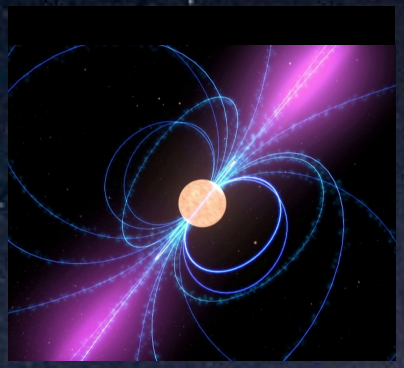
Multi-TeV Emission From the Vela Pulsar



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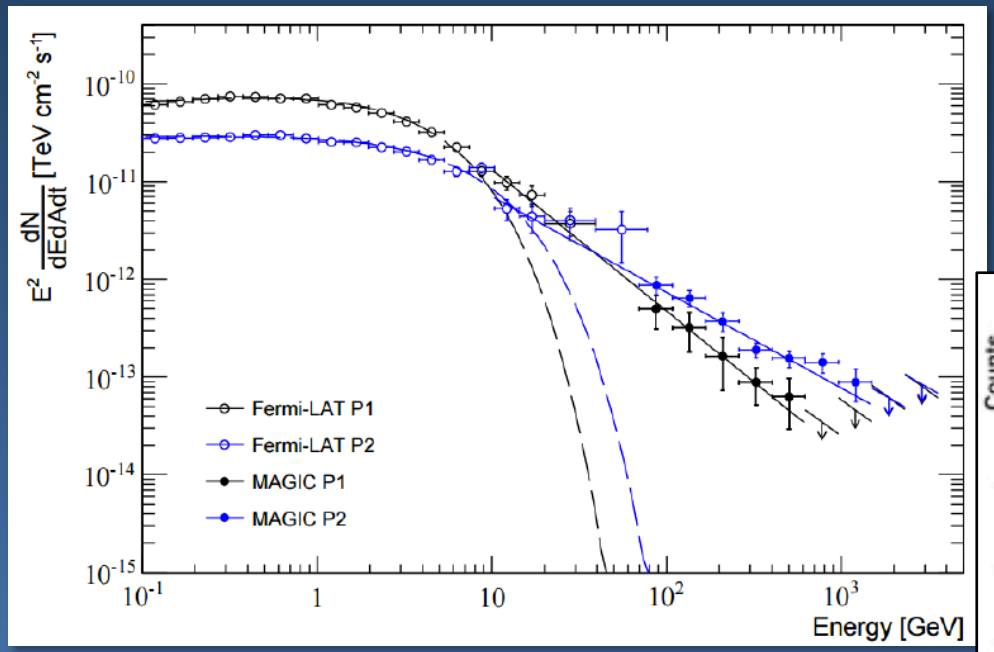
VHE emission from pulsars

Pulsed emission above 10 GeV detected from three pulsars by ACTs

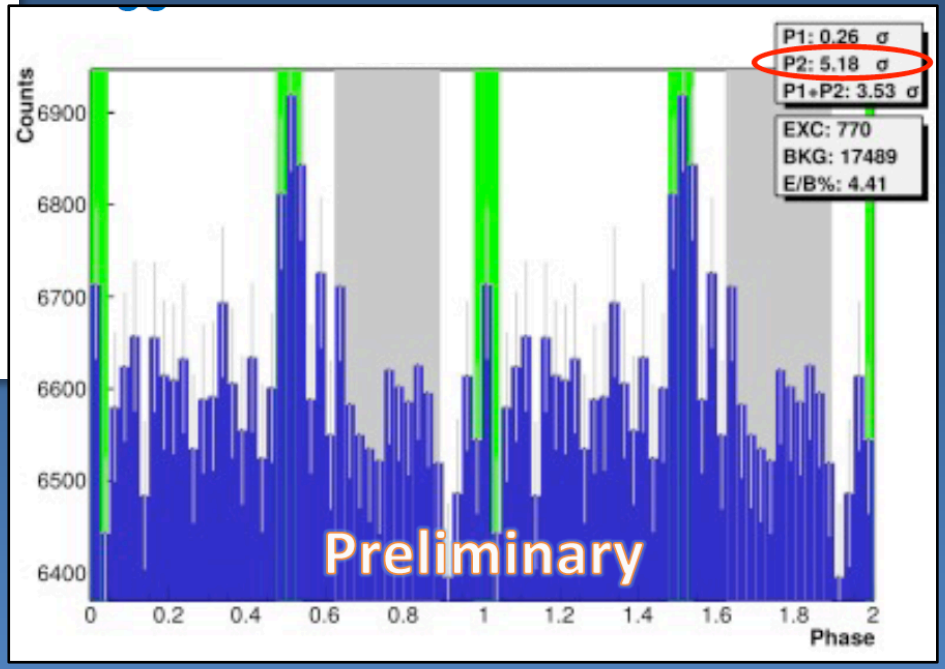
Crab: VERITAS > 120 GeV

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



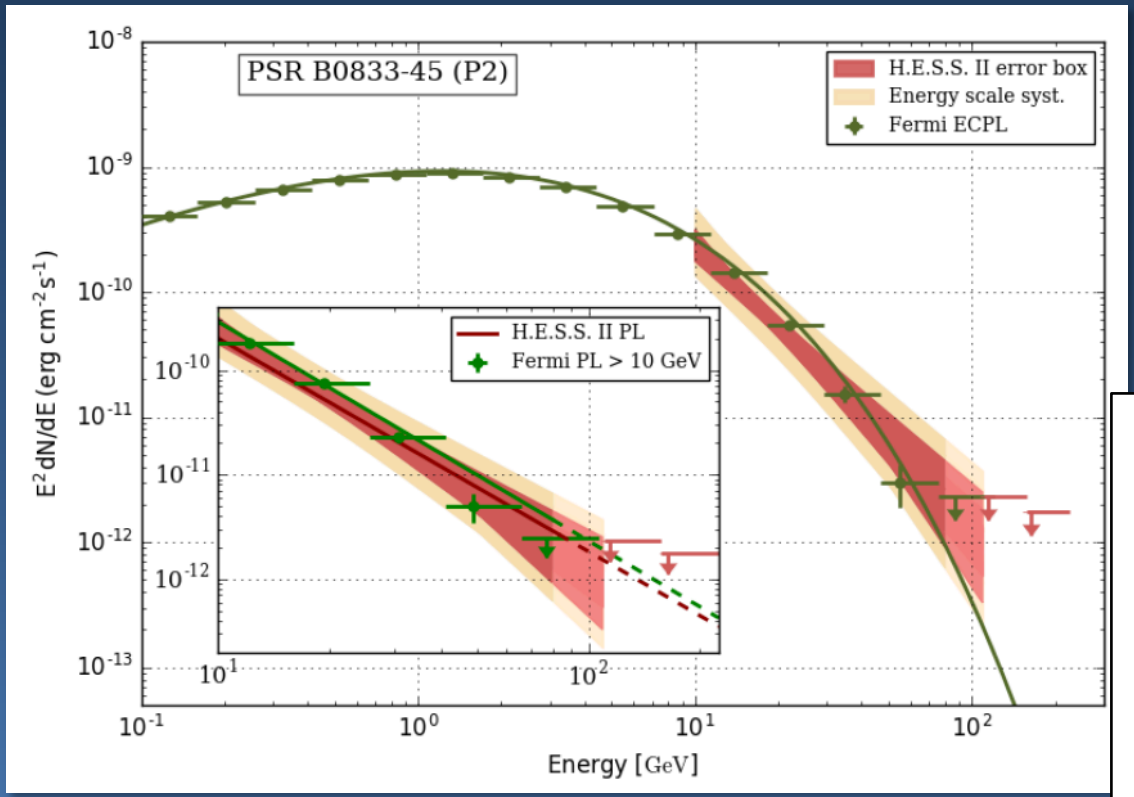
Geminga!

MAGIC: P2 > 30 GeV



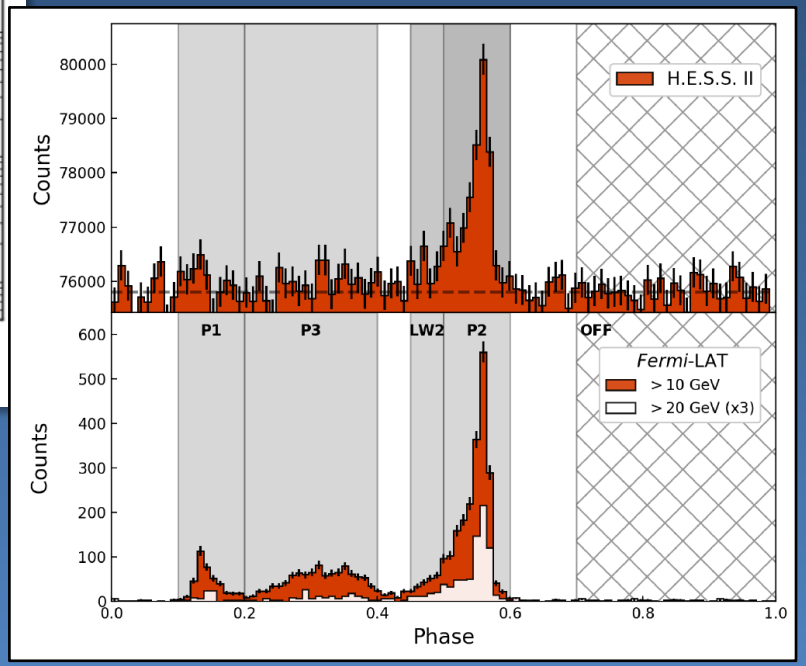
Vela pulsar – H.E.S.S. II

10 – 80 GeV (Abdalla et al. 2018)



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

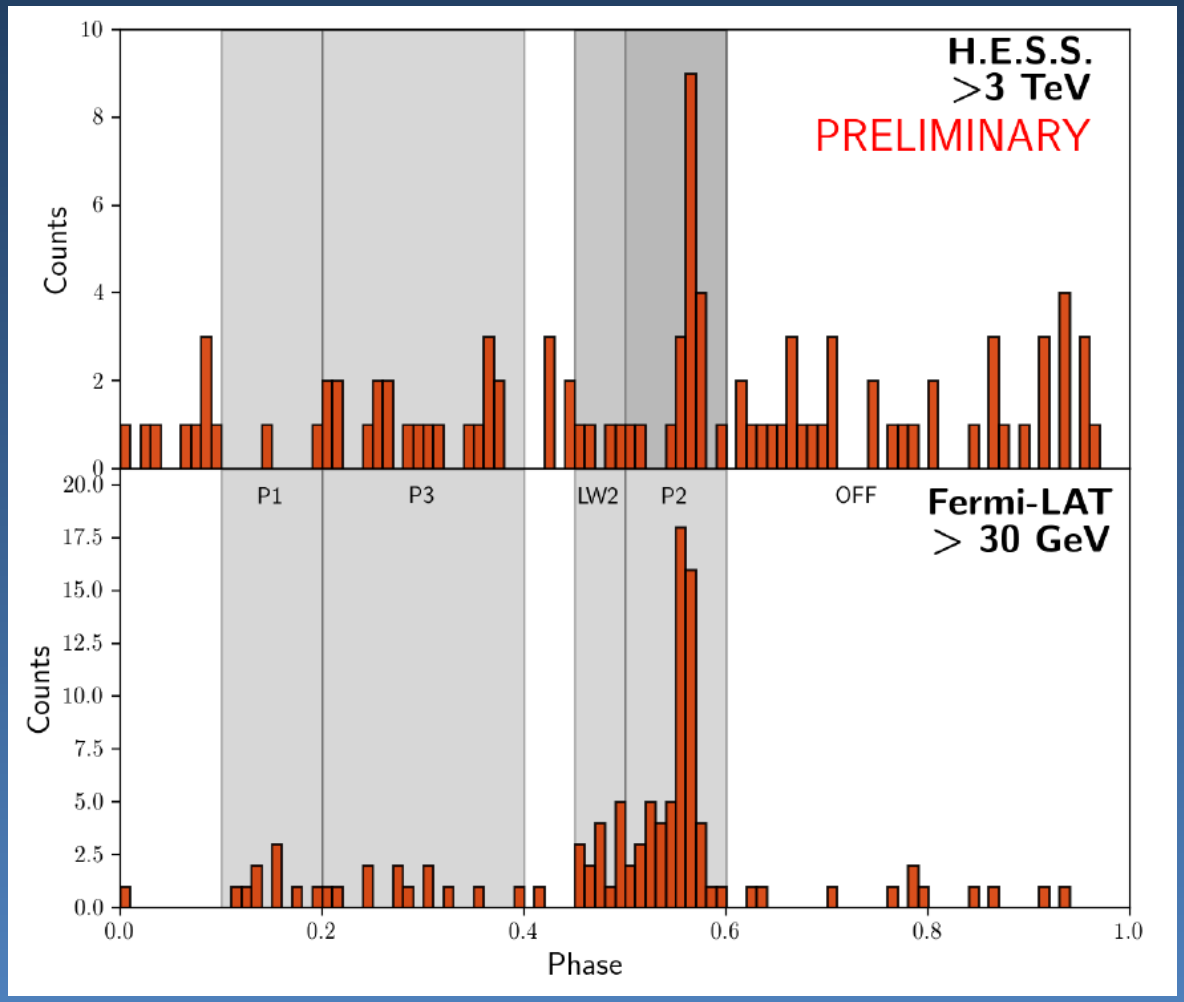
Curvature favored by H.E.S.S. II at $> 3.0\sigma$



Vela pulsar – H.E.S.S. II

2004 – 2016: 60 hours in stereoscopic mode

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

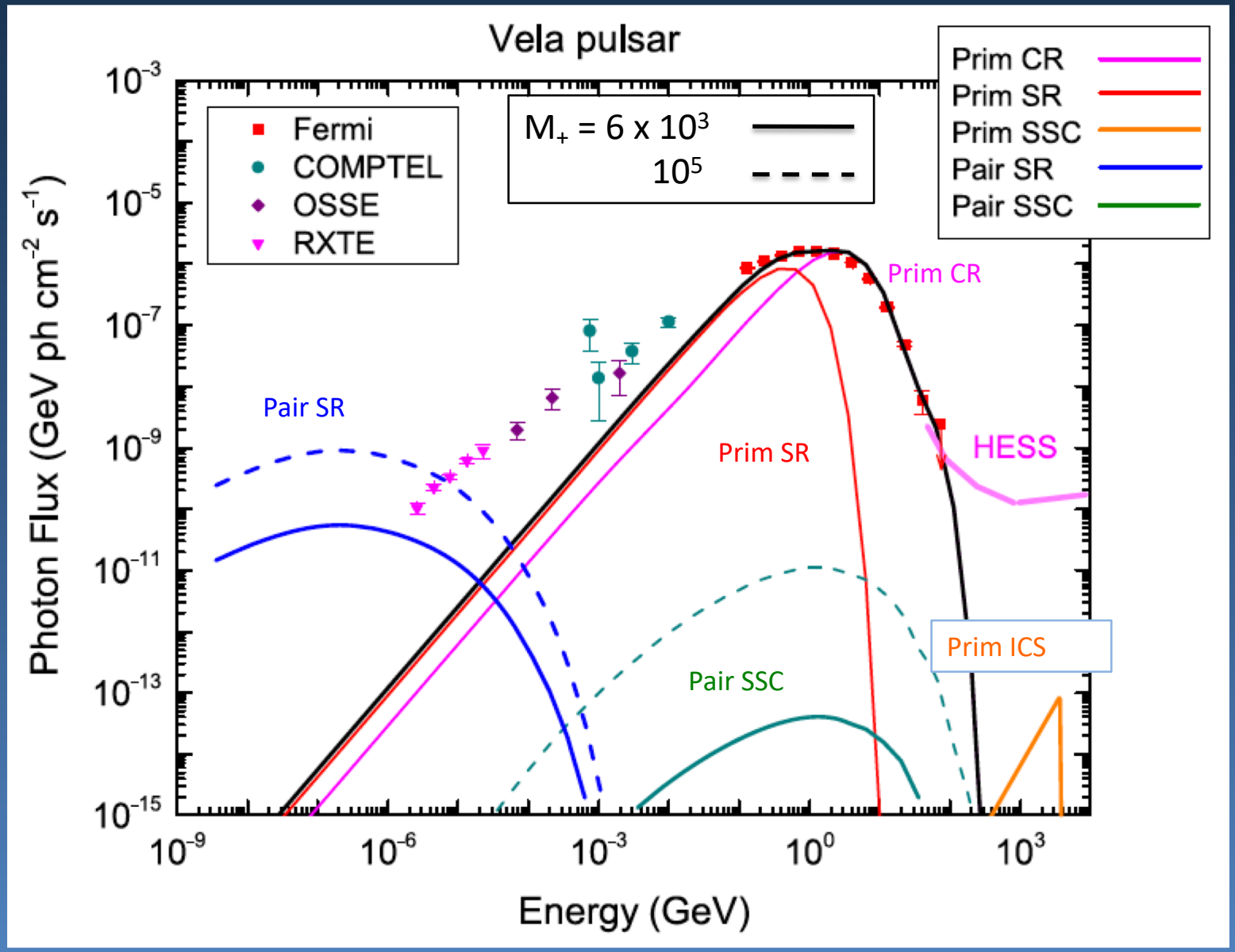


Additional component distinct from GeV spectrum?

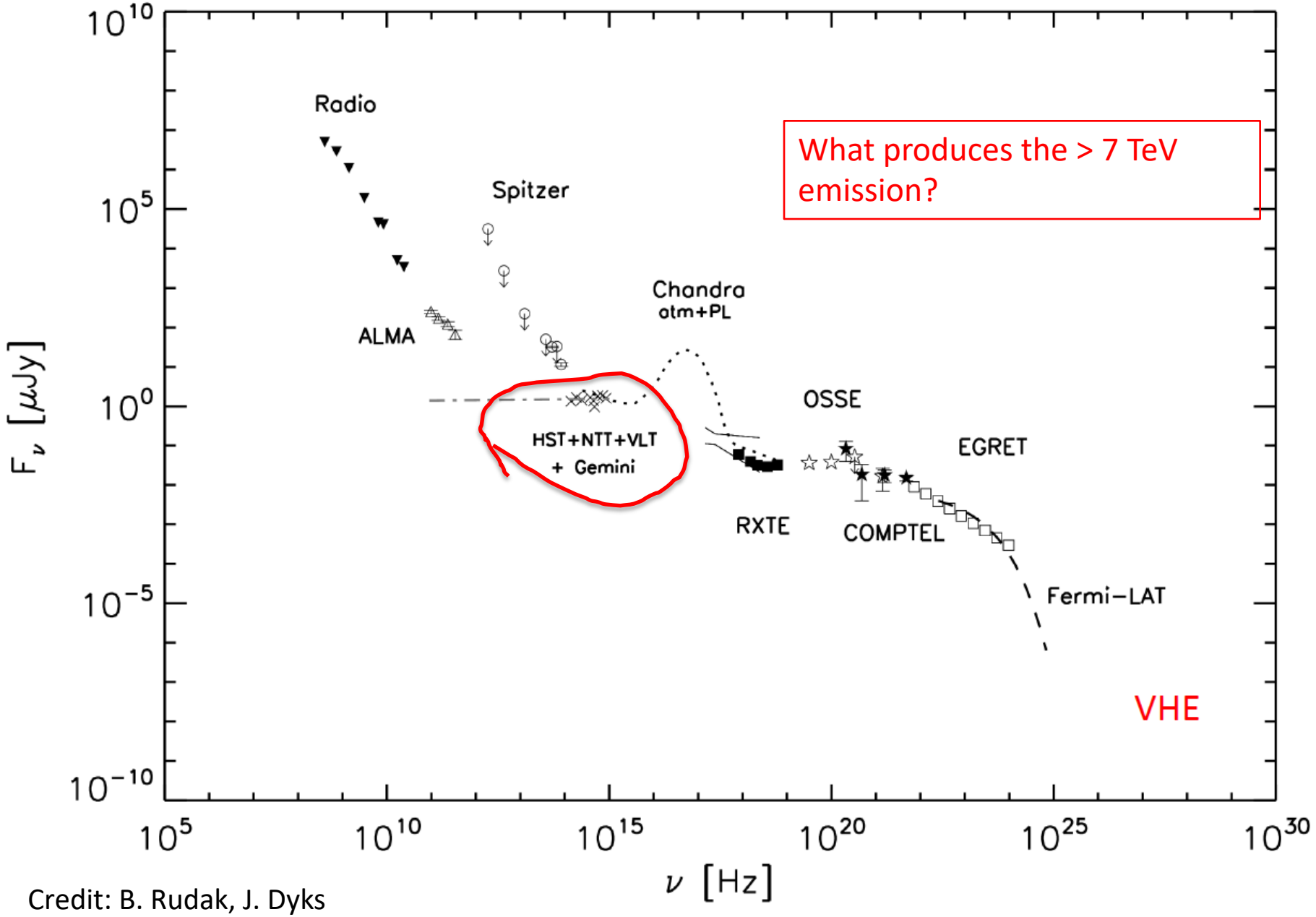
SSC emission from Vela pulsar

Harding & Kalapotharakos 2015

$\alpha = 75^0, \zeta = 60^0$



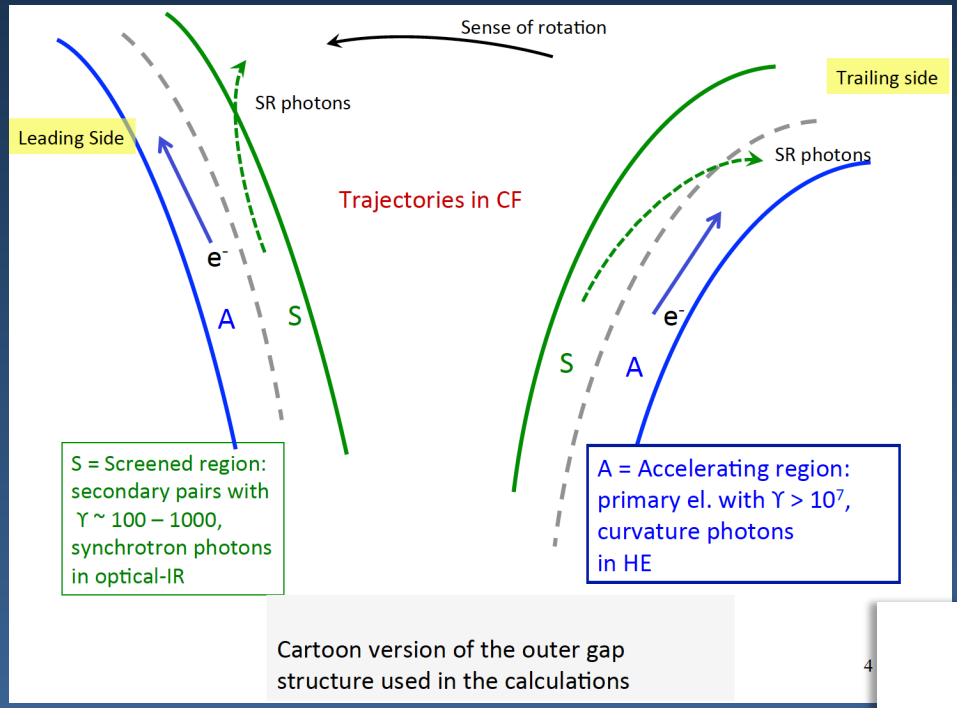
Spectral energy distribution of the Vela pulsar



Credit: B. Rudak, J. Dyks

ICS model for Vela TeV emision

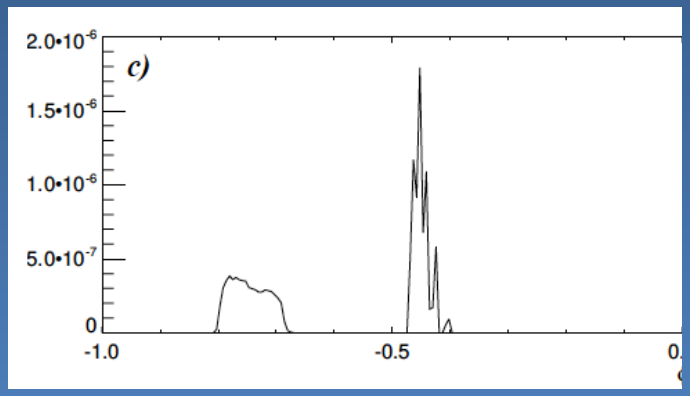
Rudak & Dyks 2017

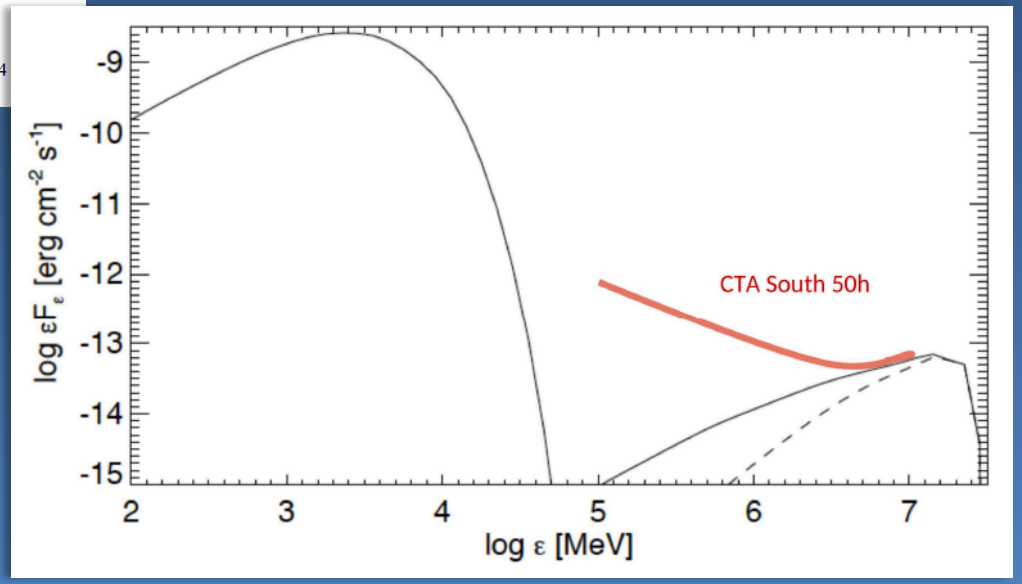


Cartoon version of the outer gap structure used in the calculations

Outer gap model

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



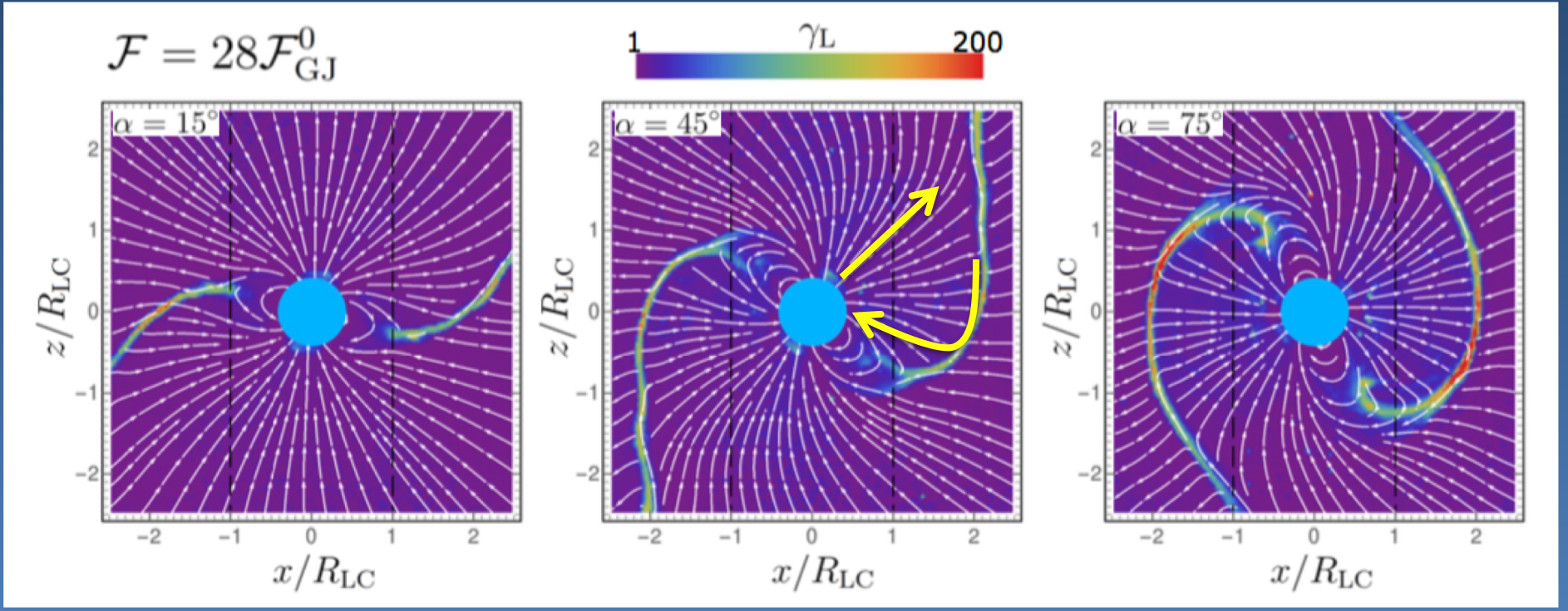


Recent pulsar models

Global particle-in-cell simulations (Chen & Belodorodov 2014, Philippov+ 2015, Cerutti+ 2015, 2016, Kalapotharakos+ 2018)

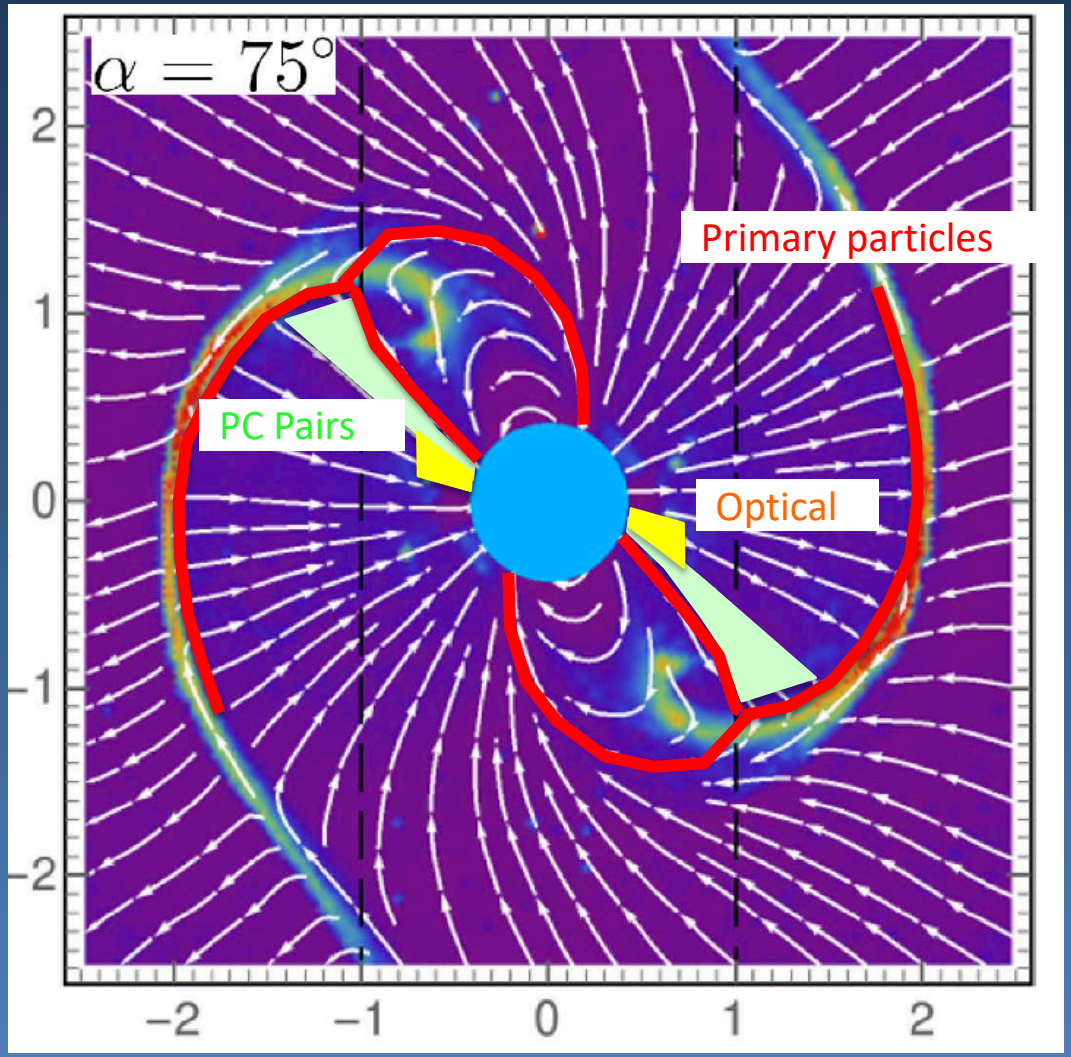
Most particle acceleration occurs in and near the current sheet

See Kalapotharakos poster



Modeling TeV+ emission from Vela

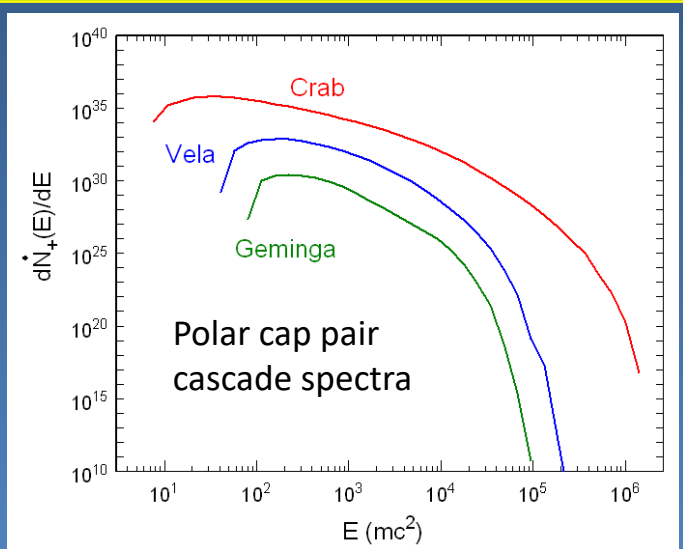
Harding et al. 2018
See also Barnard poster



From Kalapotharakos+ 2018

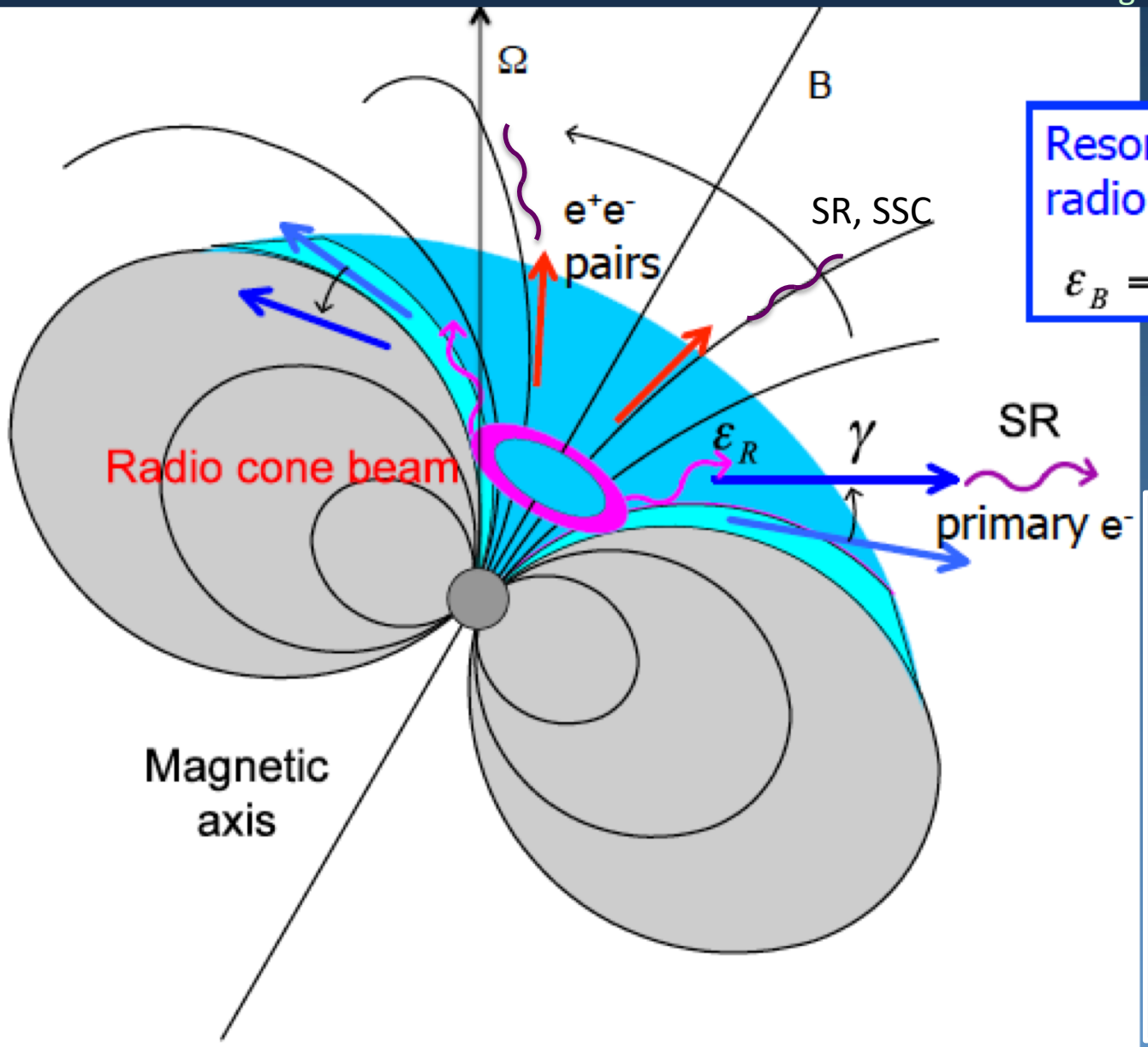
Near force-free magnetosphere

- PC pairs produce SR IR/optical at lower altitude, injected only where global model allows
- Primary particles (mostly positrons) in current sheet scatter IR/optical to produce 10 TeV ICS emission
- Pairs scatter IR/optical to produce SSC hard X-rays



Simulation of pulsar radiation

Harding & Kalapotharakos 2015



Resonant absorption of radio photons when

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

Petrova & Lybarski 1998
Harding et al. 2008

Two models for IR/Optical

1. Toy model:
Power law .005 – 4 eV
Uniform emission from
R_{NS} – 0.5 R_{LC}

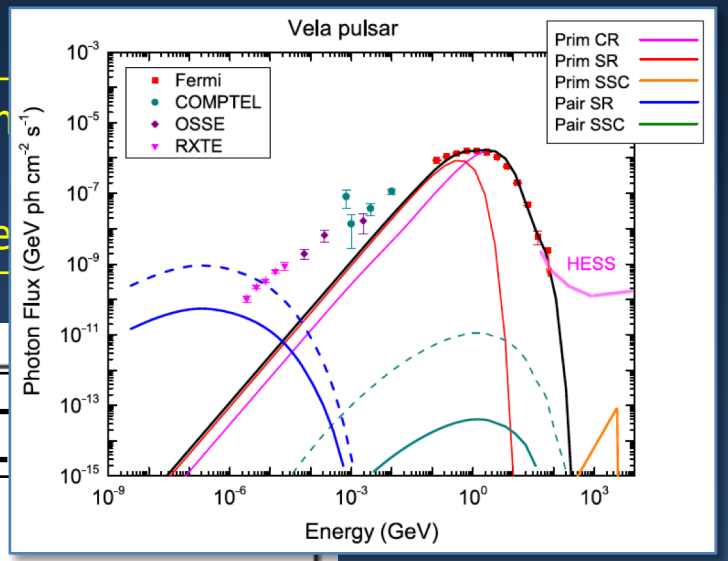
2. SR from pairs:
Radio altitude 0.3 R_{LC}

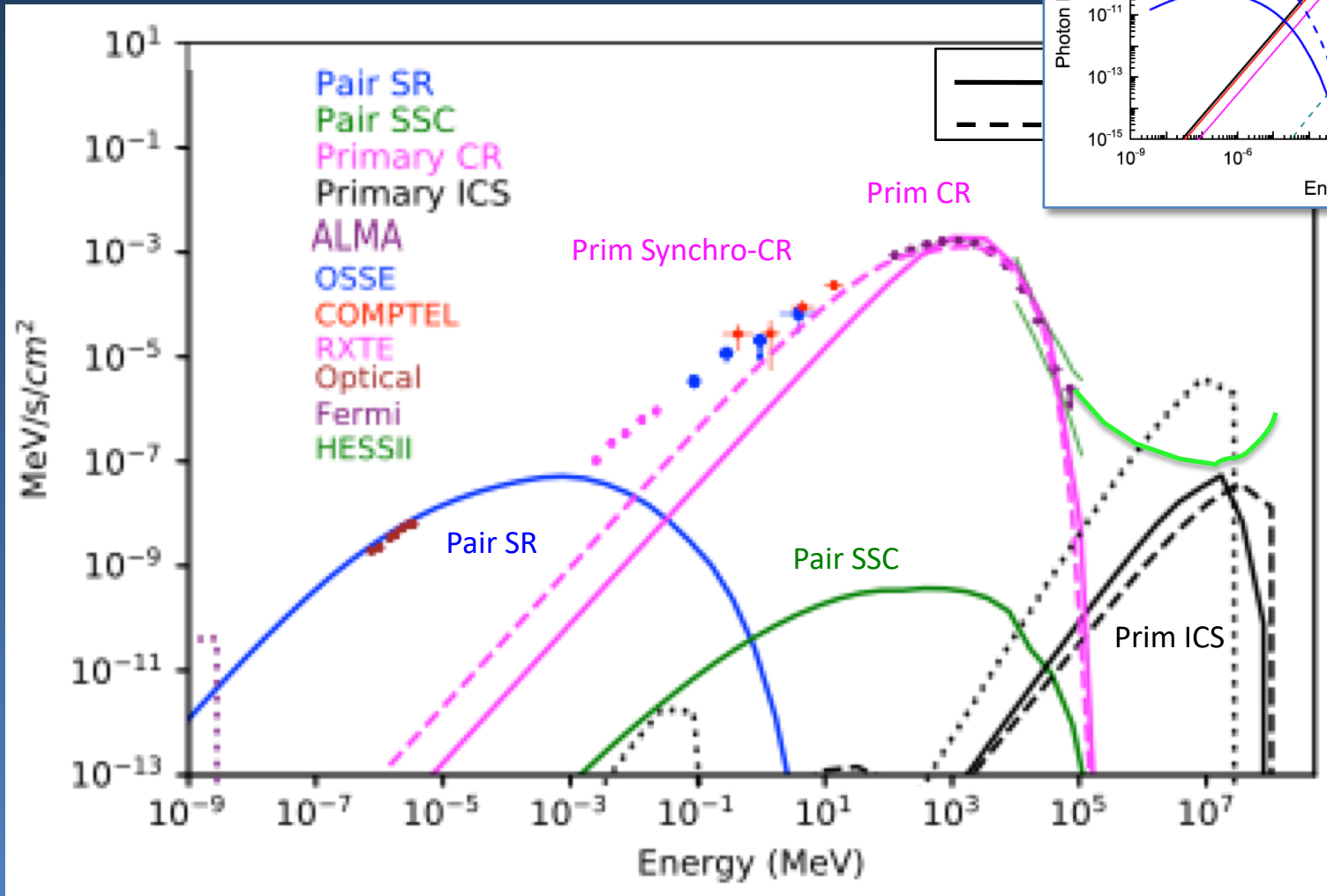
Modeling TeV+ emission from Vela

Harding, Kalapotharakos, Venter & Barnard 2018

- Detectable con
  10 TeV!
- Pair SR matche

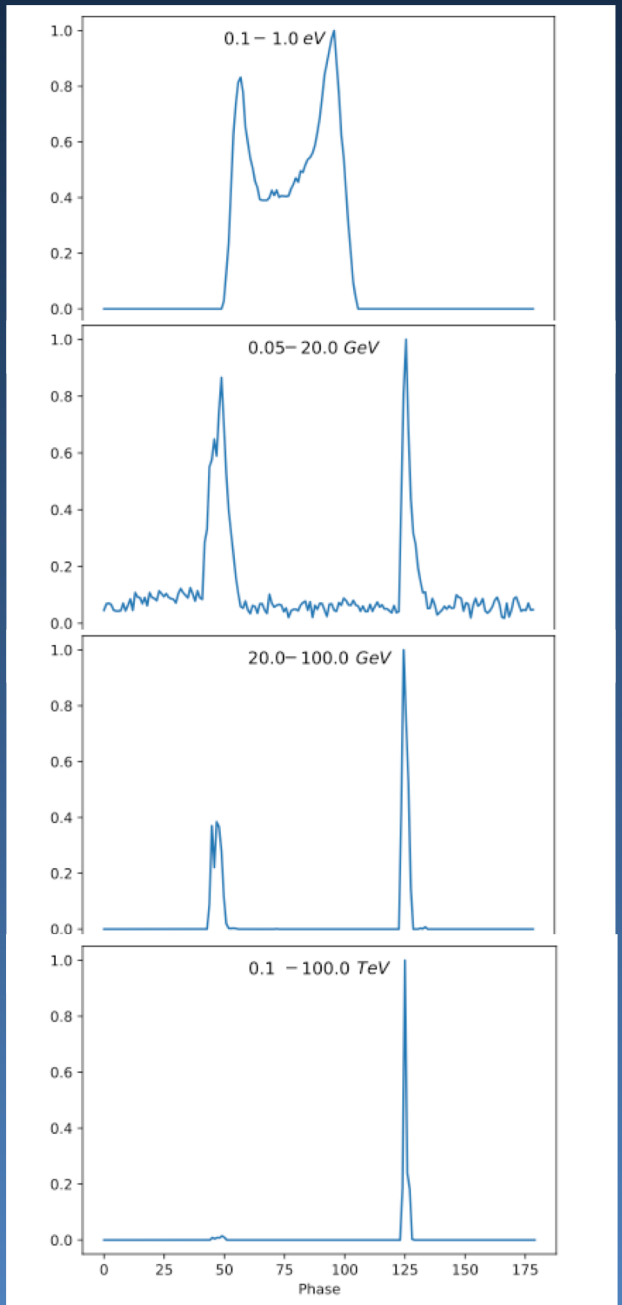
$\alpha = 75^0$, $\zeta = 65^0$, pair $M_+ = 6 \times 10^3$

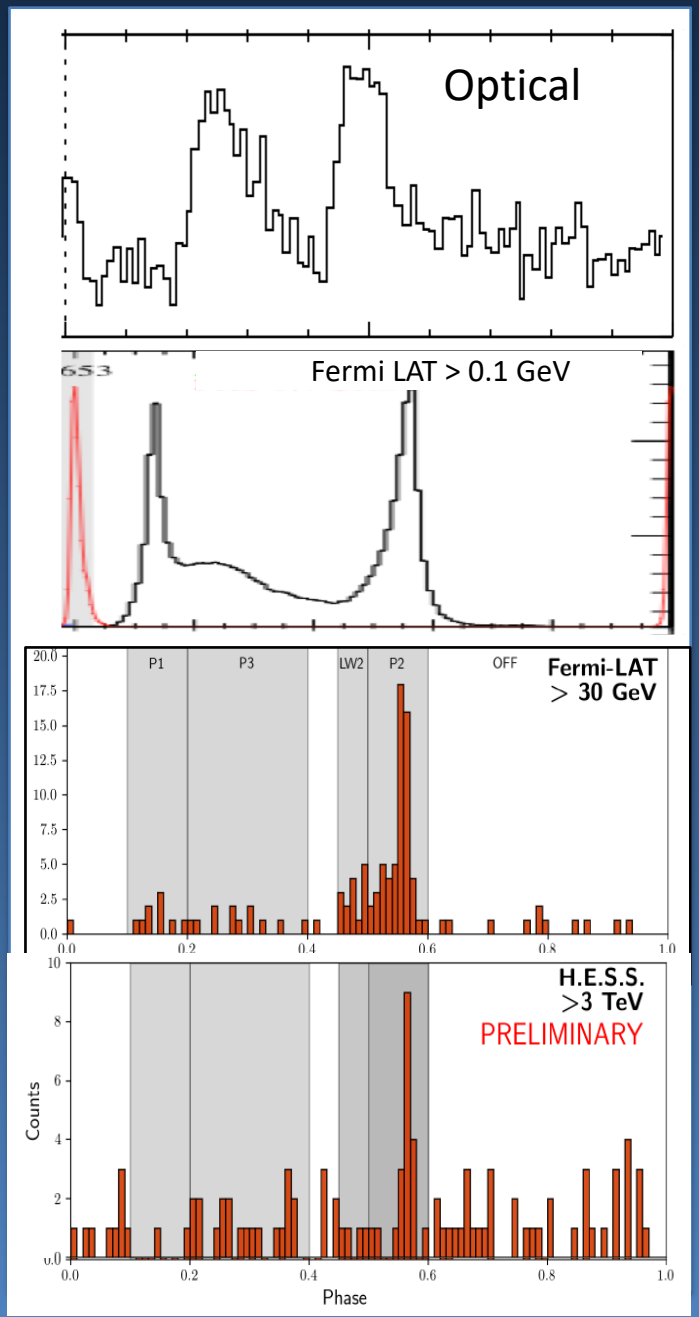




The dangers of limited energy scale! We could have predicted 10 TeV emission from Vela in 2015 …

Model light curves





Harding, Kalapotharakos, Venter & Barnard 2018

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

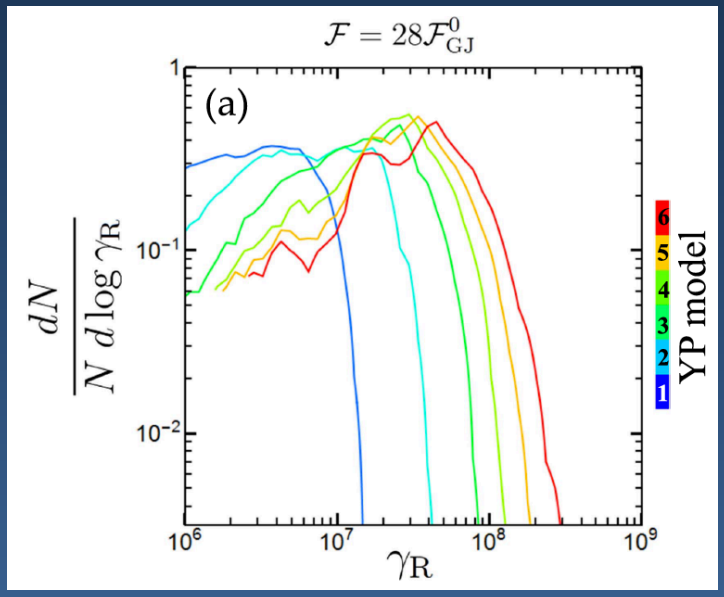
P2 only at > 3TeV – ICS from highest γ particles

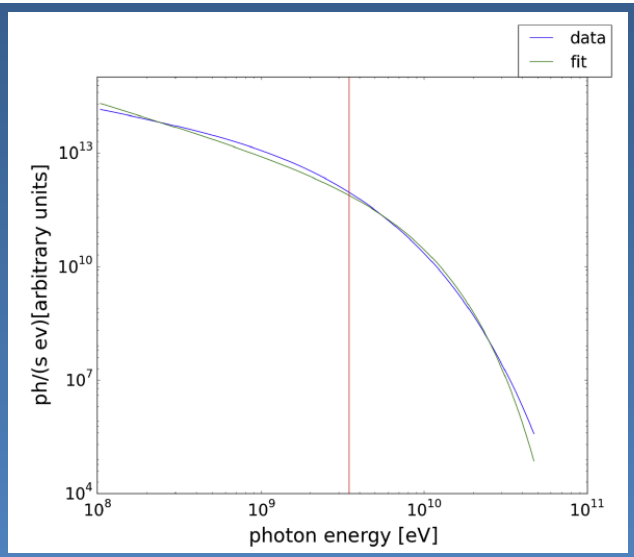
Large model γ-ray/radio phase lag due to azimuthally symmetric emission in current sheet

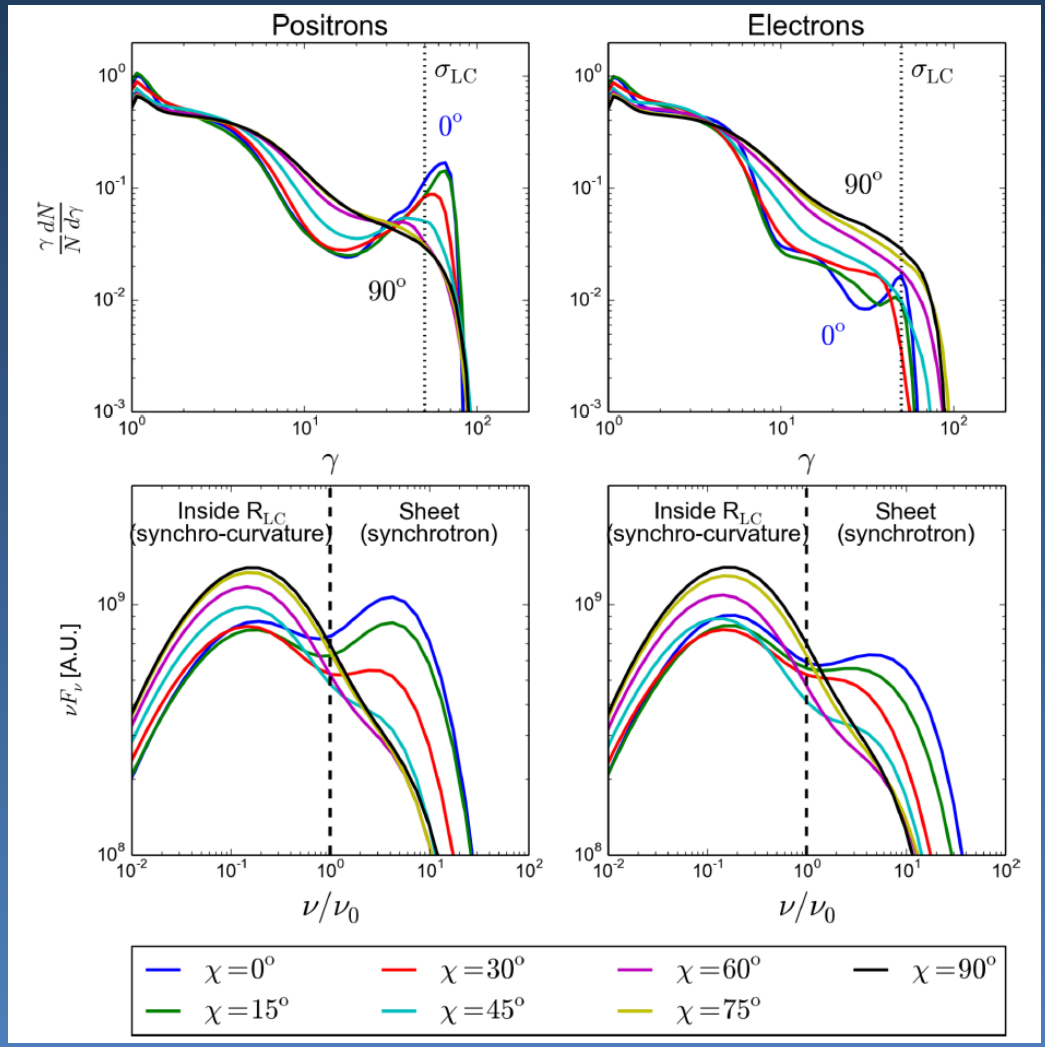
GeV emission

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

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







Summary

- Updated model for Vela pulsar emission
  - 18 decades in energy
  - “Primary” particles accelerated primarily in current sheet
  - More accurate particle trajectories
- SR from PC pairs can produce observed IR/optical
- ICS from particles in current sheet produce emission component peaking around 30 TeV (maximum particle energy)
- Pulsed > 3-7 TeV emission implies mostly CR contributes to GeV emission
- Primary ICS above 10 TeV from a number of young pulsars – more with CTA