Pulsed VHE emission from the Crab

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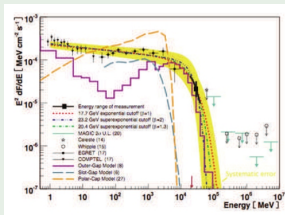Tokyo, Japan
In collaborations with F.Aharonian and S.Bogovalov

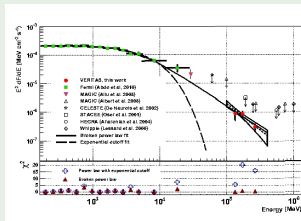5th International Symposium on High-Energy Gamma-Ray
Astronomy
July 9-13, 2012, Heidelberg, Germany
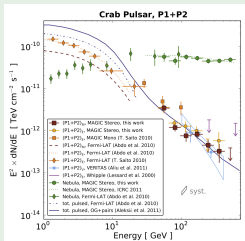
VHE observations of the Crab pulsar

MAGIC Collaboration(2008)

Veritas Collaboration(2011)
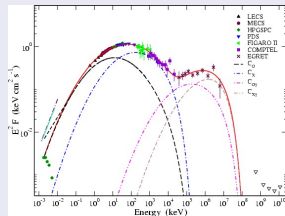

MAGIC Collaboration(2011)

Currently there is a general agreement between different experiments regarding the detection of the pulsed VHE emission from the Crab pulsar
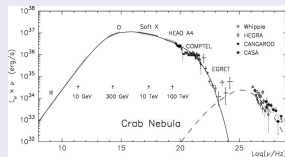
Broad band emission

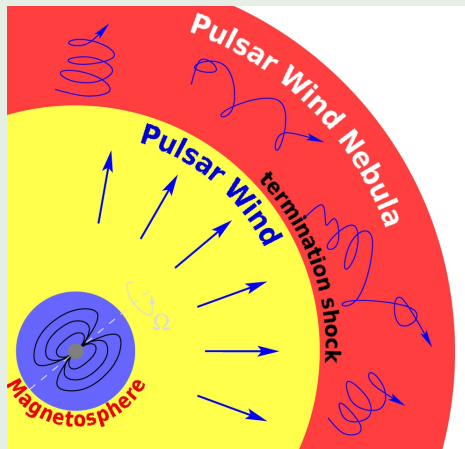## Crab Nebula with Chandra

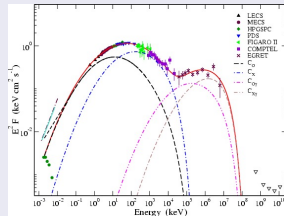## Pulsar(Massaro+)

PWN(Aharonian&Atoyan)

Crab is one of the best studied astrophysical objects displaying a few radiation components of different origin
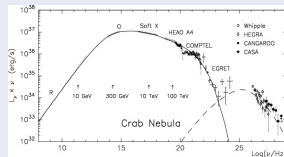
Conventional view on the Crab

Pulsar Related Emitting Zones

Pulsar(Massaro+)

PWN(Aharonian&Atoyan)

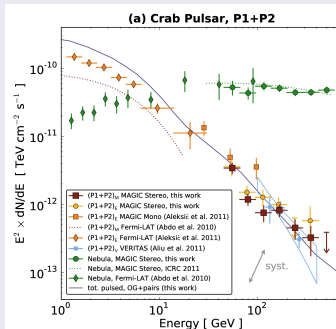There are a few plausible emissions sites, which are related to each other, but characterized by very different conditions

Where is the pulsed VHE emission produced?

- Pulsar Magnetosphere (e.g. Aleksić+2012)
- PWN
- Pulsar Wind (Bogovalov&Aharonian2001)

Calculations by K.Hirotani

The magnetospheric origin of the pulsed VHE signal is strongly favored, however the modeled lightcurve is not yet in acceptable agreement

Where is the pulsed VHE emission produced?

- Pulsar Magnetosphere (e.g. Aleksić+2012)
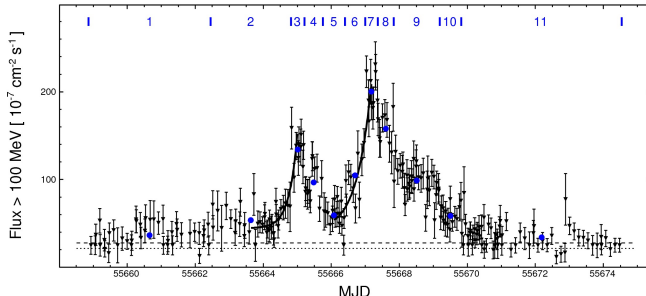- PWN
- Pulsar Wind (Bogovalov&Aharonian2001)

Production of pulsed emission in the nebula is impossible, but till recently the Crab flares were also impossible...

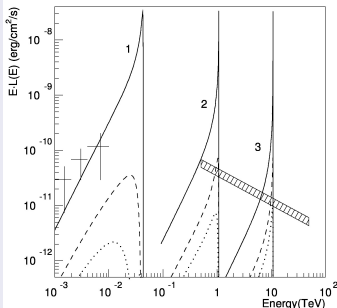## Crab Flare (Buehler+2012)

Where is the pulsed VHE emission produced?

However, it was predicted that the pulsar can also emit potentially detectable emission, which under certain conditions can be pulsed

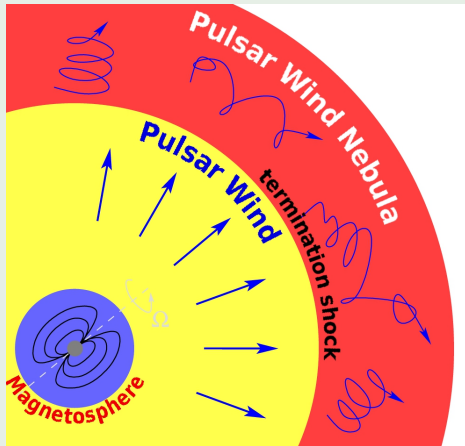- Pulsar Magnetosphere (e.g. Aleksić+2012)
- PWN
- Pulsar Wind (Bogovalov&Aharonian2001)

Signal produced by cold pulsar wind
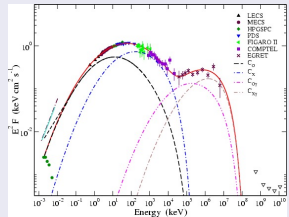
Pulsar Nebula is a colorimeter of the wind

Pulsar Related Emitting Zones

Pulsar(Massaro+)

PWN(Aharonian&Atoyan)
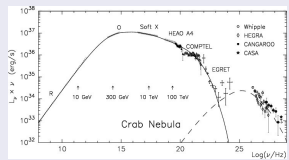
Wind is not expected to emit any obvious radiation component, however it is possible to infer its properties through the non-thermal emission of the nebula

Kennel&Coroniti1984

Sketch of the model
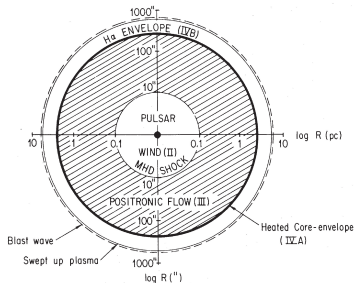
Pulsar wind

- Total Luminosity

$$L_w \simeq 6 \times 10^{38} \mathrm{erg/s}$$

- Bulk Lorentz Factor

$$\Gamma_w \simeq 3 \times 10^6$$

- Wind Magnetization

$$\sigma \simeq 3 \times 10^{-3}$$

1D MHD model by Kennel&Coroniti favored an ultrarelativistic weakly magnetized wind

2D modeling of the Crab nebula

Crab Nebula

Bogovalov&Khangulyan2002
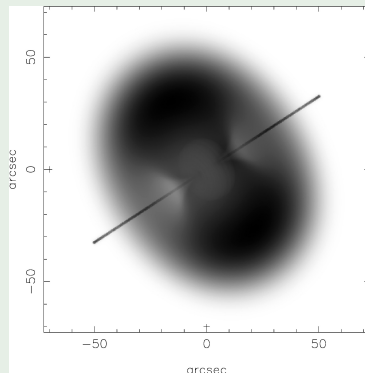
The observed structure in the Crab Nebula is likely related to anisotropy of the pulsar wind, and can be checked by 2D modeling

2D numerical modeling of the Crab nebula

Crab Nebula

Del Zanna+2006

A few groups achieved a very impressive progress in 2D modeling of the Crab nebula: Amato, Bucciantini, Del Zanna+; Komissarov+; Bogovalov+

What is the pulsar wind

Pulsar and Nebula
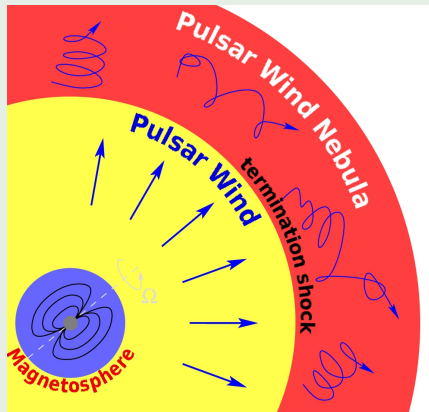
1D MHD

- Bulk Lorentz Factor $\Gamma_w \sim 10^6$
- Wind Magnetization $\sigma \sim 3 \cdot 10^{-3}$

2D MHD

- Bulk Lorentz Factor (?)
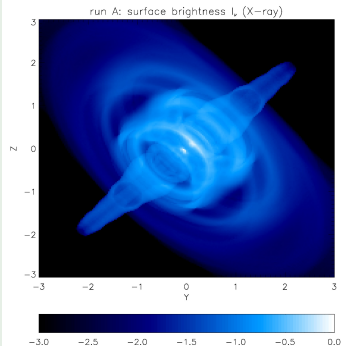- Wind Magnetization $\sigma \sim 10^{-2}$

The properties of pulsar winds are not yet firmly established, however the requirement of ultrarelativistic wind apparently remains unavoidable

Bulk Comptonization of the wind

Sketch of the scenario (Aharonian+2012)

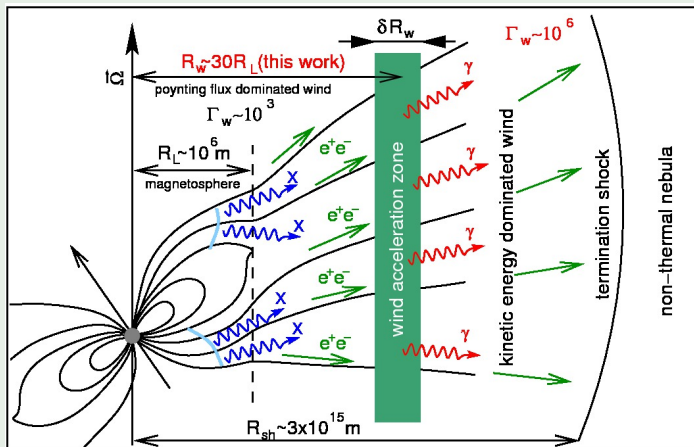If the pulsar wind is accelerated enough close to the magnetosphere, a quite strong IC emission can be generated

Is the wind IC emission pulsed?
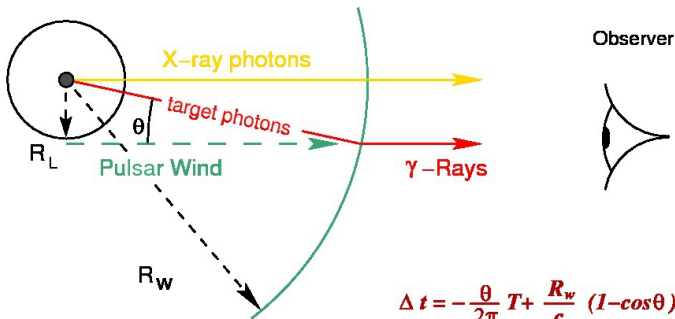
Sketch of the scenario (Aharonian+2012)

a

X–ray photons

target photons

θ

R_L

Pulsar Wind

γ–Rays

Observer

R_W

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

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

Inverse Compton interaction angle is determined from the first principles (Bogovalov&Aharonian2001)

- Energy–Angular Momentum losses of pulsar:

$$\dot{E}_{sd} = \Omega \dot{M}_{sd}$$

- Energy carried by an electron:

$$\Gamma_w mc^2$$

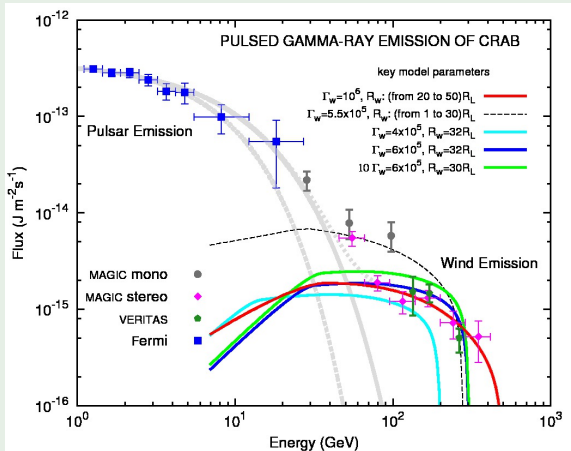- Angular Momentum carried by an electron:

$$\Gamma_w m r_\perp v$$

- Pulsar wind trajectory (if $\sigma \ll 1$):

$$r_\perp = \frac{c}{\Omega} = R_L$$

It is plausible that during the acceleration stage the wind trajectories are bended leading to a non-zero IC interaction angle
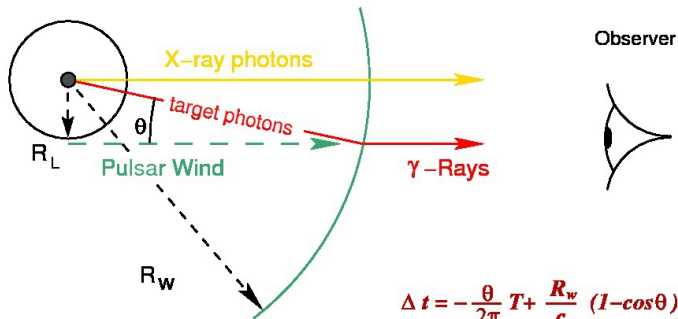
Spectrum can be explained

The flux level appears to depend strongly on the both model parameters: wind formation distance and wind Lorentz factor

Is the wind IC emission pulsed?

Sketch of the scenario (Aharonian+2012)

a

X–ray photons

target photons

θ

R_L

Pulsar Wind

γ–Rays

Observer

R_W

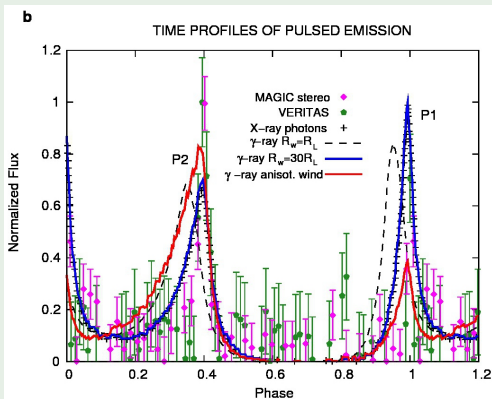$$\Delta t = -\frac{\theta}{2\pi}\, T + \frac{R_w}{c}\,(1-\cos\theta)$$

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

Wind signal lightcurve

Light Curve (Aharonian+2012)

Although the VHE lightcurve is consistent with the data points if the wind is formed not very close to the pulsar, the ratio of the lightcurve peaks indicates on presence of some wind anisotropy

Summary

- The pulsed VHE signal is the best interpreted as IC emission from the wind
- Current measurements of the pulsed VHE signal allows to constraint the key properties of the pulsar wind
  - Bulk Lorentz factor $\Gamma_w \simeq 5 \times 10^5$
  - Wind formation distance $R_w \simeq 30 R_L$
- Currently available lightcurve doesn't allow any robust conclusions, however hints on some wind anisotropy
- If the future data confirm the wind origin of the signal, this provides important information about the physics of the pulsar winds