The transient and variable VHE galactic sky

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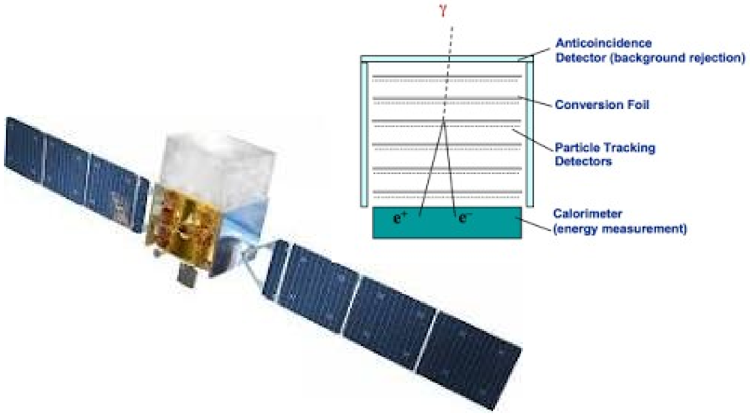
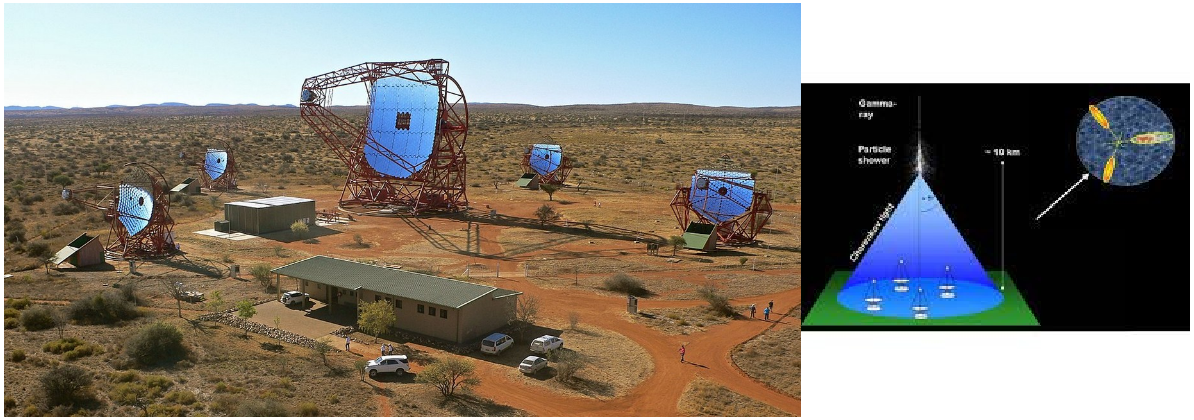
The Transient and Variable Universe 2023, 20 - 22 June, Urbana-Champaign, USA

Instruments to study VHE sky



Fermi/LAT (0.1 – 300 GeV)



HESS, MAGIC, Veritas (30 GeV – 100 TeV)

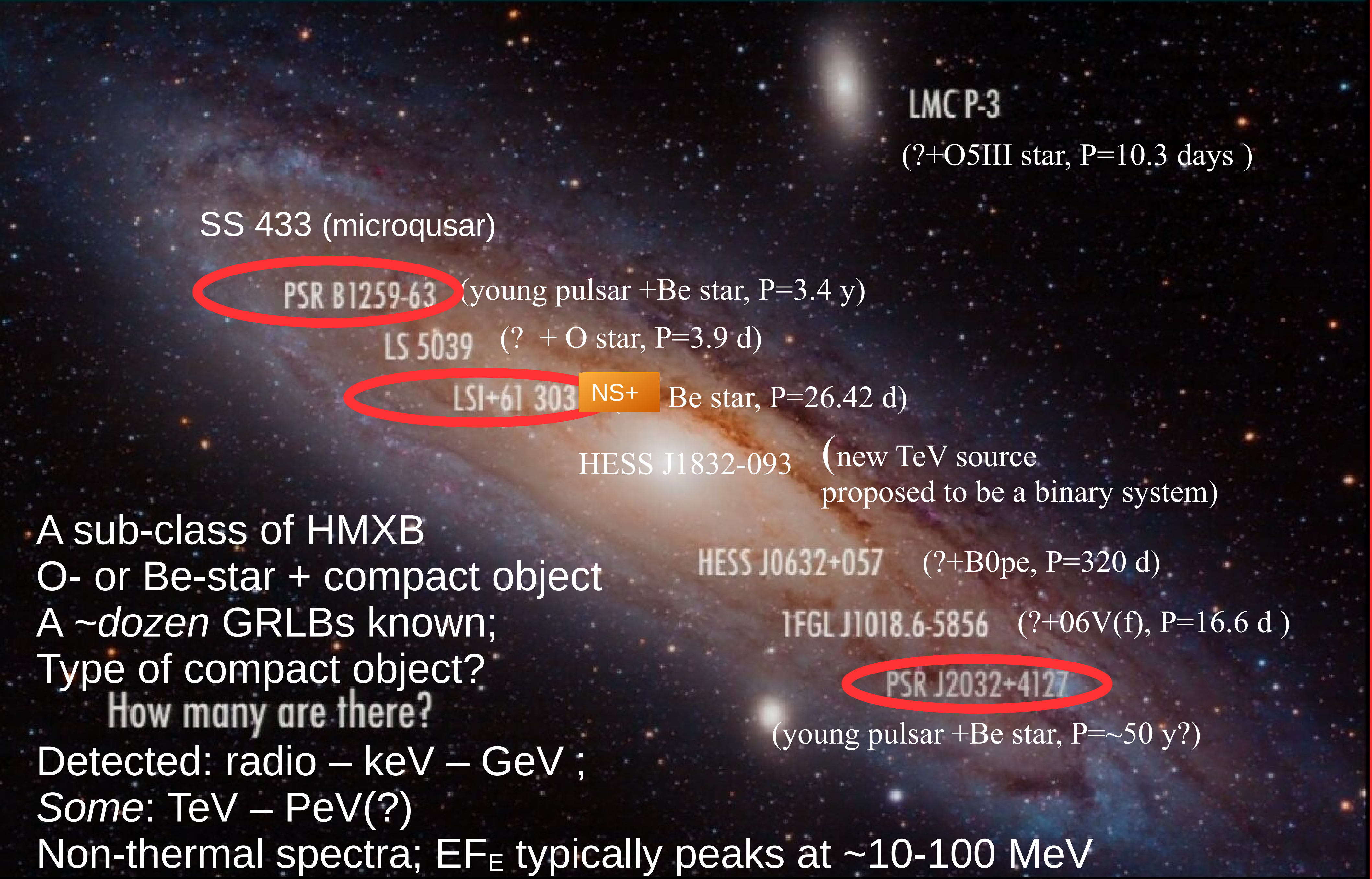
HAWC (100 GeV – 100 TeV)

LHAASO (200 GeV – 1 PeV)

Variable VHE Galactic Sources

- Gamma-ray binaries
  - Binaries with radio pulsars
  - Microquasars
  - Colliding wind binaries
- Magnetars
- Transitional Millisecond Pulsars
- Pulsar Wind Nebula
- Nova
- Supernova

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 NS+ 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)

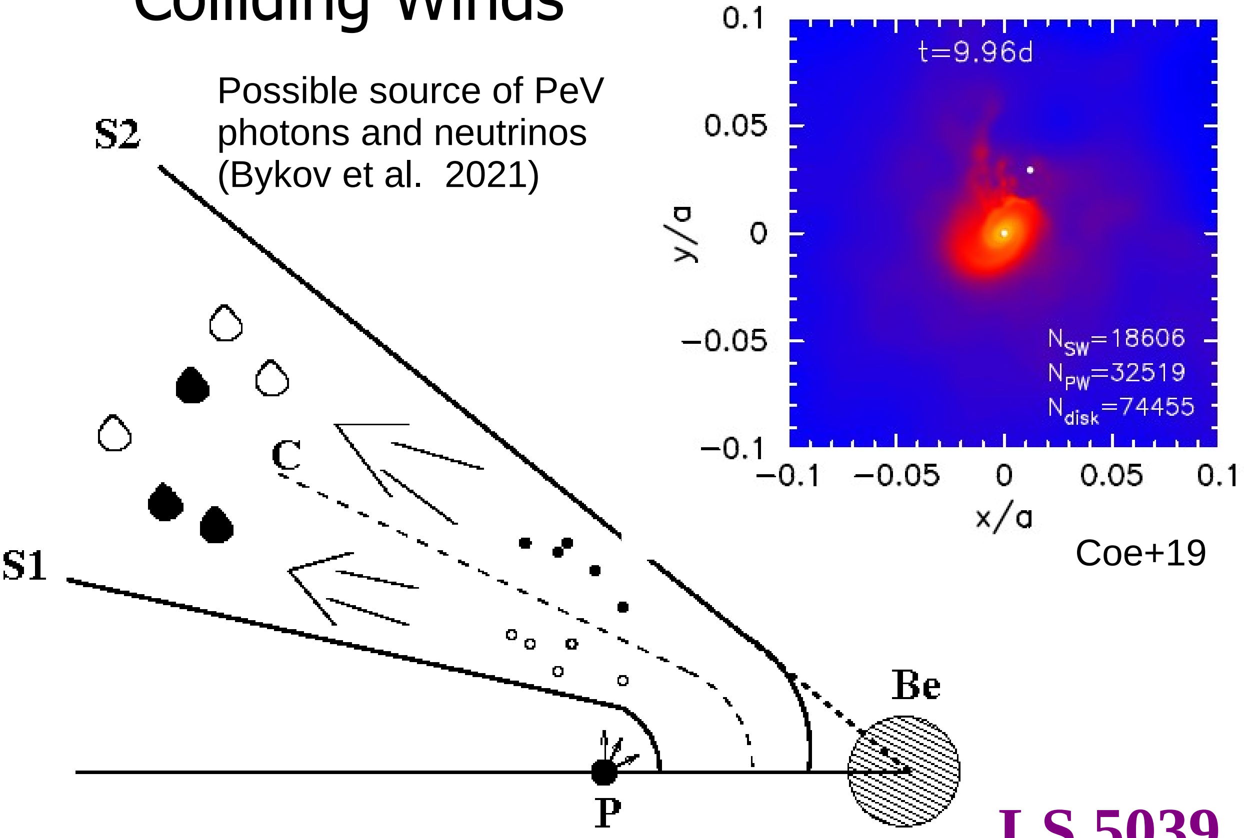
PSR J2032+4127 (young pulsar +Be star, P=~50 y?)

A sub-class of HMXB
O- or Be-star + compact object
A ~*dozen* GRLBs known;
Type of compact object?
How many are there?
Detected: radio – keV – GeV ;
Some: TeV – PeV(?)
Non-thermal spectra; EF_E typically peaks at ~10-100 MeV

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

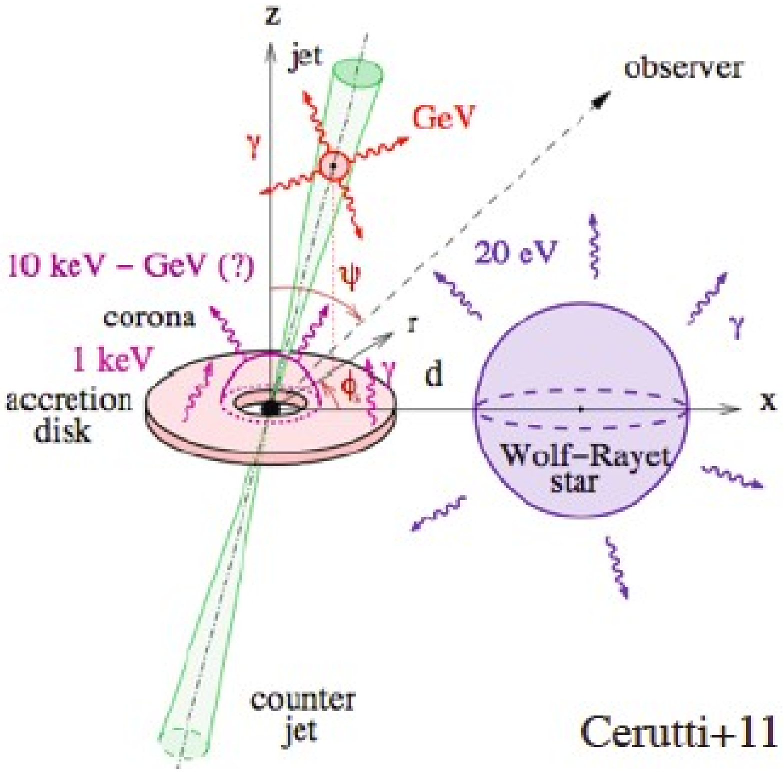
Colliding Winds

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



Coe+19

Microquasar



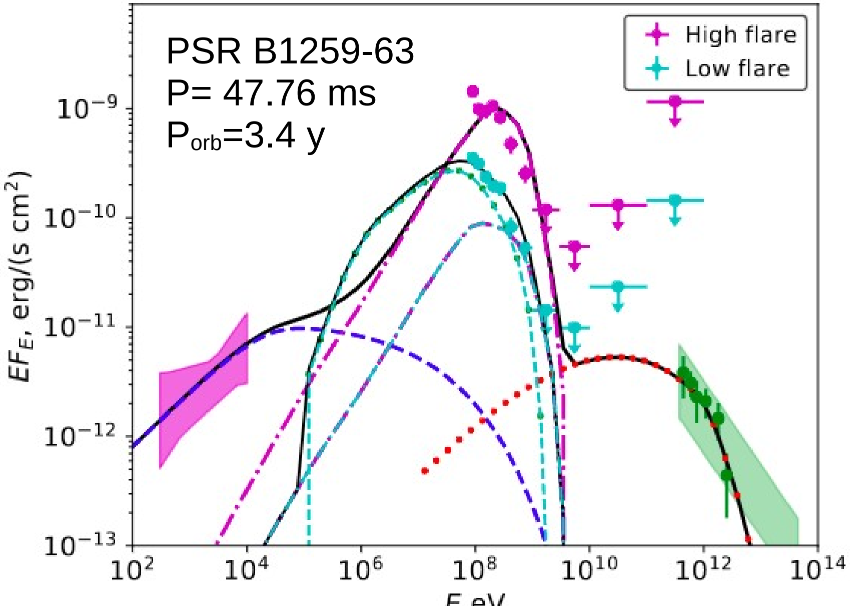
Cerutti+11

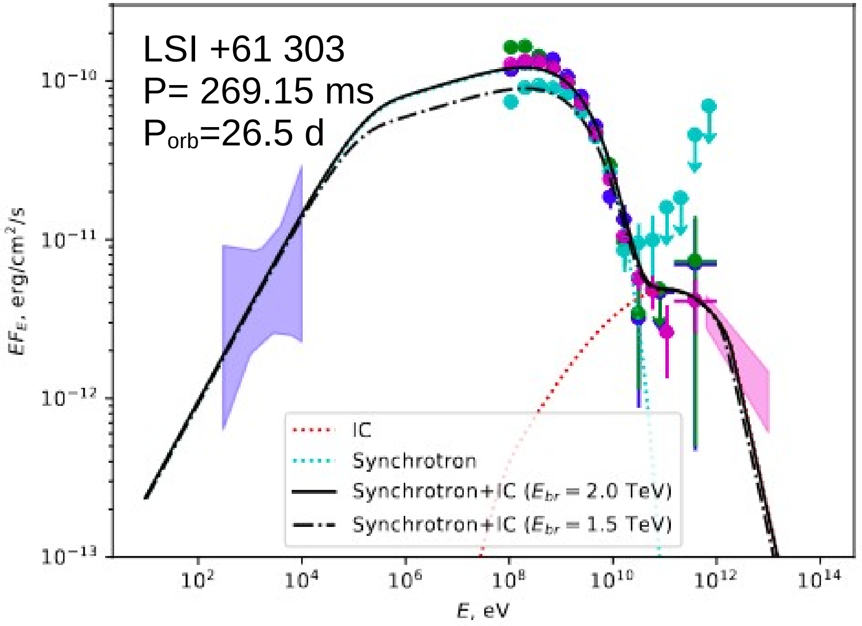
PSR B1259-63
PSR J2032+4127
LS I +61° 303 (at least at some orbital phases)

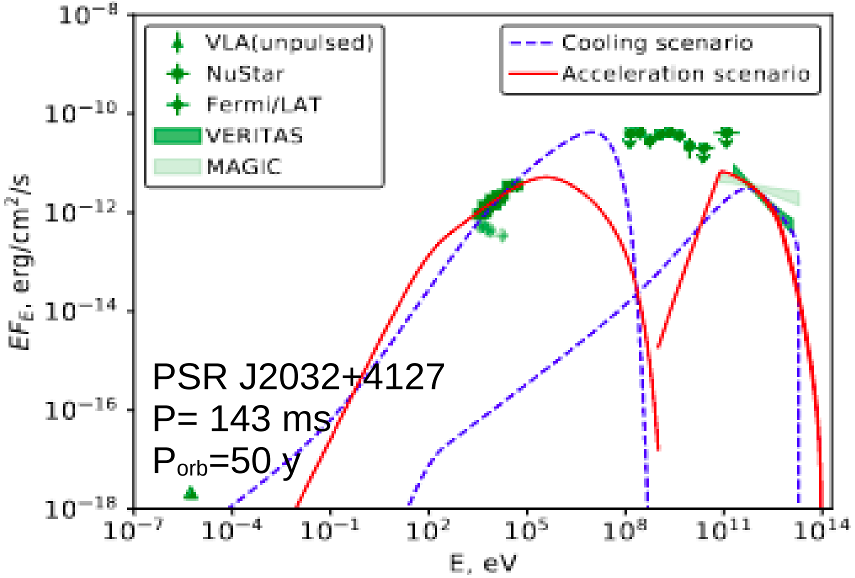
LS 5039
HESS J0632+057
HESS J1832-093
1FGL 1018.6-5856
...

Cygnus X-3
Cygnus X-1
SS 433

Gamma-ray binaries with a radio pulsar



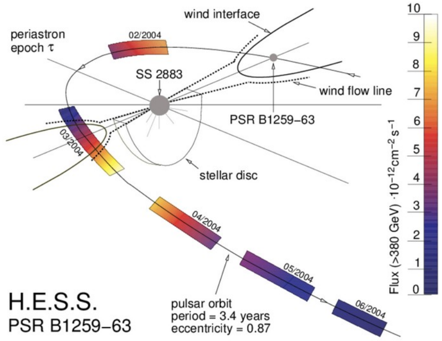




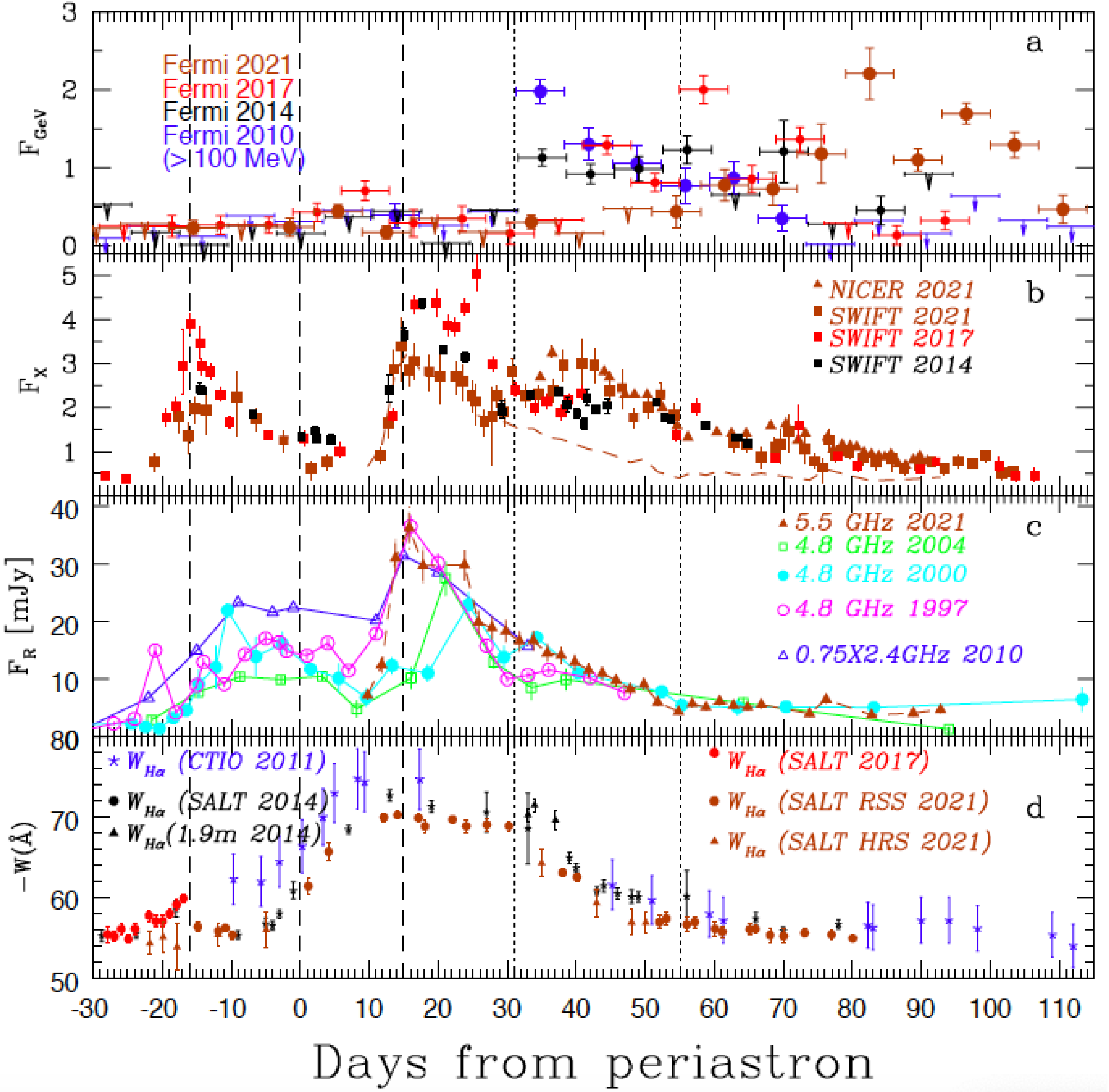
Chernyakova+ 20,23

- 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



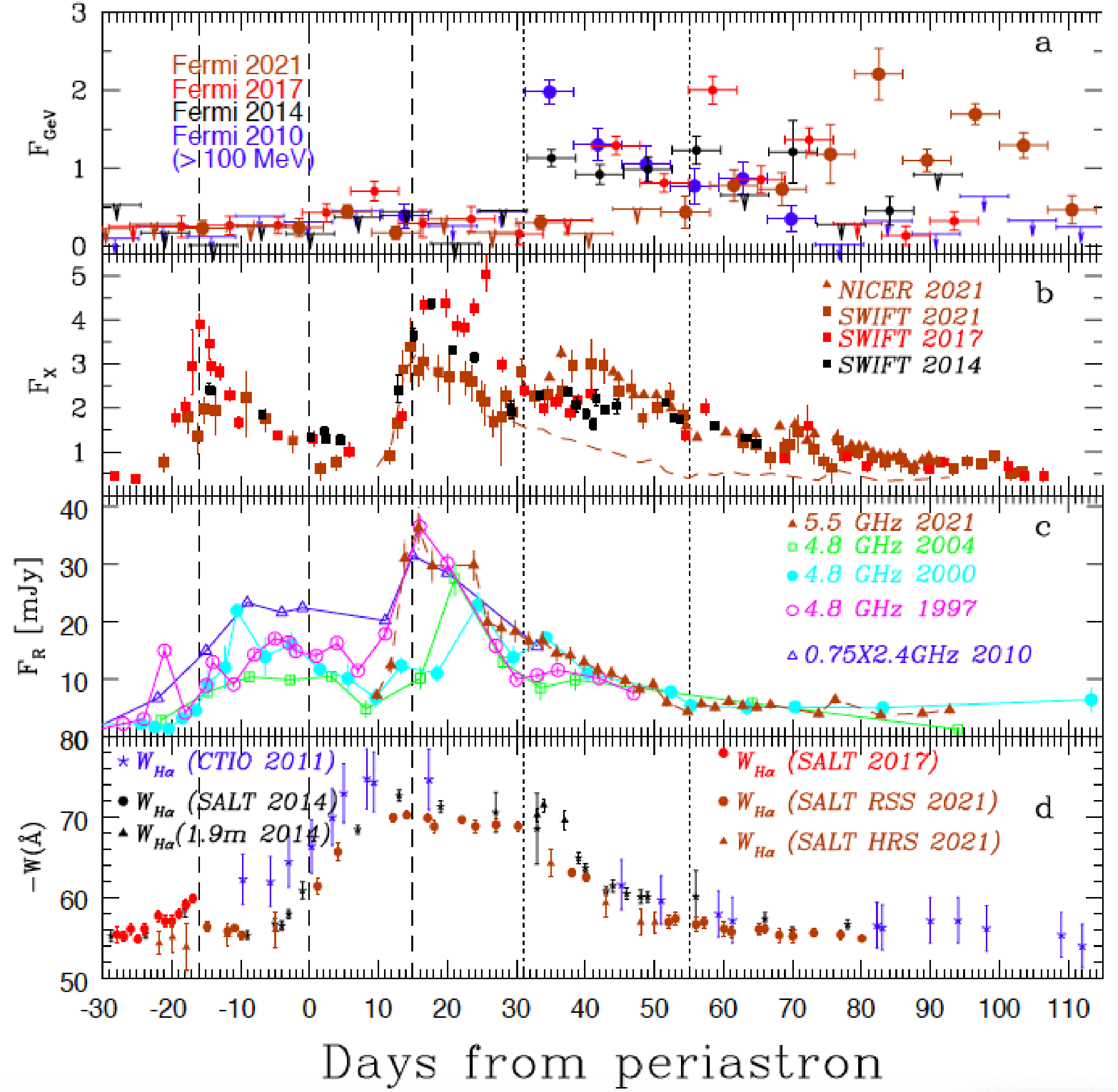
Aharonian+ 2005



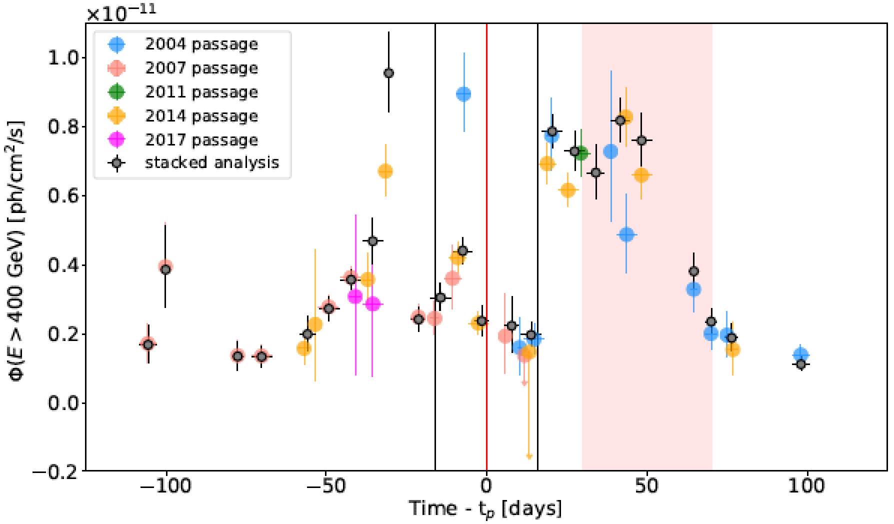
Chernyakova+ 2021

- Two peaks at X-ray and radio ~20 days around the periastron (passage through the inclined Be star disk.)
- Huge GeV flare with energy release close to spin-down luminosity on a weekly scale ~30/40/60 days after the periastron.
- No counterpart at other energies.
- 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



Chernyakova+ 2021

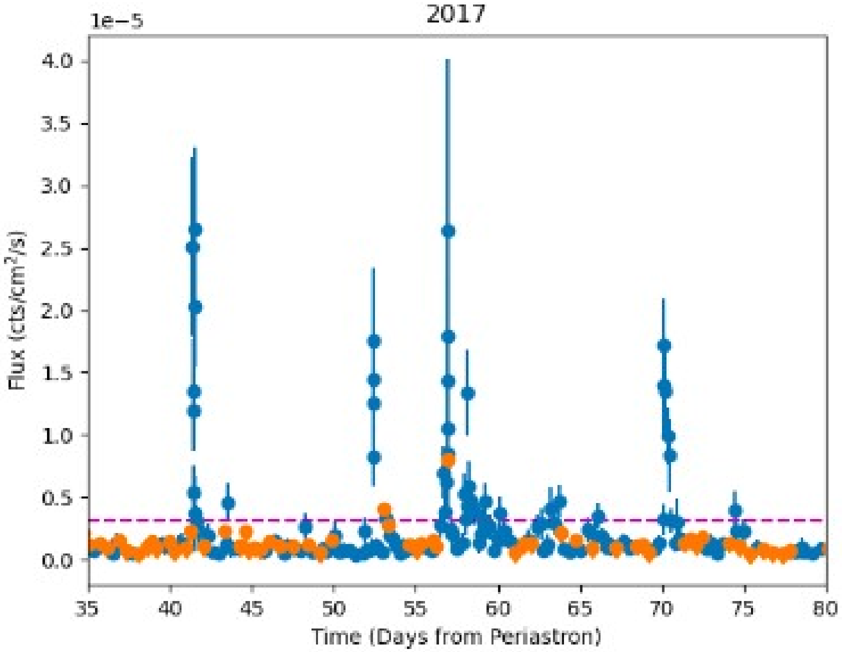


HESS collaboration, 2020

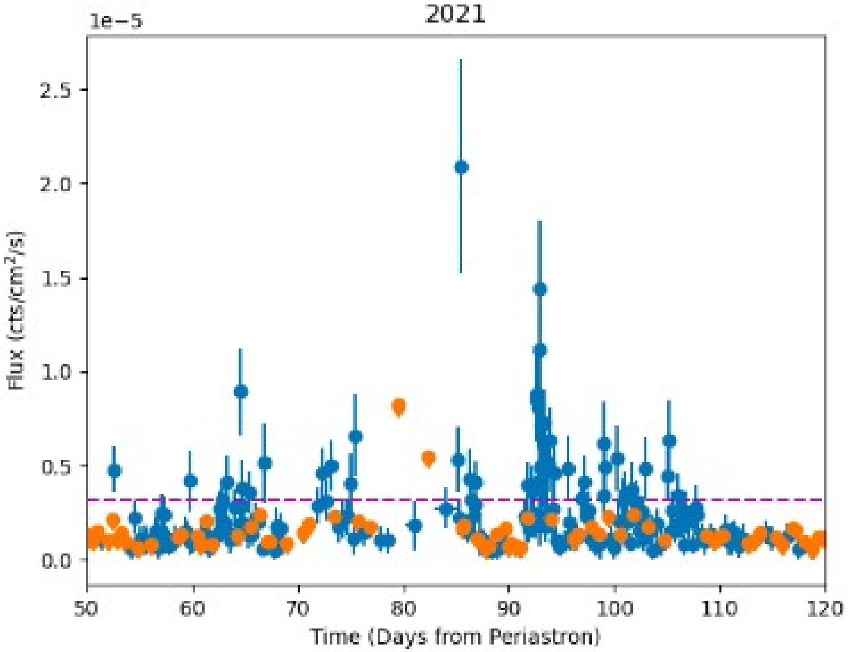
- Possible 2 peak structure at TeV as well.
- More sensitive TeV data are needed to study the multi-wavelength correlation at small time scales.

PSR B1259-63:
light curves on short time scales

Chernyakova+ 20

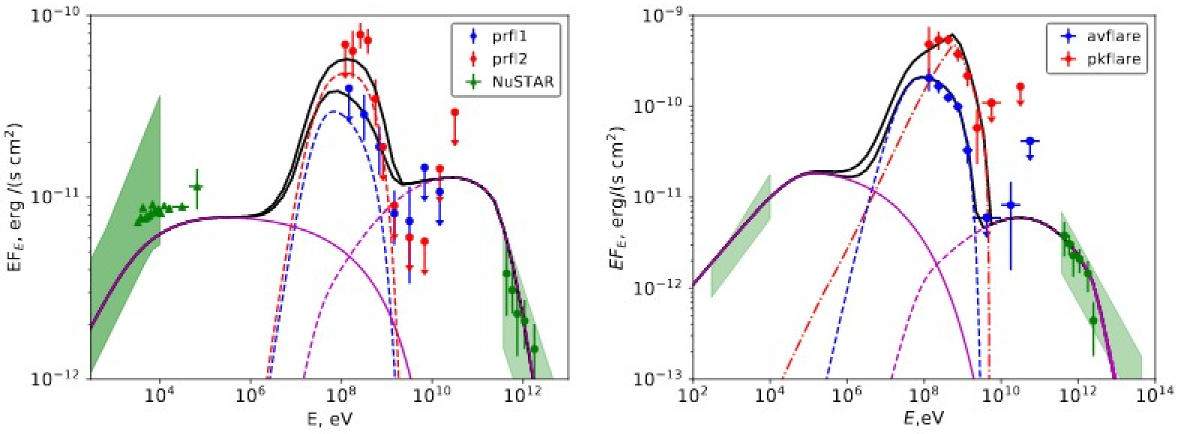


Chernyakova+ 2021

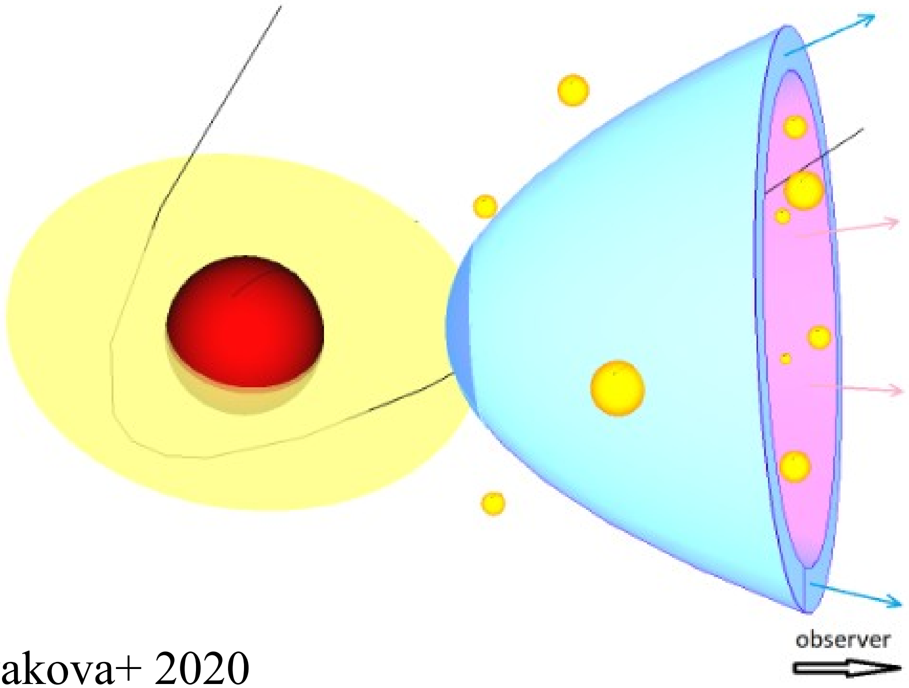


- Evidence of very fast (~15 min) gamma flares
- The isotropic gamma-ray luminosity corresponding to the short flares greatly exceeds the pulsar spin-down luminosity!

PSR B1259-63: model

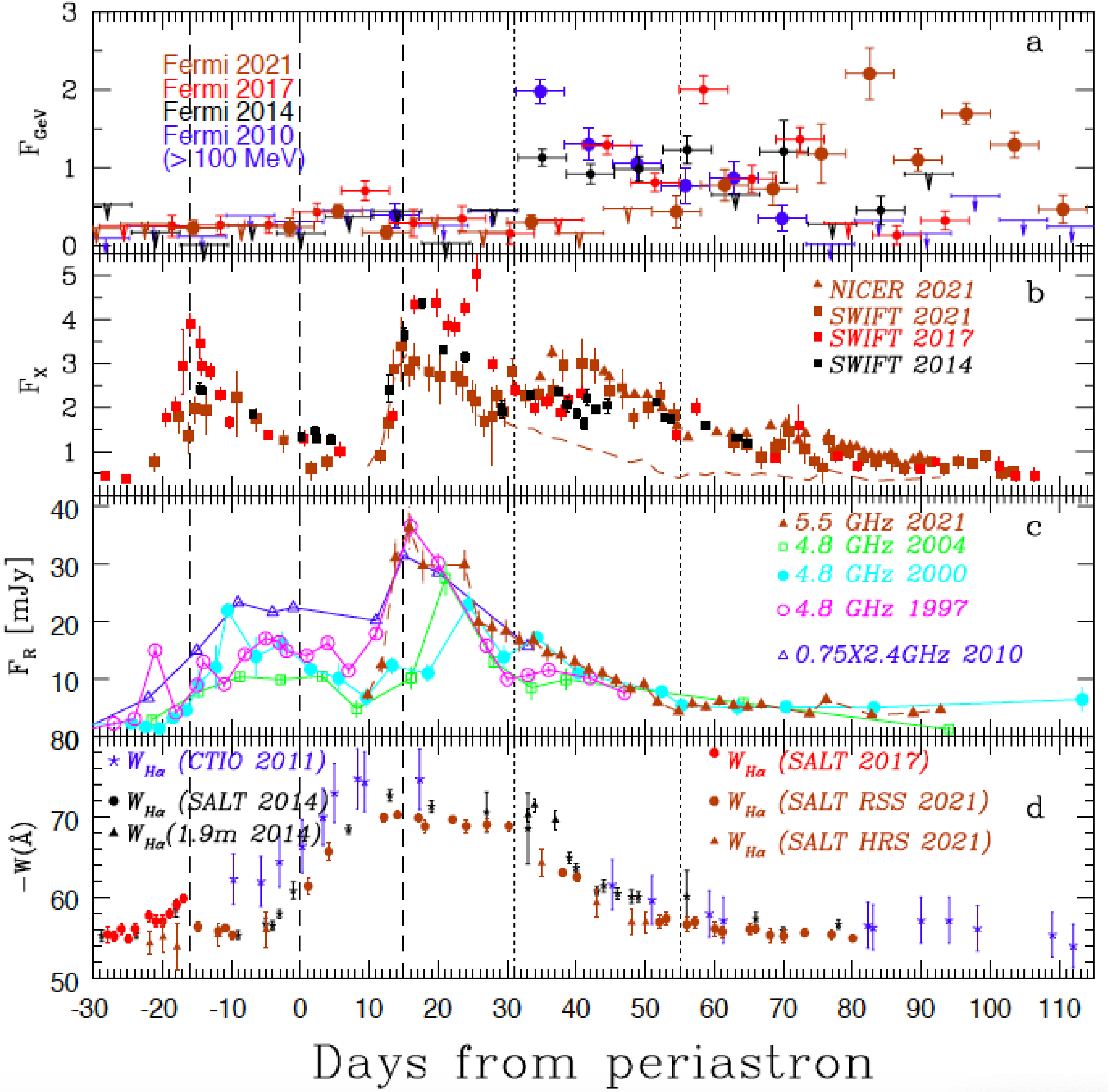


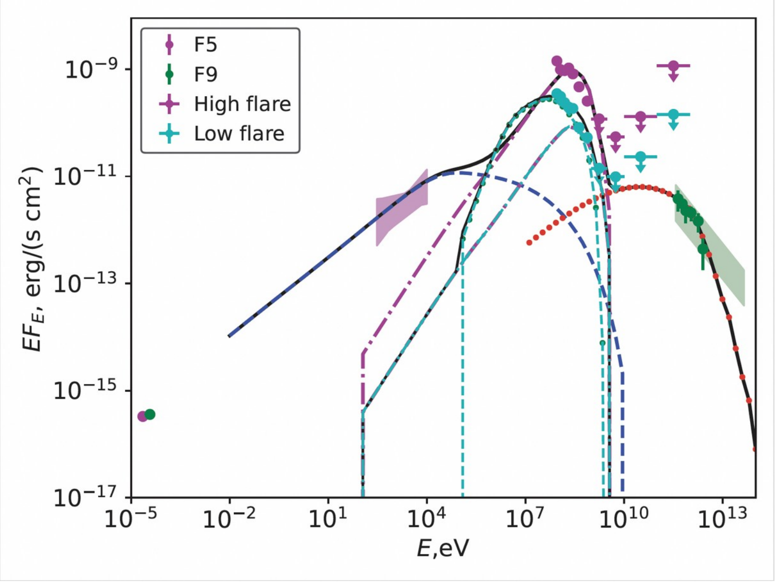
- Observed X-ray and TeV emission can be explained as a synchrotron and IC emission of the strongly shocked electrons of the pulsar wind.
- GeV component is a combination of the IC emission of unshocked / weakly shocked electrons and bremsstrahlung emission.
- Luminosity of the GeV flares can be understood 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+ 2020

PSR B1259-63: opened questions



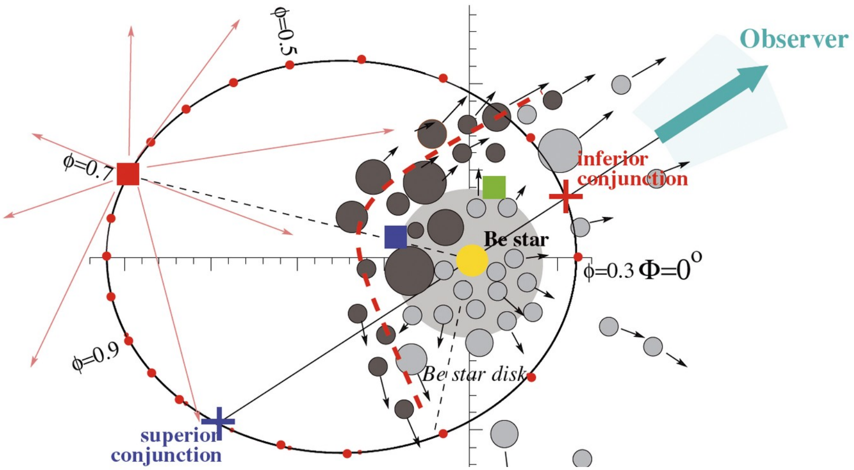


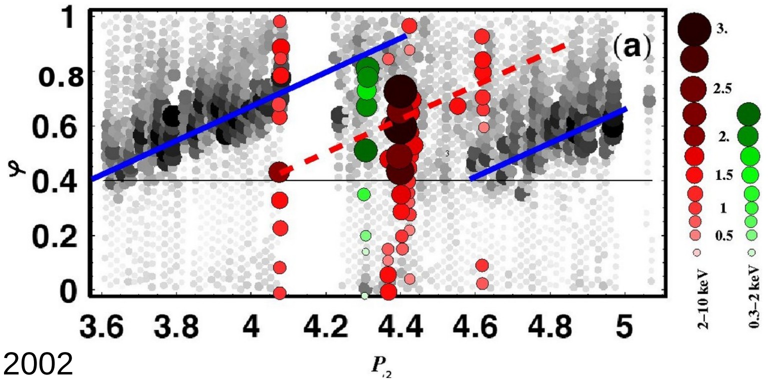
- Other explanations of short flares
  - -Turbulent magnetic field?
- Origin of radio emission?
  - - Initial correlation of Radio and X-ray data later disappears.
- Origin of the 3rd X-ray peak?
- No optical counterpart of the GeV flare.
- IR studies are crucial to study the disk closer to the edge.

Chernyakova+ 2021

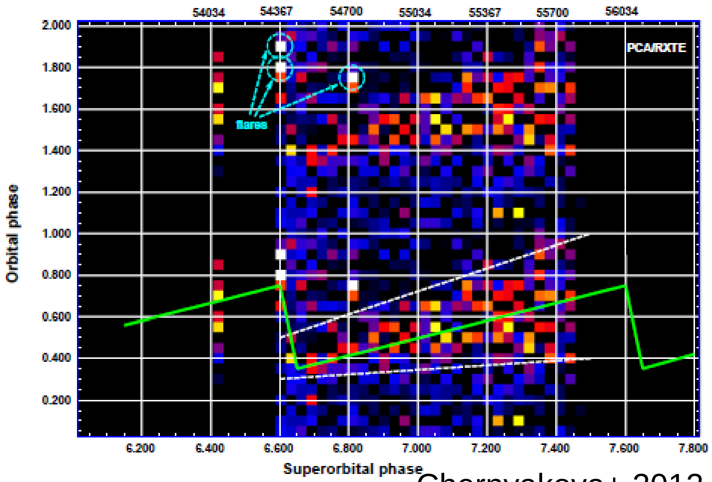
LSI +61 303

- Radio pulsar (P=269ms, Weng+ 2022) in an orbit with Be star.
- Pulsations were detected only at specific orbital phases, $\phi=0.59$
- 2 SGR-like bursts from the position of LSI (Torres+ 2012).
- Emission is modulated throughout the 26.5-day orbit (radio → TeV).
- The orbital phases of X-ray and radio flux maxima “drift” with superorbital period P=4.6 year.
- Evidence of SO modulation at Gev and TeV energies.



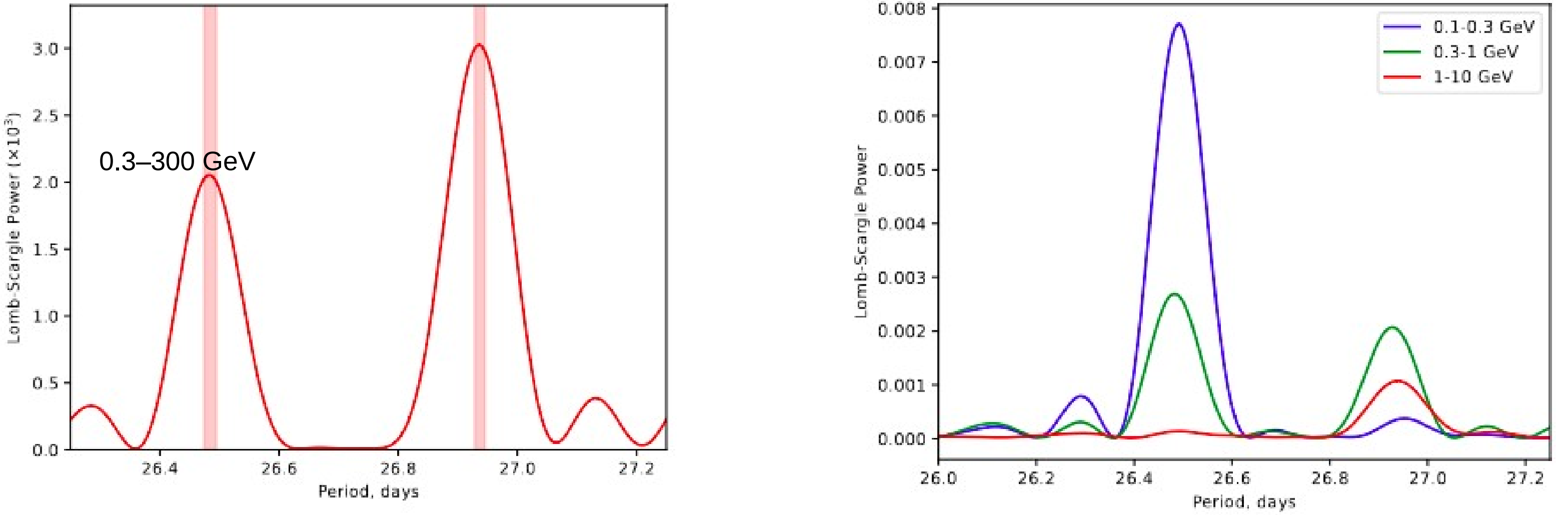


Gregory 2002



Chernyakova+ 2012

LSI +61 303



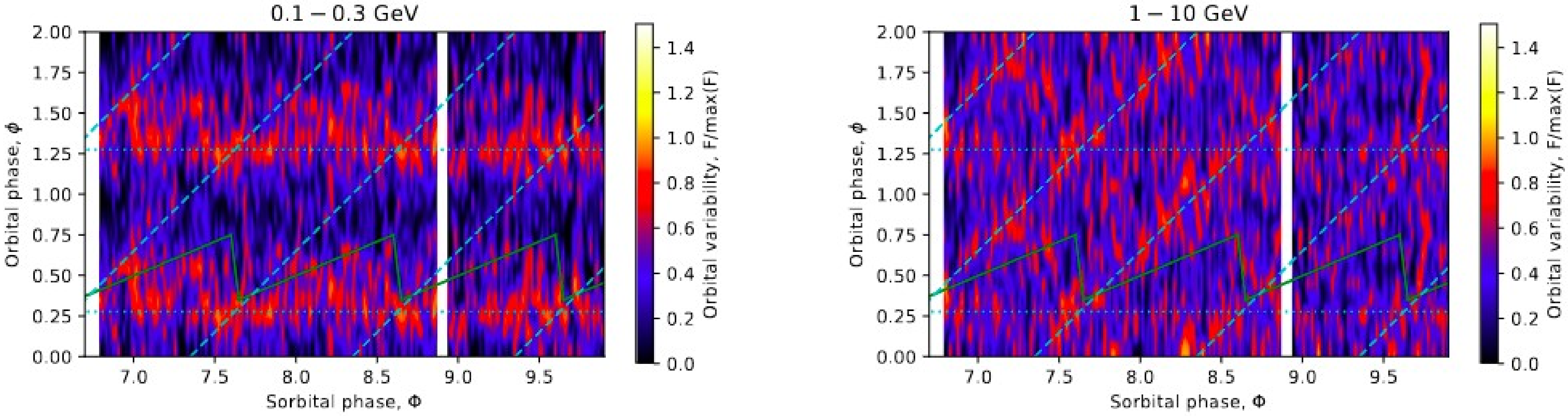
Chernyakova+ 2023

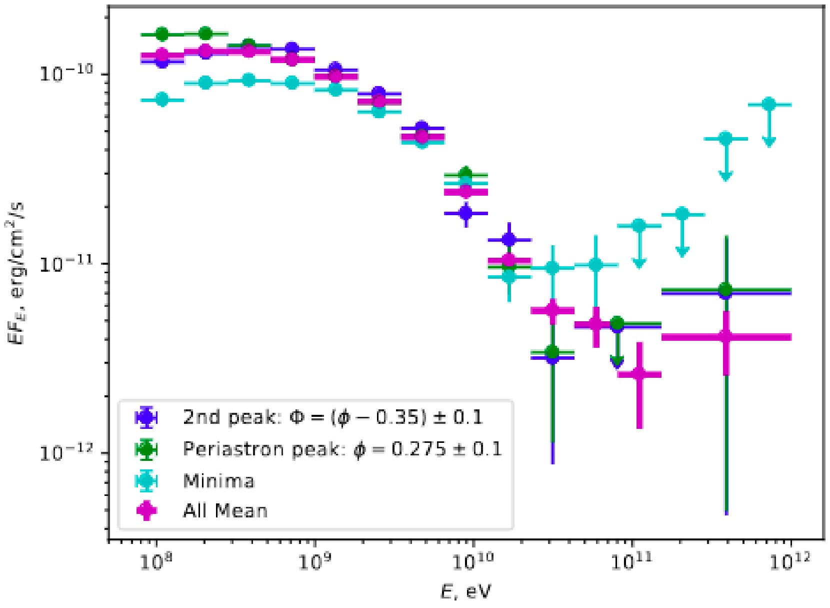
- Analysis of more than 14 years of the Fermi/LAT data.
- Similar to previous findings of Massi et al. (2013) Lomb-Scargle analysis of 0.3–300 GeV light curve reveal 2 peaks
- $P_1 = 26.485 \pm 0.012$ and $P_2 = 26.932 \pm 0.012$.
- These periods are consistent (1σ) with the orbital period $P_{orb} = 26.496$ 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



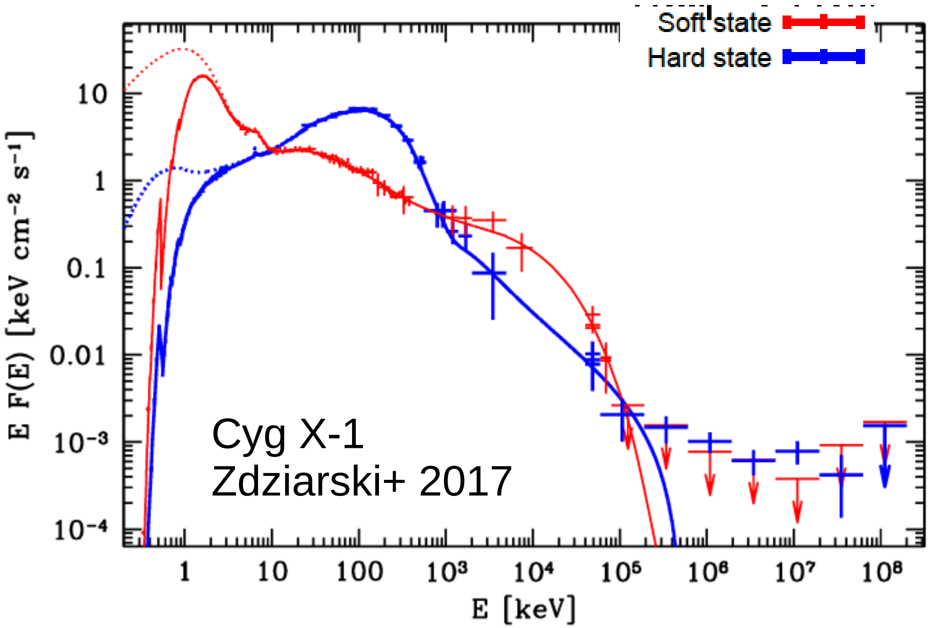


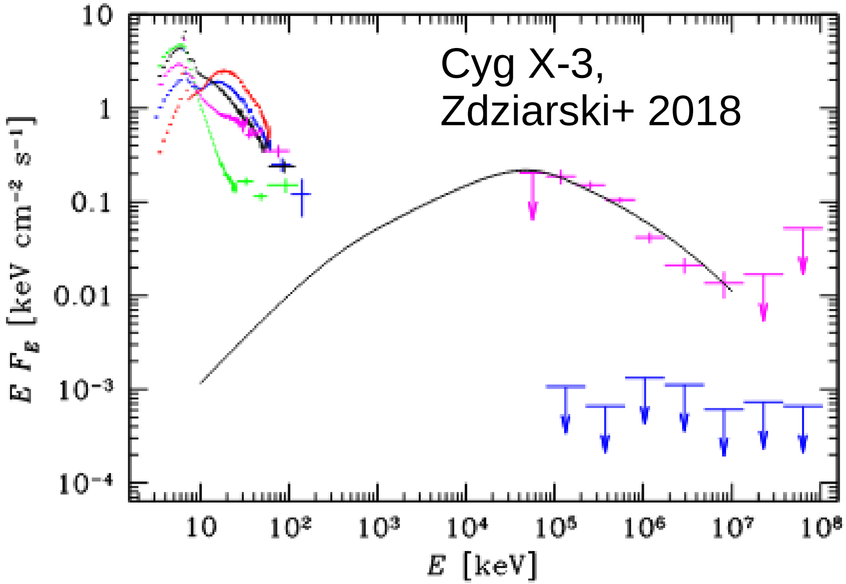
Chernyakova+ 2023

Orbital/ SO behaviour identifies distinct periods :

- periastron max: **0.1 - 0.3 GeV**; enhanced level of γ-ray emission close to periastron due to the increased magnetic and/or soft photon fields densities.
- beat-period maximum: dashed diagonal lines, clearly seen **above 1 GeV.** The drift of the maximum due to the precession of the system components? Periodic growth and decay of the Be star disk?
- “minima”: periods of low GeV emission **< 0.3 GeV**
- γ-ray emission from bow and tail of the shock?

Microquasars

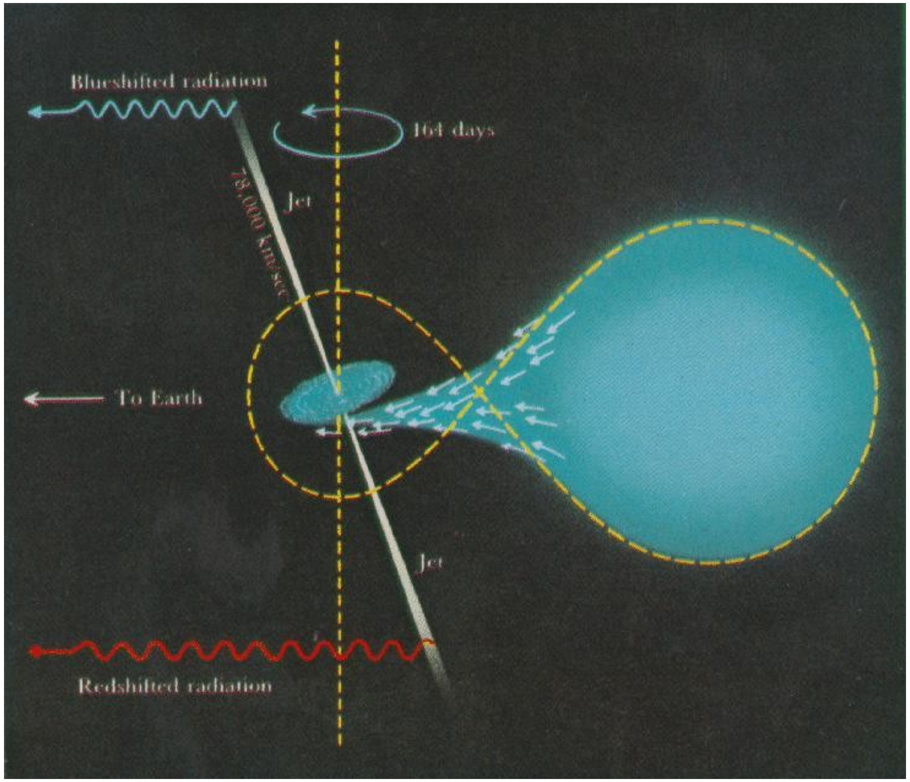




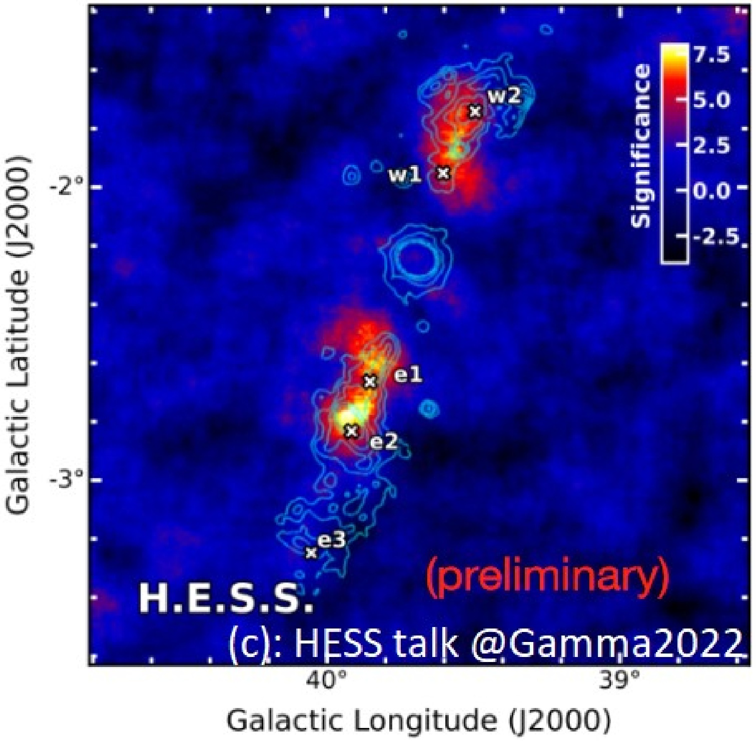
- Cyg X1: Archetypical blue supergiant + BH (20 $M_\odot$) binary, P = 5.6 d. Steady emission in the 40 MeV – 60 GeV in the **hard** and intermediate state. Detections below 0.1 GeV are well explained by the high-energy tails of the emission of the accretion flow, in all states.
- Cyg X3: Wolf-Rayet + low-mass BH (most likely), P = 4.8h. Significant LAT detections in **soft** (disc dominated) state, while only upper limits in the hard and intermediate states. The flaring-state spectrum is well modeled by Compton scattering of the blackbody photons by jet relativistic electrons.

Microquasars: SS 433

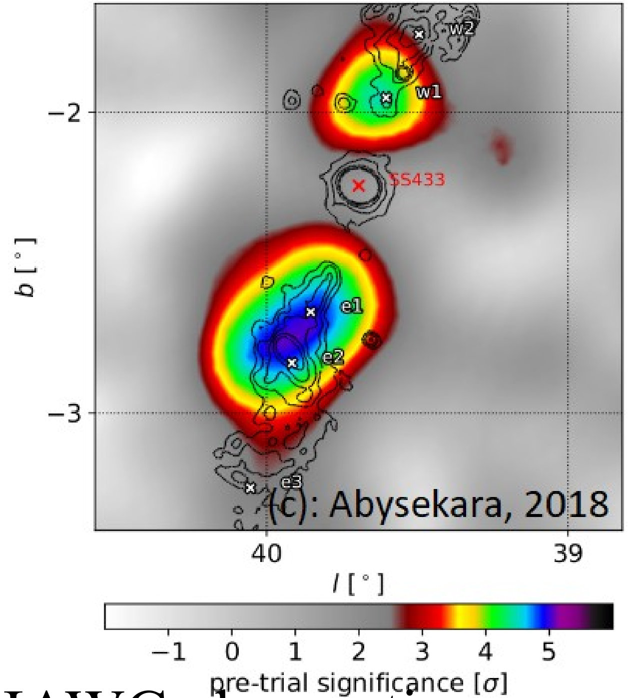
- High-mass eclipsing X-ray binary.
- Contains a supercritical (mass-accretion rate highly exceeds the Eddington's one), optically bright precessing accretion disk.
- Precessing relativistic jets (v/c ~ 0.26).
- The optical donor star is a supergiant that fills or overfills its Roche lobe.
- The nature of the compact object – most likely a black hole 10-20 M_{sun}.
- SS 433 features three kinds of variations: eclipses (~13.08223 d), precession (~162.278d), and nutation (~ 6.2876d).



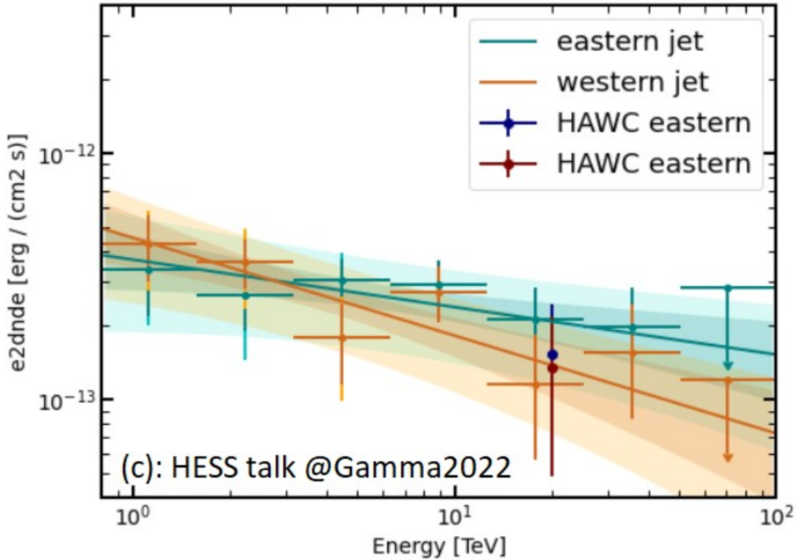
Microquasars: SS 433 (TeV)



(c): HESS talk @Gamma2022



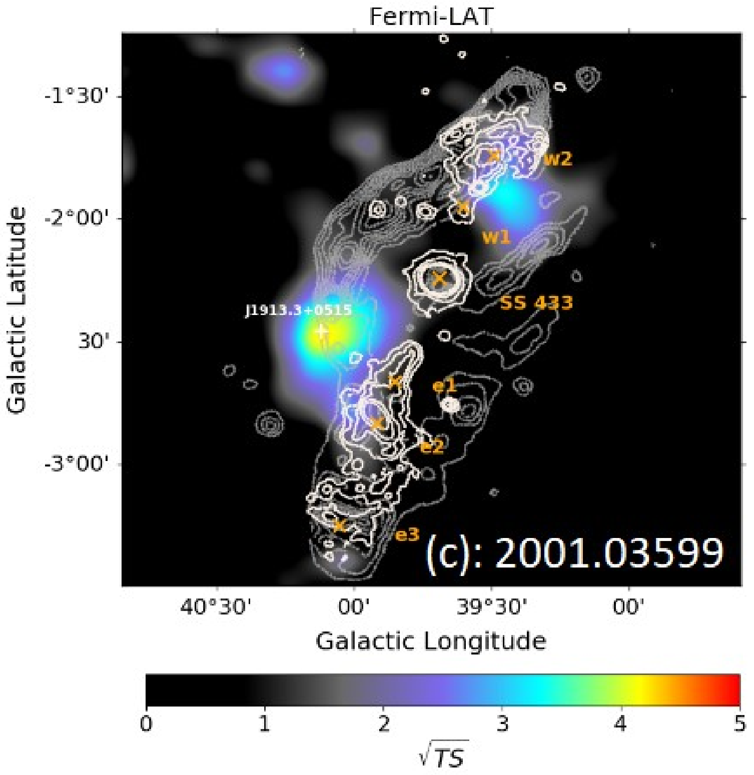
(c): Abysekara, 2018

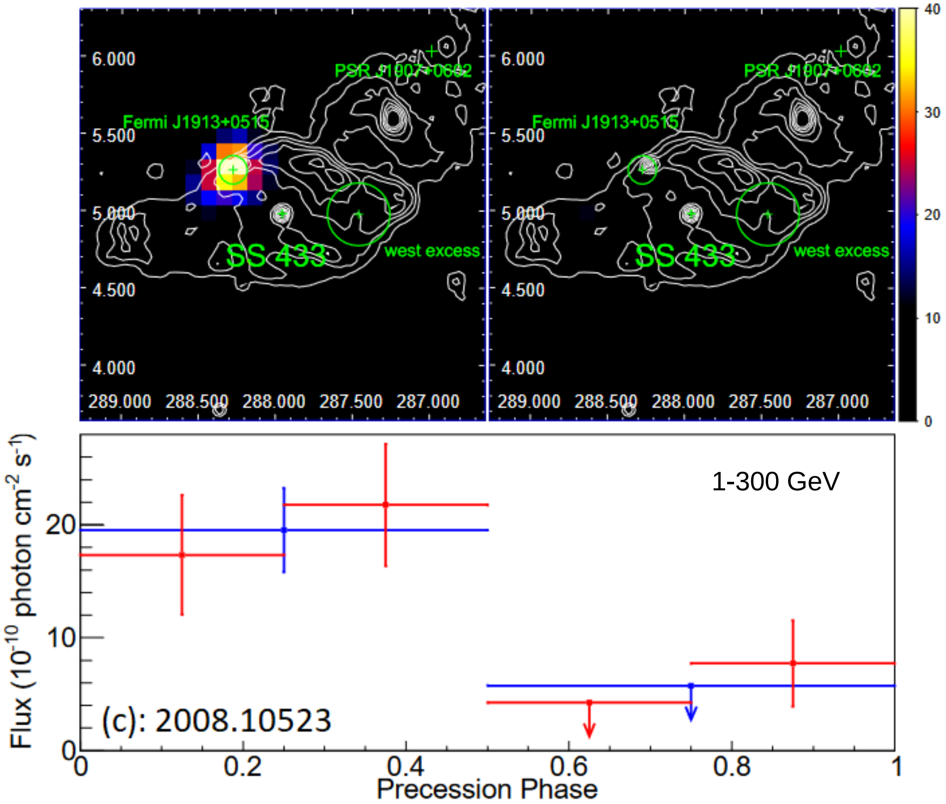


(c): HESS talk @Gamma2022

- 4 years of HAWC observations resolved emission from the e1 and w1 lobes of SS 433 with a 5.4 σ significance (Abysekara, 2018)
- Recent HESS observations: lobes detected and resolved with even higher significance.
- Power-law spectrum up to 100+ TeV

Microquasars: SS 433 (GeV)





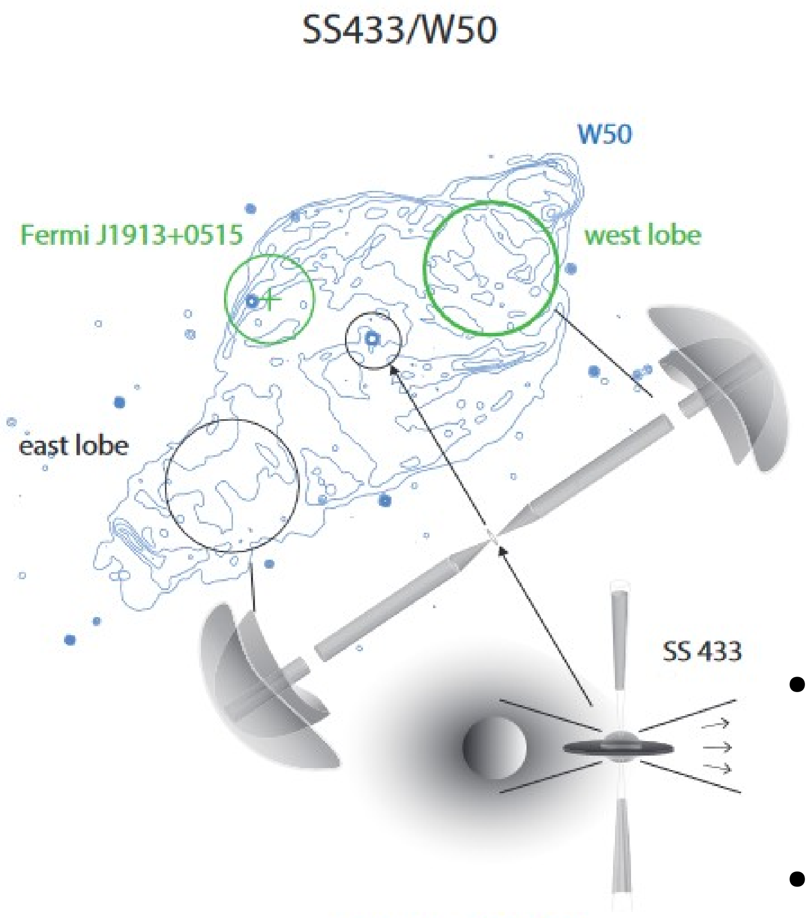
10+ years of Fermi/LAT data (Li et al ; Fang et al , 2020):

– GeV emission somewhat offset from TeV east/west regions?

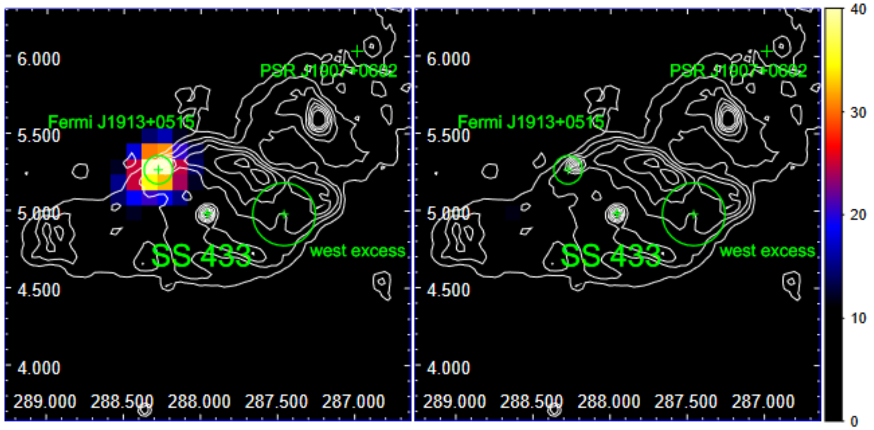
– Interaction regions detected with 3 – 5 sigma significances

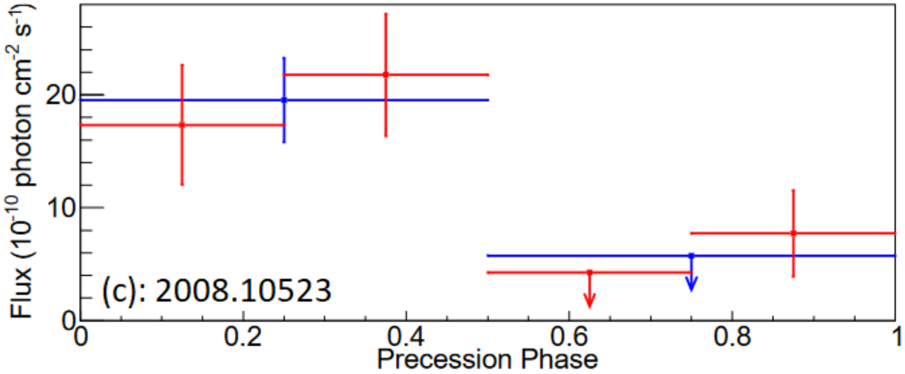
– GeV source J1913+0515 (east region?) seems to be modulated with precession period?

Microquasars: SS 433



Bordas 2020



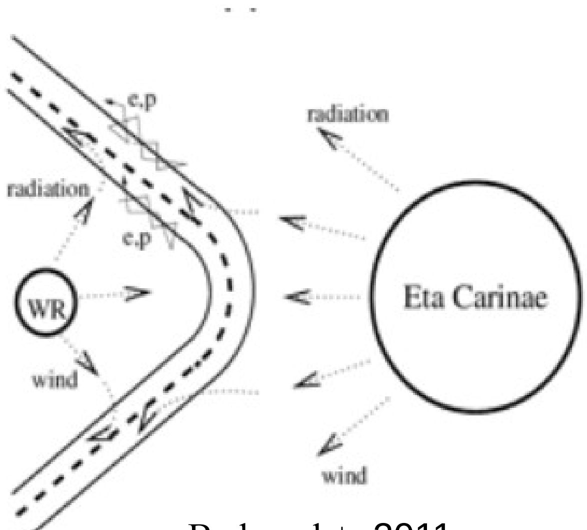


- GeV / TeV maxima offset – real or an artifact of the analysis of the extremely crowded region?

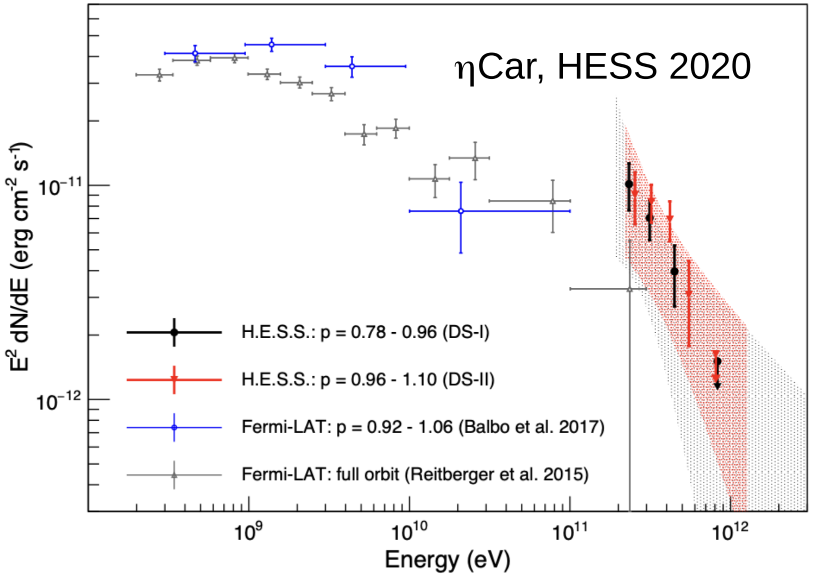
- If confirmed – J1913+0515 is located outside of jet precession cone and ~35 pc away from SS 433

- Hadronic origin of the emission – equatorial outflow? Highly-anisotropic diffusion mechanism?

Colliding wind binaries



Bednarek+ 2011

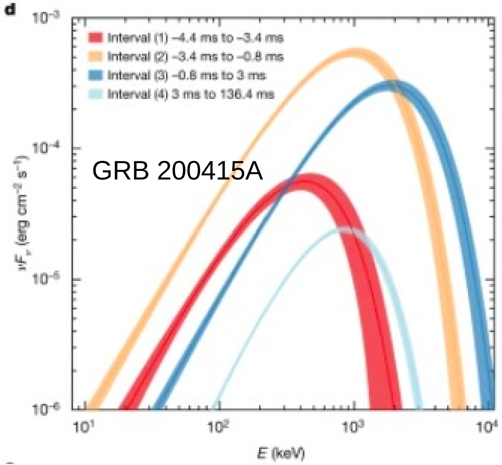


- ηCarinae is the most luminous massive binary system in our Galaxy, and the first binary with no compact object that has been detected at VHEs. It is composed of a luminous blue variable, and a WR companion on a highly eccentric (e~0.9) orbit with a ~5.5 years orbital period.
- Collision of supersonic winds form a region of hot shocked gas where charged particles are accelerated through diffusive-shock acceleration up to HEs.
- Fermi-LAT and HESS detected highly variable HE emission up to 10 TeV mostly due to hadronic emission heavily modified by γ–γ absorption. Evidence of particle acceleration in the system up to 200 TeV.

Magnetars

- Magnetars are isolated NS where magnetic field is the main energy source. Observed as pulsed X-ray sources, with spin periods of a few seconds and strong spin-down rates, and/or through the detection of short bursts and flares in the hard X-ray/soft γ--ray range. Magnetars are in possible connection with other transient sources, such as, e.g., GRBs and FRBs (e.g. Lyubarsky 14, CHIME/FRB Collaboration 20; Mereghetti+ 20).

Roberts+ 21

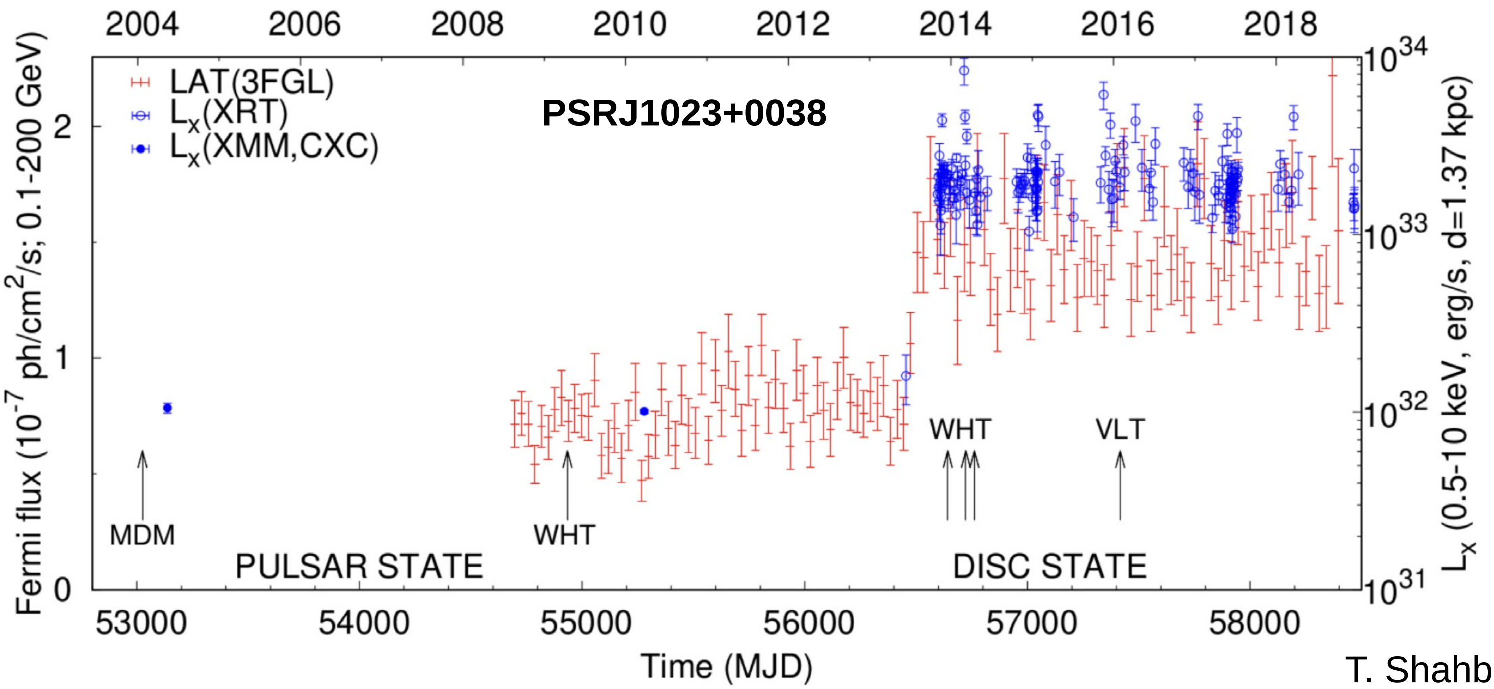


- In 2020, Fermi detected MeV and GeV gamma-ray emission from a giant flare event of a magnetar located in the NGC 253 galaxy (Roberts+ 21; Fermi-LAT 21).

- For the first time Fermi-LAT detected two photons with energies 1.3 GeV and 1.7 GeV, which are produced via Synchrotron emission considering the presence of a strong magnetic field generated in the shocks.

- It is proposed that these GeV photons are produced in the dissipation associated with the collision of the giant flare outflow and the external shell generated from swept-up material. IC scattering can also occur in these events, and giant magnetar flares have been proposed as potential GeV-TeV emitters (Lyubarsky 2014).

Transitional Millisecond Pulsars

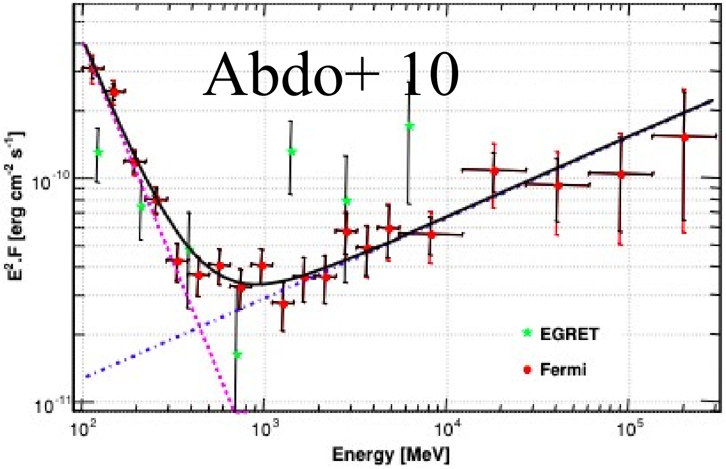


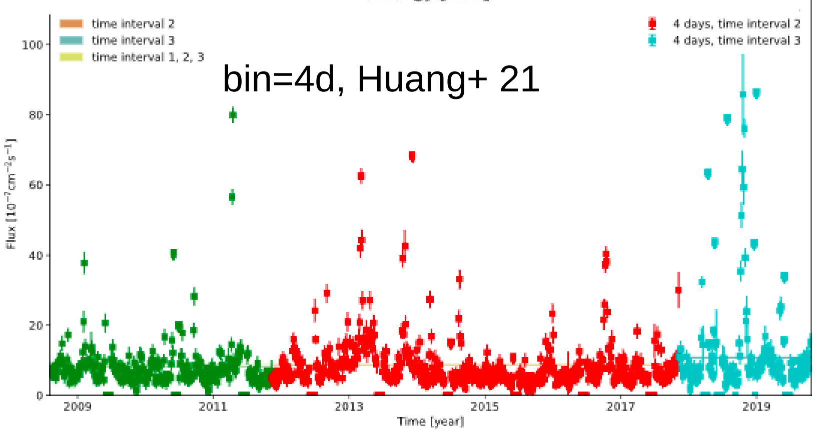
T. Shahbaz+, 2019

- tMSPs switch between a radio millisecond pulsar state, and a sub-luminous LMXB state, where an accretion disk is formed. Support for the recycling scenario.
- Sudden transitions between the two states occur on a timescale of a few days to weeks, and are accompanied by drastic changes of the spectrum.
- The transition from the RMSP to LMXB state is accompanied by brightening of optical, UV, X-ray and γ-ray emission with the disappearance of radio pulsations.
- The origin of these transitions is still debated. Veledina+ (2019) propose that γ-rays are from the pulsar wind collision with the accretion disk, outside the LC.
- No detection at TeV yet.

γ-ray flares from Crab

- HE emission from the Crab Nebula consists of two spectral components, synchrotron and IC ones.
- While IC component is stable, the fluxes of the low-energy component show significant variations.
- First gamma-ray flares from Crab have been reported by Fermi (Abdo +) and Agile (Tavani +) in 2011. Numerous flares after that (Huang+ 21).
- Models to explain the γ-ray flares include Doppler boosting of the emission site (e.g. Komissarov+ 11) and magnetic reconnection inducing a linear electric accelerator (e.g. Lyutikov+ 17).


Abdo+ 10


bin=4d, Huang+ 21

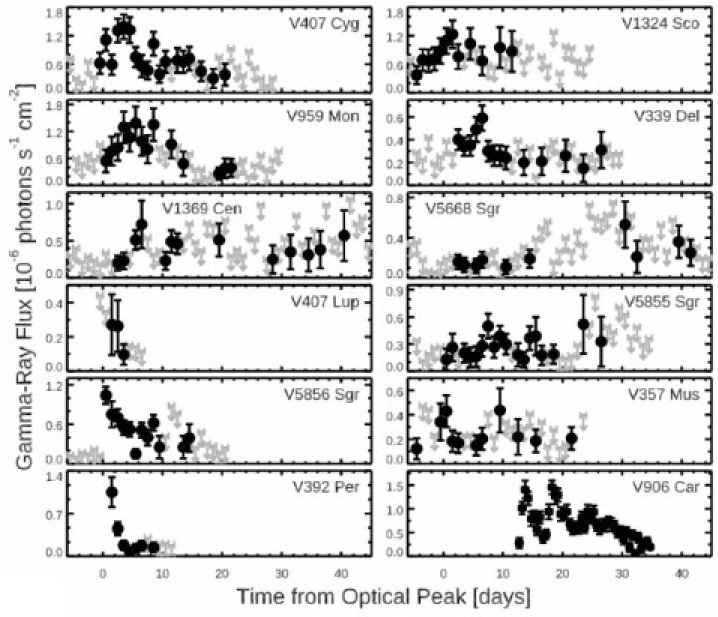
γ-rays from Novae

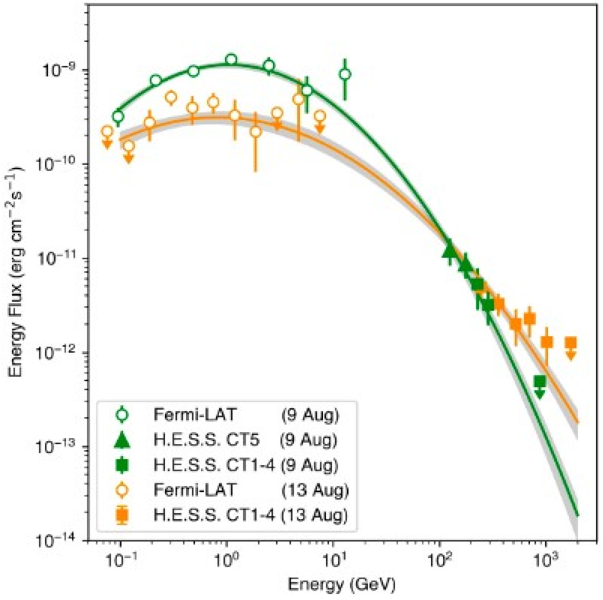
- Following the initial Fermi-LAT detection of V407 Cygni (Abdo+ 2010) 17 novae were detected in γ-rays by 2021 (Chomiuk+ 21).

- γ-ray emission due to particle acceleration at shocks (interaction with dense wind or of fast ejecta with slower material).

- In 2021 HESS and Magic detected TeV emission from RS Ophiuchi (HESS 22, MAGIC 22). Modeling of the γ-ray spectrum strongly favors the explanation of the emission via the acceleration of protons in a nova shock.

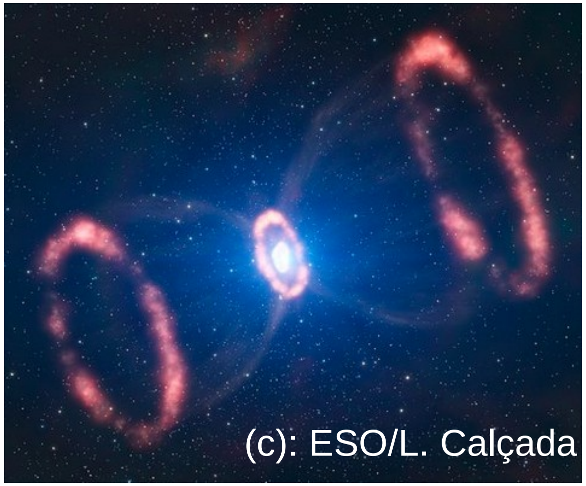
Chomiuk et al, Ann. Rev. A&A 59, 112420 (2021)



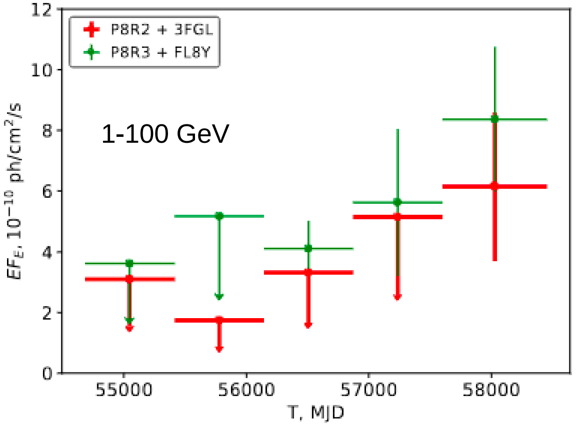


SN1987a

- SN 1987A is core collapse supernova located in the LMC. Laboratory for fundamental studies from diffusive shock particle acceleration and modeling of the expansion of supernova remnants (Ball& Kirk 1992, Potter+ 14) to sterile neutrinos (Arguelles+16) and axions (Payez+ 15).


(c): ESO/L. Calçada

- Hydrodynamic models suggests efficient cosmic ray proton acceleration at the shock of SN 1987A (Berezhko+ 2011, 2015). Interaction of the accelerated protons with the surrounding medium lead to significant level of GeV-TeV γ-ray emission in π^0-decay processes. Changes of the medium’s density by a factor of a few should lead to corresponding changes of the GeV-TeV flux of the source.



Malyshev+ 2019

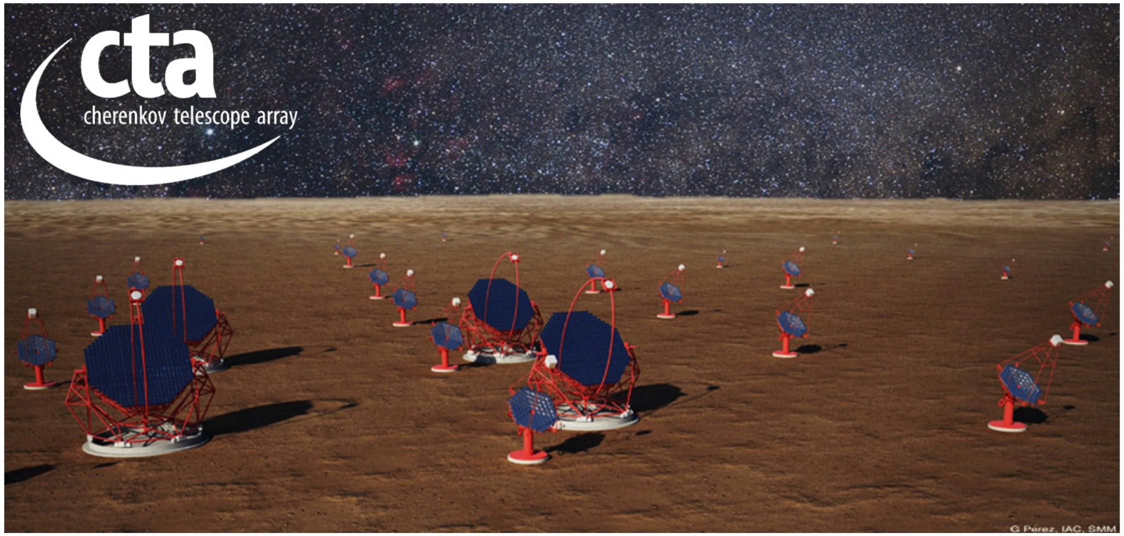
- Evidence of the enhancement of GeV emission at the ~ 5σ statistical significance level during 2016 – 2018 (Malyshev+ 2019).
- Non-detection by HESS (HESS, 2015).

Future missions

What do we need to proceed?

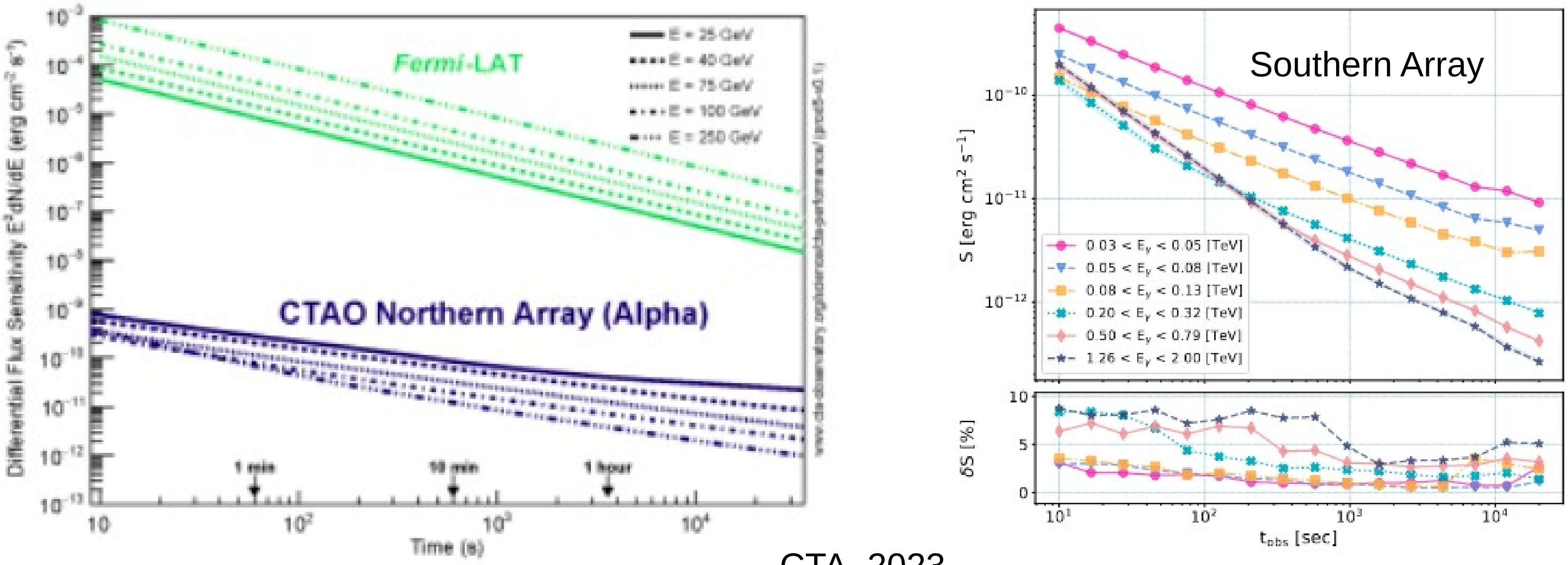
- Better sensitivity
  - to study variability on short time scales in binaries and study the multi-wavelength correlation.
  - to detect TeV emission from the central source in microquasars and learn more on the details of particle acceleration by solar mass black holes.
  - to detect flaring emission from PWNs other than Crab to better understand their origin.

Future missions



- With 64 telescopes located in the northern and southern hemispheres, the CTAO will be the first open ground-based gamma-ray (20 GeV – 300 TeV) observatory and the world's largest and most sensitive instrument to study high-energy phenomena in the Universe.

Future missions



CTA, 2023

The “Alpha Configuration” for the southern and northern arrays of the CTA Observatory, located at the Paranal Observatory (Chile) and Roque de los Muchachos Observatory (Spain) respectively, consists of:

- CTAO Northern Array: 4 Large-Sized Telescopes (23m), and 9 Medium-Sized Telescopes (12m), area covered by the array of telescopes: ~0.25 km^2
- CTAO Southern Array: 14 Medium-Sized Telescopes and 37 Small-Sized Telescopes (4.3 m), area covered by the array of telescopes: ~3 km^2

Prospects with CTA

The unique sensitivity at short timescales will allow to test the existing theoretical models and the detection and discovery of a variety of sources of different nature (Chernyakova + 2019; CTA 2023):

- Proper measurement and broad band cross-correlation of the evolution of spectral parameters (flux, slope, cut-off energy) on the characteristic time scales down to 30 minutes in gamma-ray and colliding wind binaries.
- With the CTA it will be possible to probe the spectrum and variability of ηCar above 30 GeV throughout the orbit with a resolution of a few days. This will allow to establish the nature of the high-energy component and constrain the geometry of the shock at the core of the system. For other CWB candidates, of which the CTA sensitivity will be high enough to probe the presence of TeV emission.
- VHE emission from microquasars. Simulations show that CTA will detect both transient and persistent emission from Cyg X-1 and Cyg X-3, and likely the central source in SS 433.

Prospects with CTA

- One can also expect CTA to detect emission from magnetars during a giant flare and even intermediate flares associated with an FRB. Other possible transient events are flares from SFXTs, runaway stars and young stellar objects.
- Flaring emission from the Crab Nebula will be detected by CTA at E<200 GeV in less than 1 h. In the TeV regime, integration times of <10 h will be needed. CTA will also likely detect flares from other PWNe.
- In the case of tMSPs CTA will need long integration times (>50 h) to detect emission when in the LMXB state for close-by sources. These systems might be detected during a transition from RSMP to LMXB if an additional VHE component is present, which will provide crucial information on particle interaction.
- CTA will be able to detect close-by novae of both classical and symbiotic nature. For example, CTA will detect RS Oph with high significance in only 30 min, allowing for a detailed modeling of its SED from 20 GeV.

Conclusions

- The VHE galactic sky is full of sources able to accelerate particles to very high energies.
- Variable and transient VHE emission is observed from various types of sources with interesting and diverse individual properties :
  - Gamma-ray and colliding wind binaries
  - Magnetars
  - Transient pulsars
  - Novae
  - Pulsar Wind Nebula
- The unique sensitivity of CTA at short timescales would alow it to resolve VHE emission from various sources, test various theoretical models, study details of wind collision and particle acceleration.