Modeling Very-High-Emission From Pulsars

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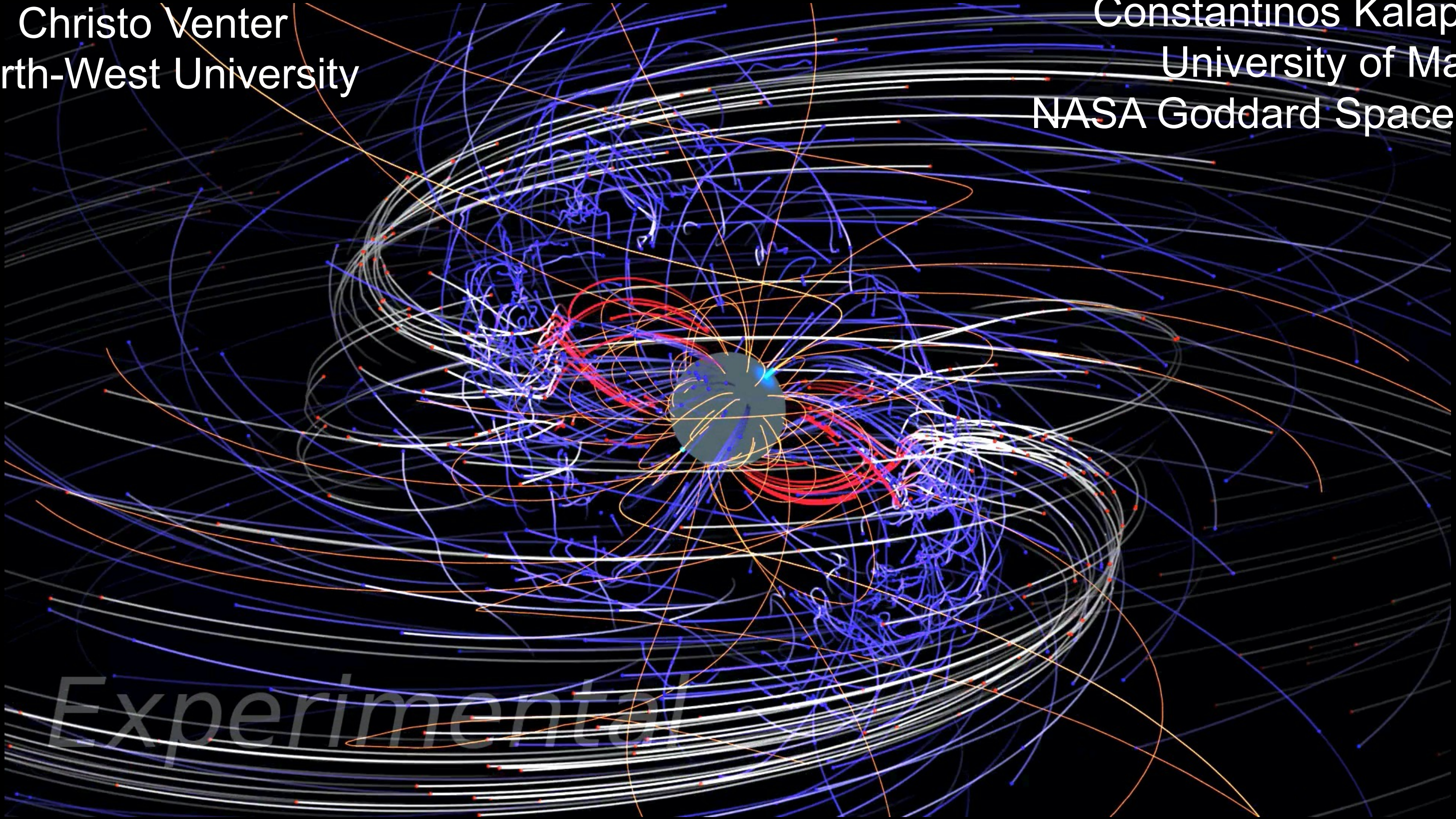
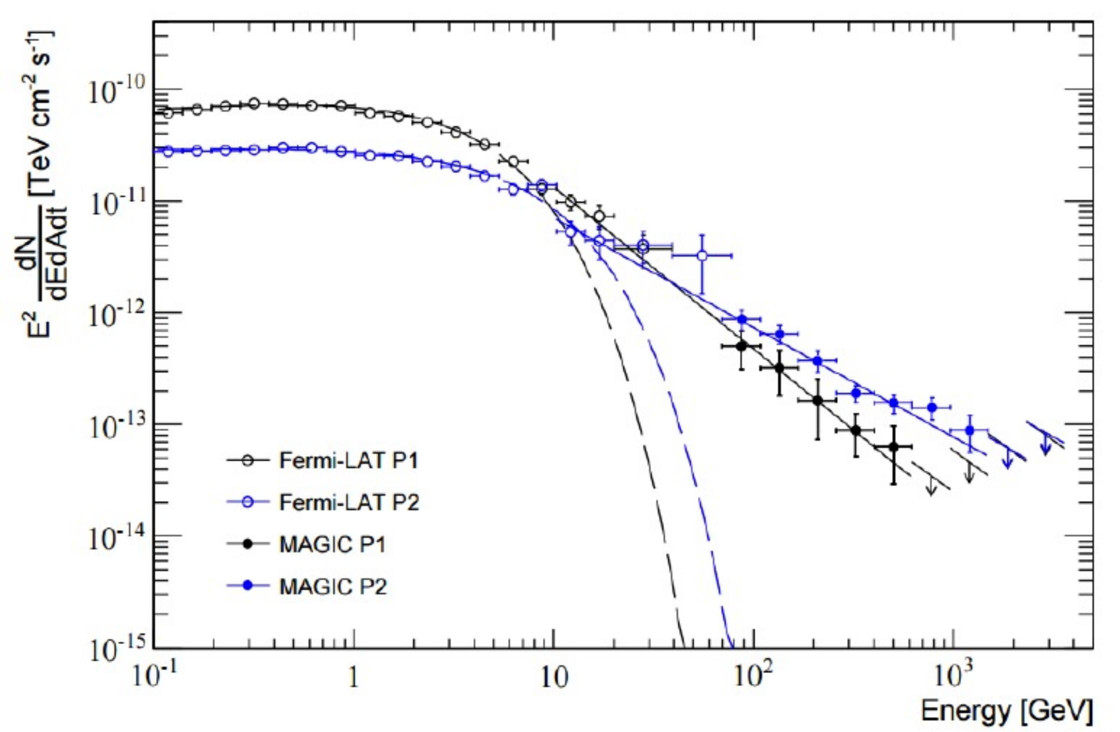


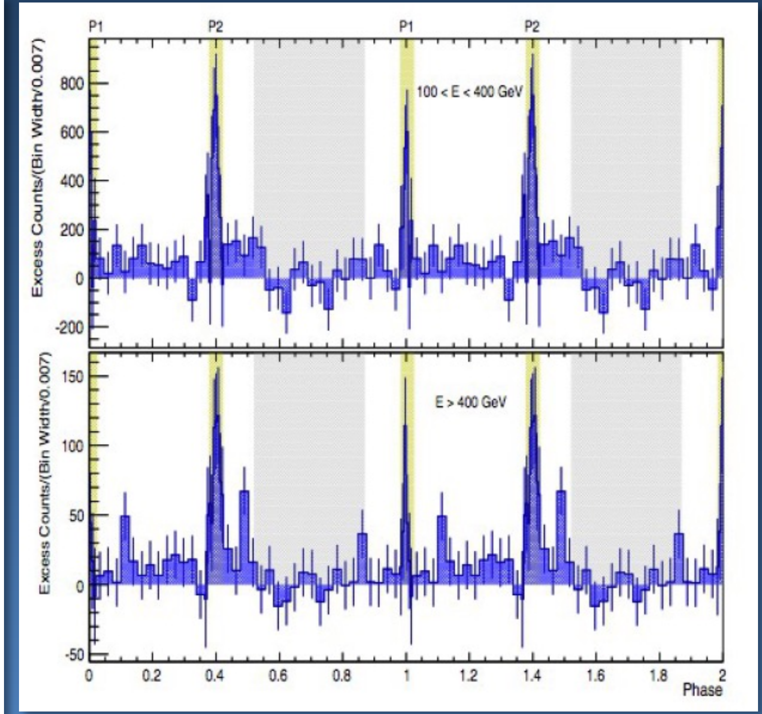
Detection of Crab pulsar up to 1 TeV

MAGIC - Aliu et al. 2008, Aleksic et al. 2012
Veritas - Aliu et al. 2011

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

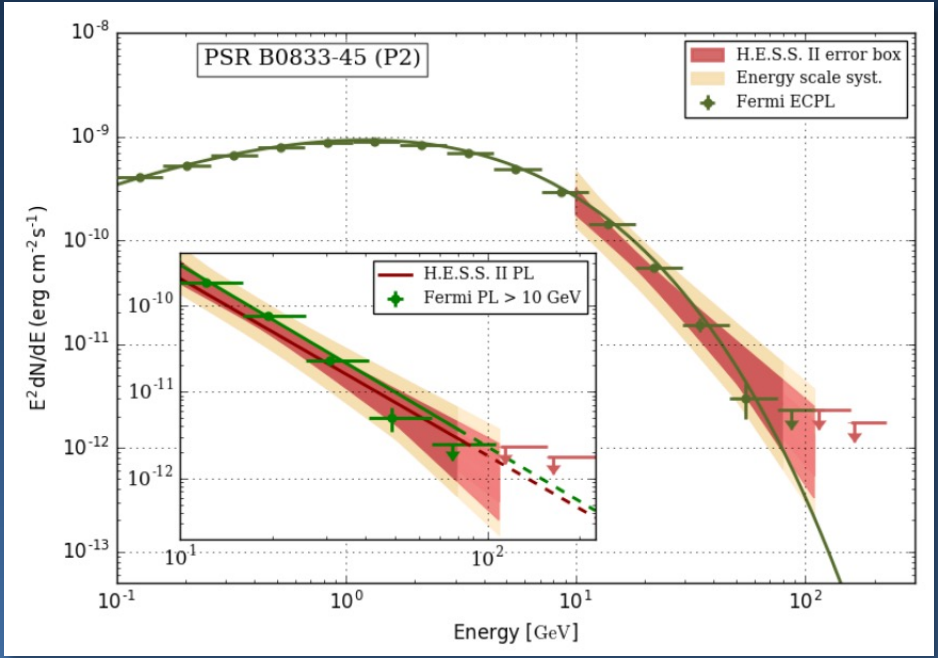
Both peaks detected!





Vela pulsar – H.E.S.S. II

10 – 110 GeV (Abdalla et al. 2018)



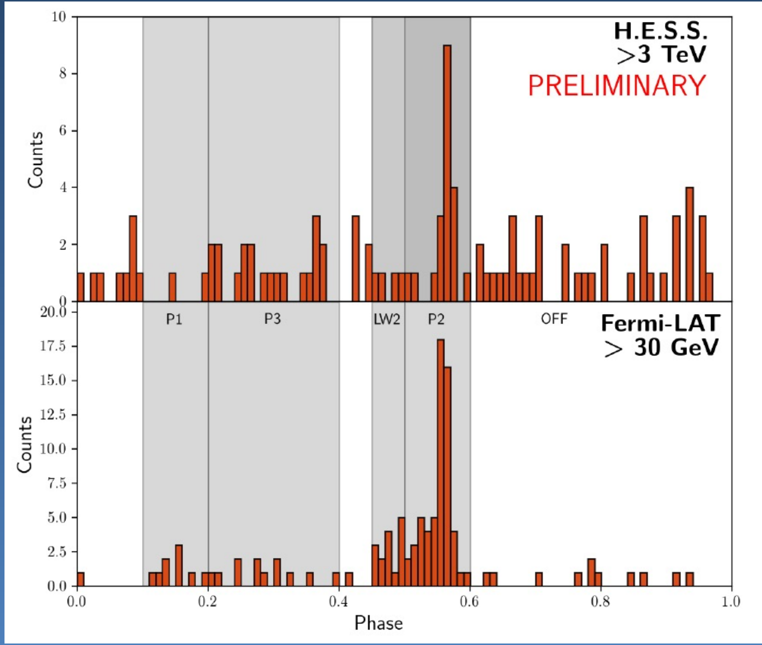
Continuation of Fermi spectrum (curved sub-exponential) or power law?

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

2004 – 2016: 60 hours in stereoscopic mode

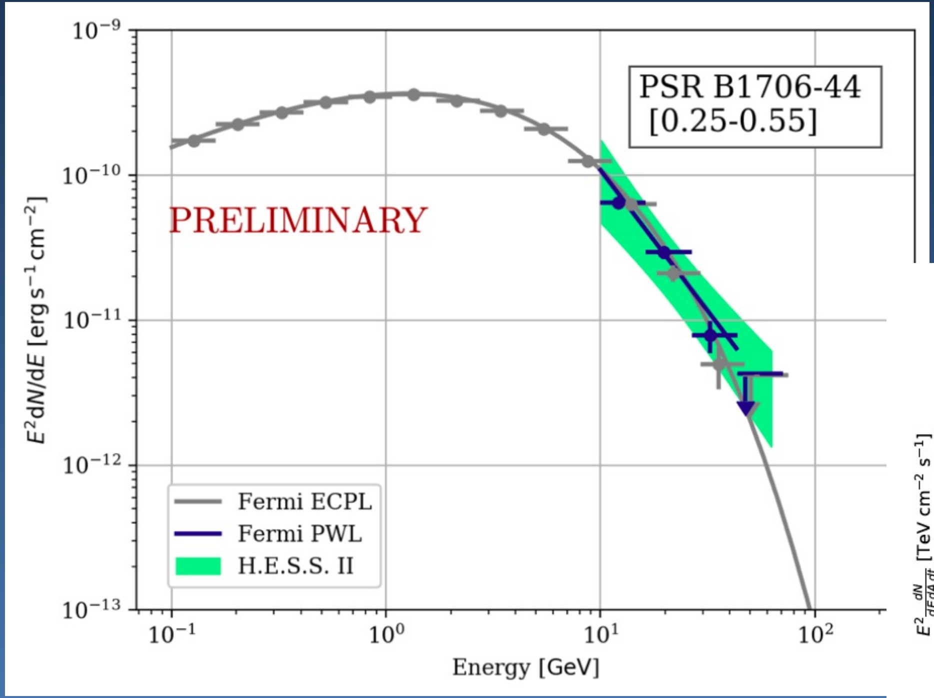
3 - > 7 TeV!! 5.6σ (Djannati-Atai 2018)

Additional component distinct from GeV spectrum?



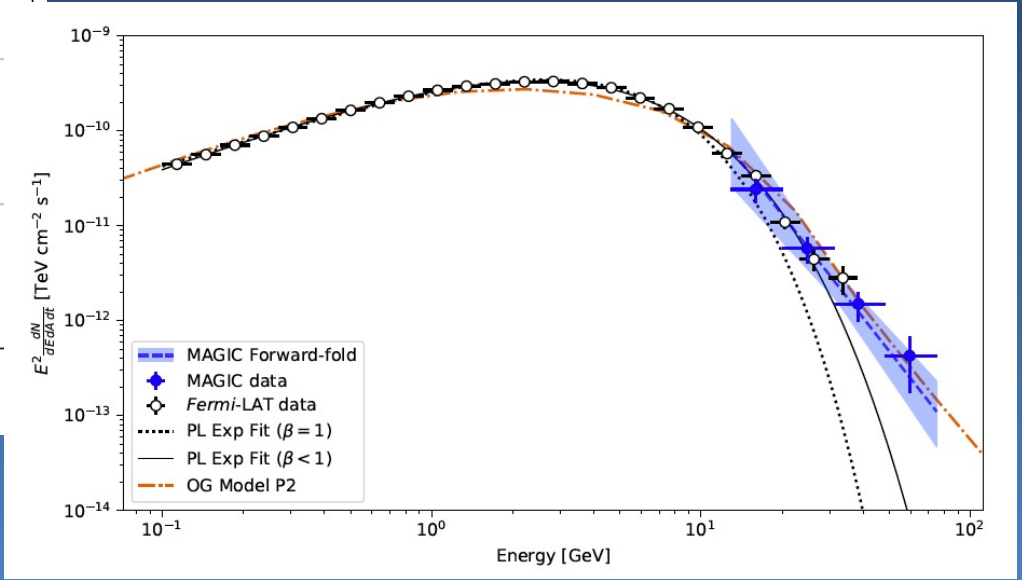
B1706-44 – H.E.S.S. II and Geminga - MAGIC

Spir-Jacob et al. 2019
10 – 70 GeV

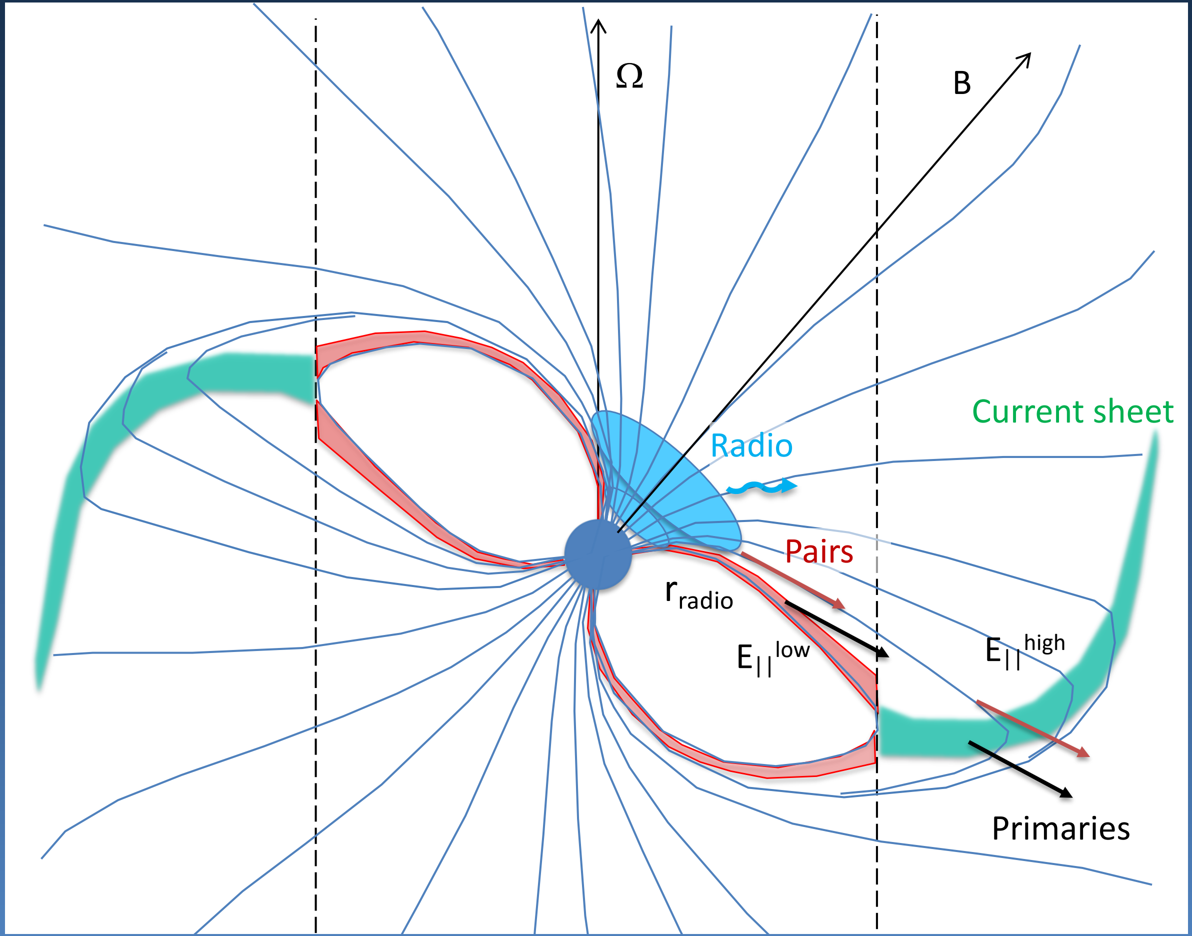


Acciari et al. 2020

Spectrum measured up to 75 GeV



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}

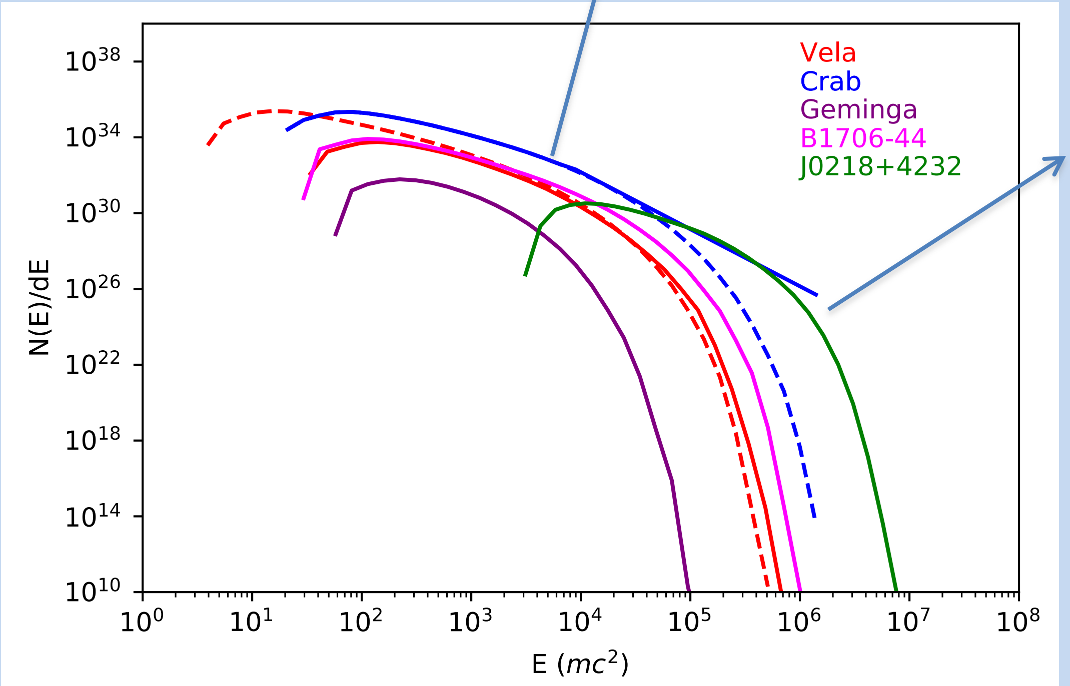
$$\boldsymbol{v} = \left(\frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2 + E_0^2} + f \frac{\boldsymbol{B}}{B} \right) c$$

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

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

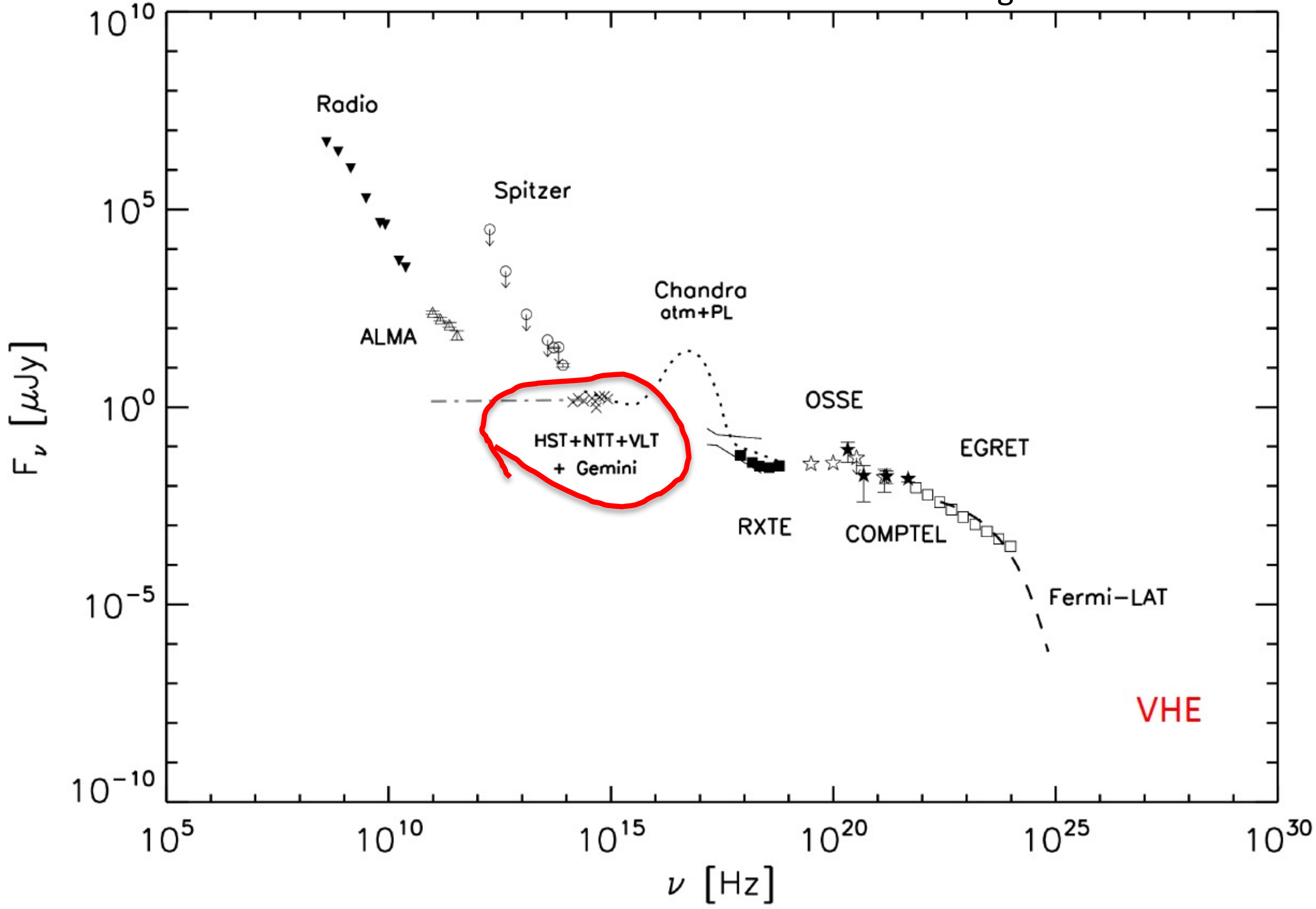
Synchrotron photon density (anisotropic)

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

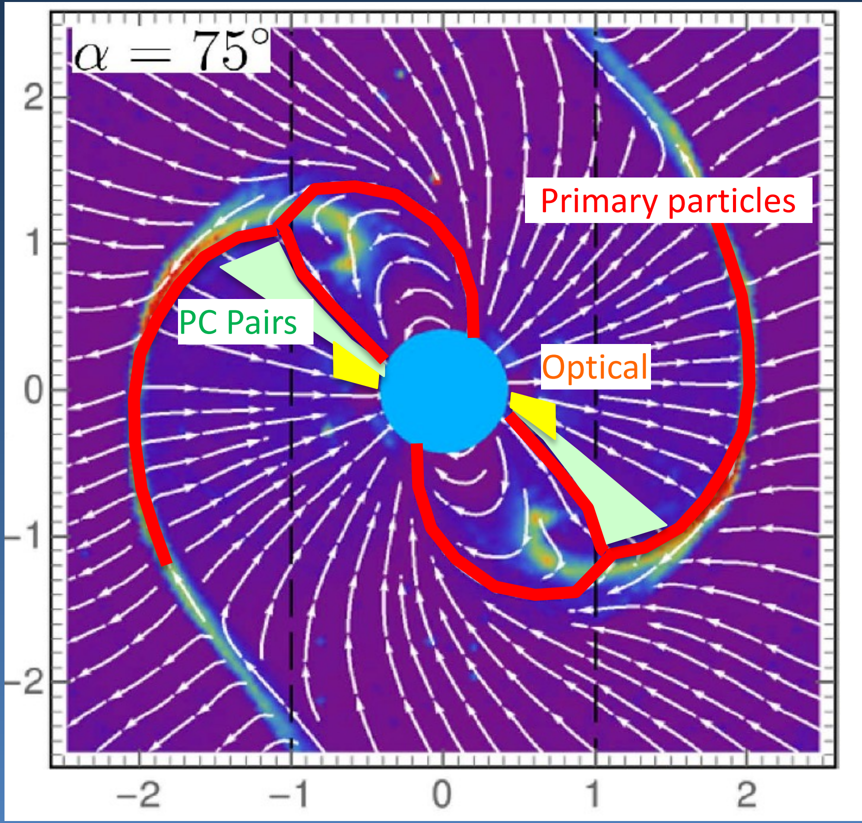
Spectral energy distribution of the Vela pulsar

Mignani et al. 2017



Modeling TeV+ emission

Harding, Kalapotharakos, Venter & Barnard 2018



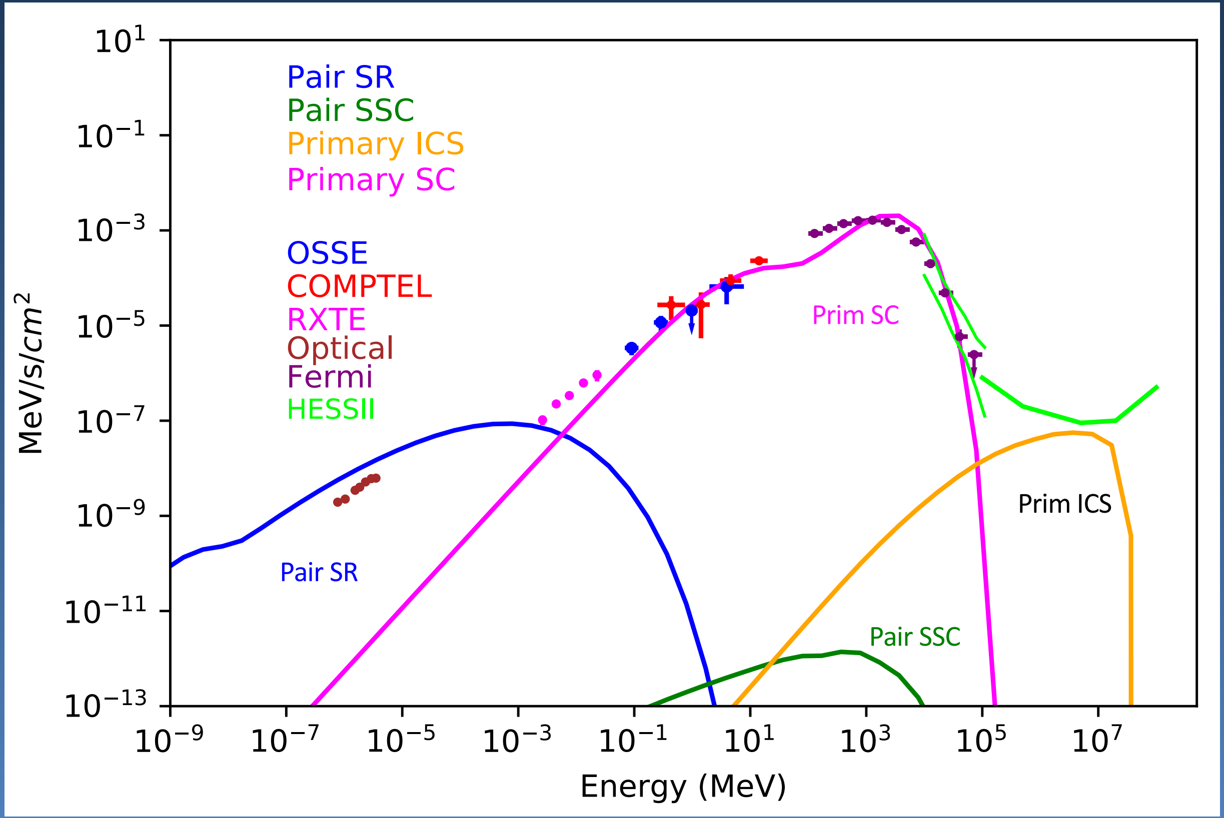
Near force-free magnetosphere

- 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

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 $M_+ = 6 \times 10^3$

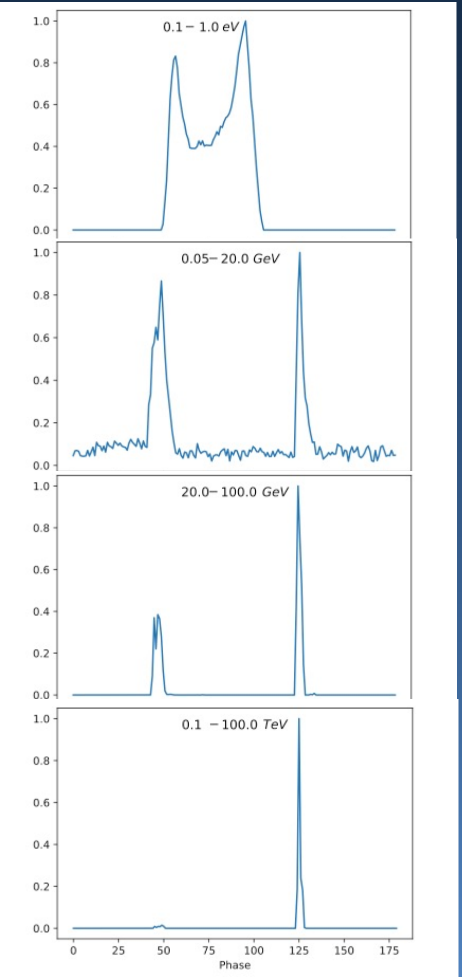
- Detectable component from primary ICS around 10 TeV!
- Pair SR matches optical spectrum

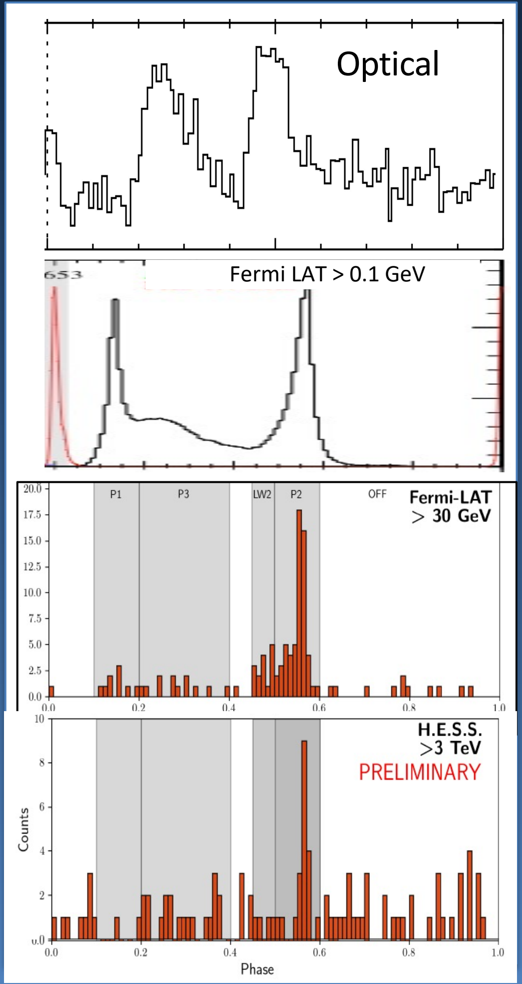


Pulsed emission ~ 10 TeV requires higher particle energy
⟶ GeV emission is CR

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 curvature radius and particle γ in P2

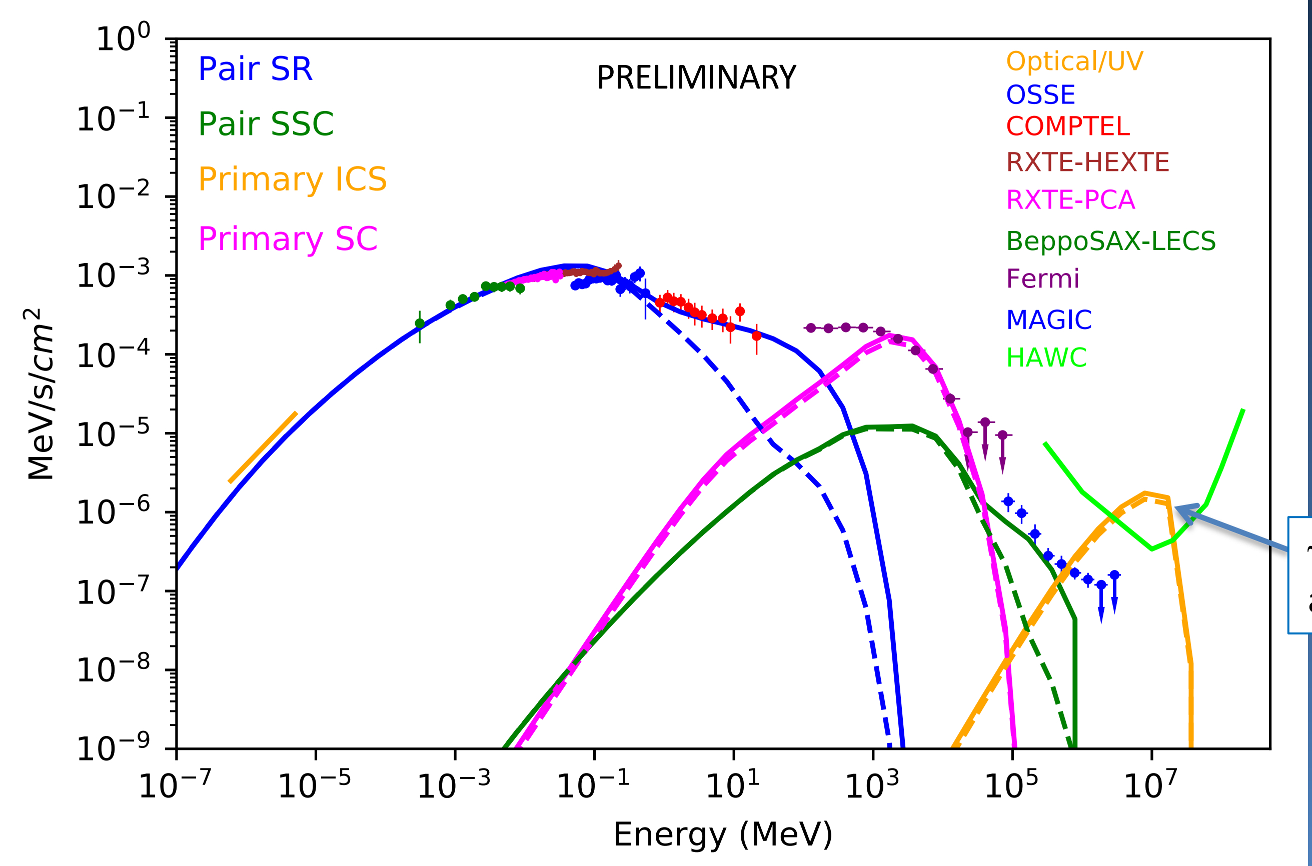
P2 only at > 3TeV – ICS from highest γ particles

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

TeV+ emission from Crab pulsar

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

Harding, Venter & Kalapotharakos 2021



γ–γ pair attenuated

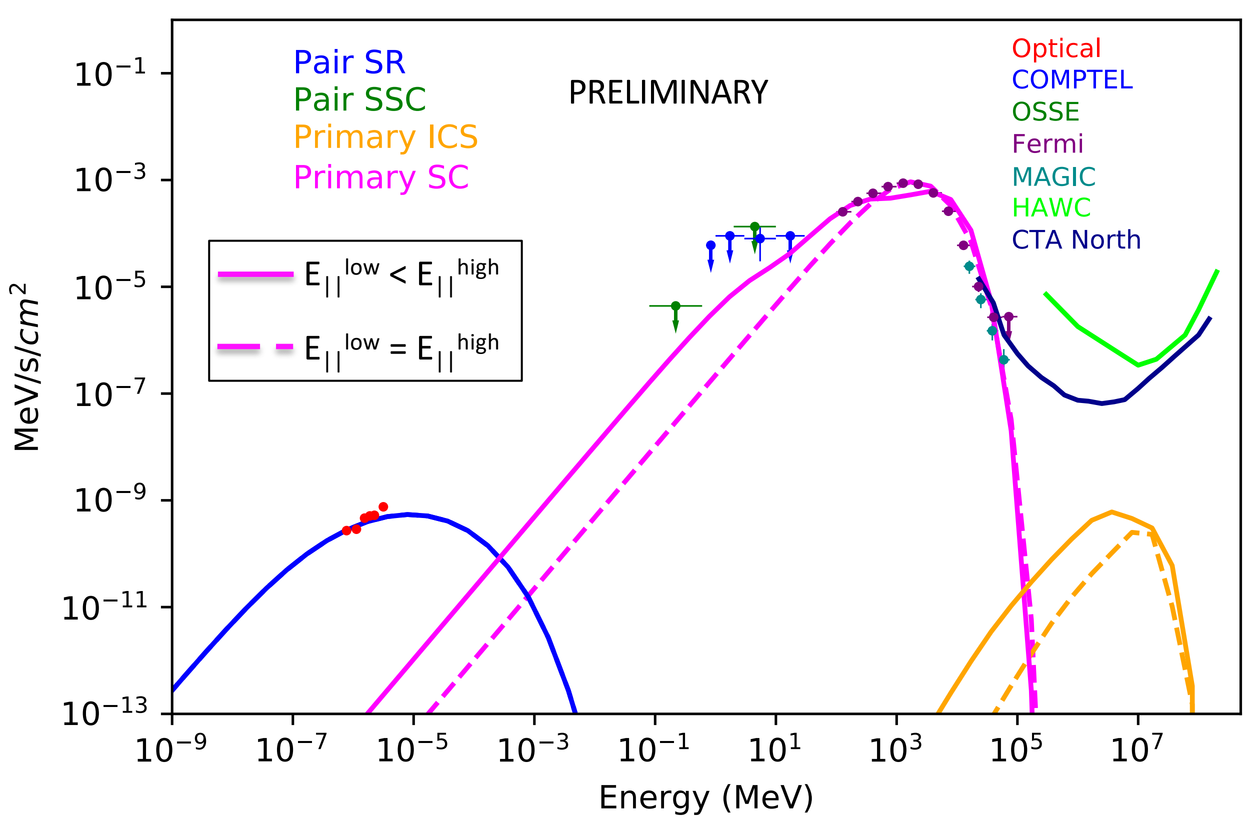
Pair emission near current sheet

TeV+ emission from Geminga

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

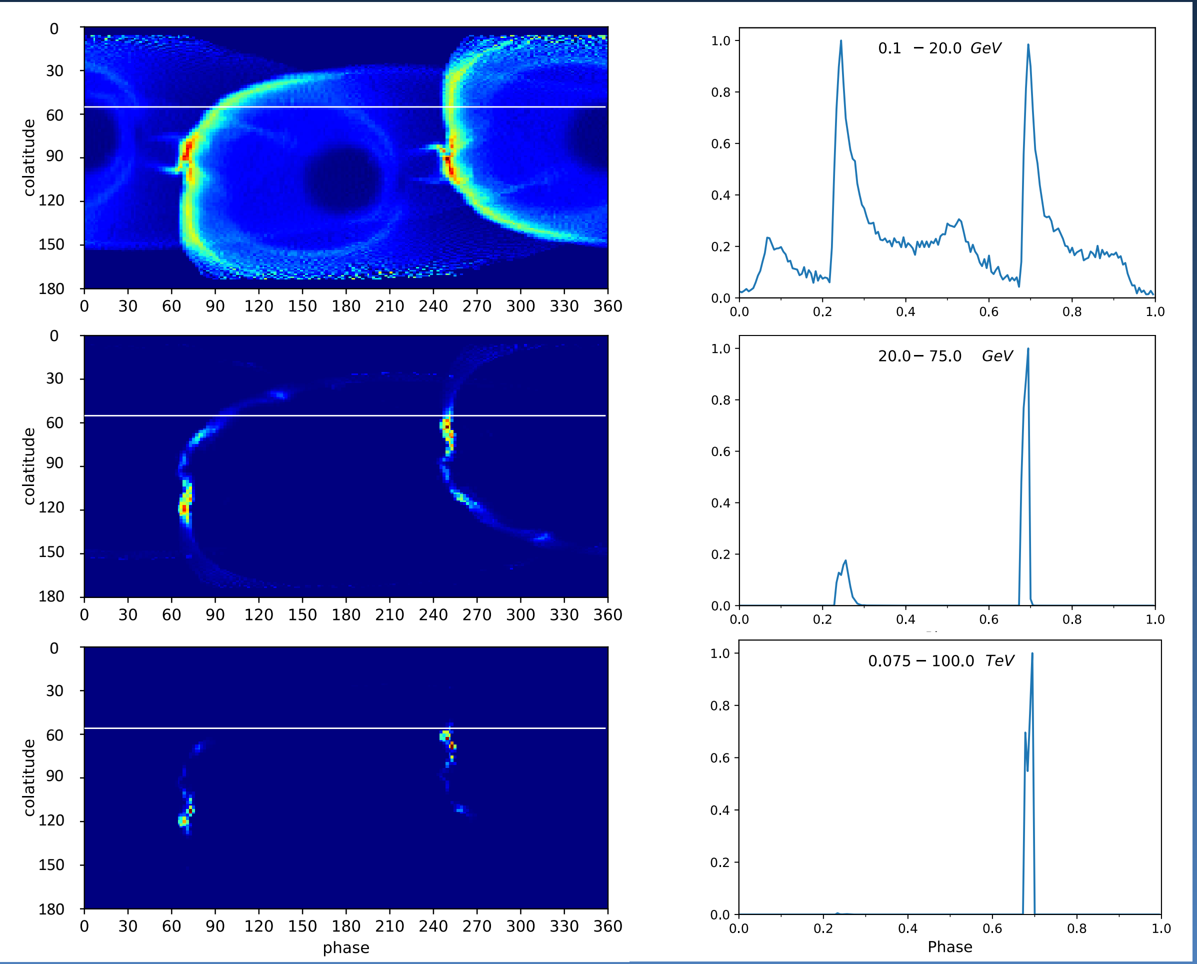
$\alpha = 75^0$, $\zeta = 50^0$, pair $M_+ = 2 \times 10^4$

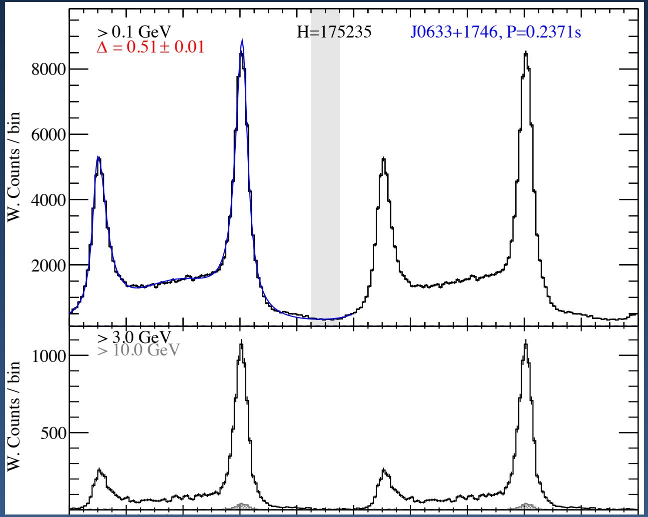
Harding, Venter & Kalapotharakos 2021

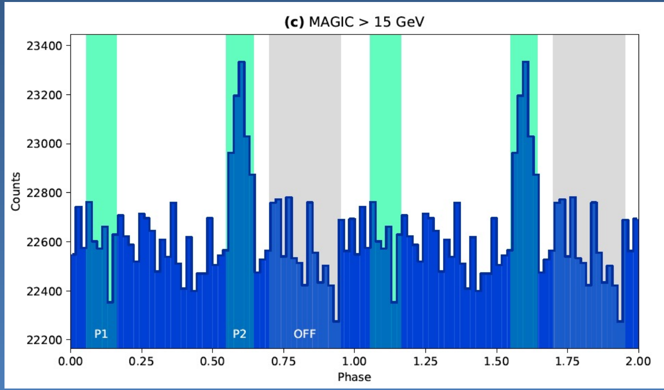


- Low pair SR UV flux
  → Very low primary ICS
- MAGIC detection explained by primary SC

Geminga model light curves



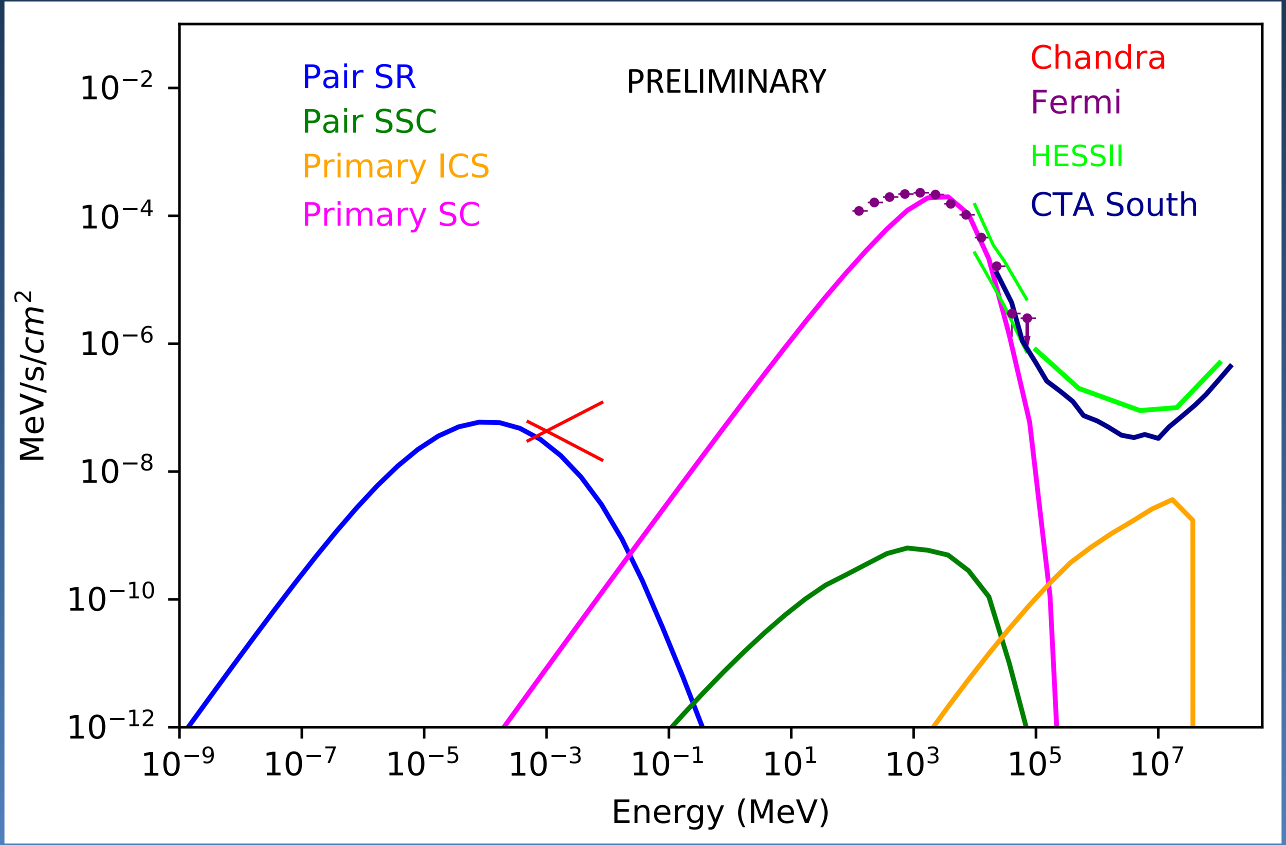




TeV+ emission from B1706-44

$P = 0.102$ s, $B_0 = 6.2 \times 10^{12}$ G, $d = 2.3$ kpc
$\alpha = 45^0$, $\zeta = 54^0$, 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

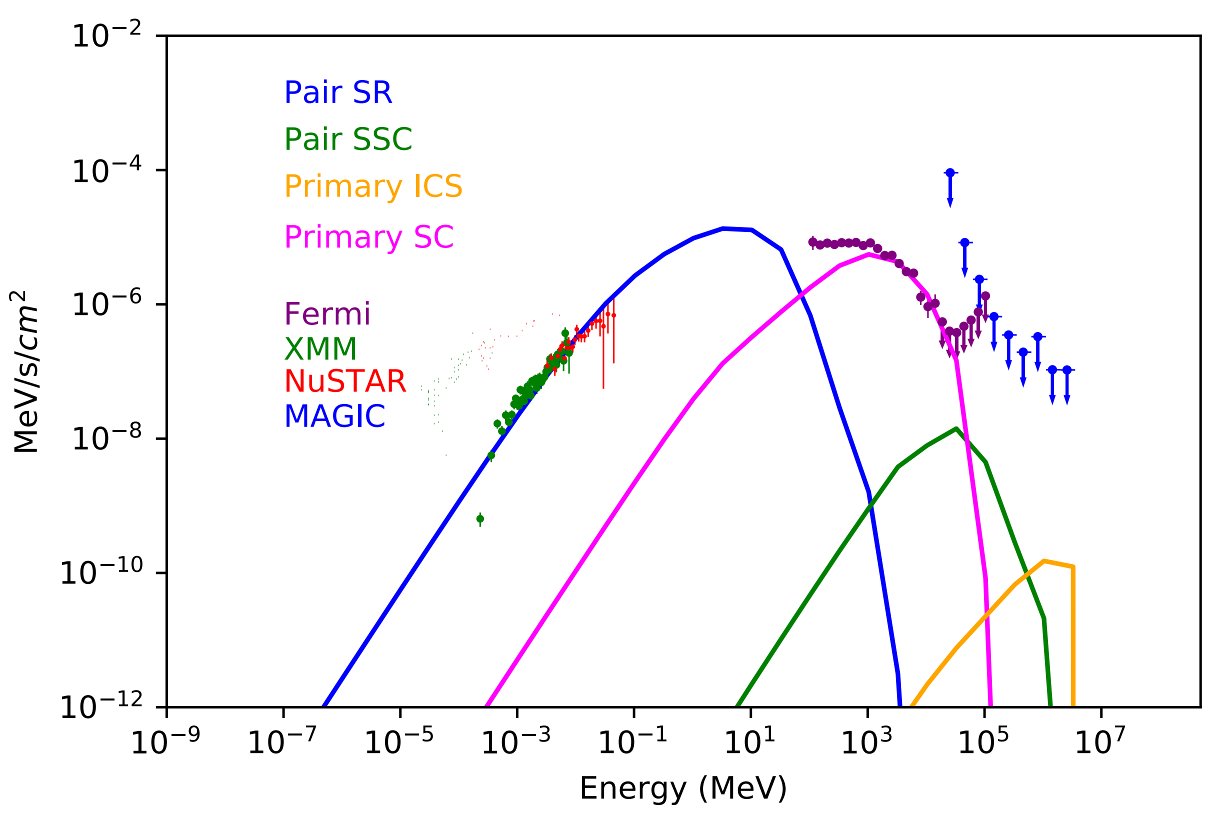
H.E.S.S. II detection explained by primary SC

TeV+ emission from MSP J0218+4232

P = 0.0023 s, B_0 = 8 x 10^8 G, d = 3.1 kpc

α = 60^0, ζ = 65^0, pair M_+ = 3 x 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

What's important for VHE emission?

TeV+ emission from primary ICS:

- 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