Pulsar Magnetospheres: An Observational Perspective

Focus on High-Energy (GeV) and Very-High-Energy (TeV) γ rays

N.B. only 10^{31} W !

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Feeling the Pull and Pulse of Relativistic Magnetospheres
Les Houches, April 7, 2025

Outline

Introduction

Some History

The Fermi-LAT revolution

HE and VHE emitting pulsars detected from ground

Implications on two main emission paradigmes

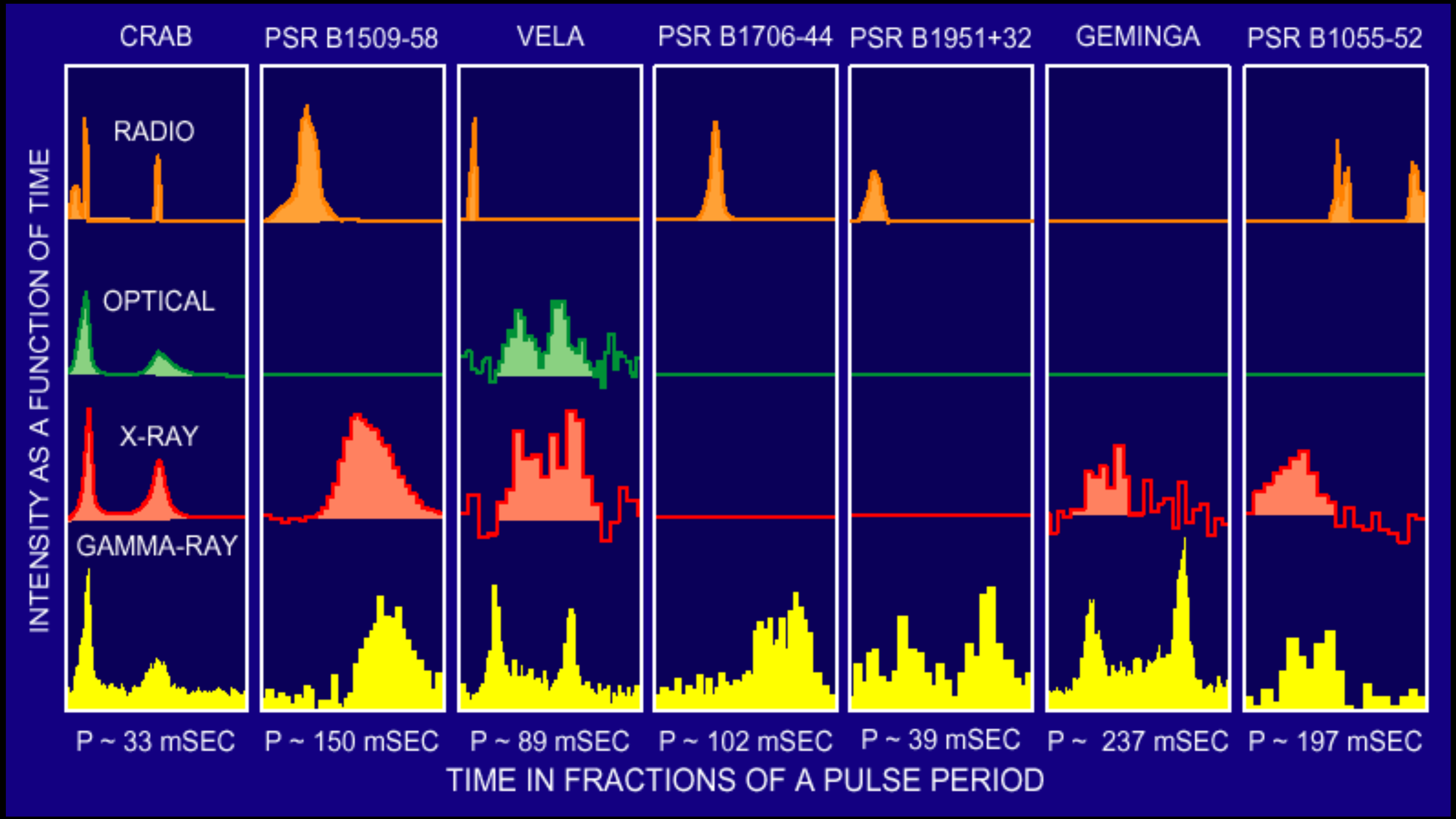
Perspectives

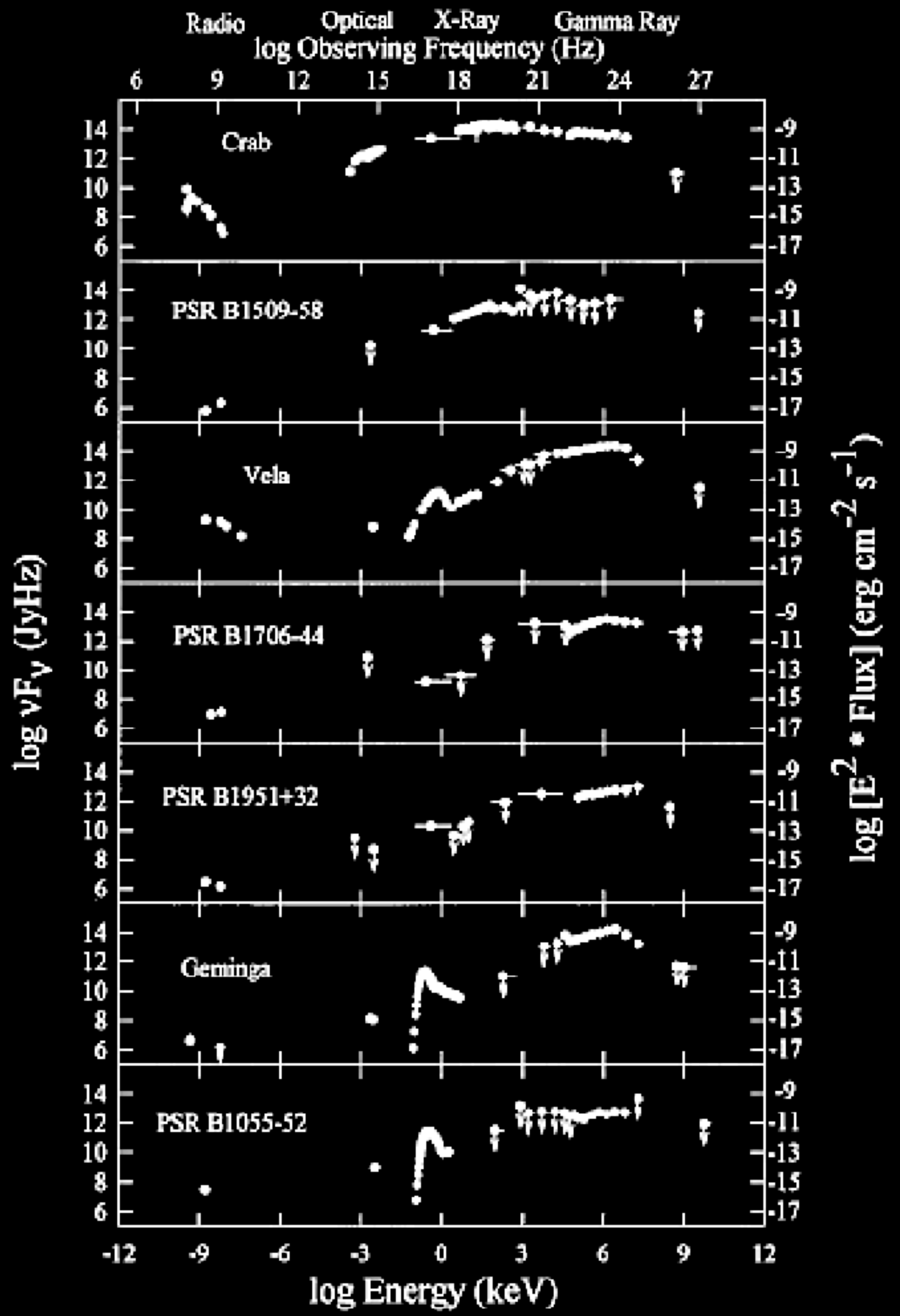
N.B. Very biased towards γ rays, will not discuss radio, X-rays…
— only isolated young pulsars

EGRET ERA < 2008

CGRO: April 5th 1991- June 4th 2000

- 7 pulsars detected
- Striking discovery : Large fraction of E in GeV γ rays
- γ-ray Light profile : 1 or 2 peaks ; lag vs radio (ex. Crab)
- Gaming : first radio-quiet pulsar





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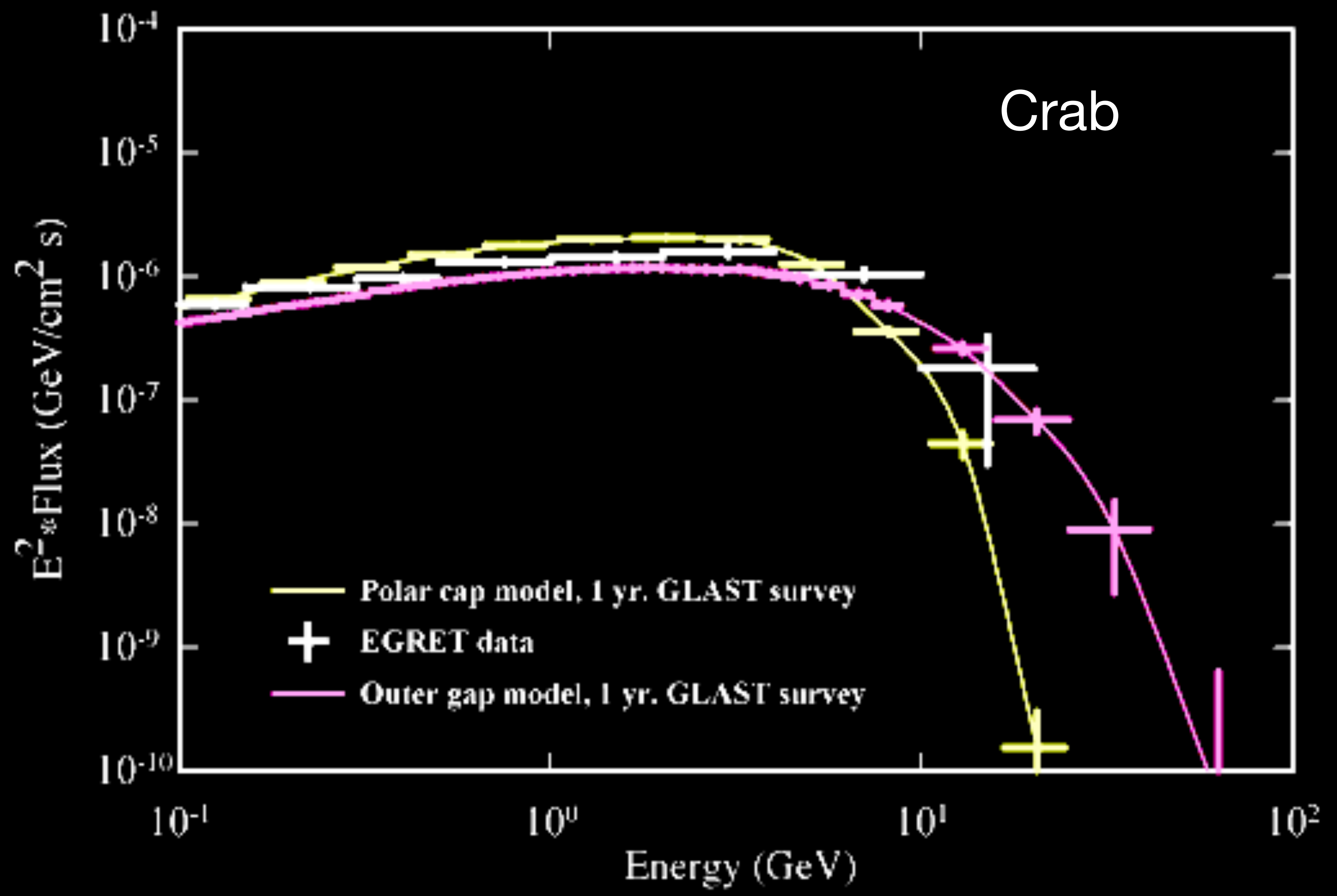
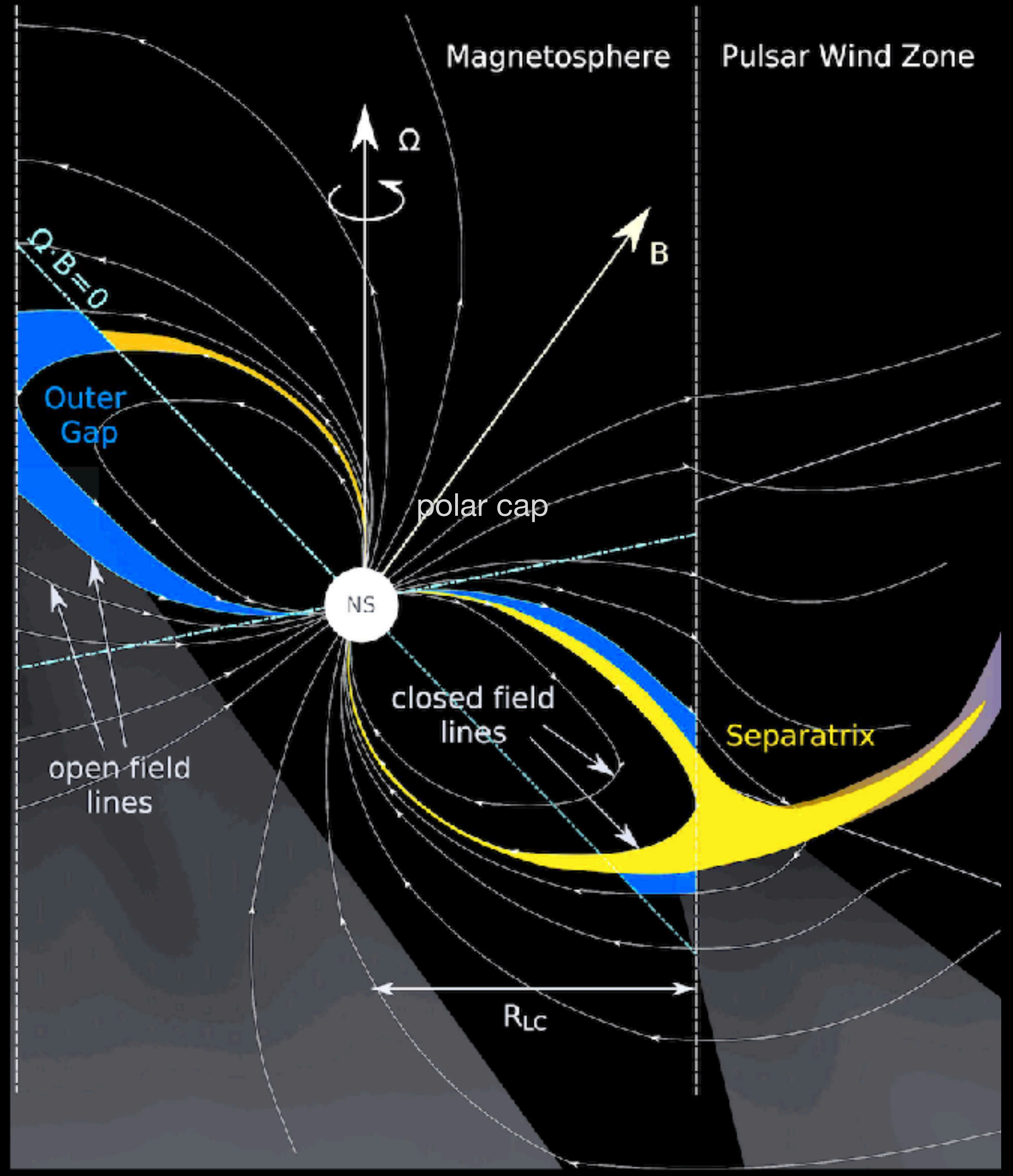




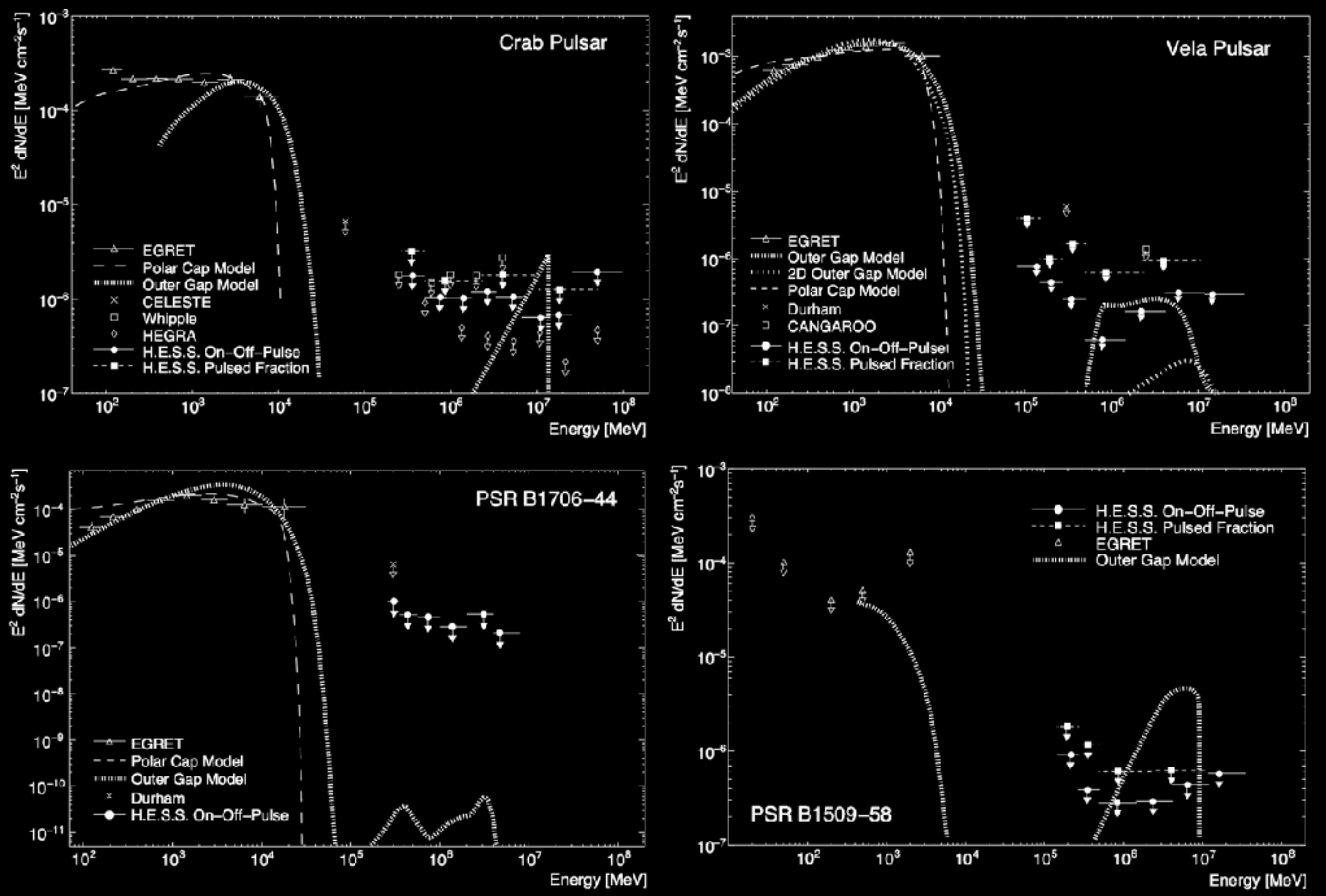
H.E.S.S. 2004-2007

CT1-4, stereo, >100 GeV

- 11 “young” pulsars selected (except the binary B1259-63)
- Flux
- Edot/$d^2 > 10^{35}$ erg/s/kpc^2
- Characteristic ages range: 1.24 to 332 kyrs
- ~350 h of total observing time
- Searching for possible IC emission > 100 GeV
- No significant excess found
- ULs: constraints for VHE emission models

[H.E.S.S. Collaboration 2007]

Pulsar	Low energy cuts						Standard cuts					
PSR	N_{on}	P_{χ^2}	P_H	$P_{Z_1^2}$	$P_{Z_2^2}$	P_K	N_{on}	P_{χ^2}	P_H	$P_{Z_1^2}$	$P_{Z_2^2}$	P_K
B0531+21	8095	0.99	0.84	0.81	0.94	0.97	10622	0.51	0.56	0.63	0.25	0.66
B0833–45	7480	0.52	0.87	0.85	0.37	0.82	1156	0.79	0.92	0.90	0.98	0.88
B1259–63	16176	0.78	0.92	0.90	0.65	0.71	4535	0.29	0.25	0.18	0.46	0.23
J1420–6048	2228	0.0093	0.0031	0.072	0.007	0.0049	968	0.67	0.60	0.53	0.53	0.62
B1509–58	12481	0.37	0.81	0.77	0.70	0.89	4308	0.048	0.055	0.027	0.11	0.04
J1524–5625	2498	0.78	0.43	0.35	0.43	0.39	745	0.87	0.79	0.75	0.96	0.97
B1706–44*	–	–	–	–	–	–	391	0.02	0.82	0.78	0.85	–
J1826–1334	14497	0.71	0.46	0.38	0.57	0.62	4016	0.46	0.42	0.34	0.34	0.42
J1747–2958**	23482	0.65	0.98	0.97	0.82	0.95	6340	0.62	0.62	0.92	0.99	0.96
J1801–2451**	3230	0.035	0.22	0.15	0.42	0.21	723	0.50	0.15	0.094	0.24	0.32



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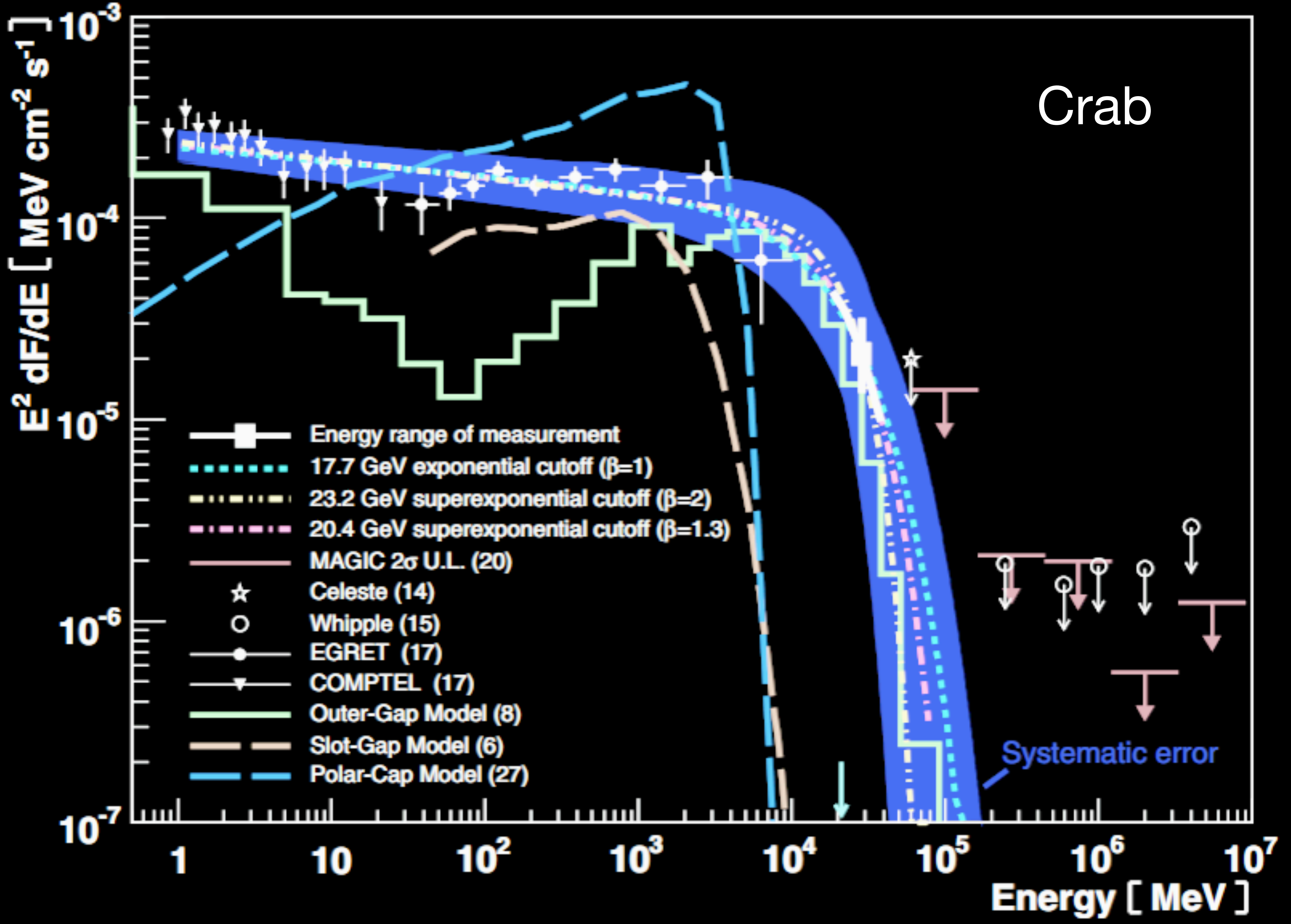
- MAGIC detection of Crab pulsar > 25 GeV
- Exp-cutoff E pushed to 17.7 GeV
- Polar Cap model disfavoured but uncertainties on energy scale forbade strong conclusions

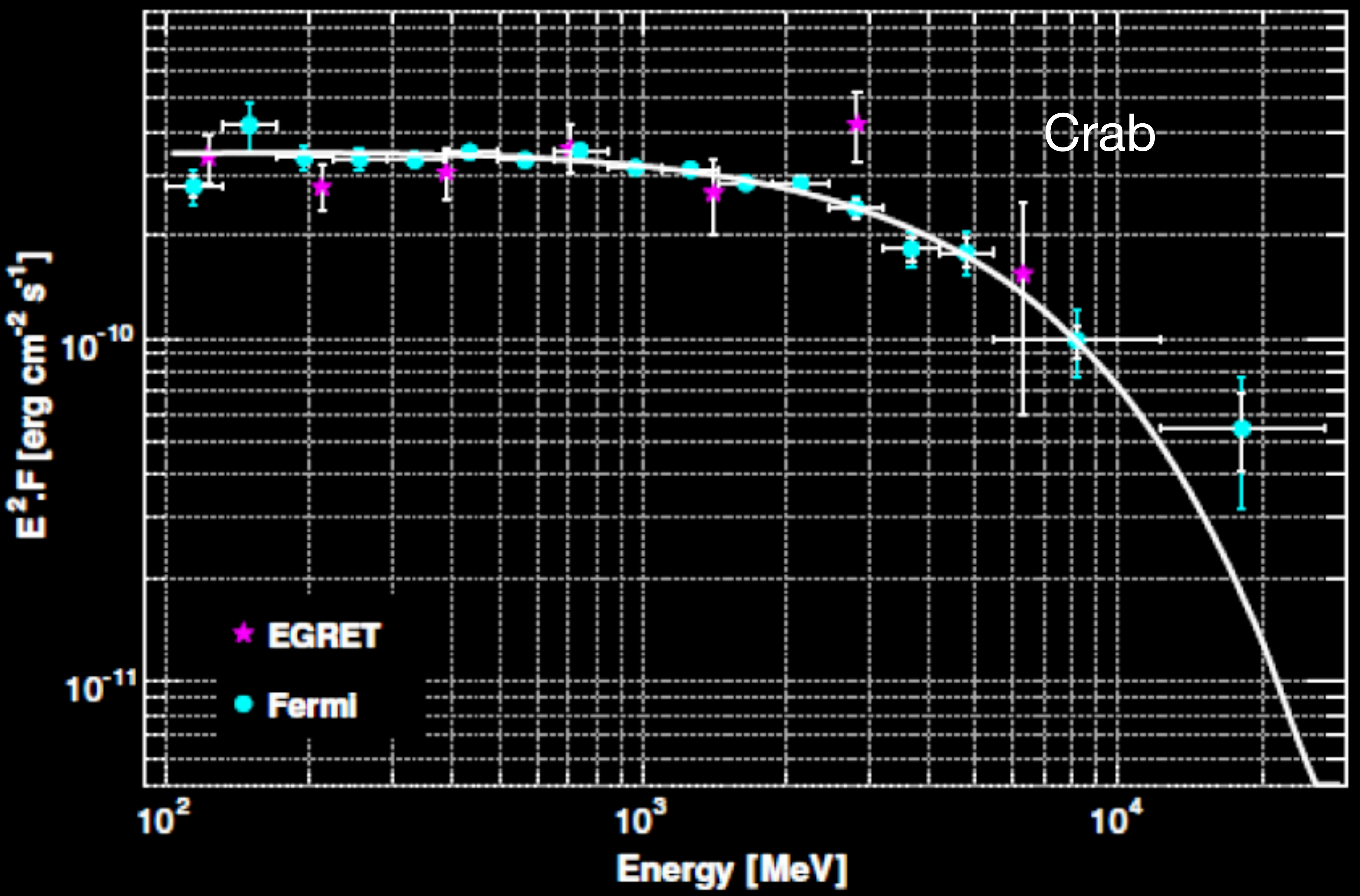


Fermi-LAT Era >2008

Launch: June 11th 2008

- As soon as September 2009:
- Super exponential cutoff excluded !
- —> Polar Cap model for HE excluded
- Brightest pulsars (Crab, Vela) :
  —> Sub-exponential cut-off
- Cut-offs in a narrow band E_cut ~1-5 GeV
  —> Curvature Radiation predicts E_cut in this range for easonable values for ρ_C and $E_{||}$

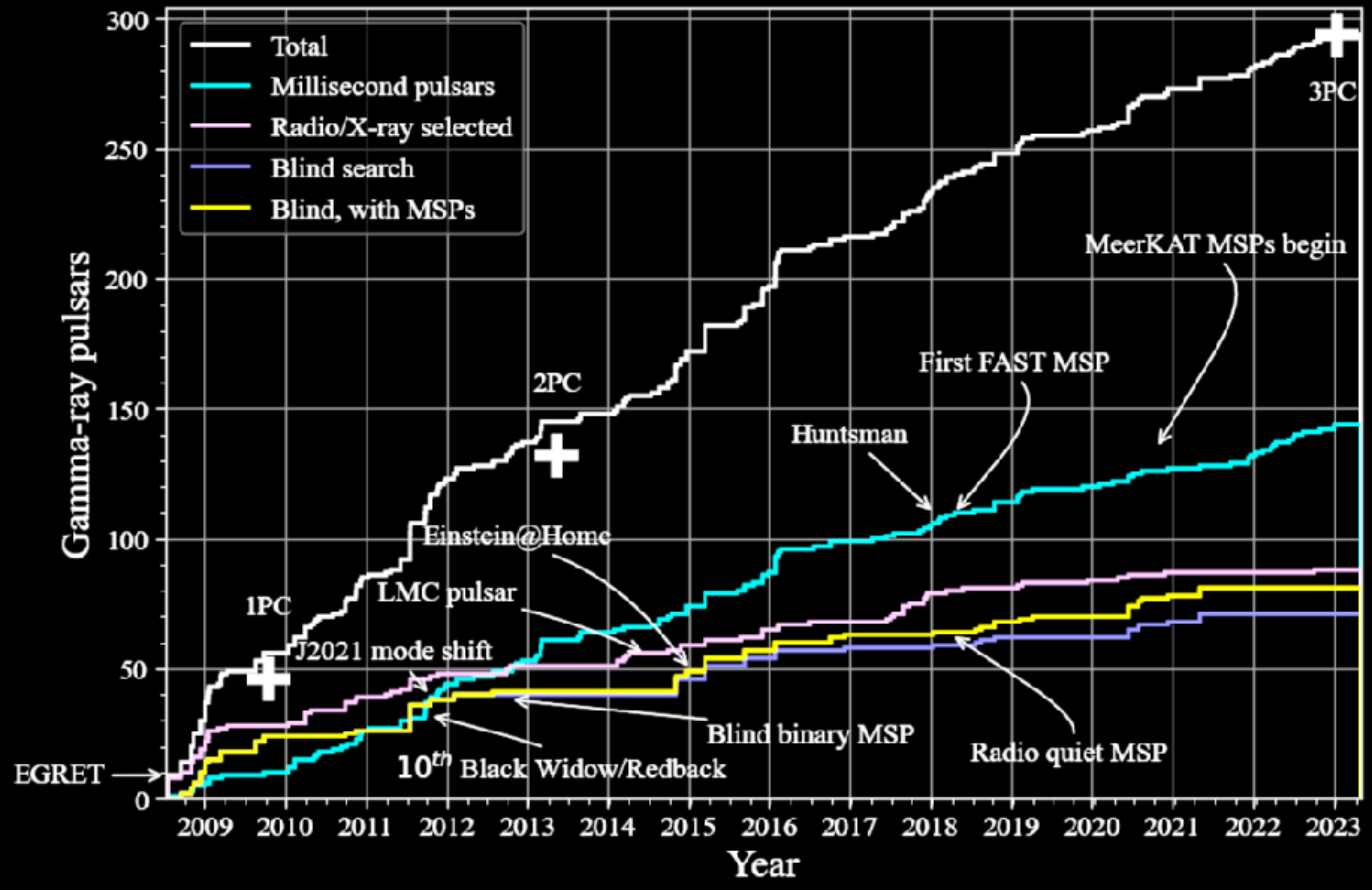
- As such no hope for VHE emission, except:
  - Tails of exponential cut-off in the <50 GeV range
  - New component e.g. IC à la Hirotani & Shibata OG model, but already severely constrained by IACTs (HESS, VERITAS, MAGIC)

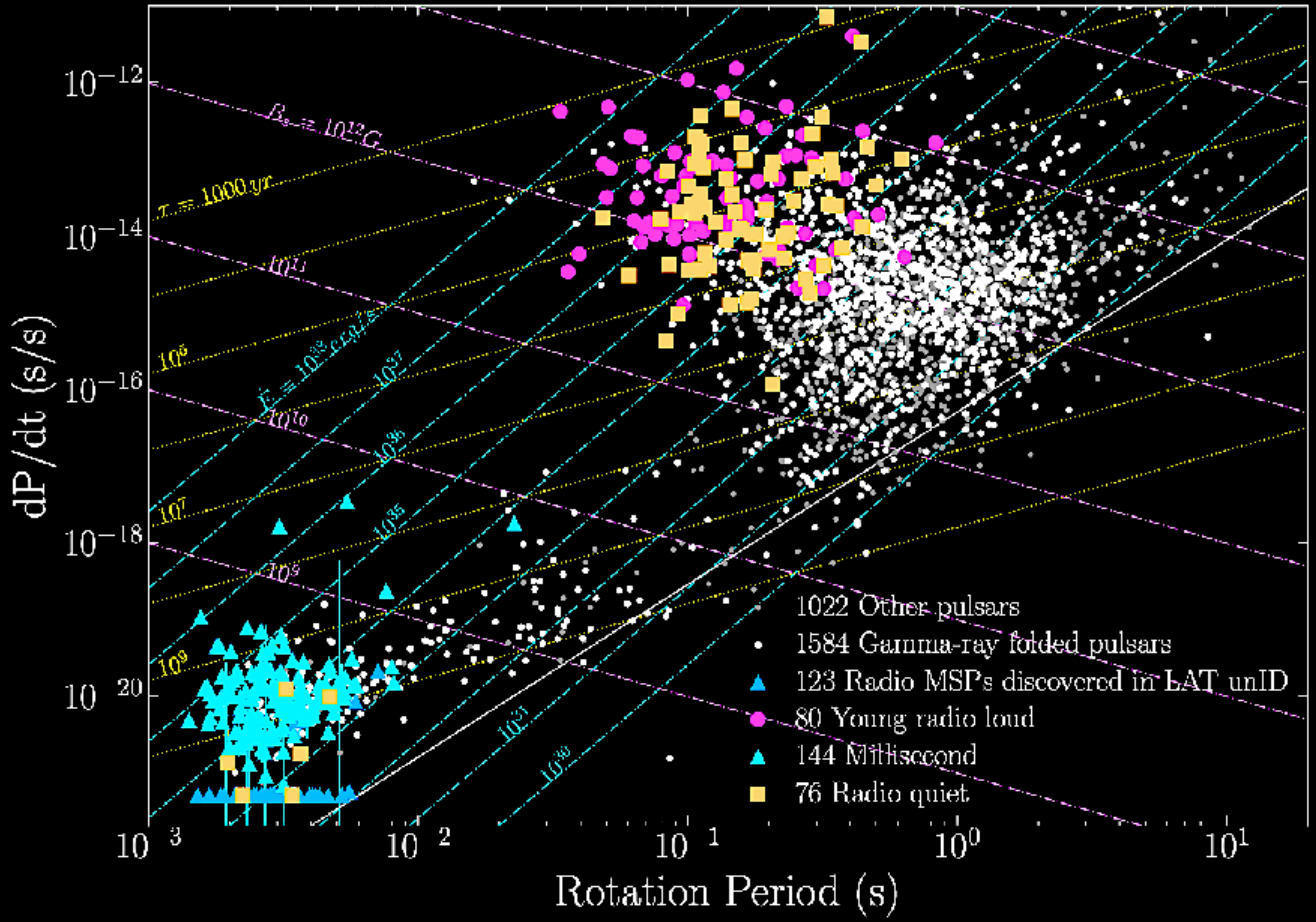


Fermi-LAT 3PC

[Smith et al. 2023]

~ 340 Pulsars , 10% of all known radio pulsars





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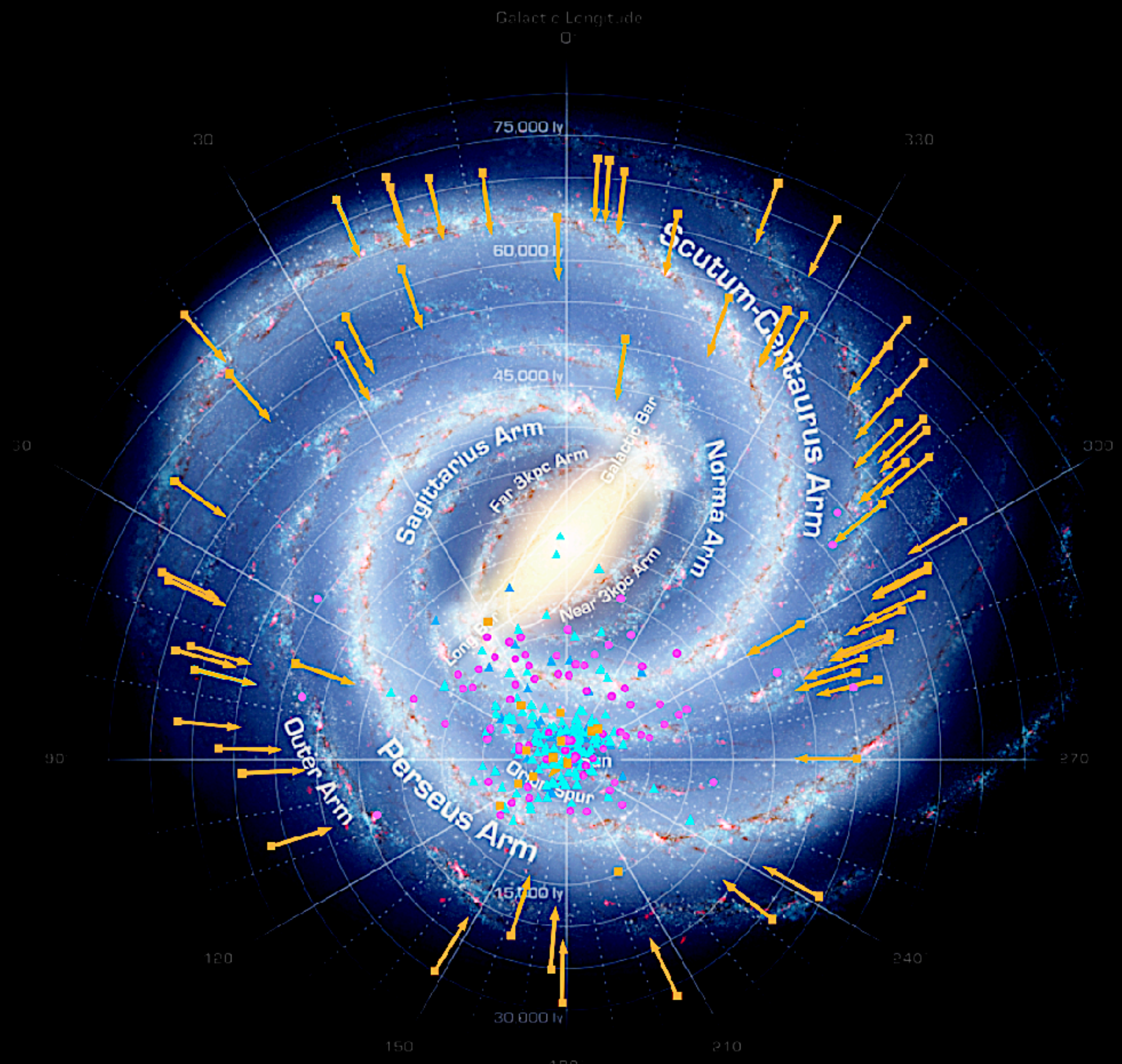
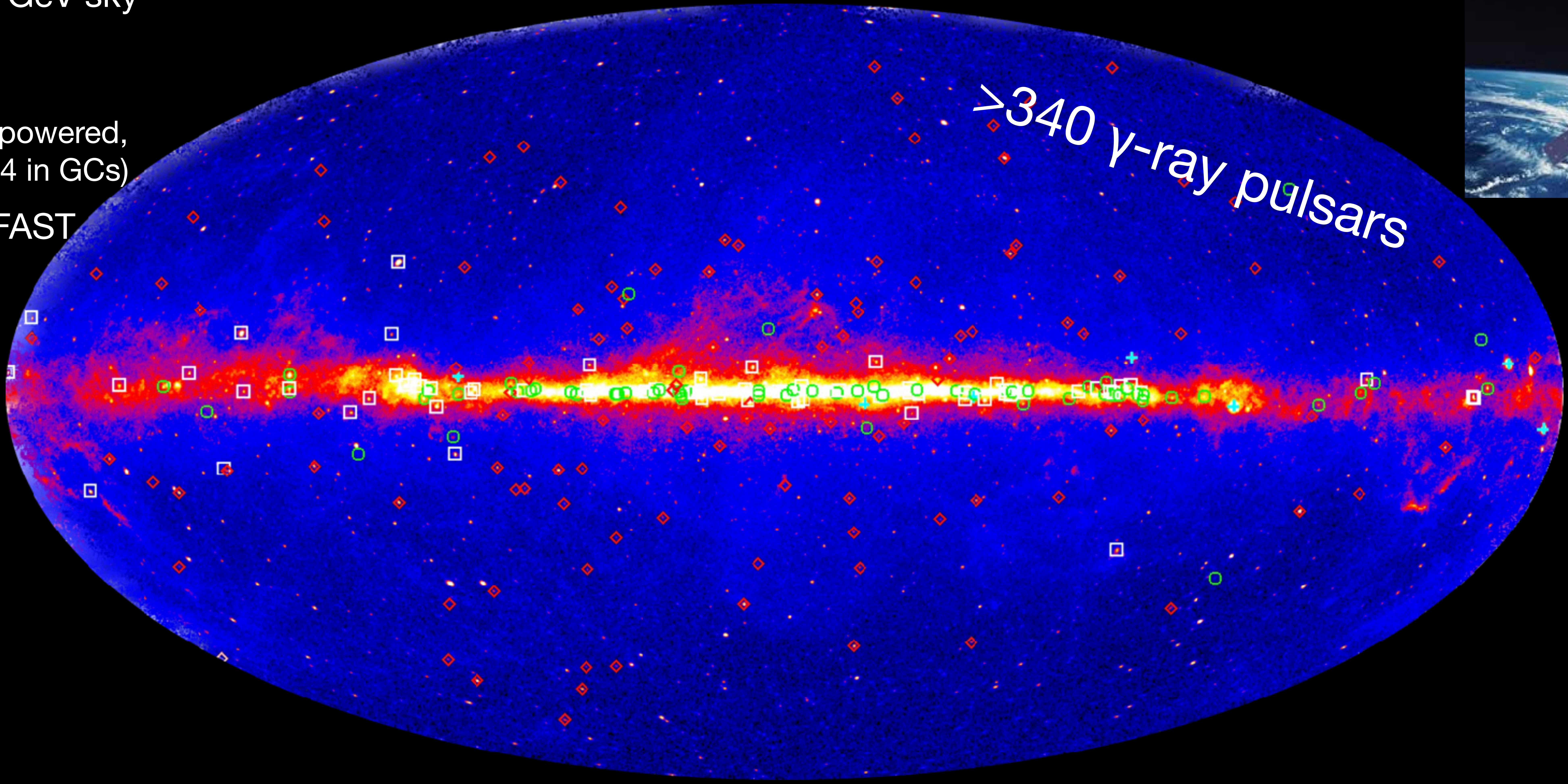


Fermi-LAT > 1 GeV sky

Radio :
~3500 rotation powered,
~681 MSPs (354 in GCs)

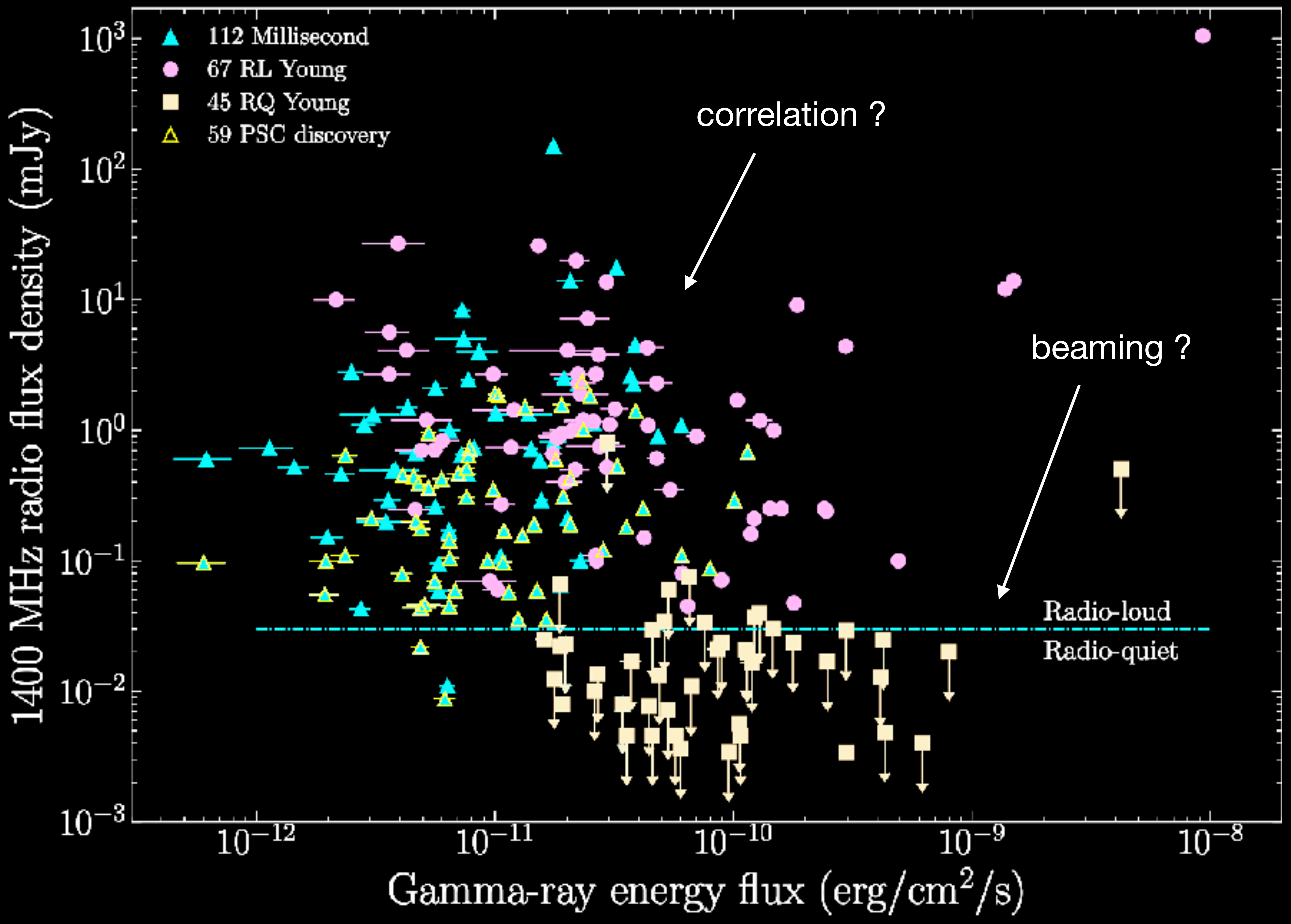
++100s with FAST

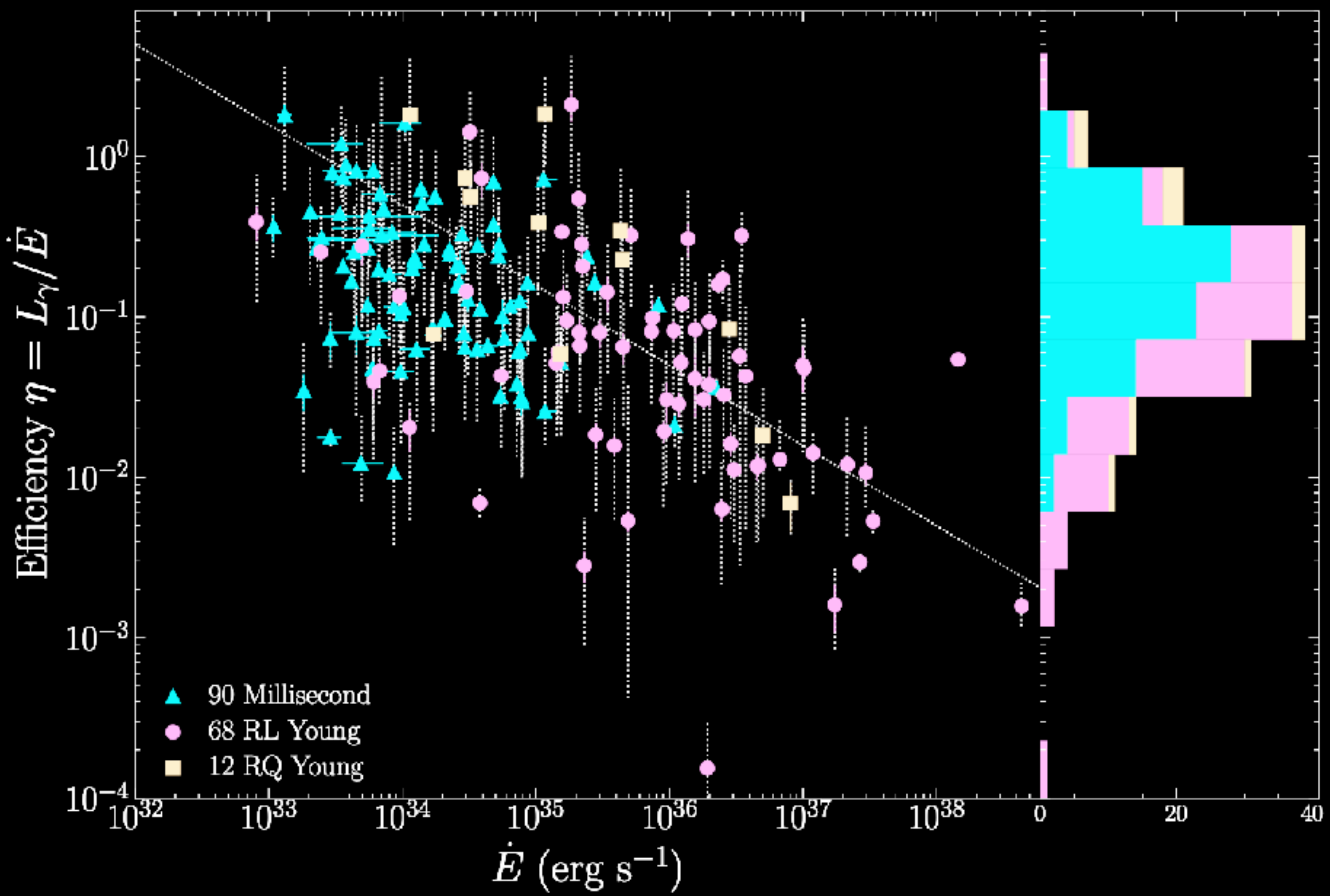


- 3PC 384 pulsars listed, 255 with 4FGL-DR3 counterparts
- 136 Young or Middle-aged
- 80 Radio-loud γ-ray (29%)
- 76 Radio-quiet γ-ray (25%)
- 123 γ-ray MSPs : 25 Isolated, 94 Binary (47%)
- 45 Black Widows (32) and Redbacks (13)

Fermi-LAT 3PC

Some selected takeaways





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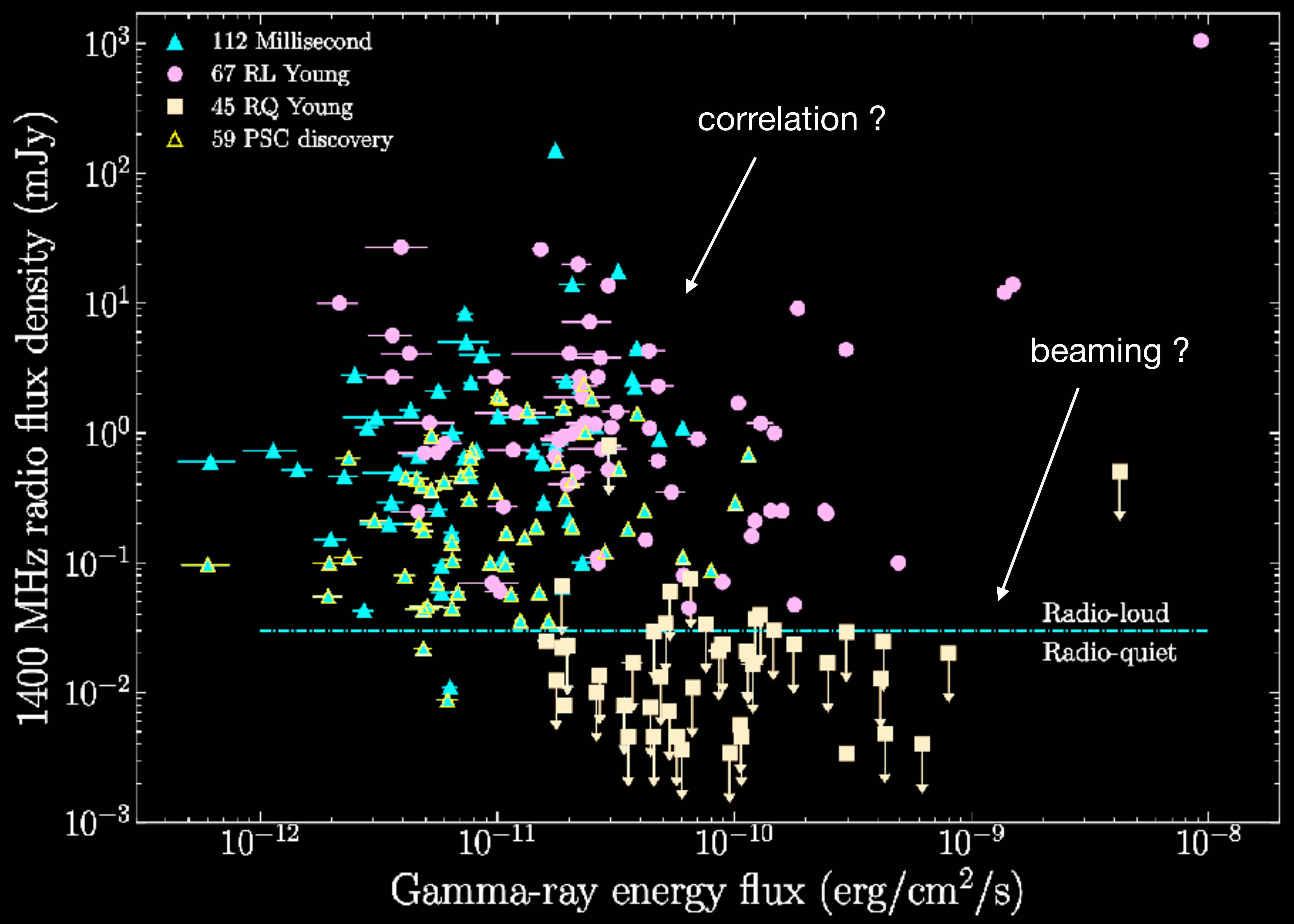
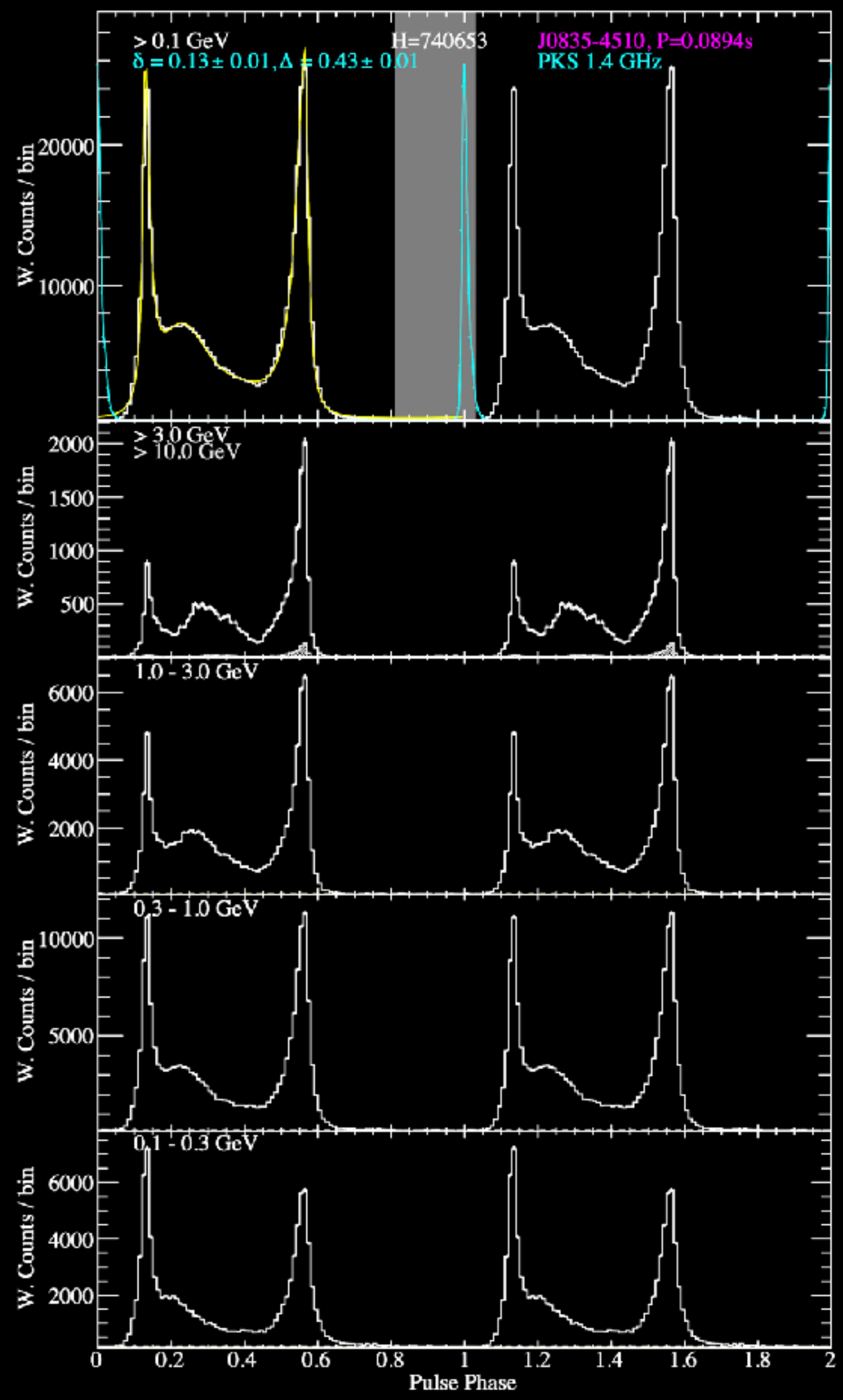
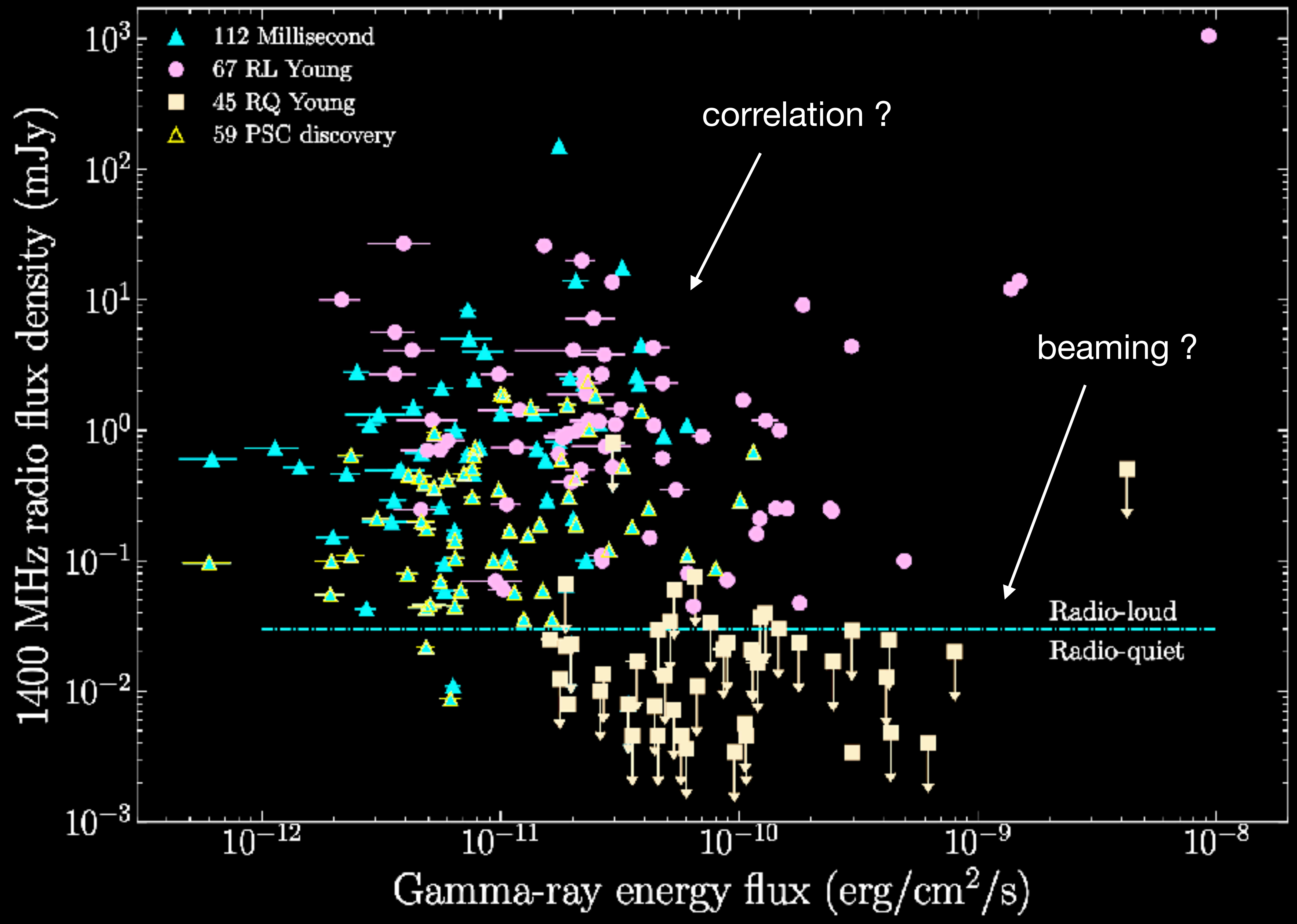


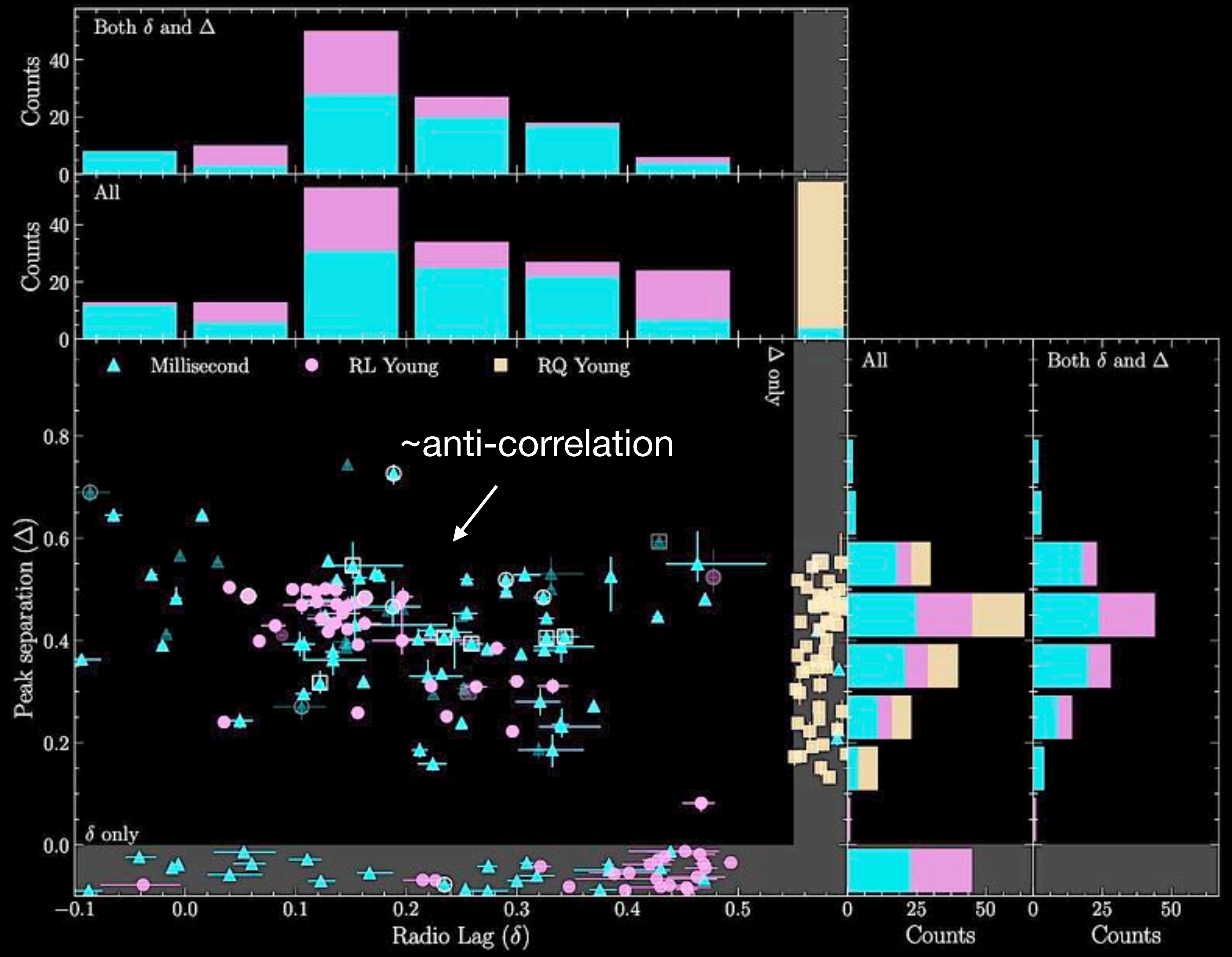


Fermi-LAT 3PC

Some selected takeaways

- A majority of gamma-ray pulsars have two principal peaks separated by $\Delta \approx 0.4 \pm 0.15$
- RL Pulsars , the first peak generally trails the radio pulse by $\delta \approx 0.2 \pm 0.2$
- No strong evolution with energy $\Delta \lesssim 0.1$
- Data point to vision of emission zones along caustic viewing lines that change little with electron energy





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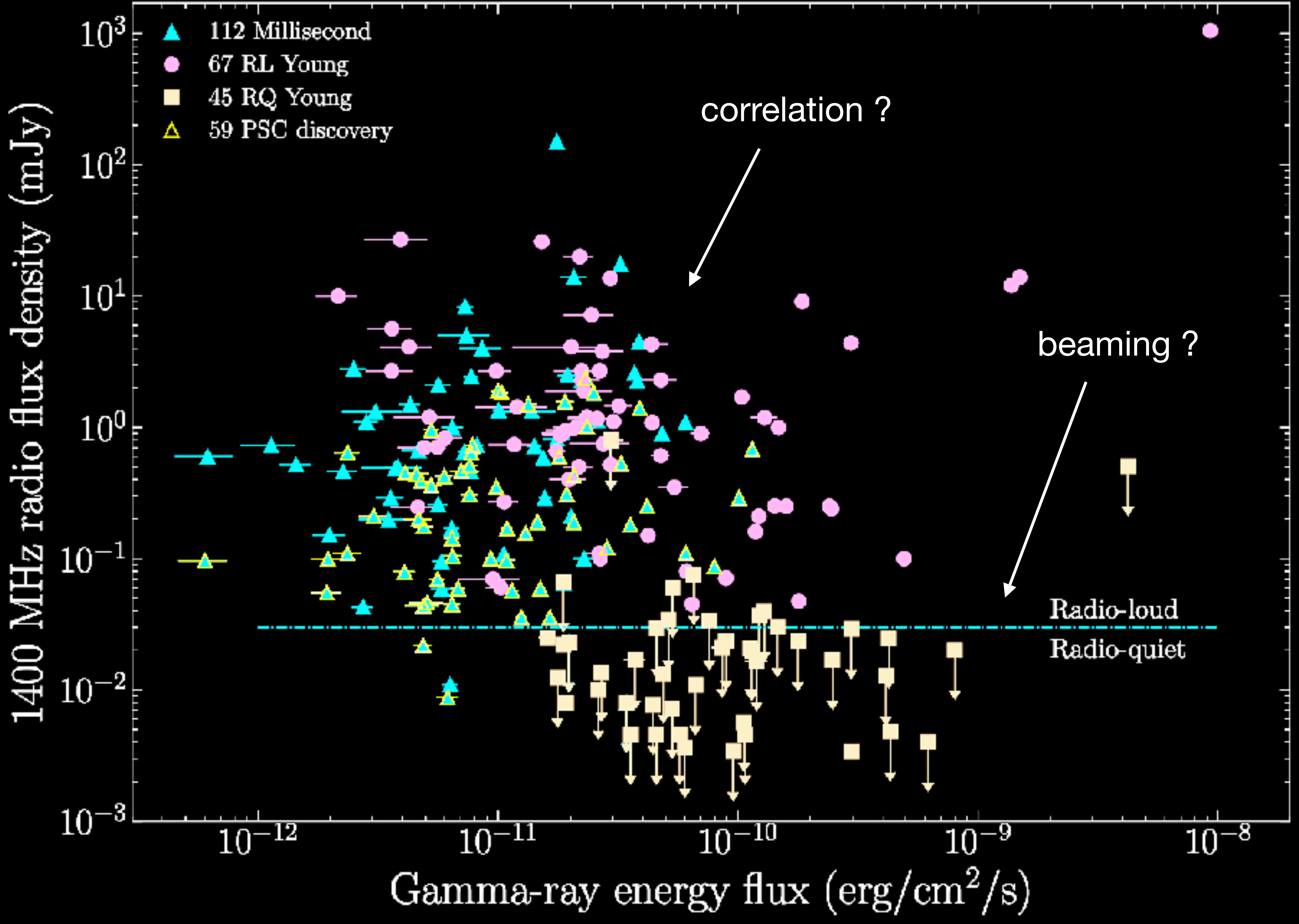
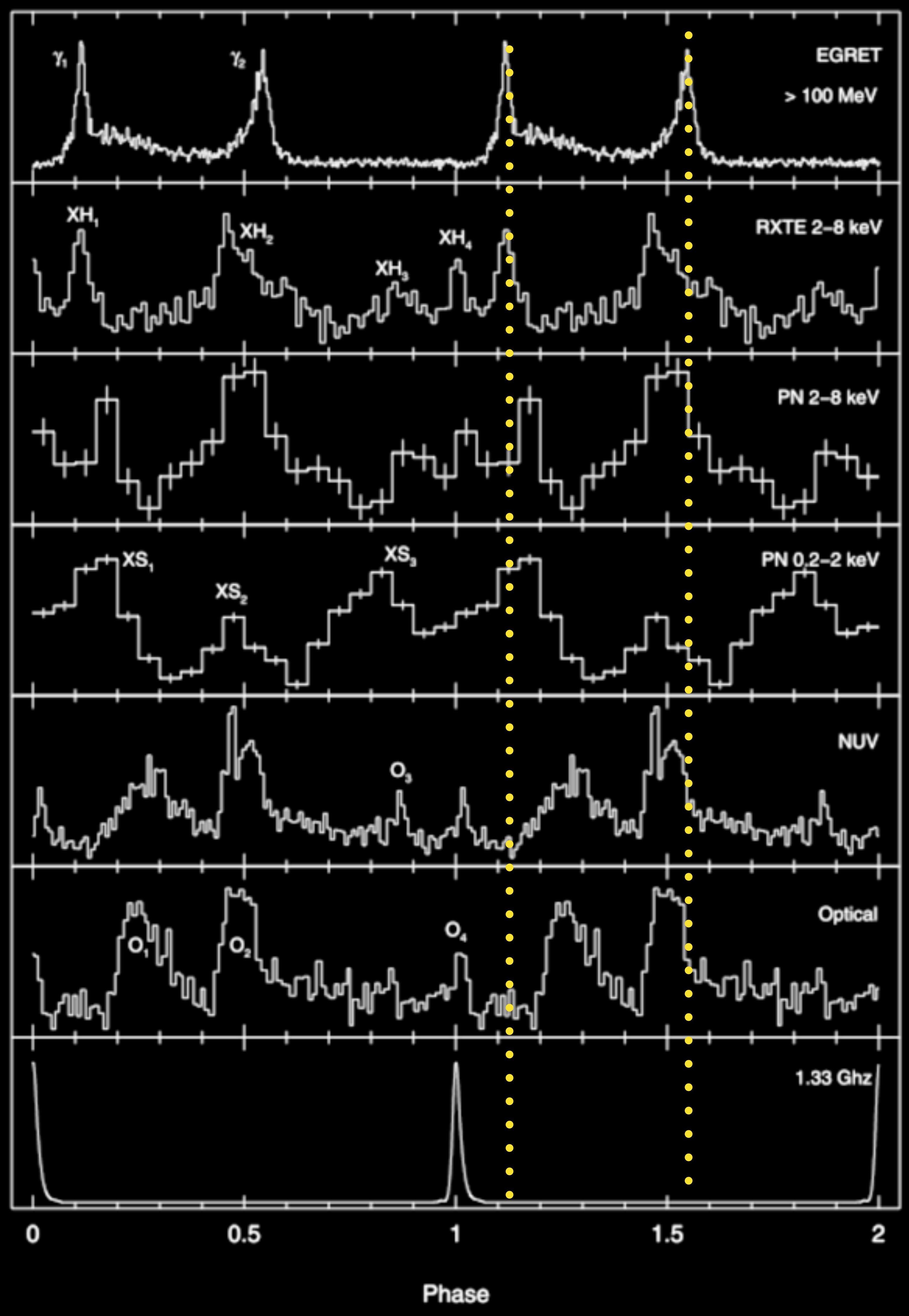


Vela from radio to γ rays



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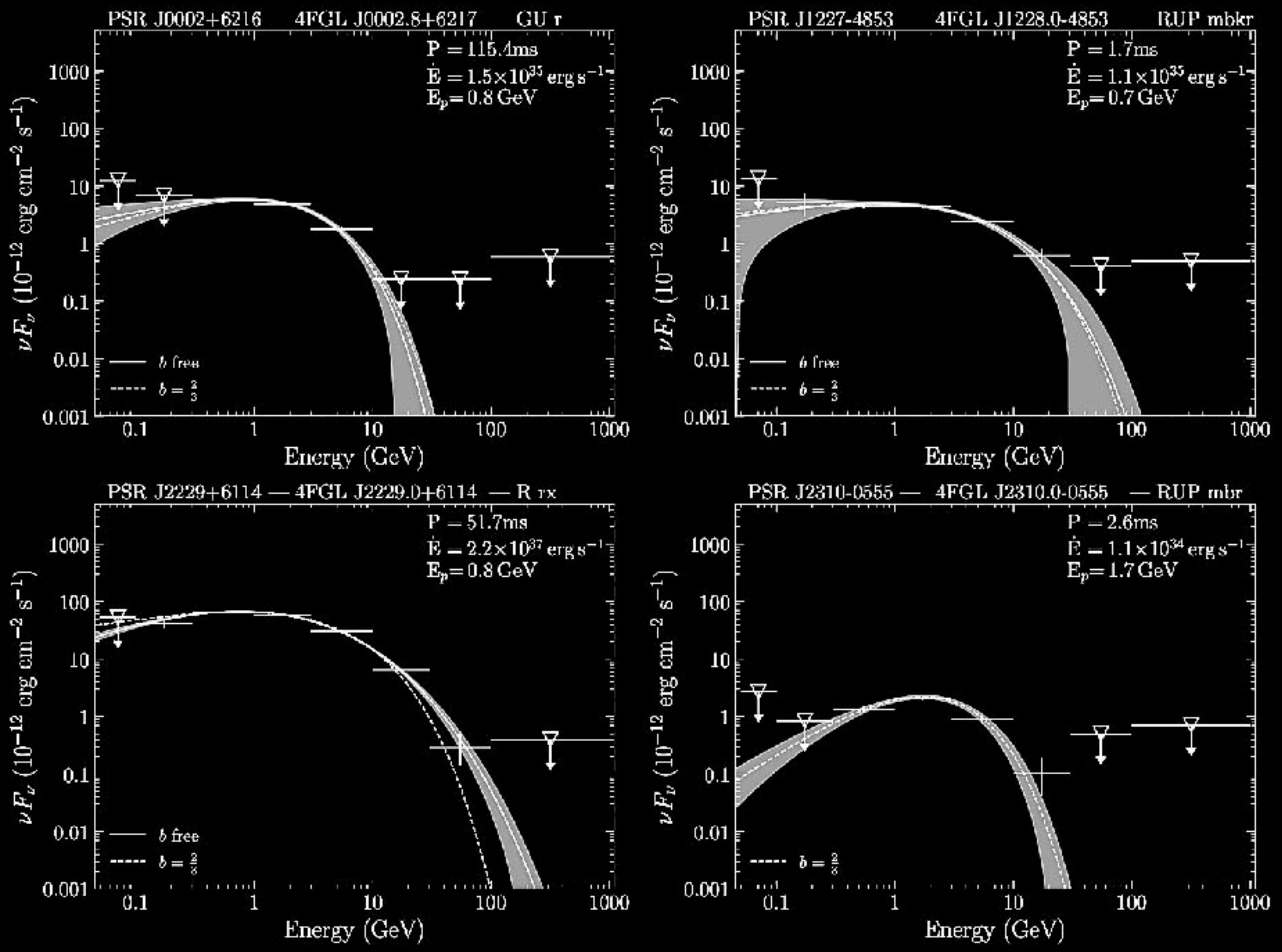
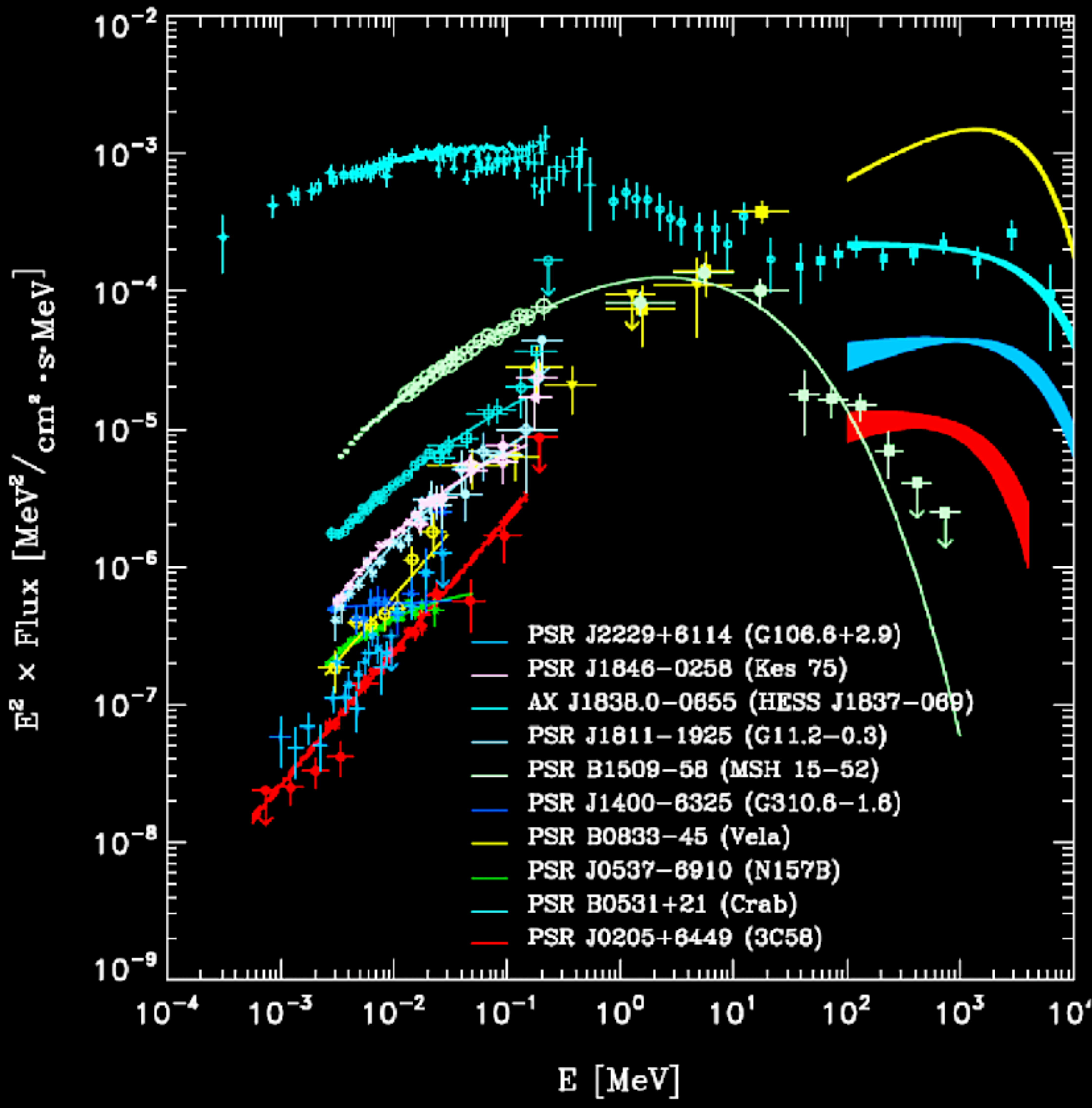


[Kuiper & Hermsen 2015]



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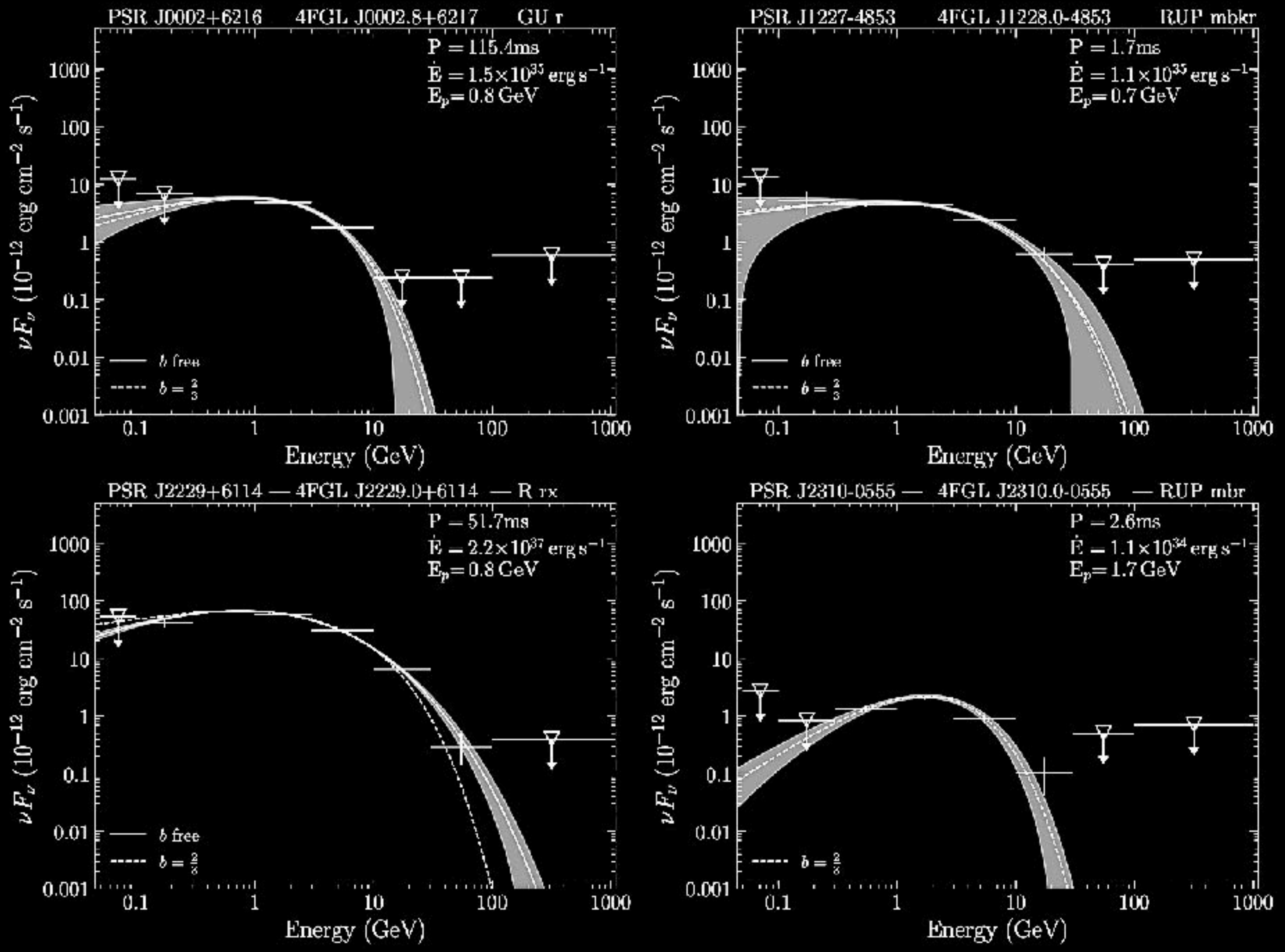
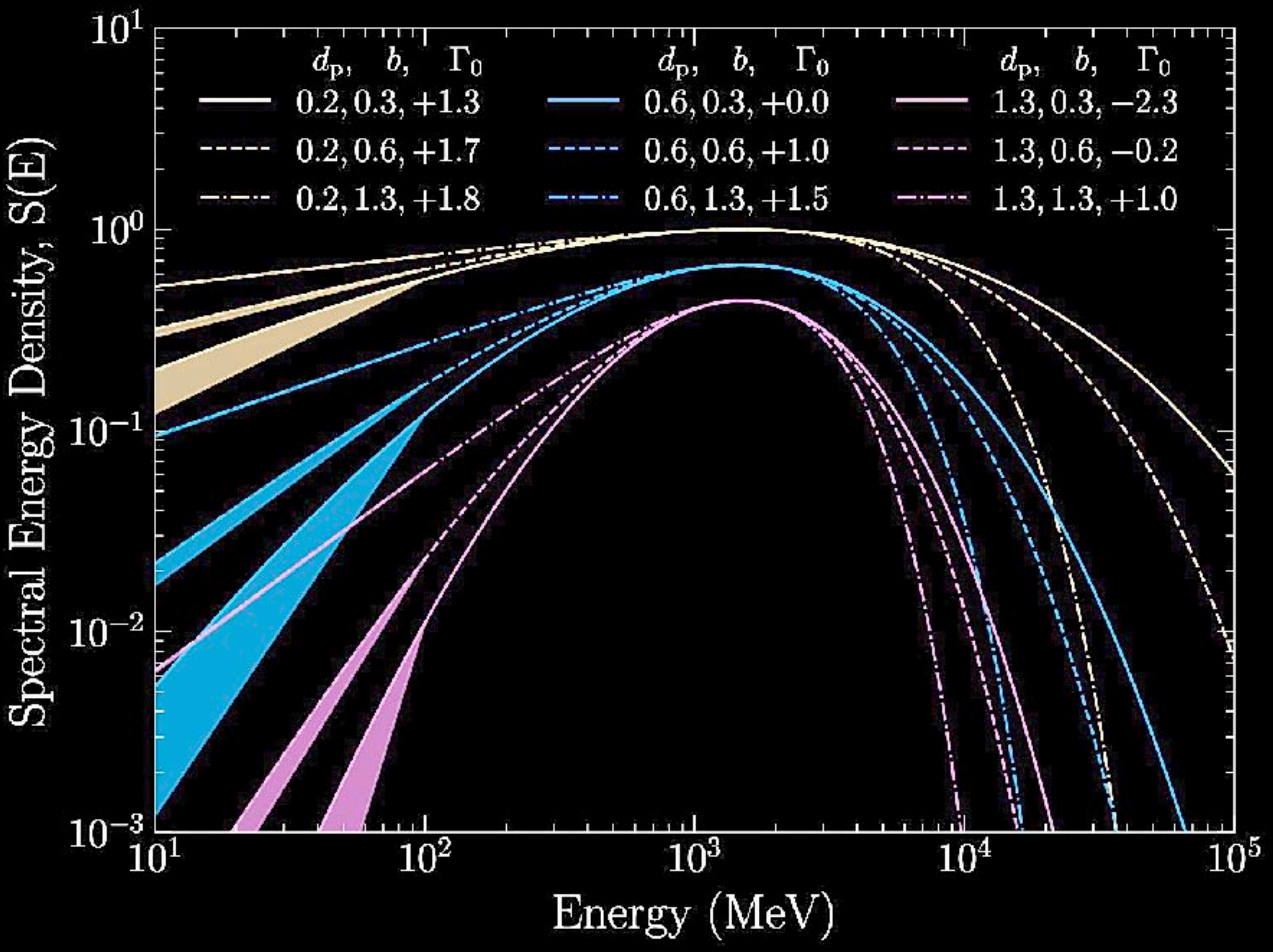
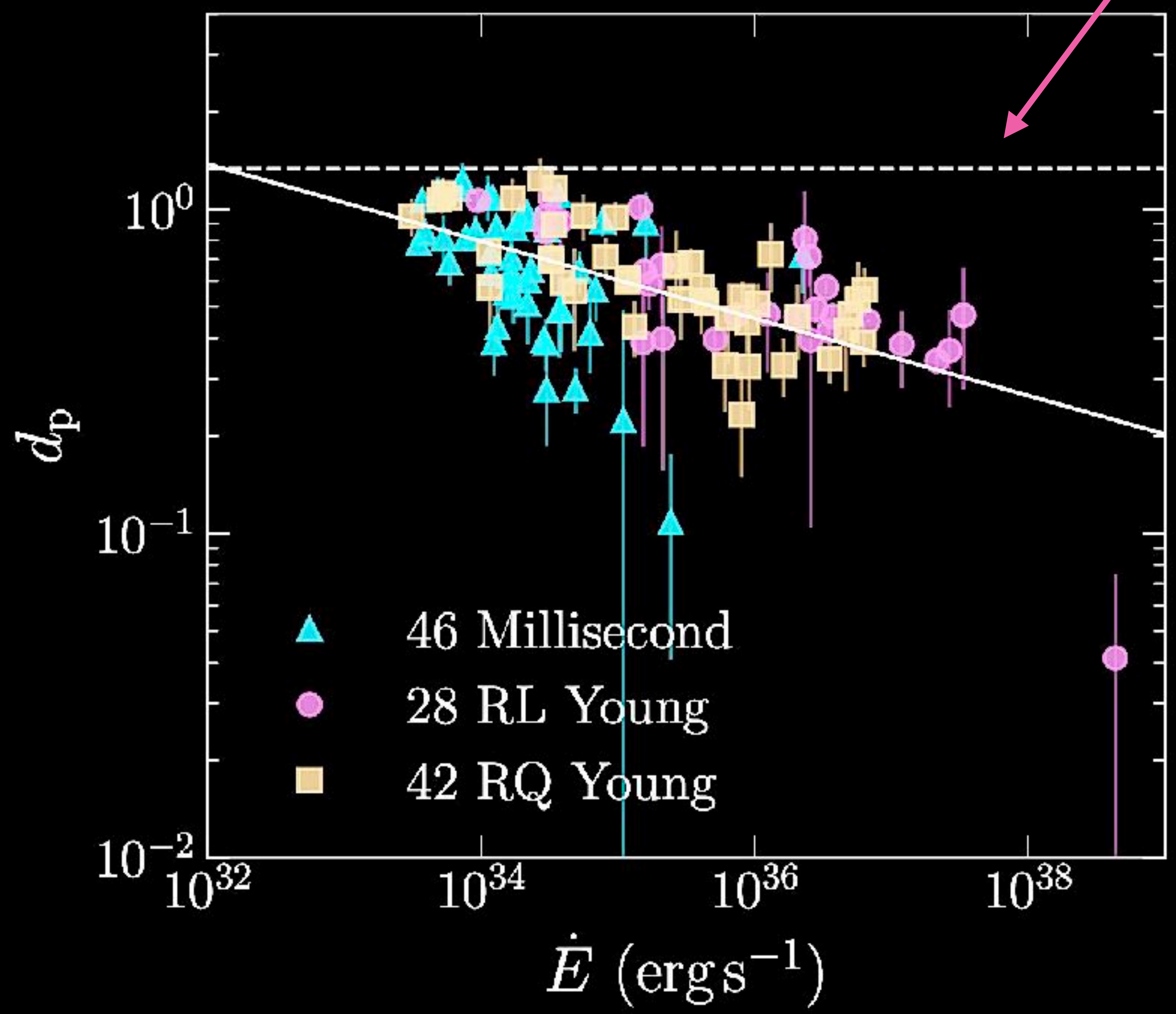


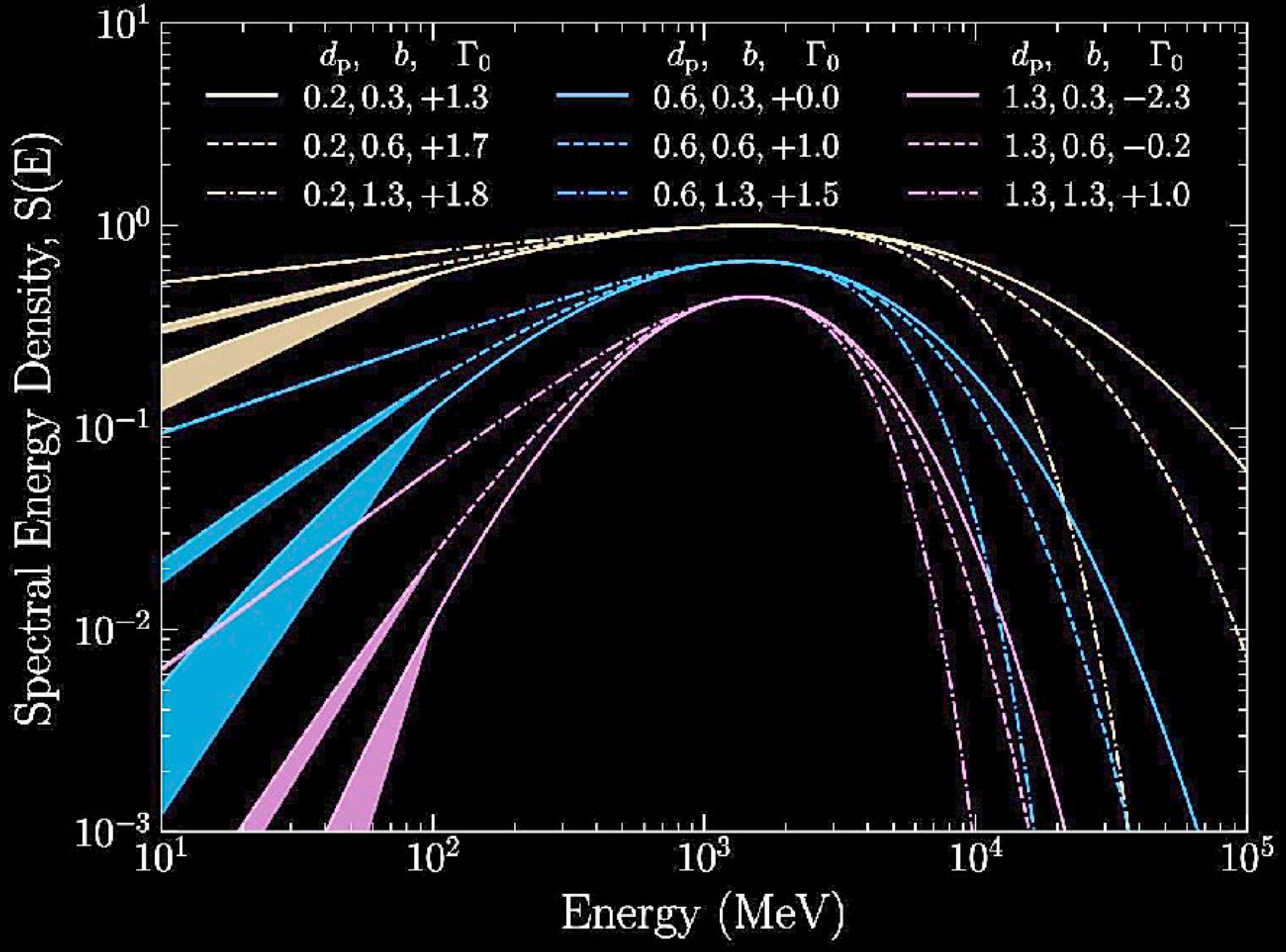


Fermi-LAT 3PC

Some selected takeaways

- Curvature (dp) depends strongly on Edot
- Variation of ~3 for main population
- Saturate at ~ 4/3, i.e. monoenergetic syn/cr spectrum
- Tight clustering of dp about the Edot scaling relation: accelerators must have broadly similar properties





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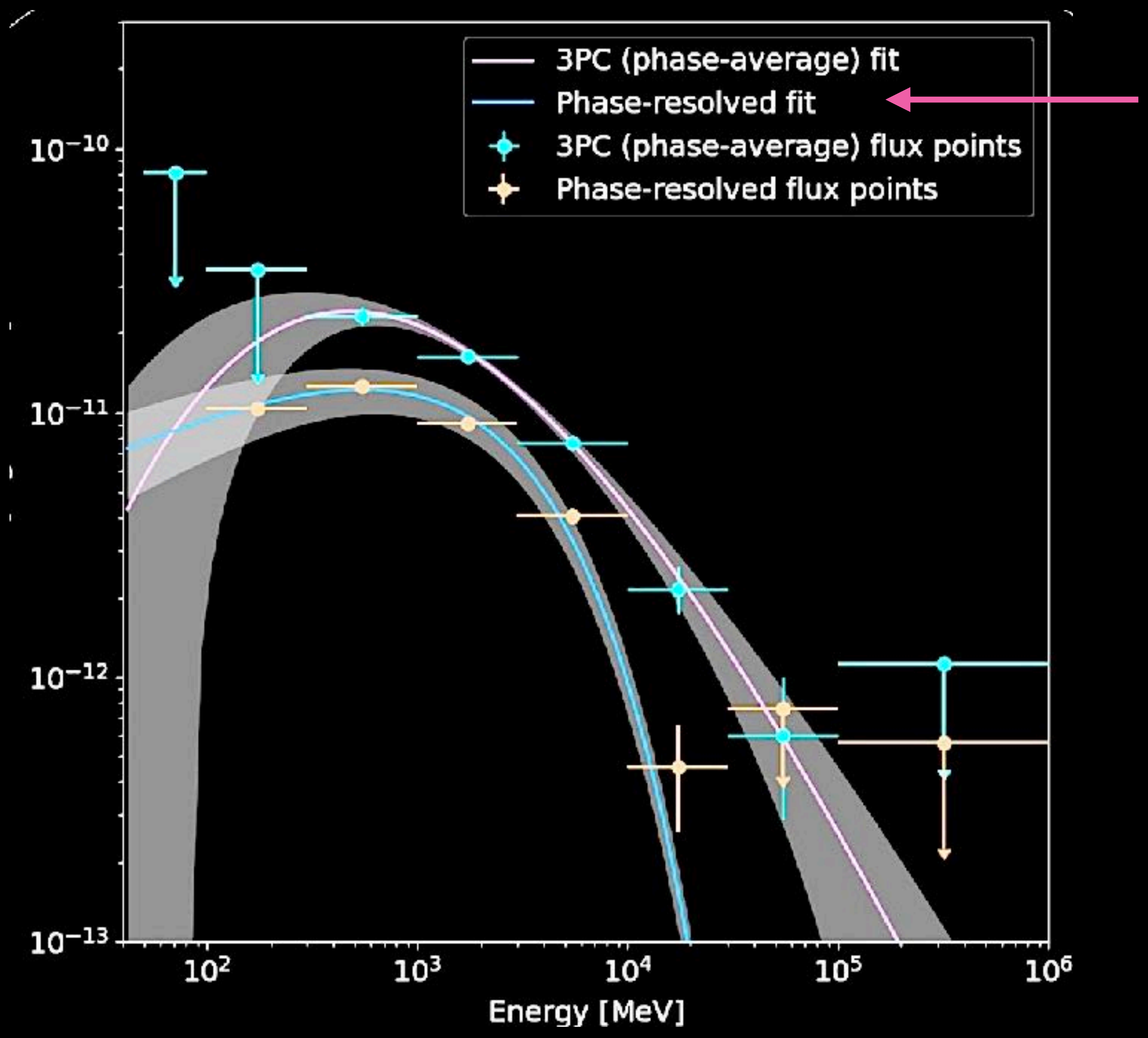
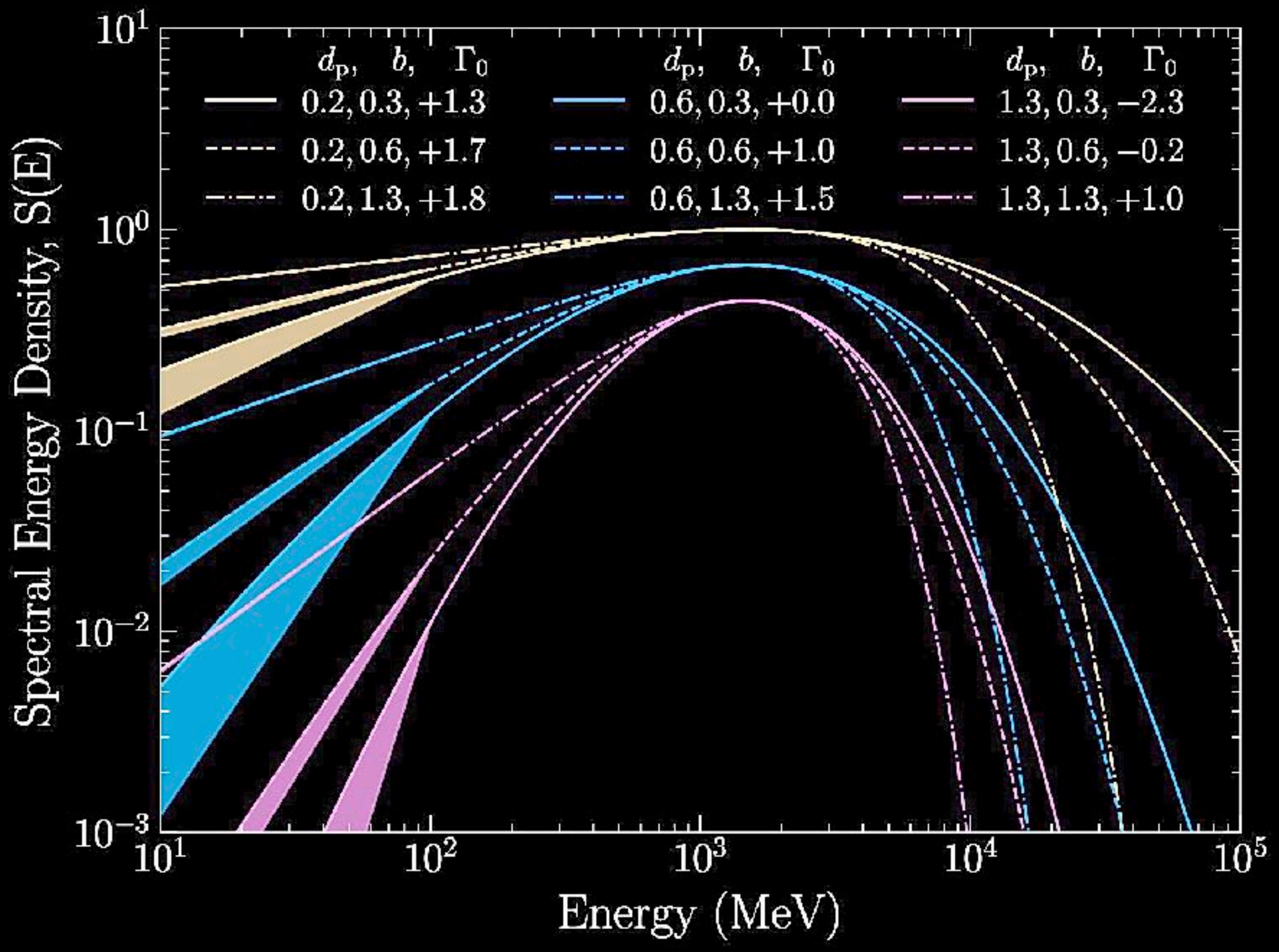
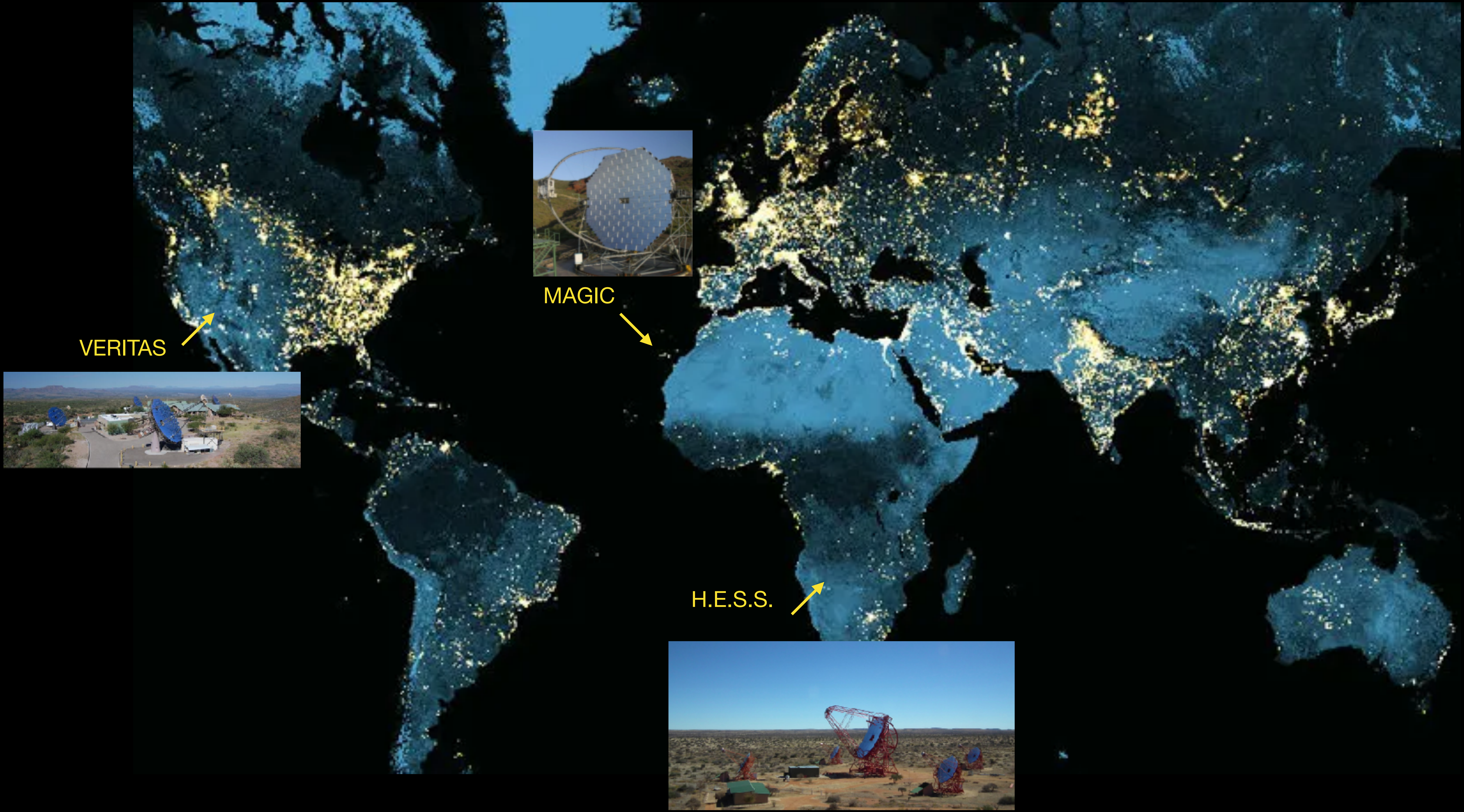
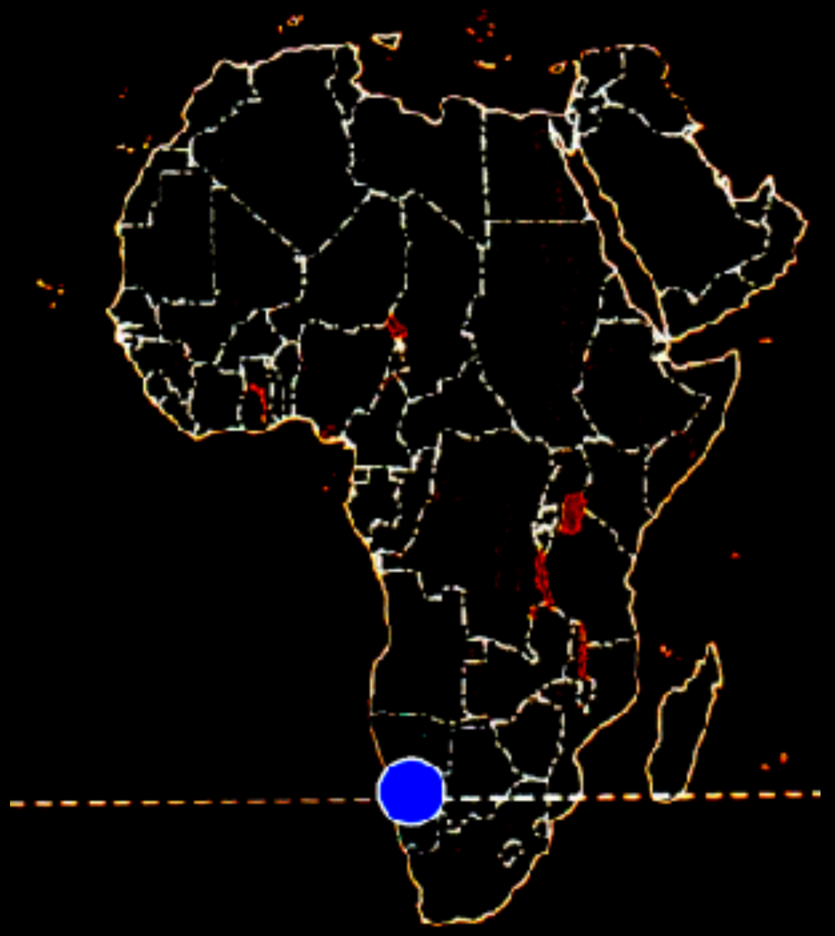


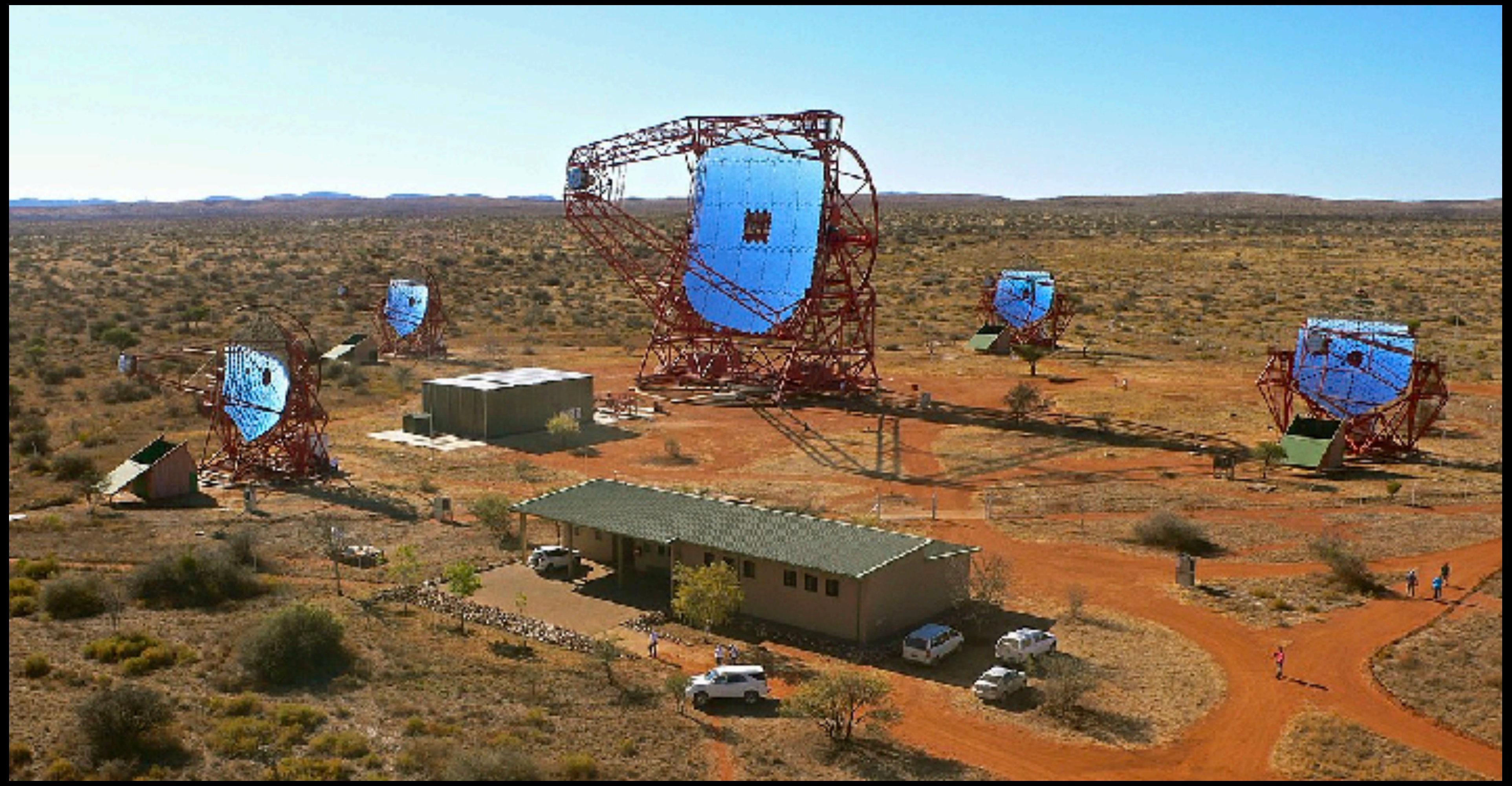



MAGIC
VERITAS
H.E.S.S.

H.E.S.S. Telescopes

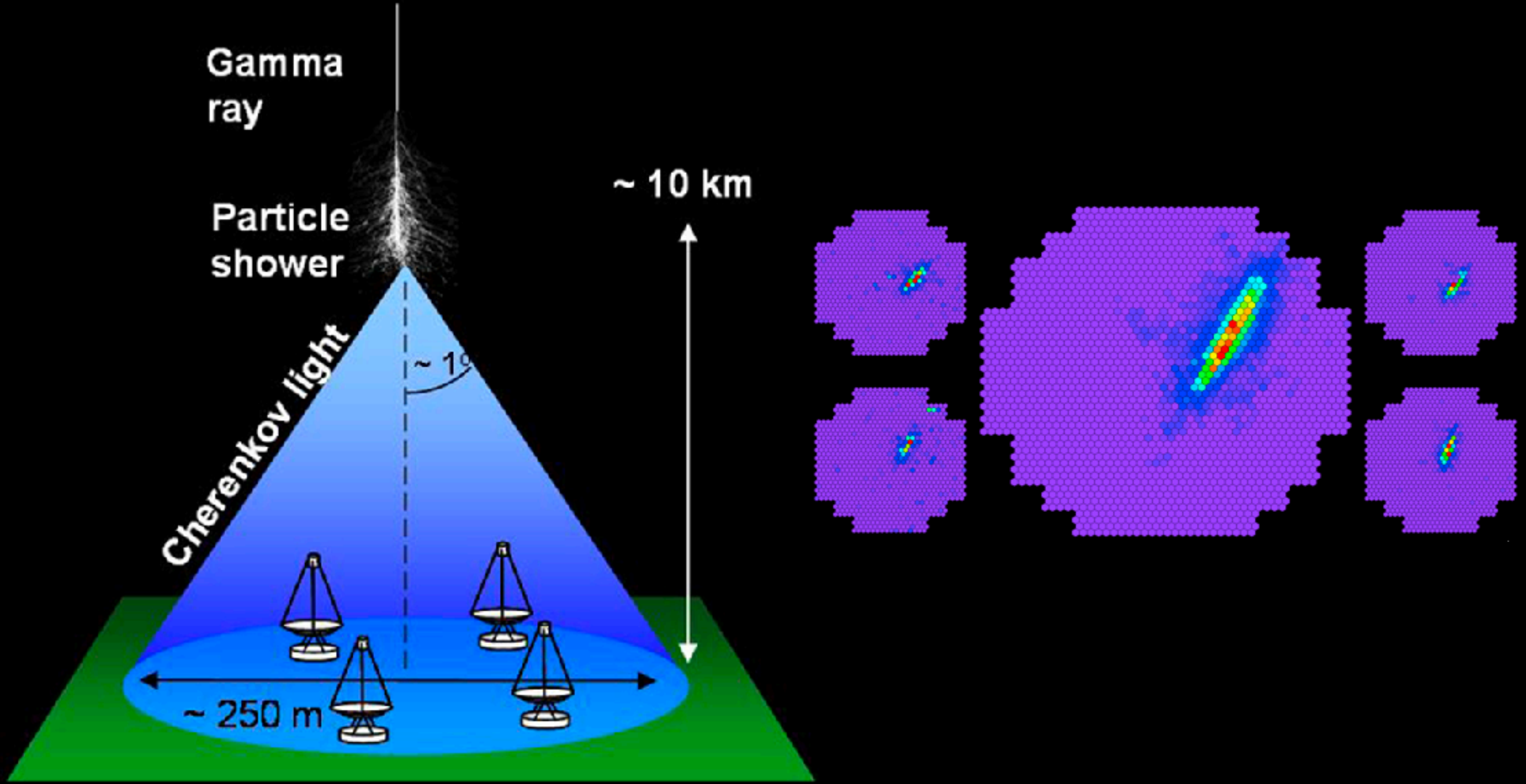
Key location : Namibia





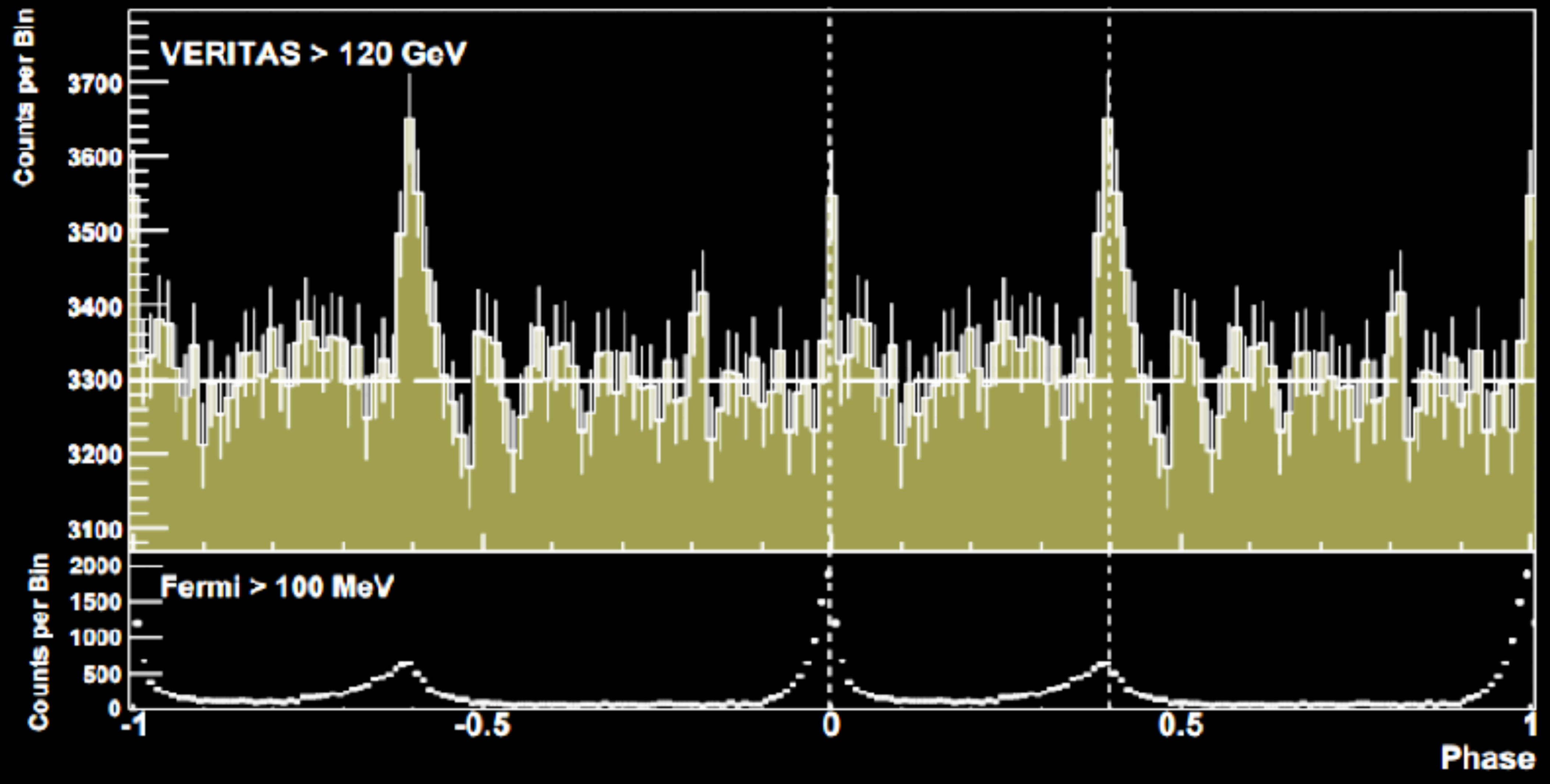
- Array of 5 Imaging Atmospheric Cherenkov Telescopes (IACTs), CT1-5
    - 4 x 12 m diametre, 960-pixel camera, CT1-4
    - 1 x 28 m-equivalent dish, 2048 pixels, CT5

- Full array energy range ~30 GeV — 100 TeV
    - CT1-4 in operation since 2002
    - CT5-only : monoscopic mode, since 2012
    - Threshold energy < 20 GeV for pulsars



The first TeV pulsar : Crab

2011: Breakthrough by VERITAS
Detection [120-400] GeV



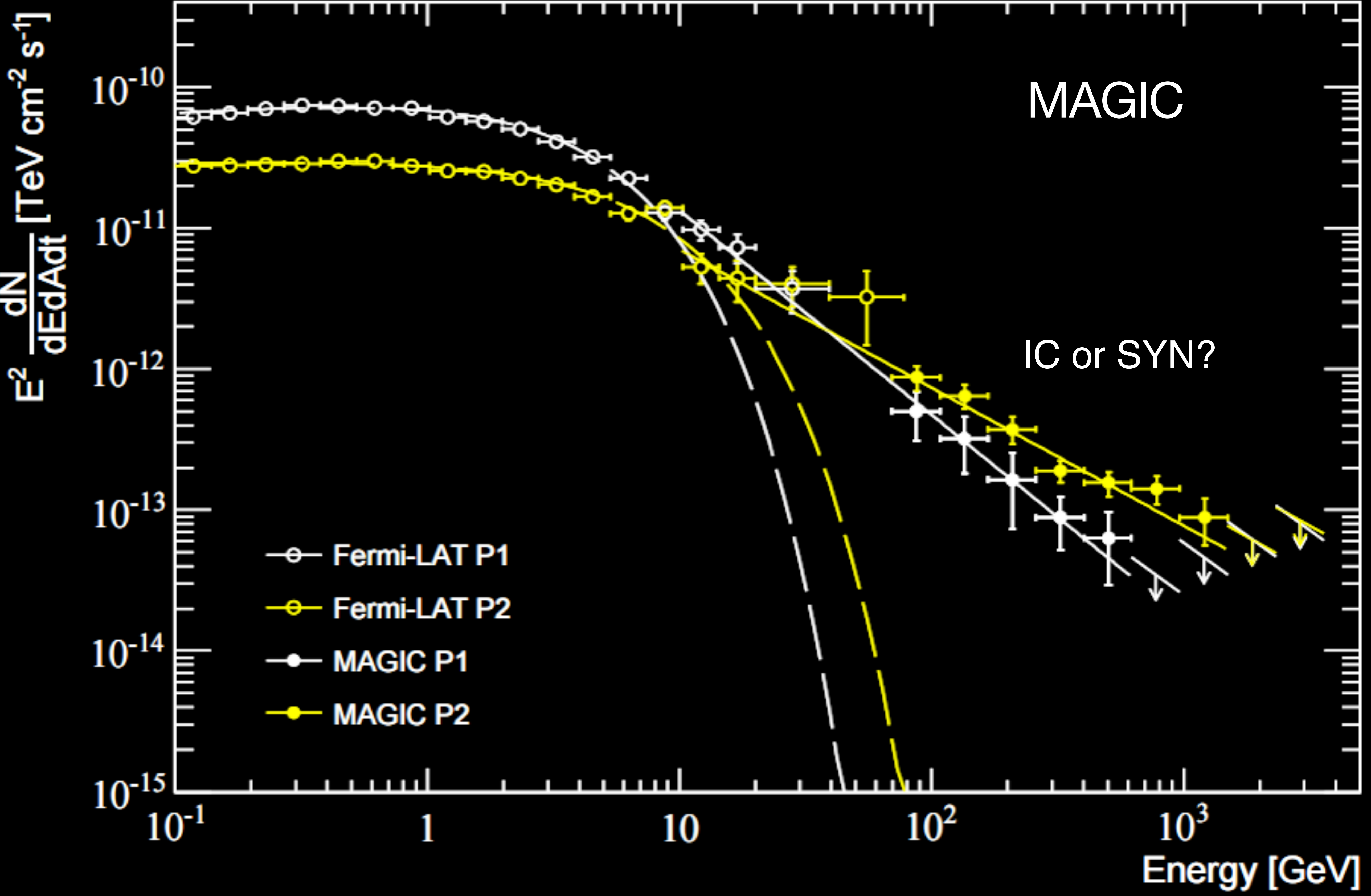
- Implications:
  - Curvature radiation (CR) excluded > tens of GeV
  - IC emission?

[VERITAS Collaboration et al. 2011]

[Ansoldi et al. 2016]

2016: Breakthrough by MAGIC

Extension to ~1.5TeV



Very Soft spectra

P1 : $\Gamma = -3.5 \pm 0.1$

P2 : $\Gamma = -3.0 \pm 0.1$

Power-law tail of the GeV component

The first TeV pulsar : Crab

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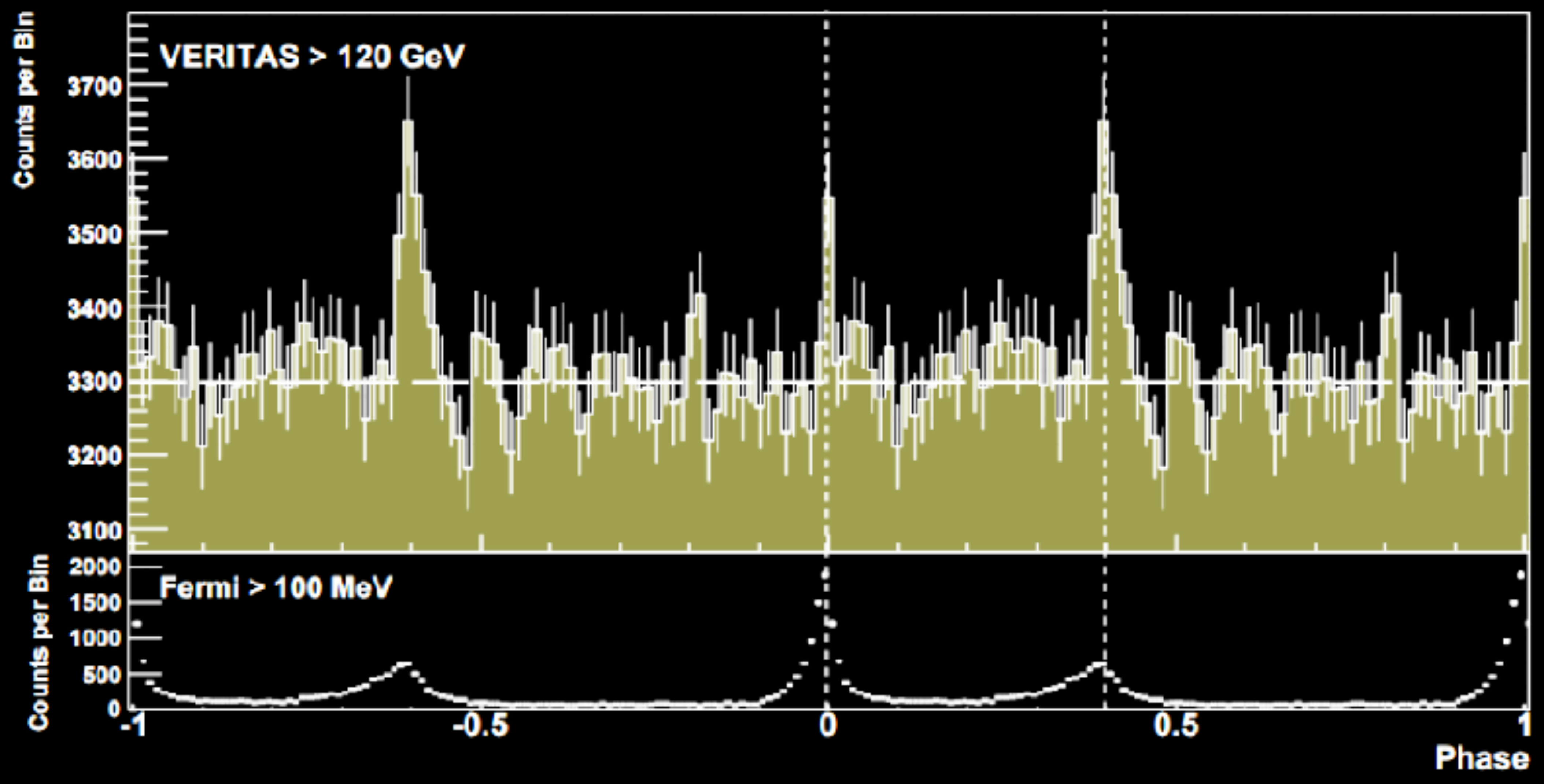

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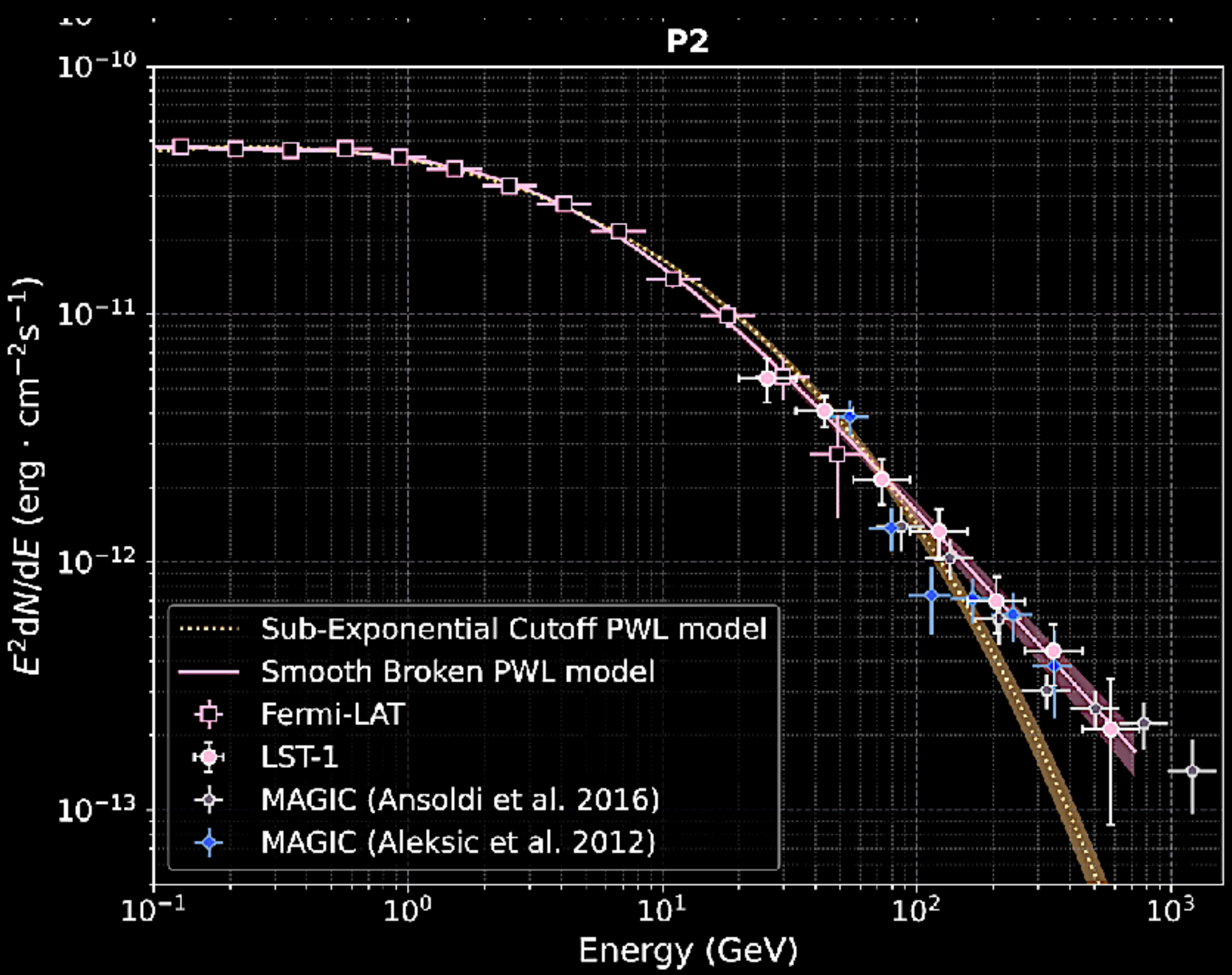
2024: CTA- LST 1



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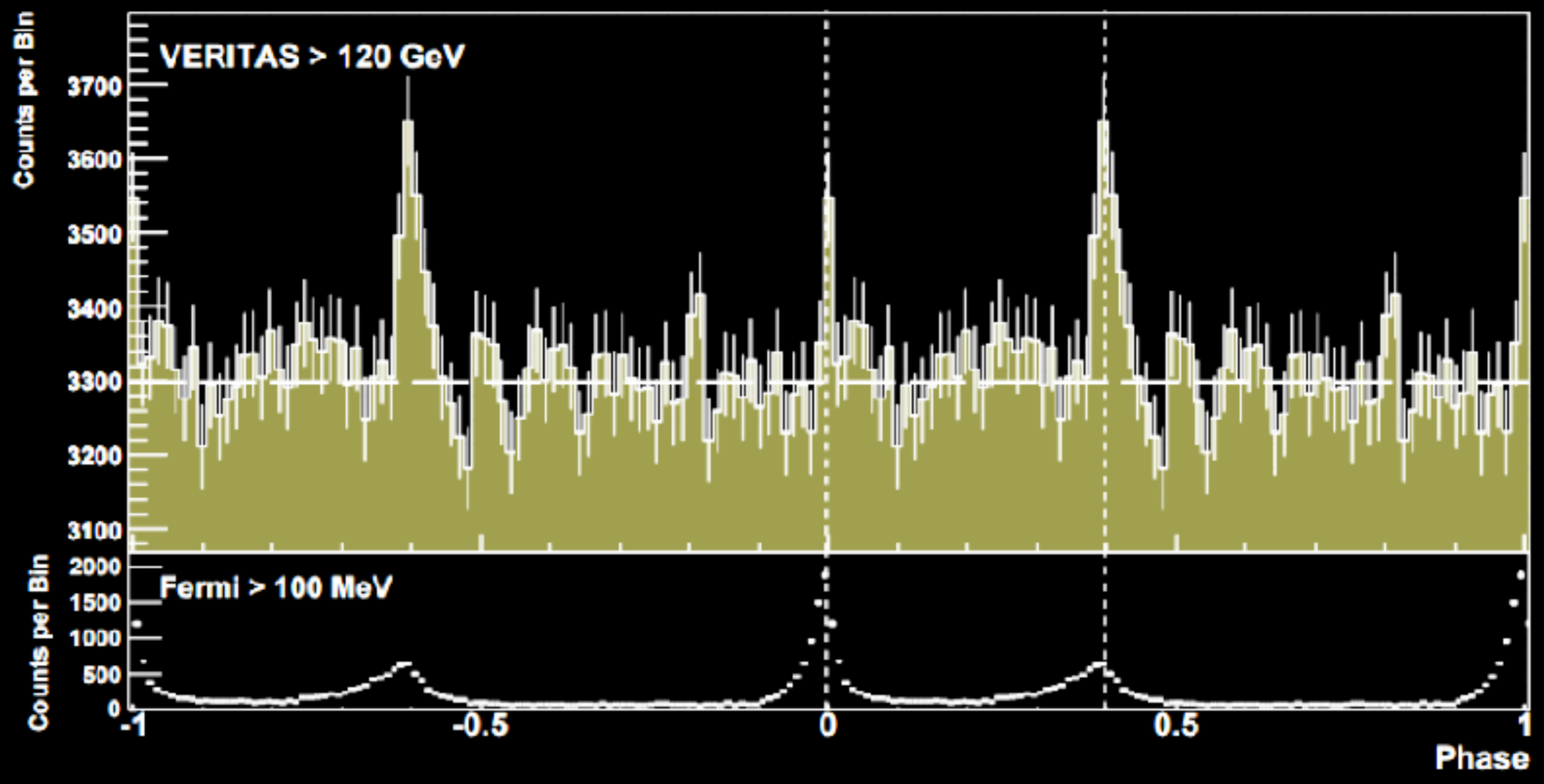

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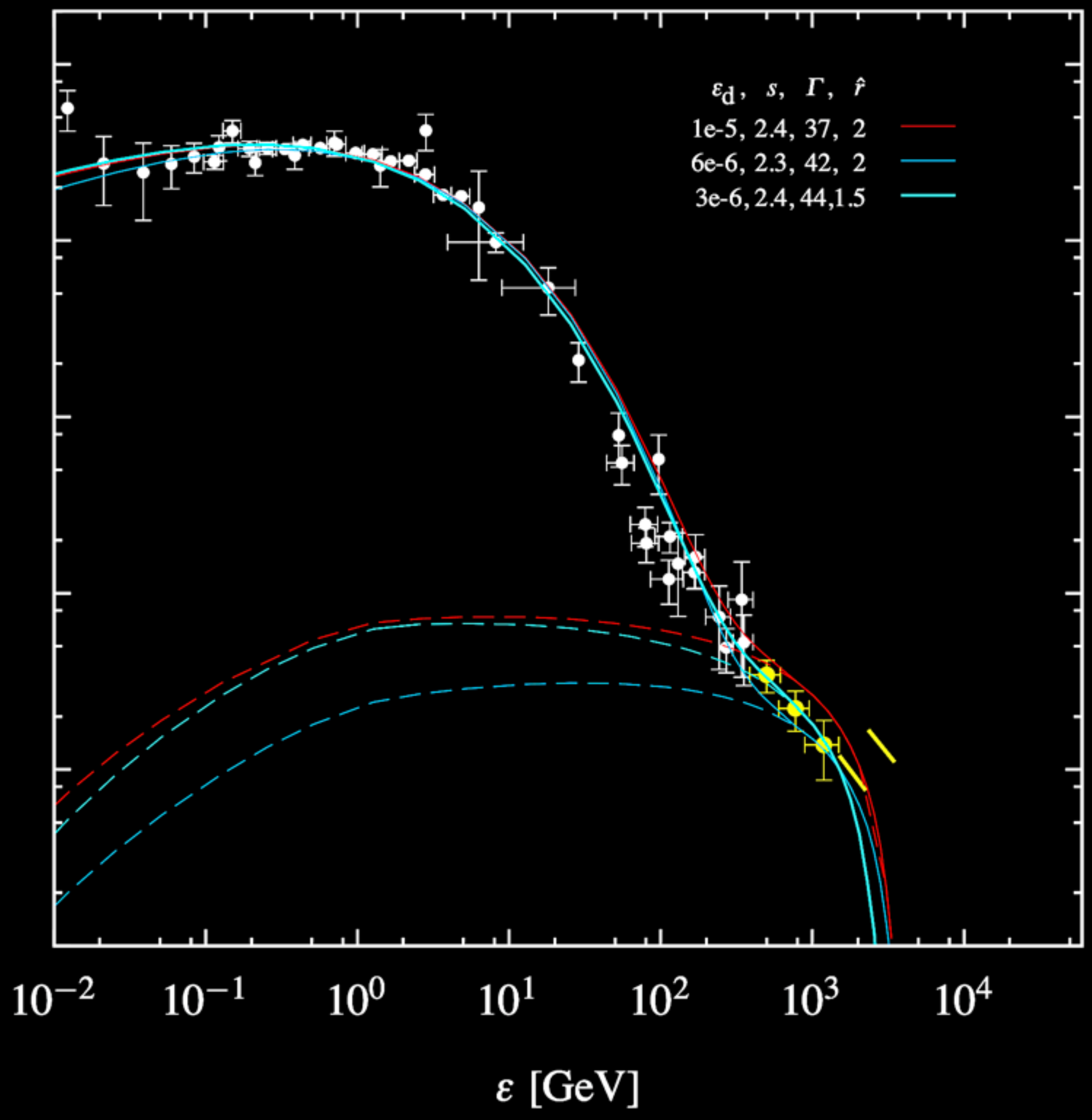
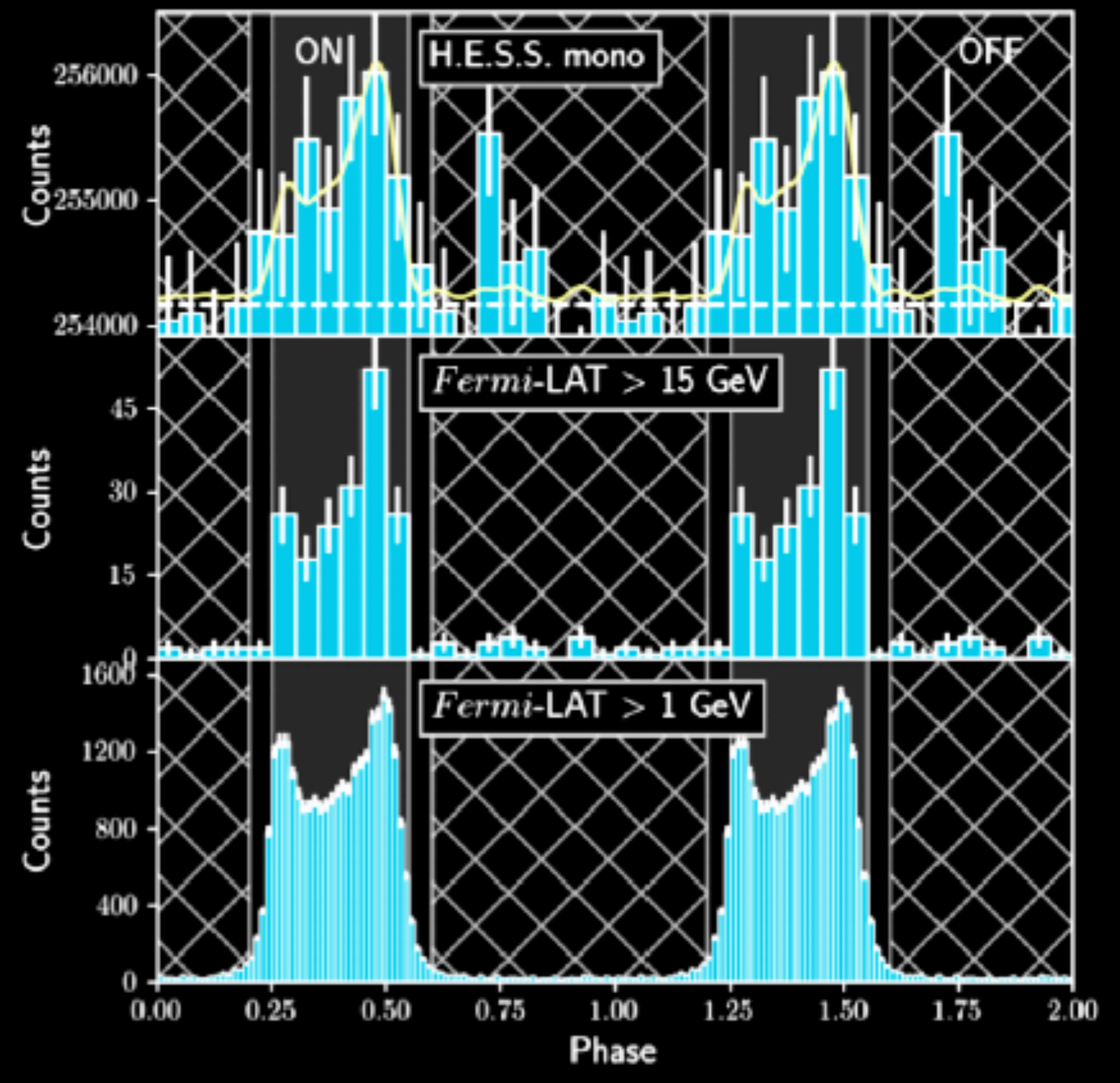
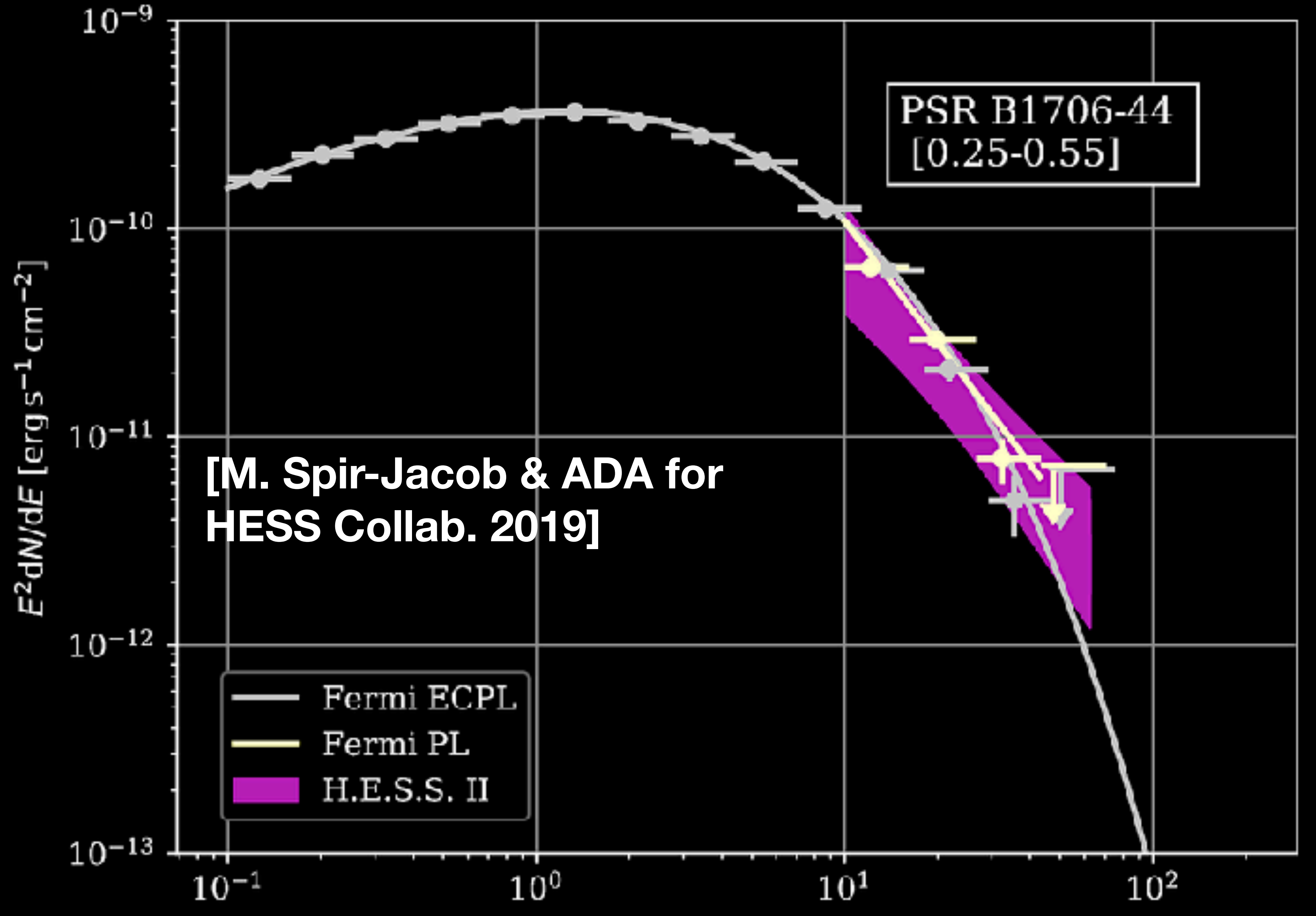
Striped wind :
e.g. [Petri 2015, Mochol & Petri 2017]



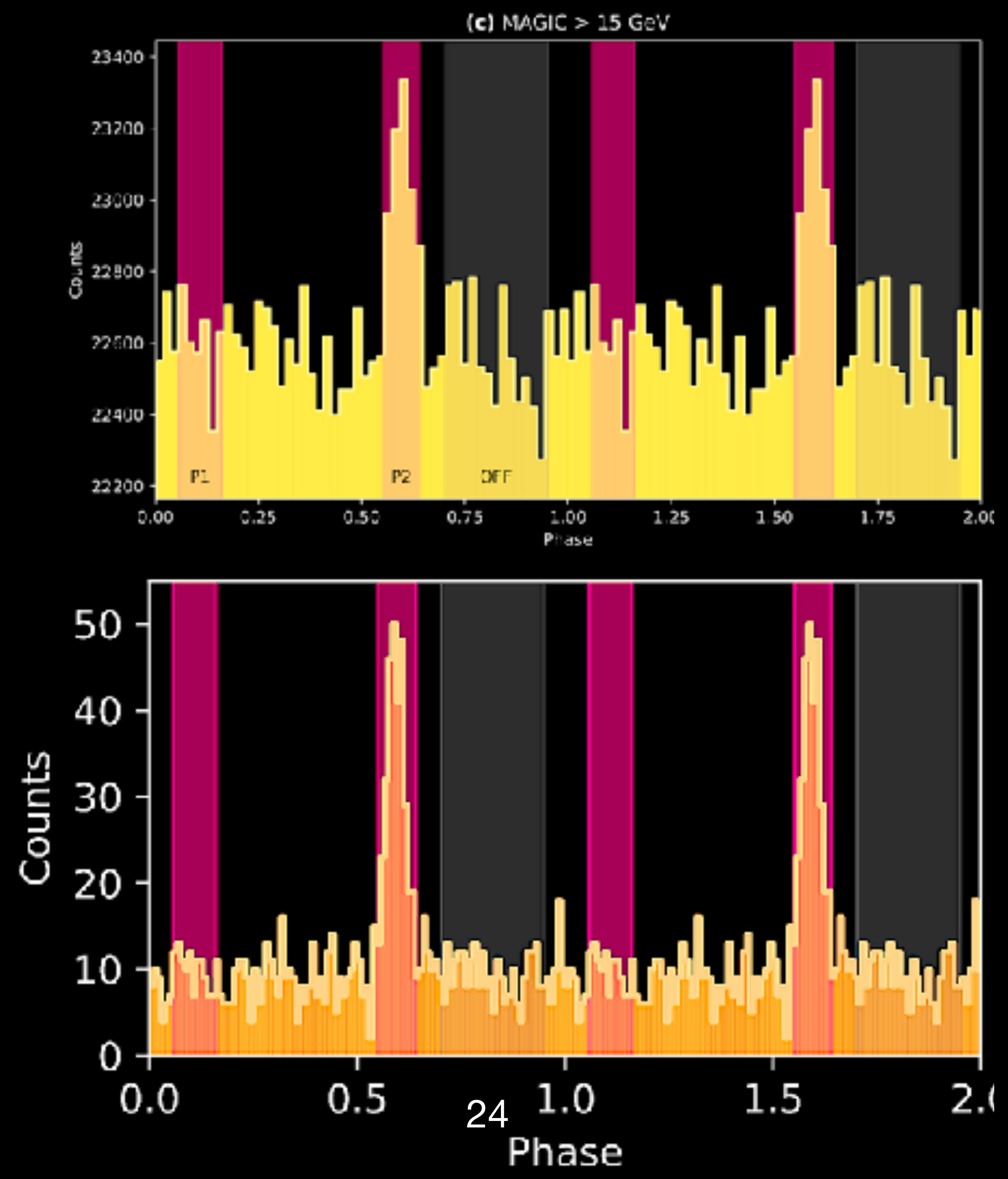
Two IACT pulsars
B1706-44 & Geminga

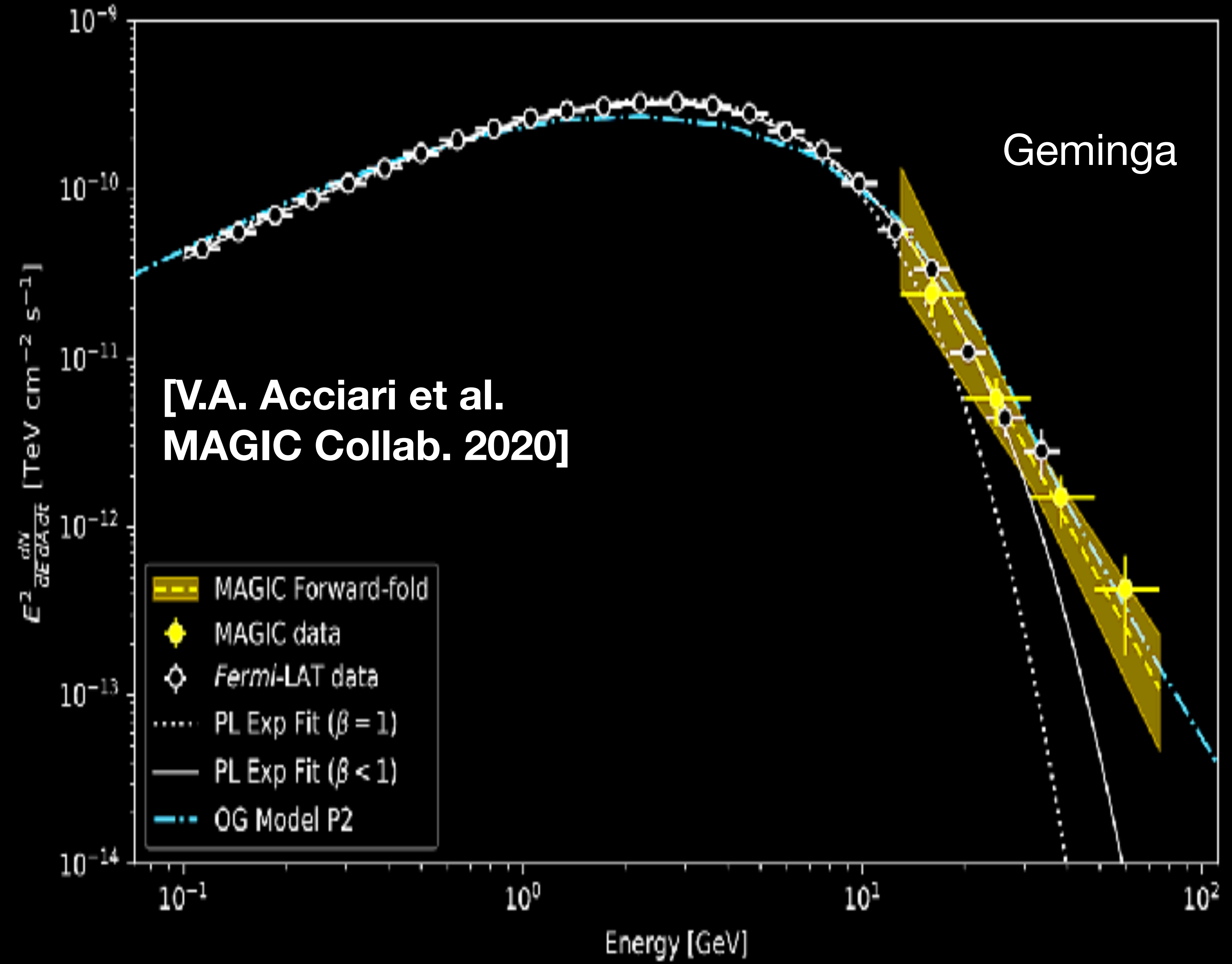
- B1706-44 H.E.S.S., CT5: 10-75 GeV
  - Power-law fits :
    LAT : Γ=3.9±0.1
    H.E.S.S. : Γ=3.8±0.4
  - Steep spectrum, ~1000 events > 70 GeV
- Power-law tail à la Crab? not enough stats





- Geminga MAGIC, 15-75 GeV
  - Power-law fits :
  - MAGIC : steep spectral index Γ=5.6±0.54
  - Joint Fermi-LAT+MAGIC fit: Γ=5.2±0.15
- Power-law tail à la Crab : weak indication





H.E.S.S. Vela < 100 GeV

CT5, mono, 10-110 GeV

- CT5 spectrum of P2: power-law fit in [10-110] GeV
- Fermi-LAT power-law fit >10 GeV: perfect agreement, including absolute energy scales

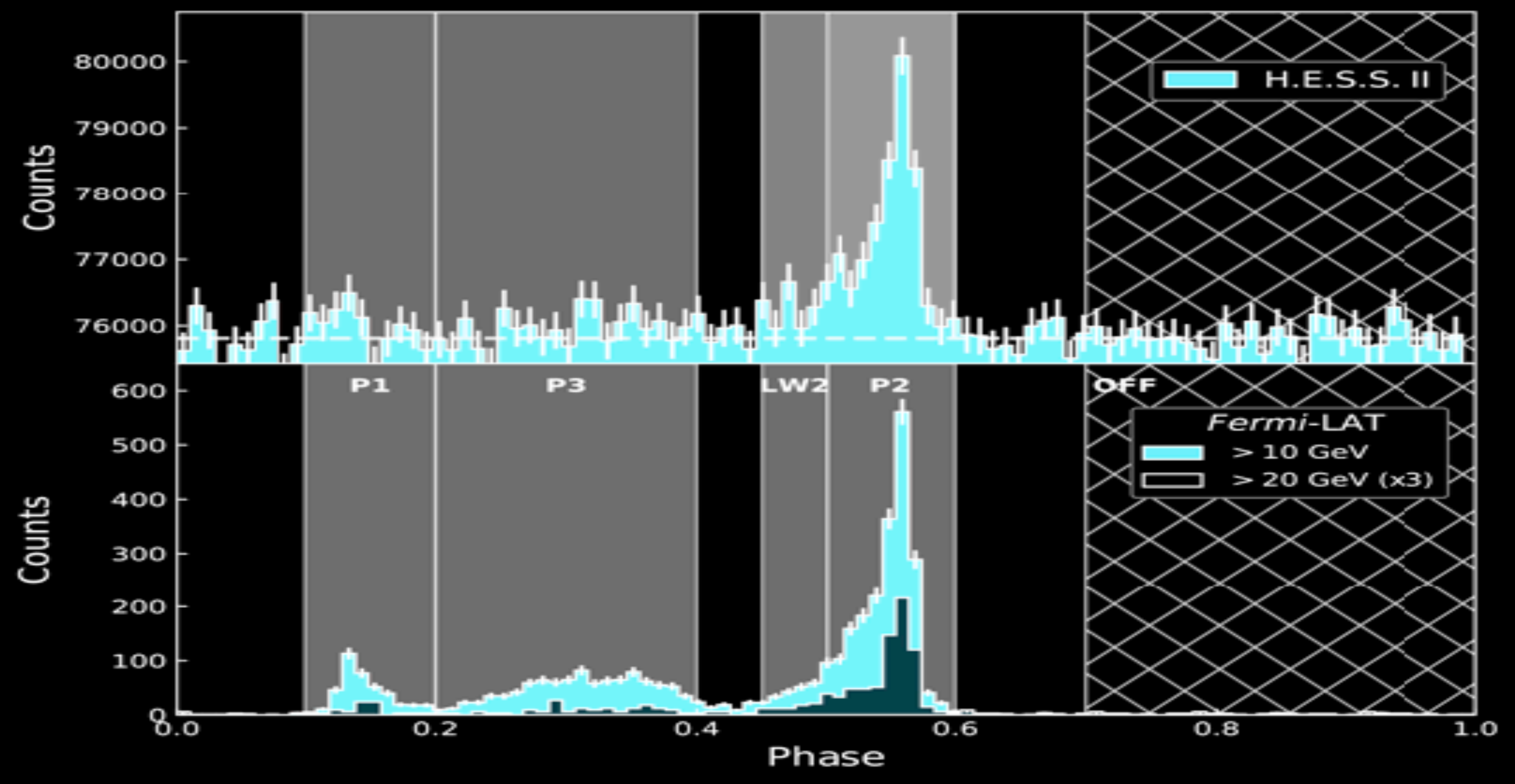
- Last significant bin:
  <E>=80 GeV, 909 events, 3.3 σ

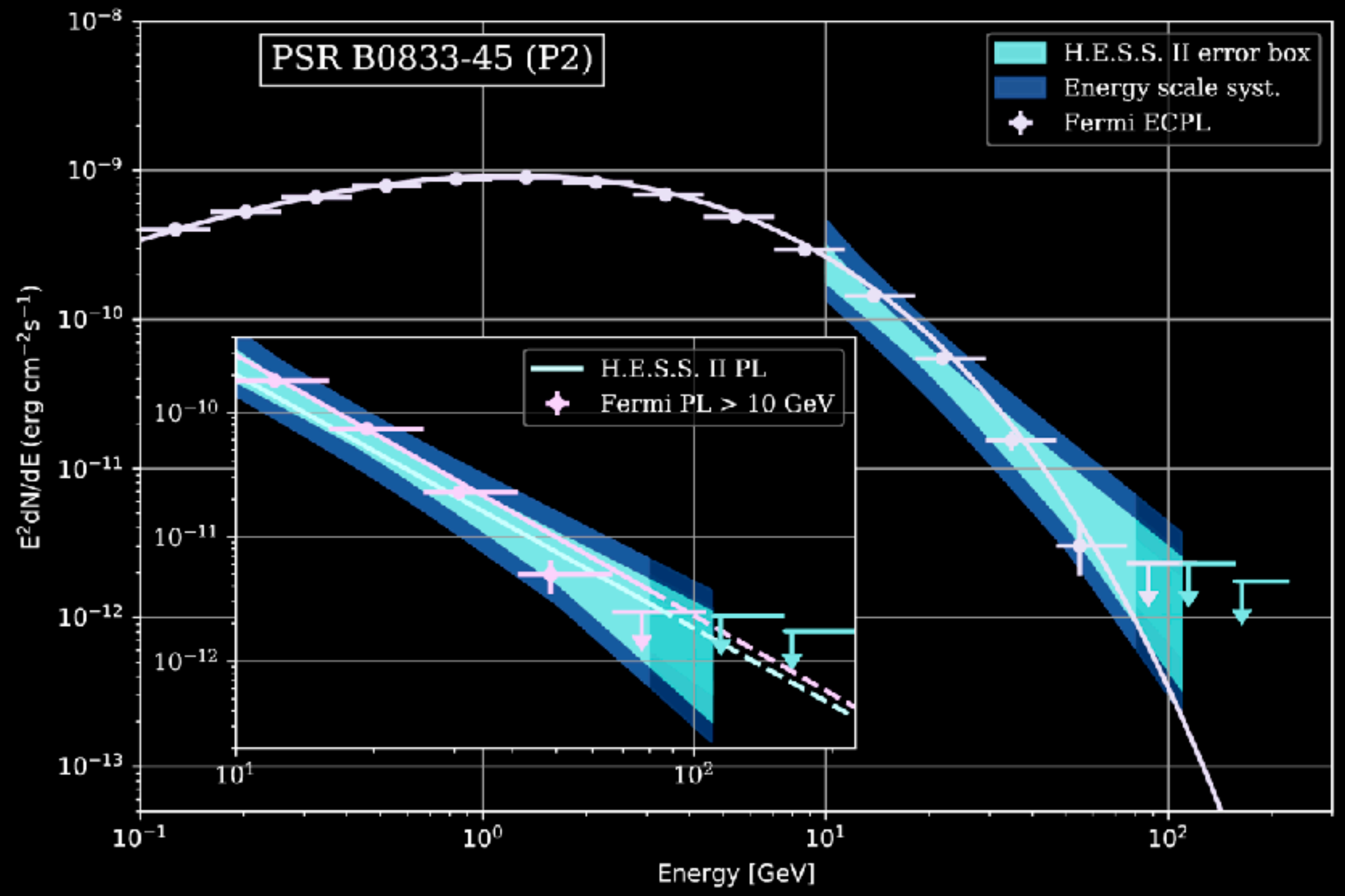
- Power-law tail à la Crab? independent (weak) evidence for curvature of P2 spectrum by:
  - Fermi-LAT: > 3.3 σ
  - H.E.S.S. : > 3.0 σ

- Variation of the power-law index as a function of energy threshold
- CR or Synchrotron (SR)?

Instrument	Threshold	Γ
H.E.S.S. II	~ 10 GeV	4.06 ± 0.16
Fermi-LAT	10 GeV	4.10 ± 0.08
H.E.S.S. II	~ 20 GeV	5.05 ± 0.25
Fermi-LAT	20 GeV	4.80 ± 0.30

[H.E.S.S. Collaboration 2017]





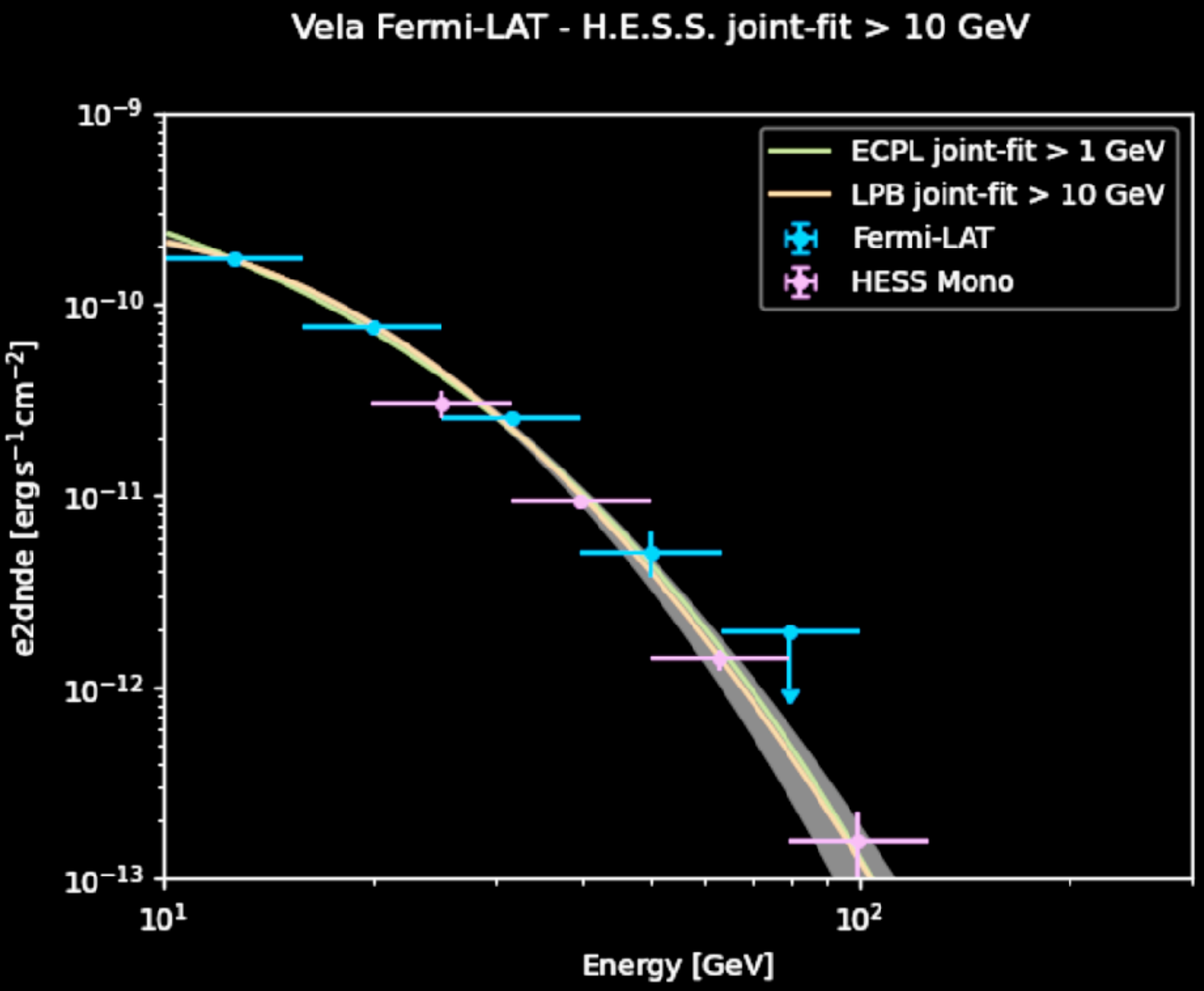
Vela: Curvature study

Log-parabola:

$$\phi(E) = \phi_0 \left(\frac{E}{E_0}\right)^{-\alpha-\beta\cdot log\left(\frac{E}{E_0}\right)}$$

$\phi(20\ GeV) = 1.2 \times 10^{-7} \pm 0.06\ TeV^{-1}s^{-1}cm^{-2}$
$\alpha = 4.2\ \pm 0.08$
$\beta = 1.1\ \pm 0.2$

Likelihood ratio:
7.3 σ in favour of the Log-parabola



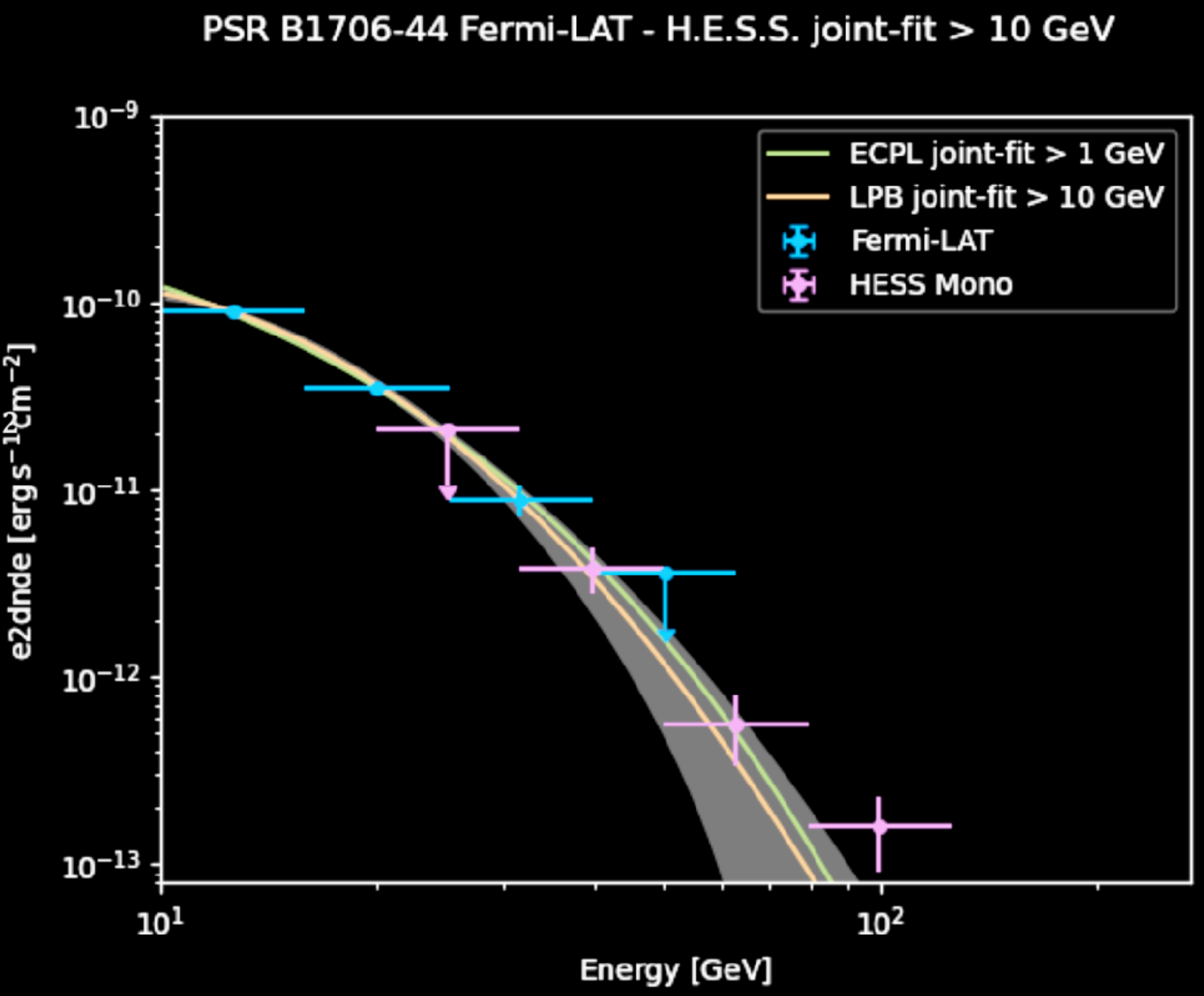
PSR B1706-44: Curvature study

Log-parabola:

$$\phi(E) = \phi_0 \left(\frac{E}{E_0}\right)^{-\alpha-\beta\cdot log\left(\frac{E}{E_0}\right)}$$

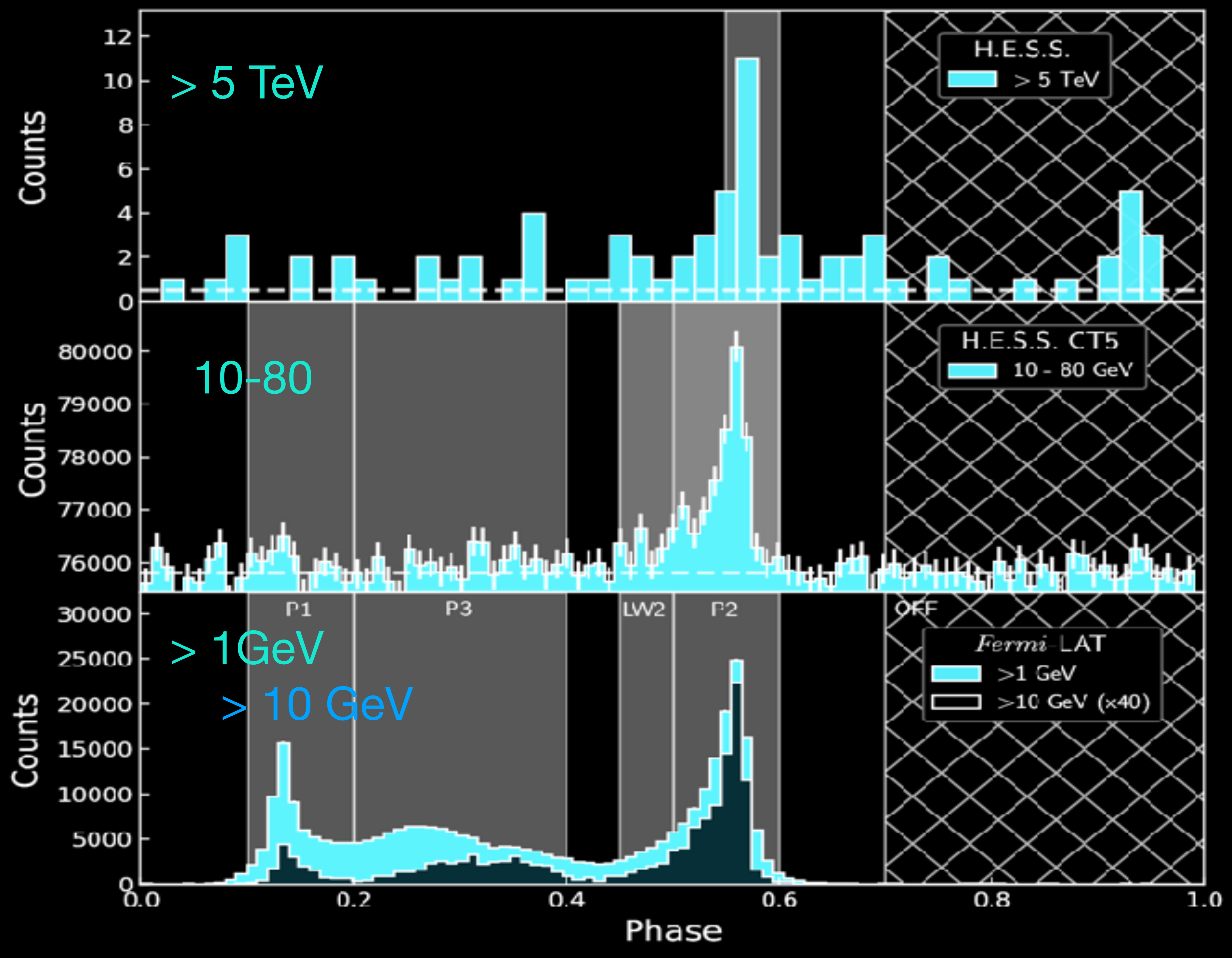
$\phi(20\ GeV) = 5.6 \times 10^{-8} \pm 0.4\ TeV^{-1}s^{-1}cm^{-2}$
$\alpha = 4.5\ \pm 0.2$
$\beta = 1.3\ \pm 0.5$

Likelihood ratio:
3.8 σ in favour of the Log-parabola



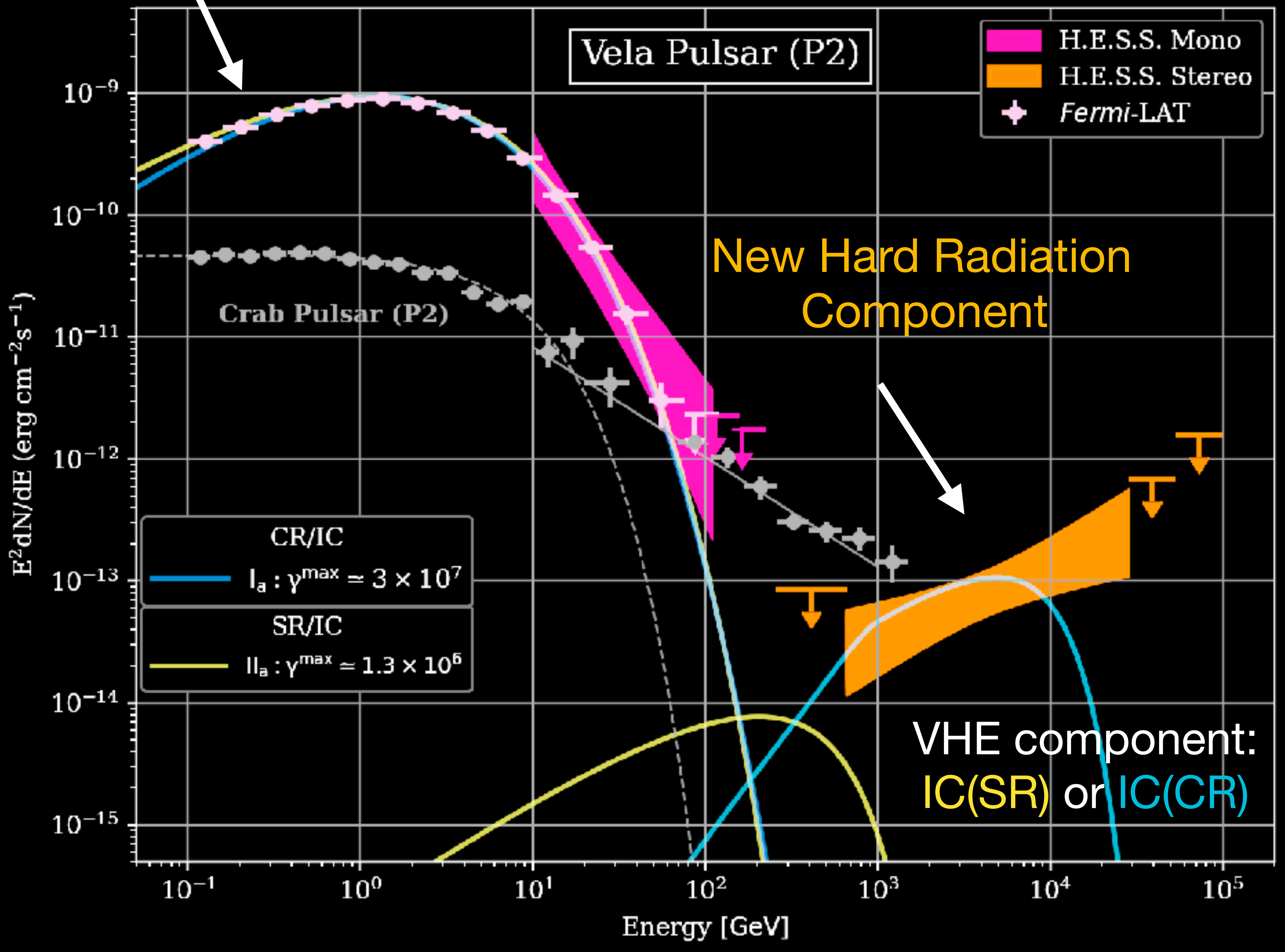
The 20 TeV emitter pulsar : Vela

2022: Breakthrough by H.E.S.S.
20 TeV Pulsations, New component (IC)



Phase & width compatible with <100 GeV pulses

HE component:
SR or CR



VHE component:
IC(SR) or IC(CR)

Very hard spectrum
P2 : Γ = -1.4±0.2
New TeV component !

[ADA Texas Symposium 2022
H.E.S.S. Collaboration 2023]

Origin of HE/VHE emission?

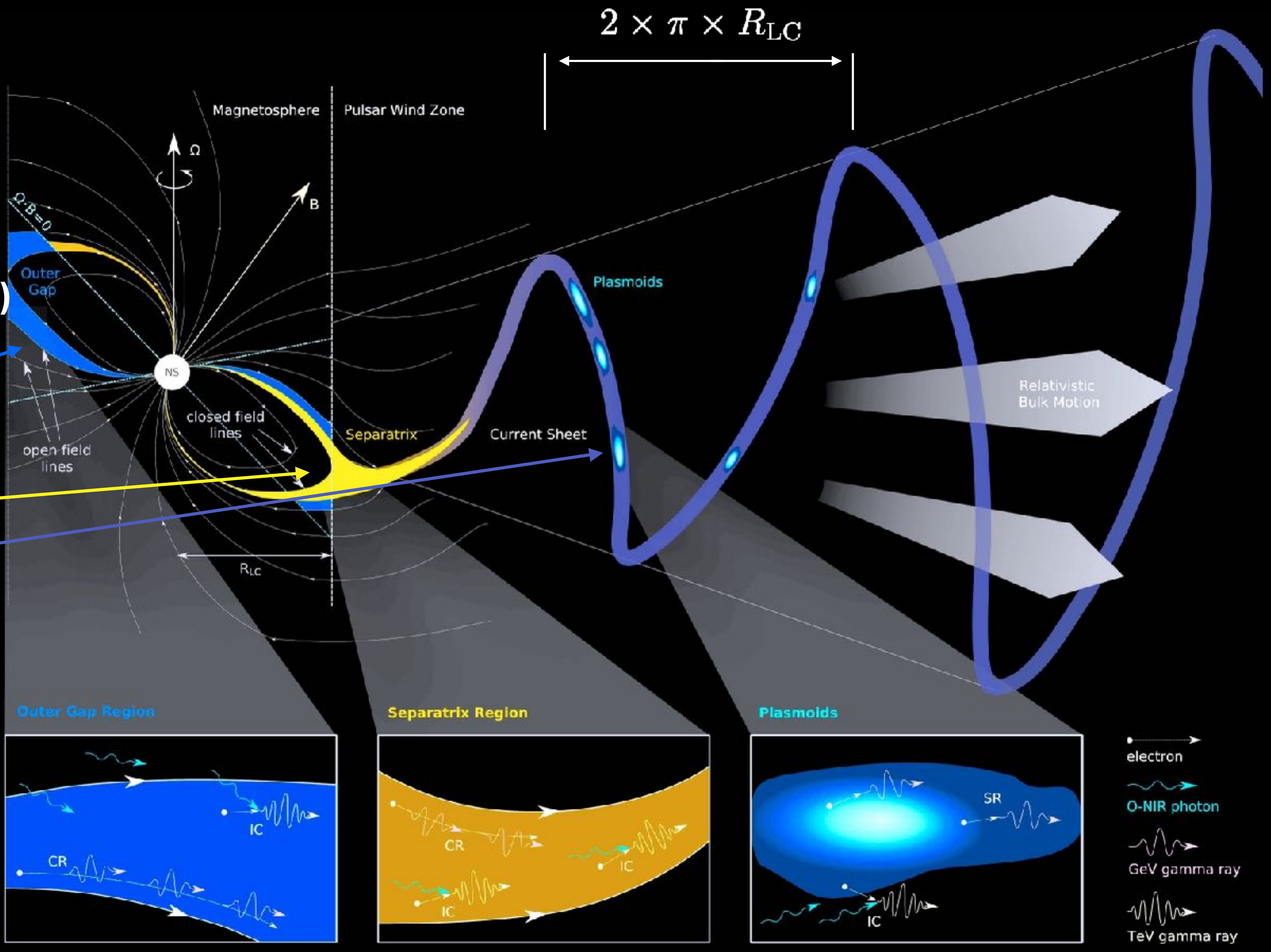
- Two main paradigms:
  - Acceleration by $E_{||}$ in gaps
  - Acceleration through magnetic reconnection in the current sheet (CS)

- Two main scenarios:

  I- Curvature Radiation CR/IC in
    - Outer Gaps
    - Separatrix-CS

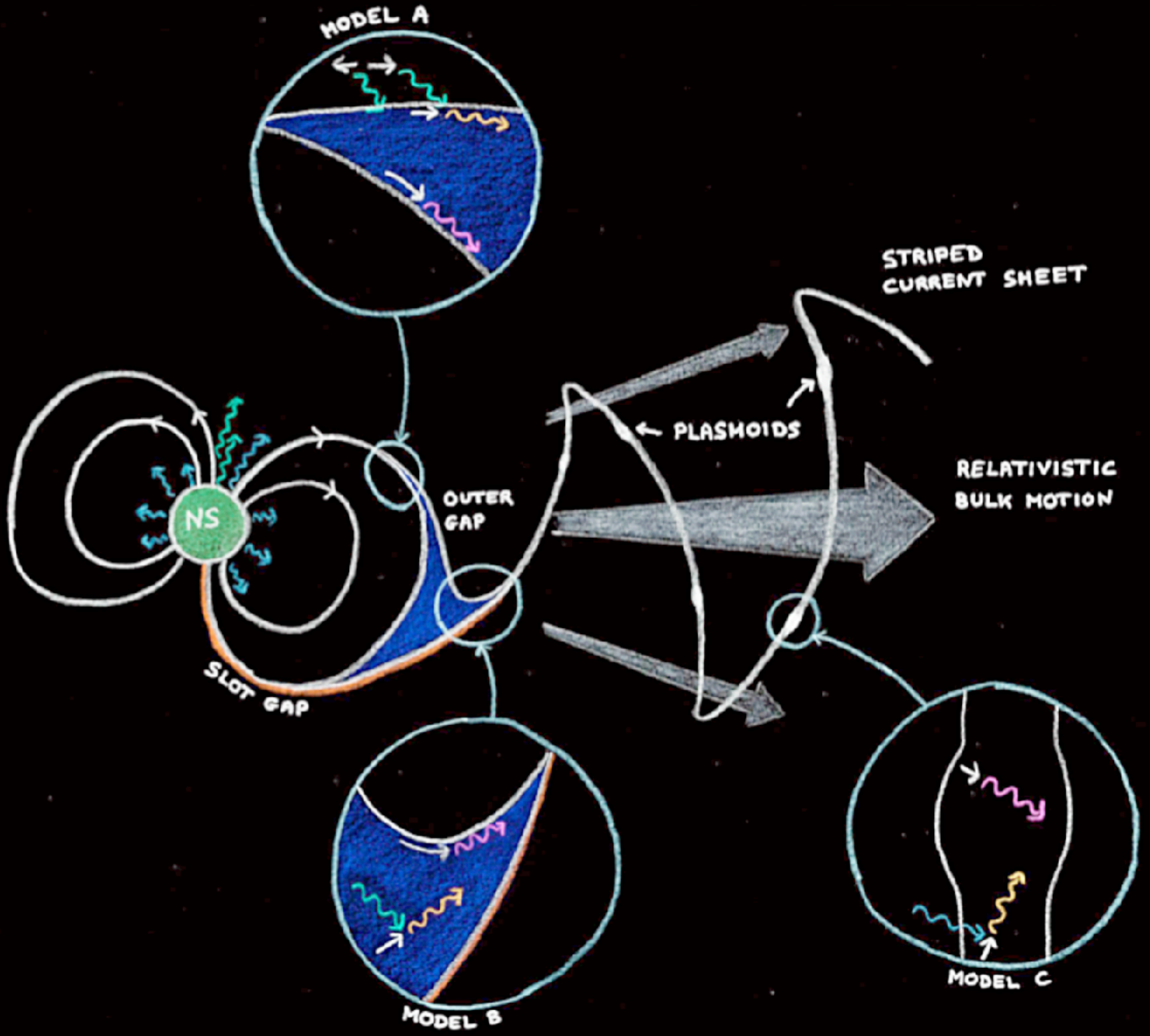
  II- SR/IC in the CS
    - near the LC
    - Boosted emission ~ >> R_{LC}

- UV-O-NIR Targets for IC scattering:
  - SR by secondary pairs
  - Along OG or between NS - 0.5 R_{LC}
  - Around CS (isotropic)



The Original cartoon!

PhD, 2019, APC



Drawn first on the white board (room 596A, APC) by Marion Spir-Jacob during a discussion with ADA (~Nov 2018)

Separatrix/CR

Fundamental Plane

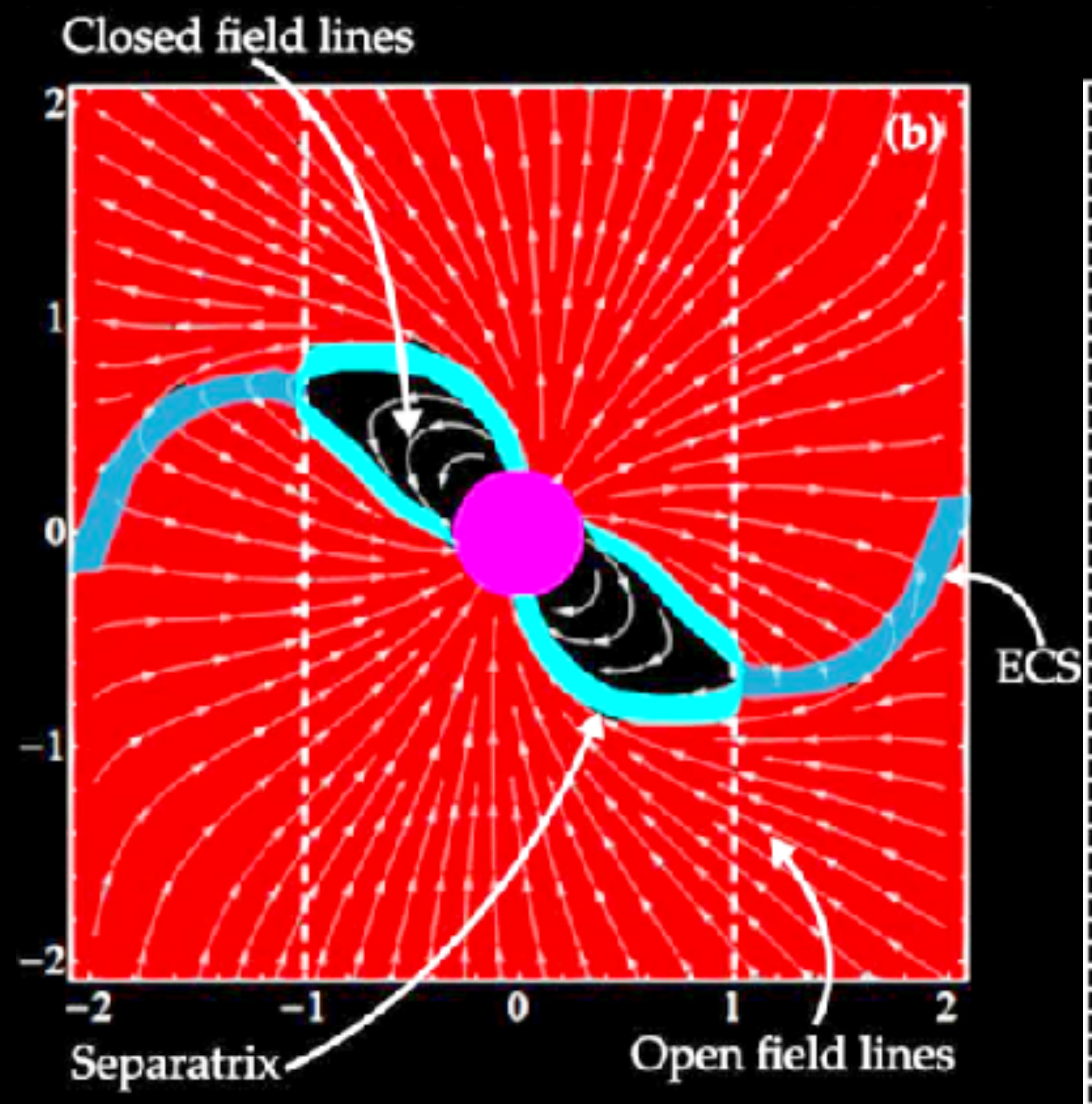
[Kalapotharakos et al. 2019, 2022, 2023]

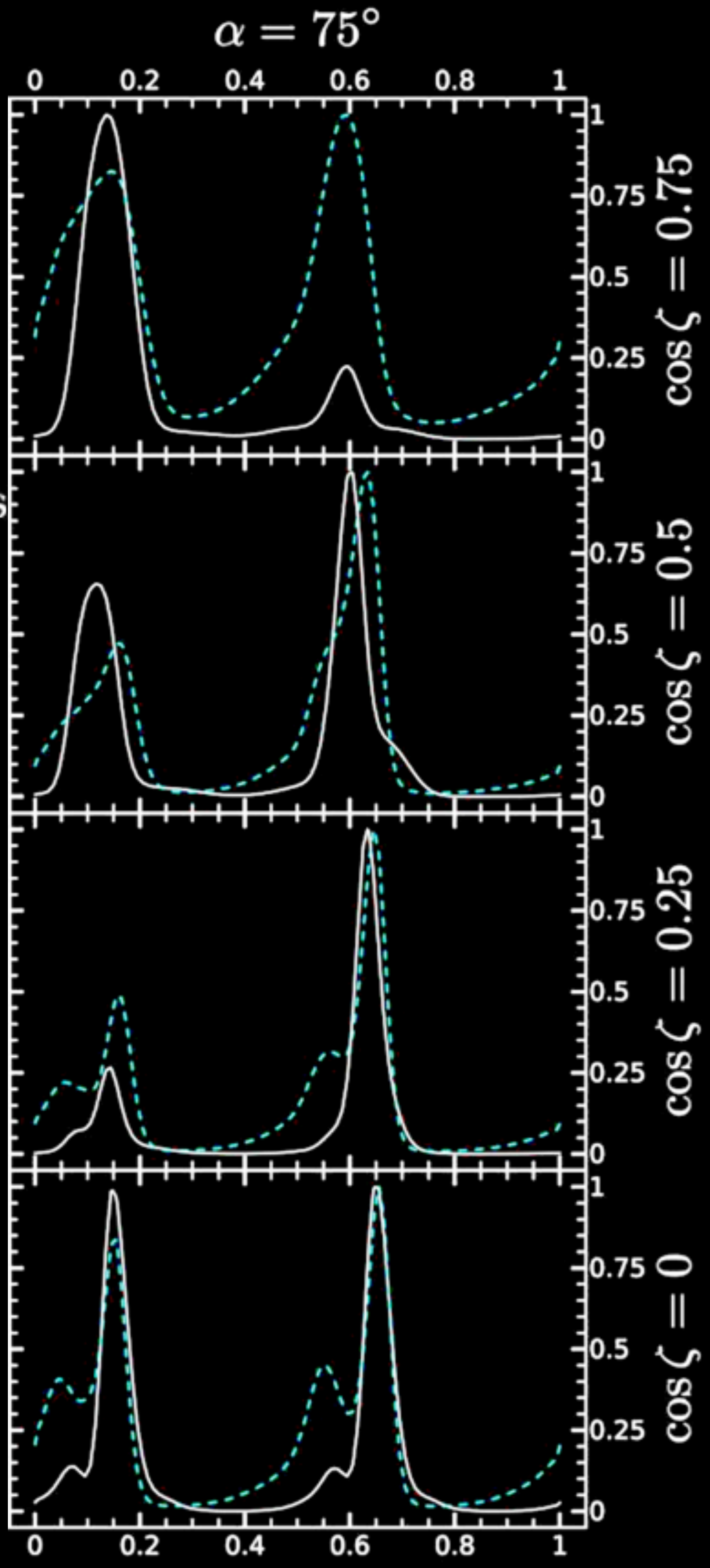
- Assumes CR in separatrix zone model
- 190 pulsars : young (YP) and ms (MS)

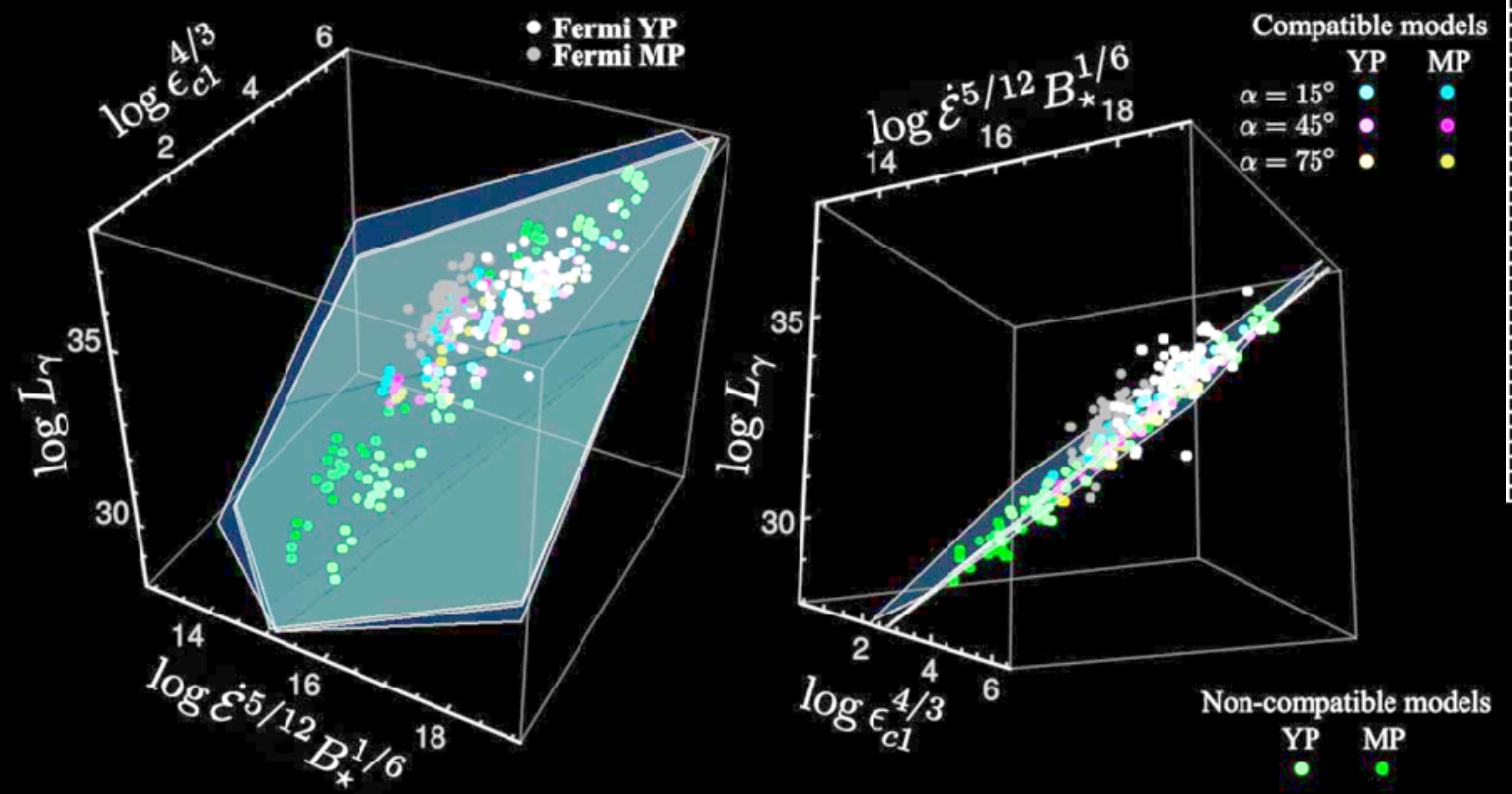
$$L_\gamma \propto \epsilon_{\rm cut}^{4/3} B_\star^{1/6} \dot{\mathcal{E}}^{5/12}$$

$$L_\gamma = 10^{14.3\pm1.3} \epsilon_{\rm cut}^{1.39\pm0.17} B_\star^{0.12\pm0.03} \dot{\mathcal{E}}^{0.39\pm0.05}$$

- Light-curve shapes
- Radio-lag vs peak separation





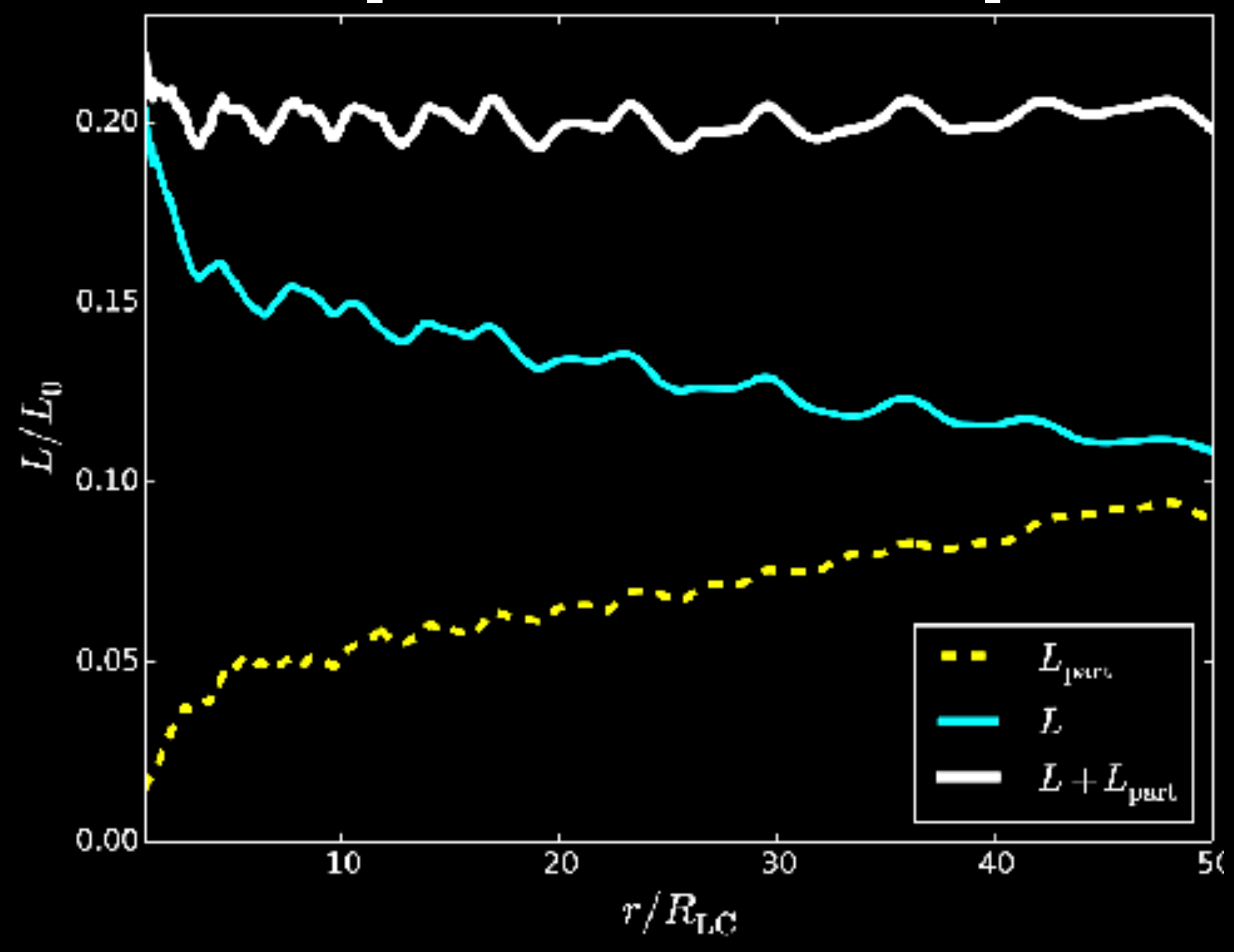


Current Sheet-B Reconnection

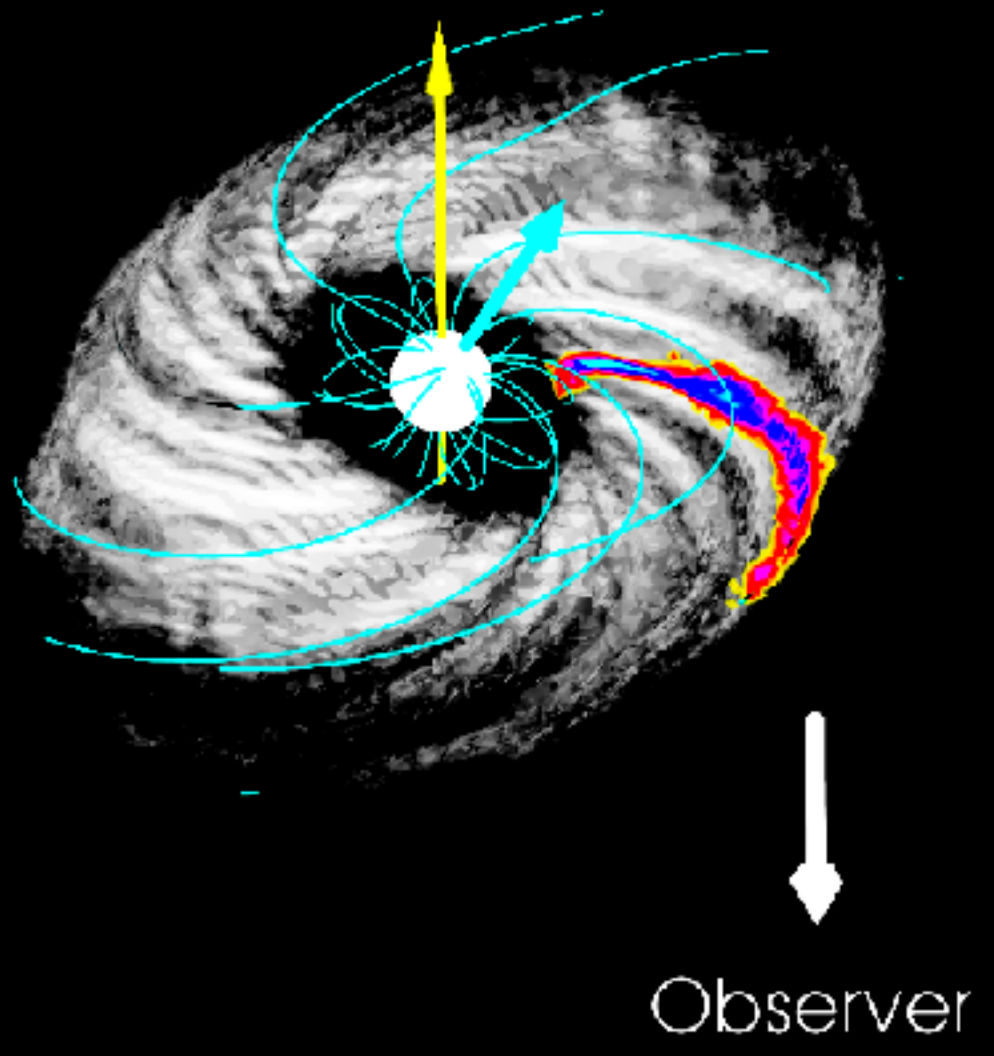
[B.Cerutti, A. Philippov, L. Sironi, A. Spitkovsky, D. Uzdensky, G. Werner,..]

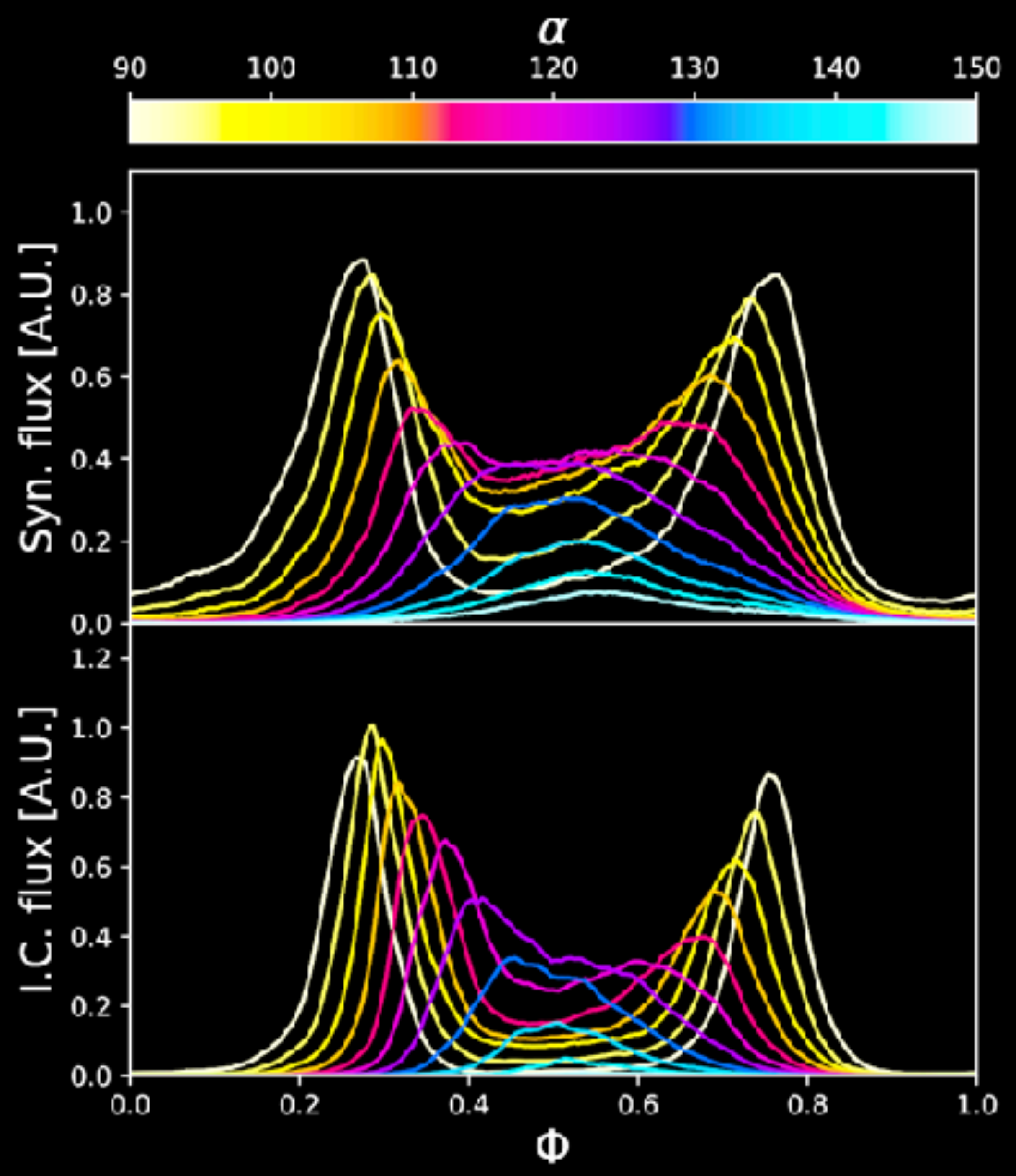
- PIC Simulations since >1 decade
- 2D & 3D
    - Striped wind structure
    - Possible formation of caustics
    - Formation of a power-law with hard index
    - Dissipation: 2D slow, large $\Gamma w >\sim 10^2$
      —> 3D full dissipation few tens/hundreds of R_lc:
      —> more modest $\Gamma w < 100$

[B. Cerutti et al. 2020]

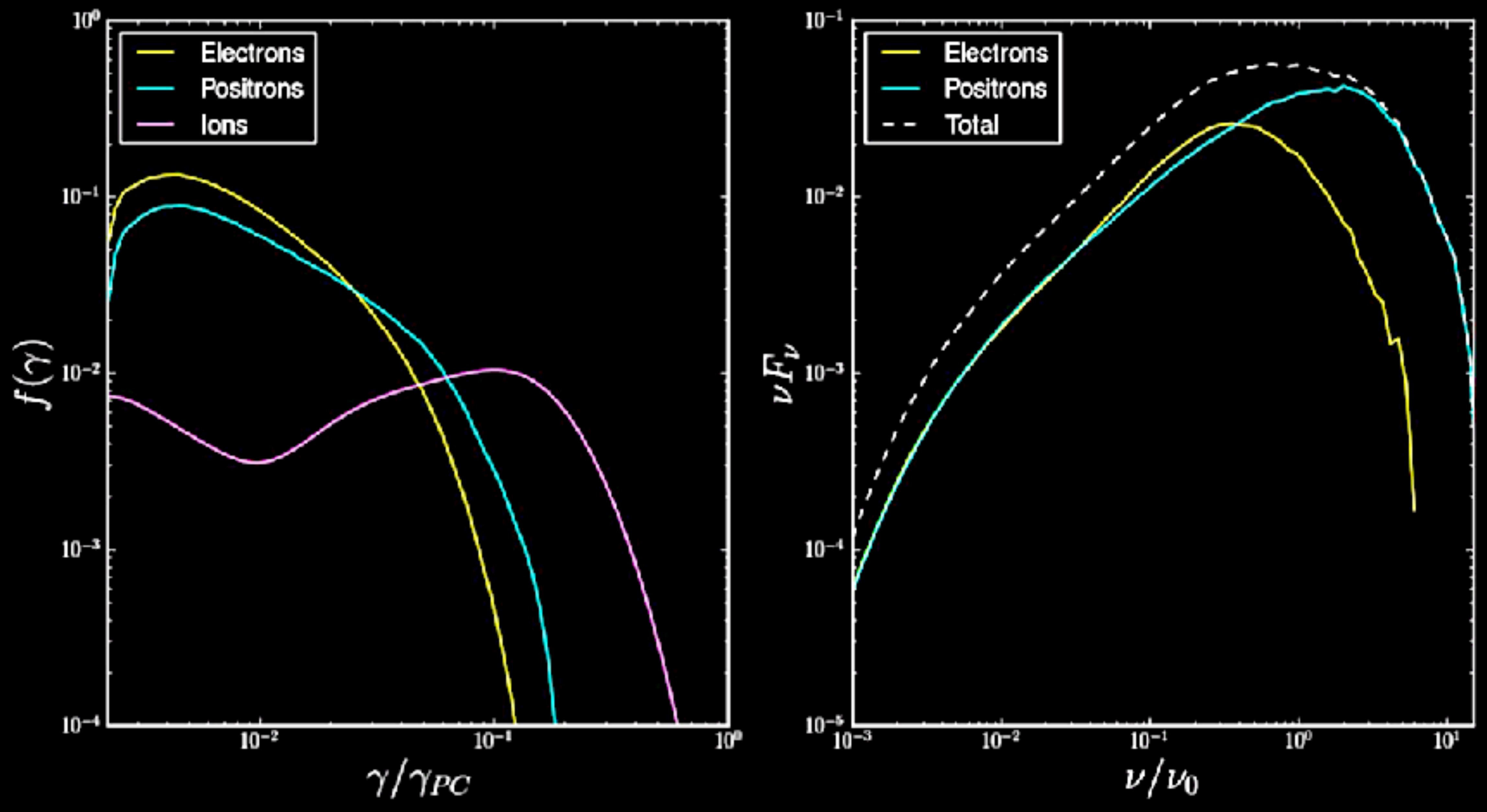


[B. Cerutti et al. 2016]





[B. Cerutti et al. 2025]



(b) 60° magnetosphere

[A. Philippov & A. Spitkovsky 2018]

Origin of TeV γ rays?

- Two main paradigmes:
  - Acceleration by $E_{||}$ in gaps
  - Acceleration through magnetic reconnection in the current sheet (CS)
- TeV phase aligned with GeV pulsations:
  - Same population & similar spatial regions
  - Not necessarily identical: caustics
- Two main scenarios:

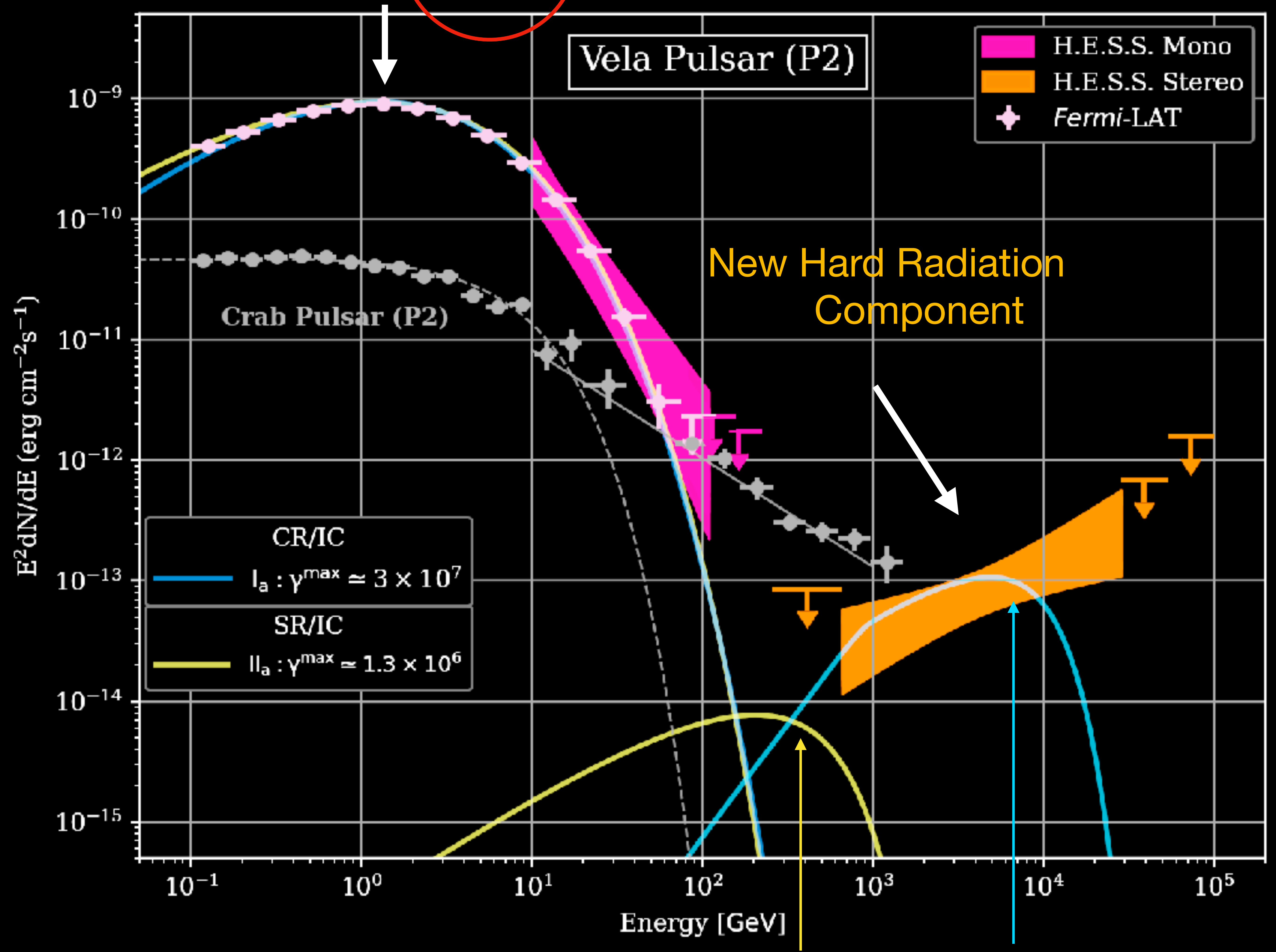
  I- Curvature Radiation CR/IC in Outer Gaps/Separatrix-CS

$$\begin{cases} \gamma_{\rm CR}^{\rm max} \simeq 4\times 10^7\, \xi^{1/2}\eta_{-1}^{1/4} \\ E_{\rm CR}^{\rm max} \simeq 5\,{\rm GeV}\, \xi^{1/2}\eta_{-1}^{3/4} \end{cases} \qquad \begin{cases} \eta_{-1} = \eta/0.1 \\ \rho_c = \xi\, R_{\rm LC} \end{cases}$$

  II- SR/IC in the CS

$$\gamma_{\rm SR}^{\rm max} \simeq 1.3\times 10^6 (B_\perp/B_{\rm LC})^{-1/2} (E_{\rm SR}^{\rm max}/1.5\,{\rm GeV})^{1/2}$$

$$E_{\rm HE}^{\rm peak} \simeq 1.5\,{\rm GeV}$$



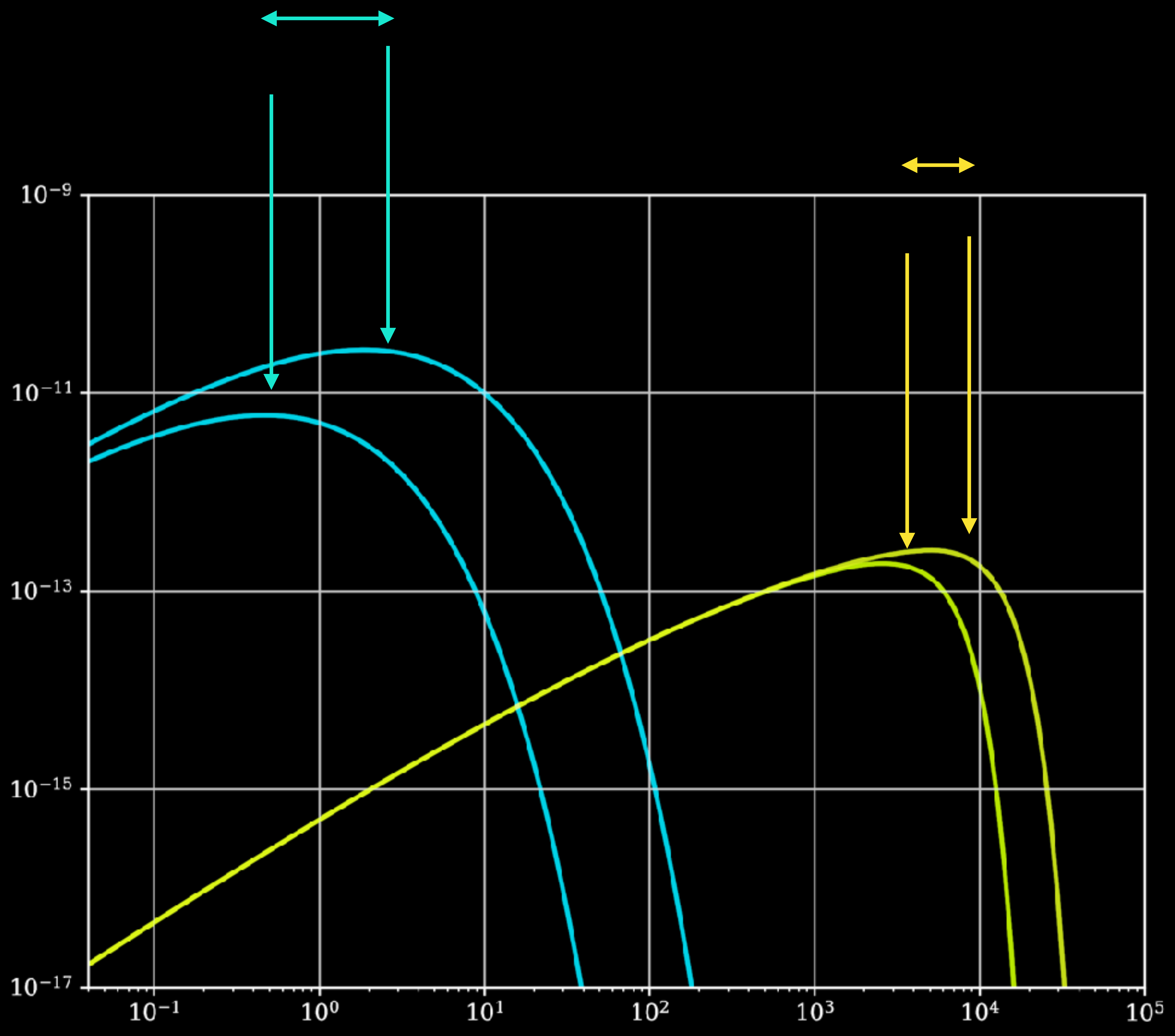
- Joint fit to GeV & TeV Components
- Insufficient maximum IC energies
- Normalisation = f(target density)

Maximum Lorentz Factor

- GeV Component
- Interpreted as CR
- Same distribution of particles

$$\frac{d^2N}{d\gamma dt} \propto (\gamma/\gamma_0)^{-p} \exp\left[-(\gamma/\gamma^{\rm max})^{\beta}\right]$$

- The GeV peak energy (or variations of it) is not the best measure of the maximum
- The IC component (in the KN regime) is unambiguous !



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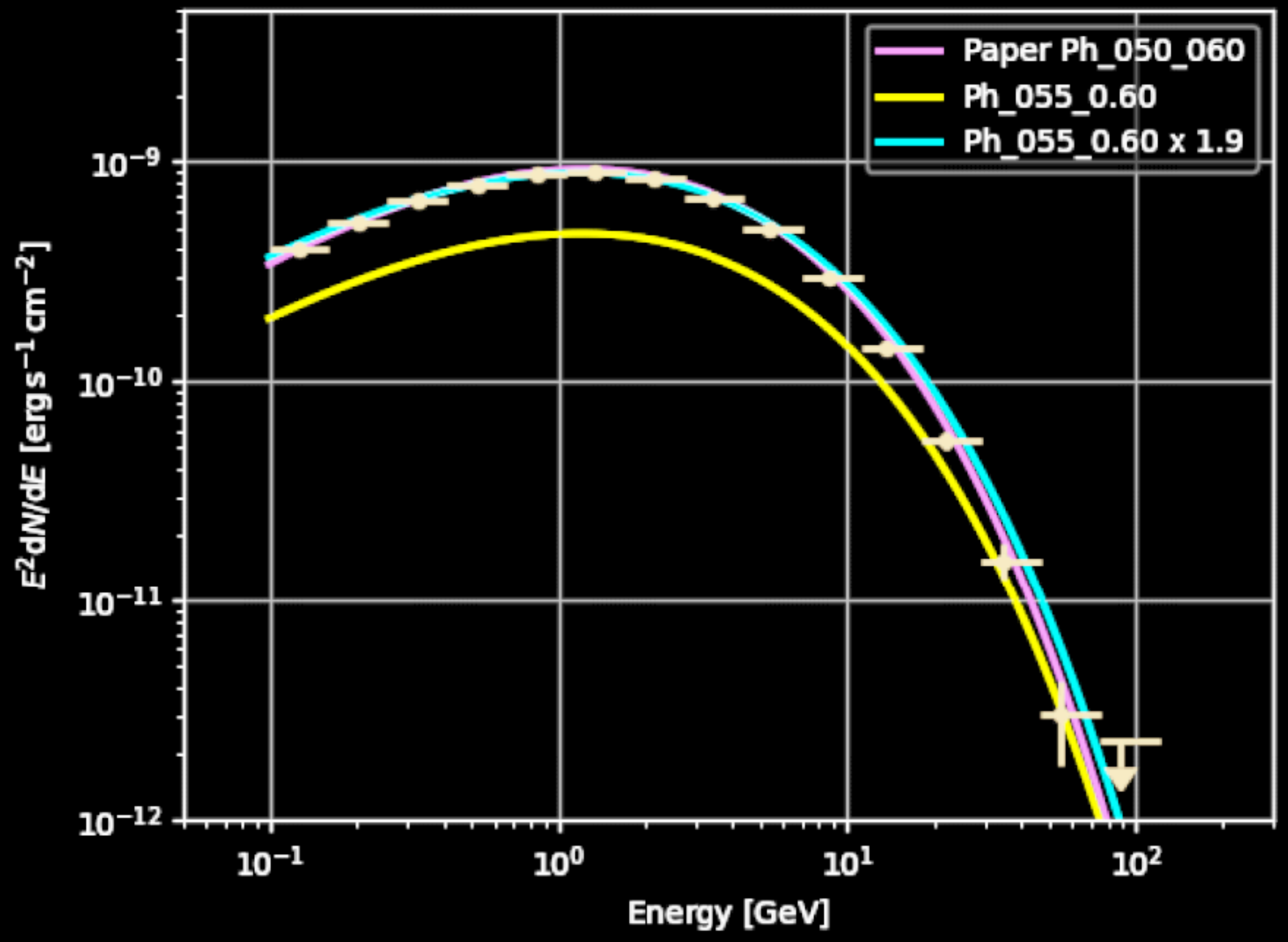
- The GeV peak energy (or variations of it) is not the best measure of the maximum
- The IC component (in the KN regime) is unambiguous !
- GeV E_peak should be derived based on a finely phase-resolved spectrum
- However even for Vela with huge statistics one still gets a sub-exponential cutoff even with very fine binning



Origin of TeV γ rays?

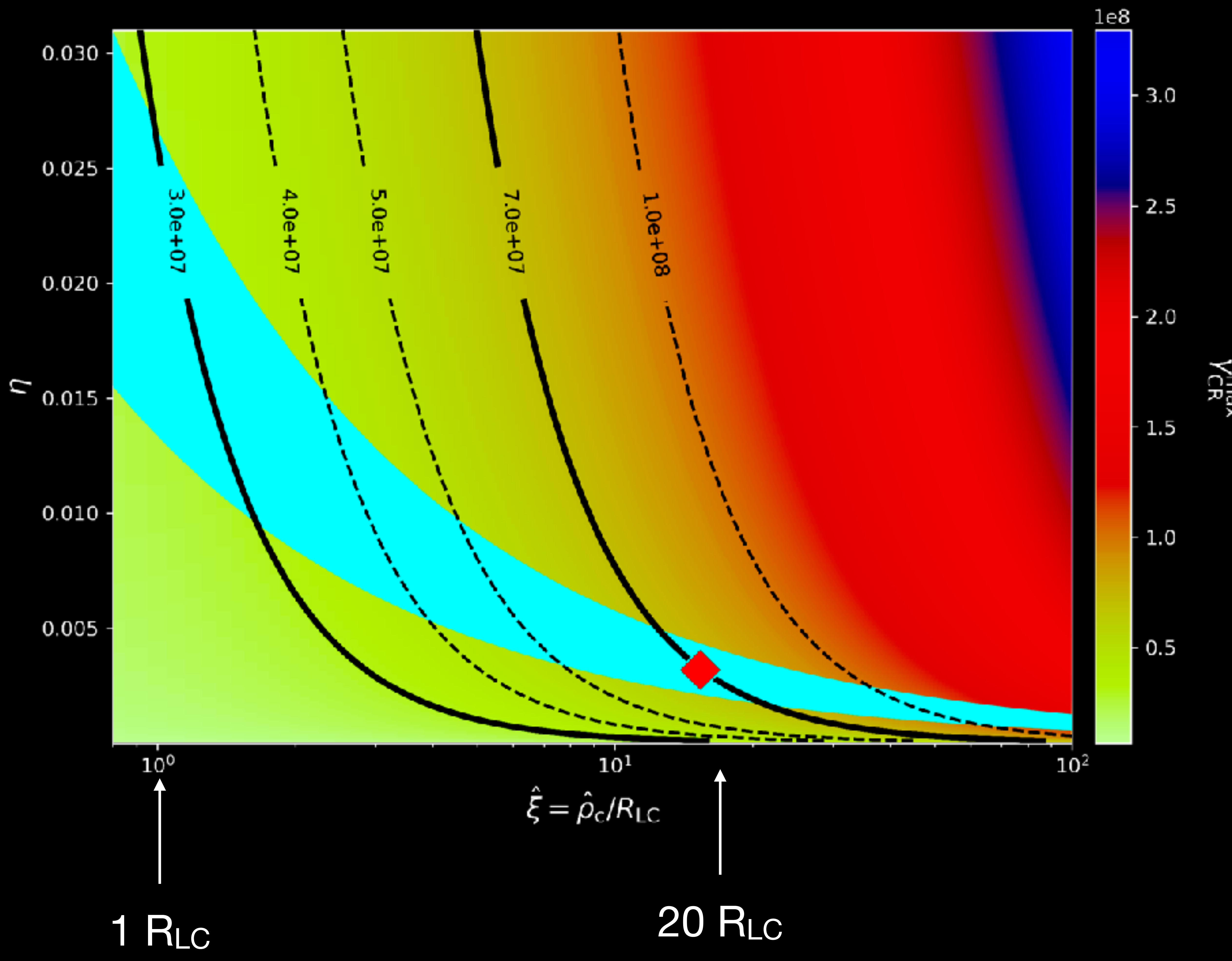
Probing
Magnetic conversion efficiency
& acceleration zone

- Fit to theTeV data: $\gamma_{\rm IC}^{\rm max} \gtrsim 7 \times 10^7$
- CR/IC scenario:
  - Constraint by GeV data:
  - Different combinations of $(\eta, \hat{\xi})$ $\boxed{\eta \ll 0.1 \text{ and } \hat{\xi} \gg 1}$
  - Implies a dissipation region beyond the LC where $\rho_c \gg R_{\rm LC}$
  - Can provide much higher energies than in traditional magnetospheric models

- SR/IC scenario:
  - Constraint by GeV data and B:

$$\gamma_{\rm SR}^{\rm max} \simeq 1.3 \times 10^6 (B_\perp / B_{\rm LC})^{-1/2} \, (E_{\rm SR}^{\rm max} / 1.5\,{\rm GeV})^{1/2}$$

  - Insufficient maximum energy
  - Particles well beyond SR cut-off
  - 2-step acceleration/SR-cooling process
    - Larmor radii > largest plasmoids
    - Re-acceleration after SR-cooling : Caustics
  - Doppler-boosted (bulk motion)



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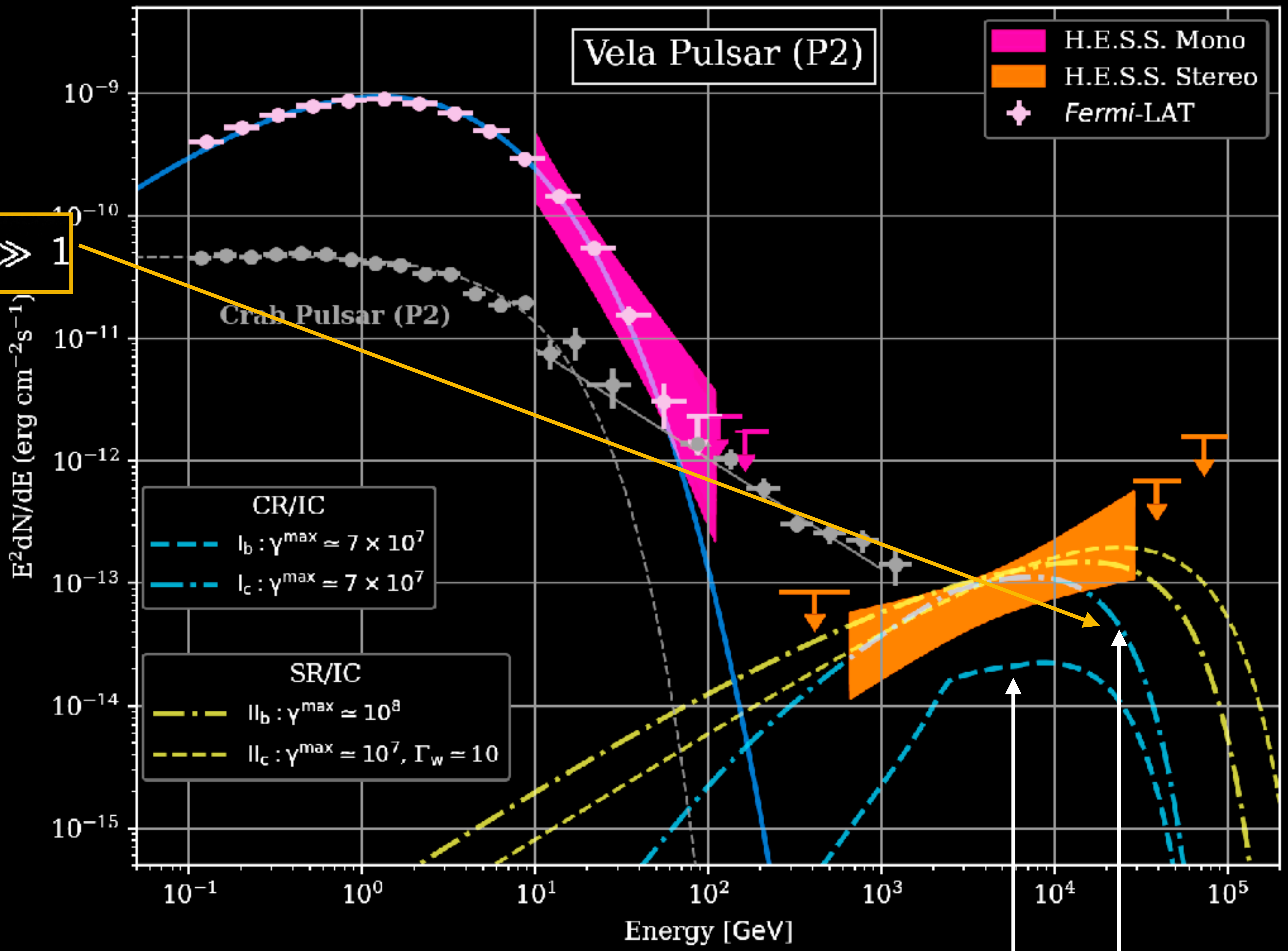

- Effect of target photons energy range: [0.1 - 4] eV, vs [0.005 - 4] eV

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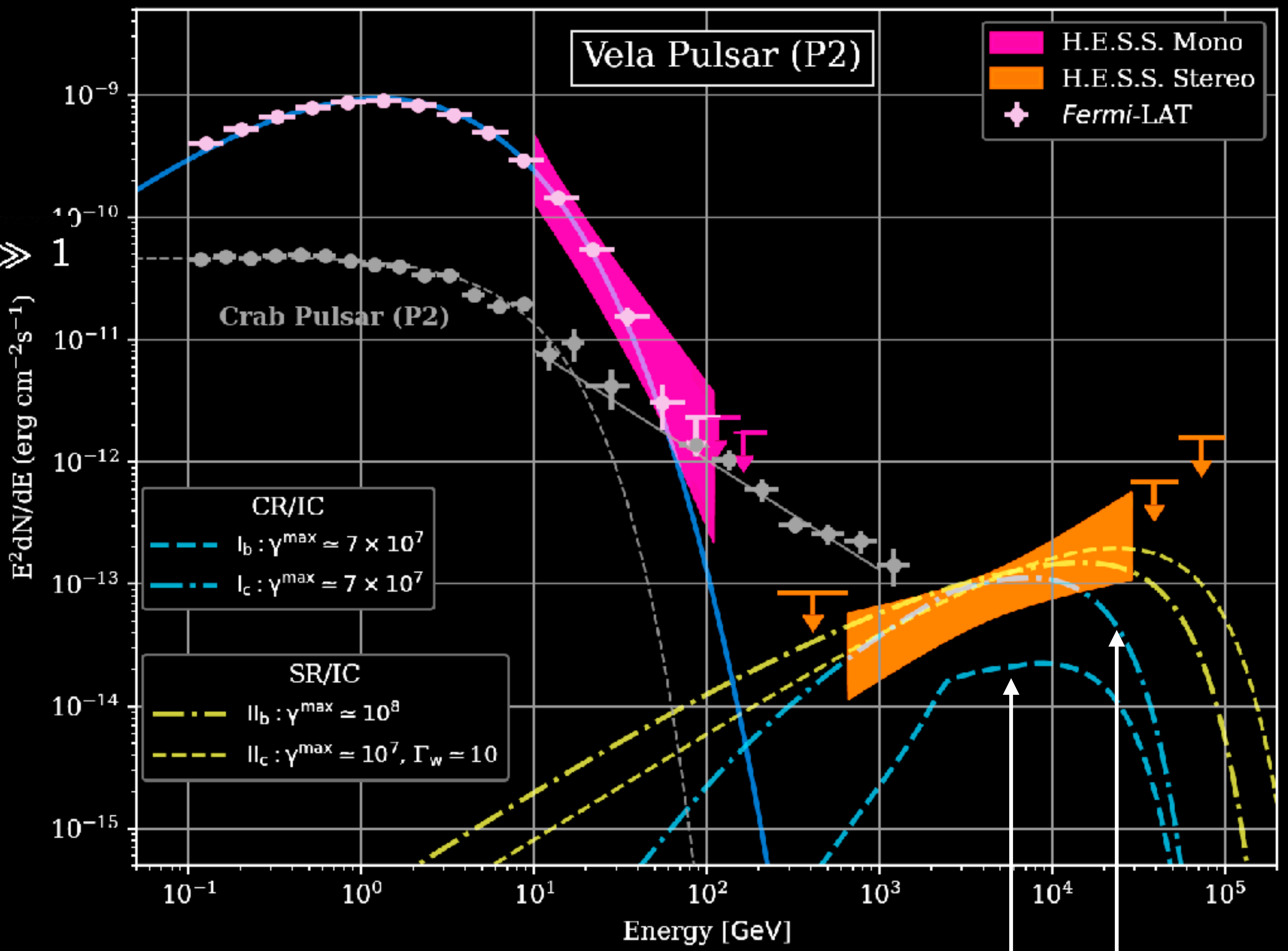

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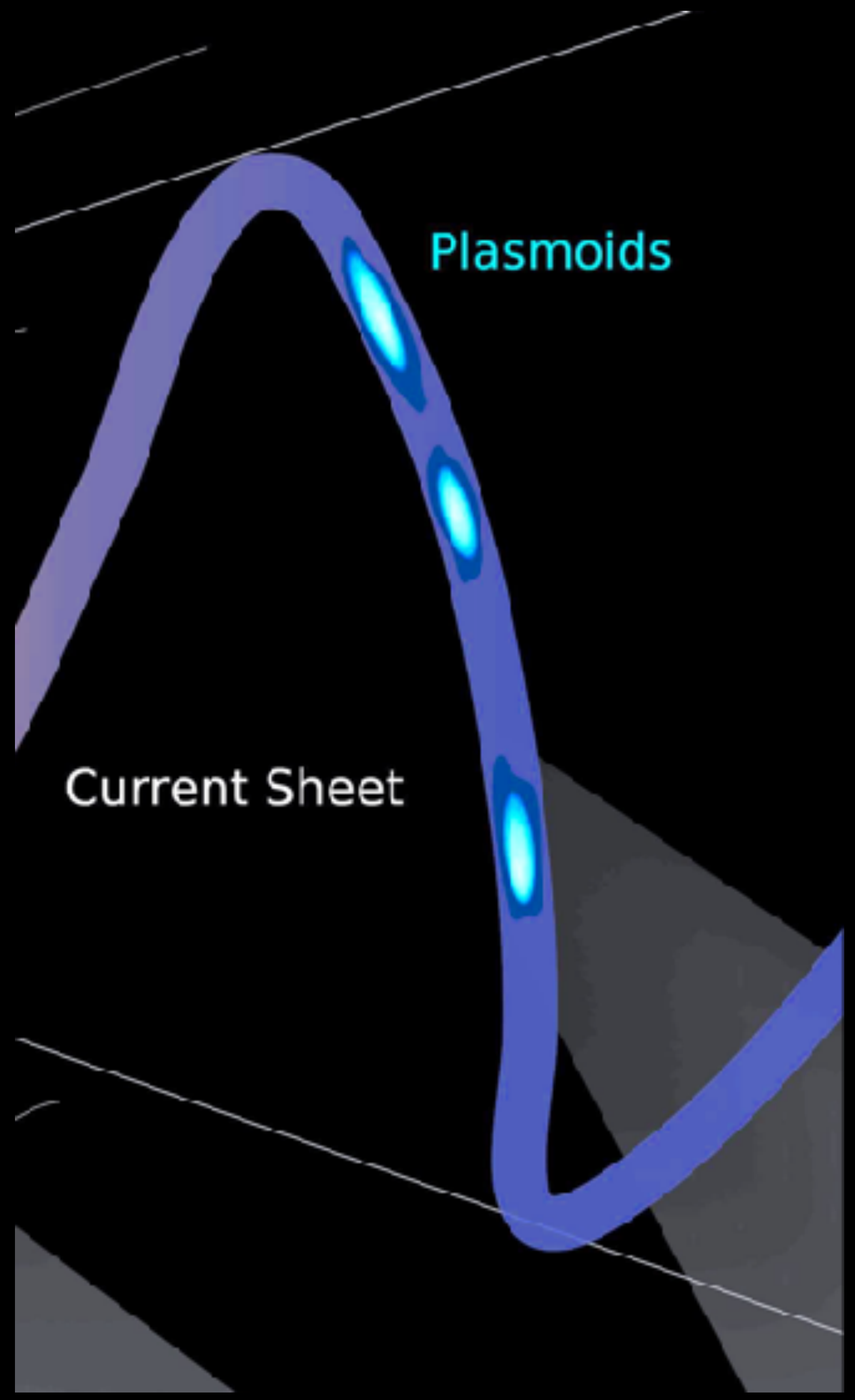
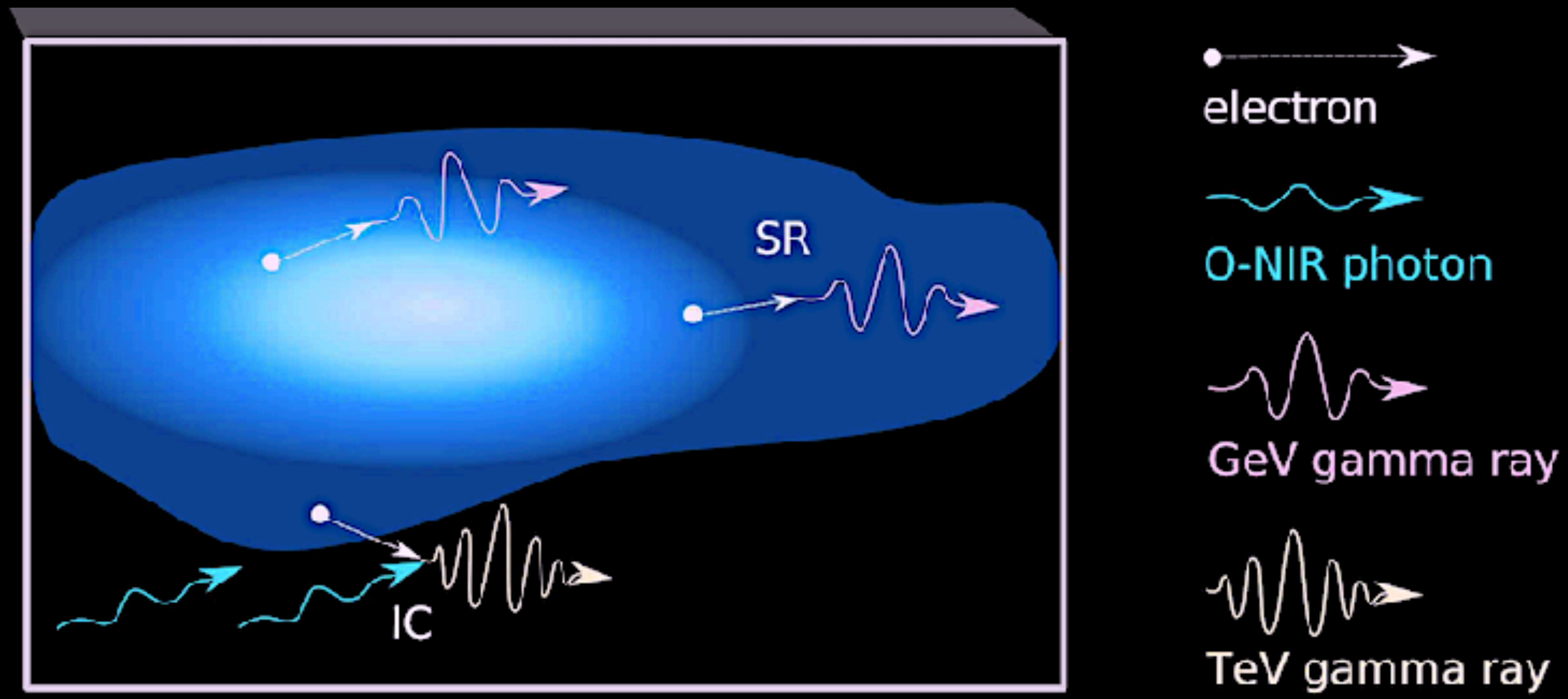
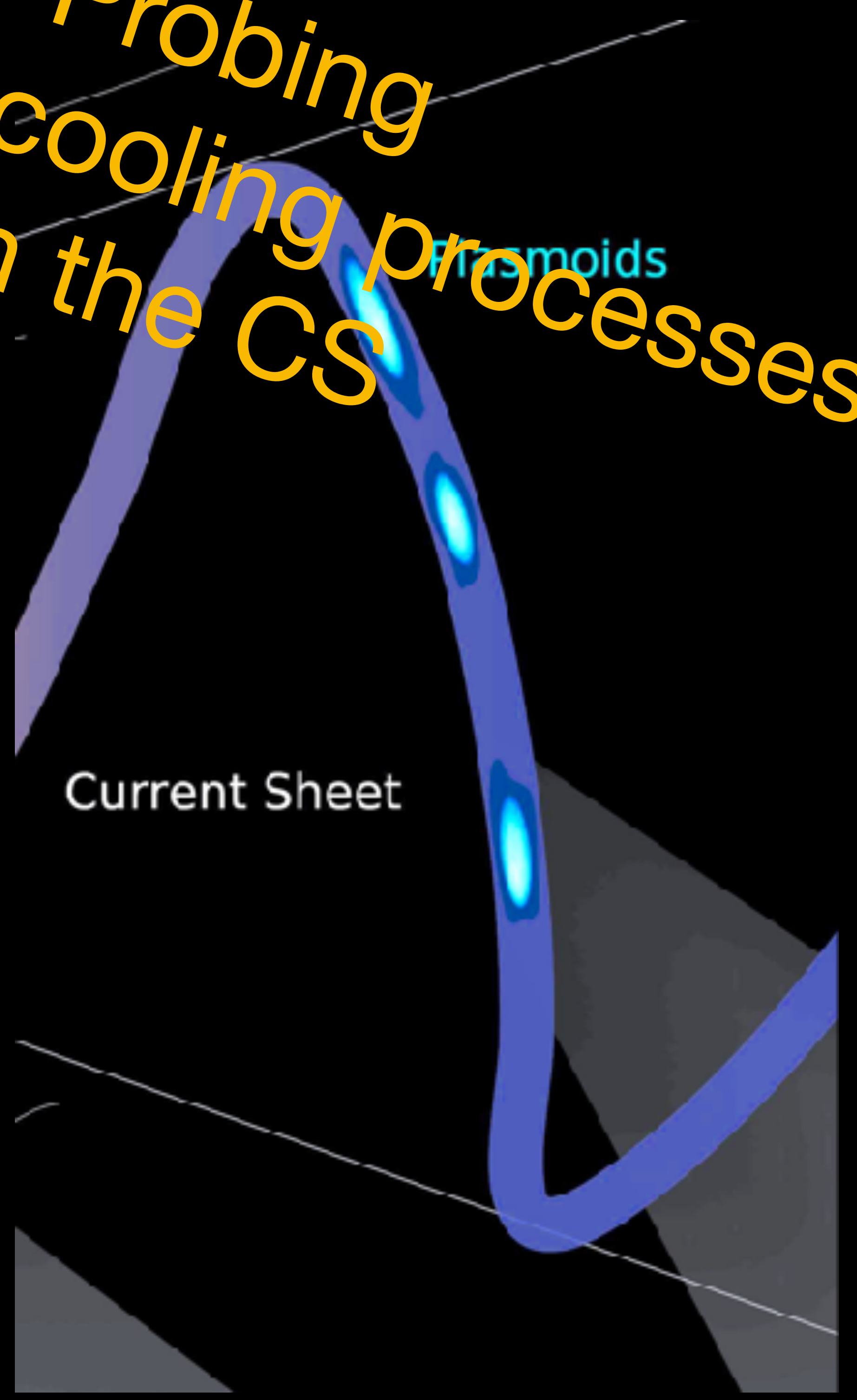




Origin of TeV γ rays?

Probing Acceleration & cooling processes deep in the CS



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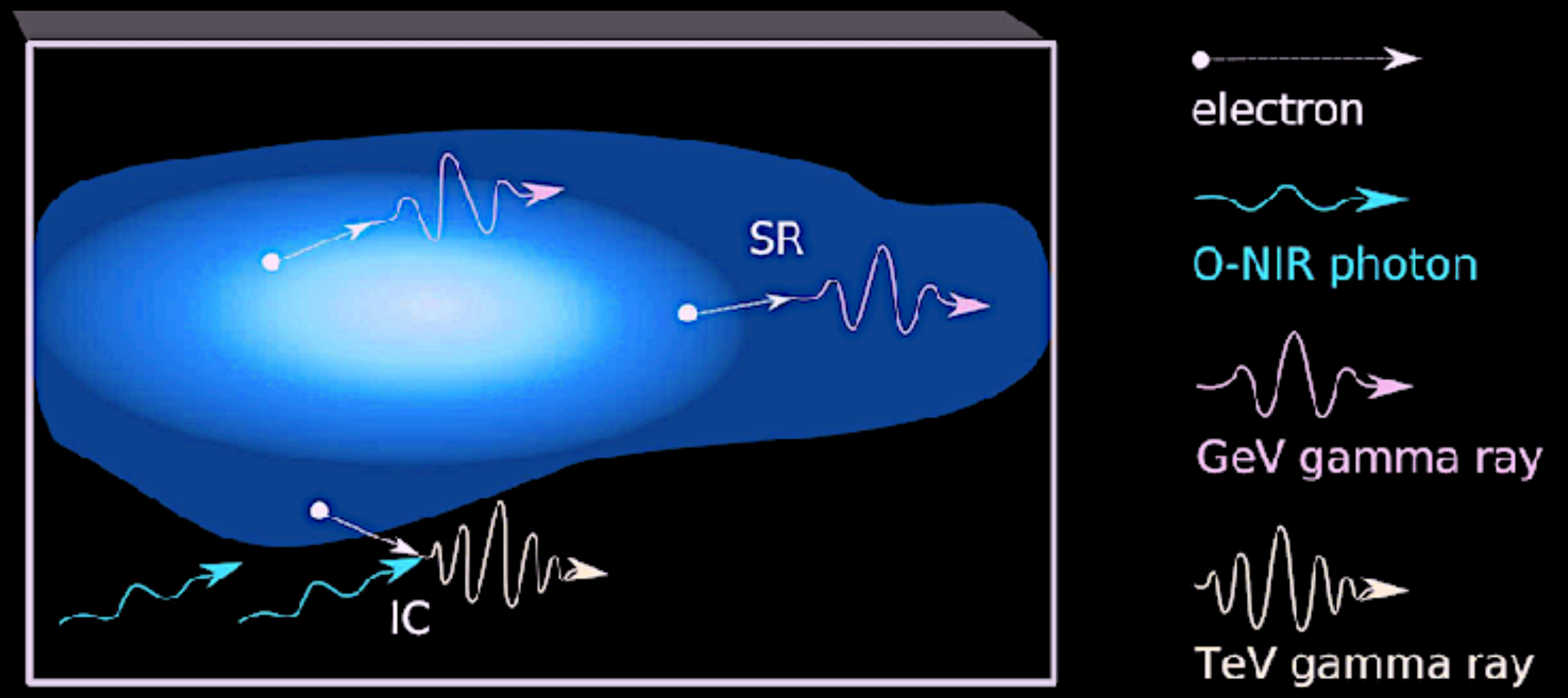

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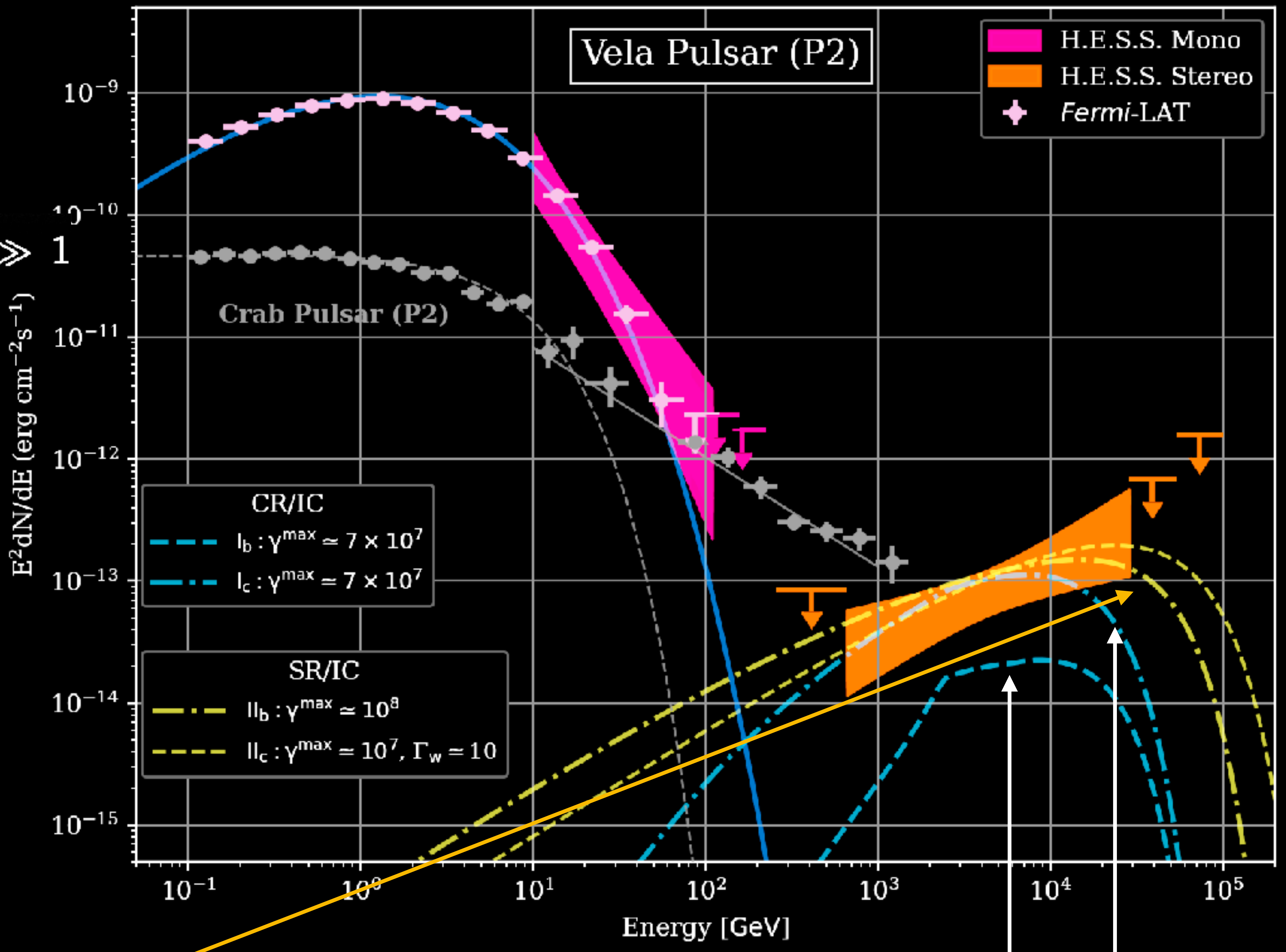
    - Re-acceleration after SR-cooling : Caustics
  - Doppler-boosted (bulk motion): $\left\{\begin{array}{l}\Gamma_{\rm w} \gtrsim 5\\ \simeq 5R_{\rm LC}\end{array}\right.$



- Effect of target photons energy range: [0.1 - 4] eV, vs [0.005 - 4] eV

Origin of TeV γ rays?

$$\alpha^{IC}_{Th} \sim -(p+1)/2 \approx -1 > \Gamma_{VHE}$$
$$\alpha^{IC}_{KN} \sim -(p+1) \approx -2$$

- Fit to theTeV data: $\gamma^{max}_{IC} \gtrsim 7 \times 10^7$
- CR/IC scenario:
  - Constraint by GeV data:
  - Different combinations of $(\eta, \hat{\xi})$ $\eta \ll 0.1$ and $\hat{\xi} \gg 1$
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- SR/IC scenario:
  - Constraint by GeV data and B:

$$\gamma^{max}_{SR} \simeq 1.3 \times 10^6 (B_\perp / B_{LC})^{-1/2} (E^{max}_{SR}/1.5\,\mathrm{GeV})^{1/2}$$

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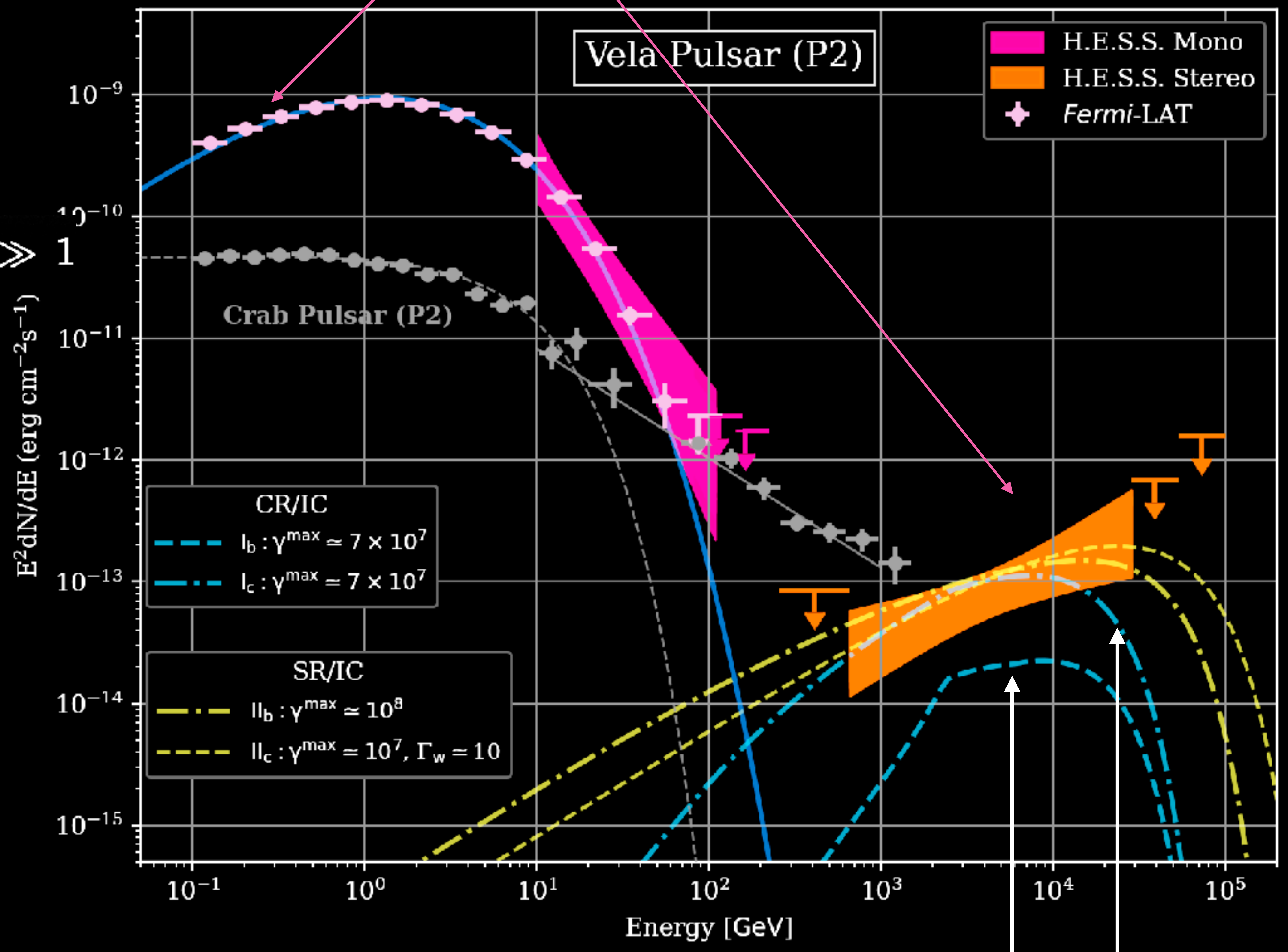
  - Doppler-boosted (bulk motion): $\left\{ \begin{array}{l} \Gamma_w \gtrsim 5 \\ \simeq 5 R_{LC} \end{array} \right.$

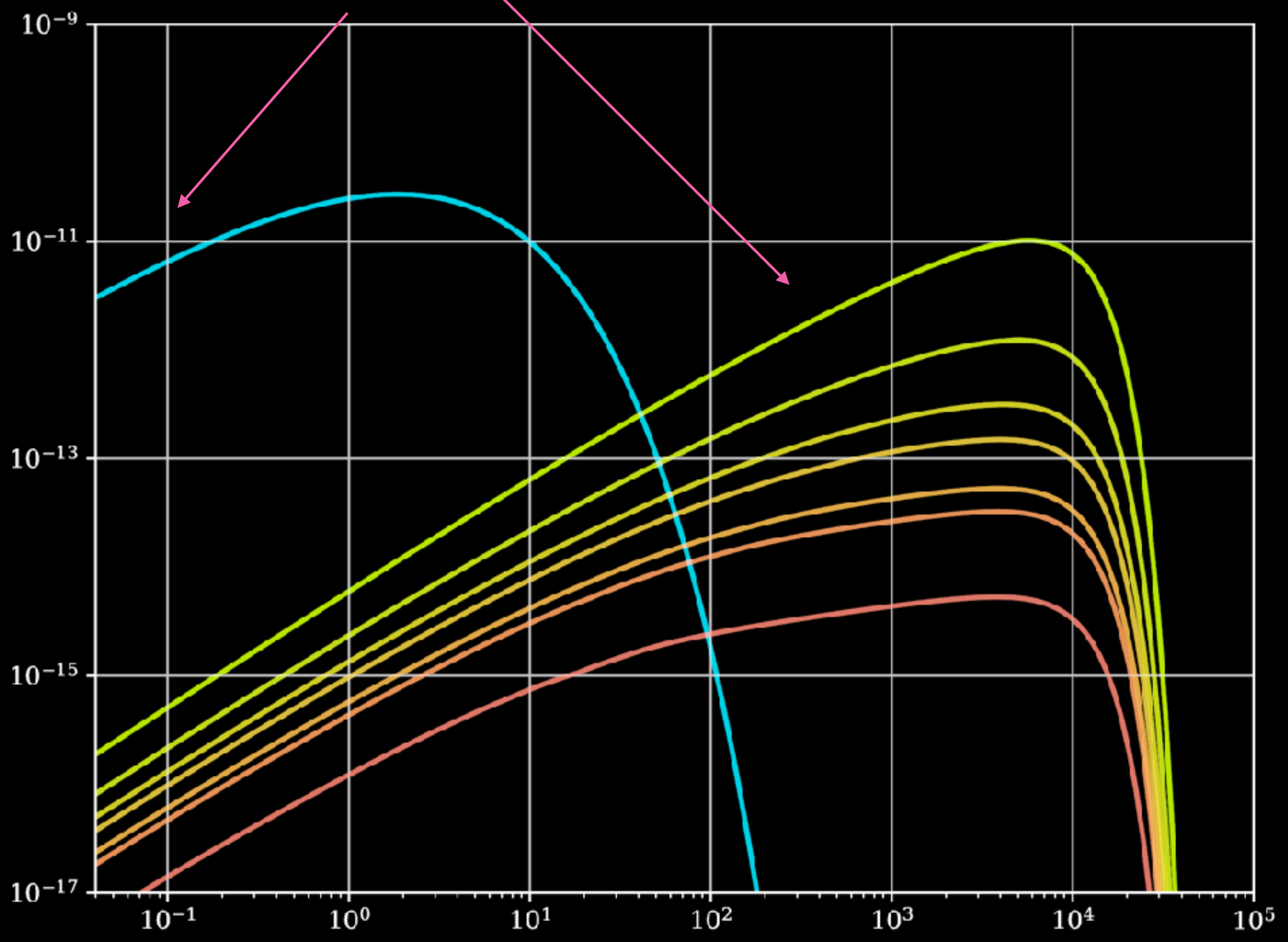


- Effect of target photons energy range: [0.1 - 4] eV, vs [0.005 - 4] eV

IC Targets

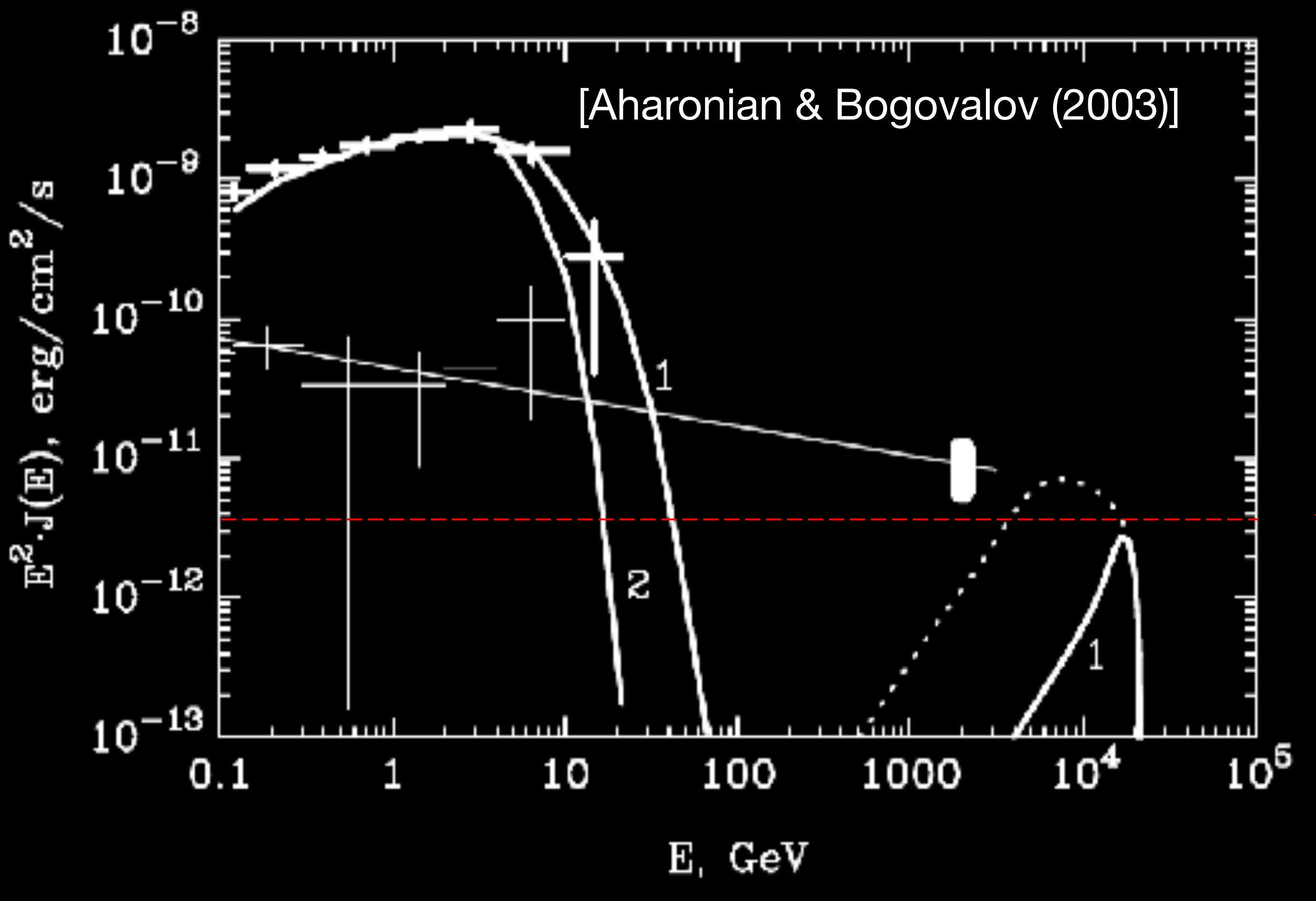
- IC targets :
  - Radio
  - Non thermal SYN (IR-O-UV, X,..),
  - Thermal X-rays (NS)
  - Other
- VHE index & luminosity is function of target εmin:
  - e.g.: NIR-O targets -> UV -X targets
  - Thomson to KN regime
- Degeneracies :
  - Target energy range (min)
  - IC Interaction volume
  - Assuming same population !
  - Underlying particle distribution

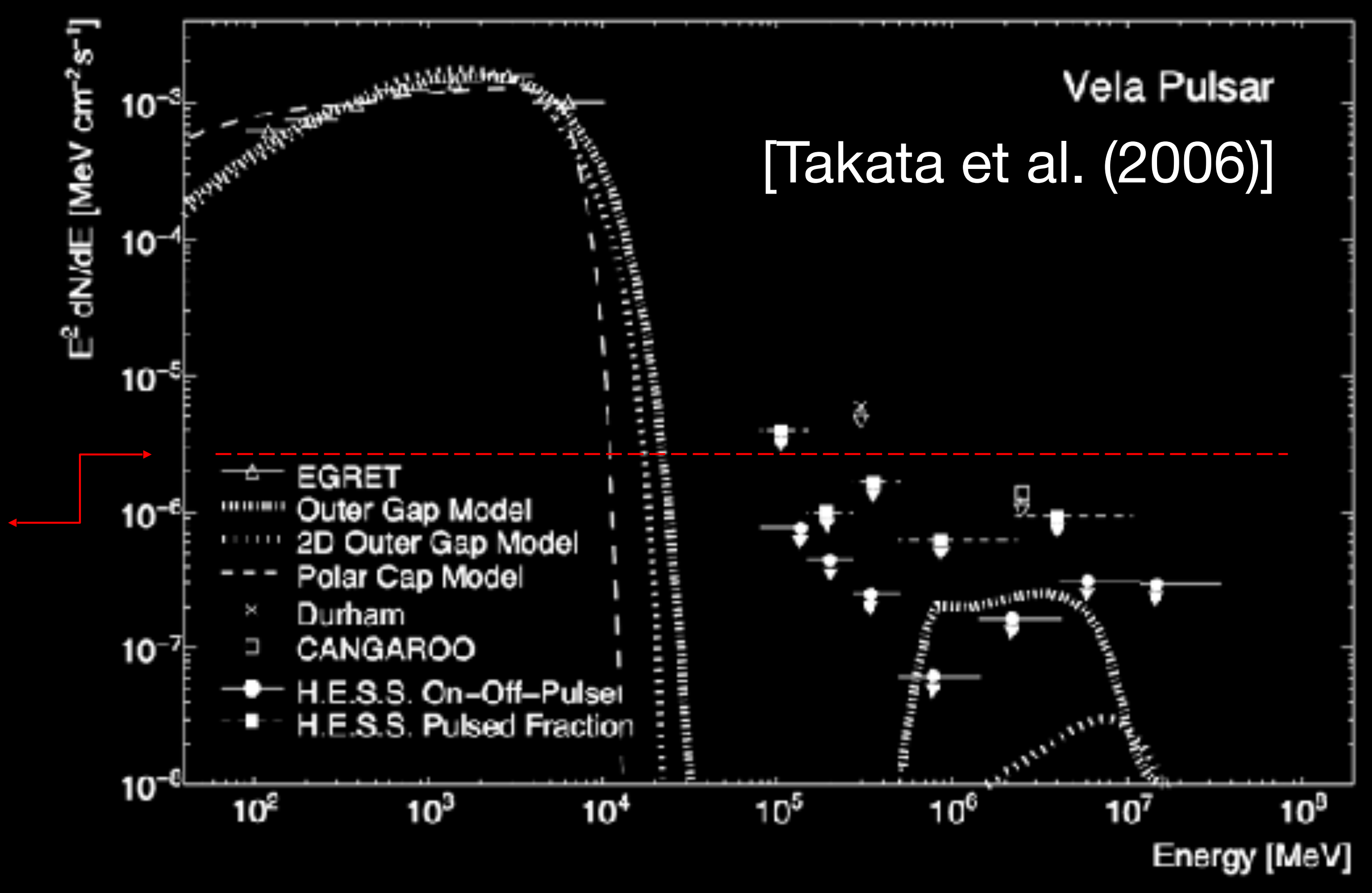
$$\alpha^{IC}_{Th} \sim -(p+1)/2$$
$$\alpha^{IC}_{KN} \sim -(p+1)$$

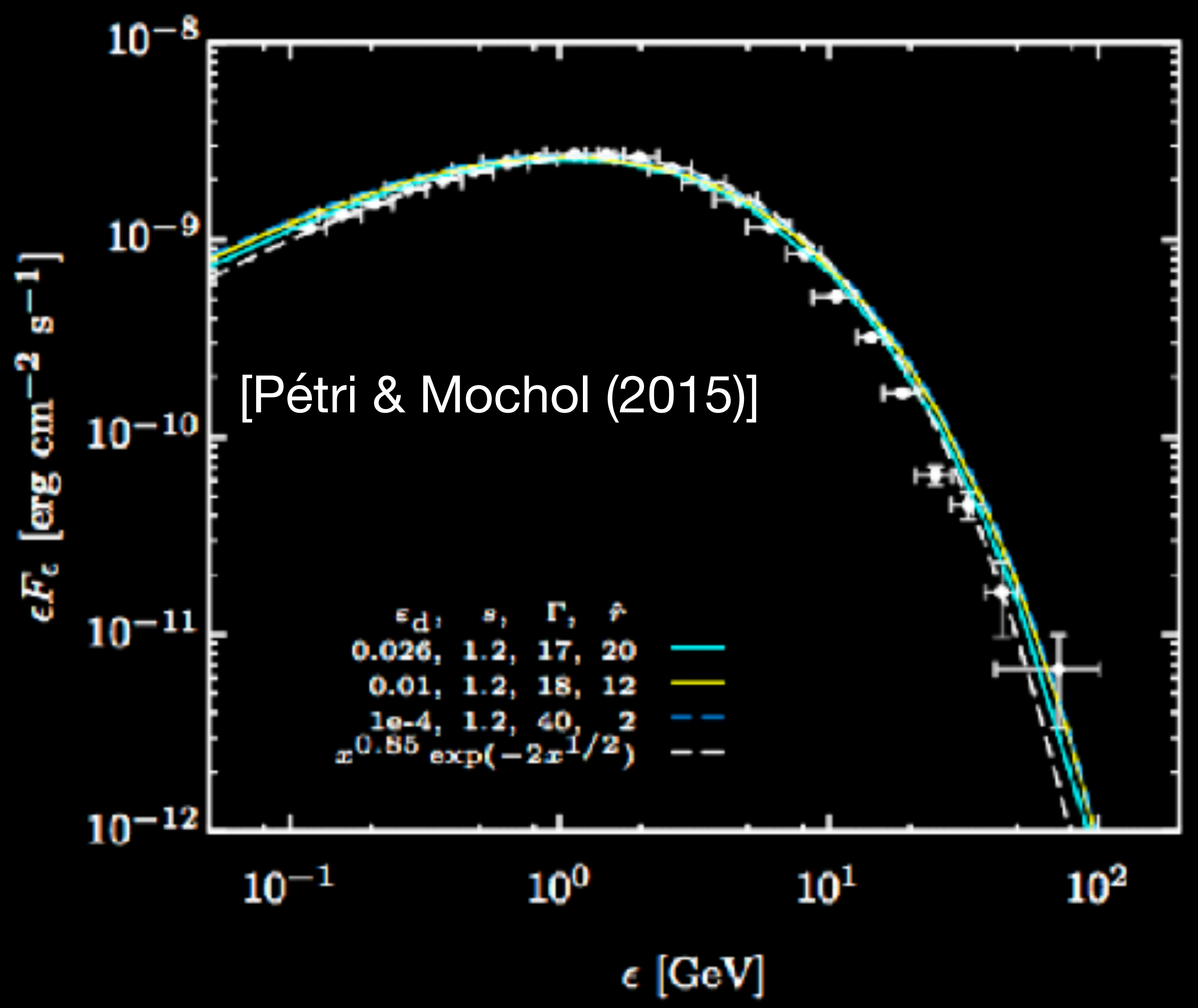


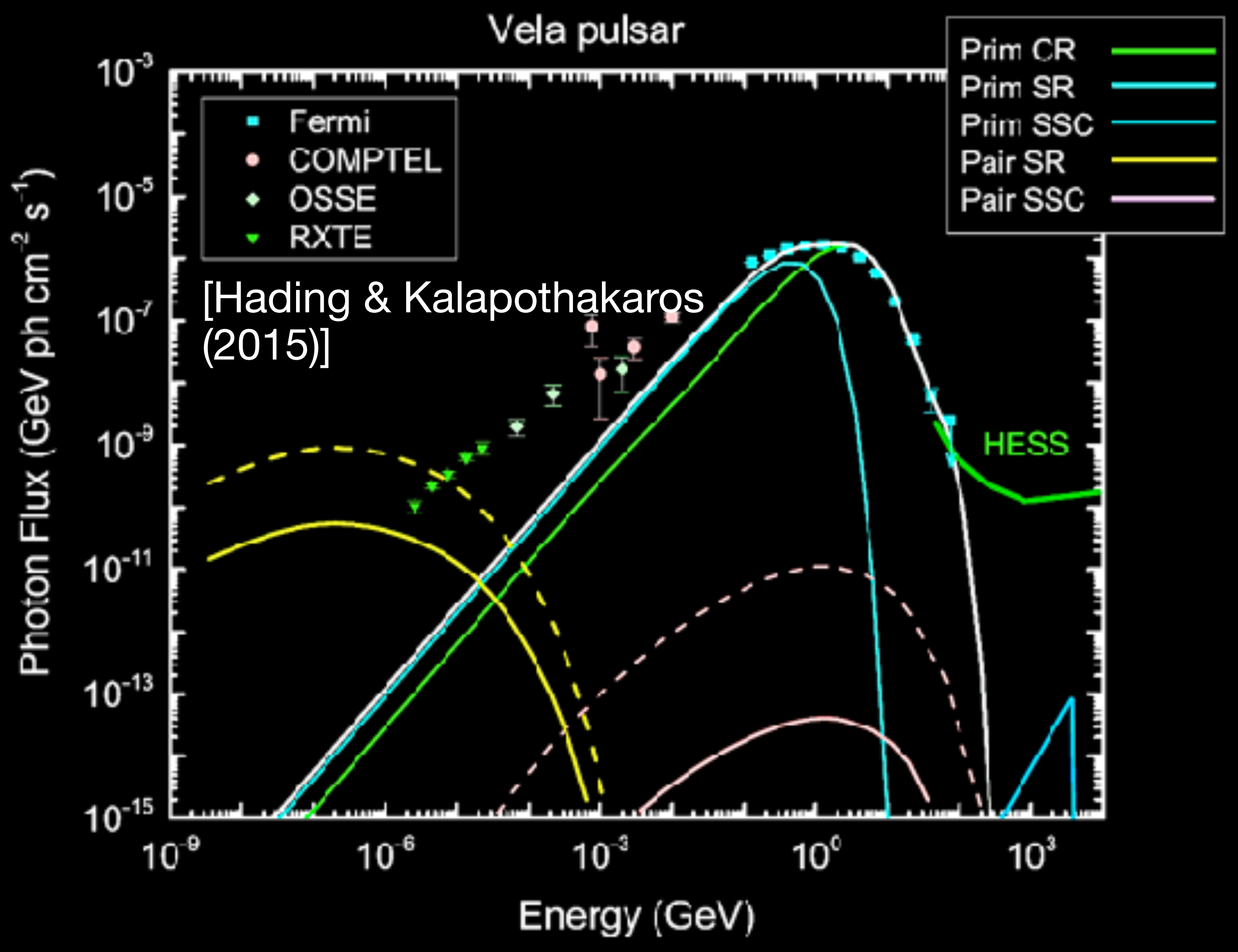
Pre-discovery Expectations

- Possibility of a second IC component: Cheng, Ho & Ruderman (1986)
- CR/IC: early Outer-Gap models
  - Romani (1996): primary e- + IR
  - Hirotani & Shibata (2001): primary e- + IR
  - Aharonian & Bogovalov (2003): primary e- + IR->FIR
- Takata et al. (2006): 2D OG model
- Wind:
  - Bogovalov & Aharonian (2000): Pulsed IC from unchecked wind scattering of non-thermal targets (Crab)
- Current sheet, magnetic reconnection:
  - Lyubarskii (1996): SR photons around CS
  - Kirk, Skjærasen & Gallant (2004): SR from striped wind (outside LC)
  - Kirk (2004): acceleration & cooling in the CS: 2 steps -> e- energies beyond SR burn-off
- Synchrotron Self-Compton (SSC):
  - Lyutikov (2012, 2013): Doppler boosted Cylcotron Self-Compton
  - Pétri & Mochol (2015): SR (GeV)
    - Crab: 100-400 GeV - 1 TeV ok
    - Vela: no measurable SSC component
  - Hading & Kalapothakaros (2015):
    - Force-free, slot-gap extended > LC, no SSC for Vela
- Osmanov & Rieger (2019): magneto-cetnrifugal acceleration





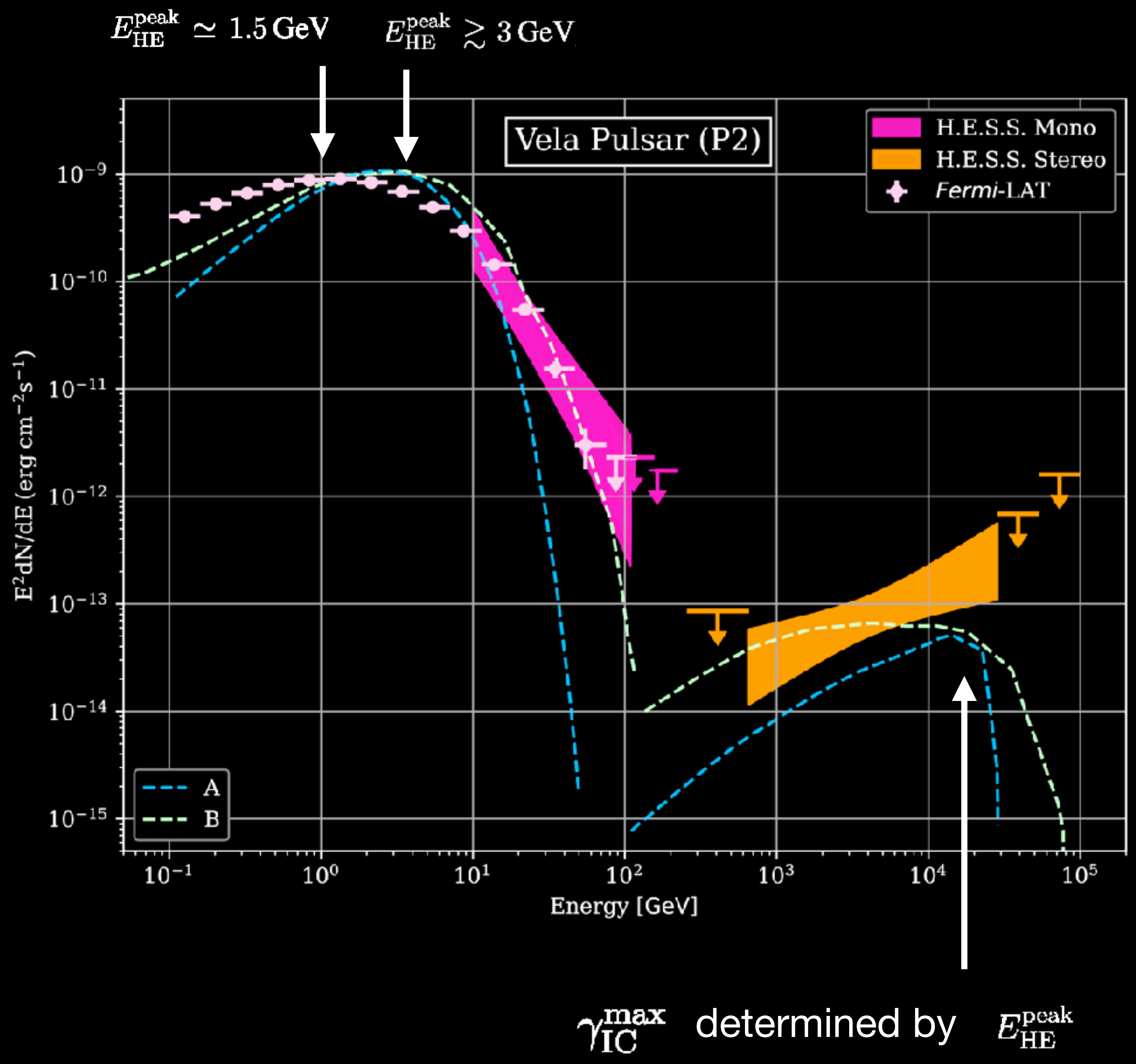




Post-discovery models

- More complex approaches than the heuristic spectral models
- Provide light curve predictions
- A : OG model [Rudak & Dyks (2017)]
  Phase-resolved SED
- B : Separatrix/Current sheet [Harding et al. 2018, update of Harding et al. 2015]
  Phase-averaged SED (normalised here)

- Notes:
- Both models predict a larger GeV peak energy
- They are not fitted on data though
- Larger GeV peak energy, provides for larger Lorentz factors for IC emitting particles
- The target SR photon spectrum is extrapolated for both models:
  E_min=0.001 eV (A) and 0.005 eV (B)

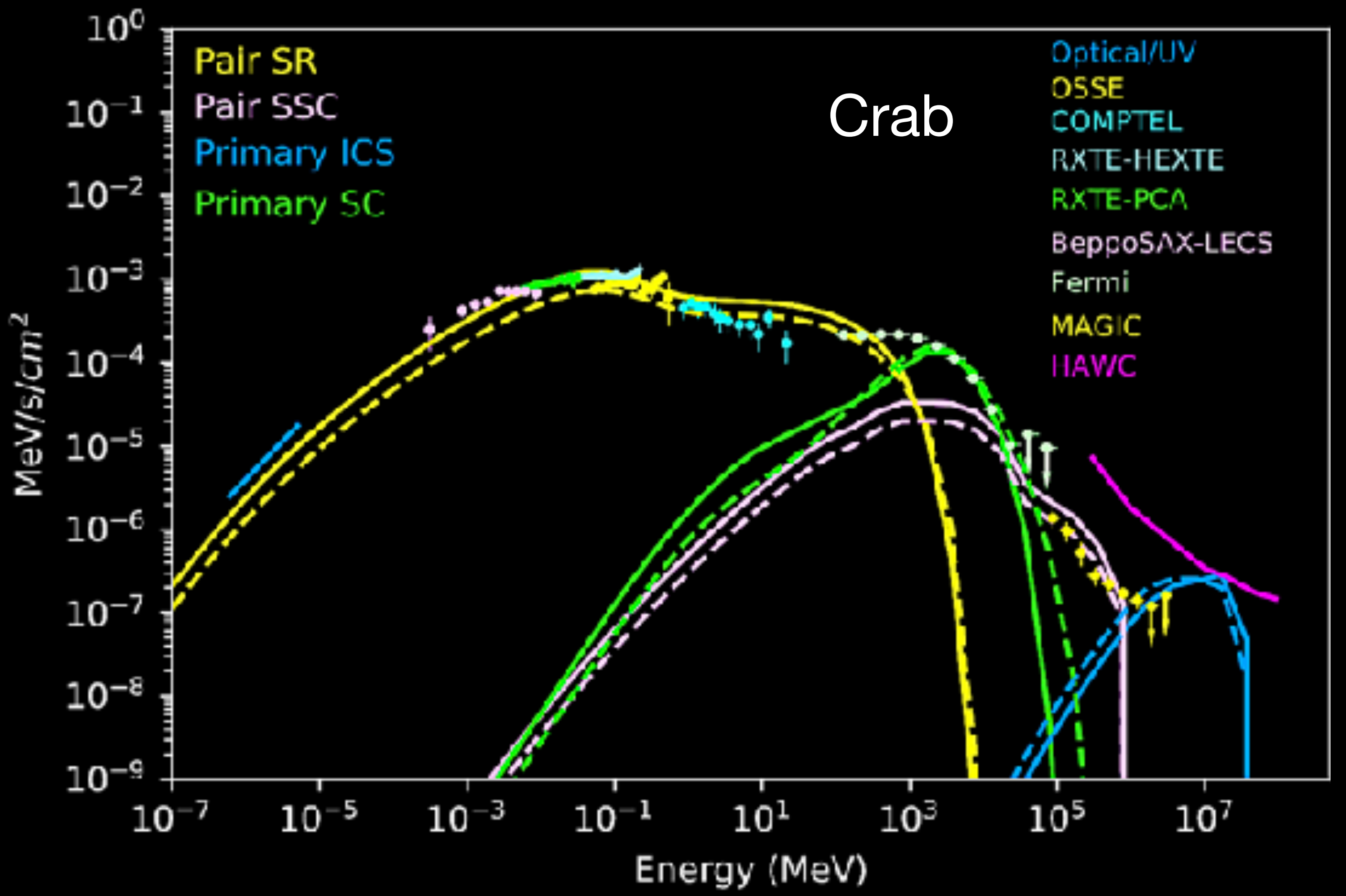


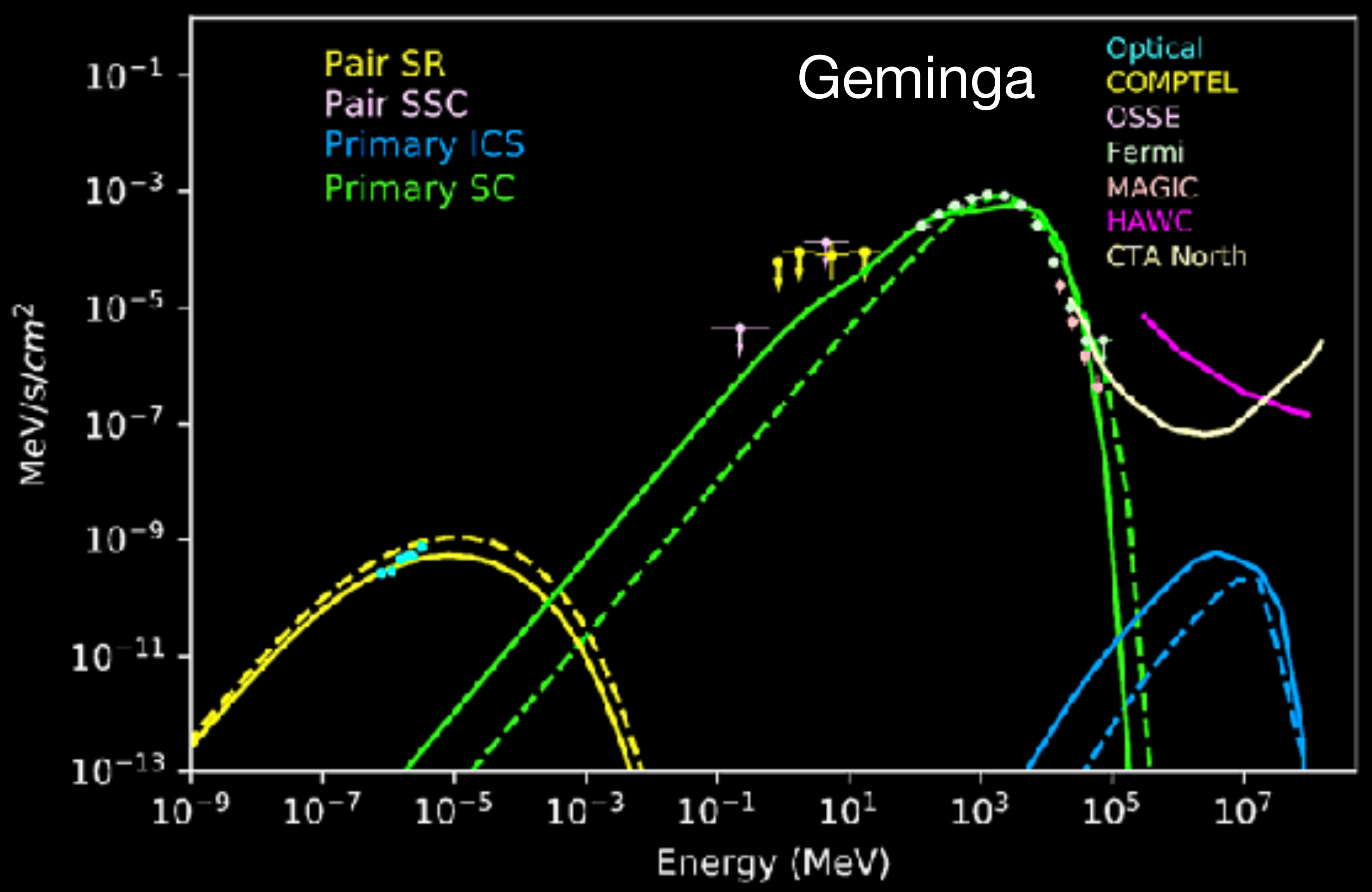
Post-discovery models

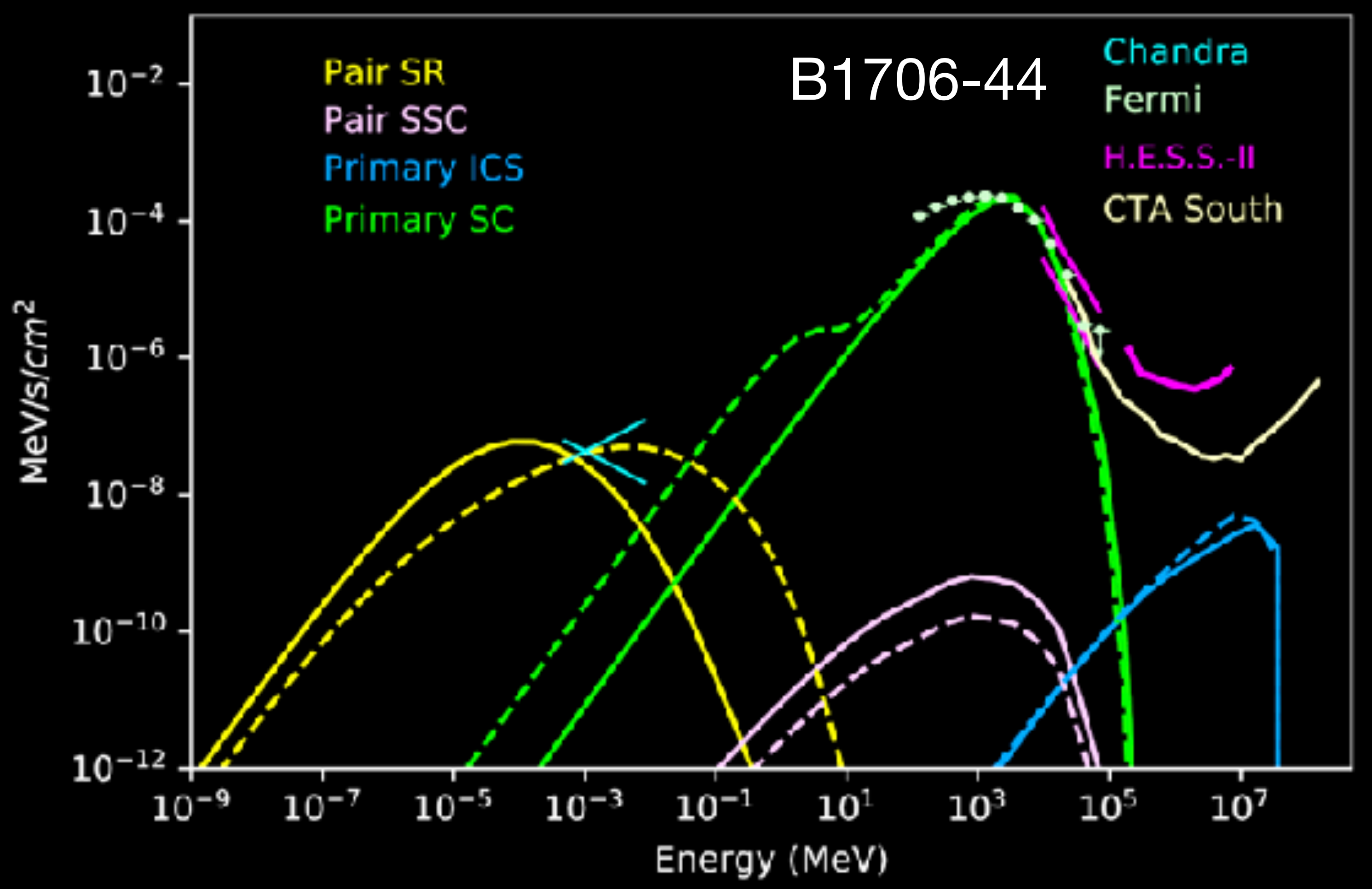
Separatrix/CS model [Harding et al. 2021]

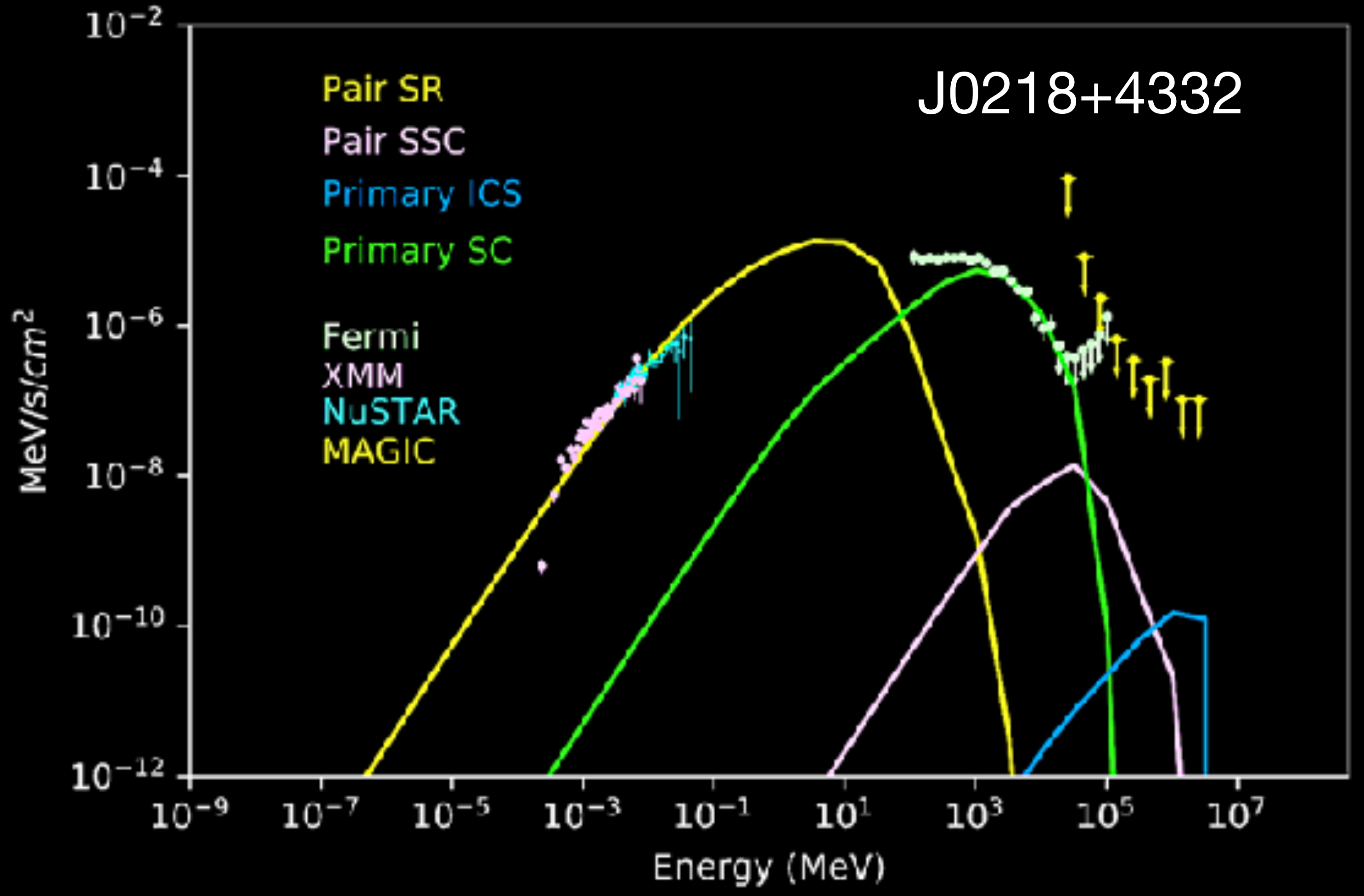
- Computation for Vela, Crab, Geminga, PSRB1706-44 & PSR J0218+4332

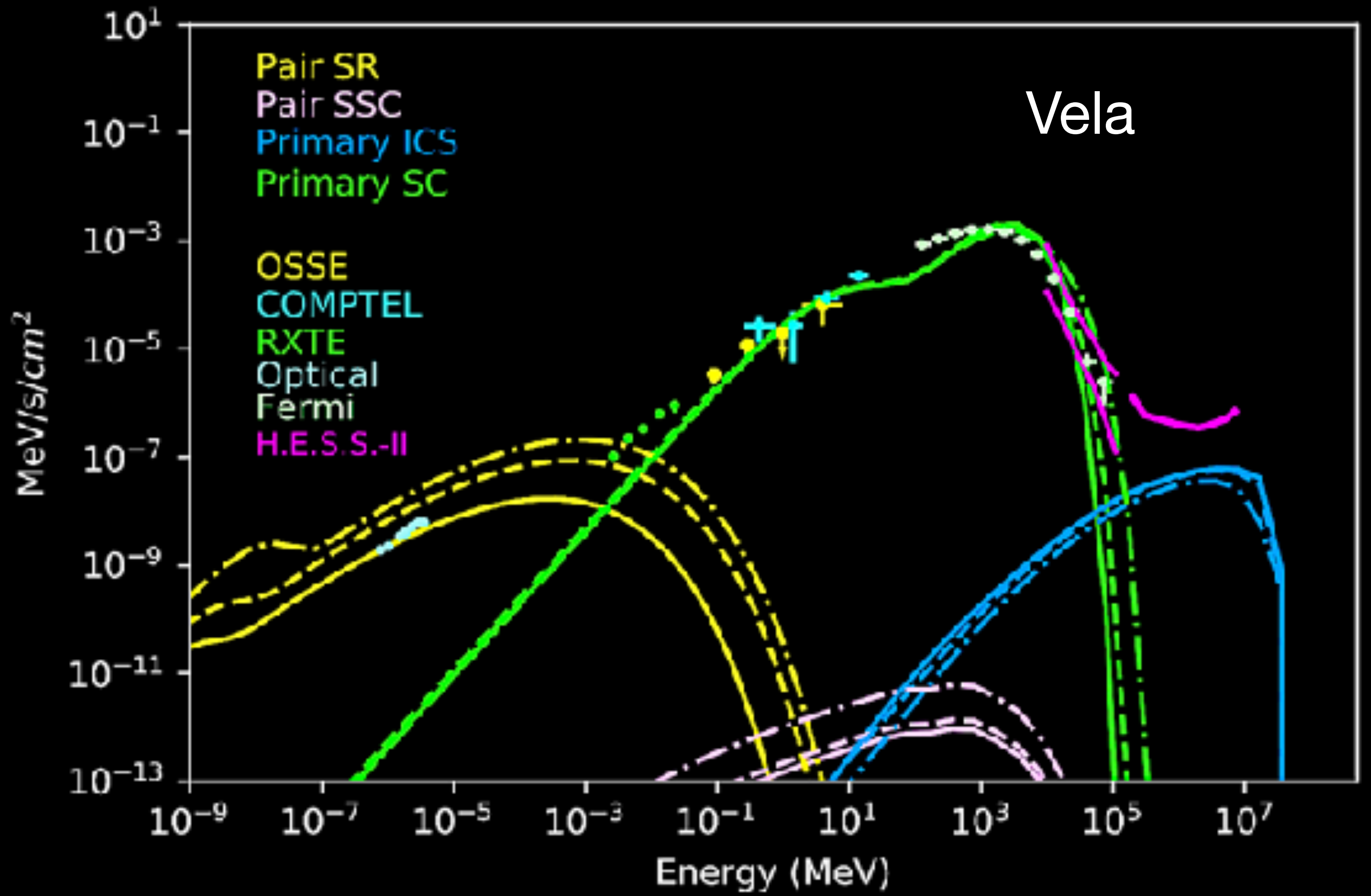
- Vacuum-retarded dipole < 0.2 R_lc
- Force-free B 0.2-2 R_lc
- Acceleration in gaps extending beyond LC
- Main IC emitting particles accelerated in the CS, though not through magnetic reconnection
- SCR from primaries -> GeV
- IC of pair SR by primaires -> IC
- Pair SSC -> MeV to TeV







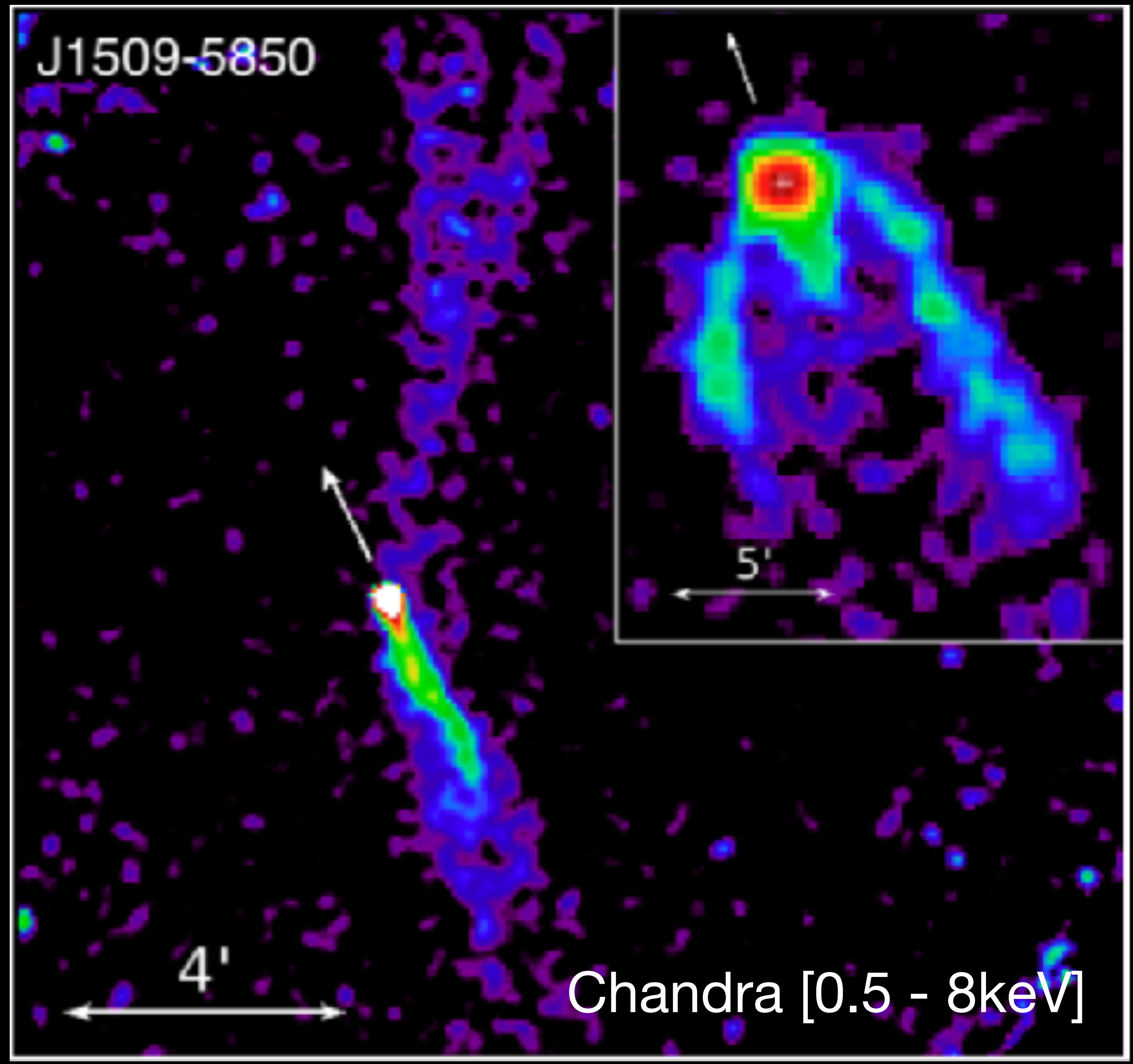


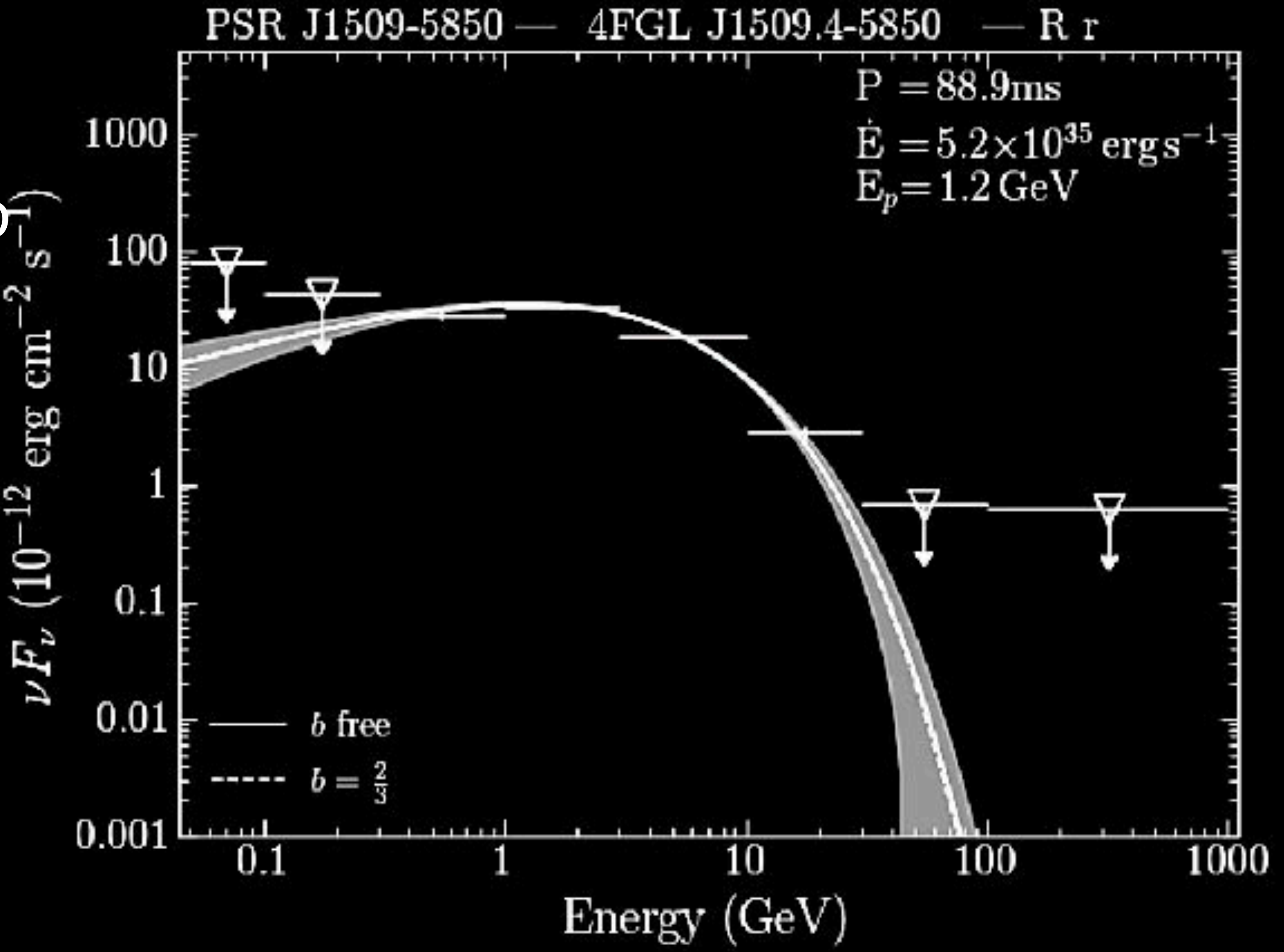


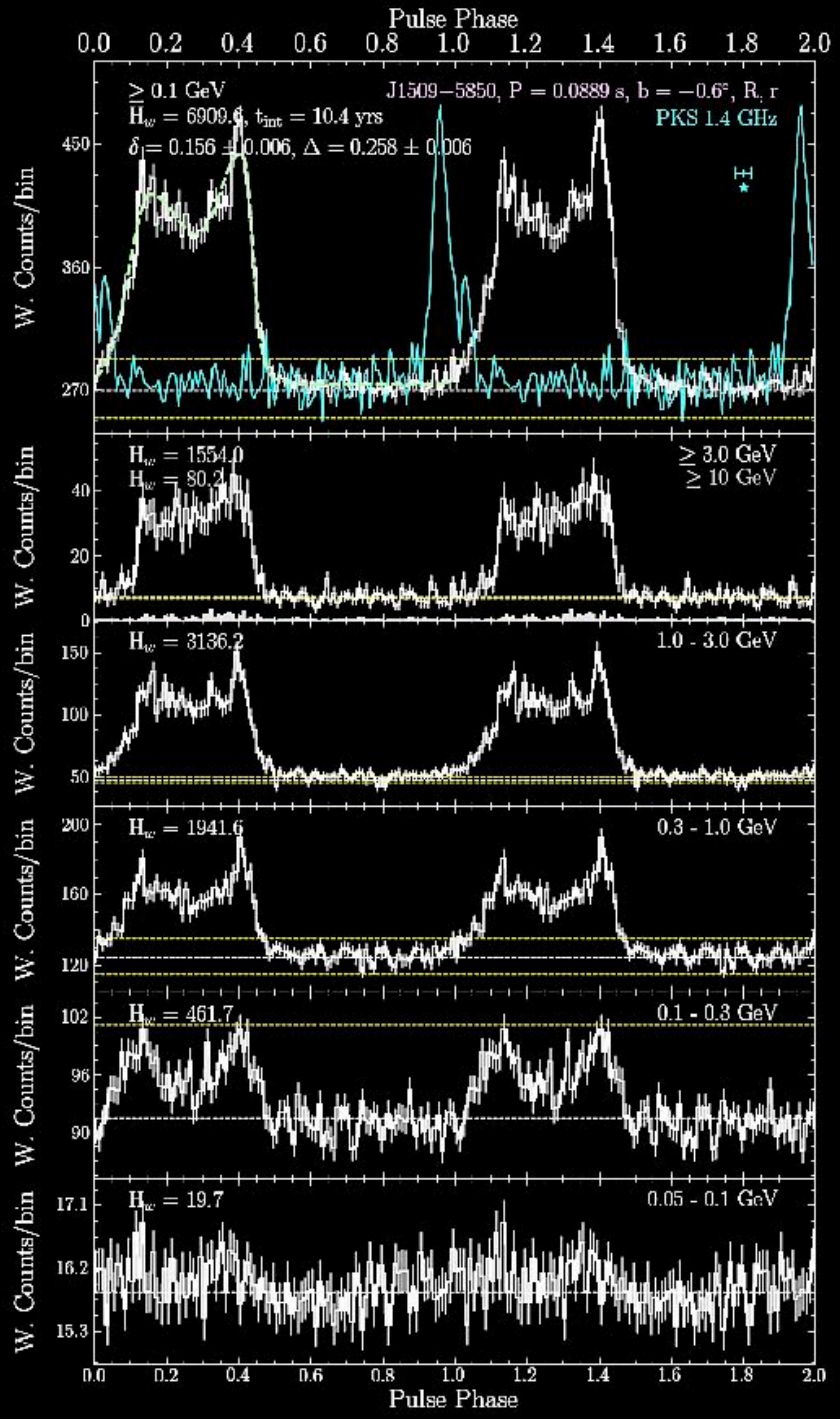
A new comer !
PSR J1509-5850

- Discovered in the Parkes survey in 2003
- Not to be confused with the close-by PSR B1509-58 in the MSH 15-52 remnant
- Embedded in a compact X-ray PWN with moving NE (similar to Geminga PWN) with a bow-shock
- E_dot = 5.1x 10^{35} erg/s : 7% Vela
- P=89 ms (as Vela), age ~153 kyr
- F~1.3 x10^{10} erg/cm^2/s
  i.e. 70 times less bright than Vela
- But d~3.4 kpc, ~4 times more luminous
- Light curve: 2 peaks connected with a bridge, but no significant evolution with energy
- As compared to Vela :
  δ(radio/γ) = 0.16 vs 0.13 : similar
  but:
  Δ(P1, P2) =0.26 < 0.43
  —> inclination, viewing angle

[Klinger et al. 2016]





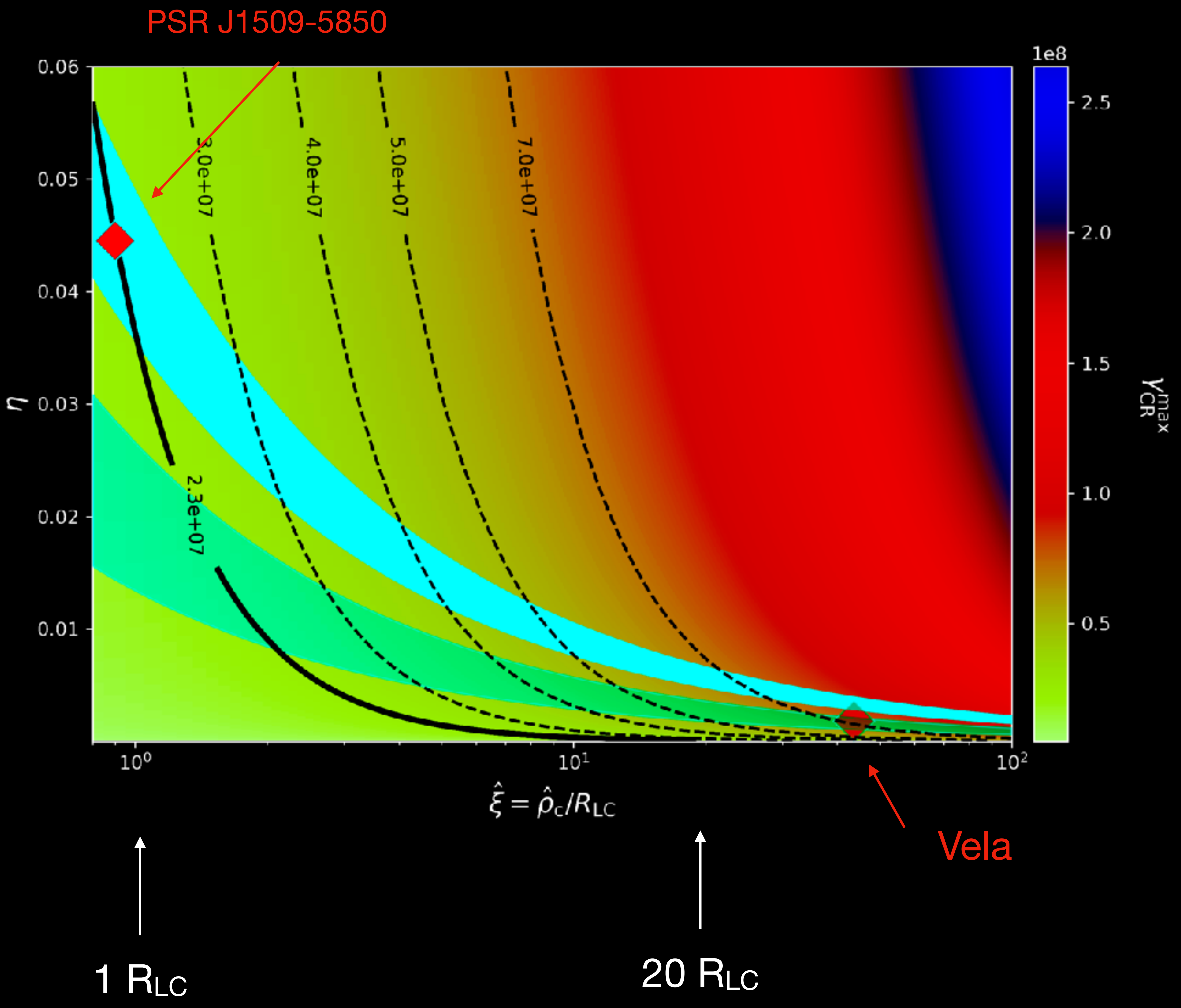


3PC [Smith et al. 2023]

PSR J1509-5850
Interpretation

- CR: $\gamma_{CR}^{max} \simeq 3\times 10^7\, \xi^{1/2}\eta_{-1}^{1/4}$
- SR: $\gamma_{SR}^{max} \simeq 2.5\times 10^6 (B_\perp/B_{LC})^{-1/2}\,(E_{SR}^{max}/1.7\,\mathrm{GeV})^{1/2}$
- $N_0^{CR}/N_0^{SR} \sim 75.$
- $N_0^{CR}(\mathrm{J1509})/N_0^{CR}(\mathrm{Vela}) \sim 10$ $\quad N_0^{SR}(\mathrm{J1509})/N_0^{SR}(\mathrm{Vela}) \sim 10$
- Not sufficient to explain $L_{TeV}(\mathrm{J1509})/L_{TeV}(\mathrm{Vela}) \sim 150$
- Emission zone ~ 1 R_LC vs Vela >10 R_LC
- Magnetic conversion efficiency >> Vela

	J1509–5850	Vela	units	ratio
dist	3.4	0.29	kpc	≈ 12
P	88.93	89.33	s	≈ 1
R_{LC}	4224	4262	km	≈ 1
B_{LC}	15.2	56.0	10^3 G	0.27
$\dot{\mathcal{E}}$	5.2	69.0	10^{35} erg/s	0.074
L_{GeV}	40	9.8	10^{33} erg/s	≈ 4
L_{TeV}	300	2	10^{30} erg/s	≈ 150
ϵ_{ffGeV}	$7.1 10^{-2}$	$1.4 10^{-3}$	–	≈ 50
ϵ_{ffTeV}	$6.1 10^{-4}$	$1.9 10^{-7}$	–	≈ 3200
$\mathcal{R}_{FP}$	≈ 1	10^{-1}	–	≈ 10

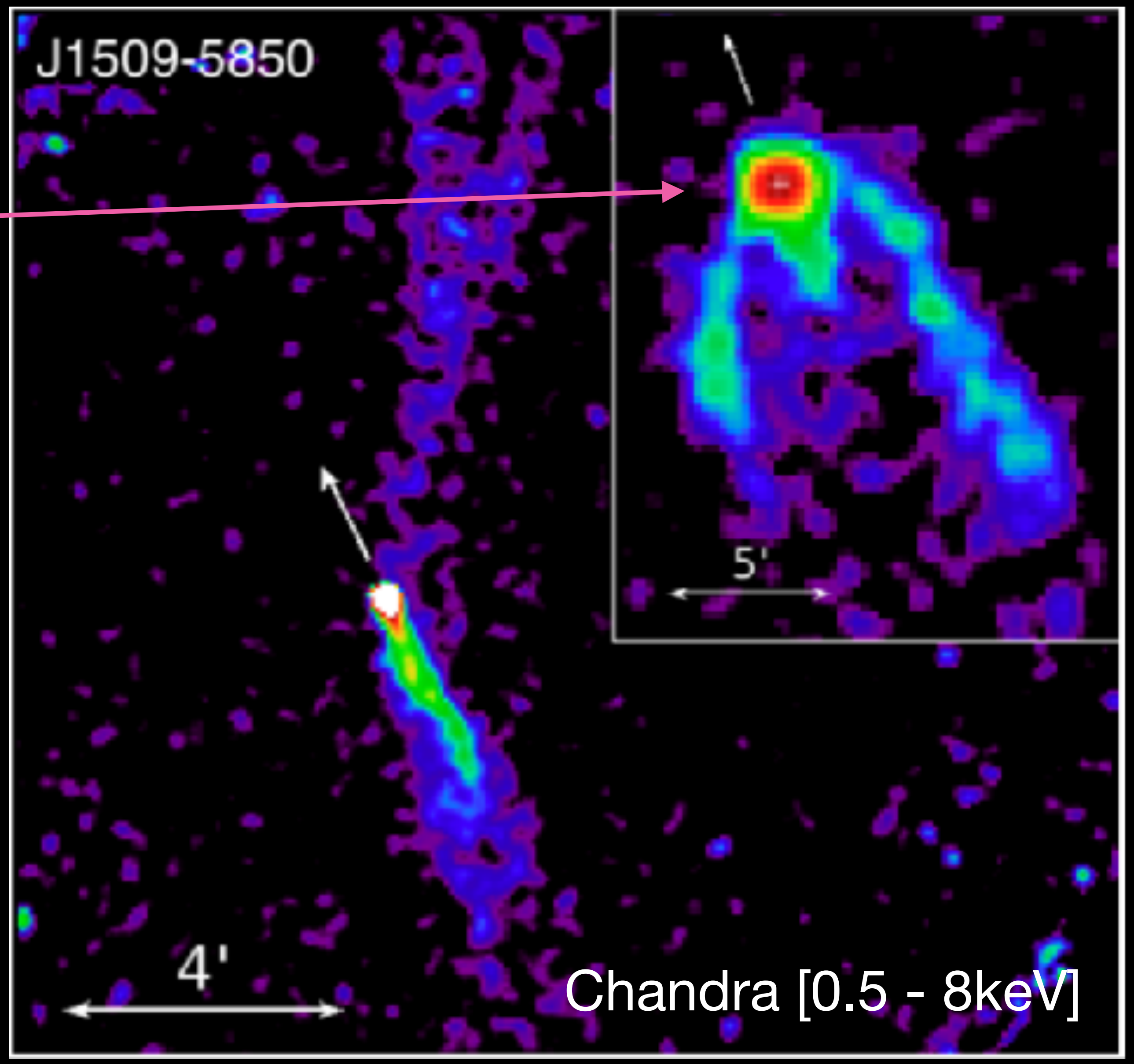


PSR J1509-5850
IC Targets /Geometry

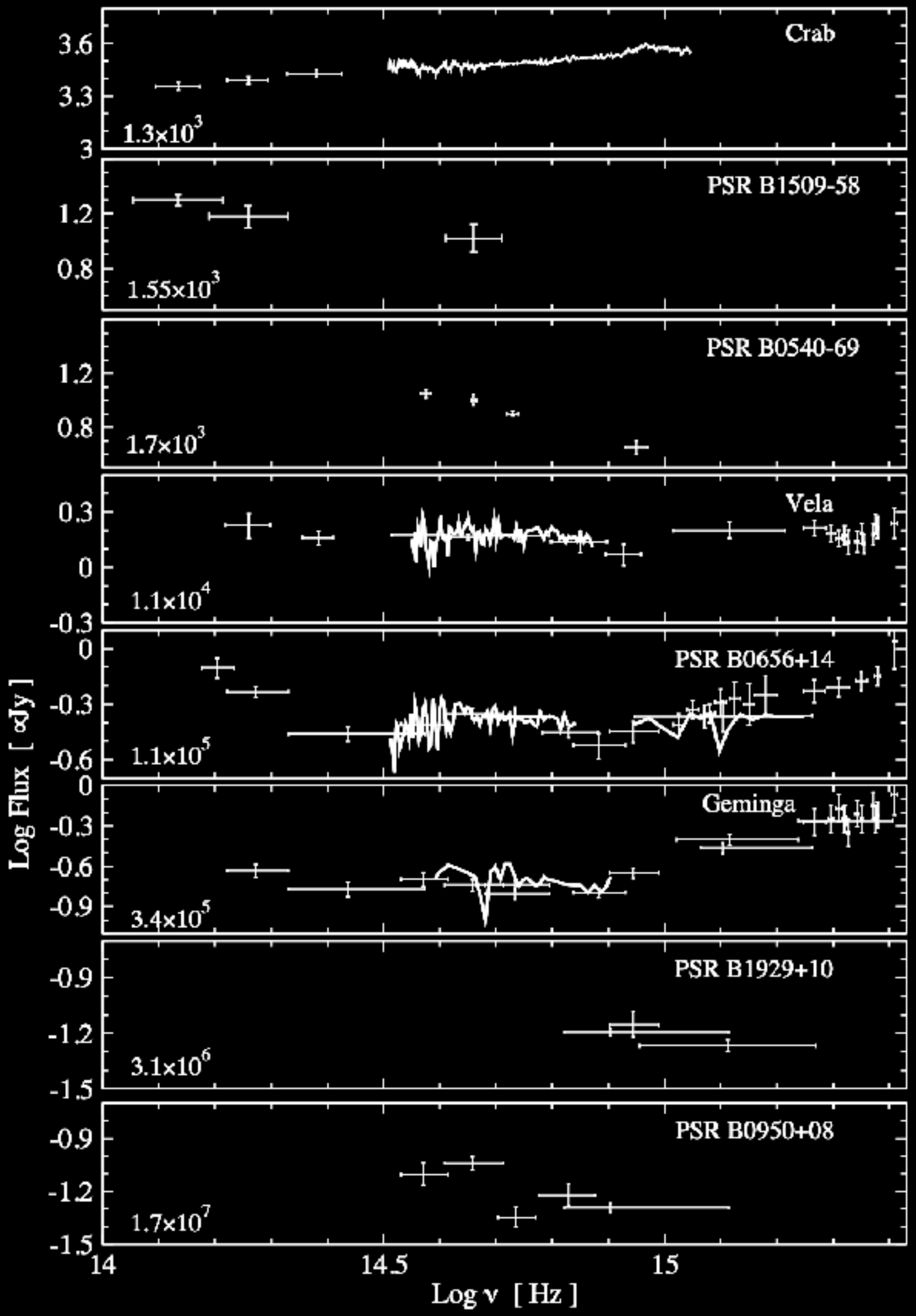
- TeV: Inverse Compton targets ?
  - Flat O-NIR for young pulsars (<10^4 yrs) transiting towards UV up to non-thermal X-rays
  - Tail of the SR emission of secondary pairs ?
  - NS thermal X-rays ?
  - Non thermal X-rays ?
    - head of X-ray PWN : 10^{32} erg/s

- Geometry of emission zone :
  - No radio polarisation : no RVM
  - γ-ray only or Radio+ γ-ray LC modelling

	J1509–5850		Vela	
$\delta_{r/\gamma}$	0.156		0.133	
$\Delta_{P1/P2}$	0.258		0.431	
Model	R+γ	γ	R+γ	γ
SG	(46, 66)	(46,43)	(43, 69)	(46,74)
OG	(85, 76)	(15, 90)	(71,83)	(48,83)
OPC	(56, 65)	(82, 18)	(56, 77)	(66, 76)
CS	–	(40, 24)	–	(65, 58)



[Magnani 2009]



PSR J1509-5850
IC Targets

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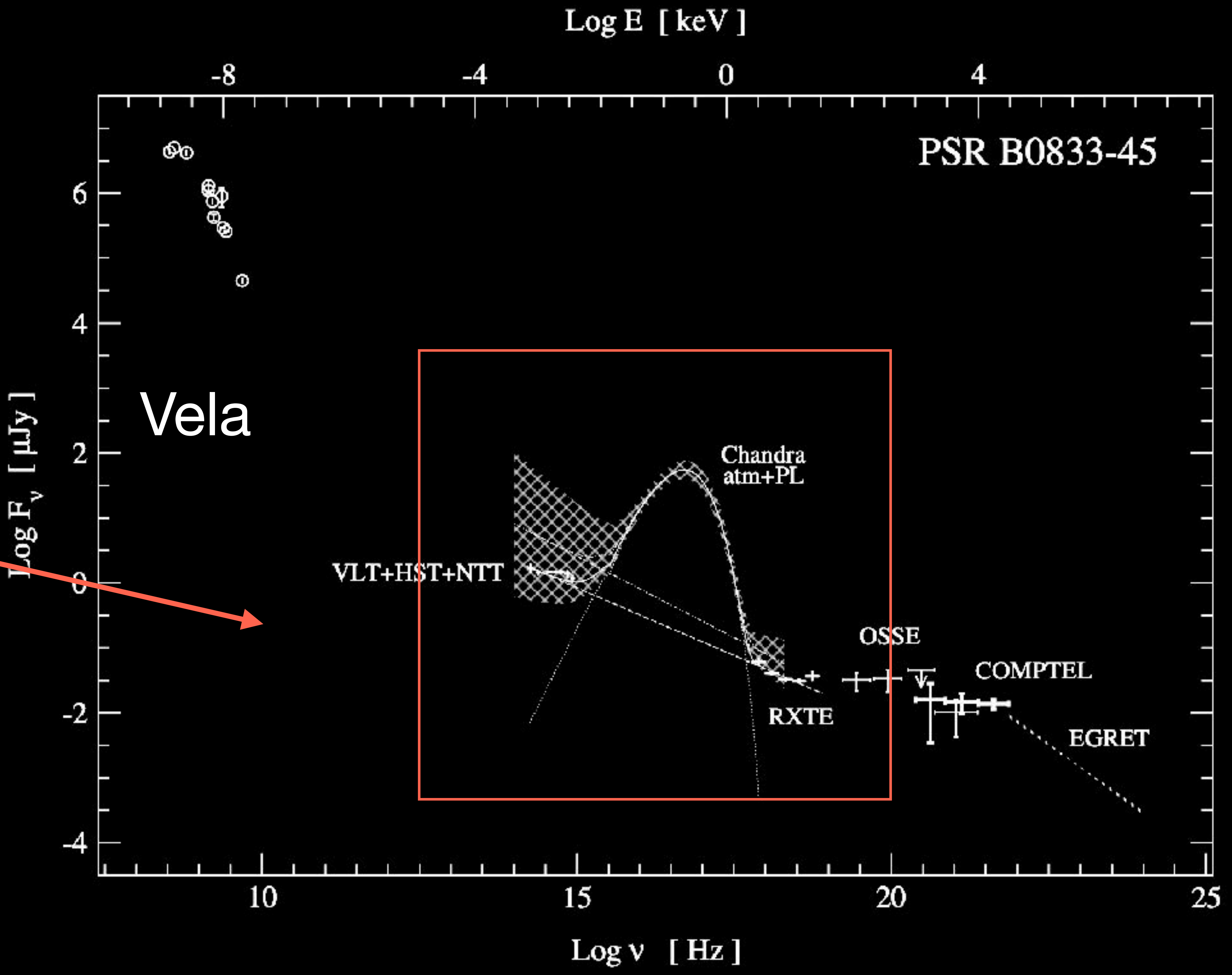
    - head of X-ray PWN : 10^{32} erg/s
    - Extrapolation into O-NIR-UV : 10^{31}erg/s
      3 orders of magnitude more luminous /Vela

    - Non-thermal X-rays as a proxy for O-NIR-UV as IC targets



Non-thermal X-rays as Proxy for O-NIR

- Flat O-NIR for young pulsars (<10^4 yrs) transiting towards UV up to non-thermal X-rays
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- Non thermal X-rays ?
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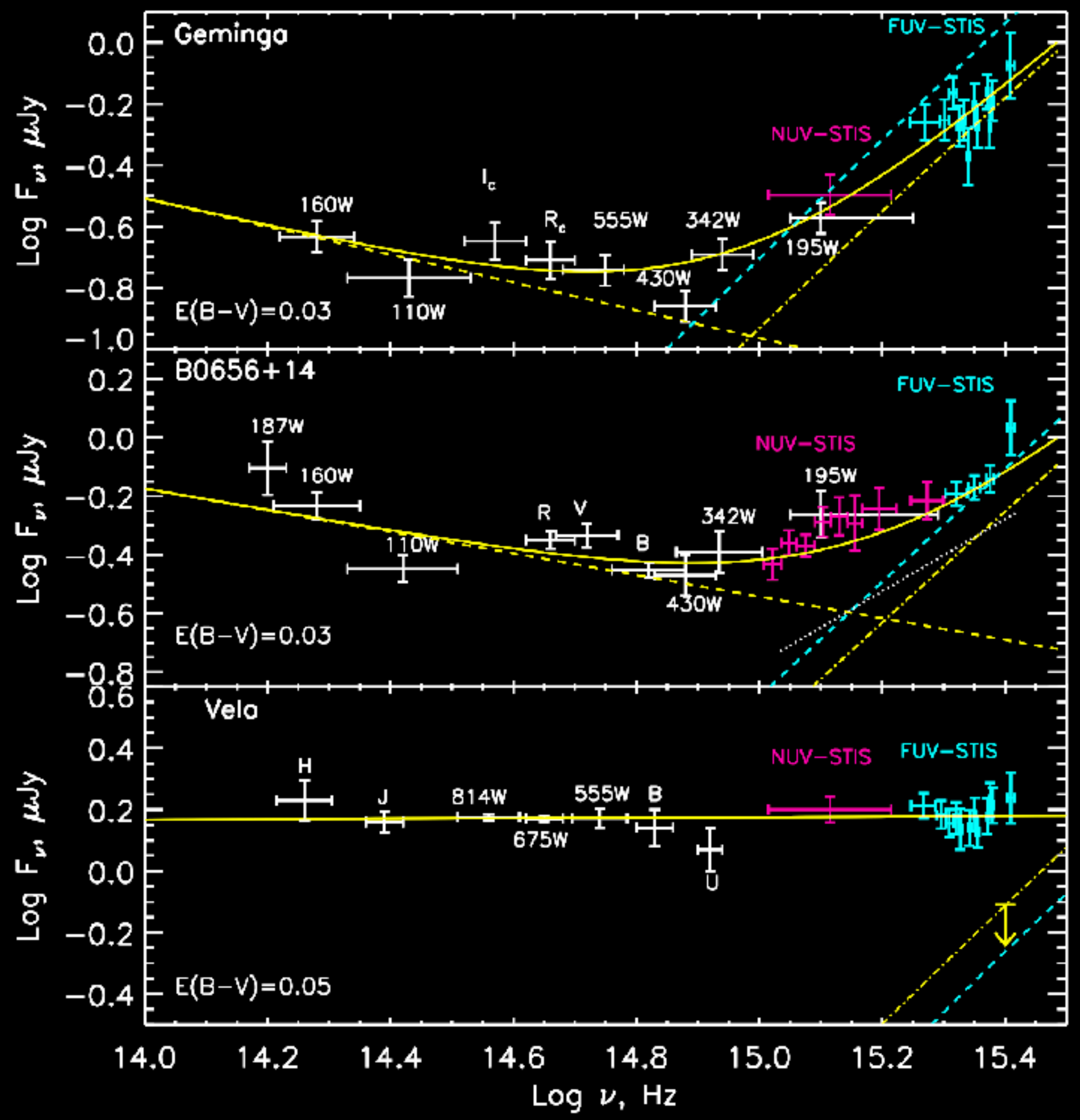
    3 orders of magnitude more luminous /Vela

  - Non-thermal X-rays as a proxy for O-NIR-UV as IC targets
  - Spectral break expected :
    - Young PSRs
    - Old PSRs



PSR J1509-5850
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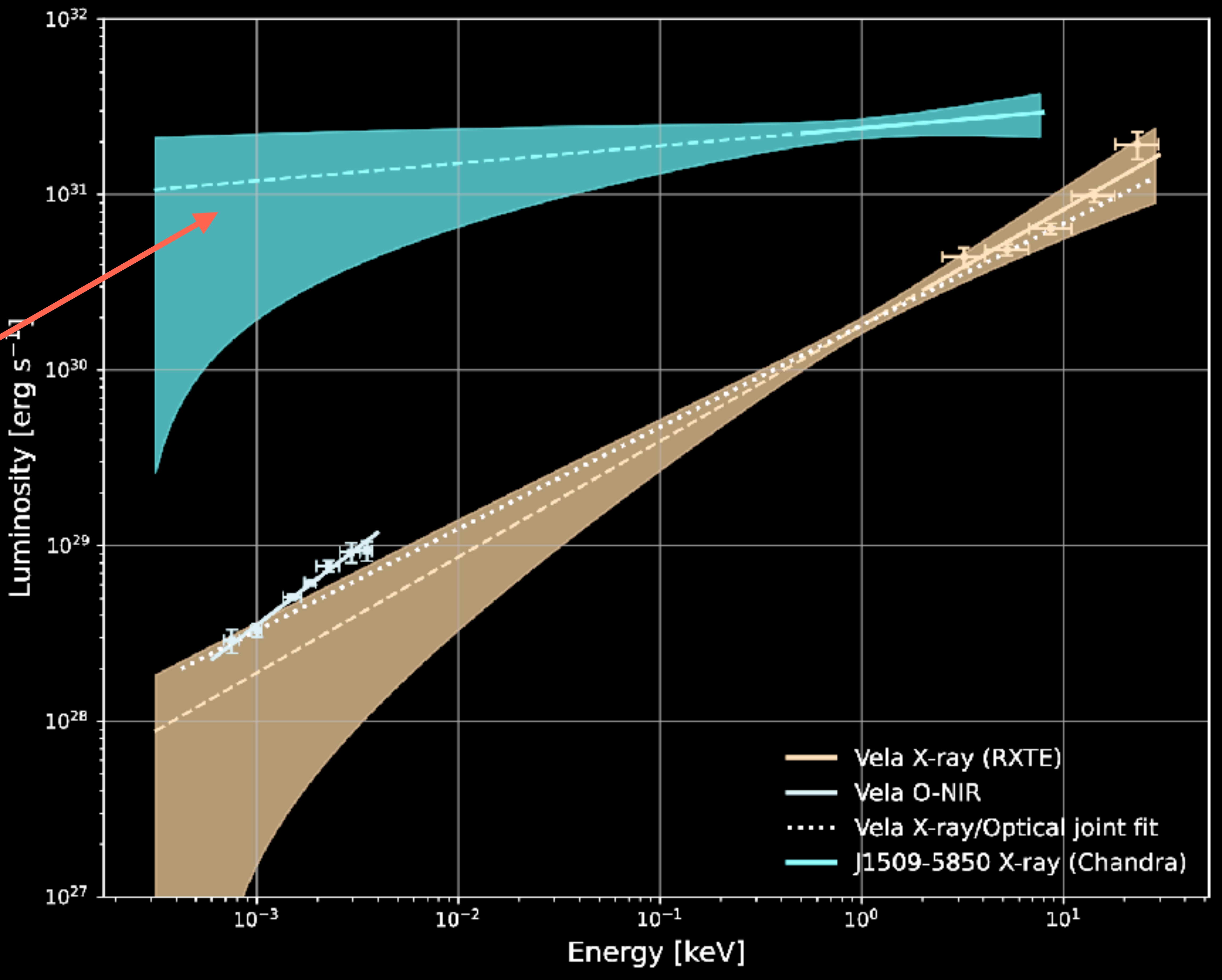
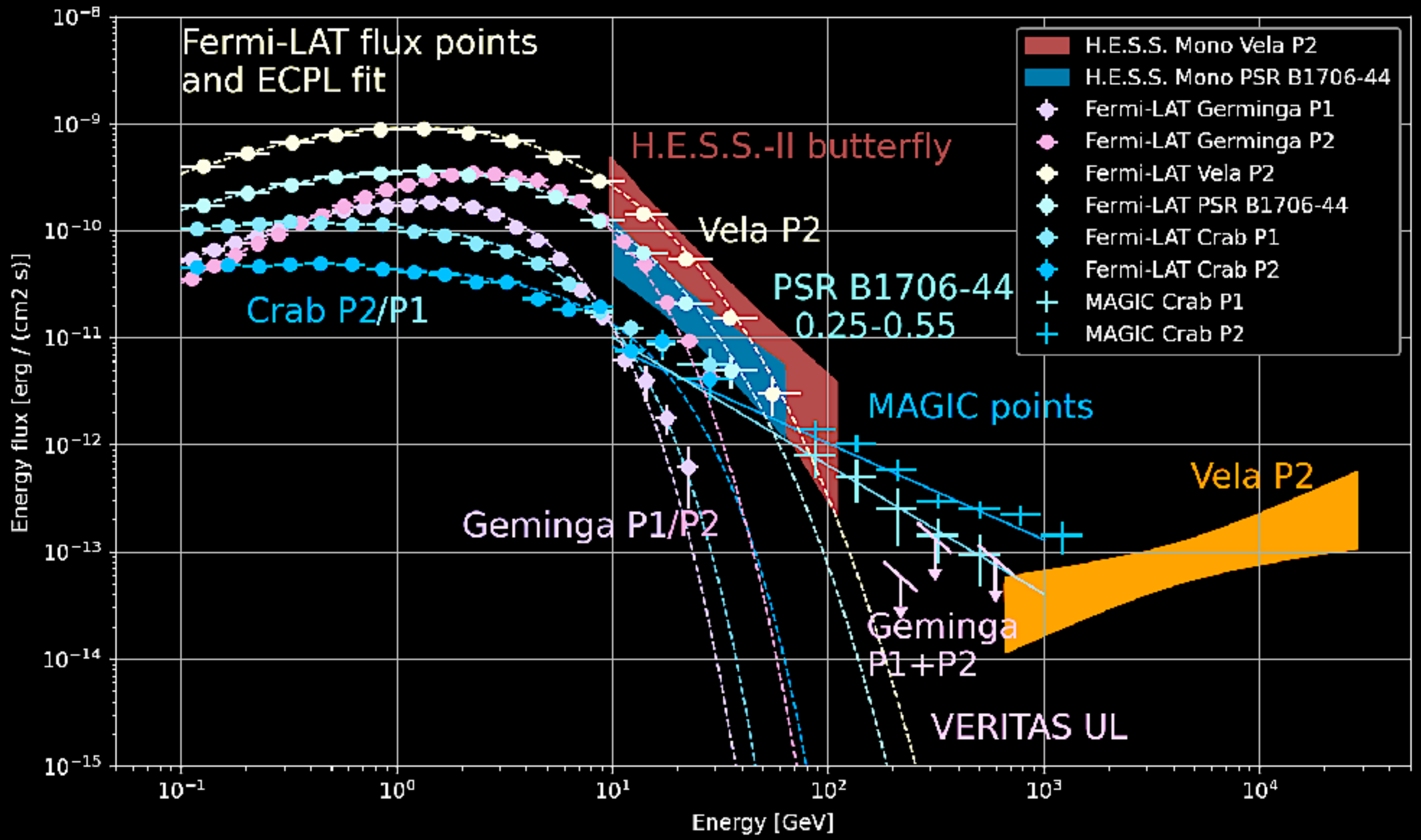


IACT & TeV pulsars
Where we stand

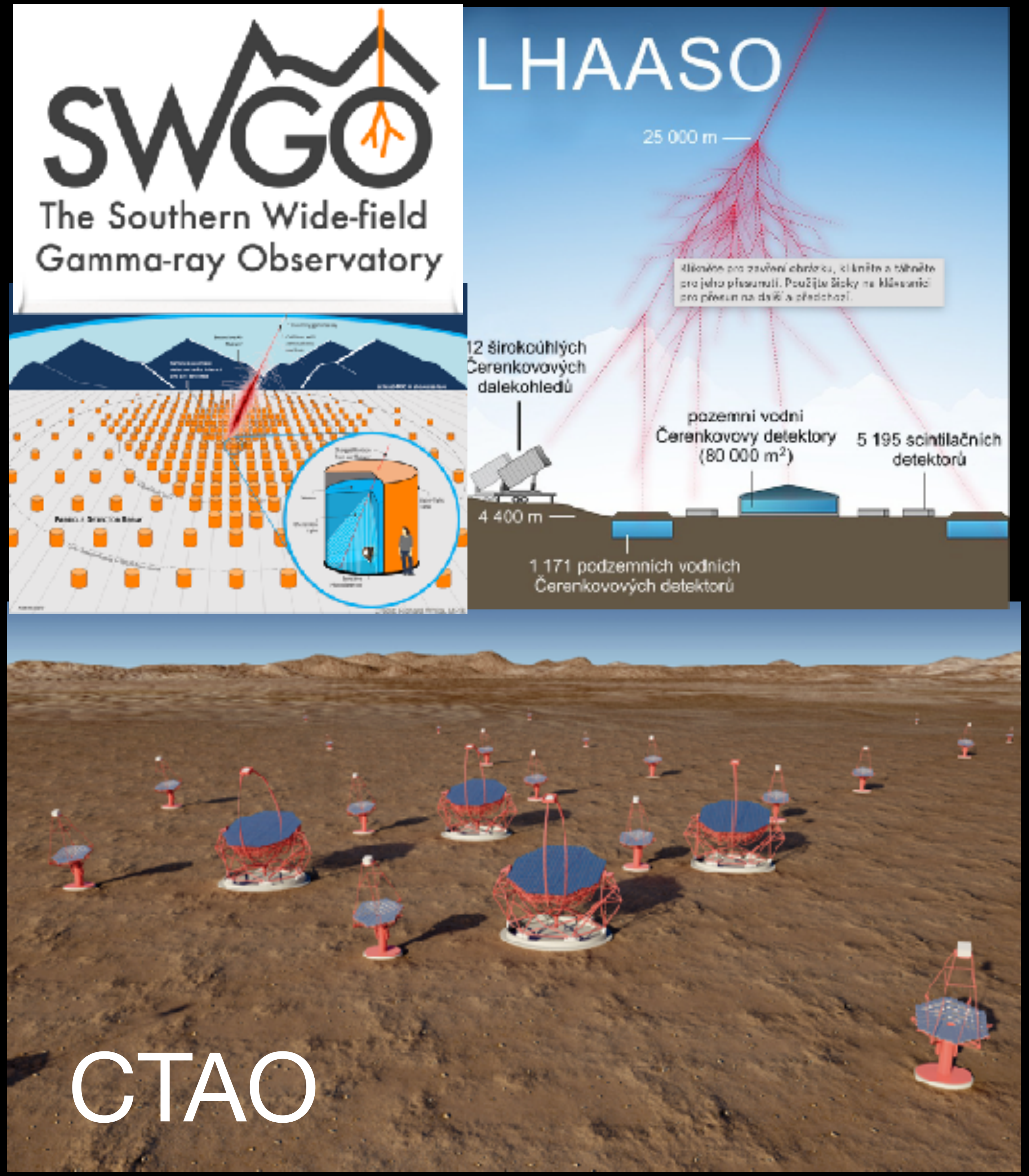
- 5 pulsars detected by IACTs from ground
- Only 3 TeV pulsars + two < 100 GeV
- Crab reaches 1 TeV
- Vela and PSR J1509-5850 exhibit a distinct multi-TeV IC component + their spectra is hard
- Their energy Flux ~ 1-2 x 10^{-13} erg/cm2/s is among faintest γ-ray sources
- Emission zone @ or beyond LC
- J1509-5850 is similar to Vela but major differences
    - Its TeV Luminosity is 150 times > Vela !
    - Is on the FP, Vela is far away !
    - Magnetic conversion efficiency >> Vela
- No hint of cut-off (stats limited)
- Precise measurement of the spectral index/form is essential



Perspectives

Observational…

- Strinking spectral homogeneity : almost all gamma-ray pulsars are "GeV pulsars", with 0.5 < Ep < 2.5 GeV: broadly similar acceleration/ radiation properties
- The paucity of Ep < 500MeV pulsars : Observational limits?
- $E_{||}$ + SCR/Separatrix (FP) vs B-reconnection/CS ?!
- The discovery of 20 TeV pulsations from Vela opened a new observation window! The discovery of the TeV luminous PSR J1509-5850 did even more so
- The TeV pulsar family has only 3 members but already many challenges to emission models Probing
- We still don't know the E_max : both CR/IC and SR/IC can work Fundamental discriminator
- If >100 TeV γ rays: boosted emission in the CS
- Many other questions: LC evolution with E, other peaks with more sensitive surveys? L_{TeV} dependence on inclination?…
- <100 GeV range is also very critical: Crab-like tails or curved Vela-like spectra?
- Multi-wavelength radio and X-rays



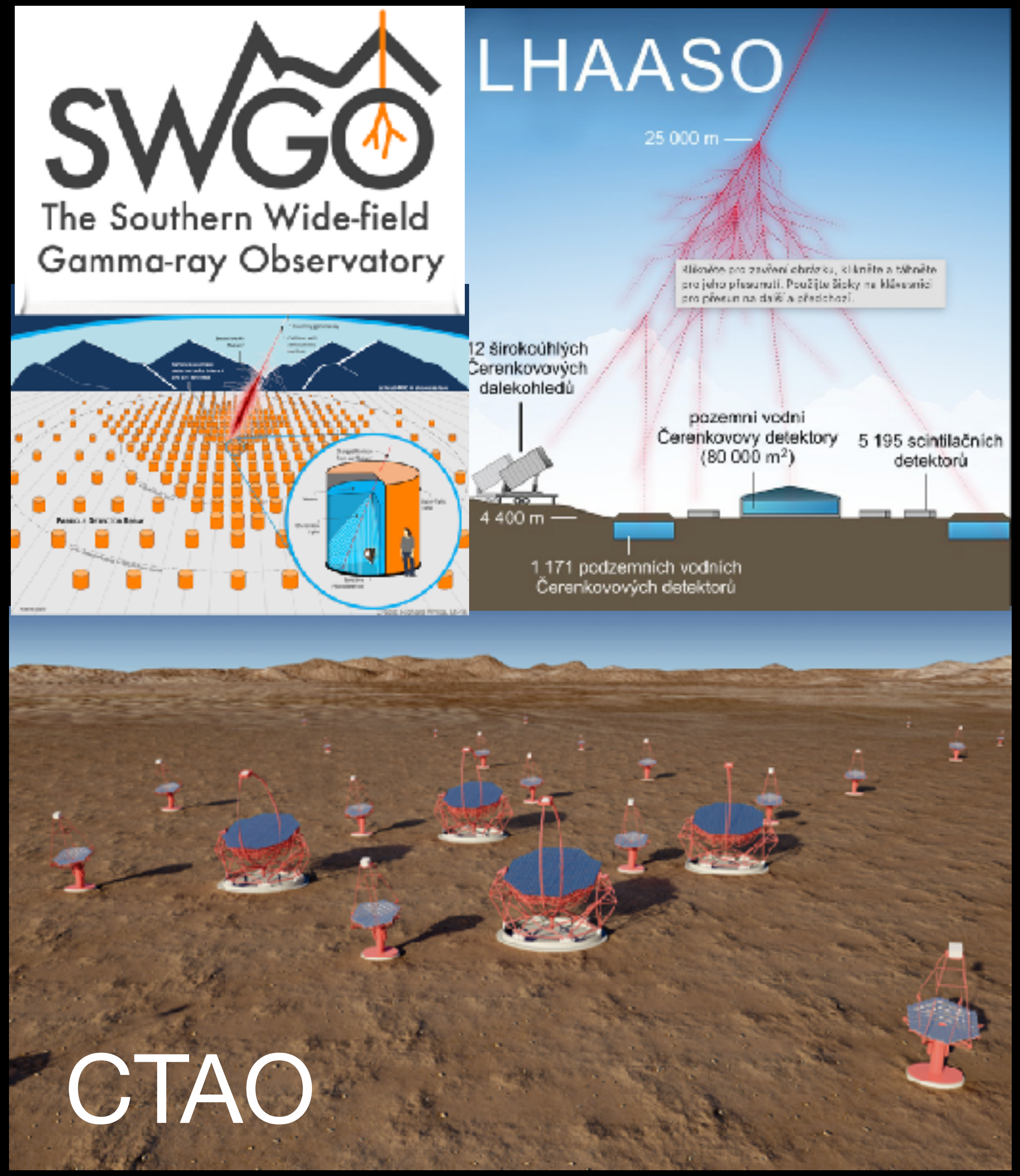
TeV rays :

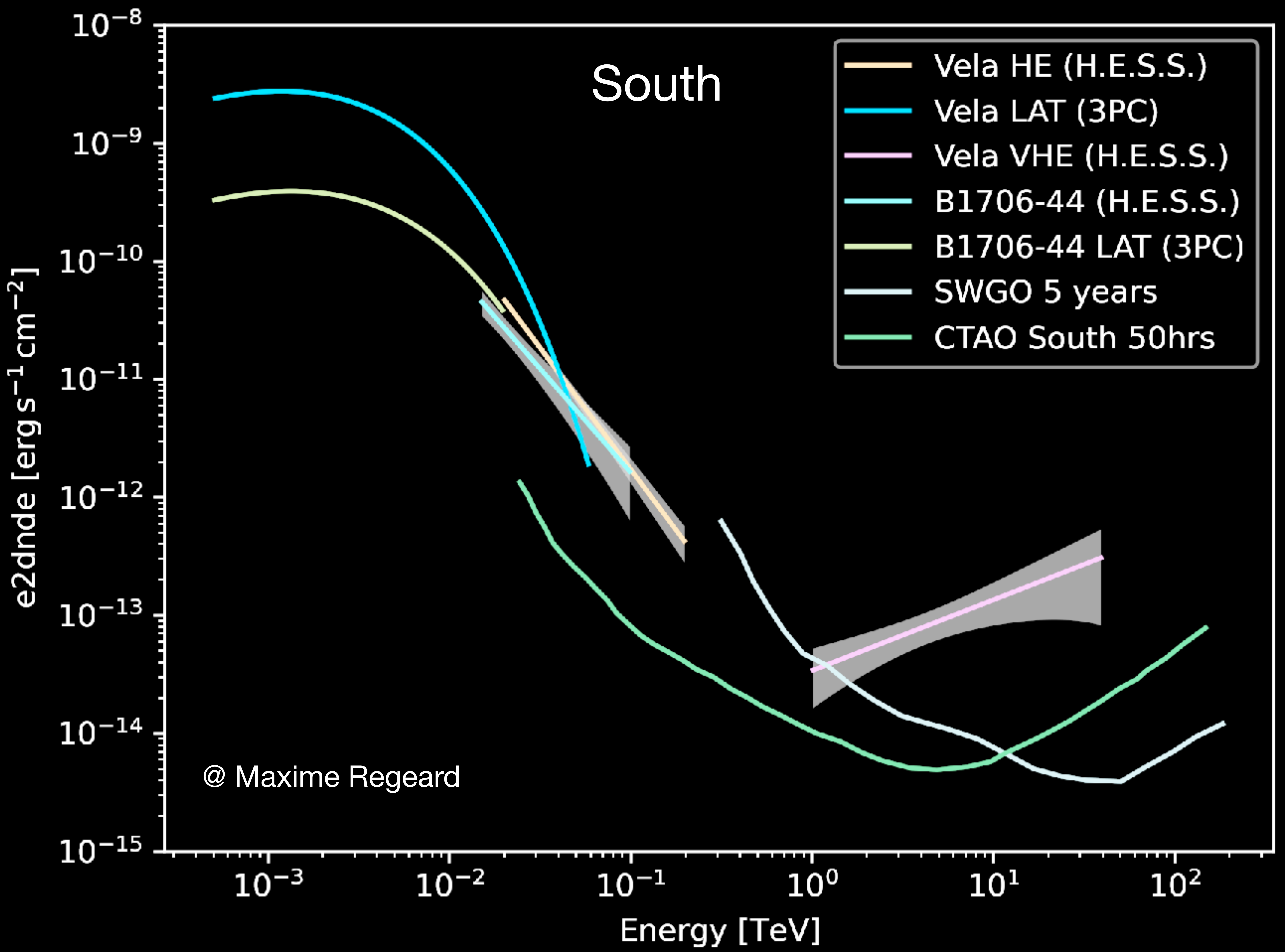
SR/IC: Acceleration & cooling processes deep in the CS

CR/IC: Magnetic conversion efficiency & acceleration zone

Perspectives

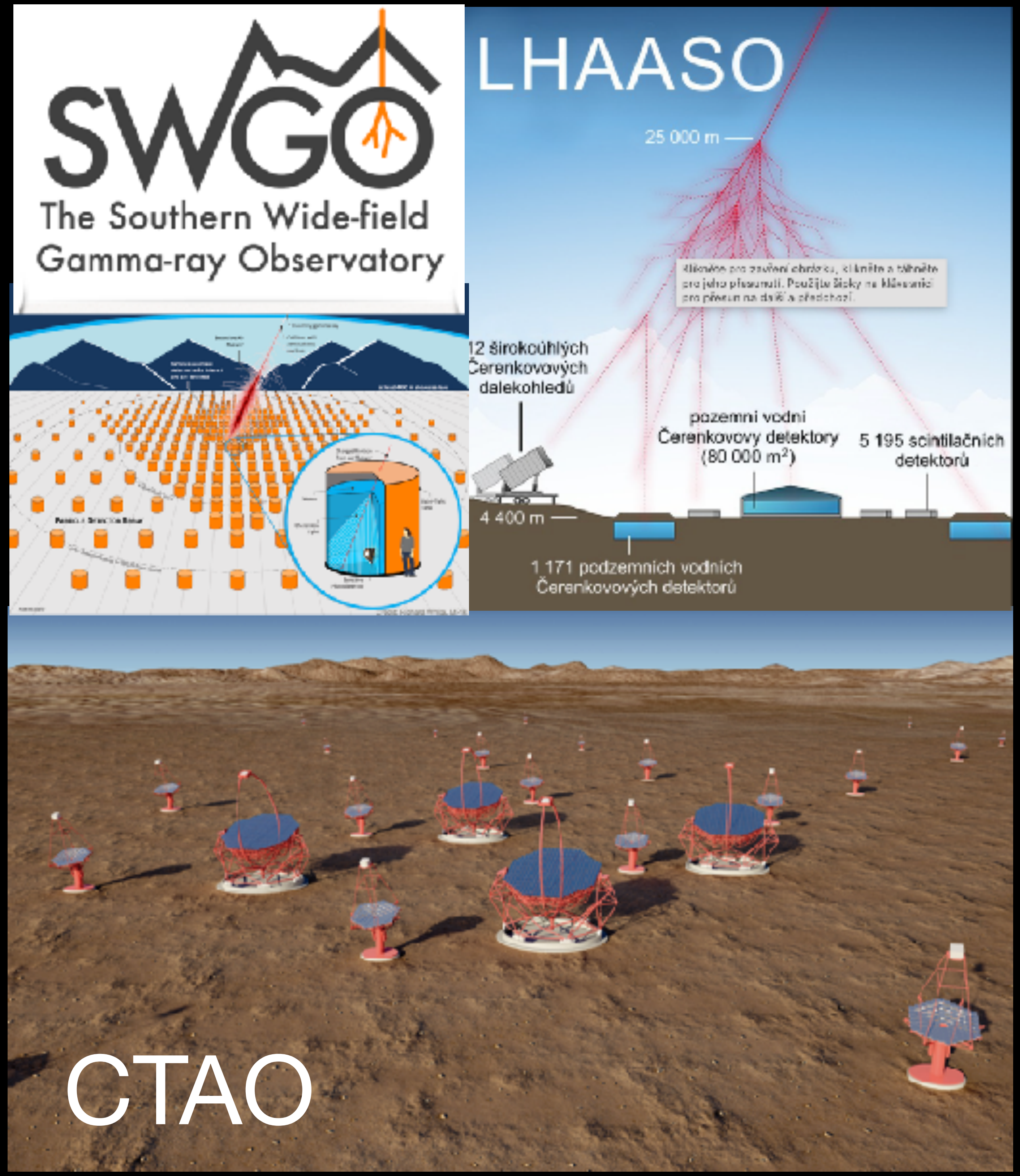
Observational

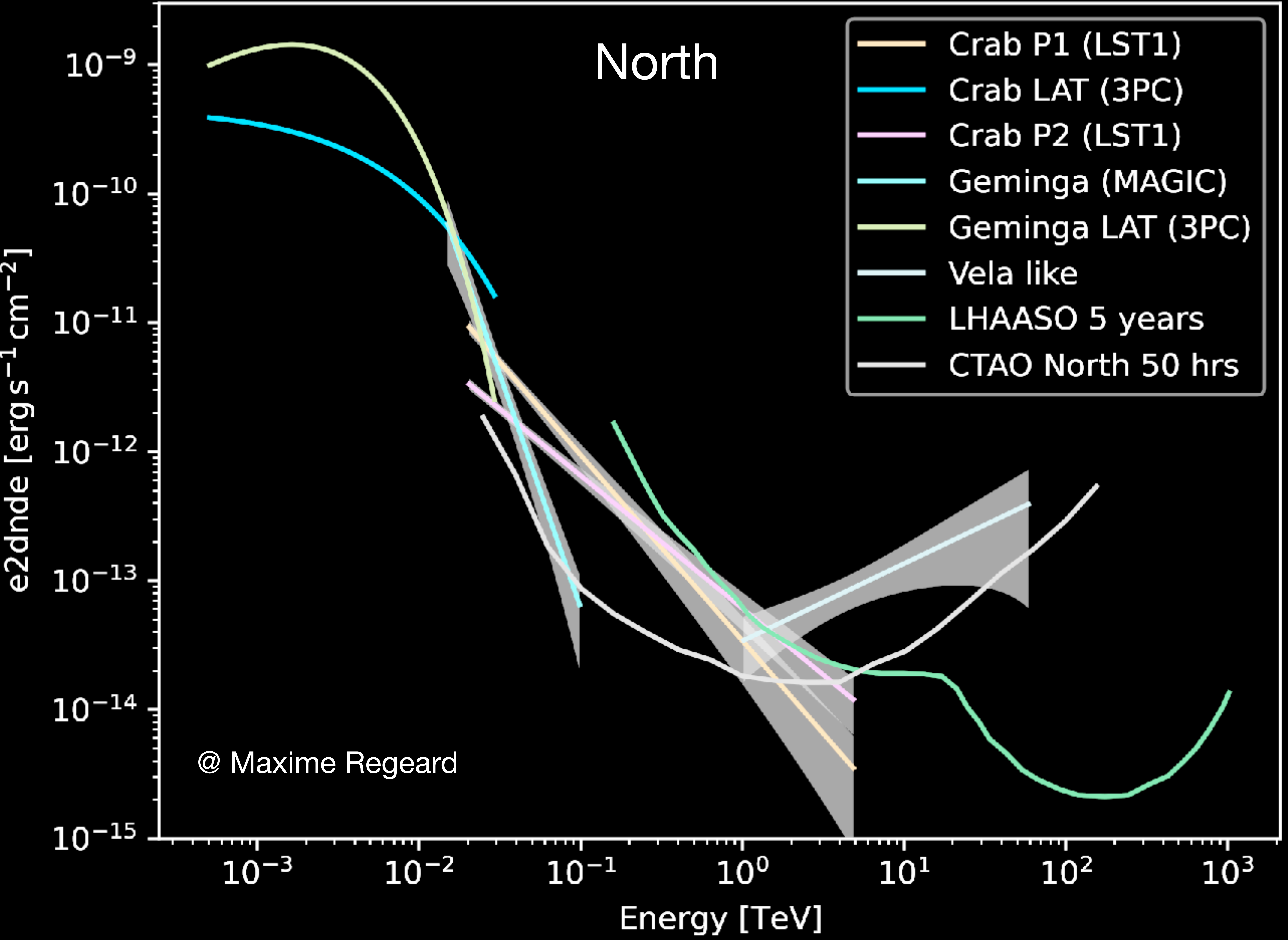




Perspectives

Observational

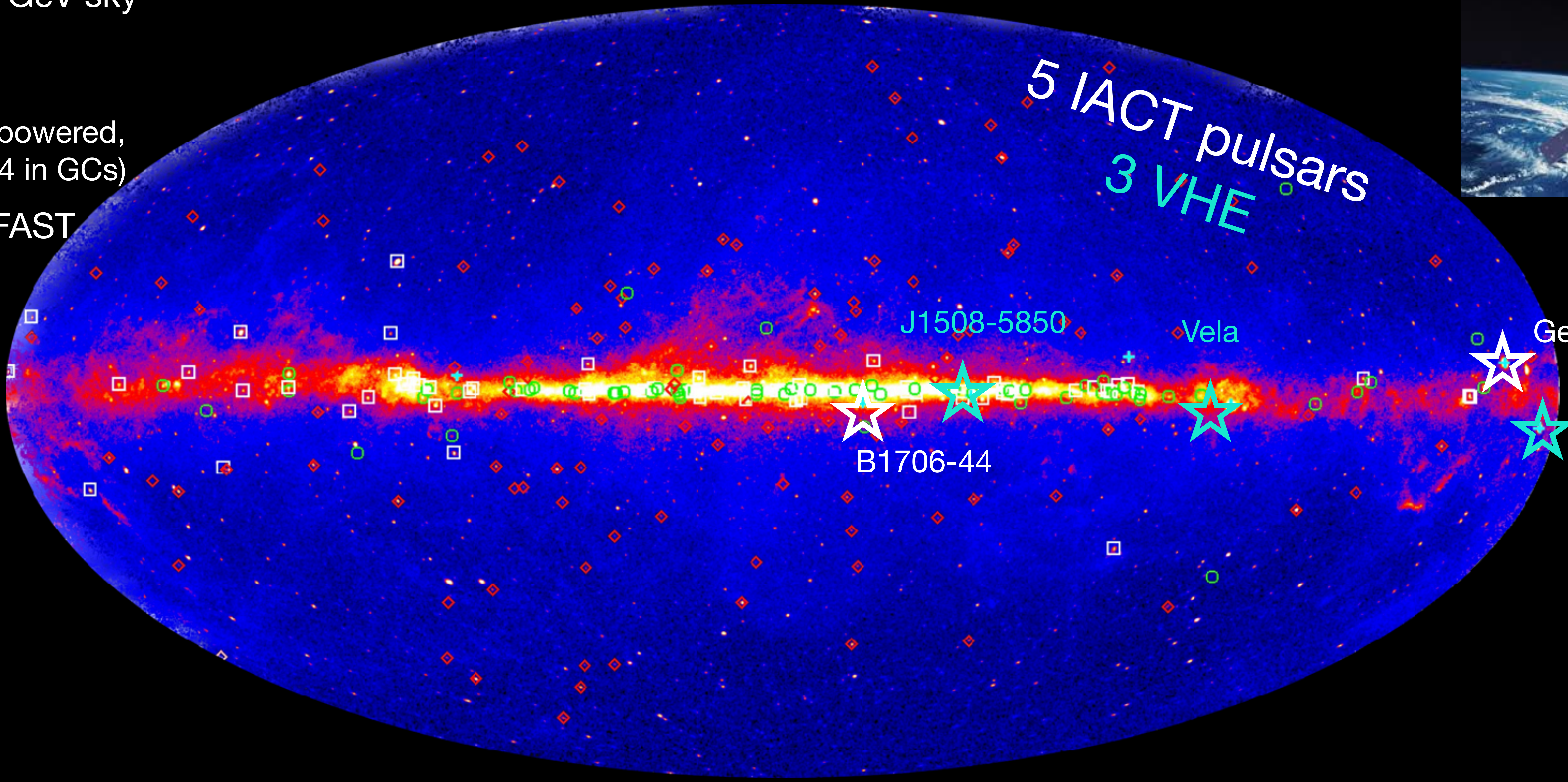




Fermi-LAT > 1 GeV sky

Radio :
~3500 rotation powered,
~681 MSPs (354 in GCs)

++100s with FAST



- 3PC 384 pulsars listed, 255 with 4FGL-DR3 counterparts
- 136 Young or Middle-aged
- 80 Radio-loud γ-ray (29%)
- 76 Radio-quiet γ-ray (25%)
- 123 γ-ray MSPs : 25 Isolated, 94 Binary (47%)
- 45 Black Widows (32) and Redbacks (13)

- 2 HE pulsars (~100 GeV):
  - Geminga
  - B1706-44
- 3 VHE pulsars (>~100 GeV):
  - Crab ~1.5 TeV
  - Vela ~ 20 TeV
  - J1509-5850 ~10 TeV