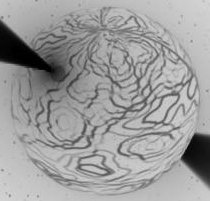
The MAGIC of Crab



G. Ceribella, G. D'Amico, R. Mirzoyan
for the **MAGIC Collaboration**

04/11/2025

TeV Particle Astrophysics
TeVPA
Valencia 2025

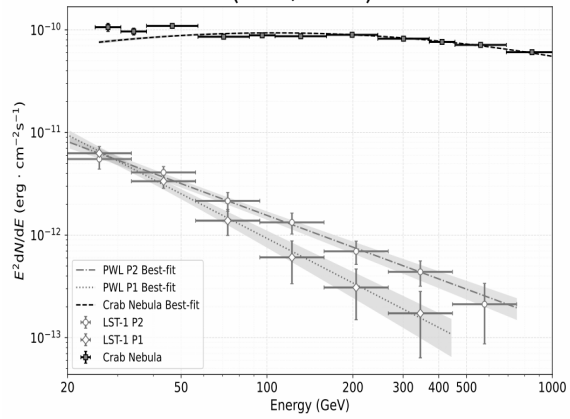
MAGIC

MAX-PLANCK-INSTITUT
FÜR PHYSIK

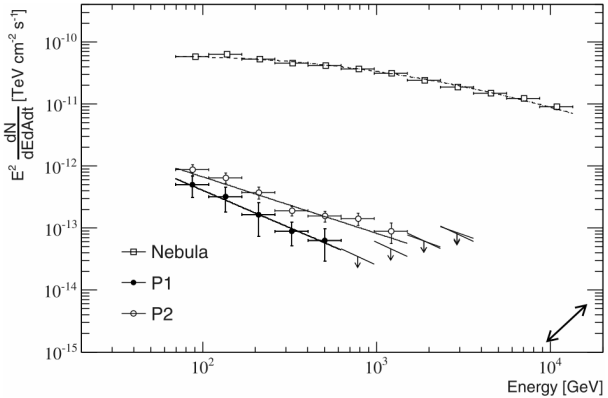
CRAB PULSAR (PSR J0534+2200)

- Spin-down luminosity **4×10^{31} W** (equivalent 10^5 $L_\odot$)
- First known pulsar beyond **few GeV** (2008) and **1 TeV** (2016)
- Unique **brightness** beyond 100 GeV:
  - **Bridge emission** persisting at VHE
- Currently interpreted as **superposition** of multiple **curvature-radiation** and **inverse-Compton** components

LST-1 Collab (A&A, 2024)

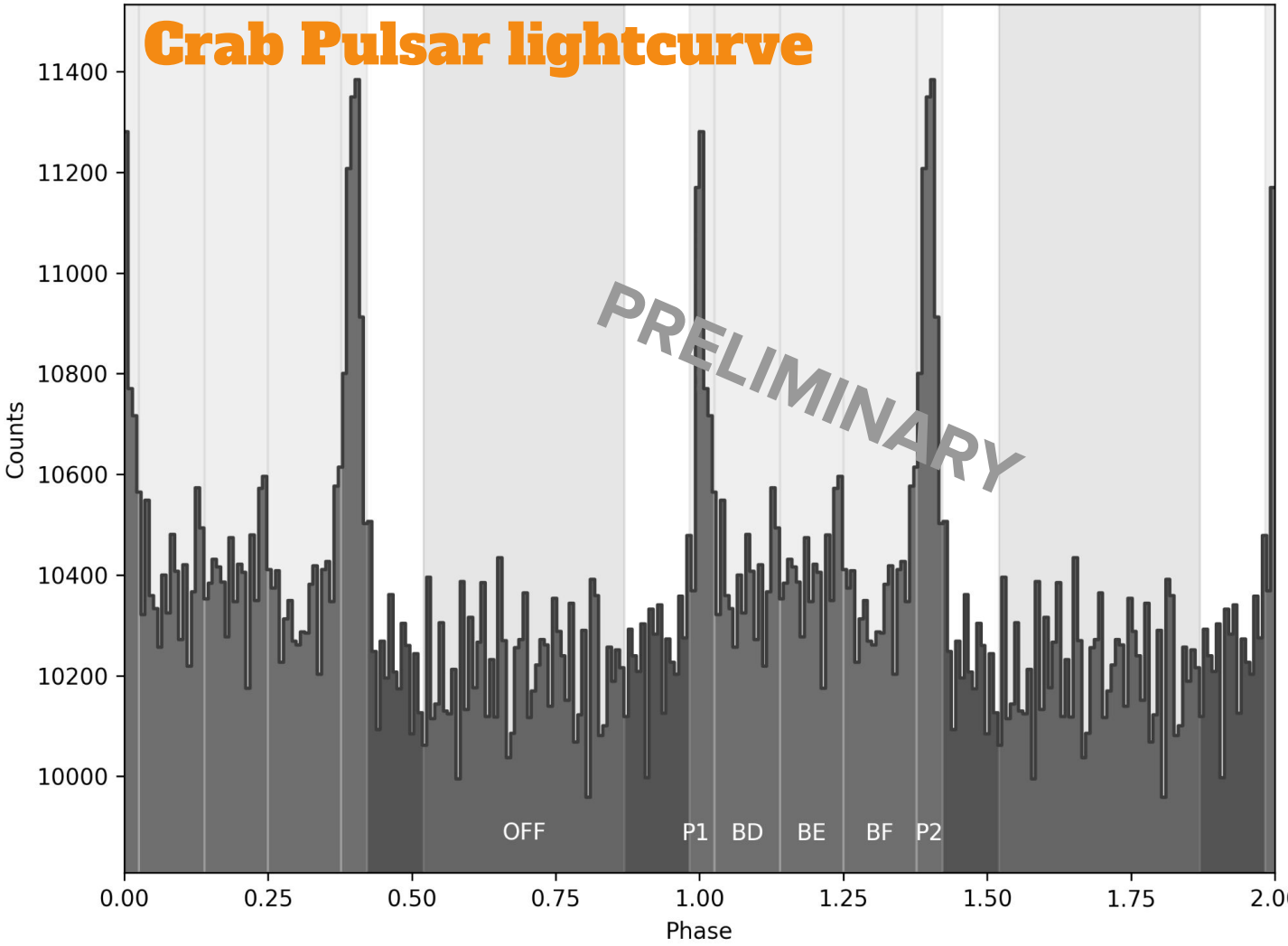


MAGIC Collab. (A&A, 2016)



MAGIC

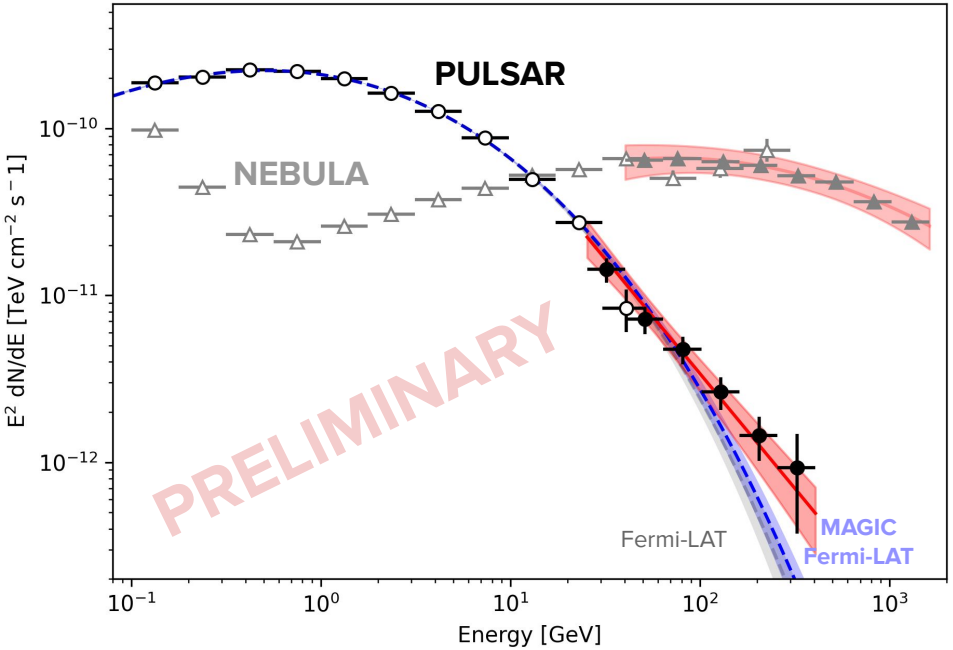
- Two **IACTs** in La Palma operating in stereo since 2009.
- Absolute time resolution: ~200 ns
- Diameter of 17 m , stereo **effective area** at 50 GeV: **2×10^4 m^2**.
- Energy range: **20 GeV** - 100 TeV
- Data used in this work:
  - **110 h** commissioning of **low-energy sum-trigger-II system**
  - Collected between 2015 and 2020
  - **Low-zenith** angle observations: cos(zenith) > 0.9 (~26 deg)
  - Energy **threshold** (pulsar spectrum): **~20 GeV**



- ★ **High-significant** detection down to **20 GeV**
- ★ Cumulative significance (P1+P2): **~22σ**
- ★ Sound statistics allows study of **bridge** emission in **sub-intervals**
  - 5σ in each of them
- ★ Background: **Crab Nebula**

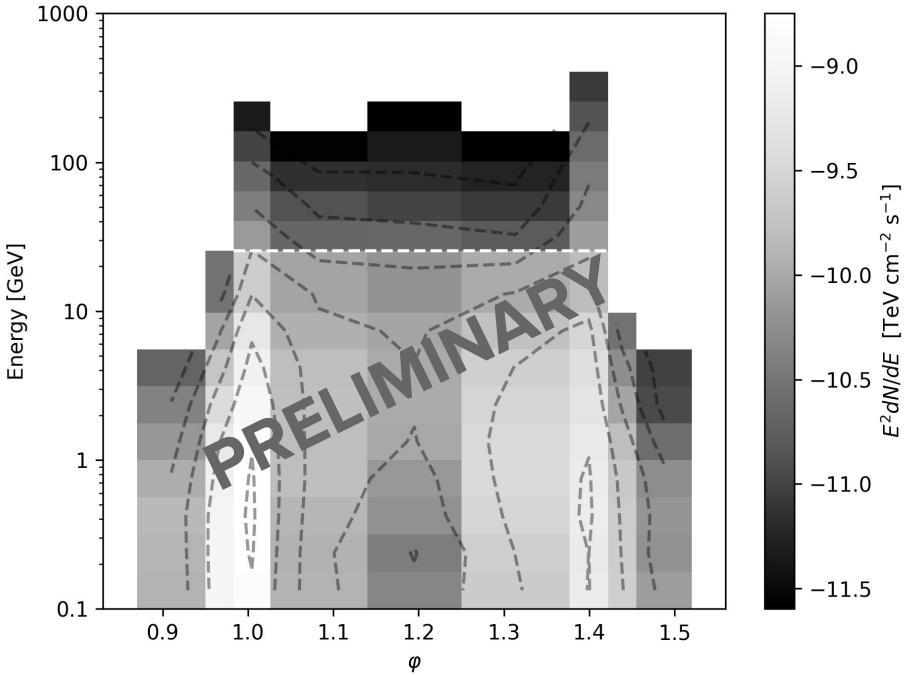
PHASE-AVERAGED SPECTRUM

- **Power-law** extension of the Fermi-LAT spectra:
  - Range: 25 GeV - 400 GeV
- **Nebula** gated in off phase interval (0.52,0.87)
- **Joint-fit** with LAT data:
  - MAGIC data "**drowned**" in LAT statistics
  - Compatible with cutoff from **curvature radiation**?

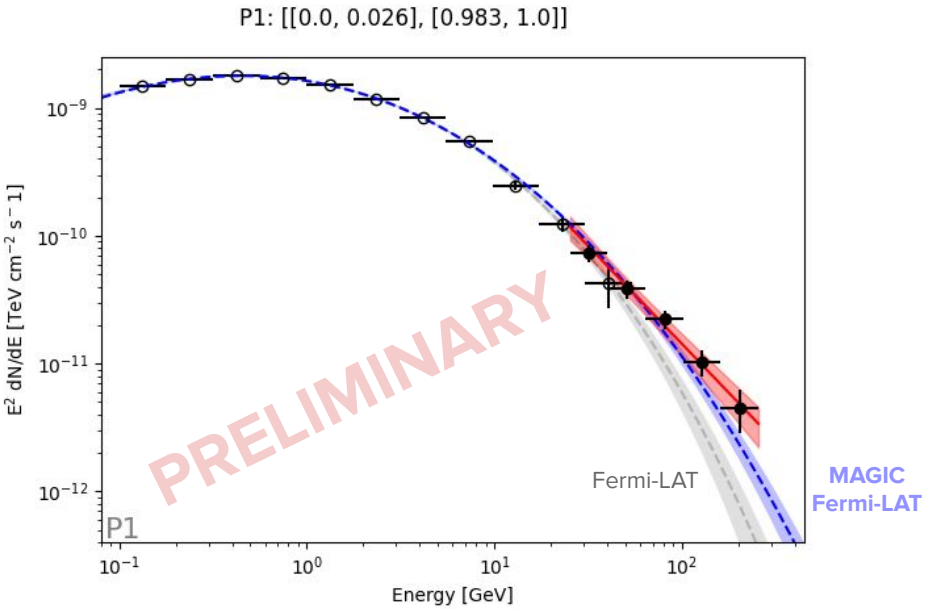


ADDING A DIMENSION: PULSED SPECTRA

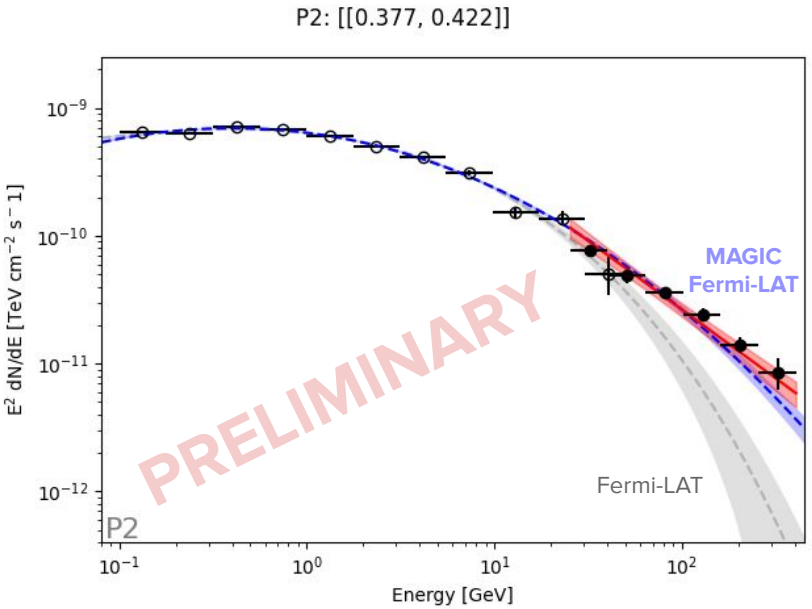
- **Broad spectral changes** within the **phase interval**
- **Not confined** to the two main **pulses** P1 and P2
- Bridge **substructure** studied for **the first time**
- **Power-law** extension tail much **more prominent** than in averaged spectrum
- **Joint Fermi-LAT + MAGIC** fits in all **phase intervals** with new **PLSECv4** model.



ADDING A DIMENSION: PULSED SPECTRA



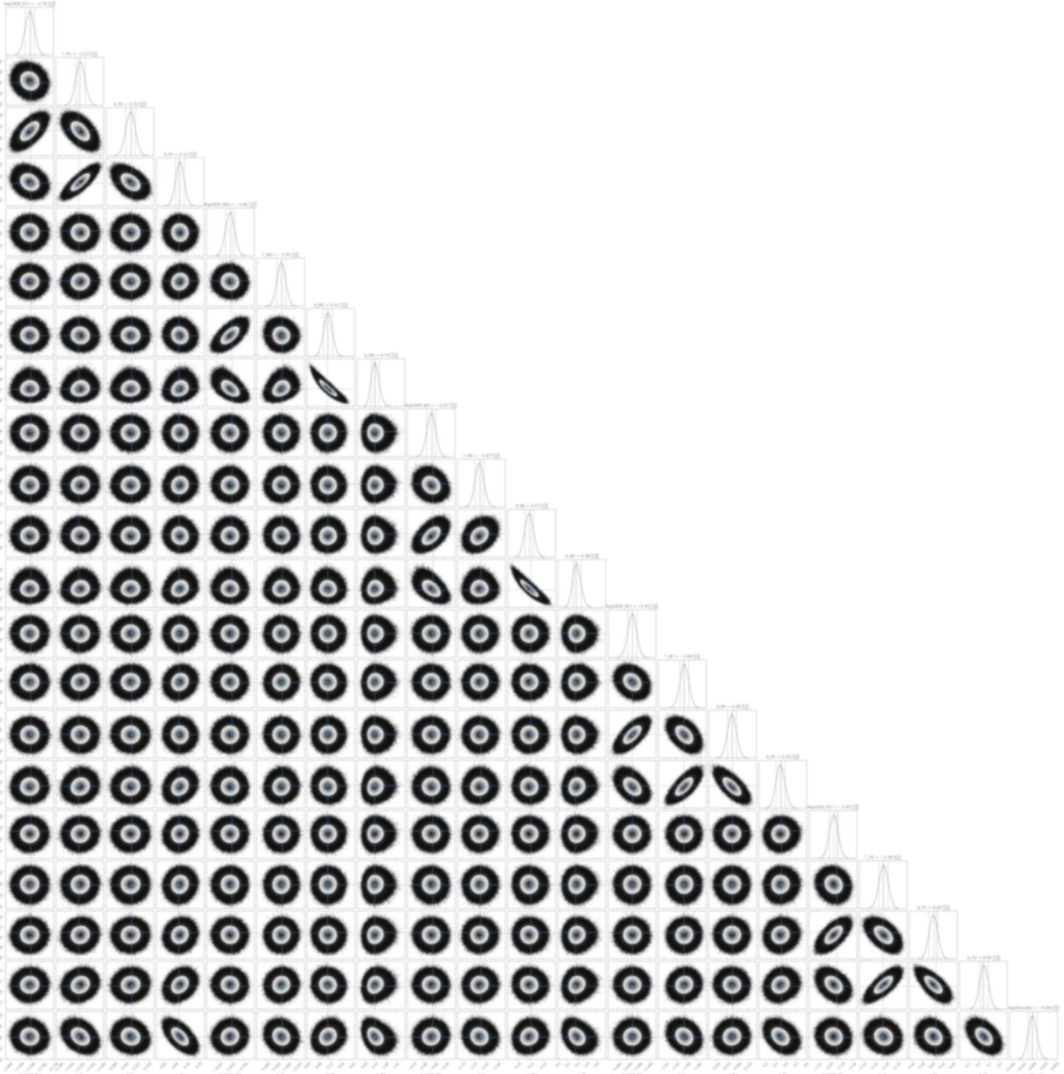
PWL Spectral Index (P1): **~3.5** (LST-1 ~3.4)
b(P1): 0.11±0.03

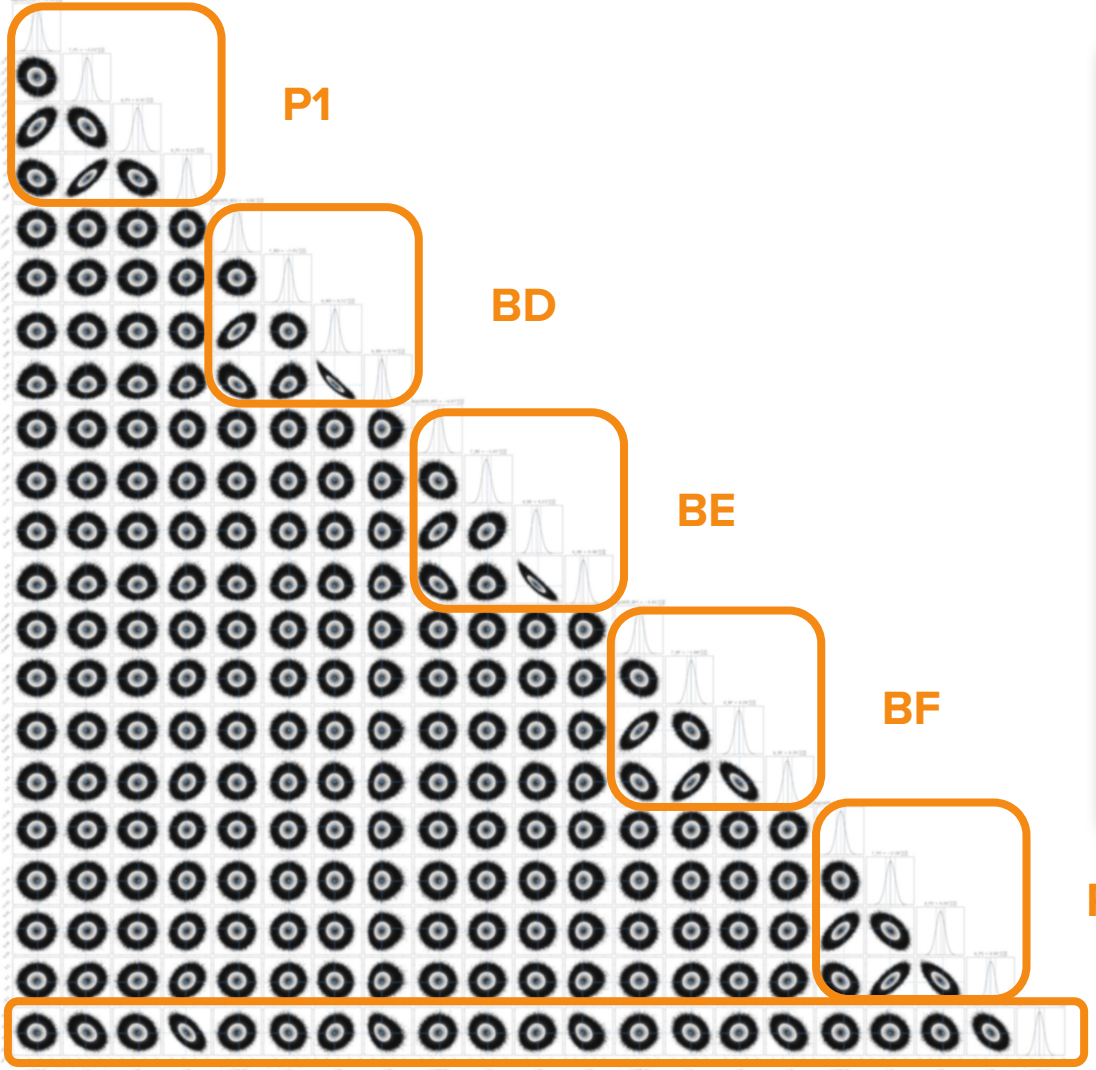


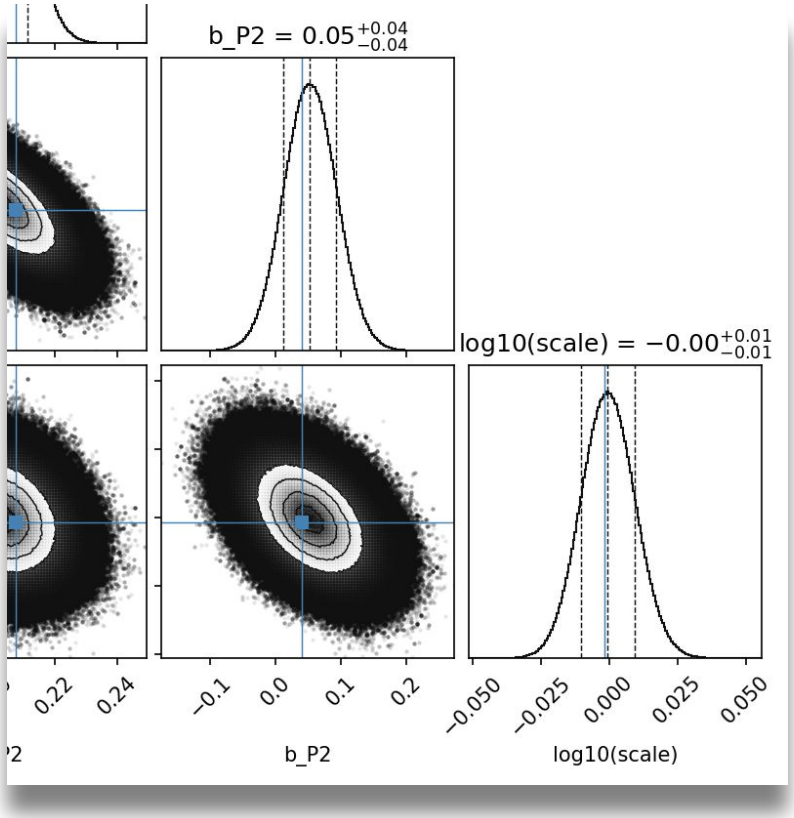
PWL Spectral Index (P2): **~3.1** (LST-1 ~3.0)
b(P2): 0.05±0.04

SYSTEMATIC EFFECTS STUDY

- **Event selection**
  - Gamma-Hadron cuts
- Pulsar **ephemeris**
- Phase gating suppressing **background-estimation systematics**
- **Joint** Fermi-LAT and MAGIC fits:
  - **Energy-scale** mismatch (equal for all phase regions)
  - MAGIC **flux-energy scaling law** determined from MC simulations
  - Energy scale modeled as **nuisance parameter**:
    - Single **simultaneous fit** of Fermi and MAGIC data in **all phase regions**
    - **Correlation** among phases through the **energy scaling** parameter
  - Results in an **estimate** of Fermi-LAT/MAGIC **energy mismatch**: **±2%**
- Sum of **systematic** contributions **comparable** to **statistical** uncertainties



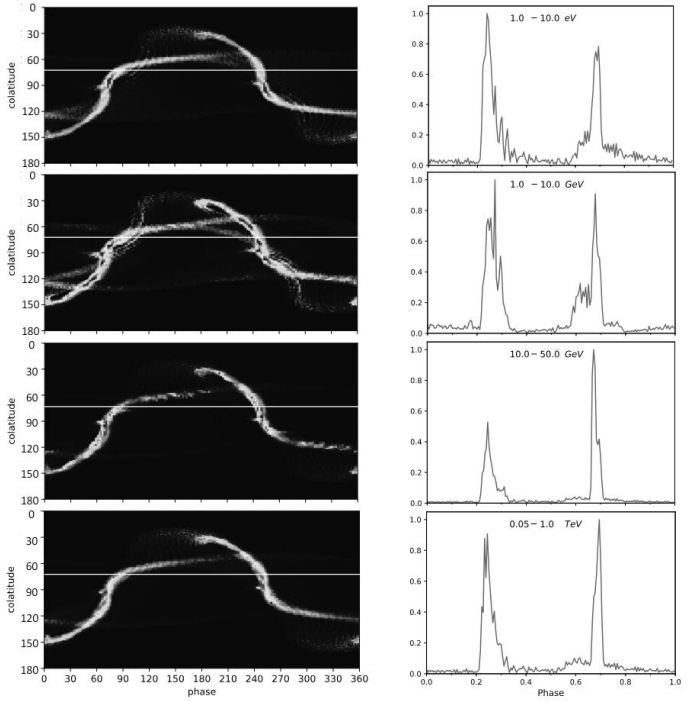

P1
BD
BE
BF
P2
SCALE


b_P2 = 0.05$^{+0.04}_{-0.04}$
log10(scale) = −0.00$^{+0.01}_{-0.01}$
0.22
0.24
−0.1
0.0
0.1
0.2
−0.050
−0.025
0.000
0.025
0.050
b_P2
log10(scale)

BATTLING MODELS

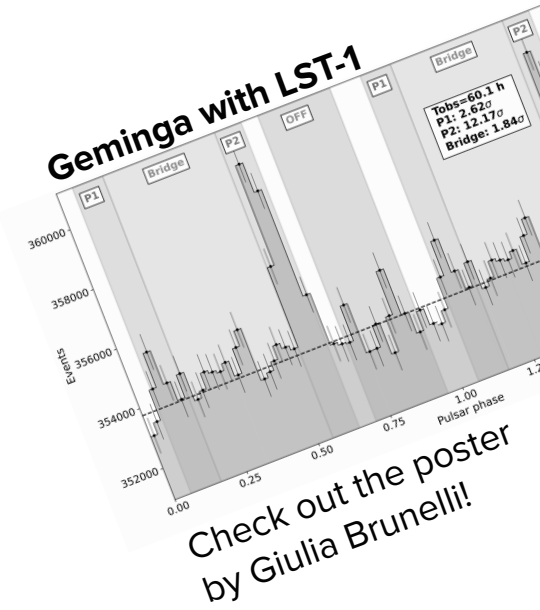
- Long march **towards** and beyond the **light cylinder**
- Two classes of models:
  - **Linear** parallel **E field** at the **Y point** (Harding et al., etc)
  - **Magnetic reconnection** in the **striped wind** (Cerutti et al, etc)
- **Model degeneracy** impacted by **phase-dependent** spectra
- Need to **<u>account phase dependency</u>** in models.

Harding et al., 2021



CONCLUSIONS

- The **Crab pulsar** still offers a **rich playground** for **VHE pulsar model testing** after almost 20 years from its first discovery
- **Deep exposure** above **20 GeV** with **MAGIC** (sum-trigger-II) **yields unprecedented dataset** for joint **phase-spectral** studies (publication soon…)
- Novel **multi-instrument joint fit strategy incorporates systematic** effects and **provides energy scale** mismatch **estimate**
- **More pulsars** are out waiting for the **CTAO** era…



Check out the poster by Giulia Brunelli!

GRACIAS!