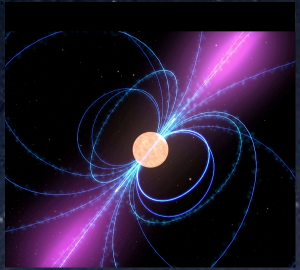
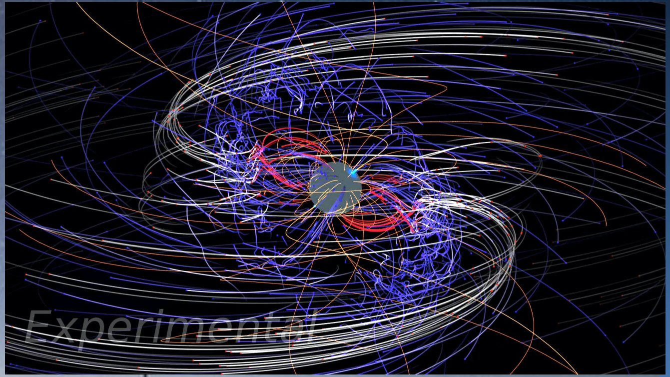
Pulsar High-Energy Emission Models



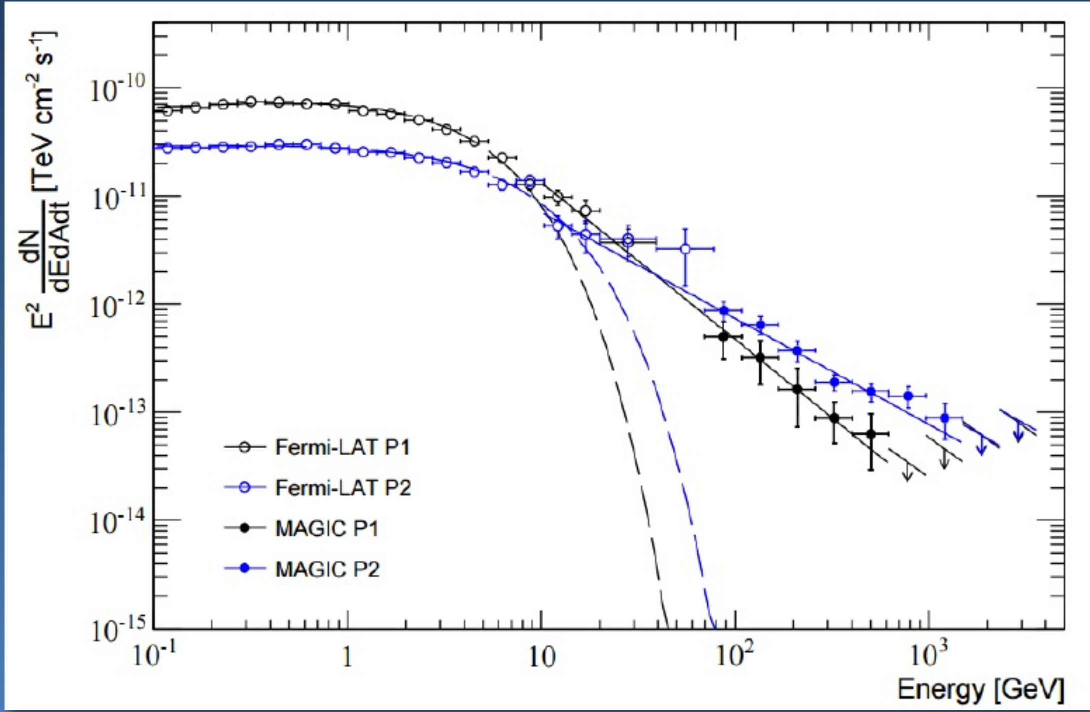
Alice K. Harding
Los Alamos National Laboratory



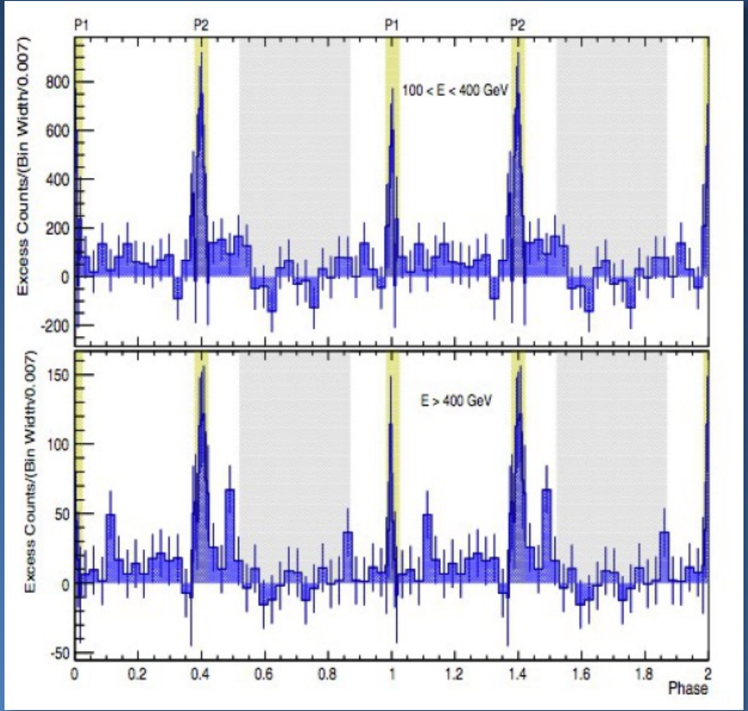
Detection of Crab pulsar up to 1 TeV

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

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

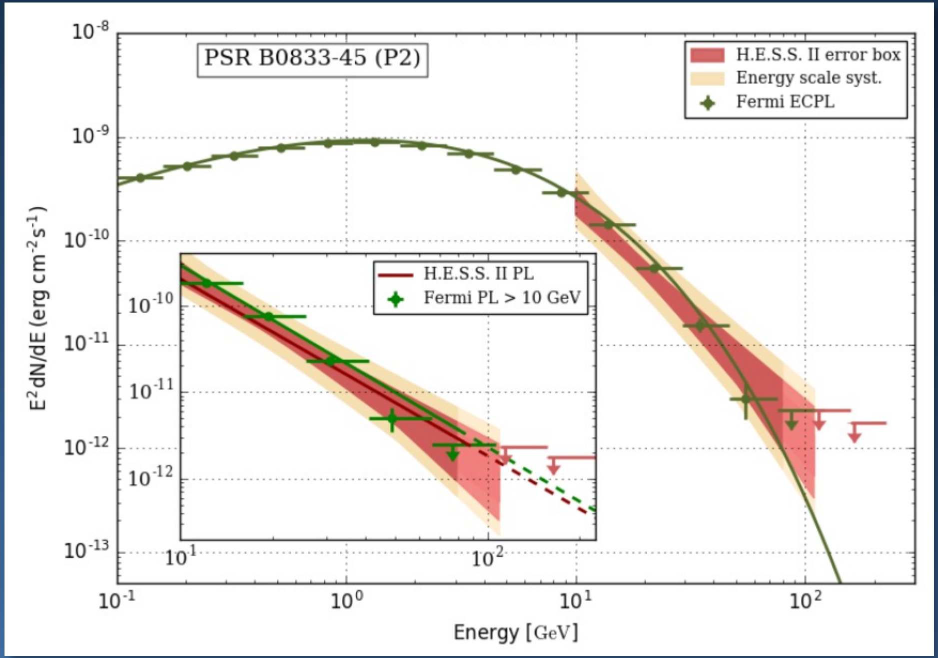


Both peaks detected!



Vela pulsar – H.E.S.S. II

10 – 110 GeV (Abdalla et al. 2018)

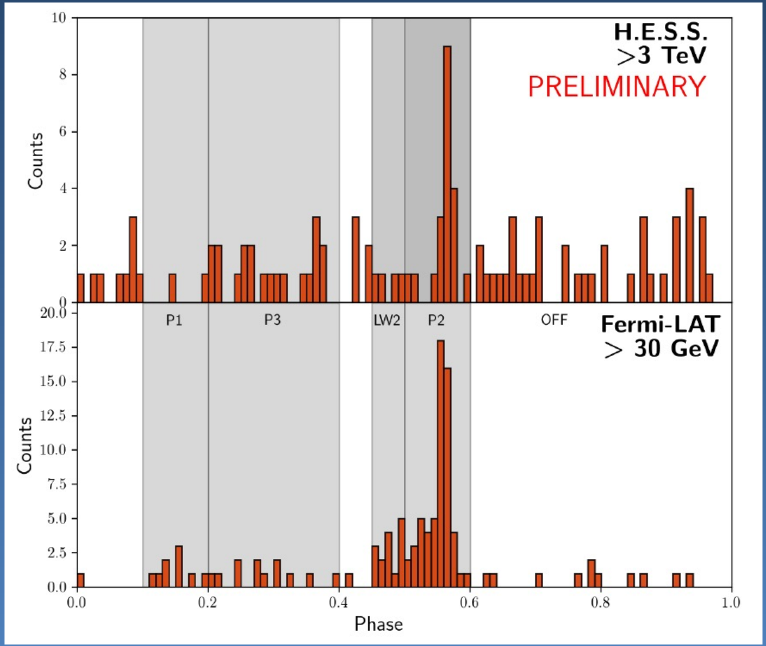


Continuation of Fermi spectrum (curved sub-exponential) or power law?

Curvature favored by H.E.S.S. II at $> 3.0\sigma$

2004 – 2016: 60 hours in stereoscopic mode
3 - > 7 TeV!! 5.6σ (Djannati-Atai 2018)

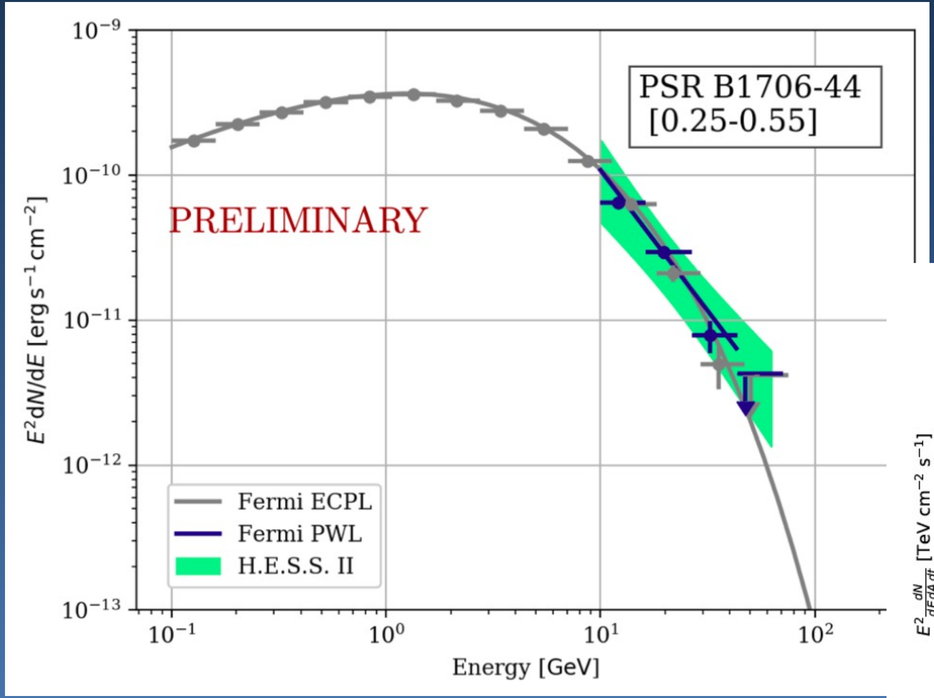
Additional component distinct from GeV spectrum?



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

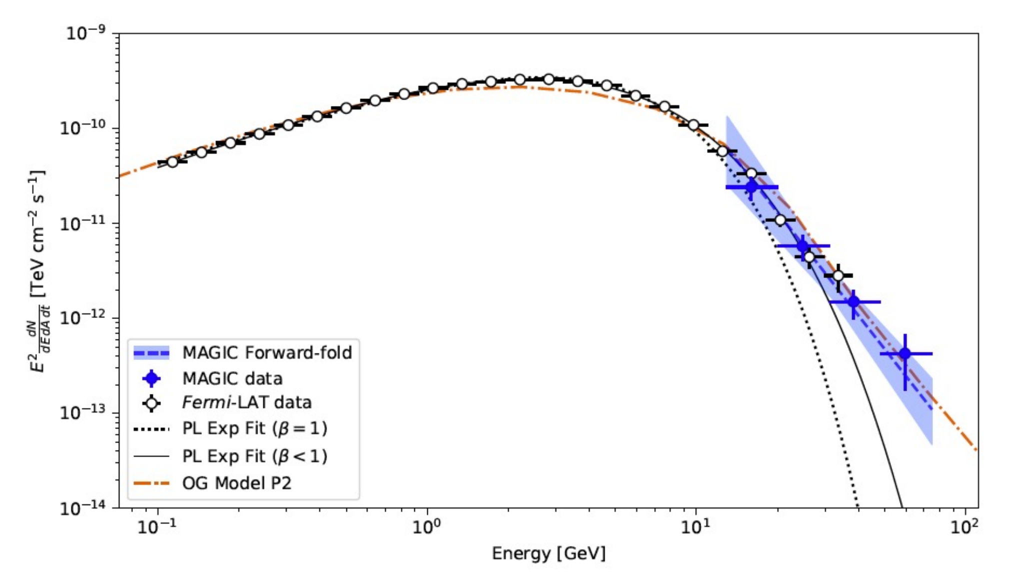
Spir-Jacob et al. 2019

10 – 70 GeV

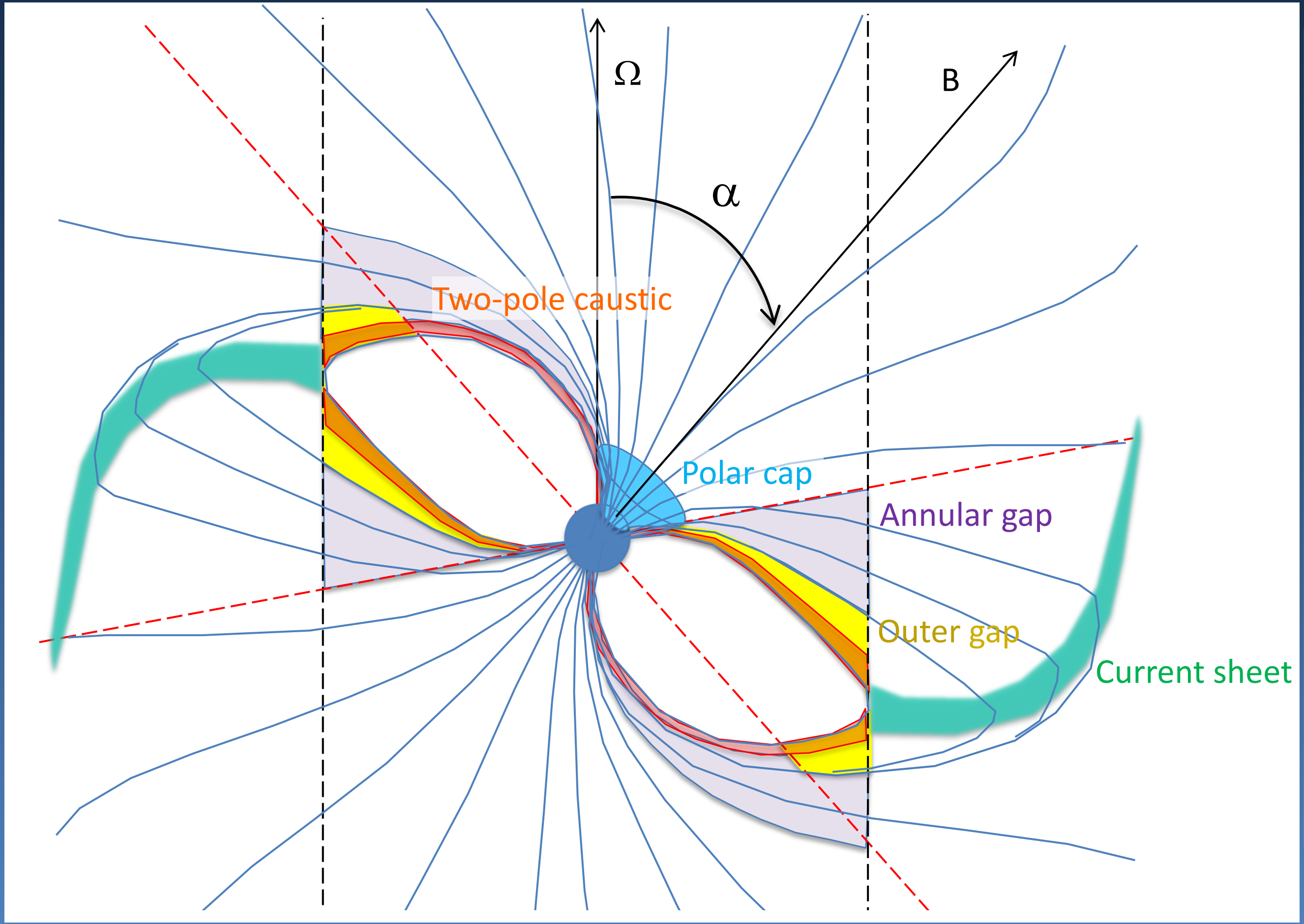


Acciari et al. 2020

Spectrum measured up to 75 GeV



High-energy emission models



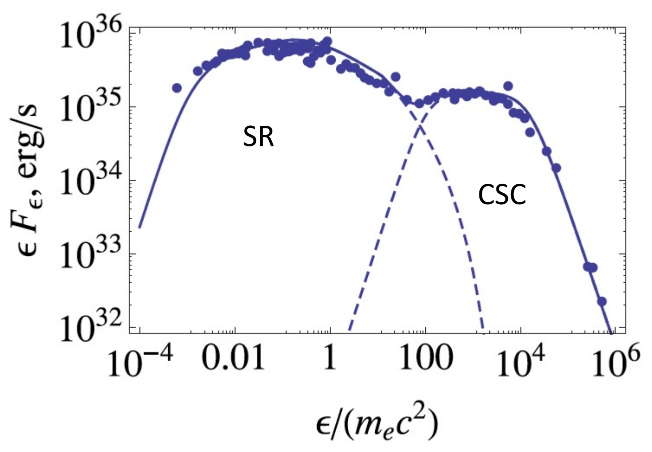
Outstanding questions:

- Location of the acceleration and emission
- Origin of the GeV emission – CR, SR or IC?
- What is the source of the radiating particles – pairs from polar cap, OG or current sheet?

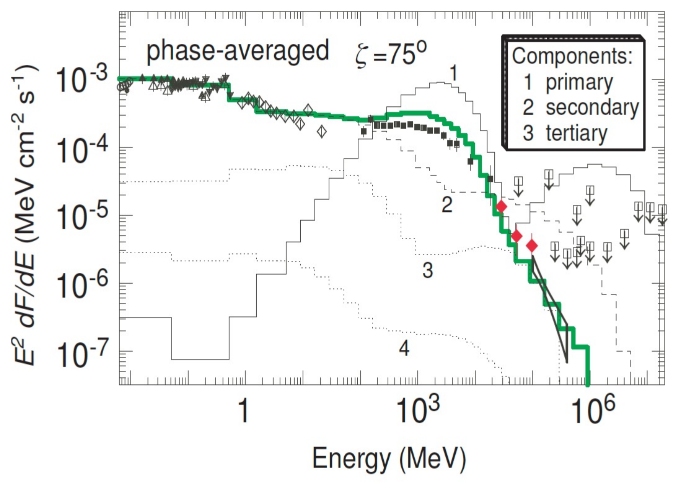
Inverse Compton models of Crab pulsar

- VHE Emission is SSC from pairs
- SSC spectrum reflects pair spectrum
- Possibility of structure in HE spectrum

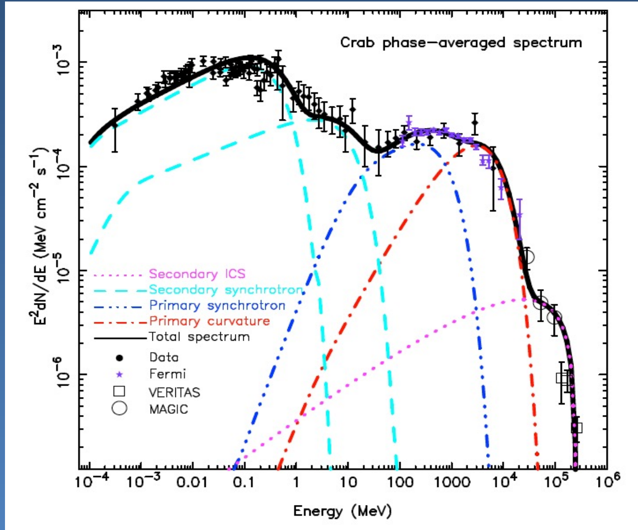
Lyutikov 2013
Outer gap



Hirotani outer gap
(Aleksic et al. 2011)

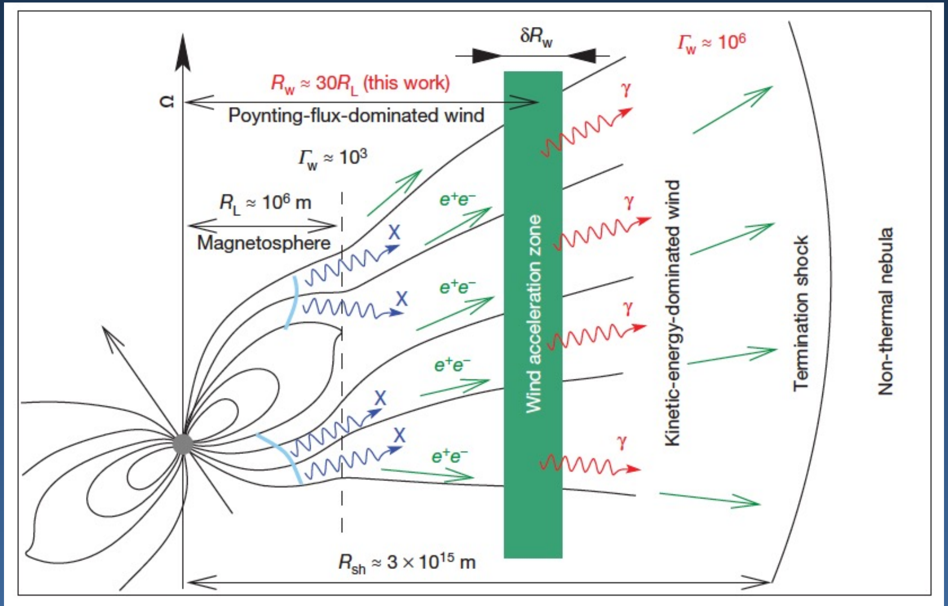


Annular gap (Du et al. 2012)

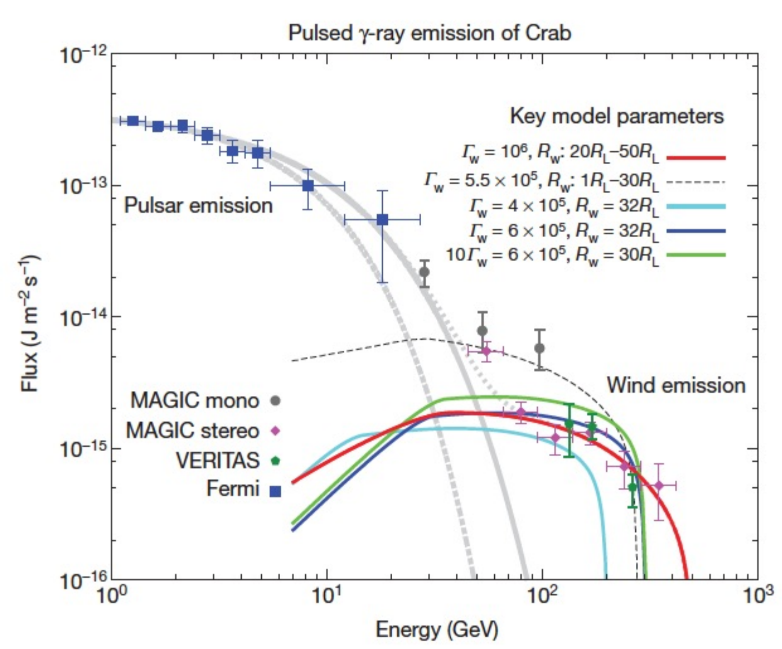


Crab pulsar – cold wind ICS

Aharonian et al. 2012

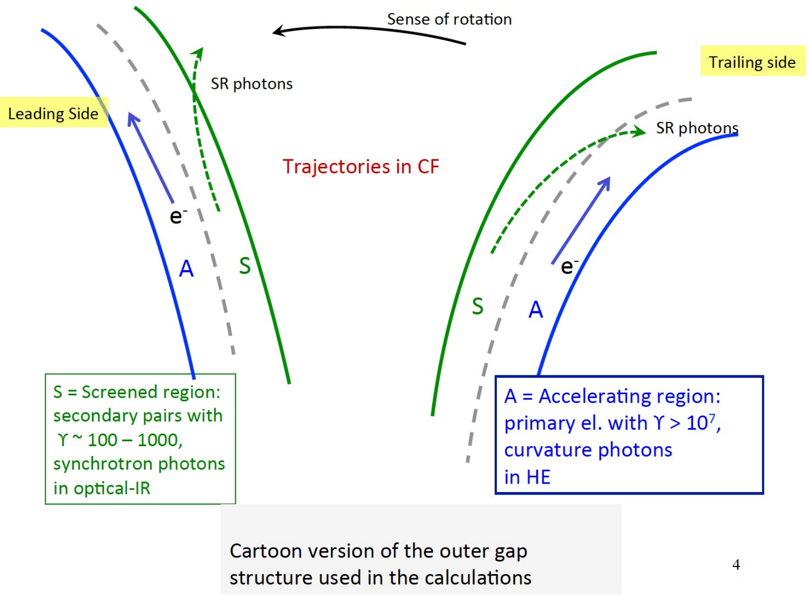


- Scattering of wind e^+-e^- off of optical/X-ray pulsed emission
- Emission at 20 – 30 R_{LC}
- Cannot reach 1 TeV nor produce lower energy emission



Outer gap model for Vela TeV emision

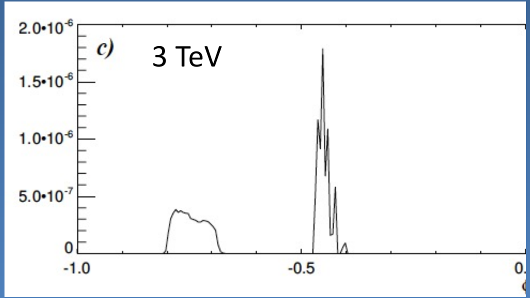
Rudak & Dyks 2017

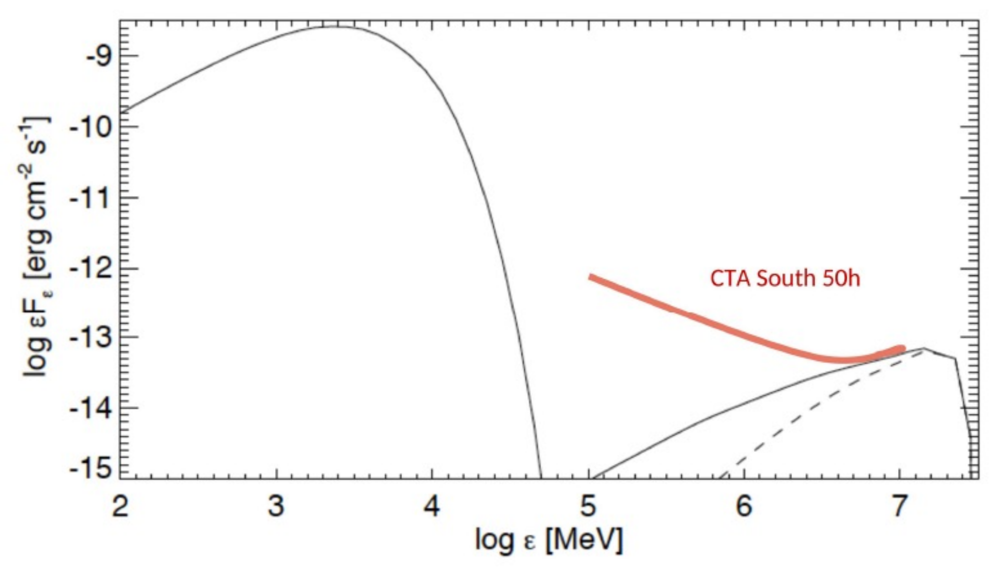


Cartoon version of the outer gap structure used in the calculations

Outer gap model

- Emission inside light cylinder
- PC pairs produce SR optical/UV
- Accelerated primaries scatter optical/UV photons

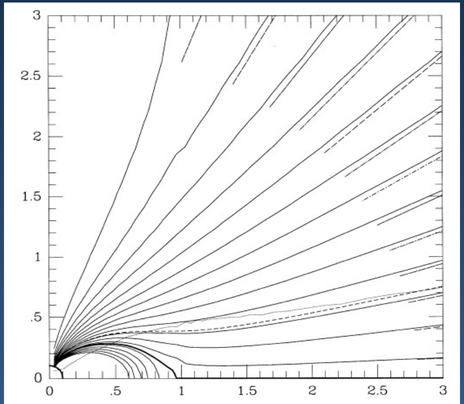




Global force-free models

$\alpha = 0^0$

Contopoulos, Kazanas & Fendt 1999



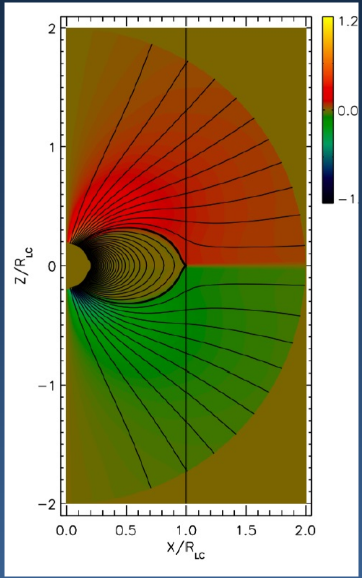
$$E = -\frac{v \times B}{c}$$

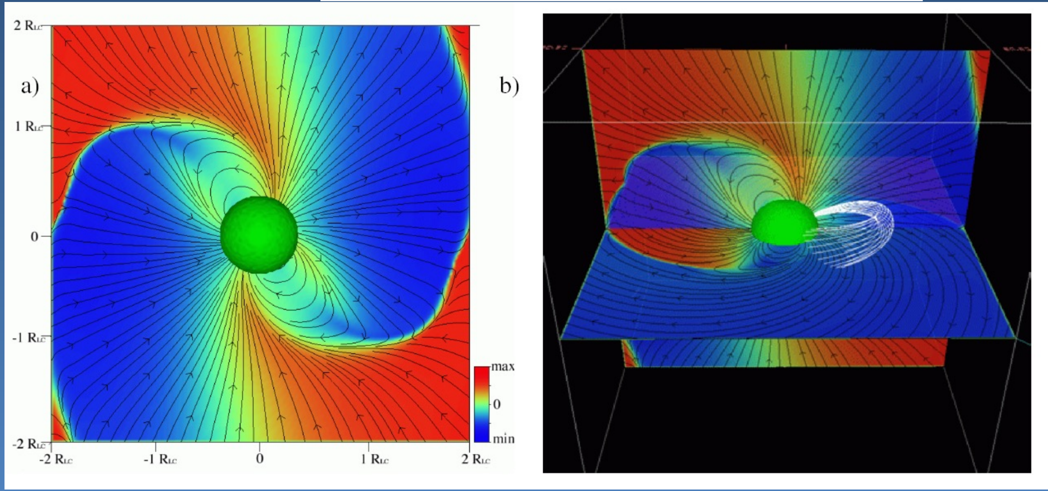
Goldreich-Julian density $\rho_{GJ} = \frac{\nabla \cdot E}{4\pi} \approx -\frac{\Omega \cdot B}{2\pi c}$

Force-free electrodynamics:

$E \bullet B = 0$ everywhere

No accelerator gaps!



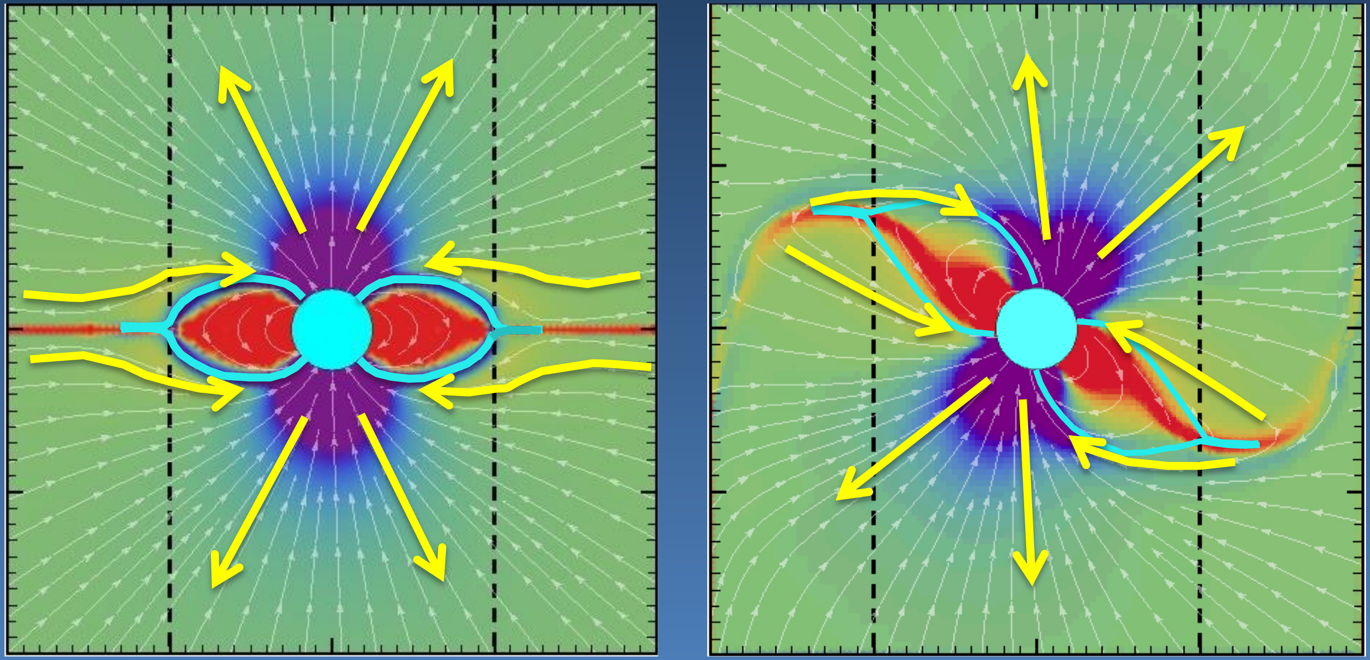


Spitkovsky 2006

$\alpha = 60^0$

Force-free pulsar magnetospheres

- Contain open and closed field regions
- Contain different signs of charge
- Current sheet forms along spin equator
- Current flows out of polar regions and returns along equatorial current sheet

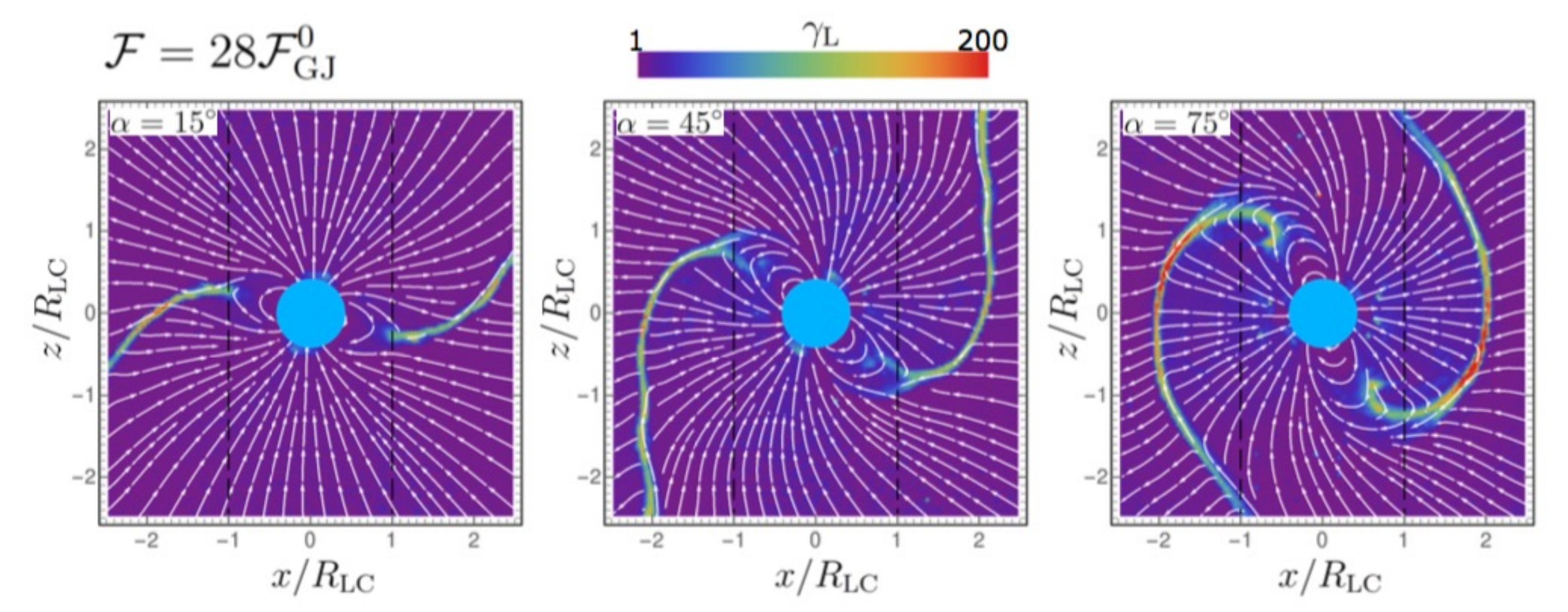


Color: charge density, Streamlines: magnetic field

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



Global kinetic plasma (PIC) simulations

Brambilla et al. 2018

Philippov & Spitkovsky 2018

Pair injection from NS surface

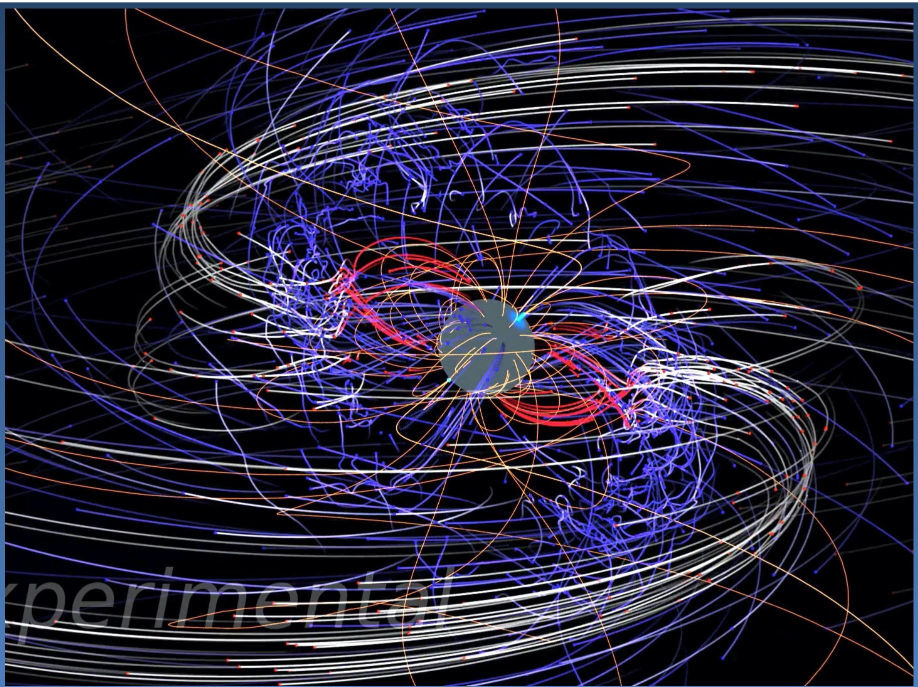
Electrons and positron both flow out from surface

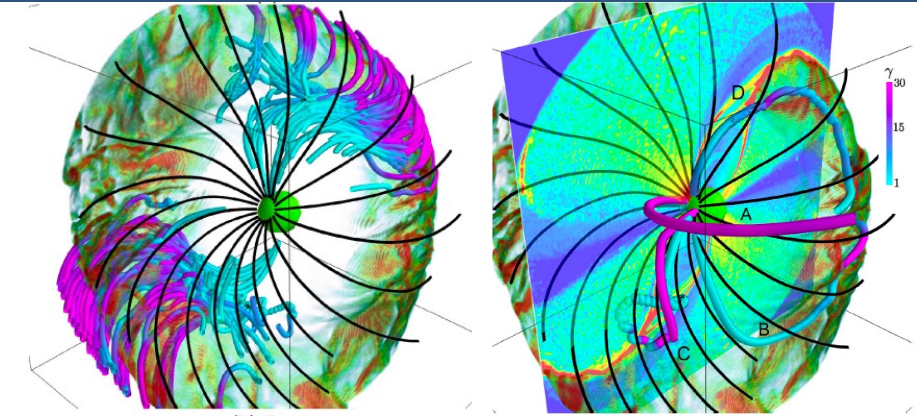
Positrons flow out past Y-point and accelerate in current sheet

Electrons turn around and precipitate inward from Y-point

Pair creation mostly at Y-point and current sheet

Counterstreaming electrons and positrons both accelerate and radiate in current sheet

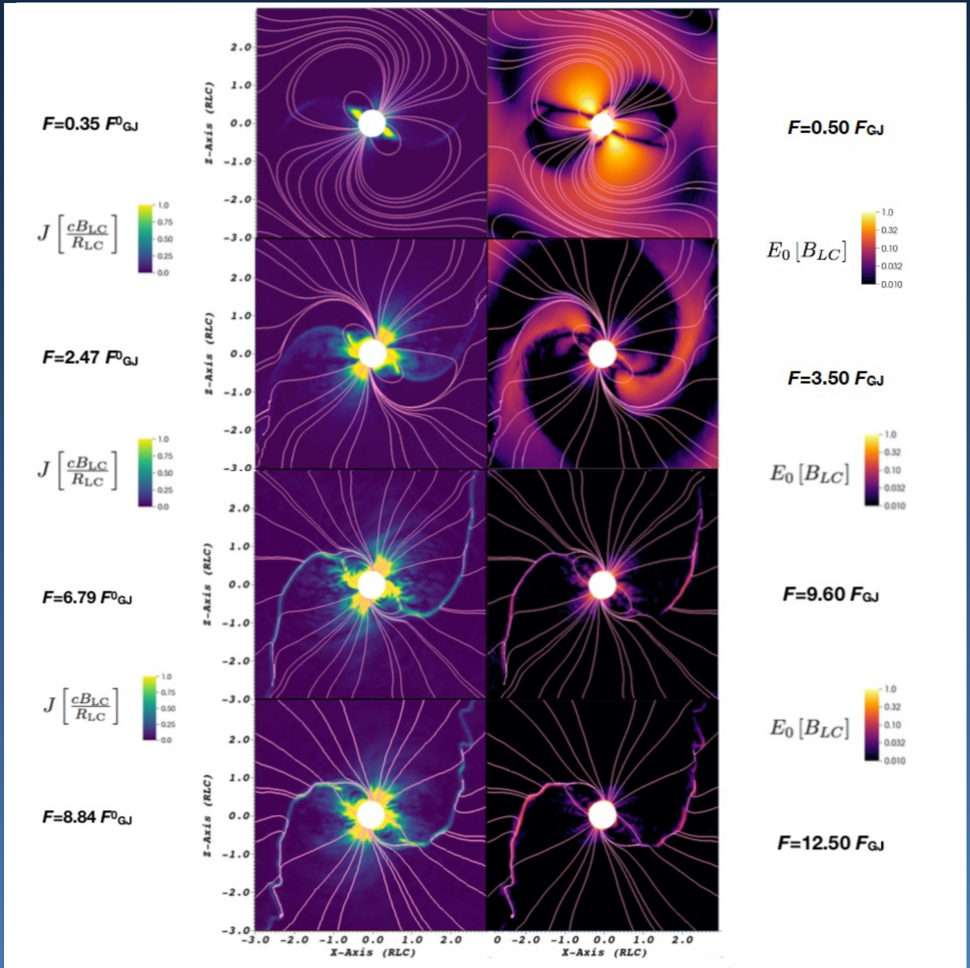




(b) Positrons

(c) Electrons

PIC simulations – Current and E0

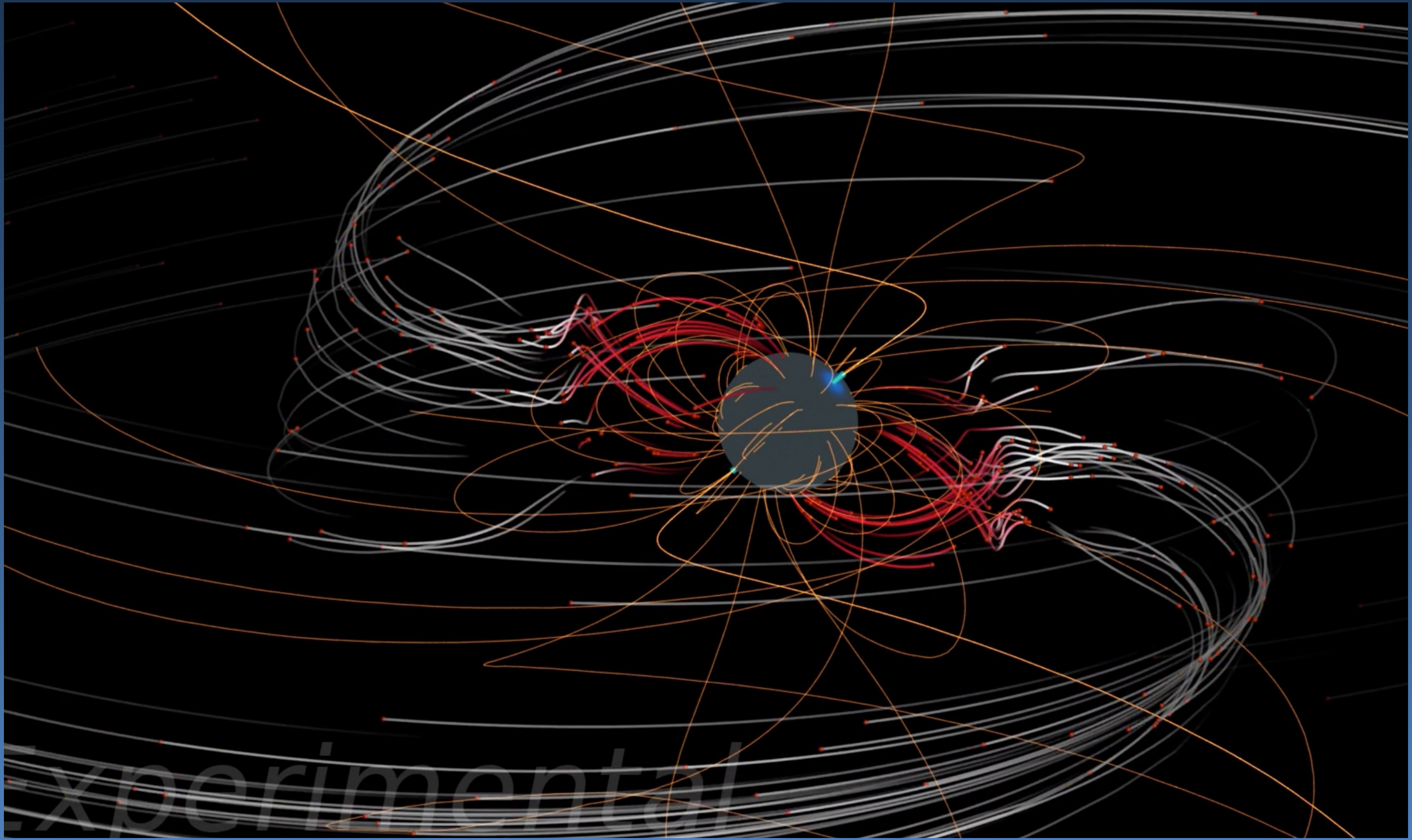


Brambilla et al. 2018

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

Accelerating positrons

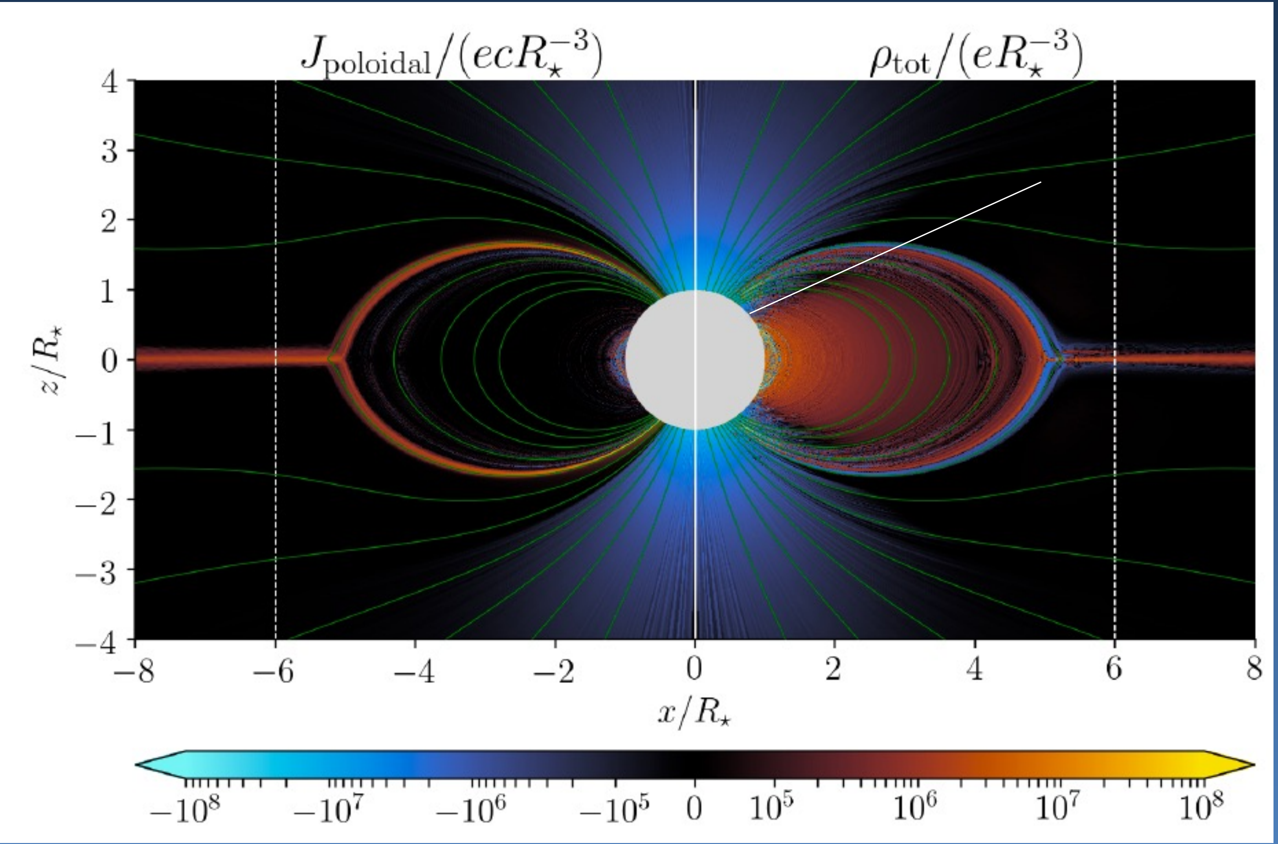
NASA visualization from Brambilla et al. 2018



PIC simulations show positrons accelerating at low rate in separatrix (red) and at higher rate at Y-point and in current sheet (white)

No outer gaps?

Hu & Belodorodov 2021



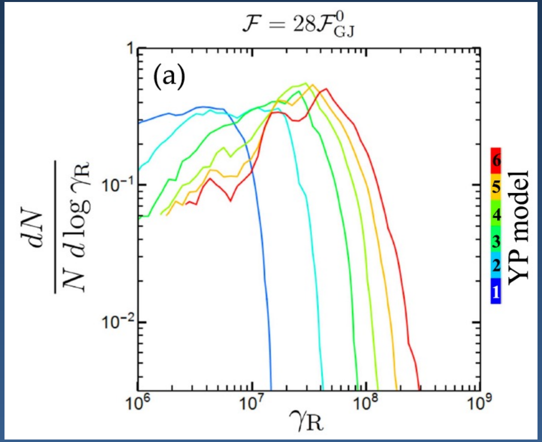
Change of charge sign across null surface

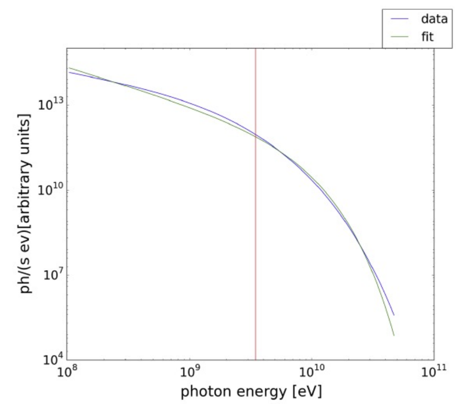
But most current flows along separatrix and current sheet

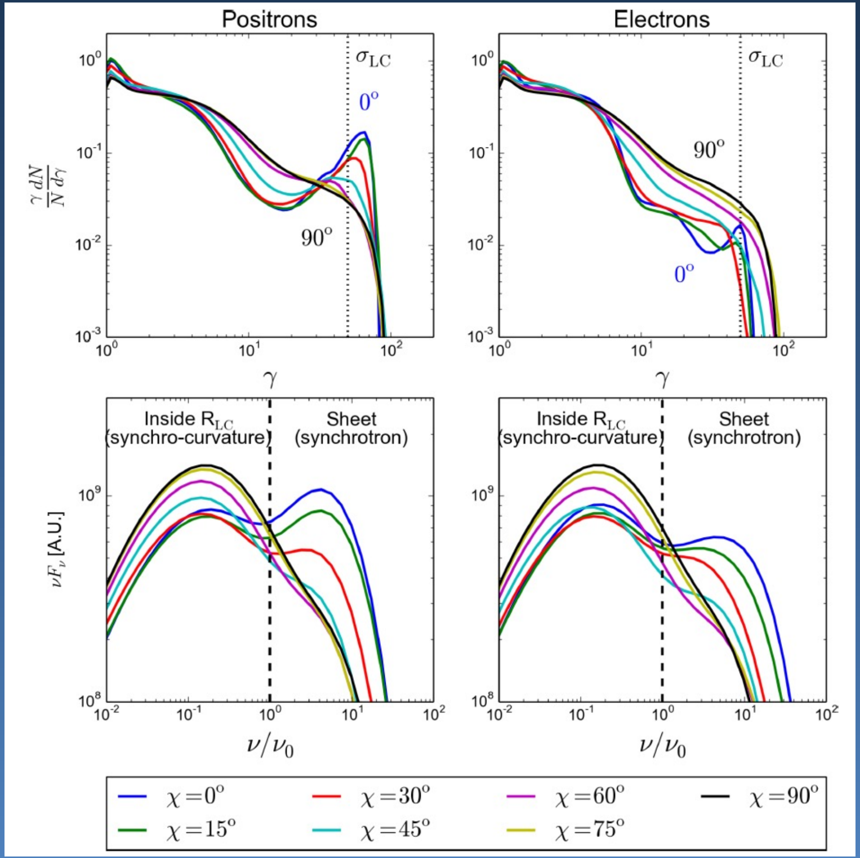
GeV emission

Curvature? (Kalapotharakos+ 2014,2017,2018) $\gamma \sim 10^7$-10^8

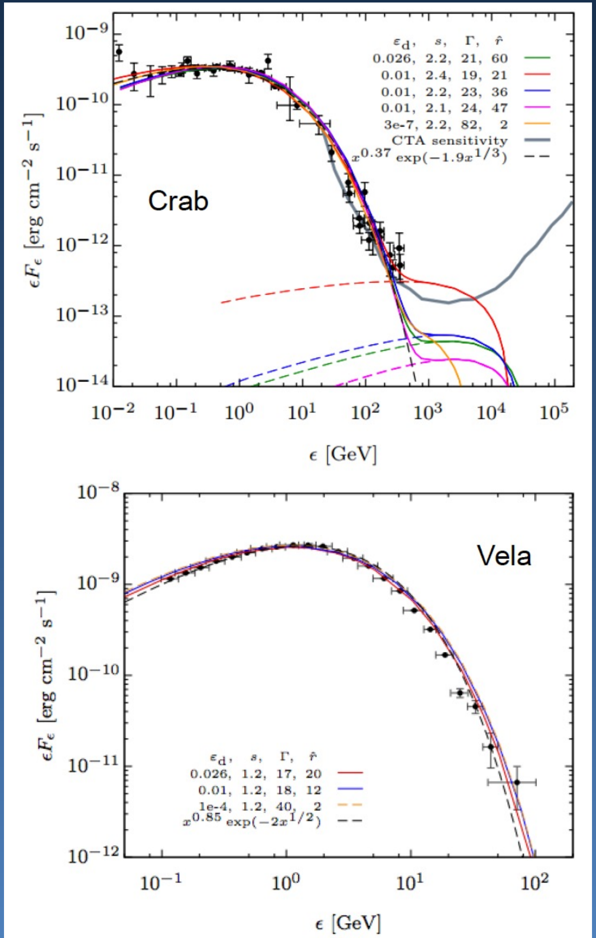
or synchrotron? (Cerutti+ 2016, Philippov & Spitkovsky 2018) $\gamma \sim 10^5$-10^6







SR from current sheet



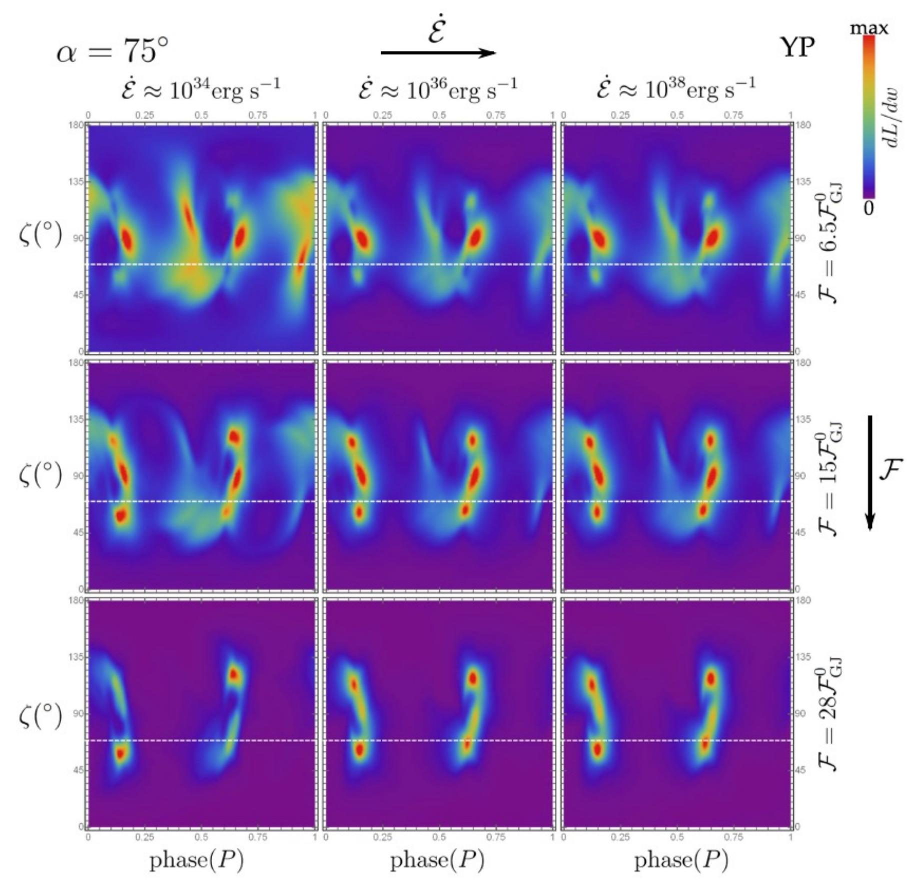
Mochol & Petri 2015

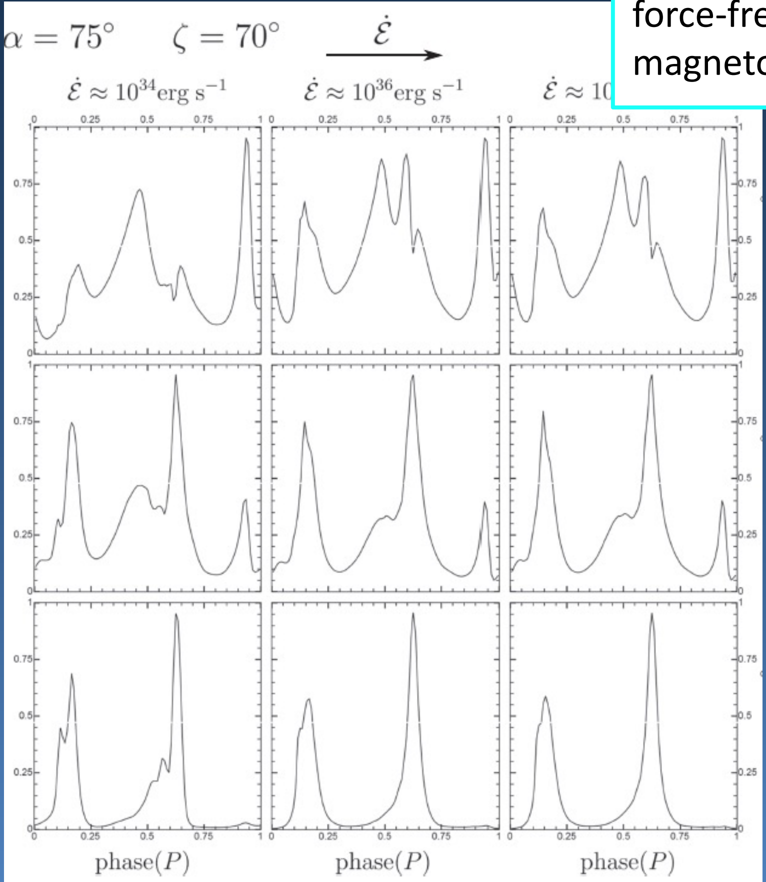
- GeV emission is SR from particles accelerated by magnetic reconnection in current sheet
- SSC component in Crab up to 3 TeV
- Particle γ ~ 3 x 10^5 so Doppler boost by wind Γ = 100 required
- SSC component for Vela is orders of magnitude lower

But see Petri 2020:
Curvature radiation from particles in radiation-reaction limit more naturally explains GeV cutoffs

High energy light curves from CR

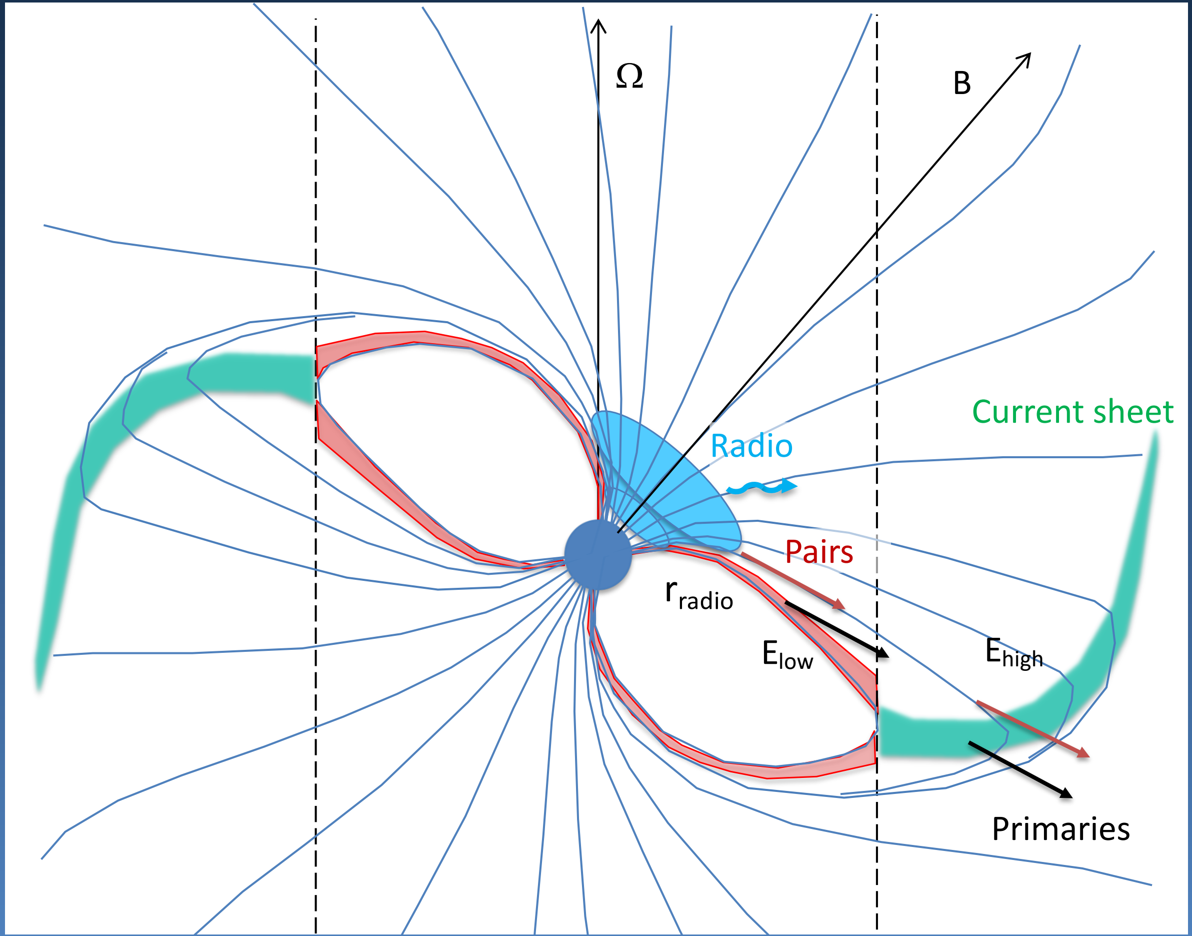
Kalapotharakos et al. 2018





Fermi pulsars have high pair injection and near force-free magnetosphere

Simulation of radiation



Harding & Kalapotharakos 2015

Pairs get pitch angles through resonant absorption of radio photons when

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

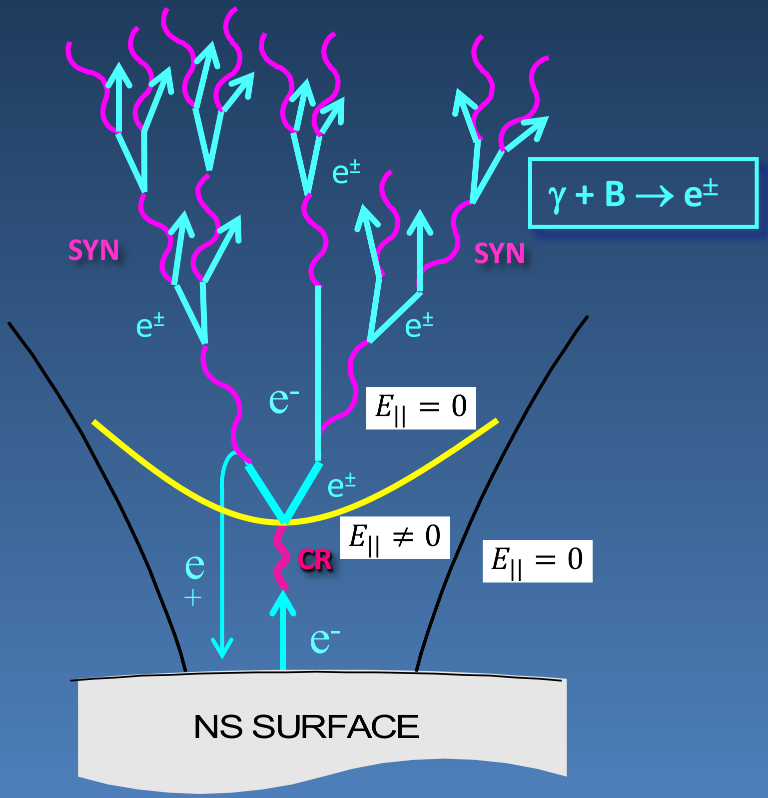
Petrova & Lybarski 1998

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

Pair cascades produce an abundance of charged particles to supply charges to magnetosphere

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

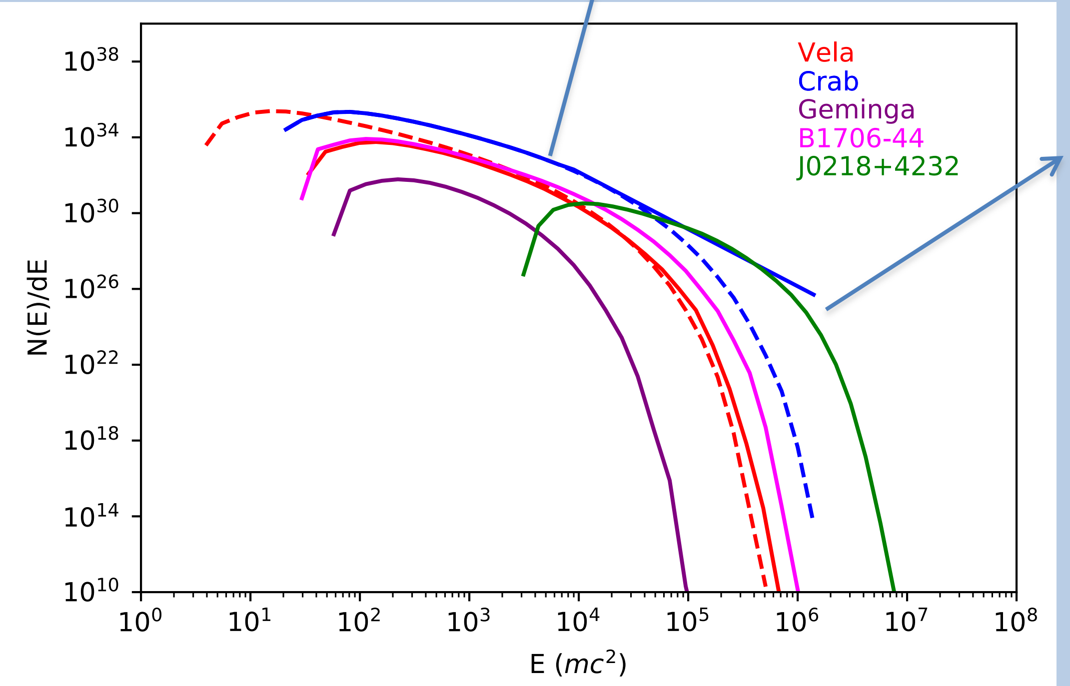
Timokhin & Harding 2015

Inverse Compton emission

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

Jones (1968)

Pair cascade spectrum (polar cap)



Synchrotron emissivity

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

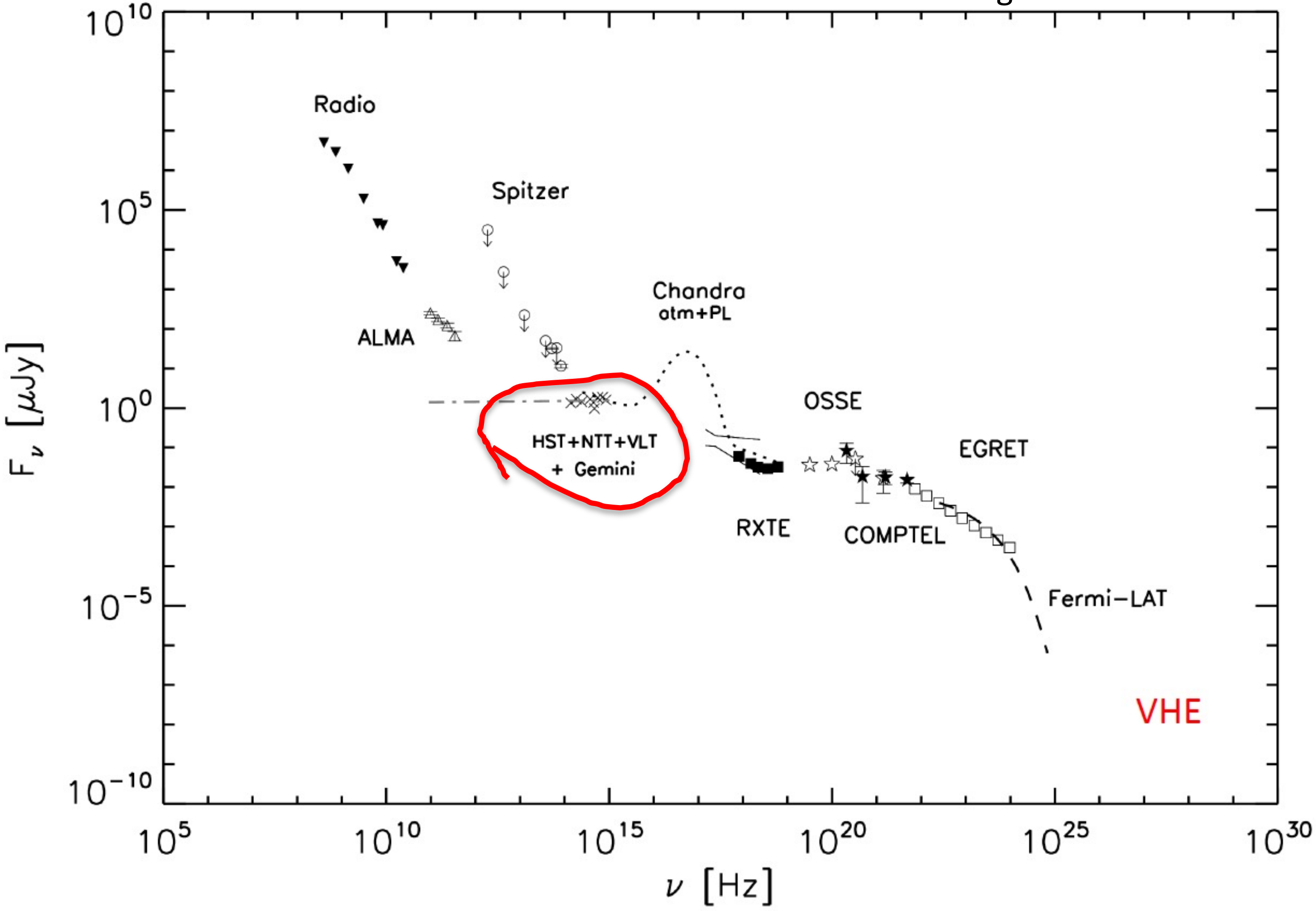
Synchrotron photon density (anisotropic)

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

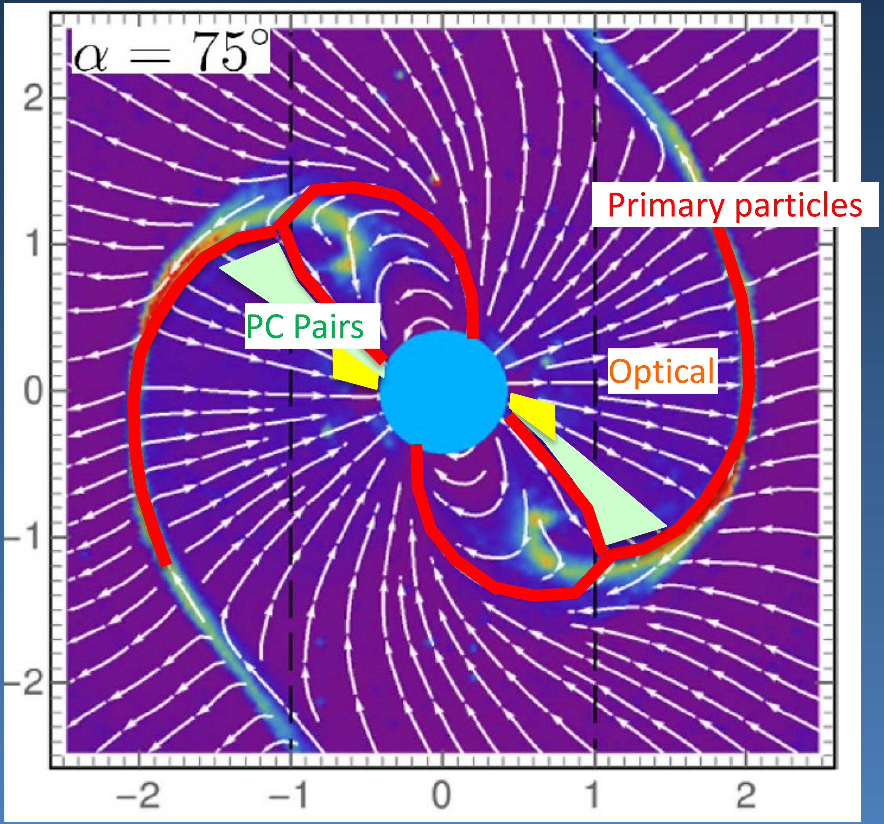
Spectral energy distribution of the Vela pulsar

Mignani et al. 2017



Modeling TeV+ emission from Vela

Harding, Kalapotharakos, Venter & Barnard 2018



Near force-free magnetosphere

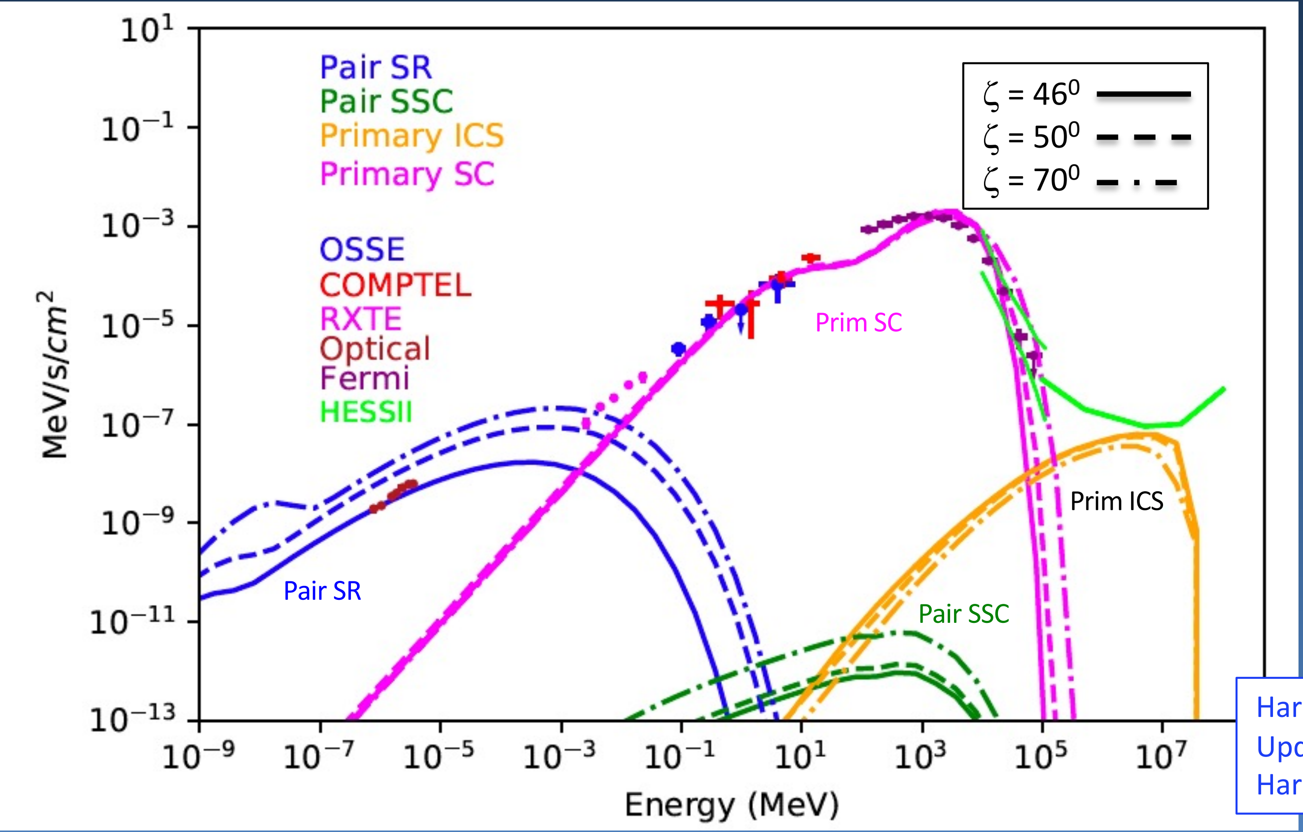
- PC pairs produce synchrotron radiation (SR) optical/UV at lower altitude
- Primary particles (mostly positrons) produce synchro-curvature (SC) and scatter optical/UV to produce 10 TeV ICS emission
- Pairs scatter optical/UV to produce SSC hard X-ray emission

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

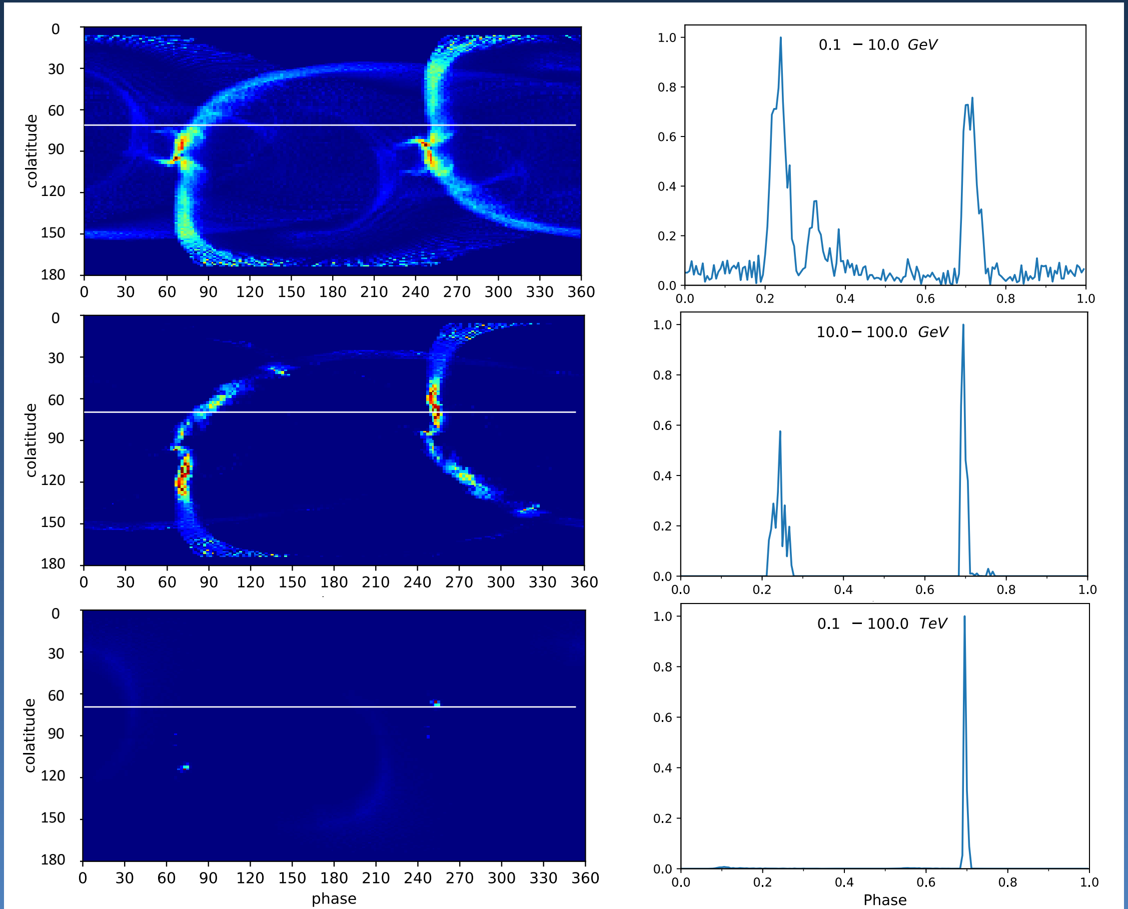


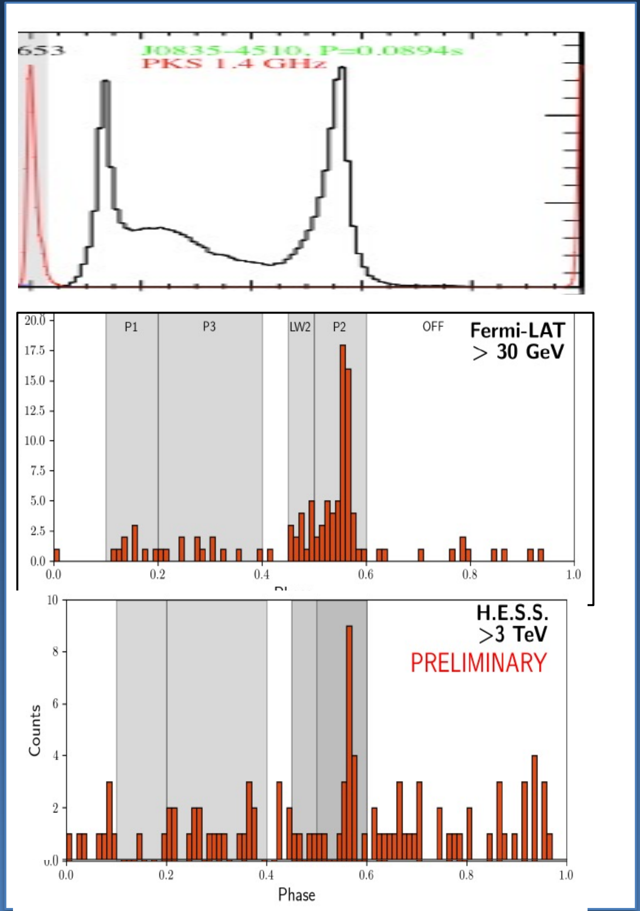
Pulsed emission ~ 10 TeV requires higher particle energy

⟶ GeV emission is CR

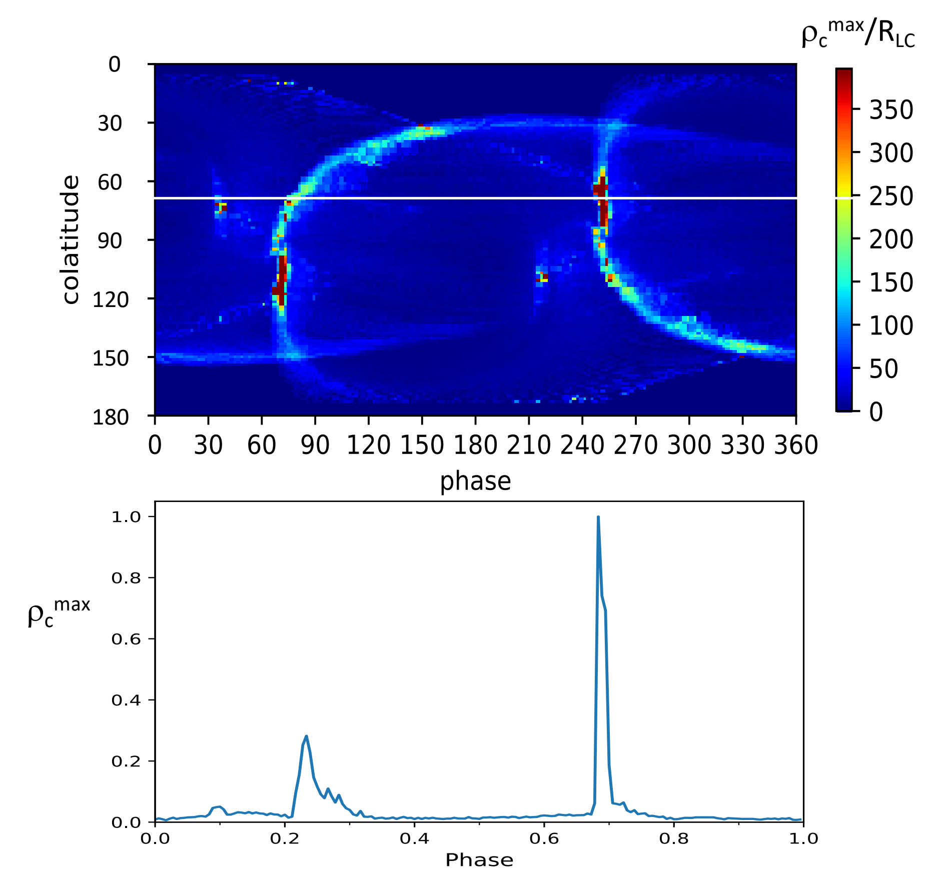
Harding, Venter & Kalapotharakos 2021
Updated from
Harding, Kalapotharakos, Venter & Barnard 2018

Vela model light curves





Vela P1/P2 evolution with energy



Harding, Venter & Kalapotharakos 2021

Lorentz factor of particles in curvature radiation-reaction limit:

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

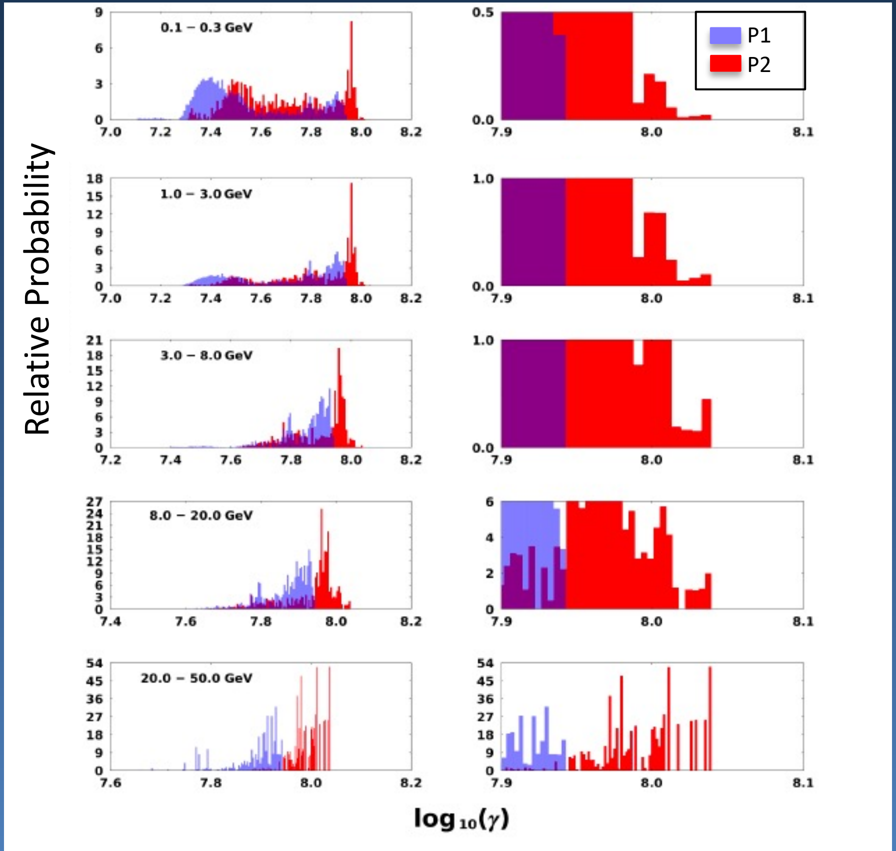
High energy cutoff

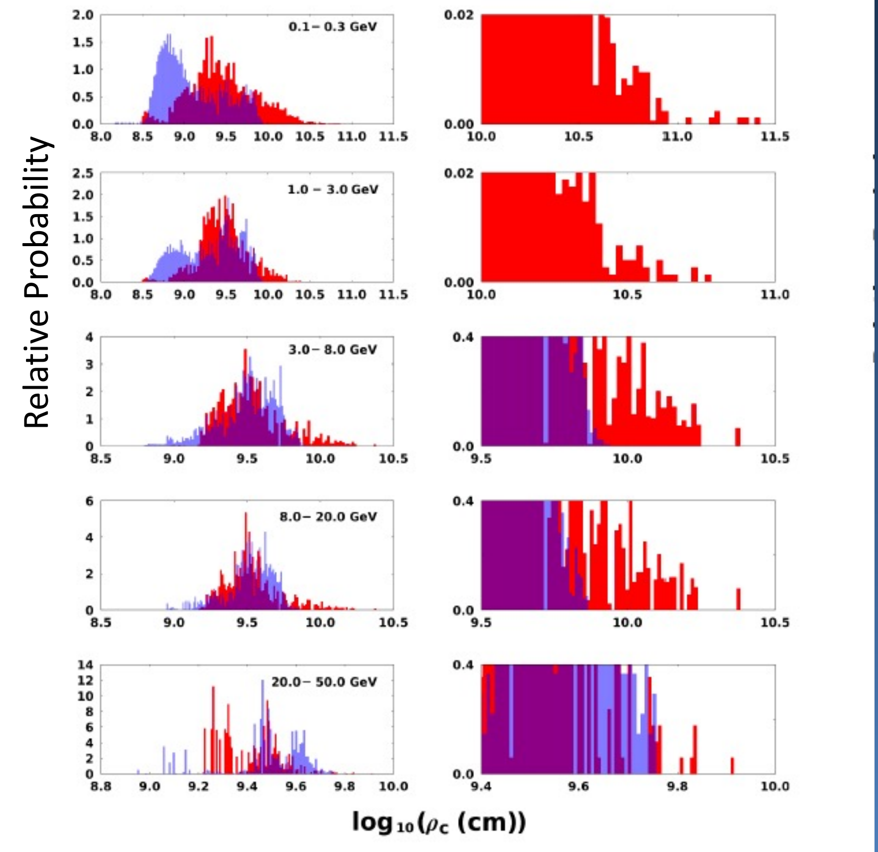
$$E_{CR} \propto E_{||}^{3/4}\rho_c^{1/2}$$

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

Curvature radius and γ for each Vela peak

Barnard, Venter, Harding & Kalapotharakos et al., in prep

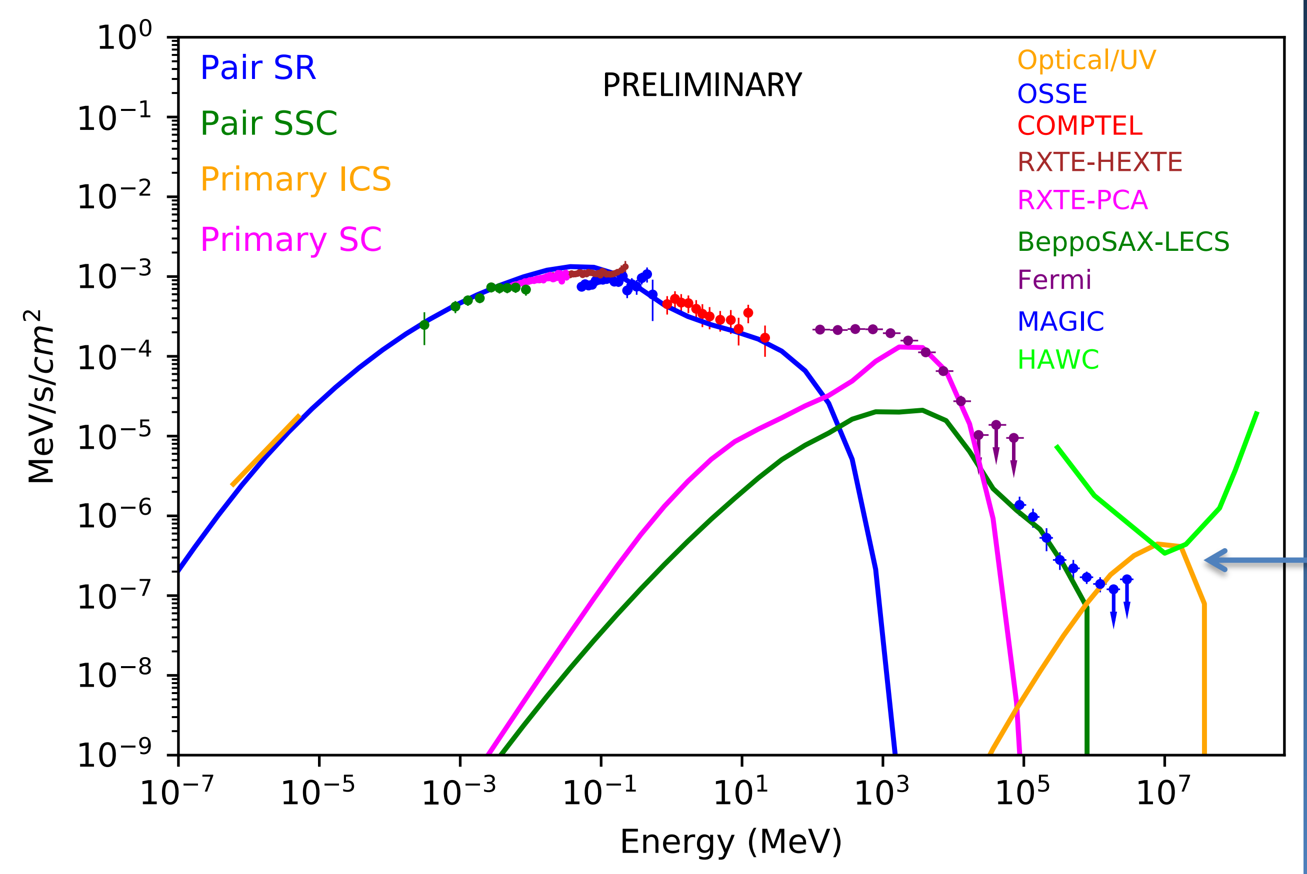




TeV+ emission from Crab pulsar

$\alpha = 45^0$, $\zeta = 60^0$, pair $M_+ = 3 \times 10^5$

Harding, Venter & Kalapotharakos 2021



Emission from pairs near current sheet

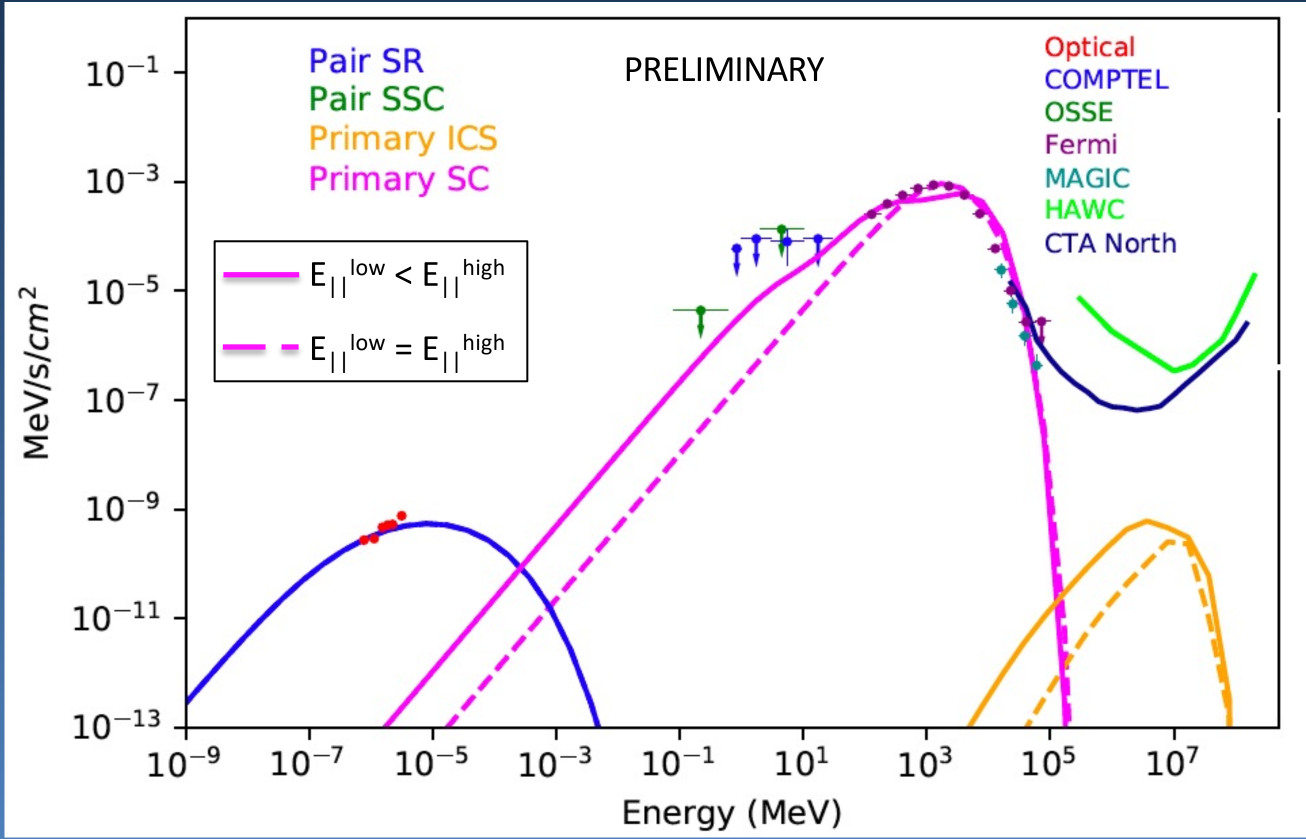
γ–γ pair attenuation

TeV+ emission from Geminga

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

α = 75^0, ζ = 50^0, pair M_+ = 2 x 10^4

Harding, Venter & Kalapotharakos 2021

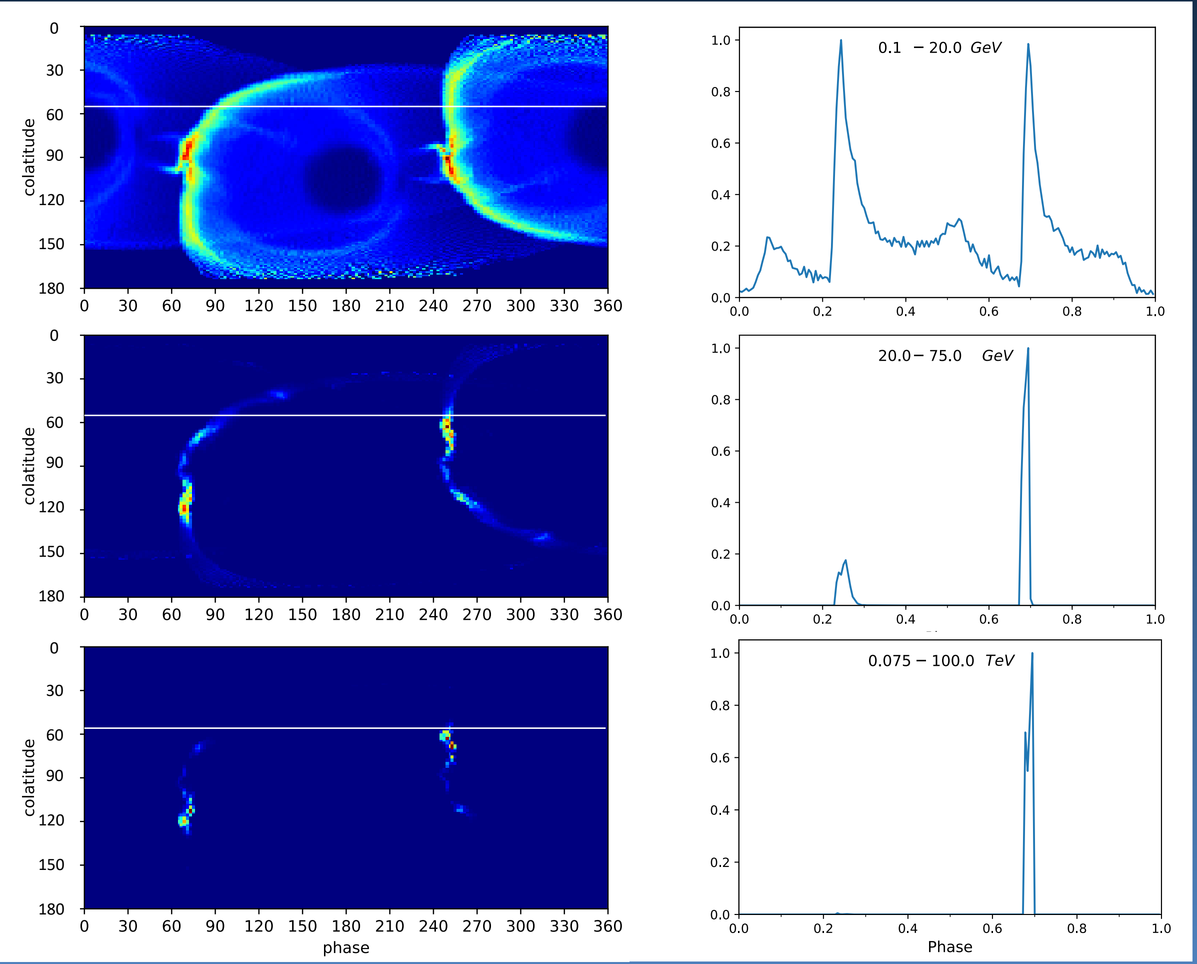


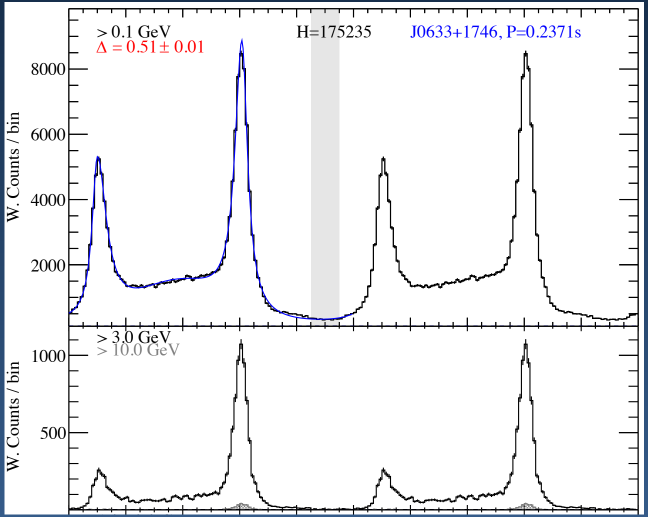
Low pair SR UV flux

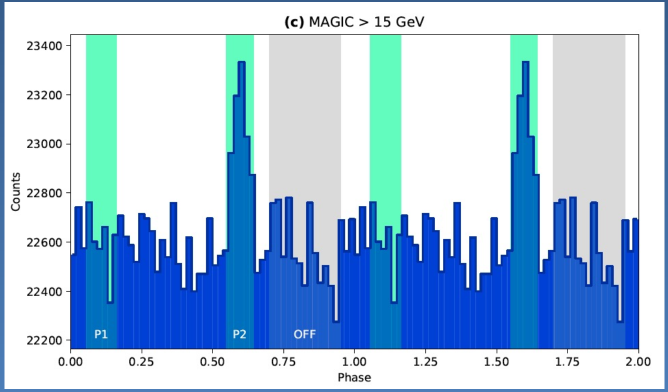
→ Very low primary ICS

MAGIC detection explained by primary SC

Geminga model light curves



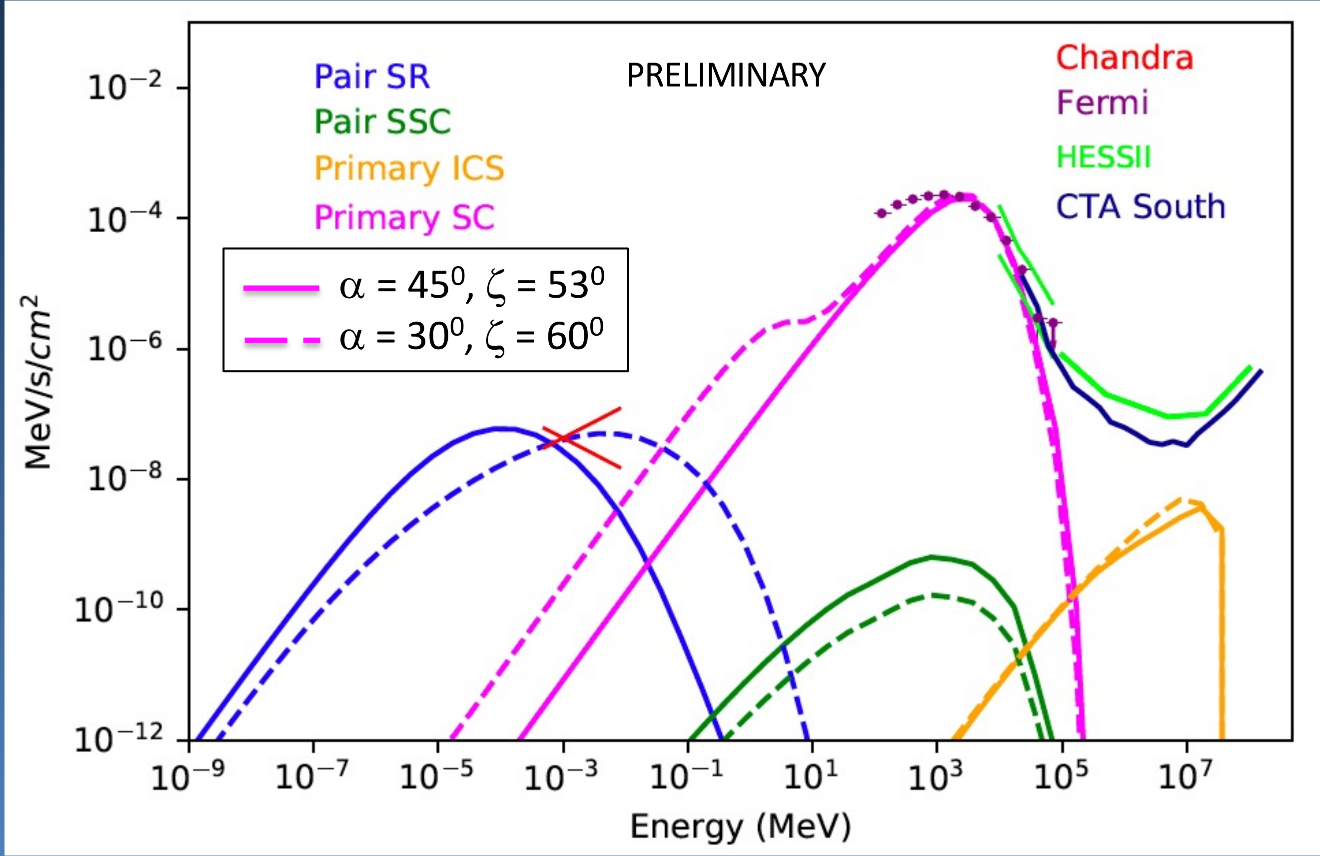




TeV+ emission from B1706-44

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

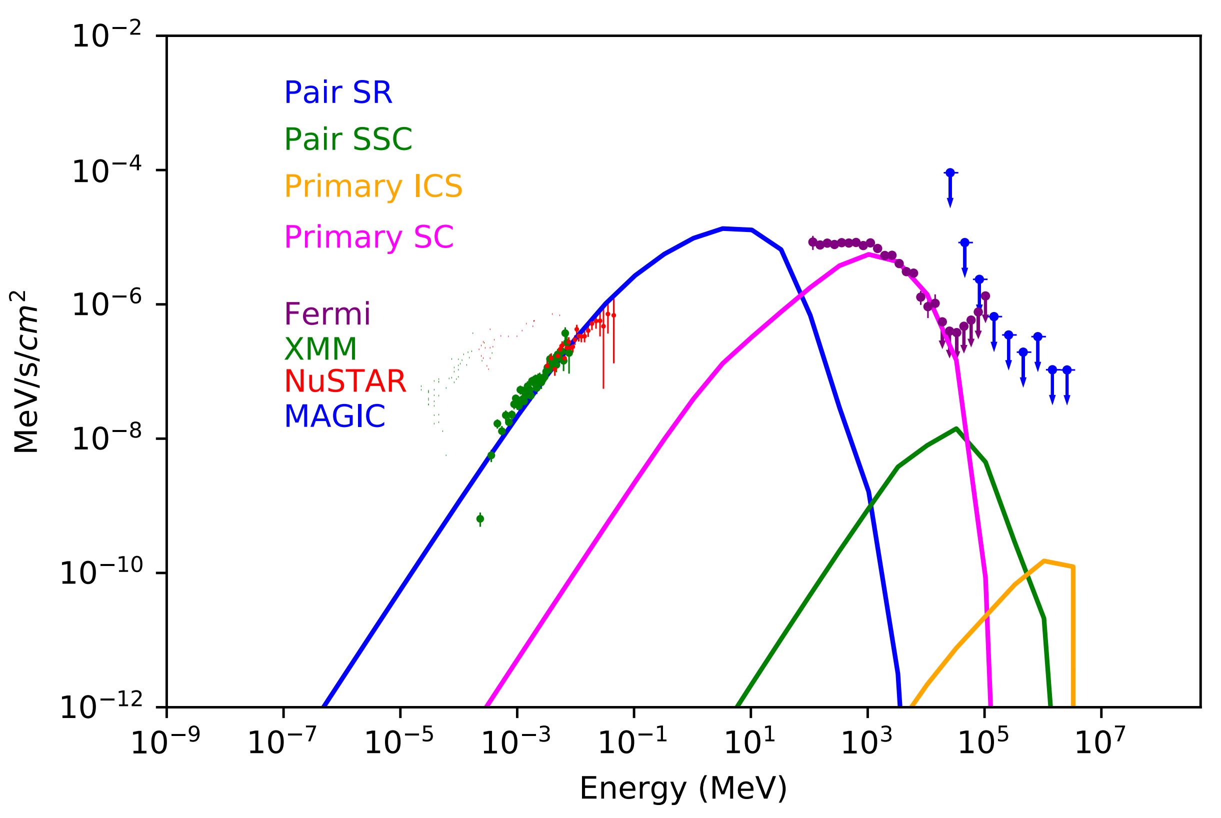
TeV+ emission from MSP J0218+4232

$P = 0.0023$ 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

Outstanding questions and GeV/VHE emission

GeV emission

- Recent PIC simulations point to particle acceleration and emission in current sheet
- Fermi light curves can constrain location of particle creation
- Curvature radiation explains P1/P2 decrease and most spectrum 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

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