Broadband properties of gamma-ray binaries with a radio pulsar

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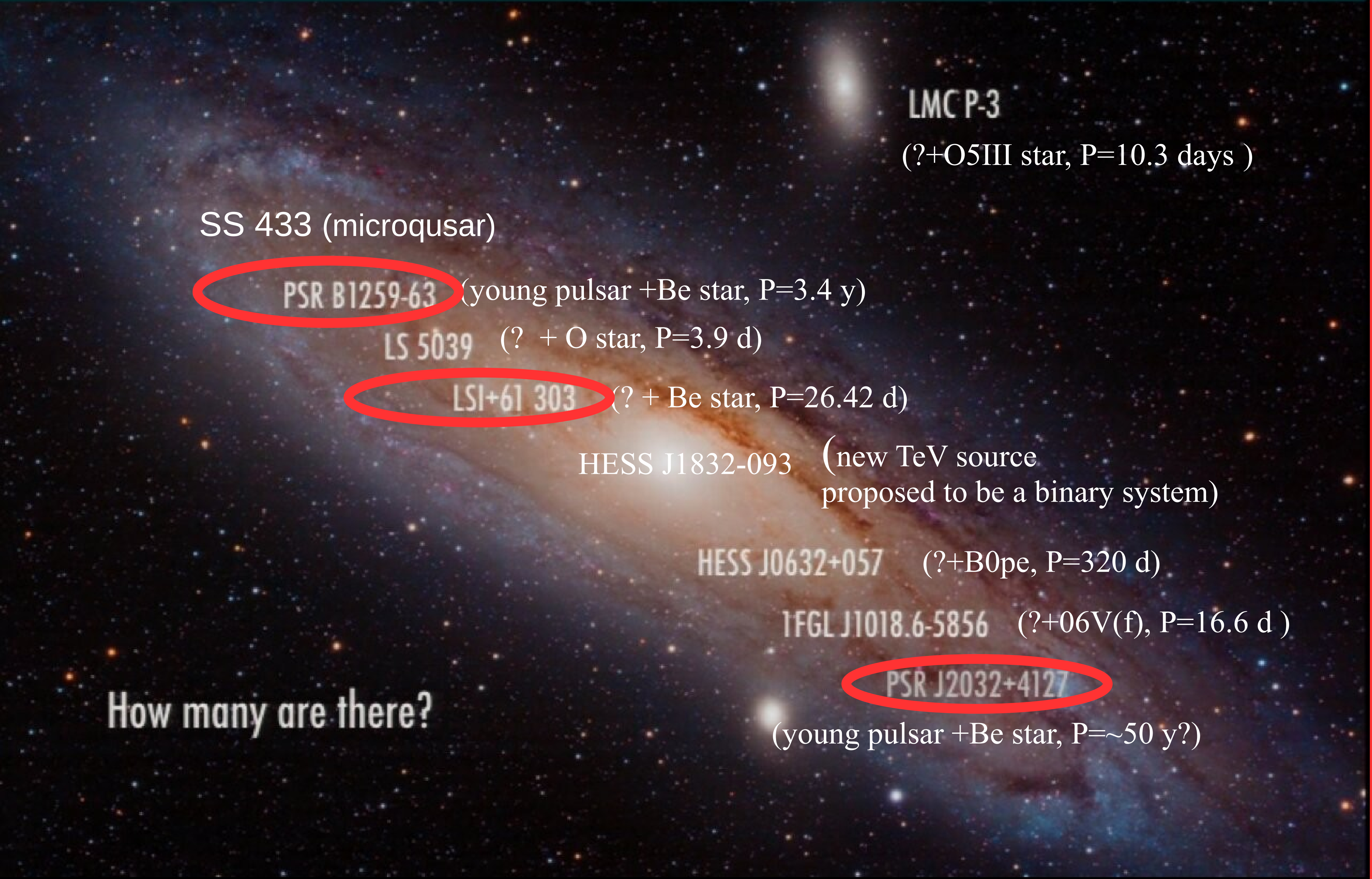
Variable Galactic Gamma-Ray Sources (VI), April 12th - 14th 2023, Innsbruck, Austria.

Known gamma-ray binaries



LMC P-3

(?+O5III star, P=10.3 days)

SS 433 (microqusar)

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

LS 5039 (? + O star, P=3.9 d)

LSI+61 303 (? + Be star, P=26.42 d)

HESS J1832-093 (new TeV source proposed to be a binary system)

HESS J0632+057 (?+B0pe, P=320 d)

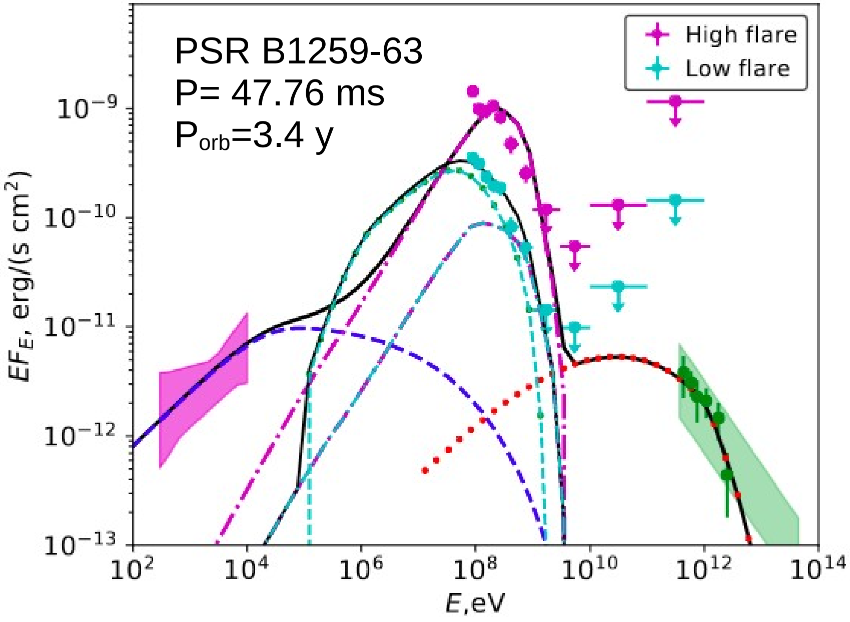
1FGL J1018.6-5856 (?+06V(f), P=16.6 d)

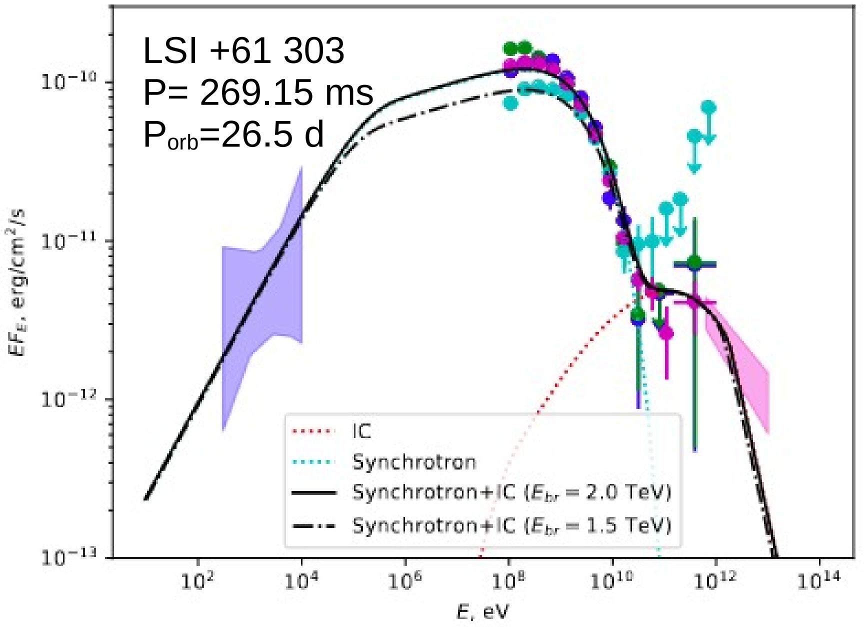
PSR J2032+4127

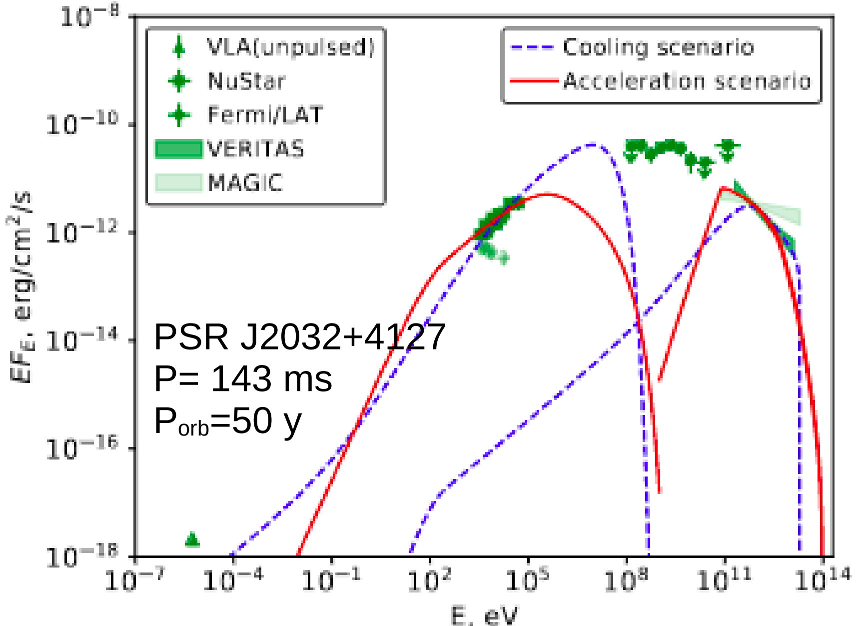
(young pulsar +Be star, P=~50 y?)

How many are there?

Gamma-ray binaries with a radio pulsar

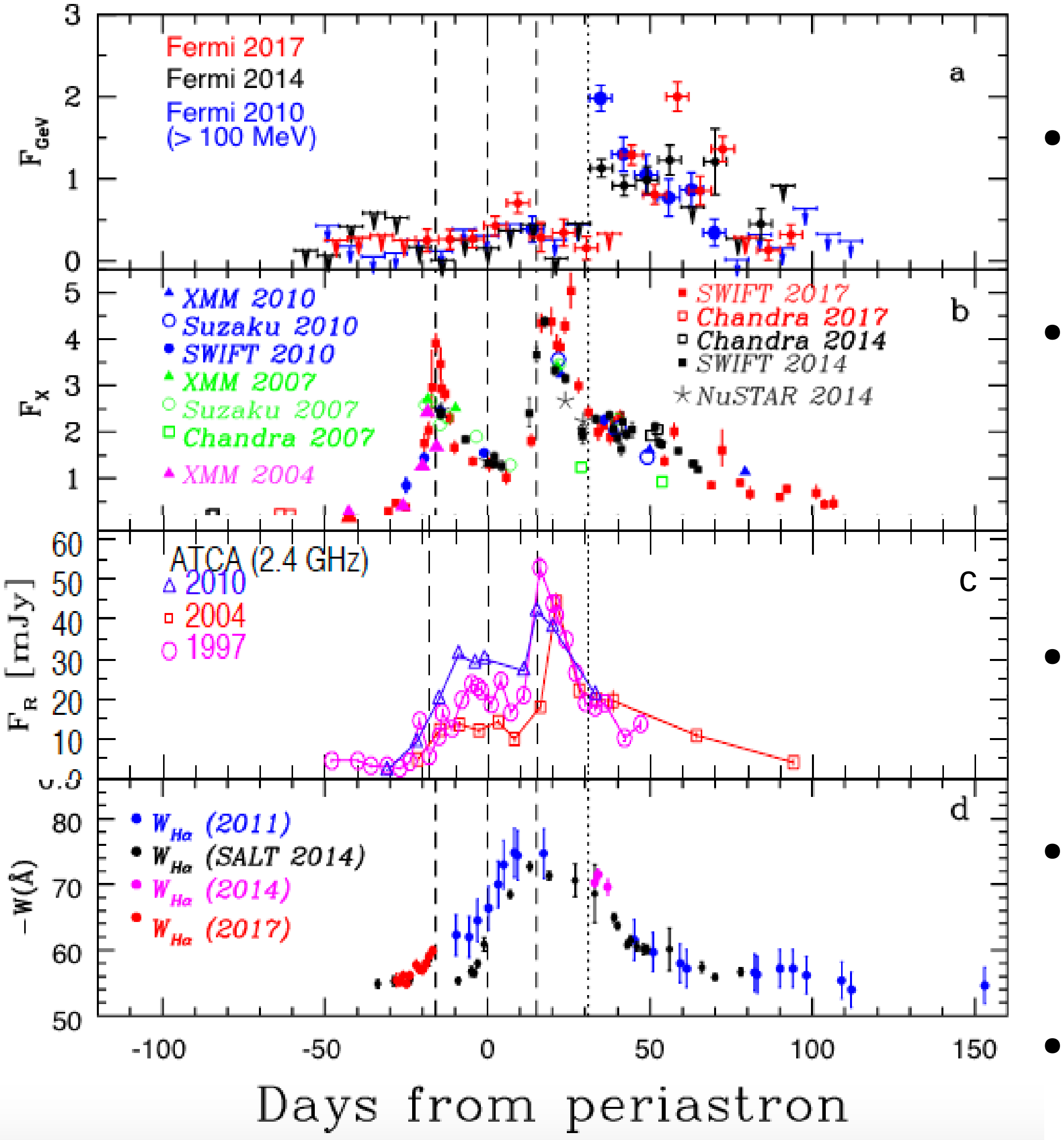






- Radio pulsar is in orbit around Be star
- Similar range of X-ray and TeV emission around periastron.
- Very different GeV appearance.
- Natural laboratories for the study of the properties of pulsar and stellar winds.

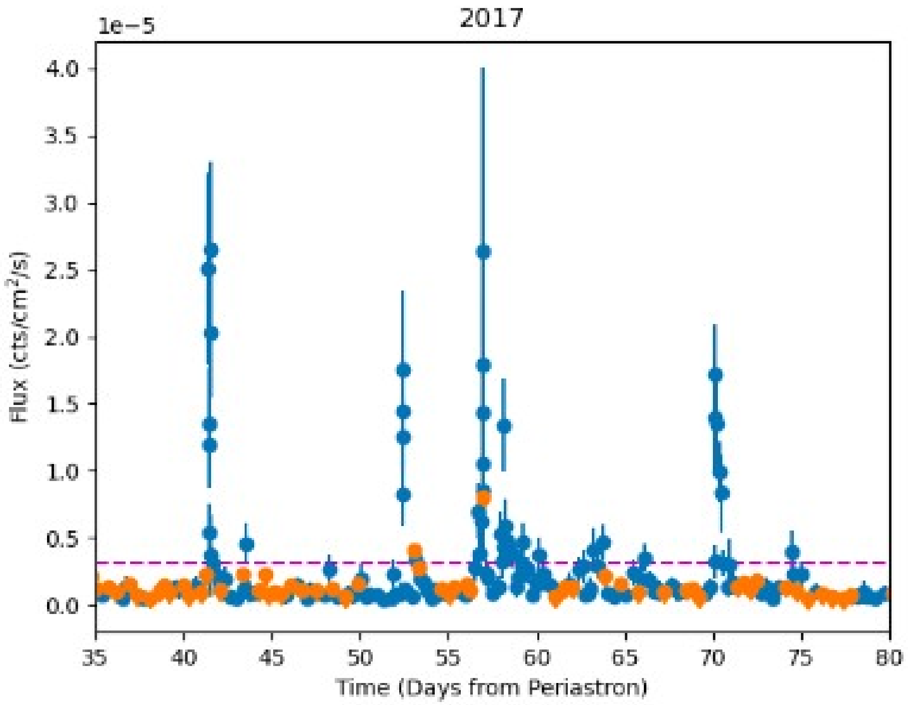
PSR B1259-63: light curves



Chernyakova et al. 2020

- Two peaks at X-ray and radio ~20 days around the periastron.
- Corresponds to the passage through the Be star disk.
- Huge GeV flare with energy release close to spin-down luminosity on a weekly scale ~30/40 days after the periastron.
- No obvious counterpart at other energies.
- In 2014 optics showed a disruption of the disk at the time of GeV flare.
- Various models to explain GeV, e.g. Khangulyan et al. 2012, Dubus & Cerutti 2013, Yi & Cheng 2017, Chernyakova et al. 2020

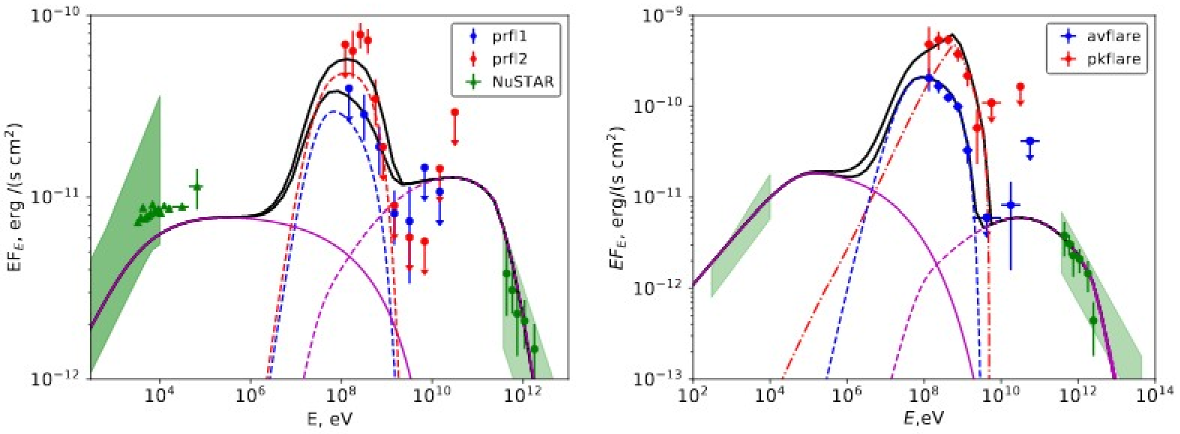
PSR B1259-63: light curves 2017

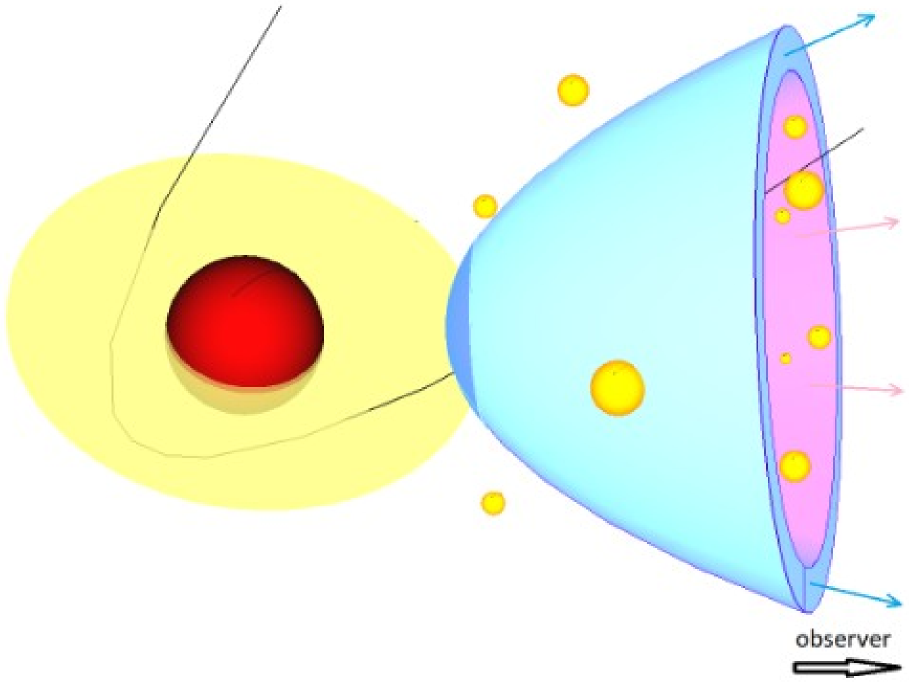


- Evidence of very fast (~15 min) gamma flares

- The isotropic gamma-ray luminosity corresponding to the short flares greatly exceeds the pulsar spin-down luminosity!

PSR B1259-63: model



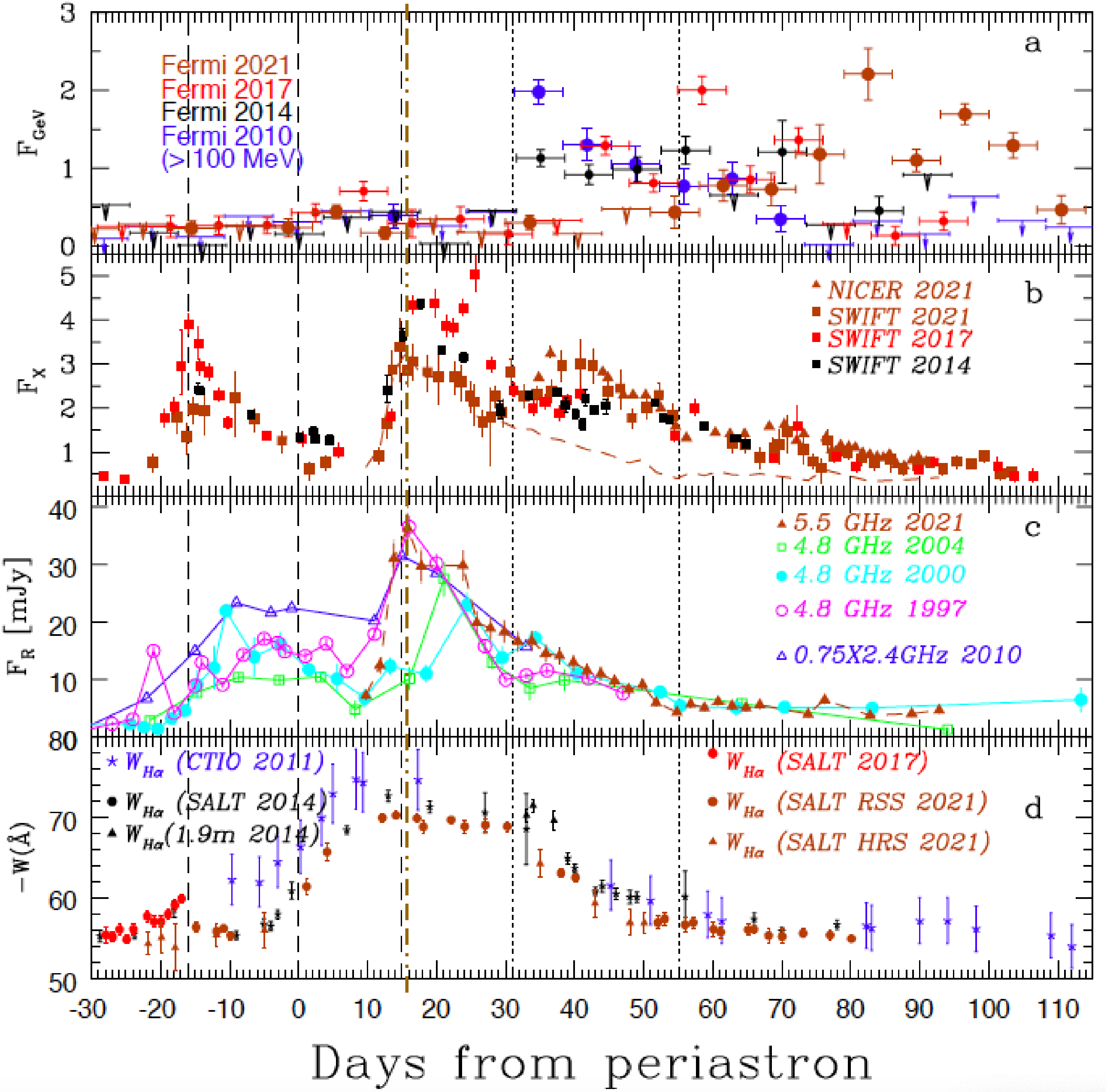


Chernyakova et al. 2020

- Observed X-ray and TeV emission can be explained as a synchrotron and IC emission of the strongly shocked electrons of the pulsar wind.
- GeV component is a combination of the IC emission of unshocked / weakly shocked electrons and bremsstrahlung emission.
- Luminosity of the GeV flares can be understood if it is assumed that the initially isotropic pulsar wind after the shock is reversed and confined within a cone looking, during the flare, in the direction of the observer.

PSR B1259-63: periastron 2021

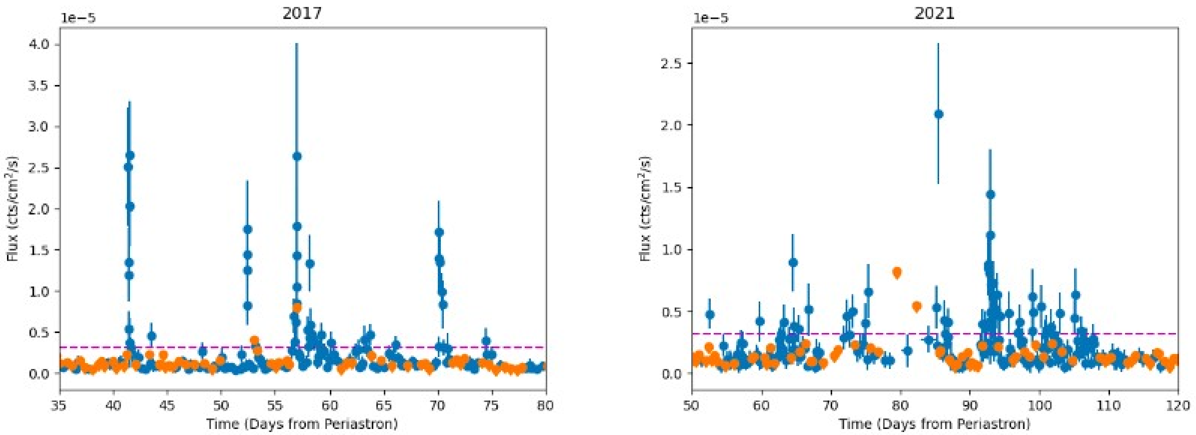
Chernyakova et al. 2021

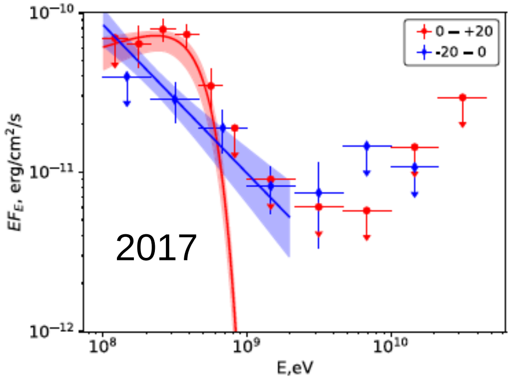


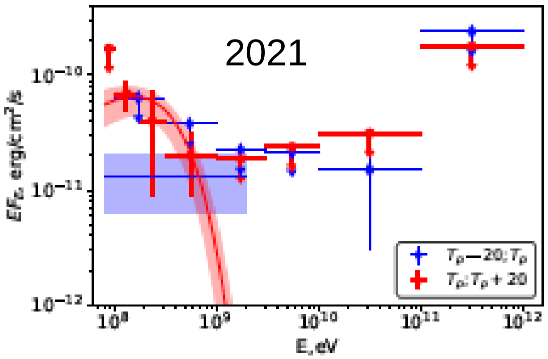
- GeV flare is delayed weaker on short time scales brighter on average

PSR B1259-63: GeV 2017 vs 2021

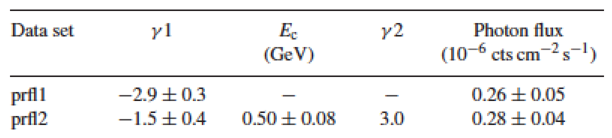
- Variable time bins to have 9 photons in 1˚
- Time bins varies from 5 min to 2.8 days with an average duration of ~6 h.



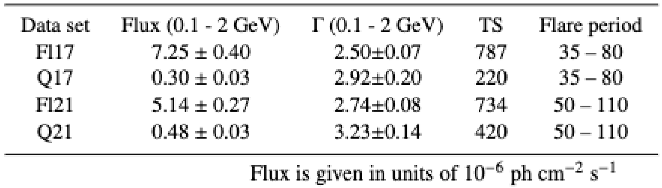




2017

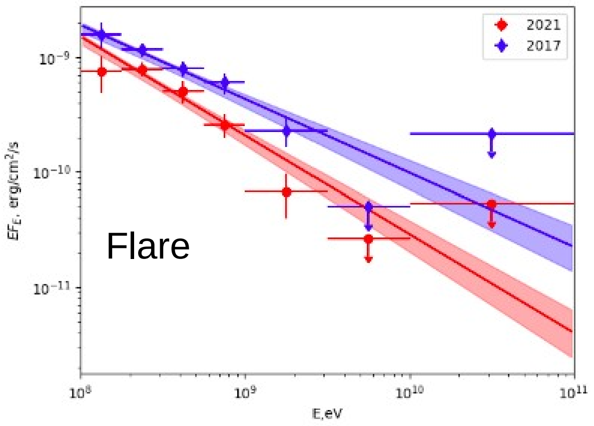


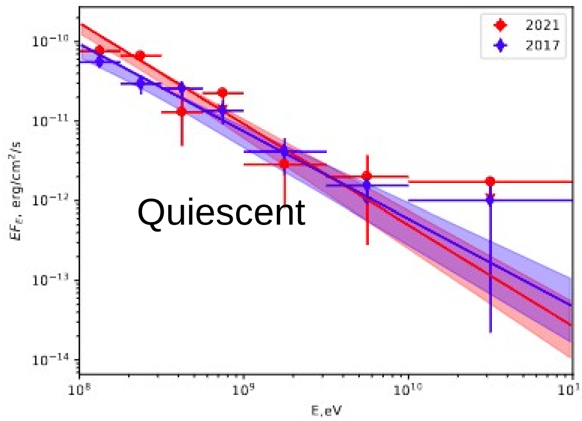
Data set	$\gamma 1$	E_c (GeV)	$\gamma 2$	Photon flux (10^{-6} cts cm^{-2} s^{-1})
prfl1	-2.9 ± 0.3	–	–	0.26 ± 0.05
prfl2	-1.5 ± 0.4	0.50 ± 0.08	3.0	0.28 ± 0.04



Data set	Flux (0.1 - 2 GeV)	Γ (0.1 - 2 GeV)	TS	Flare period
Fl17	7.25 ± 0.40	2.50±0.07	787	35 – 80
Q17	0.30 ± 0.03	2.92±0.20	220	35 – 80
Fl21	5.14 ± 0.27	2.74±0.08	734	50 – 110
Q21	0.48 ± 0.03	3.23±0.14	420	50 – 110

Flux is given in units of 10^{-6} ph cm^{-2} s^{-1}

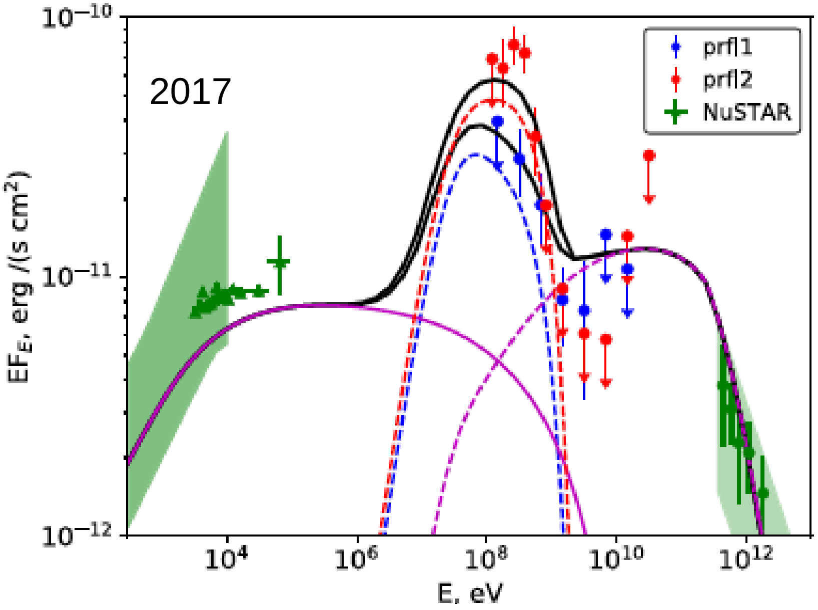




- Similar quiescent spectra
- Spectral hardening during the high flare state.
- Slight softening of the flaring state in 2021 vs. 2017

PSR B1259-63: spectral modeling

$N_{clump} < 10^9\ cm^{-3}$
$L/L_{sd}=1$



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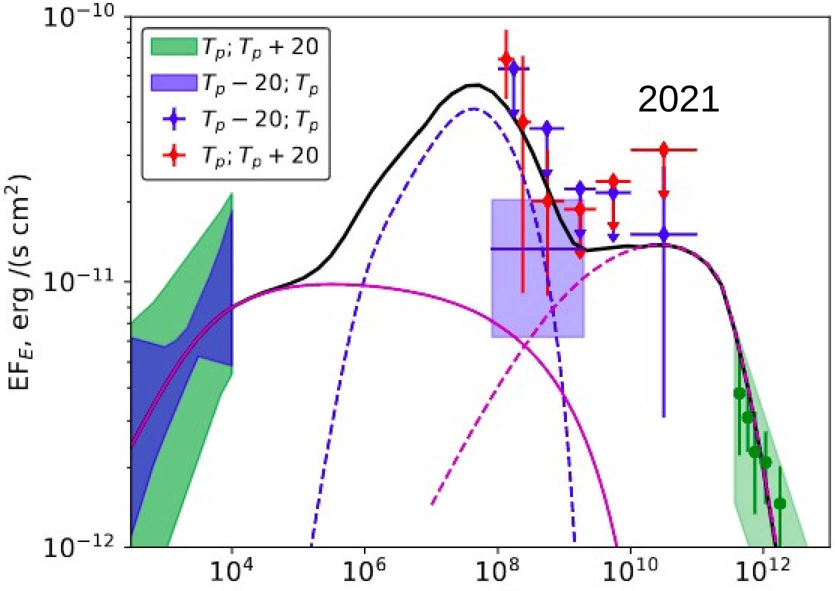
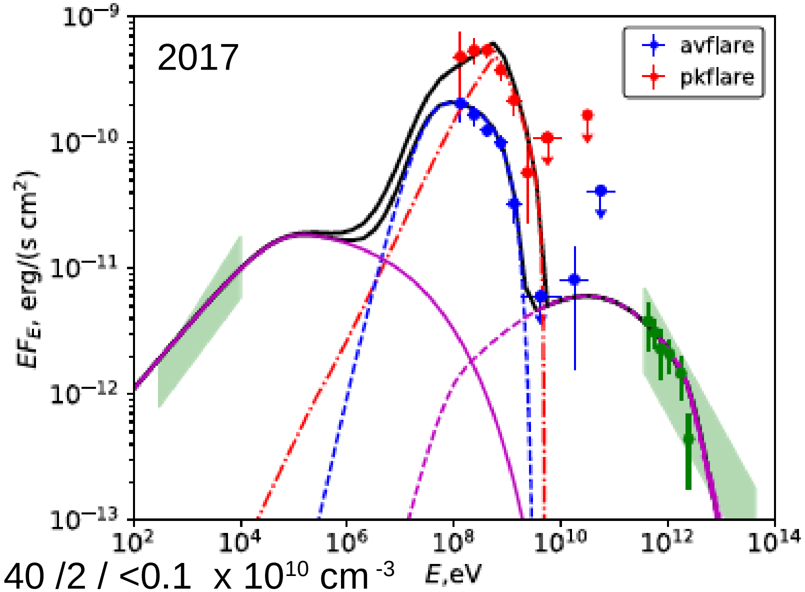
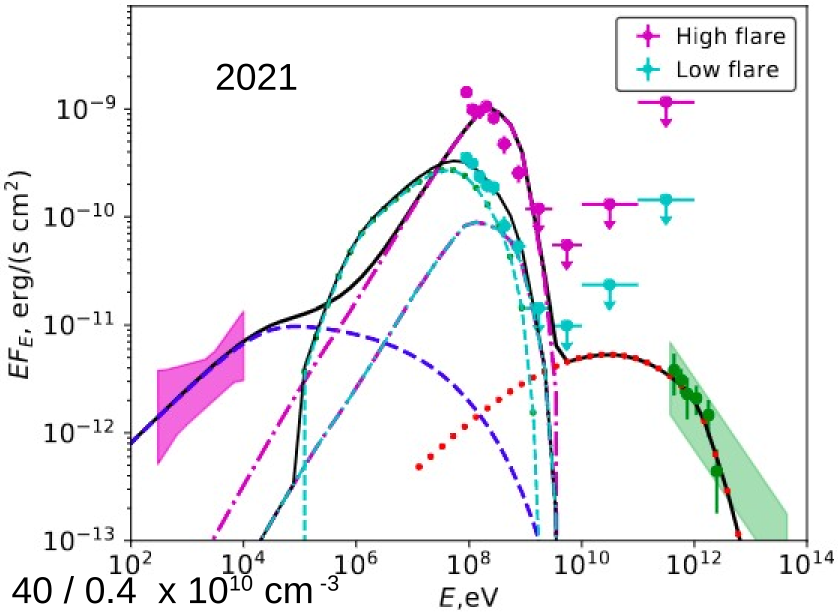




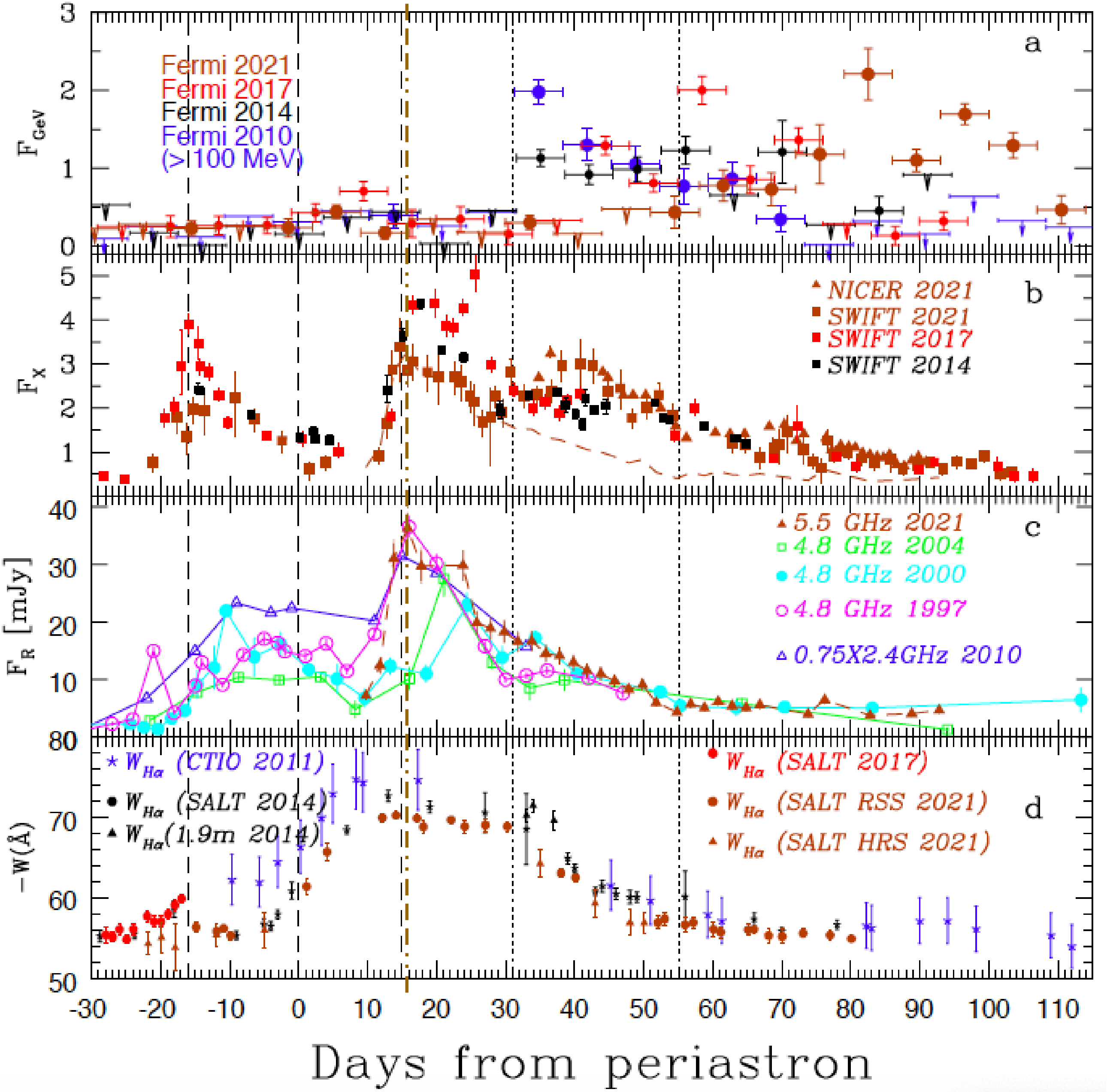
N_{clump}: 40 /2 / <0.1 x $10^{10}\ cm^{-3}$
$L/L_{sd}=30$



N_{clump}: 40 / 0.4 x $10^{10}\ cm^{-3}$
$L/L_{sd}=30$

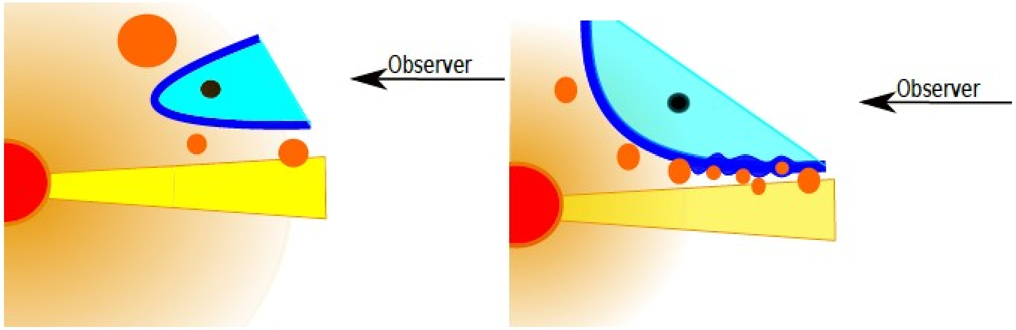
PSR B1259-63: periastron 2021

Chernyakova et al. 2021



- GeV flare is delayed weaker on short time scales brighter on average
- Very different X-ray LC:
  dim 1st and 2nd flares
  presence of 3rd peak!
- Radio - X-ray correlation during the 2nd peak
- Correlation breaks at the beginning of the 3rd peak.

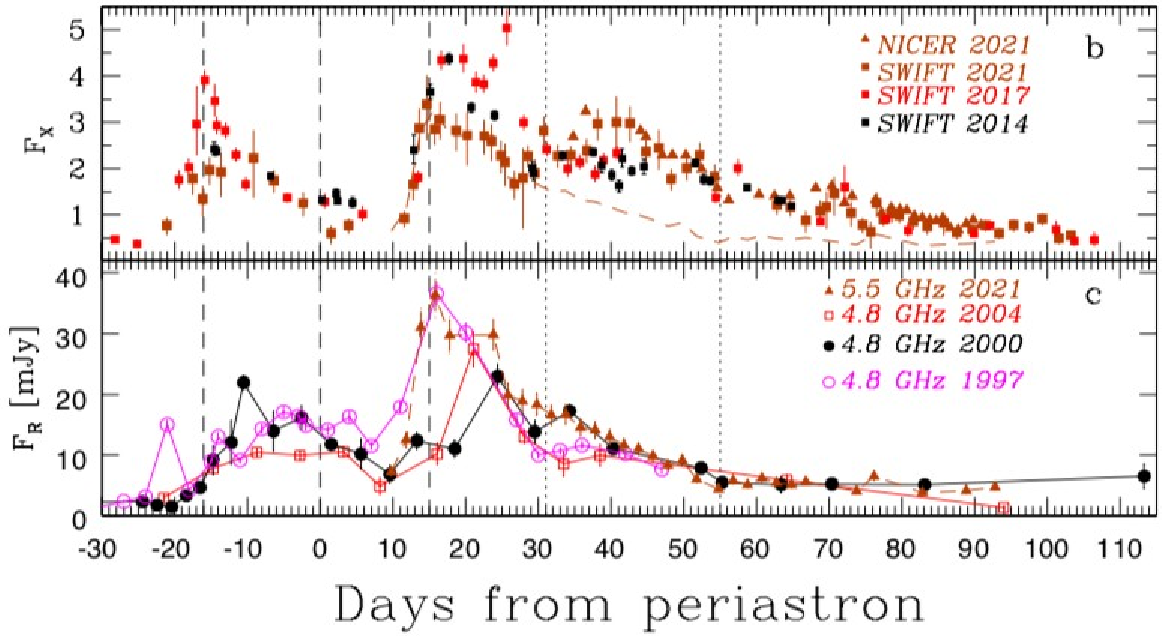
2017 vs 2021



- Sparser state of the Be star outflow in 2021 lead to a much larger opening angle of the emission cone and a weaker magnetic field (hence weaker X-ray flux)

- The peak level of the GeV emission is inversely proportional to the cone opening angle, which naturally explains the relatively low average flux level seen by Fermi/LAT in 2021. Brightest outbursts require luminosities exceeding the spin-down one by a factor of 6, which is consistent with a large (~π) opening angle of the emission cone.

2017 vs 2021

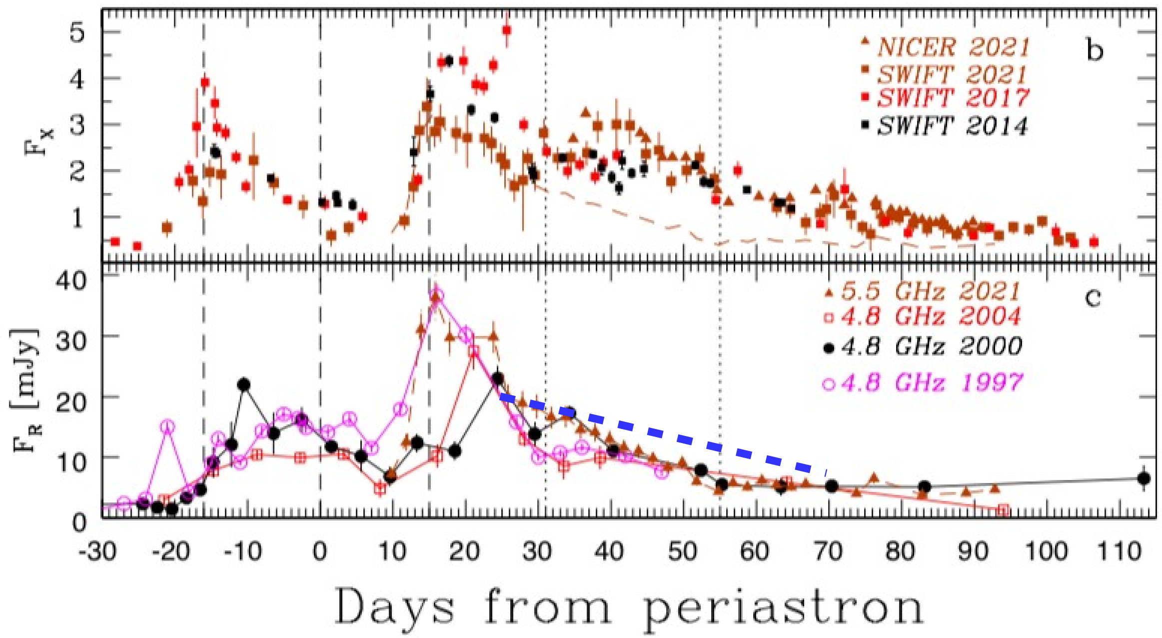


- Large number of clumps at the edge of the disk will modify the shock front, increasing the escape time of the relativistic electrons, leading to the third X-ray peak.

- No rise of radio data due to free-free absorption.

$$\tau_{ff} = 7\,x\,10^{5}\left[\frac{T}{10^{5}\,K}\right]^{-3/2}\left[\frac{n_i}{10^{8}\,cm^{-3}}\right]^{2}\left[\frac{\nu}{5\,GHz}\right]^{-2}\frac{L_{clump}}{10^{10}\,cm}$$

2017 vs 2021



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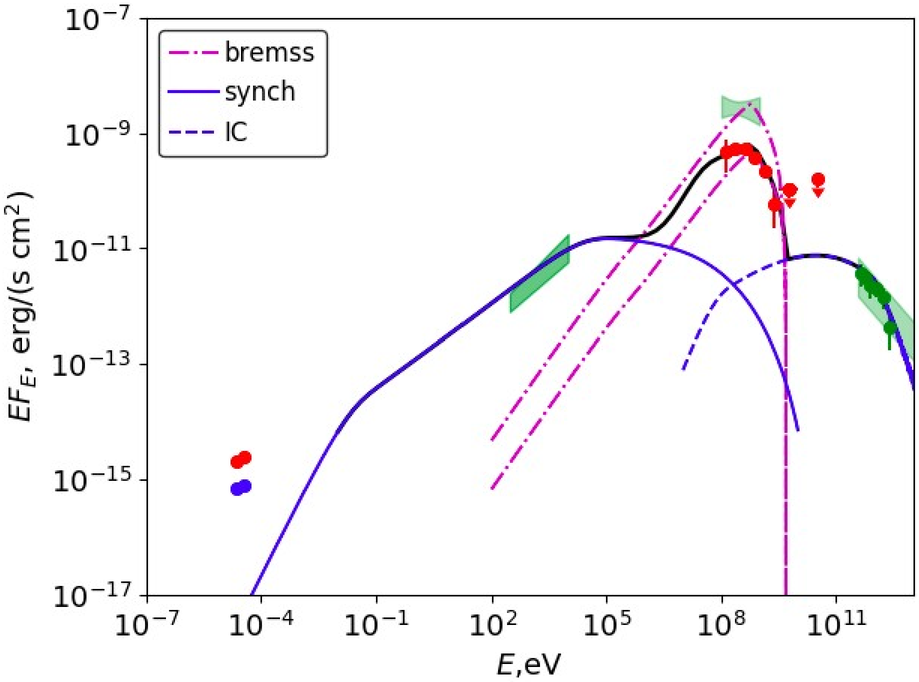
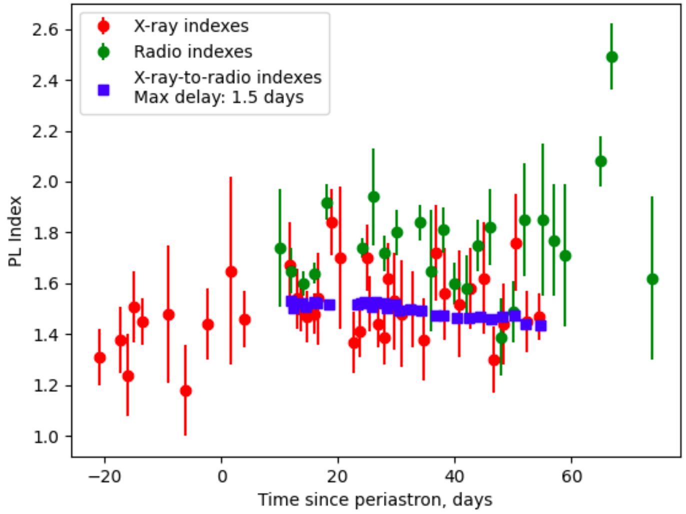
Radio/X-ray data



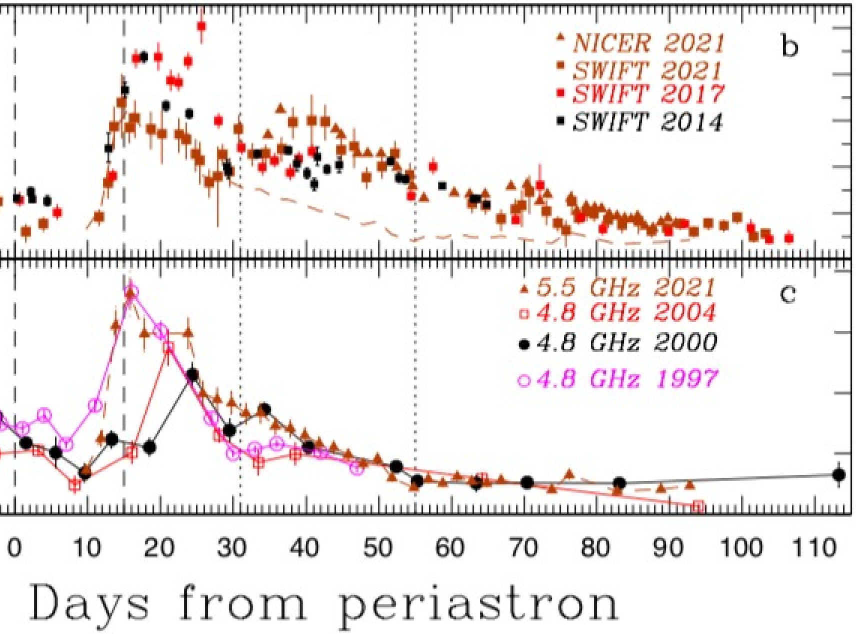


- Radio data has systematically softer spectrum than X-rays.
- Energetics constraints makes it impossible to inject electrons from radio to X-ray with a power law distribution.
- Subsequent cooling of injected electrons leads to a very long cooling time

$$t_s = 4\,x\,10^6 \left[\frac{1\,G}{B}\right]^2 \left[\frac{100\ MeV}{E_e}\right] s$$

$$t_{IC} = 6\,x\,10^4 \left[\frac{10^{38}\,erg\,s^{-1}}{L_*}\right] \left[\frac{D}{10^{13}\,cm}\right]^2 \left[\frac{100\ MeV}{E_e}\right] s$$

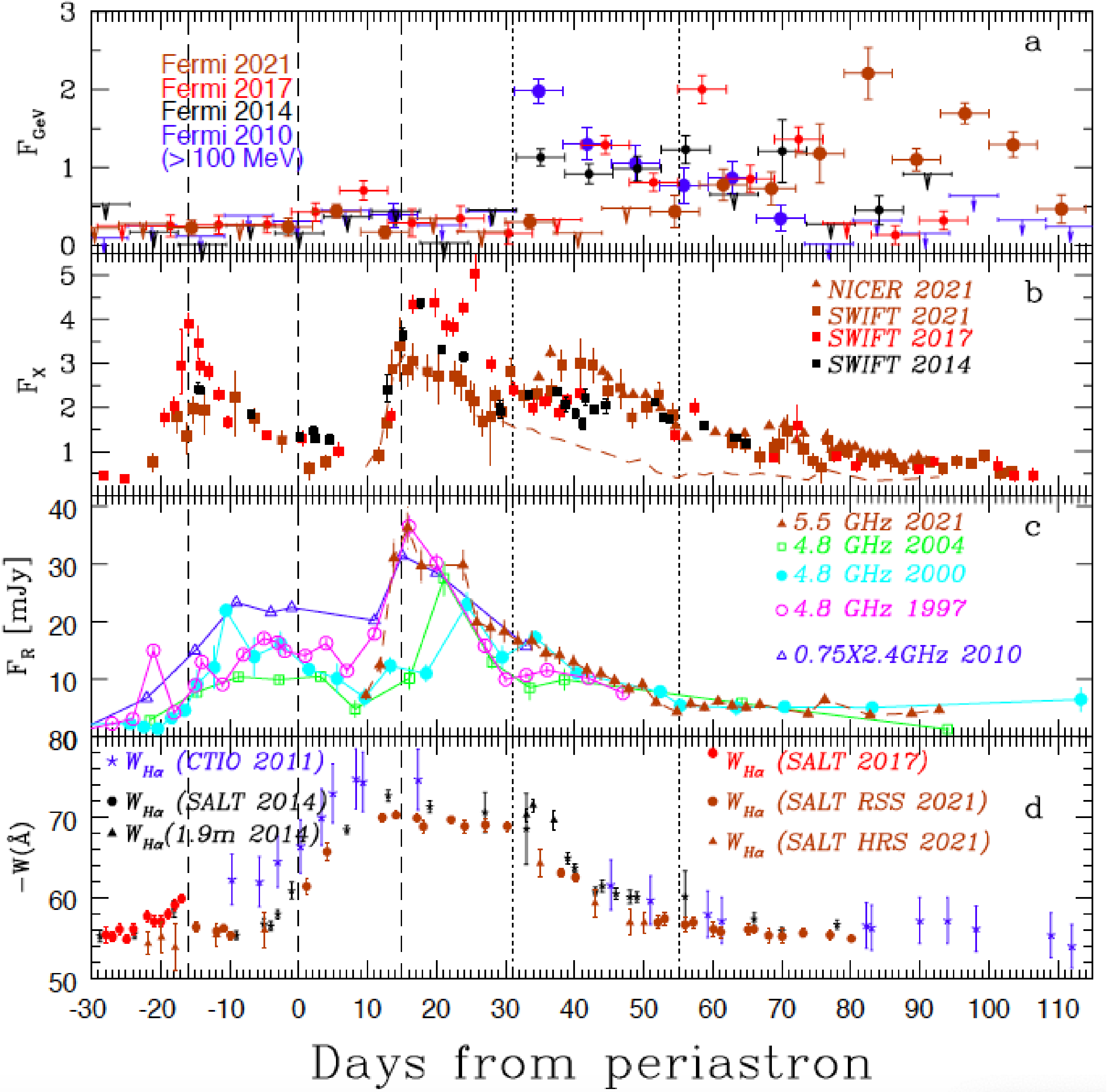
Radio/X-ray data



- Both in X-rays and radio bands we observe flux rise on a 1 day scale.
- $$\nu_{synch} = 10 \frac{B}{10\,G}\left[\frac{E_e}{10\,MeV}\right]^2 GHz$$
- $$t_s = 4\left[\frac{10\,G}{B}\right]^2\left[\frac{10\,MeV}{E_e}\right] d$$
- Thus, to see variability on a day time scale one would need a region with high magnetic field in the case of effective cooling.
- Alternatively, one can assume ineffective cooling, which would mean that radio emission is coming from accelerated stellar wind.

PSR B1259-63: periastron 2021

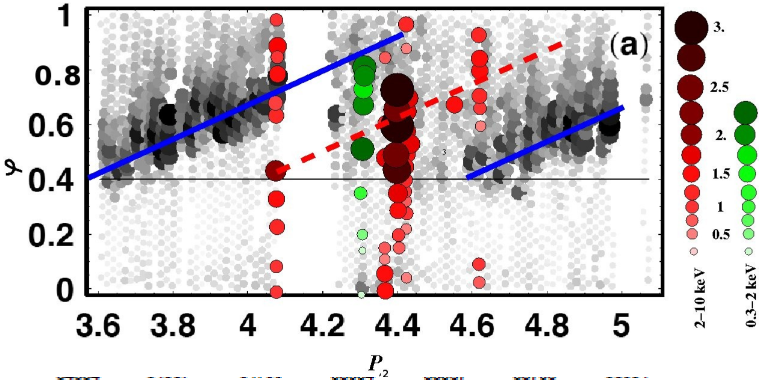
Chernyakova et al. 2021



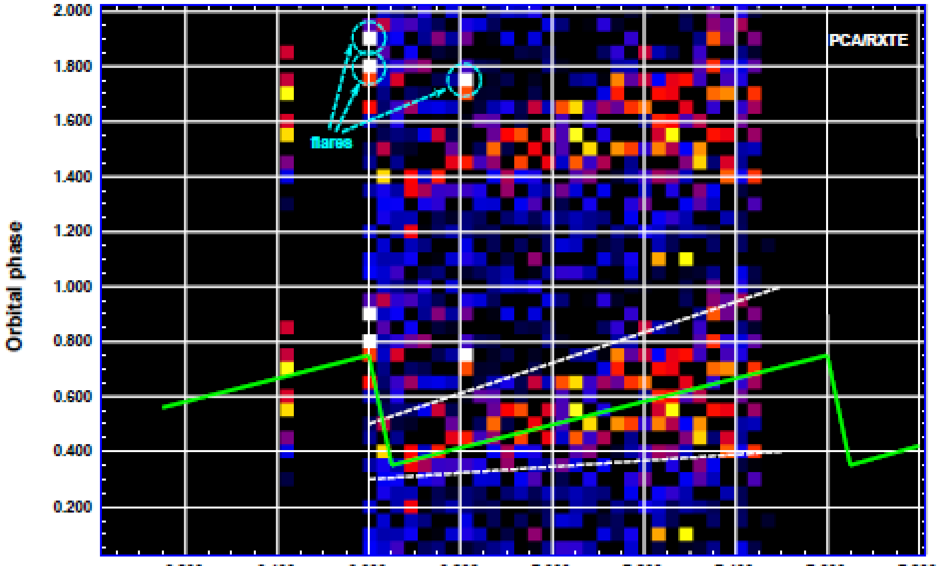
- GeV flare is delayed and weaker on short time scales brighter on average
- Very different X-ray LC:
  dim 1st and 2nd flares
  presence of 3rd peak!
- Radio - X-ray correlation during the 2nd peak
- Correlation breaks at the beginning of the 3rd peak.
- No major change in optical behaviour around GeV peak.
- IR studies are crucial to study the disk closer to the edge.

LSI +61 303

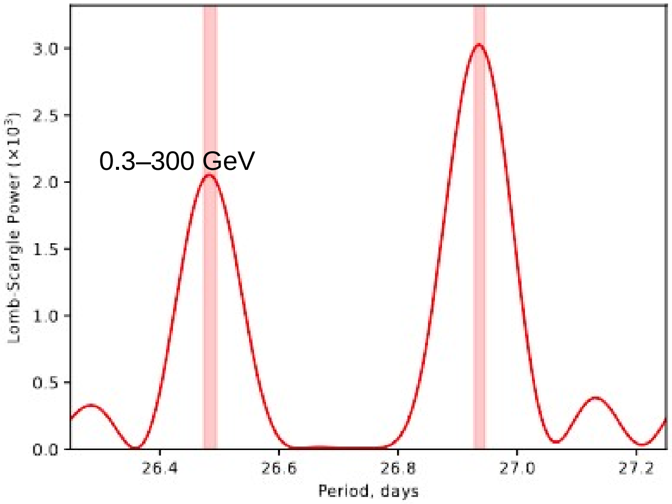
- Radio pulsar (P=269ms, Weng+ 2022) in an orbit with Be star.
- Emission is modulated throughout the 26.5-day orbit.
- The orbital phases of X-ray and radio flux maxima “drift” with superorbital (SO) period P=4.6 year.
- Evidence of superorbital modulation at Gev and TeV energies.

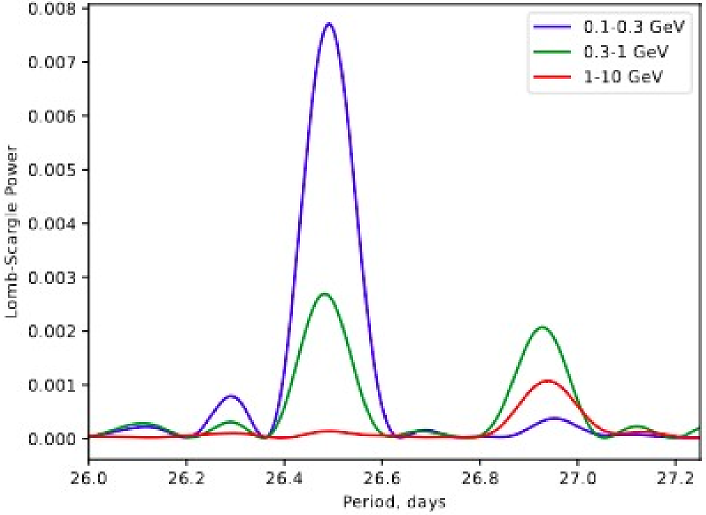


The 15th brightest γ-ray source detected by the Fermi Gamma-ray Space Telescope!
(Abdo et al. 2009, ApJS, 183, 46)



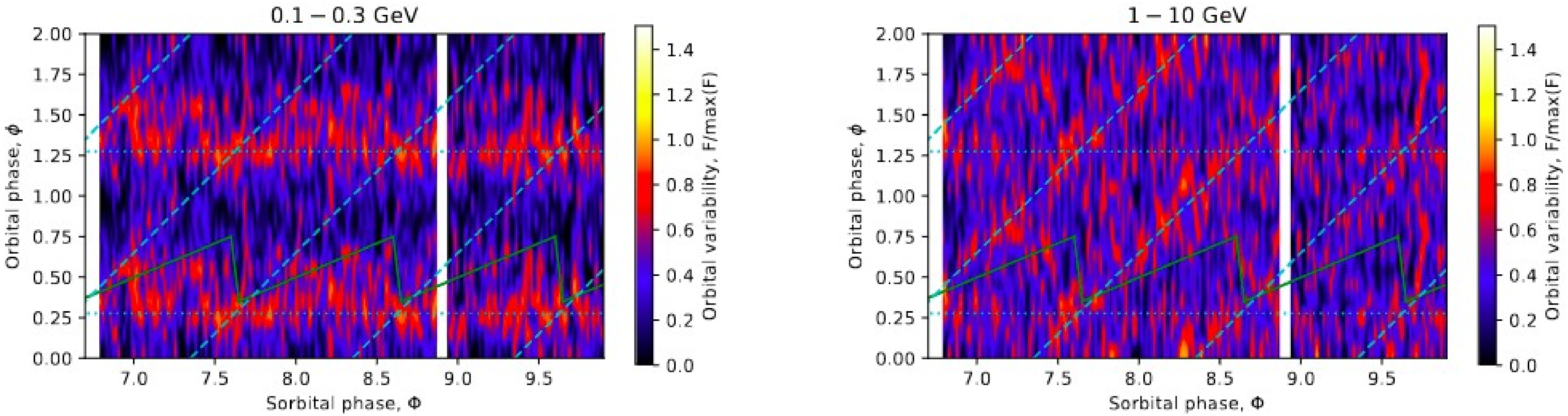
LSI +61 303

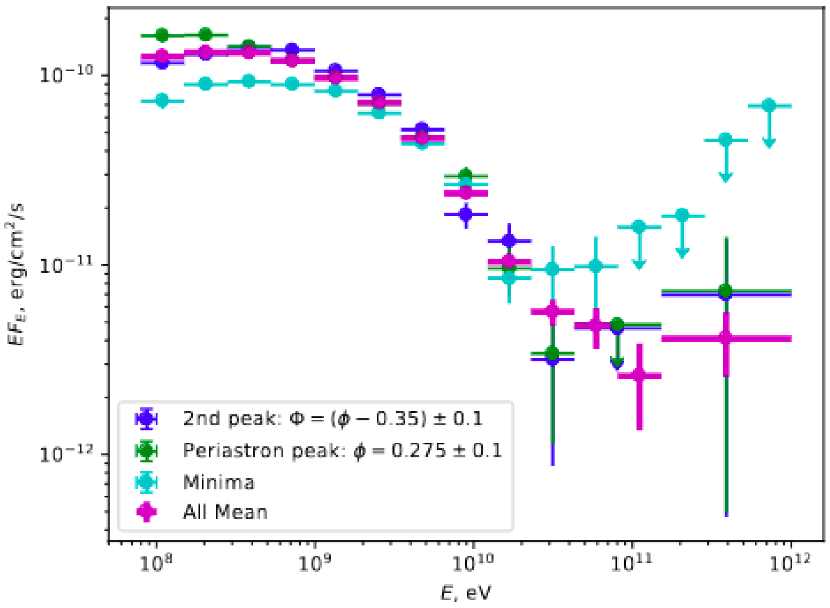




- Analysis of more than 14 years of the Fermi/LAT data.
- Similar to previous findings of Massi et al. (2013) Lomb-Scargle analysis of 0.3–300 GeV light curve reveal 2 peaks
- P_1 = 26.485 ± 0.012 and P_2 = 26.932 ± 0.012.
- These periods are consistent (1σ) with the orbital period P_{orb} = 26.496 and orbital-superorbital beat-period $P_{beat} = \frac{P_{orb} P_{so}}{P_{so} - P_{orb}} = 26.924\, d$
- More detailed analysis demonstrates energy dependence of the peak's height.

LSI +61 303

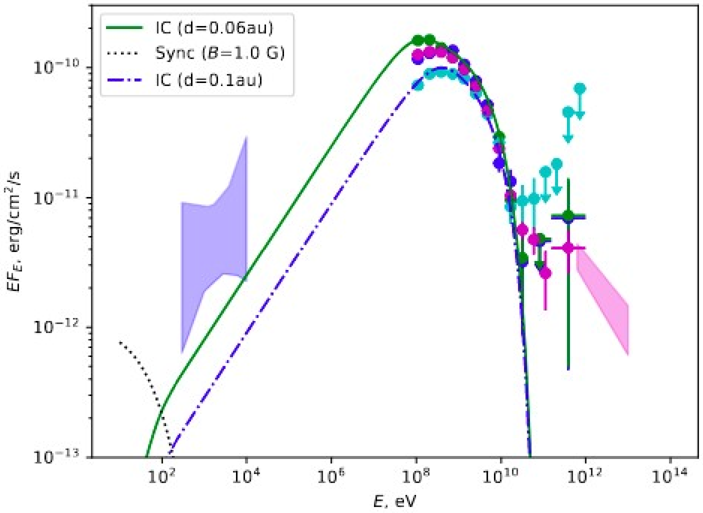


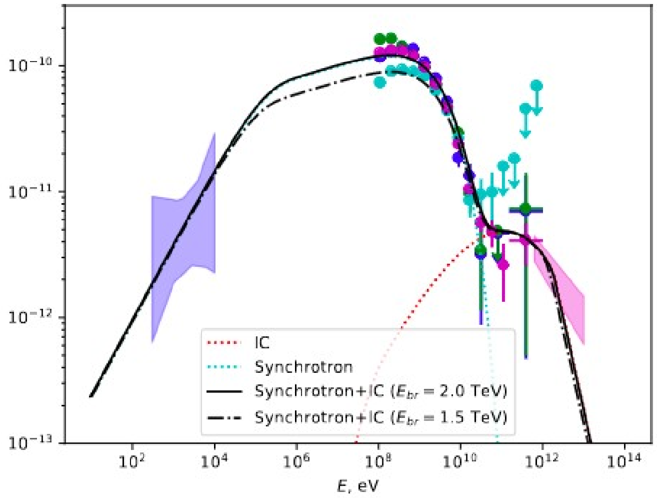


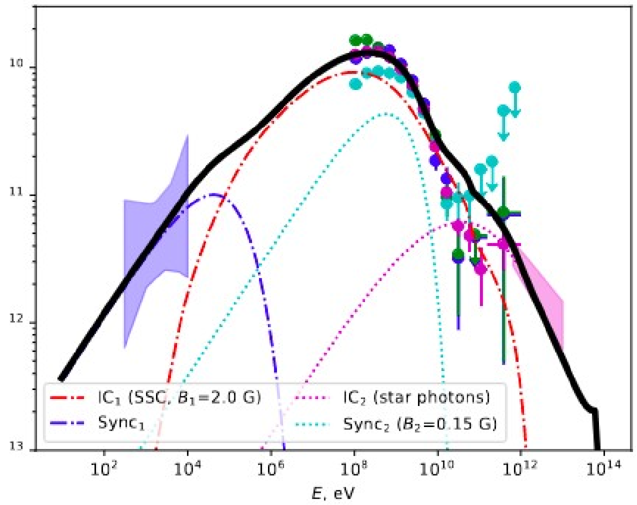
Orbital/ SO behaviour identifies distinct periods :

- periastron max ($\varphi = 0.275 \pm 0.1$); **0.1 - 0.3 GeV**;
- beat-period maximum ($\Phi = (\varphi - 0.35) \pm 0.1$); dashed diagonal lines, clearly seen **above 1 GeV**;
- “minima”: periods of low GeV emission **< 0.3 GeV** ($\Phi > 0.4$ AND $\varphi > 0.75$);
- “All Mean”: all time-averaged data.

LSI +61 303: Spectral modeling







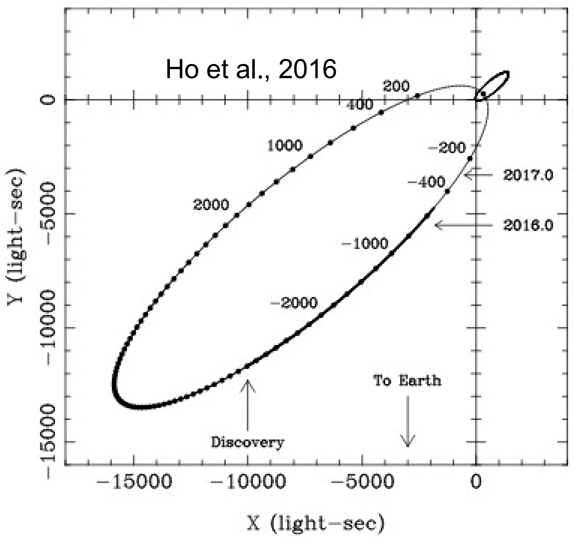
Orbital variability of the spectral shape at the GeV domain can be explained in different ways

IC emission, E_{br}~2GeV: Electrons are cooled faster closer to periastron, which lead to a higher flux **and,** in case of a **slow escape** (v~0.03c), to the shift of the peak of the GeV emission to higher energies close to apastron.

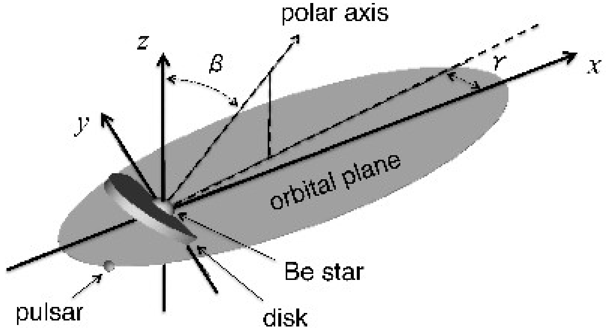
Synchrotron, E_{br}~2TeV, fast escape (v~c), if the escape time is proportional to the binary separation, then one should expect a shift of the break energy to lower values ==> lower GeV flux around the apastron.

SSC, fast escape If most of the electrons leave the system not cooled, the observed emission could be a sum on SSC emission and emission of a secondary component of accelerated electrons.

PSR J2032+4127 / MT91 213

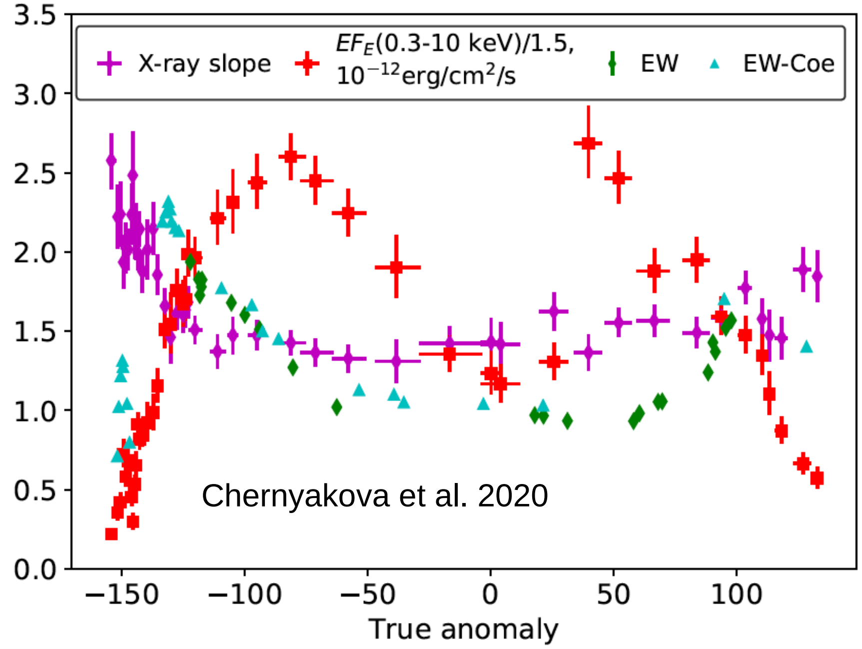


Coe et al. (2019)

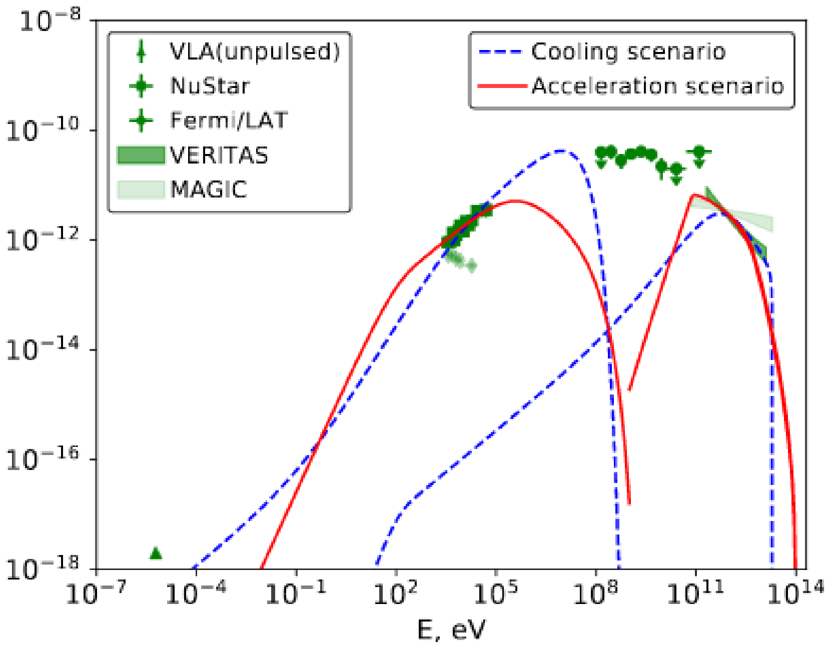


- 143 ms radio pulsar, discovered by Fermi (Abdo et al. 2009).
- The pulsar is rotating around the 15-solar-mass B0Ve star MT 91-213 in a very eccentric orbit, orbital period of 45-50 years (Ho et al., 2016).
- Periastron passage occurred on 13/11/ 2017.
- Unpulsed radio, X-ray and TeV emission are detected around the periastron.
- Stable GeV emission from the pulsar’s magnetosphere.
- Disk of the Be star is inclined to the orbital plane.
- Extensively studied by Takata et al. (2017), Li et al. (2018), Coe et al. (2019), Ng et al. (2019), Chernyakova et al. (2020a) ...

PSR J2032+4127: X-rays



Chernyakova et al. 2020



- Similar to PSR B1259-63 two peak X-ray light curve.
- X-ray and TeV emission are of synchrotron and IC origin correspondingly.
- GeV emission is dominated by the magnetospheric emission from the pulsar and thus is stable along the orbit.
- Peak and dips in the X-ray curve can be explained due to the shift of the emission region further from /closer to the star as the pulsar enters / leave the disk.
- Evolution of Hα emission line confirms this picture, tracing the enlargement of the disk due to tidal interactions and destruction of the disk due to the pulsar passage nearby.

Conclusions

- Gamma-ray binaries with radio pulsar provides a chance to study the properties of the winds and details of their interaction.
- Unique features of 2021 periastron passage of **PSR B1259-63**:
  - Presence of a third X-ray flux peak starting ~30 days after the periastron.
  - Correlation between the X-ray and radio fluxes during the 2nd X-ray peak, and an absence of such a correlation with the 3rd rise of the X-ray flux.
  - Indication that radio emission is either coming from accelerated stellar wind or highly magnetized region.
- Energy dependence of the periodicity pattern in **LSI +61° 303**.
  - $P_1 = 26.485 \pm 0.012$ at 0.1 – 0.3 GeV
  - $P_2 = 26.932 \pm 0.012$ at 1 – 10 GeV
- Broad band emission from **PSR J2032+4127** demonstrates both similarities and differences to PSR B1259-63.