GEMINGA AND MAGIC
THE RETURN OF THE PULSAR

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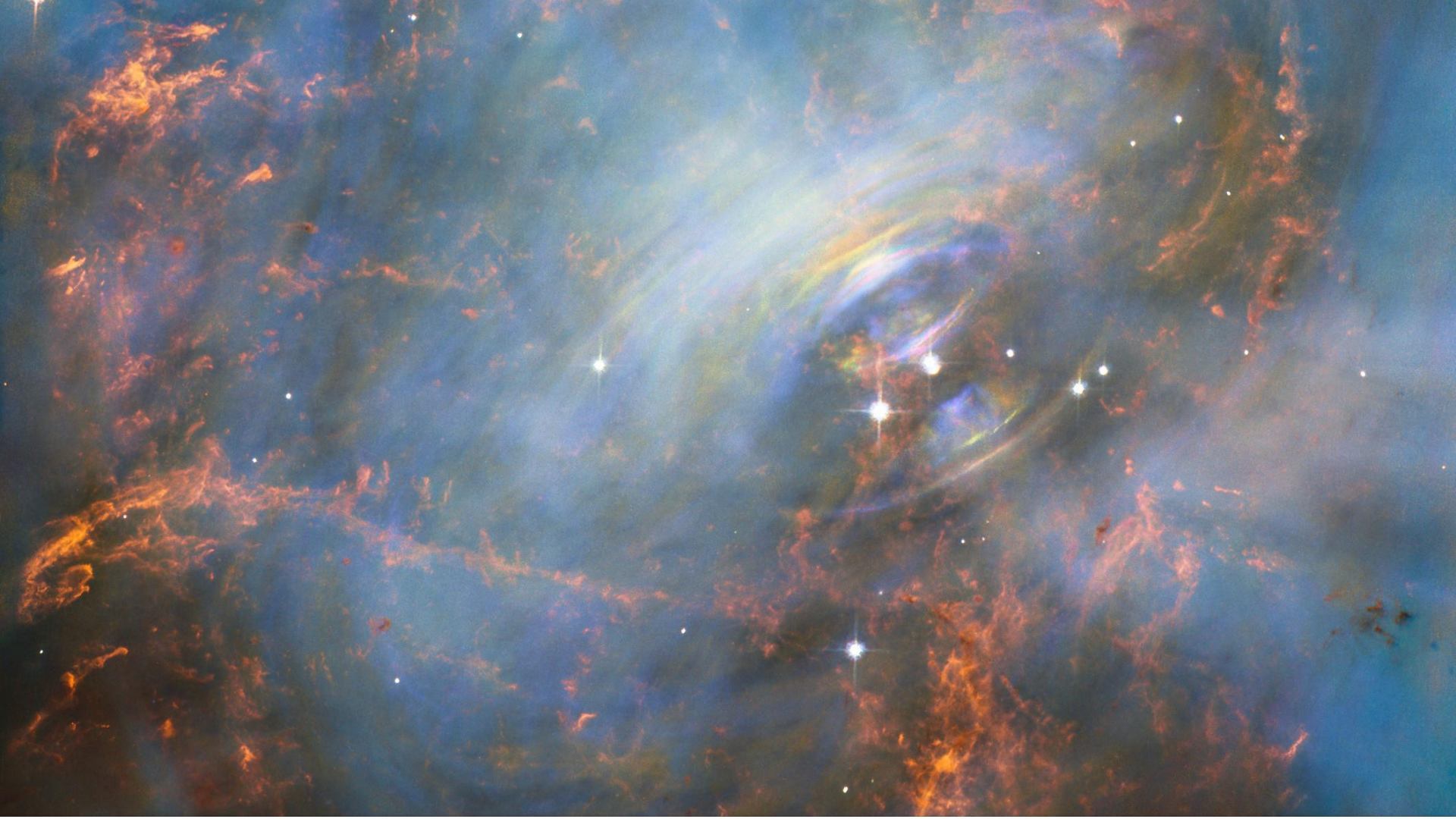
IMPRS Colloquium 25/03/2021

MAX-PLANCK-INSTITUT
FÜR PHYSIK

OUTLINE

- **Pulsars**
  - What are them? How do they work? Why do we care?
- **Low-energy (E<100 GeV) MAGIC**
  - Shower images
  - Low-energy hardware: Sum-Trigger-II
  - Low-energy software: advanced image cleaning
- **Results: discovery of the Geminga pulsar**
  - Phase diagram, spectra, modelling,…
  - Future perspectives



PULSARS

ROTATING NEUTRON STARS

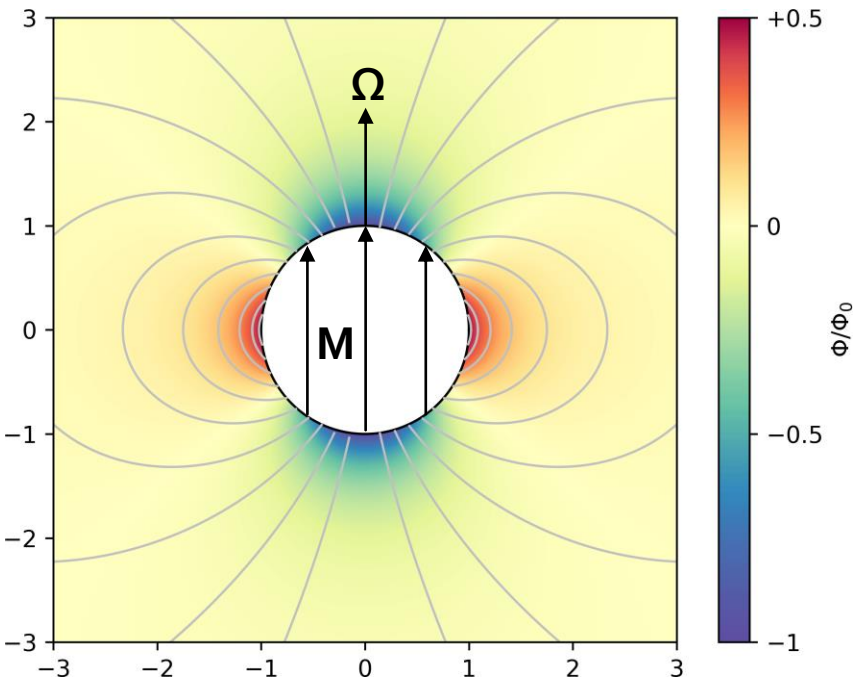
Neutron star:

- Mass = 1.4 $M_\odot$
- **B** field = 10^8 T
- Radius = 10^4 m
- Period = 10^{-3} s – 1 s

Fast spinning conductor magnet: **homopolar generator**

- $\mathbf{E} + (\mathbf{\Omega} \times \mathbf{r}) \times \mathbf{B} = 0$
- Polar Φ_0 = 10^{16} V
- **E** field = 10^{13} V/m

Large E field → **extraction of particles** (leptons) from the star.



Lengths scaled to the radius of the star, with magnetic and rotational axes parallel.

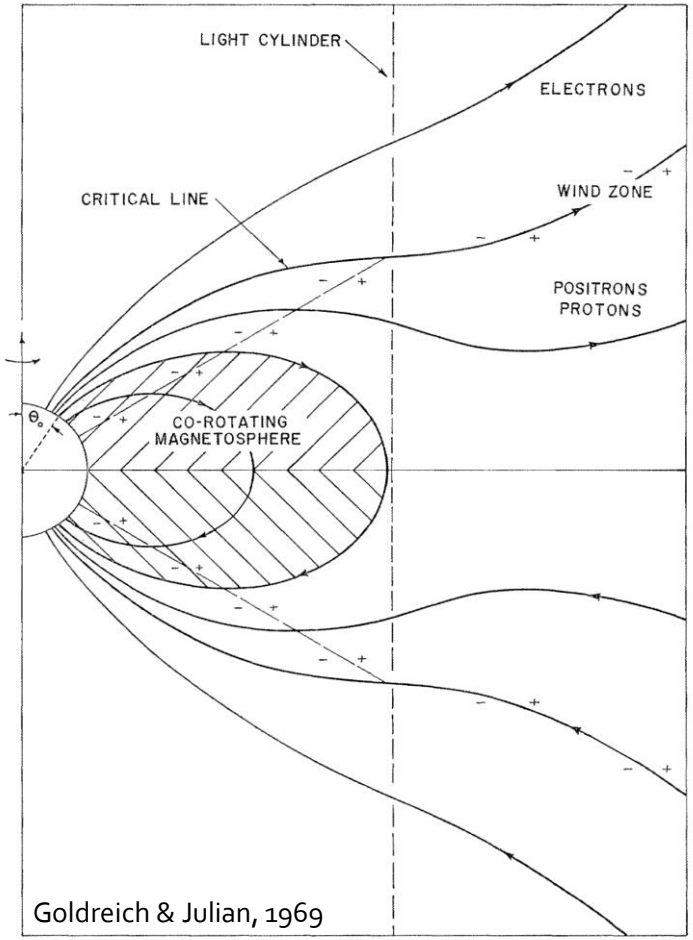
ROTATING NEUTRON STARS

Plasma filled **magnetosphere:**

- Neutralizes the E field
- $\mathbf{E} + \mathbf{v} \times \mathbf{B} = 0$
- $\mathbf{E} \cdot \mathbf{B} = 0$
- **Co-rotation** with the NS

Co-rotation limit radius:
Light cylinder $R_L = c/\Omega$

- **Open** magnetosphere
- Particles stream along field lines **leaving the star**
- Loss of energy and momentum: **pulsar spins down**



Goldreich & Julian, 1969

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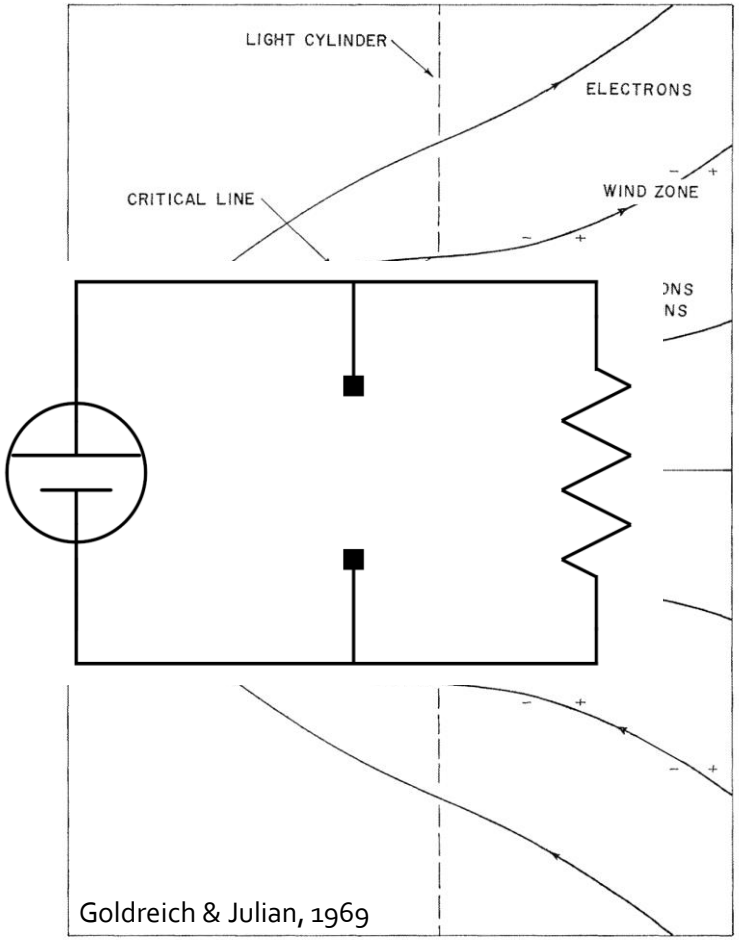


Goldreich & Julian, 1969

GAMMA RAY PULSARS

Natural particle accelerators:

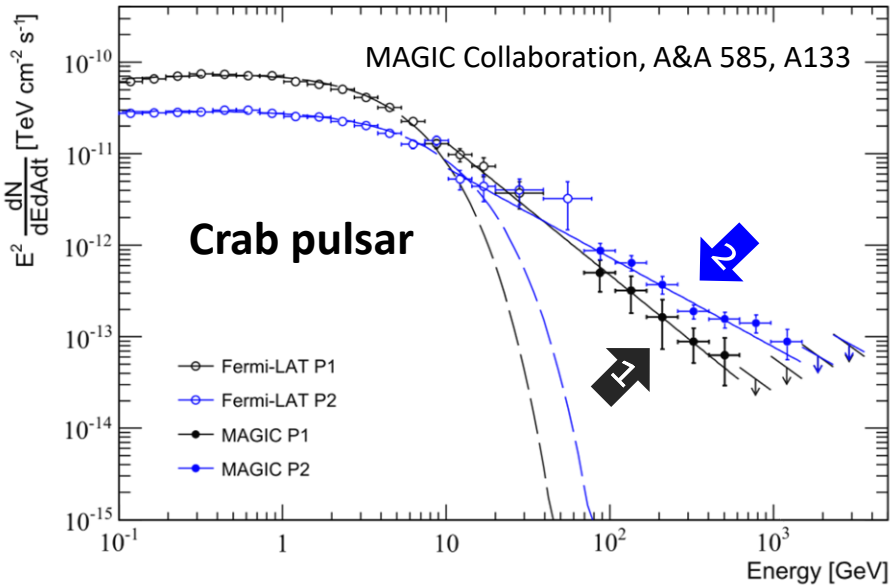
- Defects in **E·B** = 0 result in a **large E field** available
- Electrons reaching $\gamma=10^7$

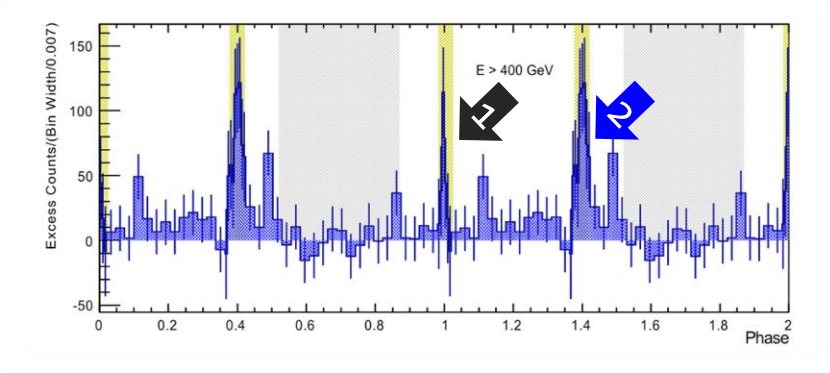
Production of **gamma-rays:**

- **Synchro-curvature** radiation
- **Inverse-Compton** scattering
- Absorption $\gamma \longrightarrow e^+ + e^-$

No clear picture of the **acceleration mechanism:**

- Gaps in the plasma?
- B reconnection in wind?
- **Details** still unknown.

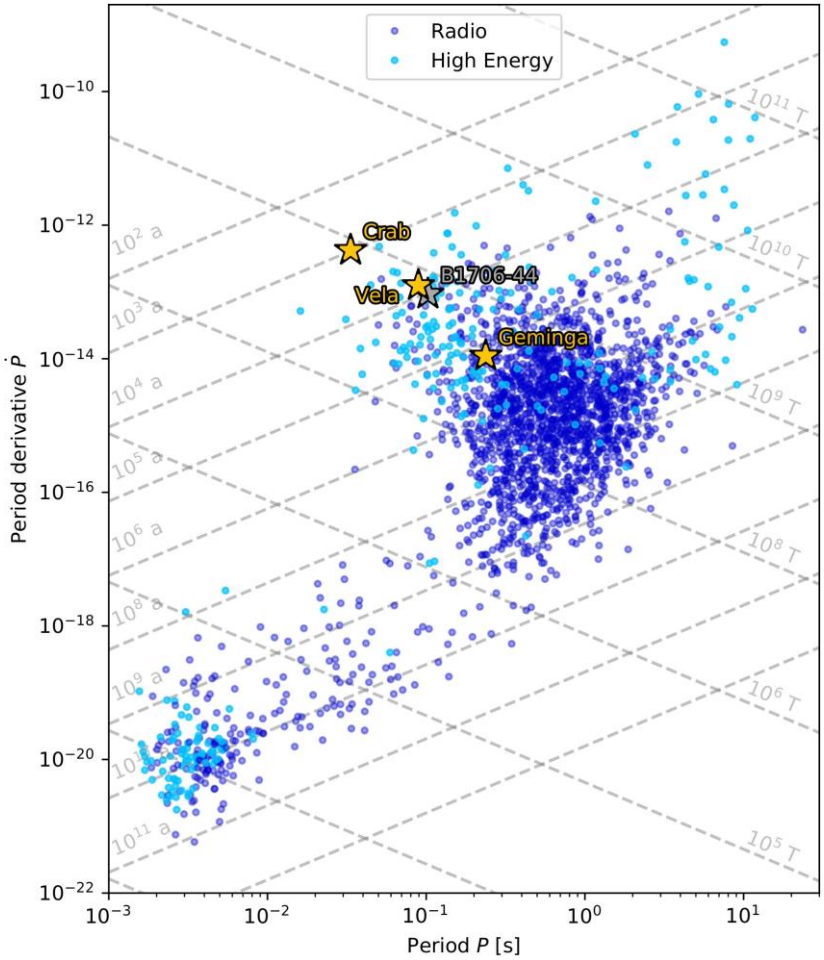




GAMMA RAY PULSARS

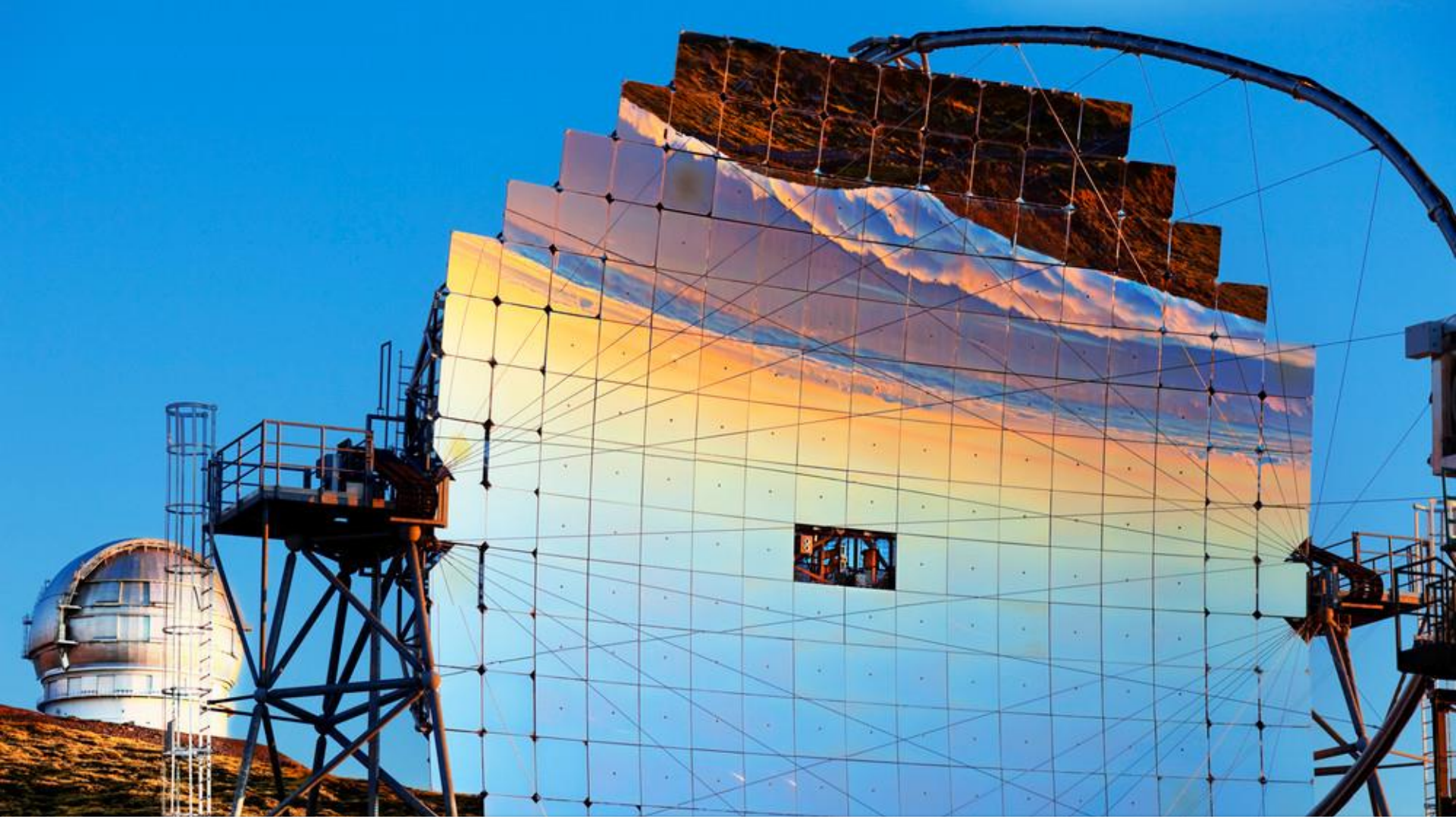
270 known gamma-ray pulsars:

- **Only 4** reach energies observable with **Cherenkov telescopes.**
- **Inverse Compton** component?
- Do they **share** any **feature**?
- Are there **more**?



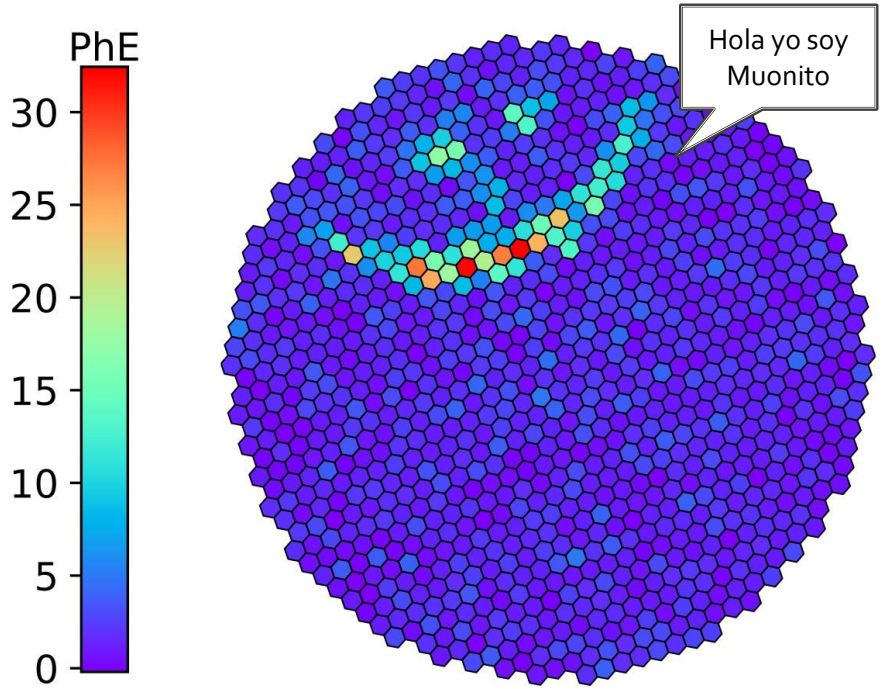
PULSARS – OPEN QUESTIONS

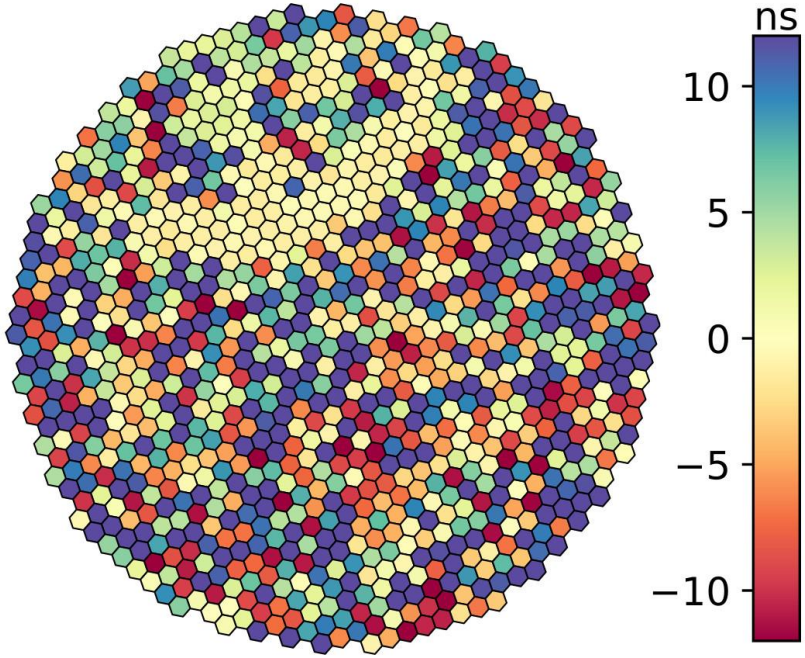
- **Where does the emission come from?**
  - *Properties and structure of the magnetosphere*
- **What distinguishes high-energy ones? Up to which energy do they emit?**
  - *Emission mechanism, population of accelerated particles*
- **How long are they active? How do they evolve?**
  - *Astrophysics, Neutron star structure*
- **How do they interact with their surroundings?**
  - *Pulsar wind nebulae, leptonic wind, positron excess*



LOW-ENERGY MAGIC

SHOWER IMAGES





- Each pixel: deposited **charge** (integrated in 3ns) and **arrival time**.
- Position in the camera: different **incoming direction**.
- **Shape** and **intensity** of shower image → properties of **primary particle**.

IMAGE PARAMETRIZATION

Parametrization of the image with few key parameters:

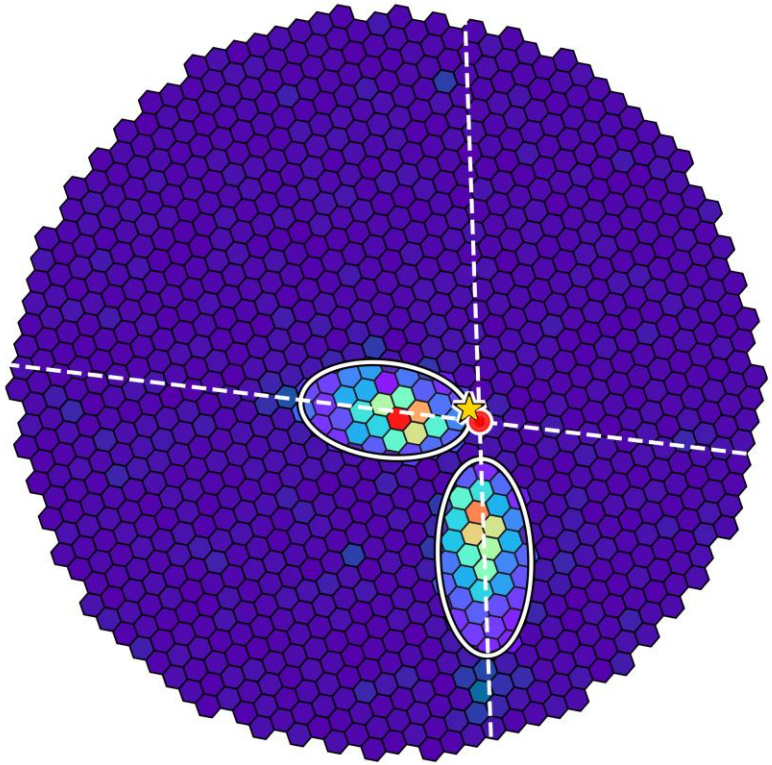
- **Total charge**: proportional to the primary **energy**
- **Shape, Time gradient**: particle **species**, event **geometry**

Two telescopes:

- **Stereoscopic** reconstruction: **incoming direction**
- **Noise rejection**

Rather simplistic technique:

- Lots of **information discarded**



LOW ENERGIES

- **Primary γ** with **lower energy**

  ↓

- **Fewer Cherenkov light** produced in the atmosphere

  ↓

- **Dimmer shower image**

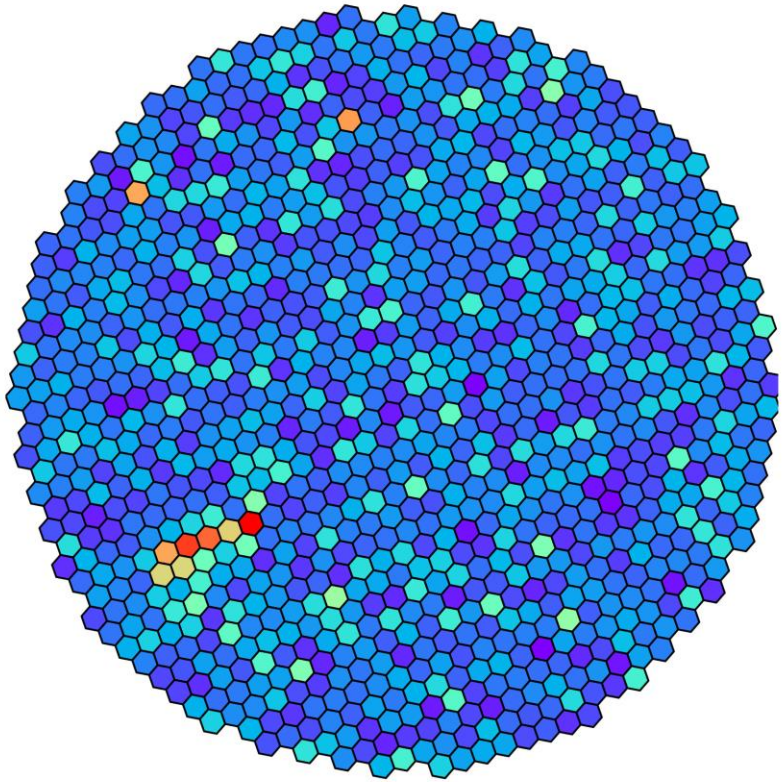
  ↓

- **Smaller charge** deposited onto MAGIC sensors

  ↓

- **Harder discrimination** from noise!

50 GeV gamma



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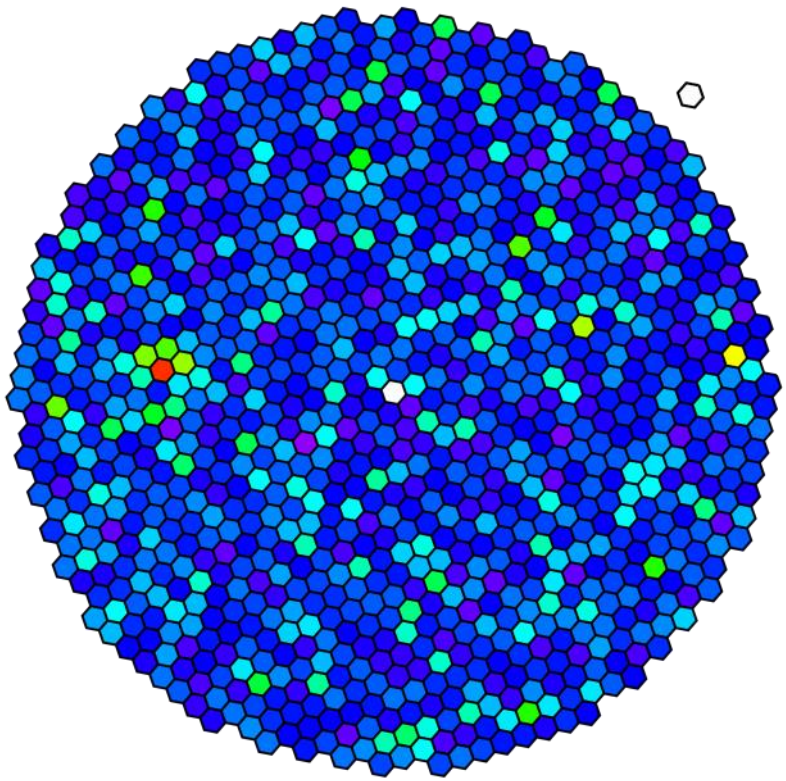
30 GeV gamma

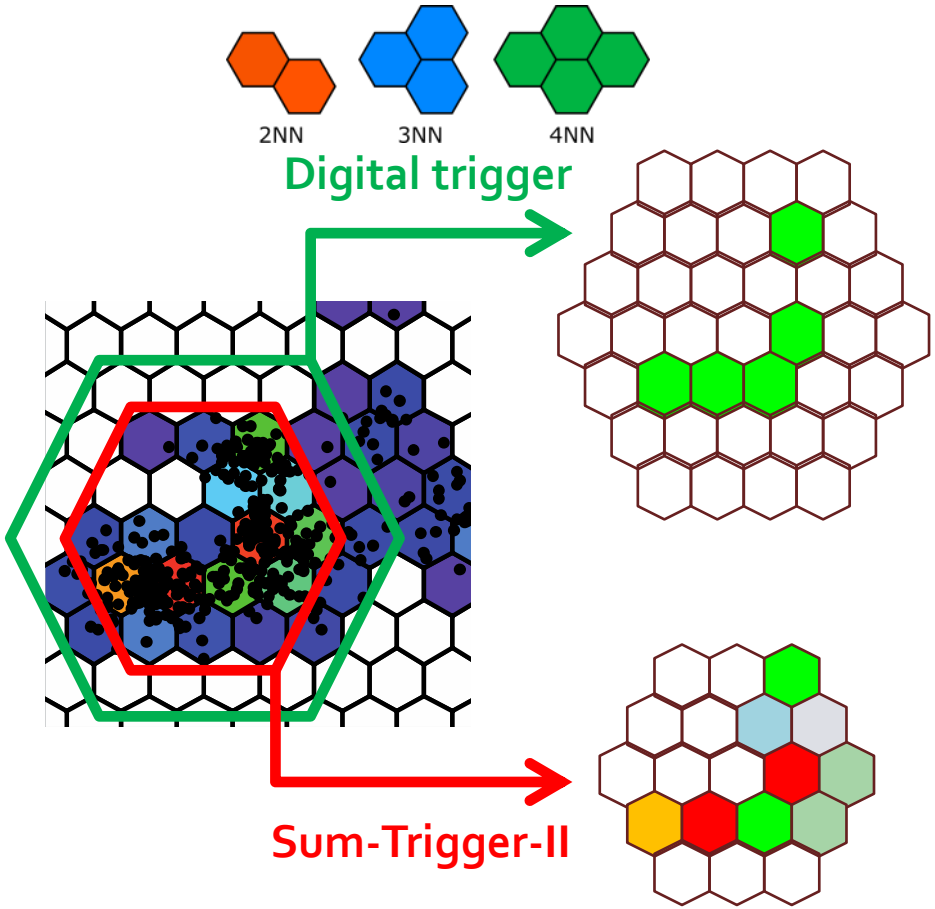


SUM–TRIGGER–II

Stereo **analog trigger** for **dim** showers:

- **Stacking PMT signals** and applying a higher threshold:
- Signal **clipping** to cope with PMT after-pulses
- Real-time software controls **delays** and attenuation between different PMTs.

Improved **energy threshold** at lower energies: < **30 GeV**



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

ADVANCED IMAGE CLEANING

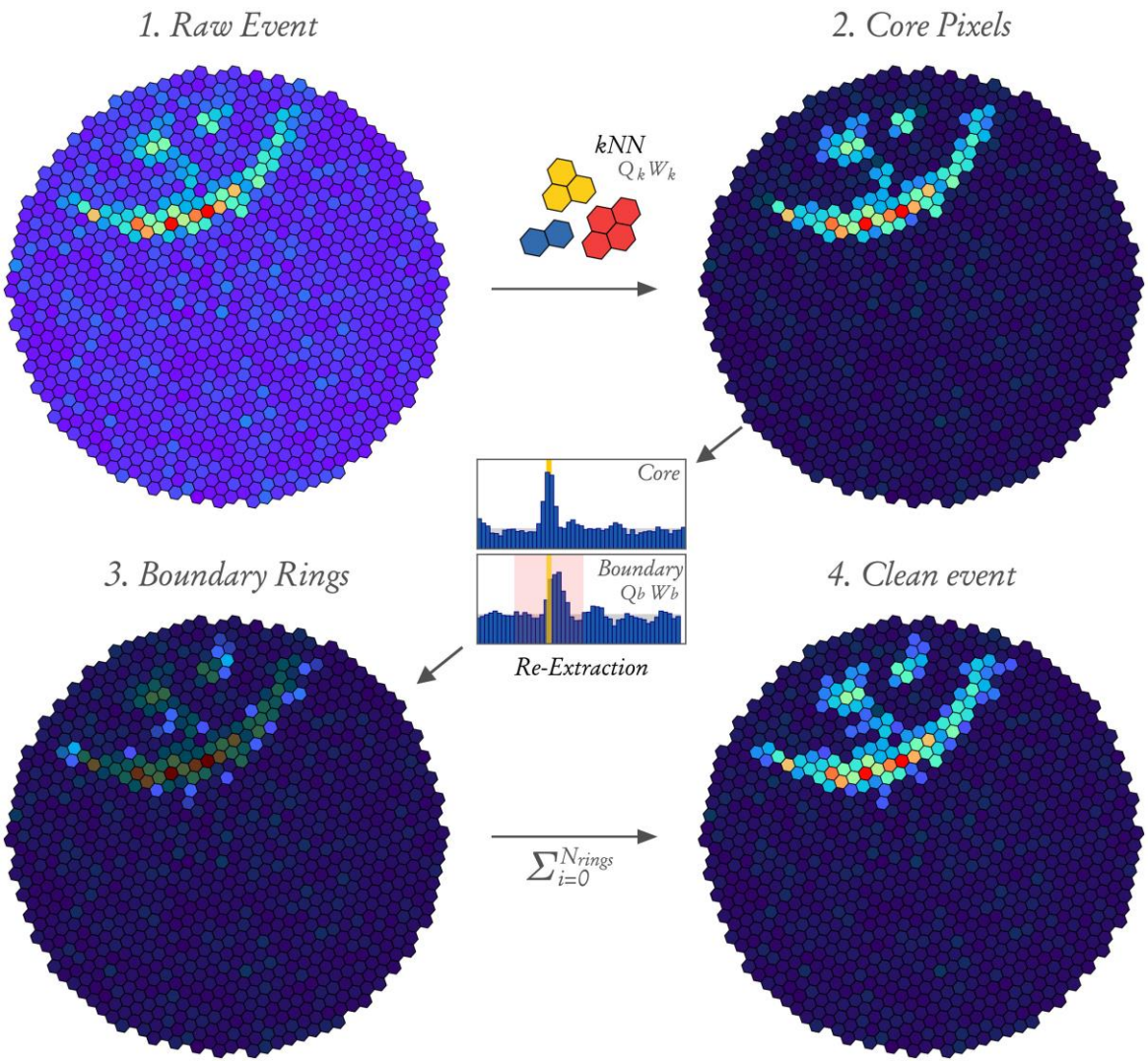
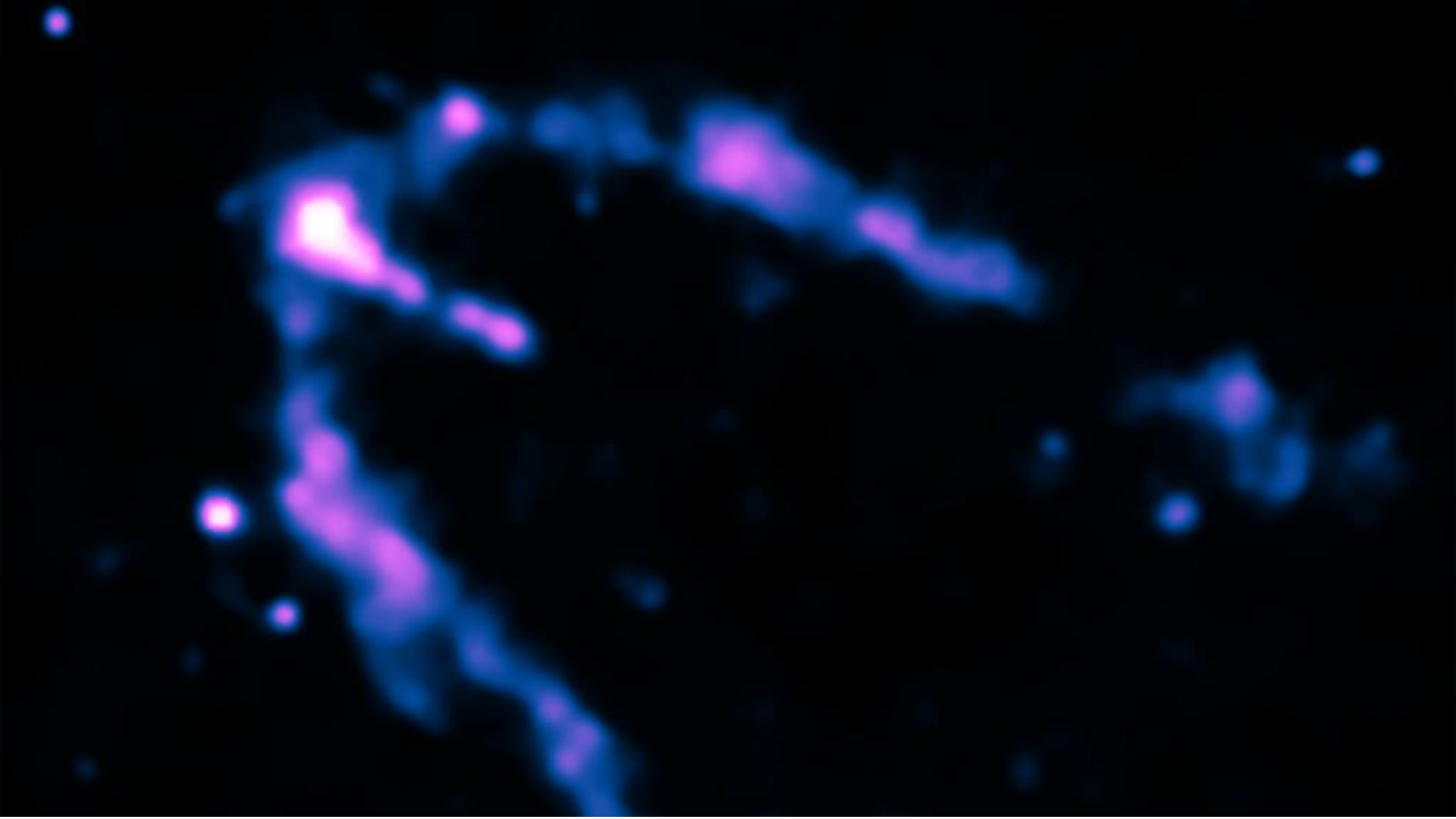


Image cleaning: keeping only relevant event information

Bright, **time coincident** pixels clustered in groups are **marked** as **interesting**

Neighboring pixels are scanned searching for **small coincident** signals

The rest is discarded.



RESULTS – GEMINGA

«The star that is not there…»

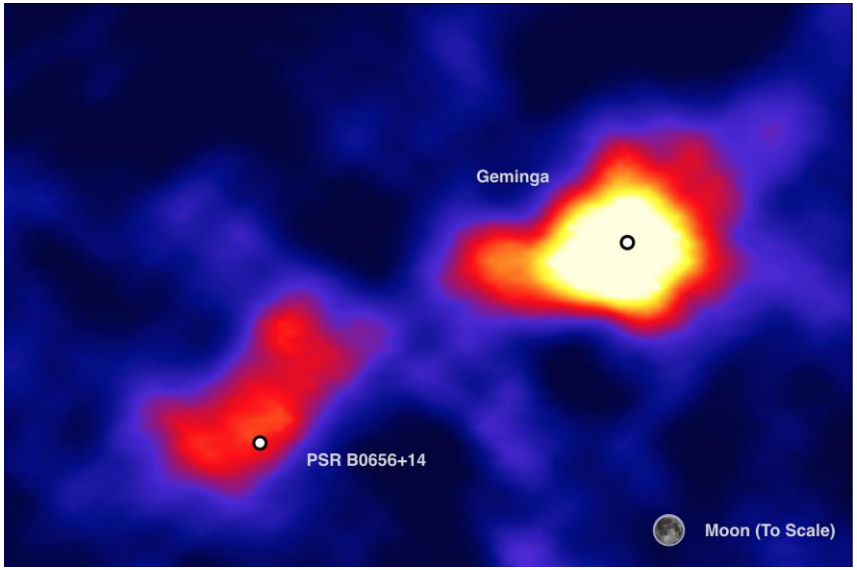
GEMINGA PULSAR

Unusual pulsar:

- Middle aged: **300000 years**
- Very close by: **250 pc**
- **Radio quiet** pulsar archetype
- Second **brightest steady source** in the GeV sky

Embedded in a **vast TeV halo:**

- HAWK / Fermi-LAT results
- **Accelerated lepton** escape diffusion
- **Contributor** to **positron spectrum** at the **Earth**

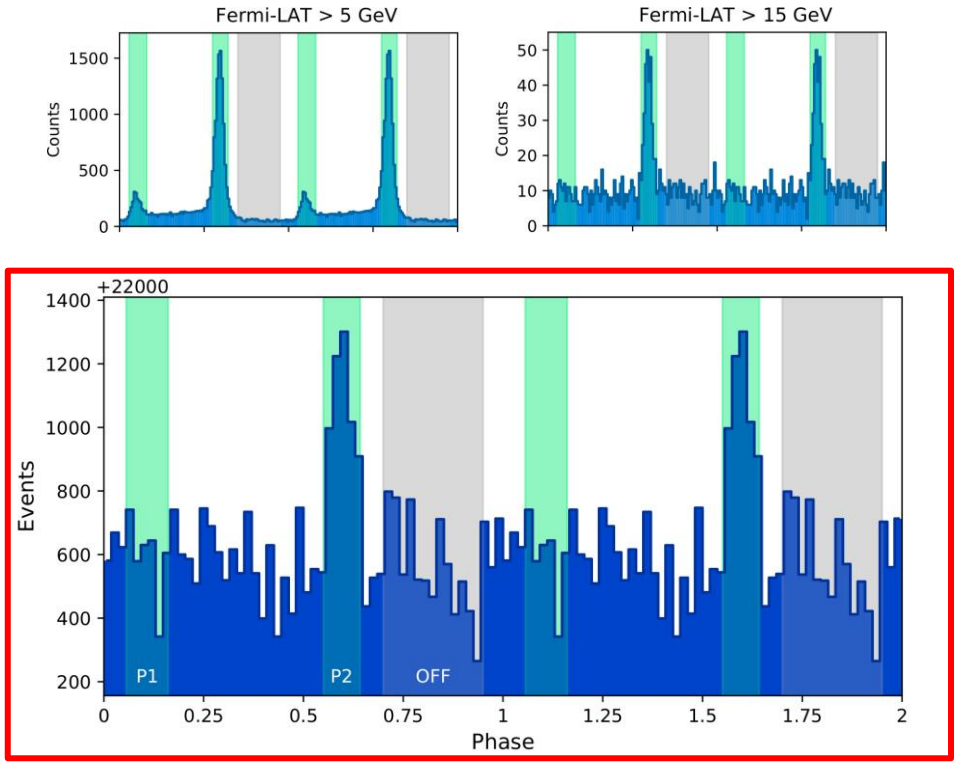


Abeysekara et al. (2017) Science, 358

GEMINGA PULSAR

First detection of Geminga from the ground, at **E>15 GeV:**

- **Third VHE pulsar**, first **middle-aged** one
- **Detection** significance**: 6.3σ**



A&A Highlight letter 2020:

- MAGIC Collaboration, et al.
  DOI: 10.1051/0004-6361/202039131

Main result of my PhD…

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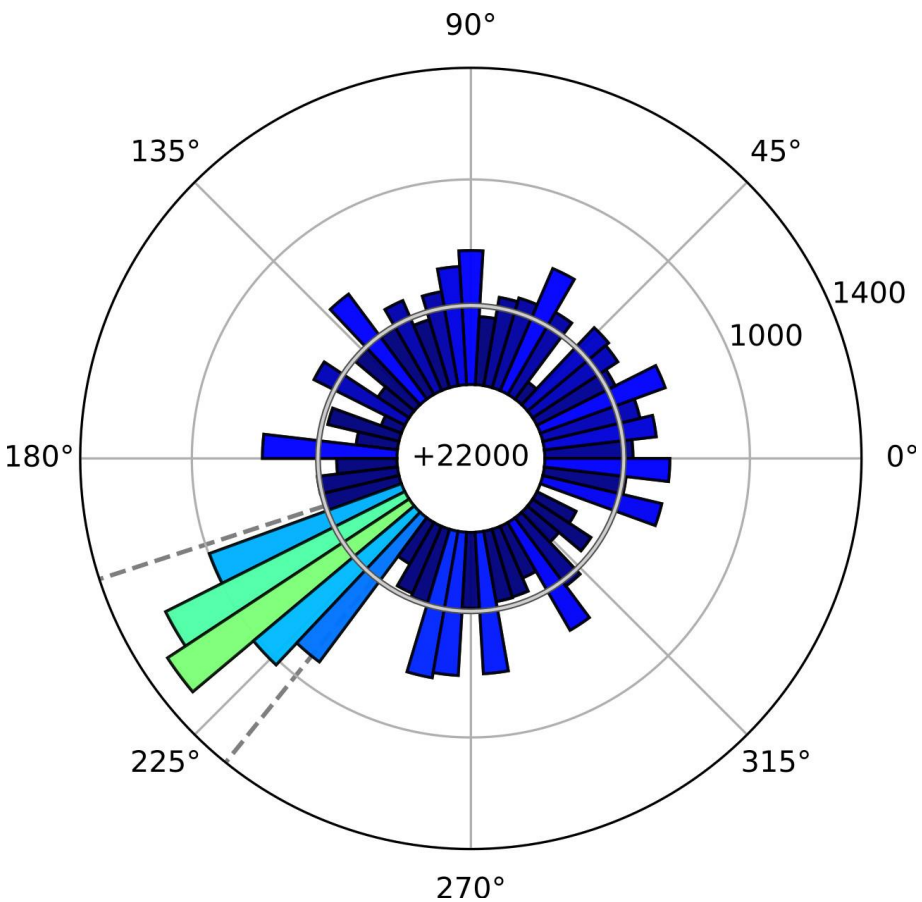

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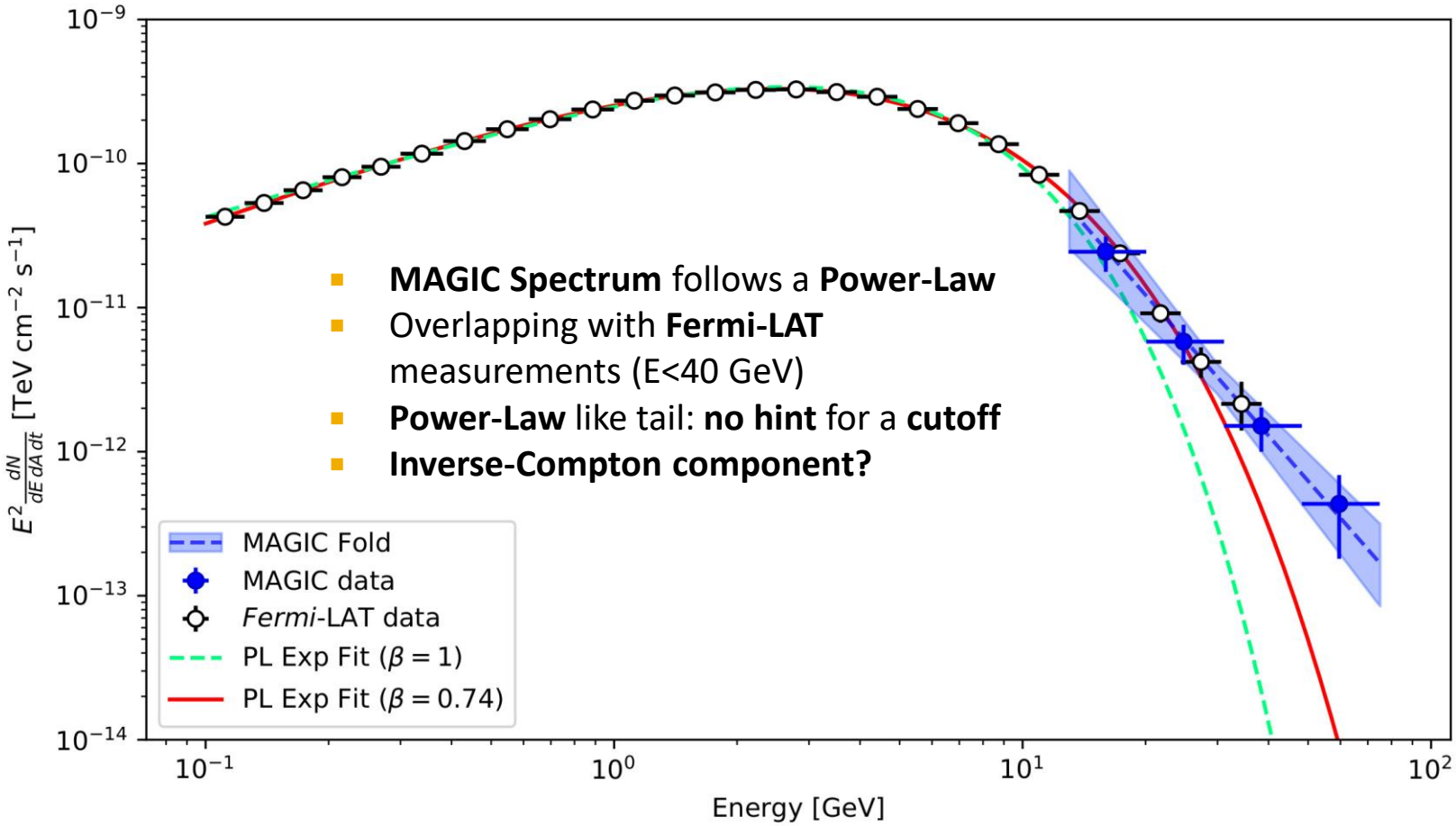
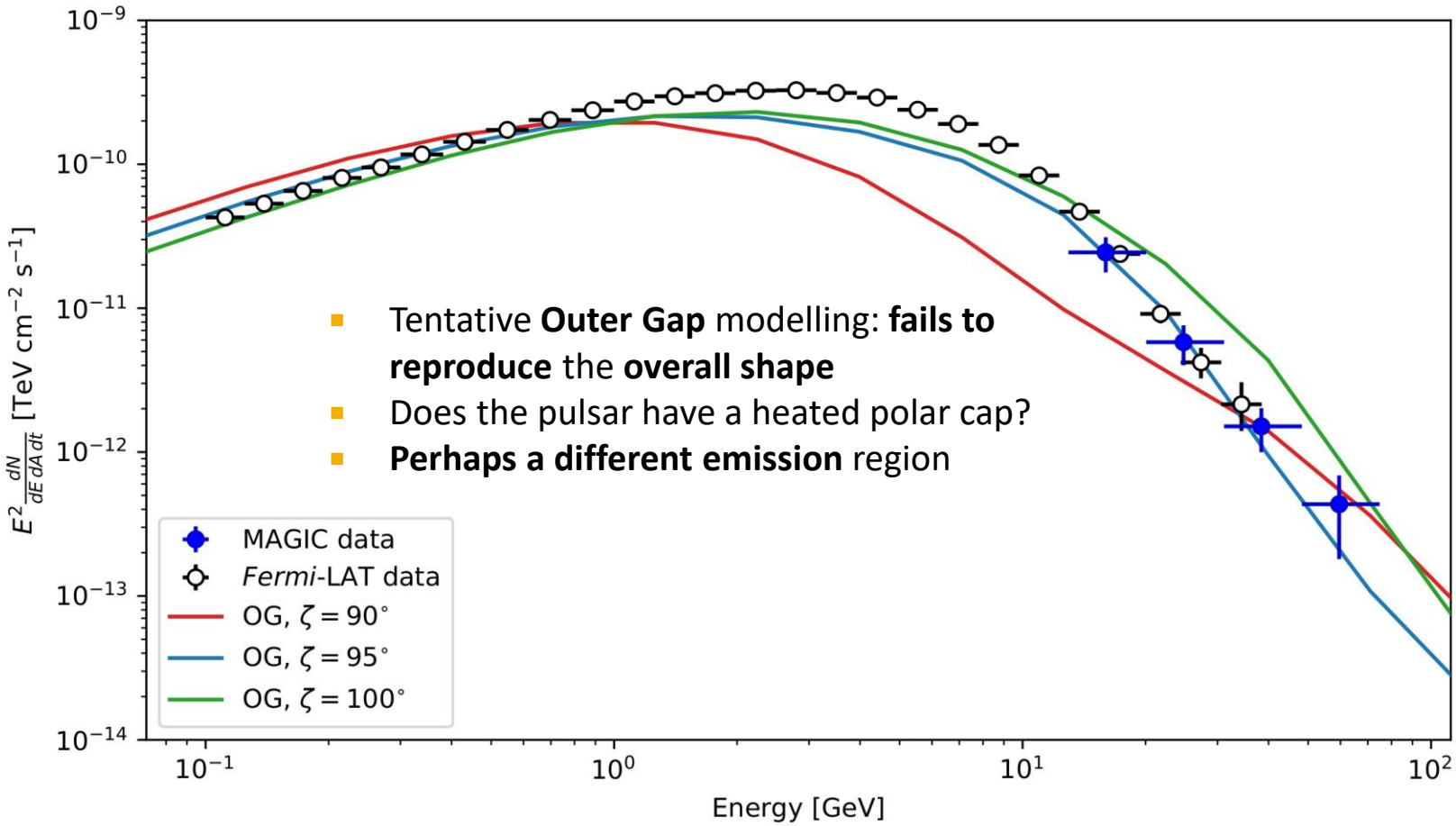


- **MAGIC Spectrum** follows a **Power-Law**
- Overlapping with **Fermi-LAT** measurements (E<40 GeV)
- **Power-Law** like tail: **no hint** for a **cutoff**
- **Inverse-Compton component?**

GEMINGA PULSAR



- Tentative **Outer Gap** modelling: **fails to reproduce** the **overall shape**
- Does the pulsar have a heated polar cap?
- **Perhaps a different emission** region

GEMINGA PULSAR

Embarrassing outreach activities…

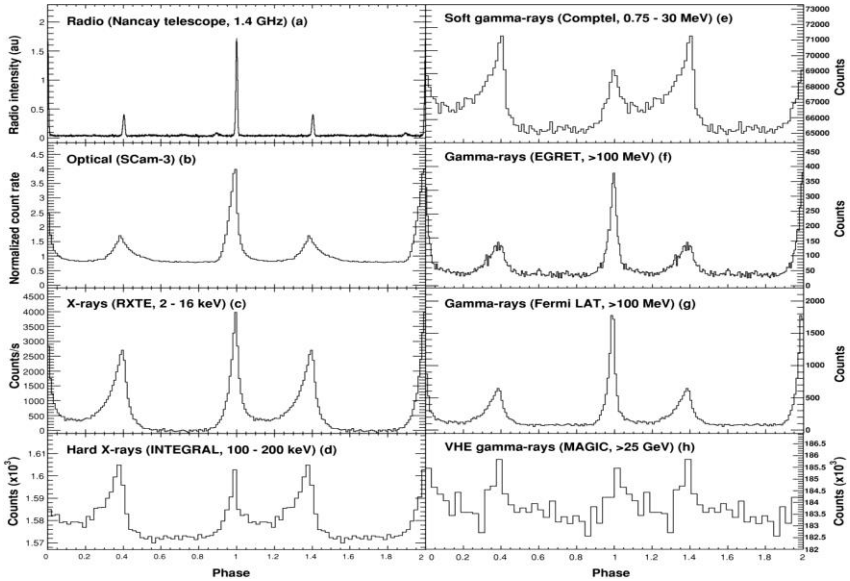
CONCLUSIONS

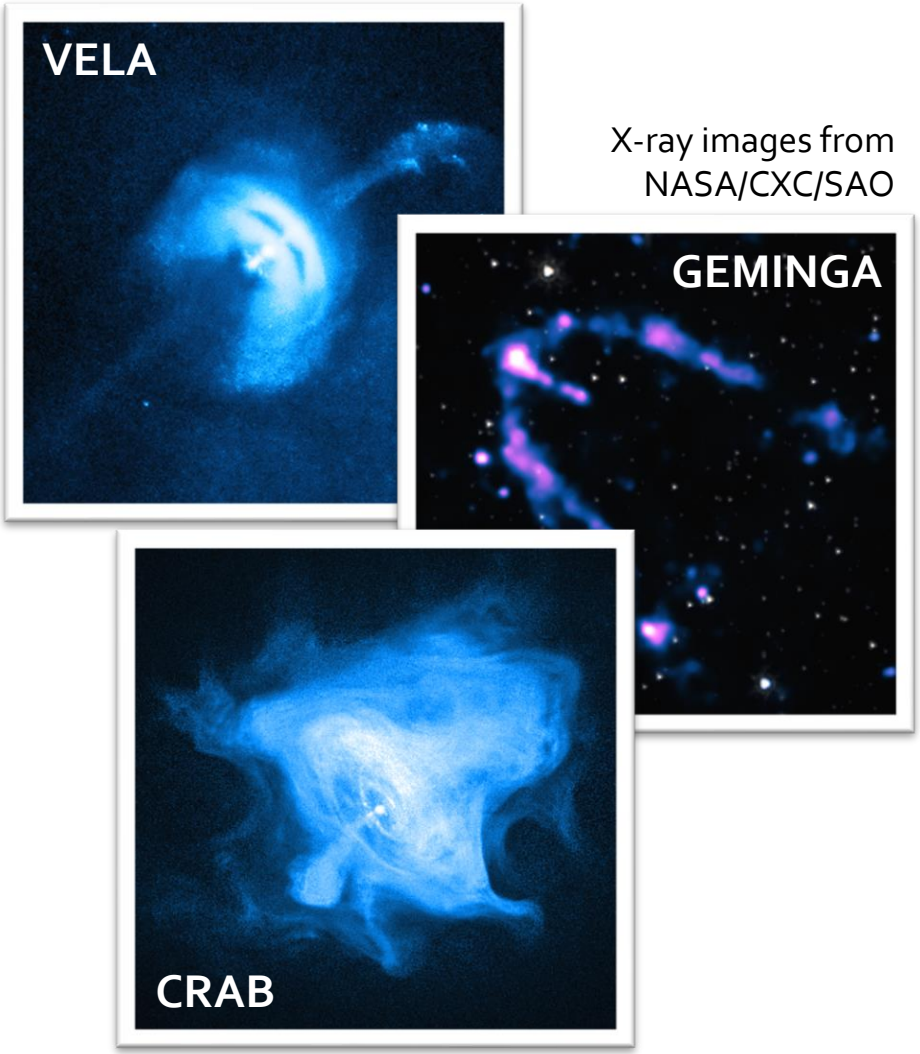
SUMMARY

- Pulsars are fascinating **natural particle accelerators**, but their **physics is still largely unknown**.
- **New detections** of pulsars: larger sample, searching for **similarities**, making **population studies** possible.
- Thanks to technical achievements **MAGIC** achieved the detection of the **third known very high energy** (E>50 GeV) pulsar: **Geminga**
- **Possible Inverse Compton** component, challenging established emission models.
- There is still a lot in the unknown out there…

PULSARS

- Detectable neutron stars
- Mostly in radio band
- Some binaries
- Some VIS / X / γ pulsars

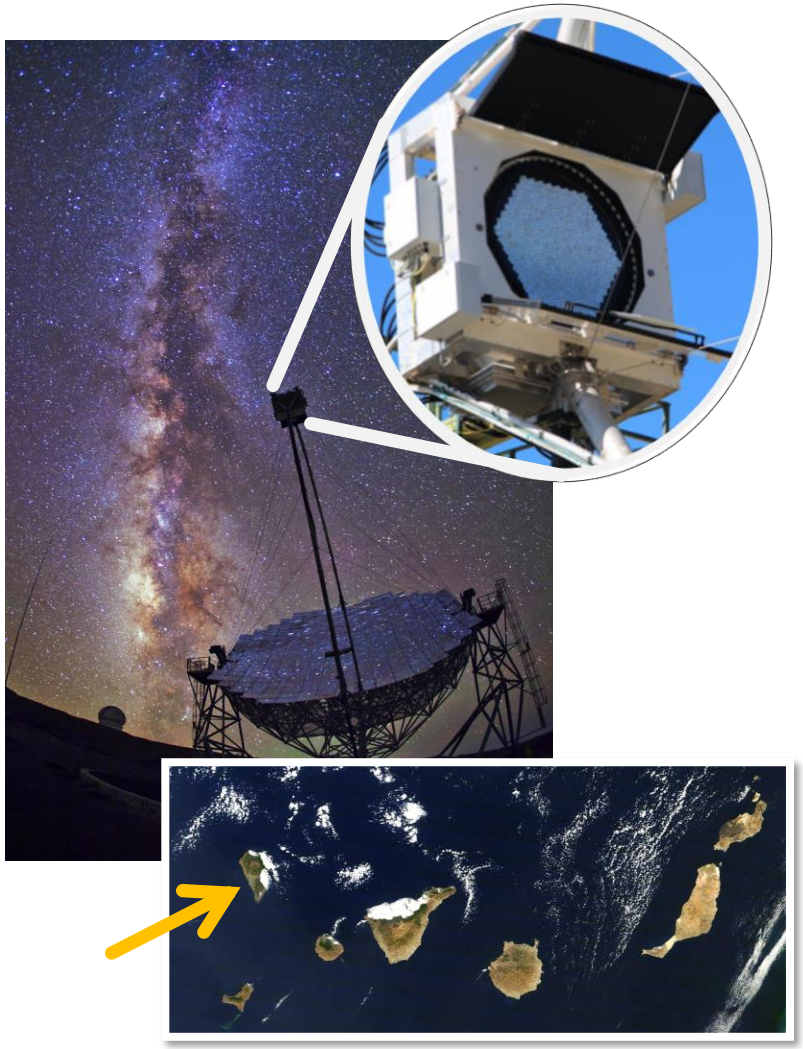




X-ray images from NASA/CXC/SAO

MAGIC TELESCOPES

- Ø 17 m actively steered segmented mirrors.
- MAGIC Camera:
  - 1039 low-gain PMTs
  - Hexagonal geometry
  - Field of view of 3,5°
  - Pulse-width: 2,5 ns
- Optical fibers to Counting House
- Readout:
  - Analog memory sampling at 1.64 GHz (width 640 ns)



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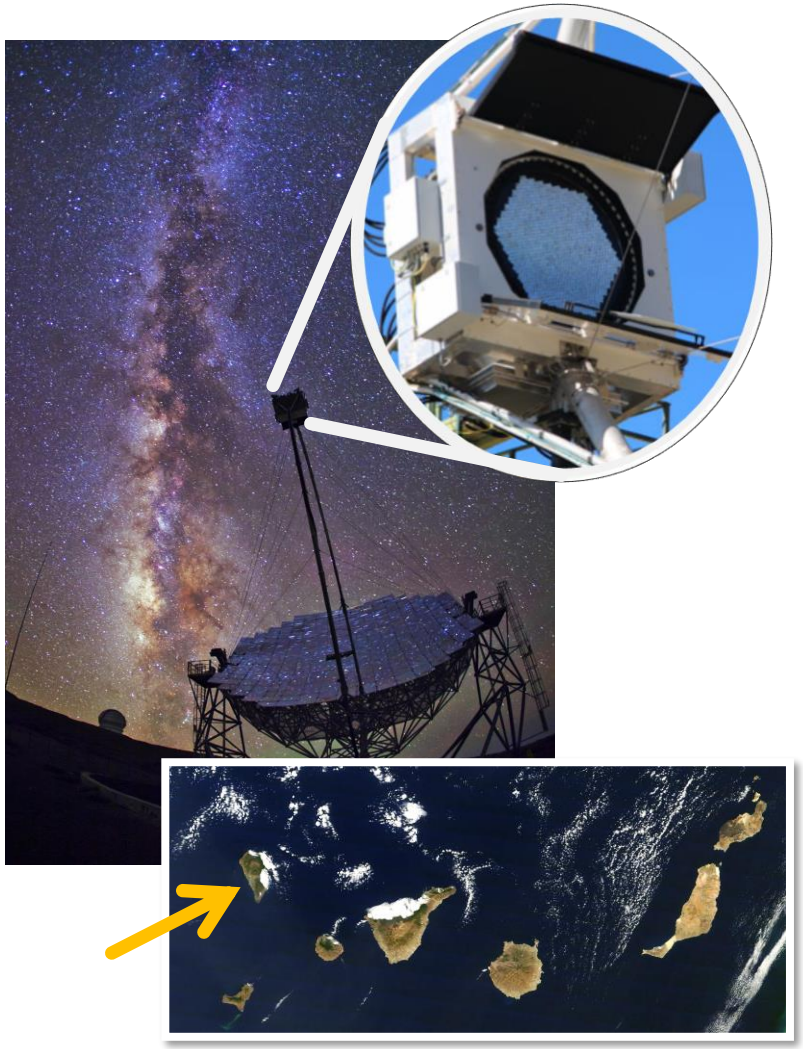
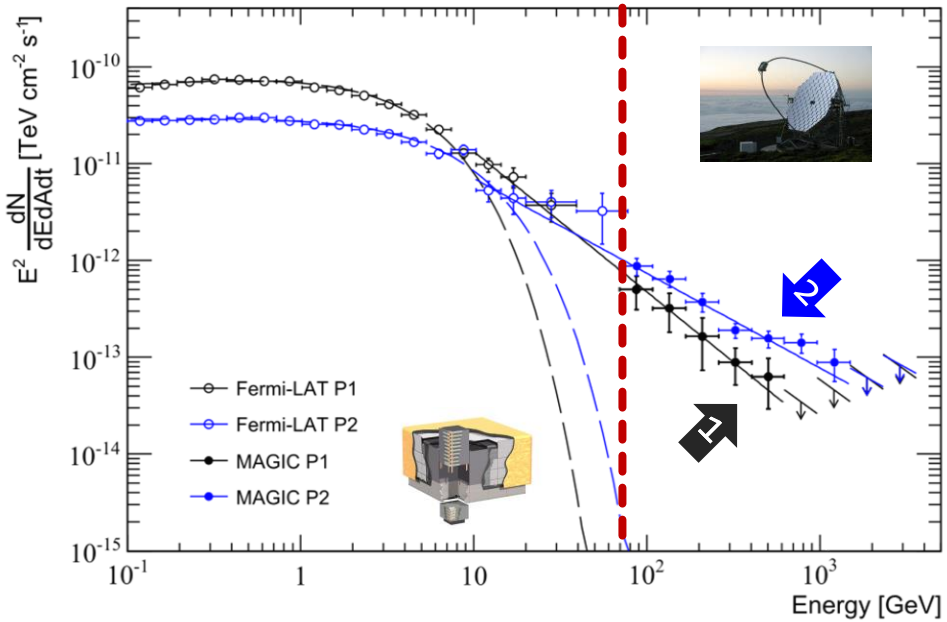
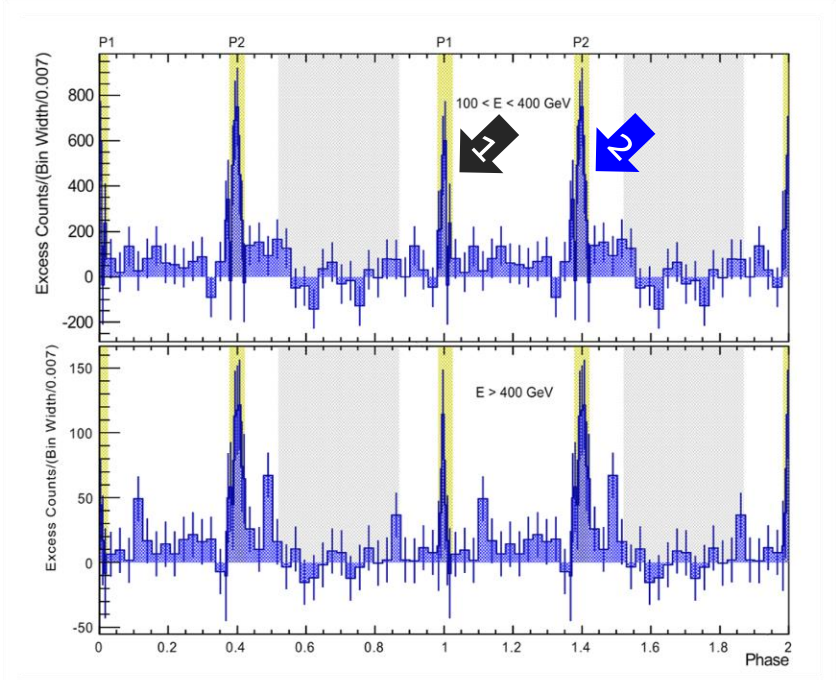


THE CRAB PULSAR

SPECTRUM



PHASEOGRAM



MAGIC Collaboration, A&A 585, A133

- Sharp **doubly pulsed emission** with hard spectrum up to TeV
- Curvature radiation up to few GeV
- Inverse Compton at TeV energies.