Широкополосное излучение от гамма-громких двойных систем с радиопульсаром.

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Brian van Soelen (Uni. Free State)

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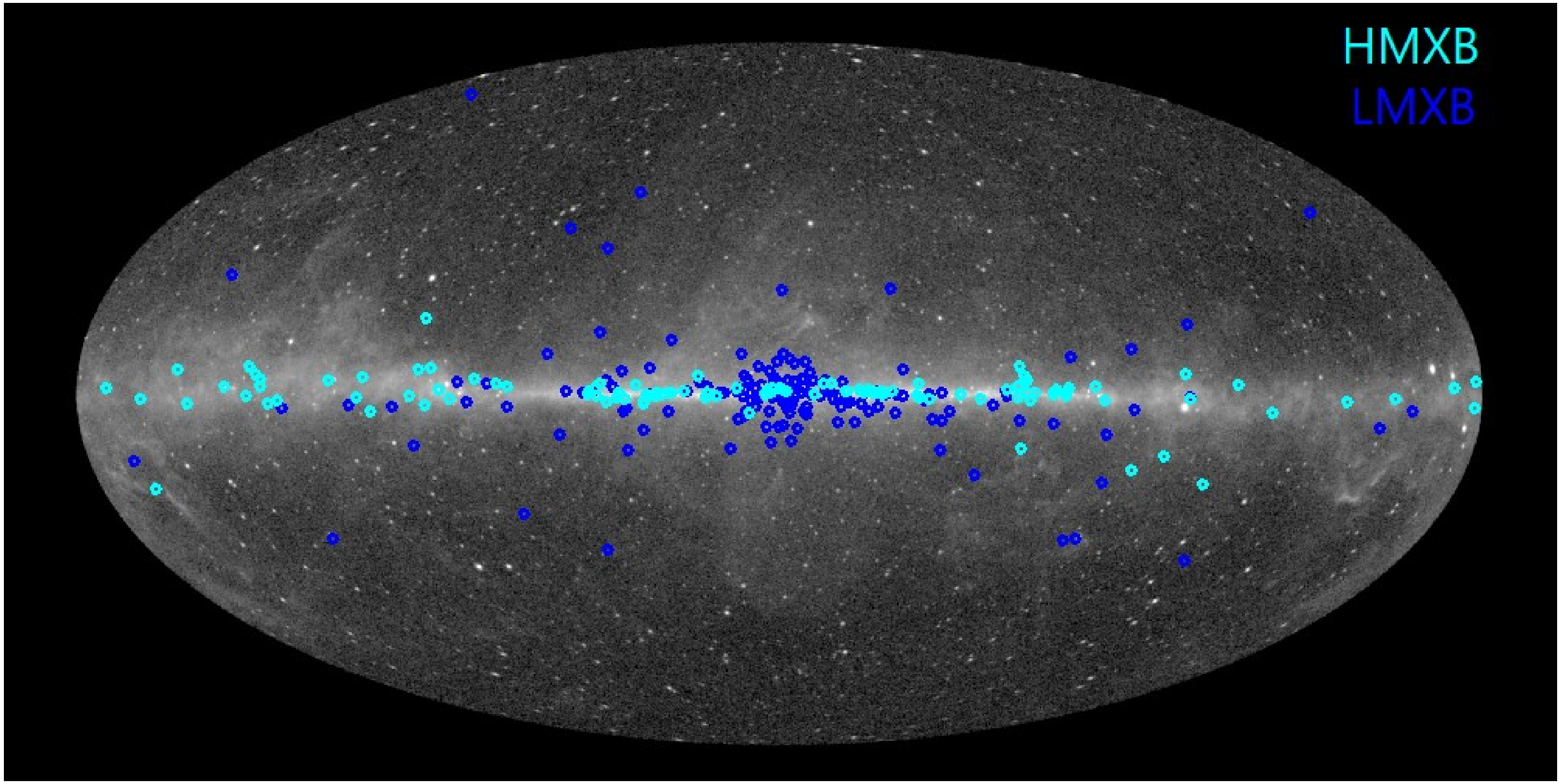
+ many others

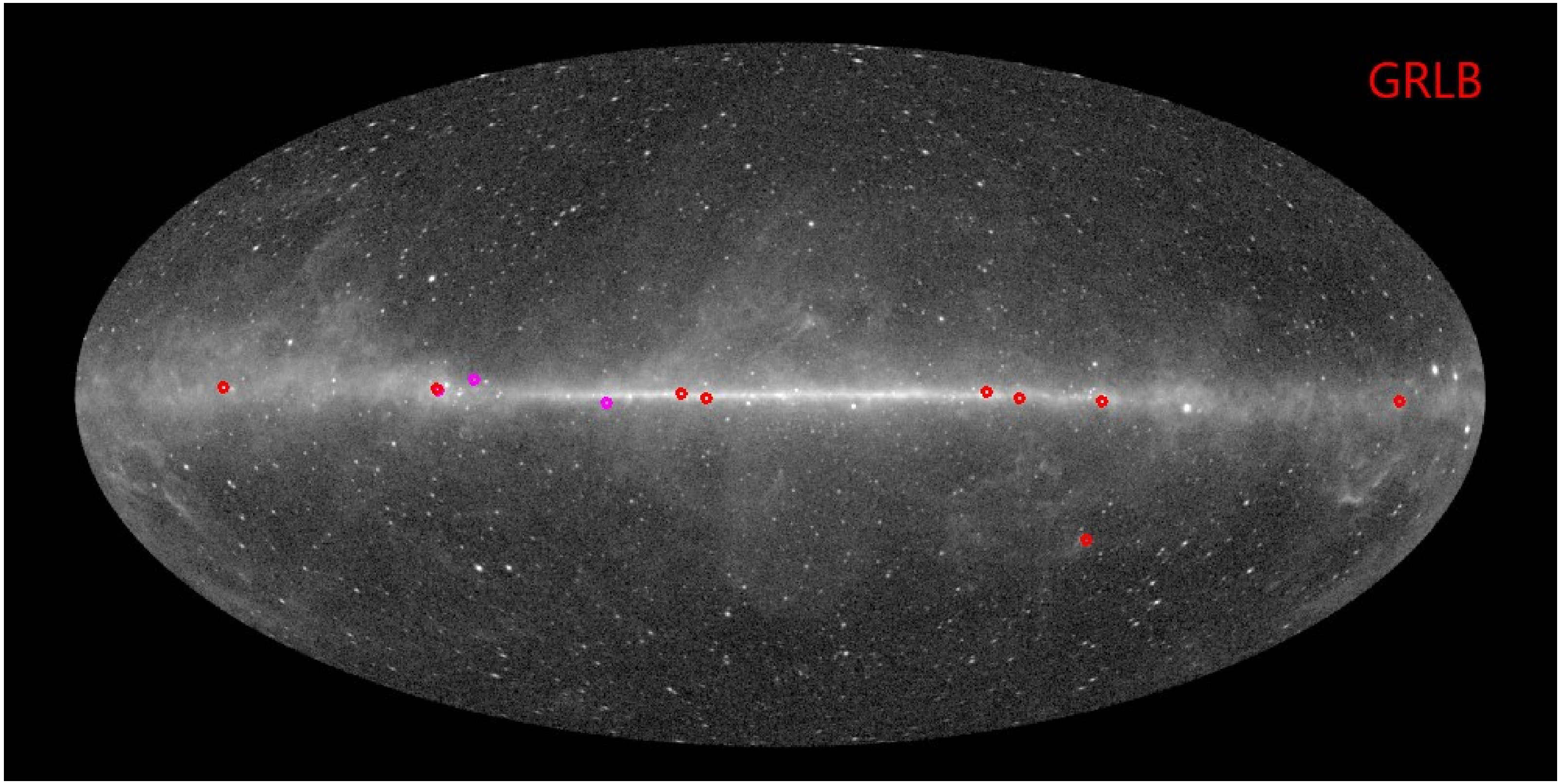
X-ray binaries



Distribution of LMXBs (blue circles) and HMXBs (cyan circles) in the Galaxy (RXTE data).

- XRBs are the dominant population of Galactic X-ray sources
  - Several hundreds known
  - Detected up to ~10-100 keVs

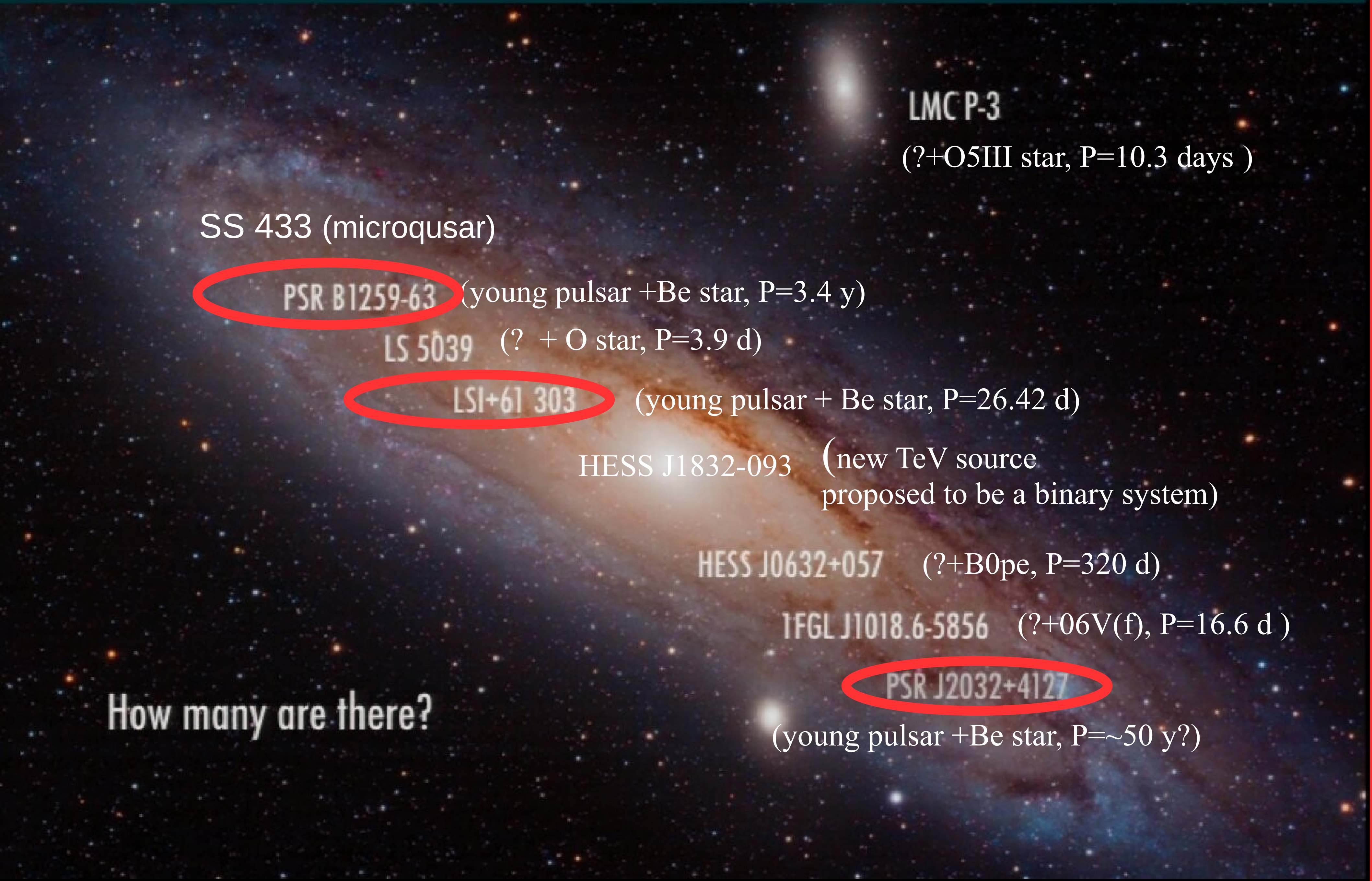
Gamma-ray binaries



Distribution of GRLBs in the Galaxy.

- GRLBs – energy spectrum peaks above high energies 100 MeV
  – detected from radio up to GeV-TeV energies
  – a fraction of Galactic GeV/TeV sources
  – only a ~*dozen* known

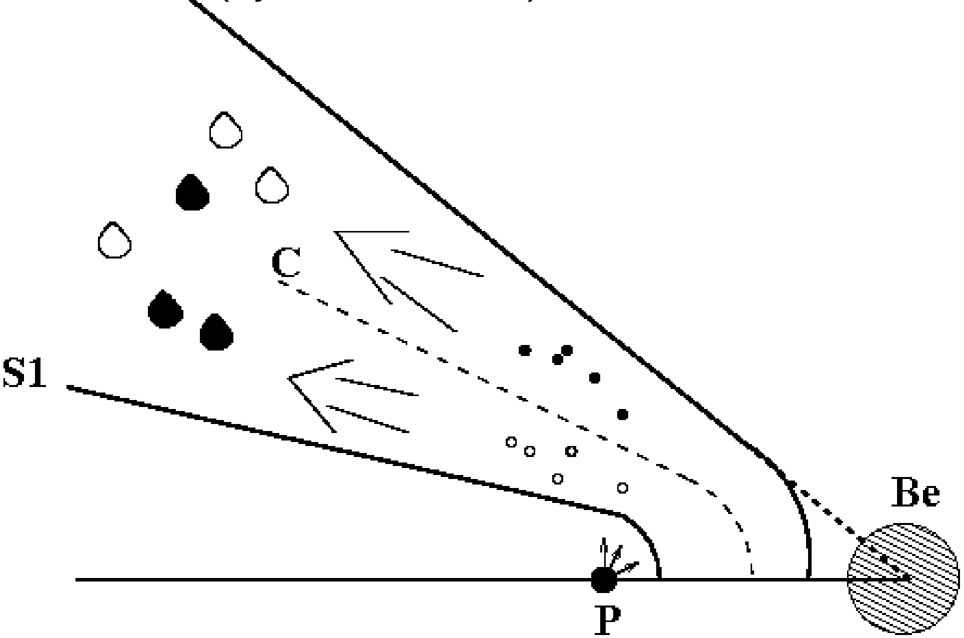
Known gamma-ray binaries



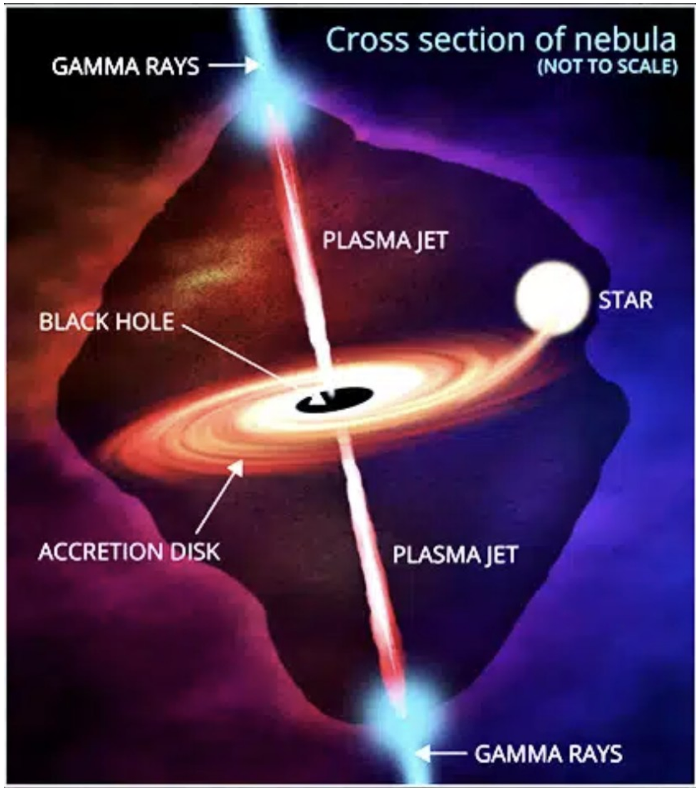
Gamma-ray binaries:
Two Paradigms of γ-ray Production

Colliding Winds

Possible source of PeV photons and neutrinos (Bykov et al. 2021)



Microquasar



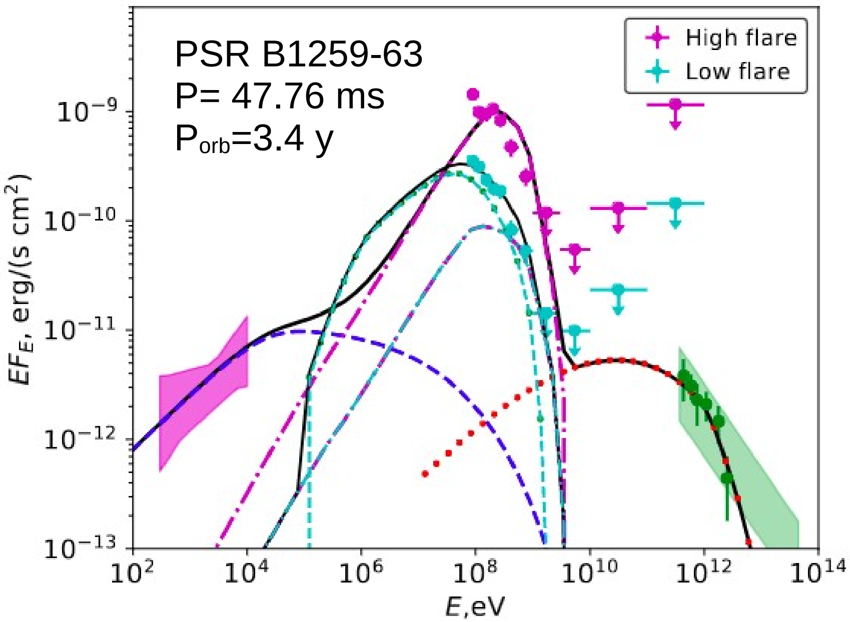
PSR B1259-63
PSR J2032+4127
LS I +61° 303 (at least at some orbital phases)

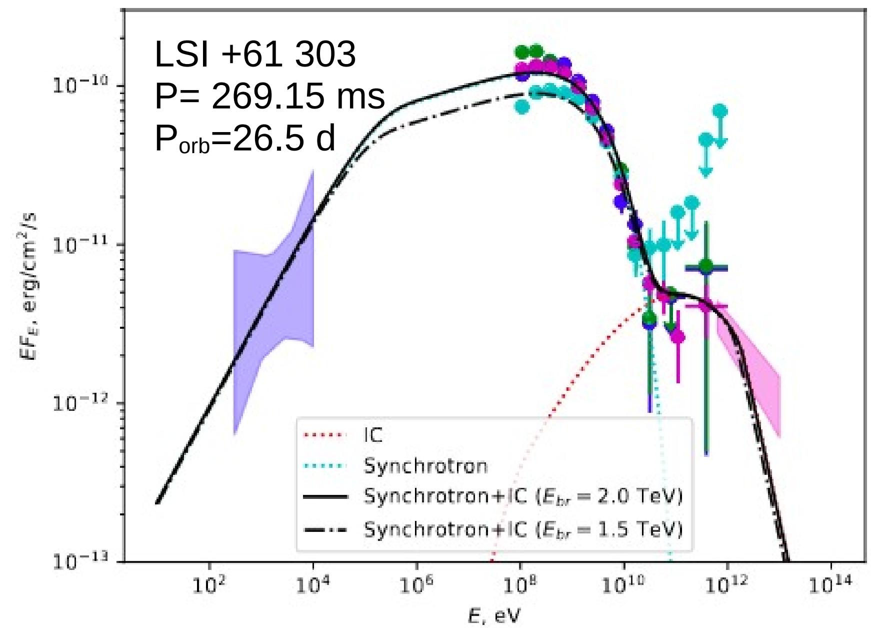
LS 5039
HESS J0632+057
HESS J1832-093
1FGL 1018.6-5856
...

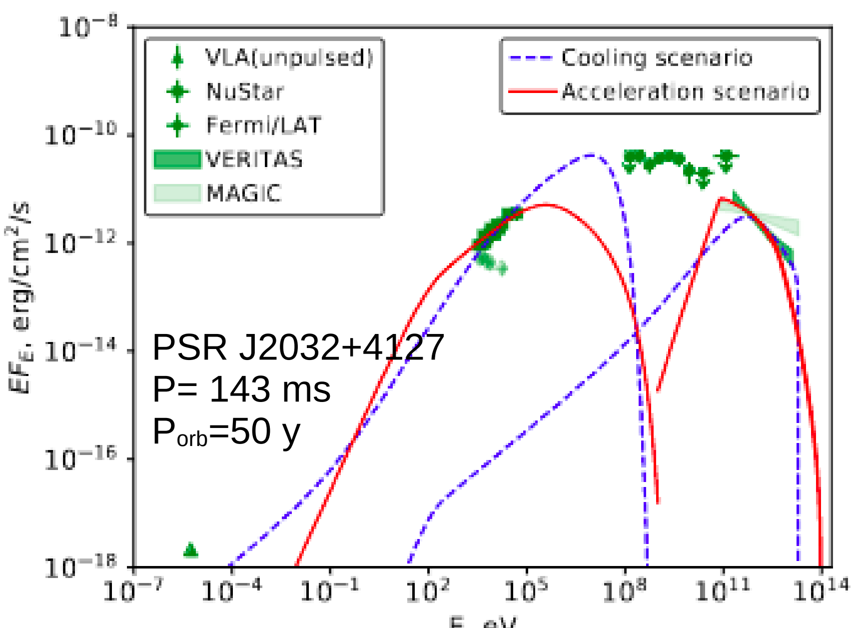
Cygnus X-3
Cygnus X-1
SS 433
GRS 1915+105
MAXI J1820+070
V4641 Sgr

(Cygnus X-1 to V4641 Sgr: LHAASO 2024)

Gamma-ray binaries with a radio pulsar

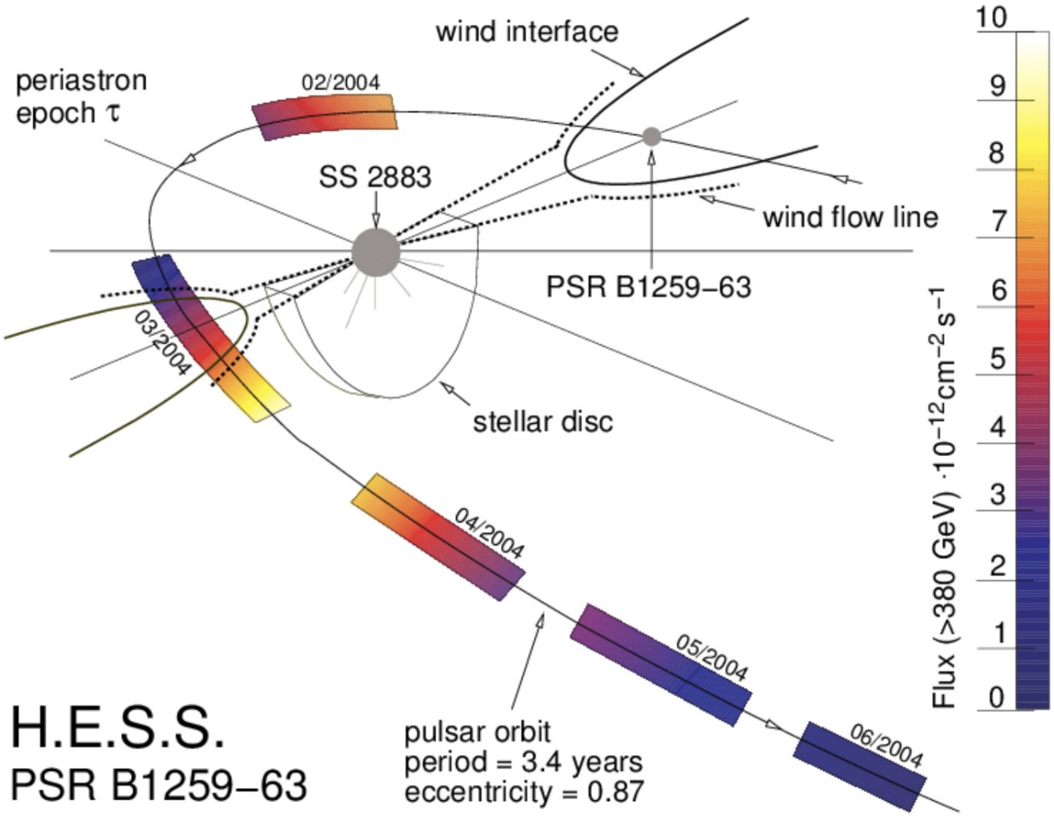






- Radio pulsar is in orbit around Be star
- Similar range of X-ray and TeV emission around periastron.
- Very different GeV appearance.
- Natural laboratories for the study of the properties of pulsar and stellar winds.

PSR B1259-63



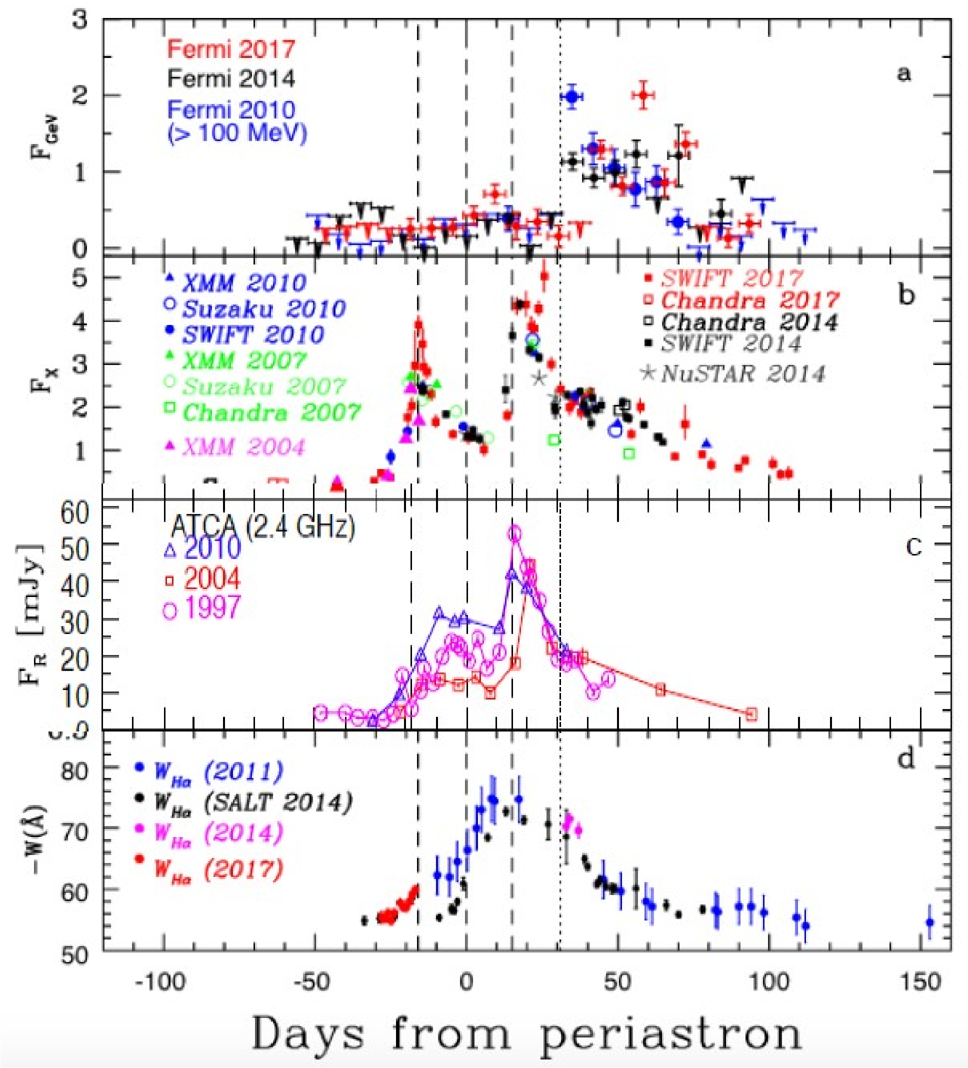
- A pulsar on ~3.4 yr orbit around Be star
- Decretion disk of Be star is inclined to the orbit of the pulsar
- Pulsar intersects the disk twice around the periastron
- A lot of non-thermal emission close to periastron: from radio to TeVs
- Most probable origin – interaction of the pulsar wind with Be star decretion disk
- Still a lot of open questions:

  -- role of *geometry/orientation* of the interaction surface

  -- role of *clumps*

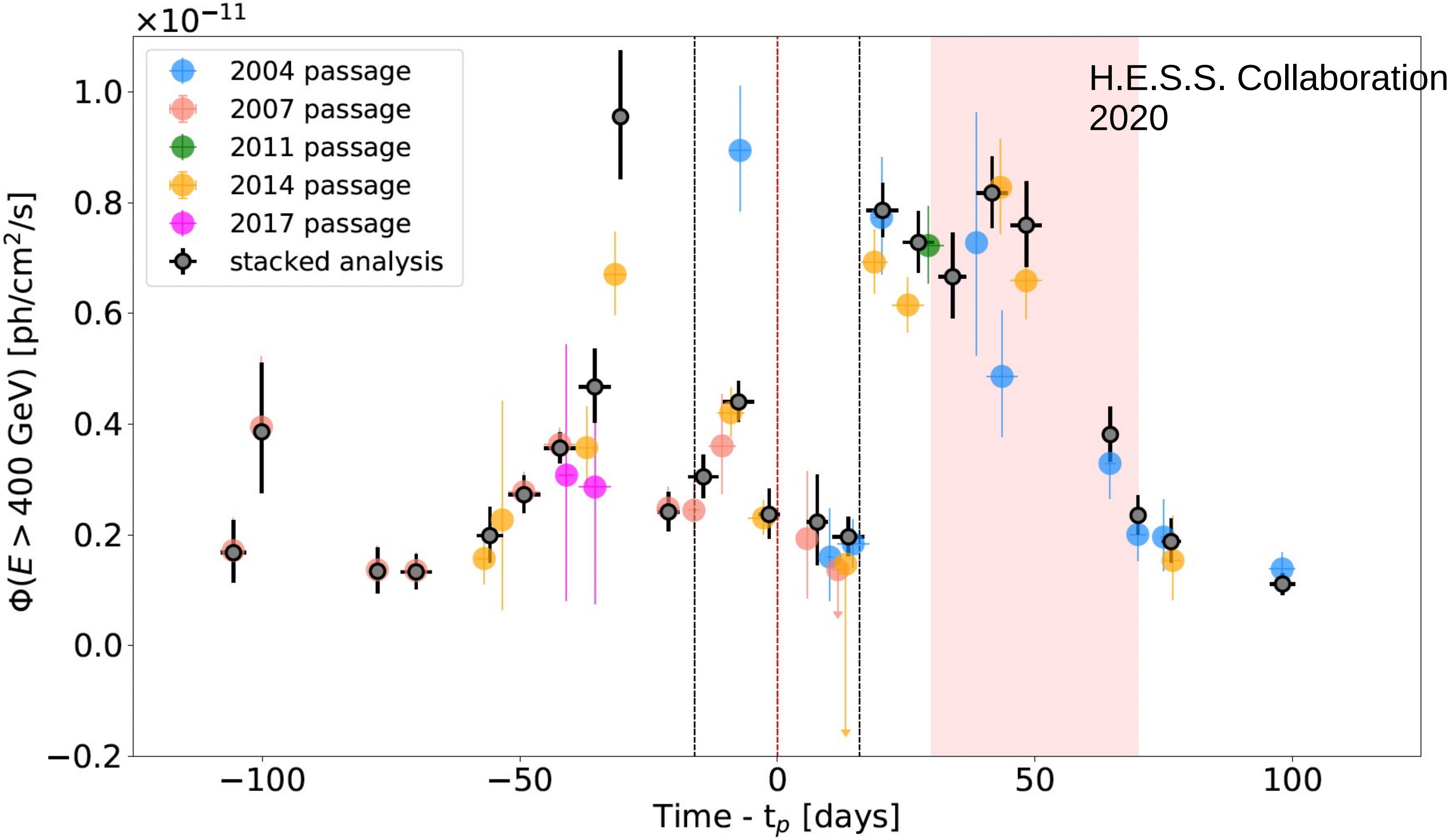
  -- exact *mechanism of production* and *population(s) of particles* responsible for the emission at different wavelengths

PSR B1259-63: light curves



"Usual" (pre 2021) behaviour:

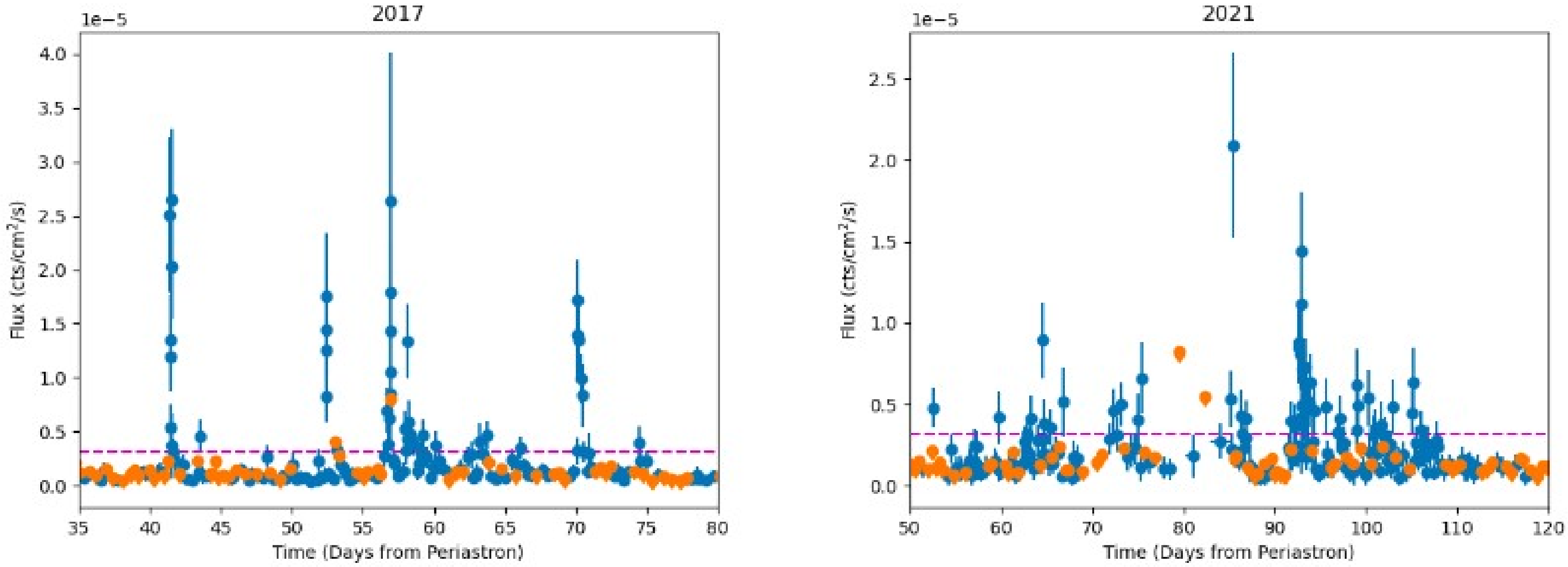
- Two peaks in X-ray and radio
- Peaks ~15 days around the periastron.
- Correspond to the passage through the Be star disk.
- High level of GeV emission ~30+ day after the periastron.
- No obvious counterpart for GeV flare at other energies.



- In TeV band system is detected at least from -100 to +100 days
- Totally different from GeV behavior in TeV band: 2-3(?) peaks LC
- No clear correlation to any other wavelength

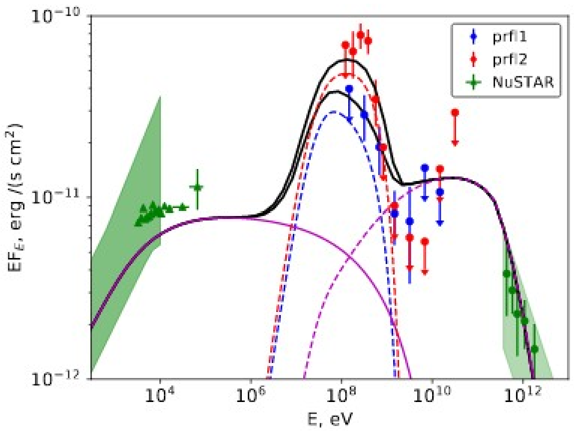
PSR B1259-63: subflares

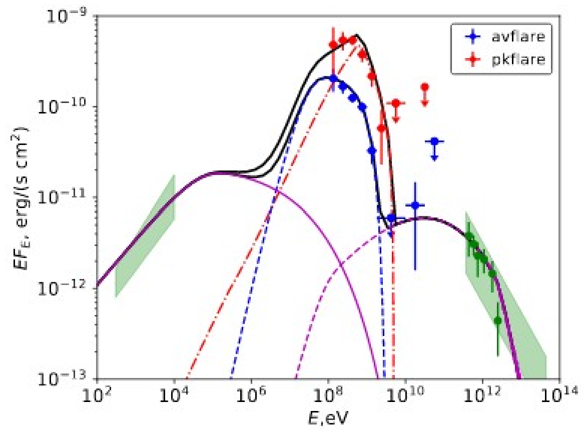
Chernyakova et al. 2024

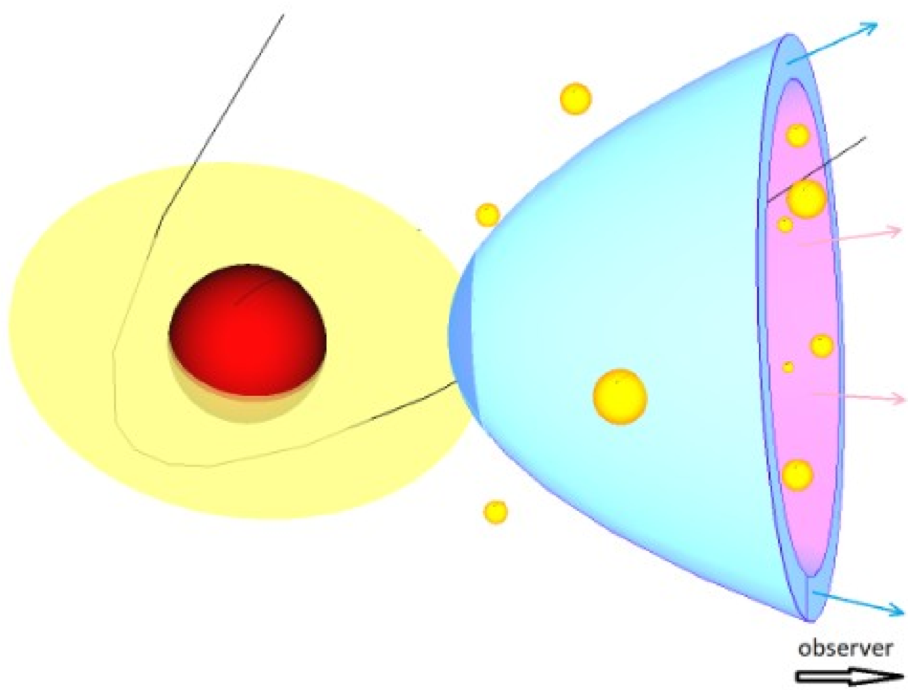


- Evidence of very strong and fast (~15 min) GeV subflares
- The isotropic gamma-ray luminosity corresponding to the short flares greatly exceeds the pulsar spin-down luminosity!
- Various models to explain GeV, e.g. Tam et al. 2011, Kong et al. 2012, Khangulyan et al. 2012, Dubus & Cerutti 2013, Yi & Cheng 2017, but the source brings new and new suprises ...

PSR B1259-63: model



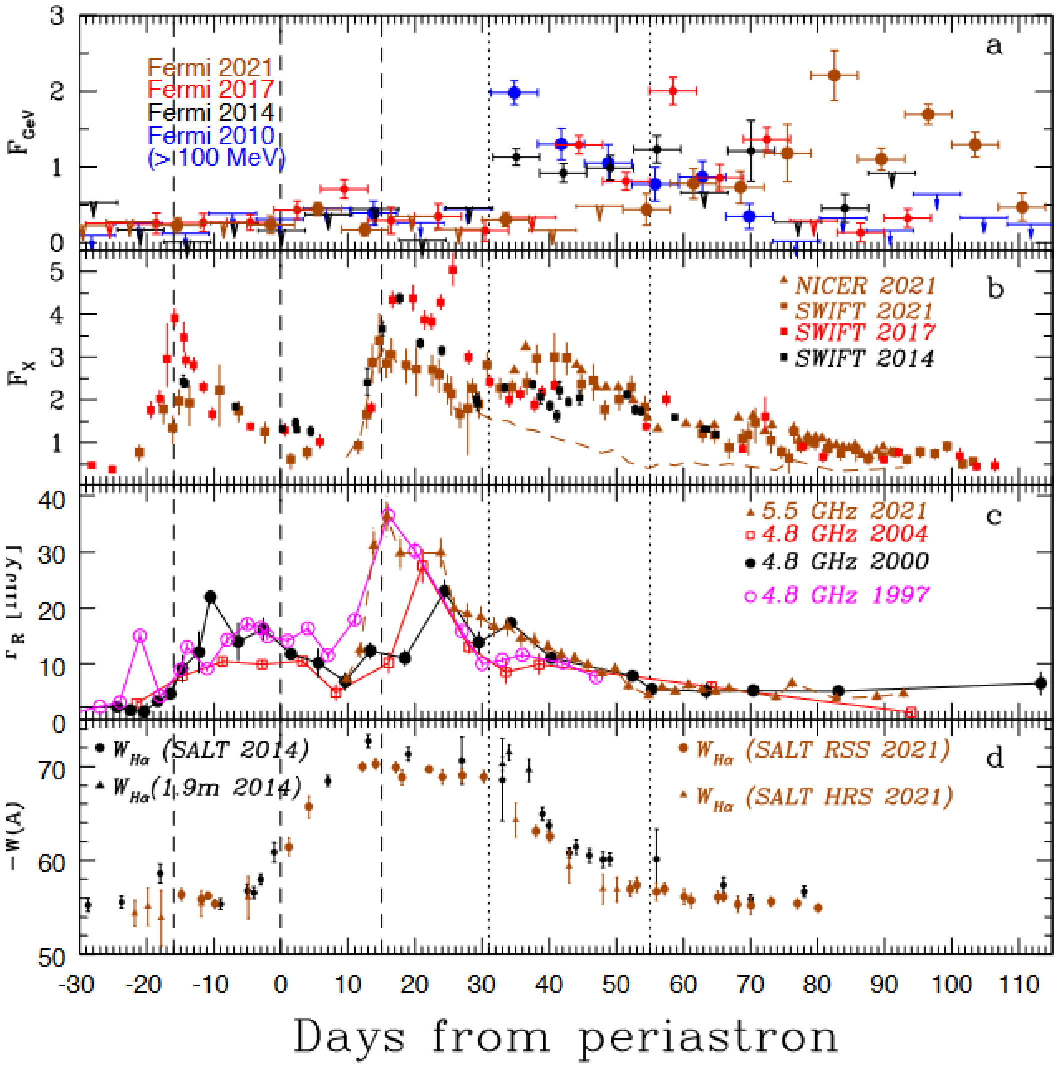




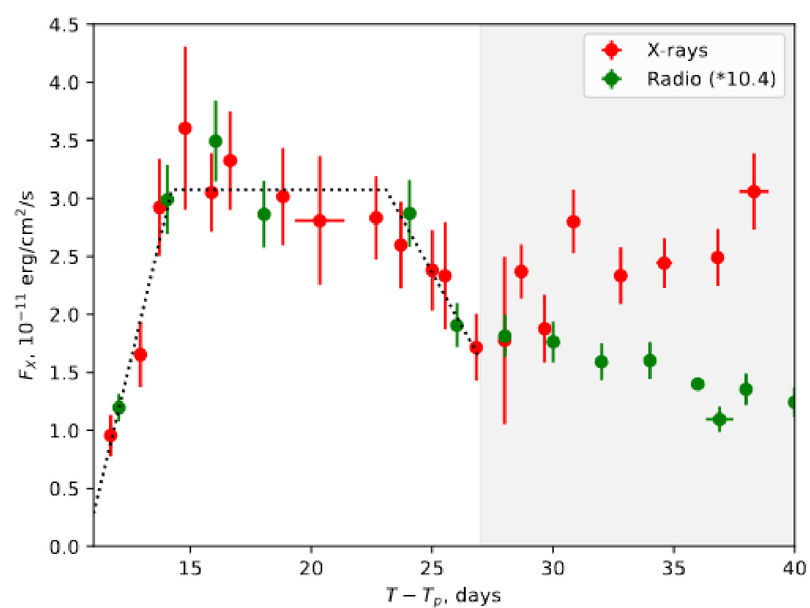
- Observed X-ray and TeV emission can be explained as a synchrotron and IC emission of the strongly shocked electrons of the pulsar wind.
- GeV component is a combination of the IC emission of unshocked / weakly shocked electrons and bremsstrahlung emission.
- Luminosity of the GeV flares can be understood 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.

Chernyakova et al. 2020

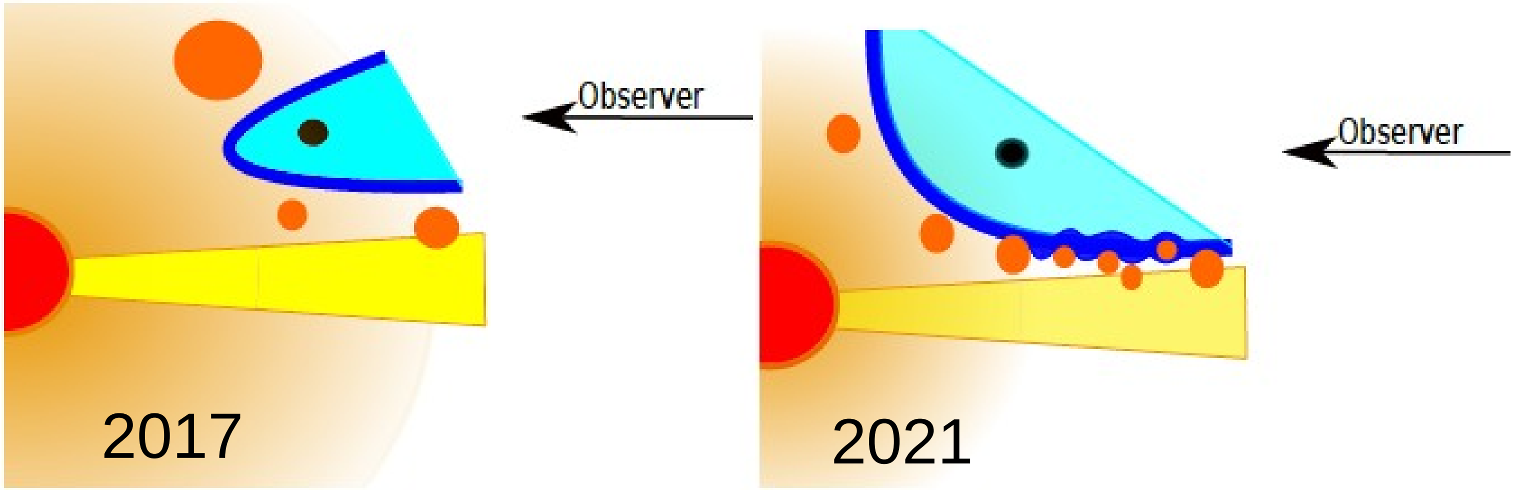
PSR B1259-63: 2021 periastron



- Somewhat delayed Fermi flare
- New LC feature: 3rd X-ray peak
- Radio – X-ray correlation broke down during 3rd X-ray peak

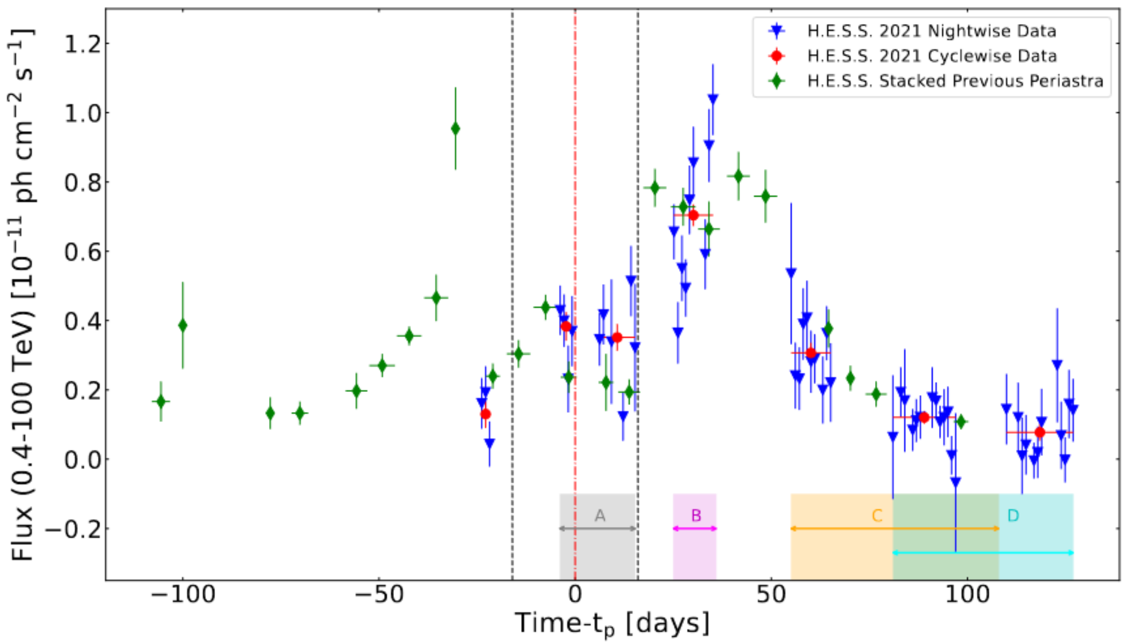


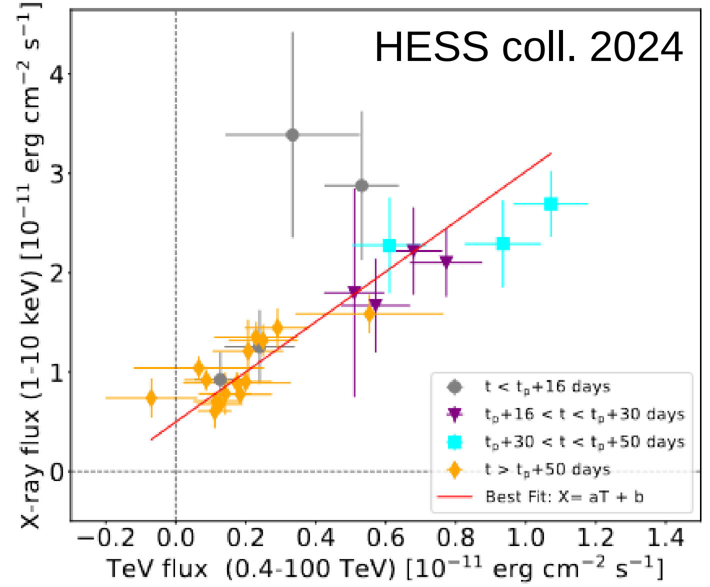
2017 vs 2021

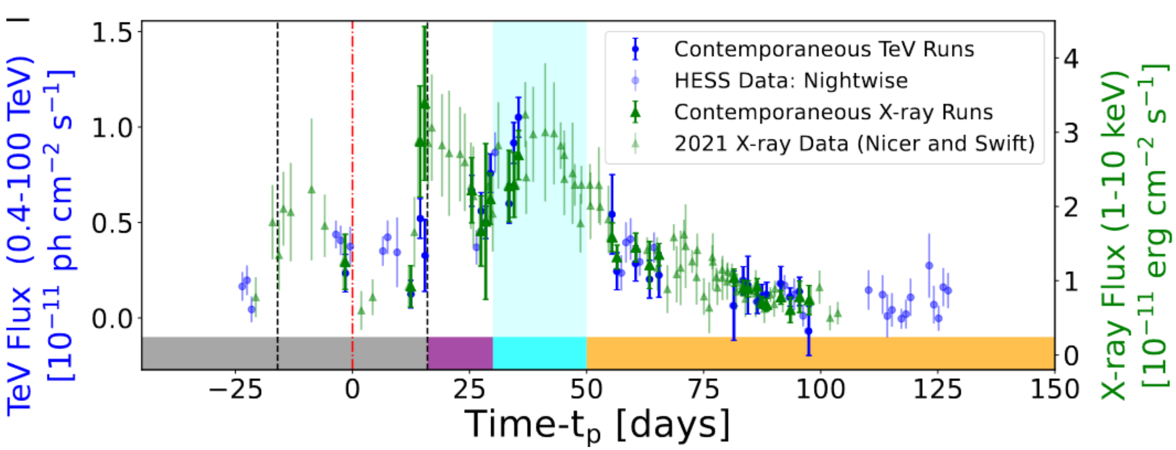


- Sparser state of the Be star outflow in 2021 lead to a much larger opening angle of the emission cone and a weaker magnetic field (hence weaker X-ray flux)

PSR B1259-63: 2021 periastron. TeV

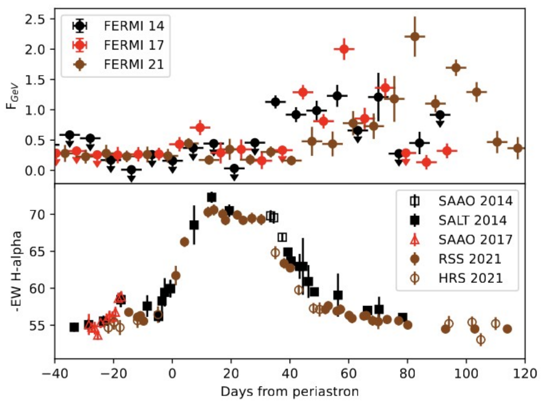




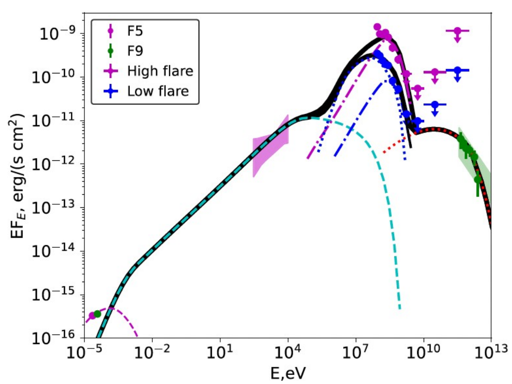


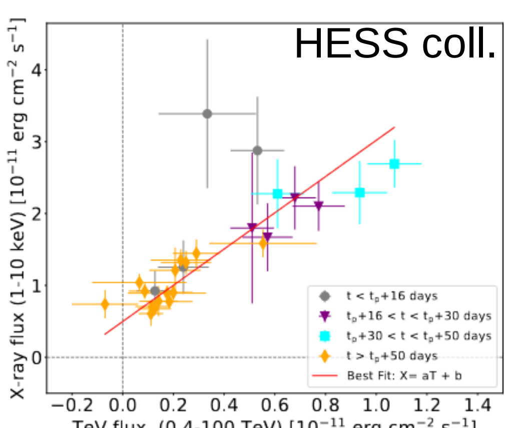
- For the 1st time reported X-ray/TeV correlation during 2nd and 3rd X-ray peaks
- Same population of electrons?
- Or similarly-changing conditions in X-ray/TeV emitting regions?

PSR B1259-63: open questions



Chernyakova + 2024

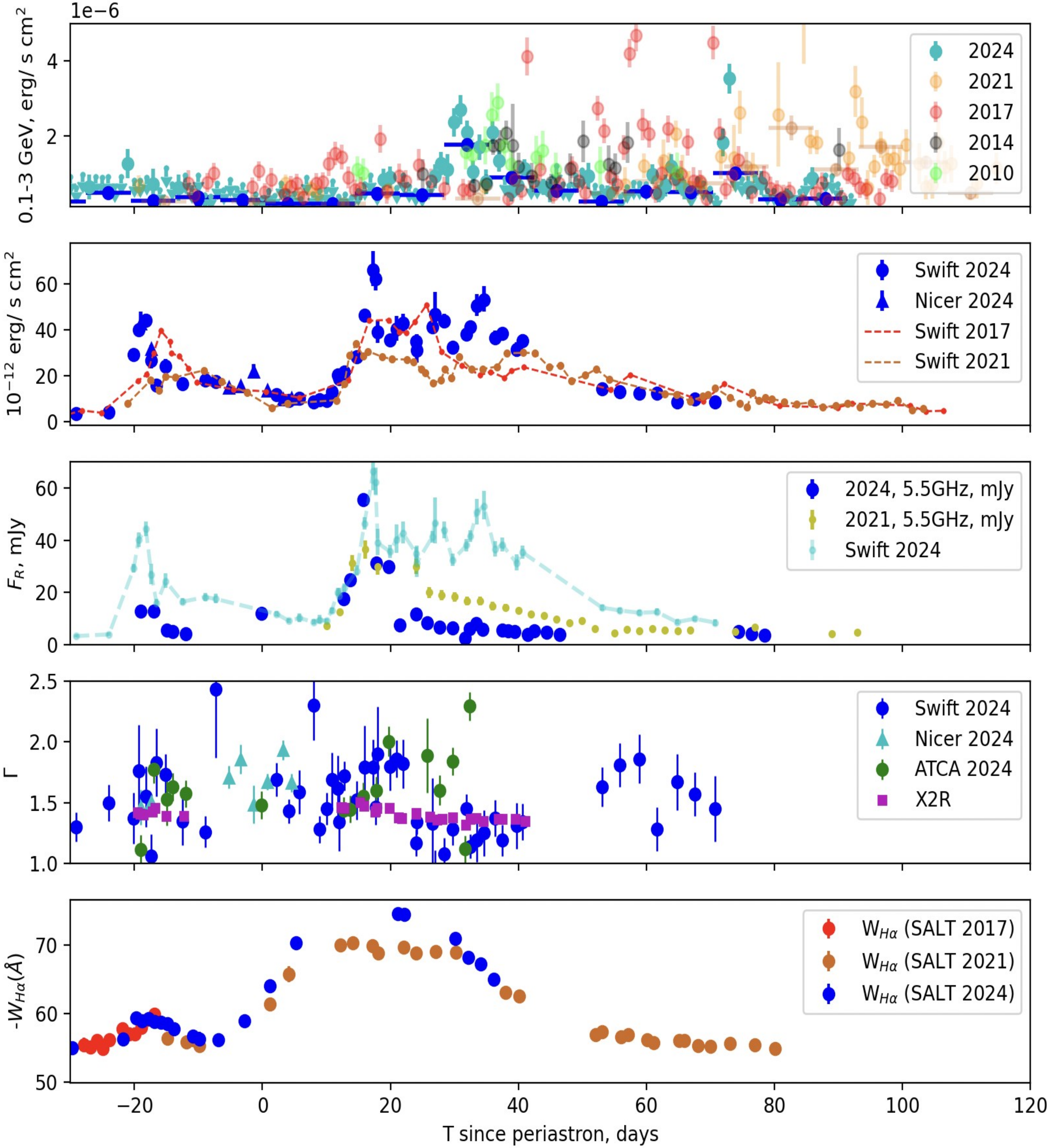




HESS coll. 2024

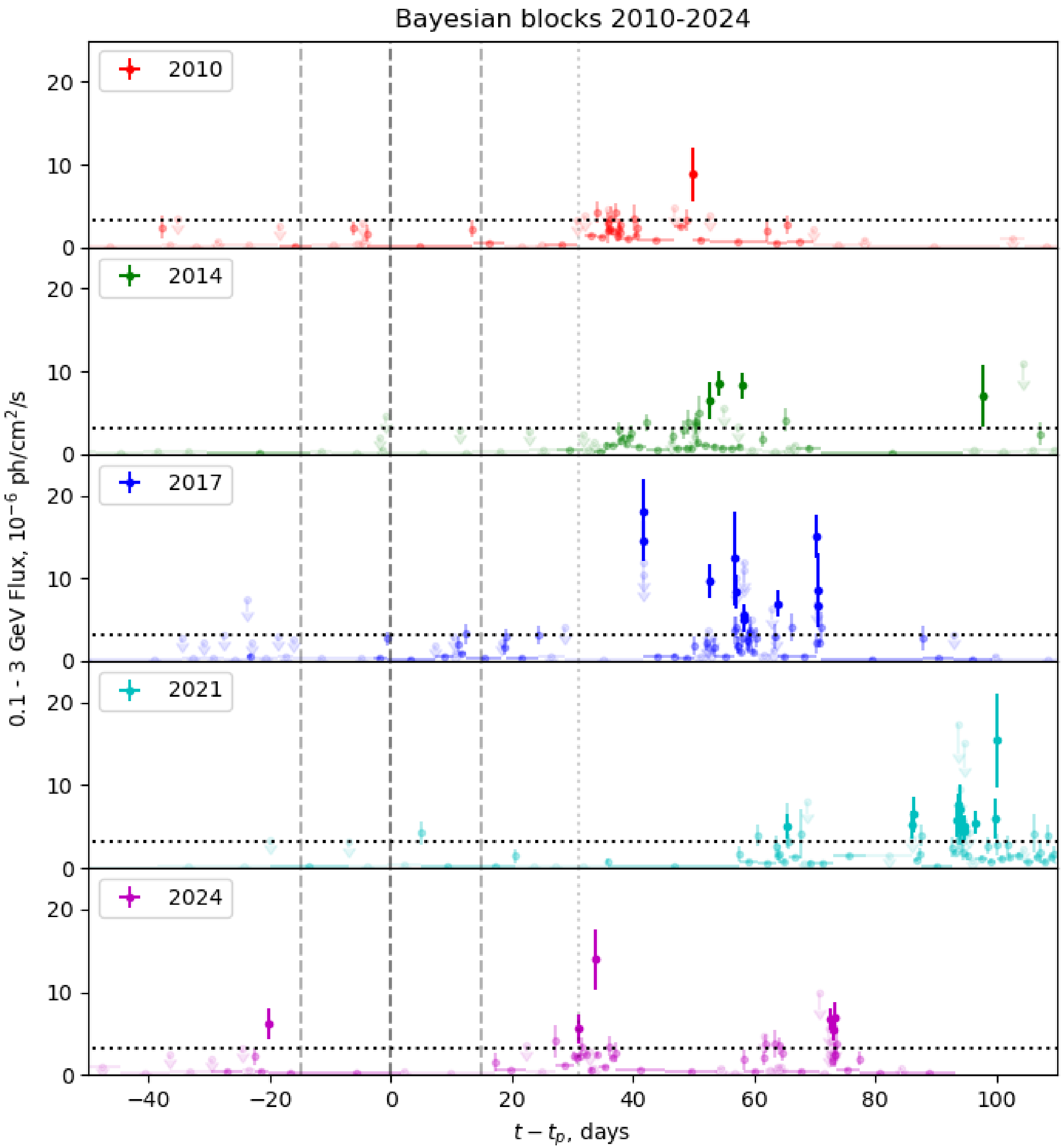
- Origin of GeV emission?
- Relation of the GeV flare to the state of the disc? IR studies are crucial to study the disk closer to the edge. ALMA observation can shed a light on it. For 2024 observations (t_p=+29) see Fujita+24.
- Origin of radio emission? Disappearance of the X-ray/radio correlation? The radio spectrum is inconsistent with a single population of electrons explaining both X-ray and radio emission. To explain observed radio variability on a day scale one needs either high magnetic field (~20 G) or ineffective cooling. Origin of the magnetic field?
- Origin of TeV emission far from periastron? Possible X-ray/TeV correlation if magnetic field in periastron is dominated by the Be star? TeV variability at short timescale?

PSR B1259-63: Periastron 2024



- Early first X-ray peak. No straightforward X-ray radio correlation during the first peak (more MeerKAT results ahead!).
- Brightest pre-periastron GeV subflare.

PSR B1259-63: Periastron 2024



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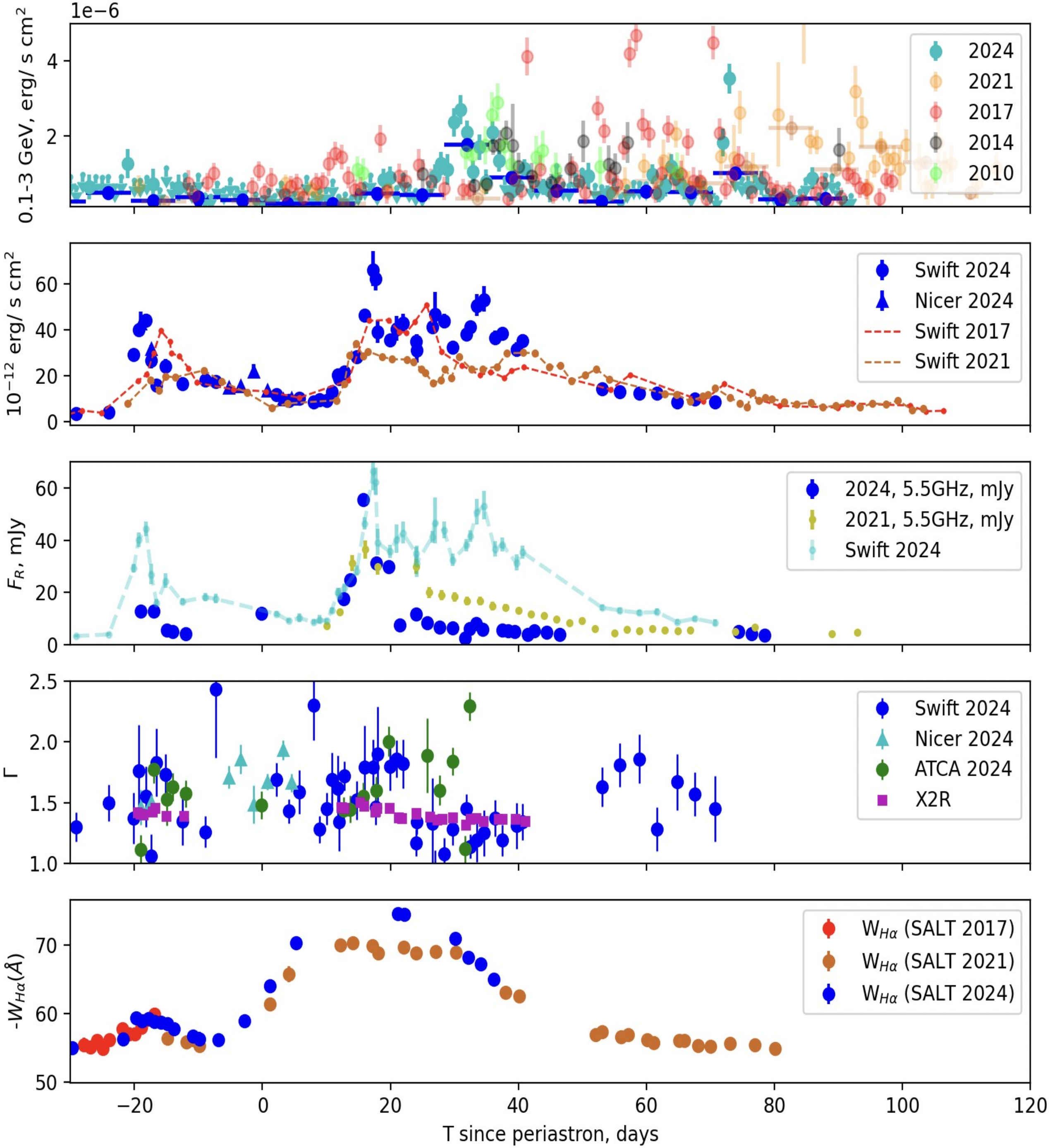
PSR B1259-63: Periastron 2024

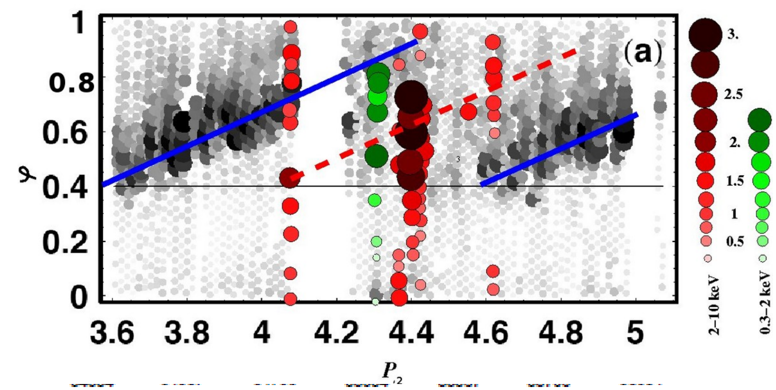


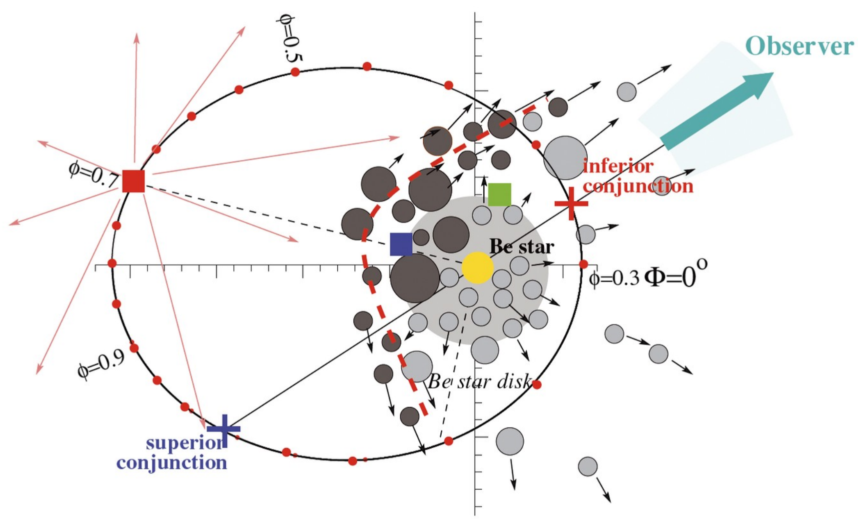
- Early first X-ray peak. No straightforward X-ray radio correlation during the first peak (more MeerKAT results ahead!).
- Brightest pre-periastron GeV subflare.
- Hint of X-ray/radio correlation during the second rise of X-rays.
- Complicated structure of the second X-ray peak.
- Noticeable hardening of X-ray emission during the third (?) peak.
- The earliest ever beginning of the Fermi flare.
- Early Fermi flare contradicts the warp disk precession model (Chang+21).
- Evidence of dense, large decretion disk of Be star? - inline with H_{α} data.

LSI +61° 303

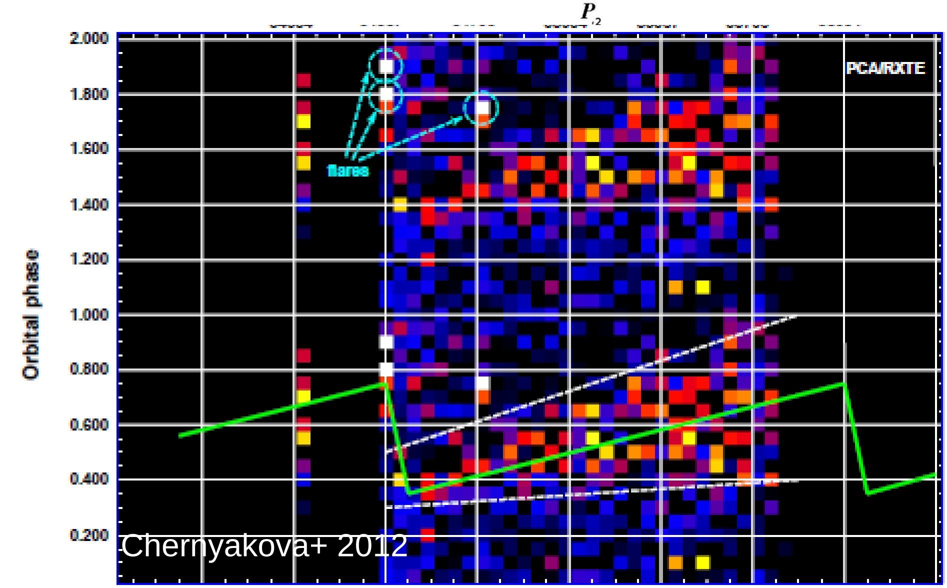
- Radio pulsar (P=269ms, Weng+ 2022) in an orbit with Be star.
- Emission is modulated throughout the 26.5-day orbit.
- The orbital phases of X-ray and radio flux maxima "drift" with superorbital (SO) period P=4.6 year.
- Evidence of superorbital modulation at GeV and TeV energies.

Gregory 2002





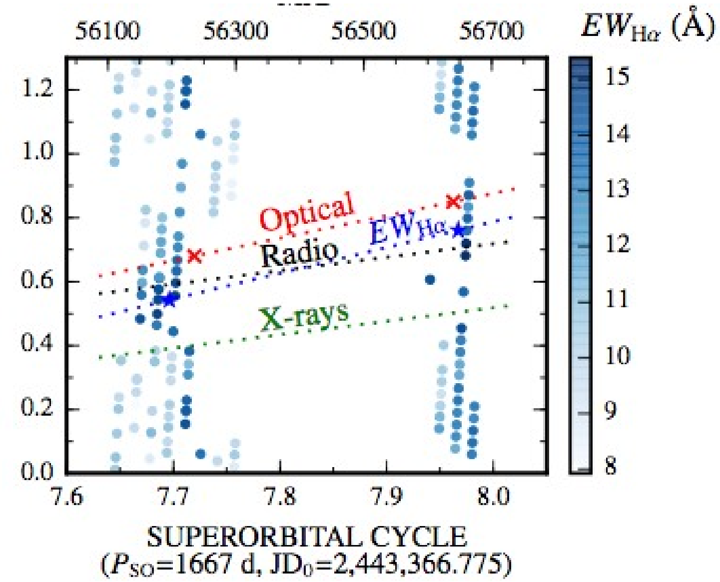
Zdziarski+ 2010



LSI +61 303

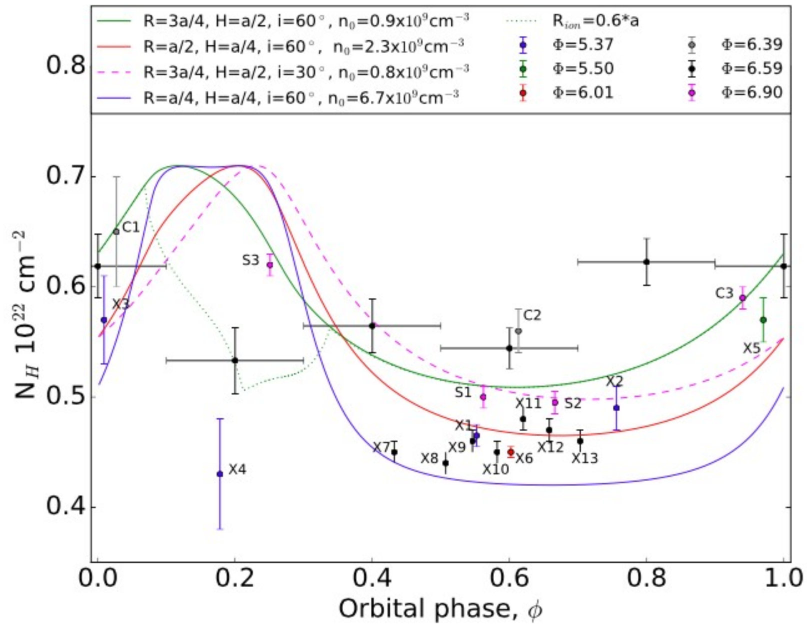
The SO variability could be either due to

- cyclic change of the Be star disk size (e.g. Chernyakova et al. 2012), supported by the hint of SO variability of Hα EW (Paredes-Fortuny 2015)
- precession of the Be disk?

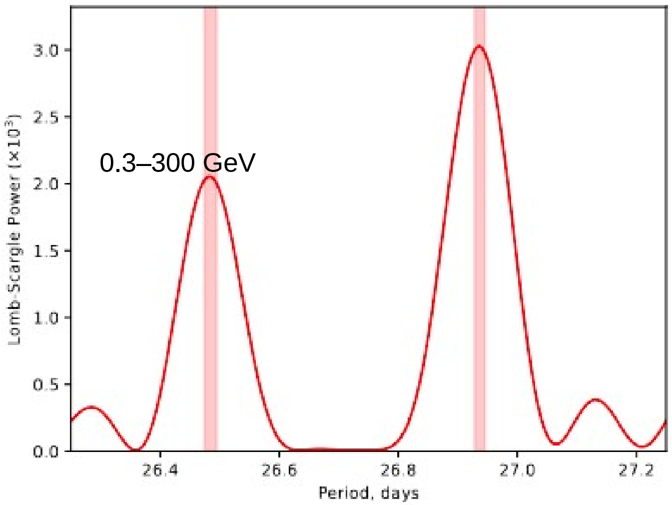


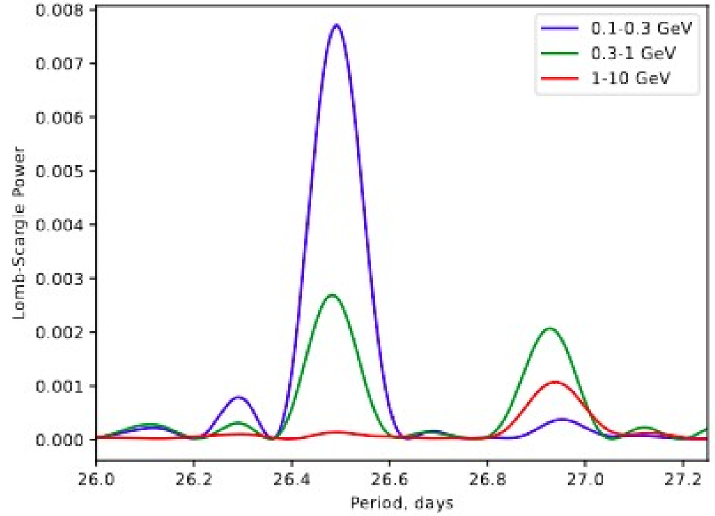
If SO variability in the system is linked with the disk build-up process one can expect the gradual change of the absorption, as the compact object moves on its orbit

- The value of N_H is clearly non-constant along the orbit at a 19.6 σ level (Chernyakova et al. 2017).



LSI +61° 303

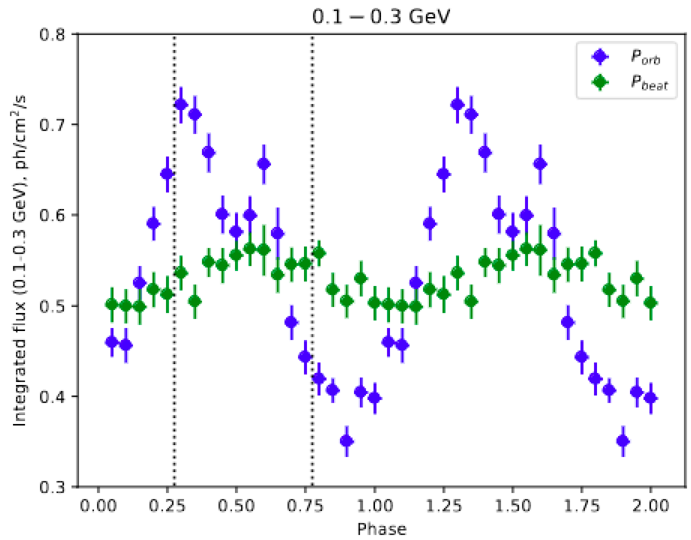


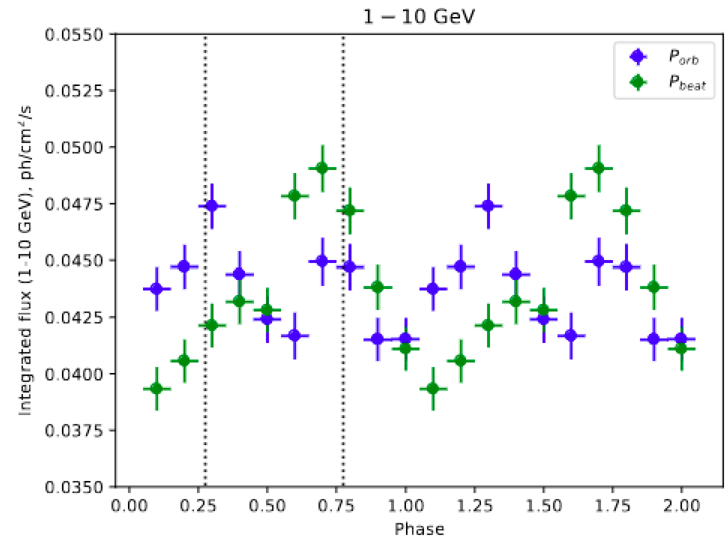


Chernyakova + 2023

- 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
- $P_1 = 26.485 \pm 0.012$ and $P_2 = 26.932 \pm 0.012$.
- 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





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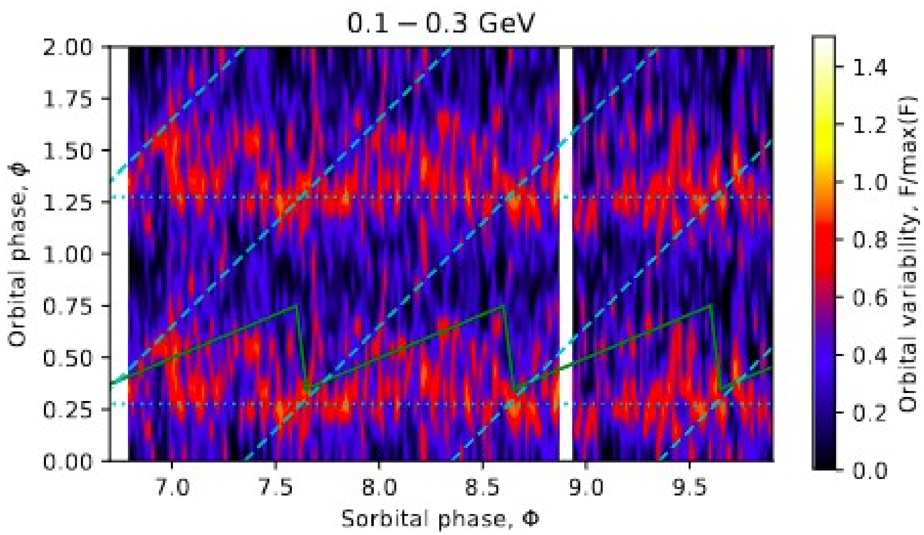
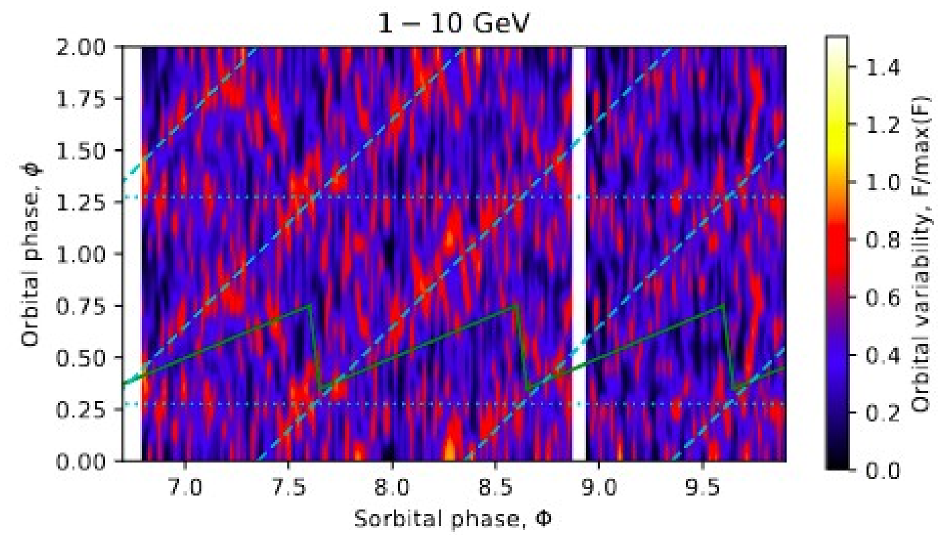
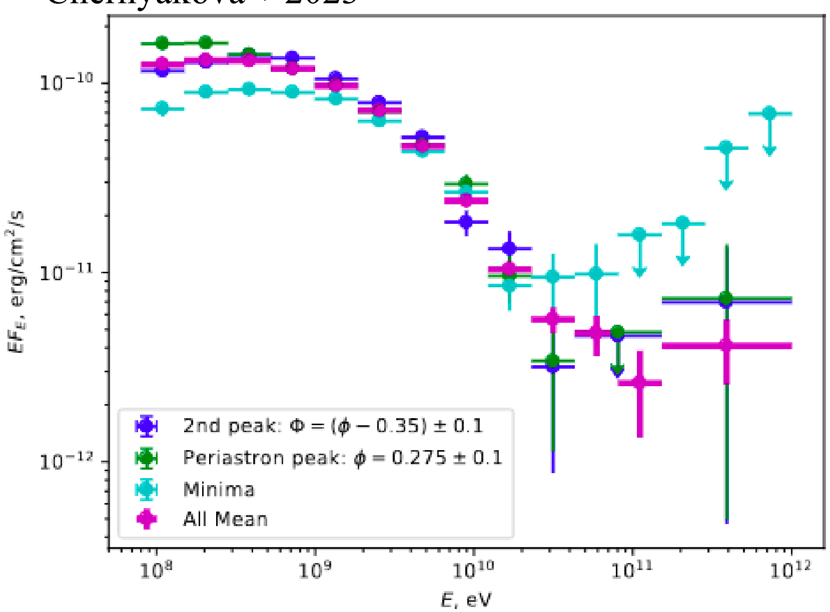




Chernyakova + 2023

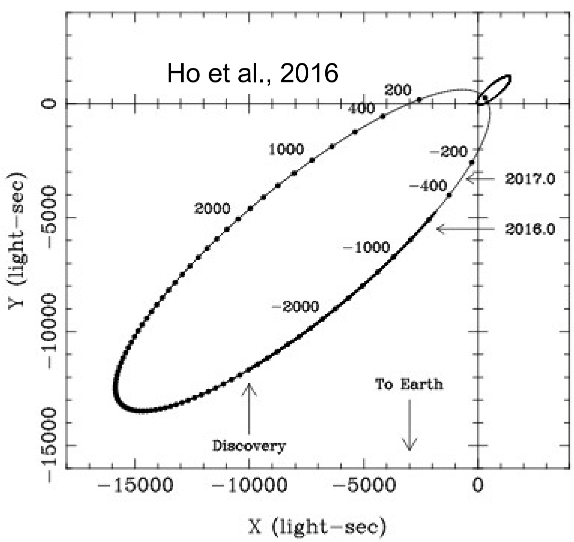


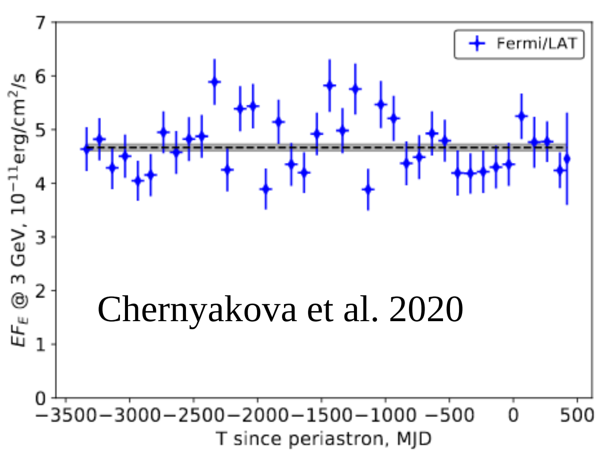
- "All Mean": all time-averaged data.

Orbital/ SO behaviour identifies distinct periods :

- periastron max (φ = 0.275 ± 0.1); **0.1 - 0.3 GeV**;
- beat-period maximum (Φ = (φ − 0.35) ±0.1); dashed diagonal lines, clearly seen **above 1 GeV.** Drift of the emission peak due to the precession of the pulsar or Be-star disk? Periodic growth and decay of the Be star disk?
- γ-ray emission from bow and tail of the shock?
- "minima": periods of low GeV emission **< 0.3 GeV** (Φ > 0.4 AND φ > 0.75);

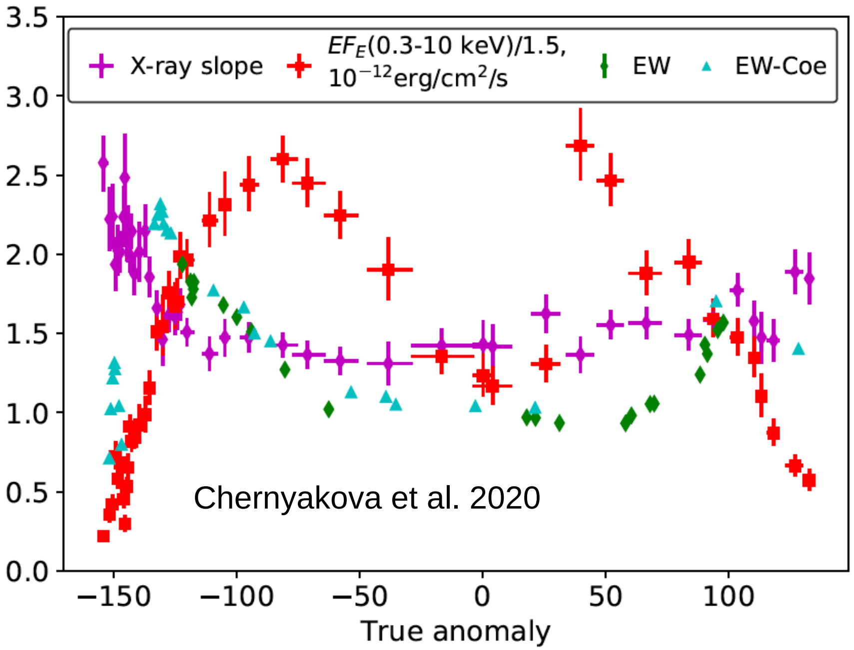
PSR J2032+4127 / MT91 213

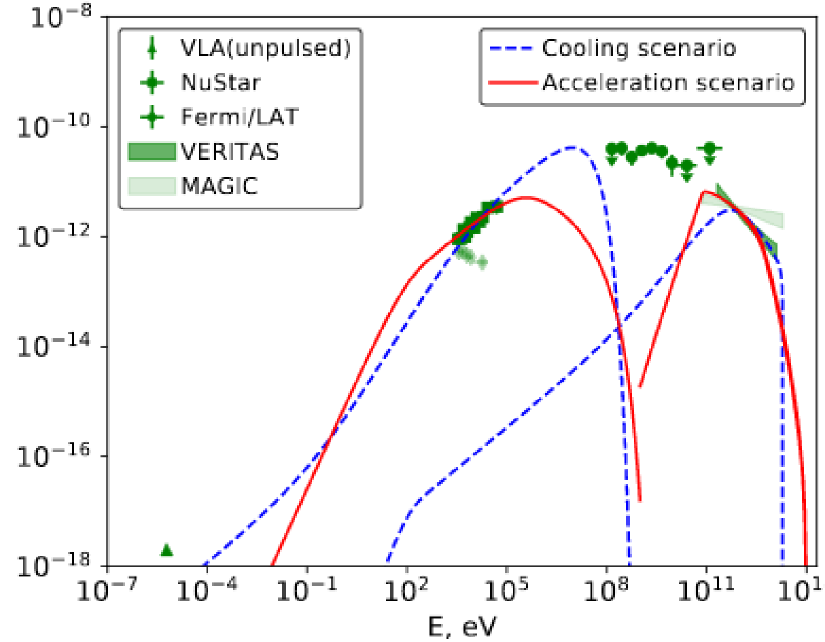




- 143 ms radio pulsar, discovered by Fermi (Abdo et al. 2009).
- The pulsar is rotating around the 15-solar-mass B0Ve star MT 91-213 in a very eccentric orbit, orbital period of 45-50 years (Ho et al., 2016).
- Periastron passage occurred on 13/11/ 2017.
- Unpulsed radio, X-ray and TeV emission are detected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

PSR J2032+4127: X-rays

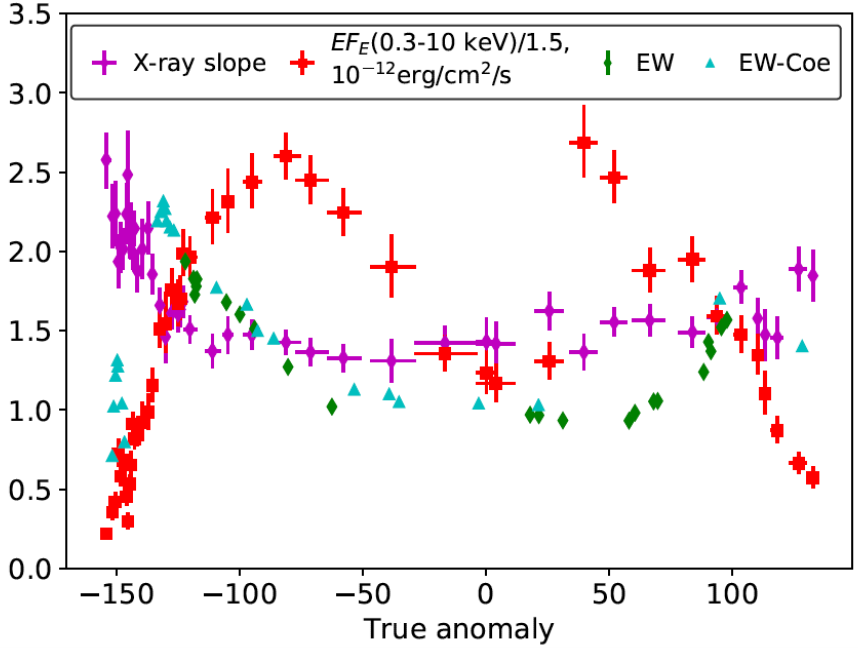


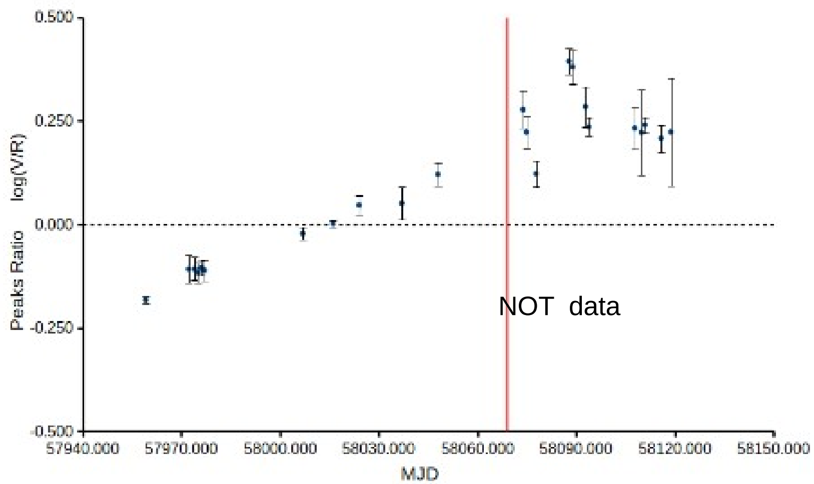


- **Similar** to PSR B1259-63 two peak X-ray light curve.
- Disk of the Be star is probably inclined to the orbital plane.
- X-ray and TeV emission are of synchrotron and IC origin correspondingly.
- GeV emission is dominated by the magnetospheric emission from the pulsar and thus is stable along the 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.

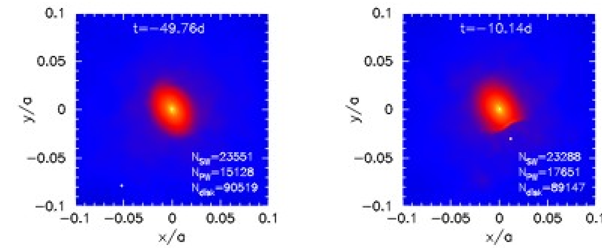
PSR J2032+4127: disk evolution

Chernyakova et al. 2020a



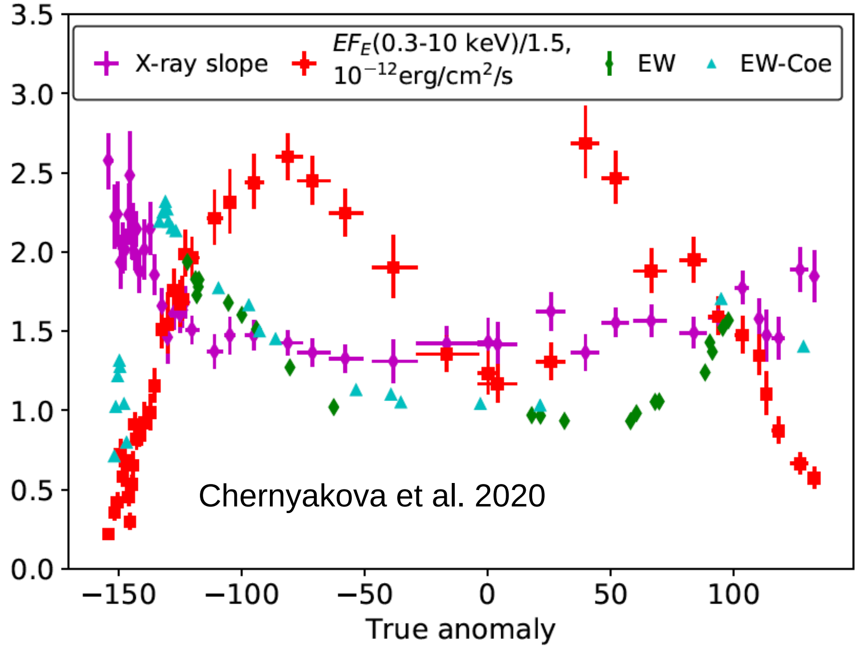


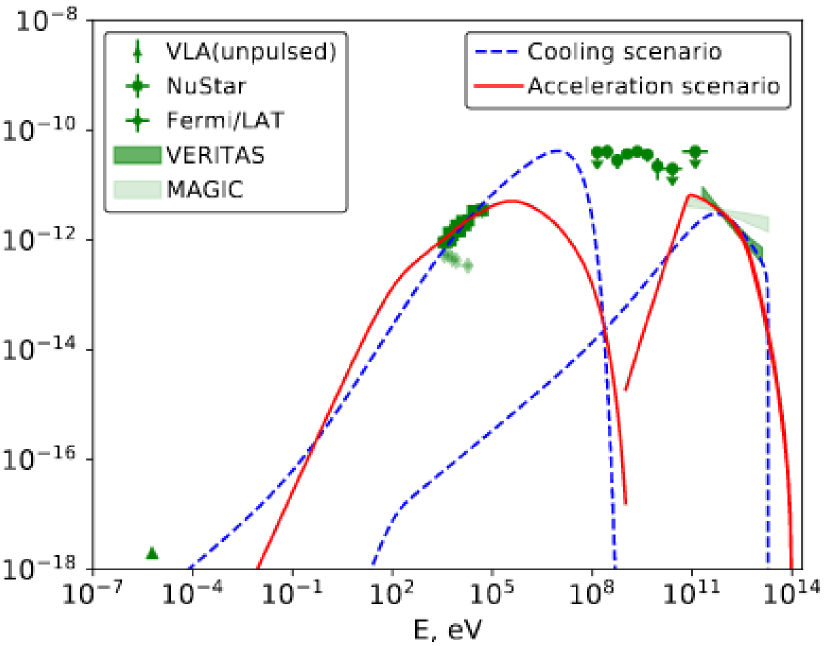
Coe et al. (2019)



- Interaction of the pulsar and stellar wind can be traced by the evolution of Hα emission line.
- Tidal interactions increase the size/density of the disk (rise of the Hα EW) until the pulsar enters the stellar wind deep enough.
- Max of the EW roughly corresponds to the moment when X-rays hardens to −1.5 (start of effective particle acceleration).
- After that external layers of the disk are destroyed, leading to the decrease of the EW.
- Cut-off of the external layers of the disk also lead to the change of the V/R ratio (part of the disk moving away from observer is destroyed).
- Gradual increase of the disk size after periastron, again due to tidal interactions.
- Gradual decay of the disk as the pulsar moves away

PSR J2032+4127: X-rays





PSR J2032+4127 (weak disk):

- X-ray index soft (-2) far from and hard (-1.5) close to periastron.
- emission region far from the pulsar → lower magnetic field → not effective cooling via synchrotron losses → hard keV index
- no cone-like specific effects (GeV flare)
- TeV maximum at periastron – increased level of soft photons

PSR B1259-63 (strong disk):

- X-ray index hard (-1.5) far from and soft (-2) close to periastron
- emission region close to the pulsar → higher magnetic field → effective cooling via synchrotron losses → soft keV index
- cone-like specific effects (GeV flare)

Conclusions

- Gamma-ray binaries with radio pulsar provide a chance to study the properties of the winds and details of their interaction.
- Peculiarities of 2024 periastron passage:
  - Early rise of X-ray flux before the periastron + early start of the Fermi flare. Indication of the larger disk? Supported by optical observations.
  - Complicated X-ray and radio structure of the second peak. Correlation during the flux rise?
  - Data analysis and detailed modeling still ongoing, stay tuned!
- 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. The main dissimilarities are due to the differences in the disk properties.