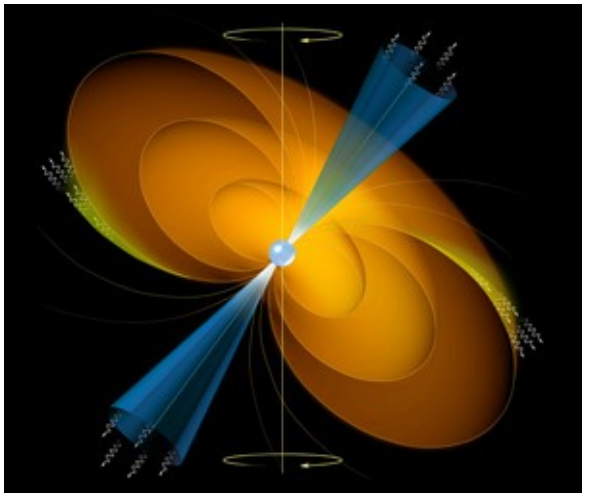
Georgia Tech Physics College of Sciences



Pulsar Observations with VERITAS

Nepomuk Otte on behalf of the VERITAS Collaboration

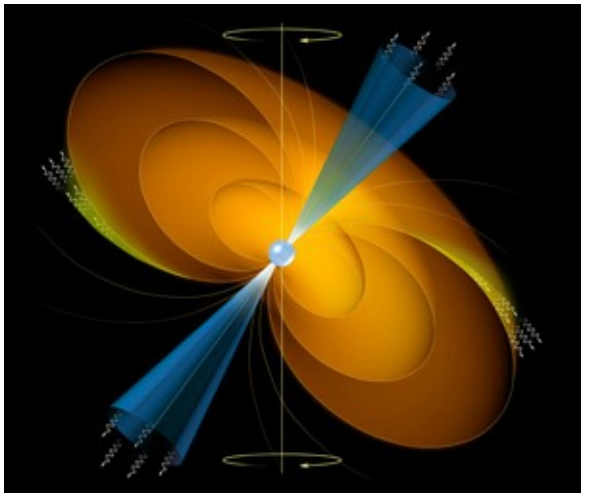
A. McCann, G. Richards, B. Zitzer

Overview

- Pulsars intro
- Crab pulsar
  - VERITAS detection of pulsed emission from the Crab above 100 GeV
  - Implications for pulsar theory
  - Search for a correlation between GRP and pulsed VHE emission
  - Pulsars as physics probes: LIV
- Where next? VHE emission from other pulsars

Pulsars

- Supernova remnant of a massive star (5-10 M_0)
- Gravitational core collapse stopped by neutron degeneracy pressure
  - Compact object of ~1.4 M_0 with radius of 10-20 km
  - Neutron star
- Conservation of magnetic energy and angular momentum during collapse
  - fast rotation ~100 Hz and
    strong magnetic dipole field ~10^{12} G
  - Rotation axis and magnetic dipole misaligned



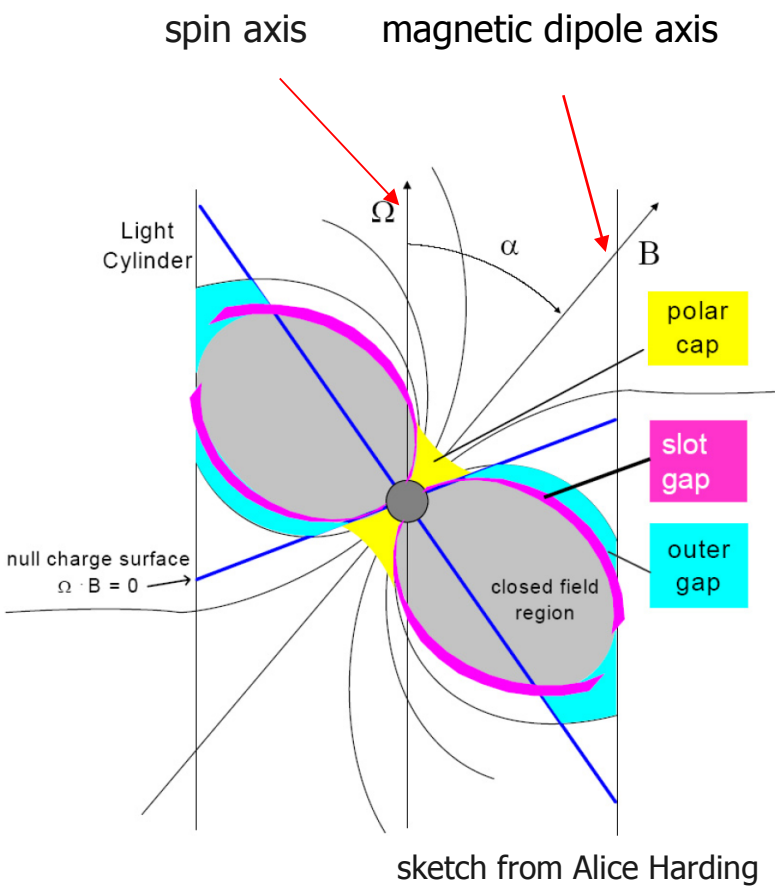
→ powerful generators of electromagnetic energy and relativistic electrons and positrons

Responsible for $e^{+/-}$ anomaly in cosmic-ray spectrum?

s. Pamela, Fermi, AMS results

Need to understand particle accelerator in magnetosphere

Gamma-Ray Emission from the Pulsar Magnetosphere

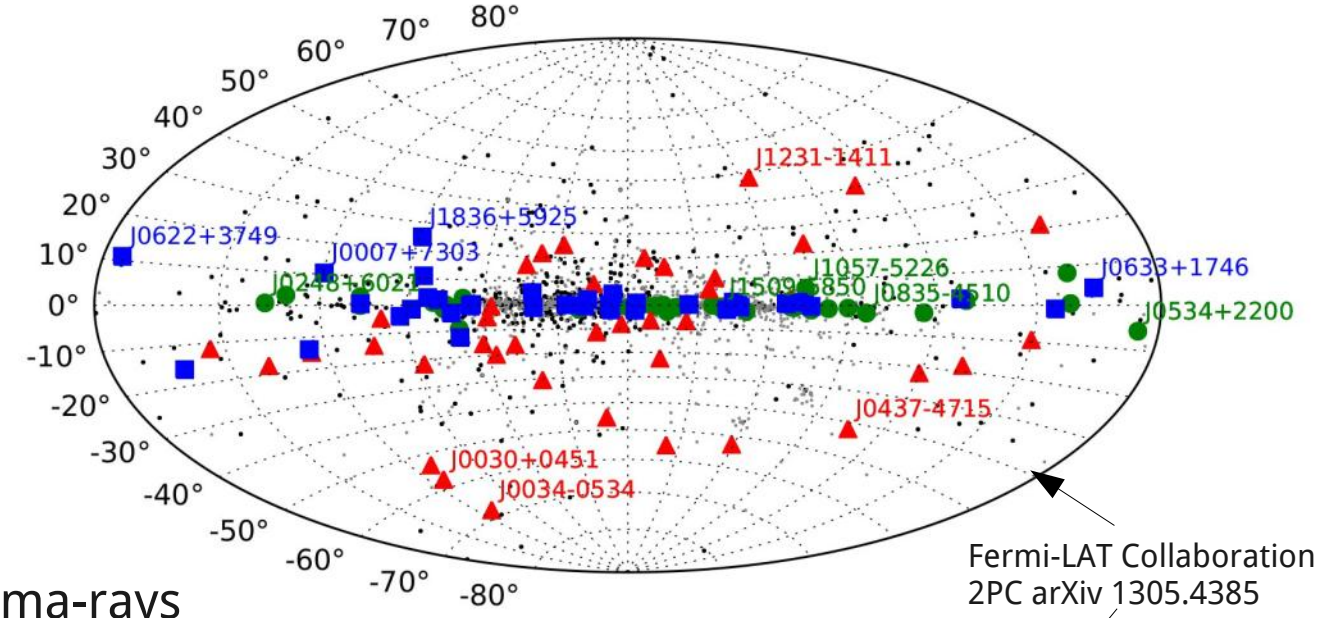


sketch from Alice Harding

- Stable vacuum gaps in the magnetosphere
  - Potentials of ~10^{12} eV
  - Particle acceleration
- Curved particle trajectory
  - Gamma-ray emission
- $e^{+/-}$ interact with low energy photons
  - Inverse Compton emission
- Gamma rays are subject to absorption in magnetosphere (gamma-gamma)

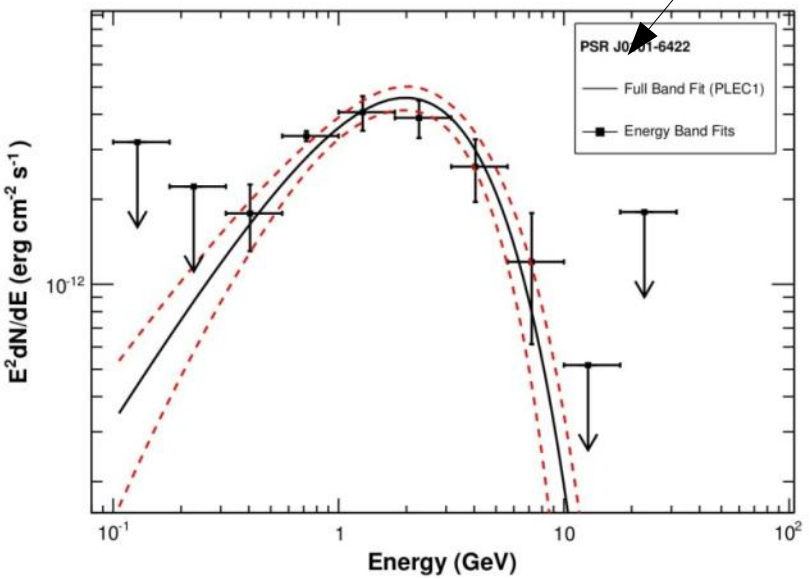
The Pulsar Gamma-Ray Sky between 100 MeV and 10 GeV

Femi-LAT



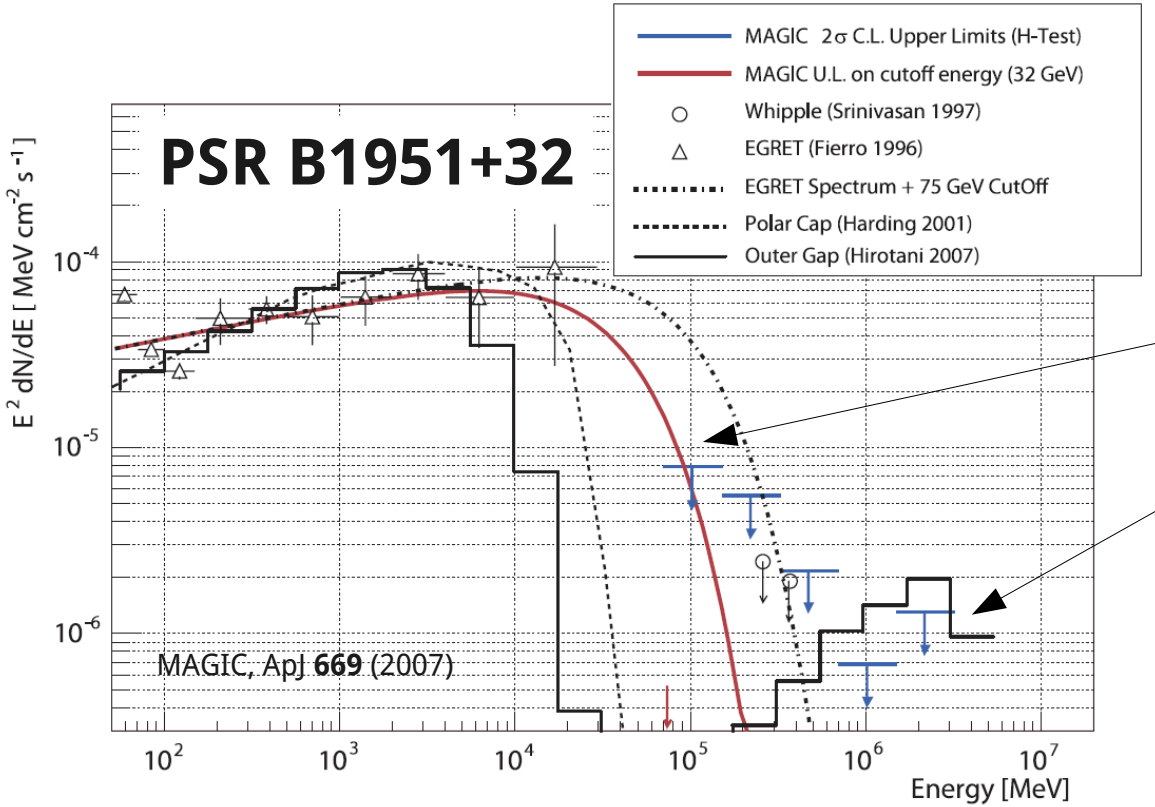
Fermi-LAT Collaboration
2PC arXiv 1305.4385

- 117 pulsars detected in gamma-rays between 100 MeV – 10 GeV since 2008
  - Crucial information about understanding particle acceleration in the magnetosphere
- Ruled out that observed gamma-rays come from close to poles
- Very little known about emission tails above 10 GeV



Georgia Tech

Catching Pulsars above 100 GeV



Objectives:

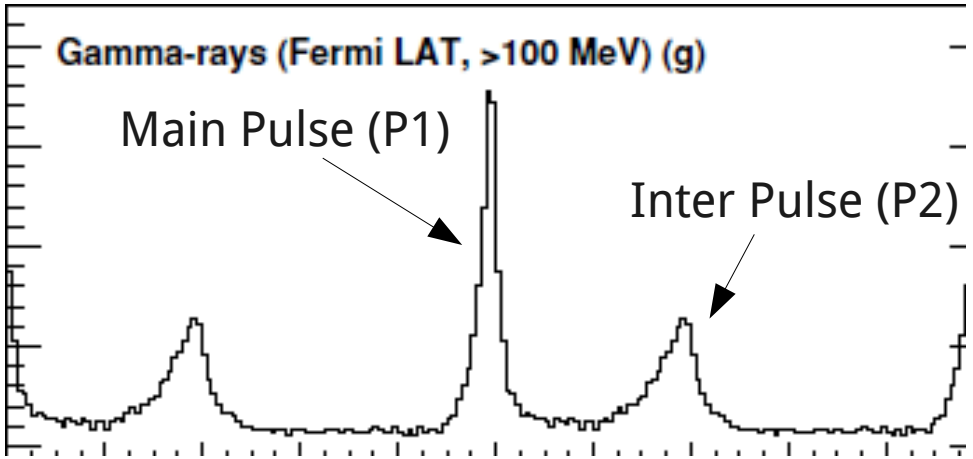
Hunting the tail of the HE emission
and
a possible IC component at TeV

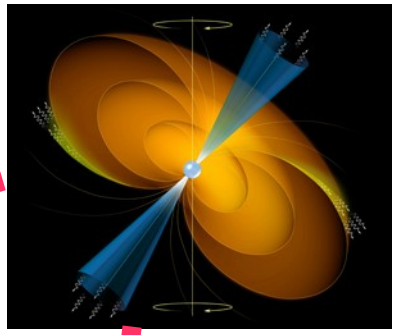
Motivation:

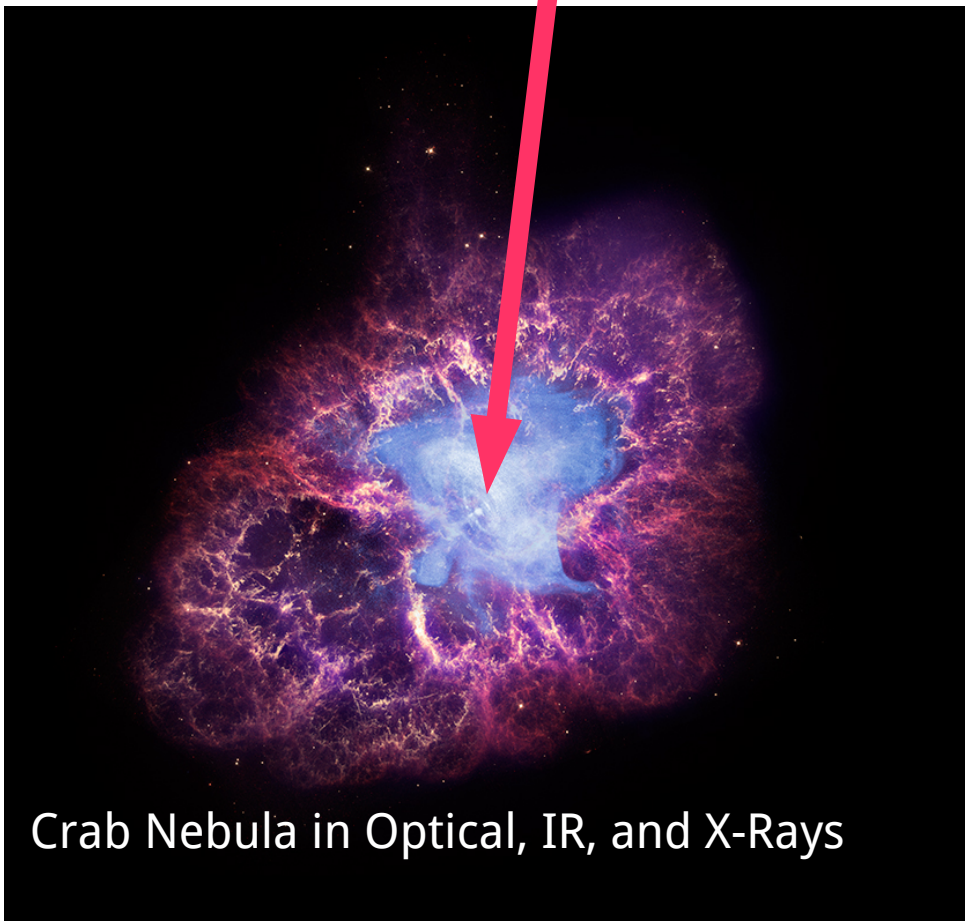
Understand the dynamics of the magnetosphere in its extremes
Significant differences between models

Only non-detections until ...

The Crab Pulsar







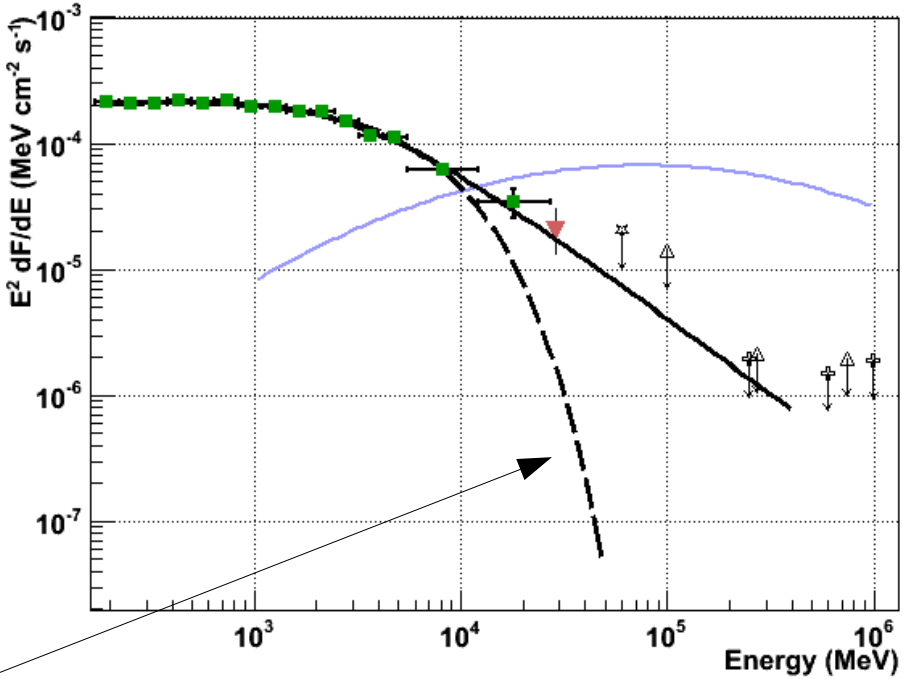
- Remnant of historic supernova in 1054 A.D.
- Distance 2 kpc
- One of the most energetic pulsars 4.6 x 10^{38} erg s^{-1} spin down power
- One of the brightest gamma-ray pulsars
- Powers the brightest VHE gamma-ray source, the Crab Nebula

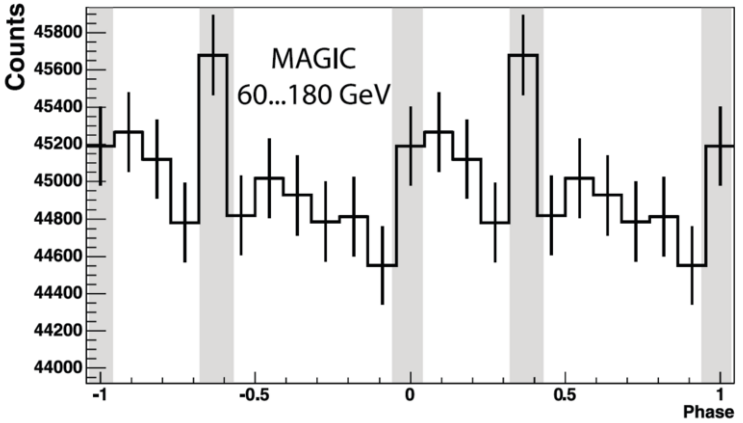
The Crab Pulsar in Gamma-Rays

- **Fermi-LAT**
  - Exquisite measurements around the spectral break at a few GeV
- **MAGIC**
  - Detection at 25 GeV (Aliu et al., 2008)
  - Hints at 60 GeV (Albert et al., 2008, Aliu et al., 2008)

Common wisdom:

- **Spectral break is described by an exponential cutoff**

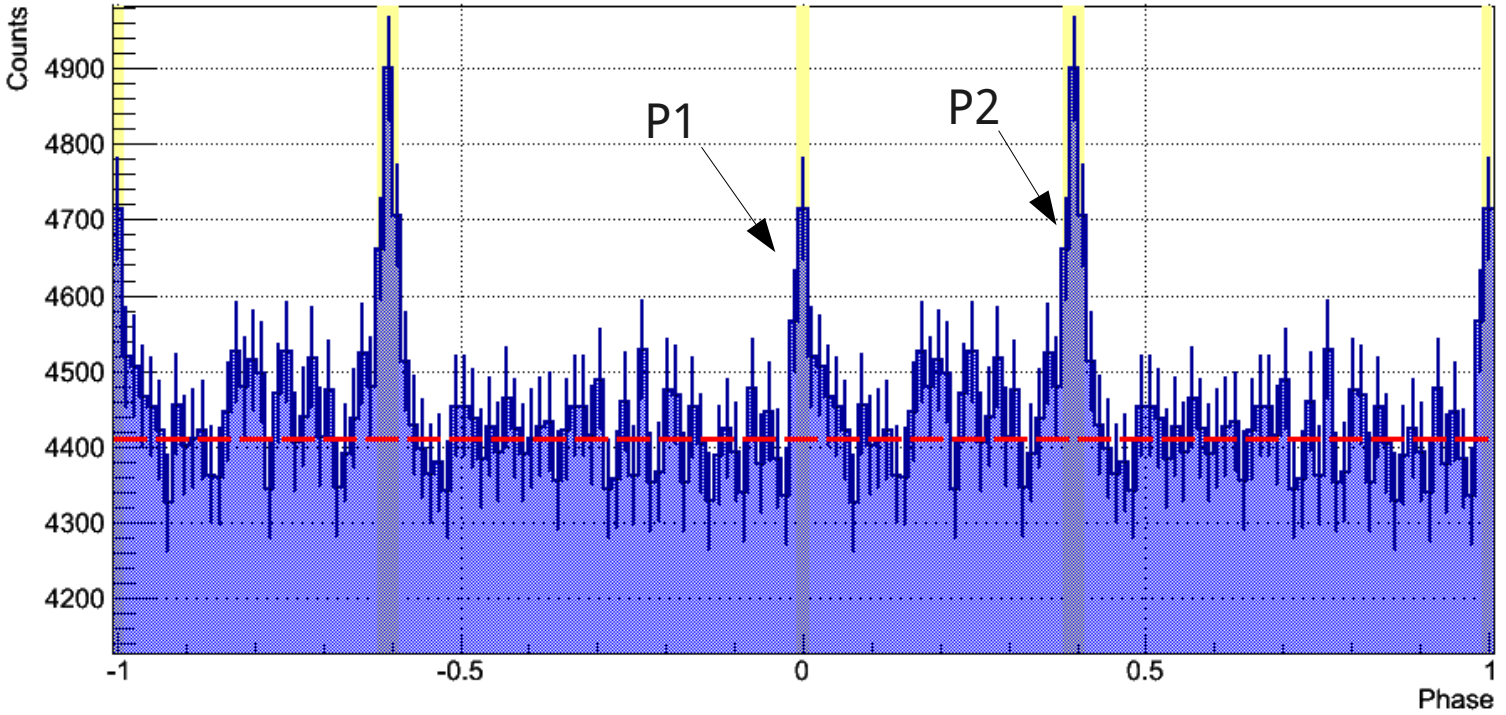




VERITAS

- **Energy range**: ~100 GeV to several 10 TeV (~75 GeV after PMT upgrade in 2012)
- **Angular resolution:** ~0.1° (energy dependent)
- **Energy resolution:** 15% (energy dependent)
- **Systematic uncertainties:** Energy ~20%; Spectral index ~0.2
- **Sensitivity: 1% Crab Nebula flux in <30 hours**

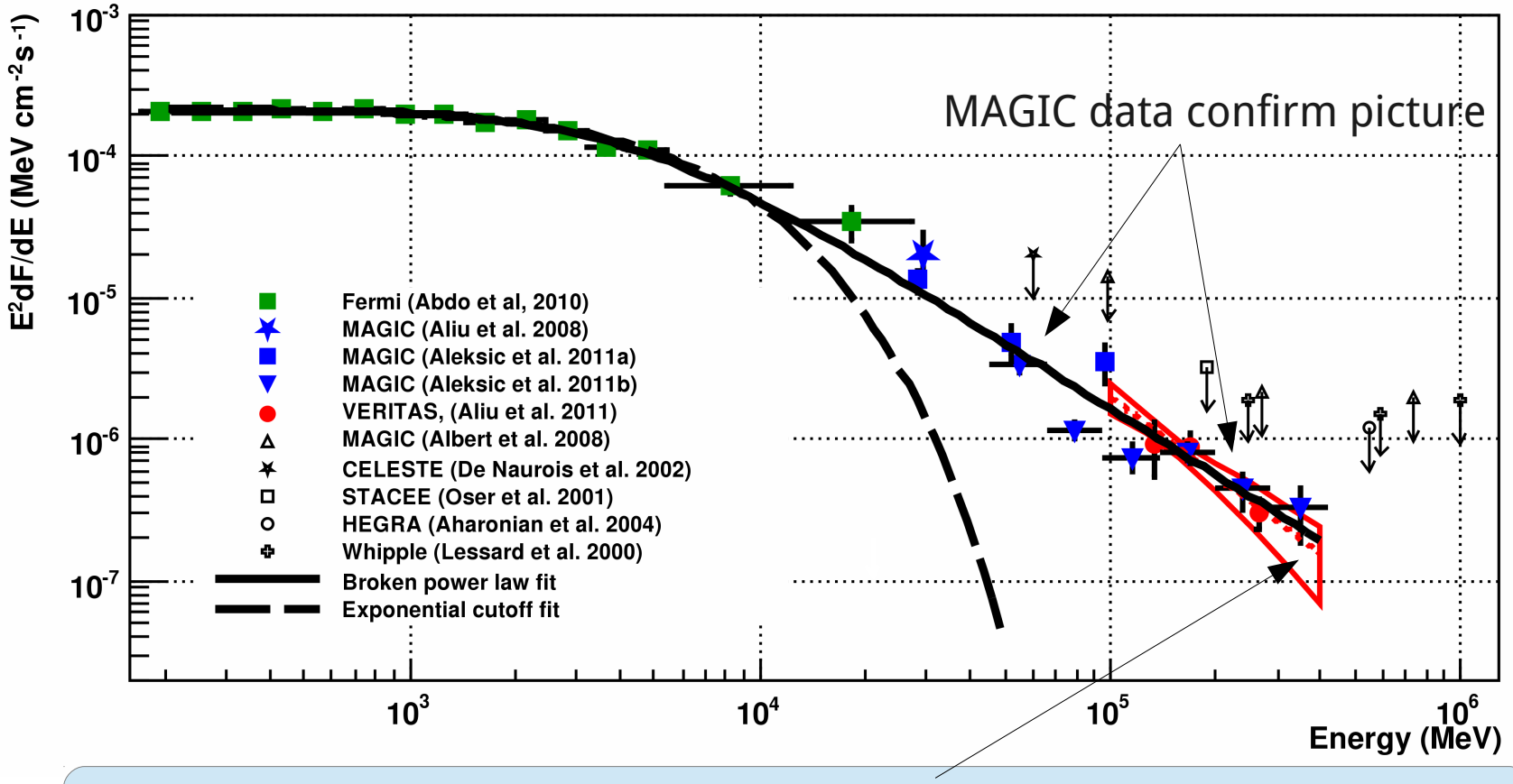
The first Pulsar Detection above 120 GeV



Includes data taken after original publication

- Original detection with VERITAS (107 hours) in 2011 with 6 sigma (H-Test), Aliu et al. (2012) Science
- 130 hours of observations between 2007 and 2012
- 2012/13 data still under analysis (upgraded VERITAS with high QE PMTs)

An unexpected shallow Turnover



Highest energy detected gamma rays ~400 GeV

→ Emission must come from several ten NS radii away from NS

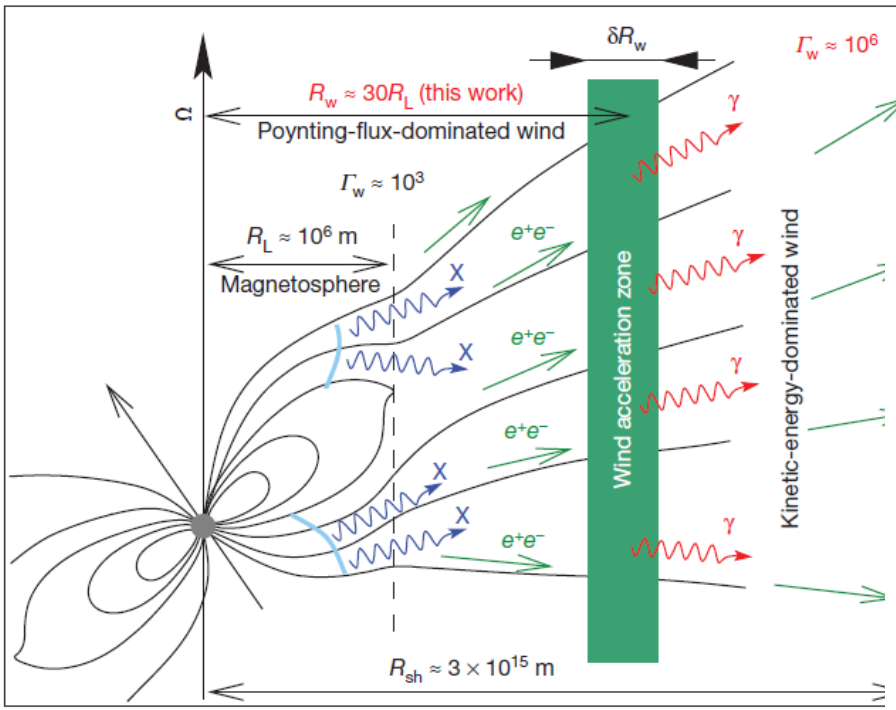
Most interpretations are even more radical:

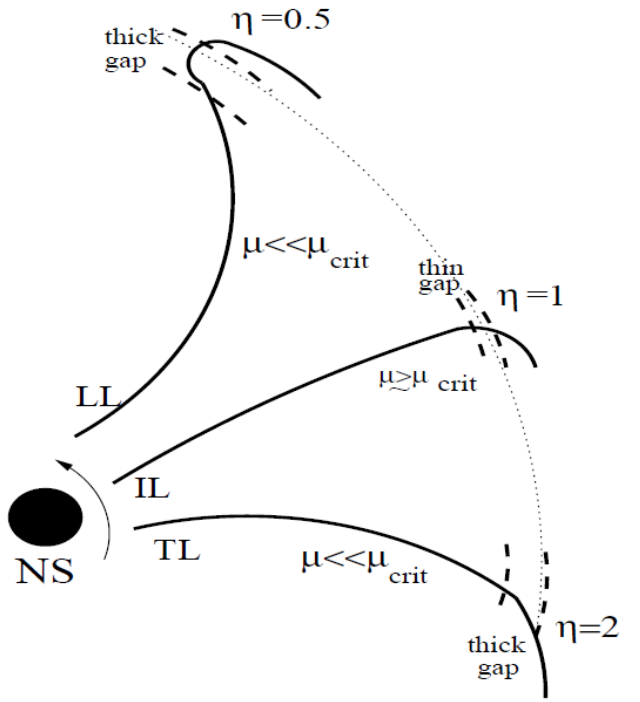
It must come from close to the light cylinder or even from beyond

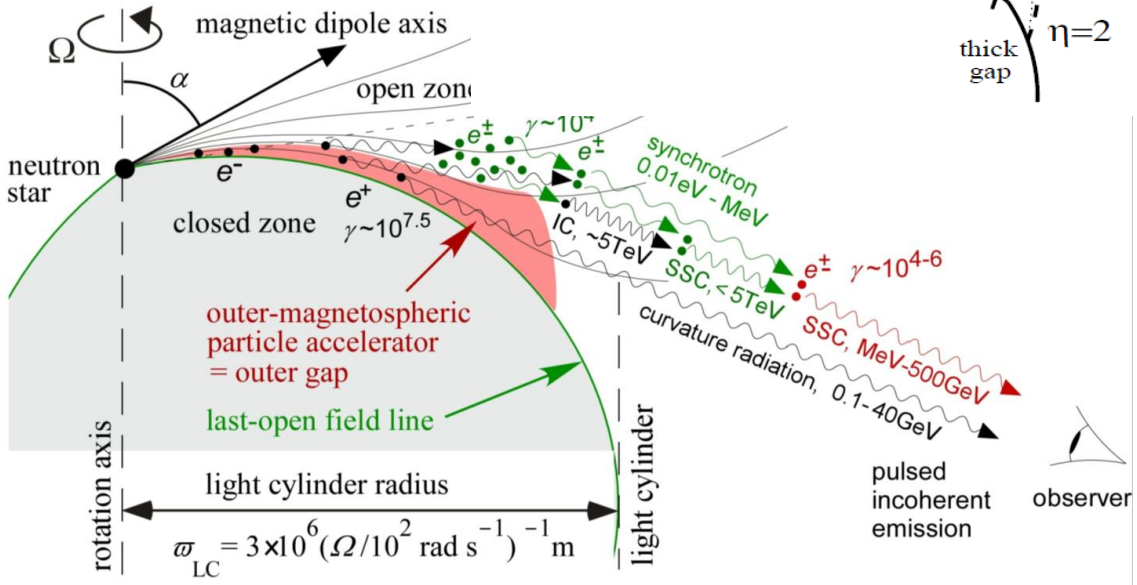
Is this the continuation of a low energy component or do we see a separate component popping up?

A Number of Possible Explanations

- Particle cascades in magnetosphere lead to significant inverse Compton scattering (Lyutikov (2012), Hirotani (2011), Du (2012))
- Topology of magnetic field allows for CR even >100 GeV (Bednarek 2012)
- Interaction of pulsed X-rays with $e^{+/-}$ in cold pulsar wind (Aharonian 2012)
- …

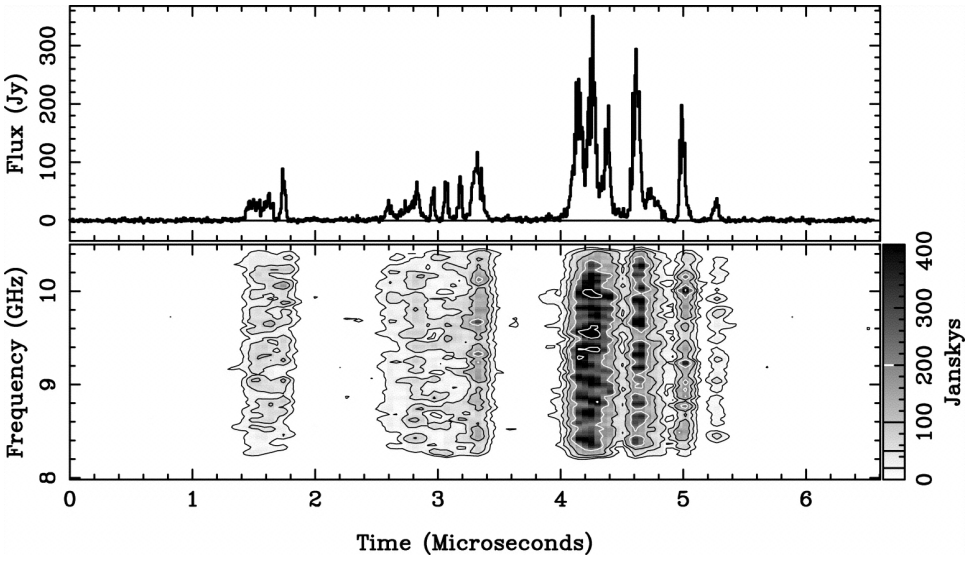


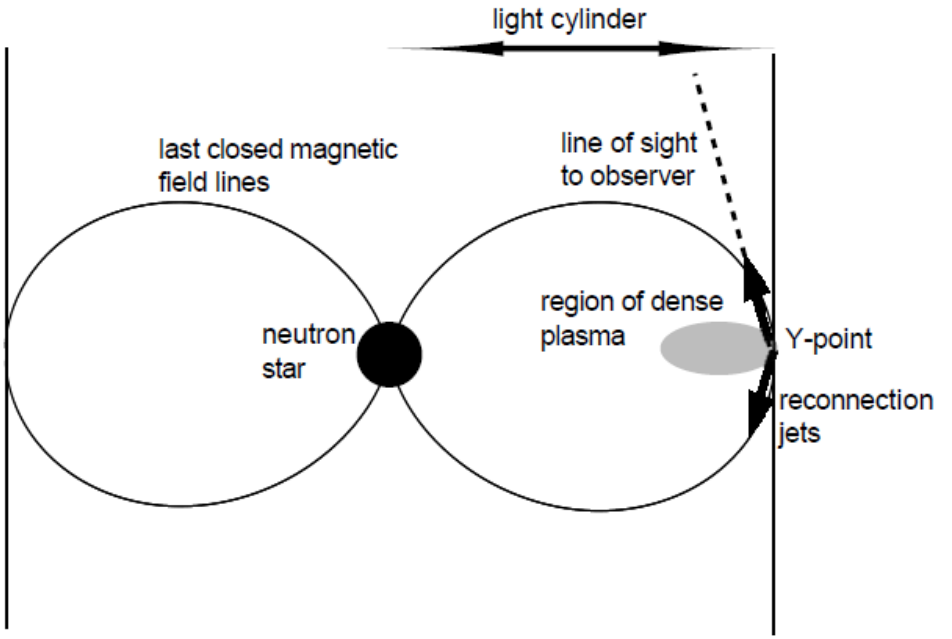




Giant Radio Pulses (GRPs)

- GRPs are short (microsecond long) very intense radio pulses
- Emission mechanism not known
- **Significant correlated optical emission (3% enhancement)** established with P1 GRPs (Shearer et al., 2003)
- **Correlated gamma-ray emission (tens of GeV) predicted** with IP GRPs (Lyutikov (2007))

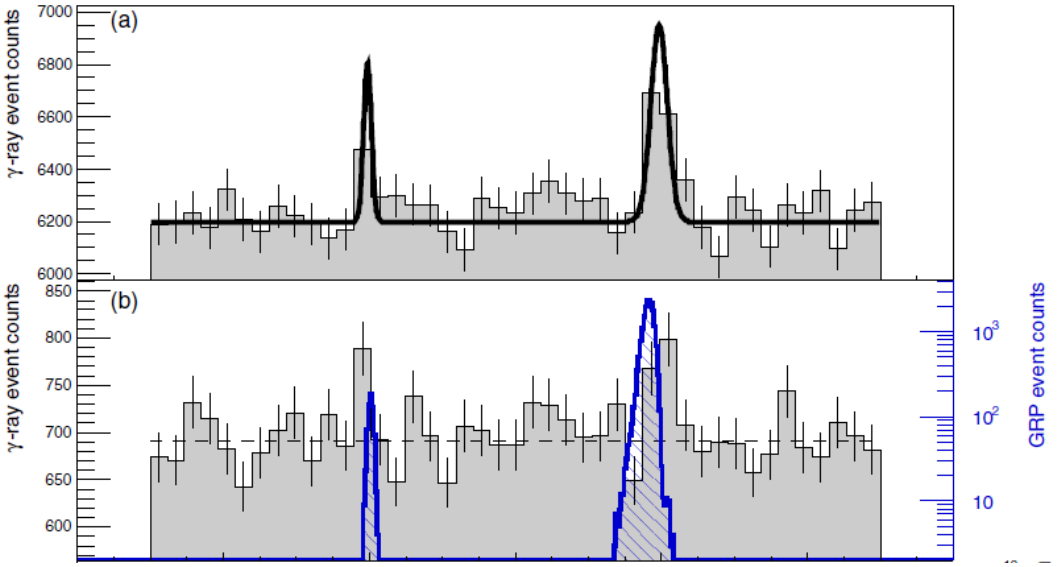




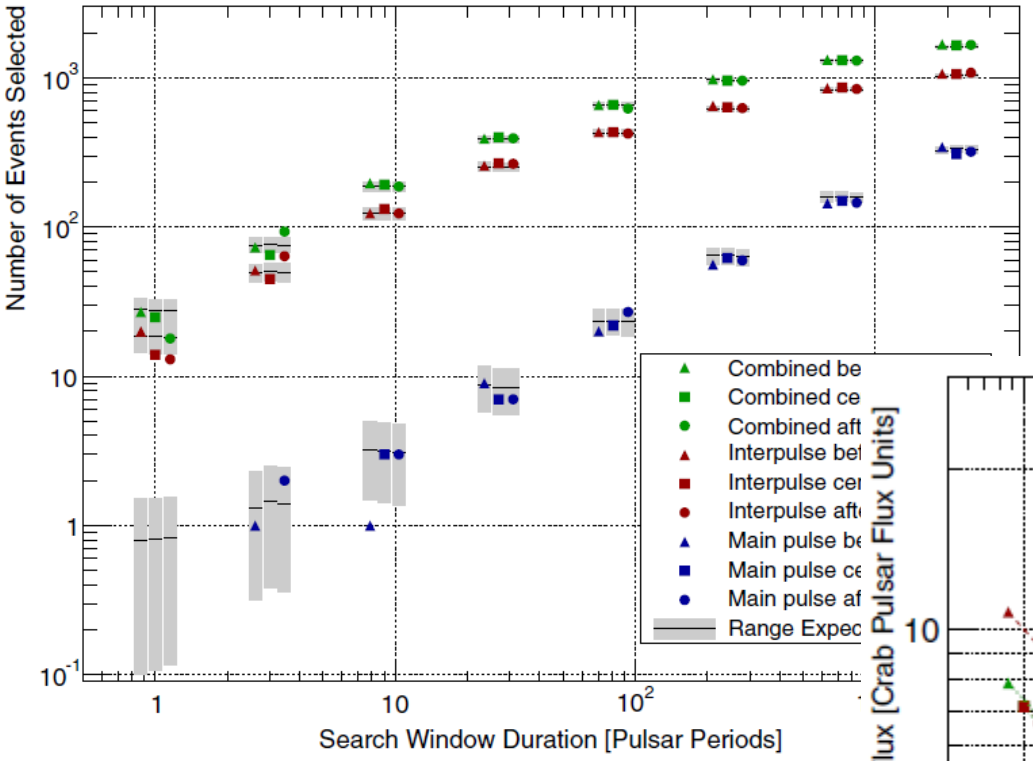
Search for a Correlation with Giant Radio Pulses

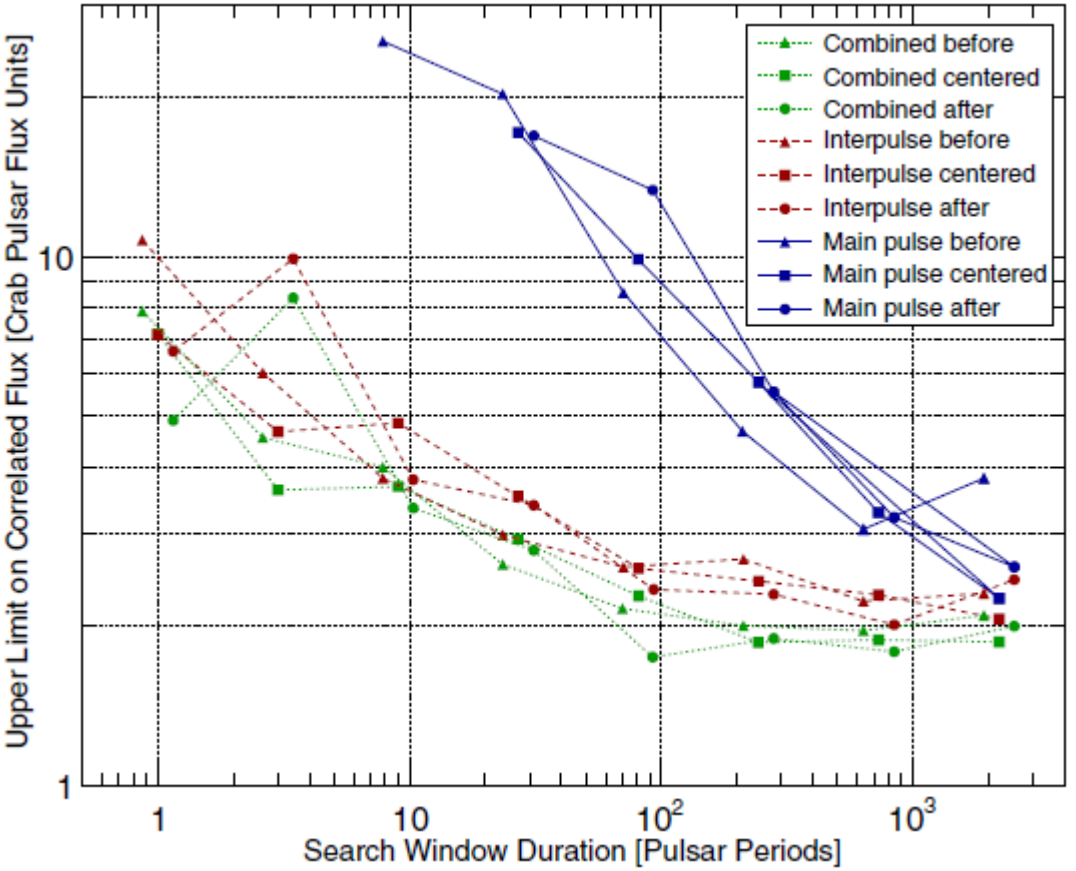
VERITAS & V. Kondratiev, ApJ 760 136 (2012)

- Four nights of simultaneous exposure with VERITAS and the Green Bank Telescope
- 11.6 hours exposure 18780 GRPs found (15366 overlap with VERITAS exposure)
- Investigated possible correlation at P1 & P2



Giant Radio Pulses & VHE Emission





- Different time windows investigated
- No correlations found
- Most constraining limits are at long search window durations

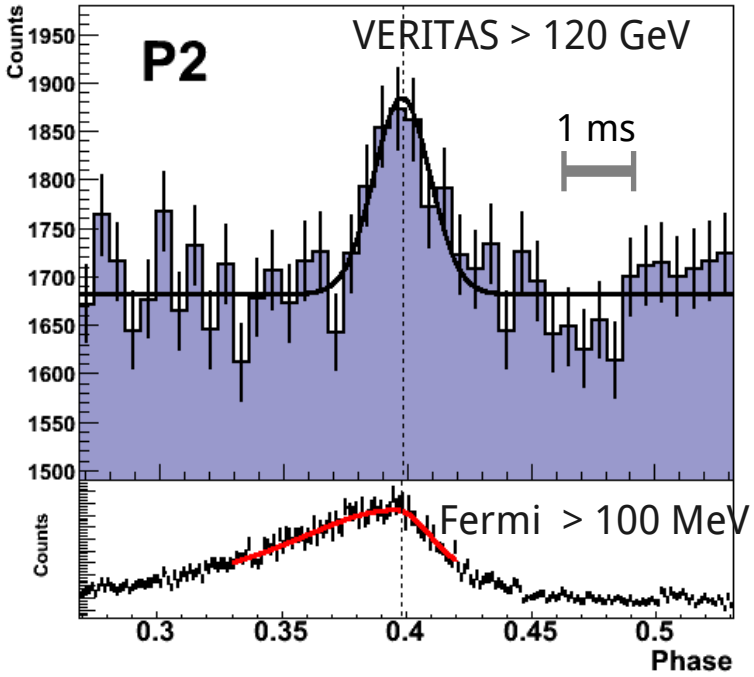
One can do more with Pulsars: Testing Lorentz Invariance

Otte, Proceedings 32nd ICRC 2011 Beijing
arXiv:1208.2033

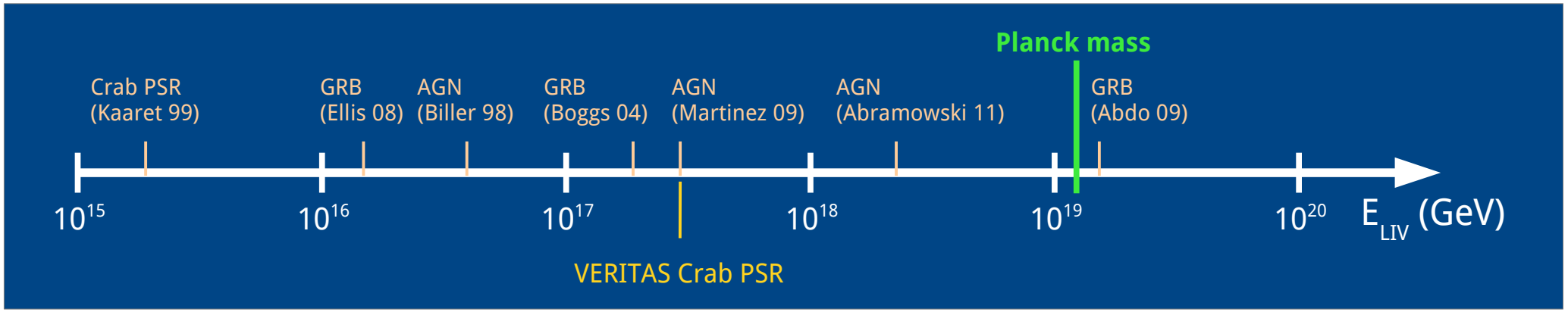
- Original idea from P. Kaaret
- Peaks at 100 MeV (Fermi) and 120 GeV (VERITAS) line up

$$\Delta t_{95\%} < 1.65 \cdot \delta \cdot P/\sqrt{2} < 100\,\mu s$$

- Linear: $E_{LIV} > 3 \times 10^{17}$ GeV
- Quadratic: $E_{LIV} > 7 \times 10^{9}$ GeV



Linear term:



Present and Future Pulsar Observations with VERITAS

Crab:

Improve spectral measurements to discriminate between models

- One or two spectral components?
- Turnover above 400 GeV?

Improve limits on Lorentz invariance violation

Other Pulsars:

Is pulsed VHE emission a specialty of the Crab?

Extrapolating Fermi-LAT measurements in the VHE (assuming one single component)

1. Harvesting archival VERITAS data
2. Dedicated campaigns on promising candidates

Search millisecond pulsars (assuming inverse Compton scenario)

More compact magnetosphere -> likelier upscattering of X-ray photons

conditional selection requirement: bright in X-rays

Extrapolating Fermi-LAT Detections into the VHE

Assume single component scenario

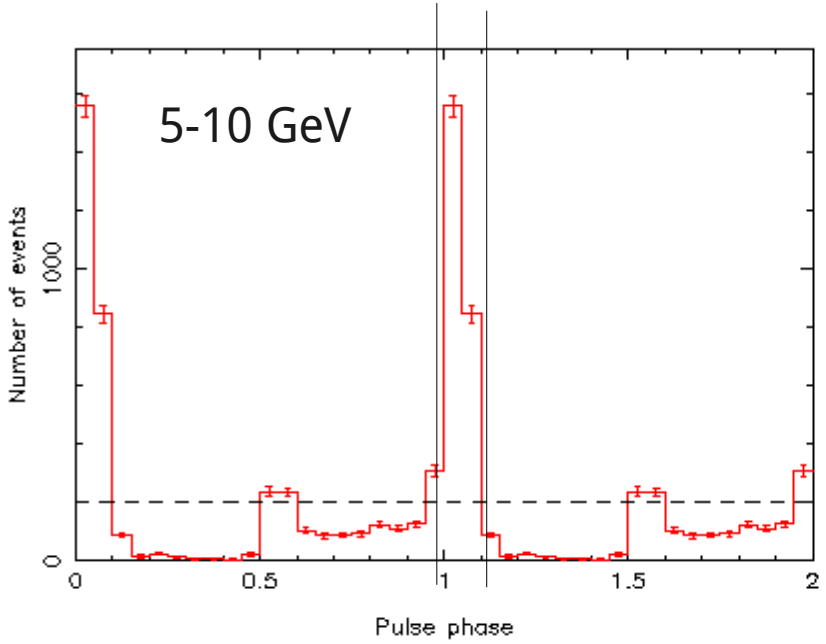
→ Extrapolation of spectrum into the VHE region a la Crab?

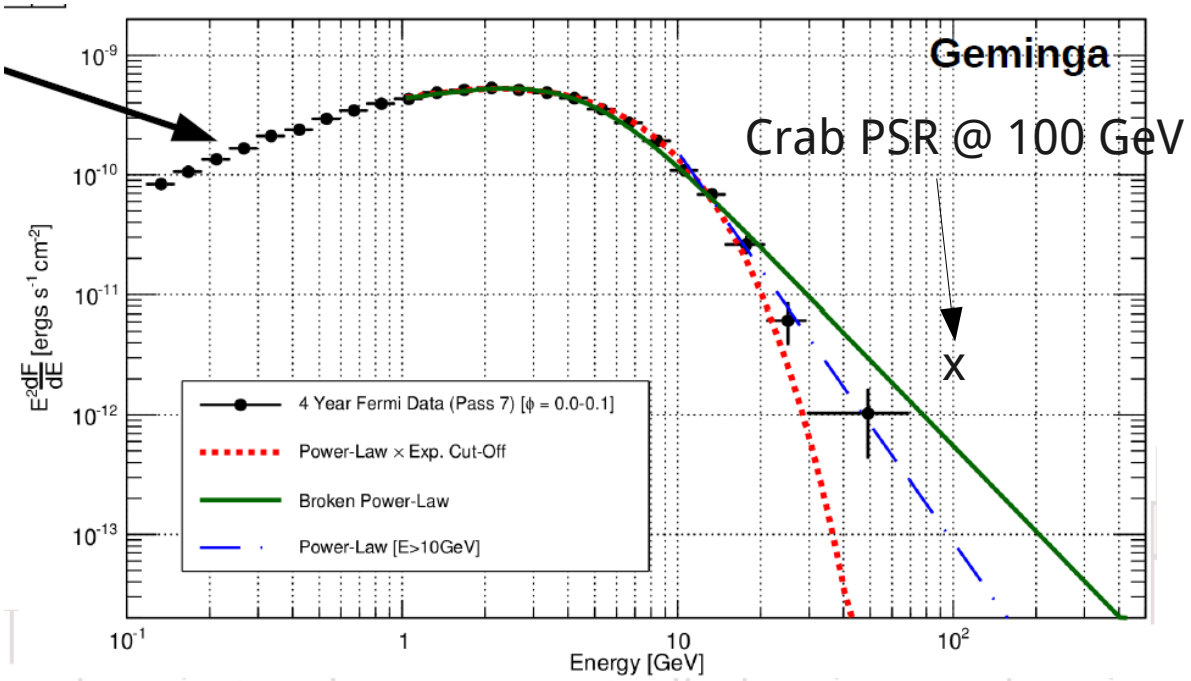
"Subject to huge uncertainties,
spectrum above cutoff not well enough determined"

Archival data:
14 sources
already observed
with VERITAS

Name	$\dot{E}$ [ergs/s]	T_{obs} [hrs]	T_{eff55} [hrs]	Pulse FWHM [% of Crab]	$Flux_{10\_100GeV}$ [cm^{-2} s^{-1}]	$Flux_{10\_100GeV}$ [% of Crab]	Limit [% of Crab]
PSR J0633+0632	1.2×10^{35}	119.0	90.1	46.4	1.89×10^{-11}	0.2	13.1
PSR J0248+6021	2.1×10^{35}	106.6	49.2	87.7	9.53×10^{-11}	1.2	24.4
PSR J2021+3651	3.4×10^{36}	91.4	72.4	32.4	3.43×10^{-10}	4.6	12.2
PSR J2032+4127	2.7×10^{35}	82.9	48.3	33.7	3.63×10^{-10}	4.8	15.3
PSR J1907+0602	2.8×10^{36}	79.7	54.9	87.7	3.37×10^{-10}	4.5	23.1
PSR J2030+3641	3.2×10^{34}	75.6	19.0	127.1	6.65×10^{-11}	0.8	47.4
PSR J2021+4026	1.2×10^{35}	74.0	36.7	109.6	5.58×10^{-10}	7.4	31.7
PSR J2229+6114	2.2×10^{37}	68.2	47.05	100.8	2.13×10^{-09}	28.5	26.8
PSR J0633+1746	3.2×10^{34}	55.8	54.95	42.5	2.8×10^{-09}	37.5	16.1
PSR J0007+7303	4.5×10^{35}	35.6	0	153.5	1.24×10^{-09}	16.6	-
PSR J0205+6449	3.0×10^{37}	19.3	9.7	122.8	1.37×10^{-10}	1.8	65.2
PSR J0659+1414	3.8×10^{34}	15.3	9.7	87.7	7.67×10^{-11}	1.0	55.0
PSR J2030+4415	-	14.3	14.2	57.0	1.04×10^{-10}	1.3	67.2
PSR J0631+1036	1.7×10^{35}	13.0	13.0	109.6	1.11×10^{-10}	1.4	53.2

Geminga


5-10 GeV
Number of events
1000
0
0
0.5
1
1.5
2
Pulse phase


Geminga
Crab PSR @ 100 GeV
X
$E^2\frac{dF}{dE}$ [ergs s^{-1} cm^{-2}]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
4 Year Fermi Data (Pass 7) [ϕ = 0.0-0.1]
Power-Law × Exp. Cut-Off
Broken Power-Law
Power-Law [E>10GeV]
10^{-1}
1
10
10^{2}
Energy [GeV]

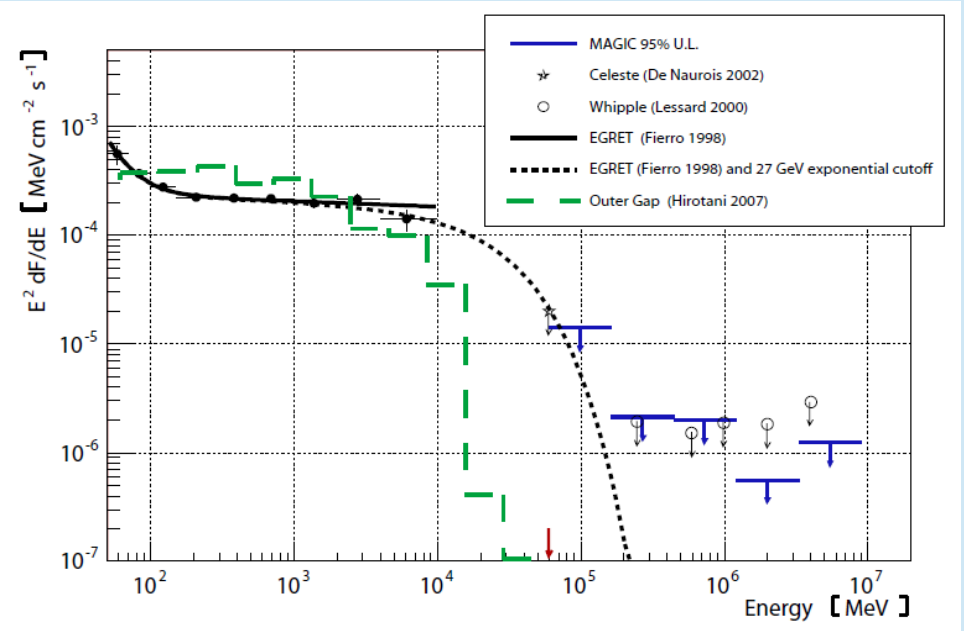
Conclusions

- Detection of first pulsar above 100 GeV
  - Opening new opportunities
    - Learn extremes of pulsar magnetospheres
    - Use pulsars to test LIV
- Mechanisms of VHE emission not clear
  - Several proposed mechanisms, which can be discriminated in future VHE observations
- Other VHE Pulsars?
  - Other pulsars based on Fermi-LAT extrapolations
  - ms-pulsars

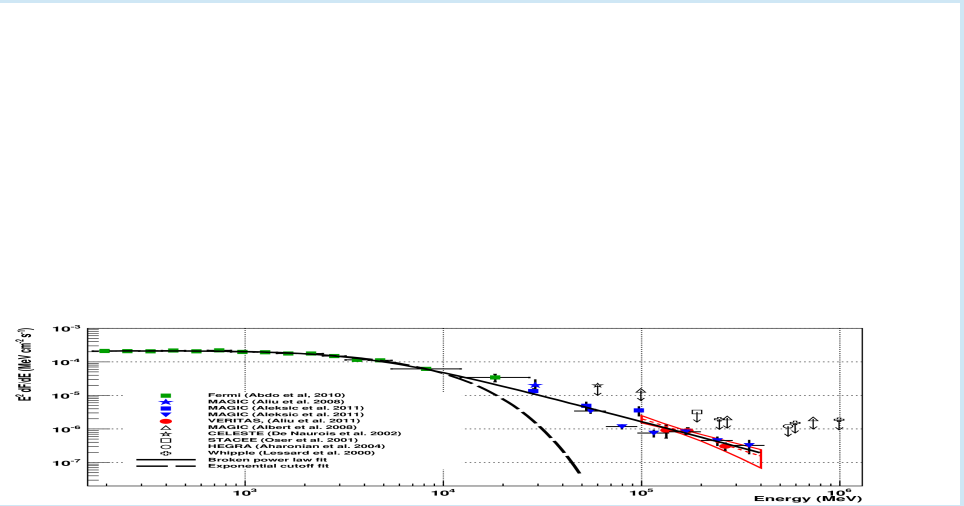
Conclusions from the past 5 years

We have made real progress in the VHE band!!

2007



2012



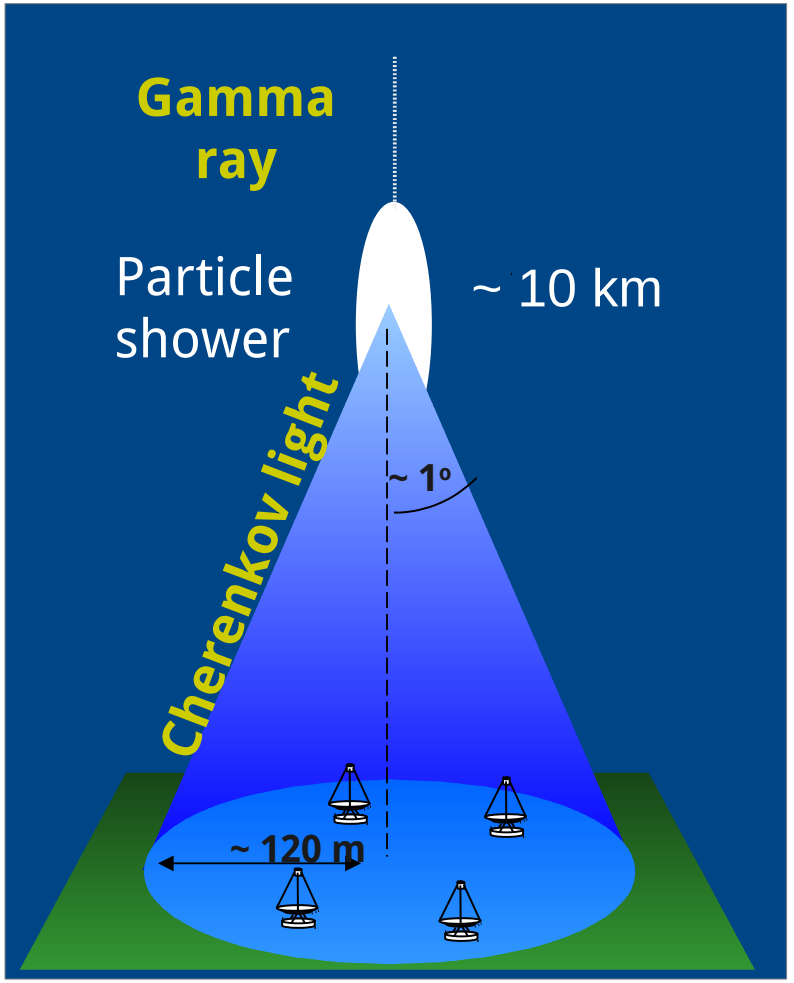
While we have answered some questions many more have been asked

- General trend to shift the emission region close to the light cylinder or beyond

We need more sensitivity in the entire VHE band

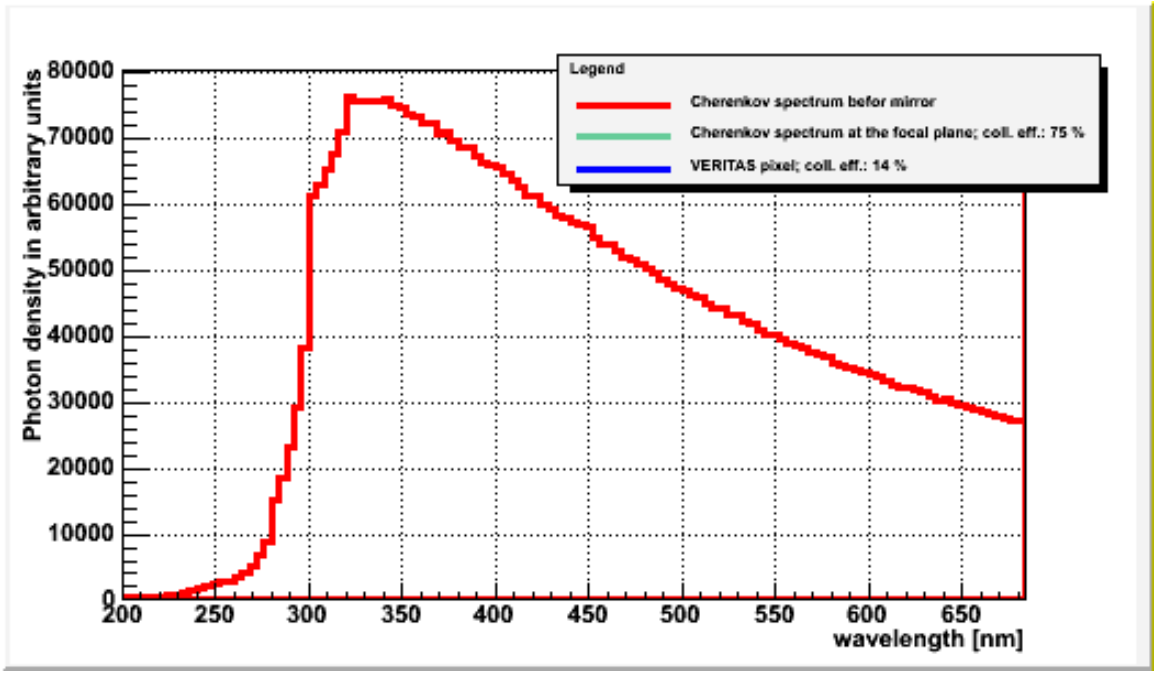
- Cutoff vs. no cutoff ?
- Phase resolved spectroscopy

Imaging Technique



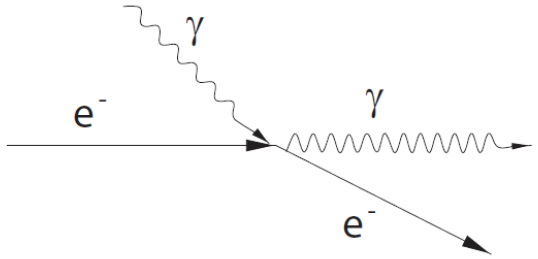
Cherenkov radiation from $e^{+/-}$

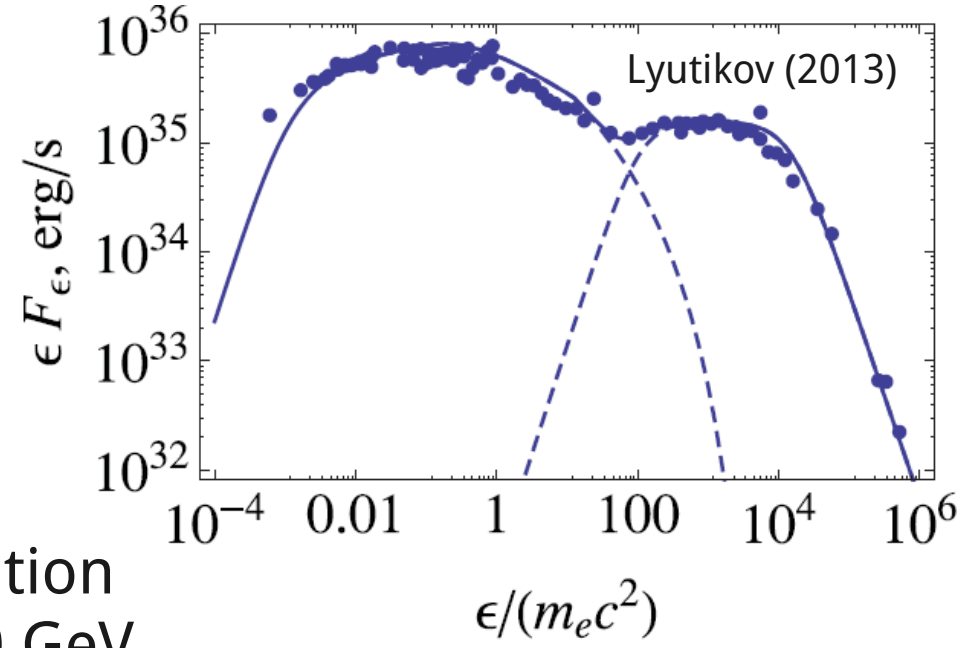
- ~1° opening angle
- 5 photons / m^2 for 100 GeV gamma ray arrive on ground
- Flash with 2-3 ns duration



Is it IC in the outer magnetosphere?

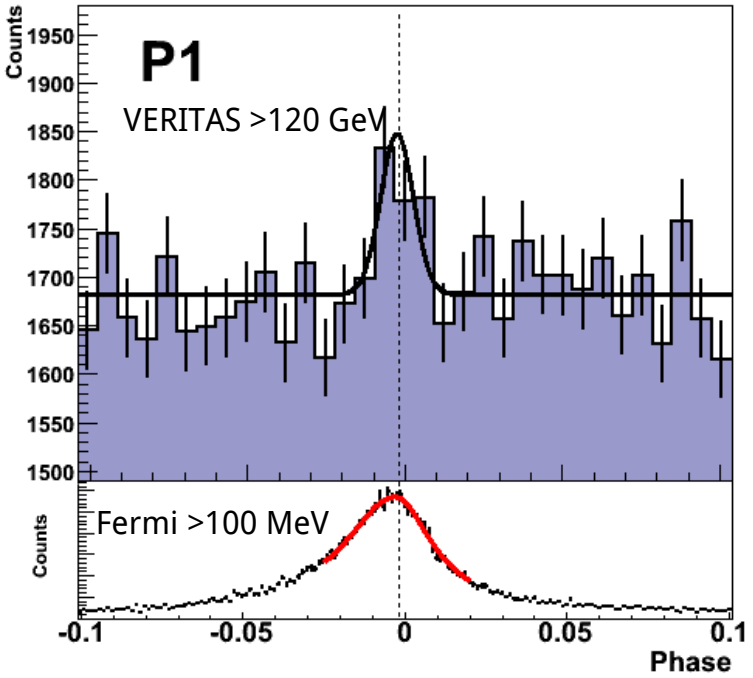
Lyutikov, McCann, Otte (2011)





- Radiation reaction limits acceleration and curvature radiation to < 100 GeV
- Curvature radiation photons absorb and cascade in the outer magnetosphere
- VHE emission due to IC upscatter of X-Ray photons by 2nd or 3rd $e^{+/-}$ generation produced in cascades

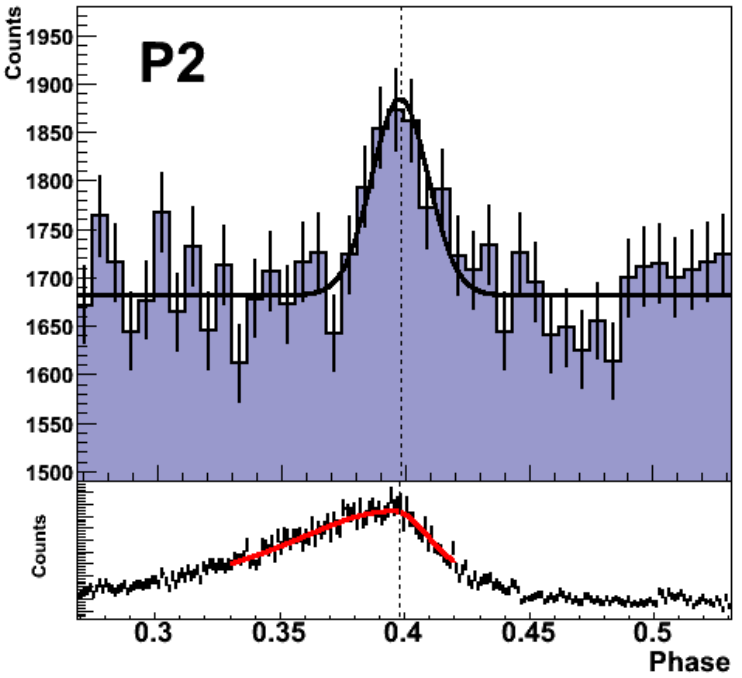
A closer Look at the Pulses



Position: -0.0026 ± 0.0028

Width: 0.0122 ± 0.0035 FWHM

Peak positions **aligned with peak positions in radio.**



Position: 0.3978 ± 0.0020

Width: 0.0267 ± 0.0052 FWHM

Pulses above 120 GeV **2-3 times narrower than in Fermi-LAT data**
-> possible interpretation: the acceleration zone tapers