The Crab Pulsar from HE to VHE

Fermi Summer School 2012

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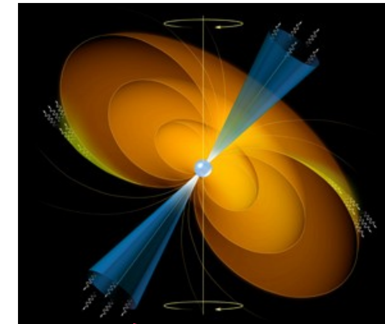
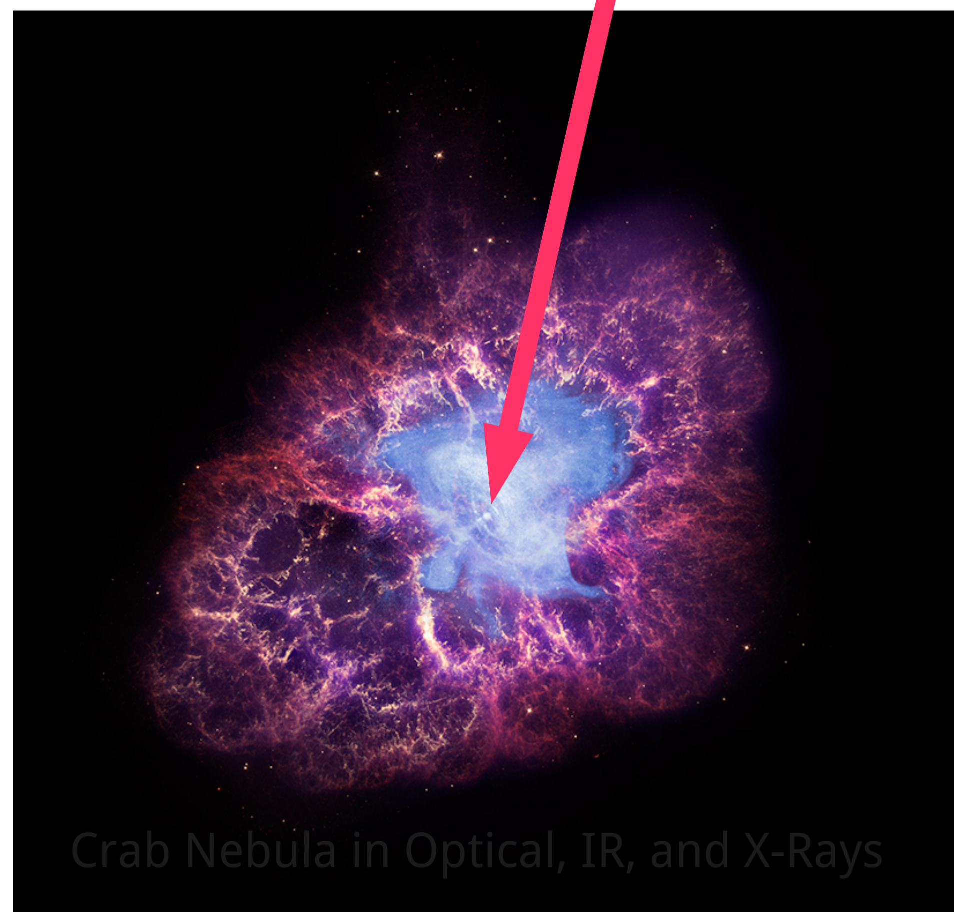
The Crab

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





Crab Nebula in Optical, IR, and X-Rays

Birth of a Pulsar

Birth of a Pulsar

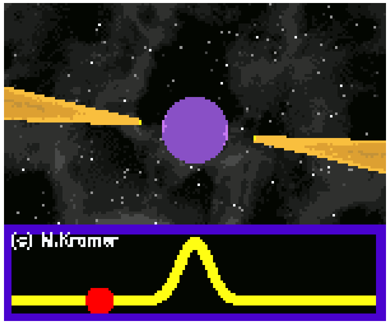
- Supernova remnant of a massive star (5-10 solar masses)
- Gravitational core collapse stopped by neutron degeneracy pressure
  - compact object of ~1.4 solar masses with radius of 10-20 km
- Conservation of magnetic energy and angular momentum during collapse
  - fast rotation ~100 Hz and strong magnetic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

→ powerful generator of electromagnetic energy

Gamma-Ray Production in the Vicinity of Pulsars

γ-ray emission (GeV and higher) is produced by relativistic particles

in the:



1. magnetosphere of the neutron star

   -> pulsed emission

2. nebula powered by the pulsar

   → steady emission

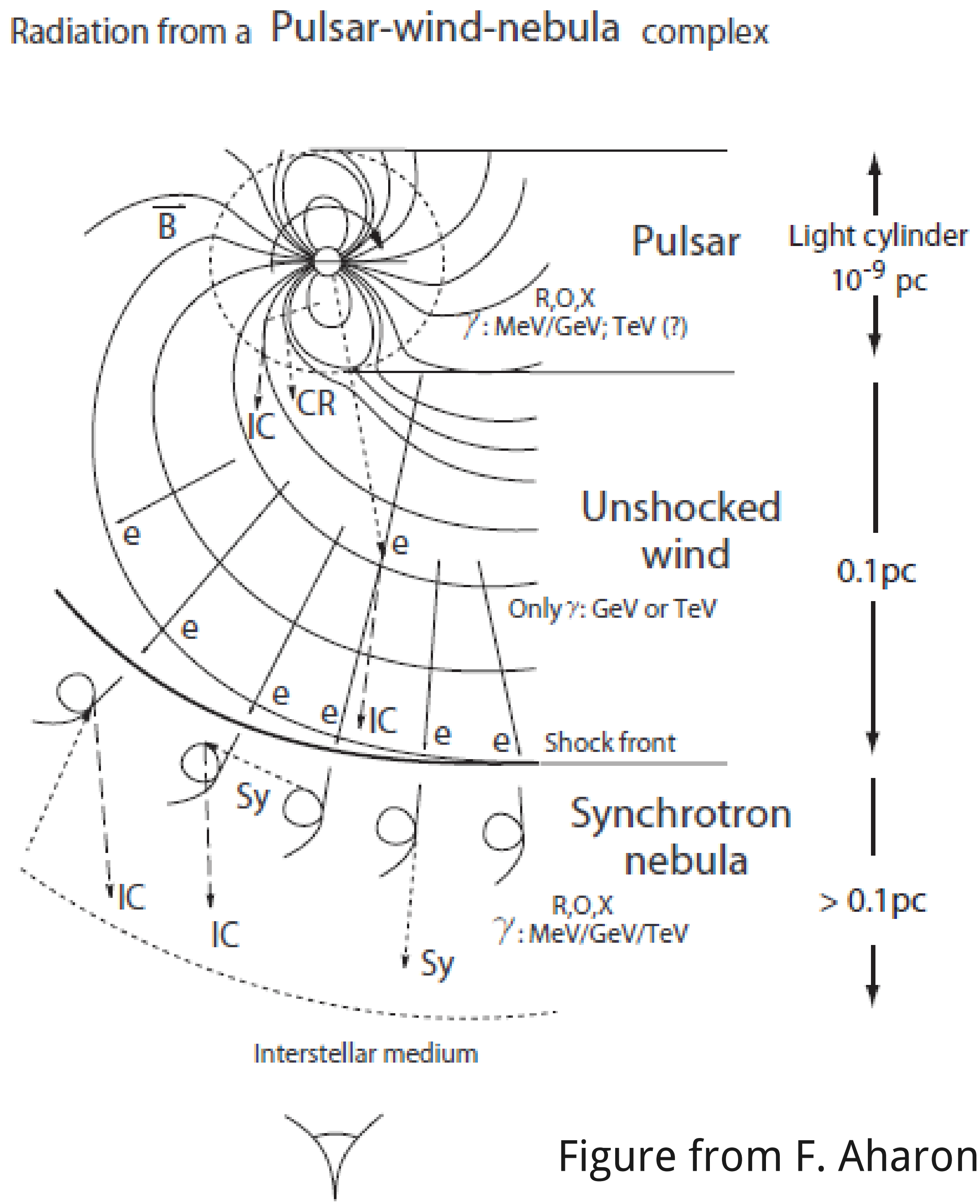
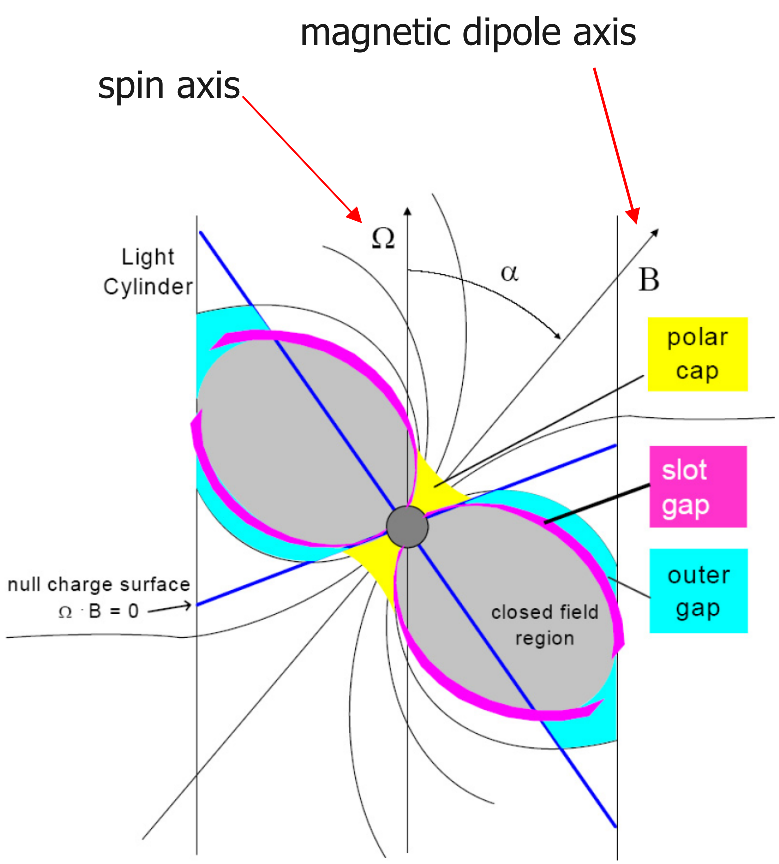


Figure from F. Aharonian

Gamma-Ray Emission from the Pulsar Magnetosphere



sketch from Alice Harding

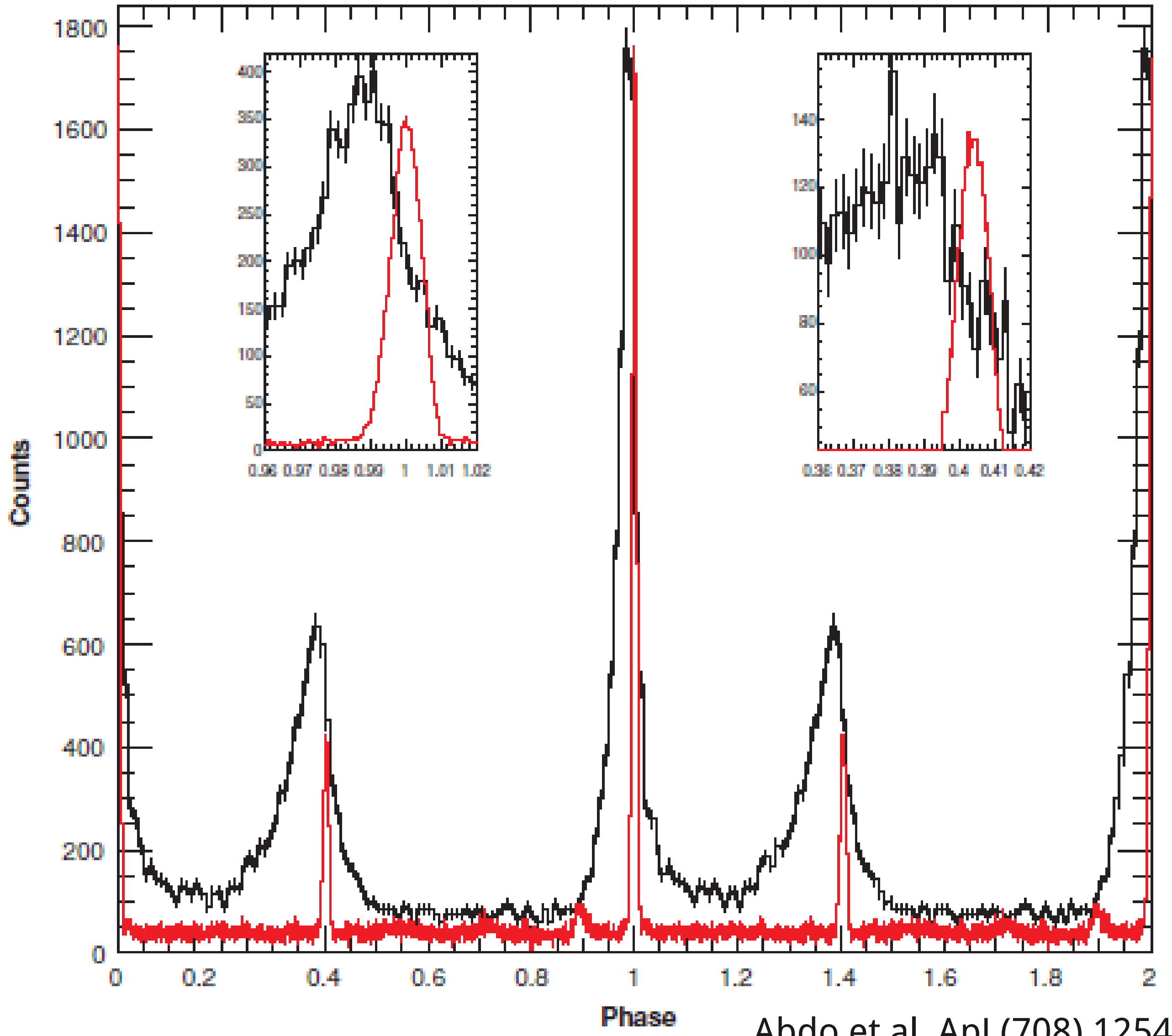
- Stable vacuum gaps in the magnetosphere
- Potentials of ~10^{12} eV

  → particle acceleration
- Curved particle trajectory

  → γ-ray emission
- Interaction with low energy photons

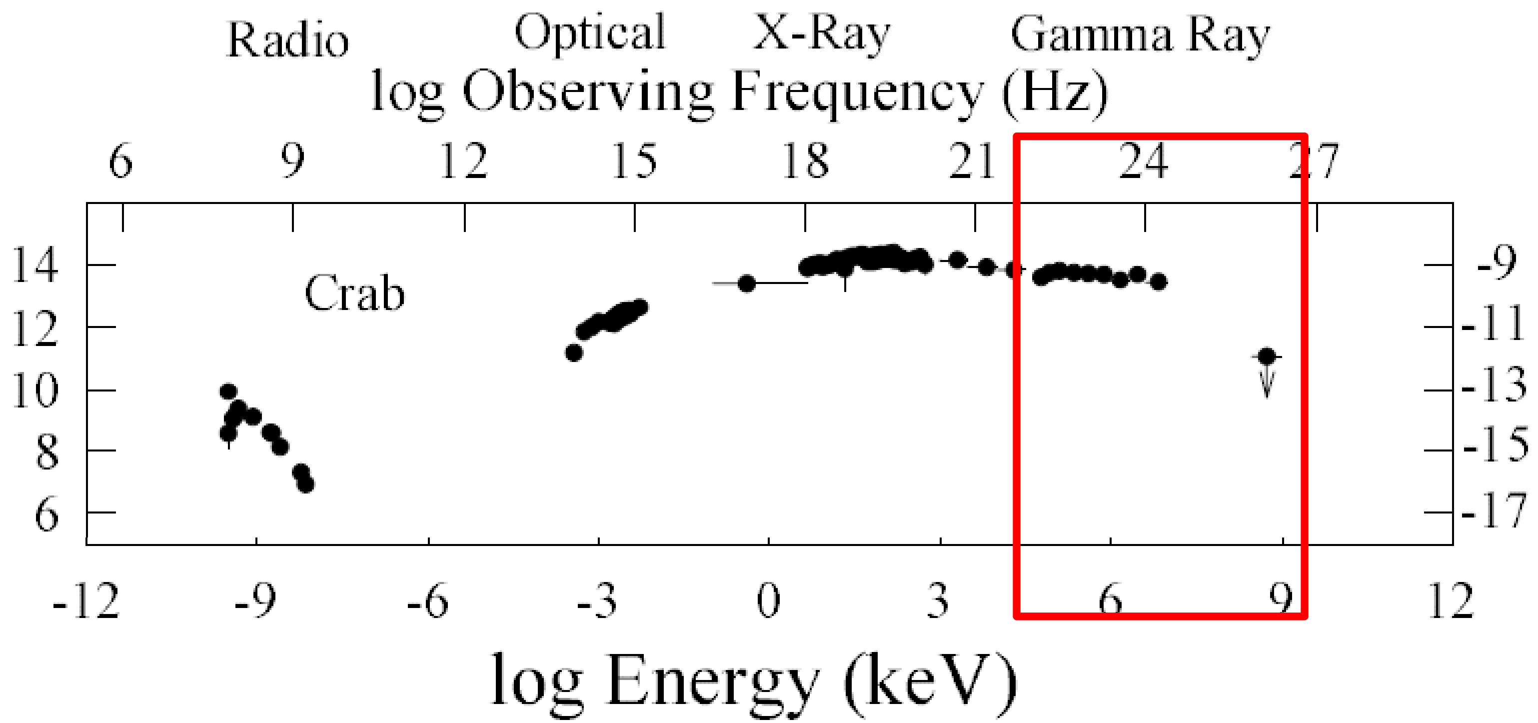
  → inverse Compton emission
- Gamma-rays are subject to absorption

Crab Pulsar Pulse Profile



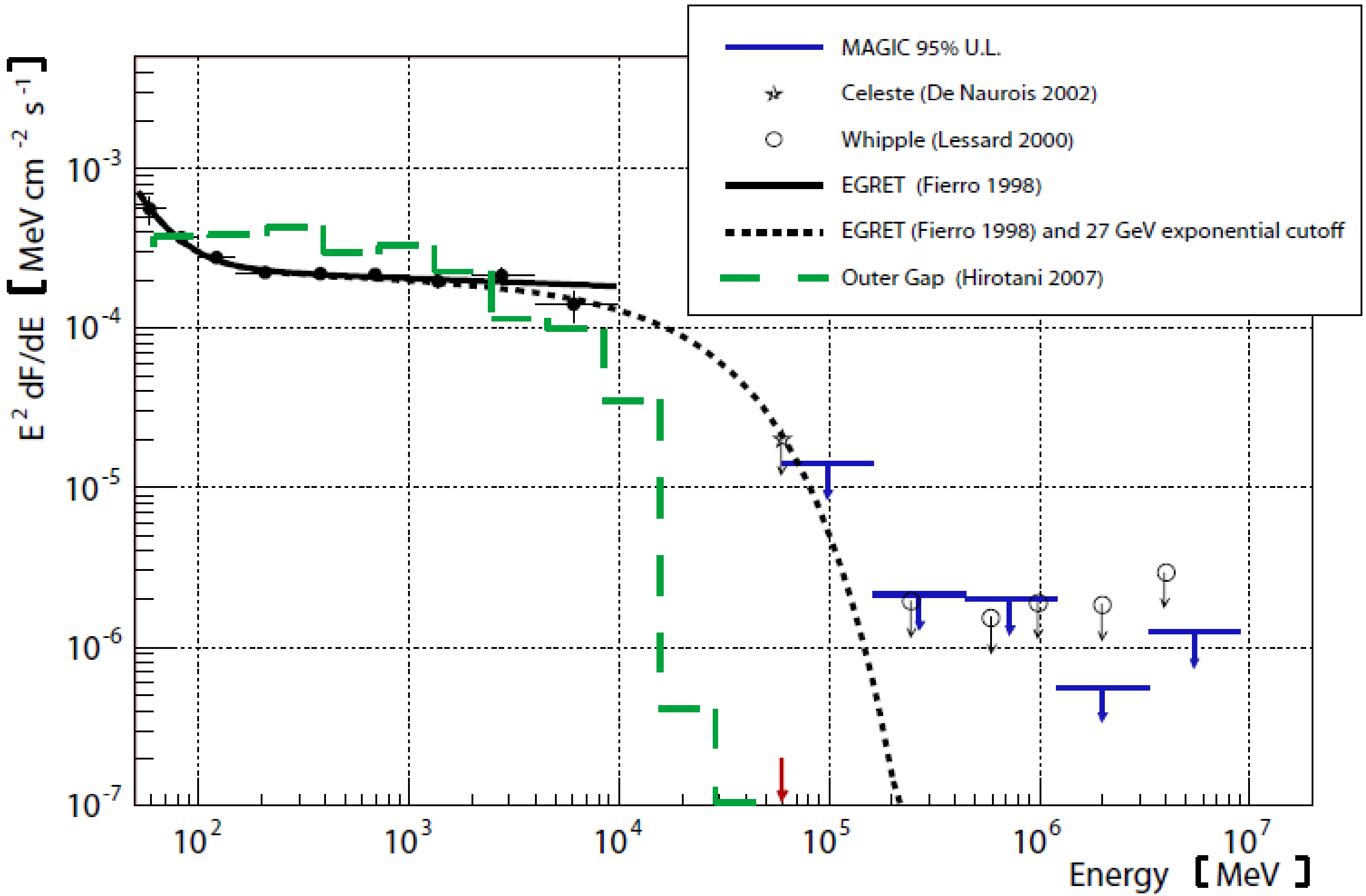
Abdo et al. ApJ (708) 1254–1267, 2010

Pulsed Emission from the Crab



From Thompson et al 1999

EGRET Era



Albert et al. (2007)

- EGRET on CGRO
- First good measurement of the HE part of spectrum
- No answer to how the cutoff looks like

Two favored models

Outer gap

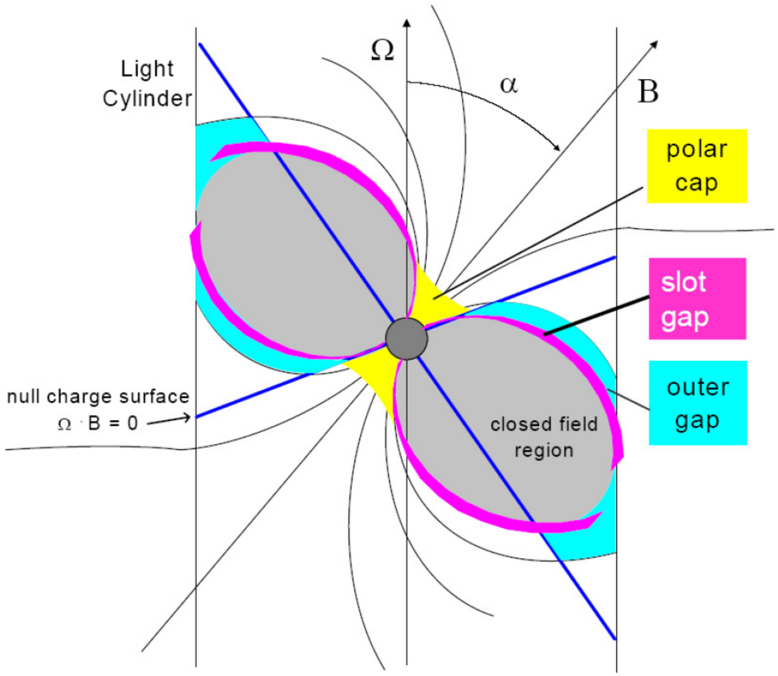
- Emission region far out in the magnetosphere -> **exponential cutoff (b=1)**

Polar cap

- Low emission region -> **super exponential cutoff (b>2)**

Parameterization of the cutoff:

$$F(E)*\exp(-E/E_c)^b$$



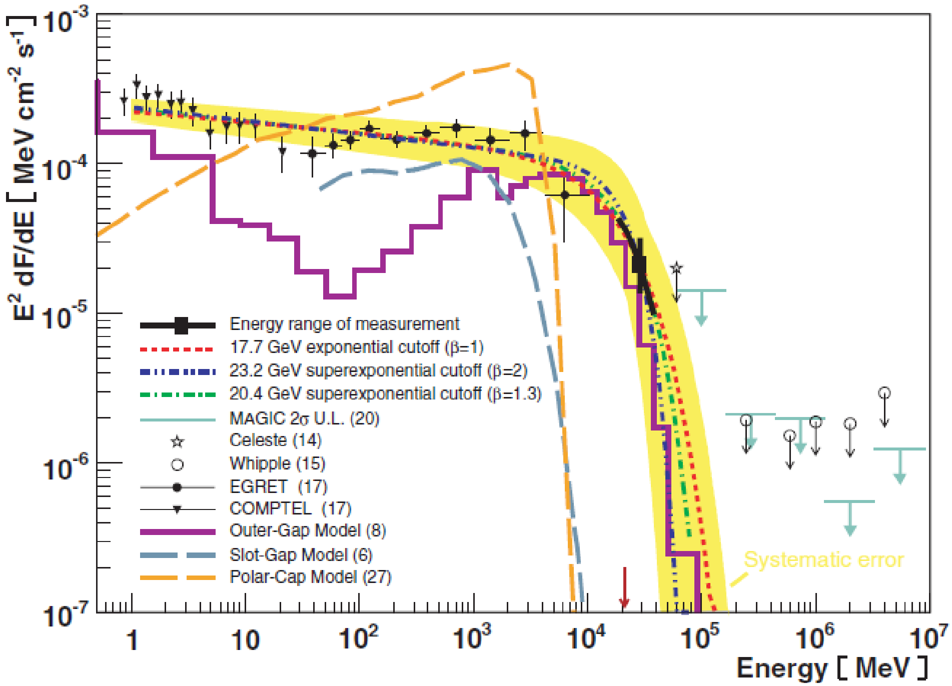
Fermi & MAGIC (2008)

Fermi launched

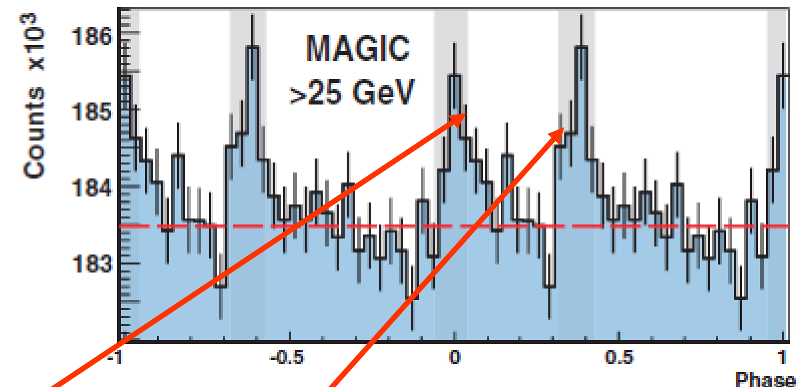
in summer 2008

MAGIC achieved
energy threshold of 25 GeV
in fall 2007

MAGIC Pulsar Detection at 25 GeV



Science, MAGIC Aliu et al. (2008)



Cutoff of the combined main pulse and inter pulse emission

$F*\exp(-E/E_c)^b$

exponential cutoff (red) : $16.4 \pm 2_{stat} \pm 5_{syst}$ GeV

superexponential cutoff (blue) : $20.5 \pm 2_{stat} \pm 5_{syst}$ GeV

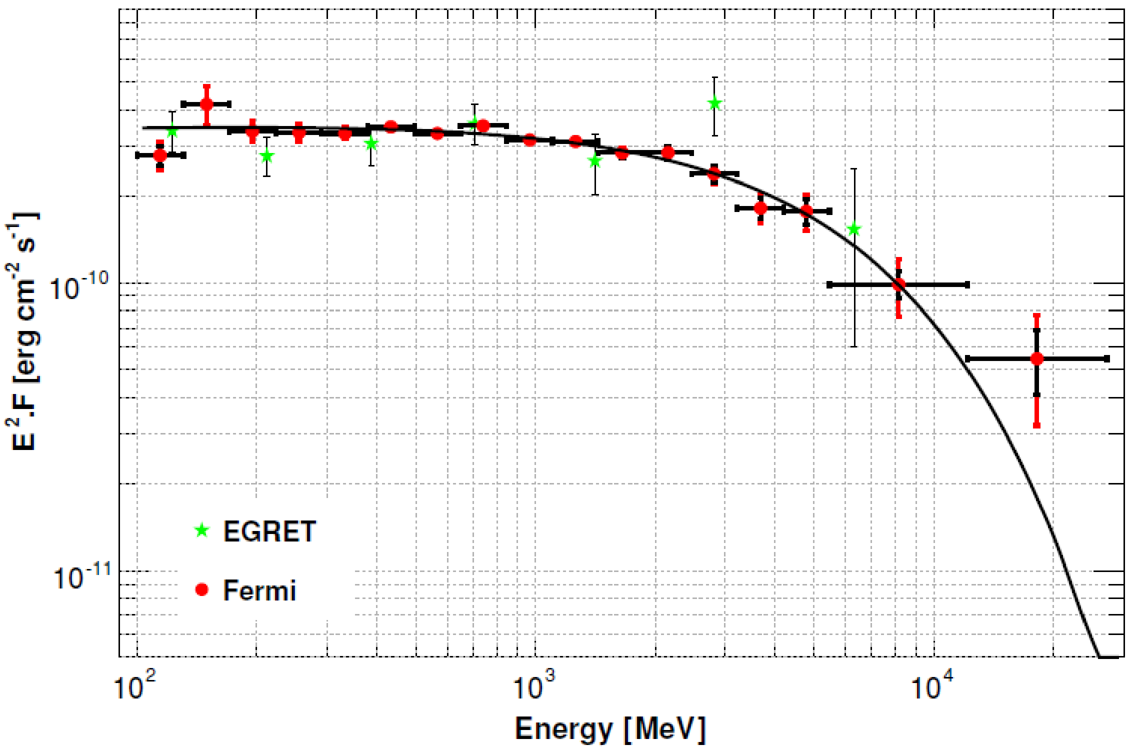
restricts the emission region to above 5 NS radii

Unprecedented Spectroscopy with Fermi: Phase Averaged

- Cutoff energy 5.8 GeV
- Detection up to 20 GeV

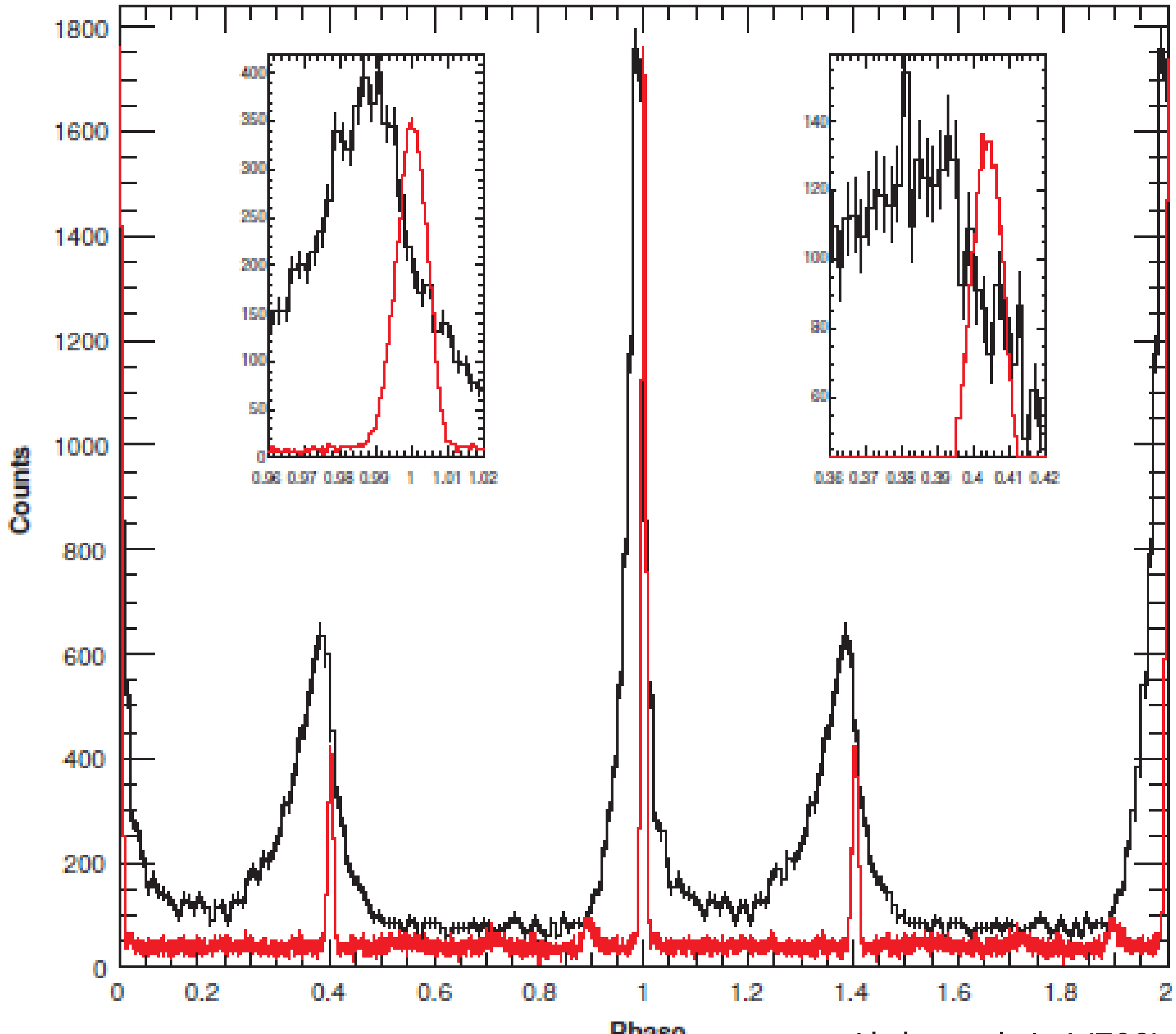
    Constrains the emission region to > 4-5 NS radii

- Exclusion of the superexponential cutoff
- Cutoff consistent with exponential cutoff

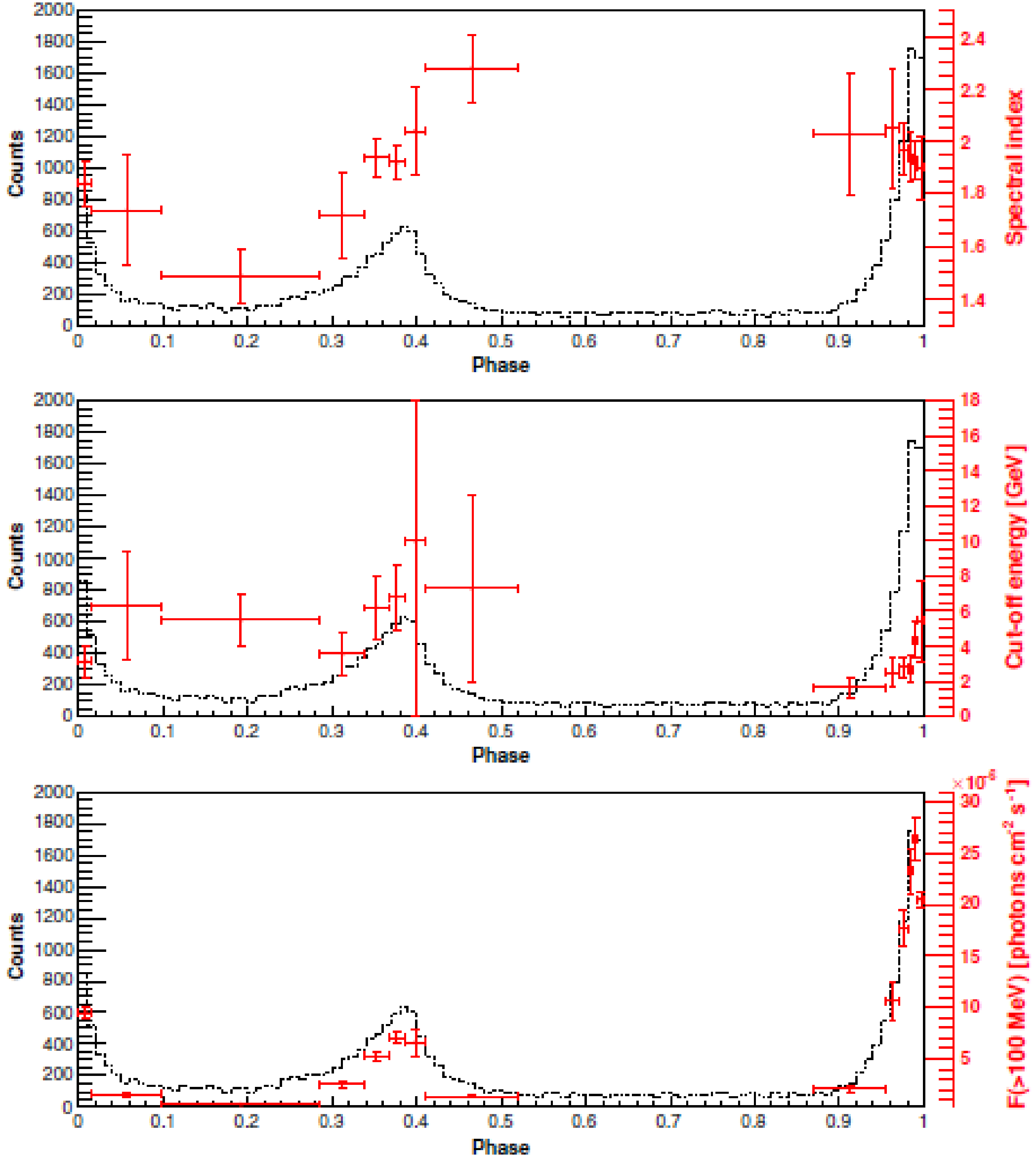


Abdo et al. ApJ (708) 1254–1267, 2010

Enough statistics to do phase resolved spectroscopy



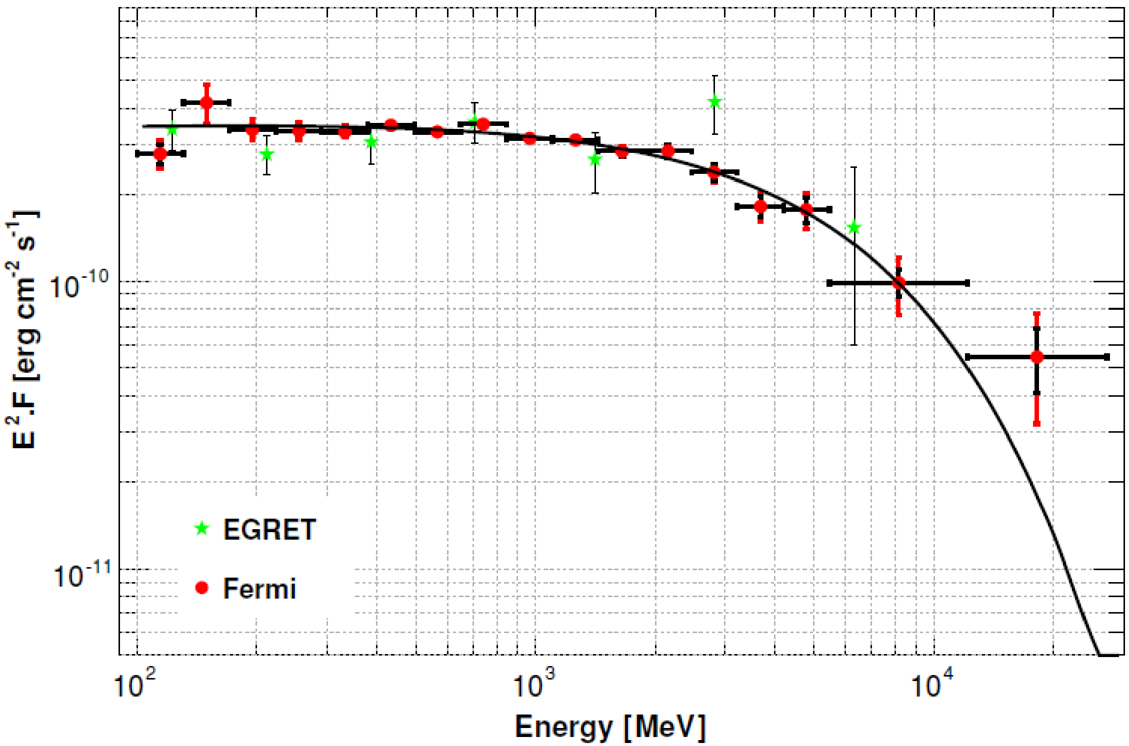
Abdo et al. ApJ (708) 1254–1267, 2010



Abdo et al. ApJ (708) 1254–1267, 2010

Is the Picture complete?

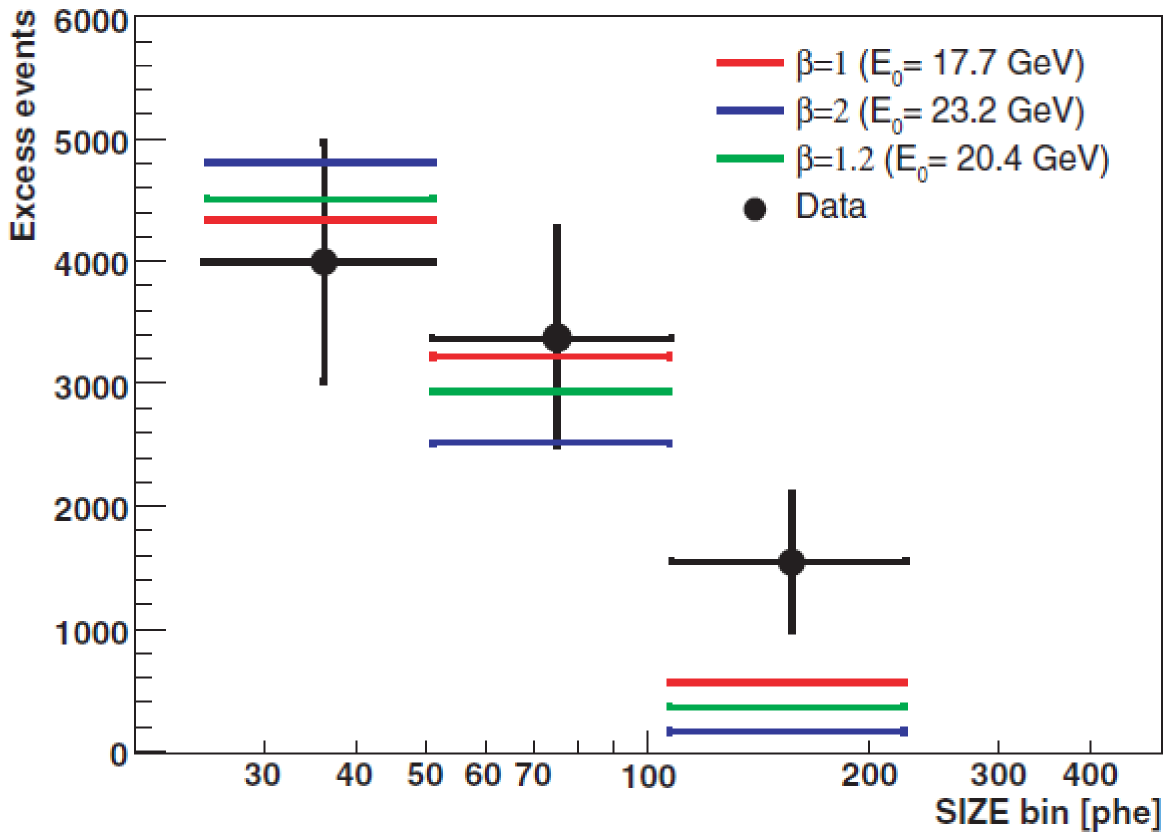
- Sensitivity limited above 10 GeV with Fermi
- Why bother, outer gap fits -> lets go home



The highest Energies

Assumption:

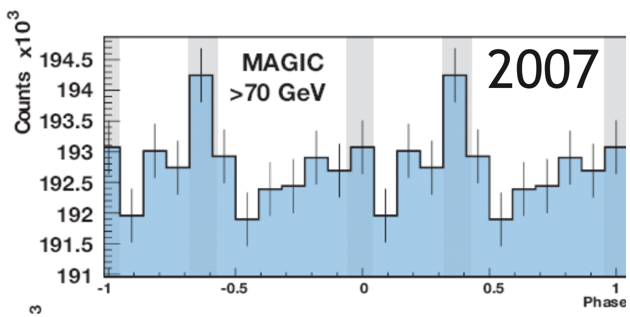
The spectrum at the highest energies is described by an exponential cutoff

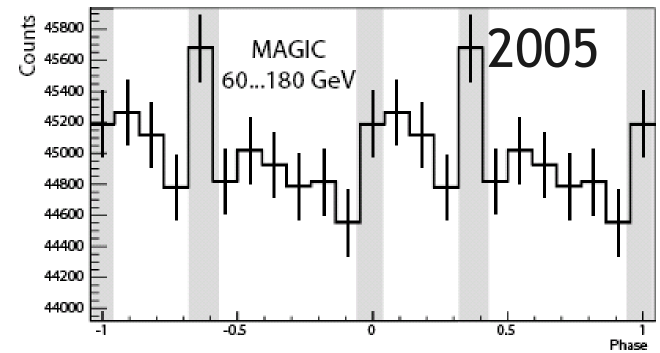


Science, MAGIC Aliu et al. (2008)

Is the spectrum harder than described by an exponential cutoff?

Pulsed Emission above 60 GeV





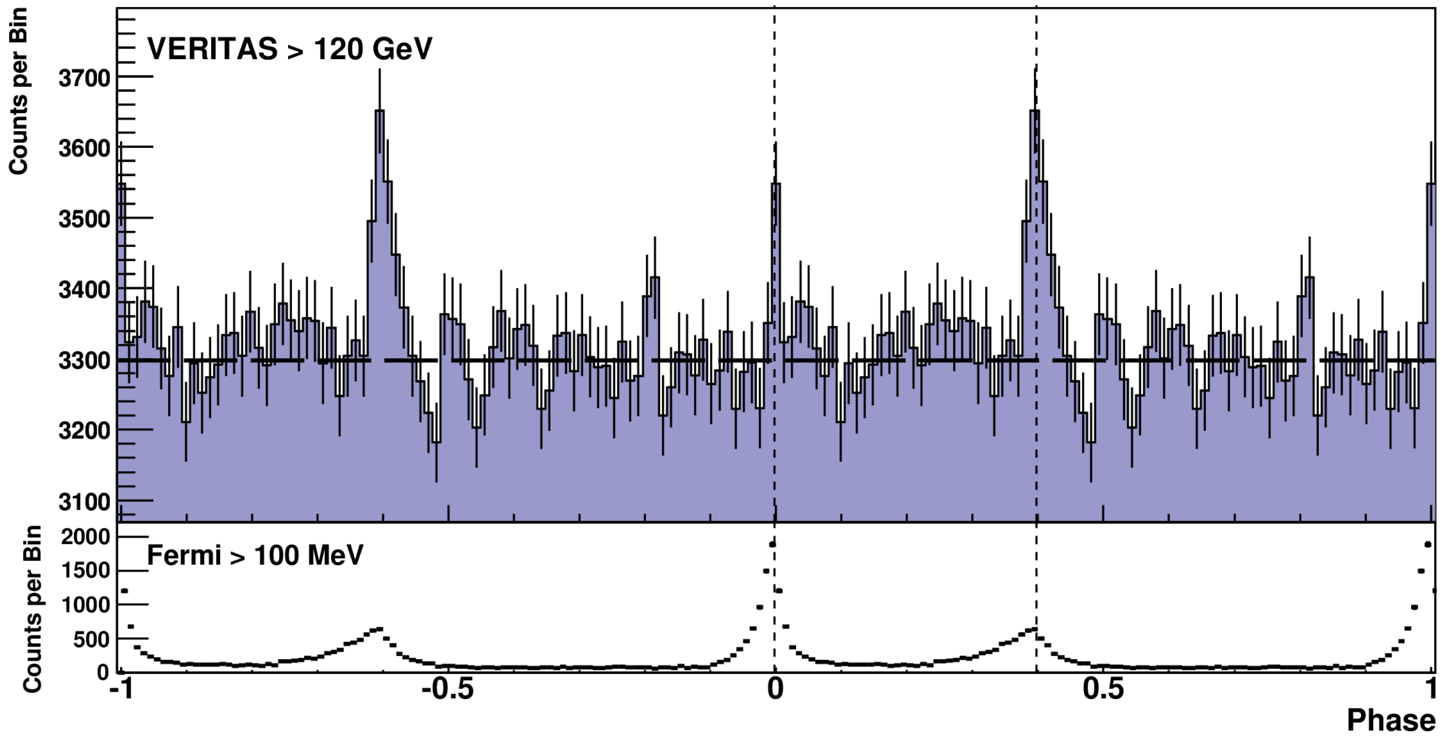
Albert et al. (2008) APJ 674, 1037+

Two independent data sets show pulsed emission above 60 GeV at the position of the interpulse

… at flux levels not predicted by model calculations!

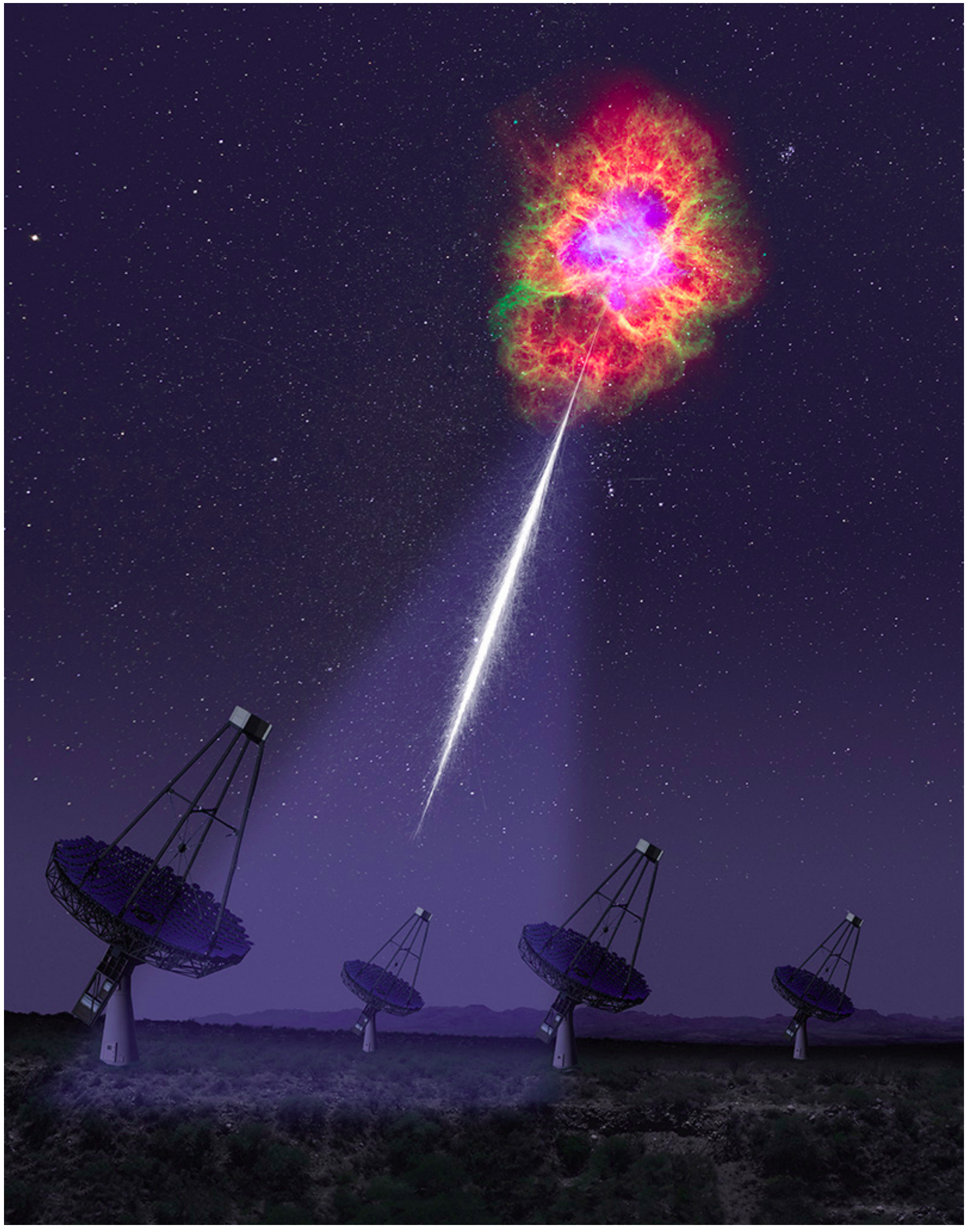
Detection of the Crab Pulsar above 100 GeV

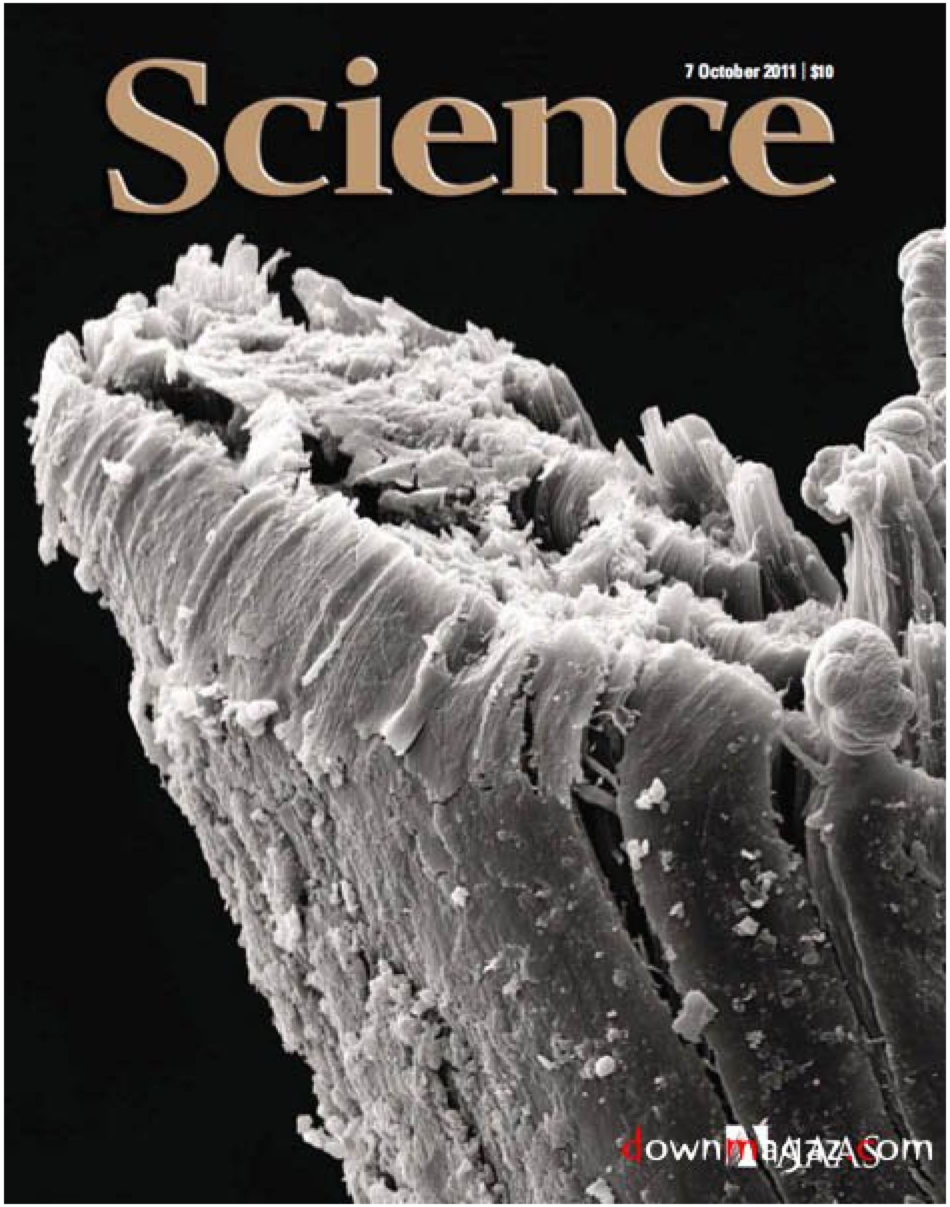
Science, VERITAS Aliu et al, 2011



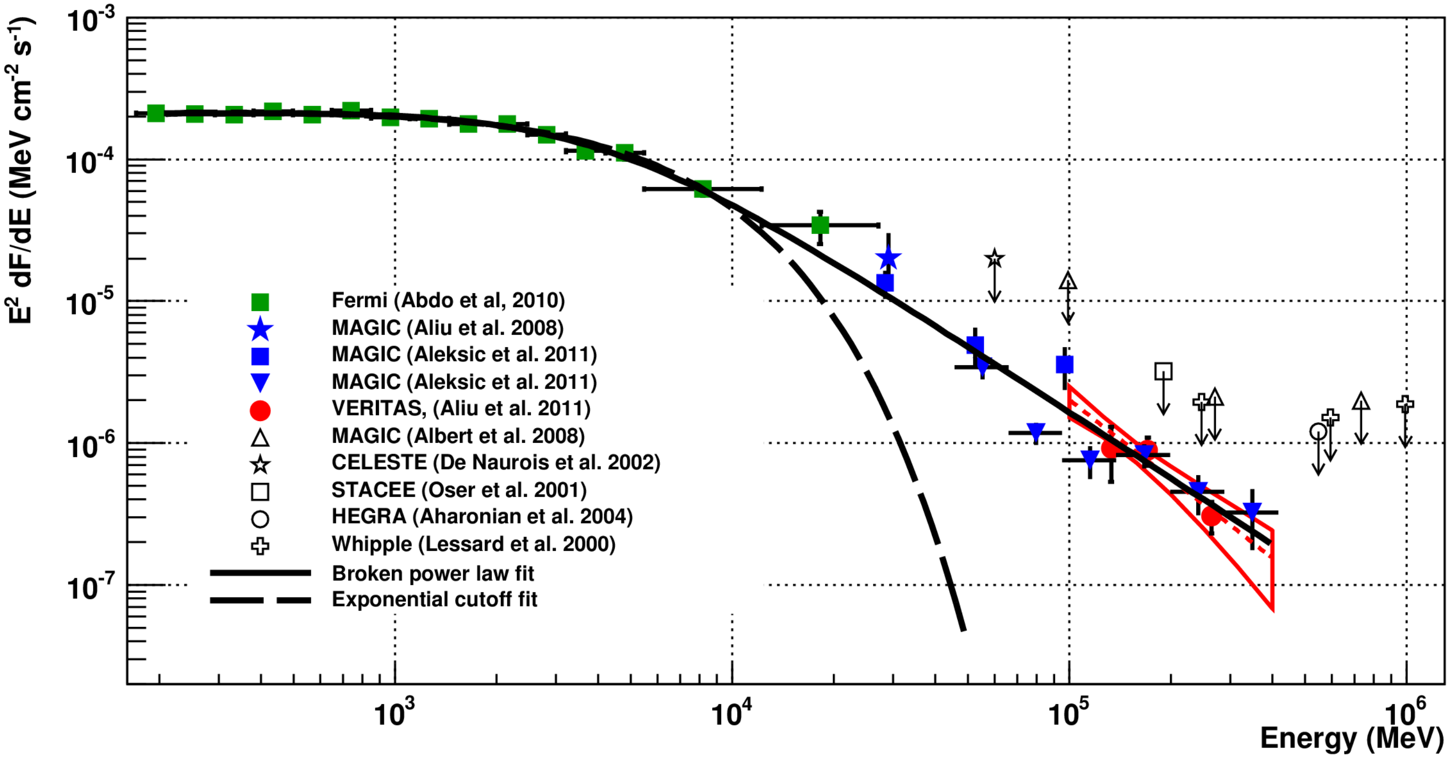
Statistical significance of pulsed signal:
H-Test: 50, i.e. 6.0 σ

Detection alone rules out exponential cutoff

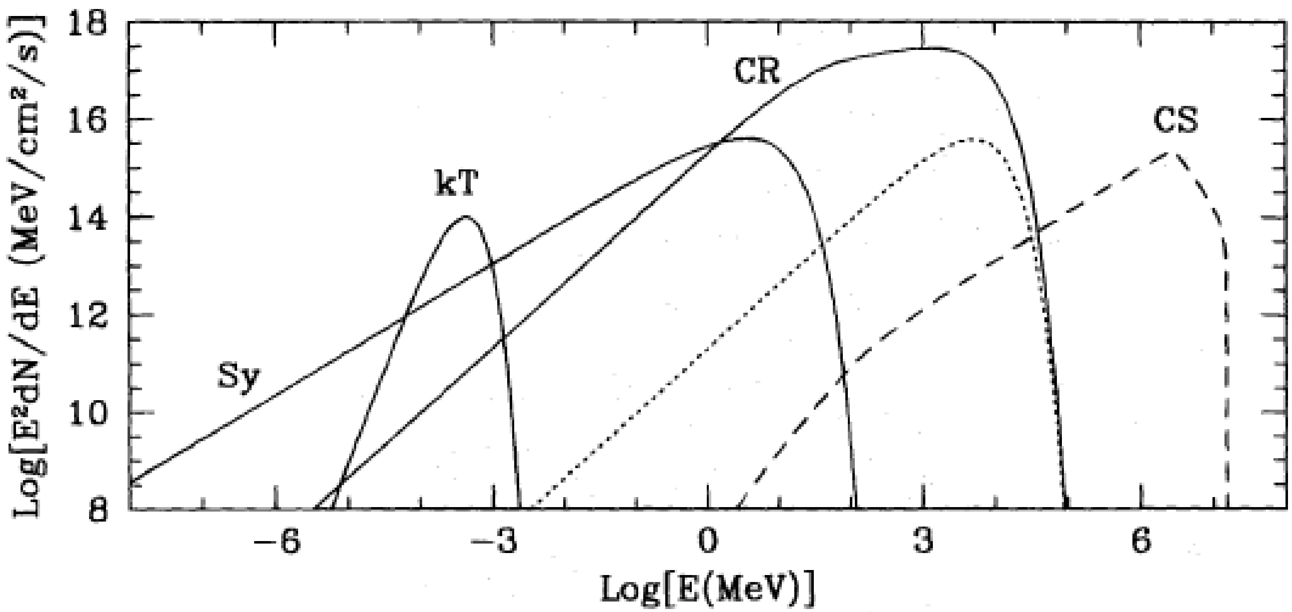



7 October 2011 | $10
Science

The GeV – TeV Connection



Good description with smooth broken power law
(does not exclude that two emission processes are at work)
MAGIC data between 25 GeV and 100 GeV fill in blank space
MAGIC stereo data released in 2011 confirm VERITAS measurements



Romani, 1996

Curvature Radiation >100 GeV?

Lyutikov, Otte & McCann (2011) arXiv:1108.3824

Acceleration in gaps is radiation reaction limited:

$$\underbrace{ec\eta B} = \underbrace{\frac{2}{3}\frac{e^2}{c}\gamma_b^4\left(\frac{c}{R_c}\right)^2}$$

Acceleration balanced by **curvature radiation** losses

For a magnetic dipole field it follows that the maximum Lorentz factor is:

$$\gamma_b = 9 \times 10^7 \eta^{1/4}\sqrt{\xi}$$

= radius of curvature of magnetic field lines in units of light cylinder radius

= strength of the electric field $E = \eta B$ typically between 0.01 and 0.1 due to screening

Curvature Radiation?

Maximum curvature radiation (CR) gamma-ray energy is:

$$\epsilon_{\rm br} = \frac{3}{2}\hbar\frac{c}{R_{\rm c}}\gamma_b^3$$

Using the maximum Lorentz factor it follows:

$$\epsilon_{\rm br} = 150\,{\rm GeV}\,\eta^{3/4}\sqrt{\xi}$$

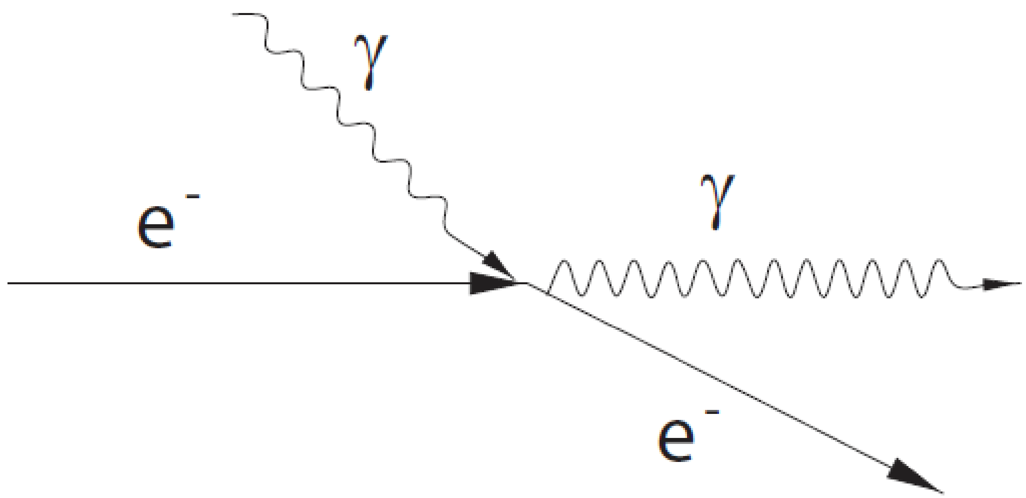
>100 GeV emission only possible if: $\eta \sim 1$

CR not excluded but unlikely because of efficient pair production:

CR photons interact with photons coming from the cooling neutron star (Crab is just 1000 years old) and create electron positron pairs -> screening of electric field: $\eta \ll 1$

Wang & Hirotani 2011

Inverse Compton Scattering



Inverse Compton (IC) Scattering

Assumed seed photon fields for IC are the observed ones

UV photon field (luminosity 10^{34} erg s^{-1} and typical photon energy 1 eV)

and

X-ray fields (luminosity 10^{36} erg s^{-1} and typical photon energy 1 keV)

Minimum Lorentz factor to be in Klein-Nishina regime:

$$\gamma_{KN} = \frac{1}{4}\frac{m_e c^2}{\epsilon_{\rm soft}} \approx 1.2\times 10^5\, \epsilon_{UV,0}^{-1} \approx 1.2\times 10^2\, \epsilon_{X,3}^{-1}$$

Energy loss/gain equation:

CR IC

$$\dot{\epsilon} = ec\eta B - \frac{2}{3}\frac{e^2}{c}\gamma^4\left(\frac{c}{R_c}\right)^2 - \frac{4}{3}\left(\frac{m_e c^2}{\epsilon_{\rm soft}}\right)^2 U_{\rm soft}\sigma_T c,$$

Inverse Compton Scattering: The Primaries

Primaries = Particles with maximum Lorentz factors

Use curvature radiation limited Lorentz factor ~ 10^7

-> IC takes place in KN regime

IC losses are comparable to CR losses if

$$L_{\rm soft,crit} = \eta \frac{B_{NS} R_{NS}^3 \Omega \epsilon_{UV}^2}{e^3} = \begin{cases} 10^{35}\,{\rm ergs}^{-1}\,\epsilon_{UV,0}^2 \eta_{-2} \\ 10^{41}\,{\rm ergs}^{-1}\,\epsilon_{X,3}^2 \eta_{-2} \end{cases}$$

-> IC losses are comparable to CR for IC on UV photons

Energetics:

Maximum IC photon energy is $\epsilon_\gamma \approx \gamma_b m_e c^2$ ~ 15 TeV

But IC luminosity not enough to explain VHE observations

Inverse Compton Scattering: The Secondaries

Secondaries = pair created electrons and positrons from CR photons

Multiplicity factor of secondaries lambda is about 100

Wang & Hirotani 2011

$$\gamma_p \approx \gamma_b/\lambda = 3 \times 10^5 \eta_{-2}^{1/4} \sqrt{\xi}\, \lambda_2^{-1}$$

-> IC takes also place in the KN regime

Energetics:

Maximum IC photon energies $\epsilon_{\gamma,p} \approx \gamma_p m_e c^2 = 150\,\mathrm{GeV}\, \eta_{-2}^{1/4} \sqrt{\xi}\, \lambda_2^{-1}$

Estimated VHE IC Luminosity matches observed one

Synchrotron Radiation from Secondaries

Use doppler boosted cyclotron emission

Secondaries also emit synchrotron radiation:

Luminosity peaks at about 3 keV (observed 100 keV)

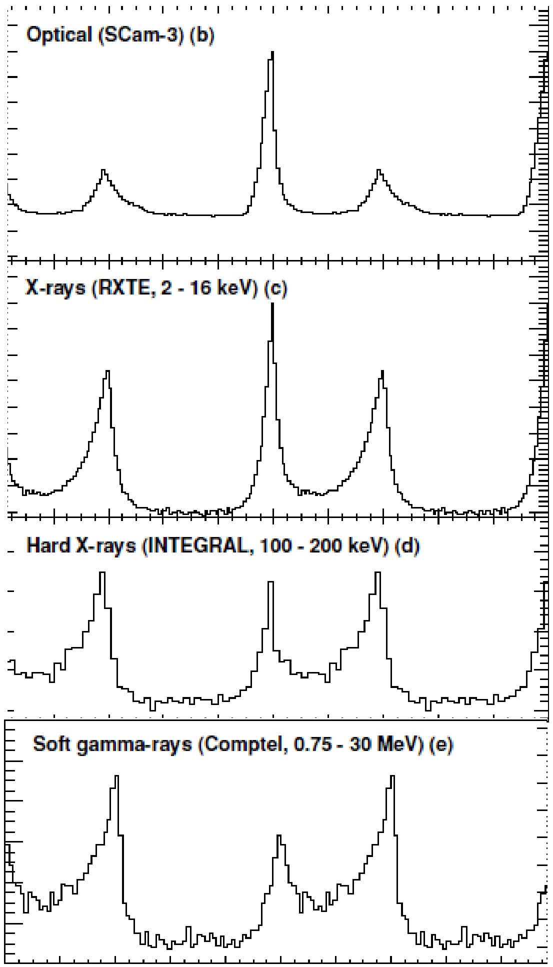
Calculated luminosity matches observed one and requires multiplicity of secondaries of ~100

Secondaries are responsible for bulk of X-Ray and VHE emission

-> Expect similar pulse profiles in X-Ray and VHE

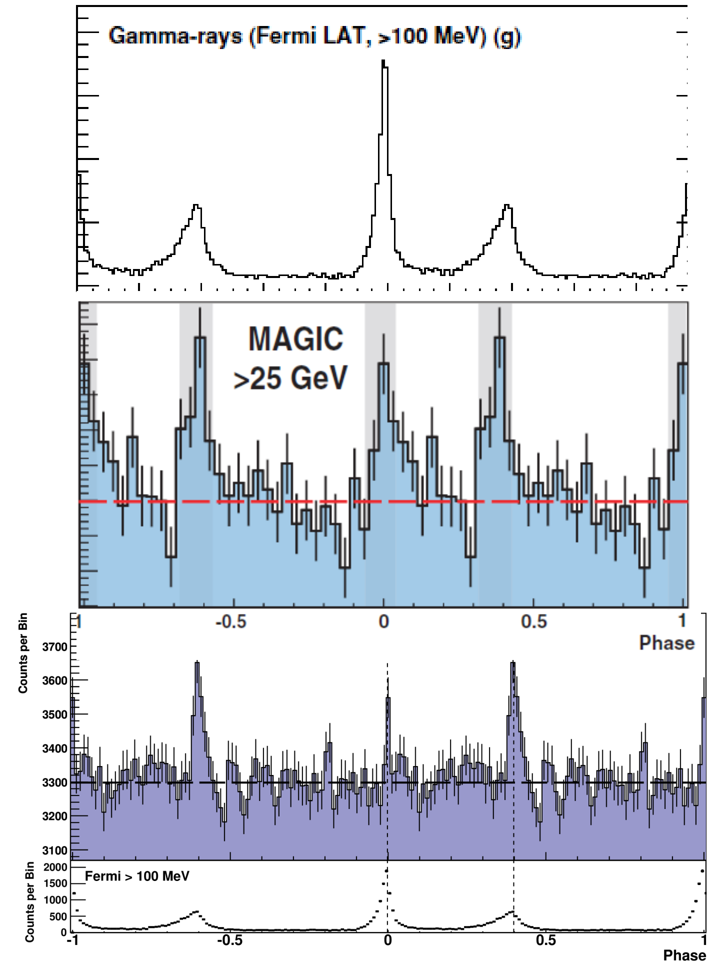
Pulse Profiles

X-Rays



Ratio of pulses changes with energy

Gamma-Rays

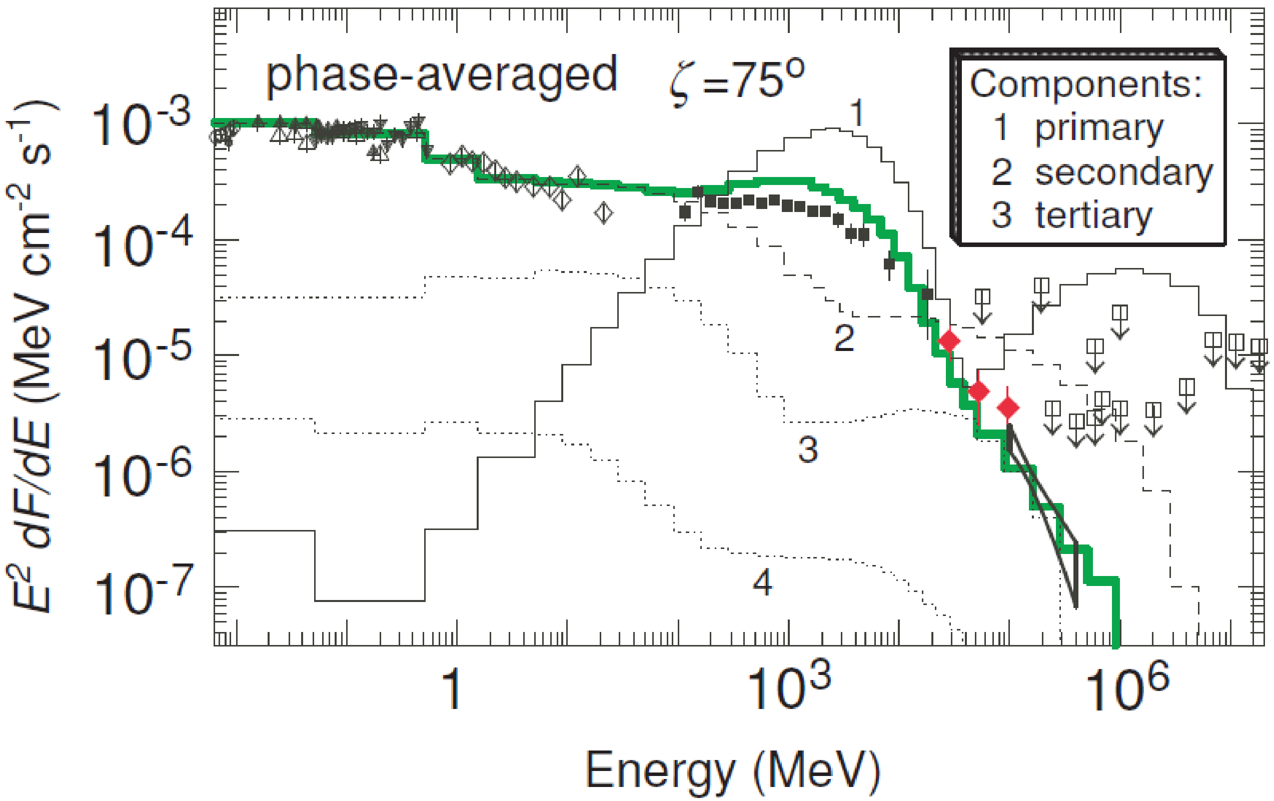


Synchrotron

same particles

Inverse Compton

A much more detailed Modelling

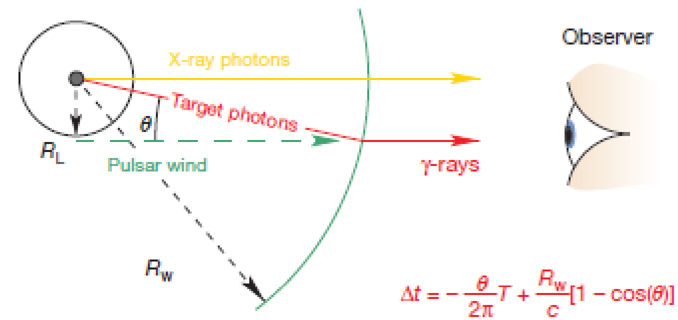


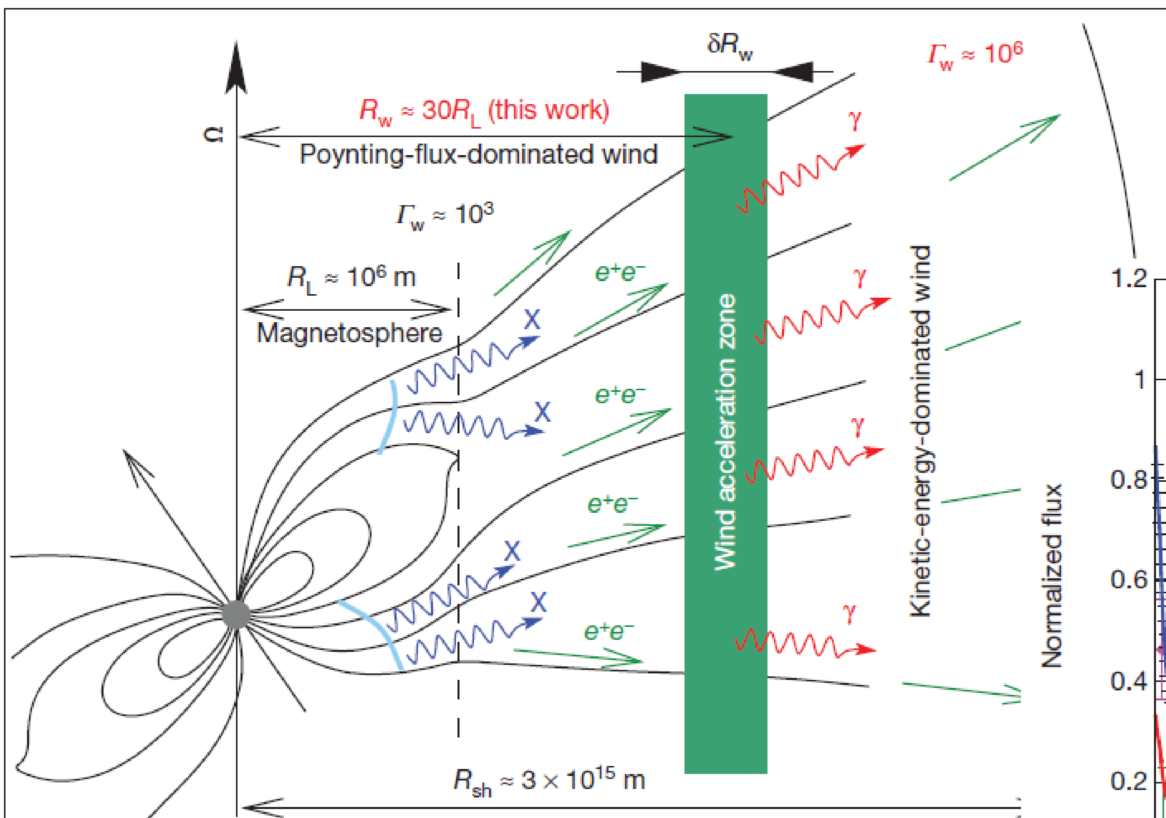
Outer gap modeling by K. Hirotani
In MAGIC Collaboration, ArXiv:1108:5391

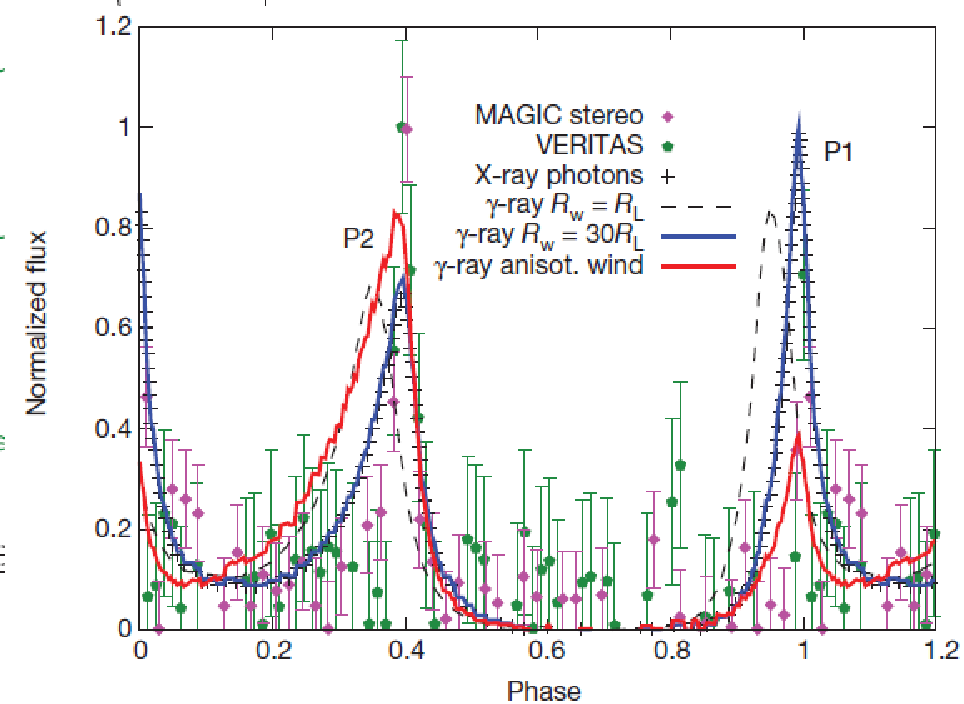
Changes with respect to older models

Emission from further out in the gap: 0.7 to 1 light cylinder radii
Emission from secondaries are taken into account

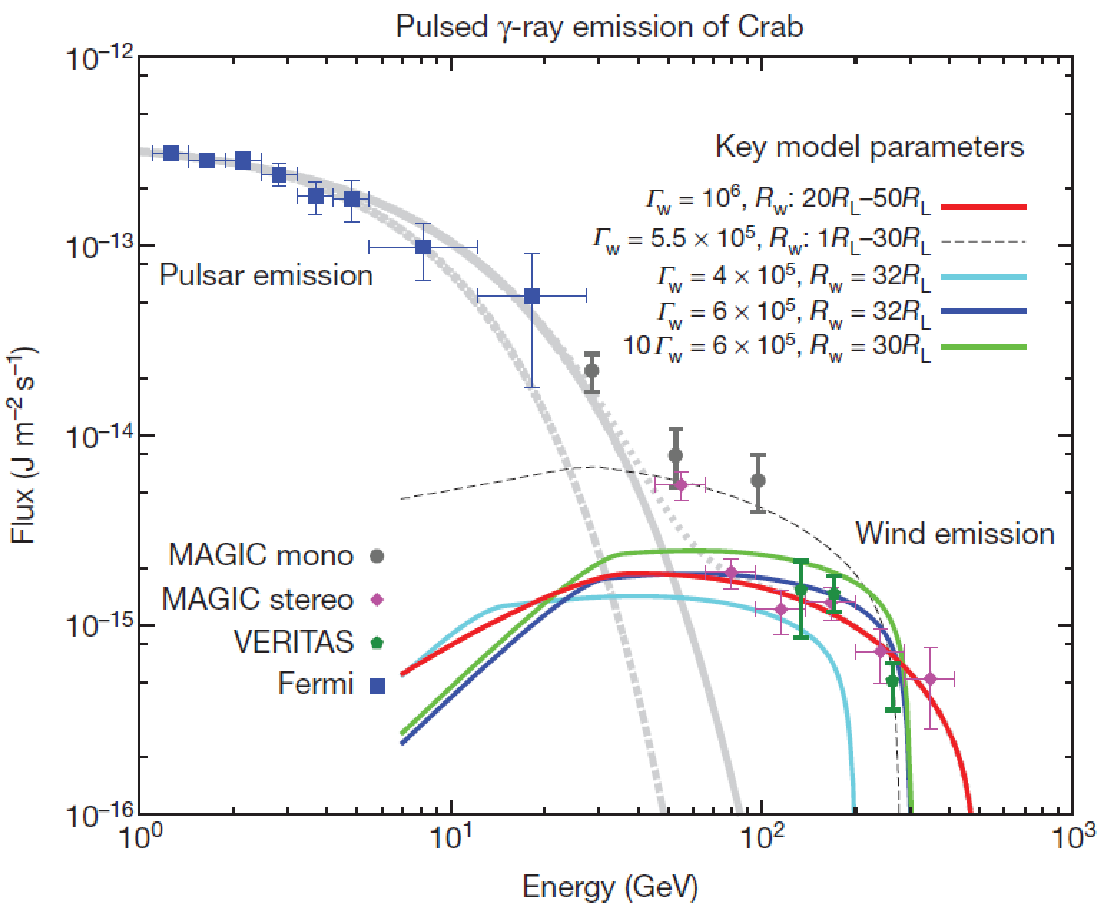
Or maybe something completely different?







F. A. Aharonian, S. V. Bogovalov & D. Khangulyan Nature (2012)

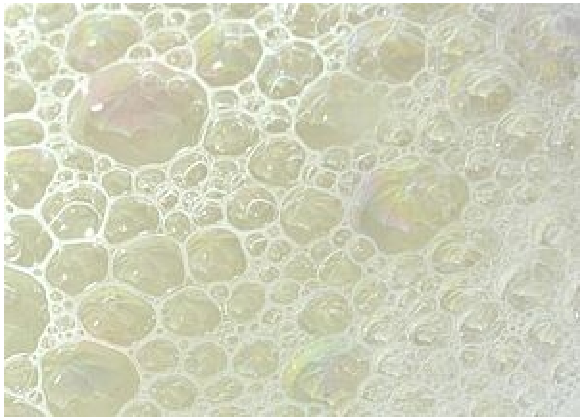


Prediction of cutoff at 400 GeV

Can be tested with future observations

F. A. Aharonian, S. V. Bogovalov & D. Khangulyan Nature (2012)

Lorentz Invariance Violation



Search for new physics

For example:

Microscopic structure of space time

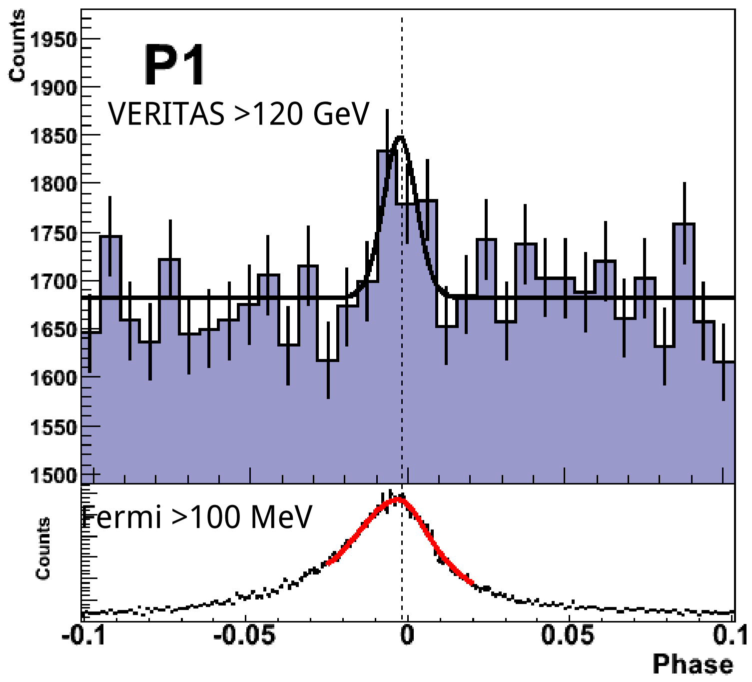
In photon sector:

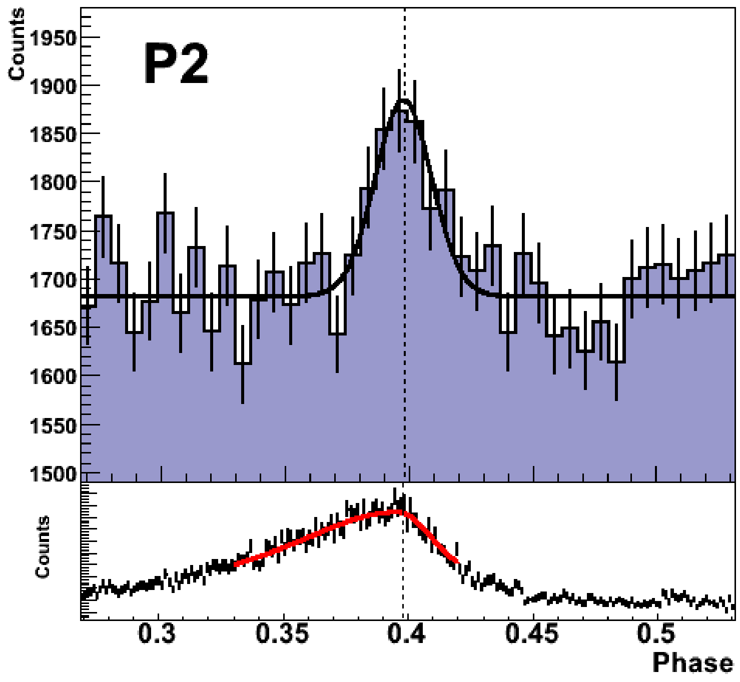
$$c'(E) = c + \underbrace{a \cdot \frac{E}{E_{\mathrm{LIV}}}}_{\Delta t_1 = \frac{d}{c} \cdot \frac{E_{\mathrm{h}} - E_{\mathrm{l}}}{E_{\mathrm{LIV}}}} + \underbrace{b \cdot \left(\frac{E}{E_{\mathrm{LIV}}}\right)^2}_{\Delta t_2 = \frac{d}{c} \cdot \frac{3}{2} \cdot \frac{E_{\mathrm{h}}^2 - E_{\mathrm{l}}^2}{E_{\mathrm{LIV}}^2}}$$

Linear term

Quadratic term

A closer Look at the Pulses





Position: -0.0026 ± 0.0028
Width: 0.0122 ± 0.0035 FWHM

Position: 0.3978 ± 0.0020
Width: 0.0267 ± 0.0052 FWHM

Peak positions **aligned with peak positions in radio and Fermi-LAT.**

Pulses above 120 GeV **2-3 times narrower than in Fermi-LAT data**

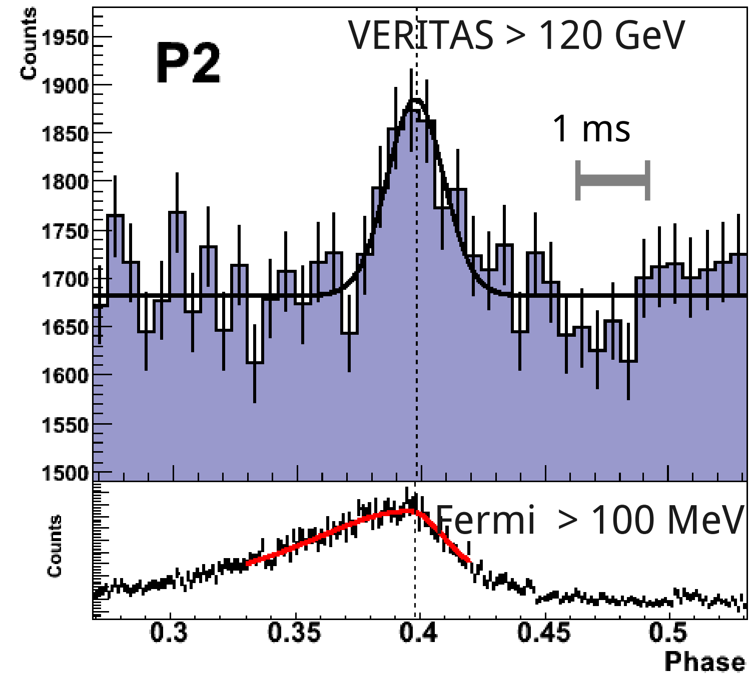
Testing Lorentz Invariance

Otte, Proceedings 32nd ICRC 2011 Beijing

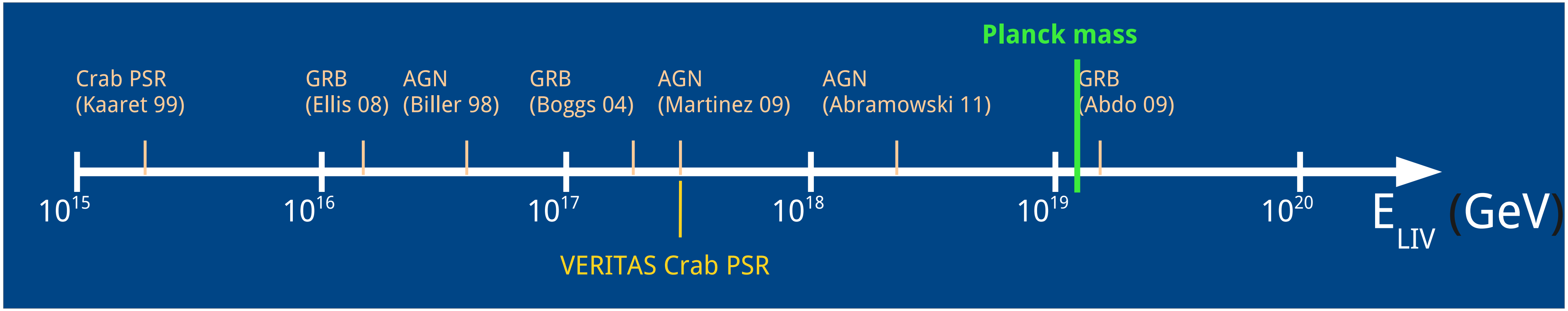
- Peaks at 100 MeV (Fermi) and 120 GeV (VERITAS) line up

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

- Linear: $E_{LIV} > 3\times10^{17}$ GeV
- Quadratic: $E_{LIV} > 7\times10^{9}$ GeV



Linear term:

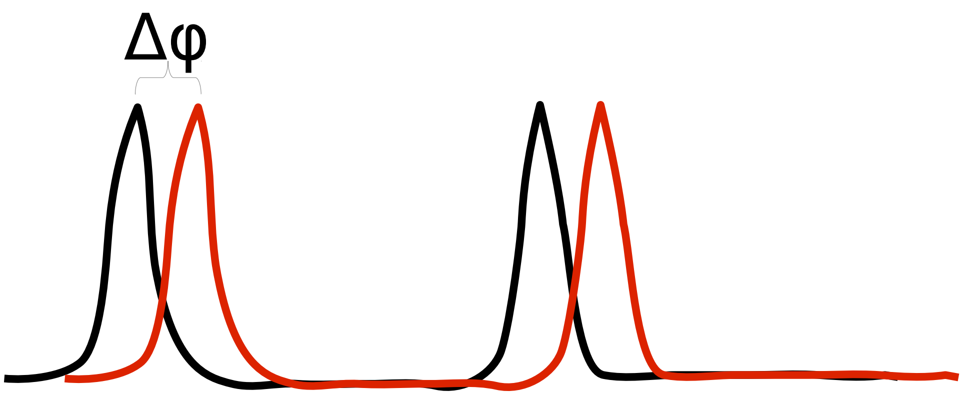


Distinguishing between Source and Propagation Effects

- Delay observed in corotating frame
- Pulsar slows down:

$$P = P_0 + t \cdot \dot{P} + \ldots$$

- 10^{-4} per year for the Crab



Monitor how delay Δφ changes over time (years):

No change : Delay is intrinsic to source

Becomes smaller : Delay is due to propagation

$$\Delta\phi(t) = \Delta t / \left(P + t \cdot \dot{P}\right)$$