Institute of Space Sciences

EXCELENCIA MARÍA DE MAEZTU

Modeling the observed spectra and light curves ofsynchro-curvature emission of pulsars

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HONEST Workshop

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Motivation

Explain the high-energy spectra and light curves of pulsars, in gamma-rays and X-rays.

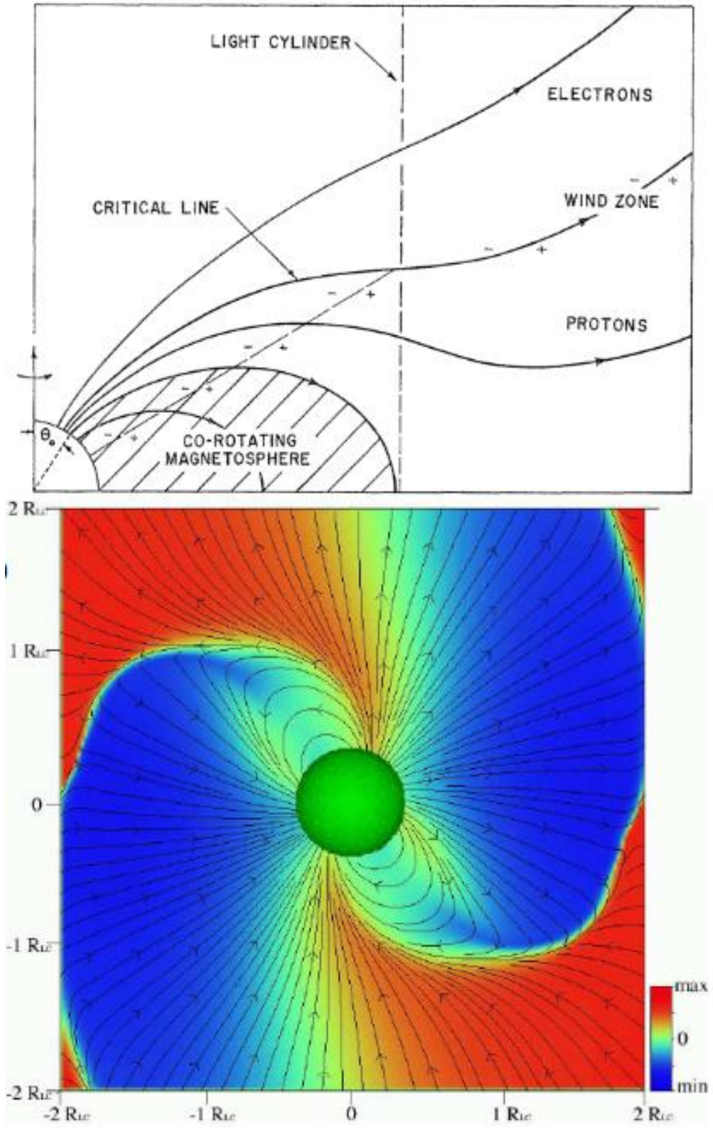
The model adopts an effective, but physically-based approach, versatile enough to:

- Fit the entire population of pulsars
- Test different emission regions
- Add/test new physics

FFE / PICS / FIDO | **These works** | **Phenom. models**

Versatility →

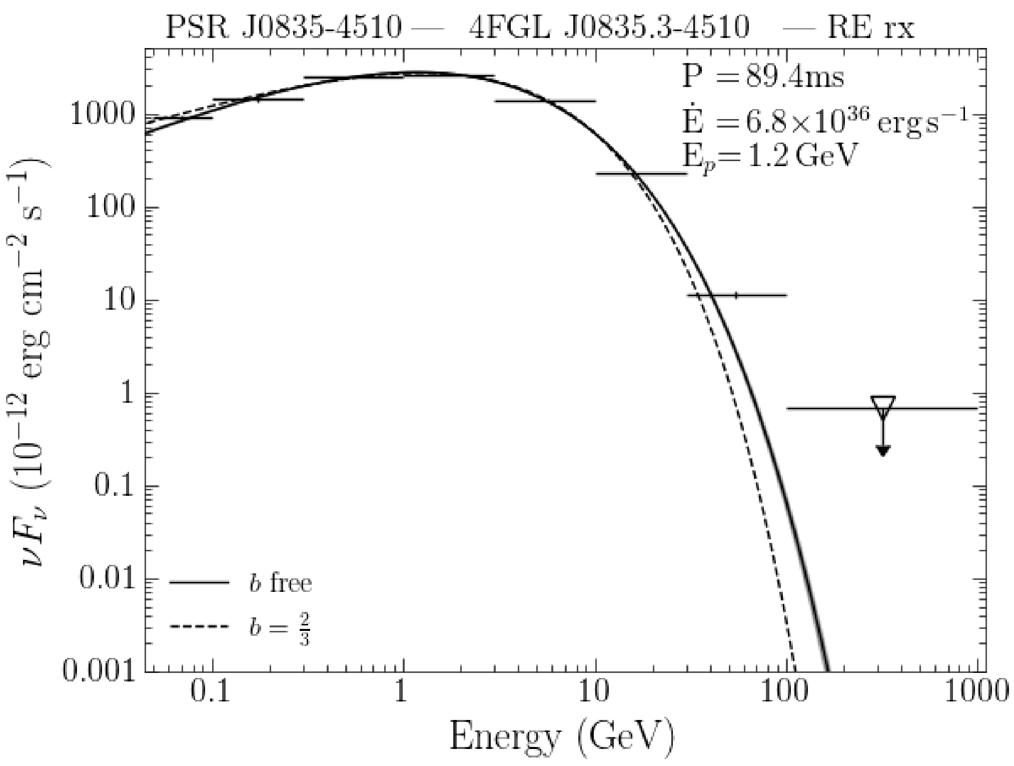
← Computational cost, Physics

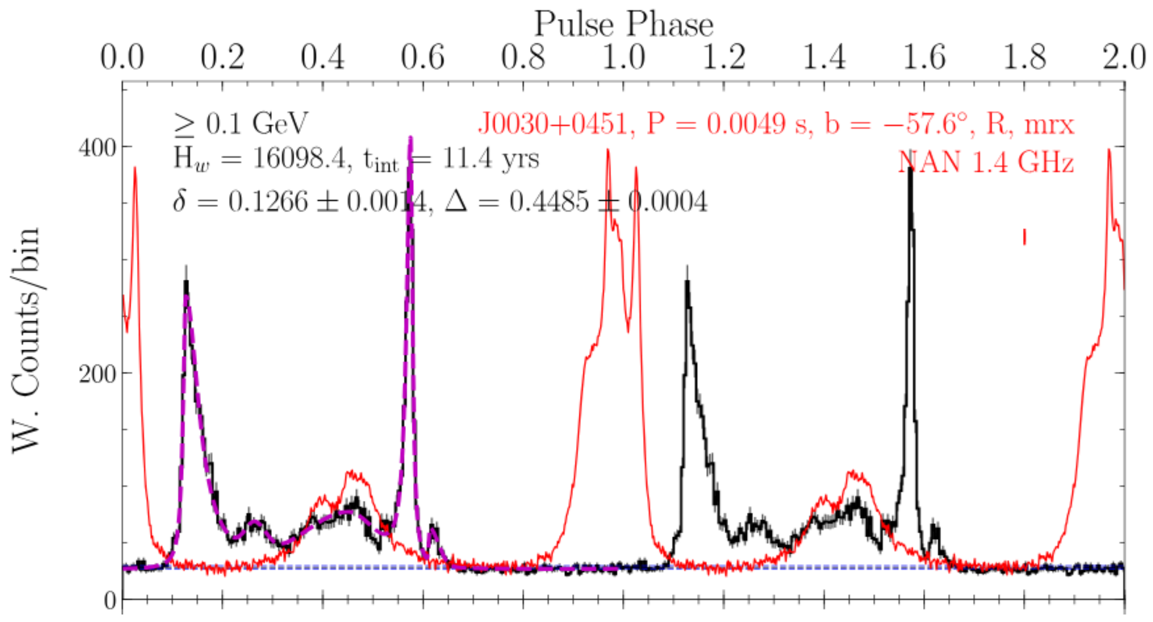


[Goldreich & Julian (1969); Spitkovsky (2006)]

Motivation

- Models aim to fit data of the gamma-ray emitting pulsars released in the 2PC and 3PC (in the latter, fewer spectral bins!)



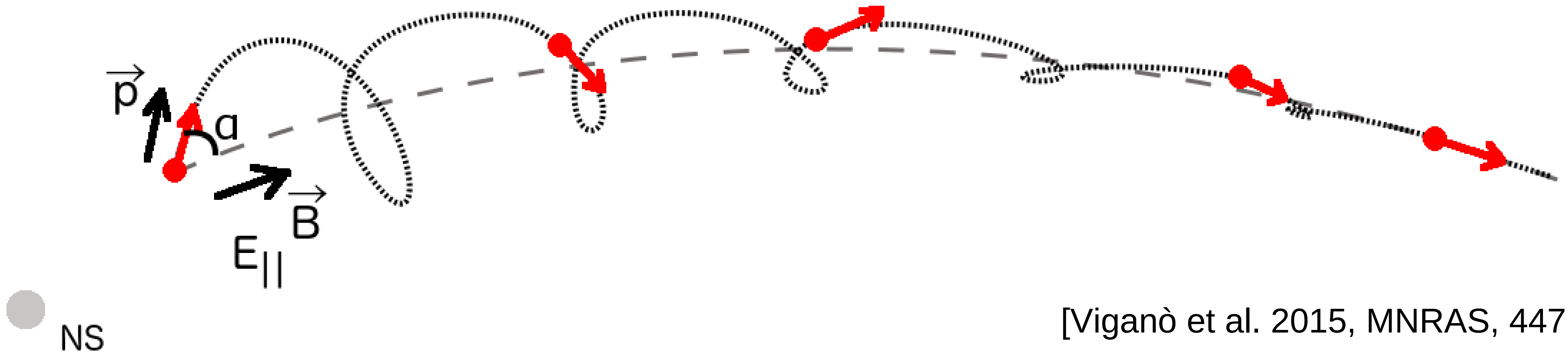


- Our goal is to reproduce observational data with a model that contains simple but realistic physics and is computationally affordable

Spectral model: particle dynamics

- We follow the dynamics of the emitting particles, ruled by electric acceleration and synchro-curvature losses and with two free parameters involved: $E_{||}$, b

- Solving the equation of motion gives the evolution of the relativistic momentum and of the Lorentz factor Γ and pitch angle α



[Viganò et al. 2015, MNRAS, 447, 1164]

Spectral model: particle dynamics

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- The equation of motion of charged particles balances electric acceleration and synchro-curvature losses

$$\frac{d\vec{p}}{dt} = ZeE_{\|}\hat{b} - (P_{sc}/v)\hat{p} \qquad \vec{p} = \Gamma m \vec{v}$$

[Viganò et al. (2014)]

- We solve it numerically, considering separately the components parallel and perpendicular to the trajectory

$$\frac{d(p\cos\alpha)}{dt} = ZeE_{\|} - \frac{P_{sc}}{v}\cos\alpha \qquad \frac{d(p\sin\alpha)}{dt} = -\frac{P_{sc}}{v}\sin\alpha$$

- Local magnetic field strength and curvature radius are parametrize in an effective way:

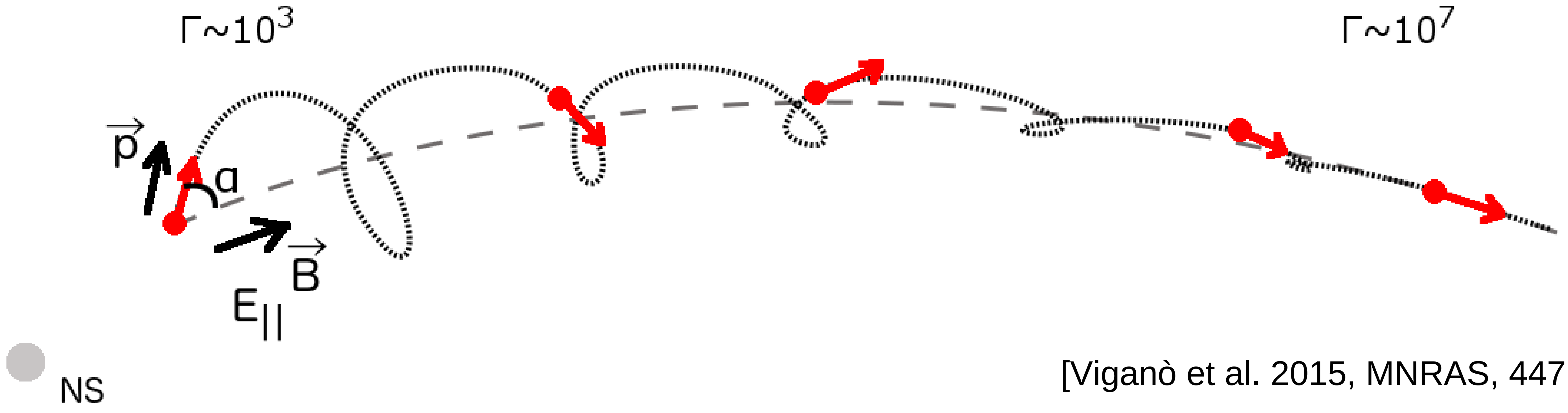
$$B = B_\star\left(\frac{R_\star}{x}\right)^b \qquad r_c = R_{lc}\left(\frac{x}{R_{lc}}\right)^\eta$$

Spectral model: particle dynamics

- Power of synchrotron and curvature radiations depend on the Lorentz factor Γ of particles differently

$$P_{syn} = \frac{2}{3}\frac{(Ze)^4 B^2 (\Gamma^2 - 1)\sin^2\alpha}{m^2 c^3}$$

$$P_c = \frac{2}{3}\frac{(Ze)^2 c \Gamma^4}{r_c^2}$$



[Viganò et al. 2015, MNRAS, 447, 1164]

Spectral model: synchro-curvature radiation

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- Single-particle synchro-curvature power spectra:

$$\frac{dP_{sc}}{dE} = \frac{\sqrt{3}(Ze)^2\Gamma y}{4\pi\hbar r_{eff}}\left[(1+z)F(y) - (1-z)K_{2/3}(y)\right]$$

- Synchro-curvature power: $P_{sc} = \frac{2(Ze)^2\Gamma^4 c}{3r_c^2} g_r$

[Cheng & Zhang (1996),
Viganò et al. (2014)]

$$r_{eff} = \frac{r_c}{\cos^2\alpha}\left(1+\xi+\frac{r_{gyr}}{r_c}\right)^{-1}$$

$$z = (Q_2 r_{eff})^{-2}$$

$$y = \frac{E}{E_c}$$

$$Q_2^2 = \frac{\cos^4\alpha}{r_c^2}\left[1+3\xi+\xi^2+\frac{r_{gyr}}{r_c}\right]$$

$$E_c = \frac{3}{2}\hbar c Q_2 \Gamma^3$$

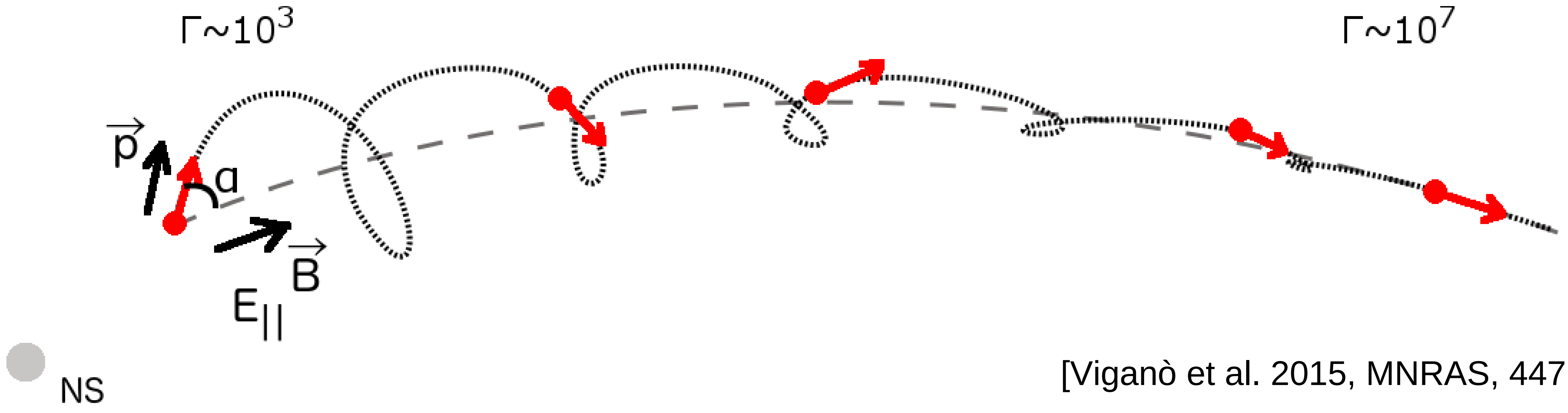
$$F(y) = \int_y^\infty K_{5/3}(y')dy'$$

$$\xi = \frac{r_c}{r_{gyr}}\frac{\sin^2\alpha}{\cos^2\alpha}$$

Spectral model: emission

- Synchro-curvature formulae gives the emission of the particles all along the trajectory, which convolved with an effective particle distribution gives the total radiation from the emission region

- We produce theoretical spectra with just three free parameter ($E_{||}$, b, x_0) and a normalization factor



[Viganò et al. 2015, MNRAS, 447, 1164]

Spectral model: effective particle distribution

- Convolving the single-particle power spectra with an effective particle distribution,

$$\frac{dN}{dx} = N_0 \frac{e^{-(x-x_{min})/x_0}}{x_0(1-e^{-(x_{max}-x_{min})/x_0})}$$

We obtain the total emission from the region:

$$\frac{dP_{tot}}{dE} = \int_{x_{min}}^{x_{max}} \frac{dP_{sc}}{dE}\frac{dN}{dx}dx$$

[Cheng & Zhang (1996),
Viganò et al. (2014)]

Spectral fitting to gamma rays

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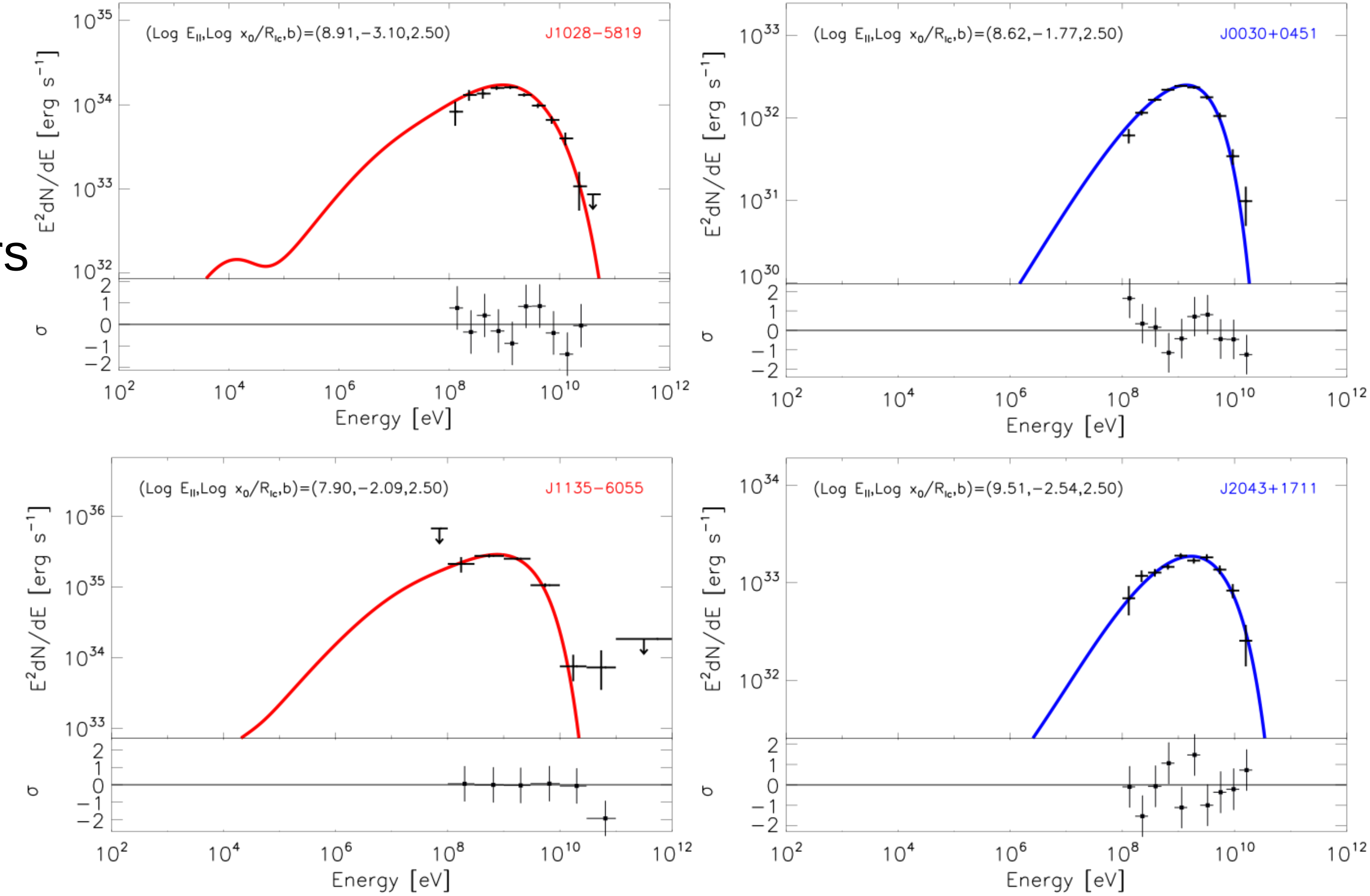
[Viganò et al. 2015, MNRAS, 453, 2599; Íñiguez-Pascual et al. (in prep.)]

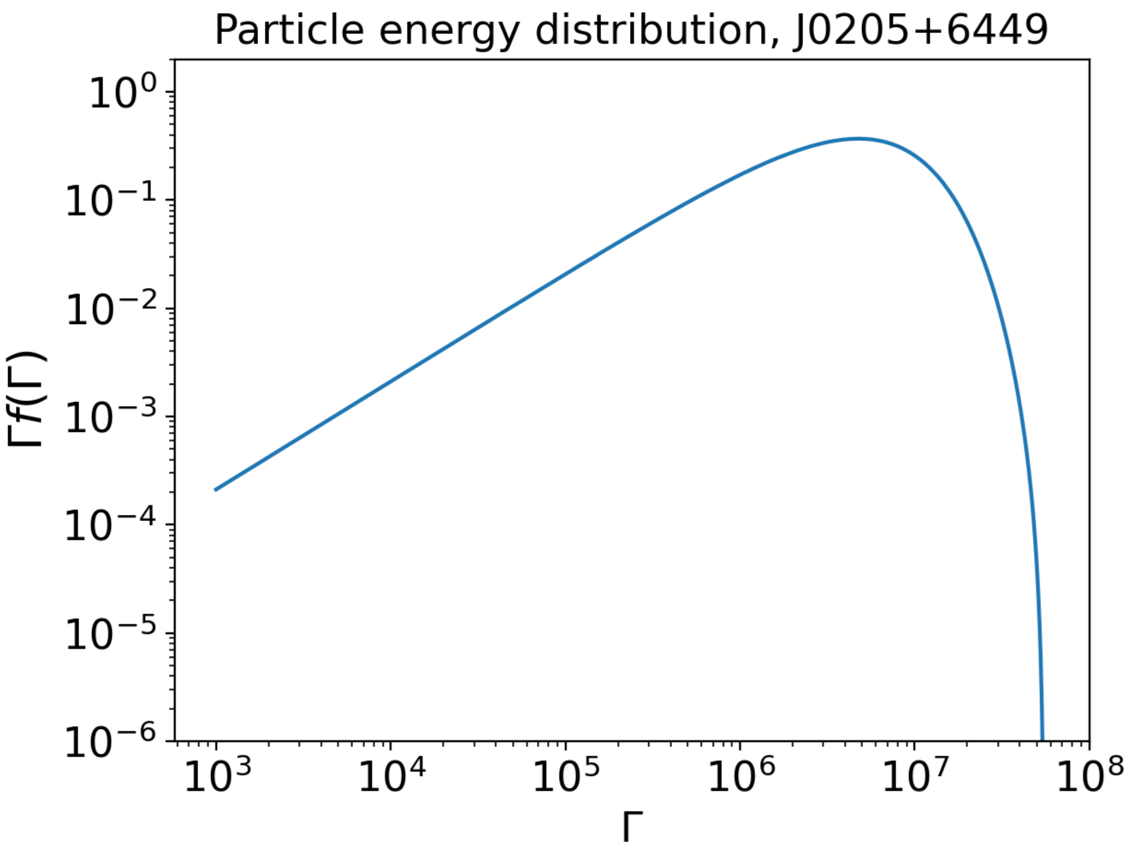
- The model successfully fitted the 117 gamma ray-pulsars on the 2PC (Abdo et al. (2013)) and the ~300 gamma-ray pulsars on the 3PC (Smith et al. (2023))

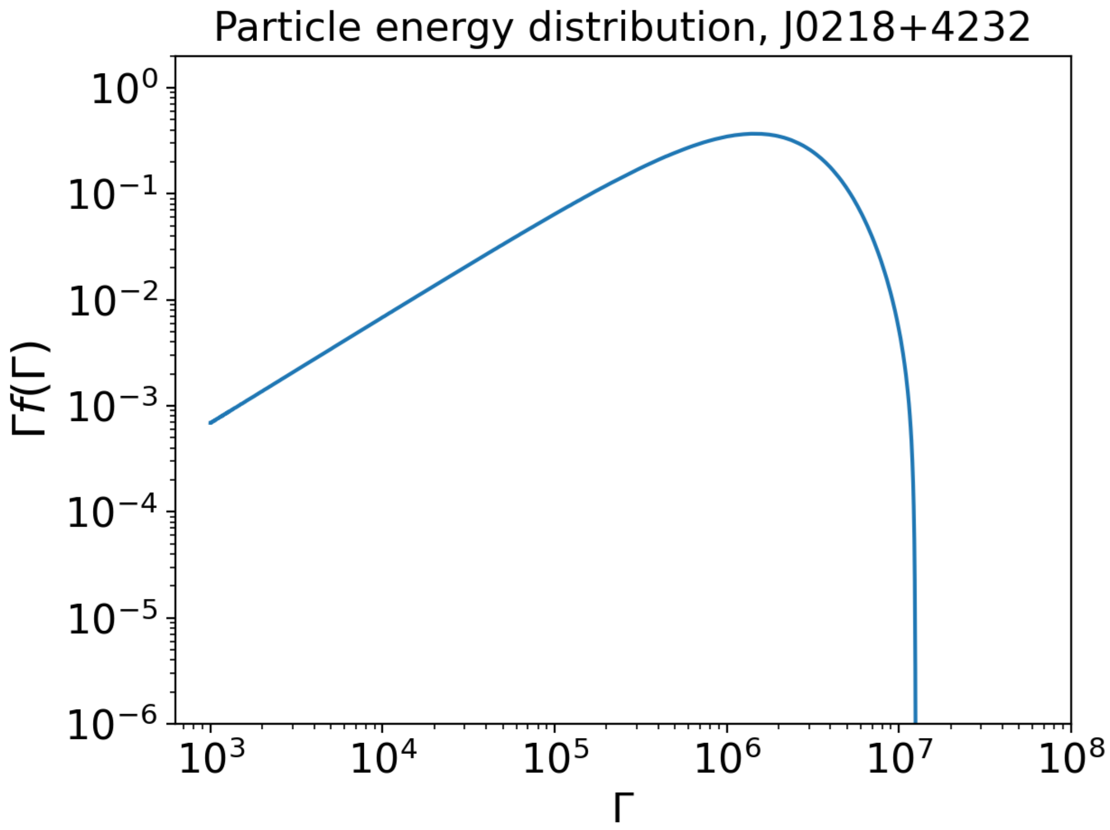
- A relevant synchrotron contribution is needed to match gamma-ray spectra, implying that synchro-curvature radiation is an appropriate mechanism to explain the emission from these objects



Spectral model: particle energy distribution

- Lorentz factors Γ typically range from 10^3 to 10^7.





Spectral fitting

[Torres 2018, Nat. Astron., 2, 247;
Torres et al. 2019, MNRAS, 489, 5494;
Coti Zelati et al. 2020, MNRAS, 492, 1025;
Íñiguez-Pascual, Viganò & Torres 2022, MNRAS, 516, 2475]

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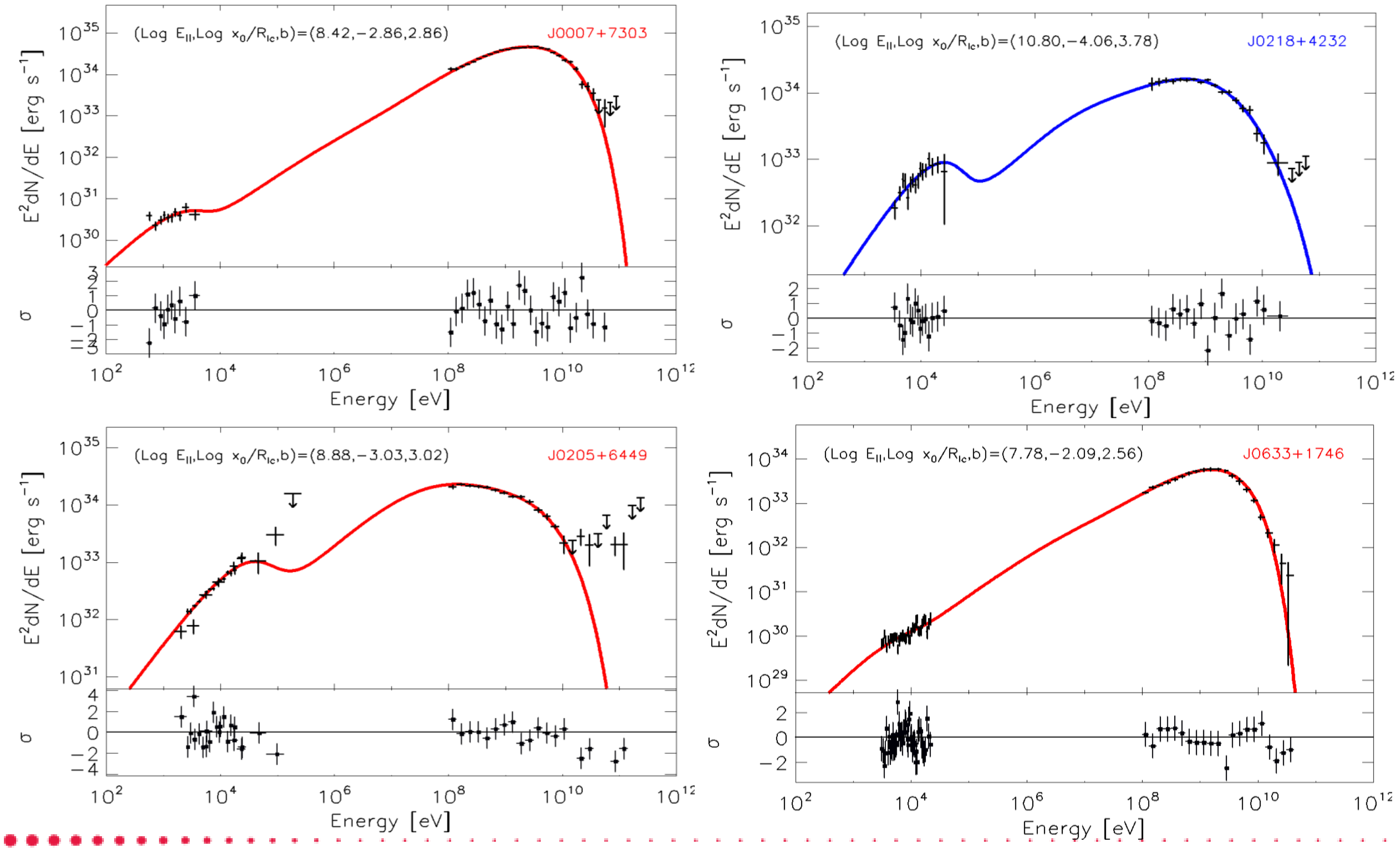
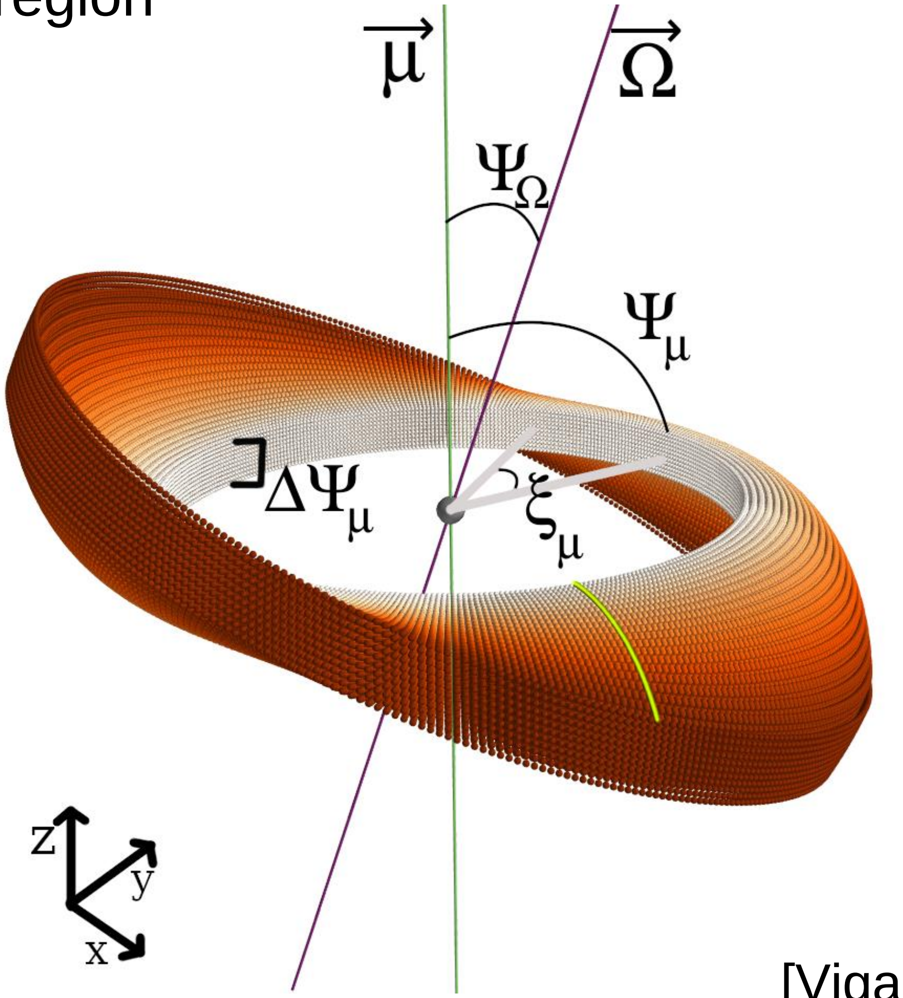
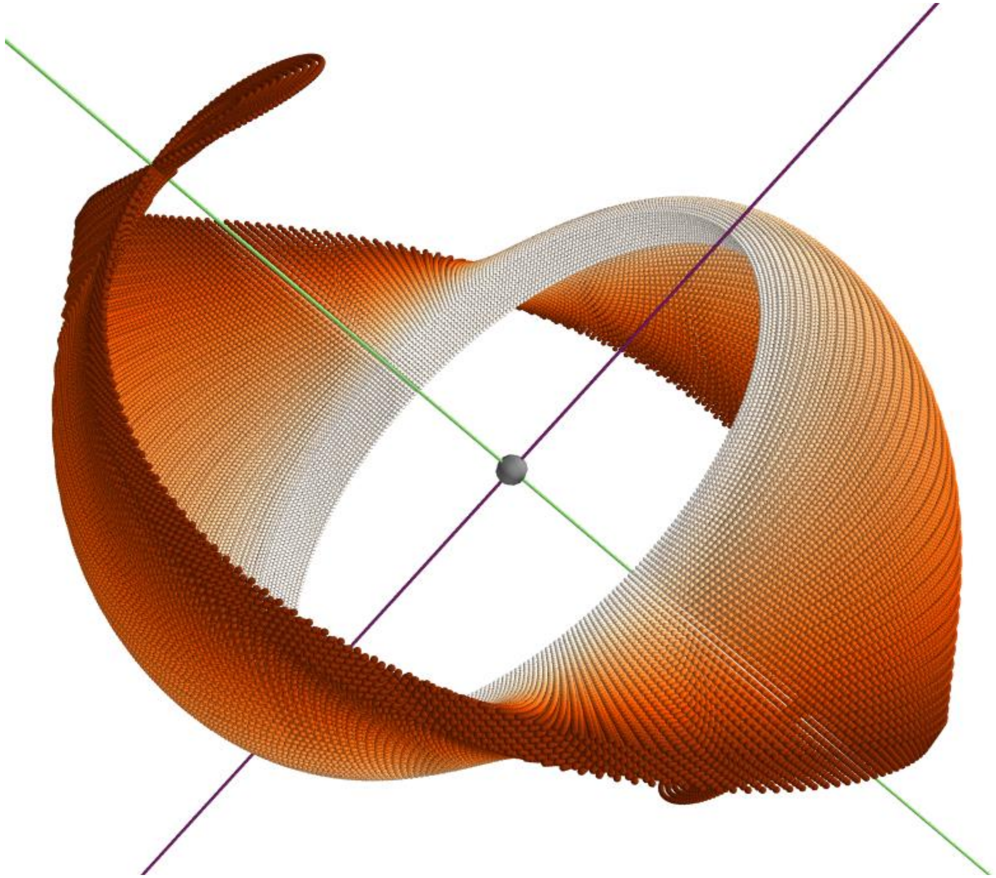


Extension to fit X-rays for the ~40 X+γ pulsars

Geometrical model

- The inclination angle and the meridional extent define the geometry of the emission region

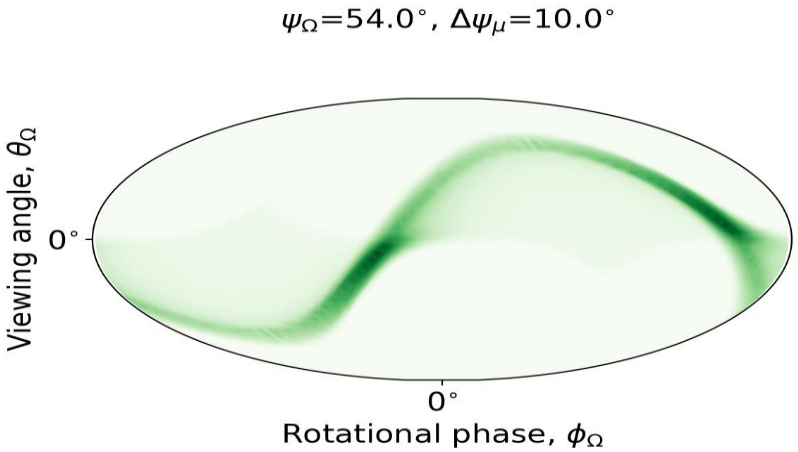


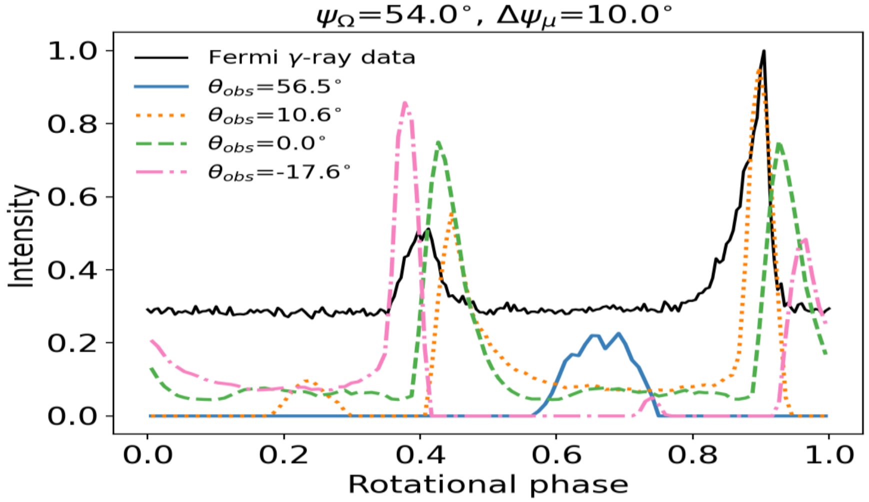


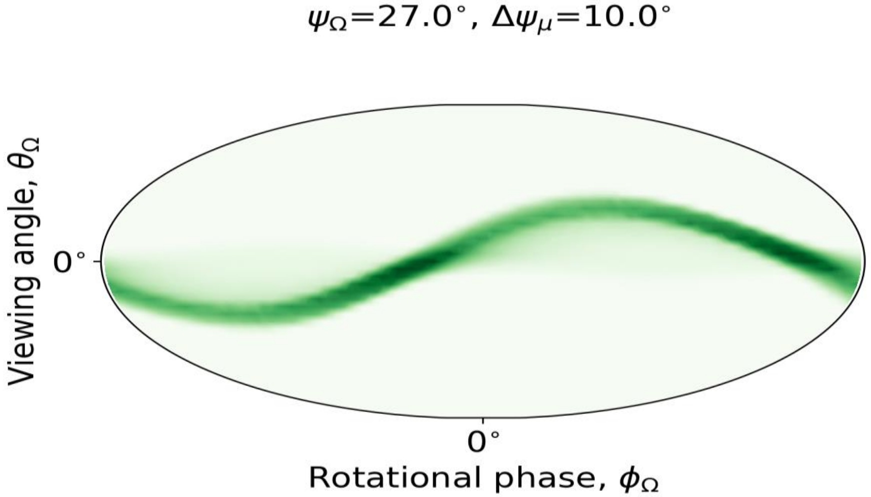
[Viganò & Torres (2019); Íñiguez-Pascual, Torres & Viganò (2024)]

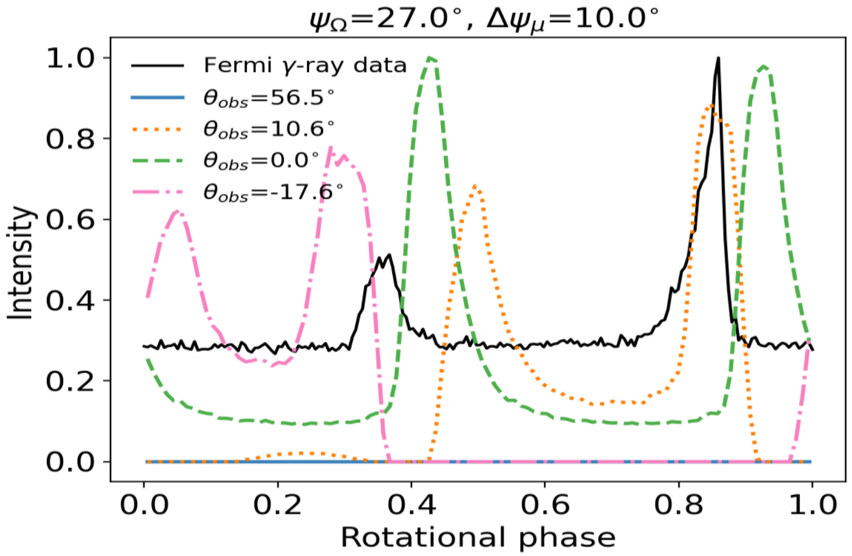
Emission maps and light curves

- We build emission maps, from which light curves are obtained









[Íñiguez-Pascual, Torres & Viganò 2024, MNRAS, 530, 1550]

Light curves statistics

[Íñiguez-Pascual, Torres & Viganò 2024, MNRAS, 530, 1550]

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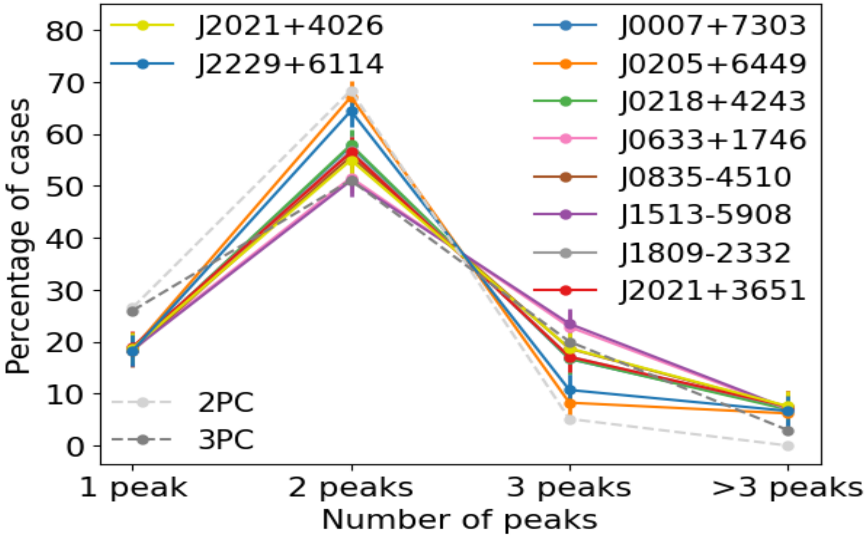
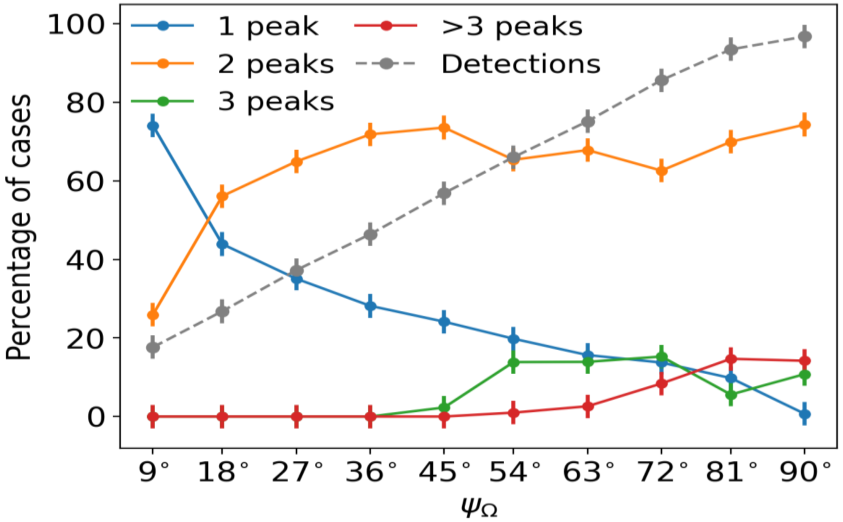
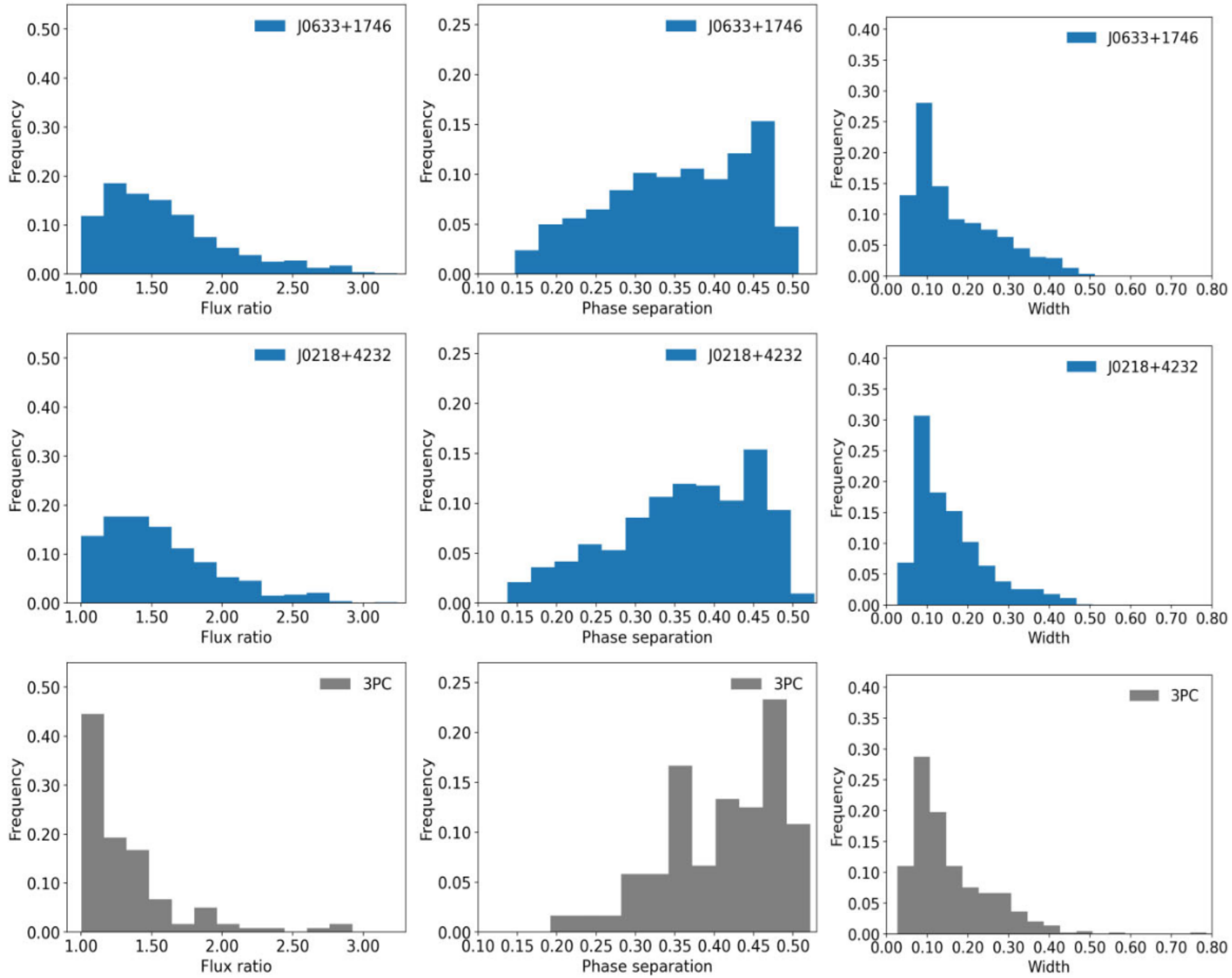
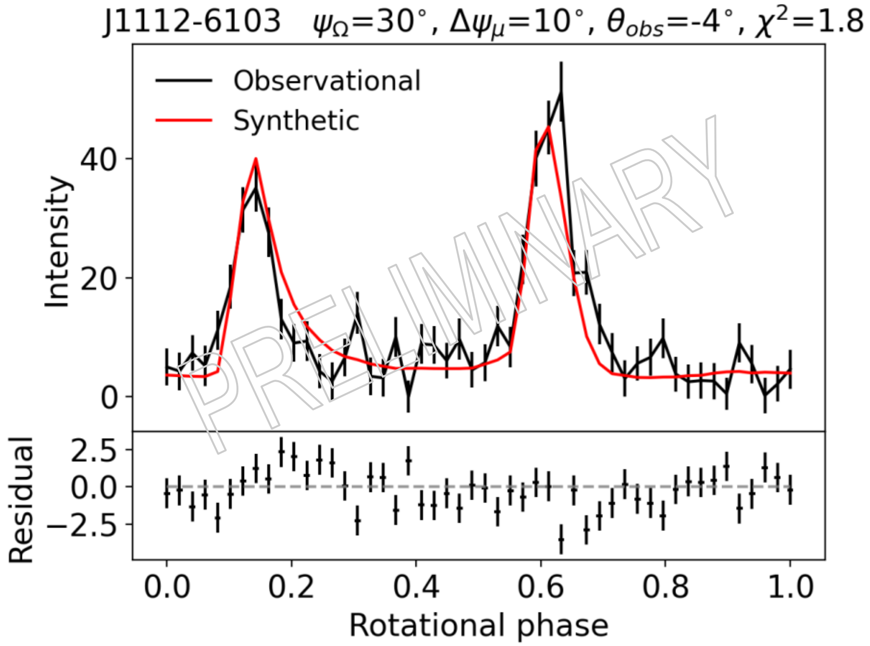


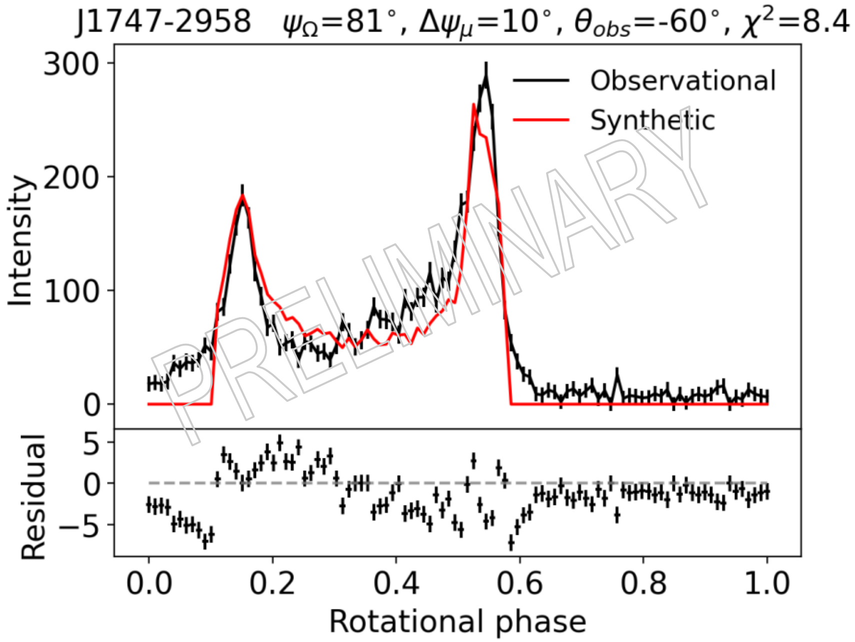




Light curves fitting

- Fitting synthetic light curves to observational ones, concurrently to the spectral fitting





[Íñiguez-Pascual et al. (in prep.)]

Light curves fitting

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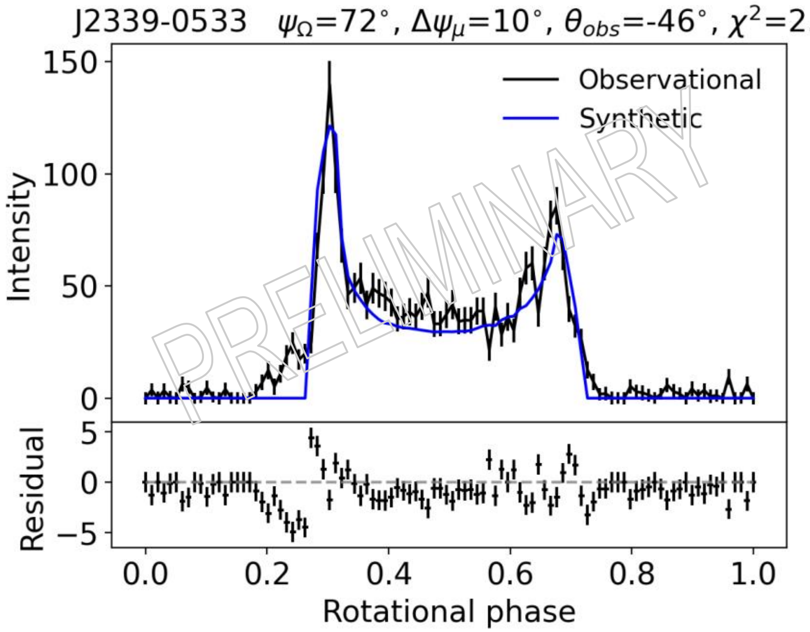
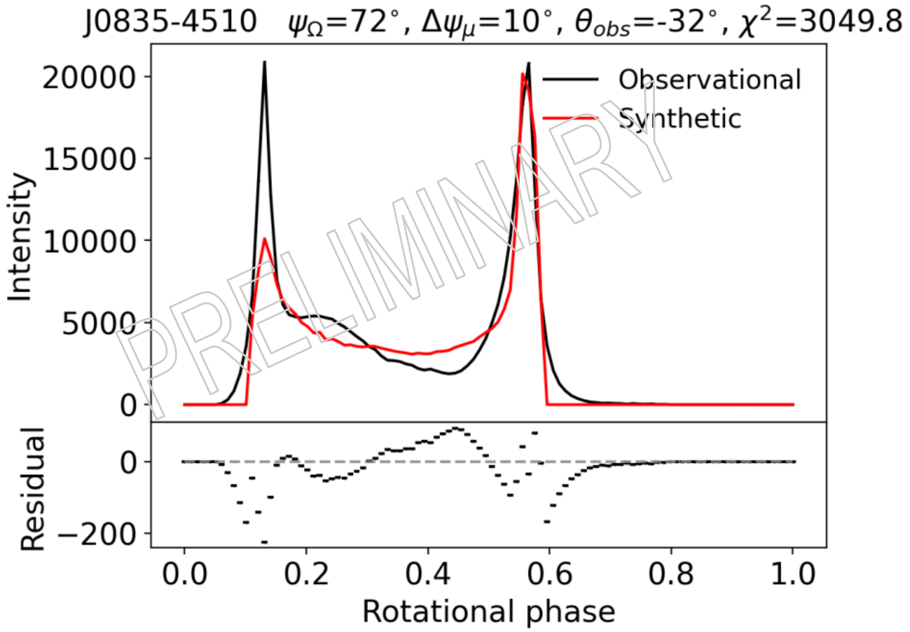


Vela



[Íñiguez-Pascual et al. (in prep.)]

Caveats

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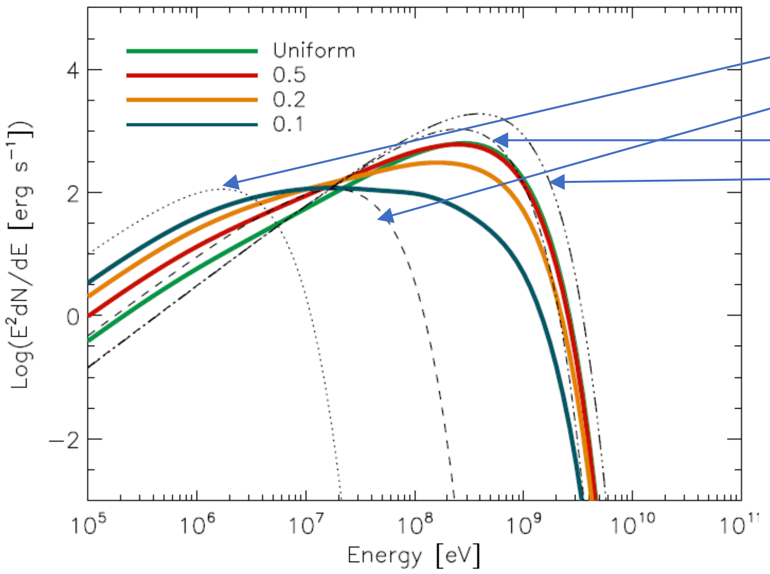

contributions at:
r/R_lc = 0.01
r/R_lc = 0.1
r/R_lc = 0.5
r/R_lc = 1

$$\frac{dN}{dx} = N_0 \frac{e^{-(x-x_{min})/x_0}}{x_0(1-e^{-(x_{max}-x_{min})/x_0})}$$

Without this "weight", the spectra would be basically the single-particle spectra (uniform), which have a fixed slope and cannot fit most of the spectra. The weight could be physically:

- A geometrical effect -> Discarded, we still need it when we compute the emission map
- The result of neglecting complications: variation of electric field along a line and across the accelerating region, presence of backward particles, better prescription for the curvature radius...

A result of this is that the spectra and gamma-ray light curves are substantially decoupled: the gamma-ray light curves are determined by the geometry, with little dependence on the spectra.

Conclusions

- Our spectral model is able to properly fit the population of high-energy emitting pulsars, showing that synchro-curvature radiation is an appropriate mechanism to explain the emission from these objects

  [*Íniguez-Pascual D., Viganò D., Torres D. F., 2022, MNRAS, 516, 2475 (2208.05549)*]

- The geometrical model reproduces the variety of observational gamma-ray light curves (though, by definition, it cannot capture their small scale features)

  [*Íniguez-Pascual D., Torres D. F., Viganò D., 2024, MNRAS, 530, 1550 (2404.01926)*]

Future prospects

- Soon to be submitted: full-sample concurrent spectral and light curves fitting
- Include more realistics physics to improve the major caveats (arbitrary weights in the spectral model, simple recipes for electric field and curvature radius), while keeping our effective approach

Thank you

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