TeV gamma-loud binaries

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NASA

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EXCELENCIA SEVERO OCHOA
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MINISTERIO DE CIENCIA E INNOVACIÓN
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NextGenerationEU
Plan de Recuperación, Transformación y Resiliencia
AGENCIA ESTATAL DE INVESTIGACIÓN
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Detecting gamma rays with ground-based experiments

- Imaging Air Cherenkov Telescopes (IACTs)
  - Very-high-energy (VHE, E> 100 GeV) regime
- Detectors:
  - Ultra-high-energy (UHE, TeV-PeV) regime

Current experiments

Future

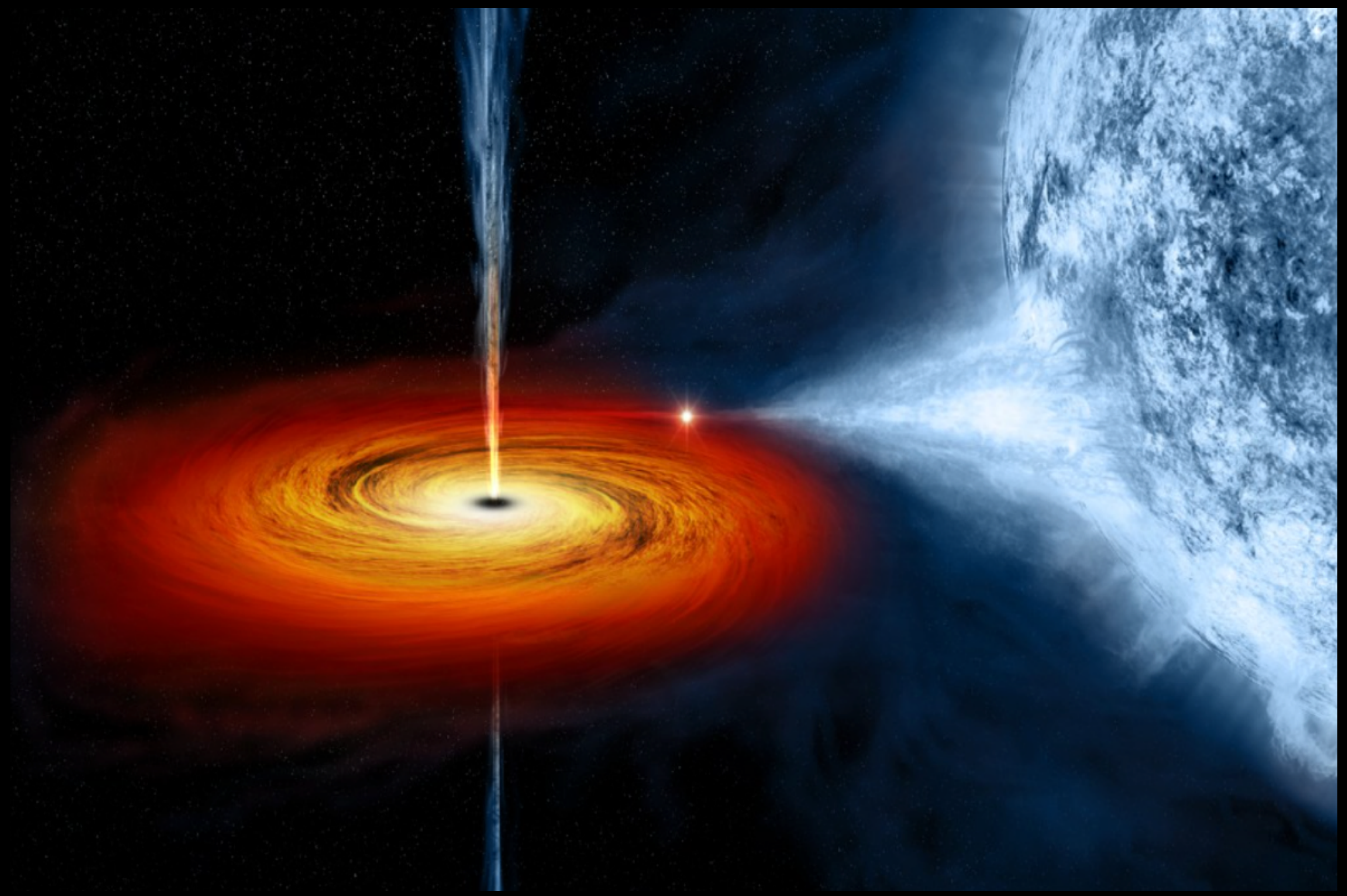
ASTRI
(Spain)

ASTRI Mini-Array

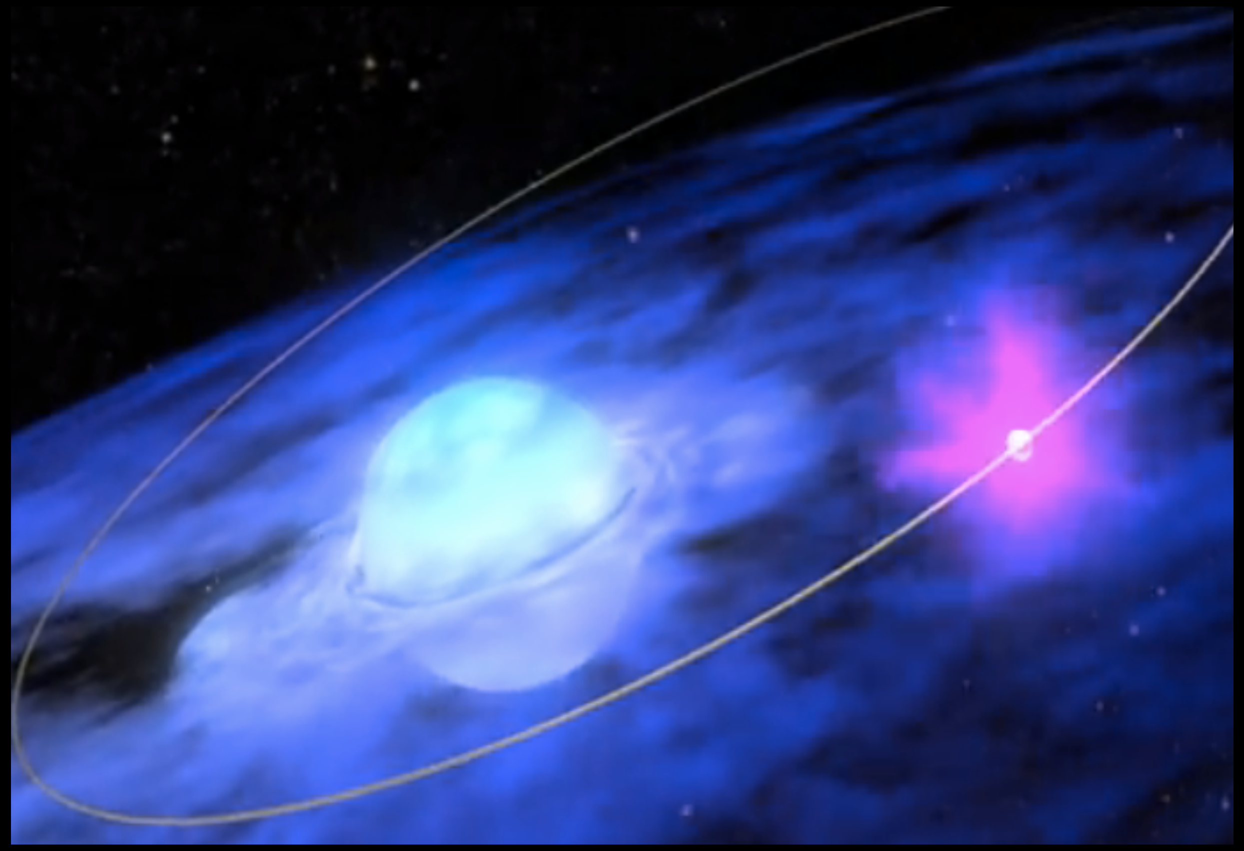
SWGO
(Chile)

SWGO
The Southern Wide-field Gamma-ray Observatory

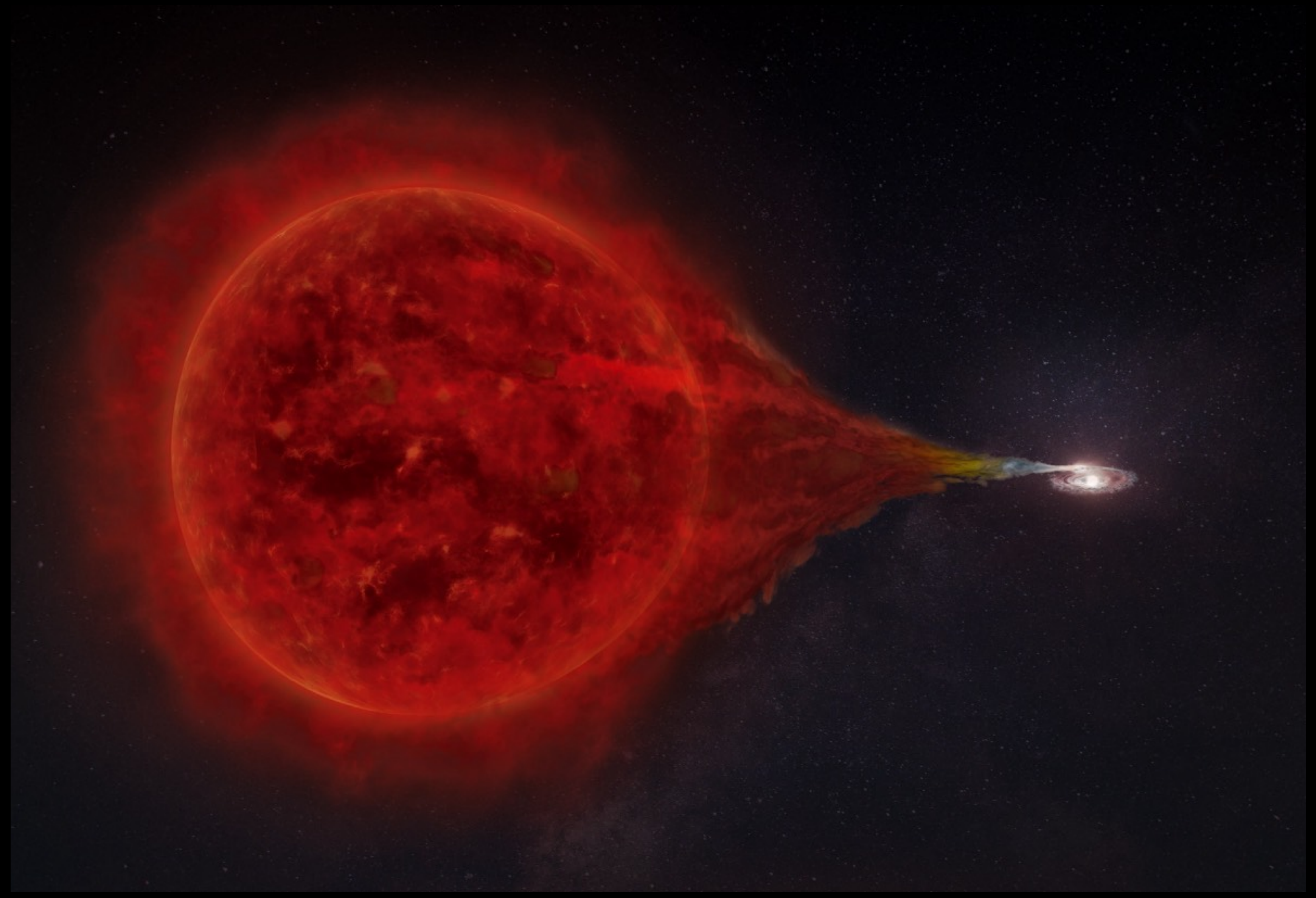
Microquasars



Non-accreting pulsars

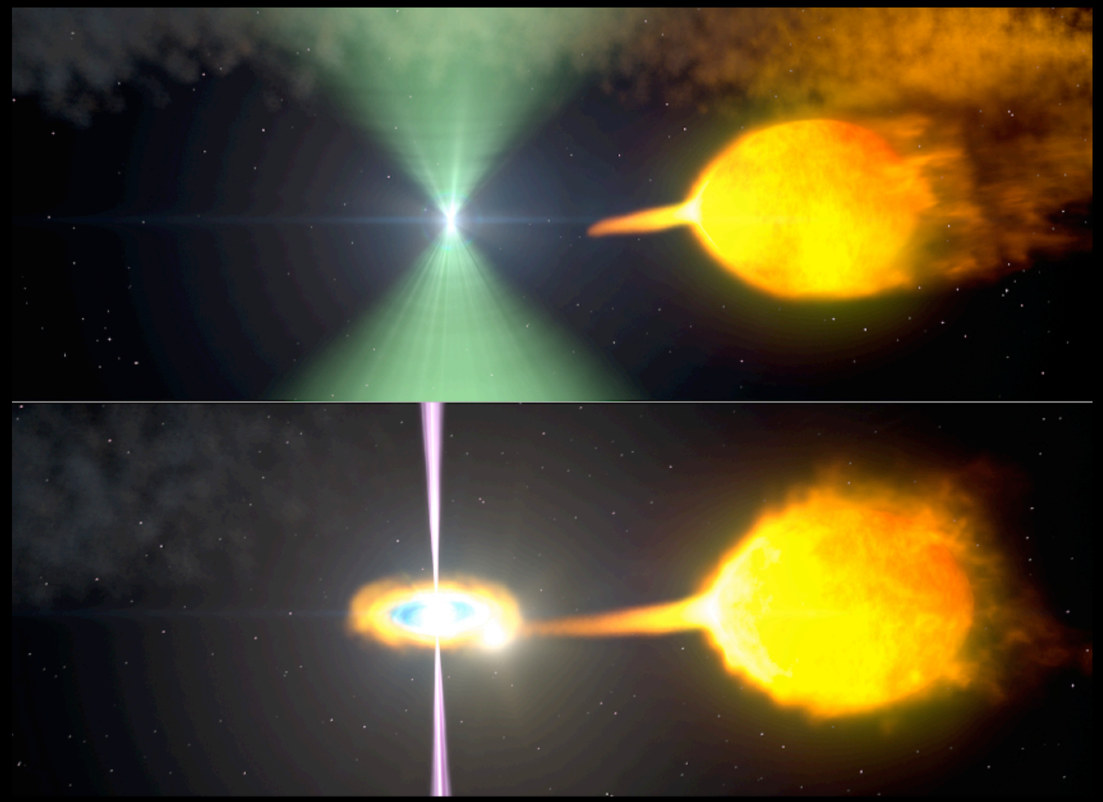


Novae

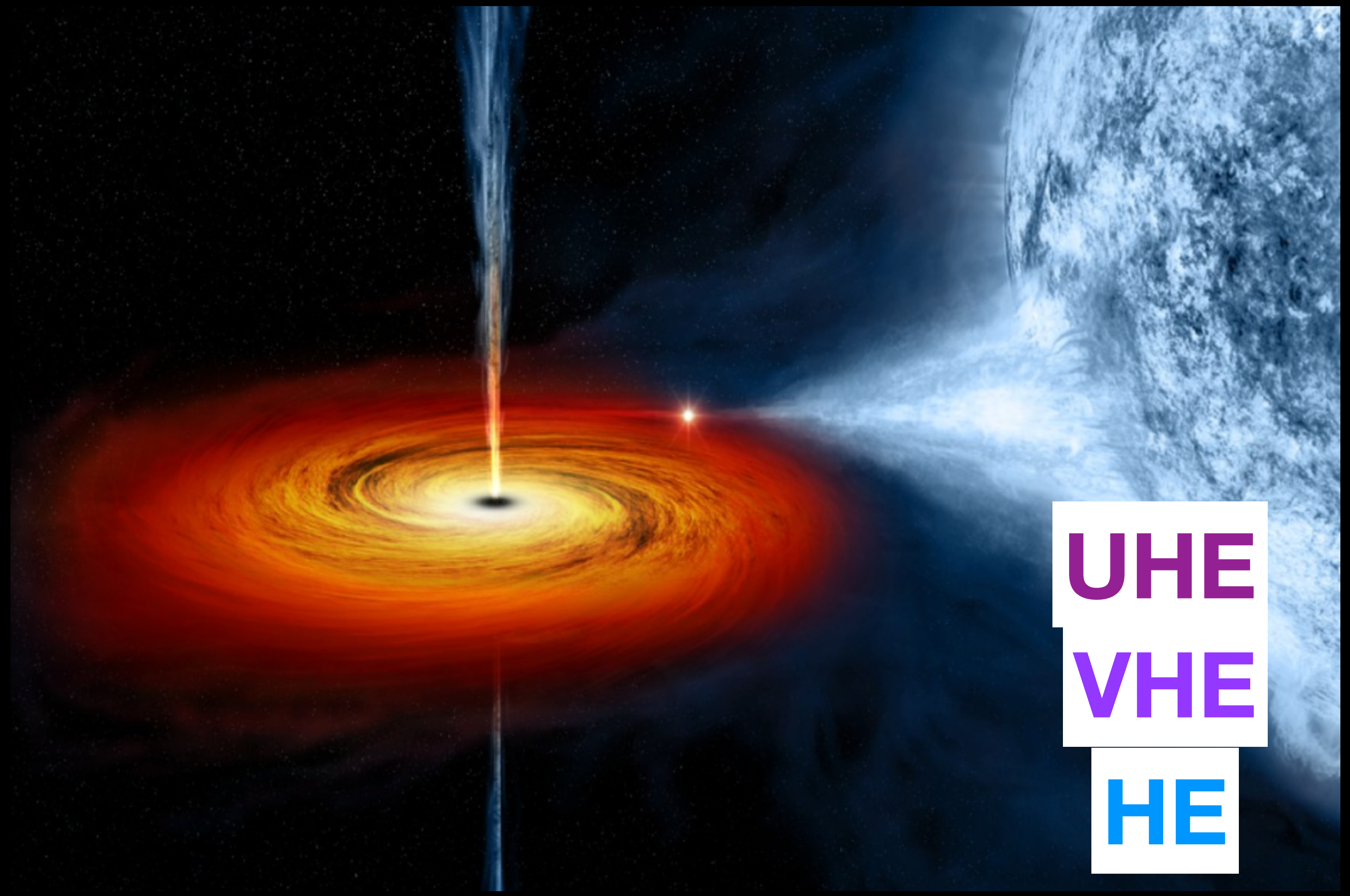


Colliding wind binary

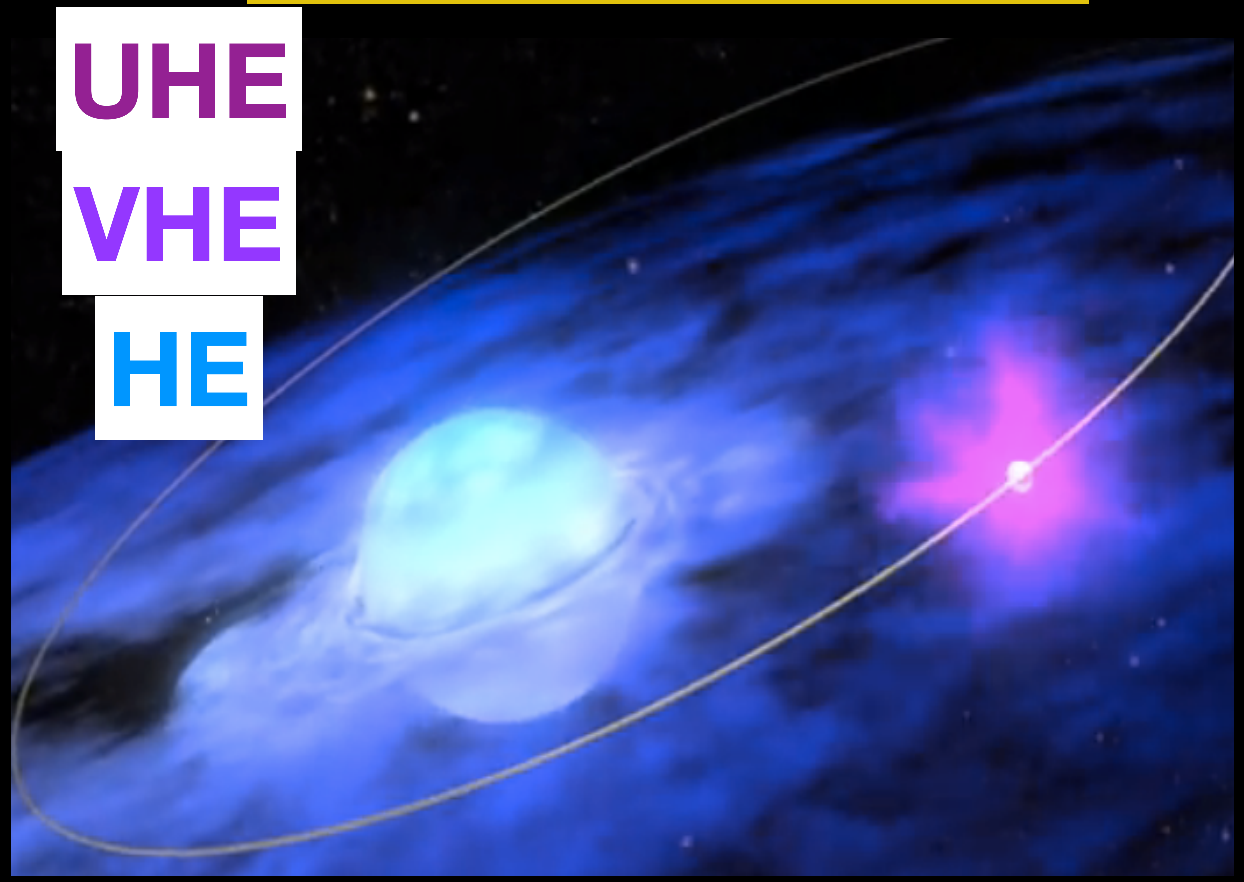
tMSPs



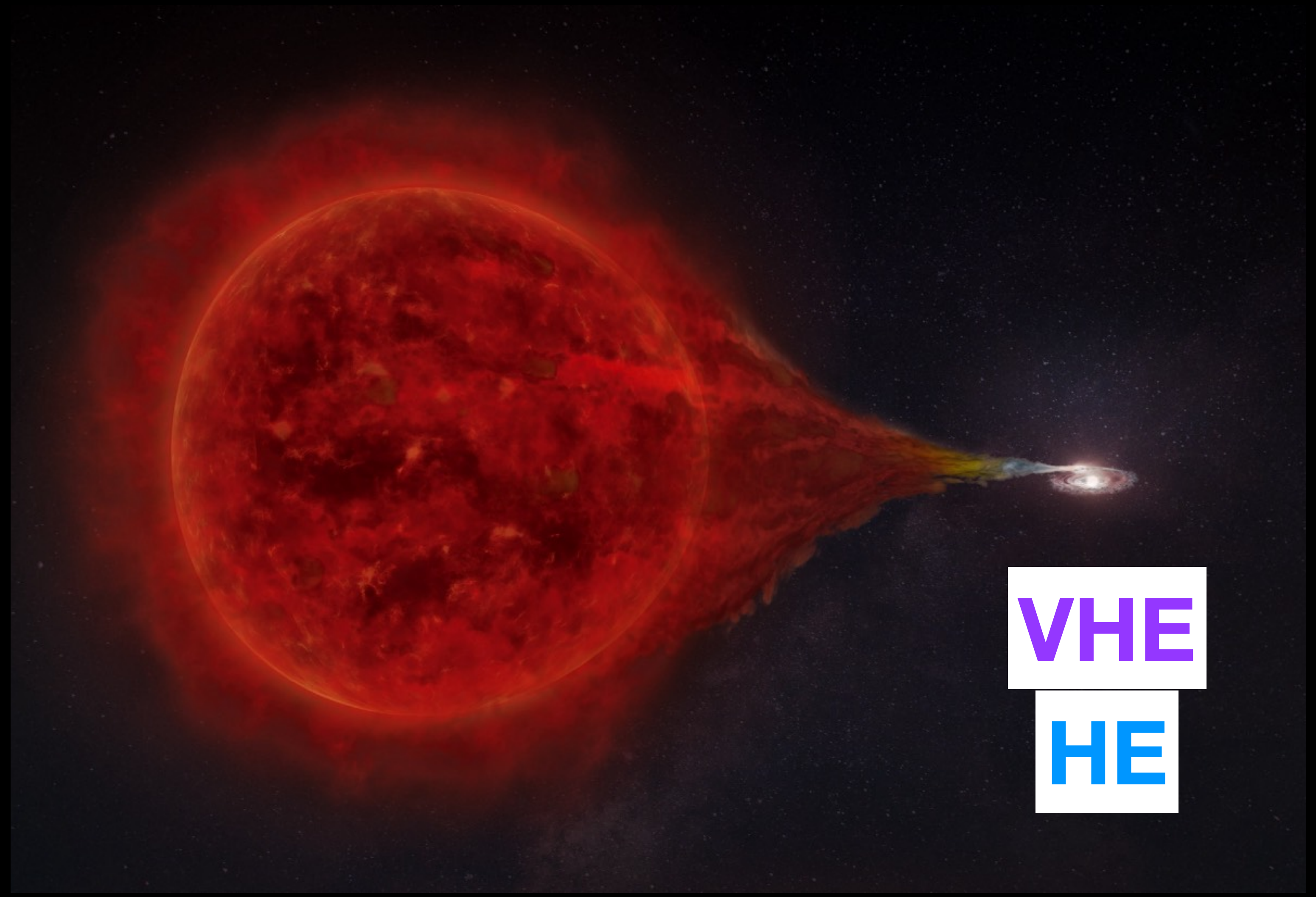
Microquasars



Non-accreting pulsars

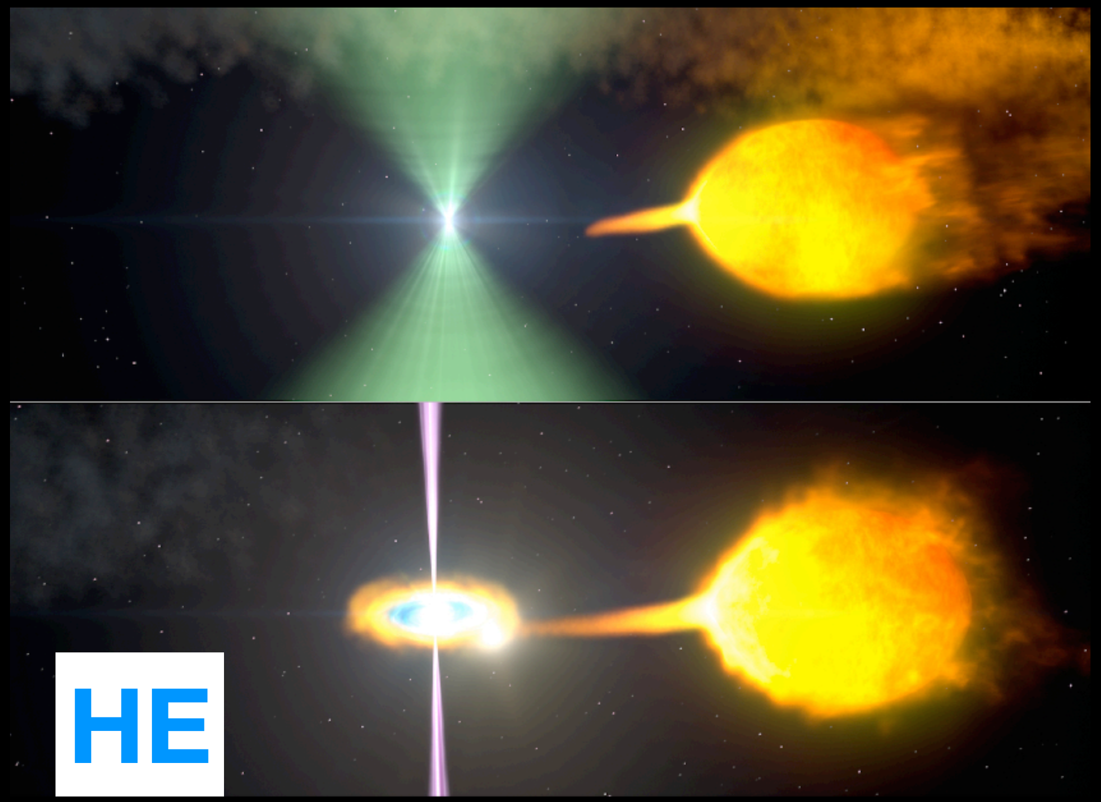


Novae



Colliding wind binary

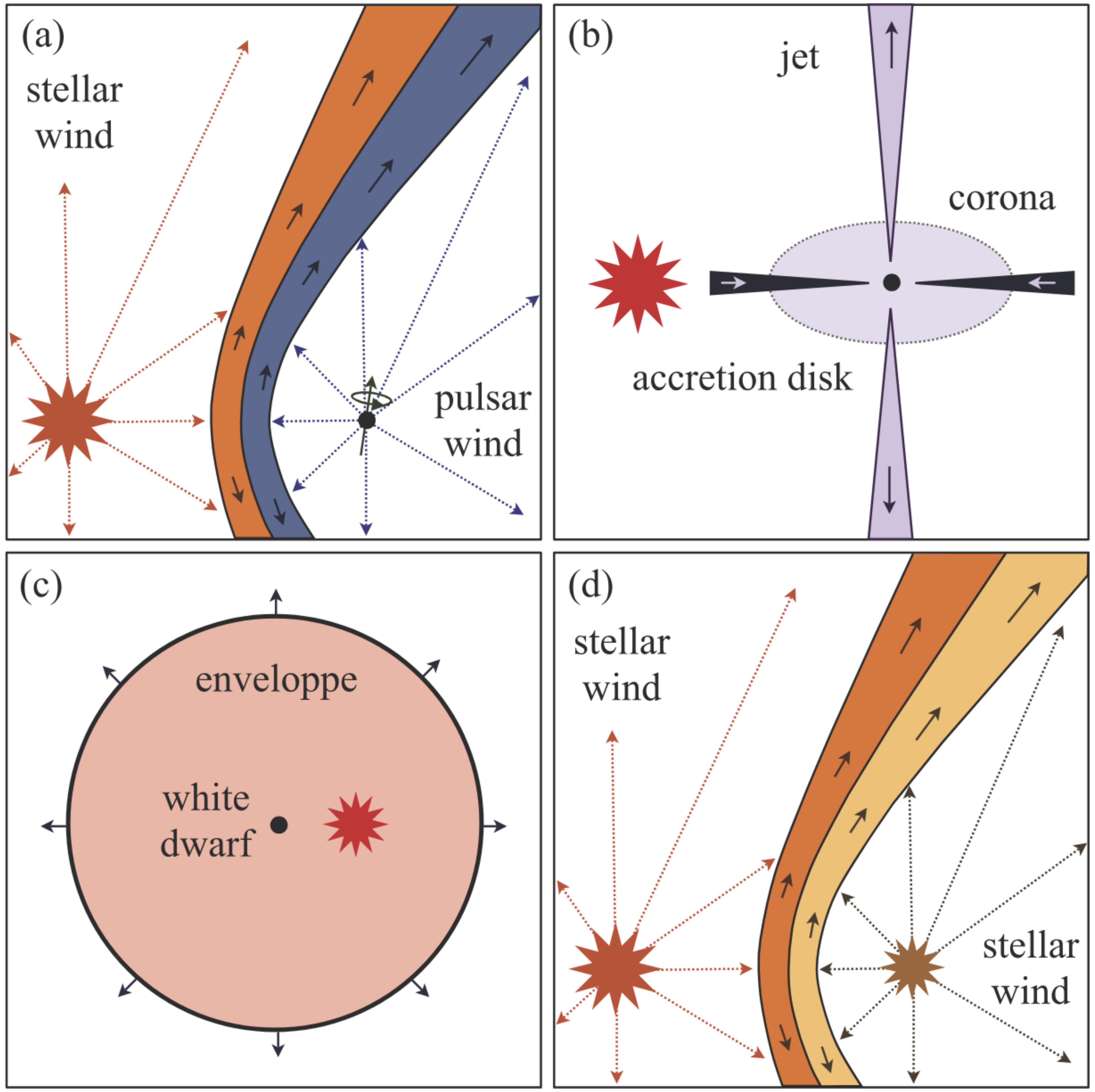
tMSPs



VHE binary emitters

Non-accreting pulsars

Microquasars



Dubus 2015

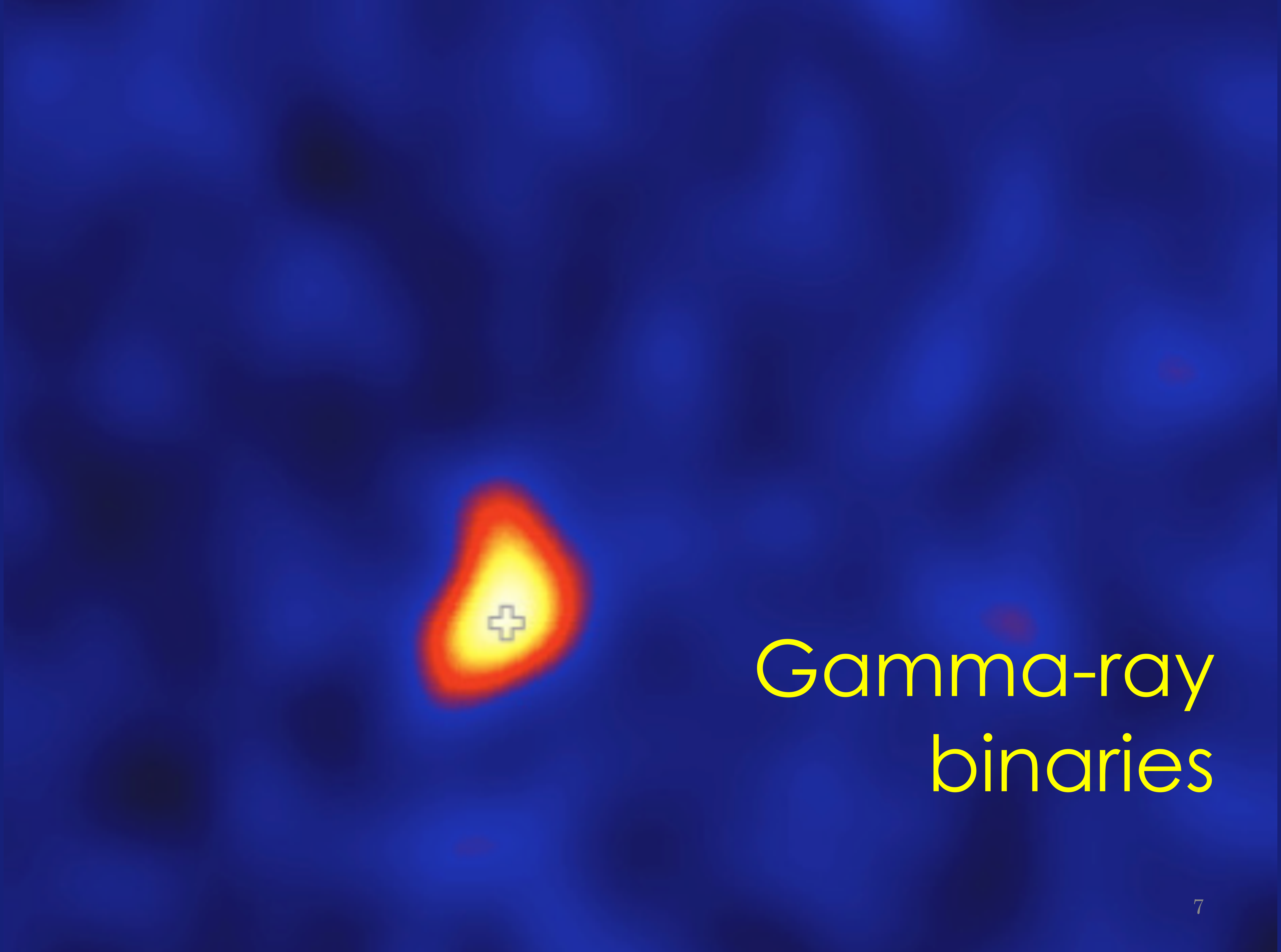
Novae

Colliding wind binary

Gamma-loud binaries at VHE*: state-of-the-art

	System	Star spectral type	Compact object	Porb [days]	HE emission	VHE emission	UHE emission
Gamma-ray binaries	PSR B1259-63	O9.5Ve	48ms pulsar	1236.72	yes	yes	
	LS 5039	O	pulsar?	3.91	yes	yes	yes
	LS I +61 303	Be	pulsar	26.49	yes	yes	yes
	HESS J0632+057	Be	-	315.50	yes	yes	
	FGL J1018.6-5856	O	-	16.58	yes	yes	
	LMC P-3	O	-	10.2	yes	yes	
	HESS J1832-093	O	-	82	yes	yes	
	PSR J2032+4127	Be	143 ms pulsar	50 years	yes	yes	
	4FGL J1405.1-6119	O	-		yes	?	
microquasars	SS 433	A	BH	13.08	yes	yes	yes
	V4641 Sgr	B9III	BH	2.8	no	yes	yes
	GRS 1915+105		BH		yes ?	-	yes
	MAXI J1820+070		BH		-	-	yes
colliding wind	eta Carinae	LBV	O/B star	5.5 years	yes	yes	-
nova	RS Ophiuchi	red giant	white dwarf	454	yes	yes	-

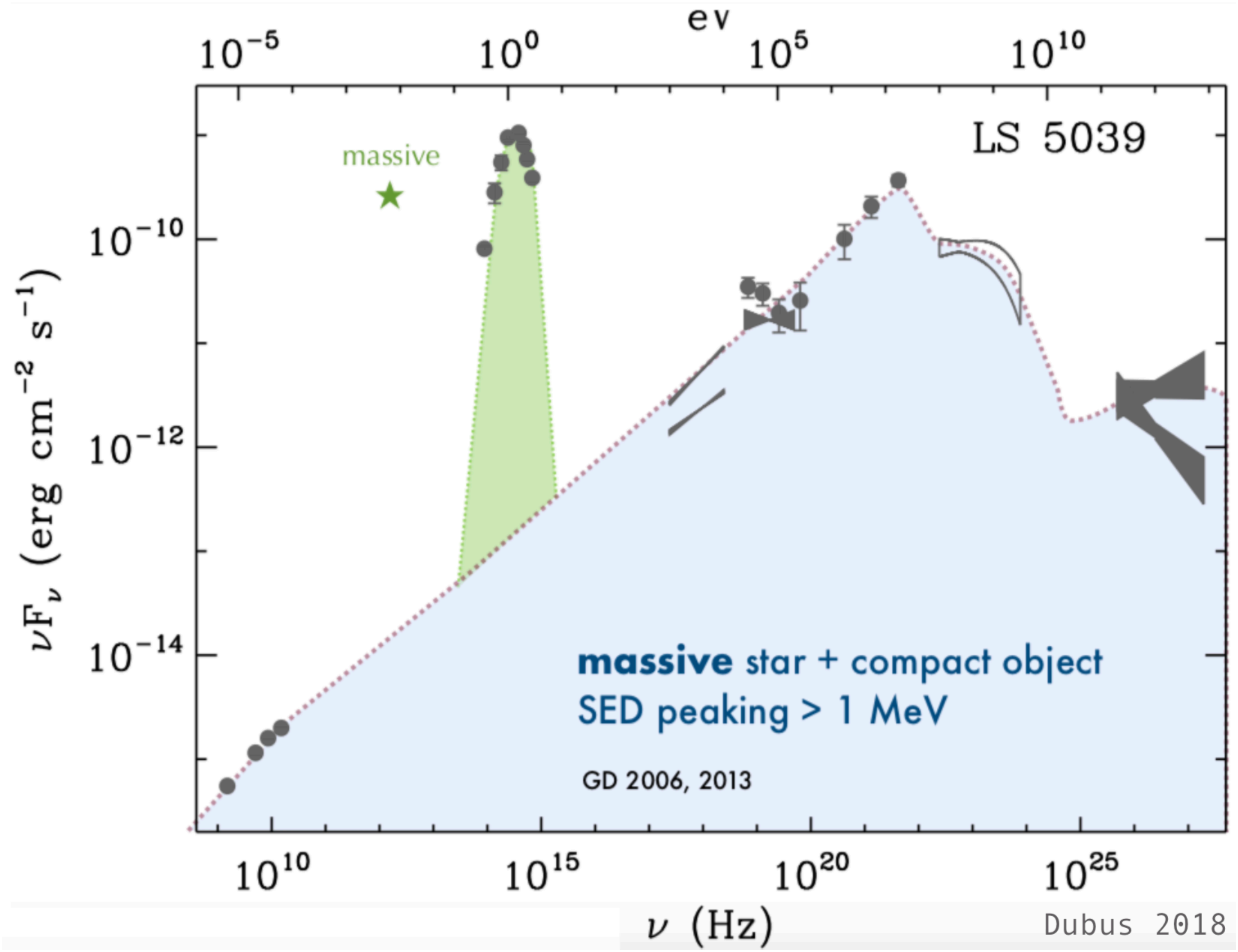
*Systems with >5σ detection



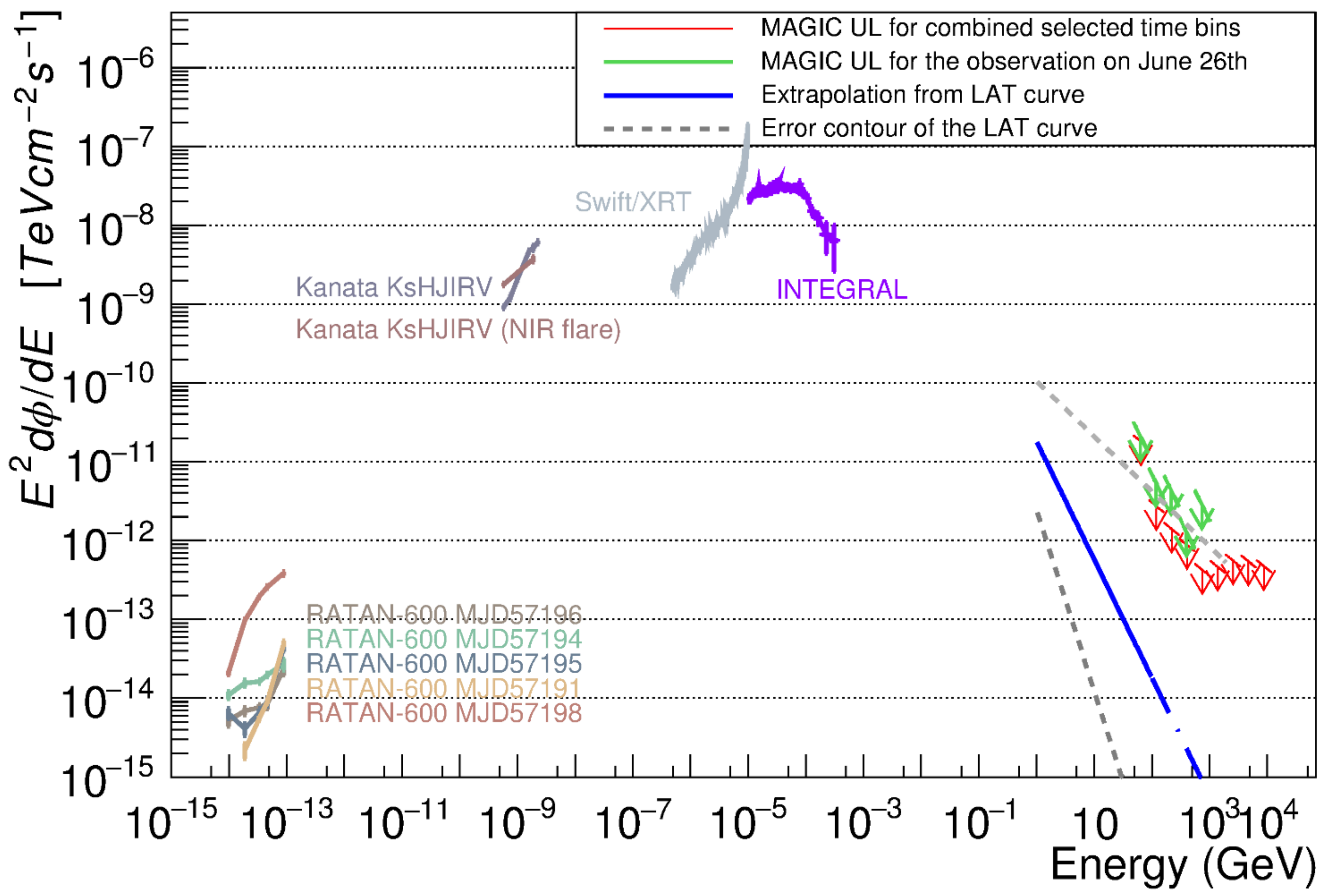
Gamma-ray binaries

Gamma-ray binaries

Gamma-ray binary LS 5039



X-ray binary V404 Cyg



Ahnen et al. 2017

- Gamma-ray binaries in a nutshell:
  - Compact binary: O/Be Star + compact object (NS/BH)
  - **Bulk of the non-thermal emission in the γ-ray domain (E>1MeV)**
  - **Only ~10 known systems** (out of ~300 X-ray binaries) **-> progenitors of HMXBs?** (Dubus 2013)

Gamma-loud binaries at VHE: state-of-the-art

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	4FGL J1405.1-6119	O	-		yes	?	yes*
microquasars	SS 433	A	BH	13.08	yes	yes	yes
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	GRS 1915+105		BH		yes ?	-	yes
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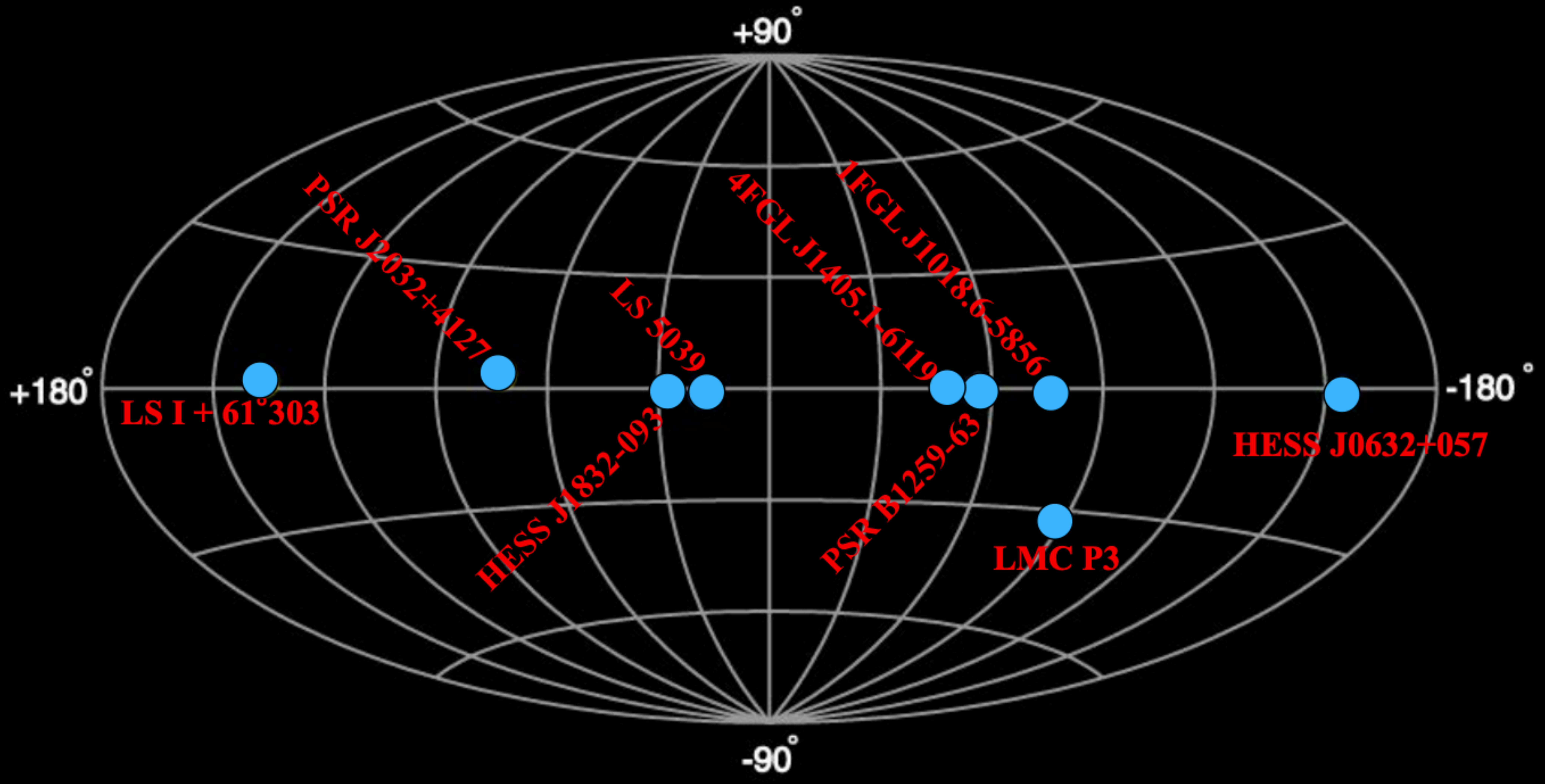
colliding wind	eta Carinae	LBV	O/B star	5.5 years	yes	yes	-
nova	RS Ophiuchi	red giant	white dwarf	454	yes	yes	-

Gamma-ray binaries: location

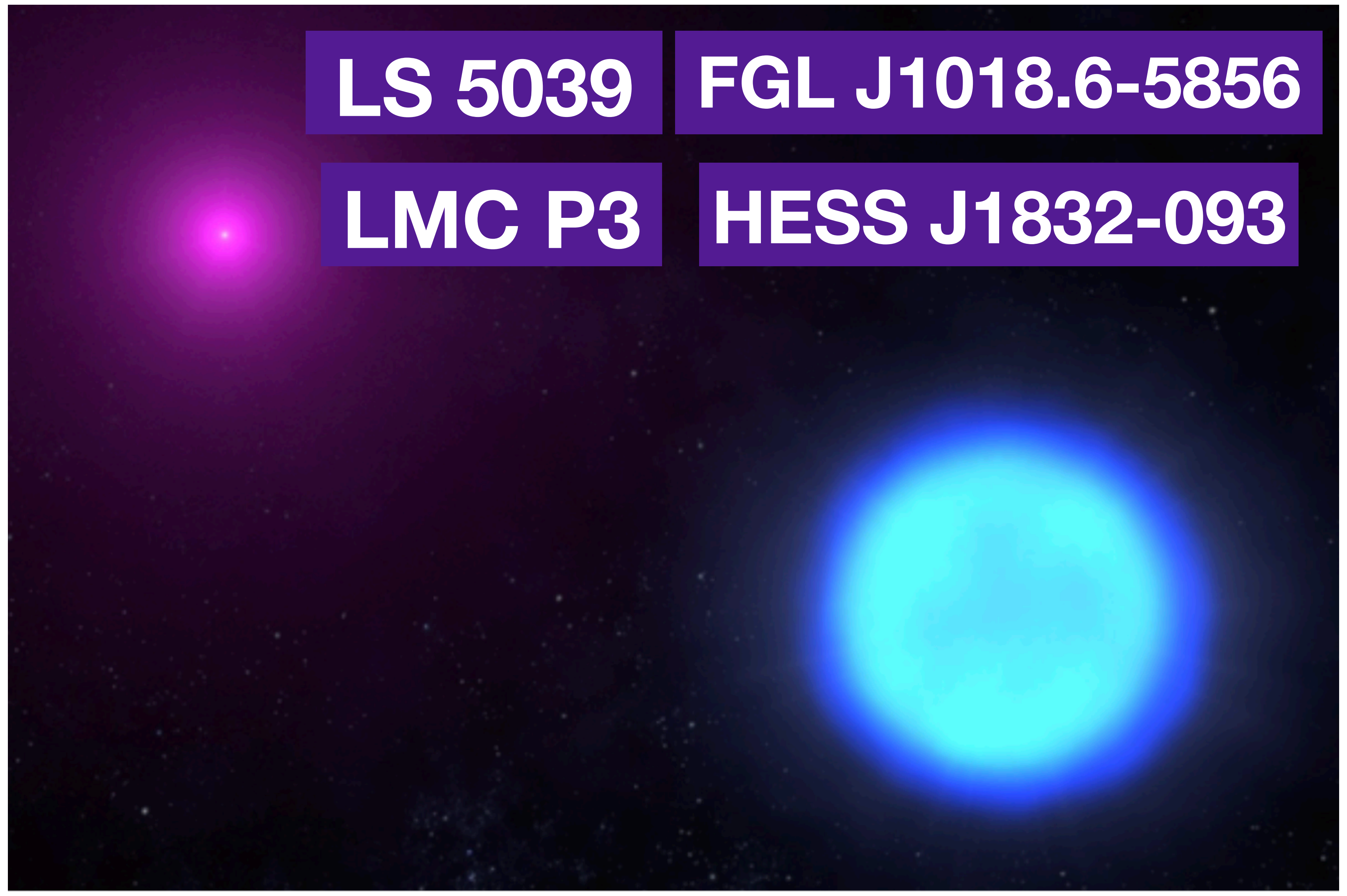


tevCat

Gamma-ray binaries

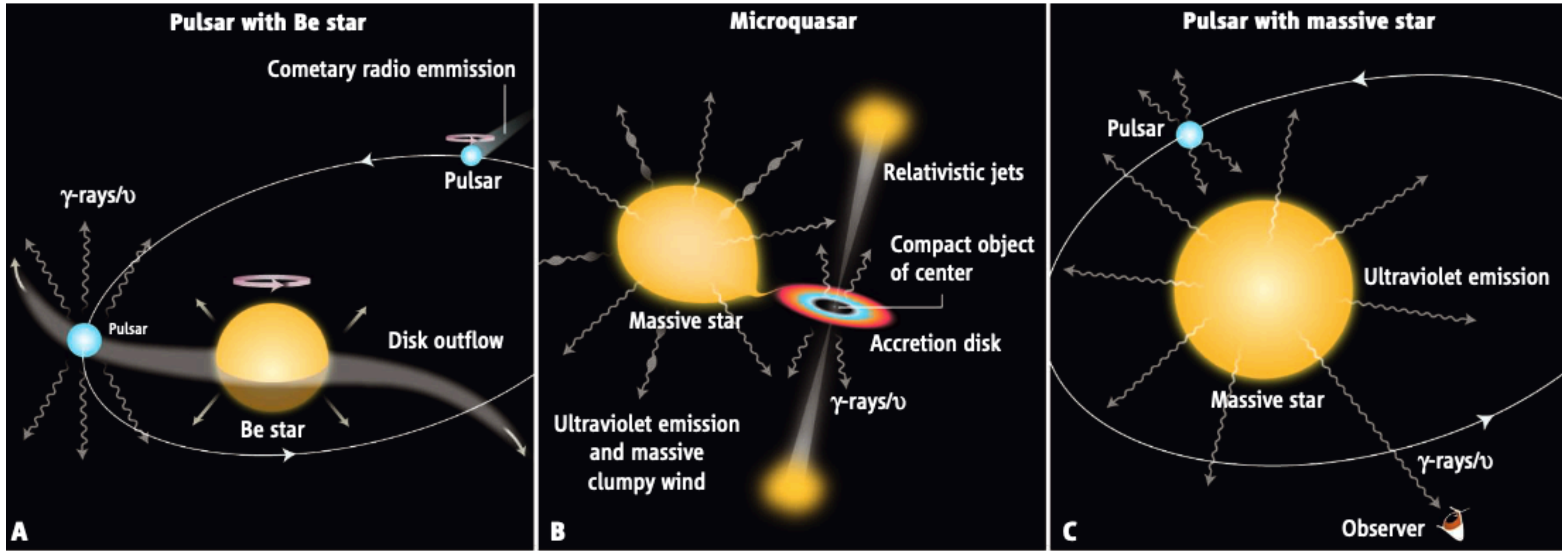
With circumstellar disk (different i)

Without circumstellar disk



Gamma-ray binaries

- **Common characteristics:**
  - **Massive** companion star
  - Similar **spectra** & γ-ray emission **variability**
    - Powerlaws, exponential cutoff
      - Some up to few tens of TeV
    - Variable VHE gamma-ray emission
  - Non-thermal radio emission
  - Moderate X-ray emission
  - **HE and VHE not necessarily correlated** (LSI, HESSJ0632, LS 5039)



Mirabel 2012

What is the nature of the compact object?

*sample of few systems collected in this table

Gamma-ray binaries

Pulsar-wind

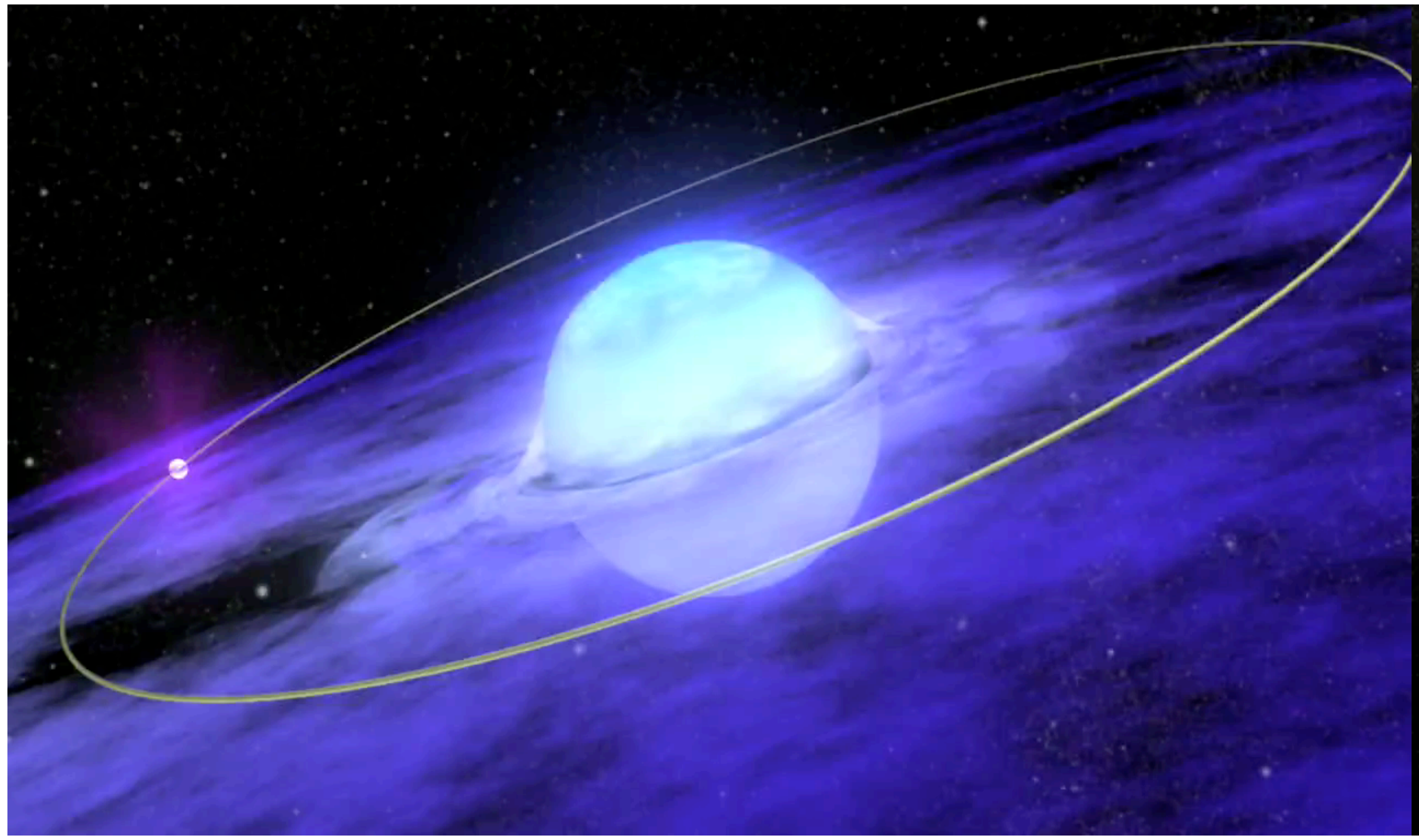
- Rotation-powered highly magnetized pulsar
- Pulsar wind+stellar wind

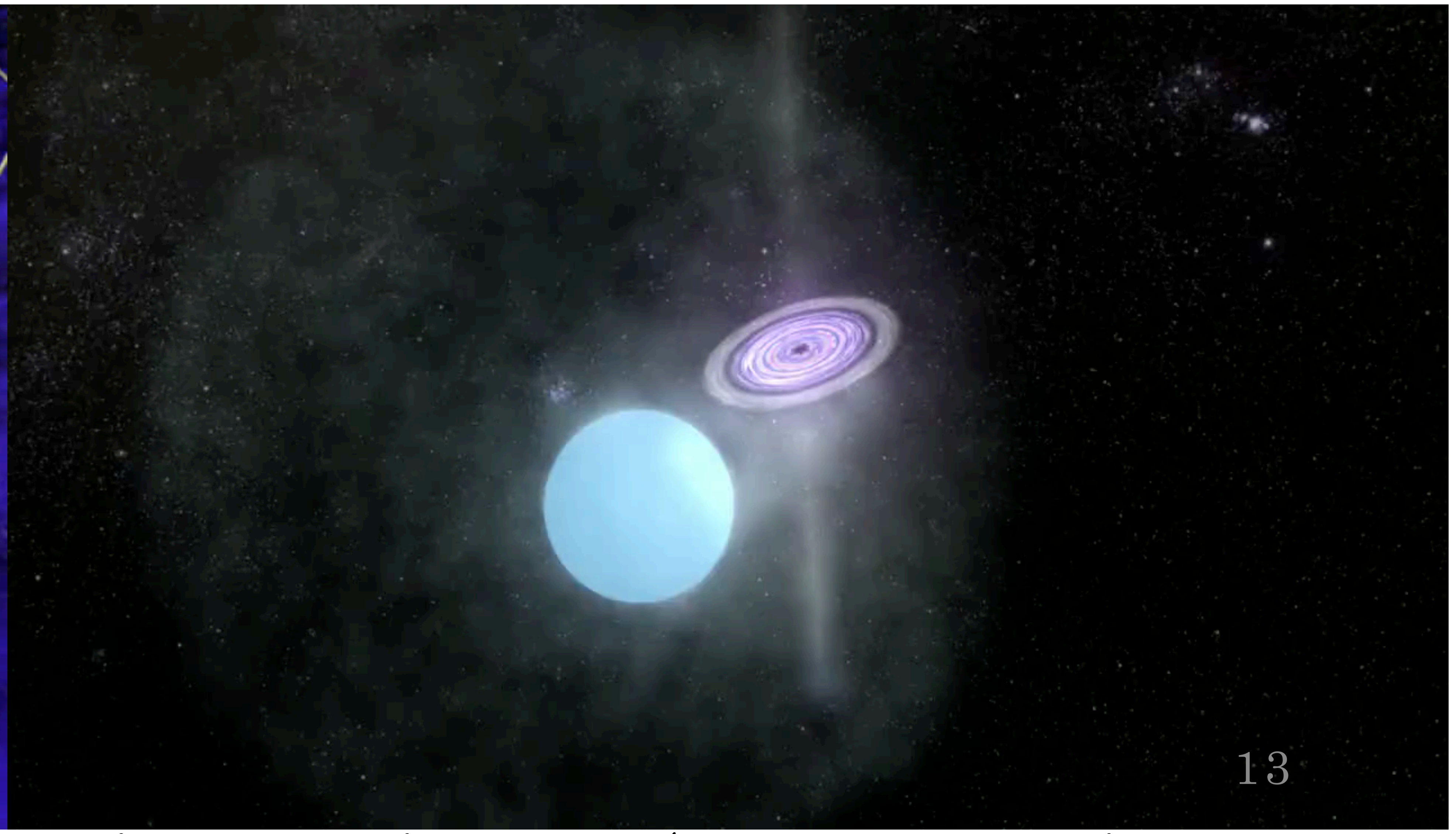
Microquasar

- Accretion onto compact object
- Ejection of plasma in jets

(Generally) No pulsations

No JETS





Credit: Walt Feimer, NASA/Goddard Space Flight Center

Gamma-ray binaries

- **Common characteristics:**
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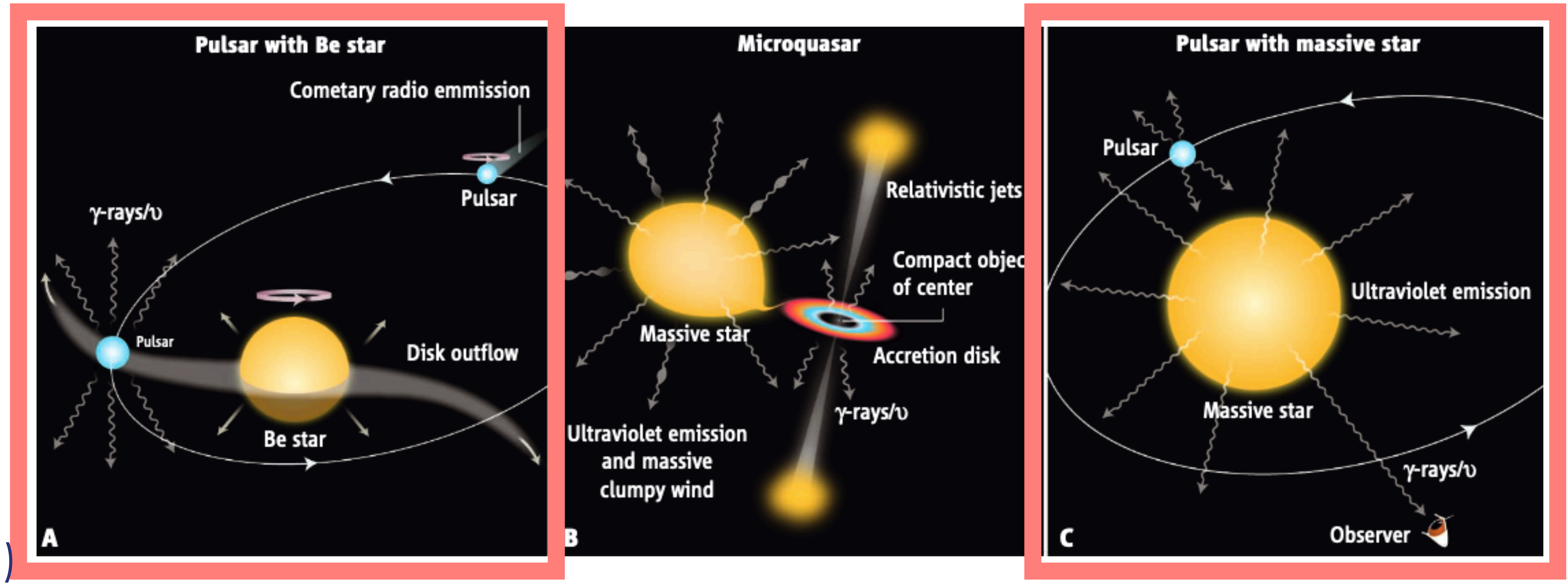


Mirabel 2012

  - Generally, **no pulsation, no jets**
    - **Some systems host a pulsar**
  - **Leptonic emission favored (IC over stellar photons)**

Gamma-ray binaries are likely non-accreting pulsar binaries

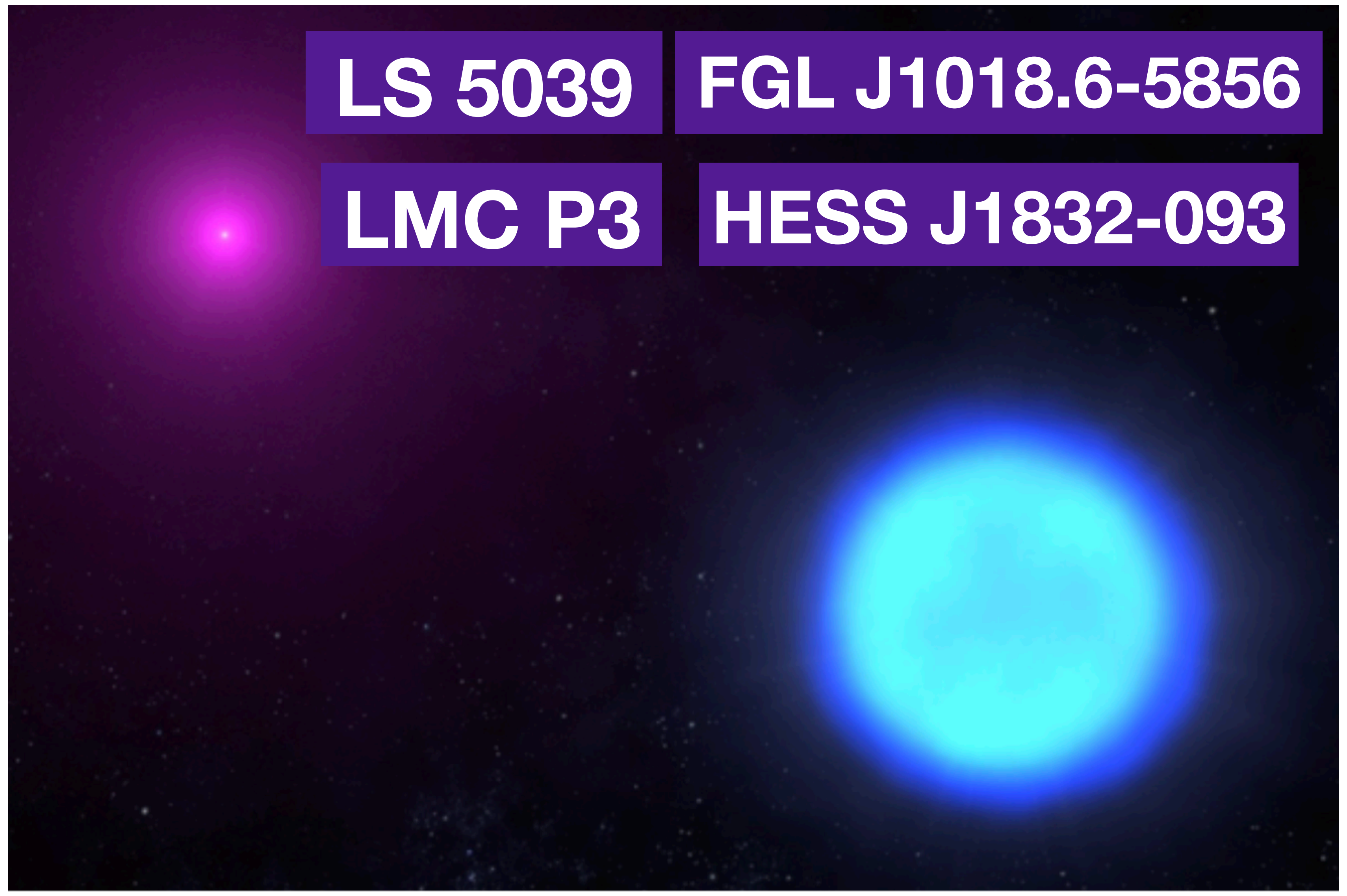
System	Star spectral type	Compact object	Star mass [M☉]	D [kpc]	Porb [days]	e	i	VHE emission
PSR B1259-53	O9.5Ve	48ms pulsar	31	2.3	1236.72	0.87	19-31	P
LS 5039	O	pulsar?	23	2.5	3.91	0.35	13-64	INFC
LS I +61 303	Be	pulsar	12	2.0	26.49	0.54	10-60	A
HESS J0632+057	Be	-	16	1.5	315.50	0.83	47-80	A/P
FGL J1018.6-5856	O	-	31	5.4	16.58	-	-	INFC
PSR J2032+4127	Be	143 ms pulsar	15	1.8	50 years	0.94-0.99	60	P

*sample of few systems collected in this table

Gamma-ray binaries

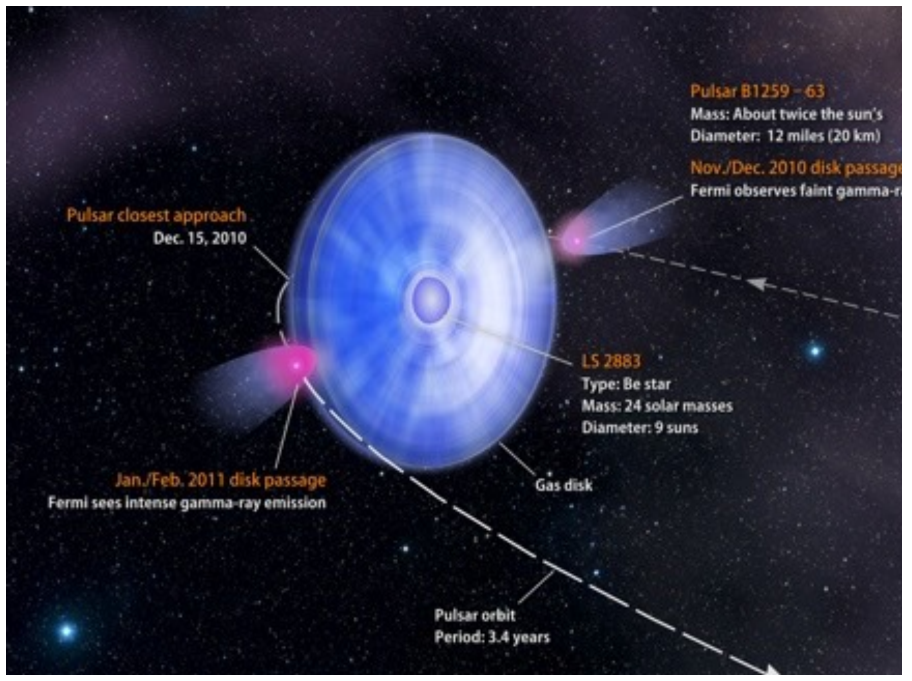
With circumstellar disk (different i)

Without circumstellar disk

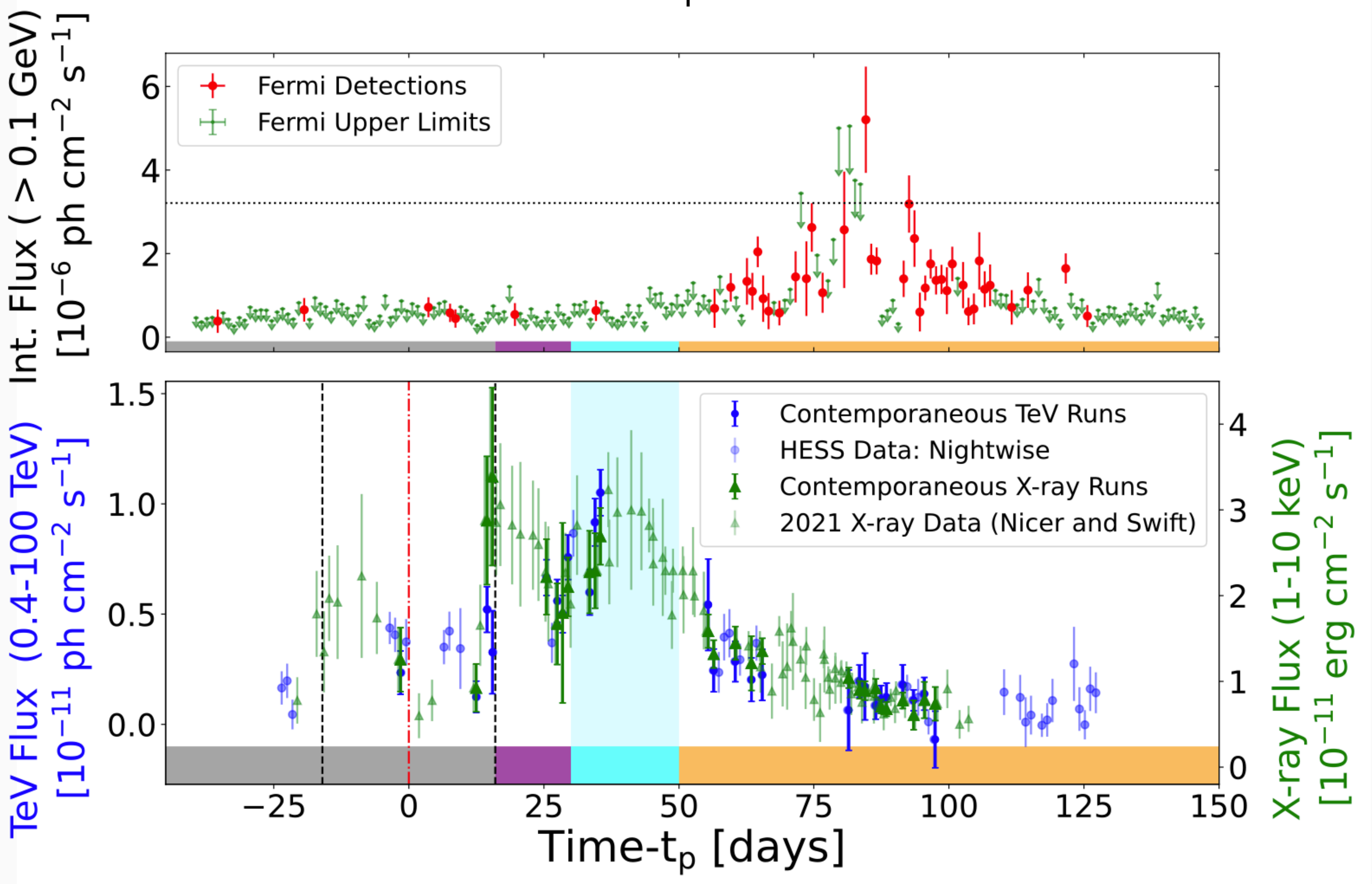


Gamma-ray binaries with long period

PSR B1259-63



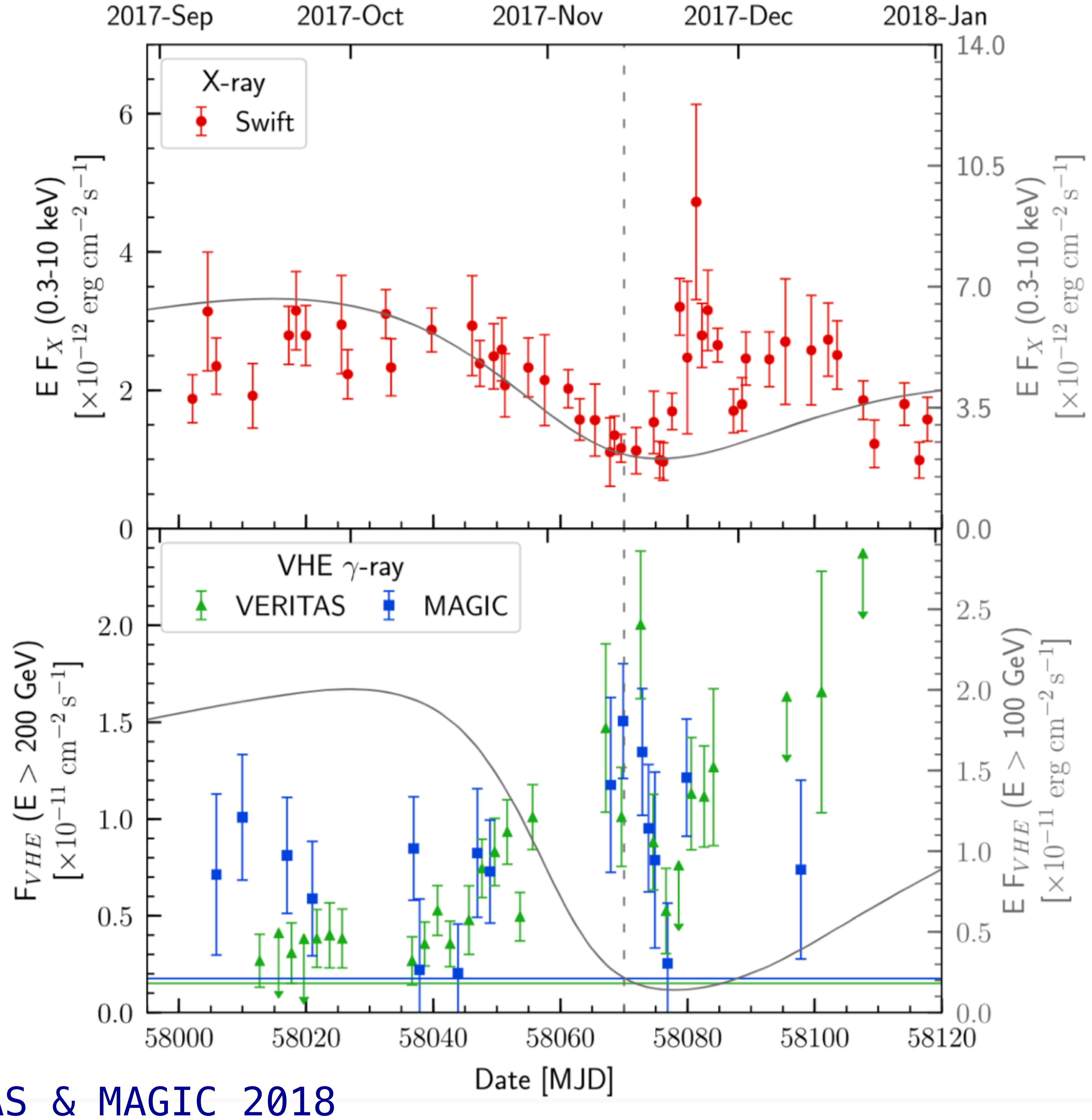
- VHE discovery by HESS (Aharonian et al. 2005)
  - O9.5 Ve star + 48ms pulsar
  - **3.4 yr orbit**
- Emission during **periastron** passage
- Previous 2021 passage just reported (H.E.S.S. Coll 2024)
  - multiple emission zone



H.E.S.S. Coll (2024)

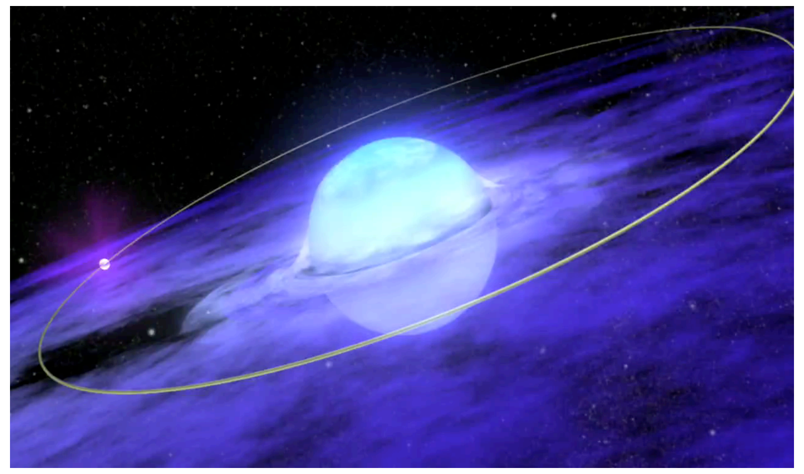
PSR J2032+4127

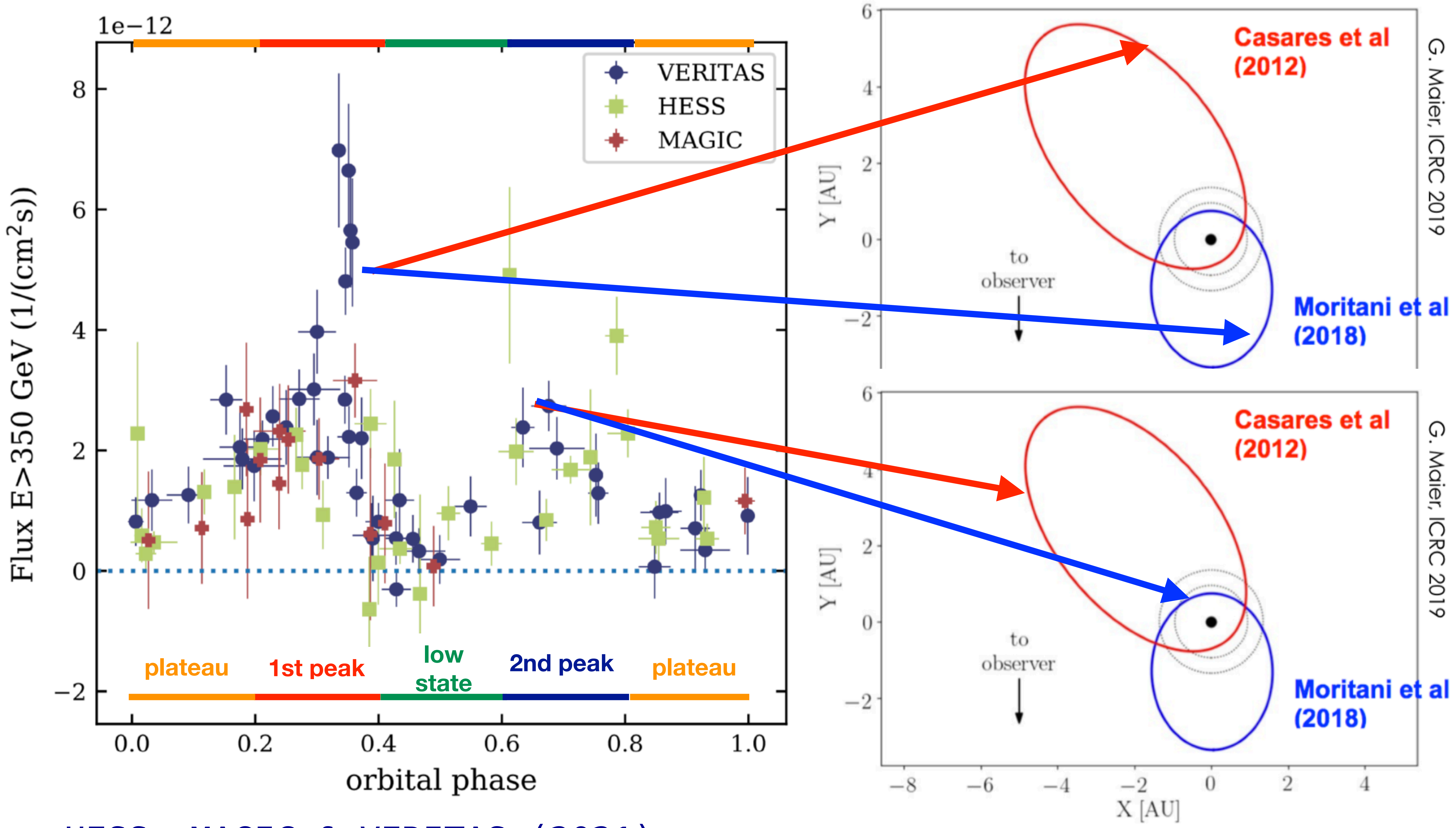
- VHE discovery by VERITAS and MAGIC (Abeysekara et al. 2018)
  - Be star + 142ms pulsar
  - **50 yr orbit** -> next 2067
- VHE peak during periastron passage



VERITAS & MAGIC 2018

HESS J0632 +057





HESS, MAGIC & VERITAS (2021)

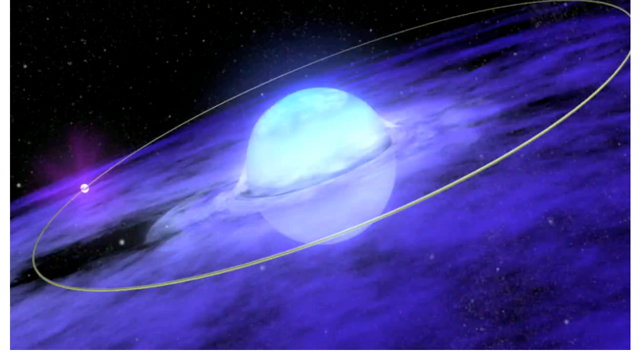
- VHE discovery by HESS (Aharonian et al. 2007)
  - Be star + unknown
    - **Pulsar scenario proposed**

Multi-year multi-IACT campaign

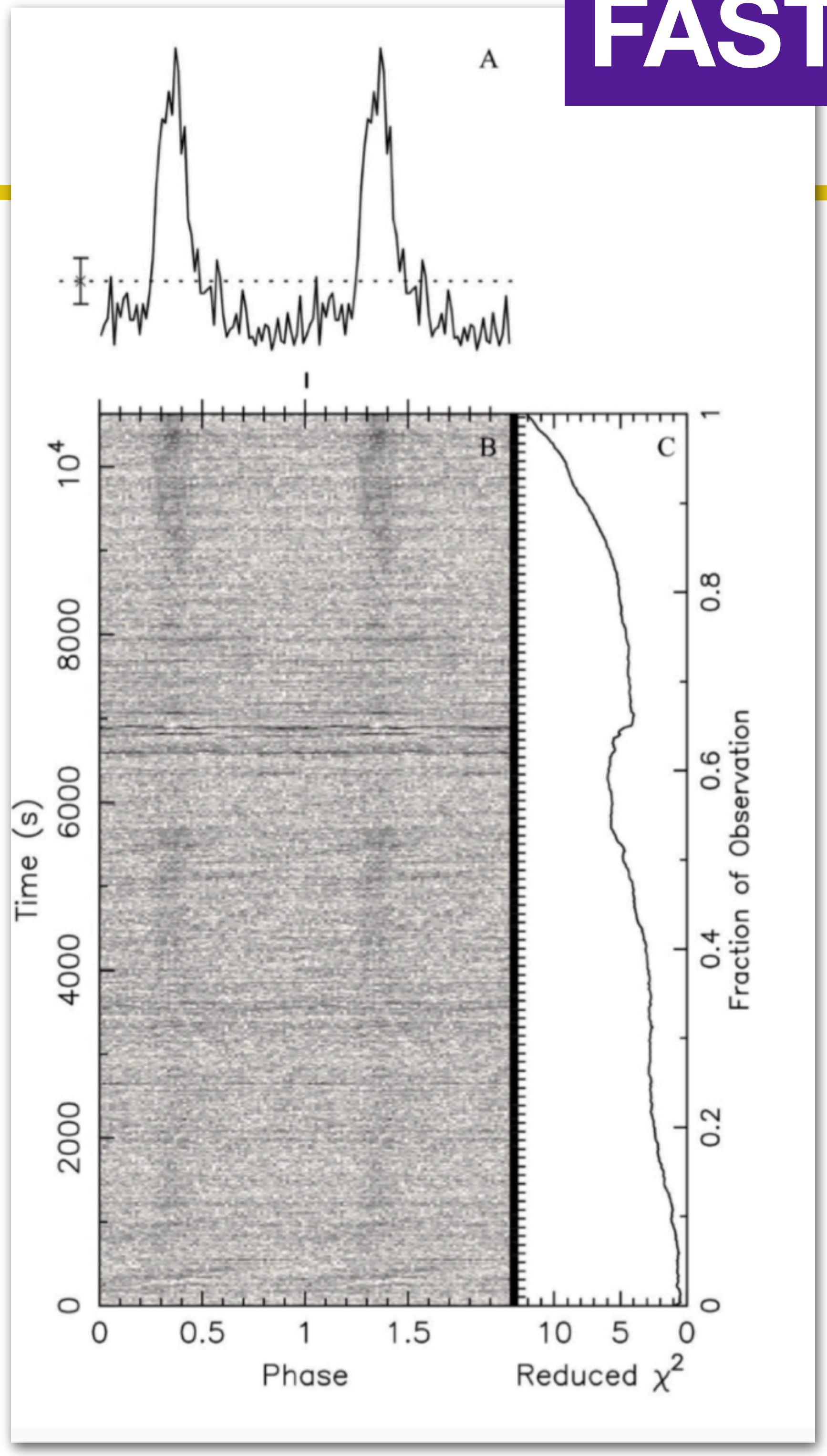
- **Orbital period at TeV: 316.7** ± 4.4(stat) ± 2.5(sys) **days** (HESS, MAGIC, VERITAS coll. 2021)
- VHE lightcurve: **double peak**
- **Orbital solution still not clear** [Casares et al. (2012), Moritani et al.(2018), Malyshev et al. (2019), Tokayer et al. (2021), Chen et al. (2021), Kim et al. (2022), Matchett (Fermi Symp 2022)]

LS I +61 303

- VHE discovery by MAGIC (Albert et al. 2006)
- Be star + **0.27 s pulsar** (Weng et al. 2022)
  - No periodicity in the pulsar signal
  - Magnetar?
  - **Orbit: 26.4 day**
  - TeV **super-orbit**: **1610 days**(Ahnen et al. 2016)
- VHE peak during **apastron**
- SED by LHAASO **up to 100 TeV without cutoff**, orbital modulation (Cong Li, Gamma 2024)

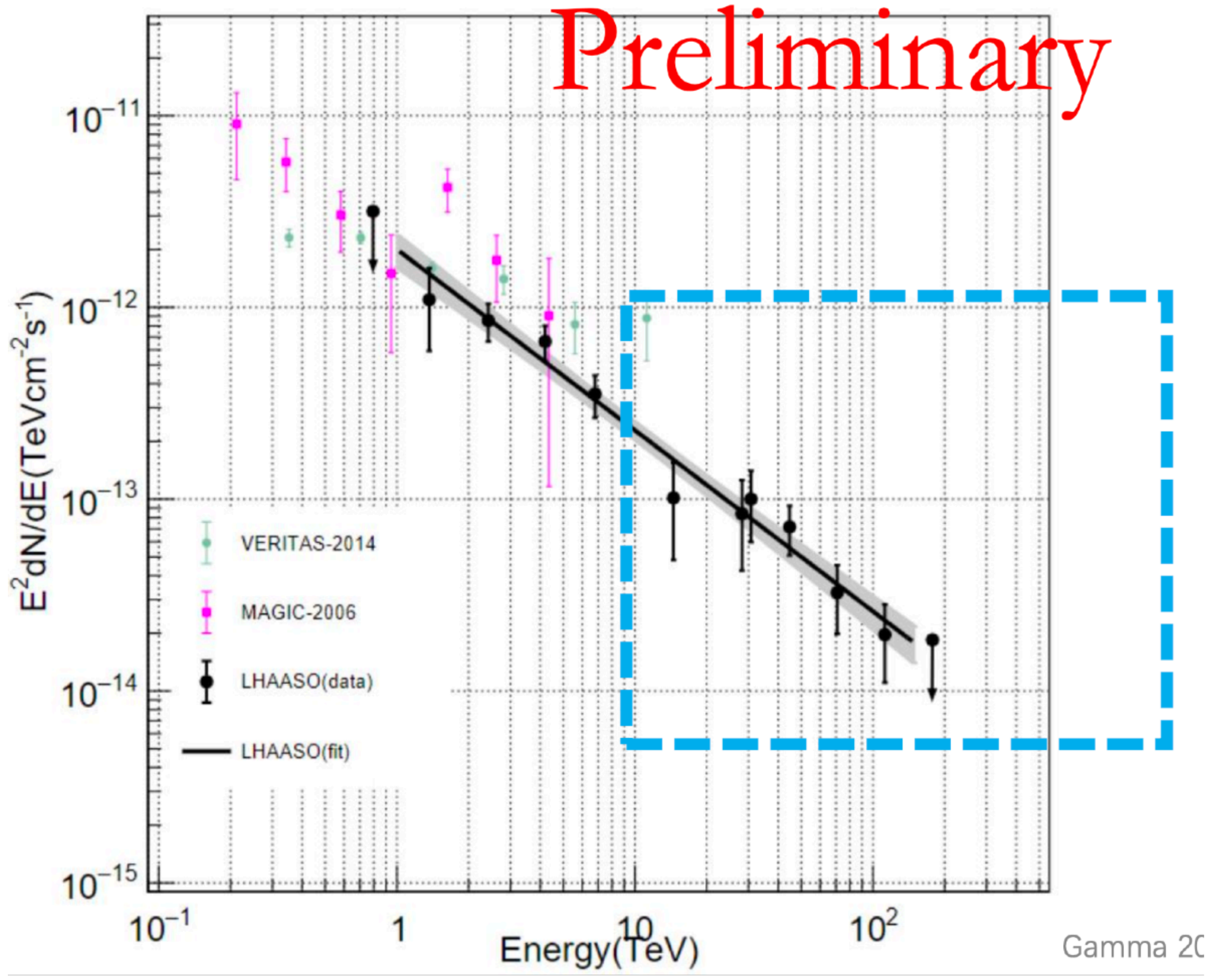


FAST

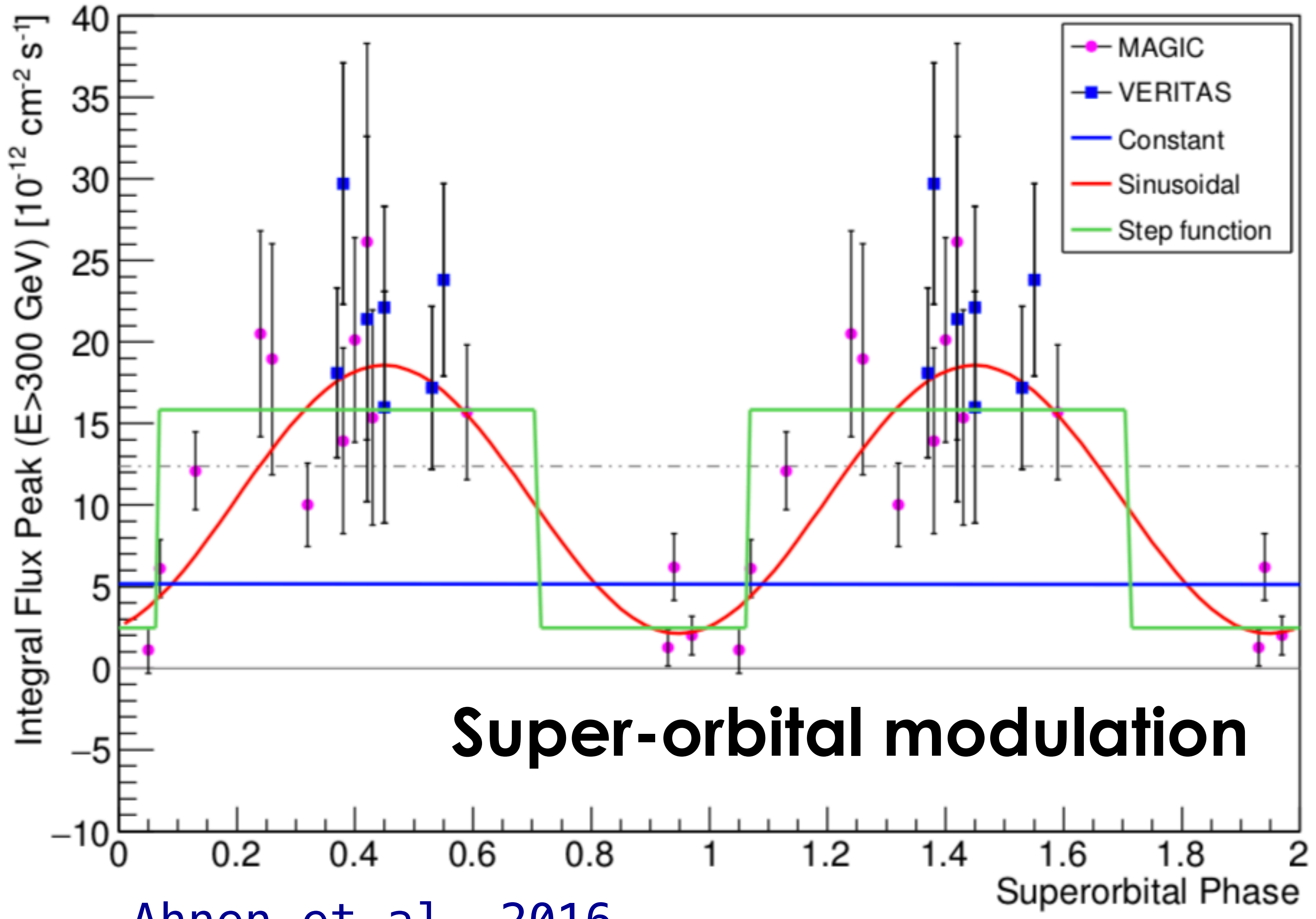


Weng et al. (2022)

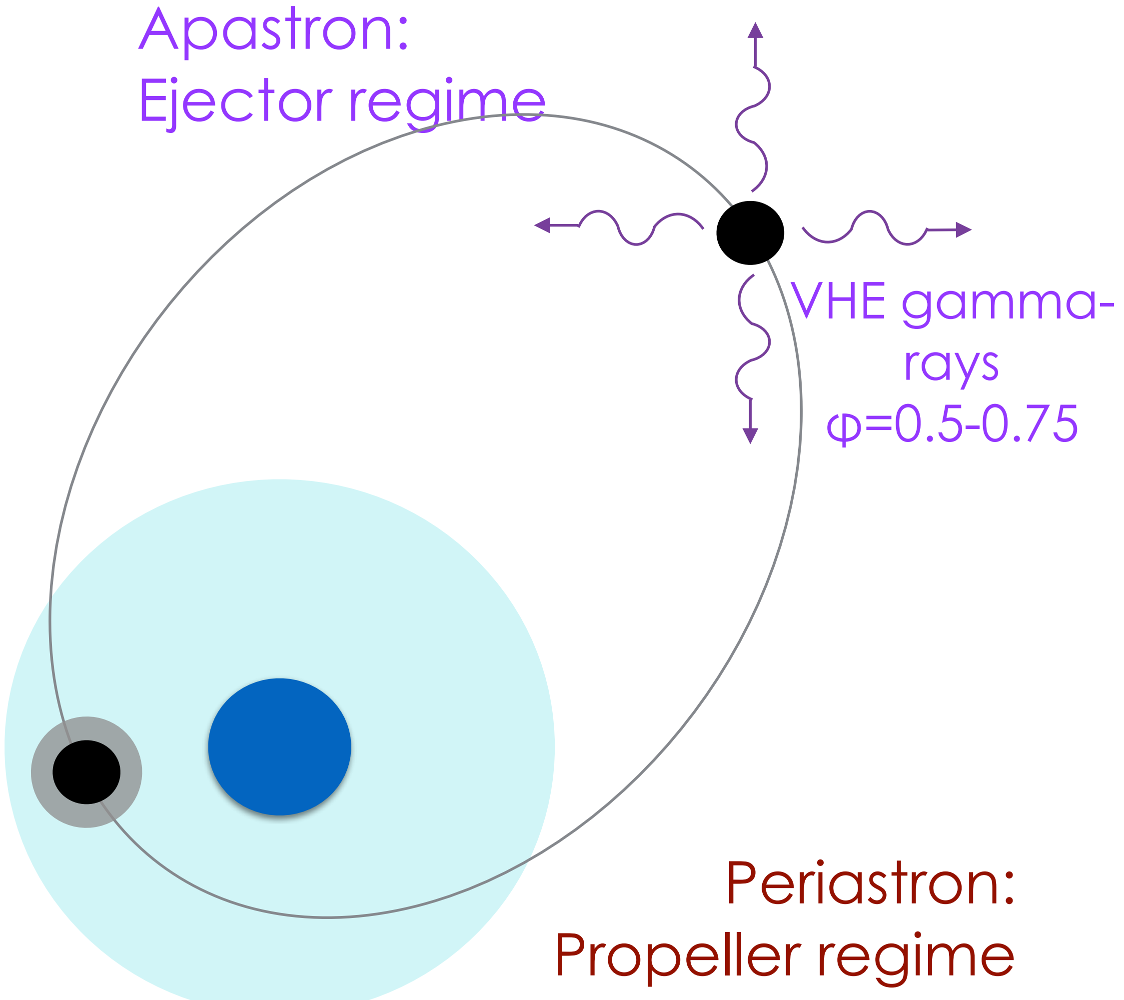
LHAASO

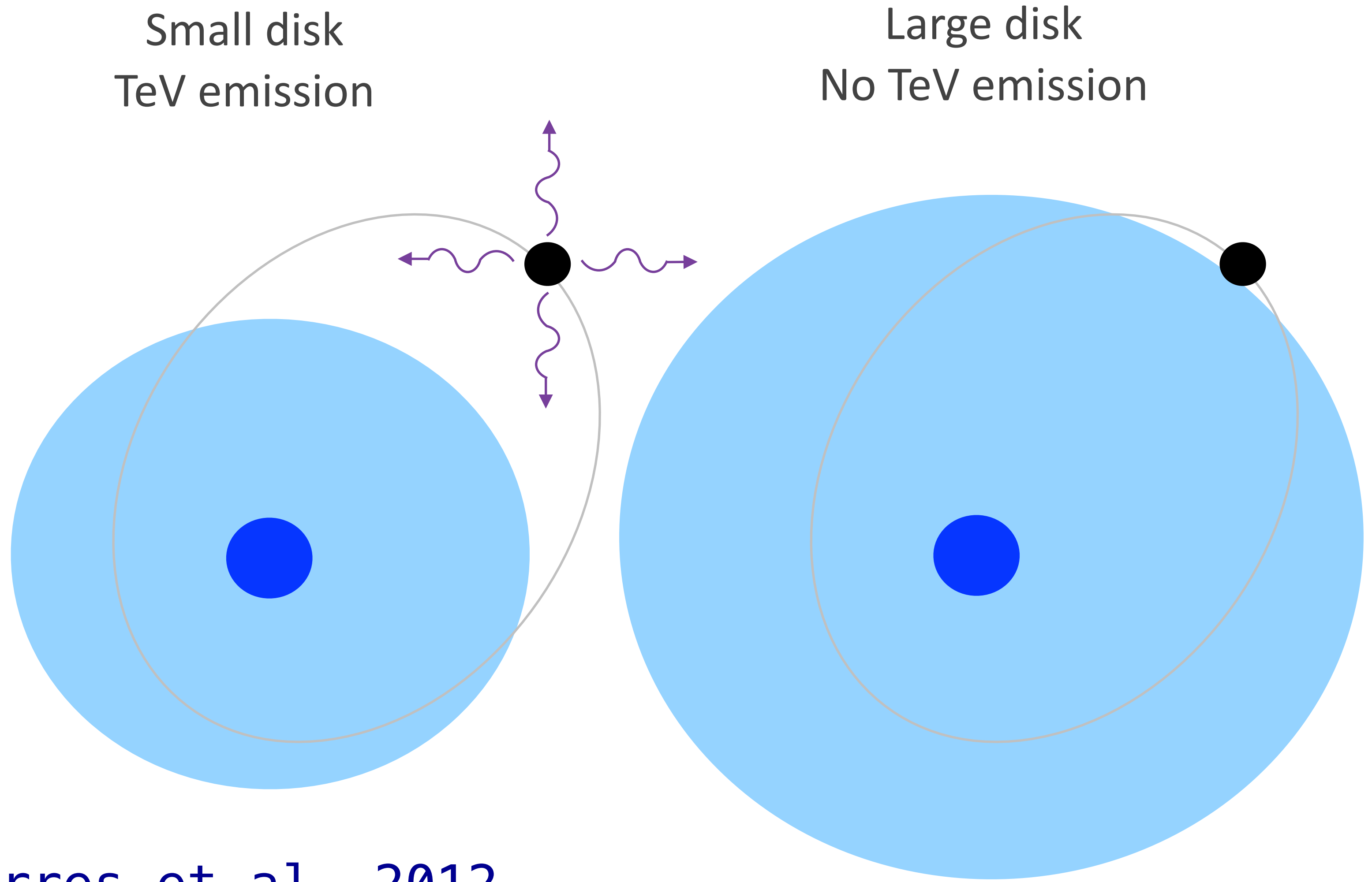


Cong Li (Gamma 2024)



Ahnen et al. 2016

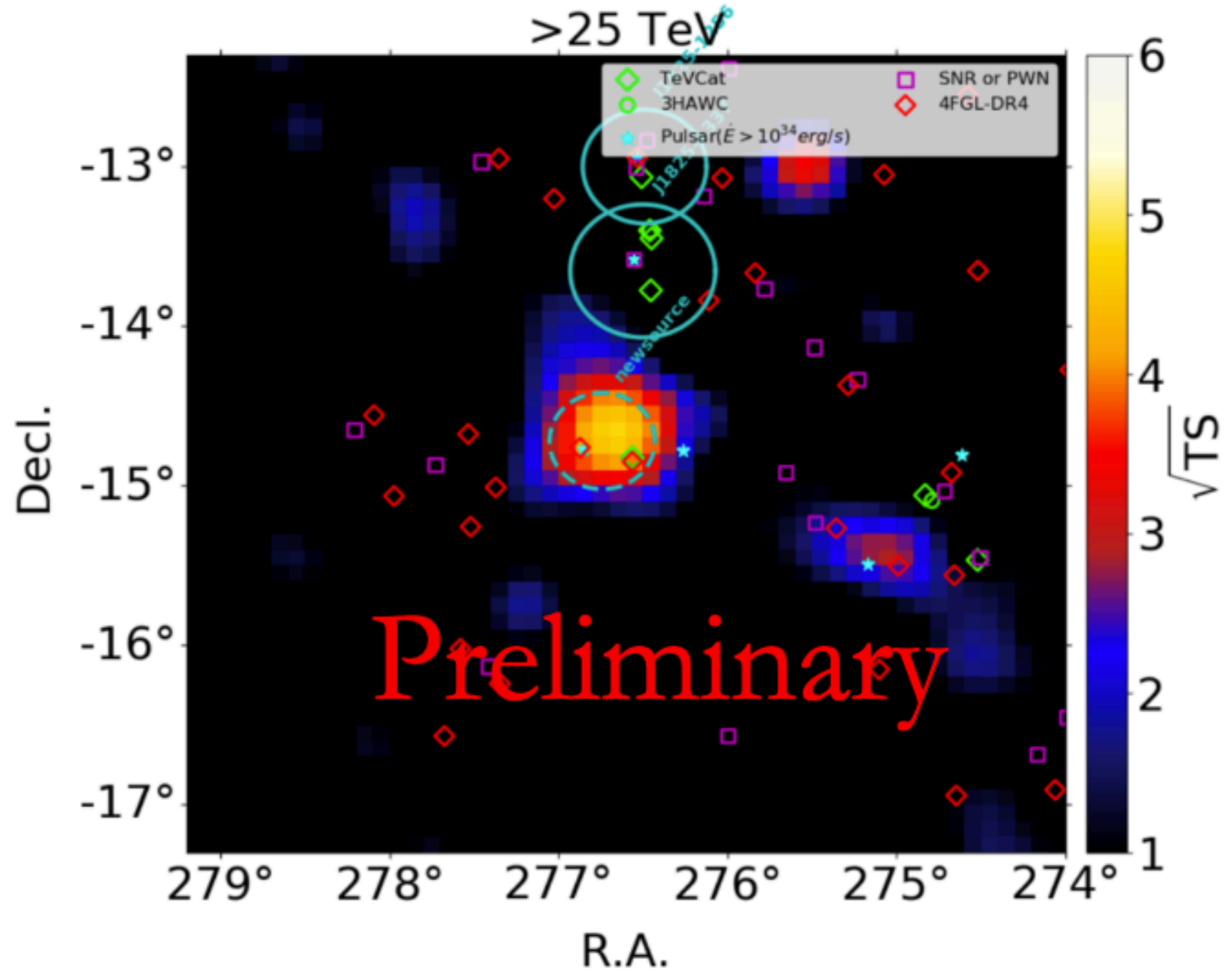




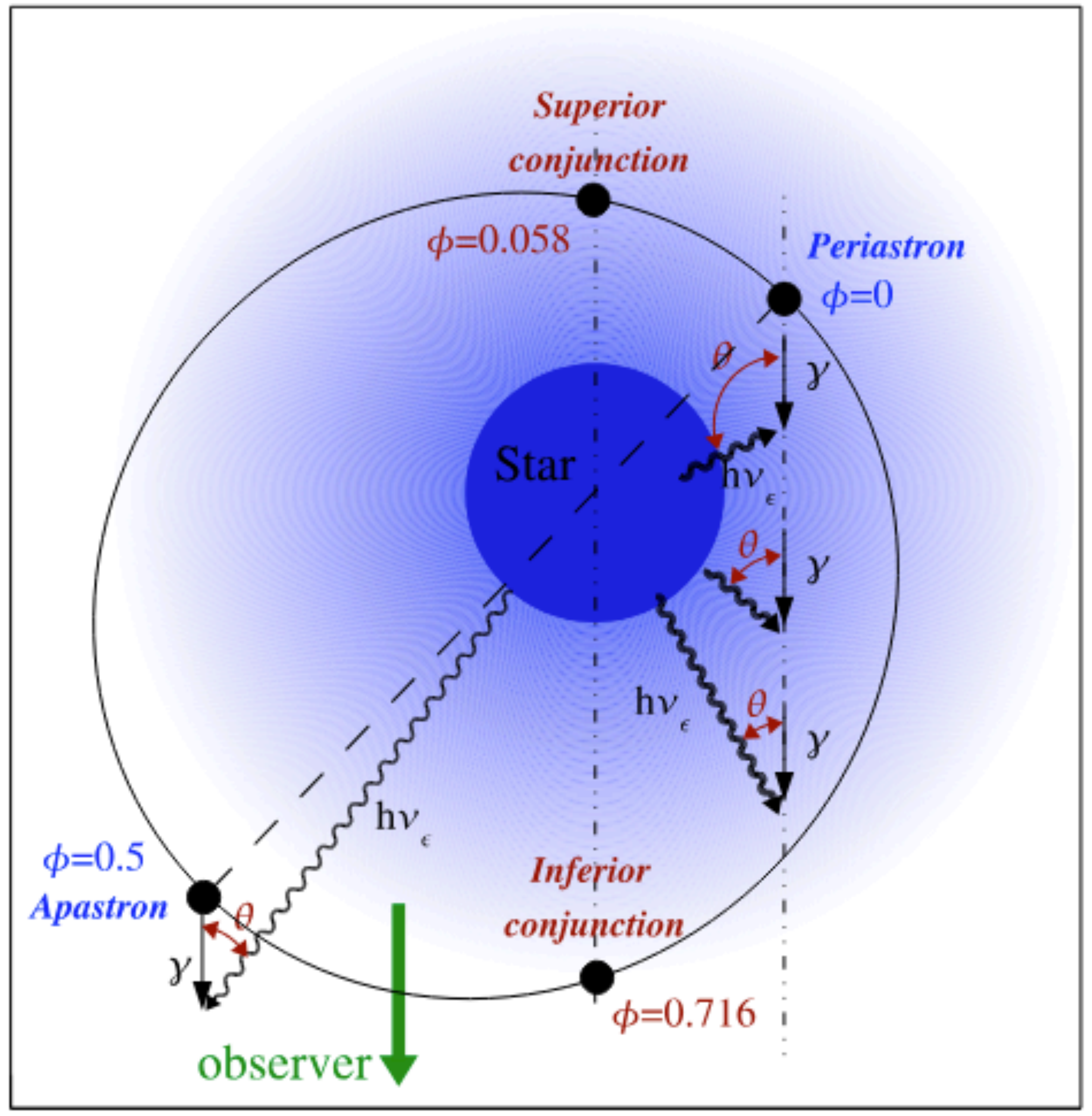
Torres et al. 2012

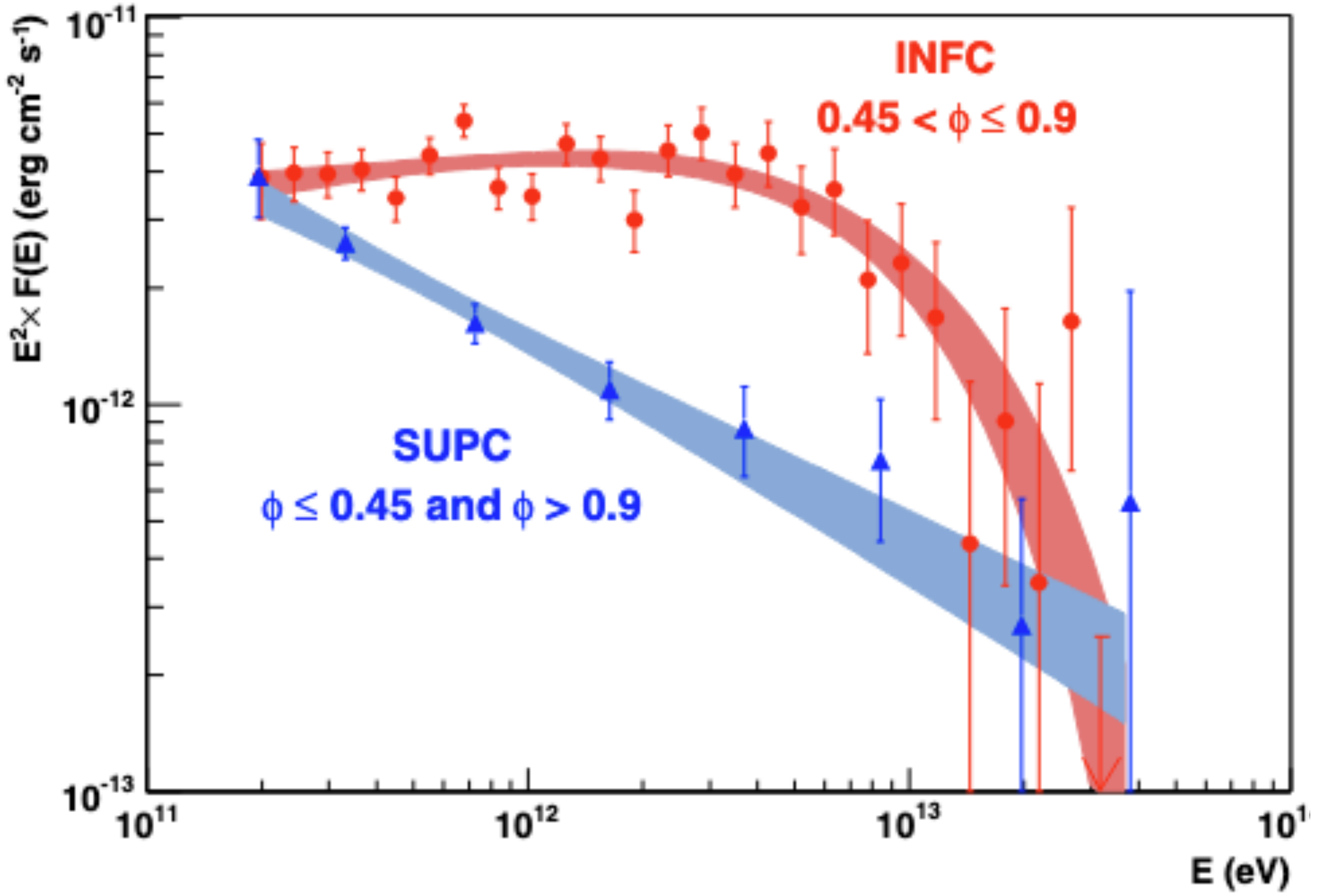
LS 5039

- VHE emission discovery by H.E.S.S. (Aharonian et al. 2006)
  - INFC and SUPC
- O6.5V star +
  - **+pulsar?:** hints of 9 s pulsations in hard X-rays (Yoneda et al. 2020) -> magnetar?
  - Triple system? (Zeng et al. 2024)
  - **3.9h orbit**
- **Short-term X-ray** variability (Yoneda et al. 2023)
- Seen by **HAWC** with flux modulations (Wang PosICRC 2023) and **LHAASO** (Cong Li Gamma 2024) up to several TeV

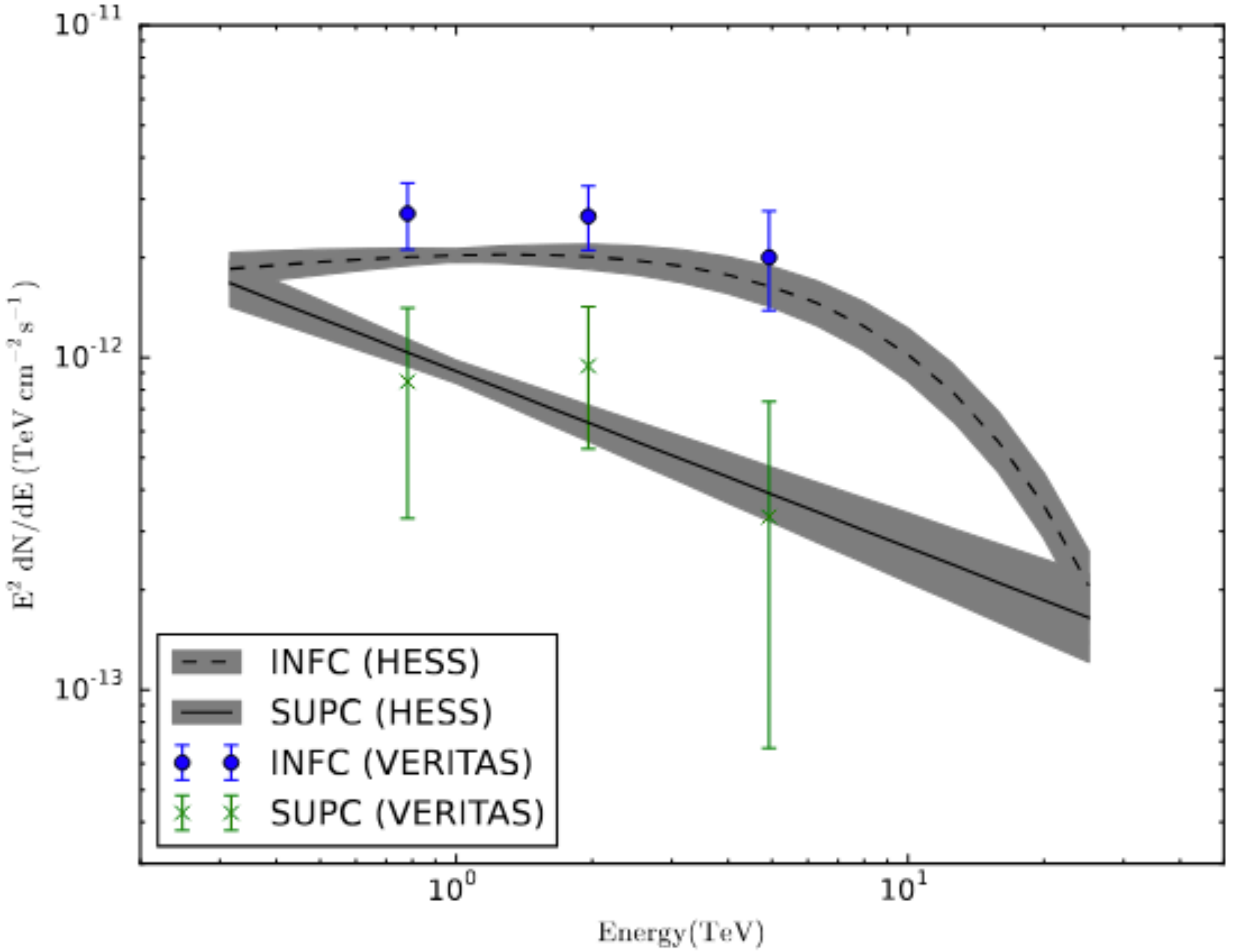


Cong Li CDY DIAS Workshop 2024



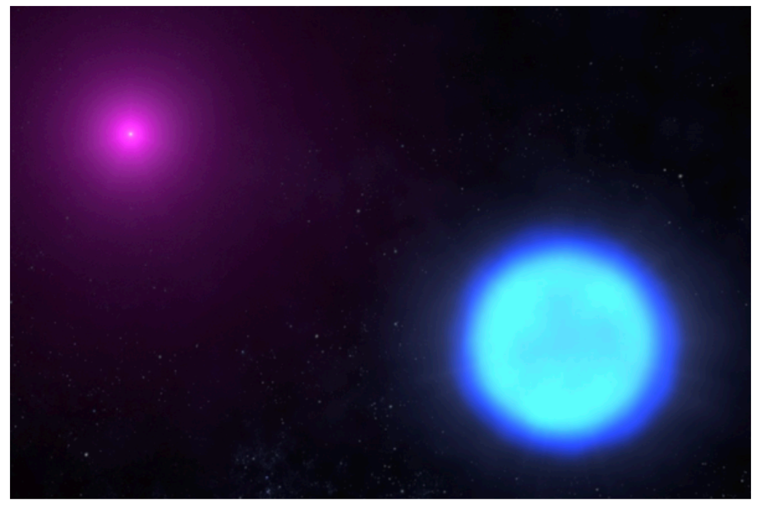


Aharonian et al. 2006



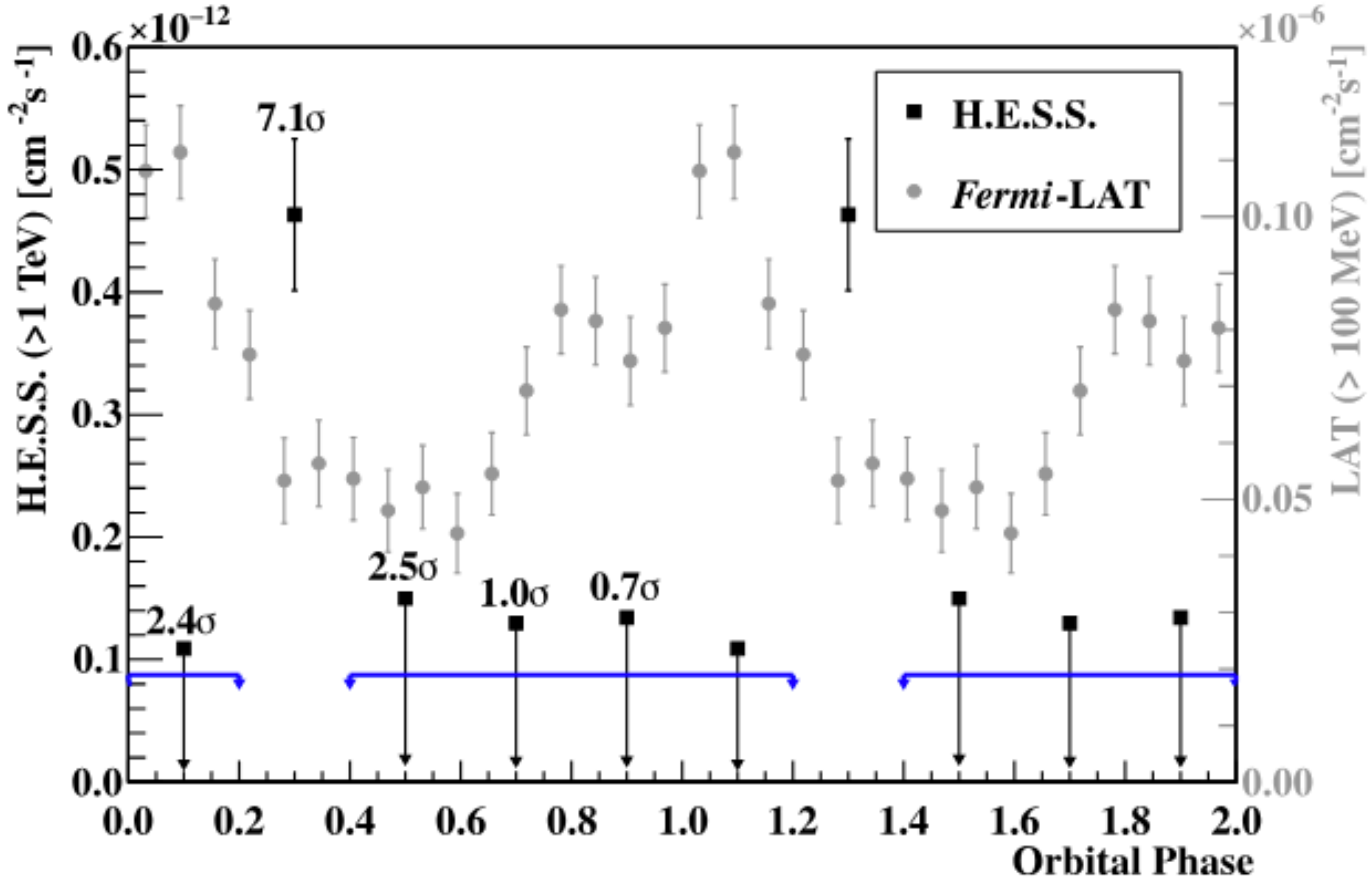
VERITAS 2020

O-type binaries



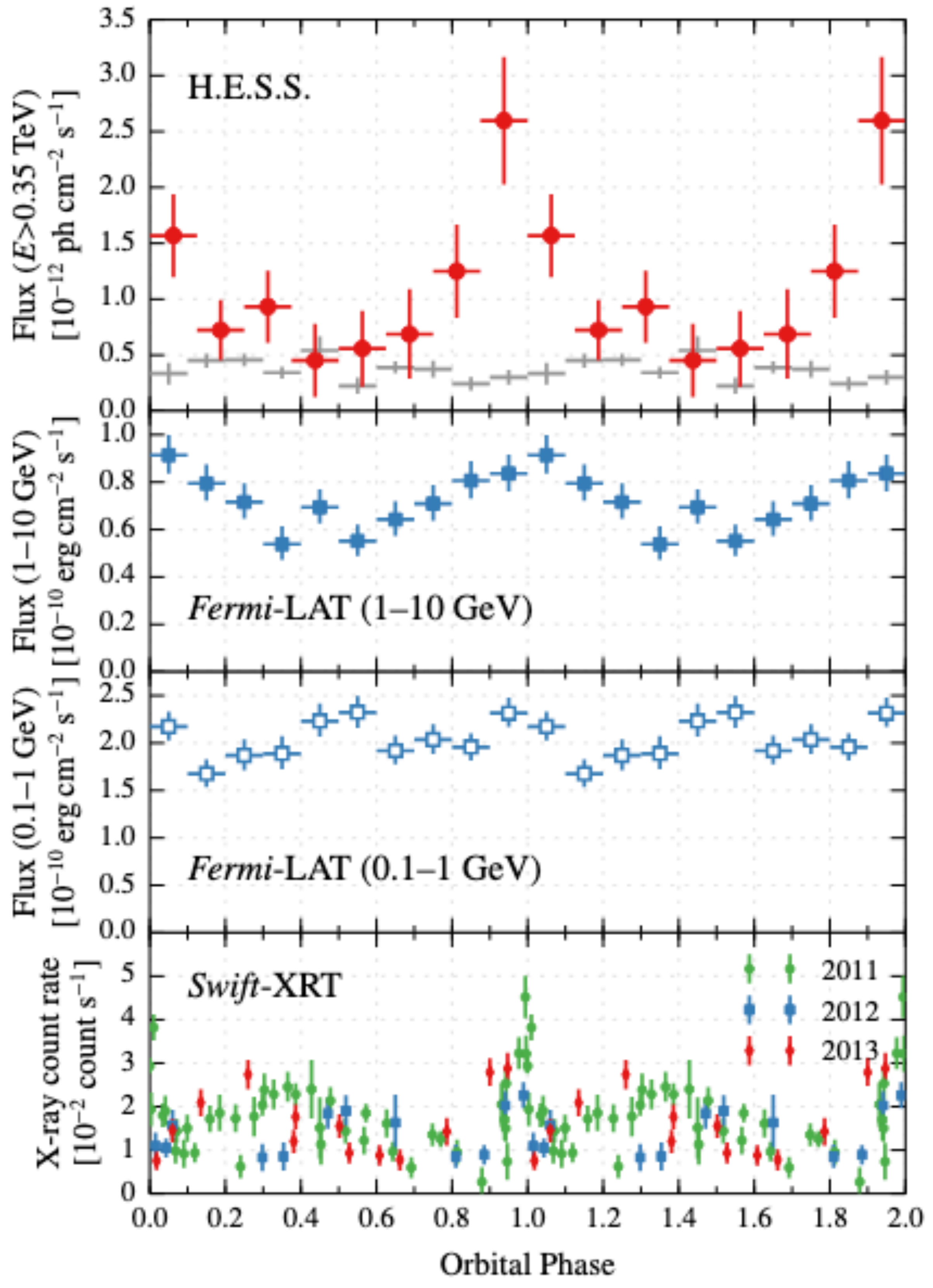
LMC P3

- Only **extragalactic** binary
- Periodic signal (10.3 days) **discovered through a blind search** at HE (Corbet et al. 2016)
- VHE emission phase-locked to the orbital period of the system (Aharonian et al. 2018).
- O5III star + unknown (Weng et al. 2022)
- Orbital parameters not well defined

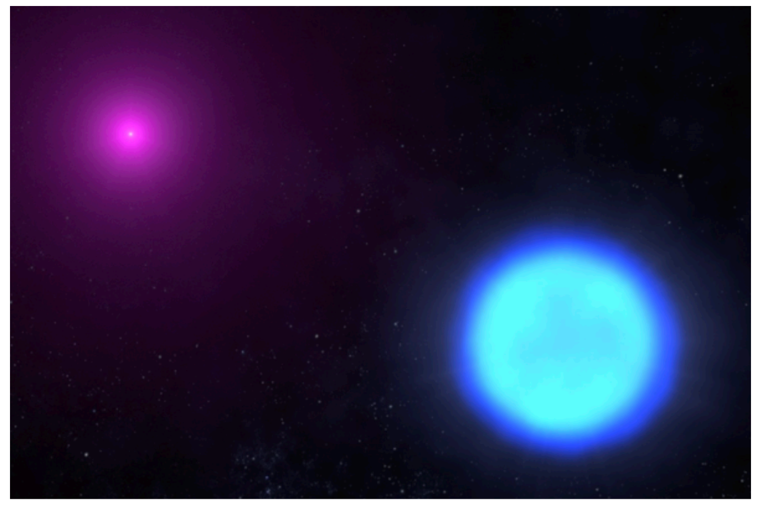


1FGL J1018.6-5856

- First binary **discovered through a blind search** at HE (Fermi 2012)
- O6V + NS favored (Strader et al. 2015)
- VHE variable with evidence of periodic flux at 3 sigma level (Aharonian et al. 2018), **SED up to 20 TeV**
- Coincidence between VHE, HE and X-ray peaks



O-type binaries



HESS J1832-093

- VHE signal discovered (Aharonian et al. 2014)
- Periodic modulation (86 days) **discovered** (Martí–Devesa & Reimer 2020)
  - **Identification as a new gamma-ray binary**
- No optical counterpart, but coincident with a NIR source
  - **Companion star is a O6 V** (van Soelen et al. 2024)

- **Apparent grouping around a given spectral type (O5/O6)** for O-type gamma-ray binaries (LS 5039, 1 FGL1018, HESS J1832, LMC P3, J1405) (van Soelen et al. 2024)
  - interplay between the initial mass function (IMF) and the wind momentum–luminosity relation (WLR)
    - to form with earlier, more luminous, O-type stars as they will have a higher wind momentum
      - However, since the IMF shows that the number of stars decreases with mass, **spectral types earlier than O5 will be rare**
    - **later spectral type massive companions if they are Be stars**, as this provides a denser wind in the circumstellar disc

How many more?

Galactic population of gamma-ray binaries

How many are there?

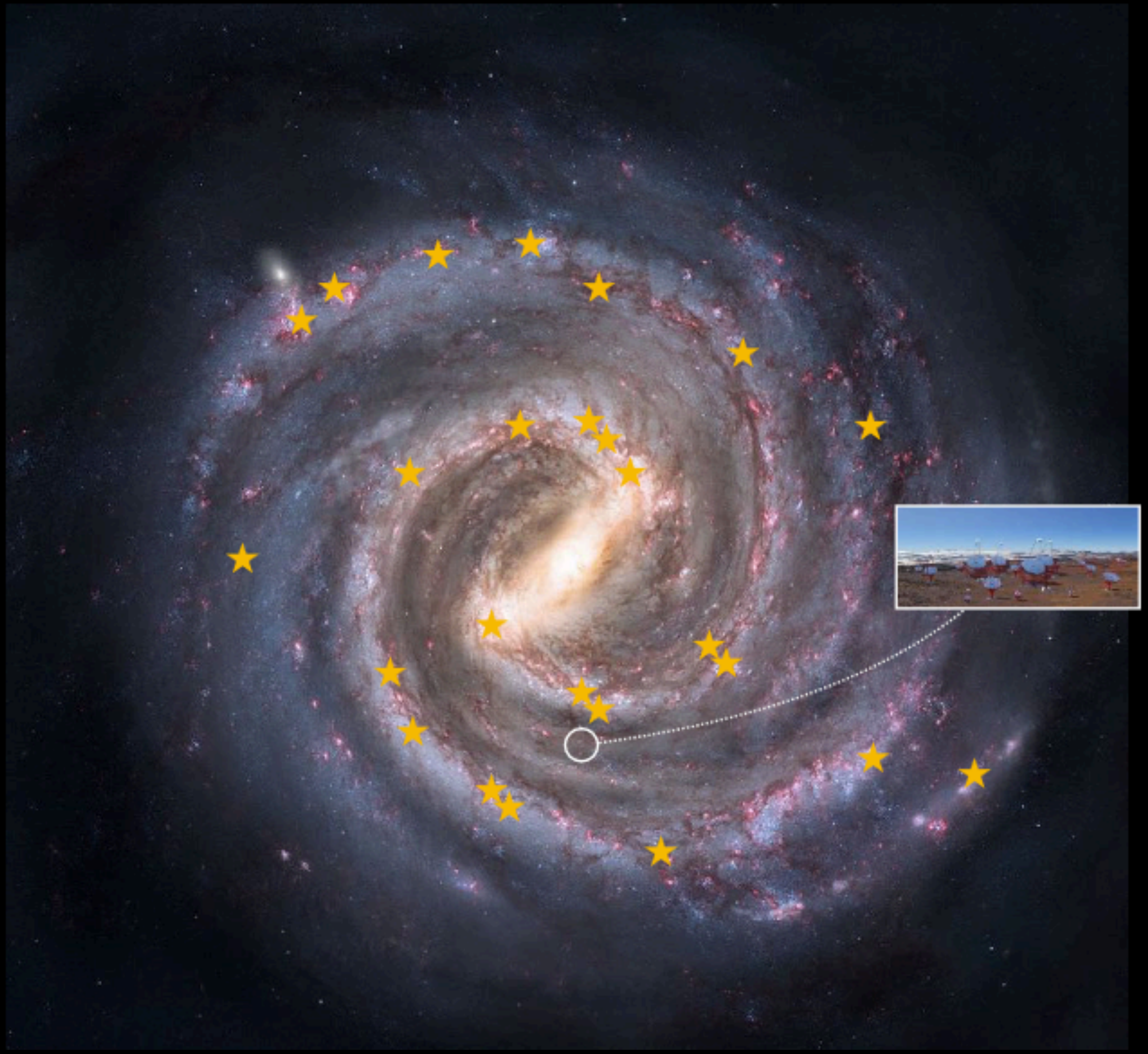
HE 124^{+125}_{-74}

VHE 172^{+328}_{-143}

Combining both estimates

145^{+107}_{-67} systems

Relative numbers of HE and
VHE detections can constrain
the relative injection efficiencies

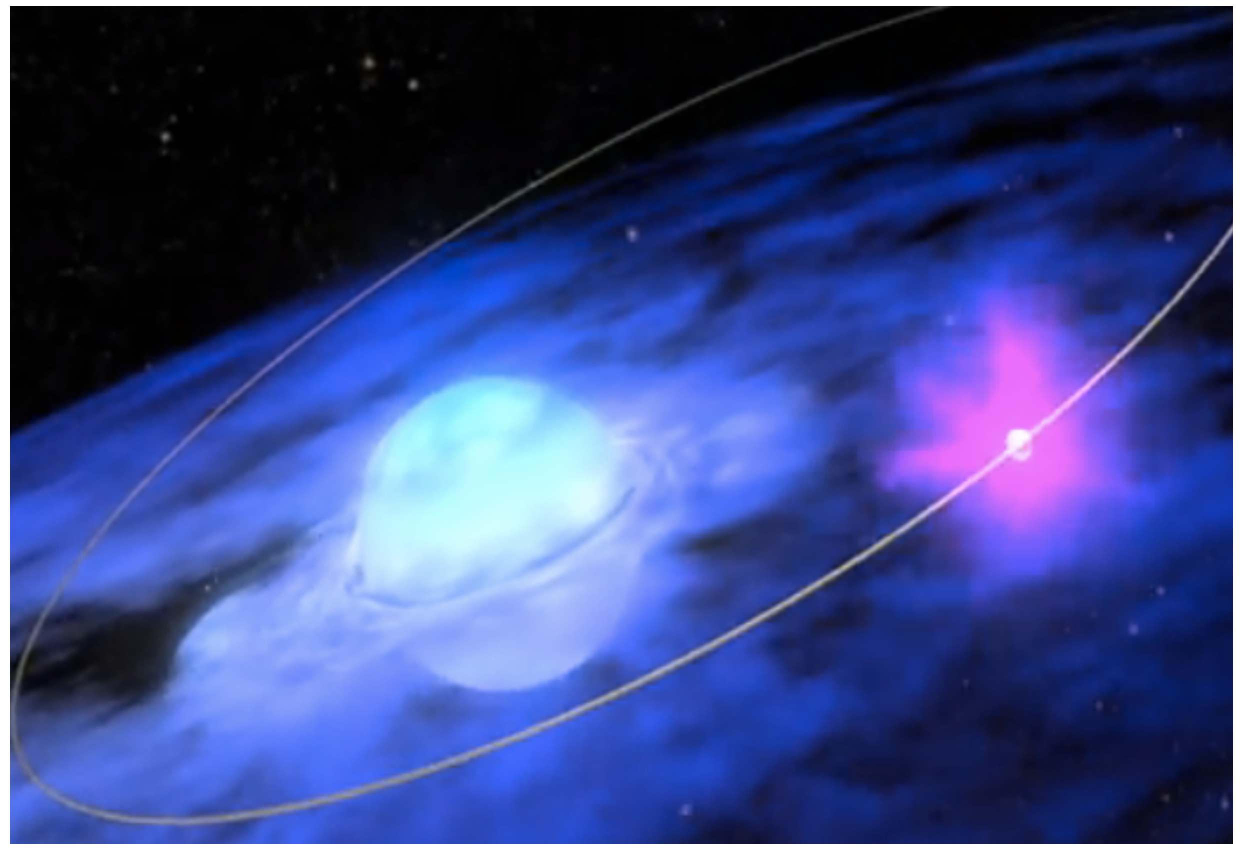


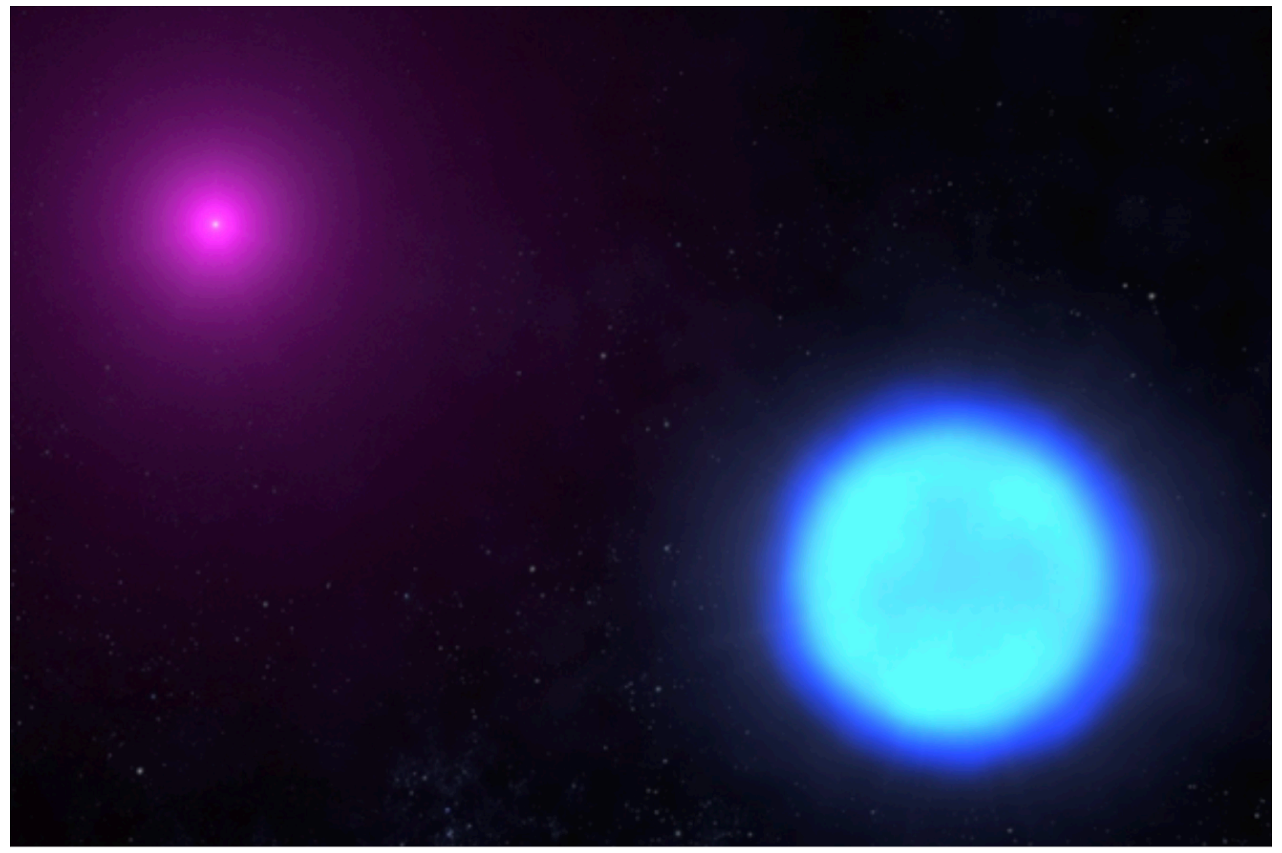
Dubus, Dublin Oct. 2024

Gamma-ray binaries

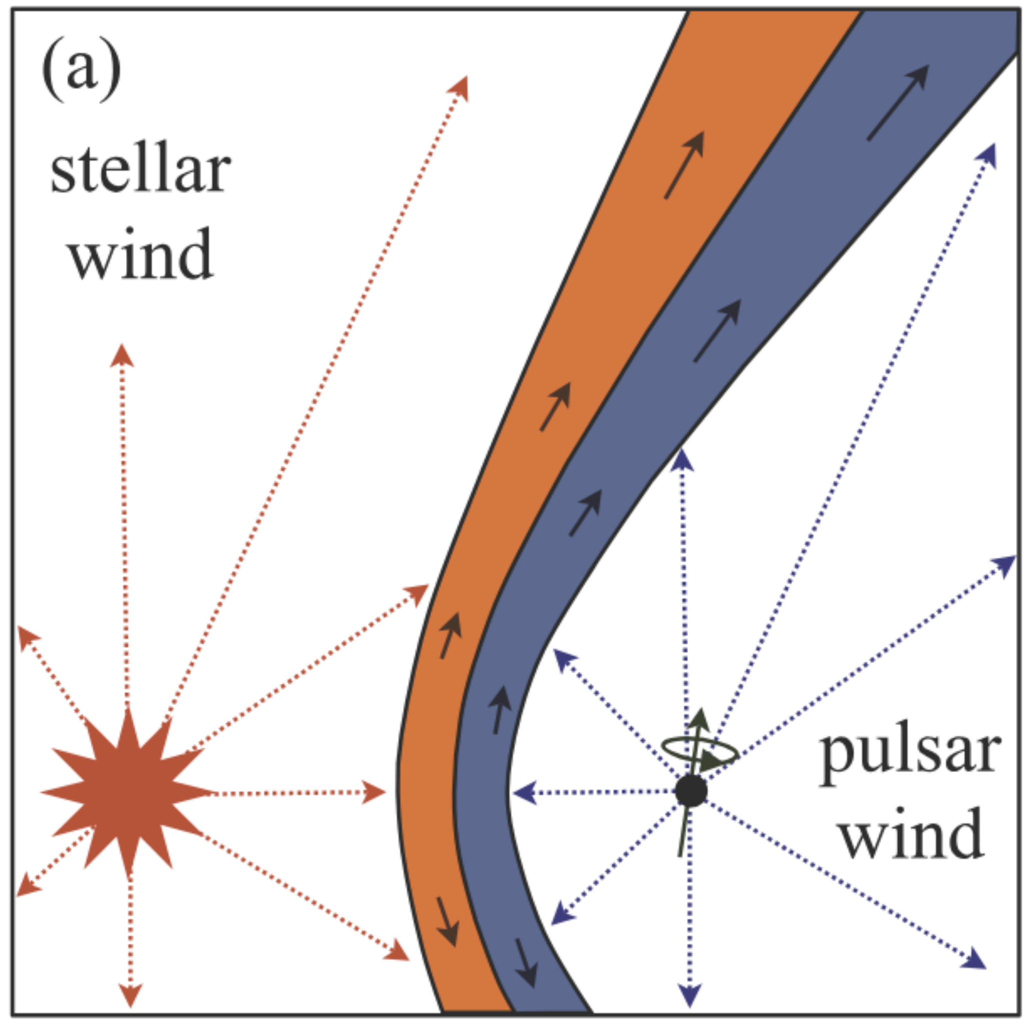
- **Gamma-ray binaries**
  - Massive stars with compact object -> **likely non-accreting pulsars**
  - **Apparent grouping on O5/O6** for O-type systems
  - Emission **up to even 100 TeV** without cutoff
  - Real population at least x10 current one

(Likely) Non-accreting pulsars





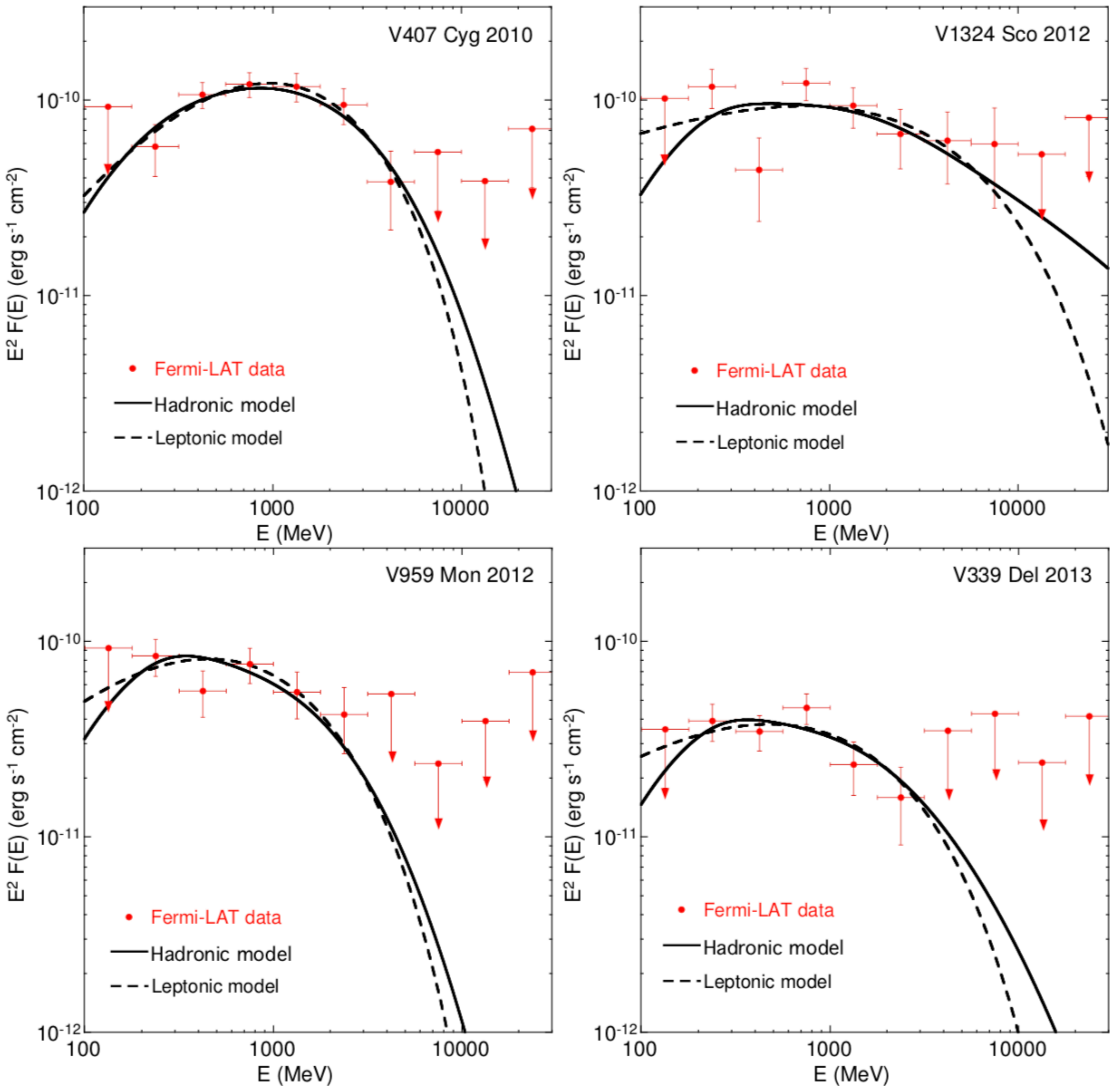
leptonic



Dubus 2015

Novae

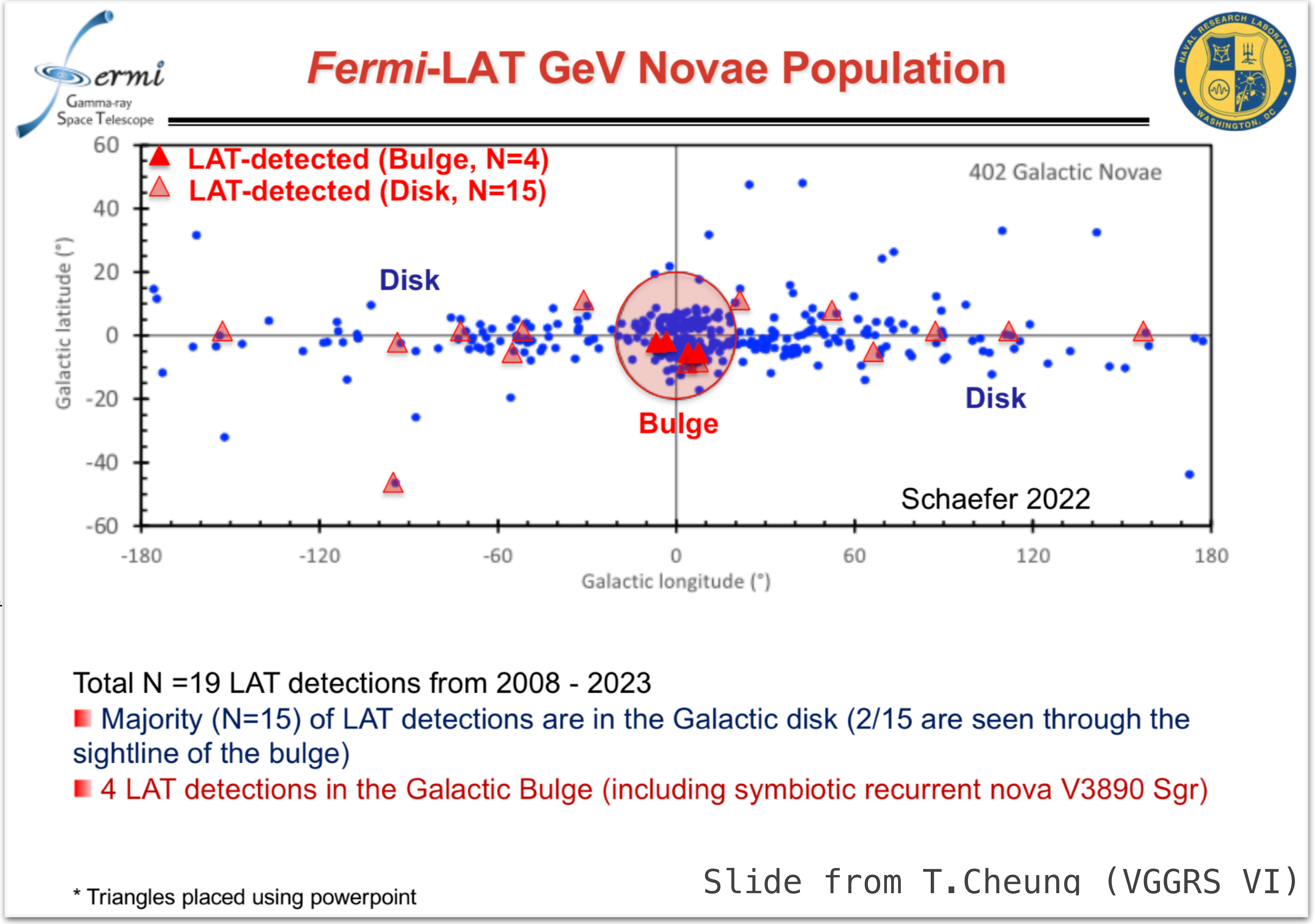
Novae: sources of HE gamma rays



- **Novae established as HE emitters (HE, E>100 MeV)** by *Fermi*-LAT (*Fermi*-LAT, Science, 2010, 2014)
  - Both symbiotic (WD+RG) and classical (WD+low-mass star)
  - Updated list: https://asd.gsfc.nasa.gov/Koji.Mukai/novae/latnovae.html
- HE emission could be explained with either with **pp interaction** or **leptonic models** (IC+Brems.)
- SED measured up to 6 – 10 GeV

Novae: sources of HE gamma rays

- 402 optical novae (Schaefer 2022)
  - Estimated eruption rate: 20-70 /year
- Discovery rate: 5-15 /year (Chomiuk et al. 2021)
- Fermi-LAT average ~1 per year (Cheung, VGGRS VI)
  - Up to know, total of 19 HE novae* (+6 hints) https://asd.gsfc.nasa.gov/Koji.Mukai/novae/latnovae.html
  - Fermi-LAT novae by detected up to 4.5 kpc

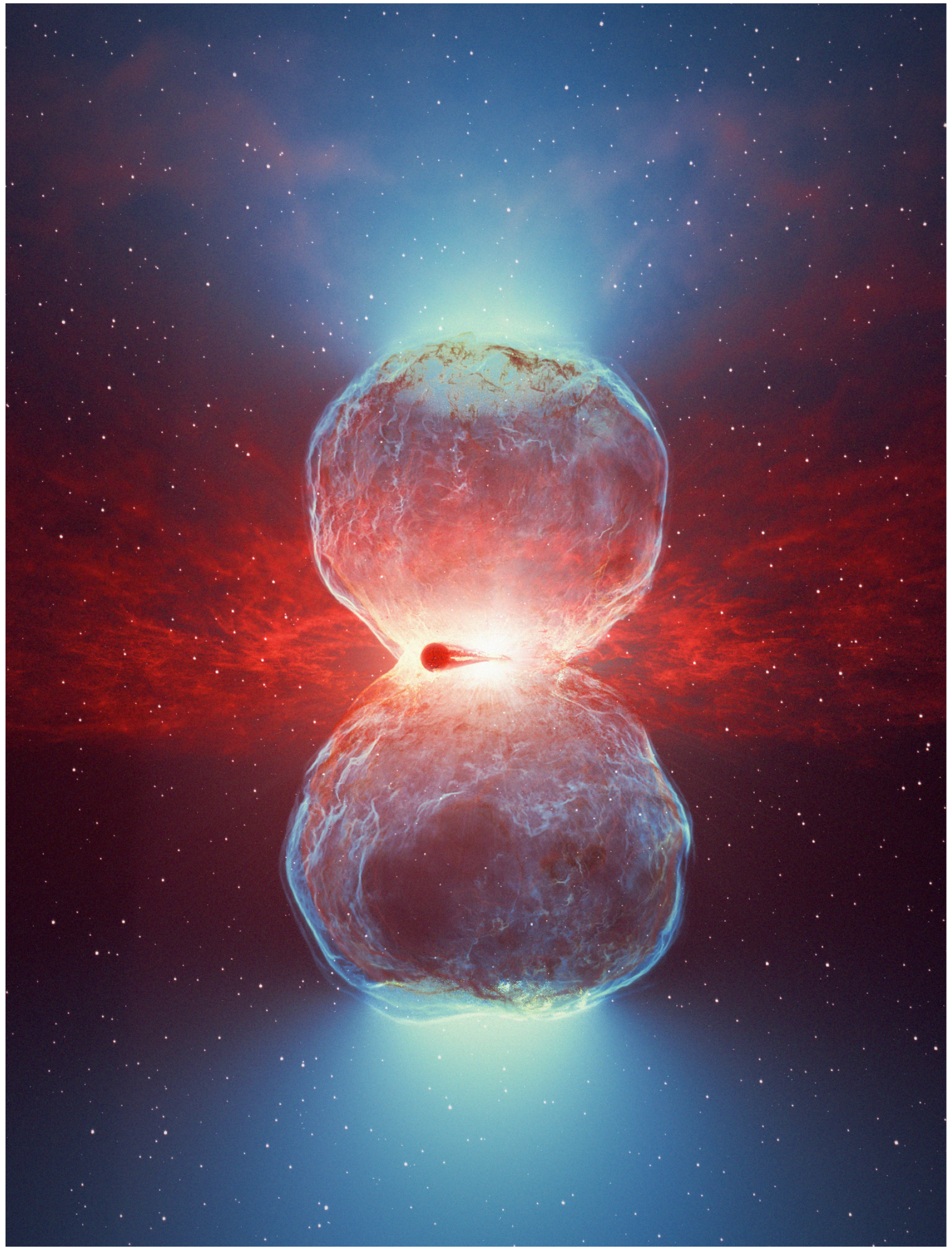


Slide from T.Cheung (VGGRS VI)

Are novae very-high-energy (VHE, E>100 GeV) emitters?

RS Ophiuchi

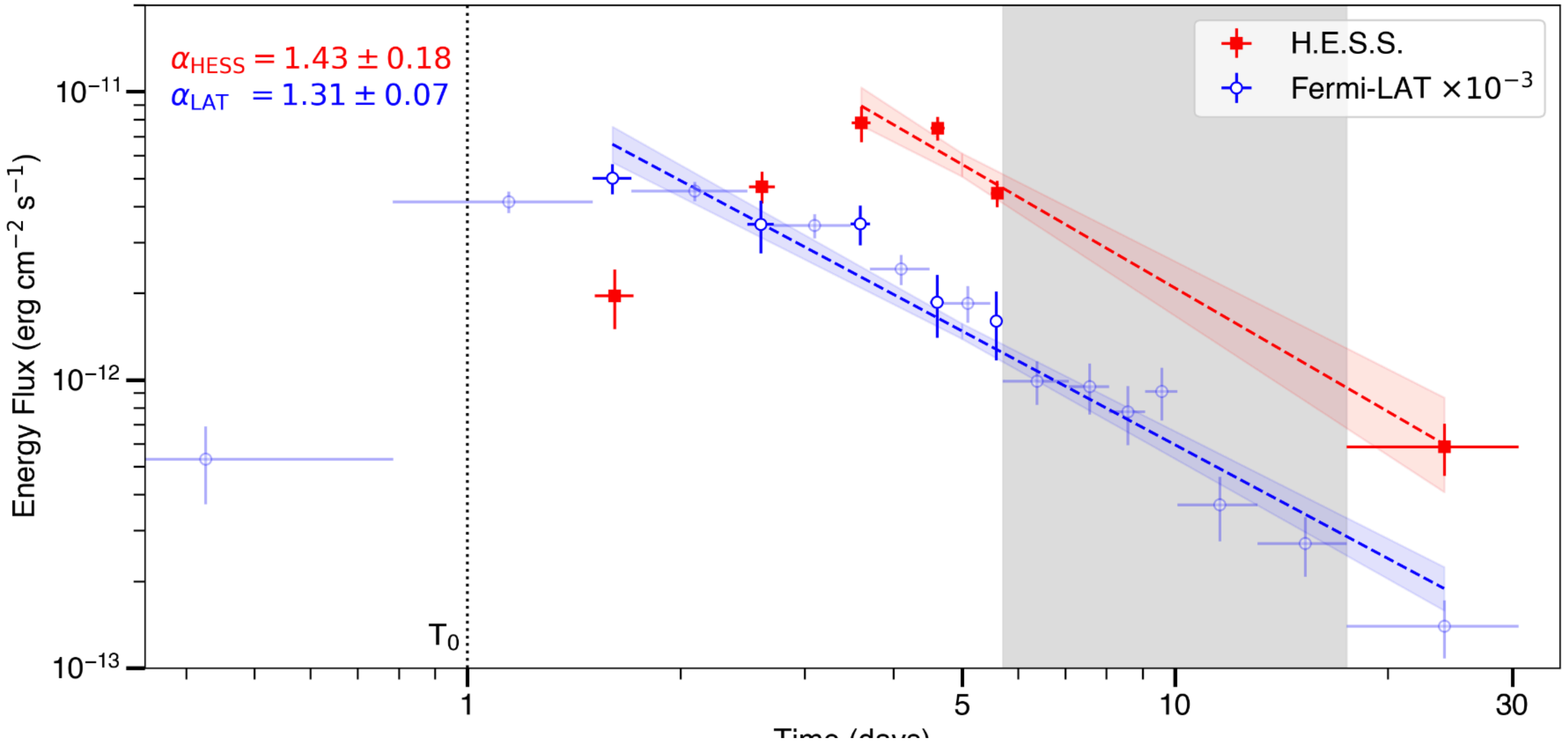
- RS Oph is a Galactic **recurrent symbiotic nova**
  - **WD + M0-2 III RG star**
  - major **outbursts every ~15 years**
  - Nine eruptions between 1898 and 2021
    - **Latest outburst: August 2021**



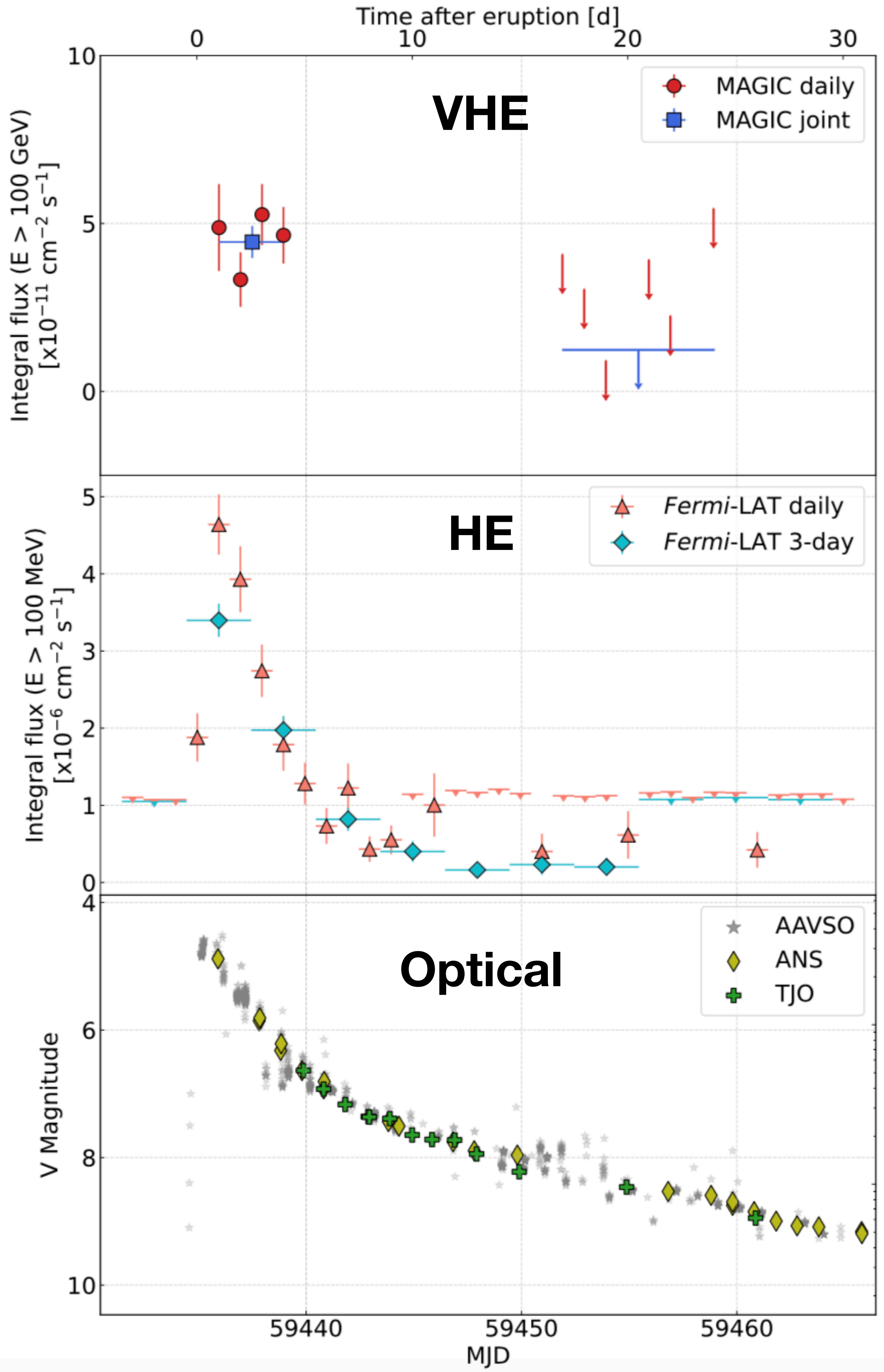
DESY/H.E.S.S., Science Communication Lab

MWL view

- **First and only nova detected in the VHE regime**
  (HESS coll 2022, MAGIC coll 2022, LST coll. subm.)



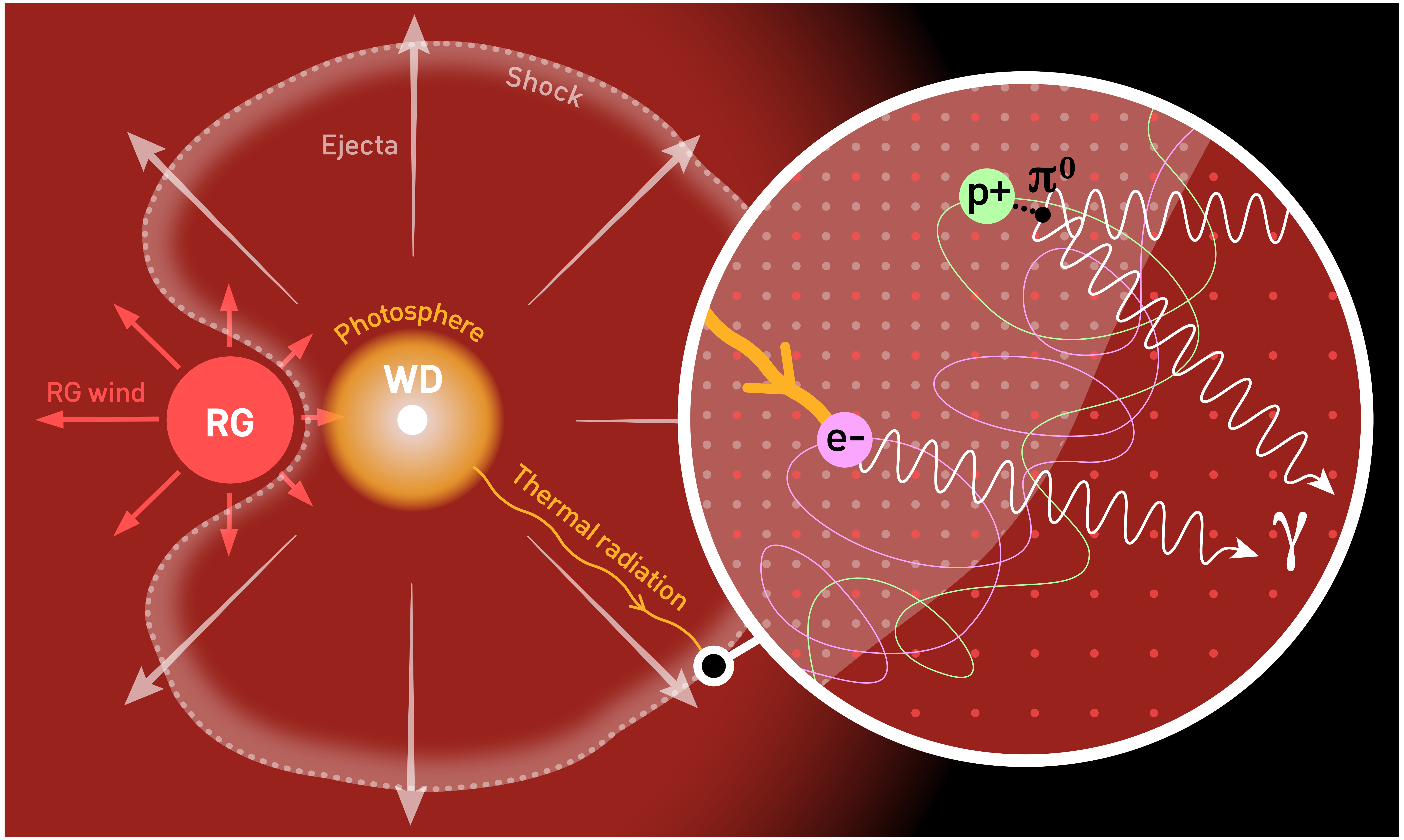
HESS coll 2022



Acciari et al. 2022

(Symbiotic) **novae** as a **new type of VHE gamma-ray emitter**

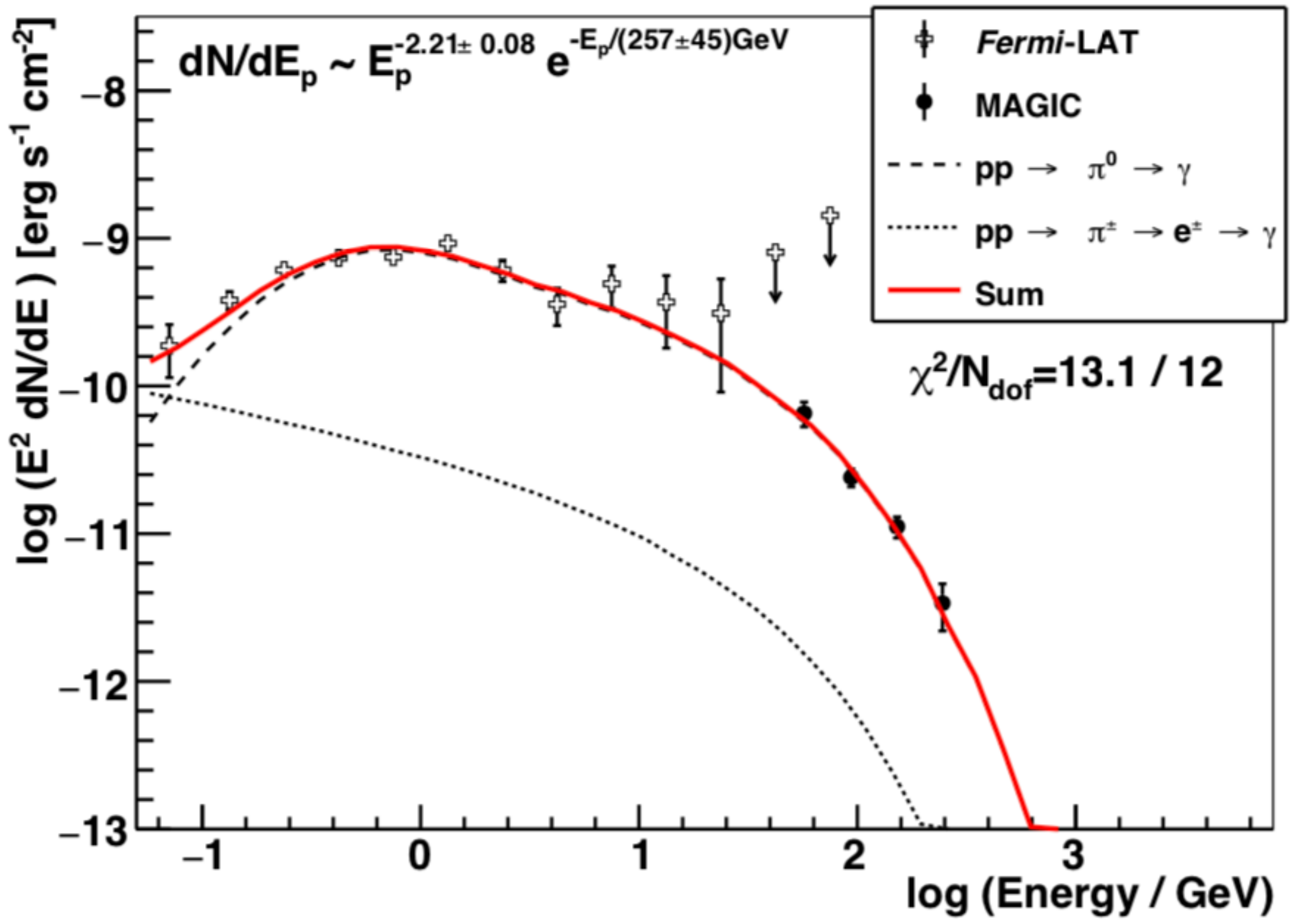
Gamma-ray emission: hadronic origin



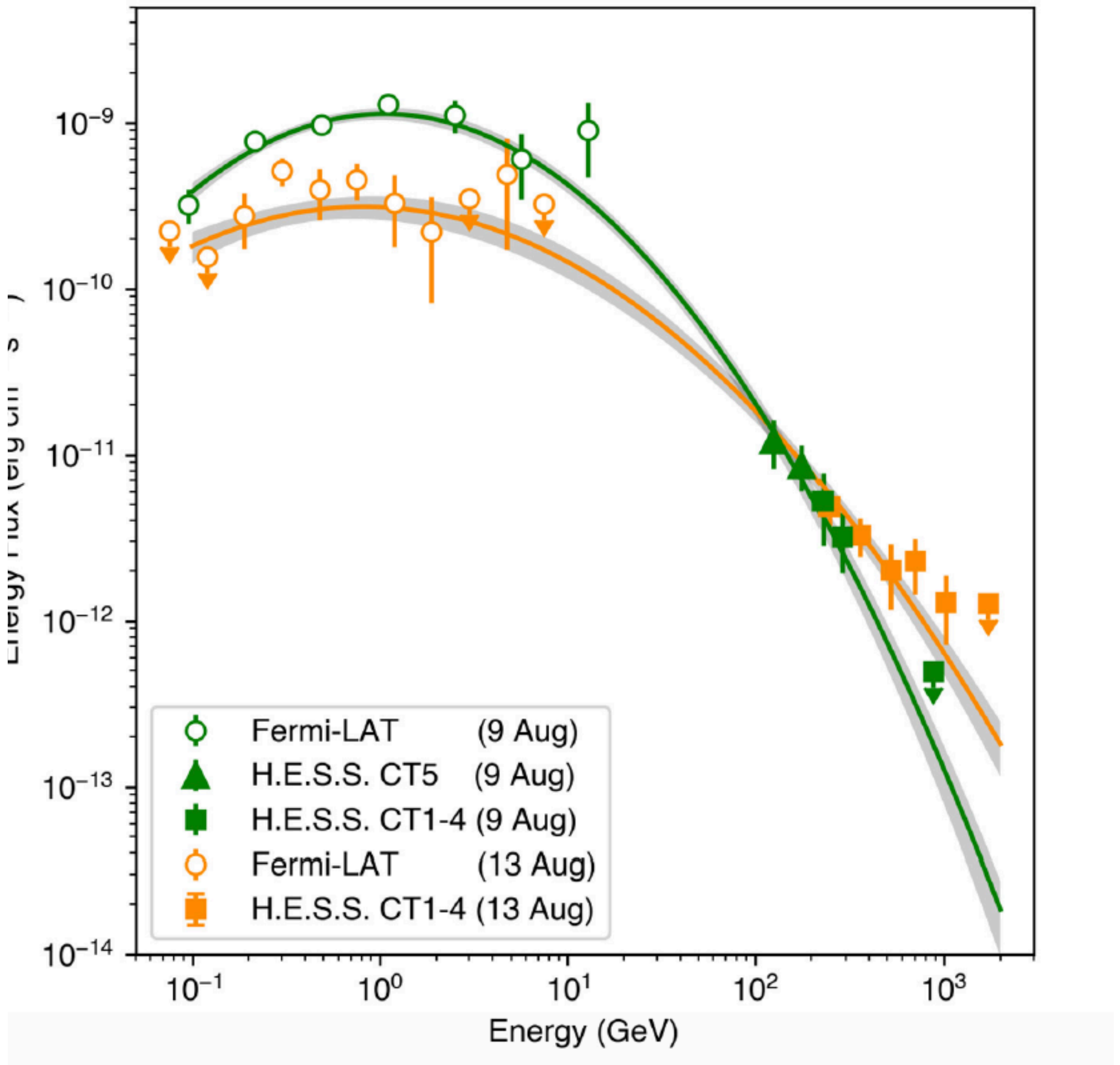
G. Pérez (IAC)

- **Protons**: pp interaction on **nova ejecta** (with some contribution from RG wind)
- **Electrons**: IC on thermal radiation of the **WD photosphere**
- Modeling: particles are injected and either **cool down completely (electrons)** or we gather their emission during the **acceleration time (protons)**

Hadronic origin

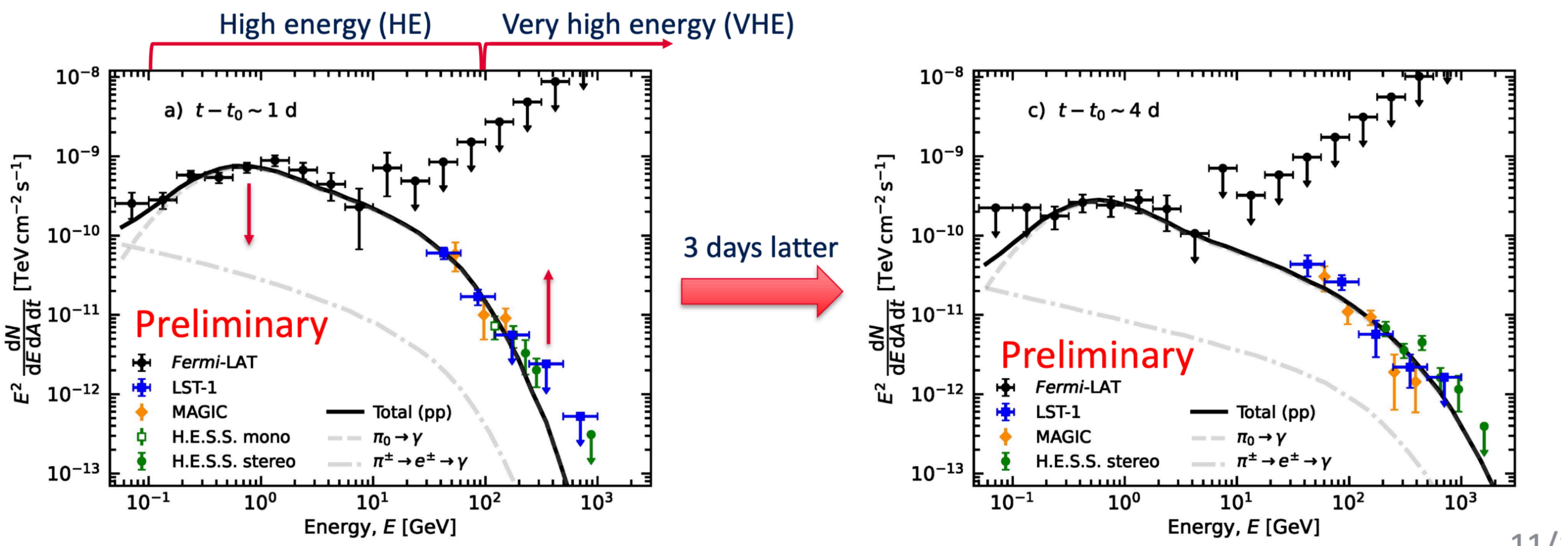


Acciari et al. 2022



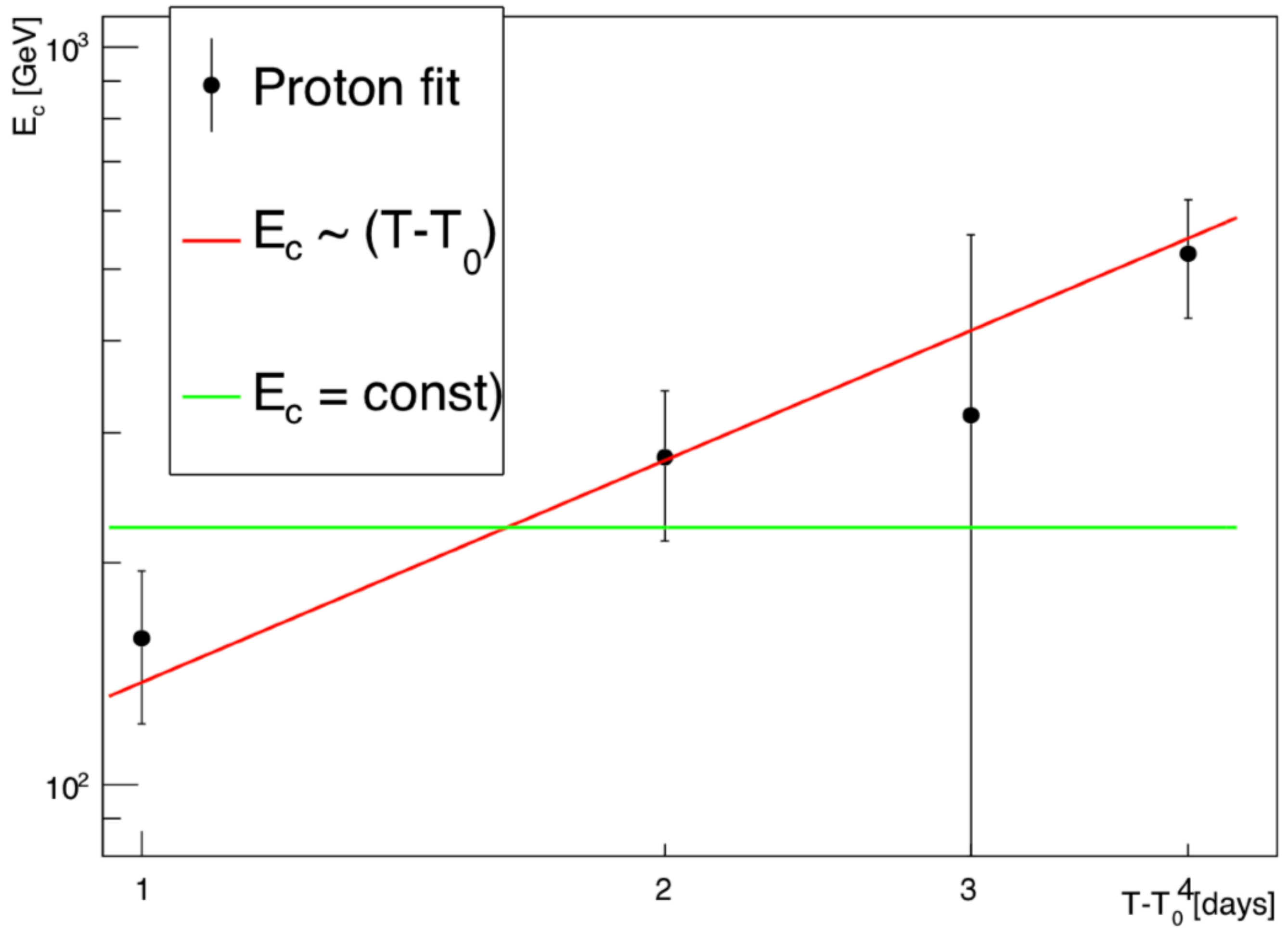
HESS coll 2022

Gamma-ray emission: hadronic origin



LST Collaboration

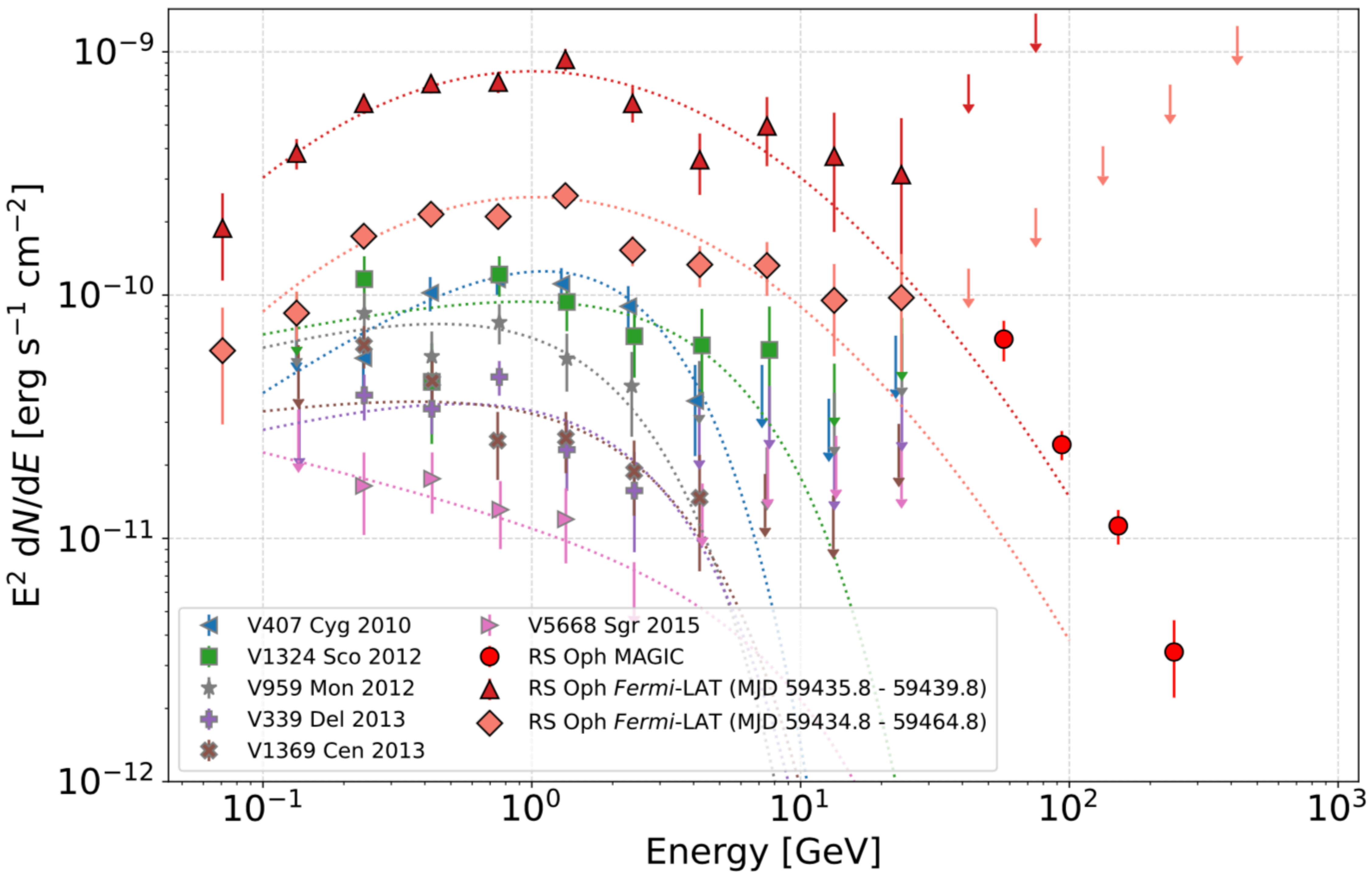
- **Increase of the cut-off energy with time:** hint of spectral hardening
  - In line with the expectations from the cooling and acceleration timescales
  - **Hadronic scenario favored**

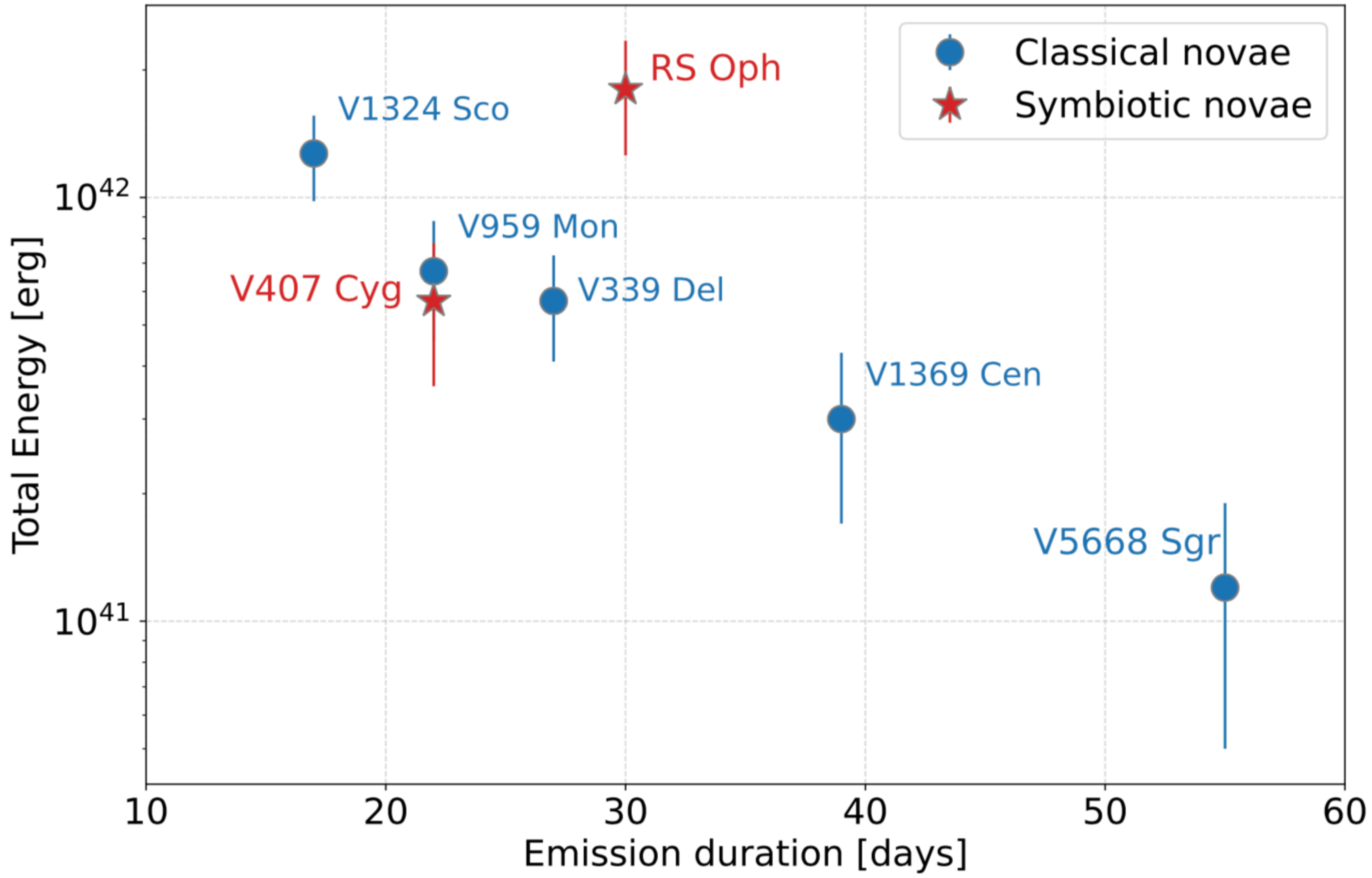


Acciari et al. 2022

- Gamma rays produced by **protons** (HESS coll 2022, MAGIC coll 2022, LST coll. subm.)

RSOph vs other novae





- RS Oph is the nova with the **highest flux** and **brightest nova**
  - Almost two orders of magnitude larger than previously-detected eruptions
- **Comparison does not reveal any peculiarity** in the emission of RS Oph, except for its brightness

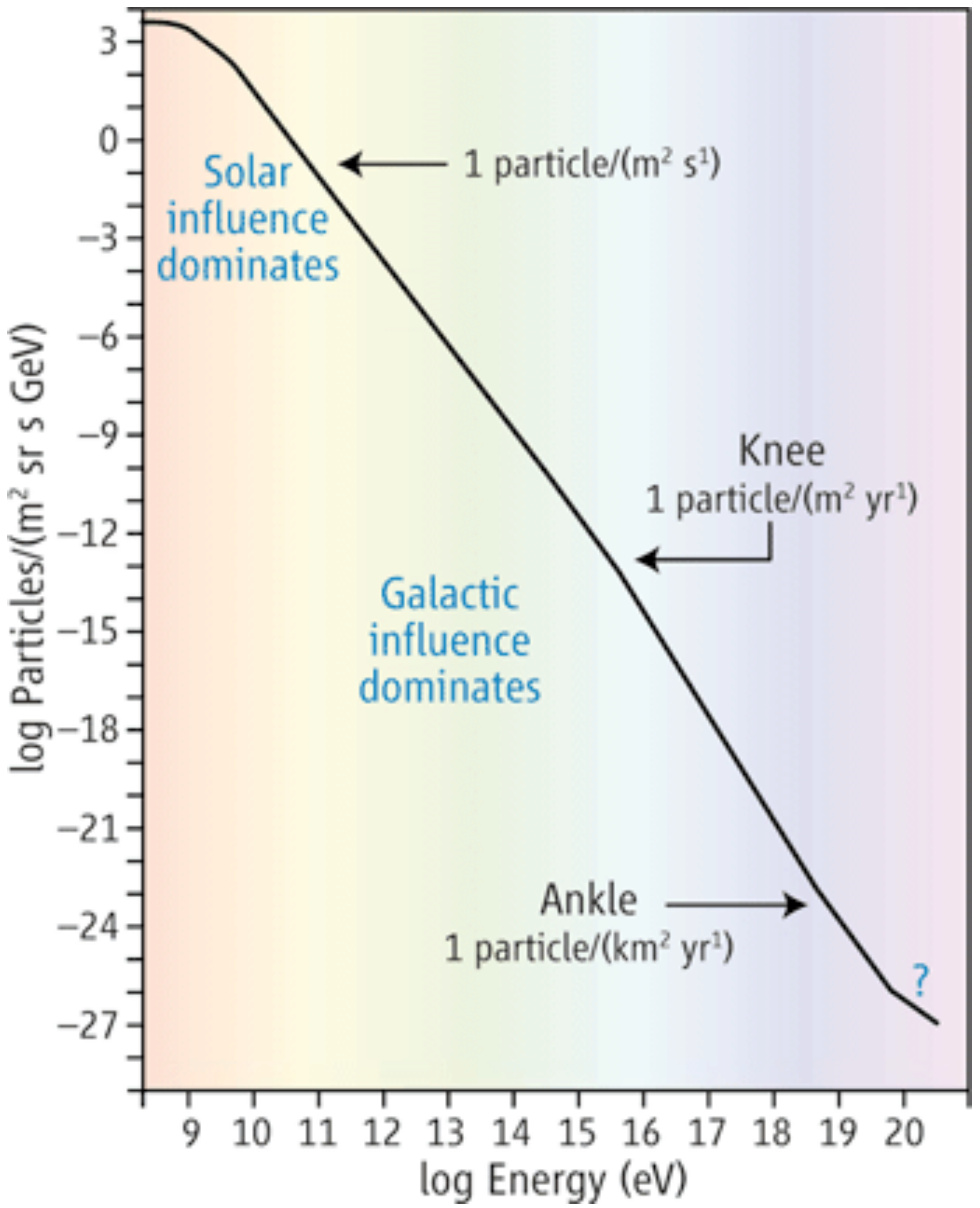
Galactic novae and Cosmic Rays

- **Accelerated protons will eventually escape the nova shock** carrying away most of their obtained energy. Such protons could **contribute to the Galactic Cosmic Ray sea**

- Using the CR energetic derived for RS Oph (~ 4.4×10^{43} erg): <**0.2% of the contribution from supernovae**

- Despite the small contribution to the overall CR sea, **novae would significantly increase the CR density in its close environment**: E_density(nova)>E_density(CR)

- In the case of **recurrent novae, protons will accumulate in a ~10 pc bubble** with enhanced CR density



Extracted from Dulgig, Science 2020

Other novae

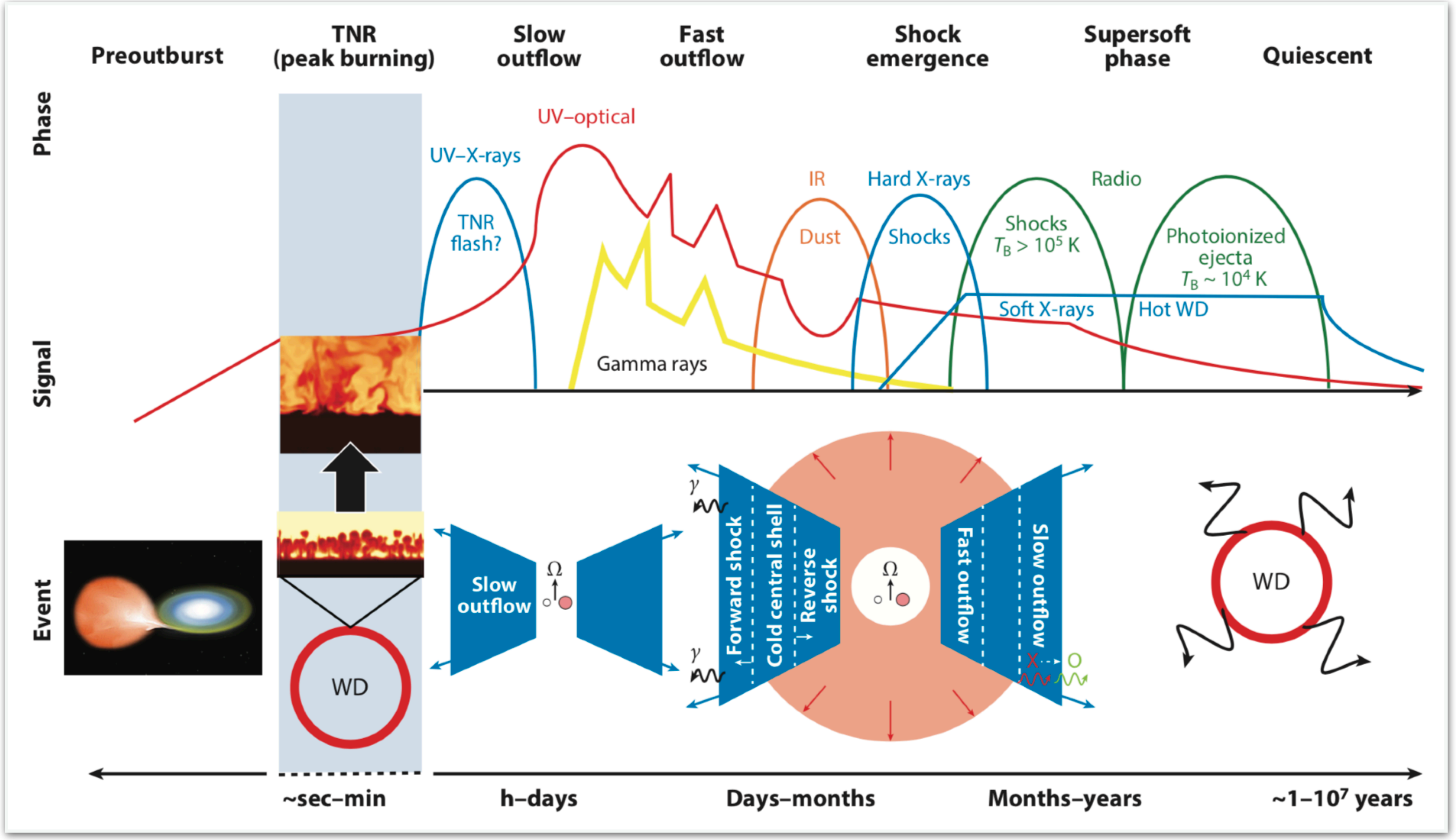
10 known recurrent Galactic novae

	Recurrence Time Scale
U Sco	10.3
V745 Sco	21
V3890 Sgr	25
V2487 Oph	18
V394 CrA	30
RS Oph	14.7
CI Aql	24
T CrB	80
IM Nor	41
T Pyx	24

Inminent (T CrB)

Schaefer 2010

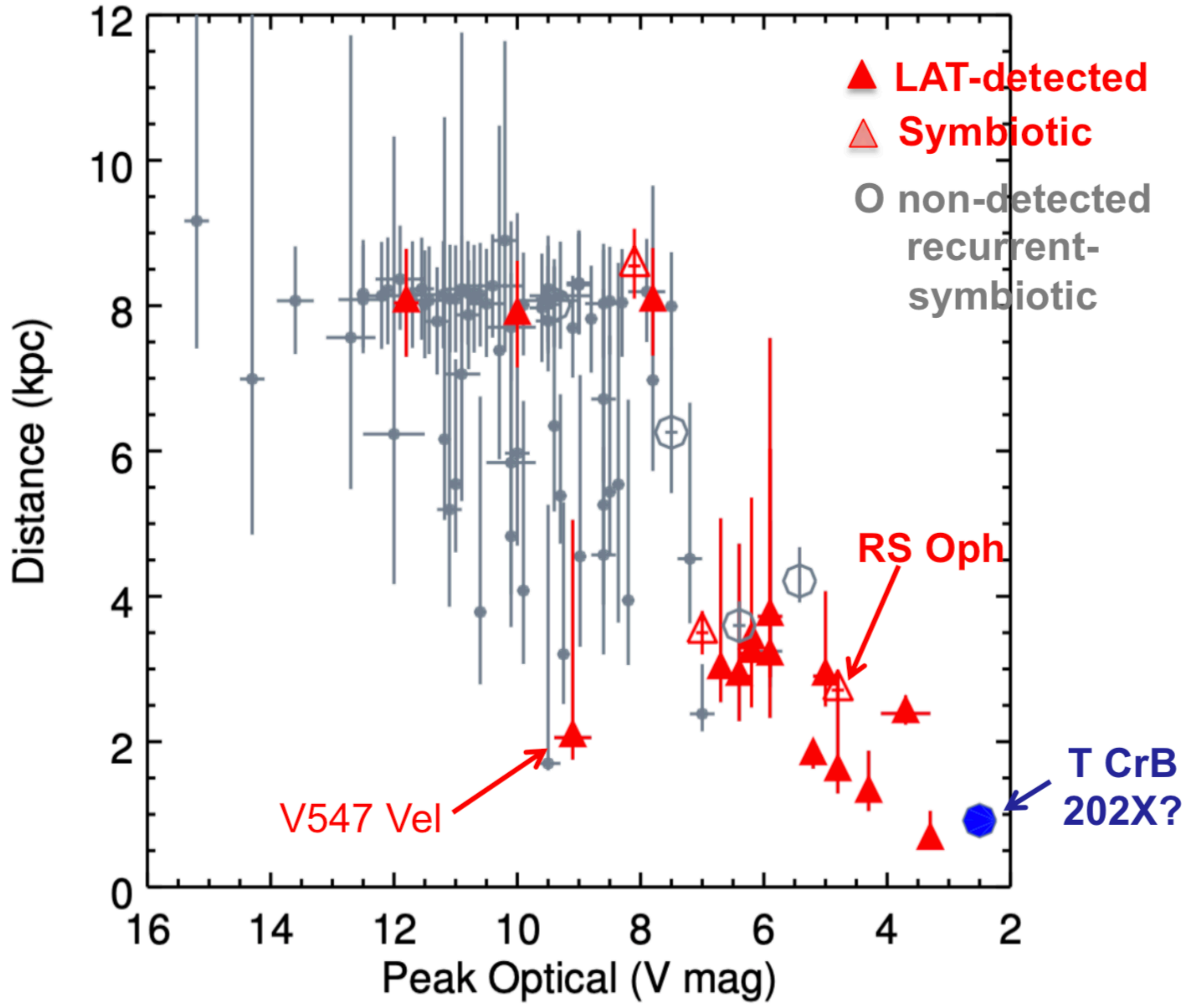
Classical novae as VHE emitters?



Chomiuk et al. 2021

- **No classical nova yet detected at VHE** (Ahnen et al. 2015, Albert et al. 2022)
  - What is the maximum particle energy?
    - Emax ~ 10 GeV–10 TeV can lead to emission extending > 100 GeV (Metzger et al. 2016)

Inmediate future: T CrB



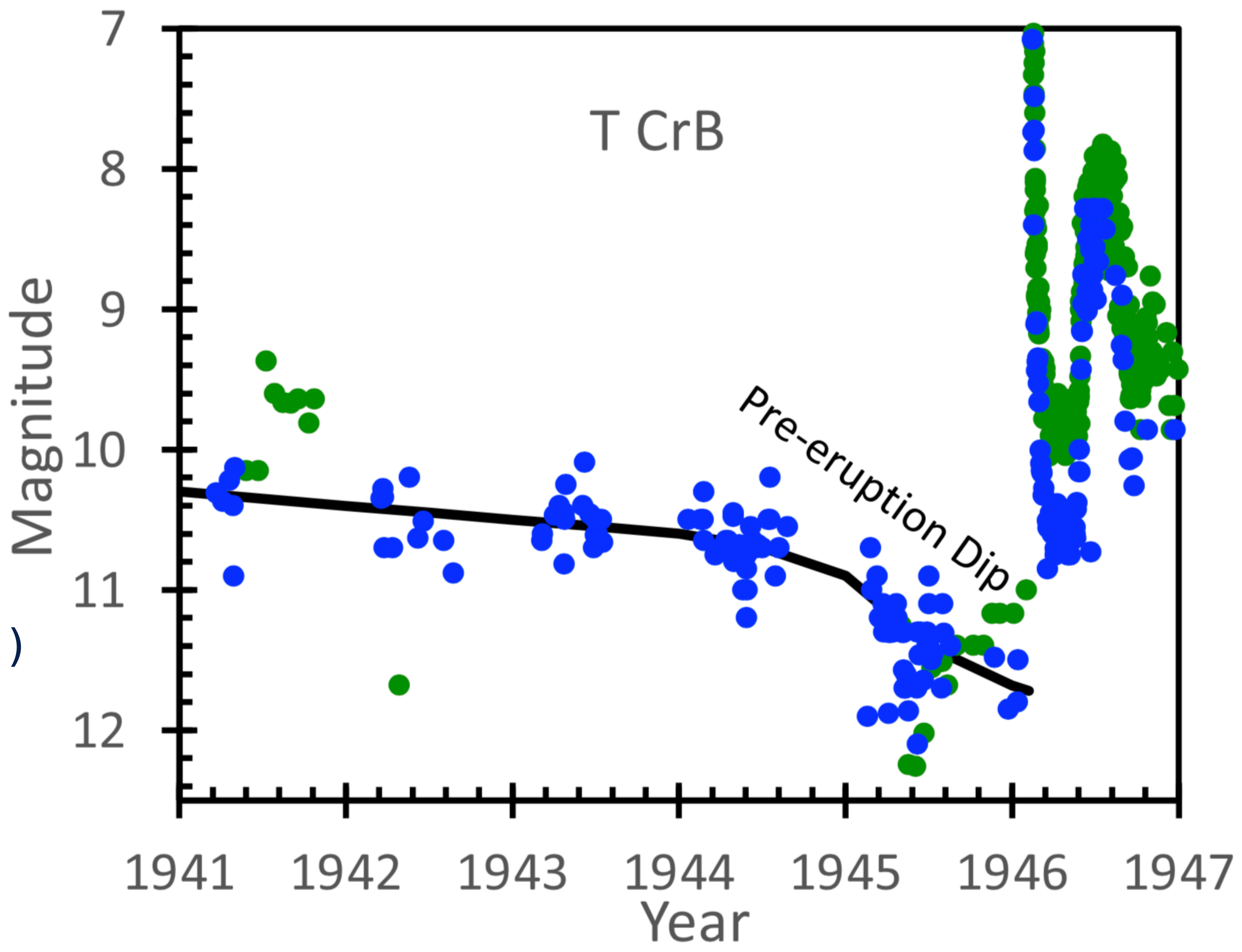
Data from Schaefer (2022), except V~5 inferred in V959 Mon 2012; added V407 Cyg 2010

From T. Cheung (VGGRS VI)

RN Symbiotic nova

WD (1.37±0.13) M⊙

M4 III

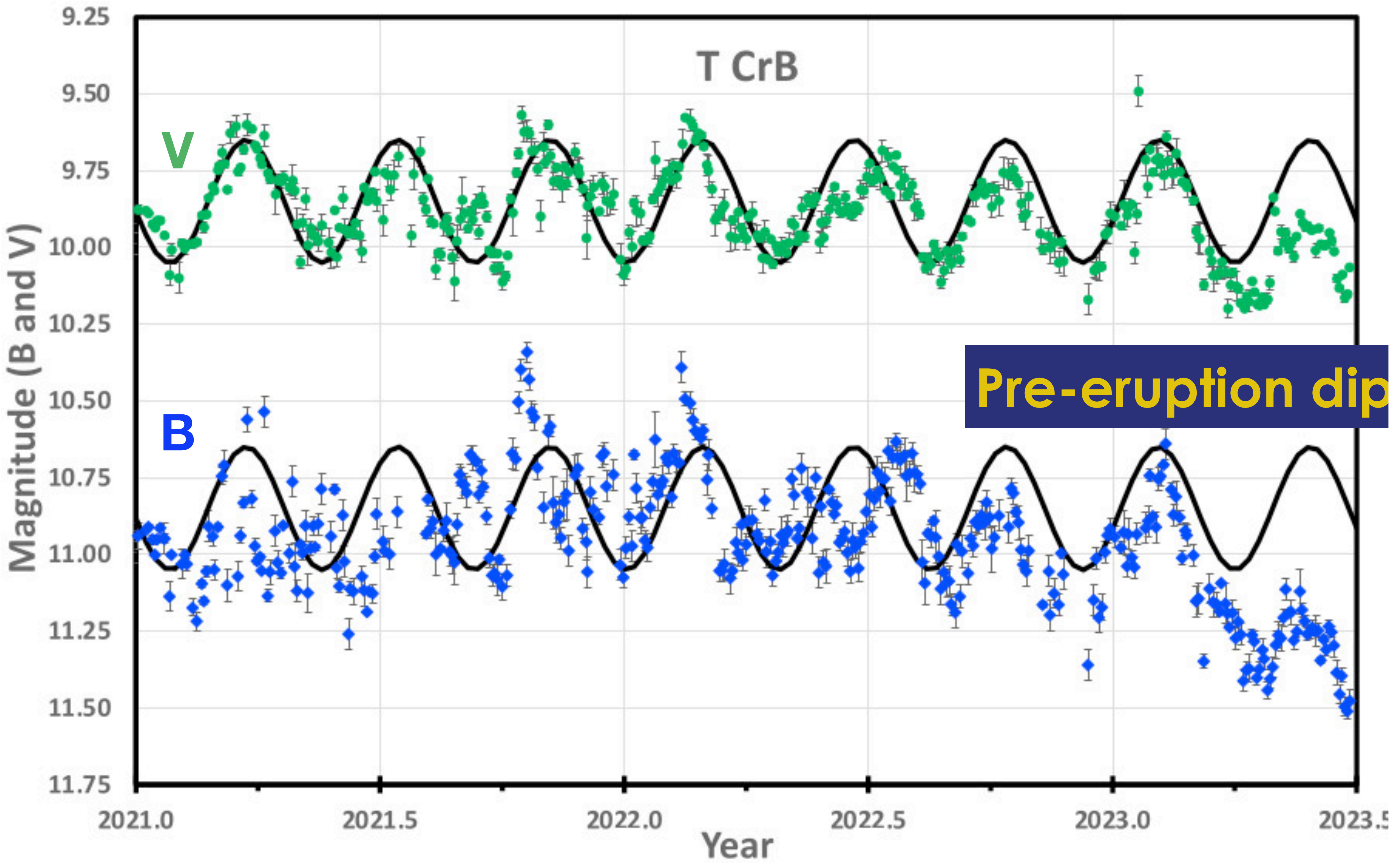


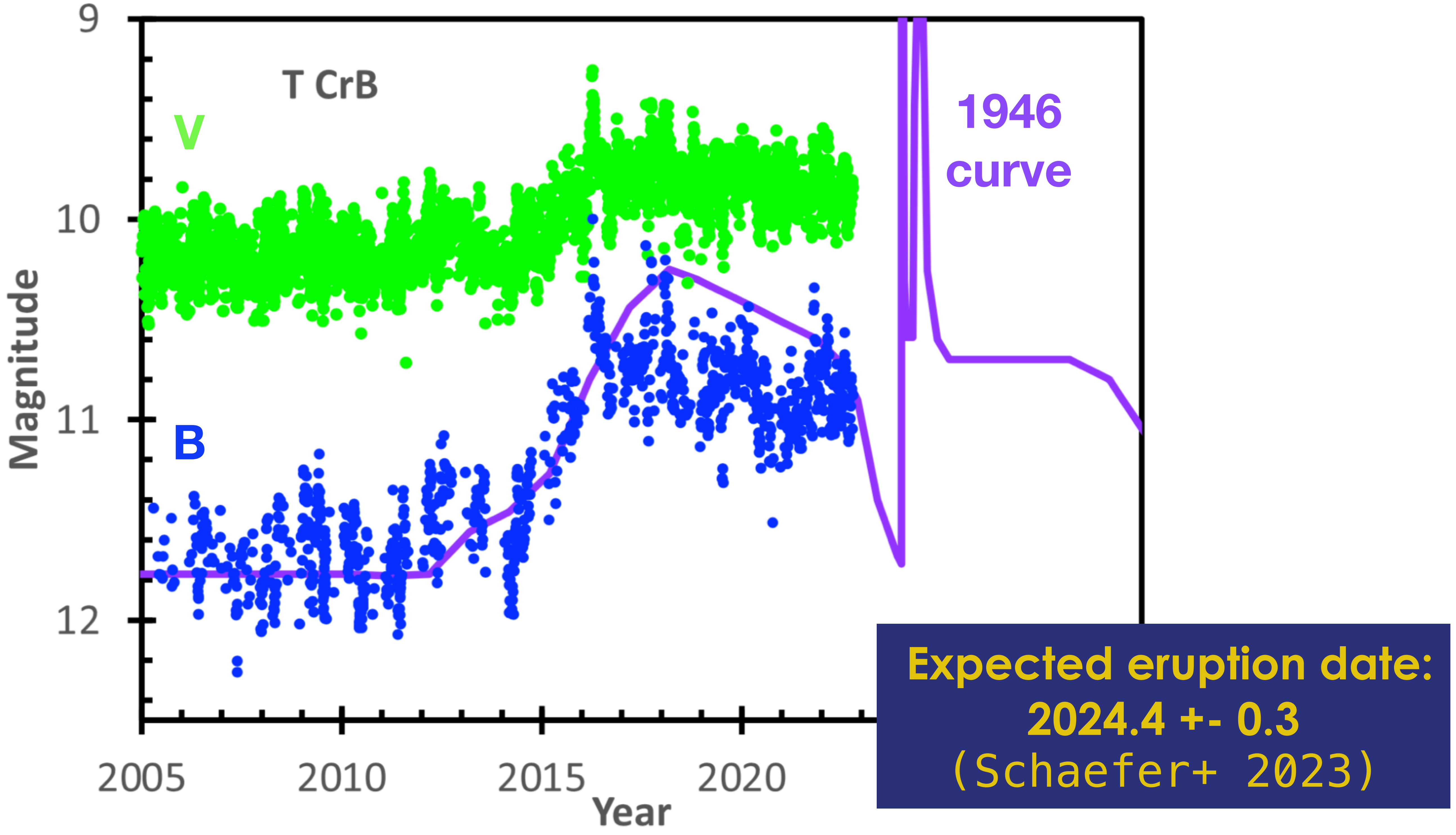
Schaefer 2022

- **Closest known RN symbiotic nova**, D = 0.91 +/- 0.02 kpc (Schaefer 2022)
  - Recurrency period of about **~80 years**
  - Two peaks
- Optical first **peak at mag~2**
- 3x closer than RS Oph; naively scale by distance => ~10x brighter?

Inmediate future: T CrB

- **Pre-eruption dip already started in March/April** (Schaefer et al. 2023, ATel #16107)
- **Expected eruption date: 2024.4 ± 0.3** (Schaefer+ 2023)

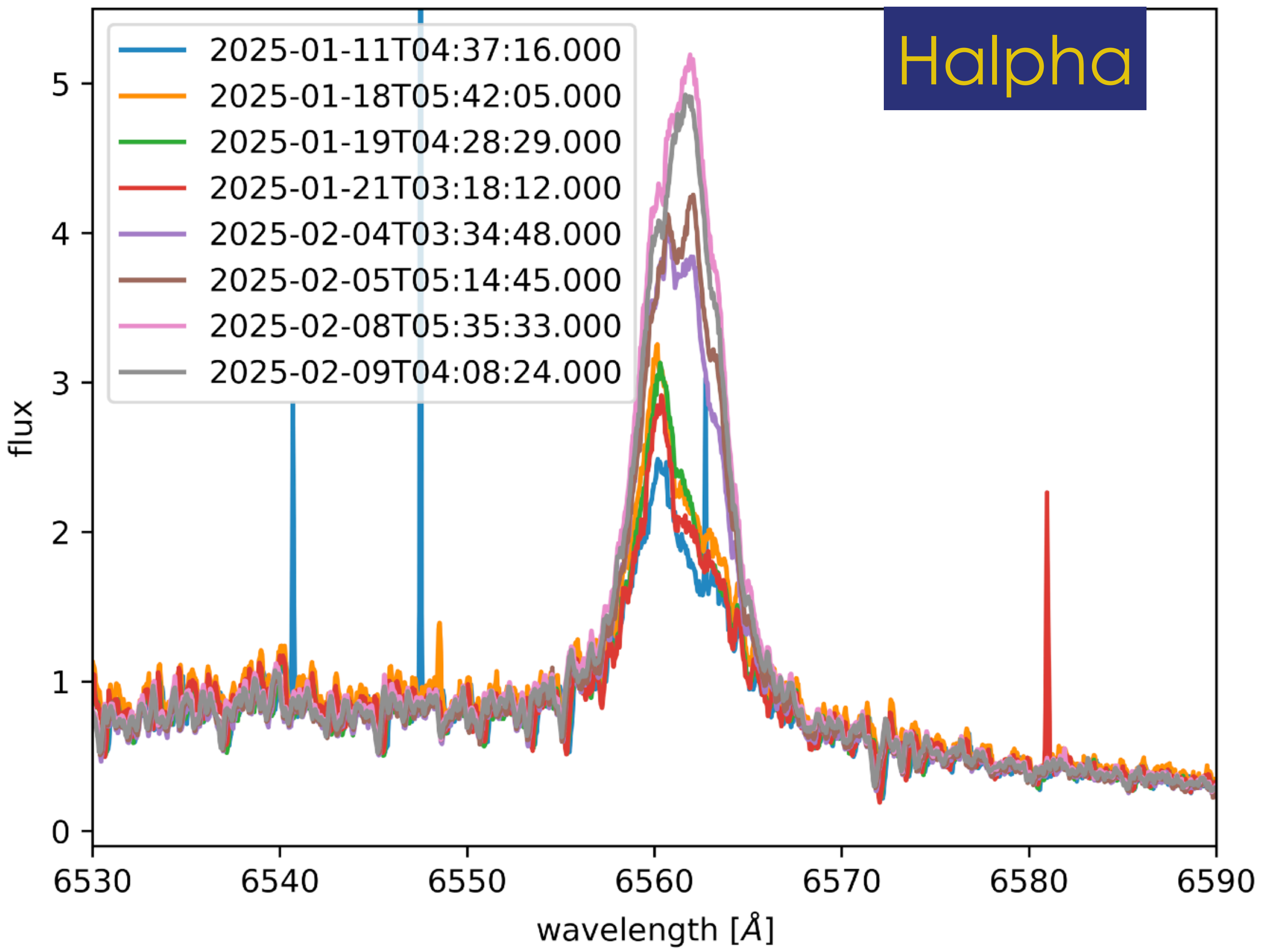


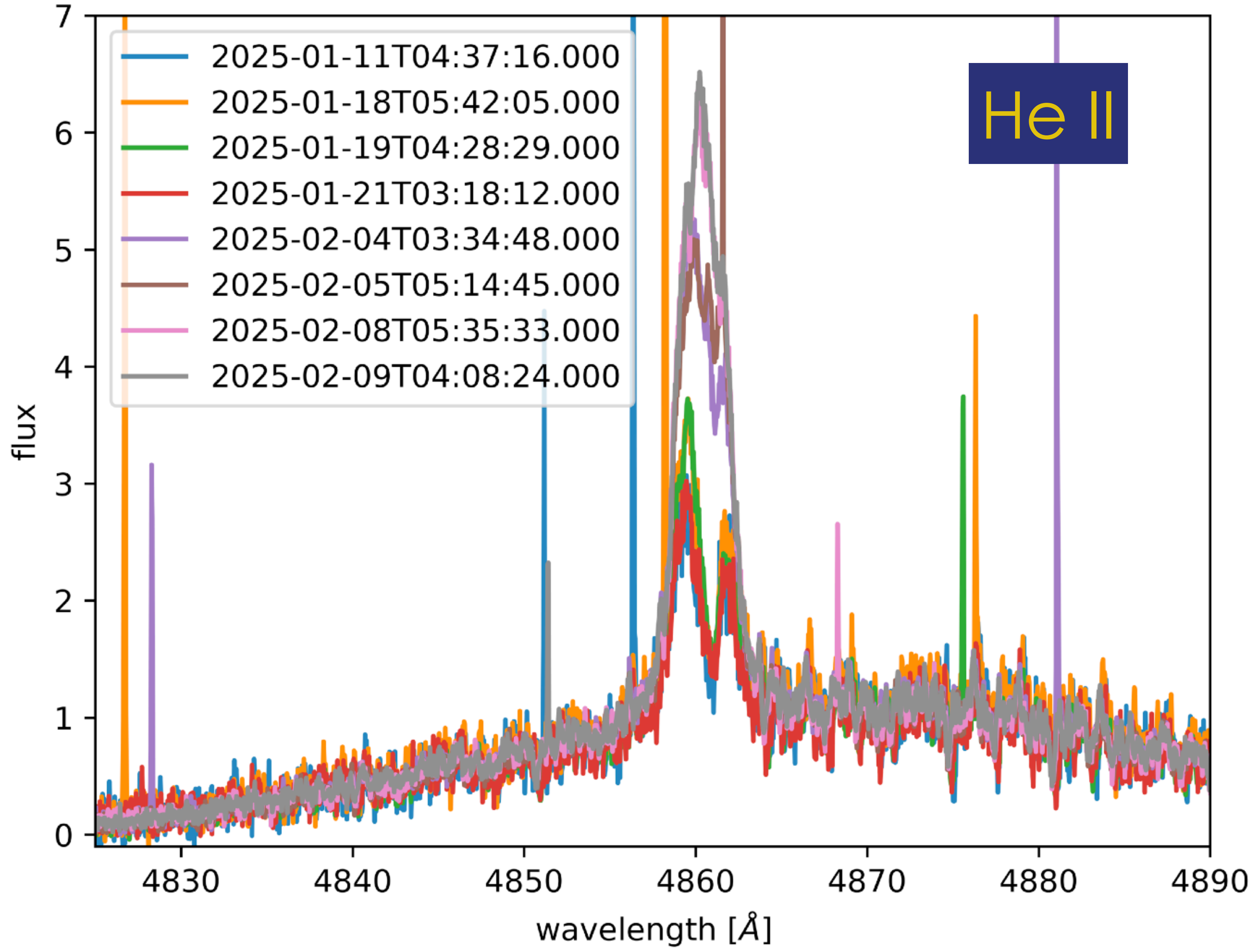


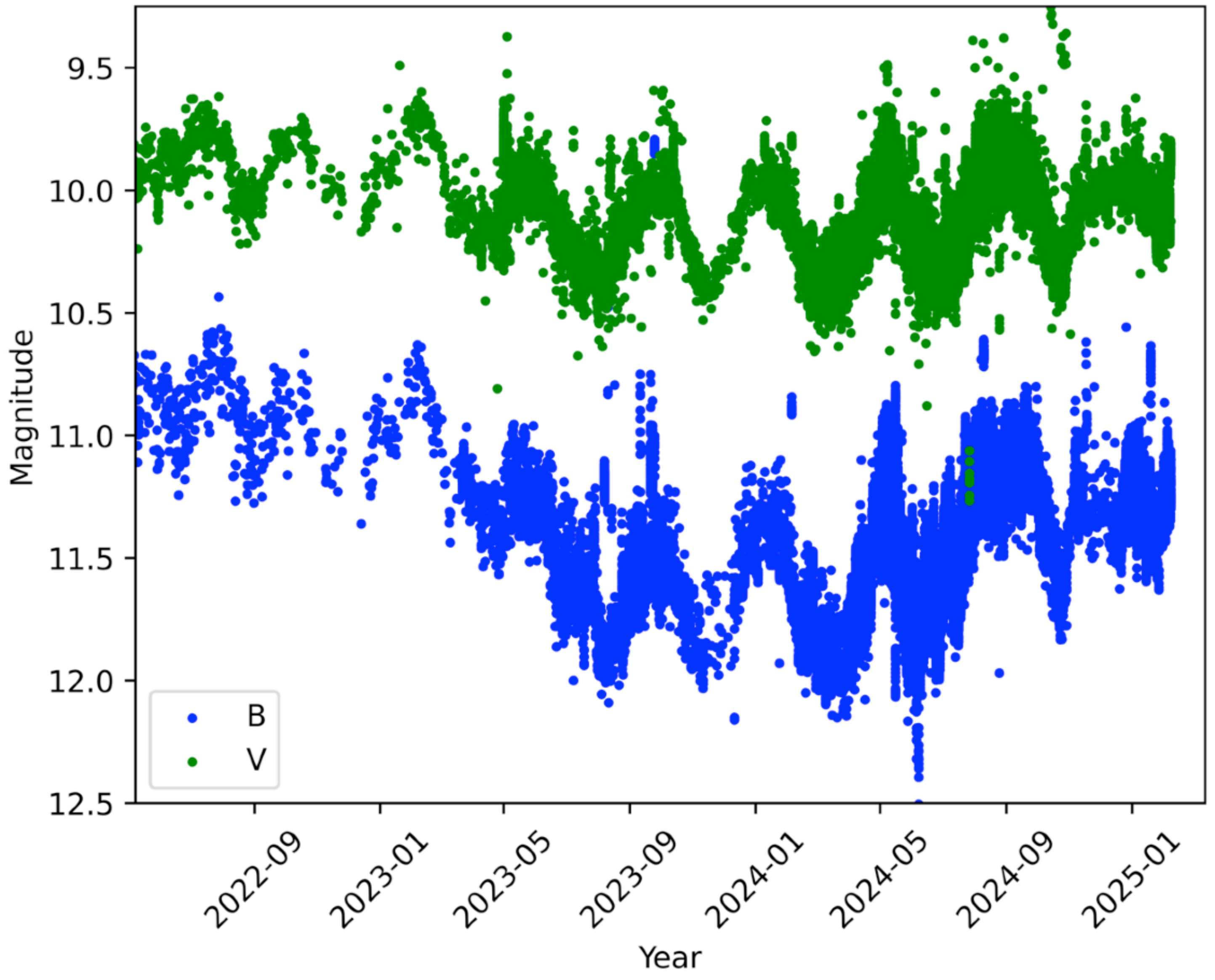
Inmediate future: T CrB

Hot news!

- **Increase in the accretion rate, but not in luminosity** (ATel #17030)
  - The equivalent width of the hydrogen lines doubled from 21.01.2025 to 09.02.2025
  - The line profile also underwent significant changes from a double-peaked shape with a central absorption to a single emission peak
    - Spectral changes indicate a strong increase in the accretion rate, **which will eventually result in a Nova eruption**, as predicted to occur this or next year (e.g., Schaefer et al. 2023).
  - **No increase in the light curve** has been observed so far







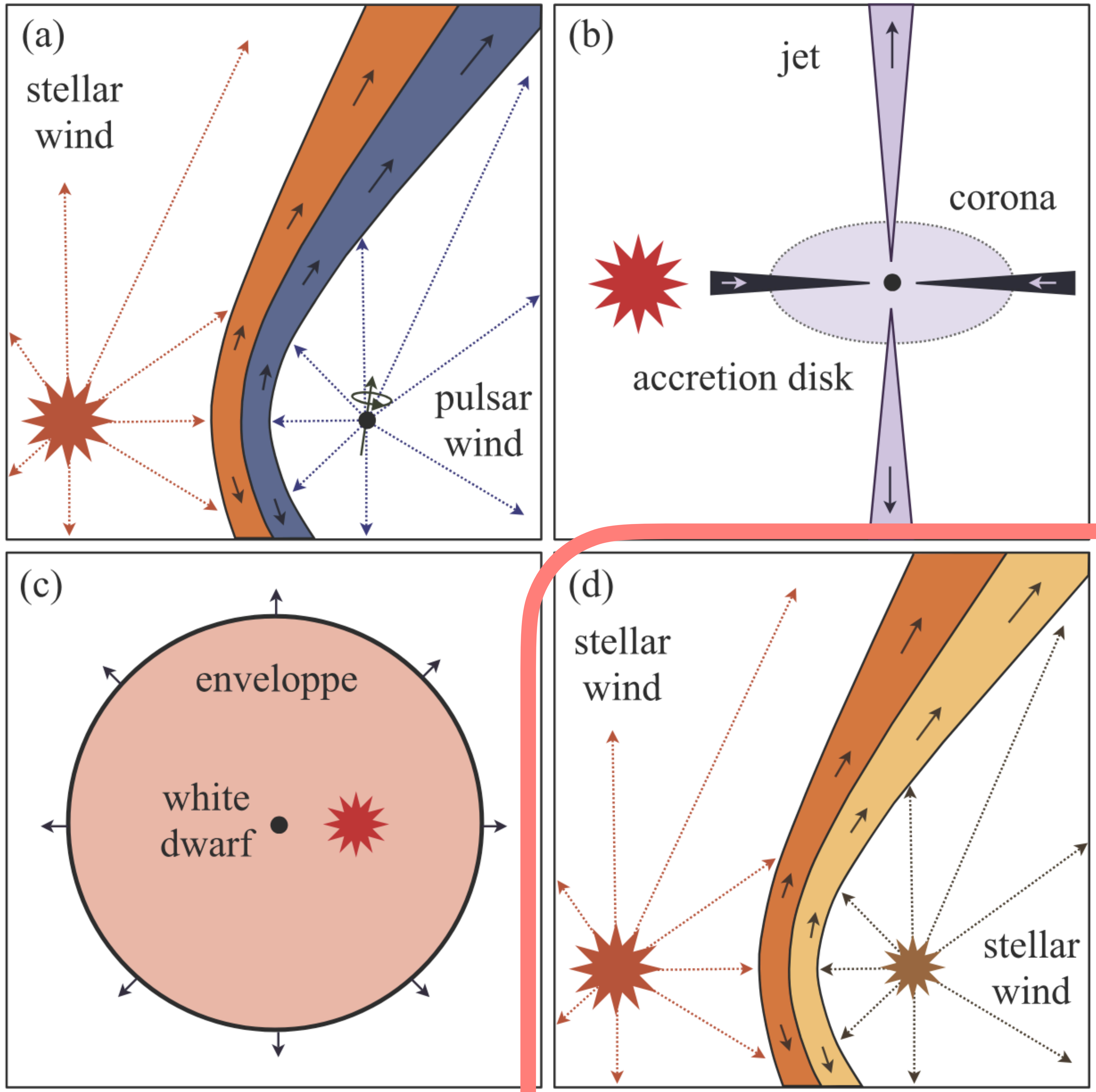
https://www.tls-tautenburg.de/en/news/tautenburger-wissenschaftler-beobachten-auffaellige-veraenderung-im-spektrum-der-wiederkehrenden-nova-t-crb-und-bleiben-wachsam-2


Colliding-wind
binaries

VHE binary emitters

Non-accreting pulsars

Microquasars

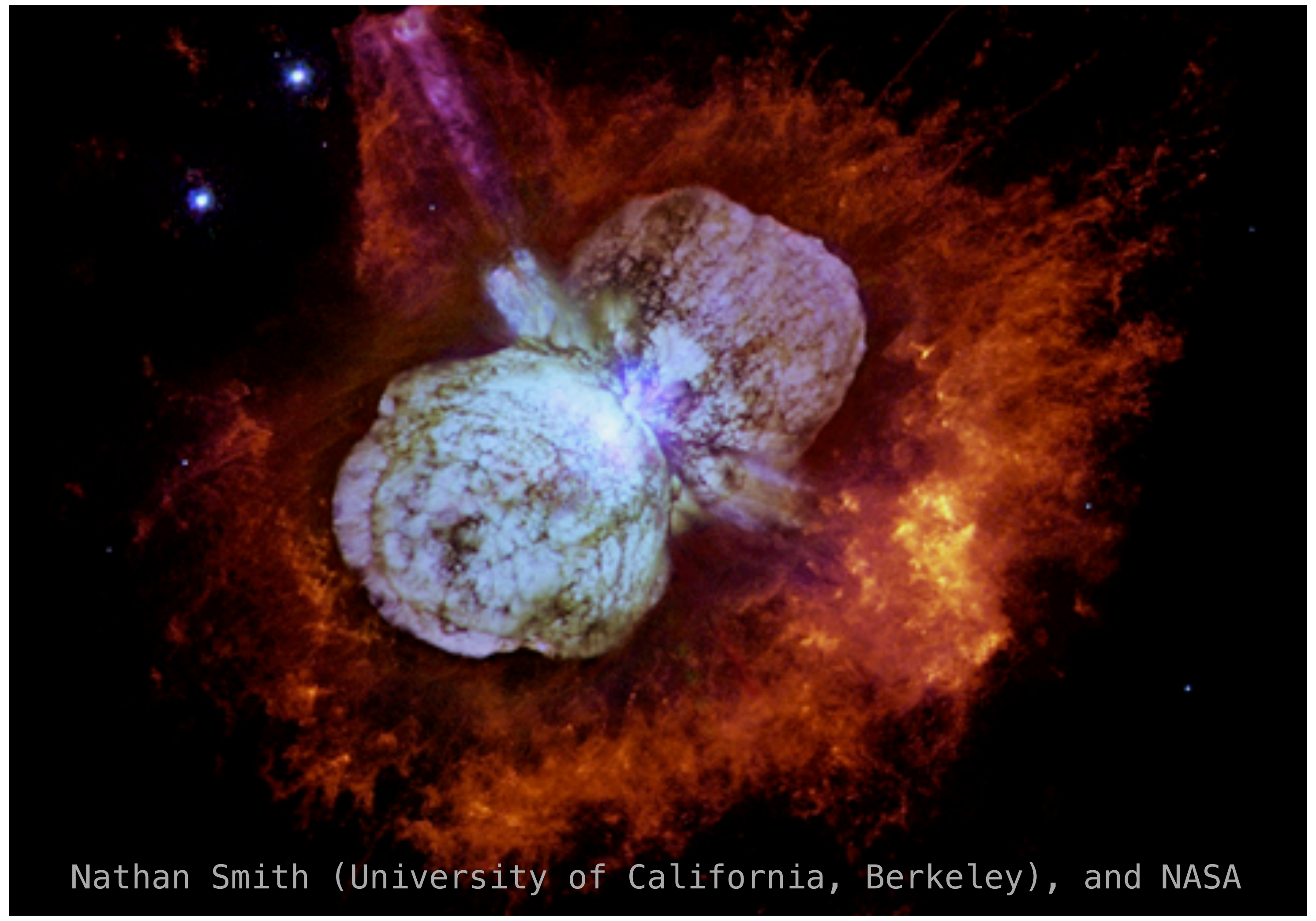


Dubus 2015

Novae

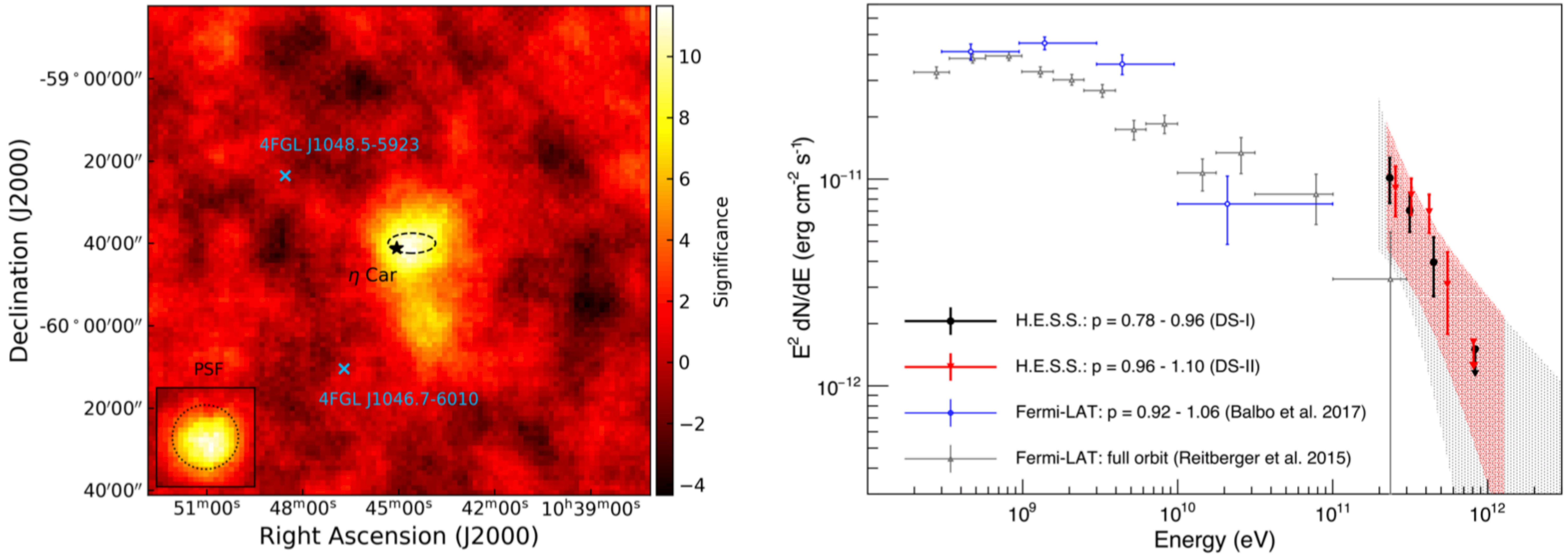
Colliding wind binary

Colliding wind binaries (CWB)



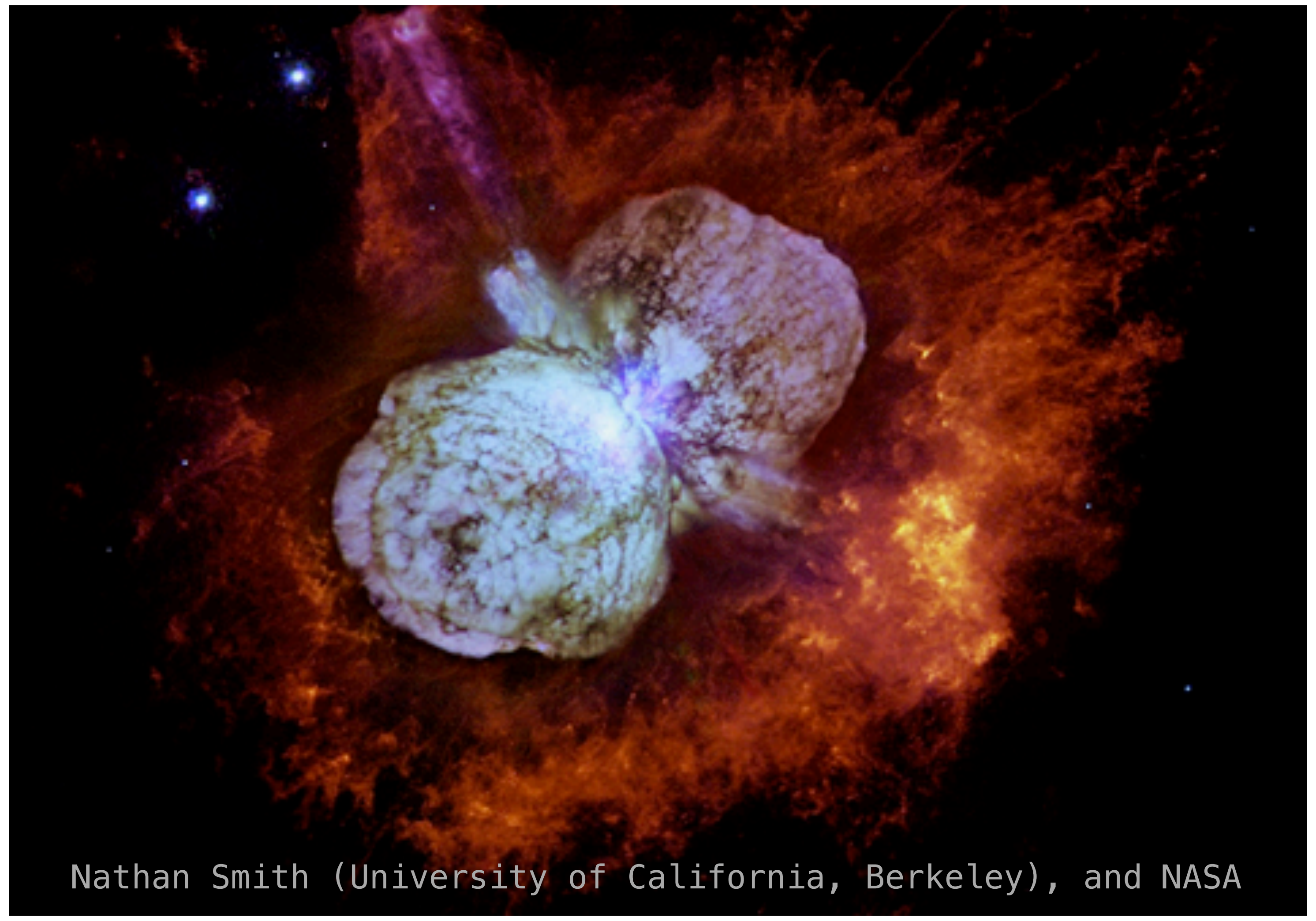
- LBV ~100 $M_\odot$ + **O- or B-type** ~30 $M_\odot$
  - orbit (e ~ 0.9) with a ~5.5 yr period
  - high mass-loss rates and supersonic winds
- **VHE emission** detected during **periastron passage** (H.E.S.S. Coll 2020)

2014

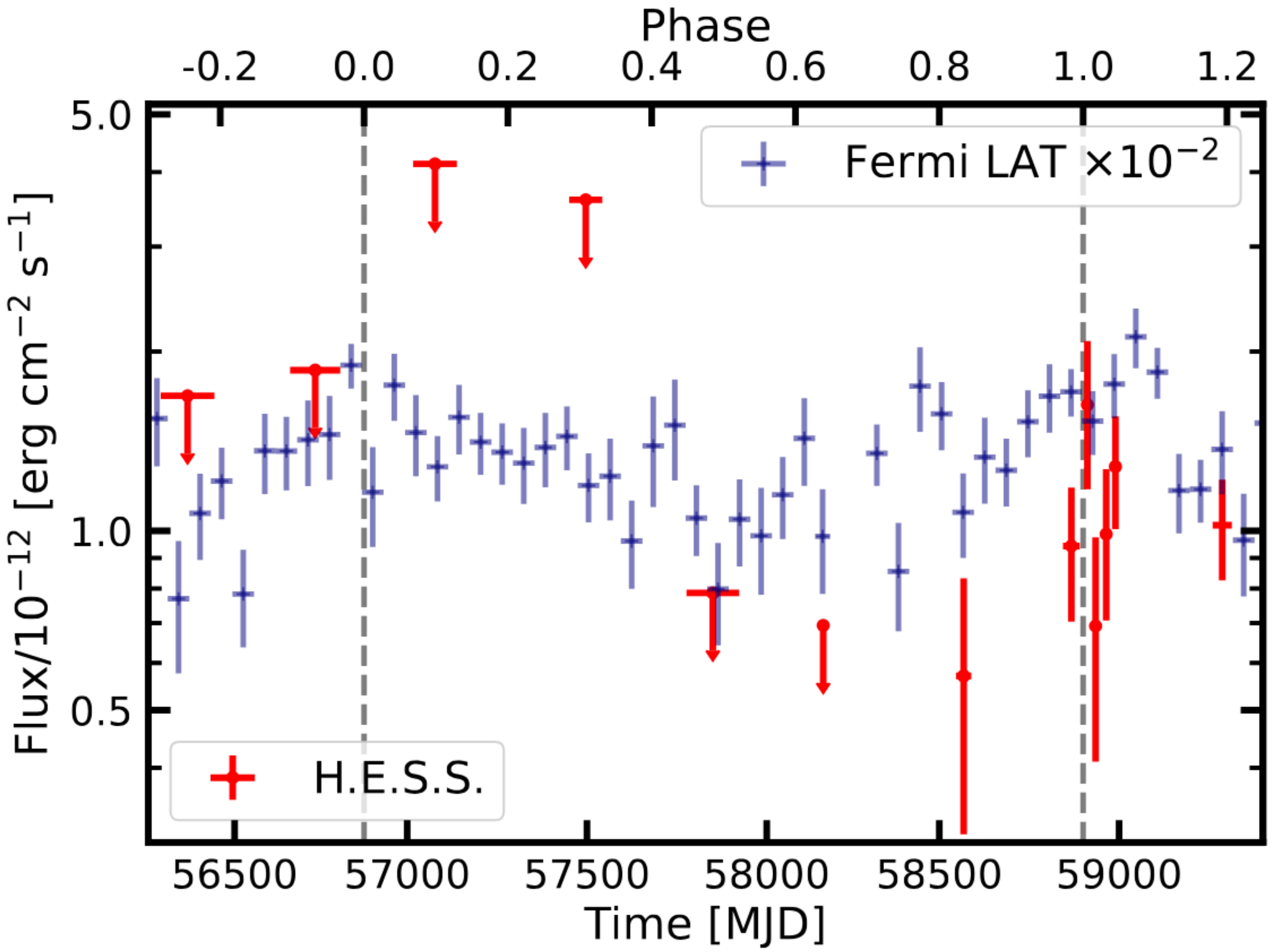


H.E.S.S. Coll (2020)

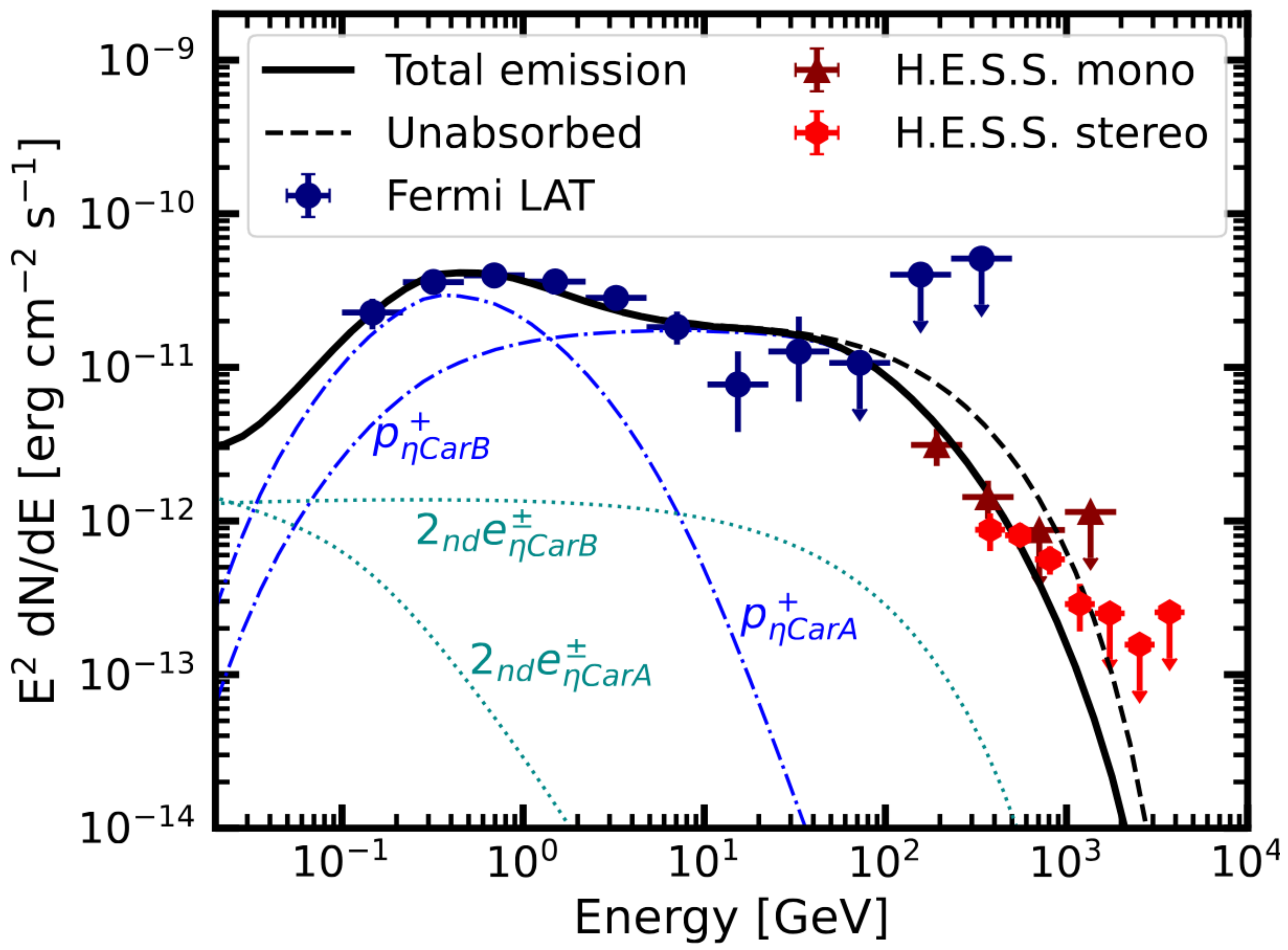
Colliding wind binaries (CWB)



- LBV ~90-100 $M_\odot$ + **O- or B-type** ~30 $M_\odot$
  - orbit (e ~ 0.9) with a ~5.5 yr period
  - high mass-loss rates and supersonic winds
- **VHE emission** detected during **periastron passage** (H.E.S.S. Coll 2020)
  - **2020 passage**: detected at energies 0.14 TeV **up to above 1 TeV** (arxiv:2501.12238)
    - **Hadronic scenario**
- Next passage: 2025

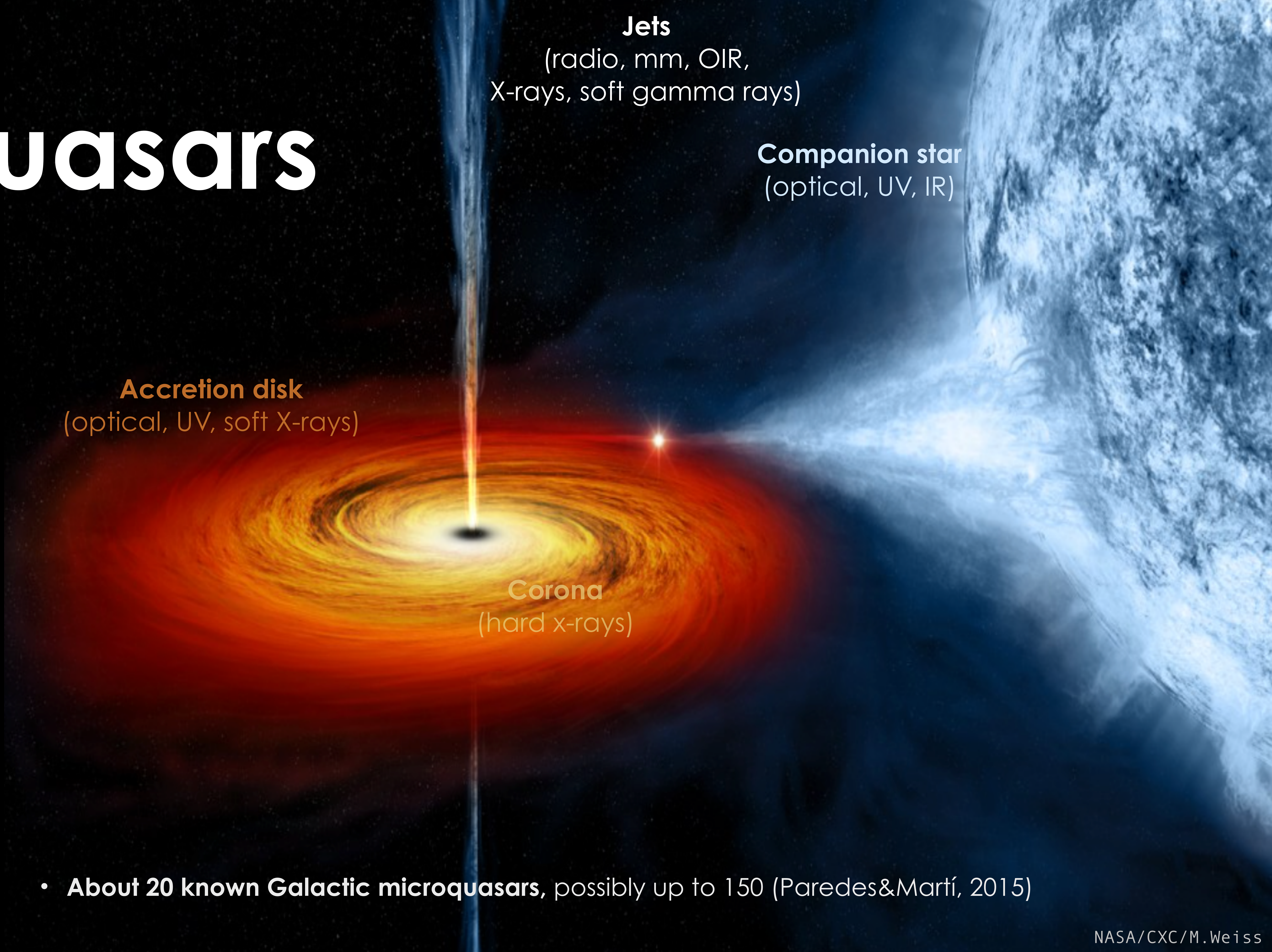


2020



arxiv:2501.12238

Microquasars



- **About 20 known Galactic microquasars,** possibly up to 150 (Paredes&Martí, 2015)

NASA/CXC/M.Weiss

Microquasars

https://cdy-institute.ie/previous-talks/

2024

Session: Microquasars

December 11

Title: Acceleration, radiation, and transport of relativistic particles in the jets of SS433
Speaker: *Dmitry Khangulyan (Institute of High Energy Physics, Chinese Academy of Sciences)*
Presentation: PDF File
Video: YouTube
Readings:

- Spatially resolved study of the SS 433/W50 west region with Chandra: X-ray structure and spectral variation of non-thermal emission

. . .

November 27

Title: Detection of microquasars by LHAASO
Speaker: *Ruoyu Liu (Nanjing University)*
Presentation: PDF File
Video: YouTube
Readings:

- Ultrahigh-Energy Gamma-ray Emission Associated with Black Hole-Jet Systems

. . .

November 13

Title: Detecting Microquasars with HAWC
Speaker: *Sabrina Casanova (Institute of Nuclear Physics, Polish Academy of Science)*
Presentation: PDF File
Video: YouTube
Readings:

- On V4641 Sgr
  - Ultra-high-energy gamma-ray bubble around microquasar V4641 Sgr
- On SS 433
  - Very-high-energy particle acceleration powered by the jets of the microquasar SS 433
  - Acceleration and transport of relativistic electrons in the jets of the microquasar SS 433
- On the pass 5 performance
  - Performance of the HAWC Observatory and TeV Gamma-Ray Measurements of the Crab Nebula with Improved Extensive Air Shower Reconstruction Algorithms

. . .

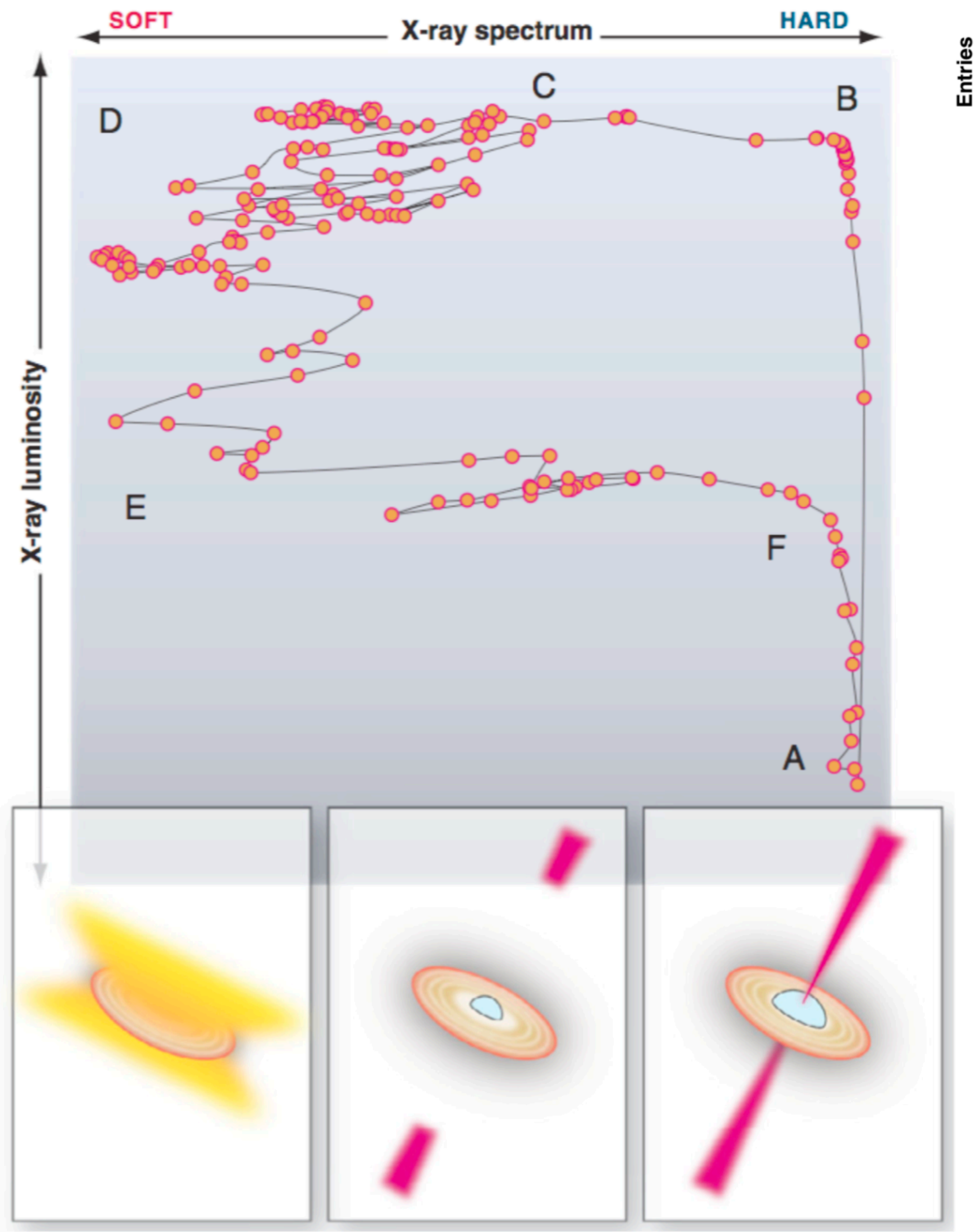
October 30

Title: Microquasars: the nearest black hole particle accelerators
Speaker: *Laura Olivera-Nieto (Max-Planck Institute for Nuclear Physics)*
Presentation: PDF File
Video: YouTube
Readings:

- Understanding the Very High-Energy Emission from Microquasars
- Microquasars: summary and outlook
- Acceleration and transport of relativistic electrons in the jets of the microquasar SS 433
- Ultrahigh-Energy Gamma-ray Emission Associated with Black Hole-Jet Systems
- Persistent GeV counterpart to the microquasar GRS 1915+105

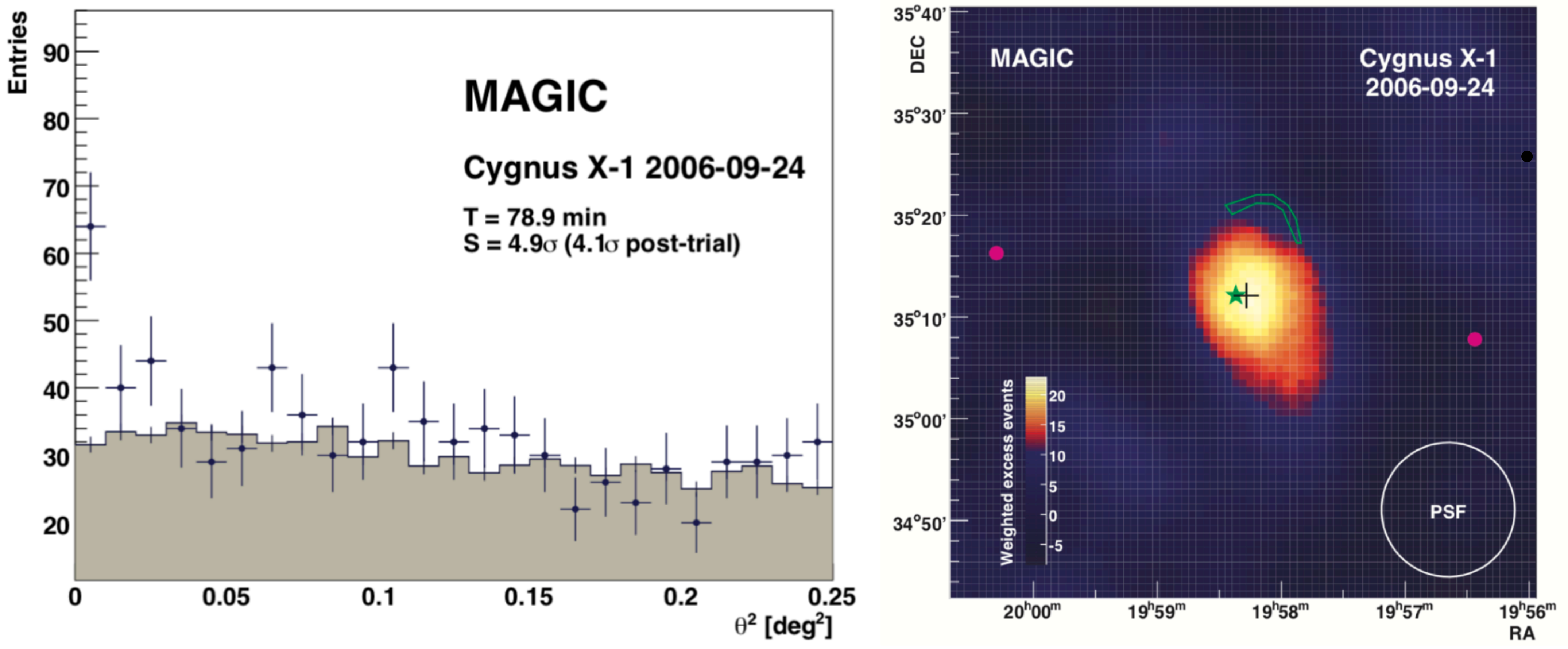
. . .

Searching for transient emission



Fender & Muñoz-Darias 2016

Cygnus X-1



The MAGIC collaboration, 2006

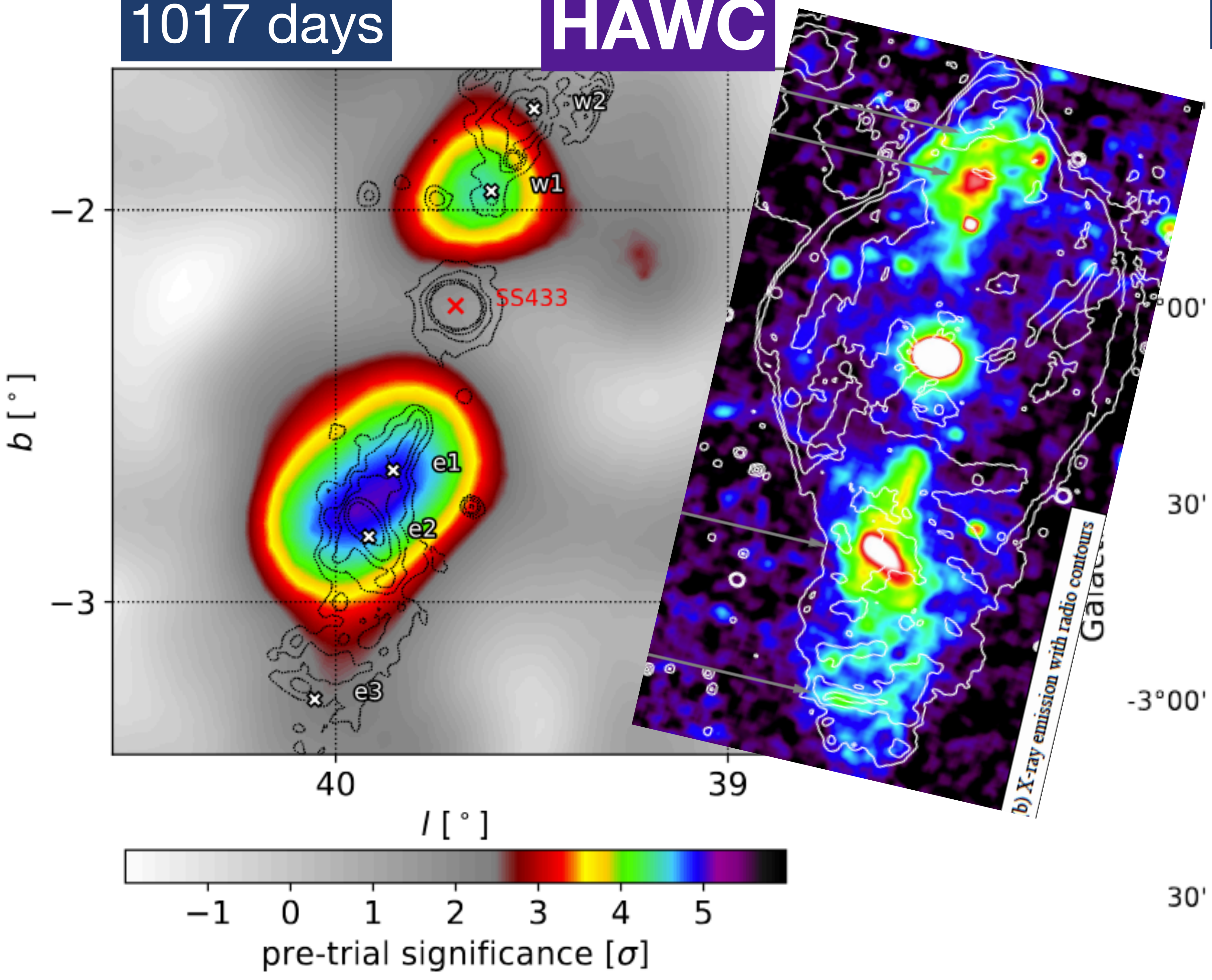
Hint of emission with MAGIC:
4.1σ in 80 min (Albert et al. 2006)

- Simultaneously with hard X-ray flare
- During hard state (HS) and SUPC
- **Strongest hint of transient TeV emission in a microquasar**

- **No transient VHE emission from system with high-mass and low-mass companions**
  - MWC 656 (Aleksic et al. 2015)
  - Cygnus X-1 (Ahnen et al. 2017b)
  - Cygnus X-3 (MAGIC 2018)
  - V4641 Sgr (Abdalla et al. 2018)
  - Sco X-1 (Aleksic et al. 2011)
  - V404 Cygni (Ahnen et al. 2017)
  - GRS 1915+105 (Saito et al. 2011, Abdalla et al. 2018)
  - Circinus X-1 (Abdalla et al. 2018)
  - MAXI J1820+070 (Abdalla et al. 2018)

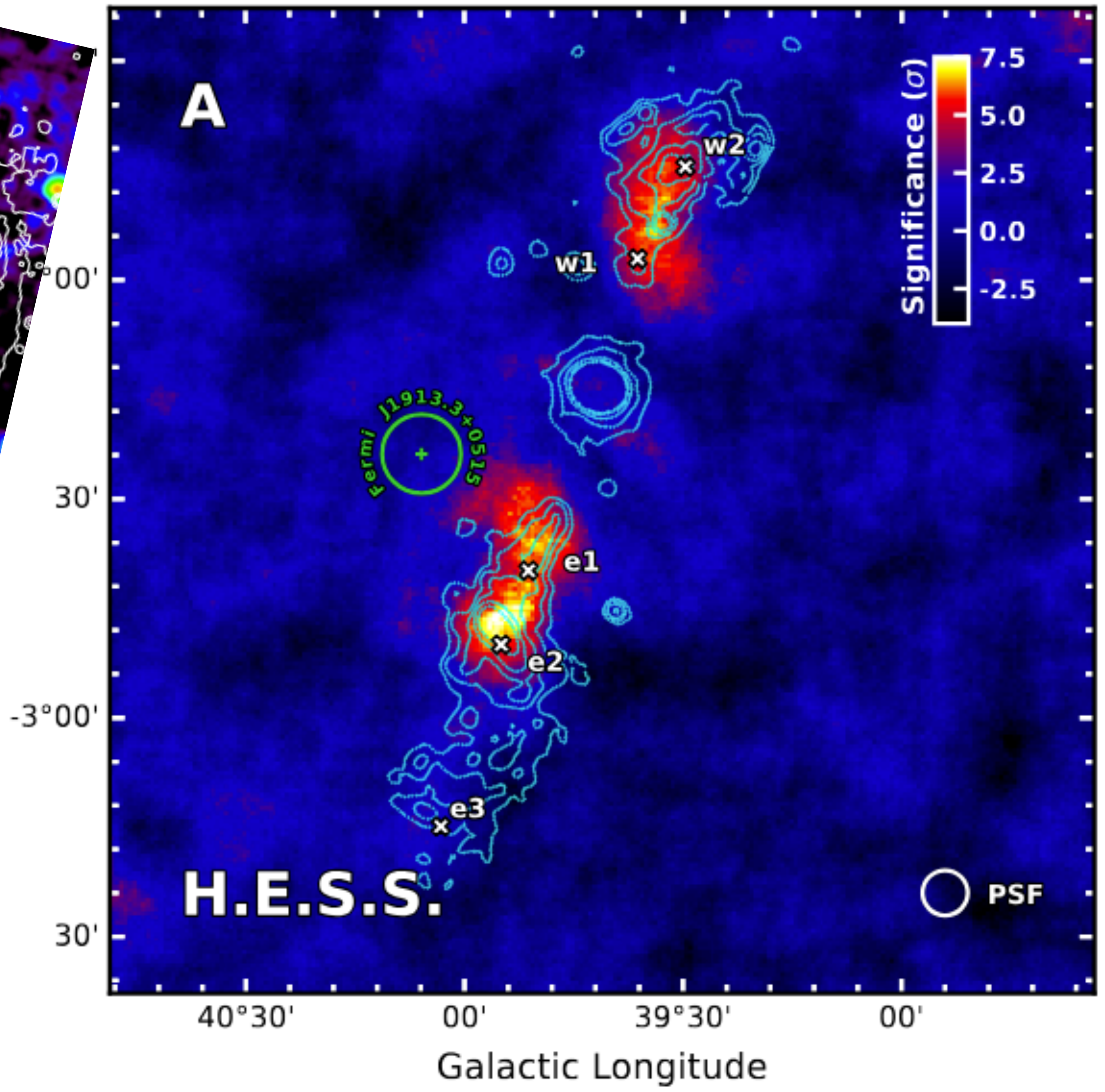
Persistent TeV emission from microquasars: SS433

1017 days **HAWC**

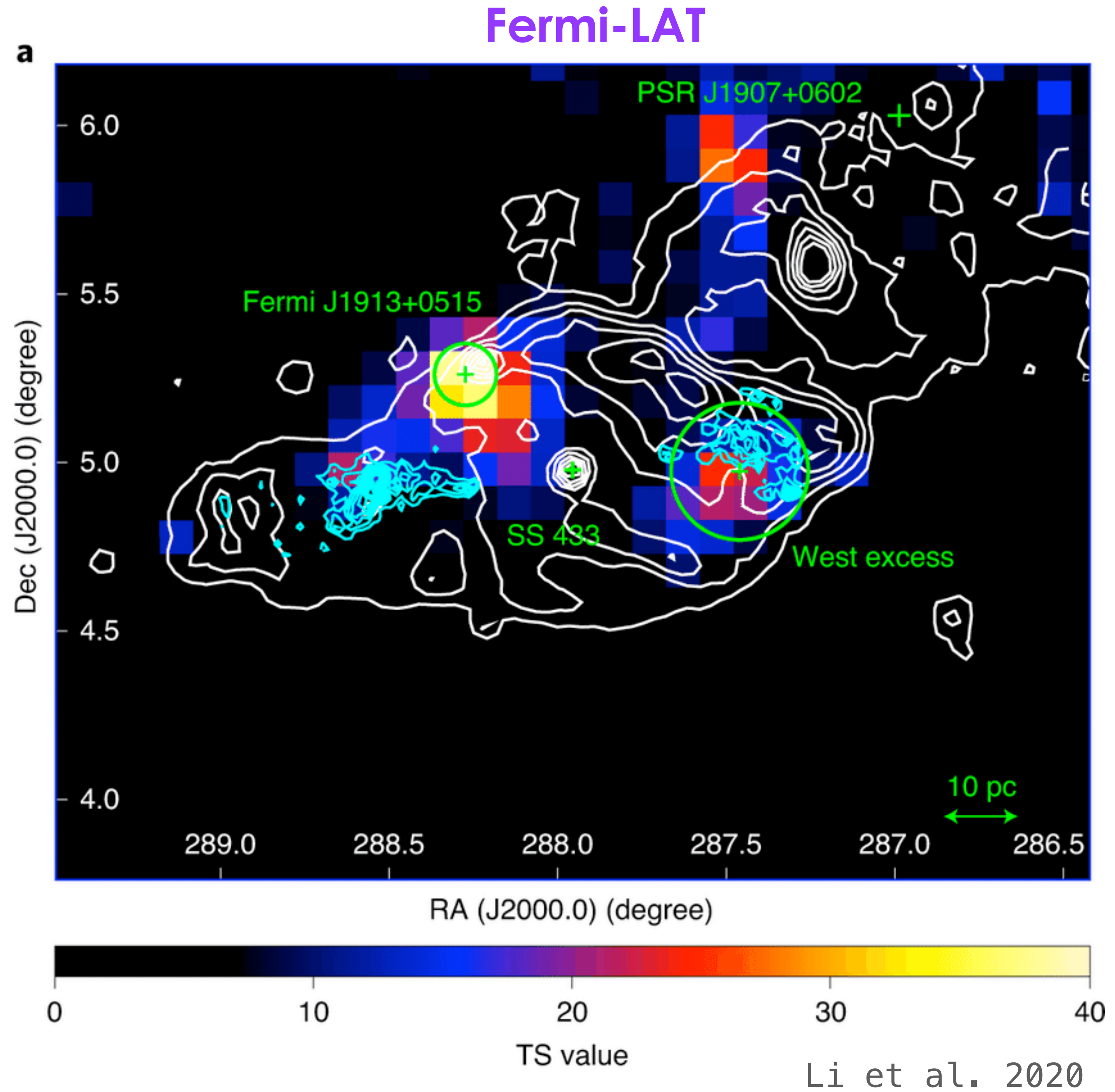


HAWC Coll. 2023

200 h **H.E.S.S.**



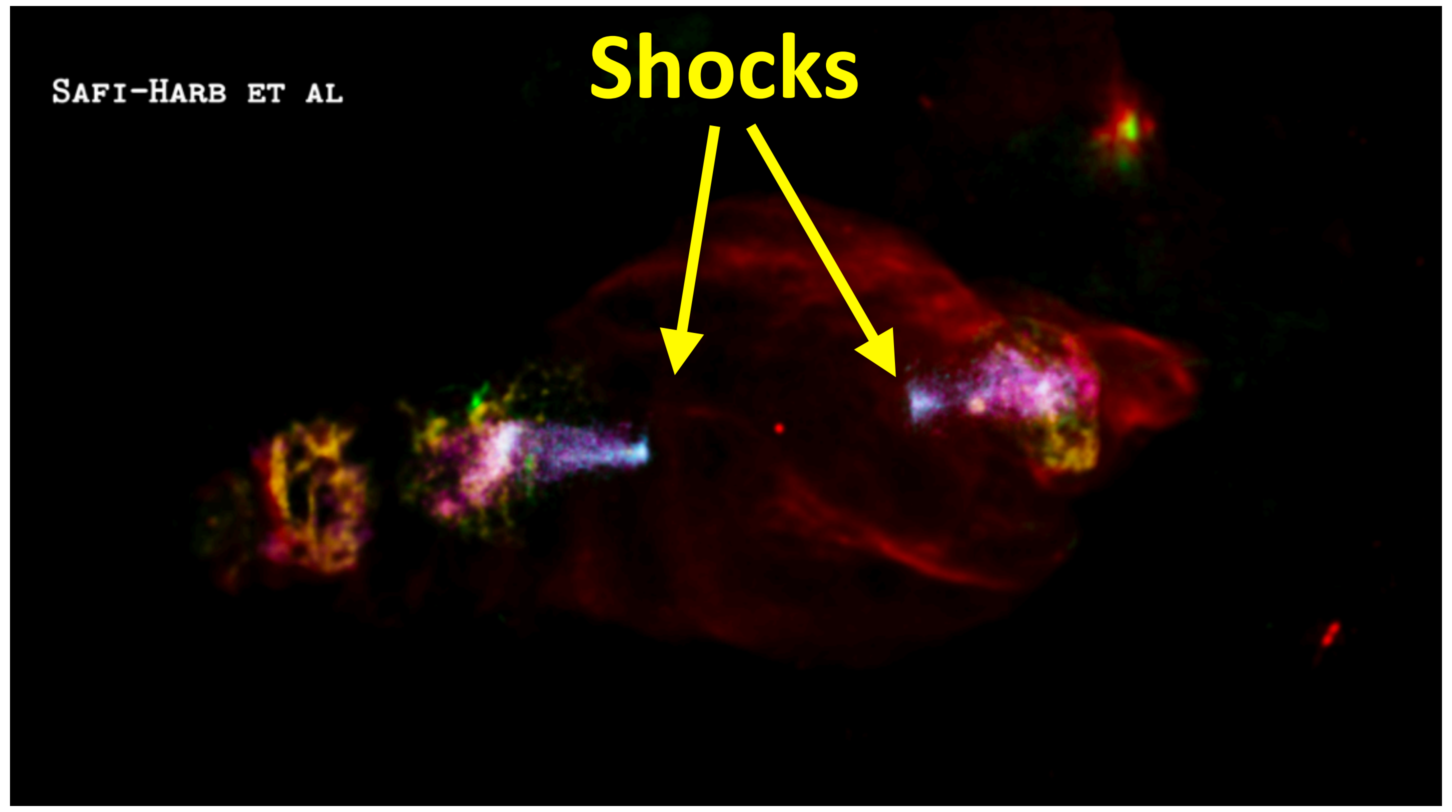
H.E.S.S Coll. 2024



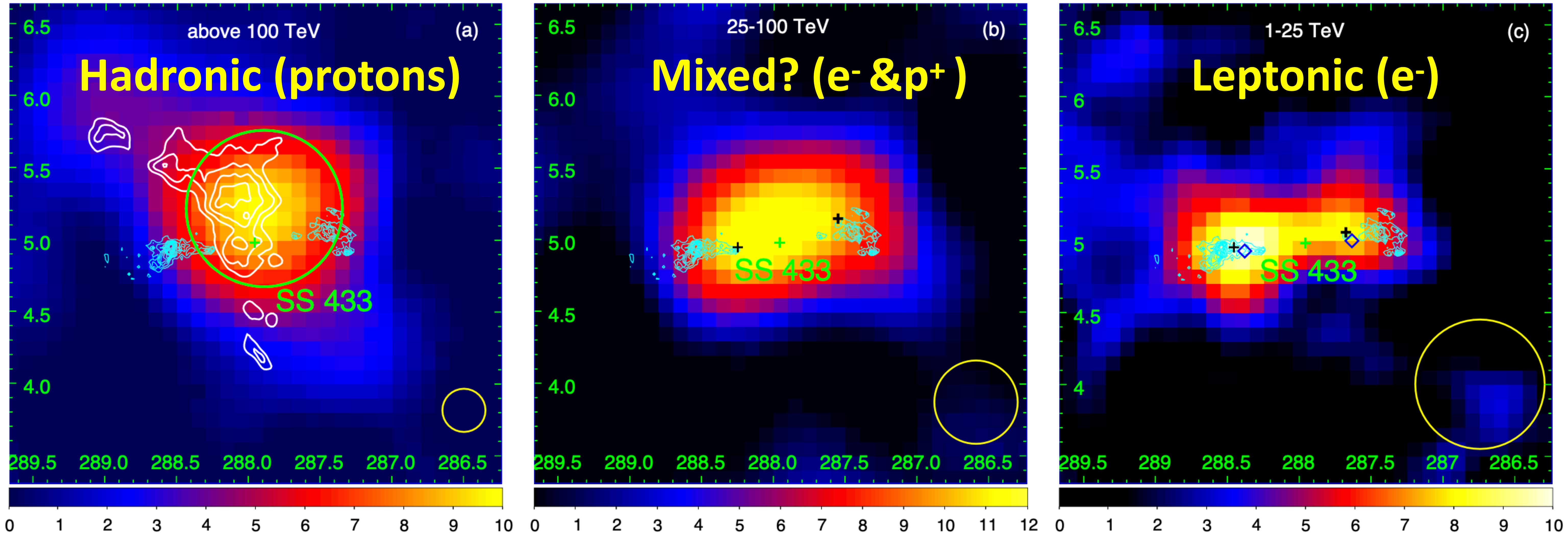
Li et al. 2020

- **TeV emission at interaction regions** (Abeysekara et al. 2023, HESS coll. 2024, LHAASO 2024)
  - **Leptonic** scenario proposed, acceleration of **electrons up to 200 TeV**

First microquasar
(interaction with medium)
detected
in the TeV regime

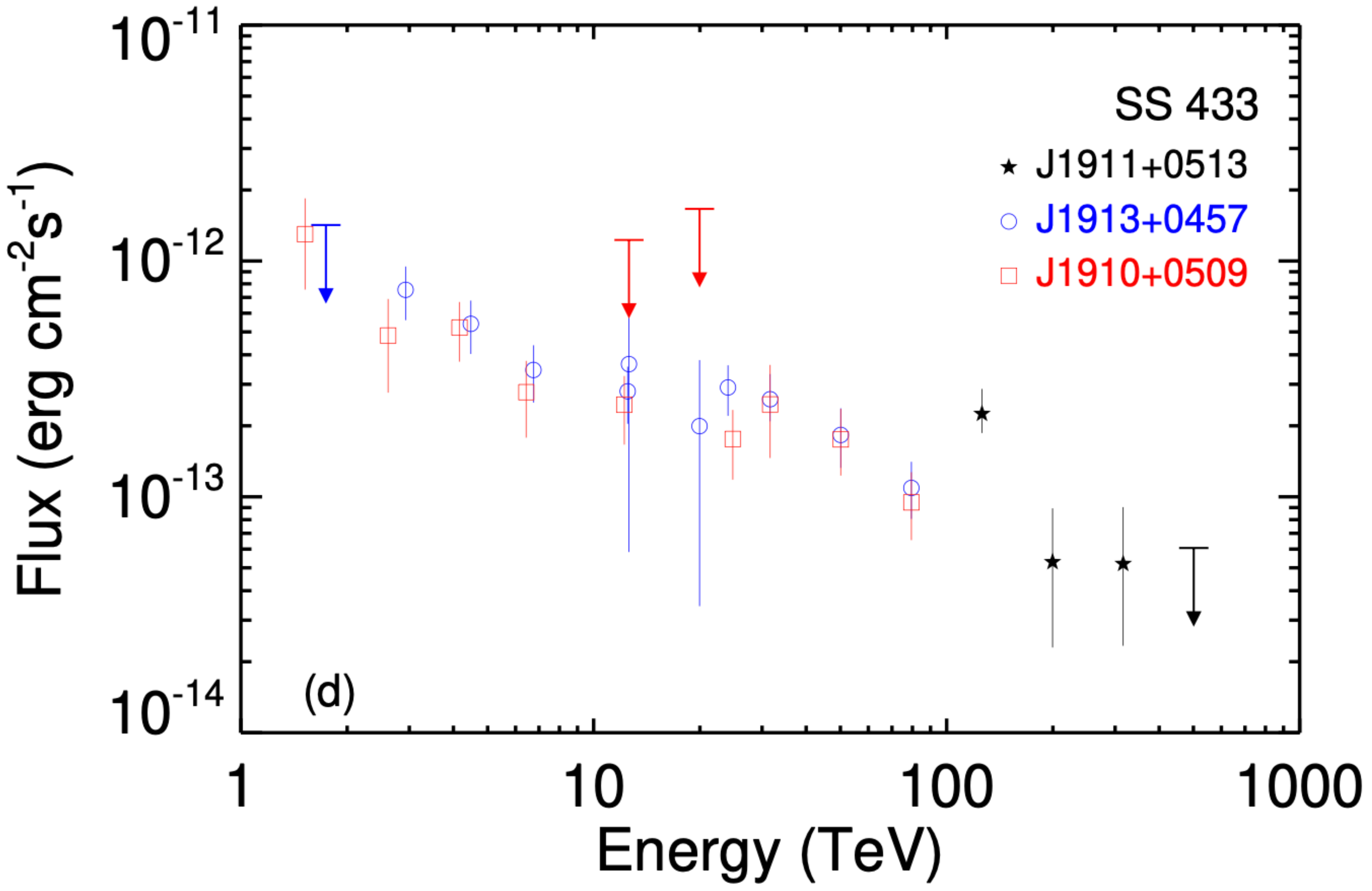


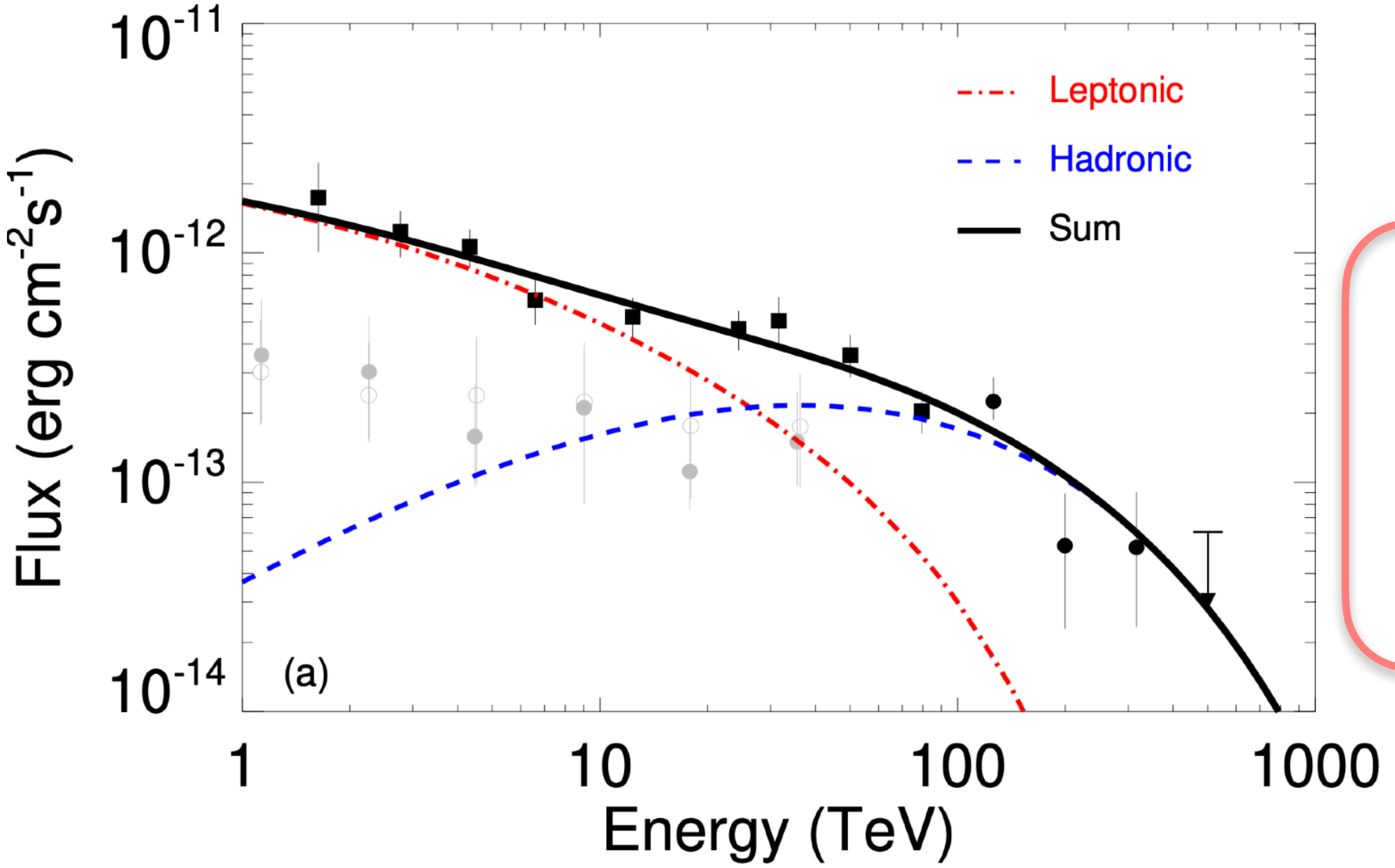
Persistent TeV emission from microquasars: SS433



(LHAASO 2024 arxiv: 2410.08988)

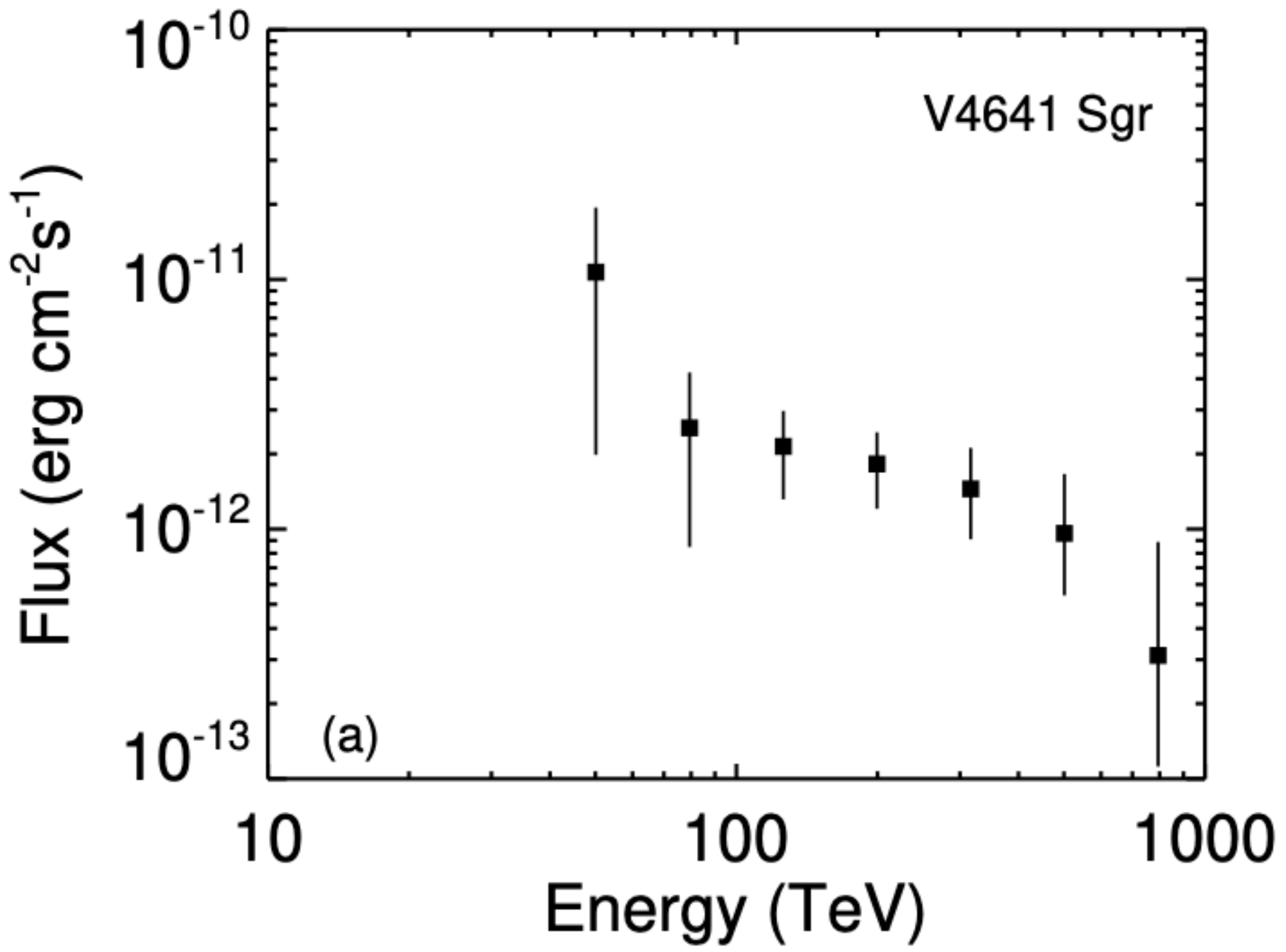
SS 433 is **continuously injecting PeV protons** at a power of ~ 10^{38} erg/s into the surrounding medium



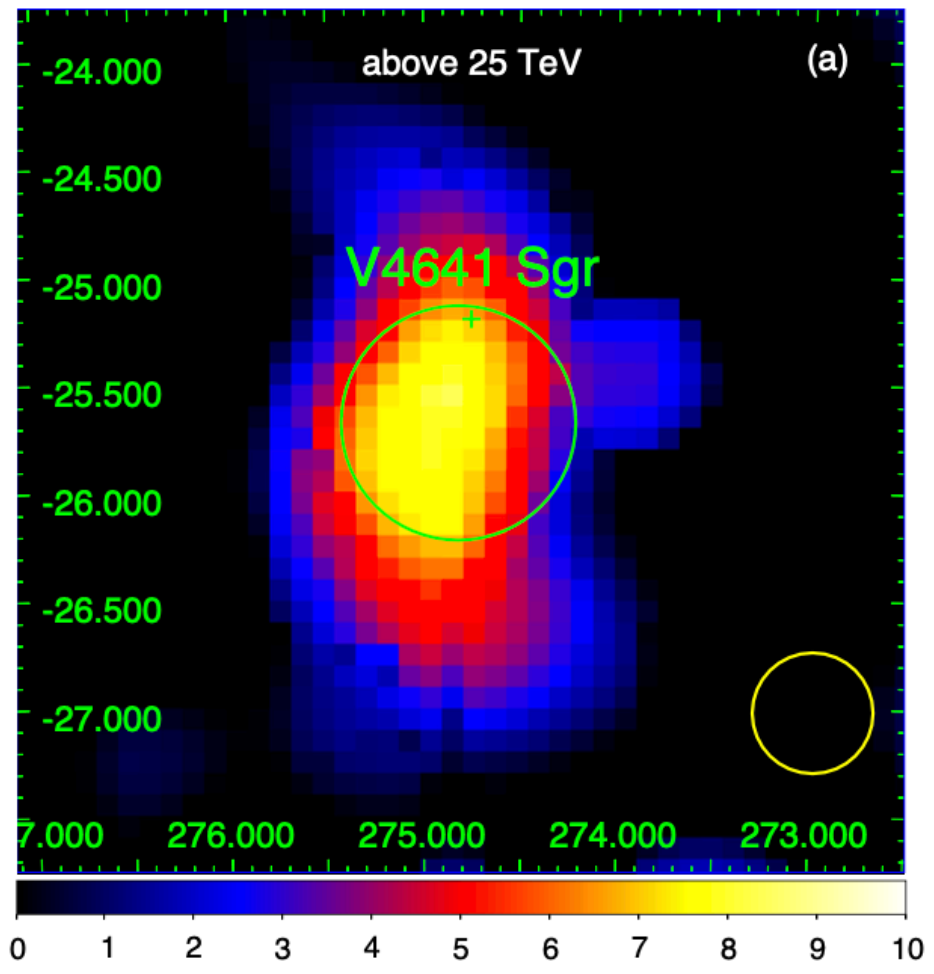


Galactic **BH-jet systems** can be potentially important **factories of CRs around and above the knee**
(LHAASO 2024 arxiv: 2410.08988)

Persistent TeV emission from microquasars: V4641 Sgr

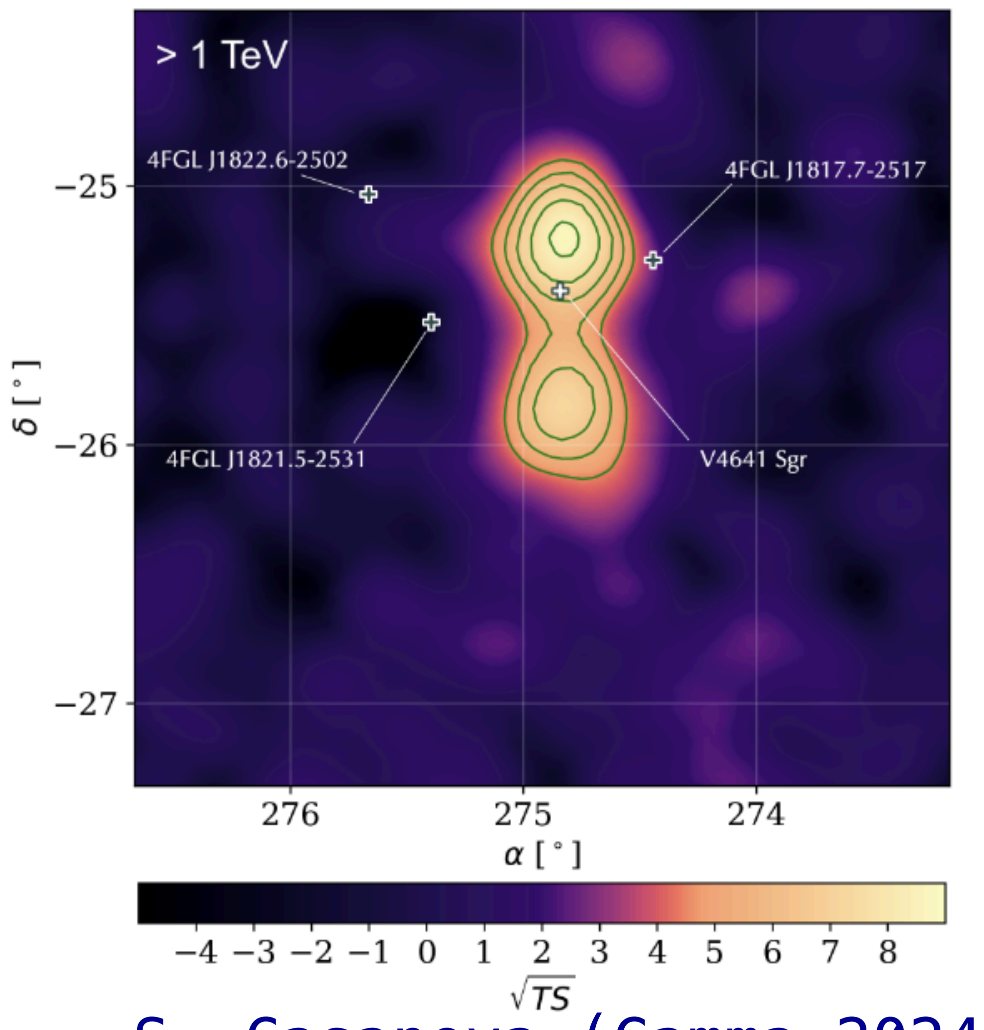


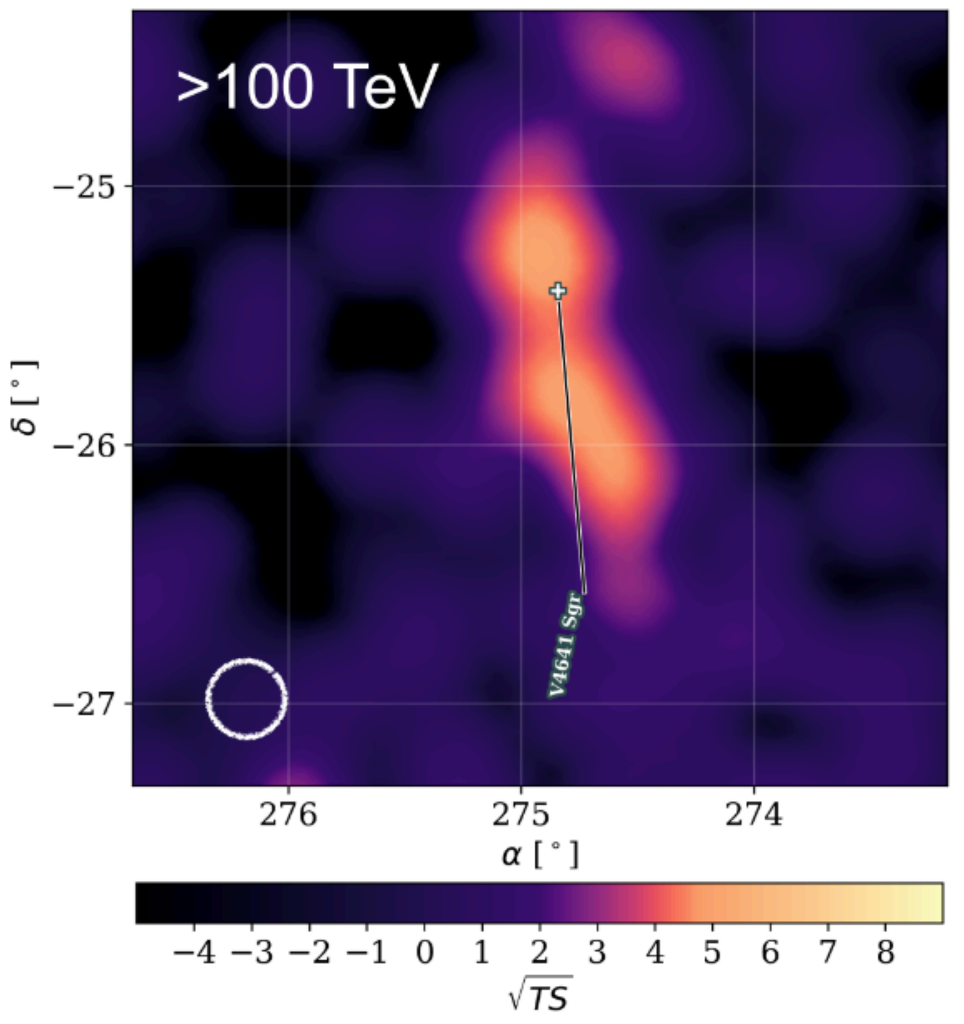
Hadronic



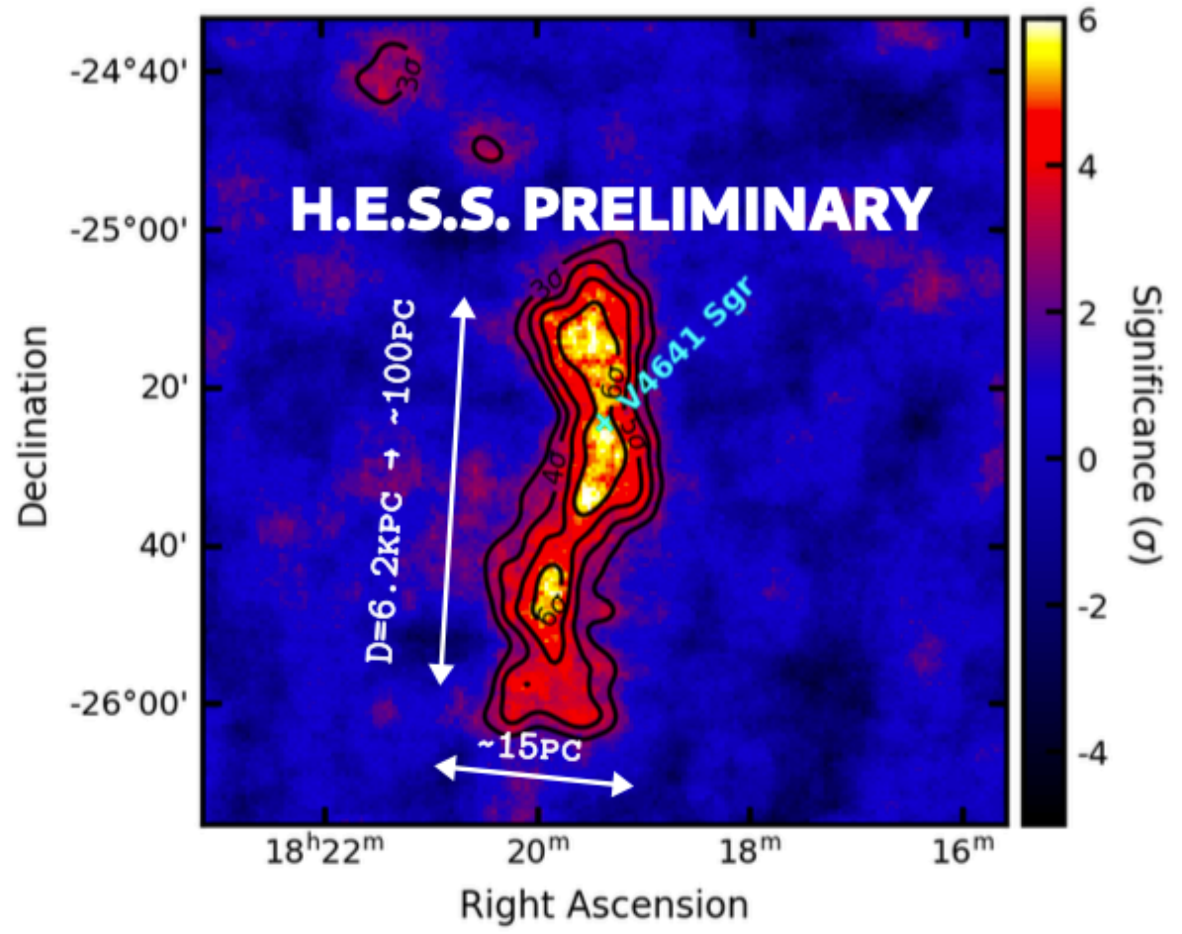
LHAASO 2024 arxiv: 2410.08988

- Supposedly a **microblazar**: jets pointing towards us
- HAWC discovery (see i.e. Goodman Gamma 2022, S. Casanova Gamma 2024) of extended TeV signal
- Confirmation by H.E.S.S (Olivera-Nieto Gamma 2024) and LHAASO (LHAASO 2024)
- **What is the origin of the TeV emission?**
  - The highest energy of photons: 0.8 PeV
  - The IC radiation of electrons cannot reproduce such a hard spectrum (due to the KN effect)
  - Reasonable spectrum of protons
  - **V4641 Sgr is most likely a so-called super-PeVatron that energizes protons up to energies at least ~ 10 PeV**
  - No detection by Fermi-LAT



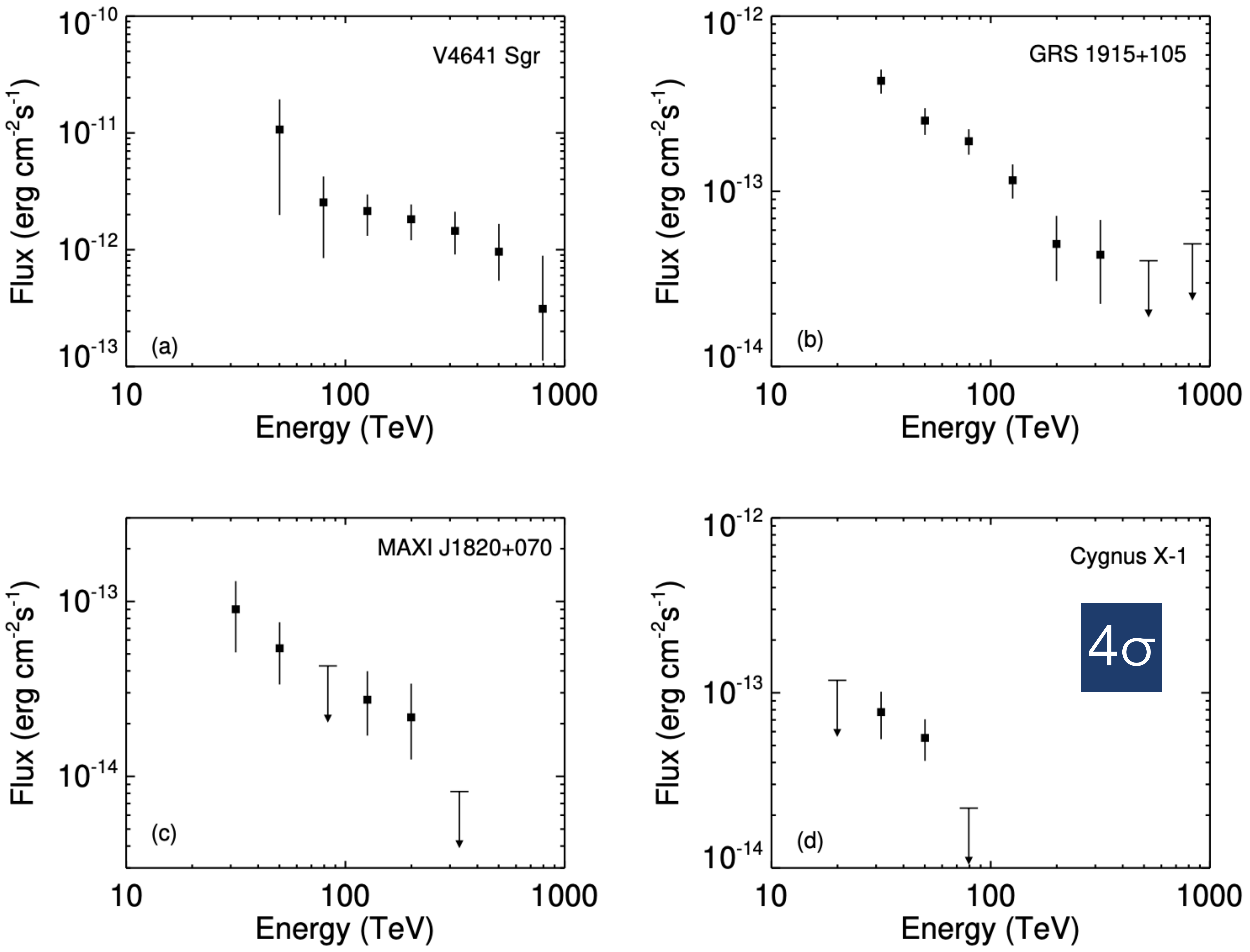


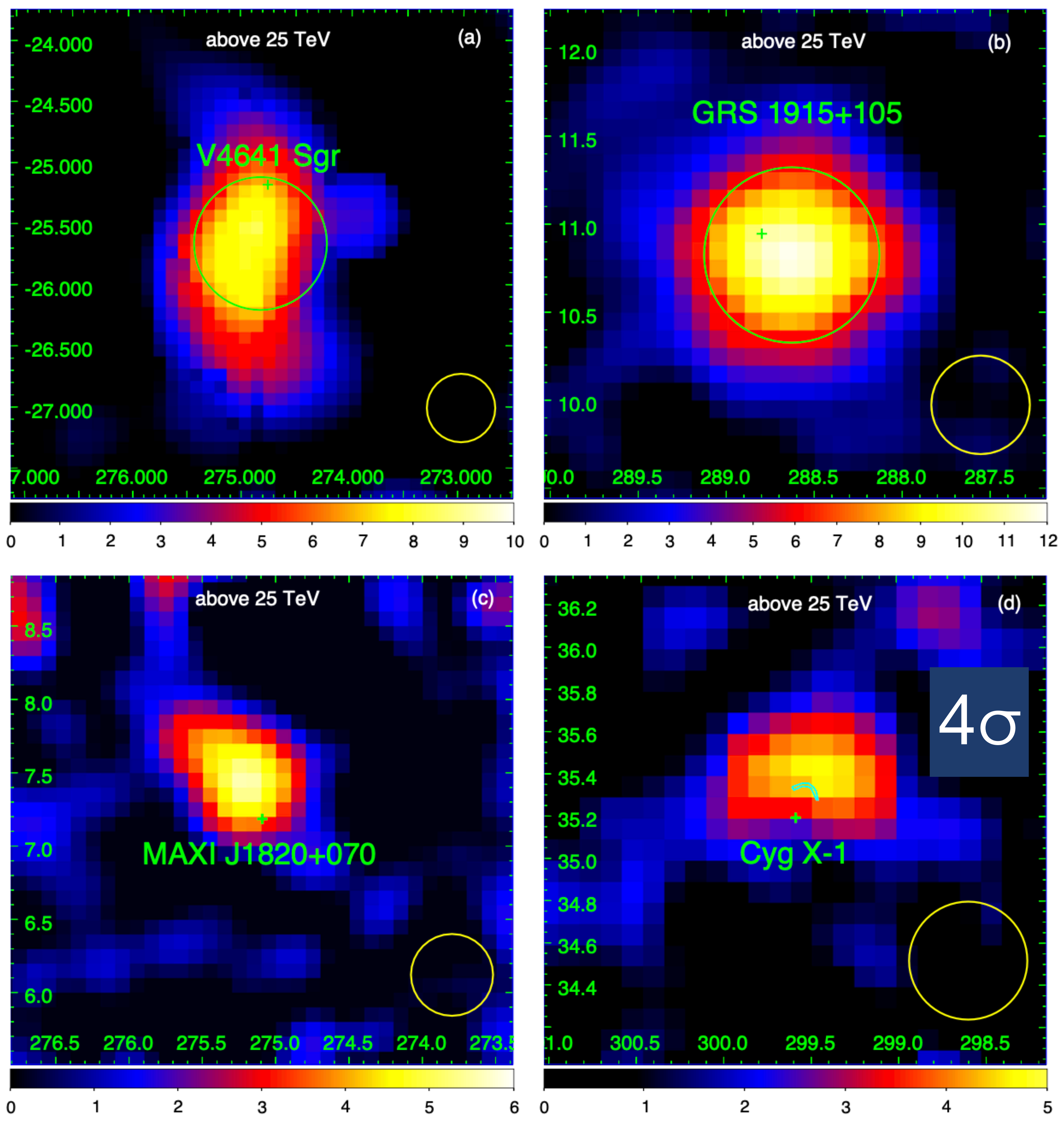
S. Casanova (Gamma 2024)



Olivera-Nieto Gamma 2024

Persistent TeV emission from many microquasars





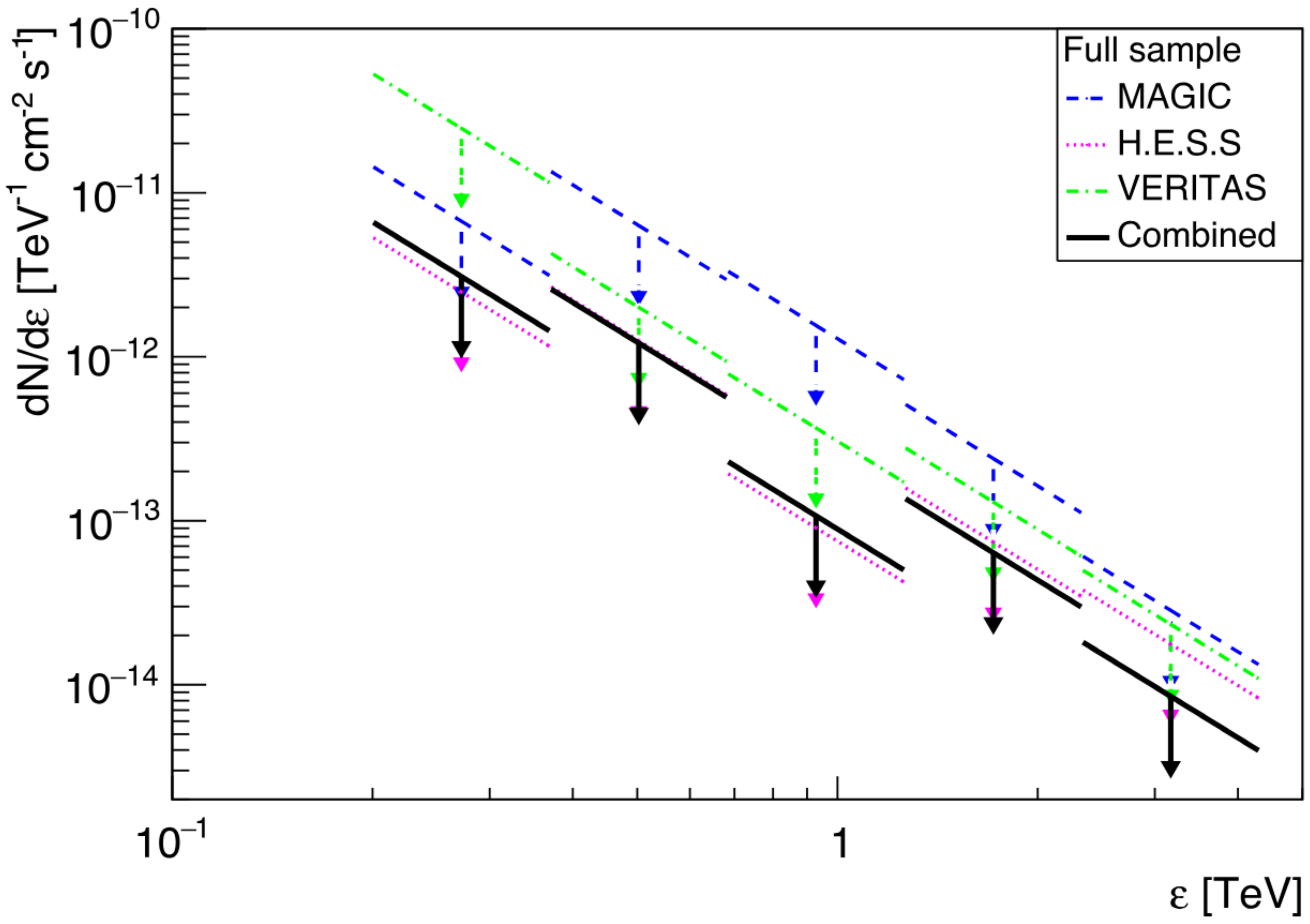
(LHAASO 2024 arxiv: 2410.08988)

- Galactic **BH-jet systems** can be potentially important **factories of CRs around and above the knee**
(LHAASO 2024 arxiv: 2410.08988)

BH-jet binaries are efficient particle accelerators

MAXI J1820+070

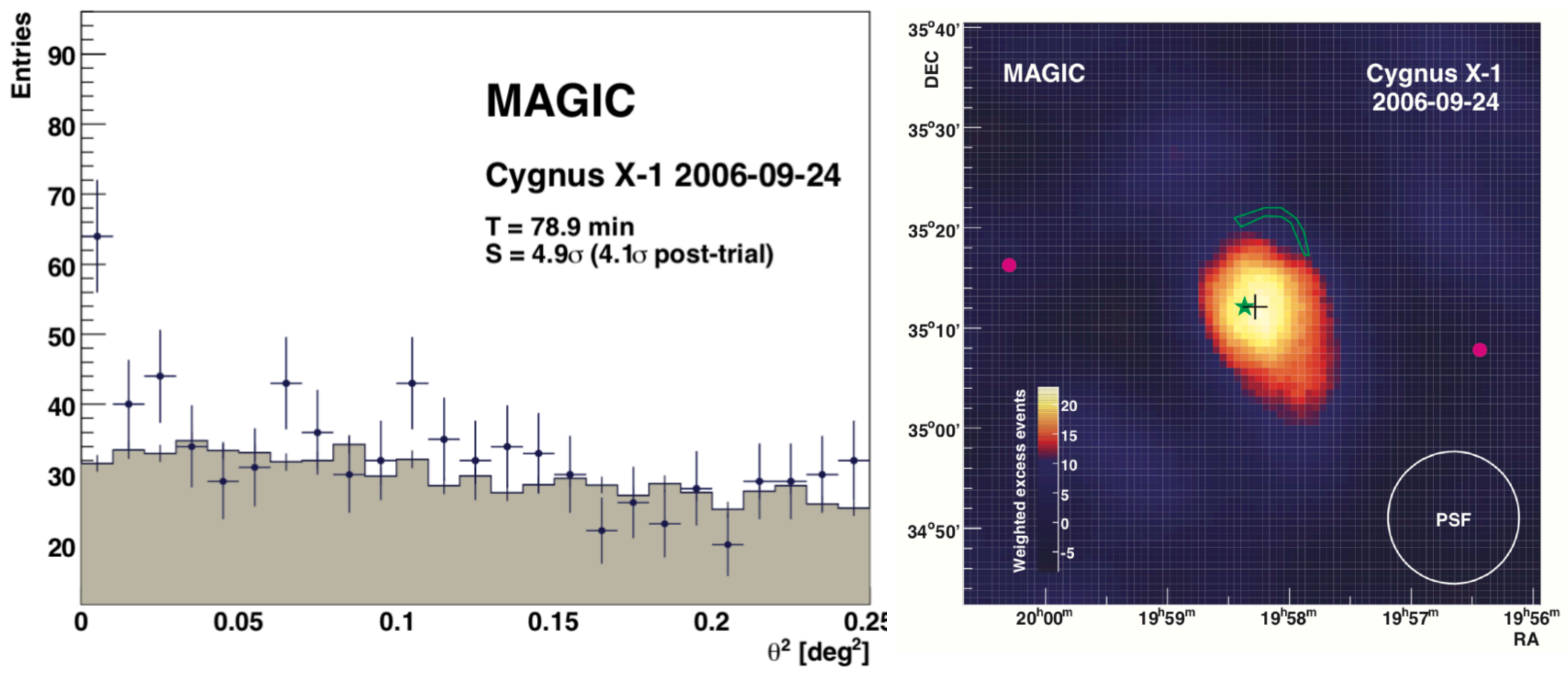
- **Multi-IACT campaign in 2018 during outburst (discovery)**
- Combined of 59.5 h of observations with H.E.S.S., MAGIC and VERITAS at E>200 GeV (Abe et al. 2022)
  - No VHE detection



Source state	*Fermi*-LAT UL (0.1–500 GeV) (ph cm^{-2} s^{-1})	IACT UL (>200/300 GeV) (ph cm^{-2} s^{-1})
Hard State I	3.1×10^{-8}	9.5×10^{-13}
HS → SS	1.6×10^{-7}	9.5×10^{-13}
Soft State	2.5×10^{-8}	1.6×10^{-12}
SS → HS	5.2×10^{-8}	2.2×10^{-12}
Hard State II	6.0×10^{-8}	–
TOTAL	1.8×10^{-8}	7.2×10^{-13}

Cygnus X-1 at VHE

- **Hint of transient emission** with MAGIC: 4σ in 80 min (Albert et al. 2006)
  - Simultaneously with hard X-ray flare
  - During hard state (HS) and SUPC

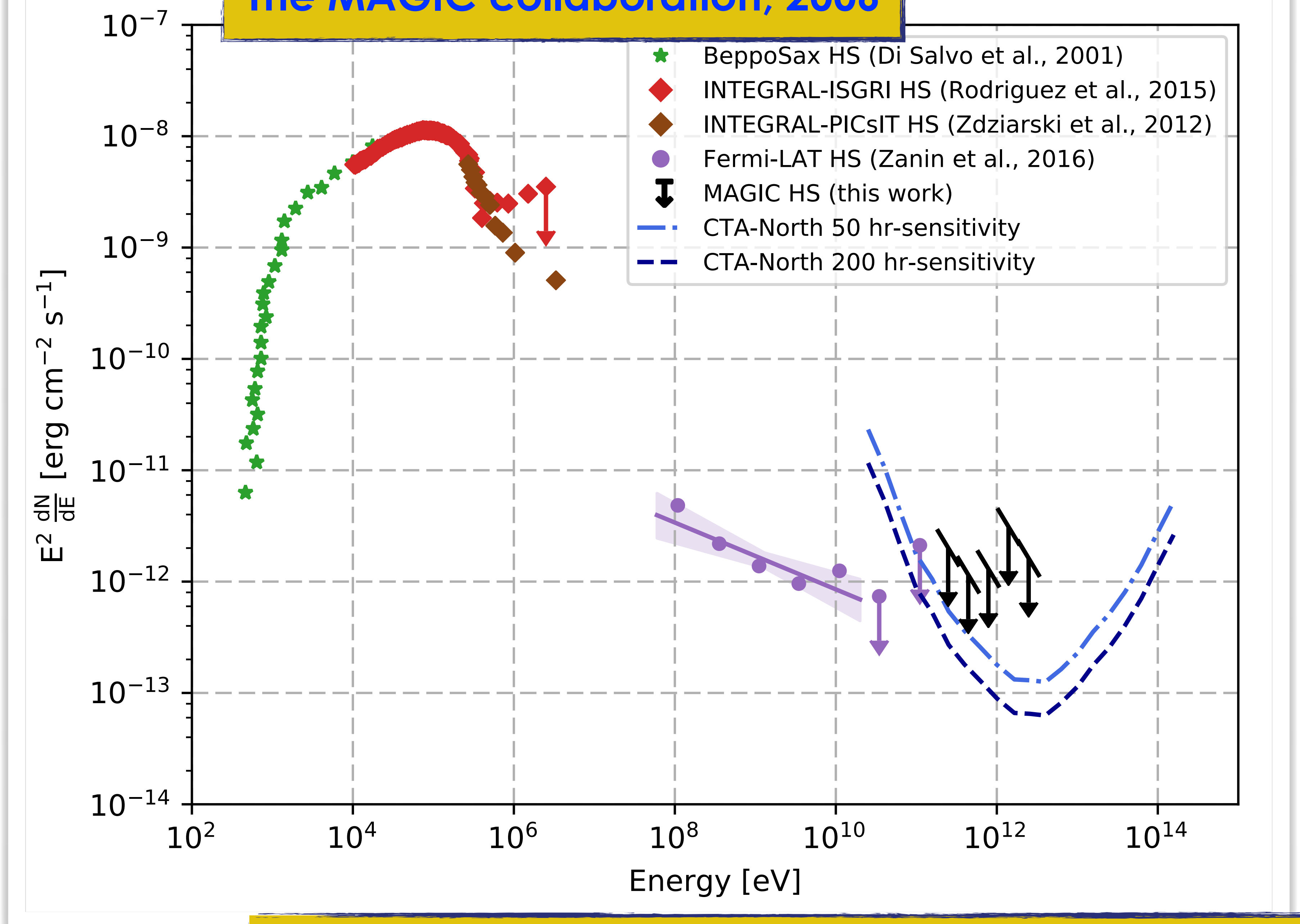


The MAGIC collaboration, 2006

- **100 h** (2007-2014) of MAGIC observations **mainly at HS** (83h)

- No significant excess at either X-ray state for steady, orbital or daily basis emission

- **Transient emission** (Albert et al. 2007) **still possible** at binary scale



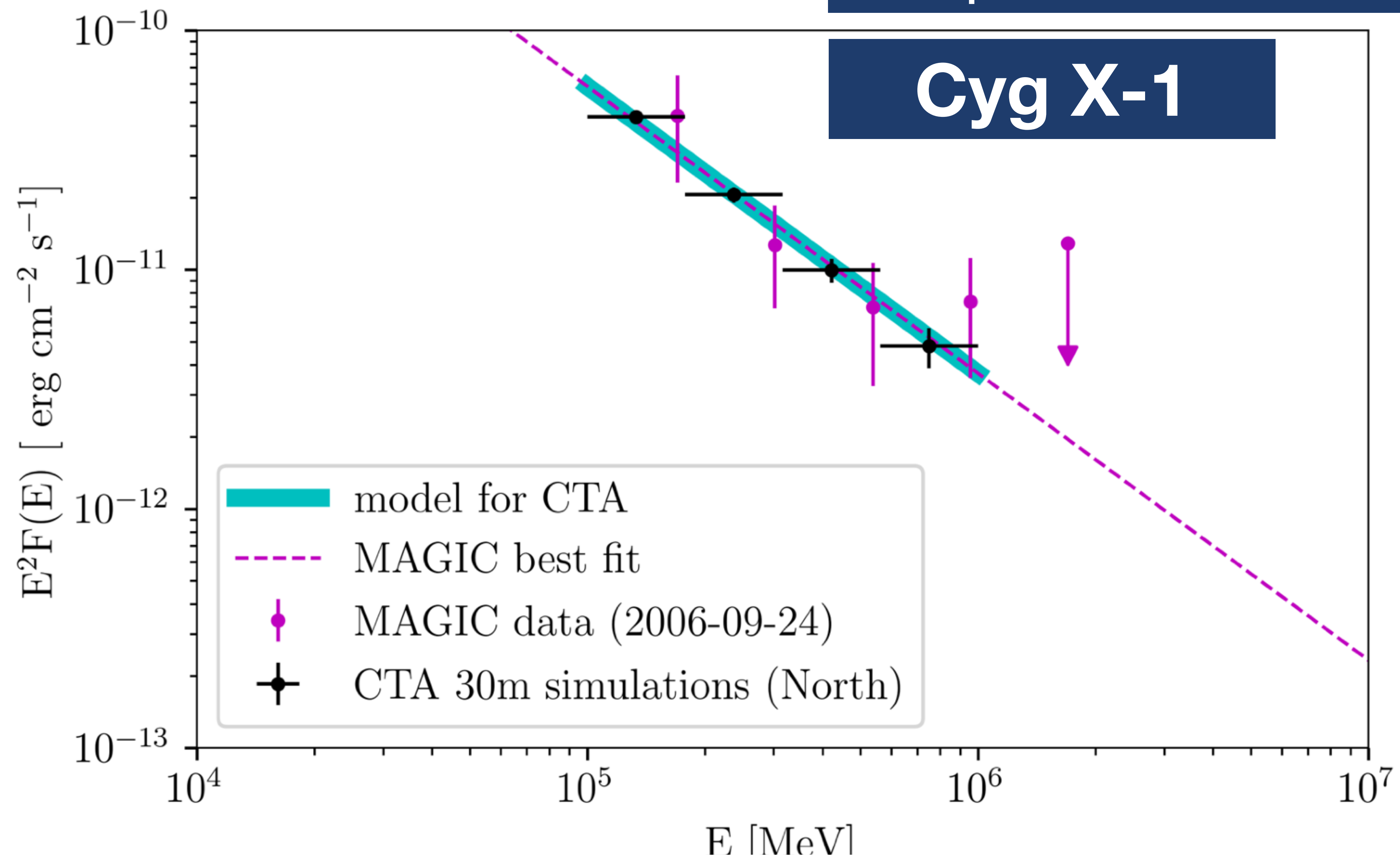
The MAGIC collaboration, 2017, MNRAS, 472, 3474

Microquasars

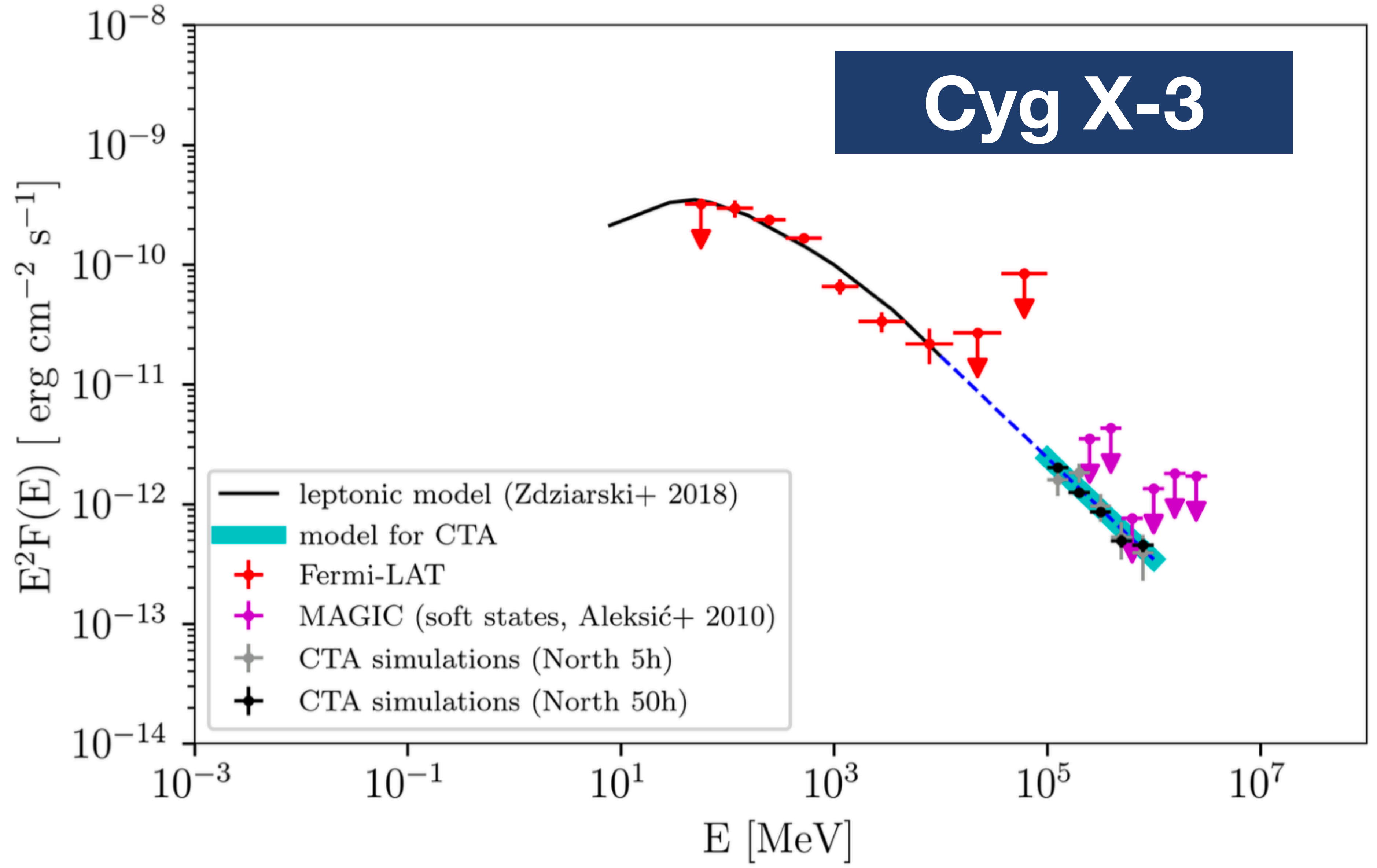
What can we expect in a future? Prospects with CTAO for transient detection

CTAO CONSORTIUM

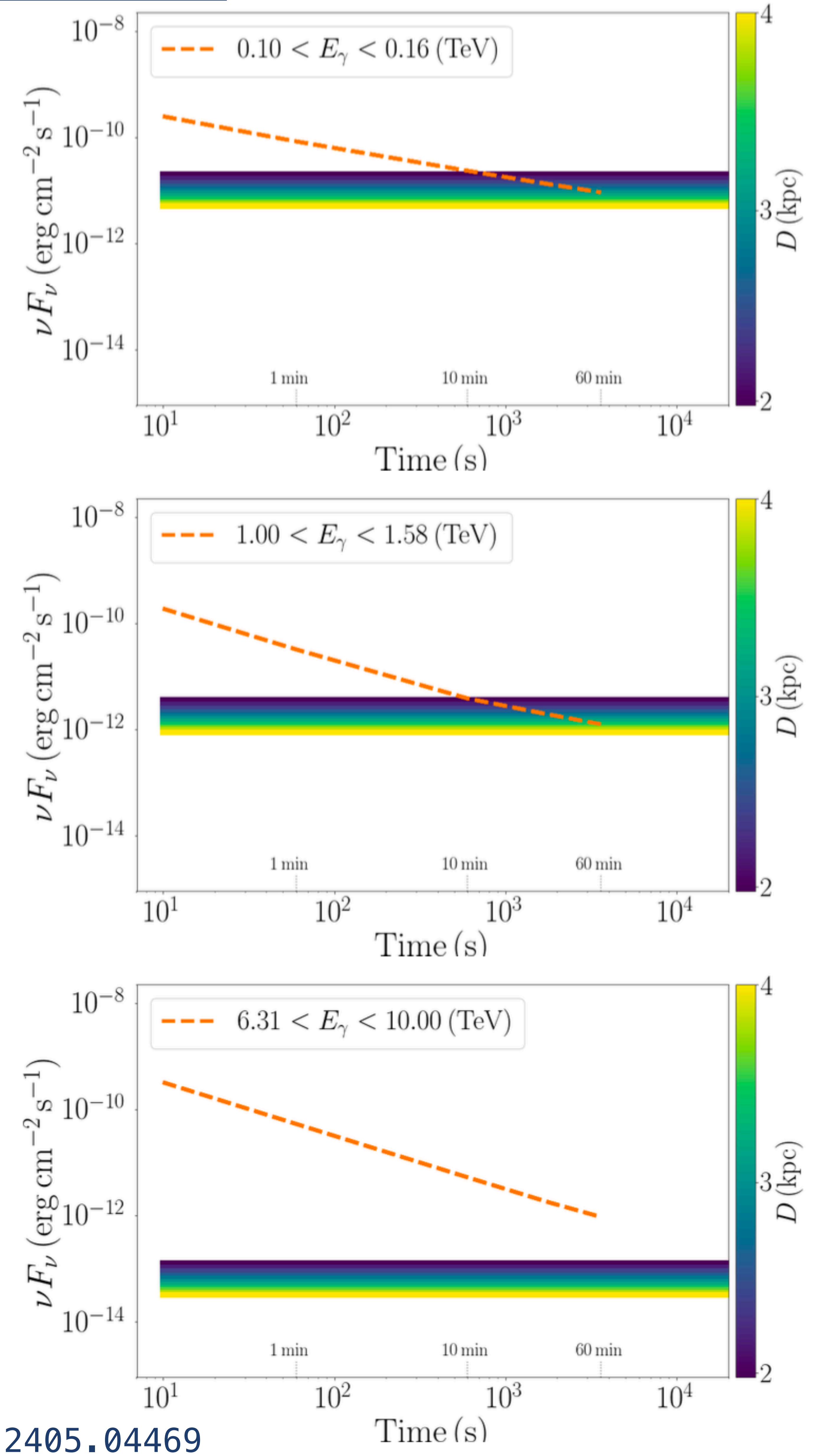
Cyg X-1



Cyg X-3

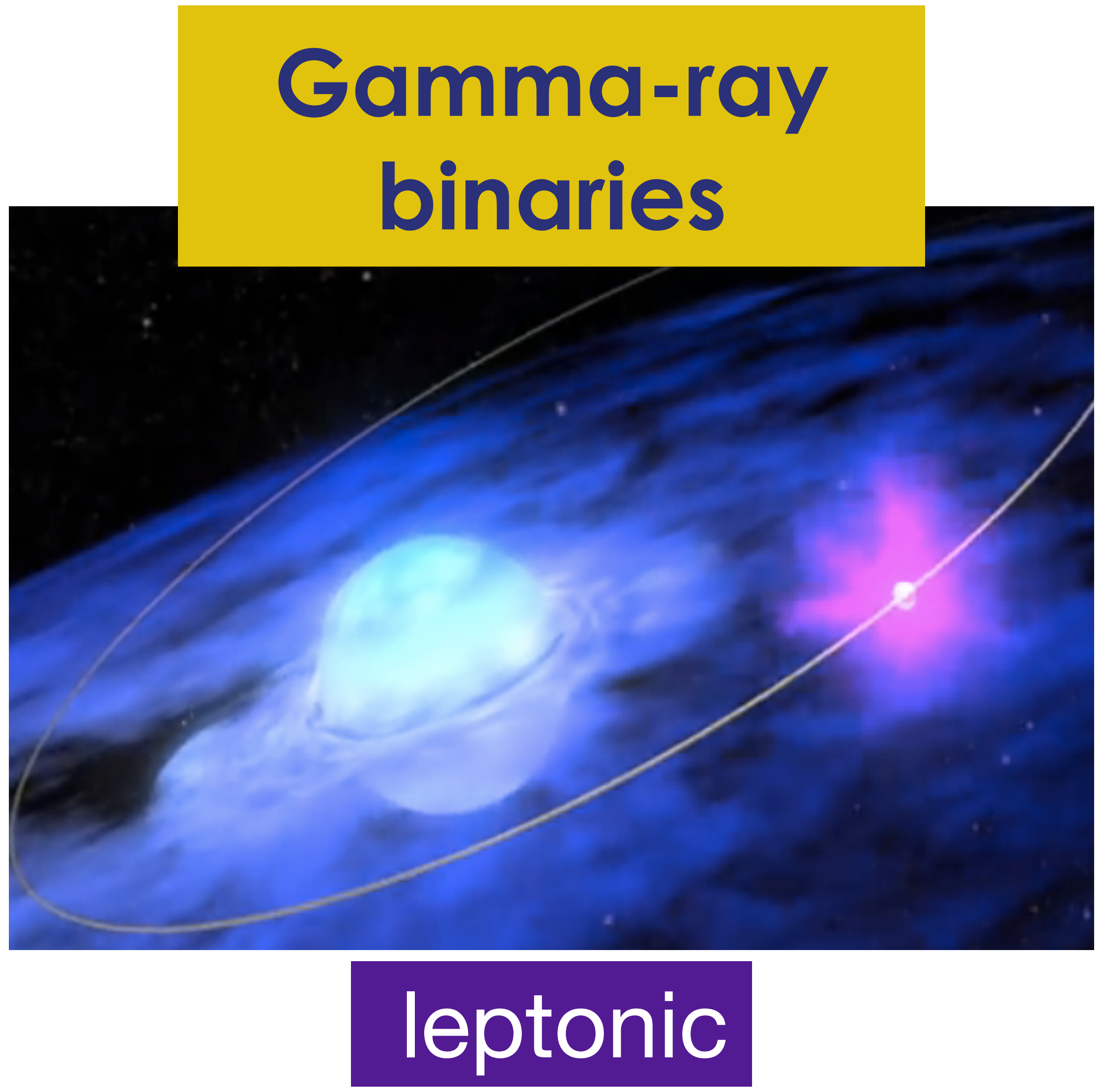


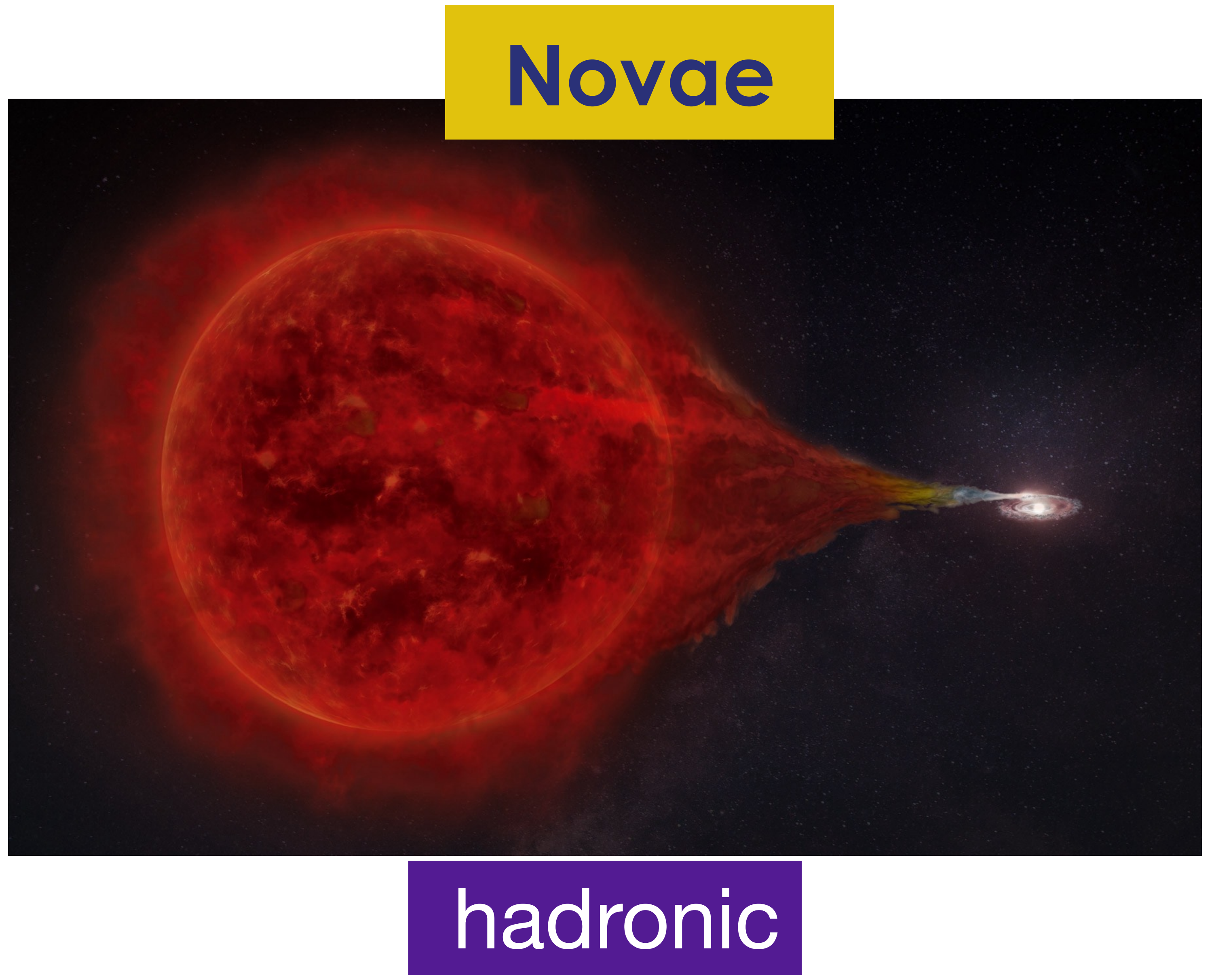
LMXBs

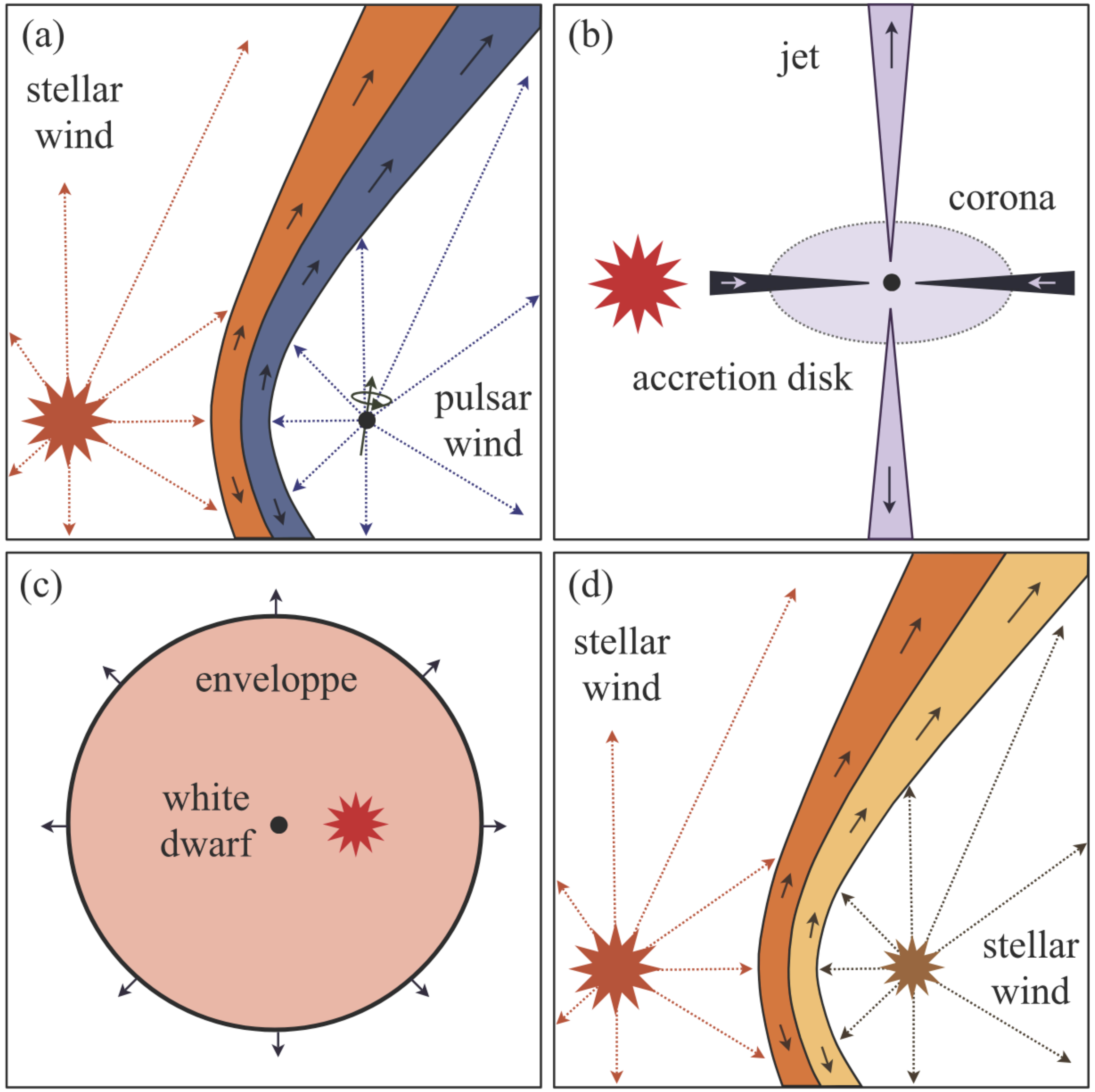


CTAO Consortium (subm) arXiv:2405.04469

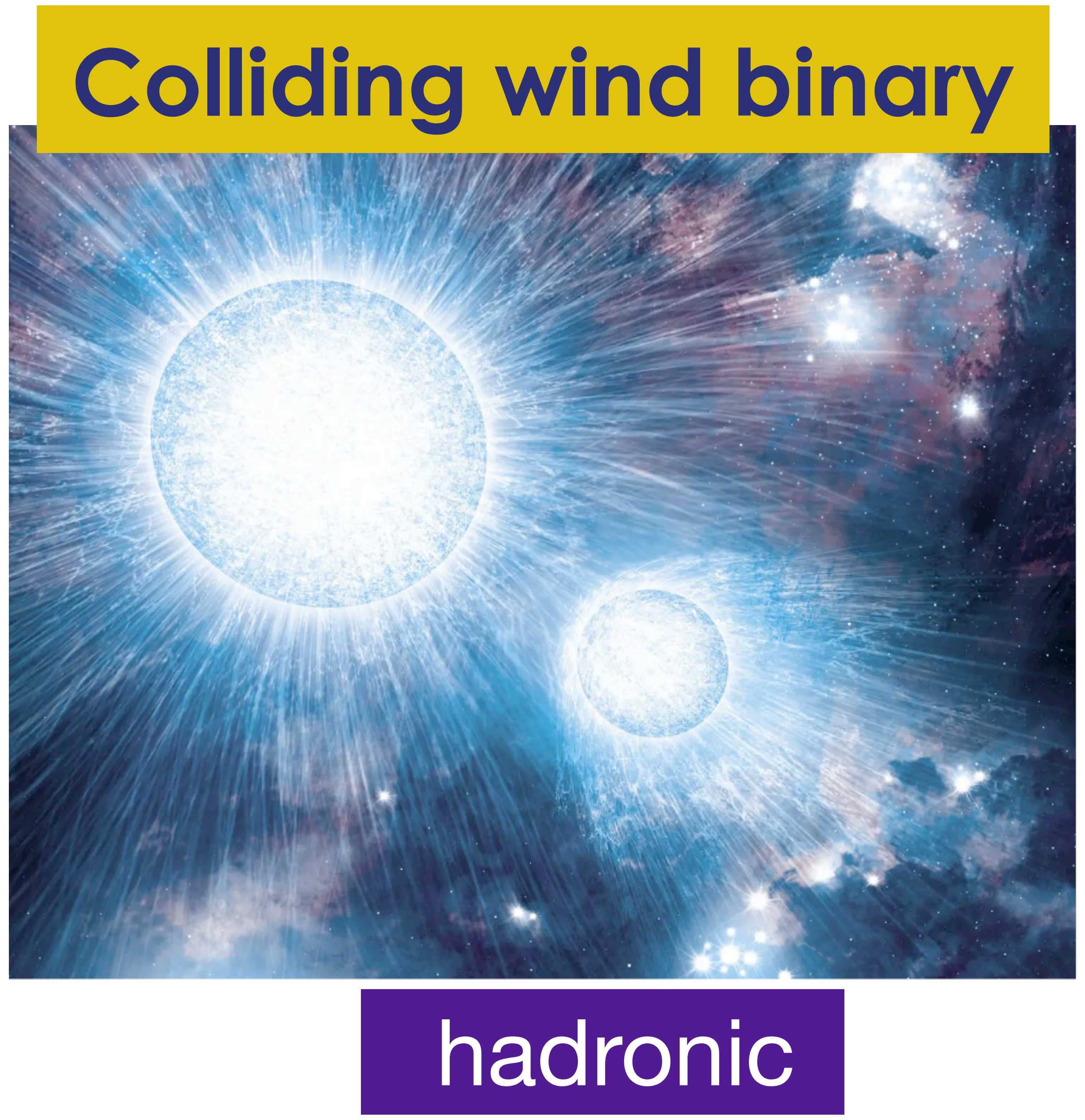
VHE emitters







Dubus 2015



Conclusions

- Plethora of **different types of binaries** emitting in the VHE regime discovered over the past few years

- **Gamma-ray binaries**
  - Massive stars with compact object -> **likely non-accreting pulsars**
  - **Apparent grouping on O5/O6** for O-type systems
  - Emission **up to even 100 TeV** without cutoff

- **Novae:**
  - **(Symbiotic) novae established as VHE emitters**
  - Emission of **hadronic origin**
  - Classical novae?

- **Colliding-wind binaries**
  - Eta carina **up to 1 TeV**
  - **Hadronic** origin of the VHE emission

- **Microquasars:**
  - Recently **confirmed as VHE emitters**
    - for **jet/medium interaction**, SS433 central source yet detected
  - **Only persistent** emission
  - **Transient hints** with IACTs

Open questions

- Compact object in gamma-ray binaries: non-accreting pulsars?
- Are gamma-ray binaries the precursors of HMXBs?
- Super-orbital modulation in other systems?
- Binaries hosting magnetars?
- Transient emission from microquasars?
- Central source in microquasars?
- Classical novae?
- When is T CrB exploding?
- Other CWB? Hadronic?
- Other types of systems: i.e. with tMSP

NASA

Thanks

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TeV gamma-loud binaries

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