VHE PULSARS WITH MAGIC

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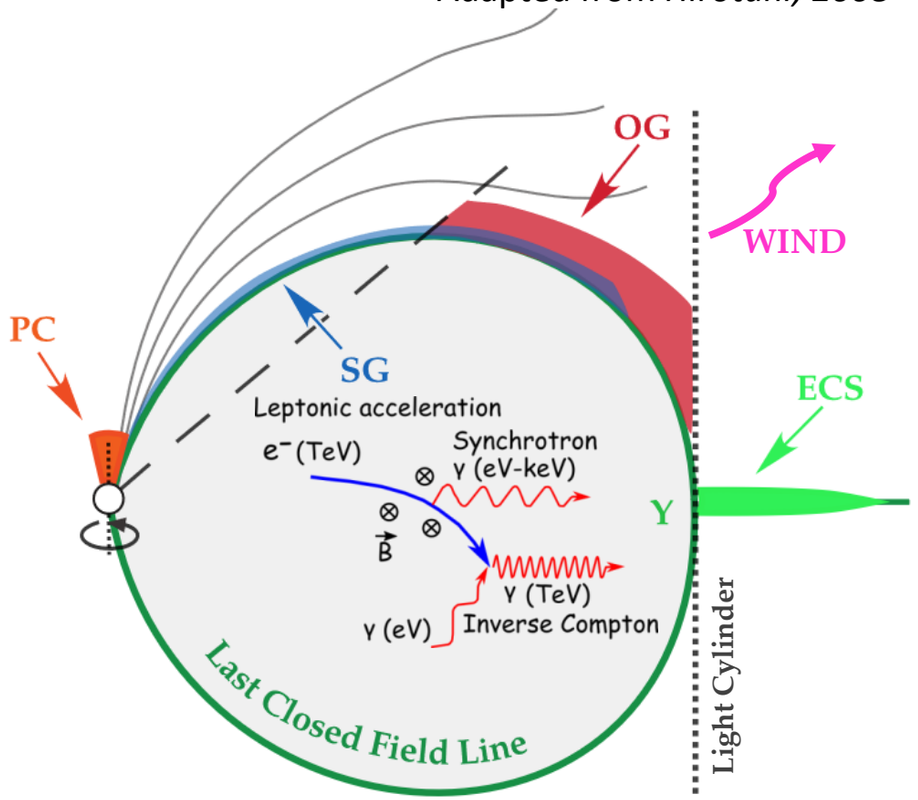
MAGIC

MAX-PLANCK-INSTITUT FÜR PHYSIK

HIGH-ENERGY GAMMA-RAY PULSARS

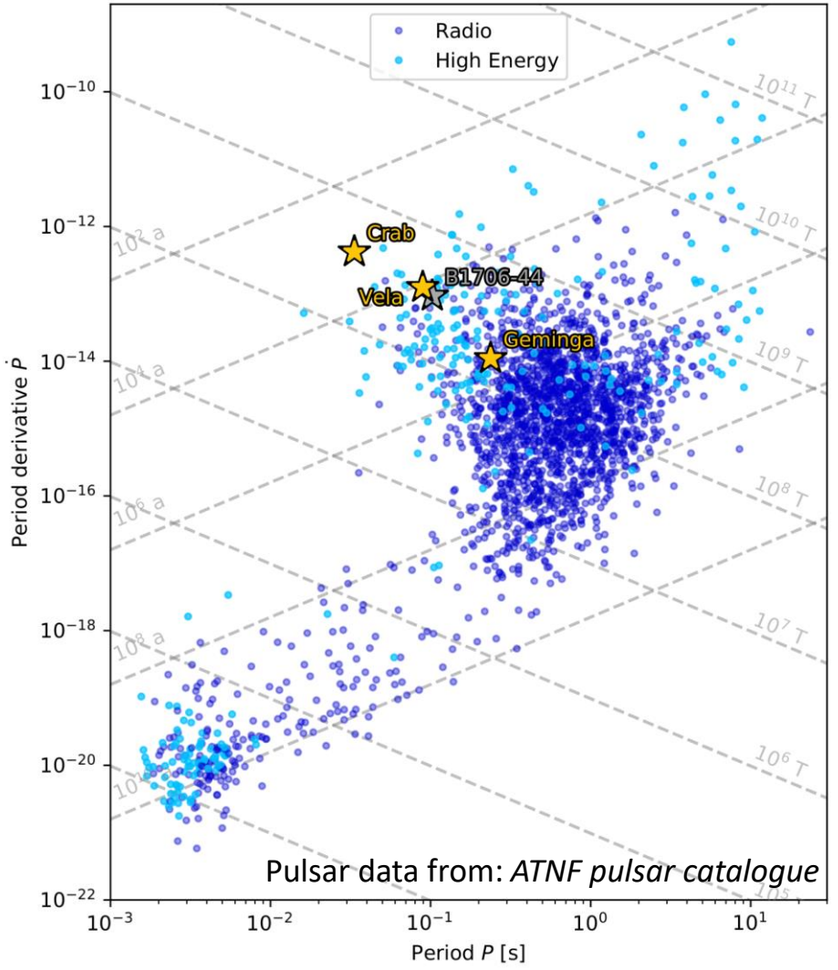
- Roughly **300 known ones** (E>100 MeV, most of them from **Fermi-LAT**).
- Gammas via **synchro-curvature** (SC) radiation, **synchrotron-self-Compton** (SSC) or **inverse-Compton** (IC) from accelerated leptons.
- Electron **acceleration** possible only in **defects** of the **ideal plasma**:
  - Where are they? How do they work?
- **Competition** with $\gamma \rightarrow e^+ e^-$ absorption in the strong B field.
- **Spectral cut-offs** at energies ~ 1 GeV.

Adapted from *Hirotani, 2008*



VERY-HIGH-ENERGY PULSARS

- **Few pulsars** known to emit at the **Very High Energies** (>50 GeV):
  - **Crab**, Vela, **Geminga**, B1706-44
- **Crab** (PSR J0534+2200):
  - Radio-loud, t = 1 ky, d=2 kpc, $L_{sp}=10^{31}$ W
  - Bright **Crab Nebula**, standard candle
- **Geminga** (PSR J0633+1746):
  - Radio-quiet, t = 300 ky, d=250 pc, $L_{sp}=10^{27}$ W
  - Embedded in vast **TeV Halo** (HAWC, Fermi-LAT,…)



MAGIC PULSAR RESULTS

2008 **Discovery** of **pulsed VHE** emission of the **Crab** (>25GeV)

- Excludes polar-cap model

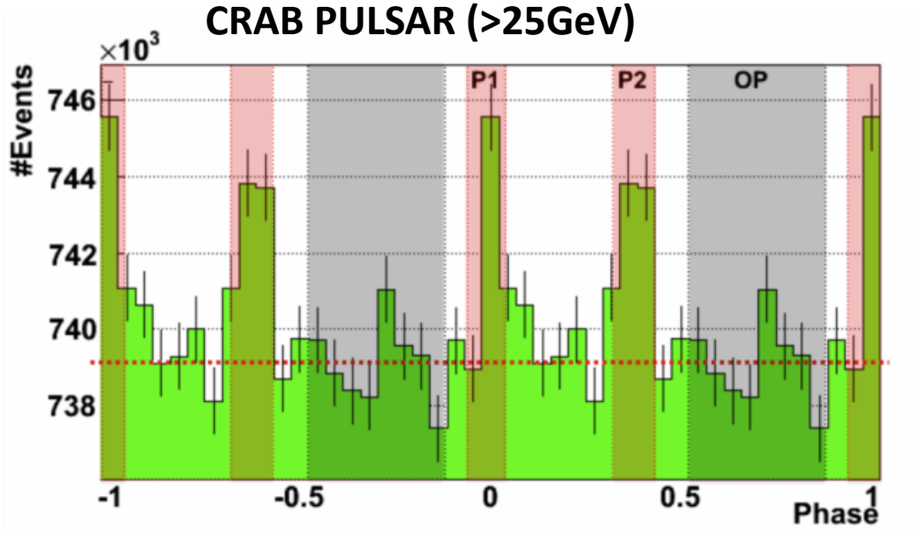
2011 **VERITAS:** Crab pulsar above 100 GeV

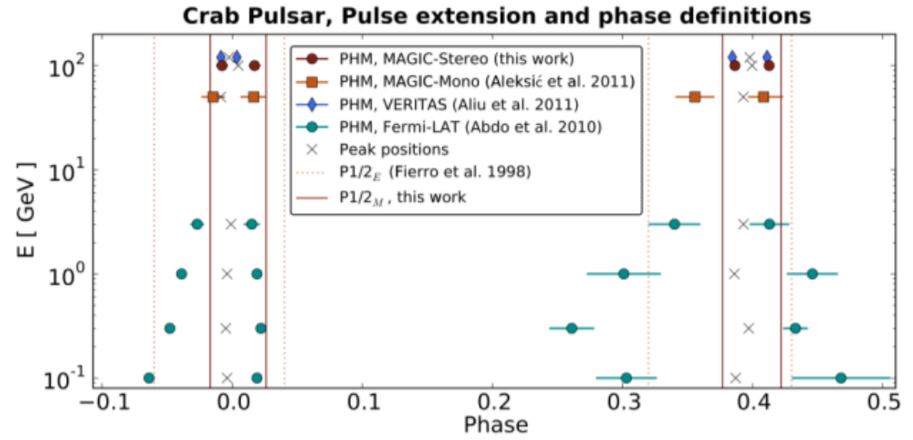
2011 Pulsed emission detected **up to 100GeV**

- Consistent with a power-law!

2012 **Phase-resolved spectrum** up to **400GeV**

- Peak width decreases with energy





MAGIC PULSAR RESULTS

2014 **Crab Bridge** emission above **50GeV**

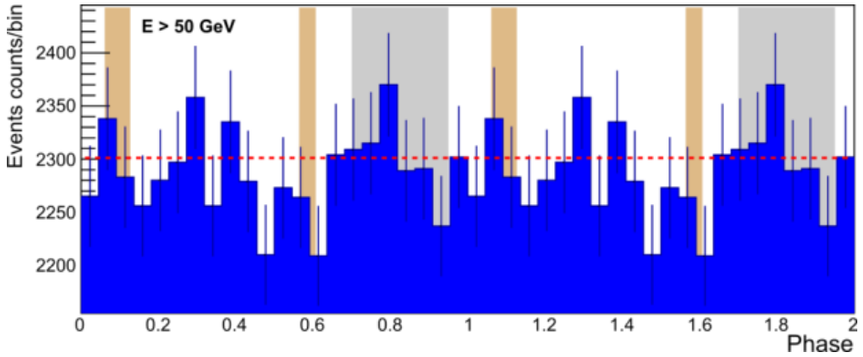
2016 **Geminga searches** with standard trigger above 70GeV

2016 **TeV pulsed emission** from the **Crab**!

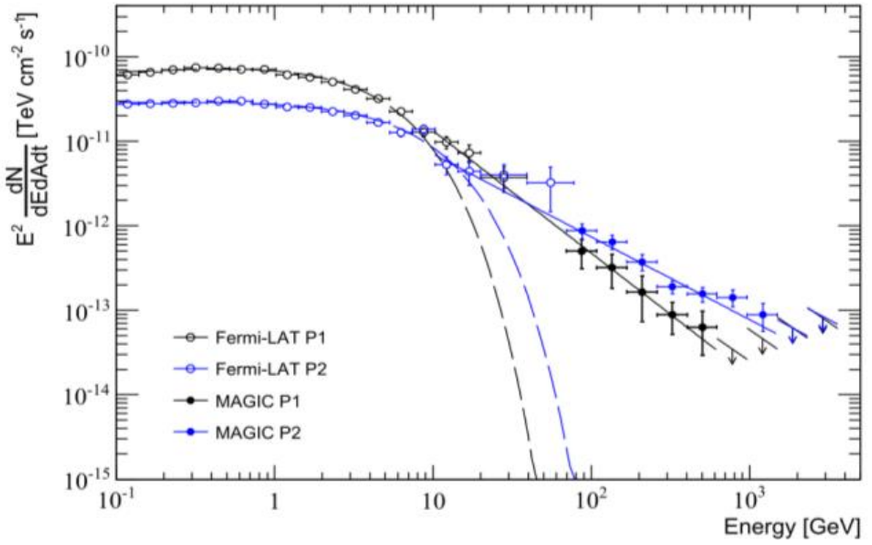
- Inverse Compton component

2017 **Lorentz Invariance Violation** studies with the **Crab pulsar**

GEMINGA PHASEOGRAM (>50GeV)

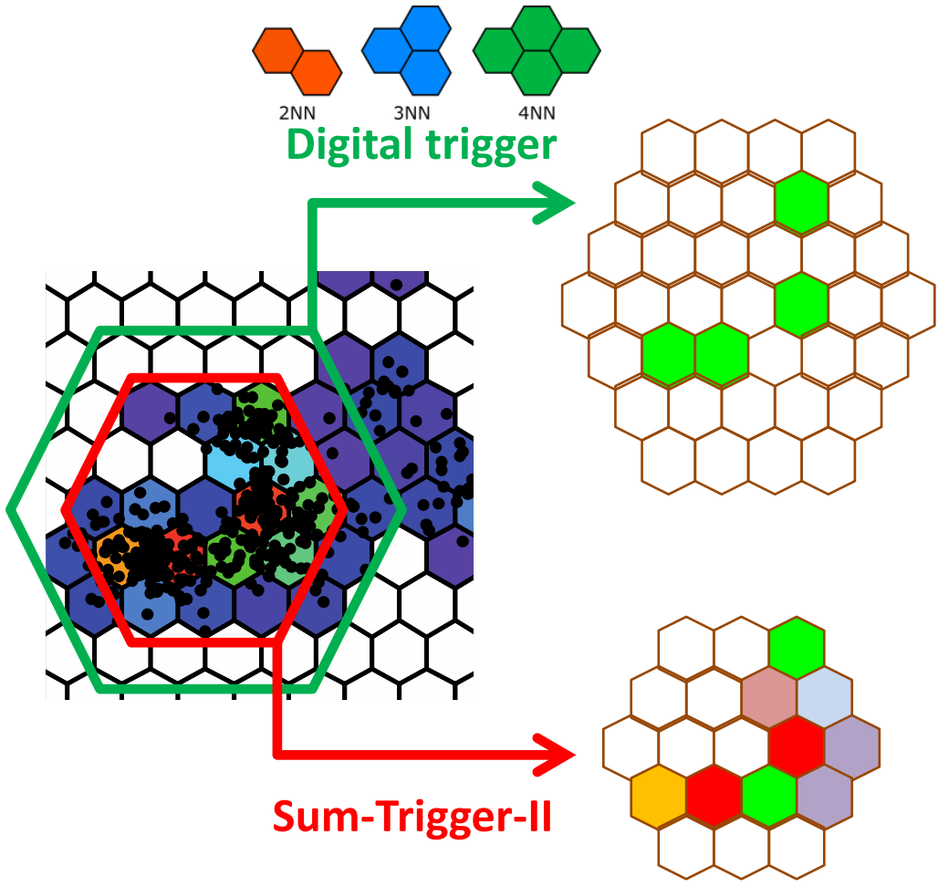


CRAB PULSAR SPECTRUM



THE LOW-ENERGY SUM-TRIGGER-II

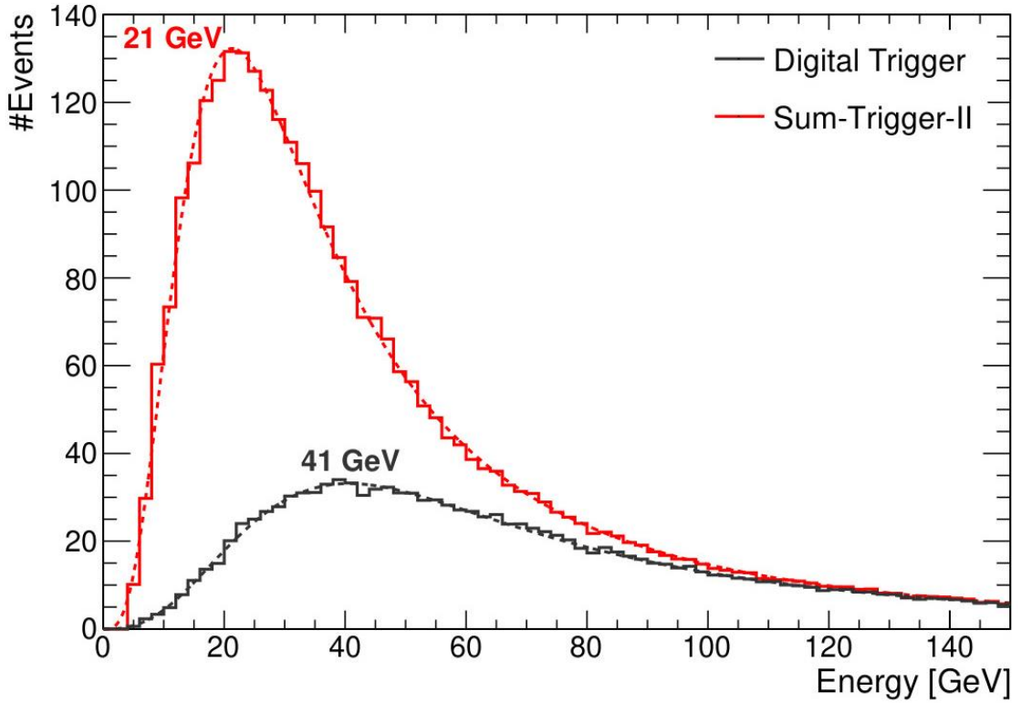
- Improve **S/N ratio** for low-energy events.
- **Stacking** the signals of **neighboring pixels** and applying a larger threshold.
- Stacking cell **size optimized** for low-energy events.
- Analog hardware approach.
- Excellent **gain uniformity** and **signal** isochrony required among different pixels



THE LOW-ENERGY SUM-TRIGGER-II

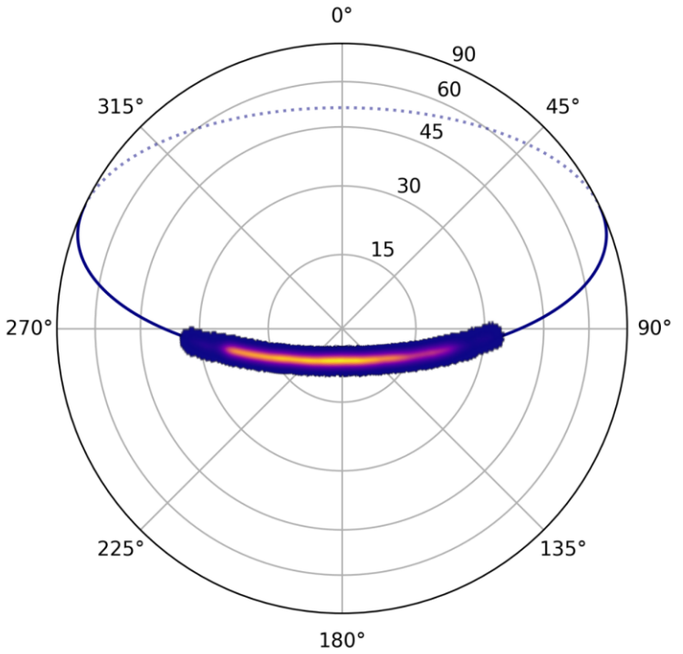
- Lowered **trigger energy threshold**: **20 GeV**.
- **Four-fold increase** of the **collection area** at 20 GeV.
- **Sum-Trigger-II** reference publication:

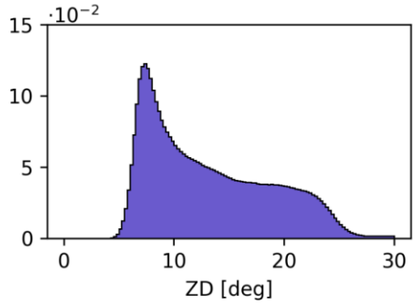
  F. Dazzi et al., ***The Stereoscopic Analog Trigger of the MAGIC Telescopes*** (2021) DOI: 10.1109/TNS.2021.3079262

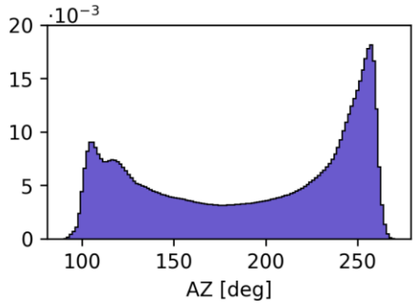


CRAB PULSAR OBSERVATIONS

- **Observation** campaign started in **2015** and carried on until **2020**.
- **Stringent requirements** for the observations, seeking the lowest possible **energy threshold**.
  - Maximum zenith distance: **25 deg**
  - Excellent **atmospheric transmission**
- A total of **~ 110 hours** of good quality data were collected.

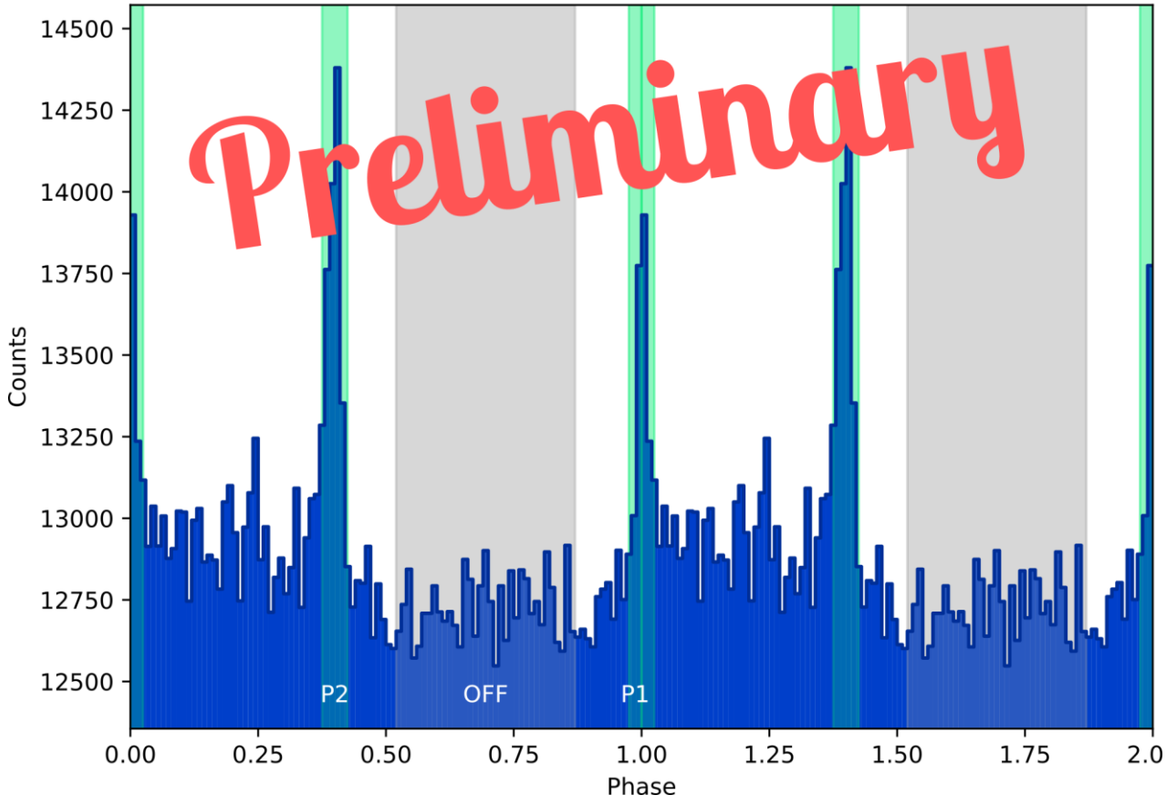






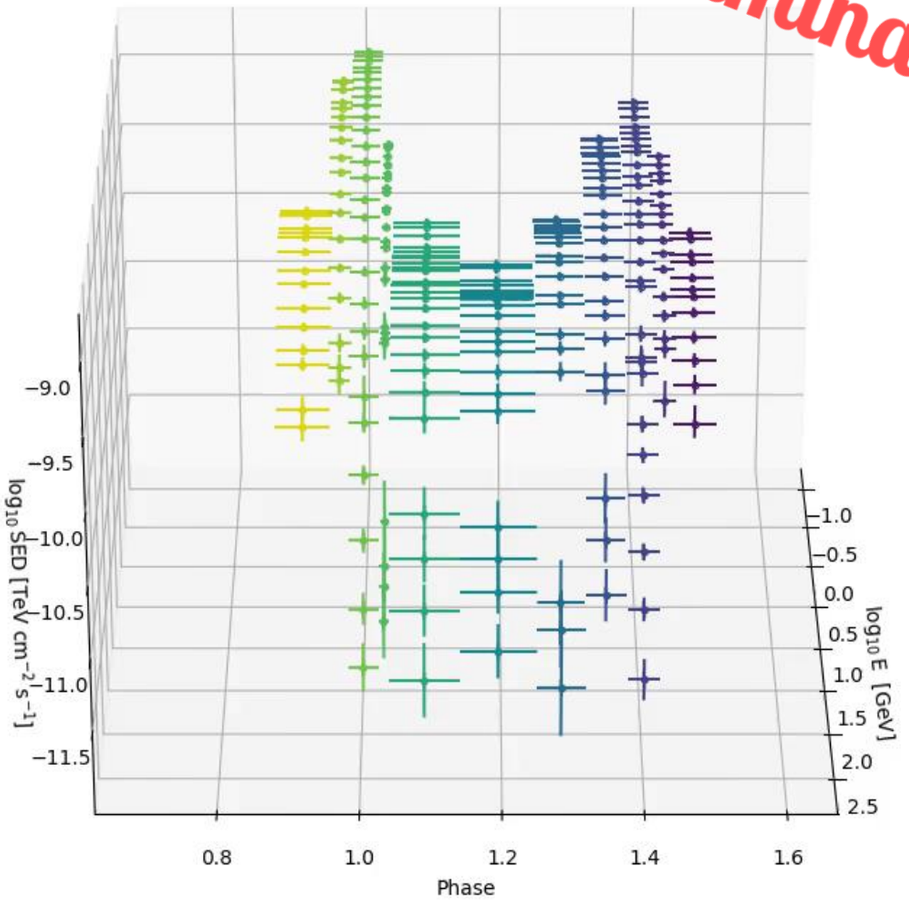
CRAB PULSAR PHASE DIAGRAM

- **Signal** and **background** selection in **phase**:
  - Suppresses the **systematic uncertainty** due to the **background estimation**.
- Combined **significance ~20 sigma** from **P1+P2** above **30 GeV**.
- Significance $\Sigma \sim \sqrt{at}$ with $a \sim 4\ h^{-1}$
- Sound **detection** of the **bridge emission** between **P1** and **P2**.



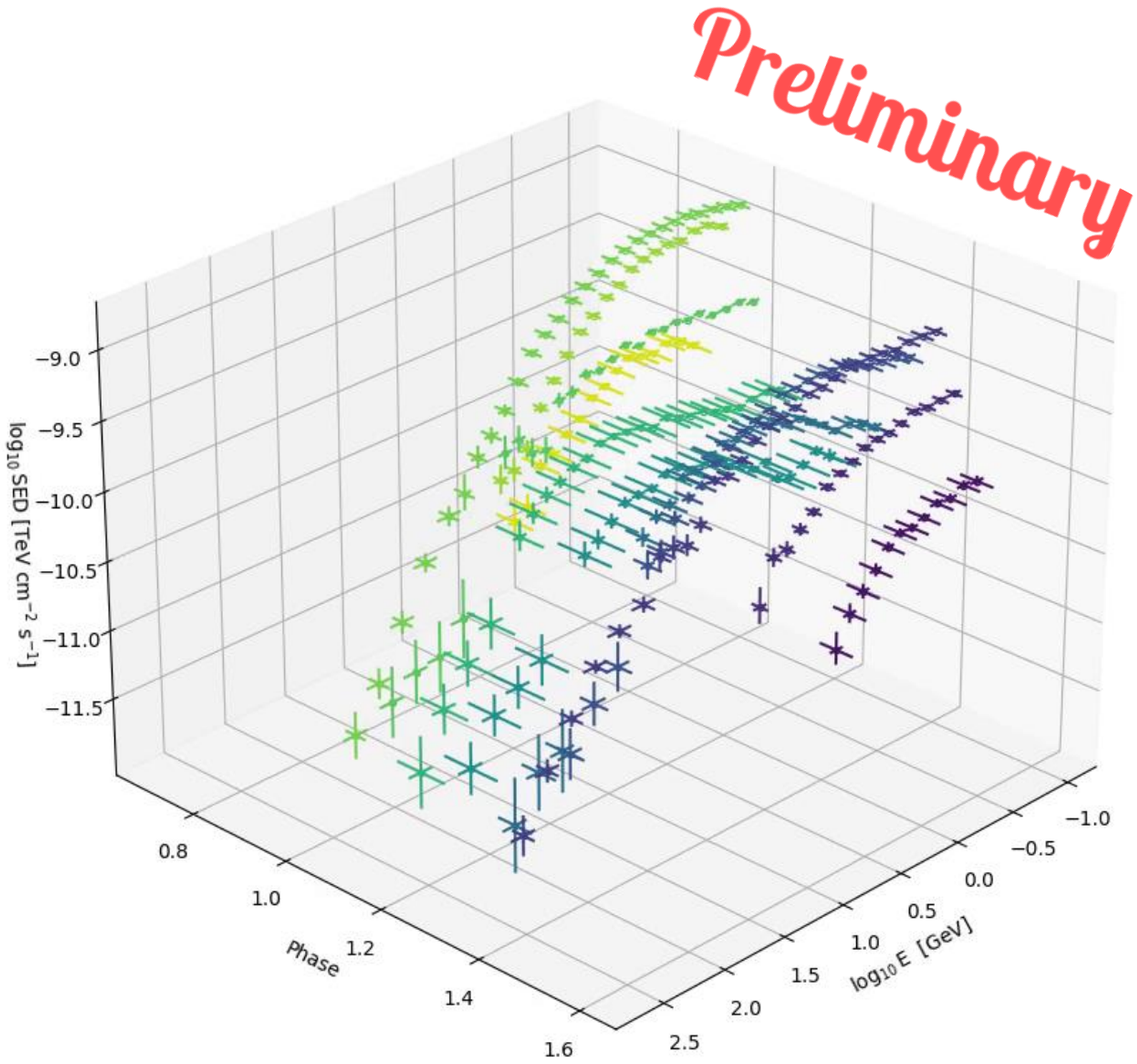
PHASE-DEPENDENT SPECTRA

Preliminary



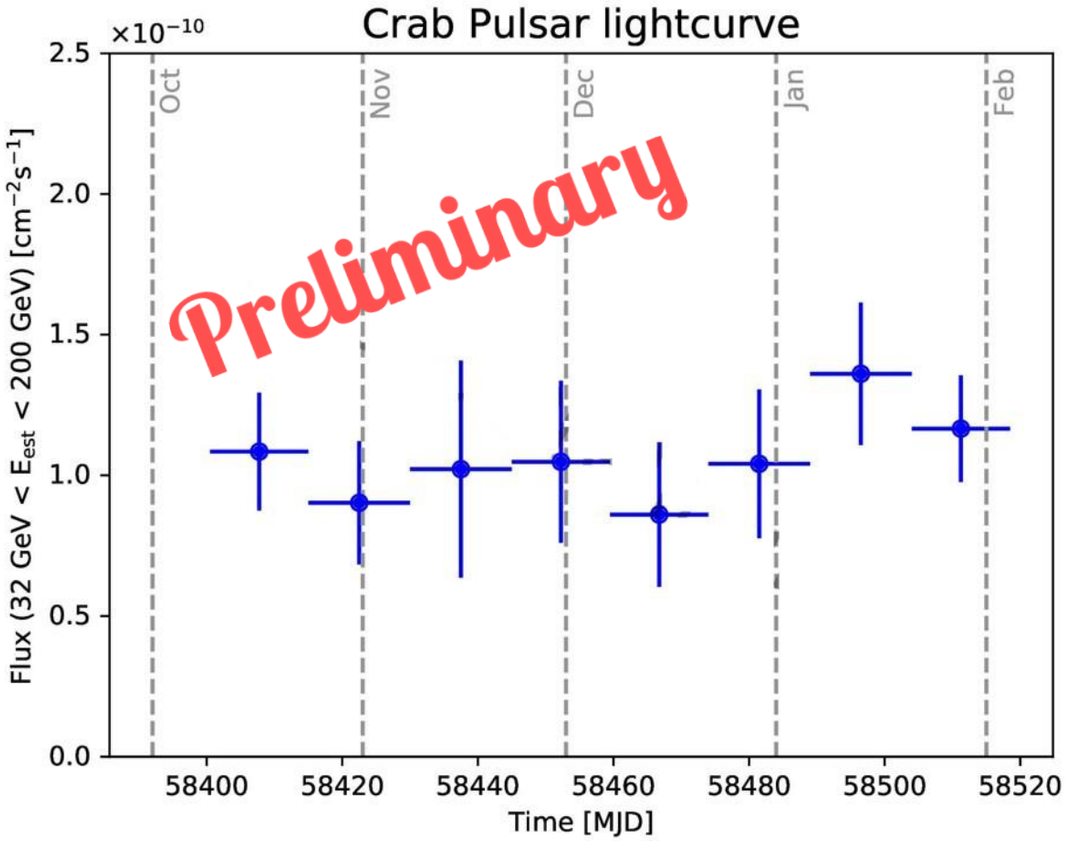
PHASE-DEPENDENT SPECTRA

- Phase interval divided in a set of **interesting regions**:
  - **P1**, **P2**, leading and trailing edges, **bridge**,…
- ***Fermi*-LAT** fluxes (12y) up to 30 GeV.
- **MAGIC** fluxes from **30 GeV** onwards.
- Plethora of possible data reductions: **spectra** vs. **phase**, flux **phase diagram** vs. **energy**, component **ratios**,…
- Finalization in progress, stay tuned.



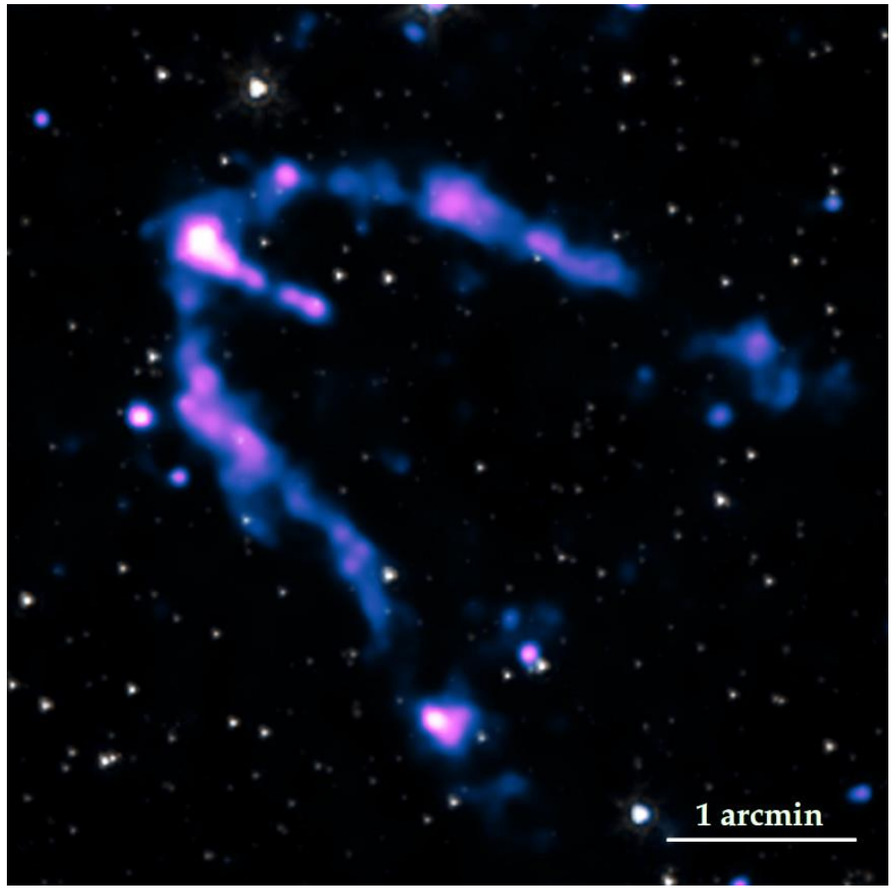
LONG-TERM LIGHTCURVE

- Sound statistics allows to **monitor** the **pulsed emission** over time.
- Crab pulsed flux over **4 months** in **2-week bins** (2018-2019 in figure).
- **Integral Flux** (30 – 200 GeV) consistent with **steady emission**:
  - Relevant for speculations on the origin of the Crab nebula flares (100 MeV).



GEMINGA PULSAR

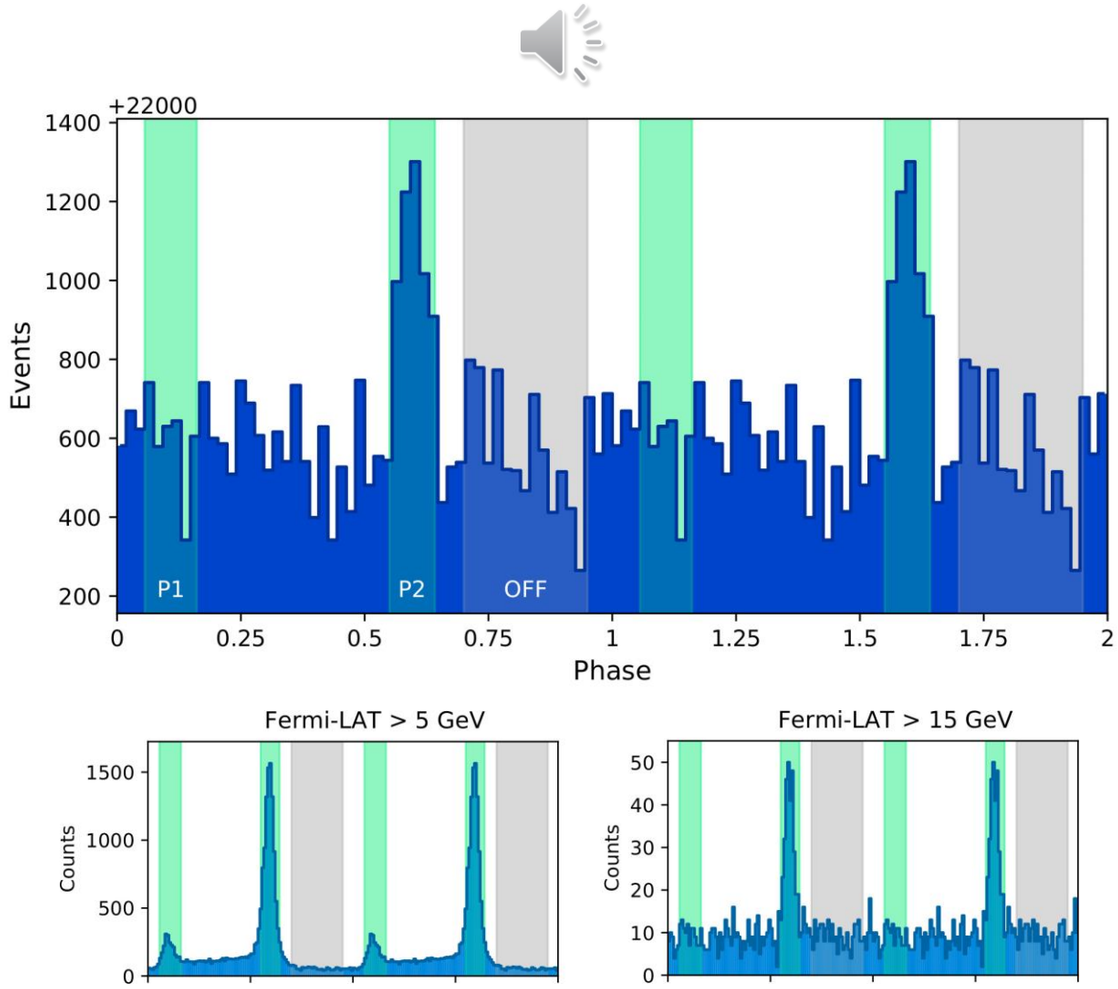
- **Middle** aged pulsar: **$3 \cdot 10^5$** years
- Less powerful than Crab: 10 · Sun
  Very close by: **250 pc**
- **Unusual** pulsar: **radio quiet**, **second brightest** steady source in the **GeV** sky
- Embedded in a vast **TeV halo**:
  - **Accelerated lepton** escape and **diffusion**
  - Possible contributor to the **positron spectrum** at the Earth



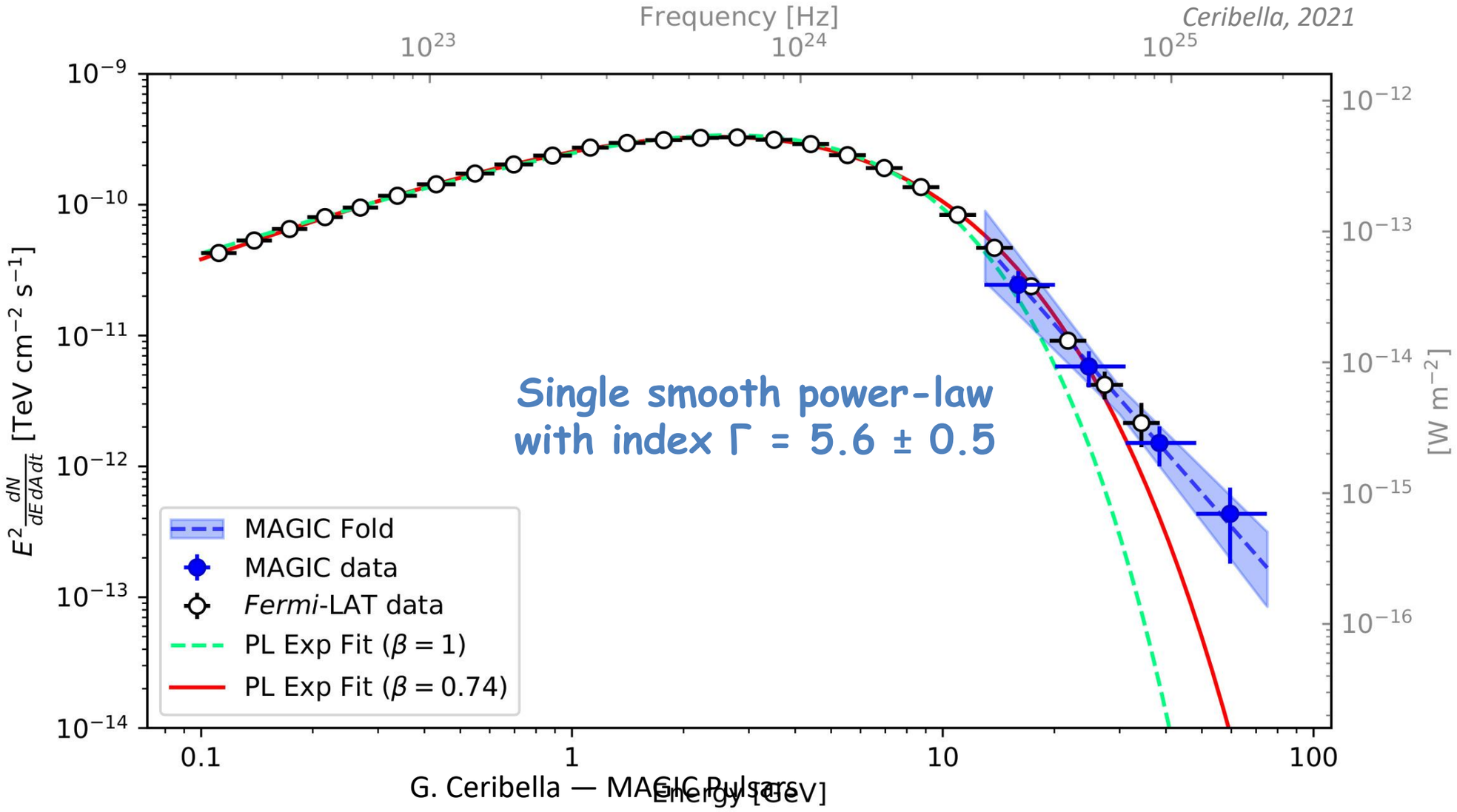
GEMINGA PULSAR

- **First ground-based detection** of **Geminga**, 15 GeV – 75 GeV
- **Third VHE pulsar** and the only **middle-aged** one so-far.
- Detection **significance**: **6.3σ**
- Reference article:

MAGIC Collaboration et al. (2020), *Detection of the Geminga pulsar with MAGIC hints at a power-law tail beyond 15 GeV*
10.1051/0004-6361/202039131



GEMINGA: SPECTRUM



GEMINGA: OUTER-GAP MODELLING

Inverse Compton efficient only with **head-on collision**

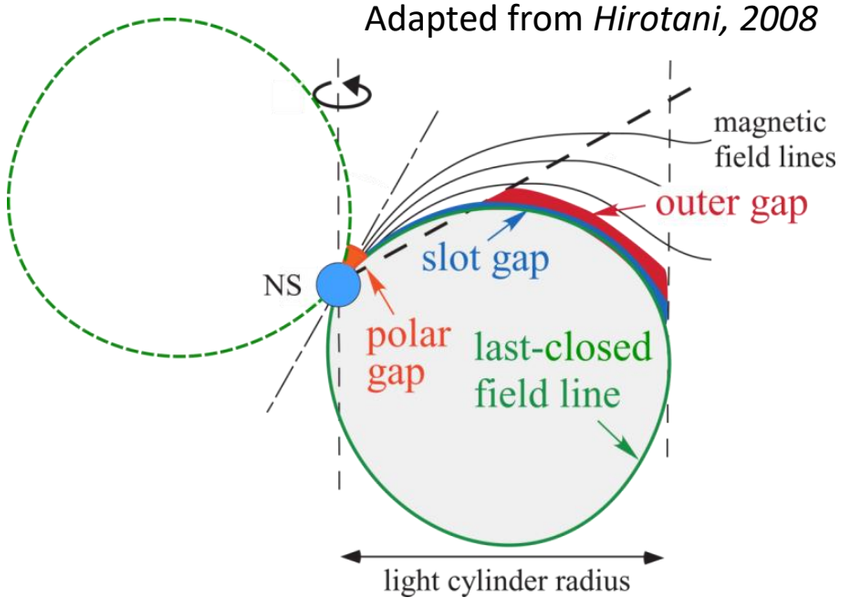
Electrons accelerated towards the star up-scatter thermal **X-rays**

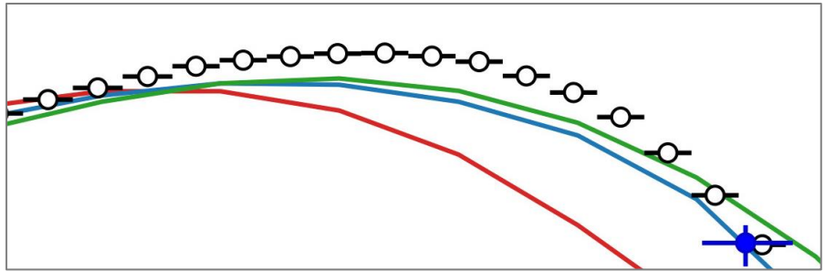
VHE emission in phase with **HE** if **viewing angle ~90 deg**

Disagreement with **GeV energy fluxes:**

- **Review** of the **OG model**
- **Alternative** scenarios

Adapted from *Hirotani, 2008*





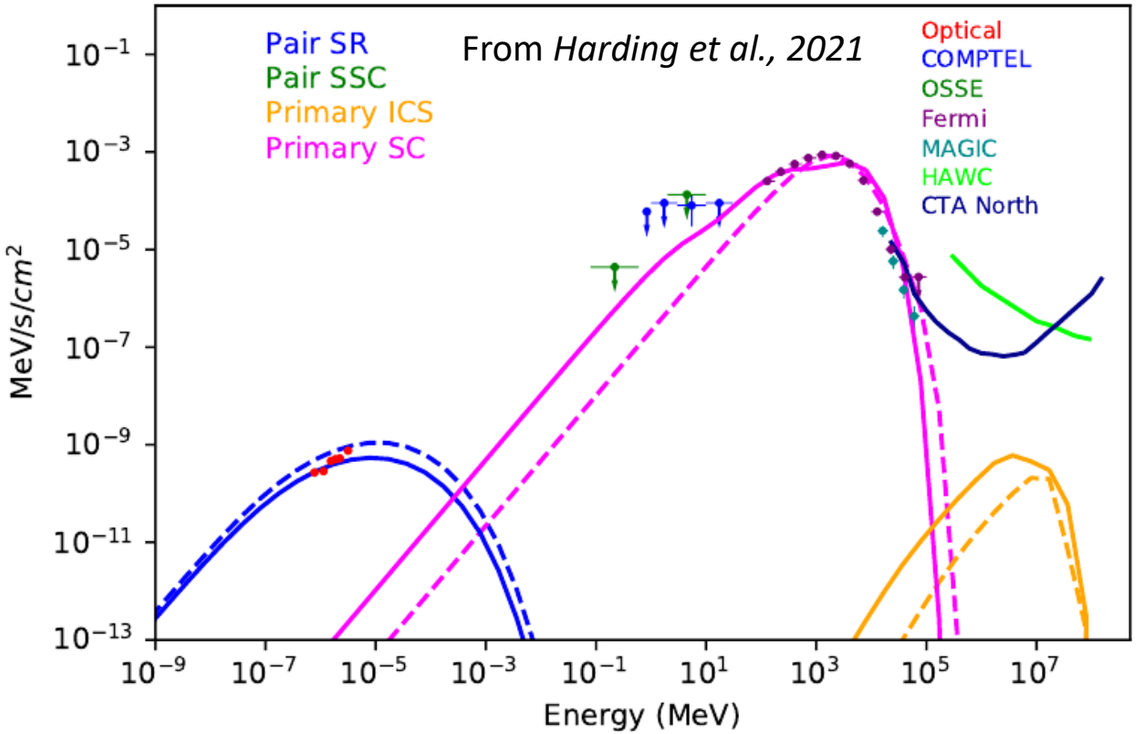
GEMINGA: CURRENT SHEET

Novel class of models supported by extensive **numerical simulations**.

Acceleration **just beyond the light-cylinder**, at the Y point.

Geminga emission explained as **primary synchro-curvature**, with **no inverse-Compton component**.

Depending on assumptions on the (unobservable) **radio flux**, based on **optical** emission.



SUMMARY

- The **acceleration** and **emission mechanisms** of gamma-ray pulsars still elude a full understanding.
- **MAGIC**, equipped with a **low-energy trigger** system, collected a unique sample on the Crab pulsar at the very-high energies consisting of **110h** with an energy threshold around **30 GeV**.
- Using also **Fermi-LAT** data, this gives a **full characterization** of the pulsed gamma-ray emission from **hundreds of MeV** to **hundreds of GeV**.
- The **sound statistics** enables for the first time to explore the emission **jointly in phase and energy**, and to derive **long-term light-curves**.
- More coming soon… stay tuned!

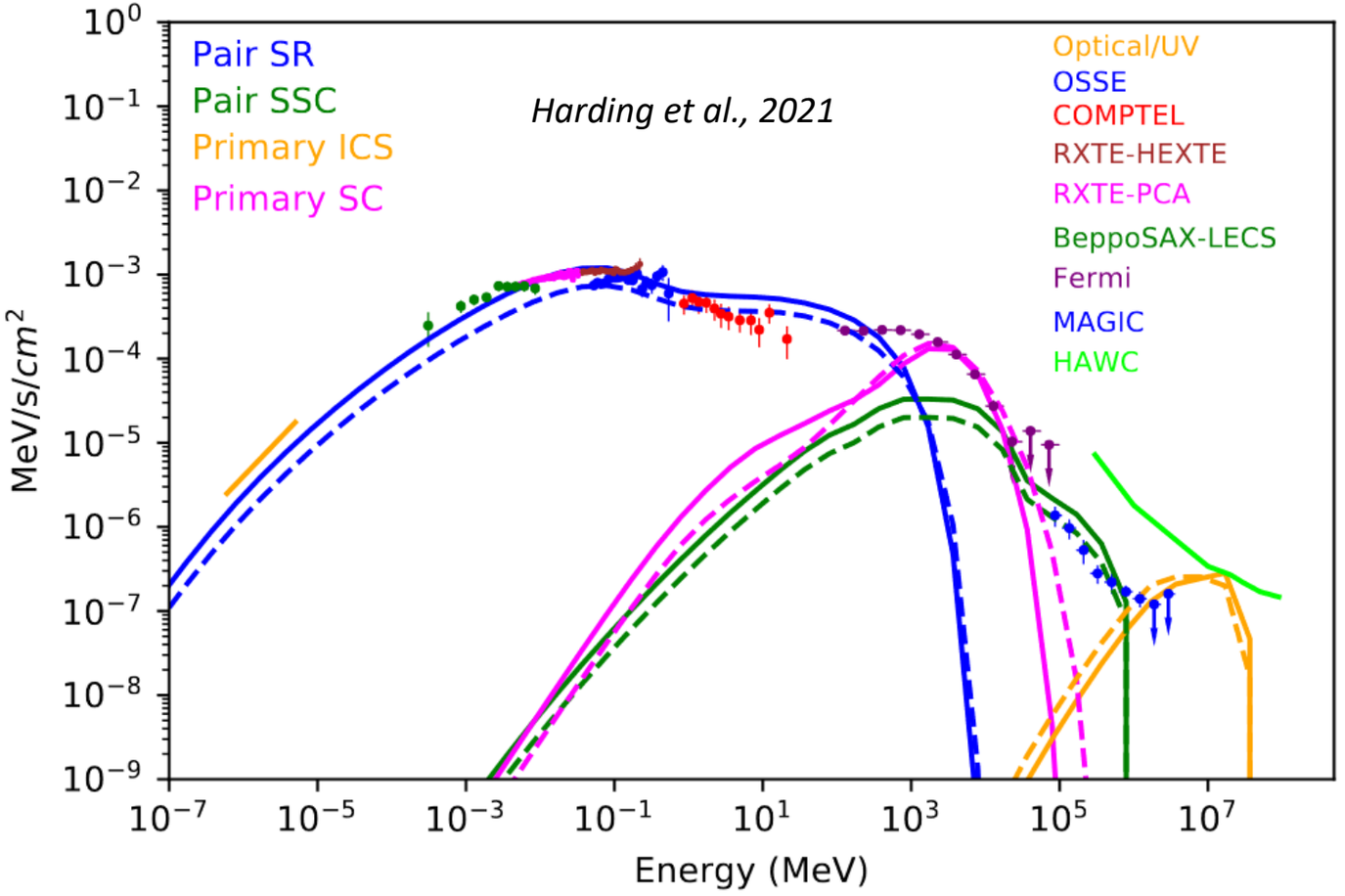
BACKUP

MAGIC AND THE SUM-TRIGGER-II

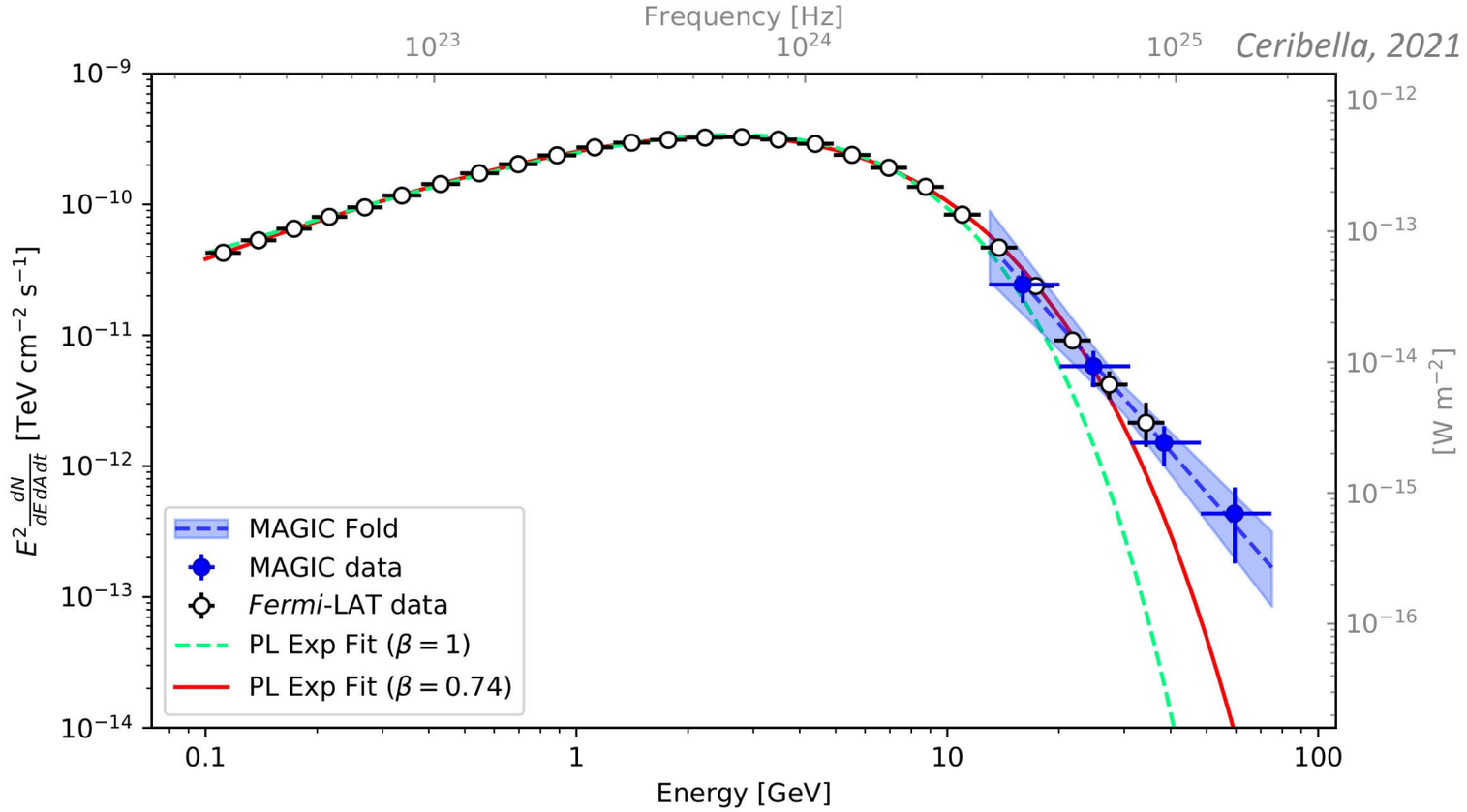
- Two imaging **Cherenkov telescopes** (⌀17m) in **La Palma** (Canaries, Spain).
- Special **low-energy trigger** for soft sources.
- Lowered **trigger energy threshold**: **20 GeV**.
- **Four-fold increase** of the **collection area**.
- **Sum-Trigger-II** reference publication:

  F. Dazzi et al., ***The Stereoscopic Analog Trigger of the MAGIC Telescopes*** (2021) DOI: 10.1109/TNS.2021.3079262

CRAB EQUATORIAL CURRENT SHEET MODEL

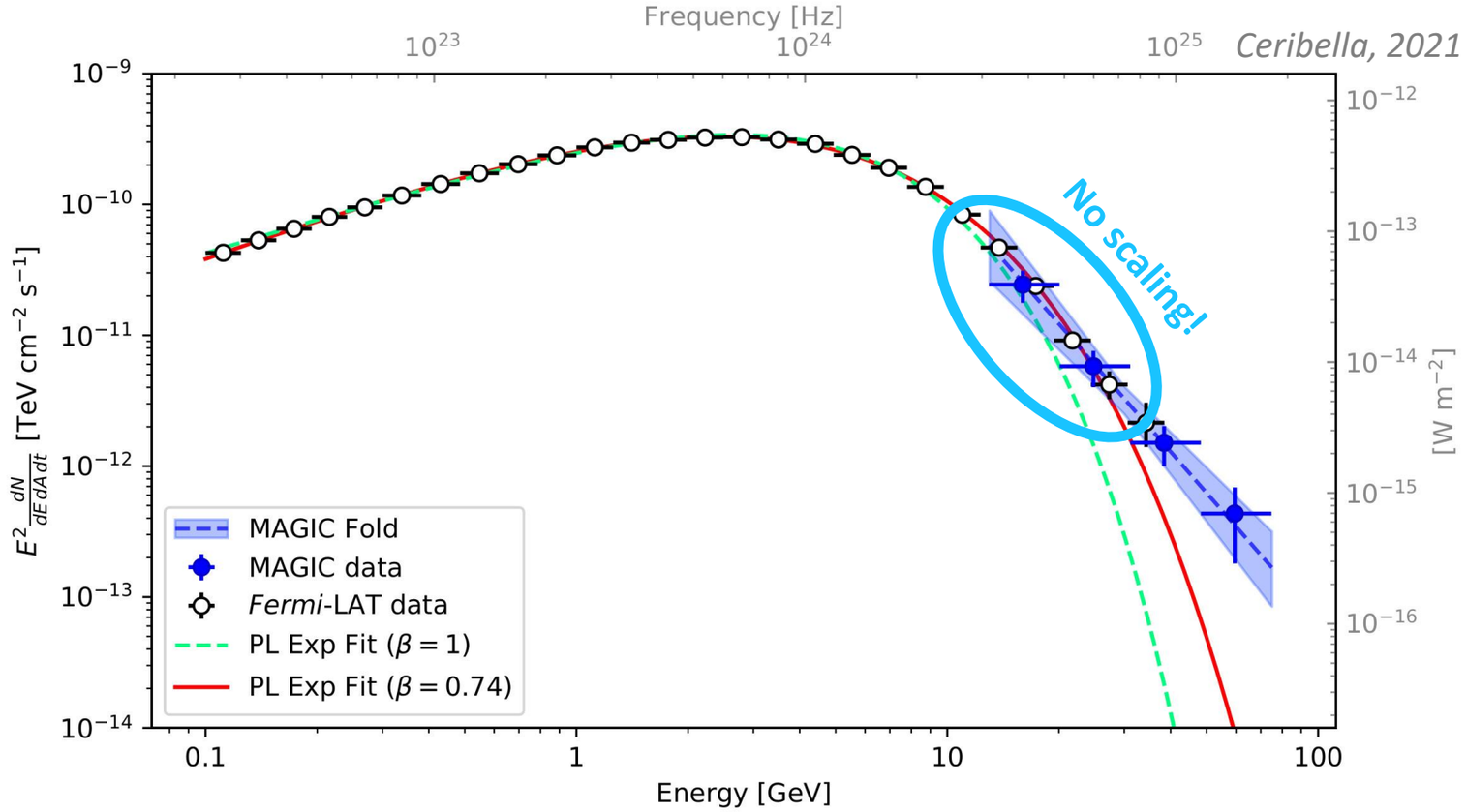


GEMINGA: SPECTRUM



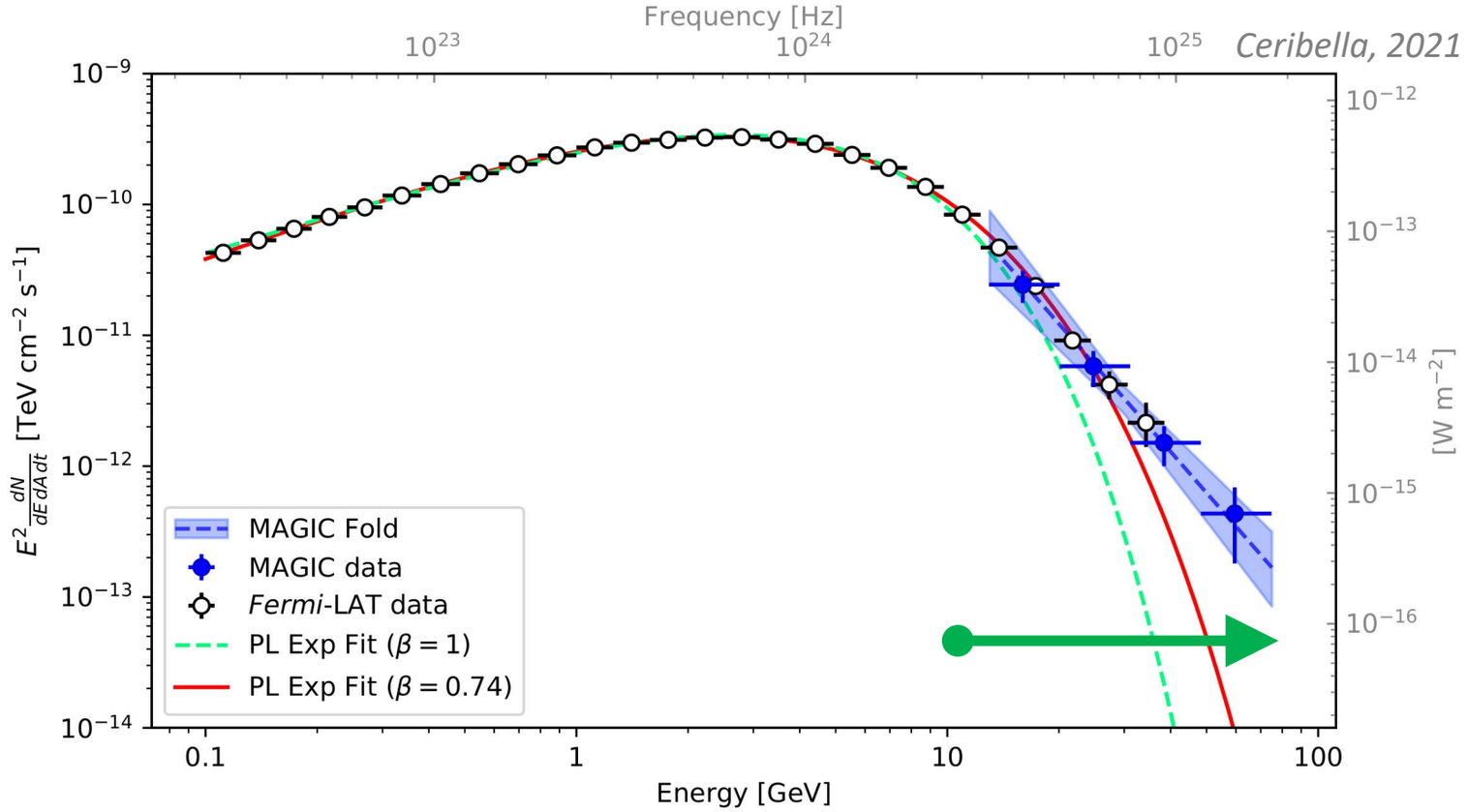
- **MAGIC** measured **P2 spectrum** in the **15 GeV – 75 GeV** range
- Apparently a **single smooth power-law** with index **Γ = 5.6 ± 0.5**

GEMINGA: SPECTRUM



- **Joint** MAGIC and *Fermi*-LAT **spectral fits** (cutoff power law)
- **Pure exponential** cutoff case **rejected** with **>18σ** significance

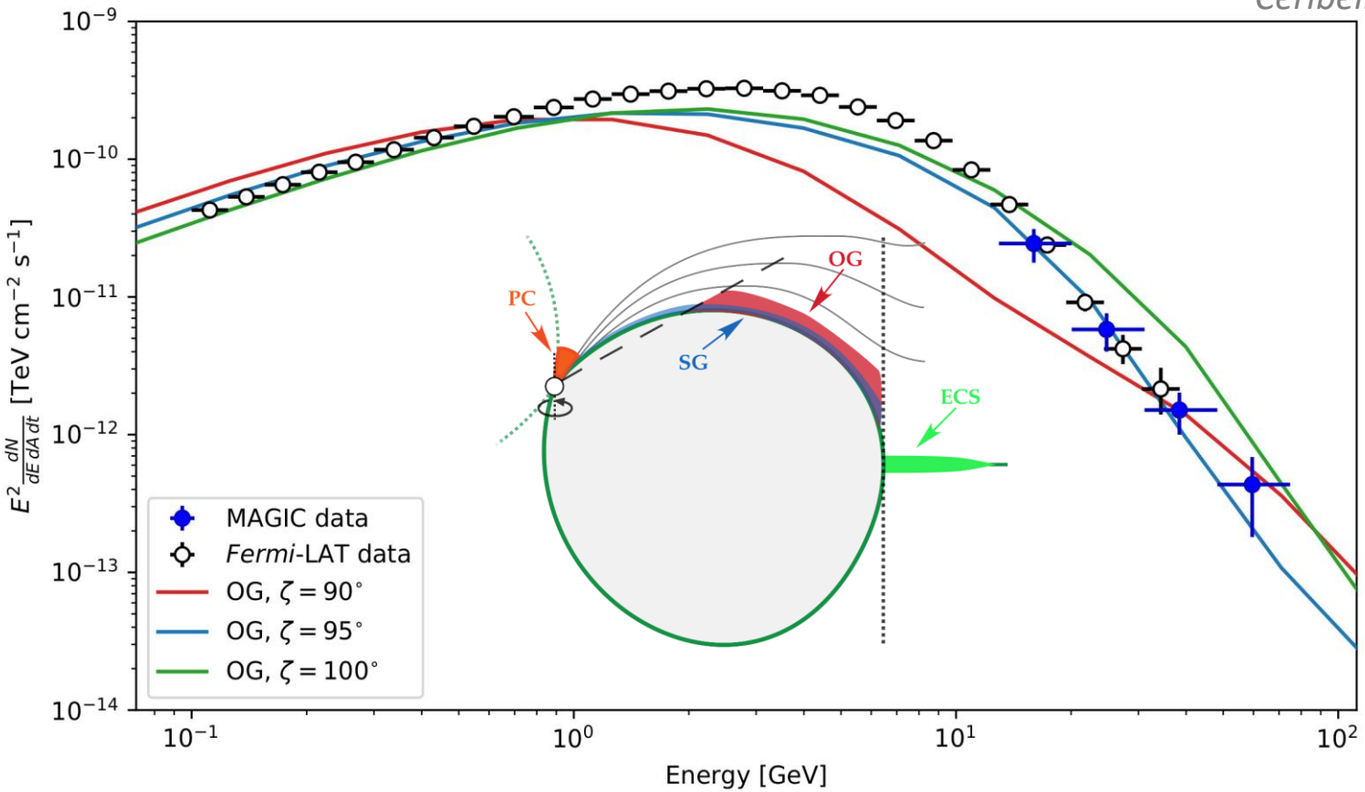
GEMINGA: SPECTRUM



- **Sub-exponential** cutoff power law **in tension** with data (3.6σ significance)
- **Power-Law** vs. **Log-Parabola** (**E>10 GeV**): **no preference for curvature**

GEMINGA: SPECTRUM

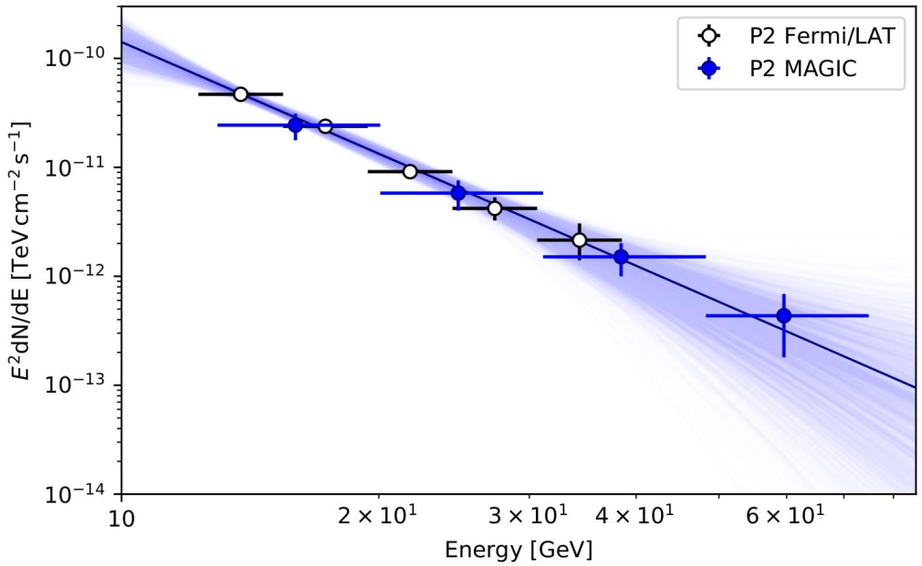
Ceribella, 2021



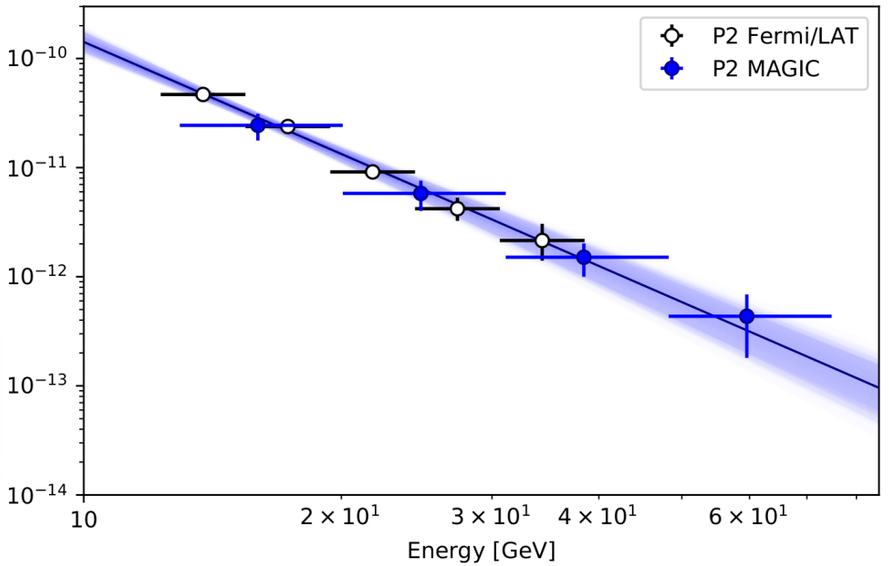
- **Inverse Compton** component?
- **Outer gap model** study: IC **possible**, but **limited agreement** with **data**

POWER-LAW VS LOG-PARABOLA

LOG-PARABOLA



POWER-LAW



GEMINGA OBSERVATIONS

- Observation time: **80h** (2017 – 2019)
- Stringent **quality cuts**
- Contemporary **Crab pulsar** and **nebula** observations
- Pulsar **ephemeris** from ***Fermi*-LAT** data (11y)
- **Signal** and **background** ROI selection in **phase space**.