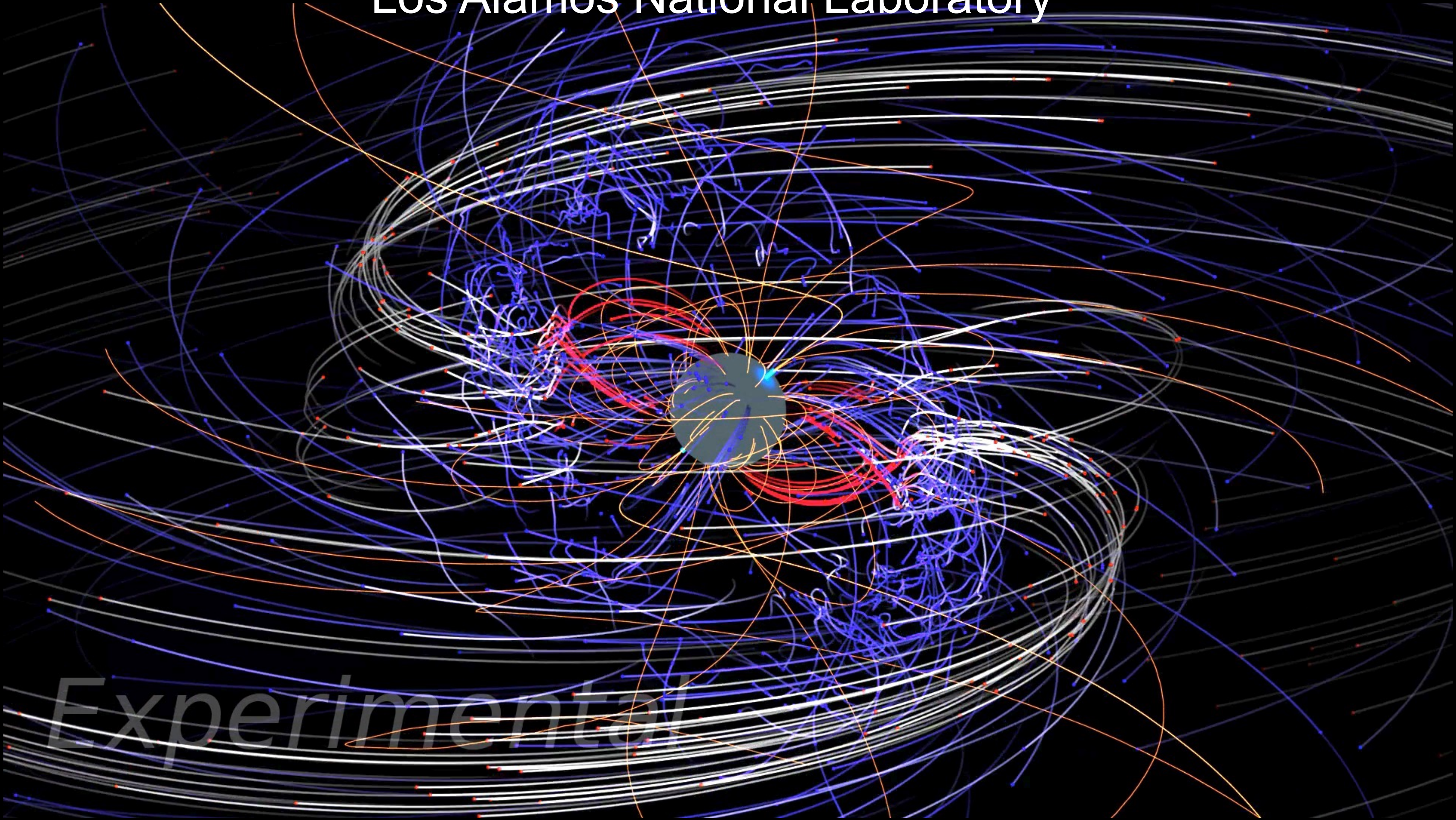
Pulsars in the High Energy Sky

Alice K. Harding
Los Alamos National Laboratory



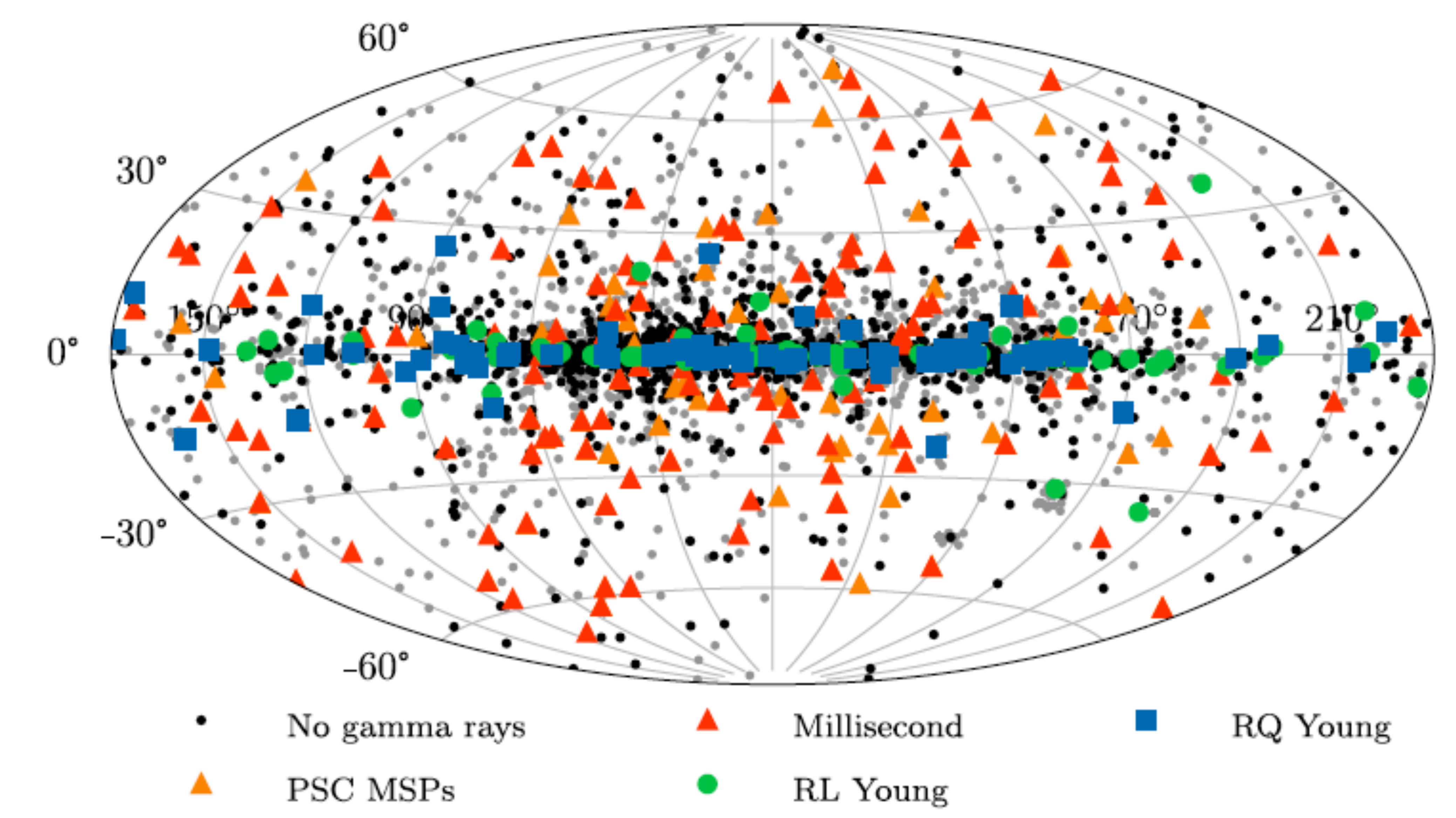

MAGIC telescope
La Palma, Canary Islands


FERMI Gamma-Ray Space Telescope


VERITAS Tuscon, AZ
Very Energetic Radiation Imaging *Telescope* Array System


H.E.S.S. Namibia, SA
High-Energy Stereoscopic System

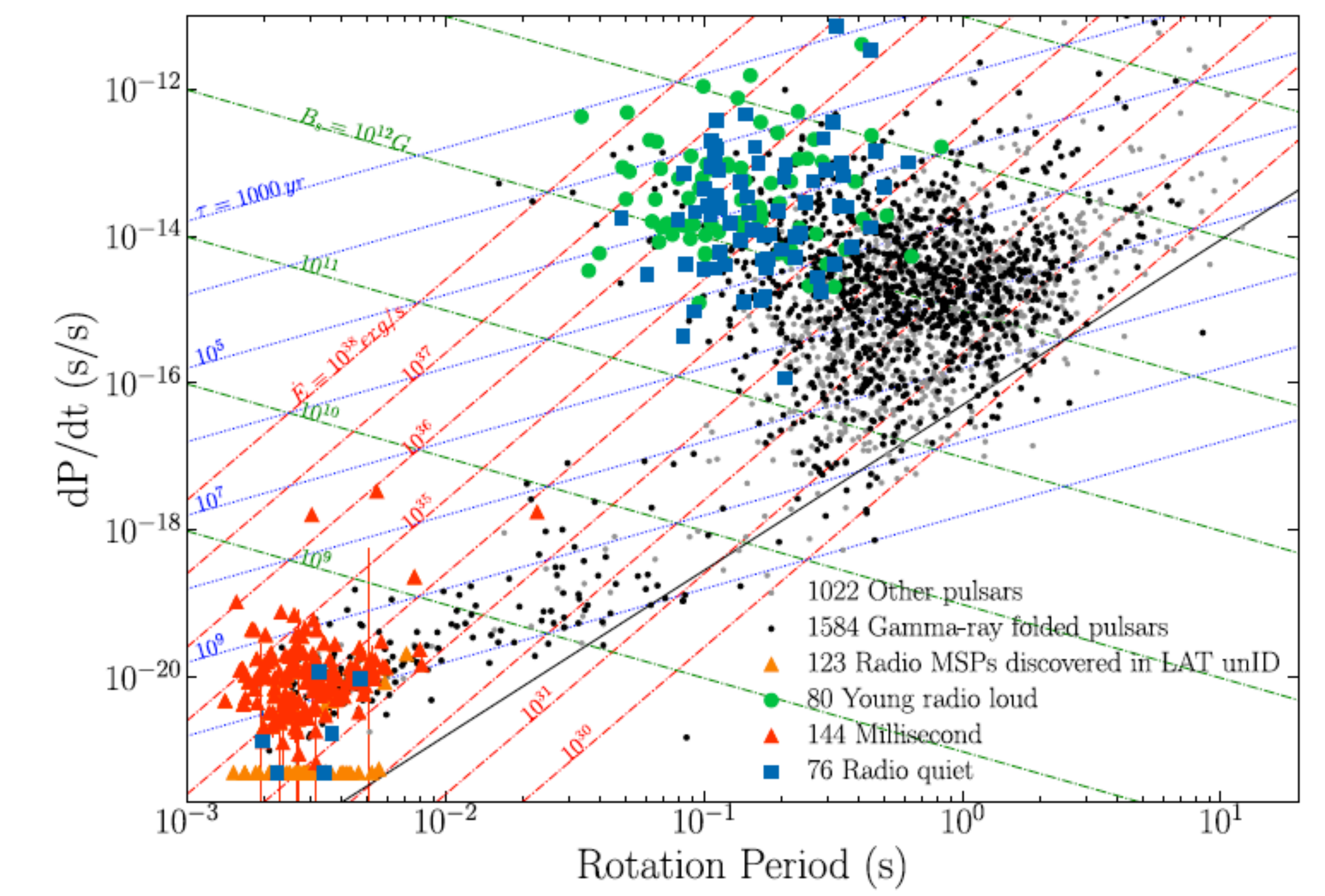
Third Fermi γ-ray pulsar catalog



https://fermi.gsfc.nasa.gov/ssc/data/access/lat/3rd_PSR_catalog/

Smith et al. 2023

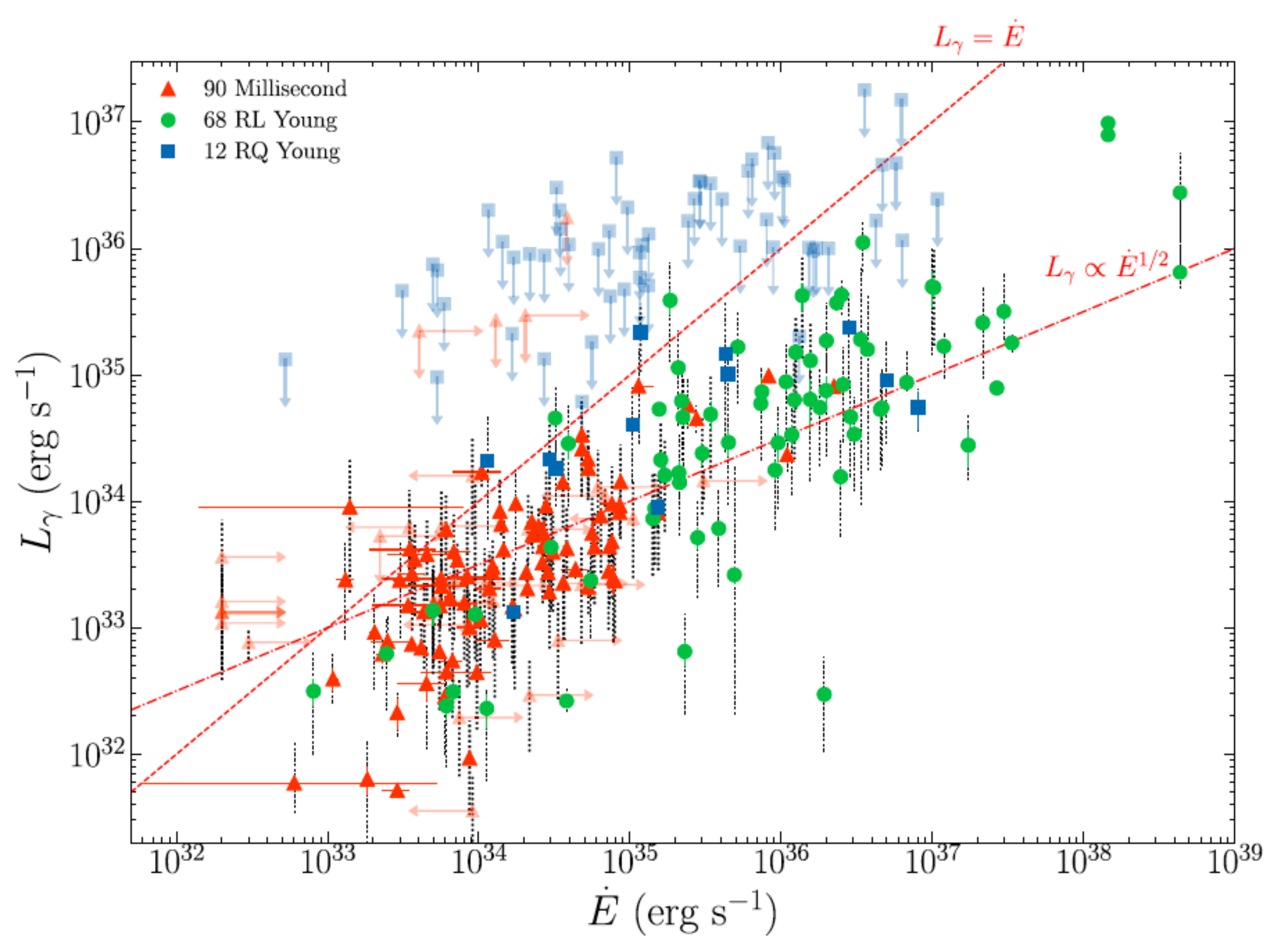
Third Fermi γ-ray pulsar catalog



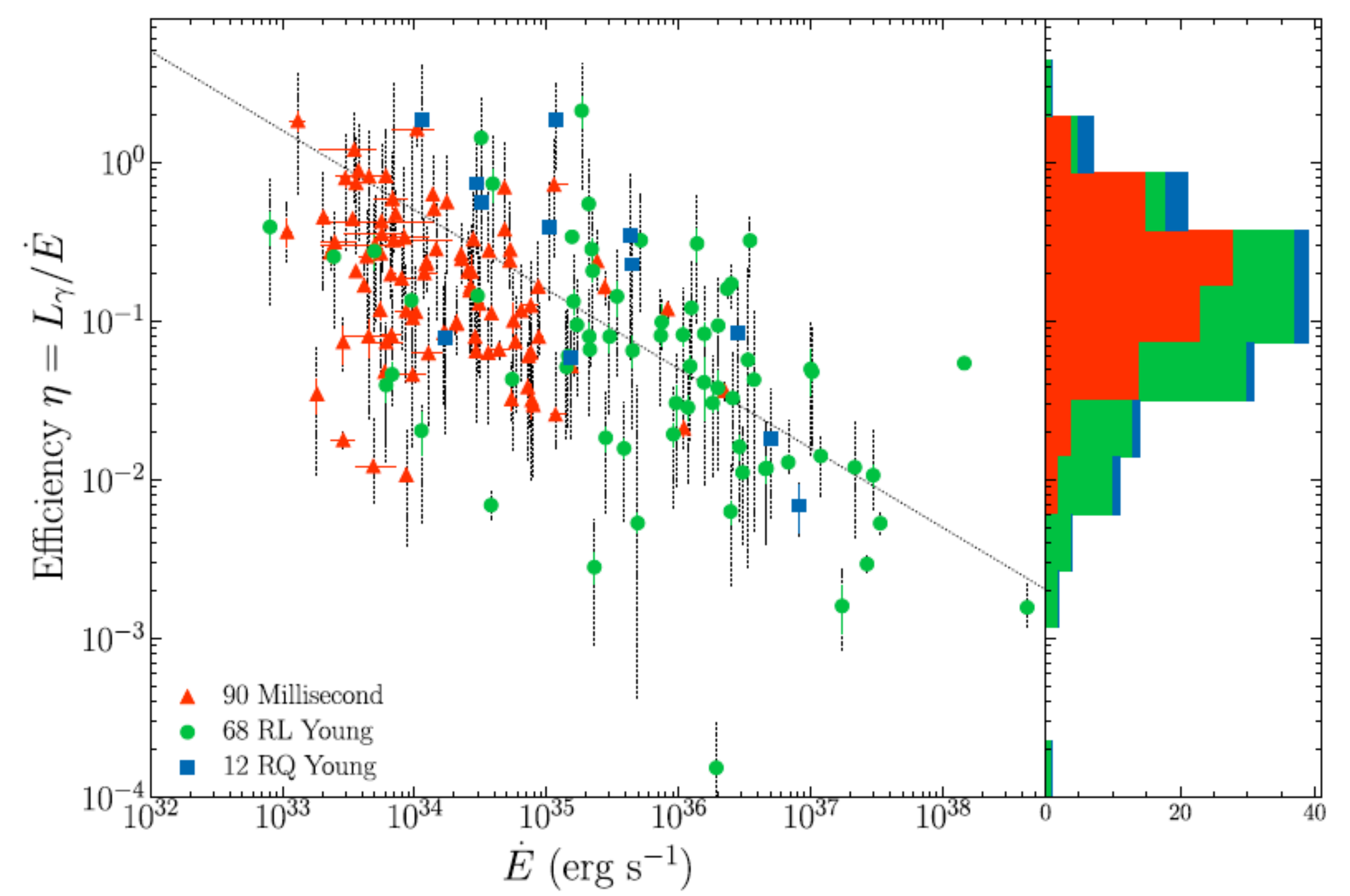
286 γ-ray pulsars + > 30 radio MSPs in Fermi sources = > 300

Smith et al. 2023

γ-ray luminosity vs. spin-down power



γ-ray efficiency vs. spin-down power

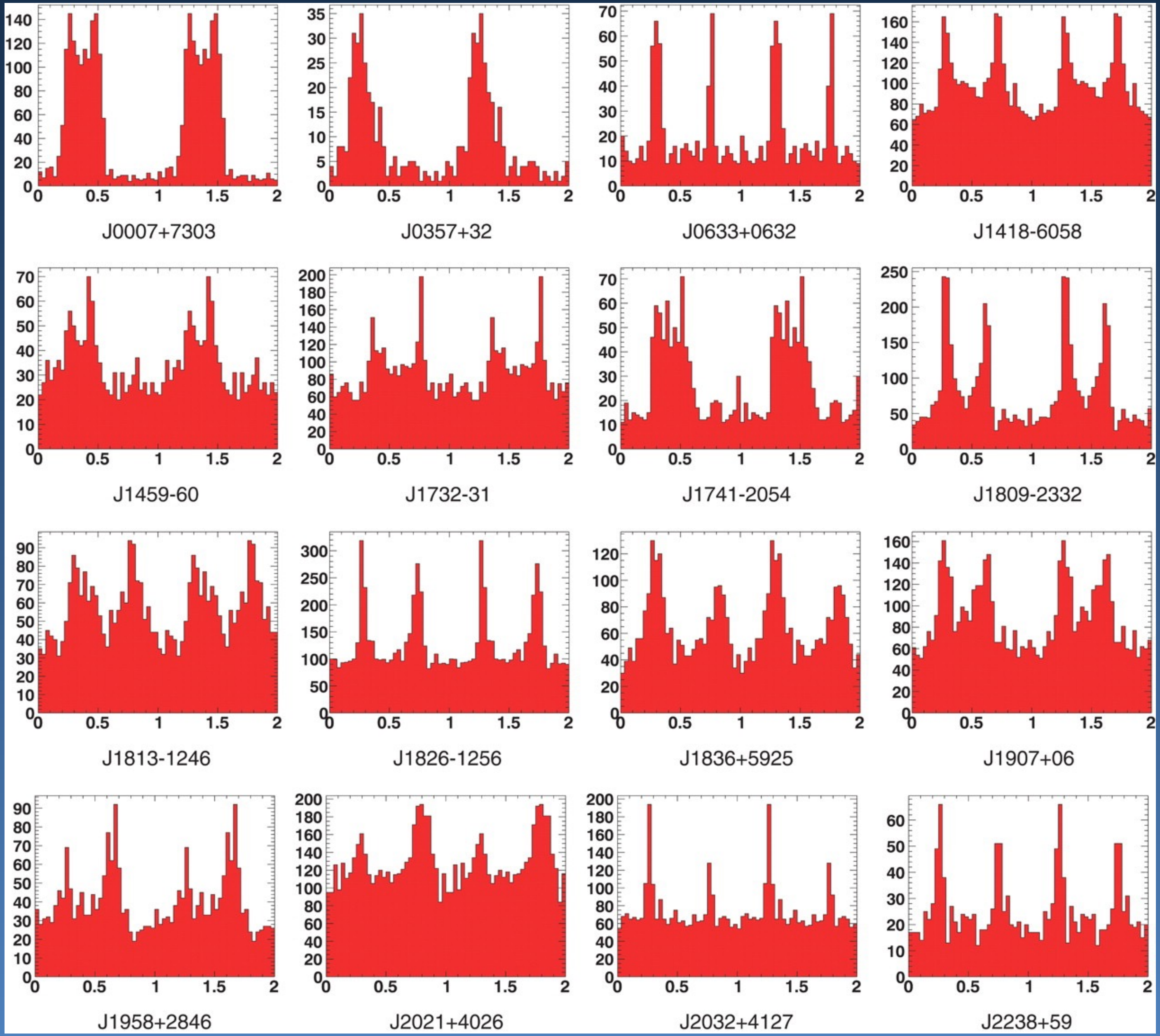


Pulsars Found in Blind γ-ray Searches

After only 4 months of data taking, 16 pulsars were found with the same technique!

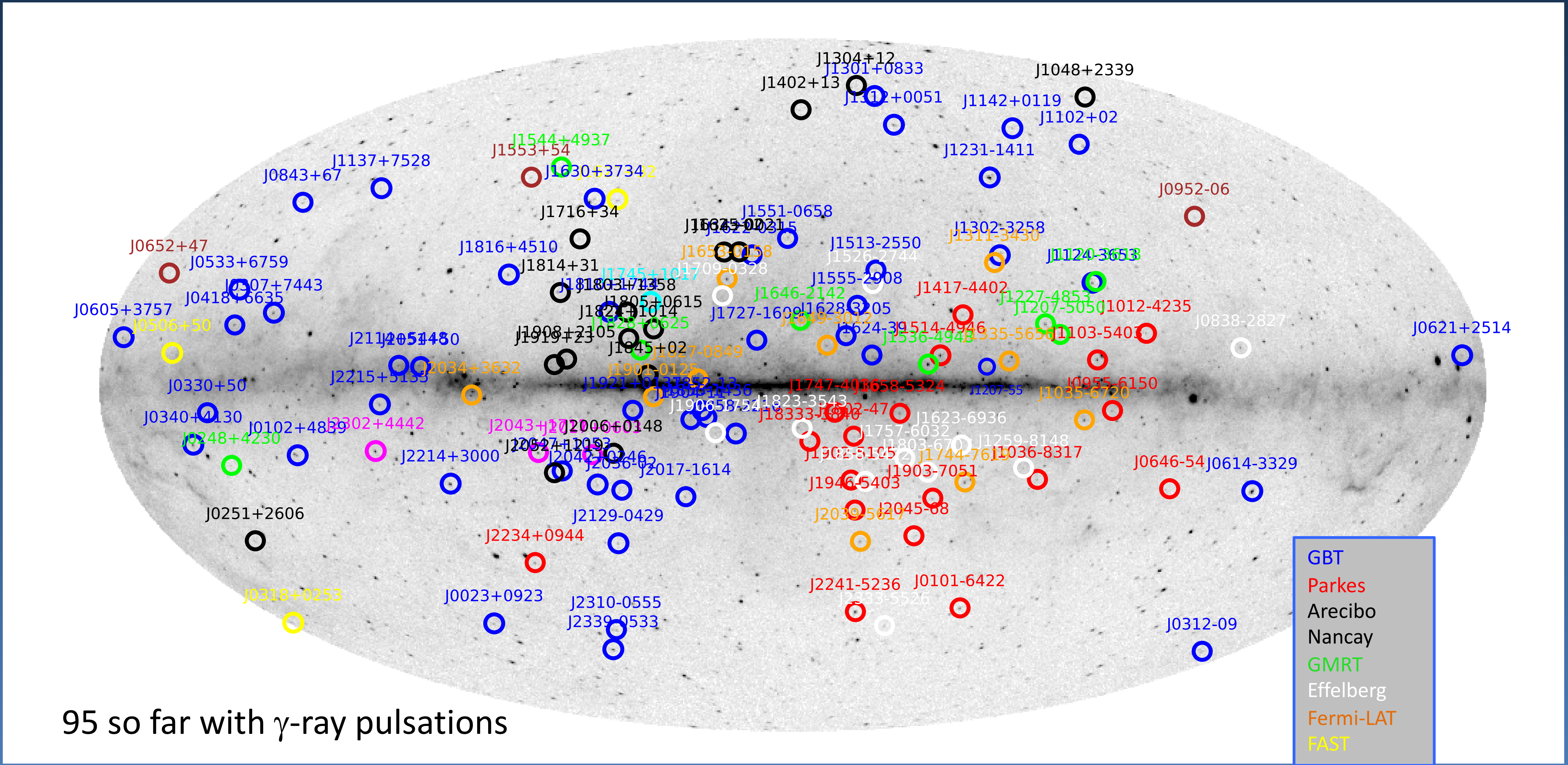
(Abdo et al., Science 325, 840, 2009).

13 were unidentified sources for EGRET



MSPs discovered in Fermi unID sources

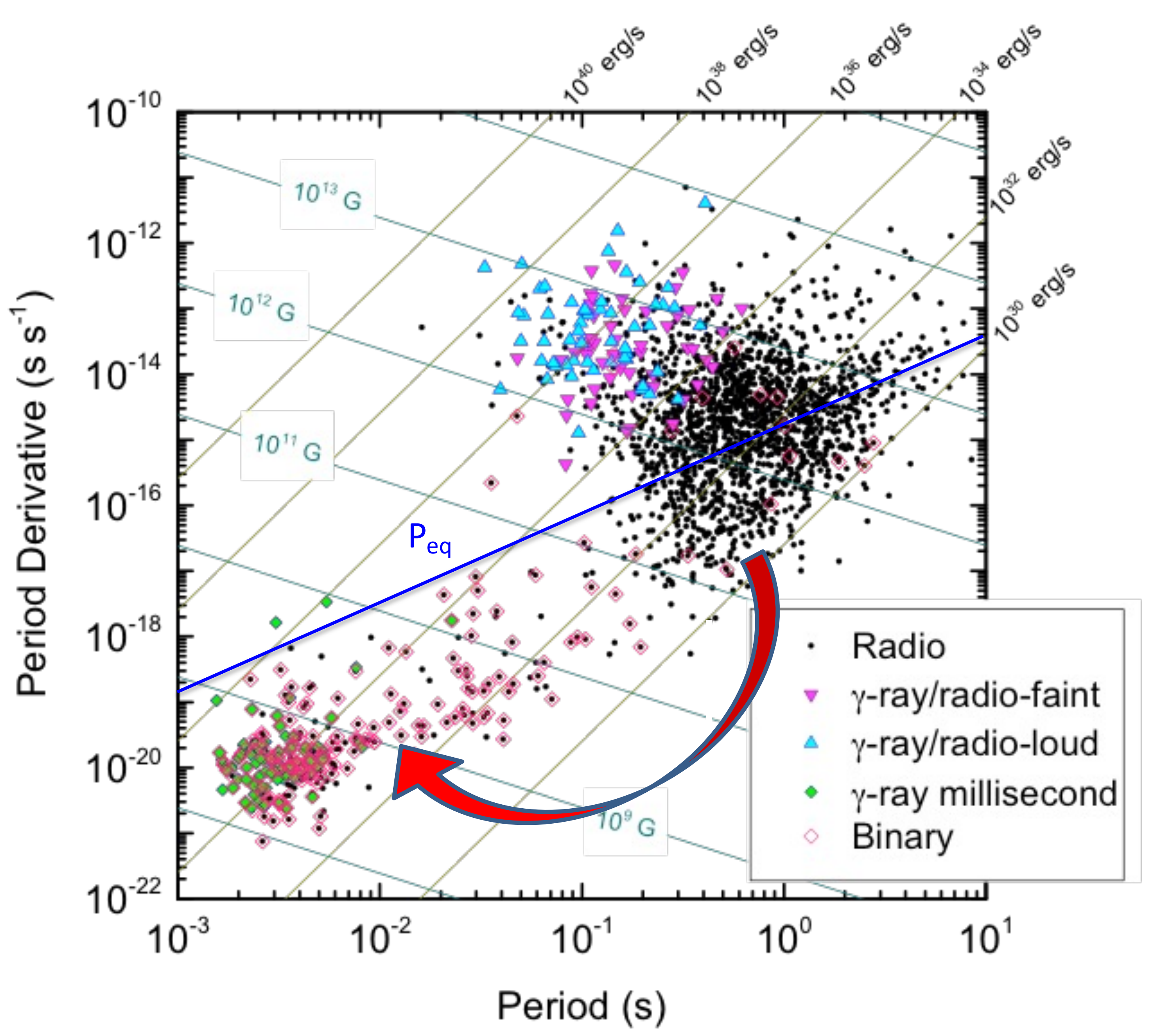
126 new radio MSPs discovered in Fermi unidentified sources!



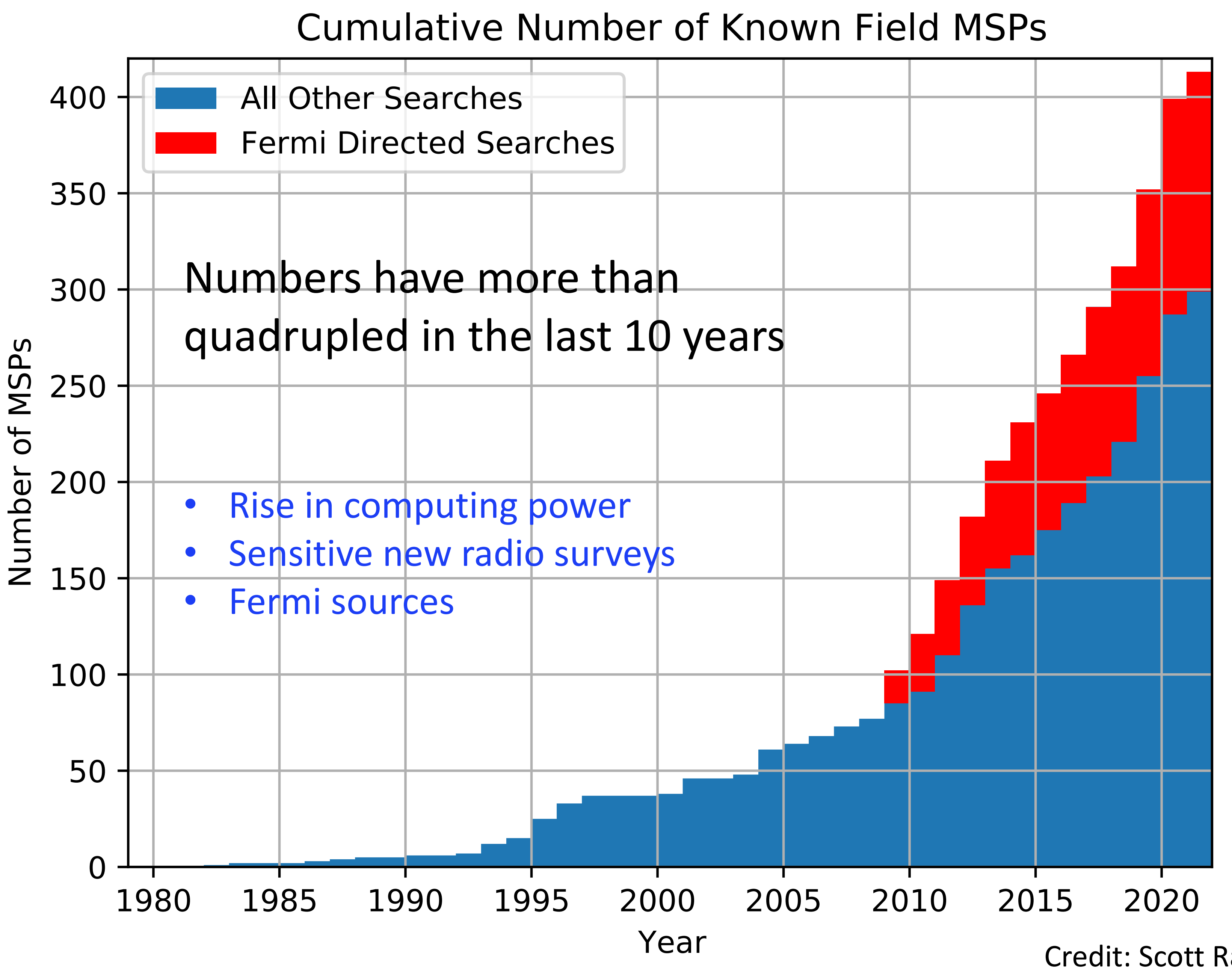
95 so far with γ-ray pulsations

Credit: Paul Ray

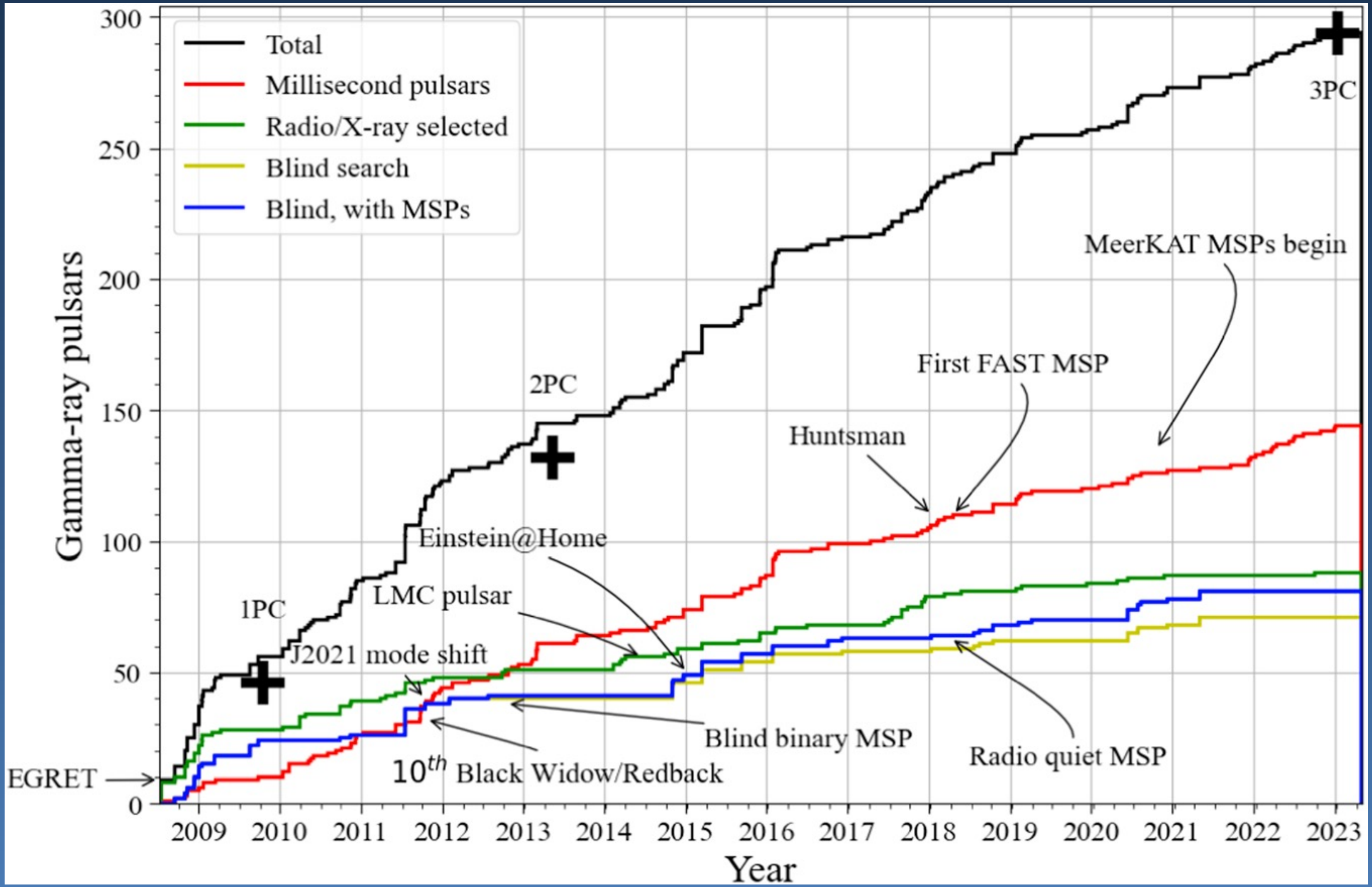
MSPs: recycled from the graveyard



- ~400 field MSPs
  ~ 80% binary
- ~300 in globular clusters
- 157 are γ-ray pulsars
- Spin periods
  1.5 - ~ 100 ms
- Magnetic fields ~ 10^8 – 10^{10} G
- Ages 10^8 – 10^9 yr
- "Recycled" pulsars spun-up by binary companion stars



Credit: Scott Ransom

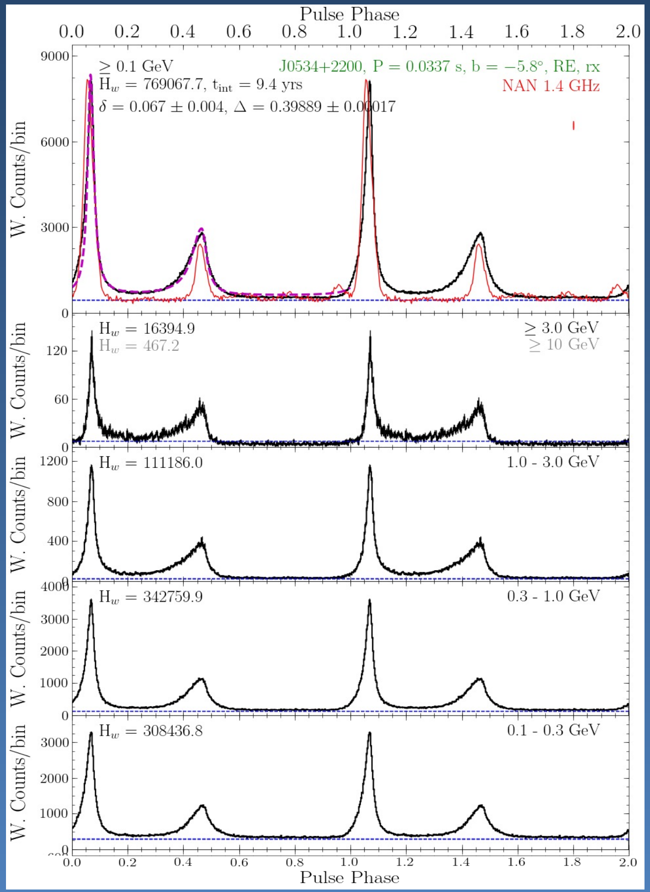


https://fermi.gsfc.nasa.gov/ssc/data/access/lat/3rd_PSR_catalog/

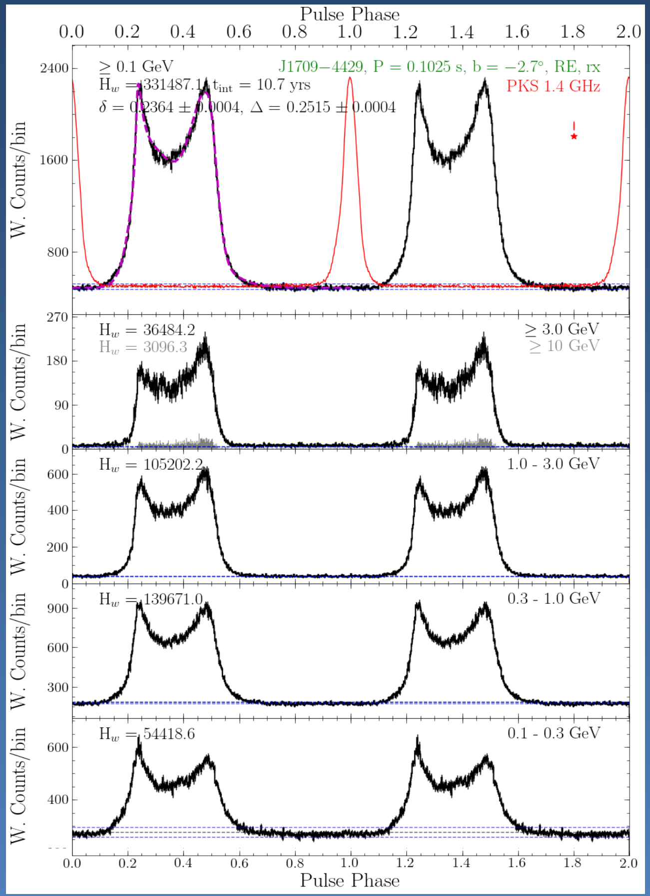
Fermi pulse profiles

Profiles of young and millisecond pulsars look similar despite large period difference - Scale invariance of magnetosphere

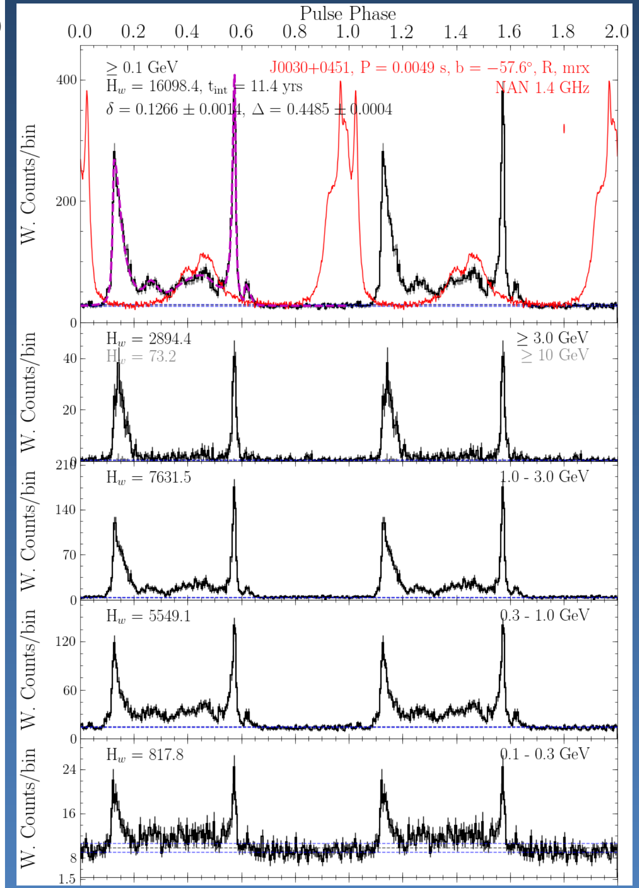
Crab

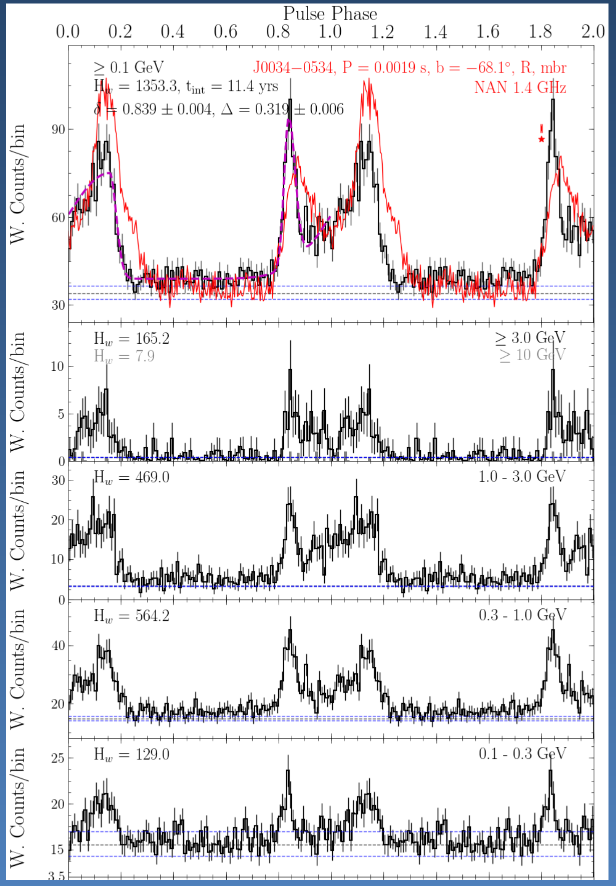


B1706-44



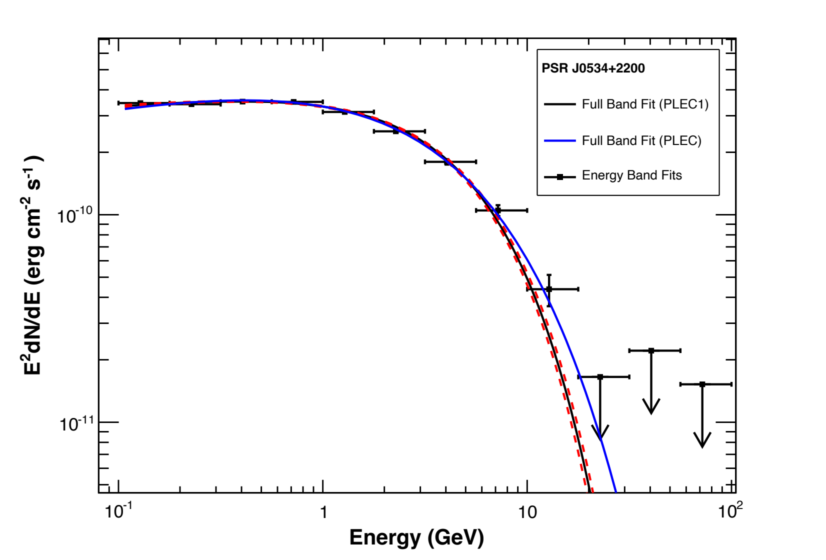
Millisecond pulsars

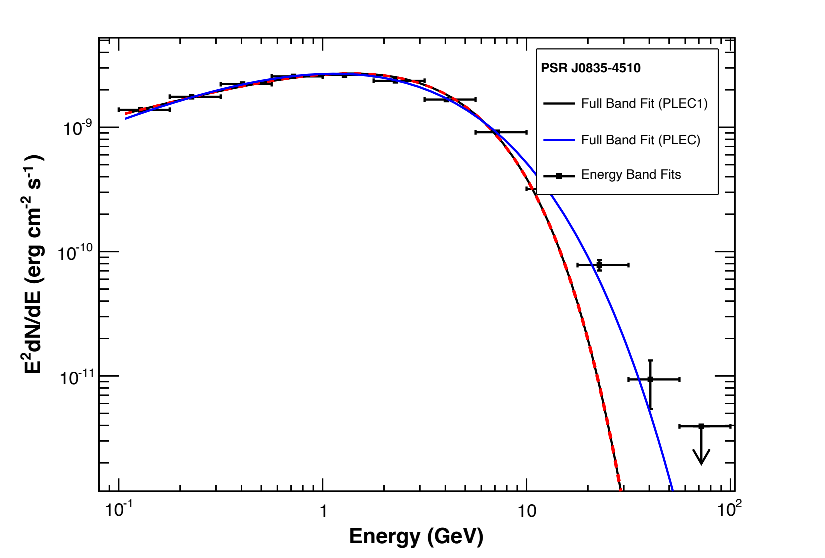




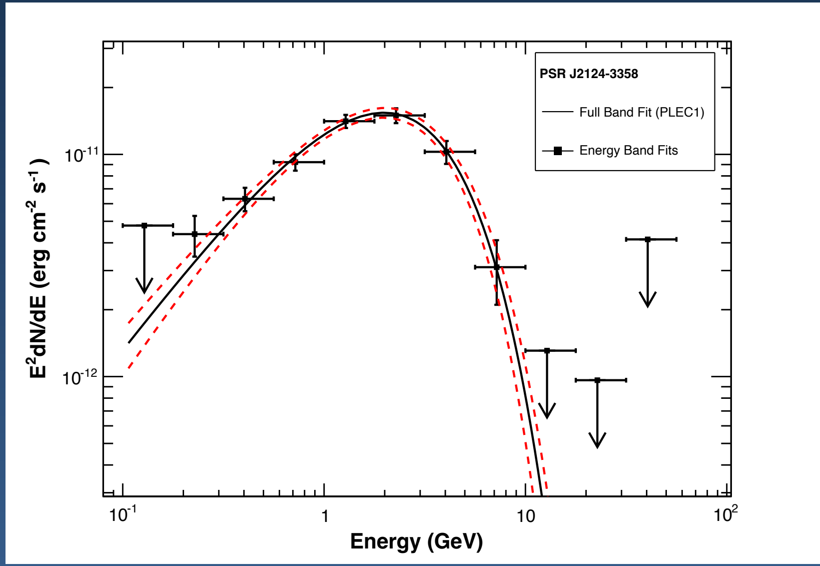
Spectra

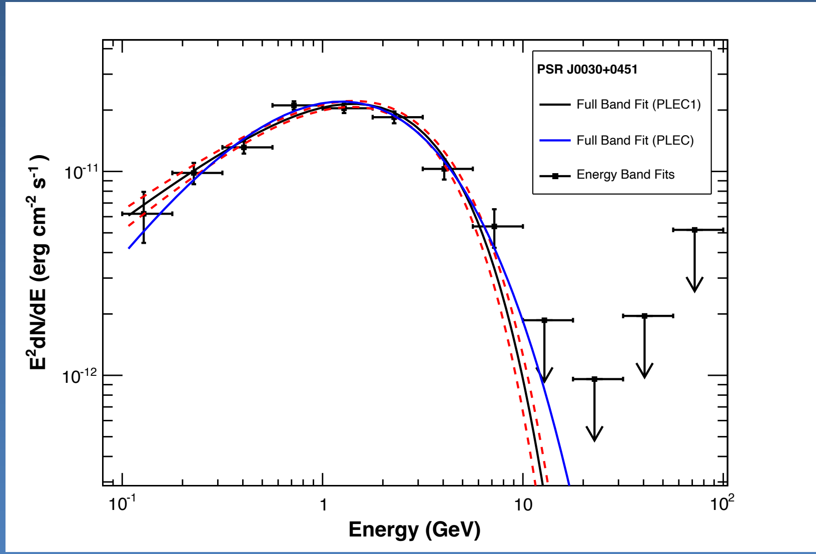
Young pulsars





Millisecond pulsars

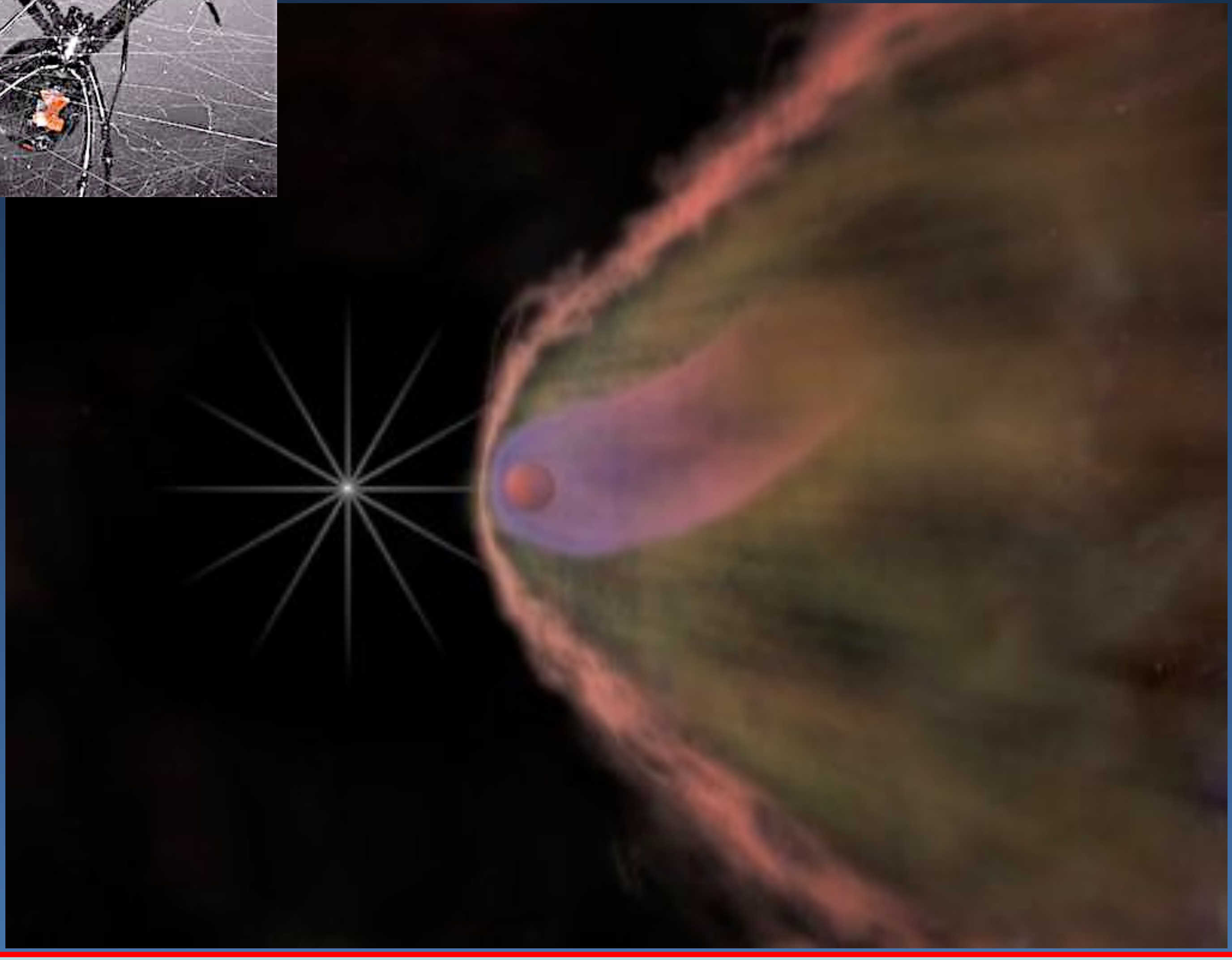




Millisecond pulsars have harder spectra than young pulsars
Peaks of SEDS are always near several GeV

$$\frac{dN}{dE} \equiv N(E) = N_0 \left(\frac{E}{E_0}\right)^{-\Gamma_0} \exp\left[-\left(\frac{E}{E_c}\right)^b\right],$$

Spider millisecond pulsars



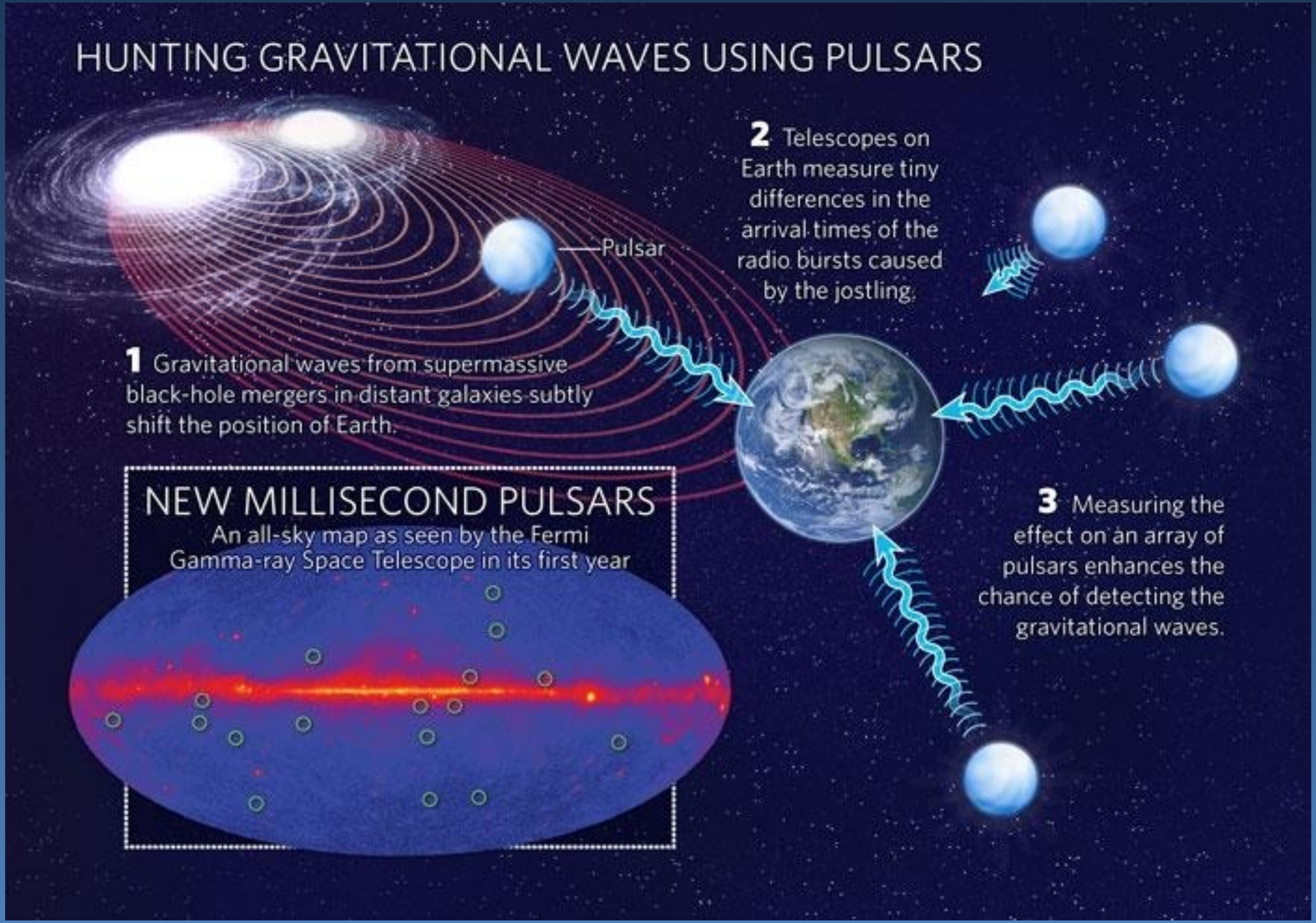
- Black Widows - MSPs with very low-mass binary companions
  - 10 – 80 Jupiter masses (< 0.1 $M_\odot$)
- Pulsar wind ablates companion by exciting stellar winds
- Redbacks (cousins)
  - > 0.1 $M_\odot$ companions

Before Fermi launch: 3 Black Widows, 1 Redback
Now: 32 Black Widows, 13 Redbacks – Total of 45!

Venter talk tomorrow

Gamma-ray MSPs and gravitational waves

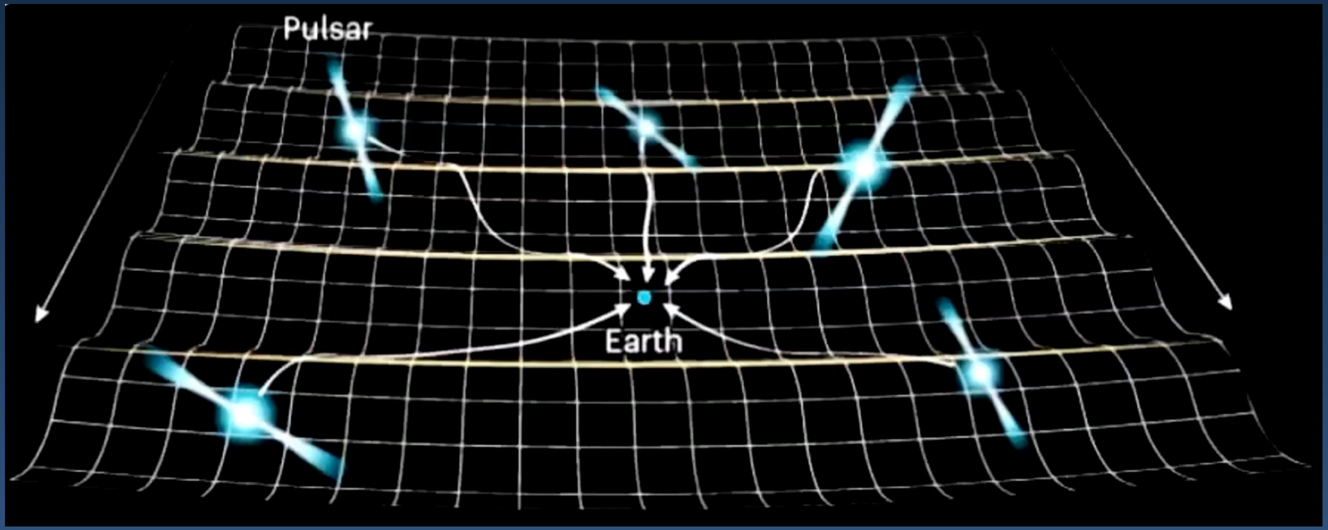
Radio pulsar timing arrays

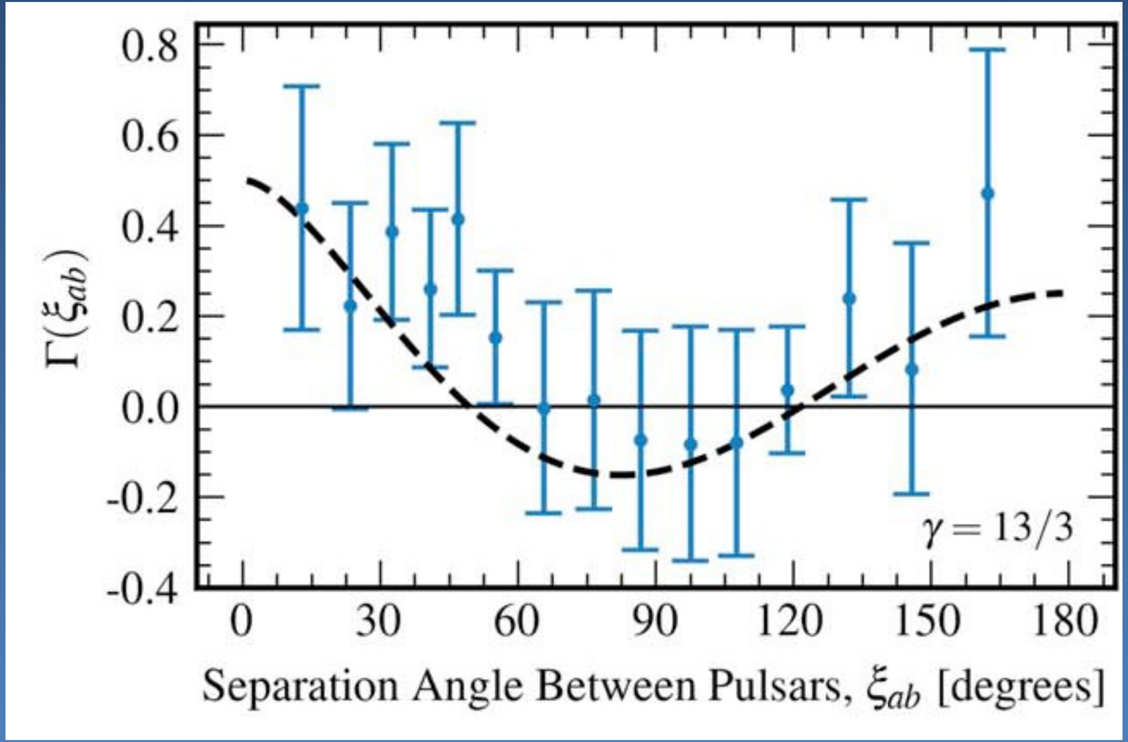


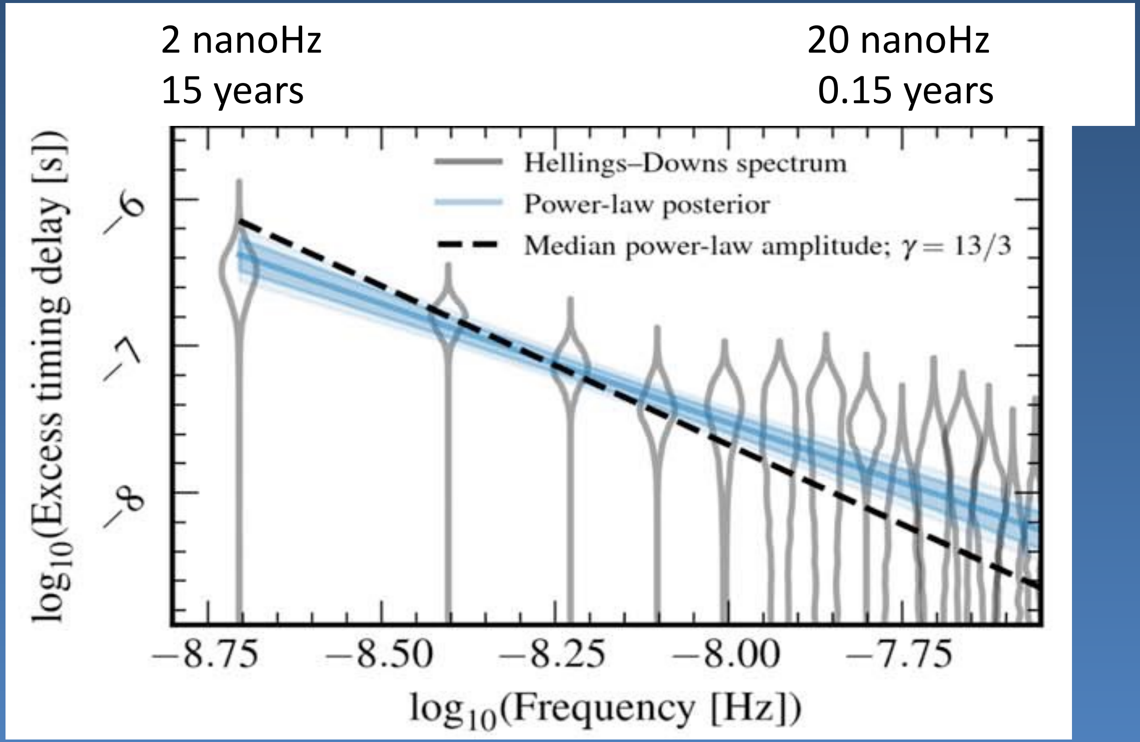
Nanograv results

15 years of timing 67 pulsars (Agazie et al. 2023)

First compelling evidence of Hellings-Downs spatial correlation!

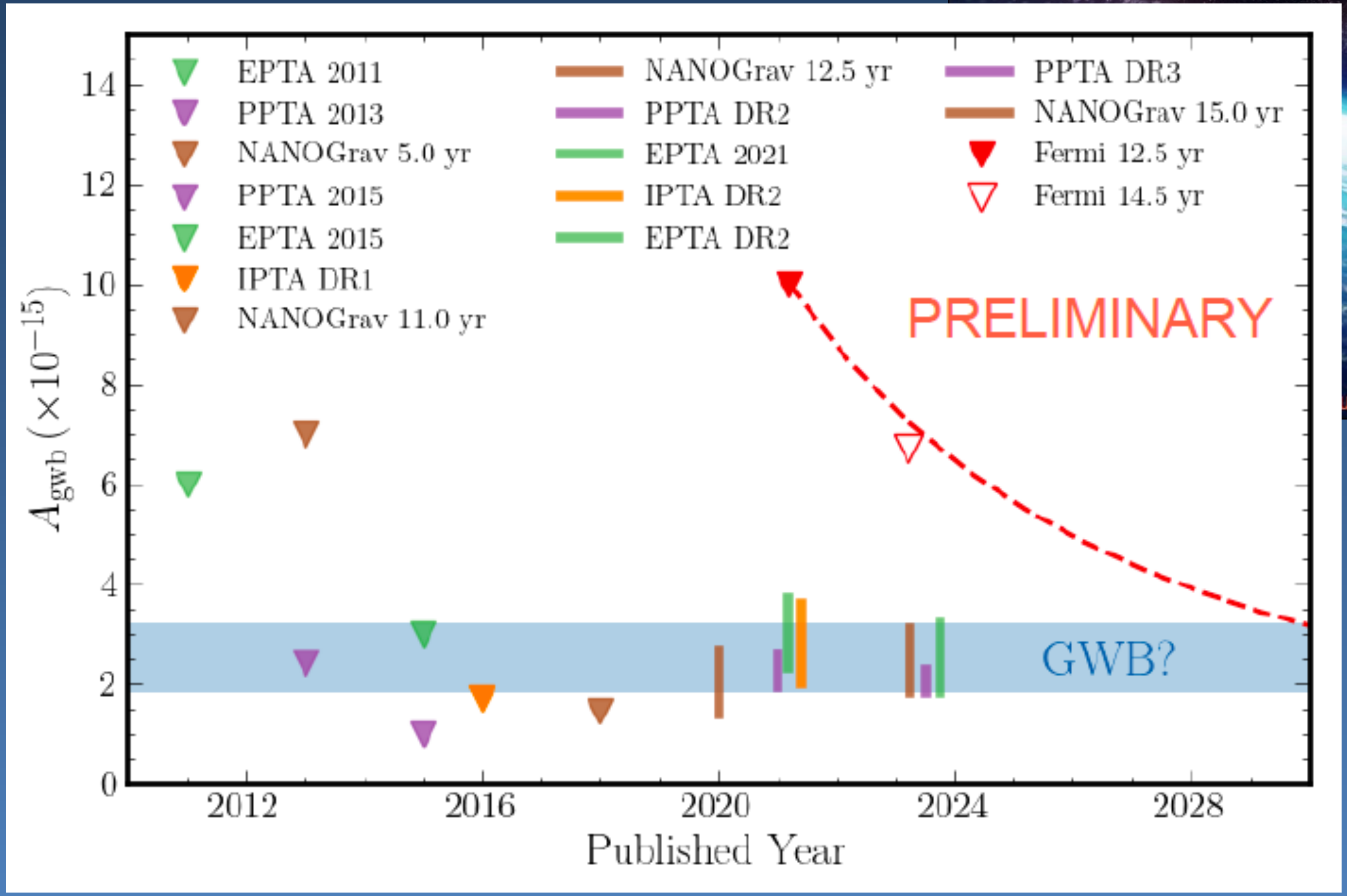


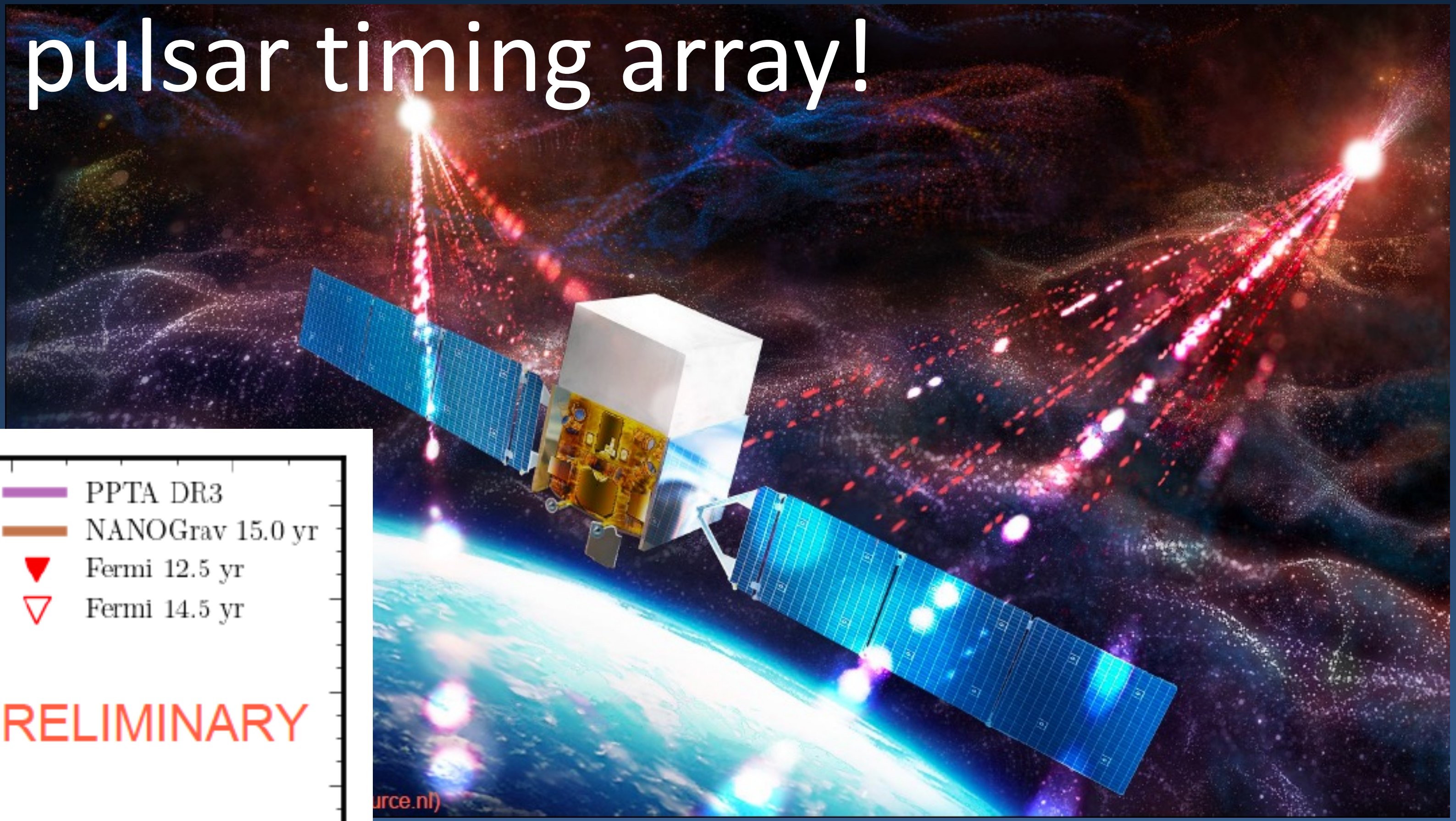




A γ-ray pulsar timing array!

14.5 years of 57 γ-ray MSPs





Gamma-rays are free of dispersion and scattering that degrades performance of radio PTAs

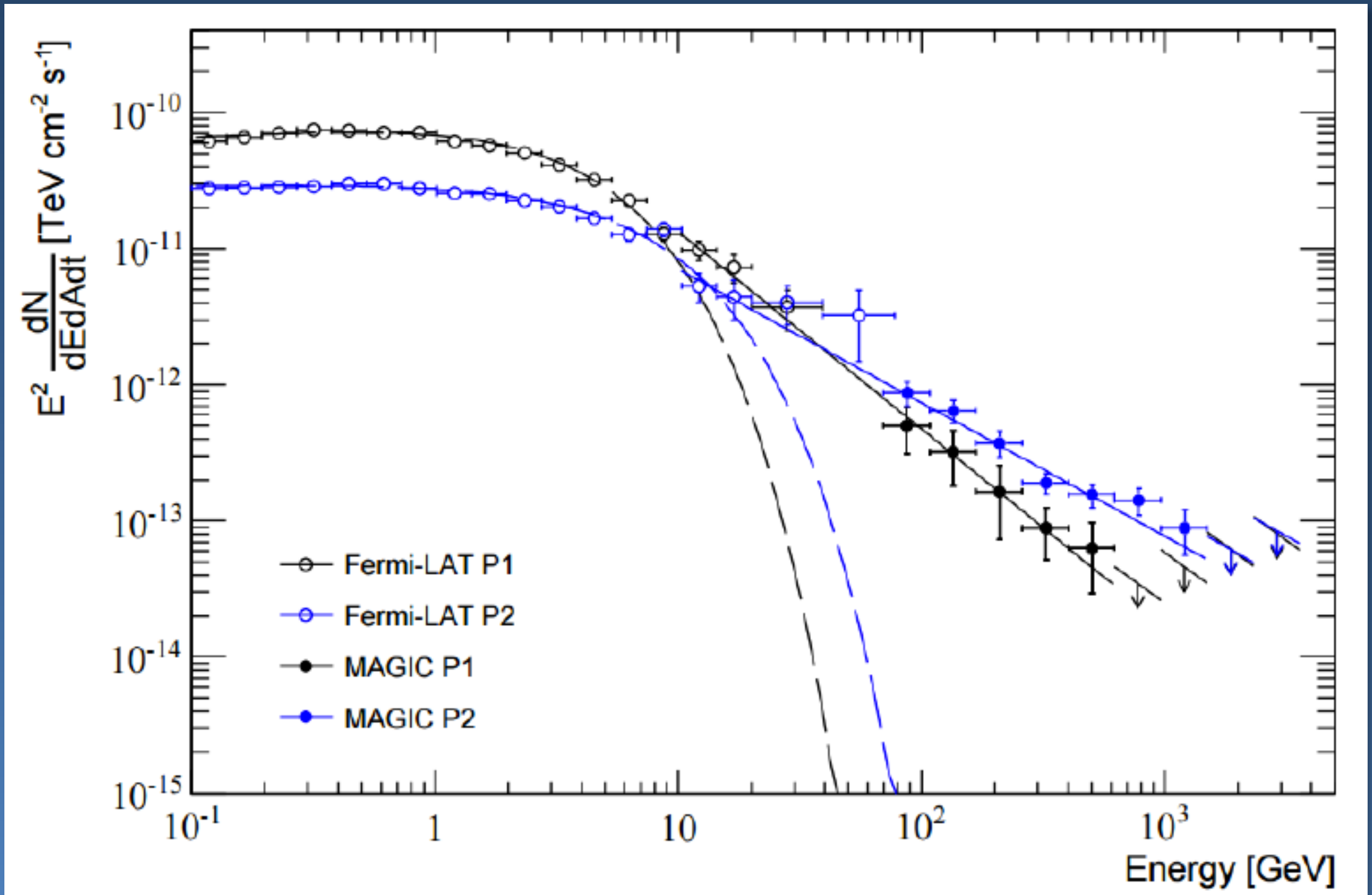
Credit: M. Kerr

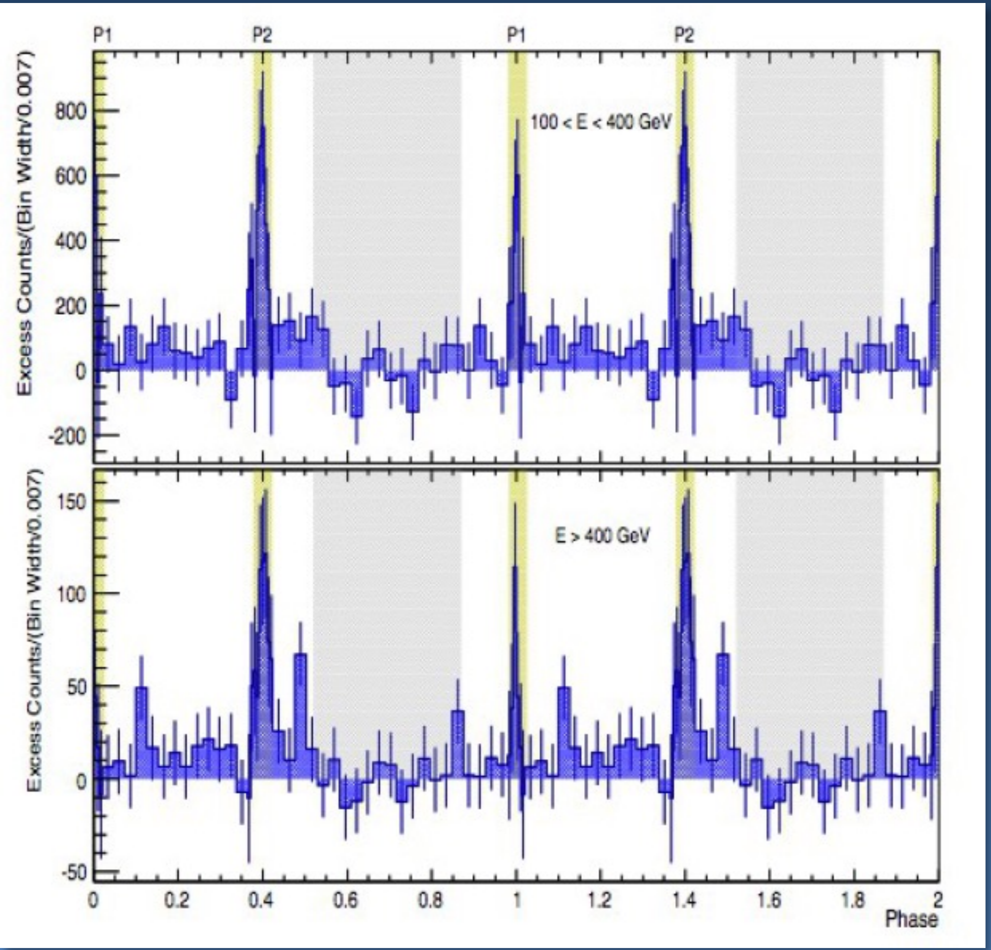
Detection of Crab pulsar up to 1 TeV

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

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

Both peaks detected!

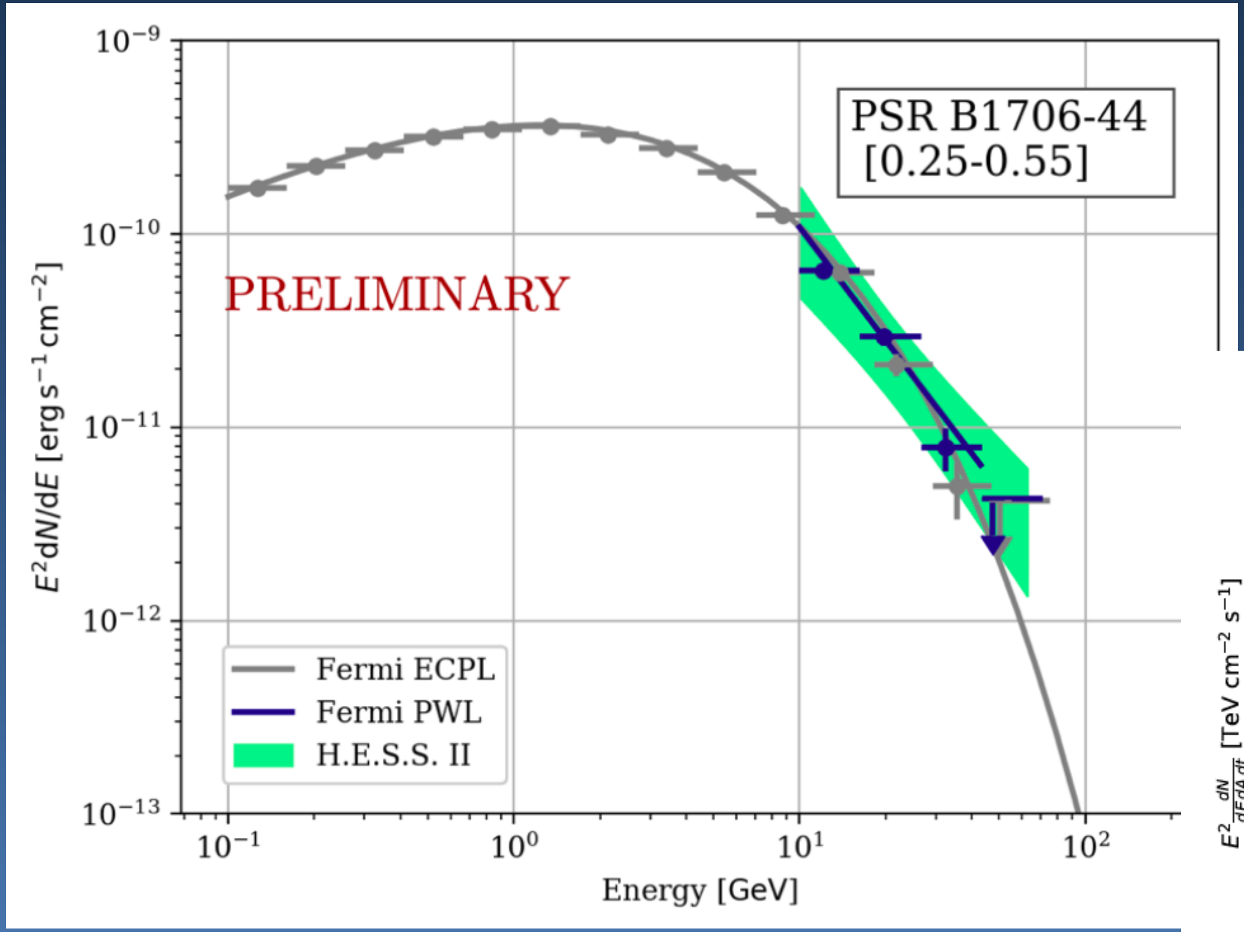




B1706-44 – H.E.S.S. II and Geminga - MAGIC

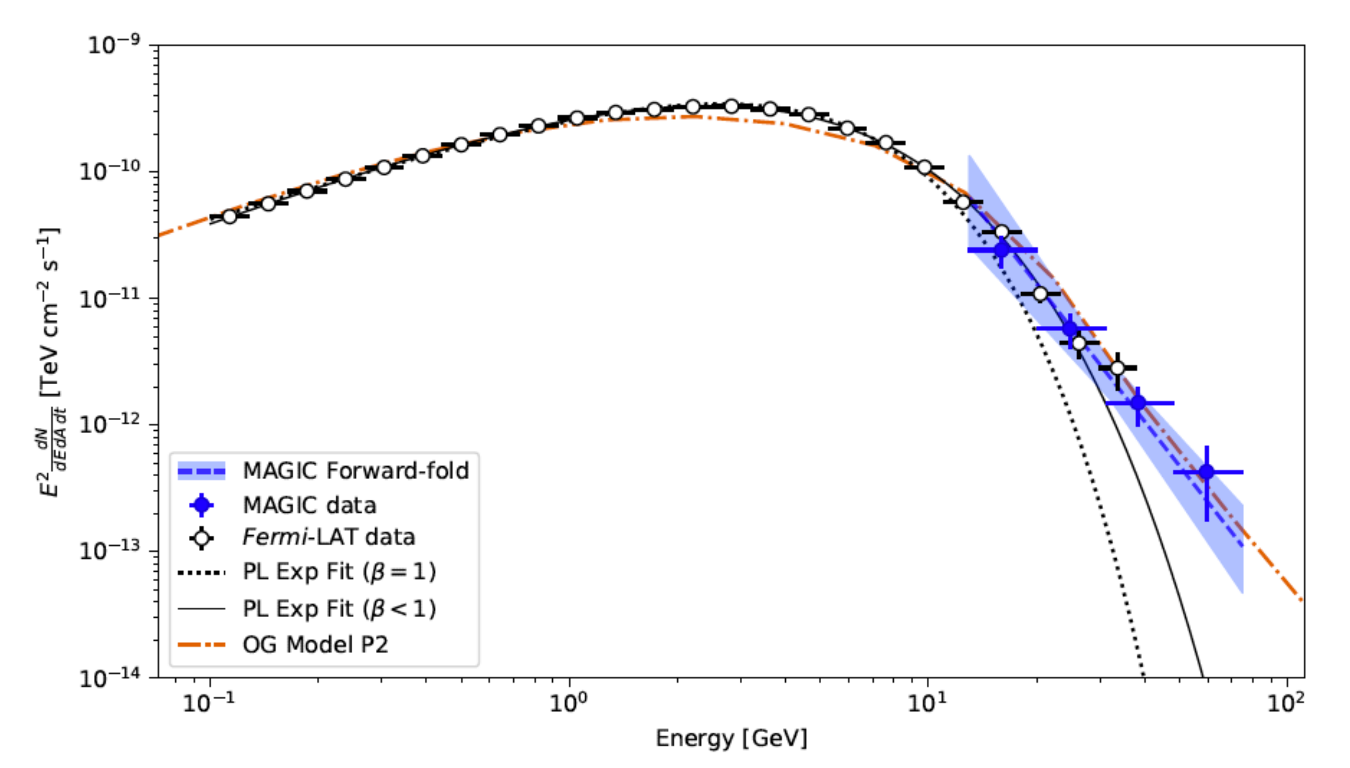
Spir-Jacob et al. 2019

10 – 70 GeV



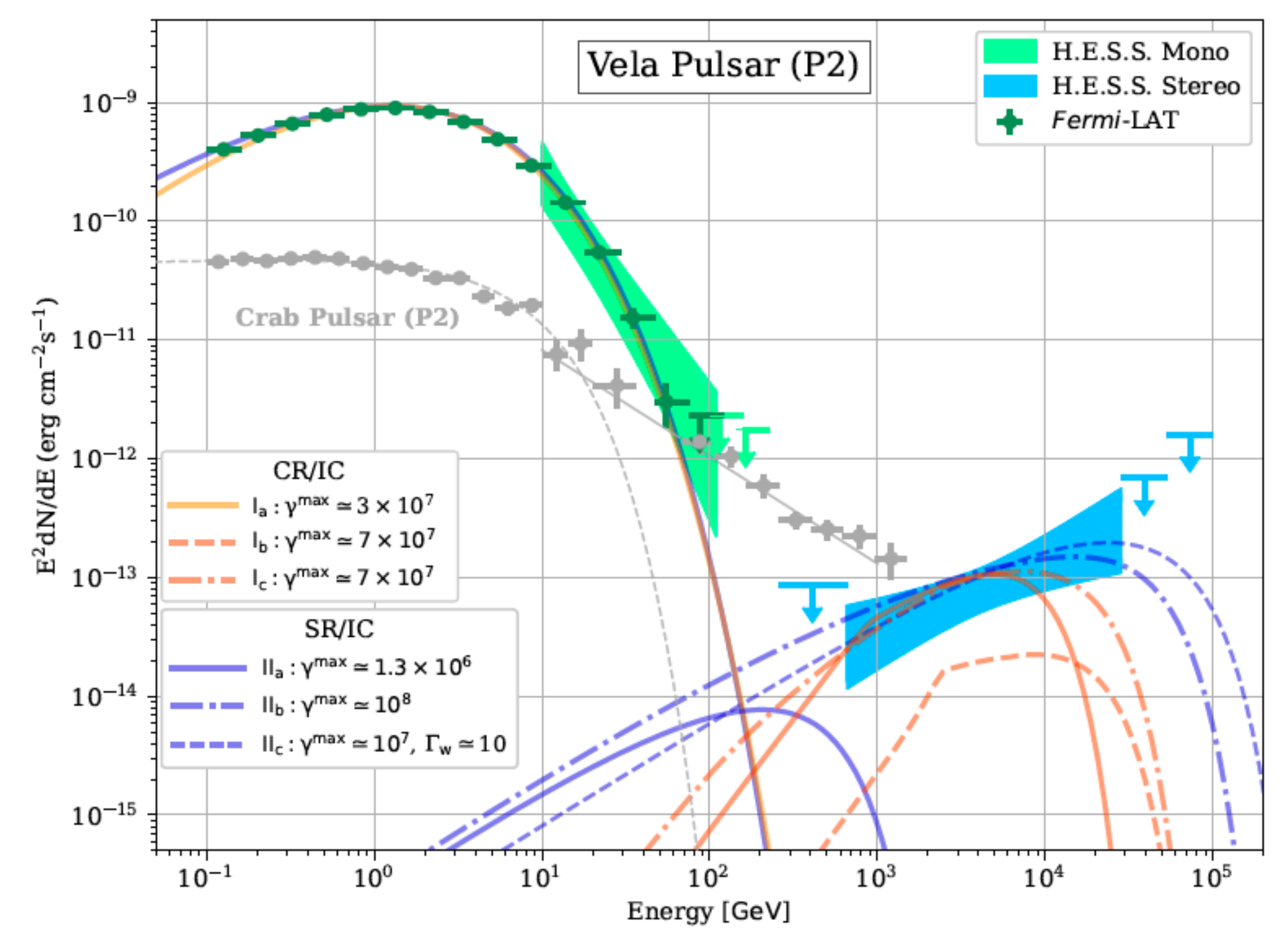
Acciari et al. 2020

Spectrum measured up to 75 GeV



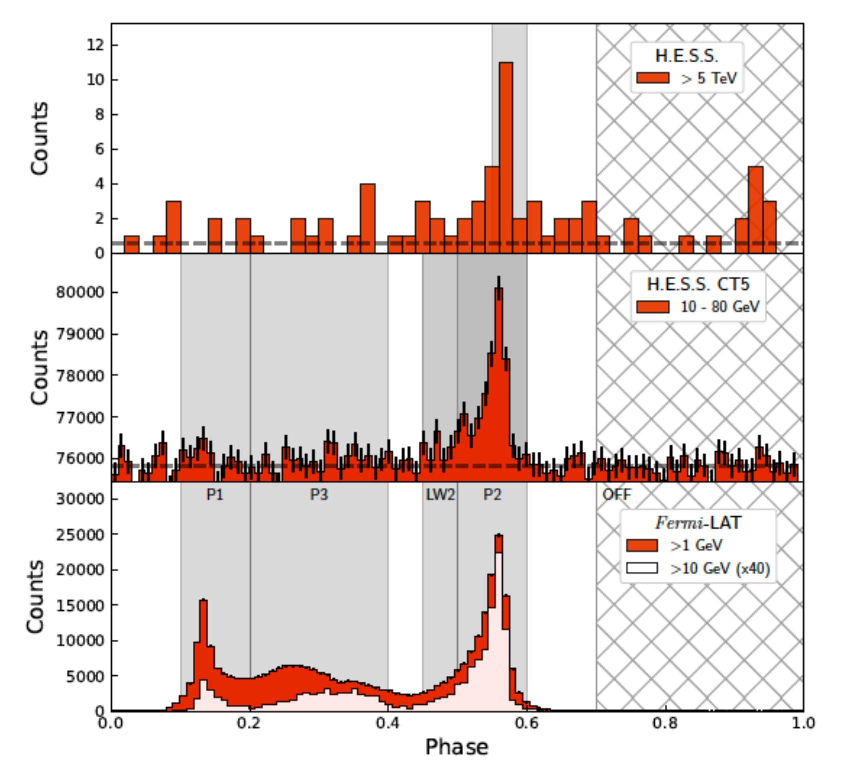
Vela pulsar – H.E.S.S. II

Aharonian et al. 2023

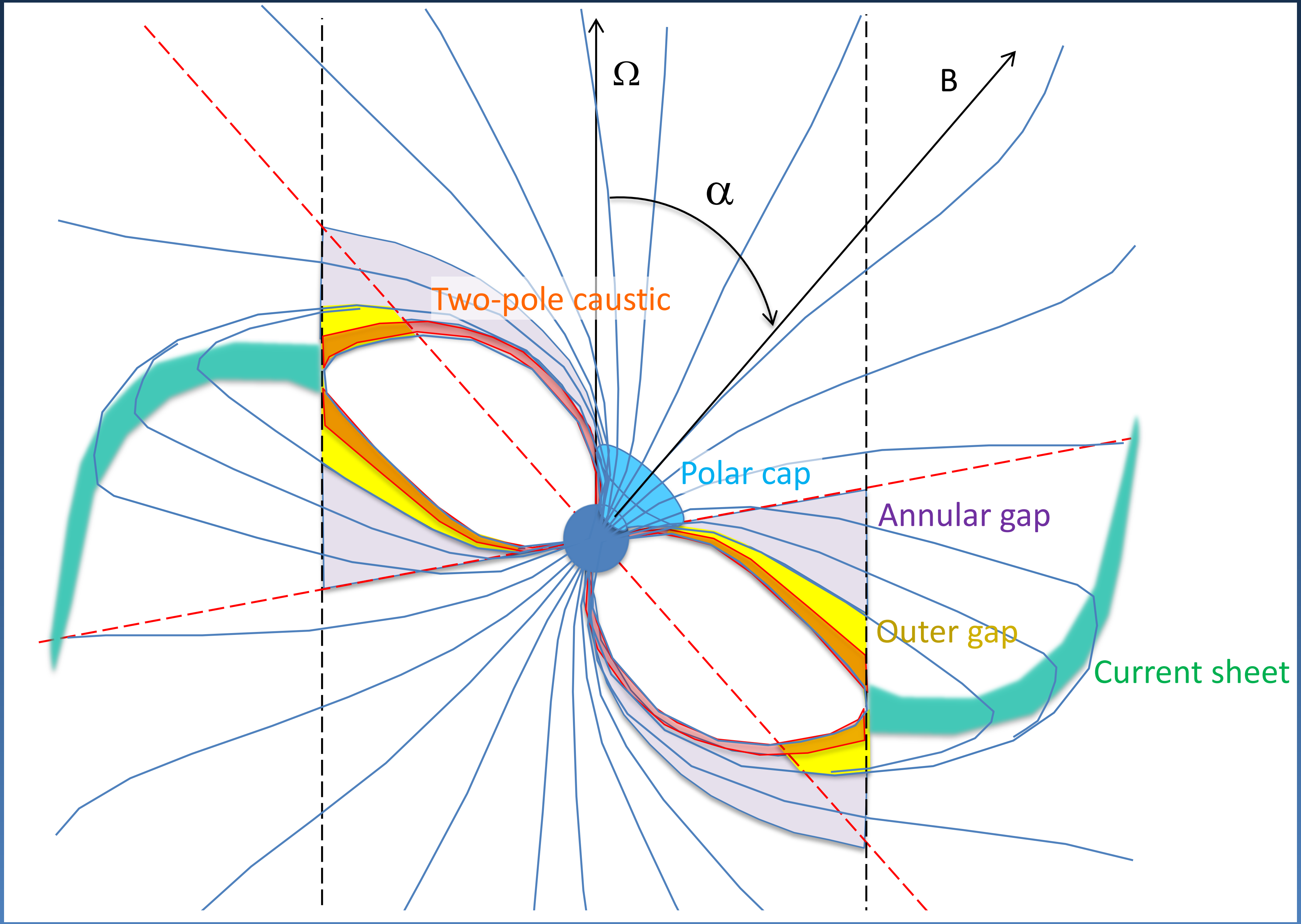


Additional component distinct from GeV spectrum

Pulsed emission to 30 TeV!!



High-energy emission models



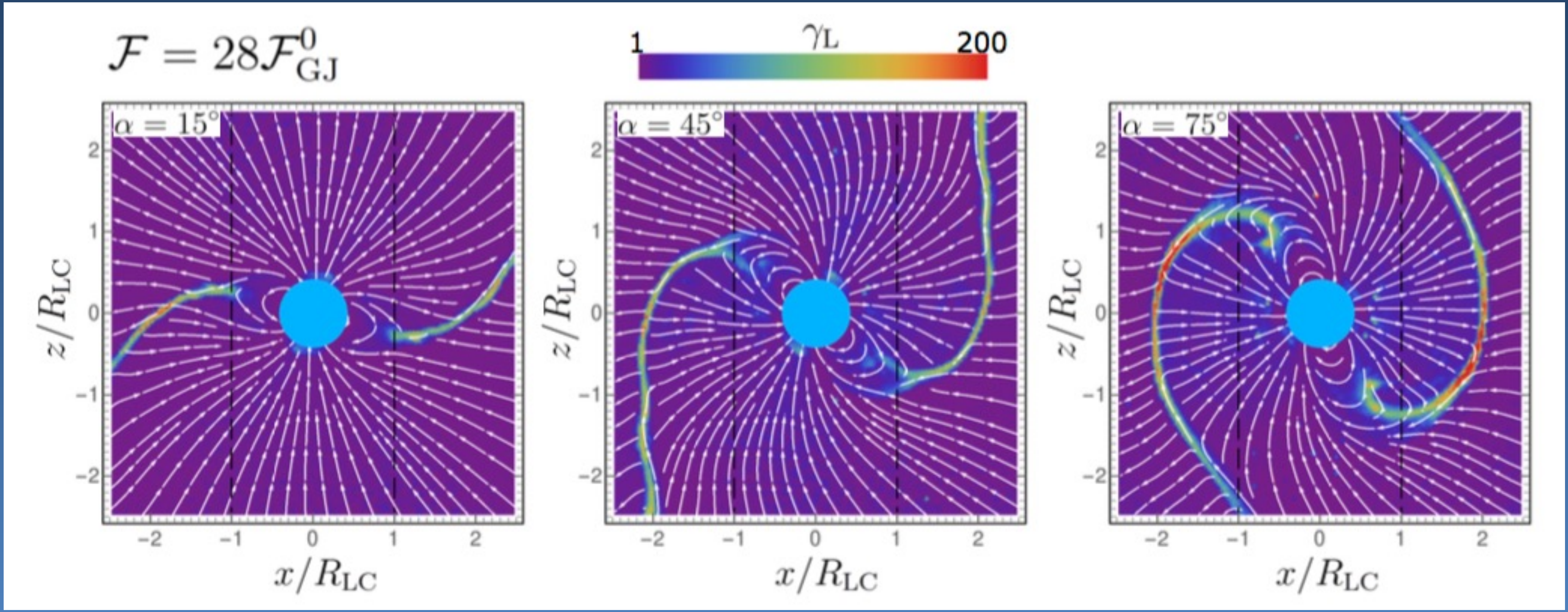
Outstanding questions:

- 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?

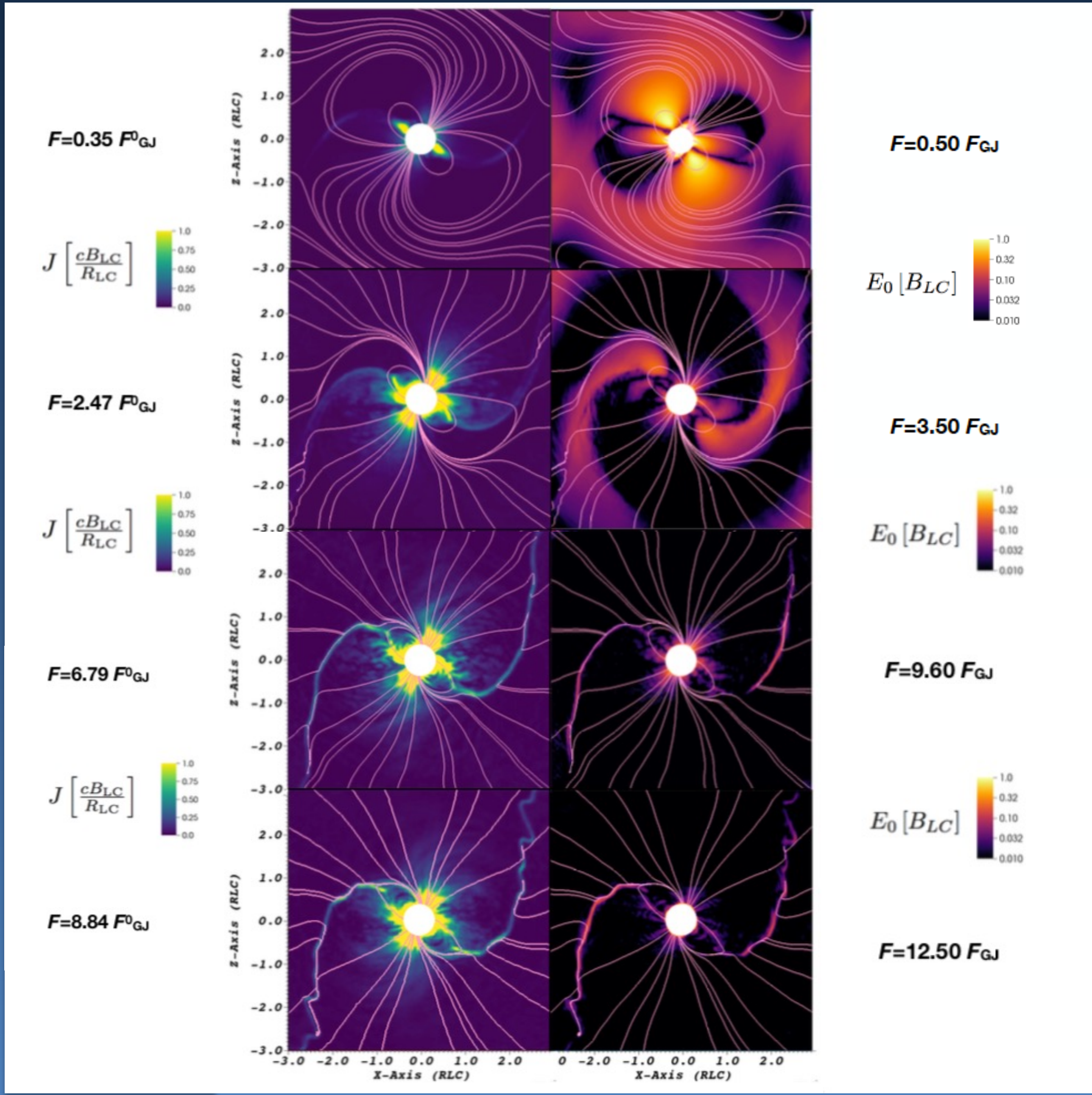
Global particle-in-cell (PIC) models

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

Most particle acceleration occurs in and near the current sheet and separatrices
BUT – limited to $B_0 < 10^6$, $\gamma < 10^3$ ⟶ must scale up to real pulsar values



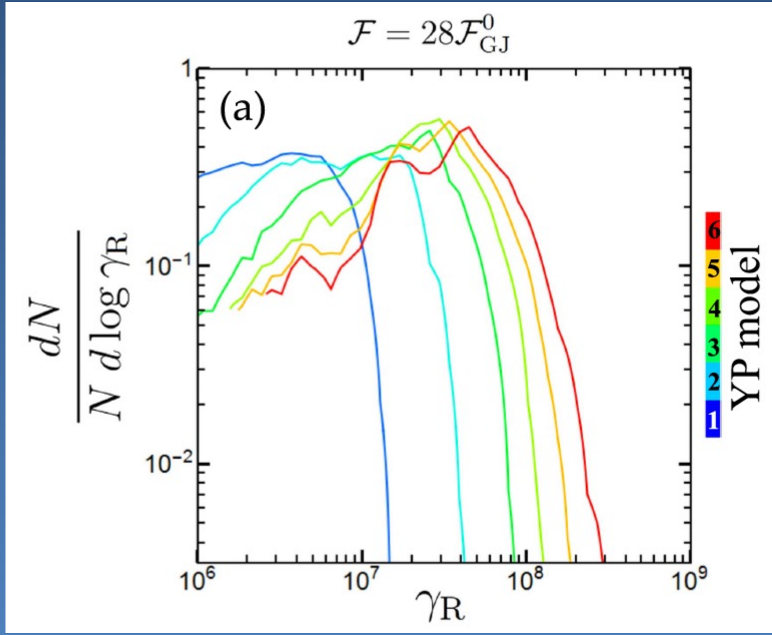
PIC simulations – Current and Electric field



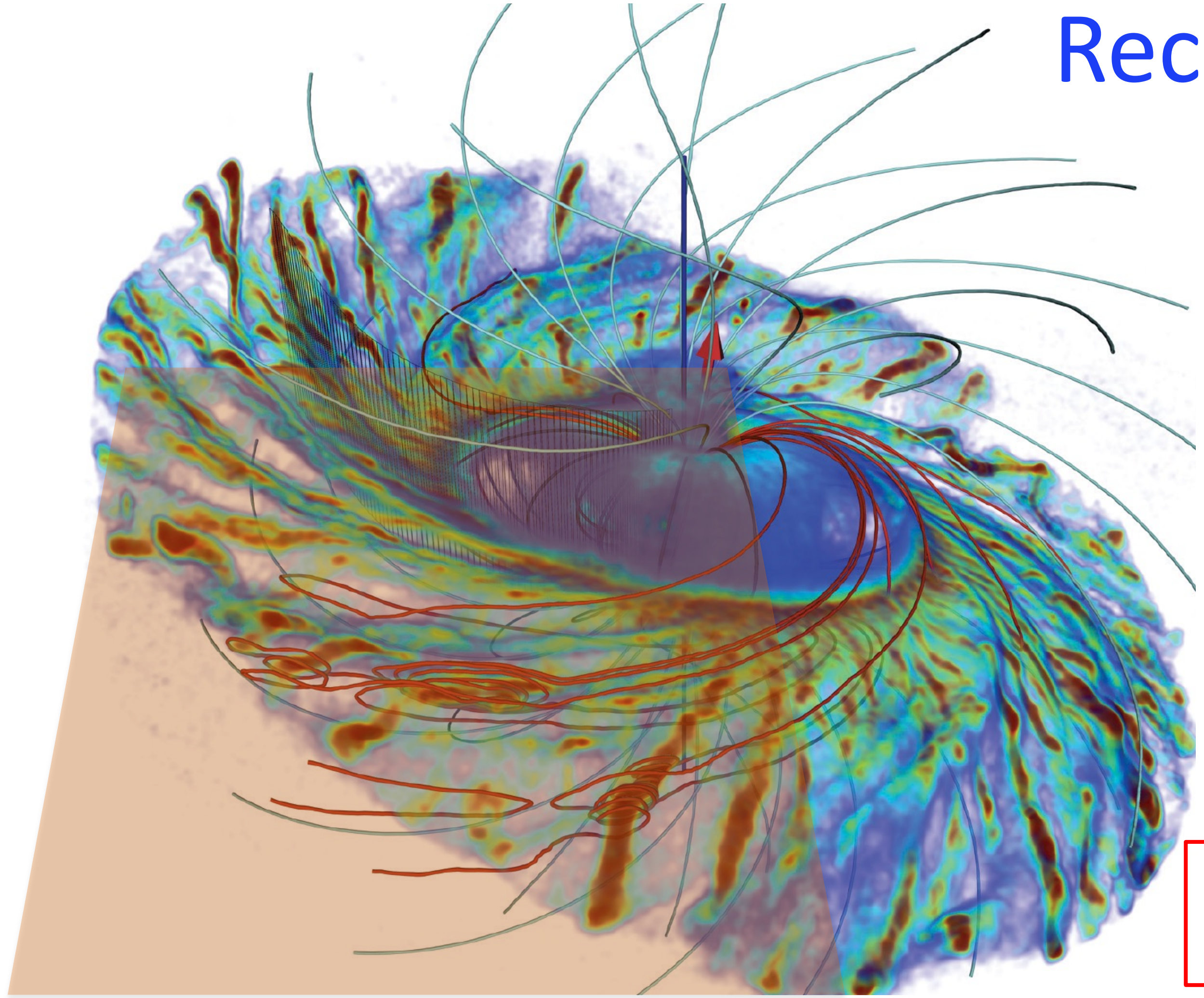
Brambilla et al. 2018.

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

Scale up B0, E0 ⟶ $\gamma \sim 10^7$-10^8 ⟶ curvature radiation (Kalapotharakos+2018)

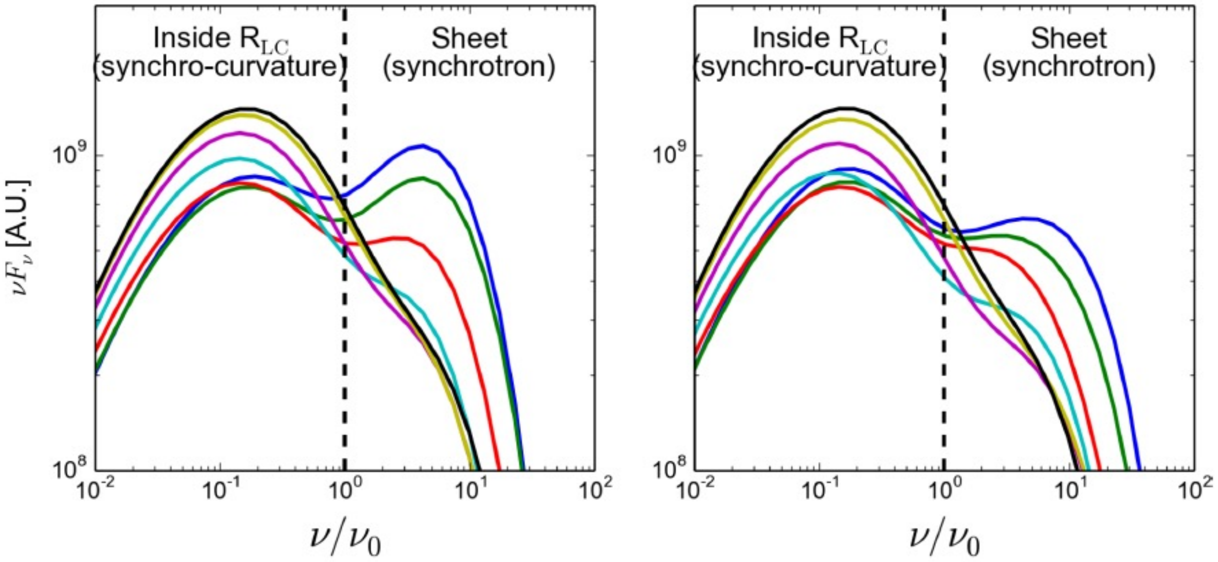


Reconnection in current sheet

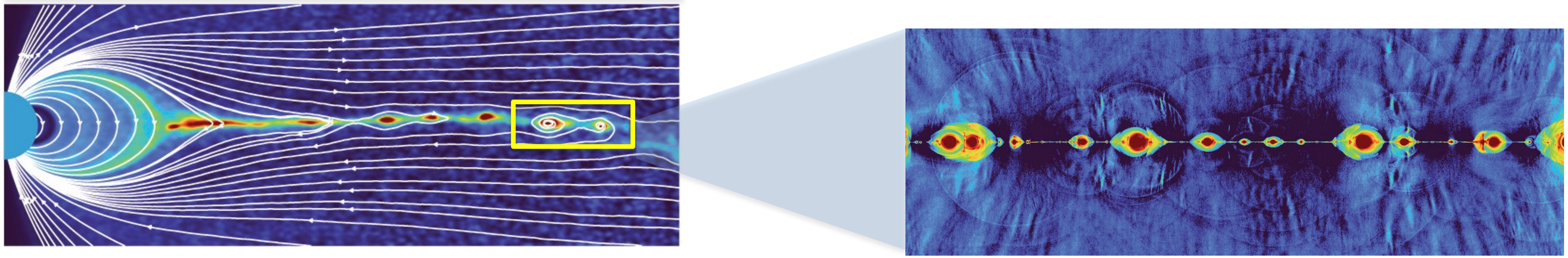


Cerutti+ 2016, Philippov & Spitkovsky 2018

γ ~ 10^5-10^6 → synchrotron radiation



But no evidence for fast flux variability in Fermi pulsars (Kerr et al. 2022)



From Philippov & Kramer 2022

Hakobyan+ 2023

Vela HE/VHE – electric field/CR model

Kalapotharakos+2014,2018,2023

Emission must happen outside the light cylinder

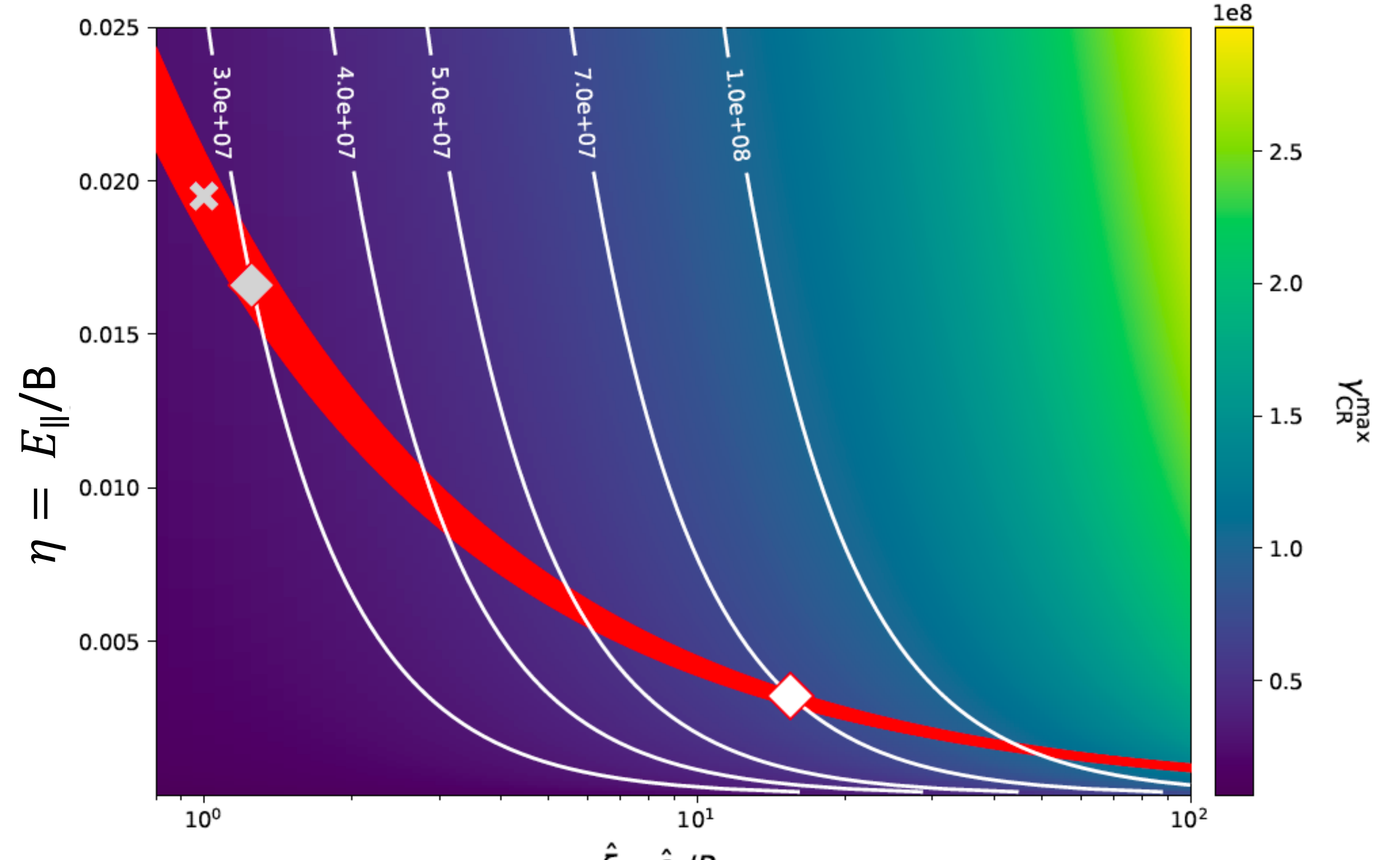
Parallel electric field acceleration near current sheet (scaled up from PIC models) – $\gamma \sim 10^7 - 10^8$

Produces CR in radiation-reaction limit – need curvature radii >> R_{LC}

$$\gamma_{\rm CR}^{\rm max} \simeq 4 \times 10^7\, \xi^{1/2} \eta_{-1}^{1/4}$$

$$E_{\rm CR}^{\rm max} \simeq 5\,{\rm GeV}\, \xi^{1/2} \eta_{-1}^{3/4} = 1.5 \text{ GeV}$$

GeV and 30 TeV emission from same particle population



Aharonian et al. 2023

Vela HE/VHE spectrum – reconnection/SR model

Cerutii et al. 2016, Philippov & Spitkovsky 2018

Magnetic reconnection maximum particle energy – γ_{max} ~ σ_{LC}

For Vela:

$$\sigma_{LC} = \frac{B_{LC}^2}{4\pi\kappa_4 n_{GJ}^{LC} mc^2} \sim 7\times10^5$$

This is OK for producing the synchrotron GeV

$$\gamma_{\rm SR}^{\rm max} \simeq 1.3\times10^6 (B_\perp/B_{\rm LC})^{-1/2} \,(E_{\rm SR}^{\rm max}/1.5\,{\rm GeV})^{1/2}$$

BUT γ_{max} is several orders of magnitude short of 30 TeV!

Could lower κ from 10^4 to 10-100, but this does not agree with predicted pair multiplicities (Timokhin & Harding 2015, 2019)

Fundamental Plane (Theory)

Assumptions

CR

Kalapotharakos et al. (2019)

1) At the current sheet near the LC

$$R_C \propto R_{LC} \propto P$$

2) Radiation Reaction Limit Regime

$$E_{BLC} B_{LC} \propto \gamma_L^4 R_C^{-2}$$

3) Radiating particle density proportional to Goldreich-Julian density

$$\rho_{GJ} \propto B_* P^{-1}$$

$$\dot{\mathcal{E}} \propto B_*^2 P^{-4}$$

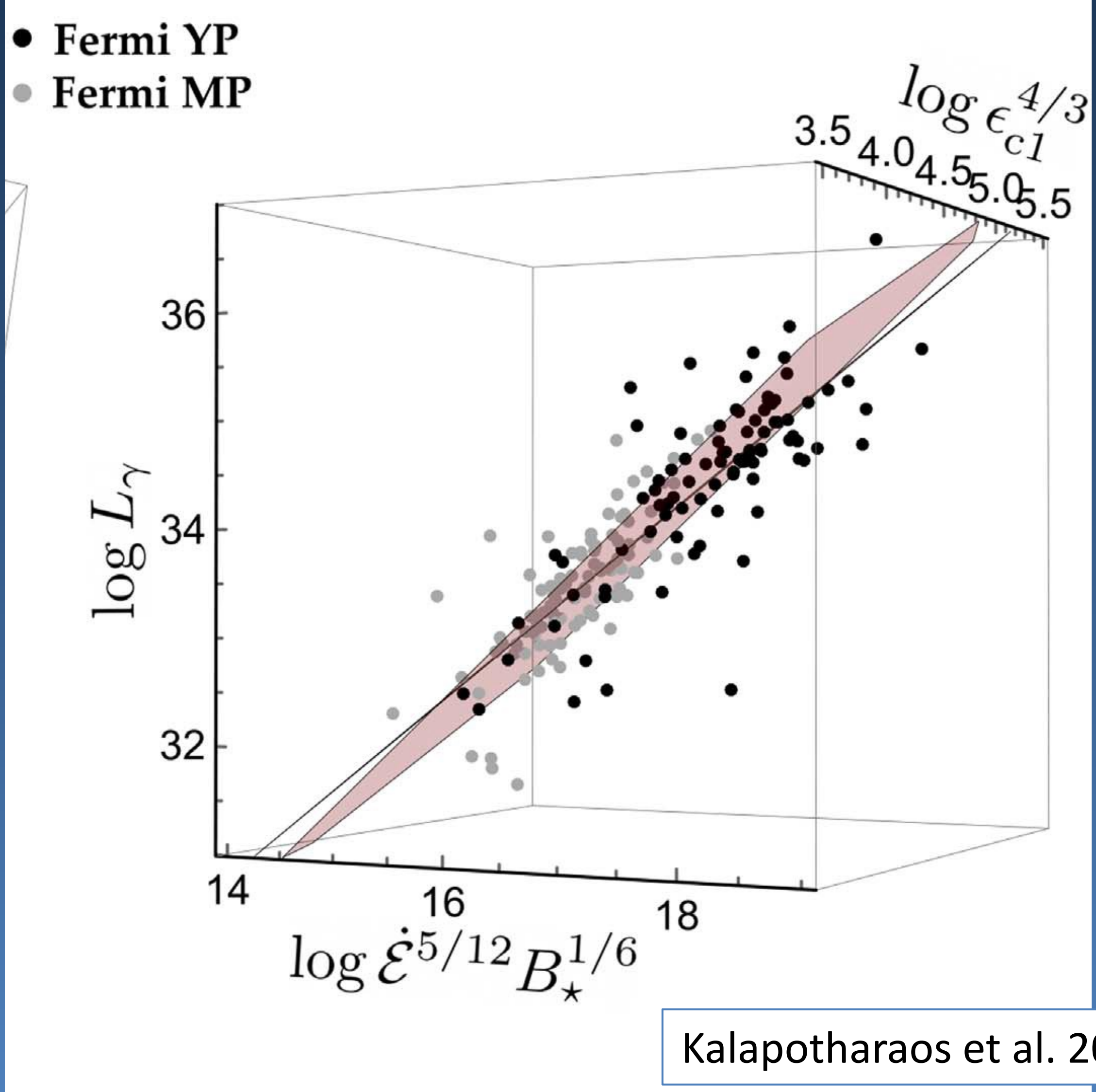
$$L_\gamma \propto \epsilon_{cut}^{4/3} B_*^{1/6} \dot{\mathcal{E}}^{5/12}$$

$$\frac{2 q_e^2 \gamma_L^4}{3 m_e c\, R_C(\theta)} = \frac{q_e \mathbf{v} \cdot \mathbf{E}}{m_e c^2}$$

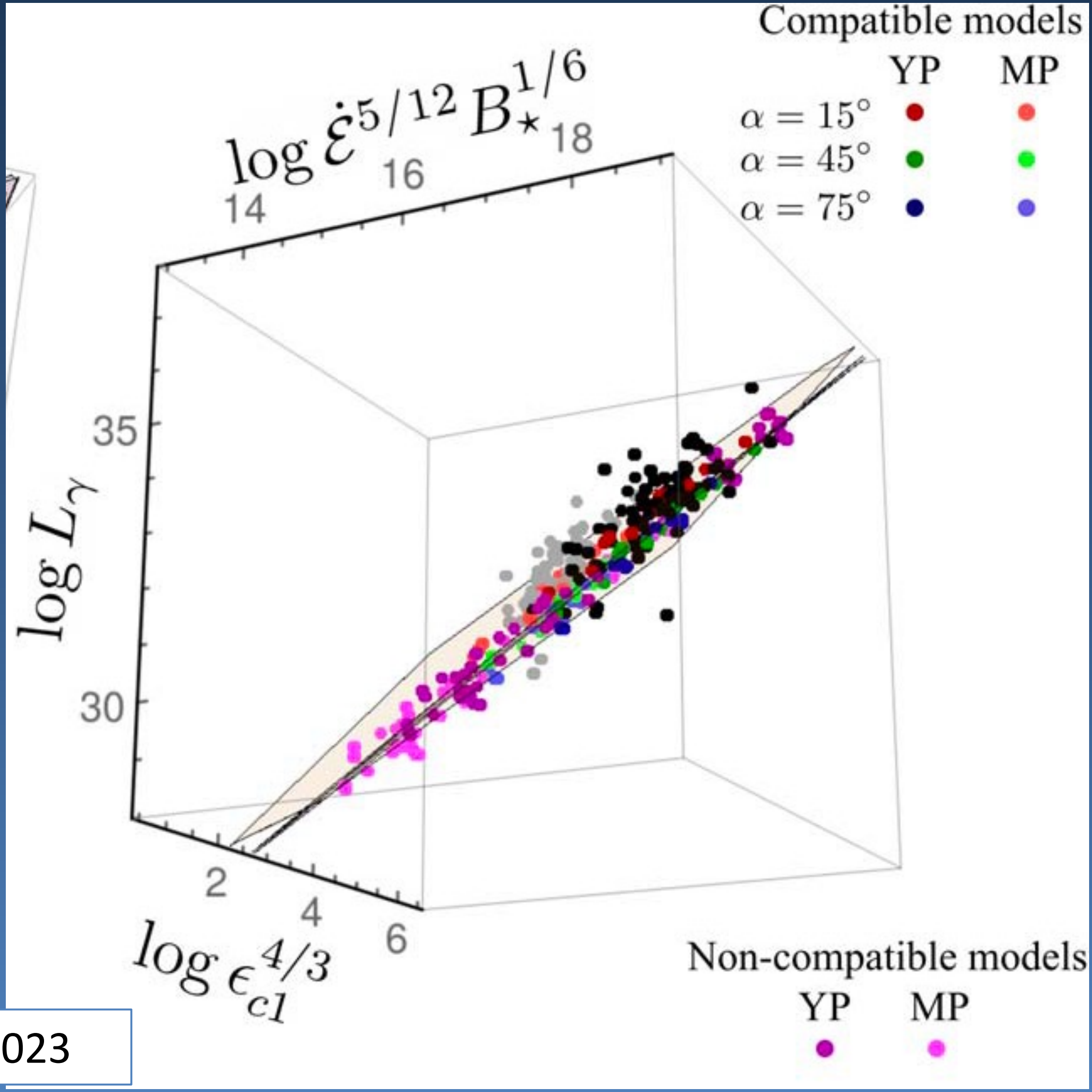
$$\epsilon_{cut} = \frac{3}{2} c\hbar \frac{\gamma_L^3}{R_C(\theta)}$$

Fundamental plane – comparison with Fermi 3PC data

Fermi data alone



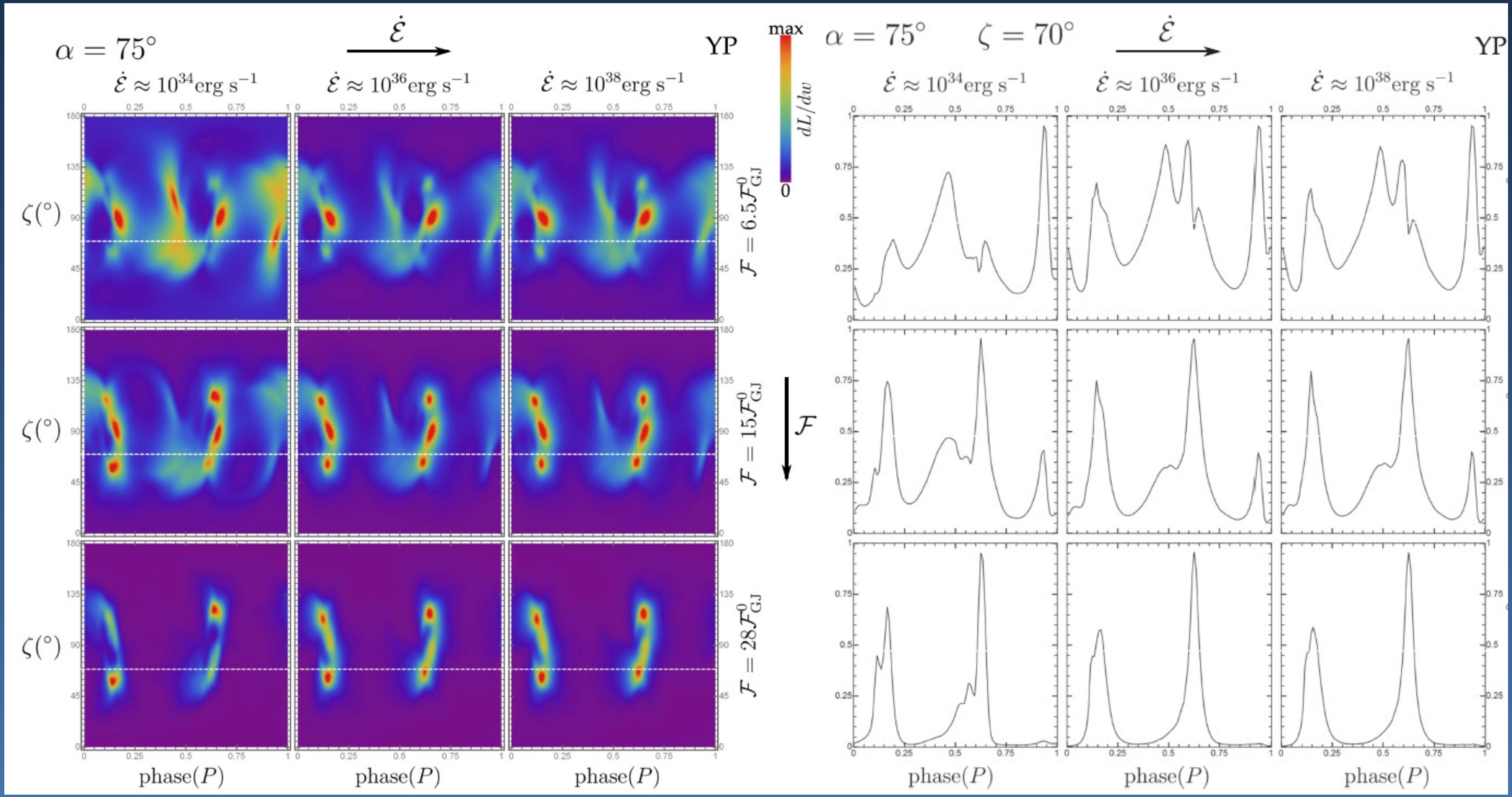
Fermi data plus PIC models



Kalapotharaos et al. 2022, 2023

High energy light curves from PIC models

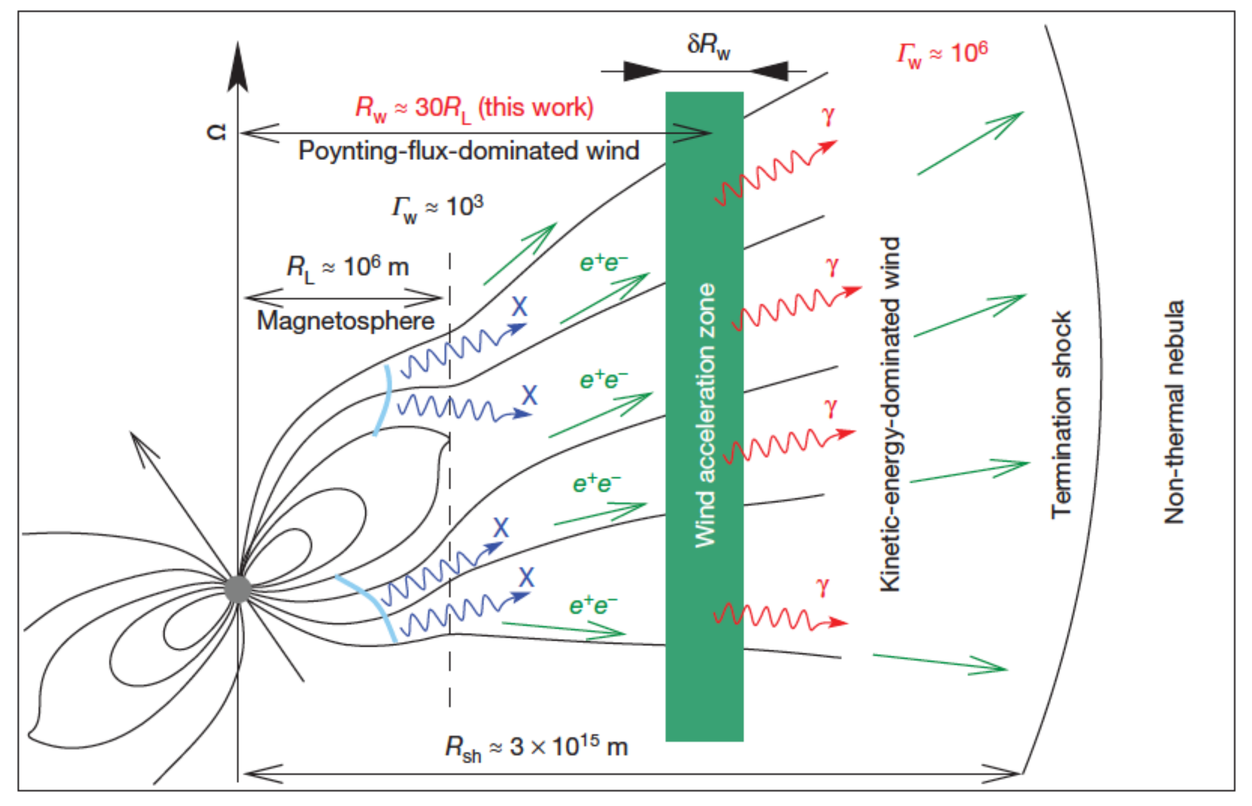
Kalapotharakos et al. 2018



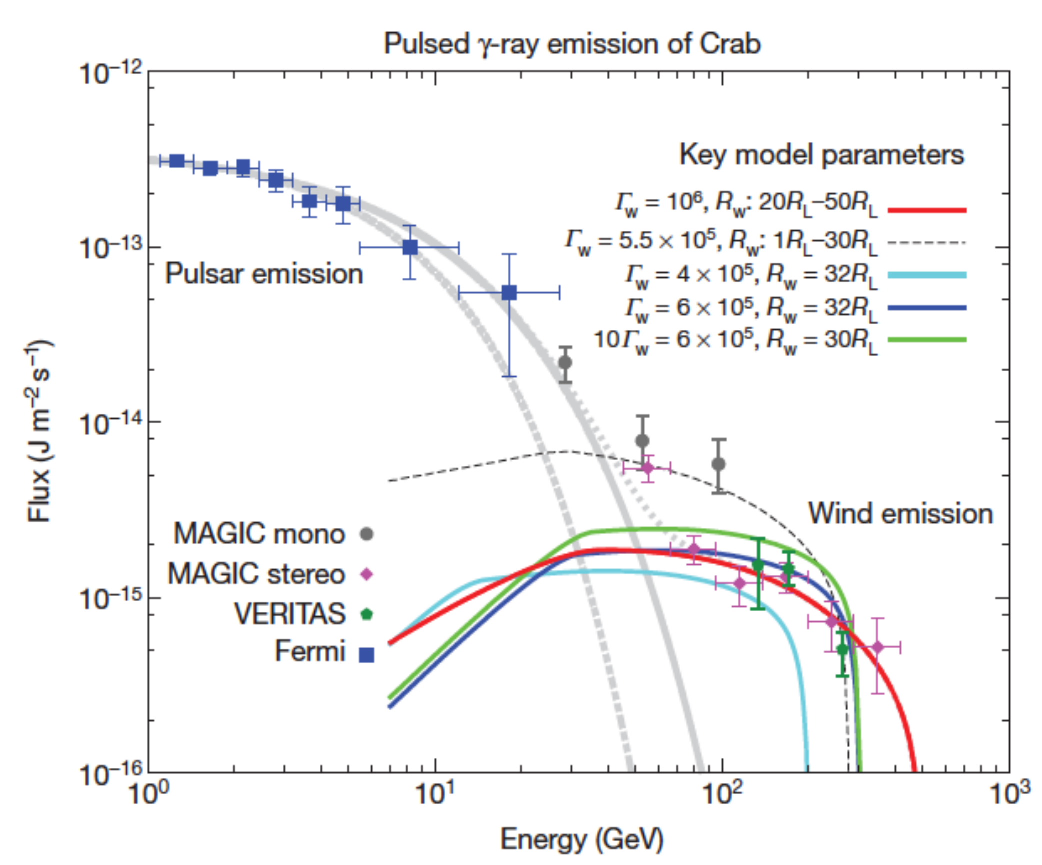
Fermi pulsars have high pair injection near force-free magnetosphere

Crab pulsar – cold wind ICS

Aharonian et al. 2012

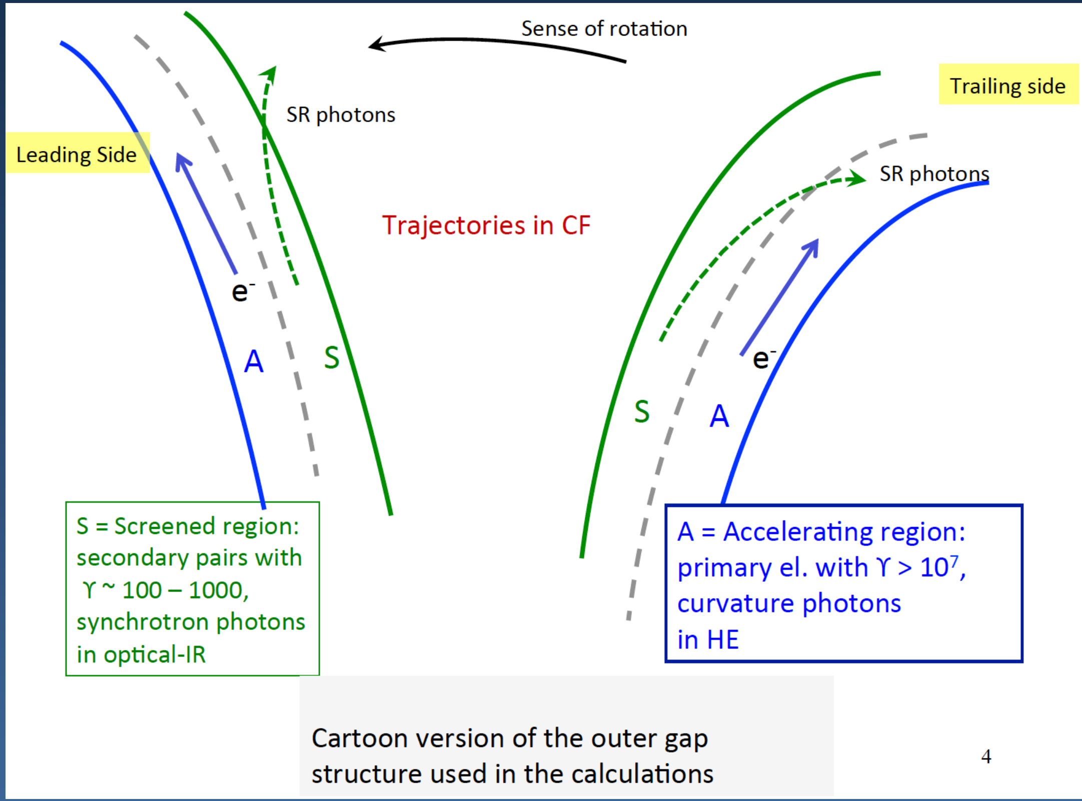


- Scattering of wind e^+-e^- off of optical/X-ray pulsed emission
- Emission at 20 – 30 R_{LC}
- Cannot reach 1 TeV nor produce lower energy emission



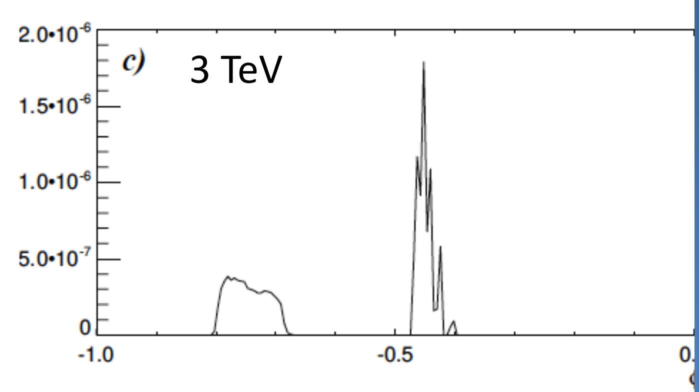
Outer gap model for Vela TeV emision

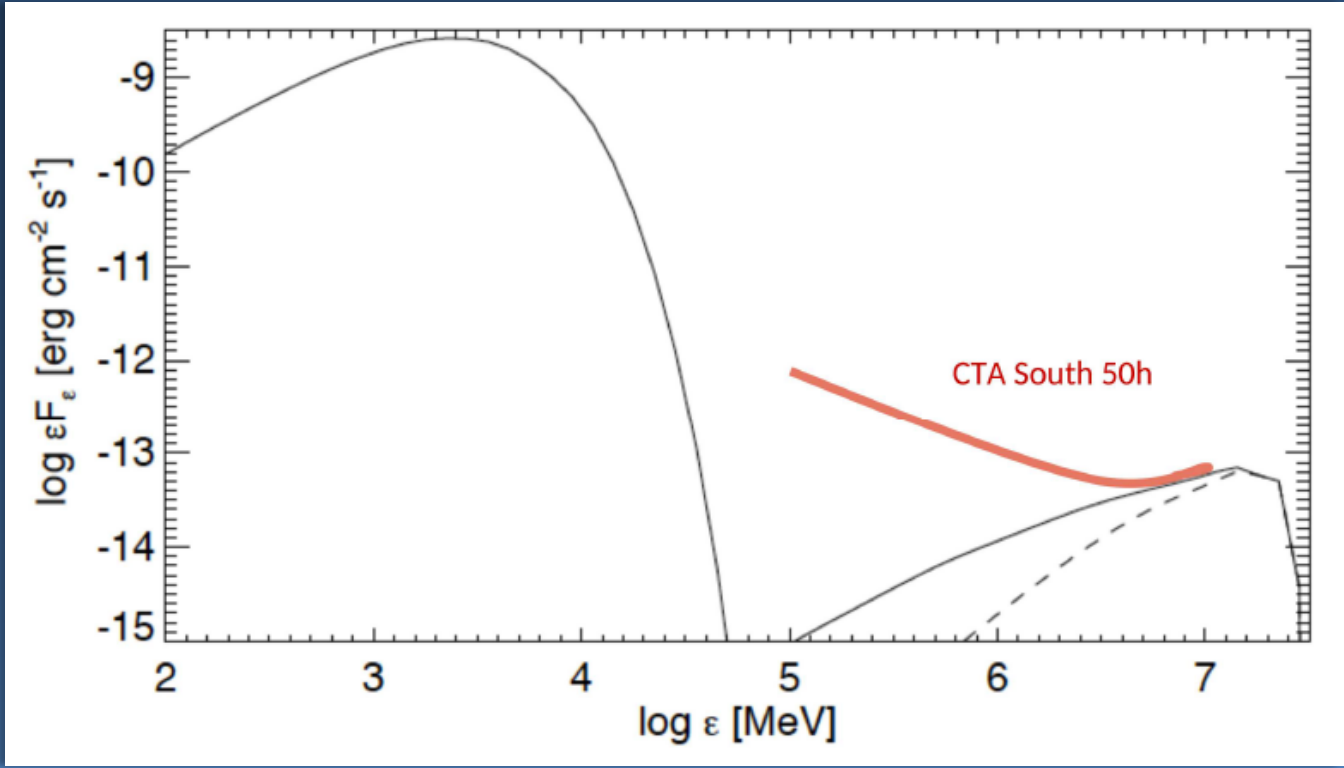
Rudak & Dyks 2017



Outer gap model

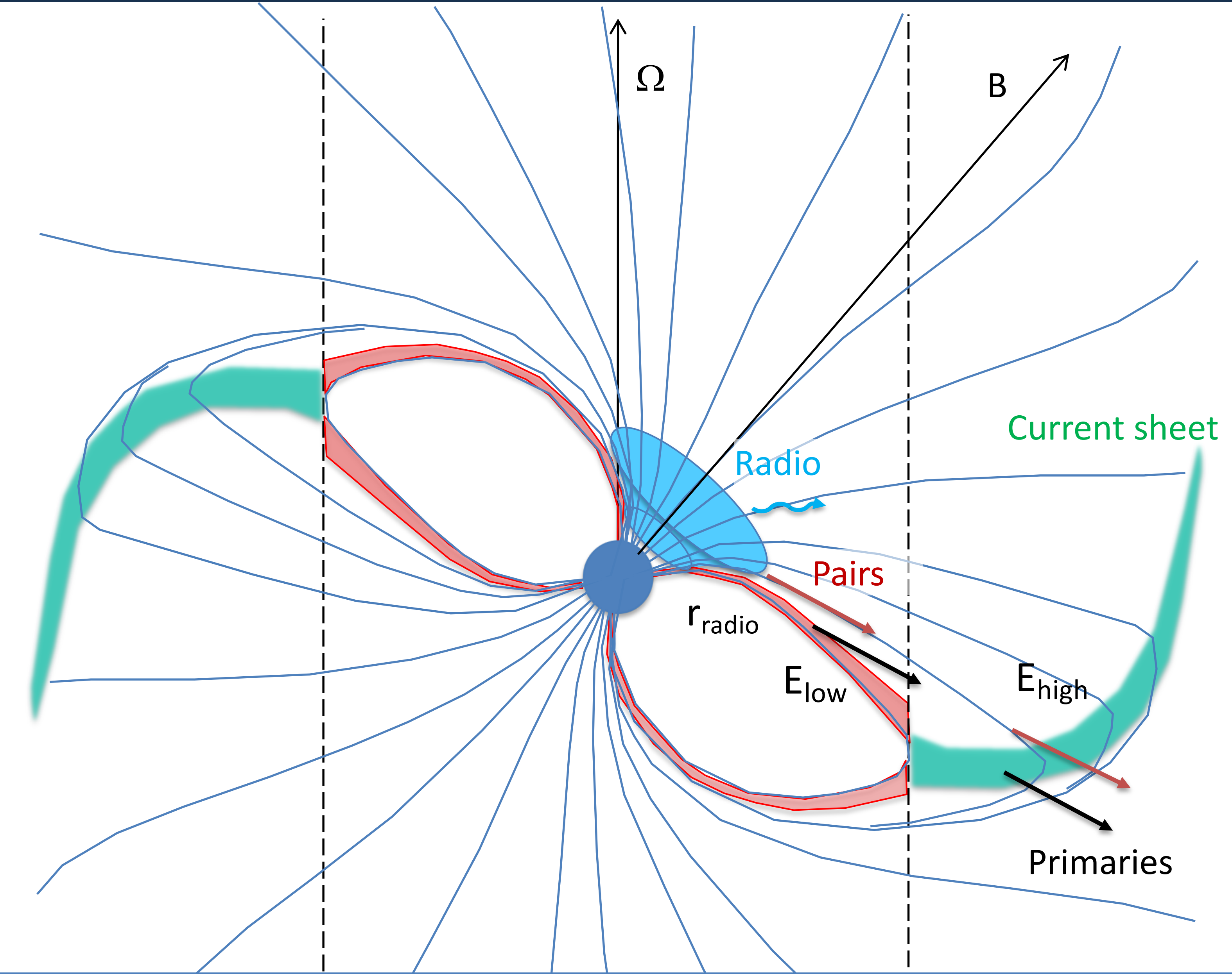
- Emission inside light cylinder
- PC pairs produce SR optical/UV
- Accelerated primaries scatter optical/UV photons





Separatrix/current sheet model

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

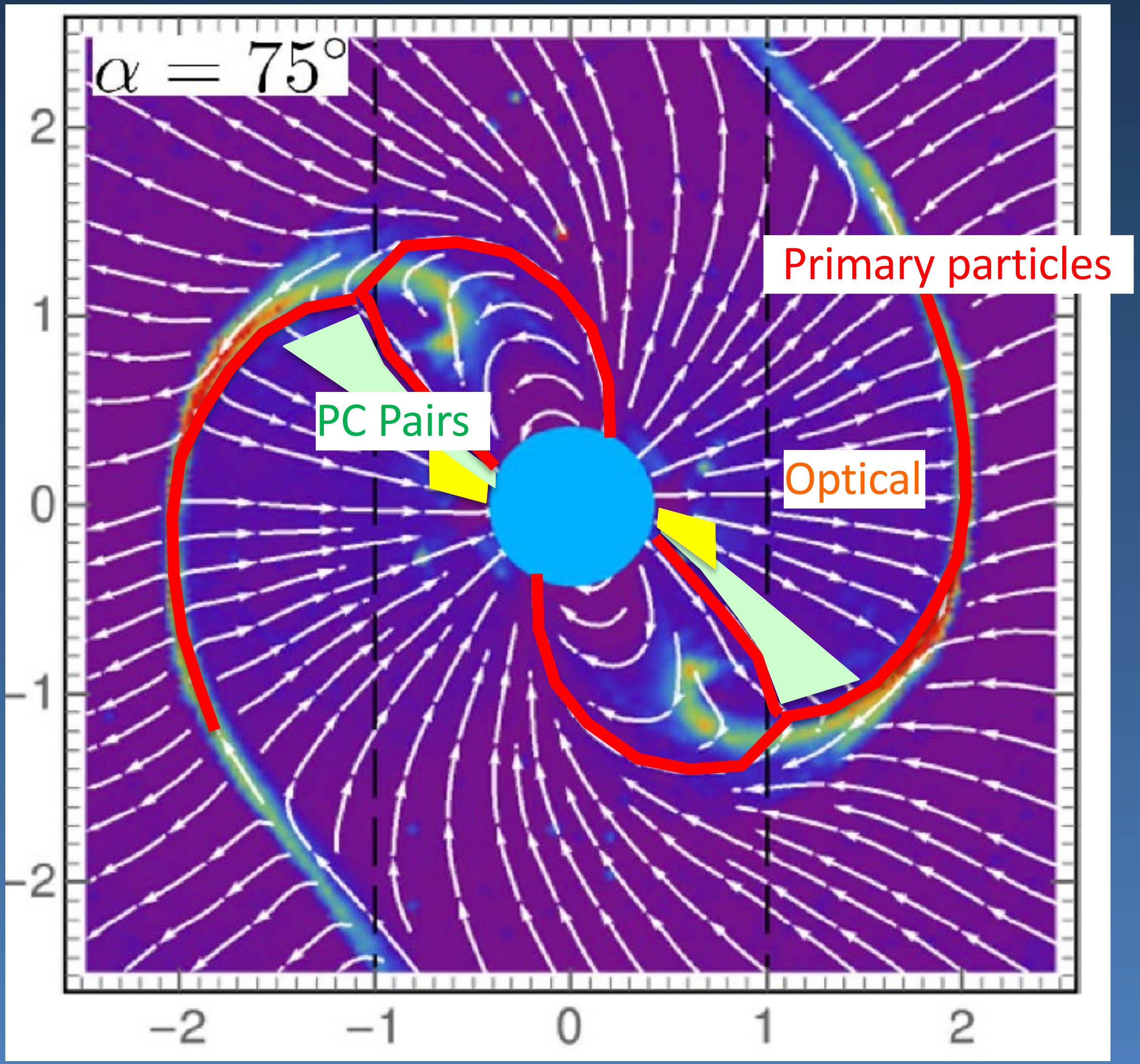
Force-free magnetic field
0.2 to 2 R_{LC}

Connect to vacuum retarded dipole below 0.2 R_{LC}

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

Modeling TeV+ emission from Vela

Harding, Kalapotharakos, Venter & Barnard 2018



Near force-free magnetosphere

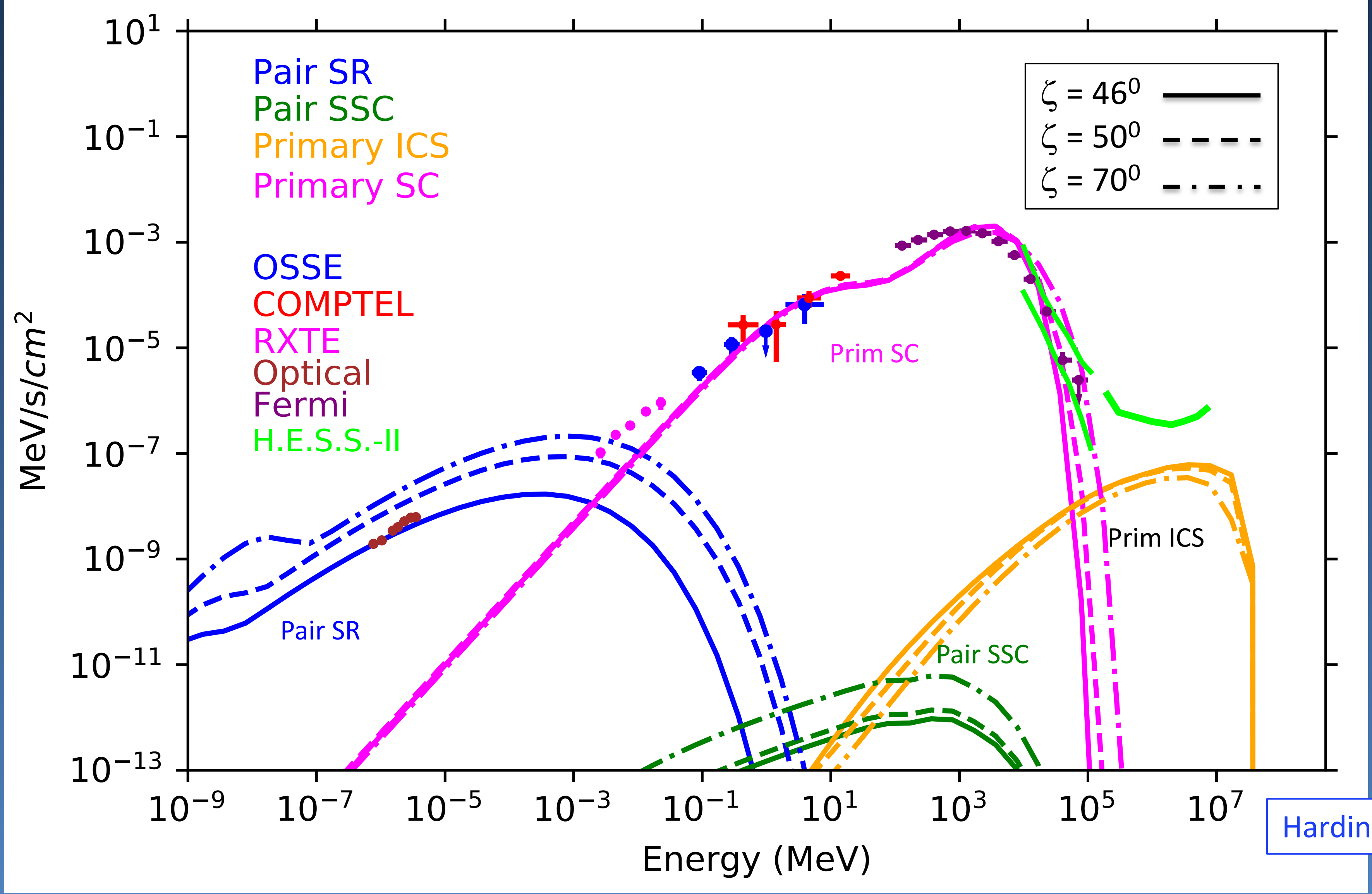
- PC pairs produce synchrotron radiation (SR) optical/UV at lower altitude
- Primary particles (mostly positrons) produce synchro-curvature (SC) and scatter optical/UV to produce 10 TeV ICS emission
- Pairs scatter optical/UV to produce SSC hard X-ray emission

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



- SR from pairs inside light cylinder
- Synchro-curvature from primaries in current sheet
- SSC from pairs
- ICS from primaries scattering pair SR up to ~30 TeV

Harding, Venter & Kalapotharakos 2021

Modeling TeV+ emission from Vela

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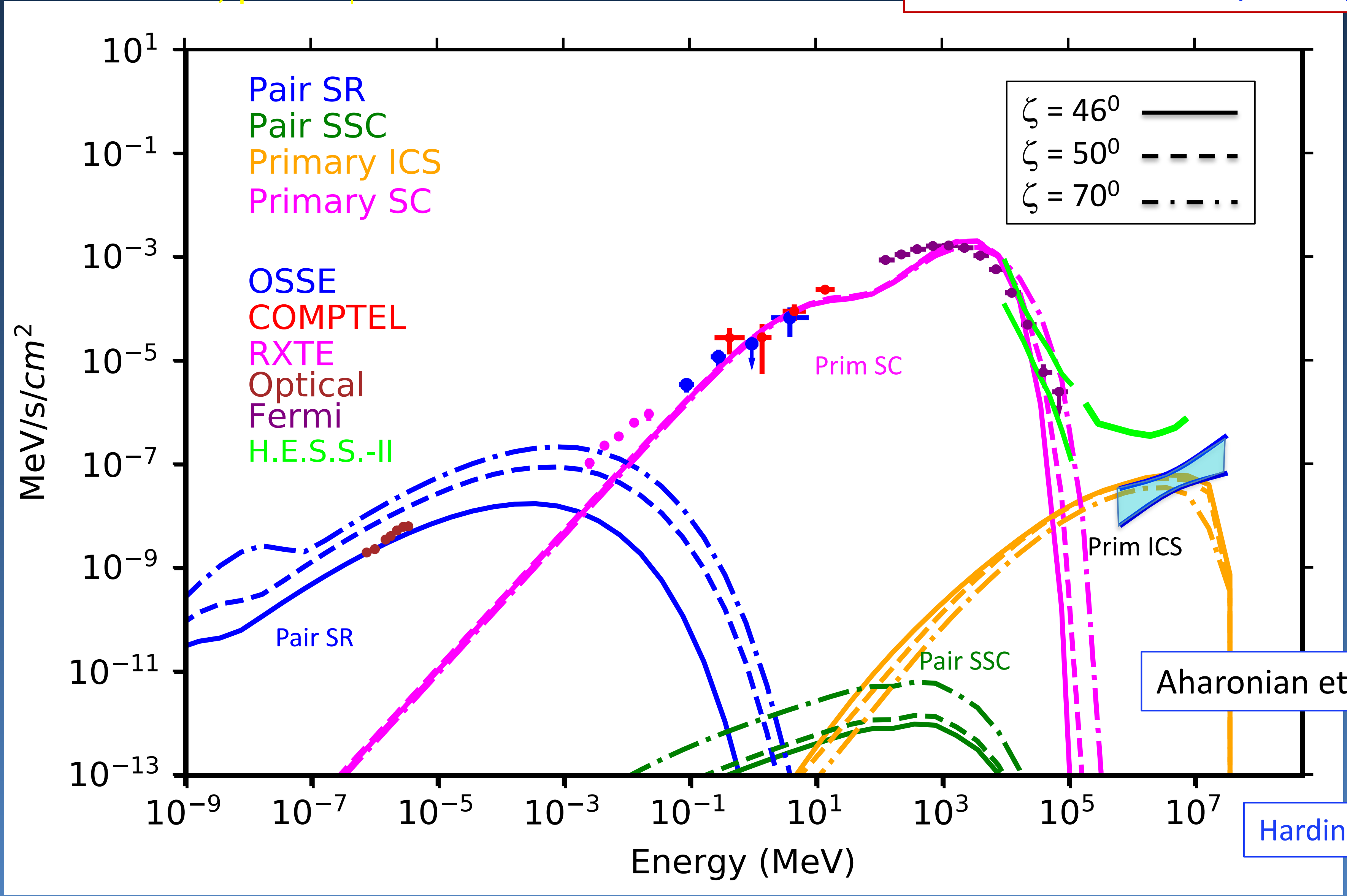

- SR from pairs inside light cylinder
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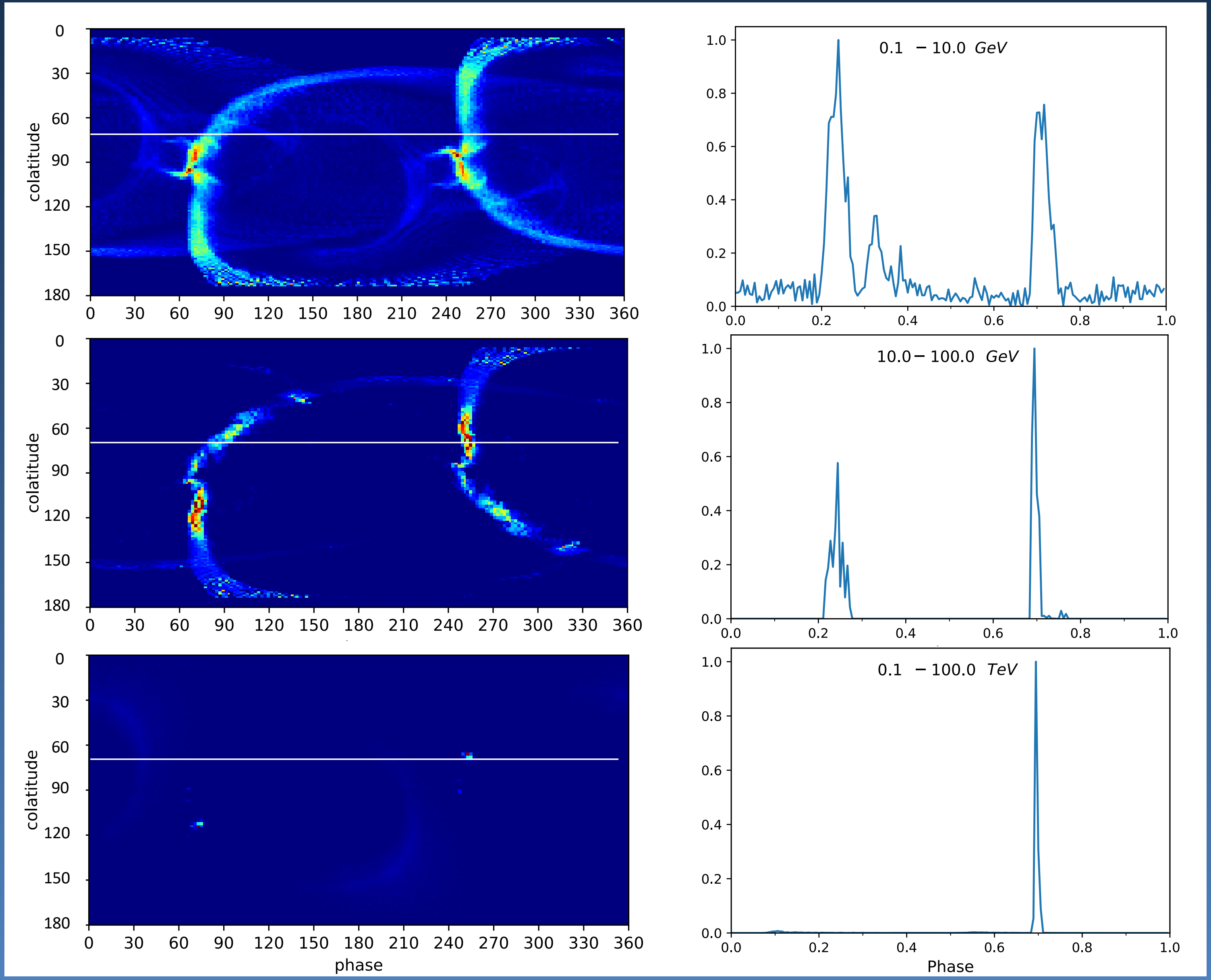
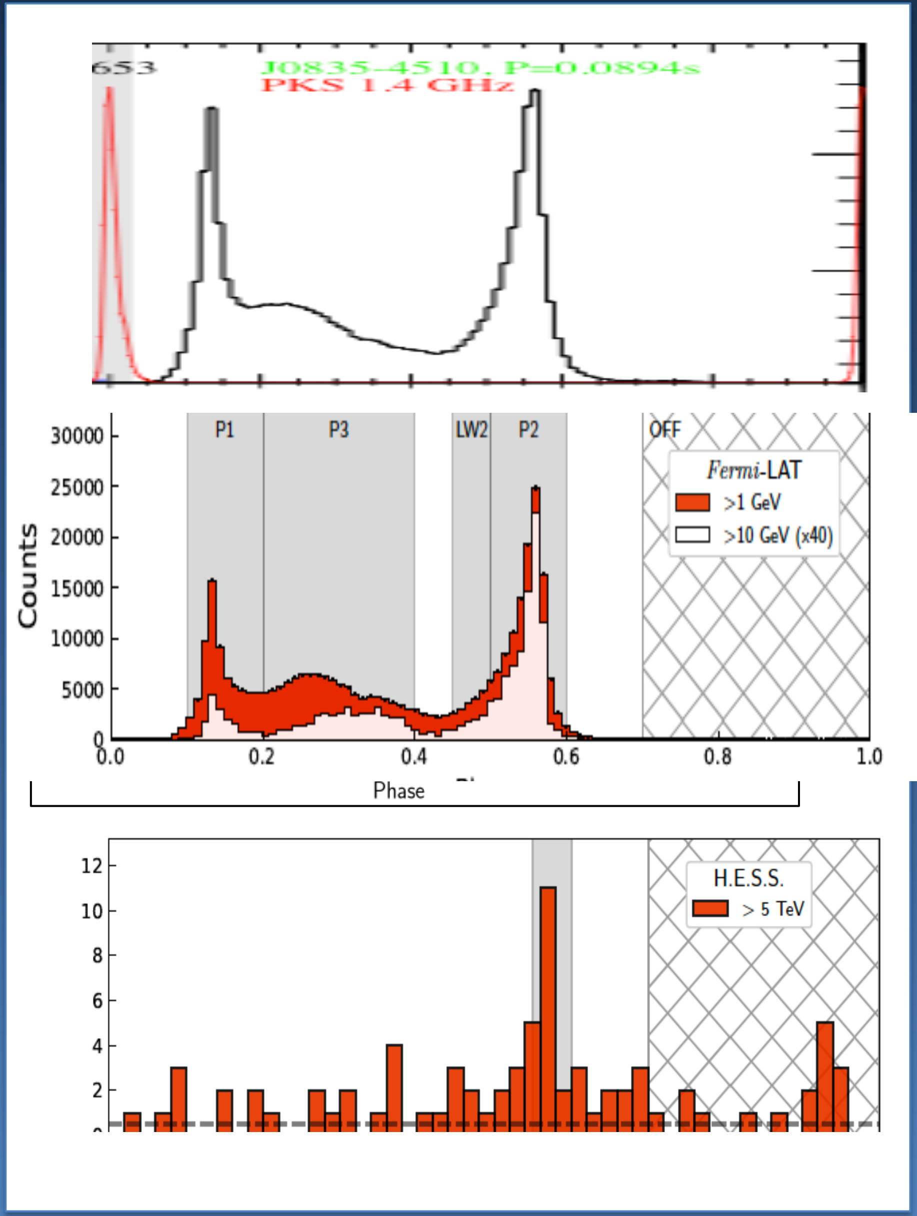
- SSC from pairs
- ICS from primaries scattering pair SR up to ~30 TeV

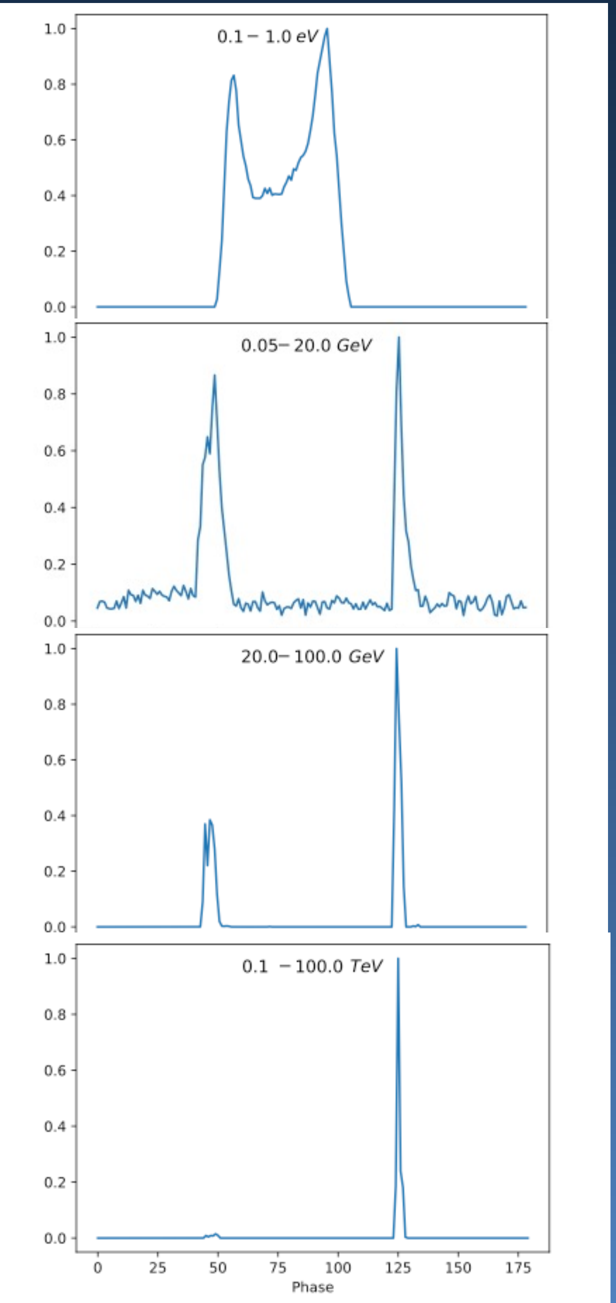
Harding, Venter & Kalapotharakos 2021

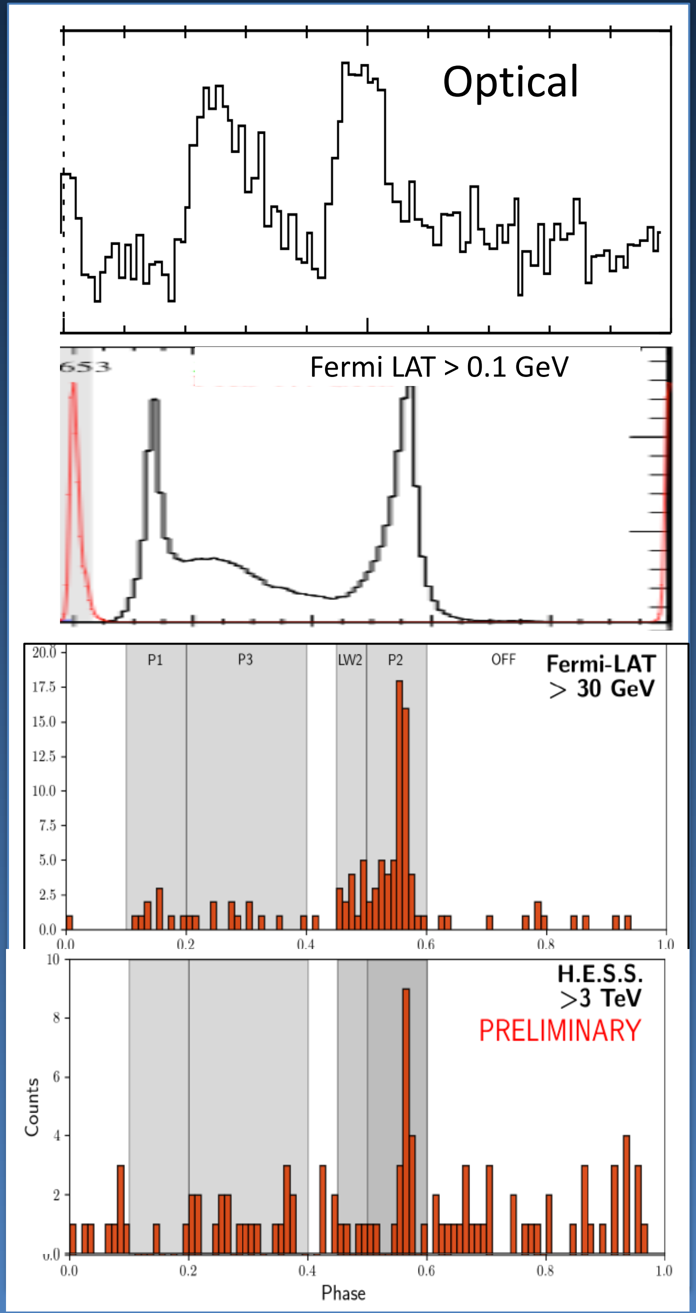
Vela model light curves





Vela model light curves





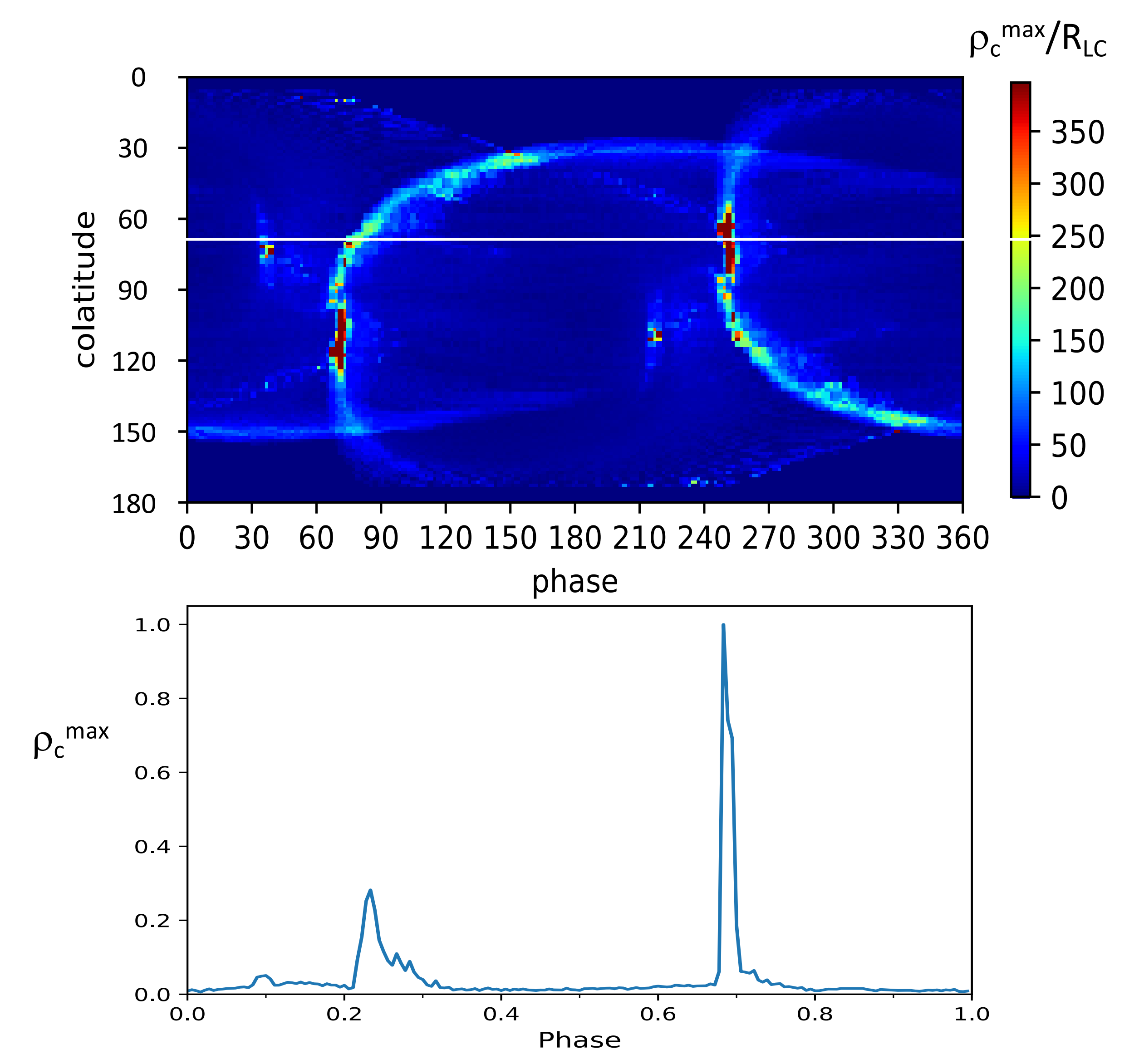
Harding, Kalapotharakos, Venter & Barnard 2018

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

Vela P1/P2 evolution with energy



Harding, Venter & Kalapotharakos 2021

Lorentz factor of particles in curvature radiation-reaction limit:

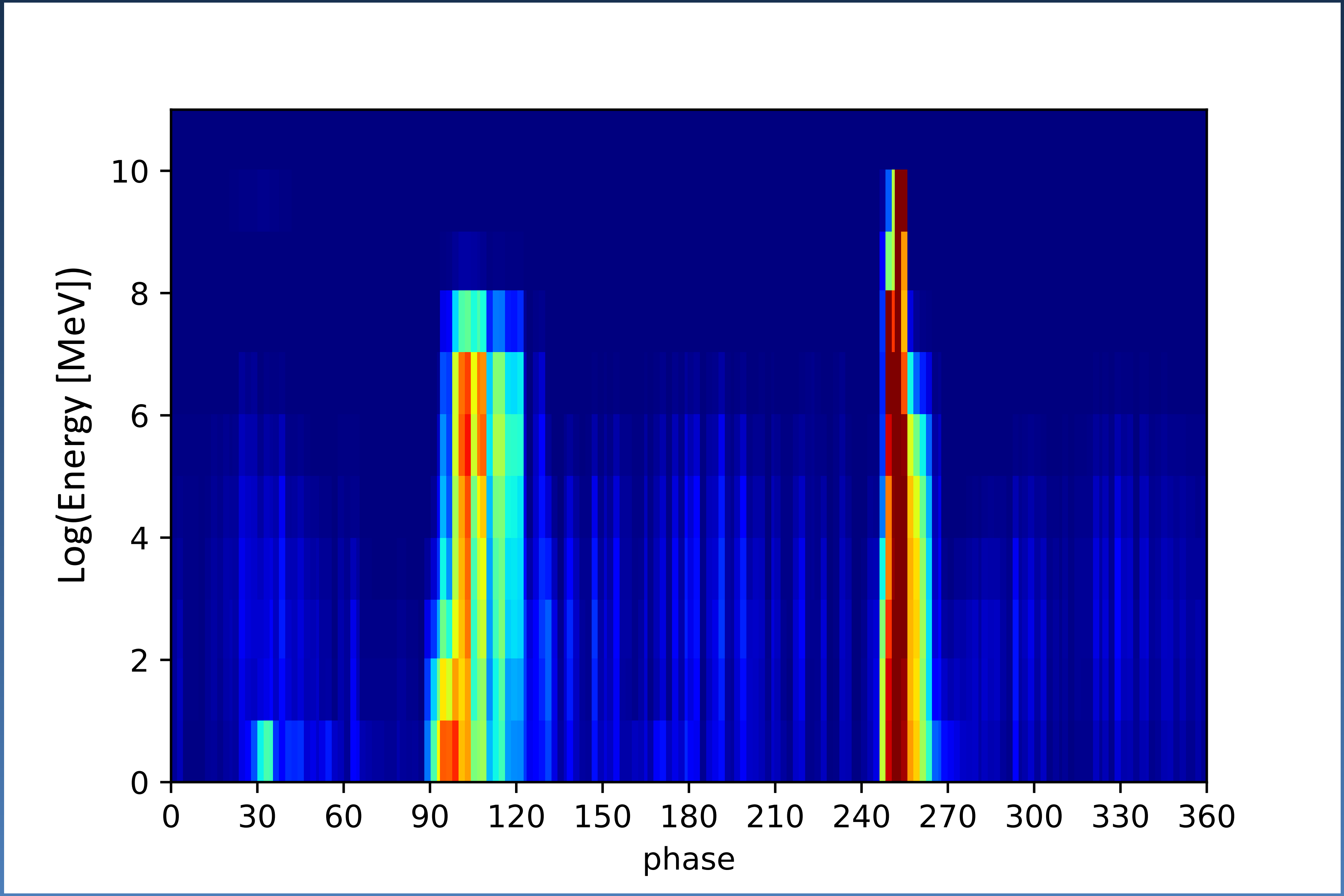
$$\gamma_{CRR} = \left(\frac{3E_{||}\rho_c^2}{2e}\right)^{1/4}$$

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

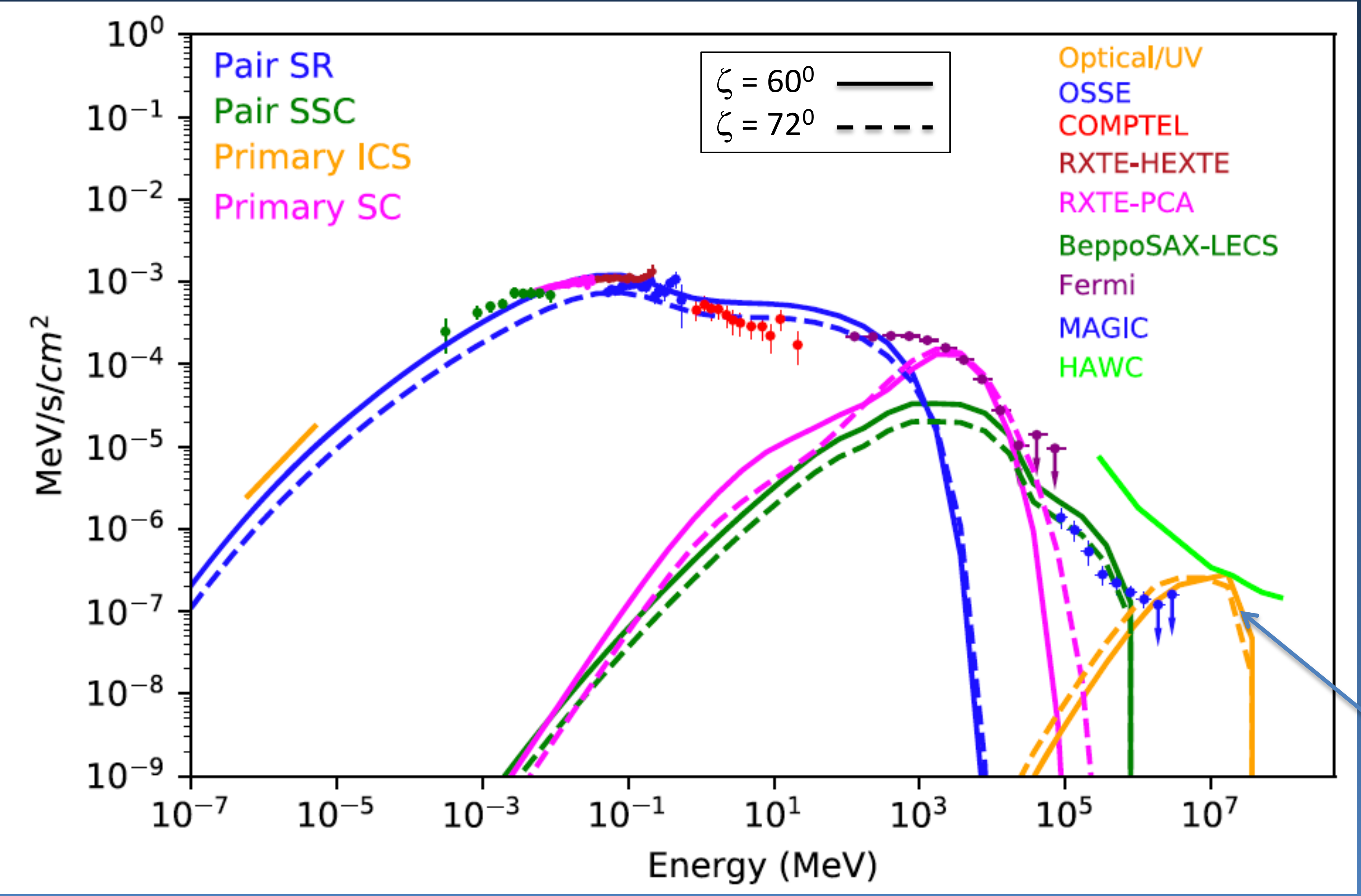
Energy vs. phase



TeV+ emission from Crab pulsar

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

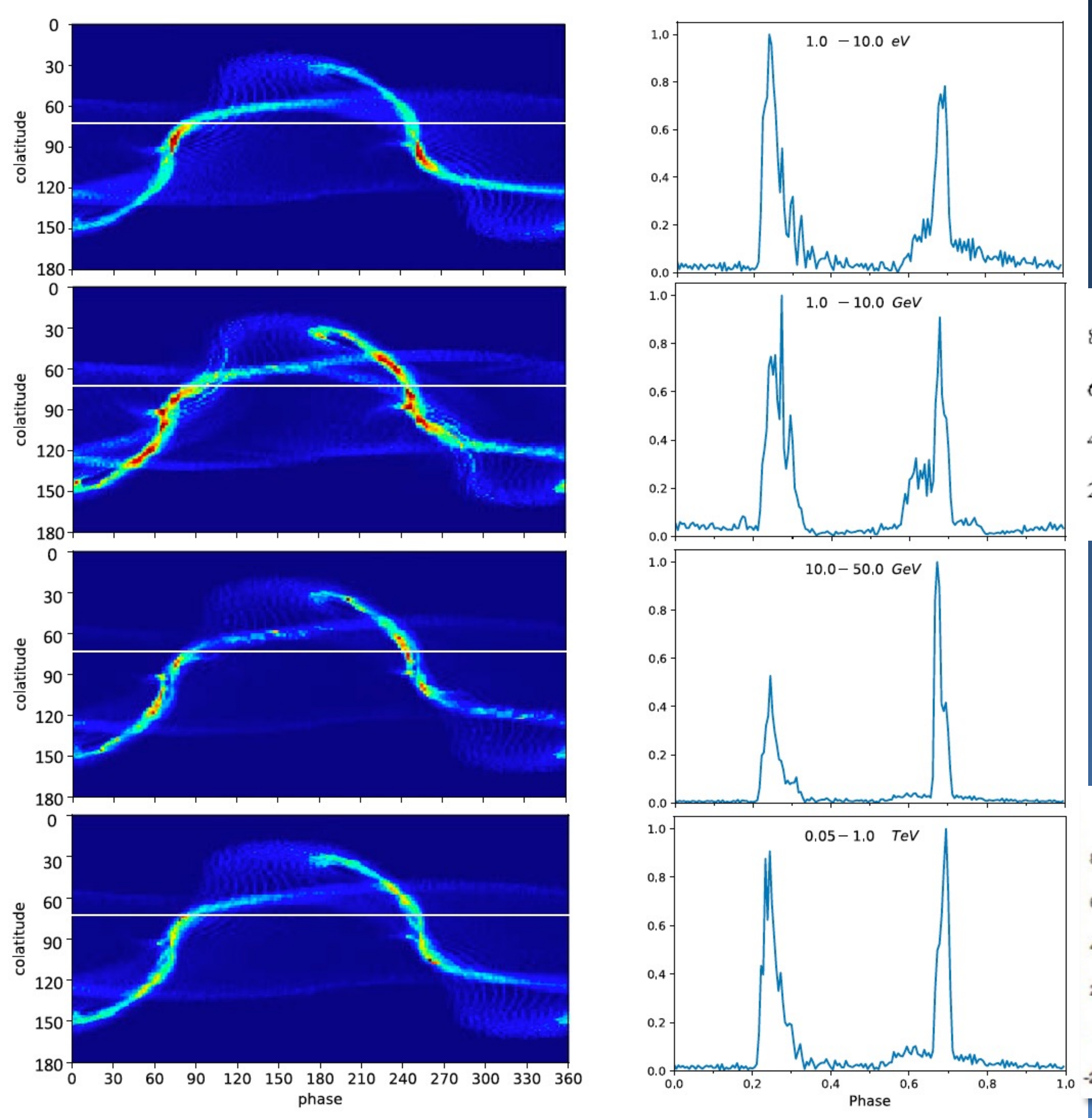
Harding, Venter & Kalapotharakos 2021

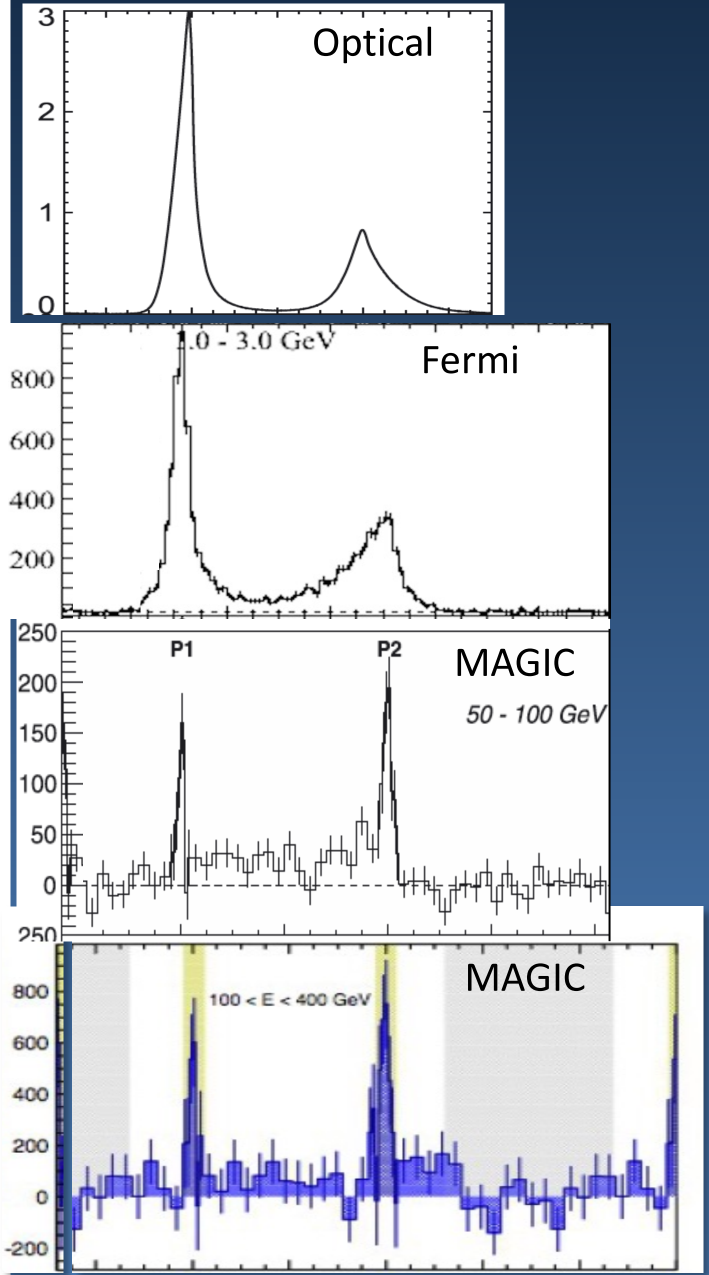


- SR from pairs near current sheet
- Synchro-curvature from primaries in current sheet
- SSC from pairs up to ~1 TeV
- ICS from primaries scattering pair SR up to ~30 TeV

γ–γ pair attenuation

Crab model light curves



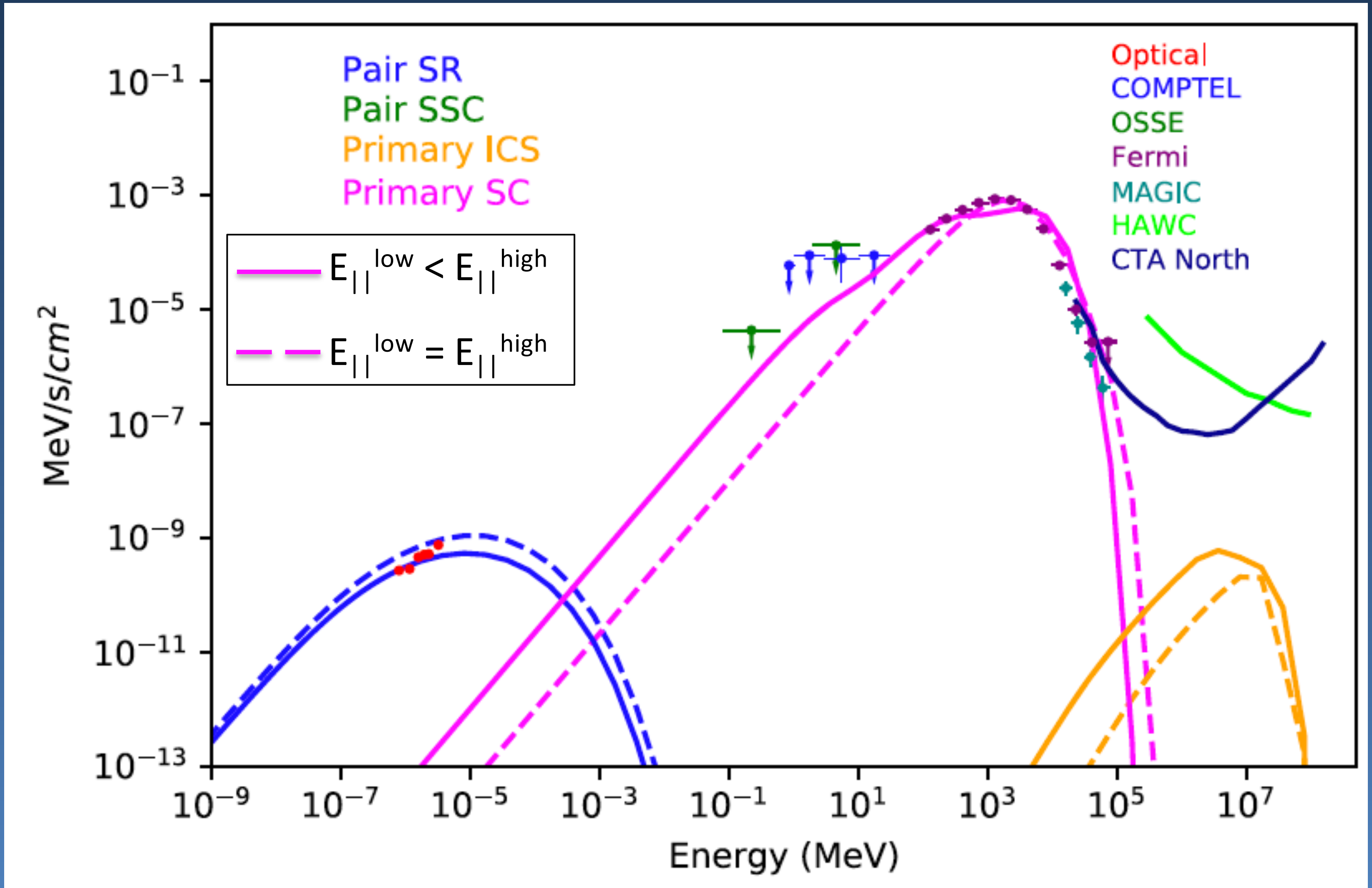


TeV+ emission from Geminga

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

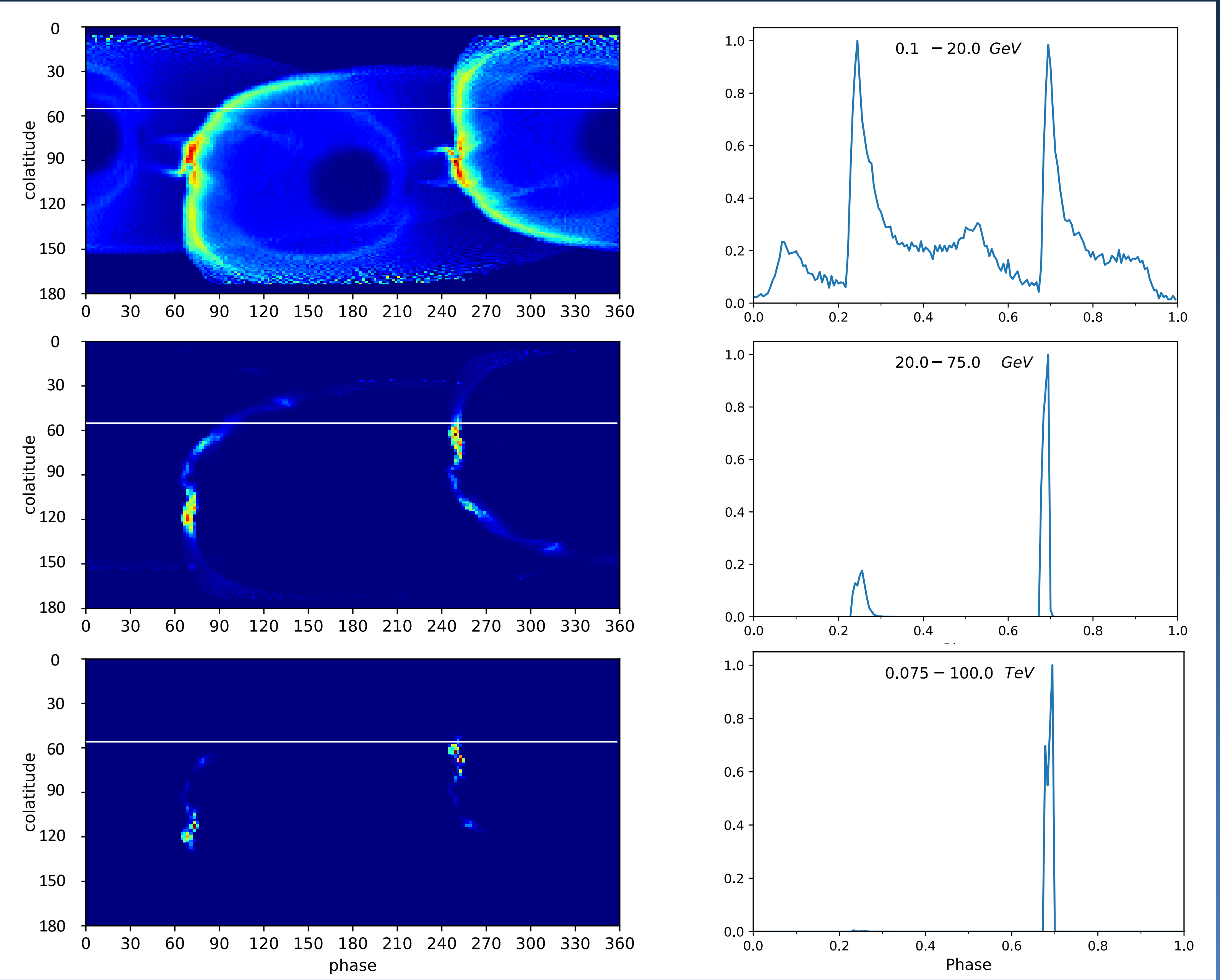
$\alpha = 75^0$, $\zeta = 55^0$, pair $M_+ = 2 \times 10^4$

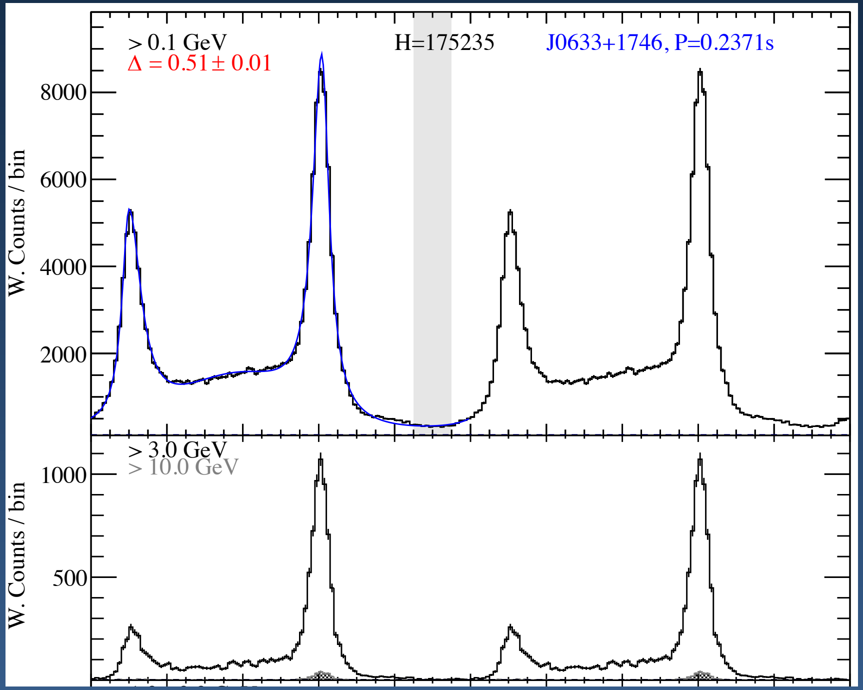
Harding, Venter & Kalapotharakos 2021

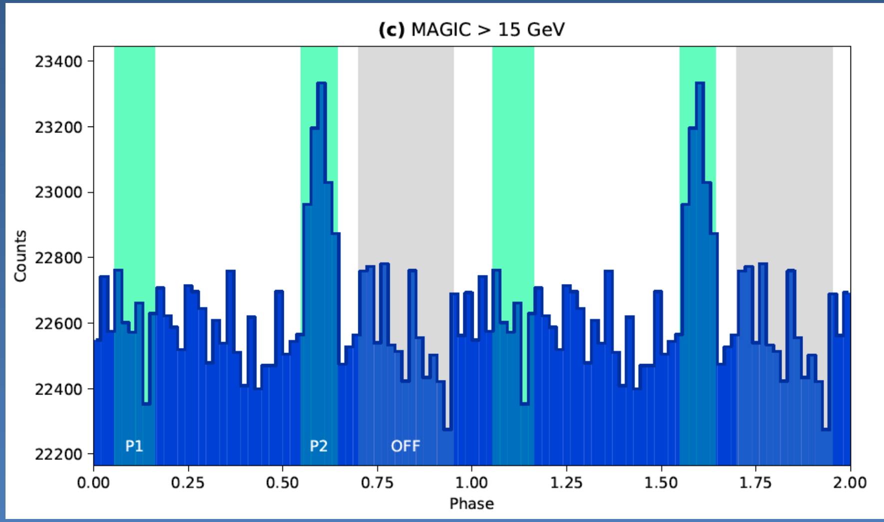


- Low pair SR UV flux
  → Very low primary ICS
- MAGIC detection explained by primary SC

Geminga model light curves



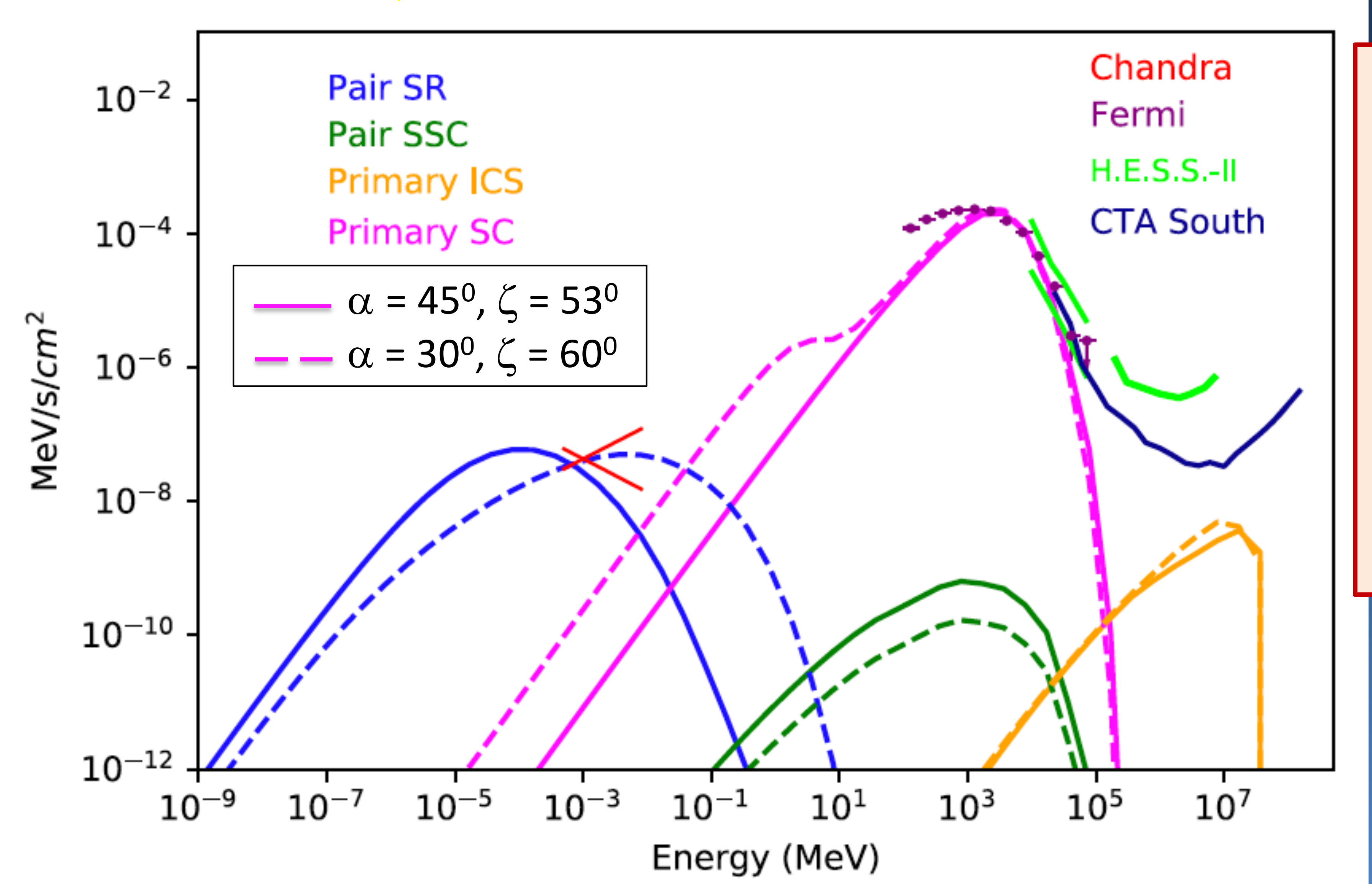




TeV+ emission from B1706-44

$P = 0.102$ s, $B_0 = 6.2 \times 10^{12}$ G, $d = 2.3$ kpc
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

Summary

- Fermi has revolutionized the study of rotation-powered pulsars, discovering 300+ gamma-ray pulsars

- Many new MSPs improve sensitivity of radio PTAs and enable a γ-ray PTA

- Cherenkov telescopes have discovered pulsed emission above 50 GeV from five pulsars!

- Combined with advances in global pulsar models we have determined the location of particle acceleration and high-energy emission in the magnetosphere

- Origin of HE/VHE pulsed emission:
  - Parallel electric field in current sheet - $\gamma_{max} \sim 5 \times 10^7$ from CR reaction limit
  - Reconnection in current sheet - $\gamma_{max} \sim \sigma_{LC}$, $\sim 10^5 - 10^6$ for Vela