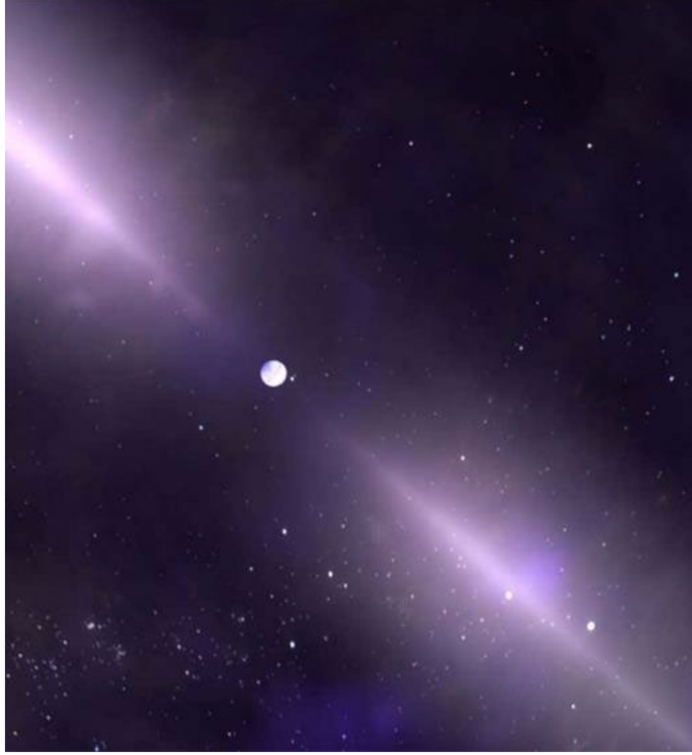
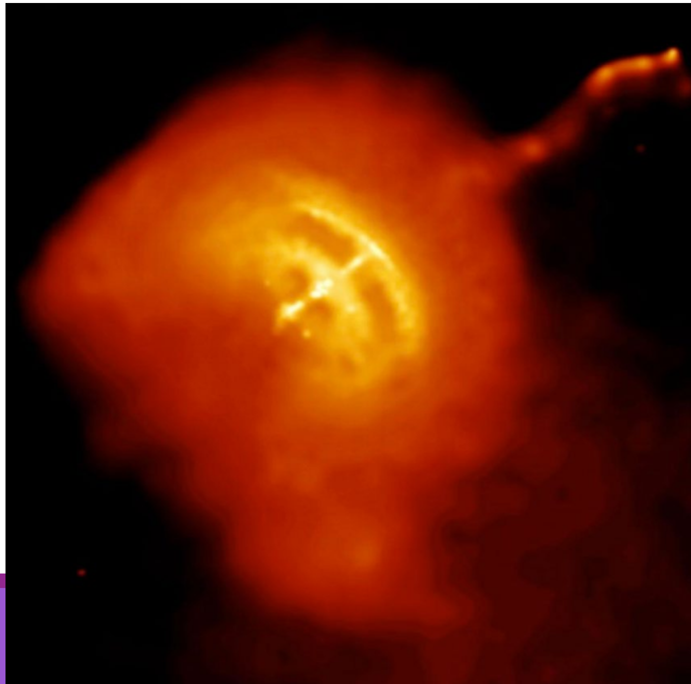
Pulsed TeV Emission from Pulsars in the Synchro-Curvature/IC Framework





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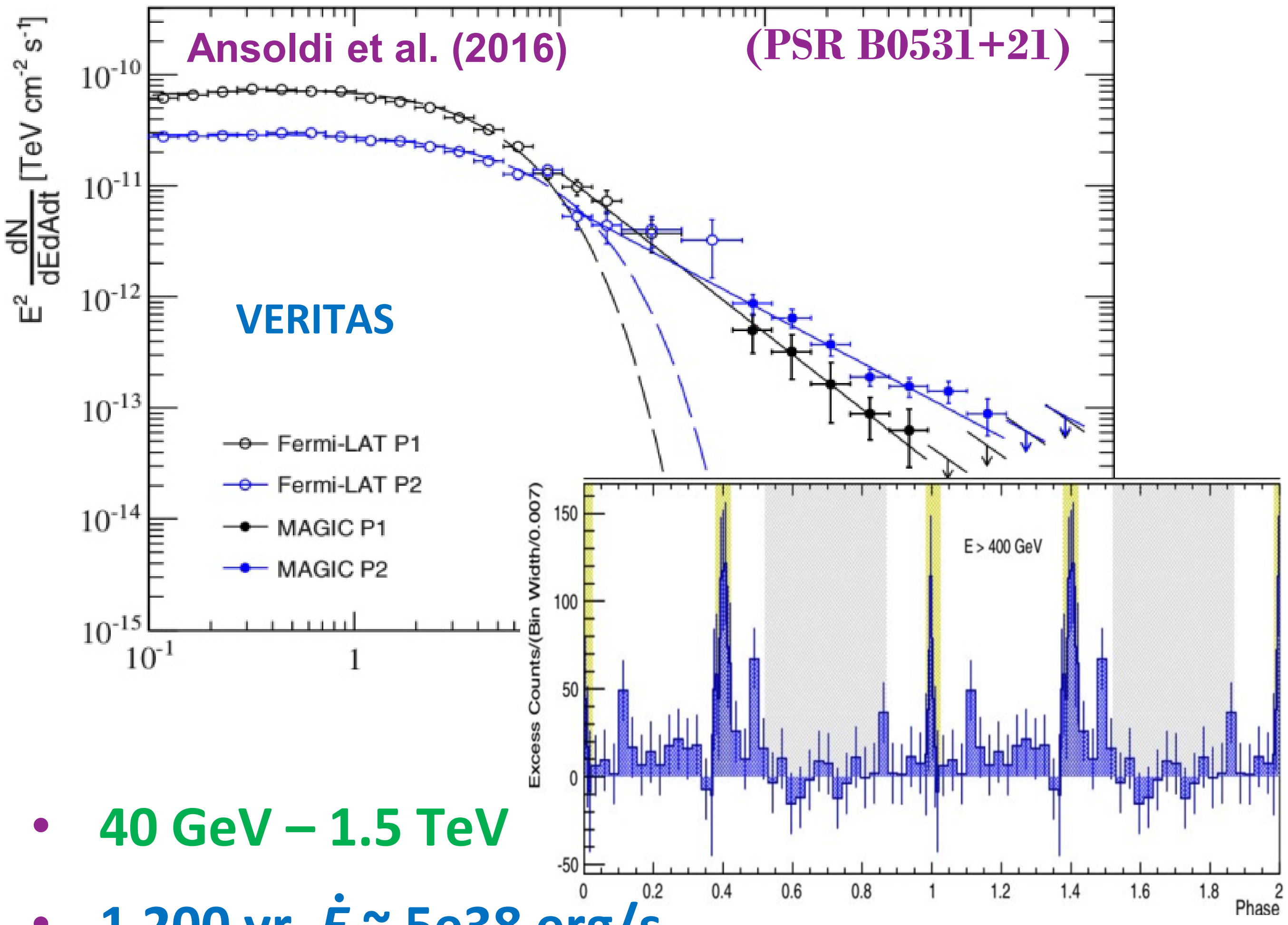
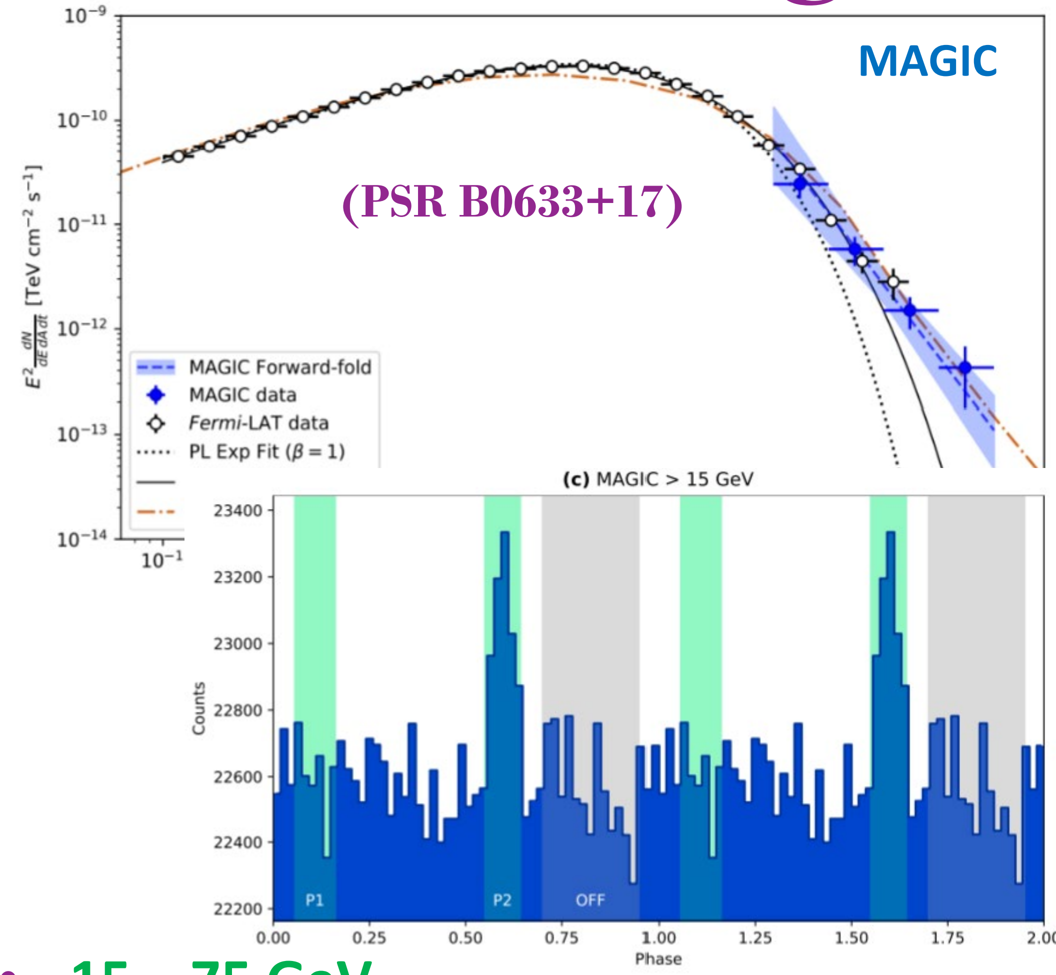
HONEST3: The High End of the Pulsar Spectra, 26 – 28 November 2024, Online

Pulsed TeV γs from Crab / Geminga

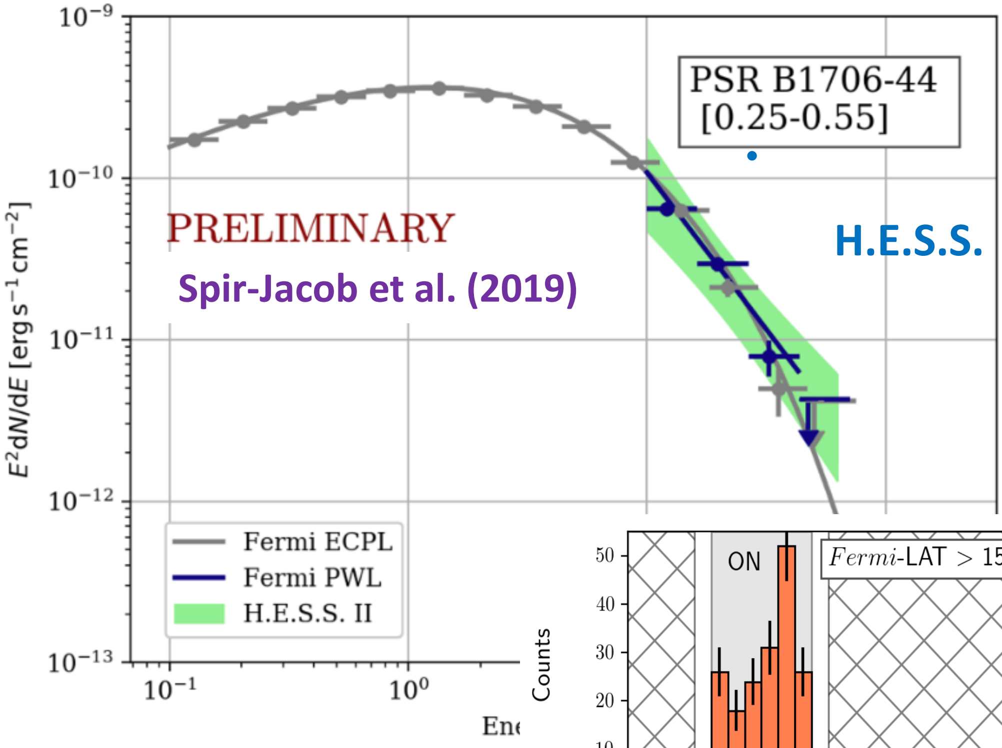


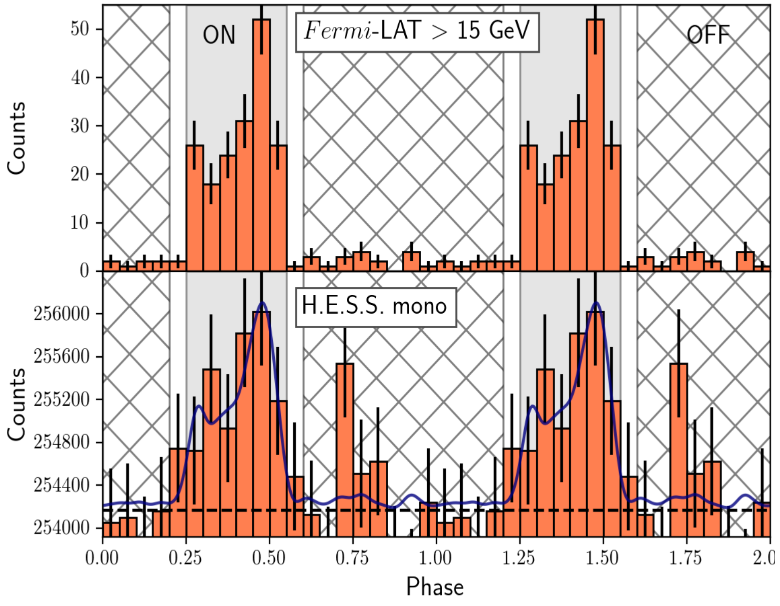
- 40 GeV – 1.5 TeV
- 1 200 yr, $\dot{E}$ ~ 5e38 erg/s
- Both P1 and P2 visible



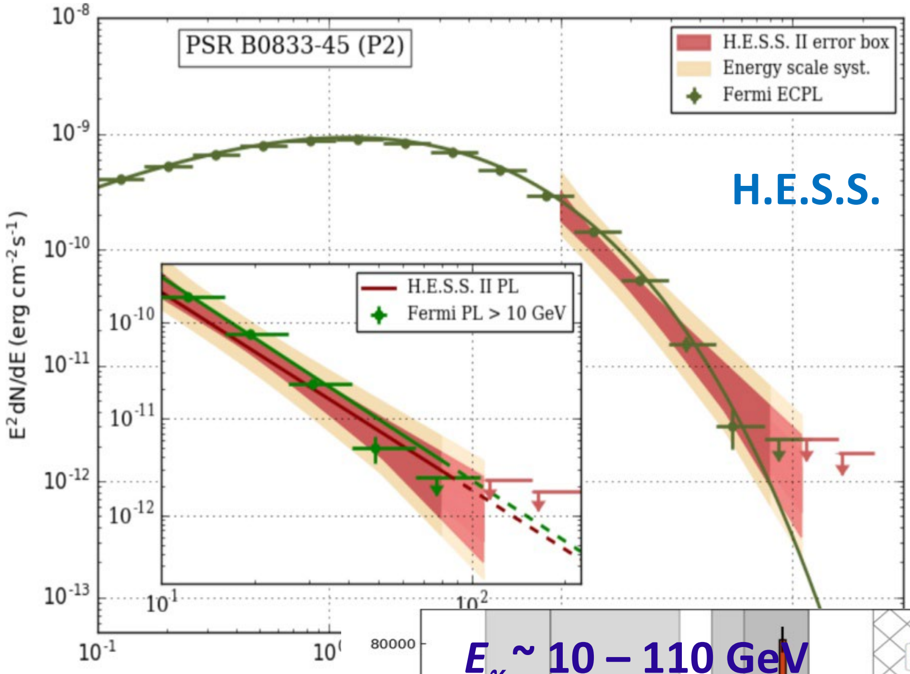
- 15 – 75 GeV
- 340 kyr, $\dot{E}$ ~ 3e34 erg/s; P2 @ 6.3σ

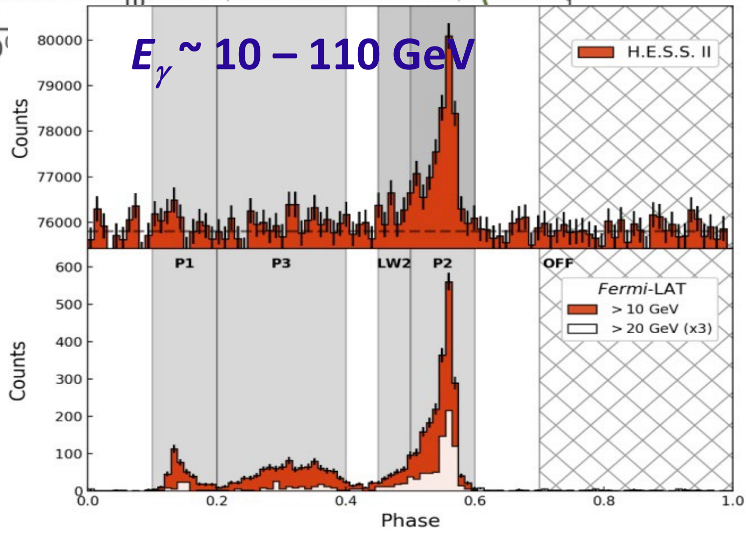
Pulsed γs from B1706-44 / Vela





- <~ 60 GeV
- 18 kyr, $\dot{E}$ ~ 3e36 erg/s
- P2 dominates P1

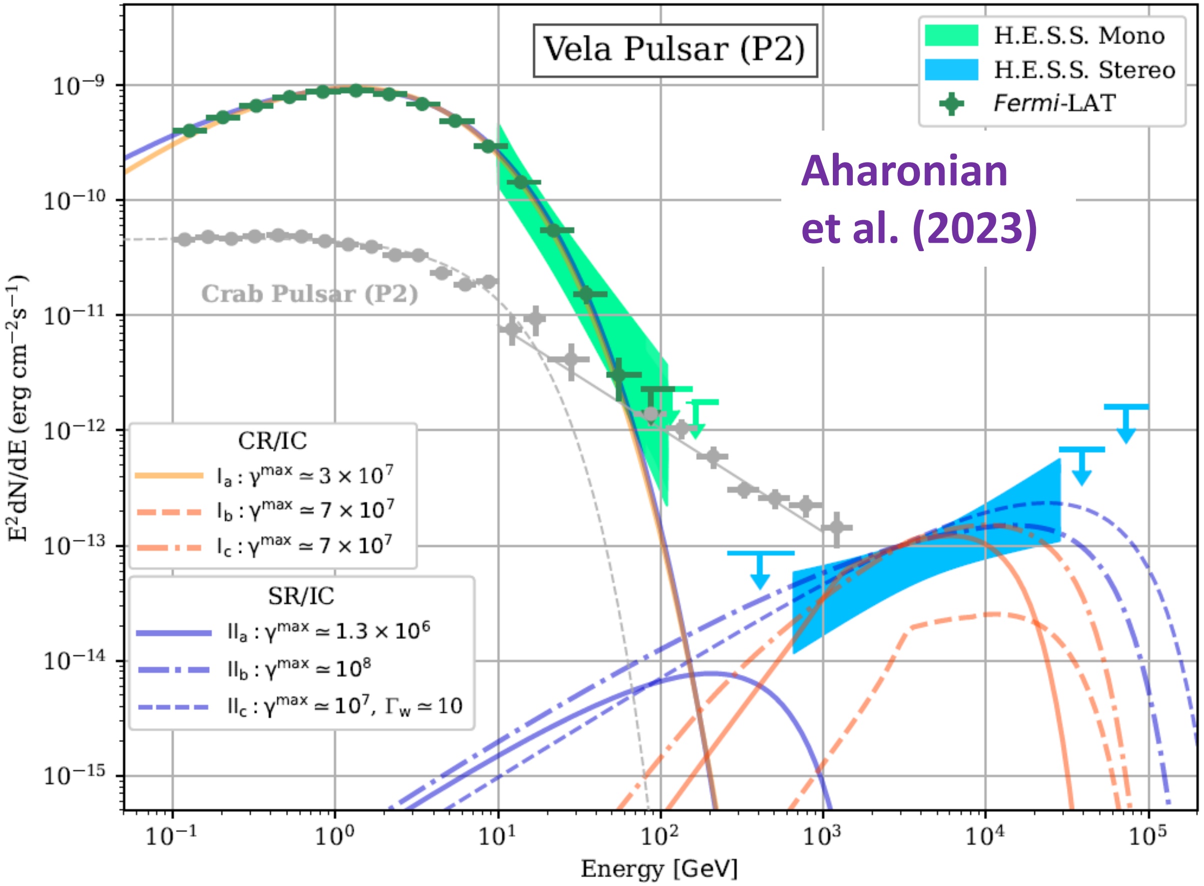


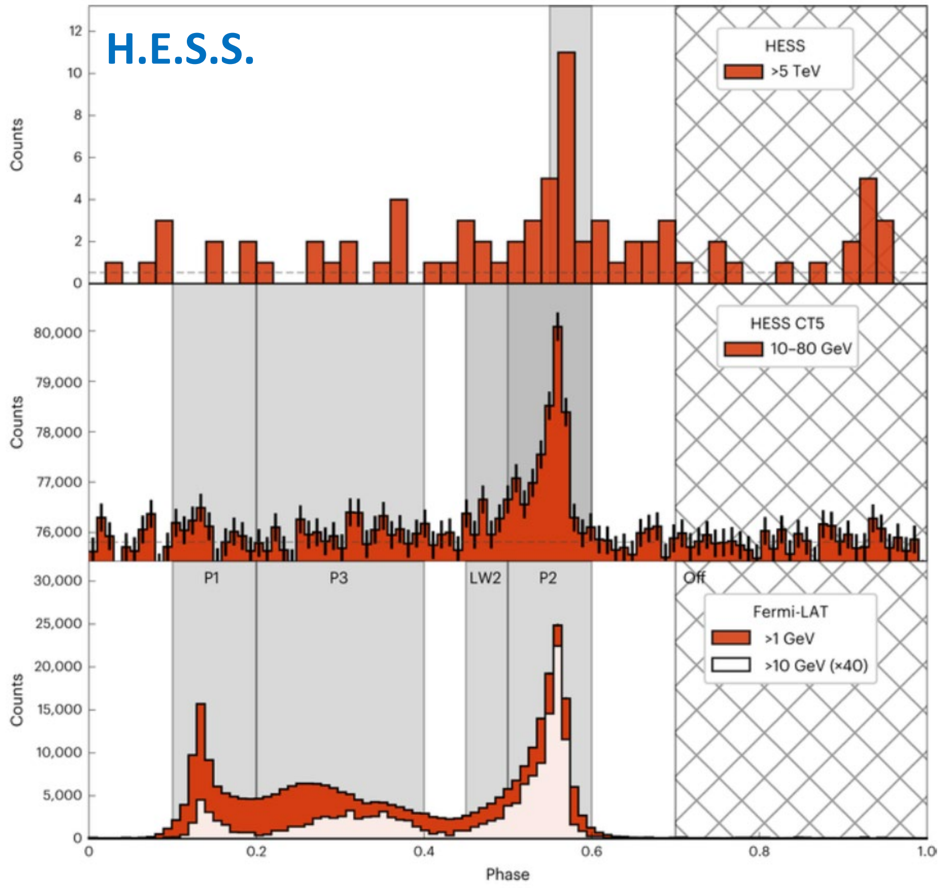


- <20 – 100 GeV
- Curved spectrum > 10 GeV

Cf. talk by Regeard

Vela Pulsations ~20 TeV!





- New spectral component
- Hard index

Cf. talks by de Ona Wilhelmi, Regeard, Djannati-Ataï, etc.

- P2 remains
- Similar P2 peak position & width in HE / VHE

Vela Pulsations ~20 TeV!

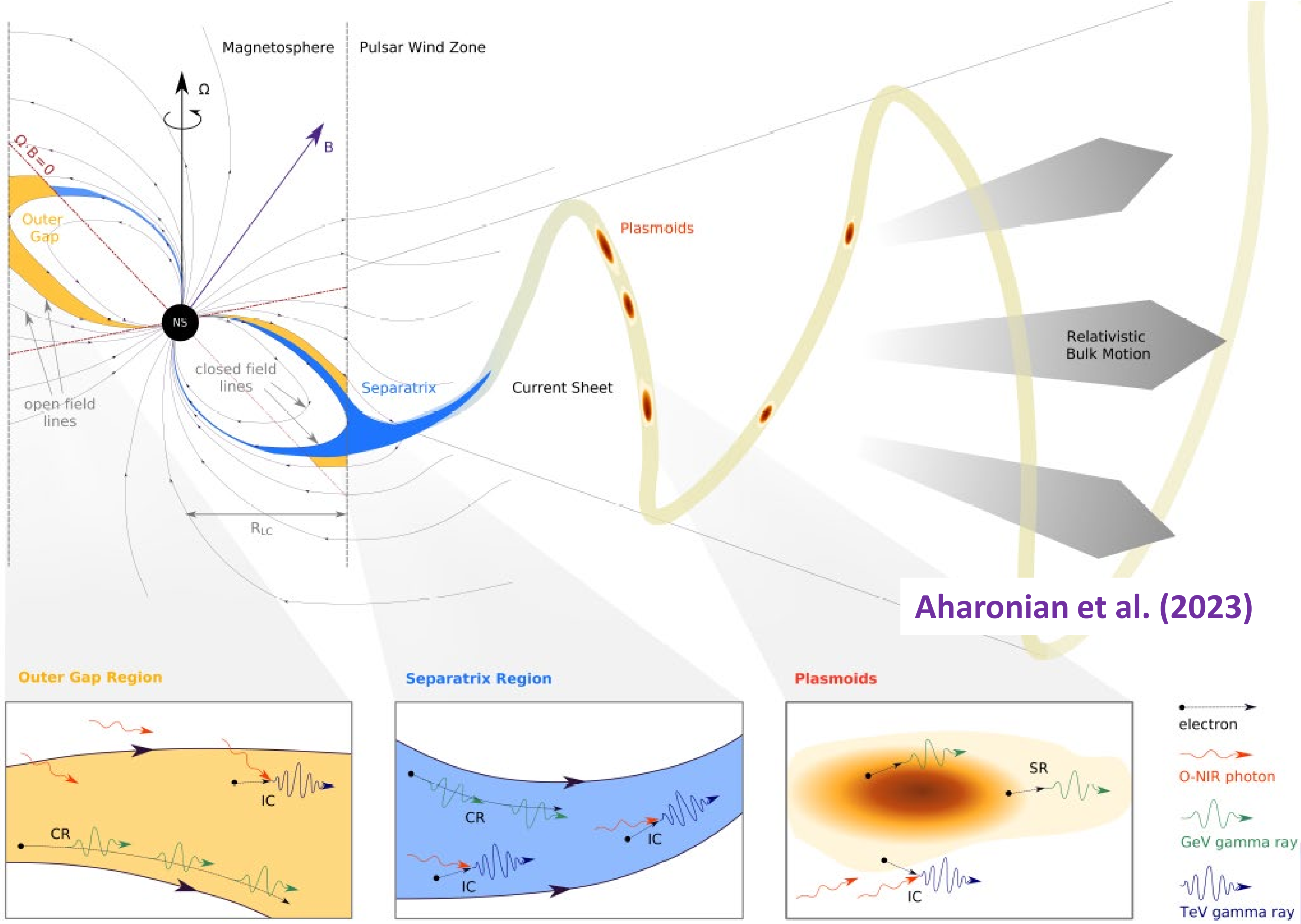
MAIN MODEL FRAMEWORKS:

(i) Local Models:
Gap models (PC / OG / SG / TPC) within the light cylinder

(ii) Global Models:
- Separatrix / current sheet model: $E_{||}$, SC / IC
- Magnetic reconnection in current sheet; Doppler boosting SR, / IC (striped wind)

Similar caustics than before

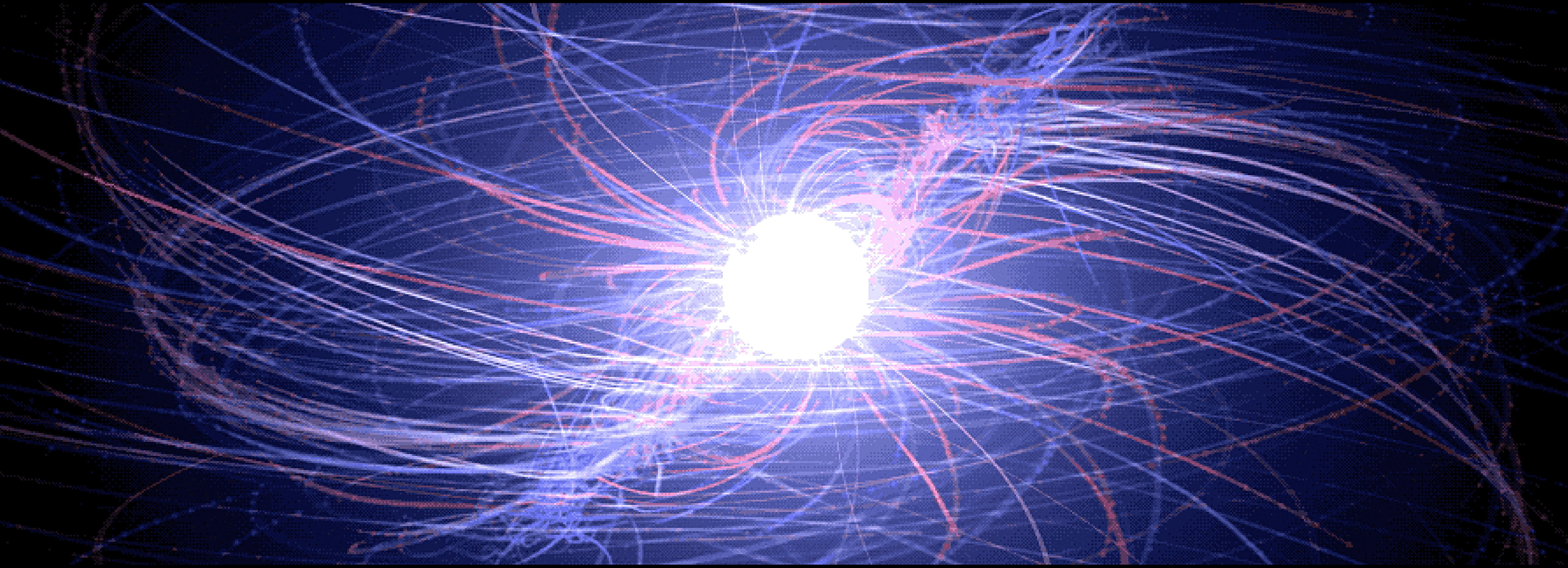
Cf. talks by Pétri, Khangulyan, Philippov, Cerutti, etc.



Aharonian et al. (2023)

Model Expectations

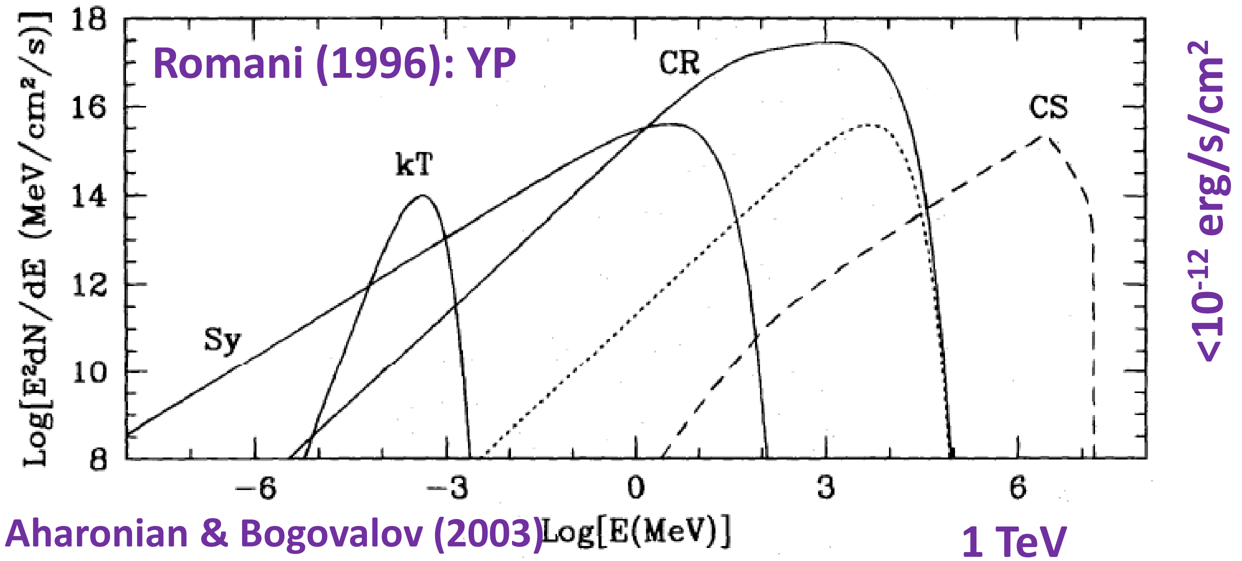
https://www.nasa.gov/feature/goddard/2018/pulsar-in-a-box-reveals-surprising-picture-of-a-neutron-star-s-surroundings



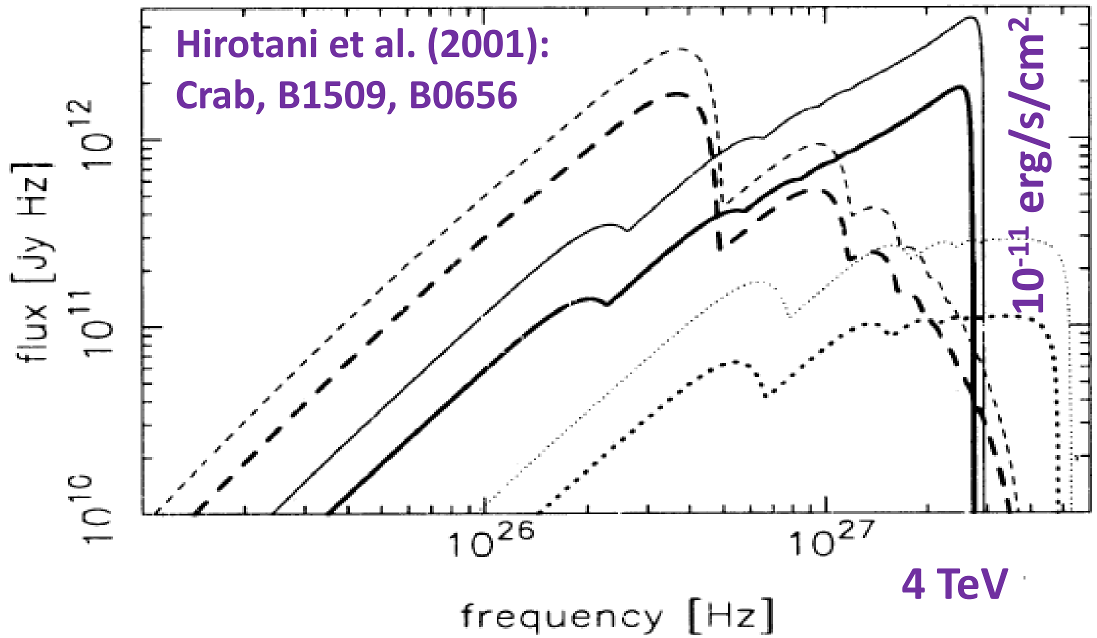
Expectations: TeV Pulsed Emission?

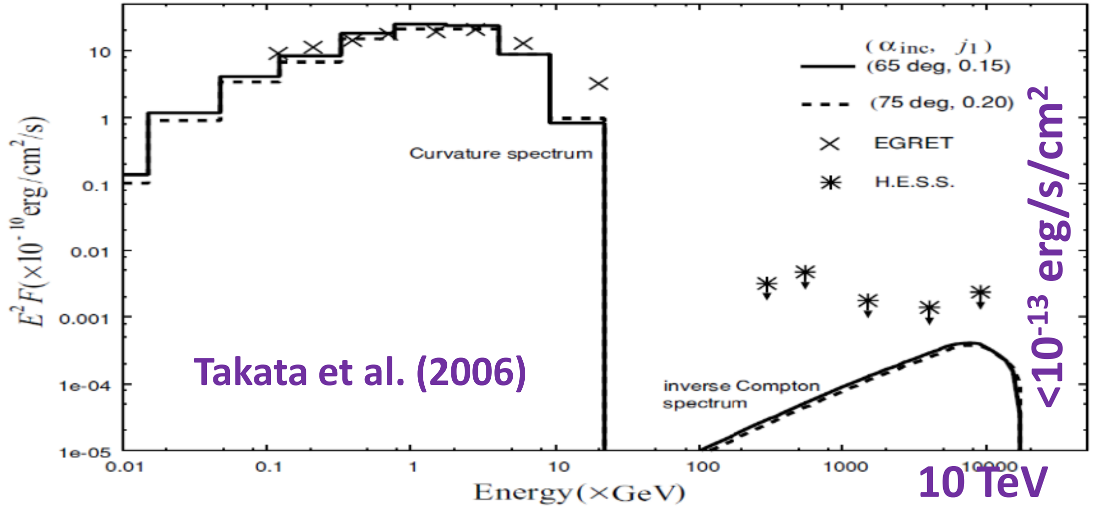
Early OG models

- Primaries scattering SR by pairs [or observational IR spectrum]
- Natural TeV bump at <1% - 5% of GeV flux
- Magnetic or two-photon pair production?



Cf. Aharonian & Bogovalov (2003)



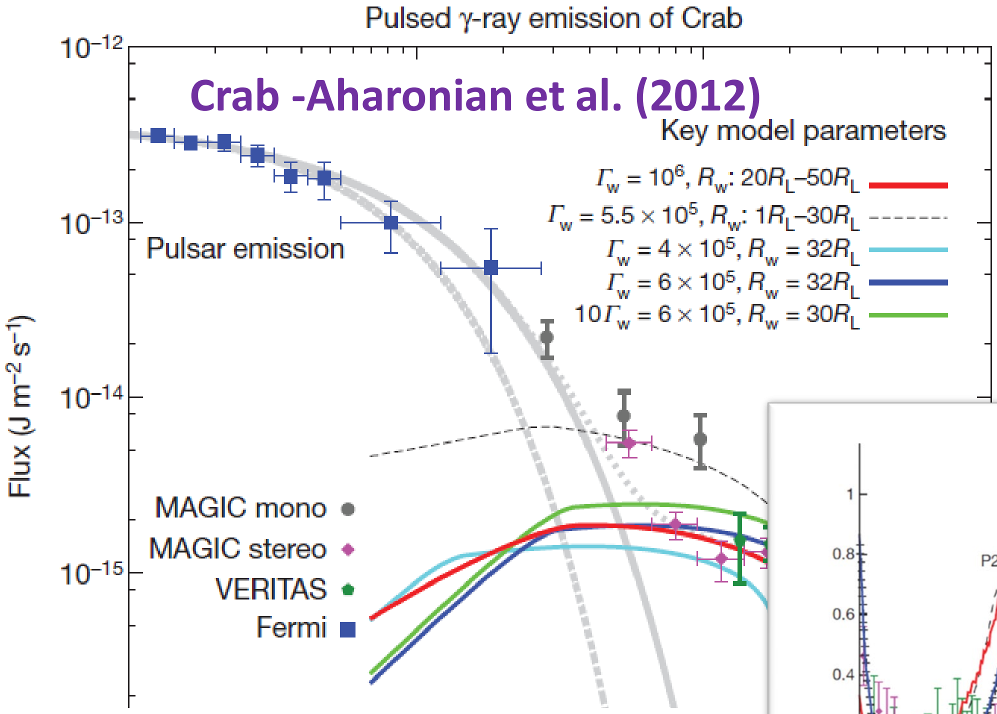


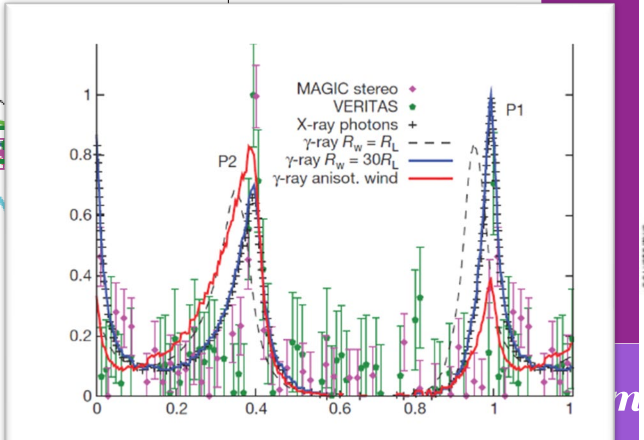
Expectations: TeV Pulsed Emission?

Cold, relativistic wind model

- Conversion of Poynting flux to kinetic energy
- 20 – 50 R_{LC}
- Observed X-rays as soft photons

Crab -Aharonian et al. (2012)



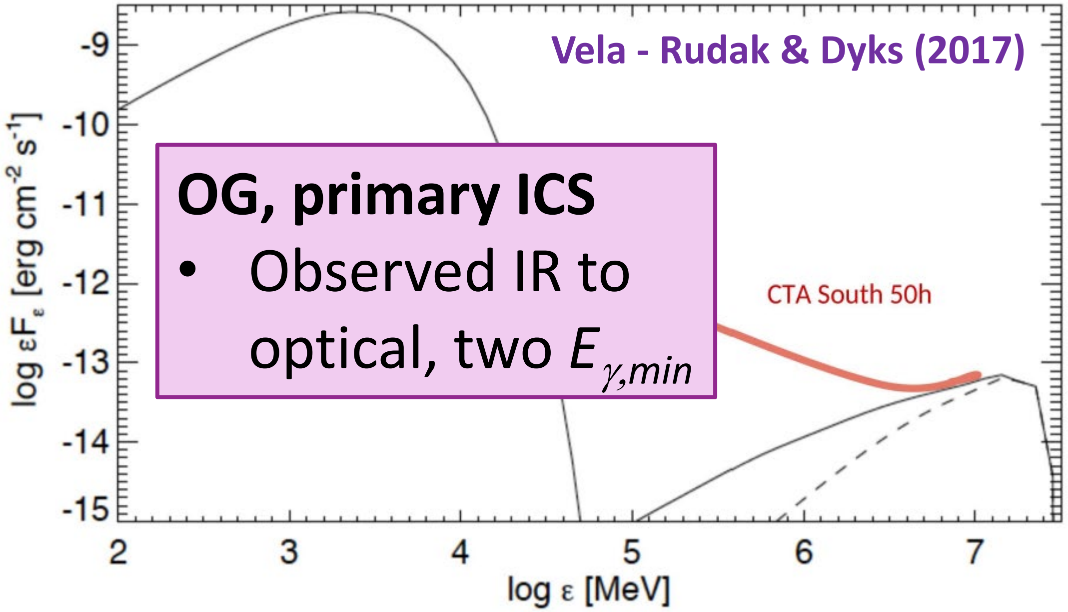


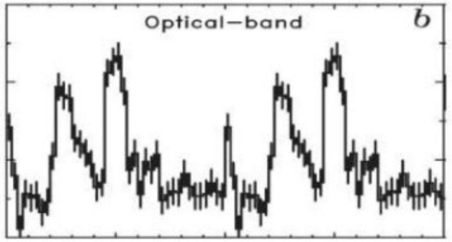
Bogovalov & Aharonian (2000)
Bogovalov et al. (2017)

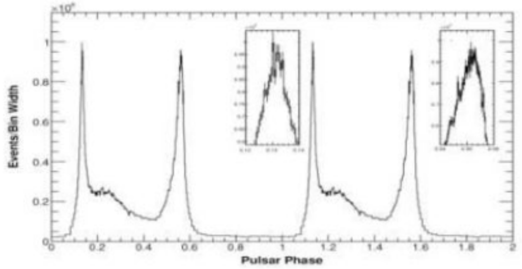
Vela - Rudak & Dyks (2017)

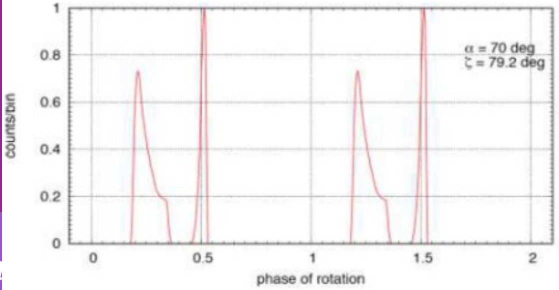
OG, primary ICS

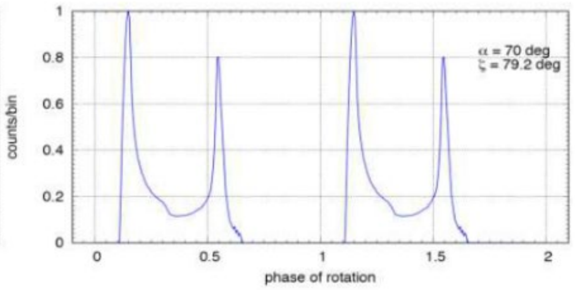
- Observed IR to optical, two $E_{\gamma,min}$







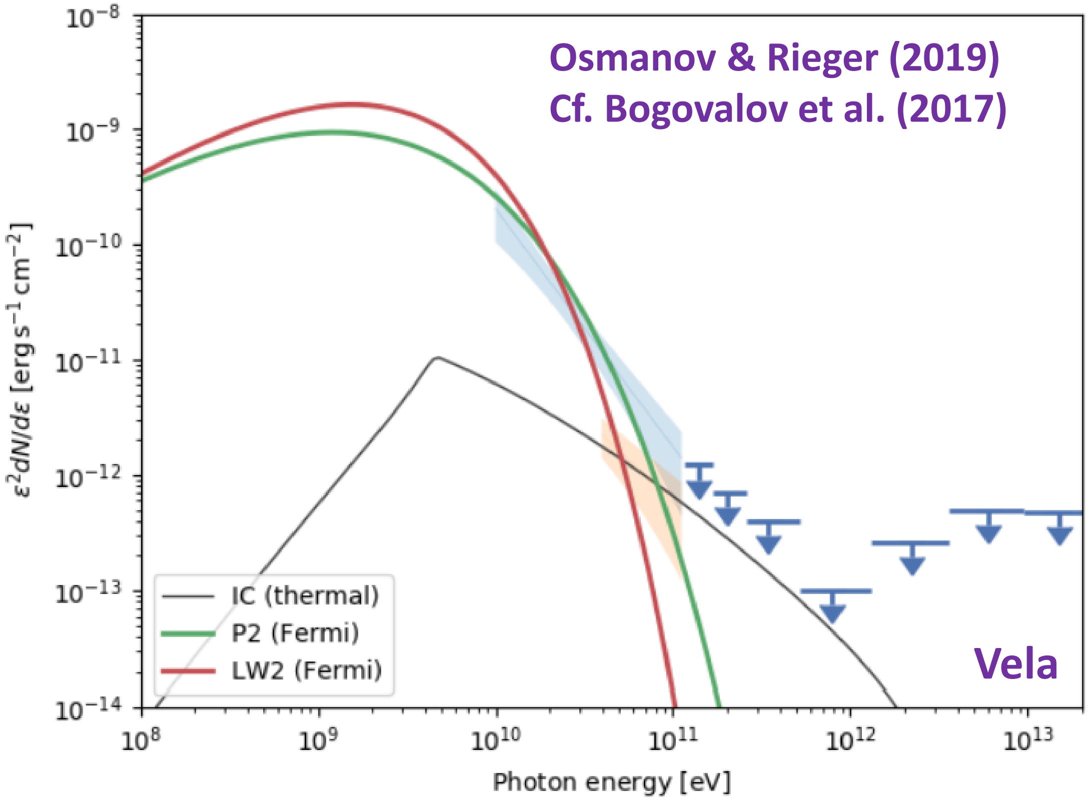


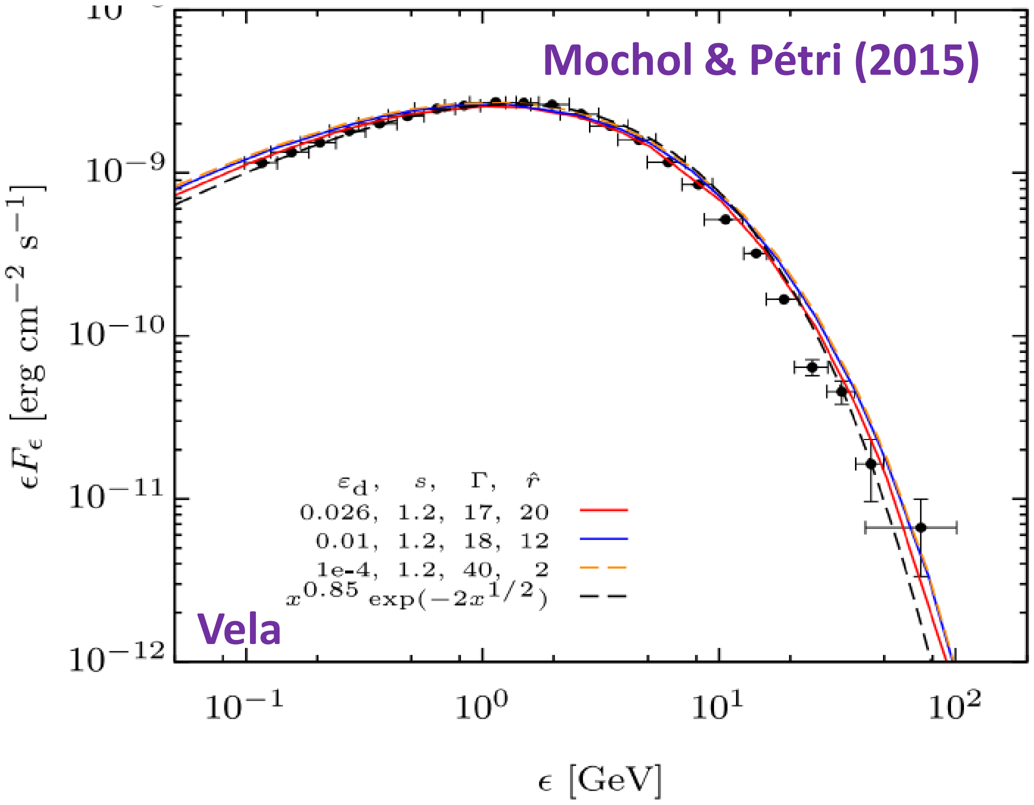


Expectations: TeV Pulsed Emission?

Magneto-centrifugal (rotationally-driven) particle acceleration

- ICS on thermal surface photons (T~10^6K)





CS / Striped-wind models

- SR in CS (magnetic reconnection)
- SSC component detectable in Crab, not Vela

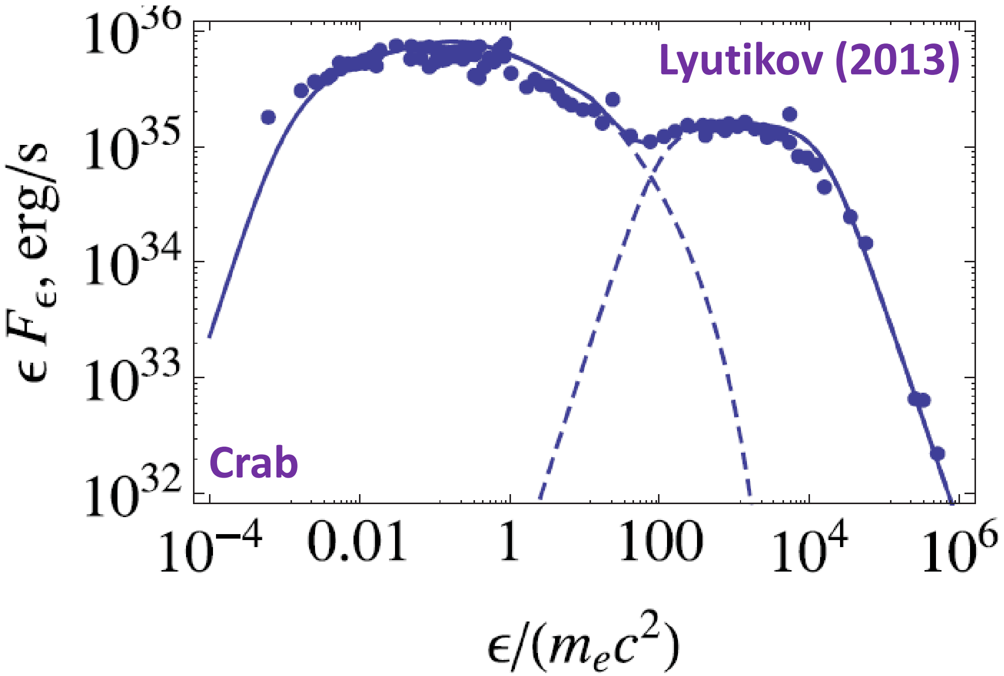
Expectations: TeV Pulsed Emission?

SSC by pairs
- Crab
- Energetics / spectra in ballpark of VERITAS results

Lyutikov (2012)

$$\epsilon_{\gamma,p} \approx \gamma_p m_e c^2 = 150\,\mathrm{GeV}\,\eta_{-2}^{1/4}\sqrt{\xi}\,\lambda_2^{-1}$$

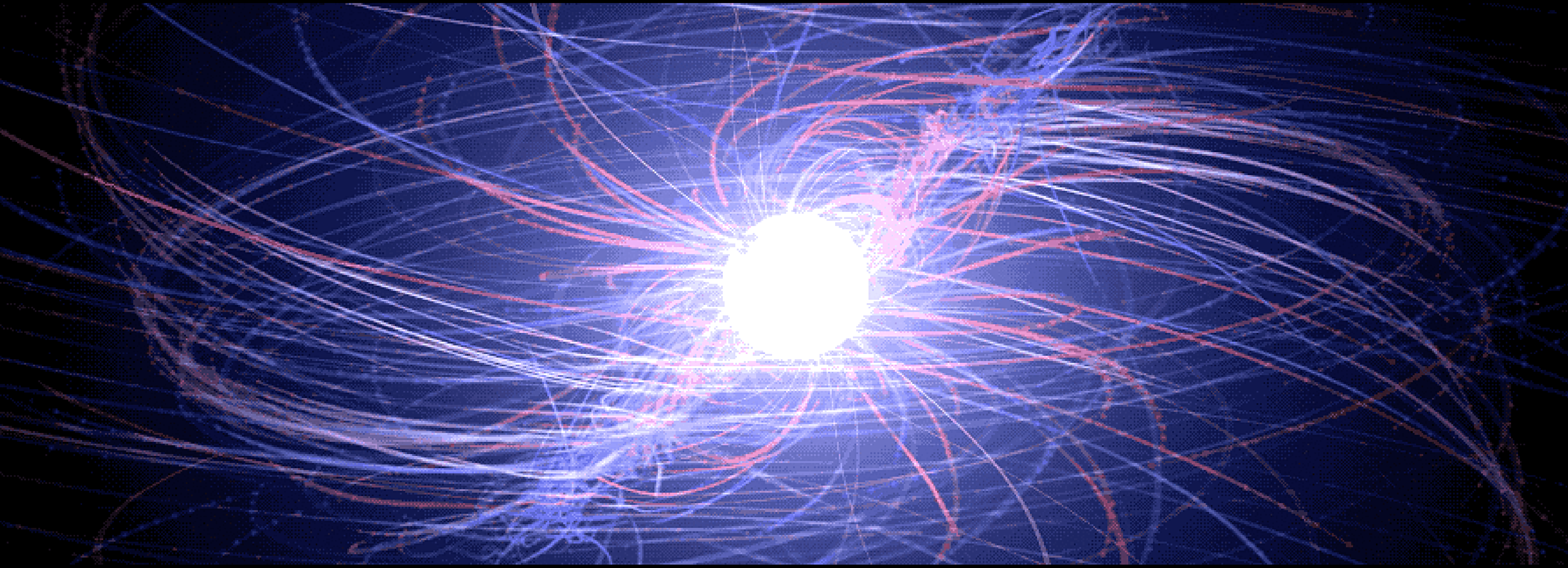
$$L_{\mathrm{KN},p} = \lambda L_{\mathrm{KN},b} = 4\times10^{35}\eta_{G,-1}\epsilon_{\mathrm{UV},0}^{-2}\lambda_2$$



Cyclotron-self-Compton
- Counter-streaming beams on OG
- Outward beam: Doppler-boosted cyclotron emission (high M_+~10^6 - 10^7)
- Inward beam: ICS on cyclotron photons

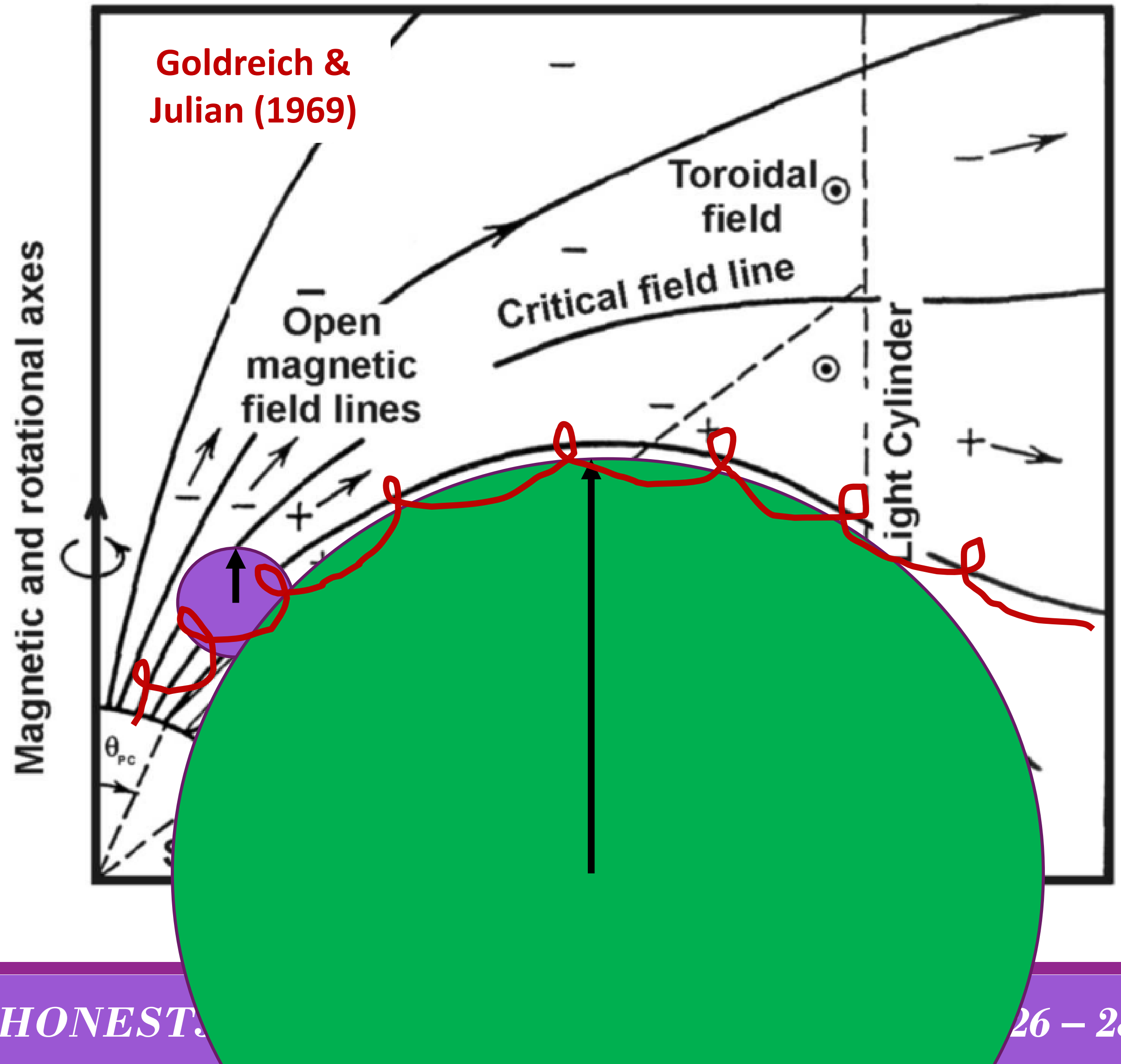
Separatrix / CS Model

https://www.nasa.gov/feature/goddard/2018/pulsar-in-a-box-reveals-surprising-picture-of-a-neutron-star-s-surroundings



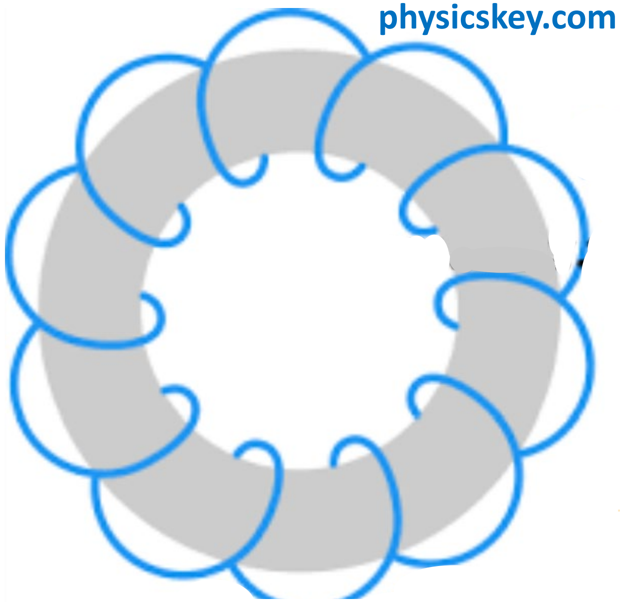
Synchro-Curvature Radiation

Cf. talk by Viganò



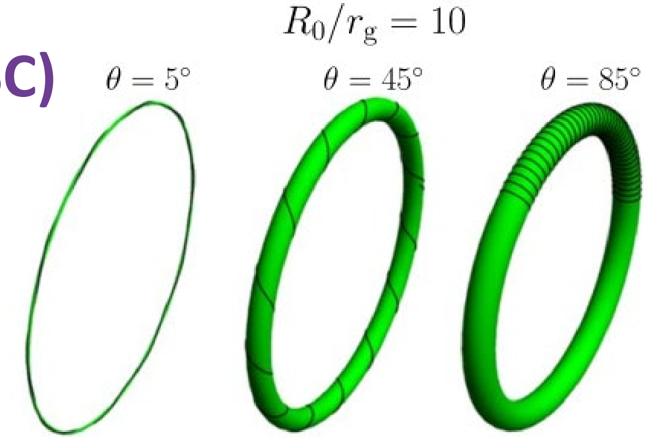
- Perpendicular: SR
- Parallel: CR

Synchro-curvature (SC)



Cheng & Zhang (1996)

Kalapotharakos et al. (2023)



Cerutti et al. (2016)

$$F_\nu(\nu) = \frac{\sqrt{3}e^3\tilde{B}_\perp}{m_e c^2}\left(\frac{\nu}{\nu_c}\right)\int_{\nu/\nu_c}^{+\infty} K_{5/3}(x)dx$$

$$\tilde{B}_\perp = \sqrt{(\mathbf{E}+\boldsymbol{\beta}\times\mathbf{B})^2 - (\boldsymbol{\beta}\cdot\mathbf{E})^2}.$$

$$\nu_c = \frac{3e\tilde{B}_\perp\gamma^2}{4\pi m_e c}$$

Synchro-Curvature Radiation

- **Encapsulates 2 limits: CR, SR**
- **“Magnetic brehmsstrahlung”**

Cheng & Zhang (1996)
Zhang, Xia & Yang (2000)
Kelner & Aharonian (2012)
Prosekin, Kelner & Aharonian (2013)
Kelner et al. (2015)
Viganò et al. (2015)
Cerutti et al. (2016)
Torres (2018)
Íñiguez-Pascual et al. (2022a,b)

Cutoff energy:

$$E_{\rm CR} = \frac{3\hbar c\gamma^3}{2\rho_c} \;\Rightarrow\; E_c(\Gamma, r_c, r_{\rm gyr}, \alpha) = \frac{3}{2}\hbar c Q_2 \Gamma^3$$

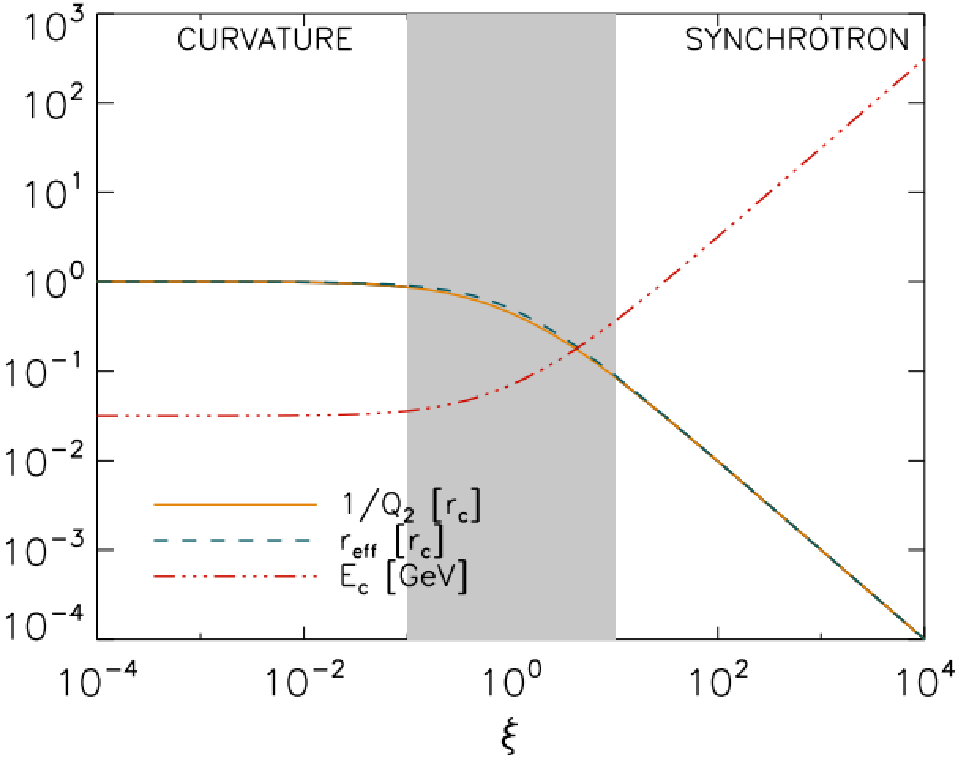
$$\xi = \frac{r_c}{r_{\rm gyr}} \frac{\sin^2\alpha}{\cos^2\alpha} \qquad Q_2^2 = \frac{\cos^4\alpha}{r_c^2}\left[1 + 3\xi + \xi^2 + \frac{r_{\rm gyr}}{r_c}\right]$$

Total power:

$$g_r = \frac{r_c^2}{r_{\rm eff}^2} \frac{[1 + 7(r_{\rm eff} Q_2)^{-2}]}{8(Q_2 r_{\rm eff})^{-1}}$$

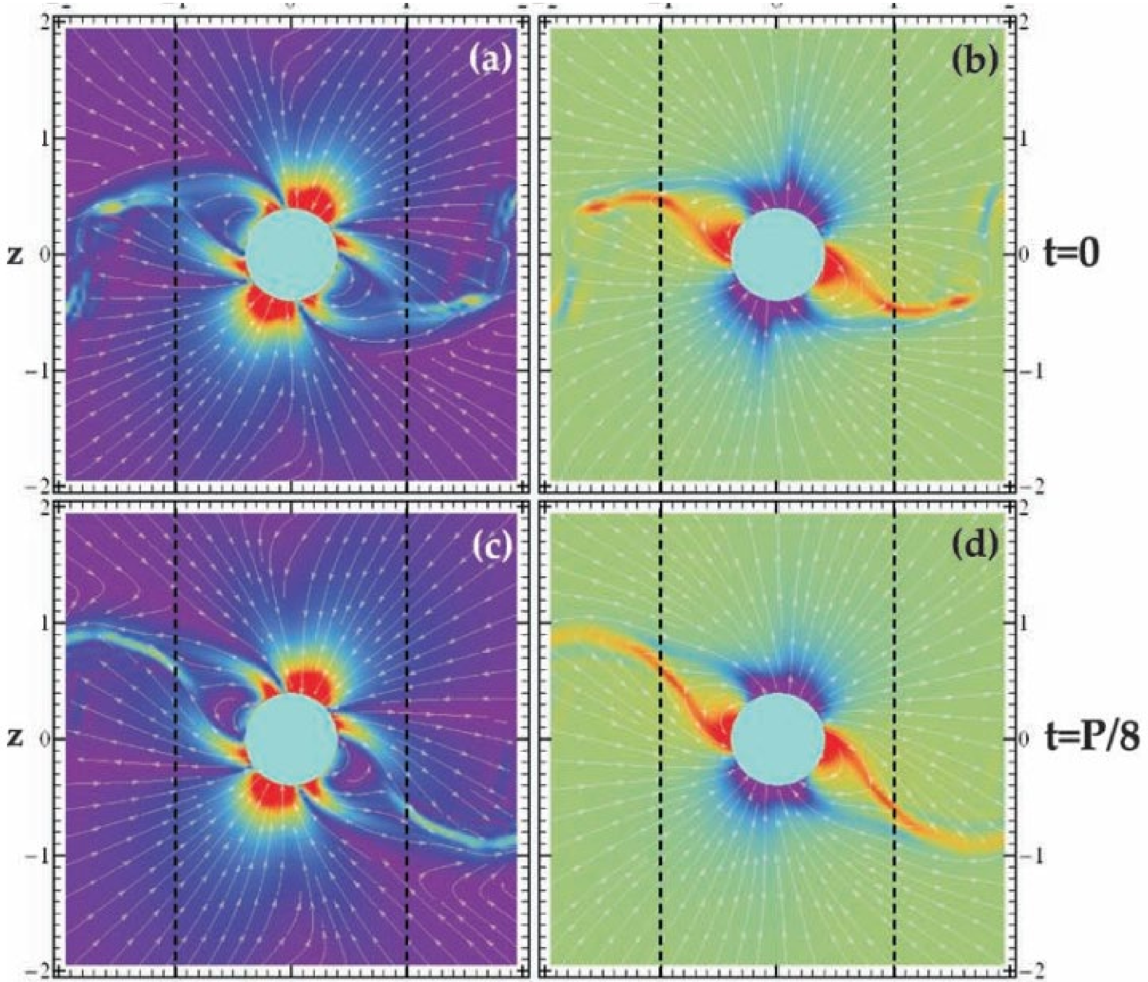
$$\int \left(\frac{dP}{dE}\right)_{\rm CR} dE = -\frac{2e^2 c\gamma^4}{3\rho_c^2} \;\Rightarrow\; P_{\rm sc} = \frac{2(Ze)^2\Gamma^4 c}{3r_c^2} g_r$$

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

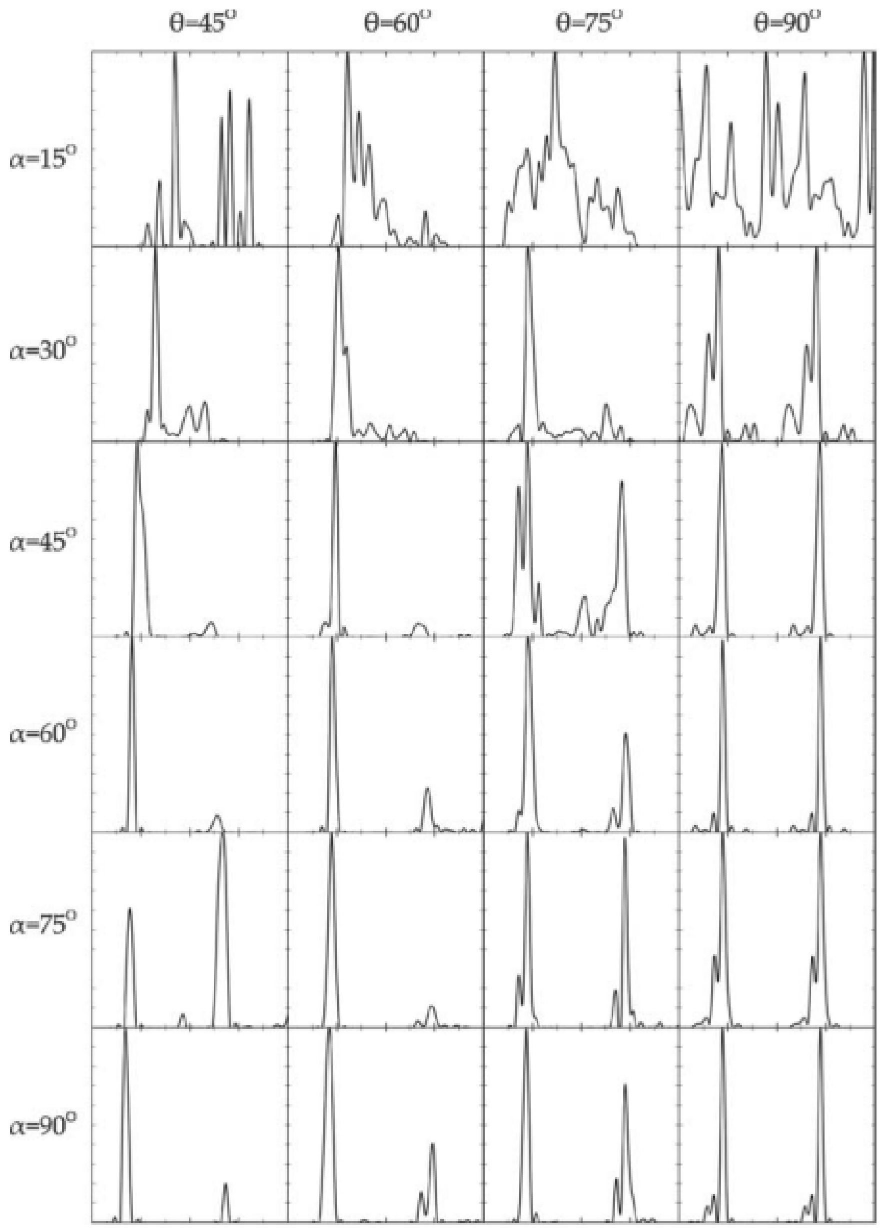


Curvature Radiation from the CS

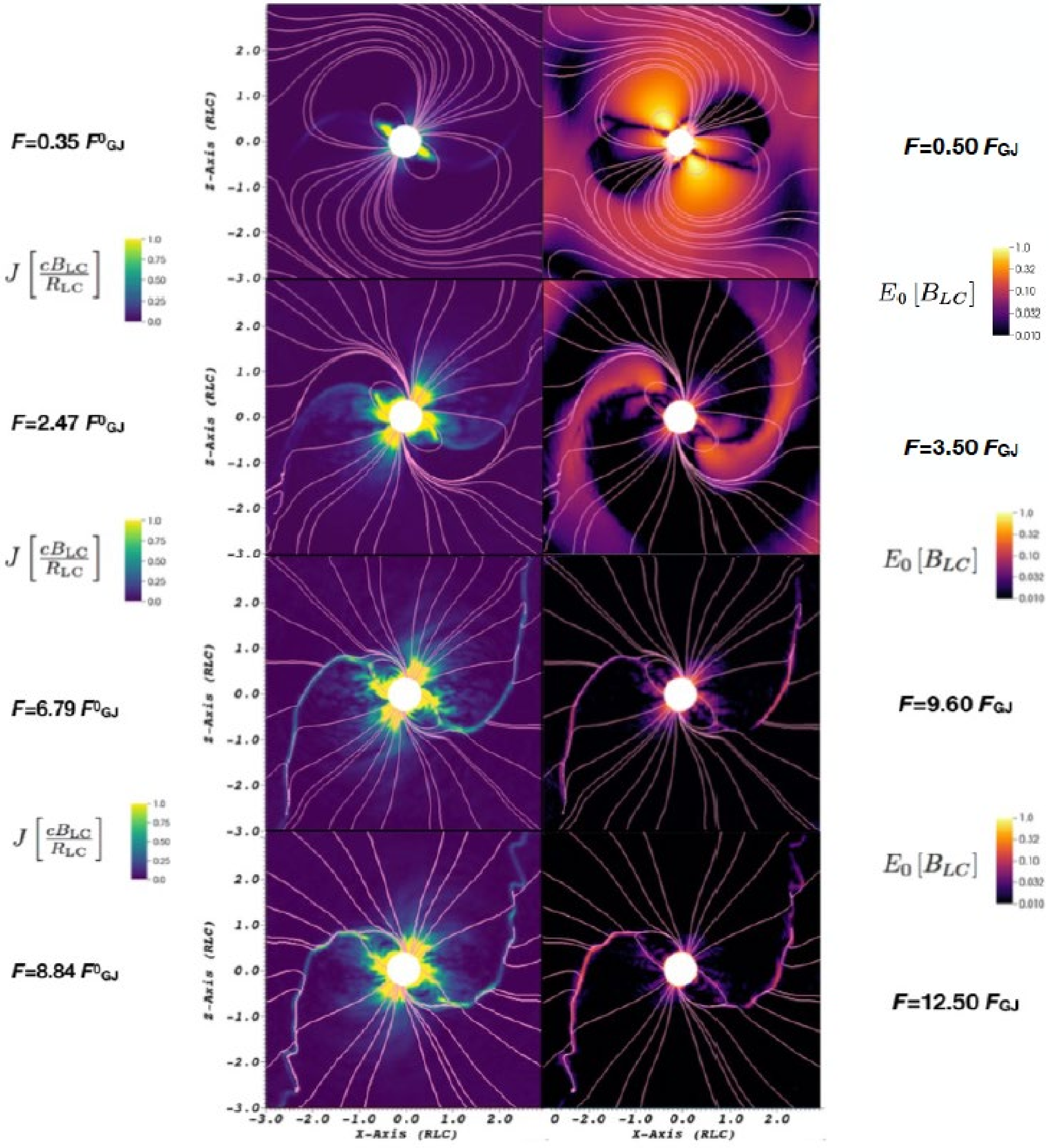
- Force-free MHD simulations indicated strong currents at tip of closed field line region and into CS
- CR from relativistic electrons / positrons in CS



Contopoulos & Kalapotharakos (2010)



Global PIC Models



Chen & Belodorodov (2014)
Philippov & Spitkovsky (2014, 2018)
Cerutti et al. (2016)
Kalapotharakos et al. (2018, 2023)
Brambilla et al. (2018)

- Most dissipation takes place near separatrix and CS
- *E*-field shrinks to CS as injection rate increases
- Scaling up of $B < 10^6$ G and $\gamma < 10^3$ [or hybrid models]

Cf. talks by Philippov, Cerutti, etc.

Credit: AK Harding

Fundamental Plane

1) Radiation-Reaction Limit Regime

2) At the ECS near the LC

CR

Kalapotharakos et al.

$R_C \propto R_{LC} \propto P$

$E_{BLC} B_{LC} \lessapprox \gamma_L^4 R_C^{-2}$

$\rho_{GJ} \propto B_* P^{-1}$

$\dot{\mathcal{E}} \propto B_*^2 P^{-4}$

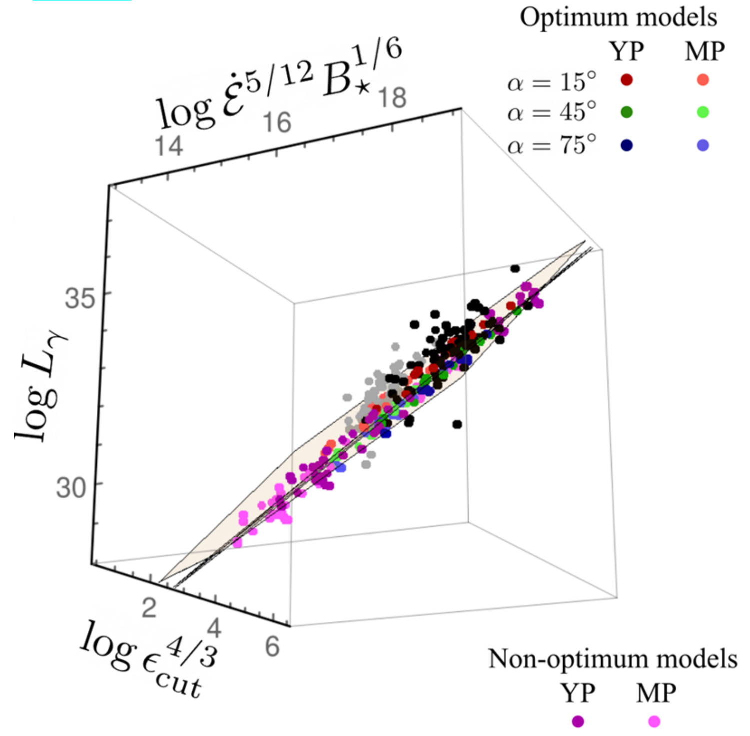
$B_{LC} \propto B_* R_{LC}^{-3} \propto B_* P^{-3}$

$E_{BLC} \propto \epsilon_{cut}^{4/3} P^{7/3} B_*^{-1}$

$\gamma_L \propto \epsilon_{cut}^{1/3} P^{1/3}$

$L_{\gamma 1} \propto \epsilon_{cut}^{4/3} P^{-2/3}$

$$L_\gamma \propto \epsilon_{cut}^{4/3} B_*^{1/6} \dot{\mathcal{E}}^{5/12}$$

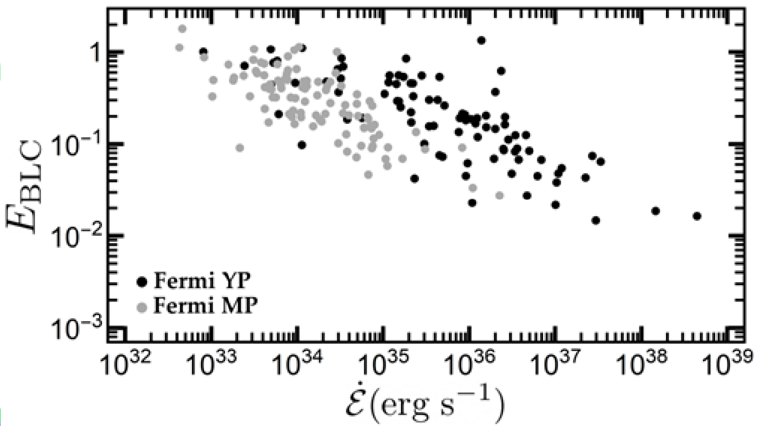


$R_C \propto r_g \propto \gamma_L B_*^{-1} P^3$

$$L_\gamma \propto \epsilon_{cut} \dot{\mathcal{E}}$$

SR

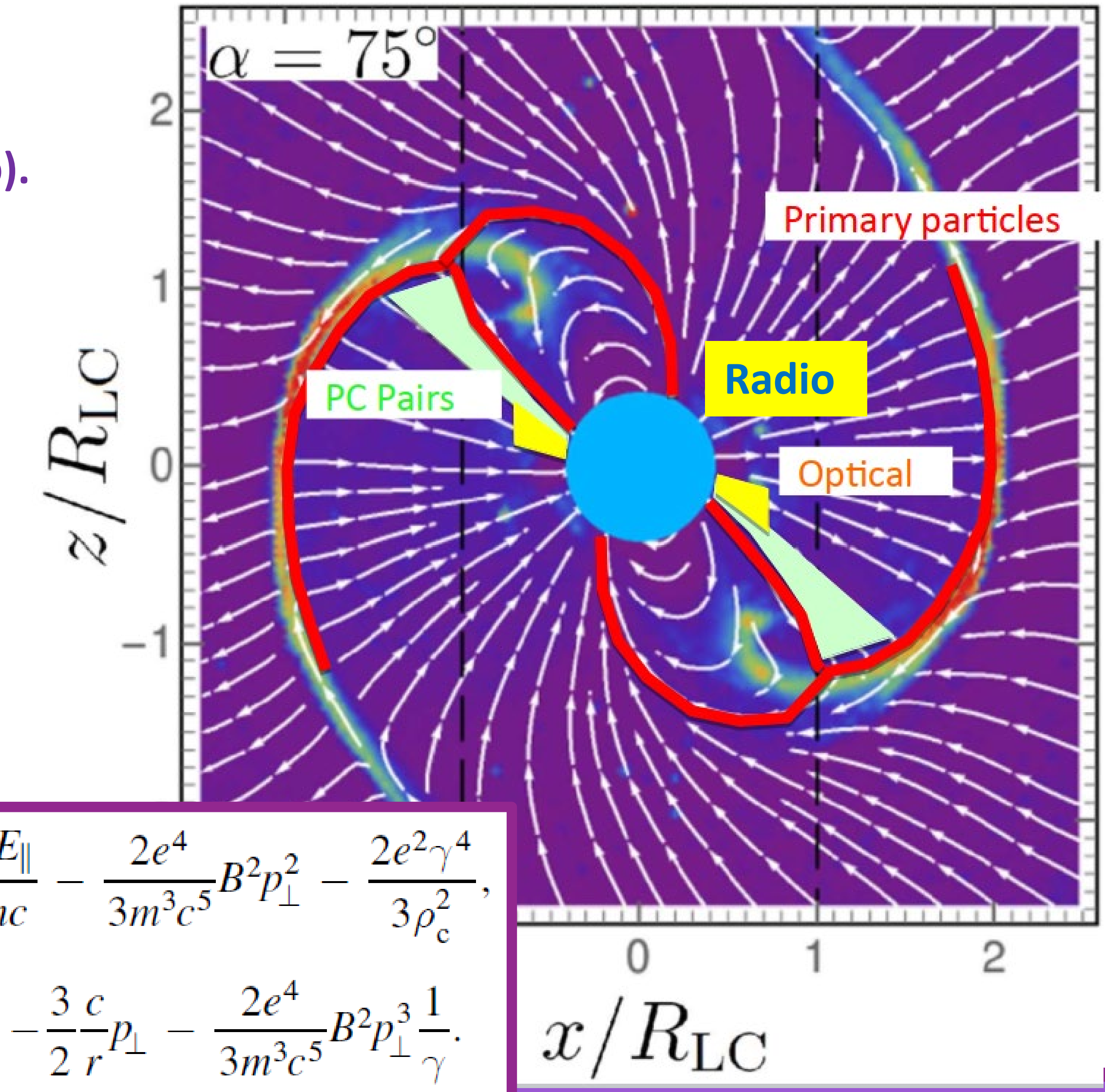
Kalapotharakos et al. (2019, 2022, 2023)



Separatrix / CS Emission Model

- Force-free magnetosphere.
- Primaries (γ_{inj}~ 10^2) from PC; pairs (γ_e ~ 10^5) from cascade in offset-PC *B*-field (Harding & Muslimov 2011a,b).
- Primaries accelerated only near separatrix and predominantly in CS (out to $r = 2R_{LC}$) assuming a constant or two-step *E*-field (reaching γ_e ~ 10^7).
- No pair acceleration. Free primary / pair multiplicities M_+. Injection at ϕ_{PC} where $J/J_{GJ} < 0$.
- Empirical radio core / cone model. Resonant cyclotron absorption of radio photons by pairs (cf. Lyubarski & Petrova 1998).
- Solve particle dynamics in observer frame.
- SC (CR+SR), ICS, SSC radiation mechanisms.

Harding & Kalapotharakos (2015), Harding et al. (2018, 2021)



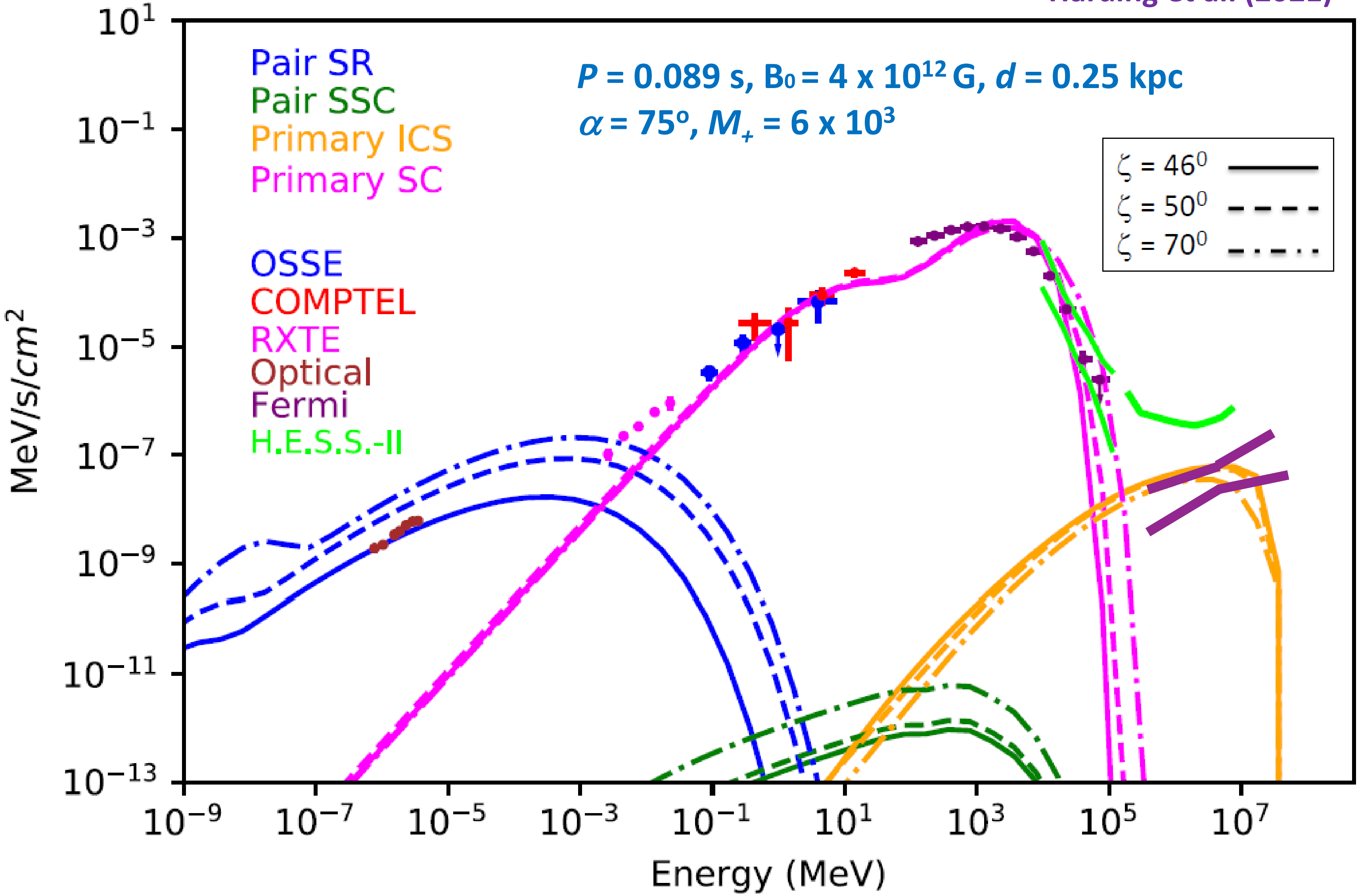
$$\frac{d\gamma}{dt} = \frac{eE_{\parallel}}{mc} - \frac{2e^4}{3m^3c^5}B^2p_{\perp}^2 - \frac{2e^2\gamma^4}{3\rho_c^2},$$

$$\frac{dp_{\perp}}{dt} = -\frac{3}{2}\frac{c}{r}p_{\perp} - \frac{2e^4}{3m^3c^5}B^2p_{\perp}^3\frac{1}{\gamma}.$$

Results: Vela Spectrum

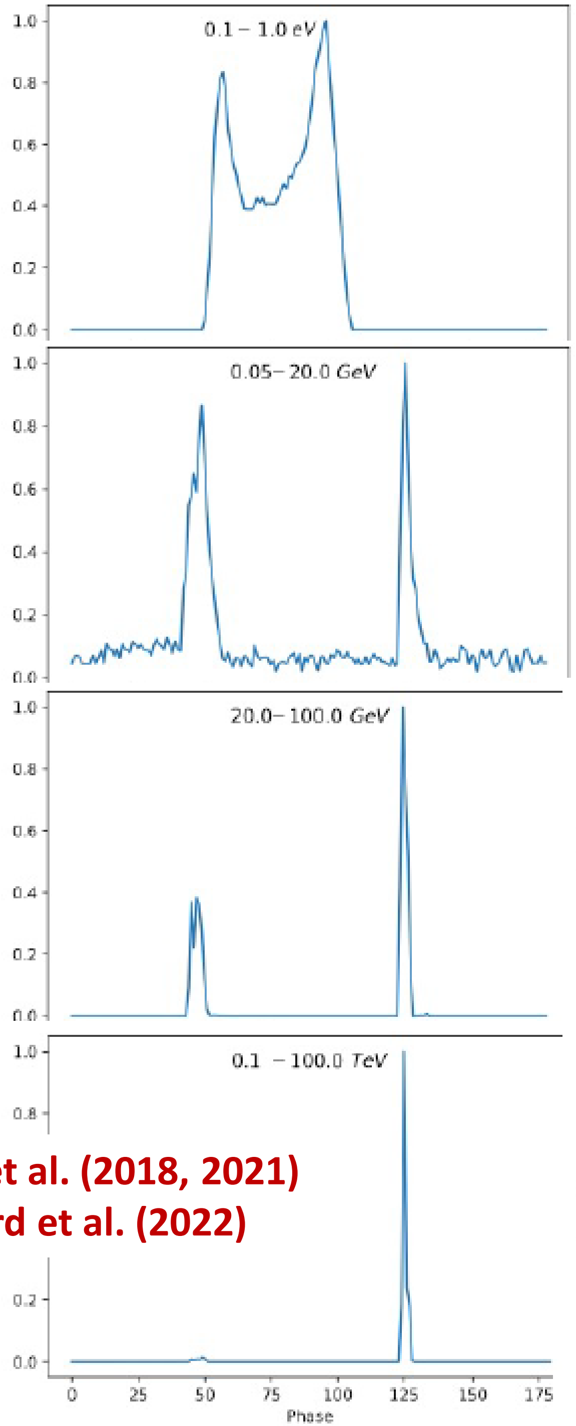
- Detectable primary ICS component around 10 TeV
- Low-energy SR can boost primary ICS (T limit)
- Difference in offset-dipolar field influences primary ICS
- Pair SR matches optical data
- 10 – 100 MeV dip: More *E*-field variation needed
- TeV emission requires high γ_{max}, pointing to CR in GeV band

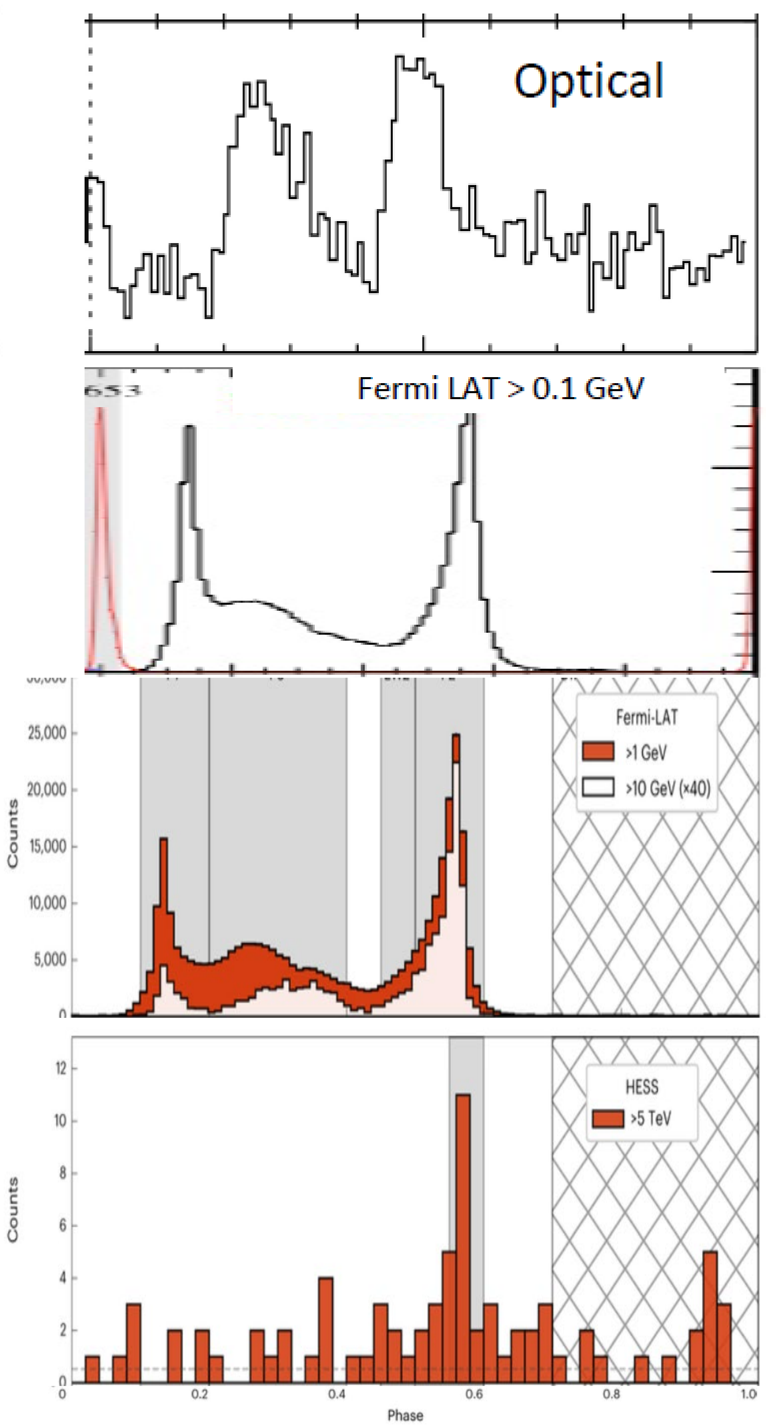
Harding et al. (2021)



Results: Vela LCs

- Reasonable multi-wavelength LC predictions
- P1/P2 vs E_γ effect: higher-energy photons in P2 – larger ρ_c
- Only P2 in TeV: highest-energy particles responsible
- Narrowing of peaks with energy
- $E_{||}(\phi)$ leading to azimuthally-dependent emissivity improves radio-to-γ lags

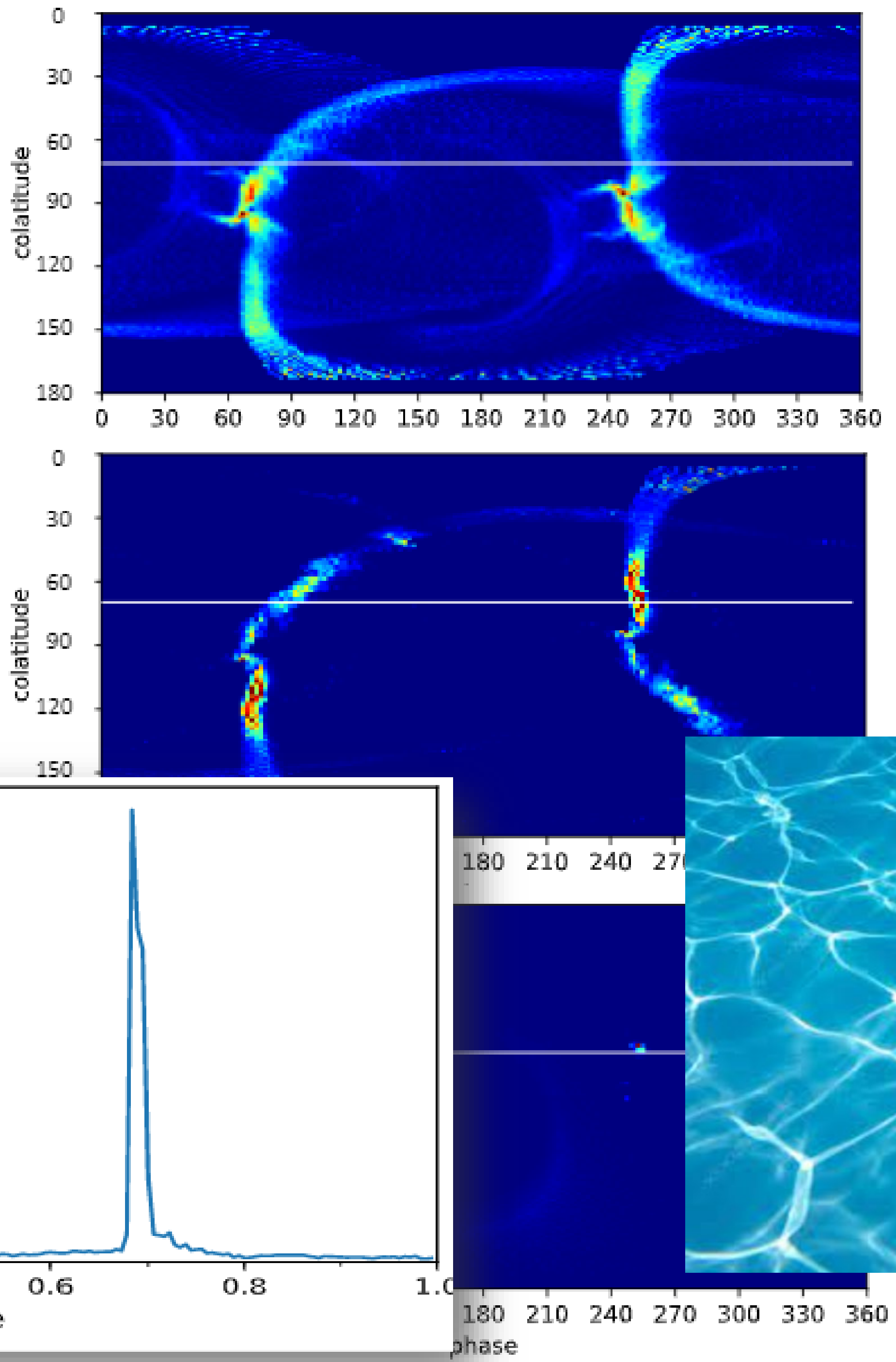


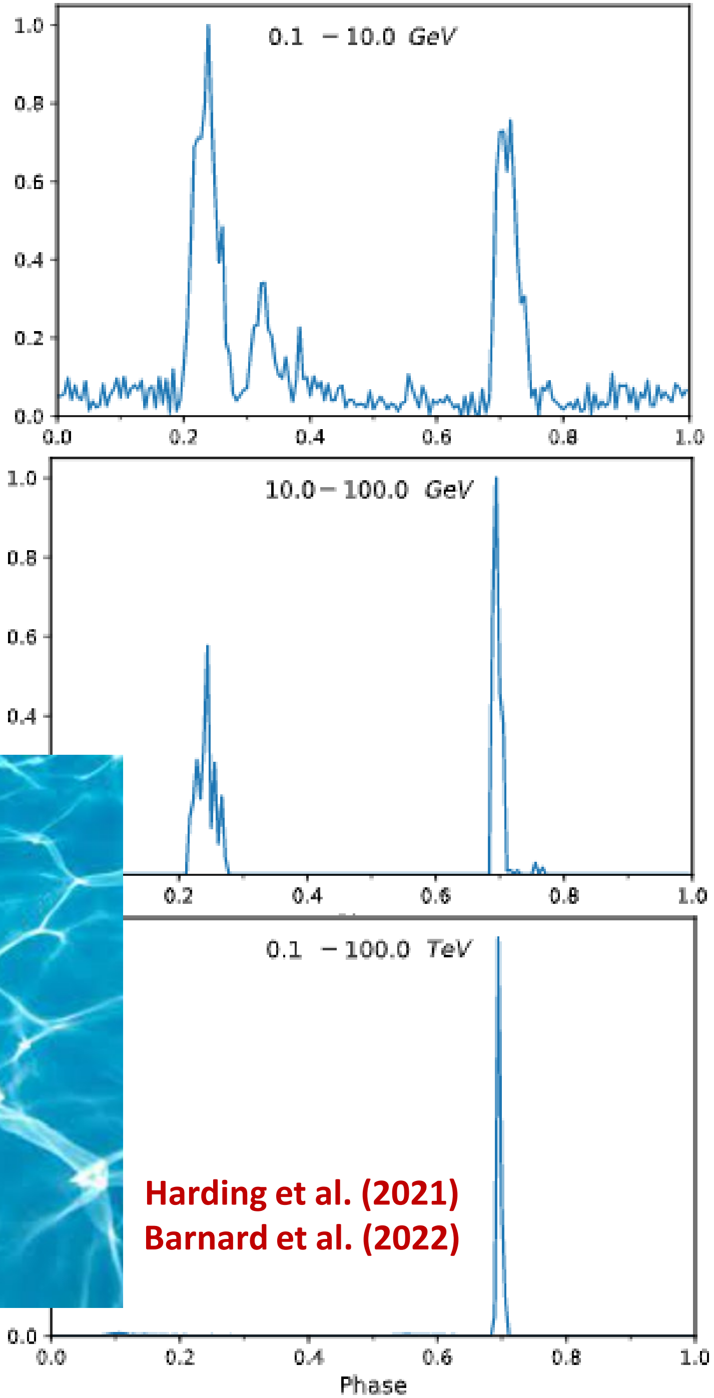


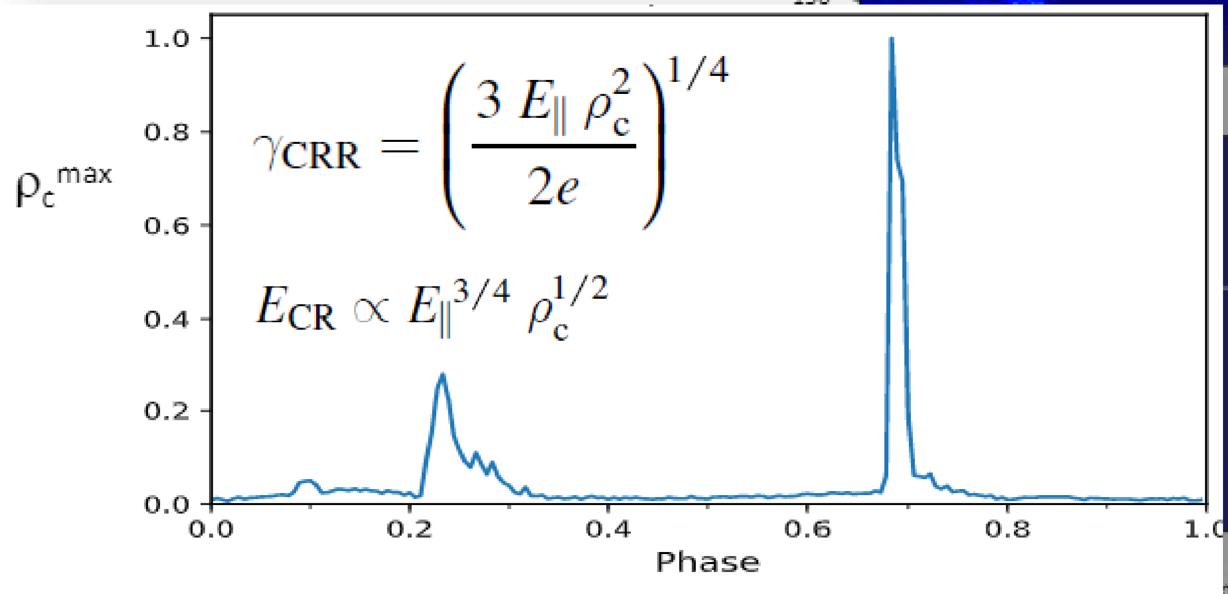
Harding et al. (2018, 2021)
Barnard et al. (2022)

Results: Vela LCs

- **P1/P2 vs E_γ effect: higher-energy photons in P2 – larger ρ_c (near CS)**
- **Narrowing of peaks vs E_γ**





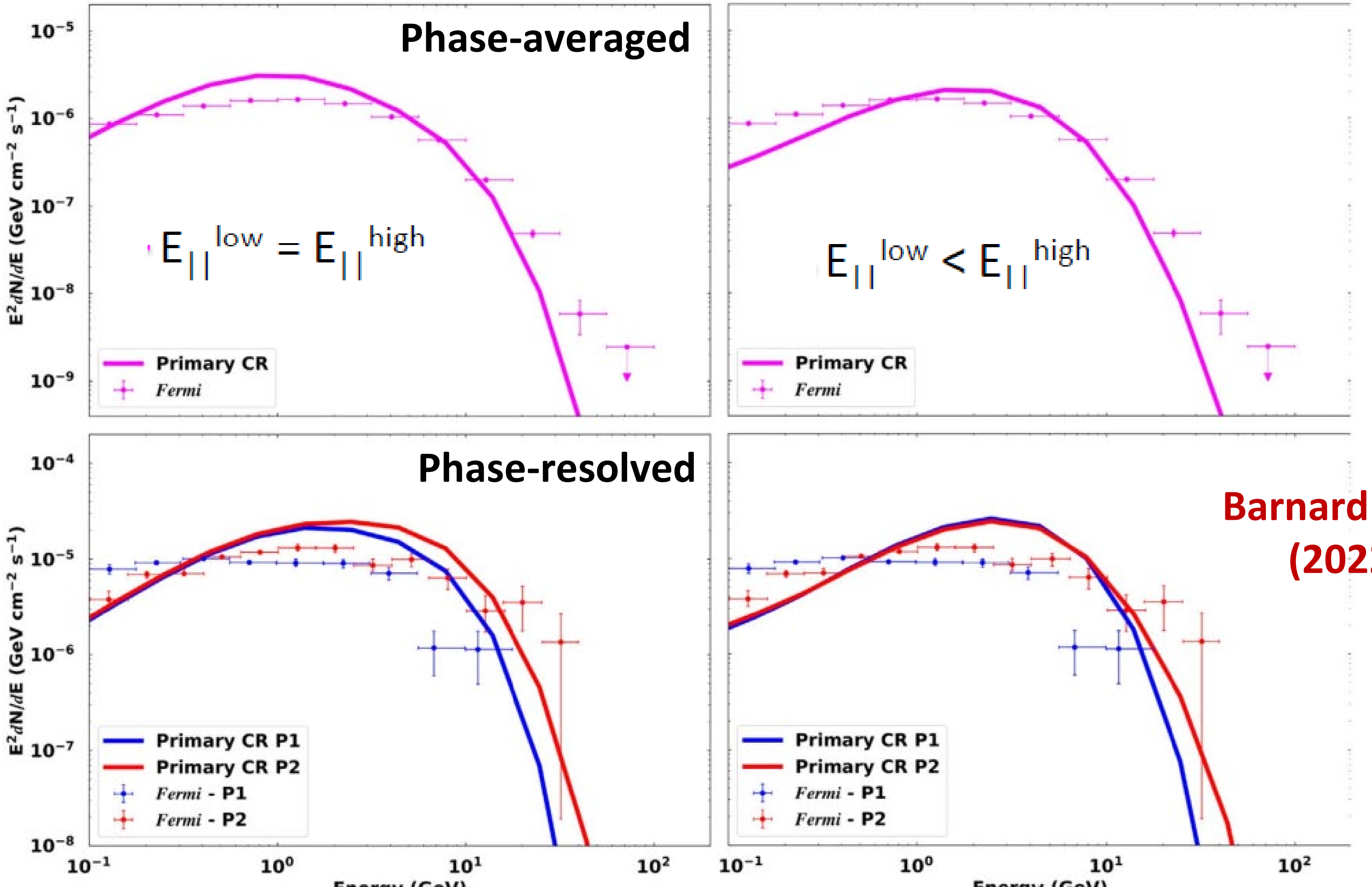


Harding et al. (2021)
Barnard et al. (2022)

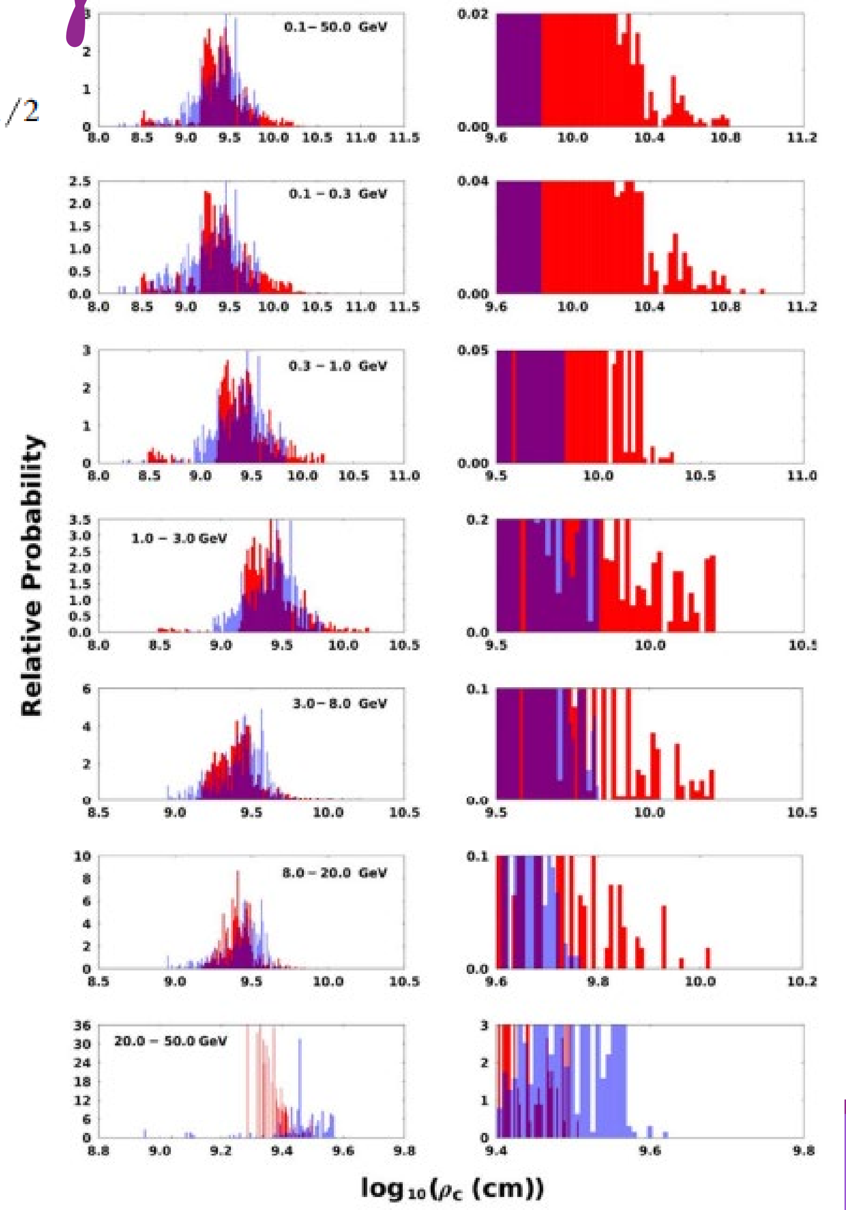
P1/P2 vs E_γ

- Curvature radiation-reaction limit
- P2 systematically larger ρ_c

$$E_{\gamma,\mathrm{CR}} \sim 4\left(\frac{E_\parallel}{10^4\ \mathrm{statvolt\ cm^{-1}}}\right)^{3/4}\left(\frac{\rho_c}{10^8\ \mathrm{cm}}\right)^{1/2}$$



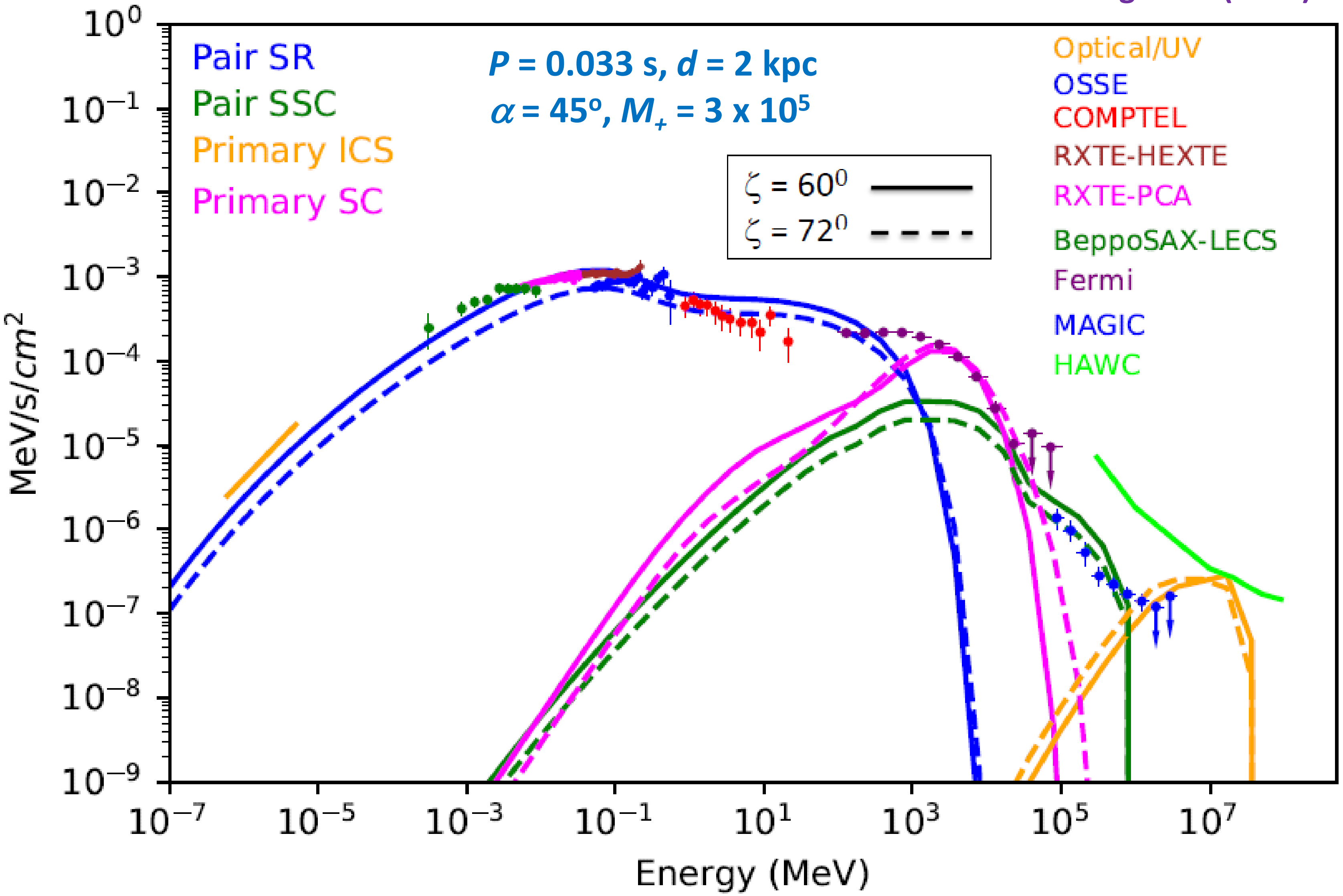
Barnard et al. (2022)



Results: Crab Spectrum

- PL extension of pair spectrum
- Constant pair pitch angle
- Higher number of pairs
- Higher pair SR flux
- SSC from pairs up to 1 TeV matches MAGIC data
- Primary IC up to ~20 TeV
- Photon-photon pair production

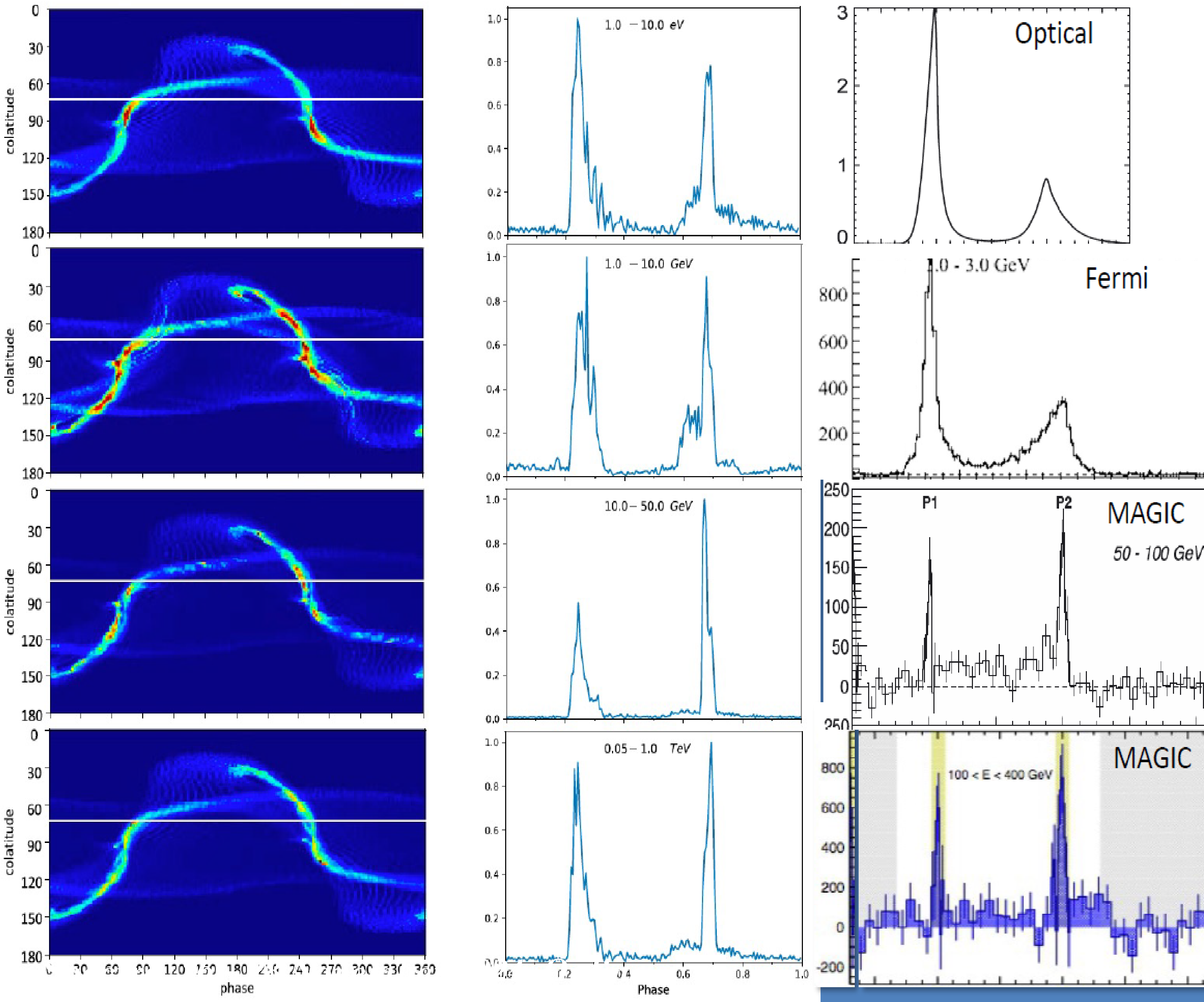
Harding et al. (2021)



Results: Crab LCs

- Gamma-ray and radio / optical peaks are phase-aligned
- Both gamma peaks survive up to highest energies
- High-altitude emission region near / in CS
- Slow P1/P2 evolution

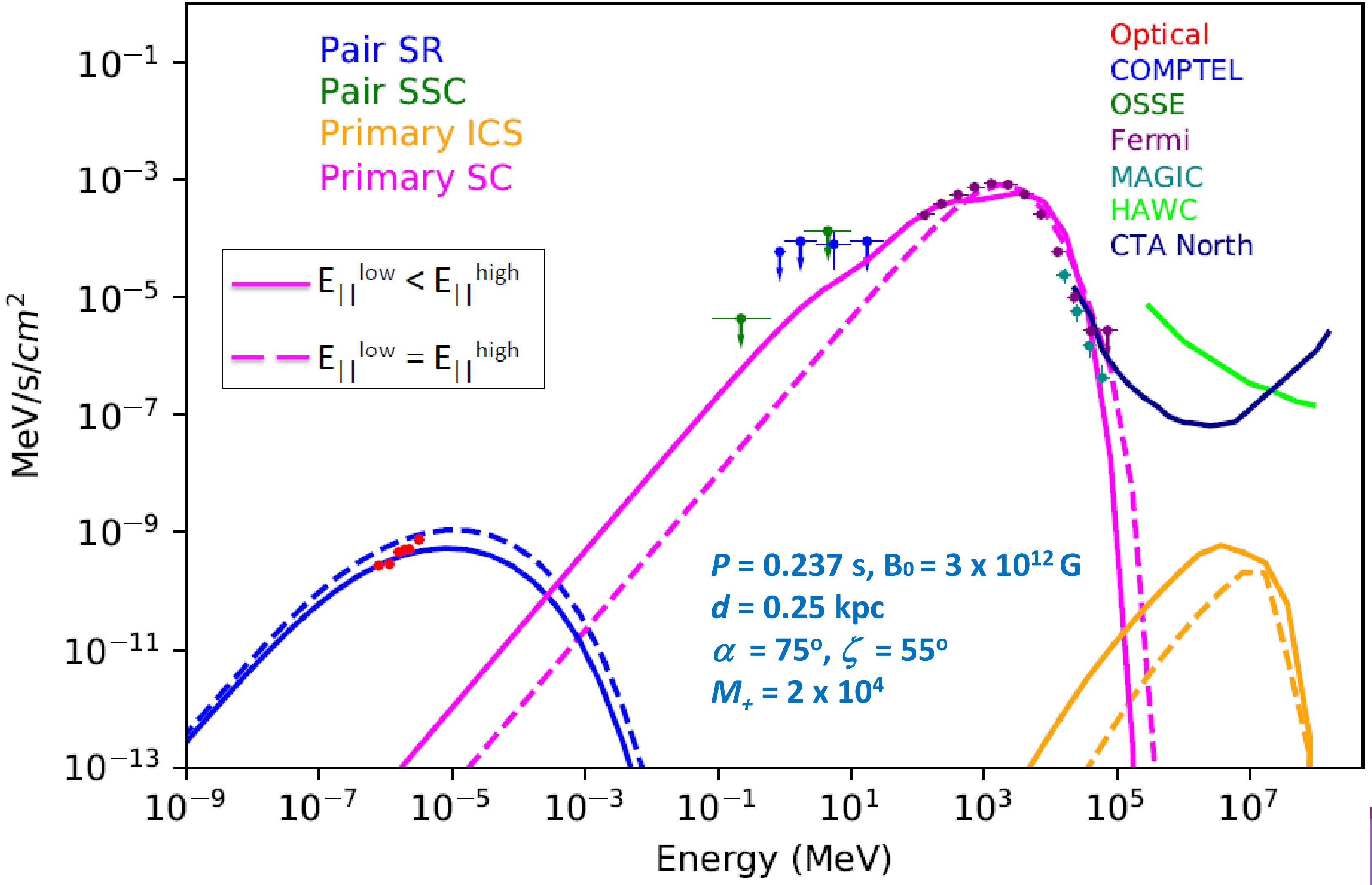
Harding et al. (2021)



Results: Geminga Spectrum

- Assuming a radio flux of 1000 mJy
- Leads to pair SR that can account for UV data
- *E*-field assumption impacts primary SC spectrum
- Larger *P*, larger R_{LC}
- Low pair SR flux (compared to Vela) leads to low IC flux prediction
- MAGIC detection: primary SC

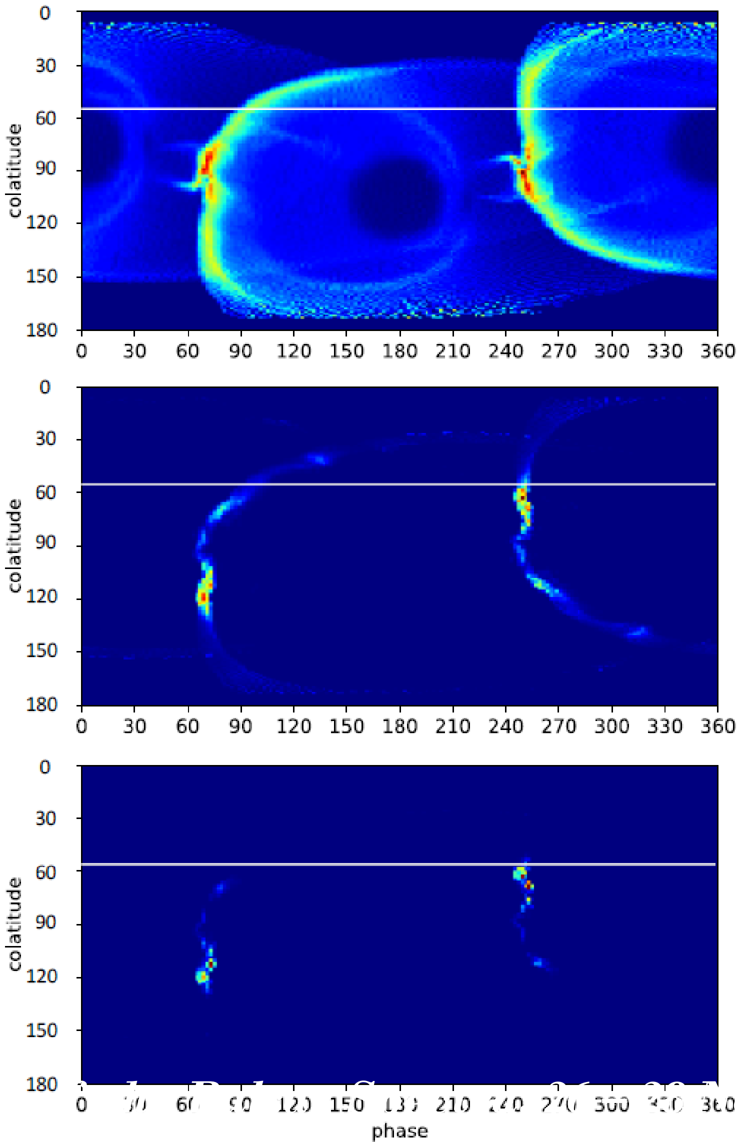
Harding et al. (2021)

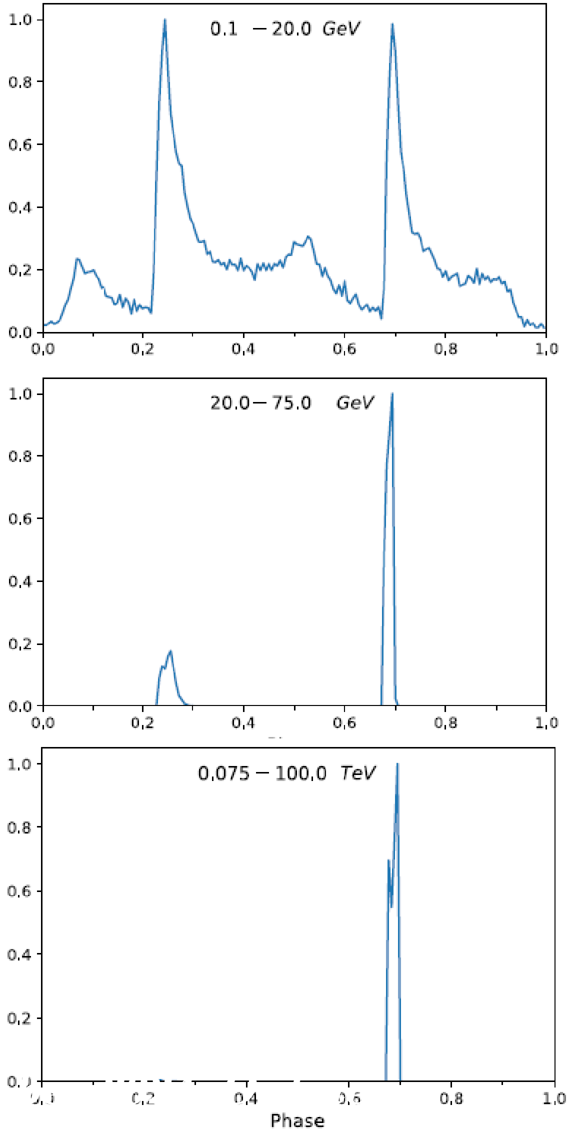


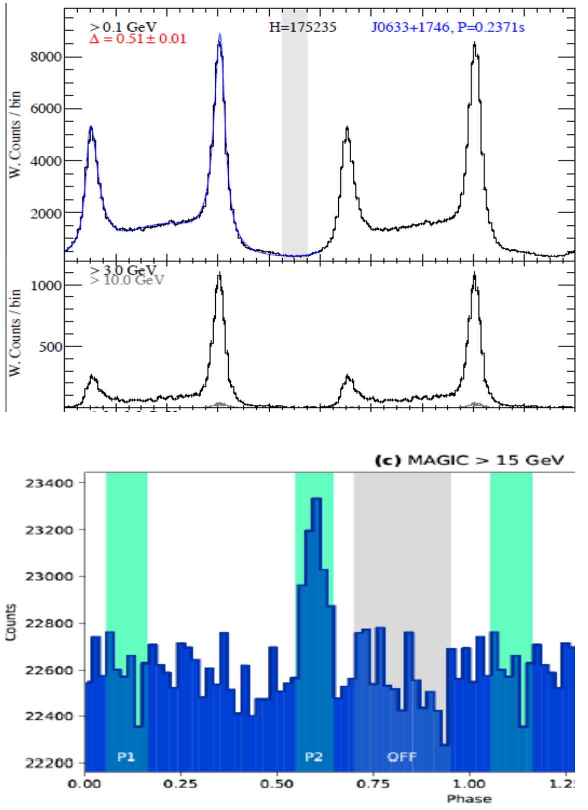
Results: Geminga LCs

- P1 disappears with energy
- Observed peak width reduction not as pronounced as predicted by the model

Harding et al. (2021)

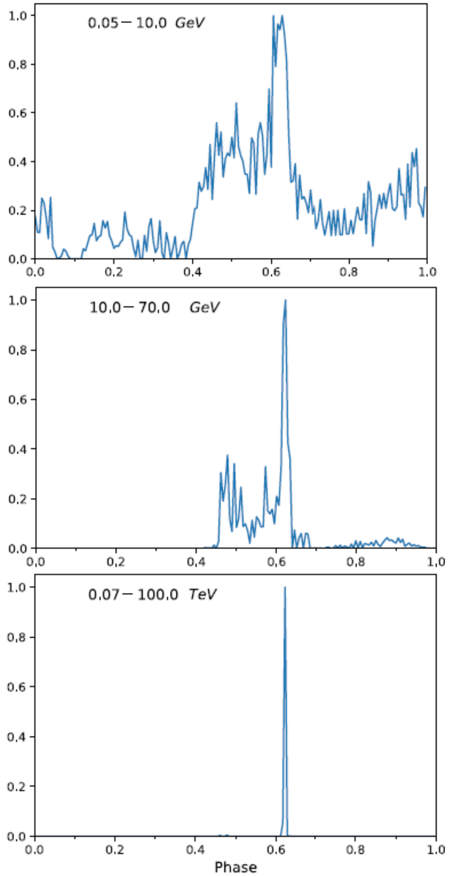




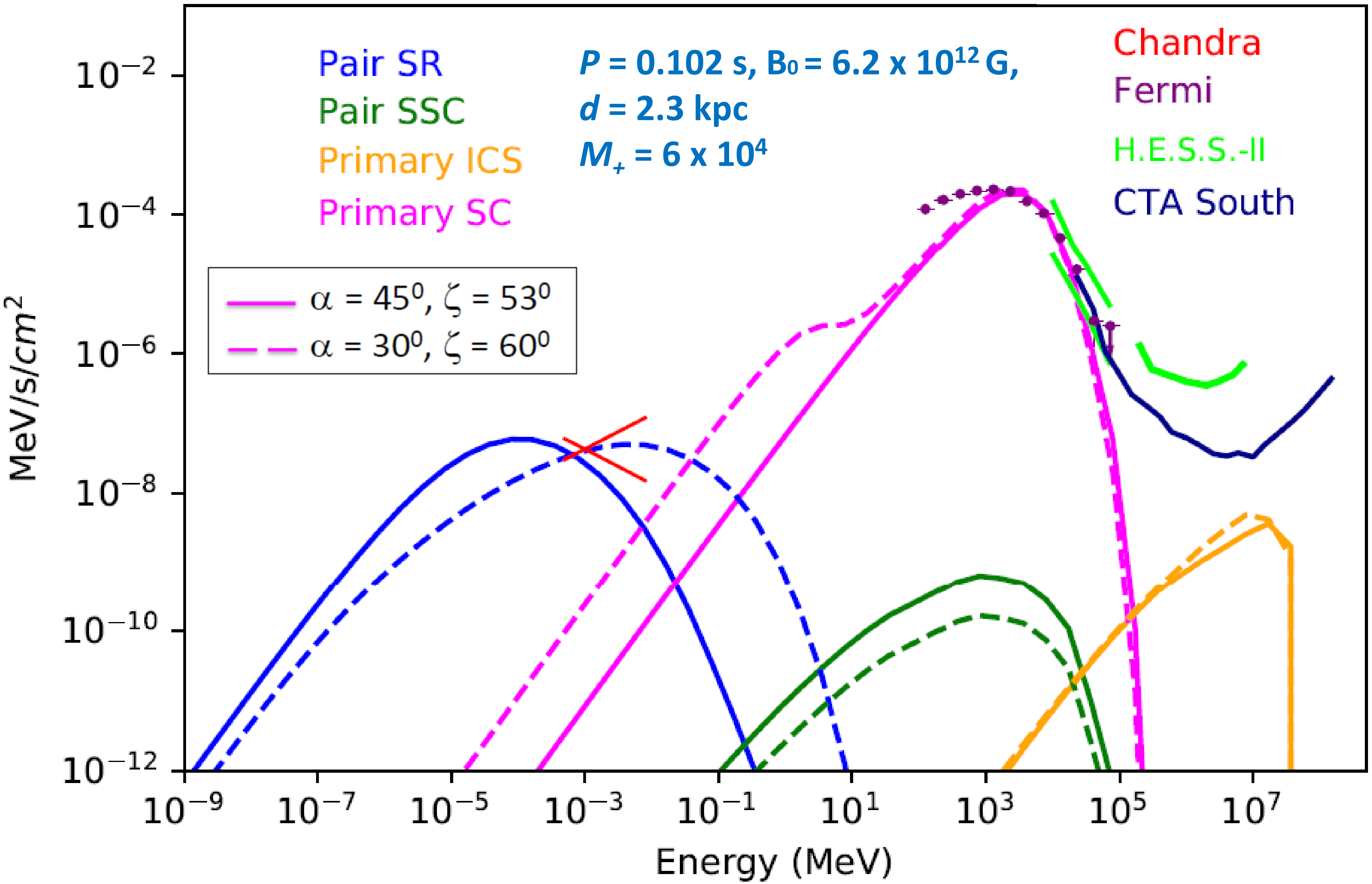


Results: B1706-44

- Lower radio luminosity
- Lower pair SR
- Lower primary IC
- H.E.S.S. data: primary SC

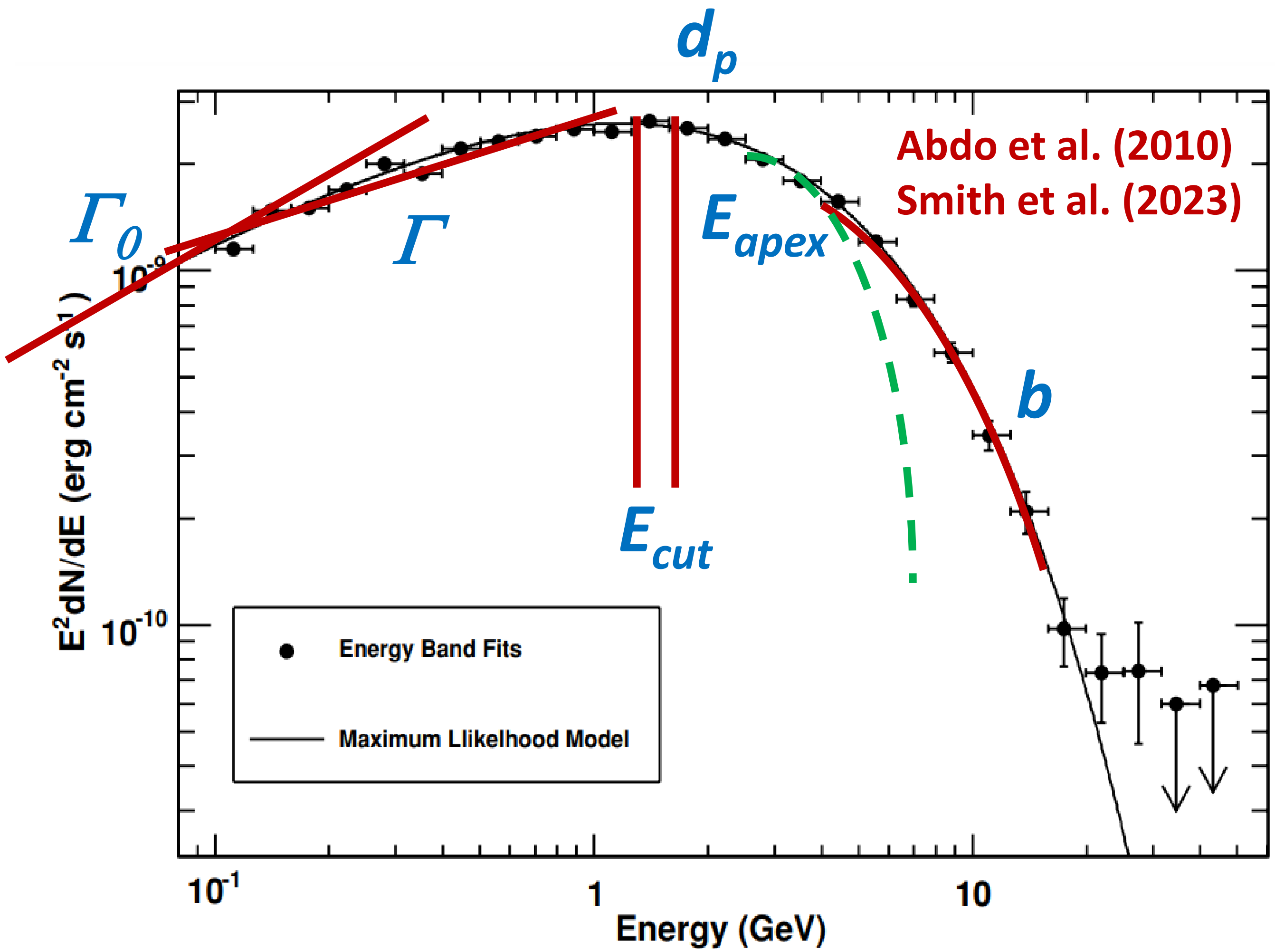


Harding et al. (2021)



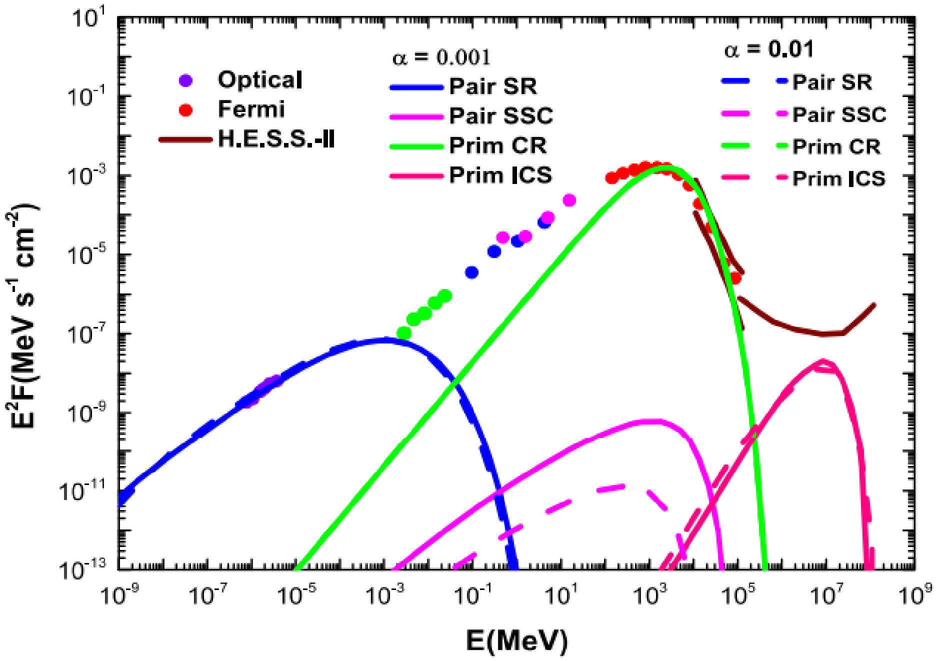
Criticisms / Questions?

- High γ implied. Which framework? Cf. talks by Djannati-Ataï, Philippov, Cerutti, etc.
- Shape of GeV tail: exponential, sub-exponential, PL?
- Do smooth particle trajectories exist in CS? What is the effective ρ_c in the CS?
- Nature of target photons?
- Acceleration? Energetics?
- Particle injection?

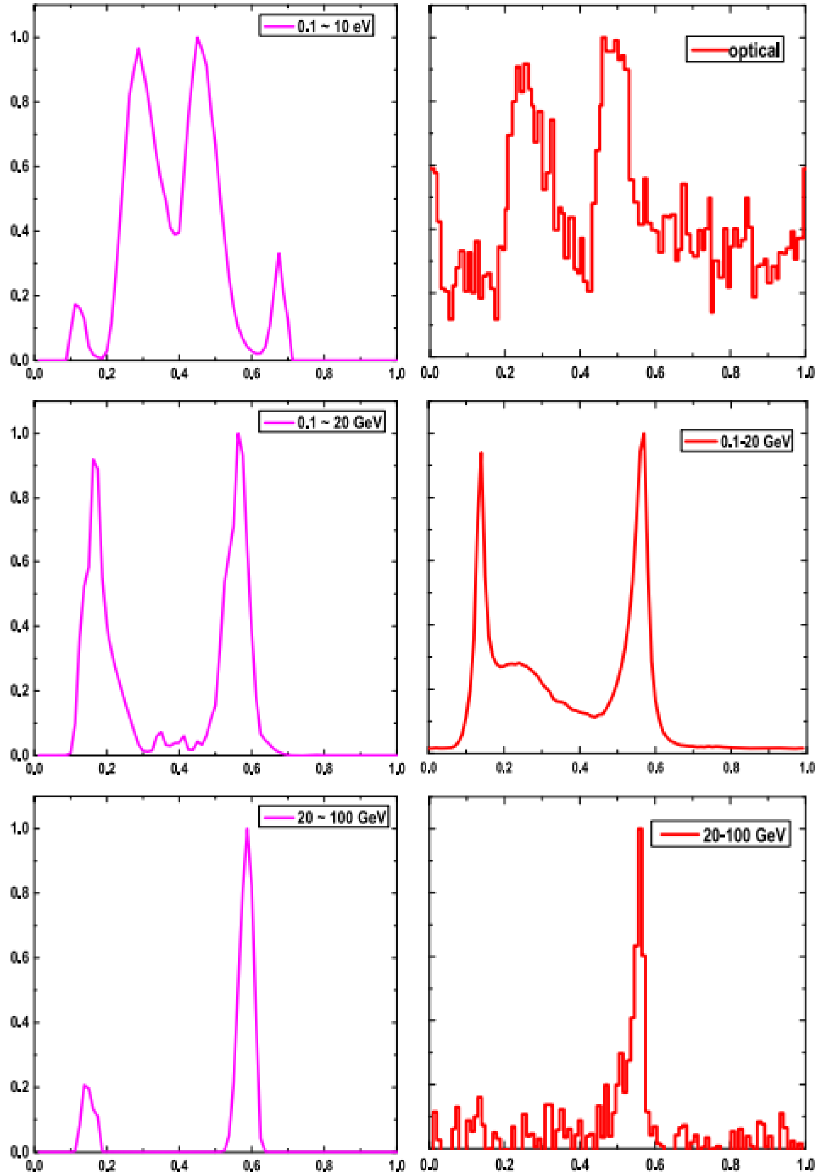


Improvements?

- Radially and azimuthally-dependent *E*-field; pitch angle α evolution
- Use light curves+spectra [phase-resolved spectroscopy] and polarisation to constrain location of acceleration / emission site(s)
- Study different particle injection / pair cascade scenarios
- Offset dipoles?
- Model discriminants?
- More than one particle population?



Yang & Cao (2024)



Conclusions

- 20 TeV pulsations from the Vela pulsar! New discoveries being made
- Convolution of particle dynamics & geometry: imprints on light curves, spectra, polarisation
- Unprecedented constraints on models:
  - Energetics and emission mechanisms
  - Emission location: In CS [Large ρ_c; nature of acceleration?]
  - Field structure via ρ_c; P1/P2 vs E_γ effect; *NICER* hotspots
  - Soft photons: Emissivity profiles and spectra of UV / optical
  - Break SC degeneracies: *E*-field strength vs ρ_c

Cf. talk by Djannati-Ataï, Zanin, etc.

- Ongoing observations by current IACTs; CTA Pulsar Programme!

Thanks!

National Research Foundation | NRF | RISA | Research and Innovation Support and Advancement

This work is based on the research supported wholly/in part by the National Research Foundation (NRF) of South Africa (grant number 99072). The grant holder acknowledges that opinions, findings, and conclusions or recommendations expressed in any publication generated by the NRF supported research is that of the author(s), and that the NRF accepts no liability whatsoever in this regard.

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https://i0.wp.com/www.redorbit.com/wp-content/uploads/2016/02/vela_lg.jpg?fit=1000%2C640&ssl=1

God is higher than anything and anyone, outshining everything you can see in the skies. Who can compare with God, our God, so majestically enthroned, surveying His magnificent heavens and earth? (Psalm 113:4-6 MSG).