8th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy (γ-2024)

Milan, 5 September 2024

Gamma rays from binaries

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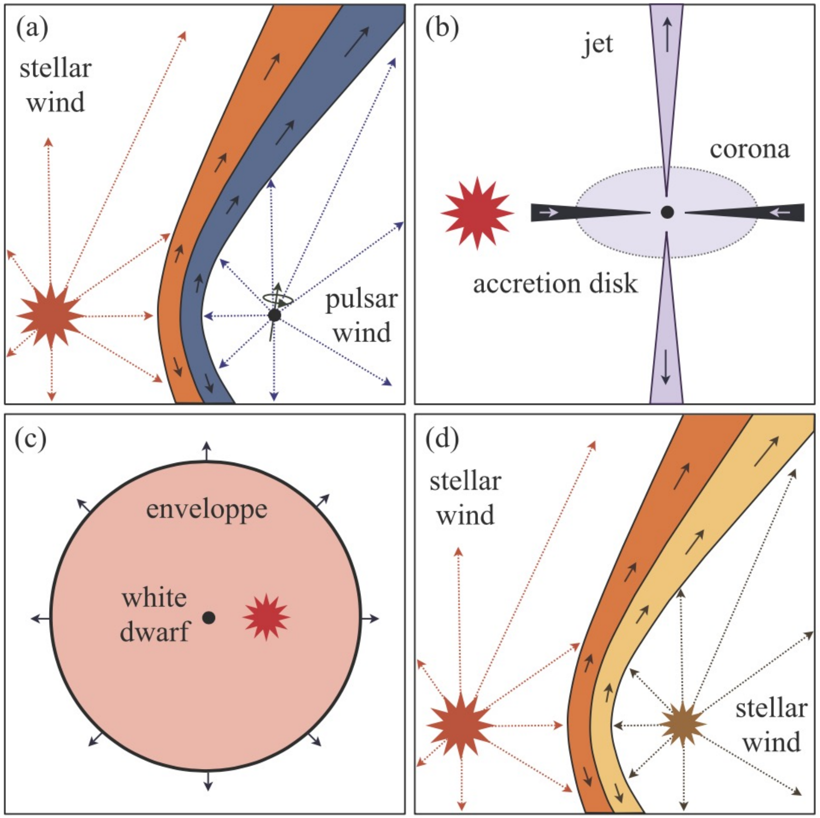
OUTLINE

1. Introduction
2. X-ray binaries
3. Gamma-ray binaries
4. Colliding-wind binaries
5. Novae
6. Conclusions

Introduction



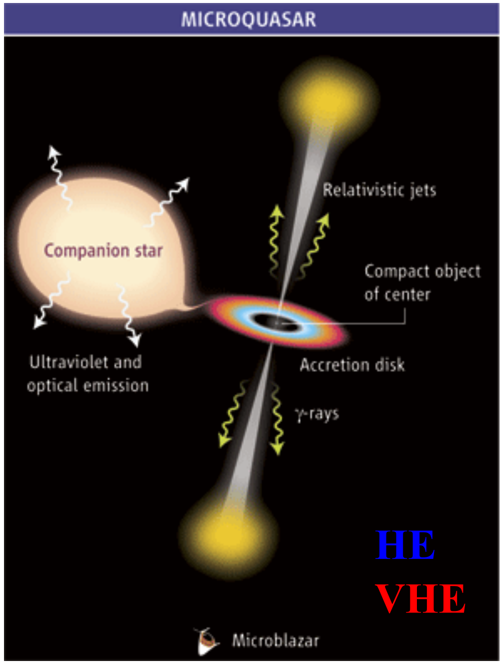
Why HE/VHE/UHE binary systems?

- **Particle acceleration**
  - Around a compact object in the system (relativistic wind, jet, etc.)
  - In a shock of winds within the binary system (relativistic or stellar)
- **Photon field** from companion to produce (anisotropic) **Inverse Compton**
- **Matter field** from stellar wind and/or decretion disk to have **pp interactions**
- **Absorption** due to photon field of the companion

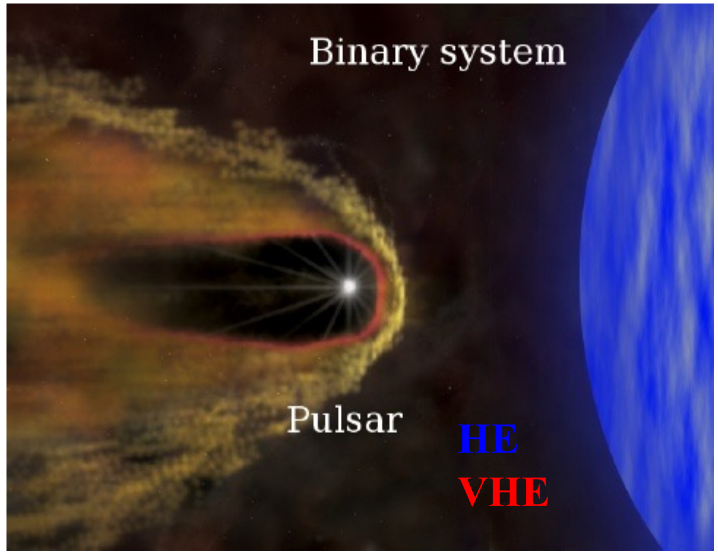
(e.g., Dubus 2015, Bordas 2023 and references therein).

Introduction

Binary systems at HE / VHE.



Accreting X-ray binaries



Young non-accreting pulsars
Gamma-ray binaries

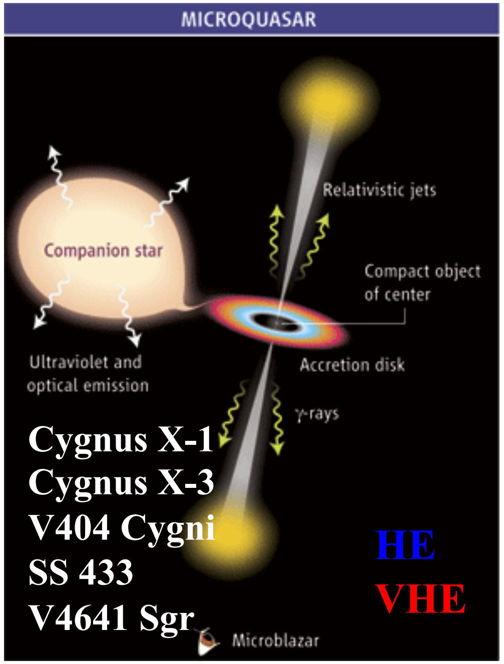
Colliding-wind binaries

Novae
Accreting WDs

Black Widows
Recycled and
transitional ms pulsars

Introduction

Binary systems at HE / VHE.



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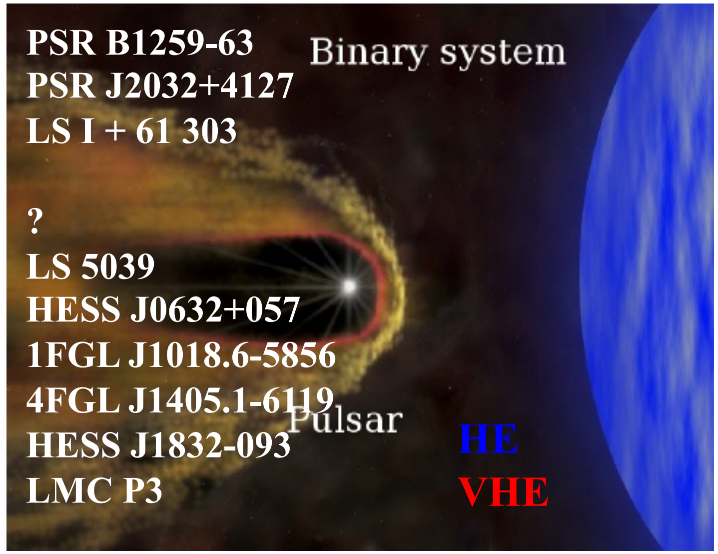

Young non-accreting pulsars
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X-ray binaries

Many ways to produce gamma rays… when the jet is active! X-ray states, transients!

Leptonic models: Inverse Compton

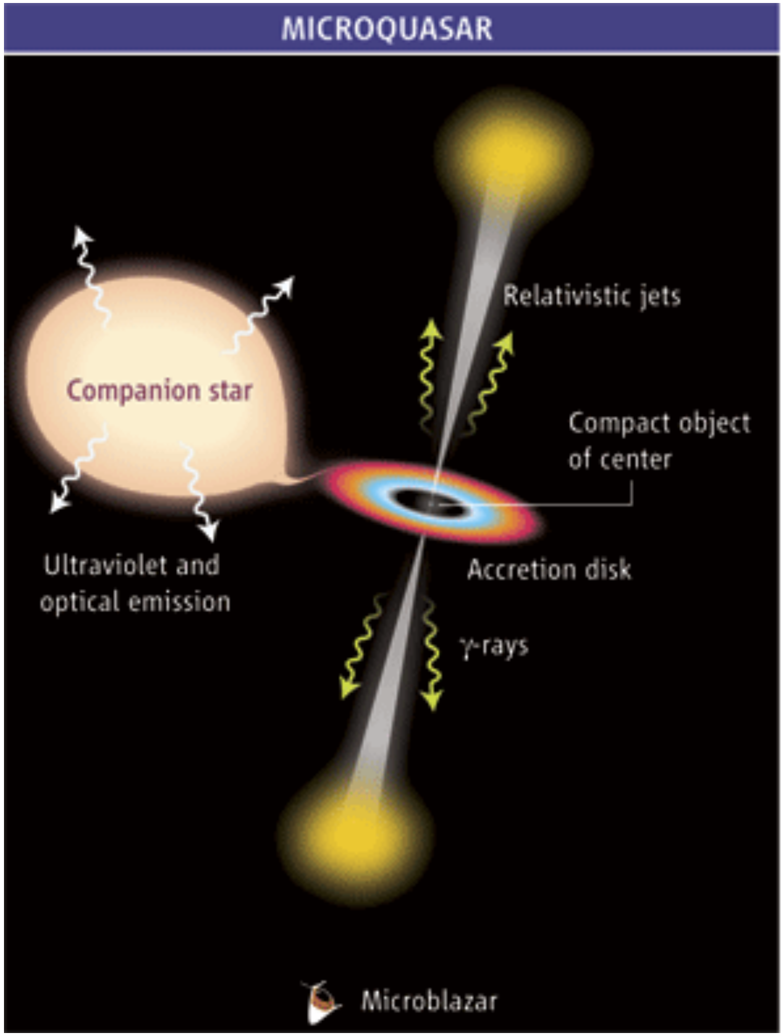
- **Synchrotron Self Compton** relativistic e^- in the jets with jet photons.
- **External Compton**: relativistic e^- in the jets with photon field of companion star

(e.g., Atoyan & Aharonian 1999, Paredes et al. 2000, Georganopoulos et al. 2002)

Hadronic models: pp interactions and neutral pion decay

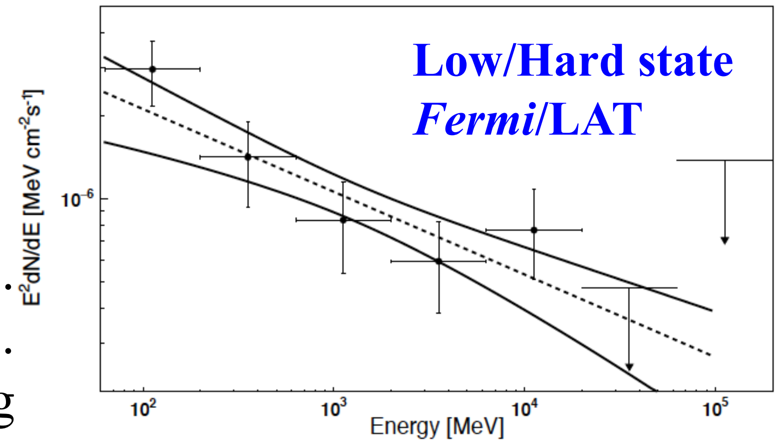
- **Jet protons with companion stellar wind**
- **Jet protons with ISM**

(e.g. Romero et al. 2003, Dermer & Böttcher 2006, Bosch-Ramon et al. 2006)



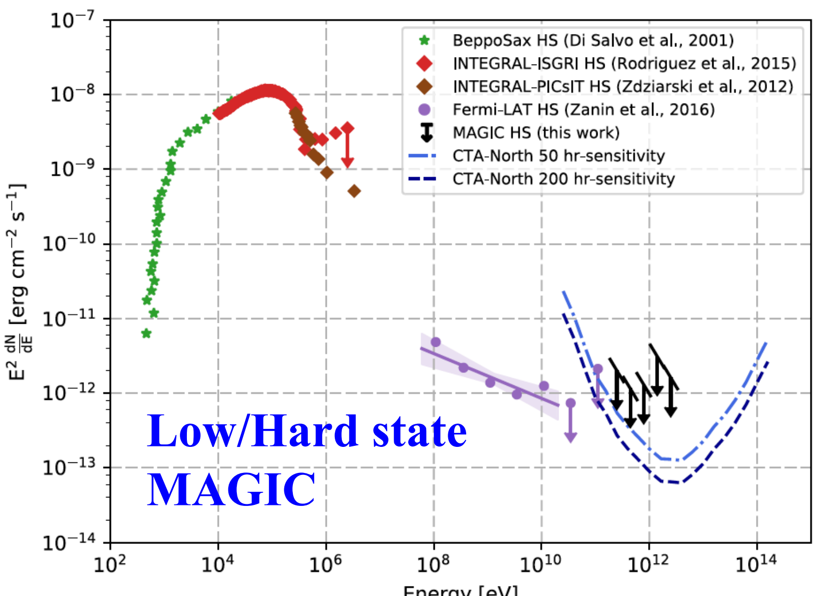
Mirabel (2006)

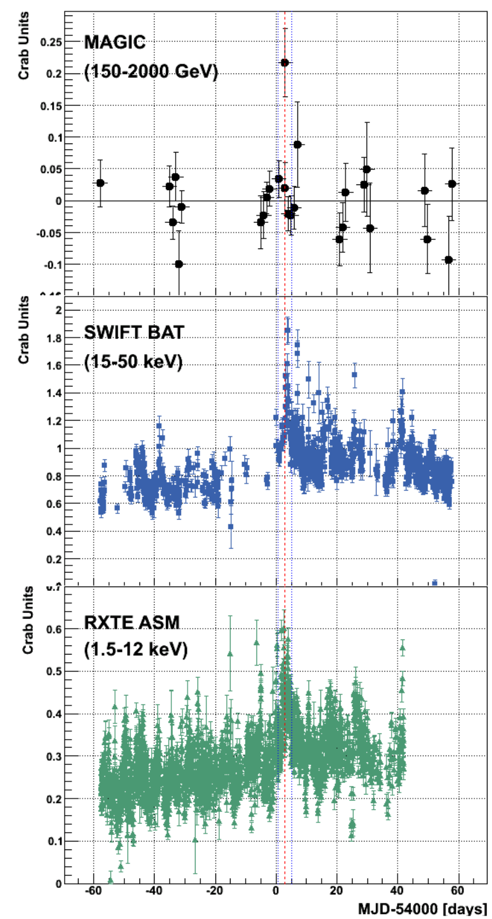
X-ray binaries

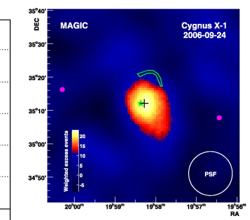


Cygnus X-1. O9.7Iab with 21 $M_\odot$ BH at 2.2 kpc.

- ➢ **GeV detection** during low/hard (jet) state. Orbital variability → anisotropic IC scattering **(Zanin et al. 2016, Zdziarski et al. 2017)**.
- ➢ TeV ULs when accumulating 40 or ~100 h **(Albert et al. 2007, Ahnen et al. 2017)**.
- ➢ **TeV excess** at onset of **hard X-ray peak** (4σ post-trial) **(Albert et al. 2007)**.

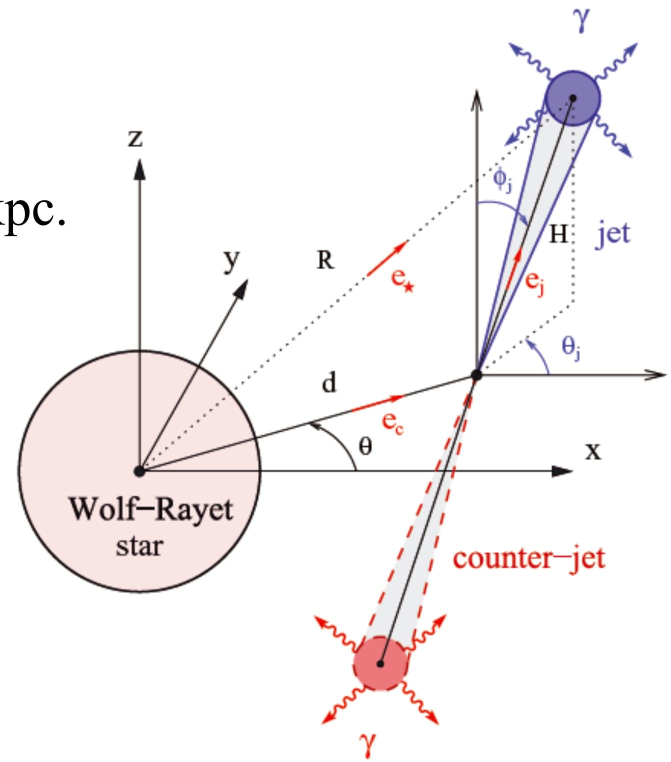




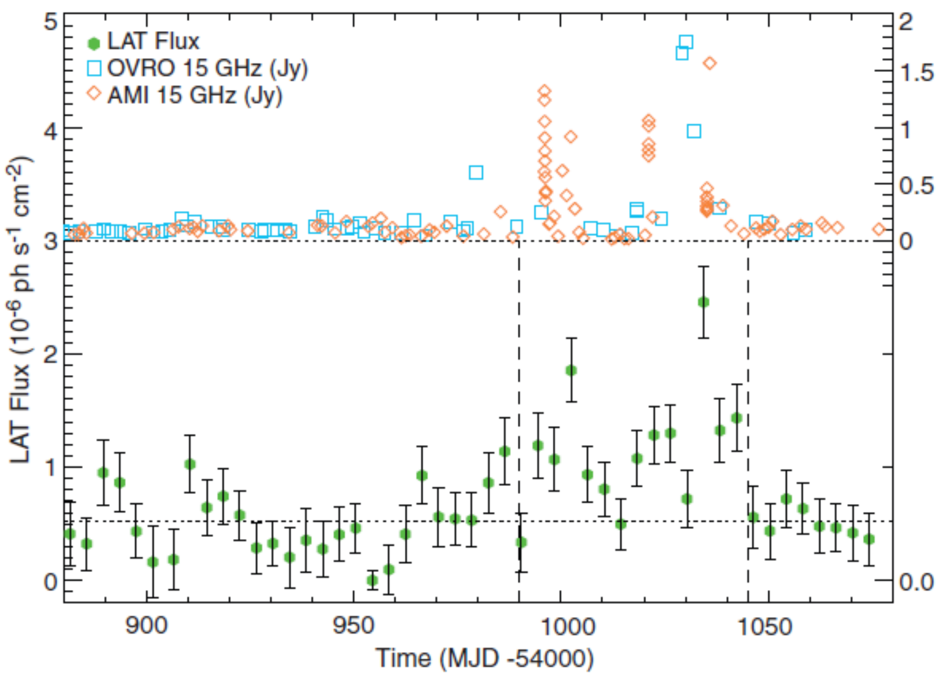


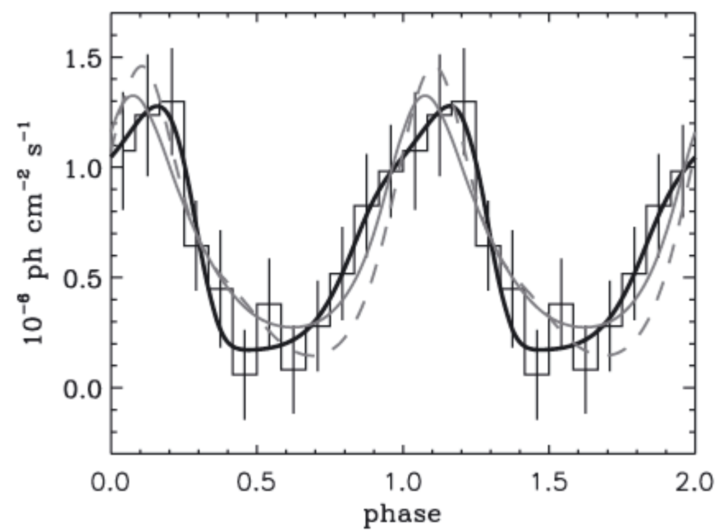
X-ray binaries

Cygnus X-3. WR of ~12 $M_\odot$ with ~7 $M_\odot$ BH at 9 kpc.



- **GeV detection** during radio flaring periods
  Orbital variability → anisotropic IC
  (Tavani et al. 2009, Abdo et al. 2009).
- Jet *i* and orbital motion → GeV lightcurve
  (Dubus et al. 2010, Bednarek 2010).





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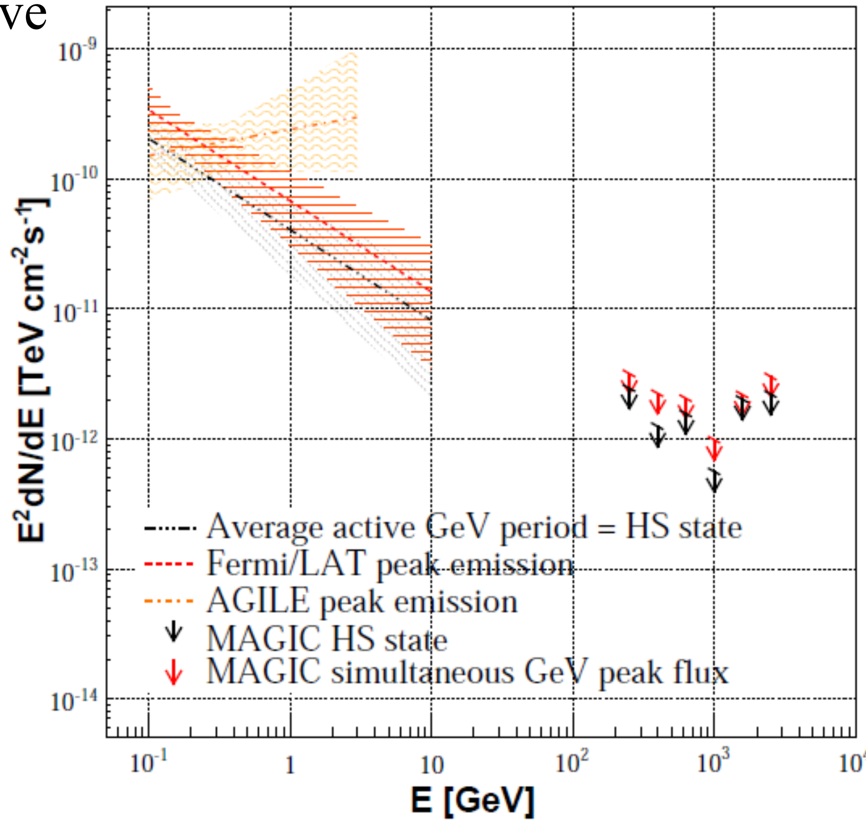
- ➢ **ULs at TeV** energies from ~60 h of
  MAGIC obs. **(Aleksic et al. 2010)**.
  - Not very constraining.
  - Cutoff ?
  - γγ absorption very relevant!

  See also VERITAS ULs
  (Archambault et al. 2013).



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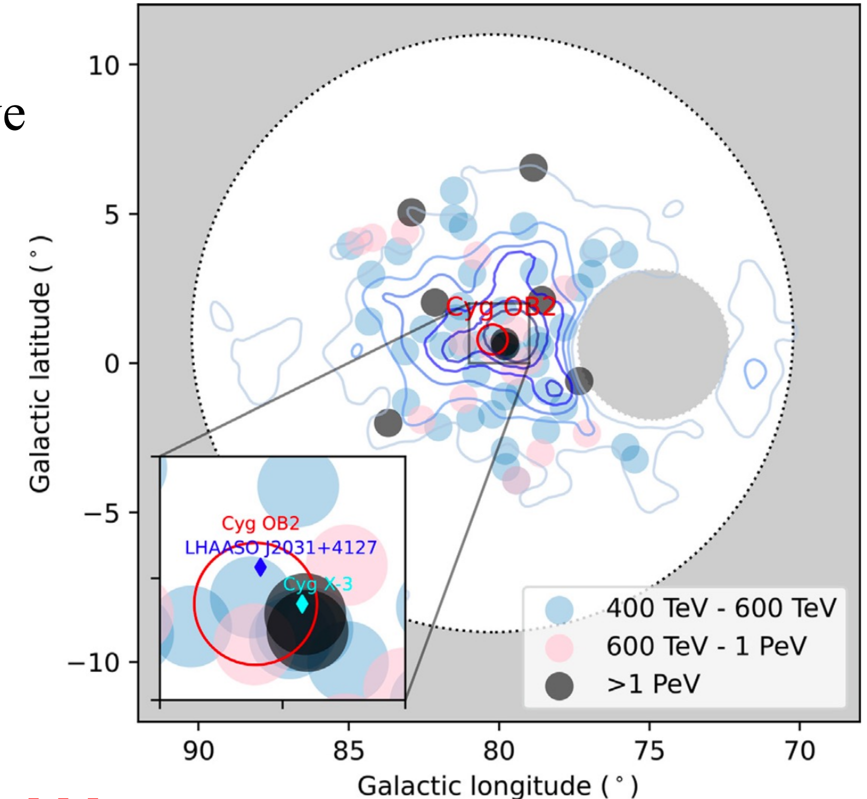
- SHALON results at 0.8-100 TeV?
  (Sinitsyna & Sinitsyna 2022).
- **UHE: Cyg X-3 in the core of Cygnus bubble**
  (LHAASO Collaboration 2024).



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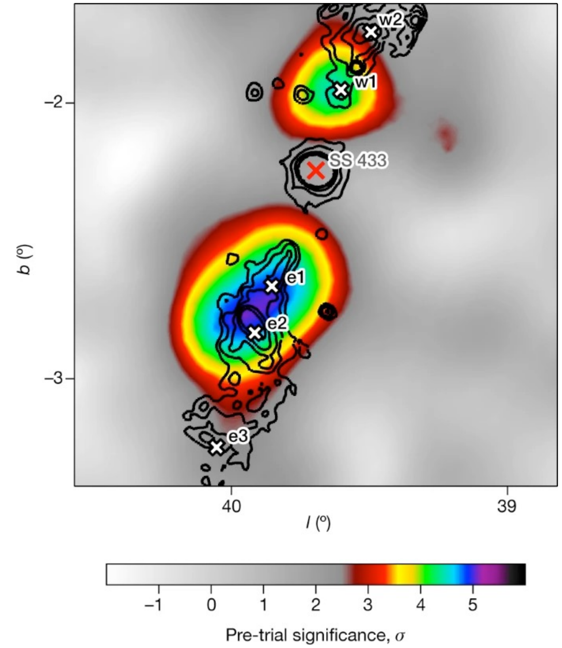
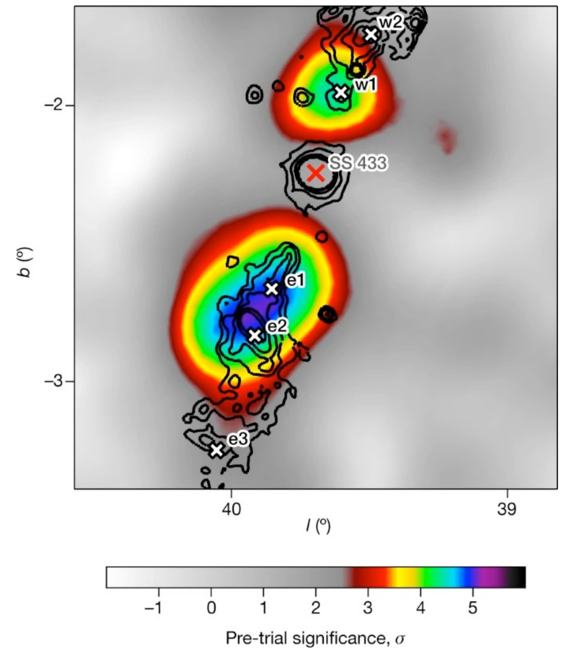


SS 433. A-type supergiant orbited by ~BH at 5.5 kpc. Super-Eddington accretion. Barion-loaded 0.26*c* jet. Inside the W50 nebula, being distorted by jets.

- **multi-TeV detection** by HAWC, compatible with leptonic scenario with e^- energies up to ~>100 TeV and B=16 μG **(Abeysekara et al. 2018)**.

X-ray binaries



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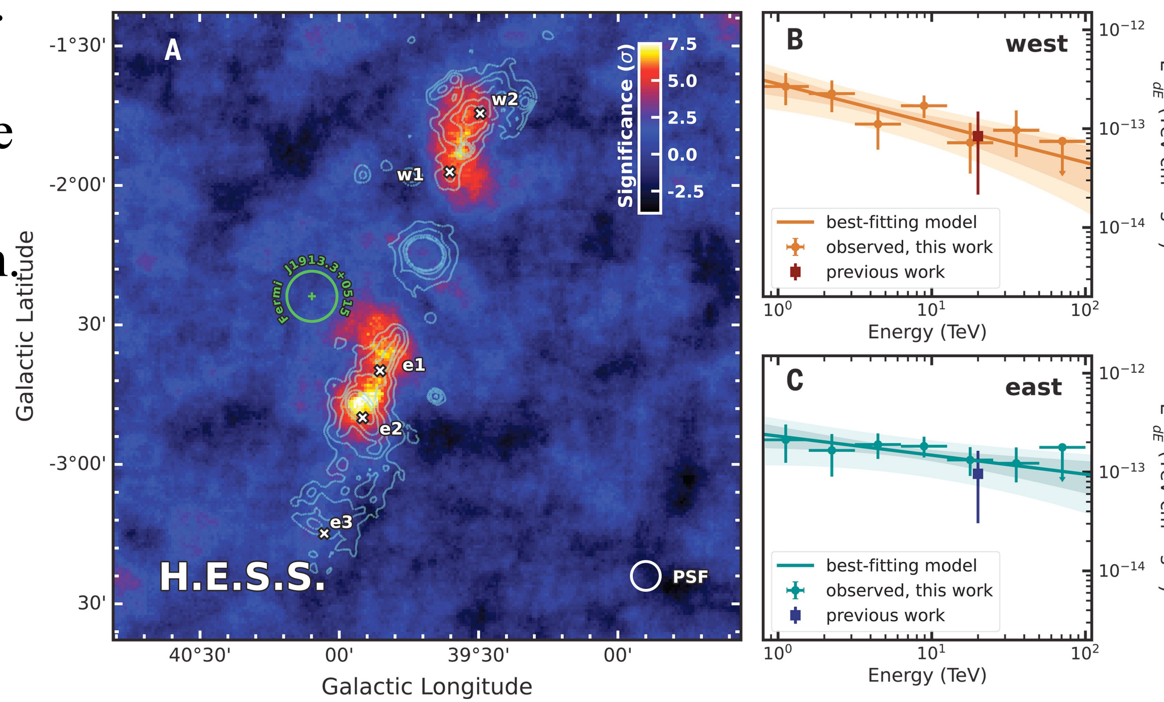
- **multi-TeV detection** by HAWC, compatible with leptonic scenario with e^- energies up to ~>100 TeV and B=16 μG **(Abeysekara et al. 2018)**.
- **TeV detection** by H.E.S.S.
  Energy range: 1-50 TeV.
  At ~30 pc from the source on both E and W.
  Similar shape & spectrum.
  Spatially consistent with the extended non-thermal X-ray jets.
  (H.E.S.S. Collaboration et al. 2024).

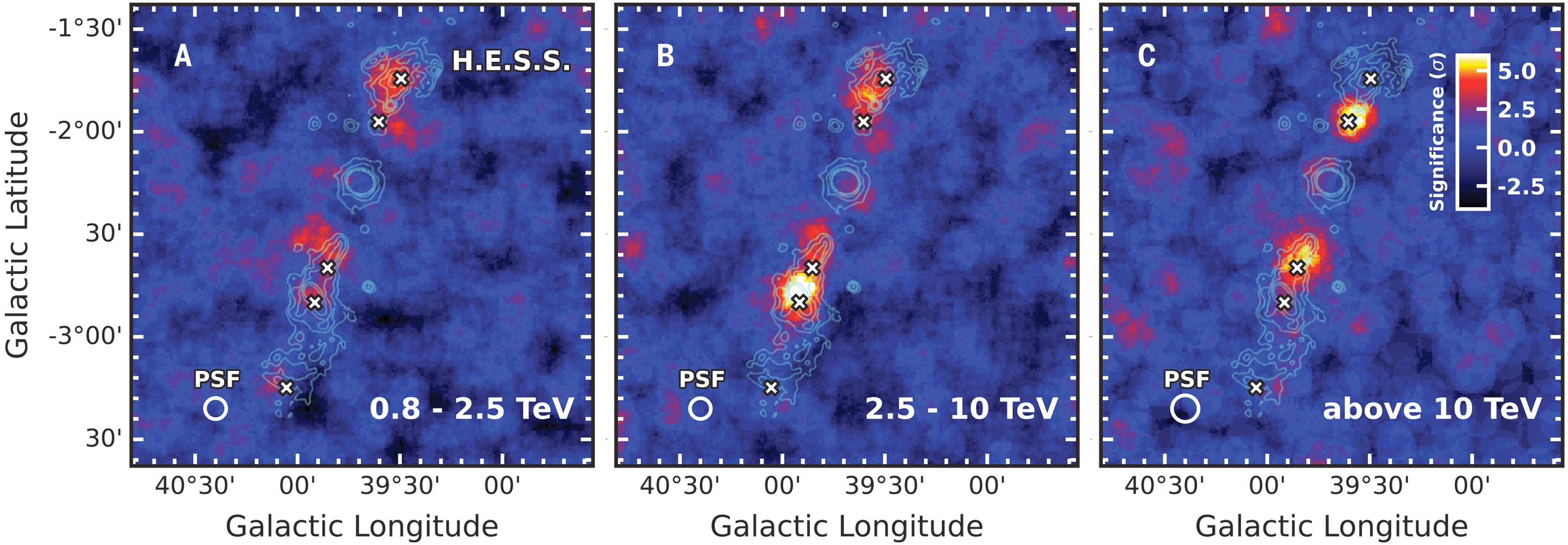


X-ray binaries

SS 433. A-type supergiant orbited by ~BH at 5.5 kpc.

- **Energy-dependent morphology** points to **leptonic origin** for TeV emission (advection and energy-dependent particle energy loss timescale).
- Gamma-ray emission: IC of synch. photons by relativistic e^- up to 200 TeV.
- Shocks where flow velocity decreases to 0.08*c*

  (H.E.S.S. Collaboration et al. 2024).

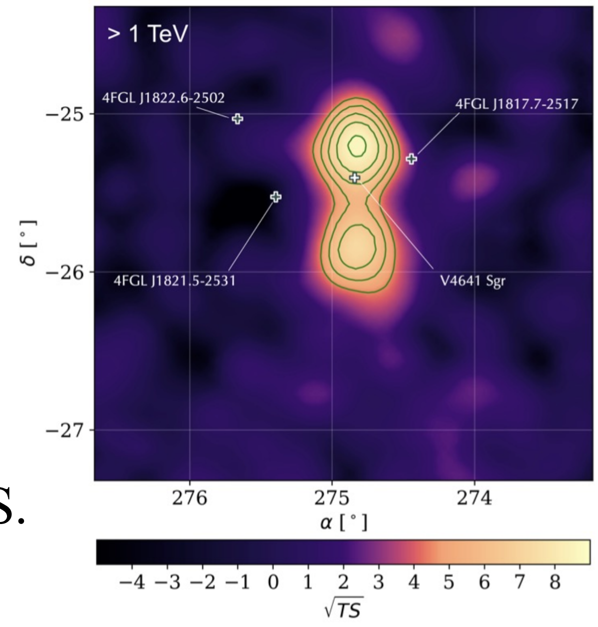


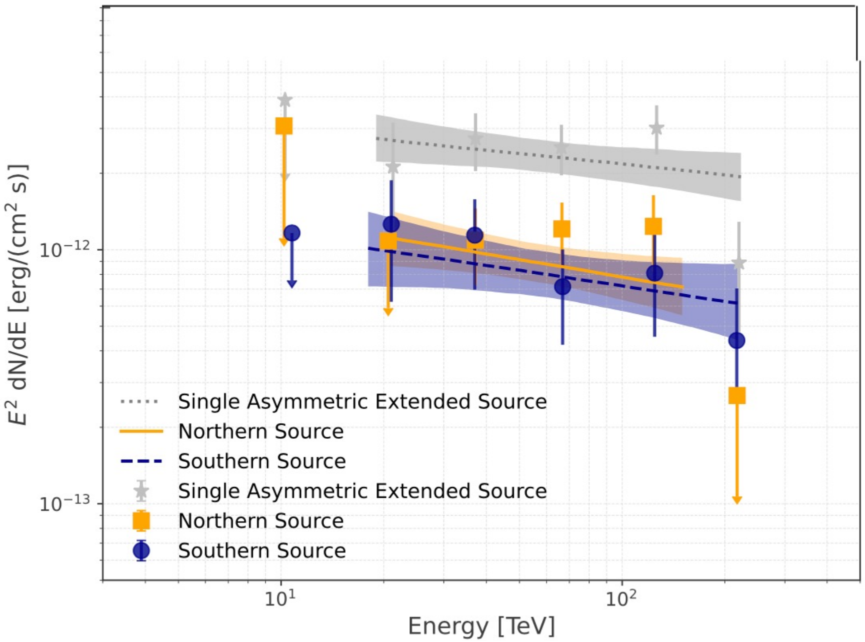
X-ray binaries

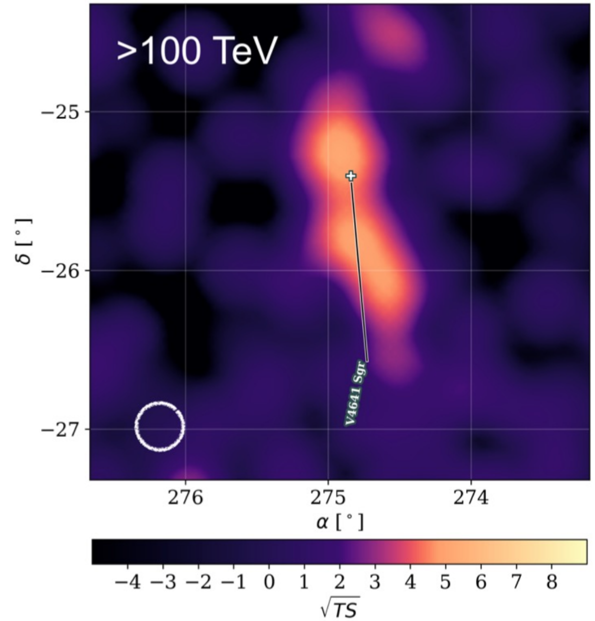
V4641 Sgr. B star of ~3 $M_\odot$ with ~6 $M_\odot$ BH at 6 kpc. Super-Eddington accretion. Superluminal 9.5*c* jets.

- **multi-TeV detection** significant above 100 TeV

  One or two sources? Spectrum up to >220 TeV. Projected in the plane of sky: 30 pc N, 55 pc S. What is their real distance? Similar to SS 433? **(HAWC Collaboration 2024, talk by Casanova)**.







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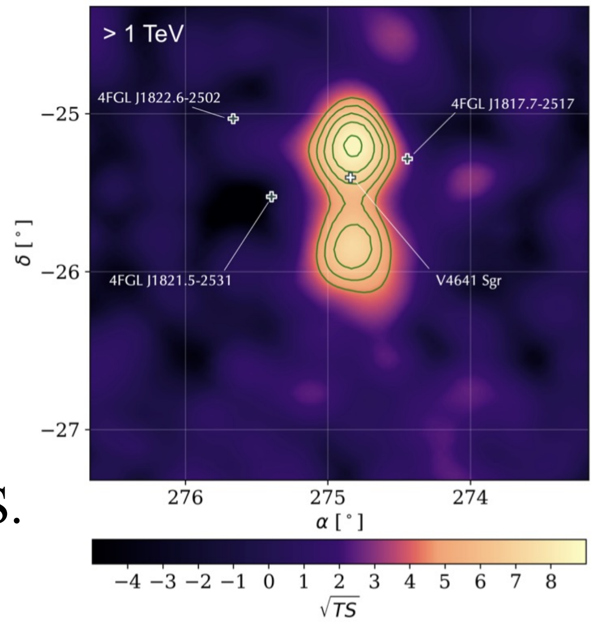
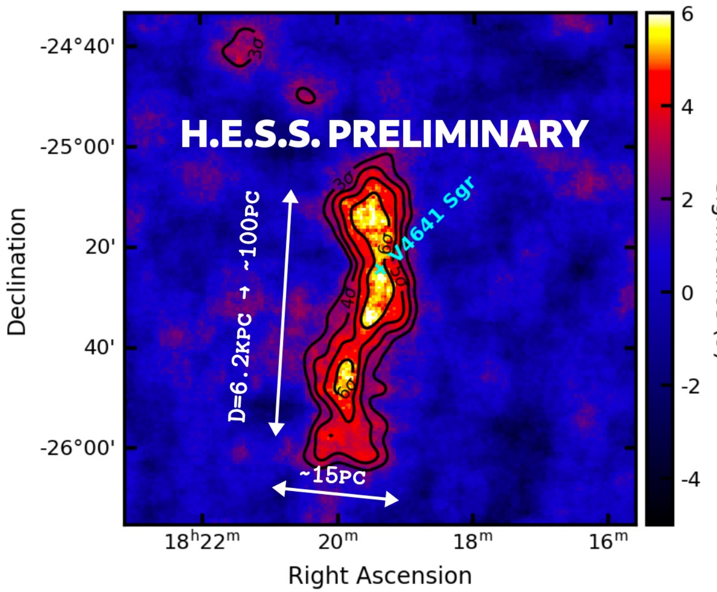
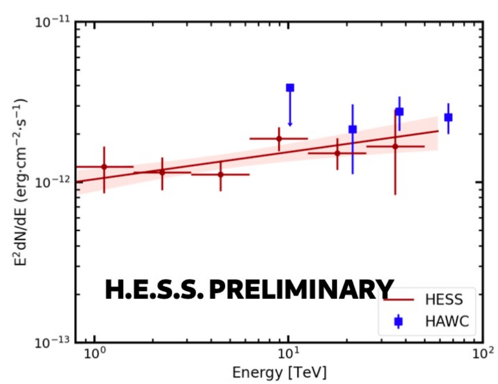
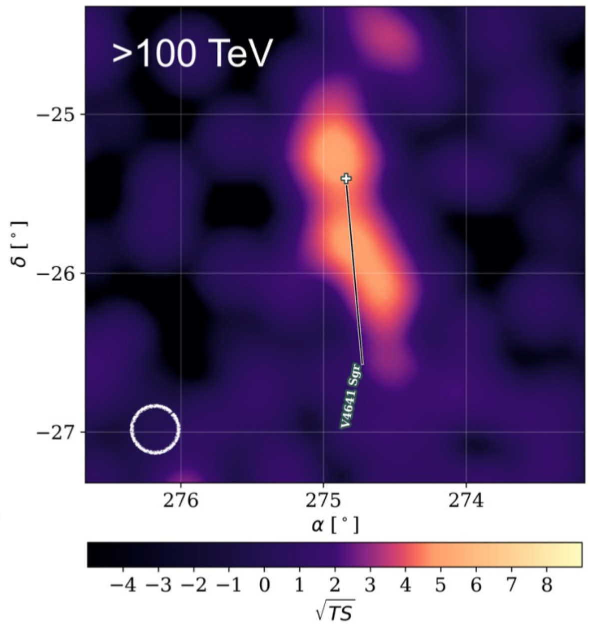
  (HAWC Collaboration 2024, talk by Casanova).
- **TeV detection (talk by Olivera-Nieto)**.









X-ray binaries

Searches for TeV emission from other X-ray binaries with jets have been conducted (non-exhaustive list):

- **Scorpius X-1 (Aleksic et al. 2011)**.
- **GRS 1915+105 (Acero et al. 2009, Saito et al. 2009, Abdalla et al. 2018)**.
- **V404 Cyg (Ahnen et al. 2017)**.
- **Cir X-1 (Abdalla et al. 2018)**.
- **MAXI J1820+070 (Abe et al. 2018)**.
- …

Gamma-ray binaries

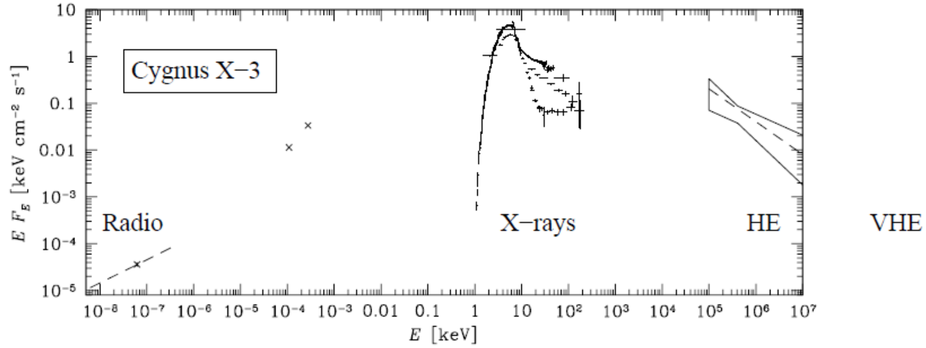
Spectral Energy Distribution (SED) maximum:

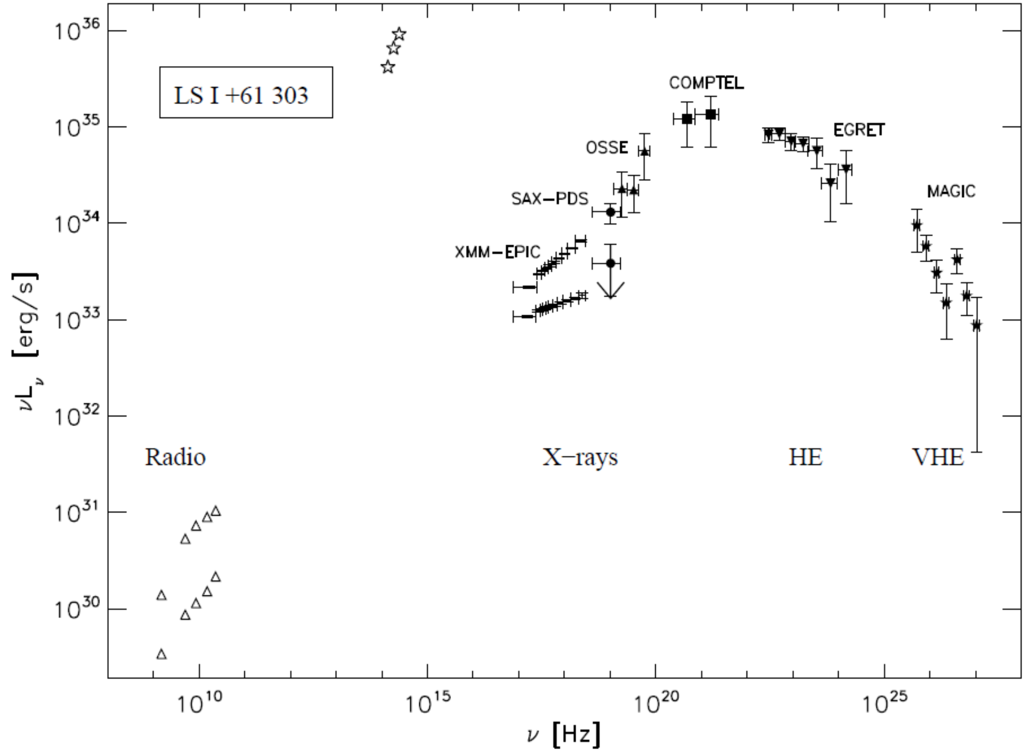
Accreting X-ray binary **Cygnus X-3** at keV.

Gamma-ray binary **LS I +61 303** (probably not accreting) at MeV-GeV.

(Zdziarksi et al. 2011; Sidoli et al. 2006).

From **Moldón (2012)**.





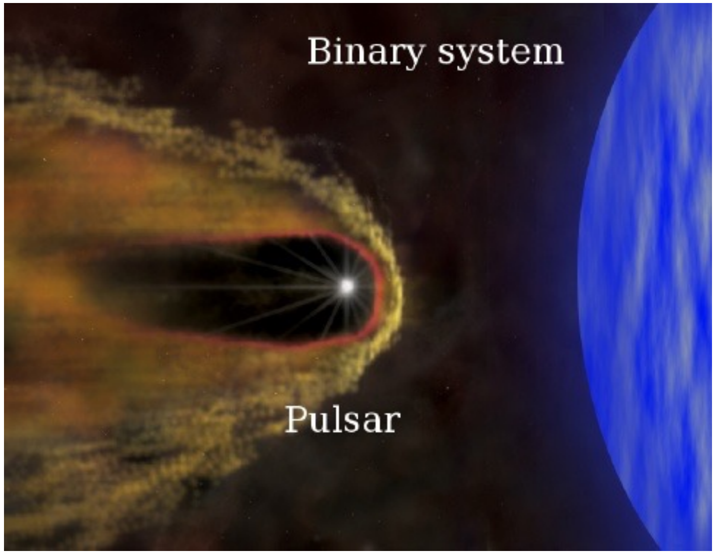
Gamma-ray binaries

System	HE	VHE	Star	CO	P_{orbit}
LS 5039	Y	Y	ON6.5 V	?	3.9 d
LMC P3	Y	Y	O5 III	?	10.3 d
4FGL J1405.1-6119	Y	-	O6.5 III	?	13.7 d
1FGL J1018.6-5856	Y	Y	O6 V	?	16.5 d
HESS J1832-093	Y	Y	O6 V	?	86.3 d
LS I +61 303	Y	Y	B0 Ve	PSR (269 ms)	26.5 d
HESS J0632+057	Y	Y	B0 Vpe	?	317 d
PSR B1259-63	Y	Y	O9.5 Ve	PSR (47.7 ms)	~3.4 yr
PSR J2032+4127	~Y	Y	B0 Vpe	PSR (143 ms)	~50 yr

Basically: O6 III-V stars and B0 Ve stars.

Gamma-ray binaries

- 9 binary systems detected at GeV and/or TeV energies: **>10 TeV, ~100 TeV !**
- 3 contain **young non-accreting pulsars**. The rest could be similar.
- Similar scenario as for PWN, but wind and photons from companion.
- **Cometary tails** detected in radio (VLBI).



LS I +61 303 cometary tail varying with orbital phase **(Dhawan et al. 2006)**.

Gamma-ray binaries

General observational properties:

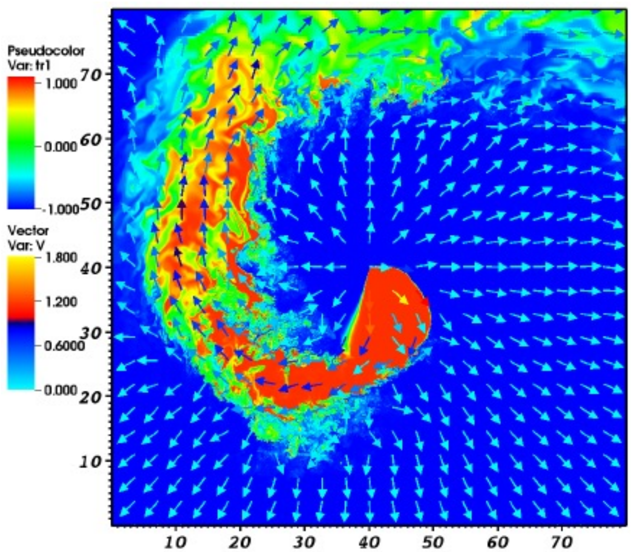
- Binary system: **massive O/Be star** and **compact object of unknown nature** (3 radio pulsars in PSR B1259-63, PSR J2032+4127 and LS I +61 303).
- **Distances** from few kpc to the LMC (50 kpc).
- Very **different orbital configurations**: periods from 4 d to 50 yr and eccentricities from 0.3 to 0.95 → very different separations (0.1-100 AU).
- VLBI observations show extended, **cometary tail-like morphologies**, sometimes forming bipolar structures like microquasars.
- The **X-ray flux** is modulated with the orbital period, but with **maximum≠periastron**. No clear accretion signatures, no X-ray pulsations.
- **GeV spectra** can be fitted with a power law + exponential cutoff, **like for pulsar magnetospheres**, but the **emission is variable(!)** and periodic.
- **TeV emission is periodic** and to first order **correlated with X-ray emission**.

Simulations.

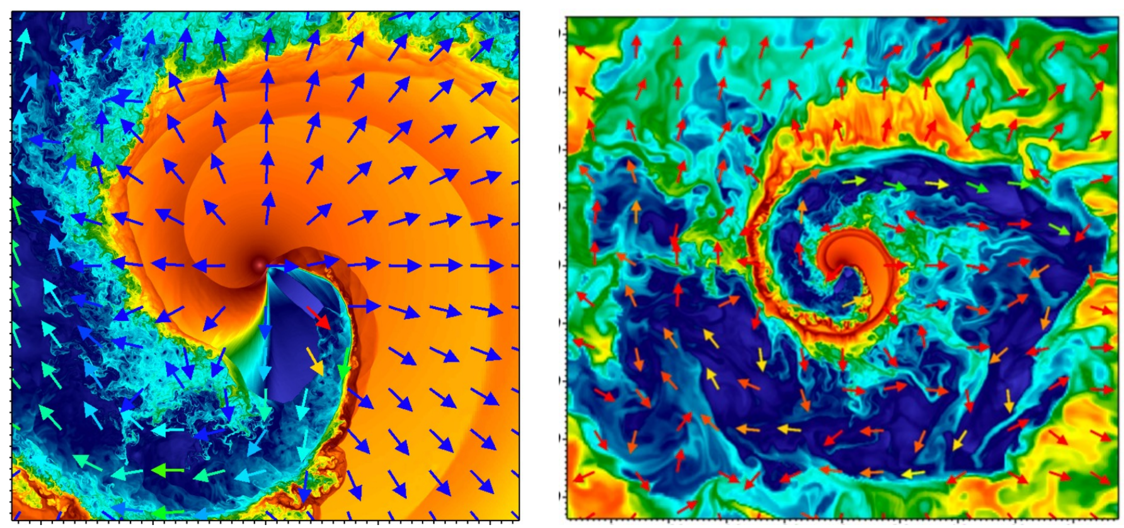
2D relativistic hydrodynamical simulations on the scale of the orbit of a pulsar wind with interacting with a stellar wind **(Bosch-Ramon et al. 2012)**.

- Particle acceleration and non-thermal emission in shock formed towards the star and in **strong shocks produced by the orbital motion** (Coriolis shock).
- Strong instabilities lead to the development of **turbulence and mixing**.
- **Doppler boosting** will have significant and complex effects on radiation.

Tracer



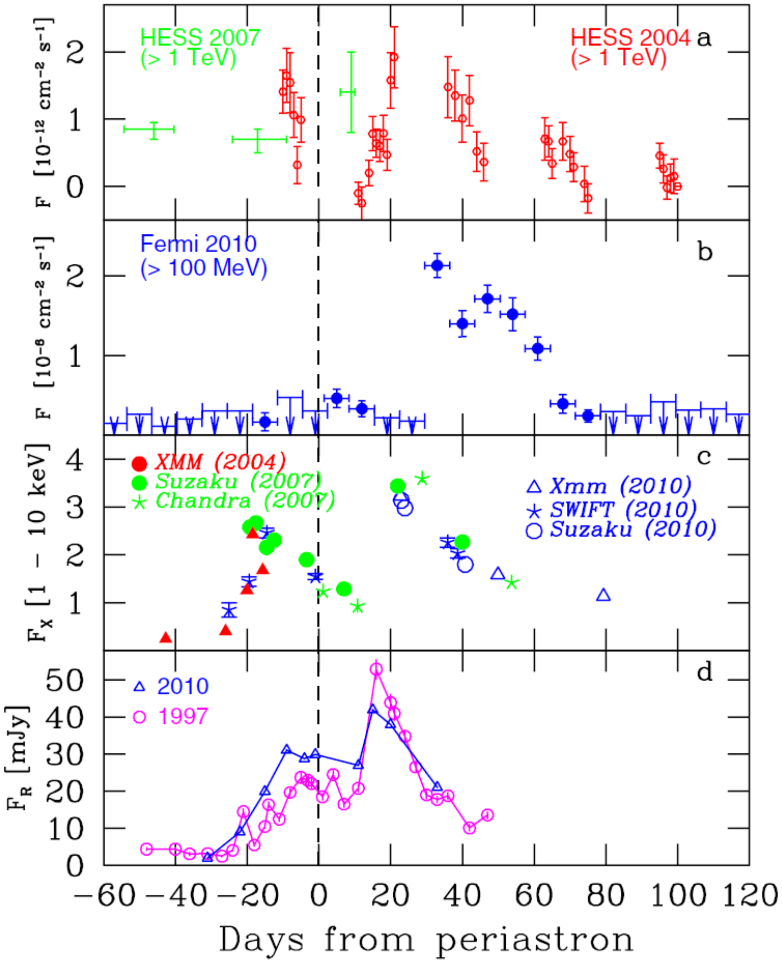
Density and velocity field

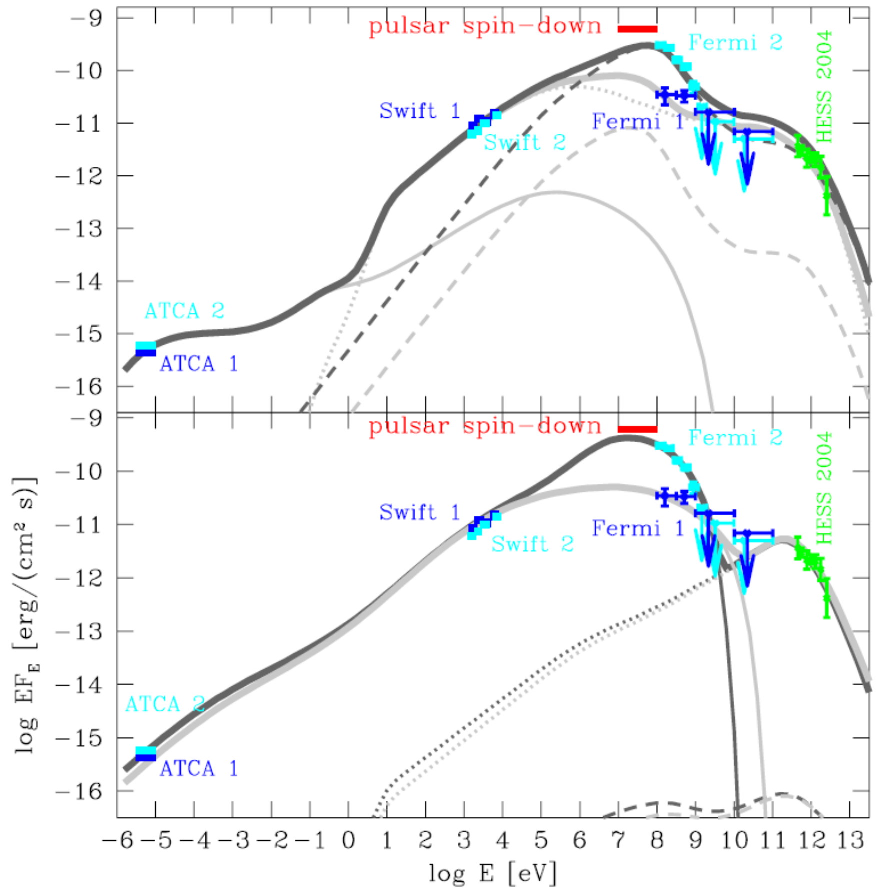


See also other works **(Bosch-Ramon et al. 2015, Lamberts et al. 2011, 2012, 2013, Dubus et al. 2015, Huber et al. 2021a,b, Kissmann et al. 2023)**.

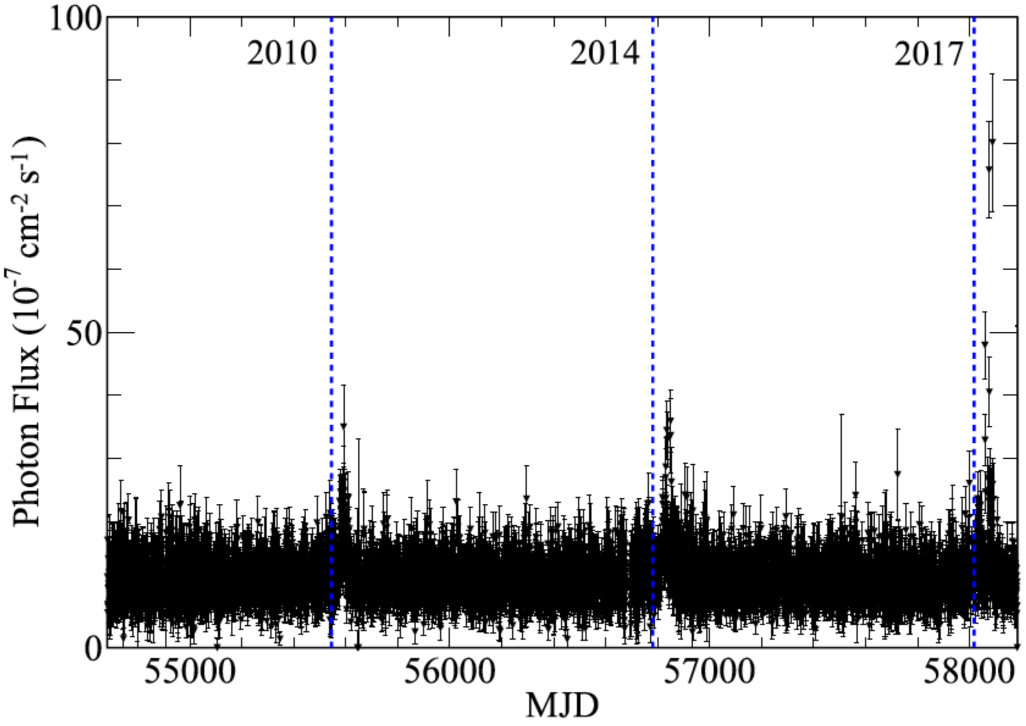
PSR B1259-63. **2010 periastron passage** by ***Fermi*/LAT (Abdo et al. 2011)**.

- Marginal detection at periastron, huge GeV flare (only) afterwards!
- **Nearly all the spin-down power is released** in HE gamma rays.
- Doppler boosting suggested **(Tam et al. 2011)**, but fine tuning is needed(!).





PSR B1259-63. **2017 periastron passage** by ***Fermi*/LAT** showed slightly different results, with more structure, later flares 70 days after periastron and a HE gamma-ray luminosity above the spin-down luminosity of the pulsar → **Doppler boosting is needed!** **(Johnson et al. 2017)**.



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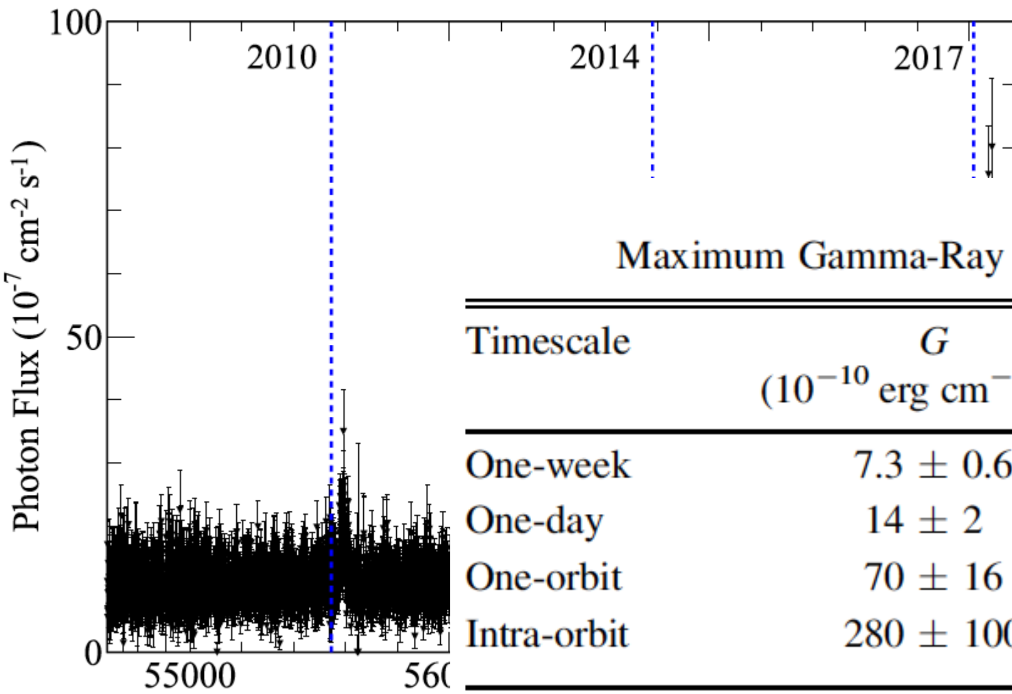

"spin-down luminosity"

$$\dot{E} = -I\Omega\dot{\Omega} = -4\pi^2 I\nu\dot{\nu} = 4\pi^2 I\dot{P}P^{-3}$$

Table 2
Maximum Gamma-Ray Energetics on Different Timescales

Timescale	G (10^{-10} erg cm^{-2} s^{-1})	L_γ (10^{35} erg s^{-1})	$L_\gamma/\dot{E}$
One-week	7.3 ± 0.6	$6.4^{+2.0}_{-1.6}$	0.8 ± 0.2
One-day	14 ± 2	12^{+4}_{-3}	$1.5^{+0.5}_{-0.4}$
One-orbit	70 ± 16	61^{+18}_{-14}	$7.4^{+2.2}_{-1.7}$
Intra-orbit	280 ± 100	244^{+74}_{-56}	$29.8^{+9.0}_{-6.8}$

Note. For the timescales listed during the 2017 periastron passage, this table provides the maximum energy flux (G), gamma-ray luminosity (L_γ), and luminosity as a fraction of the spin-down power, $\dot{E} = 8.2 \times 10^{35}$ erg s^{-1} ($L_\gamma/\dot{E}$). For the uncertainty on L_γ, we incorporate both the energy flux and distance uncertainties.

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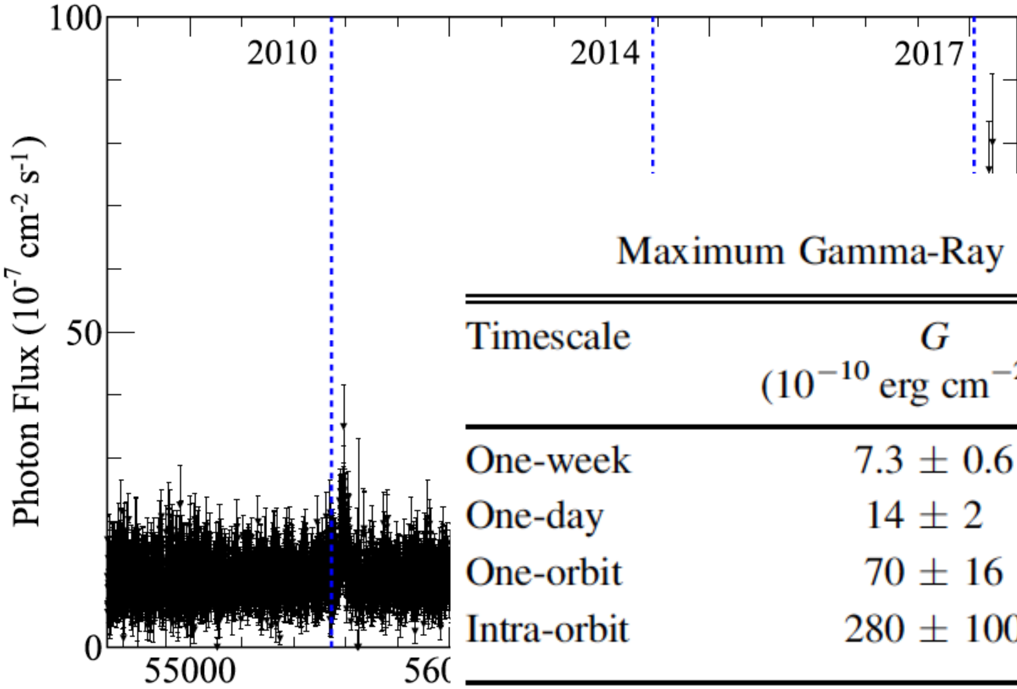

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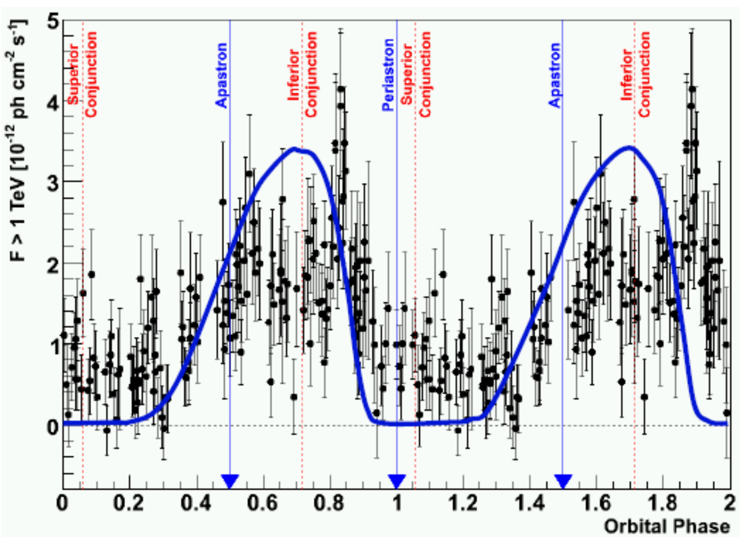
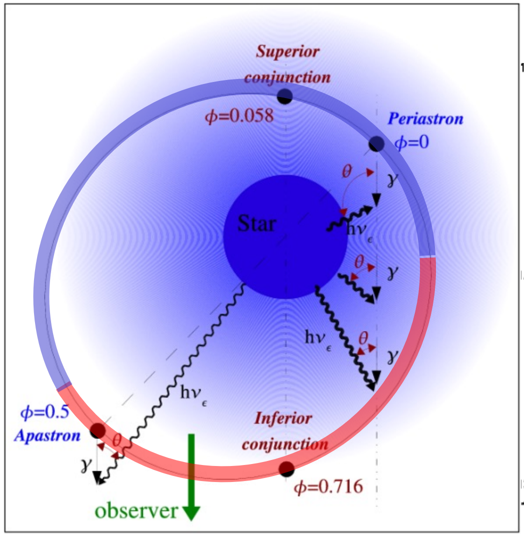
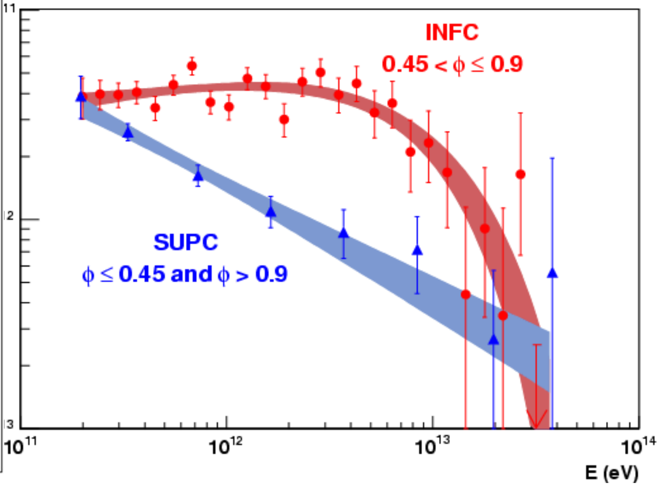
MW results of 2021 periastron passage **(Chernyakova et al. 2024)**.
GeV flares in 2024 passage **(Burnett et al. 2024, Martí-Devesa et al. 2024)**.

LS 5039.

- **Variable TeV emission** with the **orbital phase** **(Aharonian et al. 2006)**.
- Flux maximum at inferior conjunction of the compact object.
- **γ-γ absorption** (e^+-e^- pair production on stellar UV photons), which has an angle dependent cross-section, **plays a major role but…**

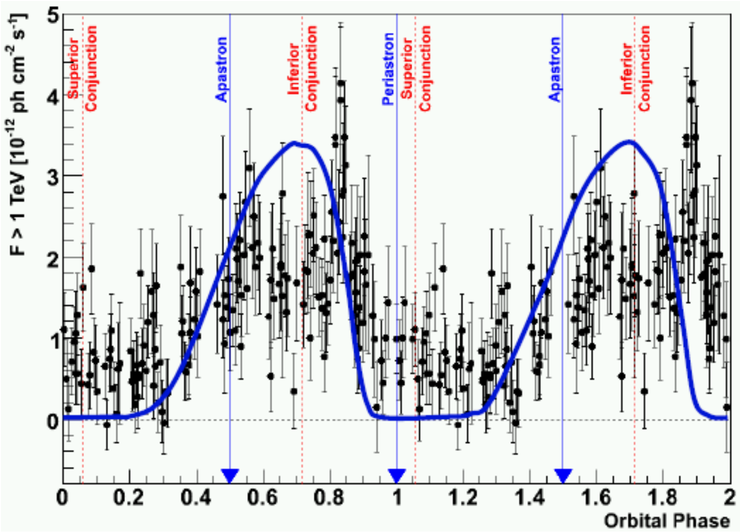


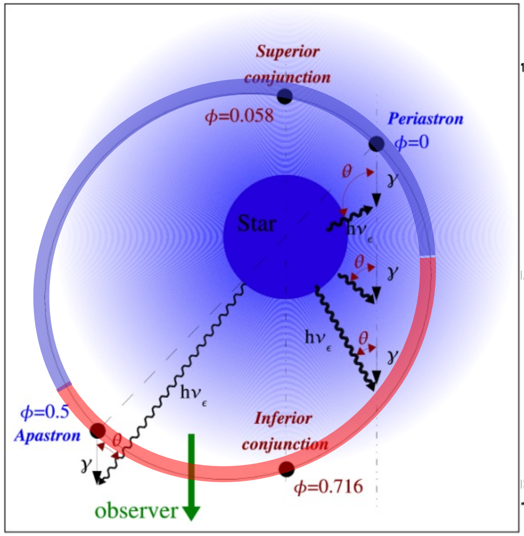


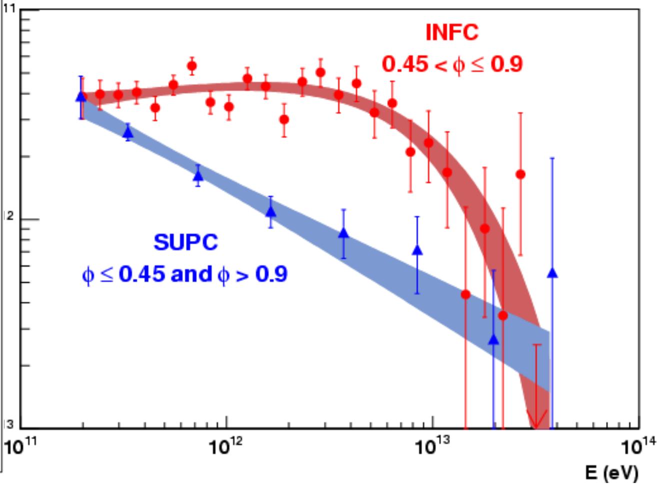


LS 5039.

- **Variable TeV emission** with the **orbital phase** **(Aharonian et al. 2006)**.
- Flux maximum at inferior conjunction of the compact object.
- **γ-γ absorption** (e^+-e^- pair production on stellar UV photons), which has an angle dependent cross-section, **plays a major role but…**







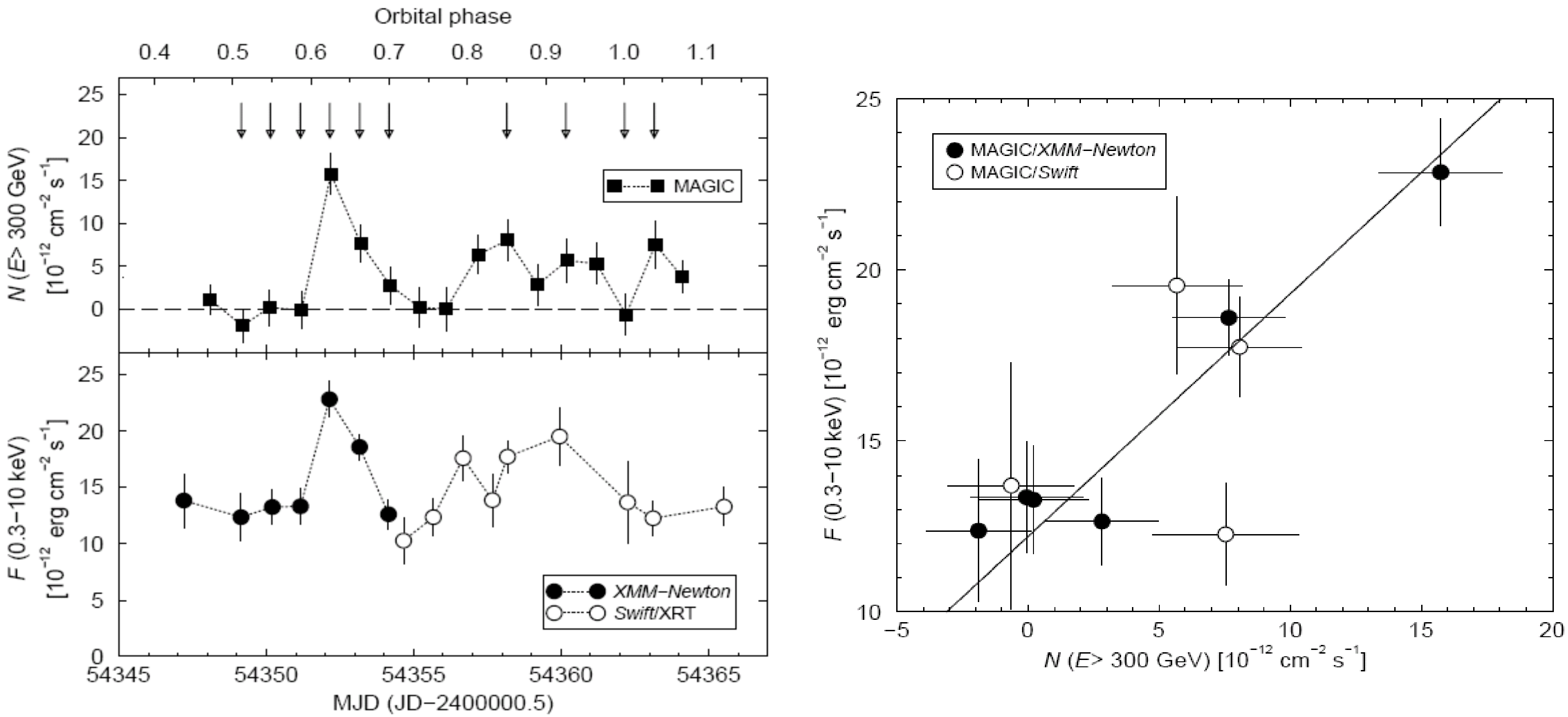
- **… the flux should be 0** at periastron and superior conjunction, **but it's not!**
- … the **spectrum** shows strong **variability**, but **not at 200 GeV** as predicted by absorption models! **(Dubus 2006, Böttcher 2007)**.

Cascading has to be modeled in detail **(Khangulyan+ 2008, Cerutti+ 2010)**.

Phase-dependent e^- acceleration? TeV emission produced away from CO?

LS I +61 303.

MAGIC reported a correlation between X-ray and VHE gamma-ray emission **(Anderhub et al. 2009)**. This suggests **leptonic processes** are at work, and that the **X-rays are the result of synchrotron radiation** of the same electrons that produce **VHE emission as a result of IC scattering off stellar photons**.



VERITAS found a similar correlation with data 0.5 h apart, not with data within 24 h **(Patel et al. 2022)**.

Simulations.

Simulations of LS 5039 HE/VHE emission with 3D relativistic hydrodynamics.

Variability on timescales of 1 h reproduced (Kissmann et al. 2023).

These are complex systems.

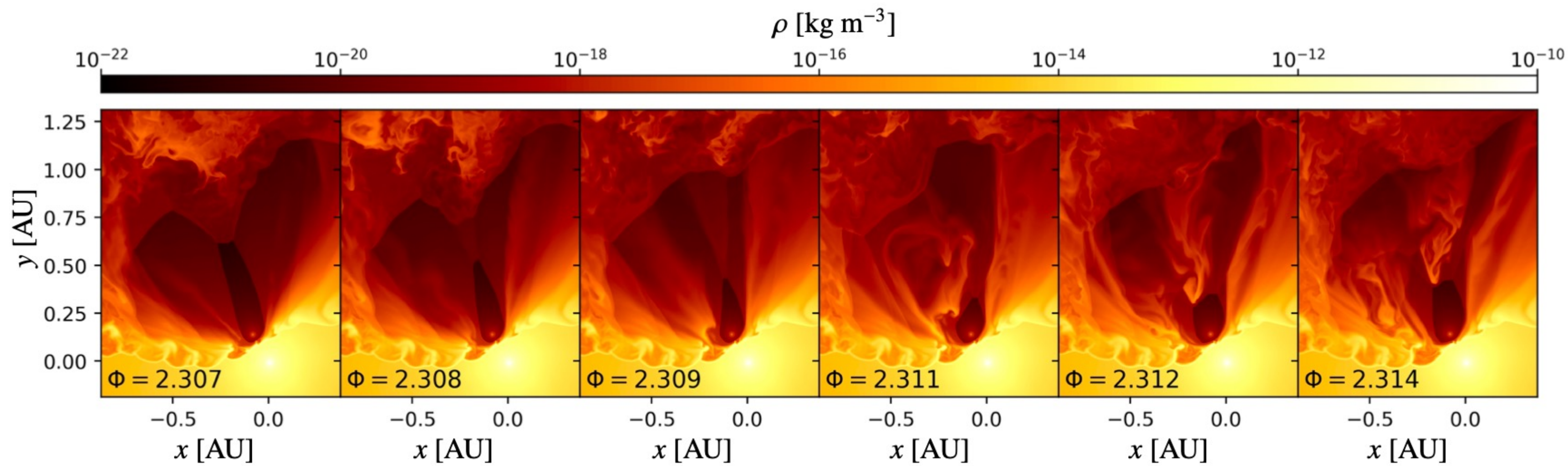
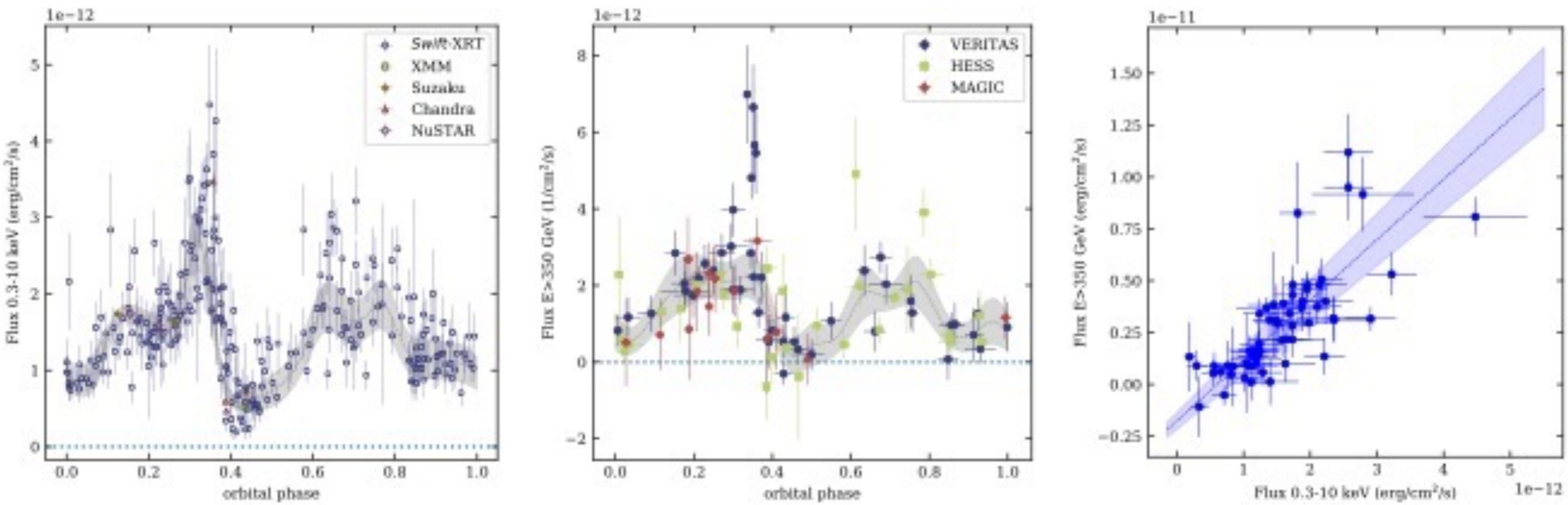


Fig. 2. Different snapshots of mass density in the orbital plane during a short period in the second full orbit as indicated in the plots. As given by the indicated orbital phases, these snapshots cover a period of slightly more than 40 min.

HESS J0632+057.

MAGIC/VERITAS/HESS around 450 h of TeV observations from 2004 to 2019:

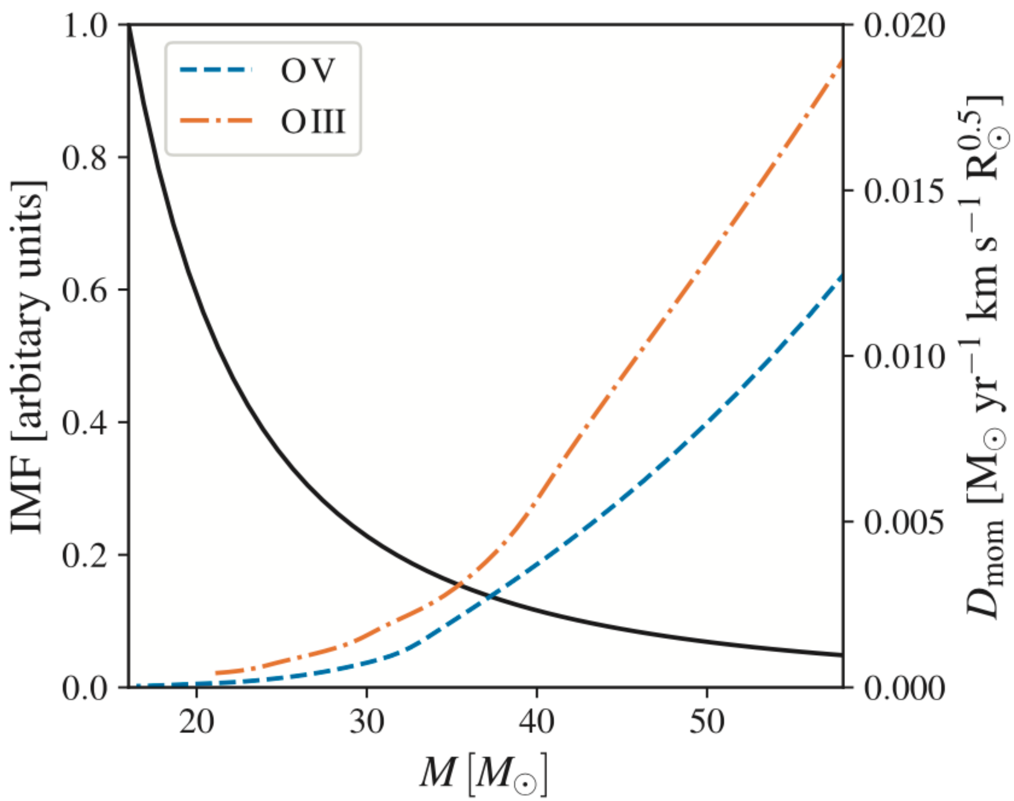
- **Orbital periodicity** from VHE data.
- Spectra compatible with power-law, requiring a cutoff for orbital phases 0.2-0.4.
- Clear **X-ray/TeV correlation** with non-zero X-ray flux when TeV emission disappears (as for LS I +61 303) **(Adams et al. 2021)**.



HESS J1832-093.

NIR observations reveal **another O6V star**. Distance around 6.7 kpc.

- Apparent grouping around this spectral type for the known gamma-ray binaries with an O-type star.
- This may be due to the interplay between the **initial mass function** and the **wind momentum–luminosity relation** **(van Soelen et al. 2024)**.
- Should we focus around this spectral type when searching for new systems?



Gamma-ray binaries

Searches for new gamma-ray binaries (non-exhaustive list):

- **Fermi/LAT periodicity searches**: previous successful discoveries include 1FGL J1018.6-5856, LMCP3 and 4FGL J1405.1-6119 **(Fermi LAT Collaboration et al. 2012, Corbet et al. 2016, Corbet et al. 2019)**.

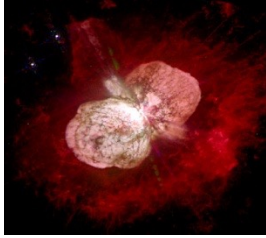
- **Runaway massive stars from Gaia DR3 (Carretero-Castrillo, Ribó, Paredes 2023)**.

- **Obscured massive stars (Martí & Luque-Escamilla, poster at this conference)**.

- …

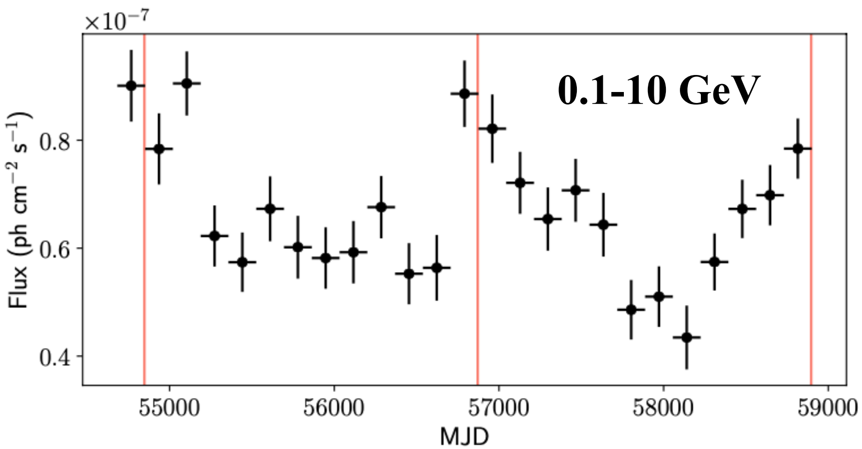
- **CTA in the future**

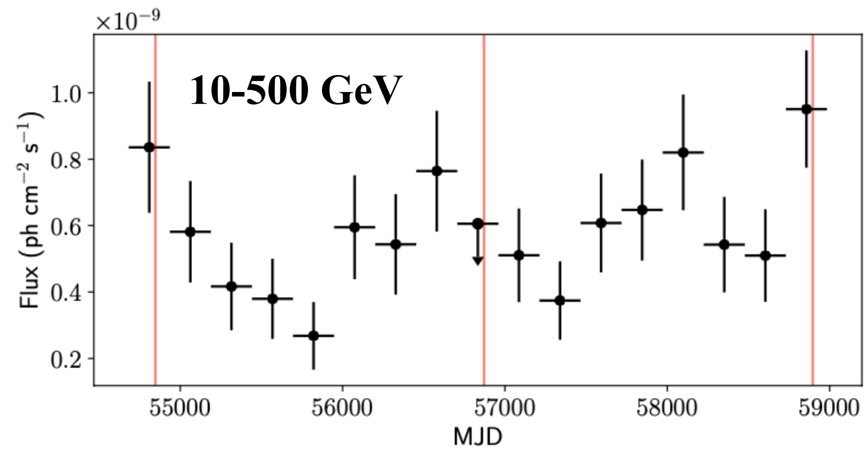
Colliding-wind binaries



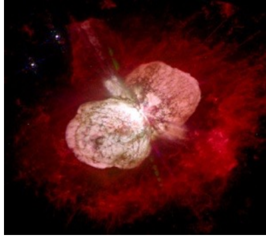
Eta Carinae

- ***Fermi*/LAT** data during 12yr show **5.5 yr orbital variability in Eta Carinae**.
- This can be understood and interpreted in a colliding-wind binary scenario for orbital modulation of the gamma-ray emission.
- The **lightcurves change from cycle to cycle**.
- The spectral shape in each periastron passage is different.
- These facts strongly suggest that **the wind collision region of this system is perturbed from orbit to orbit**, affecting particle transport within the shock **(Martí-Devesa & Reimer 2021)**.





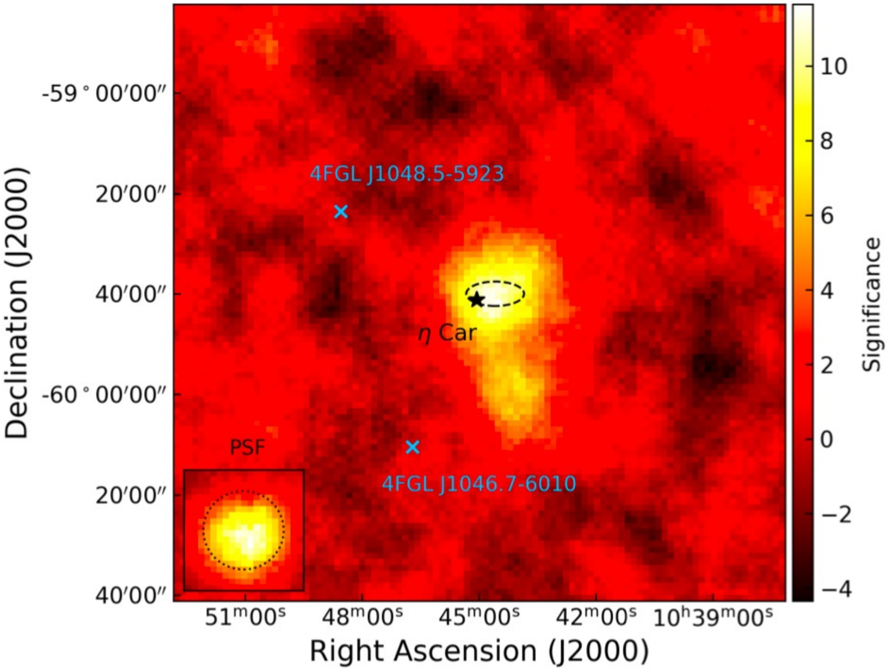
Colliding-wind binaries

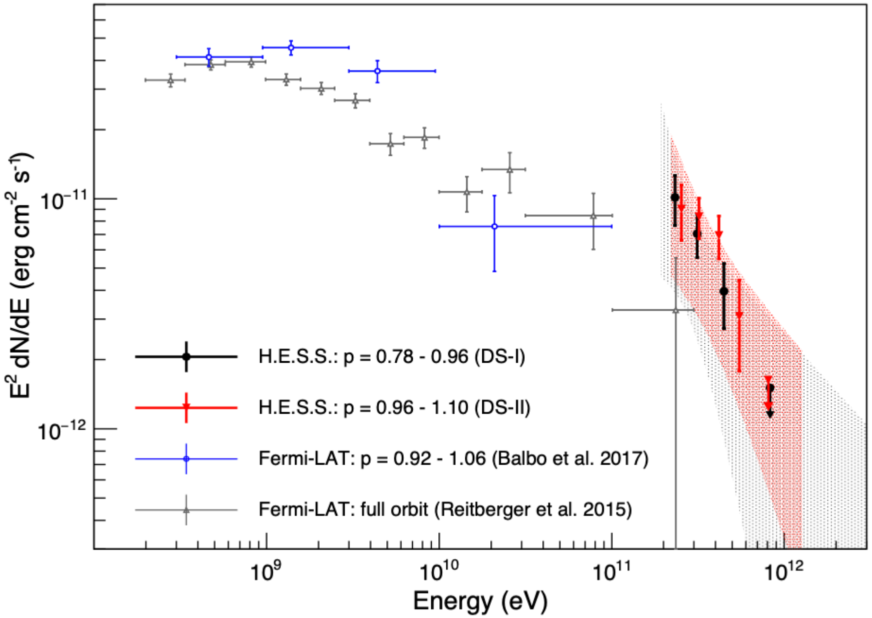


Eta Carinae

- HESS detected **VHE** γ-ray emission from **Eta Carinae close to periastron**.
- The source is point-like and the spectrum is best described by a power law.
- The γ-ray spectrum extends up to **at least ~400 GeV**.
- In a leptonic scenario this implies $B < 0.5$ G in the emission region.
- No indication for phase-locked flux variations is detected in the HESS data.

(HESS Collaboration, Abdalla et al. 2020).

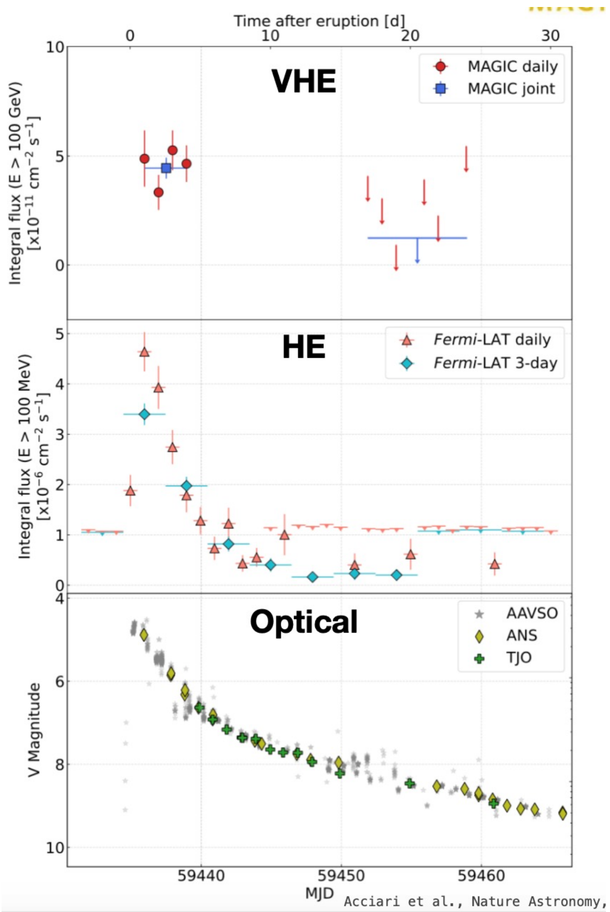


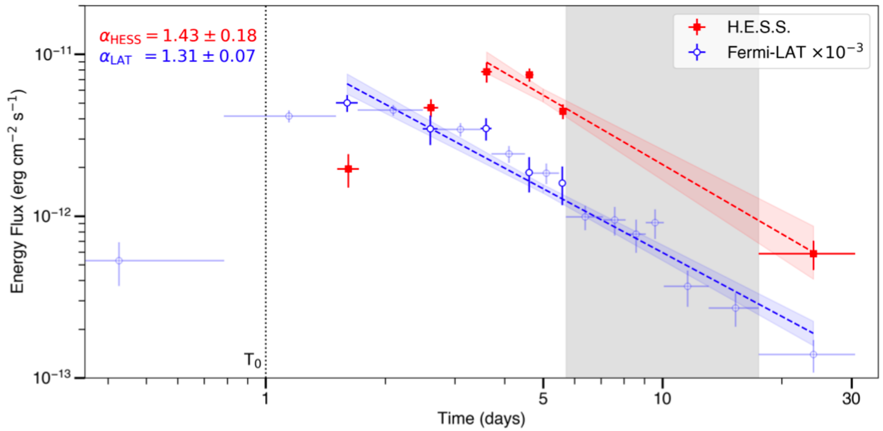


Novae

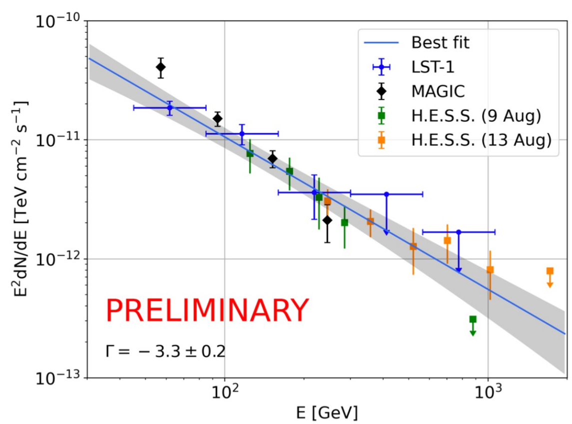
RS Oph

MAGIC, HESS, LST have reported VHE emission from the recurrent nova **RS Oph (Acciari et al. 2022, Aharonian et al. 2022, Aguasca-Cabot et al. 2022)**.





Modelling of the VHE and HE *Fermi*/LAT data clearly support **hadronic emission processes**.



Conclusions

- **X-ray binaries** are now well stablished ~100 TeV emitters in reacceleration jet regions (SS 433, V4641 Sgr?). **Leptonic emission favored**. Hints of fast TeV variability in some sources? (Cyg X-1).

- **Gamma-ray binaries** showing a diversity of behaviors with emission up to ~100 TeV with no cutoff. **Leptonic emission favored**.

- More and more evidence of clustering around O or Be stars with young non-accreting pulsars. What is their real population? **Searches** for new gamma-ray binaries ongoing.

- **Novae** discovered a few years ago at VHE. **Hadronic emission favored**. Will T CrB finally explode? Many physical parameters could be constrained in such nearby system.

- **Colliding-wind binaries** also in place but need CTA to make real progress.