A study of the very-high-energy emission of the Crab pulsar with the LST-1

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for the **CTAO-LST Project**

8th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy (03/09/2024)

This work was conducted in the context of the CTA-LST Project. We gratefully acknowledge financial support from the agencies and organizations listed here: ***http://www.cta-observatory.org/consortium_acknowledgments***

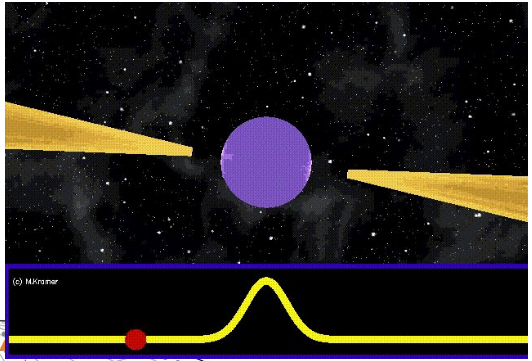
CTAO | LST COLLABORATION

IPARCOS

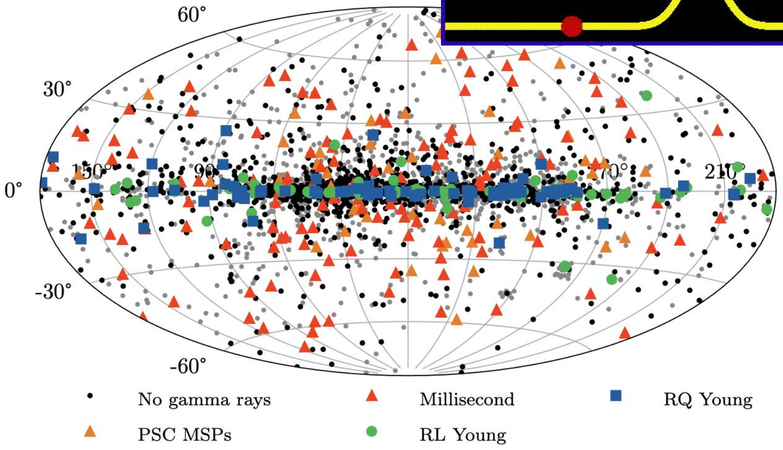
GAE

High-energy Pulsars

Pulsars are highly magnetized neutron stars in rapid rotation.
They emit pulses of radiation from radio up to gamma-rays.



- Pulsars discovered in radio in 1967. Most of them emit in radio.
- A bunch of them detected in visible (~10) and X-rays (~100)
- In gamma-rays, almost 300 pulsars have been detected by Fermi-LAT since 2008!
- In VHE gamma-rays, only 3+1 pulsars detected



Third Fermi Large Area Telescope catalog of gamma-ray pulsars

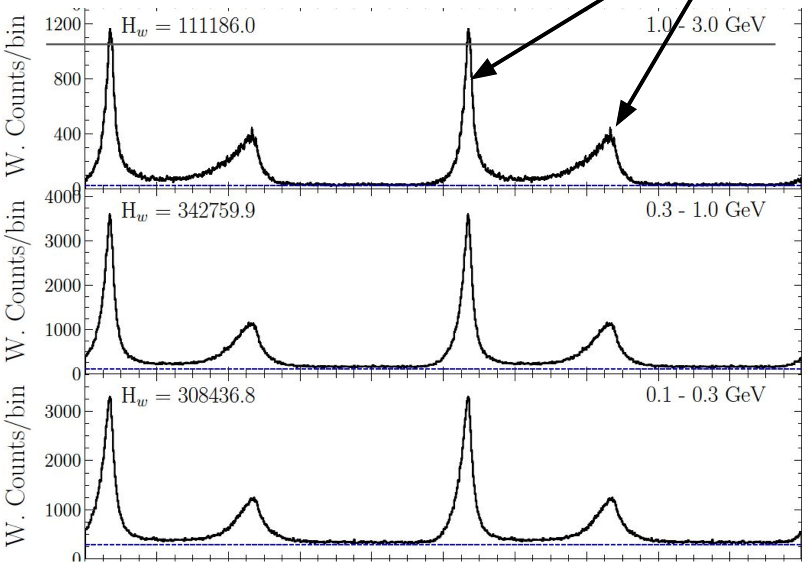
Abdo, A .et al.. (2013). The Astrophysical Journal Supplement Series, 208(2), 17.

High-energy Pulsars

Fermi-LAT pulsar features 100 MeV < E < 10 GeV

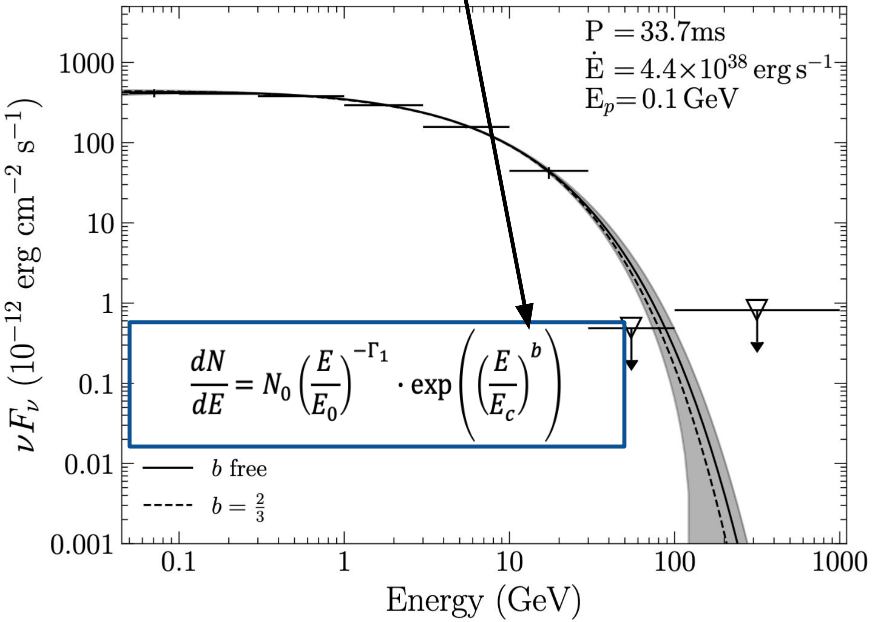
1) Light curves typically exhibit **two peaks**

Fermi-LAT Crab pulsar light curve from Third Catalogue



2) Energy spectra described by power laws + **exponential cutoff** at a few GeV.

Fermi-LAT Crab pulsar SED from Third Catalogue



$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{-\Gamma_1} \cdot \exp\left(\left(\frac{E}{E_c}\right)^{b}\right)$$

High-energy Pulsars

Gamma-ray classical models:

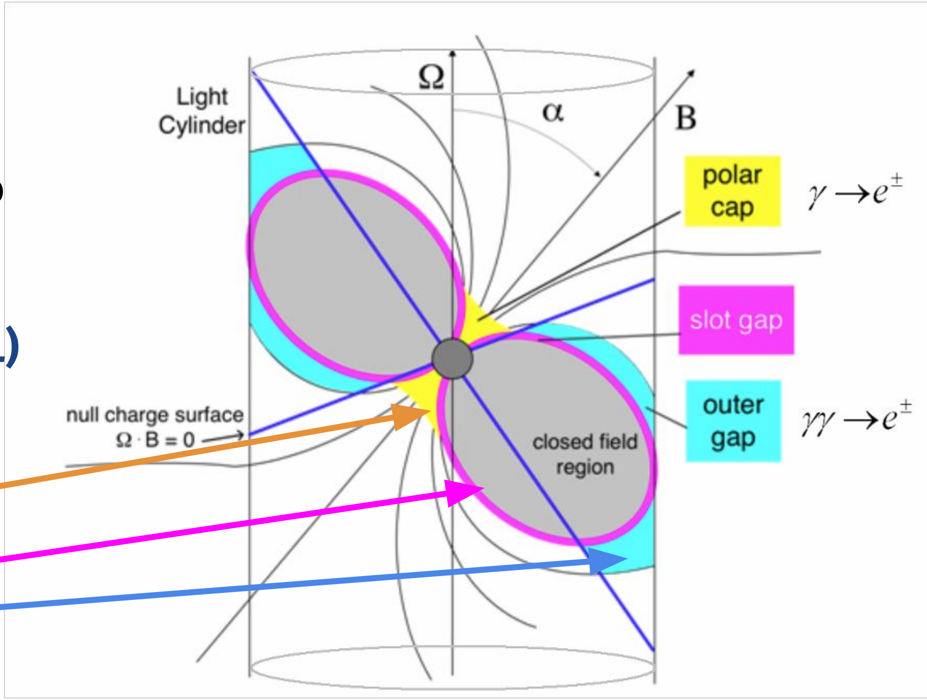
- The MeV-GeV gamma-ray emission is due to synchro-curvature radiation

- Their spectra usually follow a **power law (PL) with exponential cutoff** at a few GeV.

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{-\Gamma_1} \cdot \exp\left(\left(\frac{E}{E_c}\right)^b\right)$$

b>1
b~1
b<1

- Very weak emission expected above 50 GeV

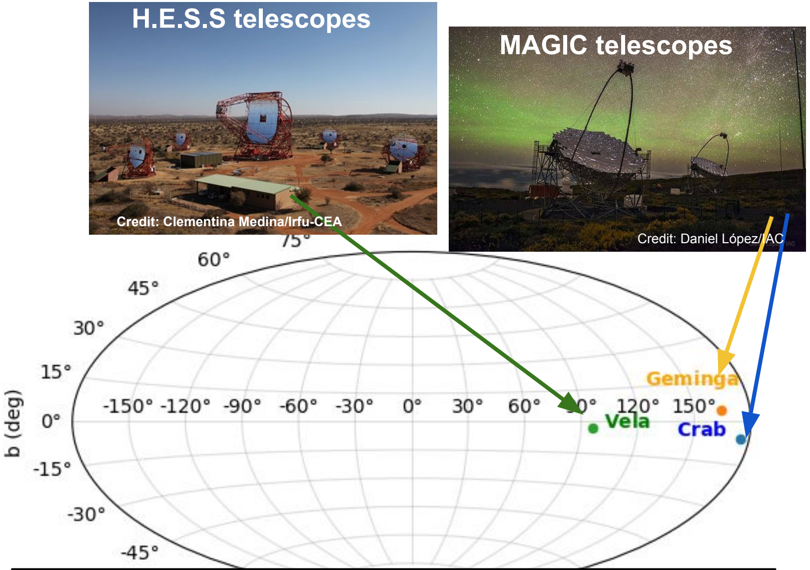


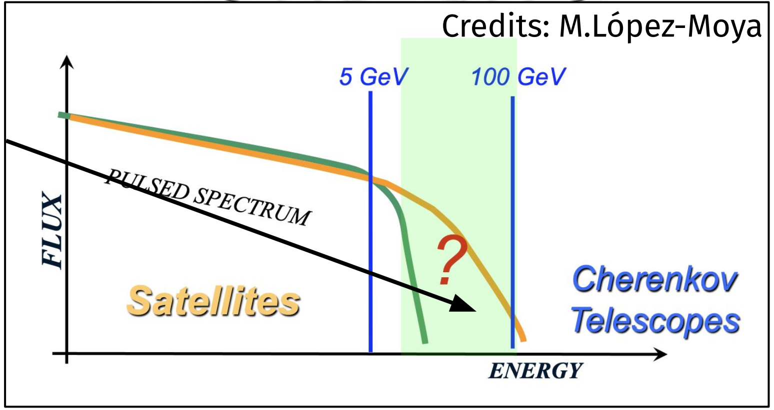
Credit: Alice K. Harding

Observing pulsars with IACTs

Up to what energies do pulsars emit?

- *Fermi*-LAT limited by statistics above ~50 GeV
- **Pulsars detected with IACTs (E>20 GeV)**
  - Crab by MAGIC, VERITAS
  - Vela by HESS
  - Geminga by MAGIC
  - PSR B1706−44 by HESS (4.7σ)
- **Power-law spectral tails extending beyond the predicted cutoffs**
- The first two detected up to TeV energies





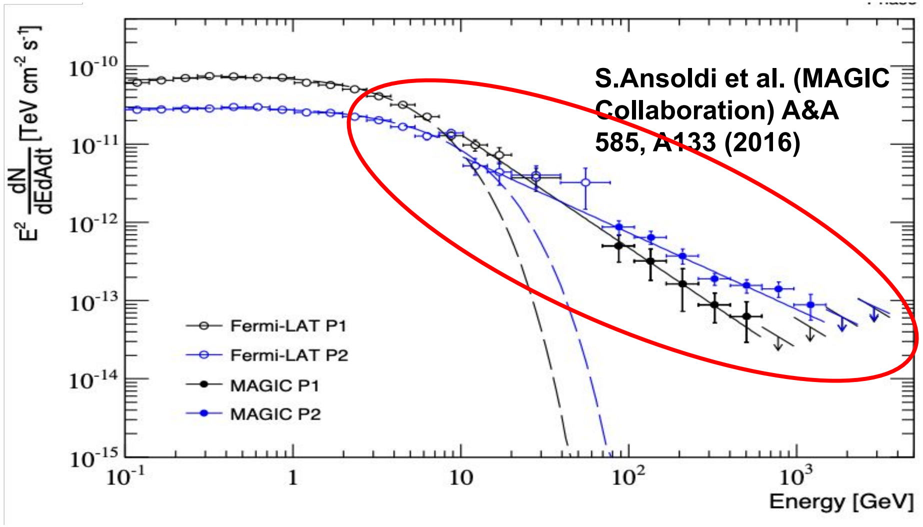
Observing pulsars at TeV

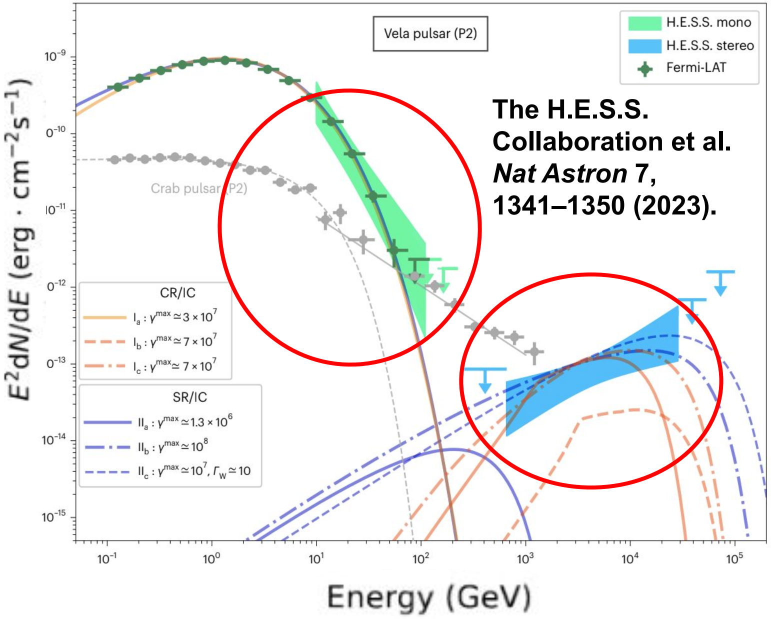
Vela Pulsar TeV emission up to 20 TeV.

2 components: 1) E < 100 GeV 2) E > TeV

Crab Pulsar P2 detected up to 1.5 TeV

1 single continuous component



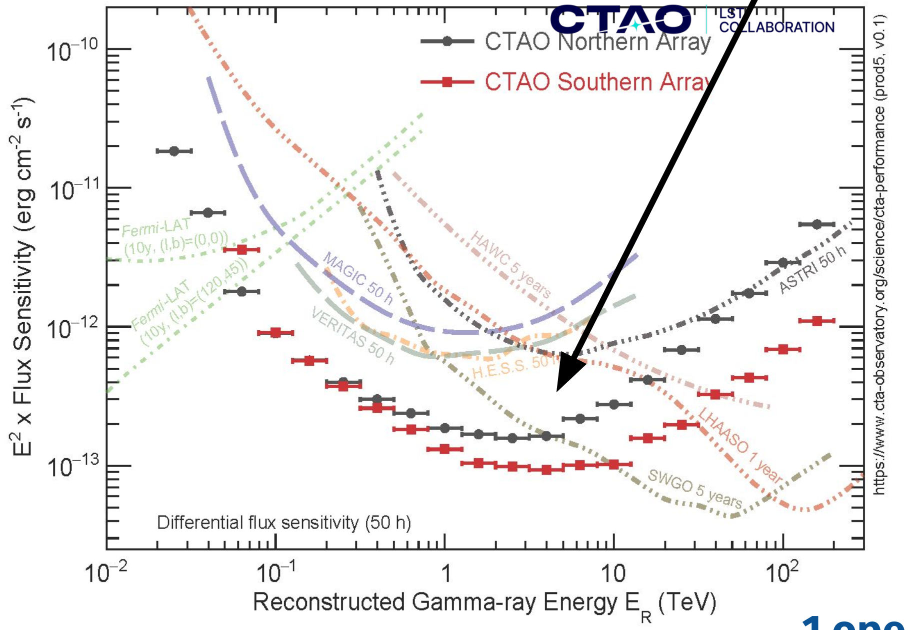


- Impossible to emit TeV photons via synchro-curvature radiation
- **Possibility: Inverse Compton on soft photon fields (outside or inside magnetosphere?)**

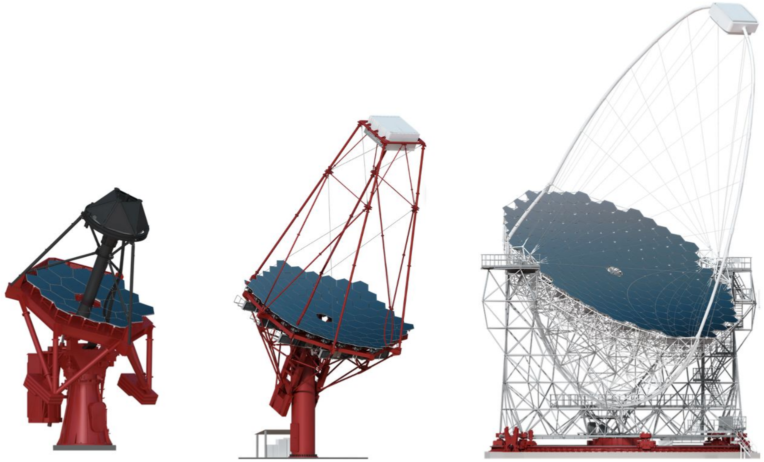
The Cherenkov Telescope Array Observatory (CTAO)

Increase sensitivity needed to detect more pulsars!

CTAO: New generation of IACTs



- Two different sites: La Palma (Spain), Chile
- Three kinds of telescopes of different sizes:



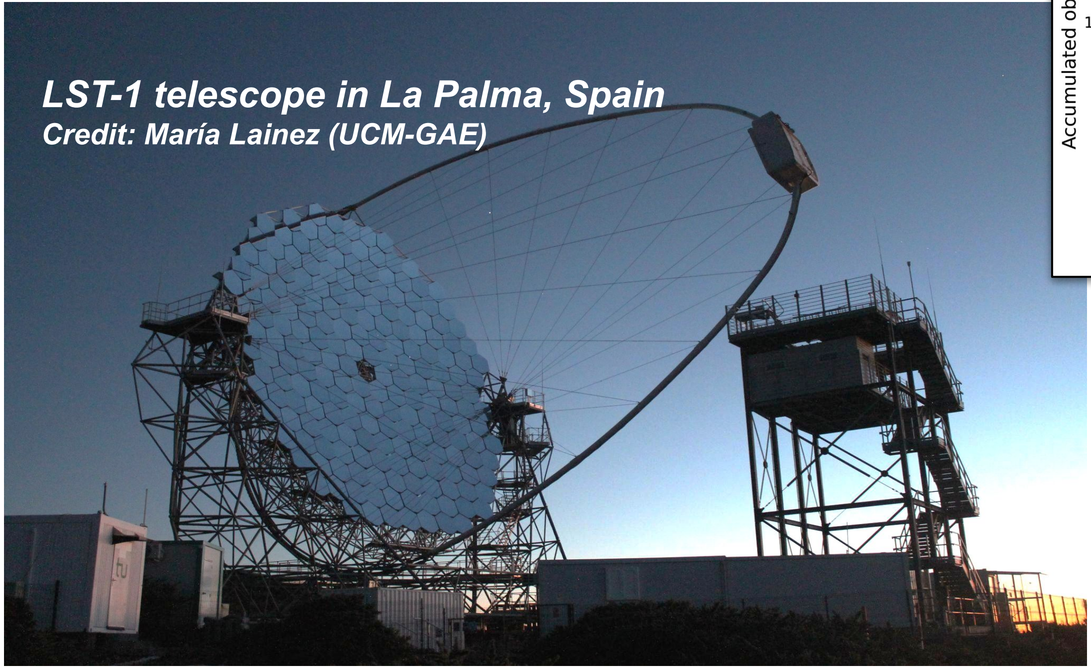
SSTs MSTs

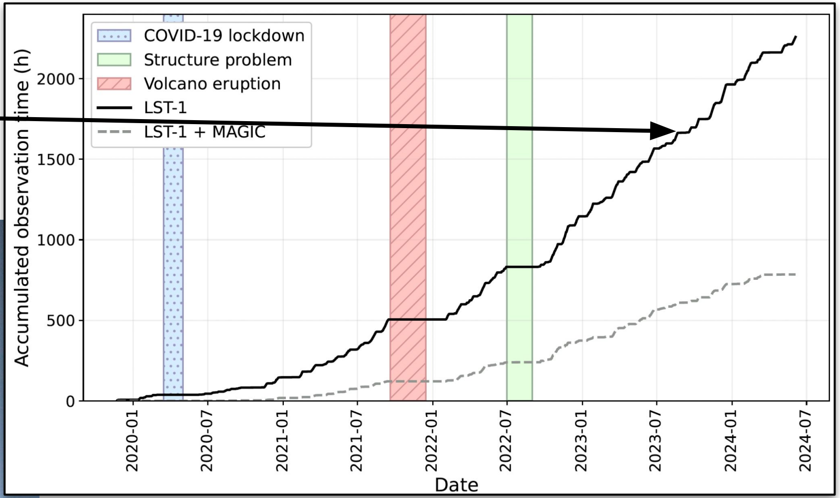
LSTs (23-m diameter)

1 operating, 3 more already being built in La Palma

The First Large-Sized Telescope (LST-1)

- **Prototype of the CTAO LSTs**
- Comissioning since 2019. Taken more than 2000 hours of data
- **Already producing first scientific results**


LST-1 telescope in La Palma, Spain
Credit: María Lainez (UCM-GAE)

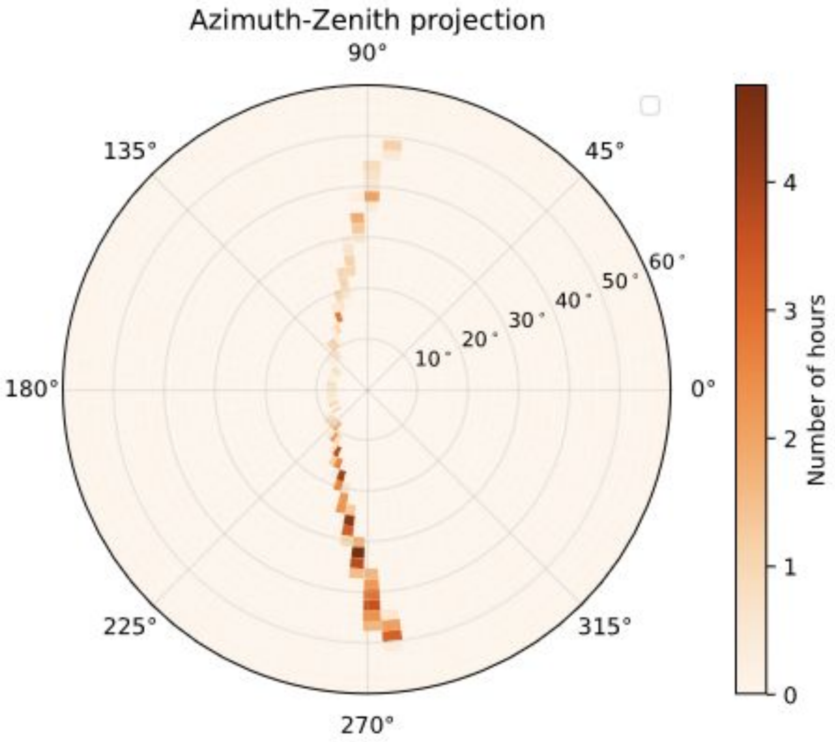


Ideal to study gamma-ray pulsars:

1) Optimized for lowest energies
2) Threshold about 20 GeV
3) Good energy overlap with Fermi-LAT

Crab pulsar study with the LST-1

Tobs = 103 h (Zd < 50 deg)



1) Observations performed:
Crab pulsar observed during the LST-1 commissioning **(Sept 2020 to Jan 2023).**

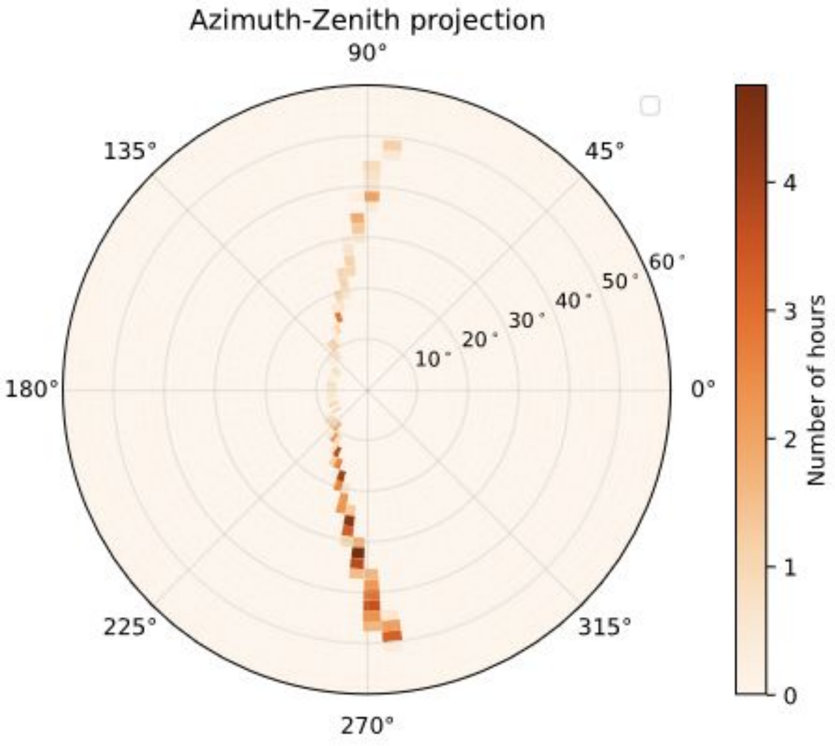
2) Motivations for the pulsar study:

a) Prove the potential of LSTs to study gamma-ray pulsars
b) Phenomenological study of its gamma-ray emission

LST-1 results published: "A detailed study of the very-high-energy Crab pulsar emission with the LST-1": doi.org/10.48550/arXiv.2407.02343

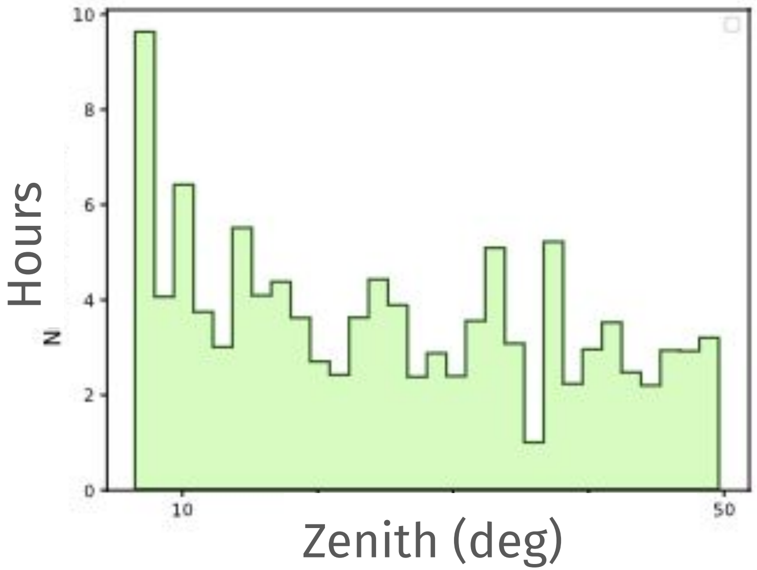
Crab pulsar study with the LST-1

Tobs = 103 h (Zd < 50 deg)



3) Data sample for the analysis:

- Include data up to Zd = 50 deg (~25 h at Zd > 35 deg)
- Strong quality selection of the data to reduce the energy threshold

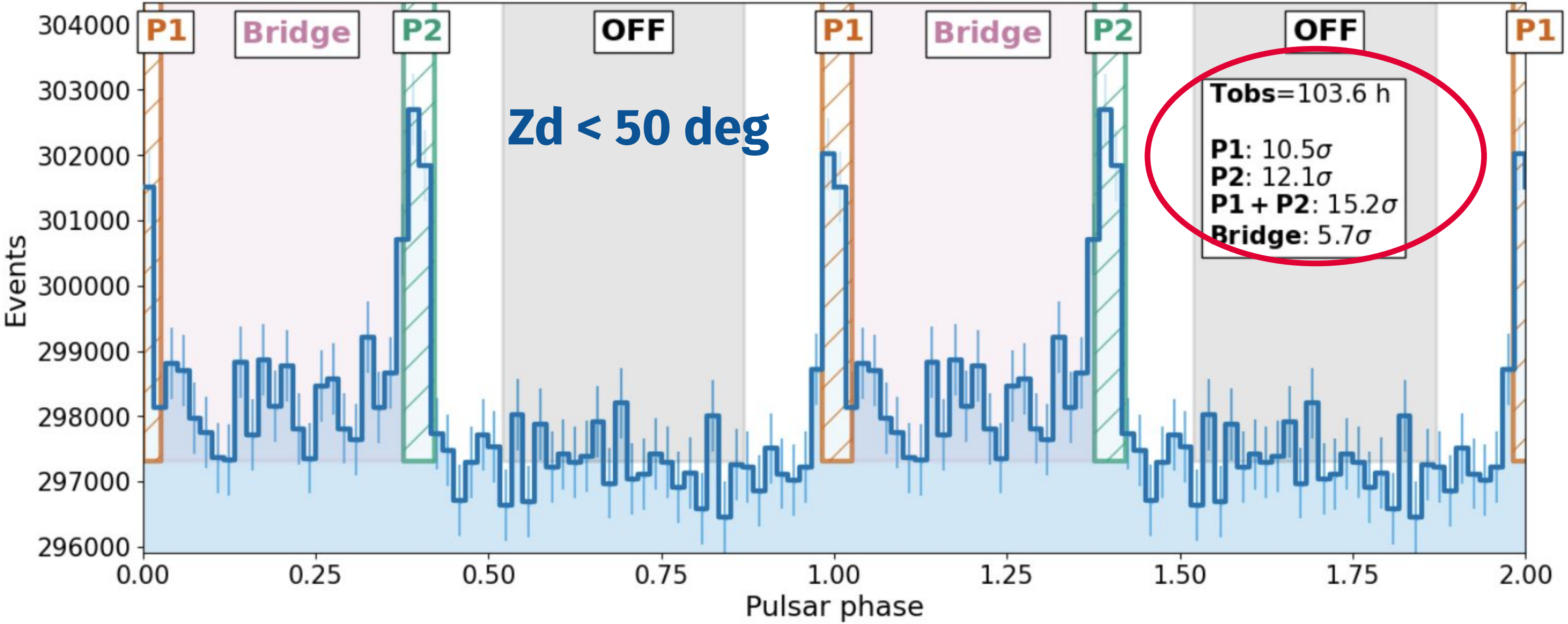


Crab Pulsar results: Phaseogram

P1 + P2 detected at > 15 σ in 100 h

Similar to best former MAGIC results but with only one telescope!

MAGIC Sumtrigger-II: Ceribella, Giovanni et al. PoS ICRC2019 (2021) 645



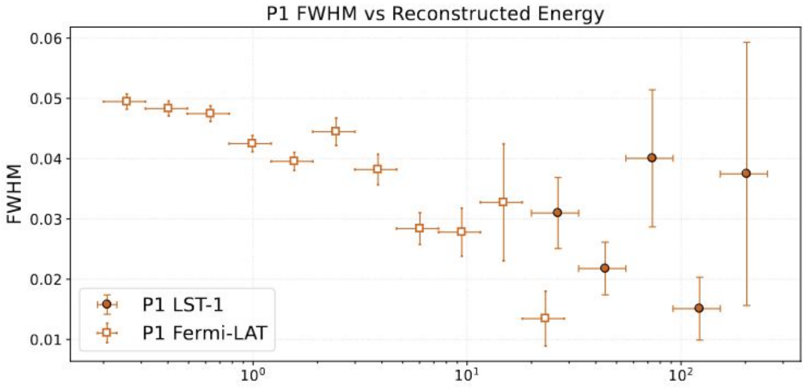
Crab Pulsar results: peaks morphology

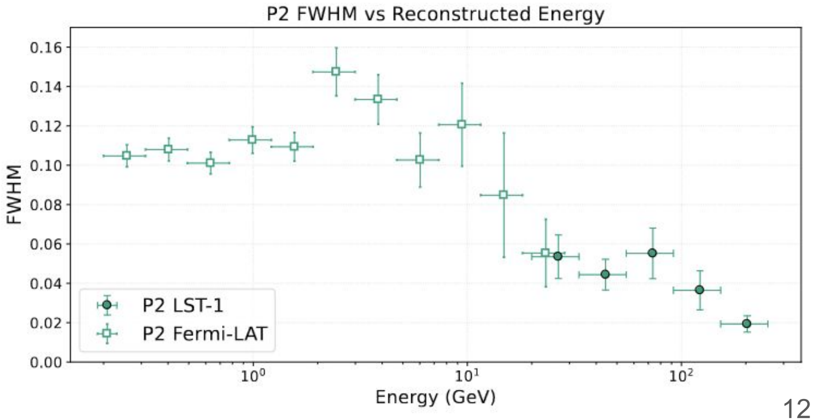
Note: New *Fermi*-LAT analysis of ~14 yrs.

Peak widths:

Energy (GeV)	μ_1	FWHM$_1$ ($\cdot 10^{-2}$)	μ_2	FWHM$_2$ ($\cdot 10^{-2}$)
20 - 33	0.999 ± 0.003	3.1 ± 0.6	0.389 ± 0.004	5.4 ± 1.1
33 - 55	1.0000 ± 0.0018	2.2 ± 0.4	0.387 ± 0.003	4.4 ± 0.8
55 - 92	0.994 ± 0.005	4.0 ± 1.1	0.388 ± 0.006	5.5 ± 1.3
92 - 153	1.0020 ± 0.0022	1.5 ± 0.5	0.402 ± 0.004	3.6 ± 1.0
153 - 253	1.015 ± 0.009	3.7 ± 2.2	0.3981 ± 0.0017	1.9 ± 0.7

- Peak location does not change significantly
- P1 width drops until 10 GeV. No significant variation beyond (limited by statistics due softer spectrum)
- P2 width decreases above 2 GeV



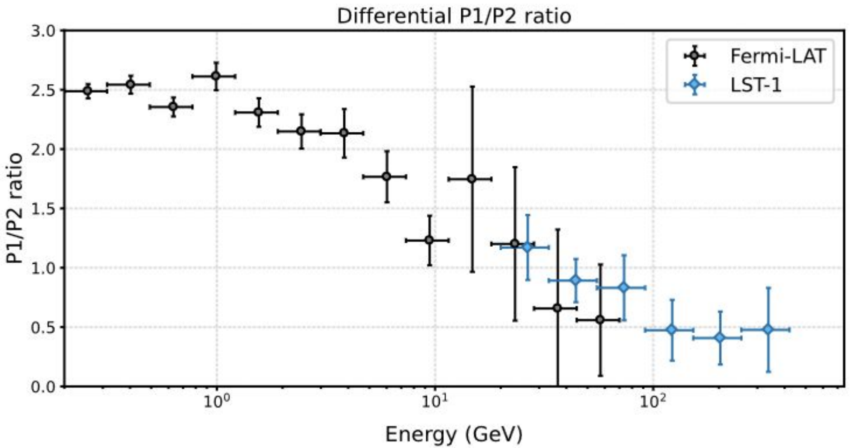


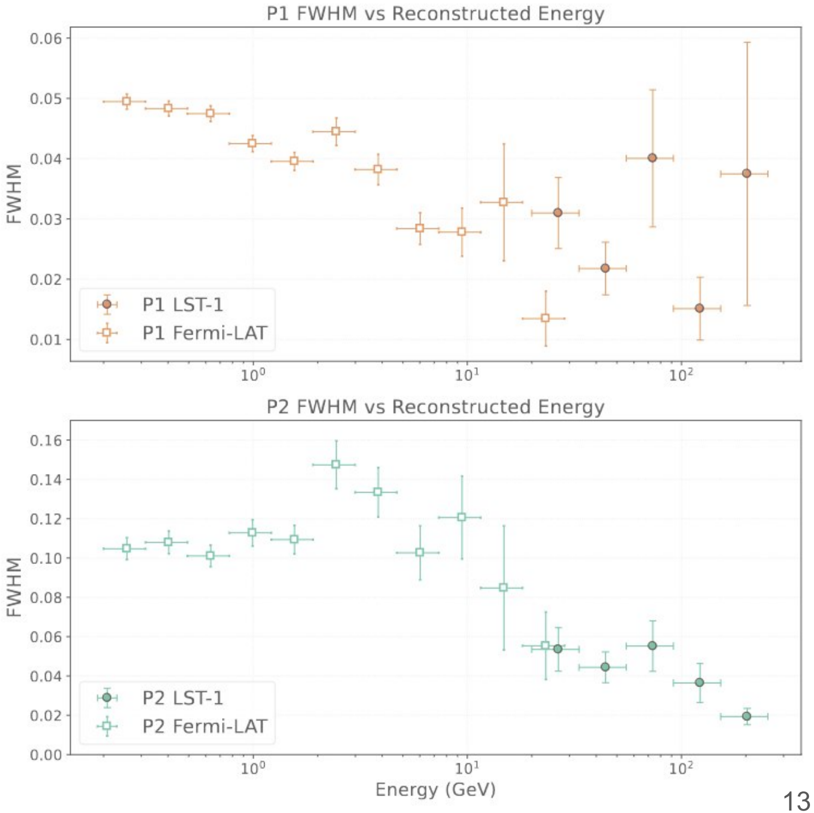
Crab Pulsar results: peaks morphology

Note: New *Fermi*-LAT analysis of ~14 yrs.

P1/P2 ratio:

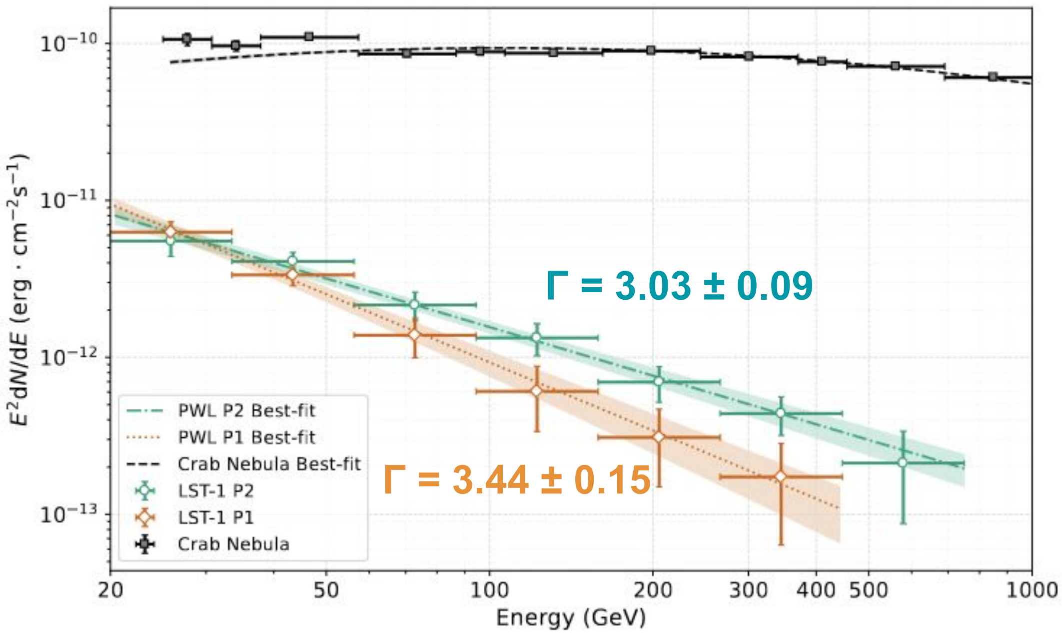
- P1/P2 ratio declines up to 100 GeV
- Constant (P1/P2 ~ 0.5) at > 100 GeV





Crab Pulsar results: LST-1 SED

- P1 SED follows power-law models up to **450 GeV (P1)** and **700 GeV (P2)**
- P2 harder than P1 (known feature)
- Confirms MAGIC results above 500 GeV



Systematic uncertainties in Γ of ~10% for P1 and ~5% for P2. Accurate characterization of the pulsar at low energies!

Crab Pulsar results: LST-1 + Fermi SED

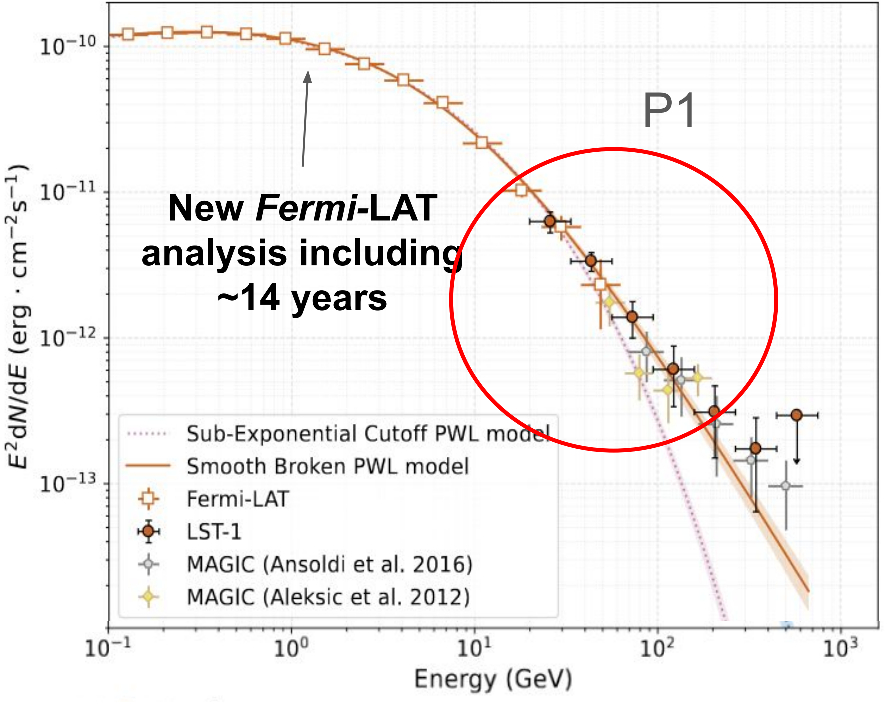
Best model by AIC and BIC statistics

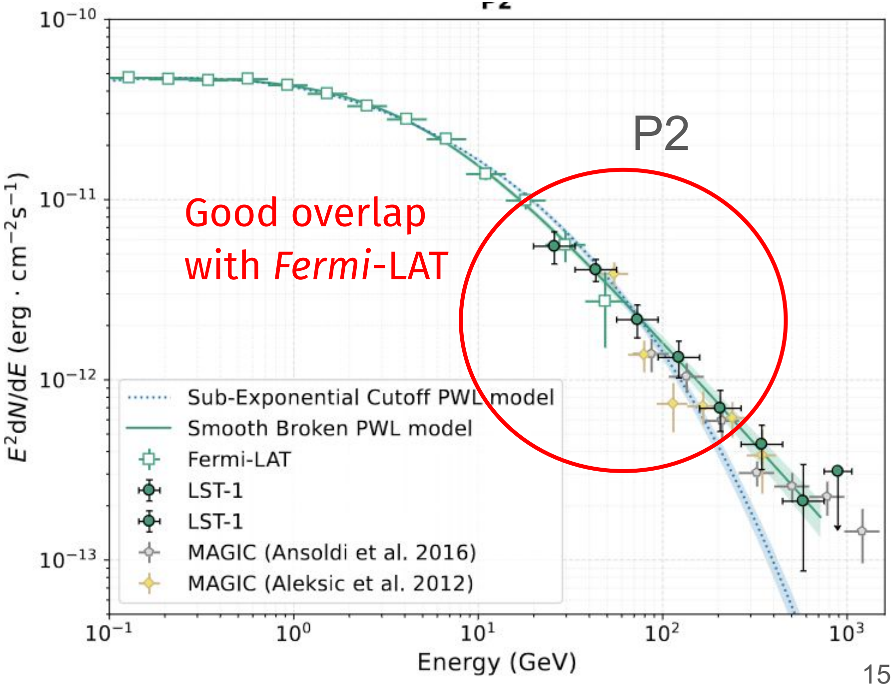
Model 1:
PL +SubExponential cutoff

$$\frac{dN}{dE} = f_0 \left(\frac{E}{E_0}\right)^{-\alpha} \exp\left(-(\lambda E)^{\beta}\right)$$

Model 2:
SmoothBrokenPL

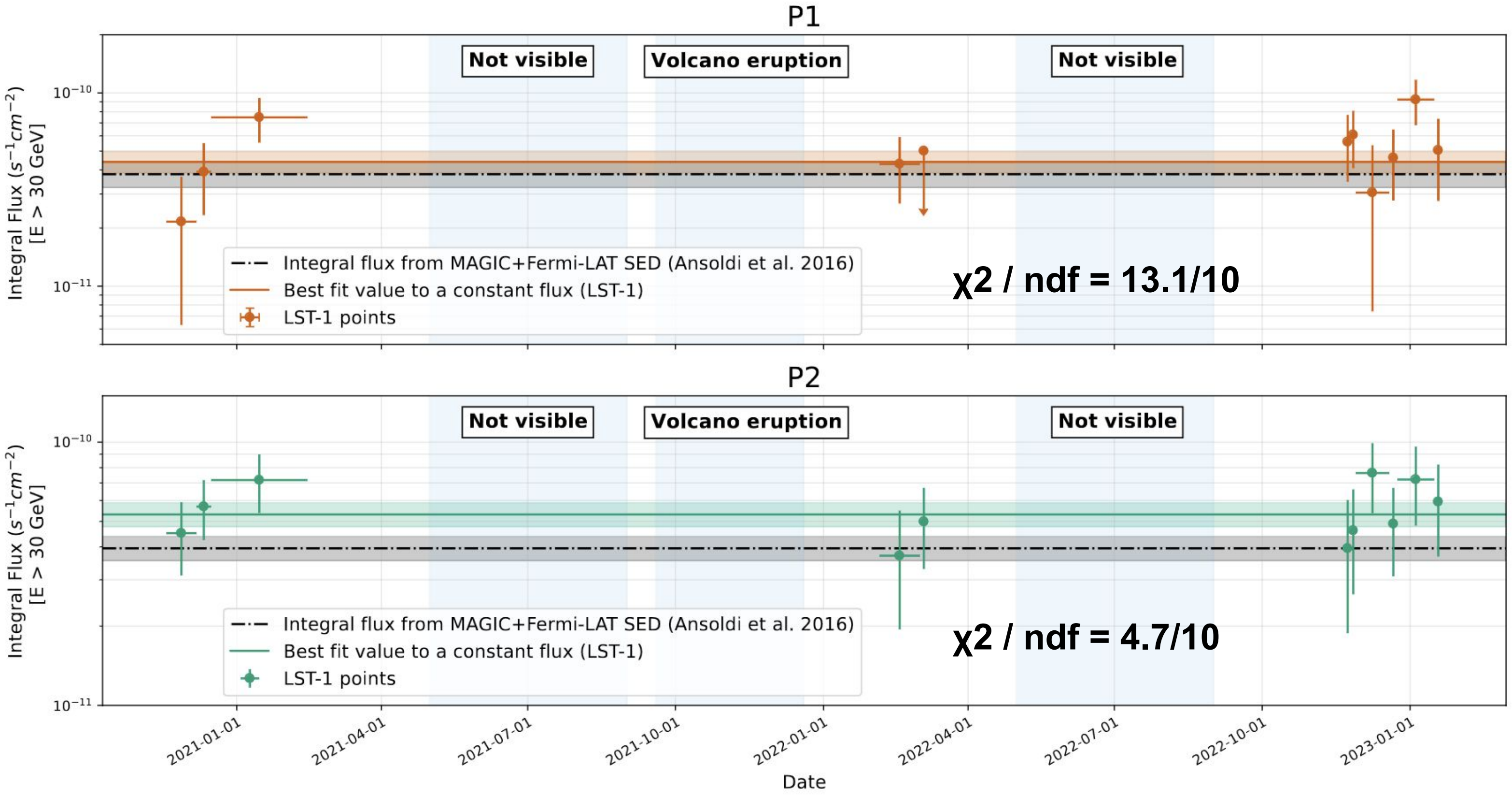
$$\frac{dN}{dE} = f_0 \left(\frac{E}{E_0}\right)^{\alpha_1} \left(1 + \left(\frac{E}{E_b}\right)^{\frac{\alpha_2-\alpha_1}{\gamma}}\right)^{-\gamma}$$



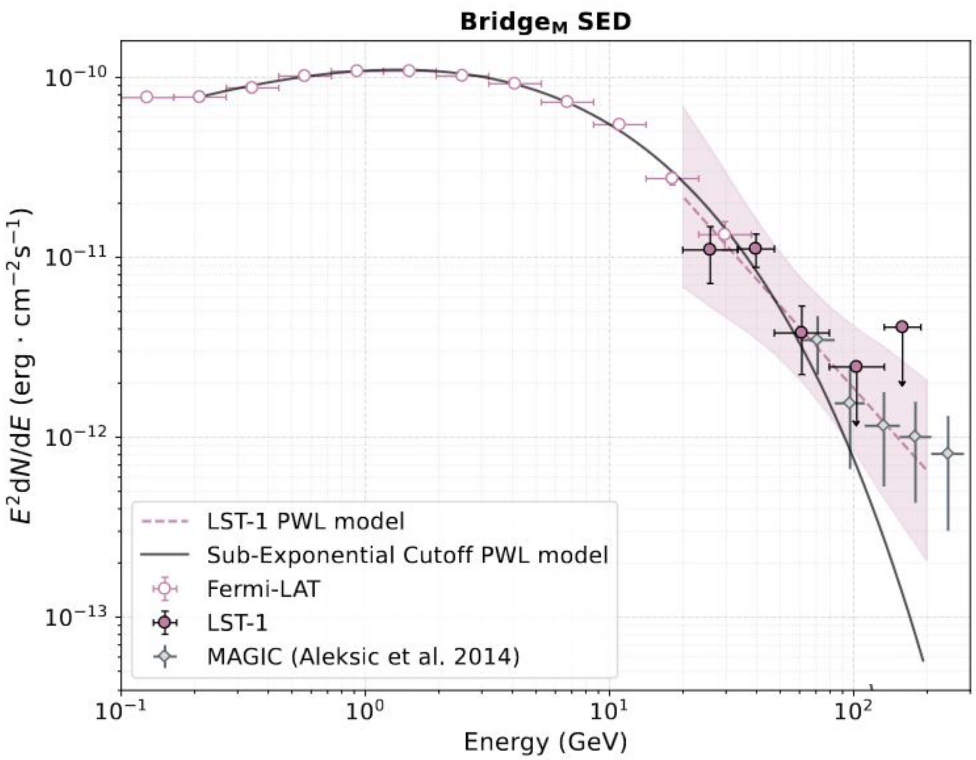


Crab Pulsar results: light curve

- No hint of variability in the sample



Crab Pulsar results: LST-1 + Fermi SED



Bridge SED

- Defined as region between peaks
- Detected up to 100 GeV. Beyond the signal is very weak (< 1.5 σ)
- **Power-Law with Γ= 3.5 ± 0.4**
- Lack of statistics to reject the existence of strong cutoff

Conclusions

Currently more LSTs are being built! A new era in the VHE pulsar search is arriving!

CTAO | LST COLLABORATION

The CTAO will explore VHE pulsar population:

- VHE pulsar gamma-ray emission requires new models involving Inverse Compton processes.
- The LSTs' low-energy threshold improves sensitivity to study pulsars.

Crab Pulsar detected at 15 σ in ~ 100 h.

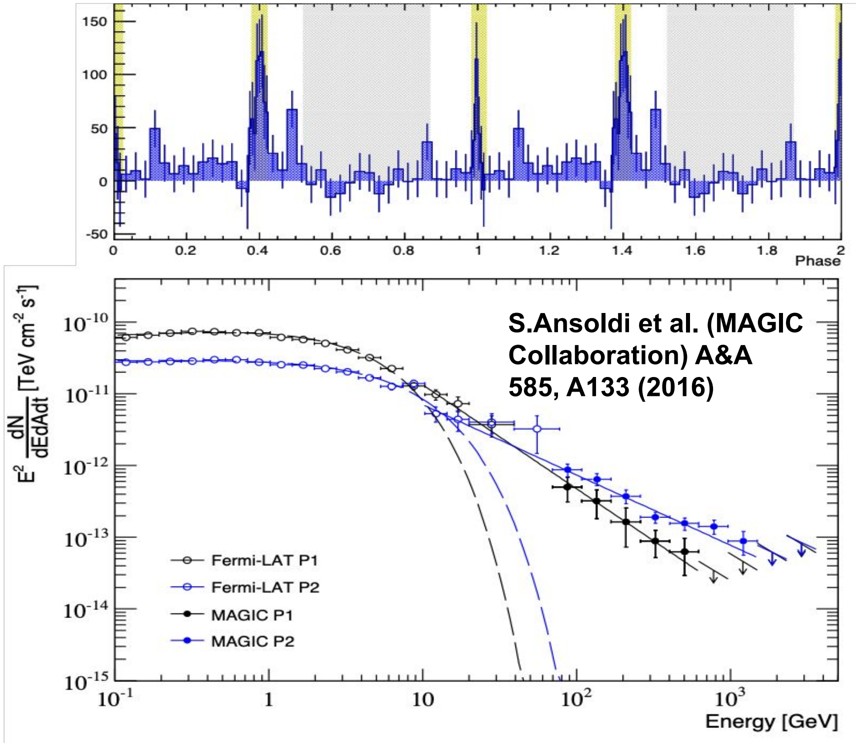
- P1, P2 SED from 20 GeV to hundreds of GeV.
- Pulse peak morphologies from 100 MeV to 200 GeV.
- LST-1 SED bridges completely with *Fermi*-LAT.
- Excellent performance at low energies for pulsar observations.

Another pulsar already detected with LST-1! See next presentation by P.K. Yeung

BACKUP

Observing pulsars with IACTs

Crab Pulsar



- Pulsation detected above 400 GeV

  P1 detected up to **0.6 TeV**

  P2 detected up to **1.5 TeV**

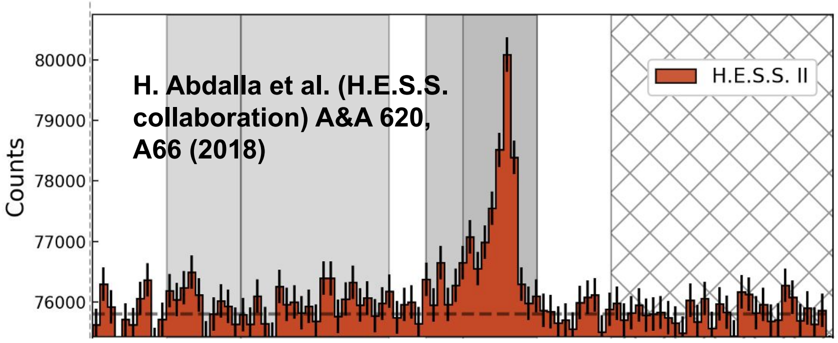
- Power Law extension for both peaks.

- Detection of TeV photons impossible to reach via synchro-curvature mechanism

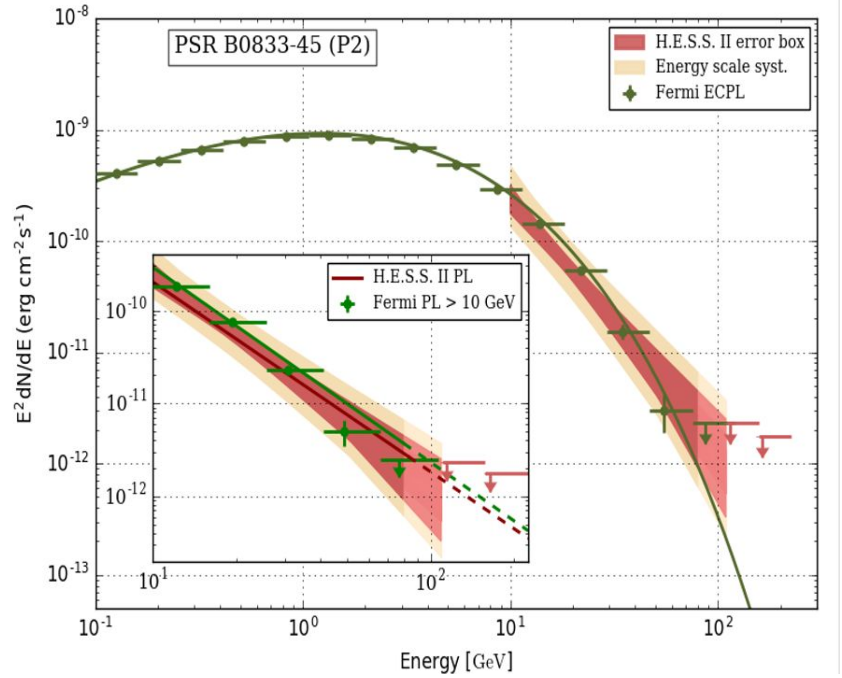
- **Synchrotron-curvature ruled out:** IC on soft photon fields

Observing pulsars with IACTs

Vela Pulsar



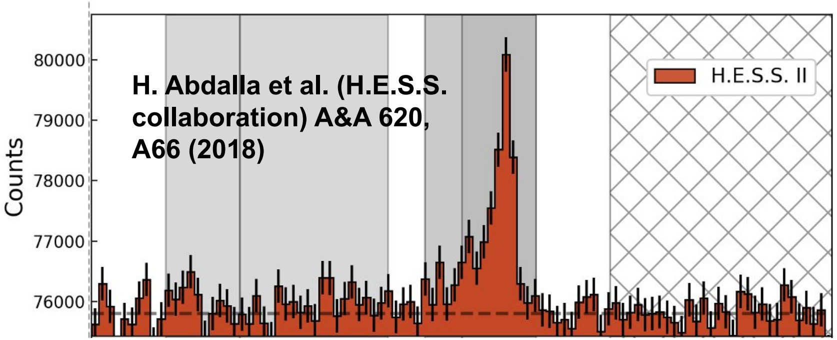
H. Abdalla et al. (H.E.S.S. collaboration) A&A 620, A66 (2018)



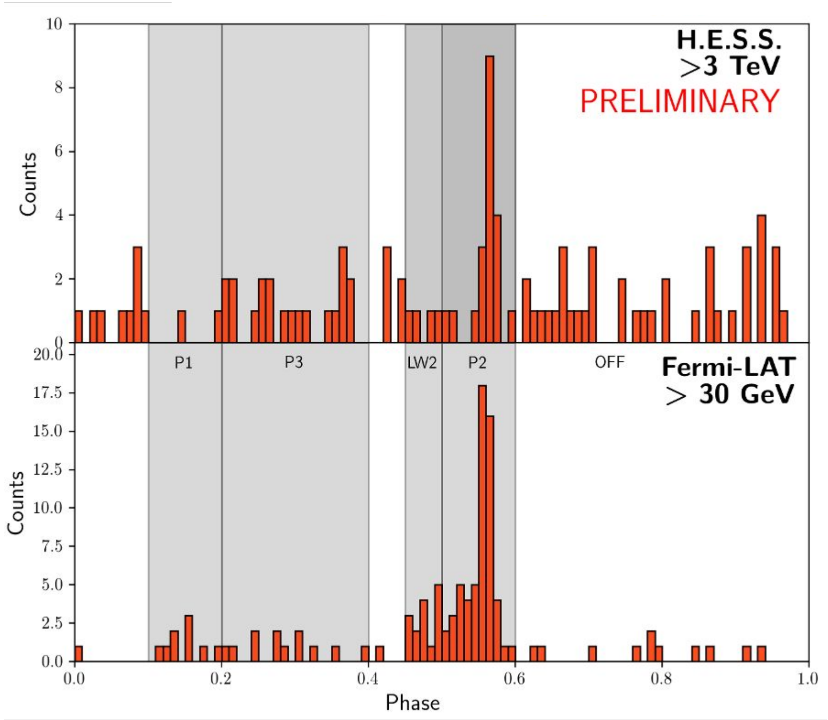
- Curvature of P2 favoured at >3σ level
- Clear hint of TeV emission: hint of a second componente

Observing pulsars with IACTs

Vela Pulsar



A. Djannati-Ataï, Texas Symp. 2017



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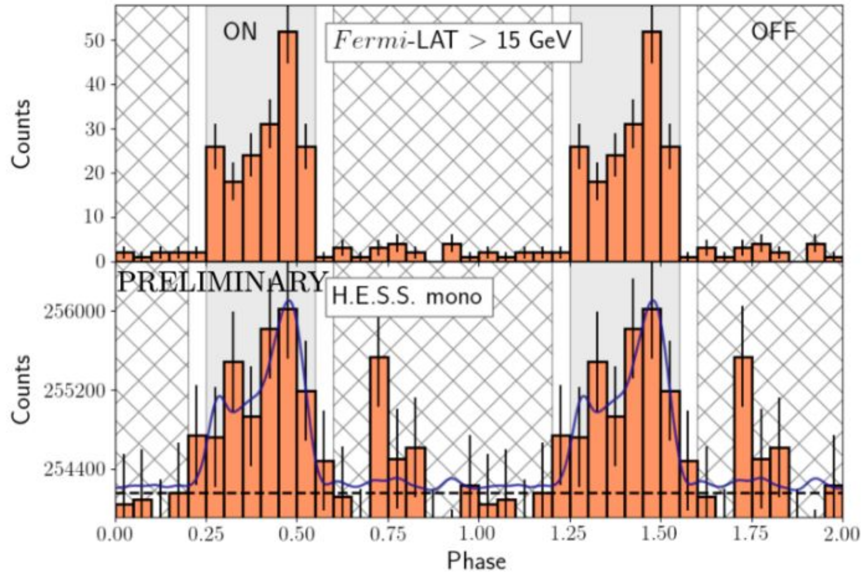
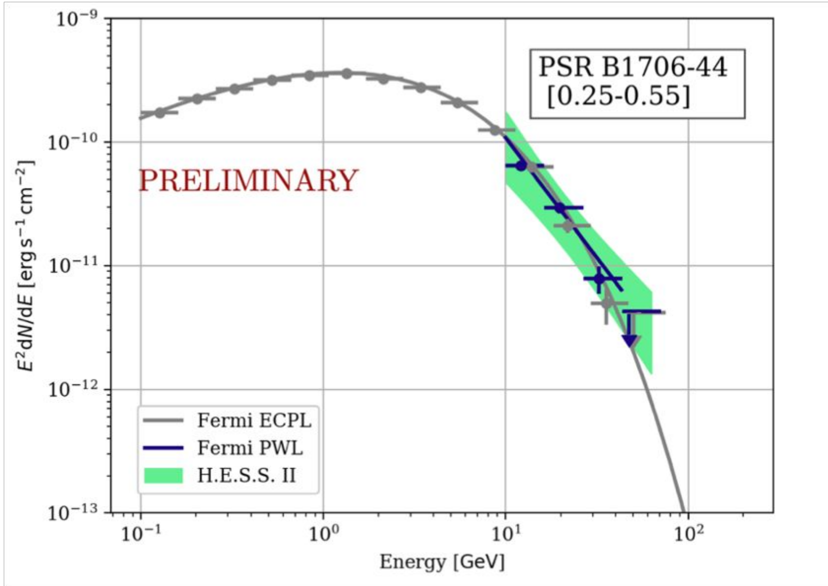
Observing pulsars with IACTs

PSR B1706-44

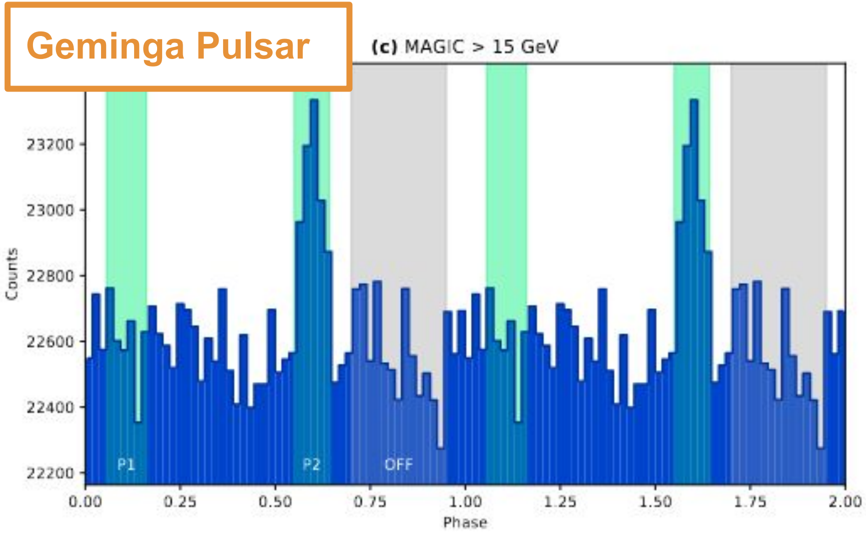
Spir-Jacob et al. (for the H.E.S.S. collaboration) arXiv e-prints, arXiv:1908.06464



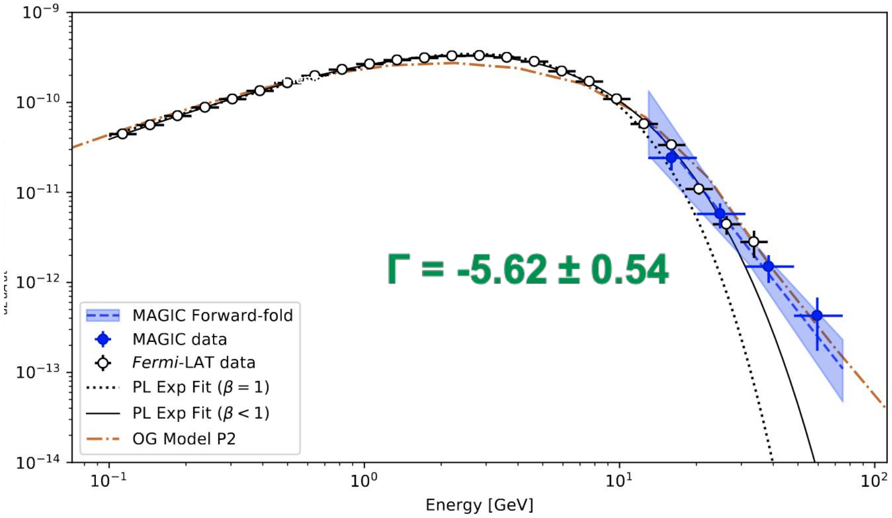


Detected at 4.7σ. Not possible to reject or accept/reject a cut-off or Power Law extension

Observing pulsars with IACTs



MAGIC Collaboration, V. A. Acciari, et al. A&A 643 L14 (2020)



- Transition between CR radiation by positrons to **IC** radiation by electrons accelerated towards the star.

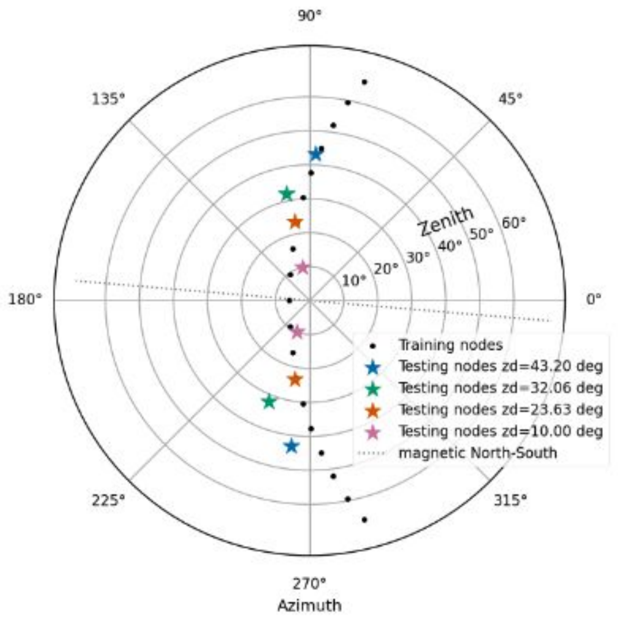
Data analysis: MC data and software

MC production:

- We used MC production at dec 22.76
- NSB tuned for the sky region
- Produced with spectral index **Γ**~-2
- Different MC test nodes for each run (based on nearest distance)
- Ephemeris from the Jodrell Bank Observatory

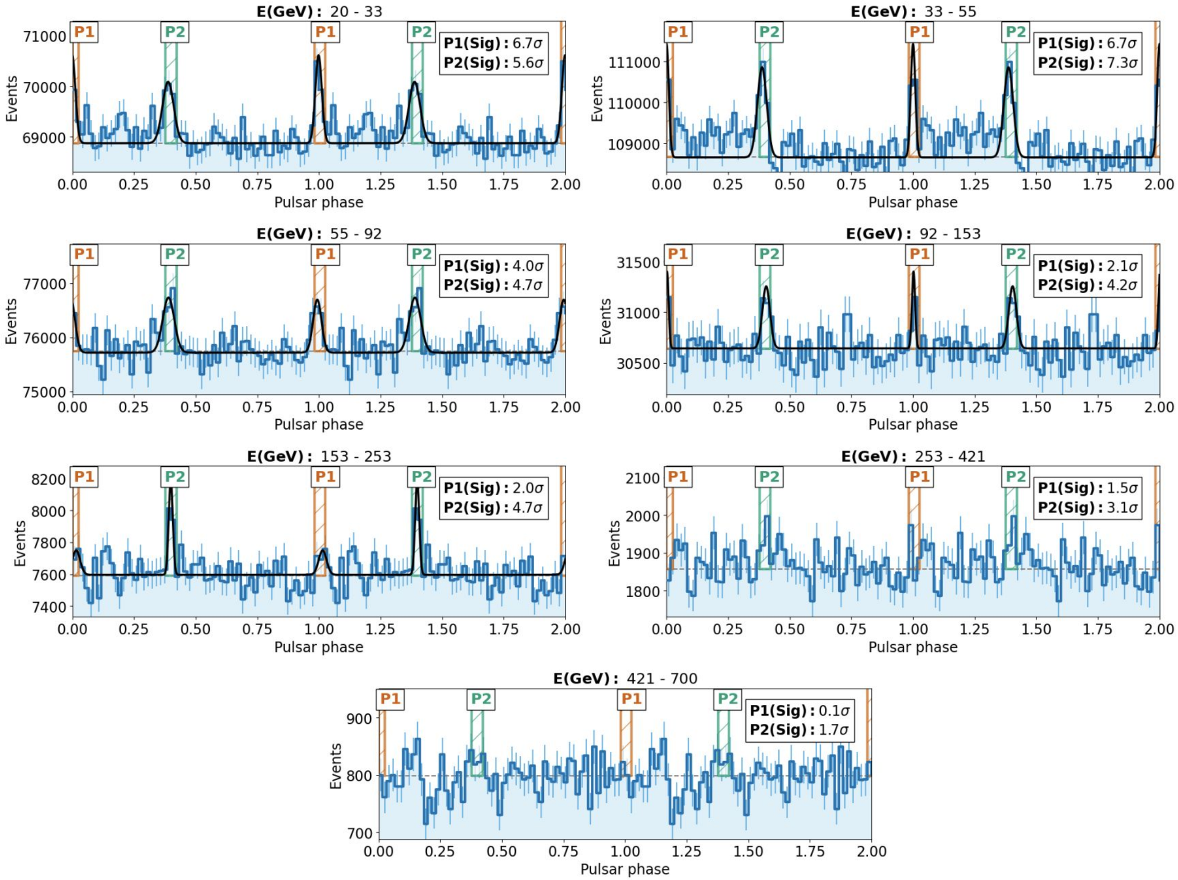
Software versions of the analysis:

  - PINT v0.9.7
  - lstchain v0.10
  - Gammapy v0.20.1



For more details see:
H. Abe *et al* 2023 *ApJ* **956** 80
(10.3847/1538-4357/ace89d)

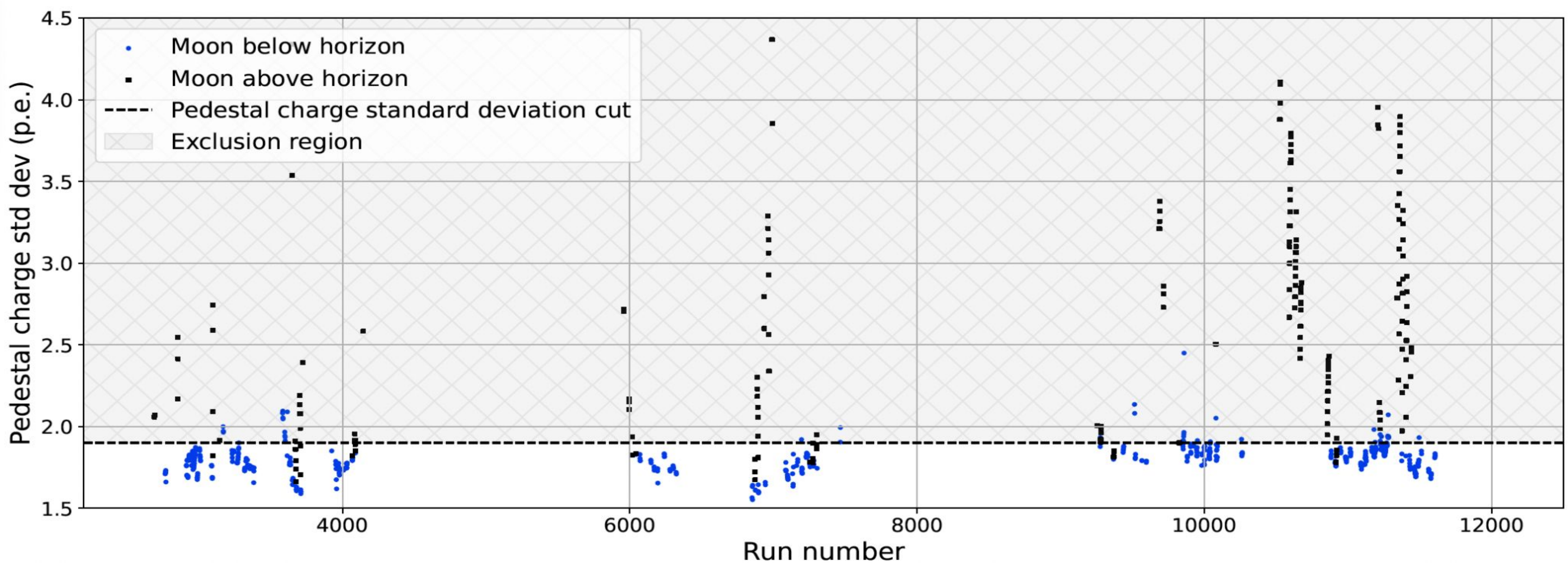
Crab Pulsar results: Phaseogram vs Energy



Data analysis: quality cuts

Quality cuts:

- Cut on pedestal charge standard deviation (removes moon data)



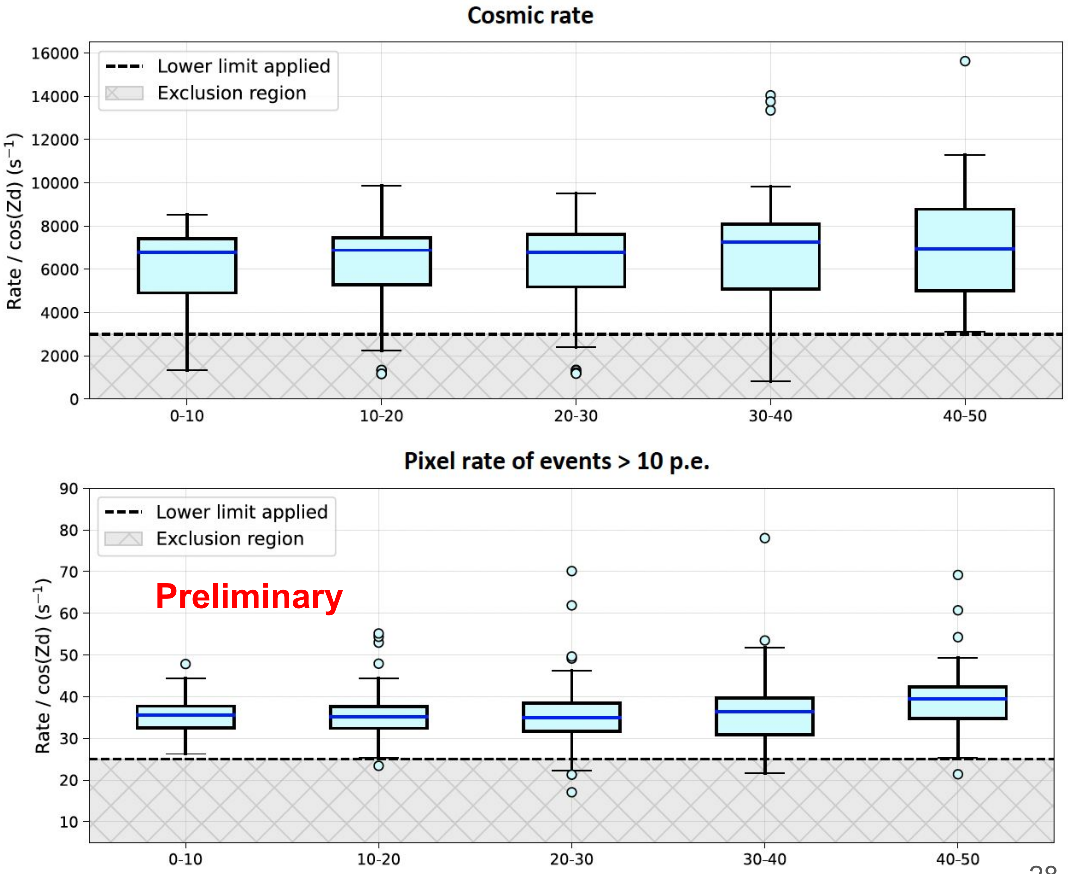
Data analysis: quality cuts

Quality cuts:

- Cuts based on the cosmic rates, pixel rates, etc.

- Hadronic rejection: energy dependent gammannes and alpha cuts (MC eff 70%)

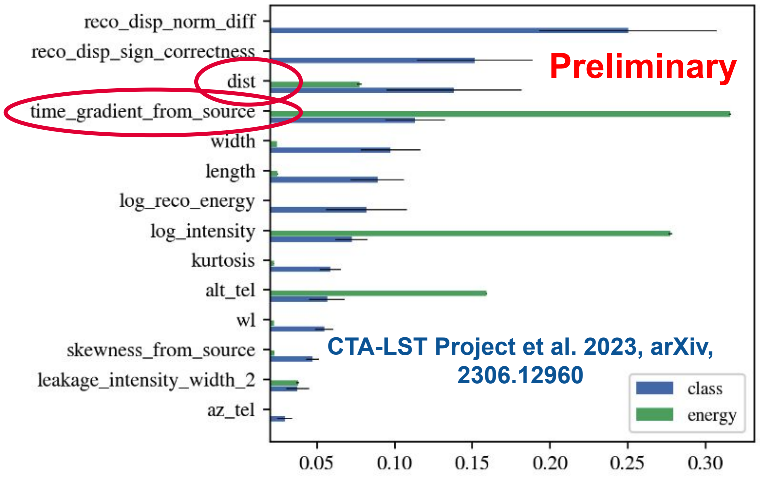
- Intensity > 80 p.e. (bef Aug2021), intensity > 50 p.e (afterwards)

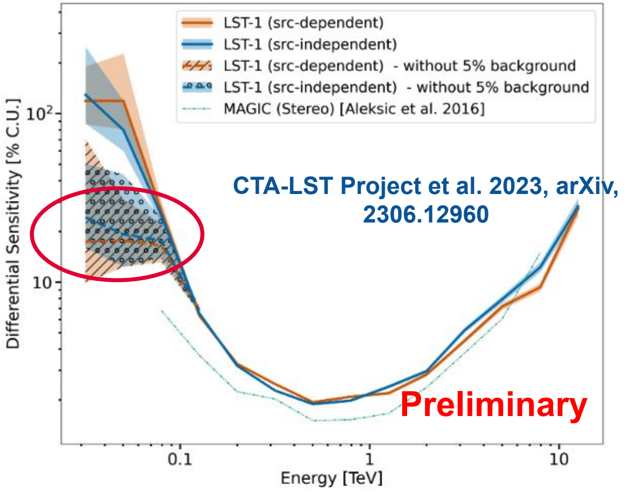


Data analysis: source-dependent analysis

Used source-dependent approach:

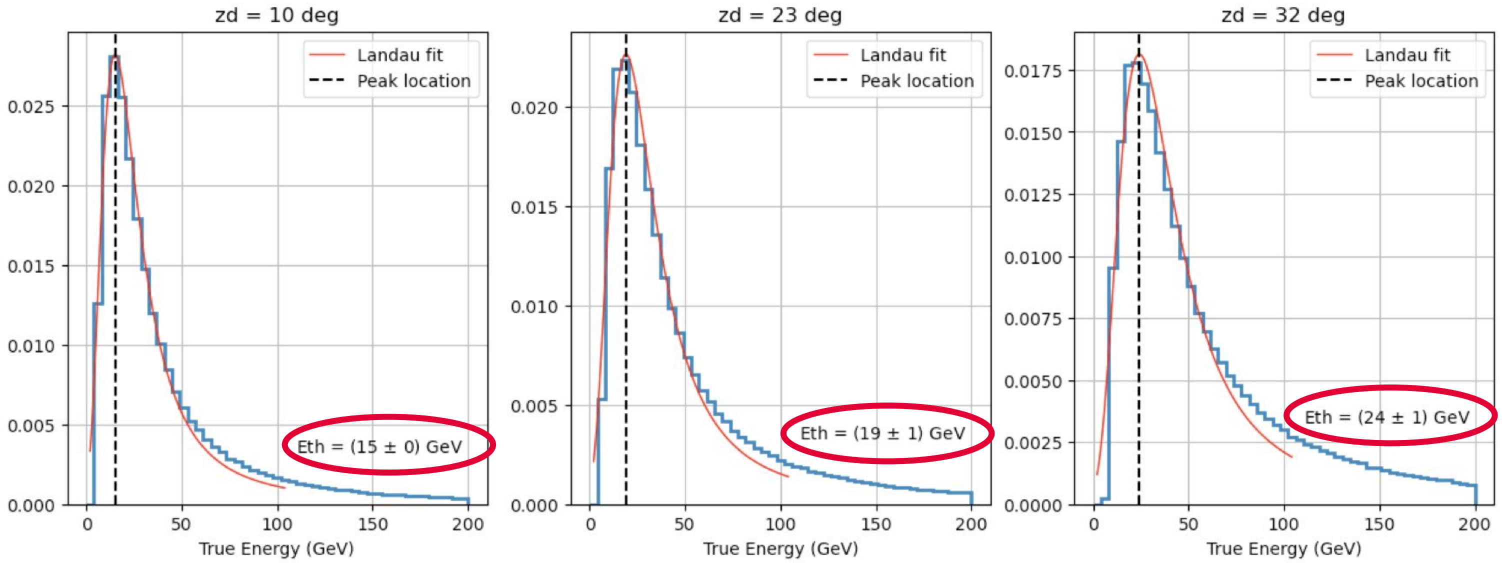
- Include source-dependent parameters in the Random Forests
- Improve performance of pulsar analysis at low energies.
- Source position needs to be known a priori





Energy threshold for the Crab pulsar spectrum

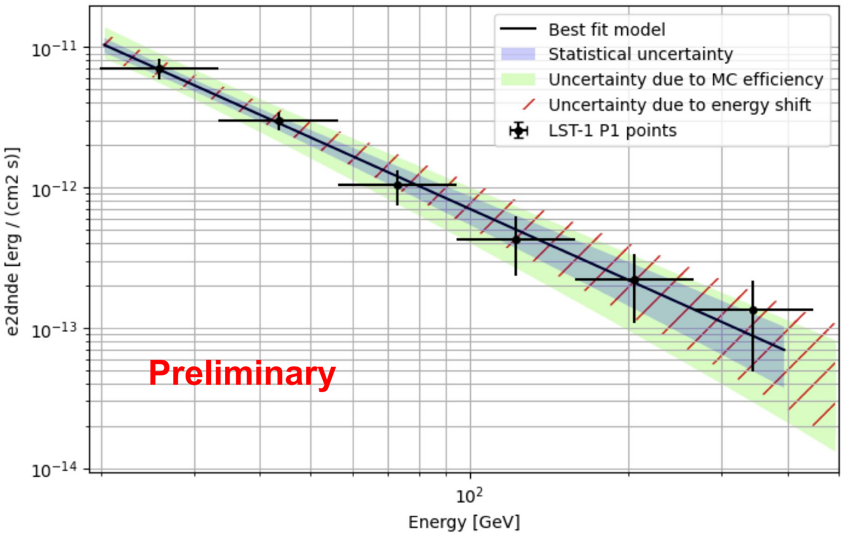
- Distribution of true energy of the MC that survives the cuts
- **Assumed SED of spectral index ~ (-3)**
- Lower for steeper spectra (e.g. Geminga pulsar)

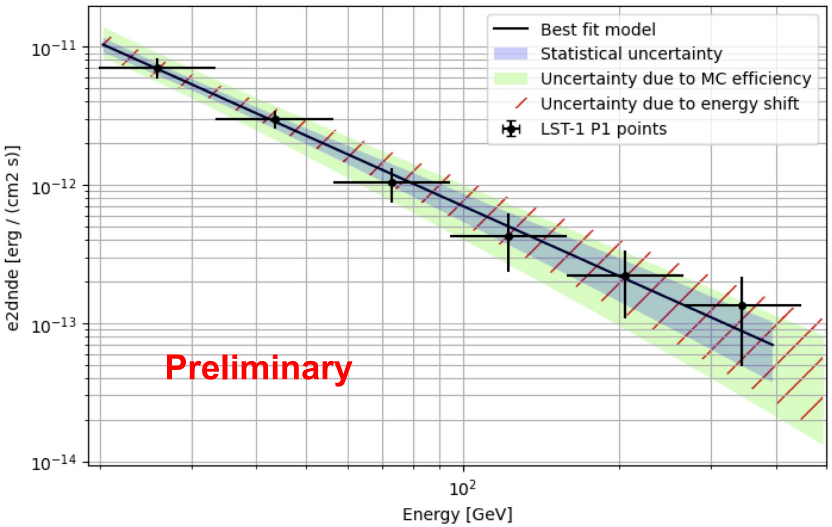


Systematic uncertainties of the analysis

Tests:

- Study of the SED of two different subsamples
- **Study the effect of the MC cut efficiency on the SED**
- **Study the effect of shifting the true energy of the MC by a factor**
- Study the effect of using an slightly different RF





Systematic uncertainties of the analysis

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Peak	Trigger threshold	Even selection cuts	Energy bias	Software versions
Maximum error in the spectral index				
P1	8.0 %	2.2 %	1.7 %	0.5 %
P2	2.2 %	5.9%	0.5%	2.6 %
Maximum error in the flux				
P1	30%	10 %	17 %	0.1%
P2	8 %	5 %	13 %	1.3 %