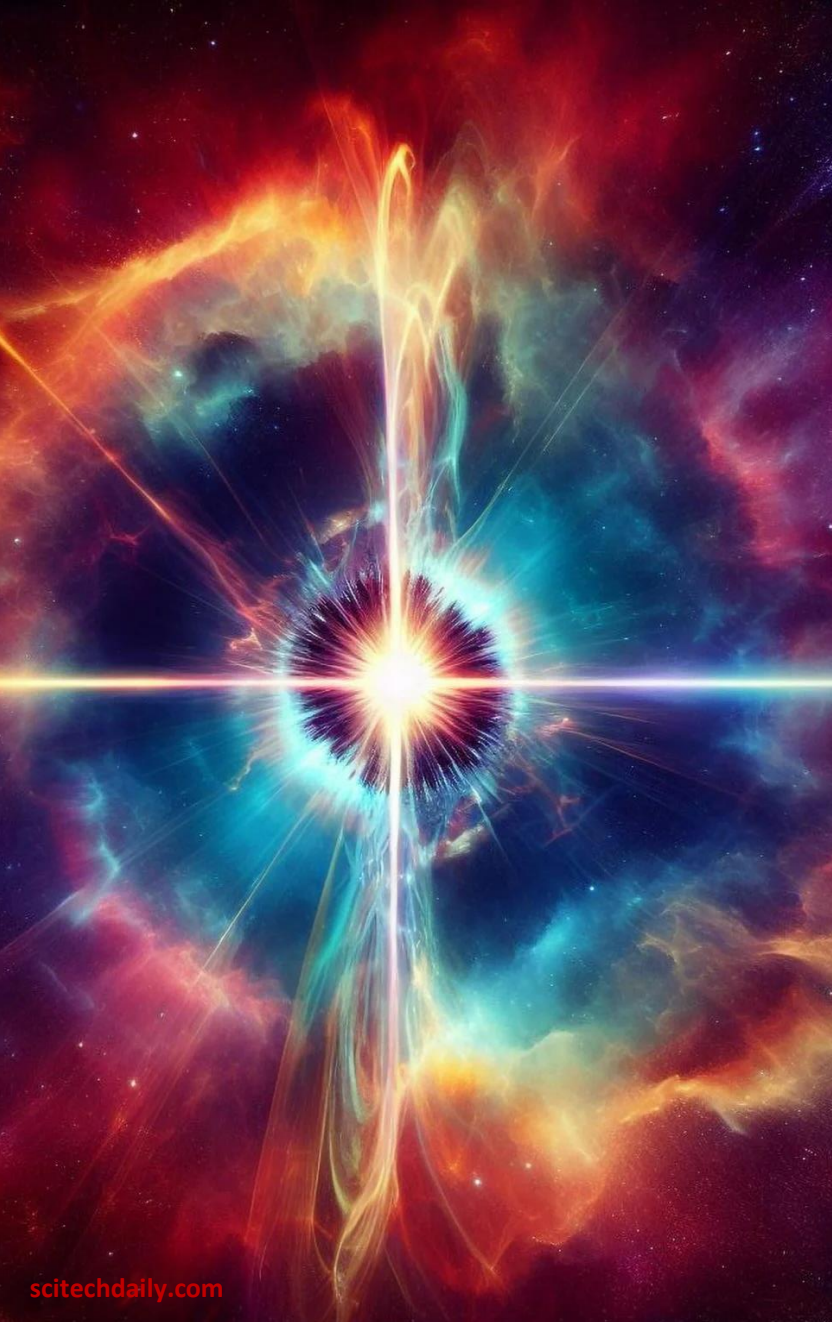




VHE Pulsar Visibility

Christo Venter^{1,2}

Alice Harding³

Constantinos Kalapotharakos⁴

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Potchefstroom, South Africa*

²*National Institute for Theoretical and Computational
Sciences (NITheCS), Potchefstroom, South Africa*

³*Theoretical Division, Los Alamos National Laboratory*

⁴*Astrophysics Science Division,
NASA Goddard Space Flight Center*





inga

$$E^2 \frac{dN}{dE dA dt} [\text{TeV cm}^{-2} \text{s}^{-1}]$$

10^{-10}

10^{-11}

10^{-12}

10^{-13}

10^{-14}

10^{-15}

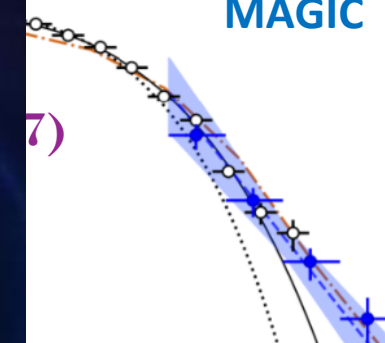
4

1

B



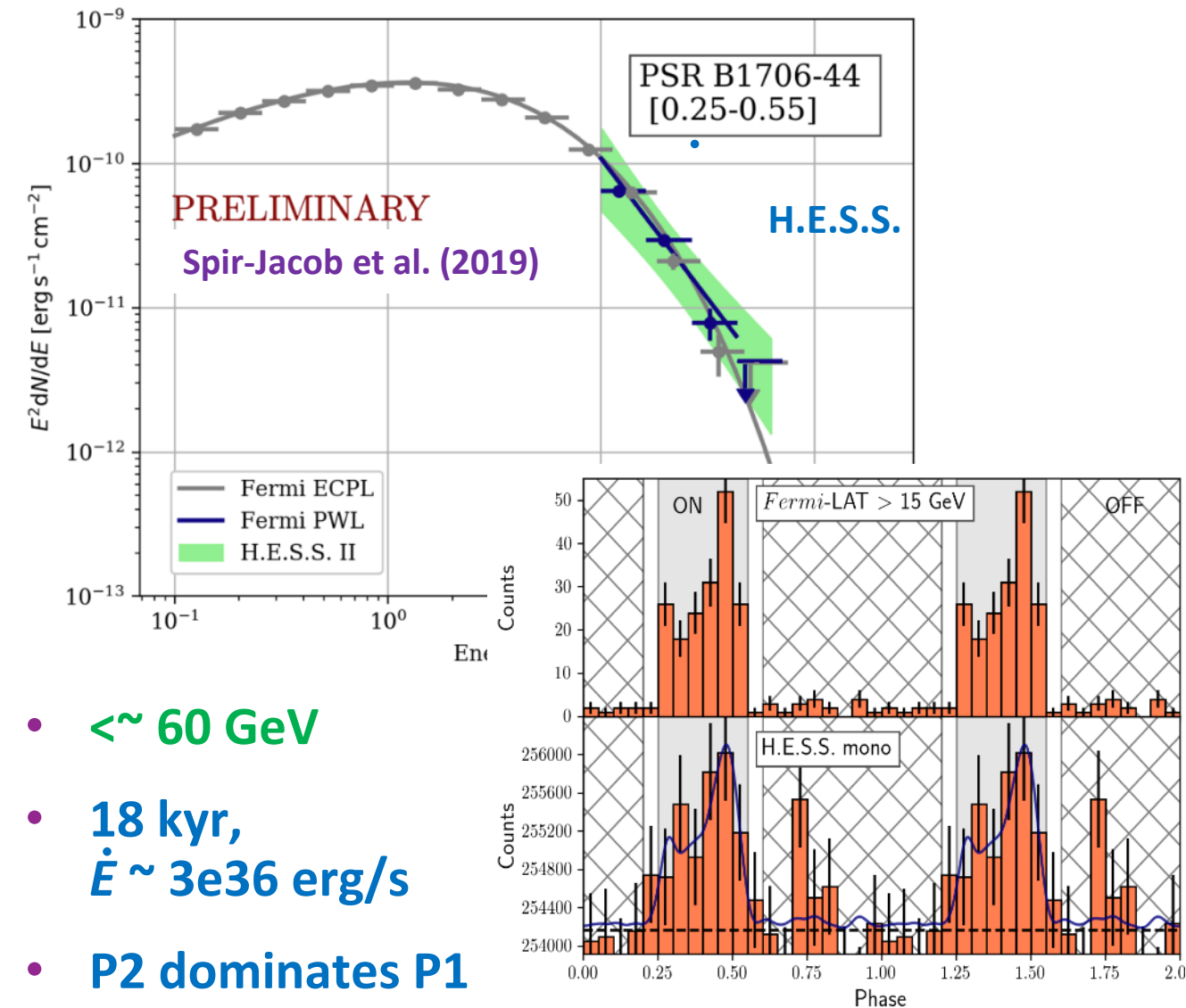
MAGIC



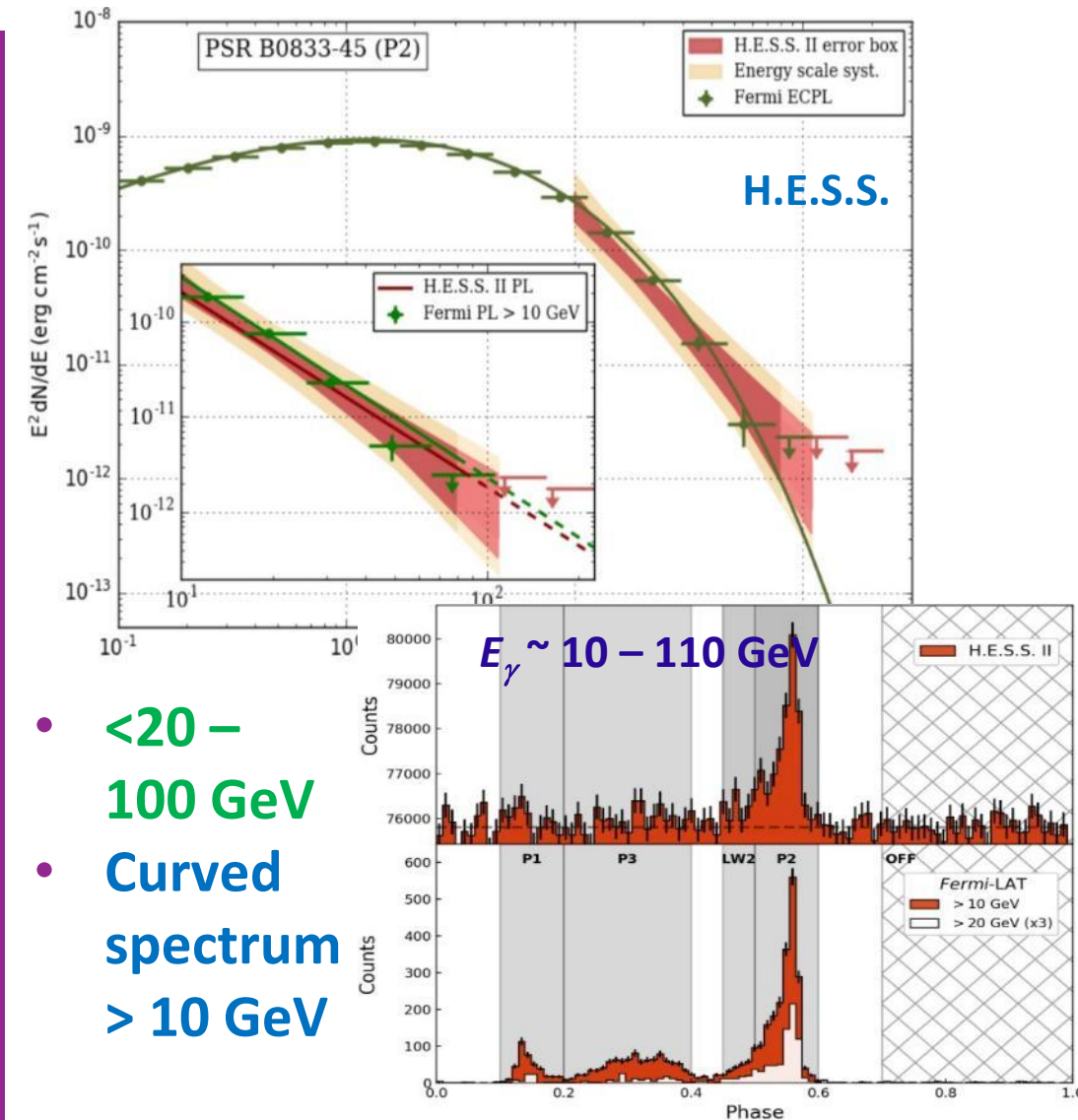
LST-1 & Fermi LAT



More Evidence: B1706-44 / Vela

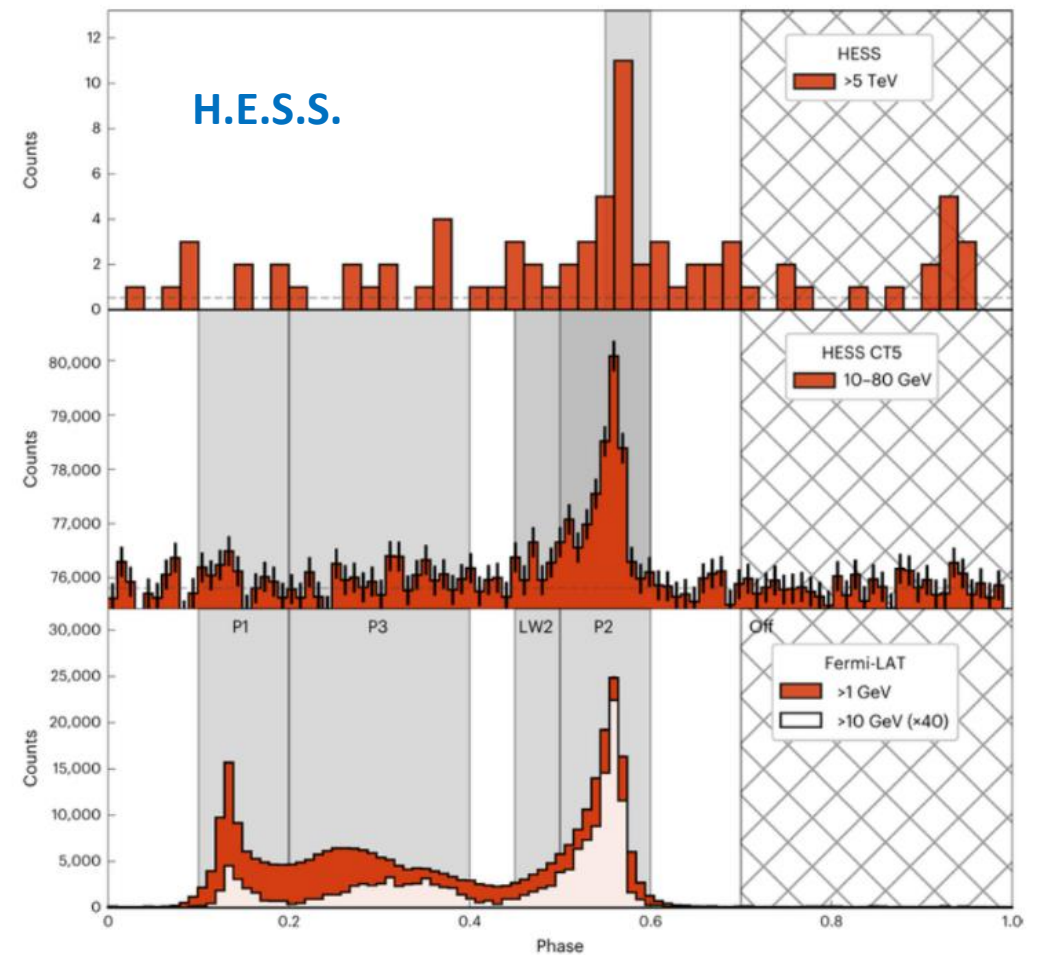
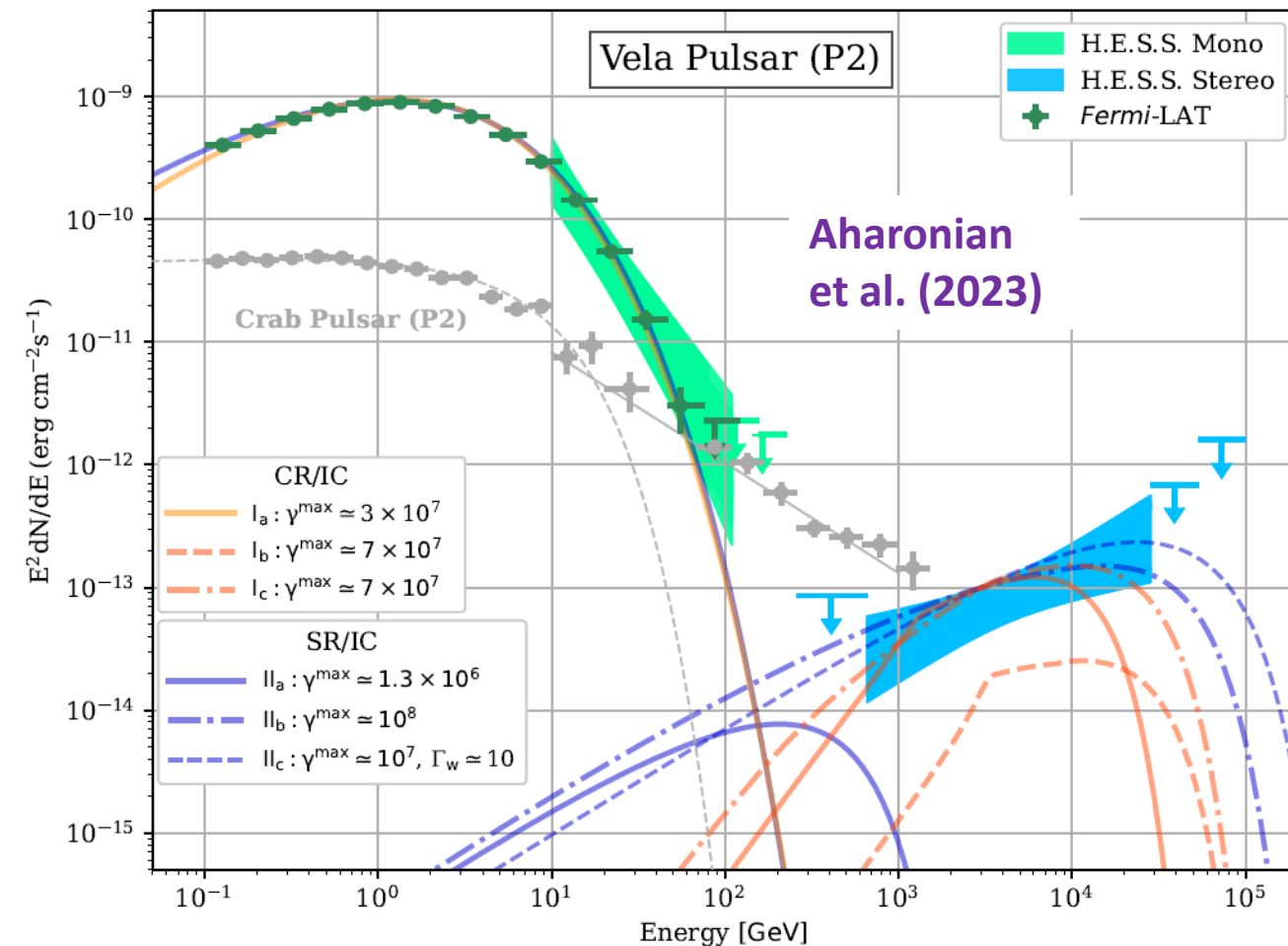


- $< \sim 60$ GeV
- 18 kyr,
 $\dot{E} \sim 3e36$ erg/s
- P2 dominates P1



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

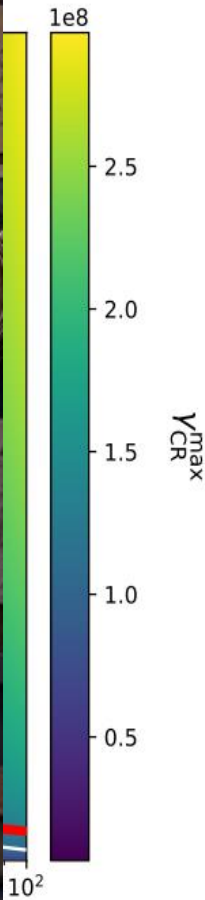
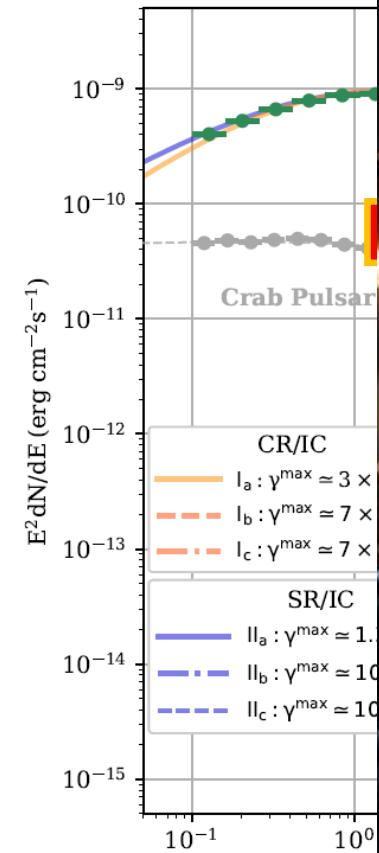
Another Clue: Vela @ 20 TeV!



- New spectral component
- Hard index

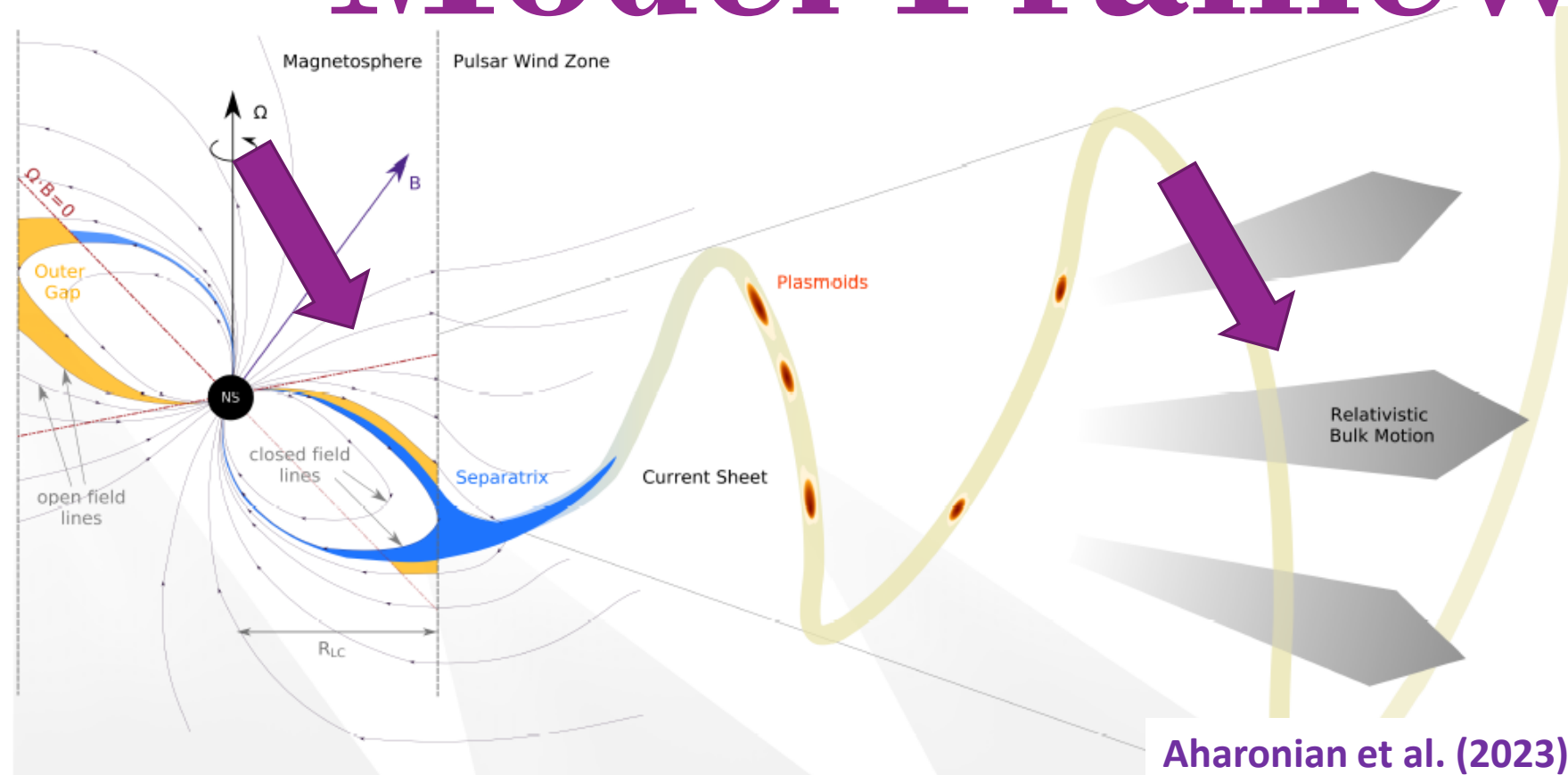
- P2 remains at VHE
- Similar P2 peak position & width in HE / VHE

E



- New spectra
- Hard index

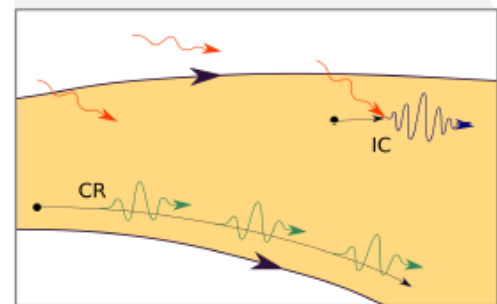
Model Frameworks



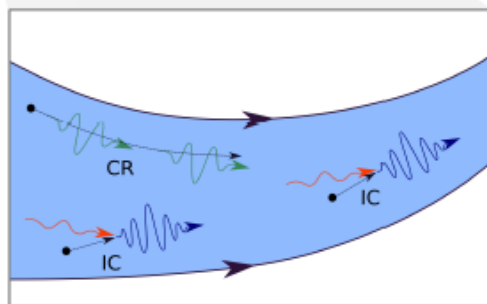
(i) **Local Models:**
Gap models (PC / OG / SG / TPC) within the light cylinder

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

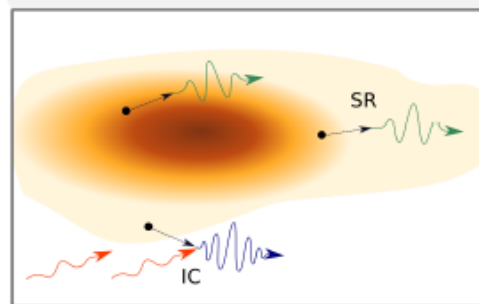
Outer Gap Region



Separatrix Region

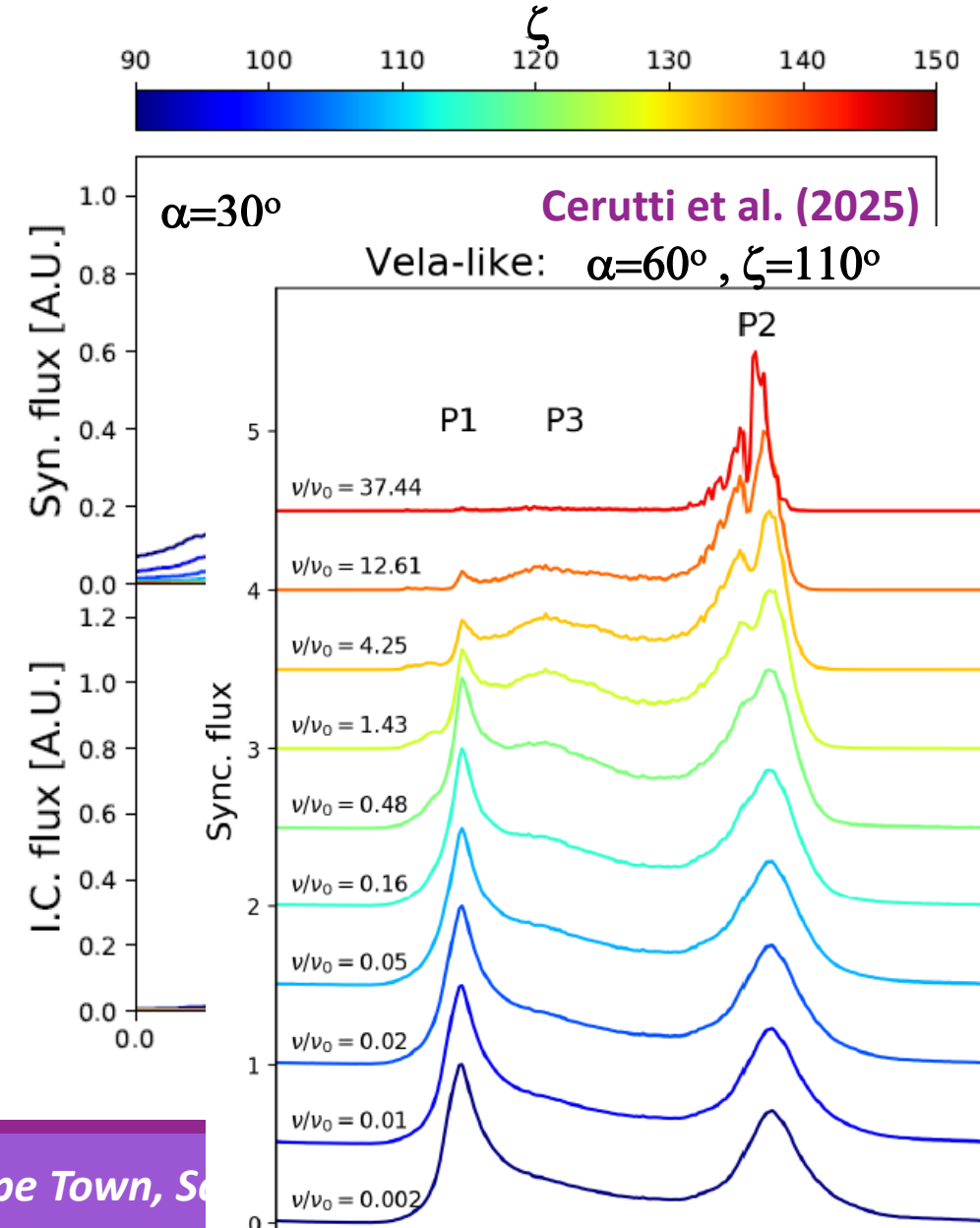
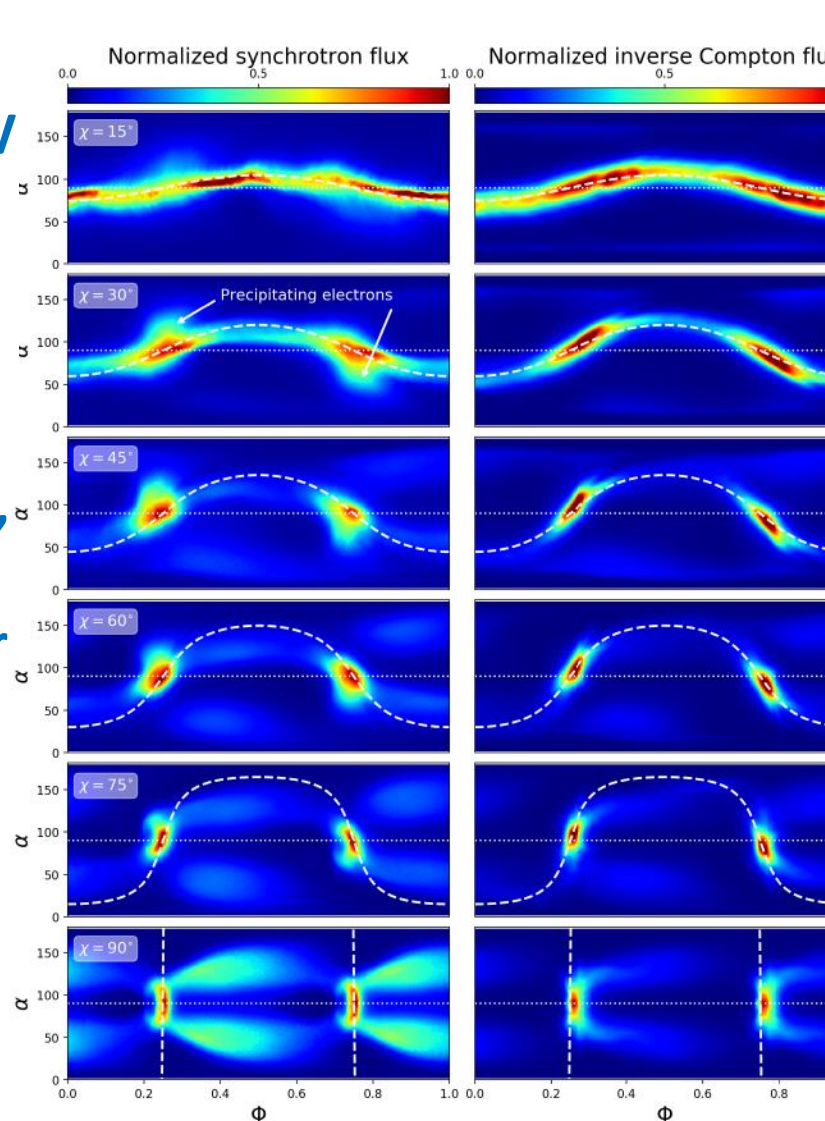


Plasmoids



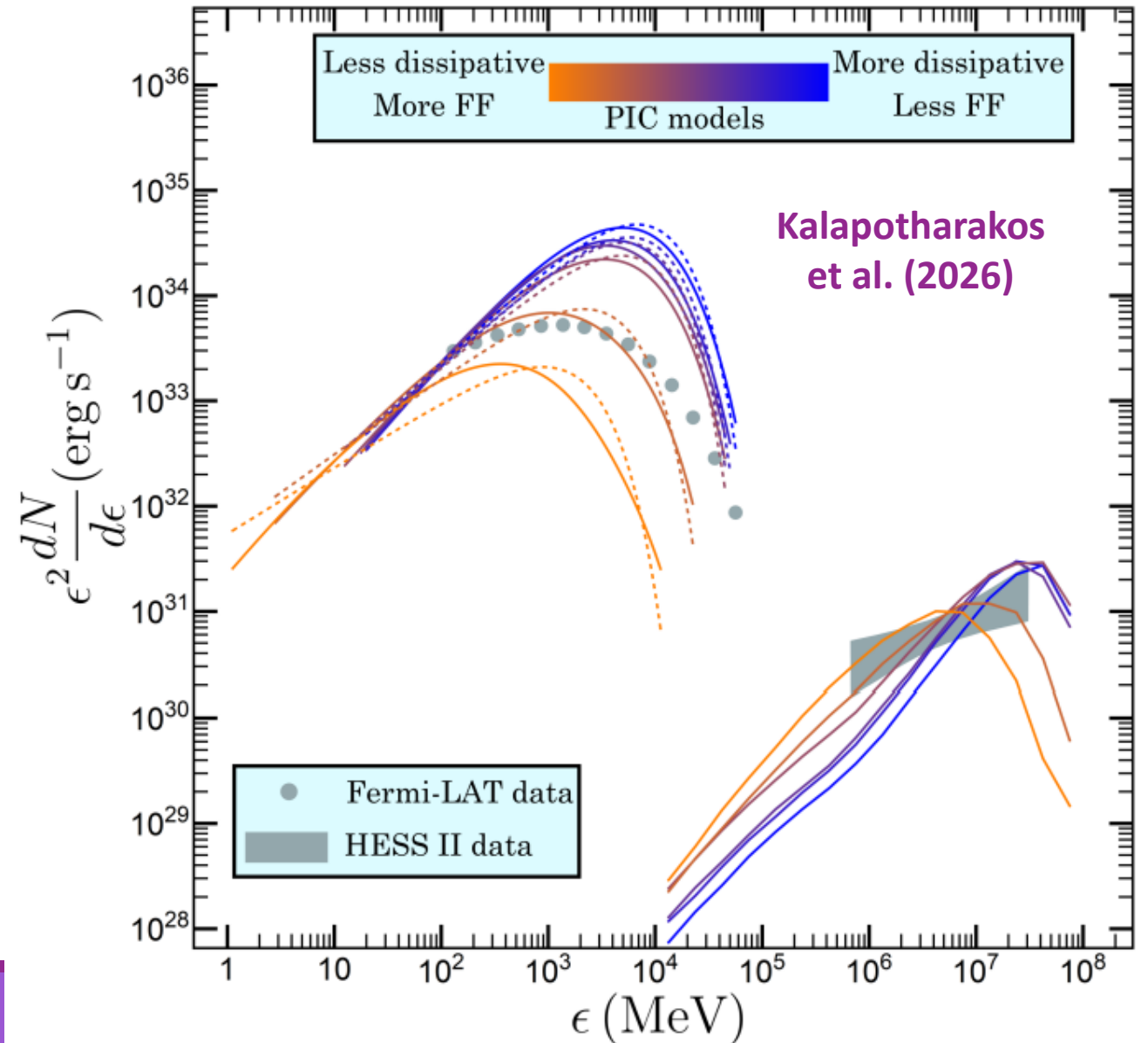
PIC Simulations: GeV / TeV Band

- PIC simulations of GeV / TeV light curves
- Two target fields assumed:
 - Uniform CMB / diffuse emission (e.g., nebula)
 - Point source at stellar centre (thermal surface hotspots)
- Reconnection: $\sigma > 1e7!$
- P1/P2 & P3 vs E_γ



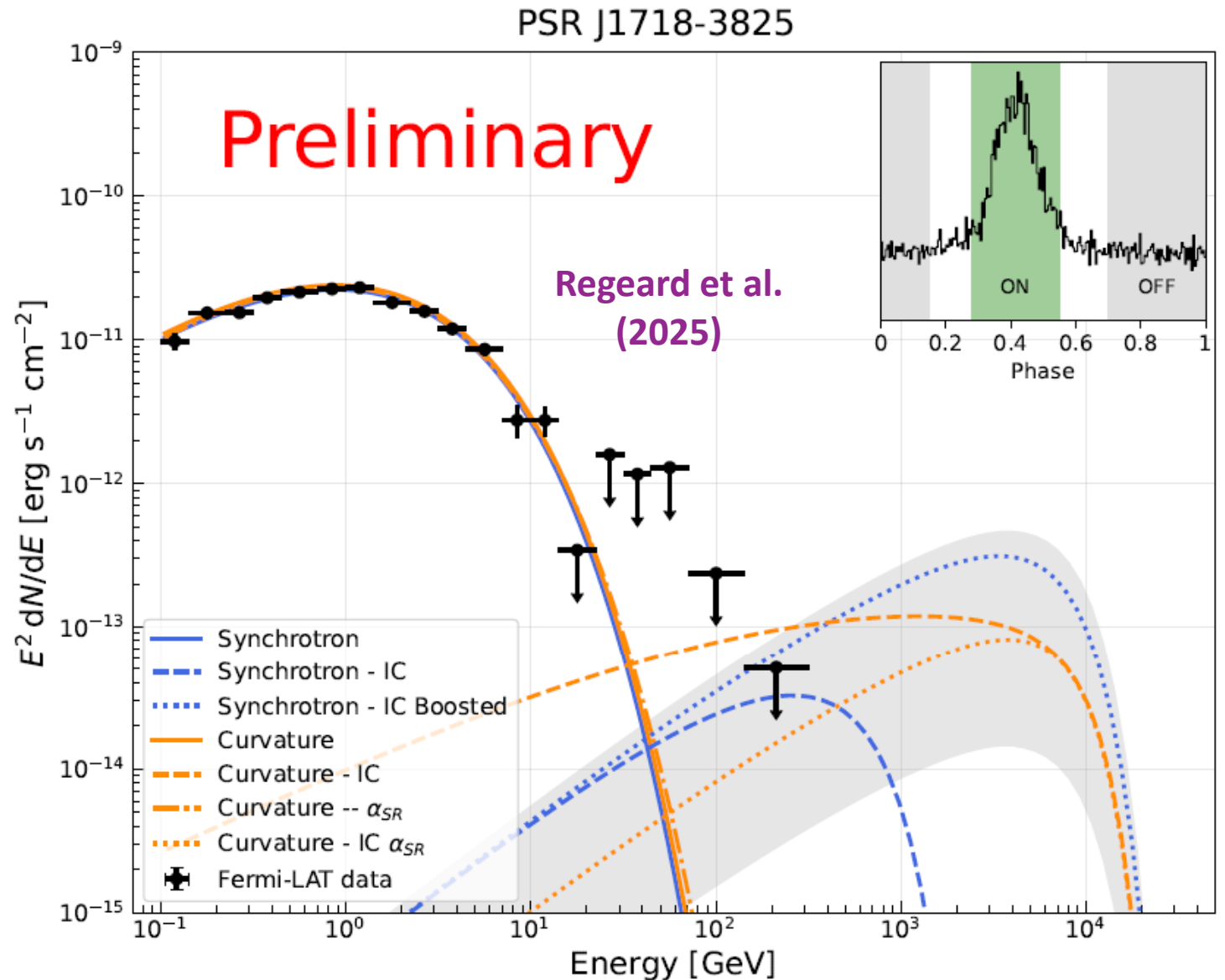
PIC Simulations: GeV / TeV Band

- **Assumptions:**
 - Power-law sub-mm to IR soft photons
 - Representative P, B, E_{dot} from PIC grid of models (injection ~ FF-ness)
 - GeV normalisation fixed, TeV free (soft photon normalisation)
- E_{||} acceleration produces $\gamma \sim 5e7$ naturally
- Joint constraints (single particle population)



Rough Predictions

- GeV bump fit by SR (+ boosting) or CR model
- Particle spectrum: PL with exp. cutoff
- IC in $\sim$ KN regime
- Extrapolation (and suppression) of X-ray spectrum to optical energies
- List of promising targets



mate

$$\propto \rho_c^{1/2} E_{||}^{1/4} \propto \eta^{1/4} \xi^{1/2}$$

for:

for magnetosphere (P)

for distance

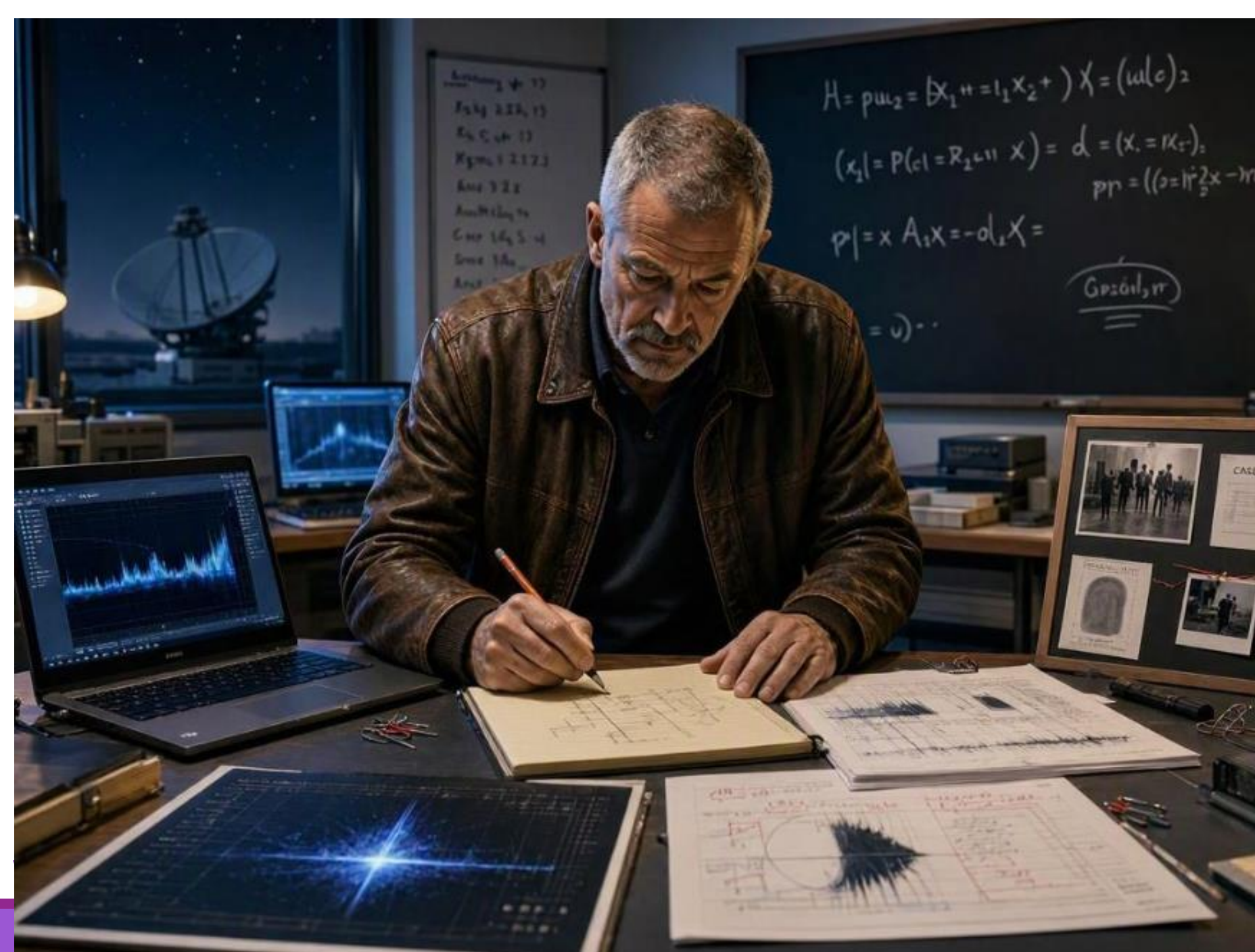
between SR and IC

on regions

for SR

ϵ_0 (boosts n_ϵ)

L_{GeV}

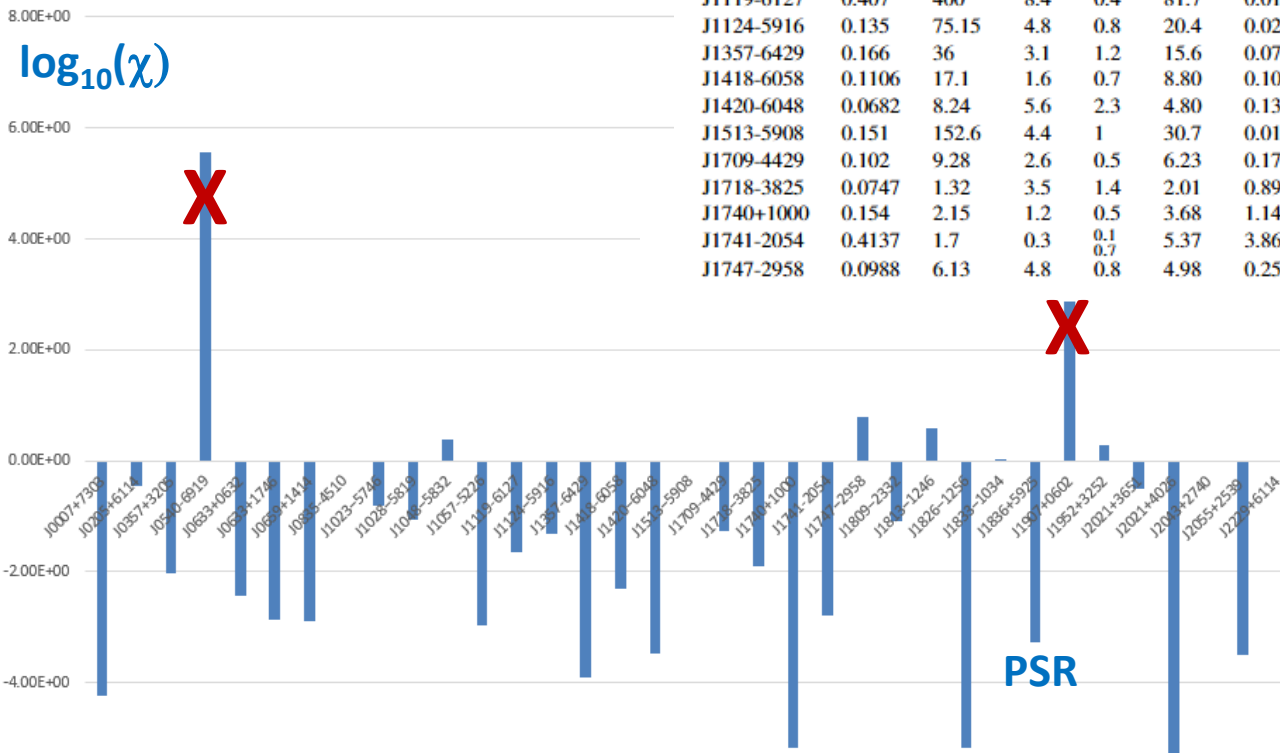


#1: Analytic Estimate

- Caveat:
photon-photon
pair production

$$\dot{N}_{\text{IC}} = \dot{N}_{\text{IC},0} \exp[-\tau_{\gamma\gamma}(\varepsilon)]$$

Figure of merit



Pulsar	P	$\dot{P}_{-16}$	d	Δd	B_{12}	τ_5	G_{-11}	E_p	$L_{\gamma,35}$	$\dot{E}_{36}$	$F_{\text{PL},-14}$	ΔE	$L_{\text{PL},32}$	Γ_{PL}	$\Delta\Gamma_{\text{PL}}$	$F_{\text{TeV},-14}$	χ	Ranking	Rel
J0007+7303	0.3159	35.592	1.4	0.3	21.5	0.141	45.6	2.44	1.01	0.446	6.86	0.3 – 10	0.152	1.30	0.18	3.87	0.0000576	31	A
J0205+6114	0.0657	19.2	3.2	0.2	7.19	0.0543	6.80	0.260	0.788	26.7	91.0		10.54	1.67	0.03	40.1	0.35	11	B
J0357+3205	0.4441	1.31	0.5		4.88	5.37	6.40	0.870	0.0181	0.00590	6.40	0.3 – 10	0.0181	2.53	0.25	0.0648	0.0094	20	A
J0540-6919	0.0506	47.89	49.7	1.1	9.96	0.0168	2.82	0.02	78.9	146	6680	0.3 – 10	186613	1.98	0.02	294000	366000	2	A
J0633+0632	0.297	7.95	1.1		9.83	0.592	9.40	1.43	0.129	0.120	15.3	0.3 – 10	0.21	2.00		1.10	0.0037	22	A
J0633+1746	0.237	1.1	0.2	0.1	3.27	3.42	420	1.63	0.182	0.0326	230	0.2 – 8	0.012	1.70	0.10	2.7	0.00133	24	C
J0659+1414	0.38	5.5	0.29	0.03	9.25	1.10	2.73	0.160	0.00260	0.00396	1050	0.2 – 8	0.0180	2.10	0.3	0.0275	0.0013	25	C
J0835-4510	0.0894	12.5	0.28	0.1	6.77	0.113	981	1.27	0.870	6.91	xxx	0.2 – 10	0.036	2.20	0.30	19.8	1.0	9	D
J1023-5746	0.1625	2.01	2.4		3.66	1.28	19.5	0.620	1.27	0.185	15.0	0.3 – 10	0.977	2.00		10.7	0.15	13	A
J1028-5819	0.0914	1.61	1.4	0.6	2.46	0.900	26.8	0.890	0.594	0.832	15.0	0.3 – 10	0.333	2.00E		4.98	0.088	14	A
J1048-5832	0.1237	9.55	2.9	1	6.96	0.205	19.6	0.410	1.86	1.99	5.00	0.3 – 10	0.476	2.40	0.50	5.20	2.35	6	A
J1057-5226	0.19	0.58	0.3	0.2	2.12	5.19	30	1.21	0.0430	0.00334	220	0.2 – 8	0.0810	1.70	0.10	1.91	0.0011	26	C
J1119-6127	0.407	400	8.4	0.4	81.7	0.0161	4.65	1.08	3.71	2.34	6.70	0.2 – 8	5.35	1.90	1.00	13.9	0.023	18	E
J1124-5916	0.135	75.15	4.8	0.8	20.4	0.0285	6.45	0.360	1.68	12.1	97.8	0.3 – 10	7.20	1.60	0.10	26.0	0.049	17	F
J1357-6429	0.166	36	3.1	1.2	15.6	0.0731	3.12	0.350	0.339	3.11		0.5 – 10	1.40	1.10	0.20	2.44	0.00012	30	G
J1418-6058	0.1106	17.1	1.6	0.7	8.80	0.103	31.4	1.00	0.910	4.99	3.00	0.3 – 10	0.0869	1.80	0.60	1.53	0.0050	21	A
J1420-6048	0.0682	8.24	5.6	2.3	4.80	0.131	13.8	0.730	4.90	10.3	16.0	0.3 – 10	5.67	0.81	0.40	43.8	0.0034	28	A
J1513-5908	0.151	152.6	4.4	1	30.7	0.0157	1.27		0.278	17.5				1.19	0.04	0.00E+00		1	I
J1709-4429	0.102	9.28	2.6	0.5	6.23	0.174	145	1.43	11.1	3.45	30.0	0.2 – 10	2.29	1.49	0.09	186	0.054	16	H
J1718-3825	0.0747	1.32	3.5	1.4	2.01	0.897	10.8	0.560	1.50	1.25	28.0	0.3 – 10	3.88	1.40	0.20	23.5	0.013	19	A
J1740+1000	0.154	2.15	1.2	0.5	3.68	1.14	0.360	1.72	0.00650	0.232	xxx	0.2 – 10	0.098	1.60	0.60	0.0219	0.0000068	33	I
J1741-2054	0.4137	1.7	0.3	0.1	5.37	3.86	12.6	1.40	0.0128	0.00948	46.40	0.3 – 10	0.047	2.10	0.30	0.332	0.0017	23	A
J1747-2958	0.0988	6.13	4.8	0.8	4.98	0.256	16.5	0.680	4.30	2.51	480		125	1.80	0.08	1150	6.23	4	J

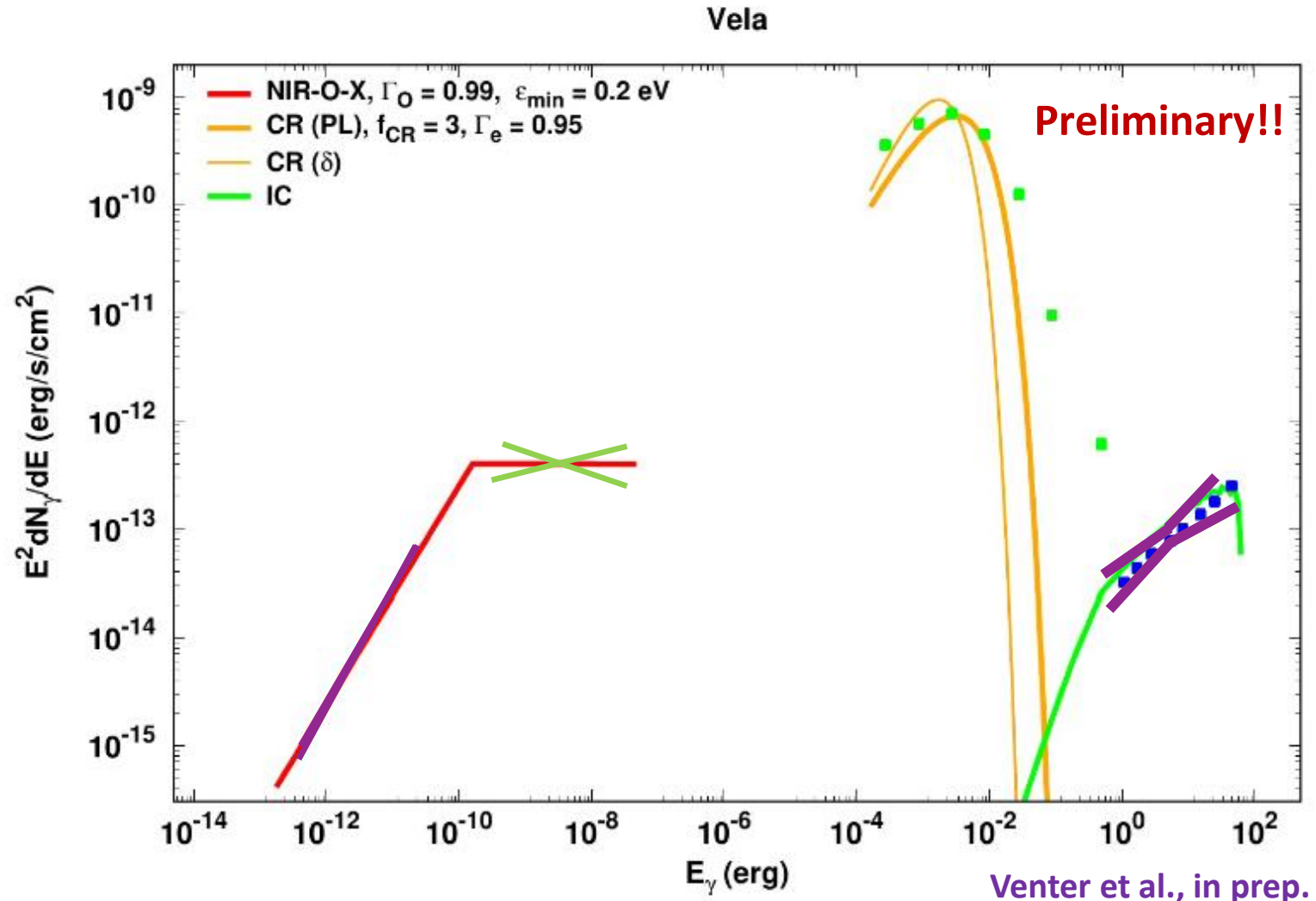
Preliminary!!

Venter et al., in prep.

#2: Basic Spectral Code

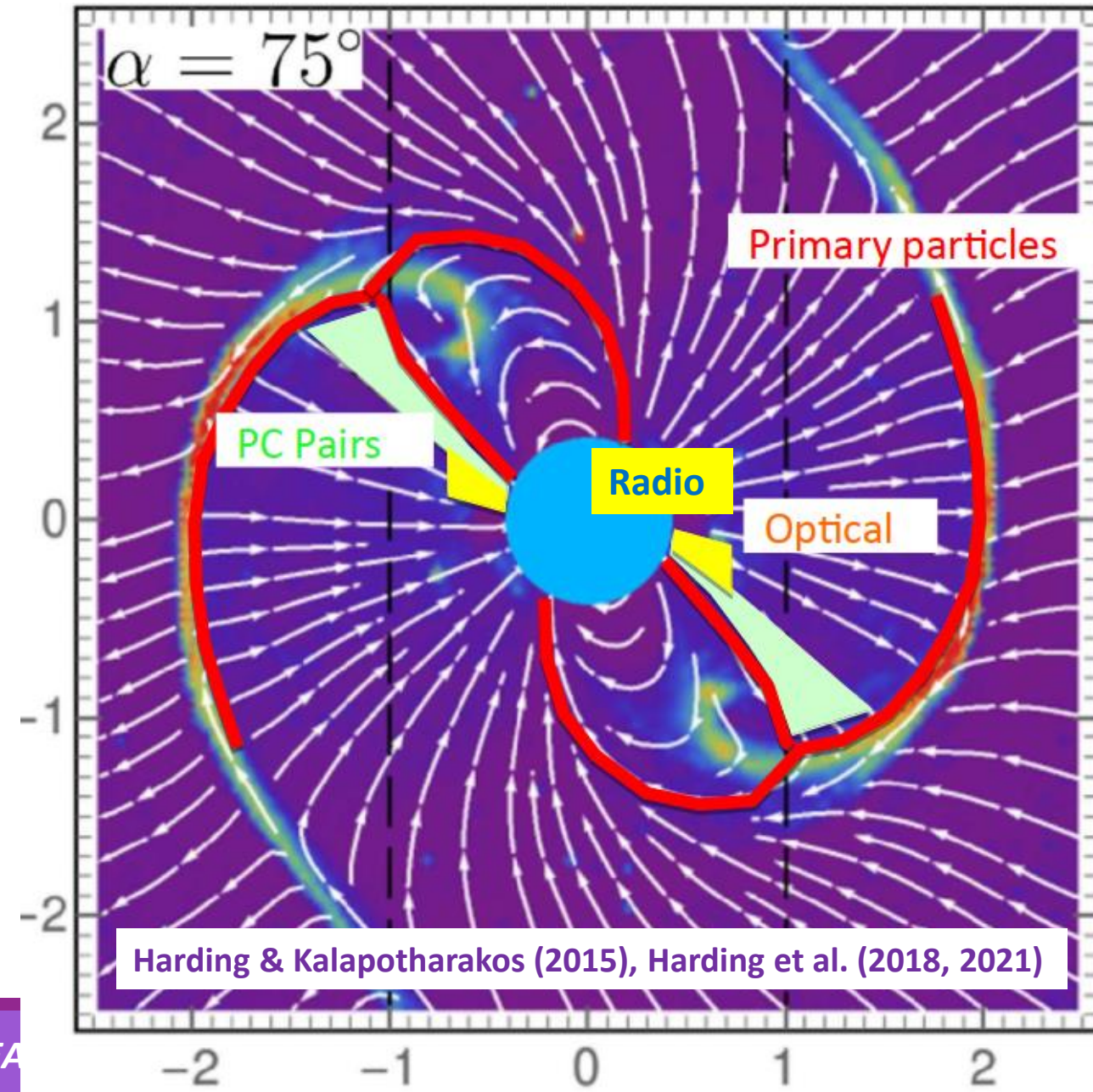
- Power-law particle spectrum (?)
- (Broken) power-law soft-photon spectrum
- Full KN cross section used to calculate IC spectrum
- No light curve predictions

- Measured Γ_{TeV} constrains Γ_e
- $E_{e,max}$ determines E_{TeV}
- High L_{GeV} , high IC flux
- (η, ξ) limited by E_{GeV} , L_{GeV} , E_{TeV}
- Lower ϵ_{min} boosts L_{TeV}
- Softer Γ_O boosts L_{TeV}



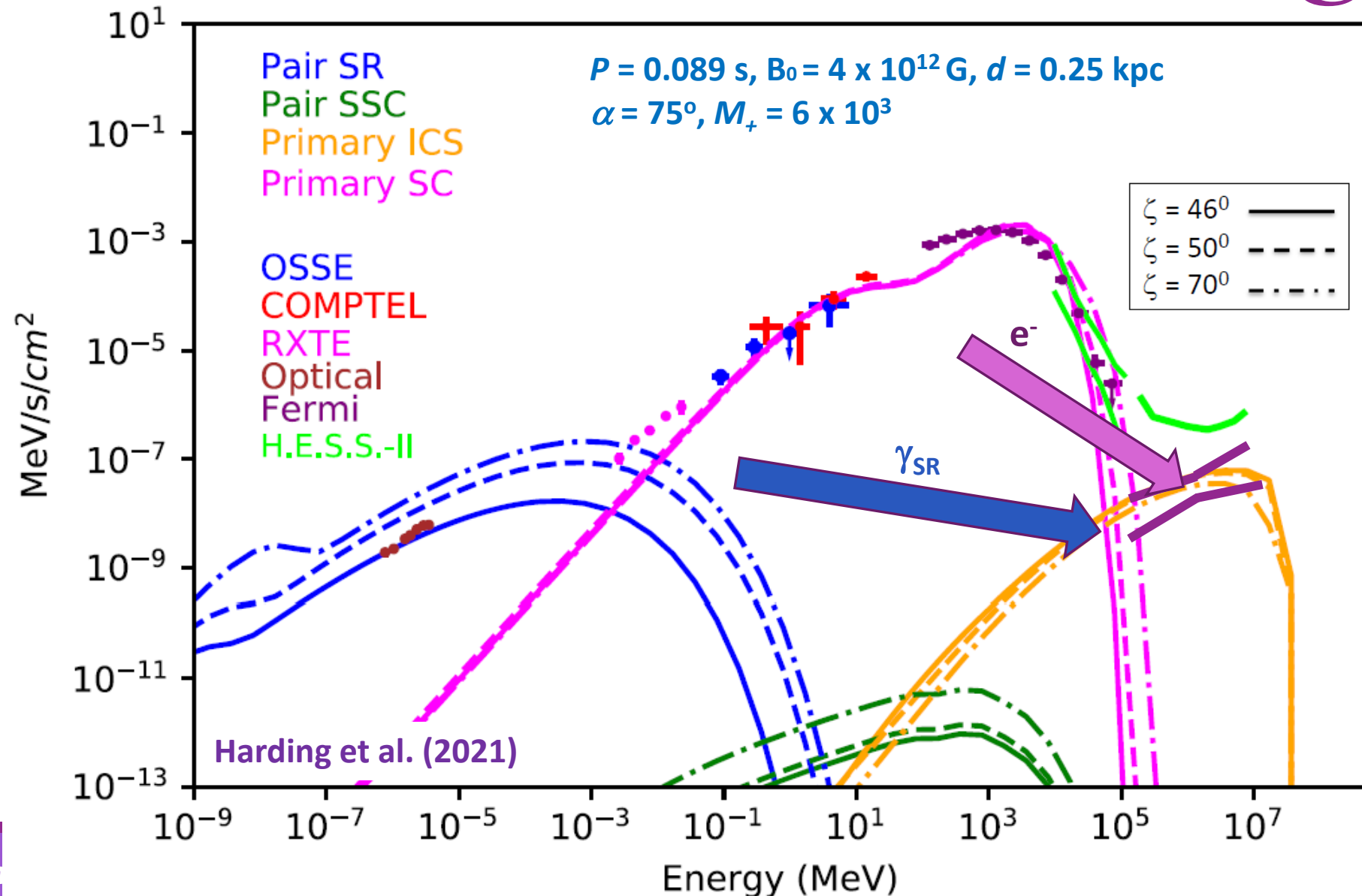
#3: Separatrix / CS Emission Model

- Force-free magnetosphere.
- Primaries accelerated near separatrix and predominantly in CS E -field (reaching $\gamma_e \sim 5e7$).
- Pairs injected at above PC ($J/J_{GJ} < 0$).
- Empirical radio core / cone model.
- Solve particle dynamics in observer frame.
- SC (CR+SR), ICS, SSC radiation mechanisms.
- **Spectra and light curves.**



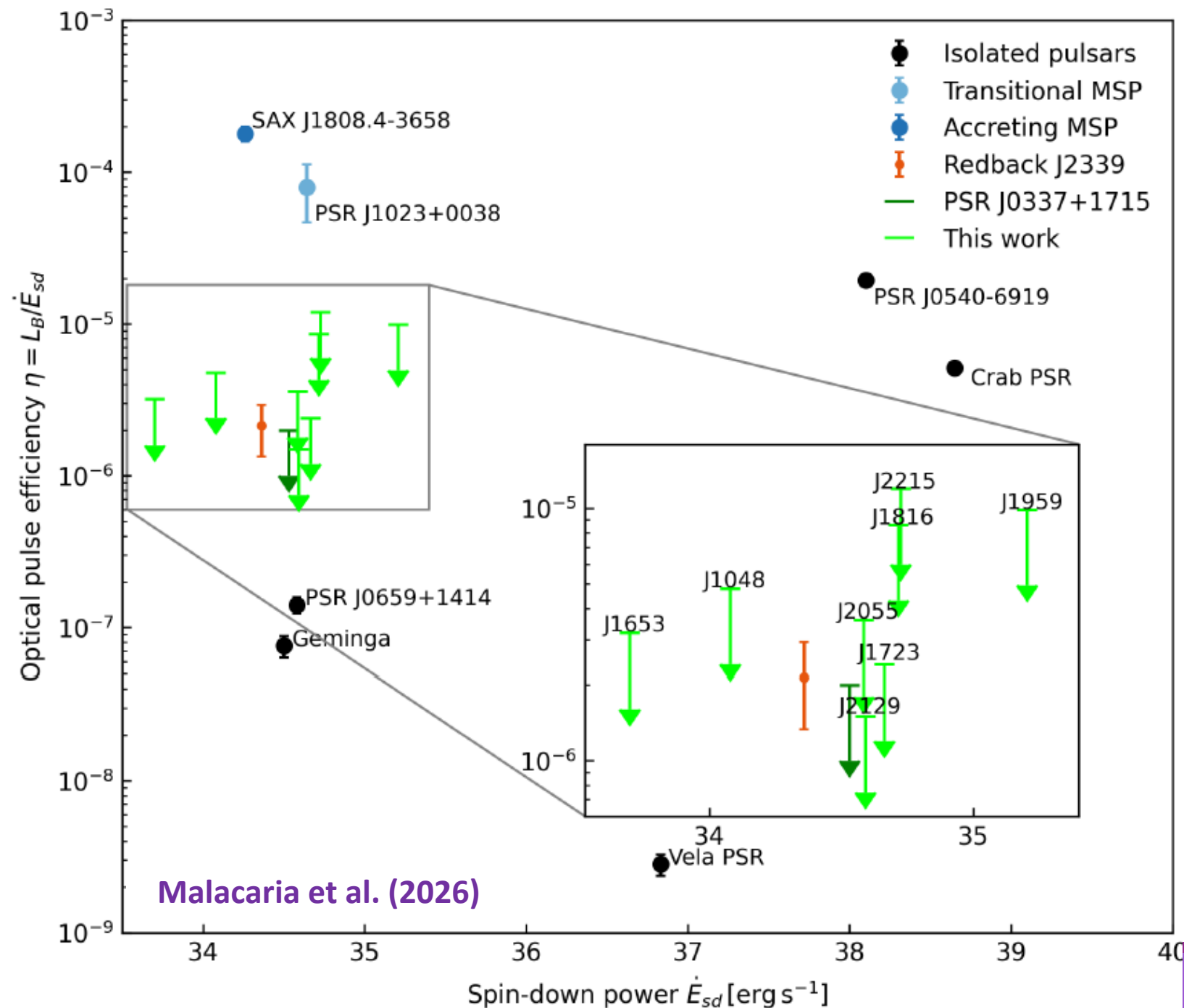
#3: Calibrate via 3D Modelling

- Pair SR matches optical data
- SCR broader GeV bump, sub-exp. tail
- Primary ICS component (primaries upscattering pair SR)
- TeV emission requires $\gamma_{\max} \sim 5e7$



A Check: Optical Pulsations

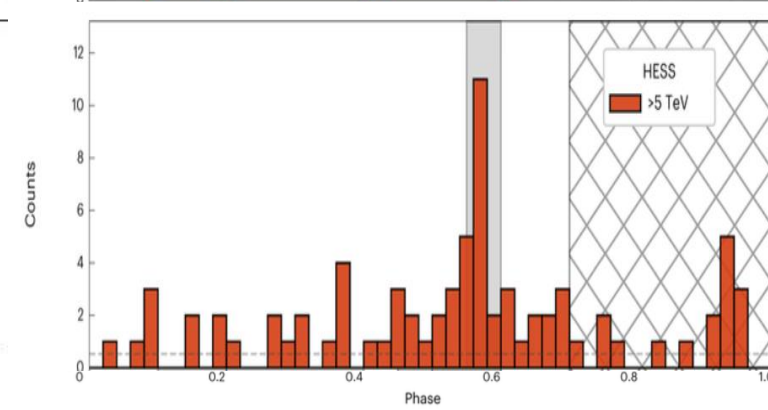
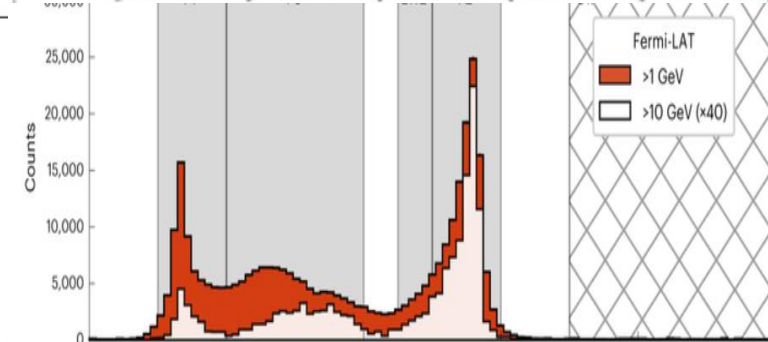
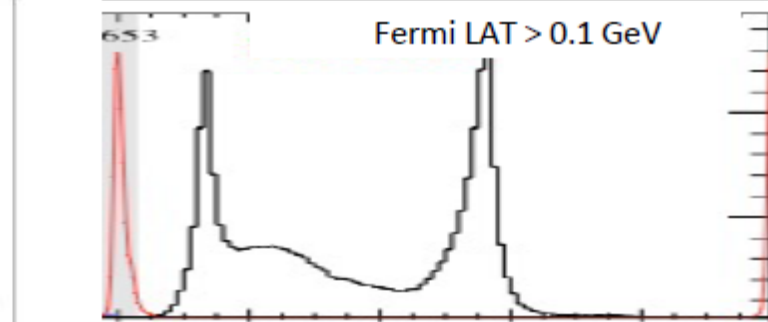
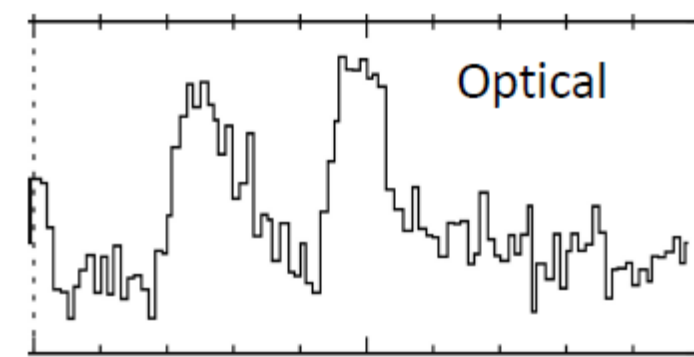
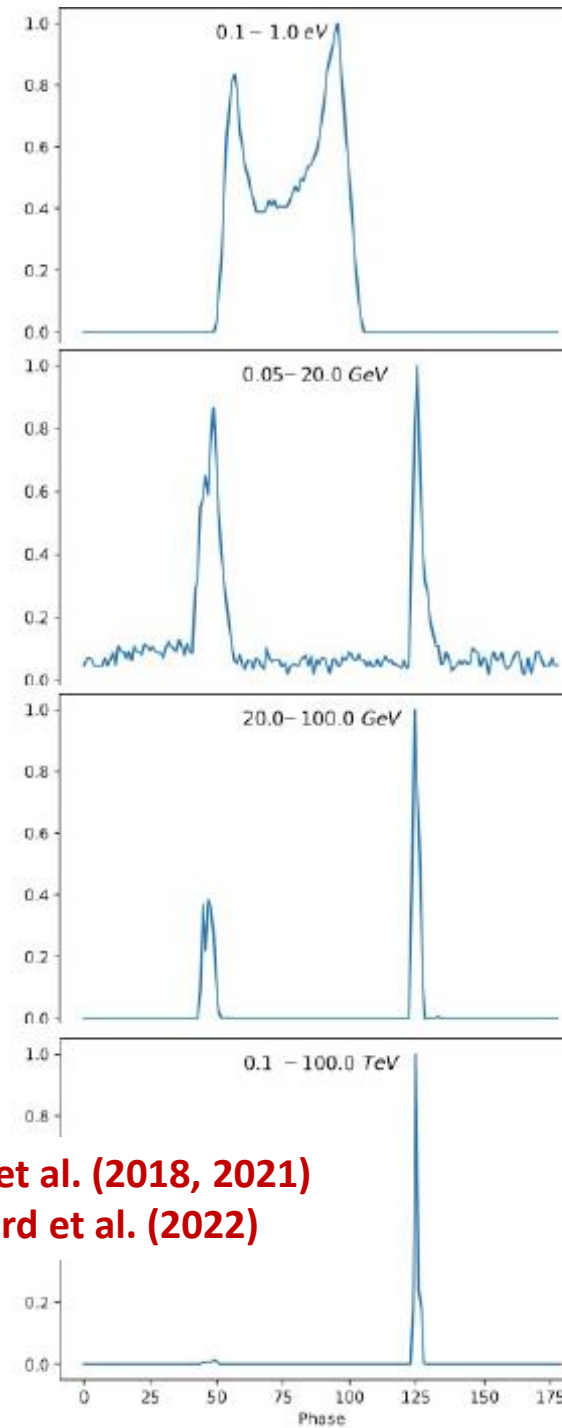
- Search for optical pulsations of spider binaries
- No detections
- Crab and twin $\eta \sim 1e-5$
- Limits on $\eta \sim 5e-6$
- Constraints on soft-photon target field!



Results: Vela LCs

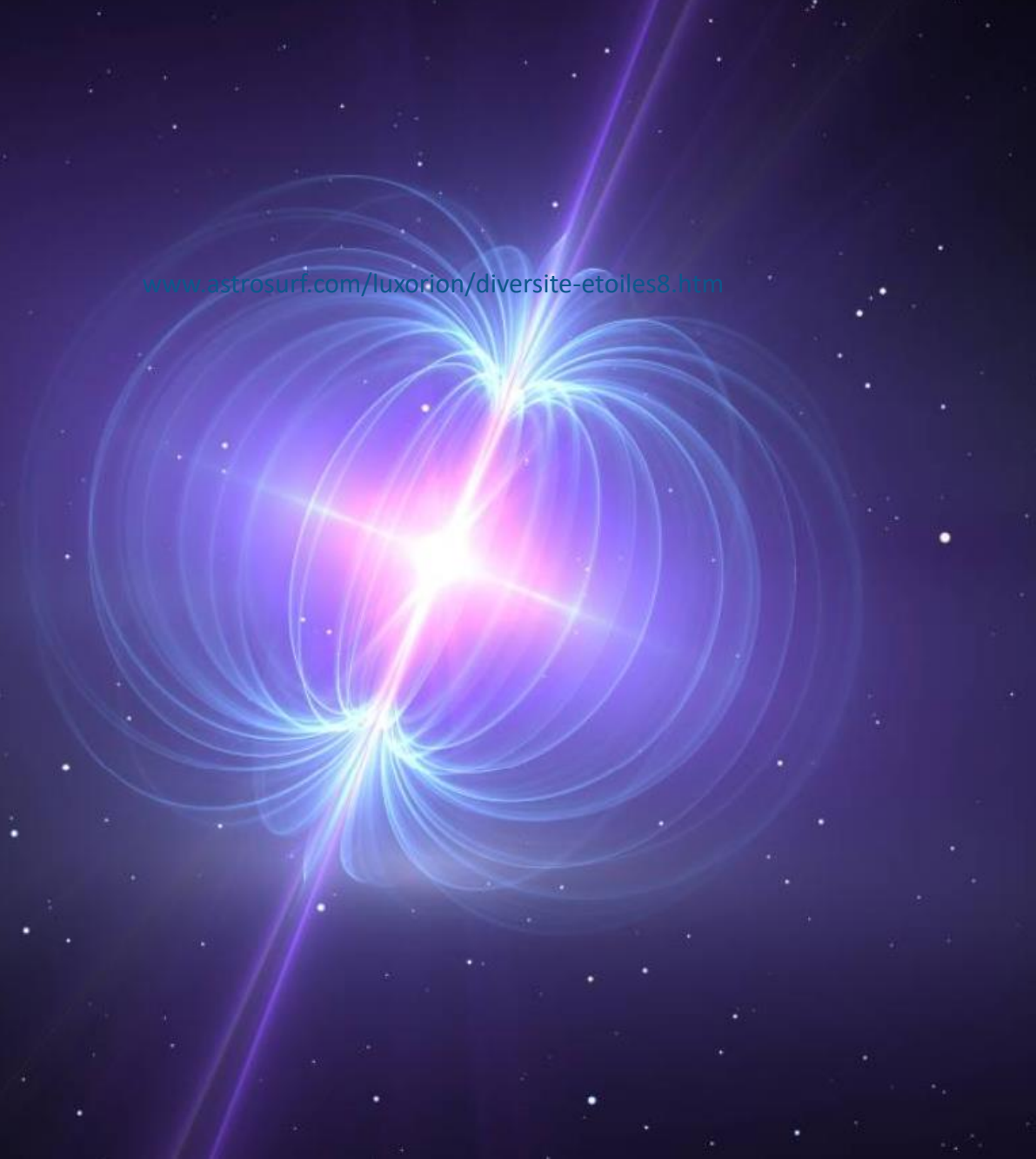
- Reasonable multi-wavelength LC predictions
- P1/P2 vs E_γ effect: higher-energy photons in P2 – **larger ρ_c**
- Only P2 in TeV: highest-energy particles responsible
- Narrowing of peaks with energy
- $E_{II}(\phi)$ leading to azimuthally-dependent emissivity improves radio-to- γ lags

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



Questions...

- IC implies high γ_e . Which framework?
- Shape of GeV tail: exponential, sub-exponential, PL?
- Shape of primary particle spectrum? Range of (η, ξ) ?
- Do smooth particle trajectories exist in CS? Effective ρ_c in the CS?
- Nature / spectrum of target photons? Thermal X-rays, CMB, Nebular, SR?
- Acceleration? Energetics?
- Particle injection? (FF-ness)

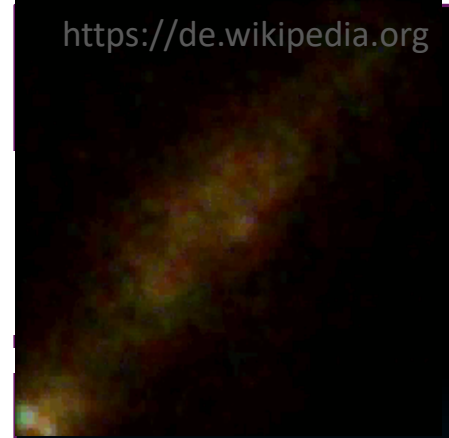


www.astrosurf.com/luxorion/diversite-etoiles8.htm

Conclusions

- 20 TeV pulsations from the Vela pulsar! **More** coming...
- **CTAO Pulsar Programme!**
- Convolution of particle dynamics & emission geometry: imprints on **light curves, spectra, polarisation**
- Unprecedented constraints on models
- Important to estimate TeV pulsar visibility

<https://de.wikipedia.org>



Thanks!



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

“The heavens proclaim the glory of God. The skies display His craftsmanship.” (Ps. 19:1 NLT).