ON THE GAMMA-RAY EMISSION FROM THE CRAB NEBULA

Włodek Bednarek & Wojciech Idec

Department of Astrophysics, University of Lodz, Poland

- Variable Crab (!): Tavani et al. (2011), Abdo et al. (2011)
- How it may happen ?
- Constraints on the variable γ-ray emission region
- Expectations at TeV γ-ray energies

Summary of observations

A few day outbursts (Oct. 2007; Feb. 2009; Sep. 2010; Apr. 2011) → sub-day structures

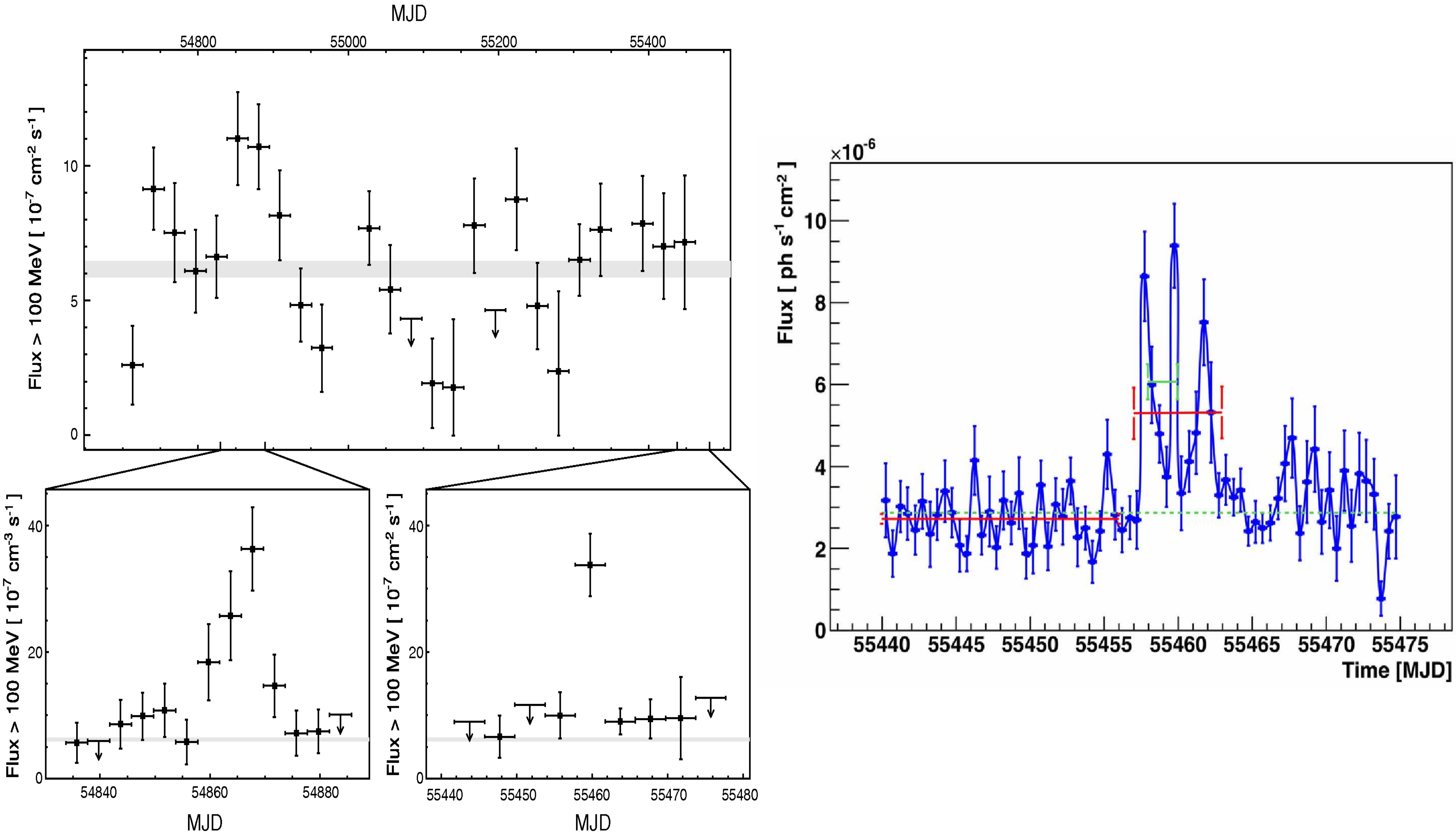


Figure 1: Gamma-ray light curves: left - Abdo et al. (2011); right - Balbo et al. (2011)

Crab GeV γ-ray spectrum (Abdo et al. 2011):

flux increases (a factor of a few), spectrum flattens (2.7 ± 0.2)

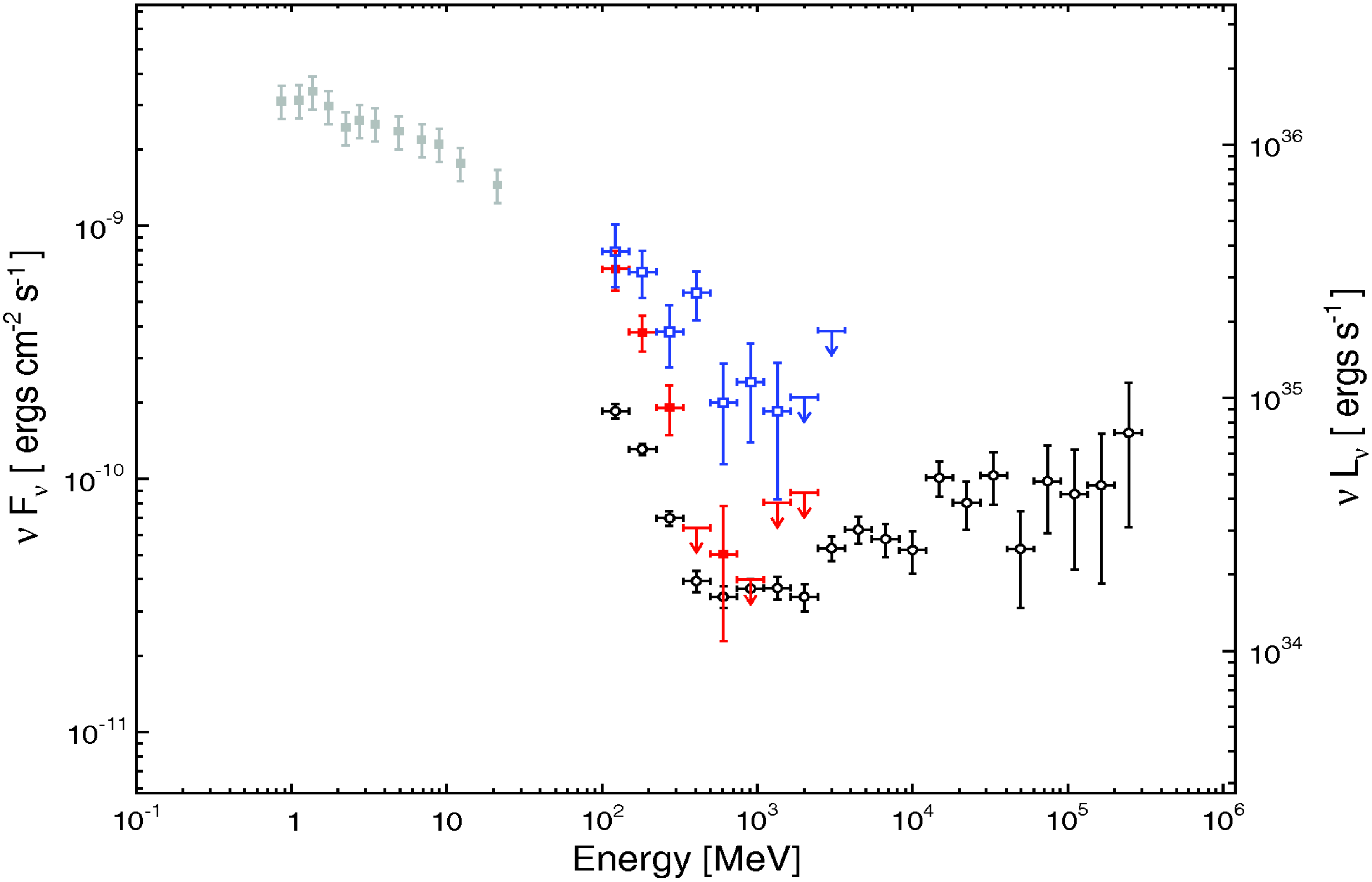


Figure 2: From Abdo et al. (2011).

What do you observe ?

- Two component spectrum: steady emission from the Crab Nebula + flickering component in the inner nebula

Considered by Tavani et al. (2011) and Vittorini et al. (2011)

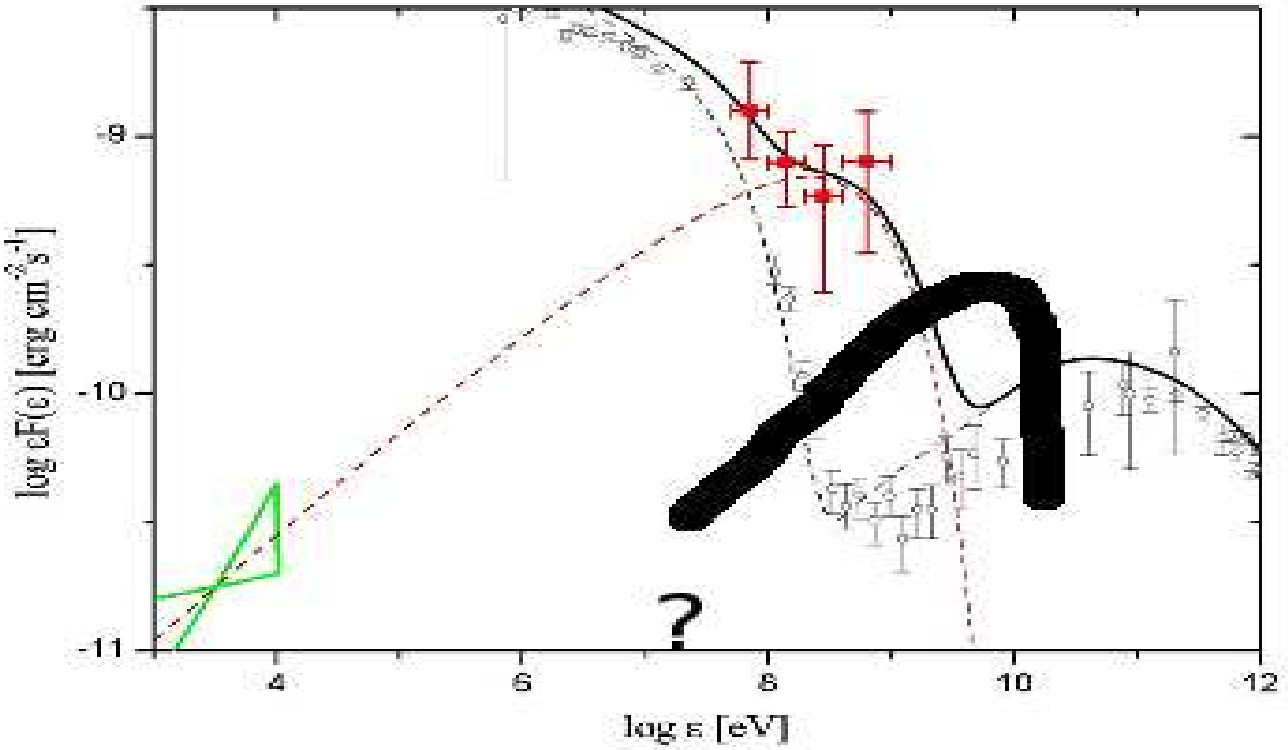


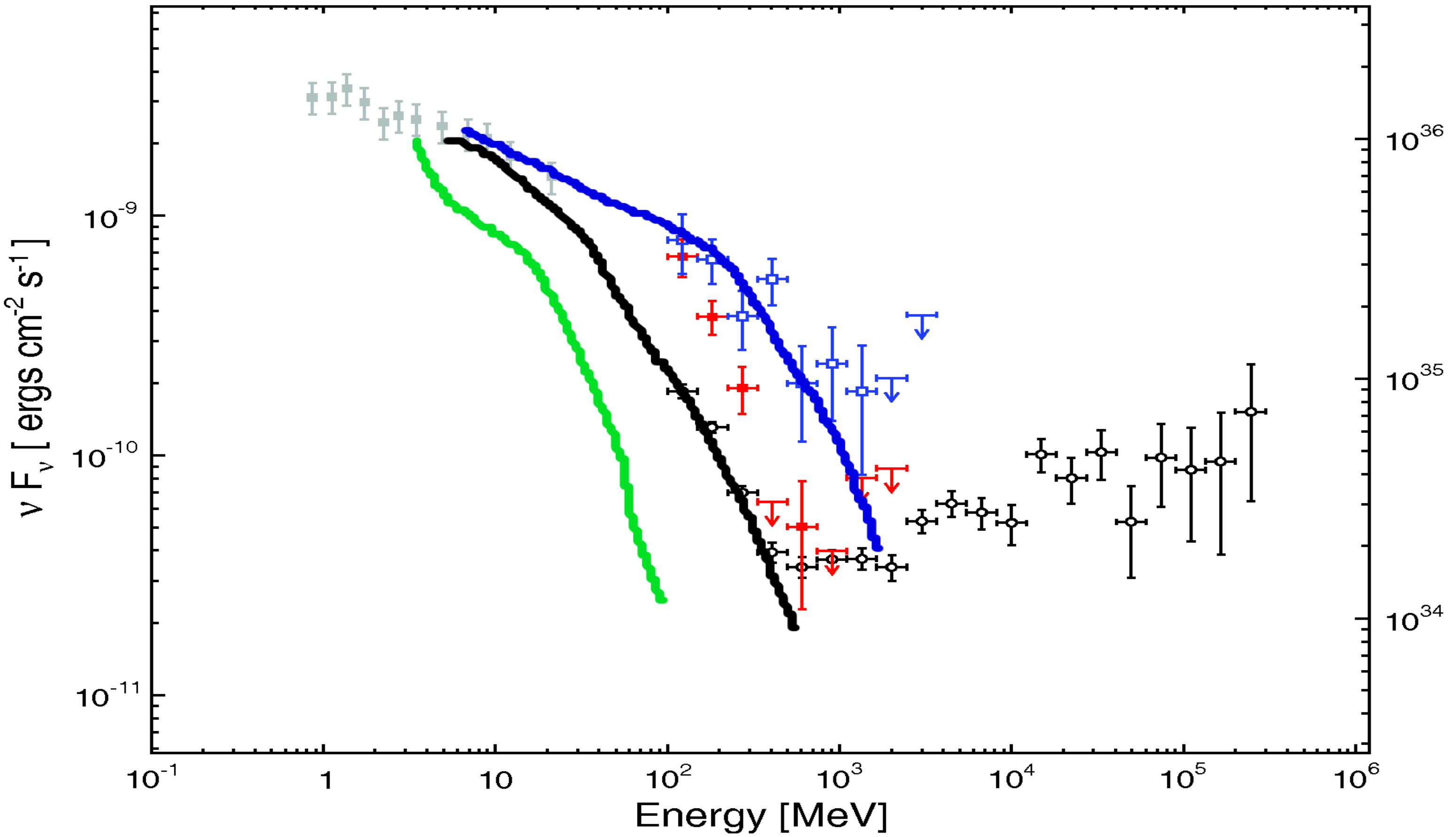
Figure 3: From Vittorini et al. (2011).

⇓

GeV flare spectrum can be seen above the baseline emission

- Single component but with flickering end of the electron spectrum. Electron spectrum can sometimes extend to larger/lower energies.

Considered by Bednarek & Idec (2011)



$\Downarrow$

GeV Crab spectrum can flare up and go down below the baseline emission ?

Possible scenario for the Crab Nebula flares

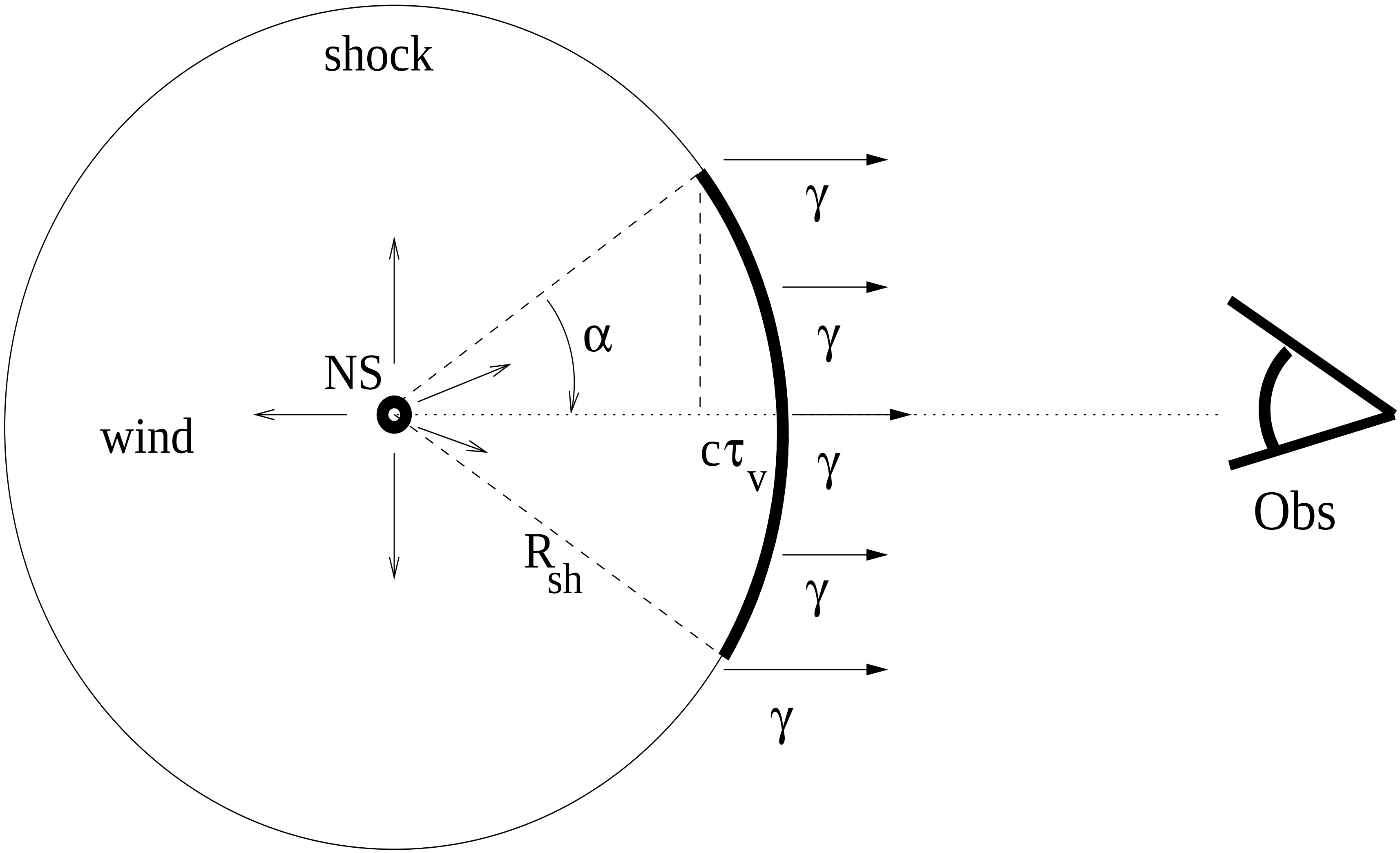


Figure 4: From Bednarek & Idec 2011: Schematic representation of the Crab Nebula. The pulsar (NS) produce relativistic axially symmetric wind which creates a shock at the distance R_{em}. γ-rays are produced behind the shock in the region of strong deceleration of the pulsar wind. Only those produced close to the part of the shock (thick part defined by the angle α) can reach the observer (Obs). However, they reach the observer at different time due to the curvature of the shock structure. This time difference is limited by the observed variability time scale of the γ-ray emission ($c\tau_{\mathrm{v}}$). It can be estimated for known R_{em} and τ_{v}. The angle α is related to the collimation of the γ-ray emission which is caused by the relativistic motion of the emission region with the Lorentz factor γ_{em}.

Constraints on the emission region

(γ-ray variability is related to the geometry of the emission and collimation of radiation due to relativistic motion)

- **Constraint on the Lorentz factor of the emission region**

$$\sin\alpha = \sqrt{2(c\tau_{\rm v}/R_{\rm em}) - (c\tau_{\rm v}/R_{\rm em})^2}.$$

We assume that radiation collimated within α due to the movement of the emission region

$$\gamma_{\rm em} \sim 1/\alpha \approx \sqrt{2c\tau_{\rm v}/R_{\rm em}},$$

which for the wisp distance $R_{\rm em} \sim 7\times10^{16}$ *cm (Caraveo et al. 2010):* $\gamma_{\rm em} \approx 3.7\tau_{\rm d}^{-1/2}$.
(see also Komissarov & Lyutikov 2011)

The limits on the Lorentz factor of electrons and the magnetic field

- **Constraint from the break in the synchrotron spectrum**

$$\varepsilon_{\rm br}^{\rm syn} \approx m_{\rm e}(B/B_{\rm cr})\gamma_{\rm br}^2 \approx \varepsilon_{\rm obs}/\gamma_{\rm em}.$$
$$\Downarrow$$
$$B\gamma_{\rm br}^2 \approx 8.8\times10^{15}/\gamma_{\rm em} \quad {\rm G}.$$

- Constraint from the cooling time scale of electrons

$$\tau_{\rm syn}^{\rm cool} < \tau_{\rm obs}\gamma_{\rm em}.$$

$$\Downarrow$$

$$B^2\gamma_{\rm br} \approx 6.5\times10^3/(\tau_{\rm d}\gamma_{\rm em}) \quad {\rm G}^2.$$

These two conditions on B and $\gamma_{\rm br}$ gives

$$B \approx 1.7\times10^{-3}\tau_{\rm d}^{-2/3}\gamma_{\rm em}^{-1/3} \quad {\rm G} \qquad \text{and} \qquad \gamma_{\rm br} \approx 2.3\times10^9\tau_{\rm d}^{1/3}\gamma_{\rm em}^{-1/3}.$$

which for above estimate of $\gamma_{\rm em}$ and $\tau_{\rm d} = 0.5$ day gives the limit
$B \approx 2.7\times10^{-3}\gamma_{\rm em}^{-1/3} \approx 1.6\times10^{-3}$ *G and* $\gamma_{\rm br} \approx 1.1\times10^9$.

Note: This estimate corresponds to the estimate of $B_{\rm wind}(R_{\rm em})$ from the pulsar magnetosphere (inner dipole and outer toroidal structure),

$$B_{\rm w} = B(R_{\rm LC})(R_{\rm LC}/R_{\rm em}) \sim 3.5\times10^{-3}\ {\rm G}.$$

Problems for the shock acceleration scenario ?

Maximum energies of electrons accelerated at the shock allowed by the synchrotron losses:

$$\gamma_{\mathrm{max}} \approx 10^{9}(\chi_{-1}/B_{-3})^{1/2}.$$

$\chi = 0.1\chi_{-1}$ *is the acceleration coefficient* (< 1) *and* $B = 10^{-3}B_{-3}$ *G.*

Maximum energies of synchrotron photons:

$$\varepsilon_{\mathrm{max}} \approx m_{\mathrm{e}}\gamma_{\mathrm{max}}^{2}(B/B_{\mathrm{cr}}) \approx 11\chi_{-1}\ \mathbf{MeV.}$$

Shock should be relativistic and very efficient → problems ?

Acceleration of electrons in the reconnection regions in the relativistic pulsar wind before reaching the shock

(see also Uzdensky, Cerutti & Begelman 2011)

$$\Downarrow$$

Injection into large B

Example calculations of the Synchrotron and IC spectra

- **Electron spectrum in the fluid frame:**

$$dN/d\gamma_{\rm e} = \gamma^{-\beta}\exp(-\gamma/\gamma_{\rm br}),$$

where $\beta = 3.0,\ \gamma_{\rm em} = 10,\ B_{\rm em} = 10^{-3}\ G$, $\gamma_{\rm br}$ *can vary (up and down)*

- **Electrons:**

Synchrotron radiation (constant B),

IC scattering of

the nebular synchrotron radiation and the Microwave Background Radiation

(boosted in the electron emission frame).

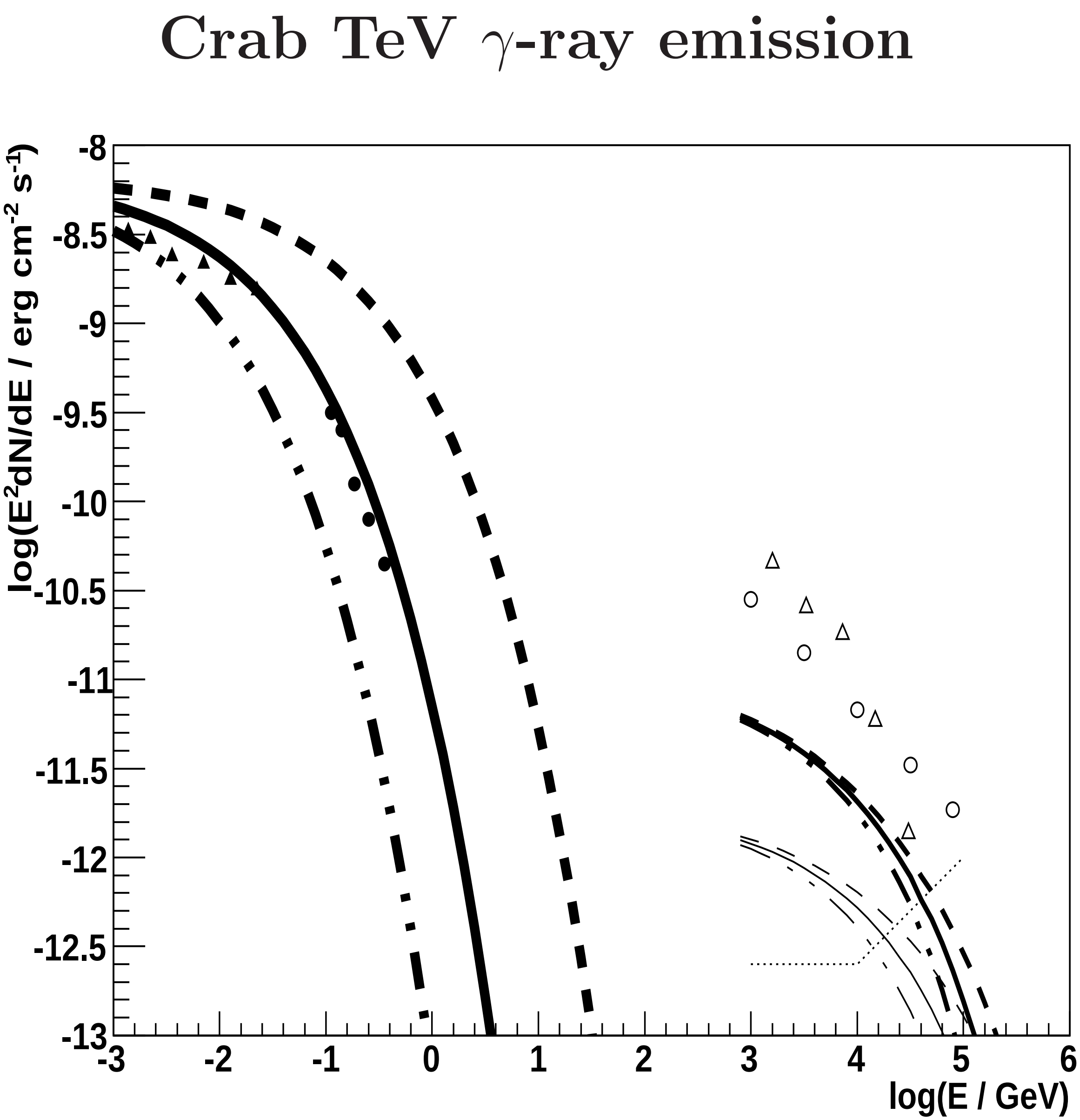

Crab TeV γ-ray emission

Figure 5: The γ-ray spectrum from the Crab Nebula is compared with the calculations of the synchrotron spectrum (thick curves) and the IC spectra produced by electrons as a result of scattering of the MBR (middle curves) and low energy synchrotron emission within the nebula (thin curves) in the quiescent, flaring, and supposed super-quiet episodes. The magnetic field in the emission region is $B_{\rm em} = 10^{-3}$ G, the spectral index is $\beta = 3$, the Lorentz factor of the emission region $\gamma_{\rm em} = 10$ and the Lorentz factors of electrons at the break in the spectrum are $\gamma_{\rm e}^{\rm q} = 3 \times 10^8$ (solid curves, for the quiescent emission), $\gamma_{\rm br}^{\rm f} = 9 \times 10^8$ (dashed curves, for the flaring emission), and 1.5×10^8 (dot-dot-dashed curves). The 20 hr sensitivity of the CTA is marked by the broken dot-dashed line.

Conclusions

- **The GeV flaring component seems to be extension of the broadband synchrotron spectrum from the Crab Nebula.**
- **It can originate in the relativistic wind of the pulsar when it slows down before reaching the shock.**
- **The emission region likely moves with the Lorentz factor of the order of ten.**
- **The end of the synchrotron spectrum might vary up and down in respect to the baseline emission.**
- **The level of variability at the TeV energies should be lower than observed at GeV energies.**
- **Synchronous several TeV variability might be detected by the CTA.**

For references and more details:

Bednarek & Idec 2011, MNRAS, doi:10.1111/j.1365-2966.2011.18539.x (arXiv:1011.4176)