Multiwavelength properties of γ-ray loud binary systems.

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X-ray Binaries in the Milky Way

~180 known low-mass X-ray binaries (LMXB)

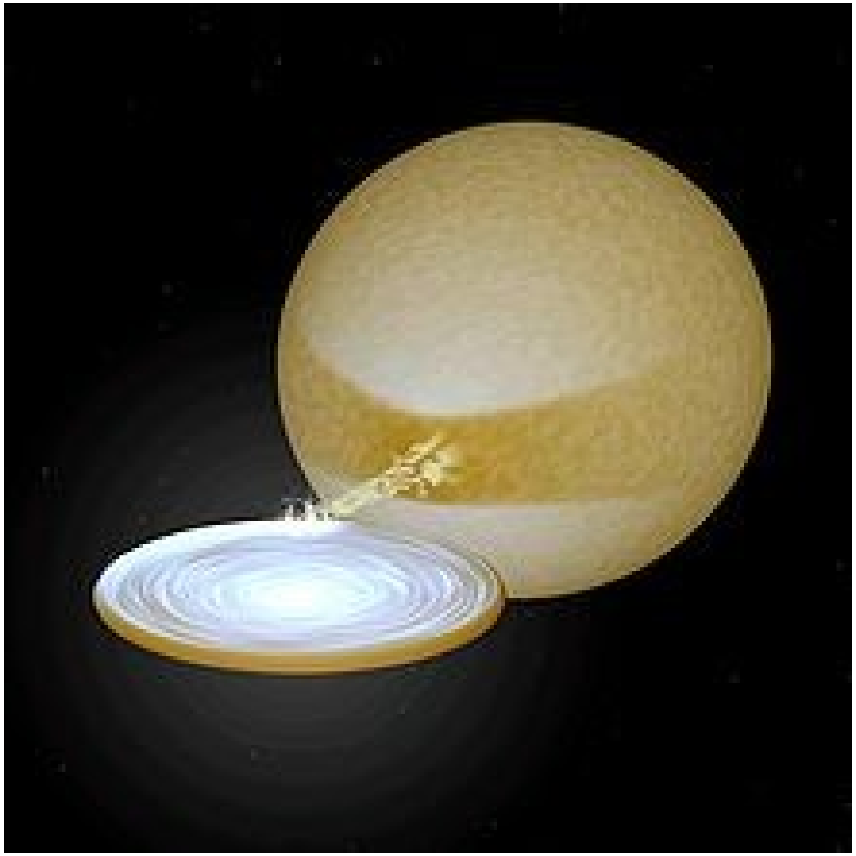
Contain an evolved star transferring mass onto a white dwarf, neutron star, or black hole

114 high mass X-ray binaries (HMXB)

Mass donor star is an O- or B-type star

60% of HMXBs contain Be stars

20 black hole systems

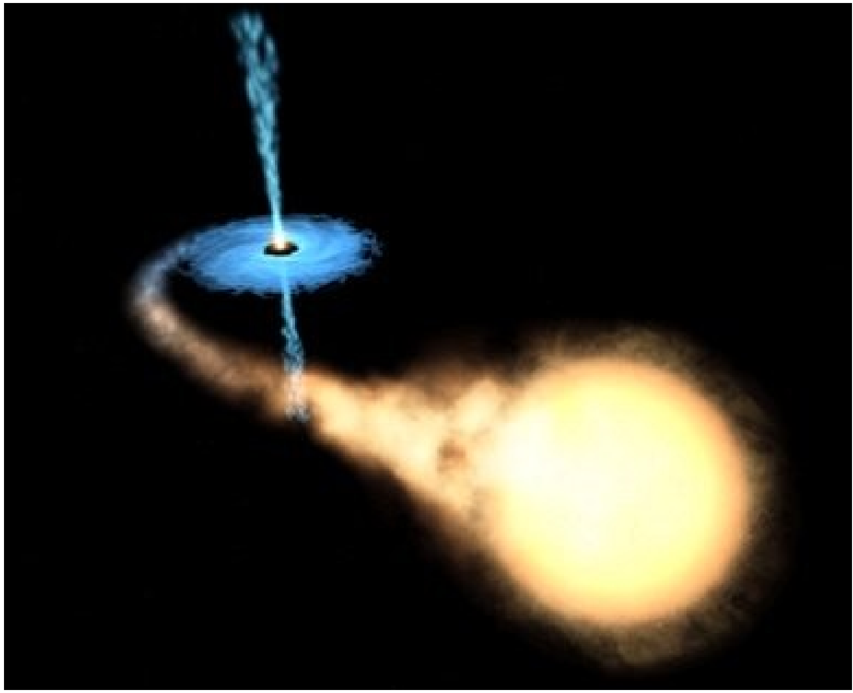


High Energy Emission from XRBs

γ-ray loud binary systems

X-rays generally produced from the gravitational potential energy of accreting matter

$$L_X \sim \frac{G M_X M_Y}{R_X}$$



HMXBs with stellar wind accretion have $L_X \sim 10^{35}$ - 10^{36} erg/s

Roche-lobe overflow systems have ~ 10^{38} erg/s

Some accreting matter may be directed into bipolar jets (microquasars).

Known γ-ray loud binary systems.

HMXBs that also exhibit very high energy emission (MeV-TeV) are called "γ-ray binaries"

Only 4 binary systems are regularly observed in TeV:

PSR B1259-63 (young pulsar +Be star, P=3.4 y)

LSI +61 303 (comp. source + Be star, P=26.42 d)

LS 5039 (comp. source + O star, P=3.9 d)

HESS J0632+57 (comp. source+B0pe, P=320 d)

Origin of the high-energy emission?

Difference from other X-ray binaries?

Powered by rotation energy rather than accretion?

GeV domain

Fermi and AGILE observations reveal more binaries active in GeV domain, e.g.

Cyg X-3 (comp. source +WR star, P=4.79 h)

1FGL J1018.6-5856 (comp. Source + O star, P=16.6 d)

V407 Cyg(symbiotic star*, P=43years (?))

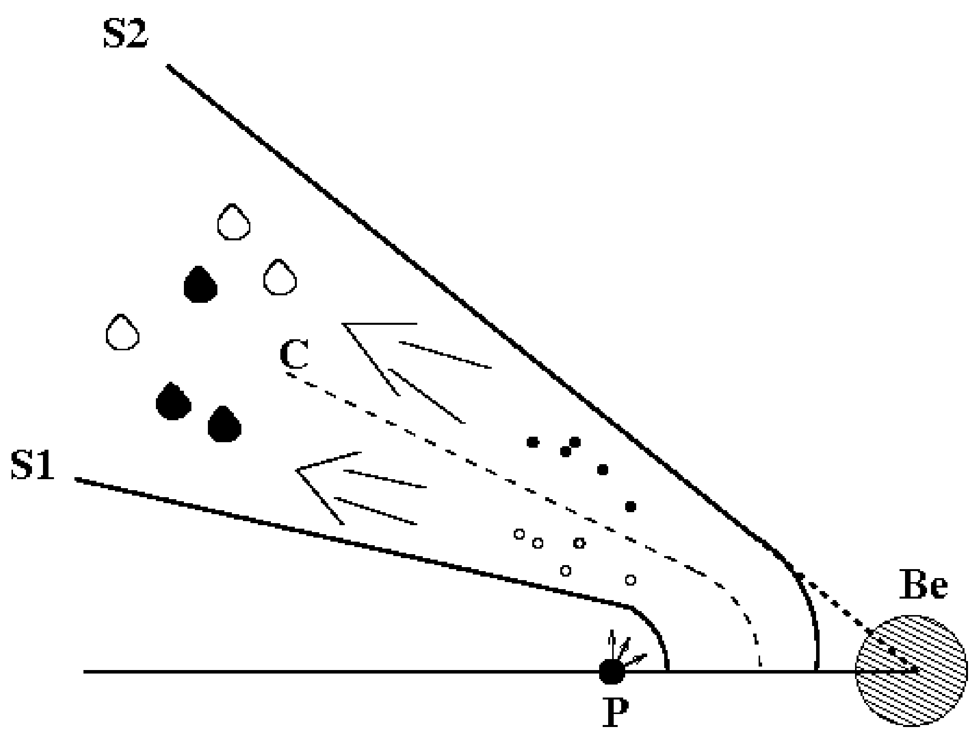
η Car (luminous blue variable star +O star, P=5.53 year)

Binary systems with millisecond pulsars

* a binary star system in which a red giant (Mira variable) transfers mass to a white dwarf companion

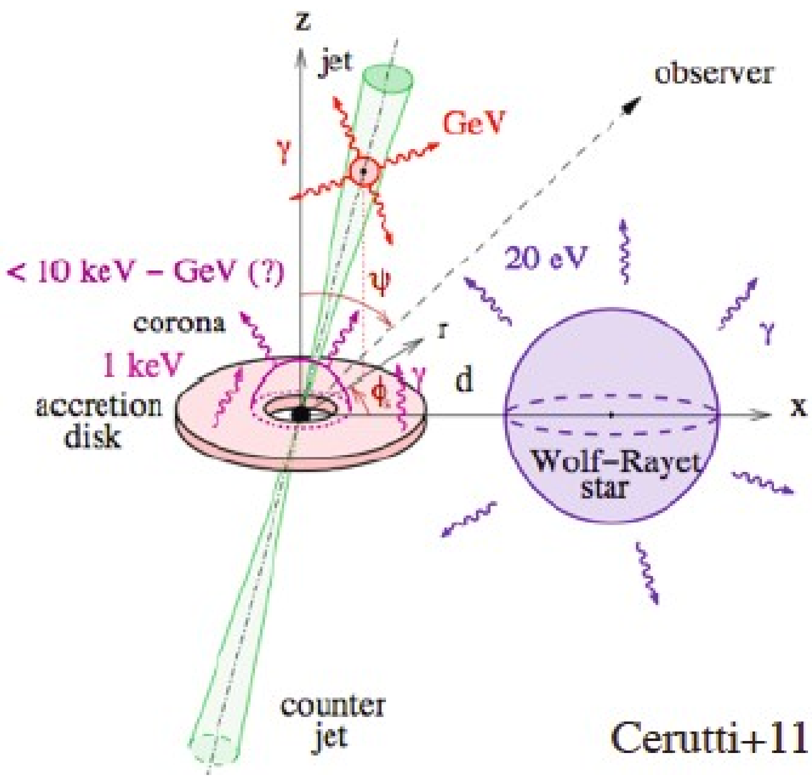
Two Theories for γ-ray Production

Colliding Winds



PSR B1259-63

Microquasar



Cygnus X-3

LS 5039
LS I +61°303
HESS J0632+057
1FGL 1018.6-5856

Two Theories for γ-ray Production

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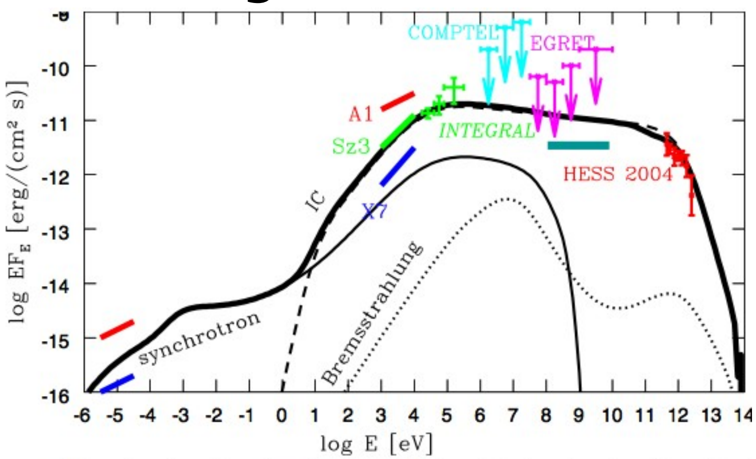
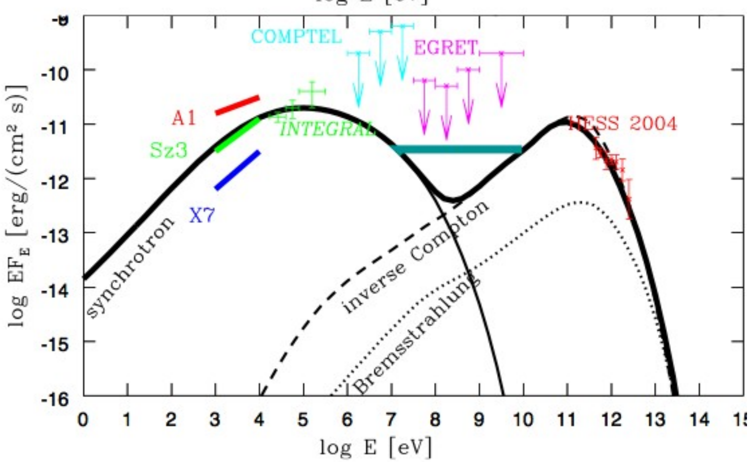
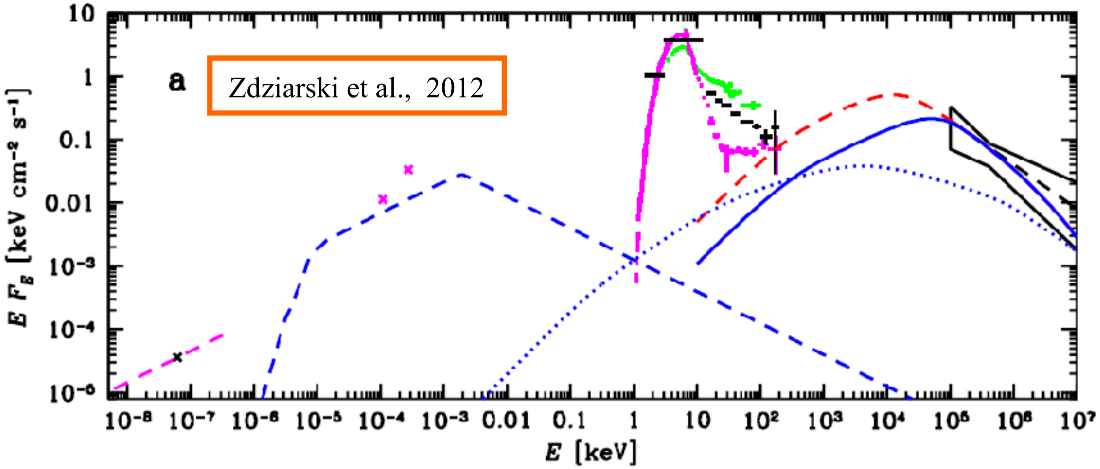




Chernyakova, Neronov, Ribordy 2009

PSR B1259-63

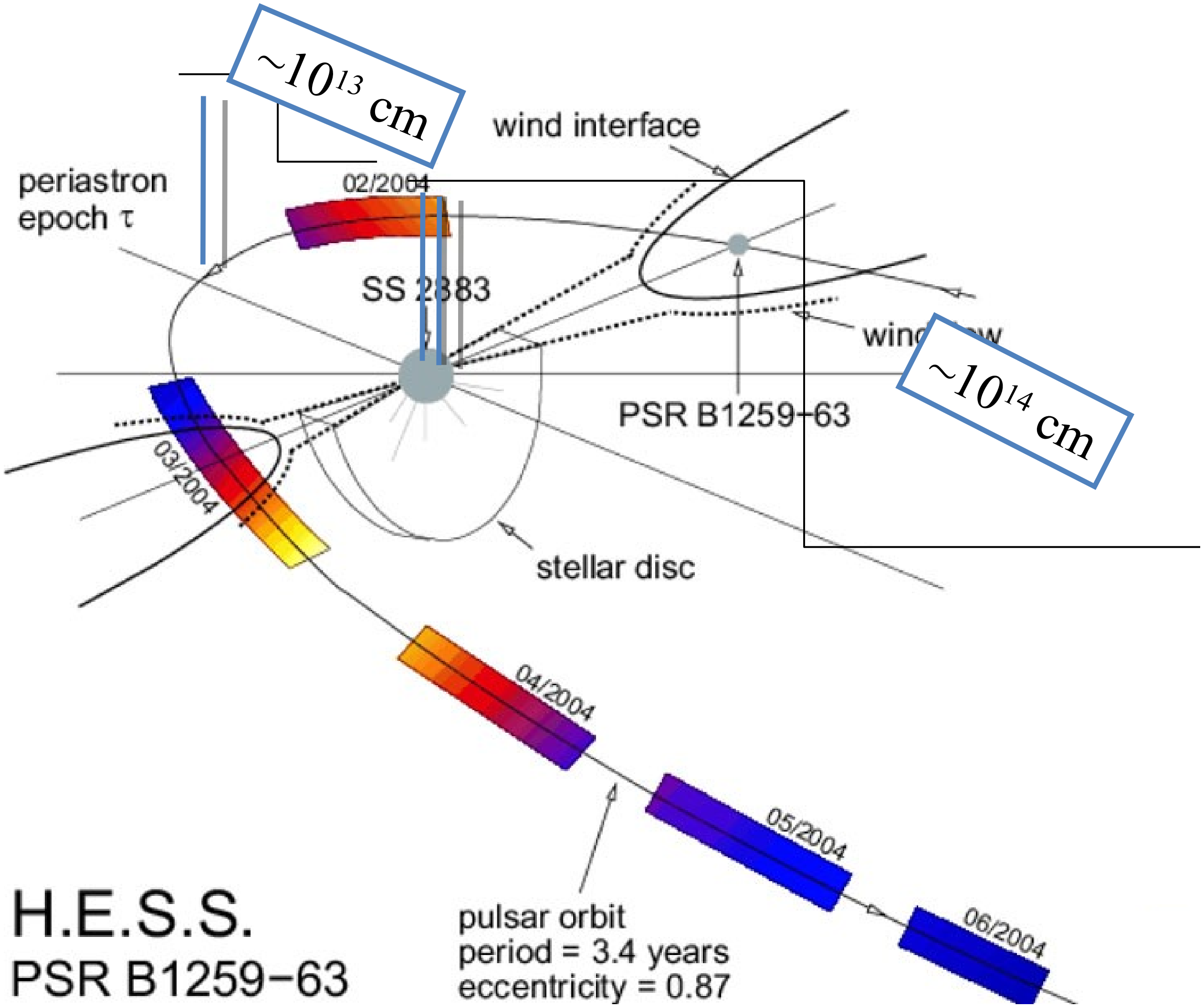
Microquasar



Cygnus X-3

LS 5039
LS I +61°303
HESS J0632+057
1FGL 1018.6-5856

PSR B1259-63 system



Pulsar:
P=47.76 ms
L_{SD}=8.3 × 10^{35} erg s^{-1}

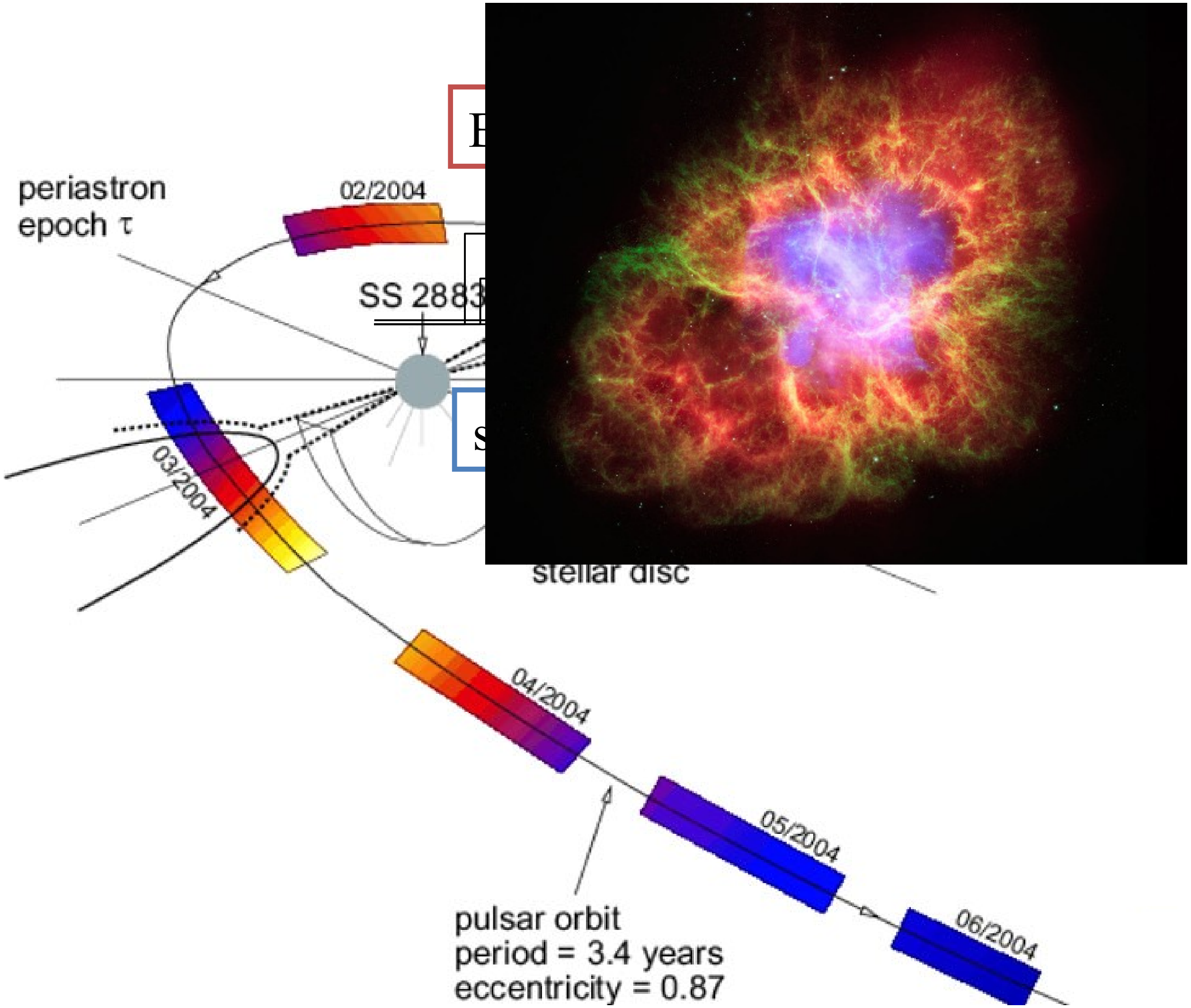
Orbit
Period ≈ 3.4 yr
Eccentricity e≈ 0.87

Distance 2.3 ± 0.4 kpc

SS 2883 parameters

- L_*=2.2E+38 erg/s
- M~10M_{sun}
- T~27000 K

PSR B1259-63 system



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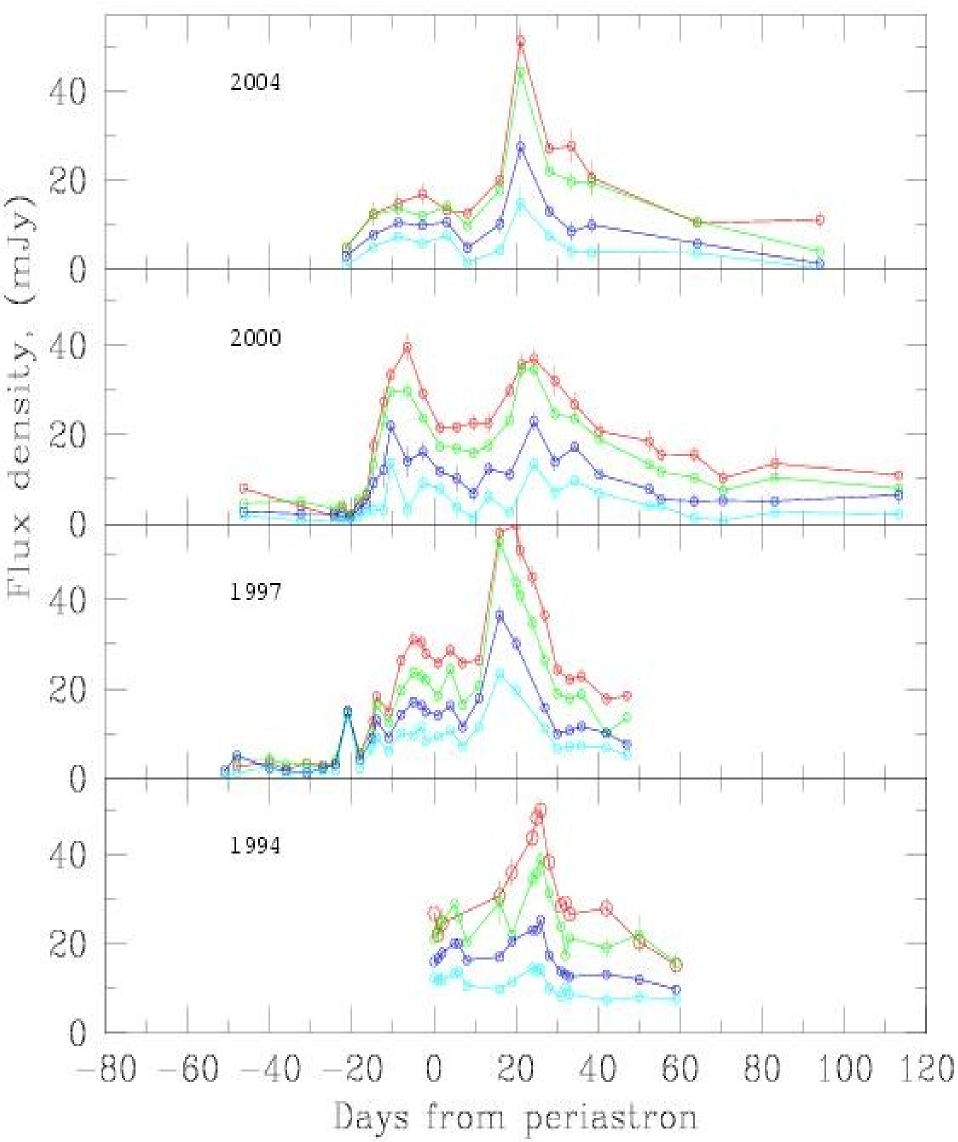
"Laboratory" for the study of the properties of pulsar winds

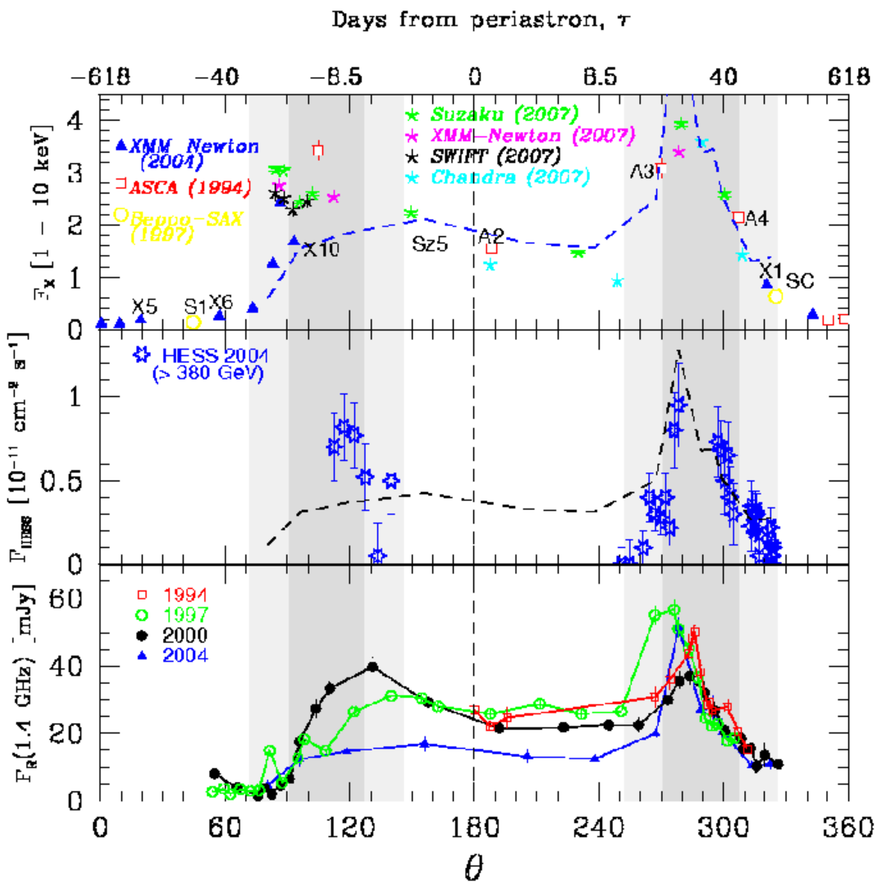
Radio Observations

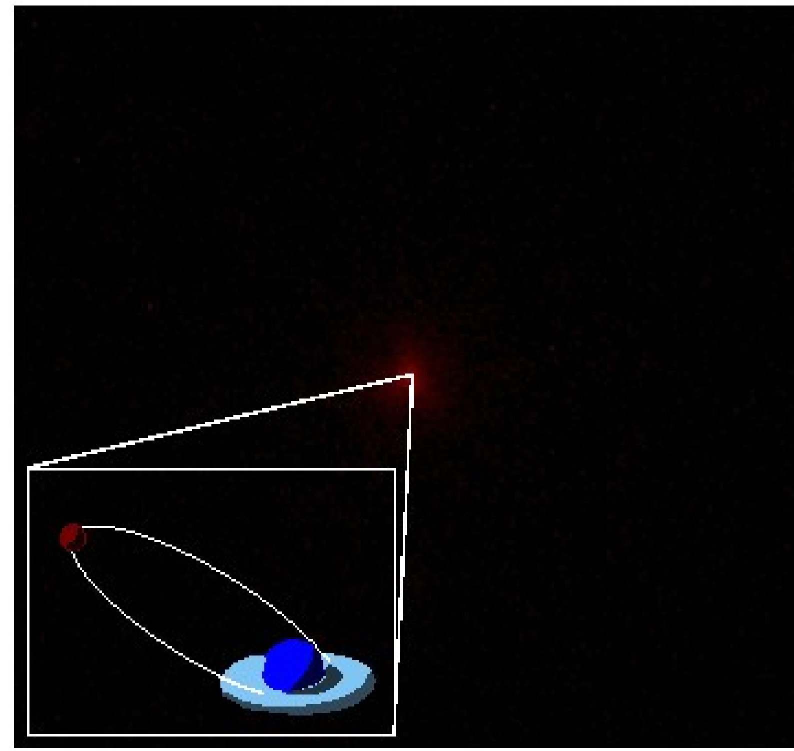
Johnston et al. 2005



- 0.843, 1.4, 2.4, 4.8 and 8.4 GHz
- Far from the periastron there is only highly linear polarized pulsating component with constant intensity.
- Since τ ~ -40 the depolarization of pulsed emission and the increase of the DM and RM occur.
- Pulsed emission disappears as the pulsar goes behind the disk.
- Unpulsed radio emission appears 20 days before periastron.
- The unpulsed radio emission is detected at lower frequencies until at least hundred days after the periastron passage.

PSR B1259-63



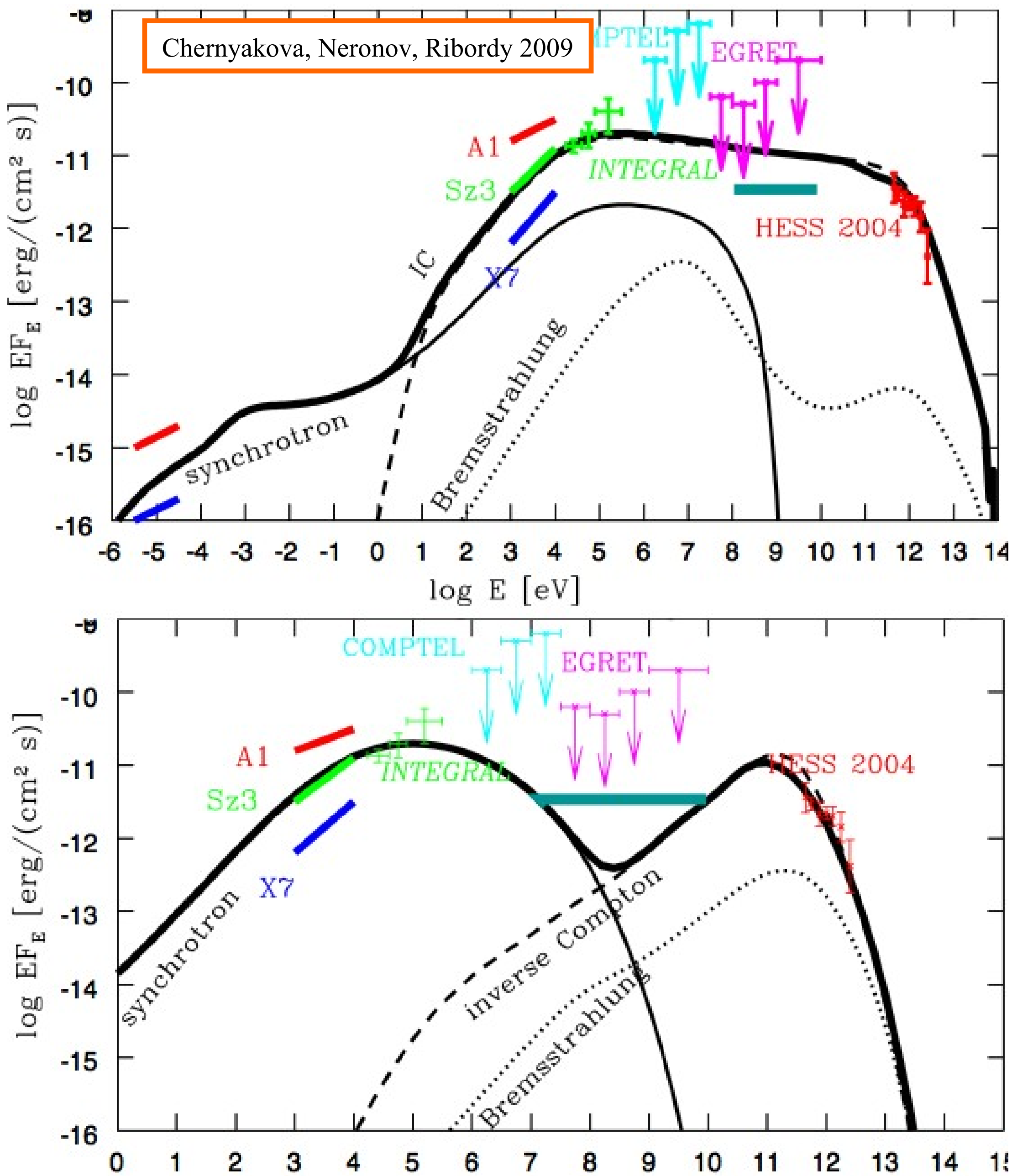


- 3.4 years orbital period. e~0.87
- Stability of the X-ray orbital lightcurve.
- Correlated variability with a sharp rise ("*two bumps structure*") is seen in radio, X-ray (and TeV?) bands.

Chernyakova et al., 2006; Neronov &Chernyakova 2007

γ-ray loud binary systems

PSR B1259-63: previous observations



Gamma-ray emission from the system was observed in 2004 and 2007 by HESS in the TeV energy range.

Similarly to large scale Pulsar Wind Nebulae (PWN), commonly considered contributions to the spectrum are

- synchrotron emission
- inverse Compton emission
- Bremsstrahlung

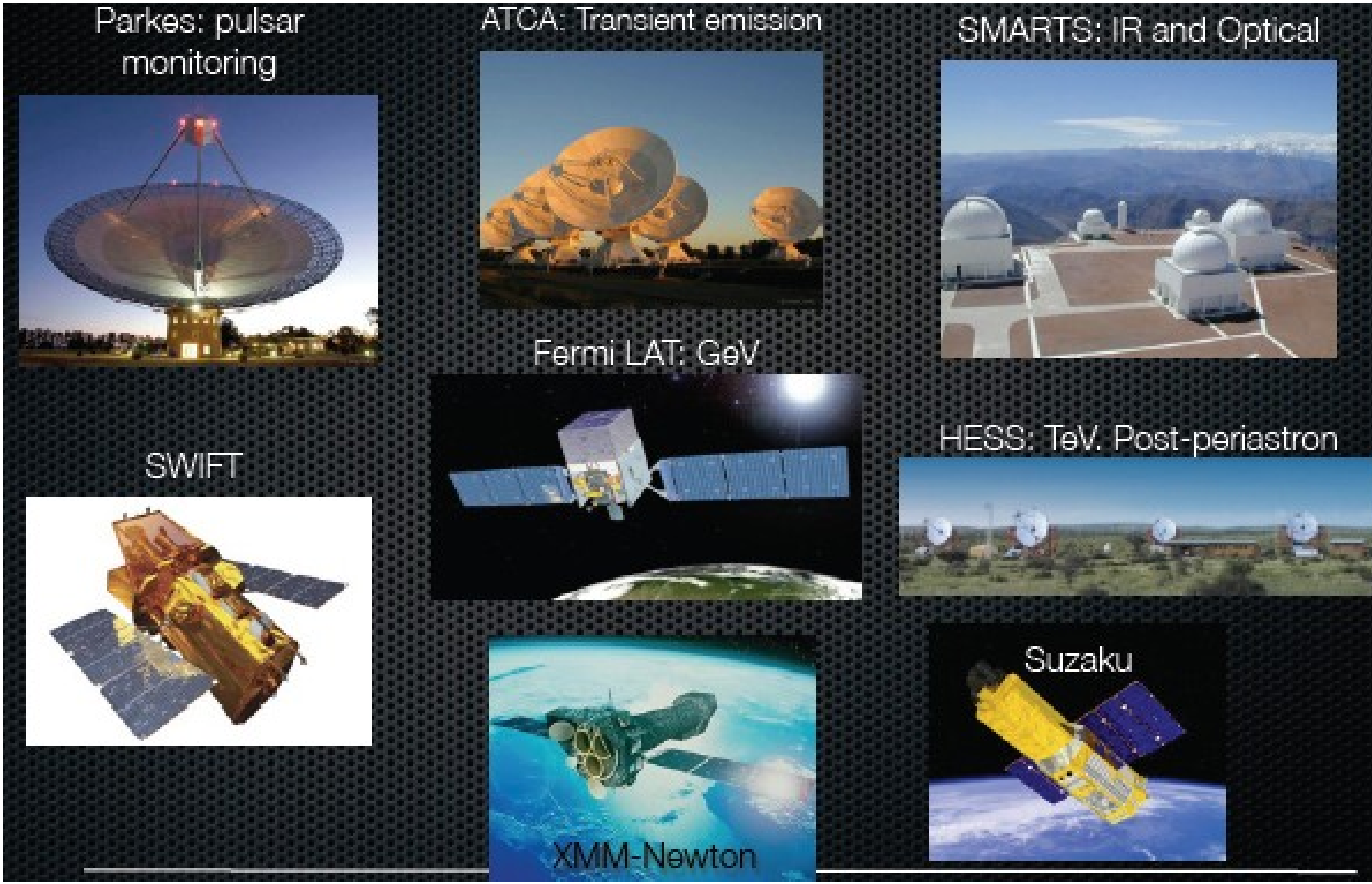
by high-energy electrons.

Electrons/positrons could be

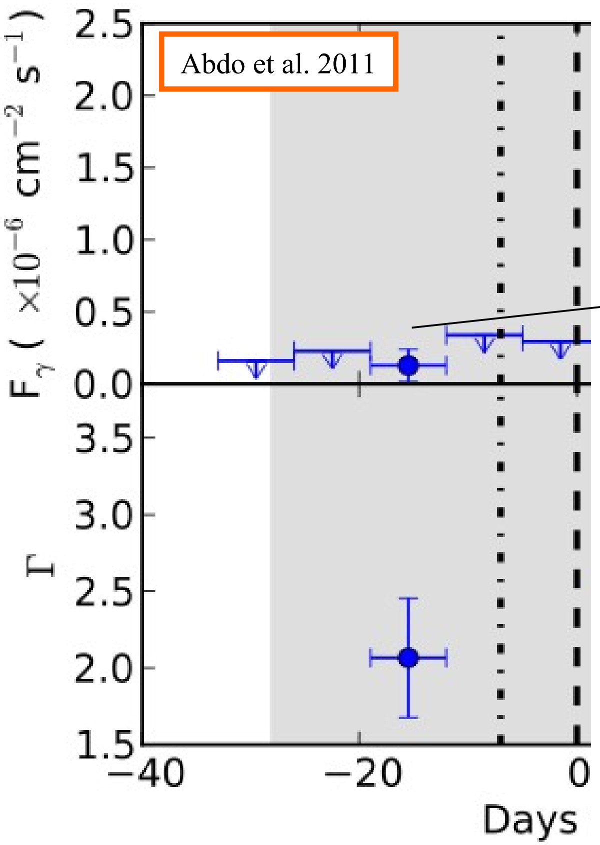
- accelerated at the bow-shock (similarly to the termination shock of the pulsar wind in PWNe)
- injected directly from the pulsar wind

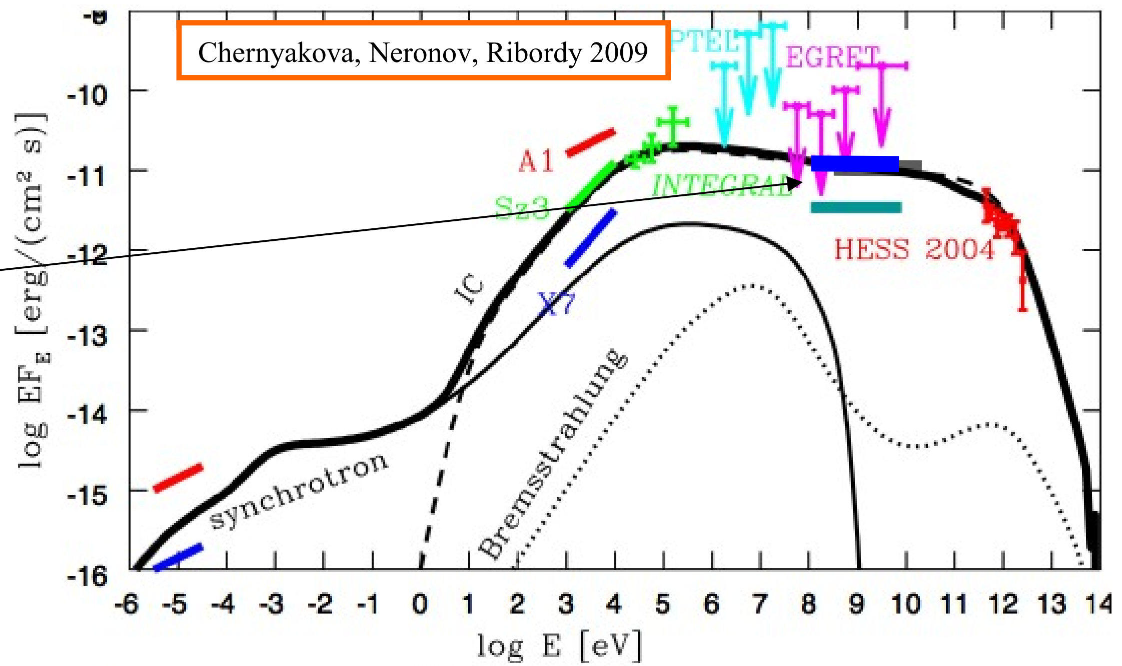
It was not clear a-priori, if Fermi sensitivity is enough to detect the source at periastron.

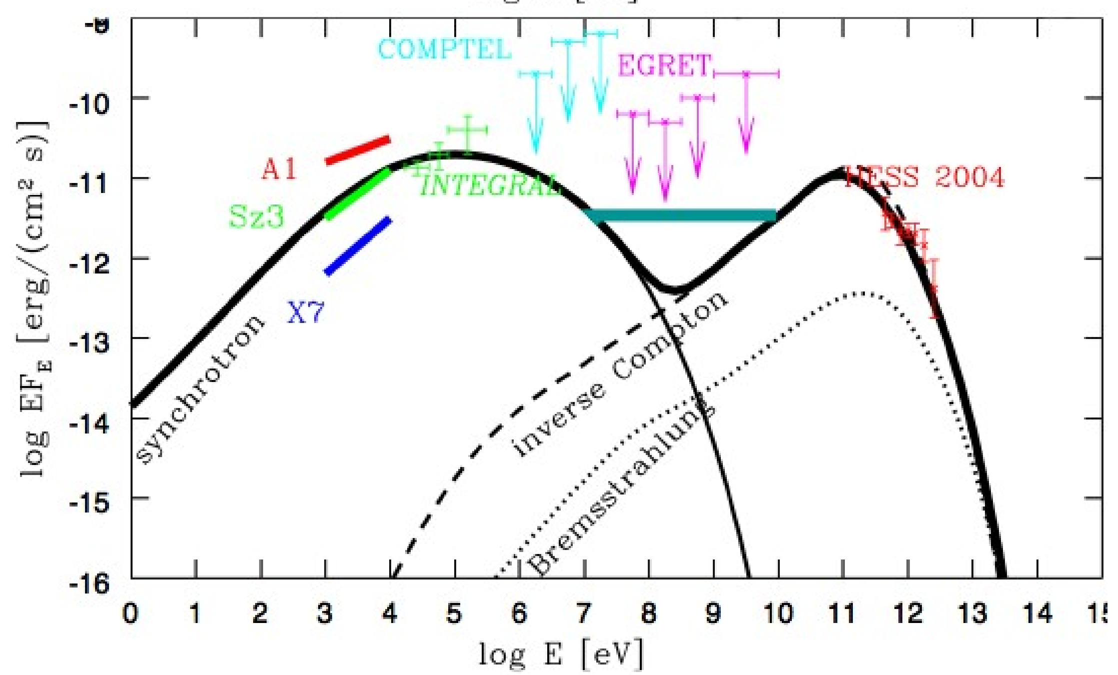
2010 Multi-wavelength Campaign



PSR B1259-63 2010-2011 pre-periastron emission





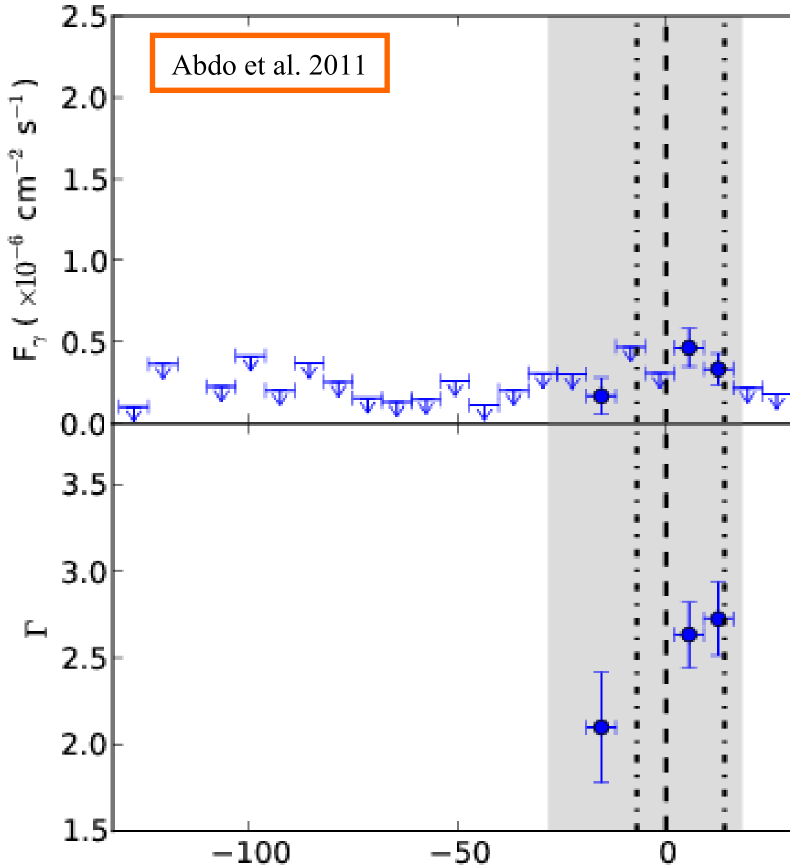


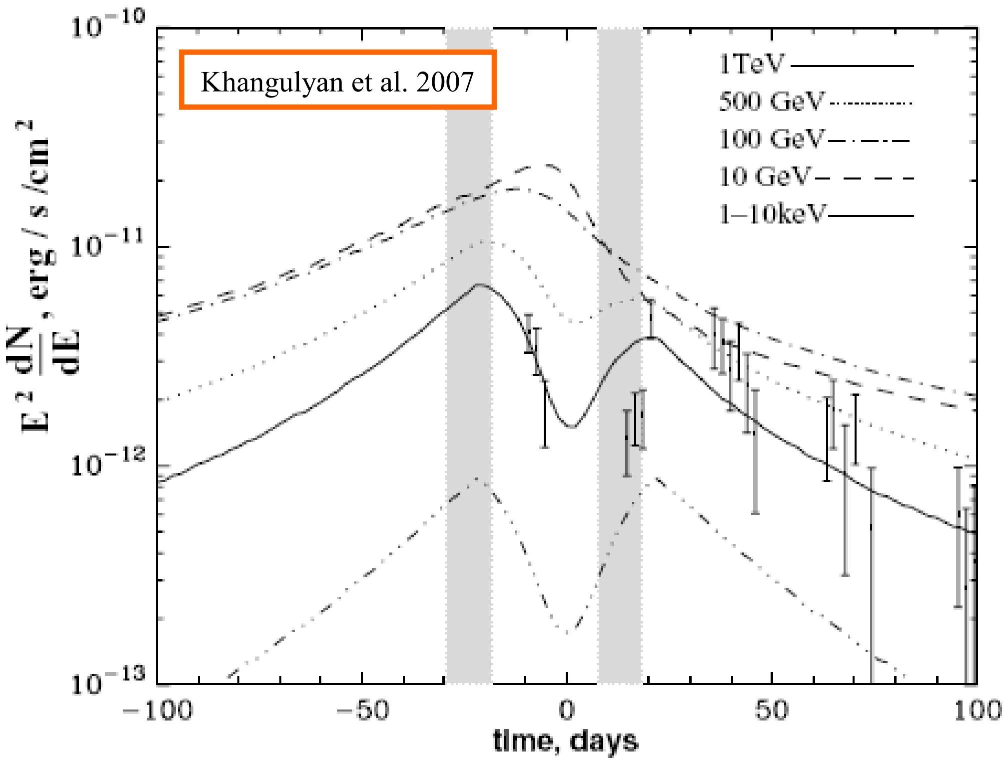
The source was first detected ~20d before the periastron, during the first passage through the Be star disk.

Spectrum was relatively hard, with photon index Γ≈2.

Source characteristics are consistent with the IC model.

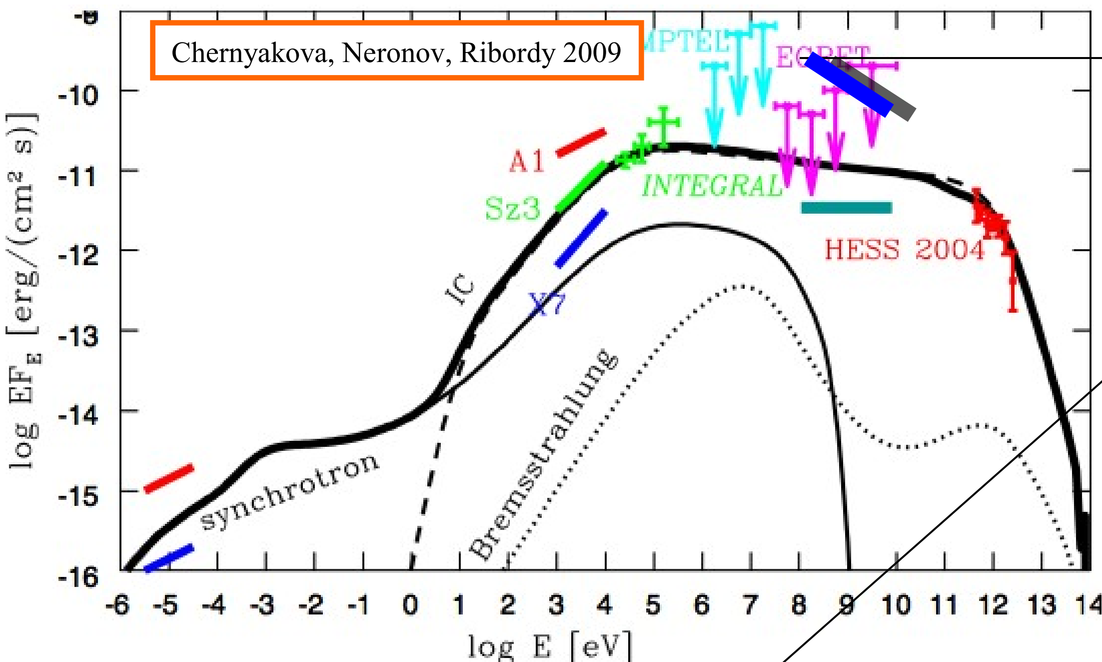
PSR B1259-63 2010-2011 periastron emission

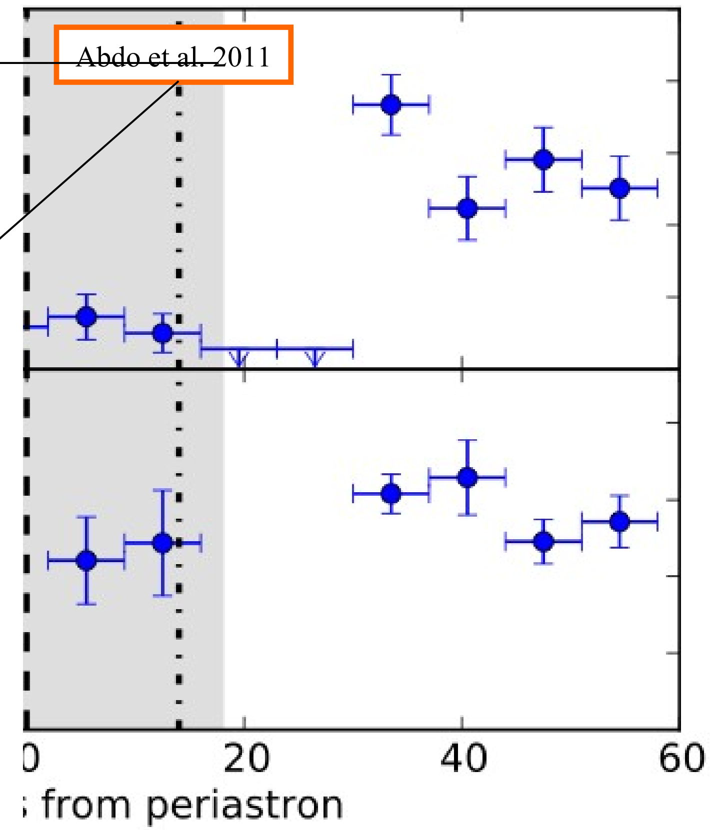


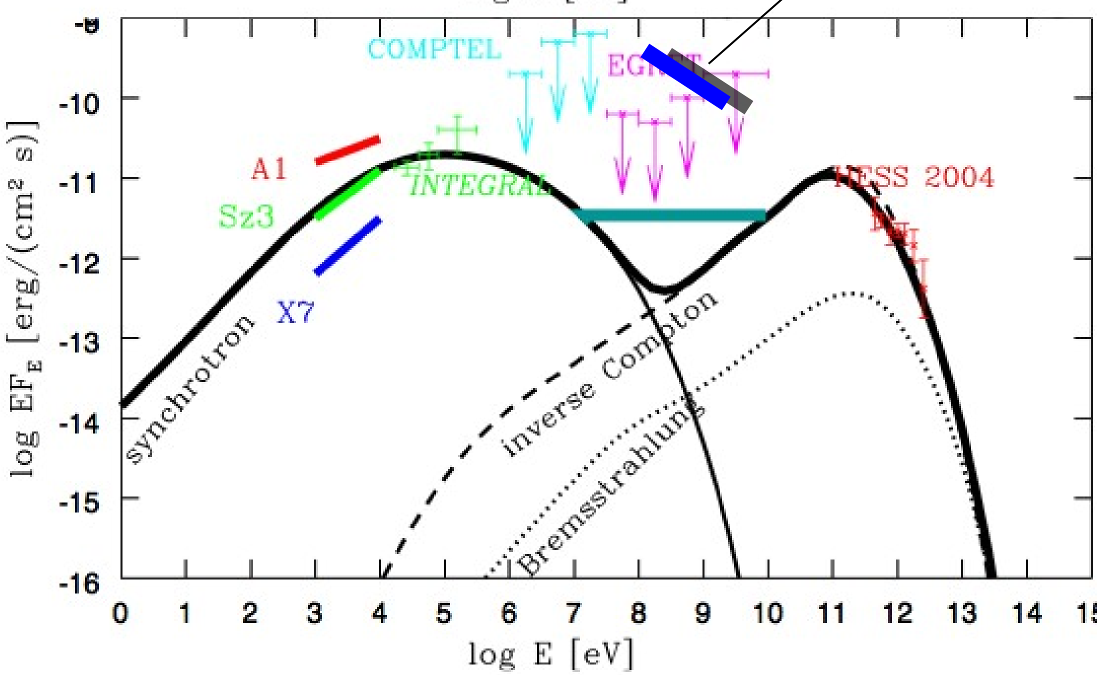


Maximum of GeV lightcurve near the periastron was first predicted by Khangulyan et al. 2007.

PSR B1259-63 2010-2011 post-periastron flare



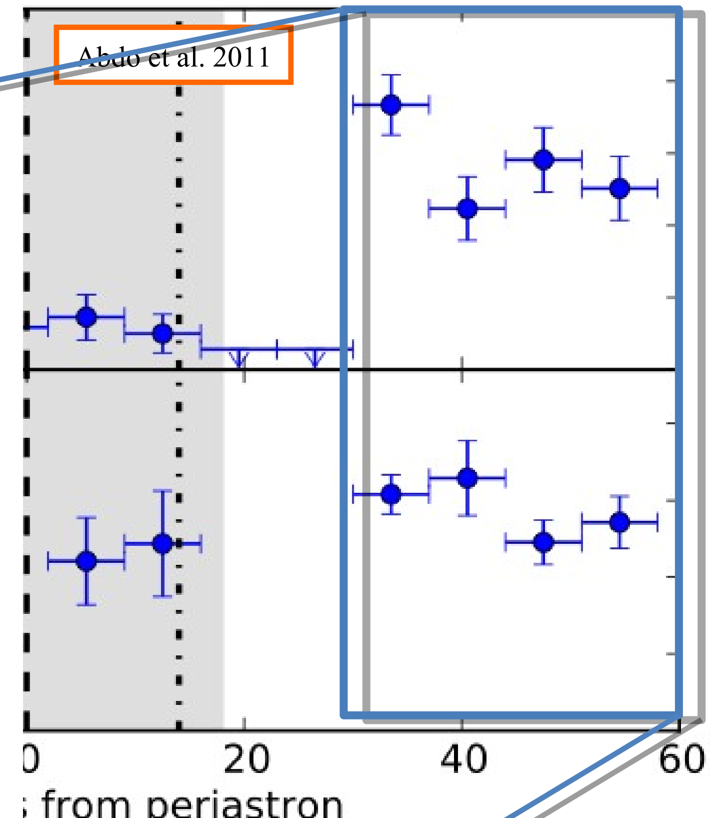


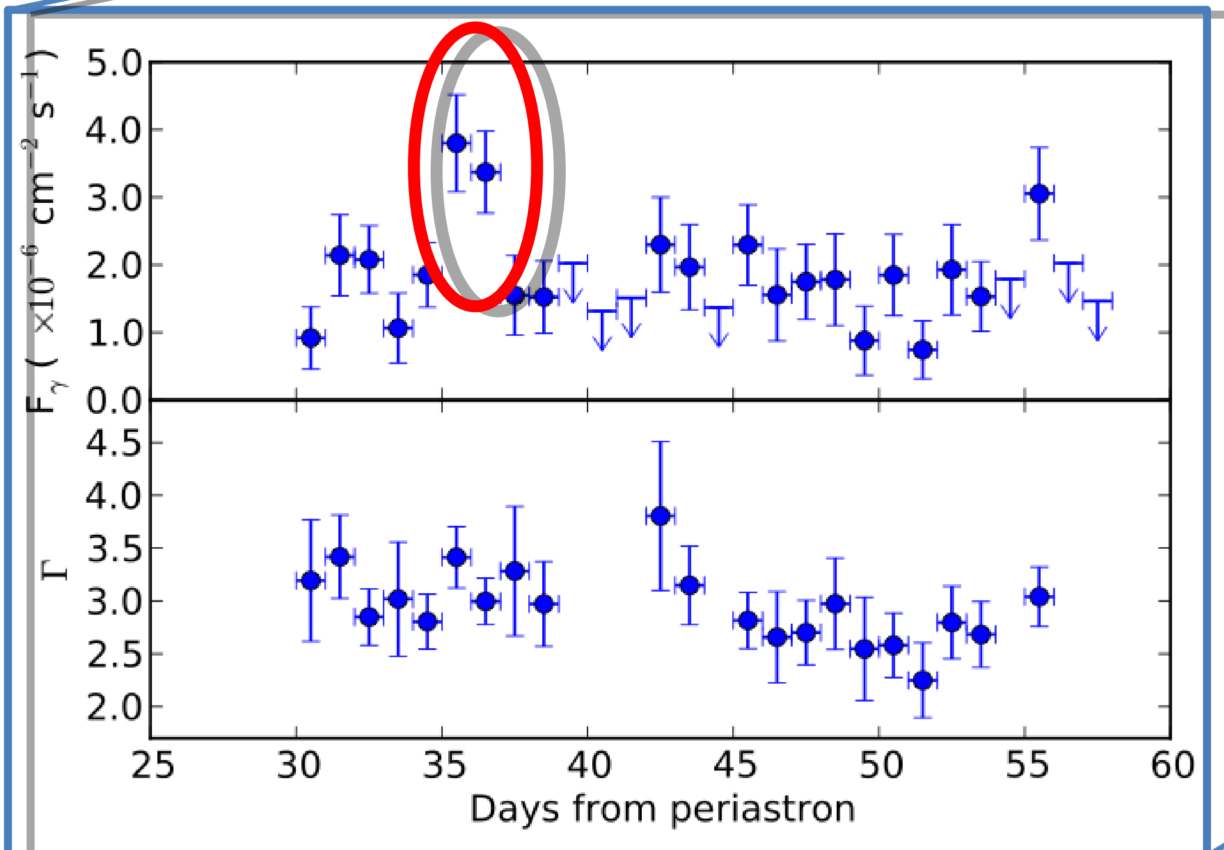


A strong flare with the flux increase by a factor of ~10 was detected ~30d post-periastron. The flare lasted for ~1 month.

The spectrum of the flare was much softer than the pre-periastron spectrum, with photon index Γ≈3.

PSR B1259-63 2010-2011 post-periastron flare





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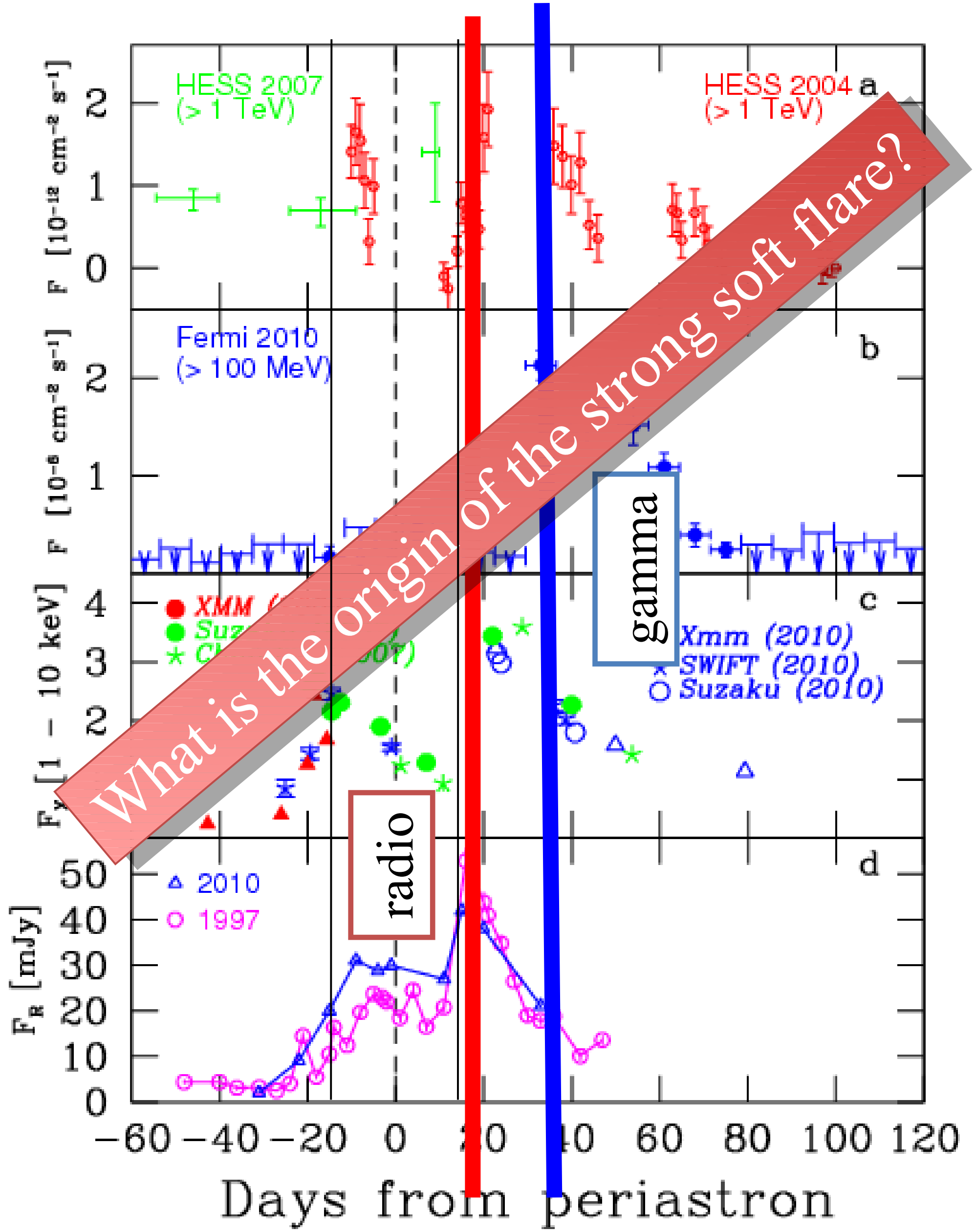

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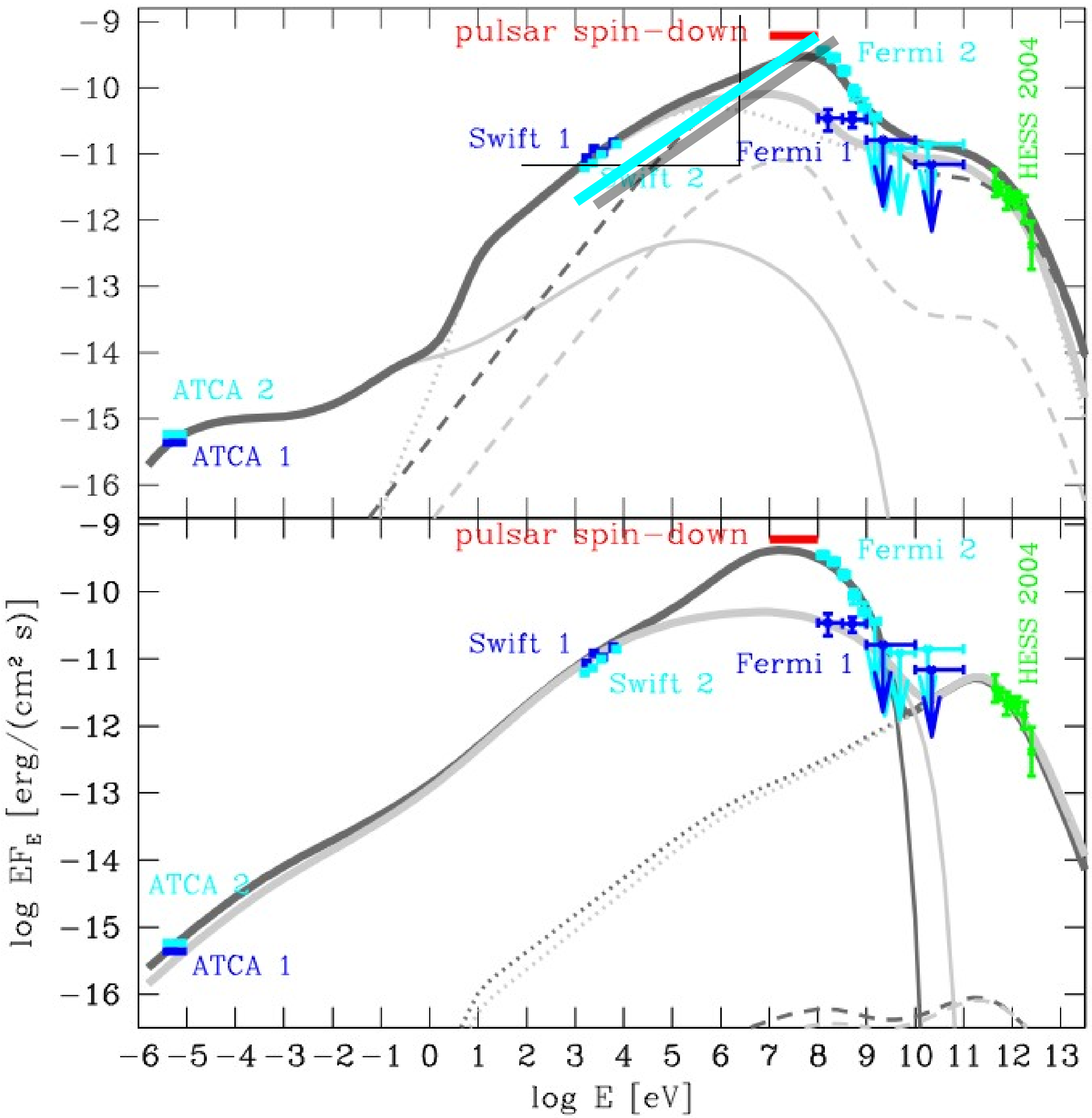


The flare observed by Fermi was, most probably, a separate spectral component:

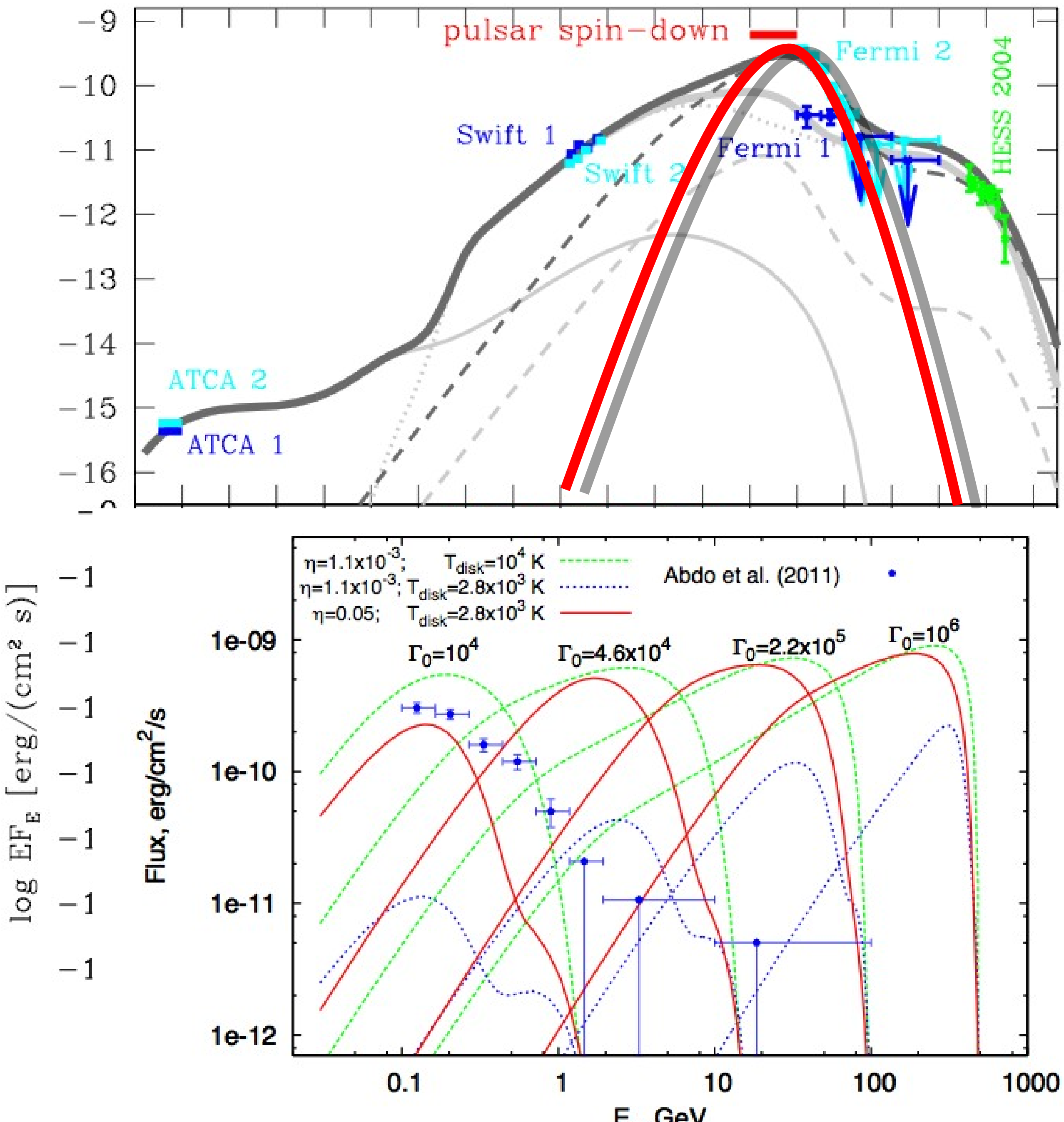
– onset time mismatch with the radio and X-ray post-periastron flare;

– assymetry between the pre- and post-periastron flares.

Gamma-ray luminosity of the source during the flare was ~100 % of the spin-down luminosity of the pulsar.

X-to-gamma-ray spectrum was very hard, with $\Gamma \approx 1.5$, much harder than the gamma-ray spectrum. The additional component had sharply peaked spectrum.

Physical mechanism of gamma-ray emisison

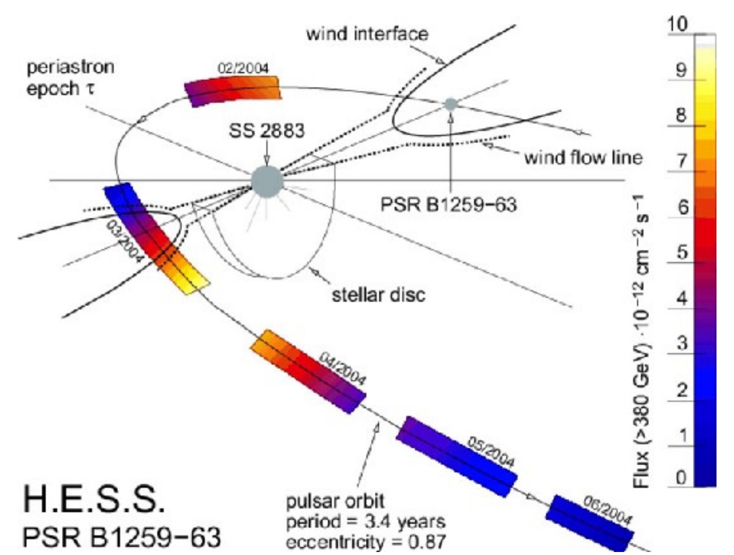


Inverse Compton emission from a sharply peaked electron distribution? $E_e \approx 1$ GeV?

Unshocked pulsar wind with bulk Lorentz factor 10^3-10^4?

Why would it appear as a flare and not as a persistent emission component with maximum around periastron?

Khangulyan et al. 2011



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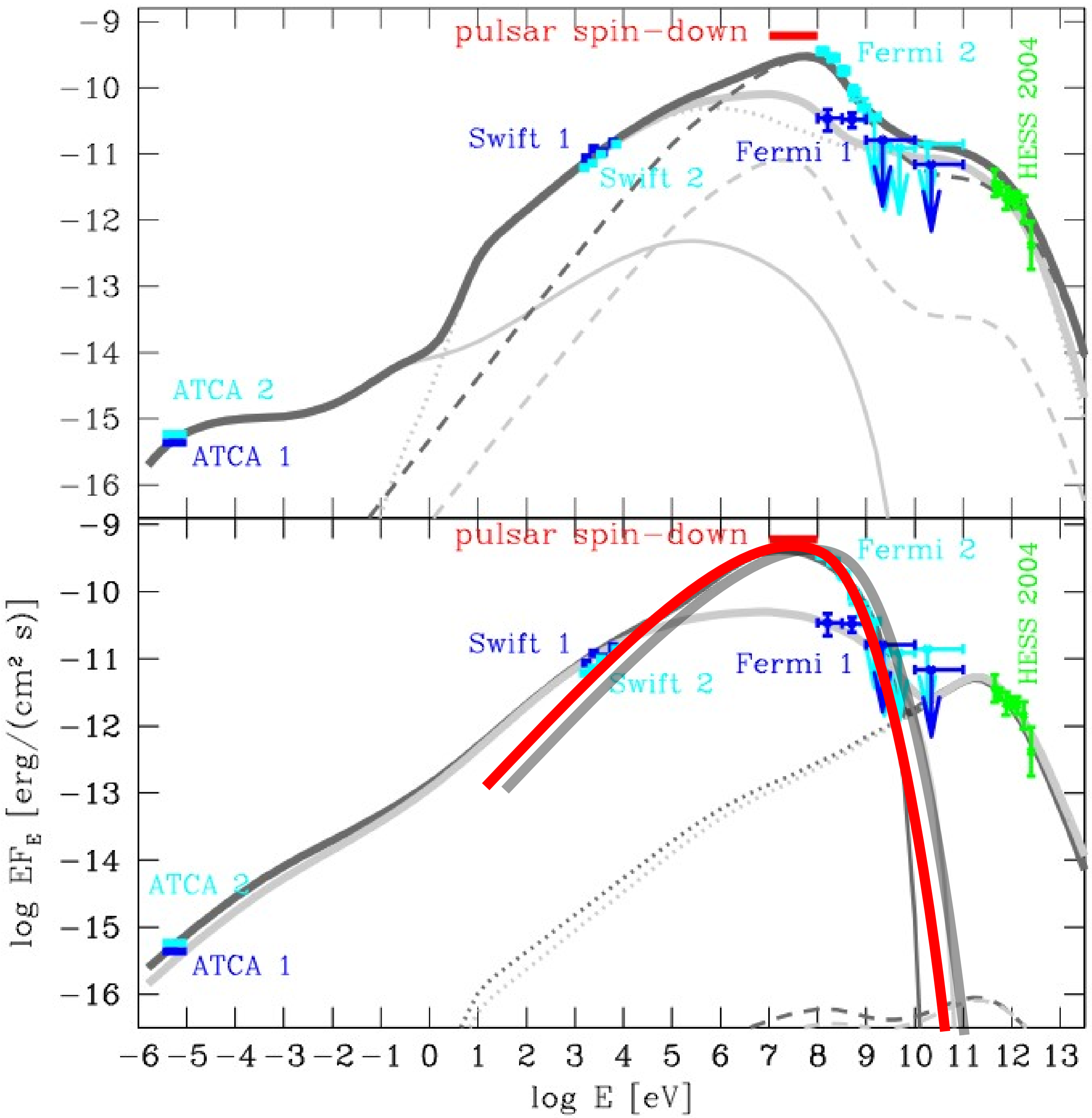

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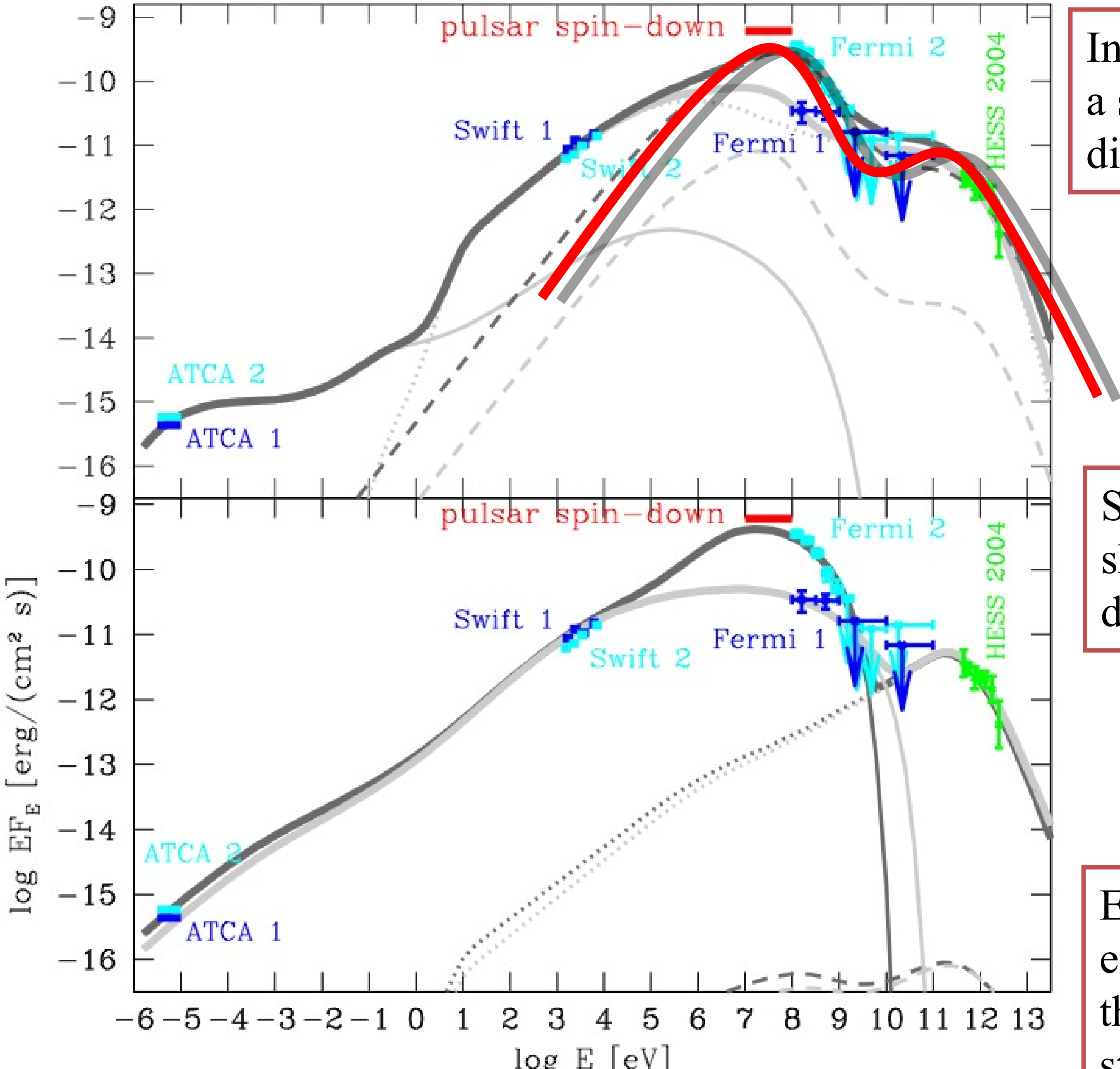
Unshocked pulsar wind with bulk Lorentz factor 10^3?

Synchrotron emission from a sharply peaked electron distribution? $E_e \approx 10^{15}$eV?

Direct injection from pulsar wind with bulk Lorentz factor 10^9?

An "exotic" scenario, but not ruled out….

Physical mechanism of gamma-ray emisison



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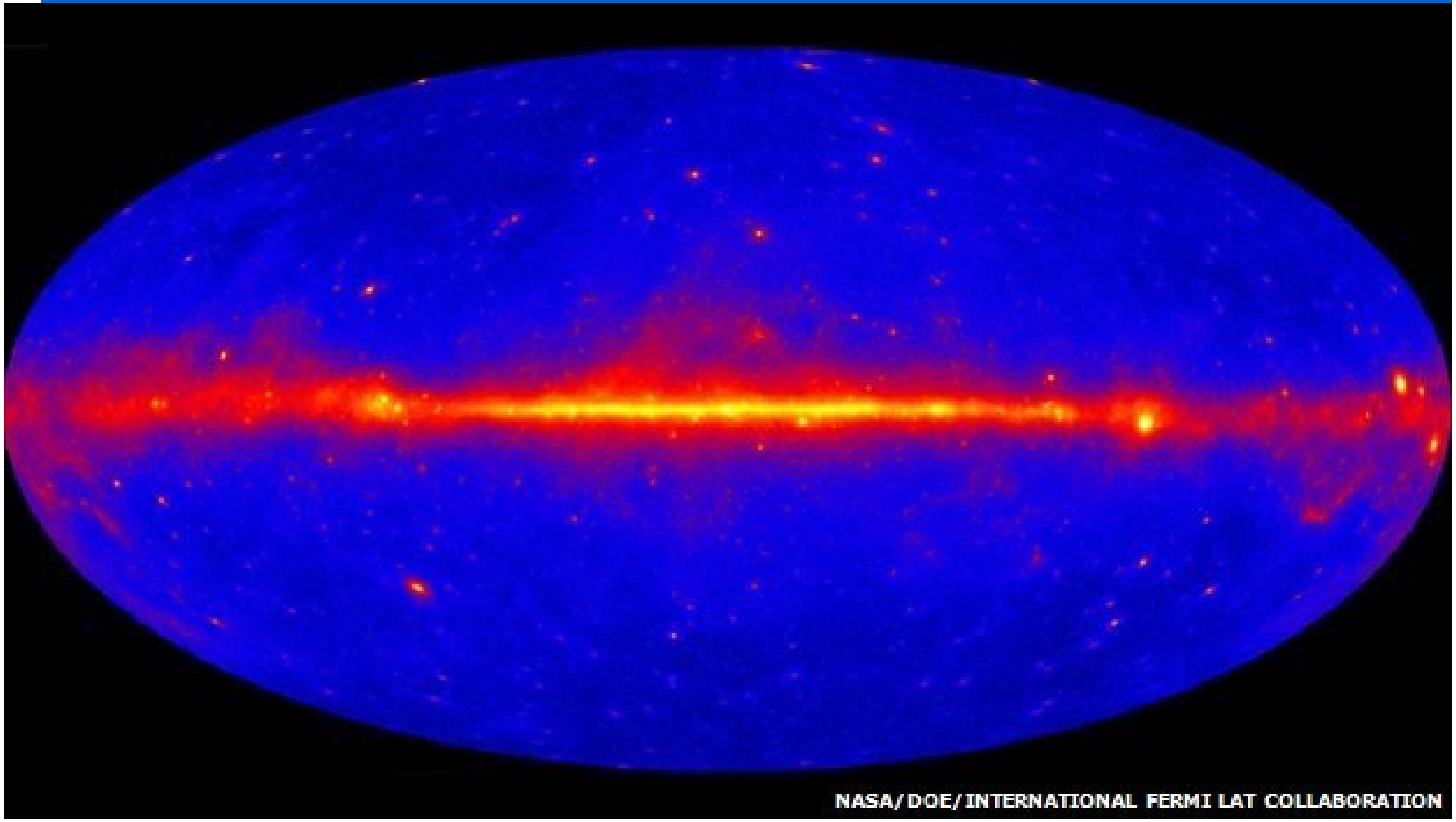
Enhanced Bremmstrahlung emission from the pulsar passage through the "debris" of the Be star disk?

Conclusions – 1

- γ-ray loud binaries apparently form a separate class of sources powered by interaction of relativistic wind from the compact object with the stellar wind.
- The emission from such a system is
- variable along the orbit,
- non-thermal X-rays, γ-rays, and very high-energy γ-rays are produced during the periods of pulsar passing through the dense regions of the companion wind.

γ-ray sky (GeV) as seen by Fermi

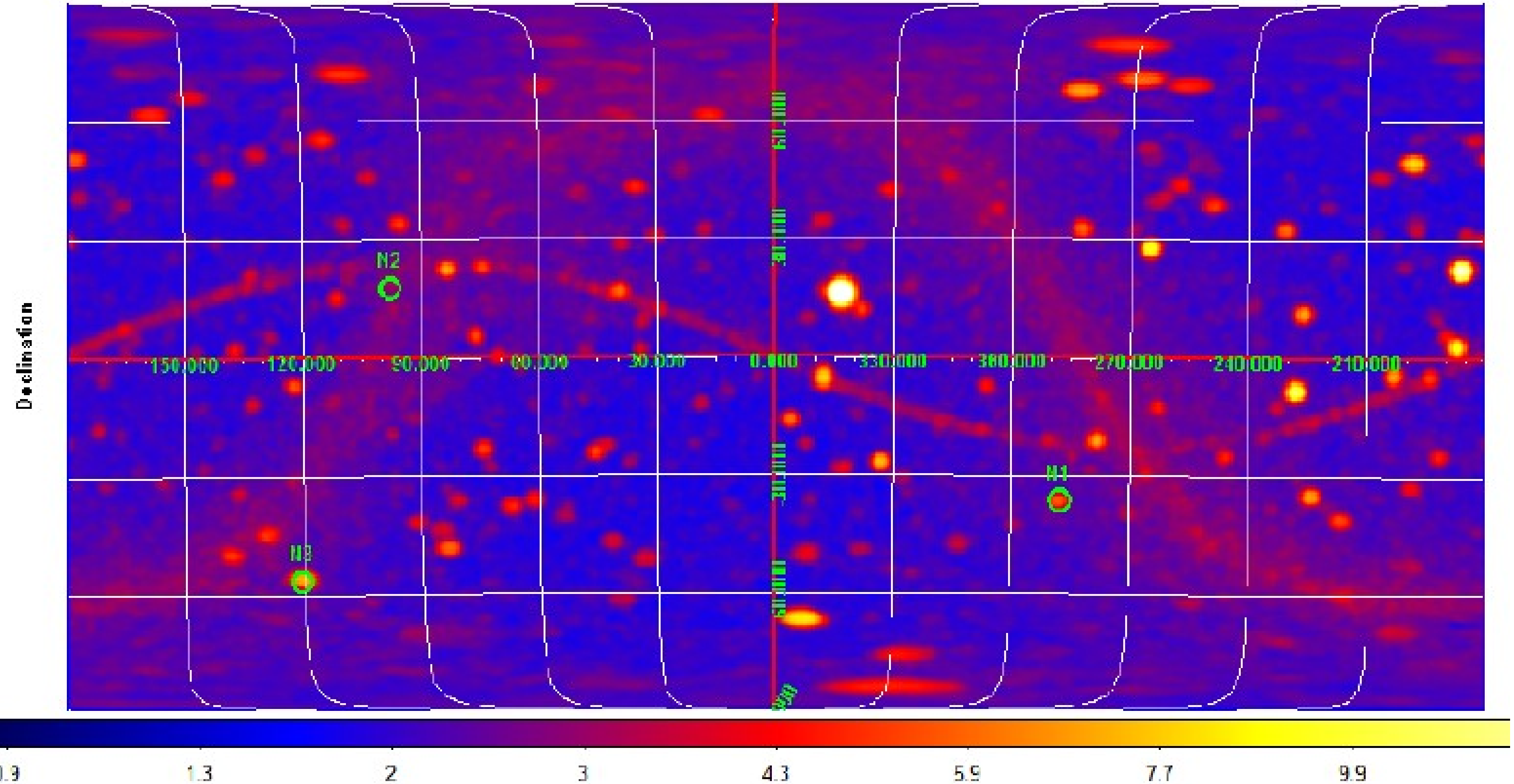


- Interactions of cosmic ray with ISM lead to bright large scale diffuse emission.
- Isolated Galactic-ray sources are superimposed on this large-scale diffuse emission.
- Inhomogeneity of matter distribution in the ISM lead to the local enhancements of the brightness of the γ-ray emission, which could be misinterpreted as isolated sources.
- The most straightforward distinguishing property of isolated γ-ray sources is variability.

Which sources would you expect to be variable?

- The only firmly established class of generically variable Galactic sources is that of γ-ray-loud binaries. These system provide a very moderate contribution to the overall γ–ray emission from the Galaxy.
  - Only a small fraction of the HMXRB are able to produce γ-rays?
  - Most of the HMXRBs are emitting γ-rays, but below the sensitivity of Fermi?
- Other known types of Galactic γ-ray sources, including the diffuse emission and supernova remnants are not variable on the day-to-month time scales. This feature could reveal the presence of γ-ray-loud binaries even at the top of much stronger diffuse emission.
- Only Crab pulsar, is known to produce γ-ray flares on hour-to-day time scale. The variable emission is produced in the inner part of the Crab PWN. A peculiar feature of the Crab pulsar? A generic property of the young-pulsar-powered systems?
- A systematic study of hour-to-month scale variability properties of other known young pulsar systems in the Galaxy is needed to clarify this issue.

Variabillity Map



- A simple way to verify if γ-ray emission from a given direction on the sky is variable or constant is to analyze the lightcurve and check if it is consistent with a constant flux.

- To measure (in)consistency with the constant flux one could either calculate the χ^2 to test the systematical variability, or measure the significance of the maximal deviation σ for the flaring sources.

$$\chi^2(l,b) = \sum_{i=1}^{N} \frac{(F_i - \overline{F}(l,b))^2}{\sigma_i^2} \qquad \sigma_{max}(l,b) = \max_{i=1}^{N}\left(\sqrt{\frac{(F_i - \overline{F}(l,b))^2}{\sigma_i^2}}\right)$$

- To separate random fluctuations from real variable sources one should consider only excesses above a certain threshold value.

Results

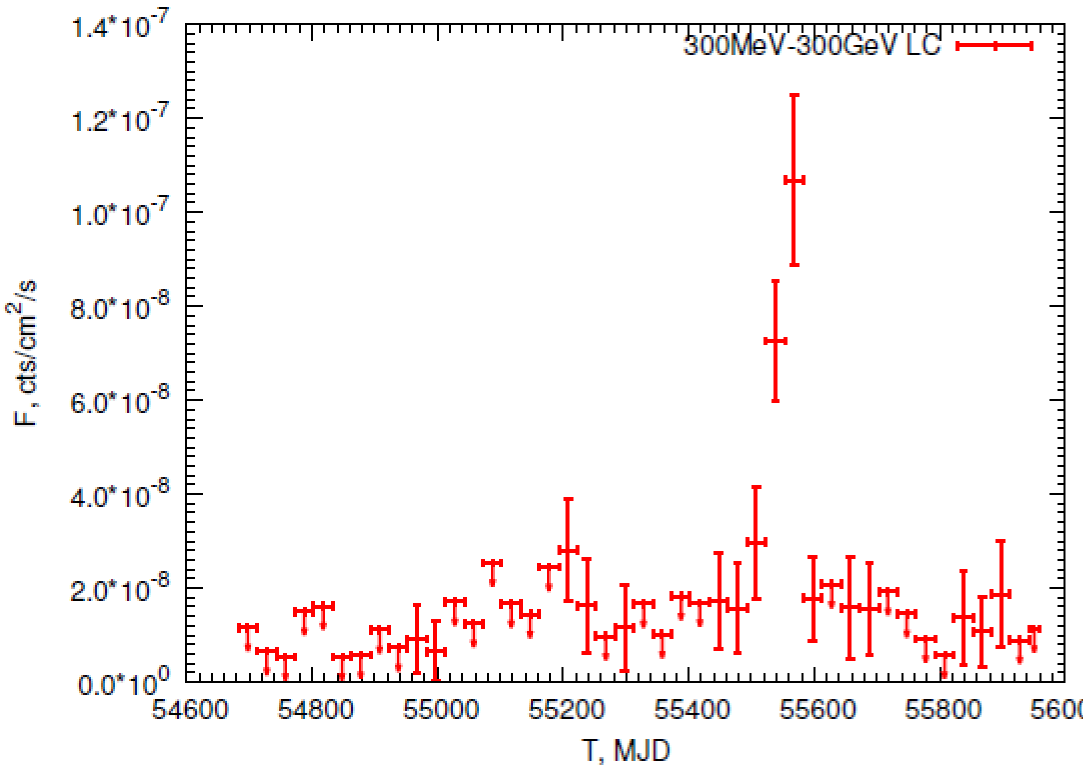
- For the period of 37 months (4Aug 2008 – 4Nov 2011) we built seria of χ^2 and σ maps on the time scale of 6 hours, day, week and month at energy above 300 MeV.

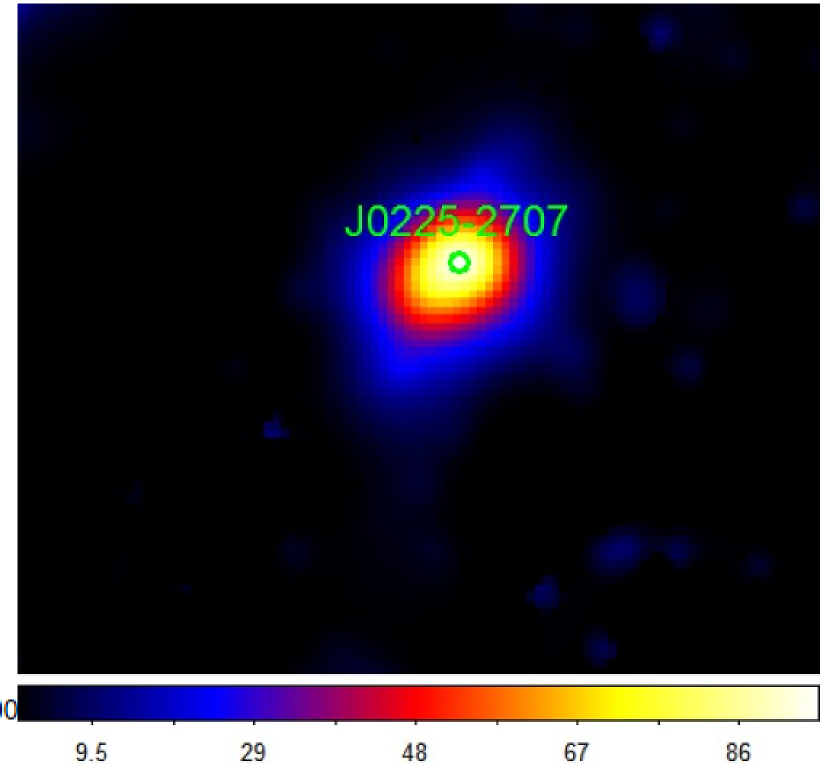
- In total we found 375 variable sources (110 of these sources are not marked as variable in the second Fermi catalogue).

- Most of these variable sources (354) are identified as different types of Active Galactic Nuclei.

- This method is great for the discovery of the flaring sources weak on average.

New source





Beside the known catalog sources above the selected threshold we found only 3 new sources. Two of these sources are identified with GRBs (GRB 090902B, GRB 090926A). The third source J0225-2607 (ra=36.27, dec=-26.11) was detected with the TS≈ 95 (> 9 σ) during the flare.

Galactic Plane

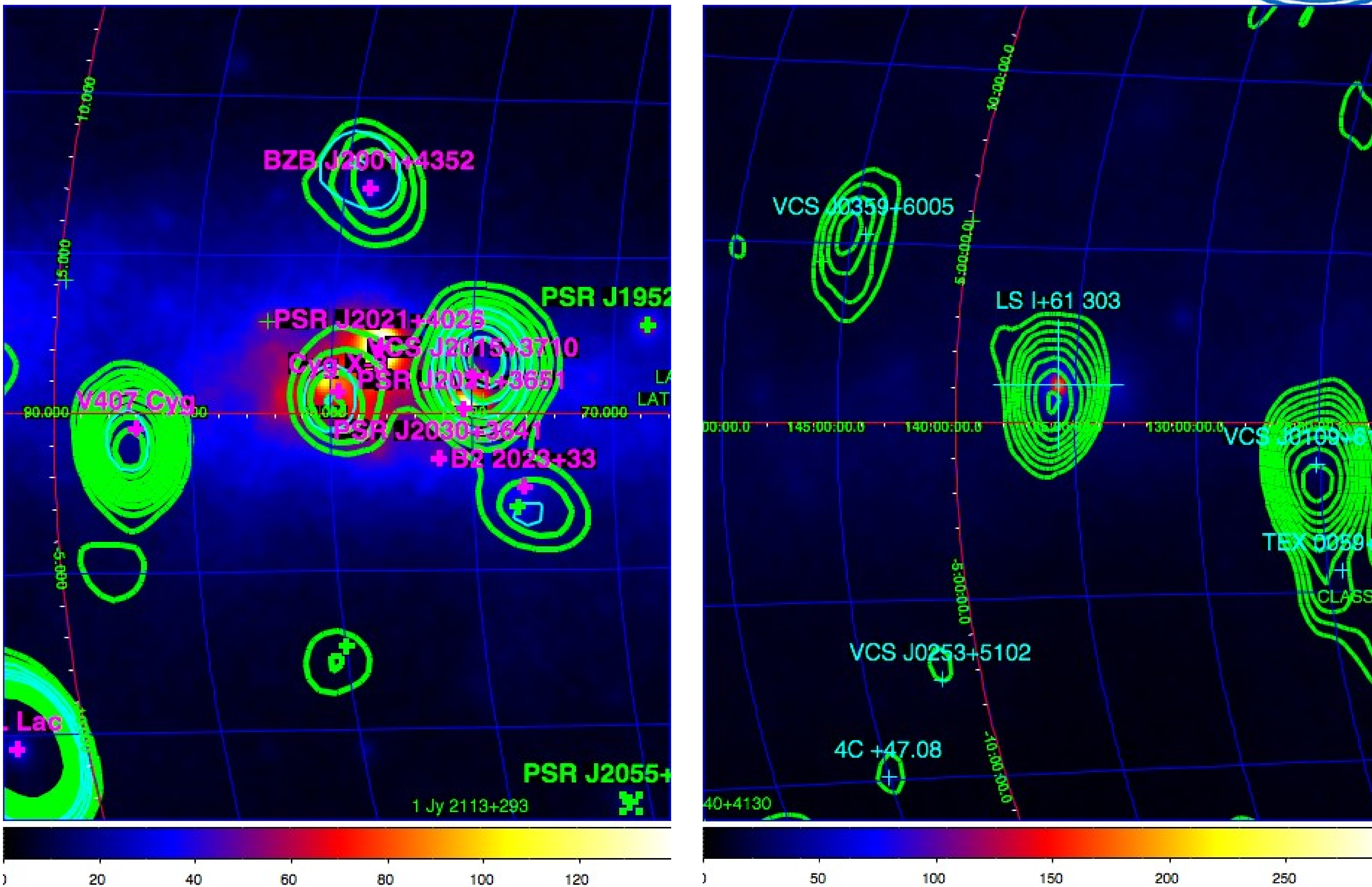
- If the flux from the entire Galactic Plane is constant, one expects to find on the moth-time-scale σ–map less than one lightcurve (on average) with $\sigma > \sigma_{thr} = 4$.

- The most variable Galactic sources are LSI +61 303, Cyg X-3 and V407 Cyg. All the three are γ-ray-loud binaries with rather different types ofvariability. LSI +61 303 is a persistent source, variable on the 26.4 d orbital period and on a longer superorbital period of 4.6 yr. Cyg X-3 is a recurrent flaring source which exhibited already several bright flares over the 3.5 yr period of Fermi/LAT exposure. V407 Cyg is a symbiotic binary which produced only one flare during the LAT exposure.

- Excess of month-time-scale variability at the level $\sigma_{max} \sim 15$ is also detected from the direction of the Crab pulsar.

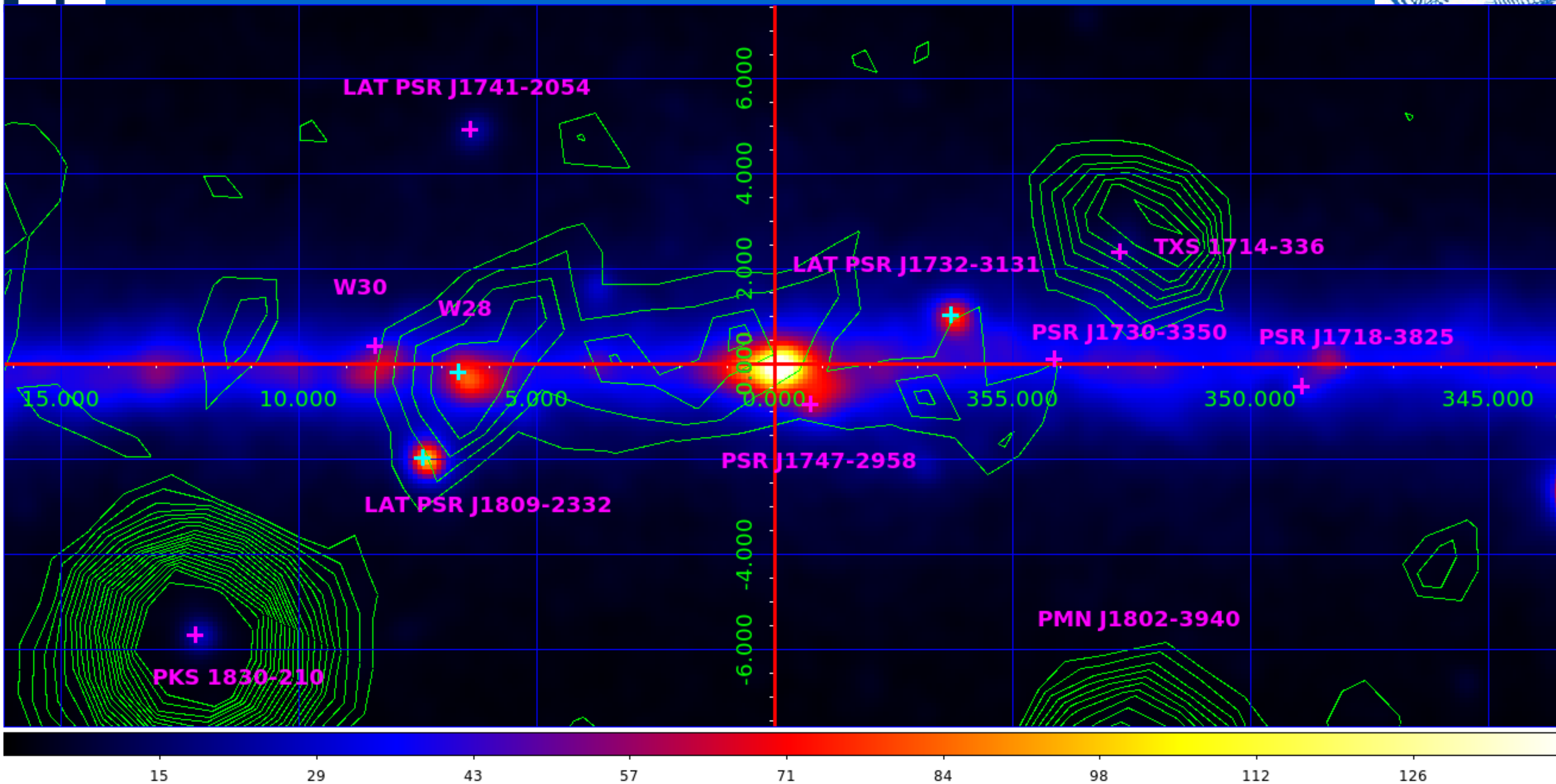
Variability in the Galactic Plane

γ-ray loud binary systems



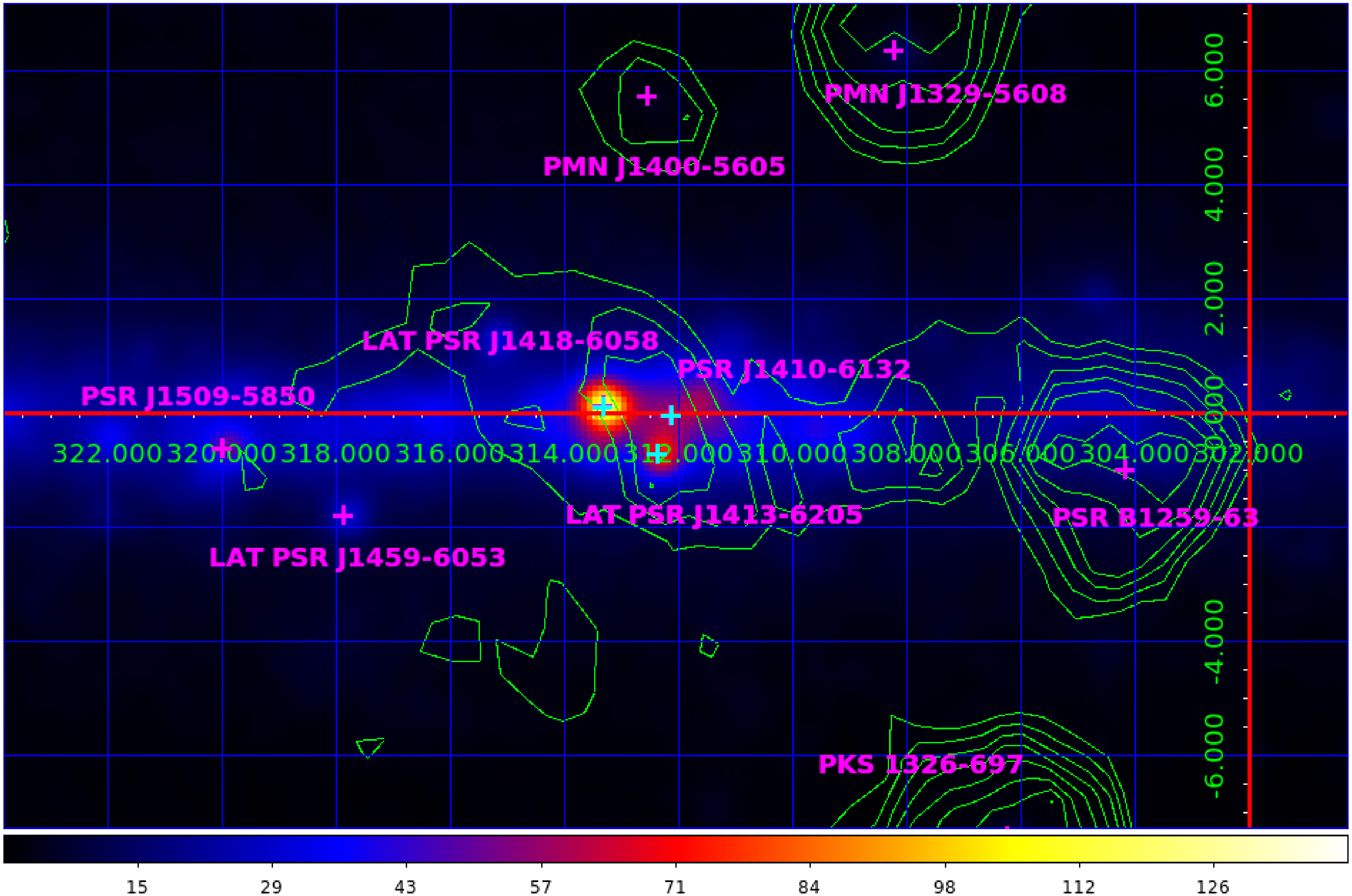
LAT countmaps (E>300 MeV) with the superimposed contours showing the σ_{max} values in lightcurves with month-length time bins. Contour levels start from 3σ with the steps 0.5σ

Around the Galactic Center



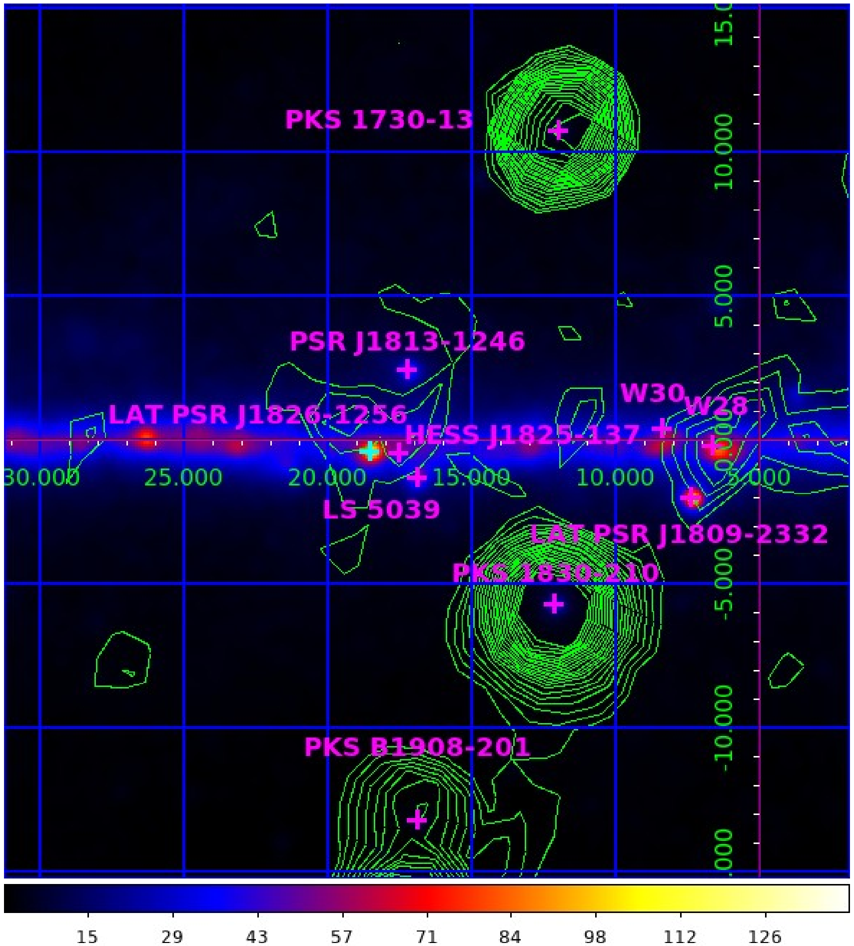
The excess variability is not centered at the Galactic Center itself, but traces the part of the Galactic Plane at positive Galactic longitude $0^{\circ} < l < 7^{\circ}$ dominated by the diffuse emission, with no clearly isolated bright sources. The end part of the variable region, with the brightest excess at the level of $\sigma_{max} \sim 4.5$ is centered at the bright supernova remnant W28. The variable region contains a number of young pulsars, including PSR J1747-2809 and PSR J1746-2850 close to the Galactic Center with the ages T = 5.3 kyr and T = 12.7 kyr, just slightly larger than that of the Crab pulsar. Closer to the W28 remnant there is PSR B1757-24, a pulsar of the age T = 15.5 kyr. Finally, the W28 itself was supposed to be associated to the pulsar PSR 1758-23

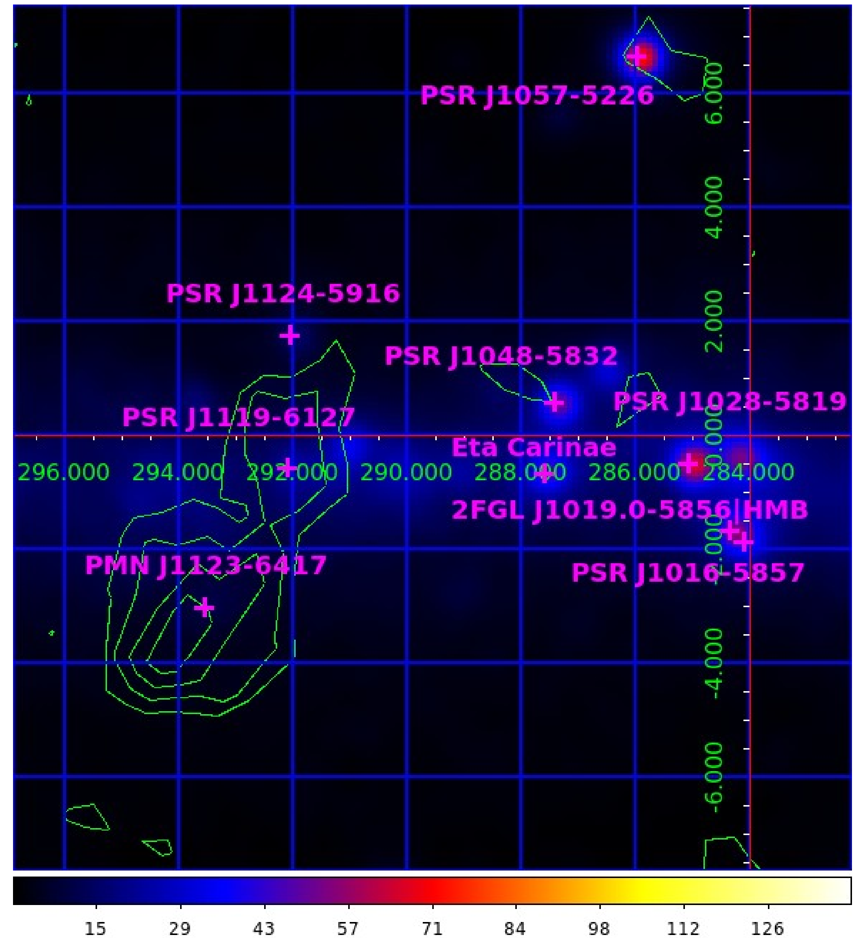
Kookaburra PWN complex



This sky region contains three young pulsars, PSR J1418-6068, PSR J1410-6132 and PSR J1413-6205, emitting pulsed γ-ray emission in the 0.1-10 GeV band.
PSR B1259-63 is not visible in the three year countmap, but appears as a very bright excess in the variability map.

Variability of the known sources





if we are interested in the variability properties of known sources, the threshold could be decreased, because in this case there is no trial factor associated to the scan of the entire Galactic Plane. The probability to find an excess variability at the level above 3.5 is just about 1% for each individual source. The excess variability at the level higher than 3.5 is found in two more directions on the sky which coincide with positions of known sources, PSR J1826-1256 and PSR J1119-6127.

Conclusions -- 2

- Variability of emission from the Galactic Plane is due to the presence of compact γ-ray sources. The only firmly established class of generically variable Galactic sources is that of -ray-loud binaries. In this respect, it is not surprising that the highest excess variability is found in the directions of known γ-ray-loud binary systems: LSI +61 303, V407 Cyg, Cyg X-3 and PSR B1259-63.
- Remarkably, there are no signatures of weaker variability which could be clearly associated to other binary systems with black holes and/or neutron stars.
- Recent discovery of the γ-ray flaring activity of the Crab pulsar shows that pulsars (or the inner compact parts of the pulsar wind nebulae, PWNe) should be also considered as possible variable Galactic source population. However, it is difficult to draw definitive conclusions about the variability of the entire pulsar population based on the study of a single source, especially taking into account the fact that the Crab pulsar could be considered as a special case because it is the youngest known γ-ray-loud pulsar.
- Our systematic study of variability of emission from the Galactic Plane shows that it is possible that long (month) time scale variability might be a generic feature of the pulsars/PWN systems.