TEV PULSED EMISSION DETECTED FROM THE CRAB PULSAR BY MAGIC

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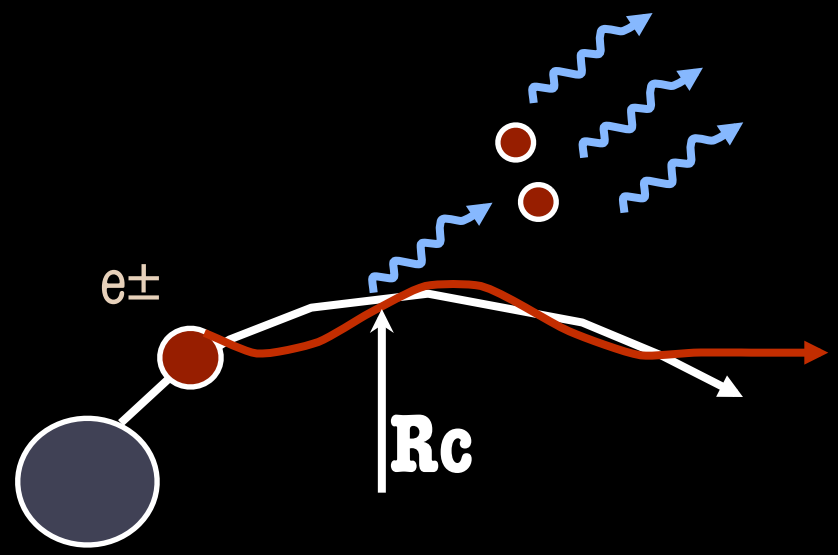
OUTLOOK

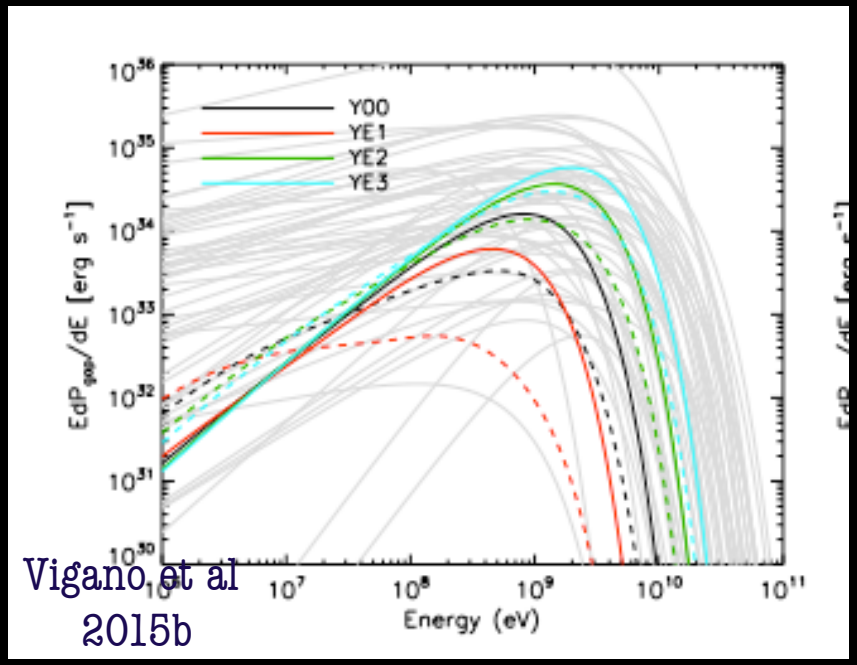
- Gamma-ray emission in Pulsars
- The Crab Pulsar
- MAGIC Observations
- Results and Interpretation
- Summary

"TERAELECTRONVOLT PULSED EMISSION FROM THE CRAB PULSAR DETECTED BY MAGIC"
SUBMITTED TO A&A

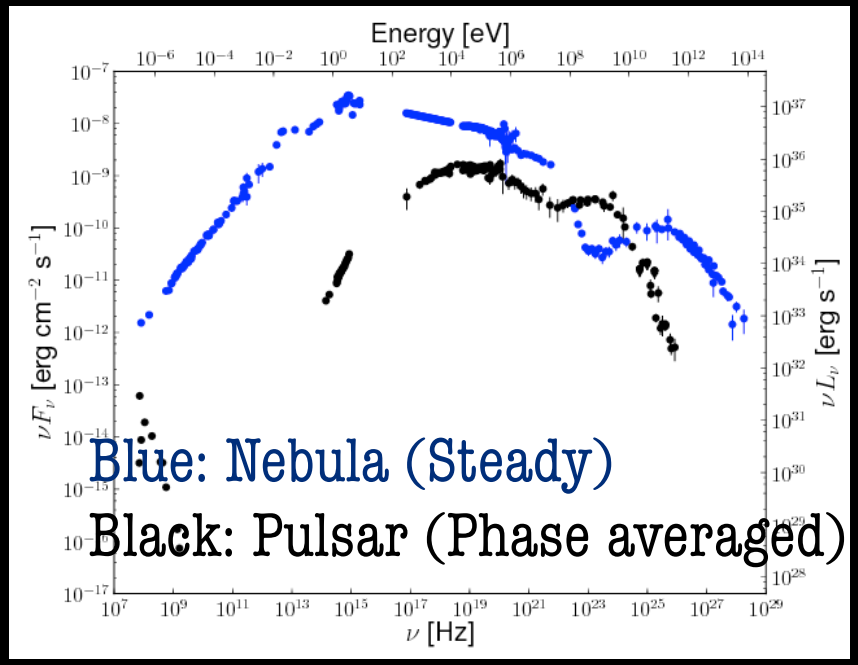
PULSARS E>100 MEV



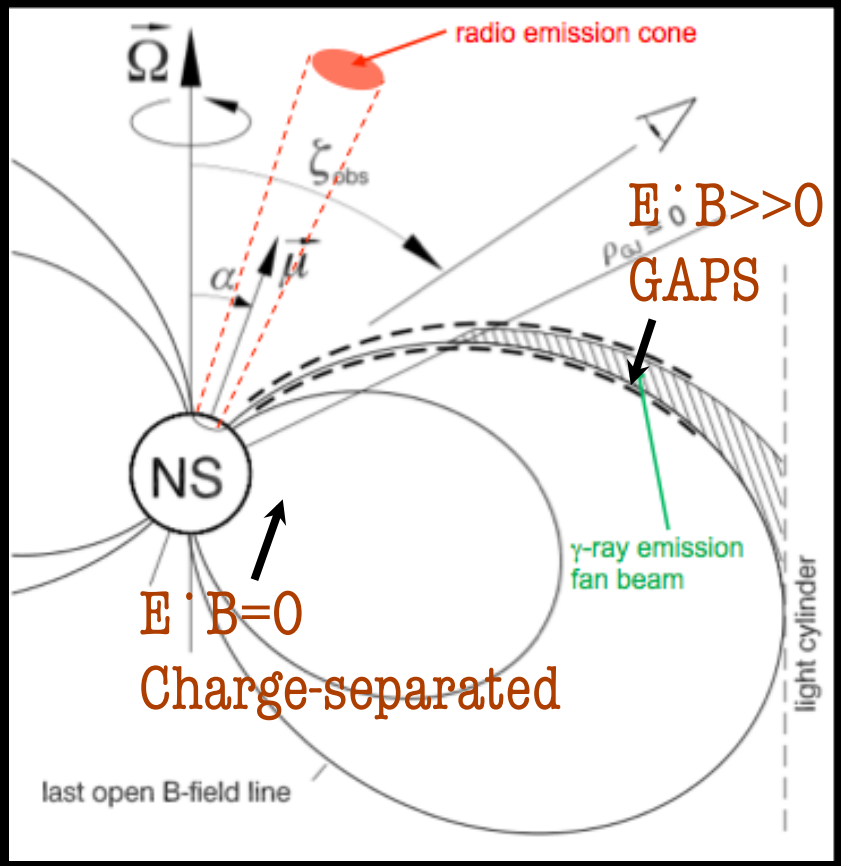
- Pulsars are rotating magnetised neutron stars that emit radiation from radio to TeV
- Broadband spectrum usually explained by synchro-curvature radiation
- At GeV energies shows an exponential cutoff at a few GeV

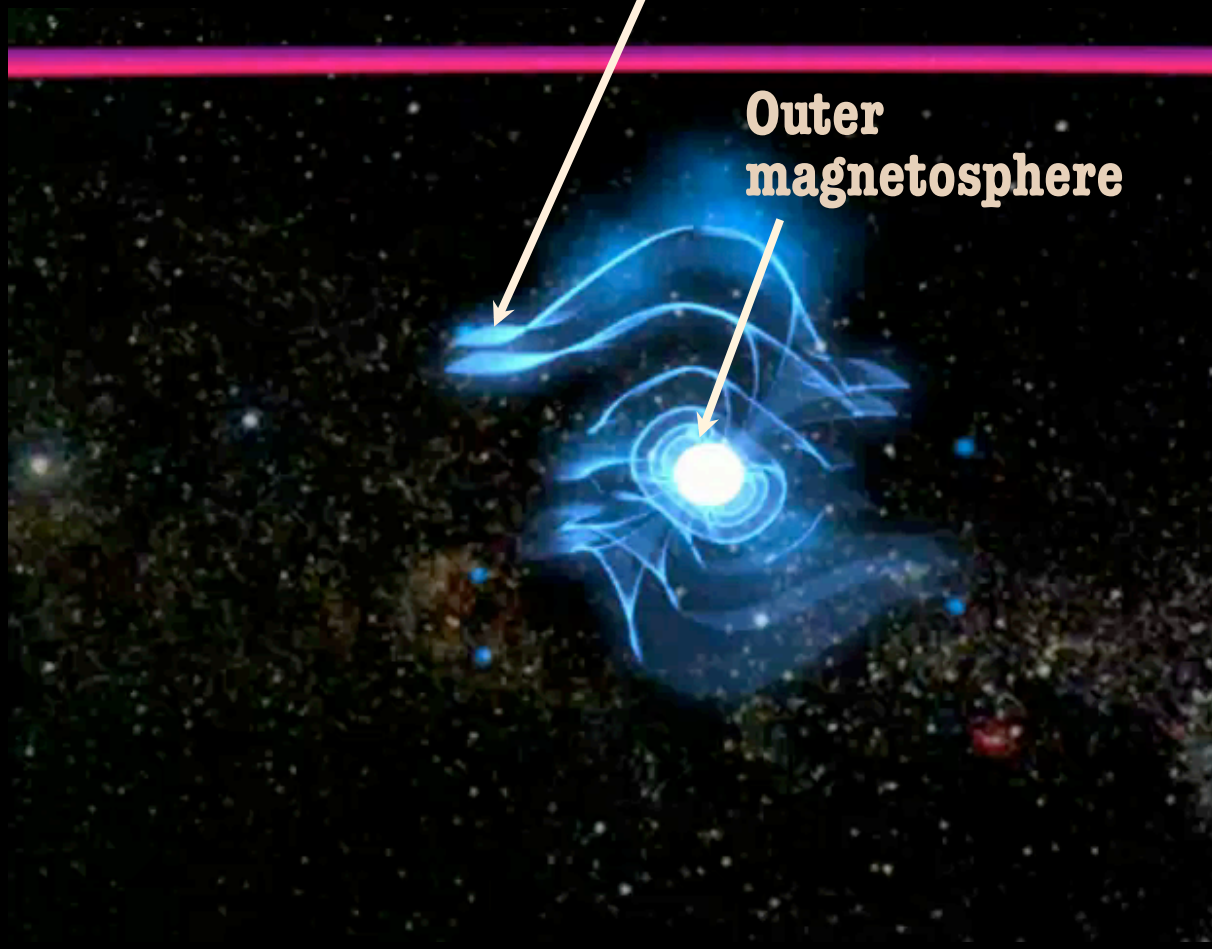


Vigano et al 2015b



PULSARS: ACCELERATION REGIONS





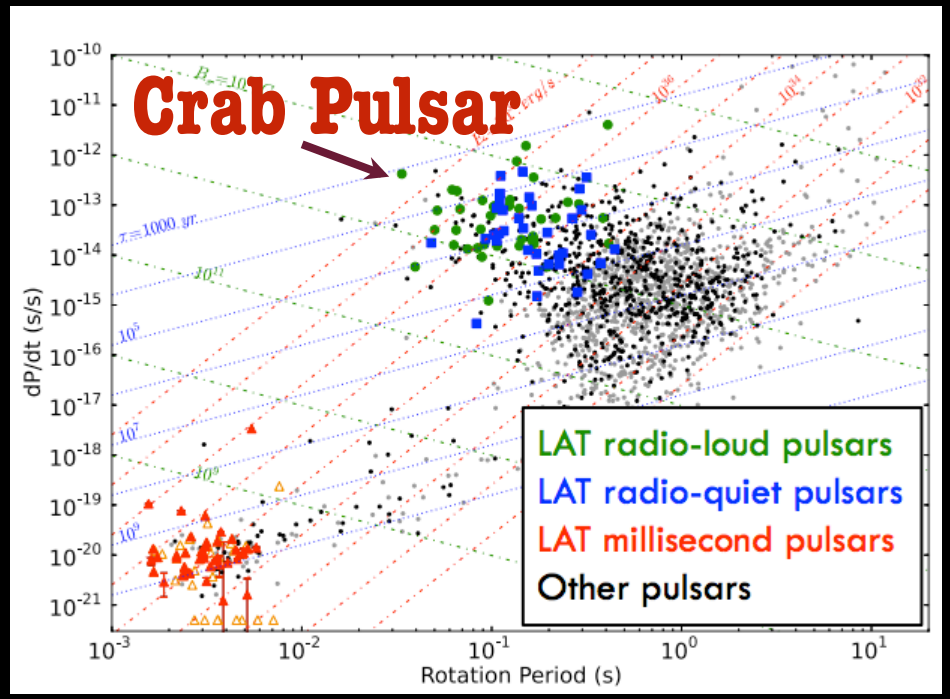
THE CRAB PULSAR

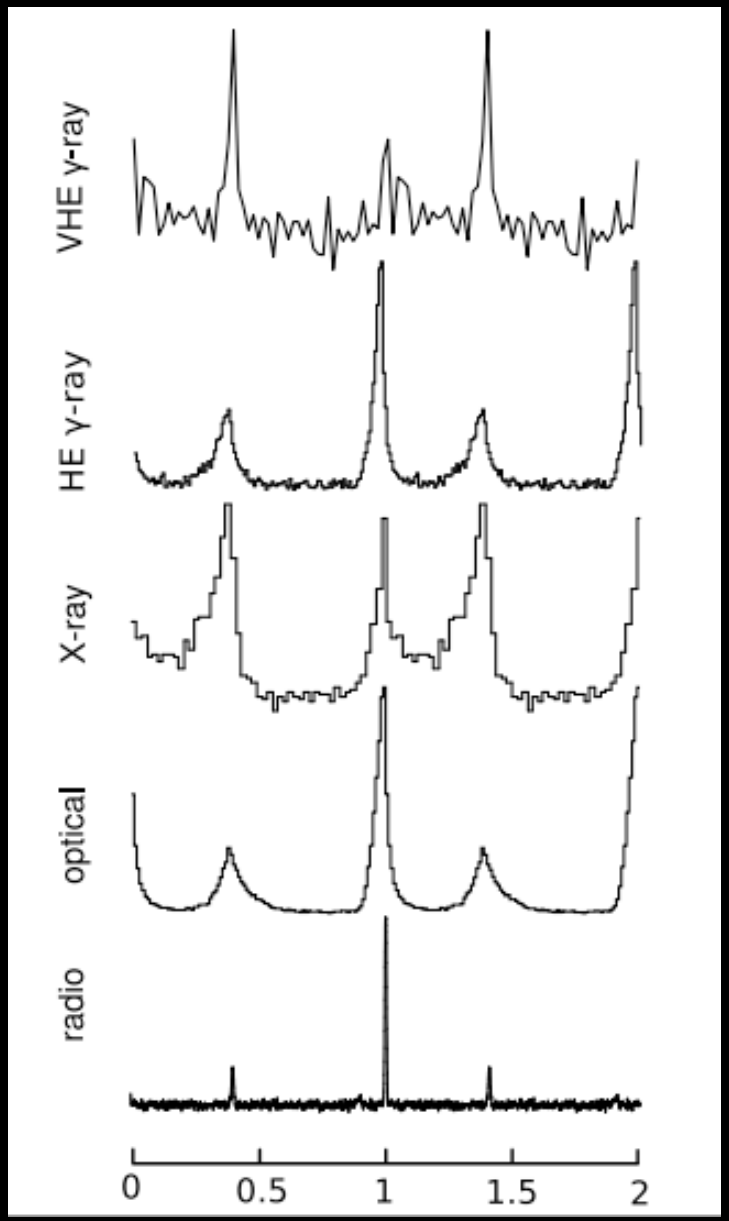
$\dot{E} \sim 5x10^{38}$ erg/s

d ~ 2 Kpc

Pulses aligned from radio to GeV

Spectrum extends up to 400 GeV





Tavani et al 2011, Abdo et al 2011

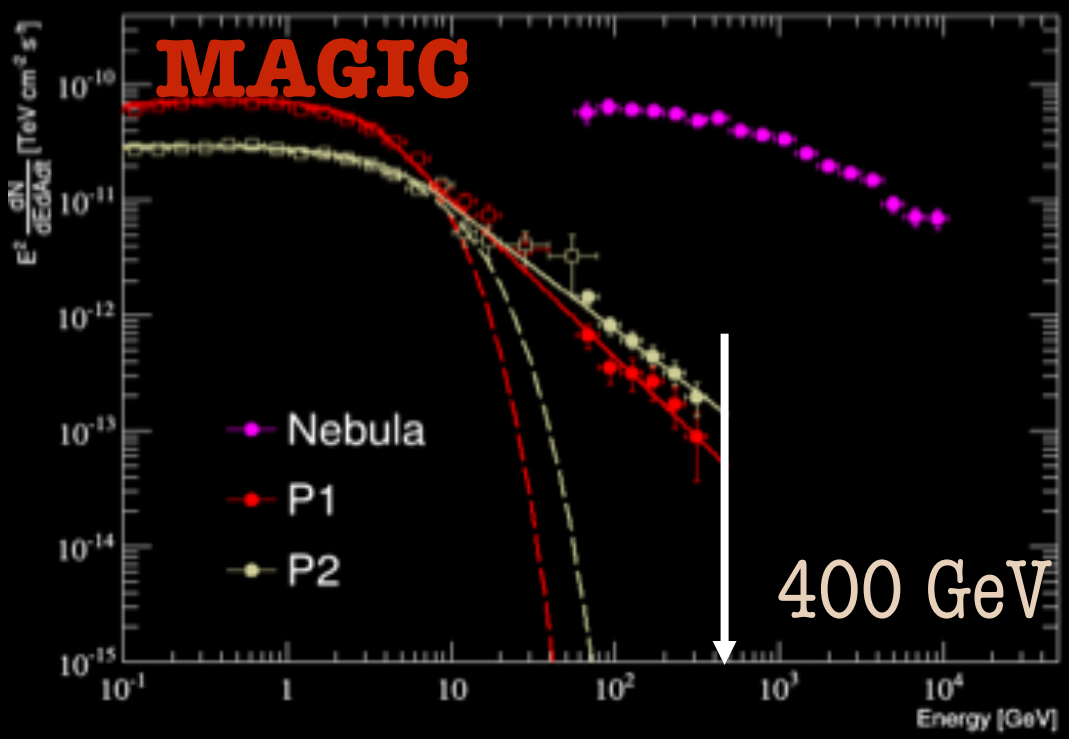
THE CRAB PULSAR AT VHE

Where and how??

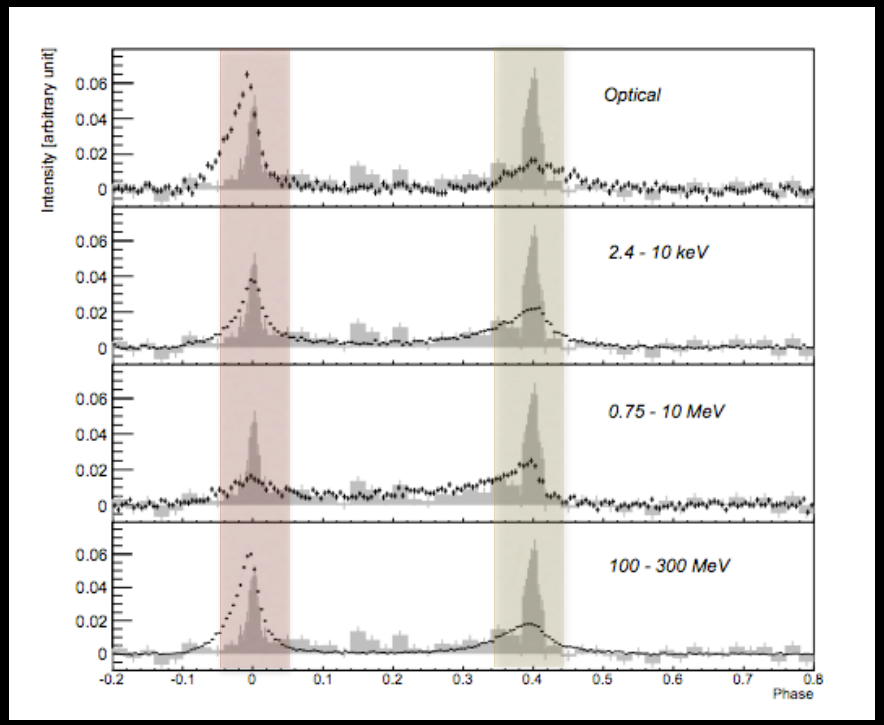
Aharonian+, Nature 2012
Bednarek, 2012
Lyutikov+, ApJ 2012
Aleksic+, ApJ 2011 (Hirotani)

VERITAS, Aliu+, Science 2011

MAGIC, Aleksic+, A&A 2012



P1 P2

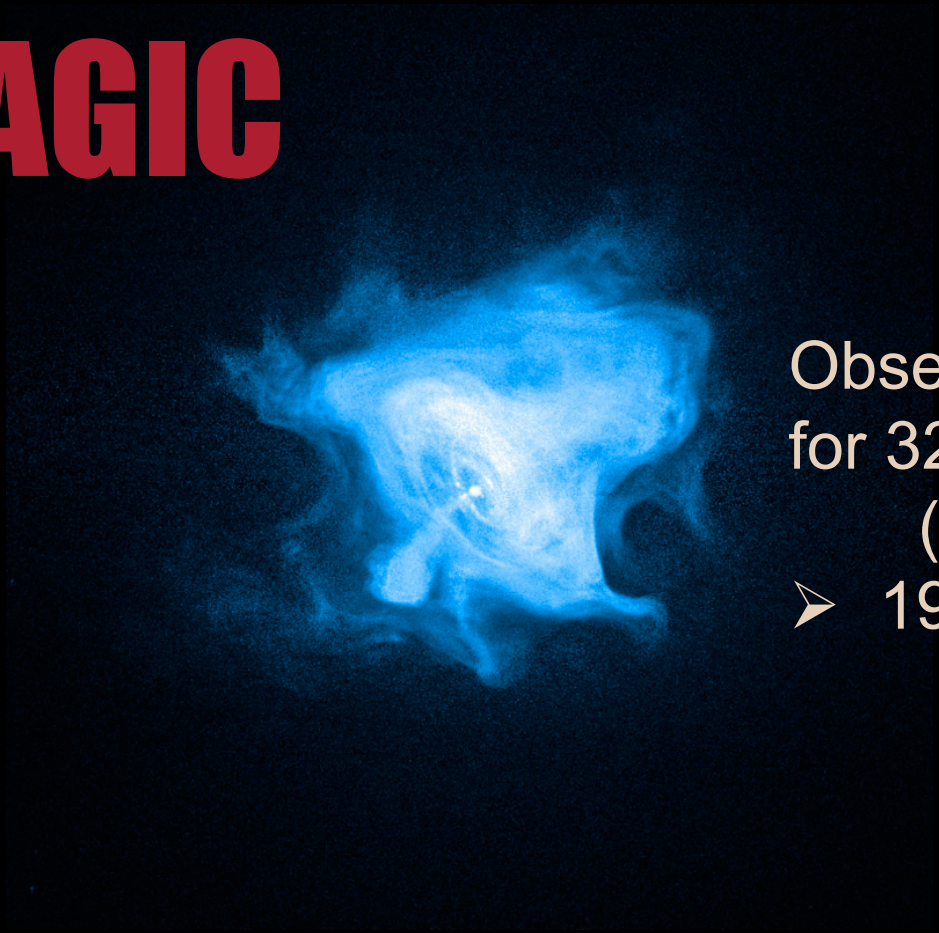


MAGIC

- 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

MAGIC



Observations of the Crab pulsar for 320 hours :

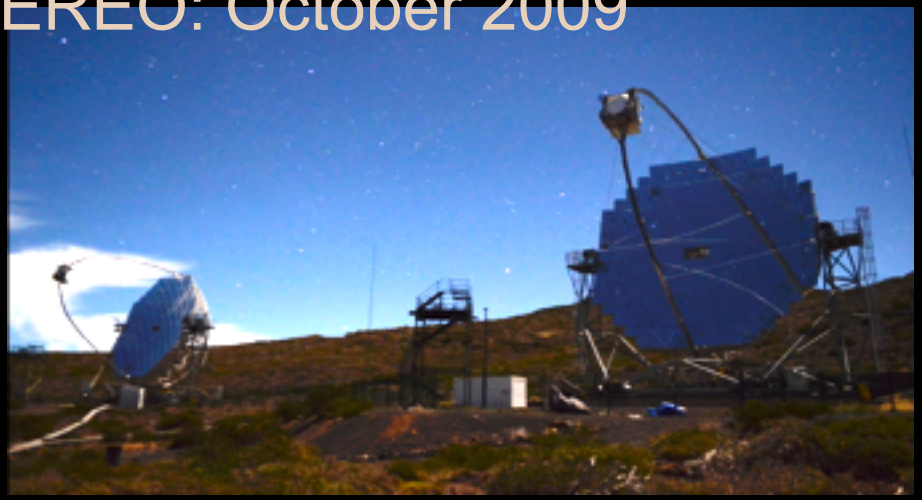
(1/3 mono + 2/3 stereo)

- 19 sub-sets of data

MONO: 2004- 2009

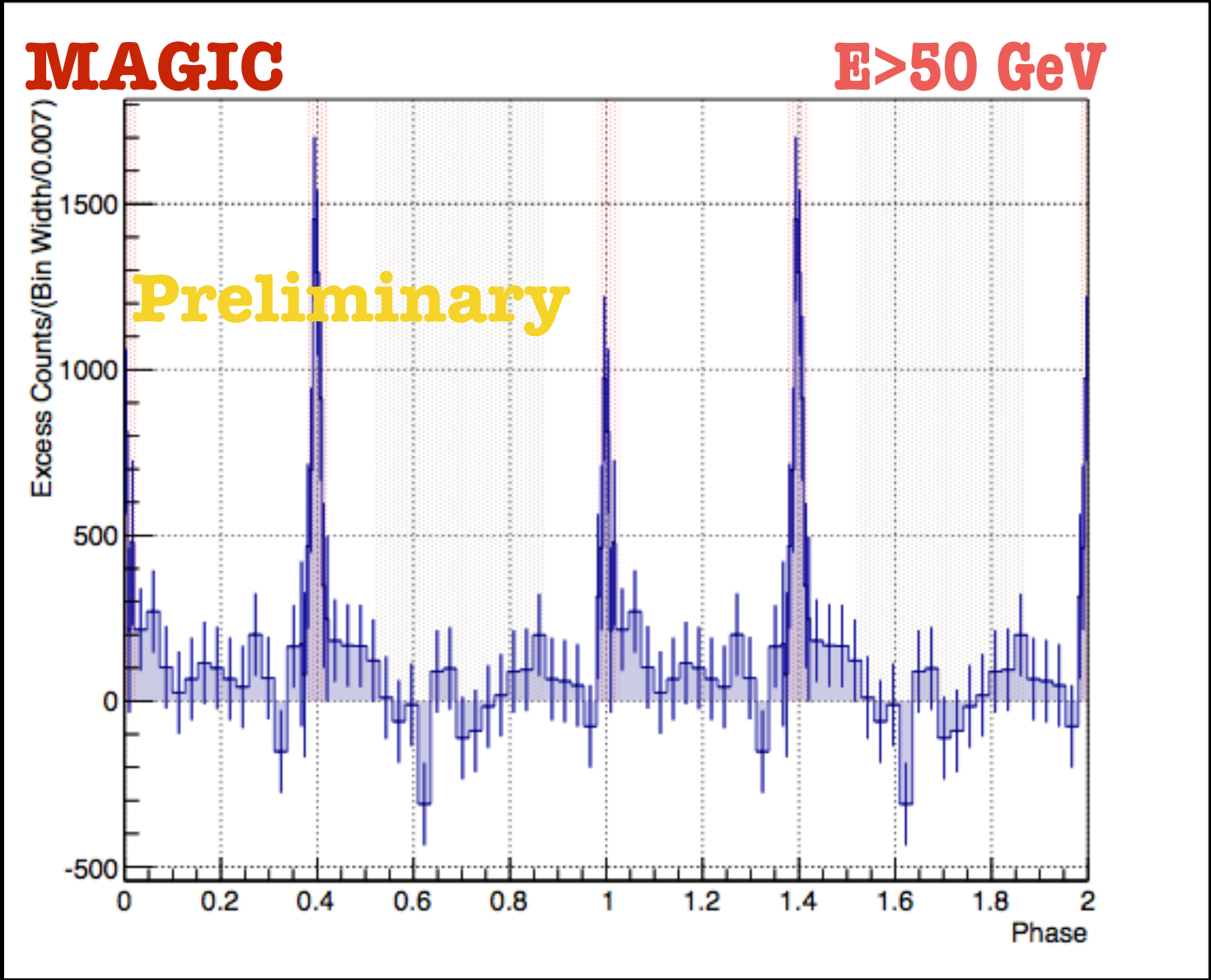
(2007 - 2009)

STEREO: October 2009

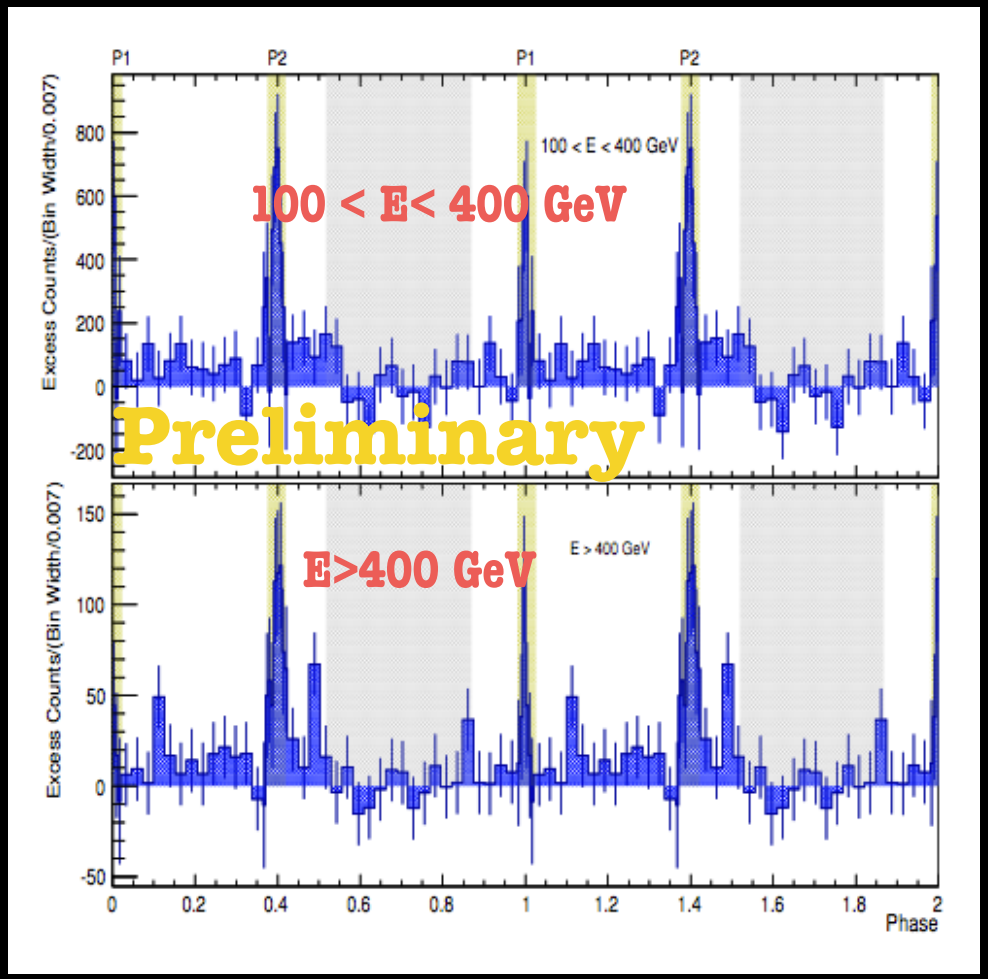


(2009 - 2014)

SPECTRUM & LIGHTCURVE

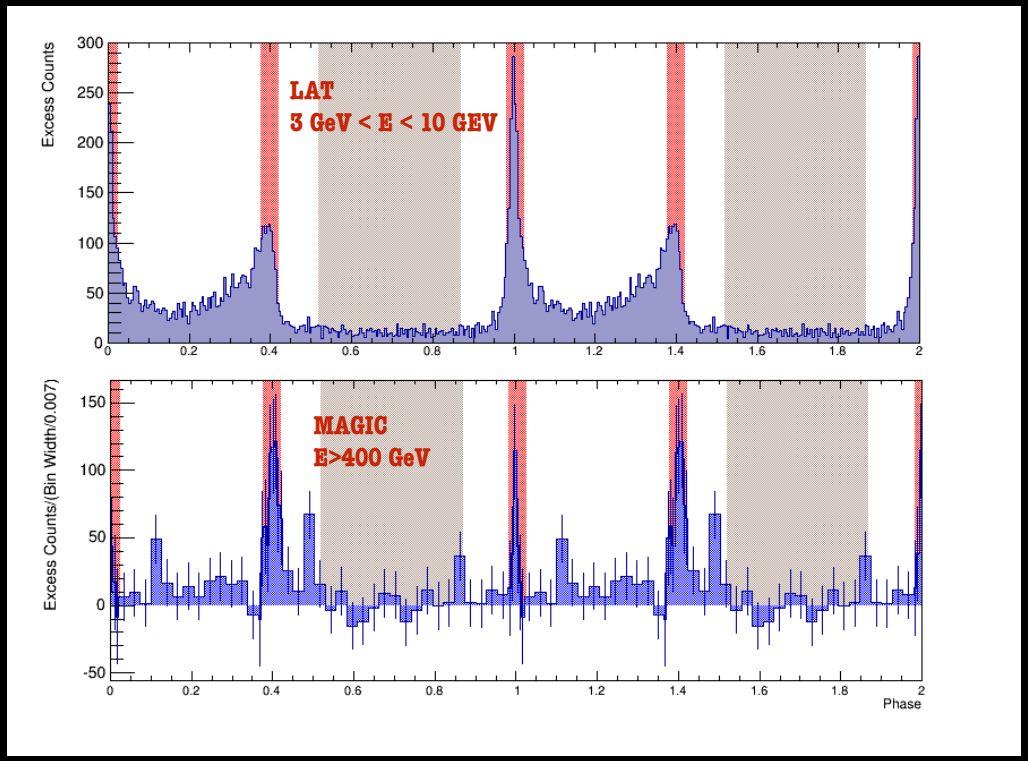


SPECTRUM & LIGHTCURVE



Energy Range [GeV]	P1		P2	
	N_{ex}	N_σ	N_{ex}	N_σ
>400	188±88	2.2	544±92	6.0
>680	130±66	2.0	293±69	4.3
>950	119±54	2.2	190±56	3.5

MAGIC



Above 400 GeV:

P1: $\Phi_o = 0.997 \pm 0.001_{sta} \pm 0.004_{sys}$

FWHM$=0.005 \pm 0.002_{sta} \pm 0.002_{sys}$

P2: $\Phi_o = 0.403 \pm 0.003_{sta} \pm 0.004_{sys}$

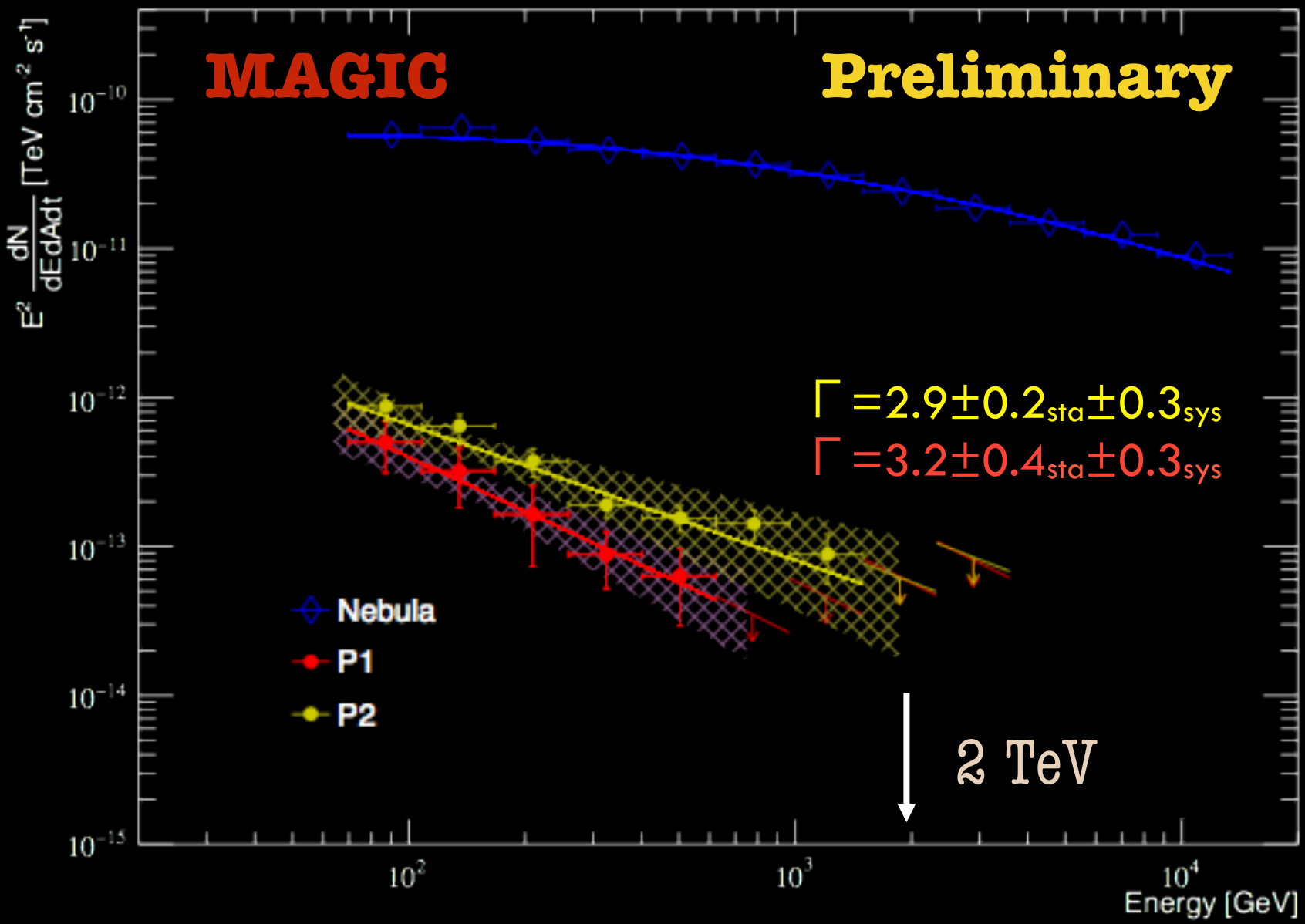
FWHM $=0.022 \pm 0.008_{sta} + 0.002_{sys}$

The measured time delay GeV-TeV:

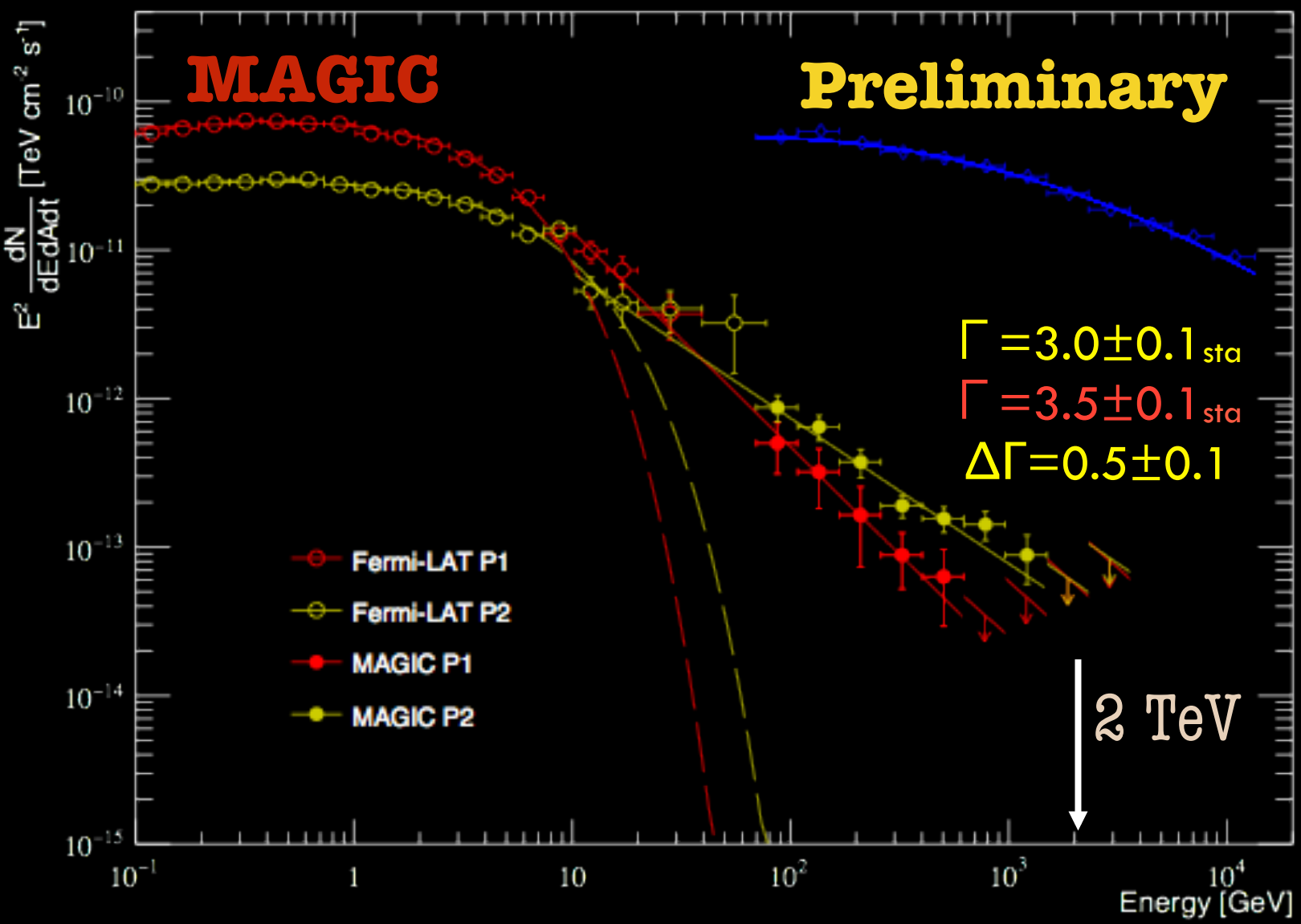
P1: $(62 \pm 34)\mu s$
P2: $(157 \pm 101)\mu s$

- Could be interpreted as very small separation between the bulk of the radiation region where the photons are generated

SPECTRUM & LIGHTCURVE

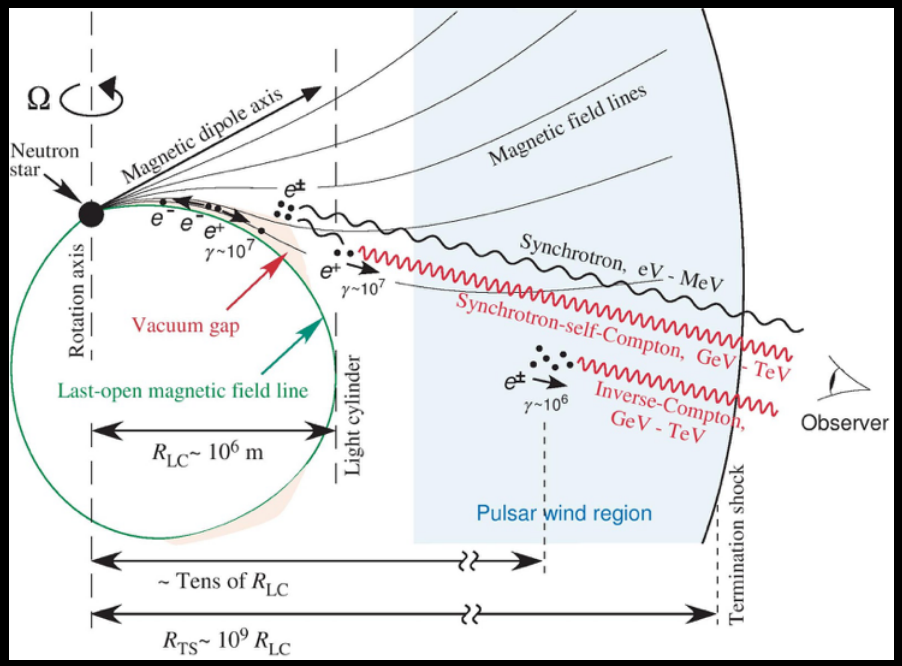


SPECTRUM & LIGHTCURVE



IMPLICATIONS

- $E \sim TeV$ emitted by a population of electrons with $\Gamma_e \sim 5x10^6$
- Impossible to reach such energy via synchro-curvature mechanism ($Rc \sim 200\ R_{LC}$!) -> Inverse Compton off soft photon fields
  - In the magnetosphere?



Ansoldi 2015, Hirotani 2013

- Primary e+ up scattering IR to TeV energies
- TeV photons quickly absorbed producing e± pairs (GeV to TeV energies).
- Secondary pairs are created at a greater distance and produce GeV-TeV emission via synchrotron self-Compton process.
- <u>Problem:</u> Difficult to explain synchronized LCs

IMPLICATIONS

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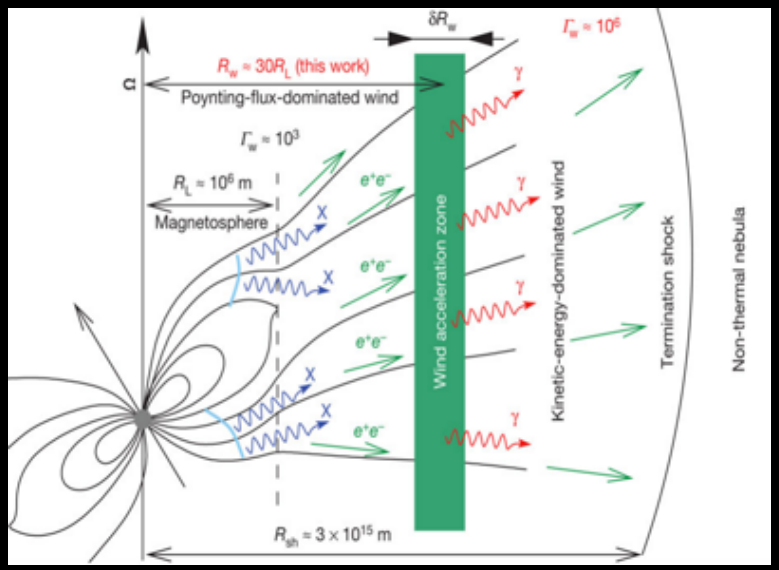
  - In the pulsar wind?



Aharonian et al 2012

- Pulsar wind up-scattering pulsed IR/X-ray photons, changing from magnetic-dominant to kinetic-dominant at 20-50 R_{LC}
- <u>Problem:</u> Difficult to reach ~TeV energies at such distances in a wind accelerated following a power-law dependence
- Larger distances -> Flux underestimated below 100 GeV

IMPLICATIONS

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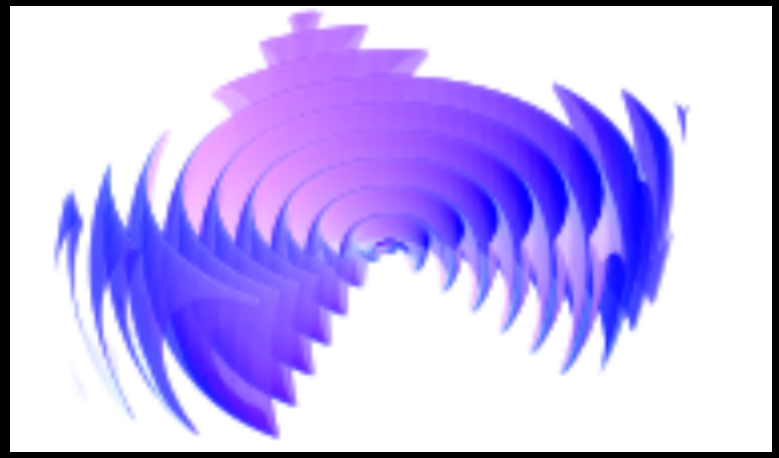


Mochol et al 2015

- IC emission on strip wind
- Still in progress
- <u>Problem:</u> GeV-TeV connection

CONCLUSIONS

- Only IC scattering can produce ~TeV pulsed photons
- P1 spectrum decays faster than P2 ($\Delta\Gamma = 0.5 \pm 0.1$) and pulses seem to be narrowing
- Spectra connect smoothly from 10 GeV to TeV energies
- The generation regions should not be too far from the GeV to keep coherence, but far enough in the magnetosphere to avoid absorption

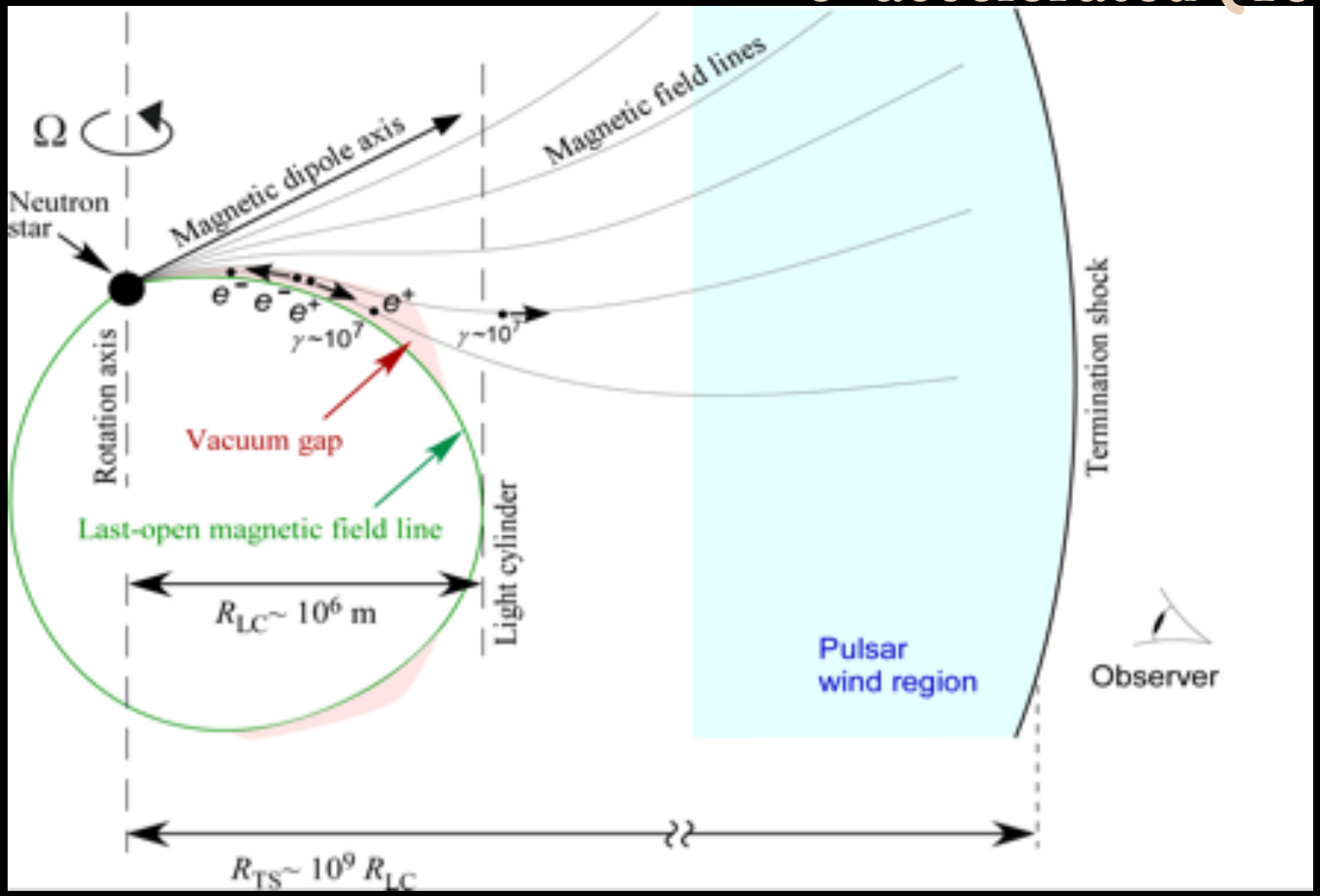
  - MAGIC results require a revision of the models to explain how and where such energetic pulsed emission is produced

THANKS!

BACKUPS

SELF-SYNCHROTRON RADIATION

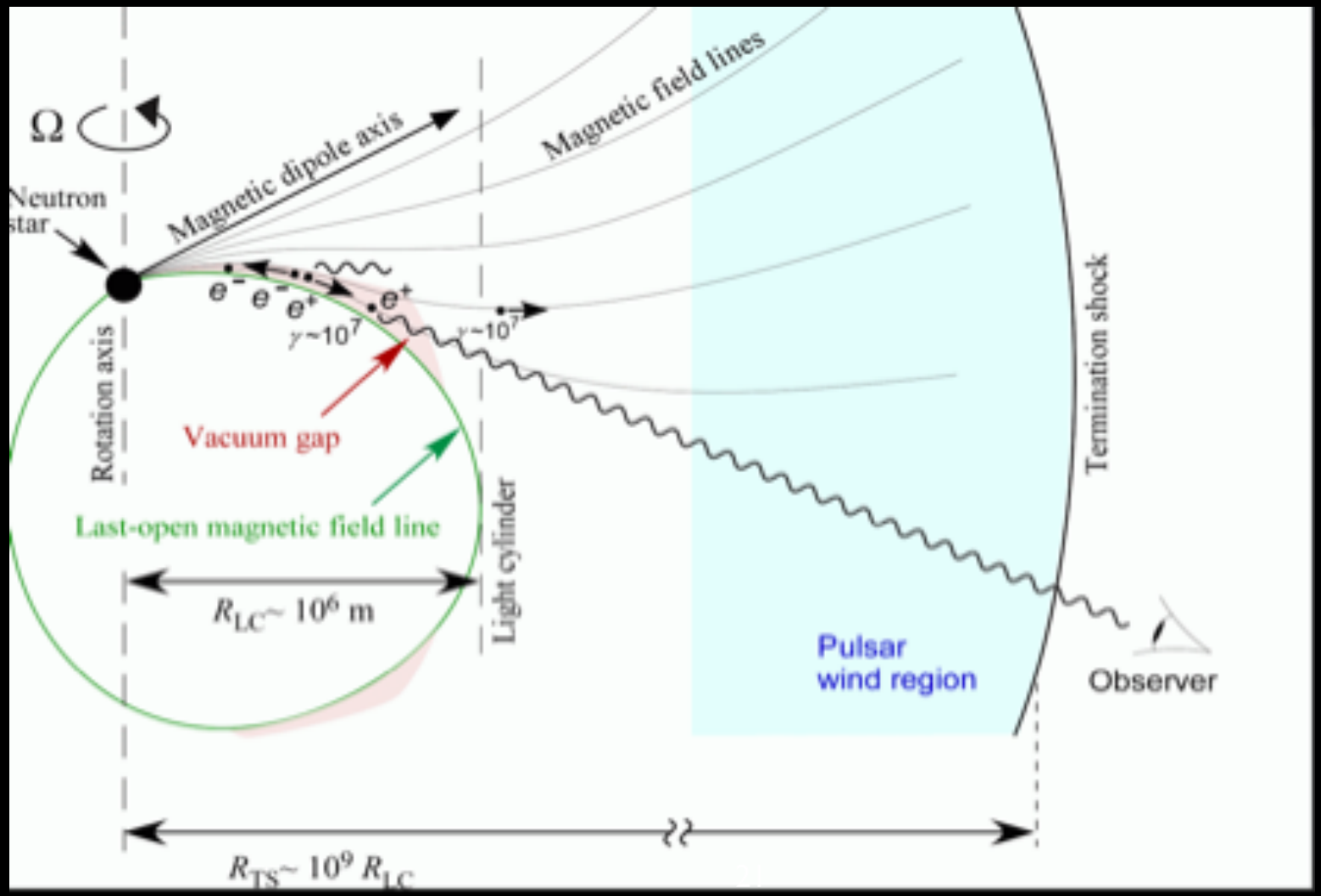
$e^{\pm}$ accelerated (10^7)



SELF-SYNCHROTRON RADIATION

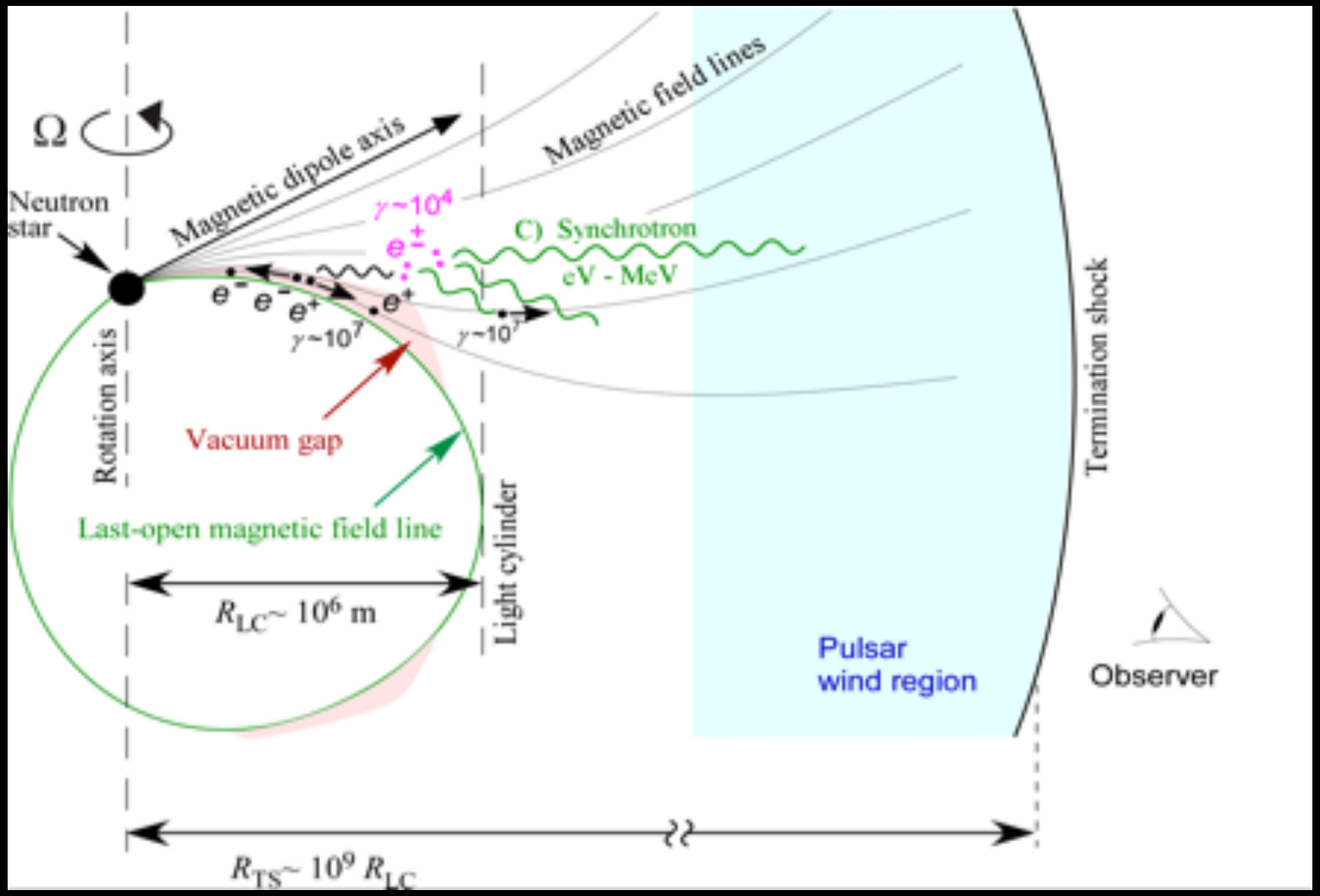
$e^{\pm} + B \rightarrow \gamma$ (observed)

A fraction $\gamma + \gamma \rightarrow e_s^{\pm}$



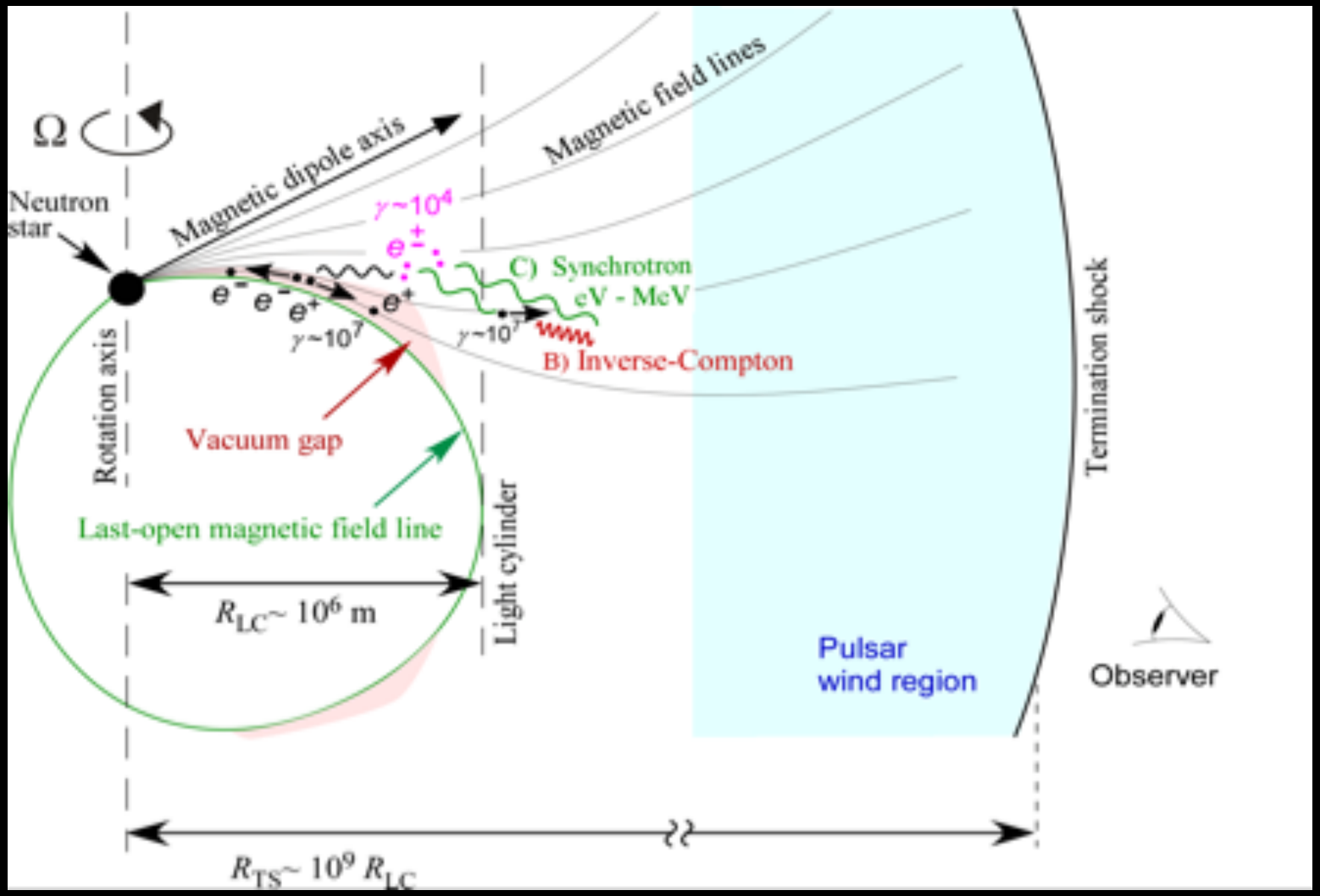
SELF-SYNCHROTRON RADIATION

$e_s^{\pm} + B \rightarrow \gamma$ (eV-MeV)



SELF-SYNCHROTRON RADIATION

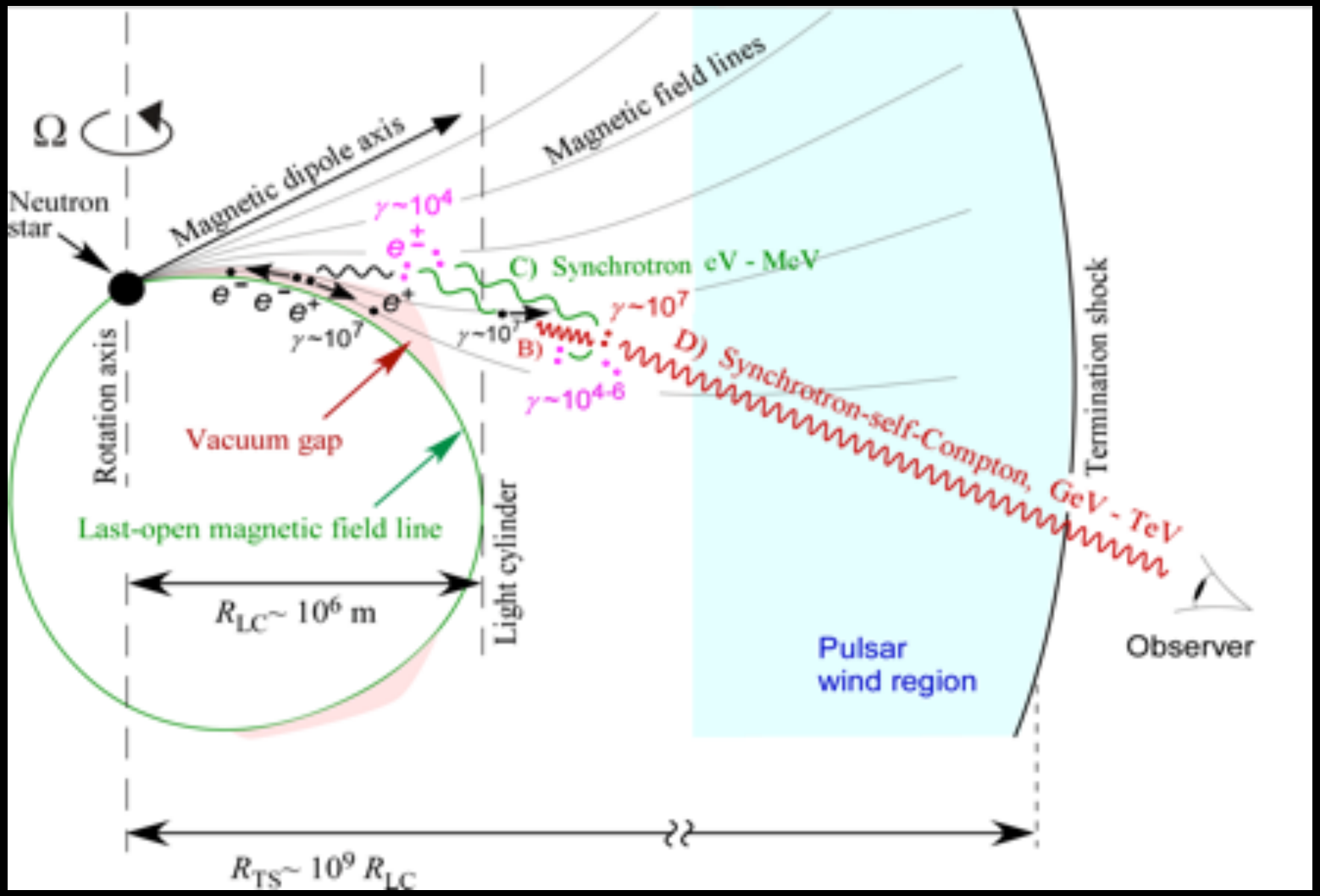
$e_p^{\pm} + \gamma$ (eV-MeV) $\rightarrow \gamma$ (GeV-TeV)



SELF-SYNCHROTRON RADIATION

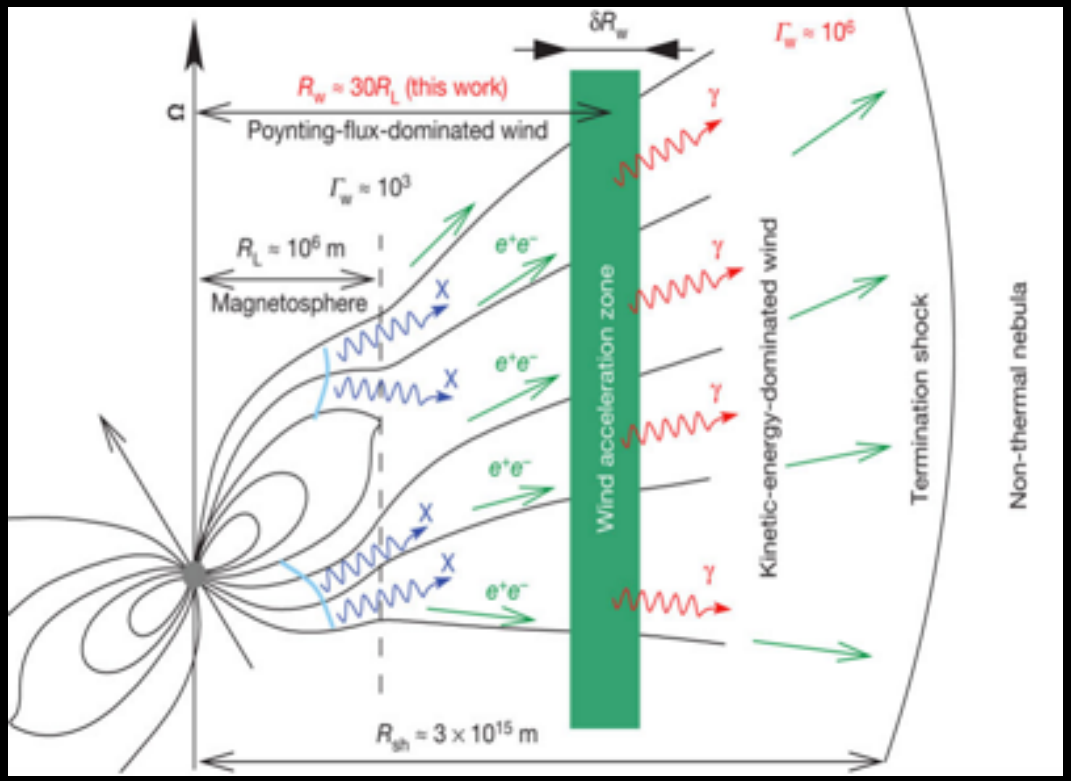
$\gamma + \gamma \rightarrow e_t^{\pm}$

$e_t^{\pm} + \gamma$ (eV-MeV) $\rightarrow \gamma$ (GeV-TeV)



PULSAR WIND MODEL

e± ($\Gamma_w \sim 10^3$) injected on the wind zone



Aharonian et al 2012

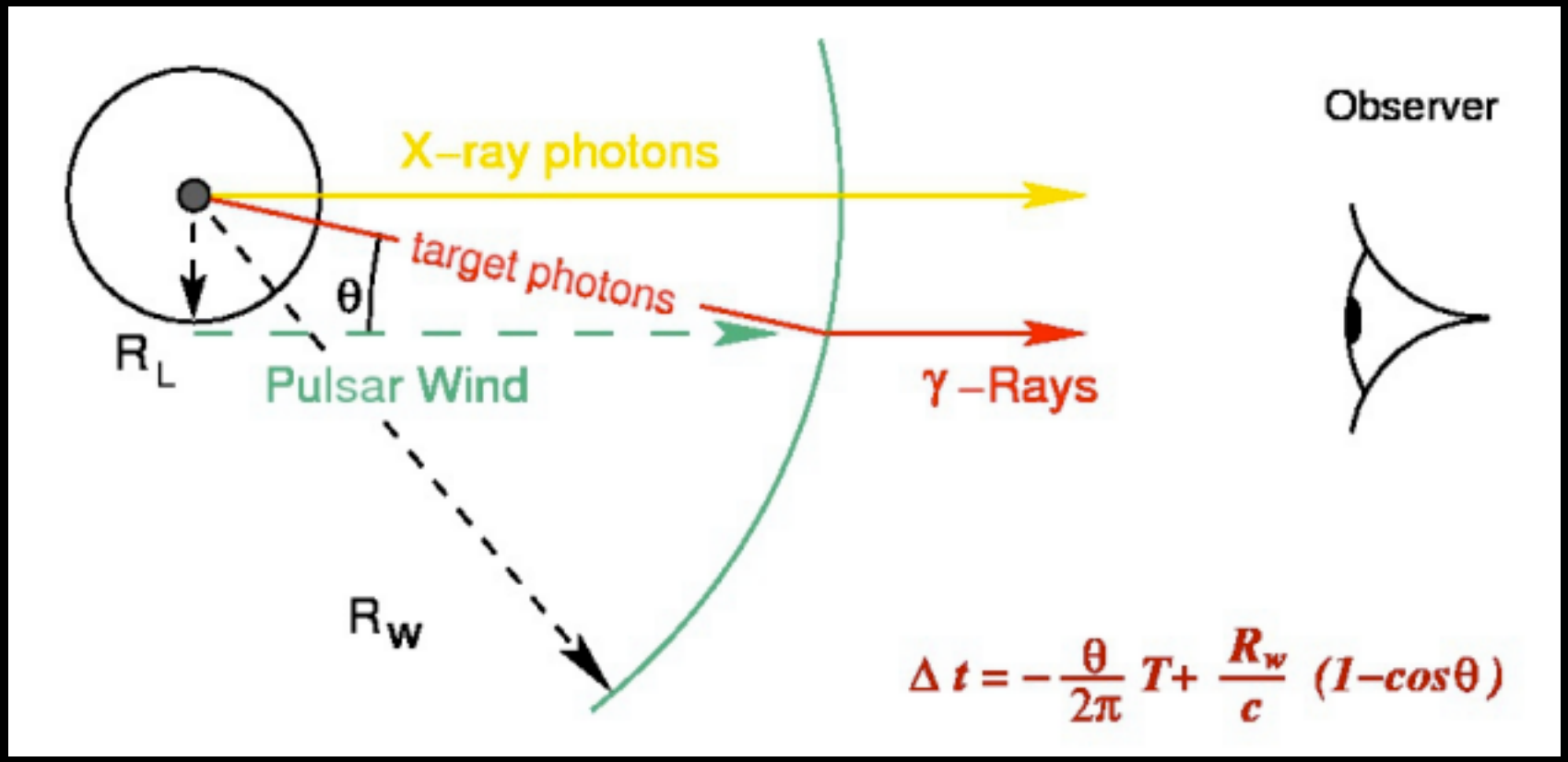
Parametrization of the wind :

$\Gamma(R) = \Gamma_o + (\Gamma_w - \Gamma_o)((R - R_o)/R_f - R_o))^{\alpha}$

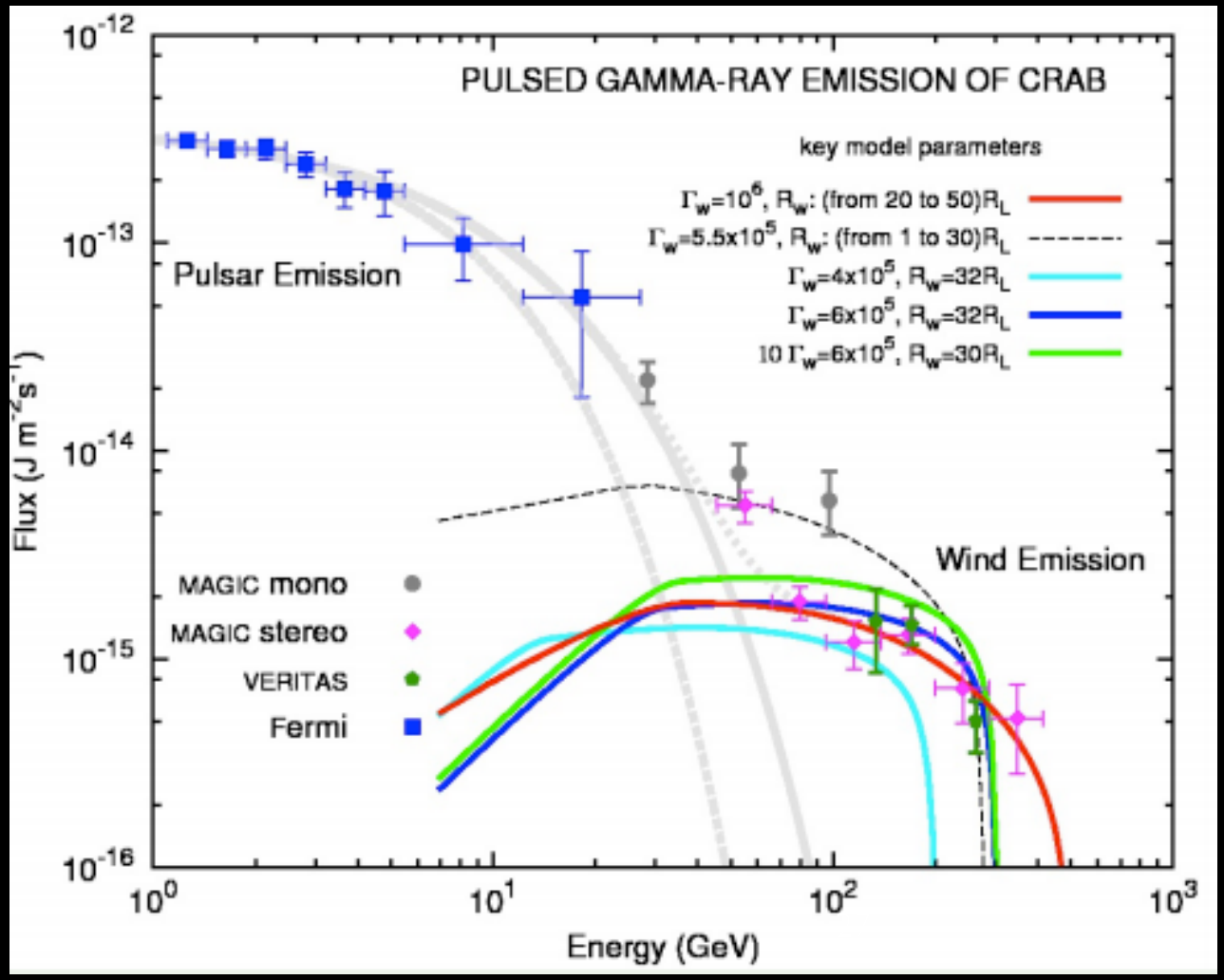
IC of accelerated electrons with pulsed X-ray pulsed photons

PULSAR WIND MODEL

- The X- and gamma-ray signals are perfectly synchronized if the wind is formed NOT very close to the pulsar and NOT very far



PULSAR WIND MODEL



- ★ abrupt acceleration in 30-50 RLC
- max $\Gamma \approx 5\times10^5$
- Ecut ~ 500 GeV

IMPLICATIONS

$P_{ac} = P_c$

$E_{max} \sim \eta^{3/4} R_c^{1/2}$

$\gamma_{max} \sim \eta^{1/4} R_c^{1/2}$

⋆E=2 TeV → Γ e=5x10^6

CURVATURE

- Impossible to reach such energy via synchro-curvature mechanism ($R_c \sim 200\ R_{LC}$!)

$B_{Crab}=10^{6\text{-}9}$G

$R_c = \xi\ R_{lc} = \xi\ cP/(2\pi$ [illegible] $_{ns}(R_{ns}/R)^3$

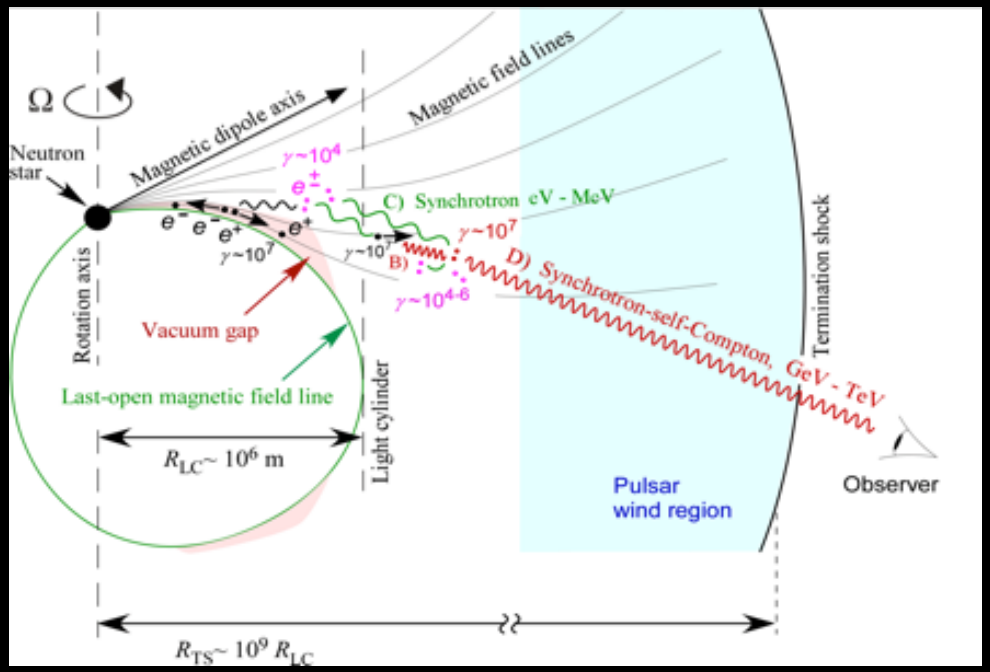
$E_{max} = (3\pi)^{7/4}$ [illegible] $(ce)^{3/4}\ \eta^{3/4}\sqrt{(\xi)}$ [illegible] $_s^{3/4} R_{ns}^{9/4}/P^{7/4}$

E_m [illegible] $0.2\ \eta^{3/4}\sqrt{(\xi)}$ TeV -> $\xi \sim 200$!!!!!

IMPLICATIONS

SSCOMPTON

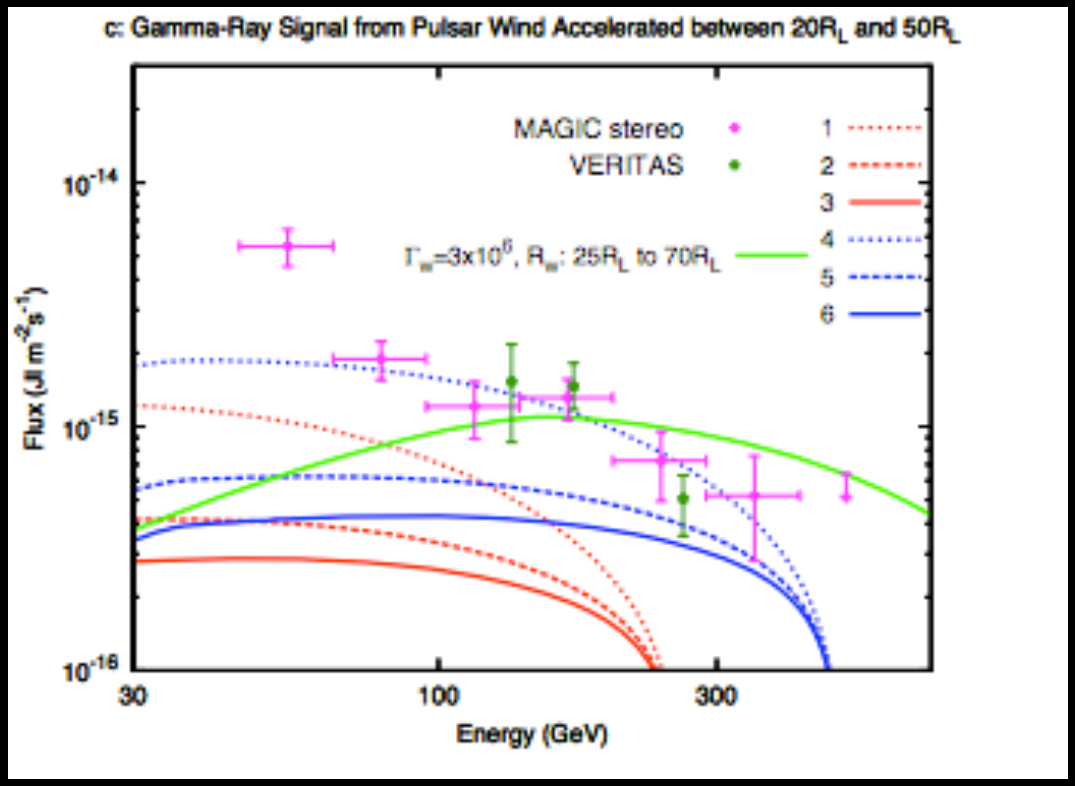
- Looking at the peak positions:
  $\Delta t \sim 62 \pm 34$ μs → $d = c\Delta t \lesssim 80$ km (in 10^3 km)
  The regions of GeV and TeV emission should be similar, imposing serious challenges to SSC model



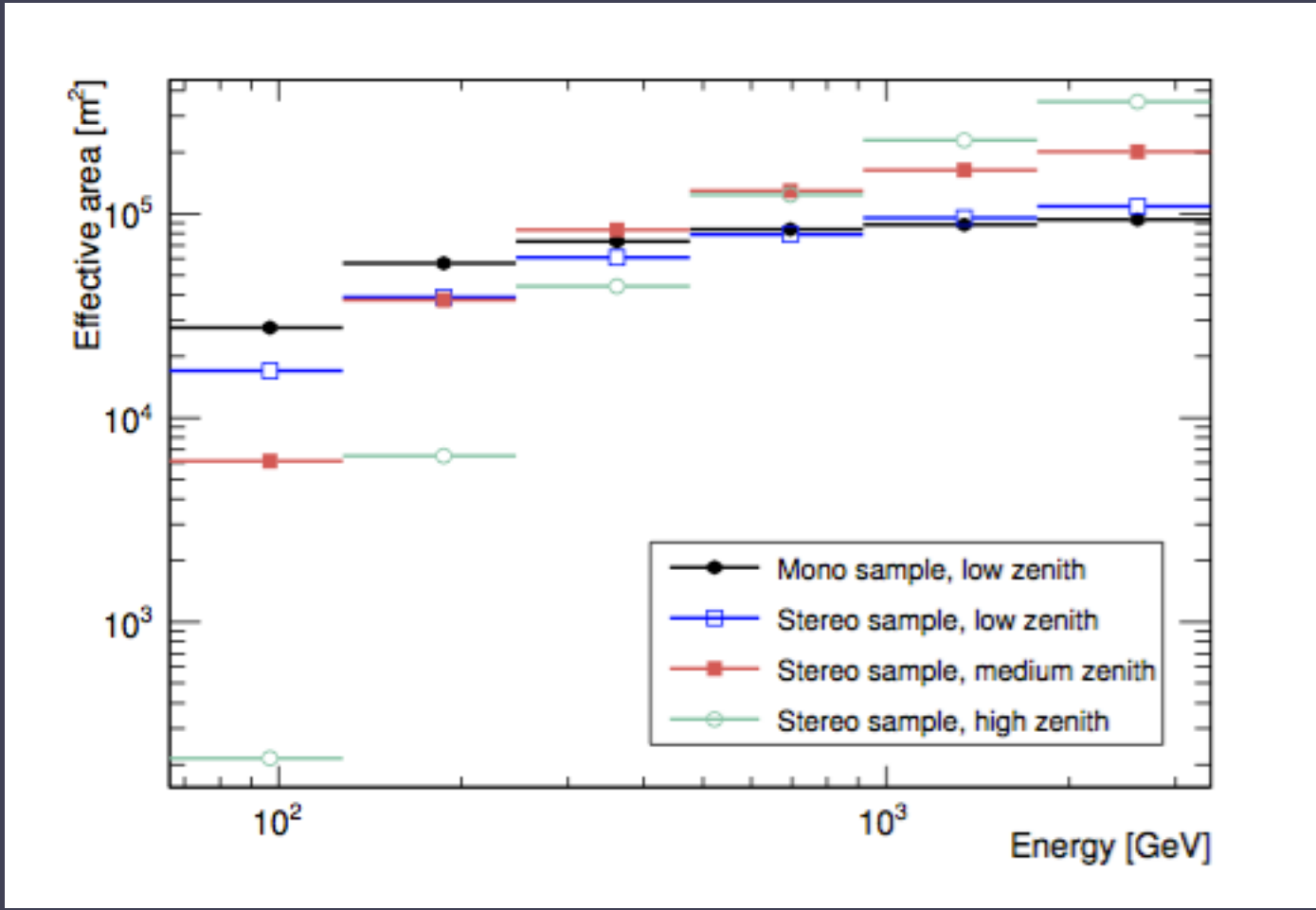
IMPLICATIONS

WIND MODEL

- Peaks narrow down (beaming?) and E_{max} reached impossible to explain at 20-50 RLC. Larger distance implies a distortion on the LC and bad fit

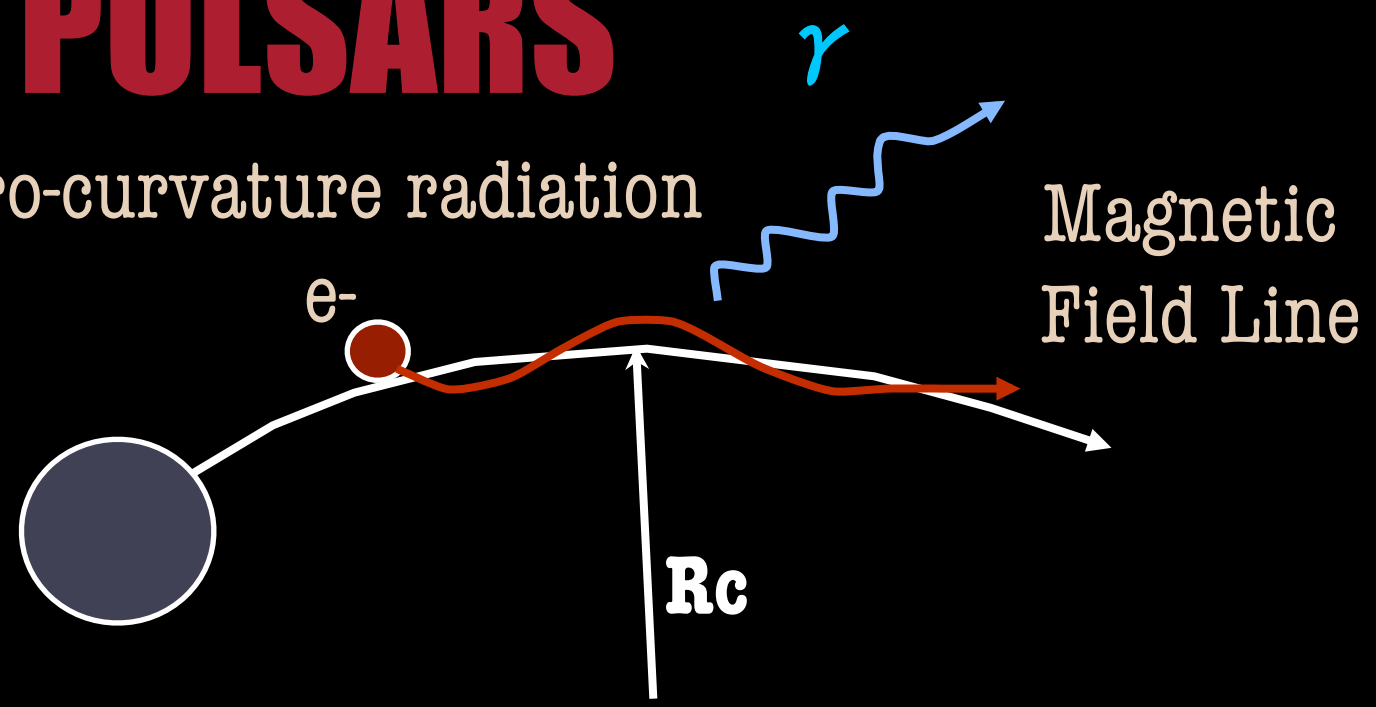


- 19 Sub-samples: April 2007 to 2014



LAT PULSARS

Synchro-curvature radiation



- ★ Acceleration in gaps :
  $P_{ac}=ec\,\eta\,B$ (where $E=\eta\,B$)
- ★ Curvature energy loses:
  $P_c=2/3\ e^2/c\ \gamma_b^4(c/R_c)^2$
- ★ K-N loses in IC :
  $P_{IC}=4/3\ (m_e c^2/e_t)^2\ U_t\ \sigma_T c = 4/3\ \gamma^2 U_t\,\sigma_T c$

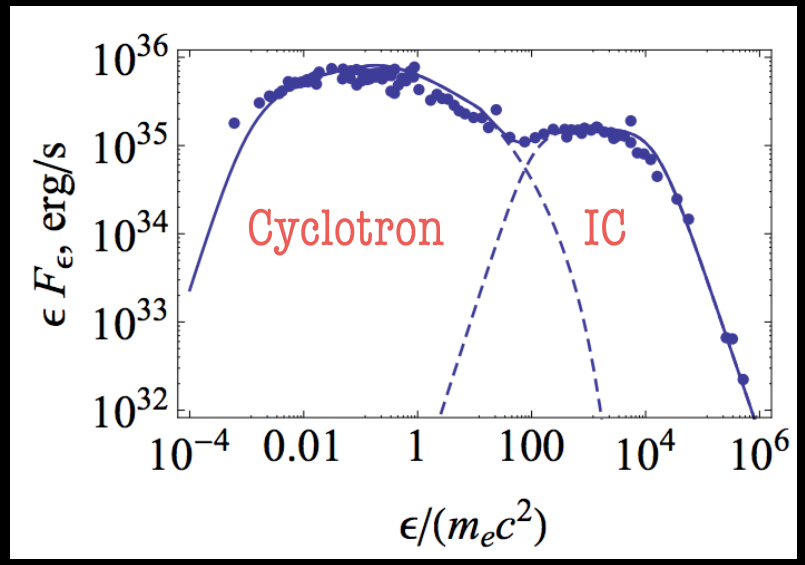
$$P_{ac} = P_c$$
$$E_{max} \sim \eta^{3/4} R_c^{1/2}$$
$$\gamma_{max} \sim \eta^{1/4} R_c^{1/2}$$

BACKGROUND

The cuts are computed using a background sample and Monte Carlo, by maximizing in each energy bin the so-called Q-factor, defined as: $Q=\varepsilon_{on}/\sqrt{\varepsilon_{off}}$, where ε_{on} and ε_{off} are the cut efficiency for on and off data, respectively. For the cuts computation, we impose that at least 50% of the Monte Carlo events survive the cuts.

IMPLICATIONS

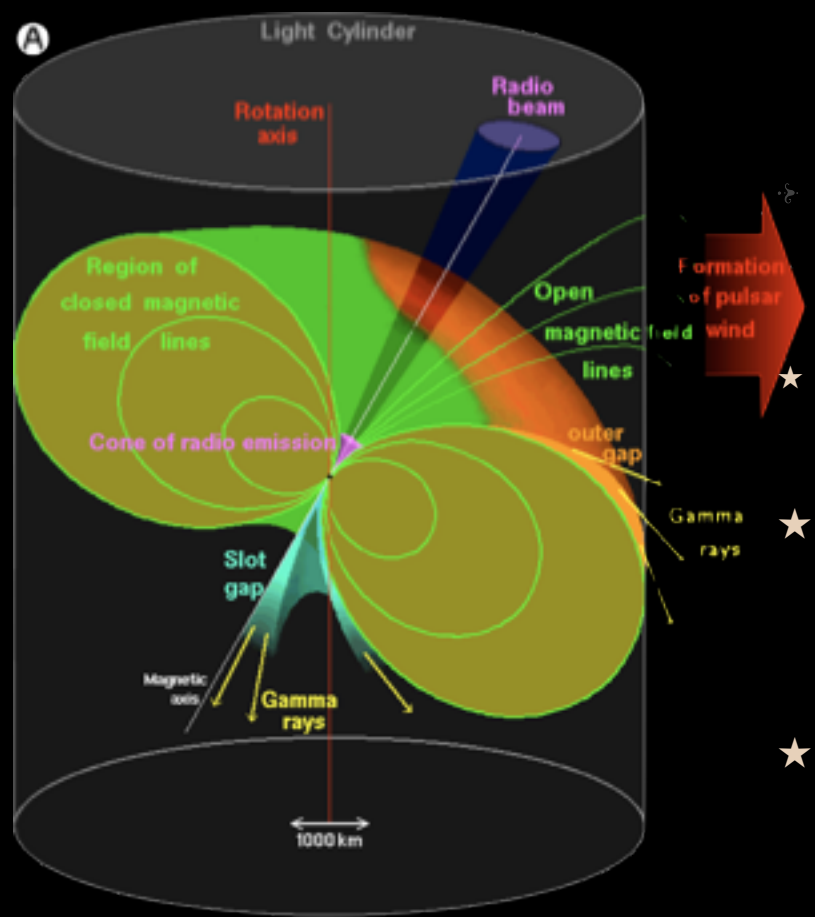
- $E \sim TeV$ emitted by a population of electrons with $\Gamma_e \sim 5x10^6$
- Impossible to reach such energy via synchro-curvature mechanism ($R_C \sim 200\ R_{LC}$!) -> Inverse Compton off soft photon fields
  - In the magnetosphere?



Lyutikov 2012

- Primary e+ up scattering UV photons to GeV-TeV energies
- <u>Problem:</u> gamma-gamma absorption & suppression of synchro-curvature emission

PULSARS E>1 GEV



- Energy loss due to slowing down ($dP/dt < 0$) called spin down luminosity/power

  In the equatorial plane

- $B \approx 3.8 \times 10^{12} (P/P_{Crab})^{1/2} (\dot{P}/\dot{P}_{Crab})^{1/2}$ G
- The rotation induces in poles: $\Delta\Phi \approx 4 \times 10^{16} (\dot{P}/\dot{P}_{Crab})^{1/2} (P/P_{Crab})^{-3/2}$ V
- Such $\Delta\Phi$ would remove particles from the surface and fill up a magnetospheric plasma

BEYOND THE MAGNETOSPHERE

- Relativistic wind is described by the magnetization parameter

  $\sigma \equiv$ Poynting flux/kinetic energy flux
  $= B^2/4\pi\rho\Gamma c^2$

- Close to LC: Energy is contained in the fields while the plasma total energy density remains small (σ<<<1)

- Termination shock (TS) is formed when the wind finds the slowly expanding nebula $P_{pw}=\dot{E}/4\pi R^2_s c=p_{ext}$ (σ>>>1)

- Lorenz factor before the TS: $10^4<\Gamma<10^7$

- Dark, relativist plasma-> Not observed!