Pulsar Winds in High Energy Astrophysics

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The extreme Universe viewed in very high energy gamma-rays, Kashiwa 09/25/2012

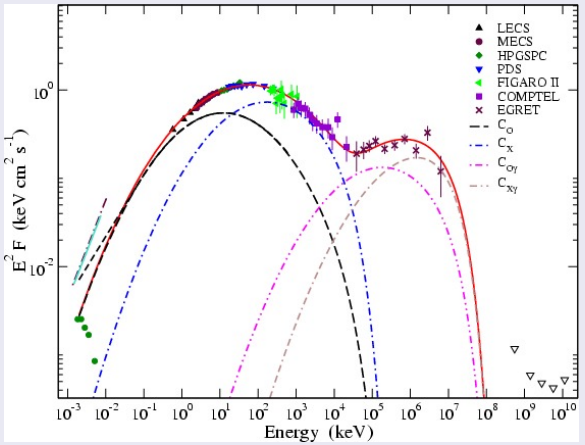
OUTLINE

- Introduction to the pulsar winds
- VHE pulsed signal from the Crab pulsar
- GeV gamma-ray line
- GeV flare from binary pulsar system

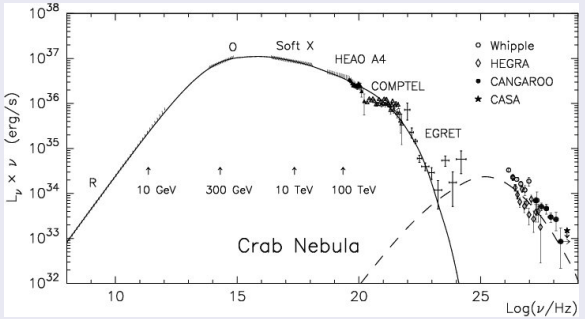
Broad band emission from pulsars

Crab Nebula with Chandra

Pulsar(Massaro+)



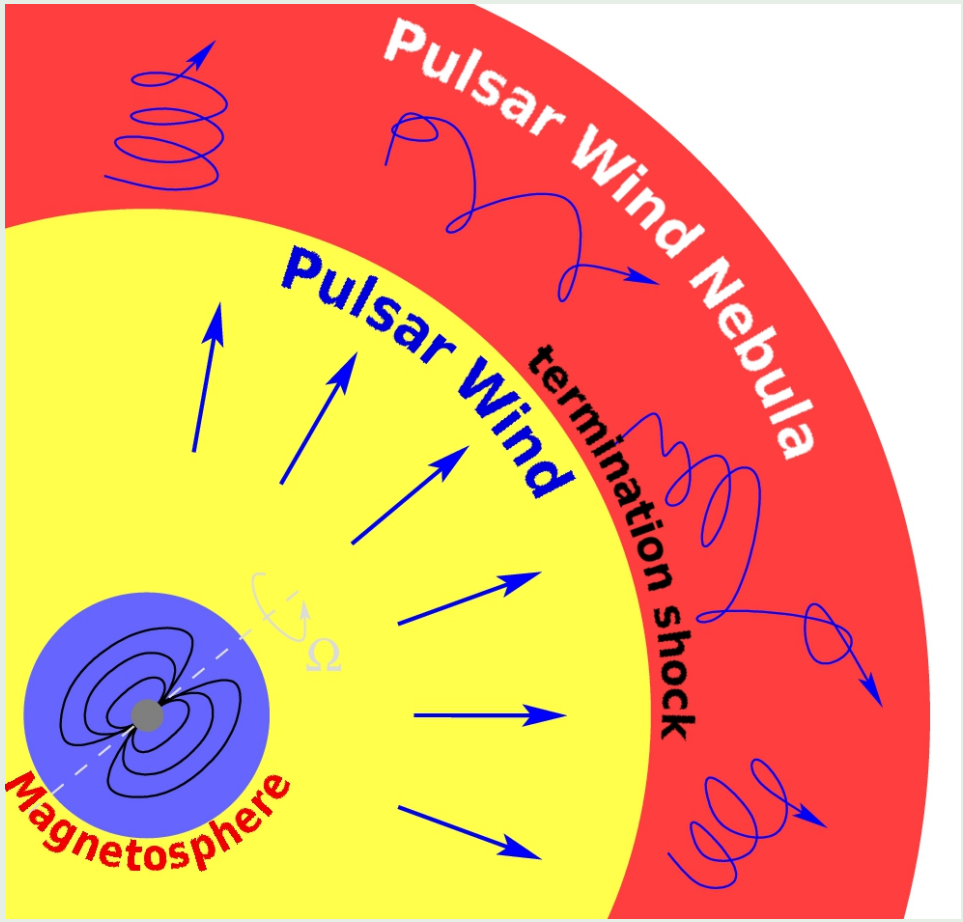
PWN(Aharonian&Atoyan)



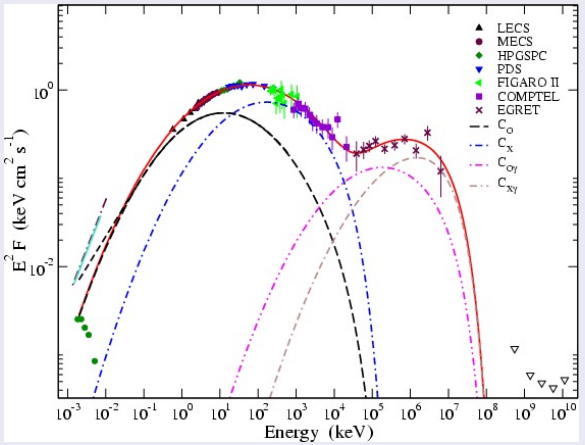
Crab is the canonical pulsar and one of the best studied astrophysical objects displaying a few radiation components of different origin

Conventional view on the Crab

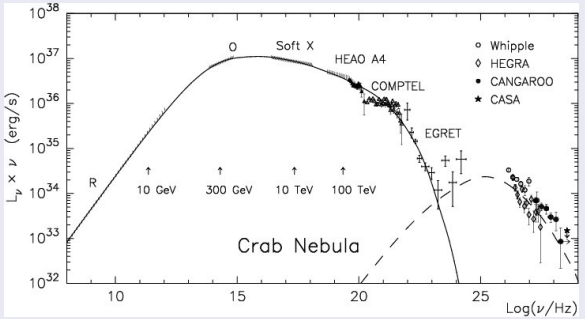
Pulsar Related Emitting Zones



Pulsar(Massaro+)



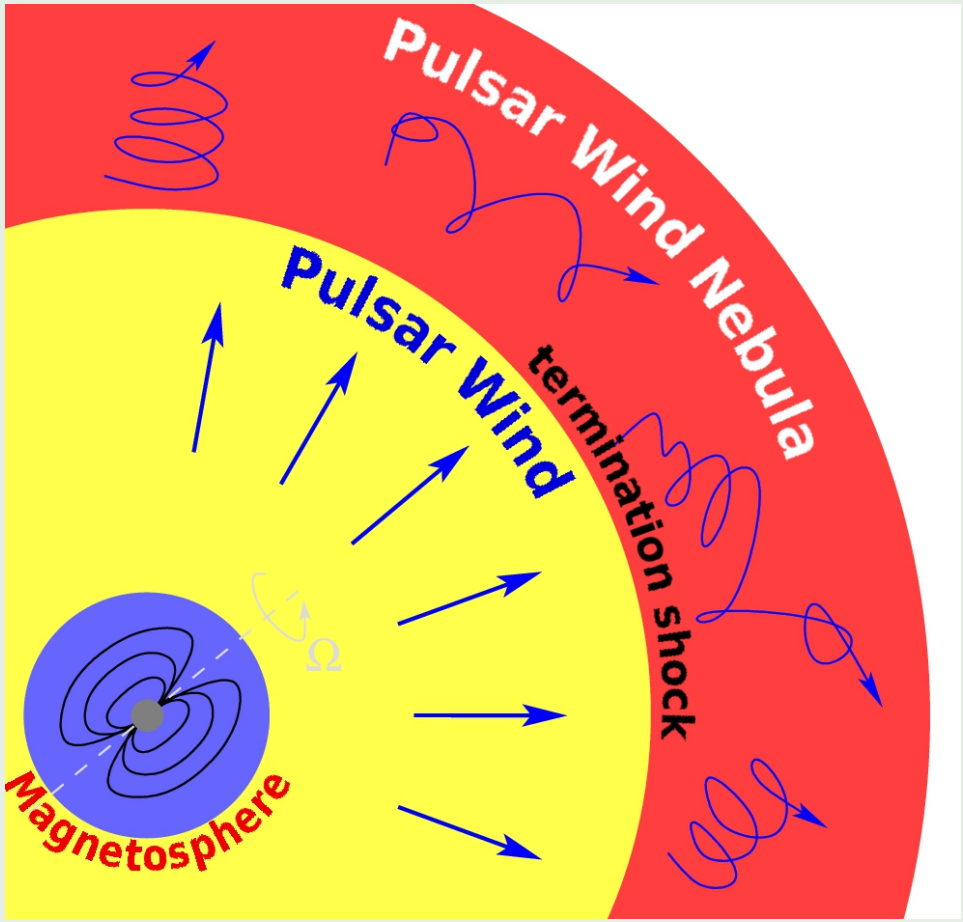
PWN(Aharonian&Atoyan)



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

Pulsar Nebula is a calorimeter of the wind

Pulsar Related Emitting Zones



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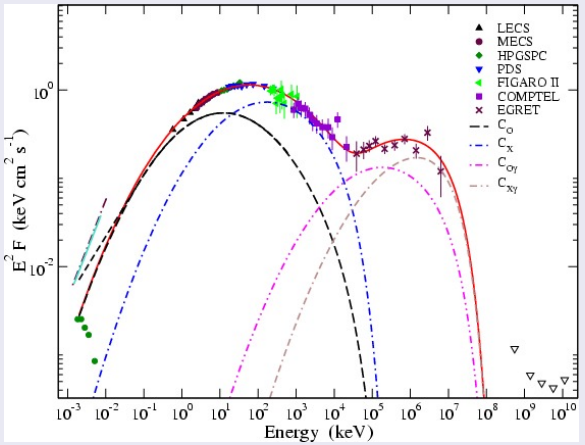

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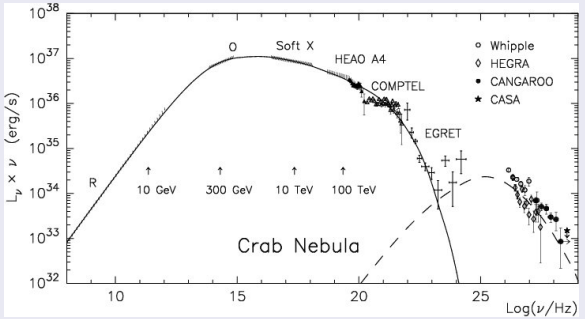
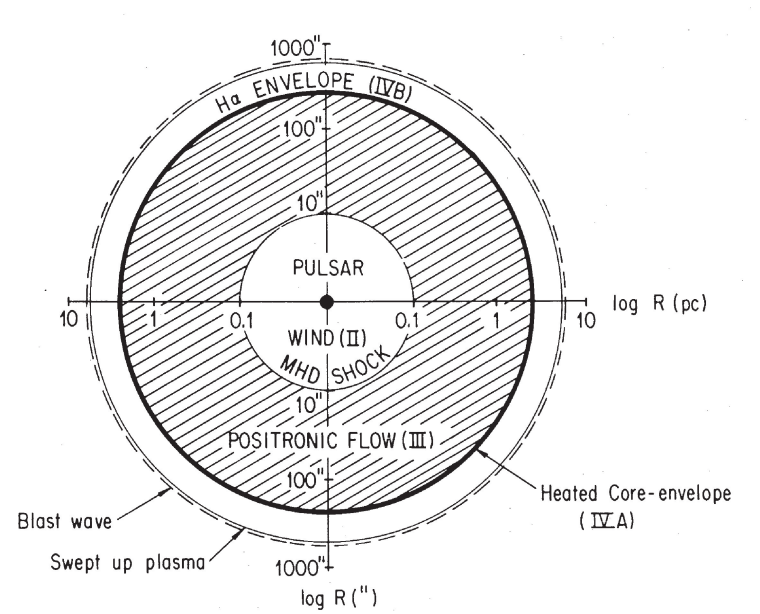


Wind is not expected to emit any obvious radiation component, however it is possible to infer its properties through the non-thermal emission of the nebula

Kennel&Coroniti1984

Sketch of the model



Pulsar wind

- Total Luminosity

$$L_{\rm w} \simeq 6 \times 10^{38} {\rm erg/s}$$

- Bulk Lorentz Factor

$$\Gamma_{\rm w} \simeq 3 \times 10^{6}$$

- Wind Magnetization

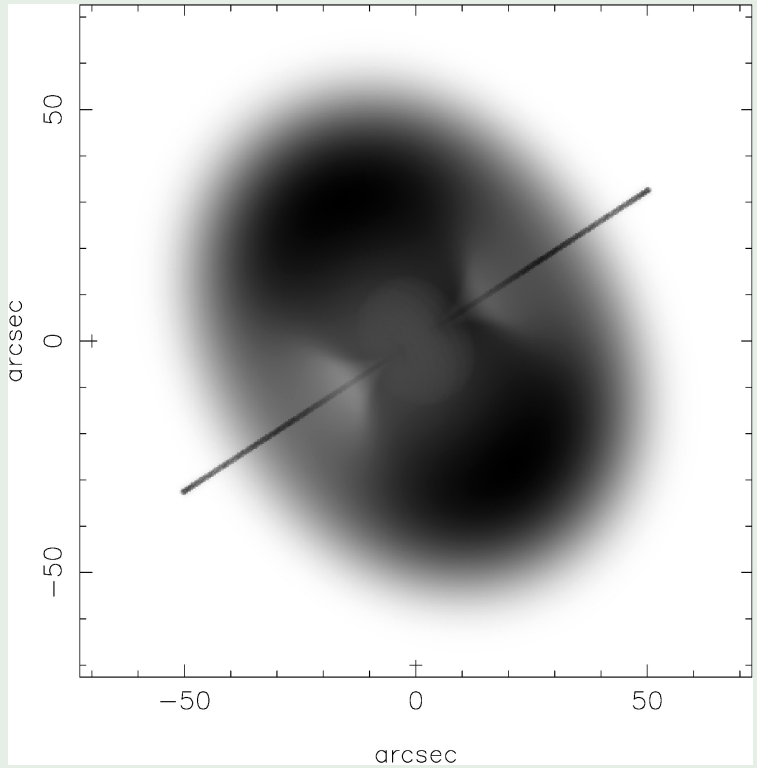
$$\sigma \simeq 3 \times 10^{-3}$$

1D MHD model by Kennel&Coroniti favored an ultrarelativistic weakly magnetized wind: this allows optical-to-VHE emission to be explained

2D modeling of the Crab nebula

Crab Nebula

Bogovalov&Khangulyan2002

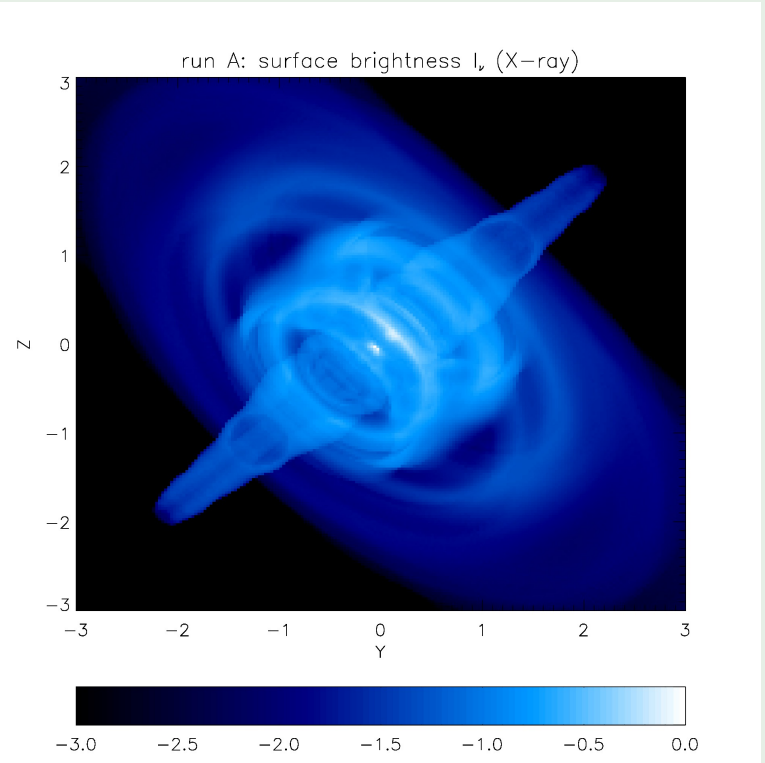


The observed structure in the Crab Nebula is likely related to anisotropy of the pulsar wind, and can be checked by 2D modeling

2D numerical modeling of the Crab nebula

Crab Nebula

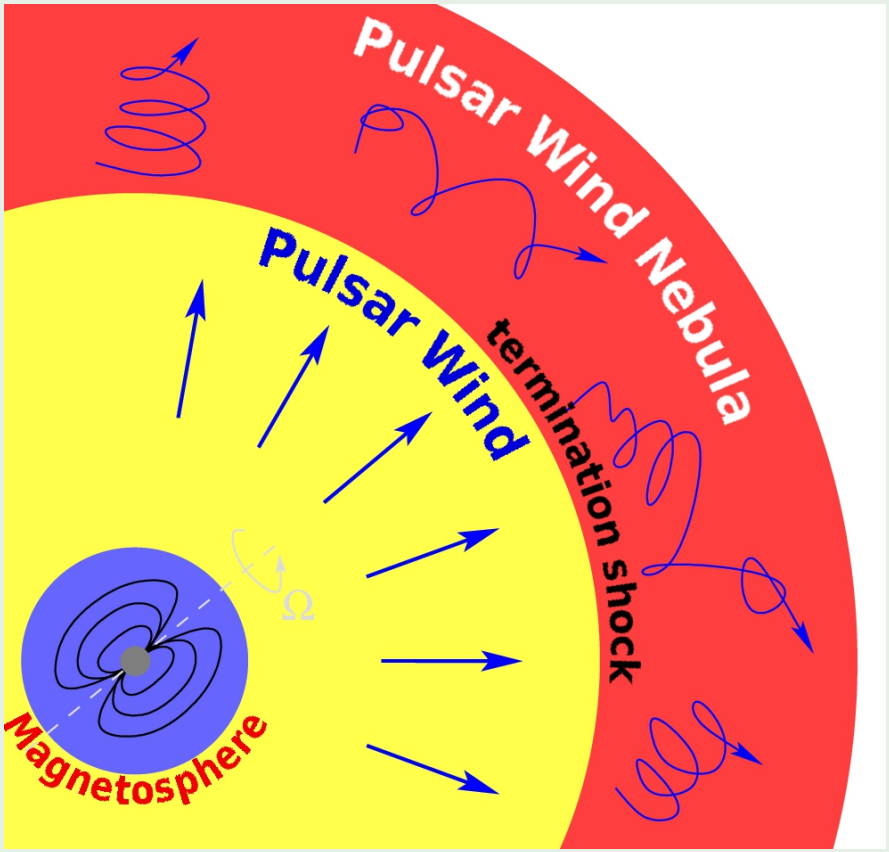
Del Zanna+2006



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

Is that the final theory?

Objections against the "Conventional Wind"

- Lack of any consistent models for the wind formation

  Despite very large efforts, there is still no (even preliminary) model for the wind acceleration

- Simplification employed in the nebula modeling, e.g.,
  - Ideal MHD

    Because of the striped structure of the wind, magnetic reconnection may play a very important role
  - Phenomenological acceleration mechanism

    It is unclear how the pulsar termination shock can accelerate particles
  - Uniformed properties of the wind

    The wind should have strong angular dependence, both in energy and in magnetic field strength

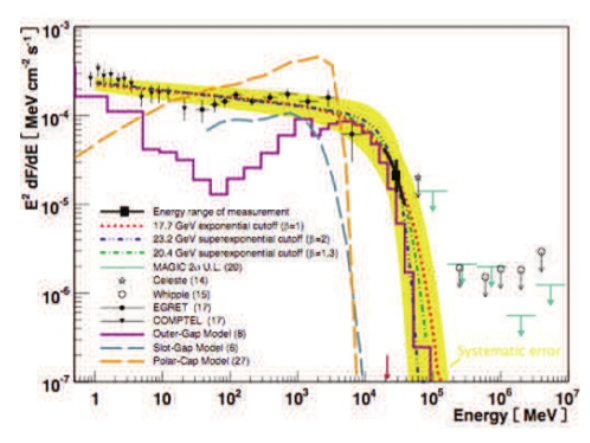
- Radio emission excess

  In the frameworks of the conventional scenario, the modeling significantly under-estimate the flux level in the radio band

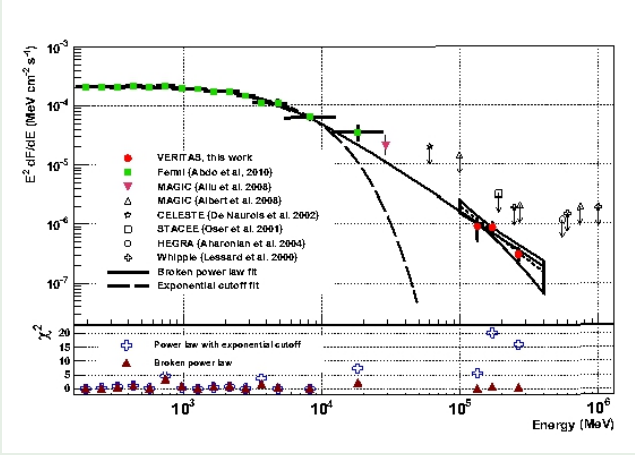
The concept of cold ultra-relativistic pulsar wind has strong advantages, however, is also challenged in a few different aspects, thus needs further observational and theoretical proofs.

VHE observations of the Crab pulsar

MAGIC Collaboration(2008)



Veritas Collaboration(2011)



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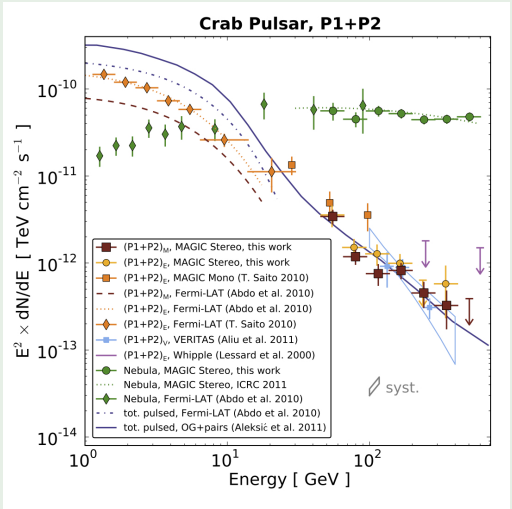
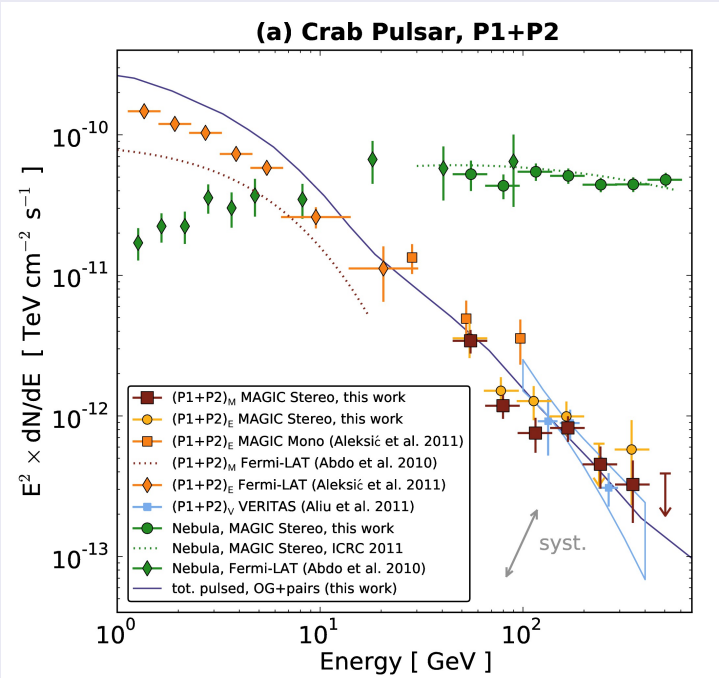


Currently there is a general agreement between different experiments regarding the detection of the pulsed VHE emission from the Crab pulsar

Where is the pulsed VHE emission produced?

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

Calculations by K.Hirotani



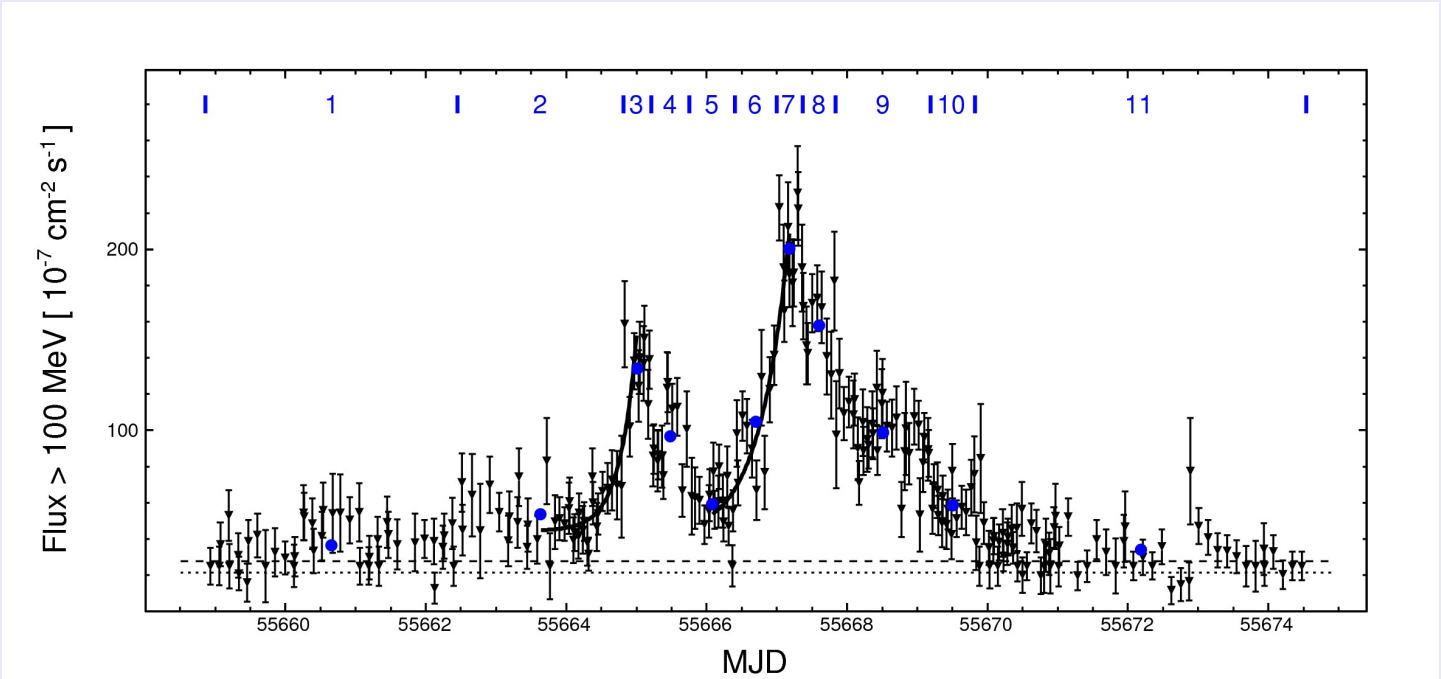
The magnetospheric origin of the pulsed VHE signal is strongly favored, however the modeled lightcurve is not yet in acceptable agreement

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)

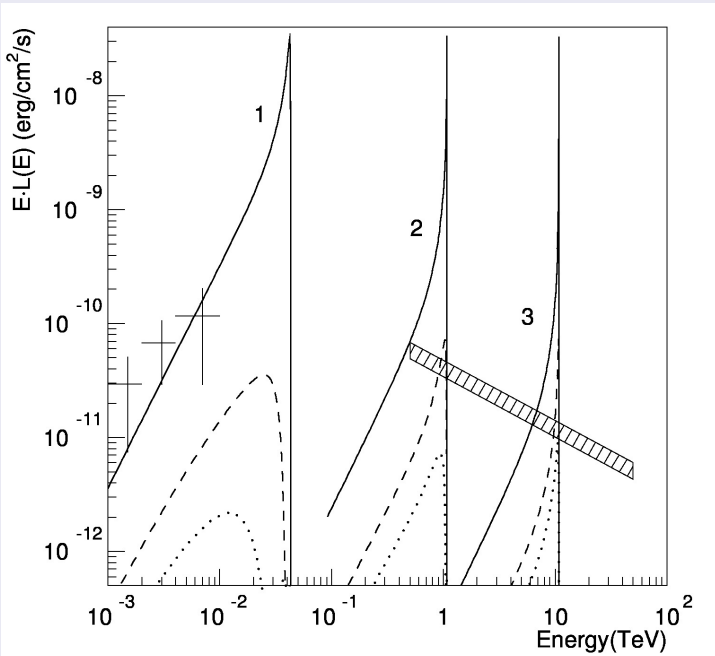


Where is the pulsed VHE emission produced?

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

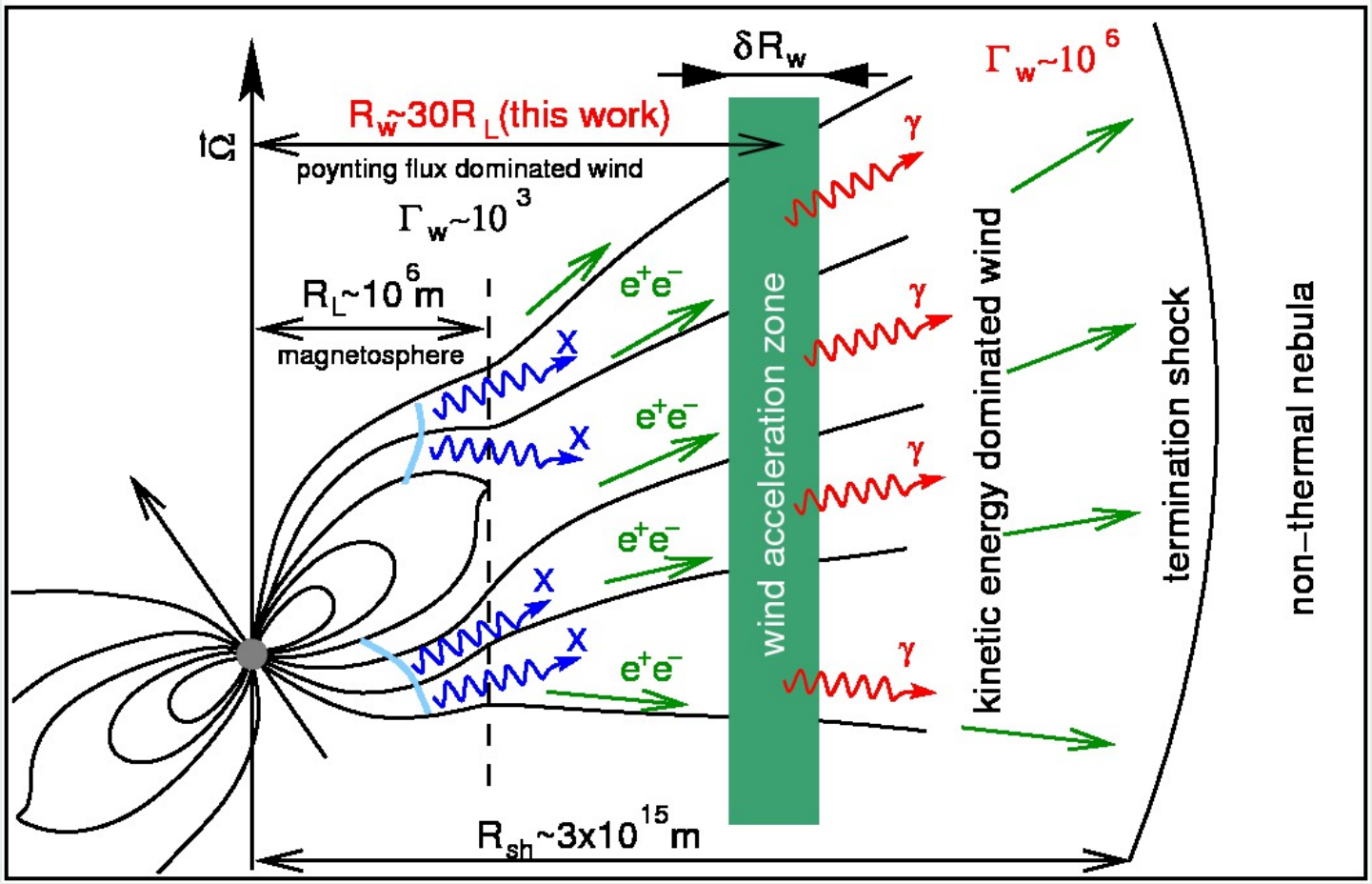
- Pulsar Magnetosphere (e.g. Aleksić+2012)
- PWN
- Pulsar Wind (Bogovalov&Aharonian2001)

Signal produced by cold pulsar wind



Bulk Comptonization of the wind

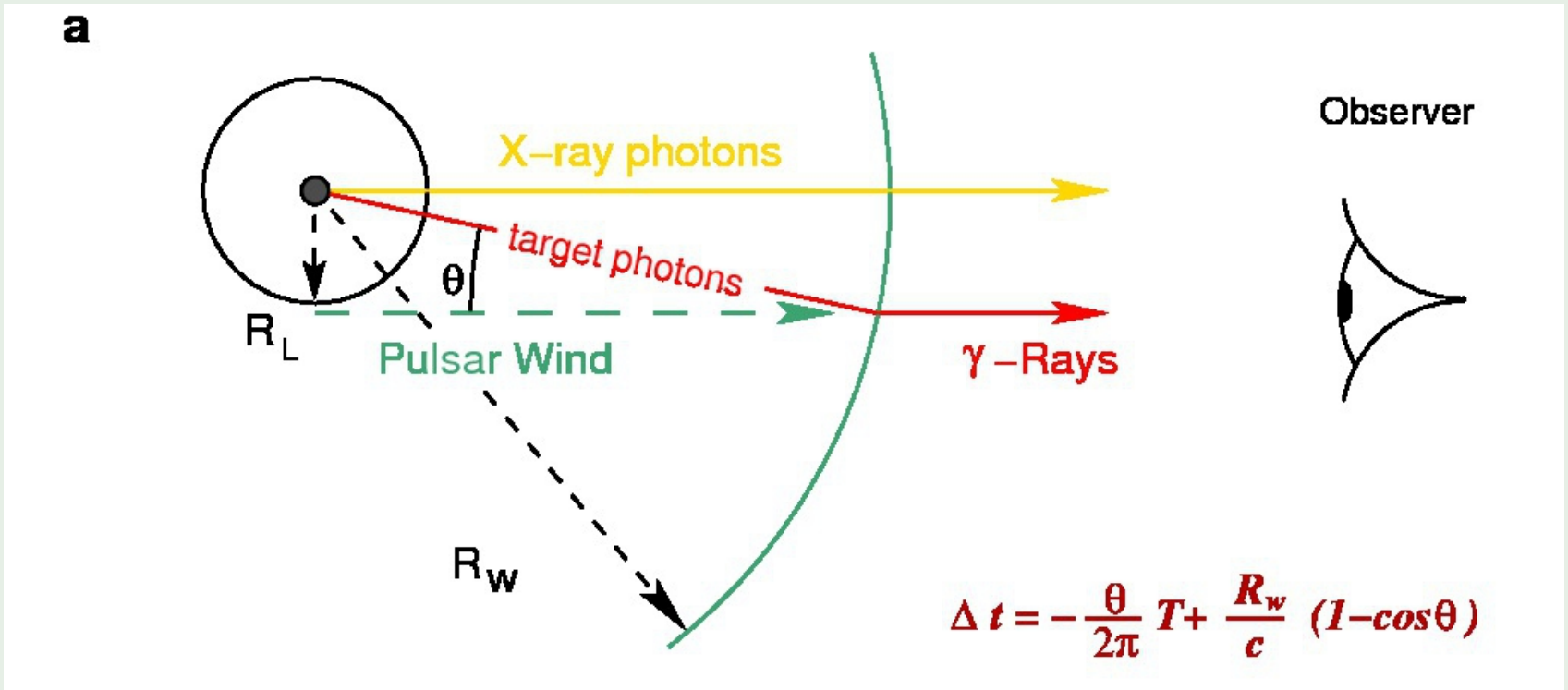
Sketch of the scenario (Aharonian+2012)



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)



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:

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

- Energy carried by an electron:

$$\Gamma_{\rm w} mc^2$$

- Angular Momentum carried by an electron:

$$\Gamma_{\rm w} m r_\perp v$$

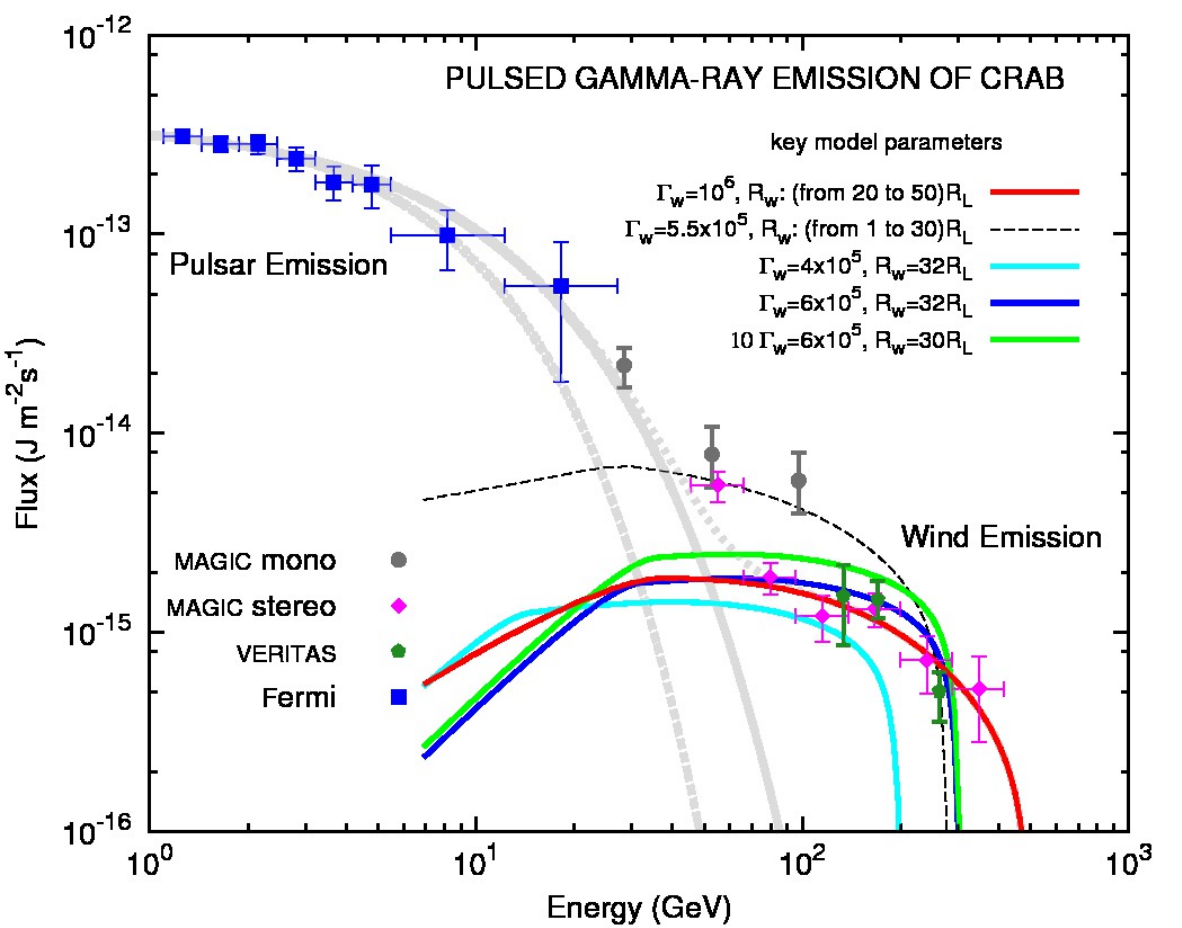
- Pulsar wind trajectory (if $\sigma \ll 1$):

$$r_\perp = \frac{c}{\Omega} = R_{\rm L}$$

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

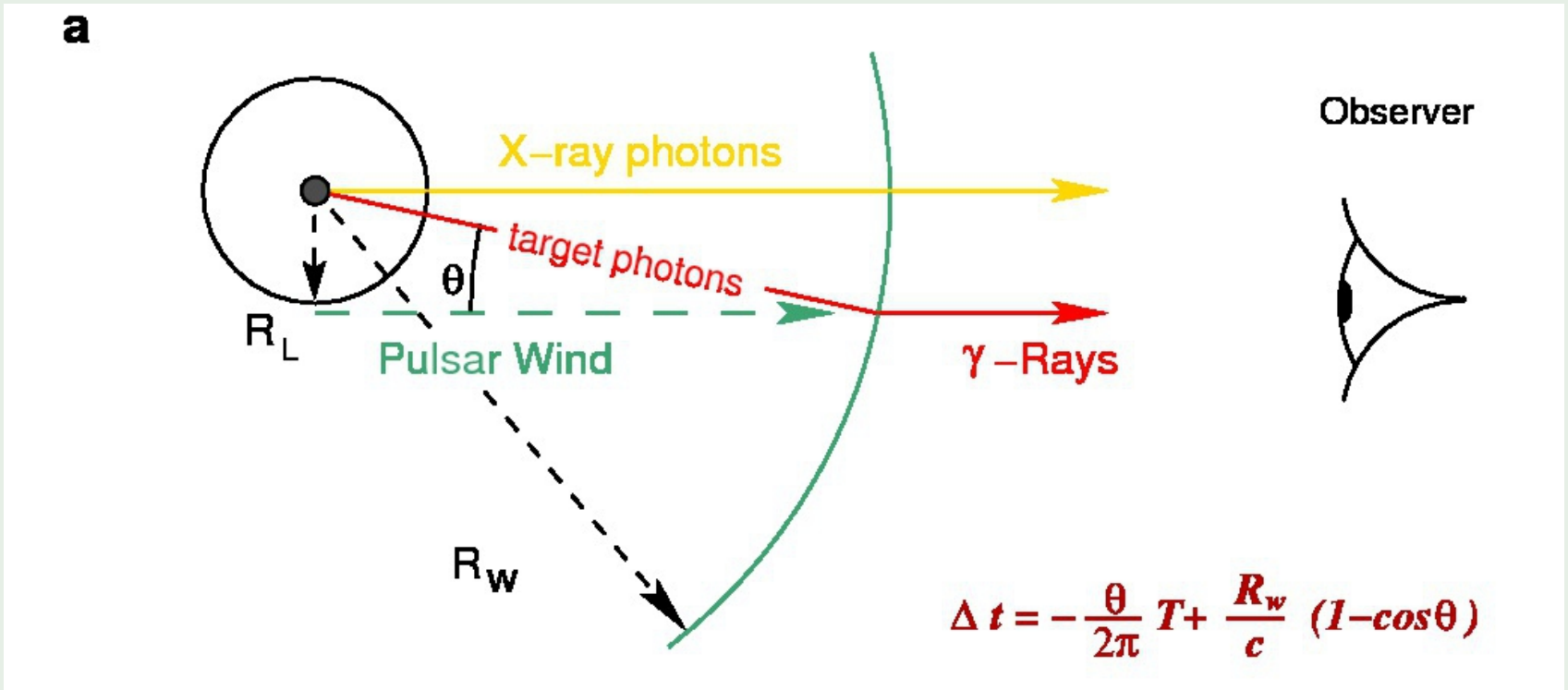
SED accounting for the wind signal (Aharonian+2012)



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)



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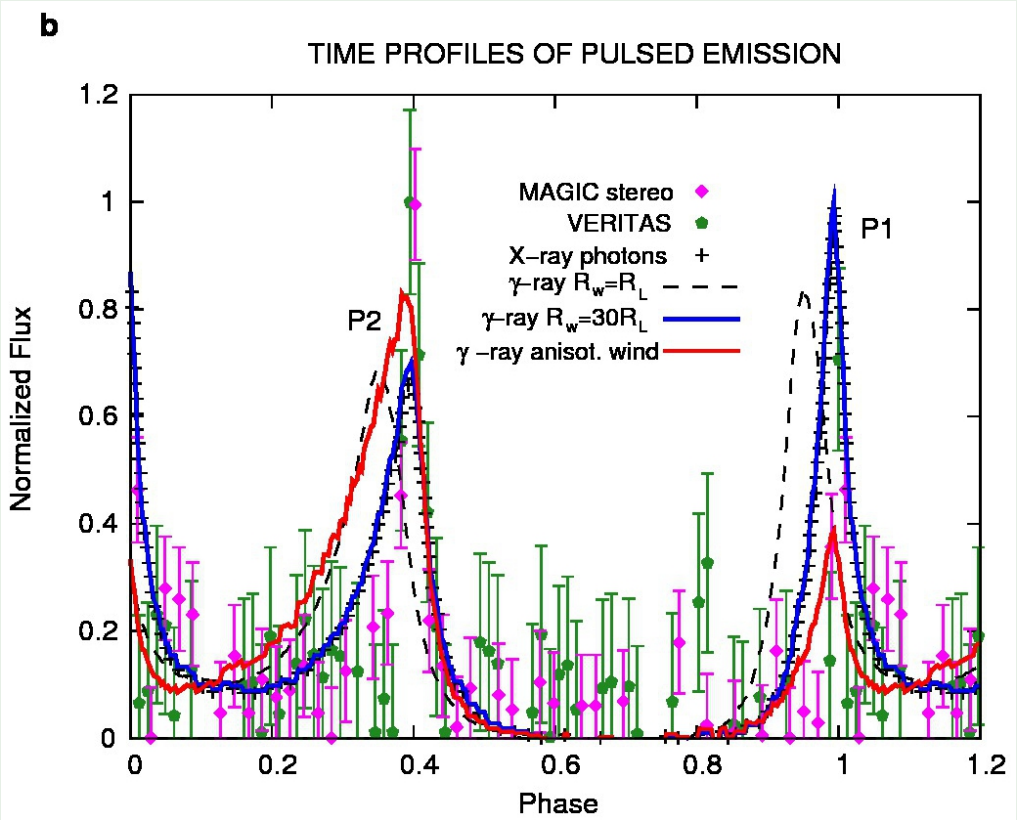
Wind signal lightcurve

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

Is that the final theory?

Objections against the "Conventional Wind"

- Lack of any consistent models for the wind formation

  Despite very large efforts, there is still no (even preliminary) model for the wind acceleration

- Simplification employed in the nebula modeling, e.g.,
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    Because of the striped structure of the wind, magnetic reconnection may play a very important role
  - Phenomenological acceleration mechanism

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- Radio emission excess

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The concept of cold ultra-relativistic pulsar wind has strong advantages, however, is also challenged in a few different aspects, thus needs further observational and theoretical proofs.

Does ultrarelativistic wind violate radio fluxes?

What one needs

$$\nu L_\nu = 10^{33} \left(\frac{\nu}{10^8 \mathrm{Hz}}\right)^{0.7} \mathrm{erg\,s^{-1}}$$

$$N_{\rm tot} = 2 \times 10^{50} B_{0.1\rm mG}^{-1} \qquad E_{\rm tot} = 7 \times 10^{47} B_{0.1\rm mG}^{-1.5}\,\mathrm{erg}$$

What one has

$$N_{\rm inj} = 5 \times 10^{49} \Gamma_6^{-1} \qquad E_{\rm inj}^{\rm b} = 4 \times 10^{49}\,\mathrm{erg}$$

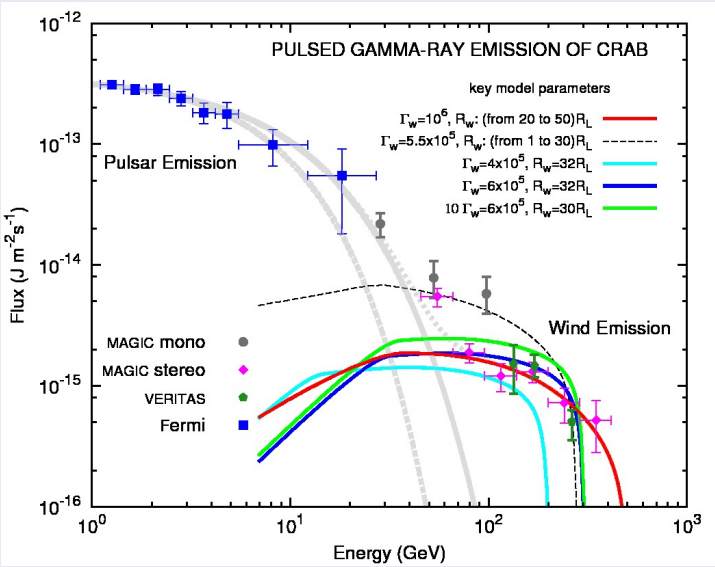
$$\Gamma_6 B_{0.1\rm mG}^{-1} \leq 0.25$$

The obtained value of the wind Lorentz factor ($\Gamma_6 = 0.5$) is consistent with the total number of electrons in the nebula for a very "comfortable" magnetic field strength of $B = 200 \mu G$

What can CTA do?

- Precise measurements around 50GeV are crucial
- Current detectors operate for $\sim$ 10 years
- CTA maybe can improve in $>$ 10years (given the expected start of operation)

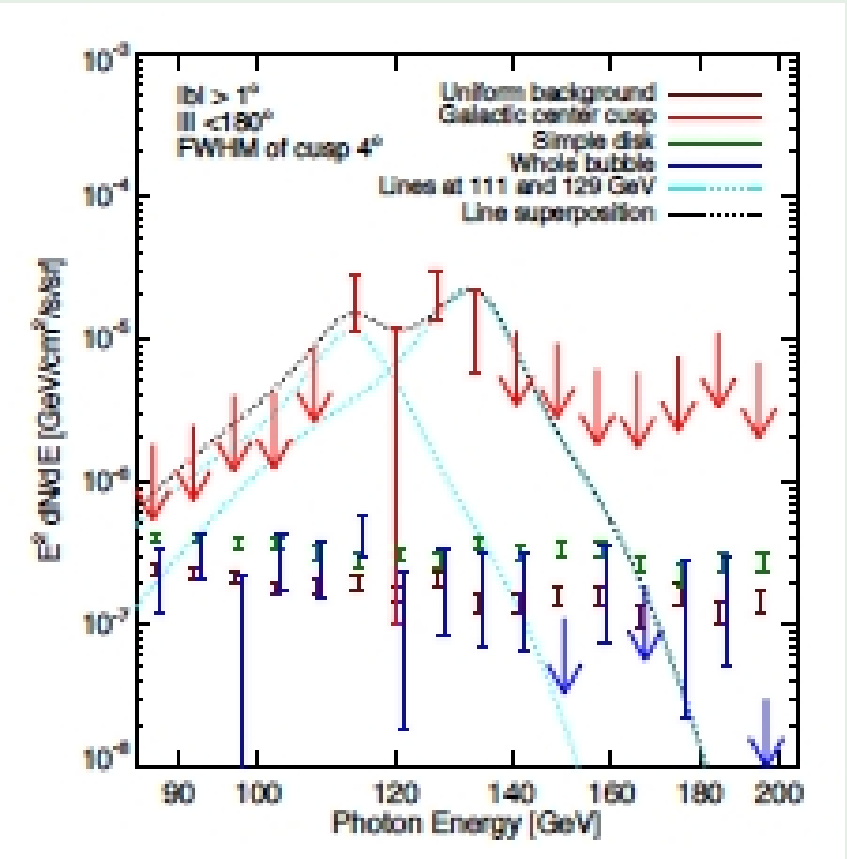
SED of pulsed emission



Since a long collection of data is required to measure pulsed signal, no immediate results from CTA are expected...

Dark Matter Annihilation Line @ 130GeV

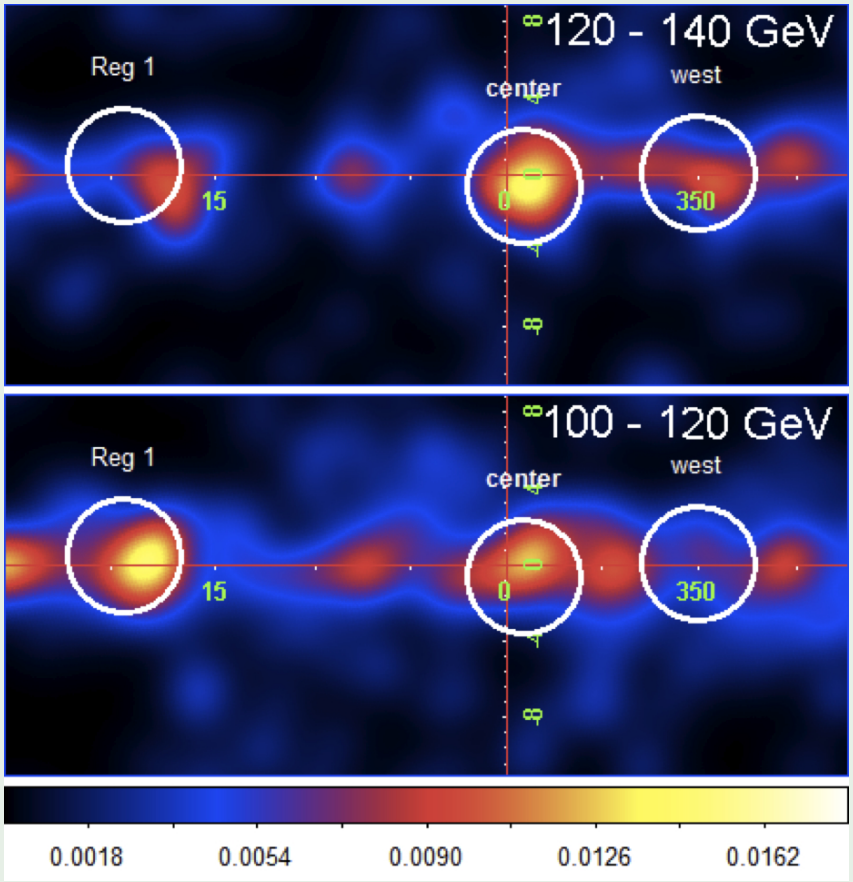
GeV excess in Fermi data (Su&Finkbeiner, 2012)



A very narrow GeV emission component was reported by several groups. This emission was interpreted as DM annihilation

Dark Matter Annihilation Line @ 130GeV

Further results by Boyarsky+(2012)



There are some hints on a several “hot spots” with slightly different emitted energy

Dark Matter Annihilation Line @ 130GeV

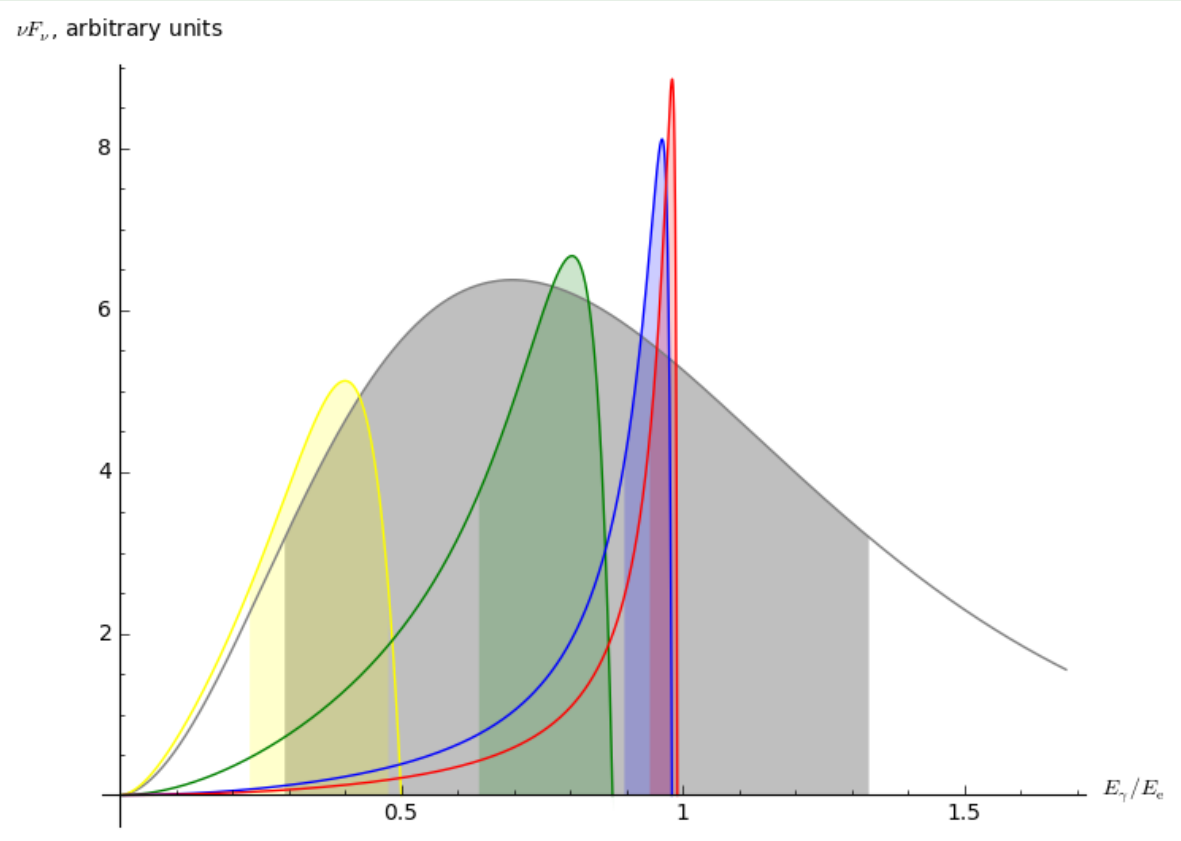
Is the "cosmological" interpretation doubtful?

- Why the center of mass of strongest excess is shifted in respect to the GC? (e.g. Su&Finkbeiner2012)
- What is the origin of the other excesses? (e.g., Boyarsky+2012)
- Why are excesses detected at different energies? (e.g. Su&Finkbeiner2012)

Standard cosmological interpretation faces a few severe challenges, thus an astrophysical solution is wanted...

Astrophysical GeV Lines

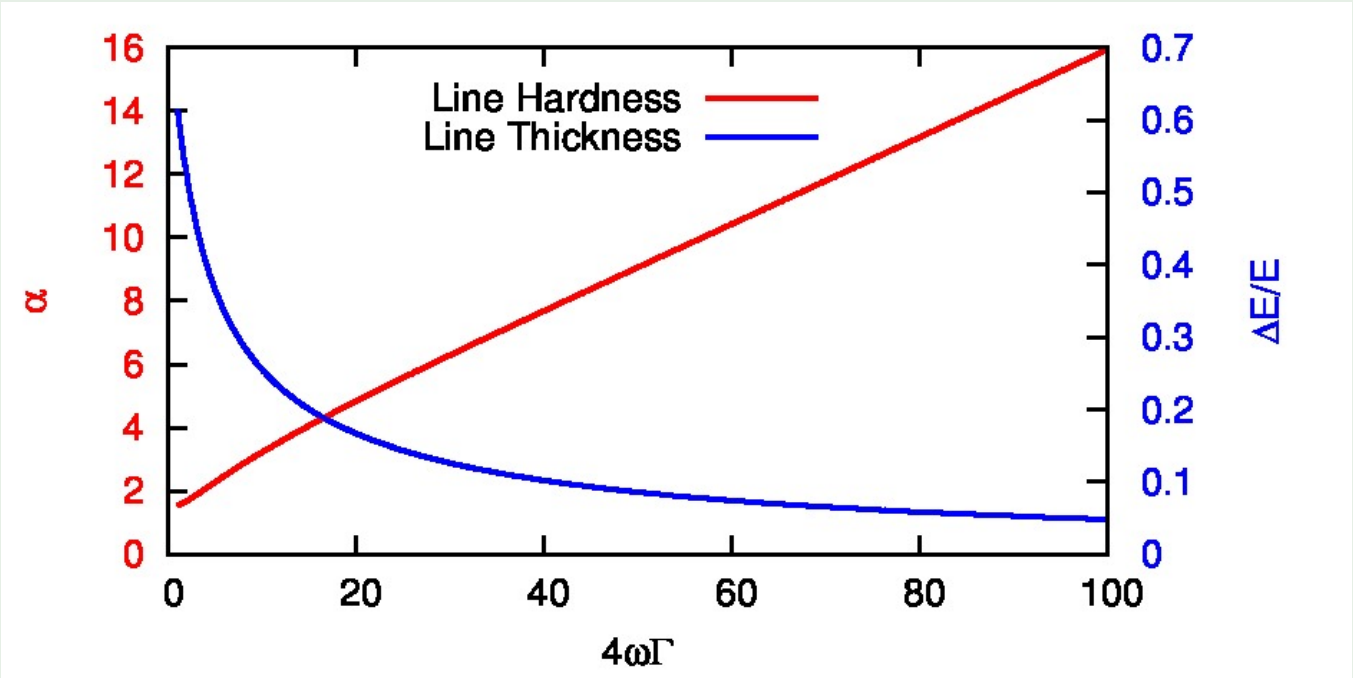
Klein-Nishina is the only mechanism (Aharonian+2012)



Typically non-thermal radiation mechanisms result in a power-law distribution, but there is one exception

Astrophysical GeV Lines

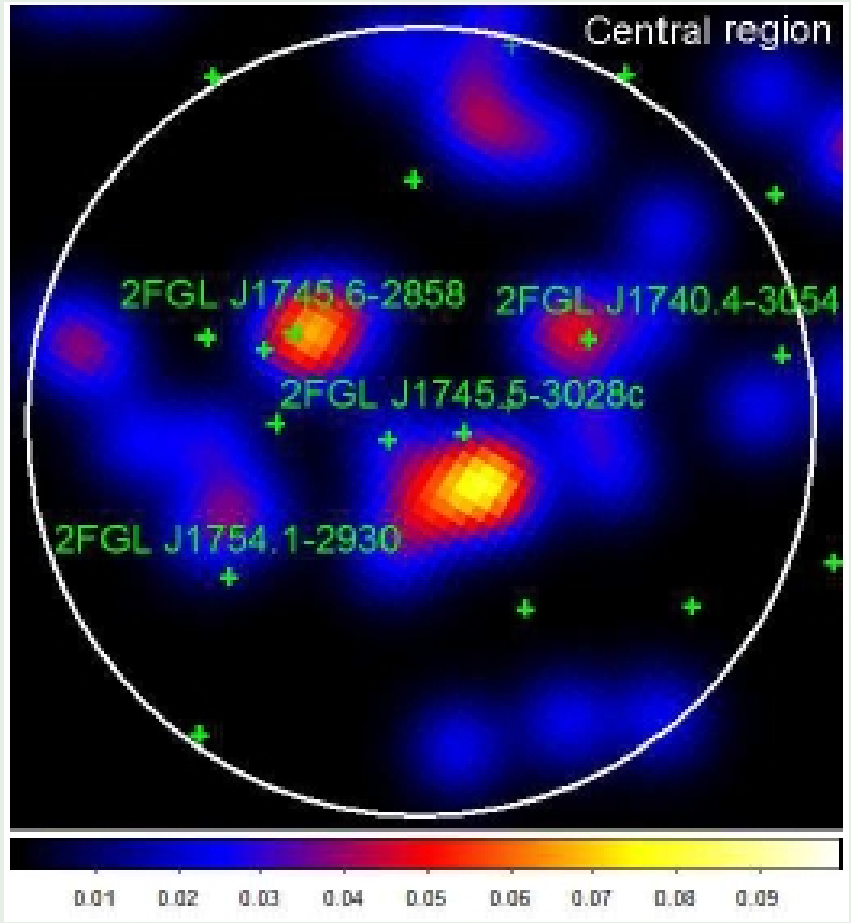
But the photon field must be very hot $> 5 \times 10^4$ K (Aharonian+2012)



GeV line emission can be produce by pulsar wind, but in this case the source is expected to be point-like

Astrophysical GeV Lines: Point Like Sources?

Currently available data (Aharonian+2012)



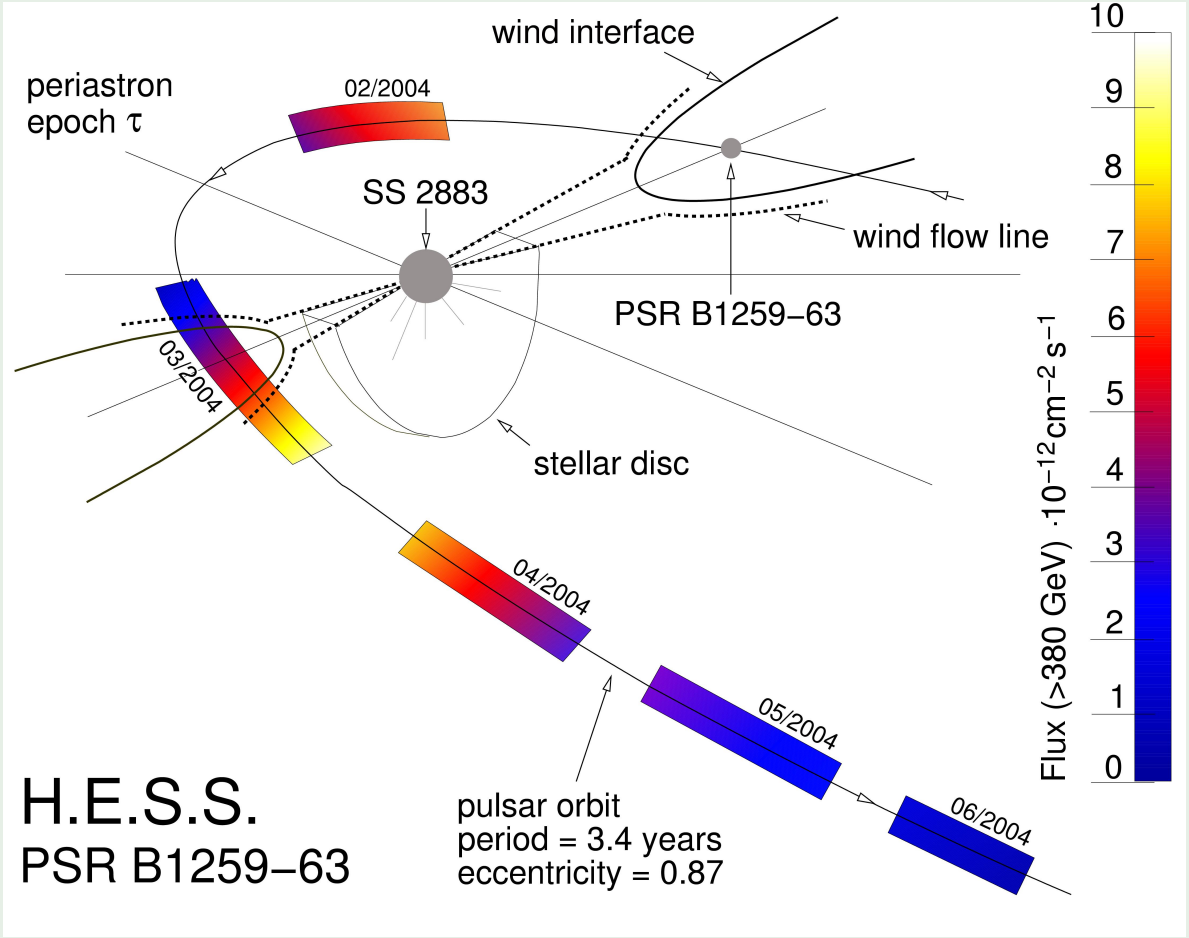
The “diffuse” components are in fact consistent with point-like contributions

What can CTA do?

Astronomy Picture of the Day, July 27

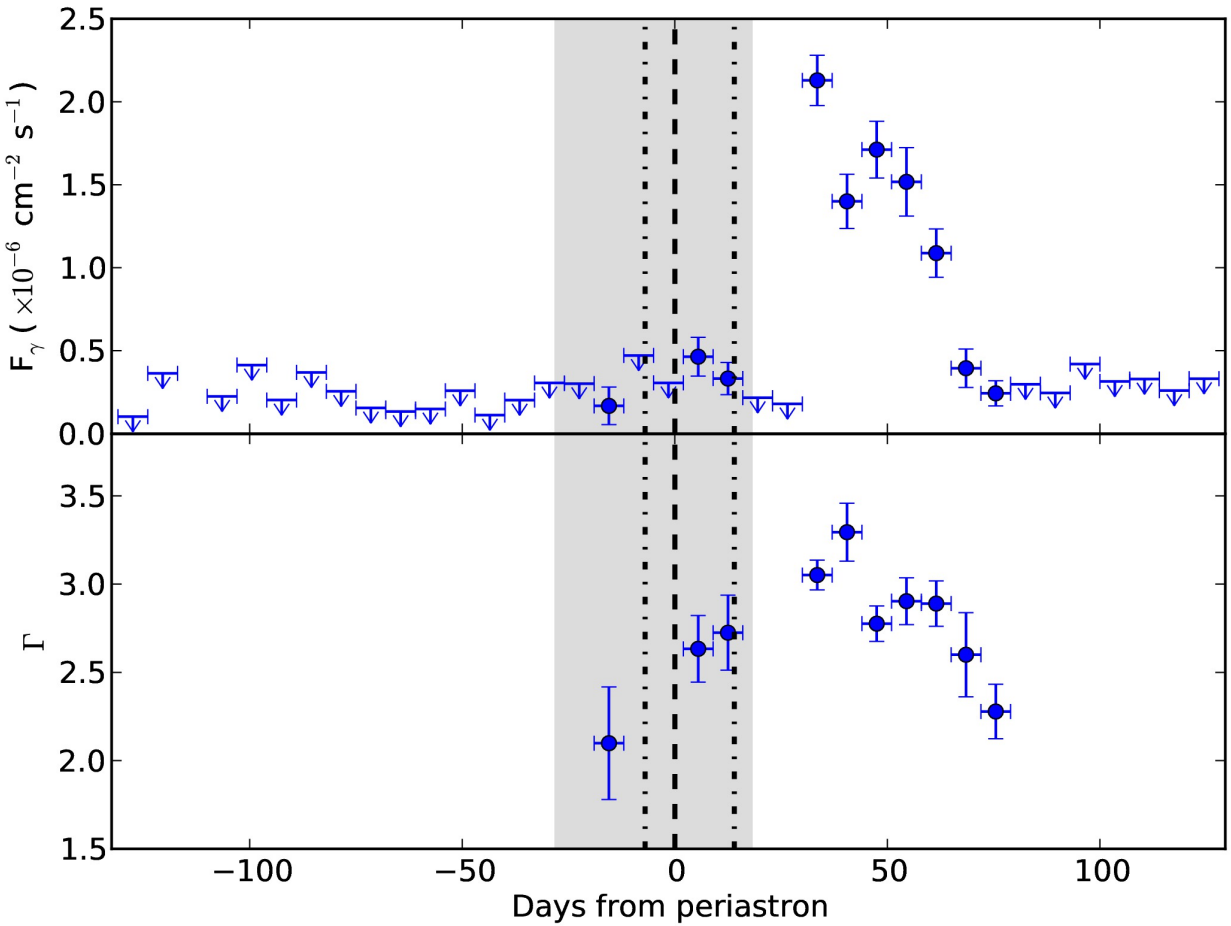
HESS II inauguration on September 27-28

Binary pulsar PSR B1259



There are a few systems where non-accretion pulsar is orbiting a massive star

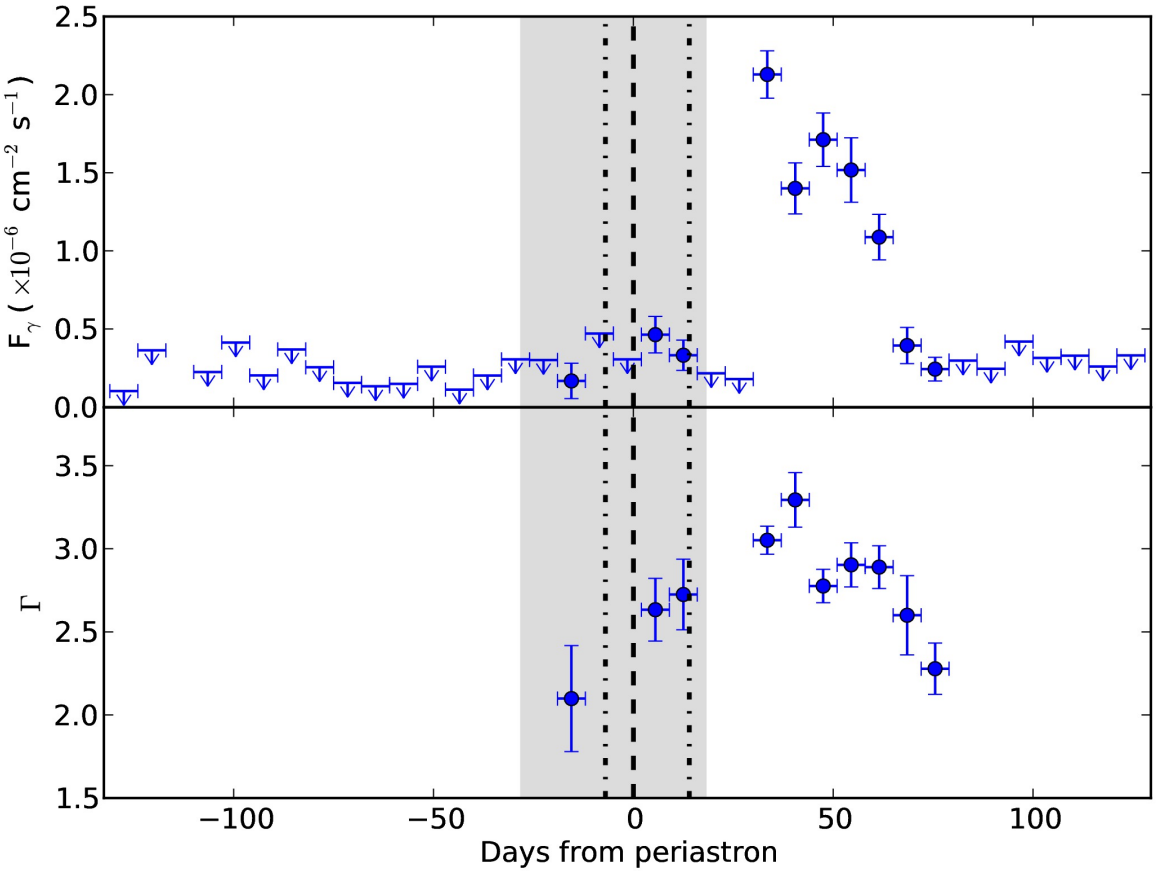
Fermi/LAT Flare from PSR B1259-63



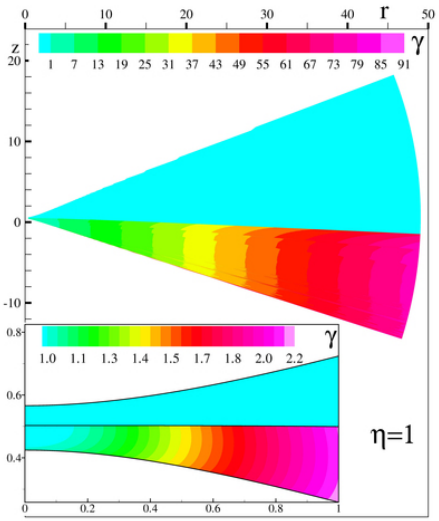
High Energy lightcurve has shown unexpected flare

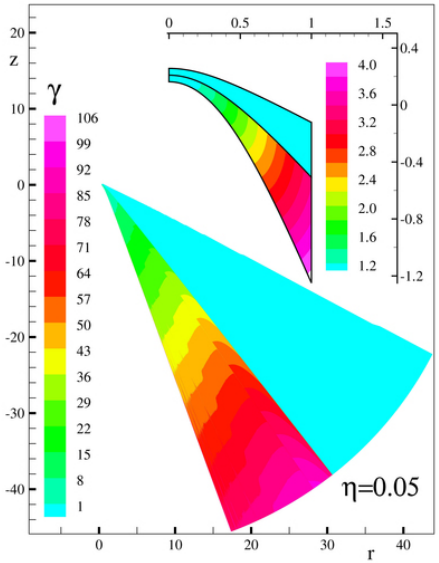
Fermi/LAT Flare from PSR B1259-63

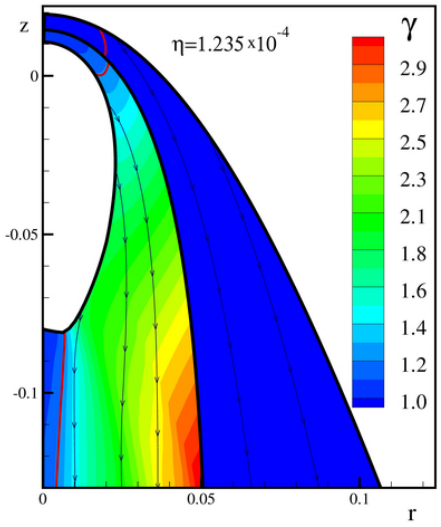
- Very Fast Rise
- Nearly SD luminosity



Hydrodynamic modeling by Bogovalov+(2007)

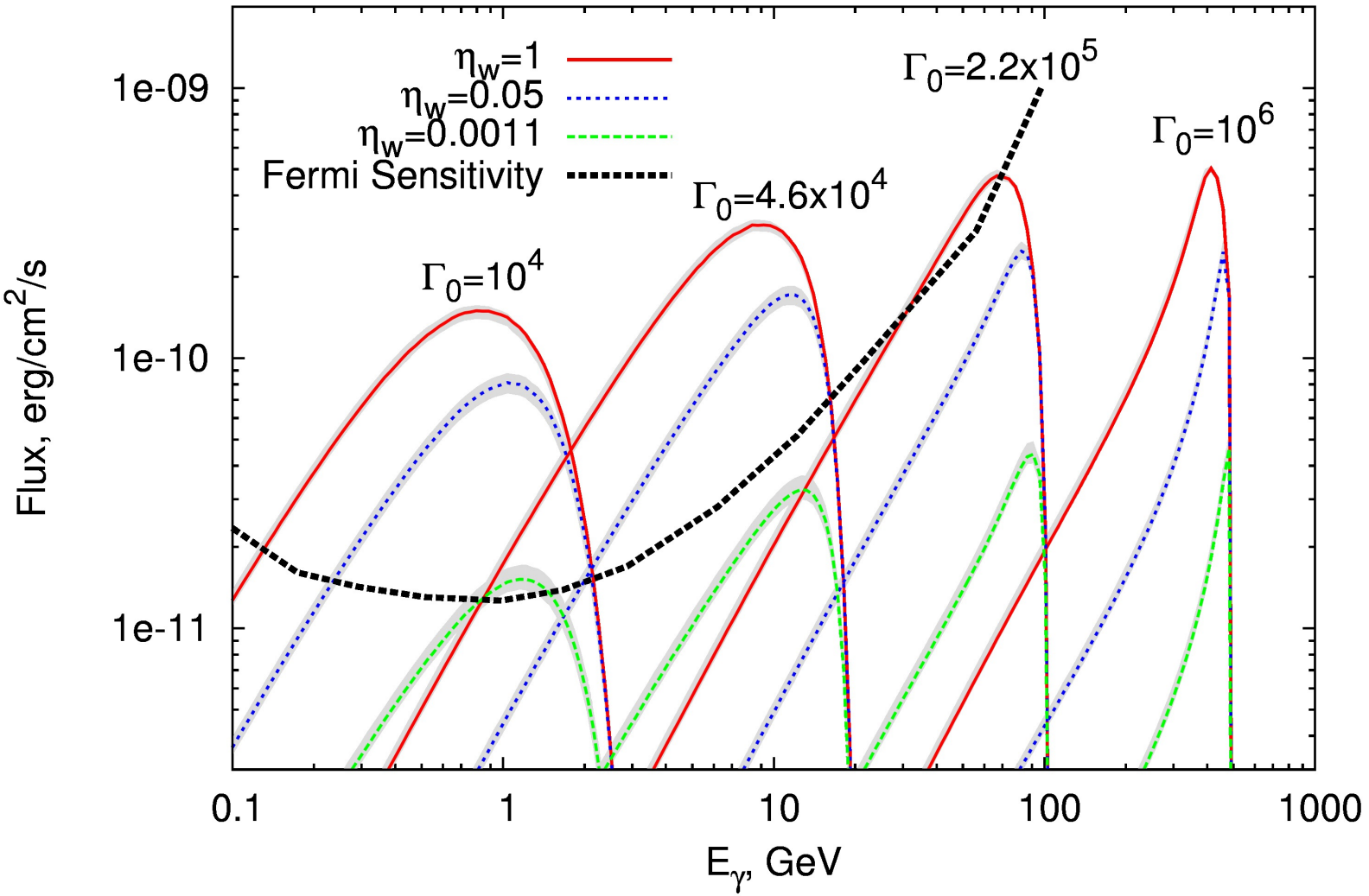






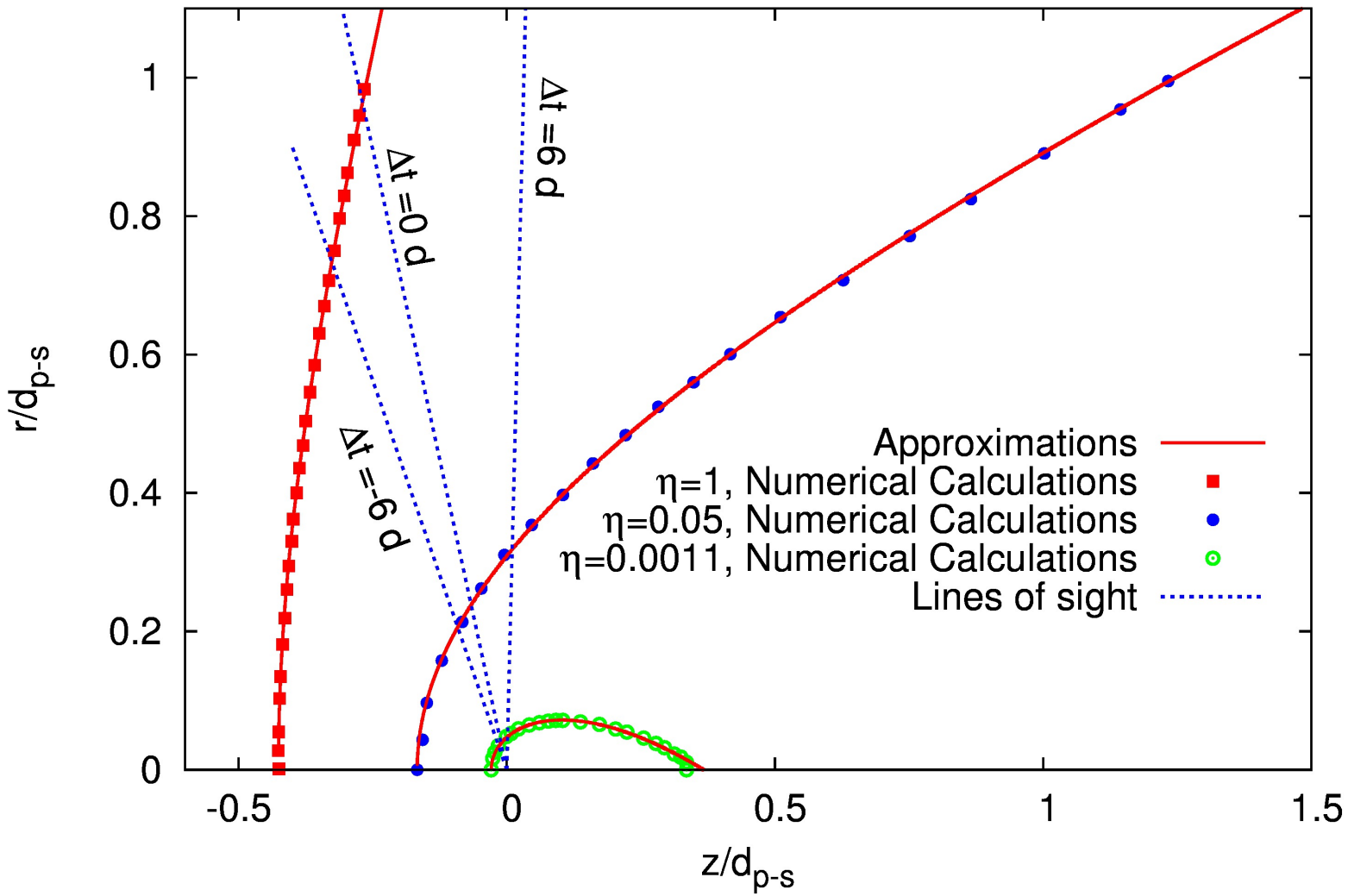
Discovered an instability in the structure of the termination shock – the transition from closed to unclosed shape. Is that the source of the flare?!

Wind Signal from PSR B1259-63

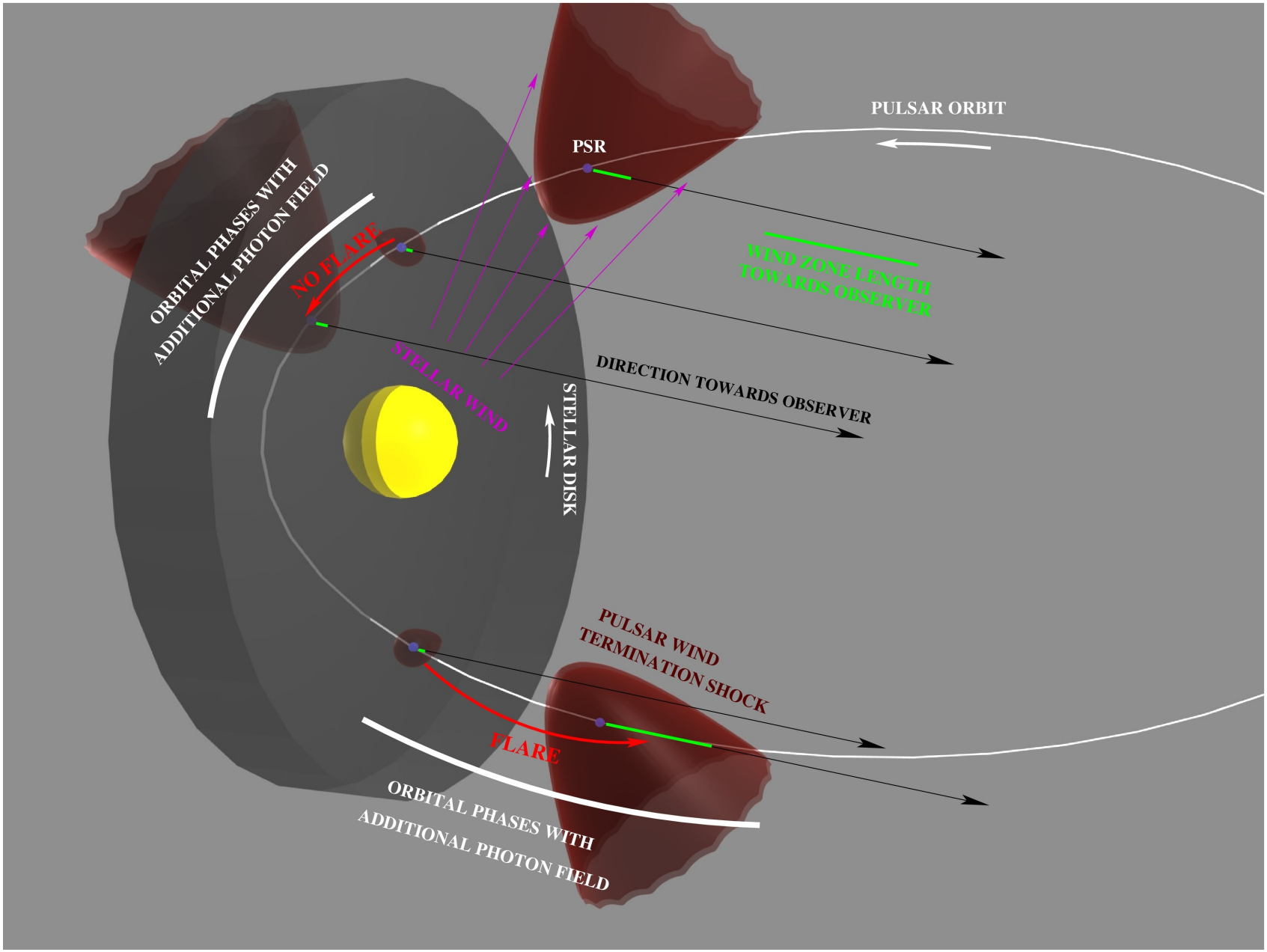


The wind signal is expected to be detectable with Fermi

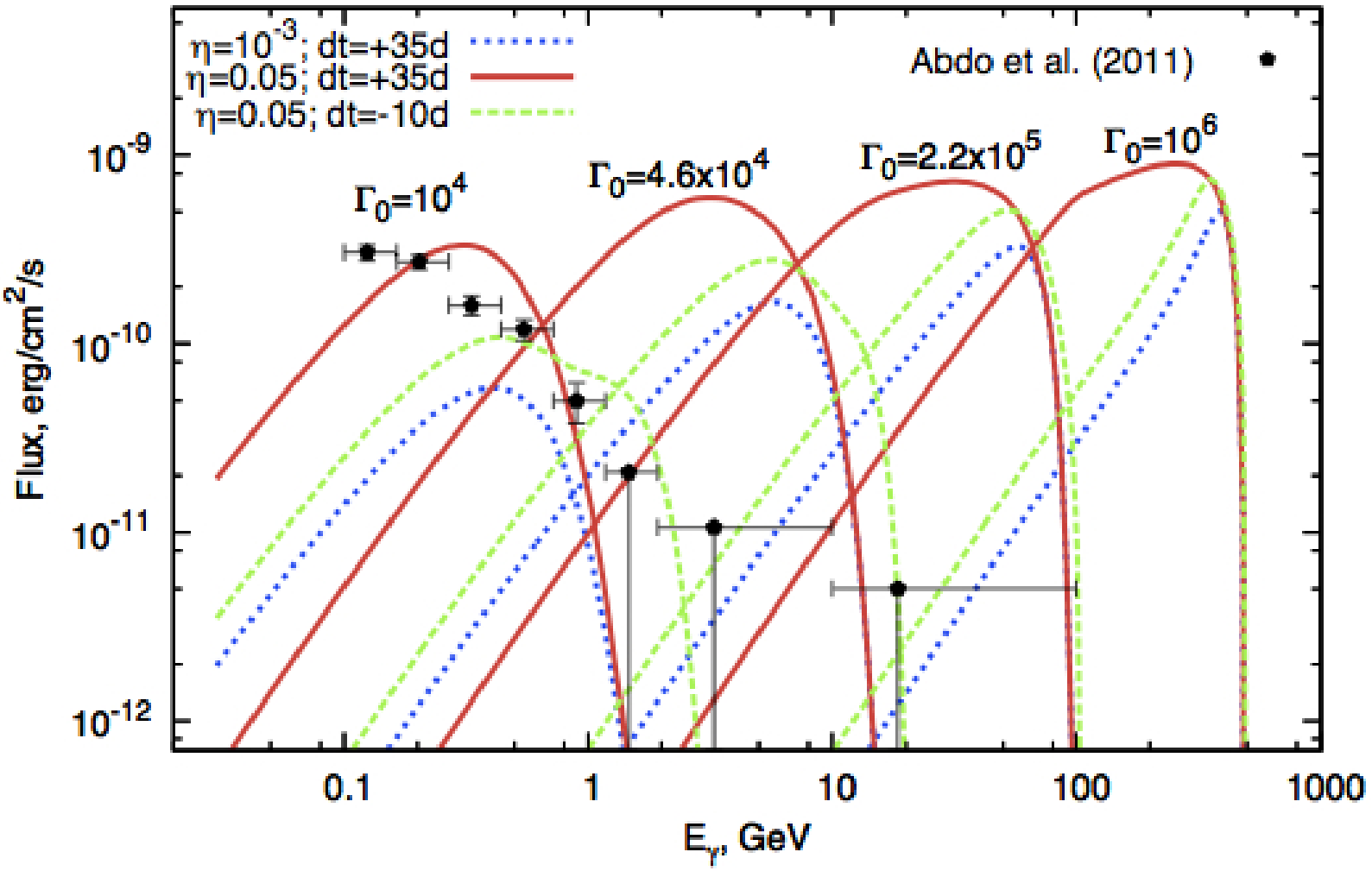
Many Impacting Factors, e.g. Geometry



However, a precise prediction can be hardly made given the uncertainties in the system parameters

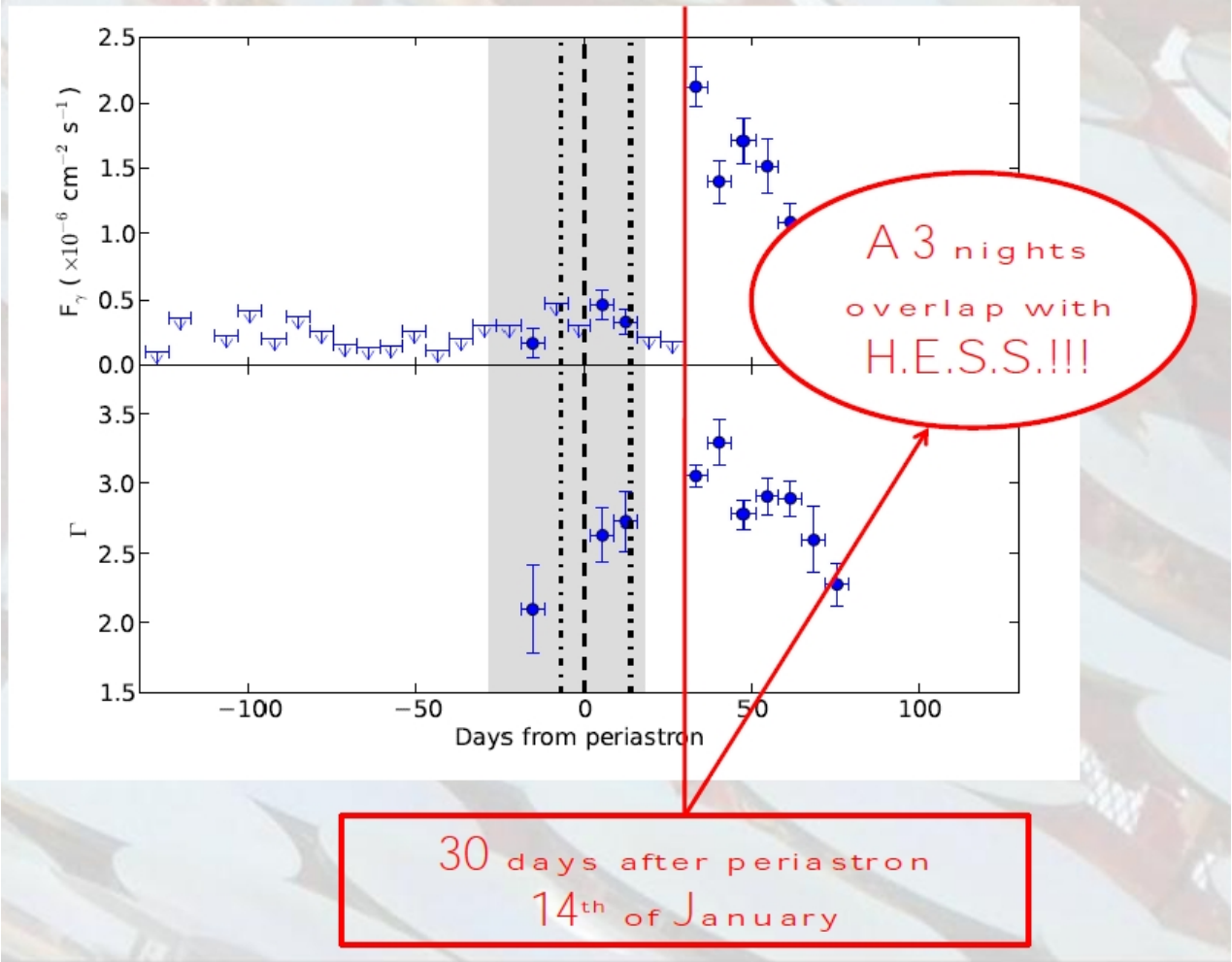

PULSAR ORBIT
PSR
ORBITAL PHASES WITH
ADDITIONAL PHOTON FIELD
NO FLARE
WIND ZONE LENGTH
TOWARDS OBSERVER
STELLAR WIND
DIRECTION TOWARDS OBSERVER
STELLAR DISK
PULSAR WIND
TERMINATION SHOCK
FLARE
ORBITAL PHASES WITH
ADDITIONAL PHOTON FIELD

Fermi/LAT Flare from PSR B1259-63



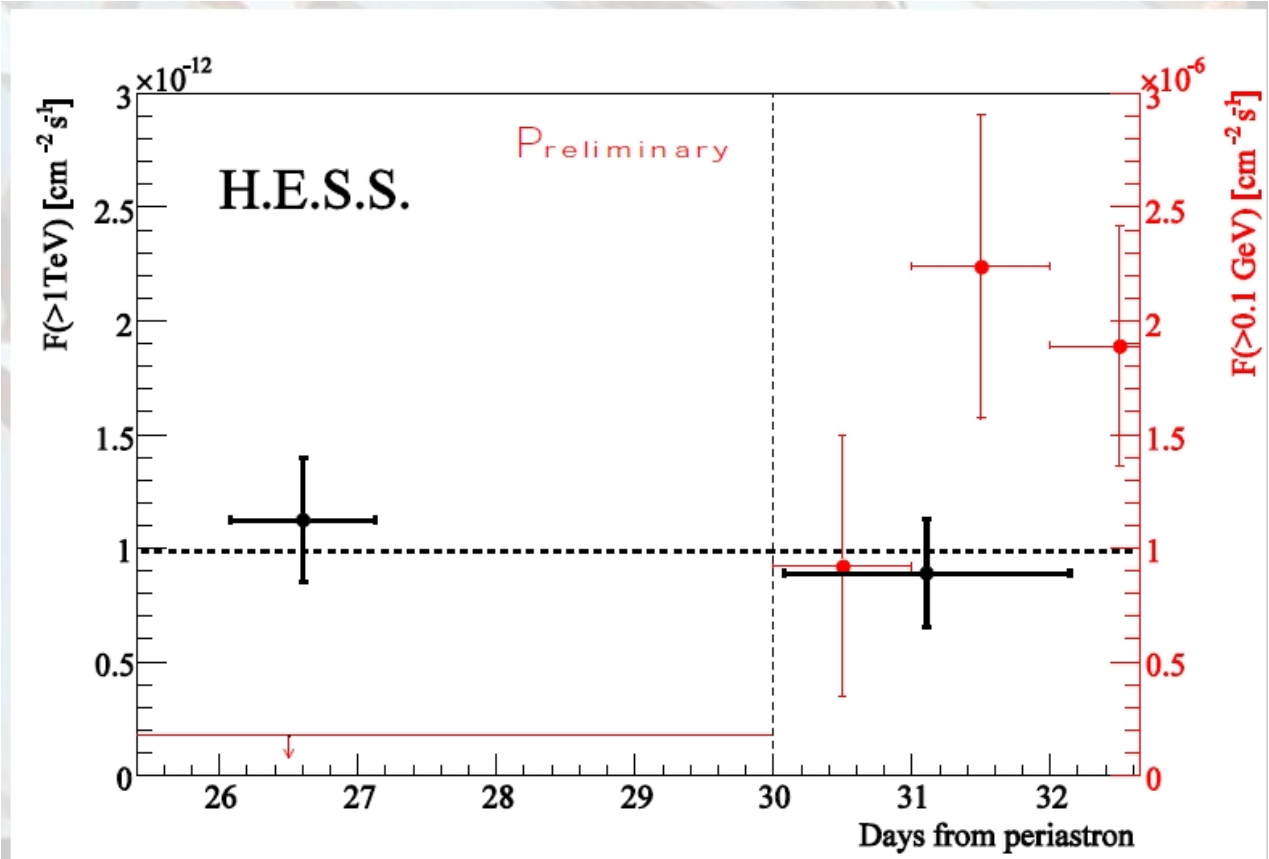
The model predictions are roughly consistent with the observations, if the disk can be strongly perturbed to provide enough dense target field

PSR B1259-63 flare in VHE (from talk by Sushch @GAMMA2012)



The flare epoch was nicely covered with observations with HESS

PSR B1259-63 flare in VHE (from talk by Sushch @GAMMA2012)



There were no changes in the VHE emission. As expected in the suggested scenario.

Summary

VHE pulsations

- 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 $\Gamma_{\rm w} \simeq 5 \times 10^5$
  - Wind formation distance $R_{\rm w} \simeq 30 R_{\rm L}$
- 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

GeV Line

- The reported GeV-line excess has a few puzzling features, which are complicated to be address in the scenario of the DM annihilation
- The only astrophysical interpretation of the GeV-line is the signal produced by cold ultrarelativistic pulsar wind
- The pulsar interpretation is (in principle) consistent with the signal morphology (in energy and spatially)

GeV Flare from PSR B1259-63

- The suggested model naturally allows to address a few very puzzling features of the flare
- Provides another measurement of the pulsar wind bulk Lorentz factor, which suggests (if compared to the value inferred in the case of the Crab pulsar) that the number of pairs generated by different pulsars is similar