Teraelectronvolts pulsed emission from the Crab pulsar detected by MAGIC

Daniel Galindo (Universitat de Barcelona),
R. Zanin (Universitat de Barcelona),
E. de Oña Wilhelmi (IEEC), D. Fidalgo (UCM),
on behalf of the MAGIC collaboration

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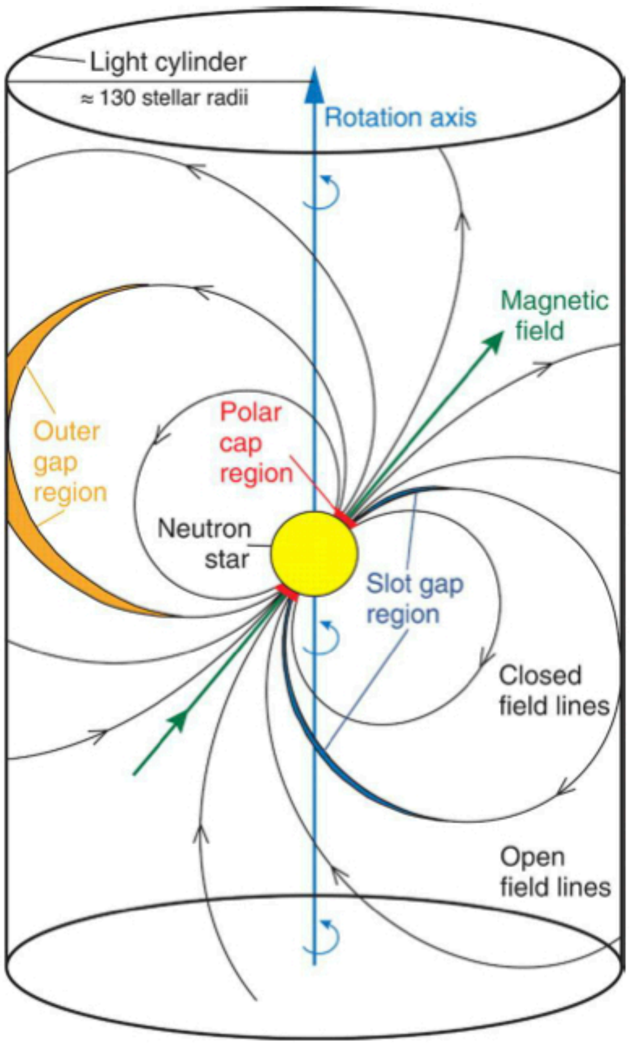
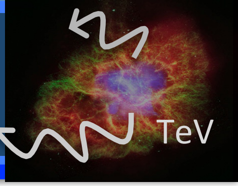
What a pulsar is

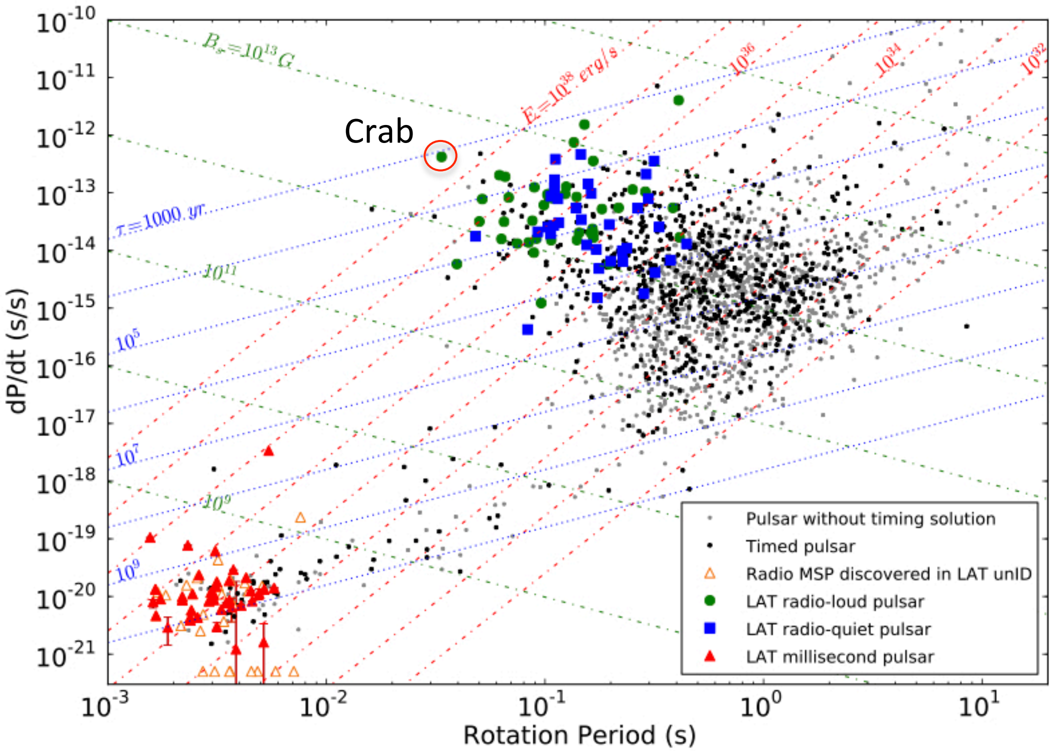
- Highly magnetized [10^8-10^{14}G], rapidly rotating neutron stars [ms - s]
- Spinning down as a result of magnetic dipole radiation (Spindown Luminosity)
- Particles and magnetic lines co-rotate with the star out to the Light cylinder
- Acceleration of charged particles take place in vacuum gaps in the magnetosphere



The Crab Pulsar



- Young 33ms period pulsar, laying in the center of the Crab Nebula at ~2kpc
- Most powerful pulsar known with a spindown luminosity of $\dot{E}$=4.6×10^{38}erg.s^{-1}



- Detected and studied across all the electromagnetic spectrum
- Double peaked Light Curve, composed of main pulse (P1) and interpulse (P2) with a bridge emission component in between
- Test bench for any pulsar emission model

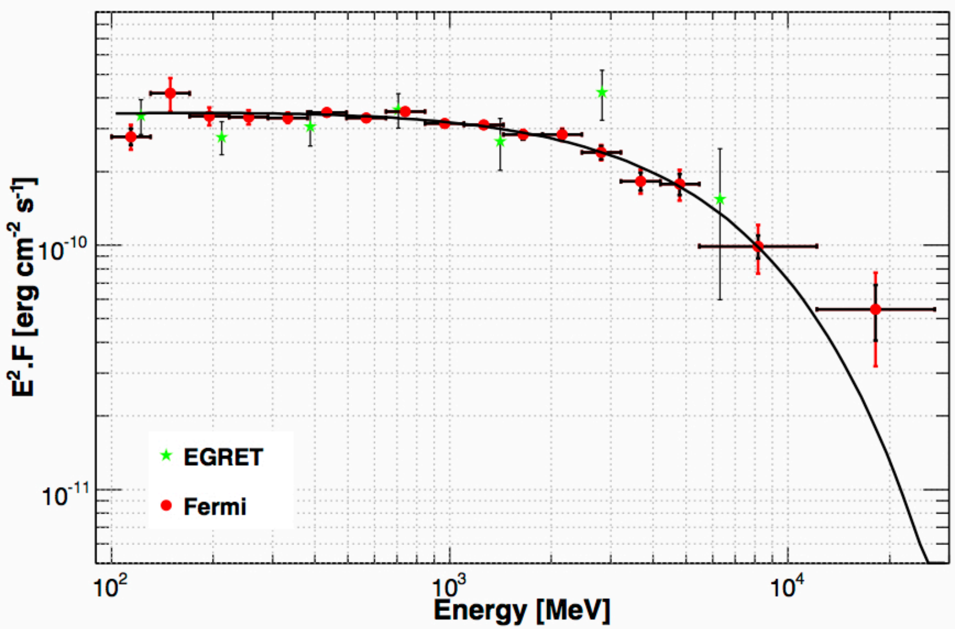
Consensus view

- HE gamma-ray emission is produced via curvature radiation

  Maximum energy limited by:

  1) magnetic absorption

  2) radiation losses



- Leading to spectral cutoffs at few GeV

- ~150 pulsars detected by *Fermi*-LAT show spectral cutoffs

  Crab pulsar spectral cutoff: $5.8 \pm 0.5_{stat} \pm 1.2_{sys}$ GeV

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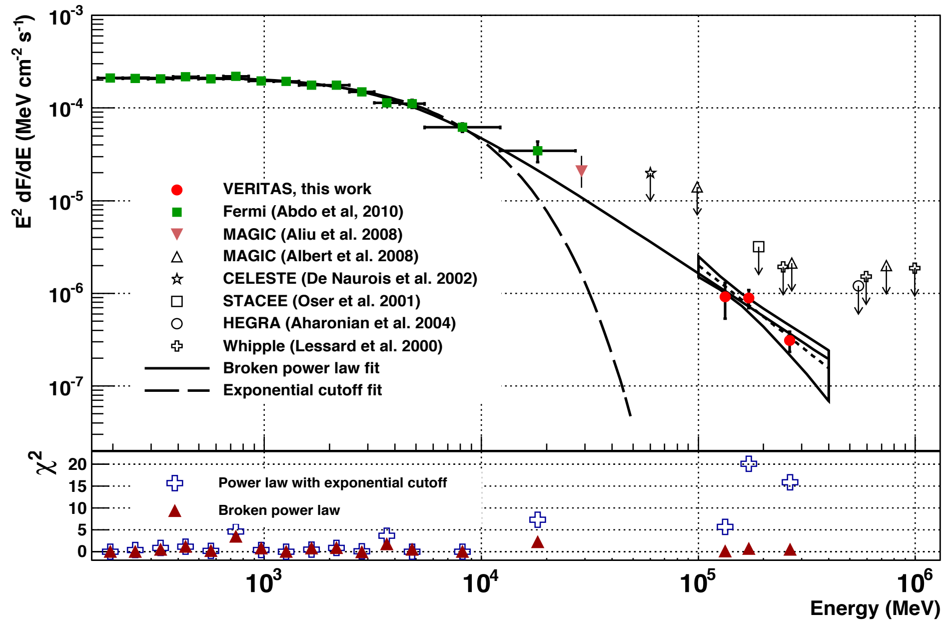

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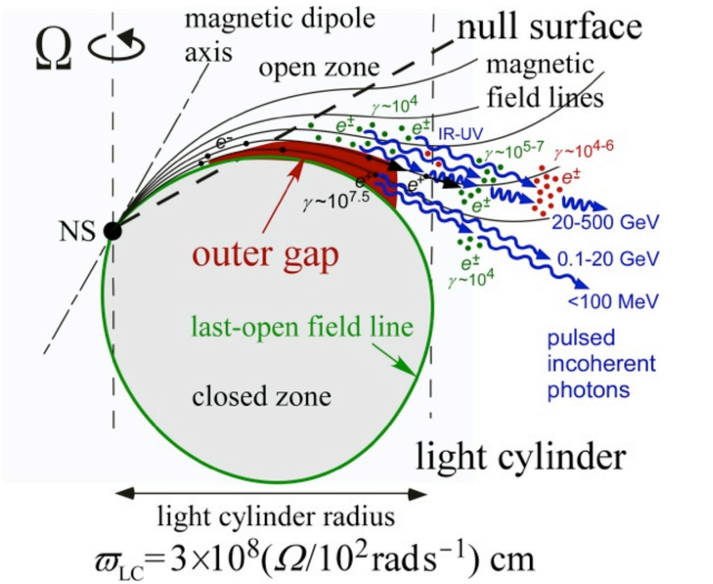
MAGIC and VERITAS came up with new VHE measurements reporting a single power-law spectrum between 25 and 400 GeV

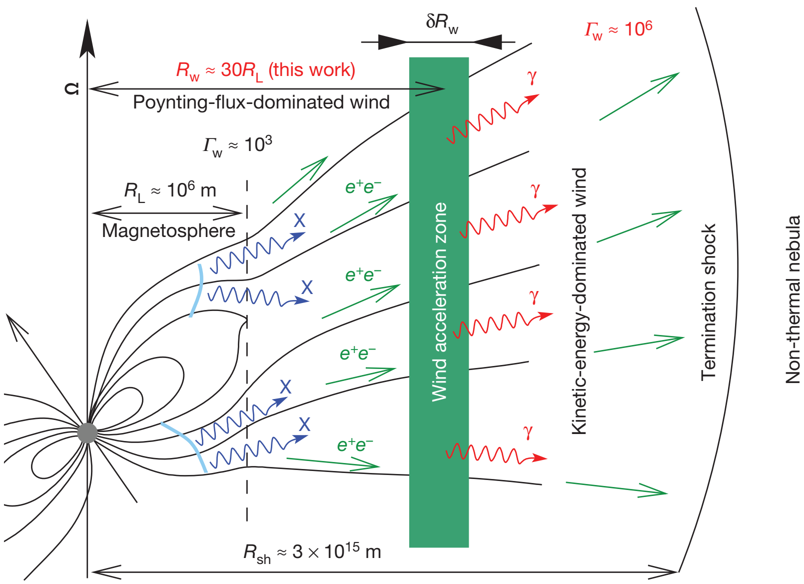
Explaining the VHE tail

- Two main and accepted models:

I. Magnetospheric cascade model (*Aleksic et al. 2011, 2012b*): Emission due to IC scattering on IR-UV photons at high altitude within the light cylinder

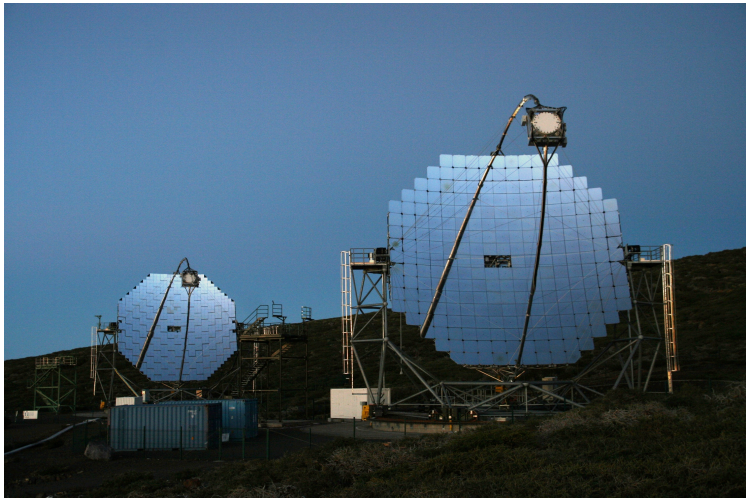


II. Pulsar wind model (*Aharonian et al. 2012*): Emission due to IC on X-ray photons in the pulsar wind region

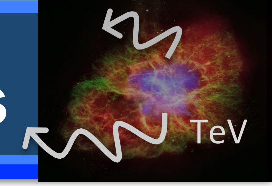


MAGIC IACT telescopes

- 2 telescopes of 17m diameter surface
- Located in the Canary Island of La Palma (Spain) at 2250m above sea level
- Fine pixelized cameras with 3.5º FoV
- Angular resolution <0.1º
- Energy threshold of 50 GeV



Crab observations with MAGIC telescopes

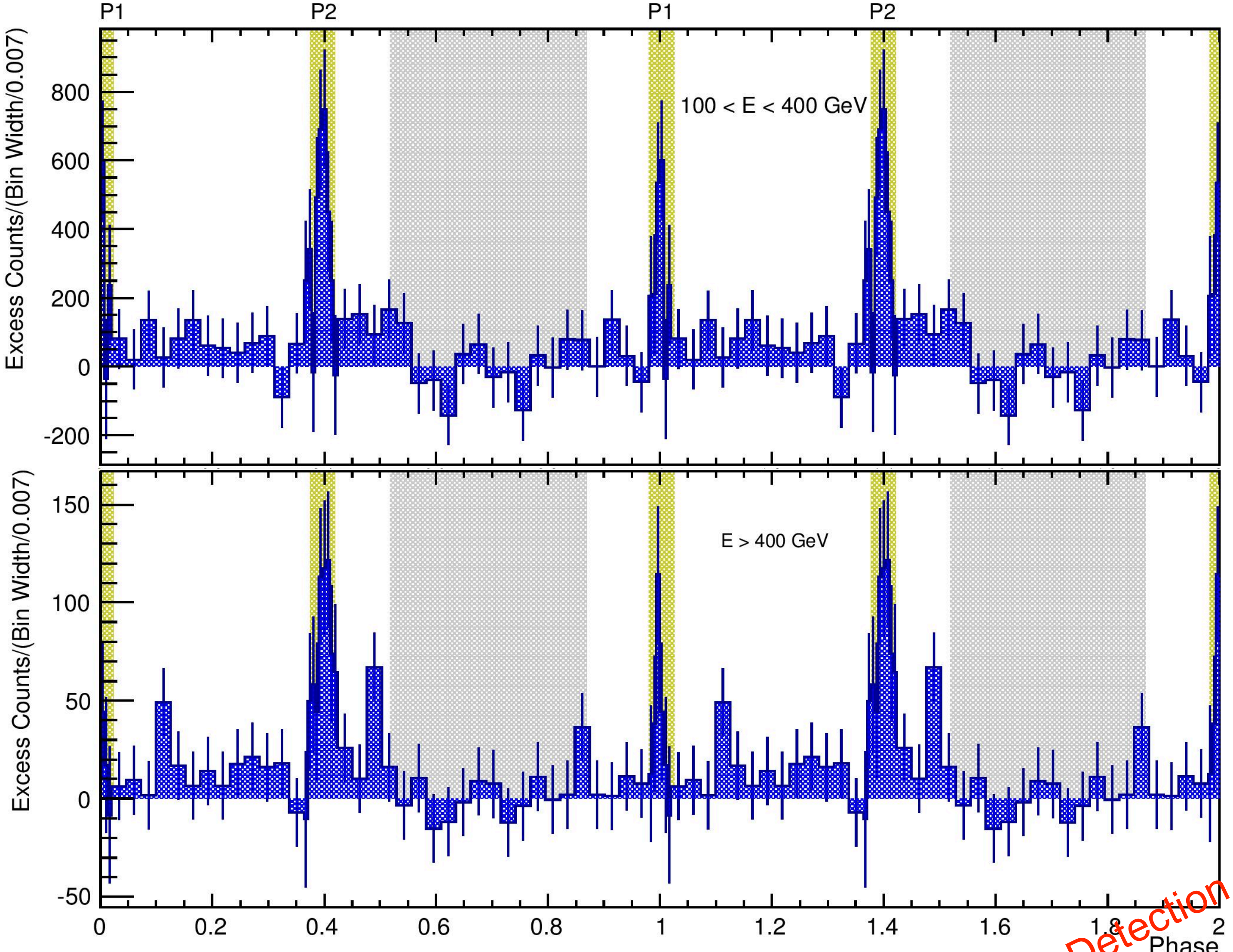


- All data was re-analyzed, data spreads over 7 years
- It was divided into 19 data sub-samples to account for differences in the hardware and observations settings
- Mono Observations (2004-2009): 97 hours
- Stereo Observations (2009-2014): 221 hours

Total of 320 hours of excellent quality data

Pulse profile detected

Phase ranges from *Aleksic et al. 2012b, 2014*:



P1 at 2.8sigma

P2 at 5.6sigma

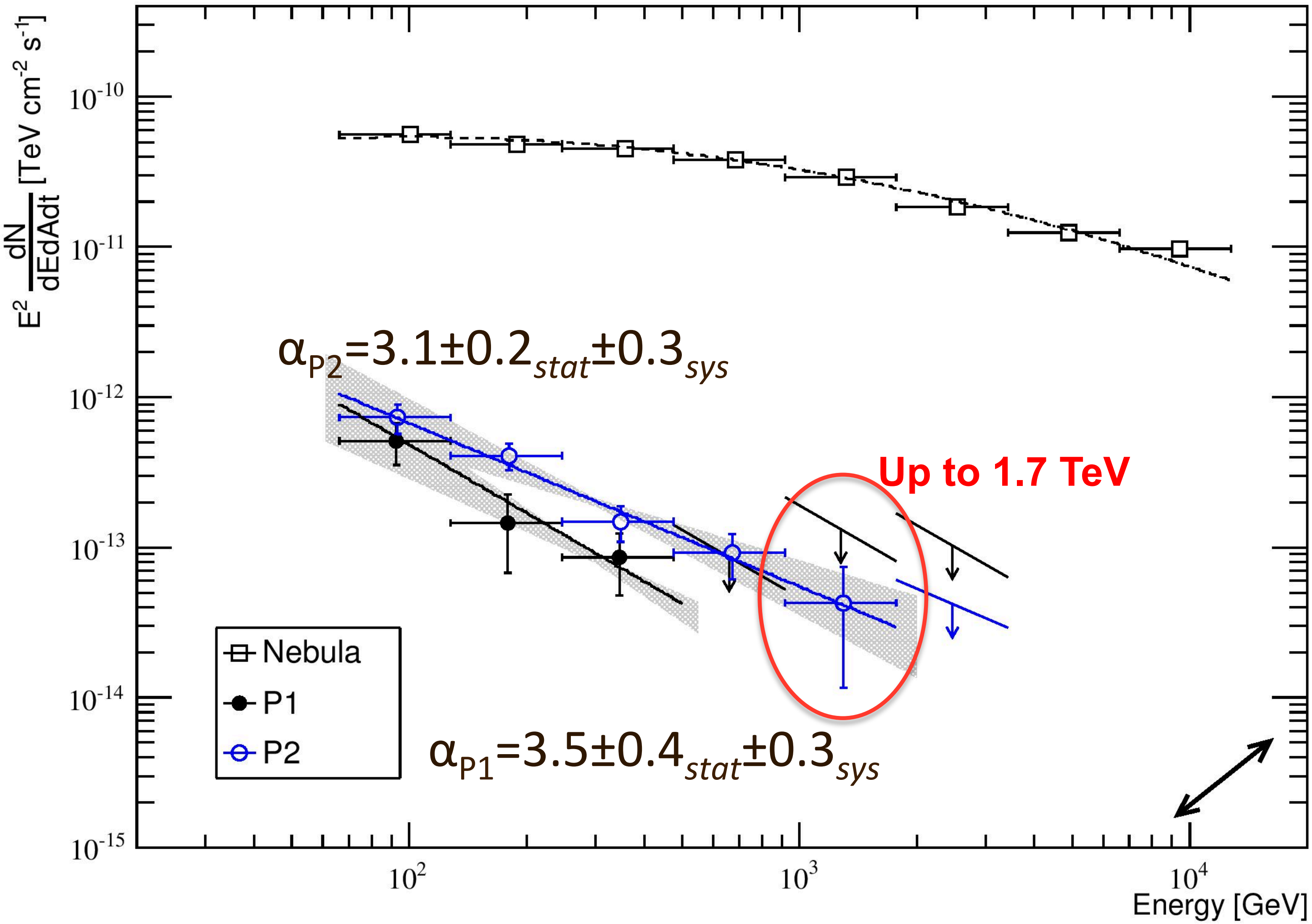
P1 at 2.2sigma

P2 at 6.0sigma

Detection of pulsed emission

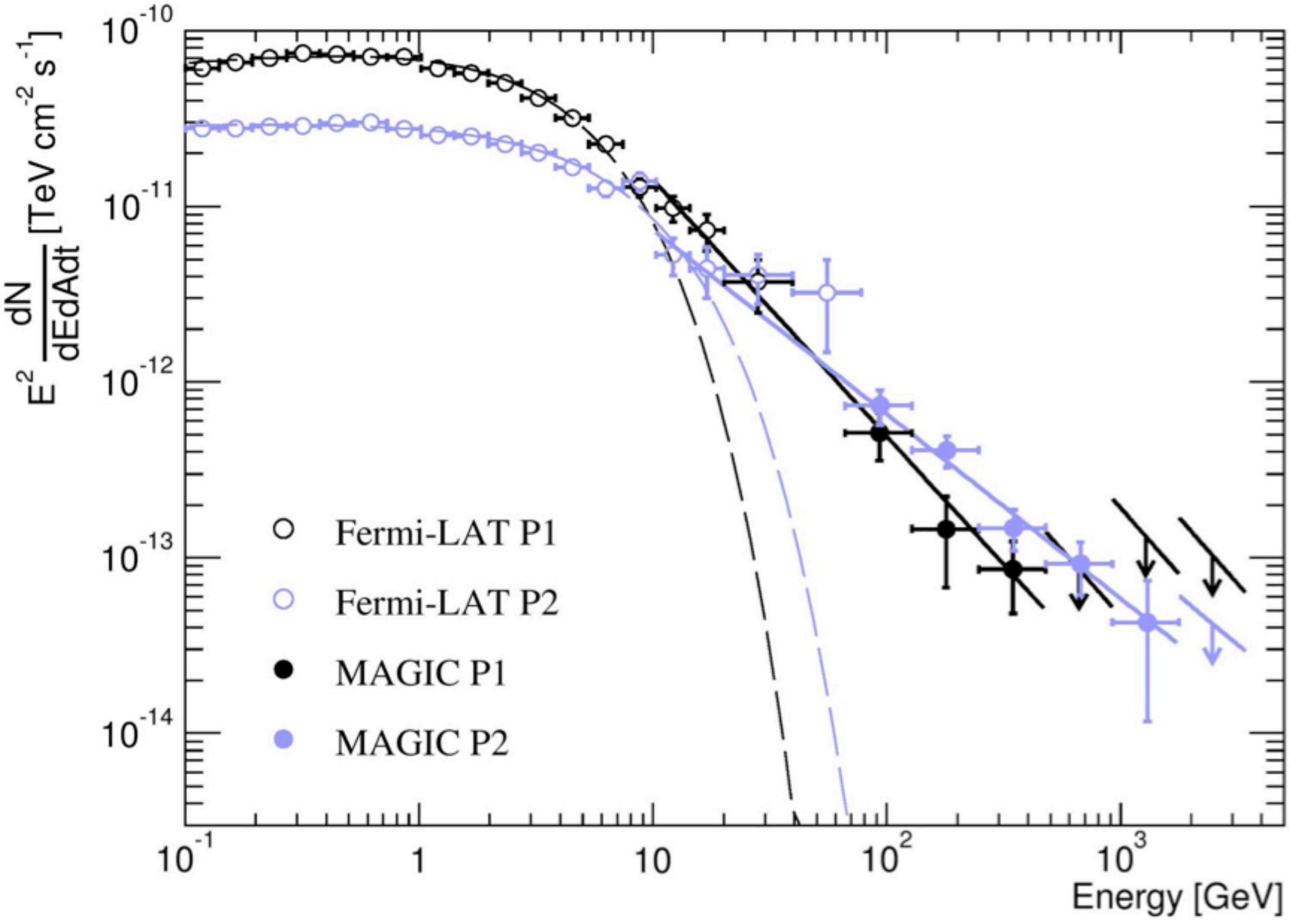
Spectral energy distribution

- Spectra described by a single power-law for both components



Spectral energy distribution

- Joint correlated fit of MAGIC and *Fermi*-LAT above 10GeV



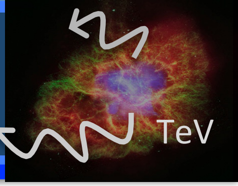
Single power-law with photon indeces:

P1: α=3.5±0.1
(χ^2/ndf=1.7/4)

P2: α=3.1±0.1
(χ^2/ndf=5.3/7)

Demands a single production mechanism for P1 and P2 from 10 GeV to ~2 TeV

What are the implications?



- TeV photons must be emitted:

  - at least at 25 stellar radii

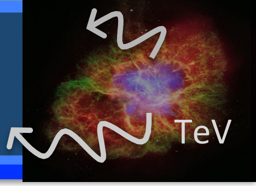
$$\varepsilon_{\rm MAX} \approx 0.4\sqrt{P}\left(\frac{r}{R_0}\right)^{1/2} \max\left\{1, \frac{0.1 B_{\rm cr}}{B_0}\left(\frac{r}{R_0}\right)^{3}\right\} {\rm GeV}$$

  - by a population of electrons with a $\Gamma > 5\times10^{6}$

  - via Inverse Compton Scattering

Curvature radiation can be ruled out due to very large required curvature radii ($R_C \sim 100\ R_{LC}$)

Constraining the emission site

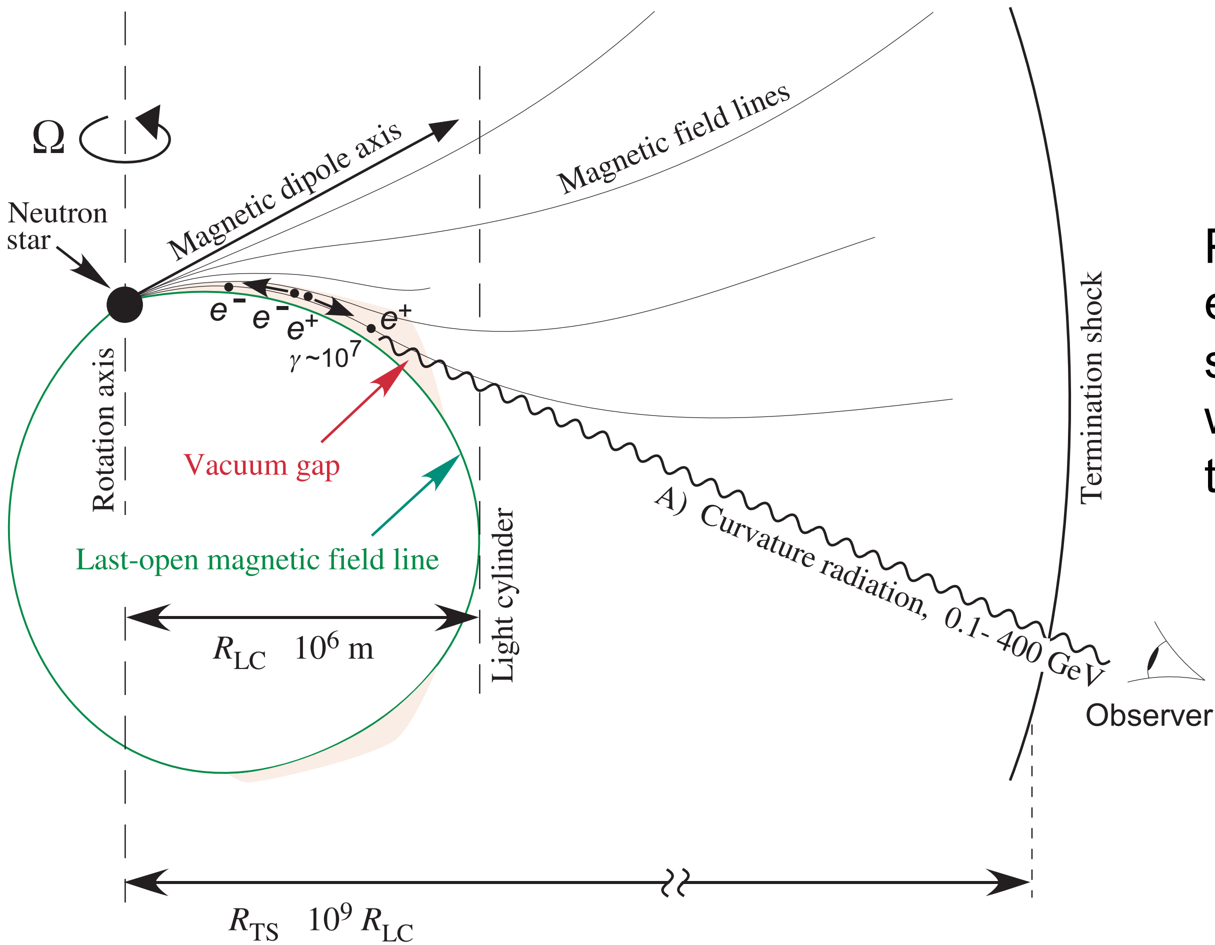


- In order to constrain the emission site two theoretical scenarios are entertained:

    1. Magnetospheric synchrotron self-Compton model

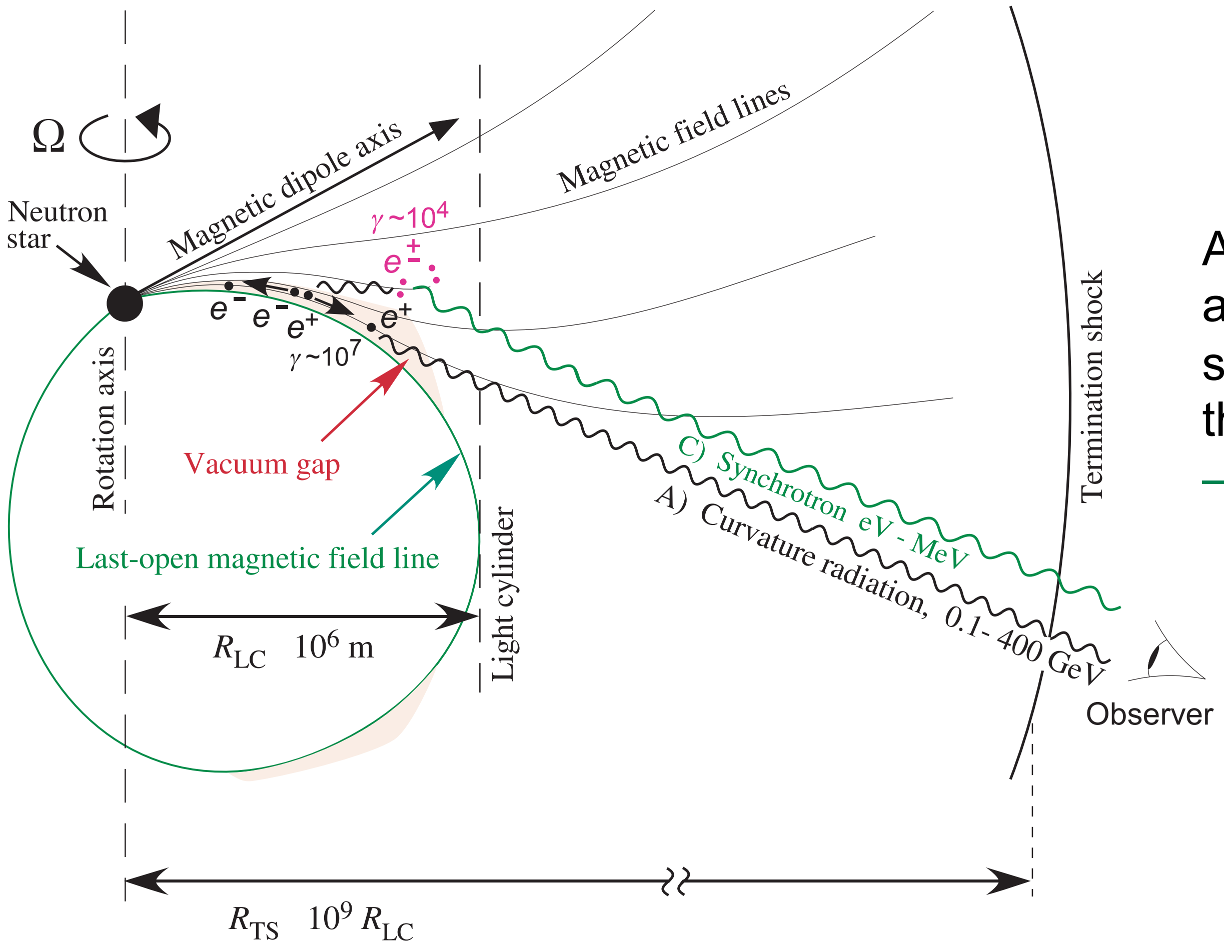
    2. IC in the pulsar wind region model

Magnetospheric synchrotron self-Compton model



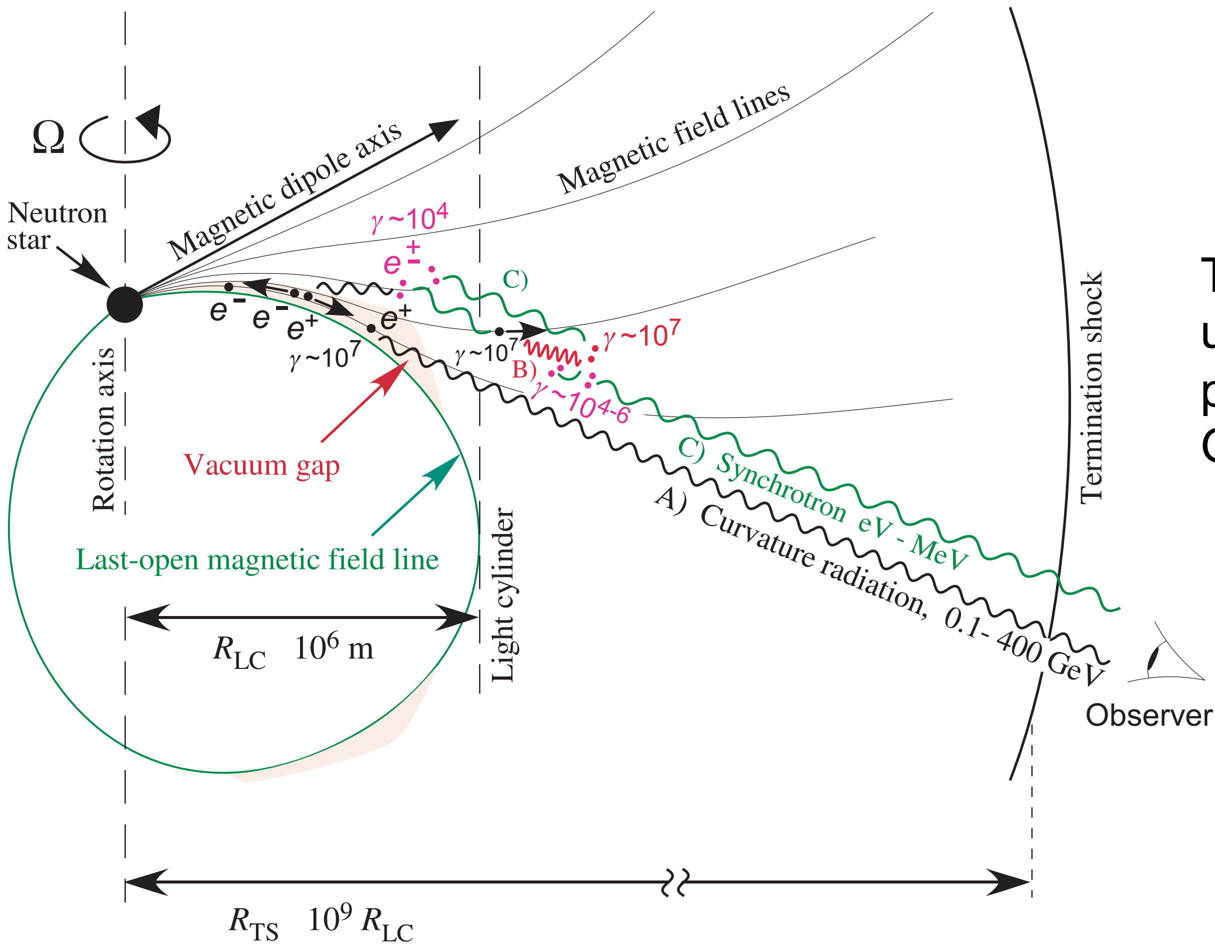
Primary particles ($\gamma \sim 10^7$) emit MeV – GeV photons via synchro-curvature radiation which are observed below tens of GeV (A)

Magnetospheric synchrotron self-Compton model



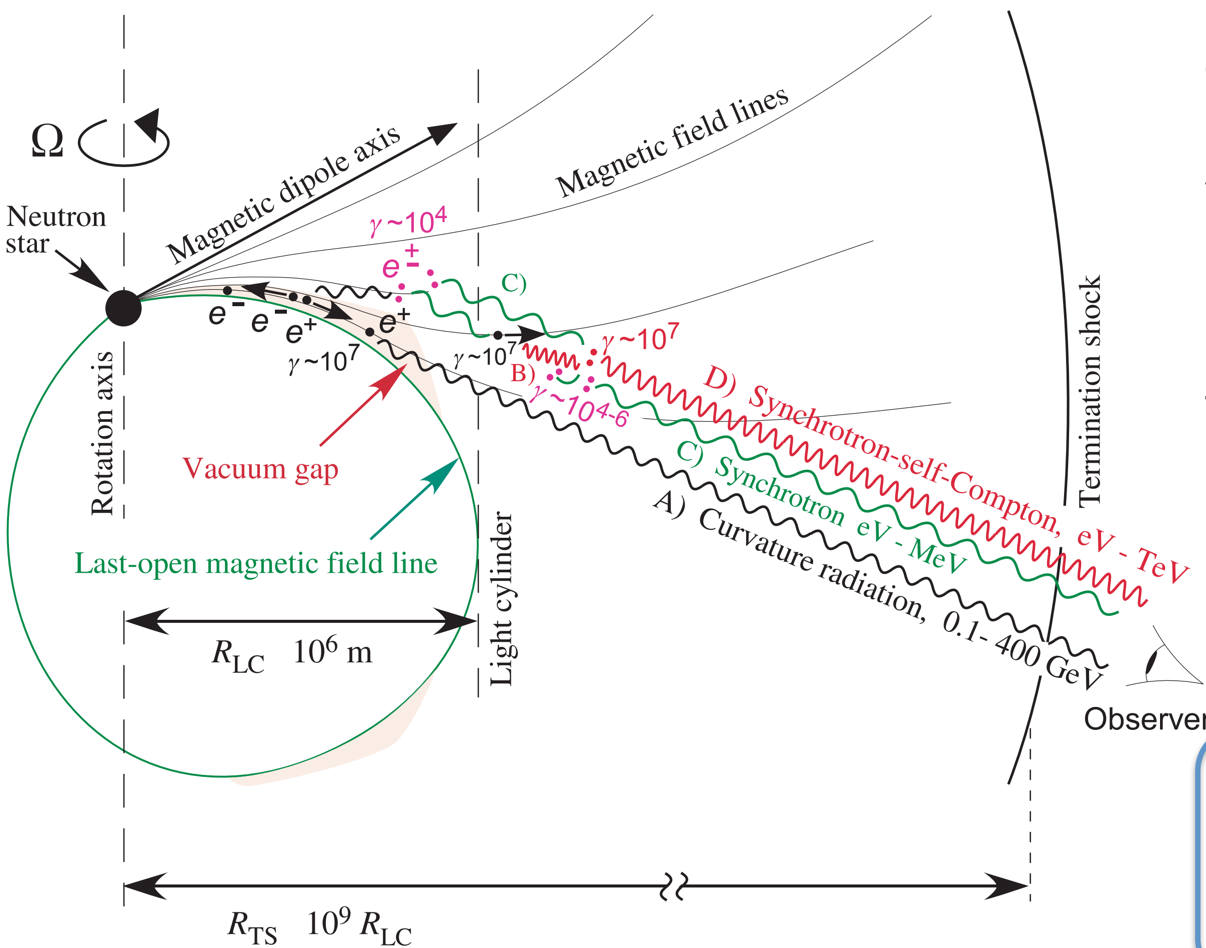
A fraction of them get absorbed and produce secondary pairs with $\gamma \sim 10^4$ that radiate synchrotron eV – MeV emission (C)

Magnetospheric synchrotron self-Compton model



The eV photons are upscattered via IC by primary positrons producing GeV – TeV photons (B)

Magnetospheric synchrotron self-Compton model



(B), in turn, are absorbed by the same IR photon field producing secondary pairs with $\gamma \sim 10^{4-7}$

The SSC component of this population is observed up to few TeV (D)

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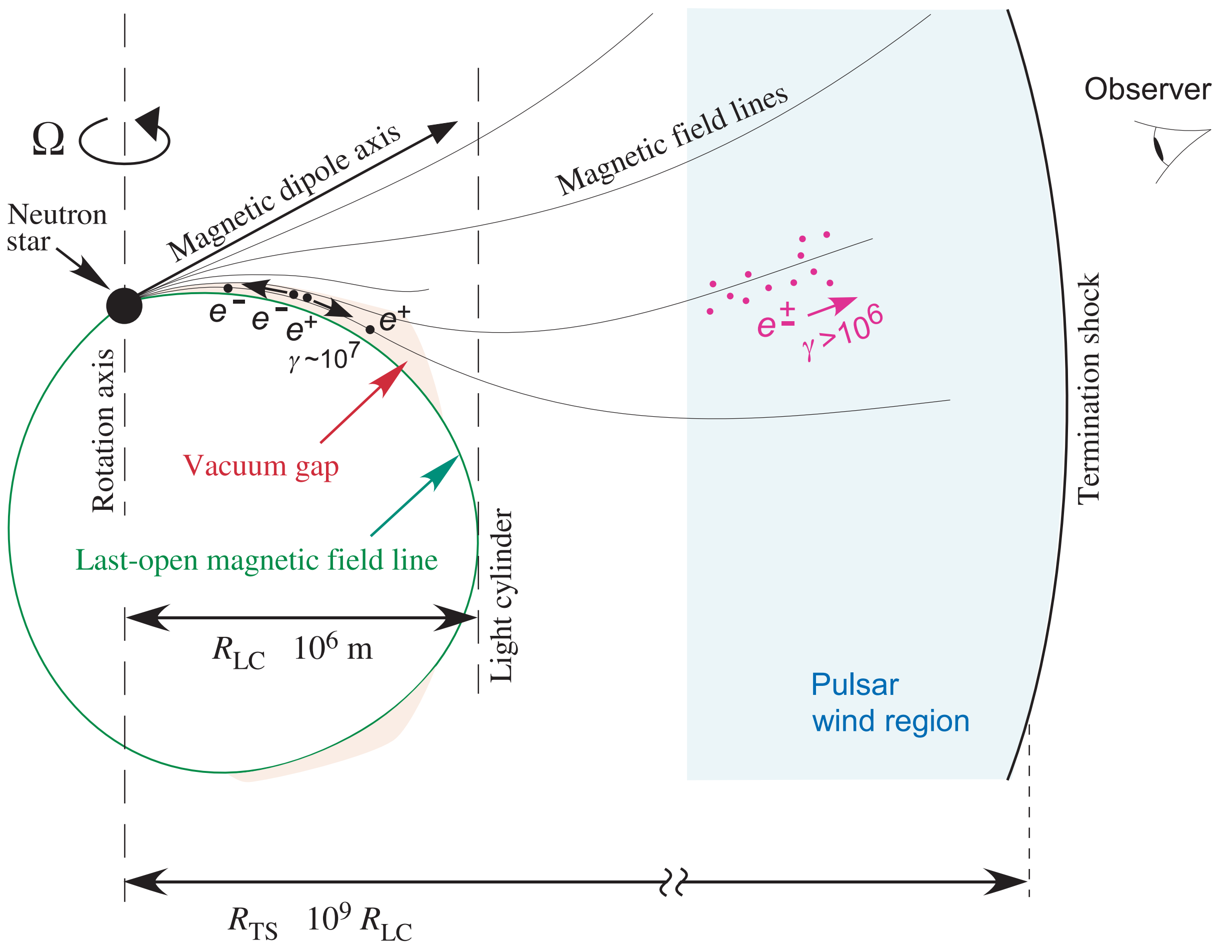
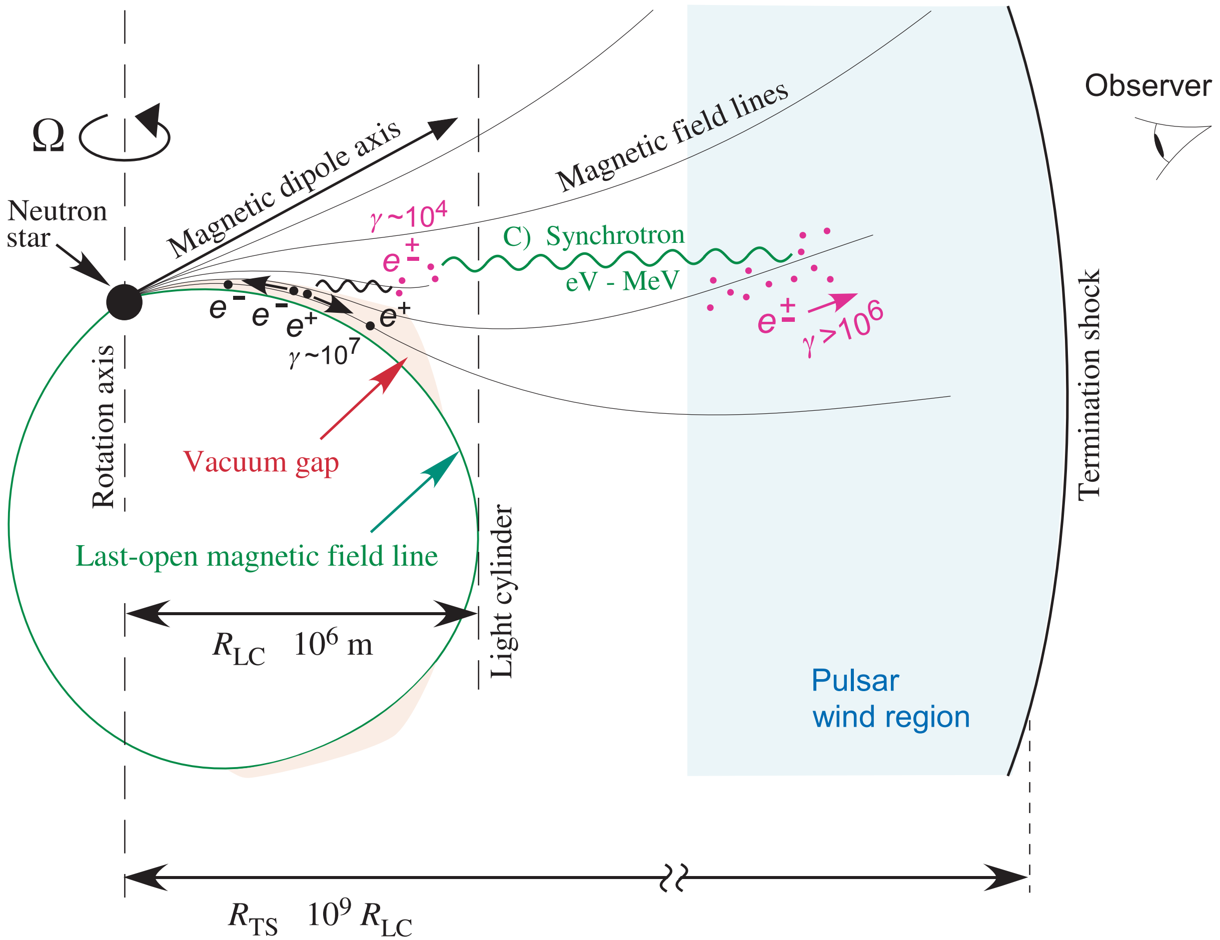
Has difficulties to reproduce the pulse profile (peak separation becomes too small)

IC in the pulsar wind region model



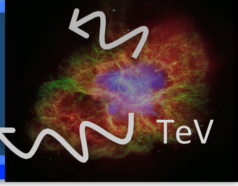
Particles are abruptly accelerated to $\gamma > 10^6$ in a narrow zone in the pulsar wind region

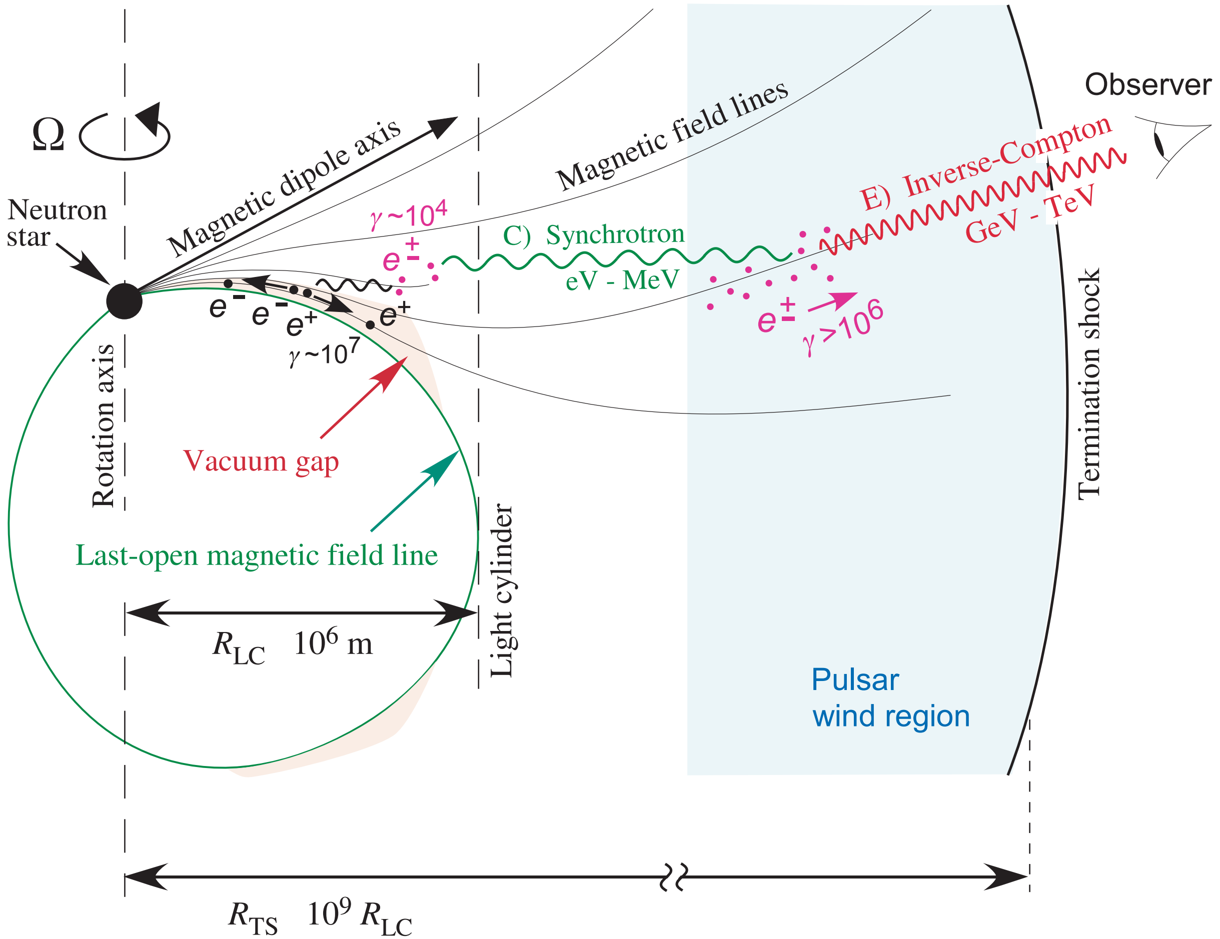
IC in the pulsar wind region model



This relativistic wind gets illuminated by the pulsed eV – MeV photons originating from the pulsar's magnetosphere (C)

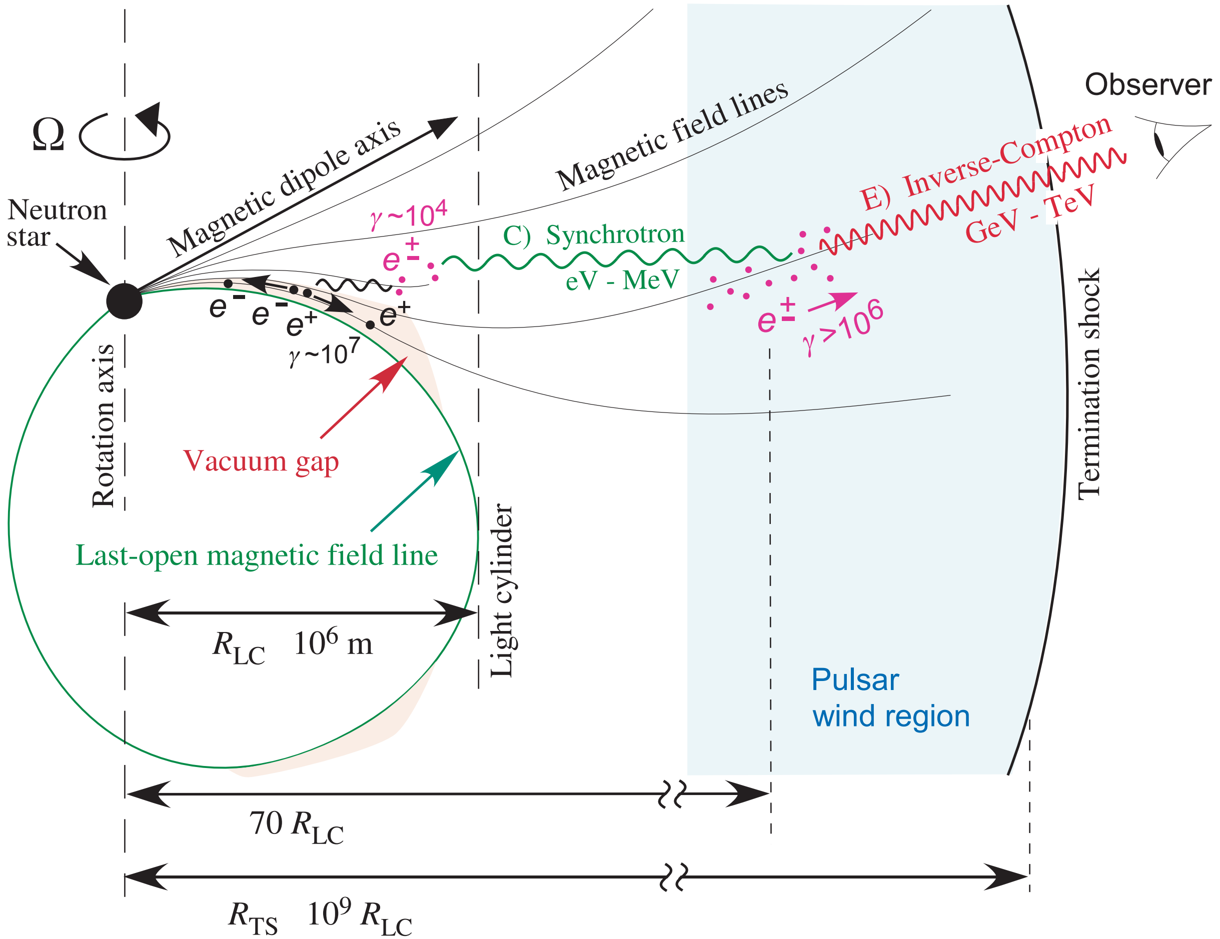
IC in the pulsar wind region model





In the wind acceleration zone gamma-rays up to TeV energies are produced via IC scattering (E) on the x-ray photons (C)

IC in the pulsar wind region model



The Lorentz factor $\gamma > 10^6$ implies that the acceleration zone must at least reach out to 70 R_{LC}

↓

Underestimate the flux below 100 GeV

Has difficulties to reproduce the peak ratio

Conclusion

- MAGIC detected the most energetic pulsed photons from the Crab, up to about 2 TeV
- Above 400 GeV, the detected pulsed emission mainly comes from the interpulse (6σ)
- P2 power-law spectrum extends up to ~2 TeV with a photon index of 3.5, whereas P1 could not be measured beyond 700 GeV
- The detection of TeV photons from the Crab pulsar implies that they are emitted:

    1) via inverse Compton scattering

    2) by electrons with Lorentz factors above 5×10^6

→ MAGIC results require a revision of the models to explain how and where such energetic pulsed emission is produced