Pair Cascades in the Disk Environment of the Binary System PSR B1259-63/LS 2883

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PSR B1259-63/LS 2883 is a very high energy (VHE; E > 100 GeV) γ-ray emitting binary consisting of a 48 ms pulsar orbitting around a Be star with a period of ∼ 3.4 years. The Be star features a circumstellar disk which is inclined with respect to the orbit in such a way that the pulsar crosses it twice every orbit. The circumstellar disk provides an additional field of target photons which may contribute to inverse Compton scattering and gamma-gamma absorption, leaving a characteristic imprint in the observed spectrum and light curve of the high energy emission. We study the signatures of Compton-supported, VHE gamma-ray induced pair cascades in the circumstellar disc of the Be star and their possible contribution to the GeV flux. We also study a possible impact of the gamma-gamma absorption in the disk on the observed TeV light curve.

Subject :	:	oral
Topics	:	Astrophysics

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North-West University

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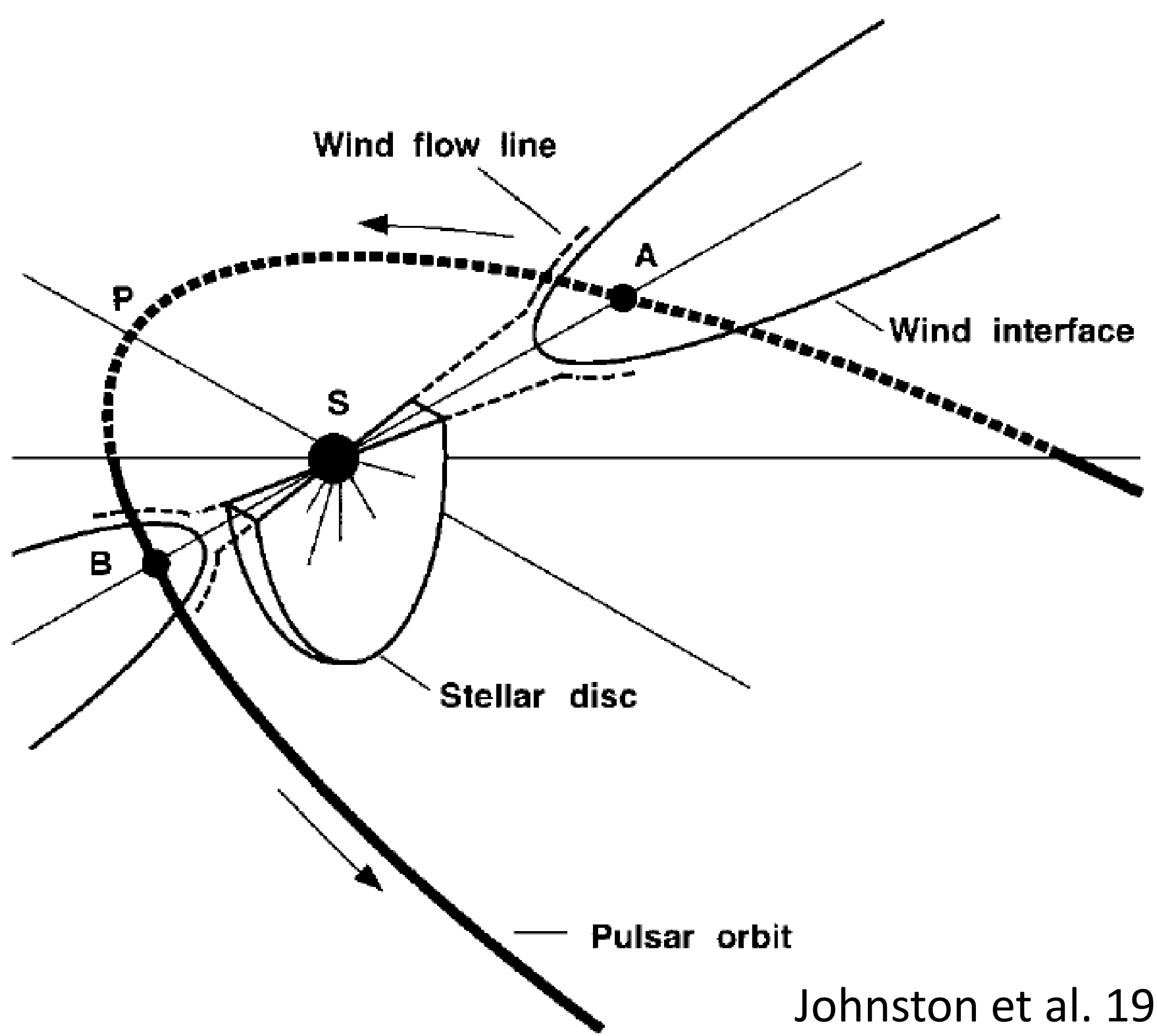
PSR B1259-63/LS 2883

PSR B1259−63

- P = 48 ms
- $L_{SD} = 8 \times 10^{35}$ erg/s
- $t_c = 3.3 \times 10^5$ years
- $P_{orb} = 3.4$ years
- Eccentricity = 0.87

LS 2883

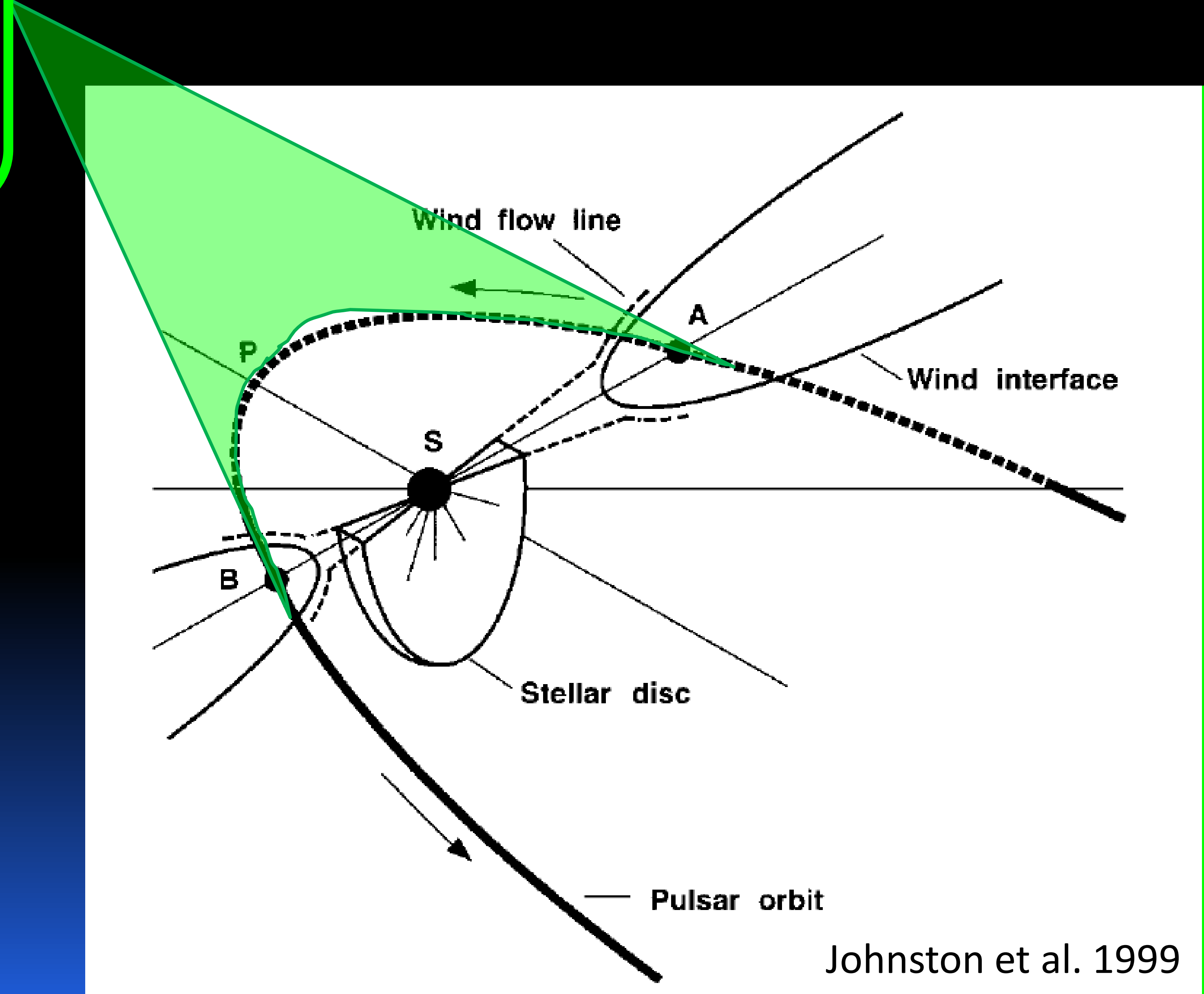
- Be star
- Circumstellar disk
- $L_{star} = 2.3\times10^{38}$ erg/s
- T = 27500 – 30000 K
- $M \approx 31\ M_{sun}$
- $R = 8.1 – 9.7\ R_{sun}$
- D = 2.3 kpc



Johnston et al. 1999

PSR B1259-63/LS 2883: unpulsed emission

Radio pulsed emission disappears as the pulsar goes behind the disk

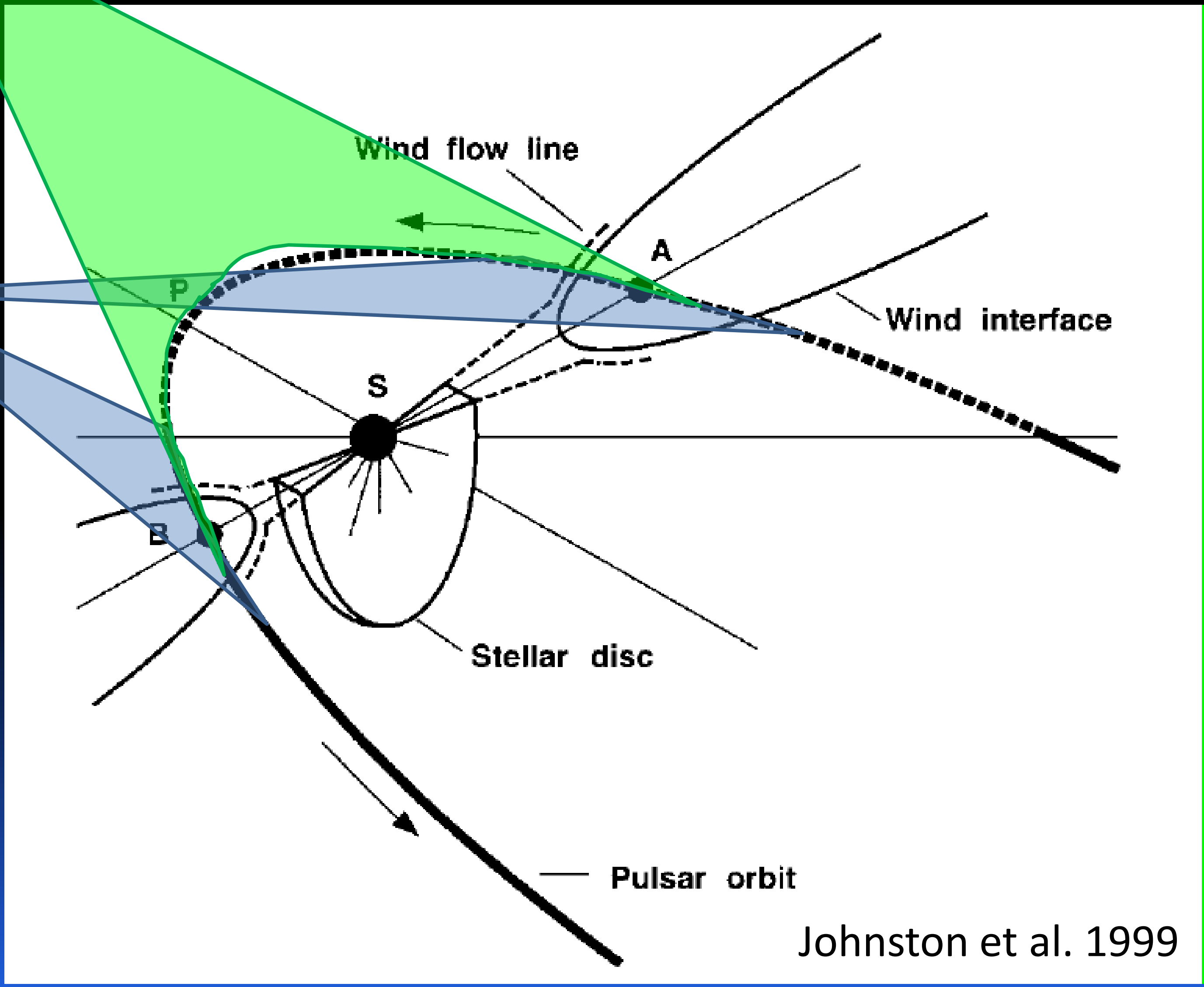


Johnston et al. 1999

PSR B1259-63/LS 2883: unpulsed emission

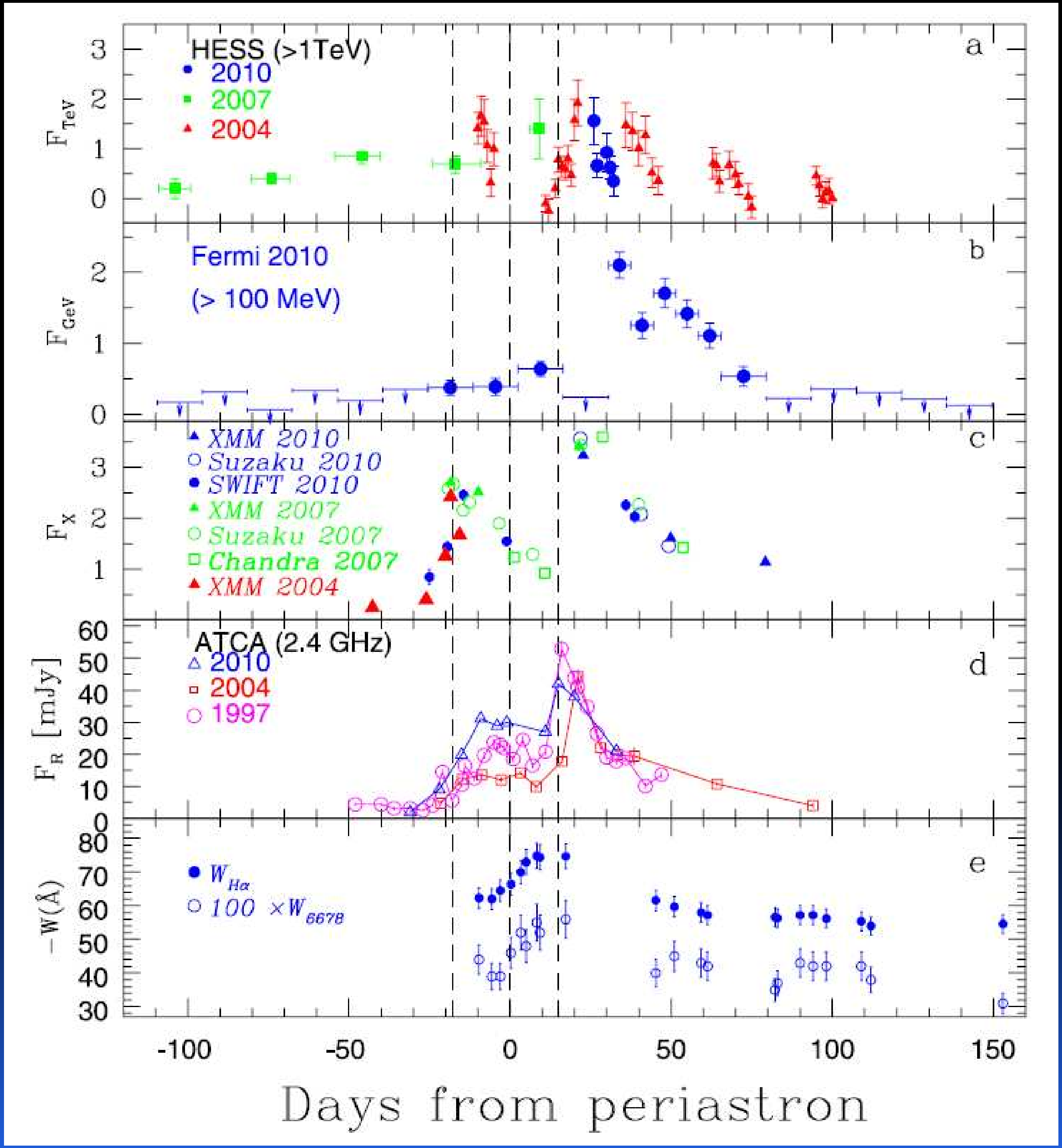
Radio pulsed emission disappears as the pulsar goes behind the disk

The unpulsed emission from the system is enhanced when the pulsar interacts with the circumstellar disk



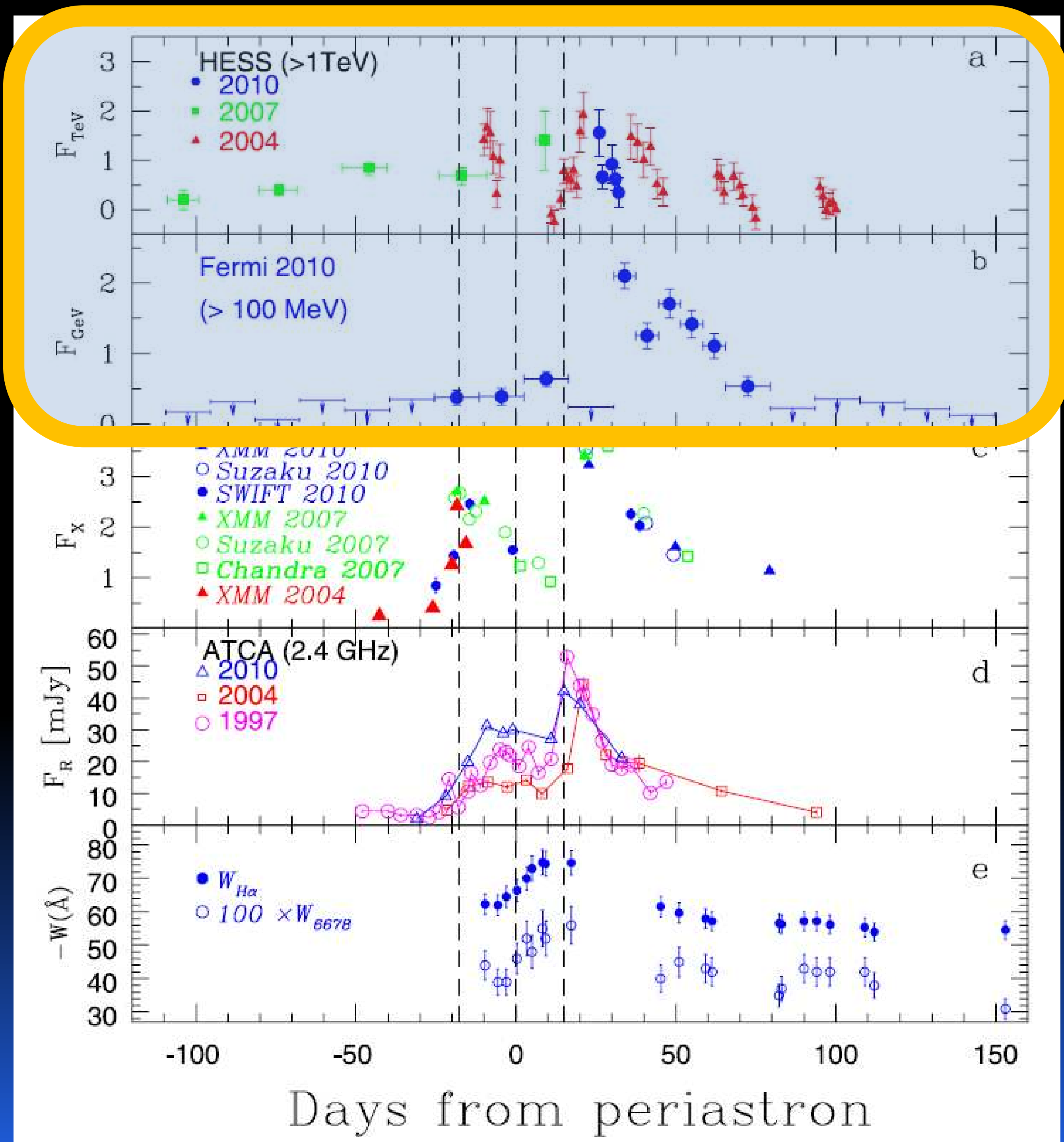
Johnston et al. 1999

Across the spectrum



Chernyakova et al., 2014

Across the spectrum

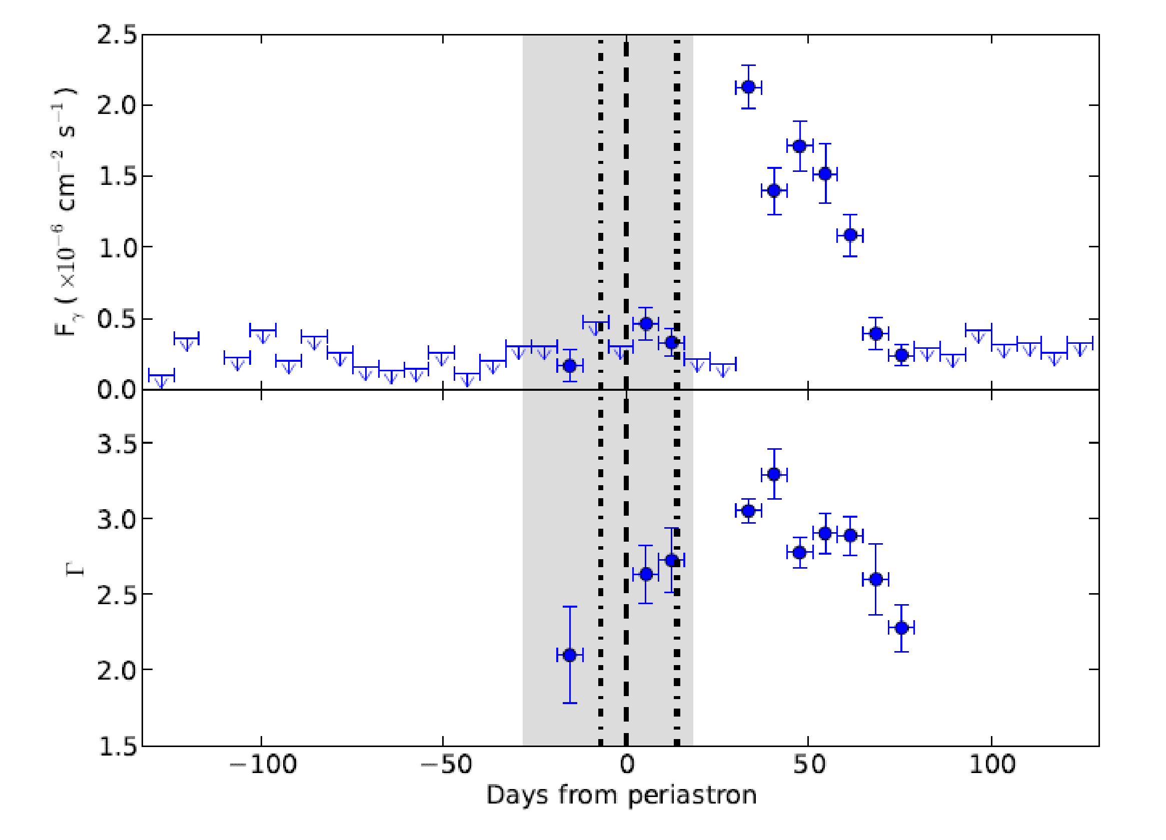


Chernyakova et al., 2014

GeV Emission

Abdo et al. 2011

- Weak emission close to the periastron
- Spectacular flare 30 days after the periastron
- GeV flare displaced with respect to the post-periastron peak at other energies
- No counterpart at other energies



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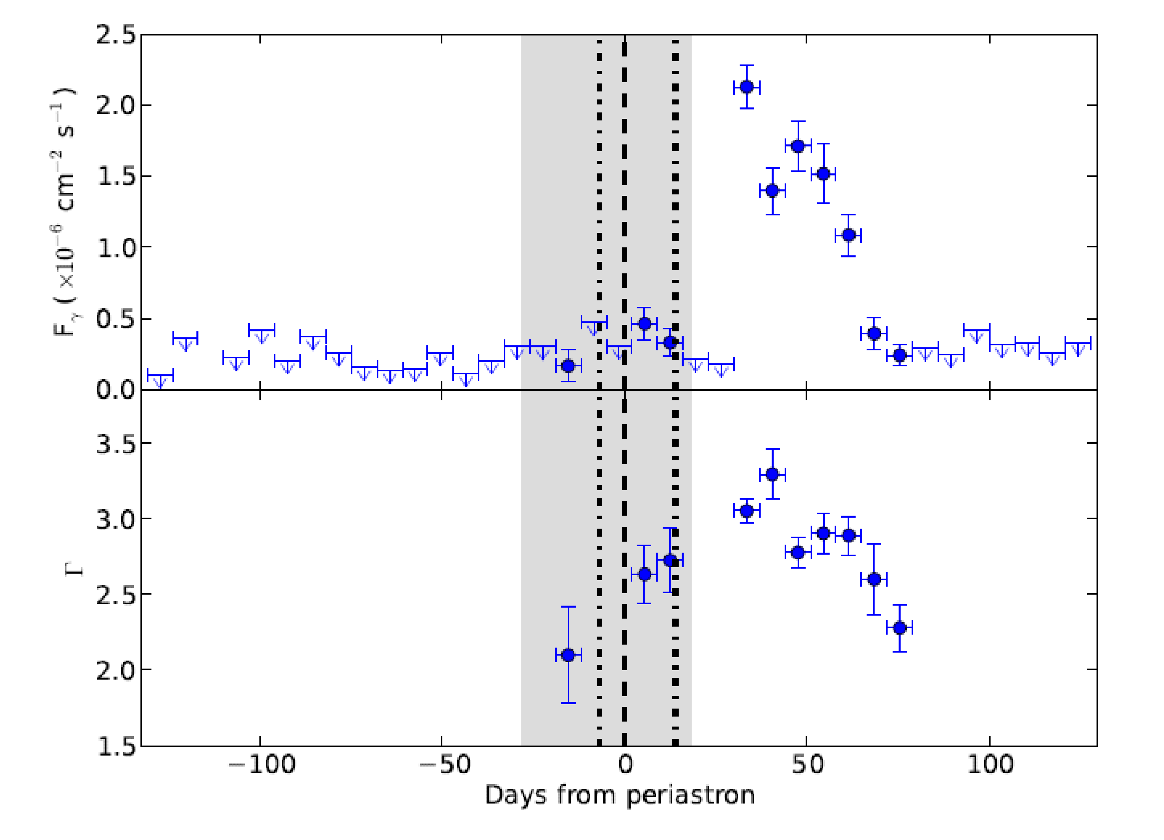
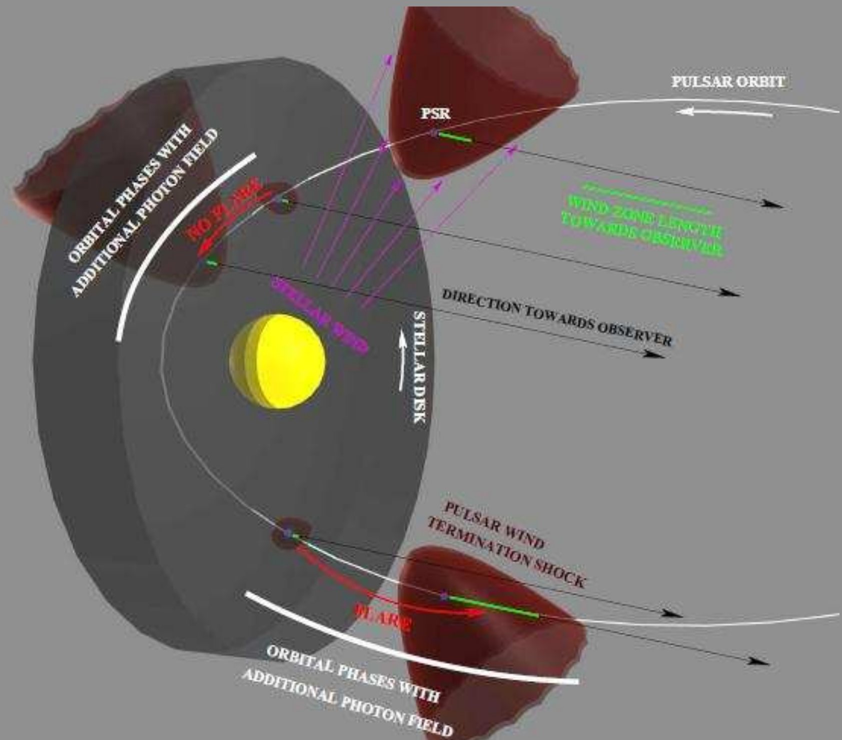


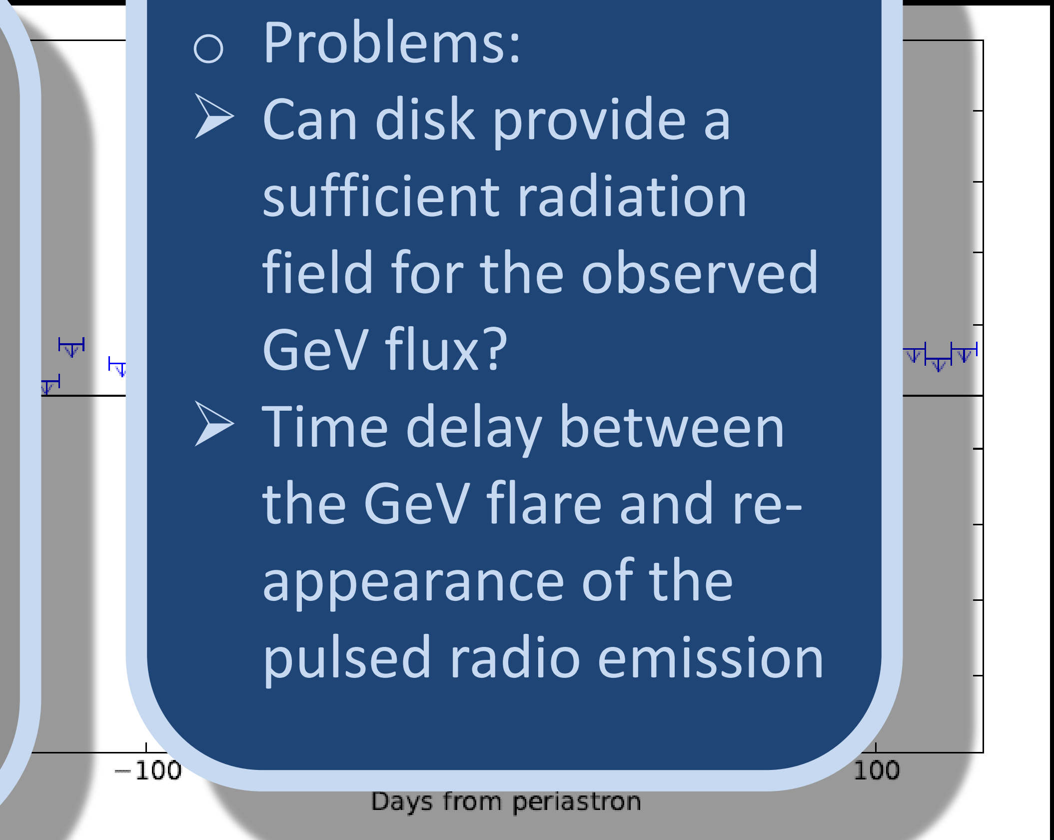
Several possible explanations:
- IC scattering of stellar and disk photons by unshocked pulsar wind
- Doppler boosting
- IC scattering of X-ray photons

GeV Emission



Khangulyan et al. 2012

2011



- *Khangulyan et al. 2012*
- Problems:
  - Can disk provide a sufficient radiation field for the observed GeV flux?
  - Time delay between the GeV flare and re-appearance of the pulsed radio emission

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- IC scattering of stellar and disk photons by unshocked pulsar wind
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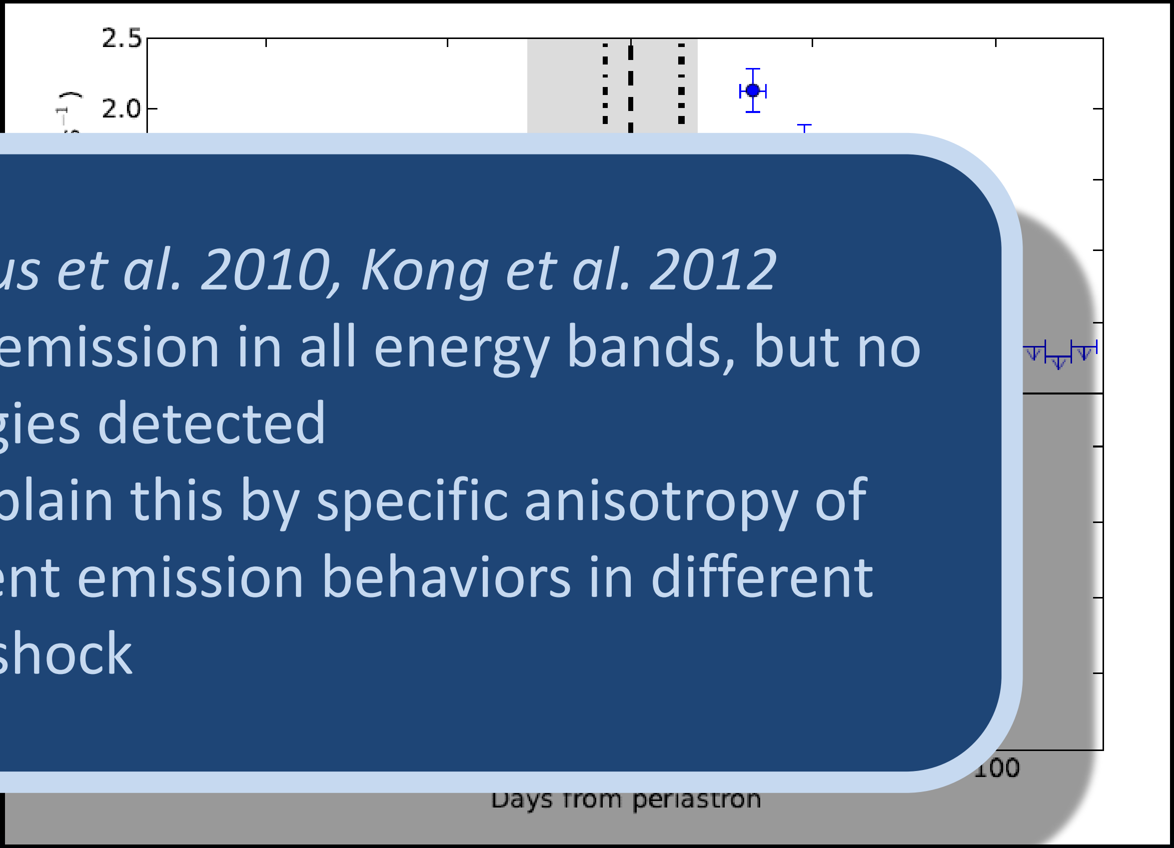
GeV Emission

Abdo et al. 2011



- Weak emission close to the periastron

- *Bogovalov et al. 2008, Dubus et al. 2010, Kong et al. 2012*
- Problem: should affect the emission in all energy bands, but no counterparts at other energies detected
- *Kong et al. 2012* tried to explain this by specific anisotropy of the pulsar wind with different emission behaviors in different regions of the termination shock

Several possible explanations:

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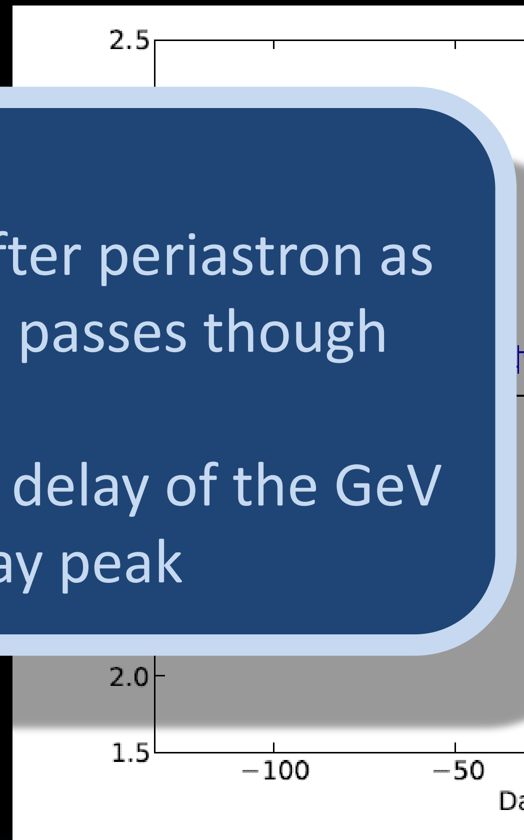
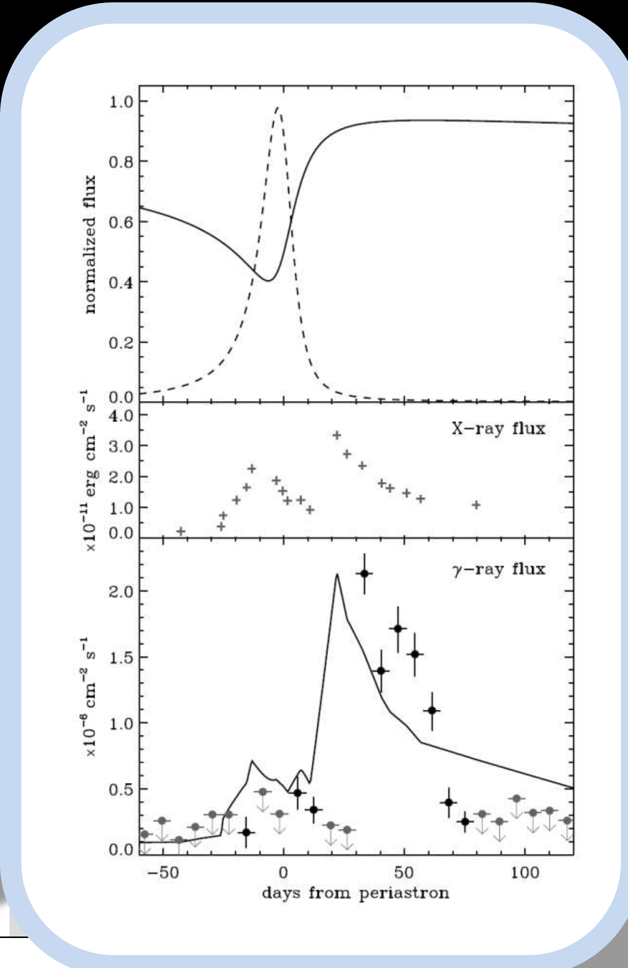
GeV Emission

- Weak emission close to the

energies



- *Dubus & Cerutti 2013*
- Light curve naturally peaks after periastron as the cone of shocked material passes though the line of sight.
- Problem: doesn't explain the delay of the GeV flare and post-periastron X-ray peak



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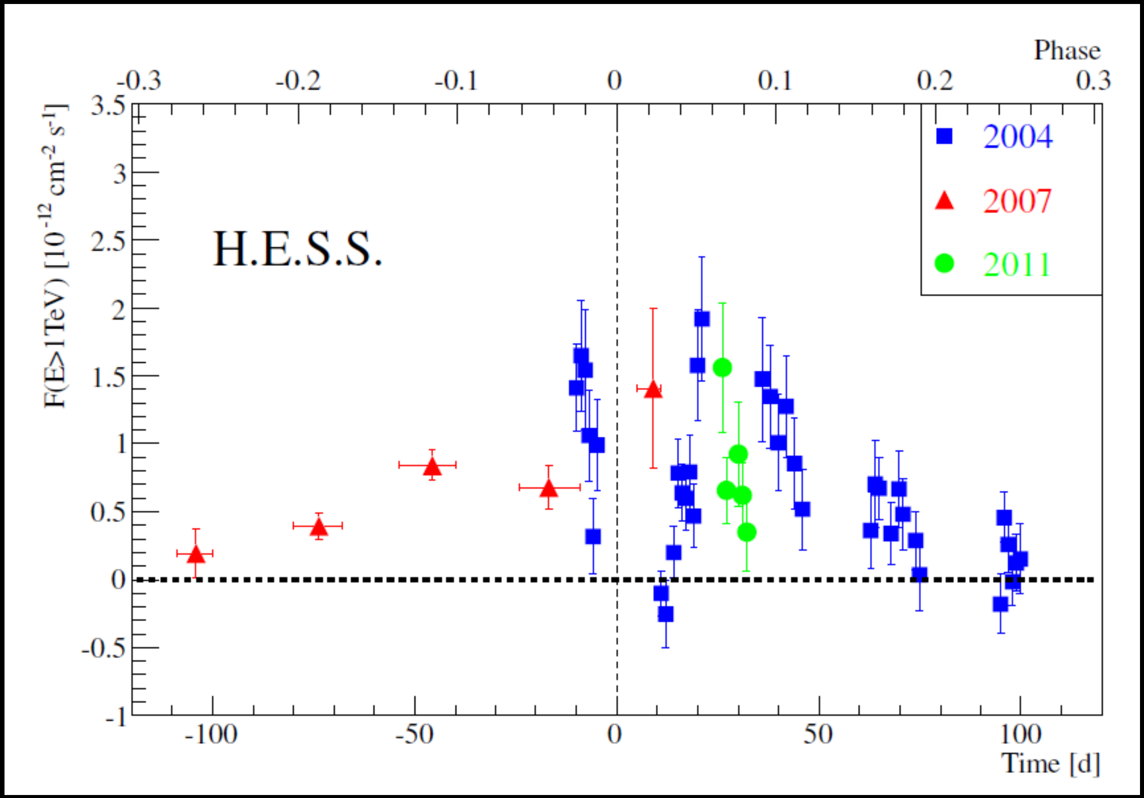
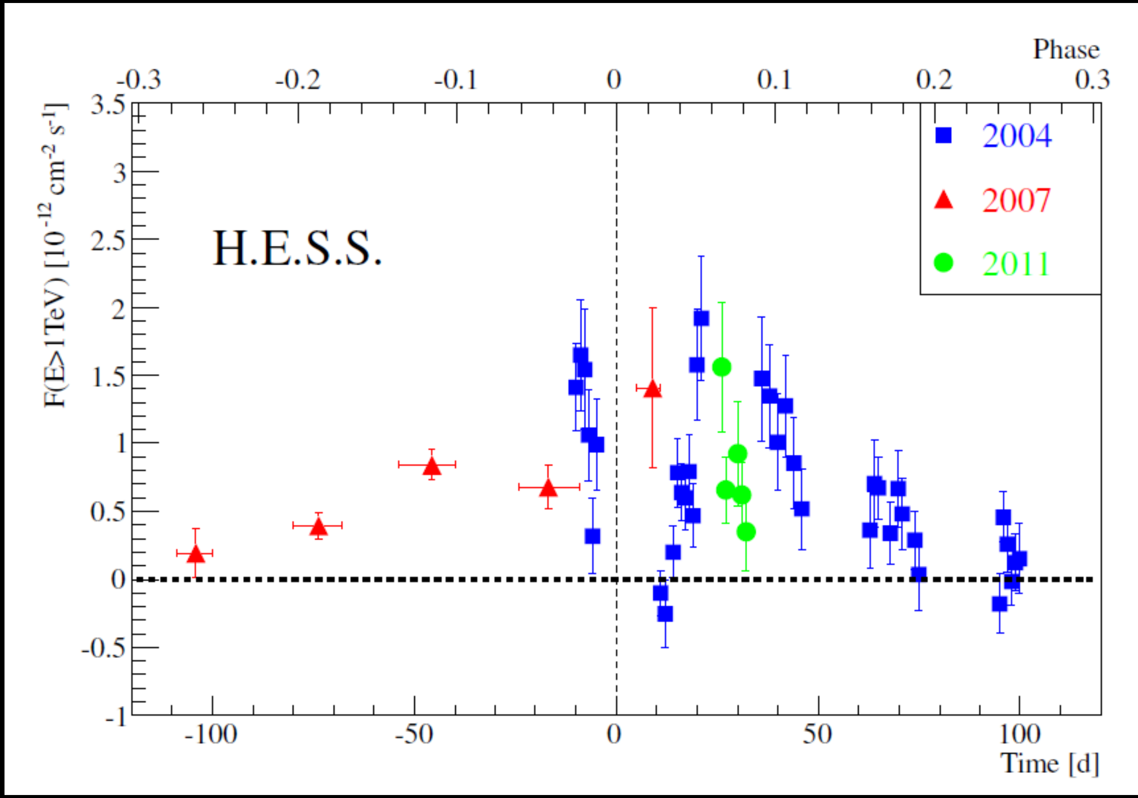
TeV Light Curve

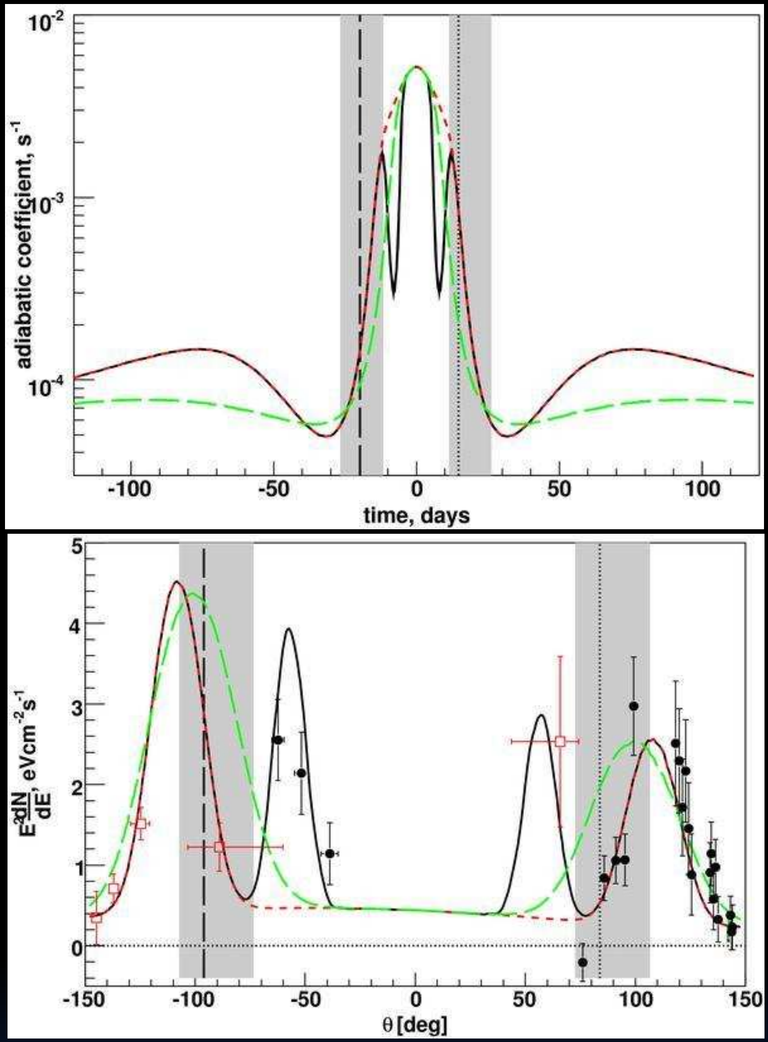


In leptonic scenario one expects:

- Peak at periastron when the separation distance is minimal
- Smooth dependence in the case of the saturation regime

TeV Light Curve





Kerschhaggl, 2011

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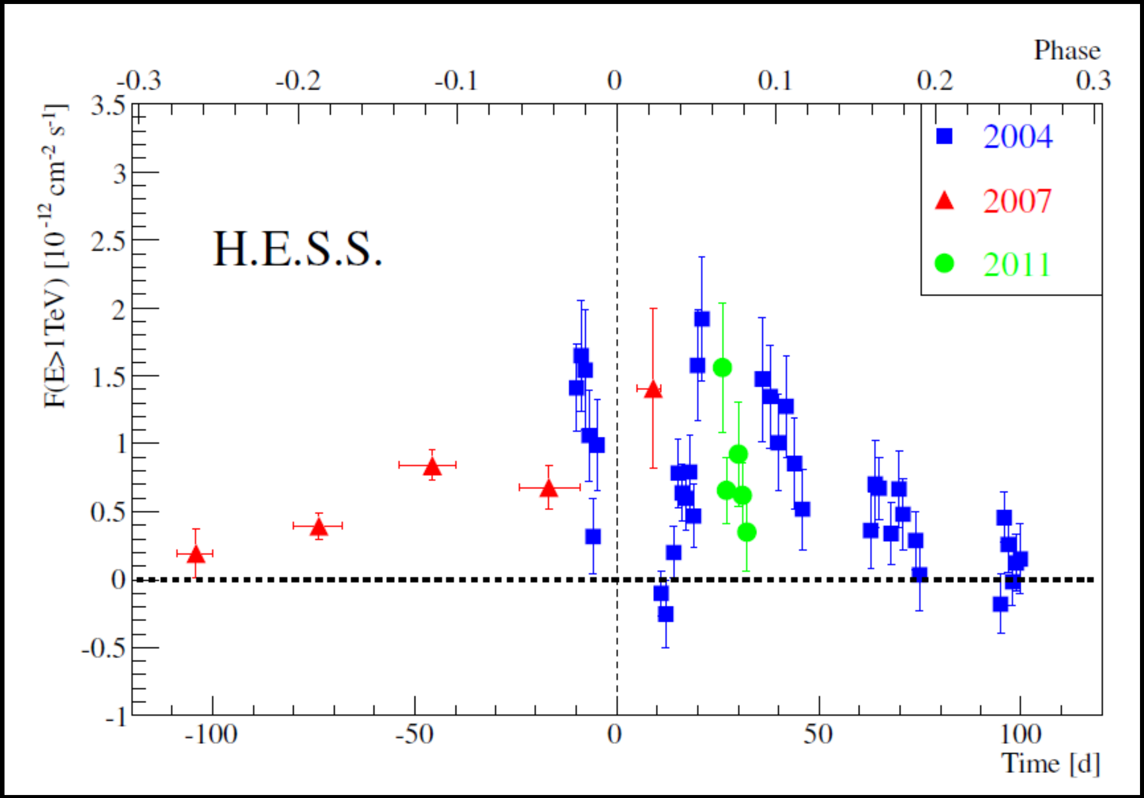
Orbital dependent adiabatic losses?

TeV Light Curve

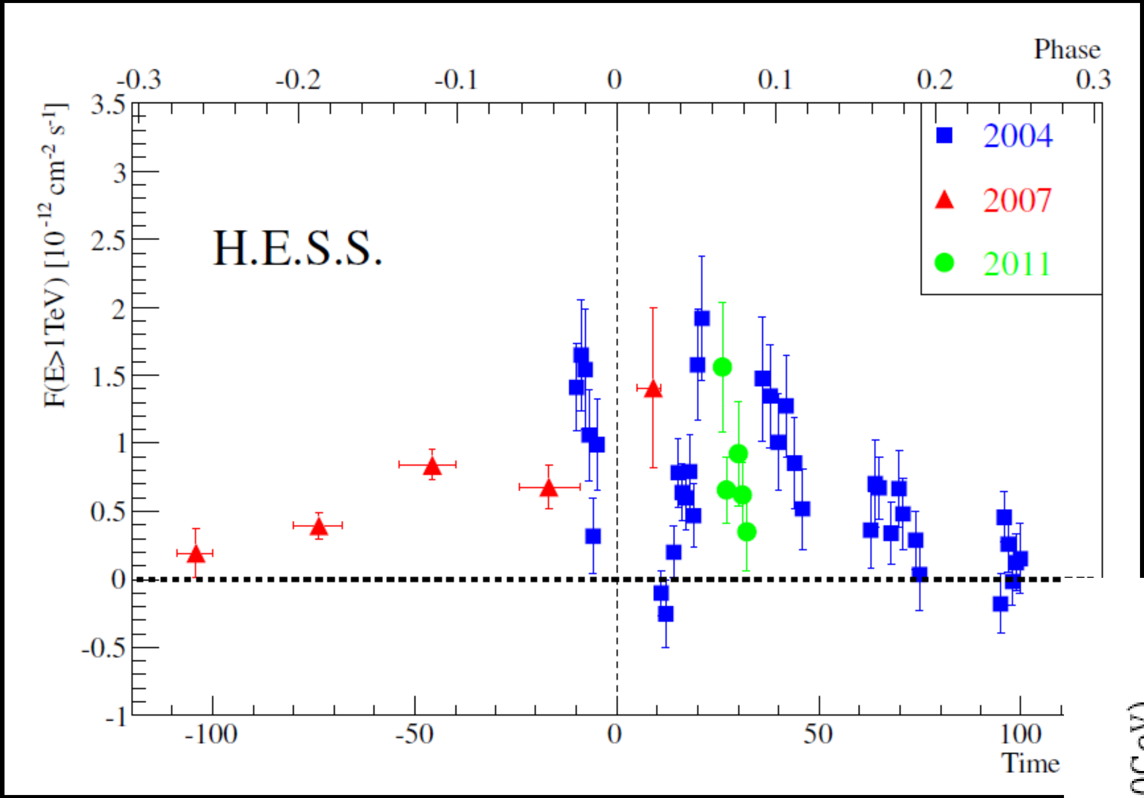


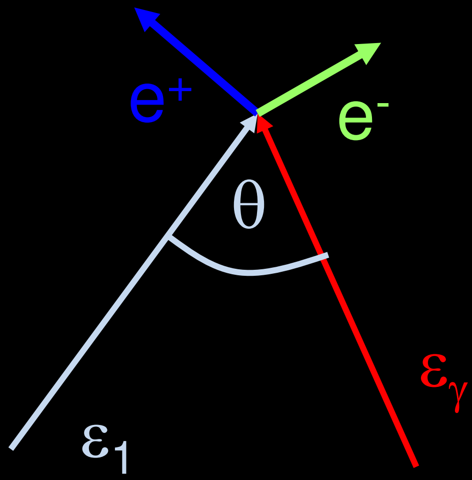
TeV light curve supports hadronic scenario:

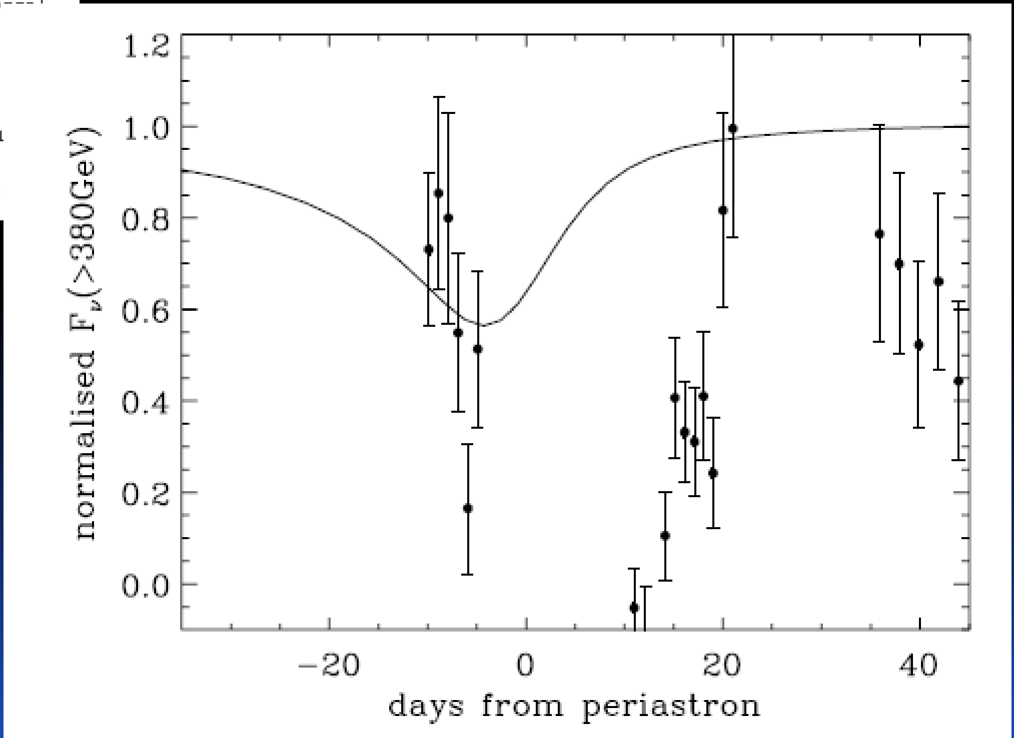
- Two sharp peaks which correspond to the disk crossings
- Secondary leptons can re-emit via IC and synchrotron at radio and X-ray energies

But:
Geometry of the disk recovered from radio observations is different from the one required for hadronic scenario

TeV Light Curve





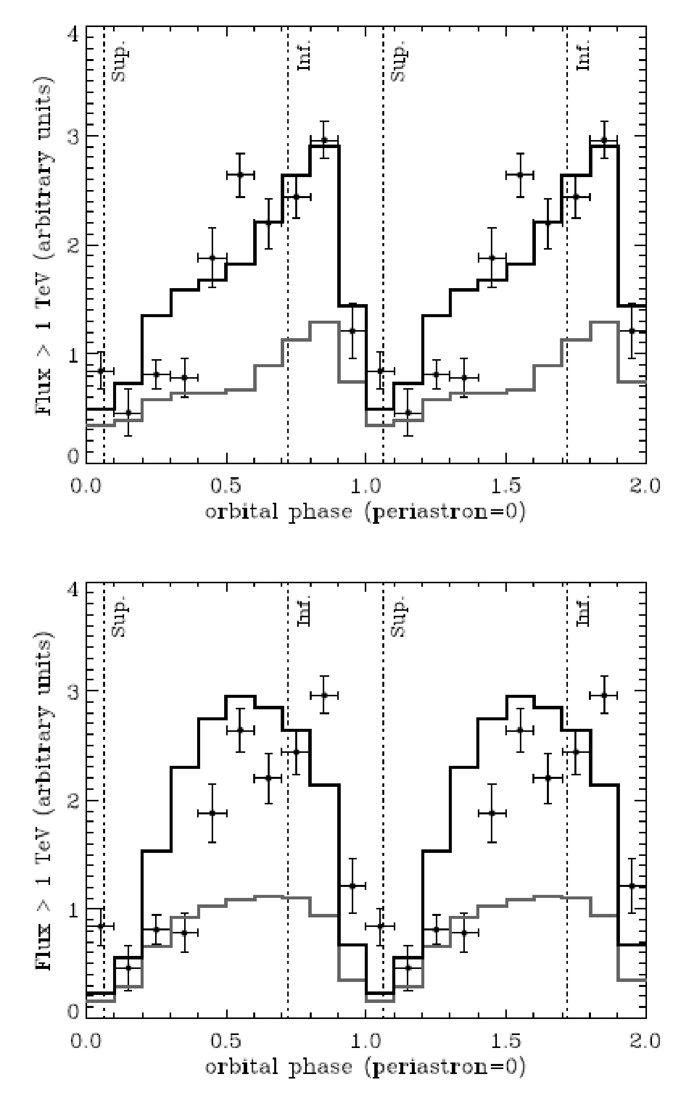


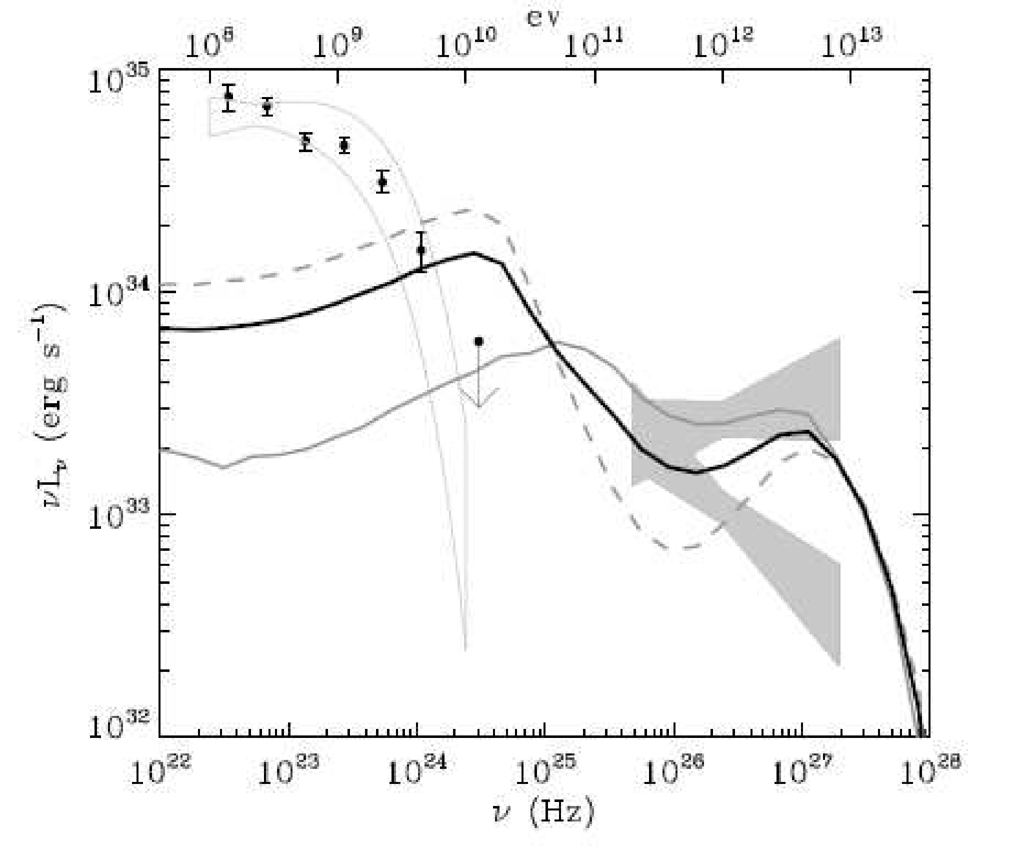
Gamma-gamma absorption?

Dubus, 2006

Pair Cascades in Binaries

LS 5039 case





Violates Fermi upper limits

Explains the flux at superior conjunction

Cerutti et al., 2010

Cascades in the disk of PSR B1259-63.

Model assumptions

- Point source assumption

$$\rho = d\frac{\sqrt{\eta}}{(1+\sqrt{\eta})},$$

$$\eta = L/(\dot{M}_* c v_*)$$

$\eta \approx 10^{-5} - 10^{-3}$

$\rho \approx (10^{-3} - 10^{-2})\, d$

- Spherically symmetrical emission
- We consider a mono-directional beam of photons to isolate geometrical effects
- Spectrum follows a power-law with an exponential cut-off photon spectral index = 1.5, cut-off energy = 1 TeV
- Toroidal magnetic field. B ~ 1 G. We consider the range 10^{-2}-10 G.

$$B(r) \approx B_S \begin{cases} \left(\frac{R_*}{r}\right)^3, & R_* \le r < R_A, \\ \frac{R_*^3}{R_A r^2}, & R_A < r < R_{tor}, \\ \frac{v_{rot}}{v_\infty}\frac{R_*^2}{R_A r}, & R_{tor} < r, \end{cases}$$

$R_{tor} \approx 3\, R_*$

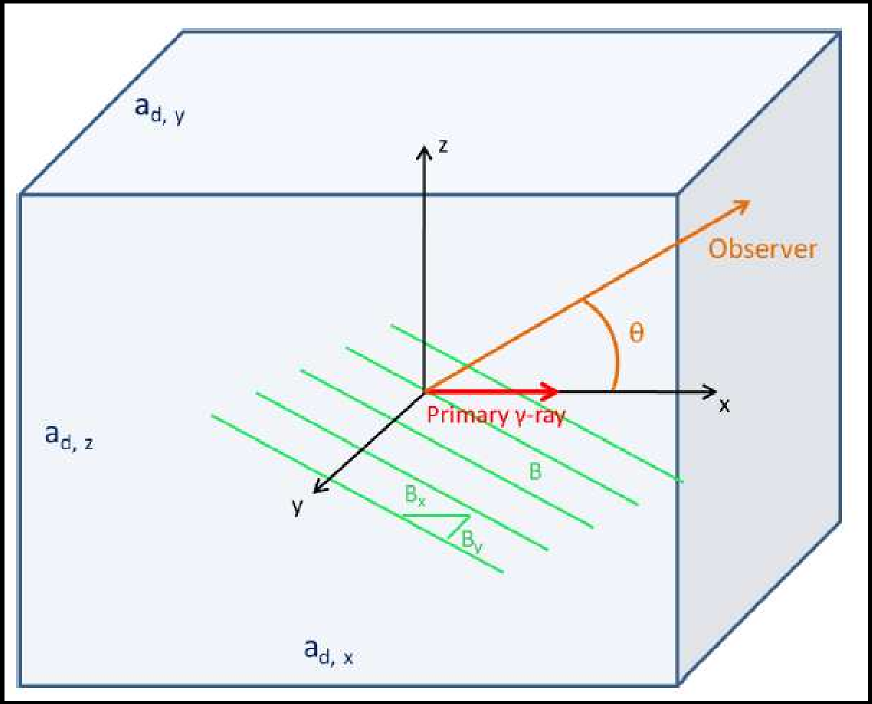
$r_{per} = 23\, R_* >> R_{tor}$

$r_d = 45\, R_* >> R_{tor}$

Usov&Melorse, 1992

Cascades in the disk of PSR B1259-63.

Disk model



- Substitute a disk by the cuboid with sides $0.5\cdot10^{13}$ cm X 10^{13} cm X $0.1\cdot10^{13}$ cm (inclination of the disk 10°, opening angle 1°)
- Disk photons are isotropized
- Blackbody distribution

$$u_d(\nu, \mathbf{r}, \mathbf{\Omega}) = \begin{cases} \frac{2h\nu^3}{c^3}\frac{A}{\exp(\frac{h\nu}{kT})-1} & \text{inside} \\ 0 & \text{outside} \end{cases}$$

$$u_d = 4\pi \int_0^\infty u_d(\nu, \mathbf{r}, \mathbf{\Omega}) d\nu.$$

- Constrains on the energy density in the disk
  - Energy density of the stellar photons
  - Total star luminosity

$$0.7 \text{ erg cm}^{-3} < u_d < 200 \text{ erg cm}^{-3}$$

- $T_{disk} = 0.6\ T_{star} = 18000$ K
- Magnetic field in the xy-plane

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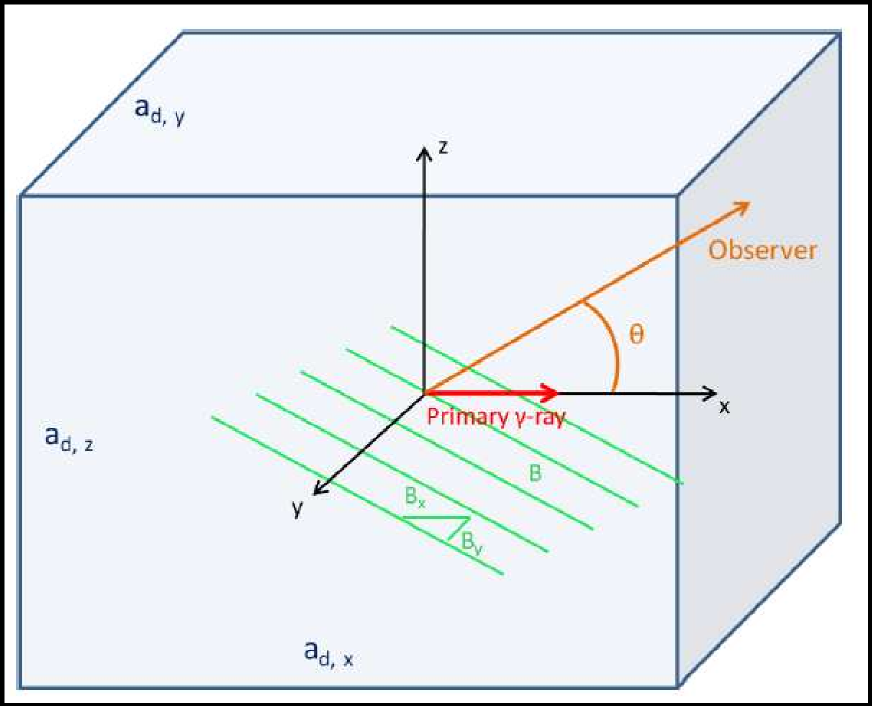
Disk model



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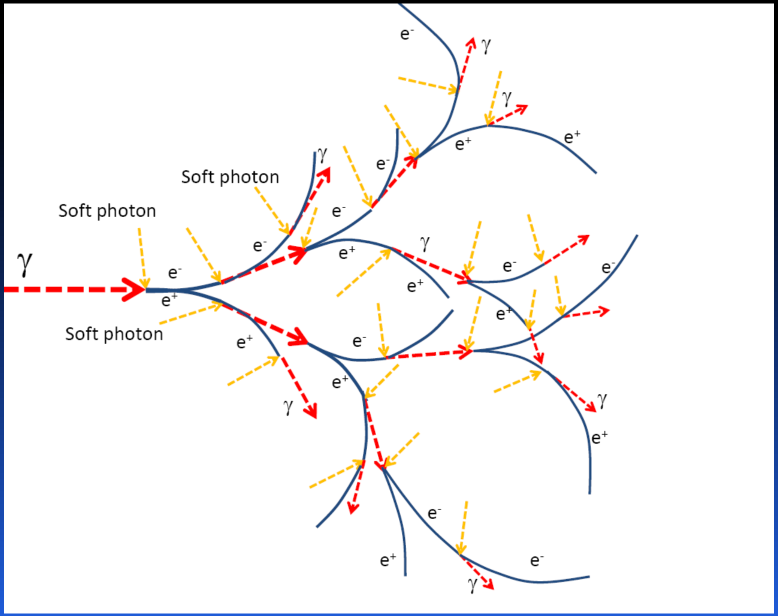


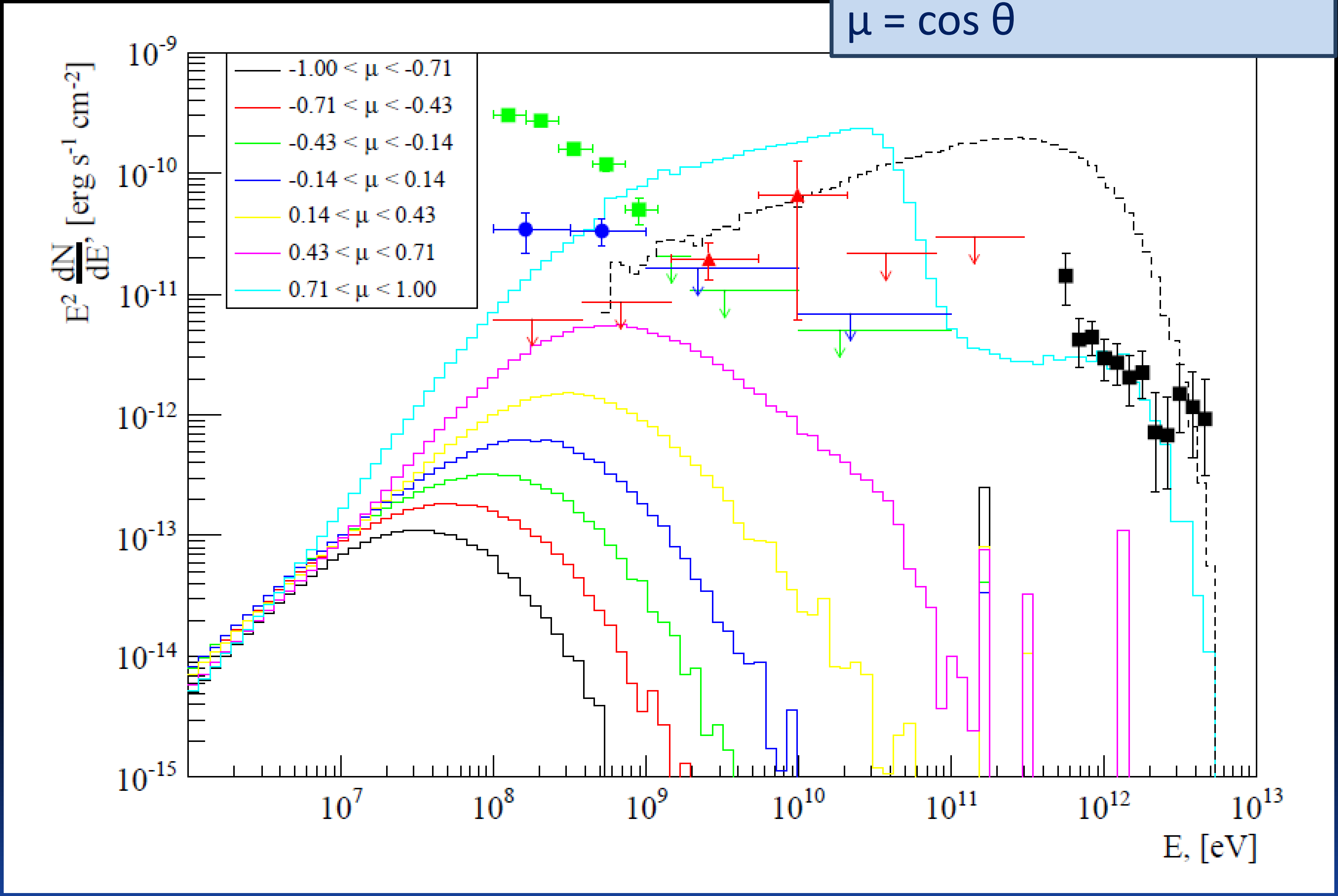
Monte Carlo simulations:

- pair production
- deflection by magnetic field
- inverse Compton scattering
- Synchrotron losses

- Magnetic field in the xy-plane

Cascade emission

u_d = 200 erg/cm^3
B_x = 0.01 G, B_y = 0.001 G
μ = cos θ



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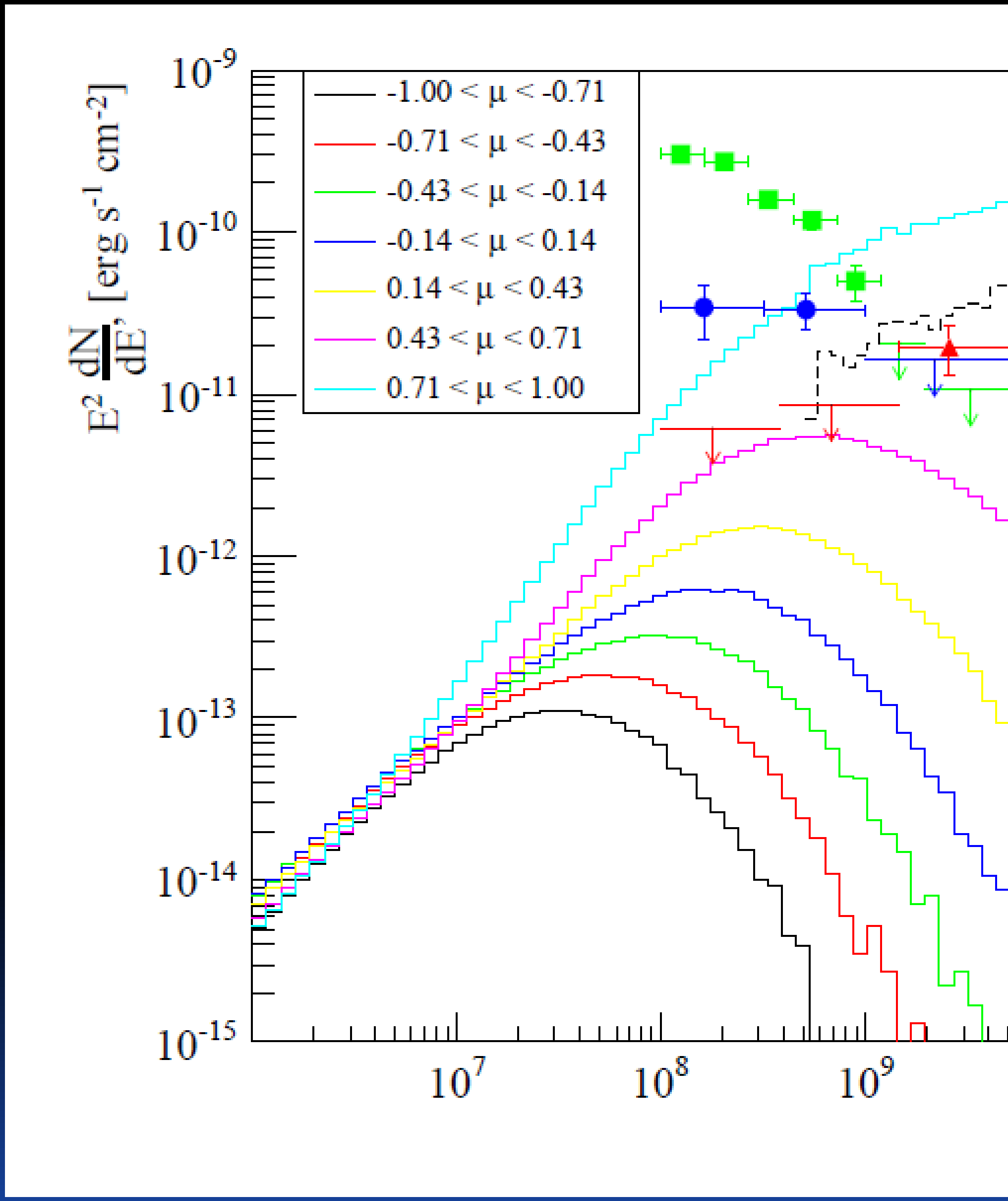
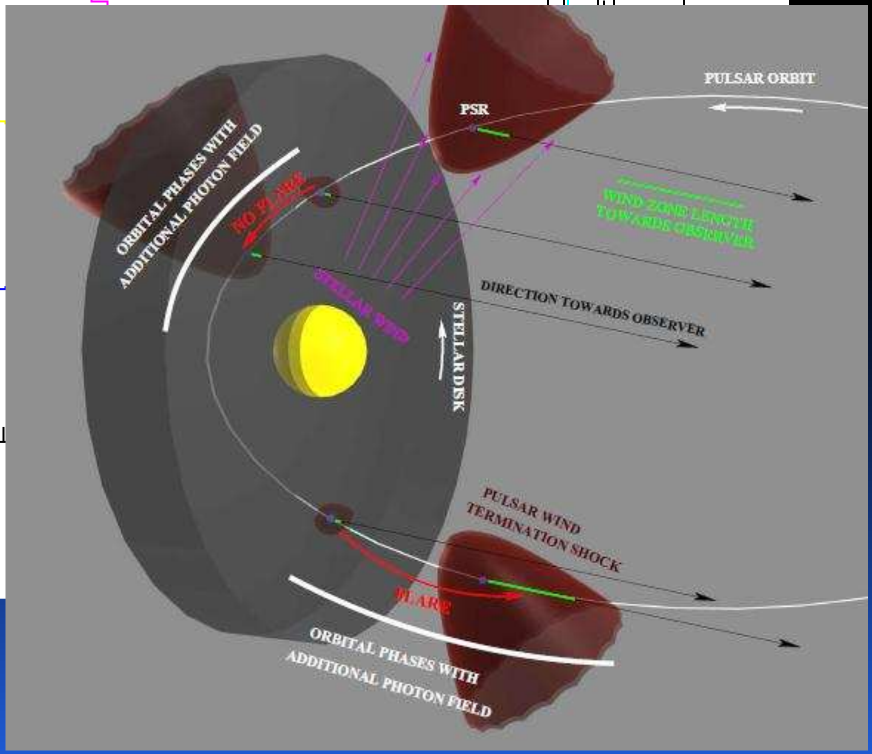
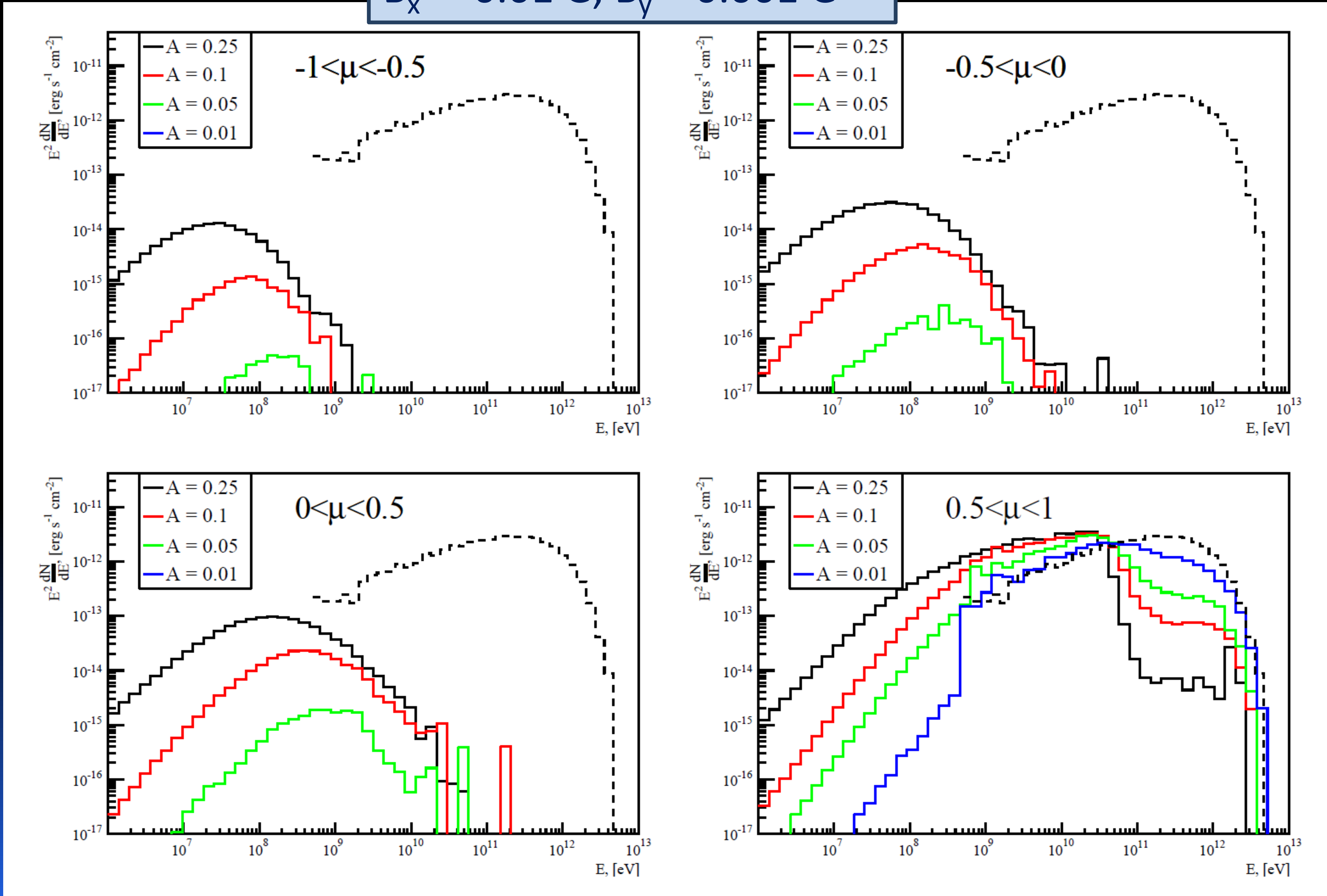




Dependence on the energy density

A = 1 => u_d = 800 erg/cm^3
B_x = 0.01 G, B_y = 0.001 G



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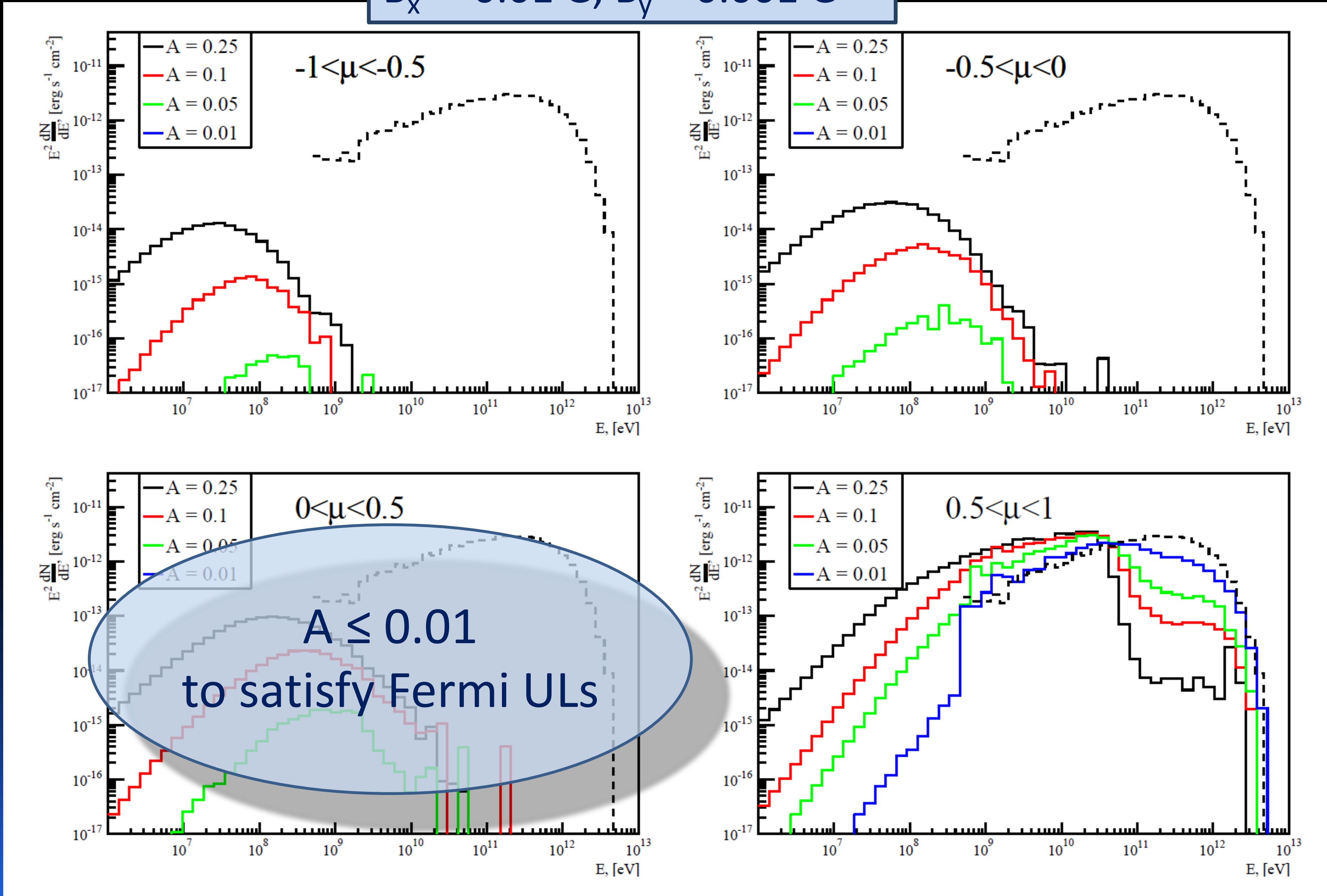
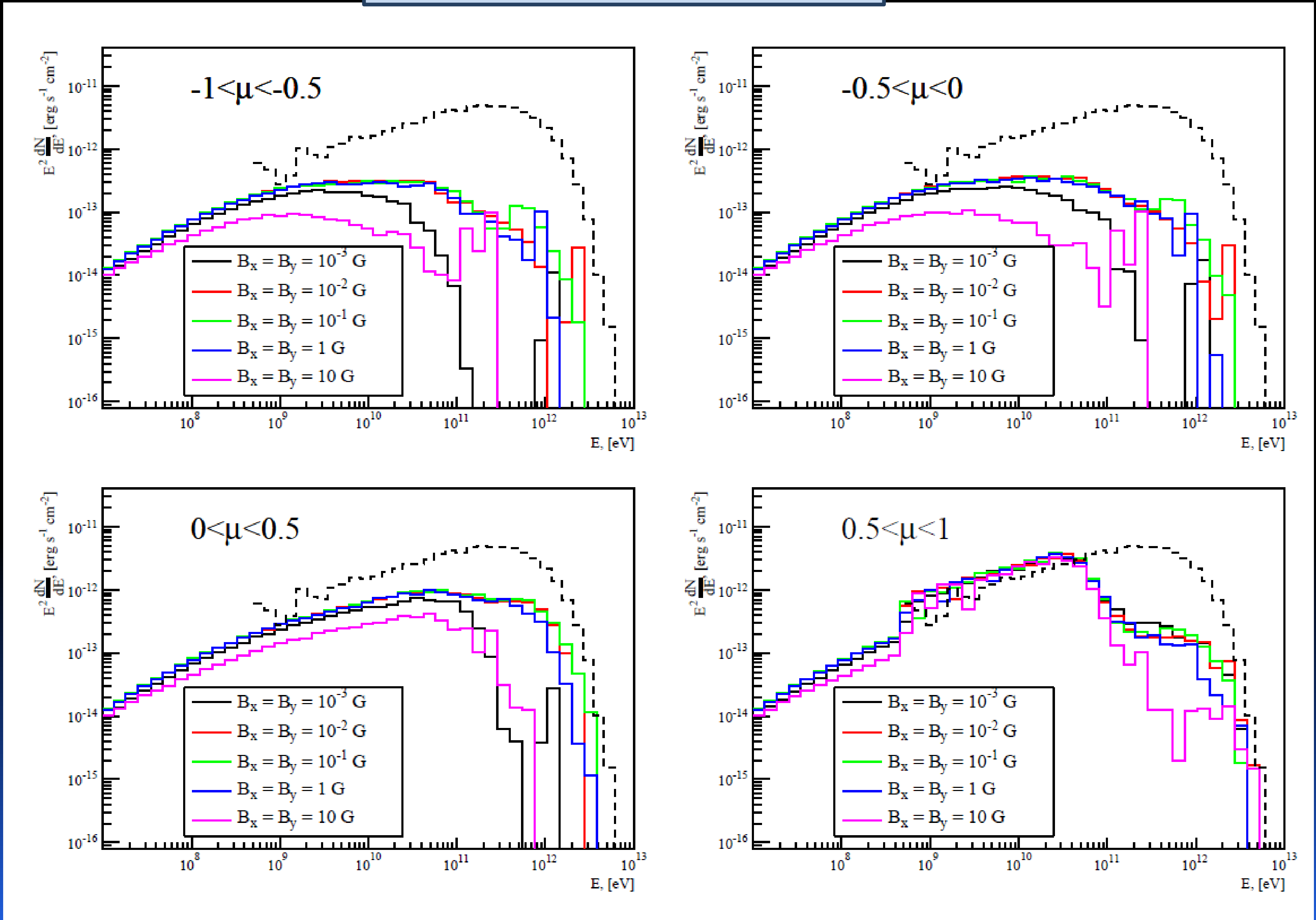


Depedence on B-field strength

A = 0.05, u_{ext} = 40 erg/cm^3



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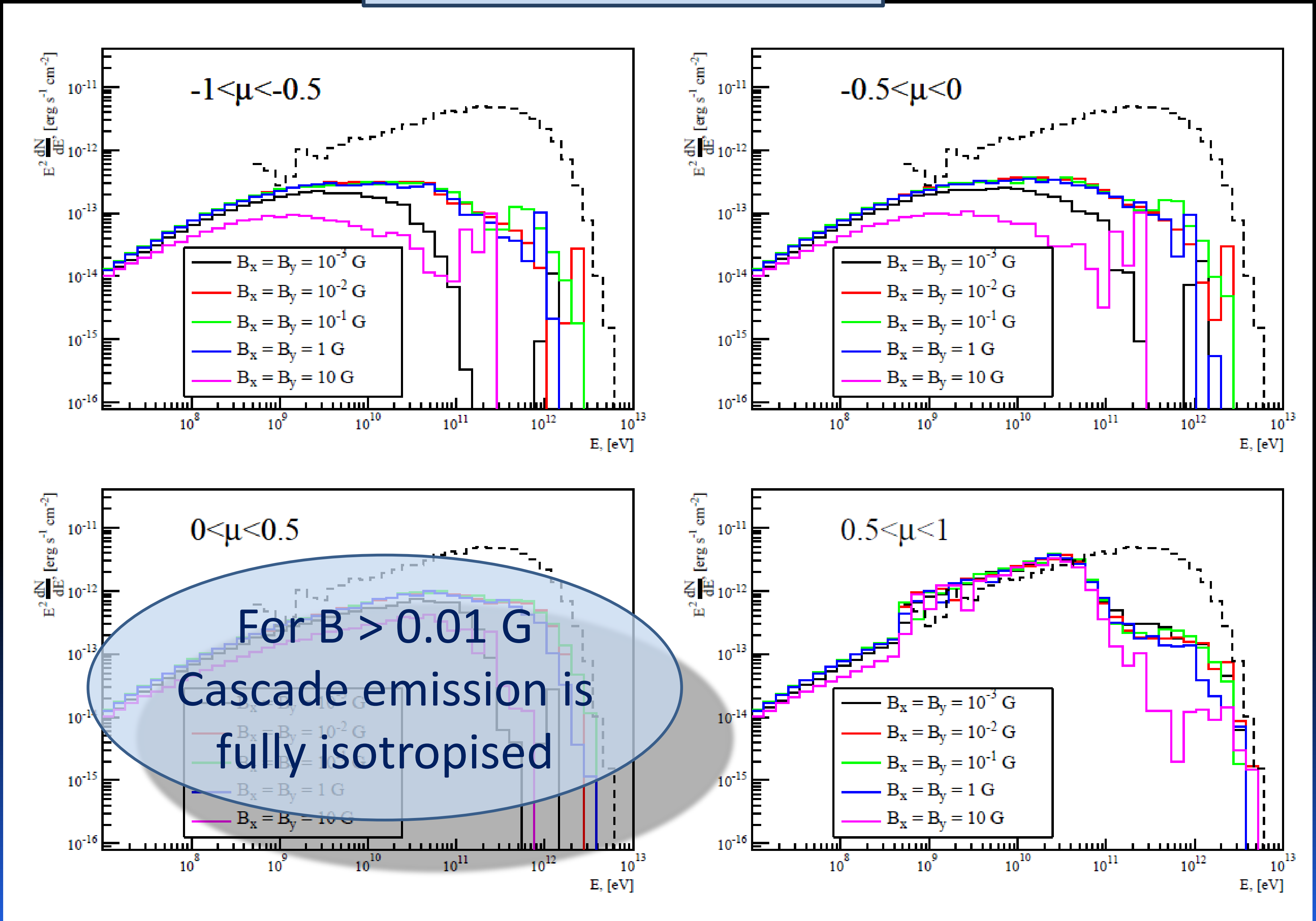

For B > 0.01 G
Cascade emission is
fully isotropised

Depedence on B-field strength

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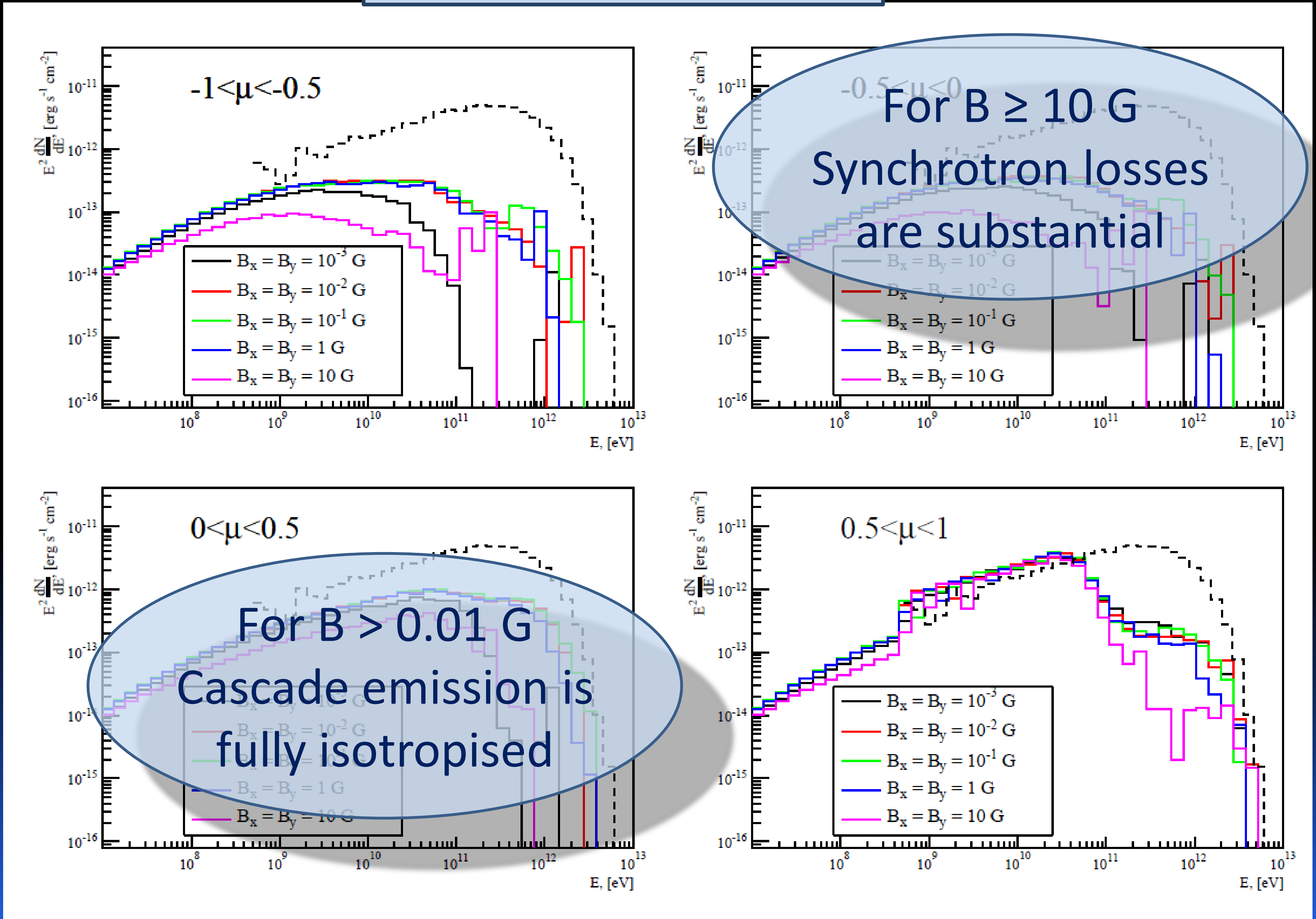
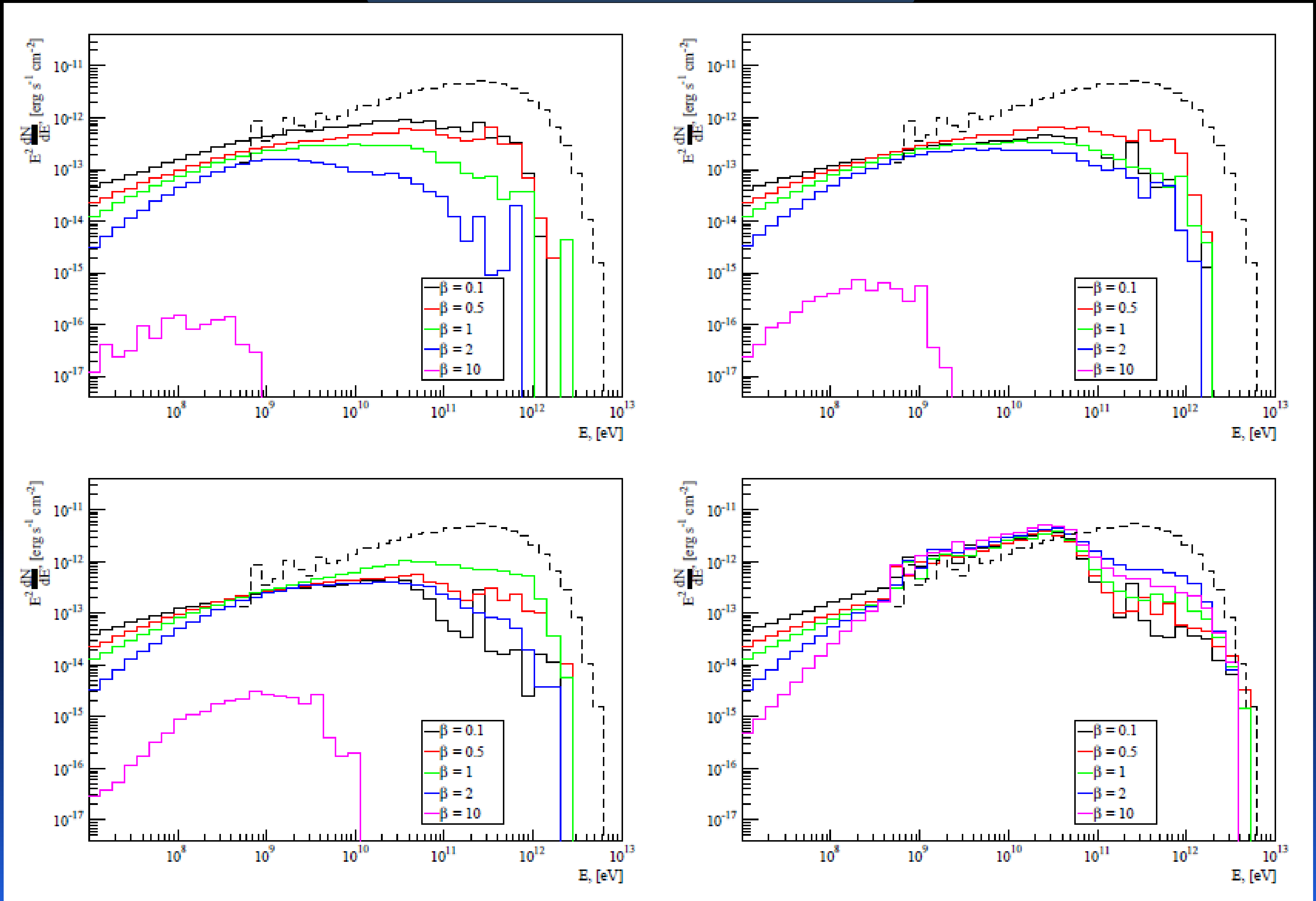


Depedence on B-field orientation

$A = 0.05$, $u_d = 40$ erg/cm^3
$\beta = B_x/B_y$, $B = 0.01$ G



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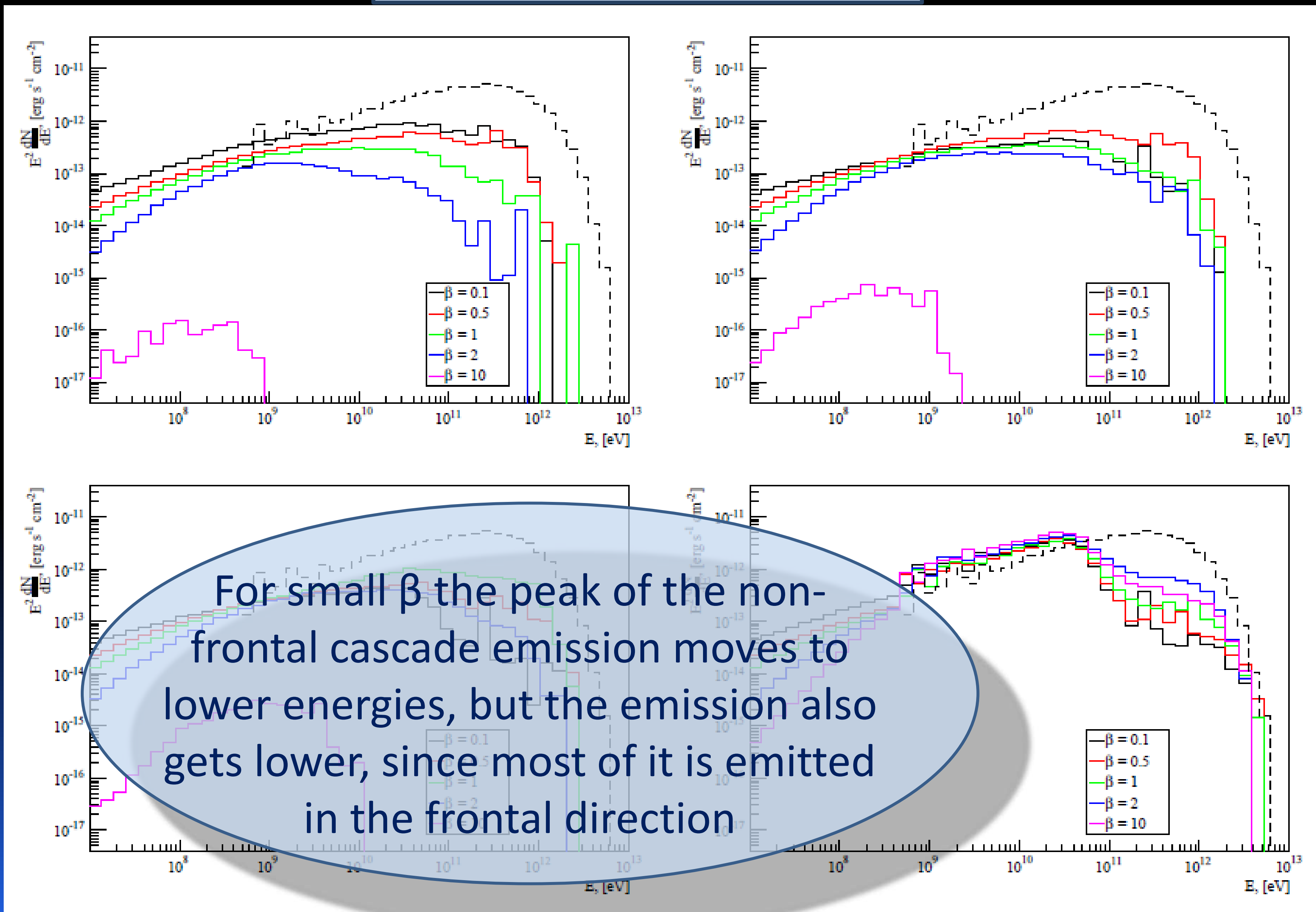
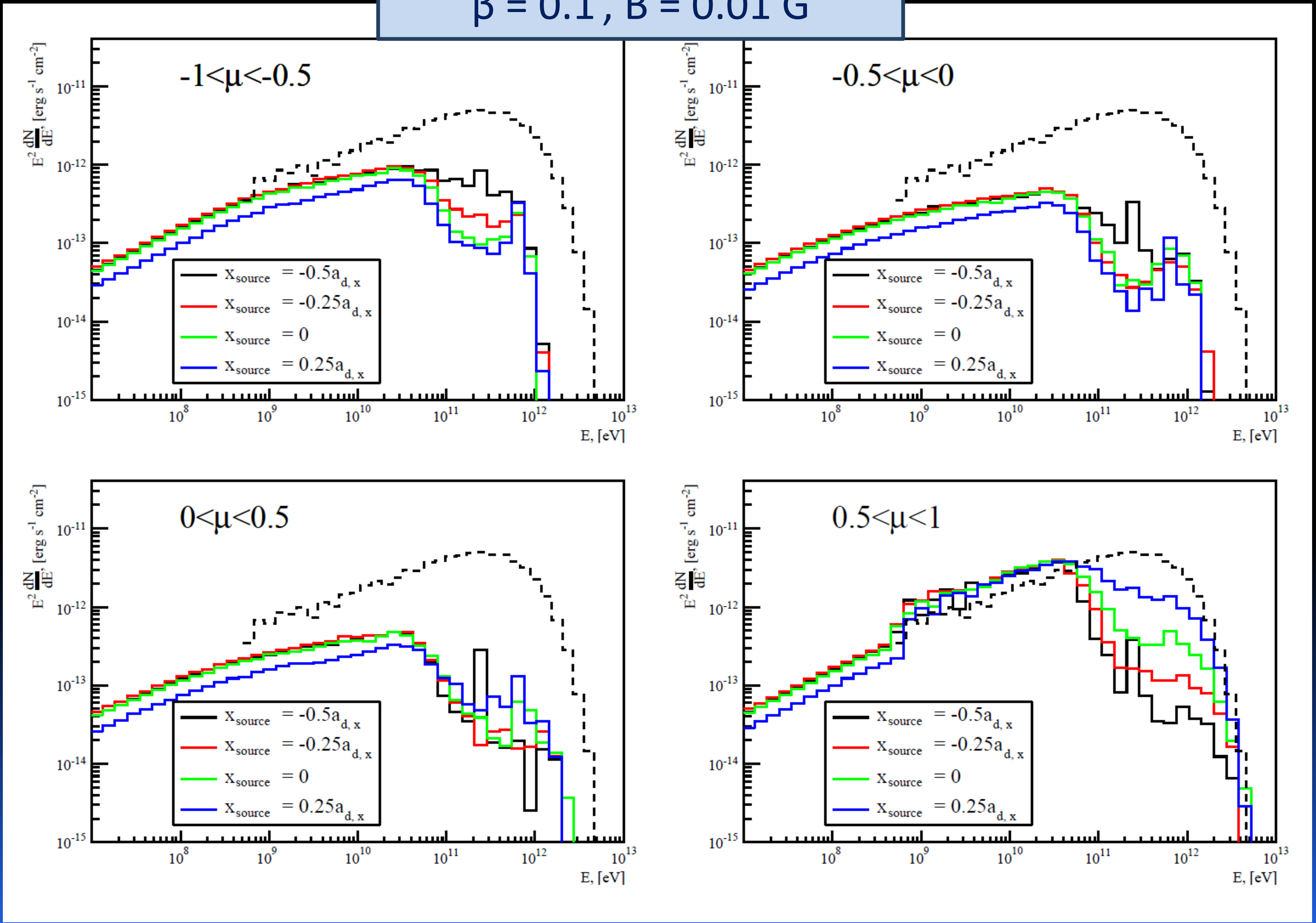


For small β the peak of the non-frontal cascade emission moves to lower energies, but the emission also gets lower, since most of it is emitted in the frontal direction

Location dependence

A = 0.05, u_d = 40 erg/cm^3
β = 0.1 , B = 0.01 G

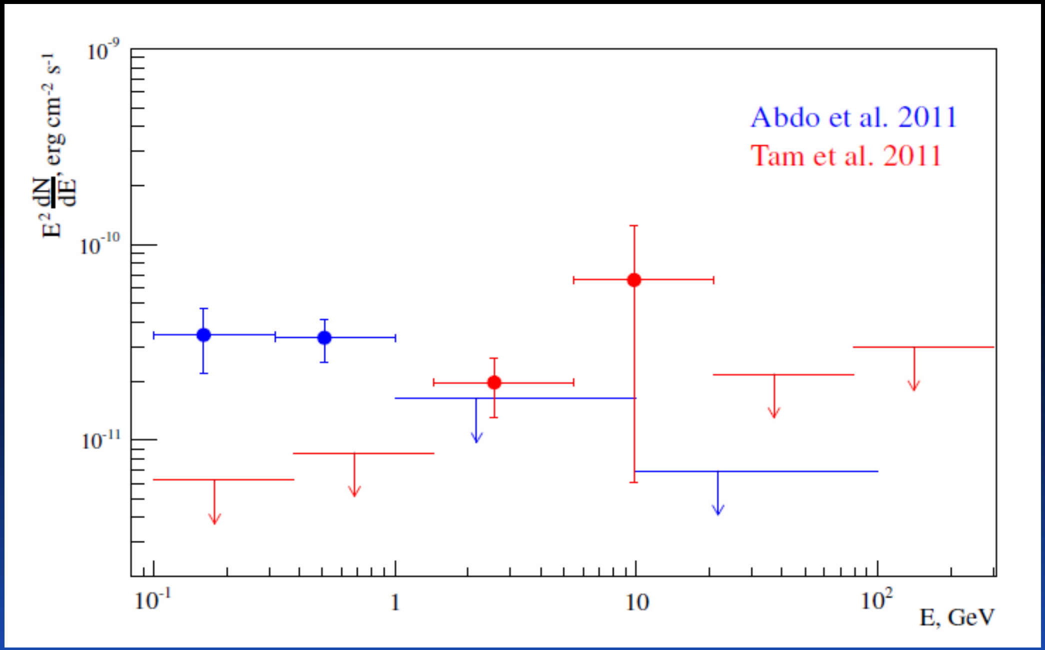


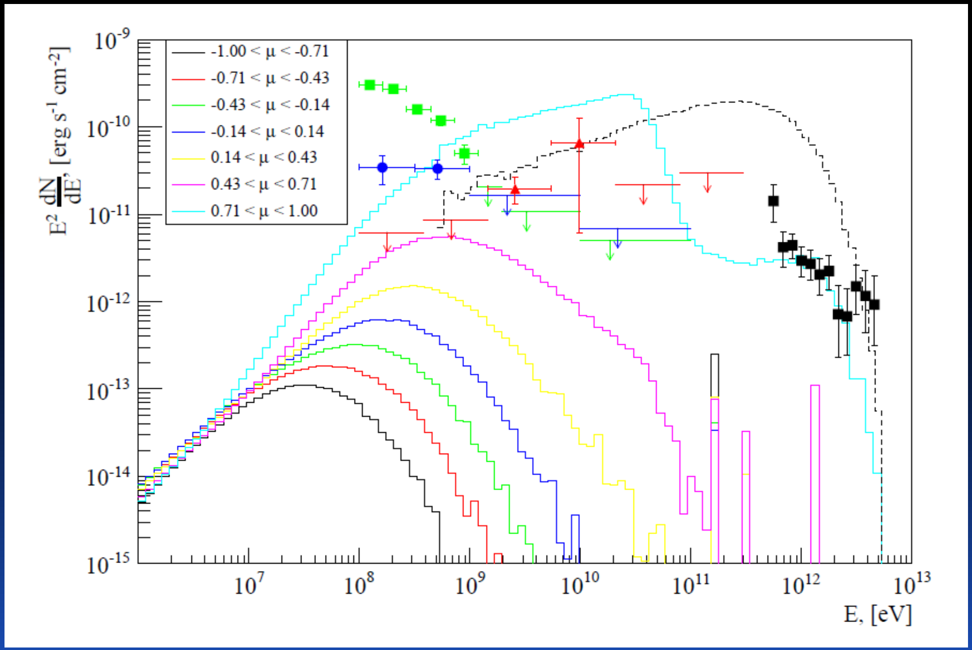
Generation of the observed GeV emission?

- GeV flare is not a result of pair cascades because
  - Cascade contribution is small
  - Cascade emission in forward direction violates limits
  - The same flare should have been observed before periastron

Generation of the observed GeV emission?

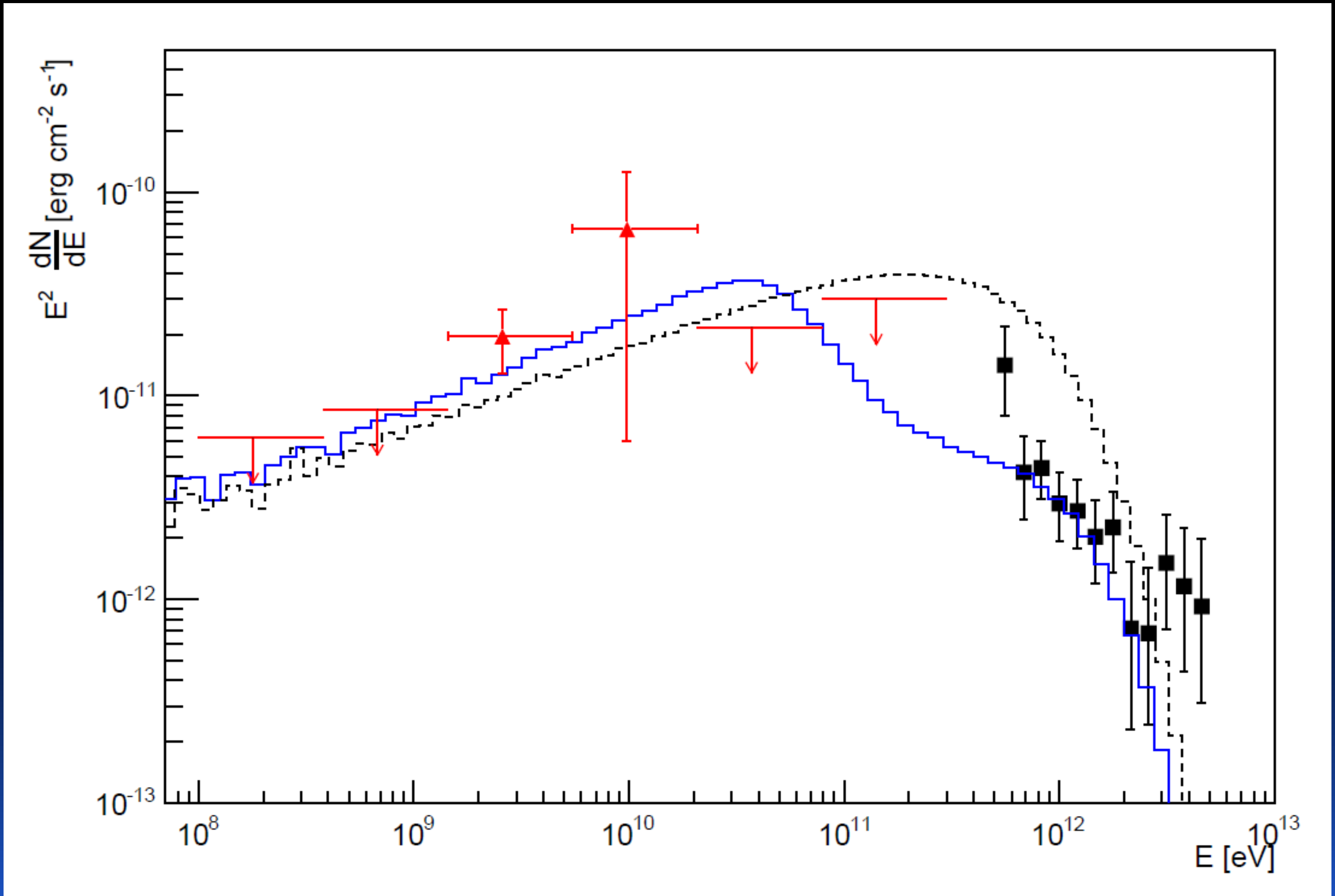
- GeV flare is not a result of pair cascades because
  - Cascade contribution is small
  - Cascade emission in forward direction violates limits
  - The same flare should have been observed before periastron
- Responsible for the GeV emission around periastron?





GeV emission at periastron

- Forward direction cascade emission into a cone with an opening angle of 11 ° (0.98 < μ < 1)
- Magnetic field aligned with the direction towards observer

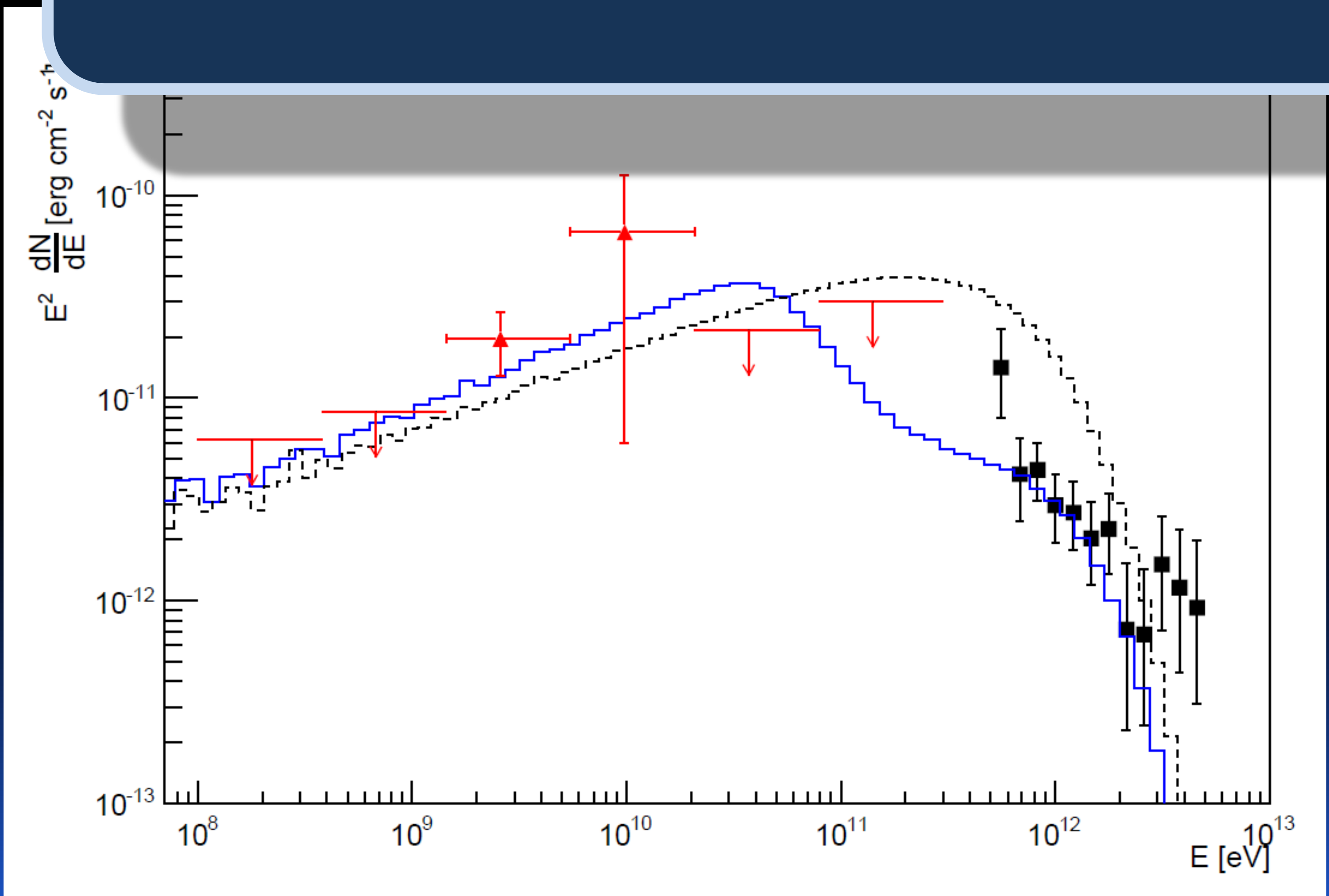


u_d = 20 erg/cm^3
B = 0.1 G

GeV emission at periastron

But

- Stellar photons should be taken into account
- Proper structure of the magnetic field should considered



rg/cm^3

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rg/cm^3

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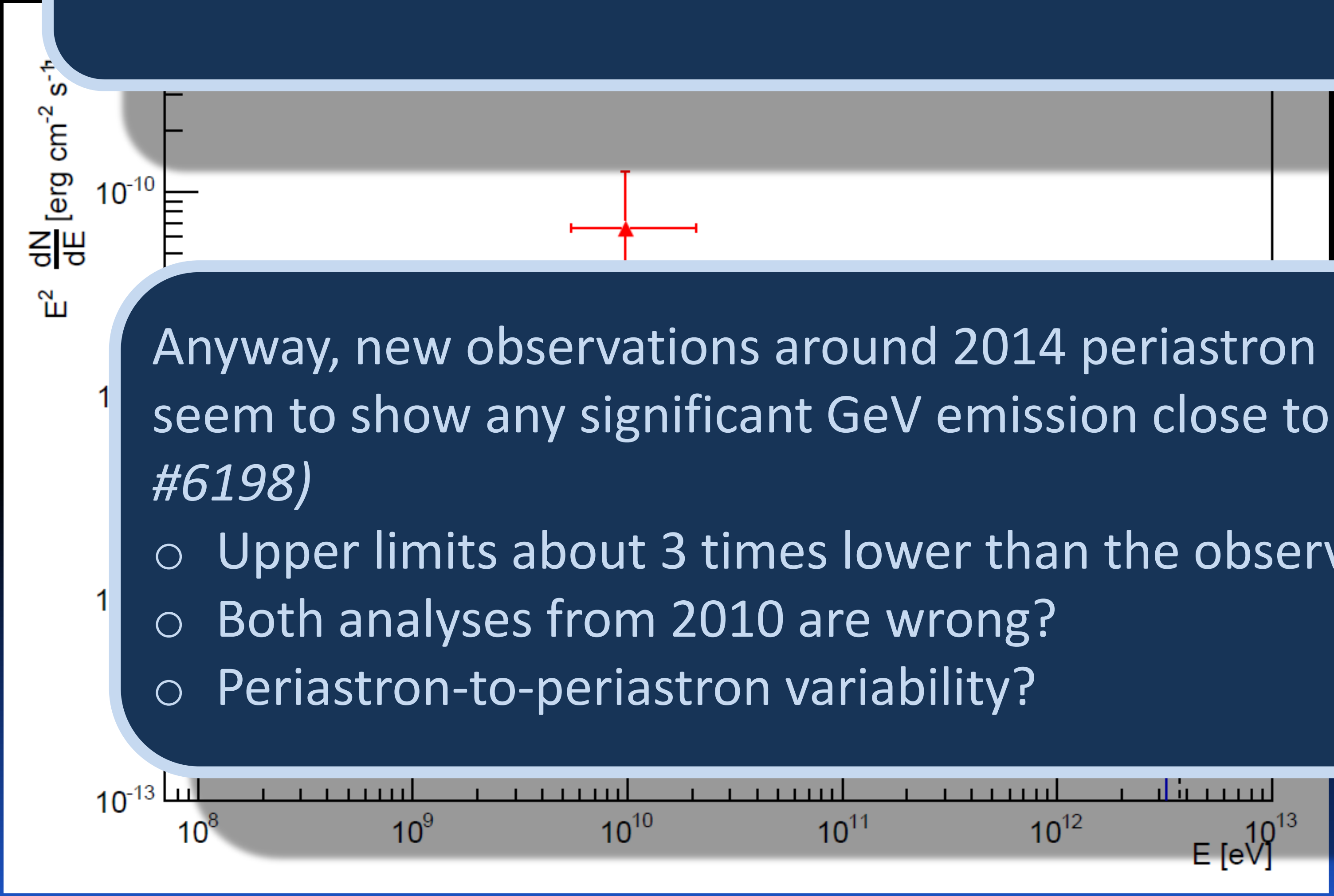
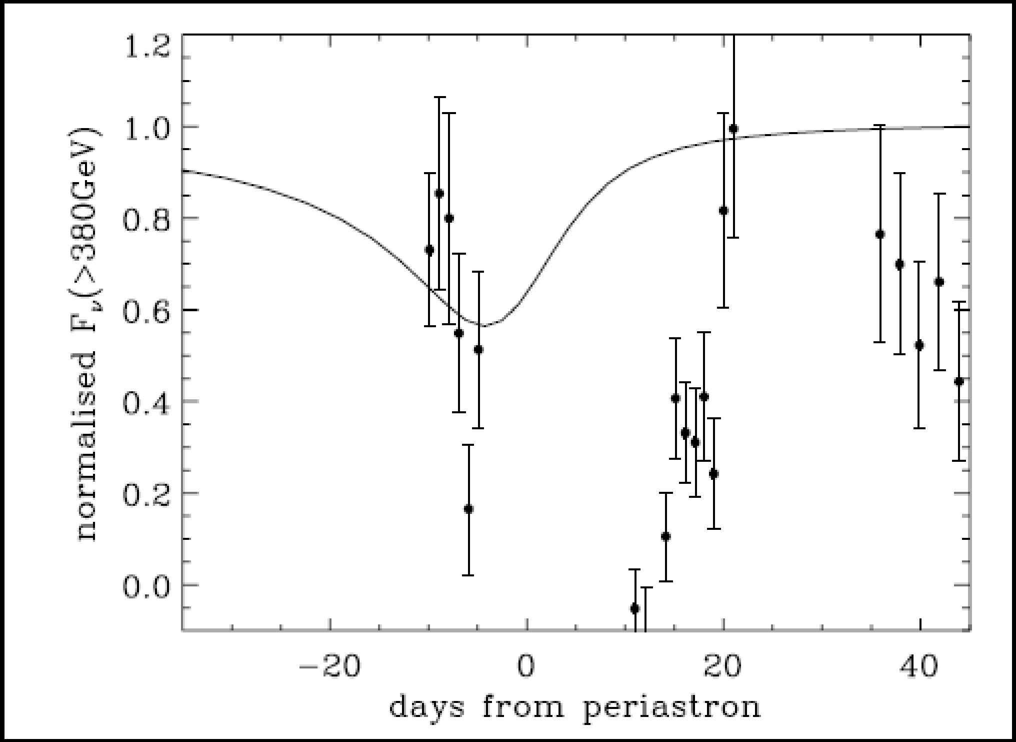


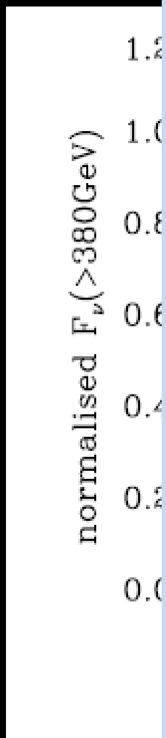
Anyway, new observations around 2014 periastron passage don't seem to show any significant GeV emission close to periastron *(ATel #6198)*
- Upper limits about 3 times lower than the observed flux in 2010
- Both analyses from 2010 are wrong?
- Periastron-to-periastron variability?

TeV Light Curve

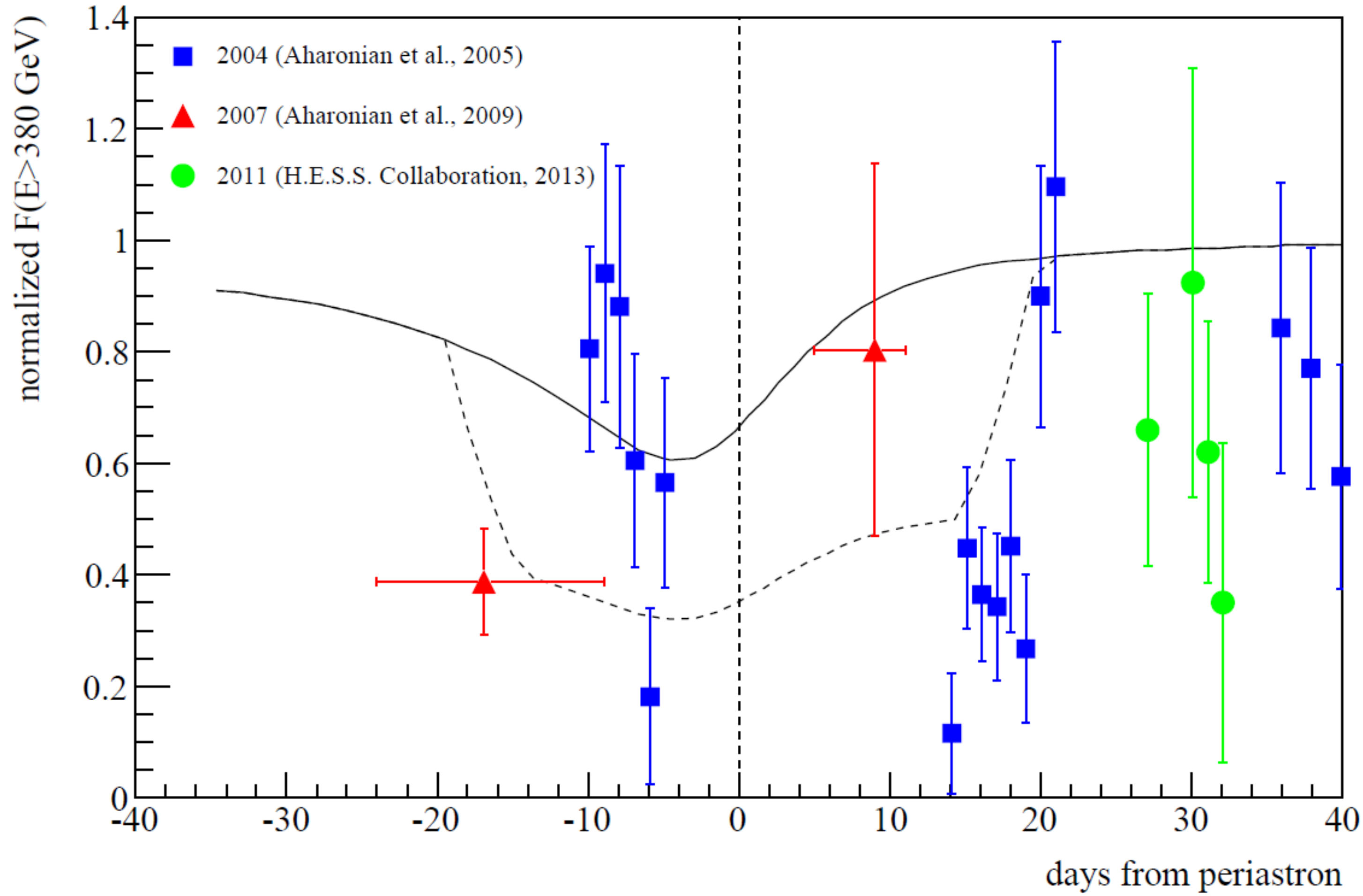


Dubus, 2006

TeV



Dubus,



Same geometry and stellar parameters as in *Dubus 2006*

Constant width (10^{12} cm) and energy density (8 erg/cm^3) of the disk

→ highest density for which Fermi ULs are not violated

Summary

- Emission generated by pair cascades cannot be responsible for the GeV flare.
- Fermi ULs constrain the photon energy density in the disk
- Pair cascades might be responsible for the GeV emission at periastron, if there is one.
- Gamma-gamma absorption in the disk might explain the observed TeV light curve.