Detection of VHE Bridge emission from the Crab pulsar with the MAGIC Telescopes

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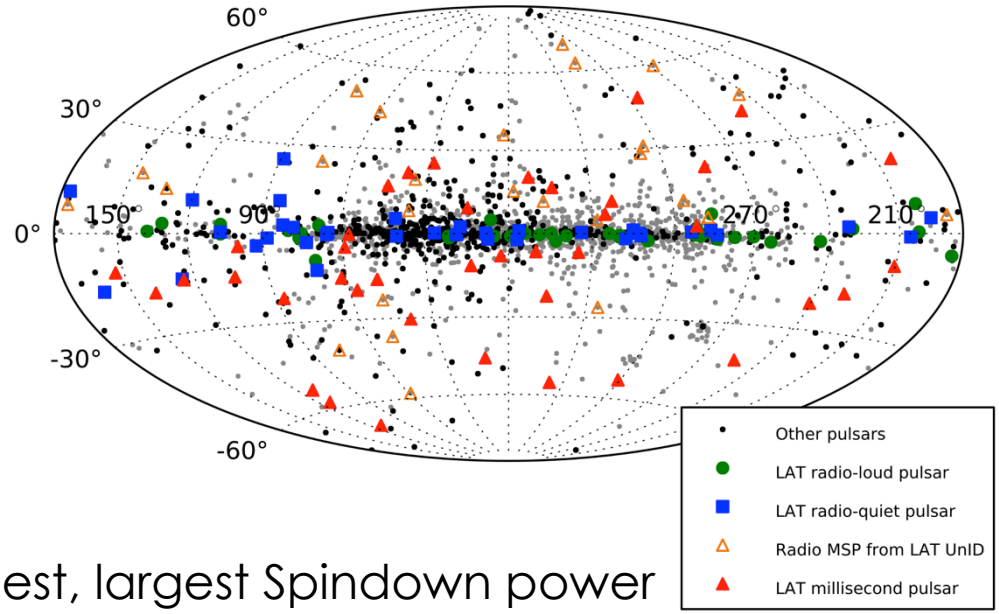
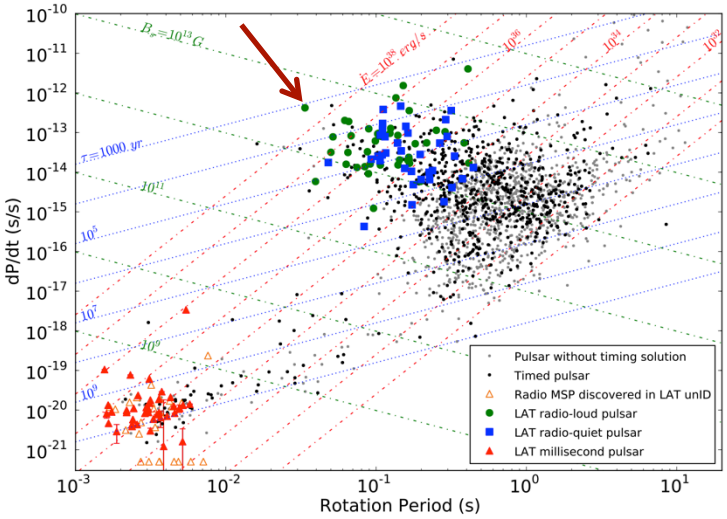
On behalf of the MAGIC Collaboration

Gamma-ray pulsars

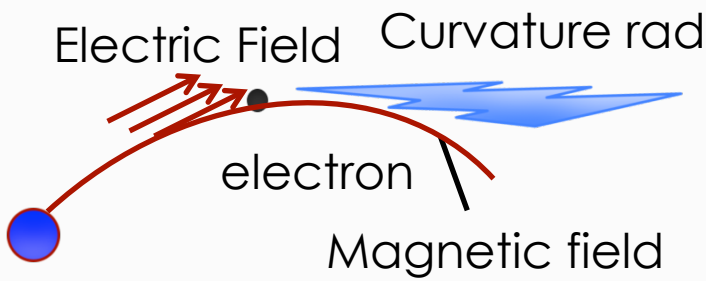


Crab, youngest, largest Spindown power

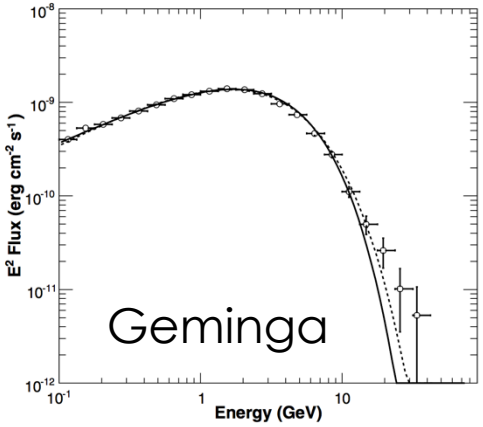


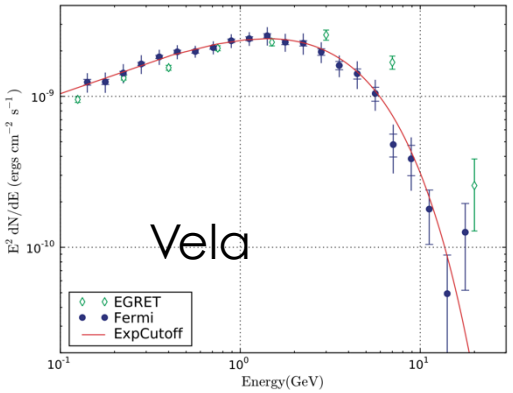
Energy	# of pulsars
Radio	~2000
Fermi, > 100 MeV	~150
Fermi, >25 GeV hint	13
IACTs, > 50 GeV	1+1 (Crab + Vela)

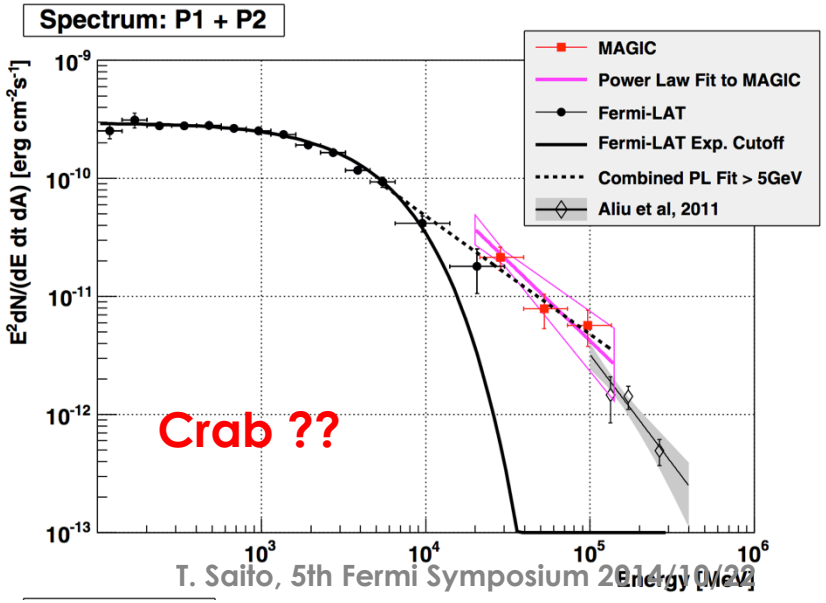
General understanding of GeV emission mechanism



- GeV emission is due to Curvature radiation
- Electrons energy is limited by C.R. cooling.
- Spectral Should exhibit an exponential cutoff at GeV range.

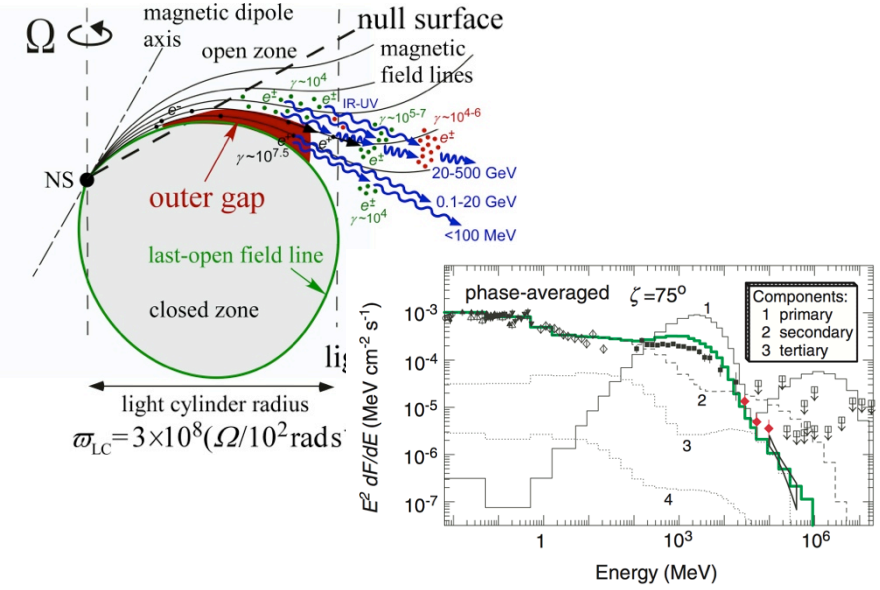




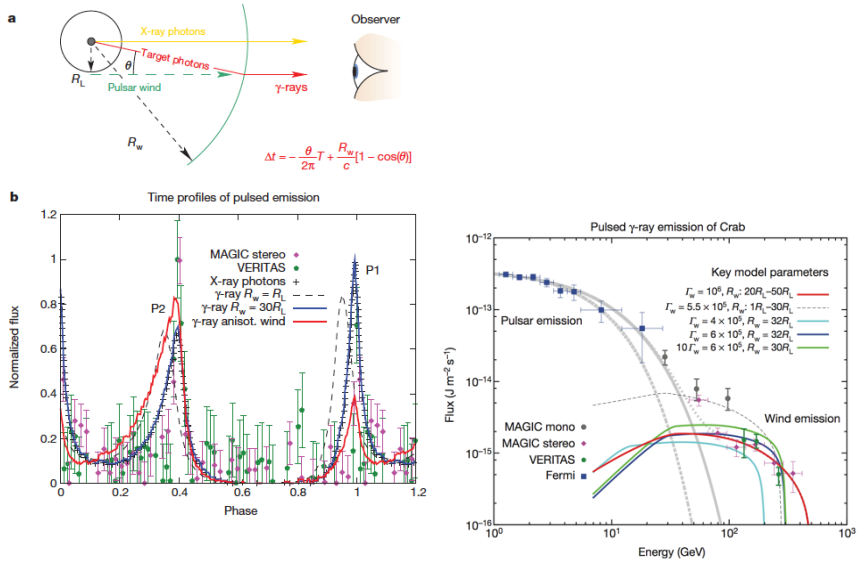


New Models for Crab

1) Magnetospheric Cascade Model
(K. Hirotani & MAGIC, Apj 742 43, 2011)



2) Pulsar Wind Scattering Model
(F. Aharonian et al. Nature 482, 507, 2012)



3) Light Cylinder Gap model
(Bednarek MNRAS 424, 2012)

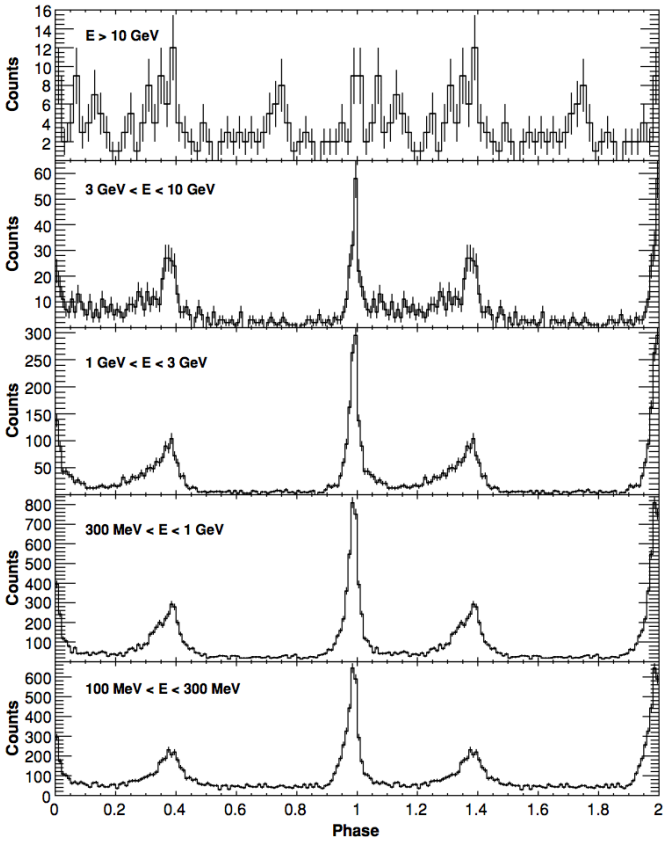
4) Current sheet model
(Arka and Dubus, A&A 550, 2013)

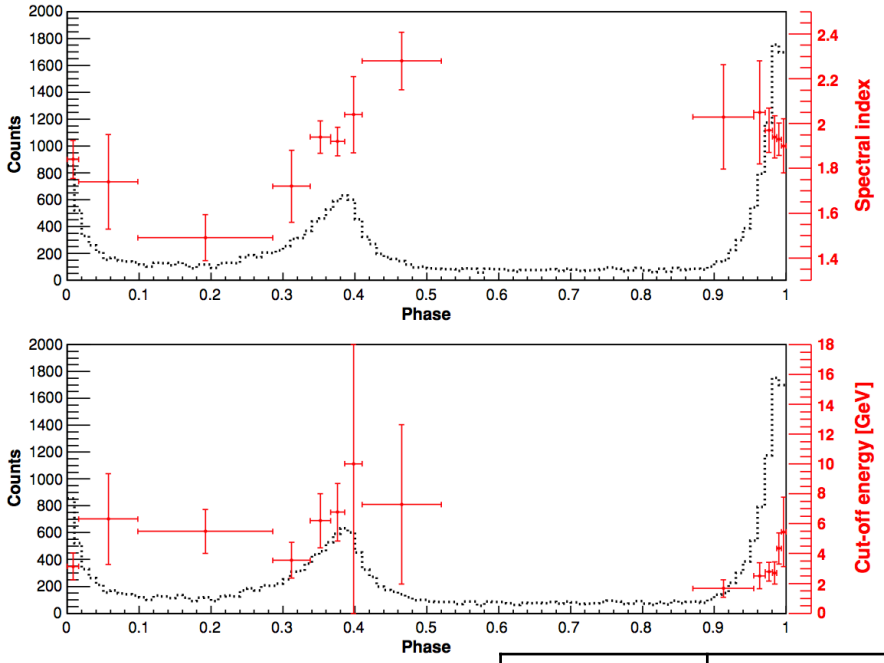
5) Cyclotron instability model
(Chkheide et al., ApJ 773, 2013)

In order to test these models:

- Spectral Approach
  -> R. Zanin talk this morning
- **Pulse Shape Approach**
  -> This talk

At Fermi energies

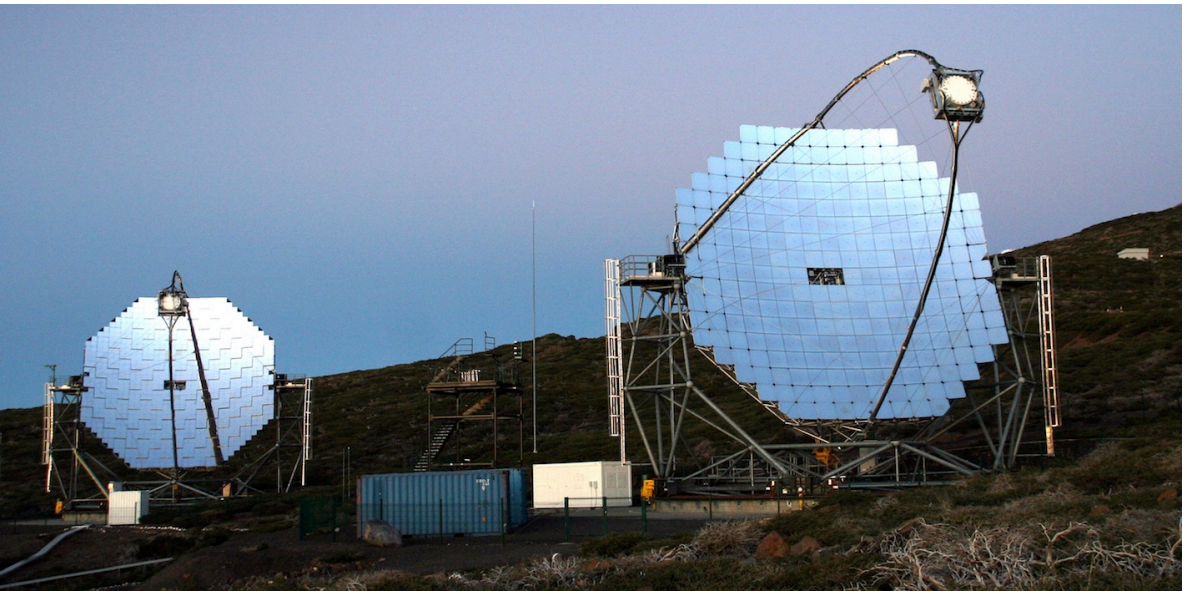




Abdo et al., Apj 708, 1254, 2010

	Index	E_{cut}
P1	Soft	Low
P2	Soft	Hard
Bridge	High	Hard

MAGIC Telescopes



MAGIC Telescopes

- 2 IACTs
- Canary Islands, La palma
- 2200m a.s.l.
- 17m diameter dish
- Energy Threshold ~50 GeV
- Sensitivity 0.6%Crab
  > 300 GeV

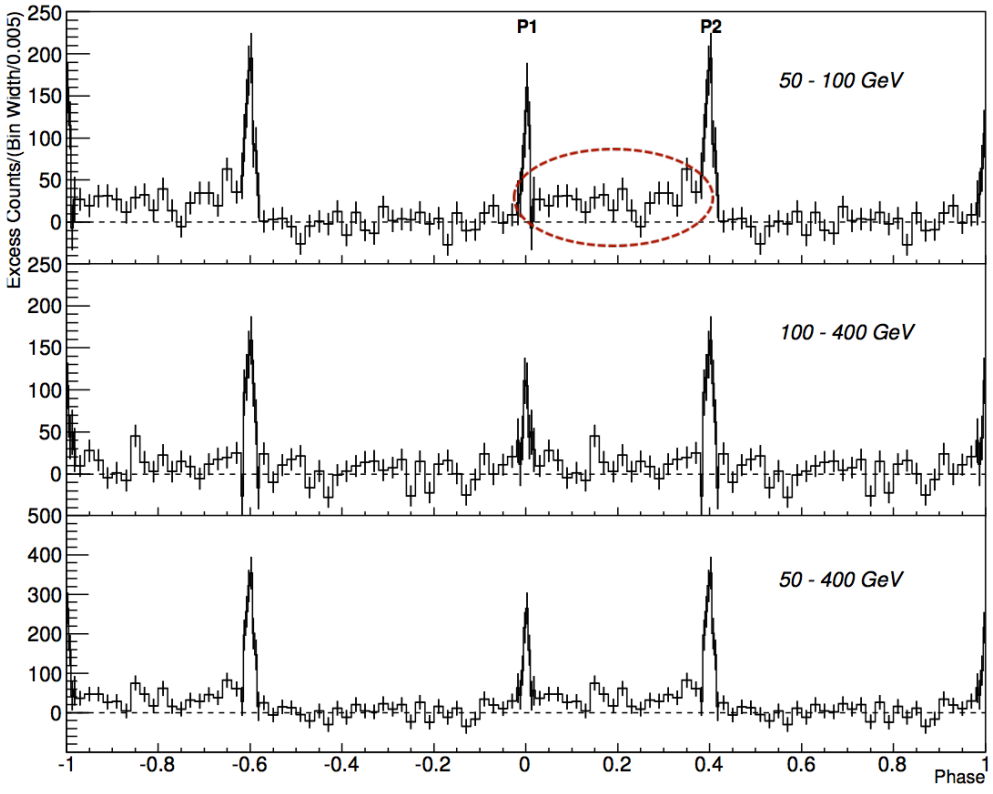
2009-2011: 70 h of Crab observation (after quality cuts)

2011-2012: Upgrades of Camera and readout system

2012-2013: 65 h of Crab observation (after quality cuts)

Total 135 hours of Stereo data used.

Bridge Emission above 50 GeV



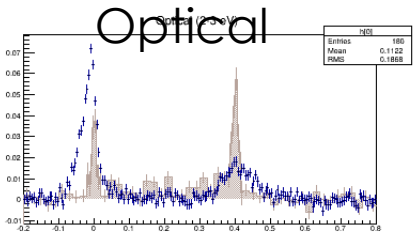
135 h of stereo data

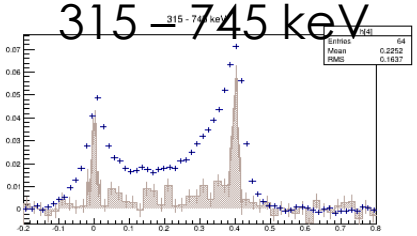
Defined by MAGIC Col. A&A 540, 69 , 2012

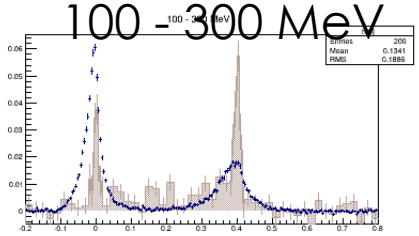
Defined by Fierro et al, ApJ 494, 734, 1998

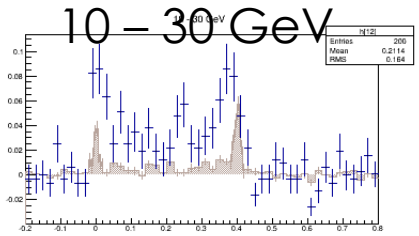
	$P1_M$	$P2_M$	$Brdg_M$	$Brdg_E$
Phase Interval	-0.017 - 0.026	0.377 - 0.422	0.026 - 0.377	0.14 – 0.25
50 - 400 GeV	8.2 σ	12.6 σ	6.2 σ	4.4 σ
50 –100 GeV	6.3 σ	10.2 σ	5.9 σ	3.5σ
100 –400 GeV	5.0 σ	7.6 σ	2.8 σ	2.8 σ

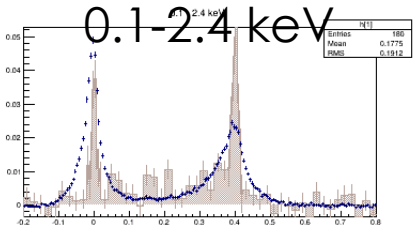
Comparison with other bands

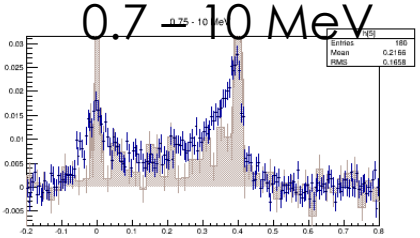


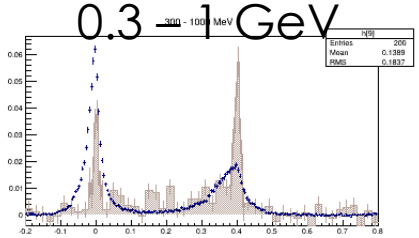




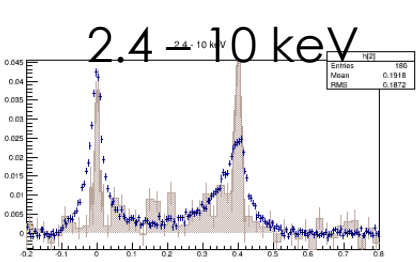


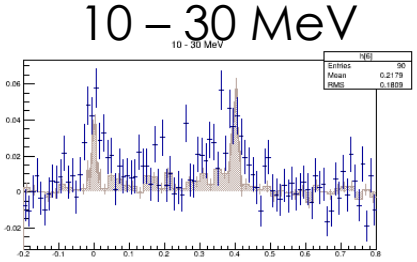


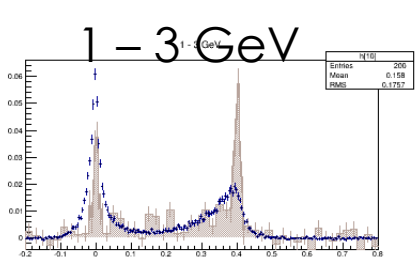




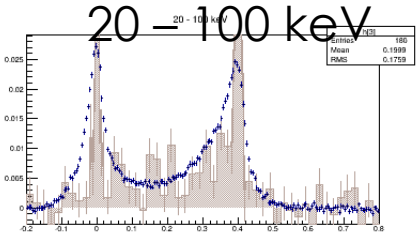
Brown histograms
In the background
is MAGIC 50-400 GeV

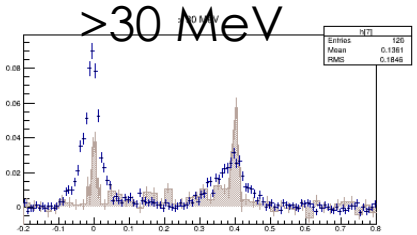


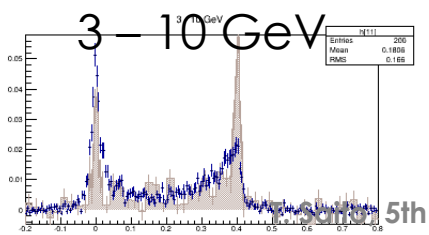




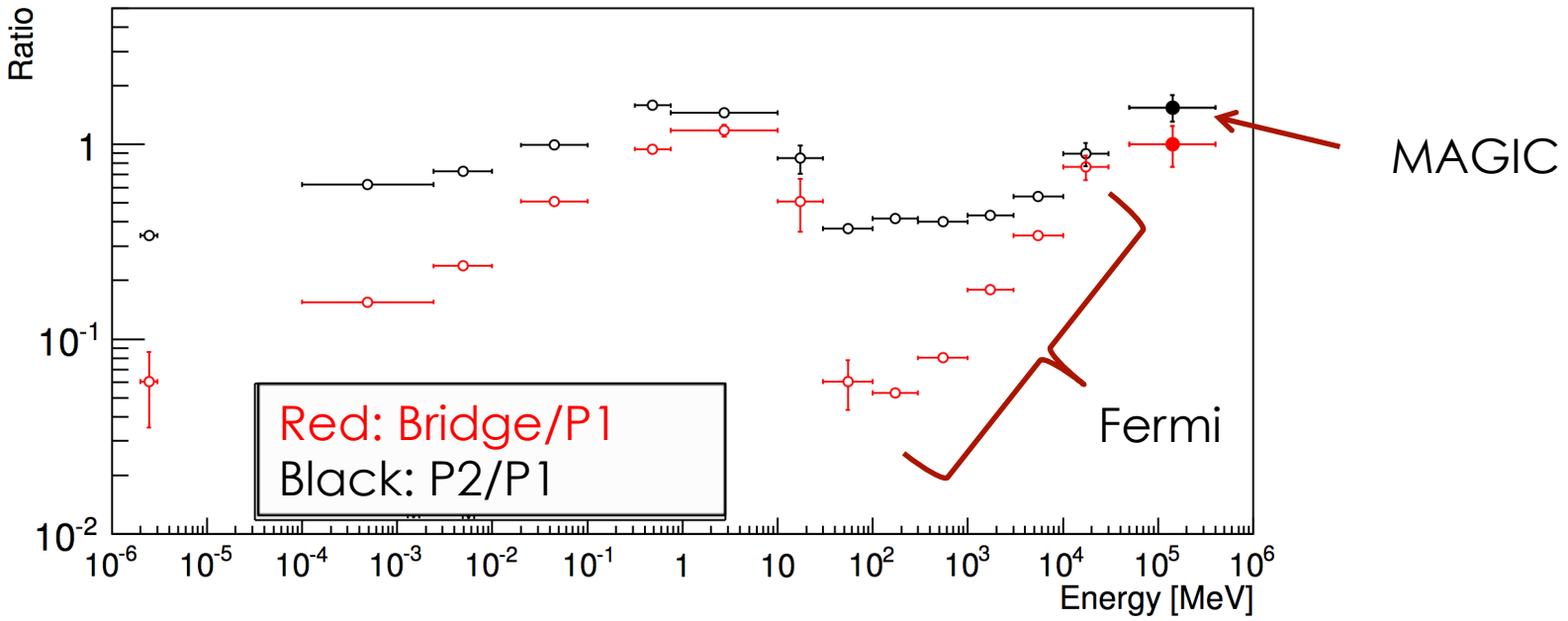
At 50 – 400 GeV, pulses are very sharp, yet bridge emission is visible.







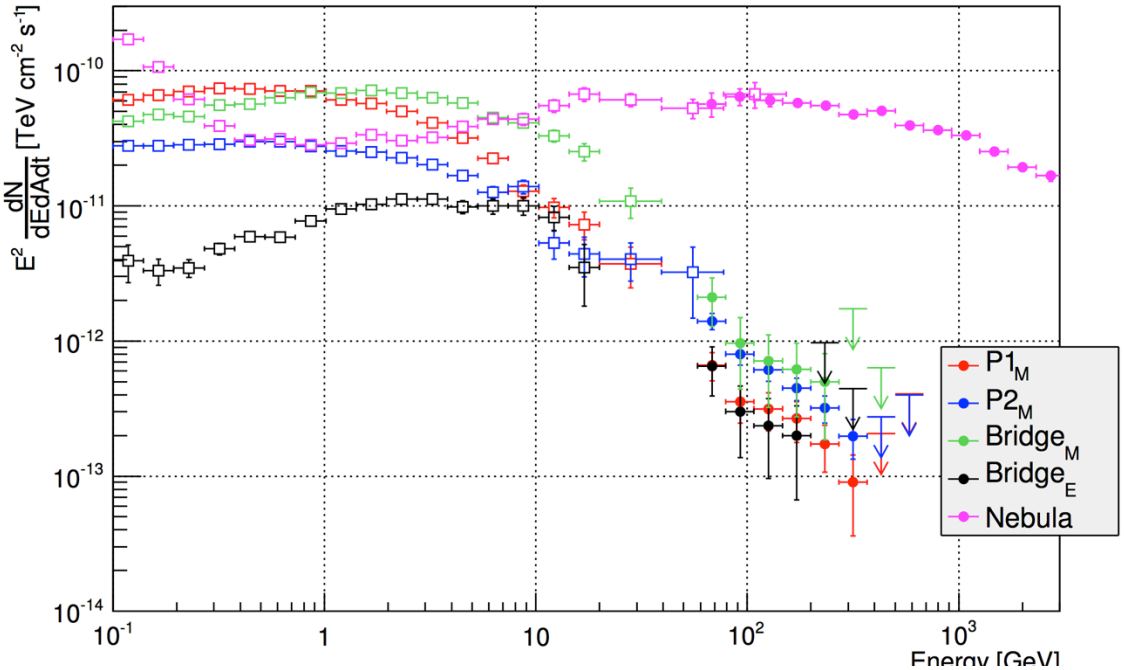
P2/P1 ratio, Bridge/P1 ratio



There is no good explanation for this behavior of ratios.

MAGIC measurements are following the increasing trend above 100 MeV.

Energy Spectrum



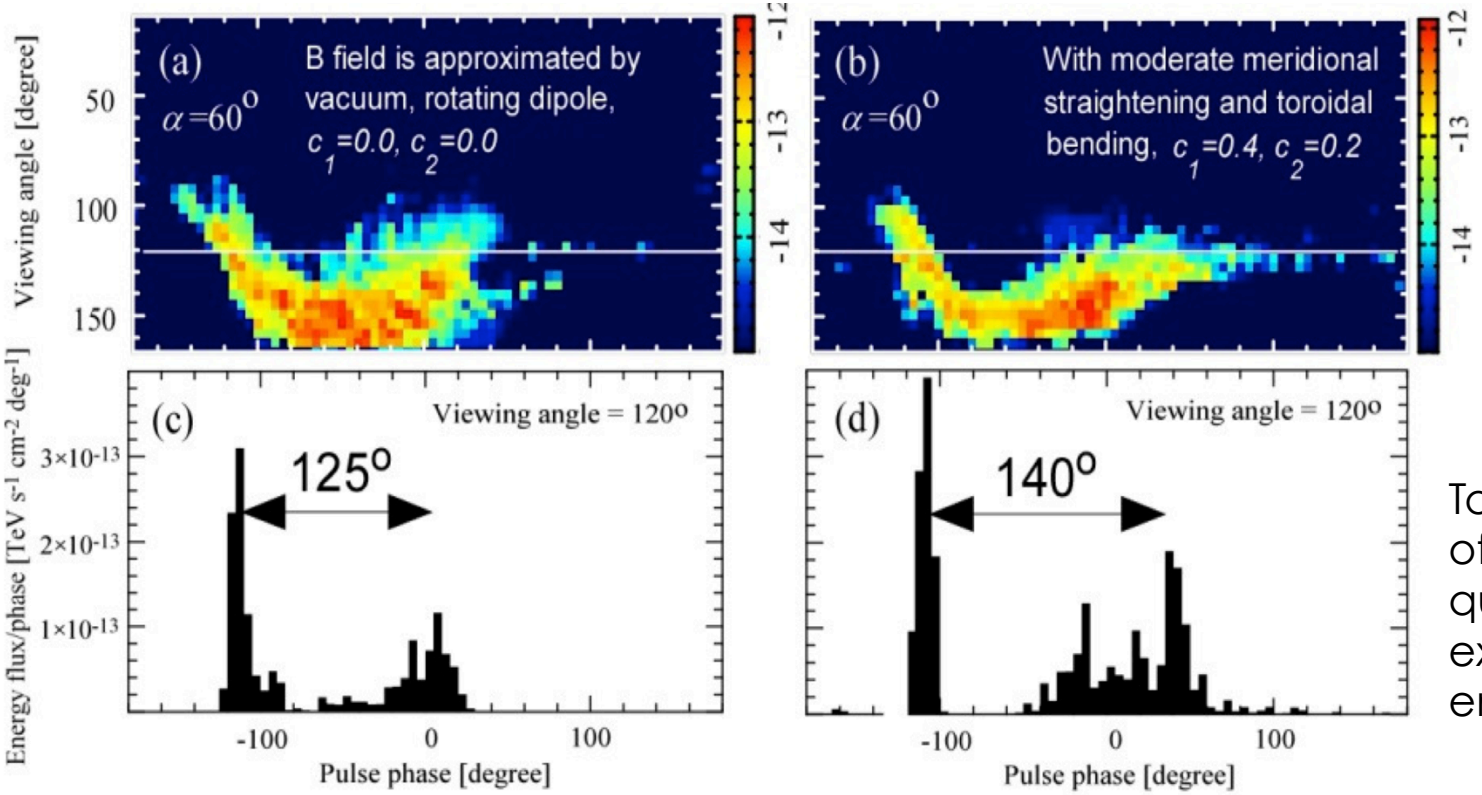
Spectral Indices below10 GeV are different between P1 , P2 and bridge, while no difference is seen above 50 GeV.

phase	$F_1{}^a$ [10^{-11}MeV^{-1}cm^{-2}s^{-1}]	$\Gamma_1{}^a$	$E_c{}^a$ [GeV]	$F_{100}{}^b$ [10^{-11}TeV^{-1}cm^{-2}s^{-1}]	$\Gamma_2{}^b$
$P1_M$	8.87 ± 0.14	1.88 ± 0.01	3.74 ± 0.15	4.18 ± 0.59	3.25 ± 0.39
$P2_M$	3.14 ± 0.07	1.97 ± 0.01	7.24 ± 0.64	8.48 ± 0.62	3.27 ± 0.23
$Bridge_M$	7.70 ± 0.11	1.74 ± 0.01	7.19 ± 0.39	12.2 ± 3.3	3.35 ± 0.79
$Bridge_E$	0.95 ± 0.04	1.44 ± 0.04	6.94 ± 0.90	3.7 ± 1.1	3.51 ± 0.97

(*a*) Spectral parameters obtained by fitting a function $F(E) = F_1(E/1\text{GeV})^{-\Gamma_1} \exp(E/E_c)$ to *Fermi*-LAT data between 100 MeV and 300 GeV

(*b*) Spectral parameters obtained by fitting a function $F(E) = F_{100}(E/100\text{GeV})^{-\Gamma_2}$ to MAGIC data between 50 GeV and 400 GeV

Modification of magnetospheric Cascade Model (K. Hirotani)

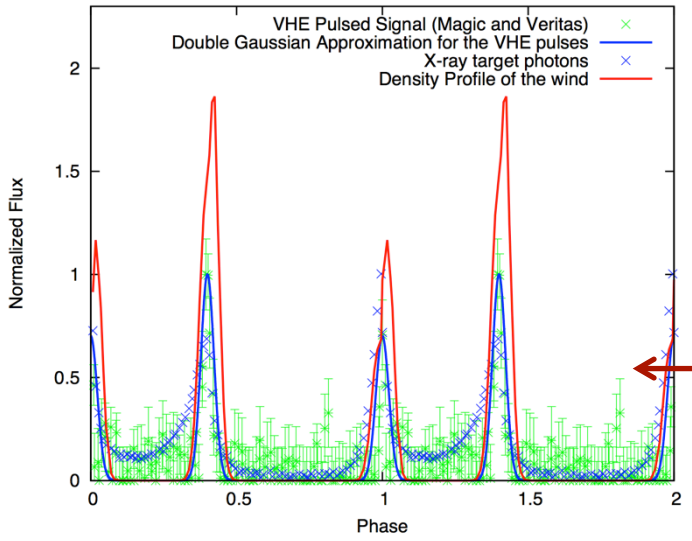


Toroidal component of B field can qualitatively explain the bridge emission.

(almost) simple Dipole

Added toroidal component

Modification of wind scattering model (D. Khangulyan et al. 2012)



× X-ray light curve

— Wind Plasma Density profile

— Expected VHE light curve

Without Bridge

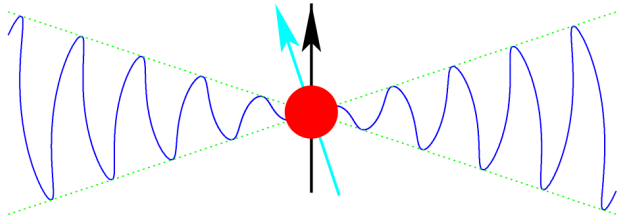
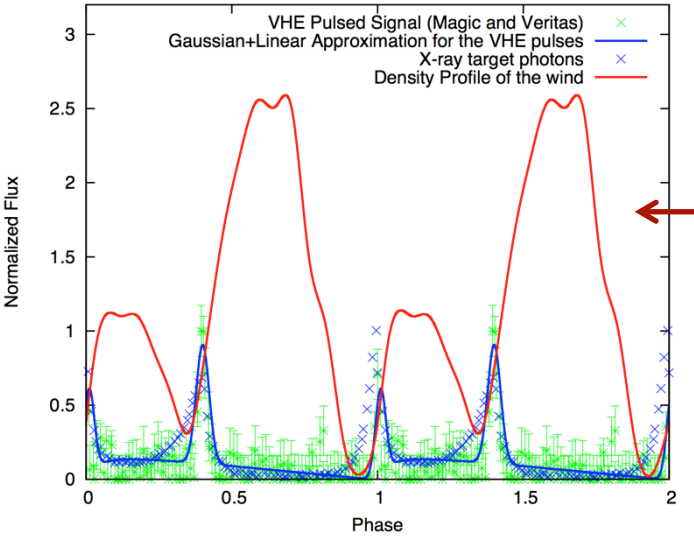
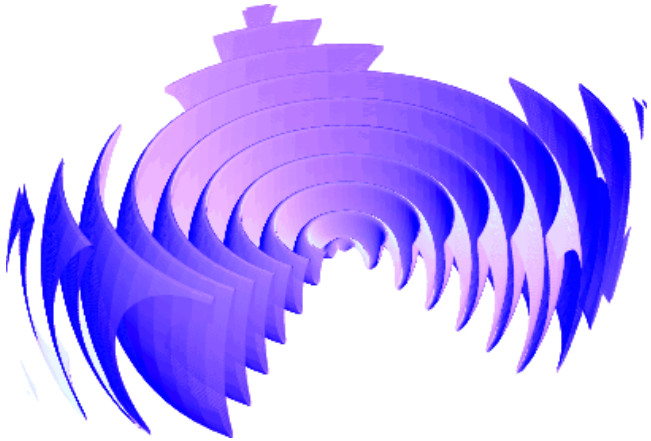


Fig. 1. A meridional section of the current sheet of an oblique rotator with a radial wind. The thin lines limiting the extent of the sheet in latitude depict the plane of the magnetic equator when the magnetic axis lies in the plane of the section.



With Bridge



Periodic density profile is needed, which may be realized by current sheet structure.

Summary

- In order to test new models for the Crab pulsar, MAGIC re-observed the Crab pulsar with the upgraded MAGIC telescopes.
- Bridge emission above 50 GeV was discovered with 6.2 σ between very narrow two peaks with 135 hours of data.
- P2/P1 ratio and Bridge/P1 ratio at MAGIC energies follows the trend of the energy dependence of these ratios above 100 MeV.
- Photon index above 50 GeV are similar between P1, P2 and Bridge, though there is a difference below 10 GeV.
- Magnetospheric Cascade model needs to be modified with toroidal magnetic filed component in Outer Gap.
- Wind scattering model needs radially periodic density profile, which could be justified by the current sheet structure.