Generation of VHE pulsed radiation by the pulsar wind from Crab

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Generation of plasma in the pulsar magnetosphere

Vacuum pulsar magnetosphere is unstable in relation to the pair production.

- Development of instability can result into a few solutions: inner gap, slot gap and outer gap.
- Recent observations (Fermi observatory) show that only the outer gap model suvive in the competition

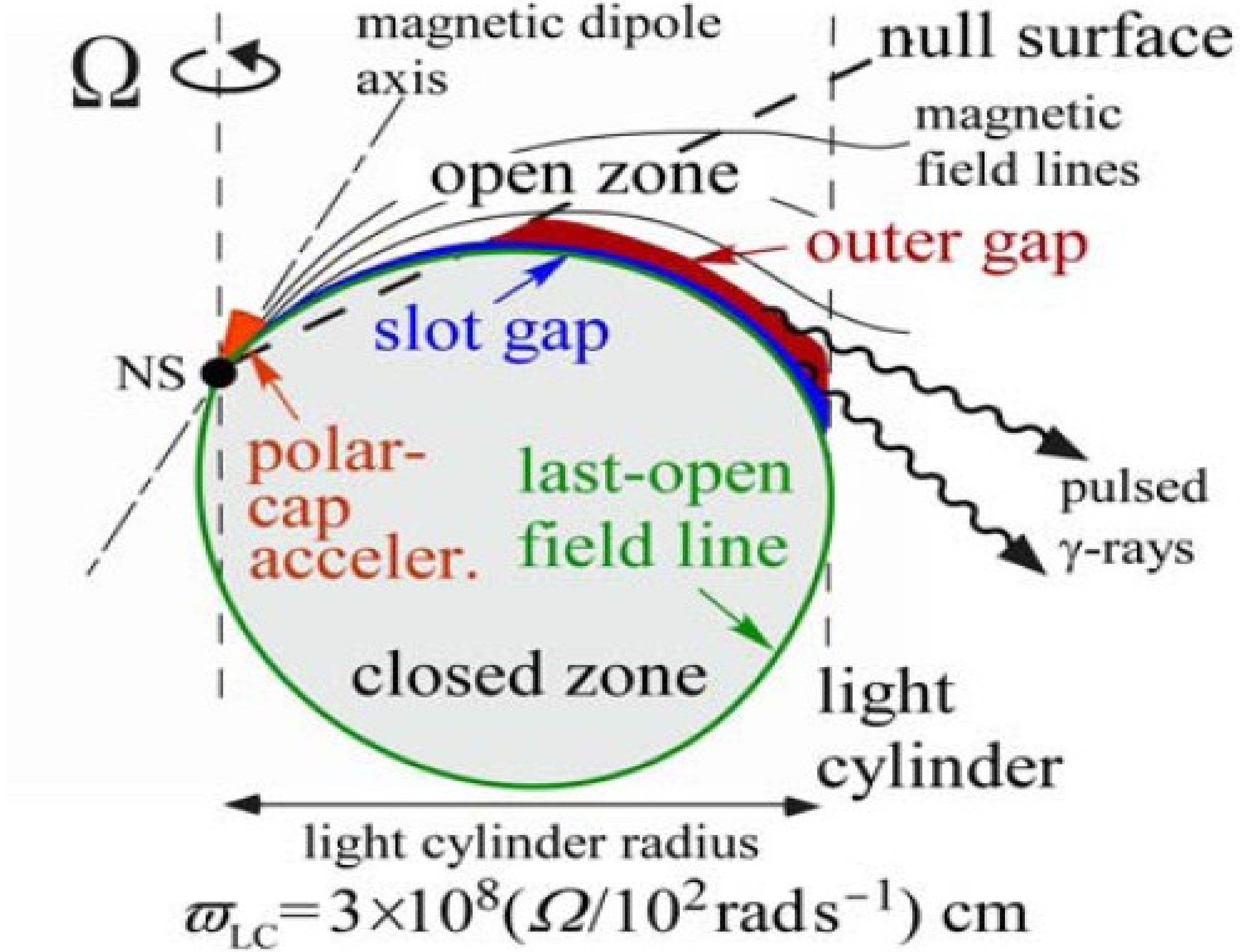
Outer gap model

Hirotani, 2008

Open

Astronomy

Journal



Properties of the wind at the light cylinder

1. Density of the particles >> Goldreich density

This provides sufficient electric charges to screen electric field. The condition

2. The energy flux of the wind is much less the total spin down losses of pulsars.

For Crab σ =Lmag/Lkin ~ 10^3.

Almost all spin down energy is carried out by electromagnetic field frozen into the plasma.

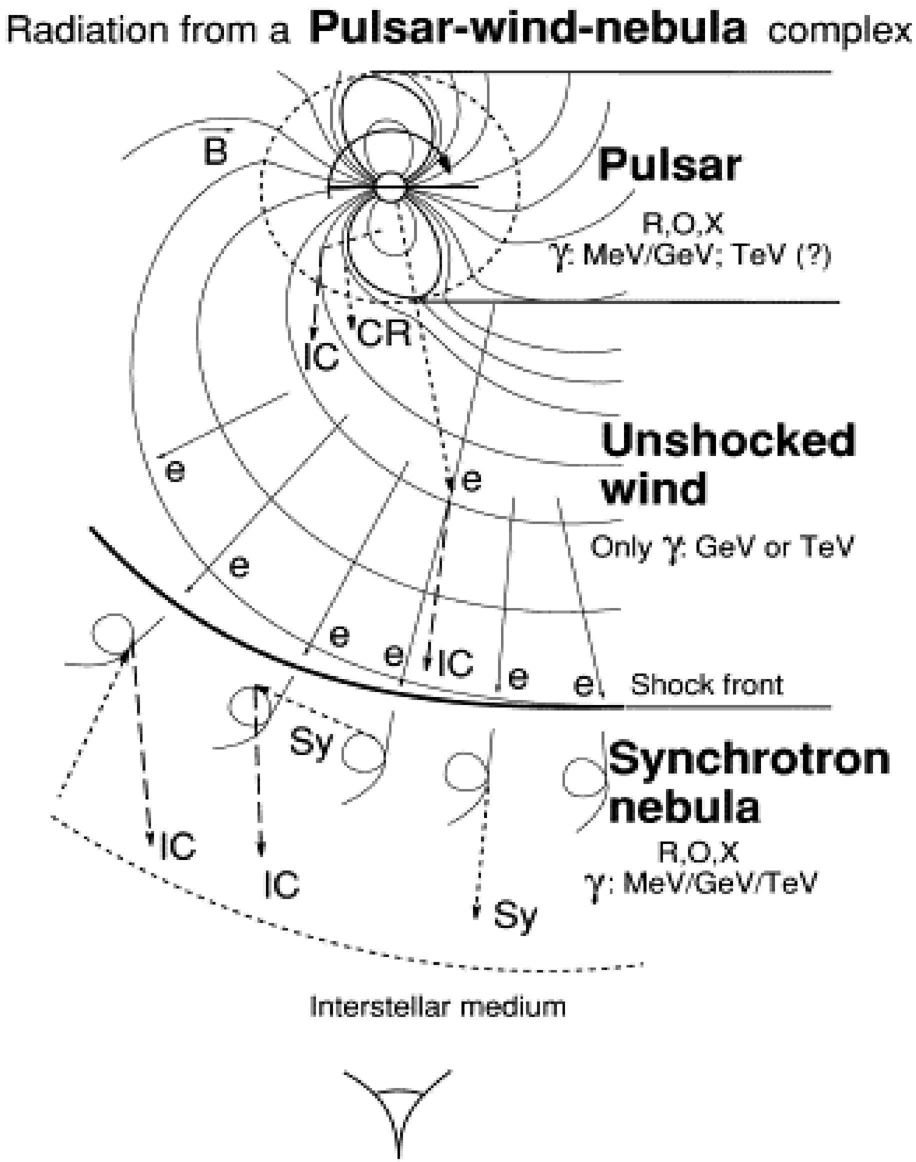
The nature of the energy flux in the wind.

The conventional approach in the text books – the pulsars loss energy due to magnetodipole radiation. Incorrect!

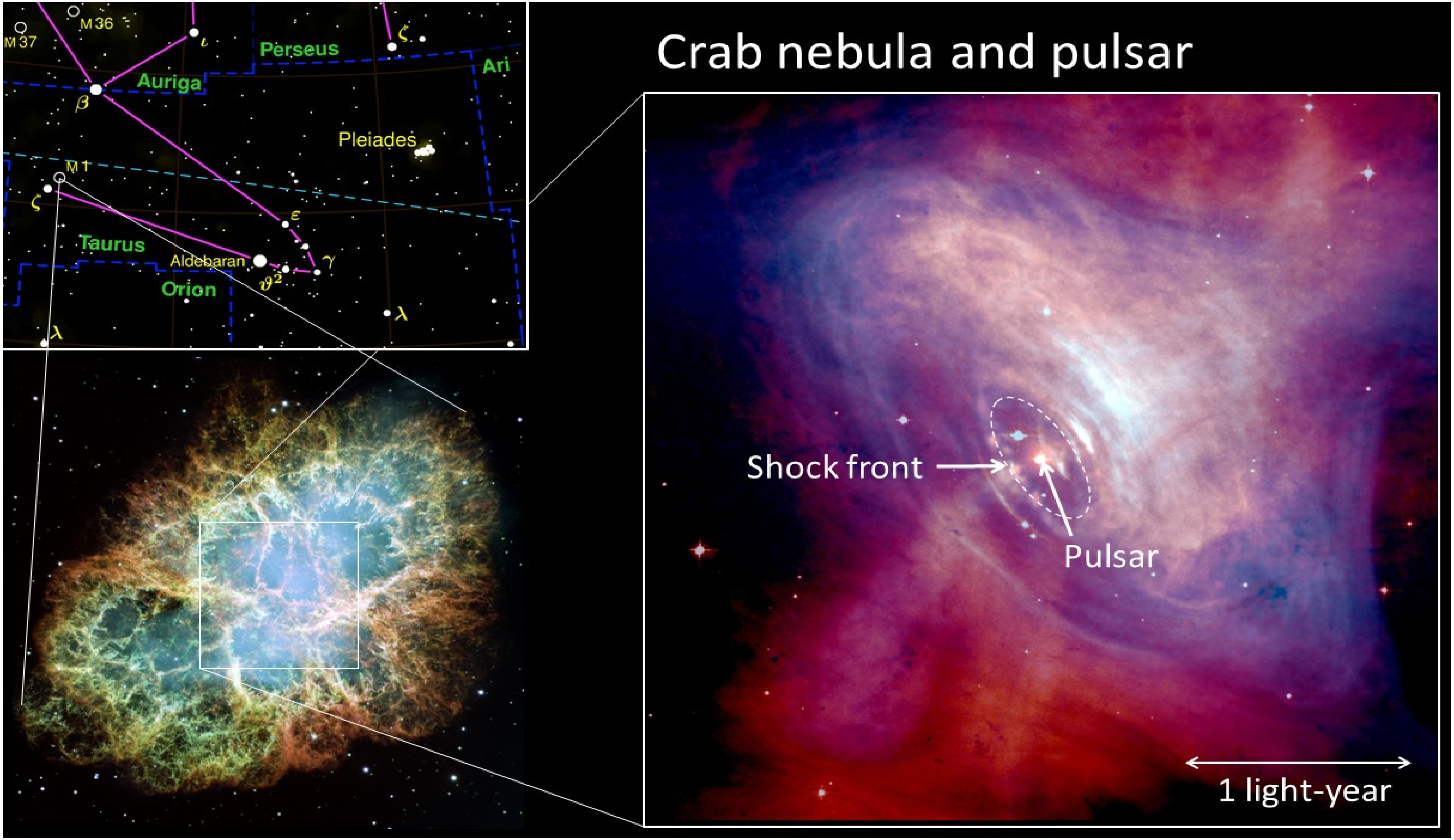
$\omega_{pe} >> \Omega$, The plasma of the wind screens the magnetodipole radiation. Magnetodipole radiation is impossible.

The electromagnetic field is frozen into the plasma. Energy flux is in the form of the Poynting flux

Structure of the magnetic field in the pulsar wind beyond the light cylinder

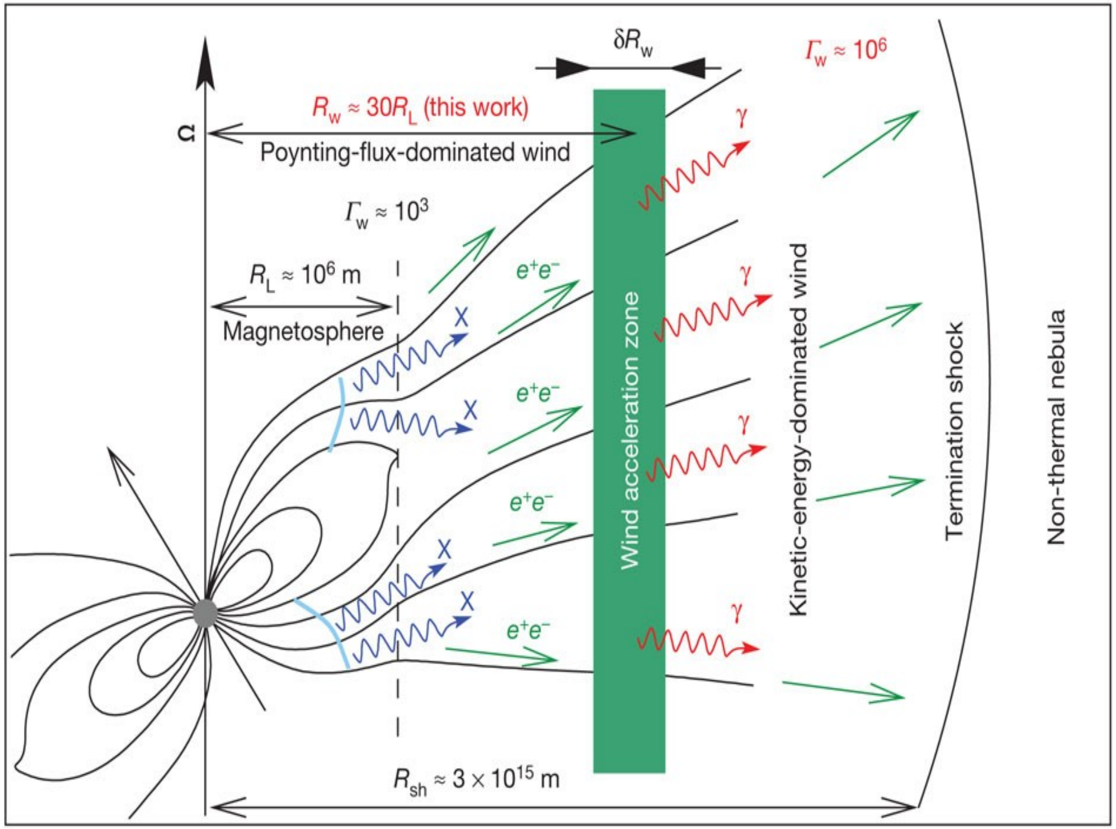


Observational signatures of the wind



Characteristics of the wind at the preshock zone.

The observational properties of the wind are well explained provided that the magnetization of the wind $\sigma \sim 3\ 10^{-3}$ (Kennel & Coronity, 1984).



This conclusion is very strong

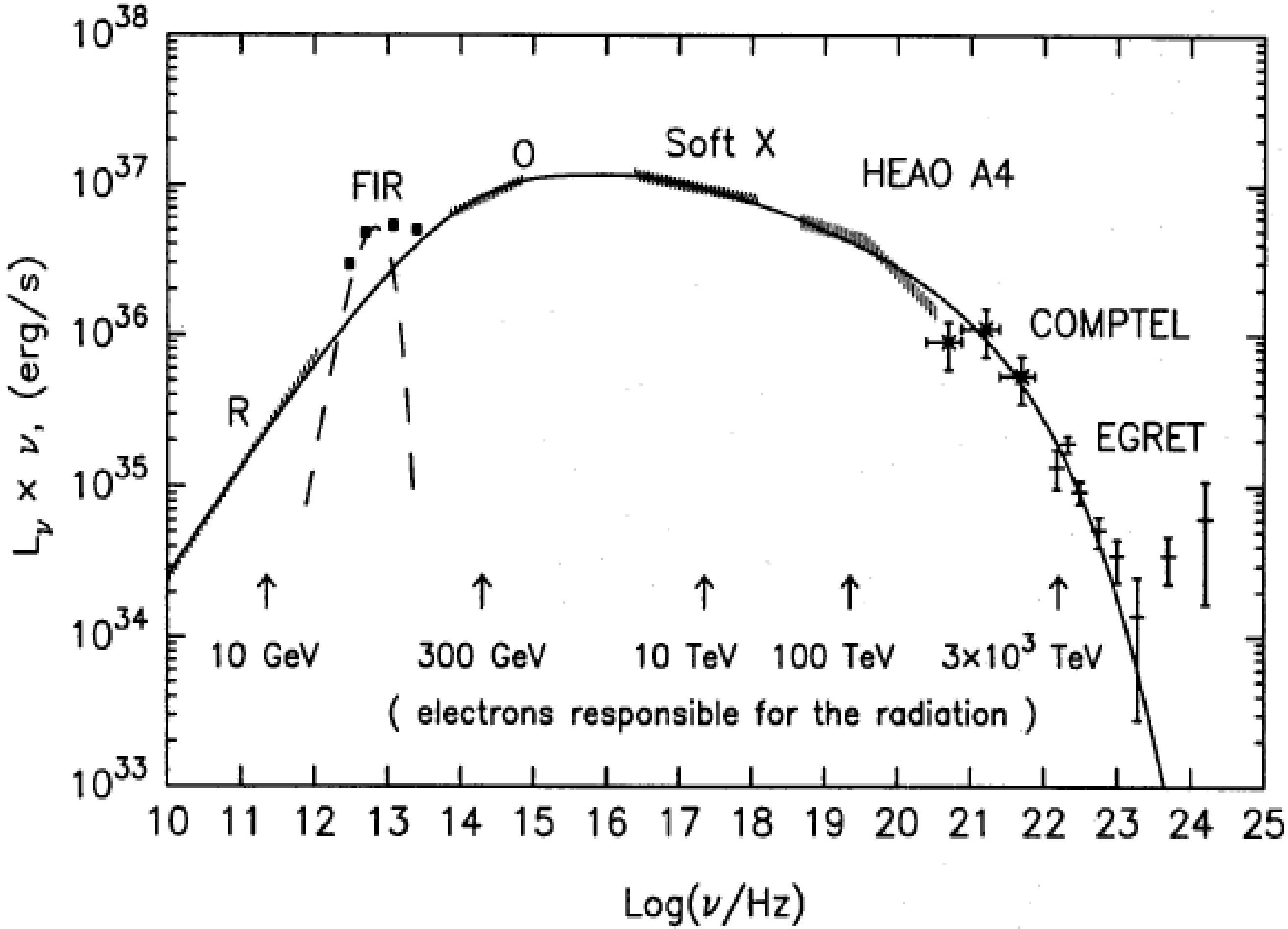
Spectra of radiation from Crab nebula

Atoyan&

Aharonian,

MNRAS,

1996



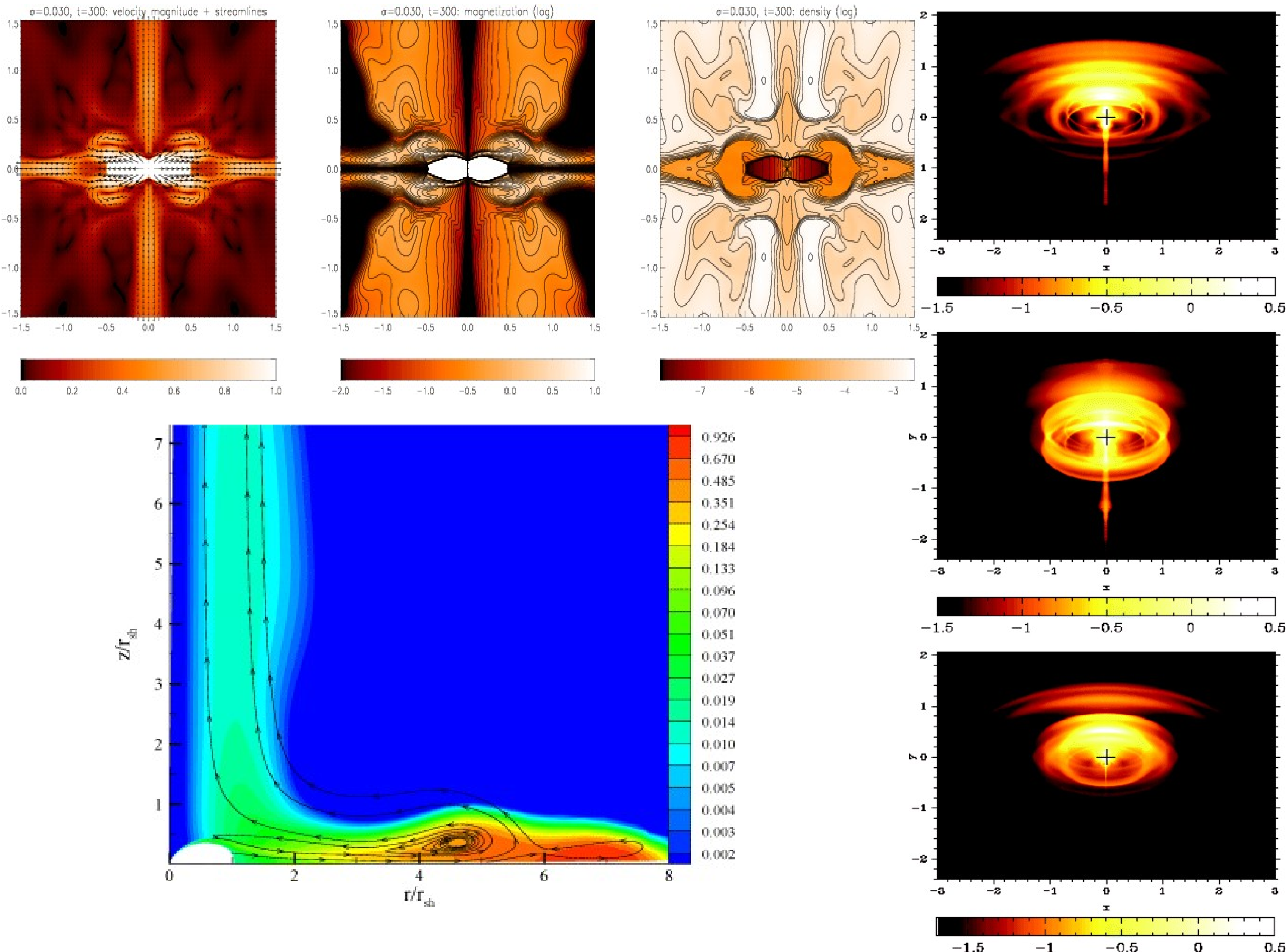
Modelling of interaction of low σ wind with interstellar medium

Lyubarskii & Komissarov, MNRAS, 2004

Bogovalov et all. , MNRAS, 2005

Del Zanna, Amato, Bucciantini, 2004

Spacial structure of the Crab nebular is well reproduced provided that $\sigma \sim 3\ 10^{-3}$ at the preshock zone



σ=0.030, t=300: velocity magnitude + streamlines
σ=0.030, t=300: magnetization (log)
σ=0.030, t=300: density (log)
z/r_sh
r/r_sh
0.926
0.670
0.485
0.351
0.254
0.184
0.133
0.096
0.070
0.051
0.037
0.027
0.019
0.014
0.010
0.007
0.005
0.004
0.003
0.002
x
y

Evident contradiction between theoretical predictions and observations.

1. The wind actually is accelerated to $\sigma > 1$ in the magnetosphere (contradicts to observations).
2. $\sigma \sim 10^3$ in the preshock region and transformation of the Poynting flux into kinetic energy occurs in the nebula (is developing by Yu. Lyubarskii)
3. $\sigma \sim 10^3$ at the light cylinder and is transformed into $\sigma \sim 10^{-3}$ somewhere between the light cylinder and the termination shock. (conventional point of view). But no conventional theory of transformation of the Poynting flux into kinetic energy of the wind exist!

General problem of modern astrophysics

Theory of gamma-ray bursts, jets from AGN need reliable mechanism of transformation of the Poynting flux into kinetic energy of bulk motion of plasma.

How to obesrve invisible wind in the region between the light cylinder and termination shock.

Wind is cold (because we do not observe any signal from the wind). No synchrotron radiation.

The magnetic field is advected together with plasma with Lorenz factor ~ $10^{(3\text{-}6)}$.

The wind produces VHE via Inverse Compton scattering of the soft radiation from the pulsar

Bogovalov & Kotov (1991, JETP Letters) proposed Inverse Compton scattering of soft photons (ultraviolet and soft X-rays) on the electrons of the wind.

This mechanism gives detectable fluxes of TeV gamma-ray radiation provided that the wind is accelerated right at the light cylinder

For operation of this mechanism it is sufficient that the Lorenz factor of electrons much exceeds the initial one.

Interaction of the pulsar wind with the thermal radiation.

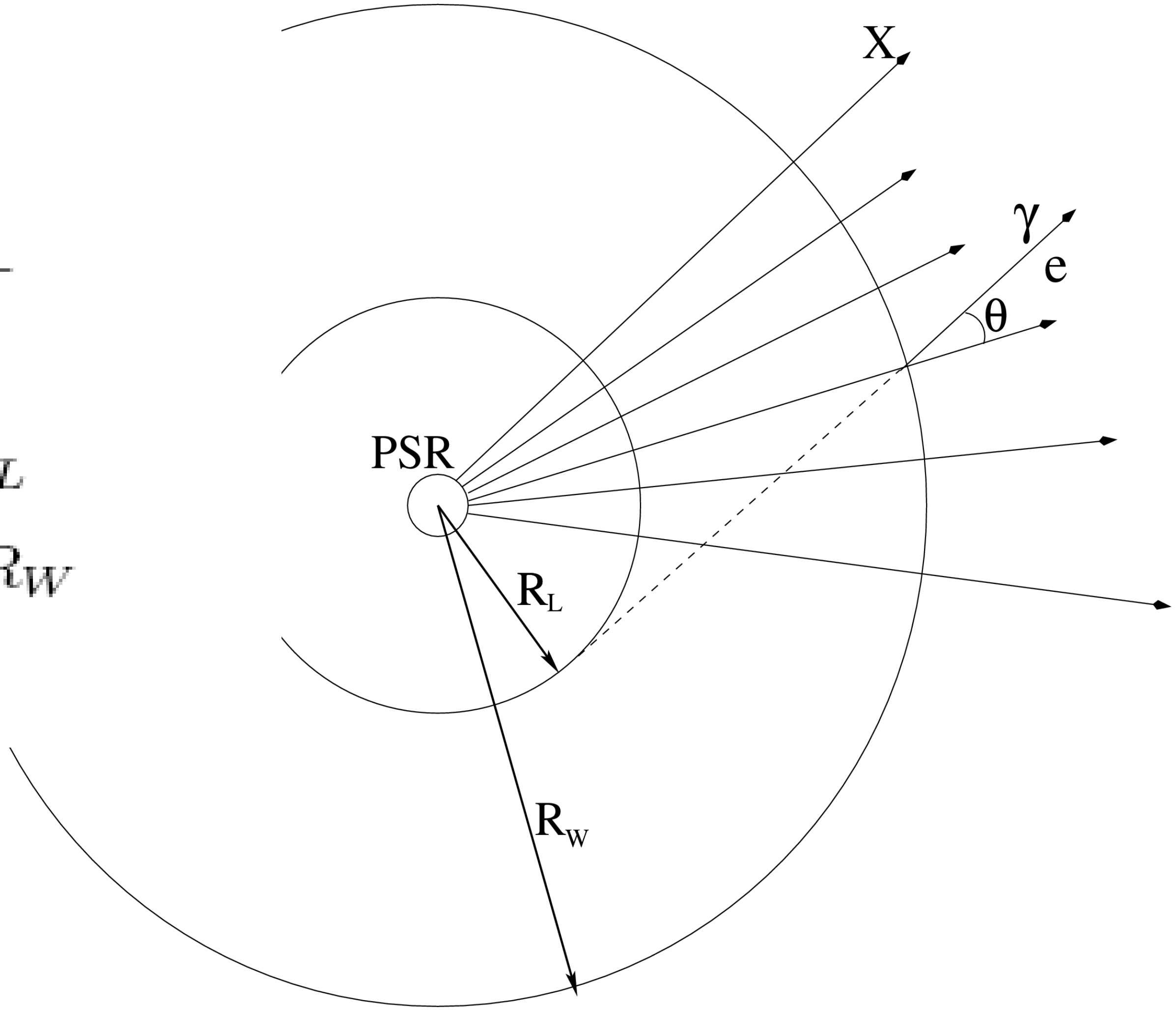
$$\dot{E} = \dot{m}\gamma c^2$$

$$\dot{L} = \dot{m}\gamma v R_\perp$$

$$\dot{E} = \Omega \dot{L}$$

$$v R_\perp \Omega = c R_L$$

$$\sin(\theta) = R_L / R_W$$



Bogovalov & Aharonian (2000, MNRAS)

Interaction of the pulsar wind with the nonthermal X-rays of the pulsar results into pulsed TeV radiation with the light curve close to the light curve of X-rays.

Prediction:

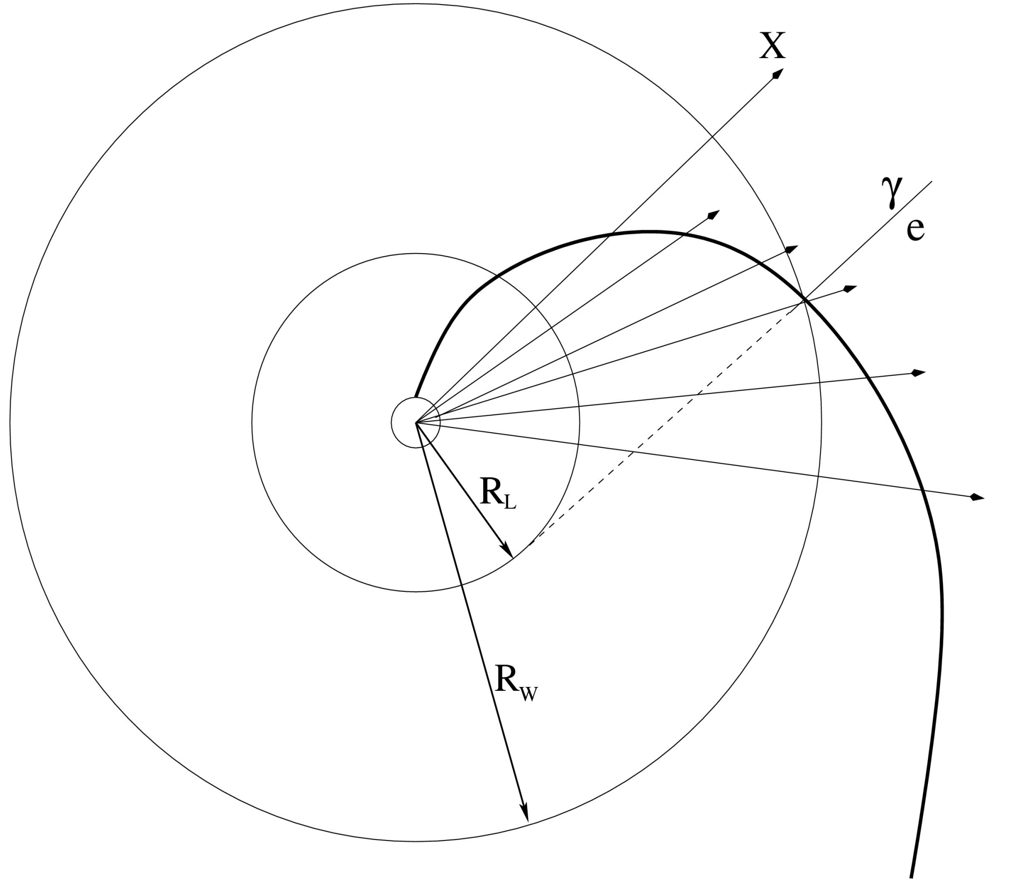
This radiation could be detectable provided that the acceleration of the wind occurs in the limits of 50 light cylinders.

Mechanism of the pulsed radiation production.

Delay in signal arrival

$$\Delta t = -\frac{\theta}{2\pi} + \frac{R_w}{c}(1 - cos(\theta))$$

$$\Delta t \approx -\frac{T}{4\pi}(\frac{R_L}{R_W})$$



Year 2011.
Pulsed gamma-radiation above 100 GeV is discovered by VERITAS (Aliu,2011).
Pulsed gamma-radiation above 25 GeV is discovered by MAGIC(Aleksic,2011).

Hirotani, 2008

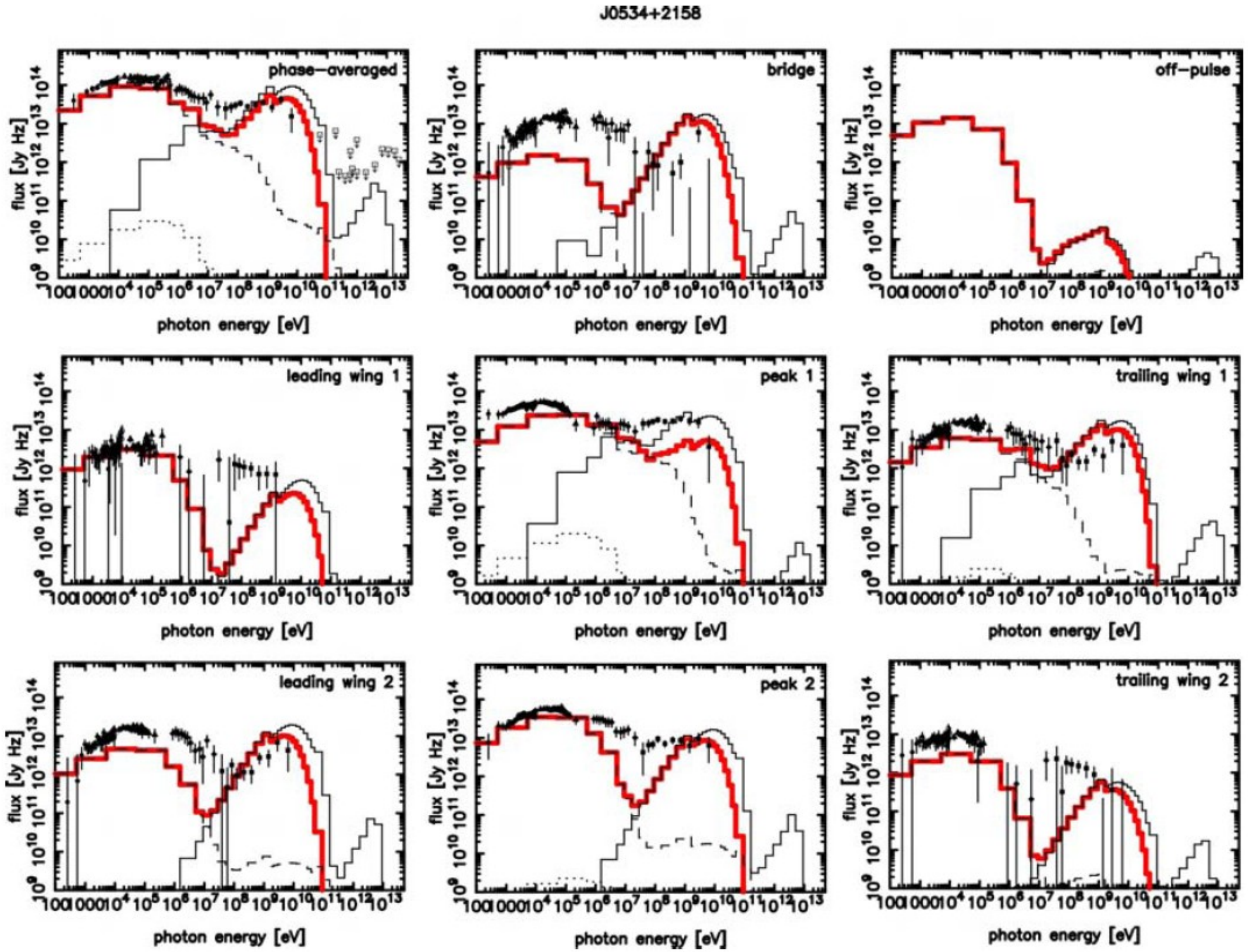
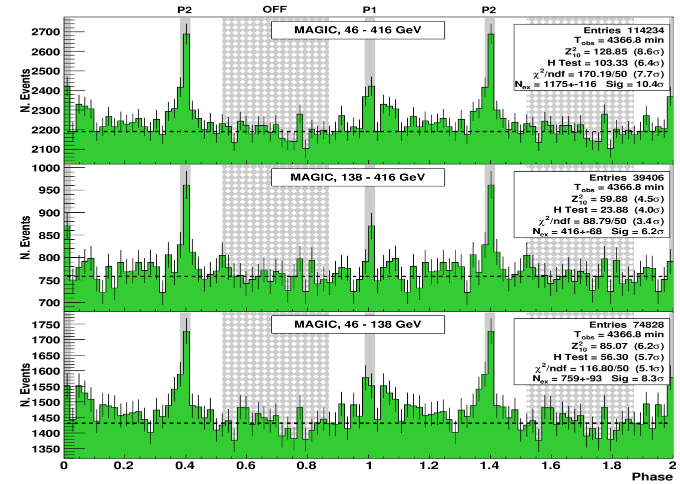
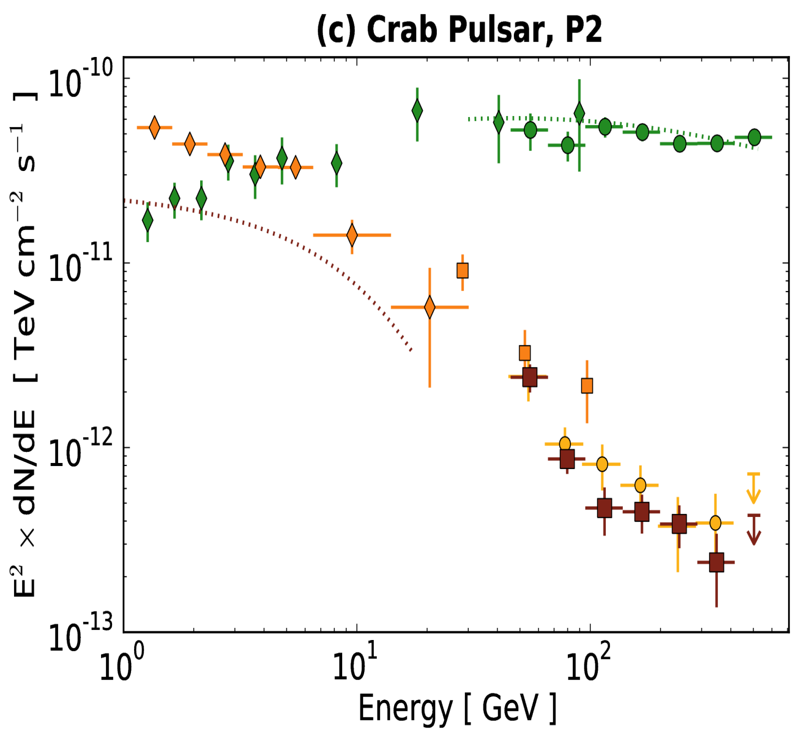


Fig. (9) Phase-averaged (top left) and phase-resolved (others) spectrum of the pulsed emission from the Crab pulsar. The thin solid, dashed, and dotted curves denote the un-absorbed photon fluxes of primary, secondary, and tertiary components, respectively, while the thick red solid one presents the spectrum to be observed, including absorption along the line of sight. Interstellar absorption is not considered. The filled circles (LECS), open circles (MECS), filled triangles (PDS) denote the Boppo SAX observations, while the open triangle the Gamma-ray Imaging Spectrometer (GRIS), and inverse filled triangles (OSSE), diamonds (COMPTEL), and filled squares (EGRET) denotes the CGRO observations. Data points are from Kuiper et al. (2001) [http://www.sron.nl/divisions/hea/kuiper/data.html]. In the top left panel, upper limits by ground-based observations are also plotted above 50 GeV.

Characteristics of the radiation.

1. Pulses of radiation well in phase with the radiation at lower energies.
2. Spectra lasts at least to 400 GeV and apparently is not a simple exponential continuation of the Fermi spectra.



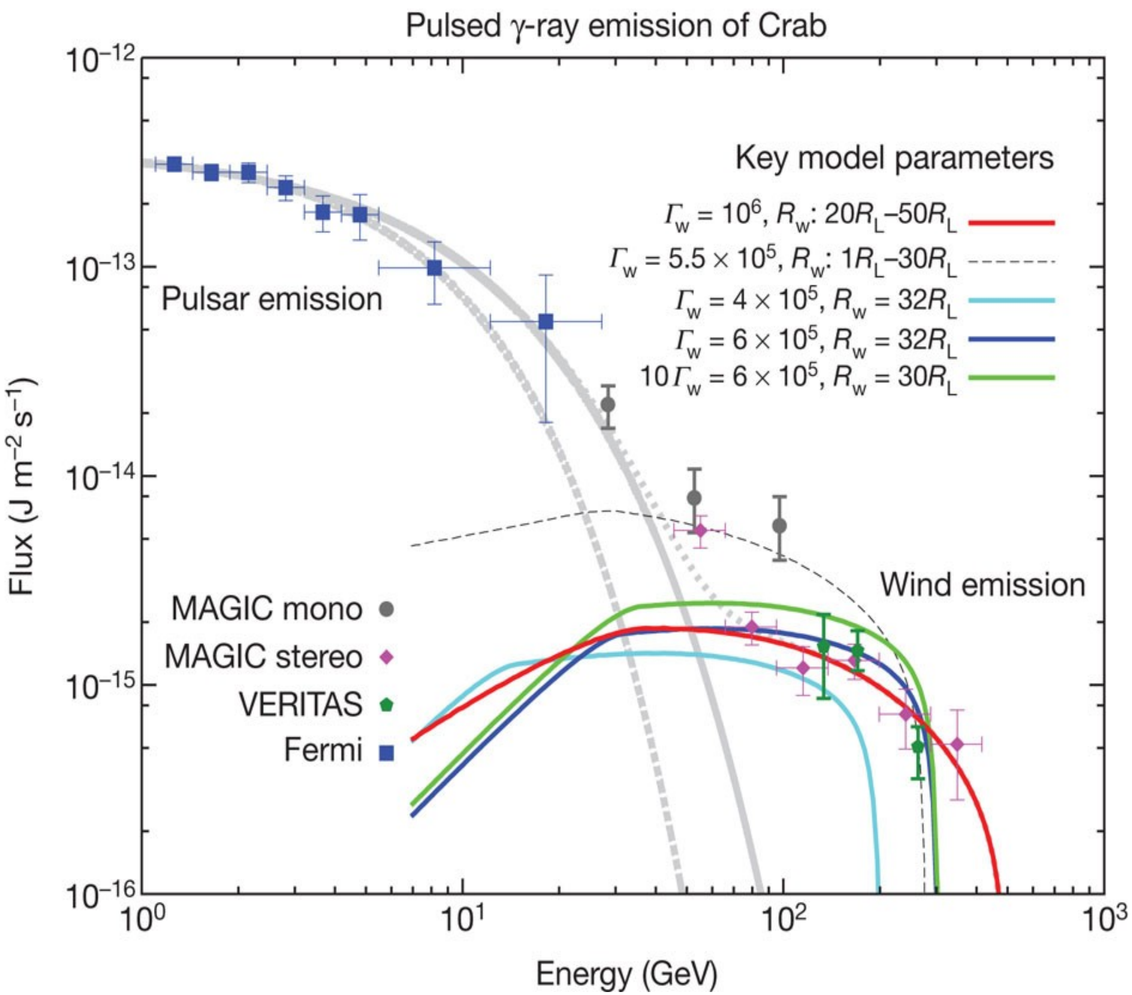


The most natural explanation.

Pulsed VHE gamma-radiation observed by MAGIC and VERITAS can be naturally explained as the result of ICS of the pulsed X-ray radiation of the pulsar on the accelerated wind.

The new observations allow us to estimate parameters of the wind: site of the acceleration and Lorenz factor of the wind.

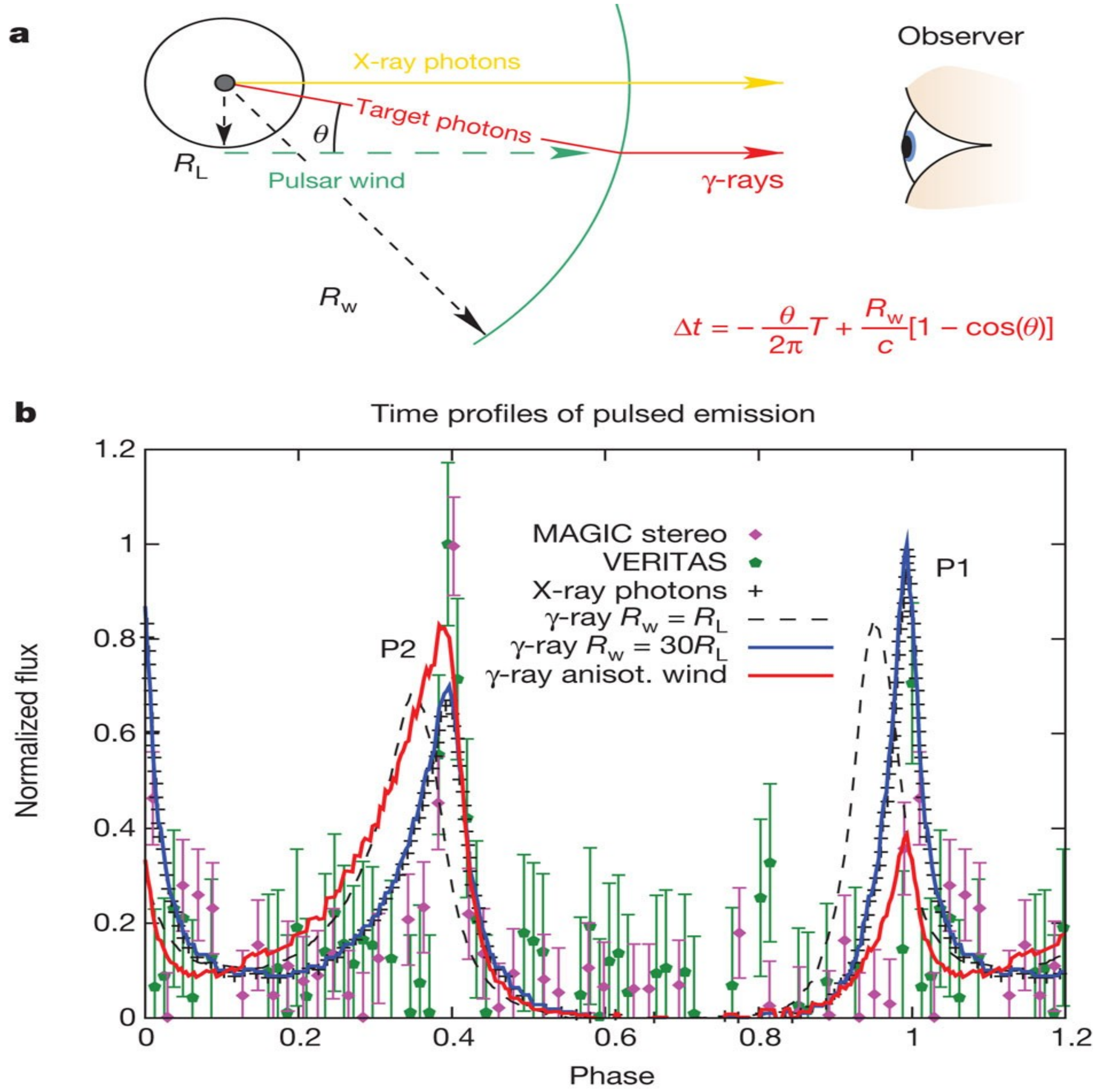
Spectral energy distribution of γ-ray radiation produced by the pulsar magnetosphere and by the pulsar wind.



FA Aharonian *et al*. *Nature* **000**, 1-3 (2012) doi:10.1038/nature10793

nature

Formation of the pulsed VHE inverse-Compton γ-ray signal in the wind of the Crab pulsar.



nature

Conclusion

Interpretation of the pulsed VHE radiation from Crab as the signal from the cold ultrarelativistic wind of Crab provide us the Lorenz factor of the wind $(0.5\text{-}1)10^6$ and the site of the acceleration, 20-50 light cylinders.

This imposes rather strong limitations on the mechanisms of the wind acceleration.