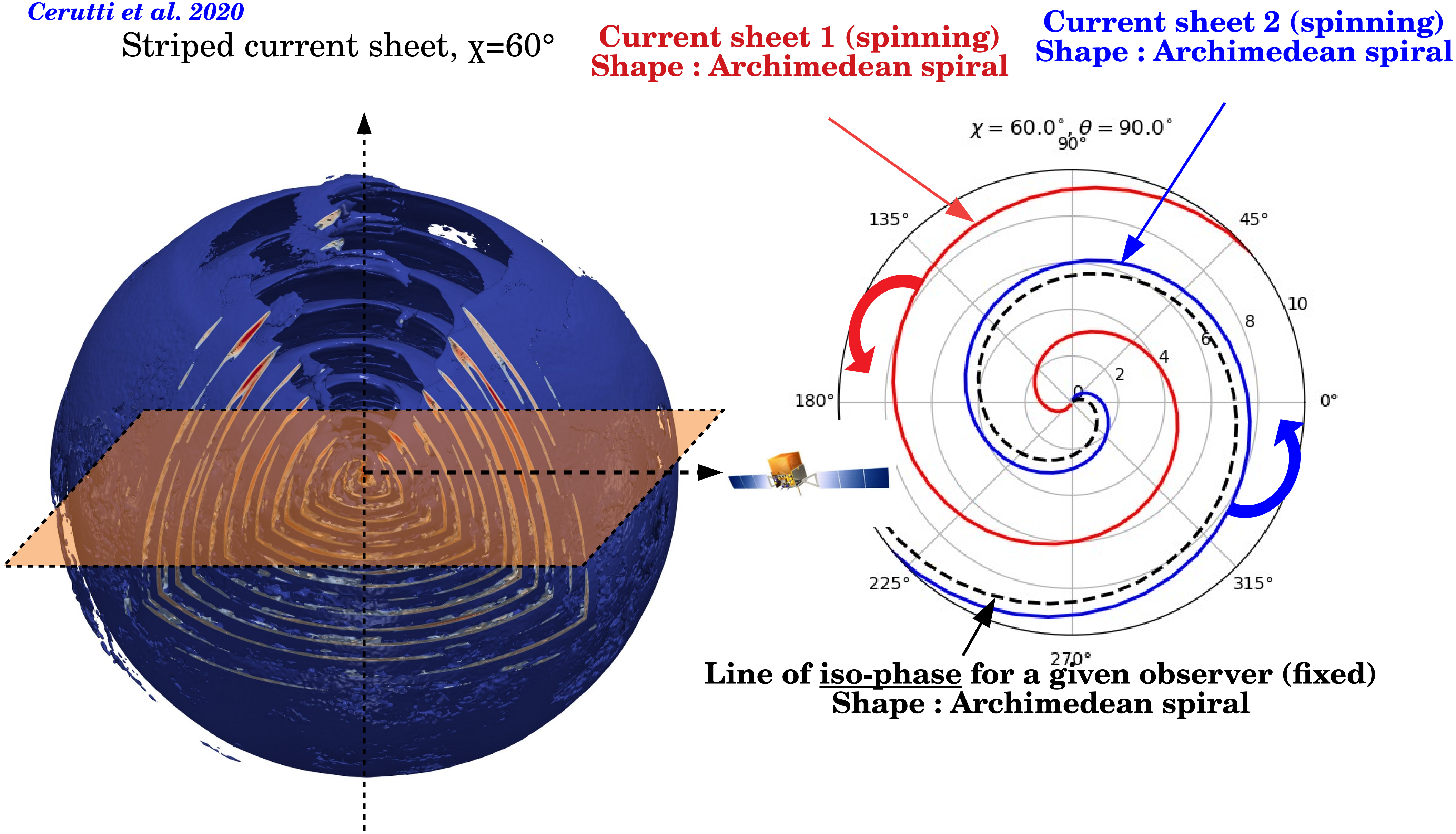
Cerutti et al. 2020

Striped current sheet, χ=60°



Geometric origin of pulses

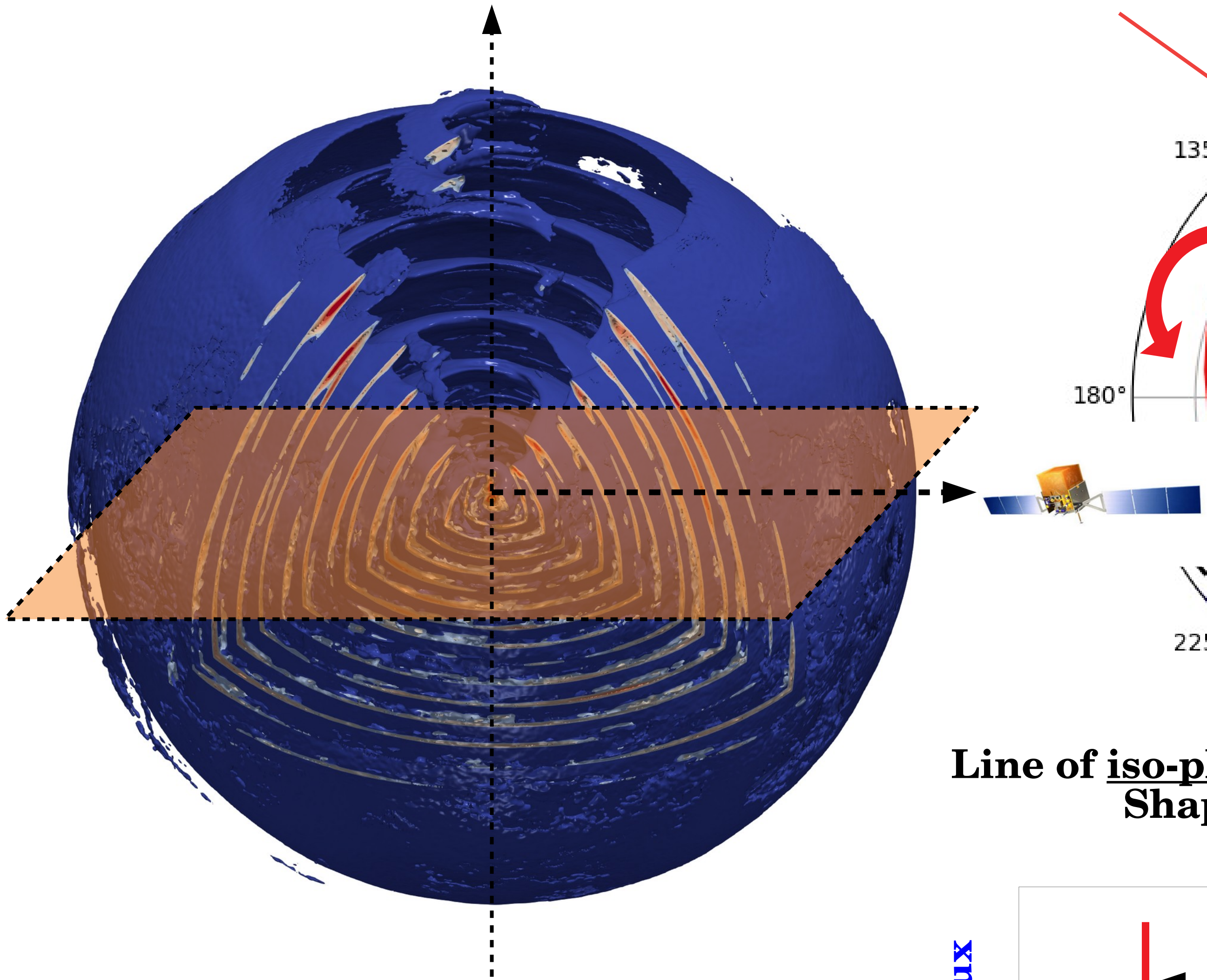
Cerutti et al. 2020



Geometric origin of pulses

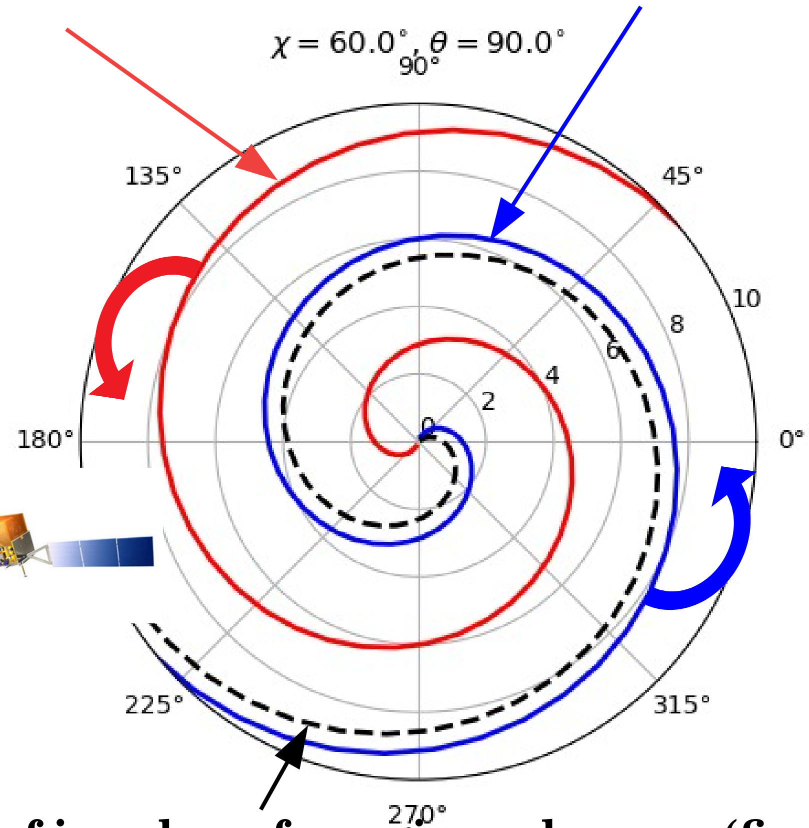
Cerutti et al. 2020

Striped current sheet, χ=60°

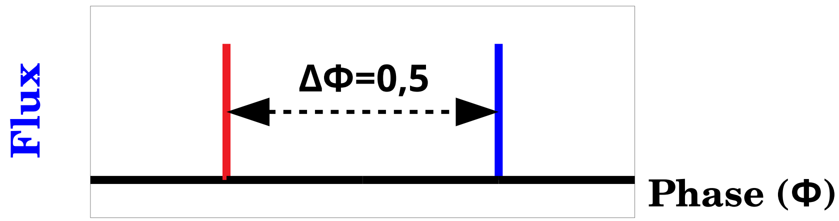


Current sheet 1 (spinning)
Shape : Archimedean spiral

Current sheet 2 (spinning)
Shape : Archimedean spiral



Line of <u>iso-phase</u> for a given observer (fixed)
Shape : Archimedean spiral

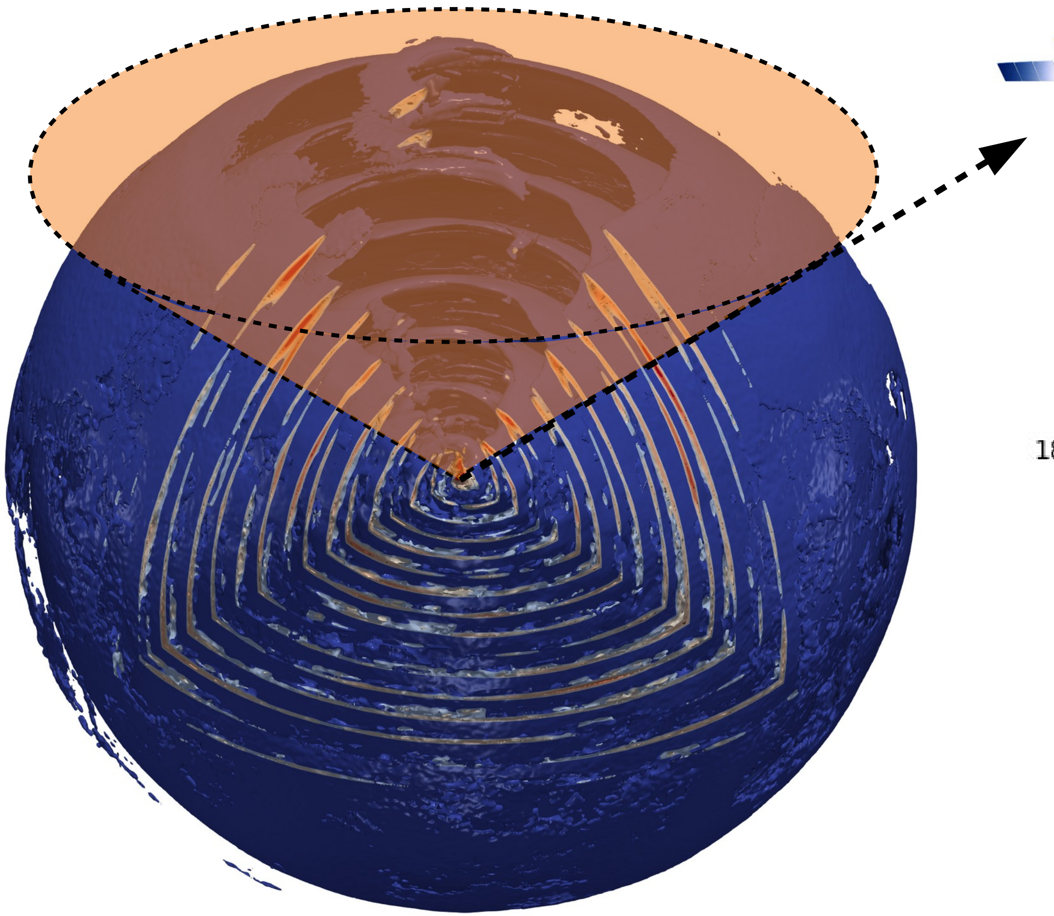


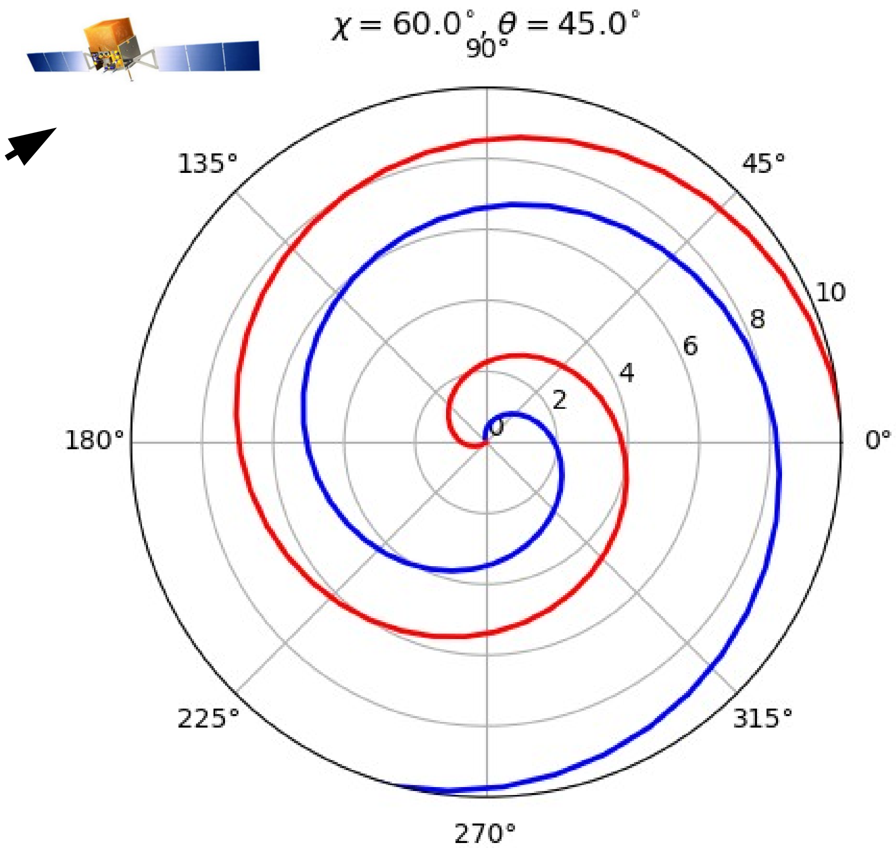
=> One pulse of light when the observer spiral overlaps with a current sheet

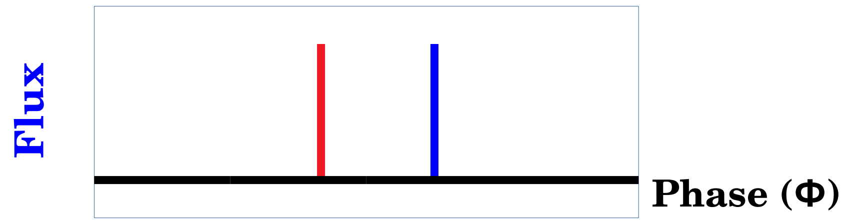
Geometric origin of pulses

Cerutti et al. 2020

Striped current sheet, χ=60°

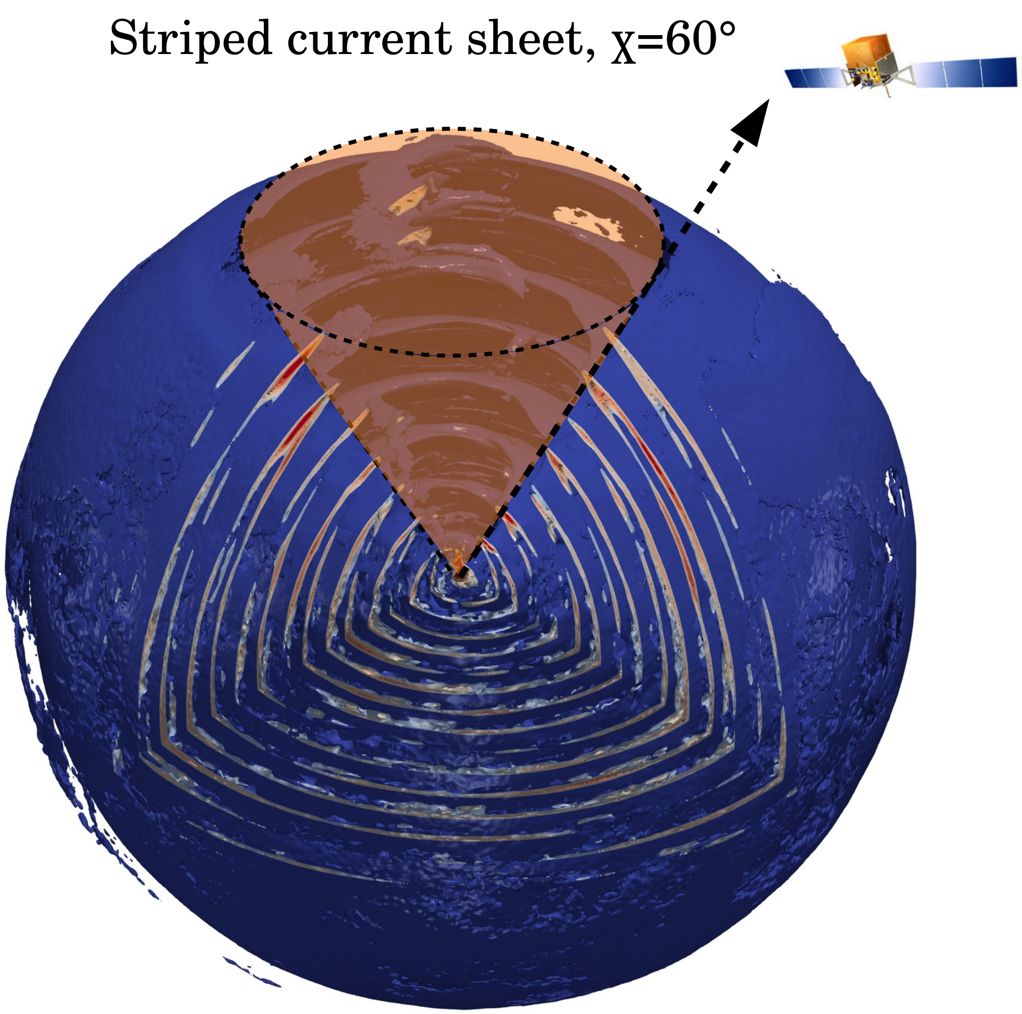


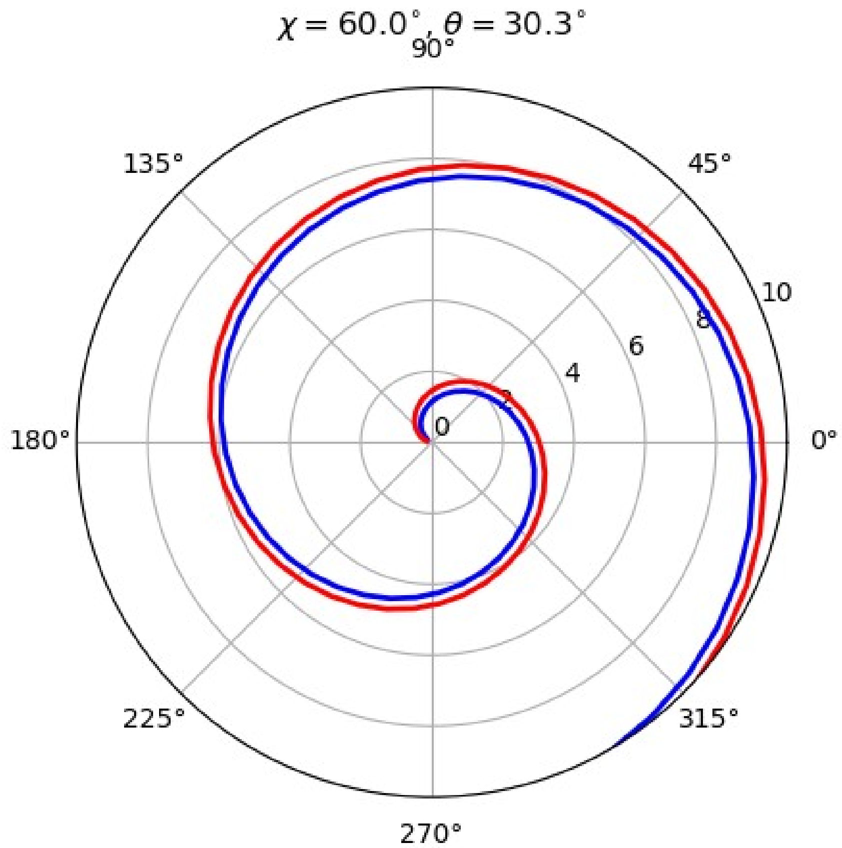




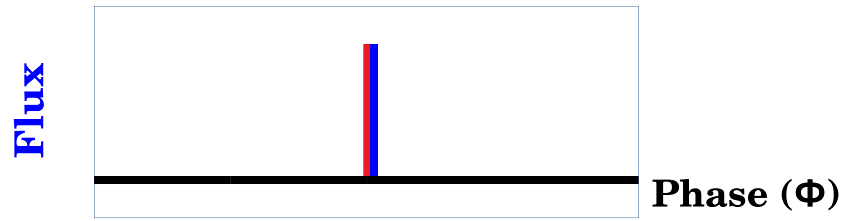
Geometric origin of pulses

Cerutti et al. 2020





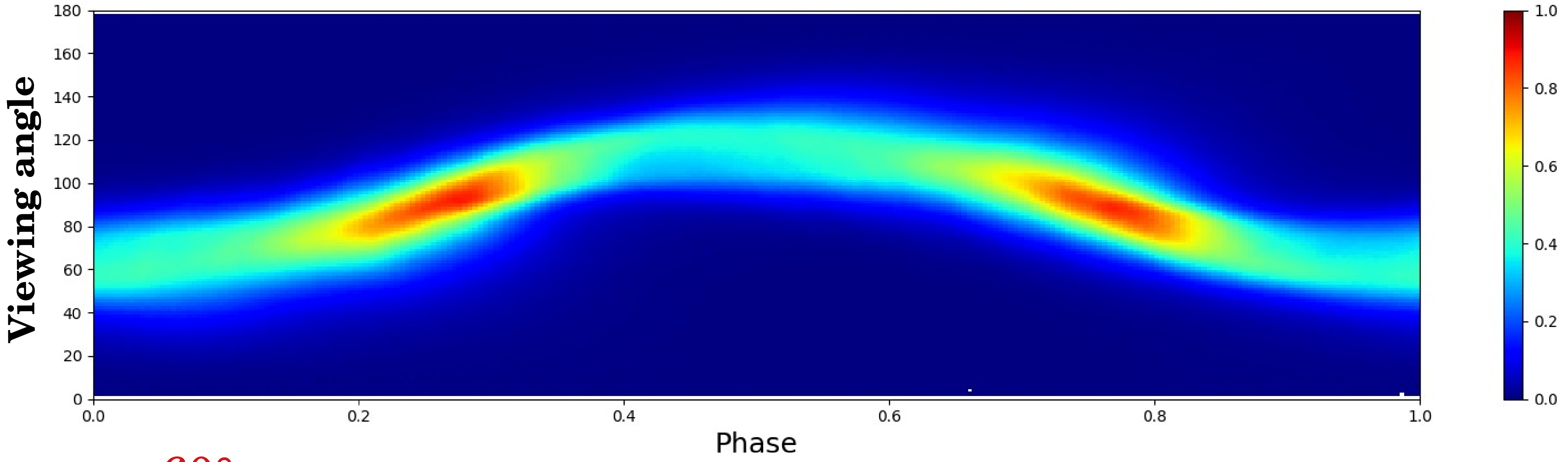
=> Single pulse !



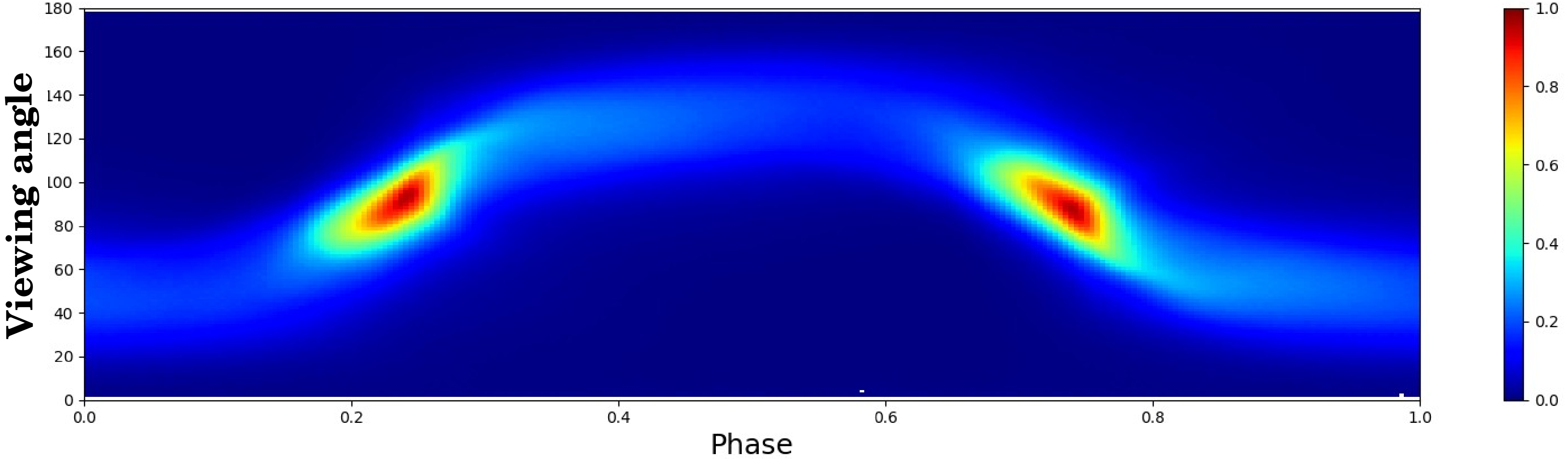
Skymaps

BC+2016; Philippov & Spitkovsky 2018

$\chi=30°$

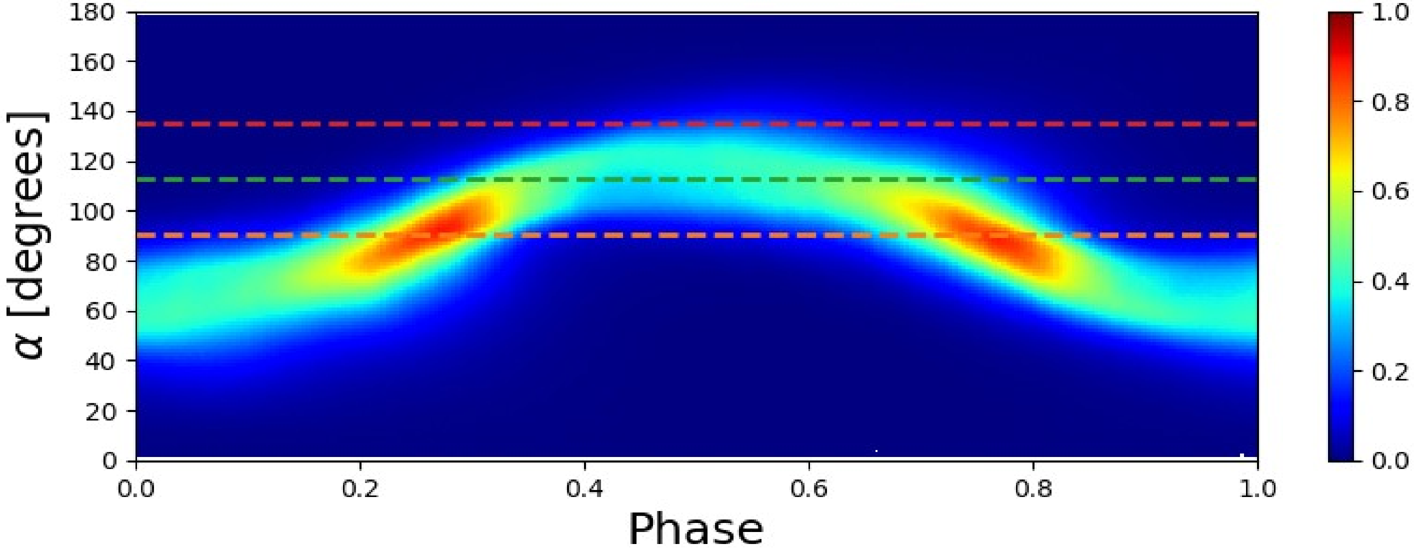


$\chi=60°$

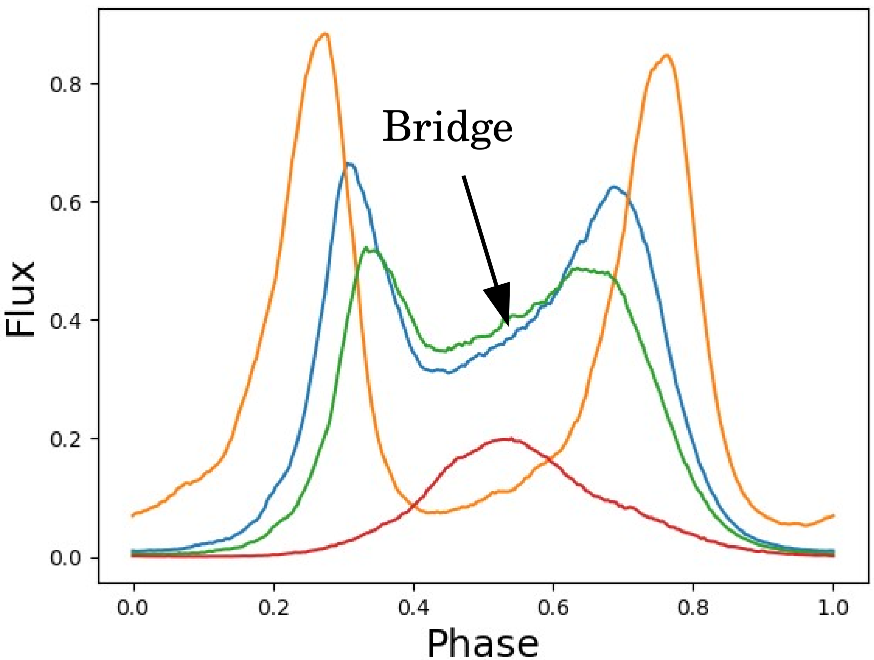


A few typical lightcurves

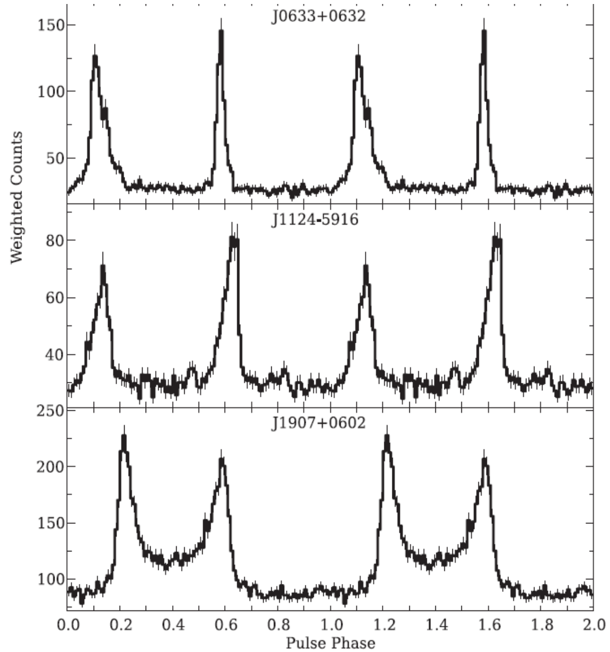
$\chi=30°$



Synthetic pulse profiles)



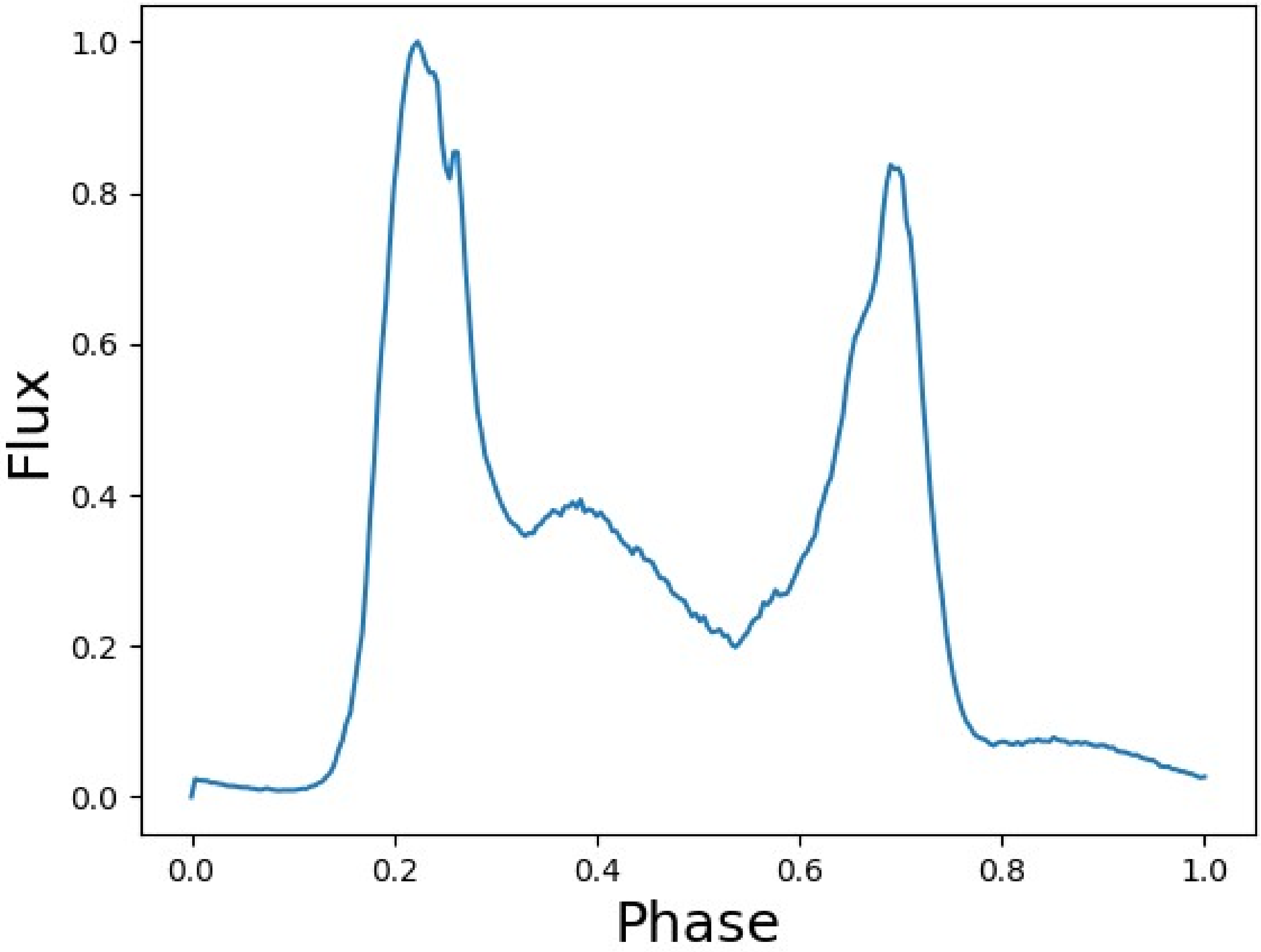
Observed Fermi-LAT lightcurves



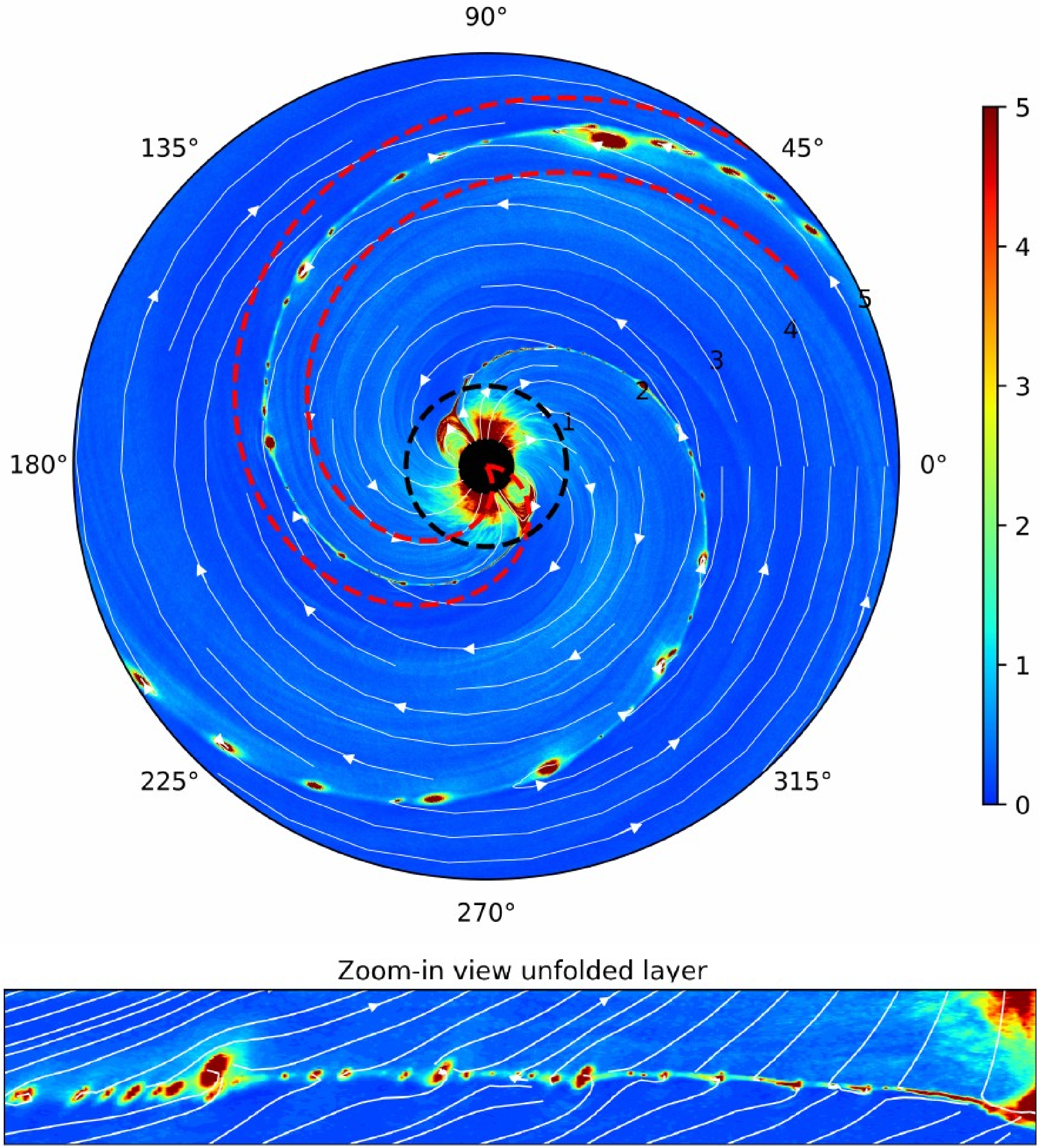
Pulse profiles reminiscent of *Fermi*-LAT double-peaked lightcurves!

We are waiting for 3PC to perform lightcurve fitting!

A “Vela”-like pulse profile

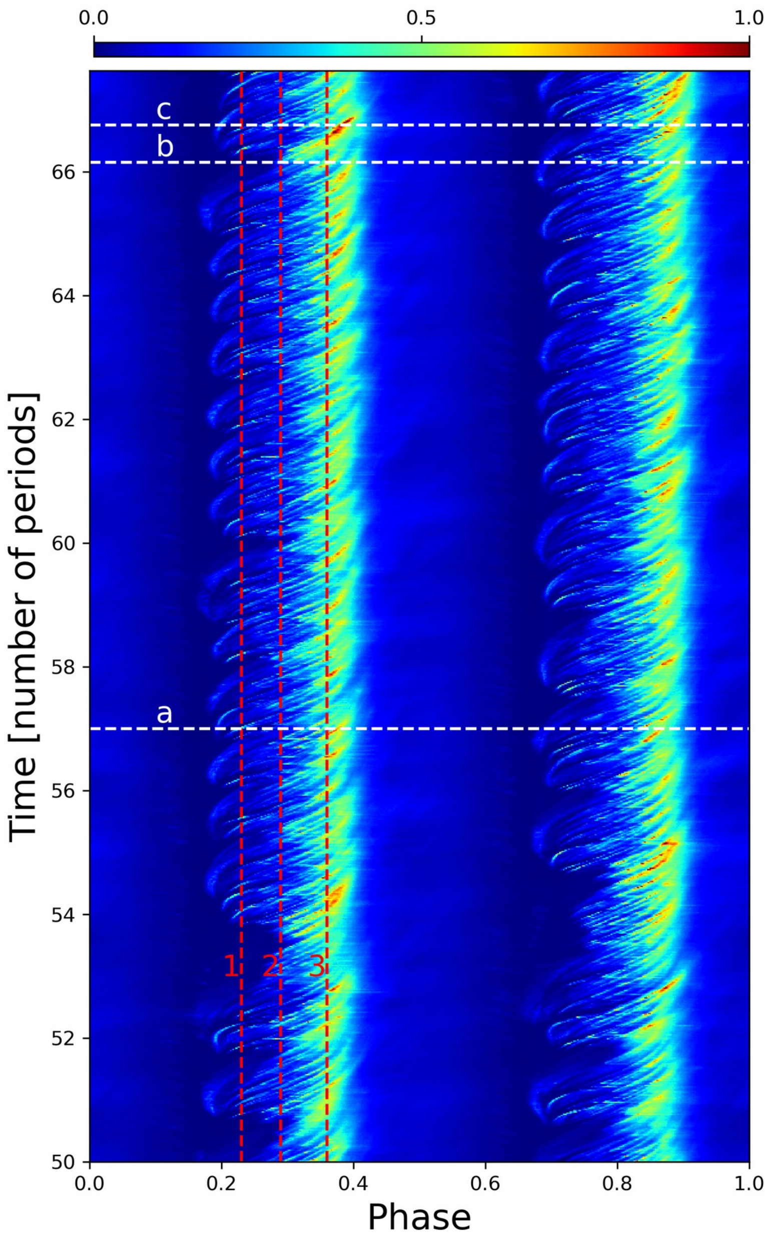


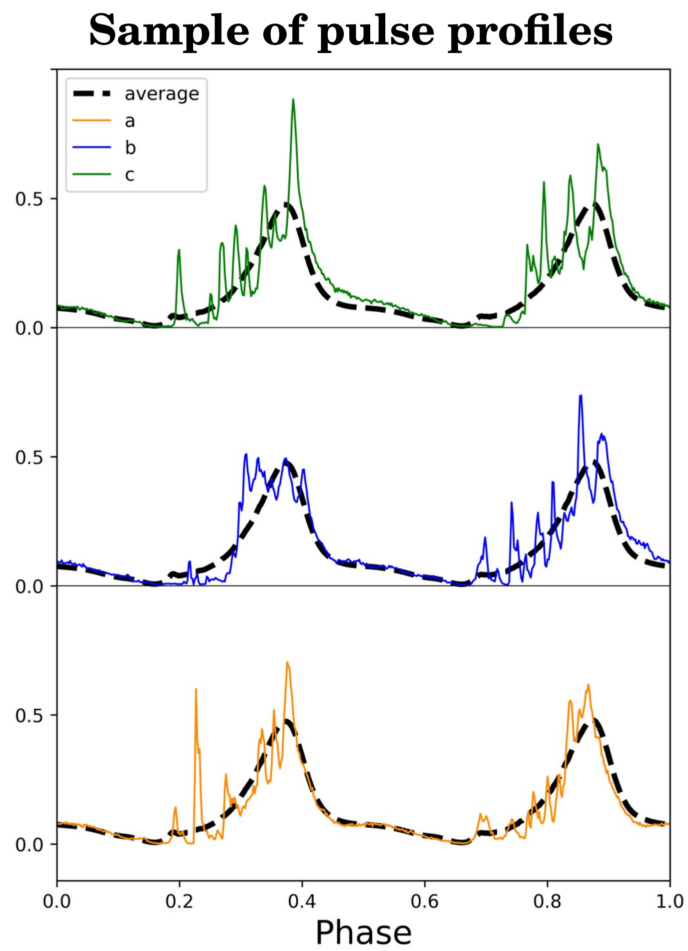
A equatorial view at the plasmoid instability



Cerutti & Philippov 2017, Andaç et al. 2022

Noisy lightcurves induced by plasmoid formation



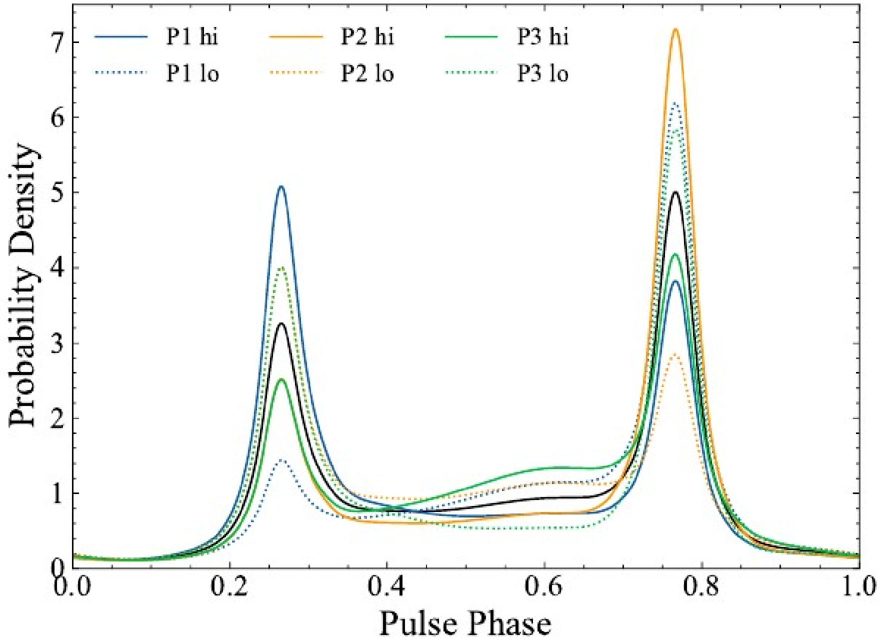


- **Noise on the leading edge**
- **Number subpulse per pulse $1/\beta_{rec}$~10 (universal) => prediction for fast optical observations ?**

Andaç et al. 2022

Observational evidence?

- **With the *Fermi*-LAT: thanks pairs of photons in a single period**

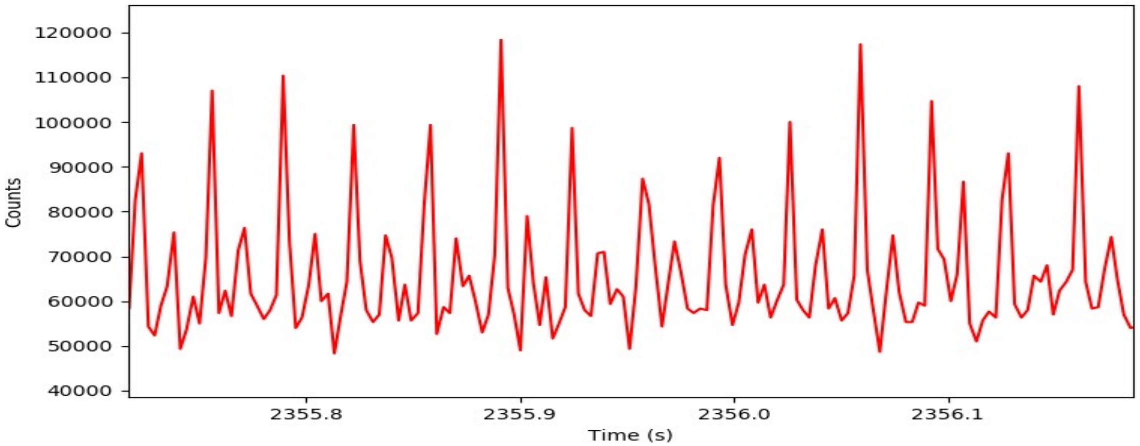


< 20% amplitude variations in Vela and Geminga

Hint of pulse shape variability in Geminga ~20%

[Kerr 2022]

- **With single pulse Crab optical data using fast and sensitive cameras *[Germanà+2012; Ambrosino+2019]***



Part 3: Hybrid simulations

Subpulses: BC + Adrien Soudais

To Adrien!