Energy-dependent Gamma-ray Light Curve Modeling of the Vela Pulsar

Monica Barnard[1]

Christo Venter[2]
Alice K. Harding[3]
Constantinos Kalapotharakos[4,5,6]
Tyrel J. Johnson[7]

[1]Centre for Astro-Particle Physics, University of Johannesburg, Auckland Park 2006, South Africa

[2]Centre for Space Research, North-West University, Potchefstroom 2520, South Africa

[3]Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 58545, USA

[4]Astrophysics Science Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

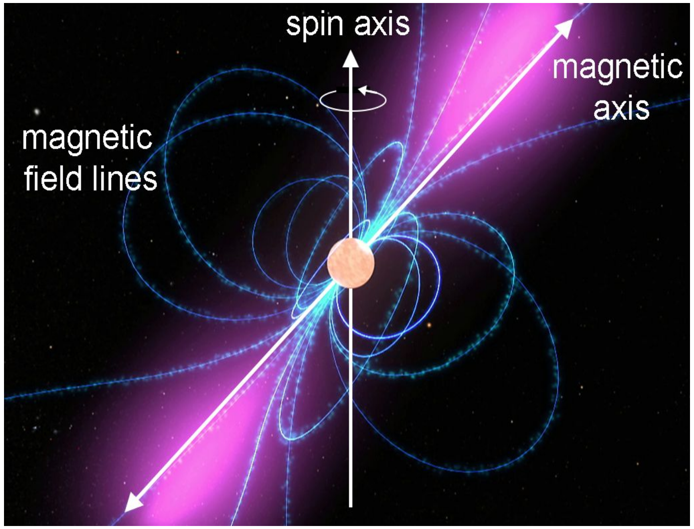
[5]Universities Space Research Association (USRA),Columbia, MD 21046, USA

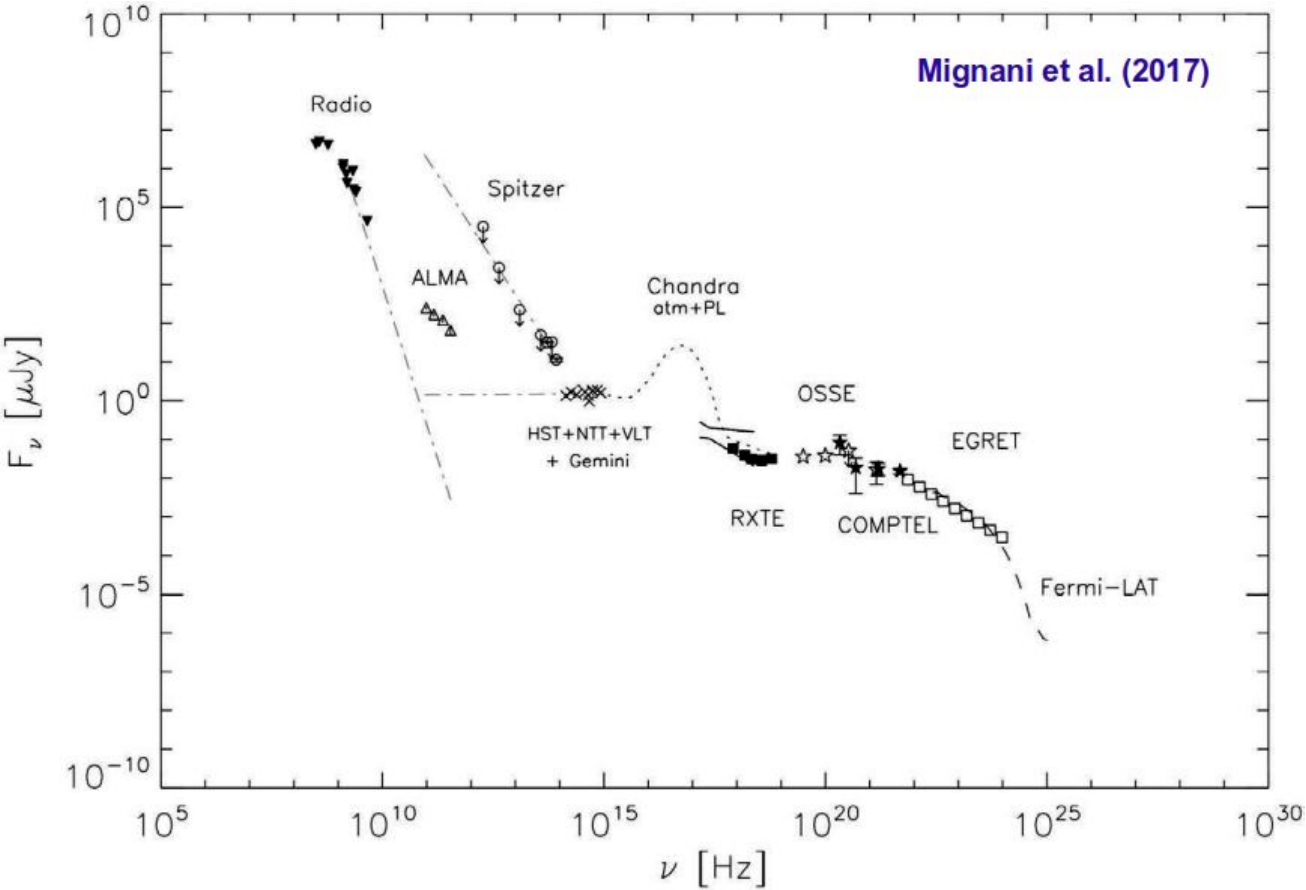
[6]University of Maryland, College Park (UMDCP/CRESST II), College Park, MD 20742, USA

[7]College of Science, George Mason University, Fairfax, VA 22030, resident at Naval Research Laboratory, Washington, DC20375, USA

Pulsars

- A compact, highly magnetized NSs, rotating at tremendous rate (compared to a lighthouse).
- R_{NS} ~ 12 km , M_{NS} ~ 1.4$M_{\odot}$ – 1.5$M_{\odot}$ (up to ~2.5$M_{\odot}$ observed for pulsars) and B_0 ~ 10^8 -10^{15} G (younger pulsars – higher B).

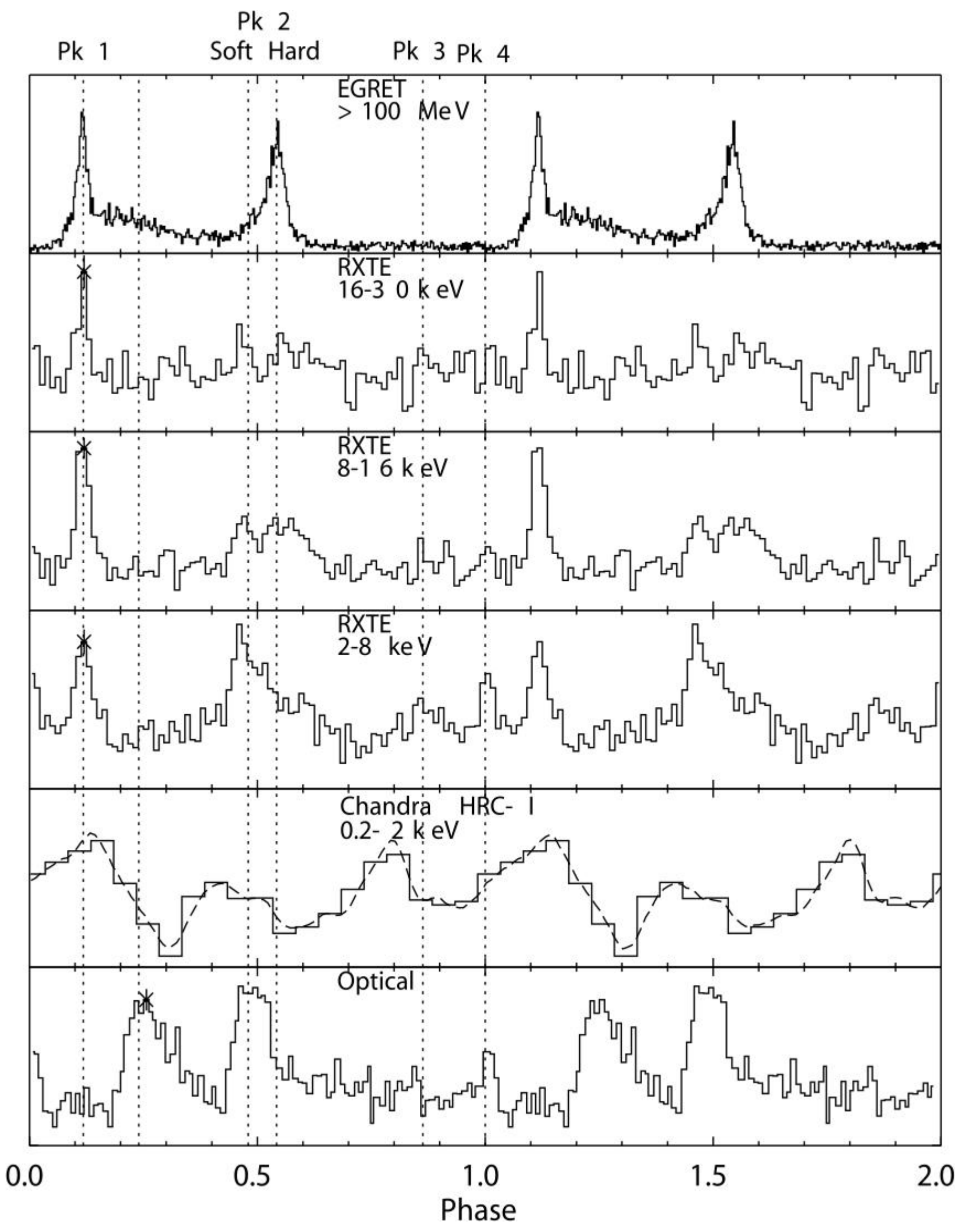


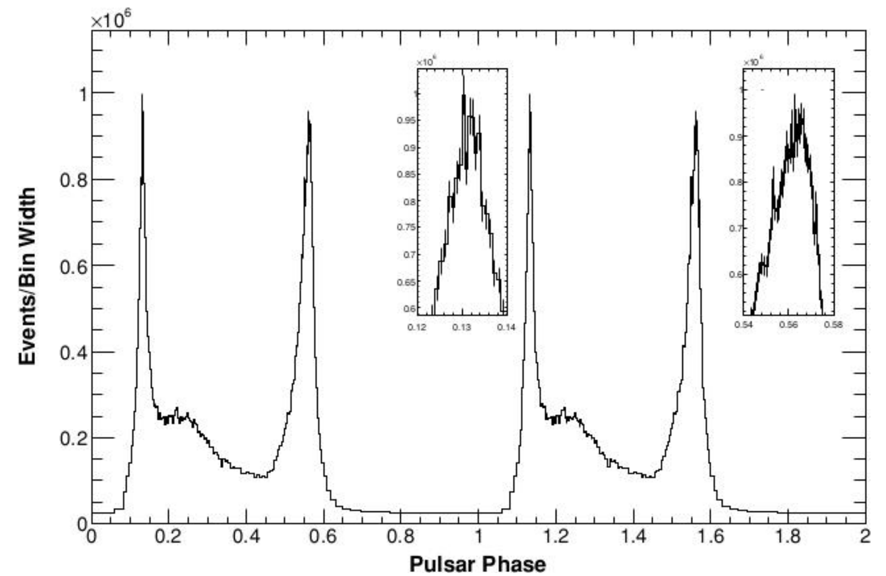


- Observed over the entire electromagnetic spectrum, e.g., Vela's broadband SED.
- Radio up to gamma rays (in GeV band).

Light curve modelling of Vela

Abdo et al. (2010)

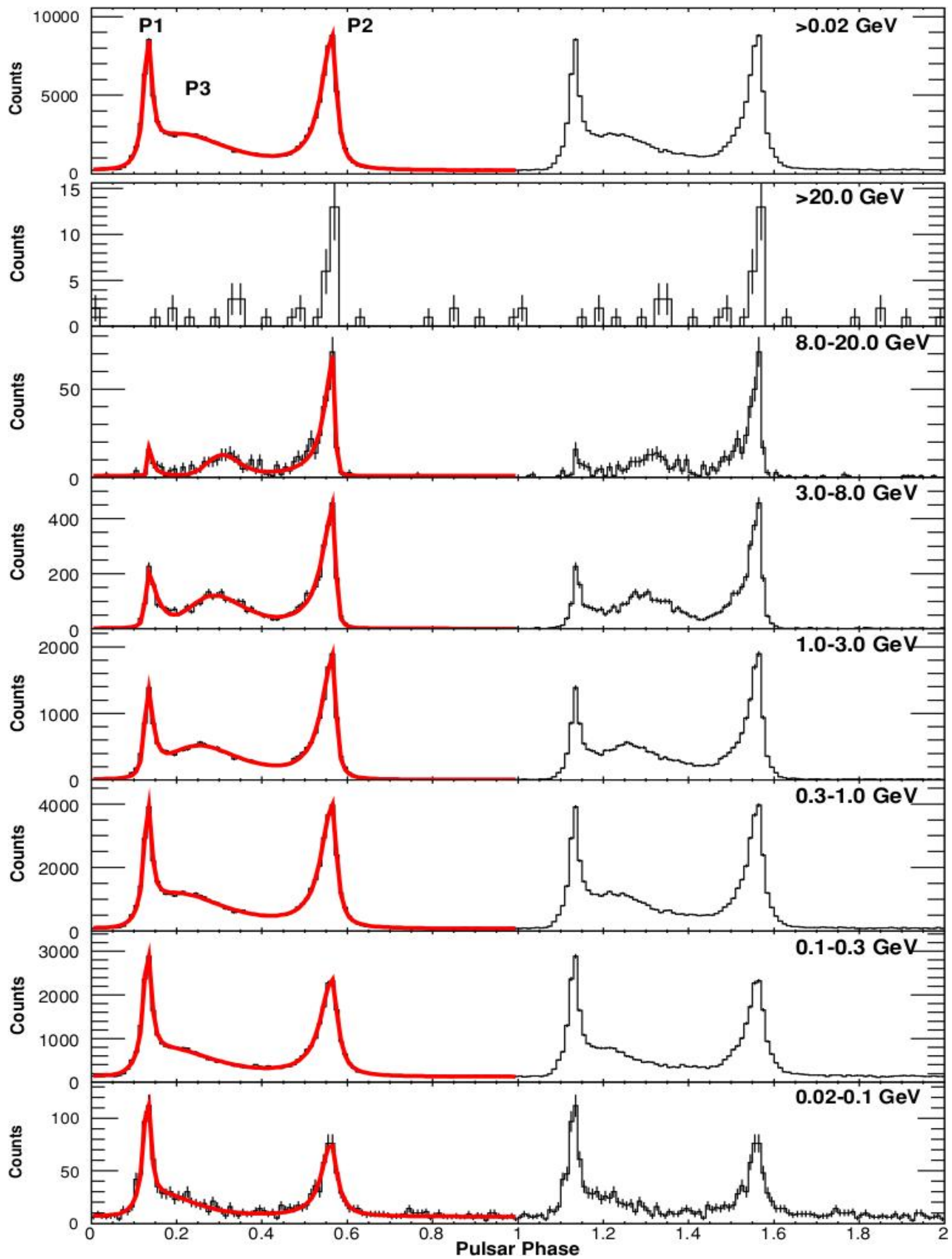




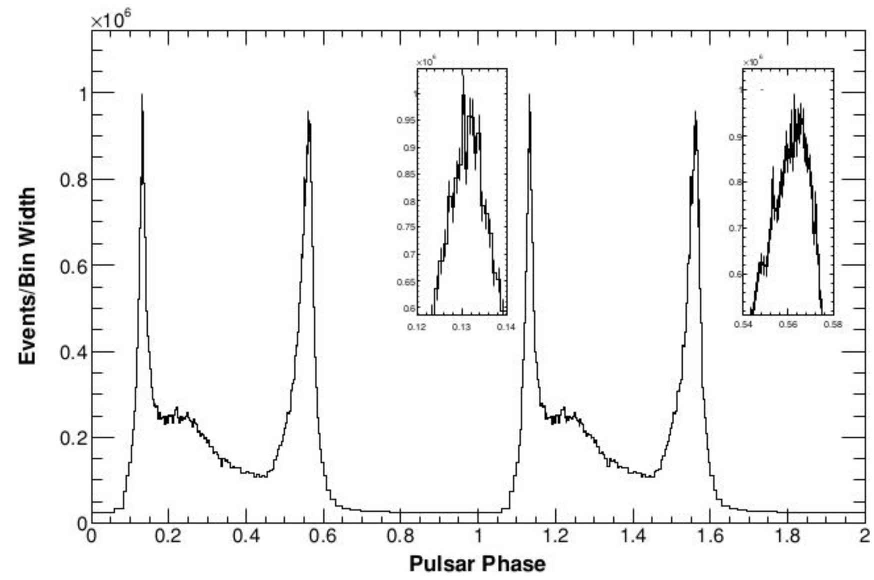
Harding et al. (2002)

Light curve modelling of Vela

Abdo et al. (2010)

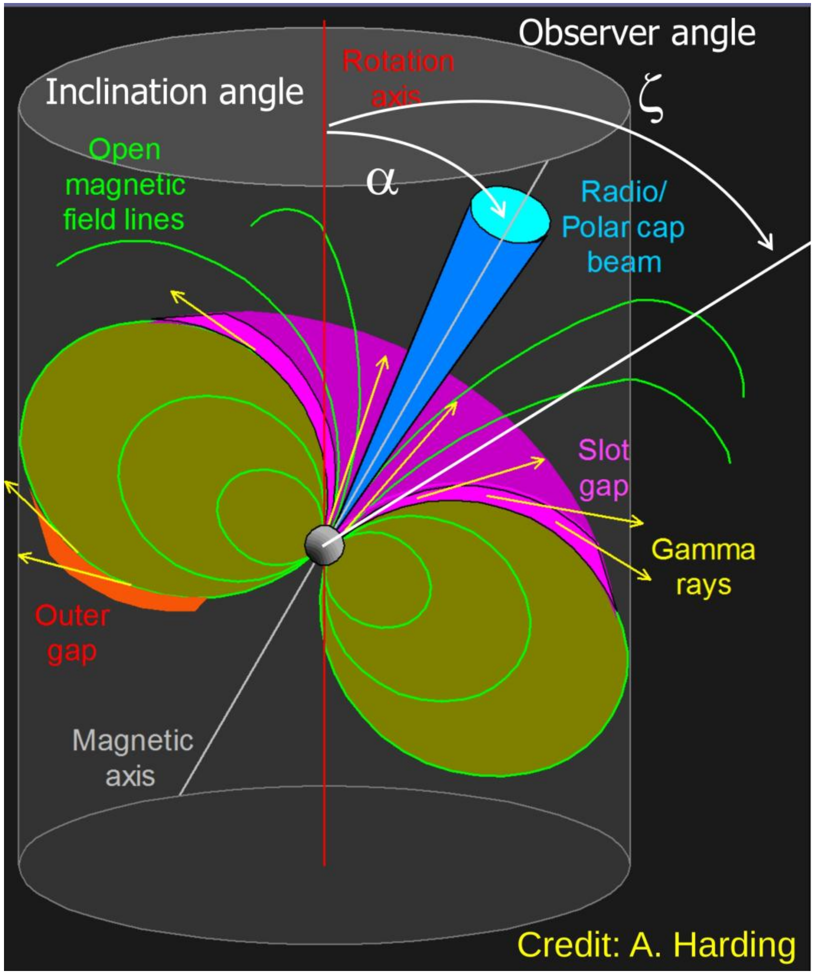


Abdo et al. (2010)



- Trends noticed in the energy-dependent light curves (LCs):
  - Decrease of flux of the first peak (P1) relative to the second peak (P2).
  - Near constant phase positions of peaks.
  - Narrowing of pulses with increasing energy.
  - Evolution of the bridge emission. It decreases with energy and shift in phase.

Sub-TeV to TeV emission from pulsars



Observations:

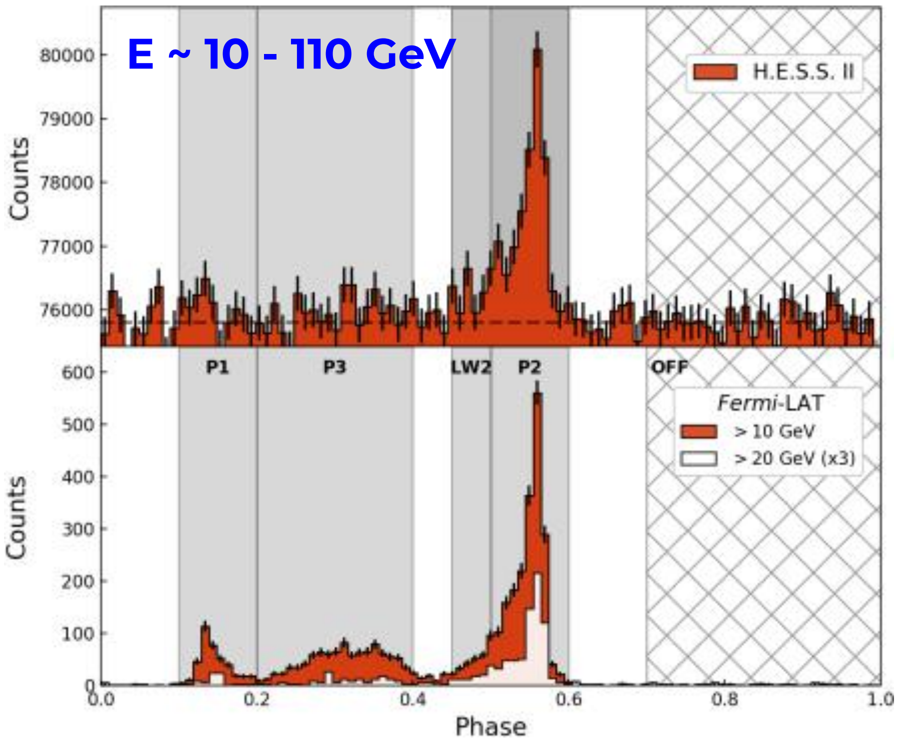
- *Fermi* LAT detected over 250 high-energy (> 100 MeV) gamma-ray pulsars.
- Four pulsars detected by ground-based telescopes (ICTAs) in the VHE range:
    - ***Crab*** (Ansoldi et al. 2016) Up to 1 TeV
    - ***Vela*** (Abdalla et al. 2018) Sub-20 GeV to 100 GeV (paper in prep. claiming up to 7 TeV).
    - ***Geminga*** (Acciari et al. 2020) Between 15 GeV and 75 GeV with 6.3σ for second peak.
    - ***PSR B1706-44*** (Spir-Jacob et al. 2019) Sub-100 GeV.

Models:

- Traditional emission models, e.g., polar cap (Daugherty & Harding 1982), slot gap (Arons 1983), outer gap (Cheng et al. 1986), pair-starved polar cap (Harding et al. 2005).
- Newer emission models, e.g., striped-wind & current-sheet (Petri & Kirk 2003, Mochol & Petri 2015, Kalapotharakos et al. 2014), annular gap (Du et al. 2012).

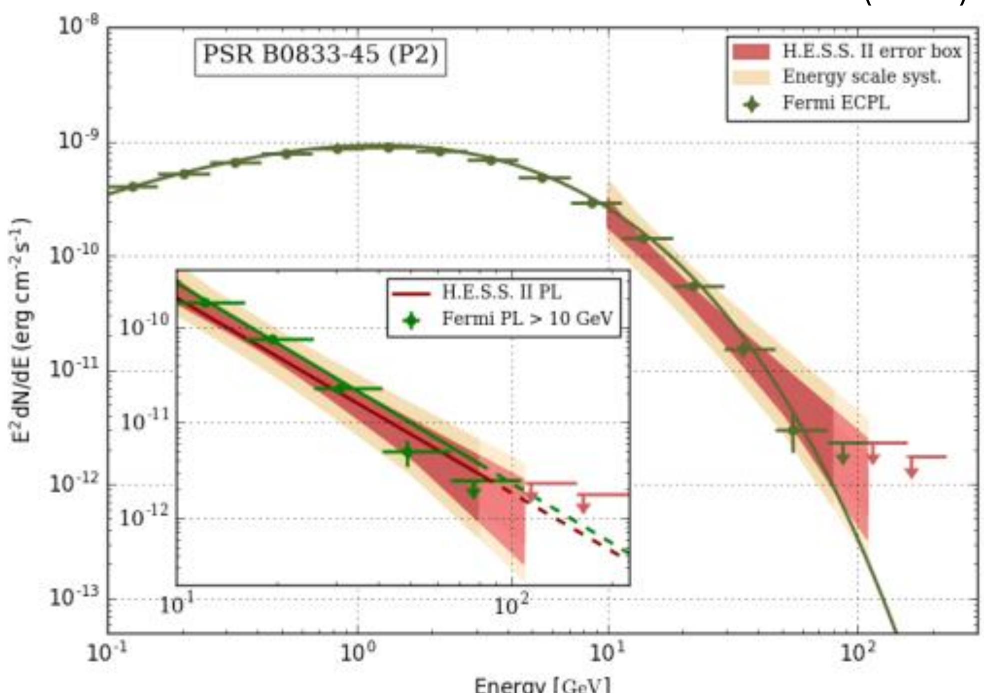
Vela's Sub-TeV phase-averaged spectra and light curves

Abdalla et al. (2018)



- P2 detected at 5.6σ level and P1 not visible.

Abdalla et al. (2018)



- **Motivation:**
  Is the observed spectrum of H.E.S.S (>3σ) a continuation of *Fermi* spectrum (curved sub-exponential) or a power law? Additional component distinct from GeV spectrum? Curvature radiation favoured > 3σ with first detection.

Open questions

- Spectral shape of emitting particles?
- Which emission mechanisms contribute to the broadband SED?
- Local and global electrodynamical properties?
- Pulsar (magnetosphere) geometry?

Aims

- H.E.S.S. and the *Fermi* LAT detection of Vela provide evidence for a curved GeV spectrum and recent kinetic simulations re-ignited the debate regarding the emission mechanism responsible for pulsed GeV-band emission (CR, SR or IC).
- We interpret this curved, broadband spectrum to be the result of curvature radiation due to primary particles in the pulsar magnetosphere including current sheet.

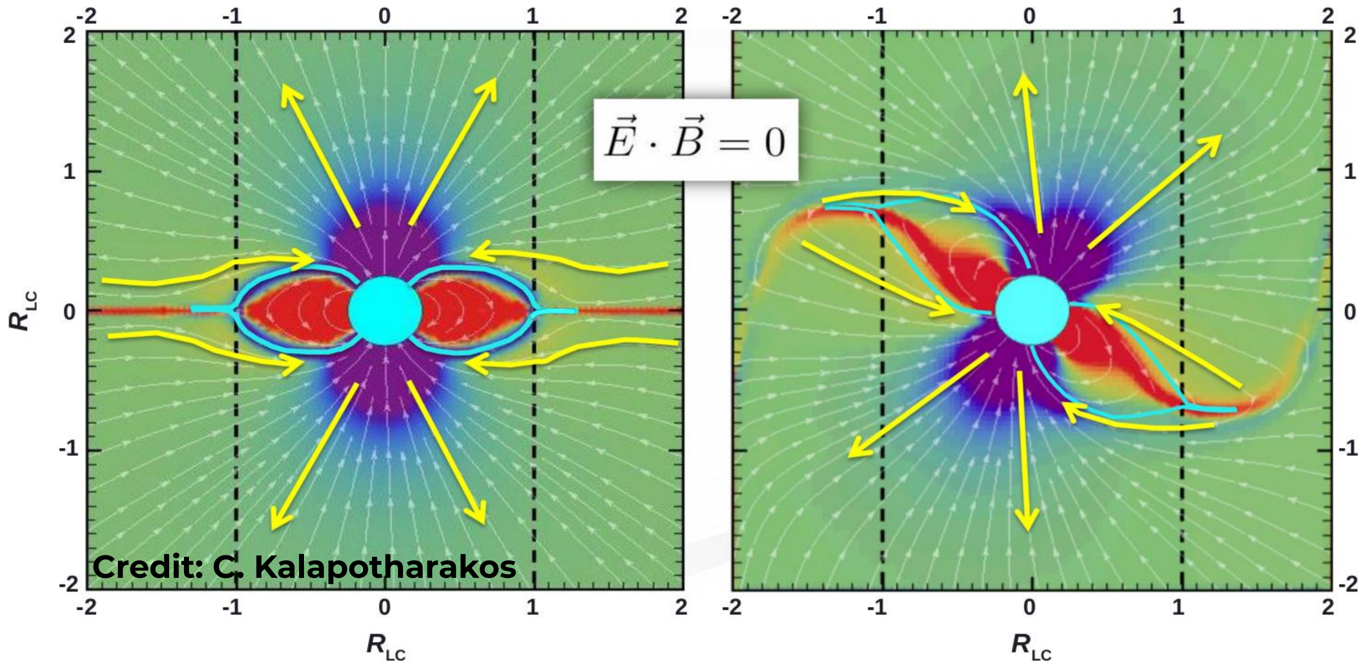
Spectral and energy-dependent LC modelling

SSC 3D Model

Harding & Kalapotharakos (2015,2018)

- Extended slot gap (SG) + 3D force-free magnetosphere (primarily the current sheet and the *E*-field completely screened outside of the slot gap).

- Pairs from steady cascade in offset-PC *B*-field (Harding & Muslimov 2011a,b).



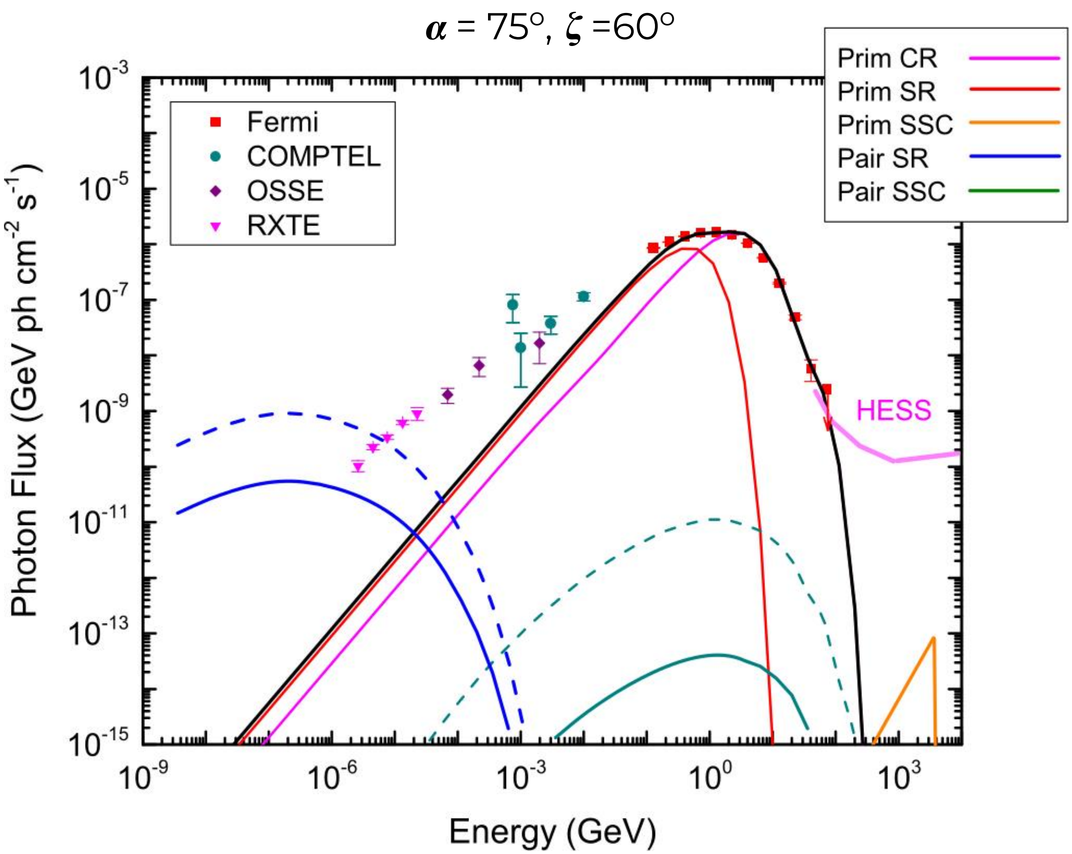
- Primaries accelerated in SG and current sheet (out to r=2R_{LC}) assuming a constant *E*-field - most emission comes from the current sheet (Mochol & Petri 2015). ***No pair acceleration.***

- One and two-step function for the accelerating *E*-field (latter motivated by kinetic simulations). $\boldsymbol{R_{acc} = eE_{||}/m_ec^2}$.

SSC 3D Model

Harding & Kalapotharakos (2015,2018)

- Empirical radio core / cone model – resonant cyclotron absorption of radio photons (cf. Lyubarski & Petrova 1998) to regain pitch angles for synchrotron radiation (SR).
- Solve particle dynamics / transport.
- Radiation mechanisms:
  Curvature / Synchrotron /
  Inverse Compton Scattering /
  Synchrotron self-Compton /
  Synchro-curvature.
- Inertial observer frame.
- Light curves and spectra.



Harding et al. (2015)

Transport

(Harding et al. 2008,2015)

$$\frac{d\gamma}{dt} = \frac{eE_{\parallel}}{mc} - \frac{2e^4}{3m^3c^5}B^2\, p_{\perp}^2 - \frac{2e^2\gamma^4}{3\rho_c^2} + \left(\frac{d\gamma}{dt}\right)^{\rm abs} - \left(\frac{d\gamma}{dt}\right)^{\rm SSC}$$

$$\frac{dp_{\perp}}{dt} = -\frac{3}{2}\frac{c}{r}p_{\perp} - \frac{2e^4}{3m^3c^5}B^2\,\frac{p_{\perp}^3}{\gamma} + \left(\frac{dp_{\perp}(\gamma)}{dt}\right)^{\rm abs}$$

See talk by Alice Harding

SSC 3D Model

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- Solve particle dynamics / transport.
- Radiation mechanisms: Curvature / Synchrotron / Inverse Compton Scattering / Synchrotron self-Compton / Synchro-curvature.
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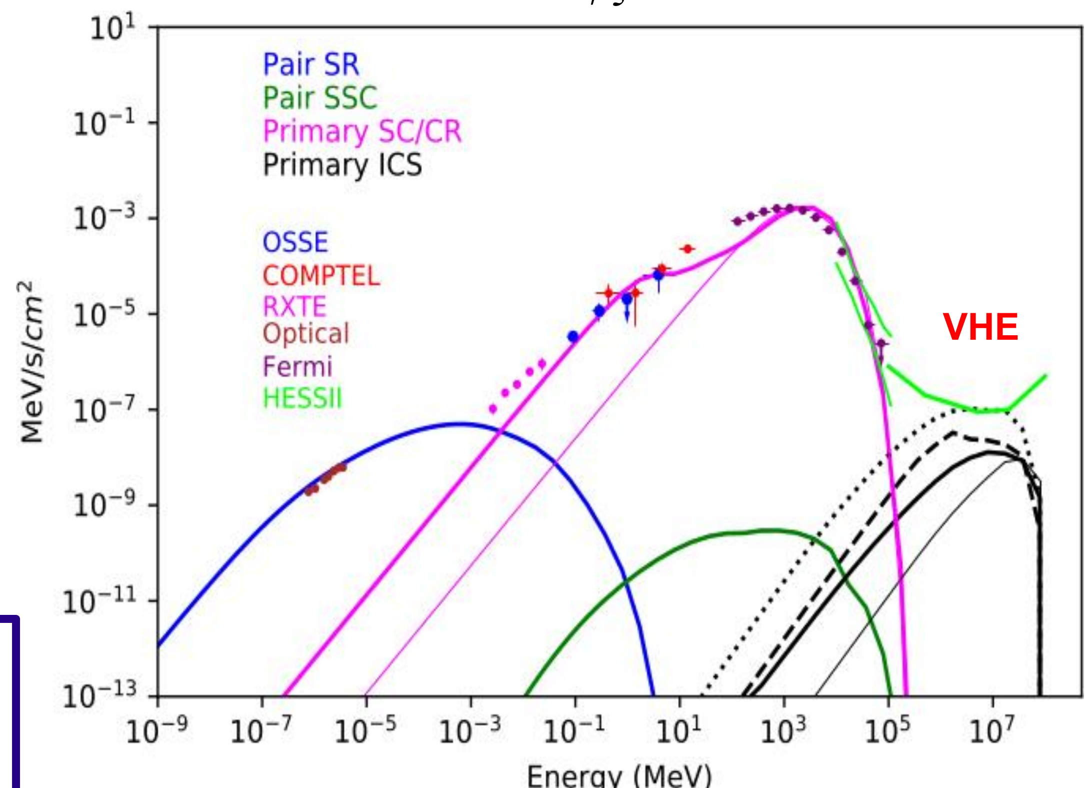
- Light curves and spectra.



Harding et al. (2018)

Transport

(Harding et al. 2008,2015)

$$\frac{d\gamma}{dt} = \frac{eE_{\|}}{mc} - \frac{2e^4}{3m^3c^5}B^2\, p_{\perp}^2 - \frac{2e^2\gamma^4}{3\rho_c^2} + \left(\frac{d\gamma}{dt}\right)^{\rm abs} - \left(\frac{d\gamma}{dt}\right)^{\rm SSC}$$

$$\frac{dp_{\perp}}{dt} = -\frac{3}{2}\frac{c}{r}p_{\perp} - \frac{2e^4}{3m^3c^5}B^2\,\frac{p_{\perp}^3}{\gamma} + \left(\frac{dp_{\perp}(\gamma)}{dt}\right)^{\rm abs}$$

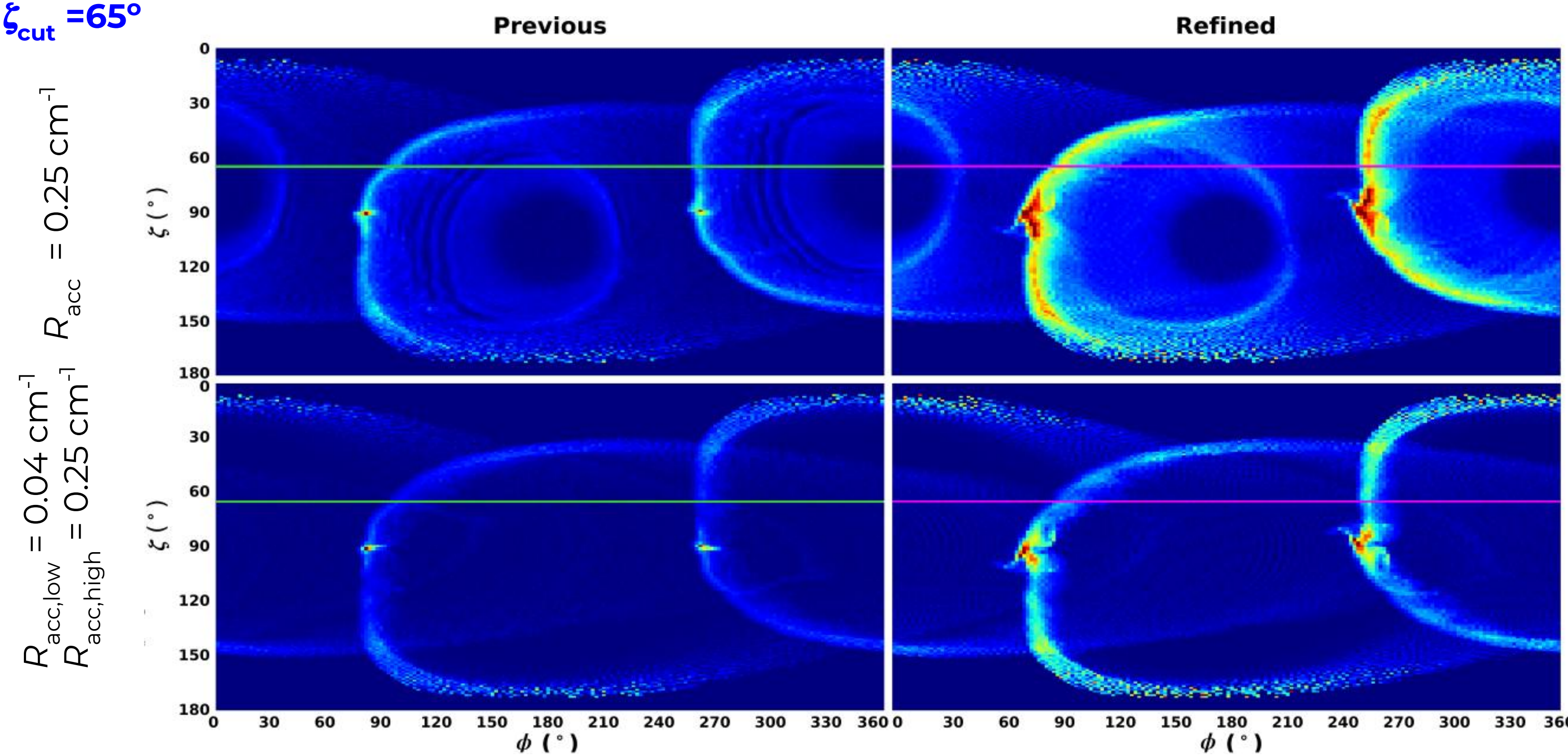
Refinement of the curvature radius

Harding et al. (2015,2018), Barnard et al. (*in preparation*)

- One and two-step function for the accelerating *E*-field (latter motivated by kinetic simulations). $\boldsymbol{R_{acc} = eE_{||}/m_ec^2}$.
- Refined calculation of the curvature radius of particle trajectories - impacts the transport, light curves, and spectra.
- Did a small parameter study to find optimal parameters, i.e., α, ζ_{cut}, R_{acc}, and selected the best resolution.

α = 75°

ζ_{cut} =65°



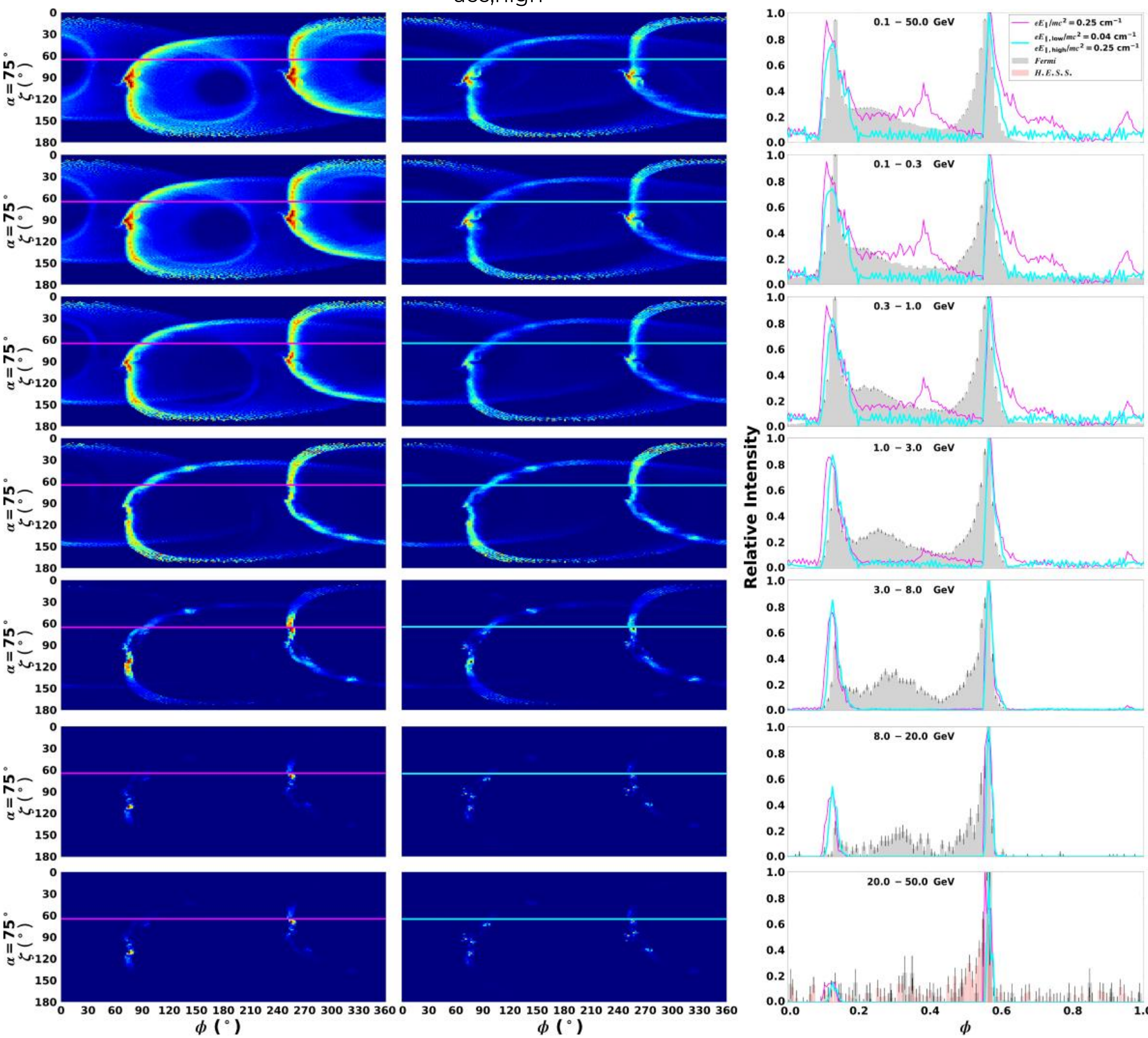
Energy-dependent CR LCs

α = 75°
ζ_{cut} = 65°

Abdo et al. (2010,2013)
Abdalla et al. (2018)

R_{acc} = 0.25 cm^{-1}

$R_{acc,low}$ = 0.04 cm^{-1}
$R_{acc,high}$ = 0.25 cm^{-1}



Energy-dependent CR LCs

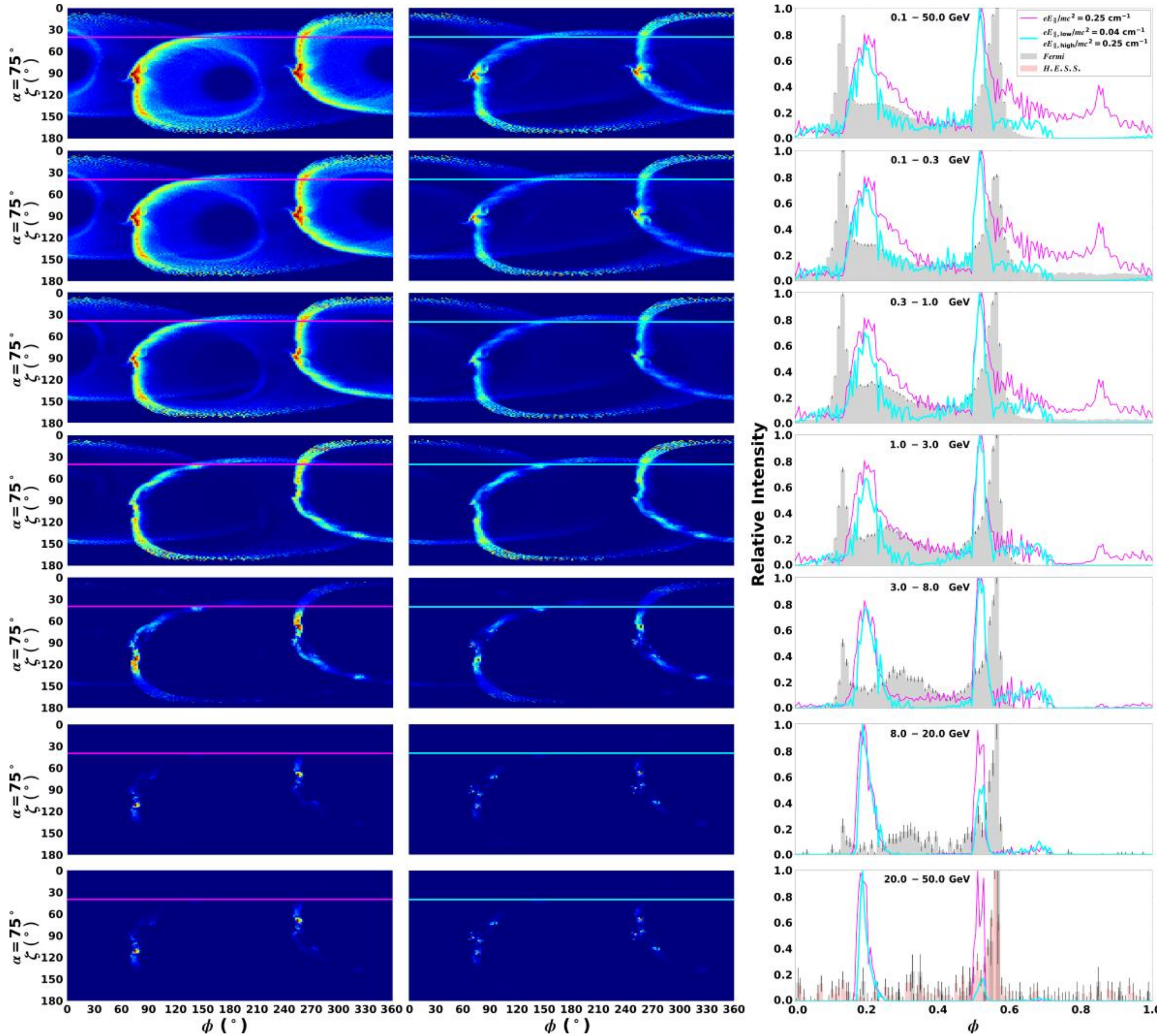
α = 75°
ζ_{cut} = 40°

R_{acc} = 0.25 cm^{-1}

$R_{acc,low}$ = 0.04 cm^{-1}
$R_{acc,high}$ = 0.25 cm^{-1}

Abdo et al. (2010,2013)
Abdalla et al. (2018)

- Test robustness of the P1/P2 vs. photon energy - obtained a counter-example.
- Light curves have a different emission structure due to a different spatial origin of the emission.
- No bridge emission (at high photon energies, see Brambilla et al. 2015).



Reverse mapping

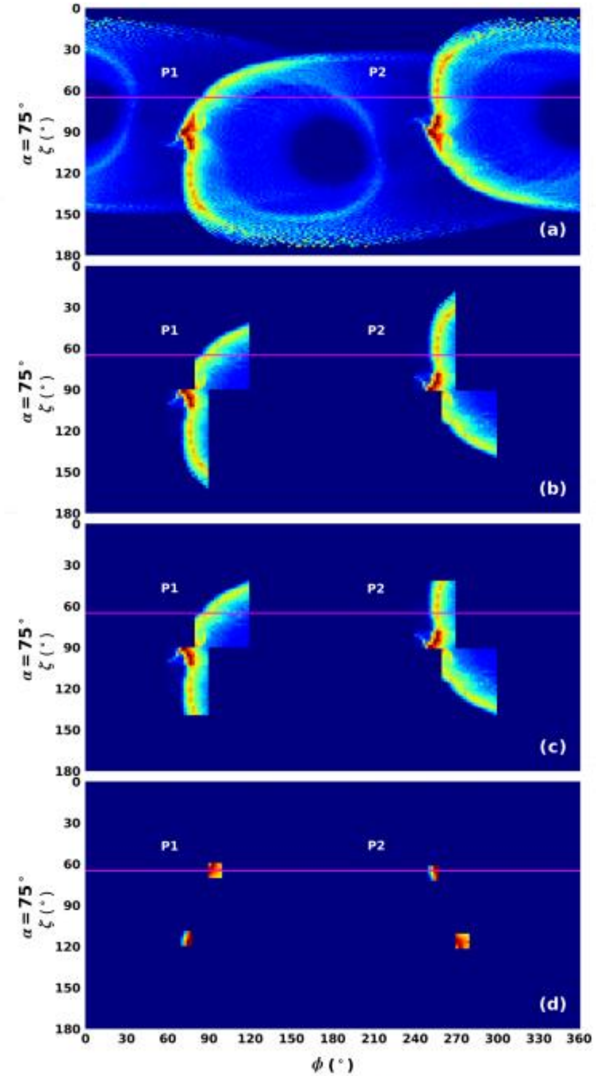
Barnard et al. (*in preparation*)

- Isolate P1 and P2:
  - Limit (ϕ,ζ) coordinate values where peaks originate i.e., “blocks”
  - Obtain spatial coordinates (and other parameter quantities) at these coordinates.

- Phase-resolved spectra.

- Need to investigate the local environment of the peaks, i.e., energy cutoff ($E_{\gamma,\rm cr}$), curvature radius (ϱ_c), and Lorentz factor (γ).

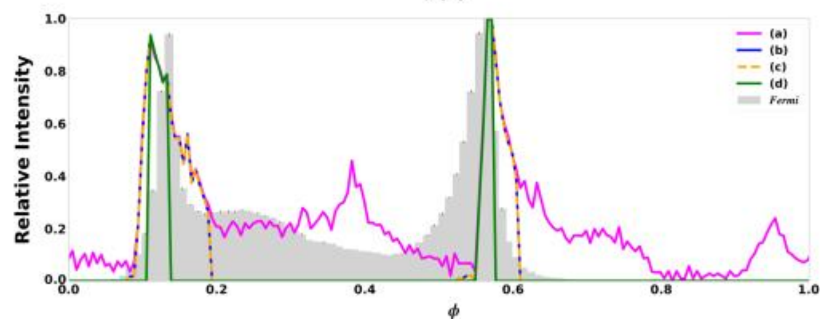
- Will explain trends in observed light curves and spectra.



α = 75°

ζ_{cut} = 65°

R_{acc} = 0.25 cm^{-1}

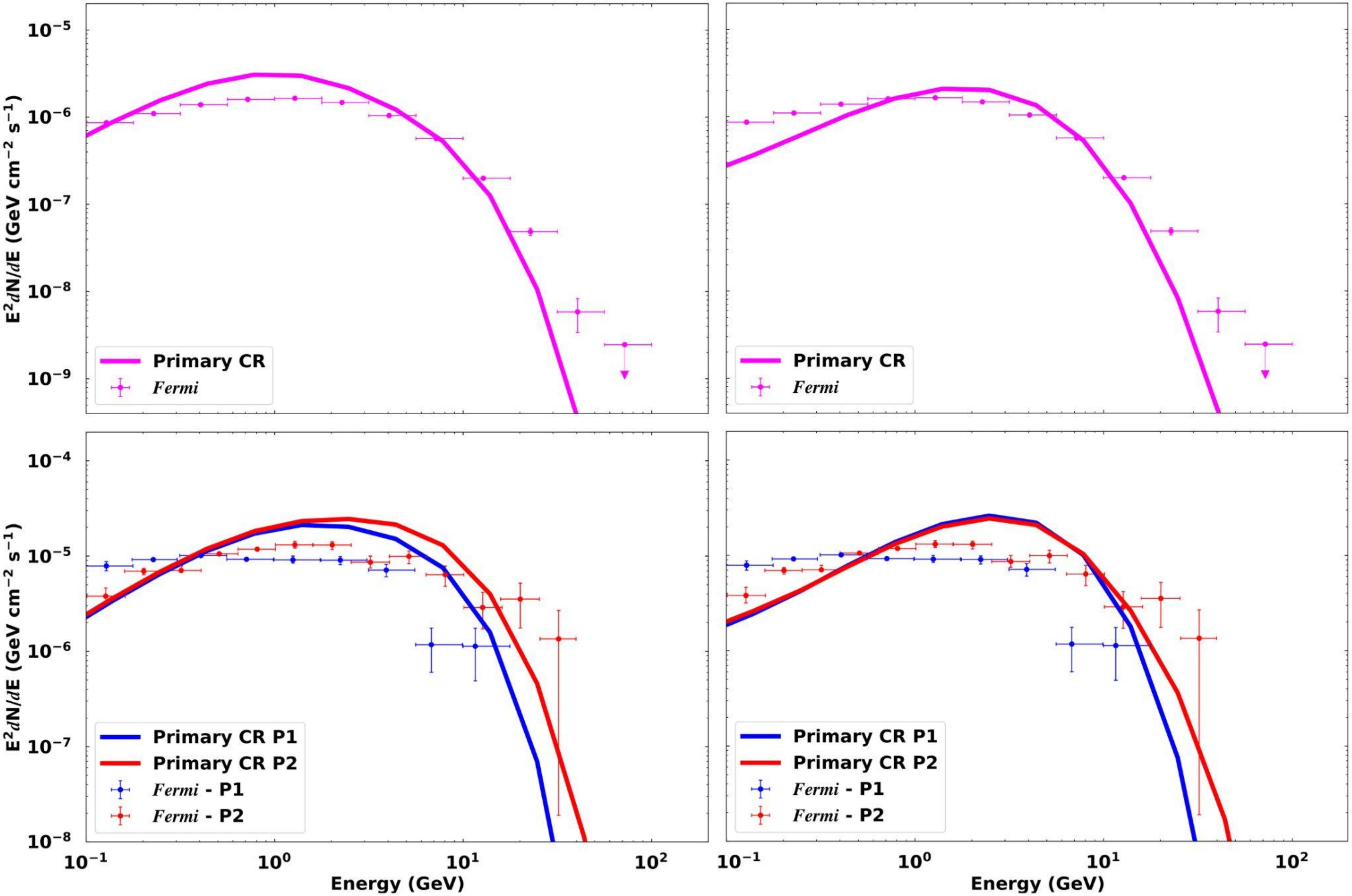


Phase-averaged and resolved CR spectra

α = 75°
ζ_{cut} = 65°

R_{acc} = 0.25 cm^{-1};
Norm = $5J_{GJ}$

$R_{acc,low}$ = 0.04 cm^{-1}
$R_{acc,high}$ = 0.25 cm^{-1}
Norm = $8.5J_{GJ}$

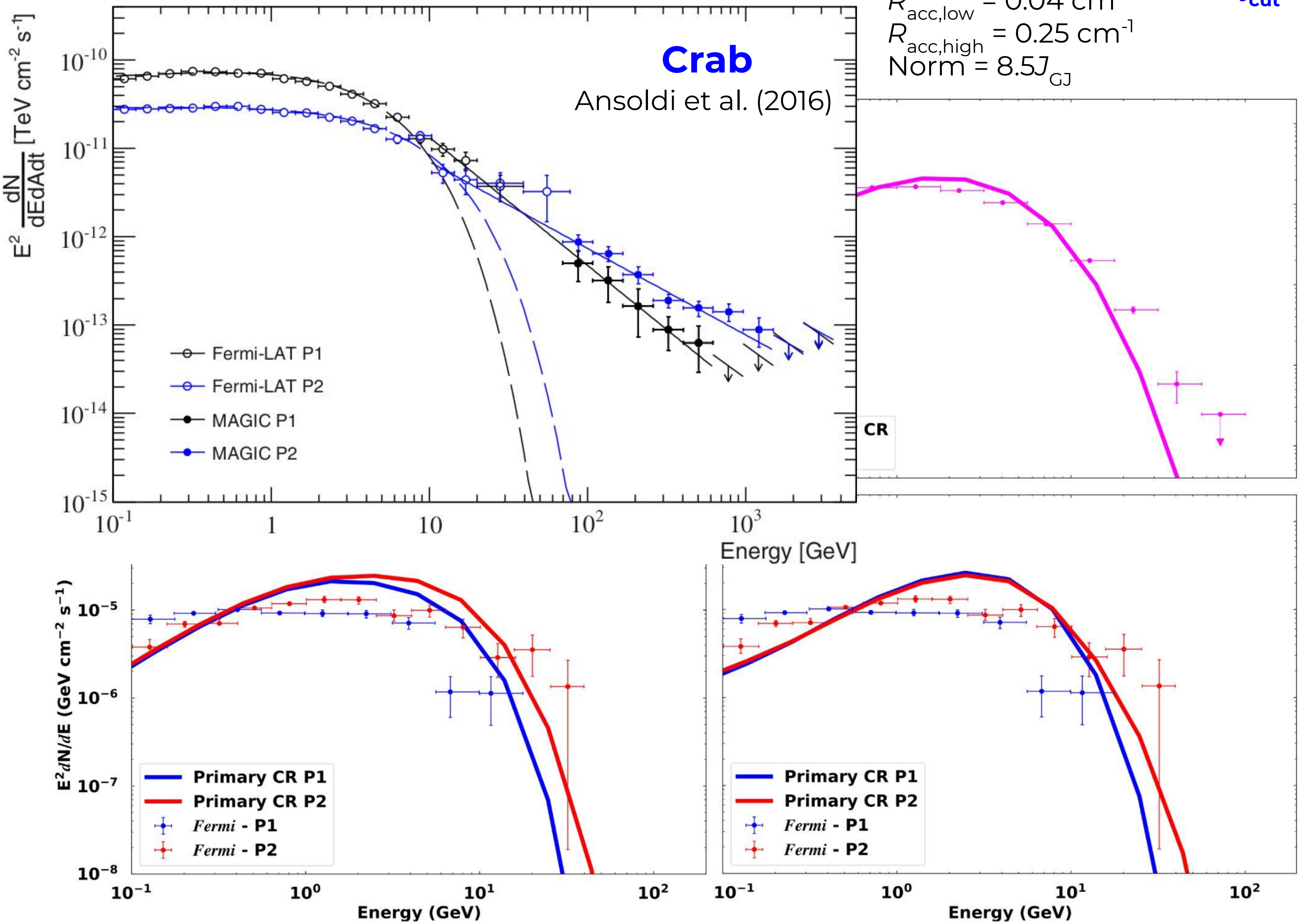


Abdo et al. (2010,2013)

Phase-averaged and resolved CR spectra

$\alpha = 75°$
$\zeta_{cut} = 65°$

$R_{acc,low} = 0.04\ cm^{-1}$
$R_{acc,high} = 0.25\ cm^{-1}$
$Norm = 8.5 J_{GJ}$



Abdo et al. (2010,2013)

Local Environment of Emission Regions Connected to Each Light Curve Peak

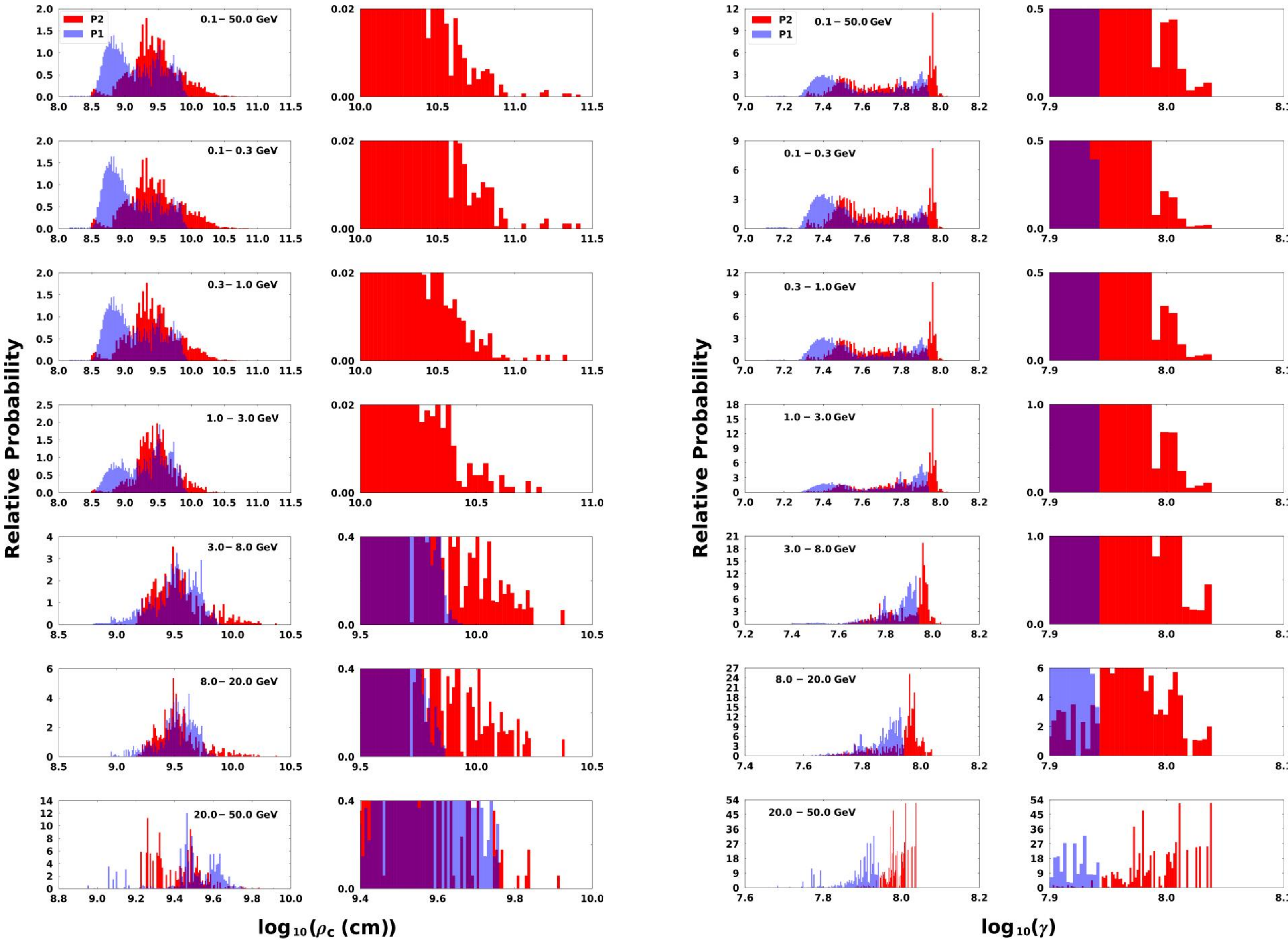
$\alpha = 75^{\circ}$

$\zeta_{\rm cut} = 65^{\circ}$

$R_{\rm acc} = 0.25\ {\rm cm}^{-1}$

Barnard et al. (*in preparation*)

$$E_{\gamma,\rm CR} = \frac{3\lambda_{\rm c}\gamma^3}{2\rho_{\rm c}} m_{\rm e}c^2$$



Local Environment of Emission Regions Connected to Each Light Curve Peak

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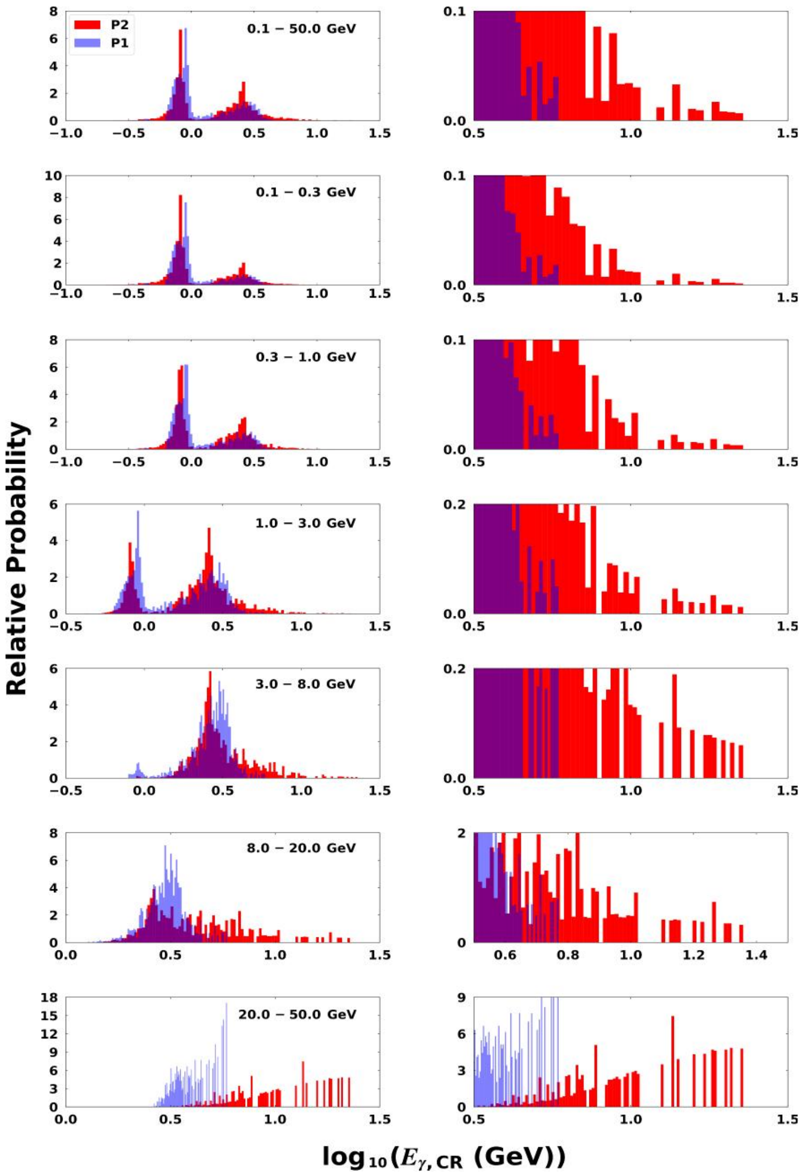
Barnard et al. (*in preparation*)

$$E_{\gamma,\mathrm{CR}} = \frac{3\lambda_c\gamma^3}{2\rho_c}m_e c^2$$



Summary

- For the refined curvature radius - emission caustics are wider, more filled out with radiation, rounded and concentrated around the polar caps. The two calculations are very similar, although the LCs are smoother for the refined calculation.

- Two-step *E*-field: $E_{||,\mathrm{low}}$ leads to suppression of emission inside light cylinder as well as disappearance of bridge.

- Our model captures the general trends of the decrease of P1/P2 vs. energy, evolution / suppression of the inter-peak bridge emission, stable peak positions and a decrease in the peak widths as energy is increased.

- We isolate the distribution of Lorentz factors and curvature radii of trajectories associated with the first and second gamma-ray light curve peaks. The median values of these quantities are slightly larger for the second peak, leading to larger cutoffs, and thus explaining the decrease in ratio of first to second peak intensity versus energy.

- Thus, P1/P2 effect is a consequence of the *B*-field structure. Dependence on curvature radius is consistent with CR.

- Ongoing debate regarding the origin of the GeV emission detected from pulsars, it being attributed either to CR or SR (or even IC; see Lyutikov et al. 2012; Lyutikov 2013).

- However, we found reasonable fits to the energy-dependent light curves and phase-resolved spectra of Vela, assuming CR as the mechanism responsible for the GeV emission.