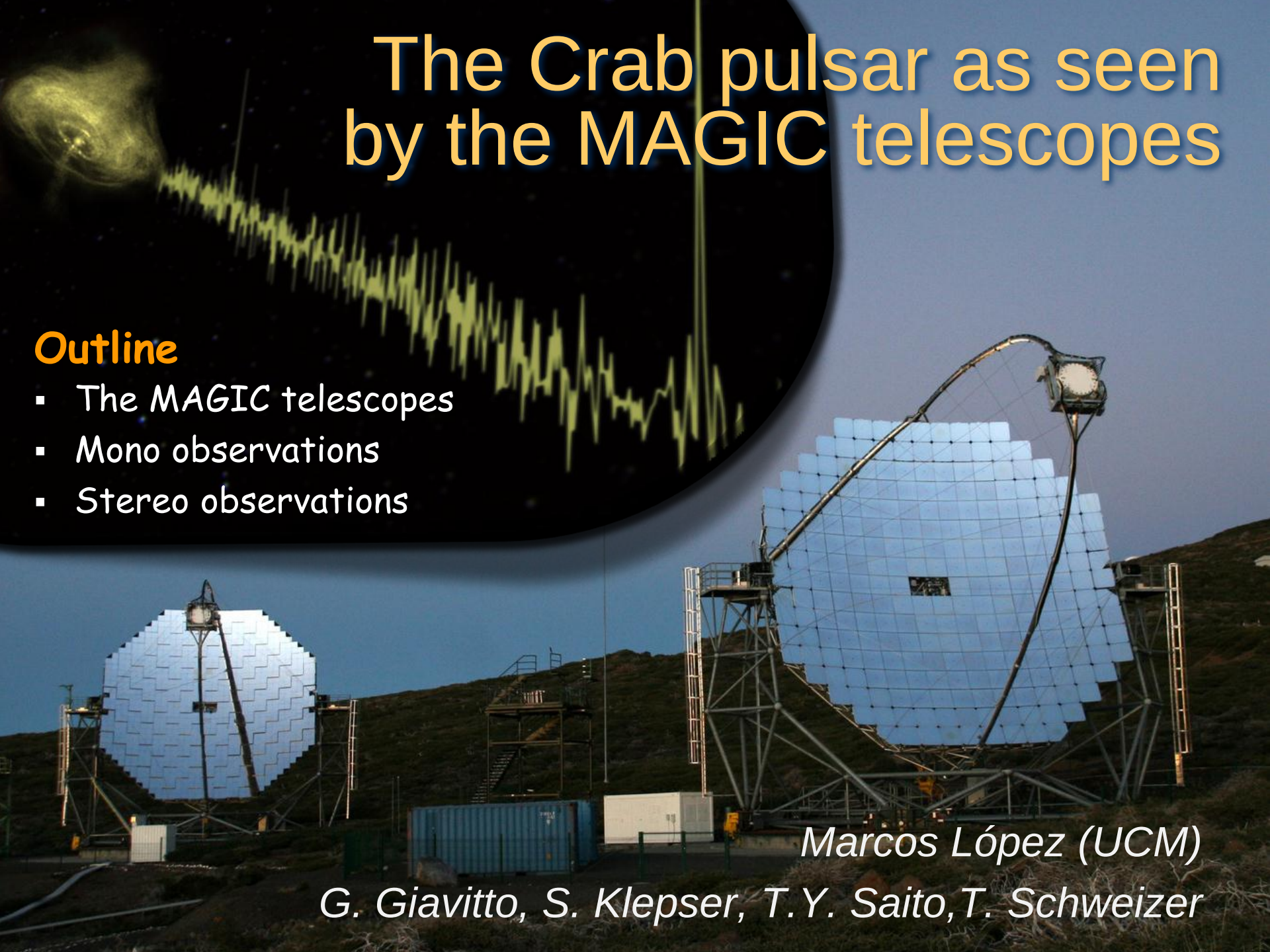
The Crab pulsar as seen by the MAGIC telescopes

Outline

- The MAGIC telescopes
- Mono observations
- Stereo observations



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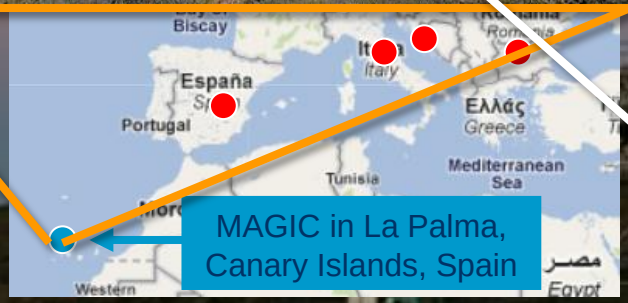
G. Giavitto, S. Klepser, T.Y. Saito,T. Schweizer

Collaboration: ~ 150 Physicists, 21 Institutes, 8 Countries:



Goal: Achieve the lowest energy threshold among CTs

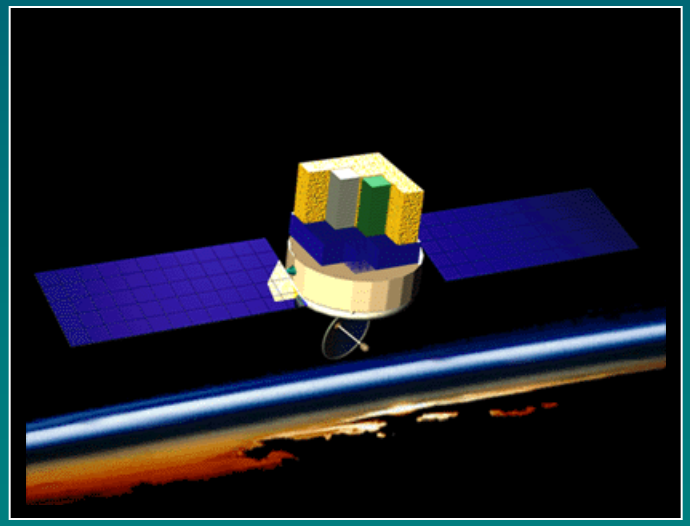
Close gap between space & ground-based gamma-ray telescopes

The Cherenkov technique

Basic fact: Gamma-rays absorbed in atmosphere

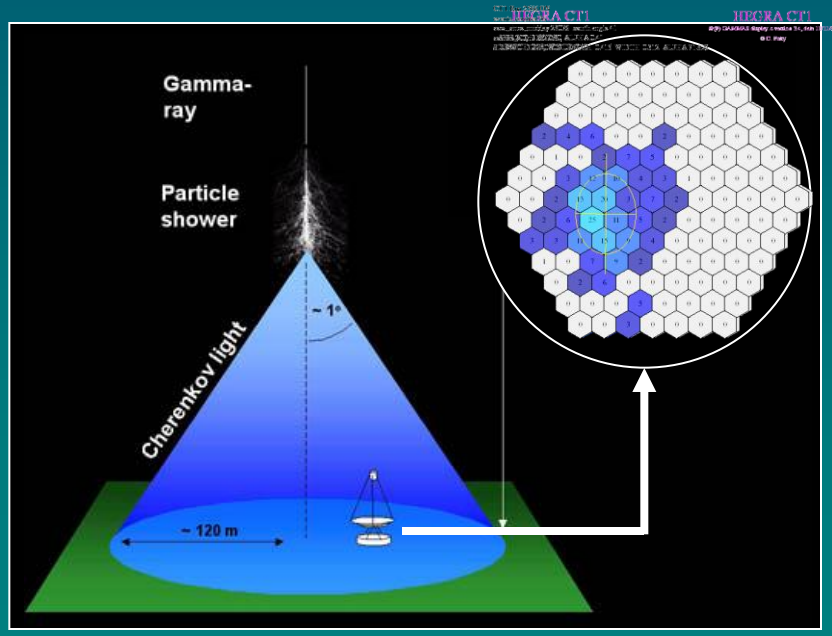
Satellites

- **Direct detection**
- Small background
- Small Effective Area ~1m^2



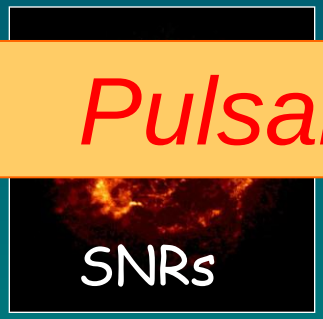
Ground Detectors

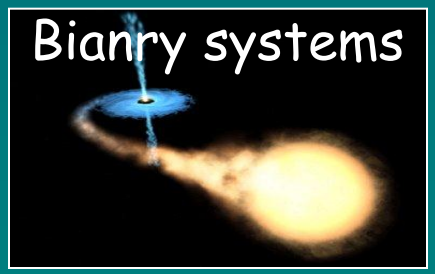
- **Indirect detection**
- Enormous hadronic background
- Huge Effective Area ~ 10^{5}m^2



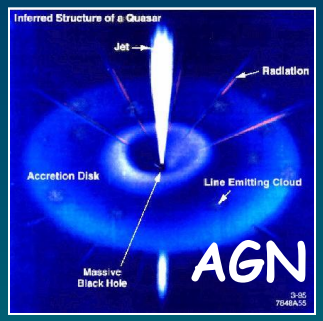
MAGIC Physics Targets

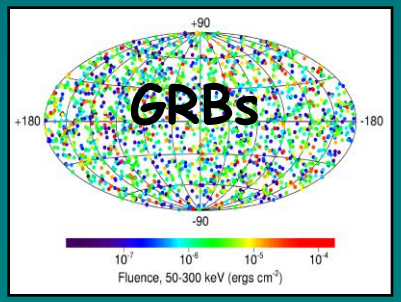
Galactic



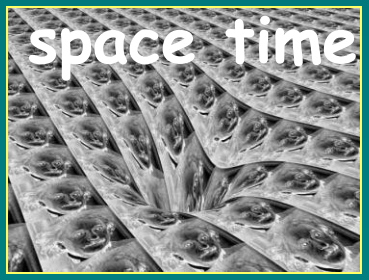


Extragalactic





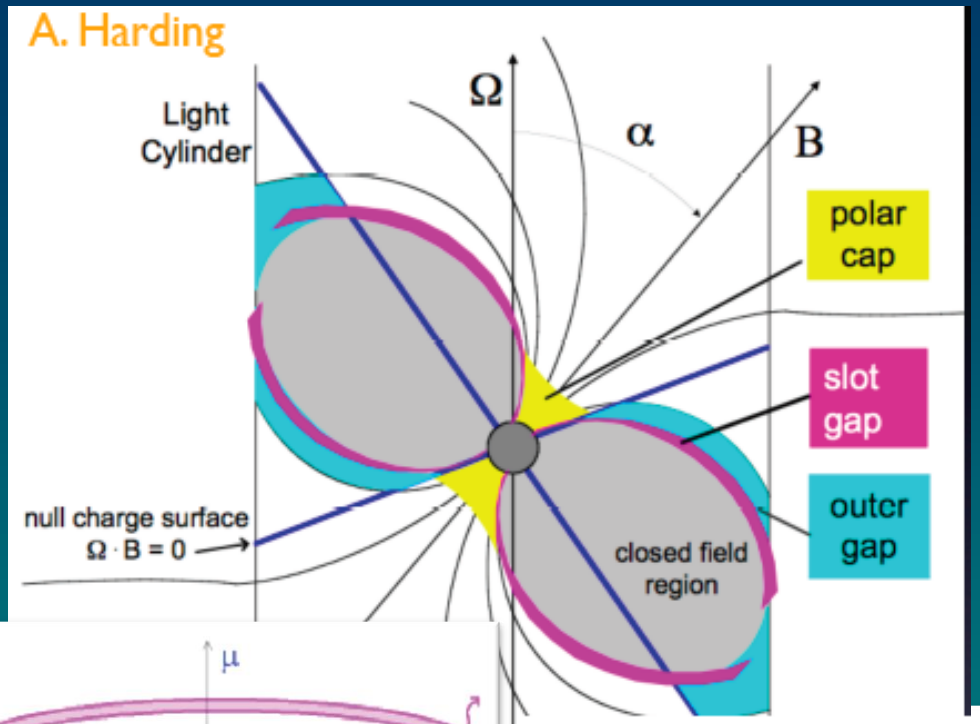
Fundamental Physics

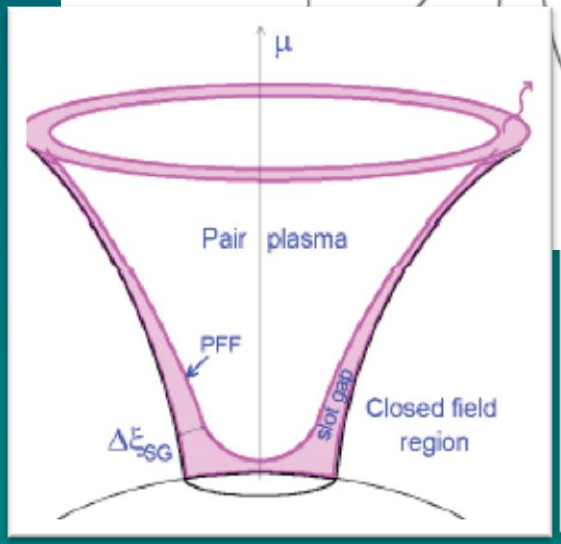


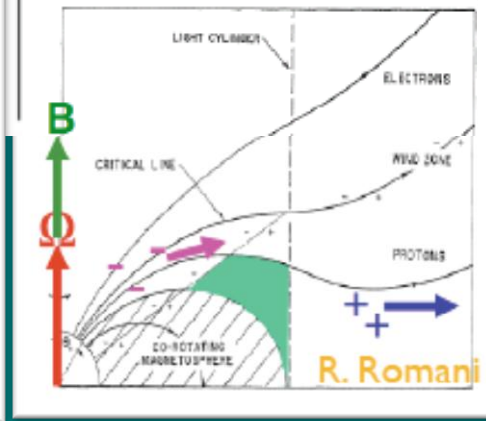
Pulsars one of the hottest topics

Pulsar models: overview

- Different models try to explain observed γ-ray emission.
  - Assume different emitting region in magnetosphere ➔ different emission geometry: PC, OG, SG
- Spectrum depends on the physics of the emitting region
- Light curves depend on geometry



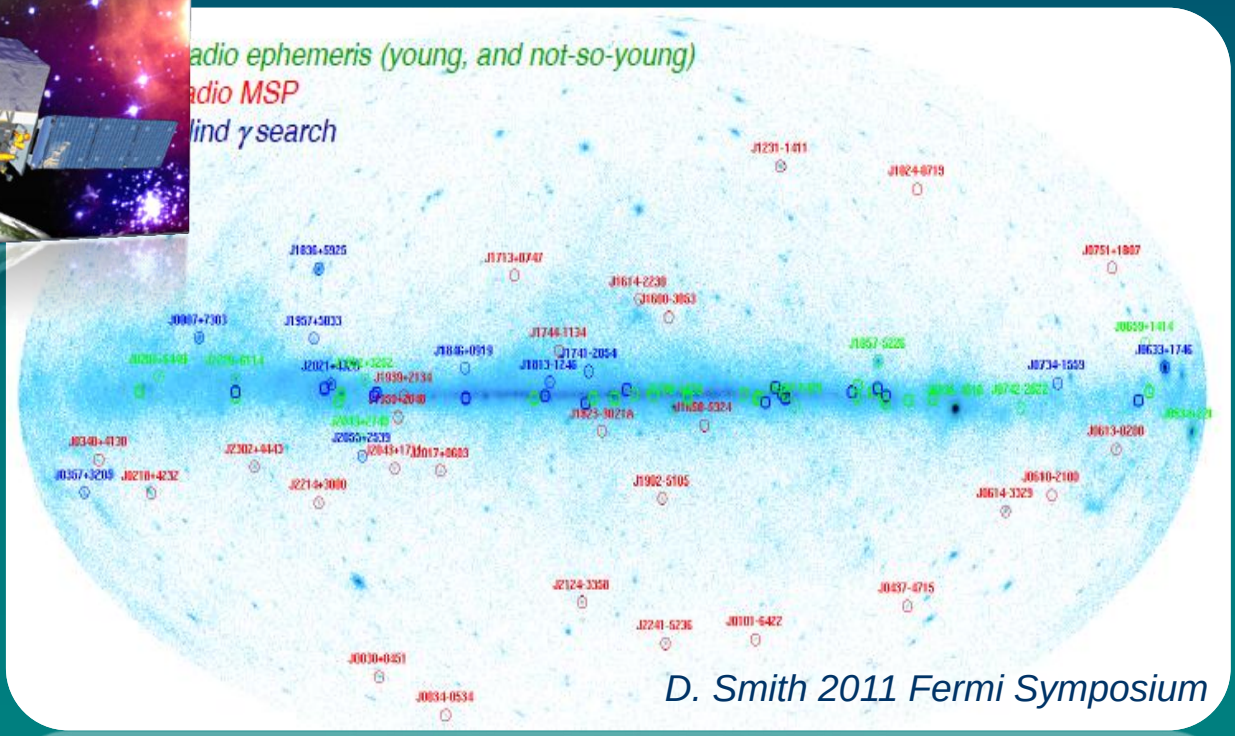




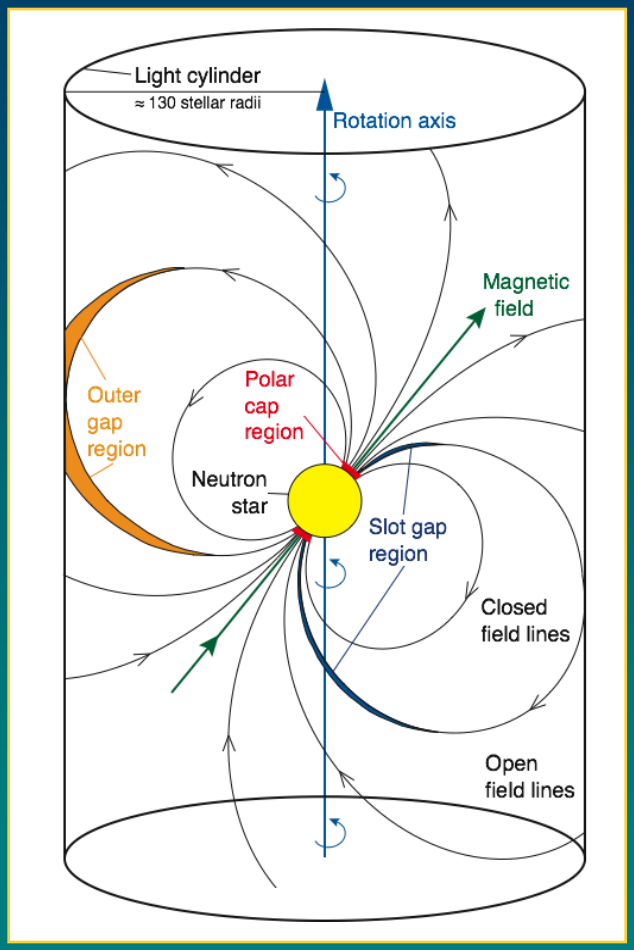
Gamma-ray pulsars with space telescopes

- 101 pulsars found by Fermi
- Spectra up to ~10 GeV consistent with exp. cutoff

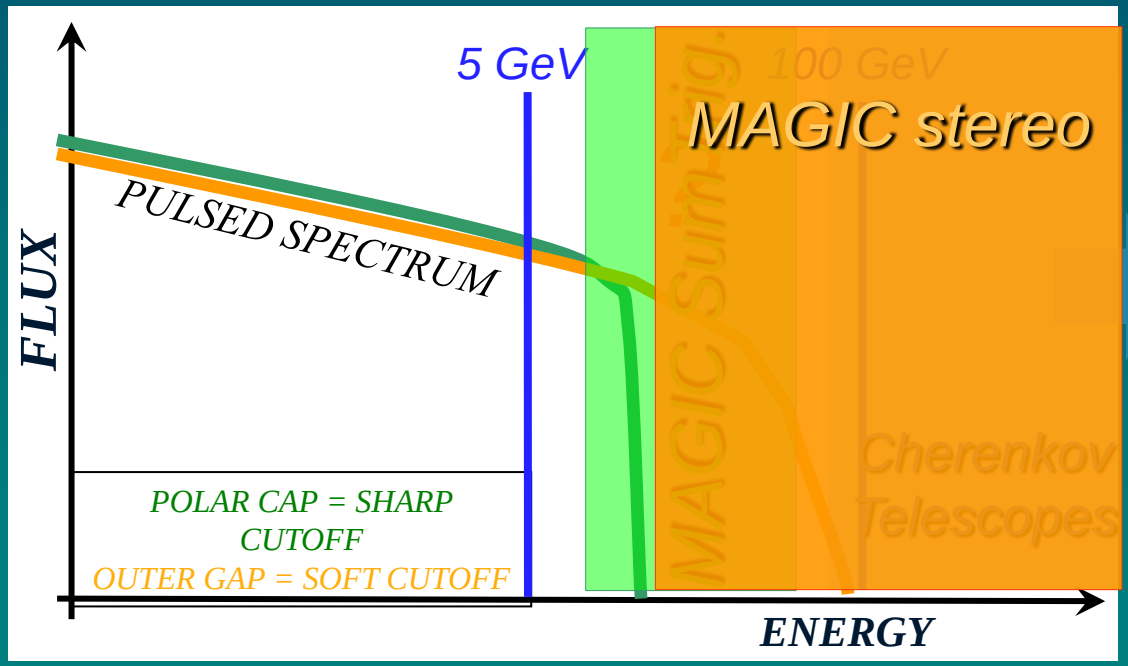
- *Polar Cap rejected*
- *Outer Gap favored*



Are Pulsars visible in VHE ϒ-rays?



- *Models for HE emission (polar cap, outer or slot gap) predict exp. or super exp. cutoffs @ few GeV.*
- *Observational challenge for CTs since 20 years*



Pulsar observations modes with MAGIC

- MAGIC tried from the very beginning to detect pulsars
  - Developed dedicated hardware to help to the pulsar program (central pixel, sumtrigger,…)

	Mono (2004-2007)	**Mono (2007-2009)**	**Stereo (2009-2011)**
Telescopes	MAGIC I	MAGIC I	MAGIC I & II
Energy threshold	60 GeV	25 GeV	50 GeV
Sensitivity > 100 GeV	7.5% Crab	4.4% Crab	1.6 % Crab
	Insufficient sensitivity	The lowest threshold	The best g/h separation

MAGIC Crab pulsar Timeline

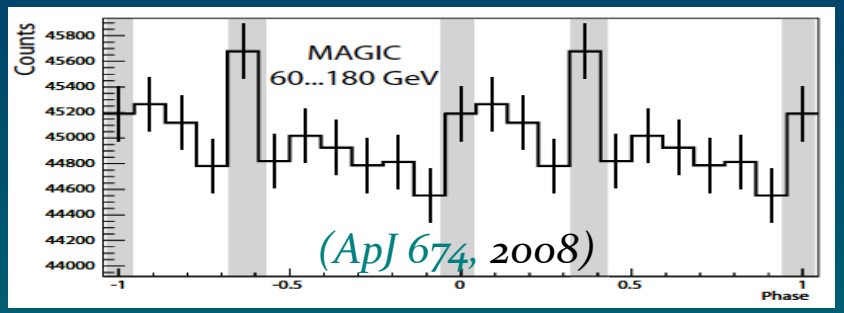
Sum trig. developed

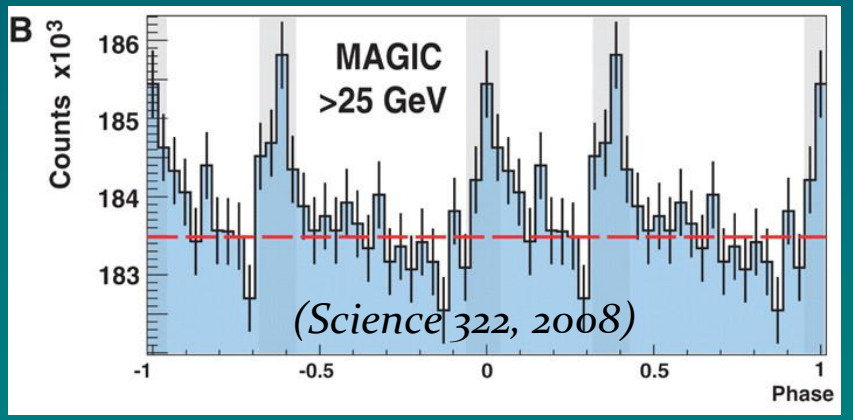
Fermi launched

MAGIC II commissioned

- *Oct. – Dec. 2005*
  std. trigger (>60 GeV)
  2.9 σ excess in P2!
- *Oct. 2007 – Feb 2008*
  sum trigger (> 25 GeV)
  6.4 σ excess in P1+P2!!
- *Oct. 2008 – Feb 2009*
  sum trigger (> 25 GeV)
- *Oct. 2009 – Feb 2011*
  stereo trigger (> 50 GeV)

Hint





Detection

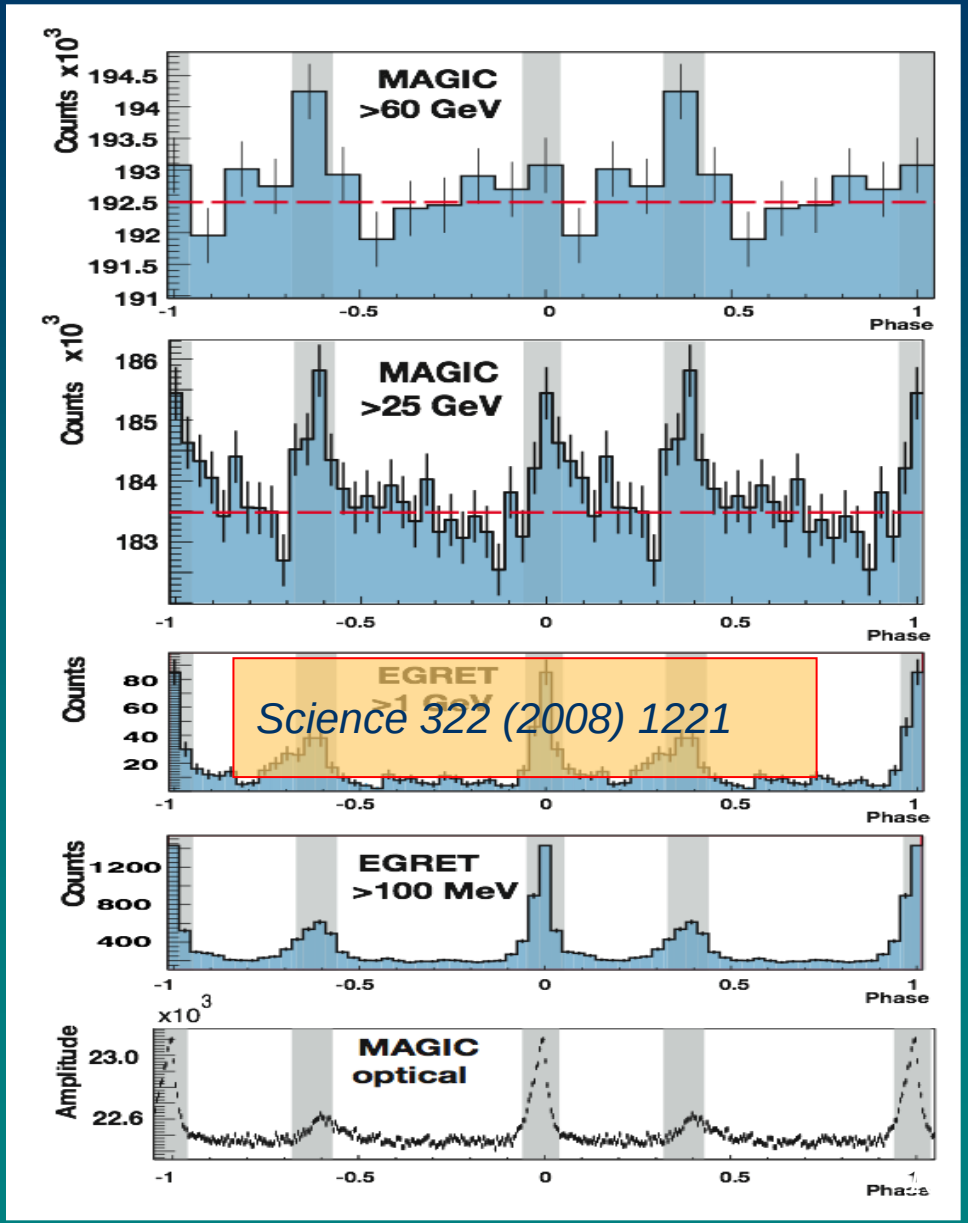
First Crab pulsar detection above 25 GeV

Mono Observations with sumtrigger
- Oct.07 to Feb.08: 22.3 h

Clear detection: 6.4σ
Pulses in phase with EGRET

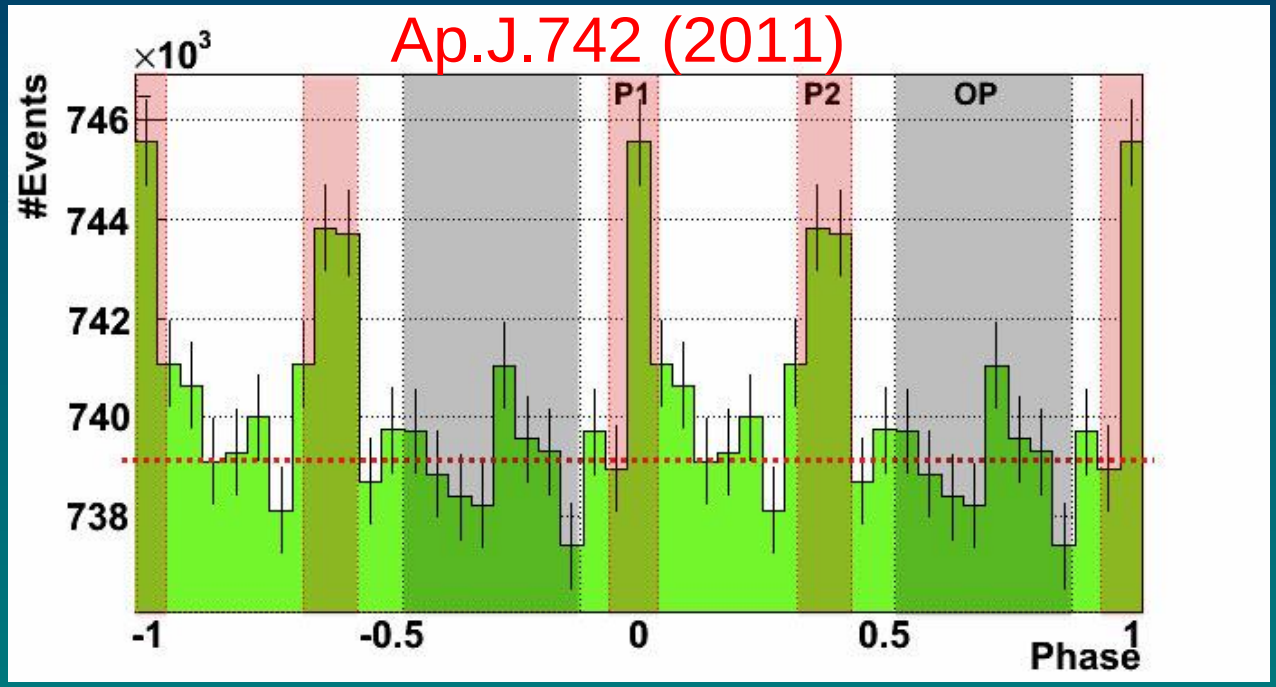
P1 clearly visible at 25 GeV →First Surprise

Pulsed emission still visible > 60 GeV ! P2 became dominant



Mono observations (2007-2009): Detection

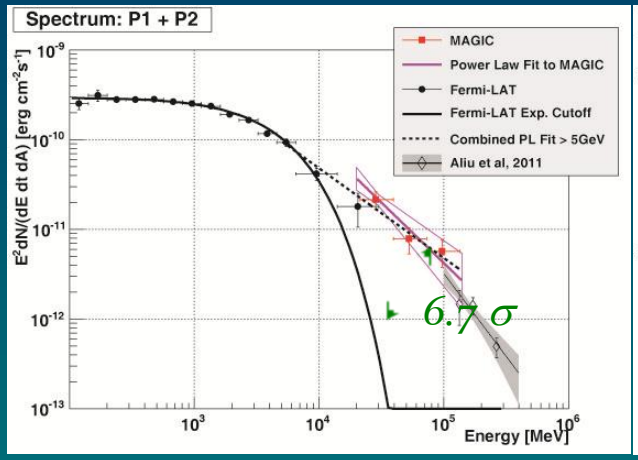
- 59 hours from Oct. 2007 to Feb. 2009 with SumTrigger

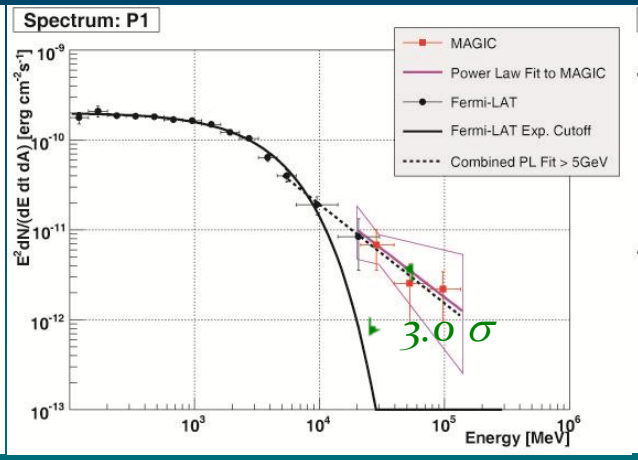


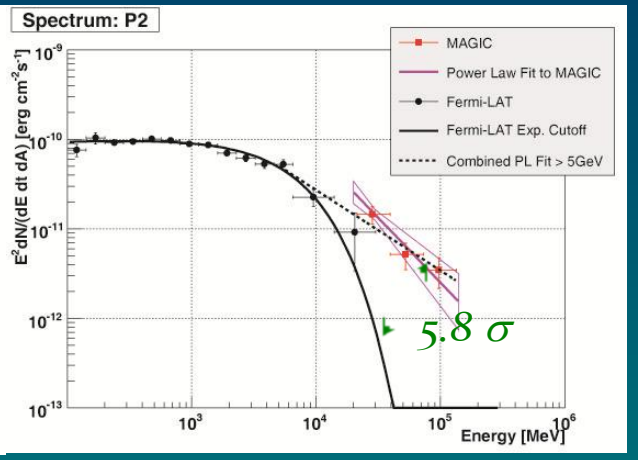
P1 (-0.06-0.04): 6200 +- 1400 events (4.3 σ)
P2 (0.32-0.43) : 11300 +- 1500 events (7.4 σ)
P1+P2 : 17500 +- 2300 (7.5 σ)

Mono observations (2007-2009): Spectrum

- Obtained total pulsed spectrum and spectra for each peak separately up to **100 GeV**







Inconsistent with the extrapolation of the exponential cutoff (>5 σ). Spectra between 25 GeV and 100 GeV show a power law.

	P1 + P2	P1	P2
F_0 at 30 GeV $[10^{-9}$ cm^{-2} s^{-1} TeV$^{-1}]$	3.1+-1.0+-0.3	4.5+-2.3+-2.6	10.0 +-1.9 +- 2.6
Index	-3.4+-0.5+-0.3	-3.1 +- 1.0 +- 0.3	-3.4 +- 0.5 +- 0.3

MAGIC stereo

Two 17m telescopes observing in stereoscopic mode since ***fall '09***

Why stereo?

Stereoscopic provides: better reconstruction of shower direction & additional shower parameters

This means:

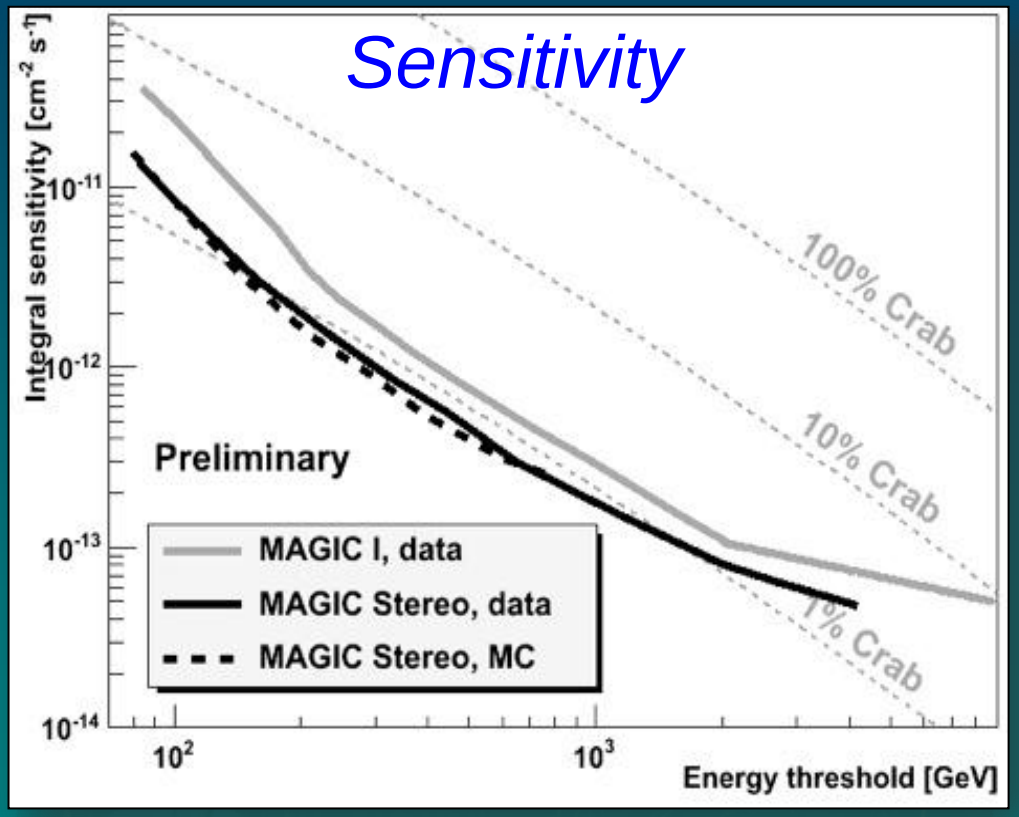
- Better hadron rejection
- Better angular resolution:

0.1º@100 GeV, down to 0.04º E>1 TeV

- Better energy resolution:

20%@100 GeV, down to 15% at 1 TeV

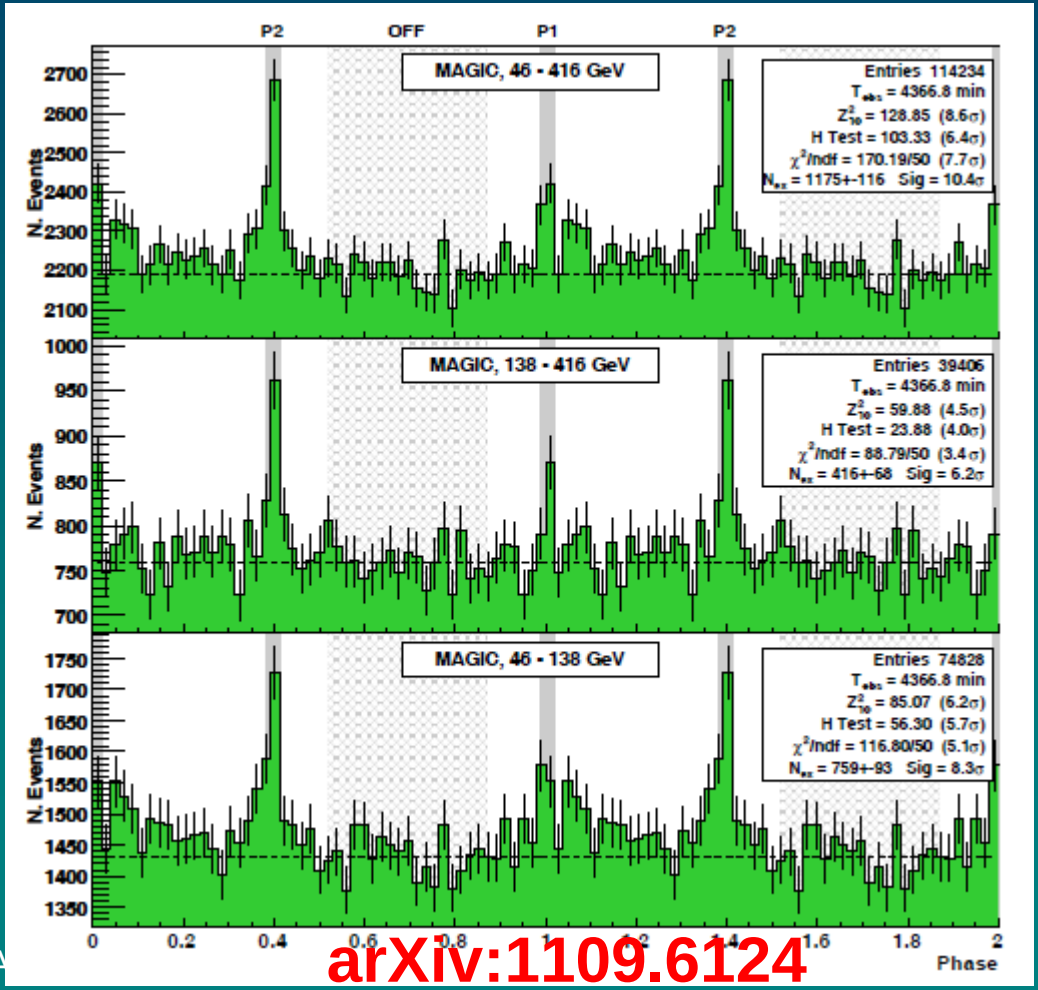
- Enhances the sensitivity over the whole energy range (2-3 better)
- Energy threshold: ~ 50 GeV



Most sensitive observatory in the range 50-200 GeV

Stereo observations (2009-2011): Detection

- Used 73 h of stereo data from Oct09 to Feb1
  - 43 Wobble, 30 ON/OFF



H-test gives 6.4 σ

P1: 356 +- 69 events (5.2 σ)

P2: 880 +- 101 events (8.9 σ)

Pulsed emission detected up to 400 GeV !!

arXiv:1109.6124

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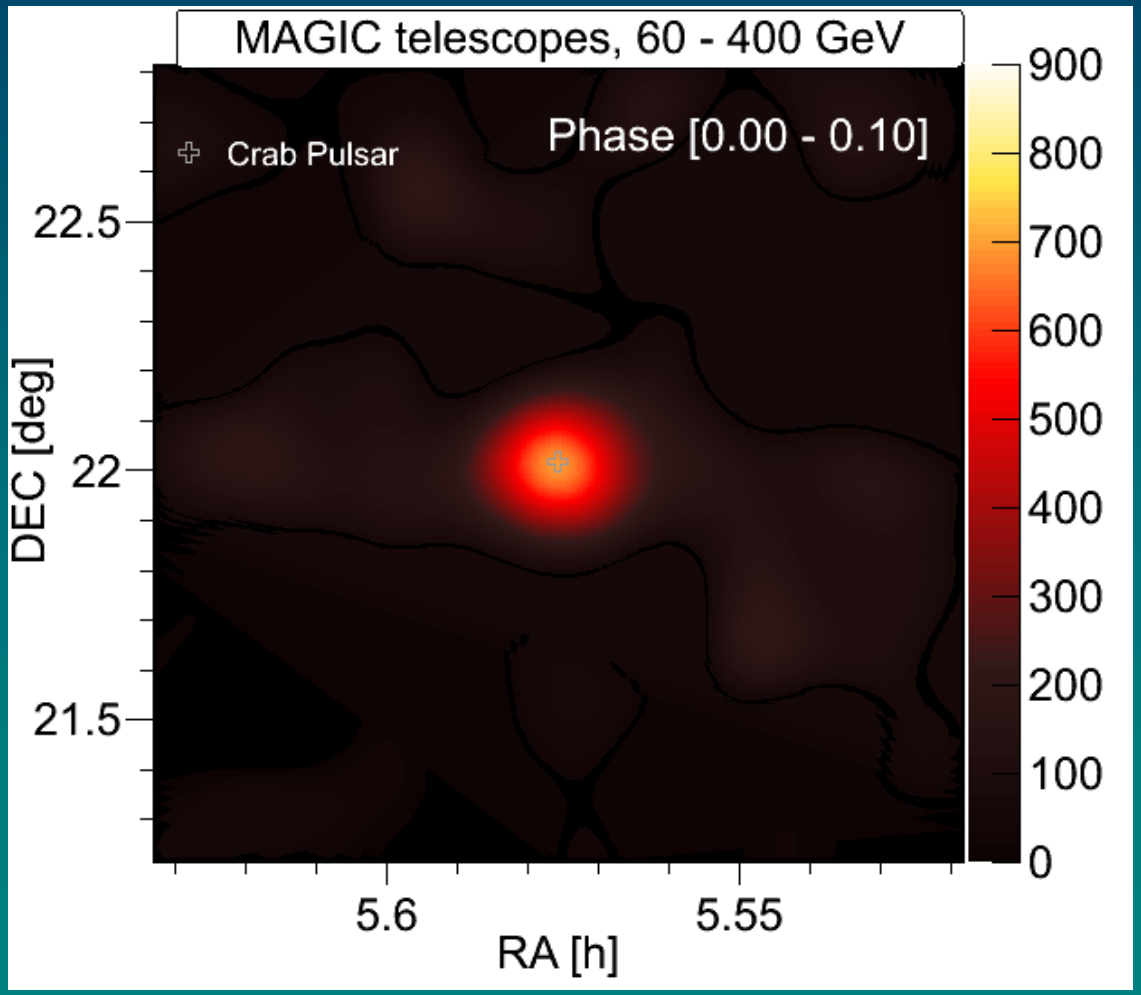

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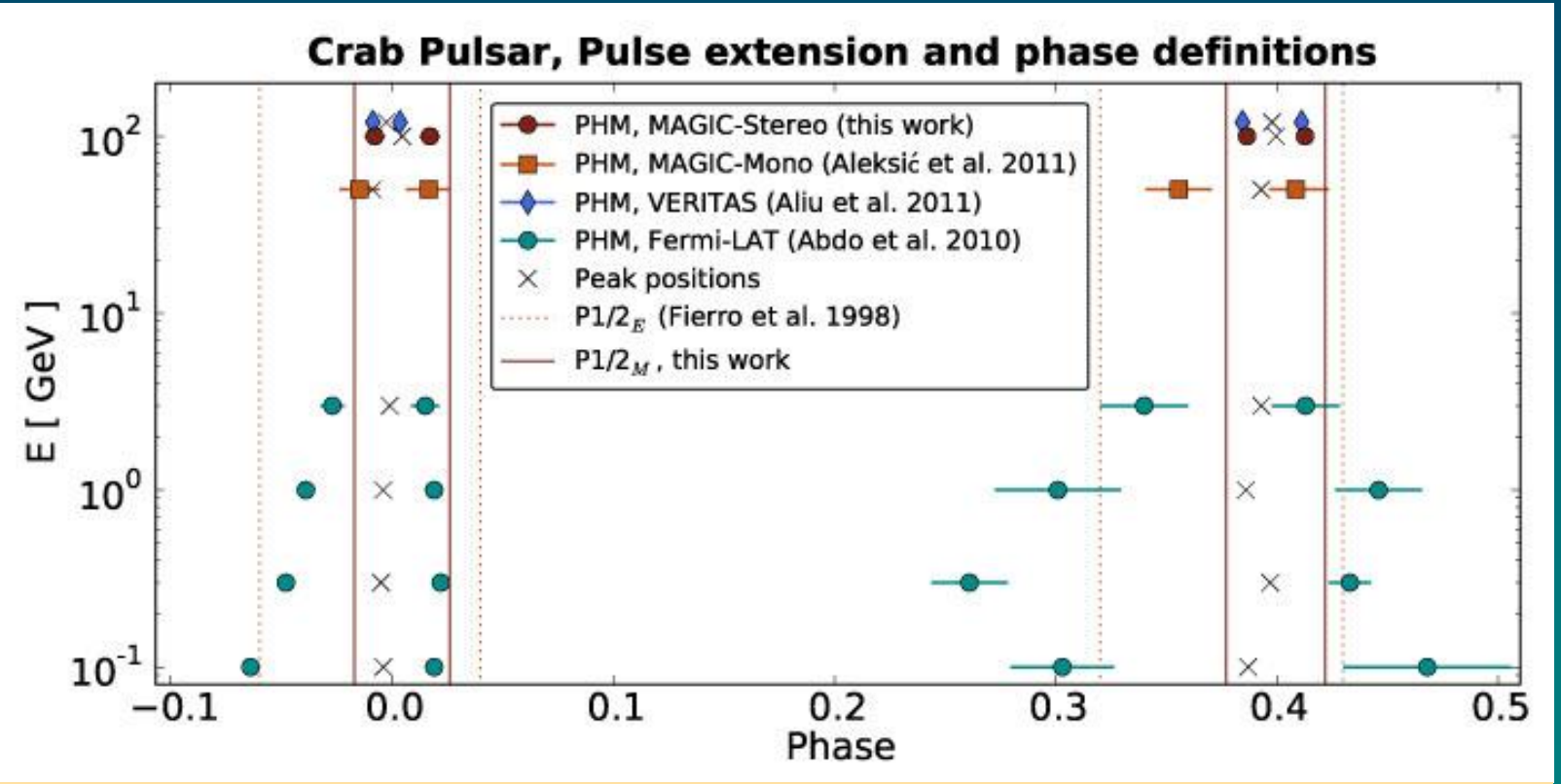
Pulsed emission detected up to 400 GeV !!

Stereo observations (2009-2011): Detection

Light curve morphology

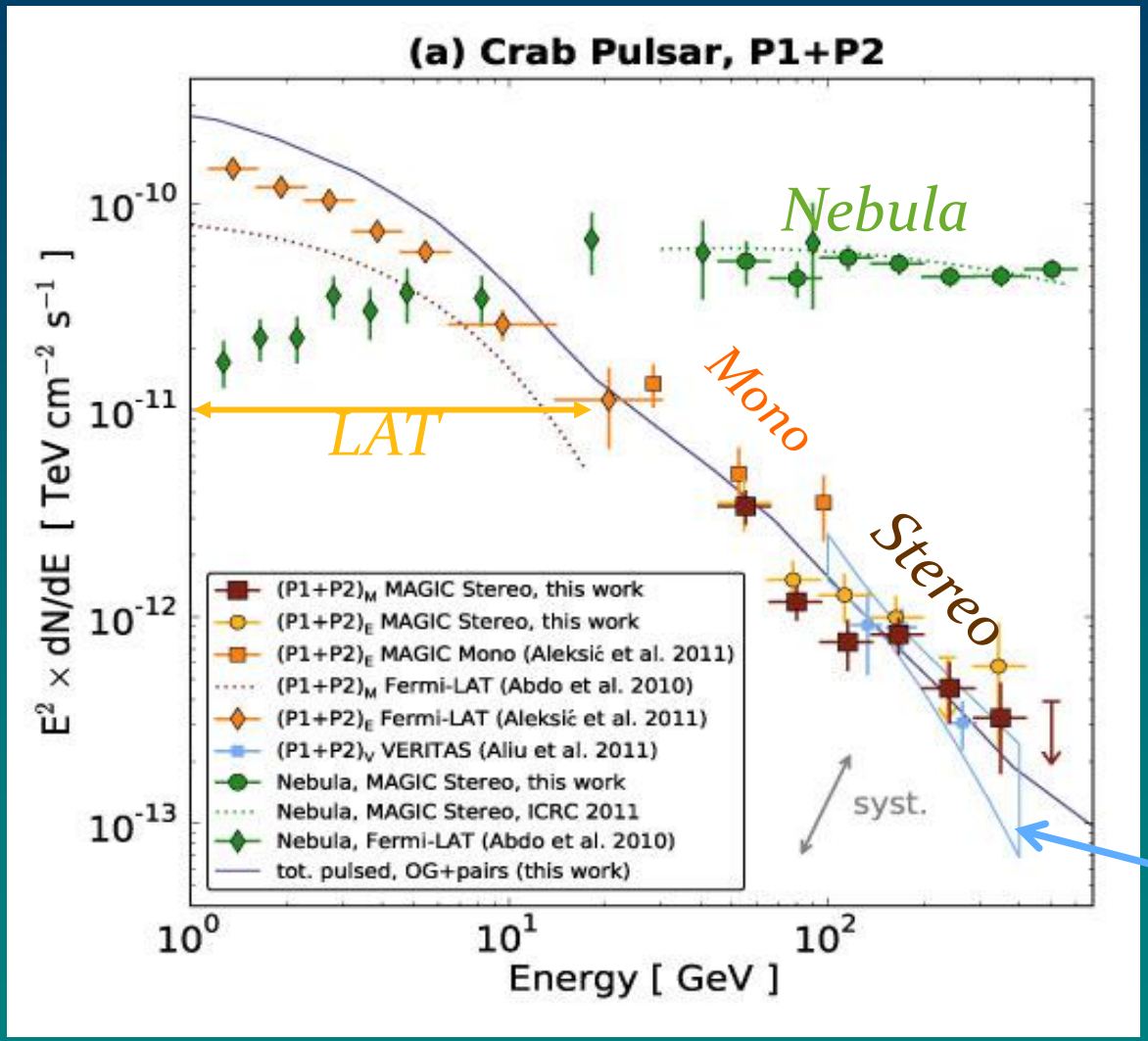
- Peaks width get narrower with energy



The pulses are aligned, becoming very narrow @ VHE

Stereo observations (2009-2011): Spectrum

VHE spectrum of Crab pulsar



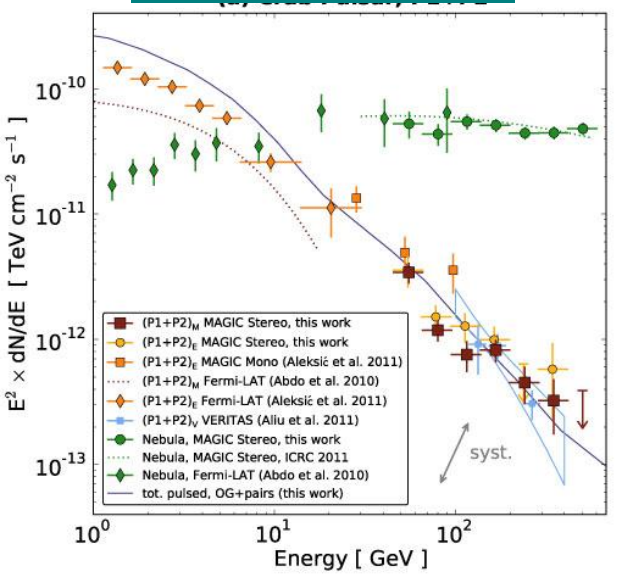
- *MAGIC Stereo provides spectra up to 400 GeV.*
- *Mono/stereo spectra agree… and go well beyond a cutoff at few GeV!*

In agreement with VERITAS (Aliu et.all 2011)

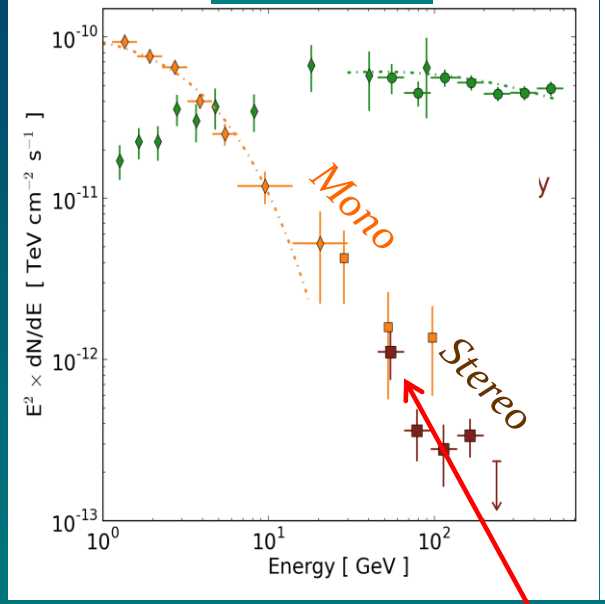
Stereo observations (2009-2011): Spectrum

First pulsar Phase-resolved spectrum @ hundreds GeV !

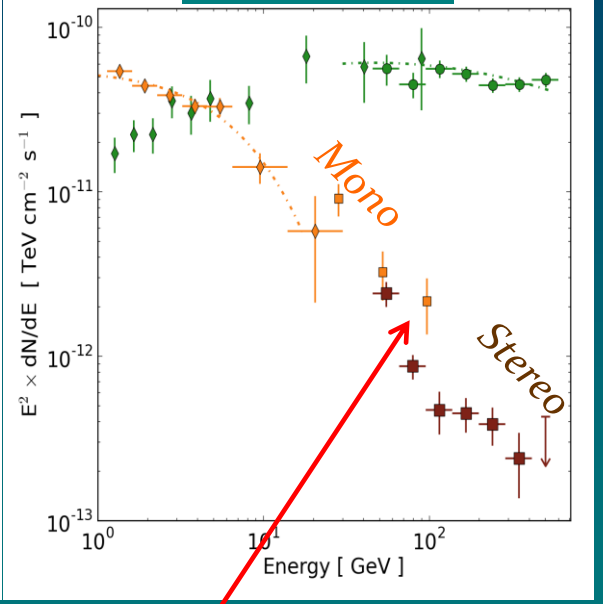
Sum of Both Peaks



First Peak



Second Peak

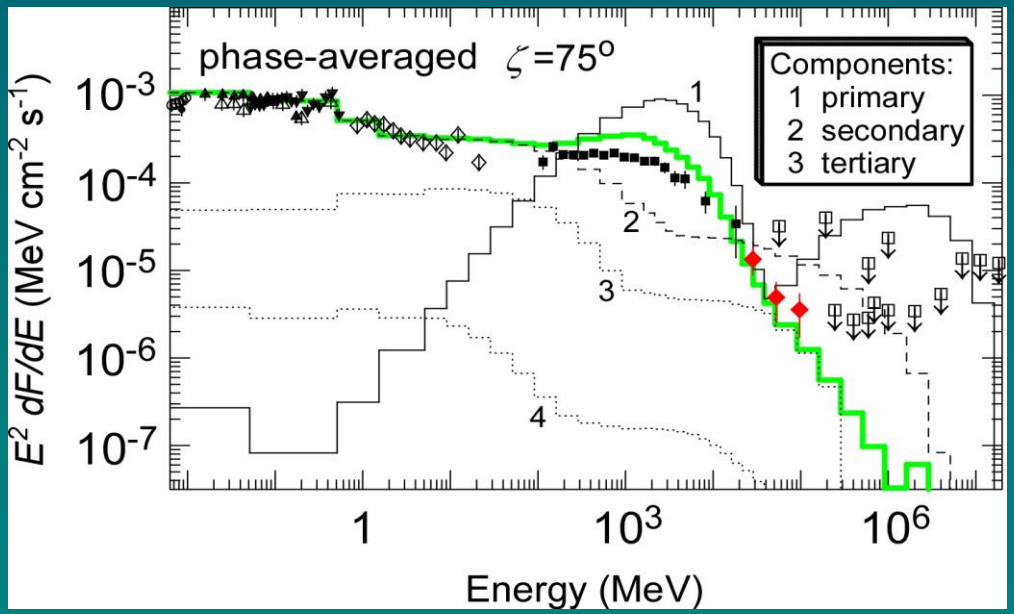


Good agreement to MAGIC-Mono
(< 2 Sigma despite different systematics)

MAGIC measurements rule out extrapolation of Fermi exponential fit.

A possible explanation for a VHE tail (I)

- Extension of Outer Gap scenario by K. Hirotani (arXiv:1108.5391)
  - Detected VHE pulsed emission caused by IC scattering of secondary & tertiary e^{+-}-pairs on magnetospheric IR-UV ph.
  - Predicted Power law component from 10 Gev up to 1 TeV
  - In the calculations, angle between rotational and B axes assumed to be 65◦, and observer's viewing angle 106◦.

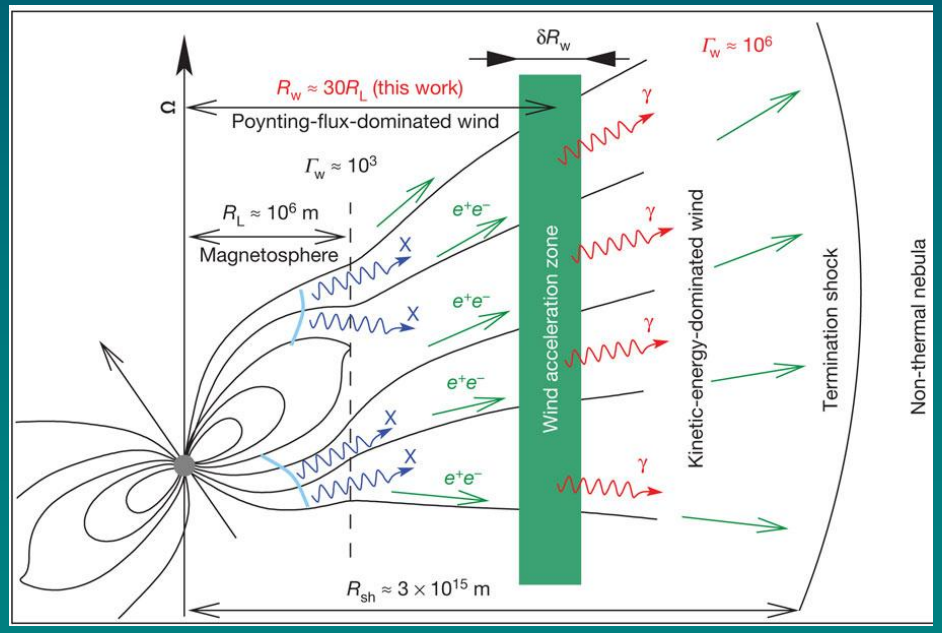


MAGIC mono & stereo spectra reproducible with self-consistent OG model

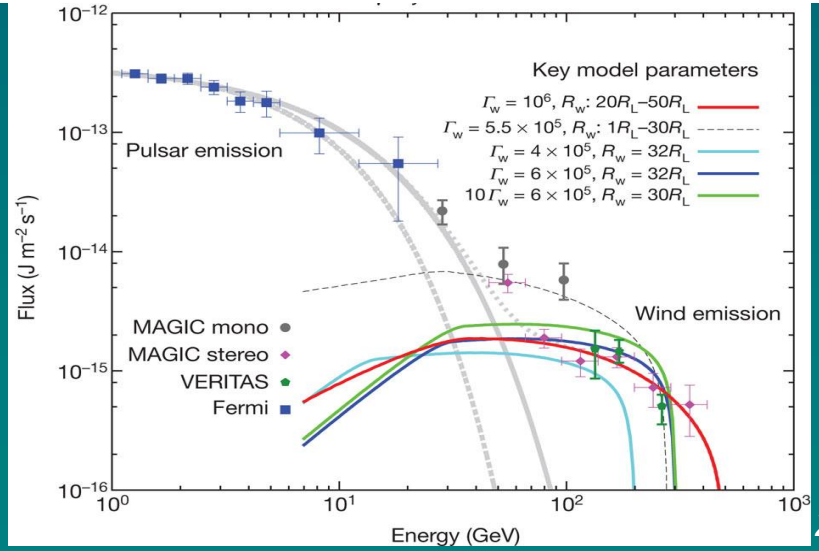
A possible explanation for a VHE tail (II)

Alternative explanation by Aharonian et al. (*Nature 482, 2012*)

- VHE component resulting from the abrupt acceleration of a cold ultrarelativistic wind
  - Wind accelerated in a narrow zone (20-50 light-cylinder radii), up to a Lorentz factor of $(0.5–1.0)\cdot 10^6$
  - IC γ-ray emission of the wind explains emission >100 GeV



Spectrum produced by the pulsar magnetosphere and by the pulsar wind



Summary

- ***In the last years MAGIC contributed to the understanding of the gamma-ray emission of the Crab Pulsar***

- MAGIC detected the Crab pulsar in mono an stereo mode, and with different trigger schemes
  - First detection of Crab pulsar with a CT
  - Both peaks visible & Cutoff higher than expected

Excludes polar cap model

- The combination of mono and stereo observations allowed to obtain spectrum from 25 to 400 GeV
  - *First time phase resolved spectroscopy at VHE*
  - *Spectra following a power law instead of exp. cutoff*

Points to IC emission

Does other pulsar have a power-law tail?