# Modeling Very-High-Emission From Pulsars

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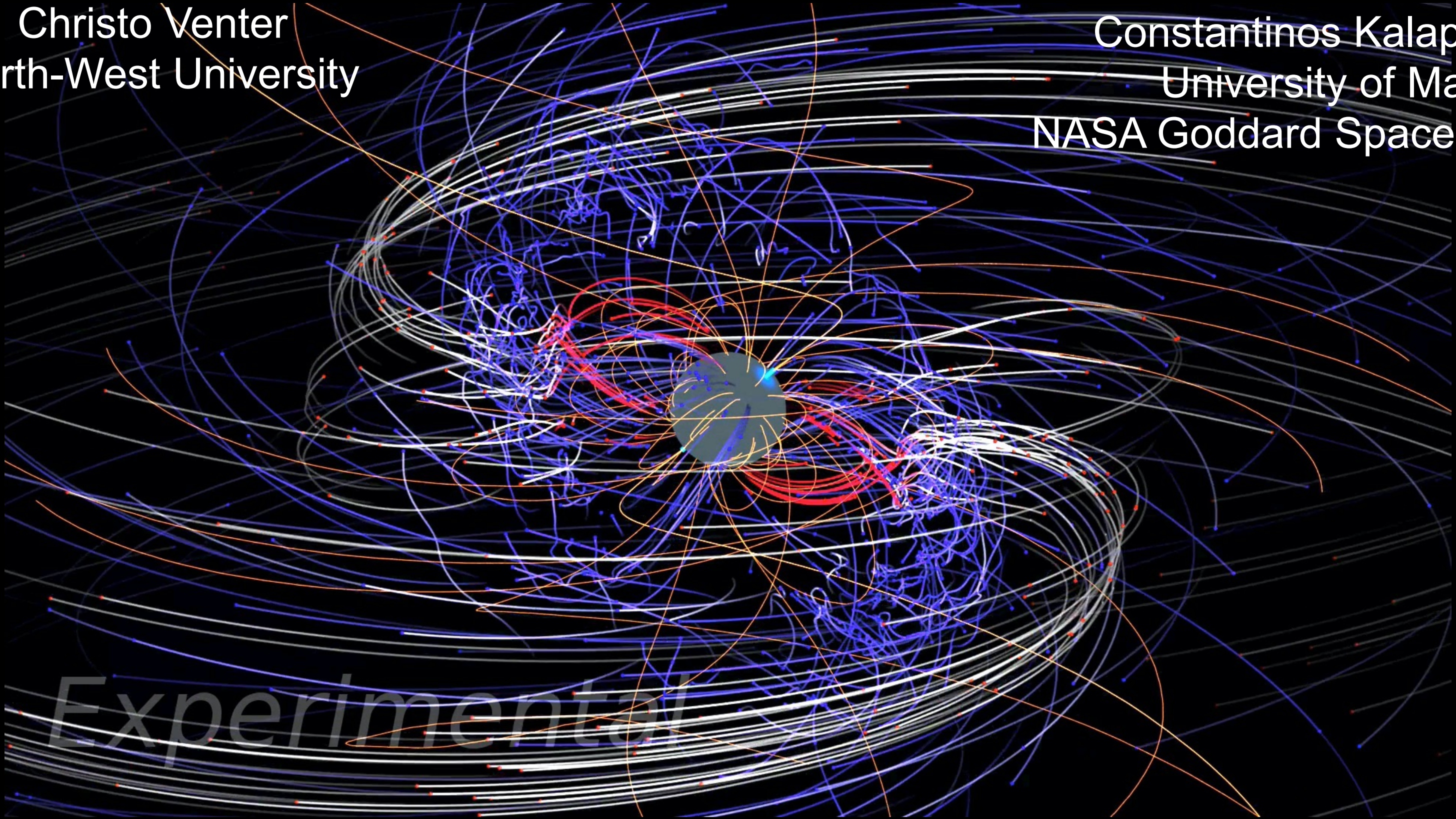
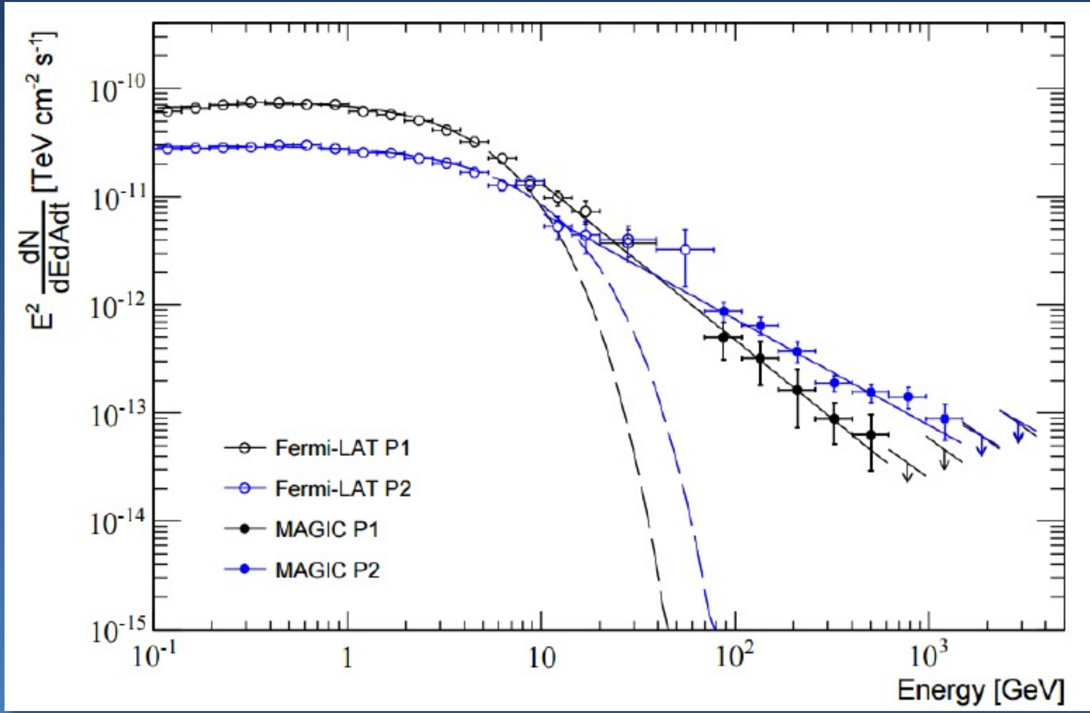


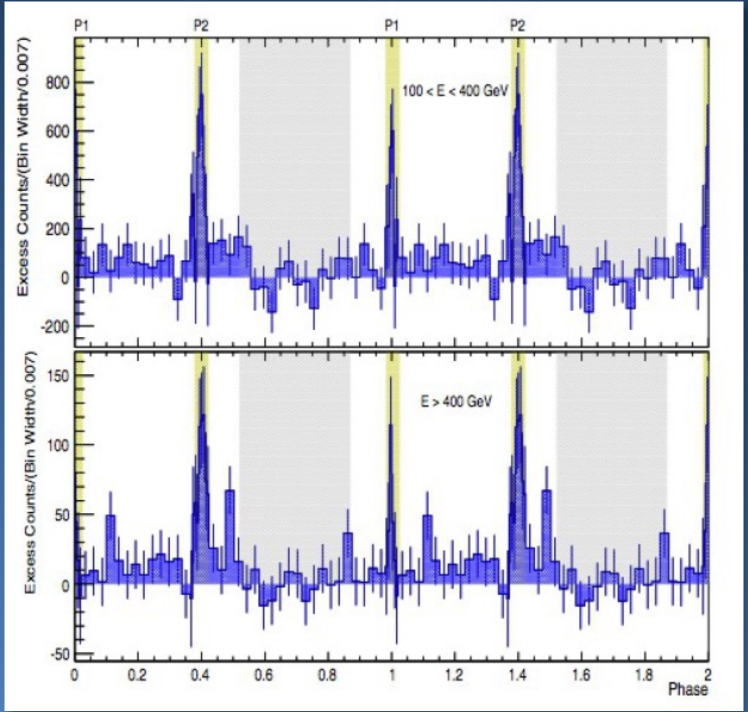
# Detection of Crab pulsar up to 1 TeV

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

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

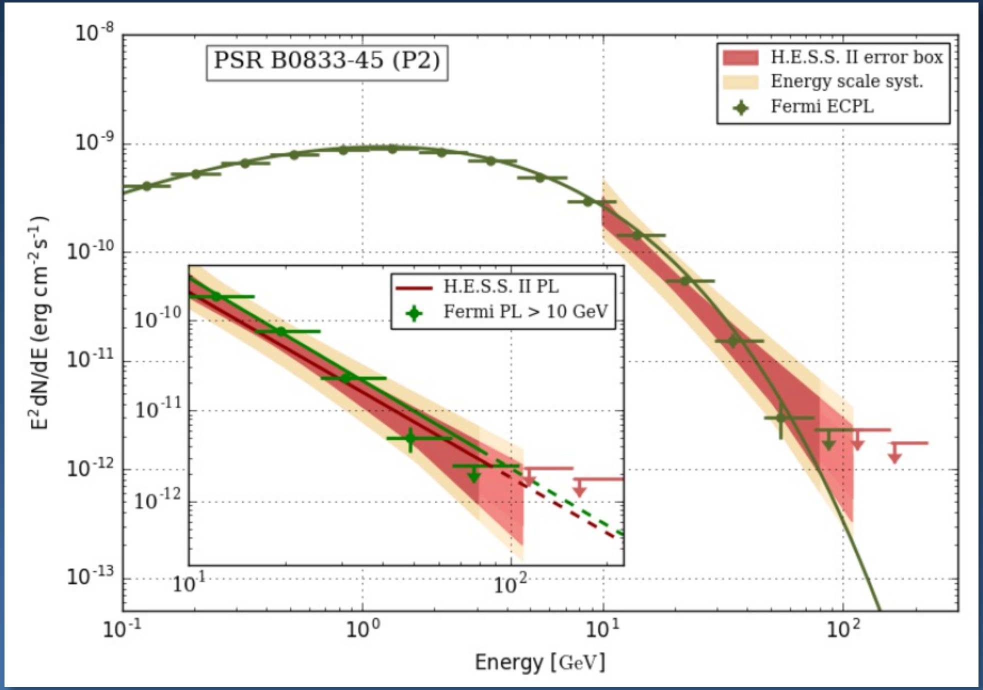
Both peaks detected!



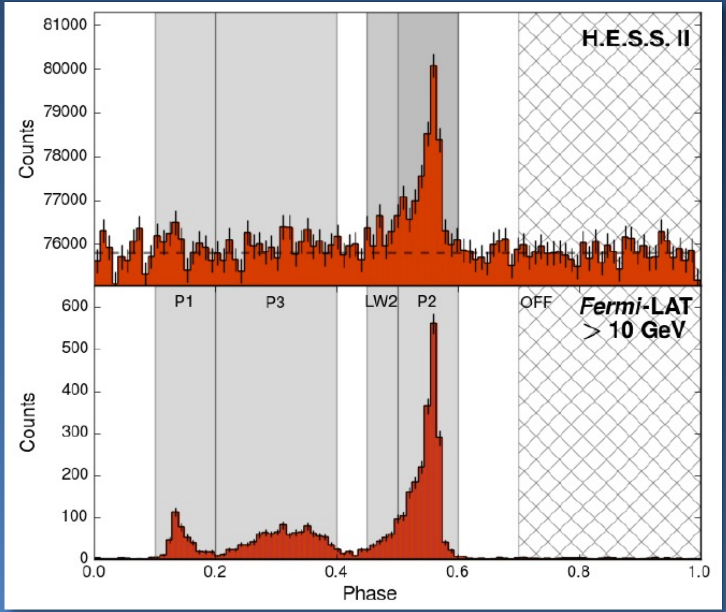
# Vela pulsar – H.E.S.S. II

10 – 110 GeV (Abdalla et al. 2018)




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

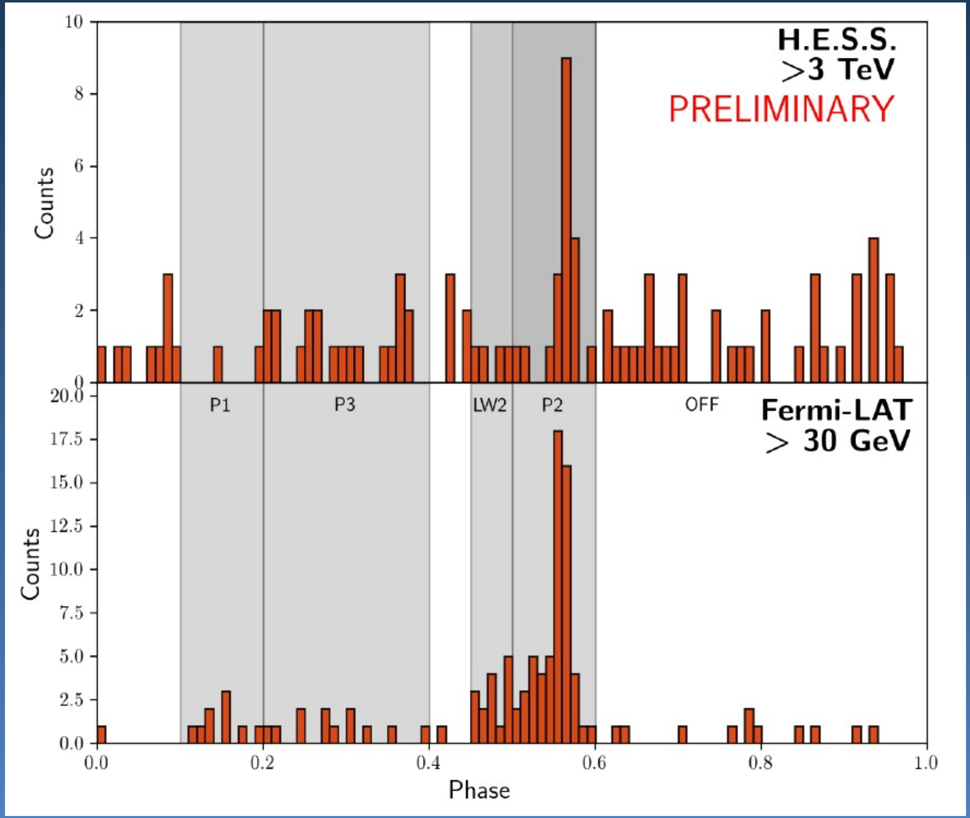
Curvature favored by H.E.S.S. II at $> 3.0\sigma$




Fundamental difference with Crab – VHE emission only seen in peak 2

# Vela pulsar – H.E.S.S. II

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

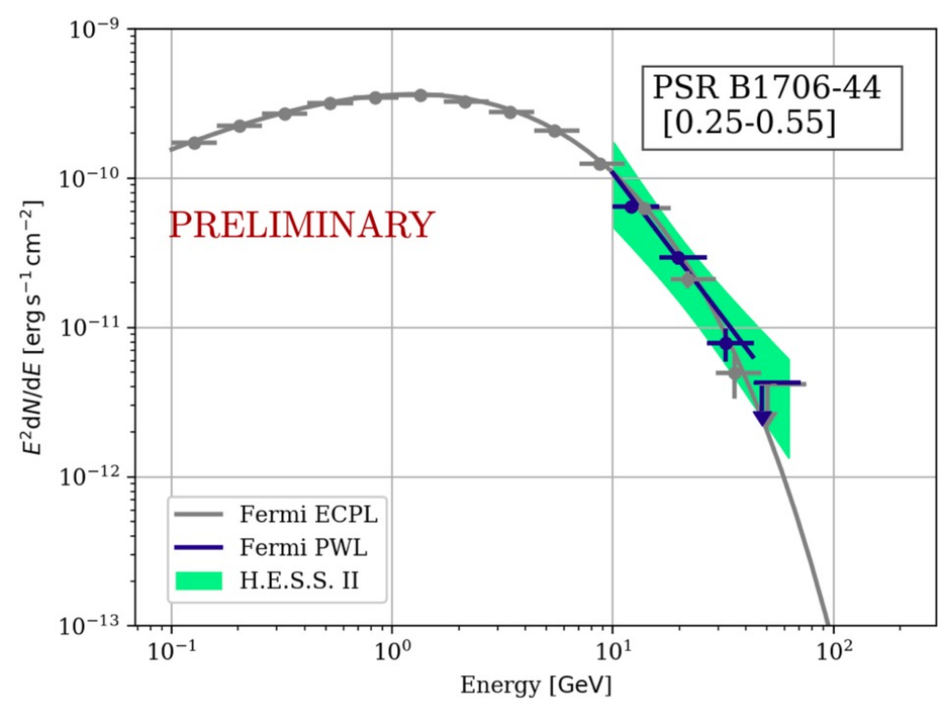


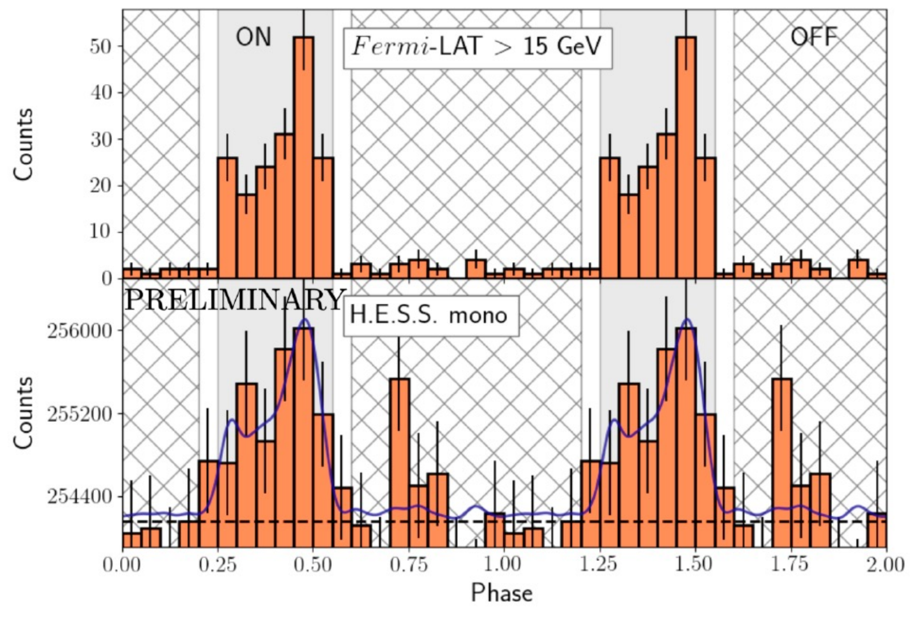

Additional component distinct from GeV spectrum?

# B1706-44 – H.E.S.S. II

Spir-Jacob et al. 2019

10 – 70 GeV

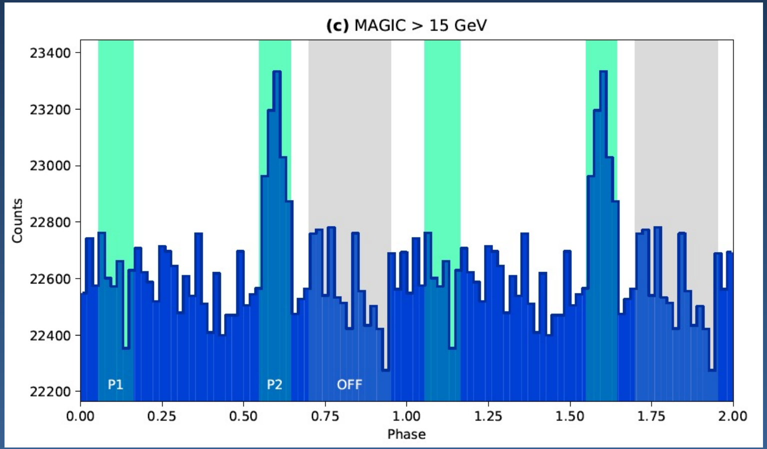


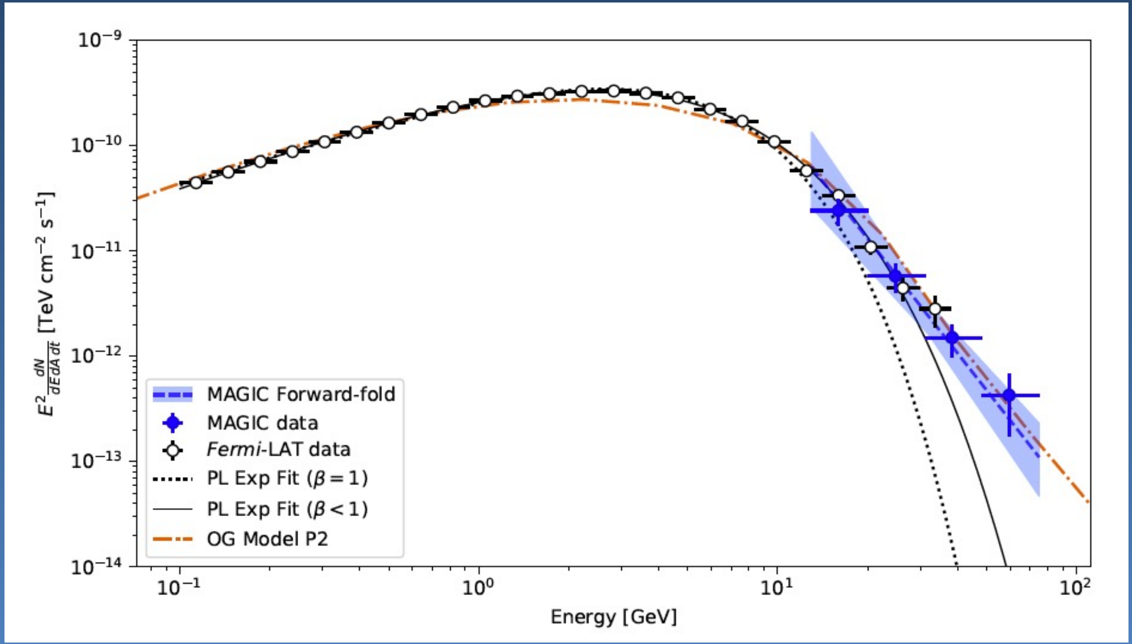
# Geminga - MAGIC

Acciari et al. 2020

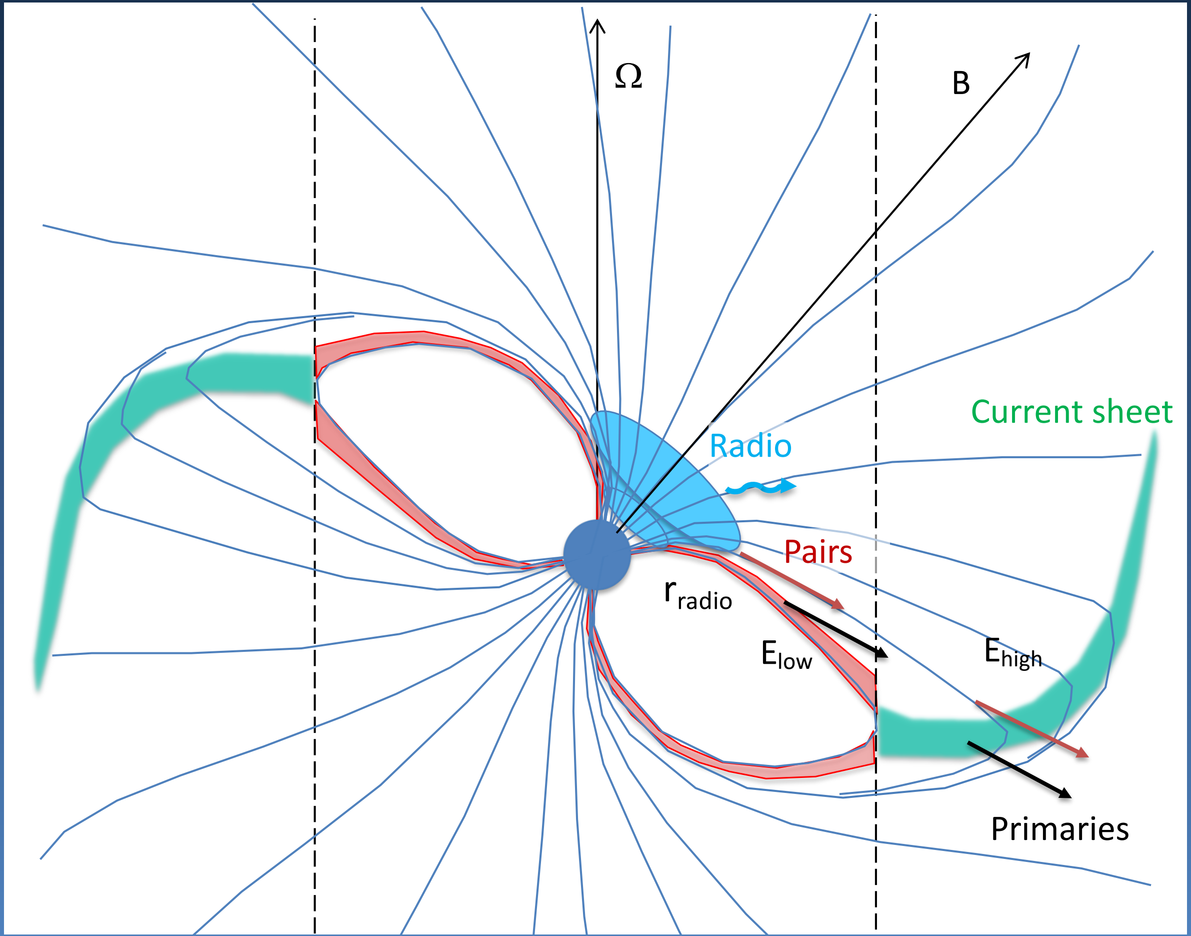
P2 > 15 GeV




Spectrum measured up to 75 GeV



# 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 $R_{LC}$

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

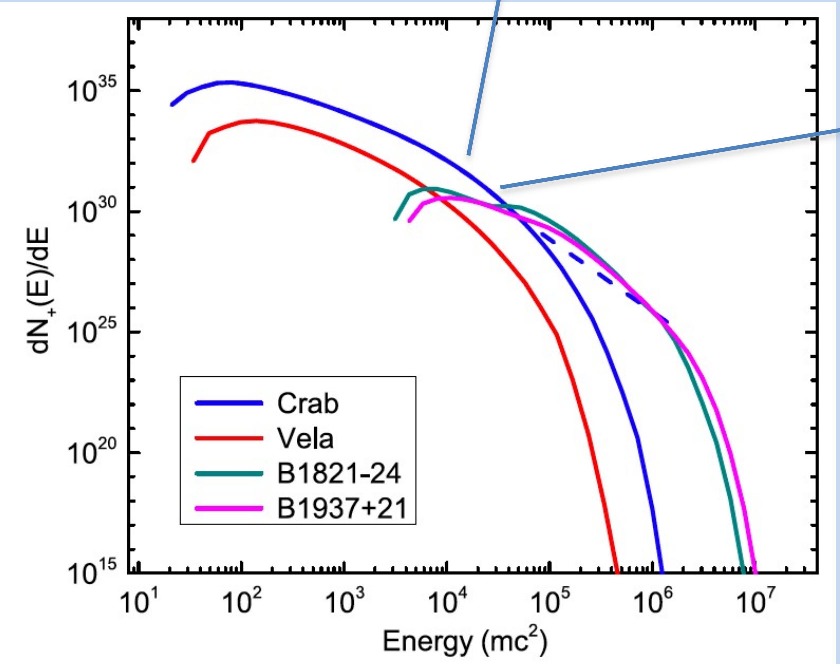
# Inverse Compton emission

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

Jones (1968)

Pair cascade spectrum (polar cap)

Synchrotron emissivity



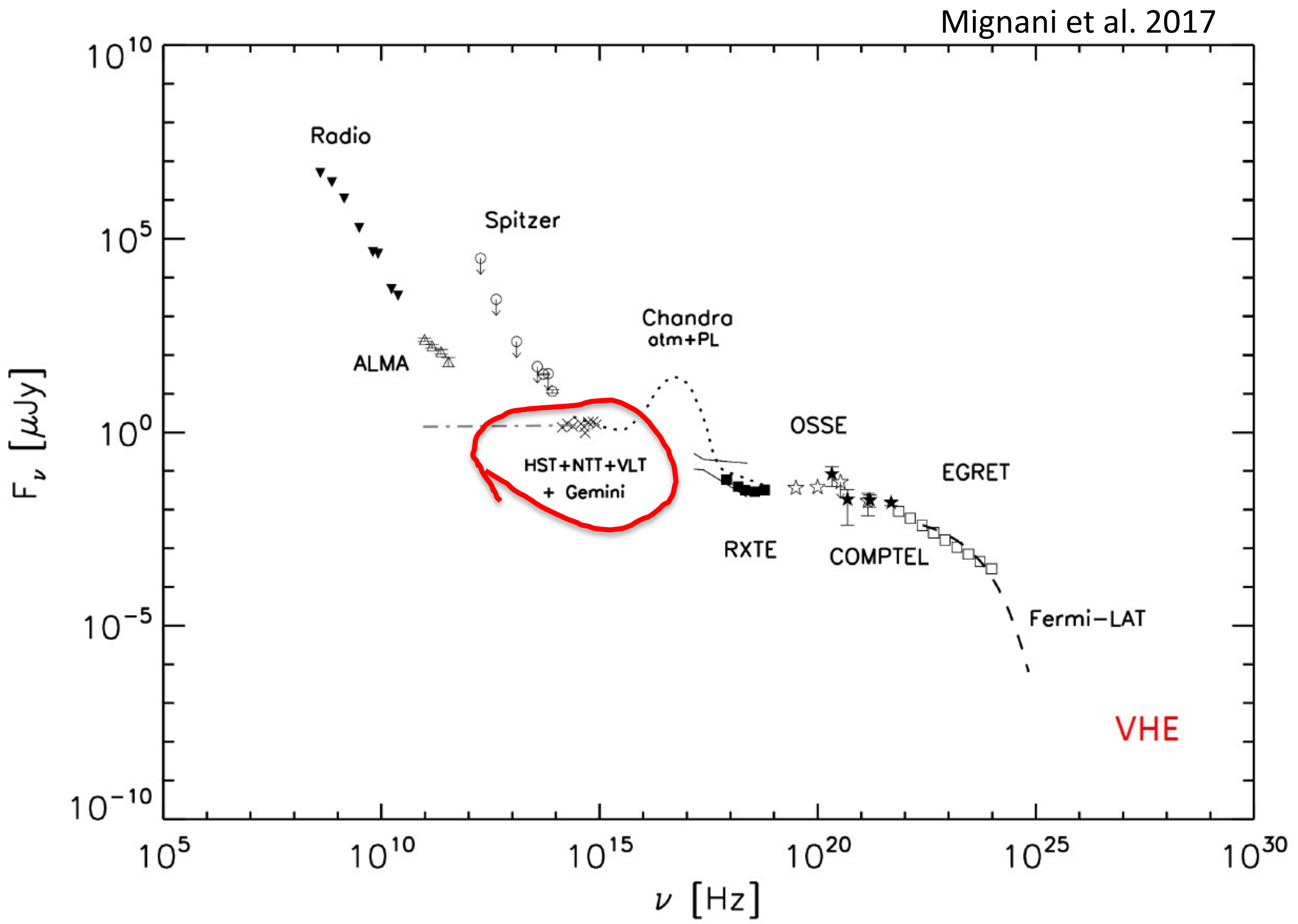

$$n_\gamma(\varepsilon,\vec{r},\Omega) = \frac{1}{c}\int d\vec{r}_s\, \frac{\epsilon_{SR}(\varepsilon,\vec{r}_s,\Omega)}{(\vec{r}^{\,2}-\vec{r}_s^{\,2})}$$

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

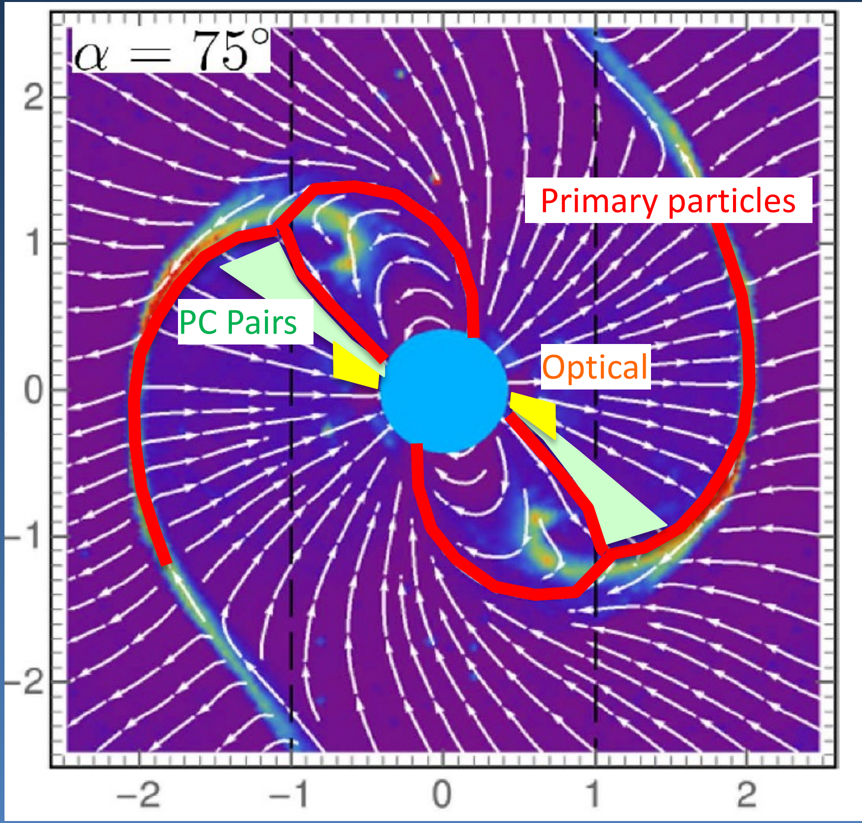
Primary IC uses this same SR photon density

# Spectral energy distribution of the Vela pulsar



# Modeling TeV+ emission from Vela

Harding, Kalapotharakos, Venter & Barnard 2018




Near force-free magnetosphere

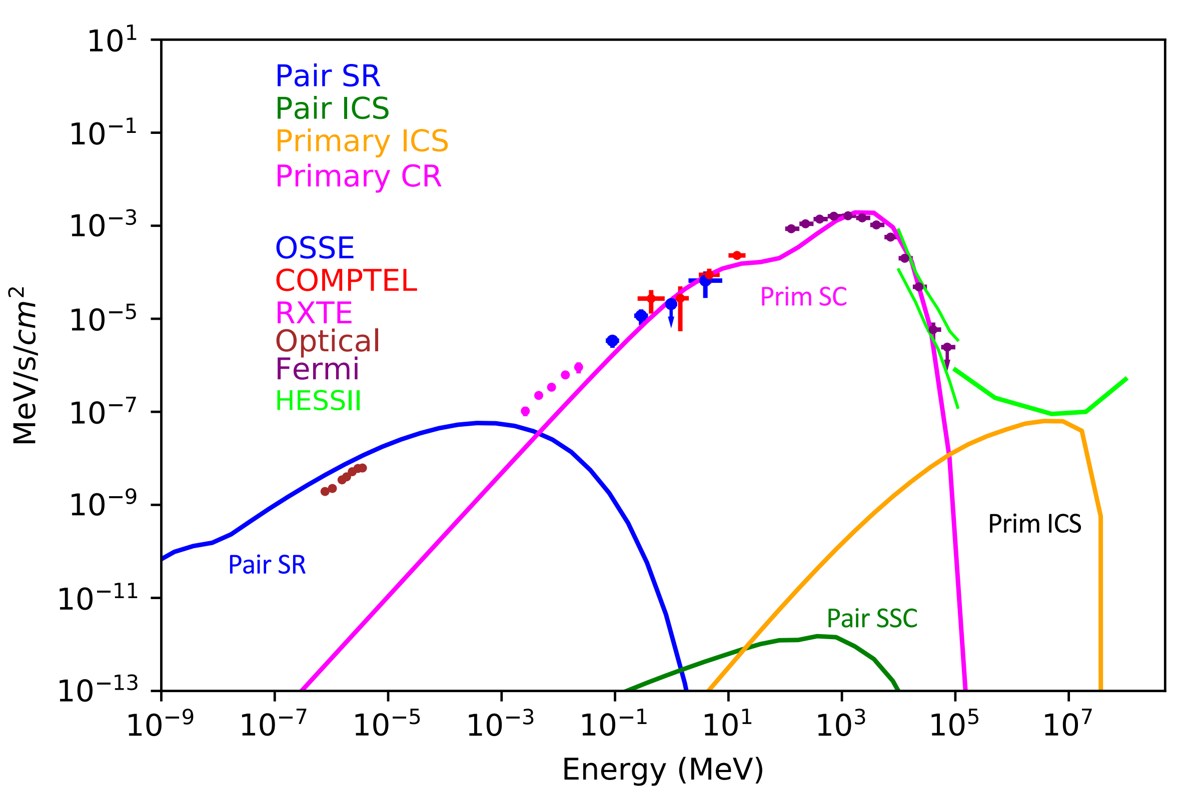
- PC pairs produce synchrotron radiation (SR) optical/UV at lower altitude
- Primary particles (mostly positrons) produce synchro-curvature (SC) and scatter optical/UV to produce 10 TeV ICS emission
- Pairs scatter optical/UV to produce SSC hard X-ray emission

# Modeling TeV+ emission from Vela

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

$\alpha = 75^0$, $\zeta = 50^0$, pair $M_+ = 6 \times 10^3$

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



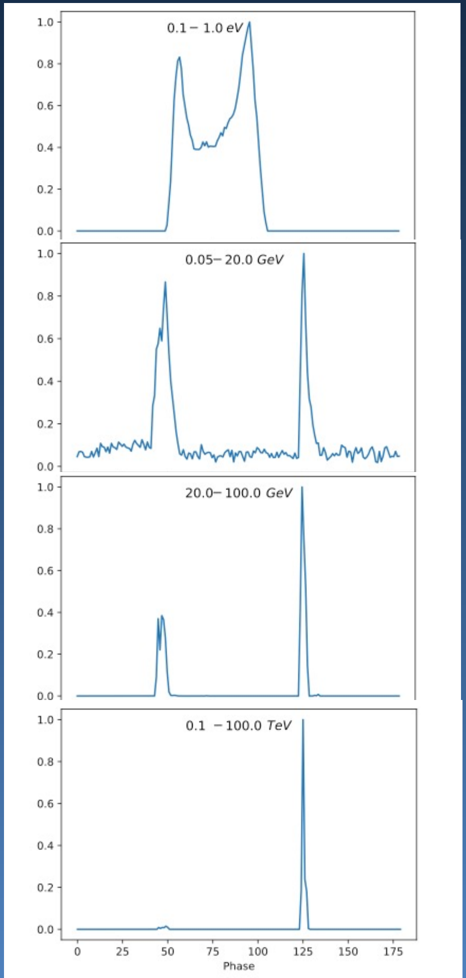

Pulsed emission ~ 10 TeV requires higher particle energy

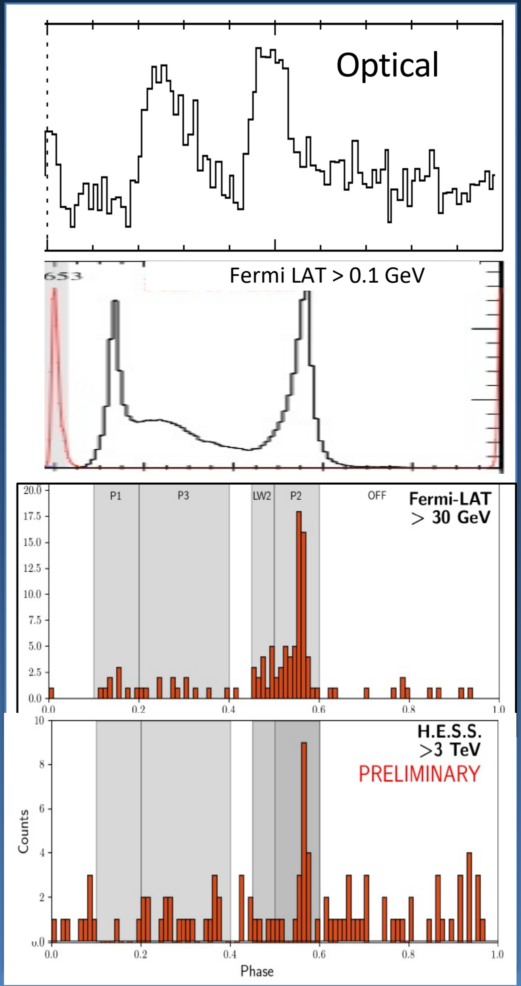
⟶ GeV emission is CR

see poster by Kalapotharakos et al. on gamma-ray fundamental plane

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

# Vela model light curves




Harding, Kalapotharakos, Venter & Barnard 2018

Fermi P2/P1 increases with energy – higher $\gamma$ particles produce P2

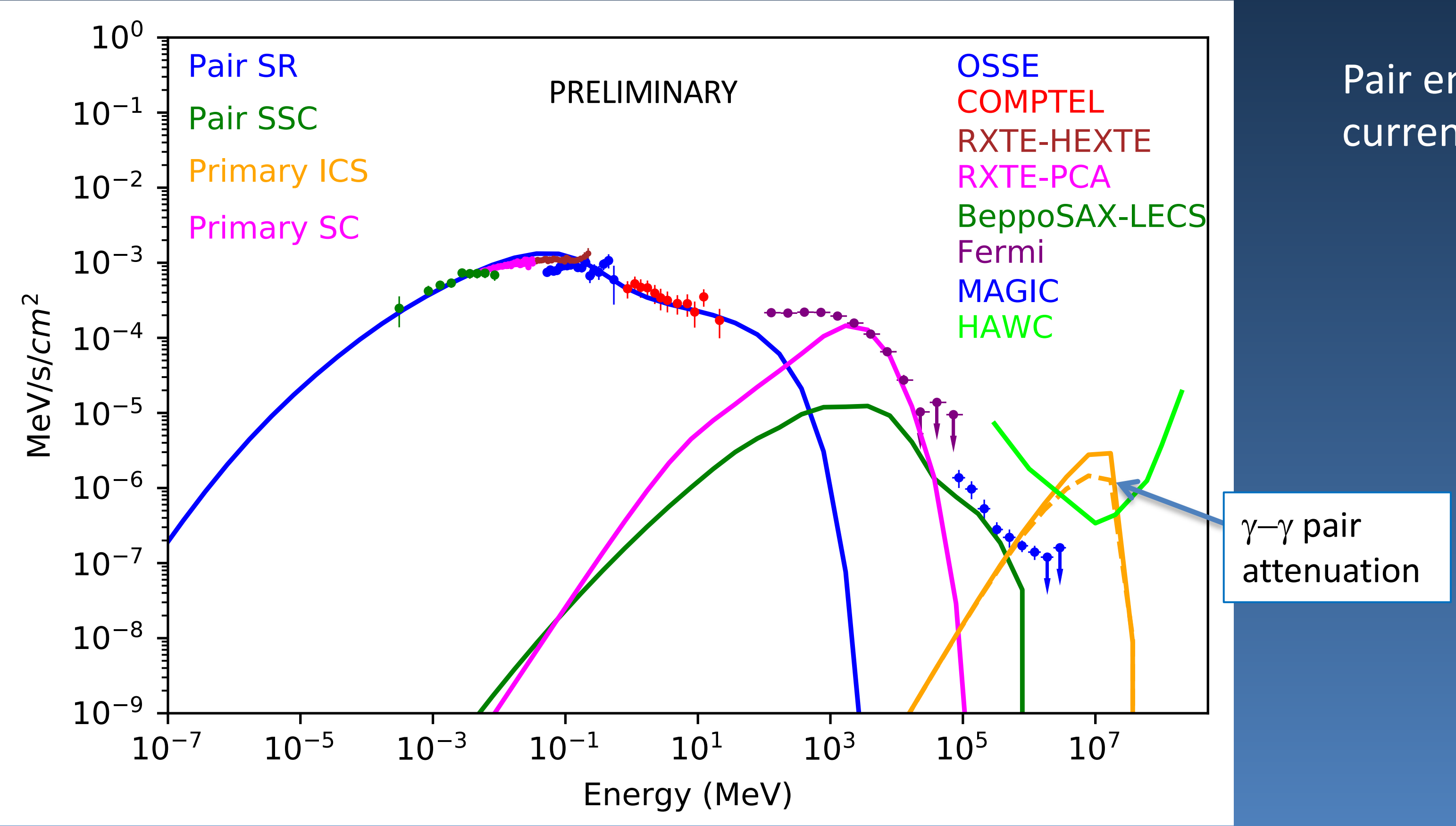
P2 only at > 3TeV – ICS from highest $\gamma$ particles

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

# TeV+ emission from Crab pulsar

$\alpha = 45^0$, $\zeta = 66^0$, pair $M_+ = 3 \times 10^5$

Harding, Venter & Kalapotharakos 2021

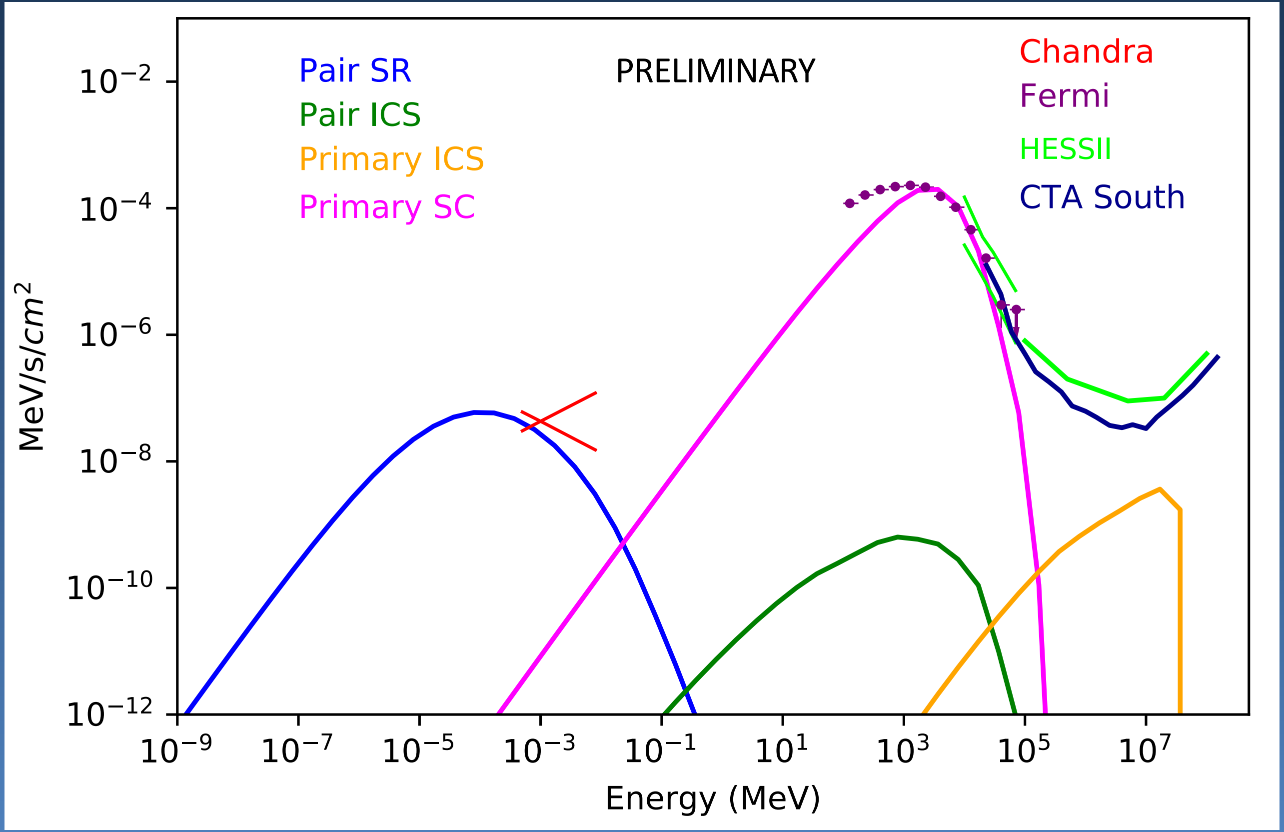



Pair emission near current sheet

# TeV+ emission from B1706-44

$P = 0.102$ s, $B_0 = 6.2 \times 10^{12}$ G, d = 2.3 kpc
$\alpha = 45^0$, $\zeta = 53^0$, 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

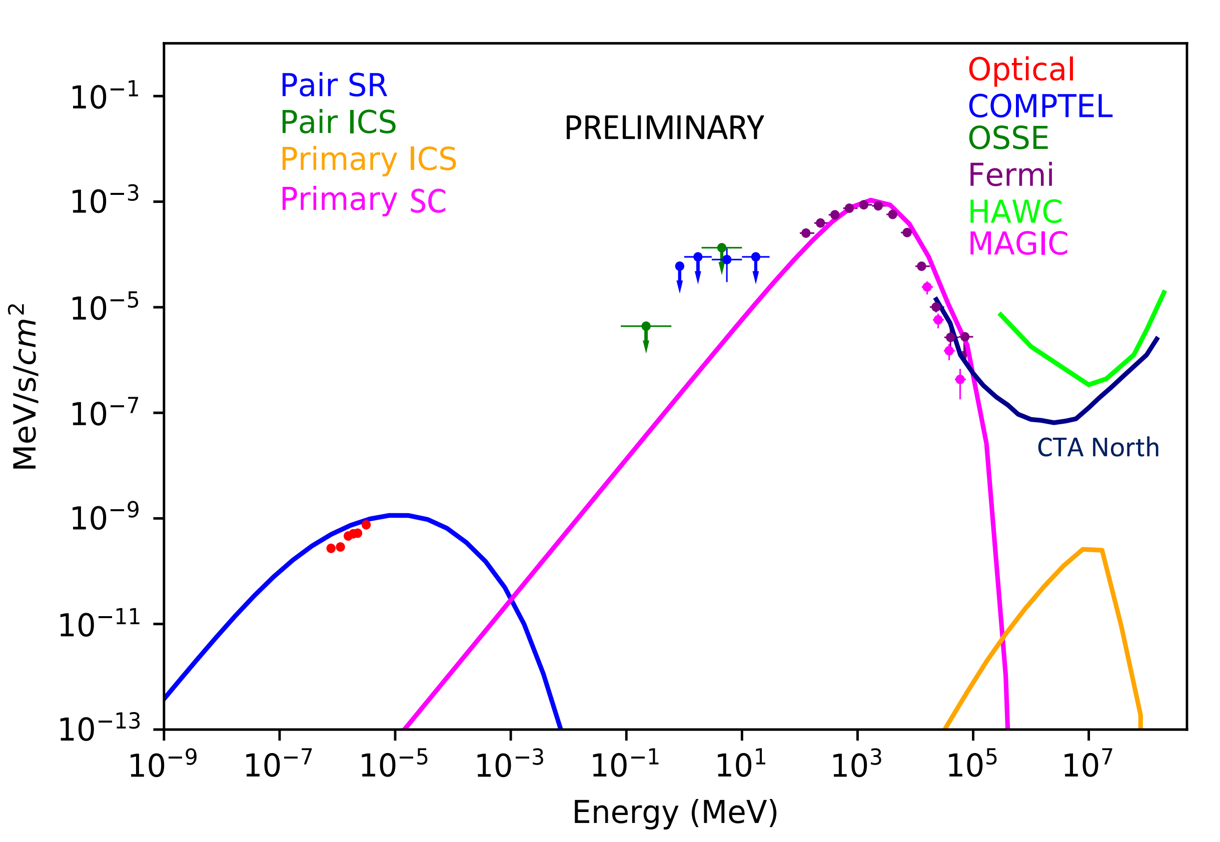
H.E.S.S. II detection explained by primary SC

# TeV+ emission from Geminga

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

Harding, Venter & Kalapotharakos 2021

$\alpha$ = $75^0$, $\zeta$ = $55^0$, pair $M_+$ = 2 x $10^4$




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

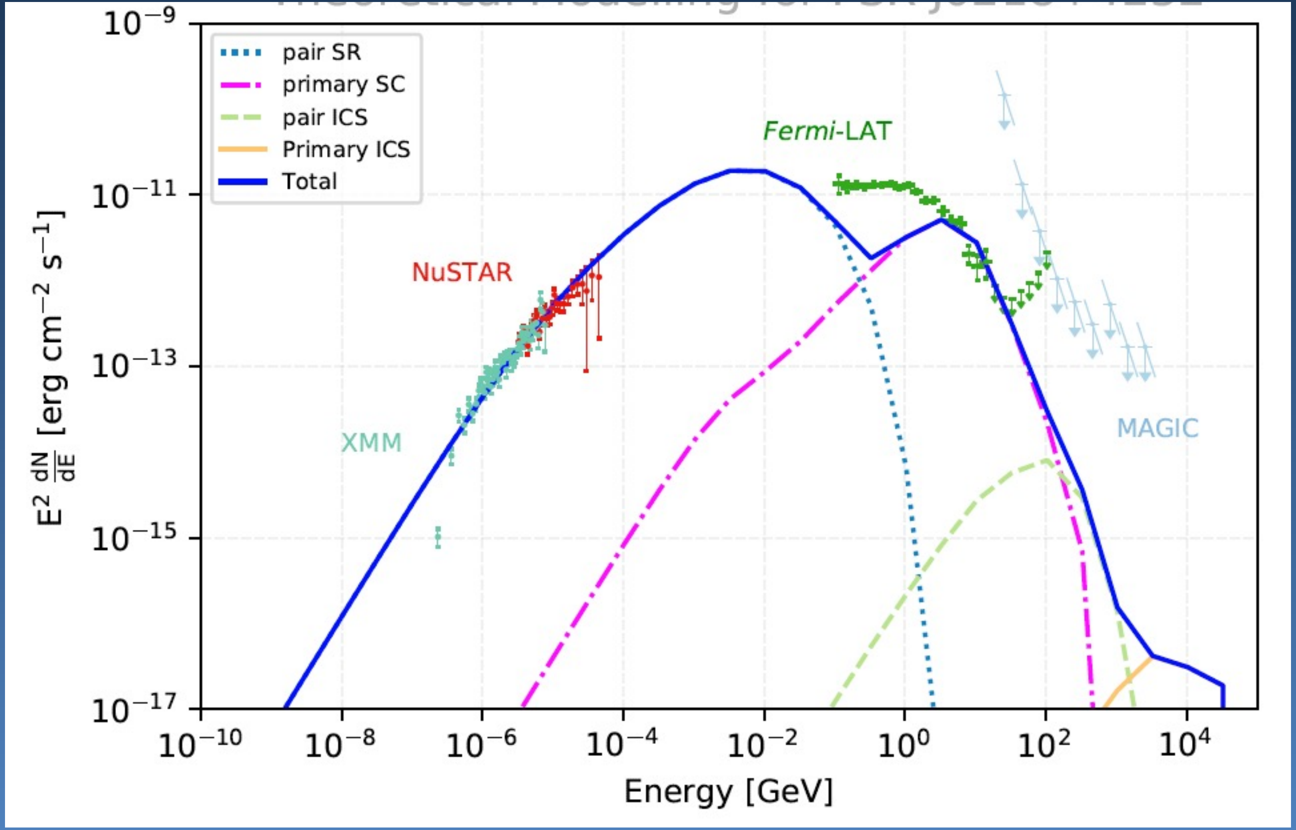
# TeV+ emission from MSP J0218+4232

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

$\alpha = 45^0$, $\zeta = 65^0$, pair $M_+ = 1 \times 10^5$

Blanche et al. 2021 (MAGIC/Fermi paper)

See poster by A. Spolon et al.




MSP pairs produced at higher energy

⟶ higher-energy pair SR peak, little optical

⟶ pair and primary ICS suppressed by KN

# What’s important for VHE emission?

TeV+ emission from primary IC:

- Particle energies at least 10 TeV -> GeV emission in curvature radiation regime
- High flux of optical/UV emission (Not necessarily correlated with pair multiplicity! But with efficiency of radio absorption and $B_{LC}$)
- Small distance between optical/UV and primaries in current sheet

SSC emission from pairs:

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