Particle acceleration and pulsars

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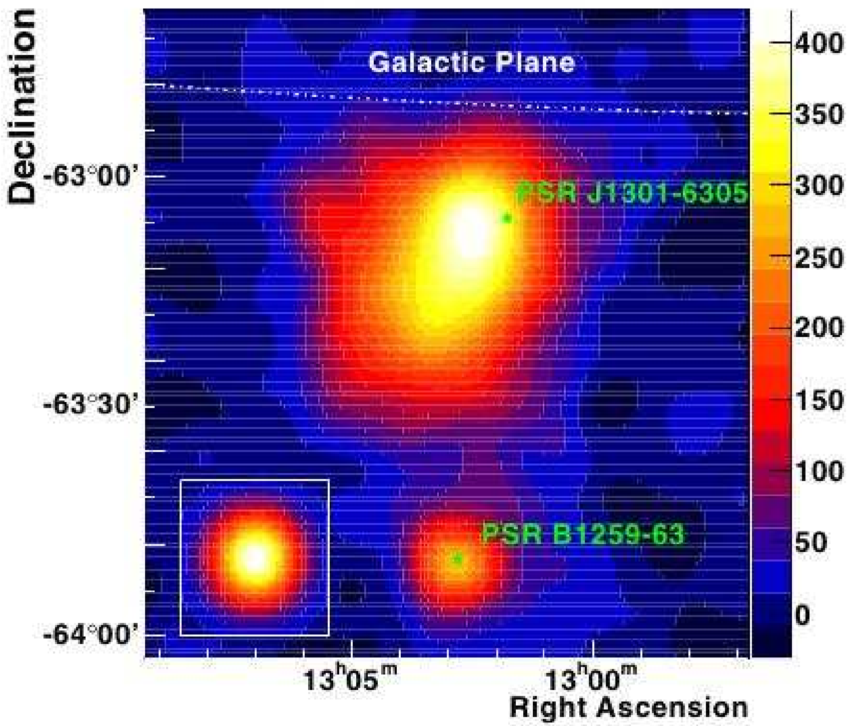
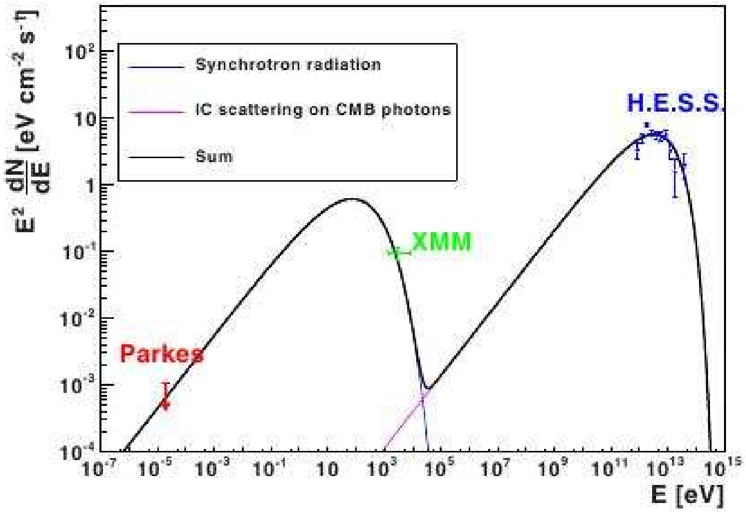
Pulsars (PSR) and pulsar wind nebulae (PWNe)



TWo PWNe (color: TeV range) and their associated radio pulsars [HESS coll., A&A 548, 2012]

- Mostly inspired from [de Oña-Wilhemi et al., Astroparticle Physics, special issue CTA, 2013]
- 27 likely PWNe sources of VHE γ rays
- These sources are associated to a pulsar (PSR) generally observed in radio.

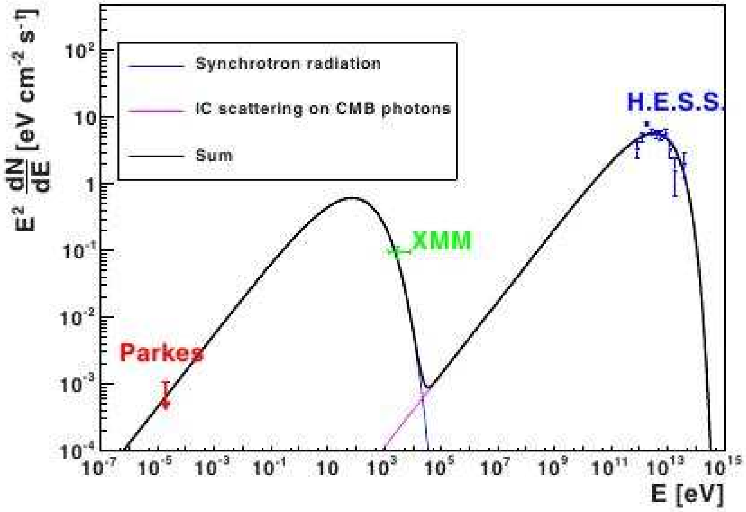
The most powerful VHE γ sources in the Galaxy



Single-zone model of SED of PWNe J1303-631, based on synchrotron and IC on CMB. [HESS coll., A&A 548, 2012]

- VHE γ ray spectra often fit: $dN/dE = N_0 E^{-\Gamma} exp(E/E_{cut-off})$
- Synchrotron radiation of energetic particles : from radio to X
- Energetic particles + photons : inverse Compton (IC) : from X to VHE γ.
- One zone models to reconstruct $\times$ wavelengths spectrum
- Free parameter : magnetic field B
- Free parameter : energy distribution of particles. Power-law, exponential cut-off, or multiple spectral indexes.

The clues about high energy particles in PWNe



Single-zone model of SED of PWNe J1303-631, based on synchrotron and IC on CMB. [HESS coll., A&A 548, 2012]

- Electron energy K to radiate synchrotron photon of energy E: $K \sim (70TeV) B_{-5}^{1/2} E_{keV}^{1/2}$.
- Synchrotron or curvature radiation by highly energetic particles $\Gamma \sim 10^6$, and $B \sim \mu$G. Synchrotron radiation generate X-ray nebula.
- IC Compton from highly energetic particles + photons (CMB, star...). Electron energy required to generate photon of energy E : $K \sim (18TeV) E_{TeV}^{1/2}$, i.e. $\Gamma = (3.6 \times 10^7) E_{TeV}^{1/2}$.
- IC radiation can generate VHE γ ray nebula.

PWNe and pulsars : two distinct kinds of sources

PULSAR WIND NEBULAE

- PWNe radiation is not pulsed
- PWNe are extended sources ($\sim$ 10 pc)
- Acceleration in PWNe expected in termination shock wave
- Many PWNe are observed in VHE γ rays
  - Young plerions
  - Evolved PWNe

NEXT SLIDES OF THIS TALK

VHE γ PULSARS

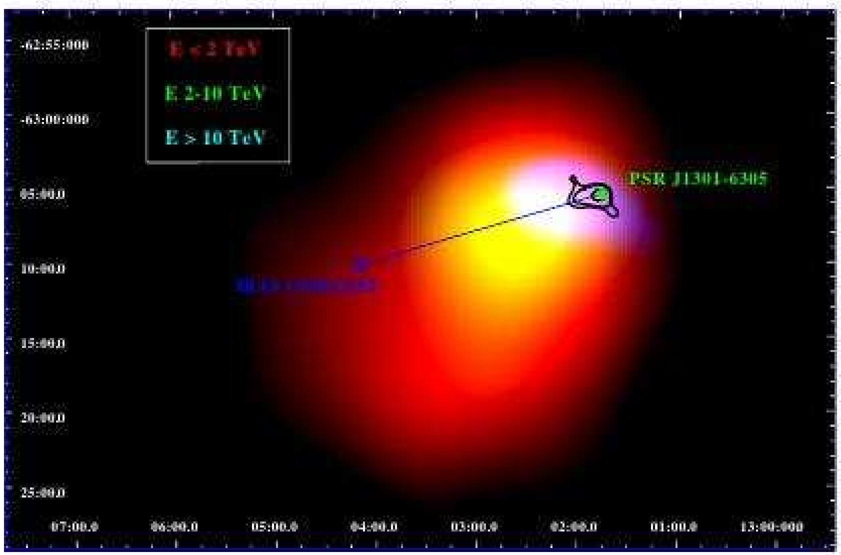
- PSR radiations are pulsed
- PSR radiations are contained within a few light cylinders ($\sim$ AU)
- Acceleration in the vicinity of the neutron star/its light cylinder
- Only the Crab is known to emit pulsed VHE γ radiations

LAST SLIDES OF THIS TALK

Non pulsed emissions: Young plerions/PWNe and old PWNe

EVOLVED PWNe

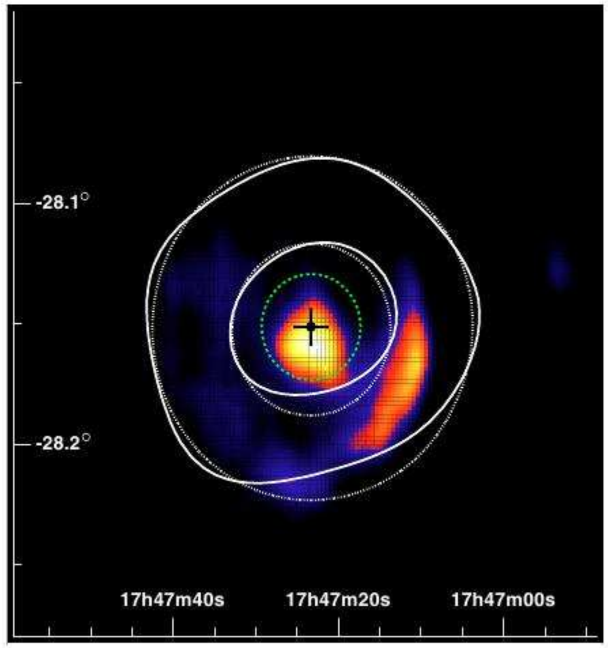
- Vela X, HESS J1825-137, J1718-385, 1809-193...
- Large size ratio γ ray / X ray regions.
- The PSR powering the plerion is offset / center of the TeV emission.



Old PWNe J1301-631. TeV (color), X (level contours), radio (green dot).

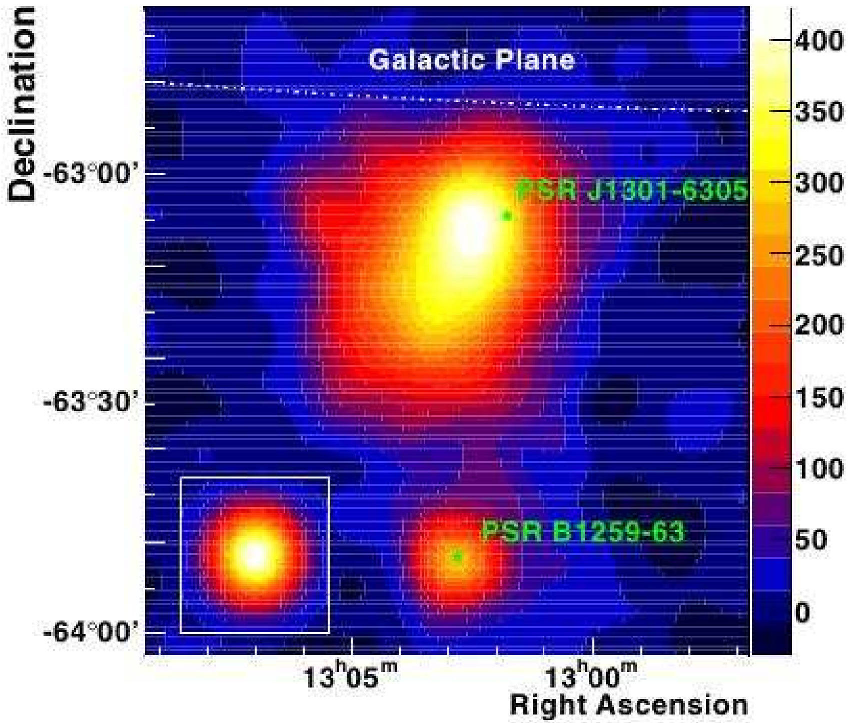
YOUNG PLERIONS

- Crab, SHR G 0.9+0.1, MSH 15-52, SNR G21.5-0.9...
- Good match with morphology seen in X rays, radio...



Young PWNe GO0.9+0.1. Radio 90cm (color), TeV (level contours).

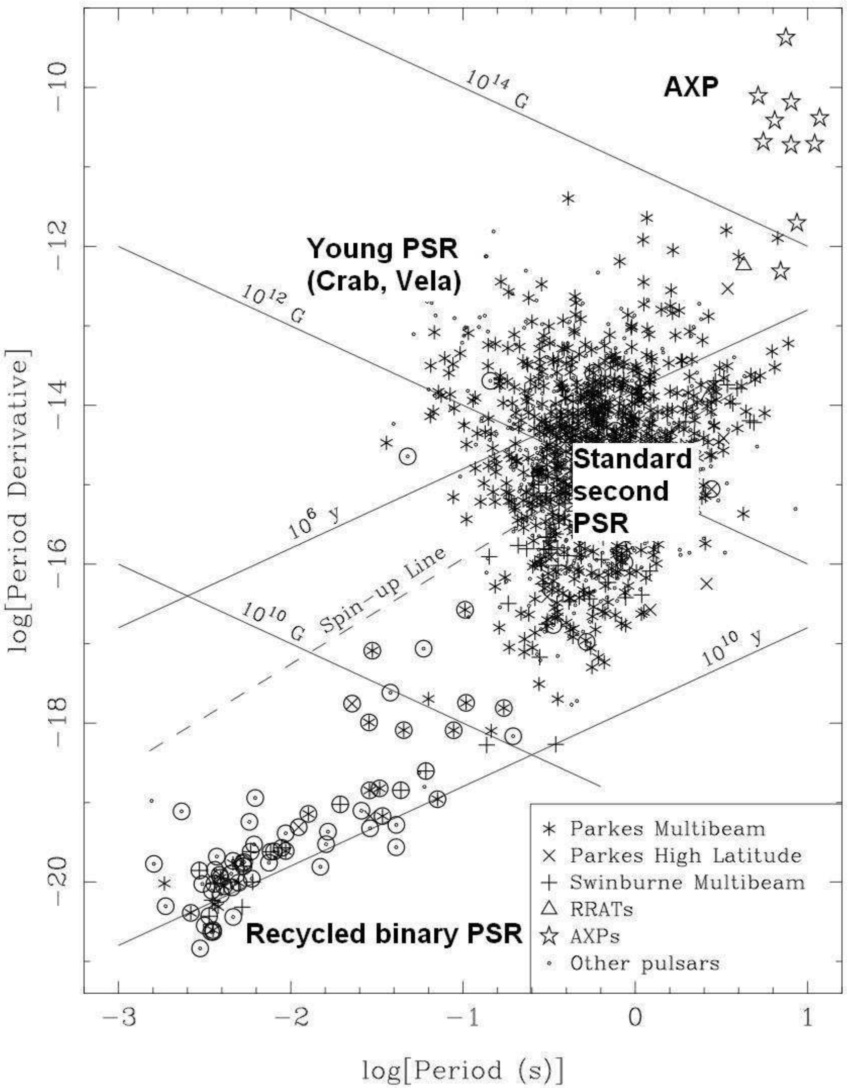
Models of particle acceleration in PWNe



Two PWNe and their radio pulsars [HESS coll., A&A 548, 2012].

- Powered by a pulsar wind. Energetic electrons (positrons)
- Only young PSR with large spin-down power ($\dot{E} > 10^{33}$ erg.s^{-1}) can produce PWNe
- Interaction PSR wind / ISM causes shock waves.
- Wind Lorentz factor $\Gamma \sim 3.10^6$ at termination shock
- Acceleration in the shock wave (Fermi related processes) is suspected in composite PWNe (interaction with SNR).
- Radiative losses of energetic particles (synchrotron). Increase with distance from the star. Lower if low B.

Models of particle acceleration in PWNe



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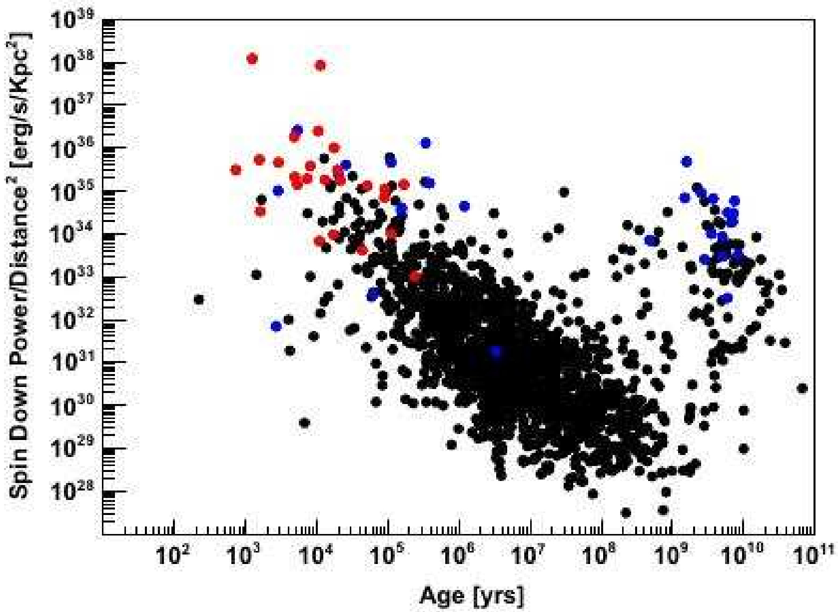

Fig. 1. Spin-down energy loss rate of radio pulsars listed in the ATNF catalog versus their characteristic age. The blue dots overlaid indicate the pulsars detected at high energies with the Fermi-LAT telescope whereas the red ones mark the pulsars associated to TeV PWNe. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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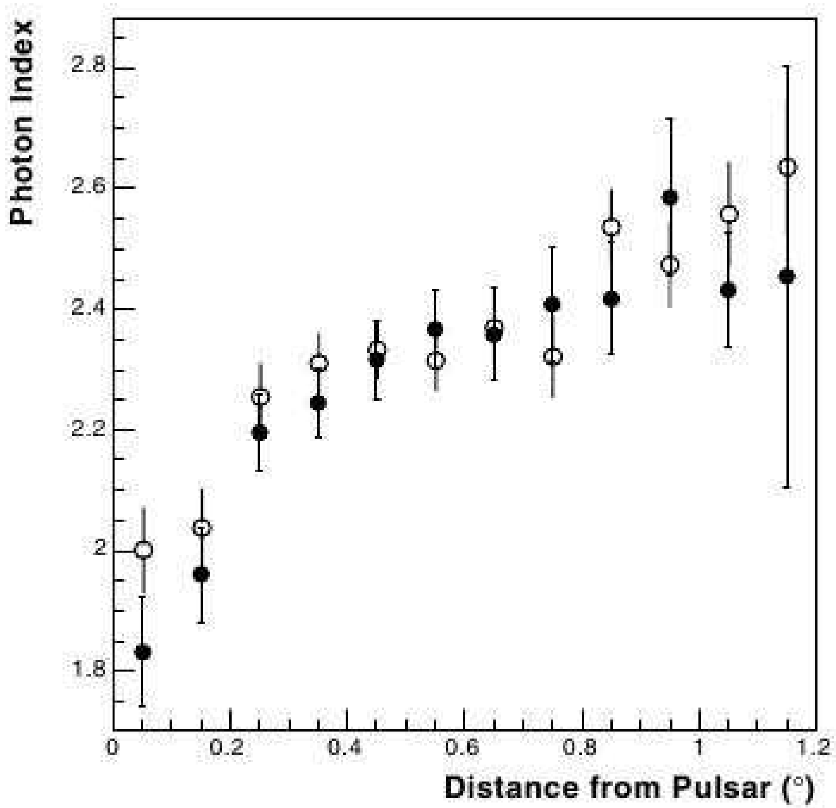

Spectral energy distribution index Γ in VHE γ range as a function of the distance of HESS J1825-137. Because of electron energy losses, it has softer spectra at lager distance from the PSR.

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PWNe science with CTA

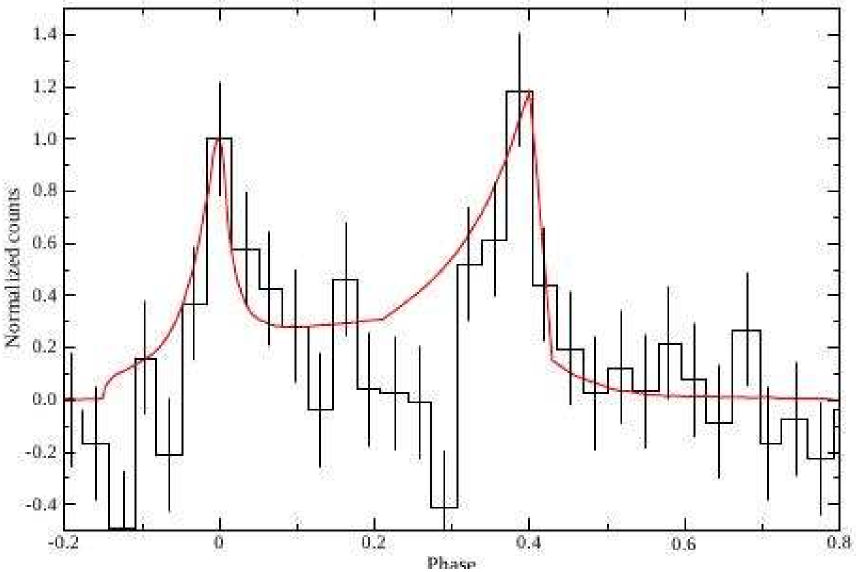
Questions

- PWN modeling, estimate of B and electron populations behind γ ray emission
- particle transport and dynamics
- particle energy losses
- inter-play between high spin-down PSR and their PWNe
- inter-play between PWNe and their hosting SNR (acceleration at shock)

CTA response

- Need a field (flat response) $> 1.5^o$.
- Composite PWNe: Useful to resolve the thickness of SNR shells. Ex. for Kes 75: $\sim 2.5'$.
- Cooling effect of electron parent populations. Internal structures, synchrotron/adiabatic losses. Large energy range of CTA.

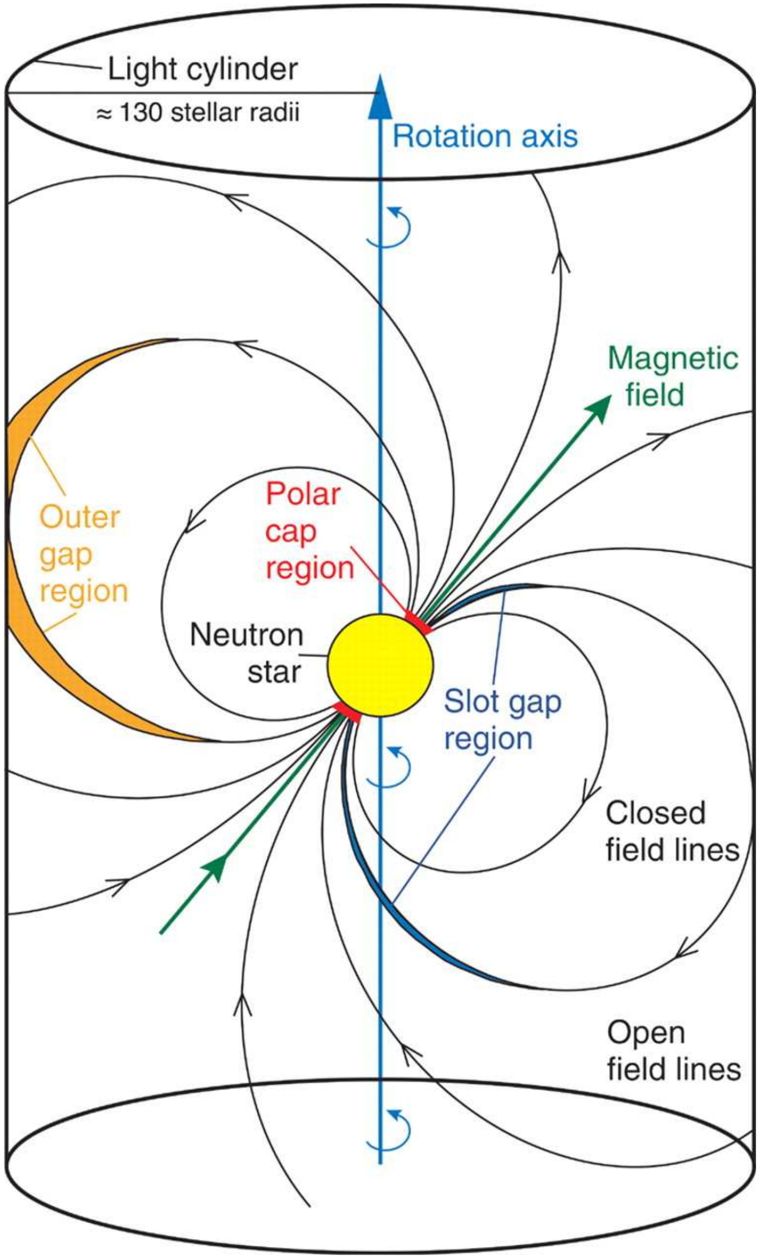
PSR magnetosphere: VHE γ pulsed emissions



Pulsed emission of Crab at $E > 25GeV$. [VERITAS, MAGIC]

- One known source in VHE γ rays : the Crab
- Many sources discovered with Fermi, including old millisecond pulsars.
- How far the non-thermal spectra from known γ ray PSR extend in energy?
- shape and position of spectral cut-off / emission models

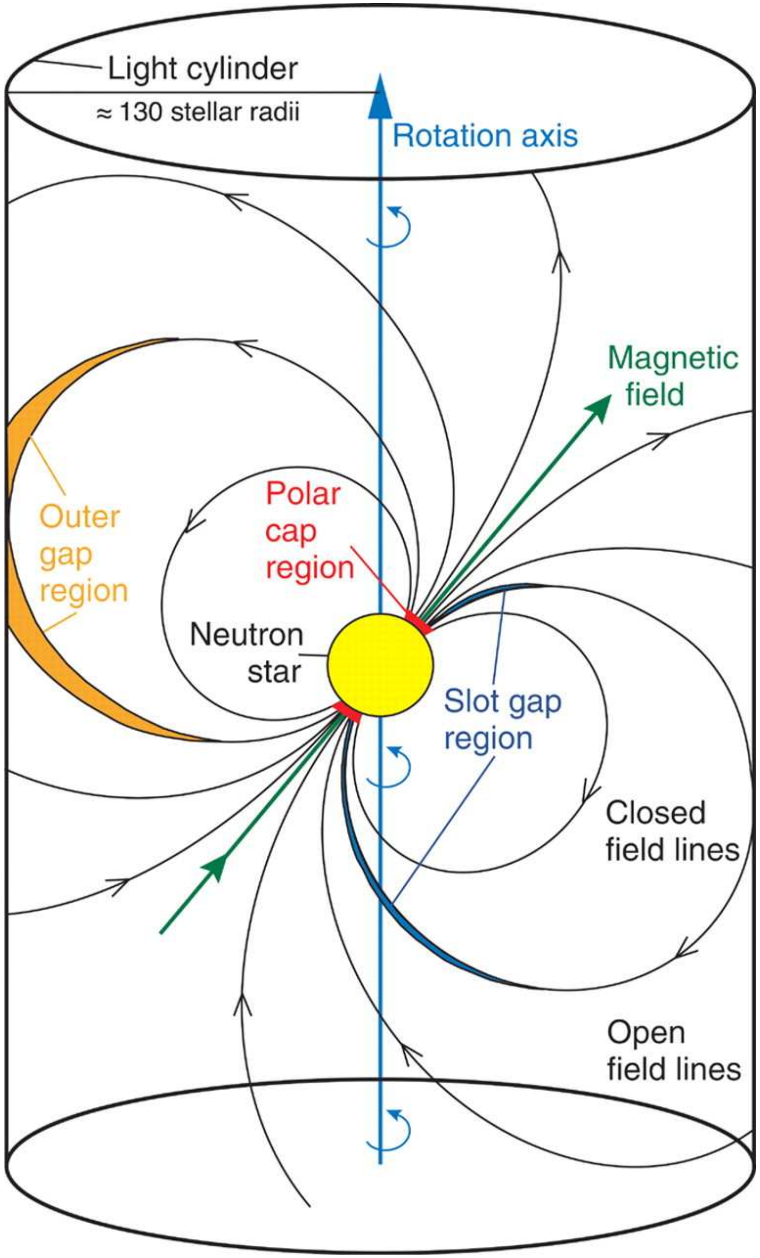
Models of particle acceleration in PSR



Radiative processes

- Energetic electrons → synchro-curvature production of γ photons.
- Inverse Compton production of γ photons.
- γ photons create electron-positron pairs
  $\nu_\gamma + B \rightarrow e^-, e^+$
  $\nu_\gamma + \nu \rightarrow e^-, e^+$, with CMB, star's thermal photons...
  Pair production : opacity to γ emissions + deep influence on plasma acceleration.

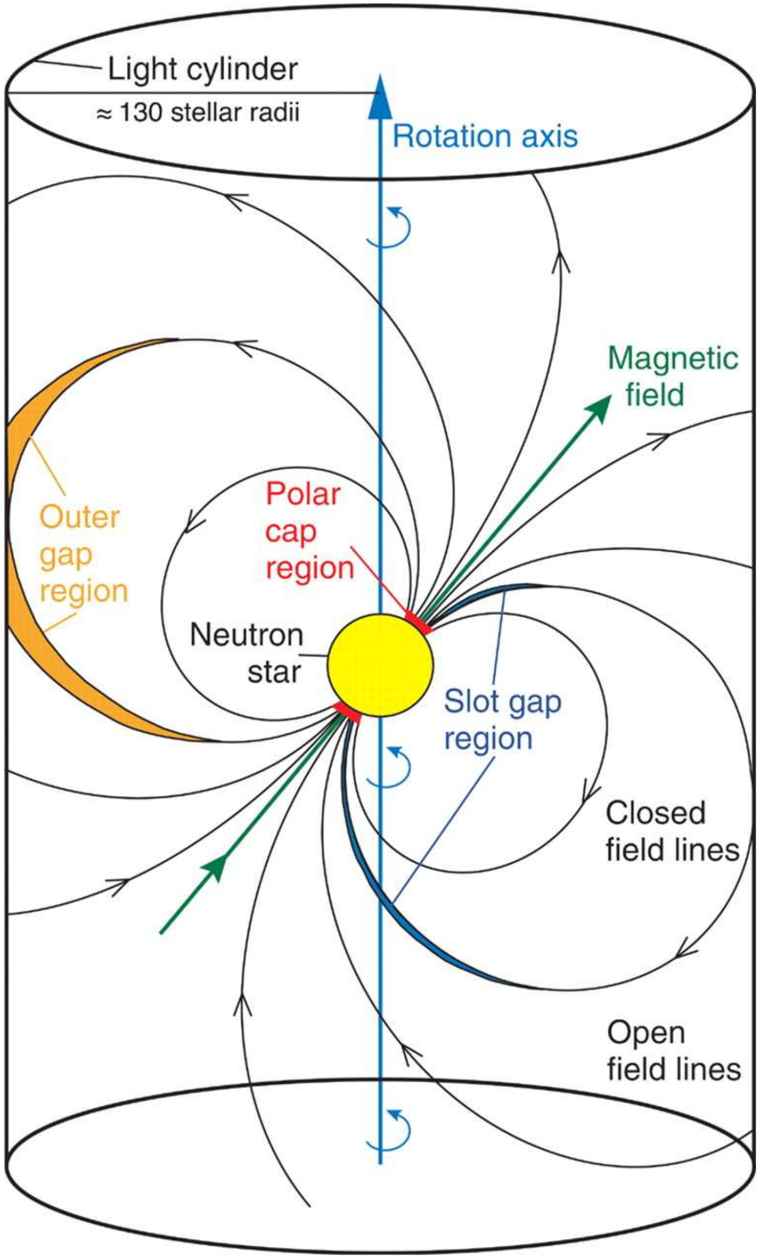
Models of particle acceleration in PSR



Where is acceleration ?

- Polar cap acceleration. In young PSR, $B \sim 10^8$ T, opacity in γ rays.
- Polar cap acceleration. In old PSR, $B \sim 10^5$ T, no pair creation with B (but with photon+ photon interaction).
- With Polar cap model, a super exponential cut-off is expected. They are not seen in Fermi-LAT spectra.
- Outer gap. B is "low", photon-photon create pairs.
- Outside light cylinder, accelerate the PSR wind.

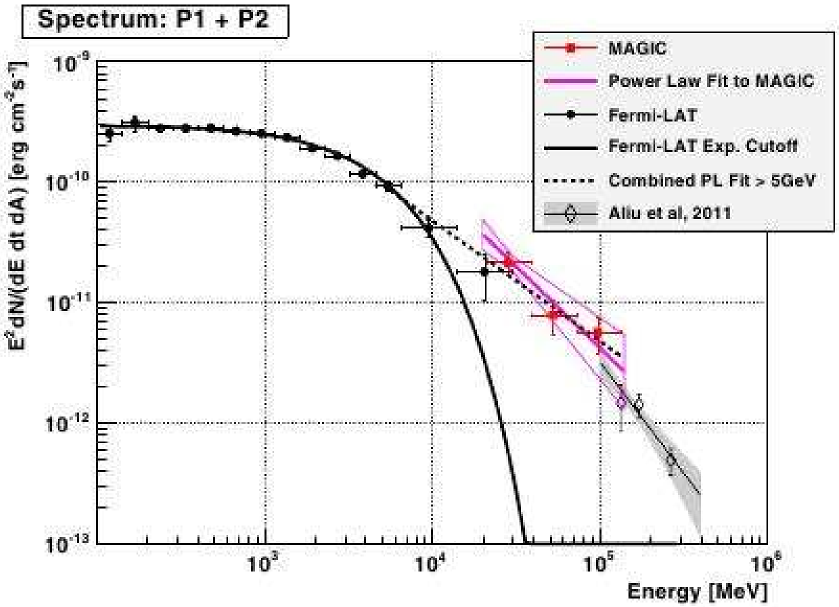
Models of particle acceleration in PSR



Ignorance

- We have general ideas + well known elementary processes. They are difficult to assemble.
- No self consistent model of acceleration.
- No self consistent model of the electric current density in PSR magnetospheres.
- No self consistent model of B that allows for acceleration (in particular, the fashionable force-free models).

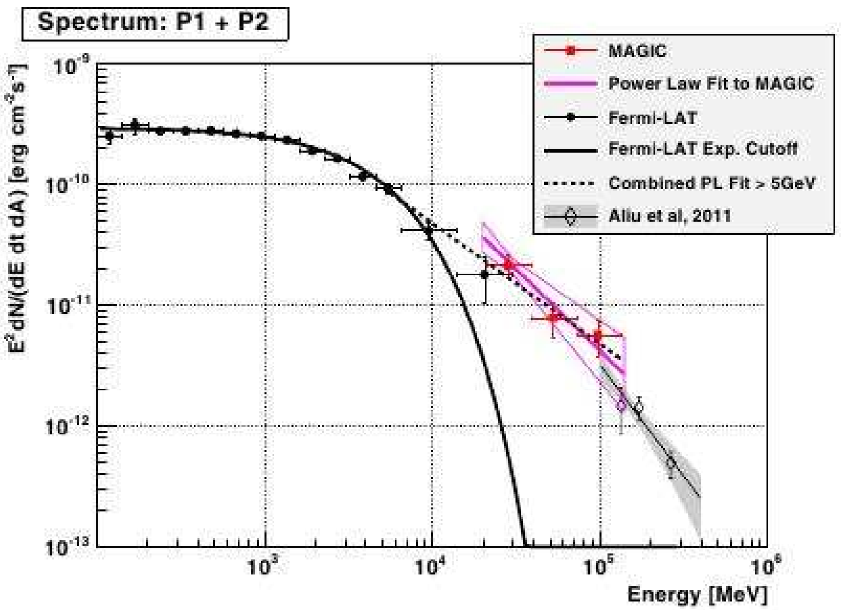
Crab nebula Fermi-LAT + MAGIC unexpected pulsed spectrum



Spectrum seen by Fermi-LAT and by MAGIC. Solid black : exponential cut-off derived from "classical" Fermi-LAT models does not fit the VHE γ data.

- An exponential cut-off is expected from Fermi-LAT observations.
- But observations at high energy show emission beyond cut-off.
- Requires a modification of the standard pulsar emission models
- Inference : Maybe the Crab is not unique, other PSR have pulsed VHE γ emission

Prospects of observing PSR with CTA



Spectrum seen by Fermi-LAT and by MAGIC. Solid black : exponential cut-off / not OK.

- If cut-offs seen by Fermi-LAT are correct, then poor prospect for CTA pulsed emissions. Even for the Crab.
- But PSR might have pulsed emission that goes beyond the Fermi-LAT exponential cut-off. (=Need more than an extrapolation from Fermi-LAT spectra.)
- Need good performances in low energy range. (Array configuration B.)
- CTA simulations (configurations B and E) show that if PSR have same SED tail as Crab, 20 over a sample of 46 Fermi-Lat PSR would be detected.
- Old millisecond PSR might also have pulsed spectral components in VHE γ rays.