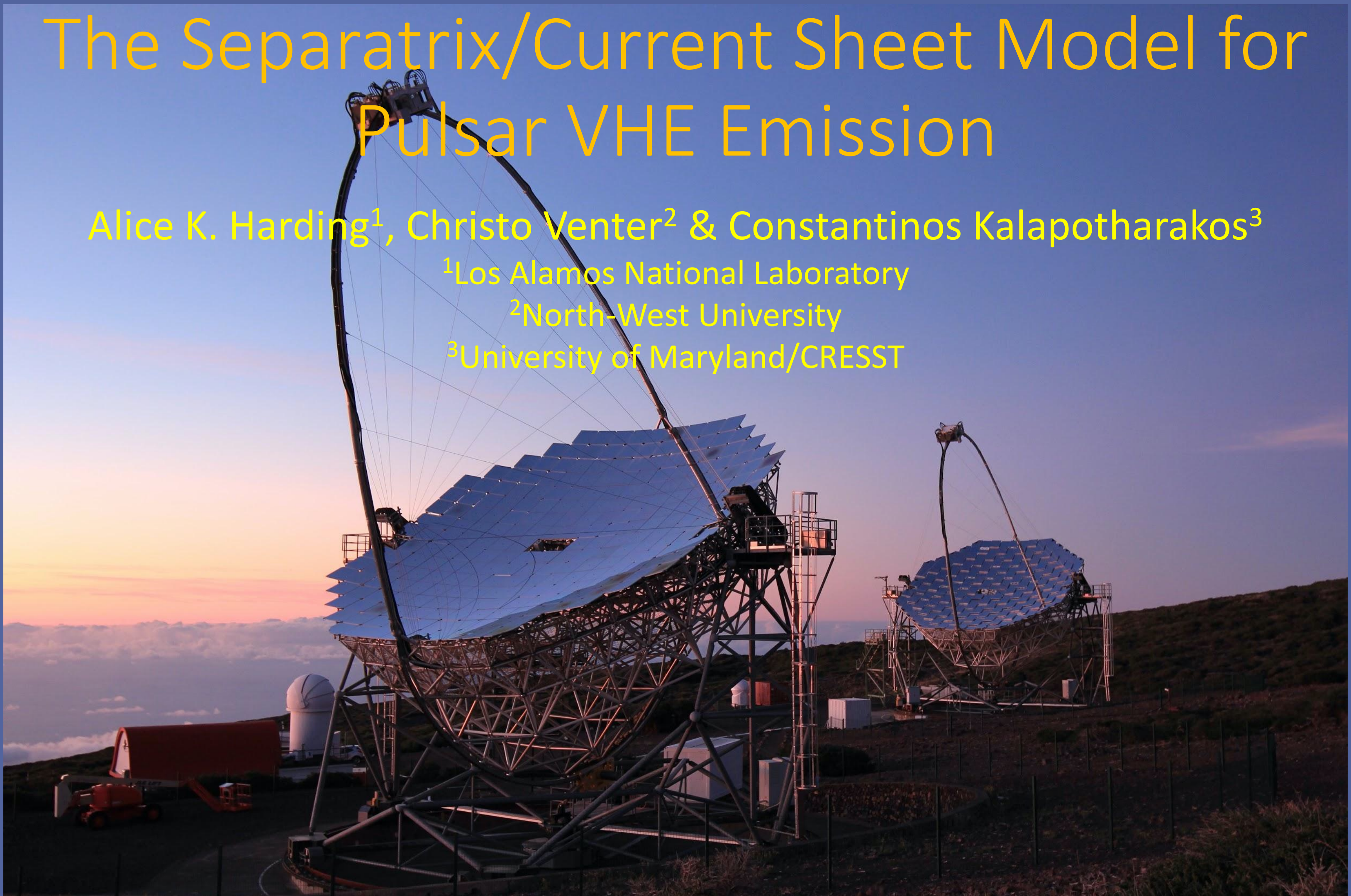
The Separatrix/Current Sheet Model for Pulsar VHE Emission



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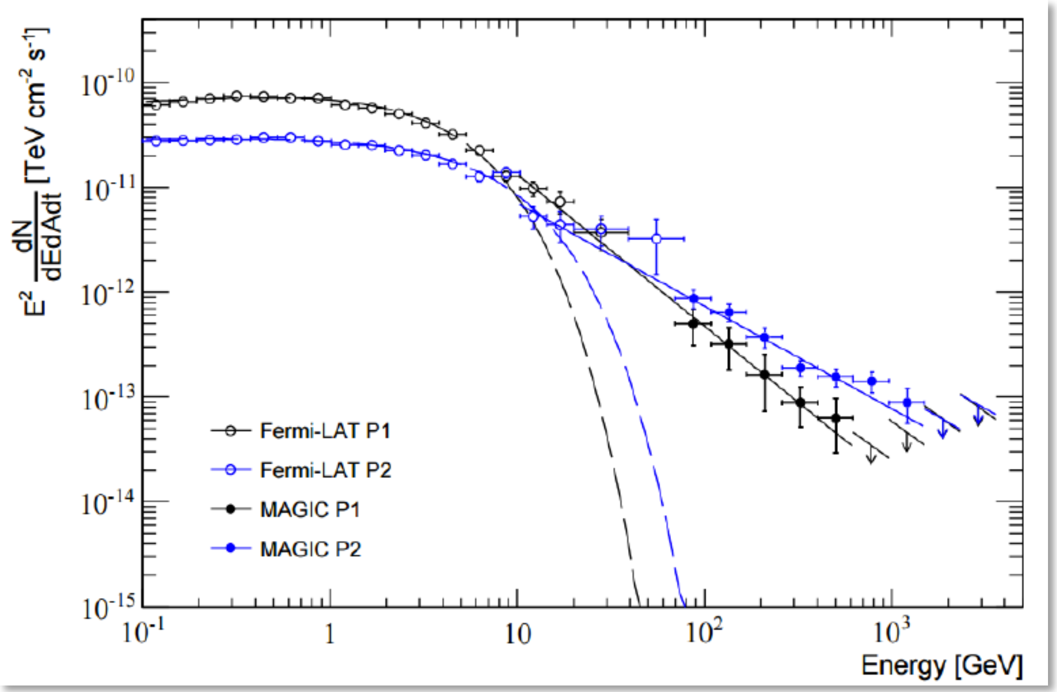
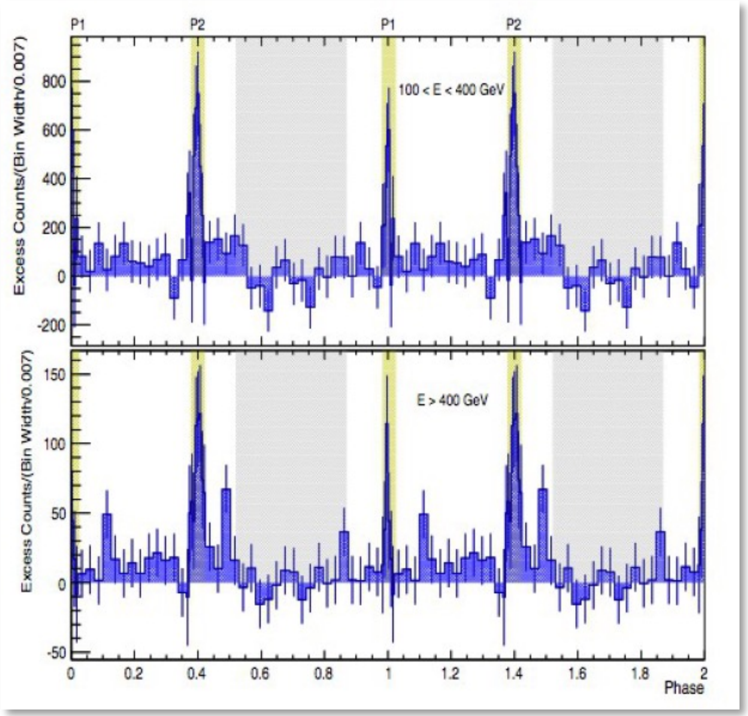
Detection of Crab pulsar up to 1 TeV

MAGIC - Aliu et al. 2008, 2011
Veritas - Aleksic et al. 2011

MAGIC 40 GeV – 1 TeV (Ansoldi et al. 2016)

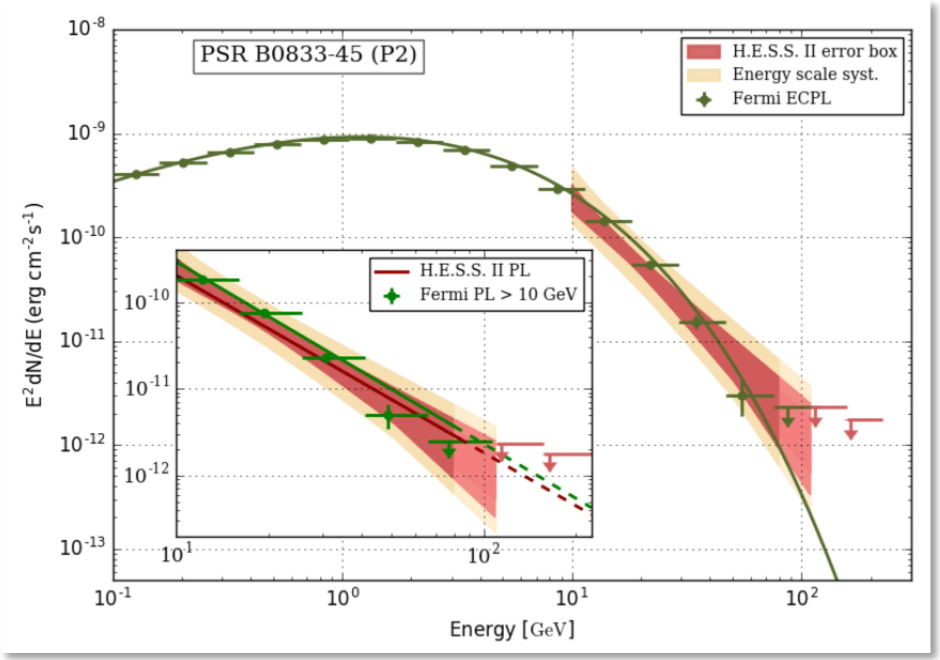
Both peaks detected!





Vela pulsar – H.E.S.S. II

10 – 110 GeV (Abdalla et al. 2018)



Continuation of Fermi spectrum (curved sub-exponential) or power law?

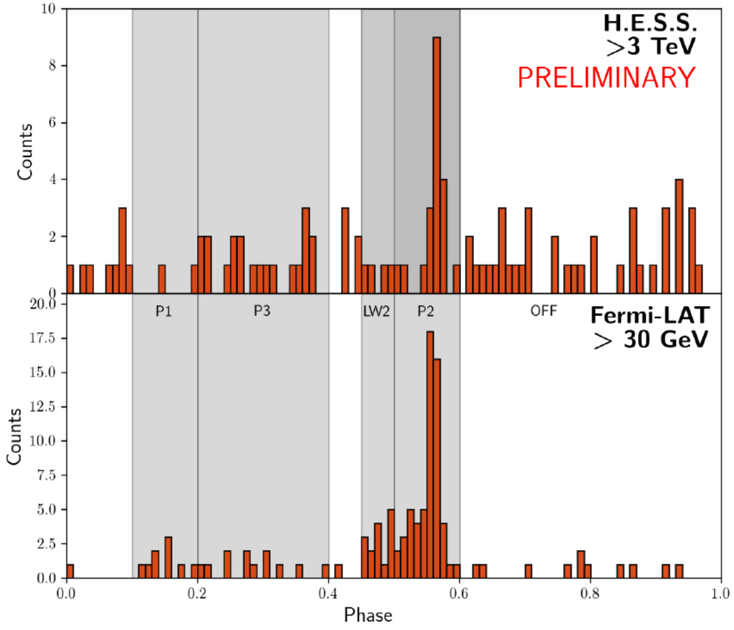
Curvature favored by H.E.S.S. II at > 3.0σ

2004 – 2016: 60 hours in stereoscopic mode

3 - > 7 TeV!! 5.6σ (Djannati-Atai 2018)

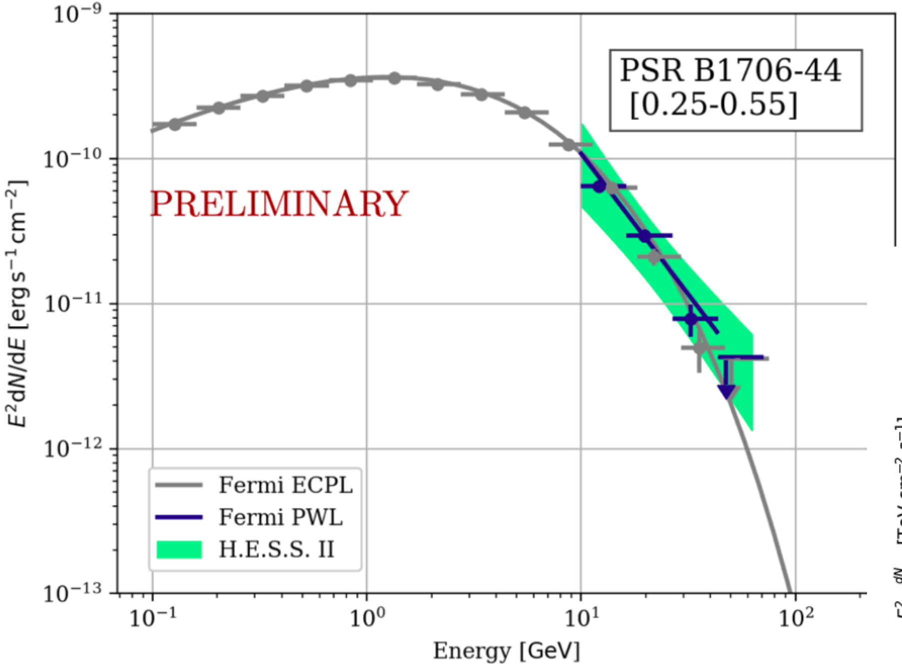
20 TeV? (Djannati-Atai 2022)

Additional component distinct from GeV spectrum?



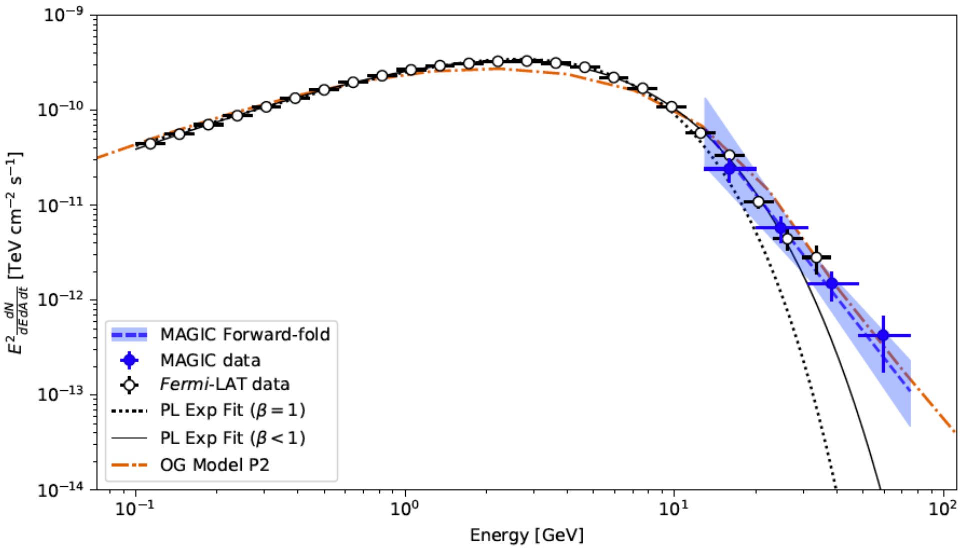
B1706-44 – H.E.S.S. II and Geminga - MAGIC

Spir-Jacob et al. 2019
10 – 70 GeV



Acciari et al. 2020

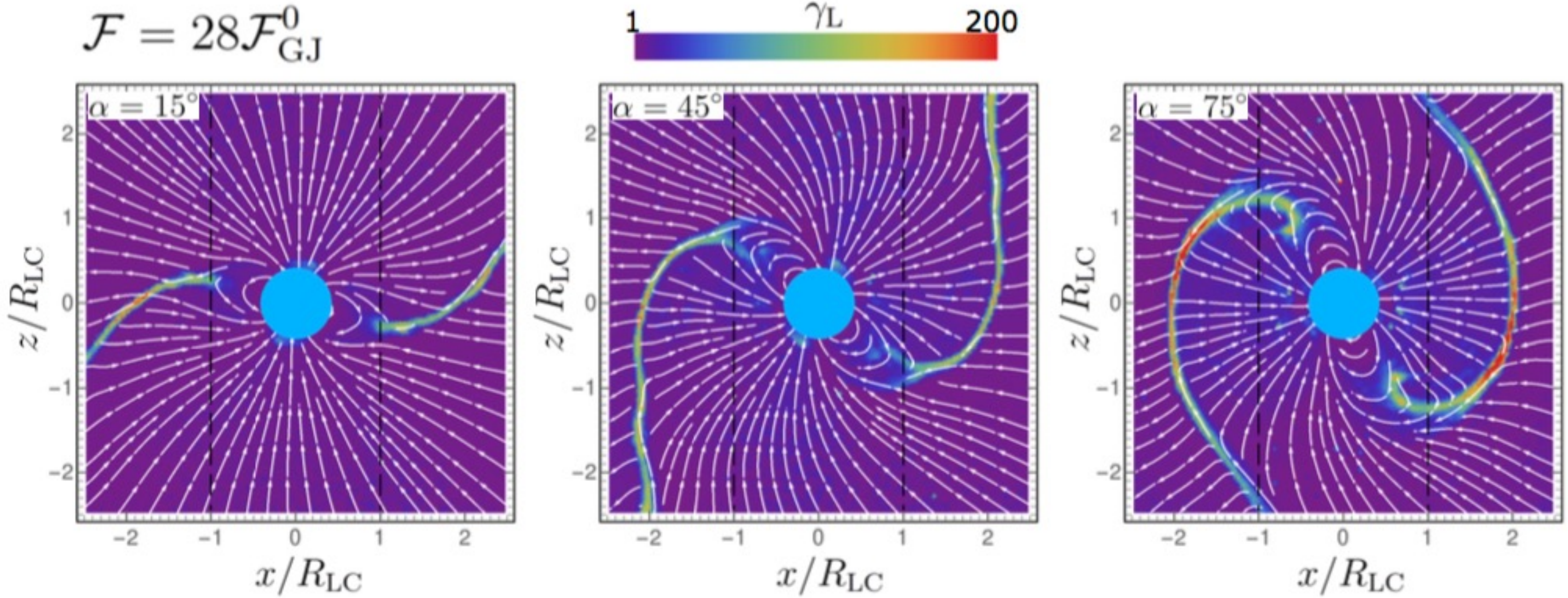
Spectrum measured up to 75 GeV



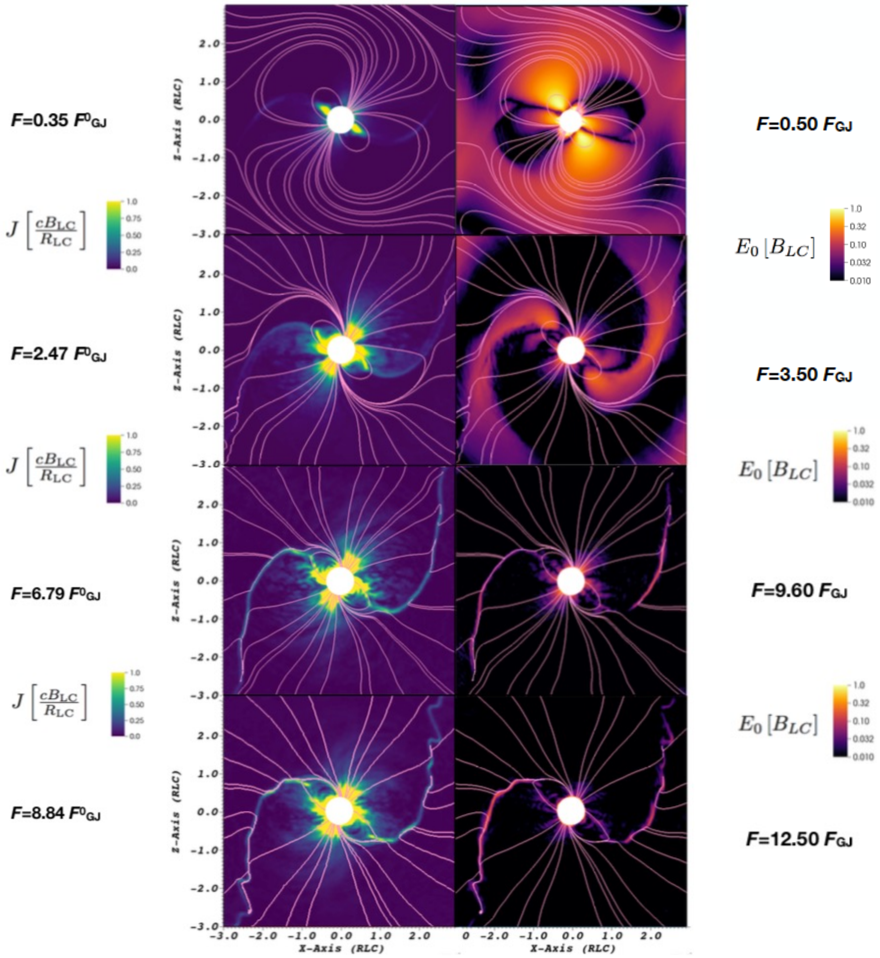
Global particle-in-cell (PIC) models

Chen & Belodorodov 2014, Philippov & Spitkovsky 2014, Cerutti et al 2016, Kalapotharakos+ 2018)

Most particle acceleration occurs in and near the current sheet and separatrices



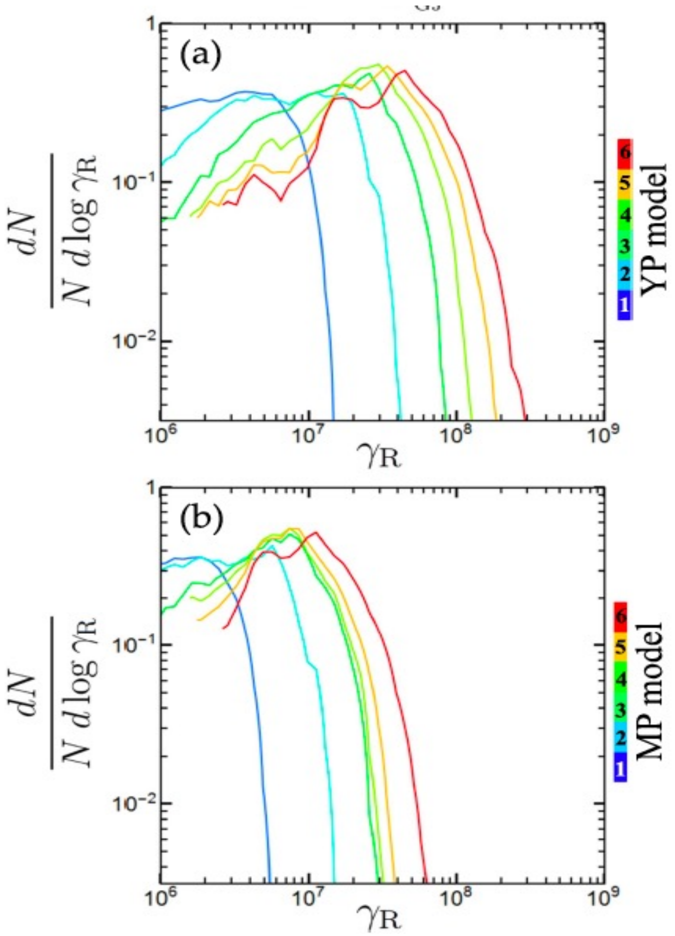
PIC simulations – Current and Electric field



Brambilla et al. 2018

As pair injection rate from NS surface increases – region of accelerating electric field shrinks to current sheet

Rescaled accelerated particle energy



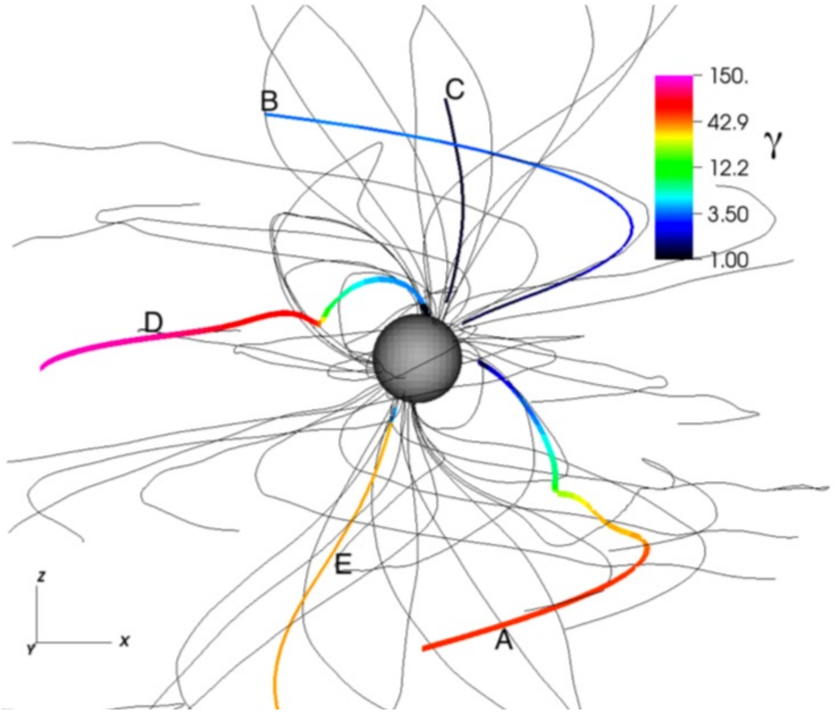
Kalapotharakos et al. 2018

Follow dynamics of particles with ”real” ***E*** and ***B*** in parallel within PIC code

$$\frac{d\gamma_R}{dt} = \frac{q_e \boldsymbol{v} \cdot \boldsymbol{E}}{m_e c^2} - \frac{2 q_e^2 \gamma_R^4}{3 R_C^2 m_e c}$$

Particle trajectories

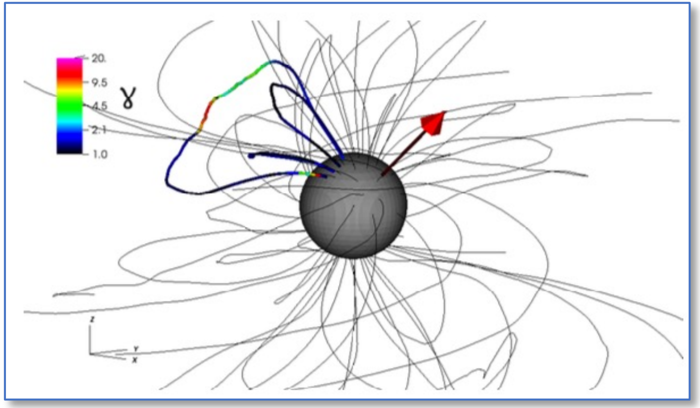
Brambilla et al. 2018



Surface injection

A, D – positrons at Y-point and in current sheet

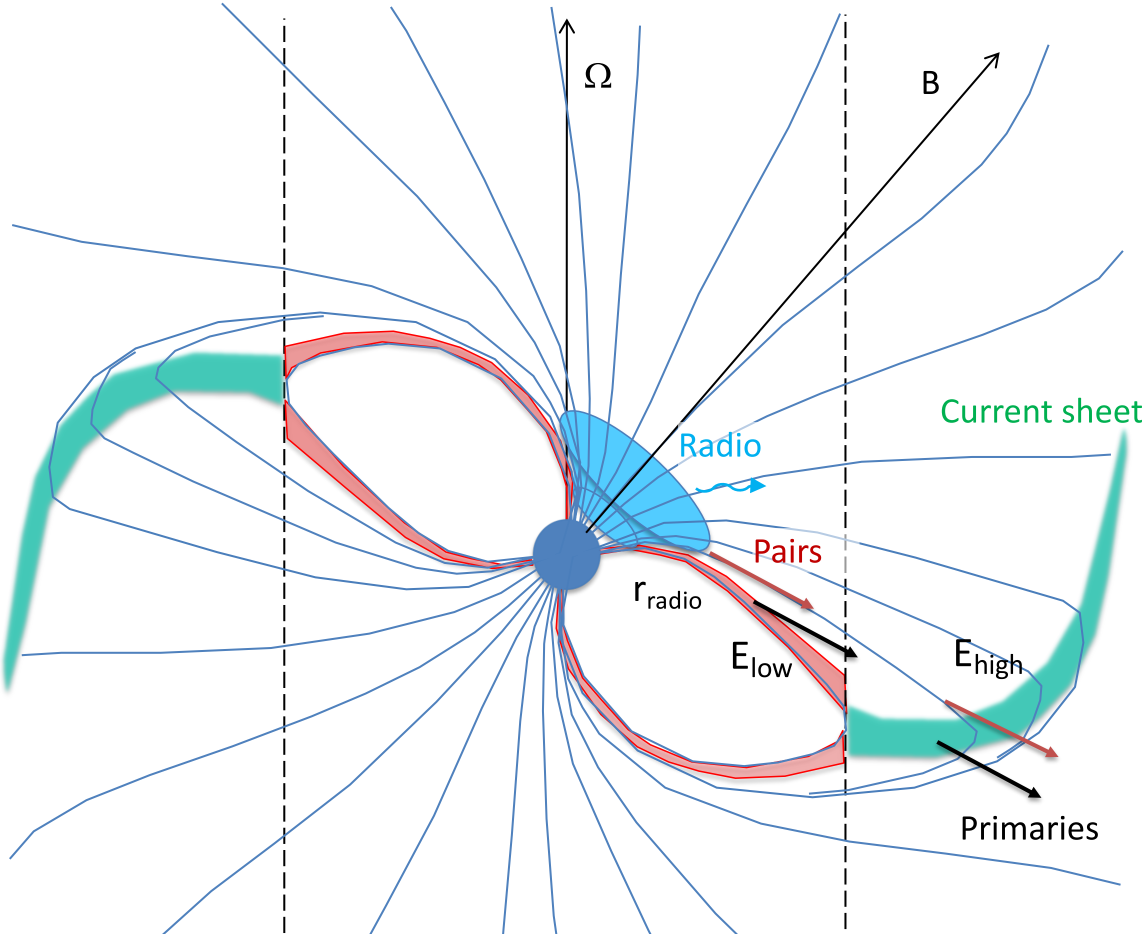
B, C, E – positrons and electrons flowing out above polar cap



Electrons falling back to the neutron star (see also Cerutti et al. 2015, Philippov et al. 2017)

Simulation of radiation

Harding & Kalapotharakos 2015
Harding et al. 2018, 2021



Pairs get pitch angles through resonant absorption of radio photons when

$$\varepsilon_B = \gamma \varepsilon_R (1 - \beta \cos\theta)$$

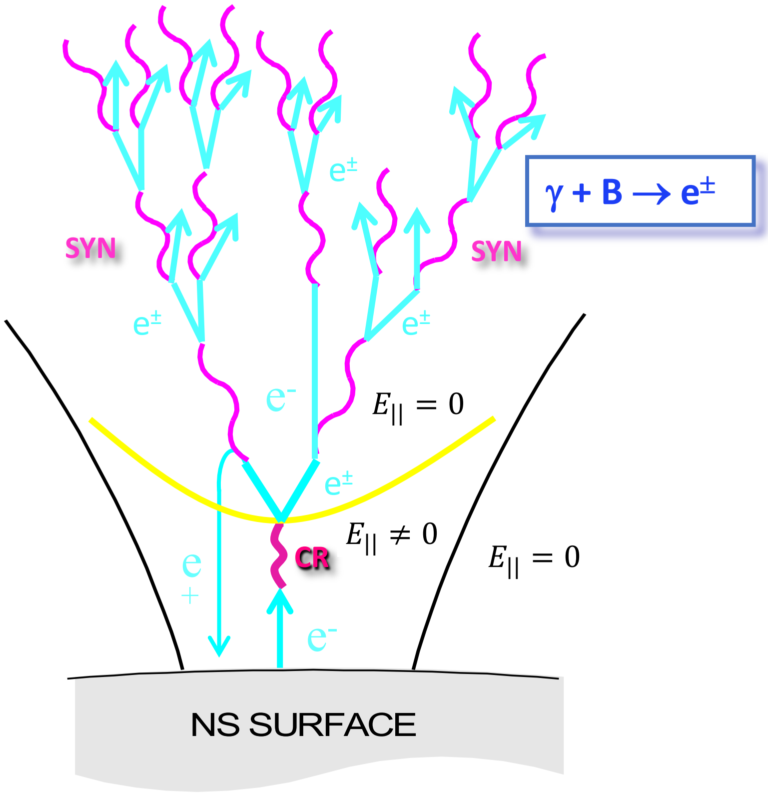
Petrova & Lyubarski 1998

Force-free magnetic field 0.2 to 2 R_{LC}

Connect to vacuum retarded dipole below 0.2 R_{LC}

$$\boldsymbol{v} = \left(\frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2 + E_0^2} + f \frac{\boldsymbol{B}}{B} \right) c$$

Polar cap pair cascades



Pair cascades above the PC are necessary for coherent radio emission

Cascades are time-varying

Timokhin 2010, Timokhin & Arons 2013

Use Timokhin & Harding (2019) estimate of particle energy from non-steady gaps

$$\gamma_{\rm gap} \simeq 3.2 \times 10^7 \, P^{-1/7} \, B_{12}^{-1/7} \, \rho_{c,7}^{4/7}$$

Weakly dependent on P and B

Sensitive to ρ_c

Pair cascades multiplicity

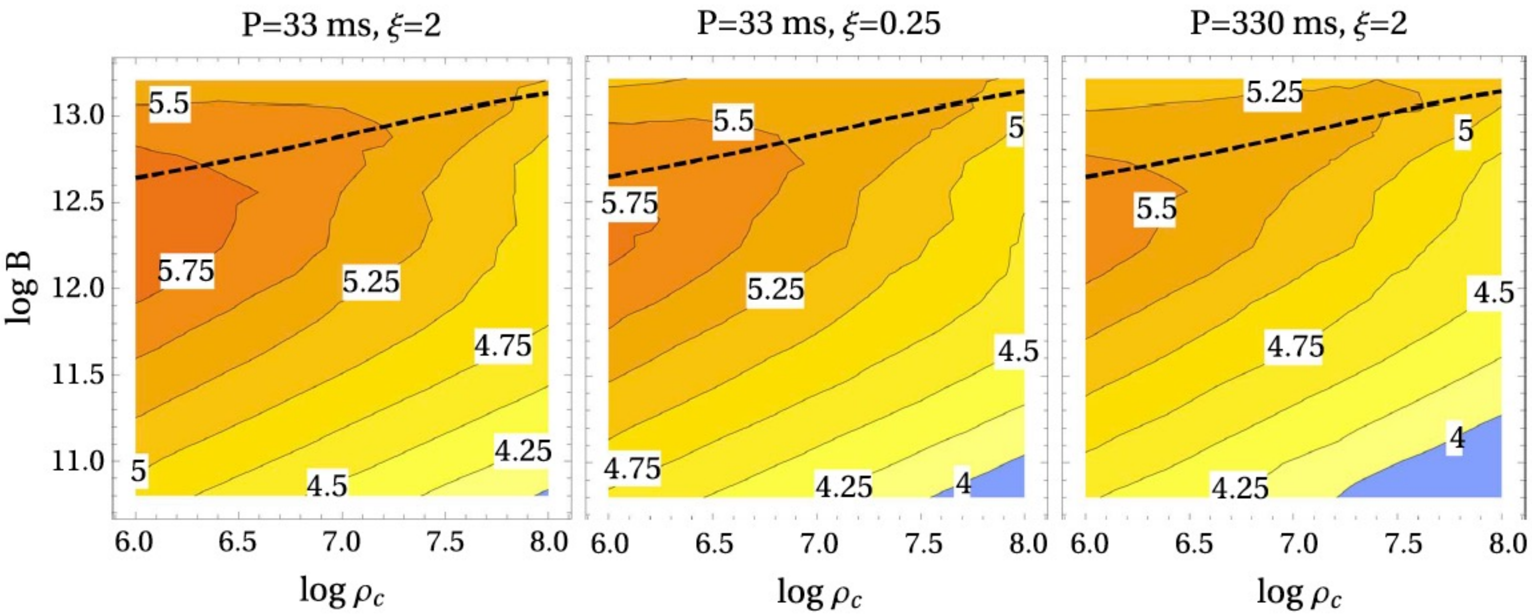
$$M_{\pm} \sim 10^3 - 3\times10^5$$

Timokhin & Harding 2015

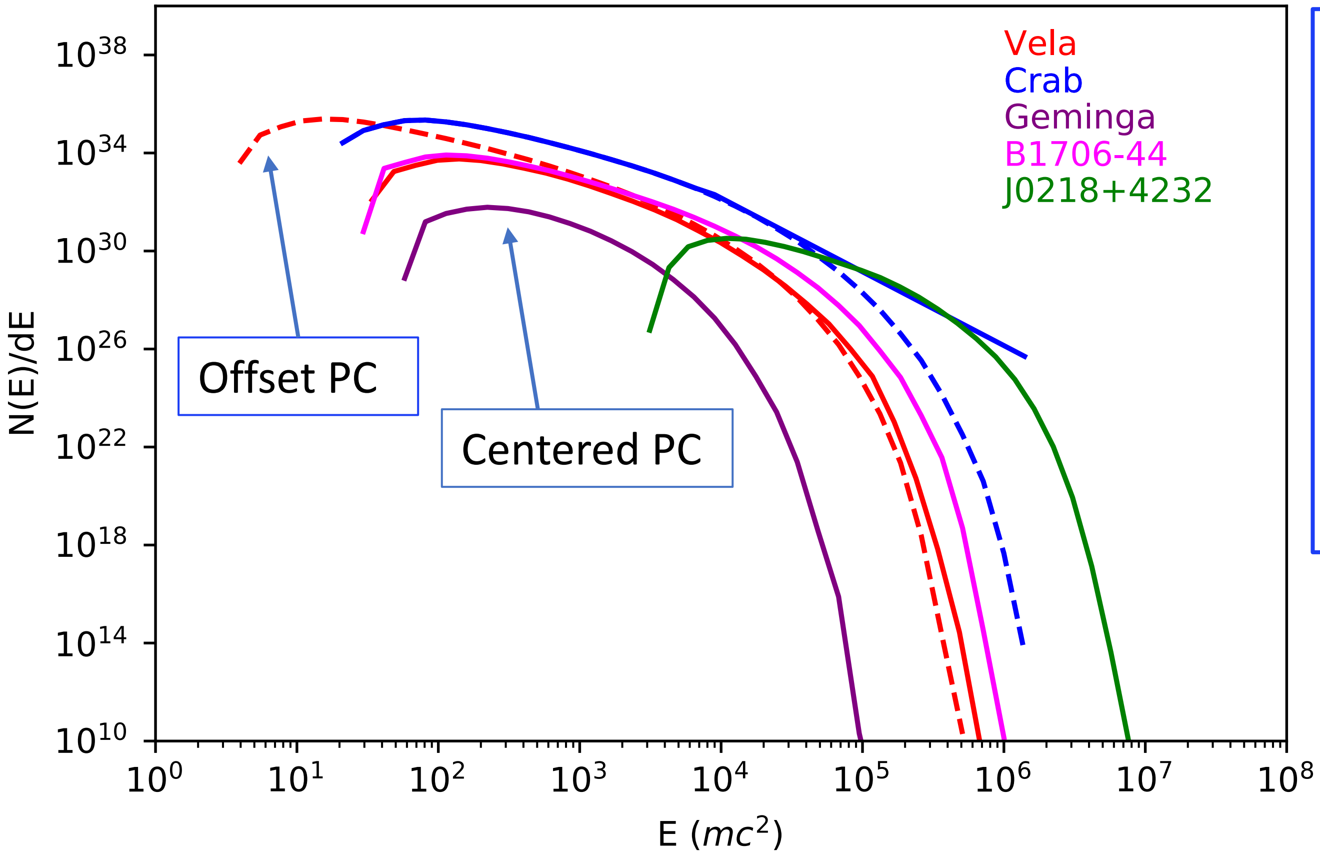
Pair multiplicity

Timokhin & Harding 2019

Curvature radiation plus resonant inverse Compton



Polar cap pair spectra



Spectra in offset PC extend to lower energies

Higher B, higher cutoff

MSP pairs have higher energy – lower B field requires higher photon energy to produce pairs

Resonant absorption of radio photons

Resonance condition

$$B' = \gamma\varepsilon_0 \left(1 - \beta\mu_0\right) \qquad \gamma_R = 2.8 \times 10^5 \frac{B_8}{\varepsilon_{0,\mathrm{GHz}}\left(1 - \beta\mu_0\right)}$$

Resonant absorption rate

$$\left(\frac{dp_\perp}{dt}\right)^{\mathrm{abs}} = D\frac{\gamma^\nu}{p_\perp} + \frac{p_\perp\gamma}{\gamma^2 - 1}\left(\frac{d\gamma}{dt}\right)^{\mathrm{abs}}, \quad \gamma < \gamma_R$$

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

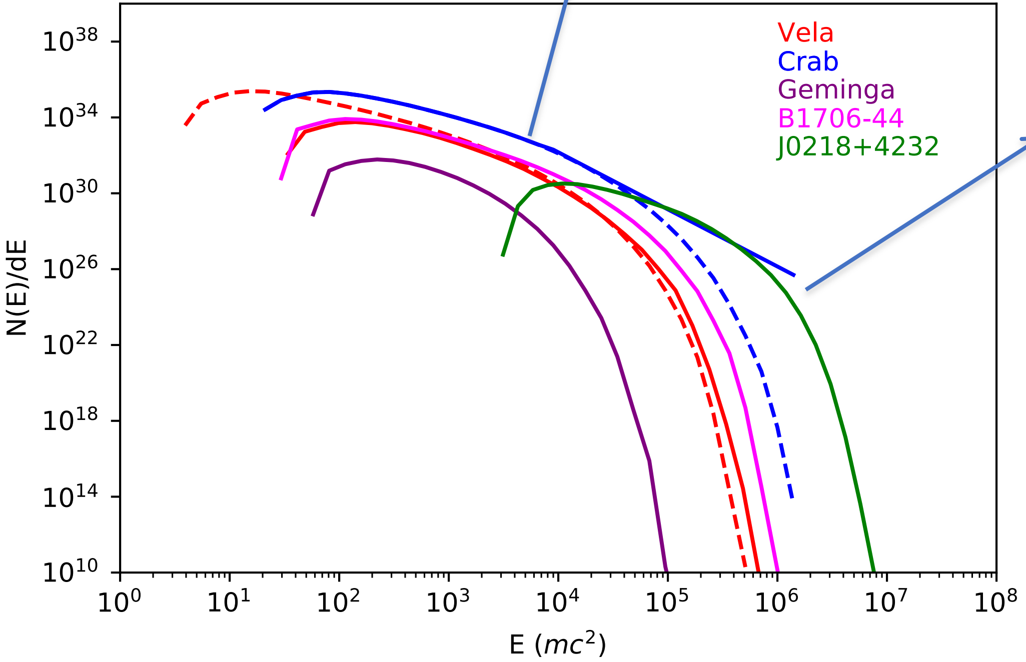
$$\frac{dp_\perp}{dt} = -\frac{3}{2}\frac{c}{r}p_\perp - \frac{2e^4}{3m^3c^5}B^2\frac{p_\perp^3}{\gamma} + \left(\frac{dp_\perp(\gamma)}{dt}\right)^{\mathrm{abs}}$$

Inverse Compton emission

$$\frac{N(\varepsilon_s,\vec{r})}{d\varepsilon_s dt d\Omega_s} = c\int dE\, n_\pm\,(\mathrm{E}) \int d\Omega \int d\varepsilon\, n_\gamma(\varepsilon,\vec{r},\Omega)\, \frac{dn_{KN}(\varepsilon,\varepsilon_s)}{dt d\varepsilon d\varepsilon_s} (1-\beta cos\theta)$$

Jones (1968)

Pair cascade spectrum (polar cap)



Synchrotron emissivity

$$n_\gamma(\varepsilon,\vec{r},\Omega) = \frac{1}{c}\int d\vec{r}_s\, \frac{\epsilon_{SR}(\varepsilon,\vec{r}_s,\Omega)}{(\vec{r}^{\,2}-\vec{r}_s^{\,2})}$$

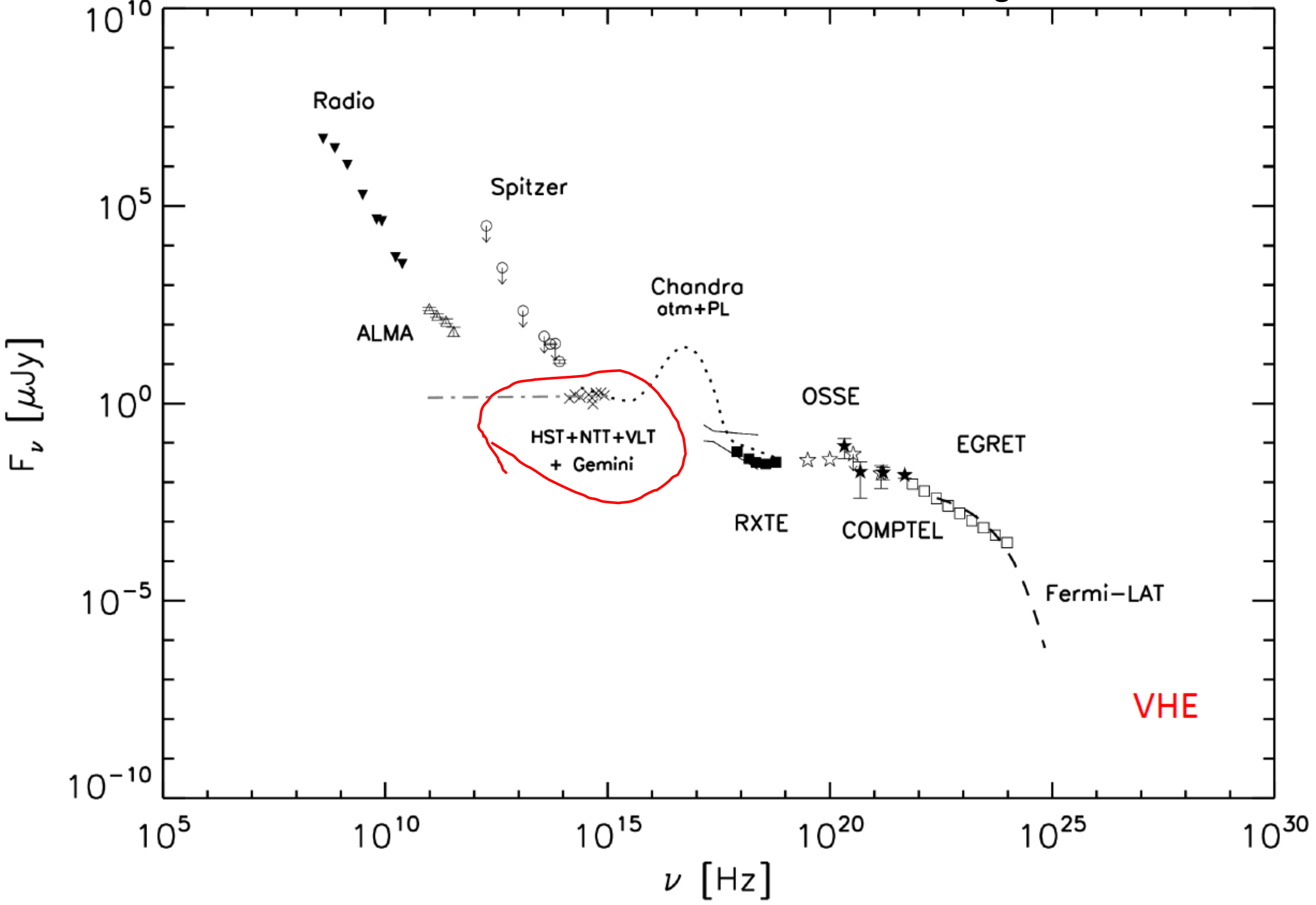
Synchrotron photon density (anisotropic)

Need two trajectories for each particle: one to create the SR emissivity, one to compute the pair SSC and primary IC emission

Primary IC uses this same SR photon density

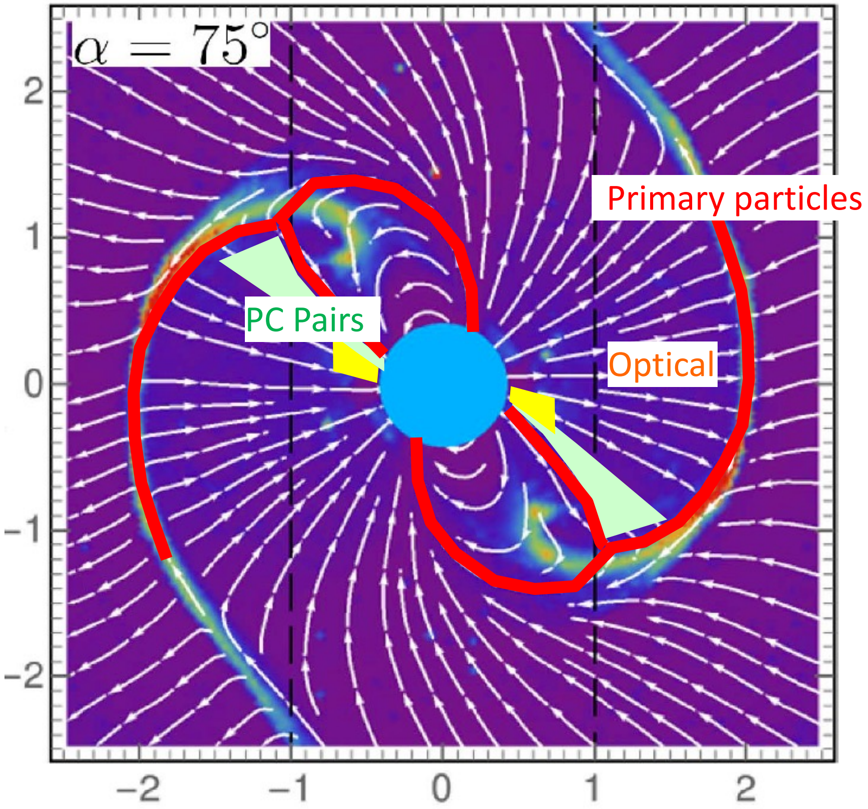
Spectral energy distribution of the Vela pulsar

Mignani et al. 2017



Modeling TeV+ emission from Vela

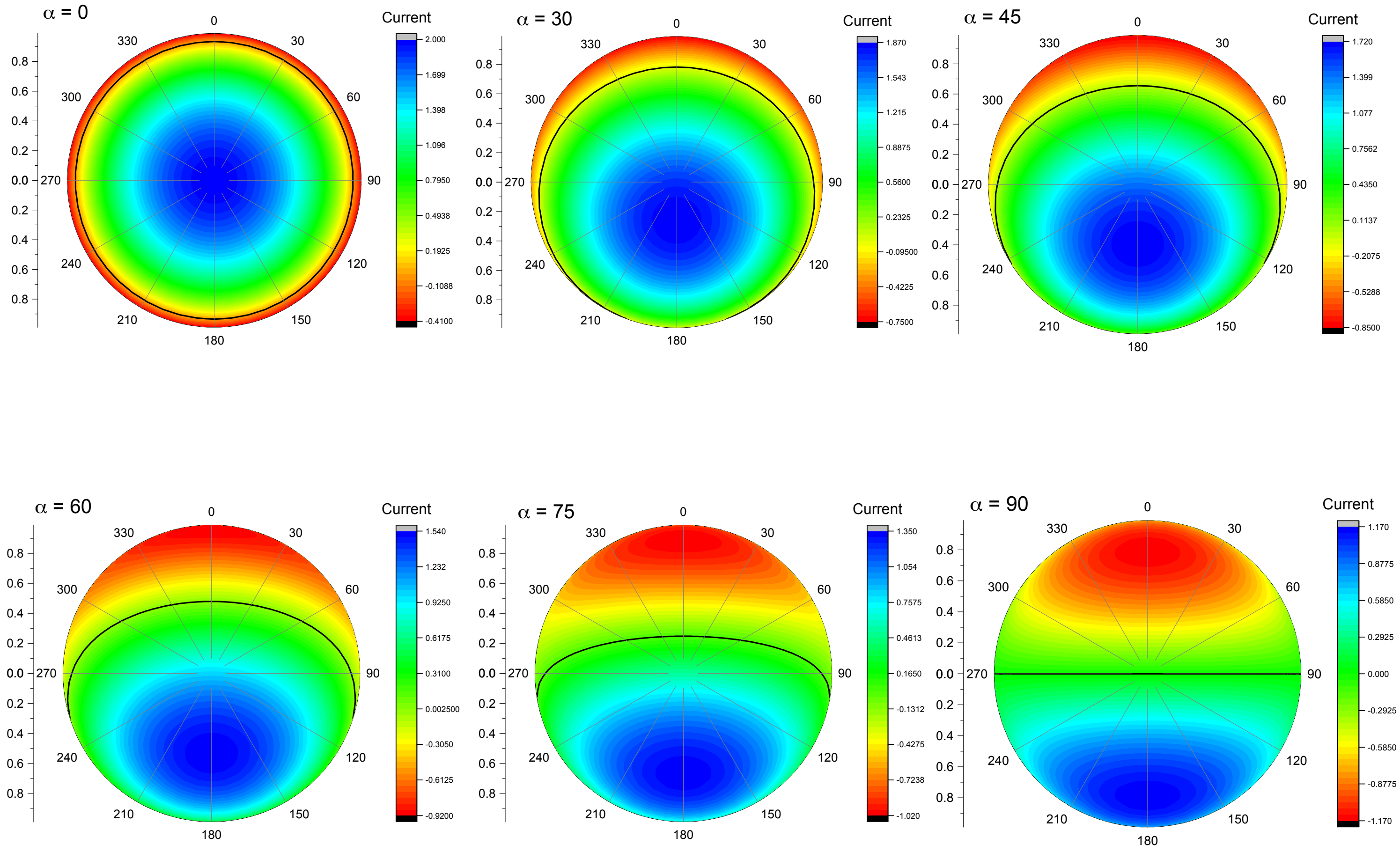
Harding, Kalapotharakos, Venter & Barnard 2018



Near force-free magnetosphere

- PC pairs produce synchrotron radiation (SR) optical/UV at lower altitude
- Primary particles (mostly positrons) produce synchro-curvature (SC) and scatter optical/UV to produce 10 TeV ICS emission
- Pairs scatter optical/UV to produce SSC hard X-ray emission

Force-free current density



Source and model parameters

Pulsar	P (s)	d (kpc)	Radio Flux (mJy)	α	R_{acc}^{low} (cm^{-1})	R_{acc}^{high} (cm^{-1})	J/J_{GJ}	M_+	r_{radio} (R_{LC})
Vela	0.089	0.25	5000	75°	0.04	0.2	18	6×10^3	0.1/0.2
Crab	0.033	2.0	700	45°	0.04	0.4	5.0	3×10^5	>0.8
B1706−44	0.102	2.3	25	45°/30°	0.04	0.2	20	6×10^4	0.08
Geminga	0.237	0.25	1000	75°	0.04	0.15	10	2×10^4	0.1
J0218+4232	0.0023	3.1	100	60°	0.5	5.0	150	3×10^5	0.38

Adjusted to match hard X-ray and Fermi SED (R_{acc}^{low}, R_{acc}^{high})

Adjusted to match optical/soft X-ray SED (M_+, r_{radio})

$$R_{acc}^{low} = eE_{\|}^{low}/mc^2 \qquad R < R_{LC}$$

$$R_{acc}^{high} = eE_{\|}^{high}/mc^2 \qquad R > R_{LC}$$

Crab: constant pitch angle $\psi = 10^{-3}$ for pairs, $\psi = 10^{-5}$ for primaries at $r > 0.8\ R_{LC}$

All others: pitch angle determined by resonant absorption of radio cone beam at r_{radio}

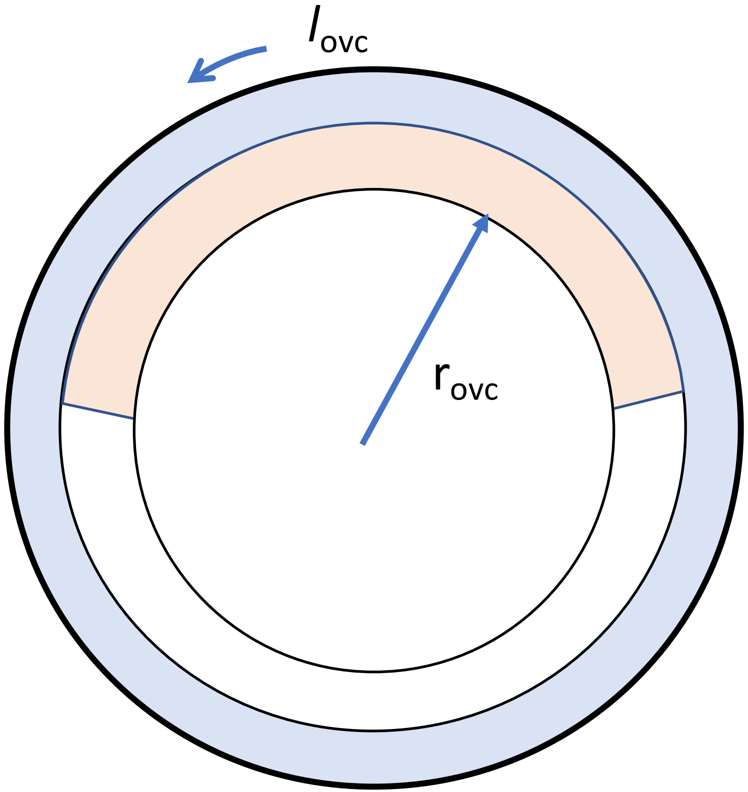
Particle injection

Pairs

r_{ovc} = 0.8 – 0.9
r_{ovc} = 0.88 – 0.91, Crab

Injection for j/j_{GJ} <0
l_{ovc} = 1.5 – 4.78

Initial γ from PC pair spectra
Initial ψ = 0



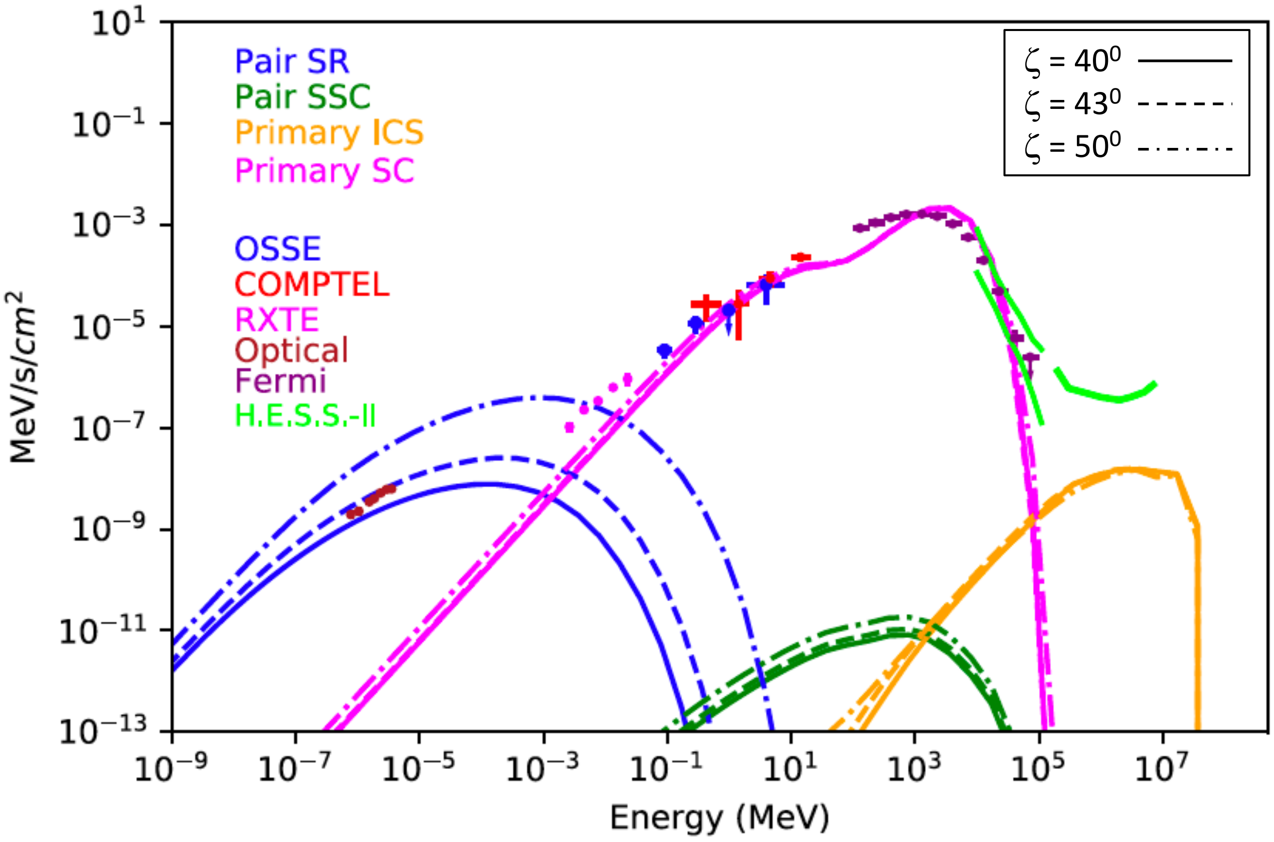
Primaries

r_{ovc} = 0.9 – 0.96
r_{ovc} = 0.91 – 0.94, Crab

Initial γ = 200
Initial ψ = 0

Modeling TeV+ emission from Vela

Harding, Venter & Kalapotharakos 2021
(same as Harding et al. 2018)



Pair spectrum for centered dipole field

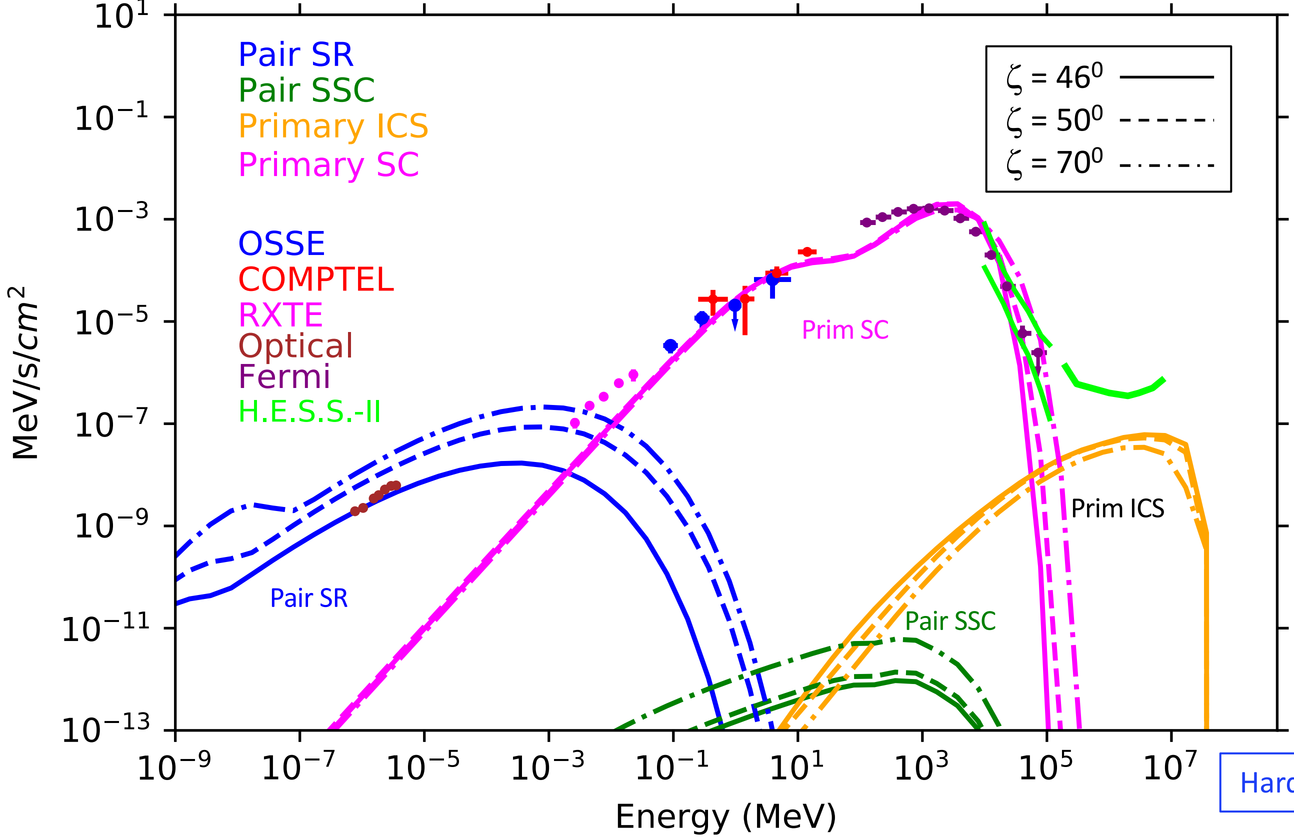
Matches optical but primary ICS well below H.E.S.S. limit

Modeling TeV+ emission from Vela

P = 0.089 s, $B_0 = 4 \times 10^{12}$ G, d = 0.25 kpc

$\alpha = 75^0$, pair $M_+ = 6 \times 10^3$

- Detectable component from primary ICS around 10 TeV!
- Pair SR matches optical spectrum



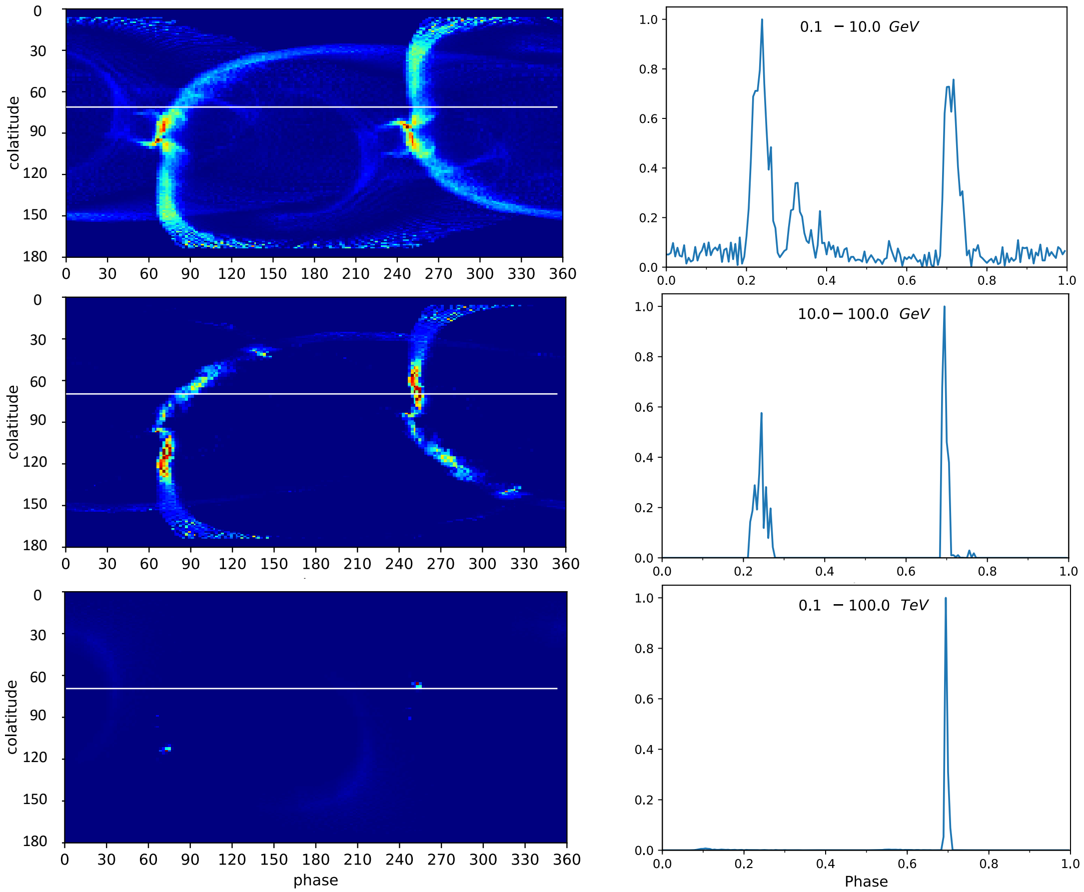
Pair spectrum for offset dipole

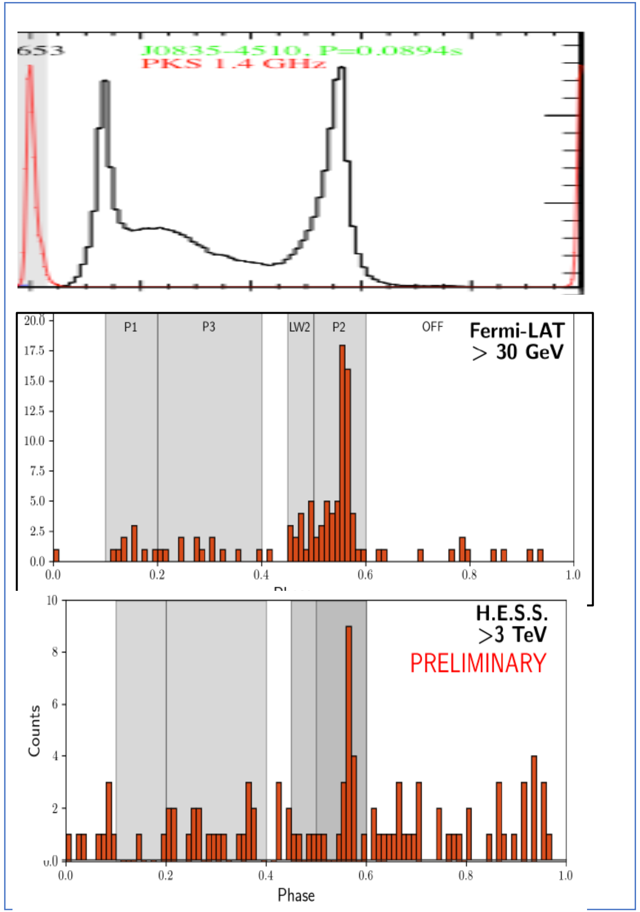
Pair SR has more UV photons ⟶ higher flux for primary ICS

Pulsed emission ~ 10 TeV requires higher particle energy ⟶ GeV emission is CR

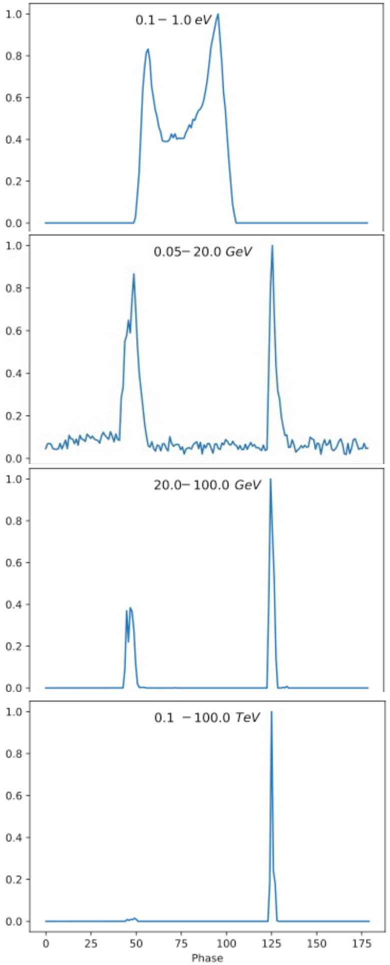
Harding, Venter & Kalapotharakos 2021

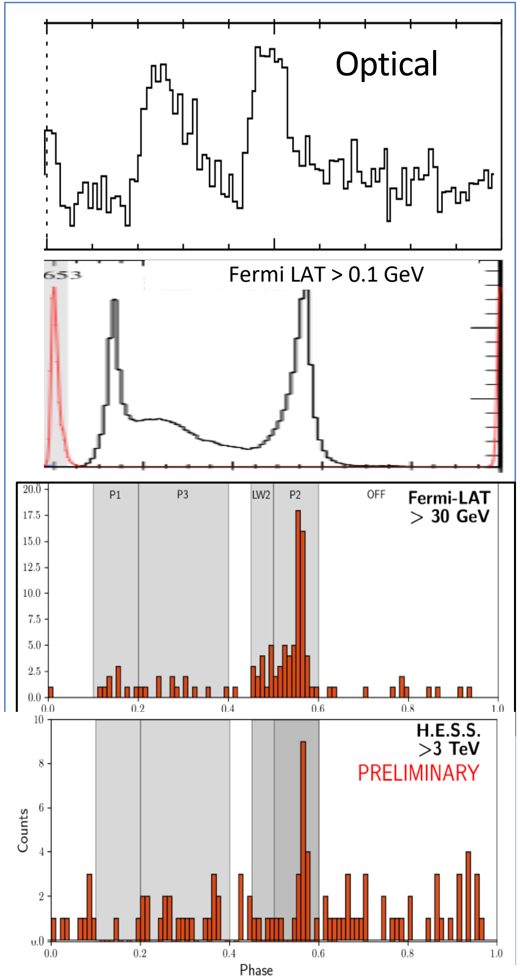
Vela model light curves





Vela model light curves





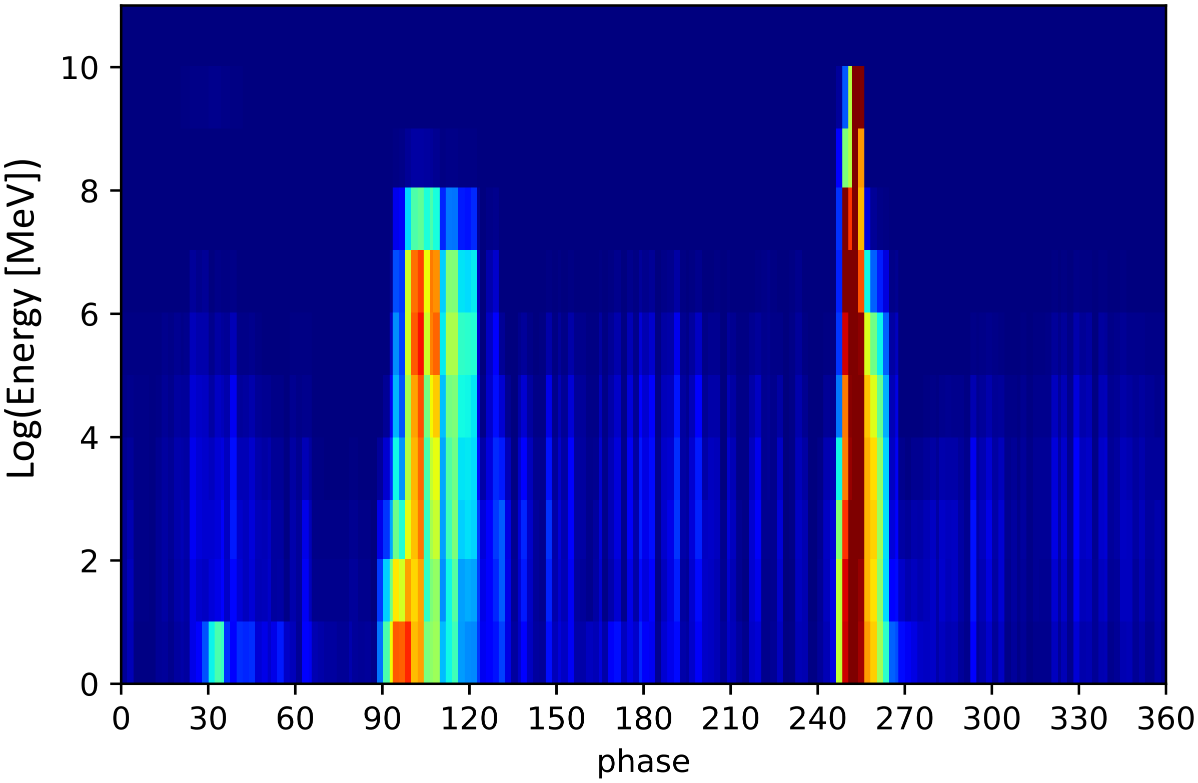
Harding, Kalapotharakos, Venter & Barnard 2018

Fermi P2/P1 increases with energy – higher γ particles produce P2

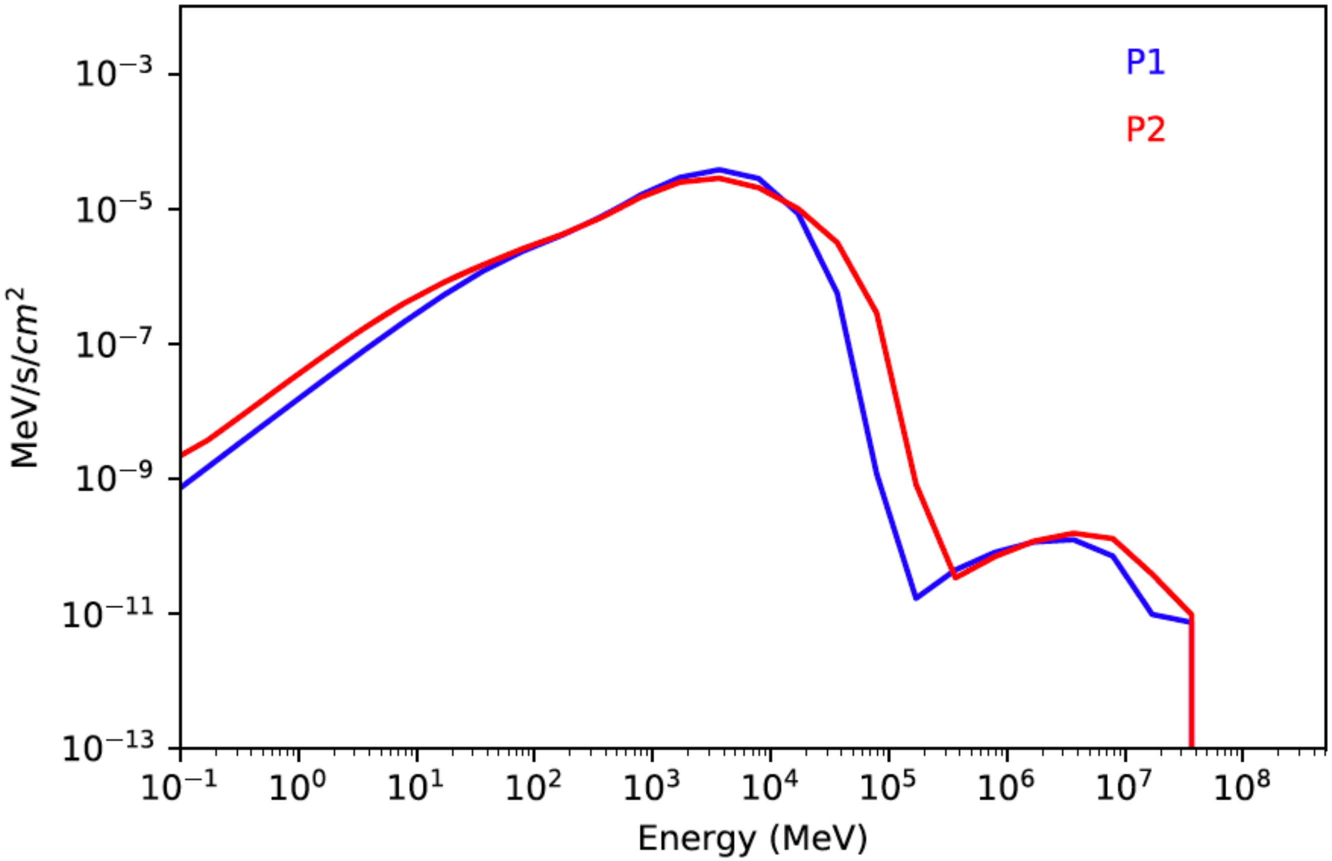
P2 only at > 3TeV – ICS from highest γ particles

Large model γ-ray/radio phase lag due to azimuthally symmetric emission in current sheet

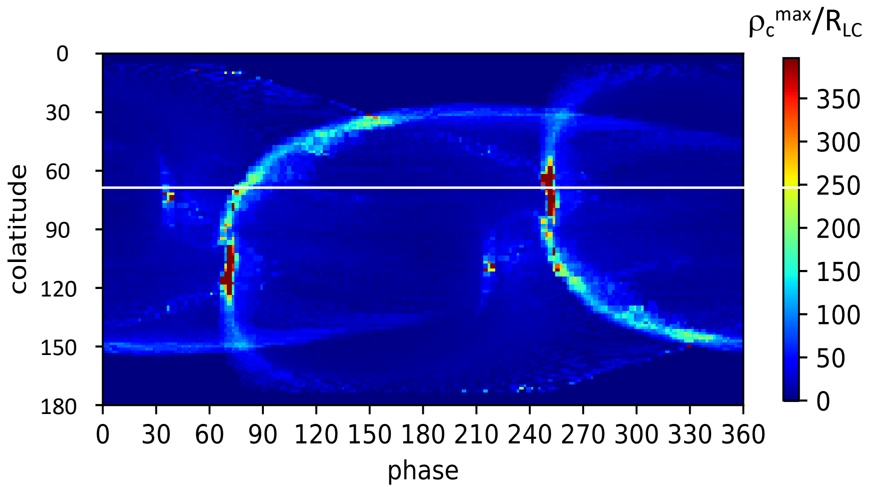
Energy vs. phase

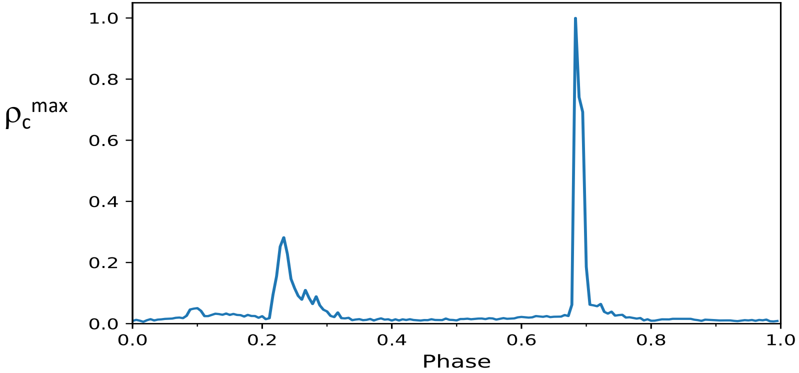


Vela P1 and P2 spectra



Vela P1/P2 evolution with energy





Harding, Venter & Kalapotharakos 2021

Lorentz factor of particles in curvature radiation-reaction limit:

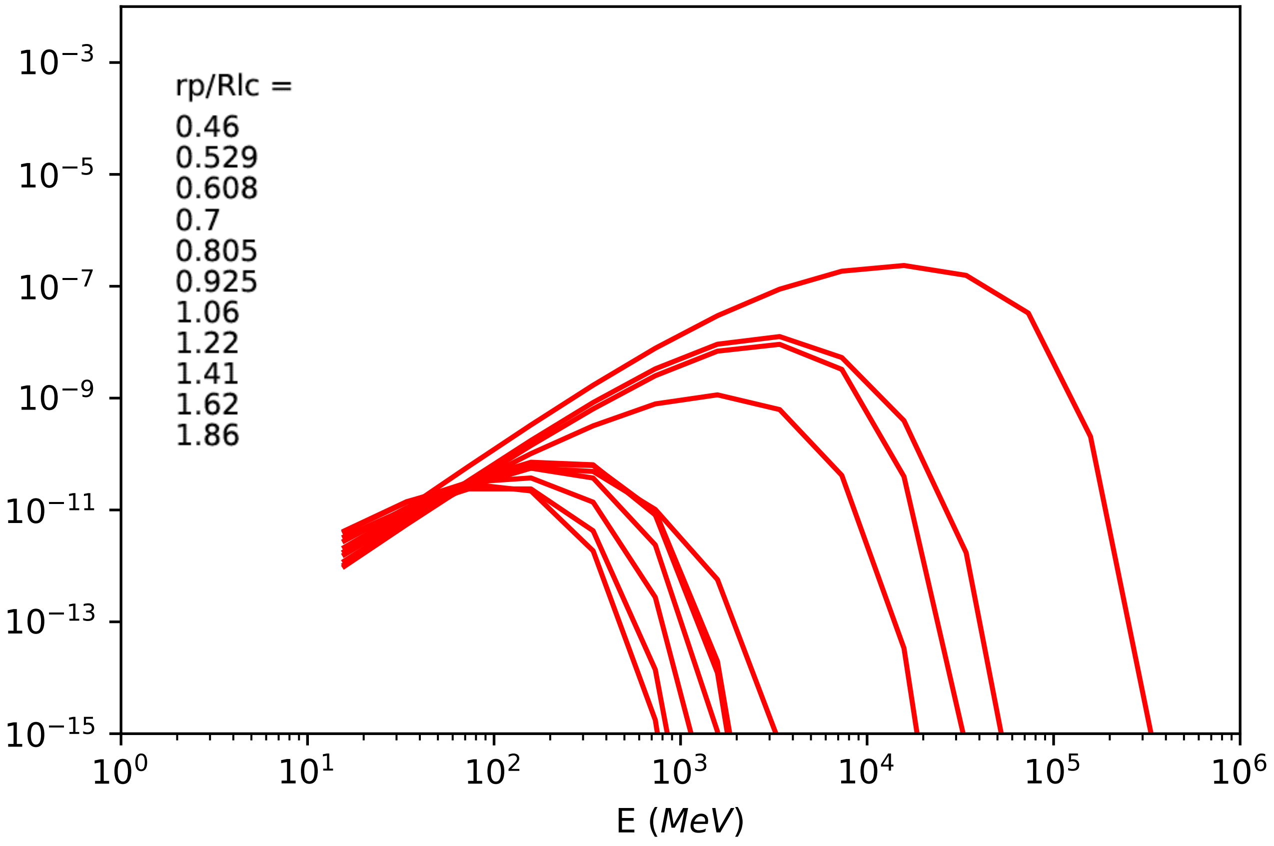
$$\gamma_{CRR} = \left(\frac{3E_{||}\rho_c^2}{2e}\right)^{1/4}$$

High energy cutoff

$$E_{CR} \propto E_{||}^{3/4} \rho_c^{1/2}$$

Maximum curvature radius of particle trajectory is higher for P2 allowing particles and photons at higher energy

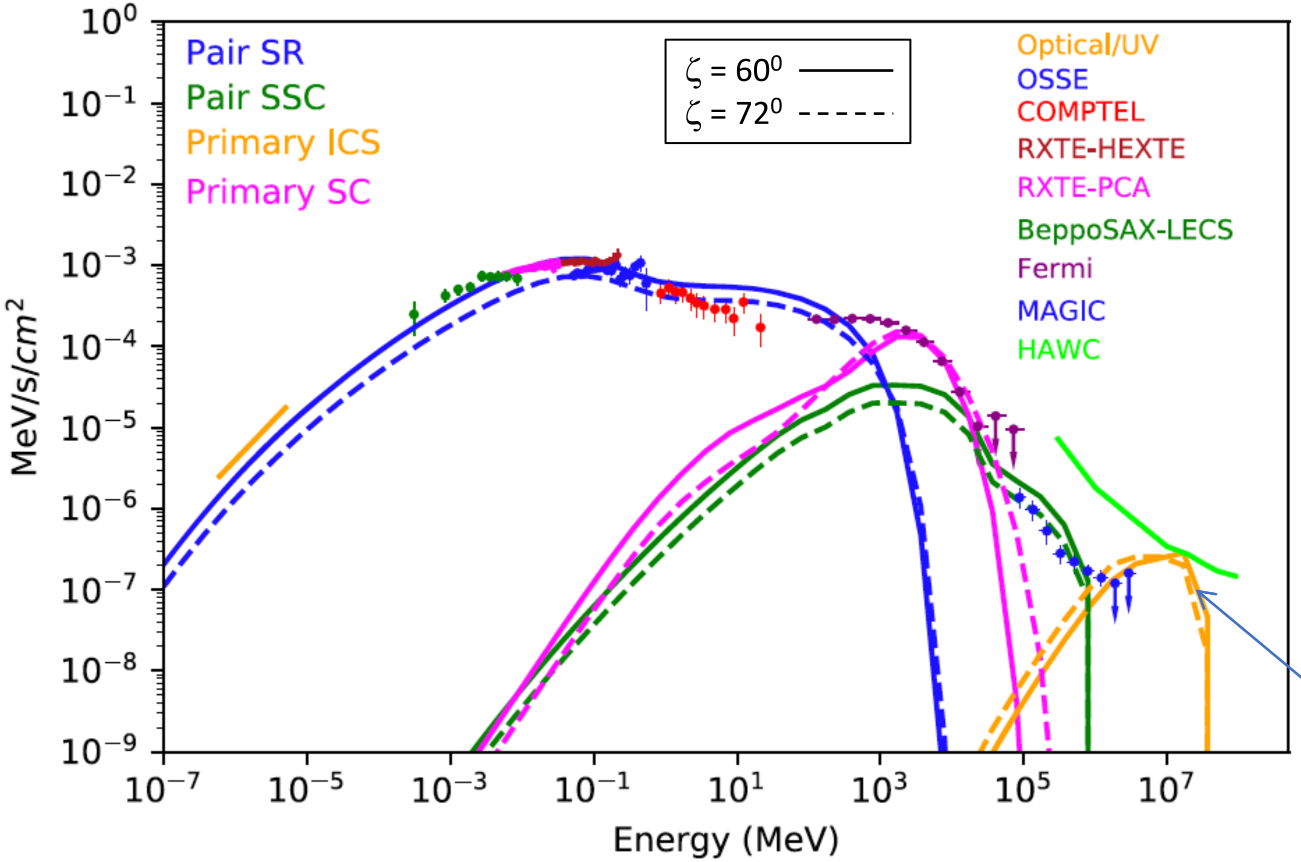
R-dependent spectra



TeV+ emission from Crab pulsar

$\alpha = 45^0$, pair $M_+ = 3 \times 10^5$

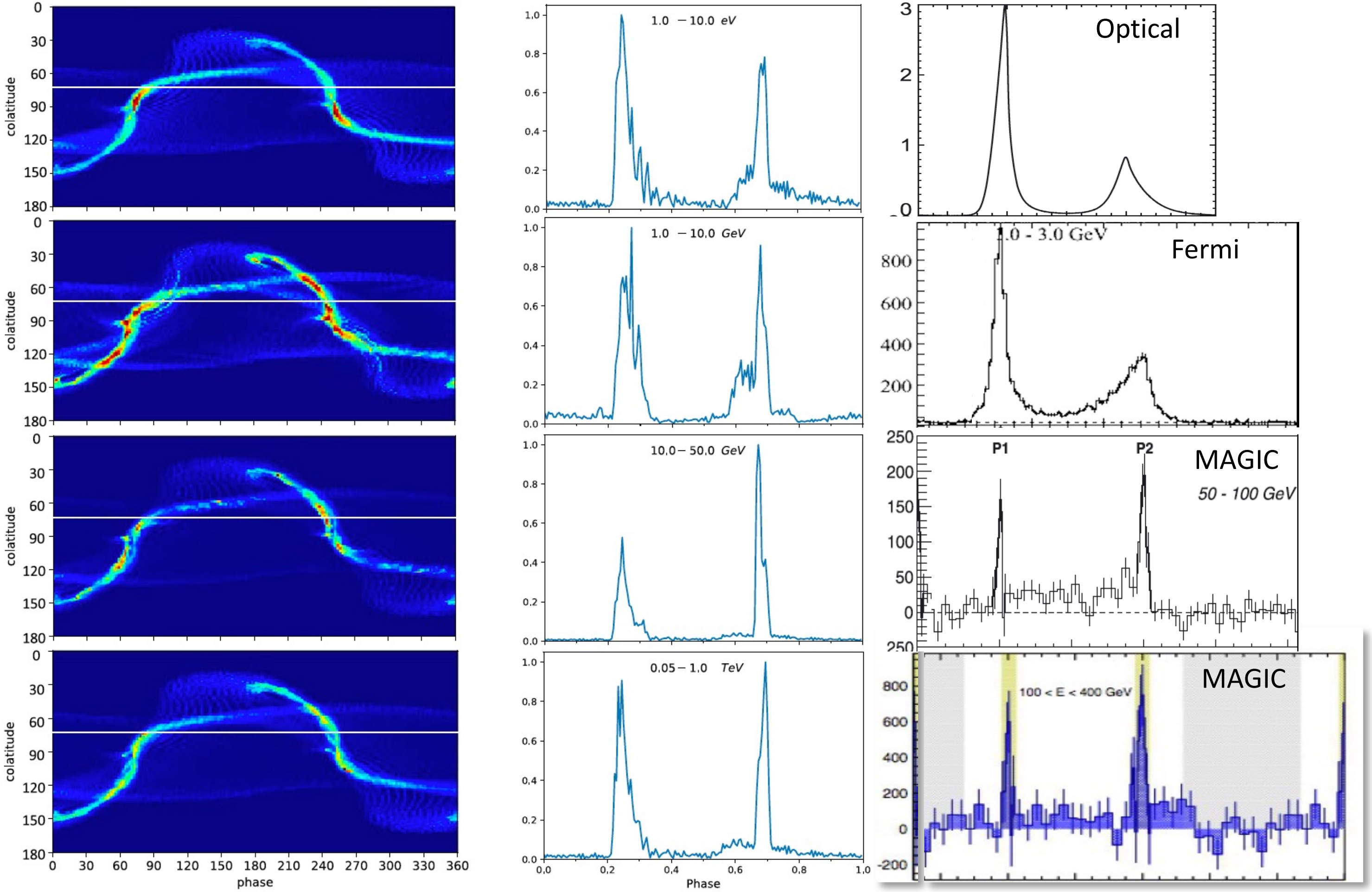
Harding, Venter & Kalapotharakos 2021



- SR from pairs near current sheet
- Synchro-curvature from primaries in current sheet
- SSC from pairs up to ~1 TeV
- ICS from primaries scattering pair SR up to ~30 TeV

γ–γ pair attenuation

Crab model light curves

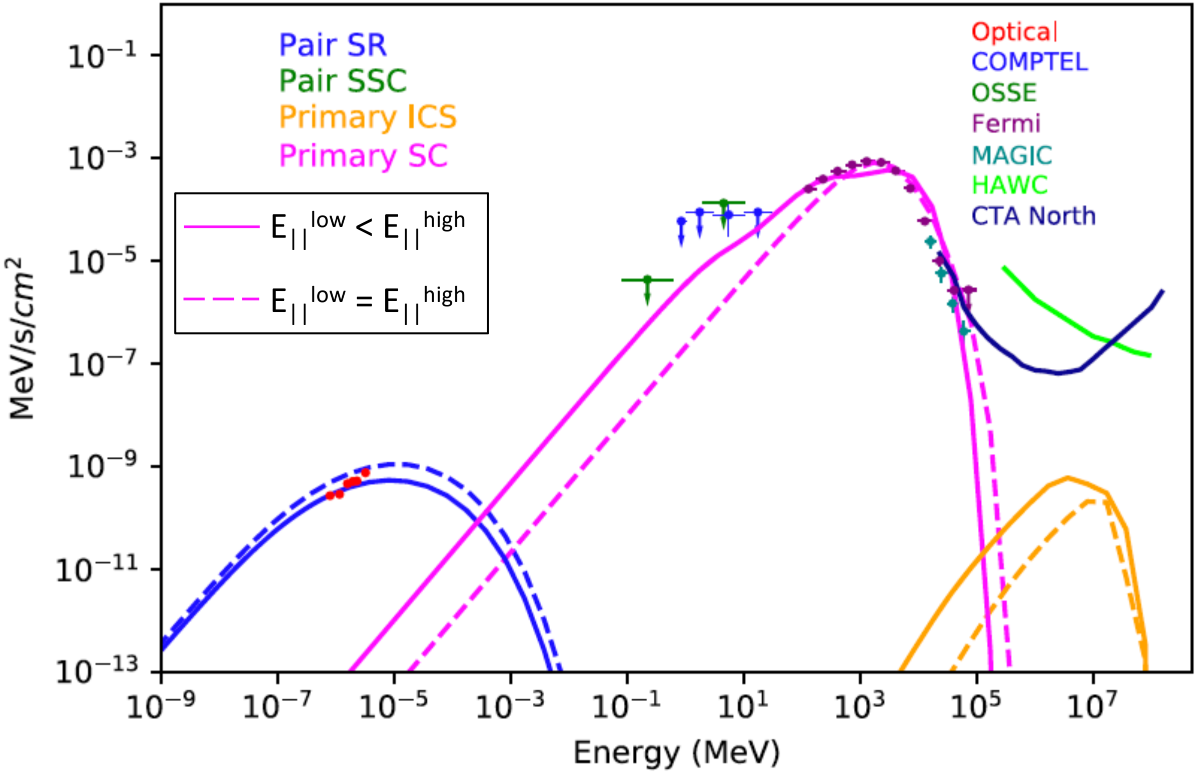


TeV+ emission from Geminga

P = 0.237 s, B_0 = 3 x 10^{12} G, d = 0.25 kpc

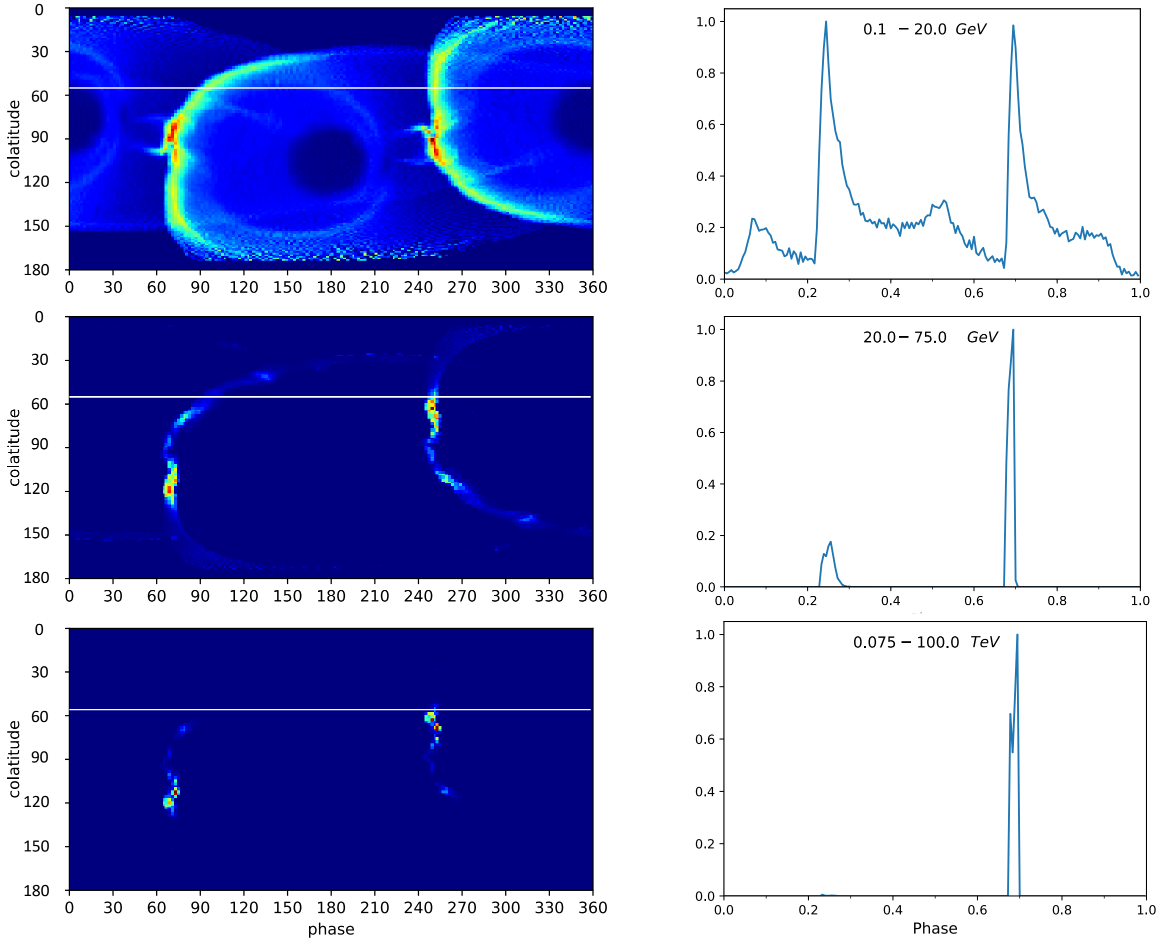
α = 75^0, ζ = 55^0, pair M_+ = 2 x 10^4

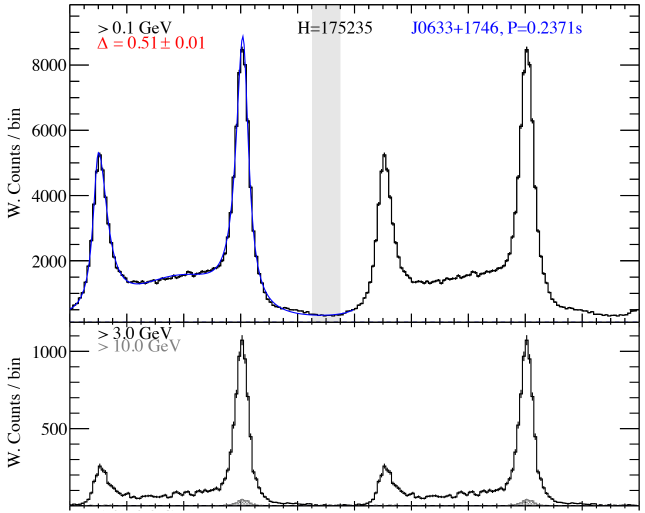
Harding, Venter & Kalapotharakos 2021

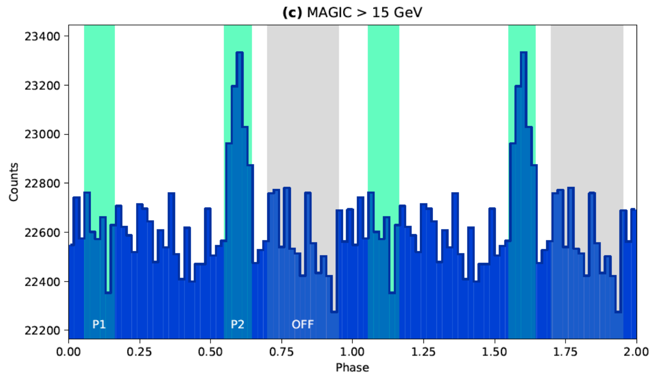


- Low pair SR UV flux
  → Very low primary ICS
- MAGIC detection explained by primary SC

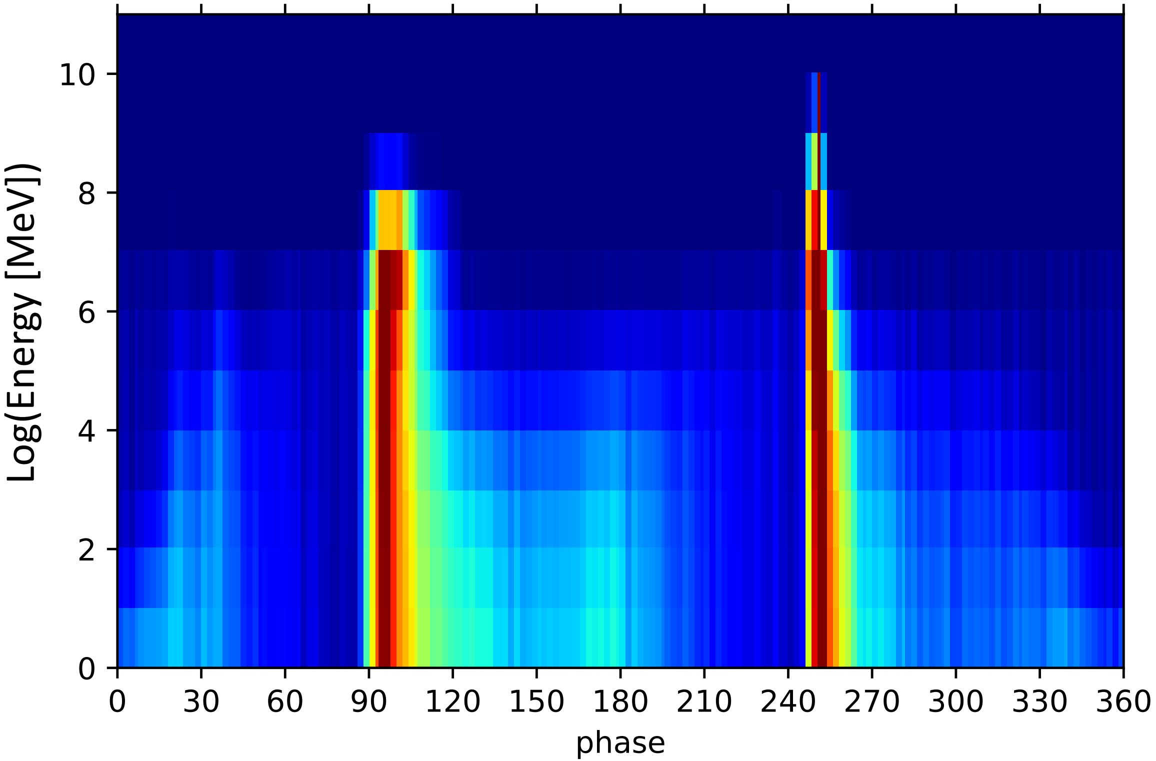
Geminga model light curves







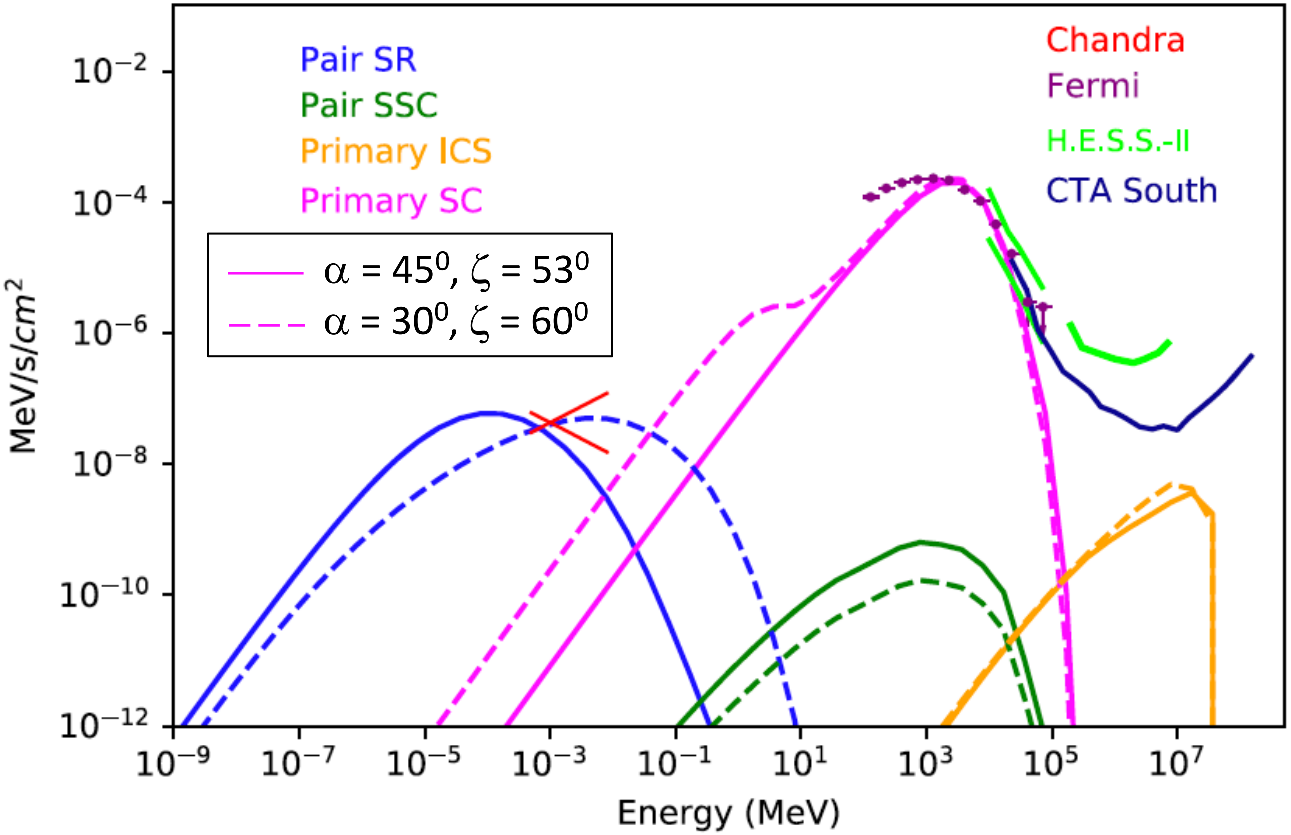
Energy vs. phase



TeV+ emission from B1706-44

P = 0.102 s, $B_0 = 6.2 \times 10^{12}$ G, d = 2.3 kpc
Pair $M_+ = 6 \times 10^4$

Harding, Venter & Kalapotharakos 2021

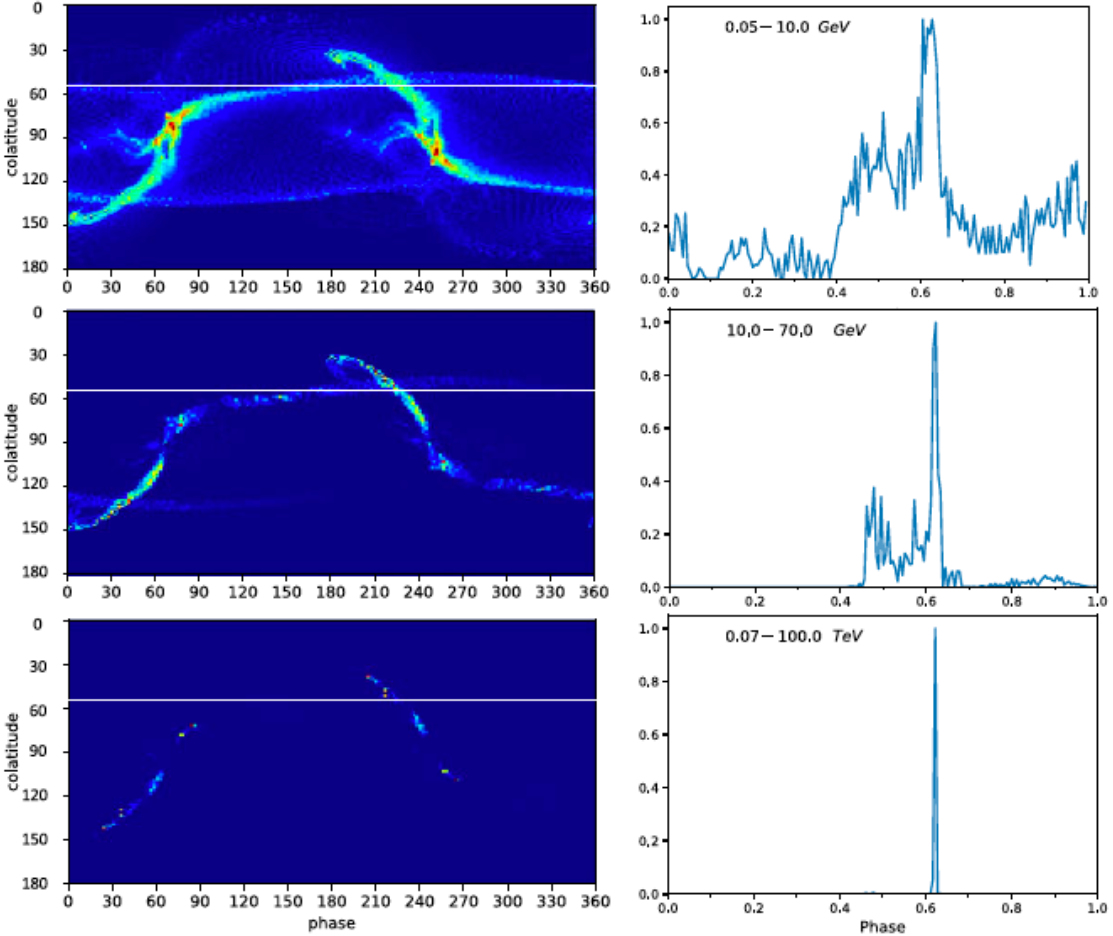


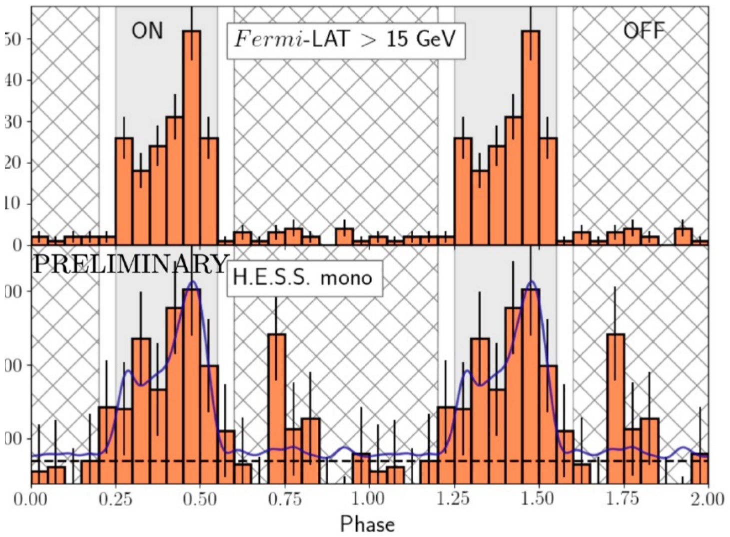
Pair emission at low altitude (like Vela) – but lower radio luminosity

Lower pair SR flux in UV ⟶ lower primary ICS

H.E.S.S. II detection explained by primary SC

B1706-44 model light curves light curves



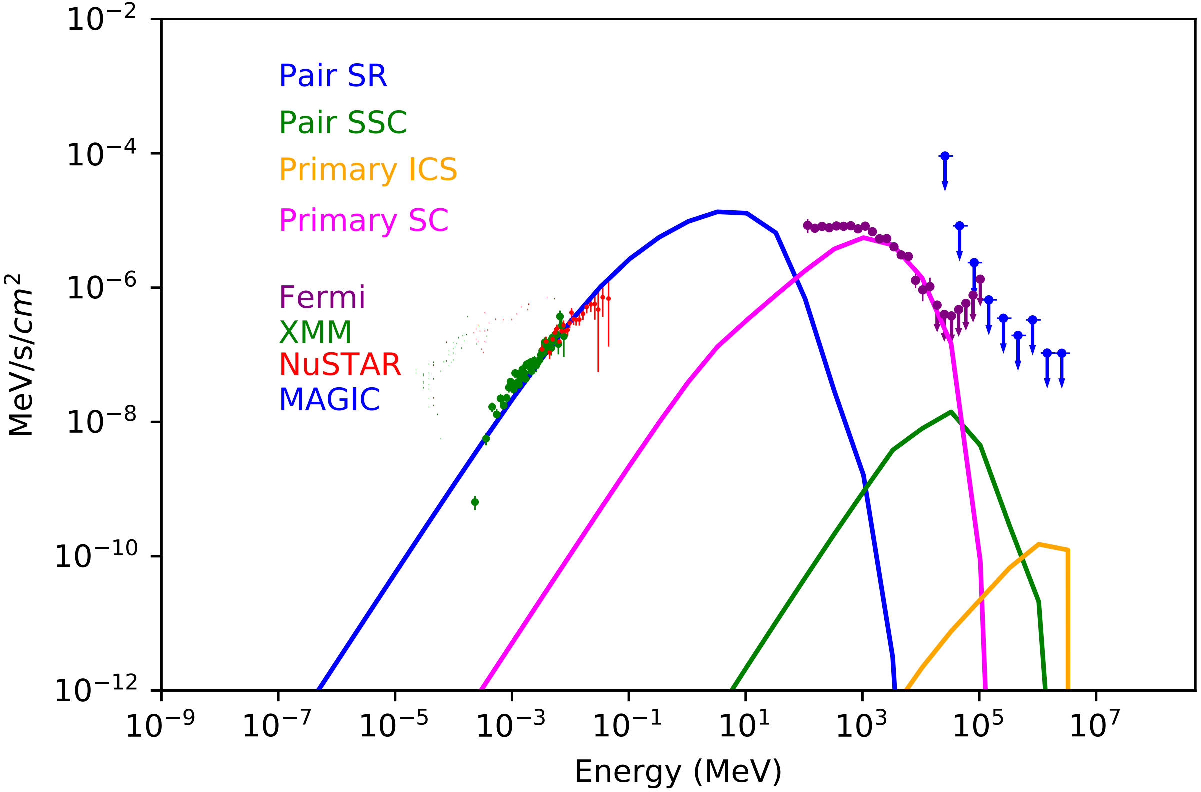


TeV+ emission from MSP J0218+4232

P = 0.0023 s, $B_0 = 8 \times 10^8$ G, d = 3.1 kpc

$\alpha = 60^0$, $\zeta = 65^0$, pair $M_+ = 3 \times 10^5$

Harding, Venter & Kalapotharakos 2021
Acciari et al. 2021 (MAGIC/Fermi paper)



MSP pairs produced at higher energy
→ higher-energy pair SR peak, little optical
→ pair and primary ICS suppressed by KN

GeV/VHE emission

GeV emission

- Recent PIC simulations point to particle acceleration and emission in current sheet
- Curvature radiation explains P1/P2 decrease and most spectra above 50 GeV

TeV+ emission from primary IC:

- Particle energies at least 10 TeV -> GeV emission in curvature radiation regime
- High flux of optical/UV emission
- 20-30 TeV particles produce both Fermi HE cutoff from CR and > 20 TeV IC emission

SSC emission from pairs:

- High pair multiplicity
- High B_{LC} – mostly Crab-like pulsars
- Lower pair energies – SR SED peak below 1 MeV – to avoid KN reduction

Future modeling and outstanding questions

- Variation of $E_{||}$ - radial and azimuthal dependence from MHD and PIC simulations
- Pair spectra from 2D time-dependent PC cascades
- More accurate photon-photon attenuation of TeV+ emission

- Does emission above 10 TeV necessarily imply particle Lorentz factors > 10^7?
- Can SR or IC produce P1/P2 decrease with energy?