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Trevenport89@gmail.com

Centre For Space Research

MODELLING CRAB-LIKE AND VELA-LIKE PULSARS AND THEIR NEBULAE

Presented by

Trevor Nyambe

Prof. Christo Venter

Prof. Benjamin Stappers

NORTH WEST UNIVERSITY

NASSP NATIONAL ASTROPHYSICS AND SPACE SCIENCE PROGRAMME

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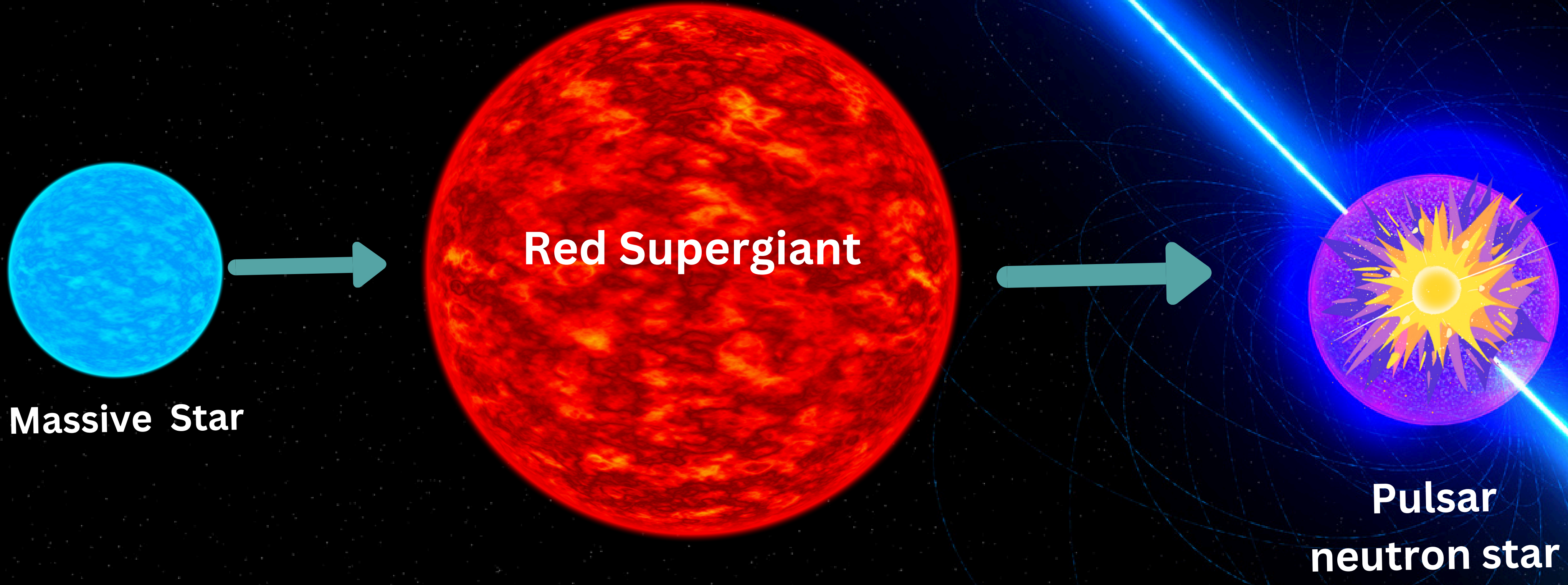
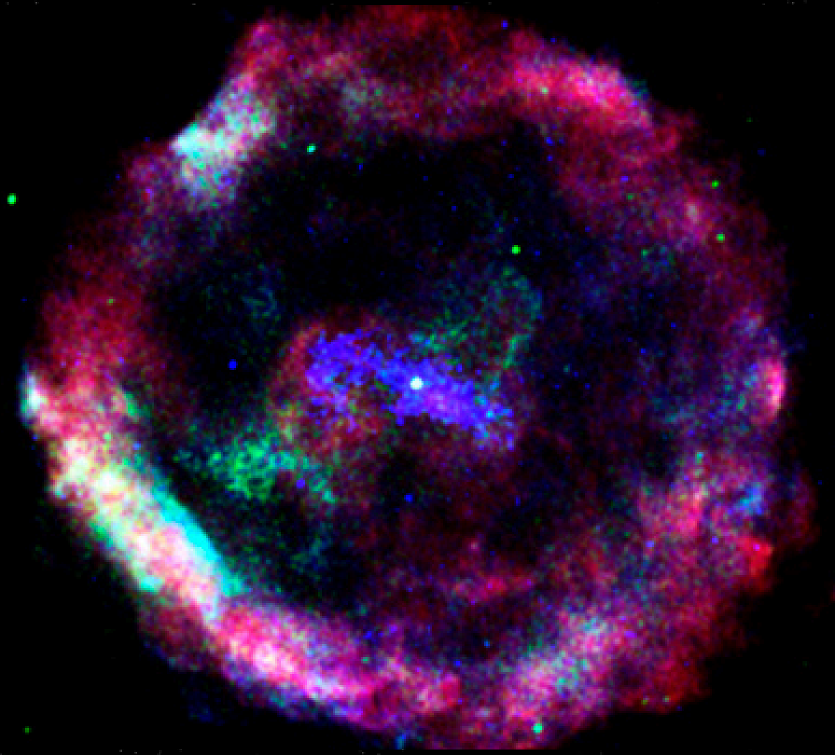
INTRODUCTION

- Formed in core-collapse supernovae.
- Rotating highly magnetic neutron stars emit beams of radiation along the magnetic poles.
- Appear as pulsating sources when beams sweep past Earth.
- They are the best cosmic clocks in the universe.





- Young pulsars often embedded in pulsar wind nebulae.
- Emit across radio, X-ray, and gamma-ray bands.

Period (P) $P = \frac{2\pi}{\omega}$

Period derivative : $\dot{P} = \frac{dP}{dt}$

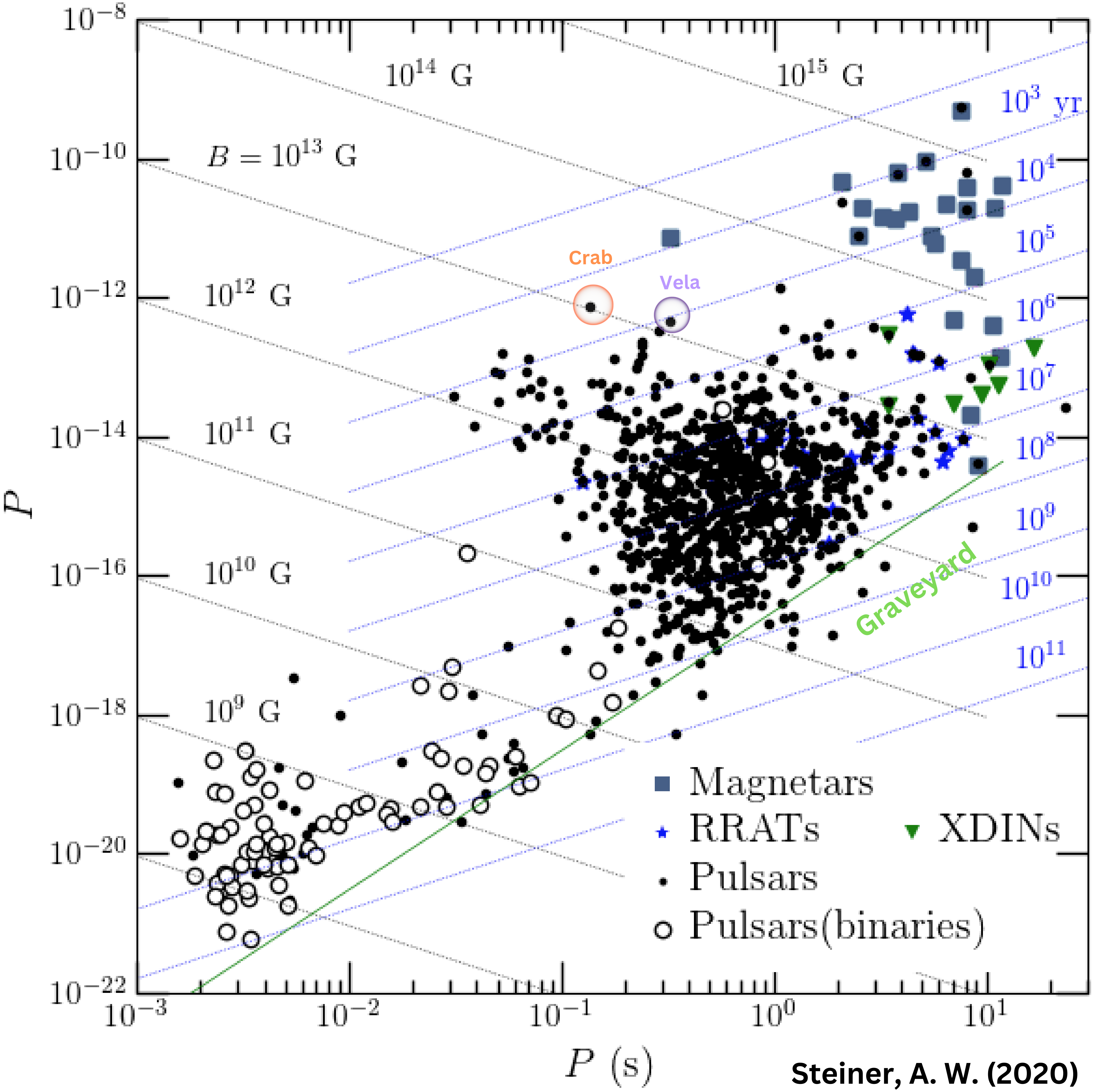
Age: $\tau = \frac{P}{2\dot{P}}$

Magnetic field:

$$B \approx 3.3 \times 10^{19} \sqrt{P\dot{P}} G$$

Spin down luminosity:

$$\dot{E} \approx 4\pi^2 I \frac{\dot{P}}{P^3}$$

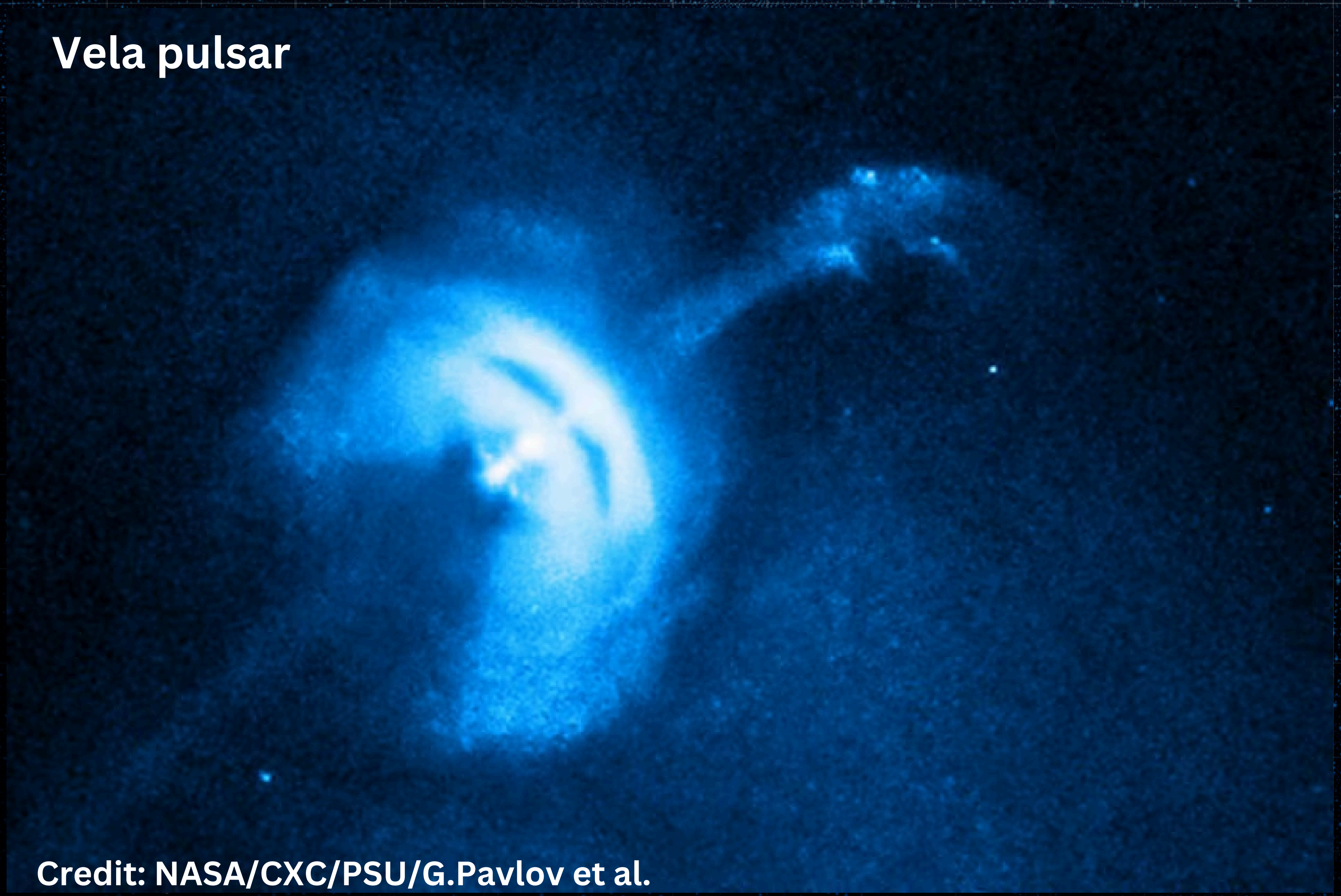


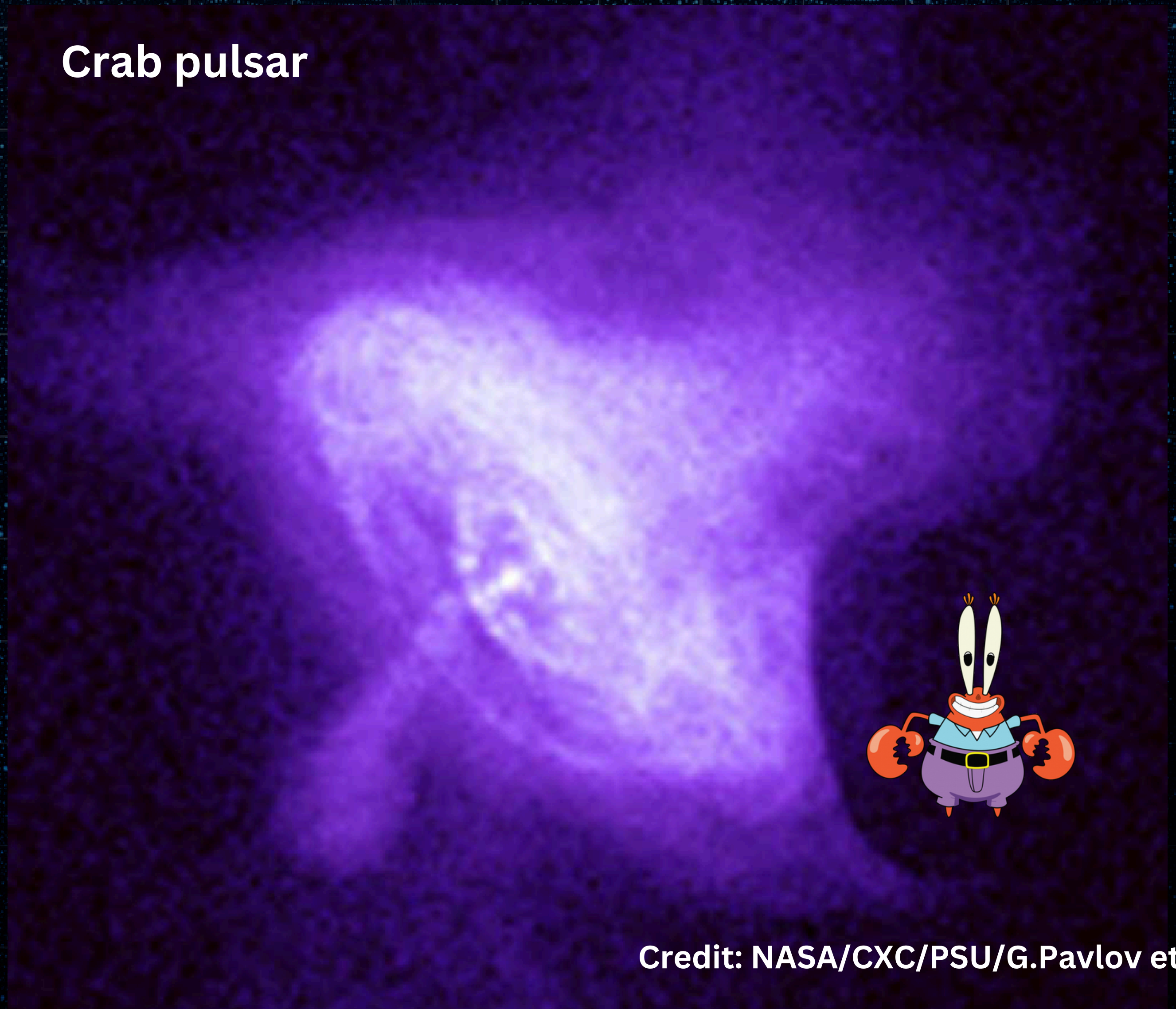
Steiner, A. W. (2020)

CRAB PULSAR VS VELA PULSAR

- ~11,000 years, high but lower spin-down power.
- Diffuse, extended, fainter nebula.
- ~89 ms (slower).
- Weaker TeV emission; softer gamma-ray spectrum.

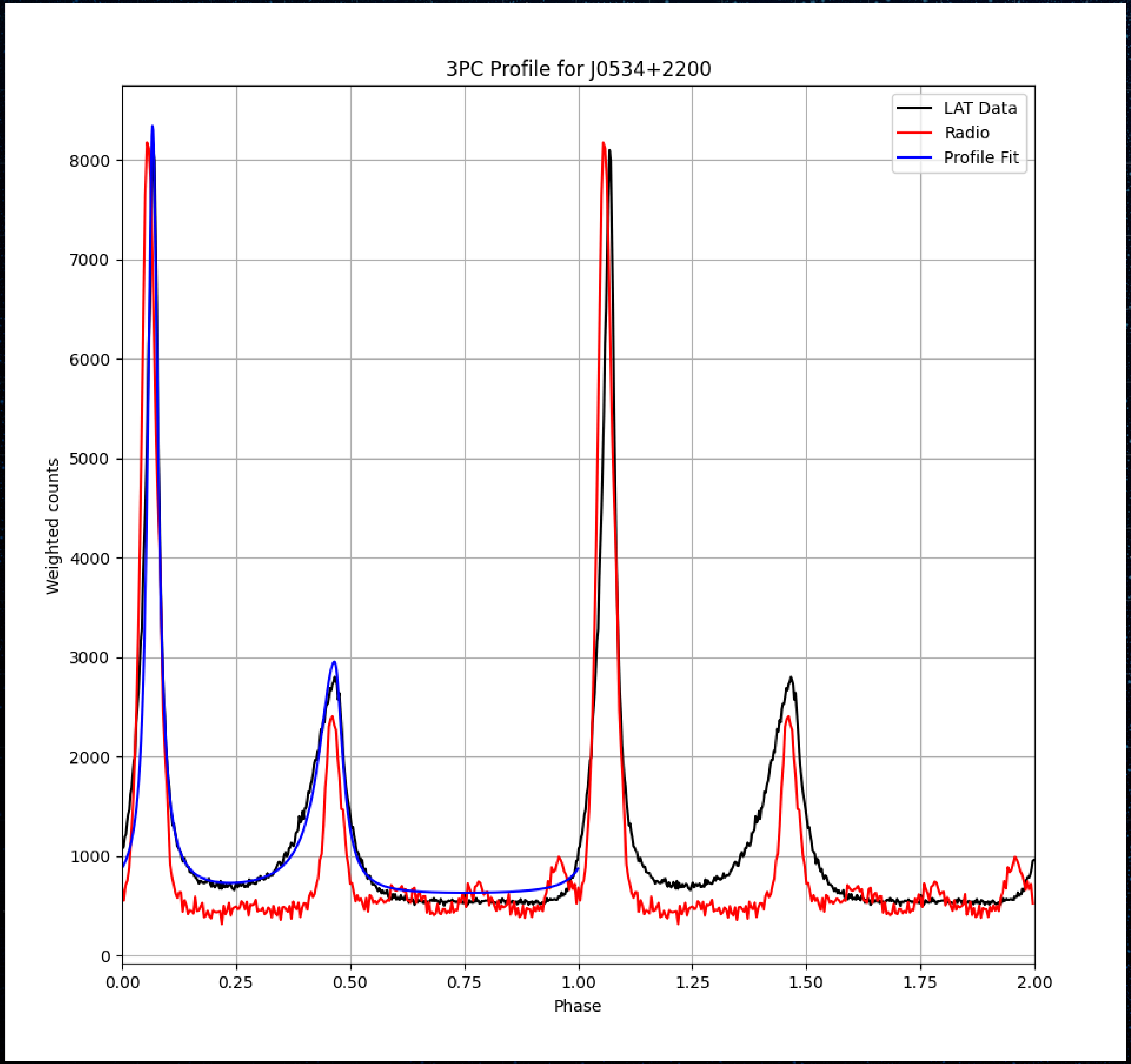
- ~1,000 years, very high spin-down power.
- Compact, bright, structured nebula.
- ~33 ms (fast).
- Emits up to TeV energies; strong across X-rays and gamma-rays.

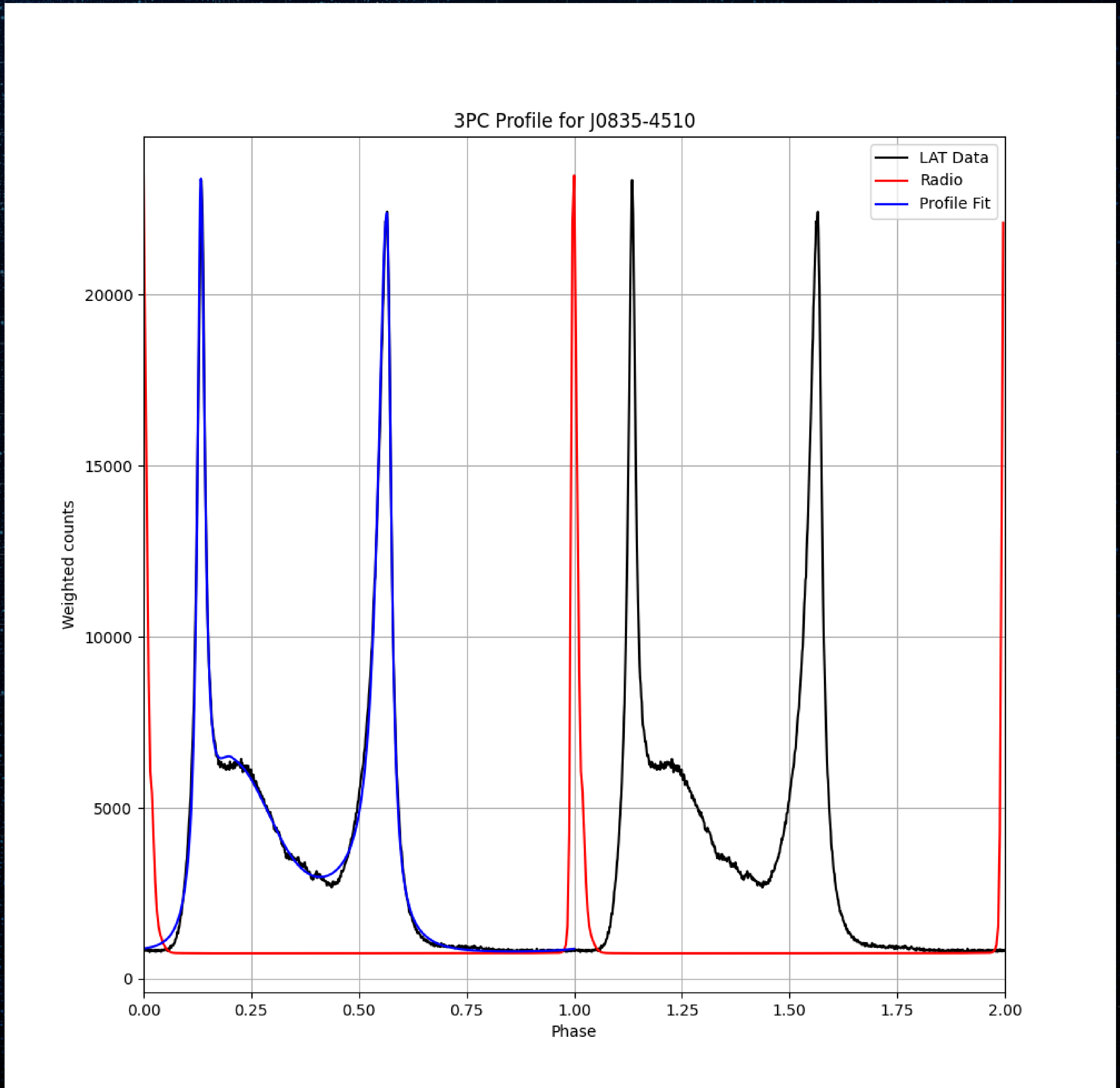




CRAB PULSAR VS VELA PULSAR

- Phase-aligned radio and gamma-ray peaks (Crab).
- Phase-offset peaks (Vela)





Emission Models

Charged particles are accelerated to ultra relativistic energies in the magnetosphere by the unscreened parallel component of the E field.

Polar cap

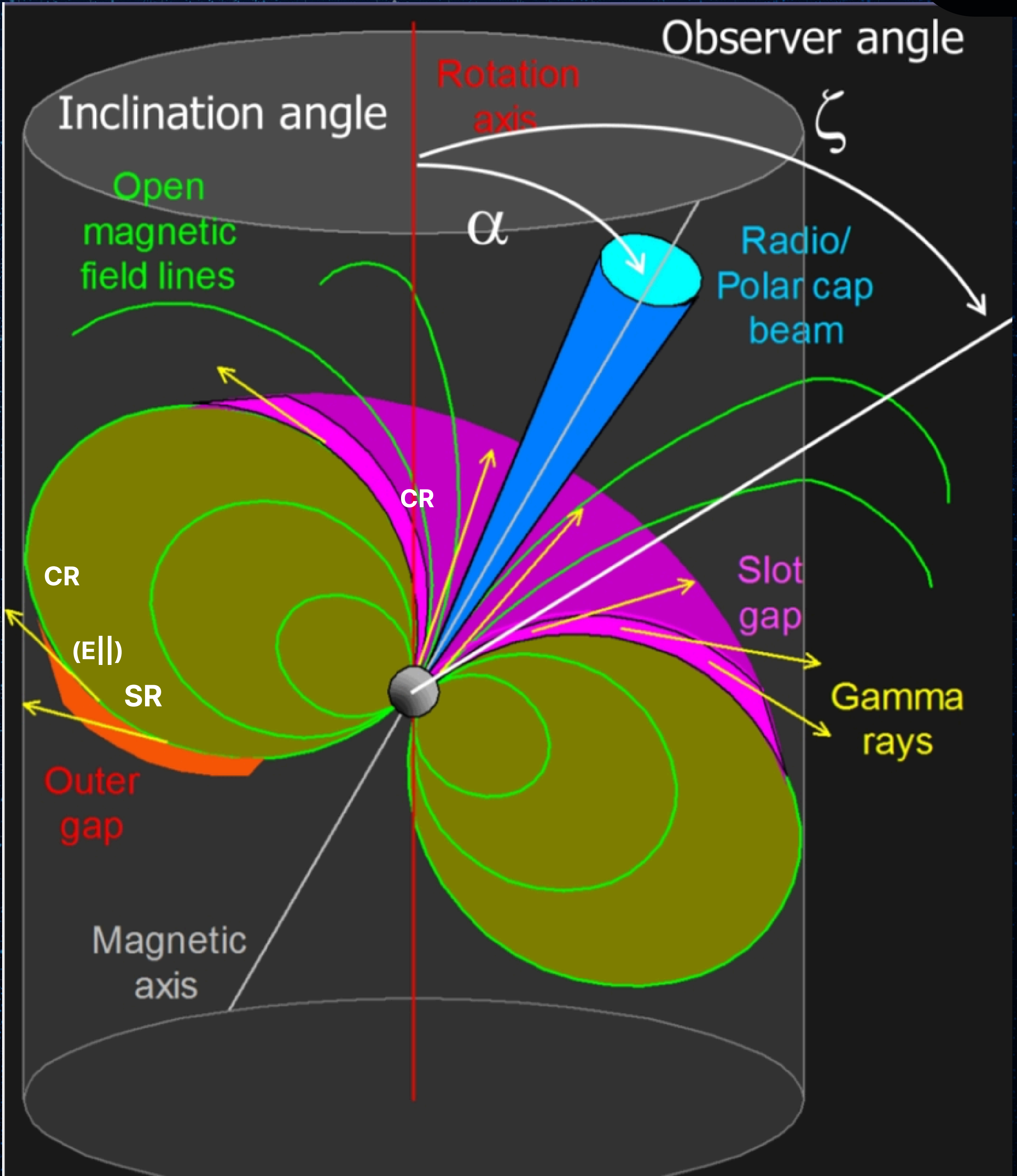
- Located just above the magnetic poles.
- Plasma flow through the open field lines
- Radio emission believed to originate here. (e.g., Daugherty & Harding 1996)

SLOT GAP/ TWO-POLE CAUSTIC

- Extension of the polar cap.
- caustic effects play a crucial role.
- charges travel to high altitudes (e.g., Dyks & Rudak 2003;Muslimov & Harding 2004)

OUTER GAP

- Located in the outer magnetosphere.
- extends from the null charge surface to the light cylinder.
- Gamma ray emission and X-ray emission.



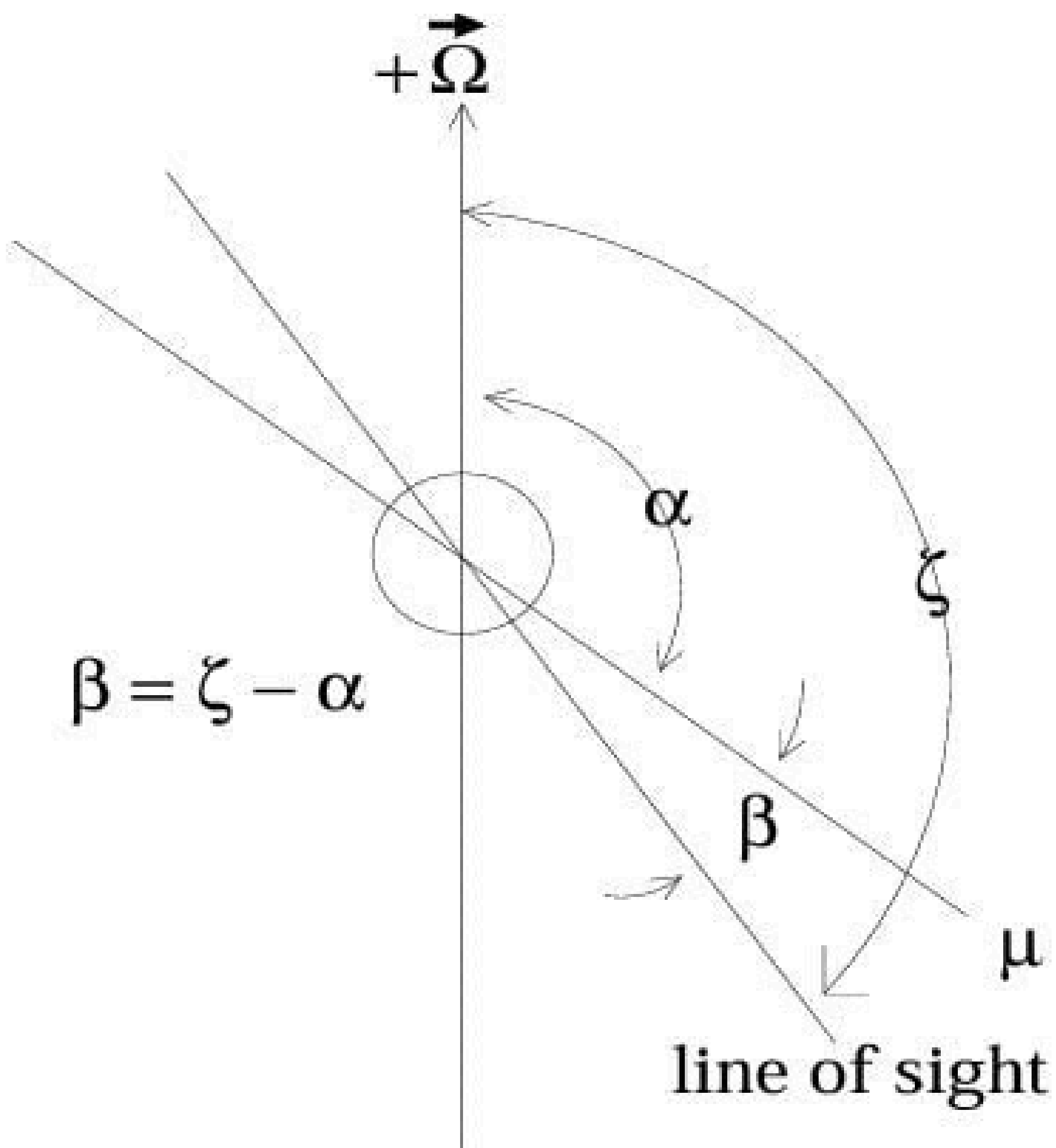
Credit: A. Harding

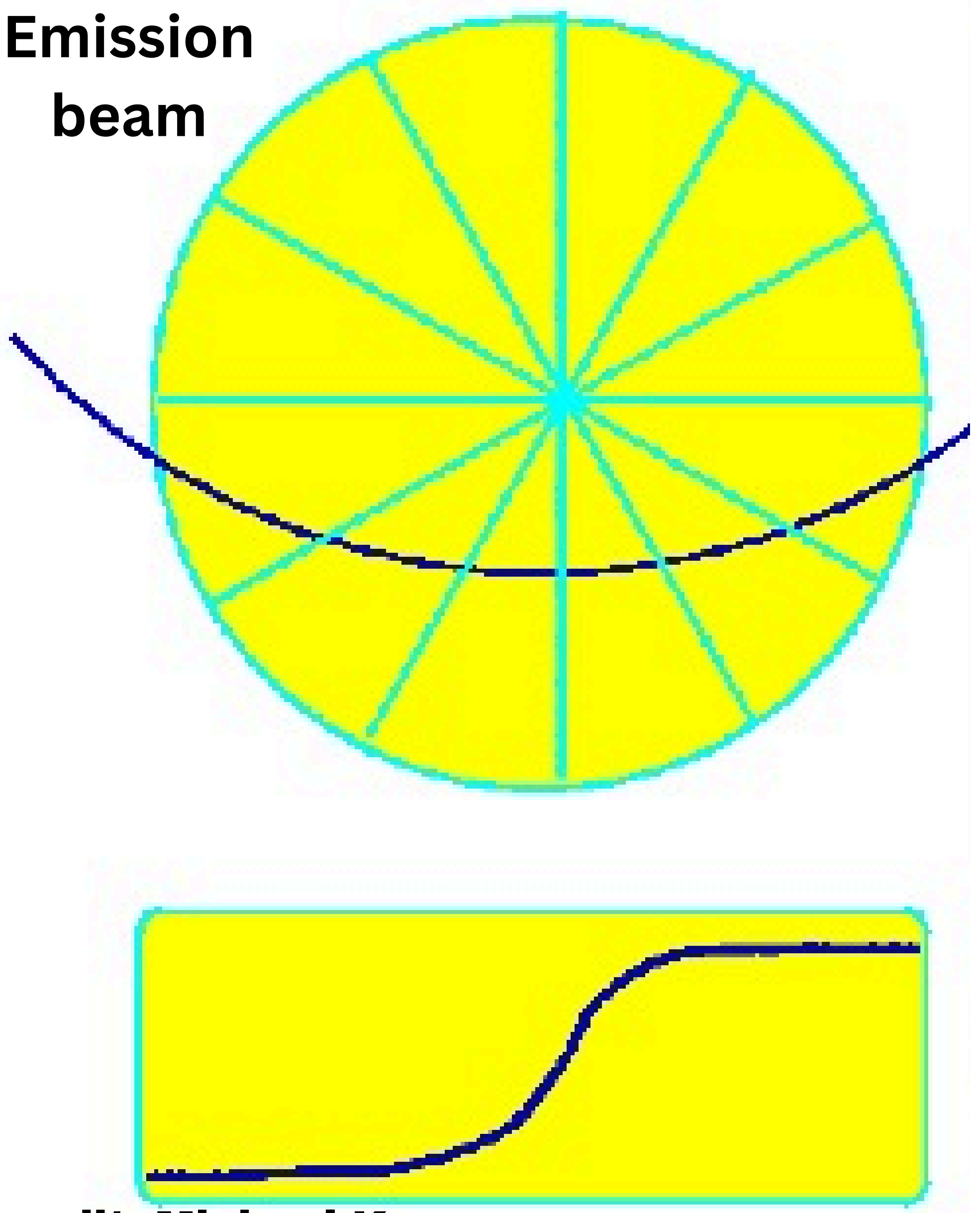
ROTATING VECTOR MODEL

- The RVM fits the swing of the position angle (PA) across the pulse
- Estimates two key geometric angles:
- **α - angle between the magnetic and rotation axis**
- **ζ = β + α - angle between the line-of-sight and rotation axis**

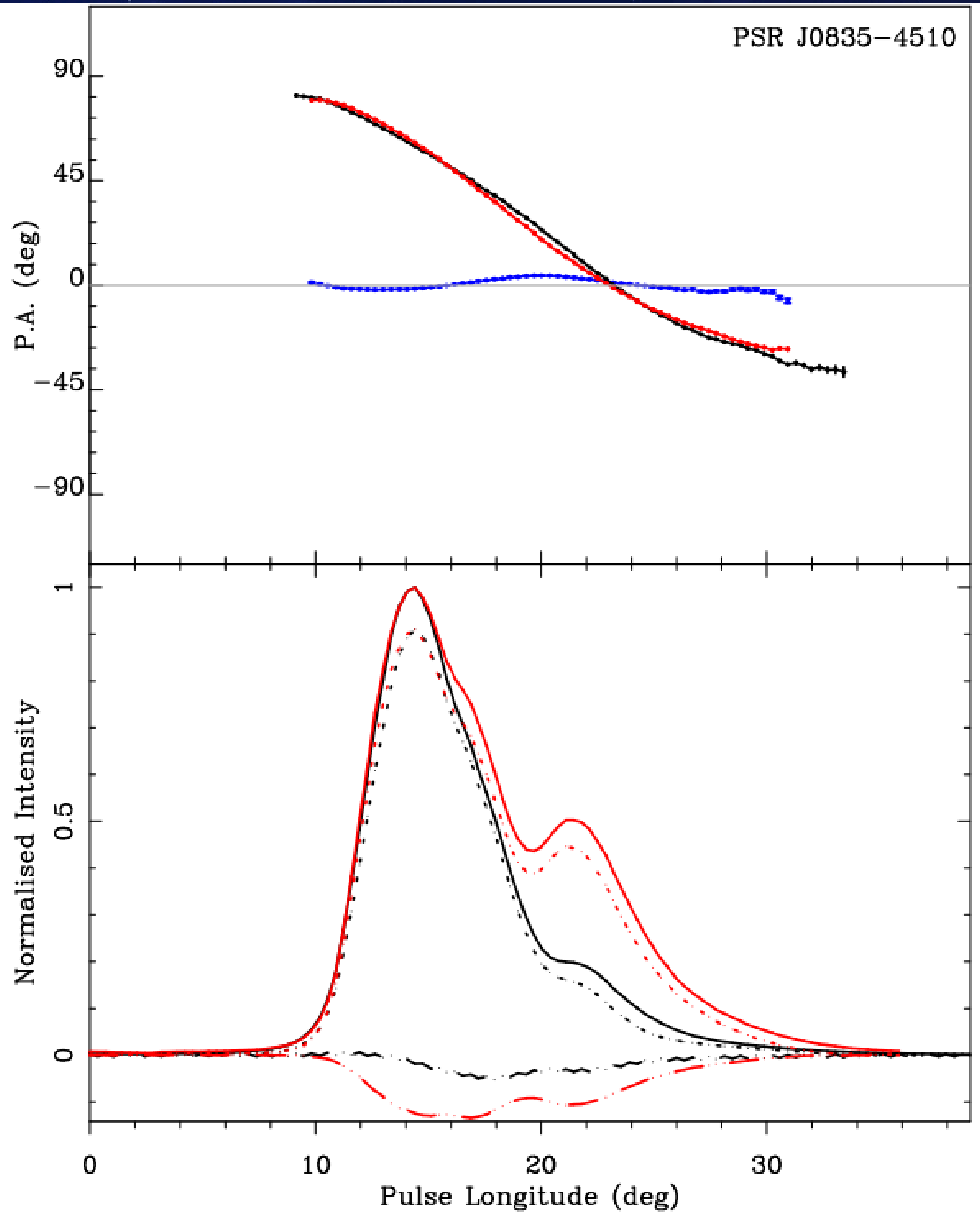
$$\tan(\Psi - \Psi_0) = \frac{\sin\alpha \sin\Phi}{\sin\zeta\cos\alpha - \cos\zeta\sin\alpha\cos\Phi}$$

Radhakrishnan & Cooke (1969)





credit: Michael Kramer.



SCIENTIFIC GOALS

Why Study These Pulsars?

- Crab-like & Vela-like pulsars are Young, energetic and emit across the radio and gamma-ray spectrum and are within a PWN.
- They have distinct features.

Four-Part Approach:

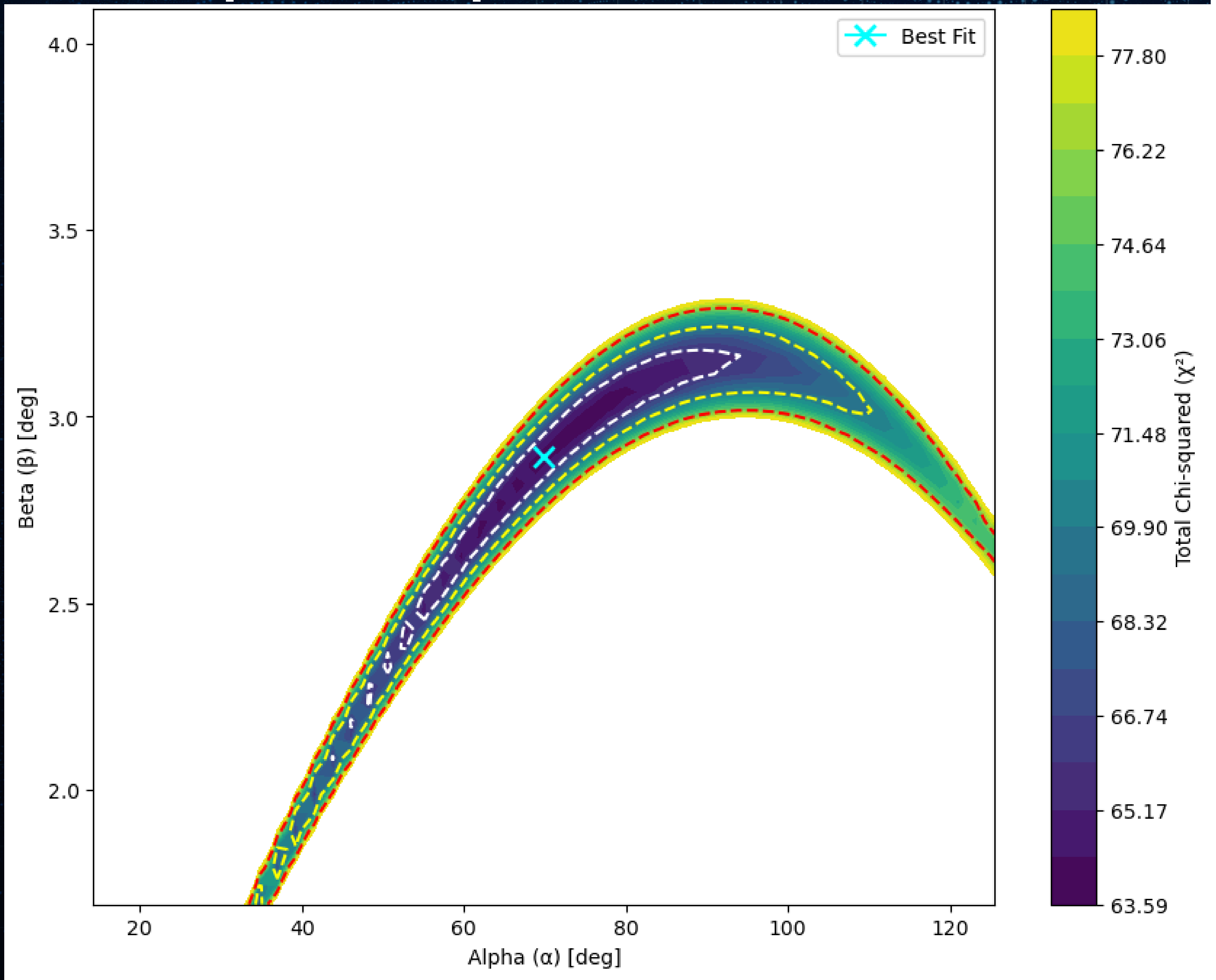
- Identify the suitable sources for the study.
- Radio Polarisation Modelling using the Rotating Vector Model (RVM).
- Joint radio and gamma-ray light curve modelling.
- Spatial-spectral analysis of their associated nebulae.

SOURCES

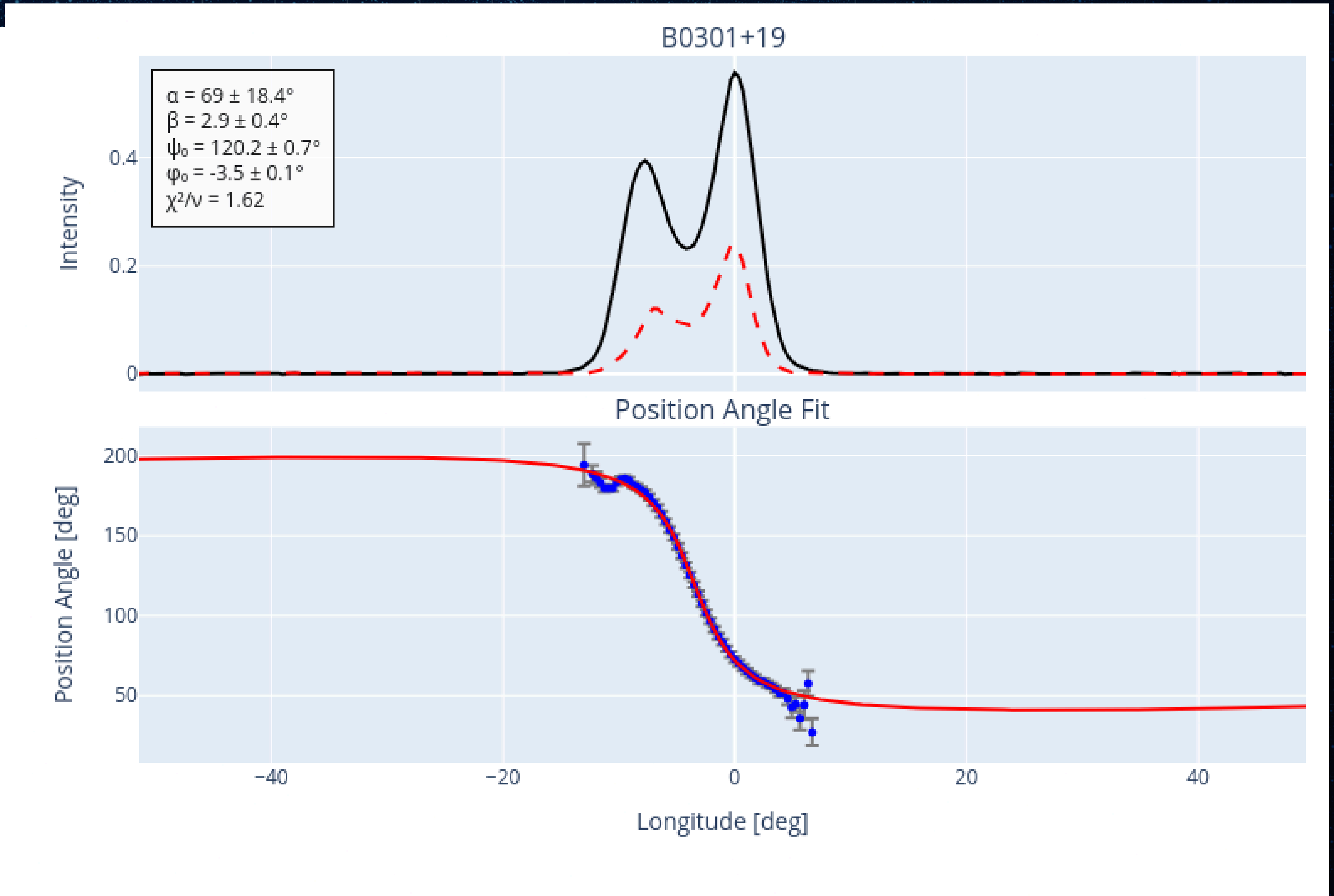
PSR JName	Age (kyr)	Period (s)	B (G)	E_sd(ergs/s)
J1048-5832	20.4	0.124	3.49e12	2e36
J0537-6910	4.93	0.016	9.25e11	4.9e38
J0540-6919	1.67	0.051	4.98e12	1.5e38
J0742-2822	157	0.167	1.69e12	1.4e35
J1718-3825	89.8	0.075	1e12	1.2e36
J1809-1917	51.4	0.083	3.49e12	1.6e36
J1846-0258	0.728	0.327	4.88e13	8.1e36

PRELIMINARY RESULTS

Chi-squared map.



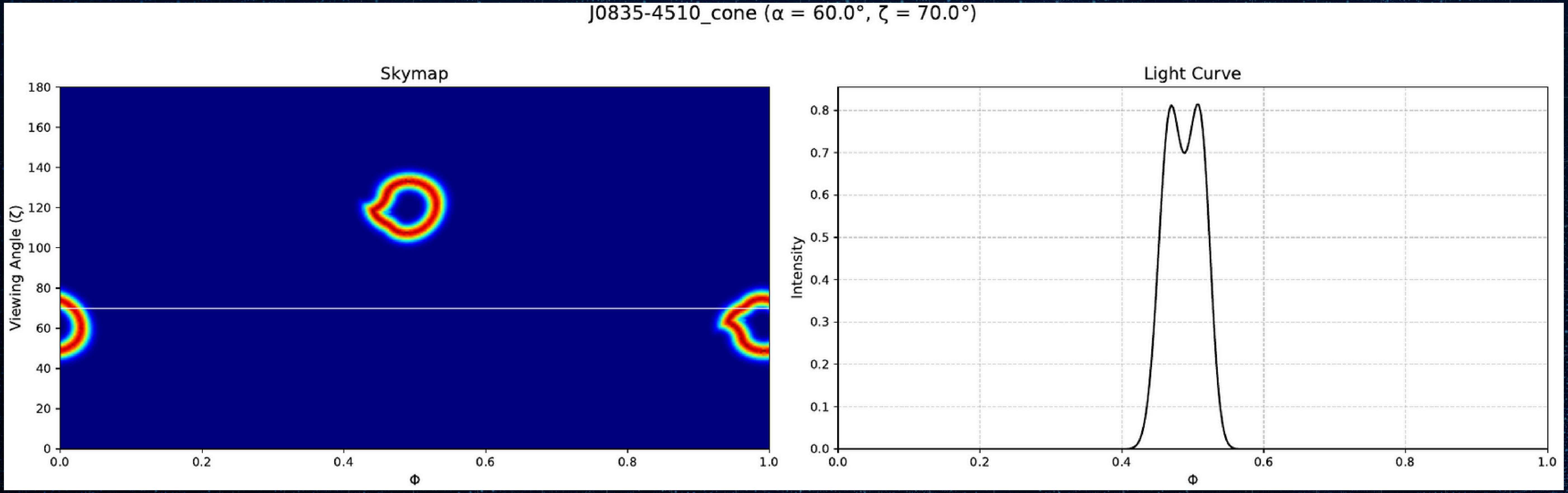
RVM Fit for B0301+19



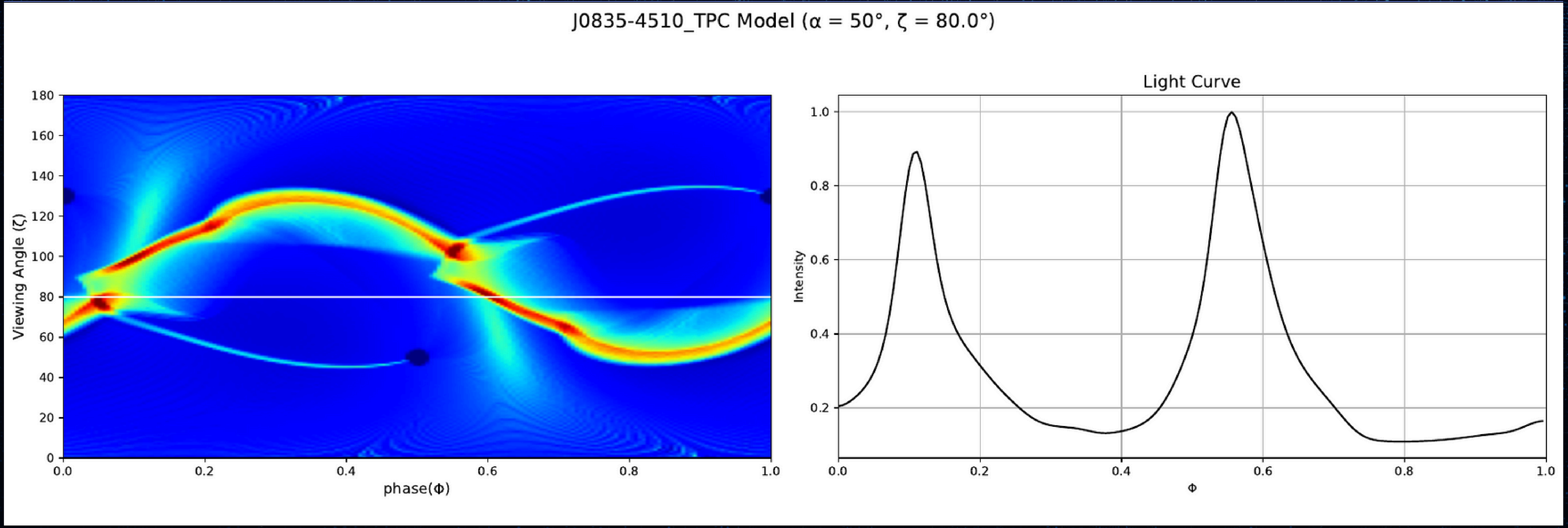
Best fit parameters: $\alpha \approx 69 \pm 18.4°$, $\beta \approx 2.9 \pm 0.4°$

LIGHT CURVE MODELLING

Models Simulations: Radio cone, Two-pole caustic (TPC), Outer gap (OG).



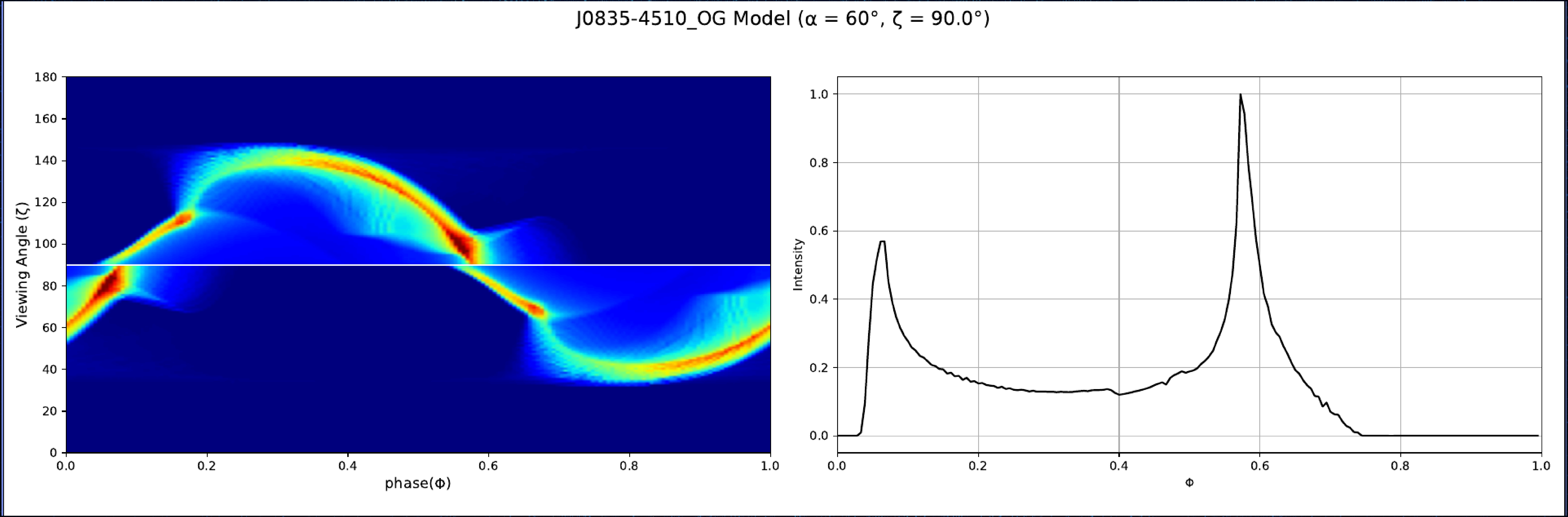
Hollow Cone Model



Two-Pole Caustic Model

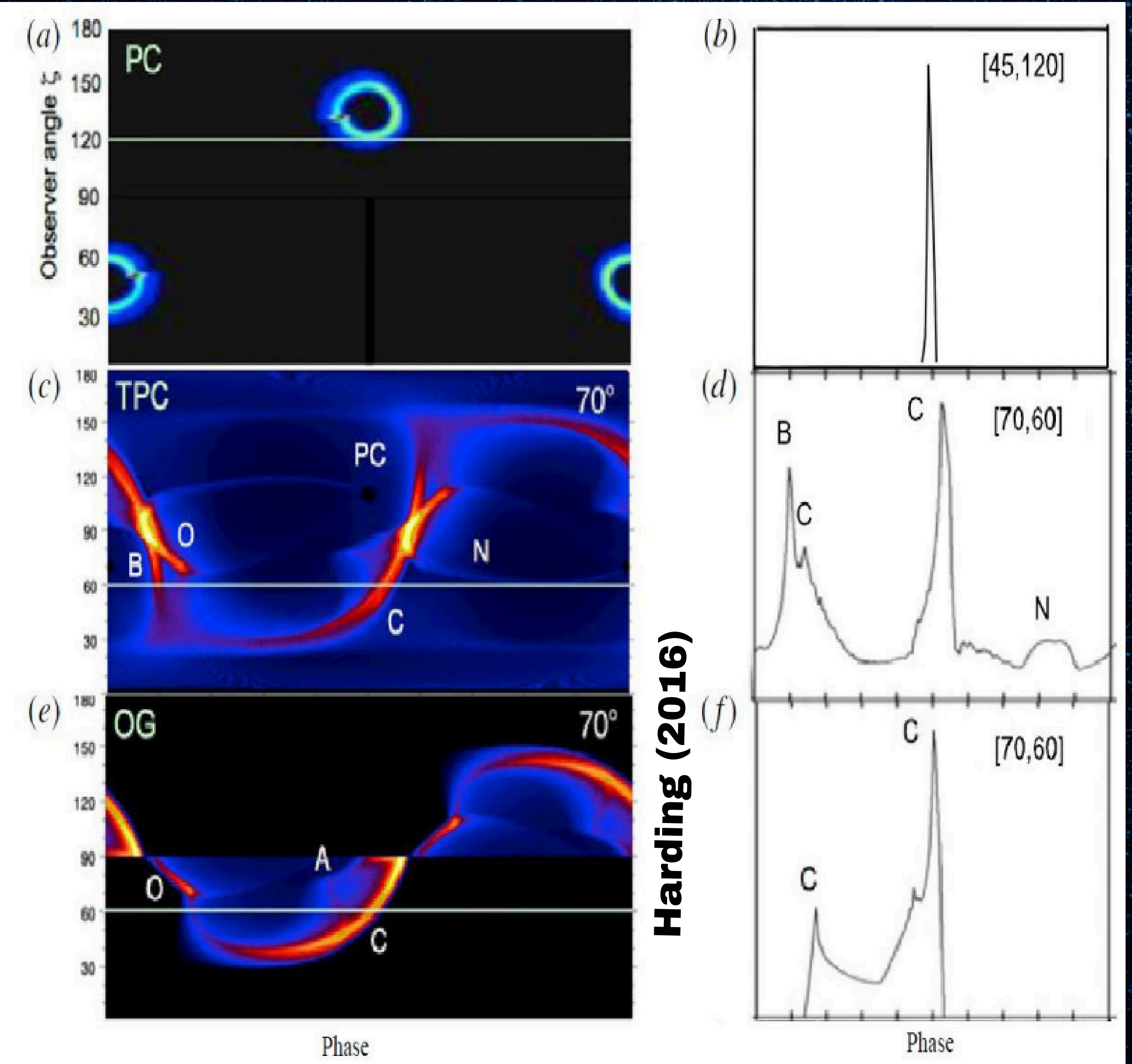
LIGHT CURVE MODELLING

Outer Gap Model

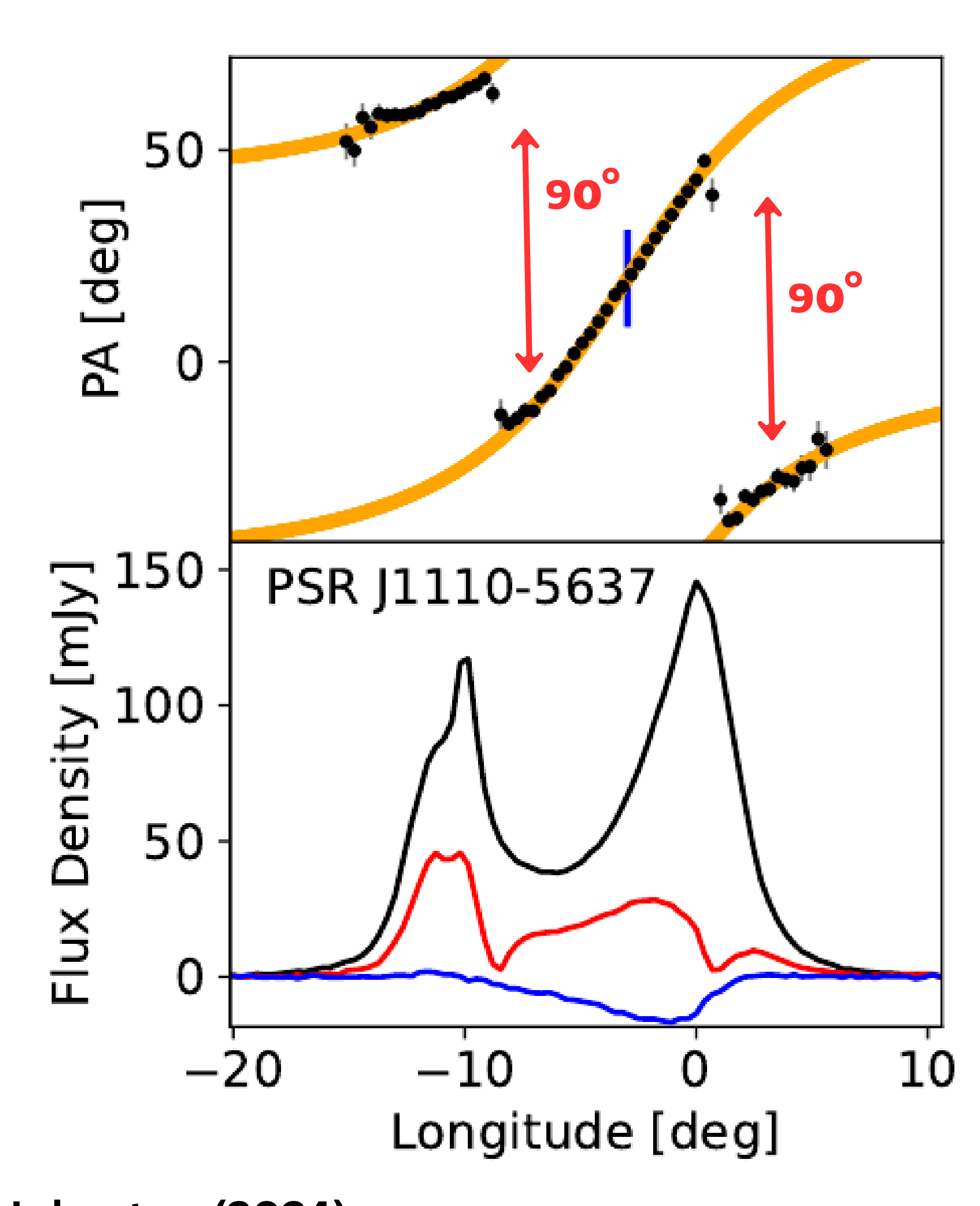


KEY CHALLENGES

- High covariance between parameters (α and β).
- Sensitivity to data range and systematic effects.
- Disruption from orthogonal polarisation modes.
- Model ambiguity.



Harding (2016)



Johnston (2024)

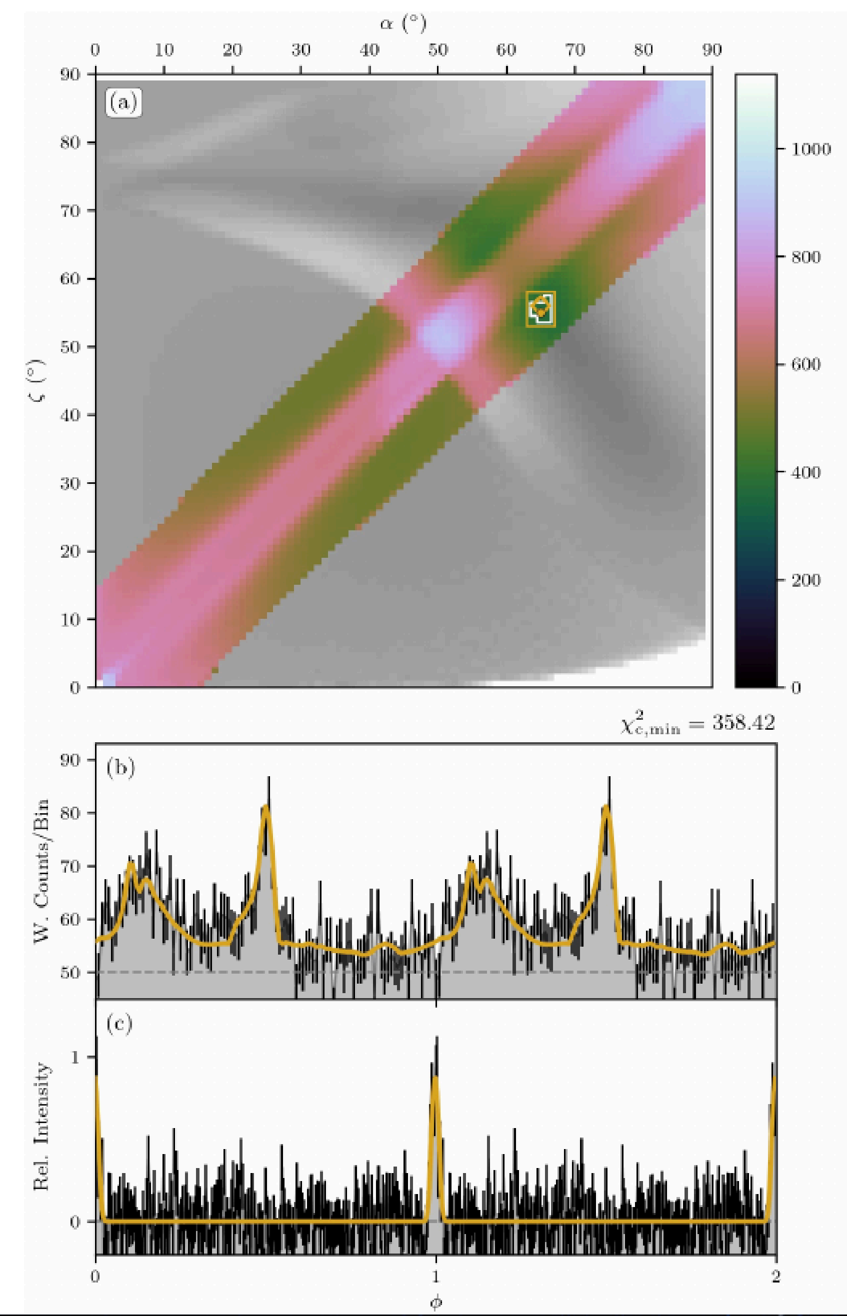
CONCLUSION

- Simulated the high energy models for a large α and ζ combination.
- Generated the skymaps and lightcurves.
- Identified the sources for the study.
- Calibrated and prepared the RVM.

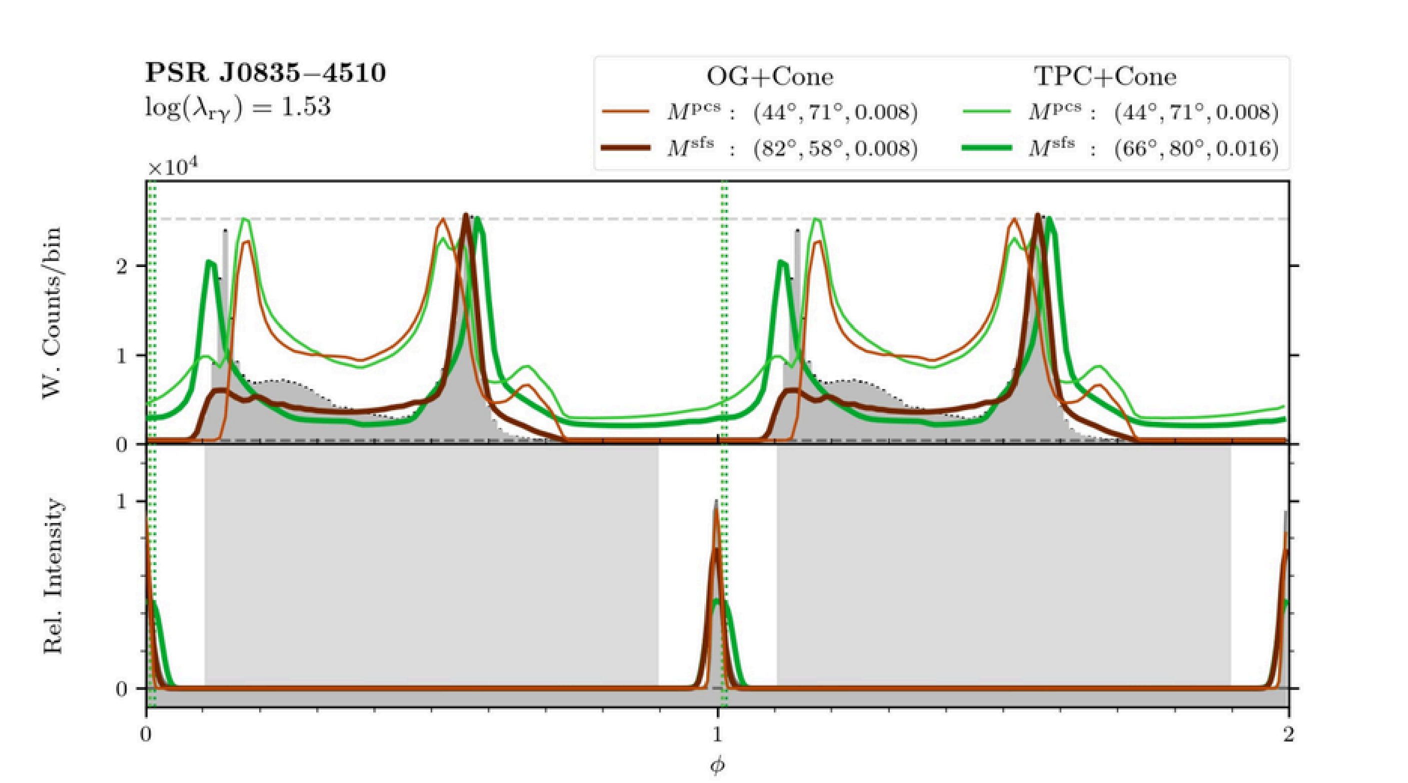
FUTURE WORK

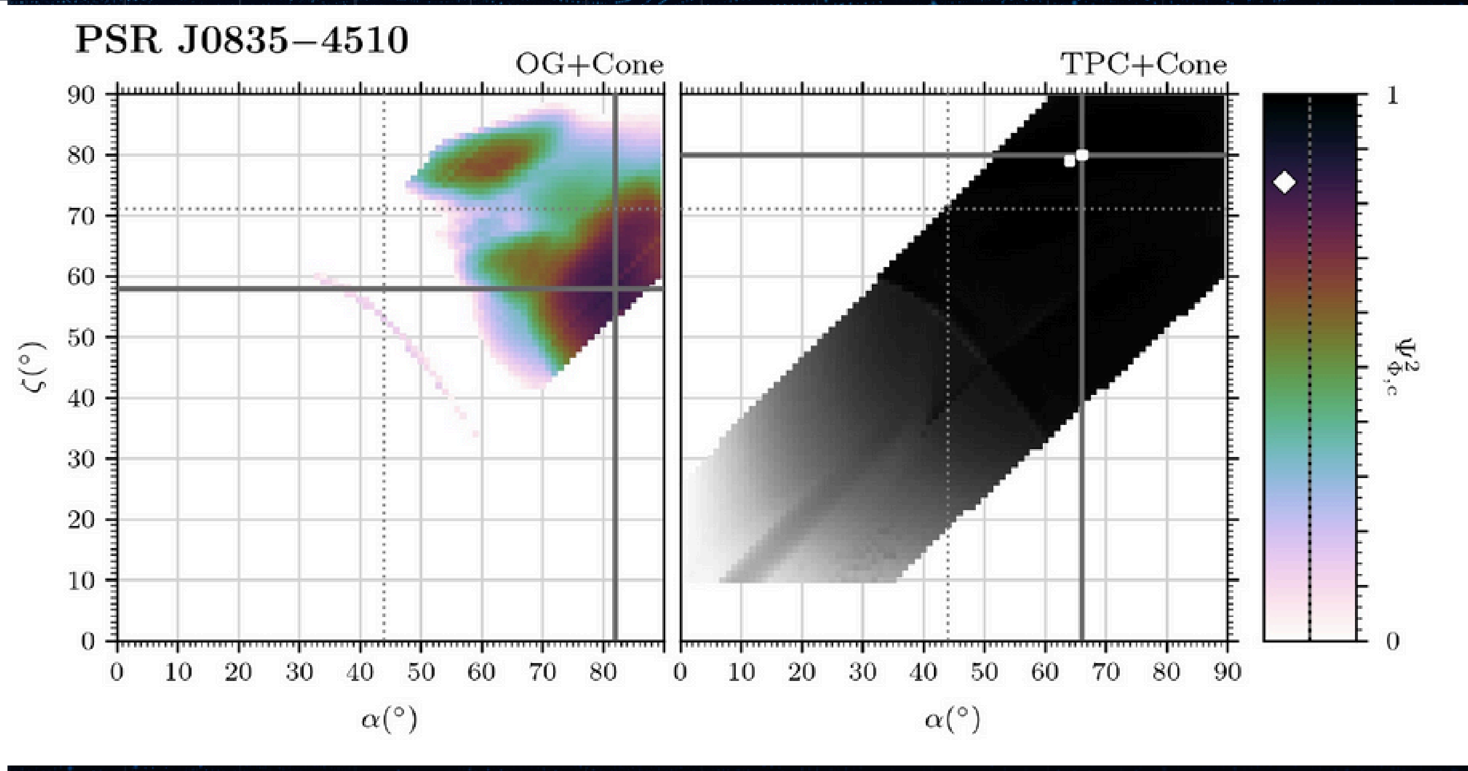
- Apply RVM to selected pulsars.
- Compare simulated light curves to fermi-LAT γ-ray and radio profiles.
- nebular SED modelling

Construct a unified picture of these systems, understanding the interplay between their geometry, emission, and energy transport.



$$\chi^2_{c}(M_{c}) = \chi^2_{r} + \chi^2_{\gamma}$$





Seyffert (2021)

Credit: Maitra et al. (2017)

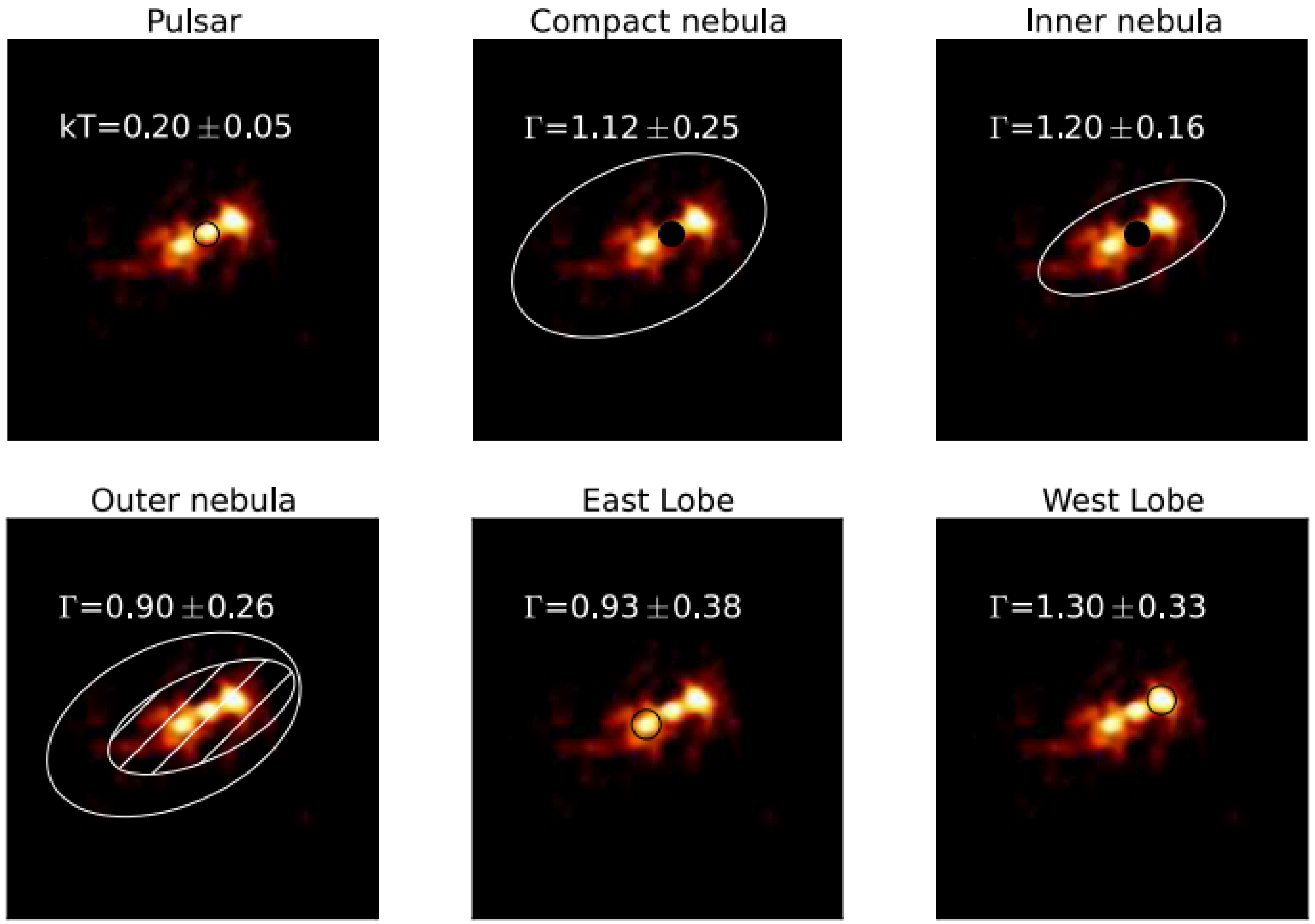
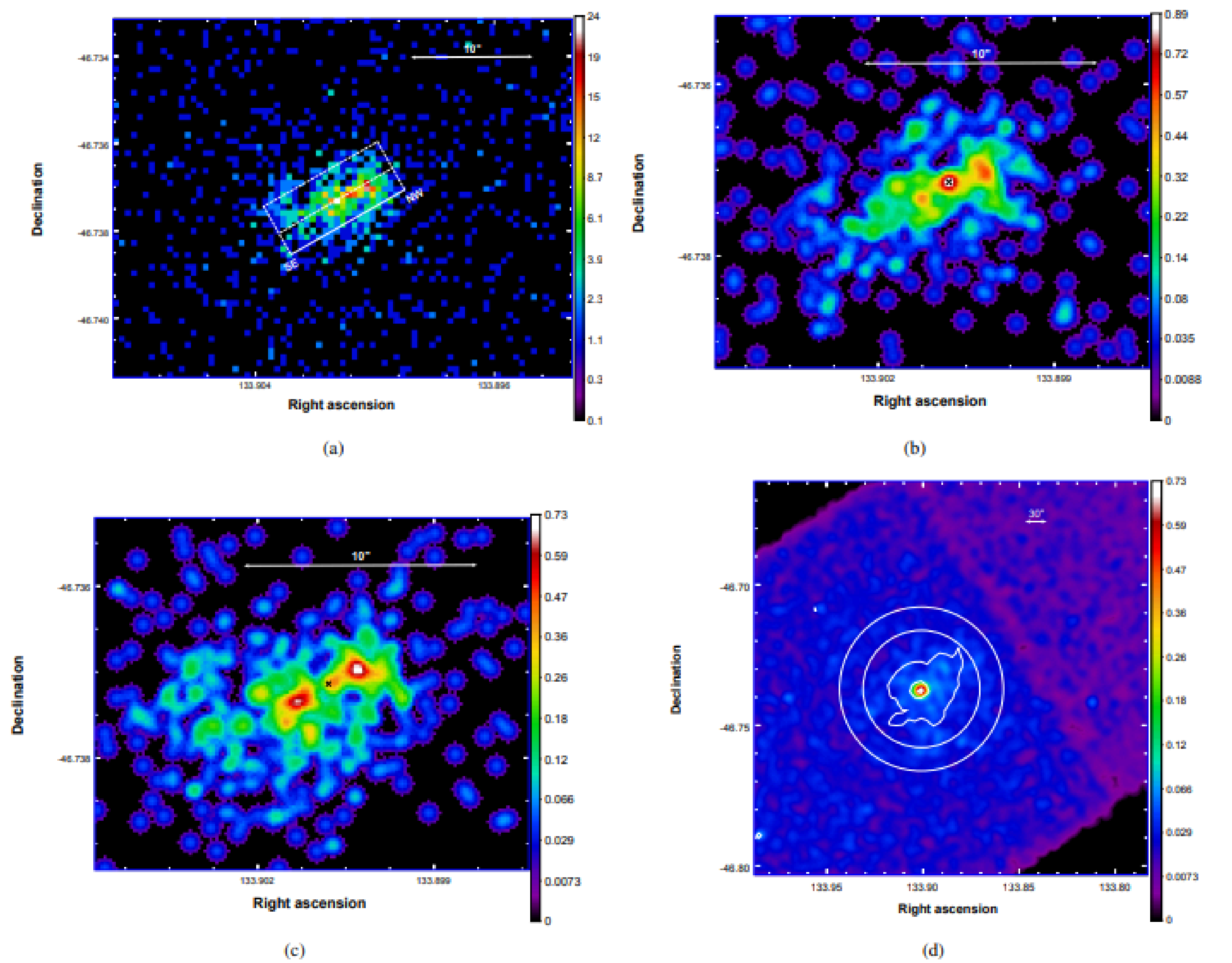


Fig. 4. *Chandra* image (0.5–8 keV) of the PWN around PSR J0855−4644 along with the regions used for spectral extraction shown in white. The value of the Γ (or *kT*) obtained from spectral fitting is also indicated in *each panel*.

Table 1. Final morphological best fit with a double-torus model.

Parameter	Value	Units
Ψ^a	114.4 ± 2.3 ± 1.1	°
ζ_{PSR}	32.5 ± 4.0 ± 1.7	°
R	2.1 ± 0.06 ± 0.08	″
β_{shock}	0.41 ± 0.06 ± 0.06	–
d	3.6 ± 0.70 ± 0.30	″
Background	0.46 ± 0.02	counts/pixel



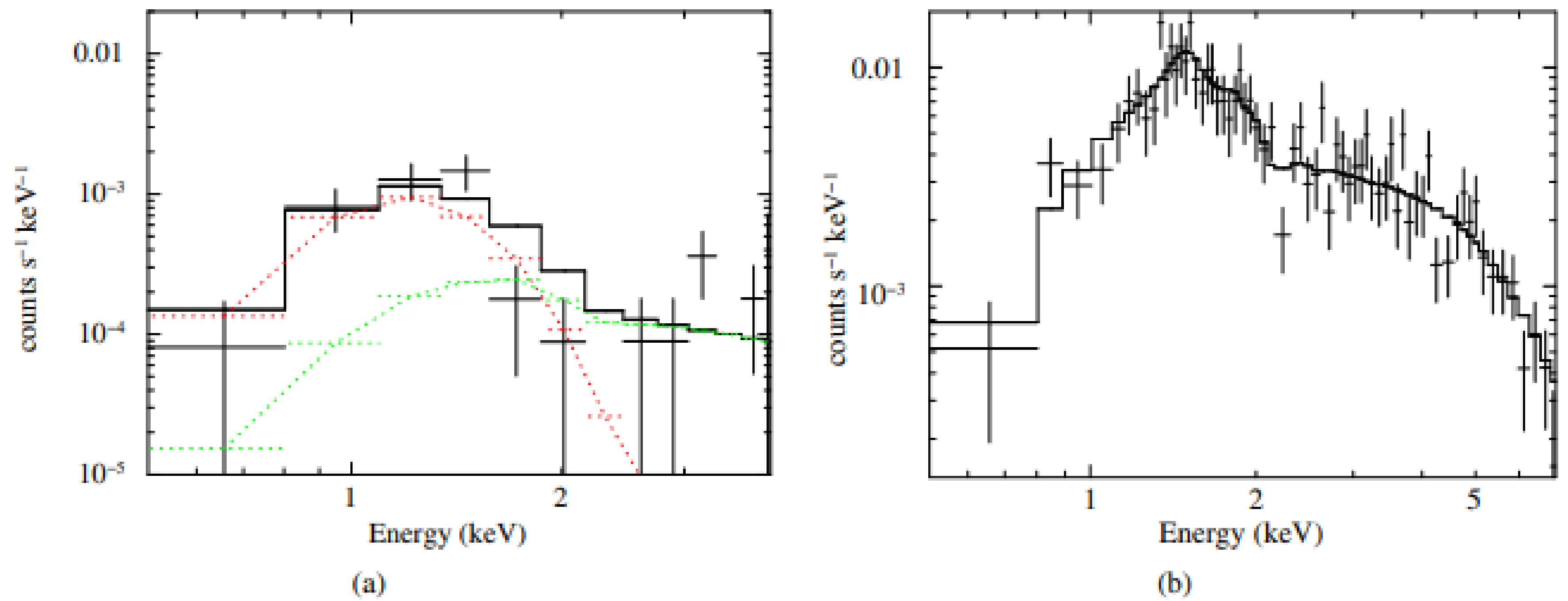


Fig. 5. ACIS-S spectra for the X-ray counterpart of the pulsar (panel **a**)) and the entire PWN (panel **b**)). The solid lines correspond to the respective best-fit spectral models (absorbed blackbody and absorbed power law, respectively). In the panel **a**), the pulsar blackbody component (red) and the nebular contribution in the same region (green) are shown. The unbinned spectrum fitted using C-statistics has been rebinned in the plot for visual clarity.

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THANK YOU

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University of the Witwatersrand, Johannesburg

69th Annual Conference of the South African Institute of Physics

South African Institute of Physics

$$\Psi^2_{\Phi,\mathrm{c}}(M_\mathrm{c}) = \frac{1}{2}\Psi^2_{\Phi,\mathrm{r}} + \frac{1}{2}\Psi^2_{\Phi,\gamma}$$