Probing Multi-TeV Emission in Pulsars: Perspectives from Fermi-LAT 3PC Phase-Resolved Spectral Analysis

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Introduction: Gamma-ray pulsars

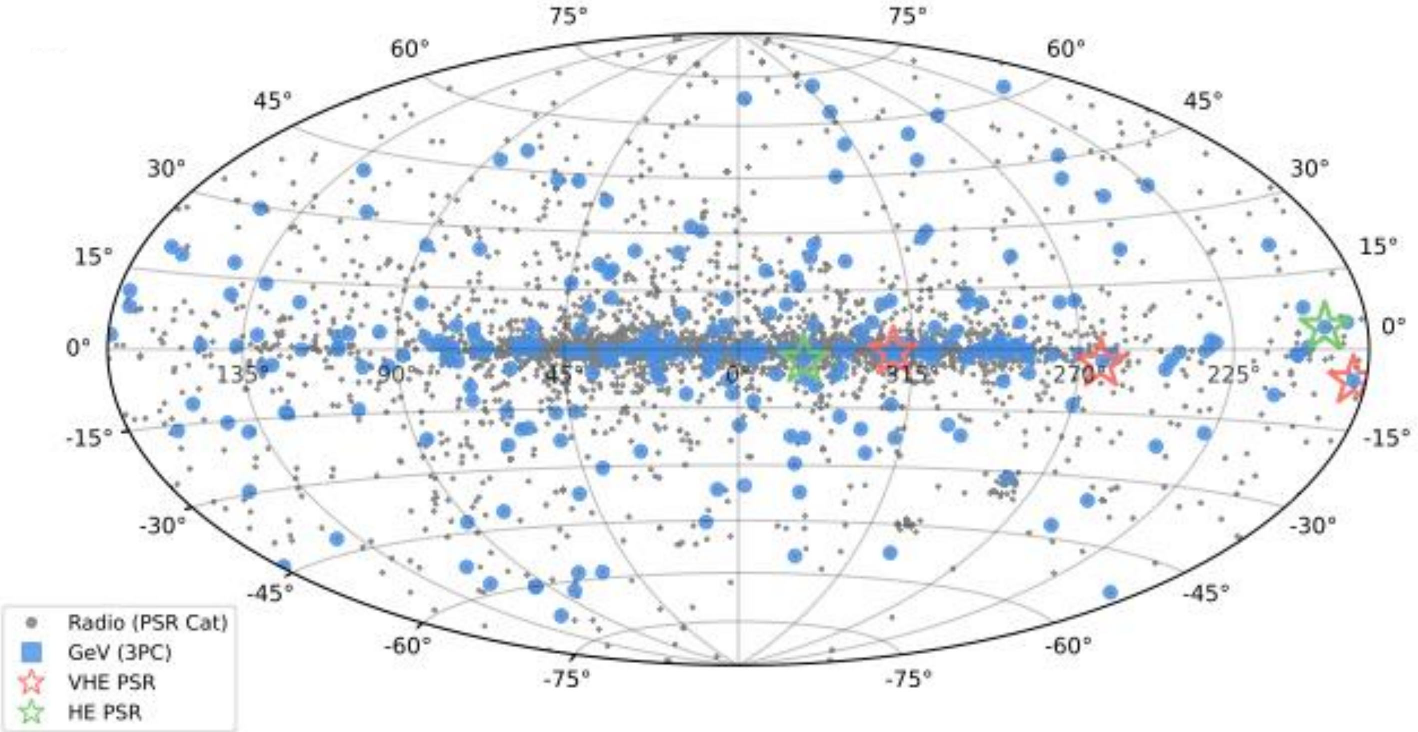
Fermi-LAT 3rd Catalog of Pulsars (3PC) Smith, D. et al. 2023
- More than 300 pulsars detected

5 pulsars detected by IACTs:

2 in the high-energy range only < 100 GeV:
- PSR B1706-44
- Geminga

3 in the very-high energy range:
- Crab (up to 1.5 TeV)
- Vela (beyond 20 TeV)
- PSR J1509-5850 (beyond 10 TeV)

→ Emerging population



Introduction: Vela and PSR J1509-5850

GeV:

- Synchrotron (SR) and Curvature (CR) fit the Fermi-LAT GeV emission

TeV:

- Inverse Compton scattering of low energy photons by high energy electrons
- Electron population:
    - GeV and TeV phase aligned → Same electrons for GeV and TeV
- Target photons:
    - IR-Optical range

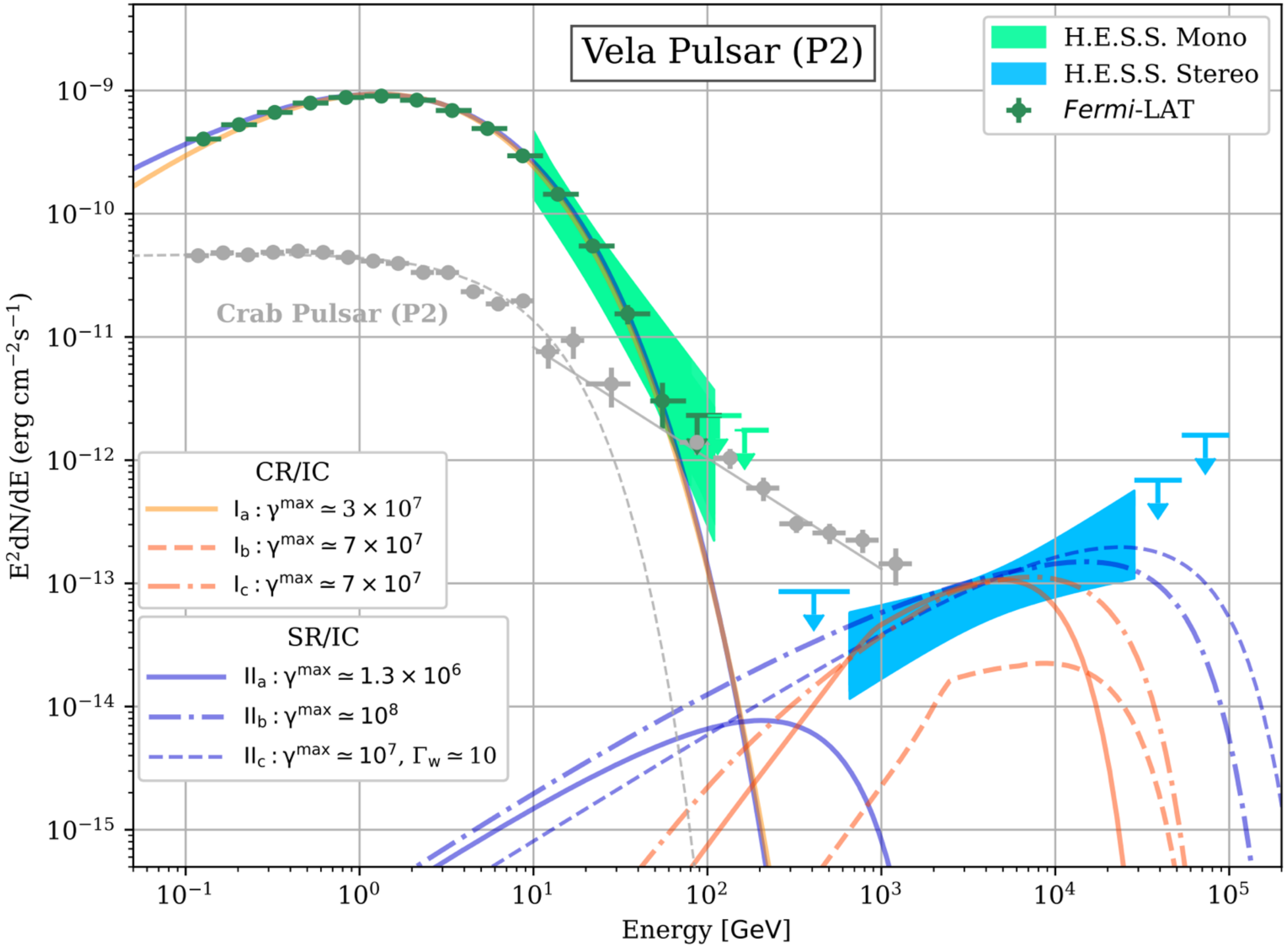


Figure 3 from [Aharonian et al. 2023]

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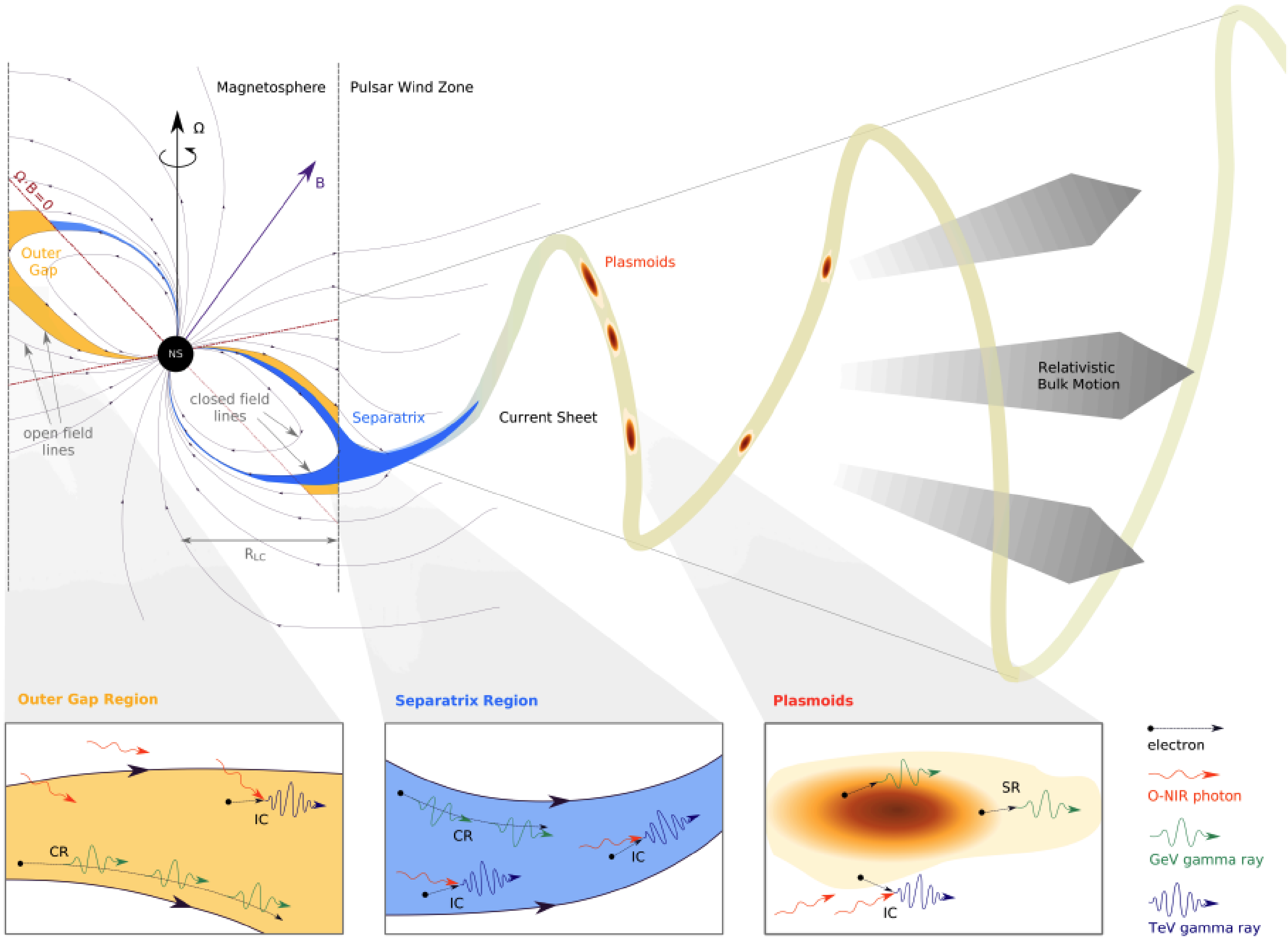

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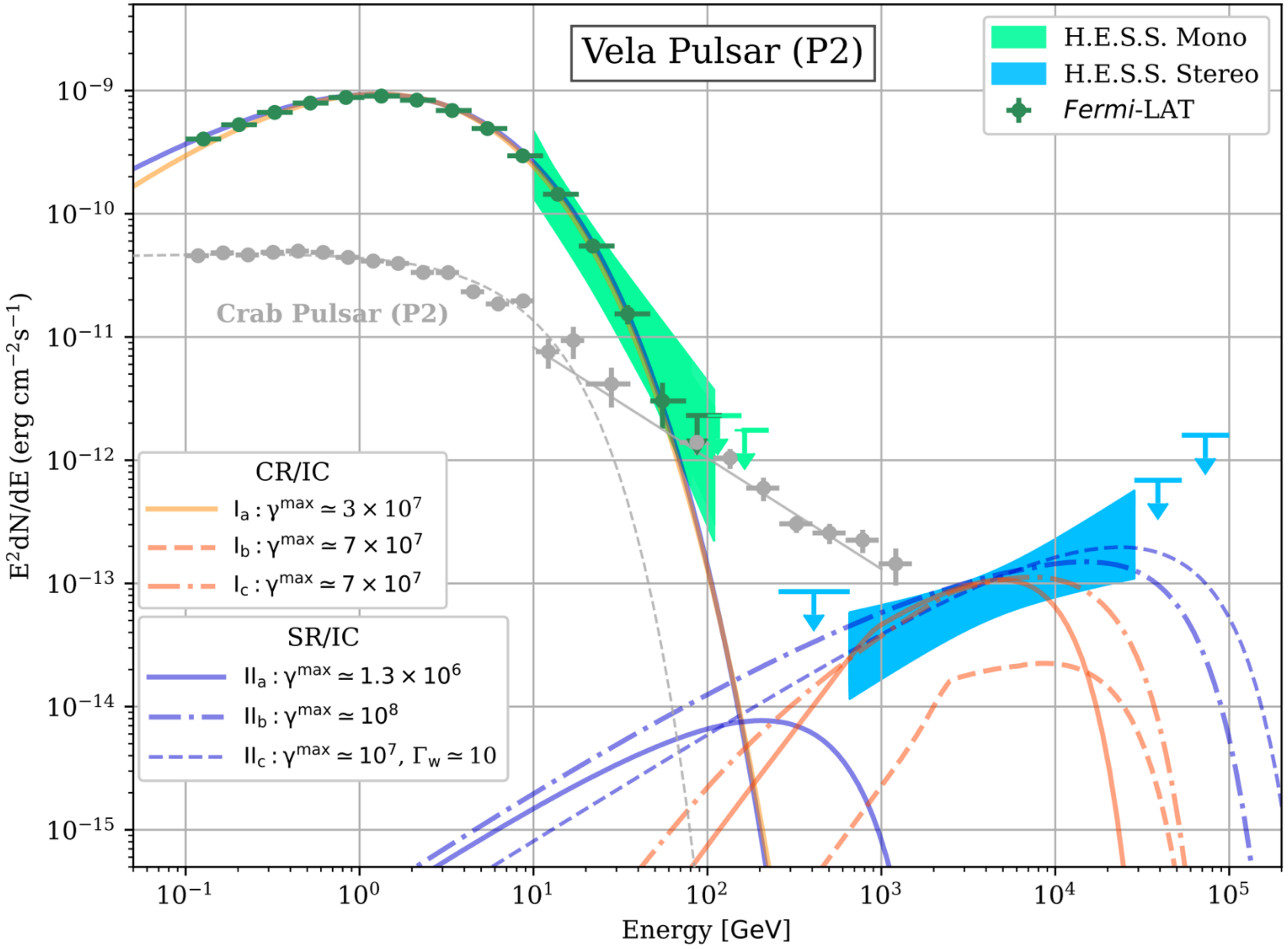
Caveats at TeV:

- SR/IC: e^- cutoff ~ 1 TeV $< 15, 20$TeV needed to fit TeV data
- CR/IC: $\Gamma_{e^-}^{CR}$ too soft to reach Γ_{IC}

- TeV challenge state of the art models



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Difference: J1509-5850 400 times more luminous than Vela !

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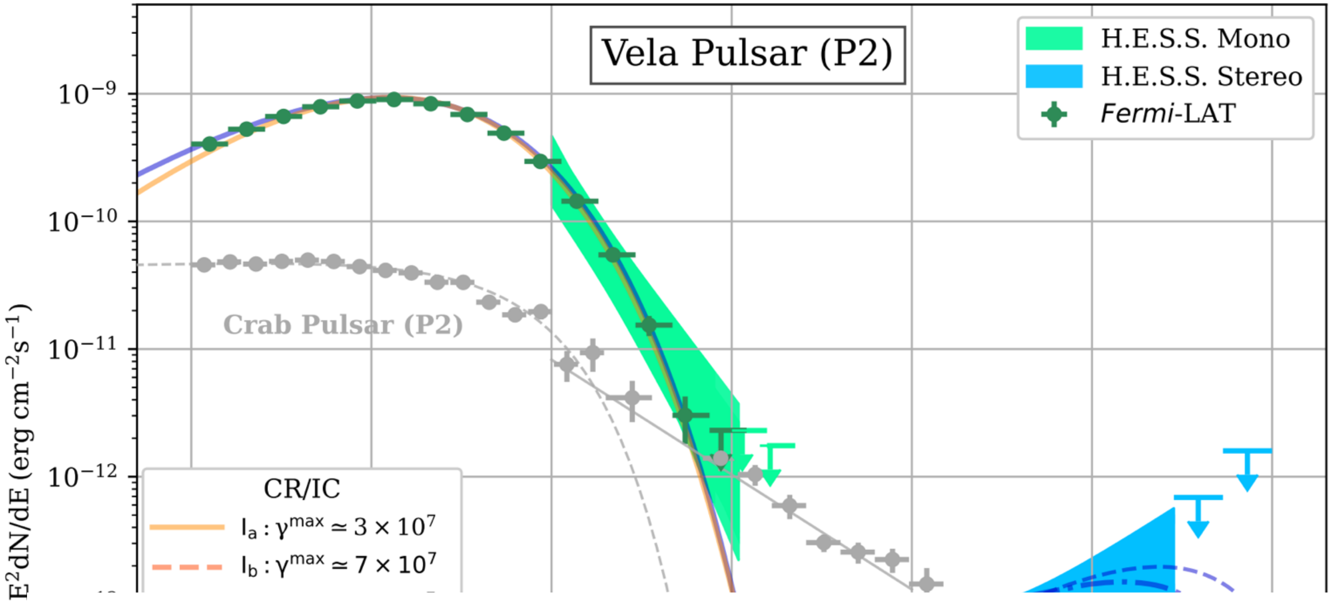

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To solve this issues: Synchro-curvature radiation (SCR) ?
- Particles transition from synchrotron to curvature cooling as they loose their pitch angle
- $\Gamma_{e^-}^{SR}$
- e^- cutoff of CR

Figure 3 from [Aharonian et al. 2023]

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Multi-TeV emission: Insight from 3PC

3 TeV pulsars with current generation of IACTs

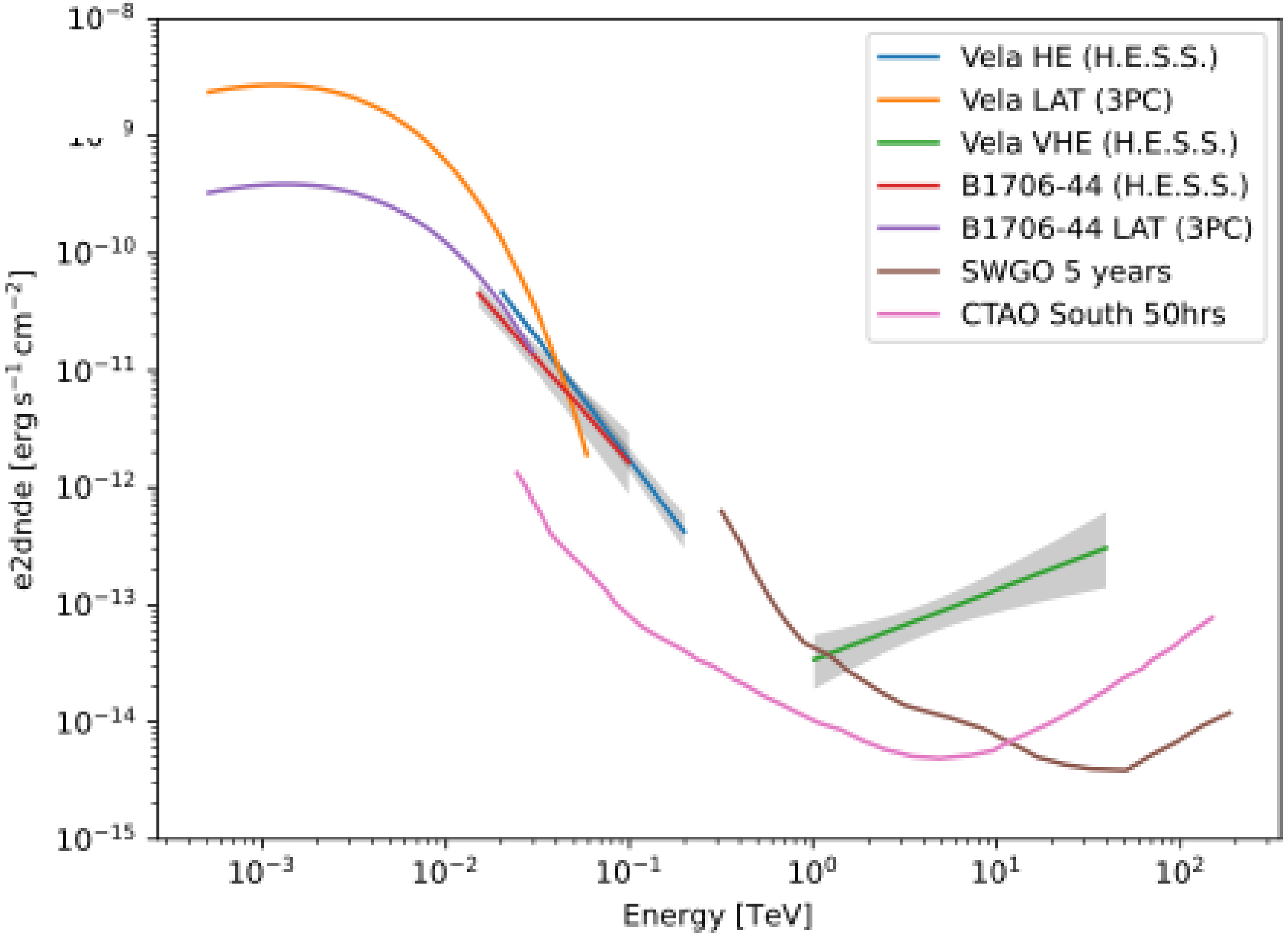
New generation of instrument: CTAO, SWGO

- Improved sensitivity
- Detection of new sources
- Measure cutoff energy
- Pulse profile
- TeV only feature ?

Constraint models: understand the TeV pulsar population

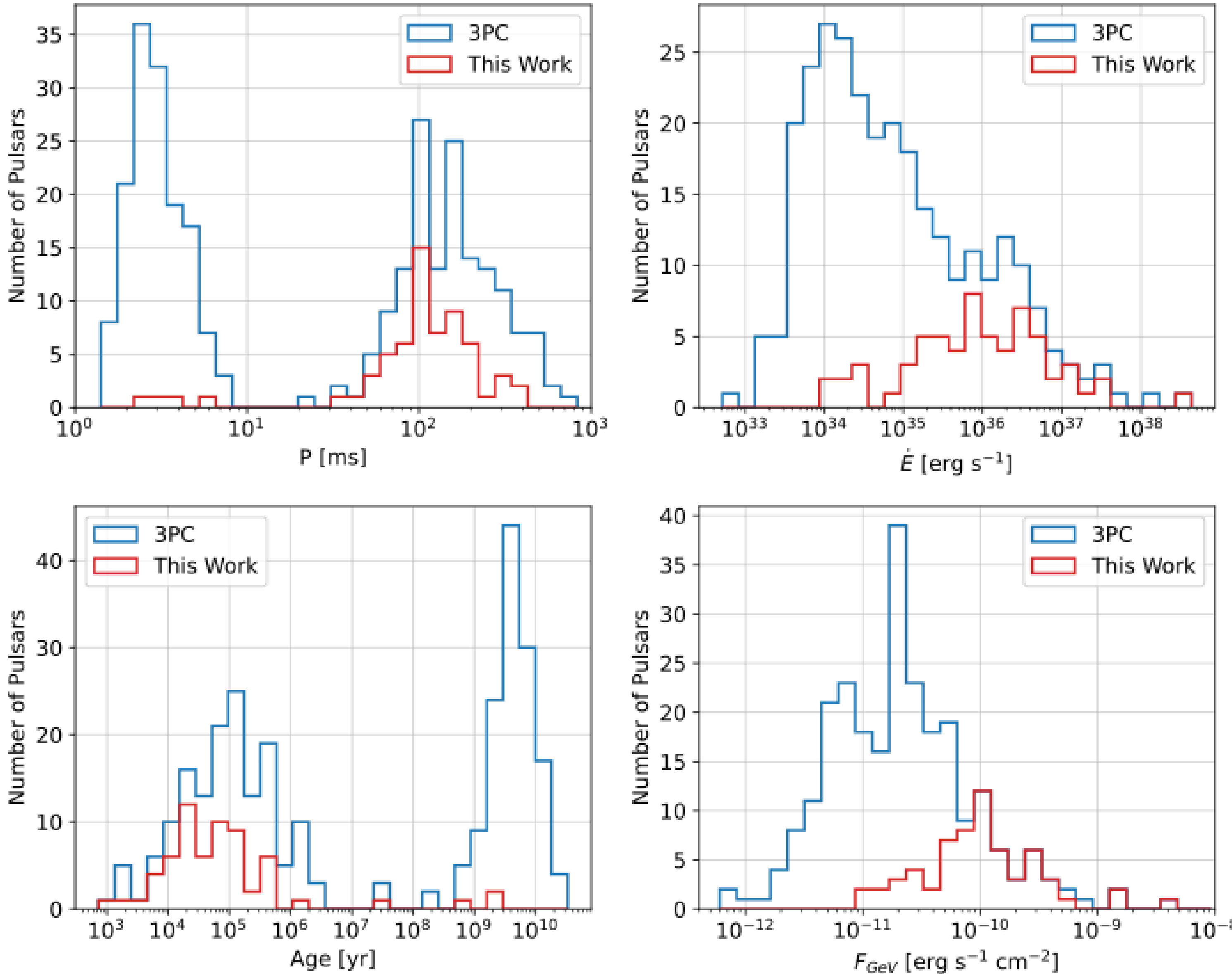
In the following:

- Expectation in terms of TeV emission and detection
- Tentative prediction based on sample of 3PC pulsars



3PC Data Selection:

- 50 brightest pulsars in 3PC
- 50 more luminous pulsars in 3PC
- 78 individual pulsars
- Remove 15 for analysis purpose:
  - Complex pulse profile
  - Very faint signal
- 63 pulsars considered:
  - 4 millisecond pulsars
  - 59 young pulsars



3PC phase-resolved analysis:

Defining phase intervals

- From Fermi-LAT pulse profile above 1 GeV:
  - Roughly the energy at the peak of the SED

- Fit asymmetric Gaussian and Lorentzian wrapped onto the unit circle + constant model for background continuum:

$$\mathscr{G}(\phi) = A_0 \exp\left(\frac{-(\phi-\phi_0)^2}{2\sigma^2}\right)$$

$$\mathscr{L}(\phi) = \frac{A_0}{1+\left(\frac{\phi-\phi_0}{\sigma}\right)^2}$$

$\sigma = \sigma_L$ for $\phi < \phi_0$ and $\sigma = \sigma_T$ otherwise

$$\mathring{\mathscr{F}}(\phi) = \sum_{k=-\infty}^{+\infty} \mathscr{F}(\phi + kP)$$

- ON phase interval defined for each peak as 2σ on each side of the peak mean.

- OFF phase interval defined where no significant pulsations are visible

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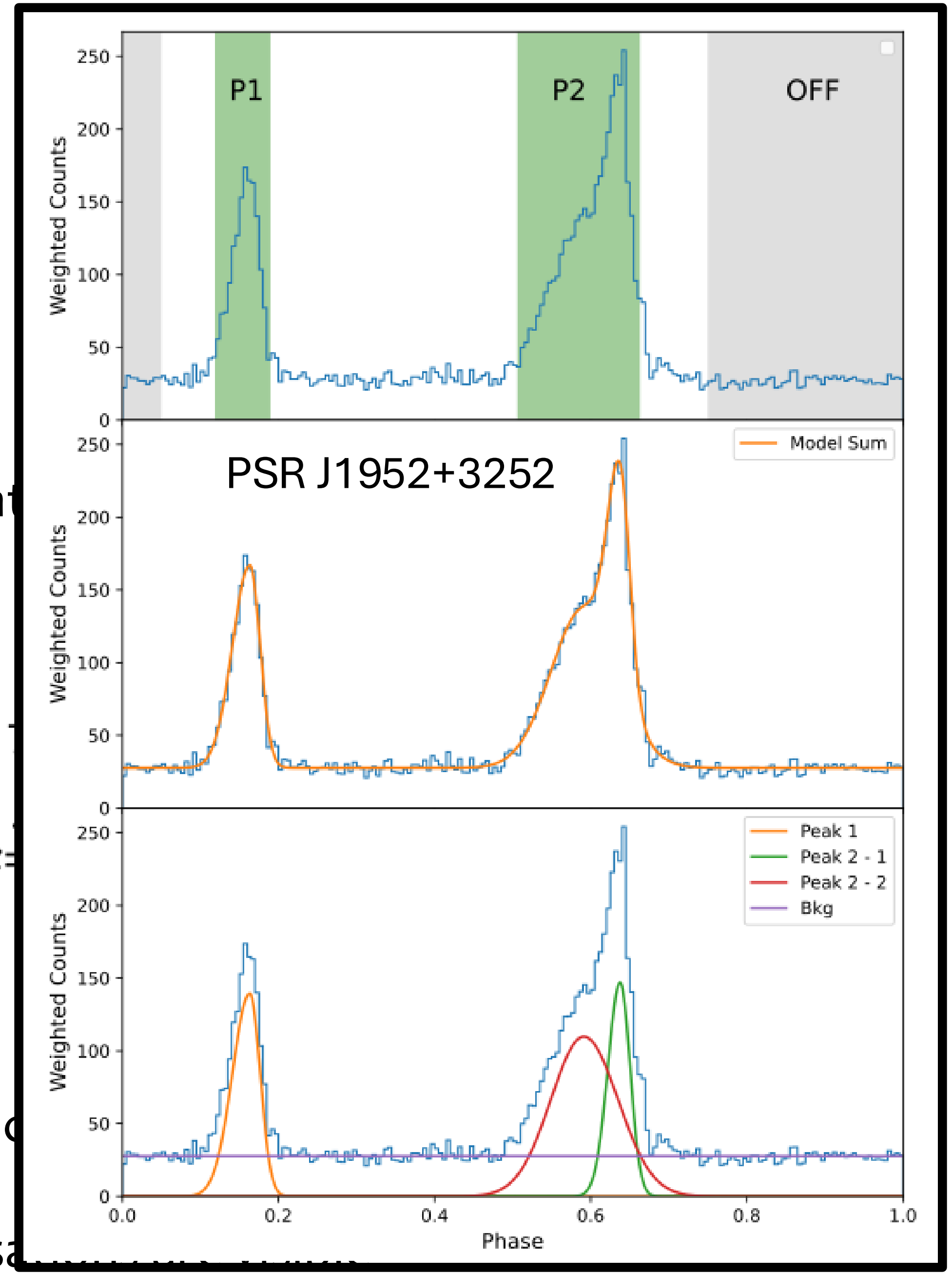
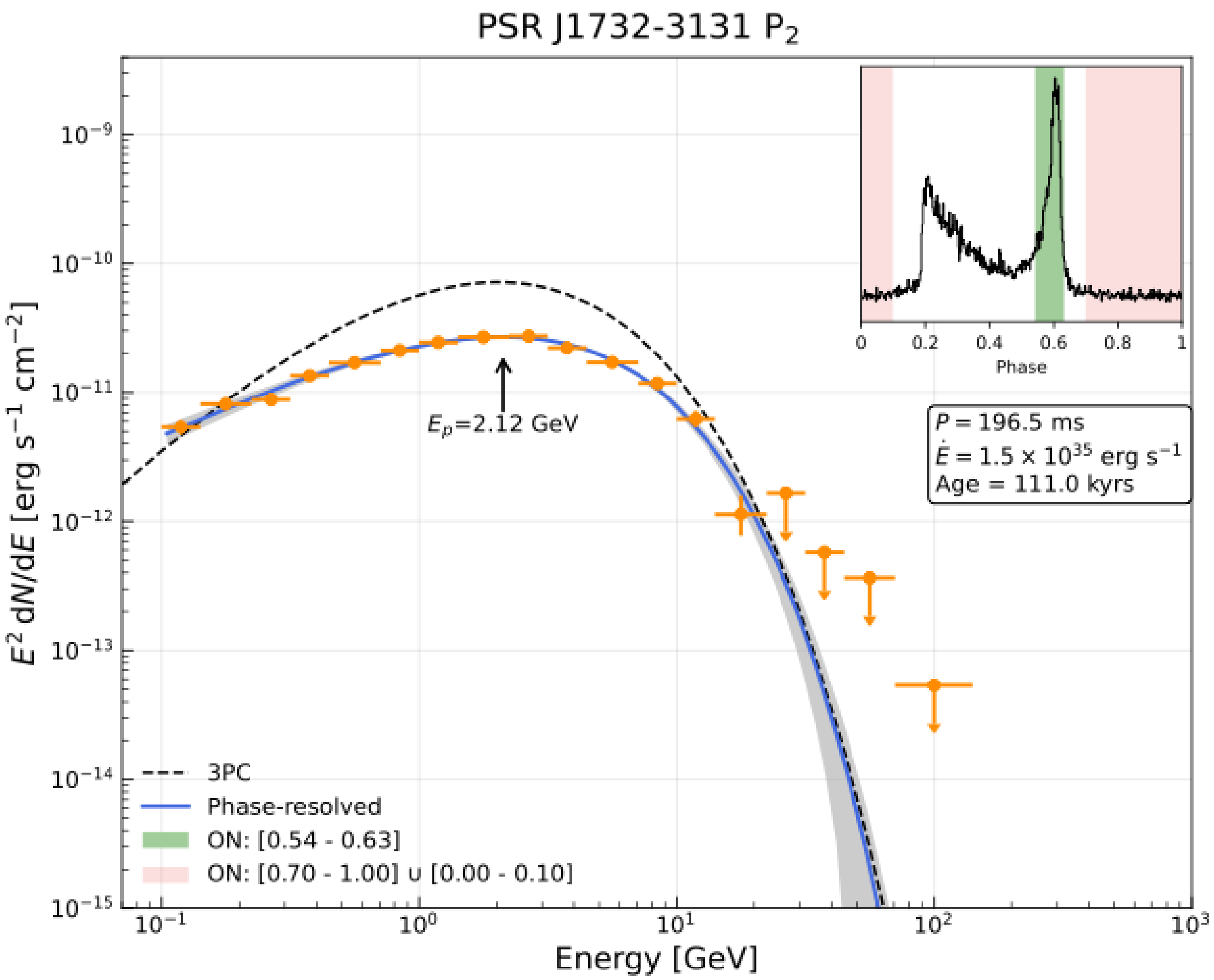
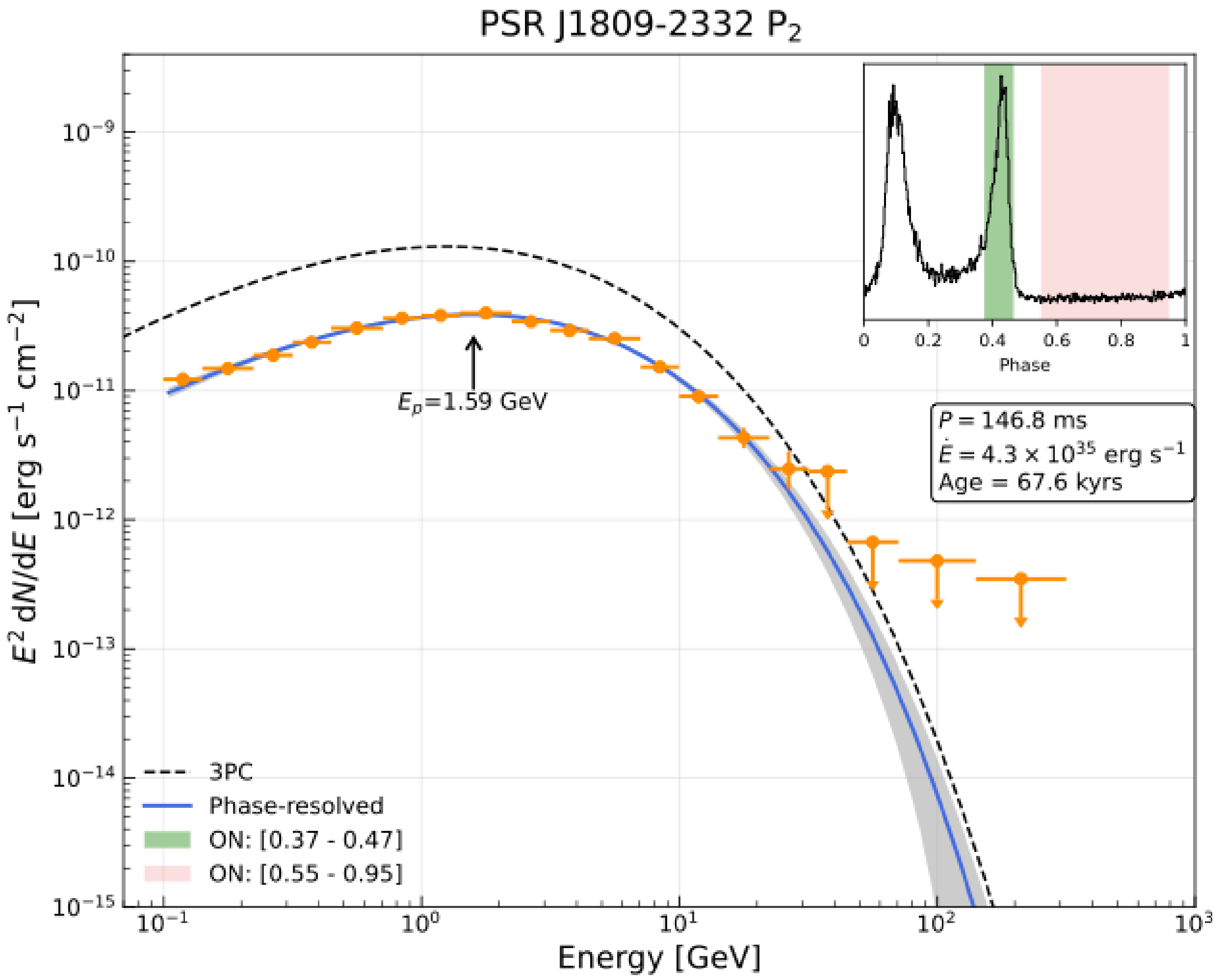


3PC phase-resolved spectral analysis:





Modelling the GeV emission:

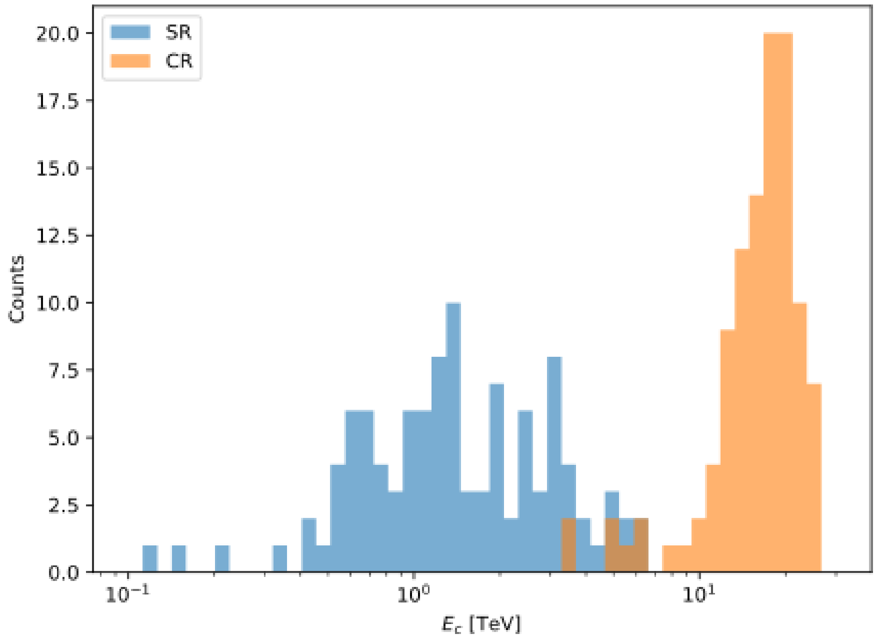
- Fit radiative model to the data with Gammapy-Naima interface

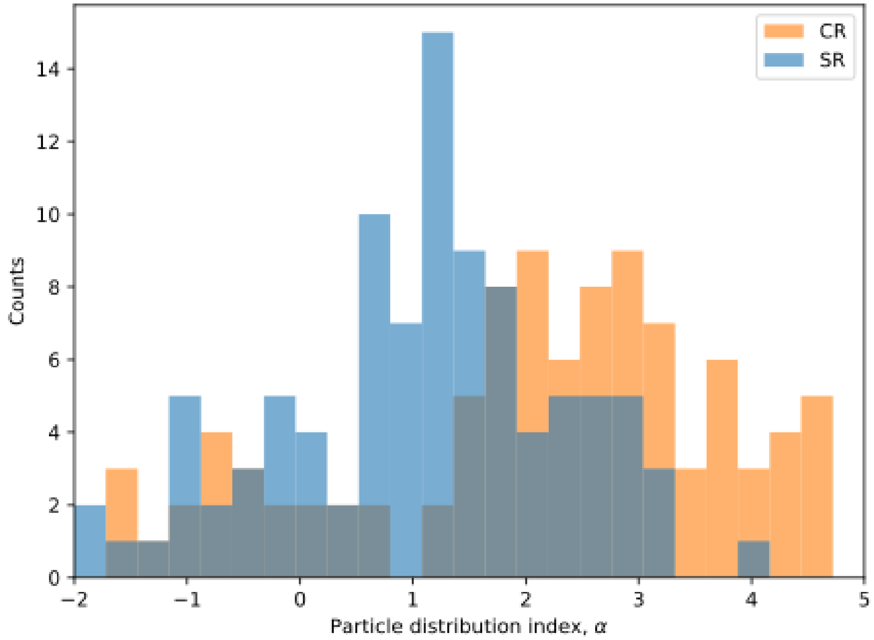
- We are able to successfully fit SR and CR to Fermi-LAT data

- Cutoff energy:
  - SR: $\sim$1 TeV
  - CR: $\gtrsim 10$ TeV
- If CR → all pulsars are potential multi-TeV emitters

- Particle index:
  - CR too soft to obtain $1 < \Gamma_{VHE} < 2$
  - SR index around 1: OK

Consistency of this modelling:
- Similar emission process across all pulsars (peaks) while different P, $\dot{E}$, B, Age, Geometry, etc.





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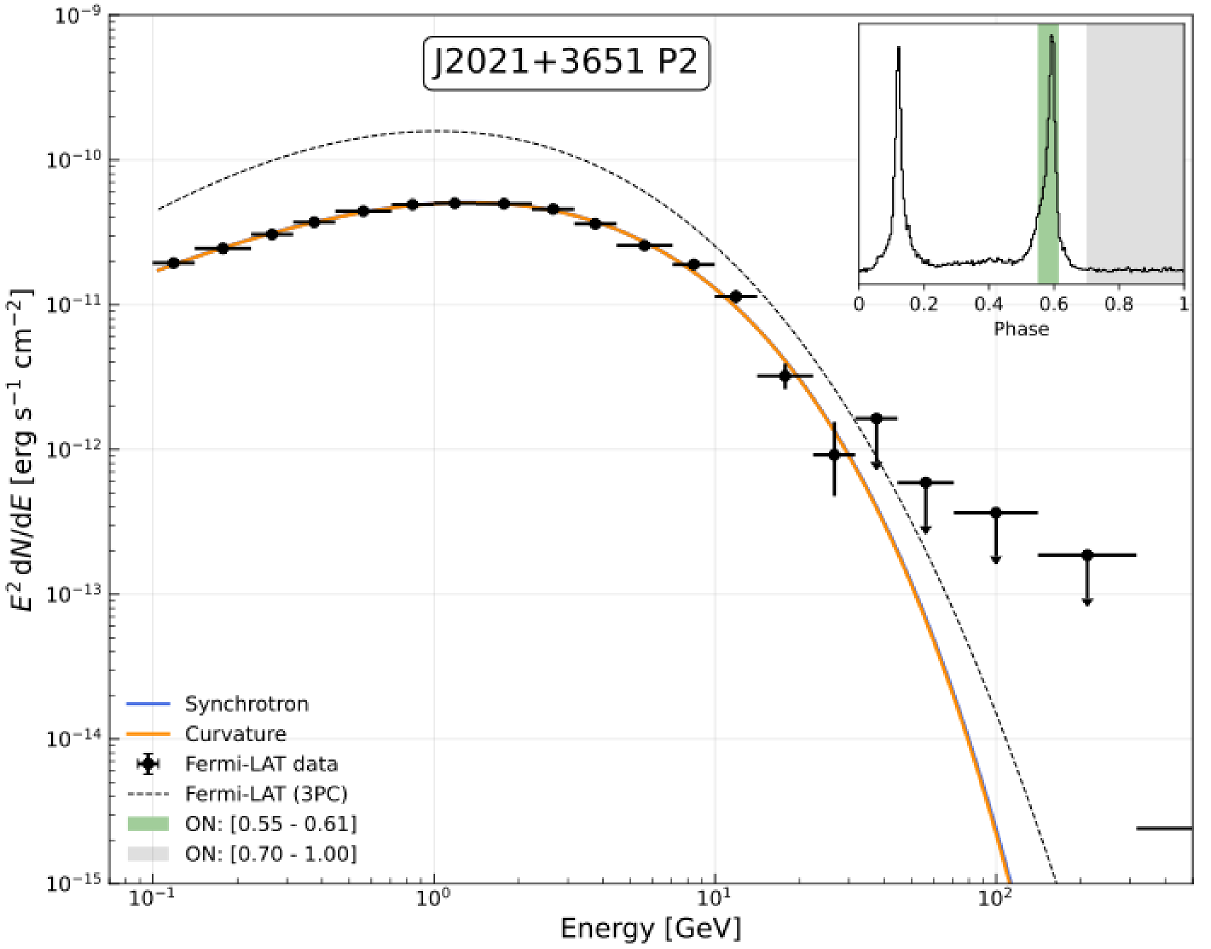

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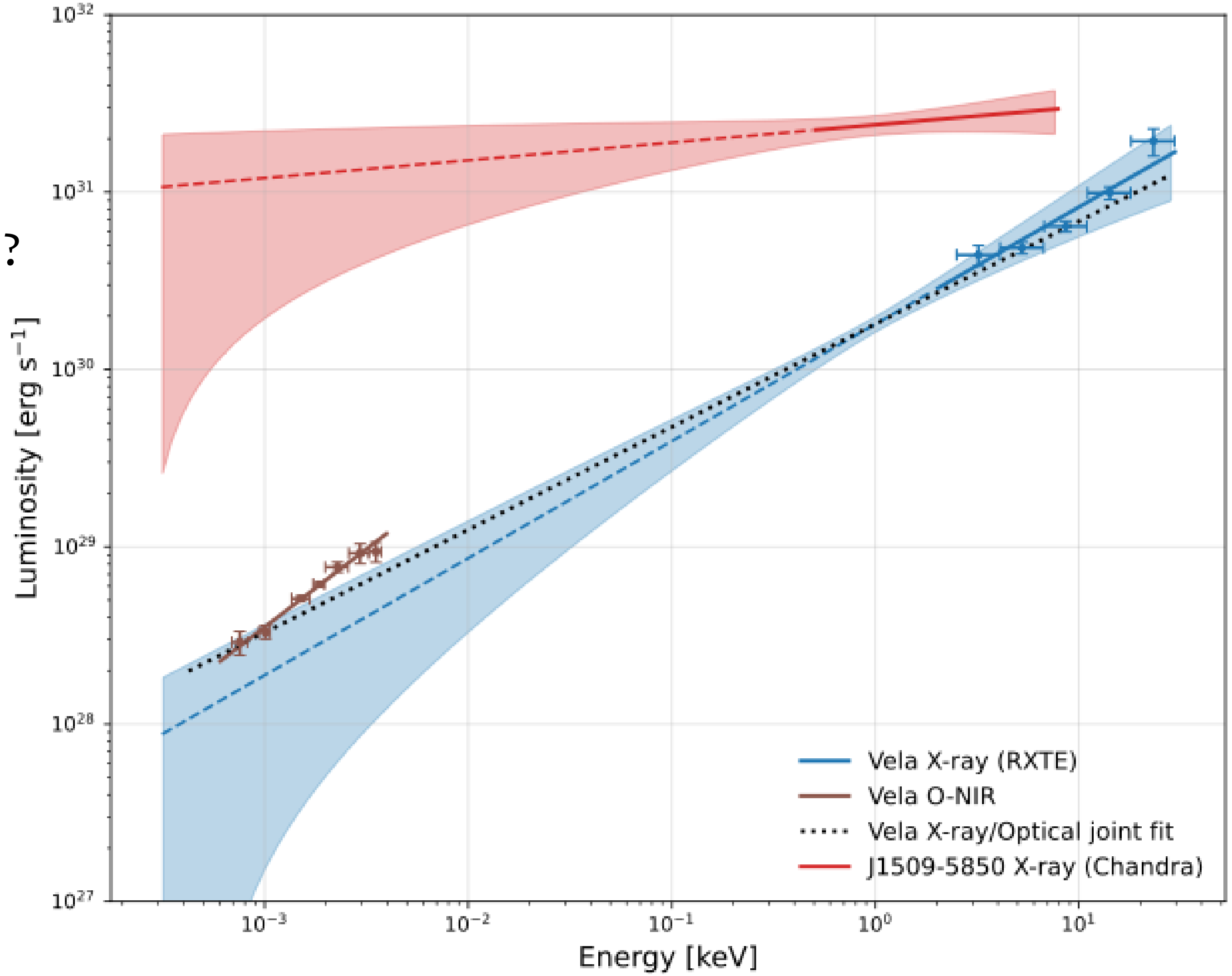
Inverse Compton target:

Inverse Compton targets: IR-O

- Only 7 pulsars with detection of pulsations
- 9 optical counterparts without pulsations

How can we estimate targets for IC prediction ?

- X-ray and optical = same emisson process
- Extrapolation from the X-ray to Optical ?
- Vela: Shibanov et al. 2003



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Not that simple

- Break(s): Extrapolation overshoot optical measurements

Empirical estimate the optical level from the X-ray based on Vela and Crab:

- Break energy: 10 eV
- $\Gamma_O = \Gamma_X - 1 \sim 1$
- Maximum factor 10 between measured and infered luminosity

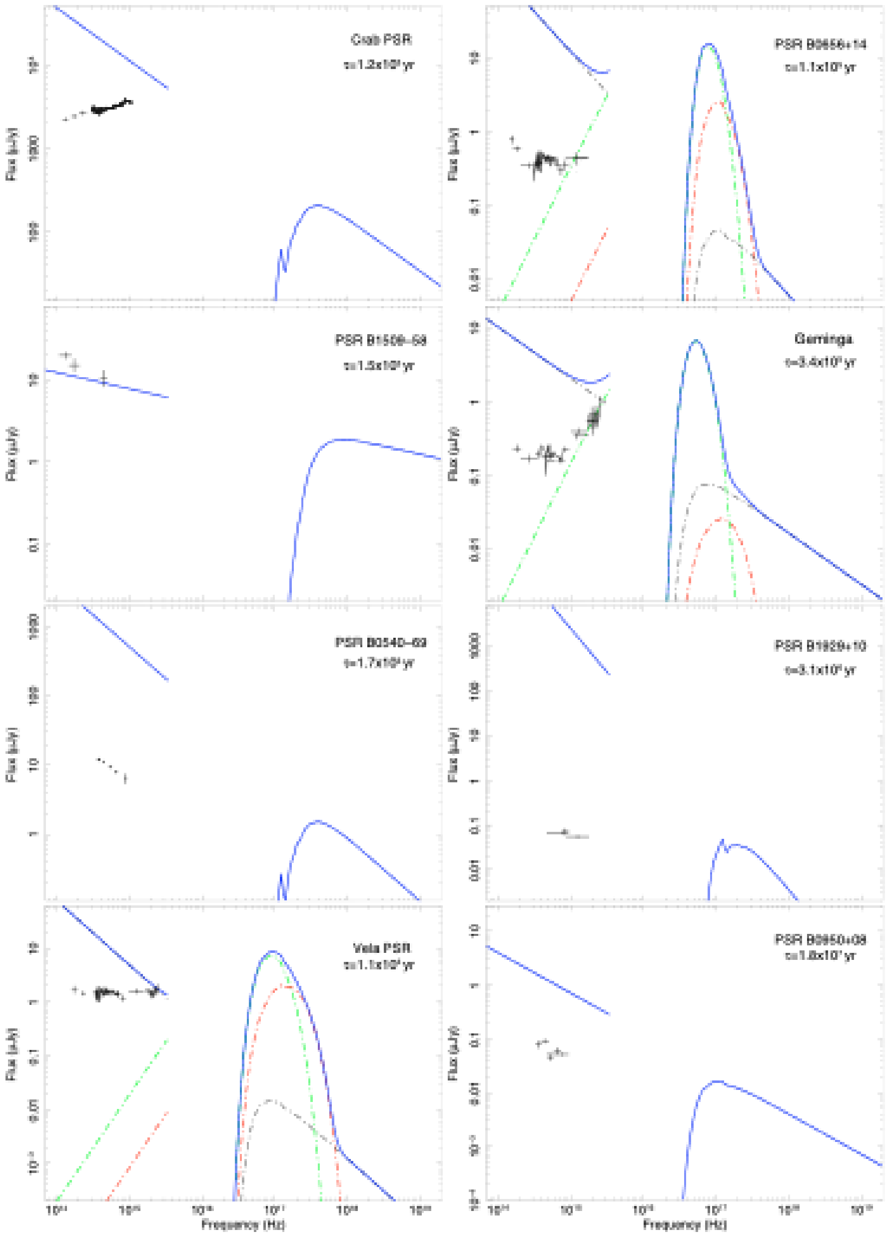

Figure 4 from [Mignani et al. 2010]

TeV prediction: Synthetic inverse Compton

Electron population from SR GeV fit

- To be consistent with Vela and J1509-5850 index

« Boost » emission by applying the CR cutoff

- Brings the emission in the > 10 TeV domain

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Inferred optical targets when no optical measurements (most of the pulsars)

Interaction volume:

- Based on PIC simulation
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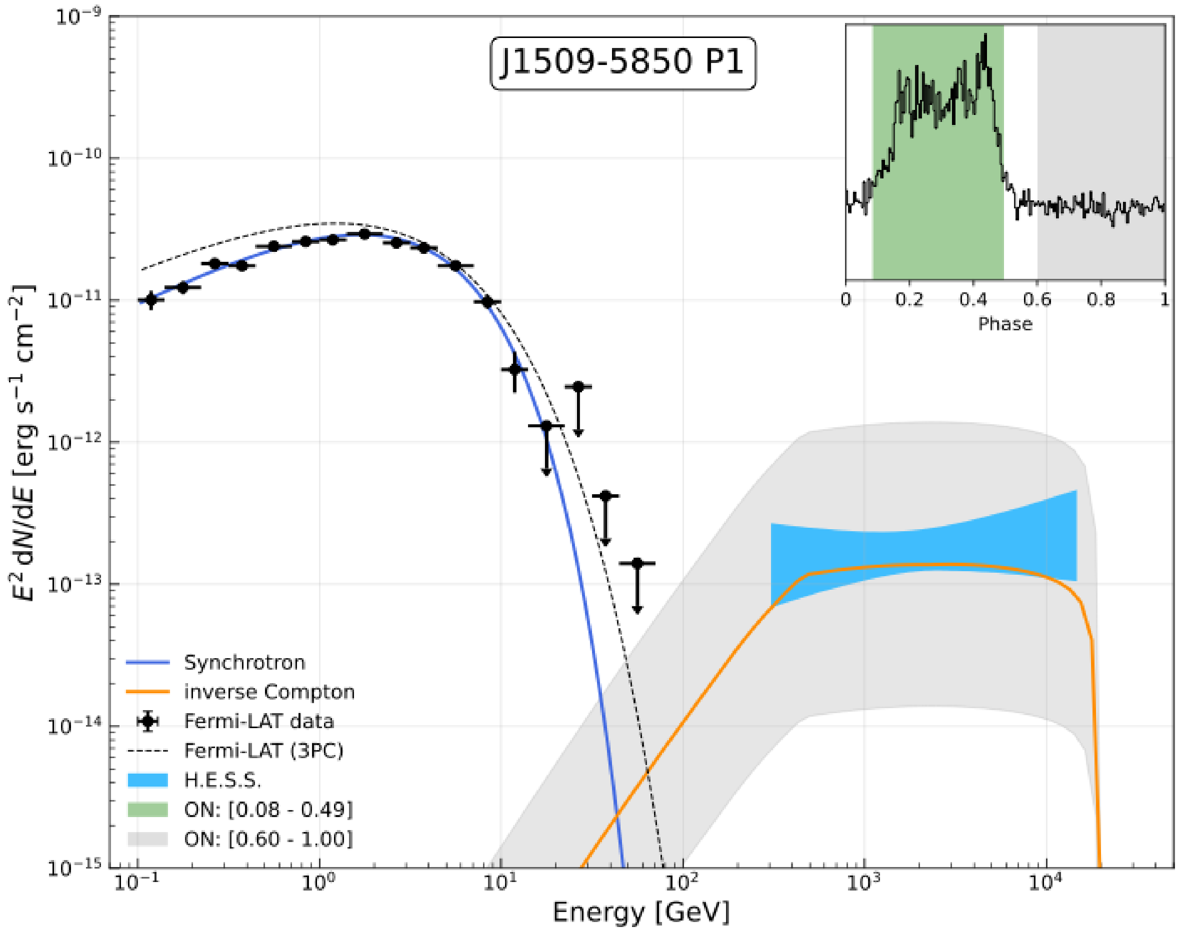
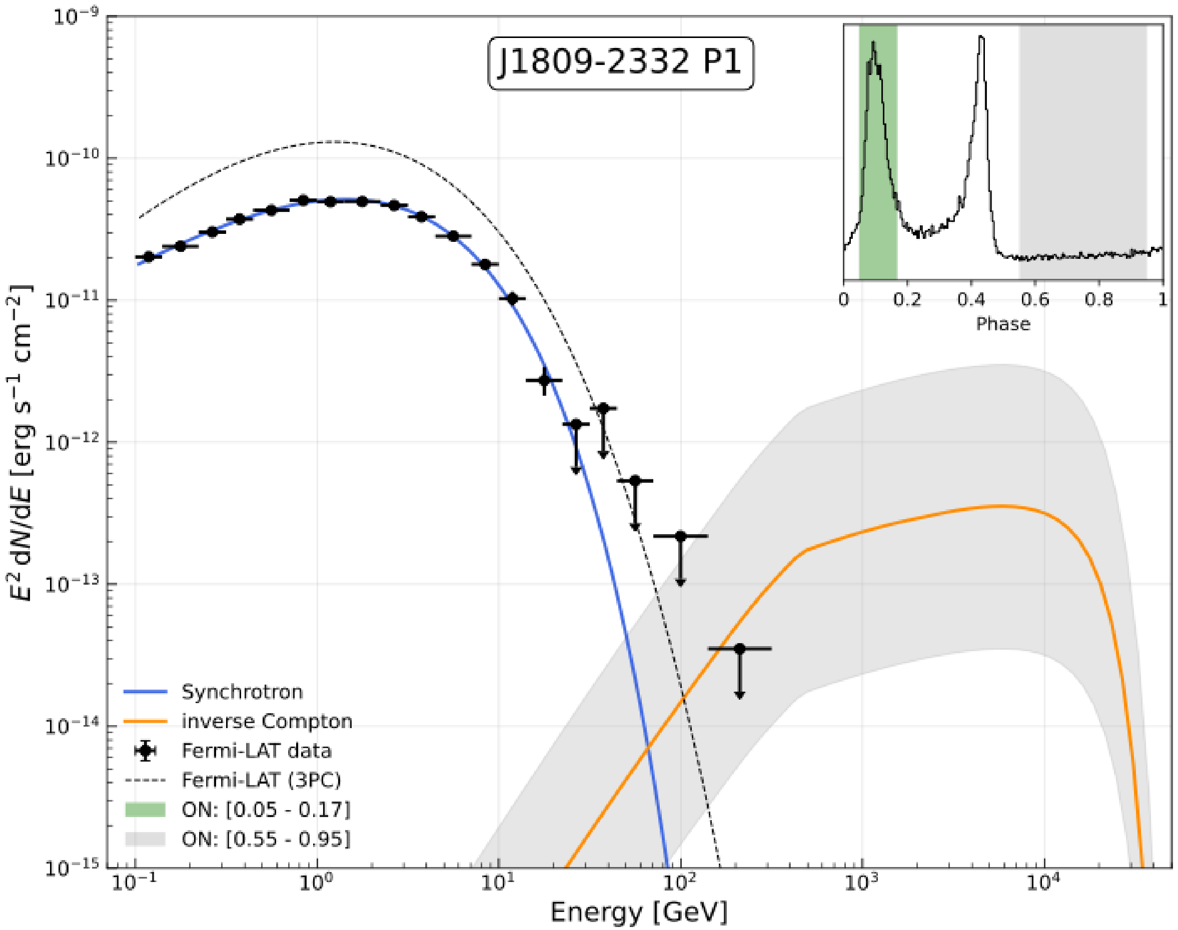
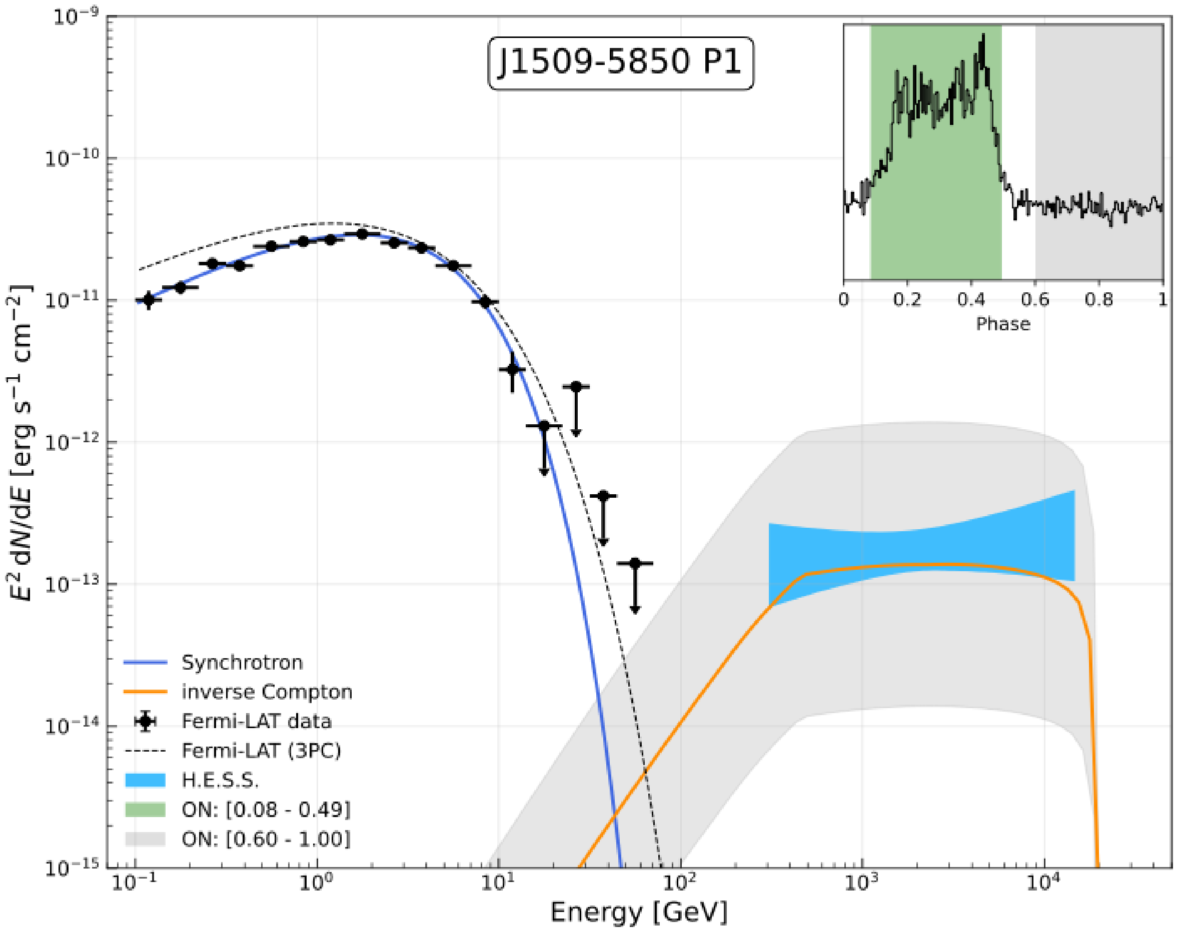
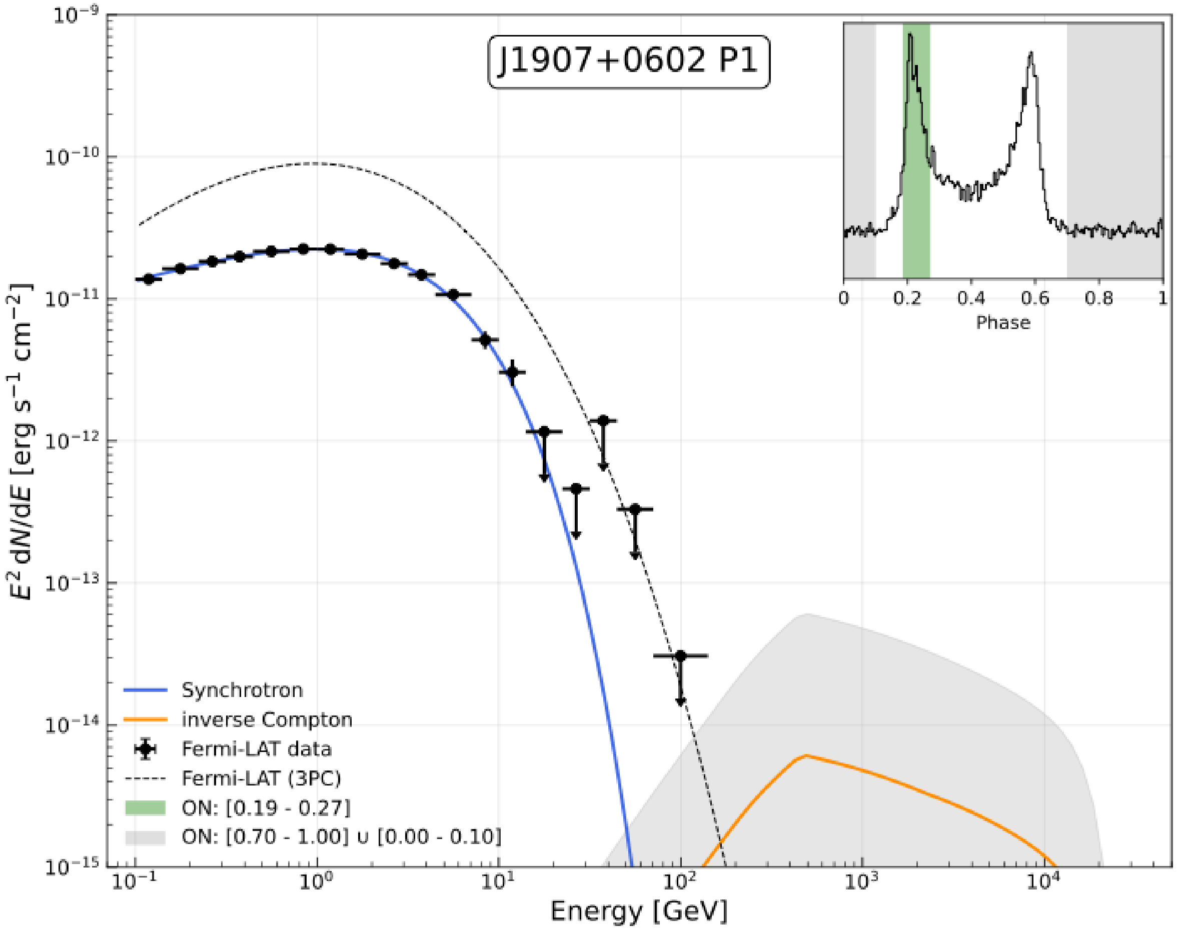


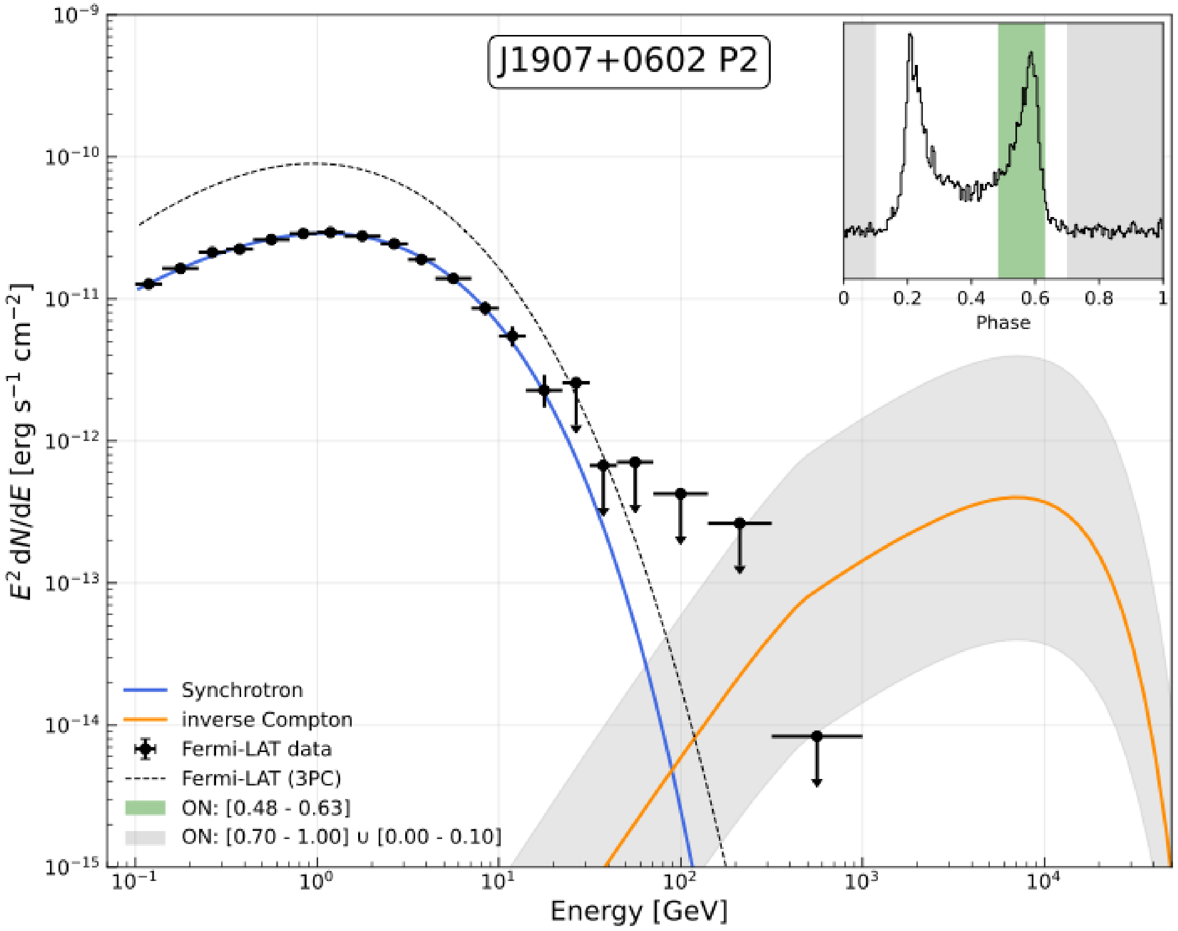
TeV prediction: Examples





TeV prediction: Importance of phase resolved analysis





Conclusion:

We are able to produce TeV emission for 35 out 63 pulsars in our sample:
- No X-ray emission found for the other half

From these 35 pulsars:
- More or less 60 different peaks (peak mixing in complex pulse profile)

Detectabilty with new generation gamma-ray instrument (CTAO):
- 18 peaks detectable → Emission above few 10^{-14} / 10^{-13} erg s^{-1} cm^{-2}
- 20 peaks below the sensitivity
- 14 with unrealistic TeV flux (Too high) → Can we mitigate this ?

Caveats of this study:
- Optical targets estimation wrong → not enough or too many targets
- Volume of interaction → Possible range from PIC simulation
- Geometry not taken into account → remove potential candidates
    - e.g. We see Vela P1 as much as P2 here, but not in H.E.S.S. data

Conclusion:

Choice of subset of 3PC pulsars:

- Appy this procedure to more gamma-ray pulsars, including MSPs ?

Some of these pulsars have been observed by current generation of IACTs:

- VERITAS Archer, A et al. 2019 search for pulsation from 13 pulsars
- H.E.S.S. HGPS → Interesting information on potential pulsar emission embedded galactic sources

If pulsars behave like Vela and J1509-5850:

- Cutoff energy in the 10-30 TeV → Perfect for CTAO SSTs
- Expected photon index: $1 \lesssim \Gamma \lesssim 2.5$
- For a given volume and target level: hard index favours detectability

With new generation of instrument the number of TeV pulsars should increase

- CTAO with high angular resolution is the perfect instrument.
- SWGO might be interesting to identify potential candidates with its high duty cycle and transit observation mode → Assess SWGO capability

It is only the beginning of TeV pulsar astronomy !

Thank you for you attention

Backup

3PC phase-resolved spectral analysis:

- We fit "PLEC4" expression of 4FGL-DR3, reduce parameters degeneracy

$$\phi(E) = \begin{cases} \phi_0 \cdot \left(\frac{E}{E_0}\right)^{\frac{a}{\Gamma_2}-\Gamma_1} \exp\left(\frac{a}{\Gamma_2^2}\left(1-\left(\frac{E}{E_0}\right)^{\Gamma_2}\right)\right) \\ \phi_0 \cdot \left(\frac{E}{E_0}\right)^{-\Gamma_1-\frac{a}{2}\ln\frac{E}{E_0}-\frac{a\Gamma_2}{6}\ln^2\frac{E}{E_0}-\frac{a\Gamma_2^2}{24}\ln^3\frac{E}{E_0}} & \text{for } \left|\Gamma_2 \ln\frac{E}{E_0}\right| < 10^{-2} \end{cases}$$

- Used by 3PC → Easy to compare

- Translate to simple ECPL model by: $PLEC \Longleftrightarrow PLEC4$

$$E_c = E_0 \left(\frac{b^2}{d}\right)^{\frac{1}{b}}$$

$$\Gamma_0 = \Gamma - \frac{d}{b}$$

$$N_0 = N_0 \exp\left(\frac{d}{b^2}\right)$$

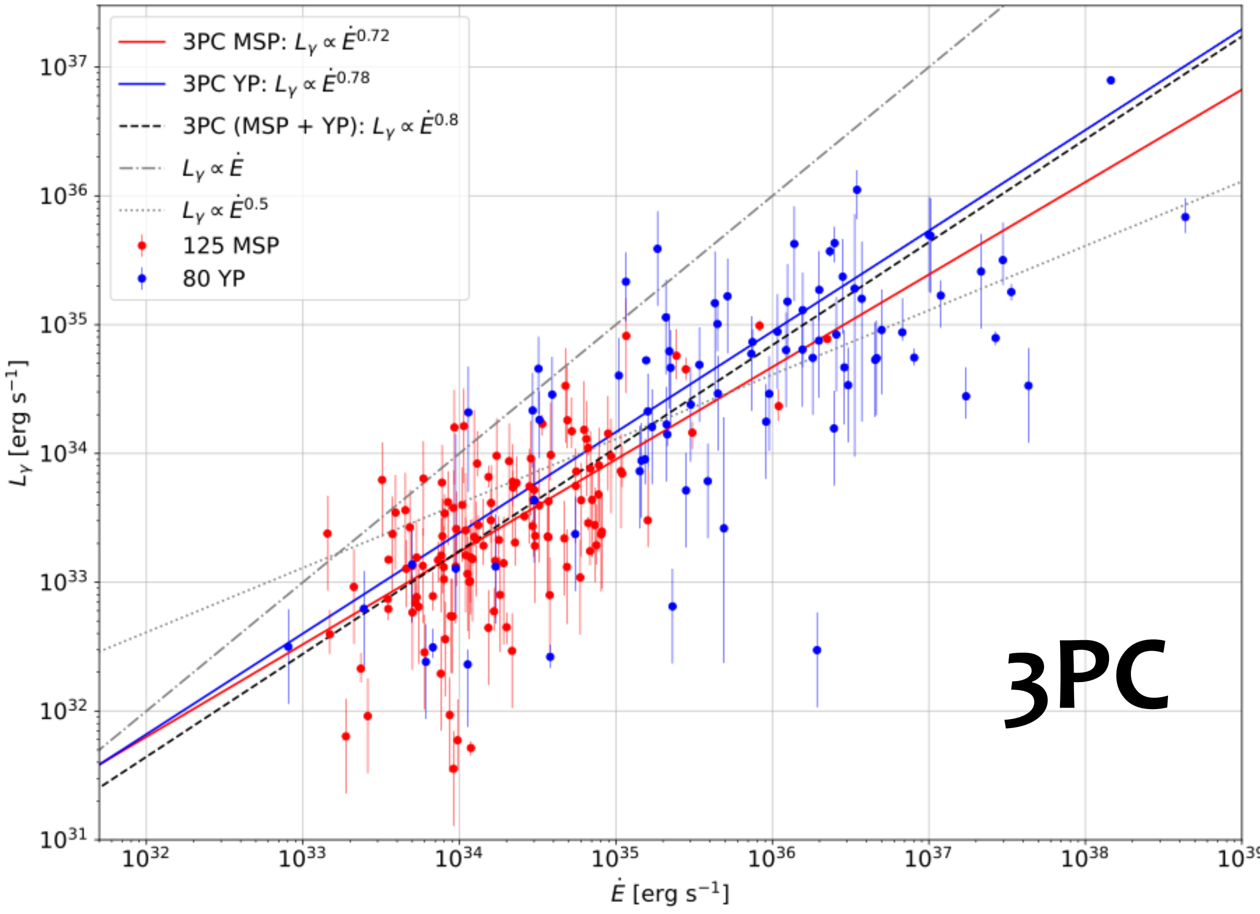
Inferring distance

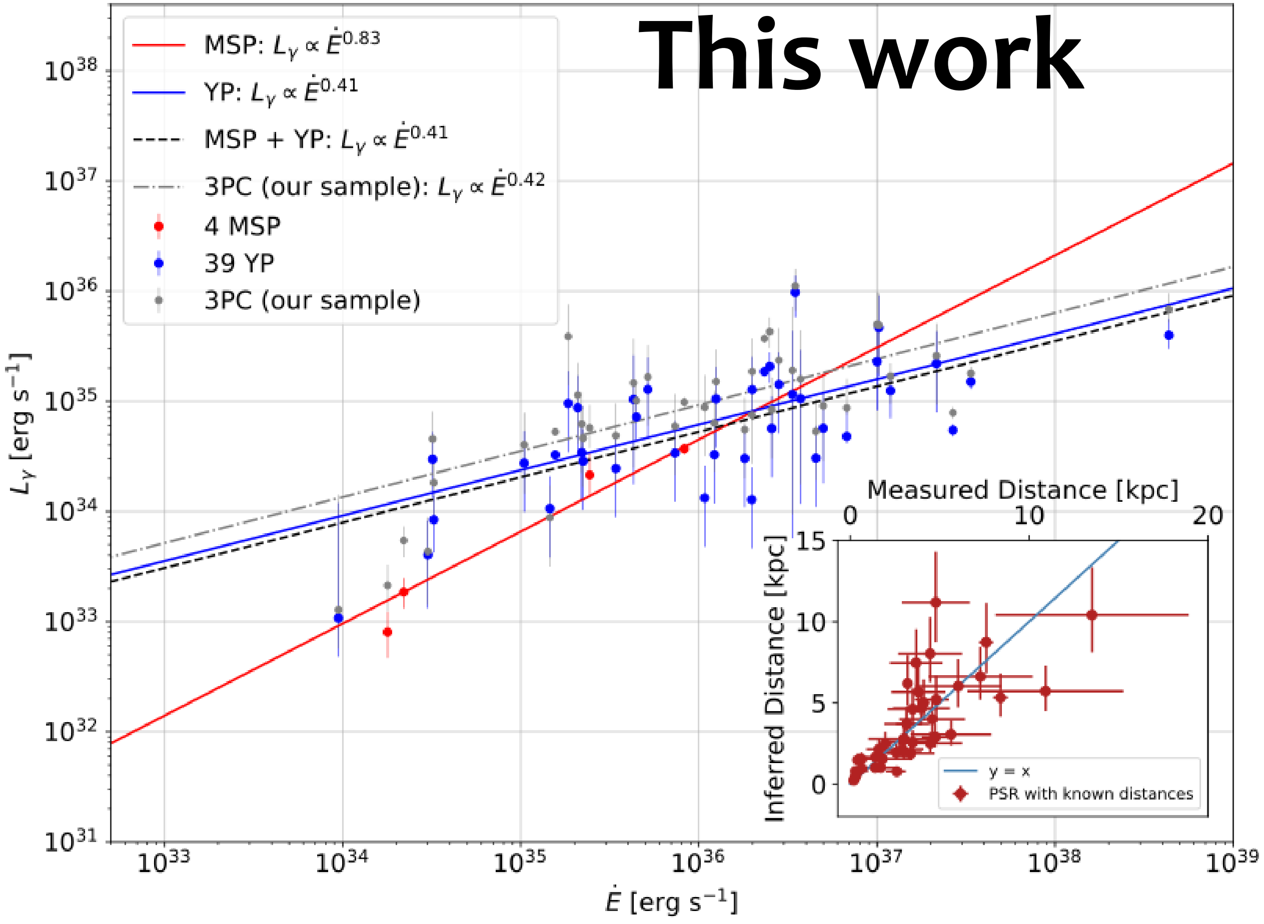
$$L_\gamma = 10^{19.891\pm0.105} \times \dot{E}^{0.412\pm0.003}$$

20 pulsars without distance measurements in our sample

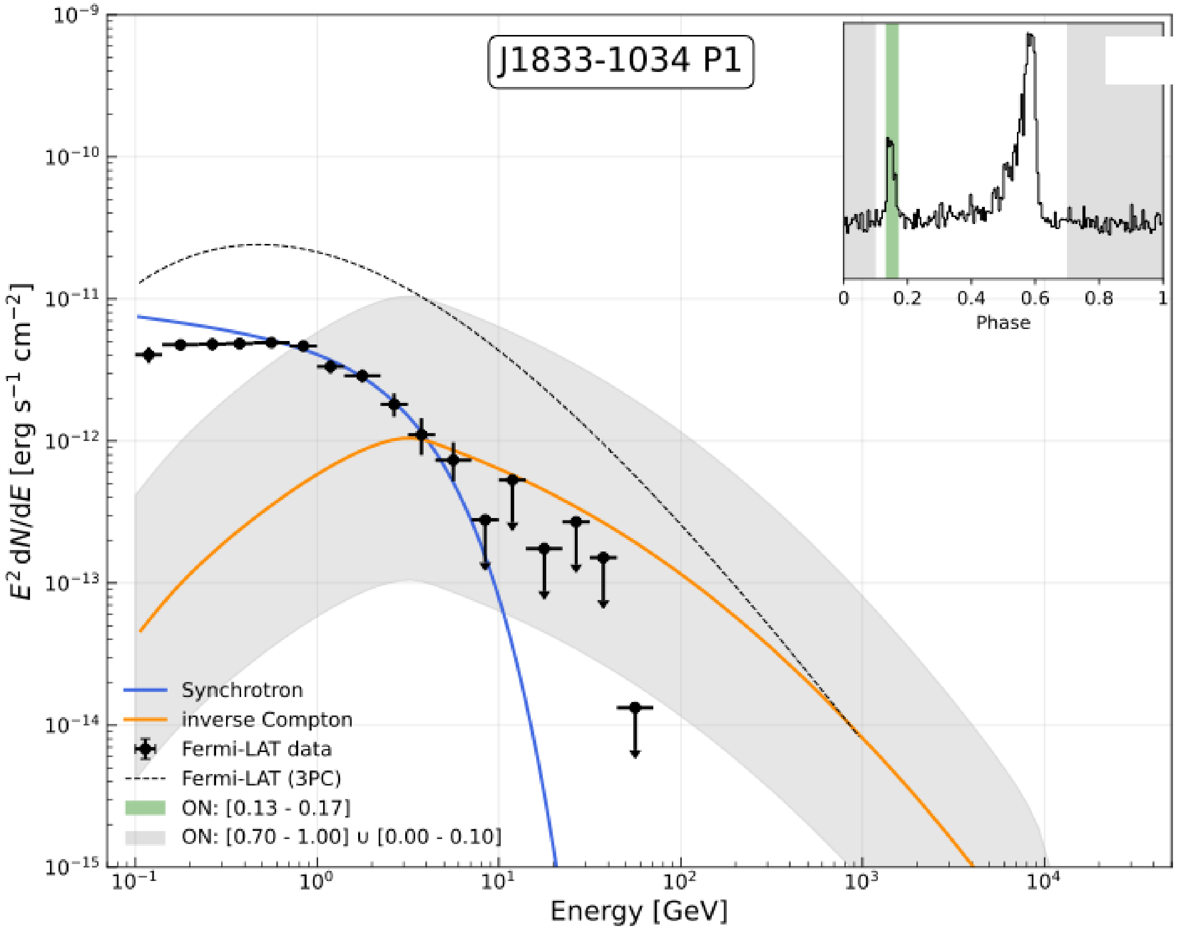
- 3PC shows correlation between L_γ and $\dot{E}$

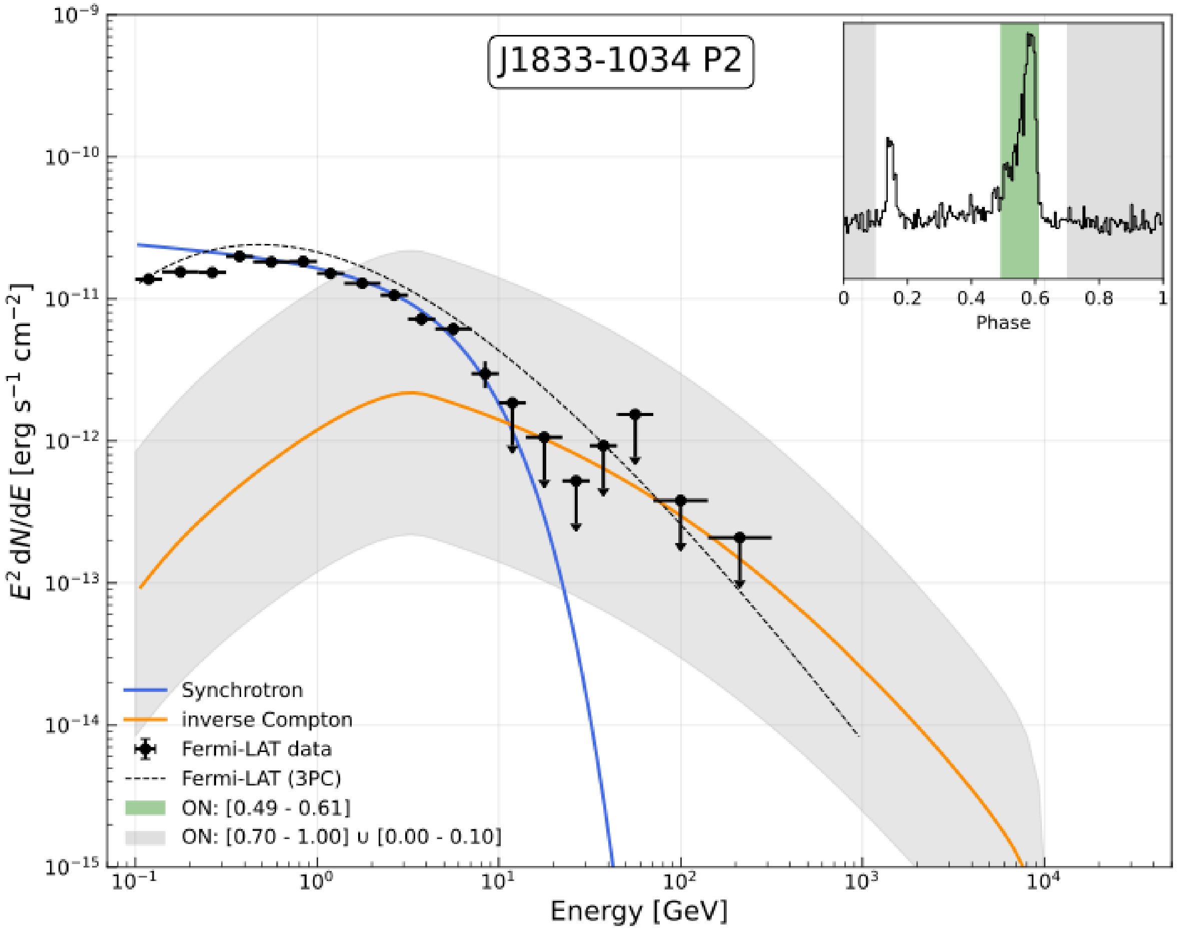
$$d = \sqrt{\frac{L_\gamma}{4\pi F_{GeV}}}$$



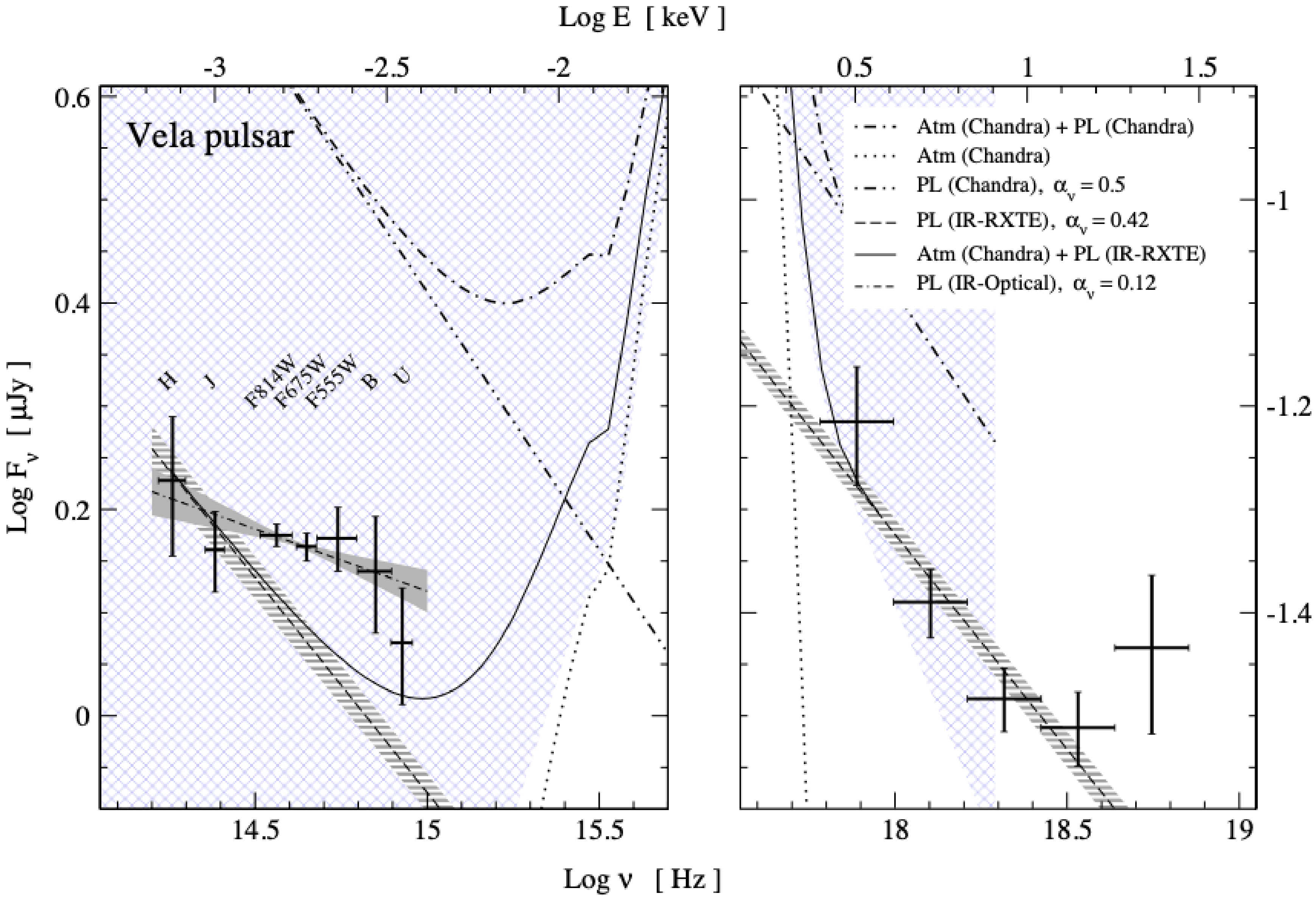


TeV prediction: Crab-like candidates ?

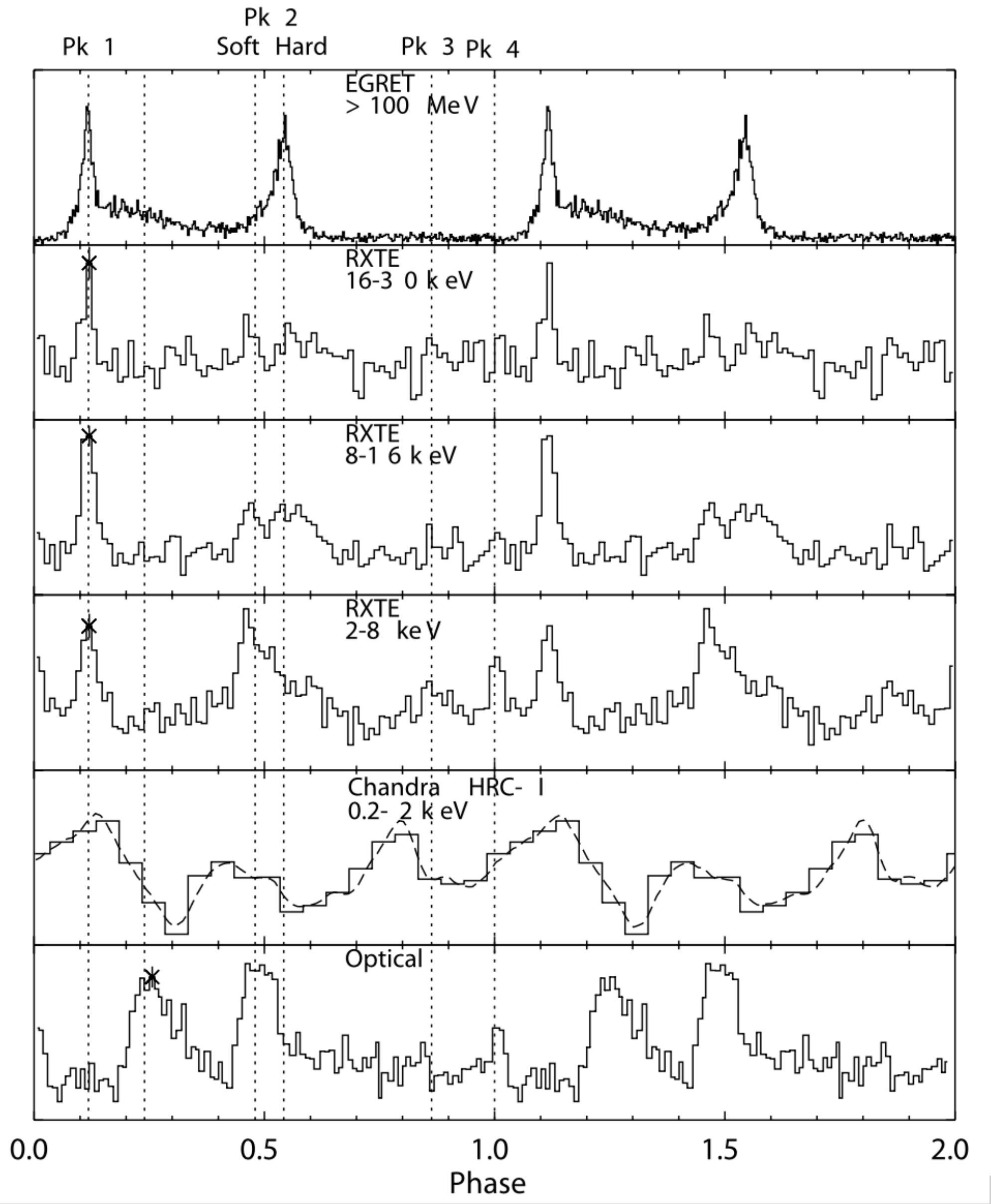


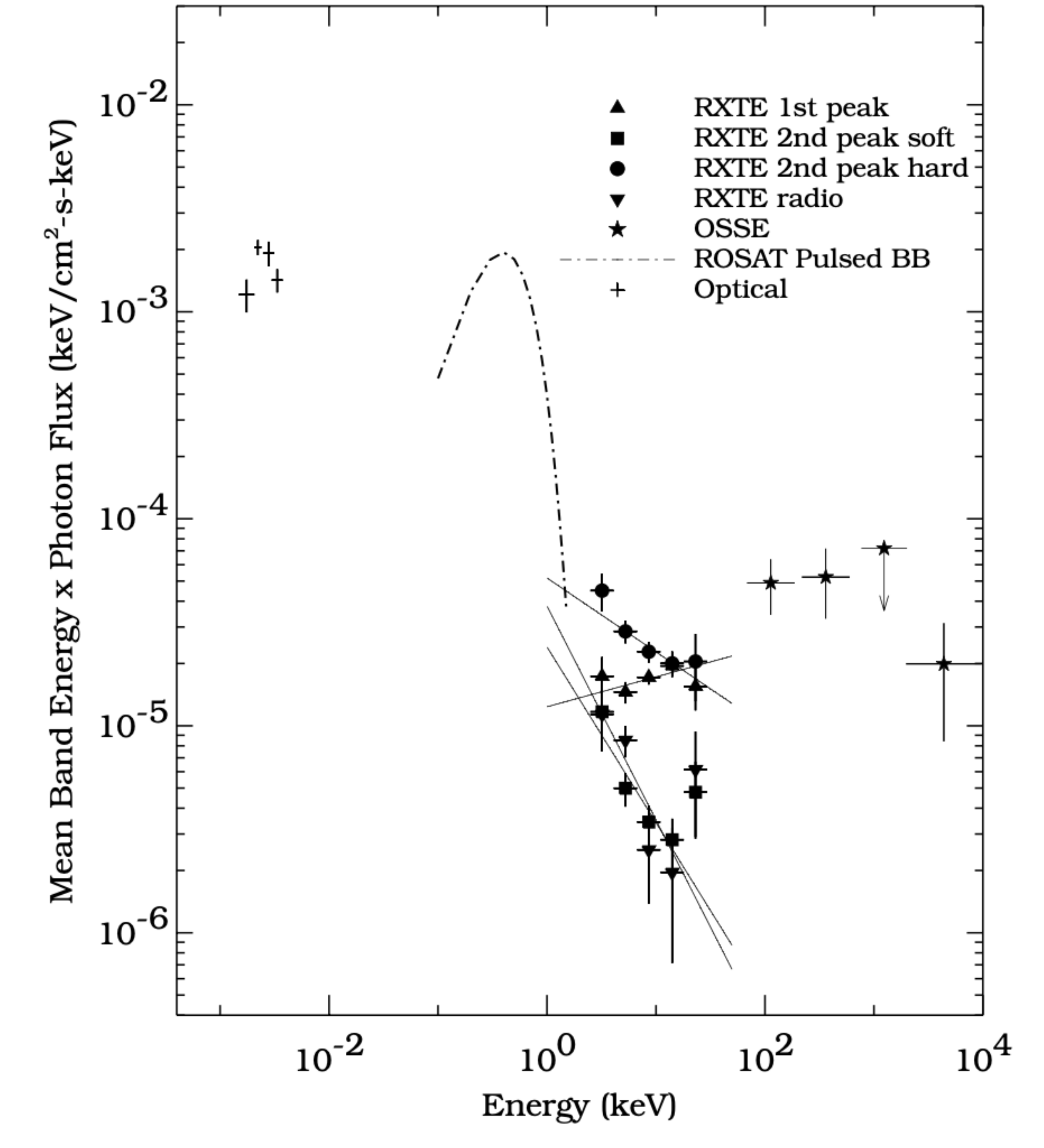


Shibanov 2003:

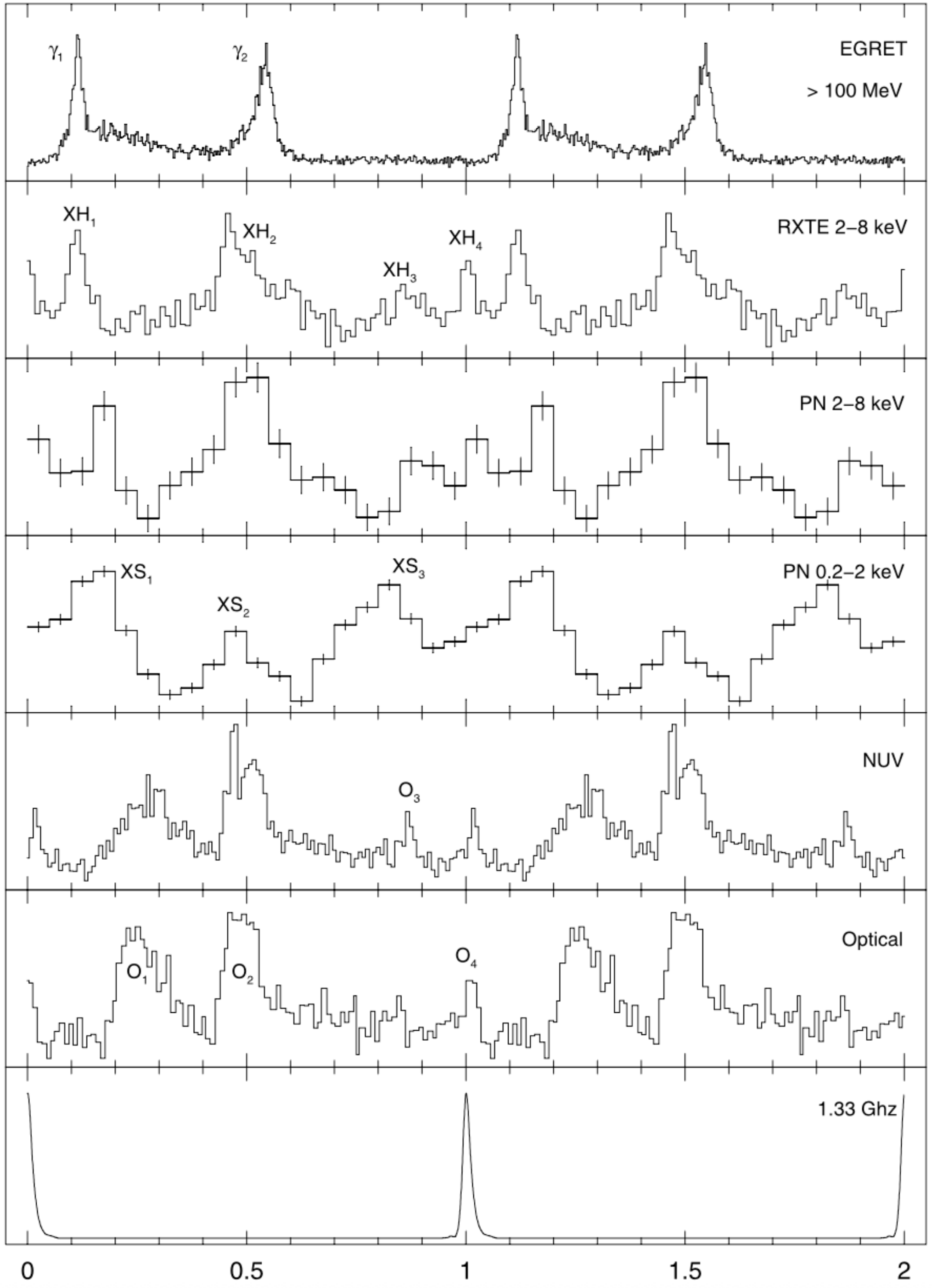


Harding 2002:

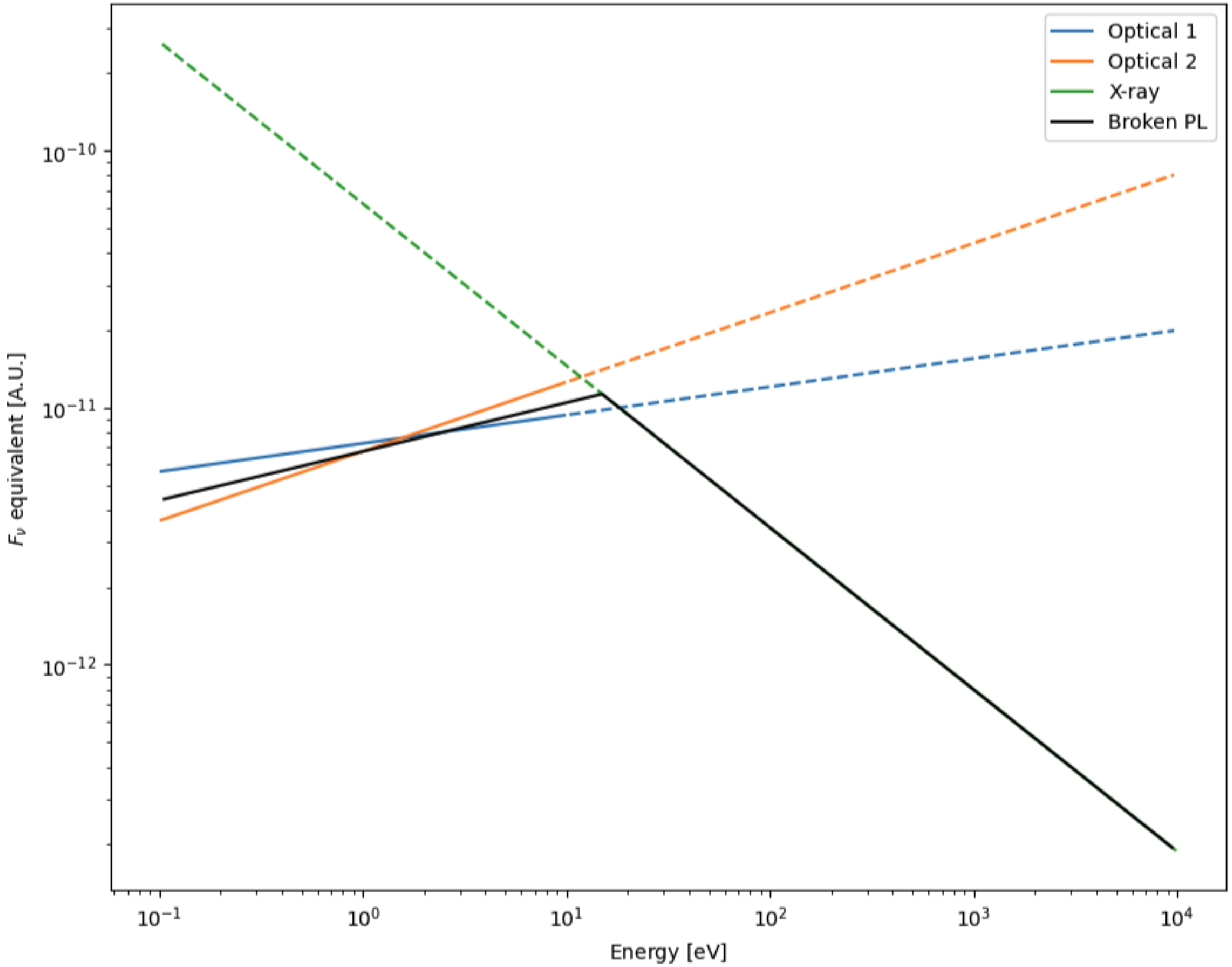




Manzani 2007:



Crab extrapolation:



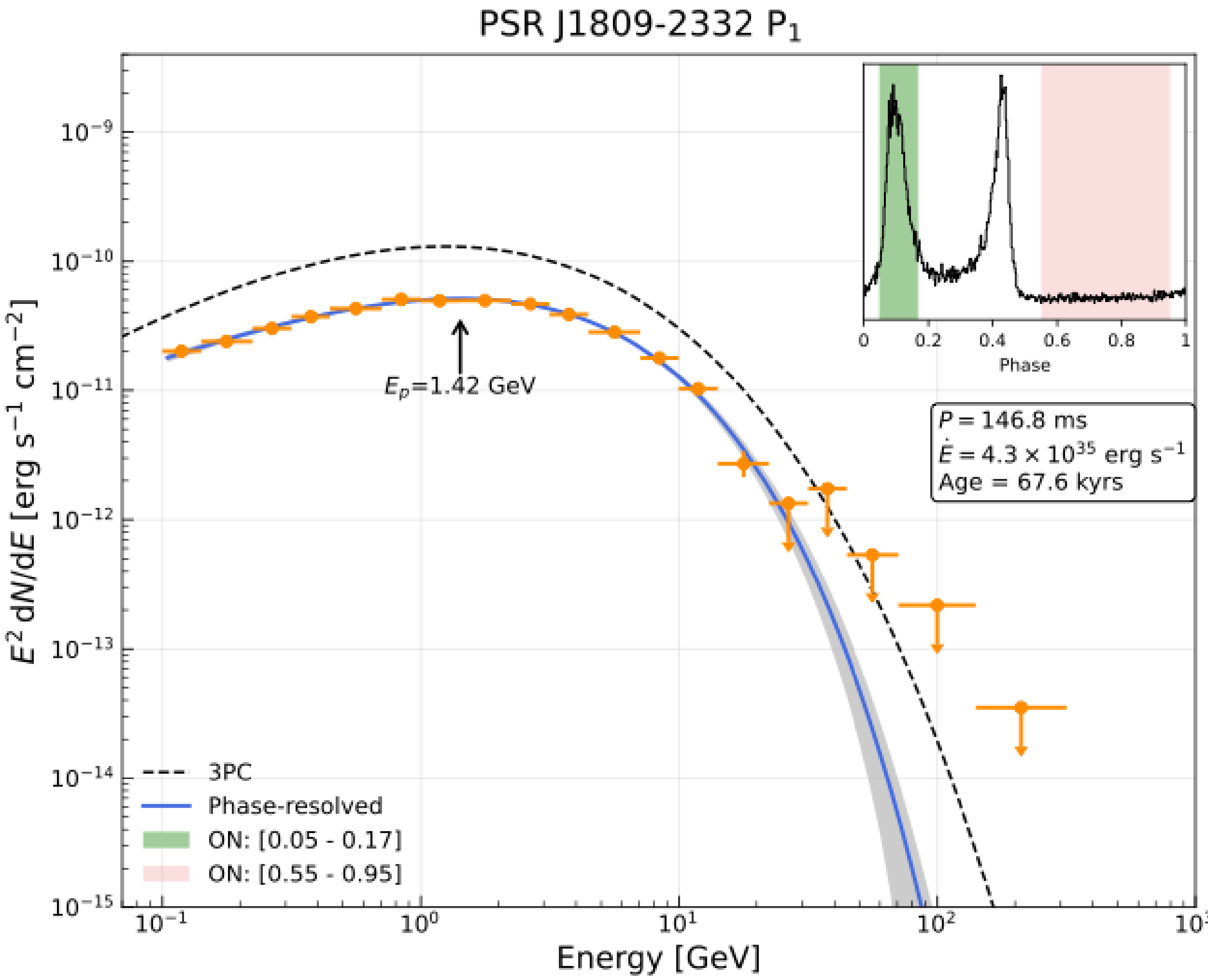
GeV radiative modelling:

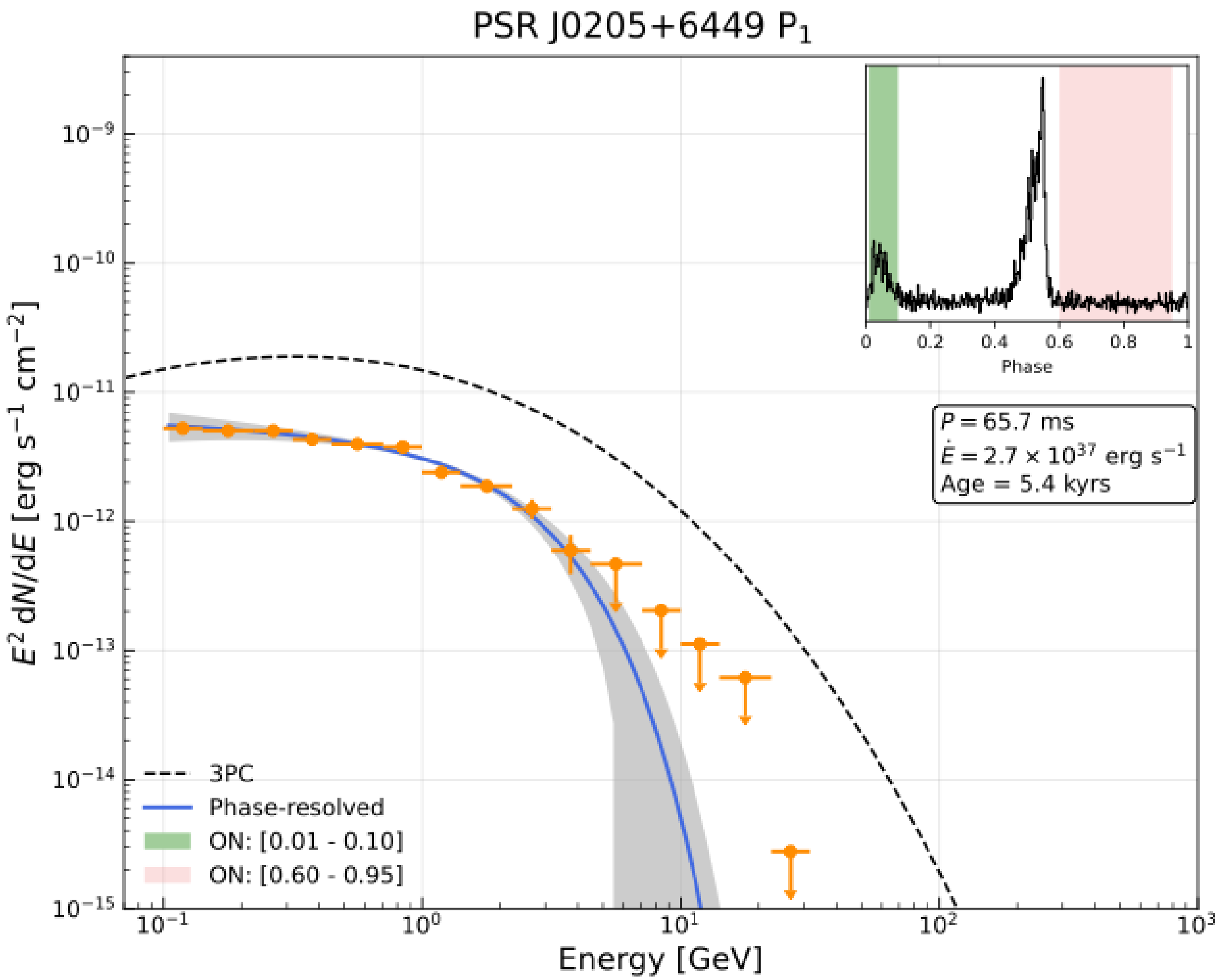
Fit of radiative model to the GeV:

- Use Naima – Gammapy interface to fit Synchrotron (SR) and Curvature (CR) radiation model to Fermi-LAT data
- Electrons distribution: ECPL
- For SR:
  - $B = B_{LC}$ fixed during the fit
- For CR:
  - $R_c = R_{LC}$ fixed during the fit

3PC phase-resolved analysis:

Spectral analysis:





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