Investigating the high-energy & very-high-energy gamma-rays of the Geminga pulsar with Fermi-LAT & CTAO LST-1

Paul K. H. YEUNG @ 8th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy; September 2024
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Scientific motivations for pulsar studies

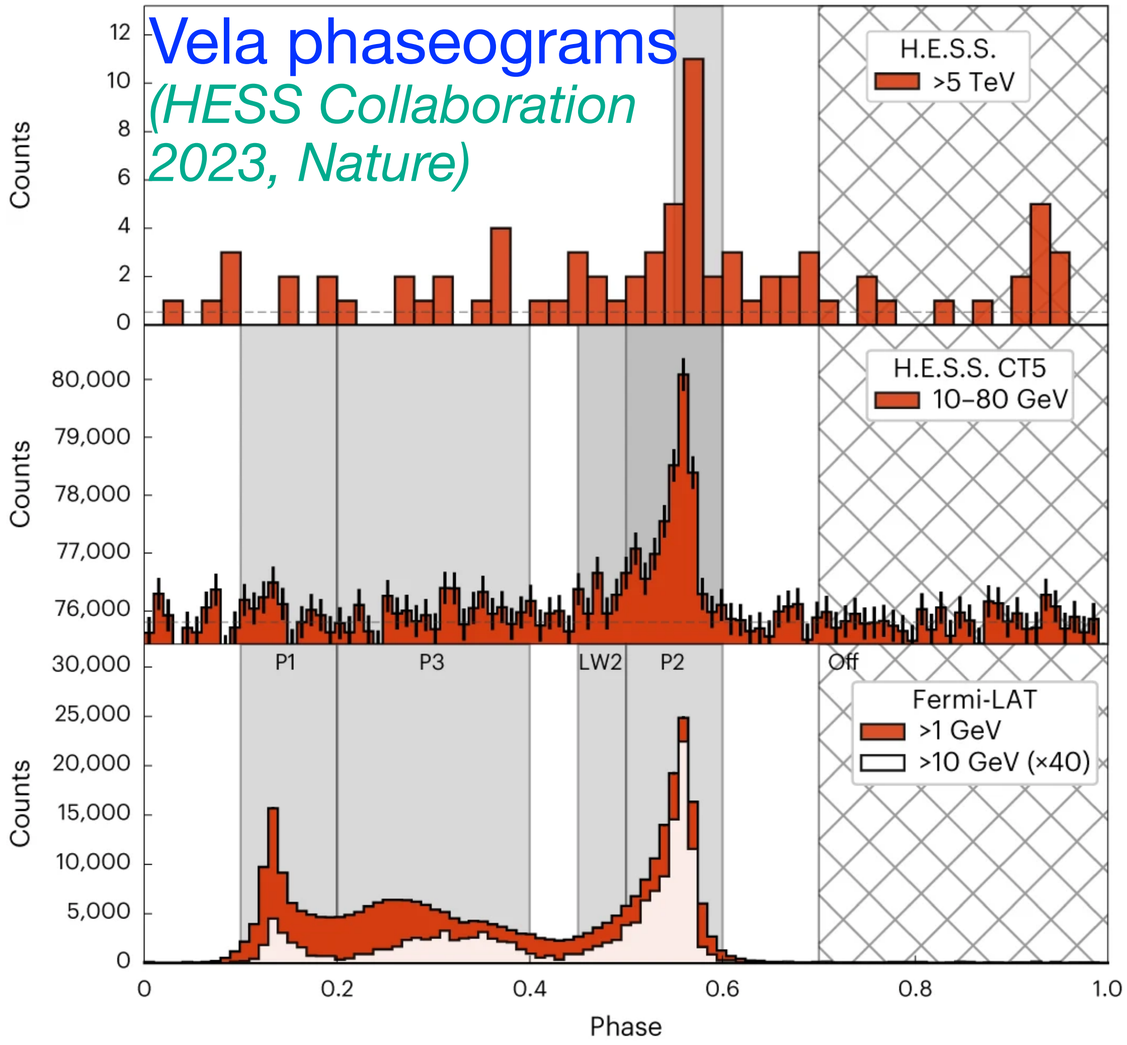
- Vela, Crab, Geminga & Dragonfly pulsars have Double Pulse (P1 & P2) and a Bridge (P3)
- Energy-dependent gamma-ray pulse shape

$\Longleftrightarrow$

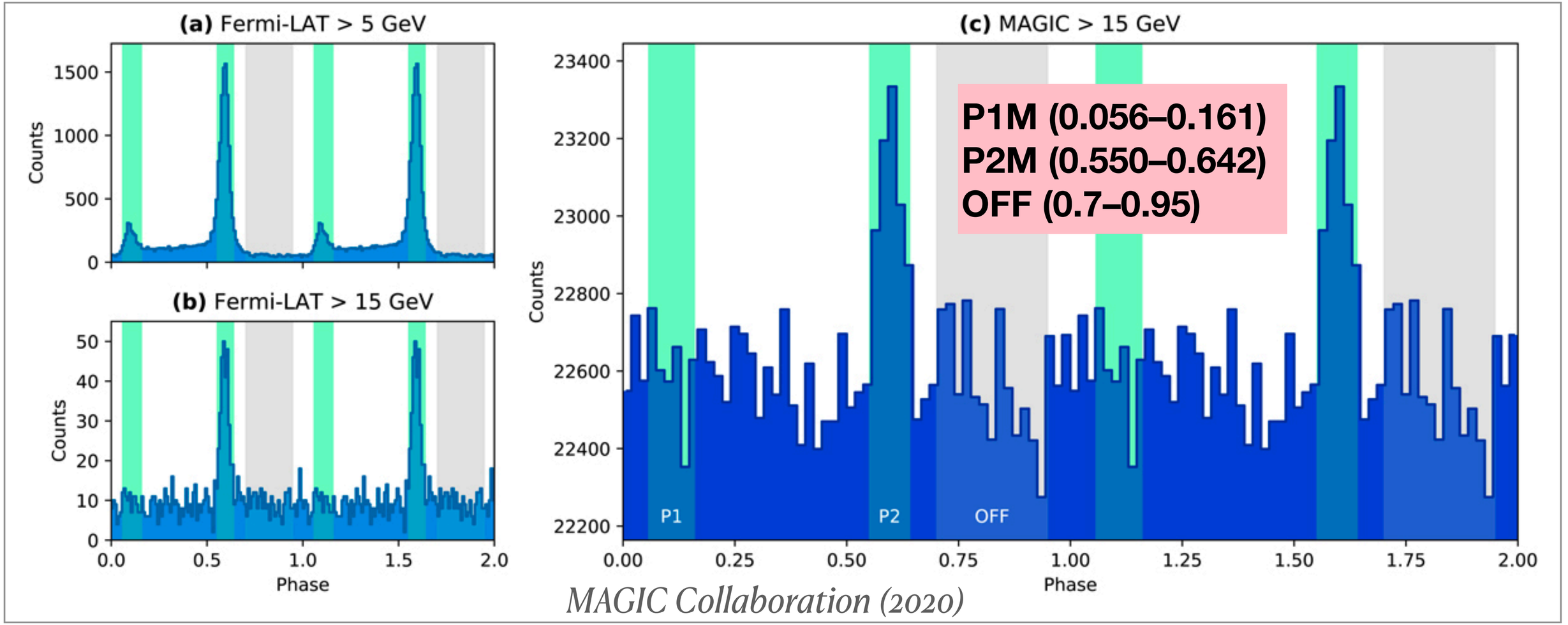
- Phase-dependent gamma-ray spectral shape

—> Multi-origins?

- Crab pulsar & Vela pulsar: with TeV pulsed emission detected *(MAGIC Collaboration 2016; HESS Collaboration 2023 Nature)*



Previous Studies for Geminga Pulsar



MAGIC Collaboration (2020)

- P1 & Bridge are detected at 5 GeV, but Undetected above 15 GeV
- P2 with MAGIC: 6.3σ in 83hr

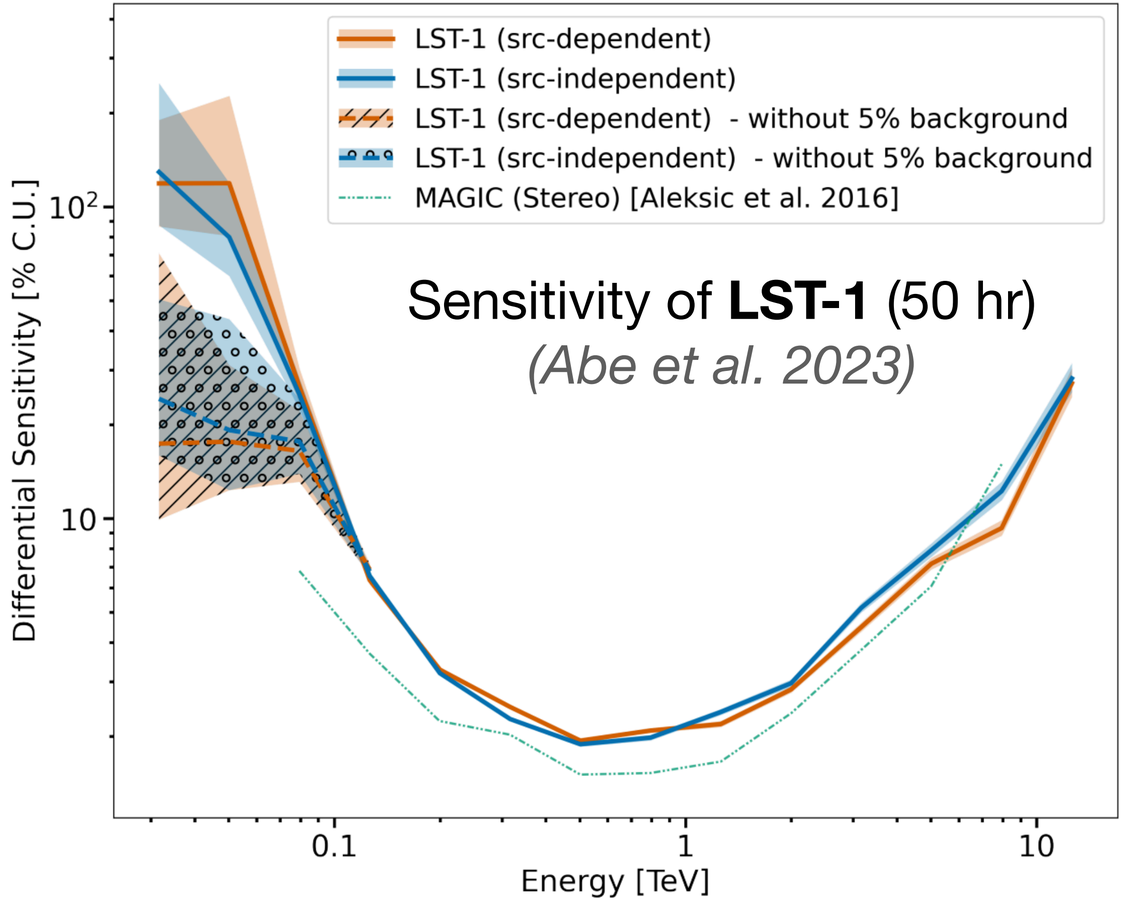
Advantages of Cherenkov Telescope Array Observatory (CTAO)

CTAO: New generation of IACTs

- Unprecedentedly good sensitivity from 20GeV to 10TeV
- Complementary with Fermi-LAT & other IACTs

First Large-Sized Telescope (LST-1)

- Prototype of the CTAO LSTs
- Threshold ~ 20 GeV
- Greatly overlapping with Fermi-LAT & MAGIC energies (suitable for crosschecks)



Data Analysis Schemes

We performed two different analysis: source-dependent and source-independent

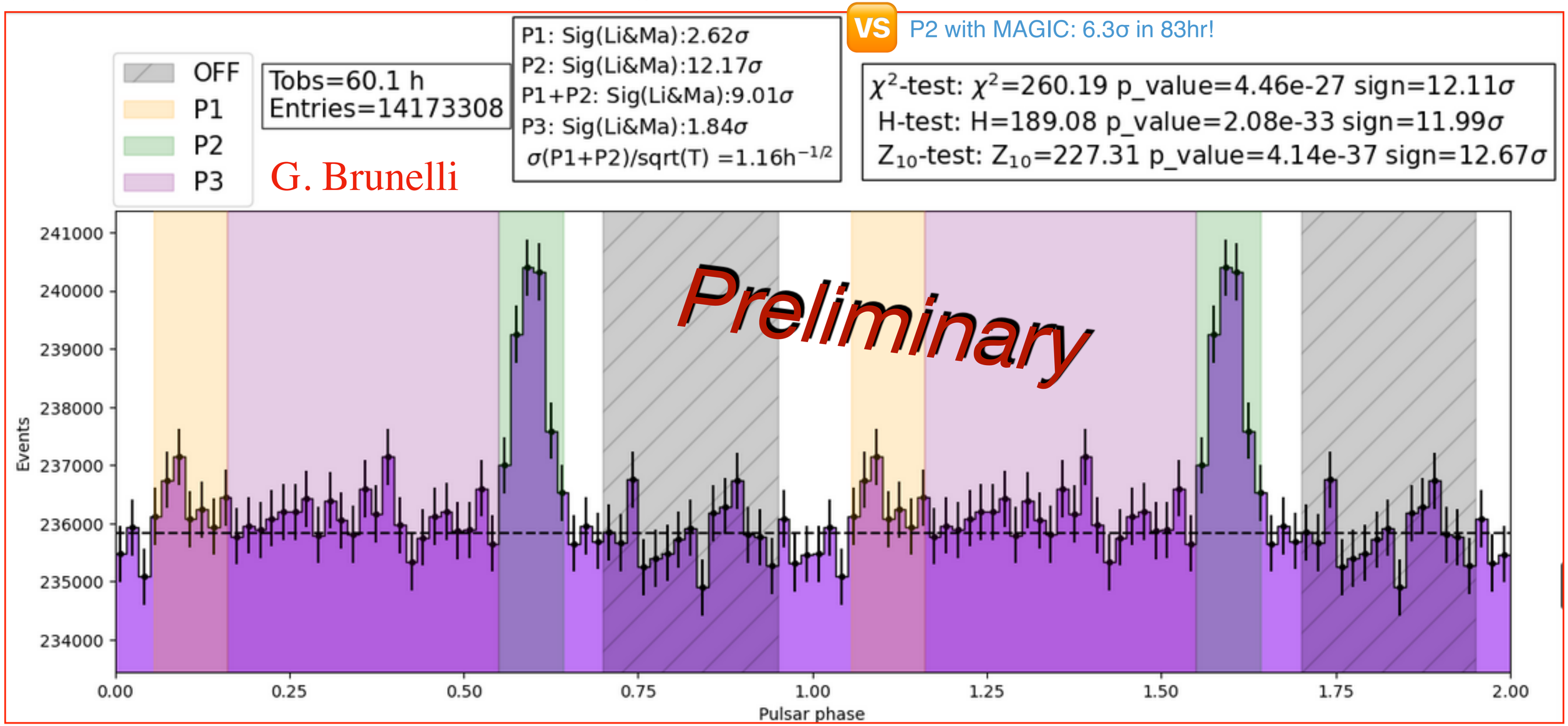
Source-dependent

- lstchain v0.10.7
- Dedicated MC for Geminga (src6)
  - Tuned NSB
  - Declination 22.76 deg
- IRF linear interpolation
- Event selection:
  - **gh-eff** = 0.7
  - **alpha-containment** = 0.7
  - intensity > 50 p.e
- Phase-folding using PINT v0.9.7.
- Ephemeris provided by G. Ceribella: https://www.mpp.mpg.de/~ceribell/geminga/

Source-independent

- lstchain v0.10.5
- MC: 20230927_v0.10.4_crab_tuned
  - Tuned NSB
  - Declination 22.76 deg
- IRF linear interpolation
- Event selection:
  - **gh-eff** = 0.9
  - **theta-containment** = 0.7
  - intensity > 50 p.e
- Phase-folding using PINT v0.9.7.
- Ephemeris provided by G. Ceribella: https://www.mpp.mpg.de/~ceribell/geminga/

LST-1 Phaseogram of the Geminga pulsar (source-Dependent analysis)



Phaseogram vs Energy (source-Dependent analysis)

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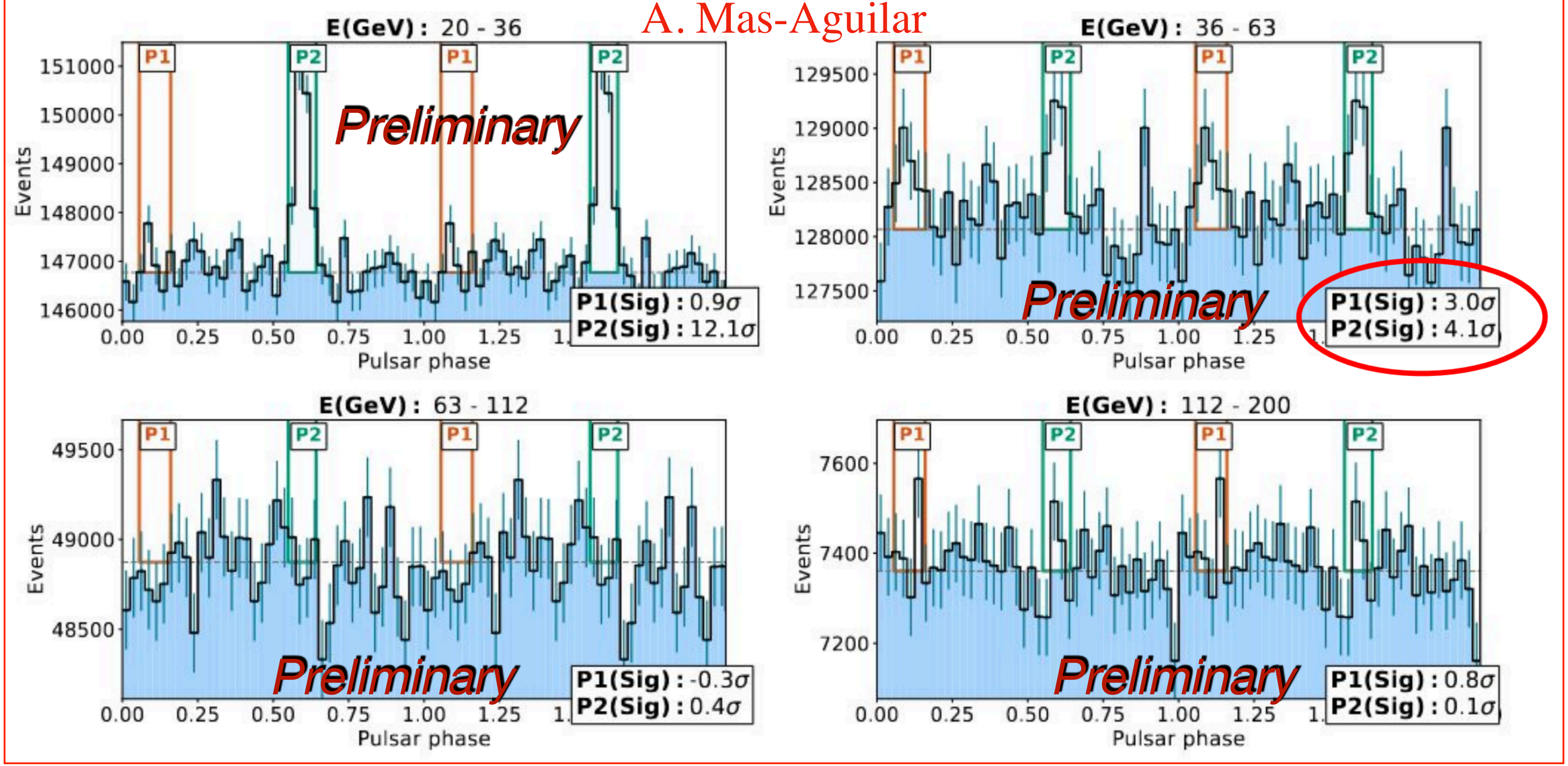
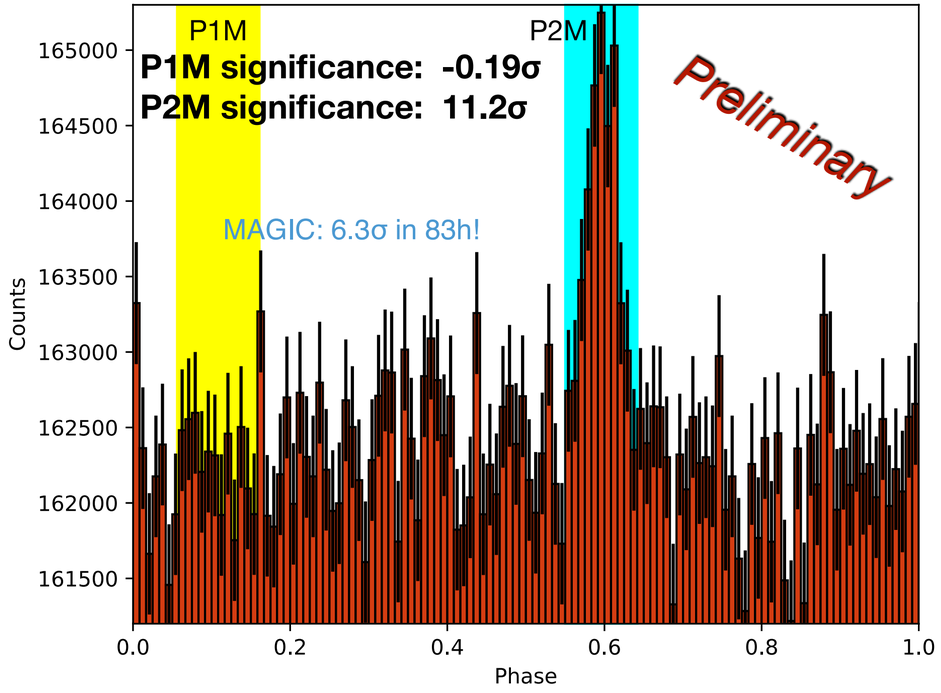


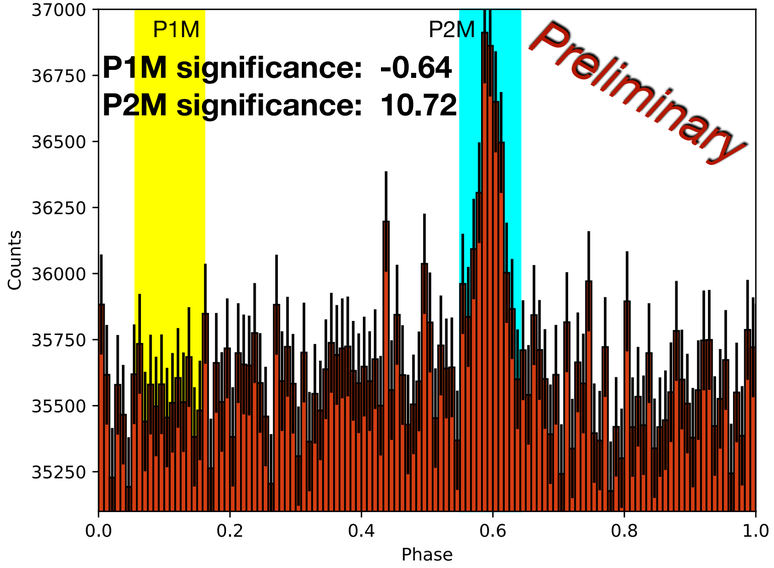
Crosschecks with source-Independent analyses

2022Dec—2024Feb; Zd<50°; 58.1 hr

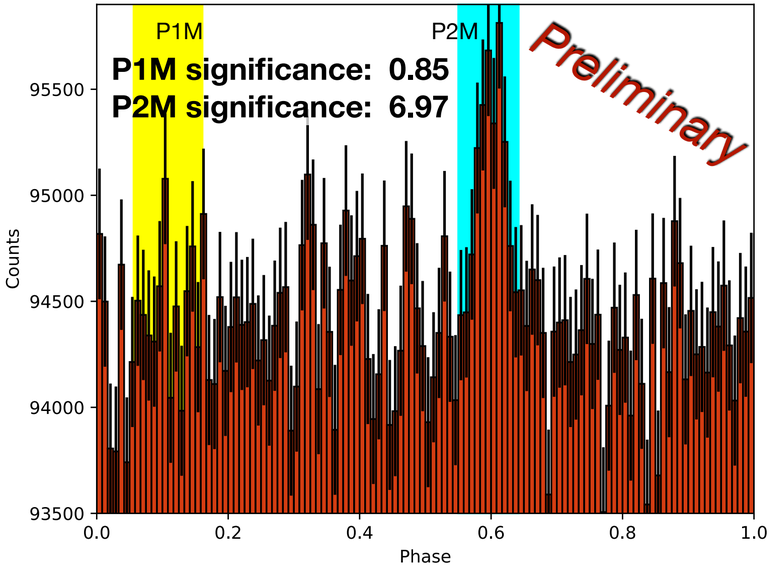
No cuts on energy (Fullband)



0.015—0.03 TeV



0.03—0.06 TeV

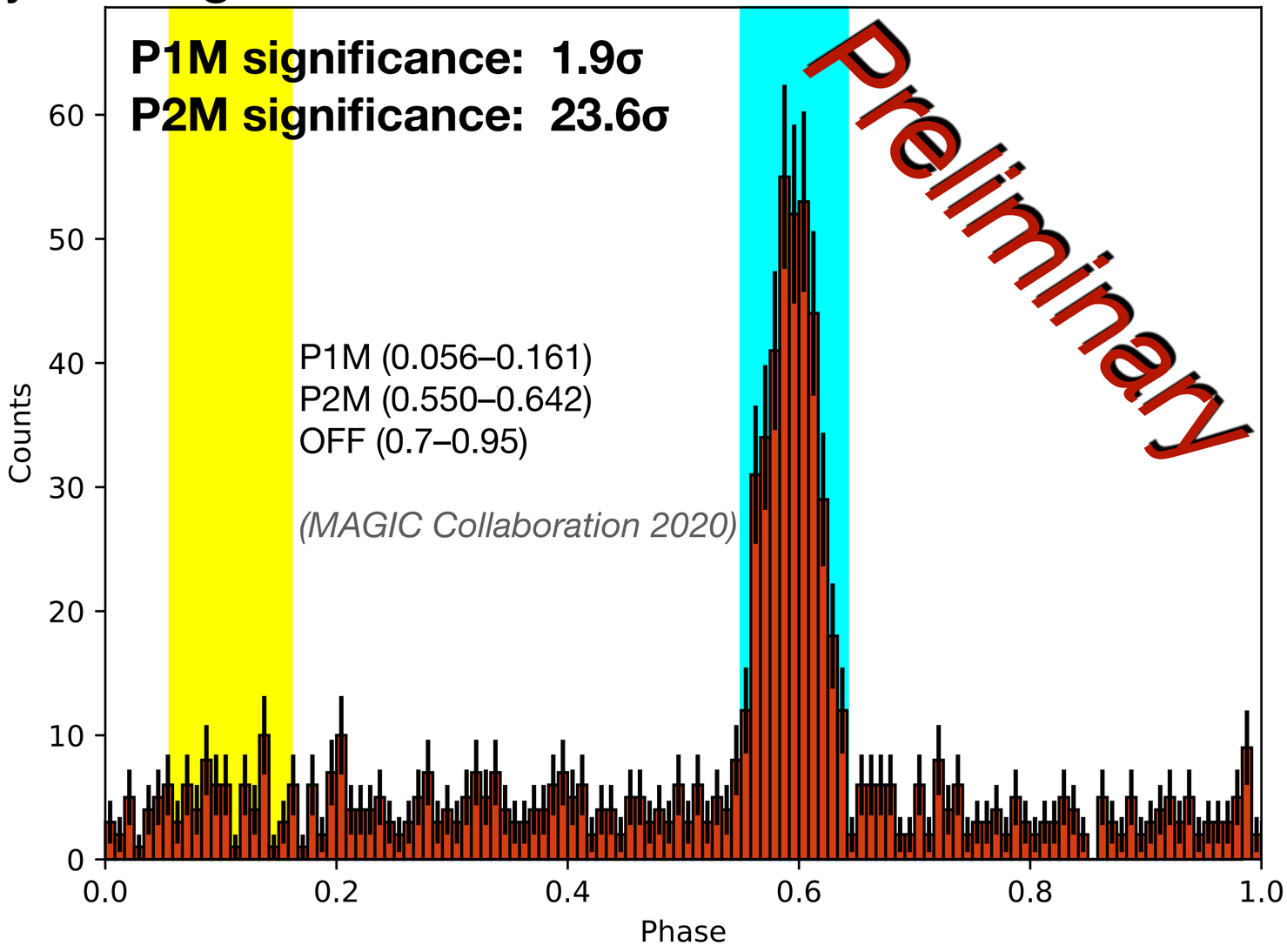


P1M (0.056–0.161)
P2M (0.550–0.642)
(MAGIC Collaboration 2020)

OFF (0.22–0.49; 0.7–1)

Comparison with Fermi-LAT Phaseogram

Fermi-LAT; 15.7 yr; 3 deg radius; 15–100 GeV



Evolutions of significances over obs. time (source-Dependent analysis)

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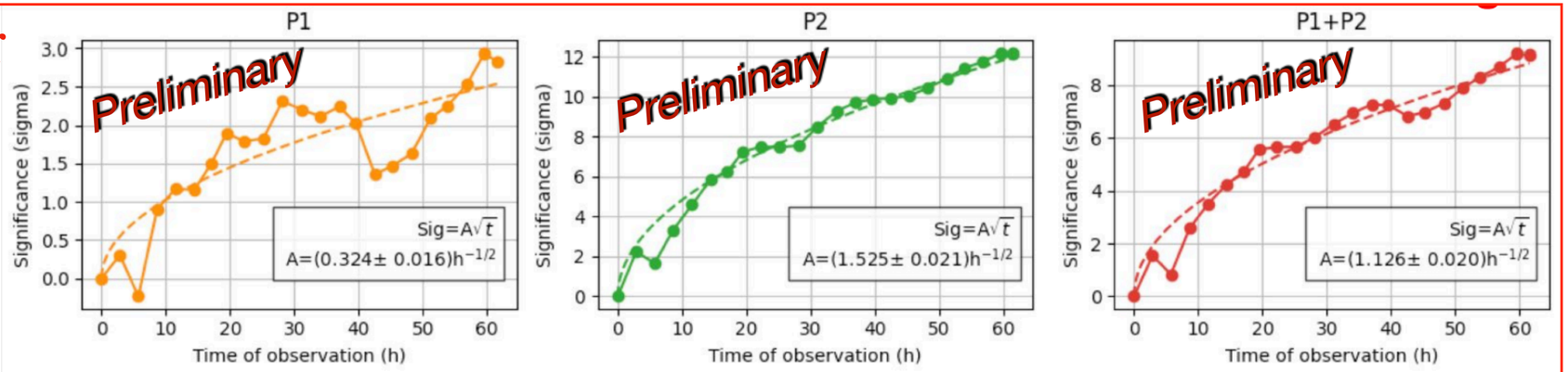
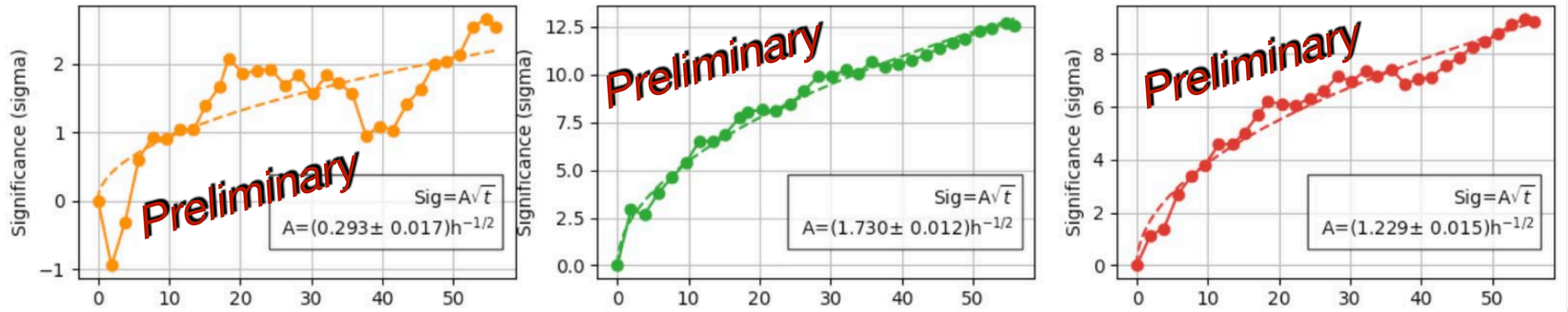
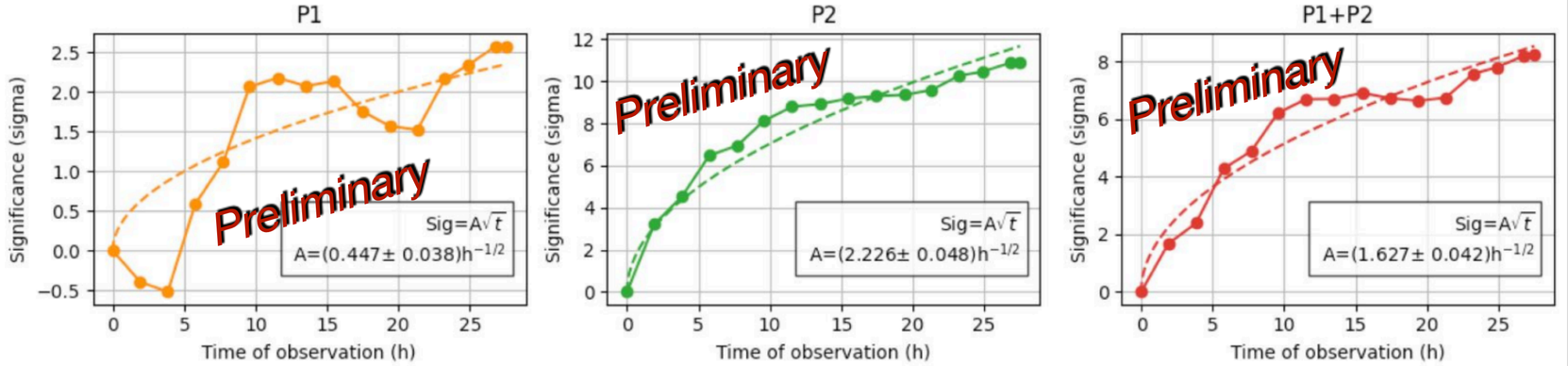
Zd < 50 deg



Zd < 25 deg



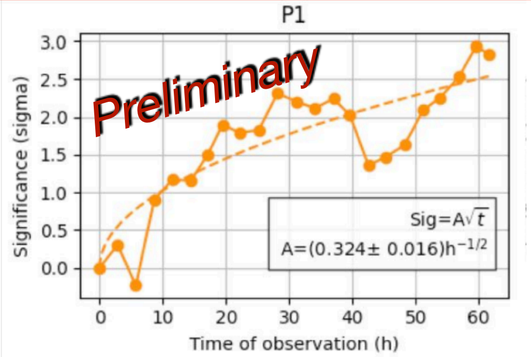
Zd < 15 deg



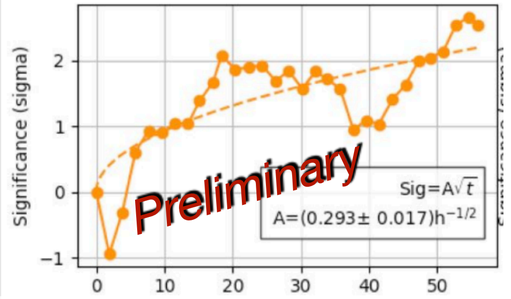
Estimating the time for P1 detection with only LST-1

- By assuming the significances of P1 are genuine, we extrapolate the time for 5σ detection based on the mean evolution of the signal over time

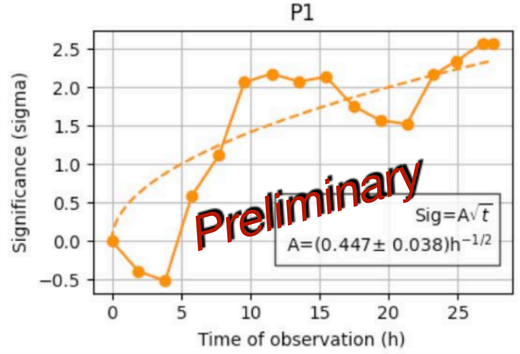
Zd < 50 deg



Zd < 25 deg



Zd < 15 deg



$$T_{5\sigma} = \left[5\sigma \cdot \left(\frac{\sigma}{\sqrt{t_{\mathrm{obs}}(h)}} \right)^{-1} \right]^2$$

Zd range	Mean $\sigma/\sqrt{t_{\mathrm{obs}}(h)}$	$T_{5\sigma}$ (h)
< 50 deg	0.324	238
< 25 deg	0.293	291
< 15 deg	0.447	125

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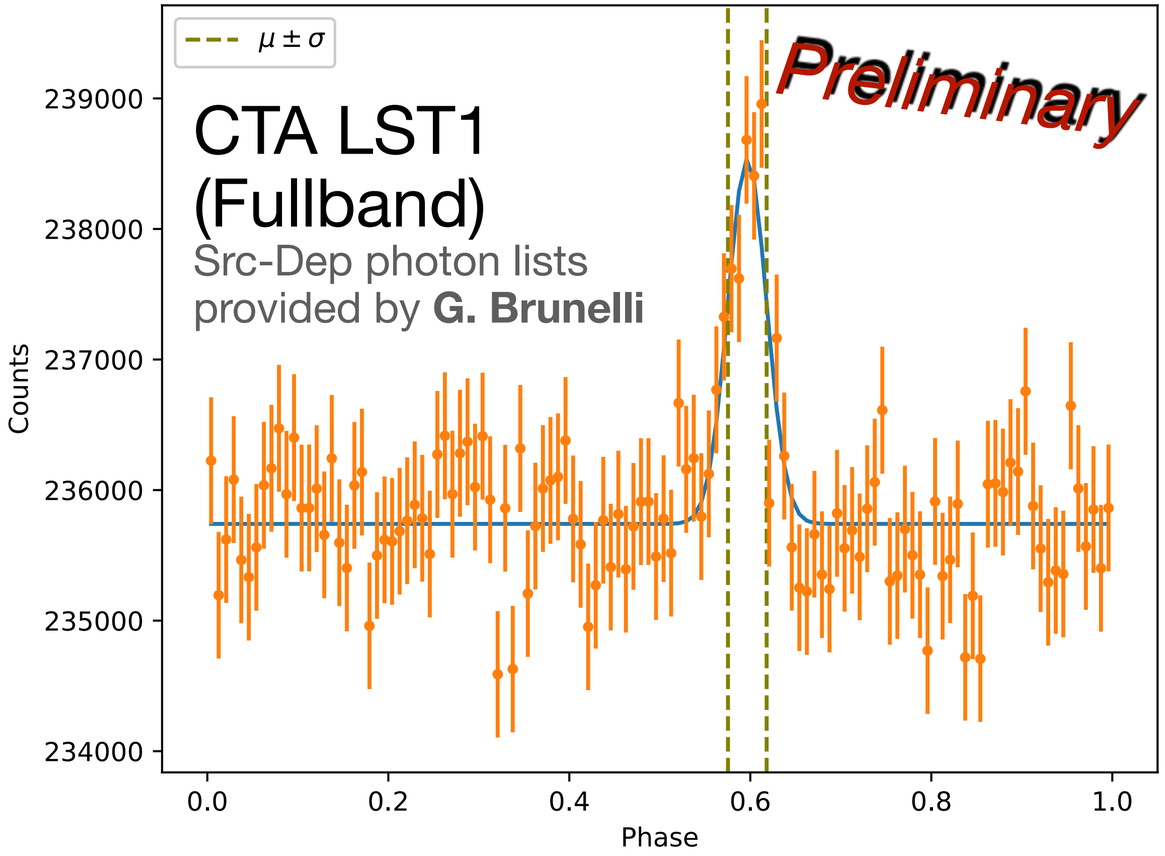
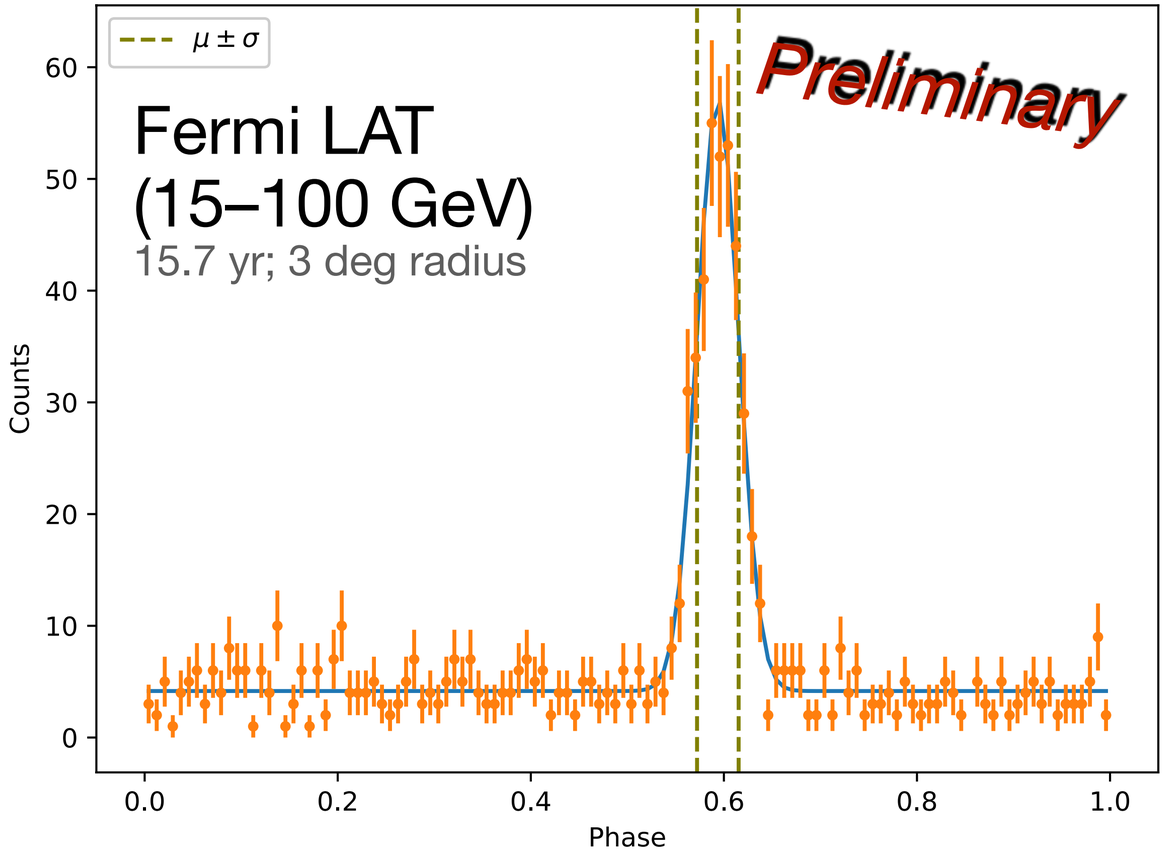
Longer than a reasonable timescale

Measuring the pulse width of P2 (Gaussian fit)





	Peak phase (μ)	stat. error	Gaussian width (σ)	stat. error
CTA LST1 (Fullband)	0.5967	0.0025	0.0214	0.0025
Fermi LAT (15–100 GeV)	0.5937	0.0014	0.0215	0.0011

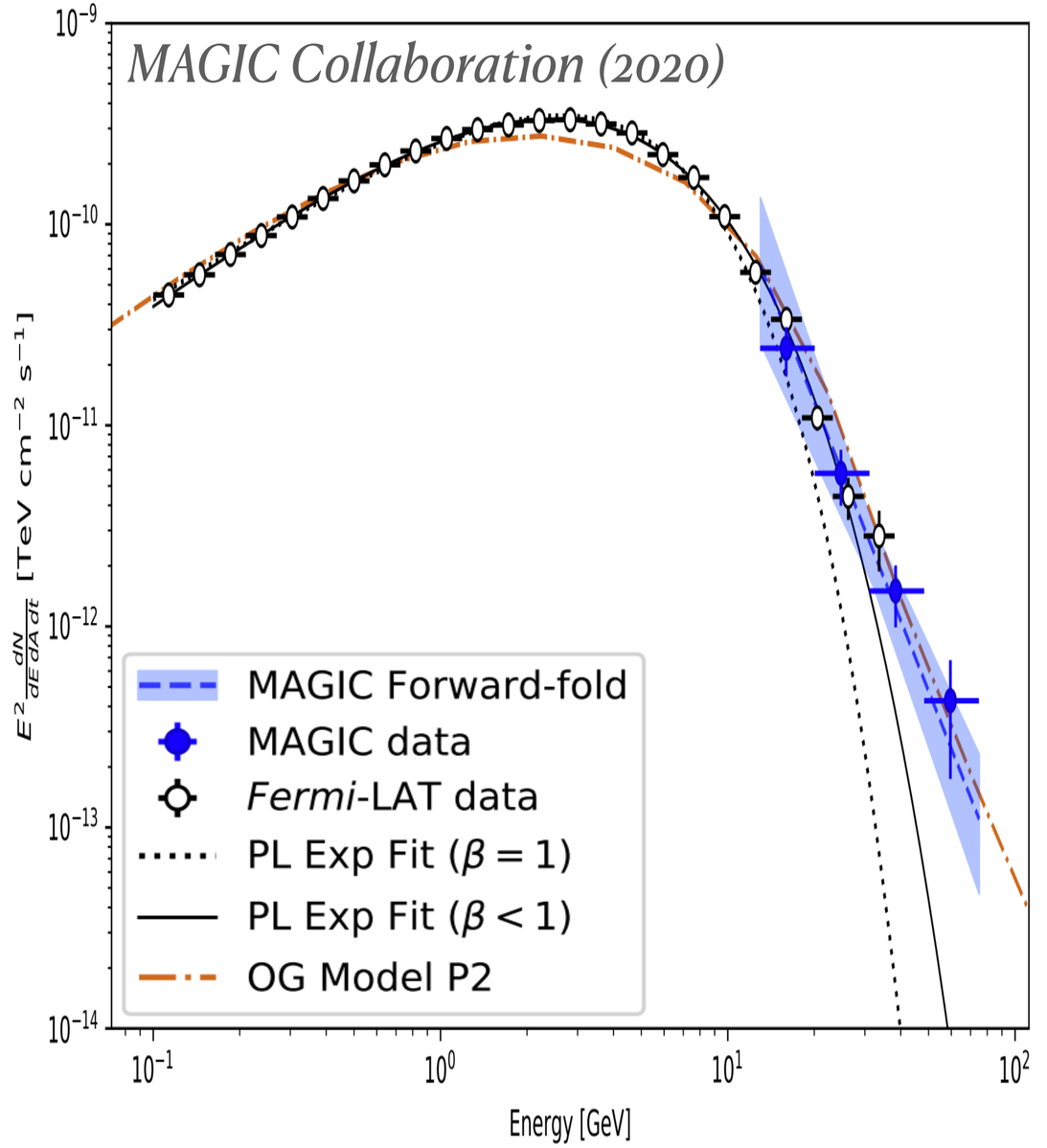
MAGIC 25—100 GeV *(G. Ceribella 2021)*: σ = 0.026 ± 0.005

Errors are purely statistical, *Not* taking into account the effects of changing bin size, data selection criteria, etc

Spectral Analyses

In progress…

- Compare MAGIC & LST1 spectra
- Joint-fit with Fermi-LAT, LST1 & MAGIC data
- Quantify the systematic error of LST1 spectral index:
  - Different cuts on source-dependent Monte-Carlo efficiency
  - Different energy scale factors
  - Changing max. Zenith-angle
- Compare the spectral shapes of Geminga pulsar with other pulsars'



Keep Calm & Study Pulsars