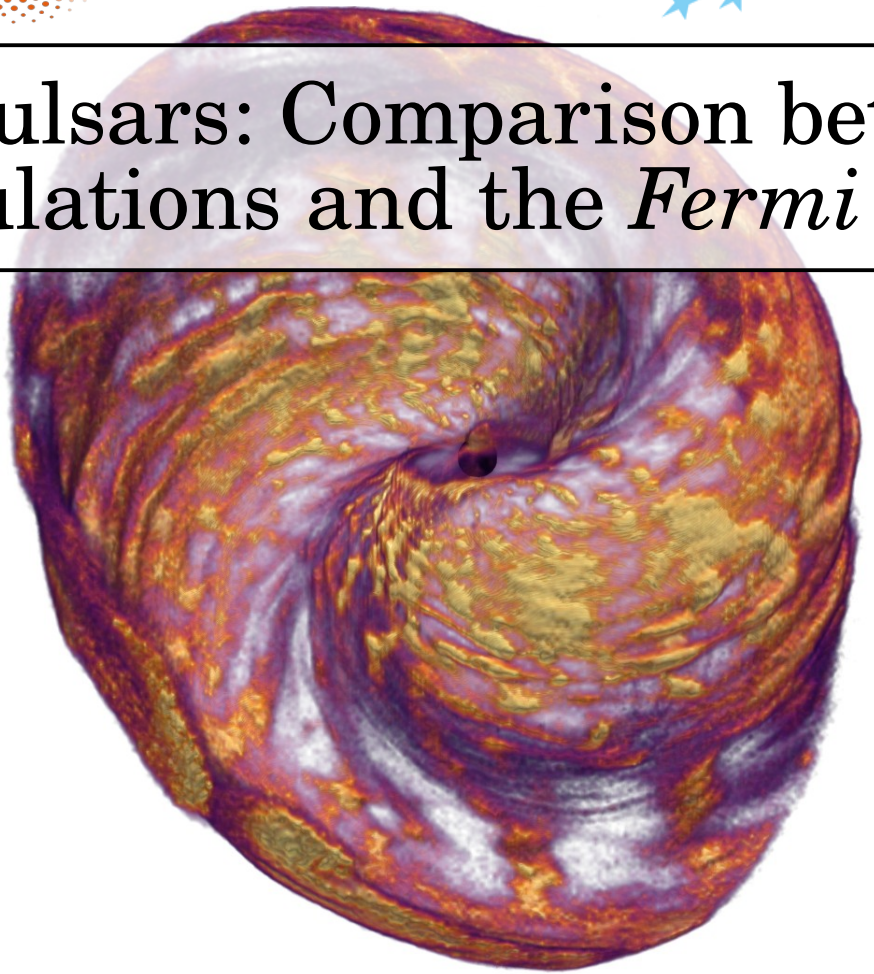
Gamma-ray pulsars: Comparison between global PIC simulations and the *Fermi* catalog

Benoît Cerutti
Univ. Grenoble Alpes, CNRS, IPAG
France



Collaborators :

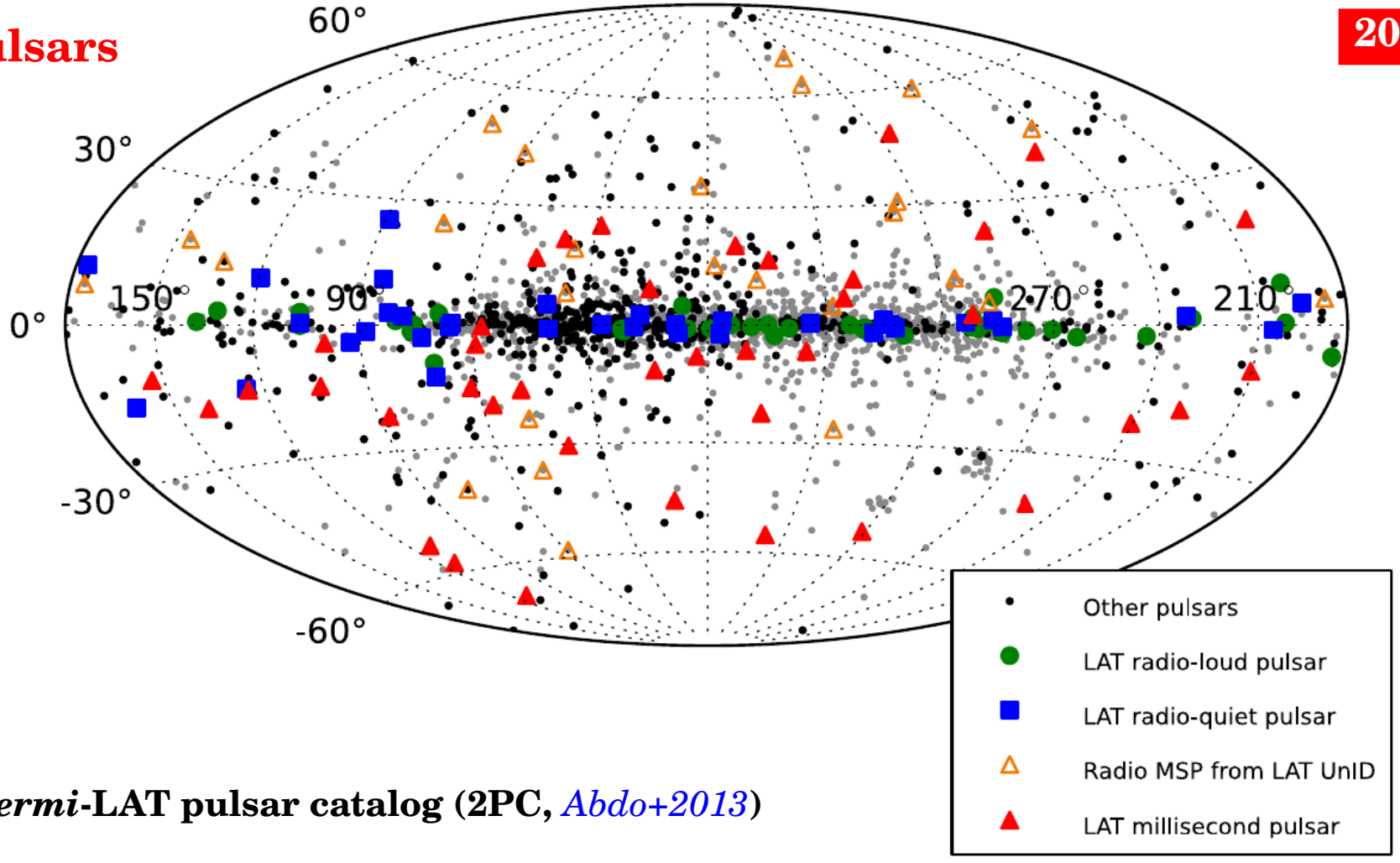
G. Dubus (Grenoble)
E. Figueiredo (Grenoble)
A. Soudais (Grenoble)

Eleventh international Fermi Symposium, College Park, September 9, 2024

Pulsars are the dominant Galactic gamma-ray sources

117 pulsars

2013

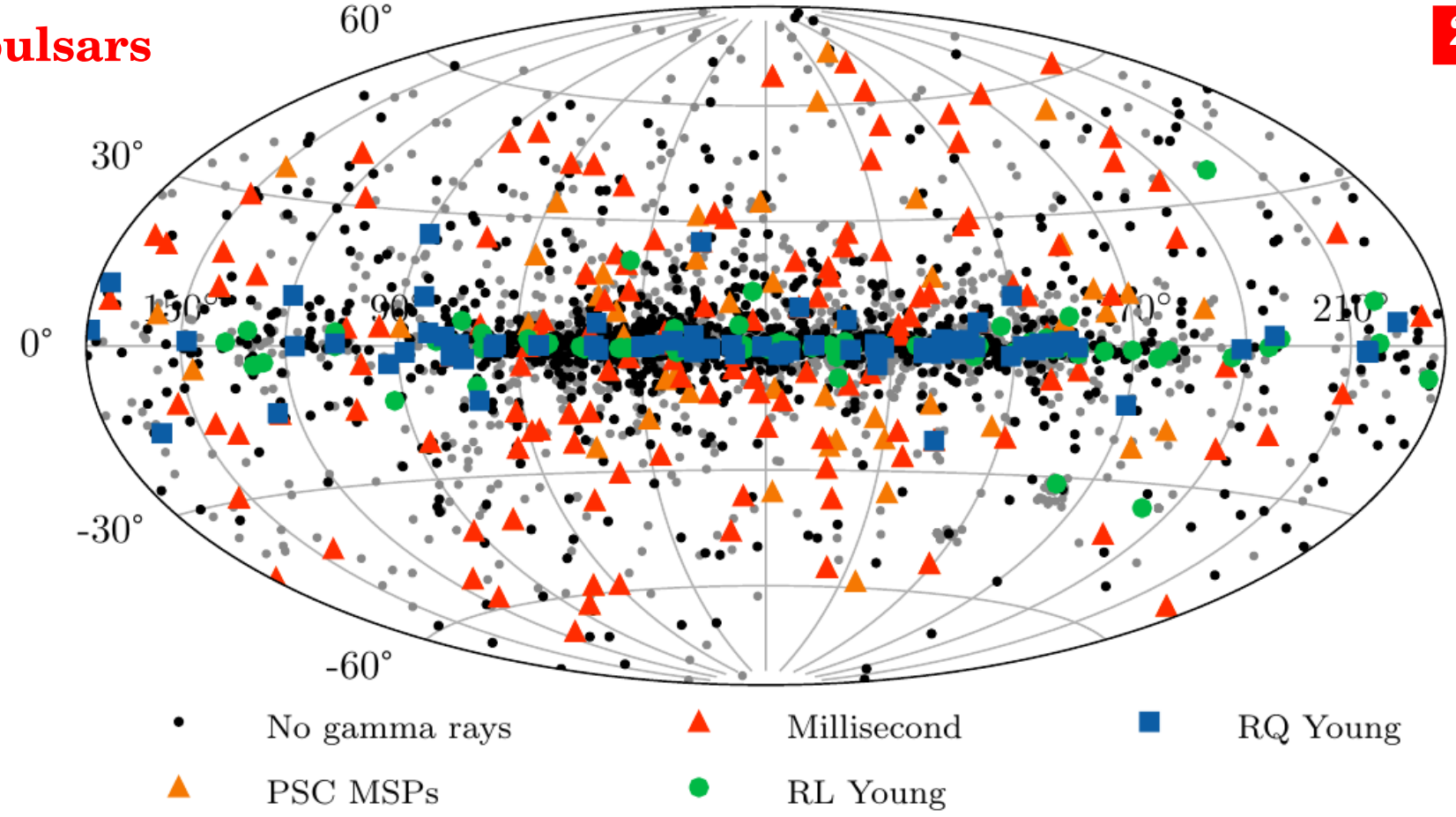


Second *Fermi*-LAT pulsar catalog (2PC, *Abdo+2013*)

Pulsars are the dominant Galactic gamma-ray sources

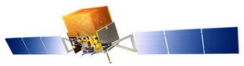
294 pulsars

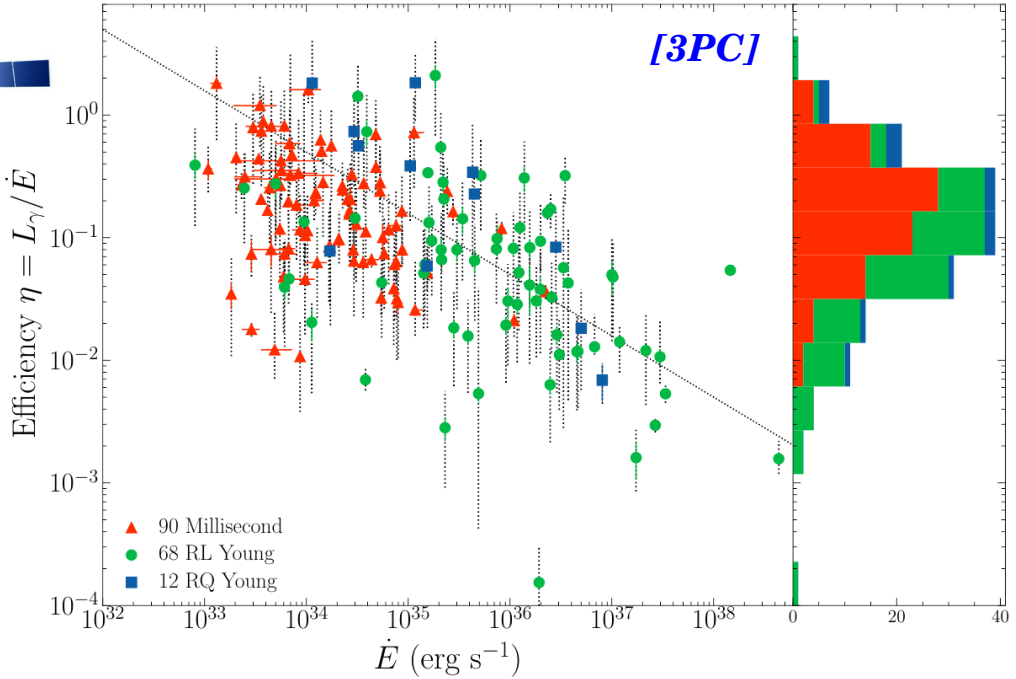
2023



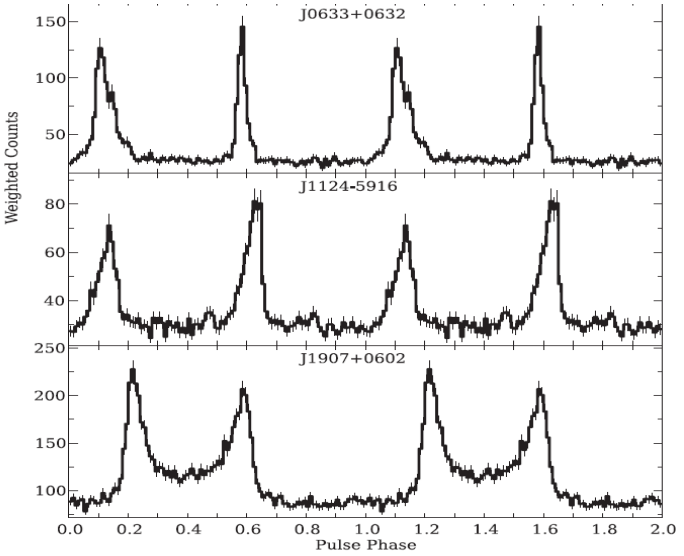
Third *Fermi*-LAT pulsar catalog (3PC, *Smith+2023*)

Pulsars are (extremely) efficient particle accelerators





Double-peaked γ-ray lightcurves



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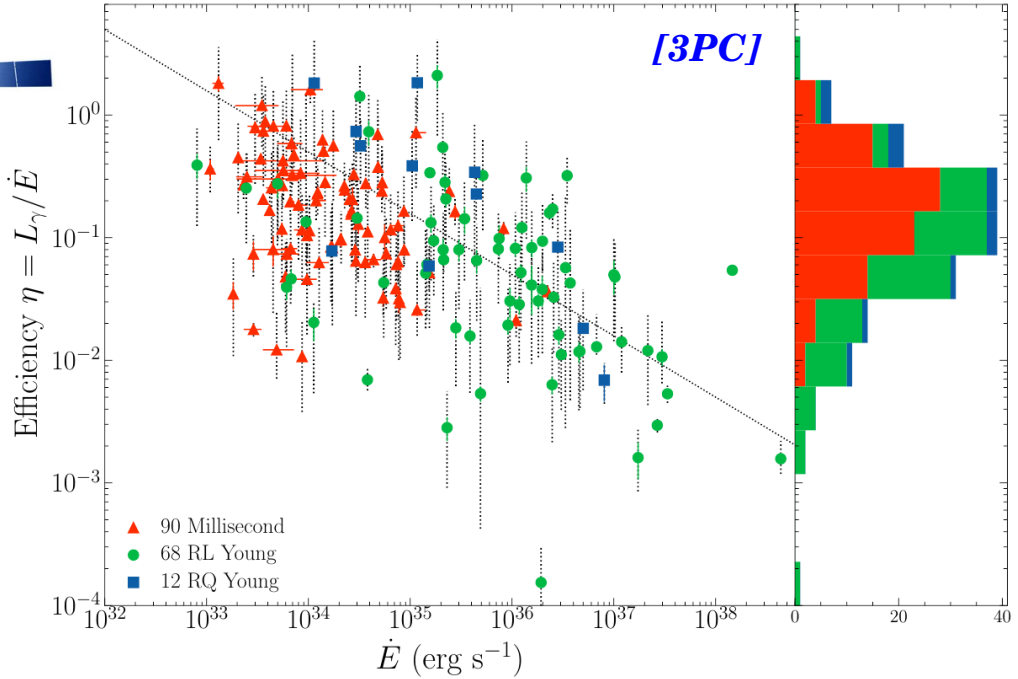

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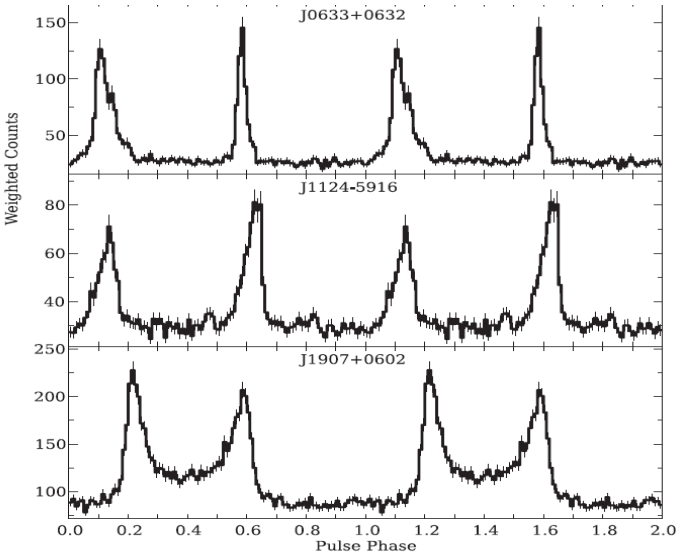
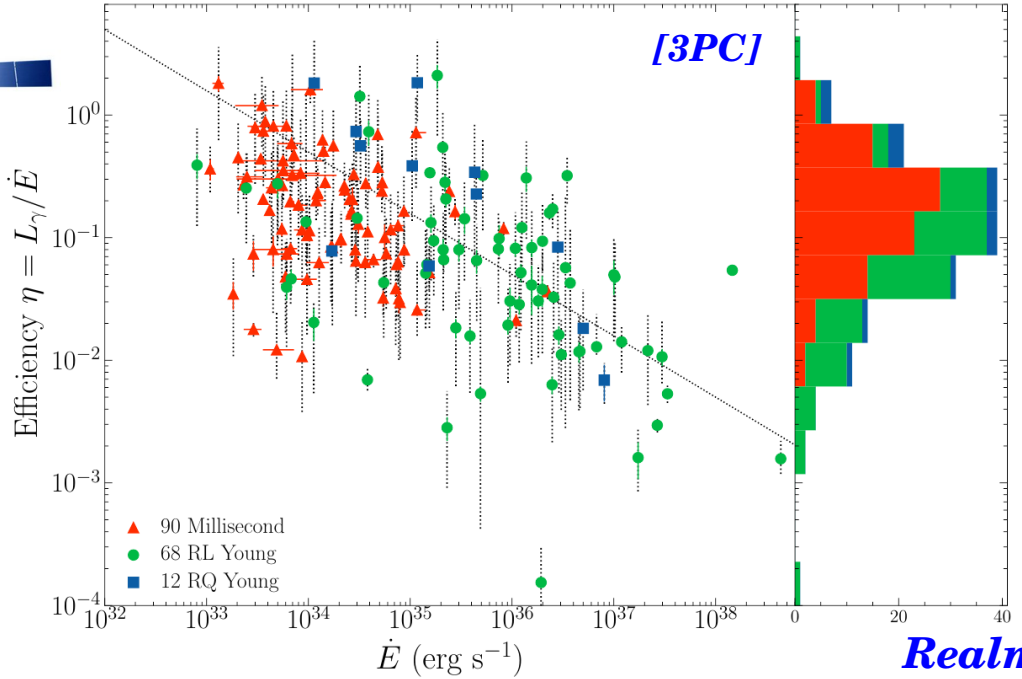


Energy reservoir — **Dissipation !** — **L_γ~1-100% L_0**

Spin down $\dot{E}$ → **Poynting flux** → **Particle acceleration** → **Non-thermal radiation**

=> Magnetospheric phenomena most likely at work (coherence, timescale)

Pulsars are (extremely) efficient particle accelerators



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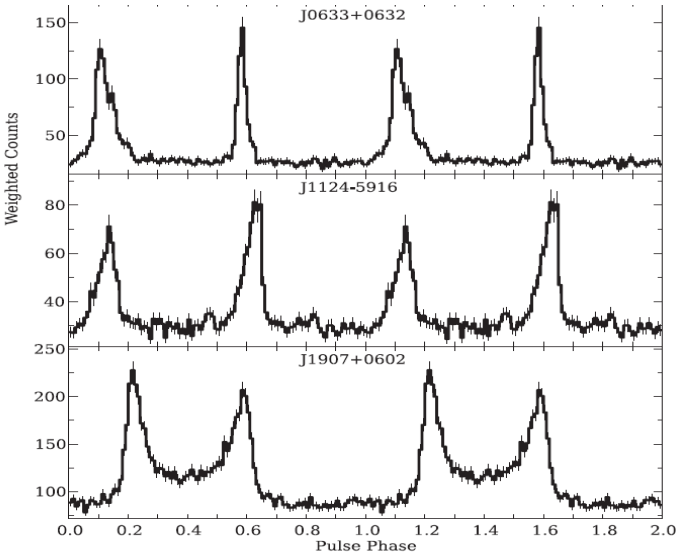

Realm of plasma physics 😓

Energy reservoir

Spin down $\dot{E}$

→ **Poynting flux** → **Dissipation !** → **Particle acceleration** →

L_γ~1-100% L_0

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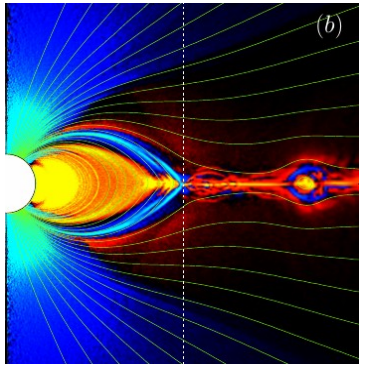
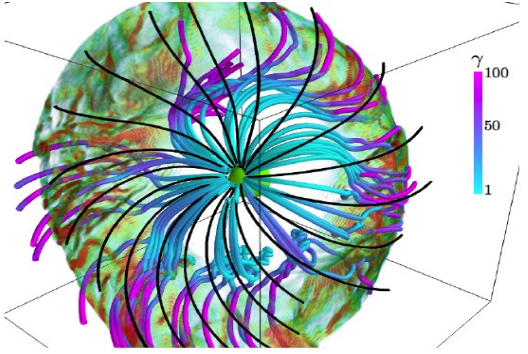
Global PIC model (2014-): A mini-revolution in the field



Columbia

Andrei Beloborodov
Alex Chen
Rui Hu

Code : Aperture



Princeton/UMD

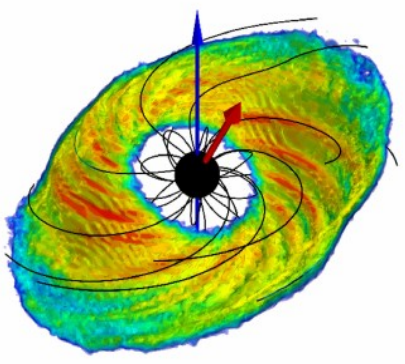
Sasha Philippov
Anatoly Spitkovsky
Hayk Hakobyan

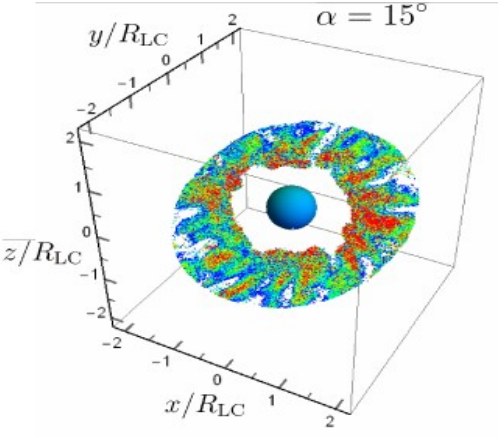
Code : Tristan

Grenoble

Benoît Cerutti
Guillaume Dubus
Enzo Figueiredo
Claire Guépin
Valentina Richard-Romei
Adrien Soudais

Code : Zeltron





NASA/UMD

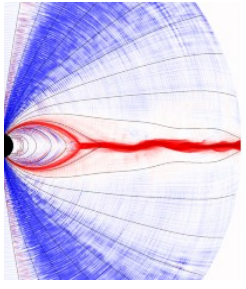
Brambilla
Alice Harding
Konstantinos Kalapotharakos
Andrei Timokhin

Code : C-3PA

Lisbon

Fabio Cruz
Thomas Grismayer
Luis Silva
Rui Torres

Code : Osiris

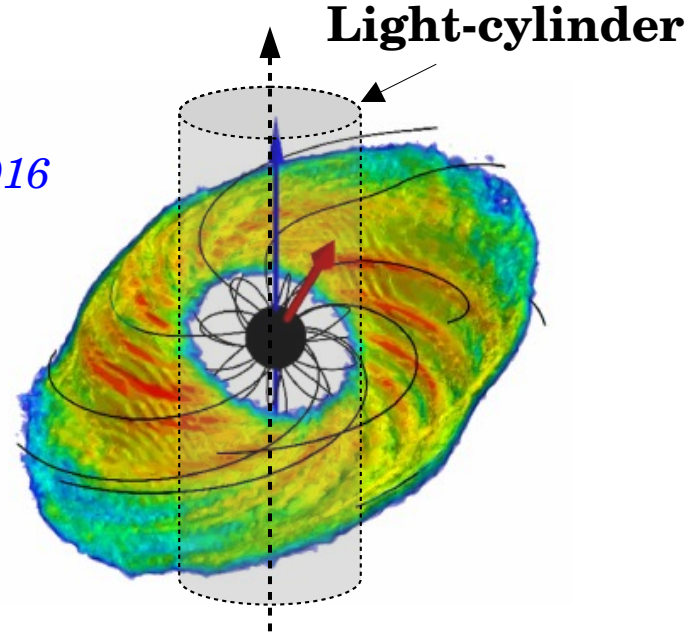


<u>Consensus :</u> γ-rays originate from the wind current sheet
=> See Sasha Philippov's talk on Thursday !

Global PIC model: reconnection-powered pulses

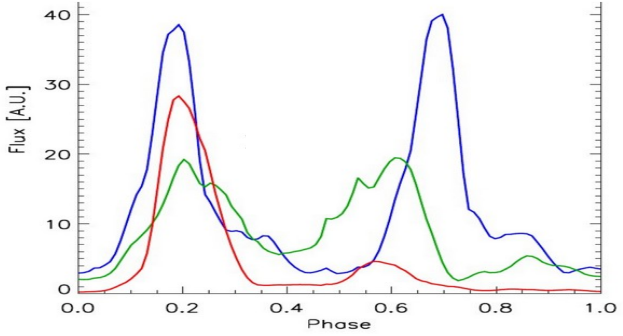
2016

Cerutti et al. 2016



Synchro-curvature

Synthetic pulse profiles



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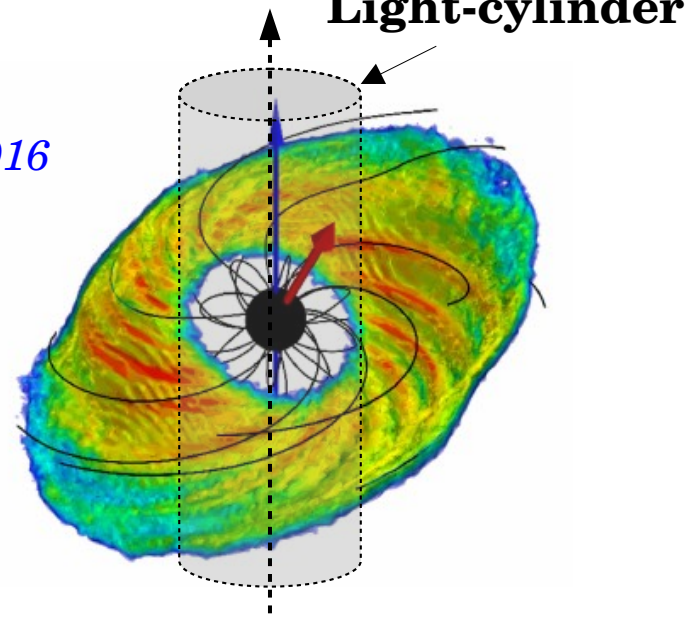
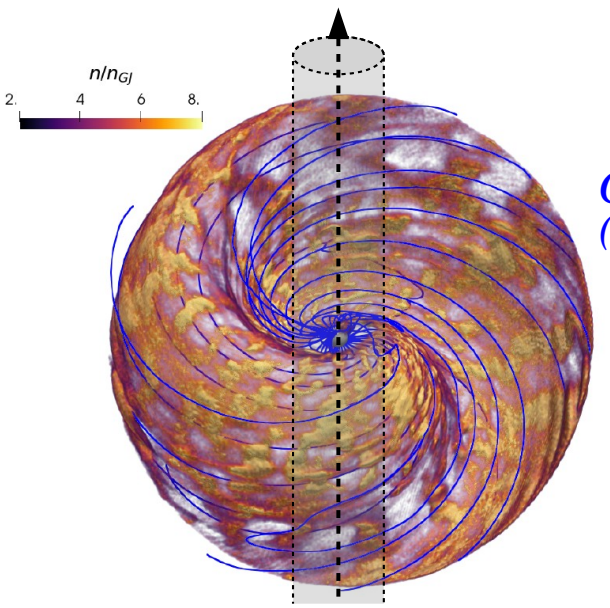


This work

2024

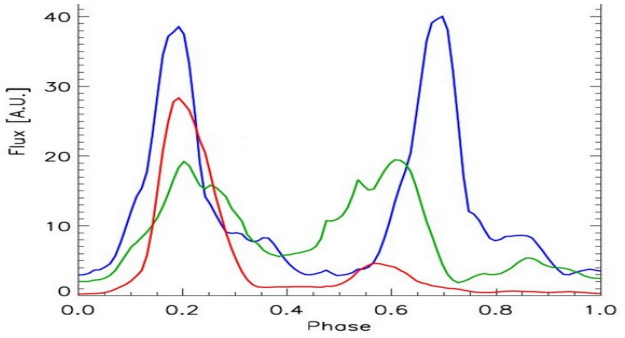


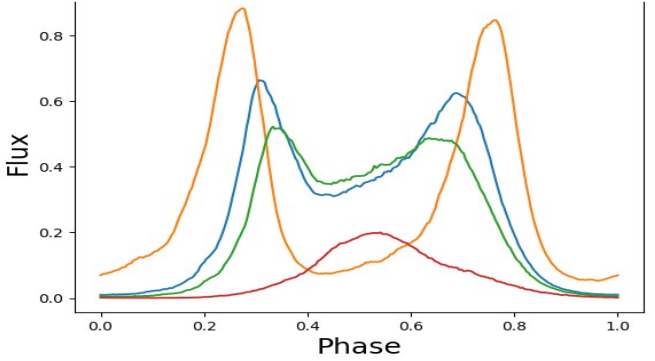
Cerutti et al. (submitted)

Synchro-curvature

Synchro-curvature + Inverse Compton

Synthetic pulse profiles

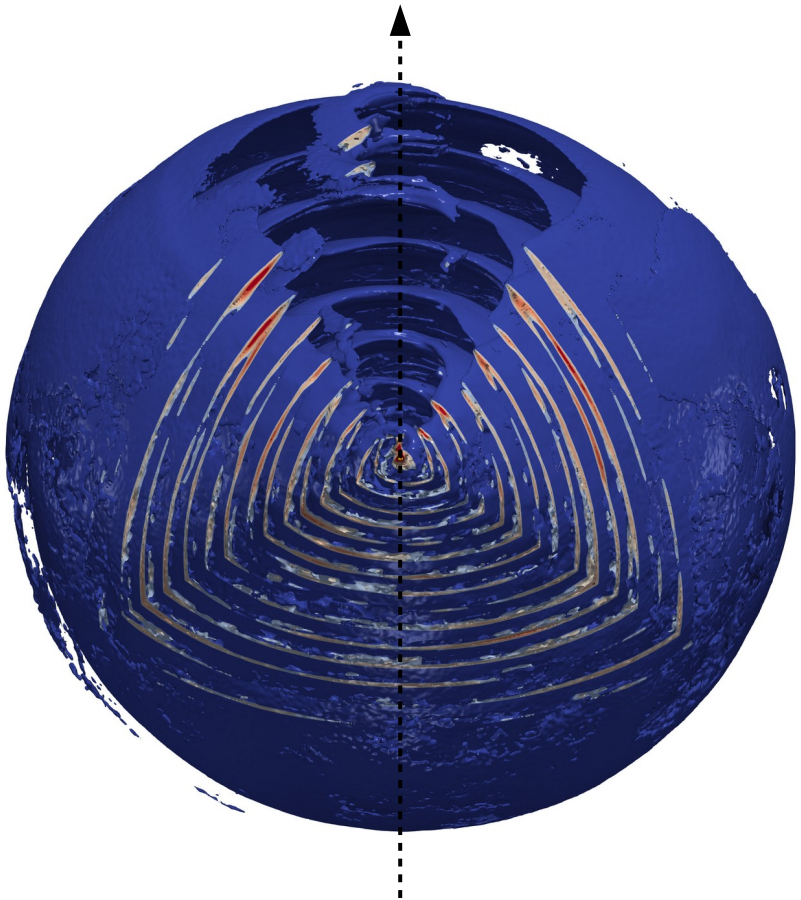




Shinning current sheet: geometric origin of pulses

Cerutti et al. 2020

Striped current sheet, χ=60°



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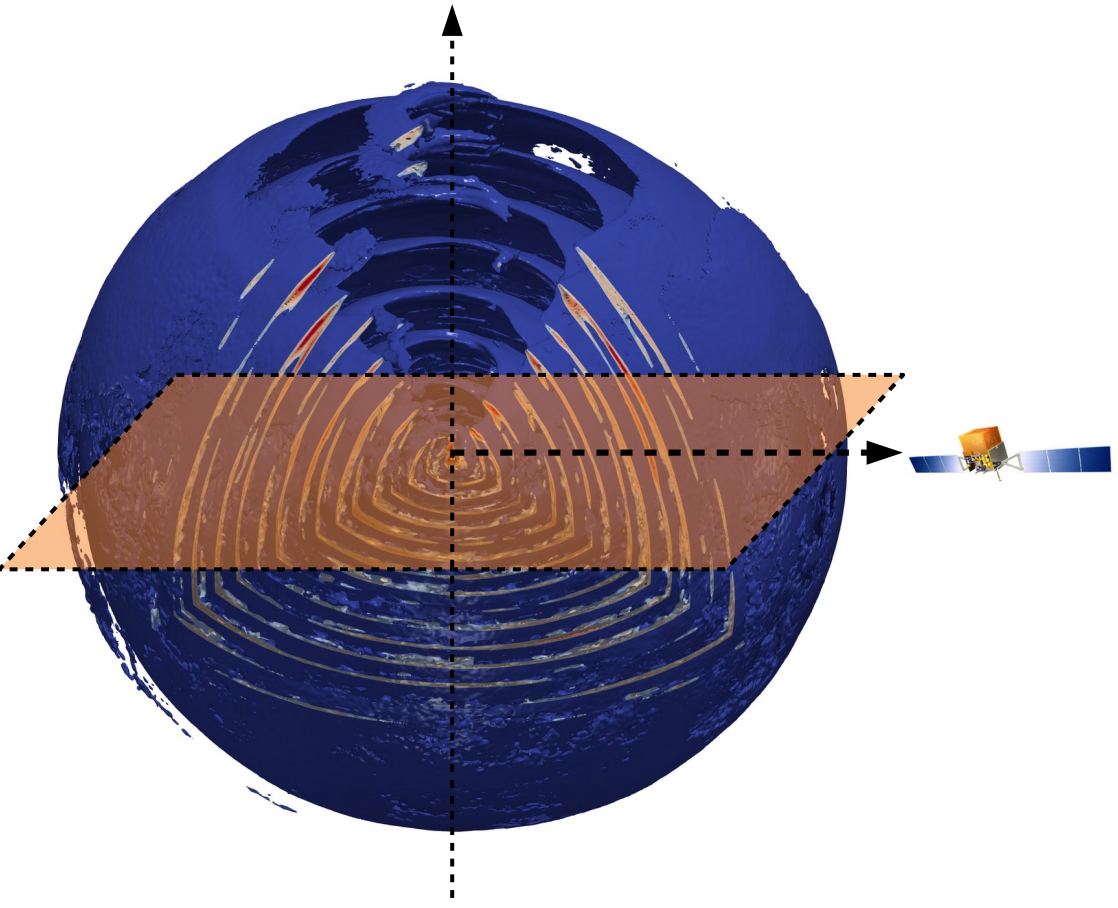

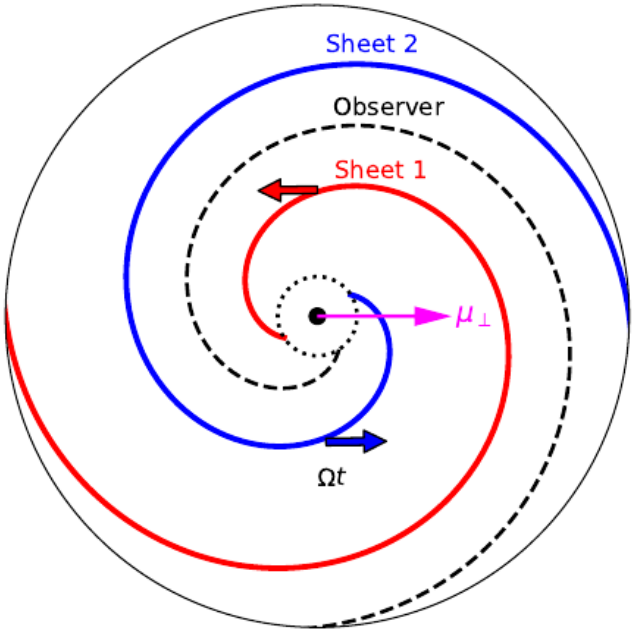

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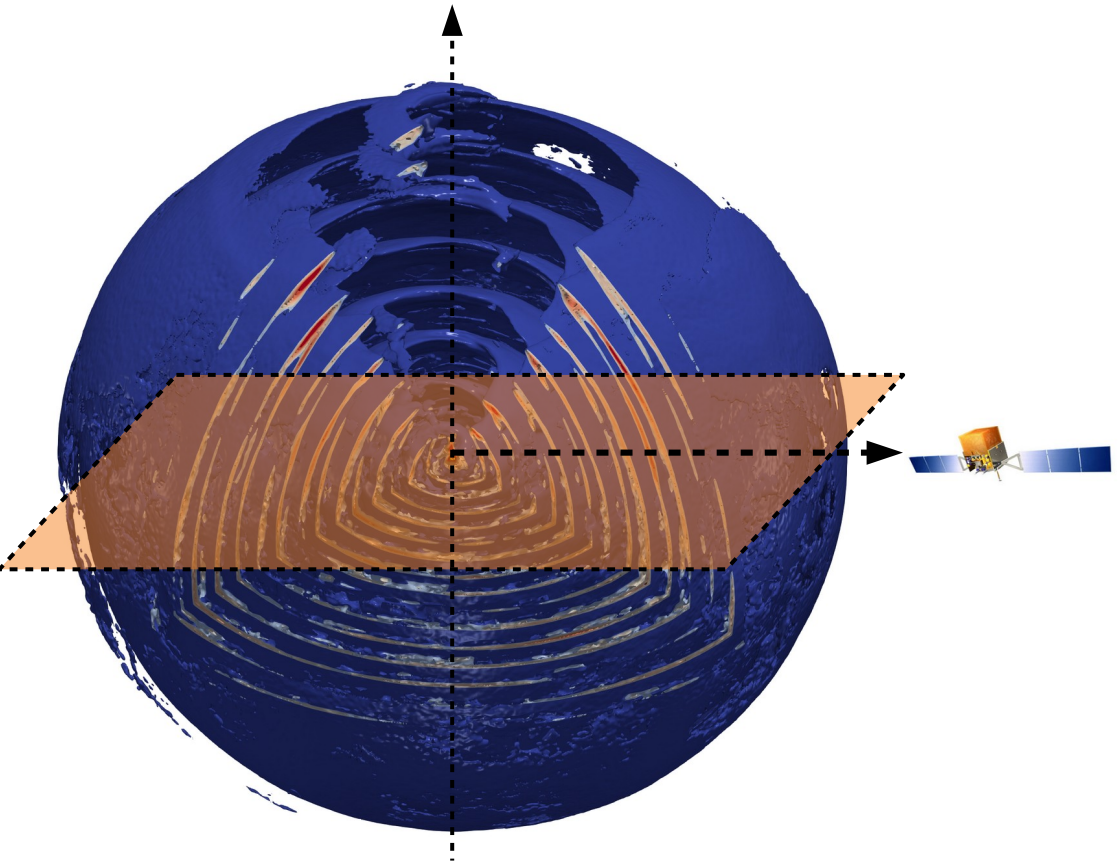

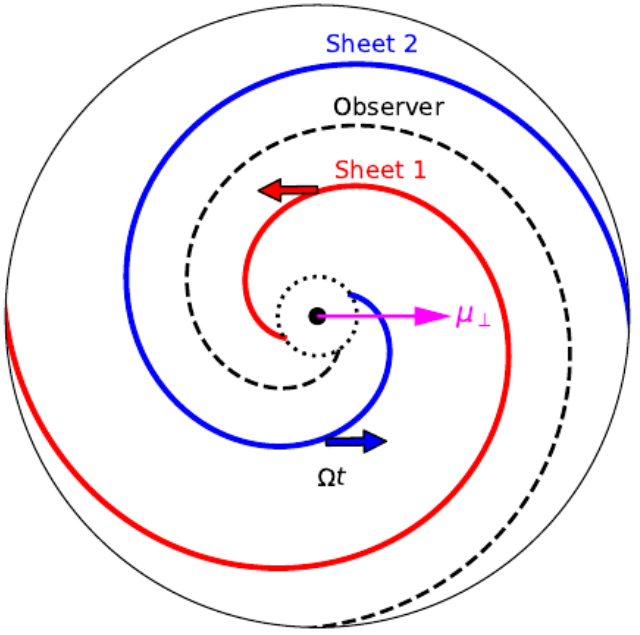

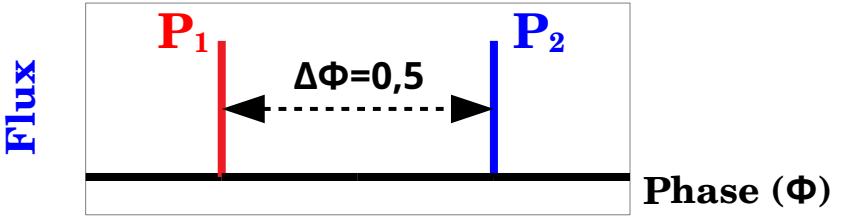

=> One pulse of light when the observer spiral overlaps with a current sheet

Shinning current sheet: geometric origin of pulses

Cerutti et al. 2020

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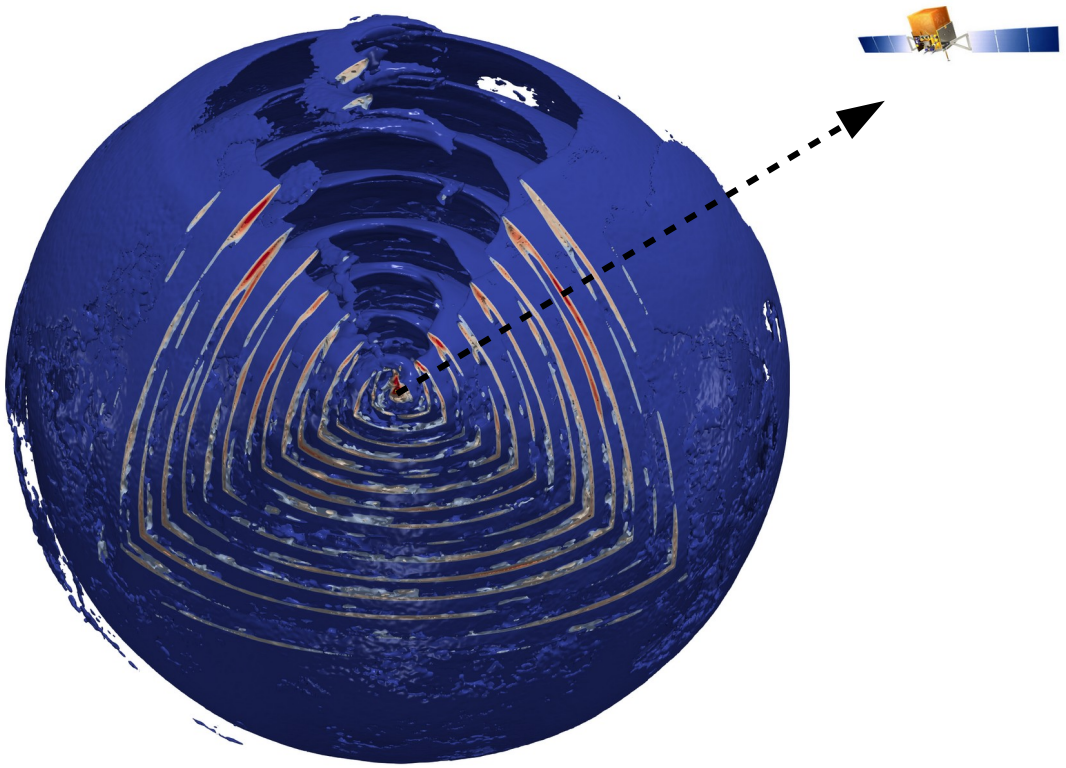

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Cerutti et al. 2020

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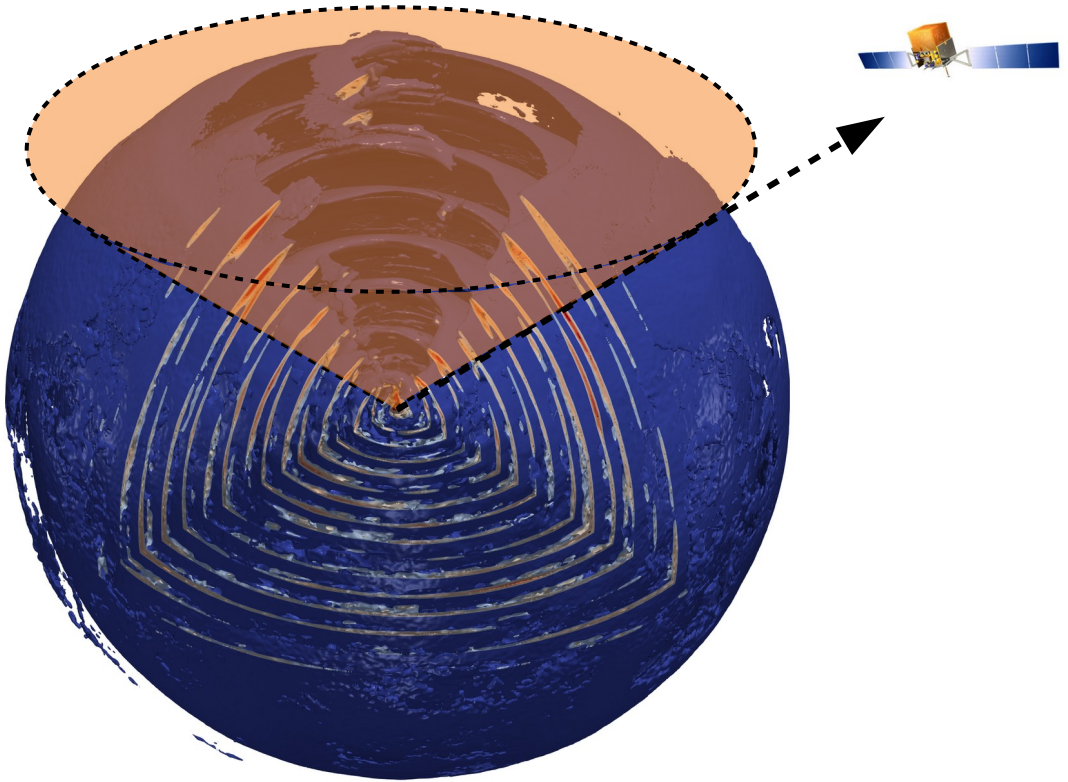

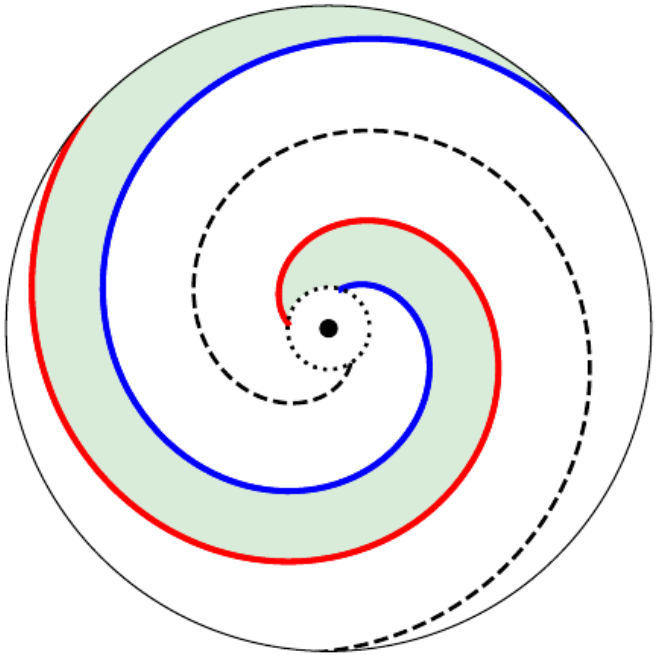

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Cerutti et al. 2020

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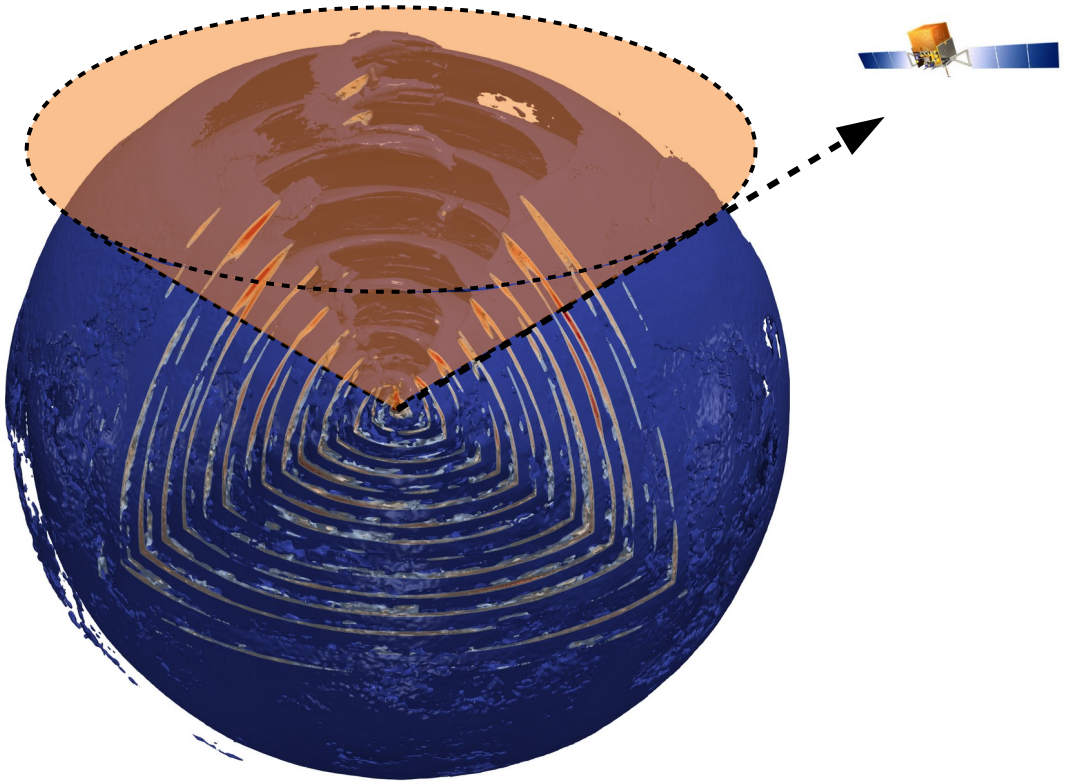

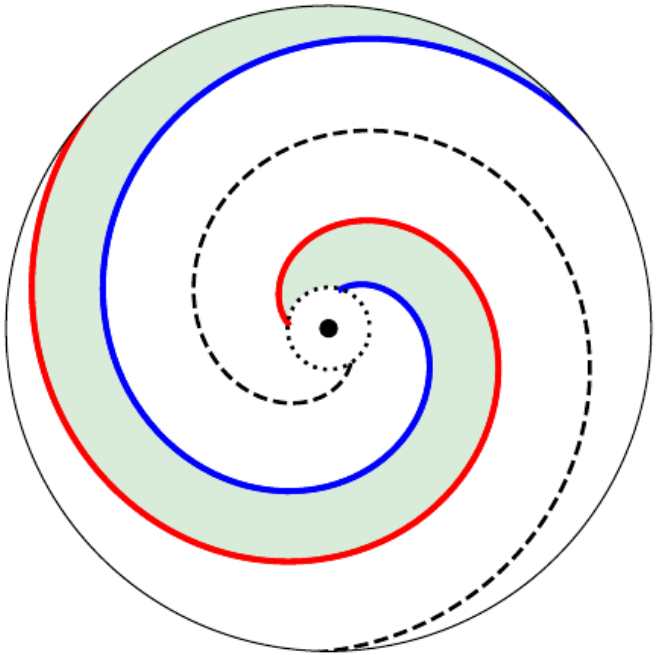

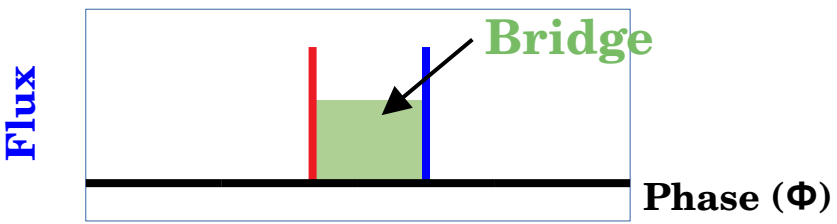

Shinning current sheet: geometric origin of pulses

Cerutti et al. 2020

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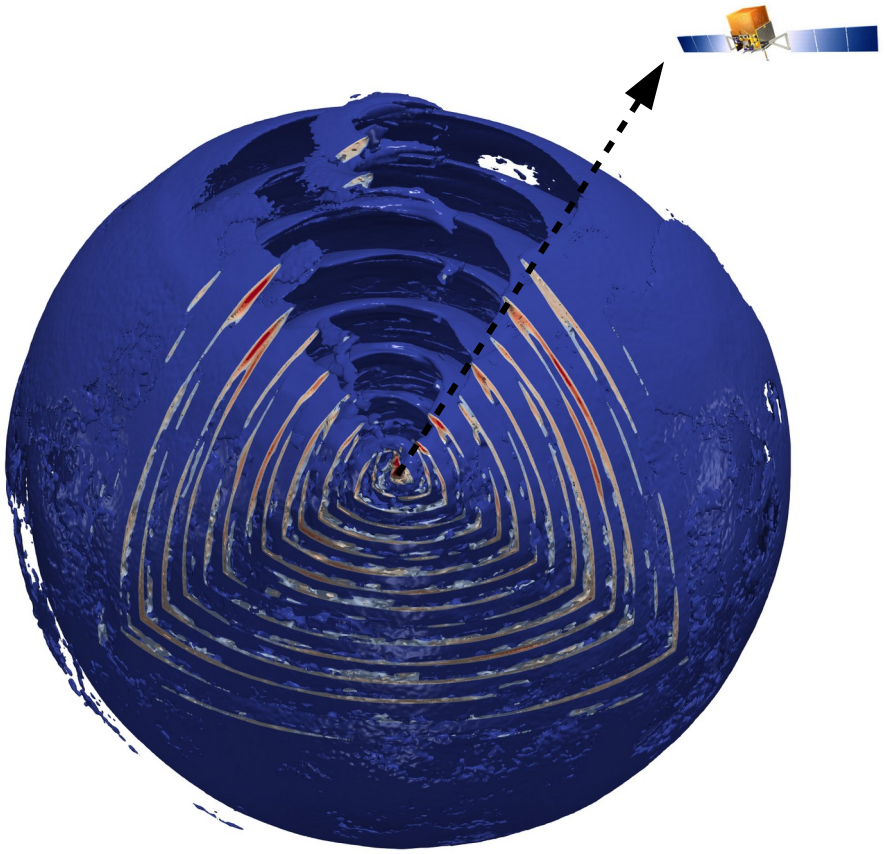

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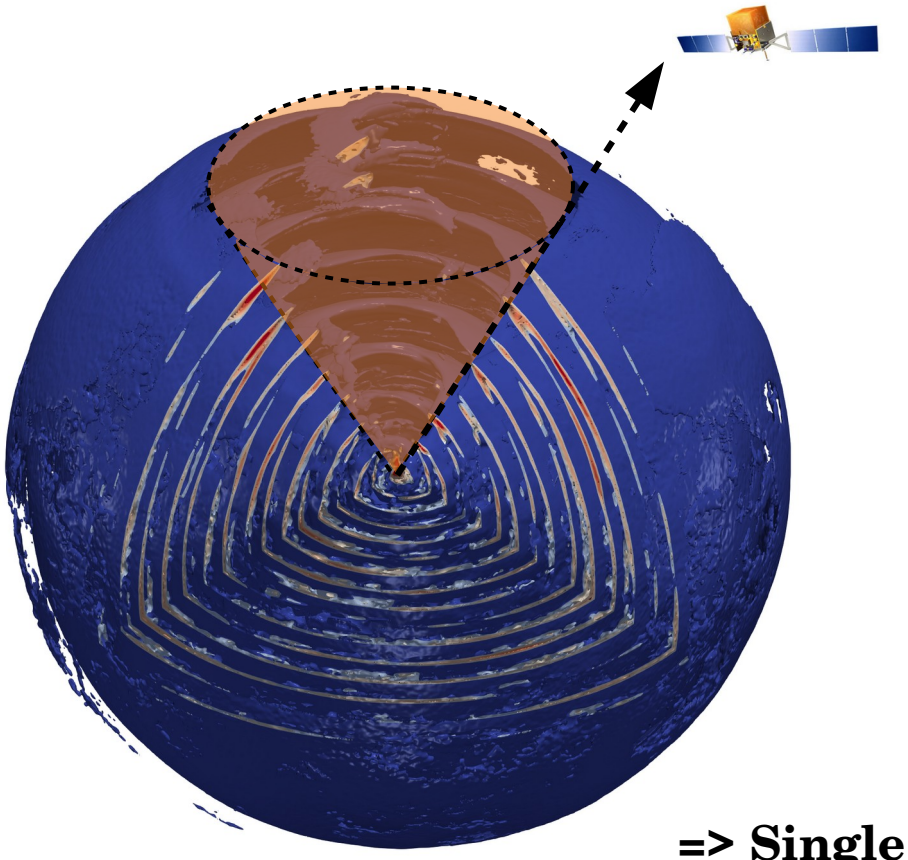
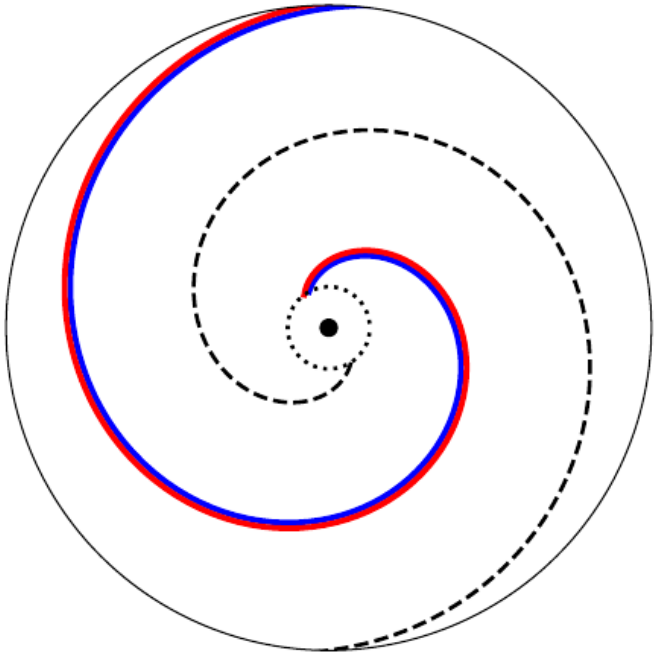
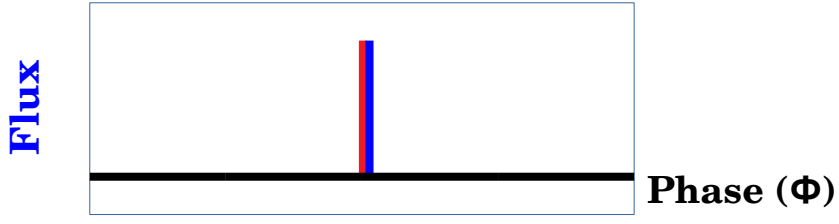


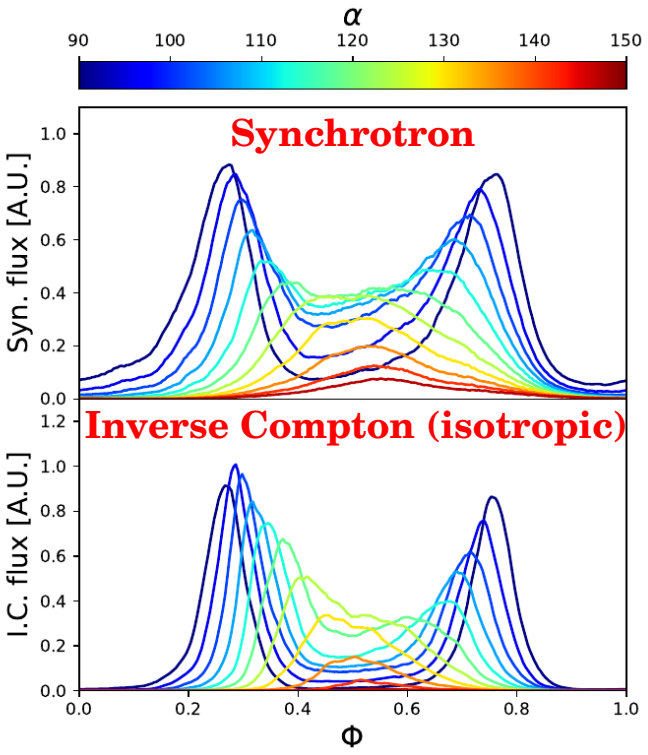


=> Single pulse !



The model can reproduce generic feature of *Fermi* pulse profiles

Synthetic skymap



IC lightcurves (TeV) thinner but similar to synchrotron (GeV)

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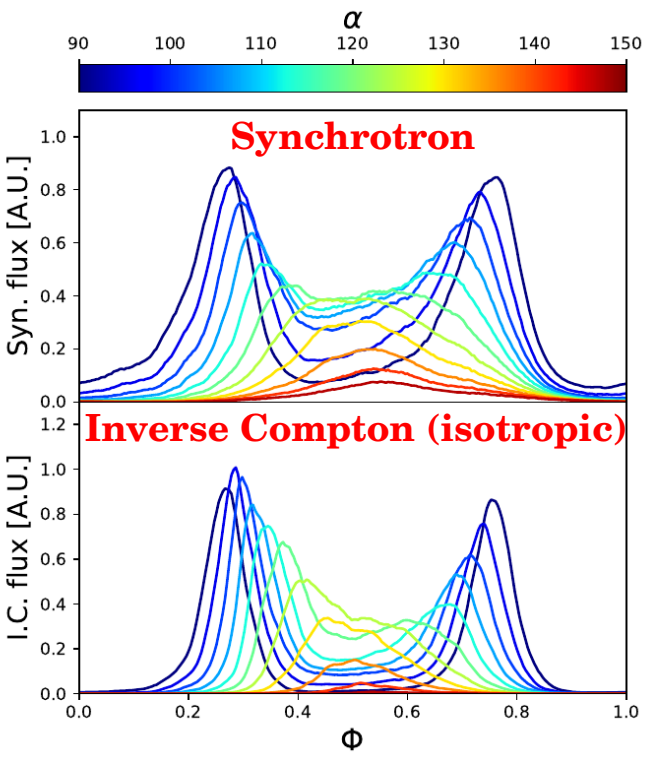

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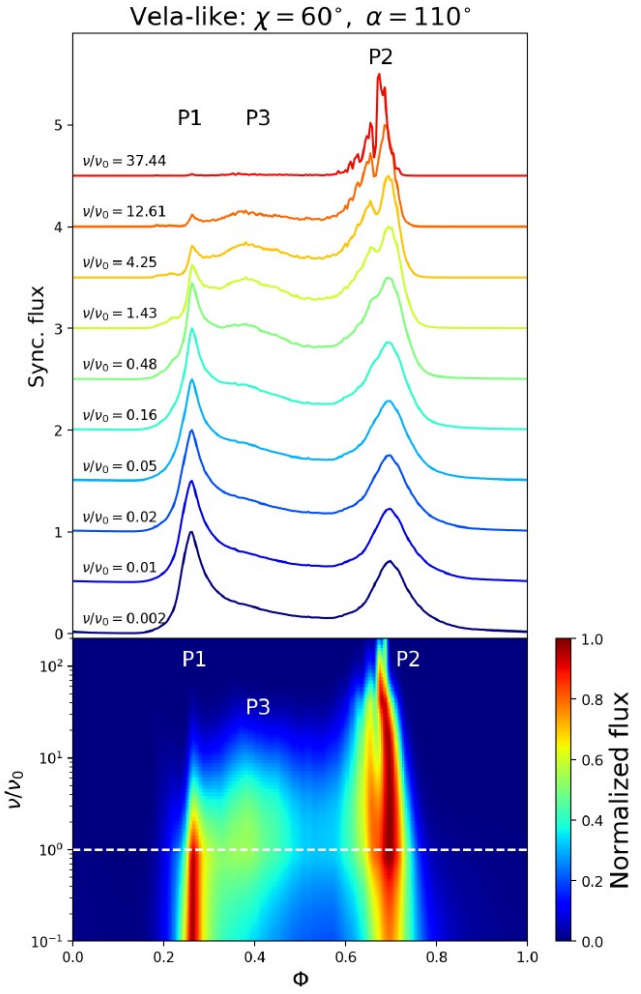
Energy evolution



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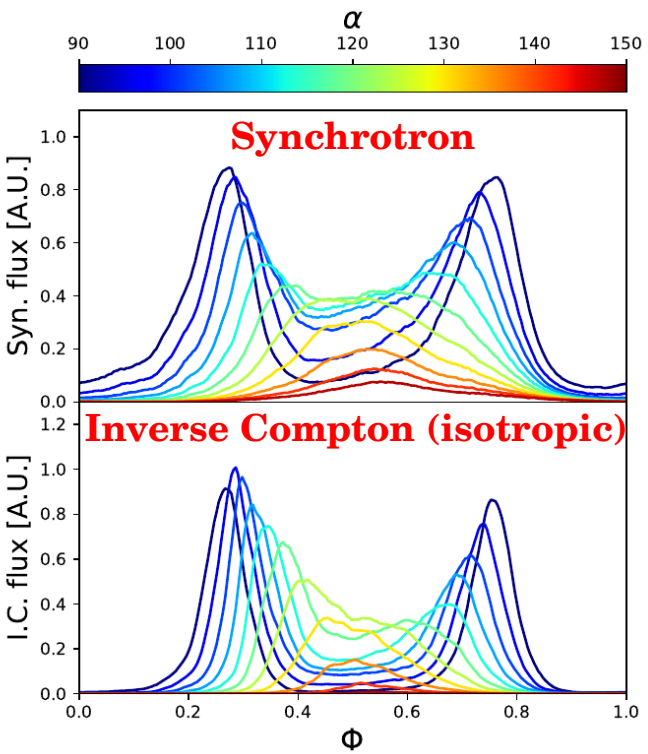

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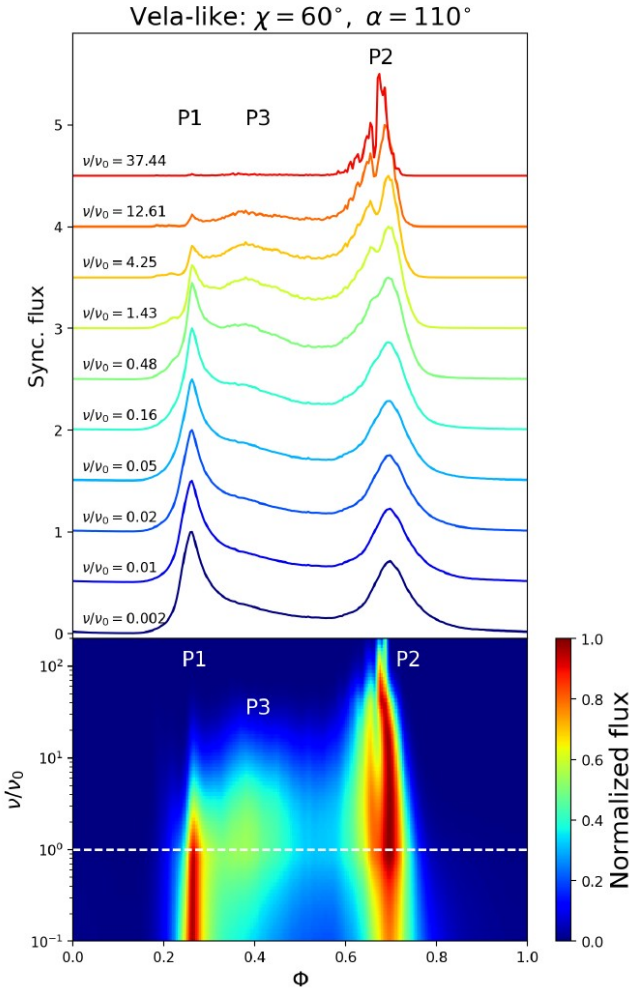
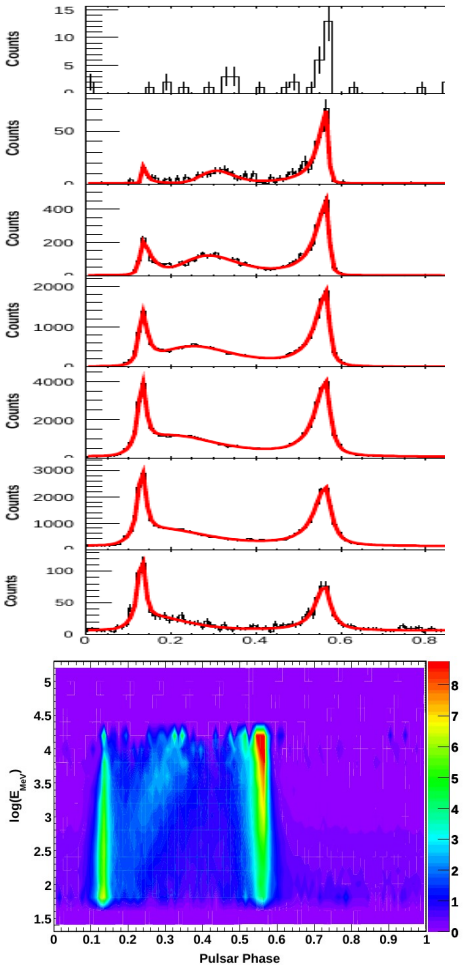
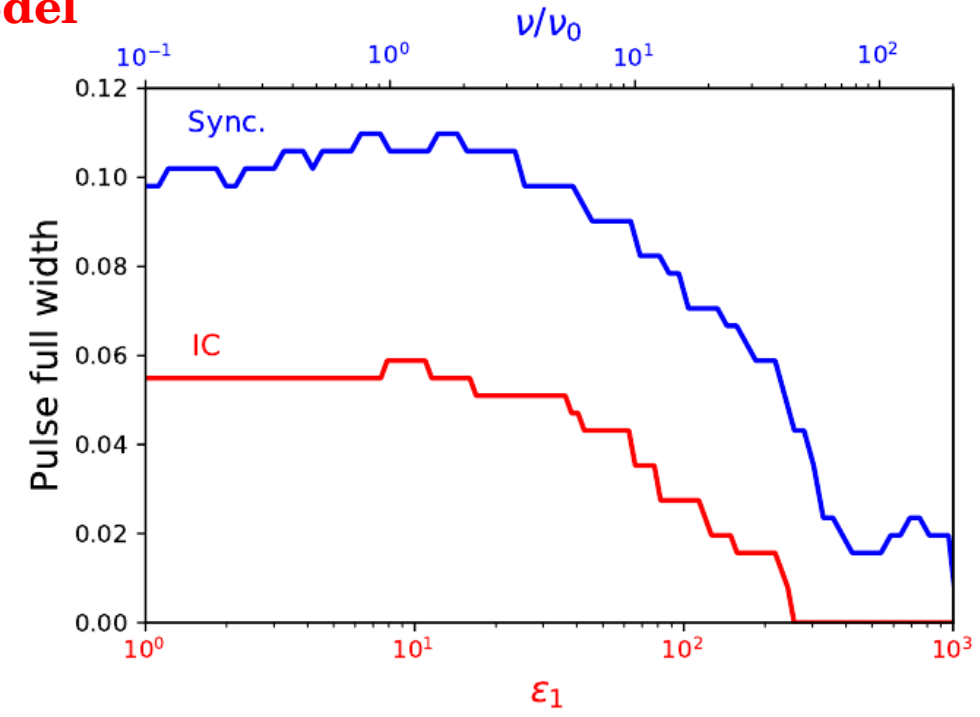


Vela *(Abdo+2010)*



Origin of pulse width: radial and energy evolutions

Model



Pulses become thinner at higher energies

=> Higher energies are produced further away where the wind is more relativistic (stronger beaming)

Origin of pulse width: radial and energy evolutions

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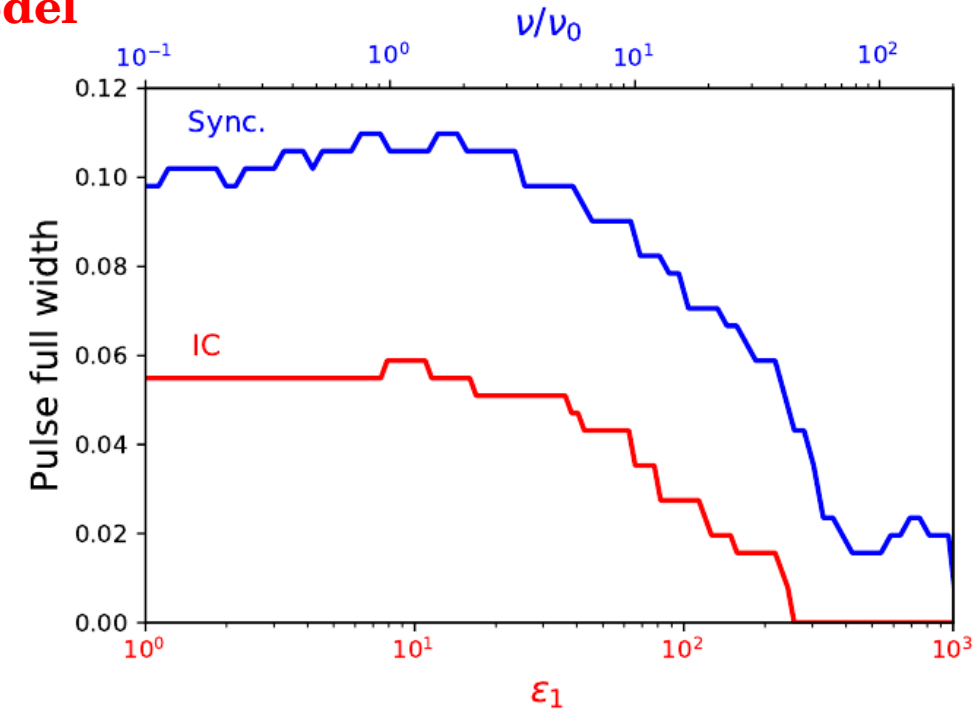

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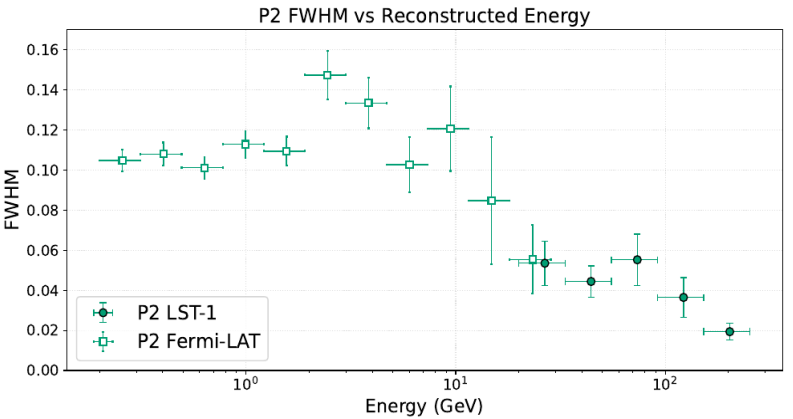
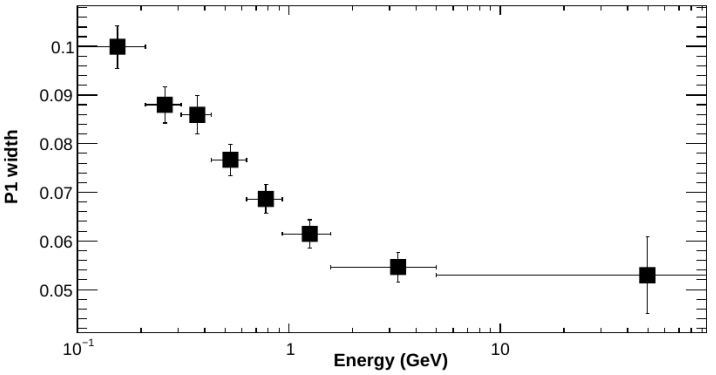
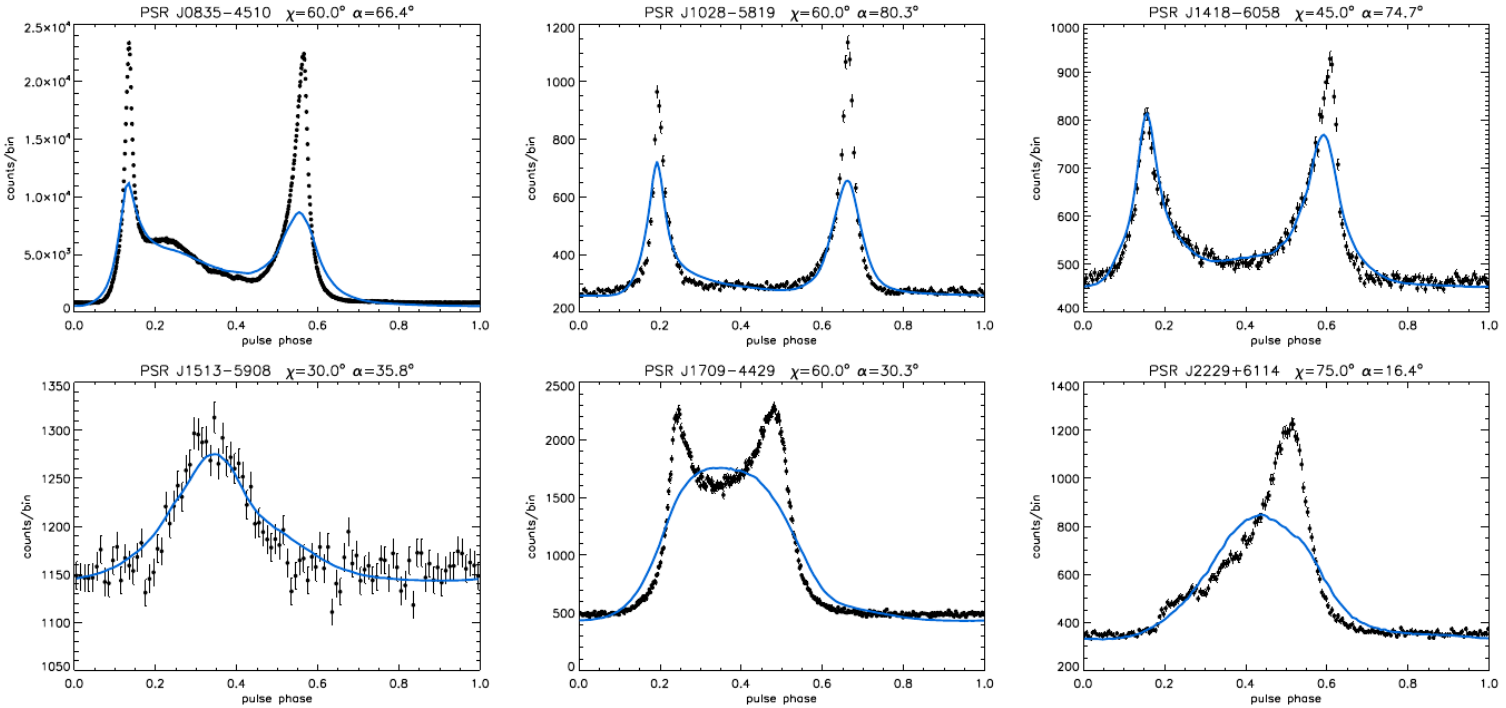
Crab *(Abe+2024)*



Geminga *(Abdo+2010)*



3PC lightcurve fitting (χ^2 minimization)



✅ Main features reproduced (peaks, bridge, energy evolution)

❌ Main peak amplitude underestimated, asymmetric pulses not explained

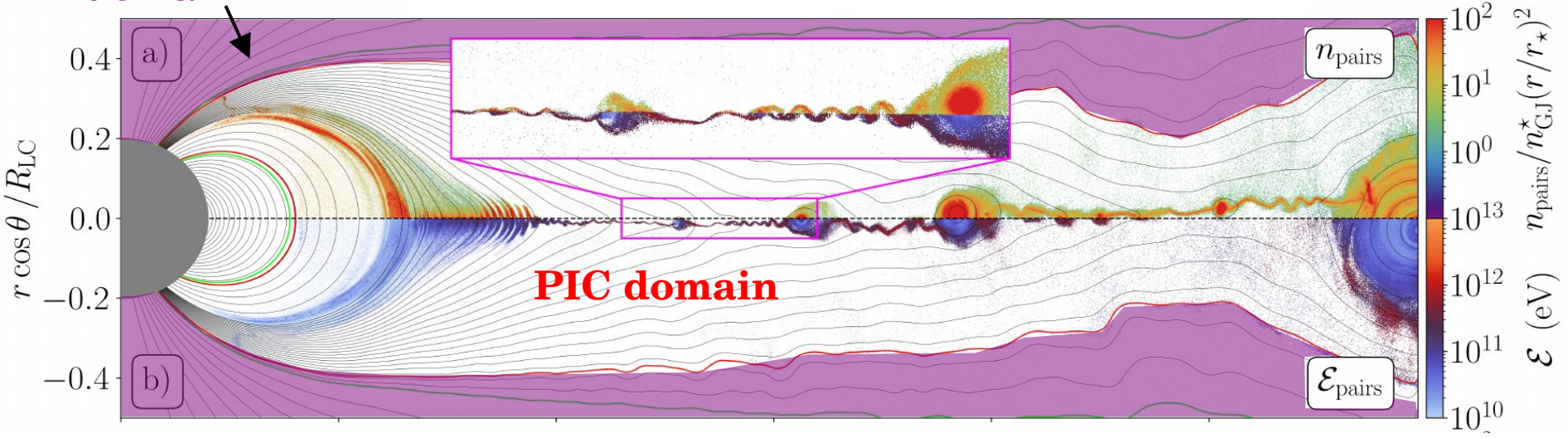
Encouraging, but we need a better model => higher scale separation
Still not good enough to fit observed lightcurves.

Hybrid PIC/MHD model: a (weak) ms *Fermi* pulsar in a box

(Soudais et al. 2024)

Pulsar period : **1ms**
Surface magnetic field : **10^7 G** **(no rescaling)**

MHD domain



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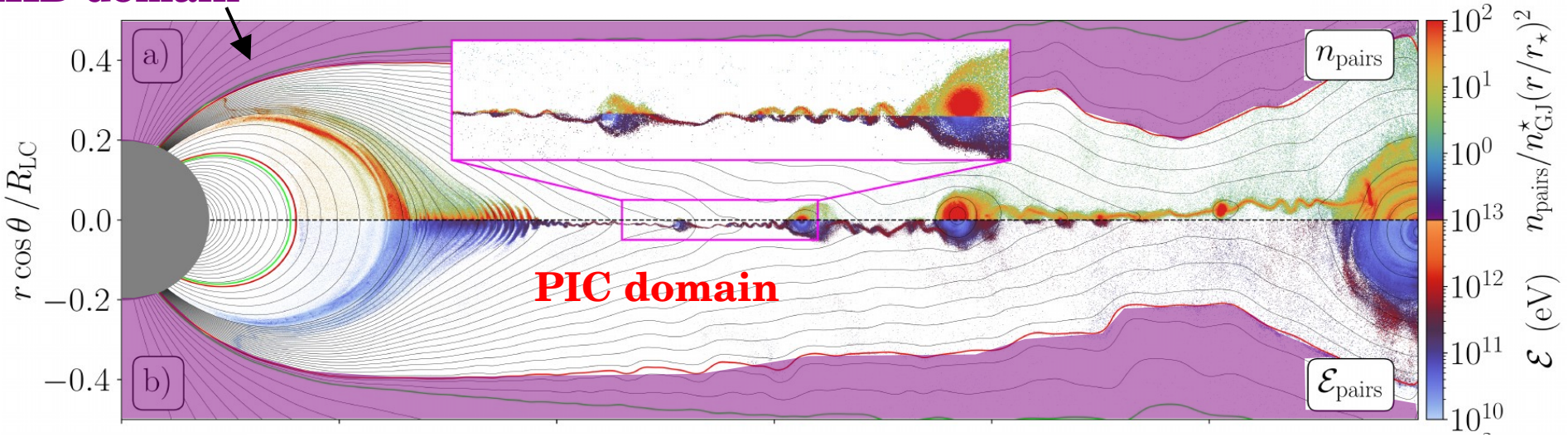
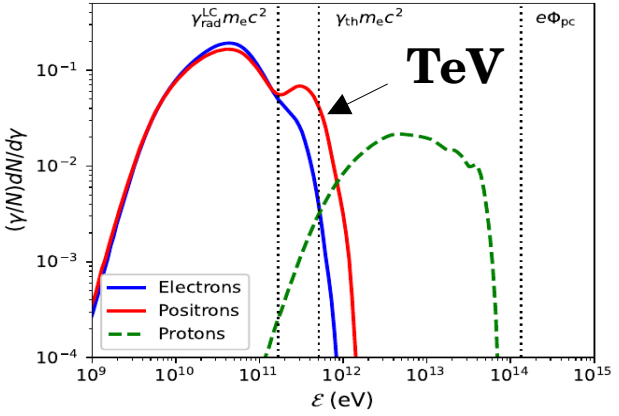
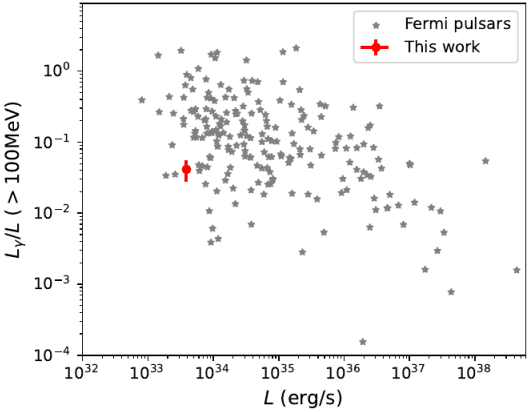


Particle acceleration

Pairs : TeV
Protons : >10TeV



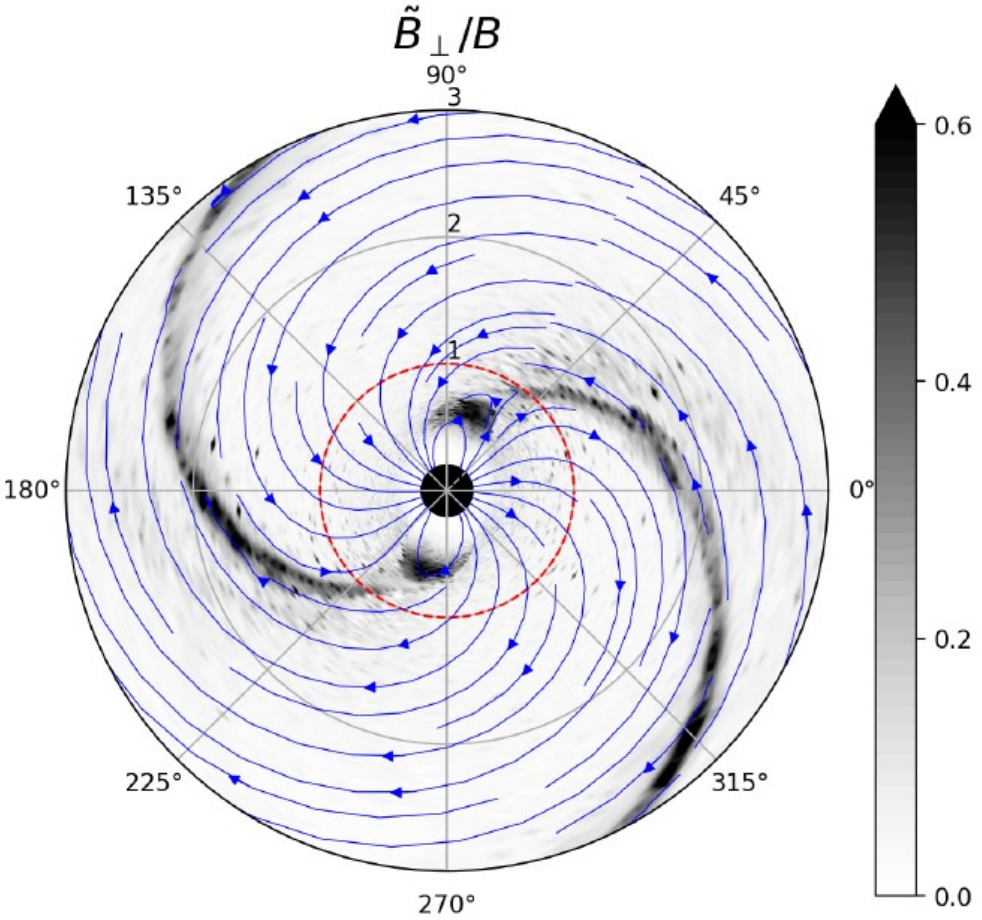
Radiative efficiency



Some takeaway messages

- **Reconnection** in the wind current sheet powers **synchrotron** (GeV) and **inverse Compton** (TeV) radiation
- The **global PIC model** explains the salient features of observed pulse profiles (# peaks, bridge, width, energy evolution)
- Lightcurve fitting gives encouraging results, but the model is still not good enough
- **Scale separation problem** : Need to scale simulations up !
  Develop innovative methods (GPU, hybrid => *Soudais et al. 2024*)
- Please stay tuned and check out our upcoming paper : *Cerutti, Figueiredo & Dubus (submitted)*

Synchrotron or curvature radiation?



$$\frac{\tilde{B}_\perp}{B} = \sin\zeta \qquad \textbf{Pitch angle}$$

$$\frac{P_{\rm curv}}{P_{\rm sync}} = \left(\frac{\text{Larmor radius}}{\text{Light cylinder radius}}\right)^2 \sim 10^{-7}$$

Synchrotron radiation dominates beyond the light cylinder

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Overview

This workshop aims at bringing together world experts in the field of relativistic plasma astrophysics to discuss recent progress in the understanding of magnetized plasmas surrounding neutron stars and black holes and related astrophysical phenomena from an observational, theoretical and computational perspectives.

Important dates

Conference dates: Sunday April 6, 2025 - Friday April 11, 2025.

Open to registration next week!

Confirmed invited speakers

- Andrei Beloborodov, Columbia University, USA
- Roger Blandford, Stanford University, USA
- Arache Djannati-Ataï, APC, France
- Gwenael Giacinti, Tsung-Dao Lee Institute, China
- Hayk Hakobyan, Columbia University, USA
- Yuri Lyubarsky, Ben-Gurion University of the Negev, Israel
- Monika Mościbrodzka, Radboud University, Netherlands
- Kohta Murase, Penn State, USA
- Nanda Rea, CSIC-ICE, Spain
- Bart Ripperda, CITA-University of Toronto, Canada
- Dmitri Uzdensky, University of Oxford, UK

SOC :
- B. Cerutti (chair)
- B. Crinquand
- N. Globus
- C. Guépin
- A. Levinson
- K. Parfrey
- A. Philippov

https://r-magnetosphere.sciencesconf.org/