Extreme VHE Universe Workshop
CTA Japan 4/12/2020

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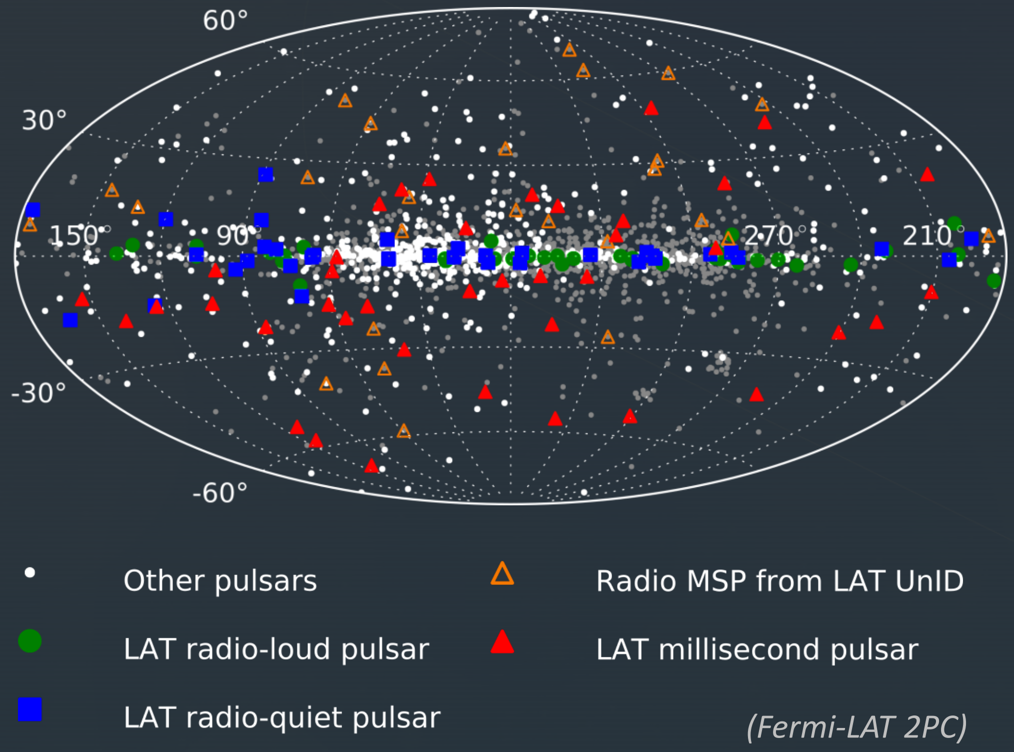
Extreme Pulsars
The MAGIC detection of Geminga

OUTLINE

- Why are **pulsars** (and **Geminga**) interesting?
- **Technical challenges**: lowering the **energy threshold** of **MAGIC**
  - Hardware: the stereo **Sum-Trigger-II**
  - Software: the **MaTaJu** cleaning
- **Very high energy** emission from **Geminga**
  - Is a new pulsar emission model required?
- **Future** perspectives

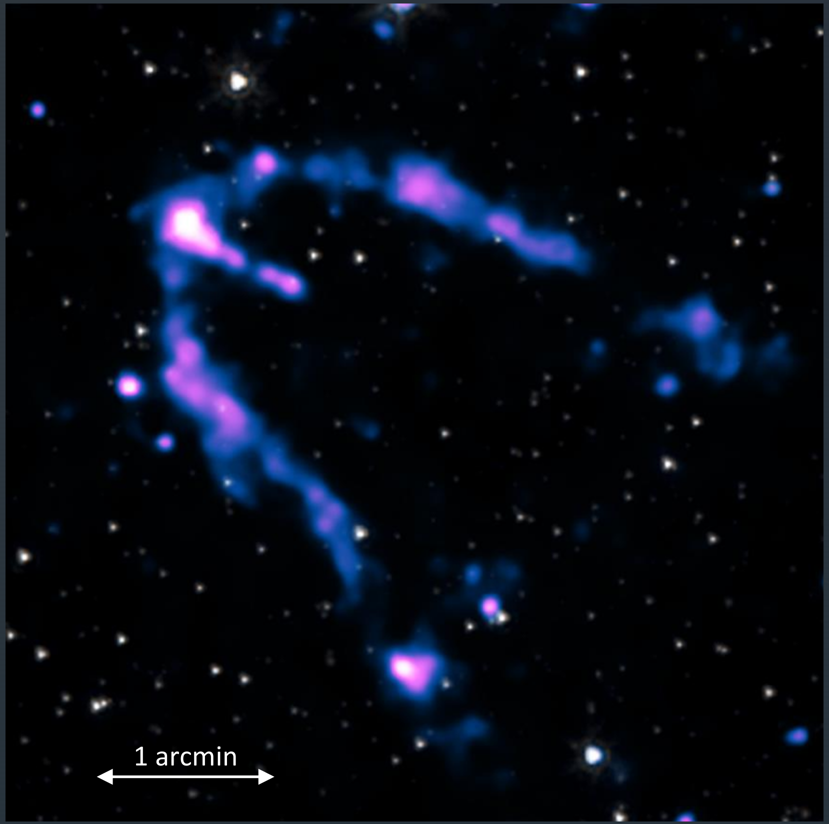
GAMMA RAY PULSARS



(Fermi-LAT 2PC)

- **Most populous galactic objects:**
  - **270** pulsars detected by Fermi-LAT (*3PC, to be published*)
  - **Only 3(+1)** detected by **IACTs** (Crab, Vela, Geminga)
- Very **compact particle accelerator**
- Magnetospheric **gamma-ray emission**
  - Curvature radiation (E<10 GeV)
  - **Inverse Compton** Scattering? (E>10 GeV)
- **Details** and physics of the emission **still debated**

GEMINGA

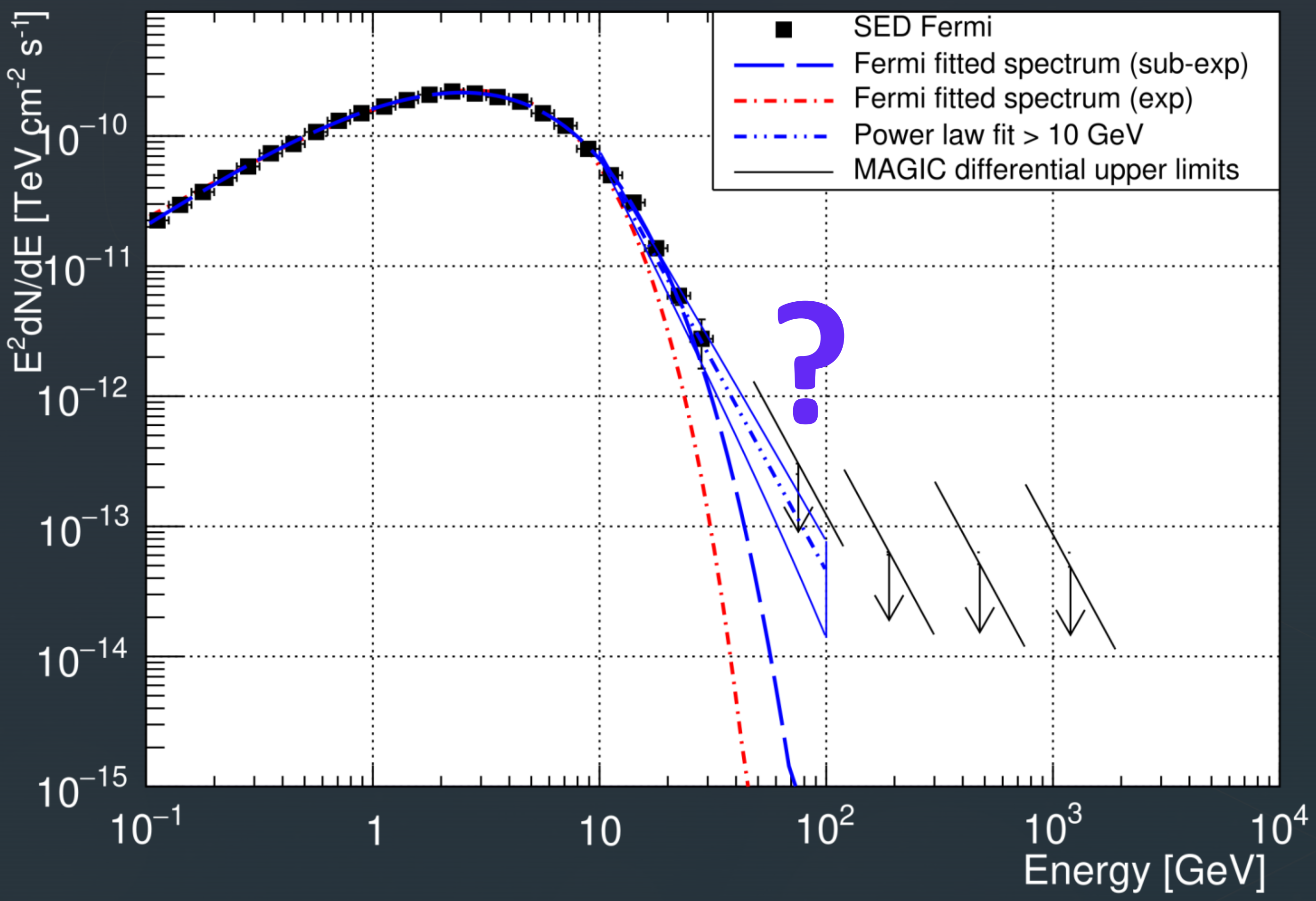


X-ray: NASA/CXC/PSU/B.Posselt et al
Infrared: NASA/JPL-Caltech

- Middle aged: **300 000 years**
- Close by: **175 – 250 pc**
- Second **brightest steady source** in the Fermi-LAT gamma-ray sky
- Embedded in a **vast TeV halo**(HAWK, Fermi-LAT):
  - **Accelerated lepton** escape
  - **Contributor** to **positron excess** at **Earth?**
- **Previous searches** by MAGIC and VERITAS

MAGIC

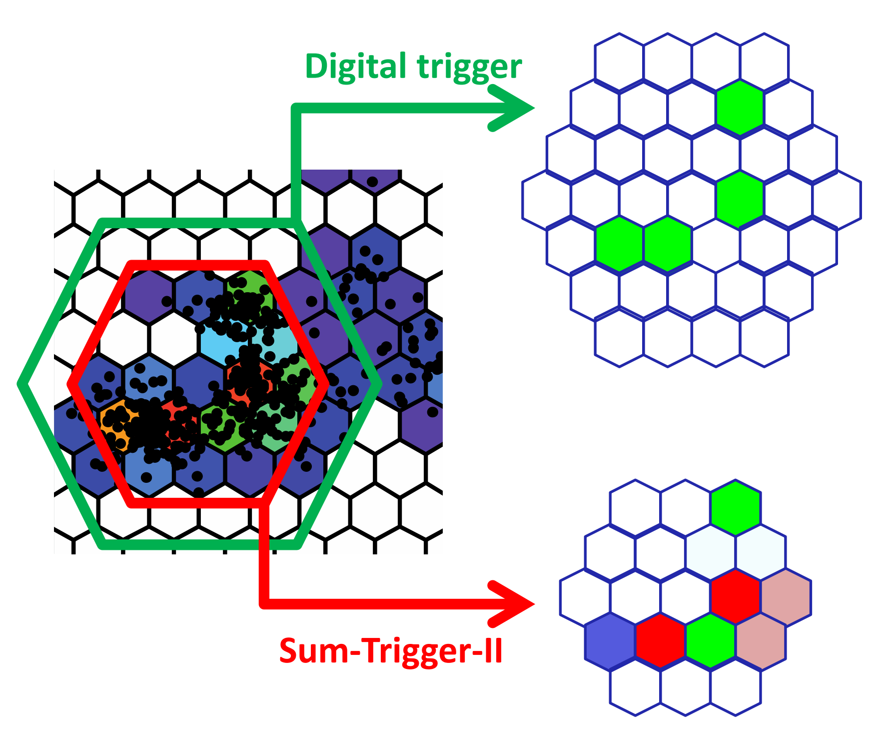
GEMINGA: PREVIOUS RESULTS



MAGIC Collaboration: Ahnen M. L., et al. (1603.00730)

LOW-ENERGY MAGIC

SUM-TRIGGER-II



MAGIC Sum-Trigger-II principle. Adapted from *F. Dazzi, 2012*

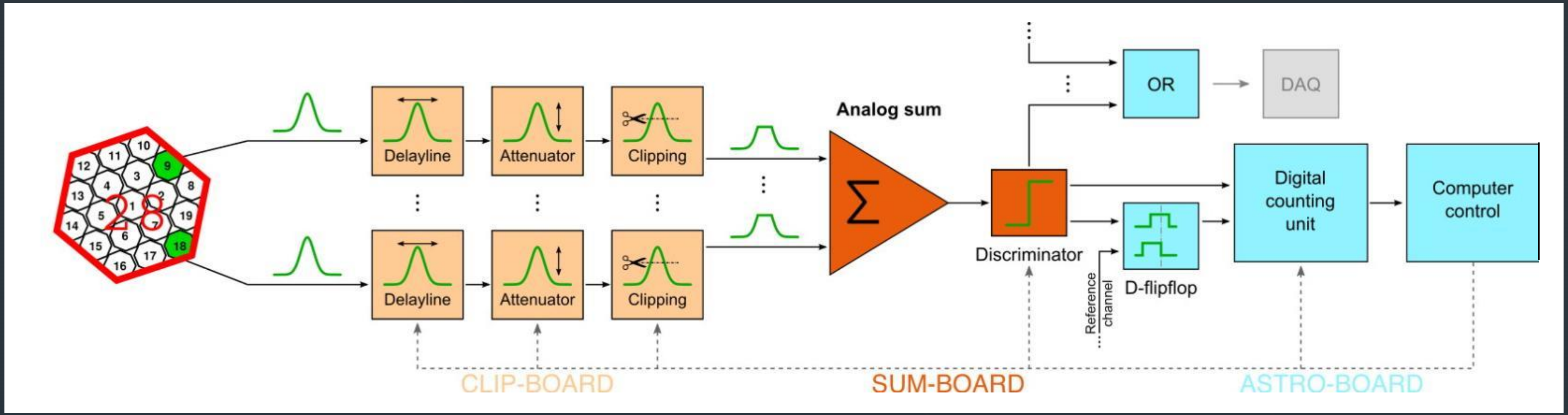
- **Stereoscopic analog trigger** for **low-energy** air showers
- **Stacking signals** of neighboring pixels
  - Increased **S/N ratio**
  - **Signal clipping** to cope with after-pulses
- 55 hexagonal patches:
  - **Overlapping** regions
  - **Global OR** as single telescope trigger
- Stereo trigger rate: **600 Hz**

SUM-TRIGGER-II

Delay/amplitude adjustment

Coping with afterpulsing

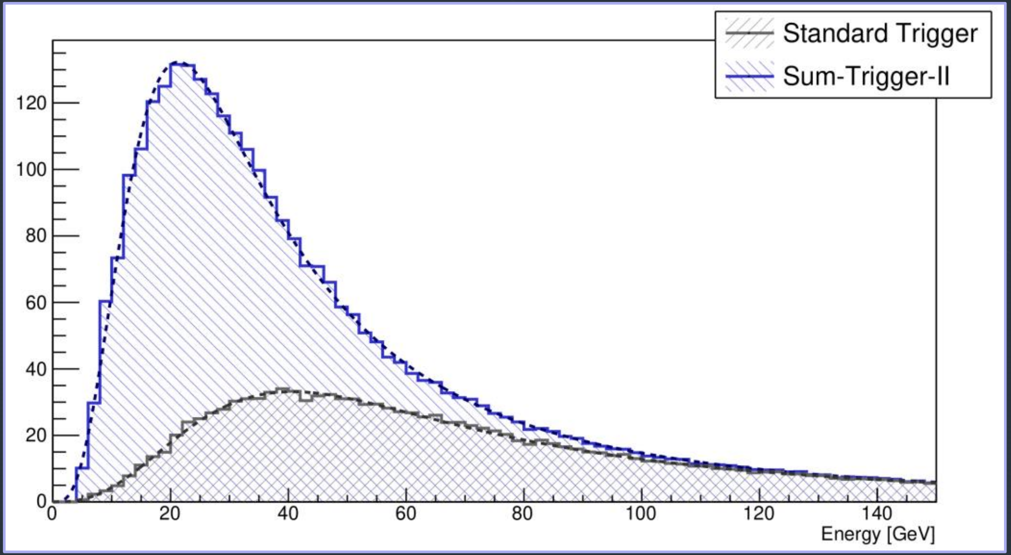
Signal sum and trigger formation



Workflow of the Sum-Trigger-II. Adapted from *F. Dazzi, 2012*.

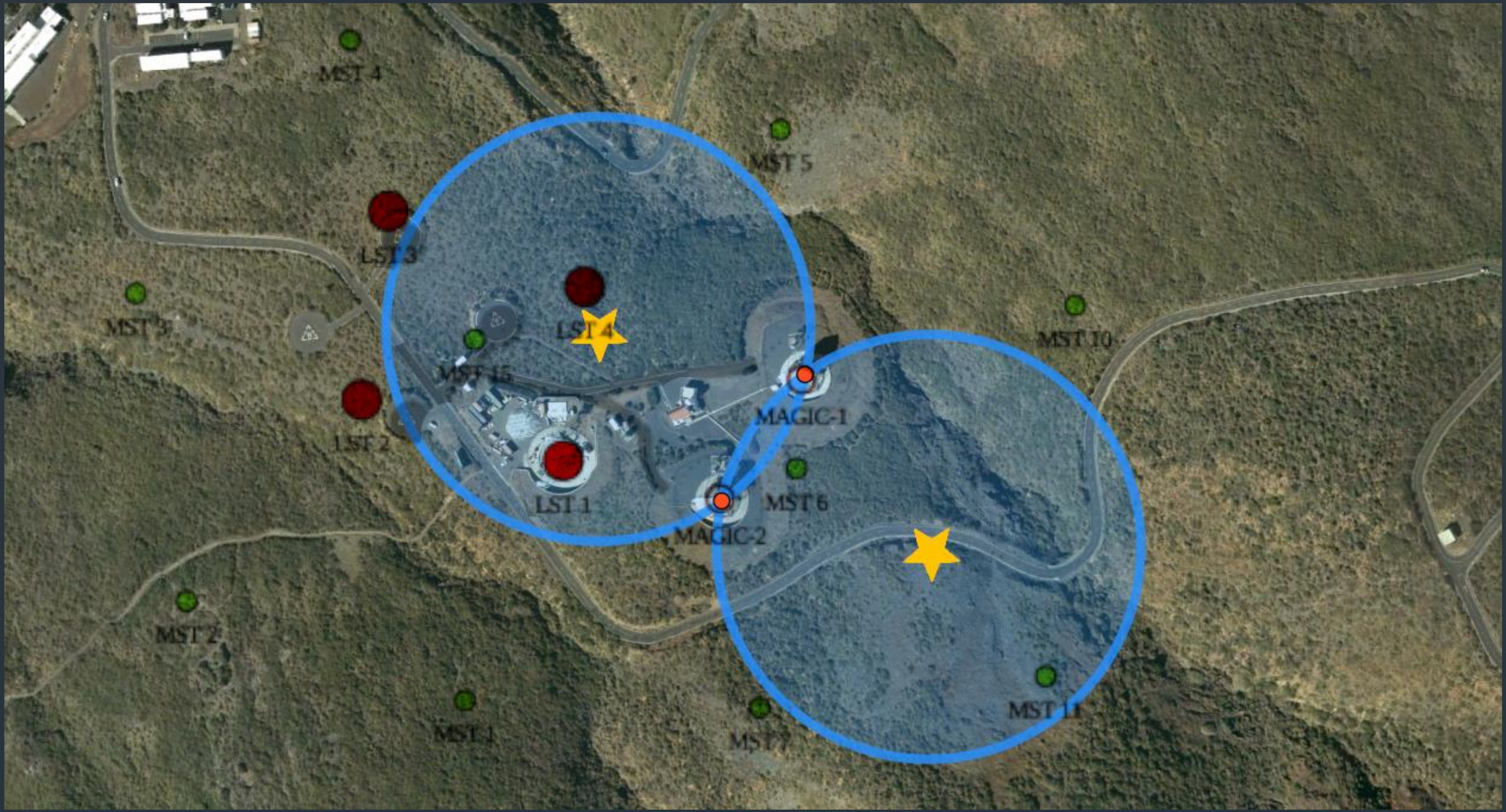
Threshold and timing controller

SUM-TRIGGER-II

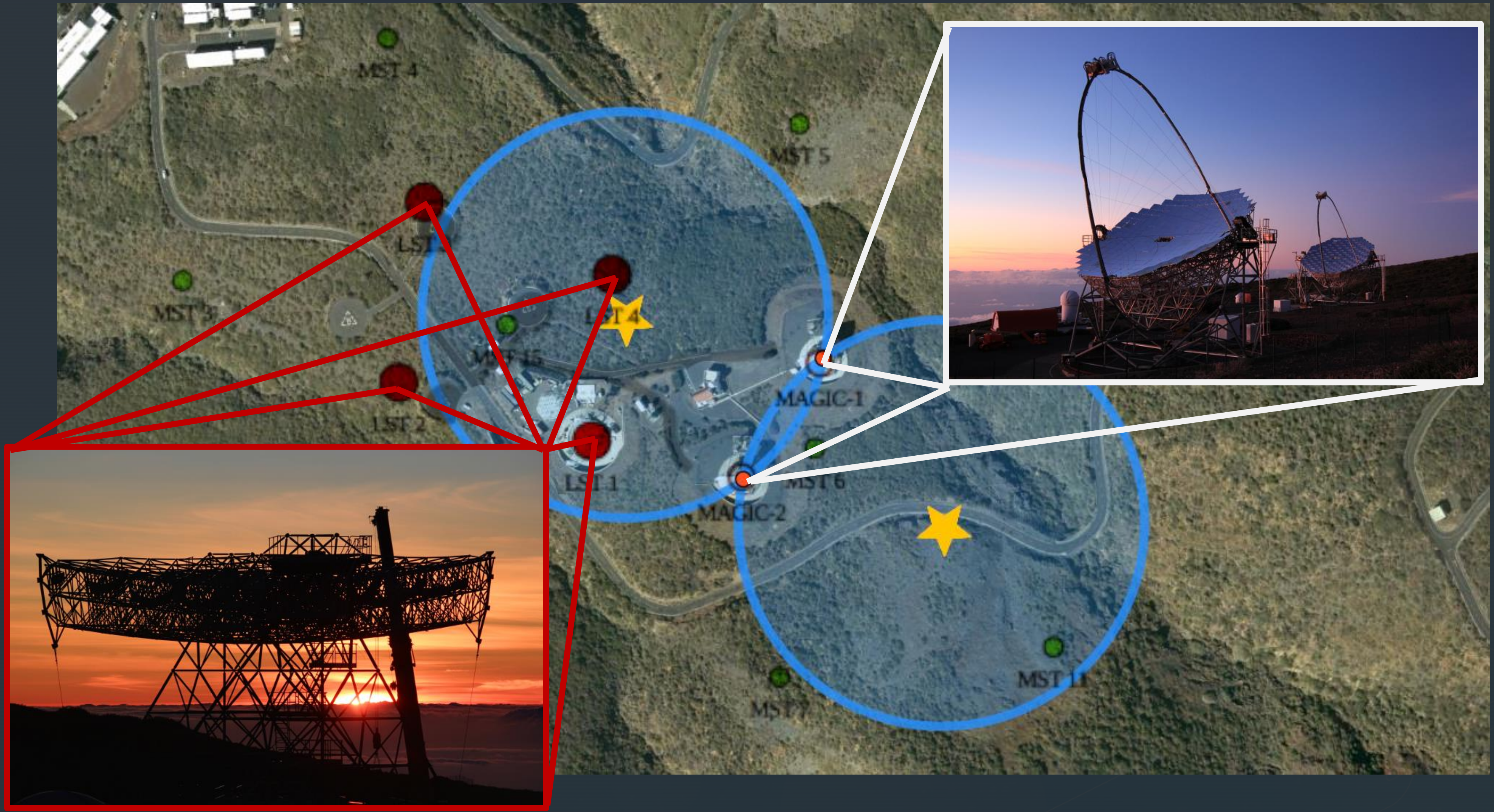


- **Energy threshold** at trigger level: **21 GeV** (for Γ=2.6)
- Useful for **pulsars**, far AGNs, GRBs
- Standard trigger: 40 GeV
- **Sweet spots** for showers with E<15 GeV:
  - Mostly **low first interaction point** (upward fluctuation in the Cherenkov light)
  - Difficult to properly **assign an energy**

SWEET SPOTS


MST 4
MST 5
LST 3
LST 4
MST 3
MST 15
MAGIC-1
MST 10
LST 2
LST 1
MST 6
MAGIC-2
MST 2
MST 1
MST 7
MST 11

SWEET SPOTS


MST 4
MST 5
LST 3
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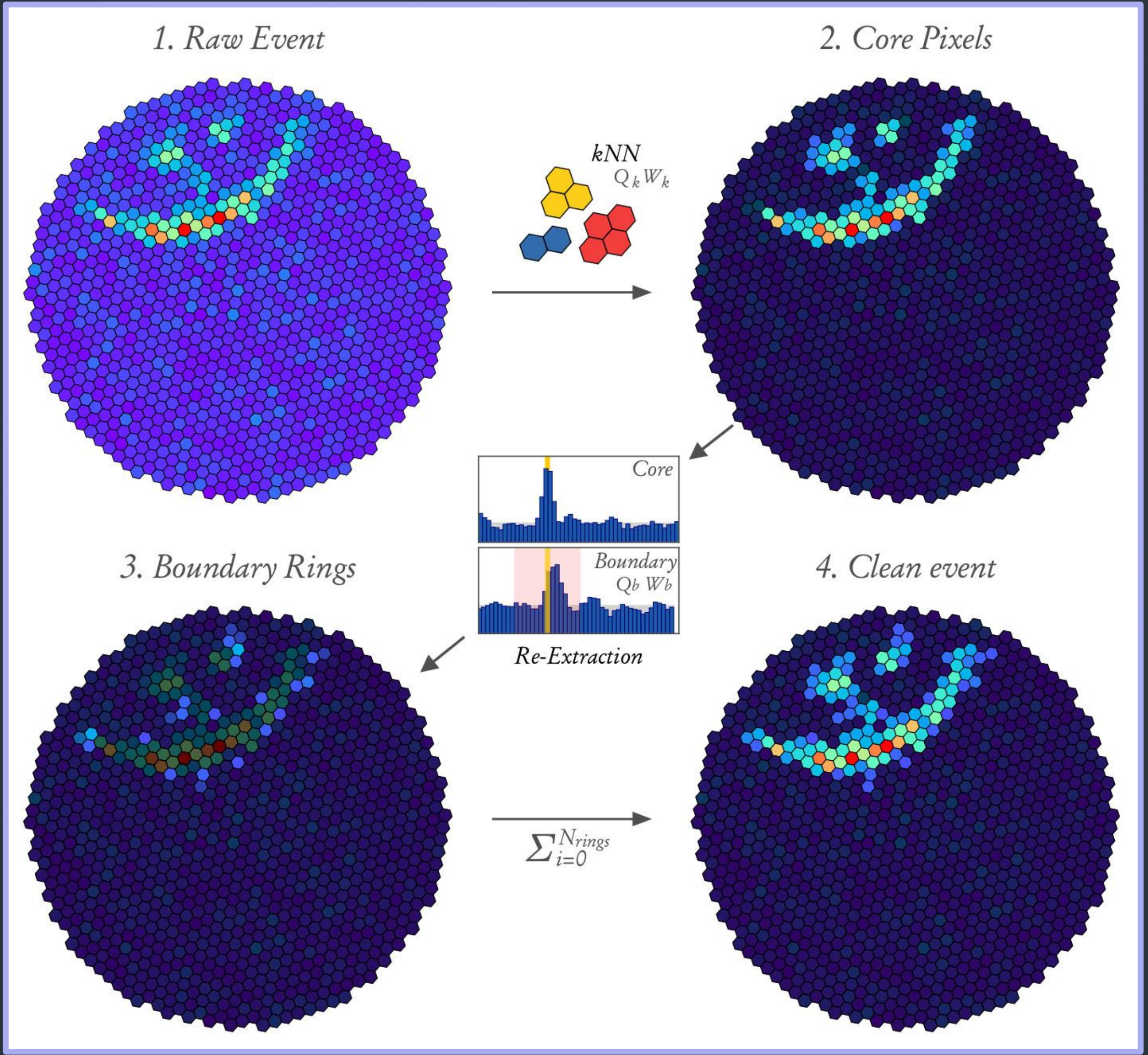
MST 3
MST 15
LST 2
LST 1
MAGIC-1
MAGIC-2
MST 6
MST 11
MST 7

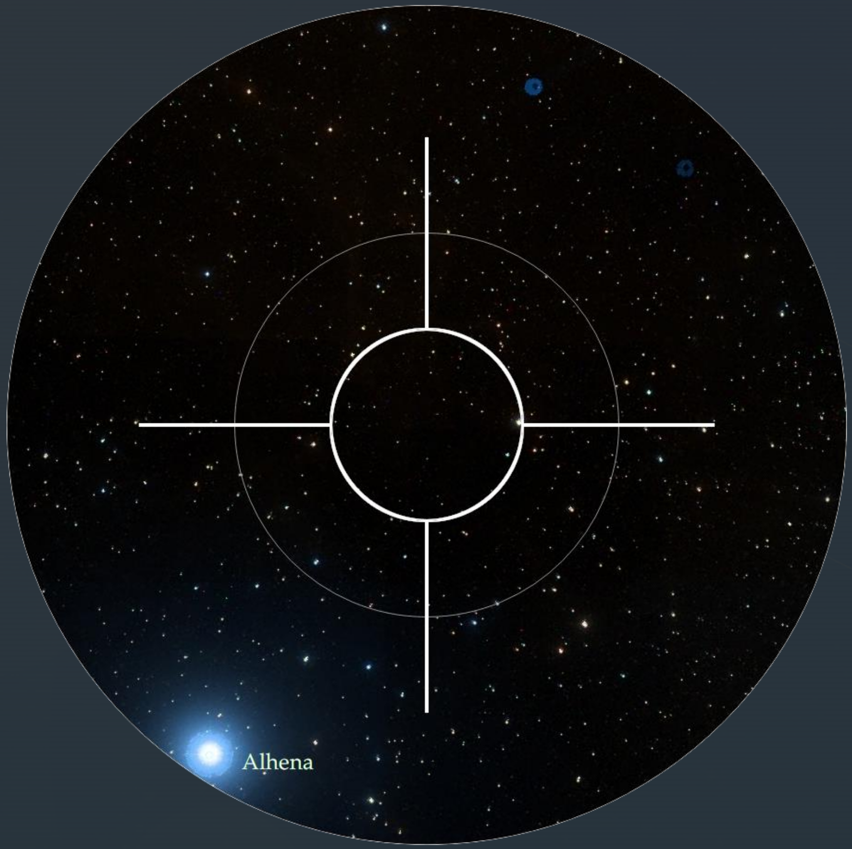
MATAJU CLEANING

- Identification of **core pixels**:
  - **kNN** groups
  - Charge and timing **thresholds**
- **Re-extraction** of **neighborhood**:
  - In coincidence with core pixels
  - Suppresses fluctuation
- **Iterative** addition of **boundary rings**



MAGIC

DATA ANALYSIS



- **Crowded field:**
  - **Light** from the **nearby star Alhena** (m=2.0)
  - Large impact on **low-energy events**
- **Bright-star** removal:
  - Circular exclusion zone : **0.4°**
  - Surviving pedestals <5%
  - **Effective area loss** modeling
- **Adaption** of quality cuts
- Energy threshold: **15 GeV**

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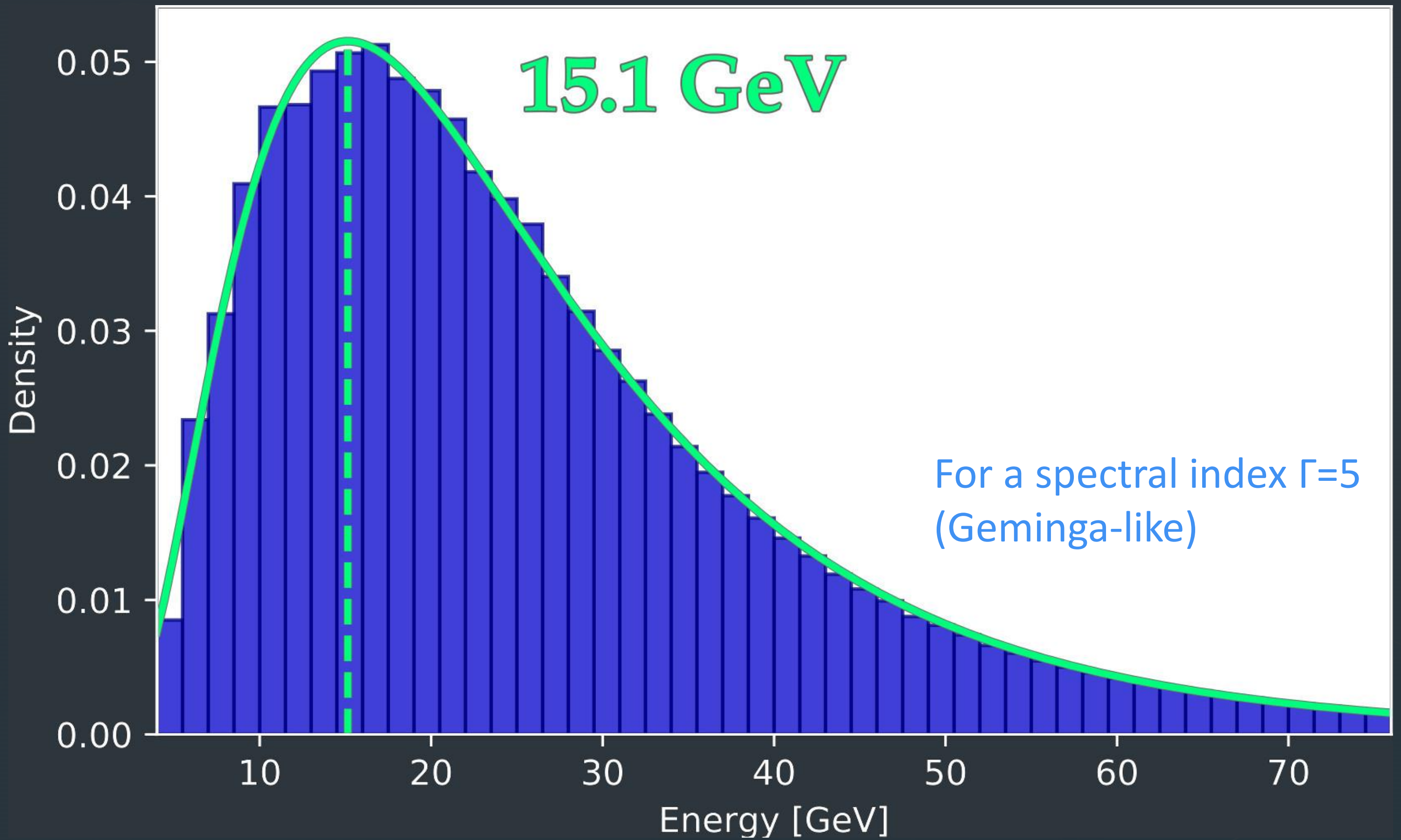
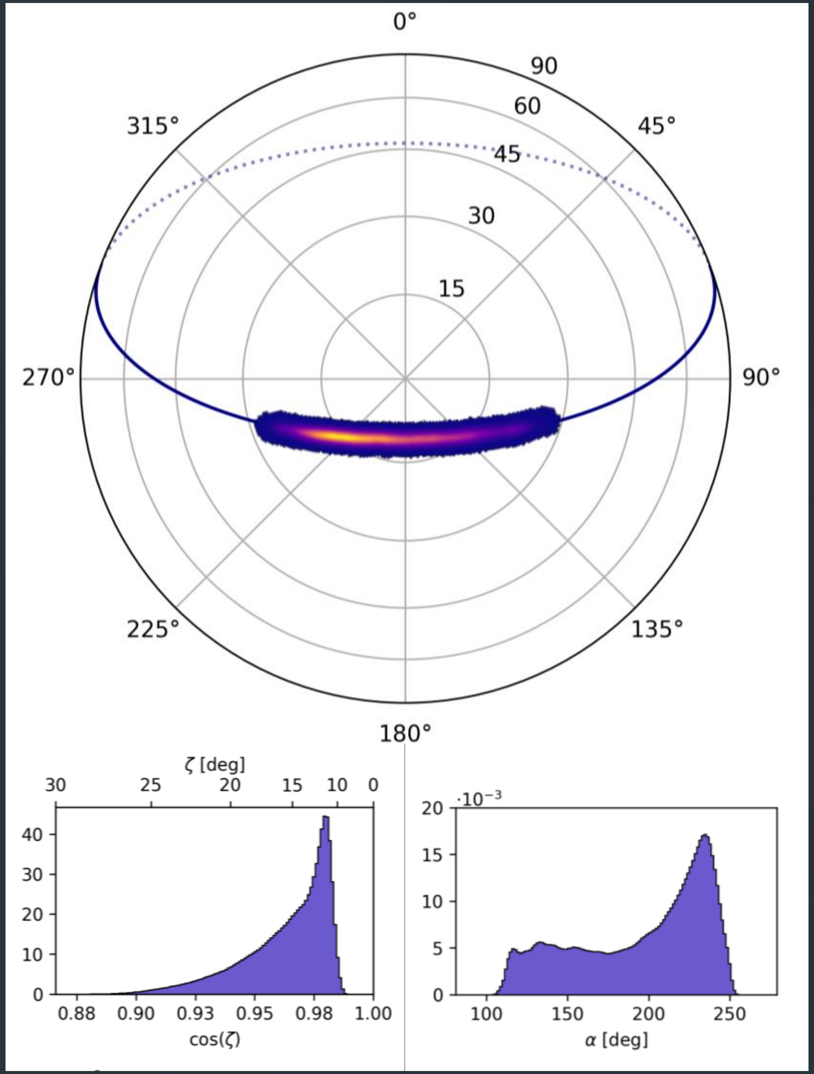
ANALYSIS THRESHOLD



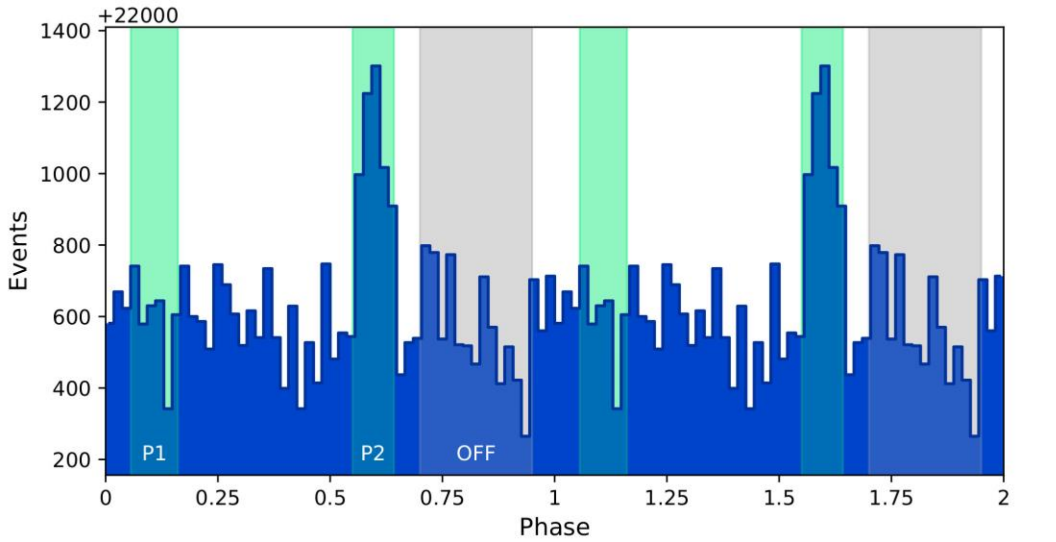
RESULTS

GEMINGA PULSAR



- **80h** of good data (2017-2019)
- Stringent **quality cuts**:
  - Low zenith: **$\zeta < 25$ deg**
  - **LIDAR** Transmission > 0.9
  - **L3 Rates** > 500 Hz
- Contemporaneous **Crab Pulsar/Nebula** observations
- **Pulsar ephemeris** with Fermi-LAT data

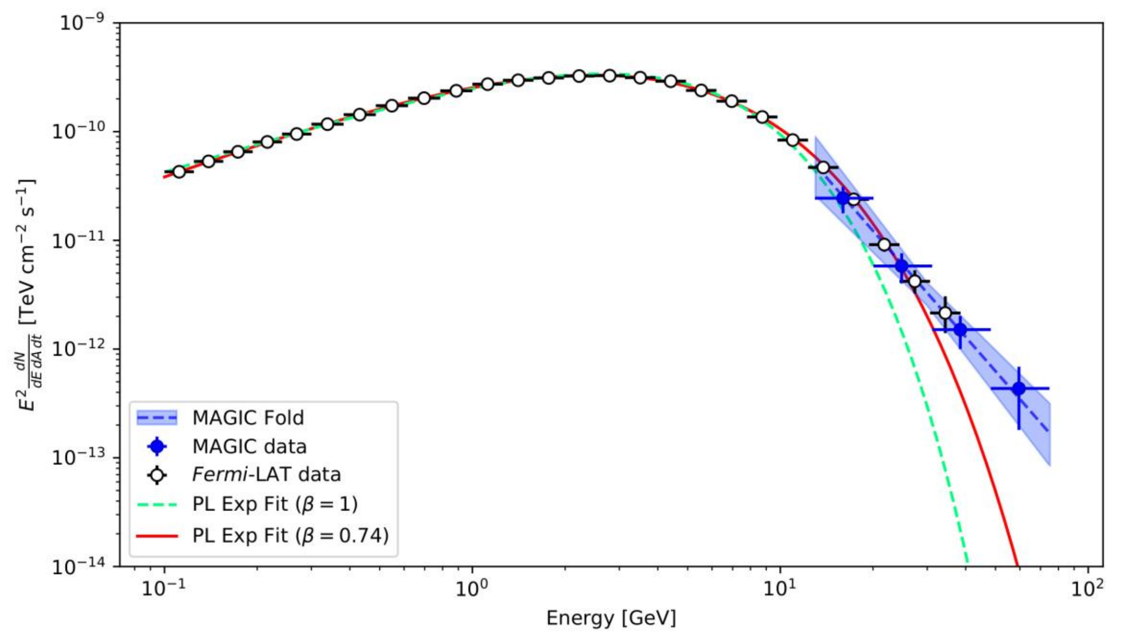
GEMINGA PULSAR



- **First detection** of Geminga from the ground, at **E>15 GeV**
- **Third VHE pulsar**
  First middle-aged one
- **Detection** significance**: 6.3σ**
  - In phase with Fermi-LAT P2
- **A&A Highlight** letter 2020: MAGIC Collboration: Acciari V, et al. (2011.10412)

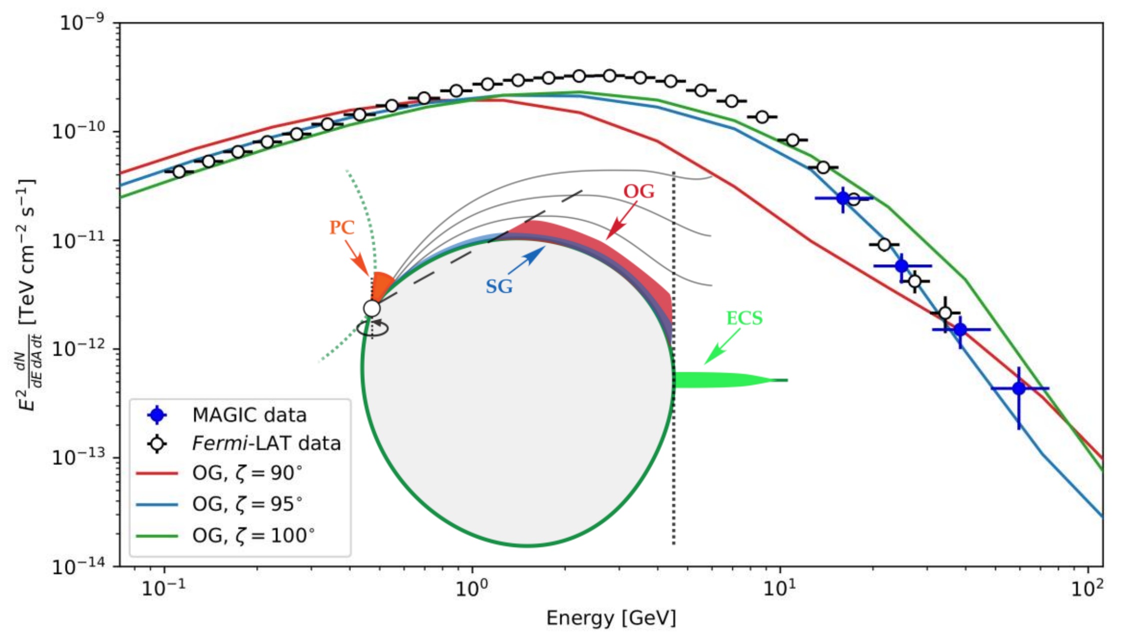
https://ui.adsabs.harvard.edu/abs/2020A%26A...643L..14M/abstract

GEMINGA PULSAR



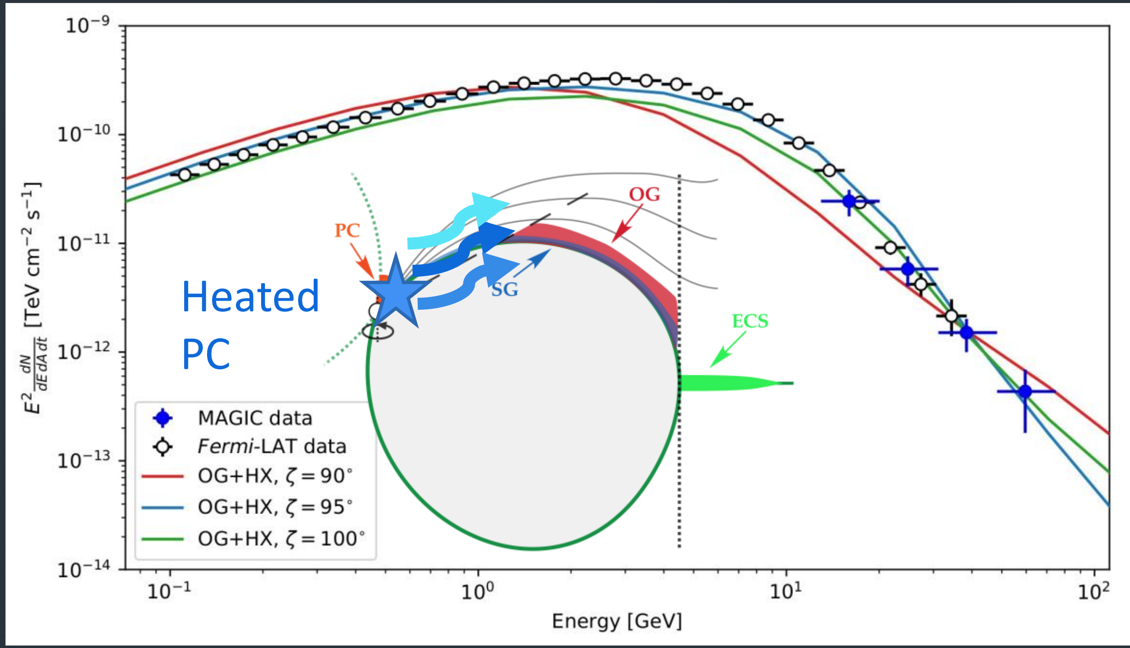
- **VHE Spectrum** is a **Power-Law**
  - Steep spectral index **Γ=5.2**
- Overlapping with **Fermi-LAT** measurements (E<40 GeV)
- **No hint** for a **cutoff**
  - **Exponential cutoff** ruled out
  - **Sub-exponential** in tension at **3.5σ level**
- **Inverse-Compton component?**

GEMINGA PULSAR



- **Modeling** with the **Outer Gap:**
  - **IC** with **in-going electrons**
- **Observations challenge** the model:
  - Contribution from **heated polar cap**? (Caraveo et al., 2004)
  - **Review of the model** needed
- How is it **related to other pulsars**?

GEMINGA PULSAR



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SUMMARY AND MORE

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SUMMARY

- The **MAGIC Telescopes** extended their range in the **10 GeV – 100 GeV** domain:
  - Hardware developments: **Sum-Trigger-II**
  - Software improvements: **MaTaJu cleaning**
- Achieved lowest **energy threshold: 15 GeV** (Γ=5)
- **First detection** of the **Geminga** pulsar with **IACTs**:
  - **Third VHE pulsar** in the sky (first “middle-aged” one)
  - **Power-law spectrum** extending up to 75 GeV, no hint for a **cutoff**
- **Inverse Compton** component in the Geminga spectrum?
  - Requires **a review** of current **theoretical models**

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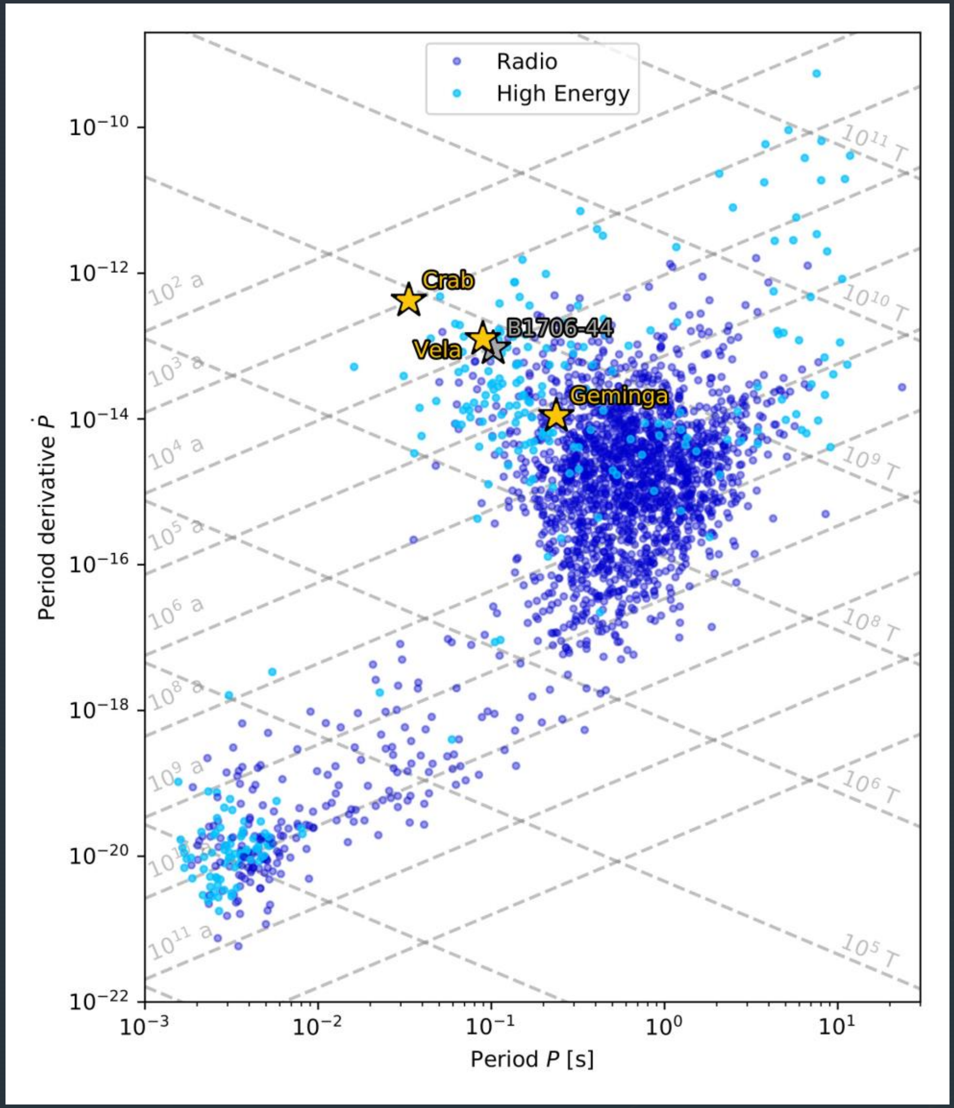
PULSARS DIAGRAM

- **Three known VHE Pulsars** (fourth one recently announced by H.E.S.S)
- Enlargement of the VHE pulsar family
- Still plenty of space to explore…



PULSARS & LST

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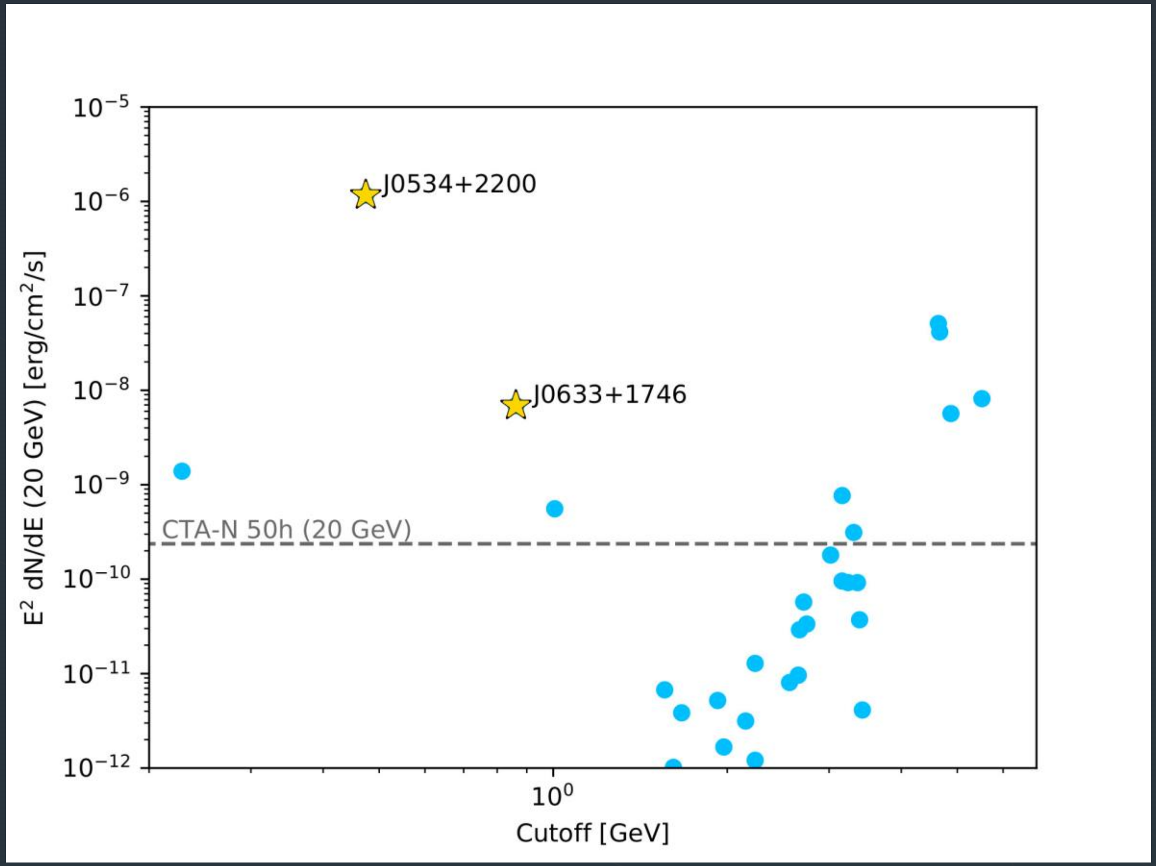


REFERENCES

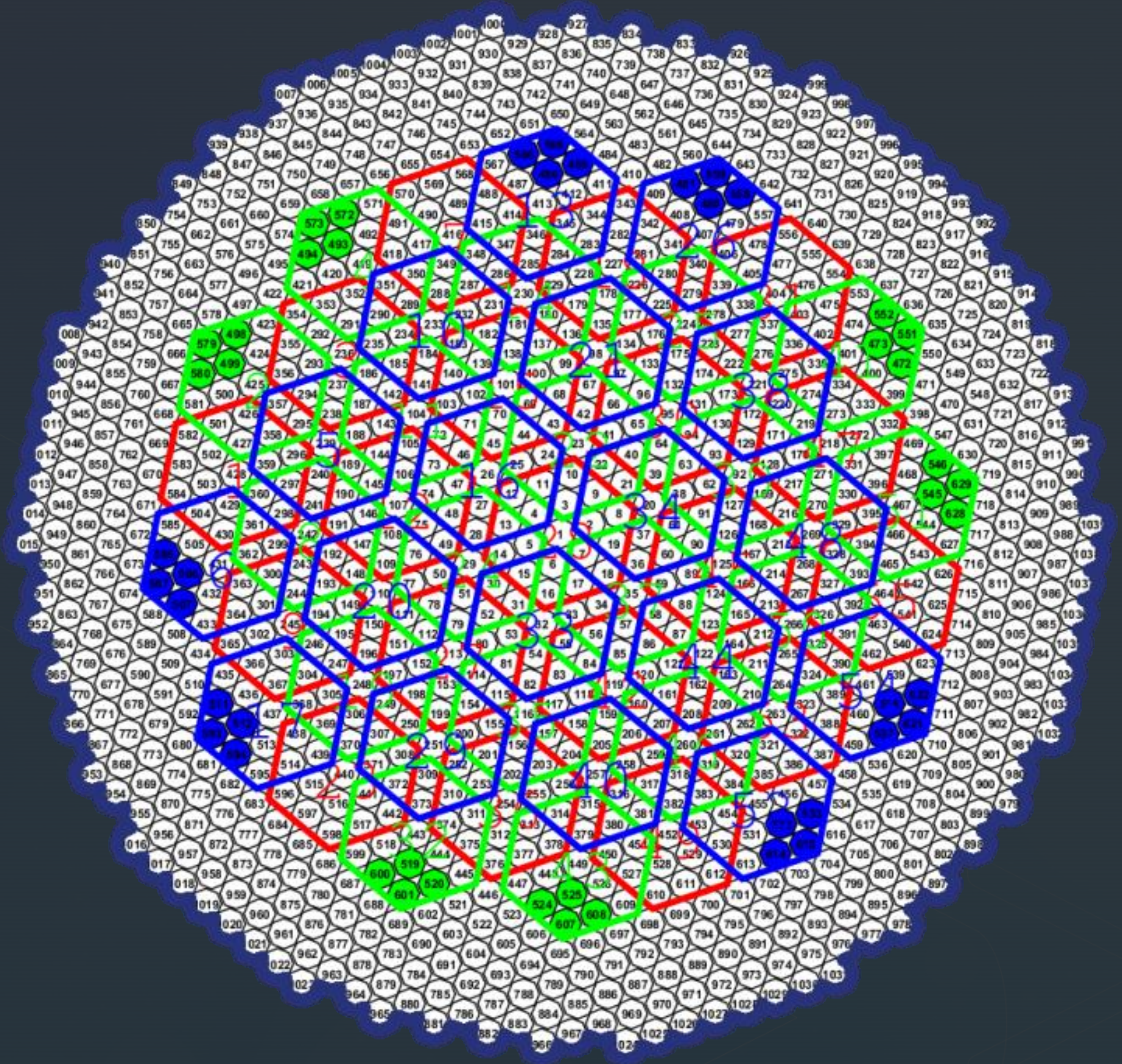
- MAGIC Collaboration: Acciari V. et al., "**Detection of the Geminga pulsar with MAGIC hints at a power-law tail emission beyond 15 GeV**" (2011.10412)
- MAGIC Collaboration: Ahnen M. L. et al., "**Search for VHE gamma-ray emission from Geminga pulsar and nebula with the MAGIC telescopes**" (1603.00730)
- VERITAS Collaboration: Aliu E. et al., "**A Search for Pulsations from Geminga Above 100 GeV with VERITAS**" (1412.4734)
- FERMI-LAT Collaboration: Abdo A. A. et al., "**Fermi LAT observations of the Geminga pulsar**" (1007.1142)
- Abeysekara A.U. et al., "**Extended gamma-ray sources around pulsars constrain the origin of the positron flux at Earth**" (1711.06223)
- Di Mauro M. et al., "**Detection of a γ-ray halo around Geminga with the Fermi-LAT and implications for the positron flux**" (1903.05647)
- Caraveo P.A. et al., "**Phase-resolved spectroscopy of Geminga shows rotating hot spot(s)**" (0407402)

MAGIC

… do you really want more?!

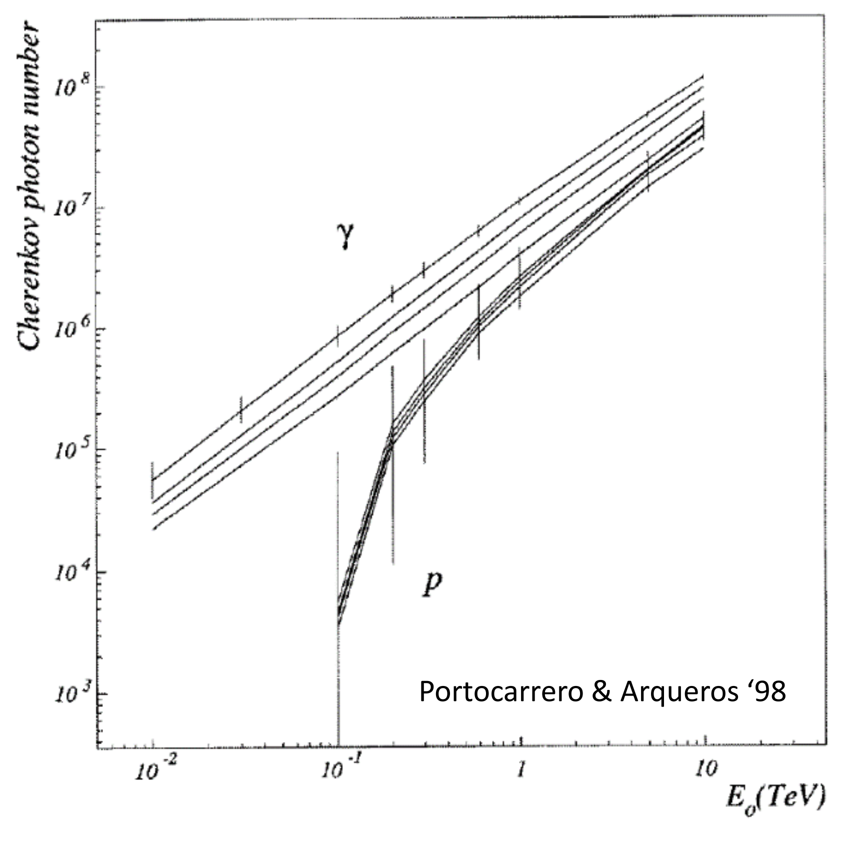
BACKUP

Sum-Trigger-II macrocell layout



ULTRA-LOW ENERGY SHOWERS

- **Events well below 20 GeV** in the steep slope of the **effective area.** A_{eff}(<10 GeV) = $\mathbf{2.8 \cdot 10^3\ m^2}$. To check whether they are real or not, I produced a very long series of diagnostic plots.
- At **10GeV** one expects **0.5 Cherenkov photons per square meter**. With 230 m^2 we should get **100 photons** and accounting for a 10% efficiency we get **10 PhE**.
- An **upward fluctuation** may bring this higher. Also showers may **randomly interact lower in the atmosphere**, and NSB summed on top of showers could bring them up.
- Check **Height of the first interaction**, **Number of photons from the shower**, **Impact parameter, Core position**. Again, one needs to do a full ON-OFF like the one for the threshold.

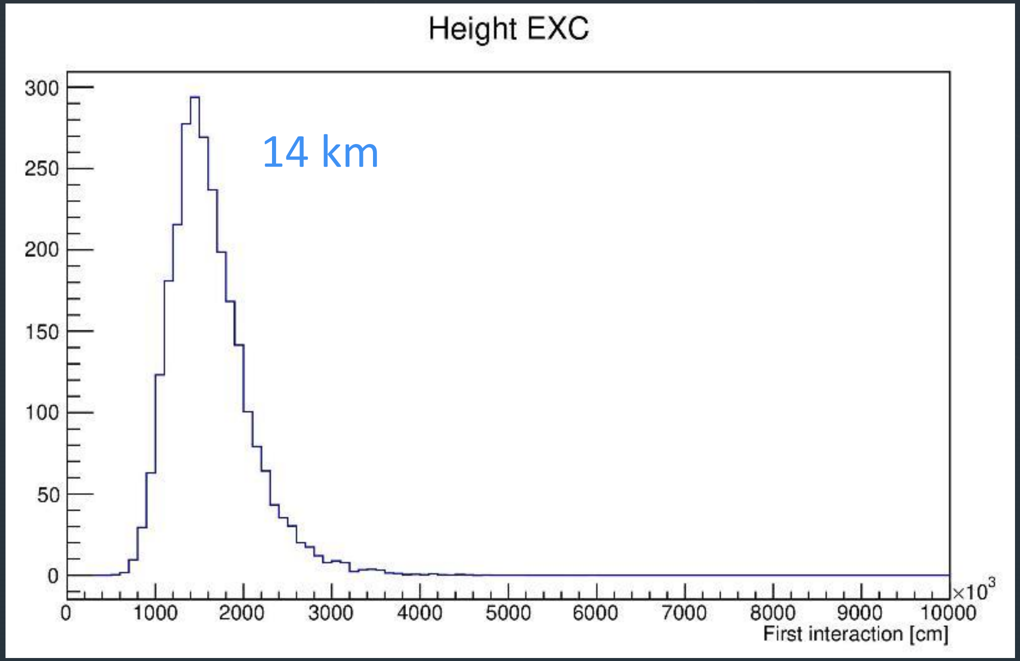


Portocarrero & Arqueros ‘98

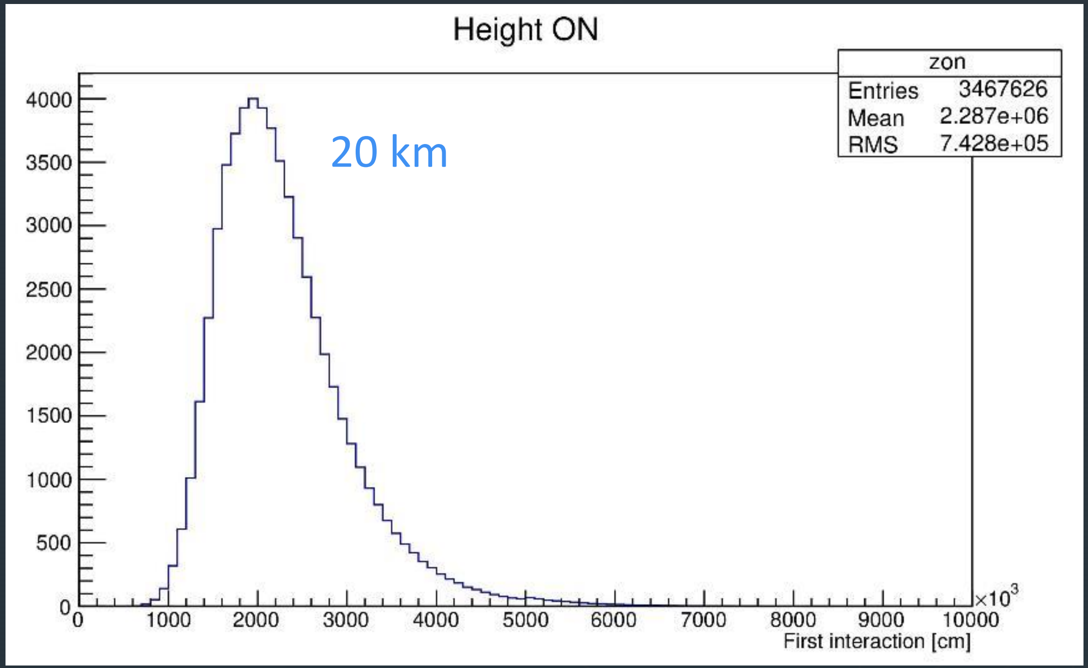
Z FIRST INTERACTION

Triggered Low-Energy gamma showers interact **deeper in the atmosphere** than regular ones

ULTRA LOW ENERGY E < 12 GeV



FULL RANGE E < 500 GeV



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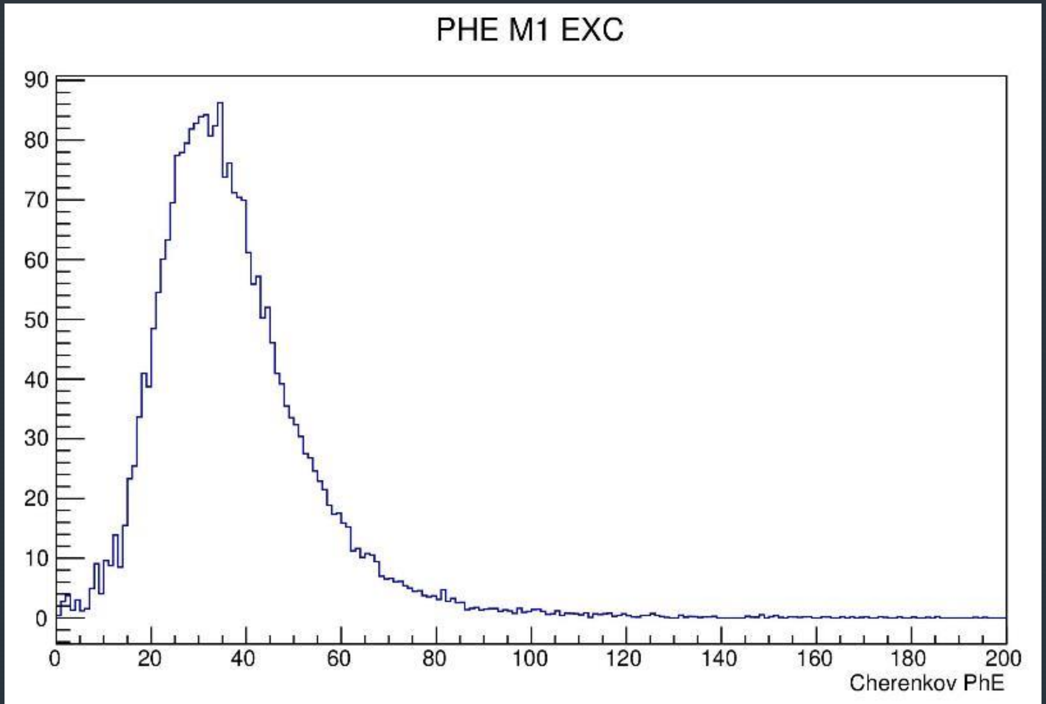
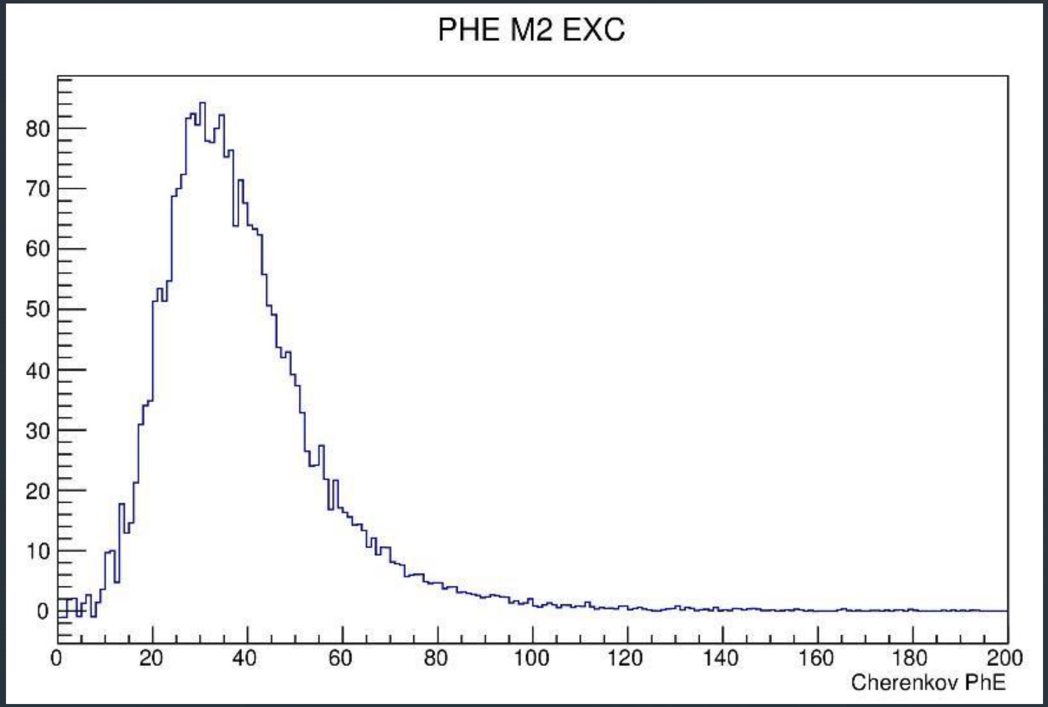
CHERENKOV PHE COUNTS





Cherenkov photoelectron count is on average **30 PhE = 3×Expected**. Combined effect of lower interaction and lucky impact (see later). Plots for **E < 12 GeV**

LIGHT DENSITY IN THE CHERENKOV POOL

Portocarrero & Arqueros '98

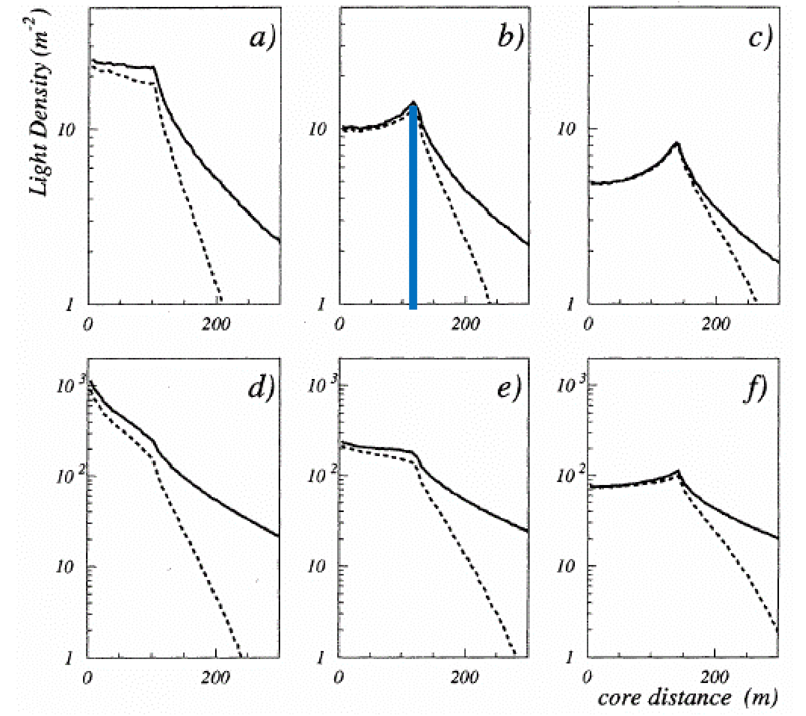
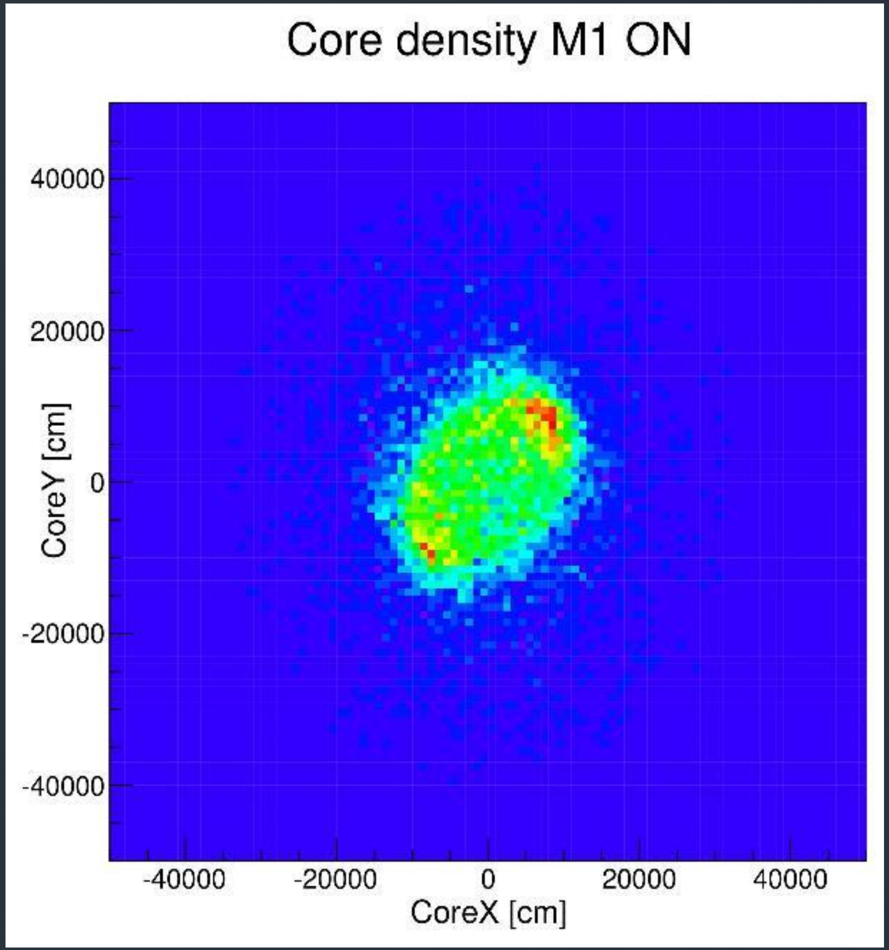


Figure 5. Lateral distribution for all Cherenkov photons (full curves) and for those with a zenith angle lower than 1.4 degrees (broken curves) for vertically incident γ-ray showers of 0.1 TeV at: (a) 600 g cm^{-2}; (b) 800 g cm^{-2}; and (c) sea level; and of 1 TeV at: (d) 600 g cm^{-2}; (e) 800 g cm^{-2}; and (f) sea level.

- Take the middle column for MAGIC & LST
- The light density at the external "light-ring" at 10 GeV can be 50% larger than in the center.

CORE POSITIONS

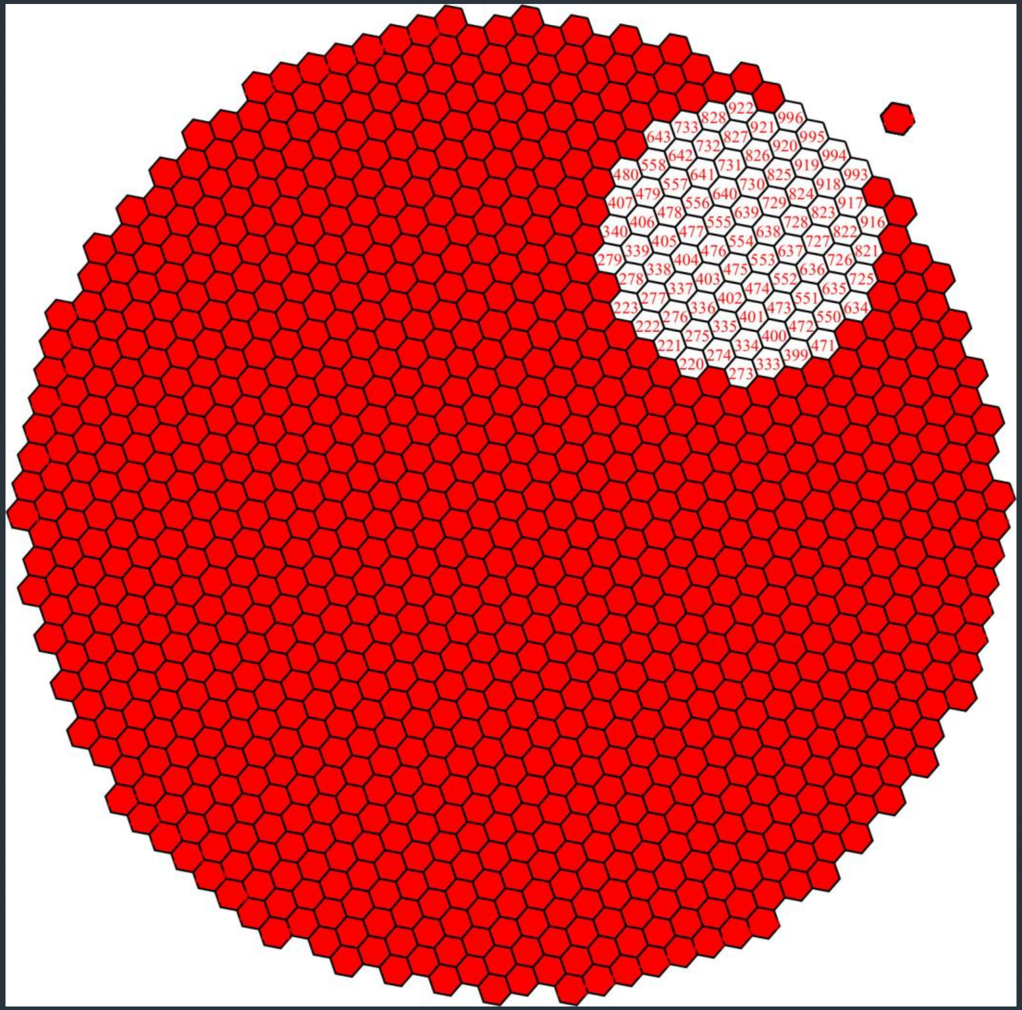


- **Excess plot**
- Stereo triggers are preferably clustered in the **lucky spots where the Cherenkov light ring passes through both telescopes.**
- **“Ring of light”**

MAGIC

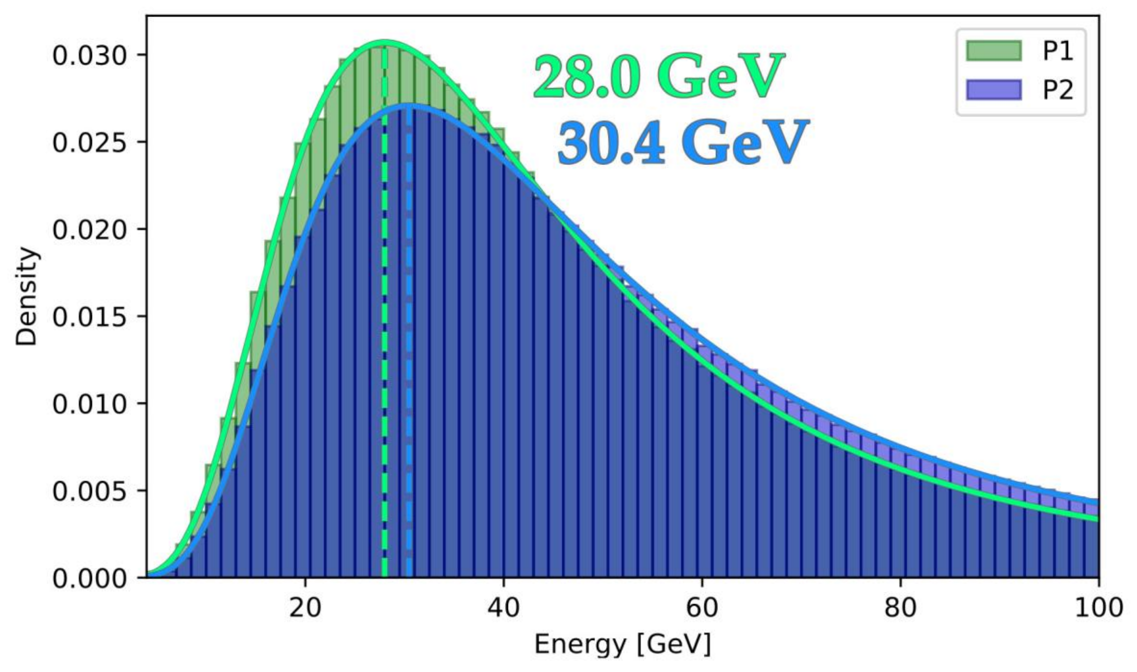
STAR REMOVAL

The bright star Alhena (m=2) requires a very large exclusion zone (R=120mm / 0.5 deg) to remove its effect on surviving pedestals

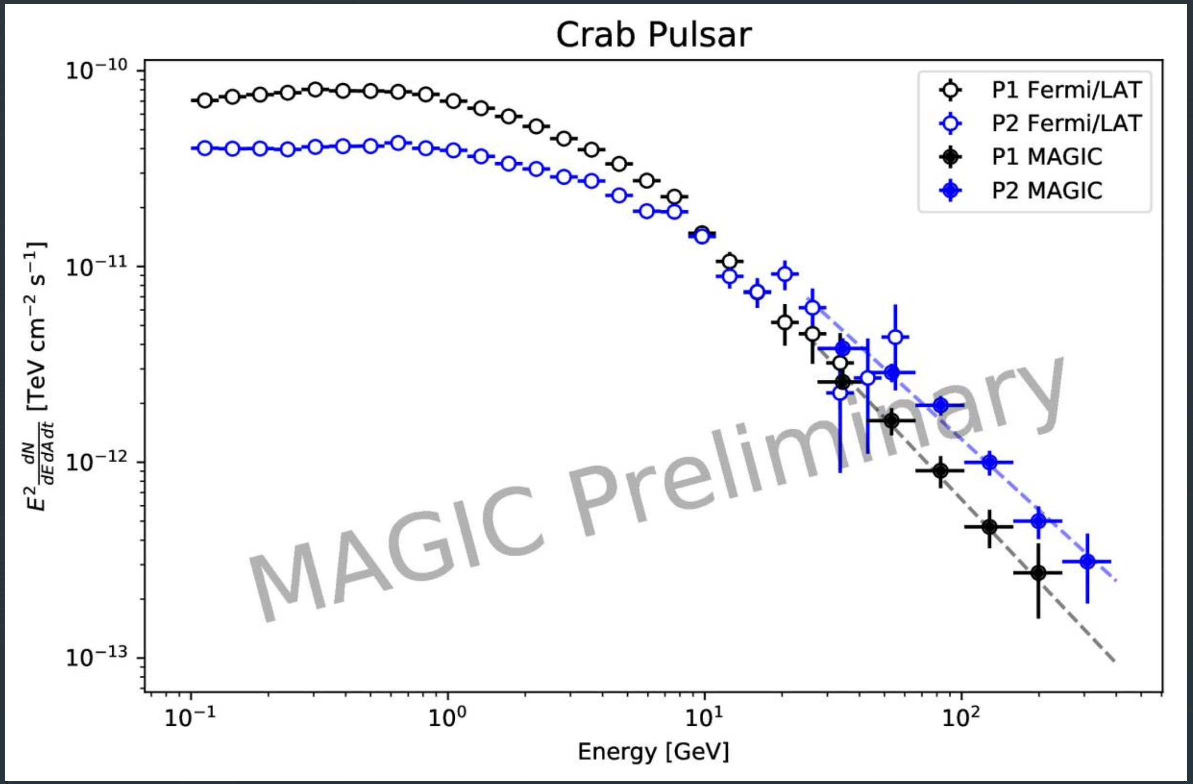


THRESHOLD FOR THE CRAB PULSAR

- **P1** Γ=3.5 : 28 GeV
- **P2** Γ=3.2 : 30 GeV
- «NEB» Γ=2.6 : 37 GeV



CRAB PULSAR SPECTRA



- Spectra reconstructed down to **27 GeV**
- Spectral indices:
  - **P1: -3.38 ± 0.15**
  - **P2: -3.20 ± 0.09**
- Smoothly **joining** with **Fermi-LAT** measurements
- No significant feature, **power law continuation**

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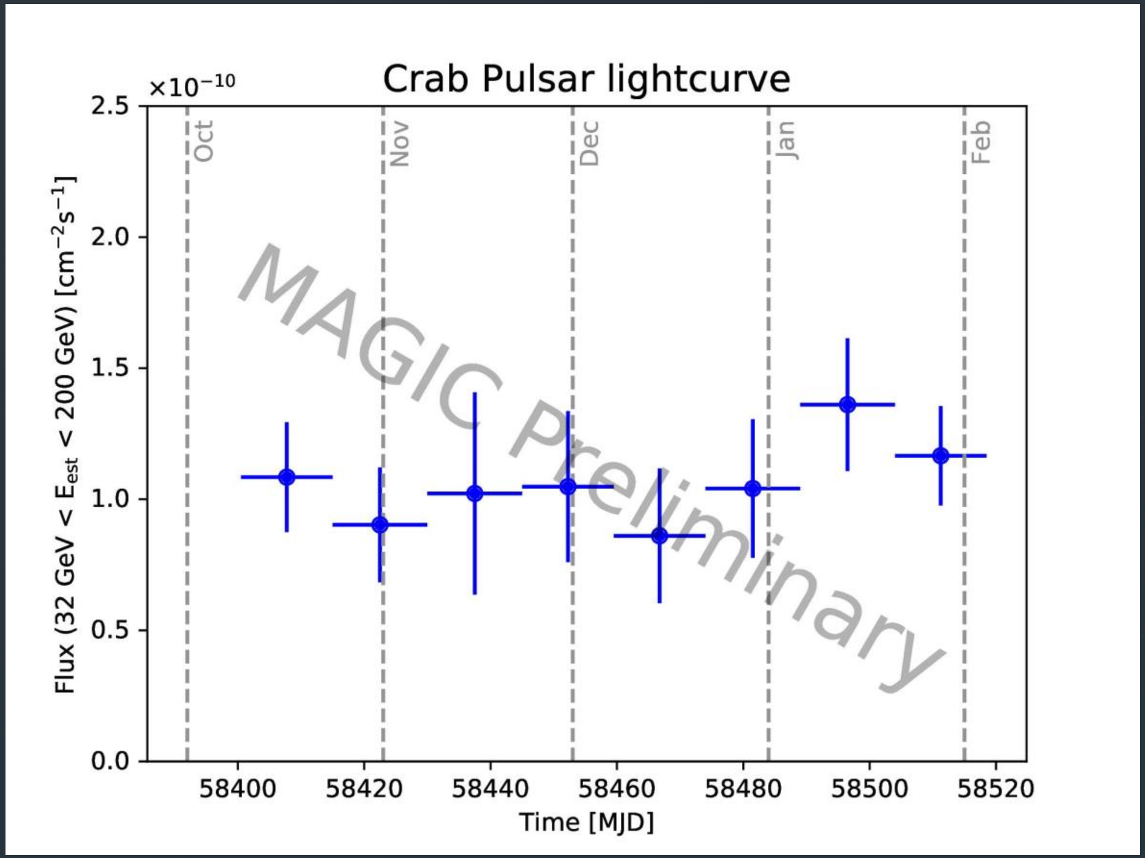
CRAB PULSAR LIGHTCURVE



- Sound statistics allows to **monitor** the **pulsed emission** over time
- Crab pulsed flux over **4 months** in **2-week bins**
- **Flux** (30 – 200 GeV) consistent with **steady emission**:

Flux = $(1.07 \pm 0.09) \times 10^{-10}\ cm^{-2}s^{-1}$

$\chi^2/_{NDF}$ = 2.9/7 (**0.1σ**)