Vela Pulsar and Vela-X with 13+ years of Fermi-LAT

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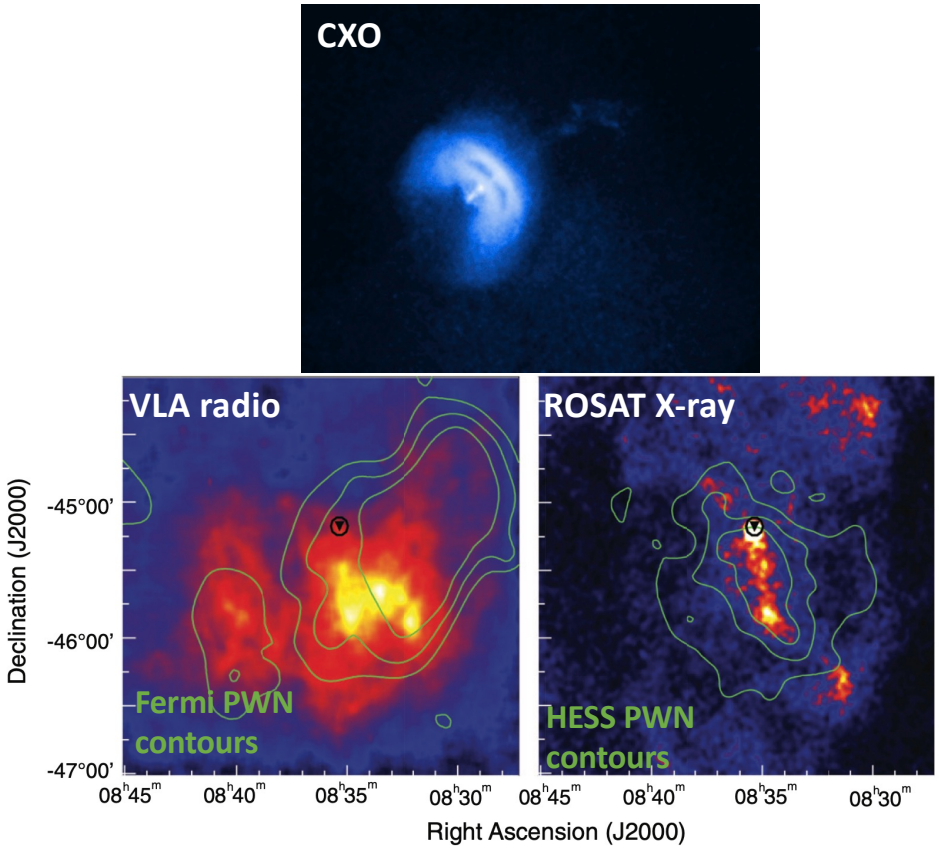
Vela Pulsar and Pulsar Wind Nebula Vela-X



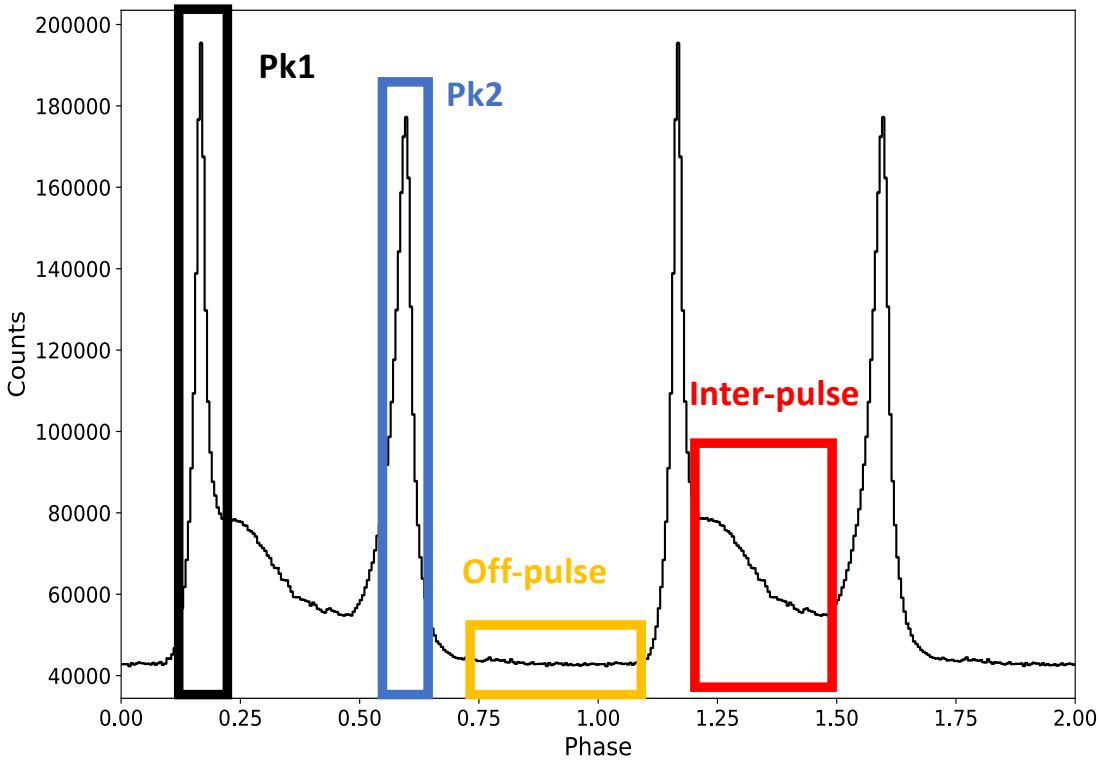
Top: CXO, Durant, et al., 2014
Bottom: VLA and ROSAT, Hinton et al., 2011.

- Vela is among the brightest Gamma-ray sources in sky
- ~ 89 ms rotational period, characteristic age ~11kyr and distance ~ 287 pc
- Spin-down power of $\dot{E} = 6.3 \times 10^{36}$ erg/s
- Visible across electromagnetic spectrum and largely studied
- Pulsar powers the PWN Vela-X
- 13 years of Fermi-LAT data from 60 MeV – 2 TeV will improve on previous gamma-ray analyses:
  - Abdo2010 (1 year)
  - HESS2018/Tibaldo2018 (~9 years)

Fermi-LAT Data Selection

- FermiTools version 2.2.0, FermiPy version 1.2.0
- 13 years of Fermi-LAT observations with Pass 8 data (< 15°), using:
  - 4FGL-DR3 catalog,
  - gll_iem_v07.fits for galactic diffuse emission,
  - iso_P8R3_SOURCE_V3_v1.txt for isotropic emission,
  - zmax=90.0, evclass=128, evtype=3,
  - 36 log-spaced energy bins
- Fermi-LAT ephemeris from Matthew Kerr to assign Pulse Phases with Tempo2

1. Off-pulse data to analyze PWN
2. Phase-integrated and phase-resolved to analyze pulsar

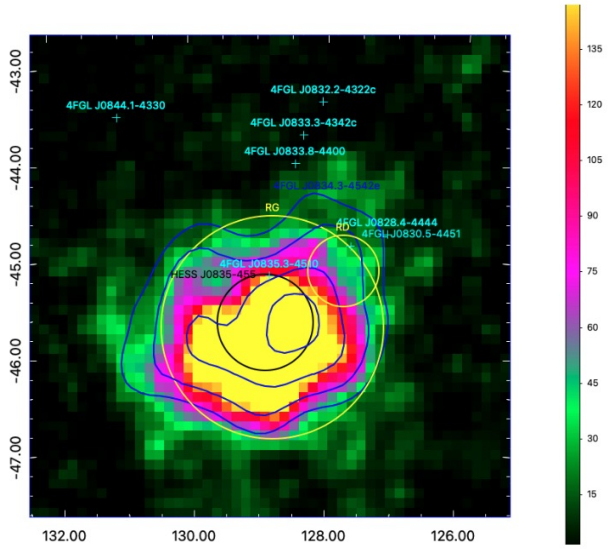


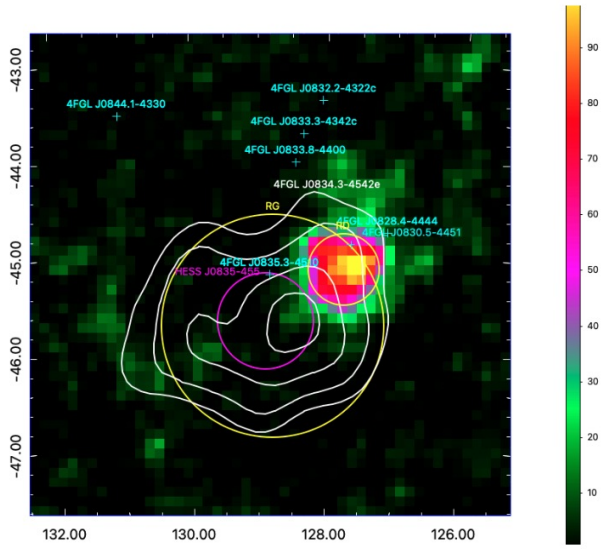
Pulse Profile of Vela Pulsar from 13 years of LAT data in 200 phase bins between 60 MeV – 10 GeV. Peak 1, 2 and the off-pulse and inter-pulse periods are defined.

Pulsar Wind Nebula (PWN) Vela-X Spatial Modeling

- Selected off-pulse phases 0.00 – 0.08, 0.80 – 1.0
  - PWN analysis ranges from 1 GeV – 2 TeV
- 4FGL PWN is re-characterized as two extended components: Radial Gaussian (RG) and Radial Disk (RD) component
  - Significant improvement to the fit
- Significance of RG (left) and RD (right) components below:

Sources Tested	Spatial Model	Power Law Index	$\log L$	G_E ($\times 10^{-4}$ MeV cm^{-2} s^{-1})	TS
4FGL J0834.3–4542e	330MHz radio template	2.12 ±0.01	386647	2.04	3934
RG	1.12° Radial Gaussian	2.10 ±0.01	386692	2.04	3434
RG	1.12° Radial Gaussian	2.12 ±0.01	386750	1.89	2766
RD	0.37° Radial Disk	2.09 ±0.04		0.37	247





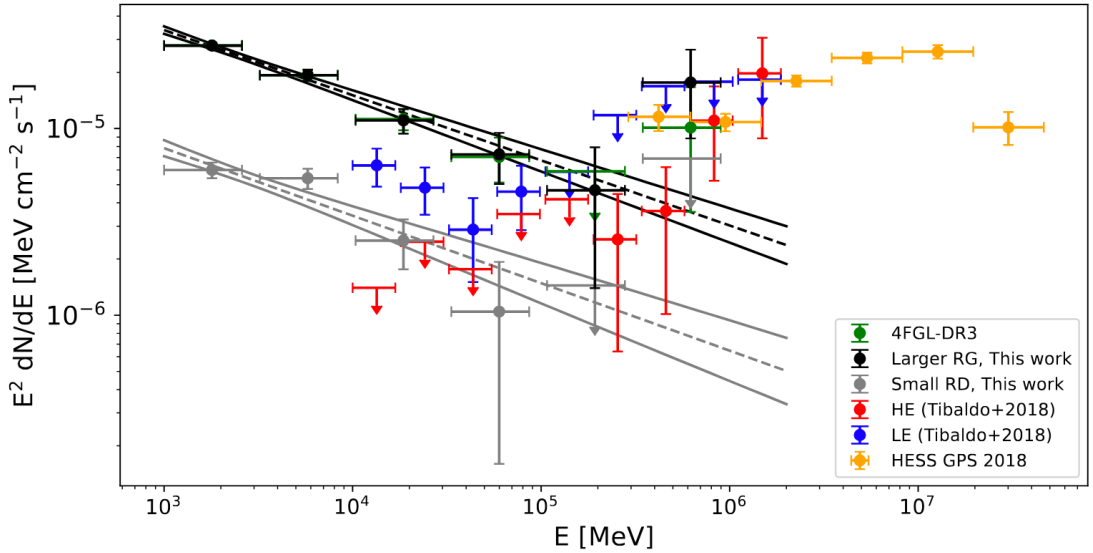
*** ∝ detection significance**

TS =25 for 4DOF ~ 4σ

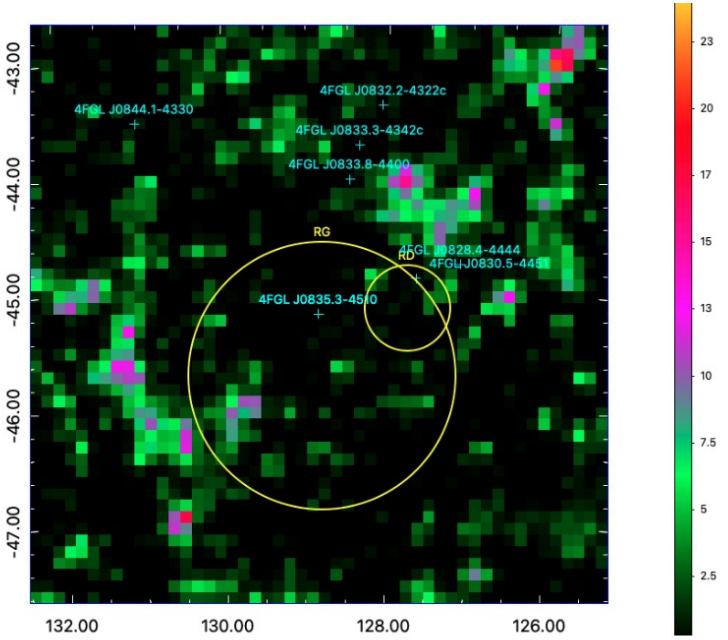
E > 1 GeV TS Maps of the RG (left) and RD (right) in yellow. PSR is shown as cyan cross. 4FGL spatial template (based on 330MHz) contours shown in blue/white. HESS PWN extent shown in black/magenta.

Pulsar Wind Nebula (PWN) Vela-X SED

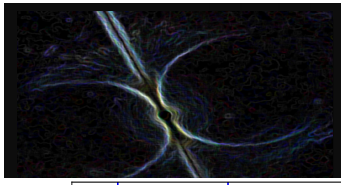
- Modeling of the Vela-X SED shows consistent results to prior work
  - No clear High-energy component as is found in Tibaldo+2018



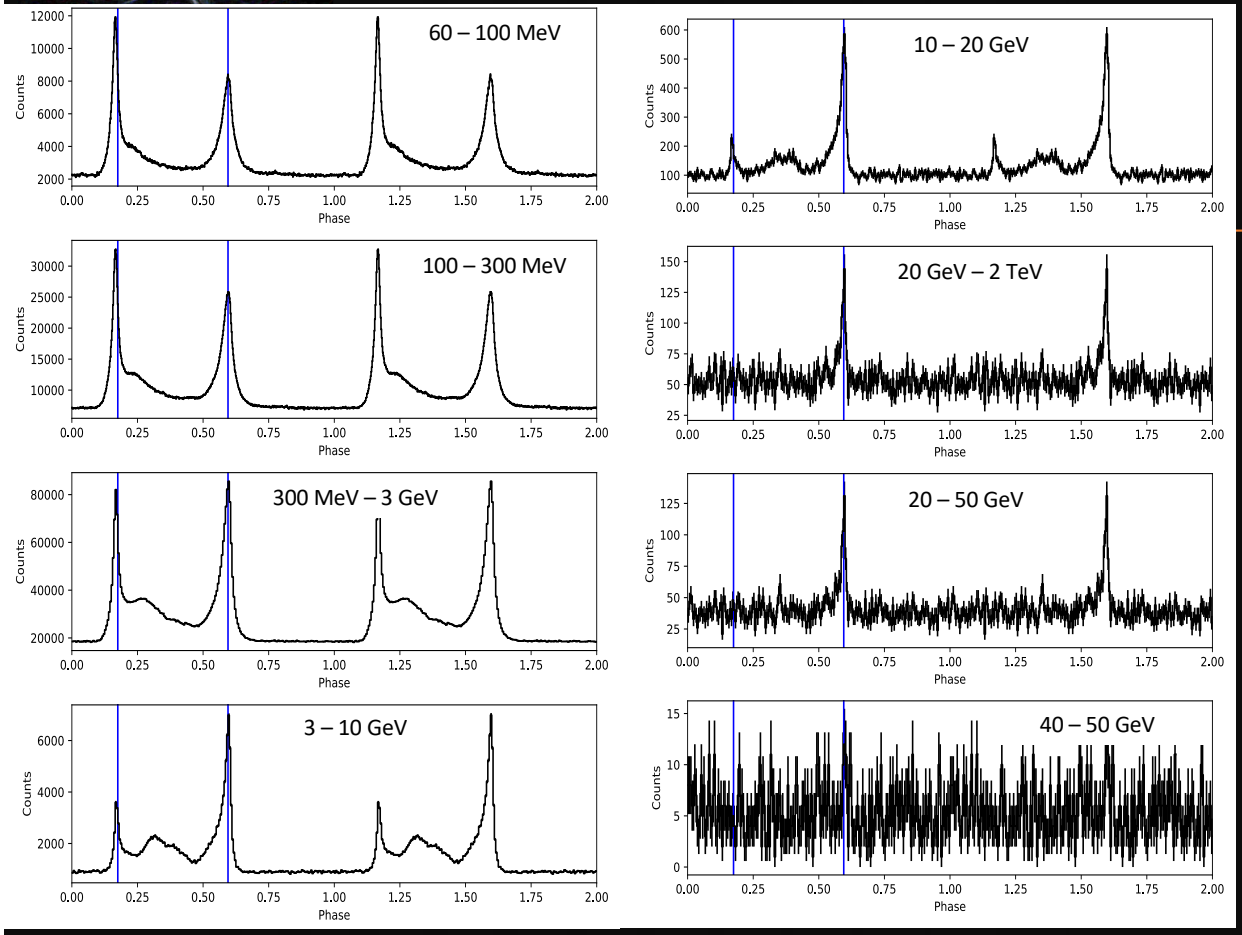
SED comparing the RG and RD (black and grey) high-energy and low-energy spectral fits from Tibaldo+2018 (red and blue, respectively), the 4FGL-DR3 catalog fit (green) and HESS GPS, 2018 (orange).



E > 1GeV TS map of RG+RD (yellow).



Vela Pulsar: Pulse Profiles

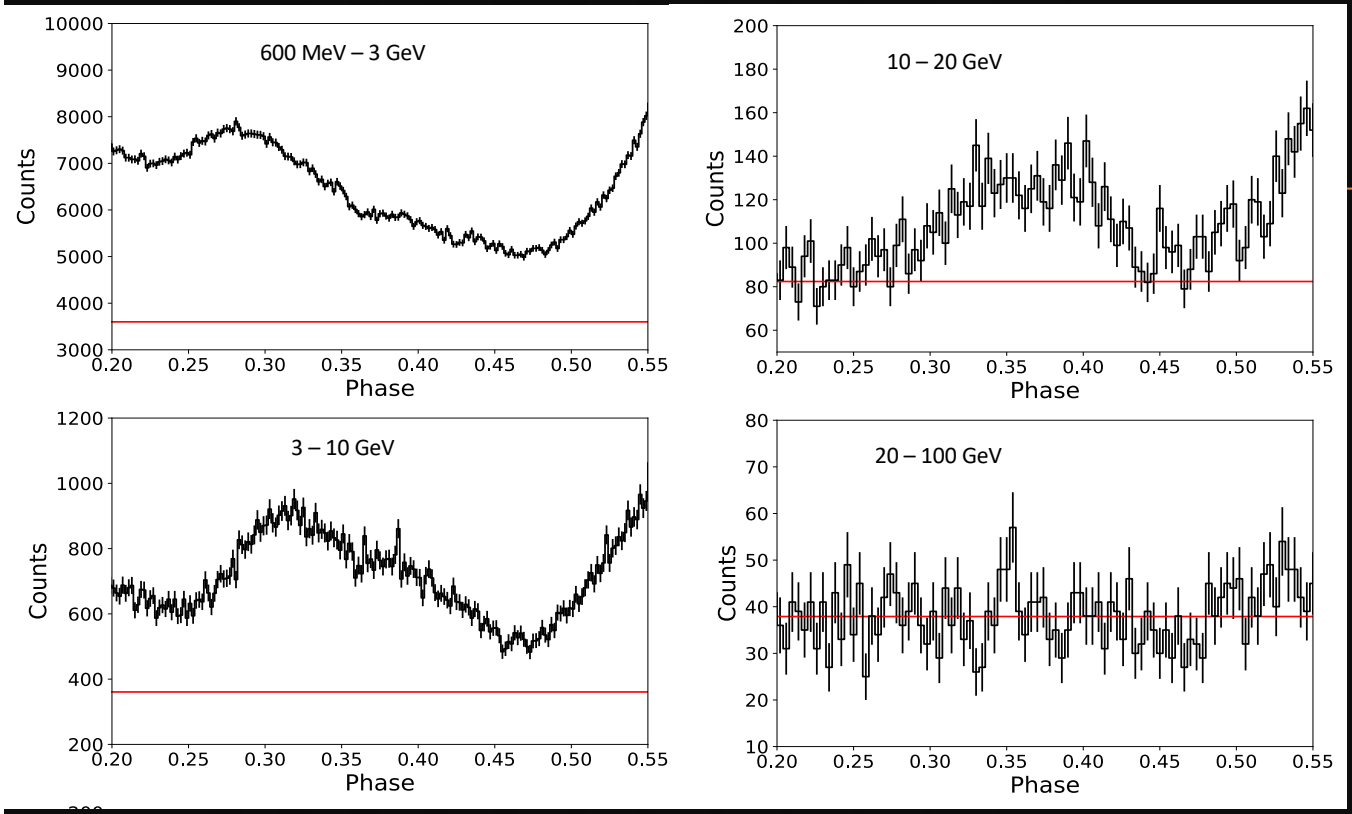


Energy-resolved pulse profiles.

- From 60 MeV - 2 TeV
- 100 phase bins (left)/50 phase bins (right)
- 8 distinct energy ranges
  - 60 – 100 MeV
  - 100 – 300 MeV
  - 300 MeV – 3 GeV
  - 3 – 10 GeV
  - 10 – 20 GeV
  - 20 GeV – 2 TeV
  - 20 – 50 GeV
  - 40 – 50 GeV

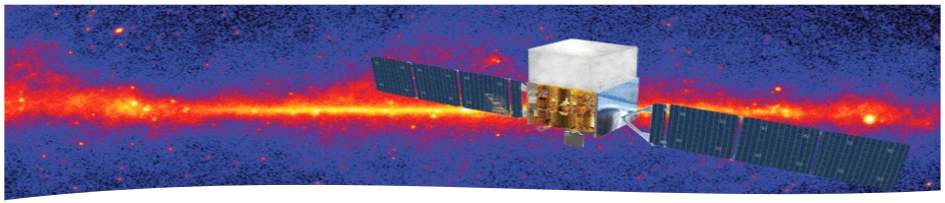
1st peak disappears > 20 GeV, Inter-pulse structure between 300 MeV and 20 GeV

Vela Pulsar: Inter-pulse (P3)



- From 60 MeV - 2 TeV
- 100 phase bins (left)/50 phase bins (right)
- 4 distinct energy ranges
  - 600 MeV–3 GeV,
  - 3–10 GeV,
  - 10–20 GeV,
  - 20–100 GeV
- Clear evolution of P3 emission

Energy-resolved pulse profiles.

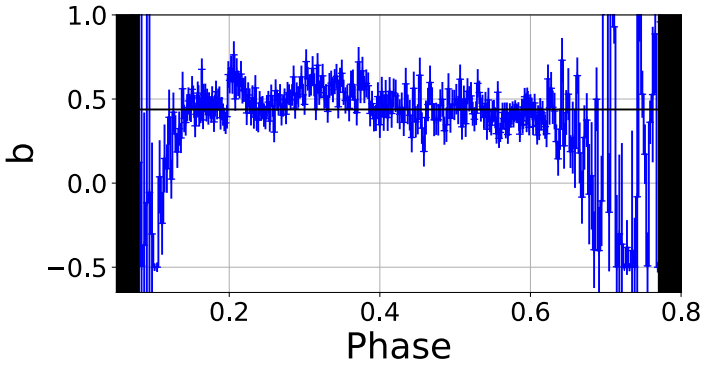


Fermi-LAT Phase-Resolved Analysis

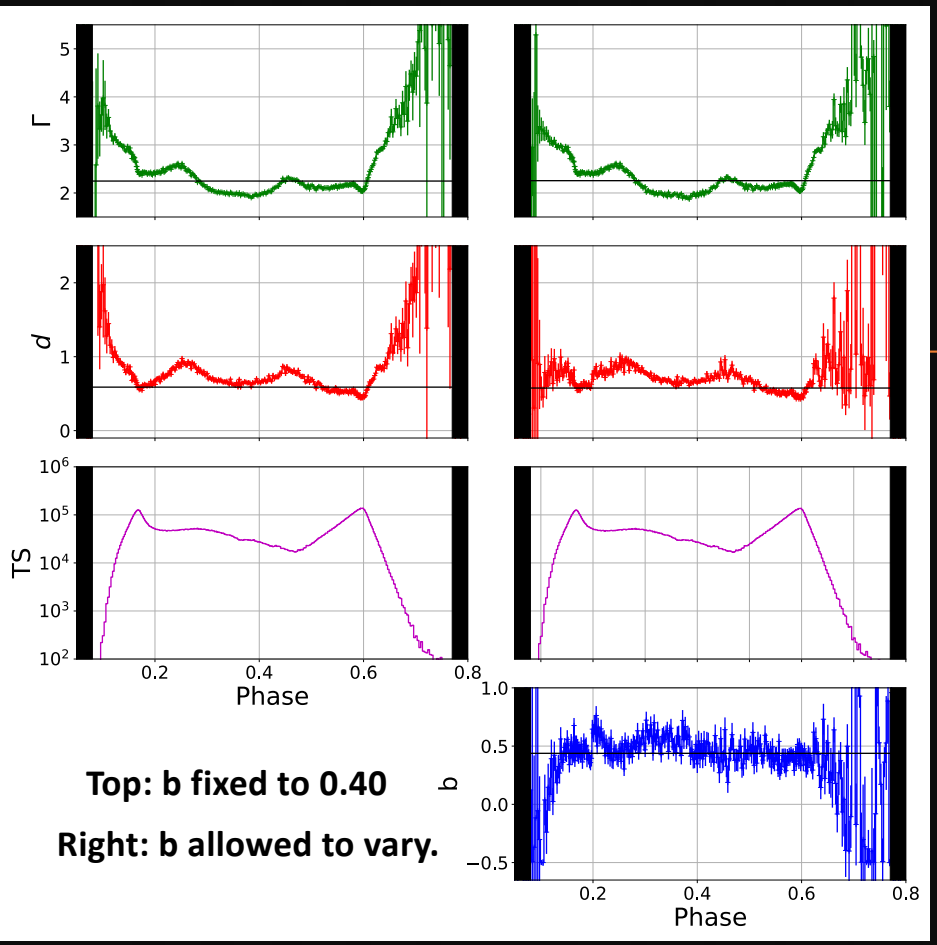
- Source model:
  - Global fit of all sources within 15° of Vela between 60 MeV – 100 GeV
    - Normalizations are freed and fit if < 15° or if TS > 25
  - Vela-X modeled with the Radial Gaussian (**RG**) and Radial Disk (**RD**) components
  - Dynamic binning (30,000 total cts per phase bin; 20x more than Abdo, 2010)
    - ~420 phase bins
  - Use Powerlaw Exponential Cutoff 4 (PLEC4); Tested variability of SED asymmetry parameter “b” w.r.t phase (fixed/freed)
- Explored spectral parameter evolution with phase
  - Specifically, on-pulse phases 0.08 – 0.77

$$\frac{dN}{dE} = \begin{cases} N_0 \left(\frac{E}{E_0}\right)^{\gamma_0 - \frac{d}{2}\ln\frac{E}{E_0} - \frac{db}{6}\ln^2\frac{E}{E_0} - \frac{db^2}{24}\ln^3\frac{E}{E_0}}, & \text{if } |b\ln\frac{E}{E_0}| < 1e^{-2} \\ N_0 \left(\frac{E}{E_0}\right)^{\gamma_0 + d/b} exp\left(\frac{d}{b^2}\left(1 - \left(\frac{E}{E_0}\right)^b\right)\right) & \text{otherwise} \end{cases}$$

Top: PLEC4 from 4FGL-DR3
Bottom: Variability of spectral parameter “b”



Phase-Resolved Results



Top: b fixed to 0.40

Right: b allowed to vary.

Spectral parameter evolution with respect to phase. From top to bottom: Γ, d, Test Statistic, Spectral parameter "b"

- Γ is softest at peak 1 and peak 2, hardens during inter-pulse phases
- Asymmetry parameter "b": Peak 1 and inter-pulse phase SEDs are more asymmetric compared to before and after peak 1, as well during and after peak 2
- Conversions to convert PLEC4 ↔ PLEC from 3PC (Smith et al., 2023)
- Loglikelihood values of model with "b" free higher than when fixed to 0.40

$$PLEC \Longleftrightarrow PLEC4$$

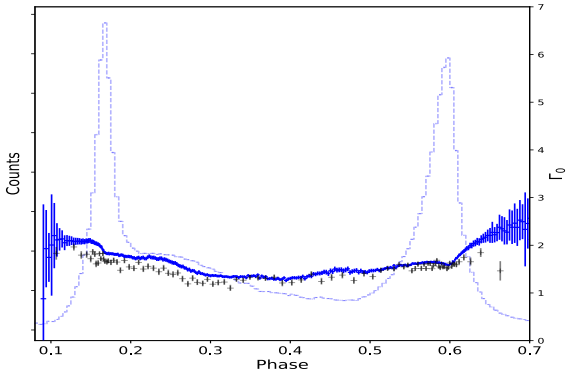
$$E_c = E_0 \left(\frac{b^2}{d}\right)^{\frac{1}{b}}$$

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

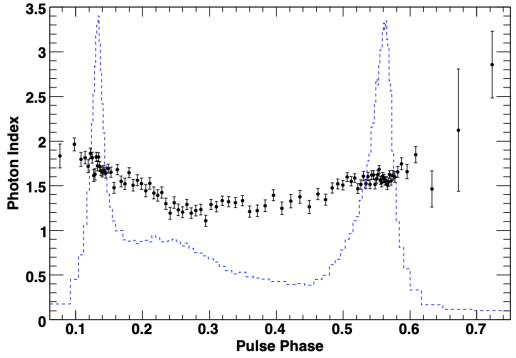
Comparison with Abdo+2010

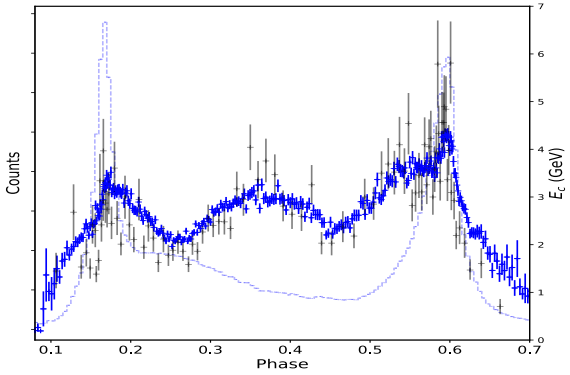
- Using a free-b model doesn't return the results from Abdo+2010
  - b=1 in Abdo+2010, despite best-fit value of 0.69
- We set b=1 in our fits, and regain the same values
- Similar behavior is seen
  - Spectral index softening during peaks, hardens during inter-pulse phases
- Cutoff Energy fluctuates between 1-5 GeV
  - increases at Peak 1, inter-pulse and Peak 2

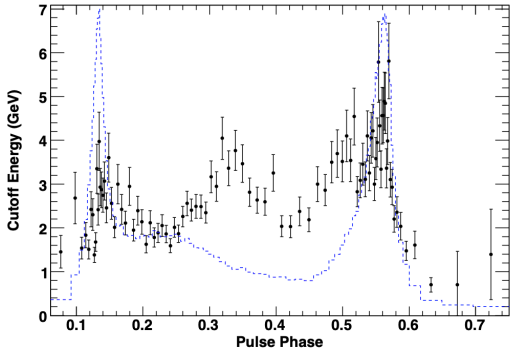
Our own work



From Abdo+2010:



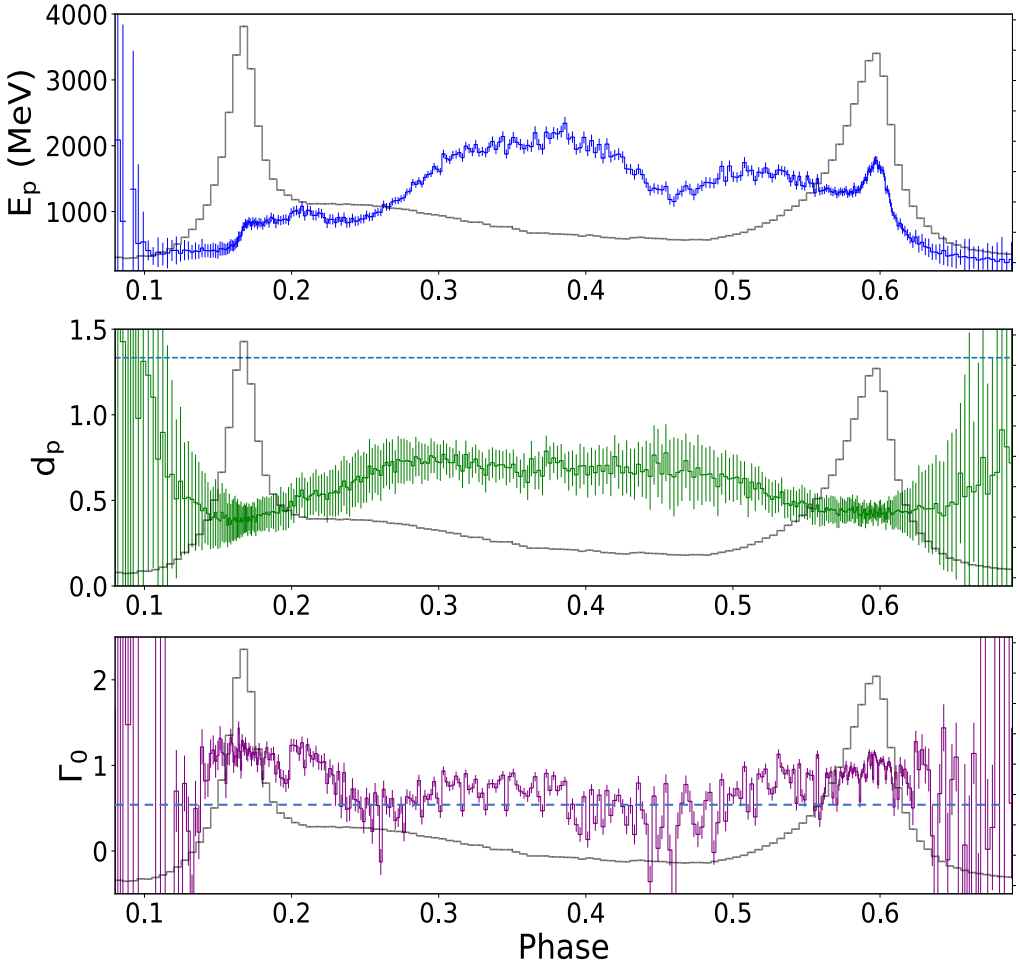




Top: Phase vs Spectral Index. Our work (left), Abdo+2010 (right)
Bottom: Phase vs Cutoff Energy. Our work (left), Abdo+2010 (right)

Physical Implications

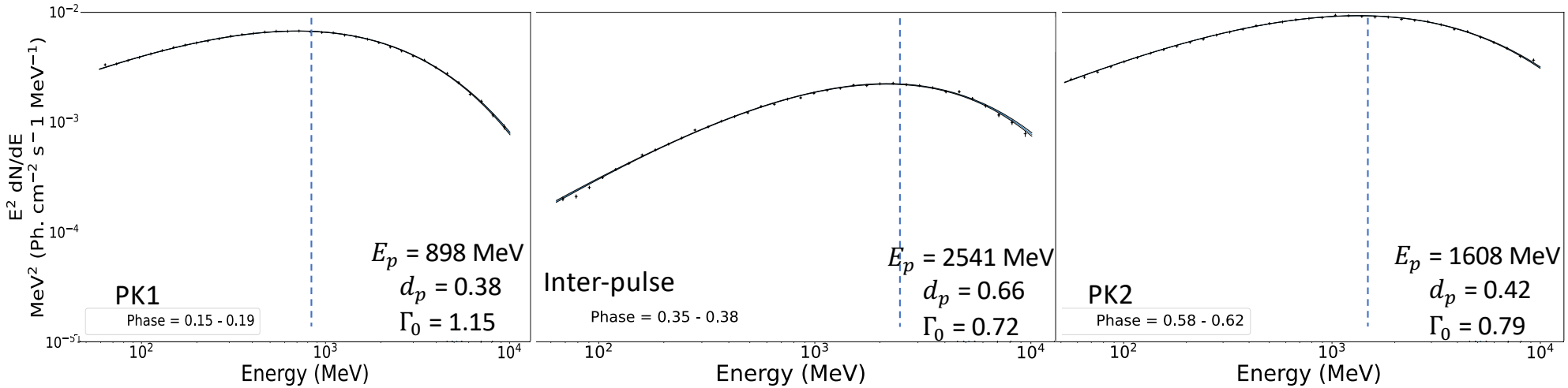
- Calculate physical parameters of **Peak energy**, **peak width** d_p and **Asymptotic Photon index** (Γ_0)
  - "b" must be free (3PC; Smith et al., 2023)
- Higher peak energy during inter-pulse and lower at Peak 1, 2
- Peak width less than 4/3 (max width for mono-energetic synchrotron radiation)
- Photon Index softer at peak 1 and peak 2, harder during inter-pulse
  - In agreement with 3PC; largely above 2/3 (minimum spectral index for mono-energetic synchrotron radiation)



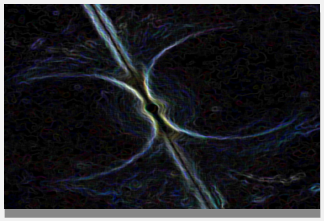
Evolution of Peak energy (E_p) Peak width (d_p) and Asymptotic Spectral index (Γ_0) with respect to pulse-phase, respectively.

Phase-Resolved Results

- SEDs show clear evolution between Pk1 and Pk2
  - E_p, Γ_0 have noticeably shifted
  - d_p shows shift in symmetry

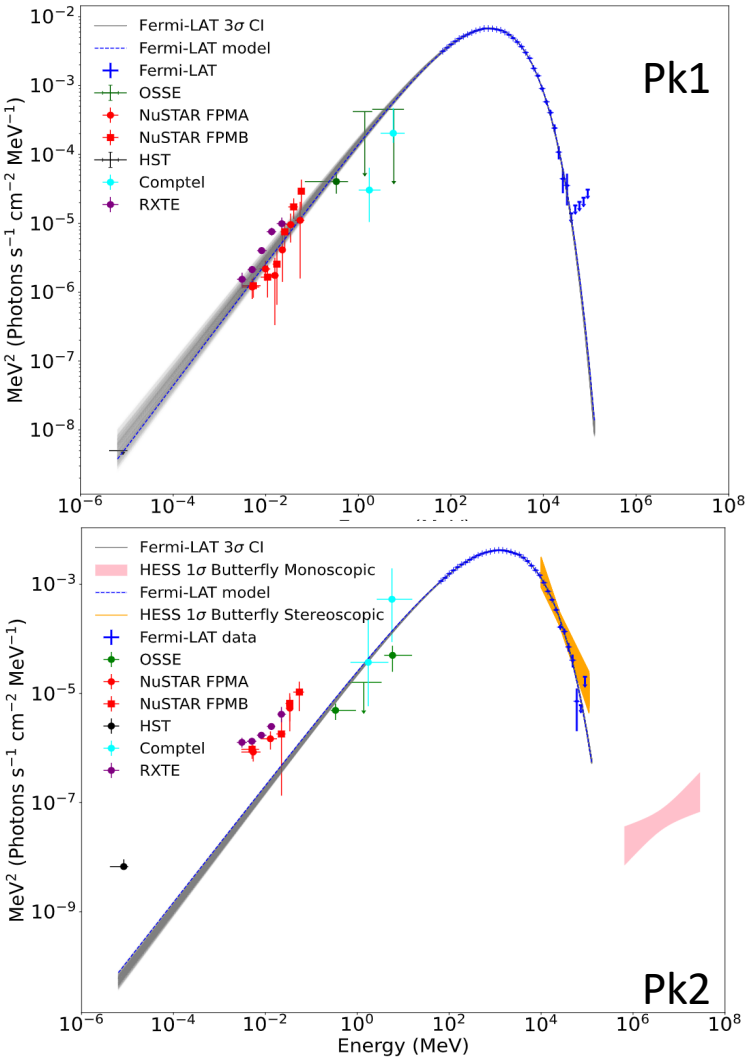


SEDs at Peak 1, Inter-pulse and Peak 2 phases with Physical parameters. (Not to scale)



Broadband Modeling

- Butterfly plots of ~1000 simulations based off of Fermi-LAT best-fit spectral model 3σ uncertainty and extrapolated to UV energy
- Overlay optical (HST), X-ray(NuSTAR, RXTE), and MeV (OSSE, Comptel) and TeV (HESS)
- Overall, Peak 1 is in reasonable agreement down to UV upper-limit
  - UV UL due to difference
- Peak 2 not so much
  - Maybe the soft γ-rays
  - Unsure of OSSE and COMPTEL normalizations



Archival data from HST, NuSTAR, RXTE, Comptel, and OSSE are from: Kargaltsev et al., 2023, al., 2002, Hermsen et al., 1993, Strickman et al., 1996, and Romani et al., 2005.
HESS monoscopic and stereoscopic from HESS Collaboration et al., 2018 and HESS Collaboration et al., 2023.

In Summary…

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- An update of the Vela Pulsar and PWN with 13 years of Fermi-LAT
- Re-characterized the PWN Vela-X, introducing Radial Gaussian and Radial Disk components
  - In agreement with Tibaldo+2018 for E>10GeV, with no clear low- or high-energy components
- A intensive phase-resolved analysis of the on-pulse phases:
  - Explored pulse profile and spectral changes with energy and phase,
  - Compared to the most recent phase-resolved analysis Abdo+2010, finding agreeable results,
  - Expand and find physical parameters: Peak energy, peak width, Spectral Index at 100 MeV (E_p, d_p, Γ_{100})
- Broadband comparison to extrapolated Fermi-LAT pulse peak spectra
  - We see Peak 1's Fermi fit in agreement with broadband data
  - Peak 2 in agreement soft gamma-ray, but not with X-ray/UV