VHE emission from binary systems

image credit
NASA / GSFC/F. Reddy

Guillaume Dubus

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It all starts with Berrie

```
De: Berrie Giebels <berrie@poly.in2p3.fr>
Objet: emergency
Date: 5 mars 2004 à 10:39:46 UTC+1
À: gd@poly.in2p3.fr


Yo, on a besoin de toi ici. psr1259-63 a 5 sigma
la nuit derniere. apparemment on est pas loin du
periastre prevu pour Mars 2004. Il faudrait
probablement lancer toutes les observations
possibles.

- Berrie

/-----------------------------------------------\
| Berrie Giebels                     ,~         |
| LLR Ecole Polytechnique            |\         |
| Route de Saclay                   /| \        |
| 91128 Palaiseau         ~^~ ^~ /_|__\~^~ ~^~ |
| (33) 016933-3958 Voice ~^~^ ~ `======' ~^ ~^~|
| (33) 016933-3002 Fax      ~^~ ~^ ~^~ ~^~ ~^  |
\-----------------------------------------------/
```

Variability of astrophysical sources across the wavelengths, a tribute to Berrie

November 17-21, 2025
Institut Pascal, Orsay, France
https://indico.ijclab.in2p3.fr/event/11699/

Organised by:
Deirdre HORAN (LLR)
Jonathan BITEAU (IJCLAB)
Stephen FEGAN (LLR)

With the support of:
CNRS Nucléaire et Particules
École Polytechnique
Université Paris-Saclay
Laboratoire Leprince-Ringuet

PSR B1259-63 (spring 2004)

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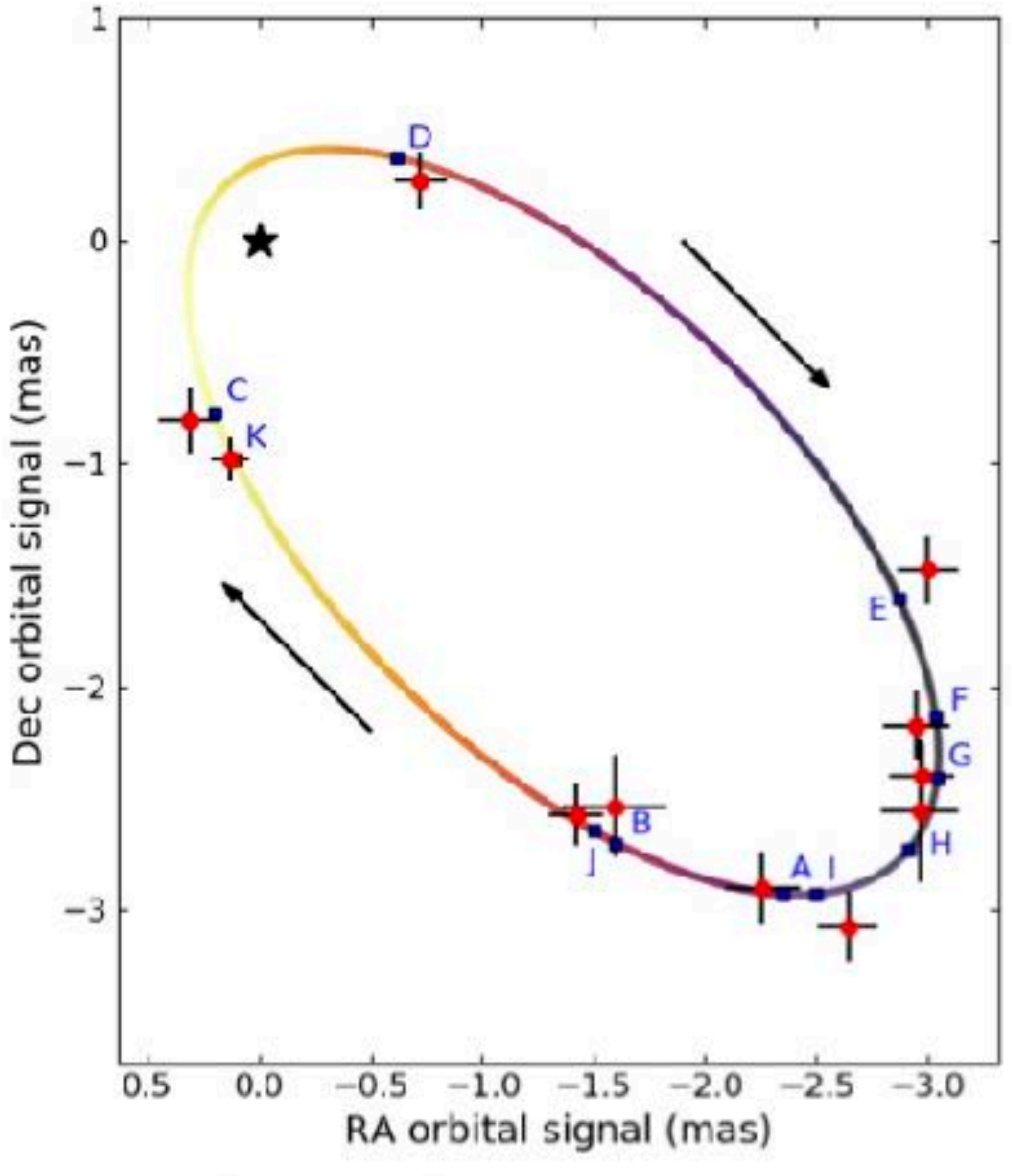
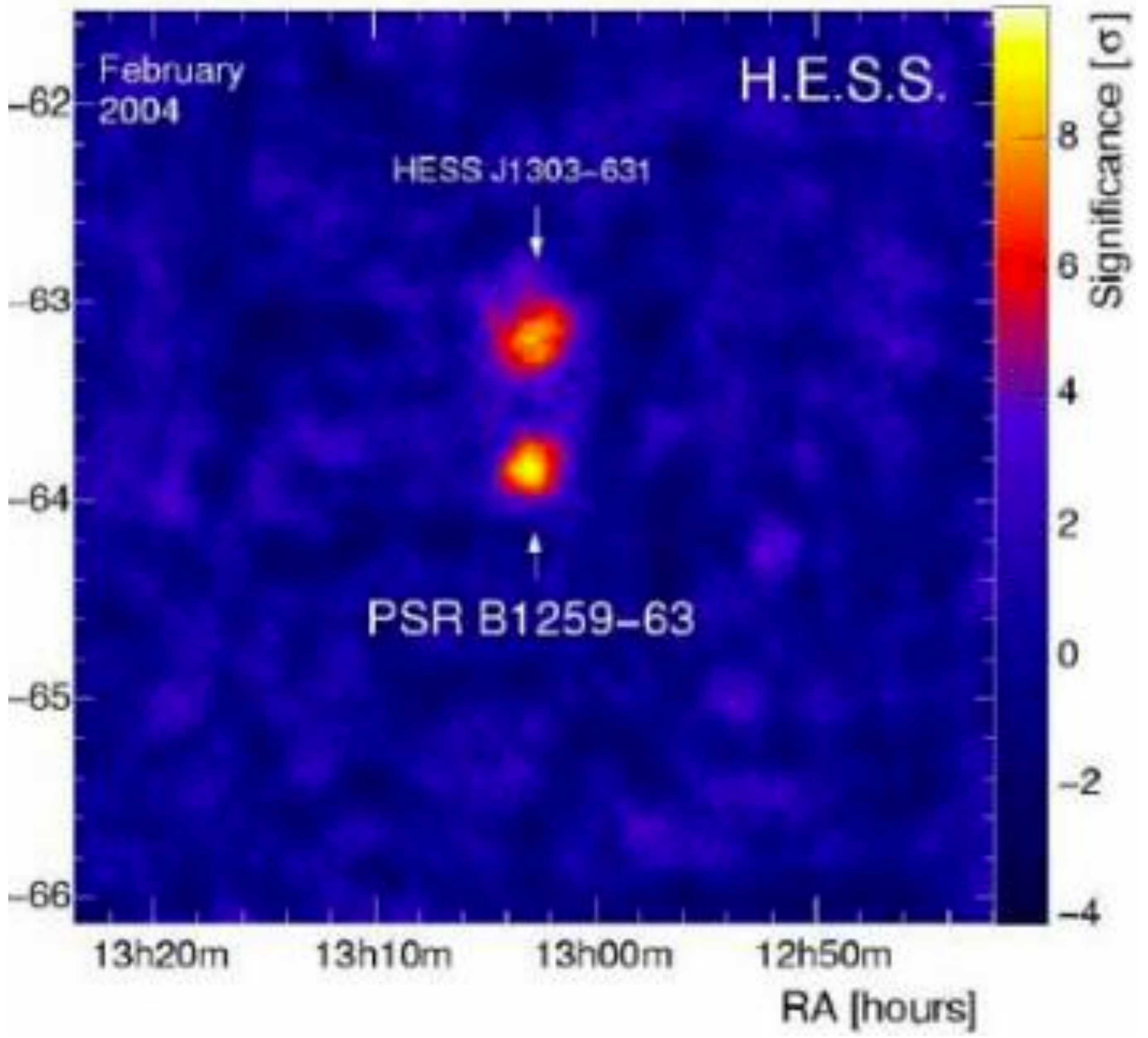
```

Berrie drafted IAU Tel 8300 announcing the discovery, followed by ATel#249

Miller-Jones+ 2018



HESS coll. 2005

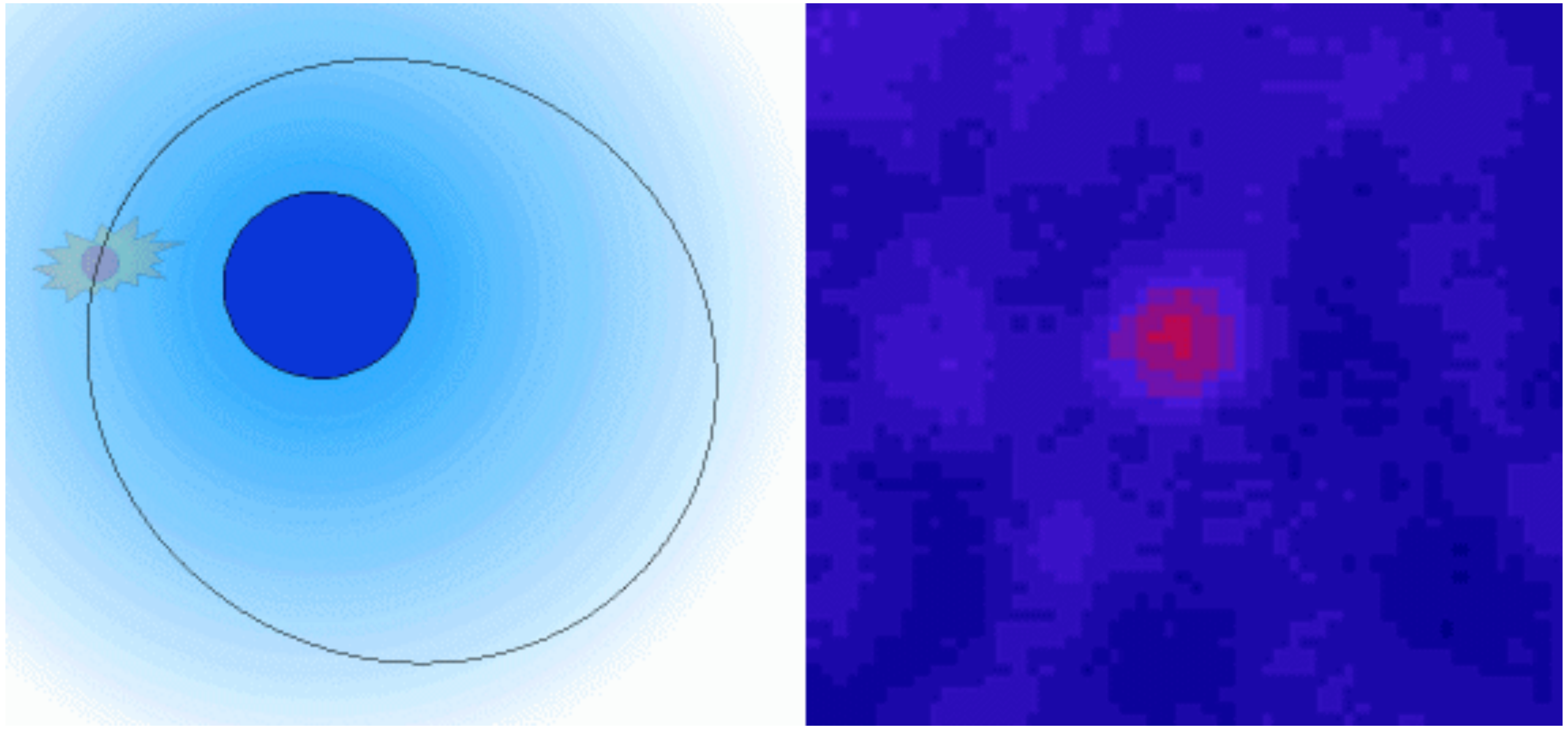


PSR B1259-63, a 48 ms radio pulsar in a 3.4 yr orbit around a 30 Msol Oe star, discovered in 1992 in a radio pulsar survey

pulsar spinning down on timescale ~ 3e5 yr, spindown power $\dot{E}$ ~ 8e35 erg/s. Proposed as possible VHE source

Tavani & Arons 1995, Kirk+ 1999

LS5039's orbital modulation (winter 2004)



HESS coll. 2006

A new era

TeV RADIATION FROM GALACTIC SOURCES

TREVOR C. WEEKES

Whipple Observatory, Harvard–Smithsonian Center for Astrophysics, Amado, AZ 85645–0097, U.S.A.

"Time will bring to light whatever is hidden; it will conceal and cover up what is now shining with the greatest splendor."

HORACE

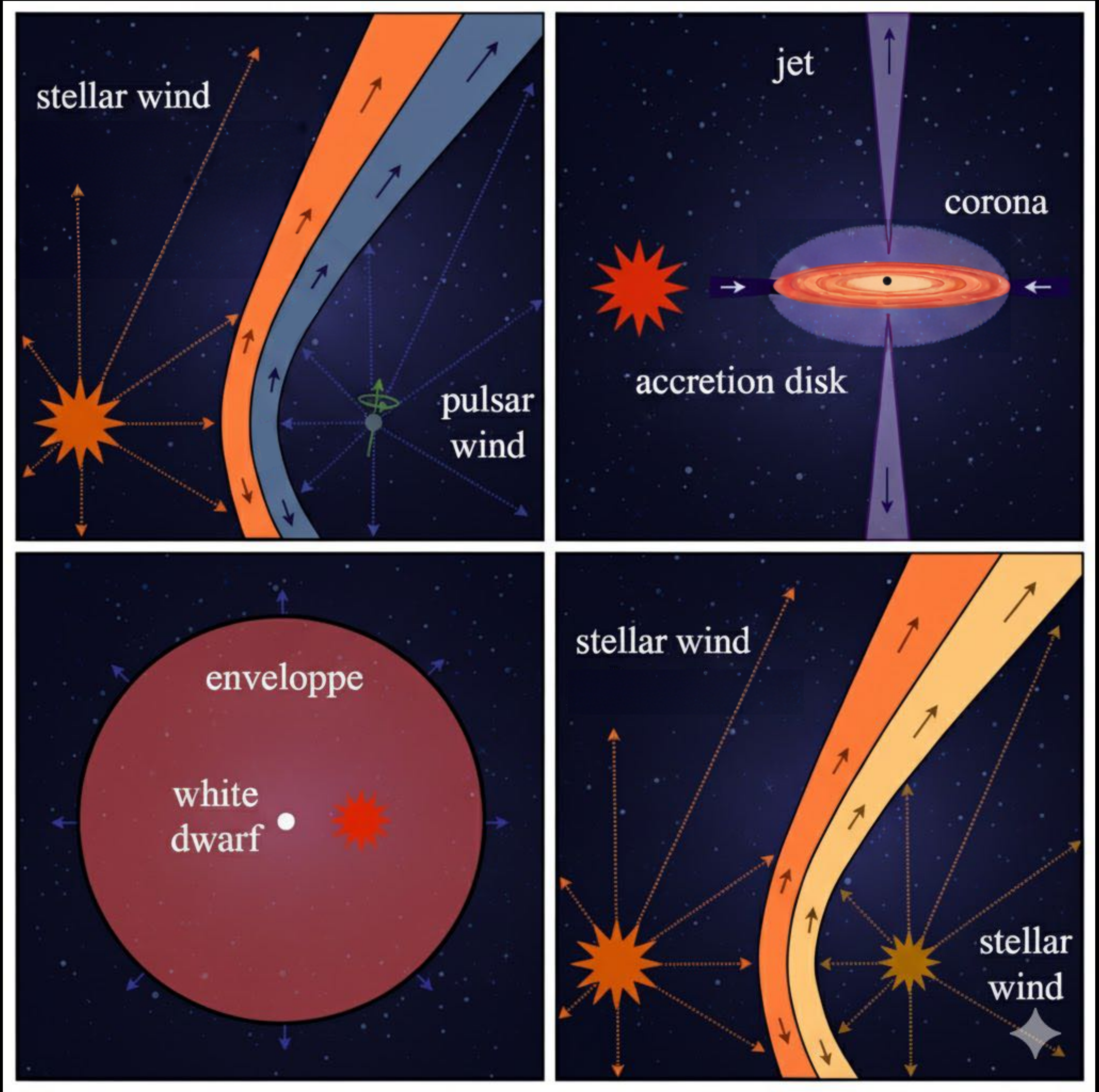
Abstract. The detection of the Crab Nebula as a steady source of TeV gamma rays puts the field of Very High Energy Gamma-Ray Astronomy on a firm observational basis and permits a critical re-assessment of the claims for the detection of a multitude of episodic binary sources. A new generation of detectors in the TeV and PeV energy regions is coming on-line; together with the telescopes of the Gamma-Ray Observatory these instruments will present a new perspective on one of the last frontiers of astronomy.

Weekes, SSRv, 1992

These detections allowed to move beyond the historical role played by binaries in the 1980s

gamma-ray binaries (9)
binary MSPs (~50)
(pulsar-driven)

microquasars (6)
(accretion-driven)



novae (~20)
(ejecta-driven)

colliding wind binaries (2)
(wind-driven)

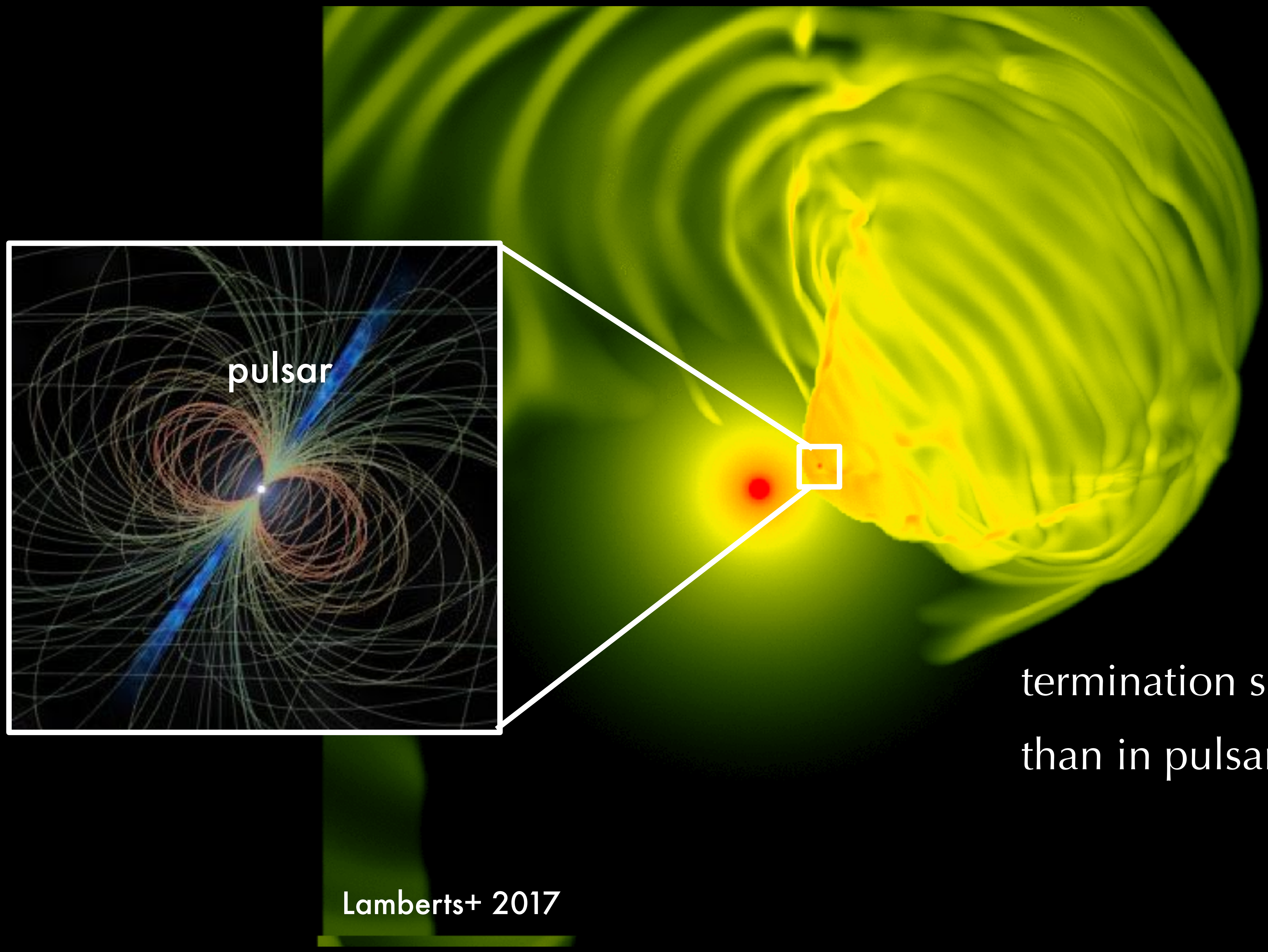
GD 2015

Gamma-ray binaries

probing pulsar winds

Binary pulsar wind nebulae

bow shock where pulsar wind interacts with massive star wind

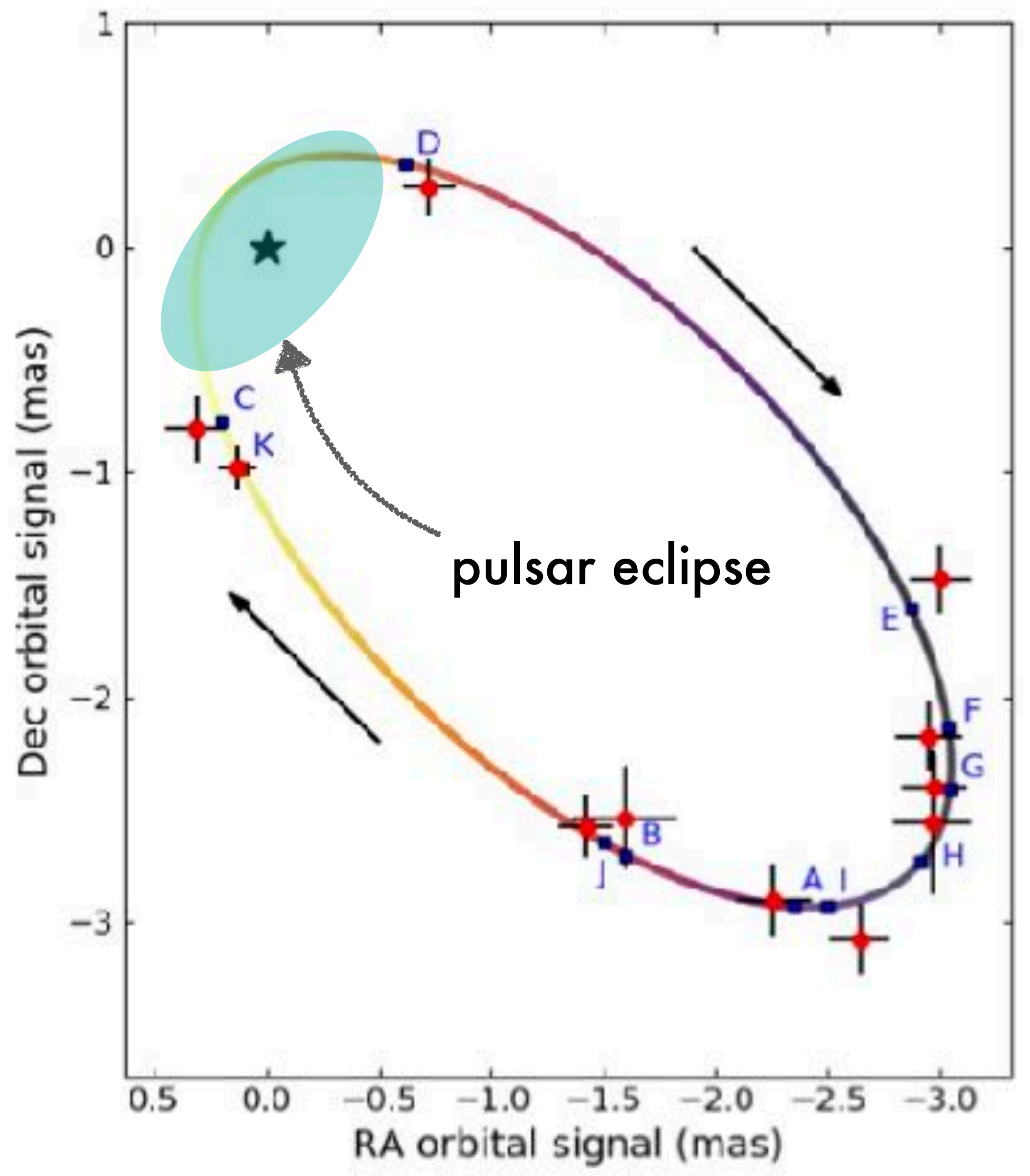


termination shock closer to pulsar
than in pulsar wind nebulae

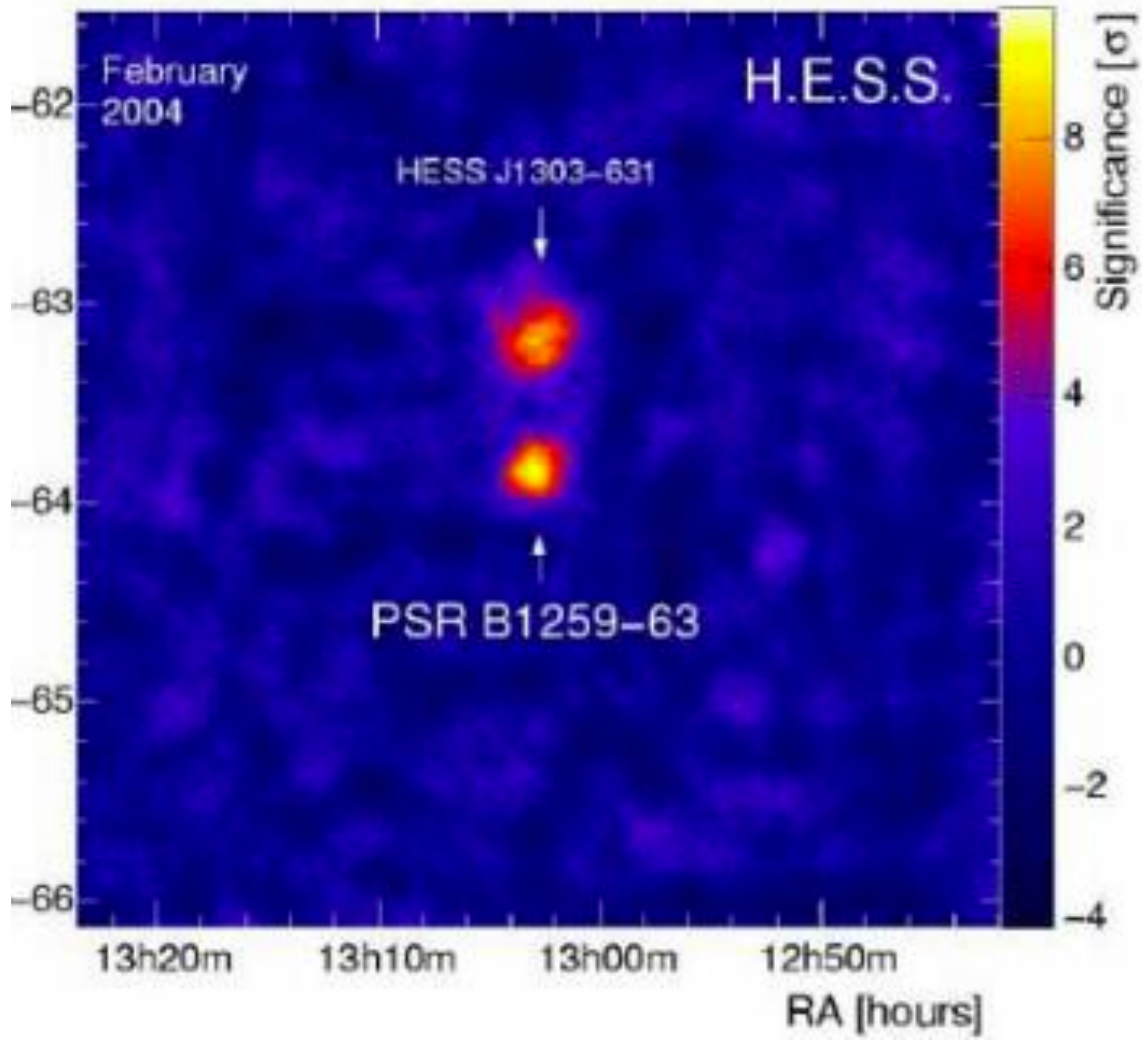
$$R_s \sim (10^4 \text{ to } 10^6) R_{lc}$$

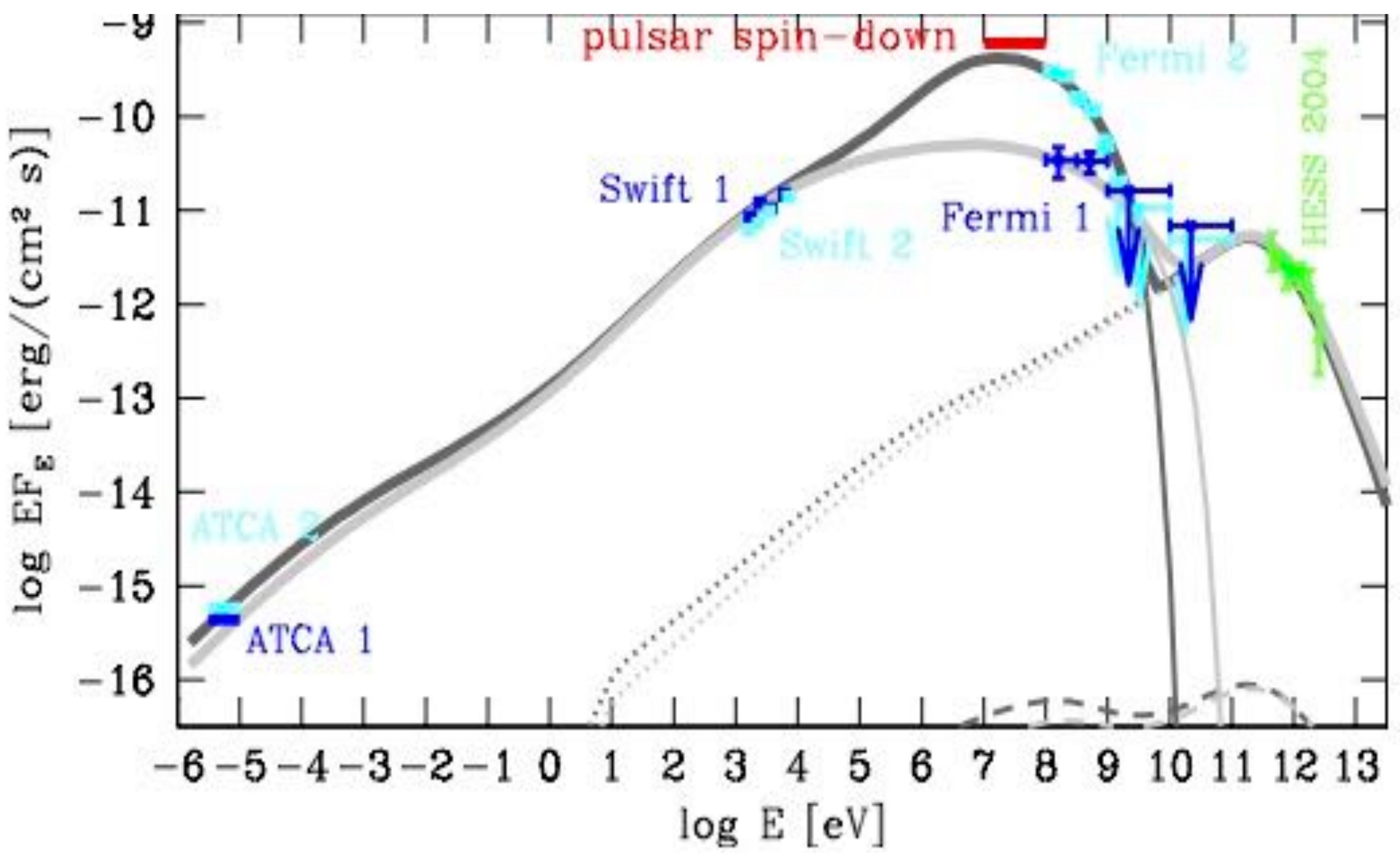
PSR B1259-63: a gamma-ray binary

Pulsar with high spin down power, radio pulsations eclipsed over part of the orbit, SED peaks in gamma rays, orbital modulation



Miller-Jones+ 2018

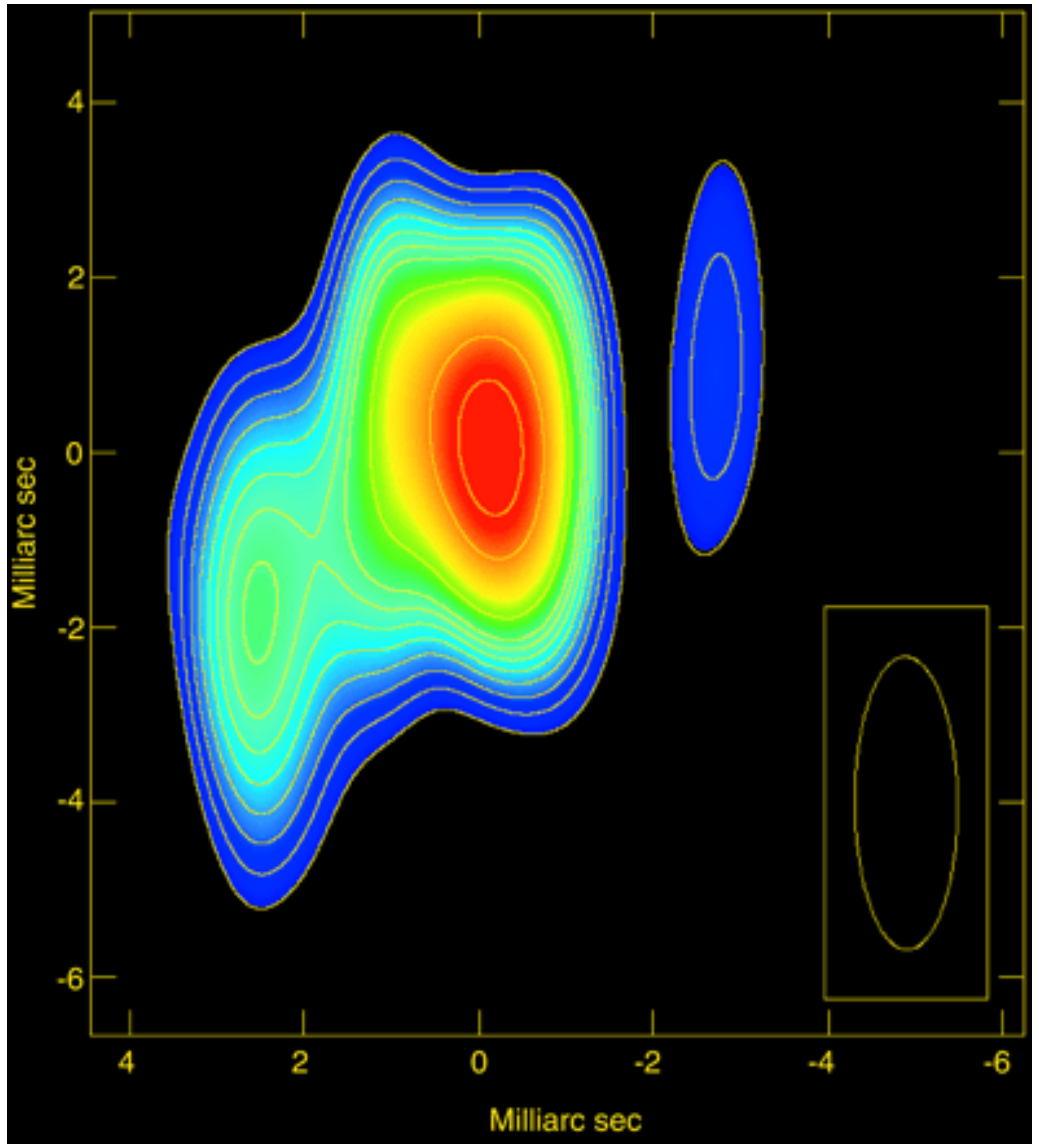




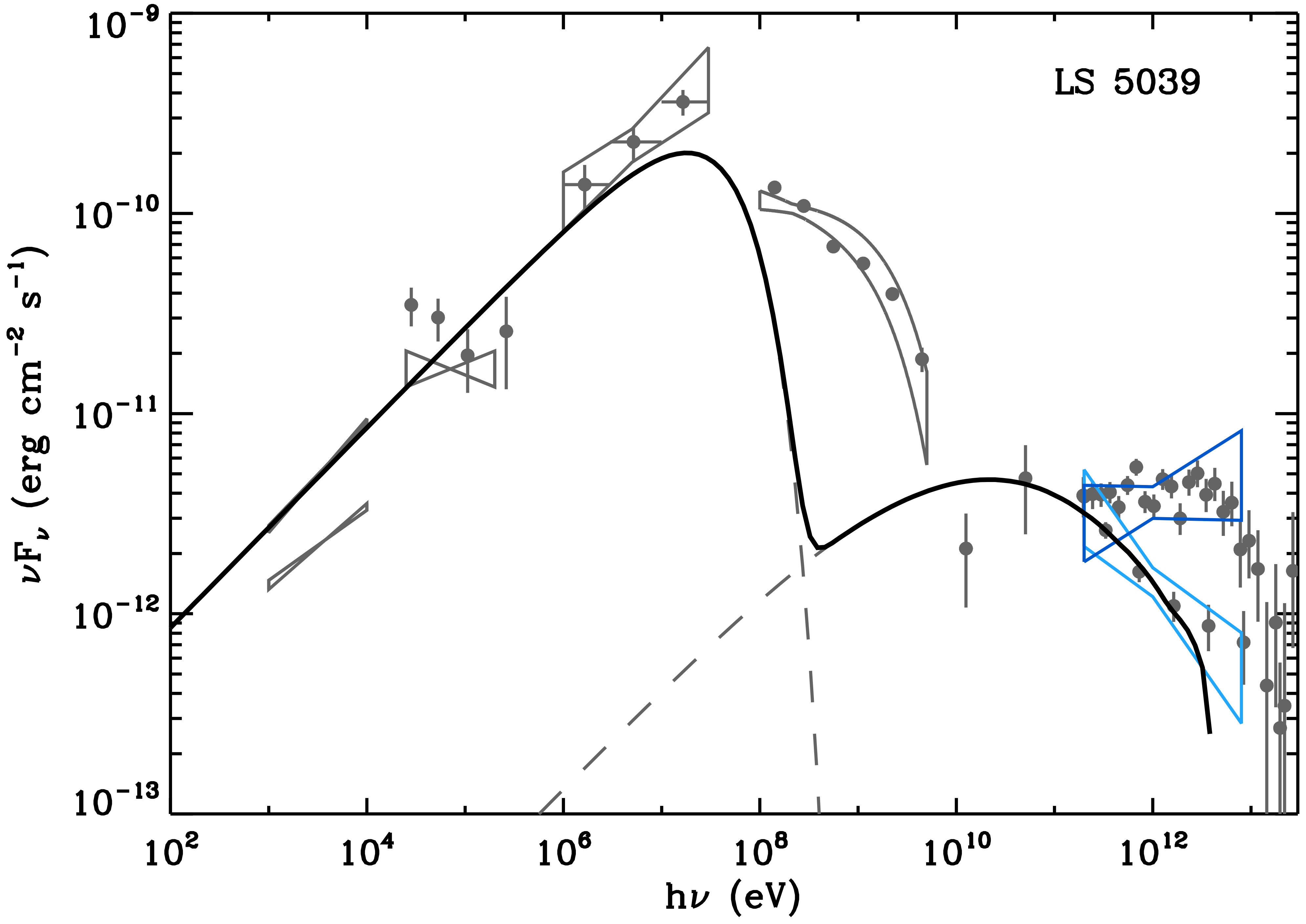
Fermi/LAT coll. 2011

LS 5039 : microquasar or "binary plerion" ?

Paredes+ 2000 Radio VLBI



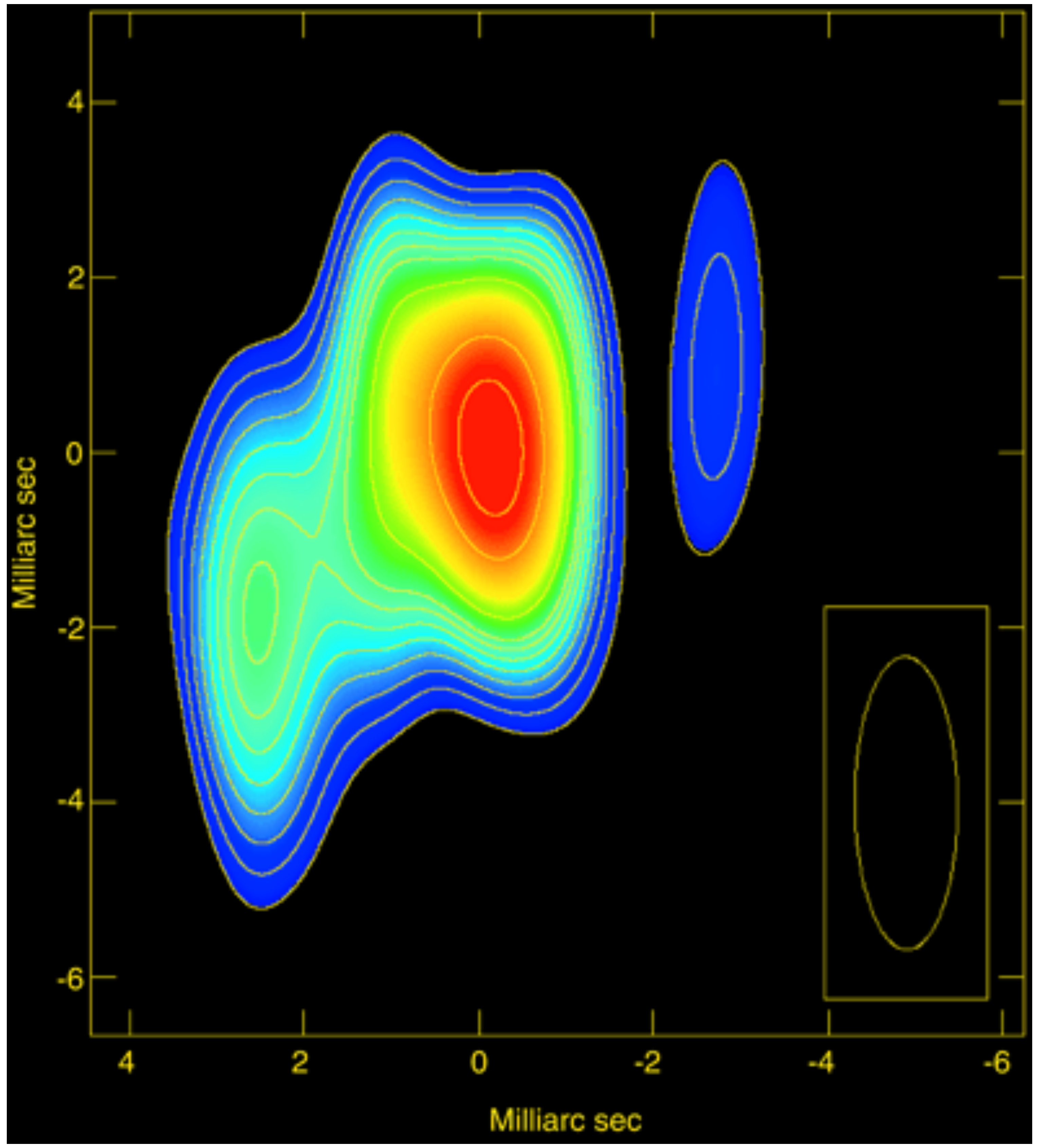
LS 5039 SED



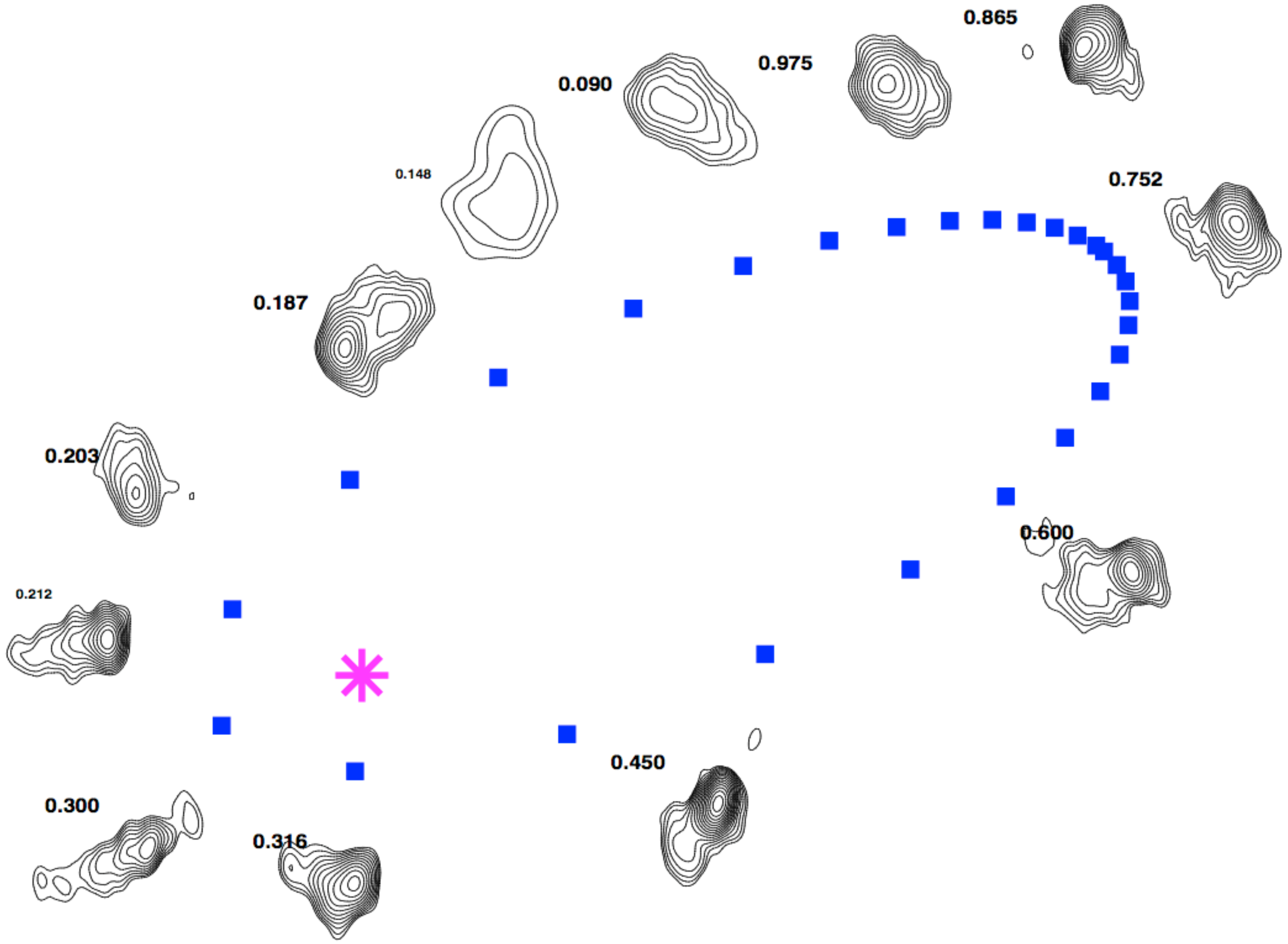
GD 2015

LS 5039 : microquasar or “binary plerion” ?

Paredes+ 2000 Radio VLBI



Dhawan+ 2006 Radio VLBI of LSI +61 303



De Pasquale+ 2008 Swift/BAT detects magnetar bursts at LSI loc.

Weng+ 2022 FAST detects 269 ms radio pulsation from LSI

Gamma-ray binaries evolution

van den Heuvel 1974

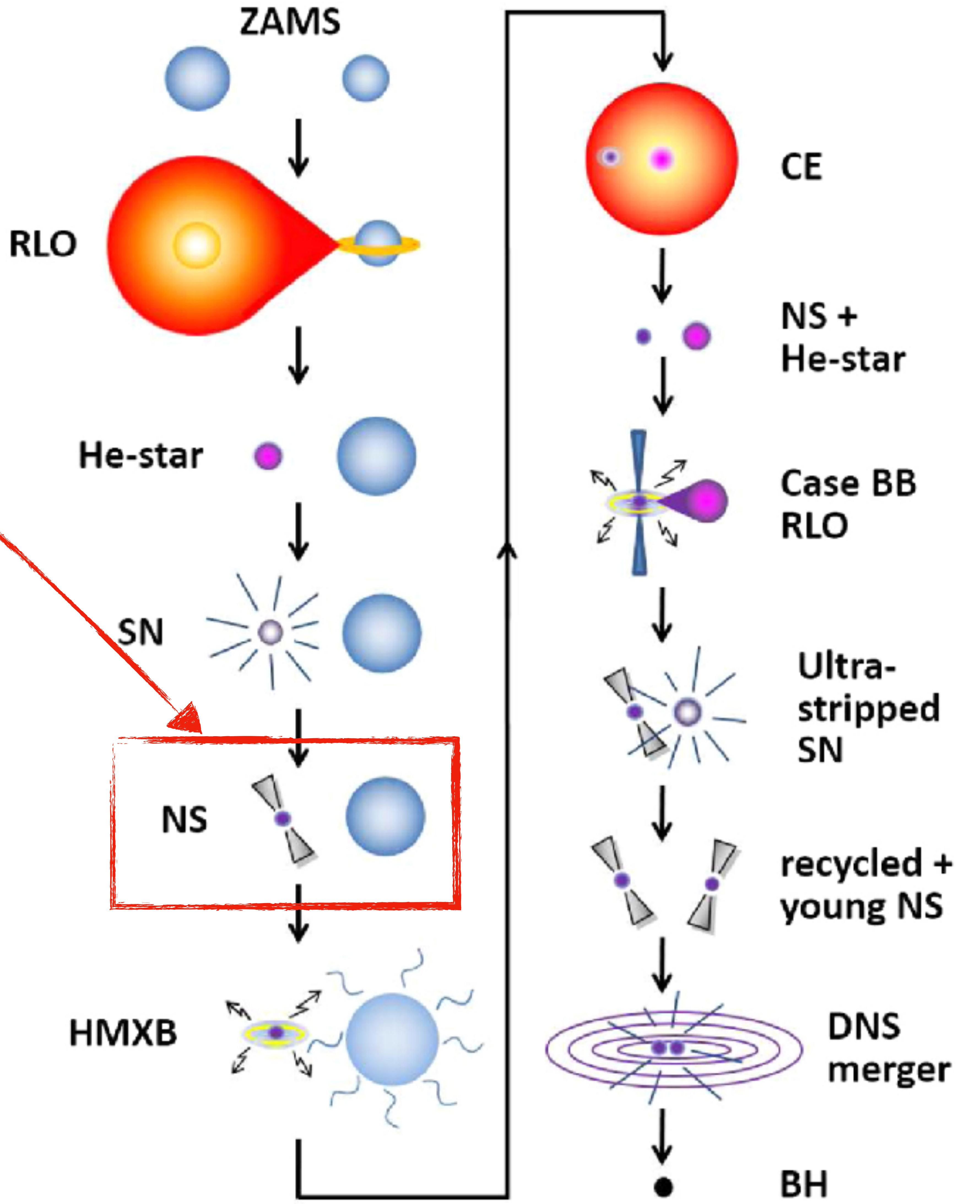
> If the remnant is a neutron star it will, for a short time after the explosion rotate very rapidly. Similar to the Crab pulsar it will during a few thousand years be a source of relativistic particles, X rays and γ rays.

Expected phase of binary massive star evolution

Accretion (HMXB) turns on once pulsar spindown power drops below

$$\dot{E} < 4 \times 10^{33} \left(\frac{\dot{M}_{\rm w}}{10^{-6}\,{\rm M}_\odot\,{\rm yr}^{-1}}\right)\left(\frac{10^3\,{\rm km\,s}^{-1}}{v_{\rm w}}\right)^3 \left(\frac{0.1\,{\rm AU}}{a}\right)^2 {\rm erg\,s}^{-1}$$

Illarionov & Sunyaev 1976



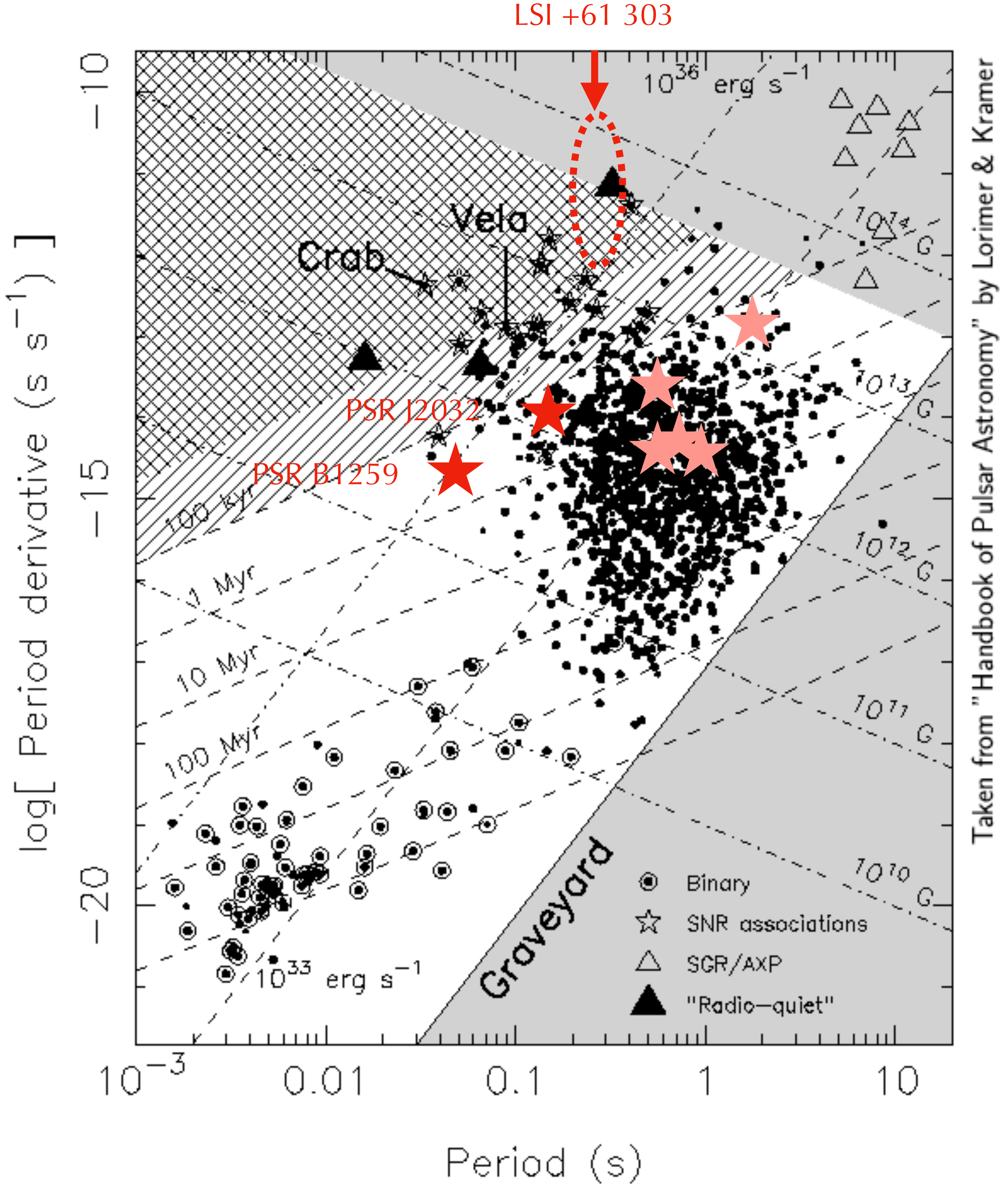
Tauris+ 2017

(Candidate) pulsars with massive stars

system	spectral type	pulse (s)	Edot (erg/s)	P_{orb} (d)	e	gamma rays
PSR B1259-63	O9.5Ve	0,05	8E+35	1237	0,87	HE,VHE
LS 5039	O6.5V(f)	?	?	3,9	0,35	HE,VHE
LS I +61 303	B0Ve	0,27	?	26,5	0,54	HE,VHE
HESS J0632+057	B0Vpe	?	?	315	0,83	HE,VHE
1FGL J1018.6-5856	O6.5V(f)	?	?	16,6	0,53	HE,VHE
LMC P-3	O5III(f)	?	?	10,3	0,4	HE,VHE
PSR J2032+4127	B0Ve	0,14	1E+35	16835	0,97	HE,VHE
4FGL J1405.1-6119	O6.5III	?	?	13,7	?	HE,?
HESS J1832-093	O6V	?	?	87	?	HE,VHE
PSR J1740-3052	>11 Msun	0,57	5E+33	231	0,58	-
PSR J1638-4725	>6 Msun	0,76	4E+32	1941	0,96	-
PSR J0045-7319	>4 Msun	0,93	2E+32	51	0,81	-
PSR J2108+4516	>12 Msun	0,58	9E+32	269	0,09	-
PSR J0210+5845	B6V	1,77	1E+33	17155	0,46	-

Don't forget radio pulsars with massive stars !

The pulsars of gamma-ray binaries



radio pulse obscured at low P_{orb}

gamma-quiet at high P_{orb}

orbital modulation of the emission

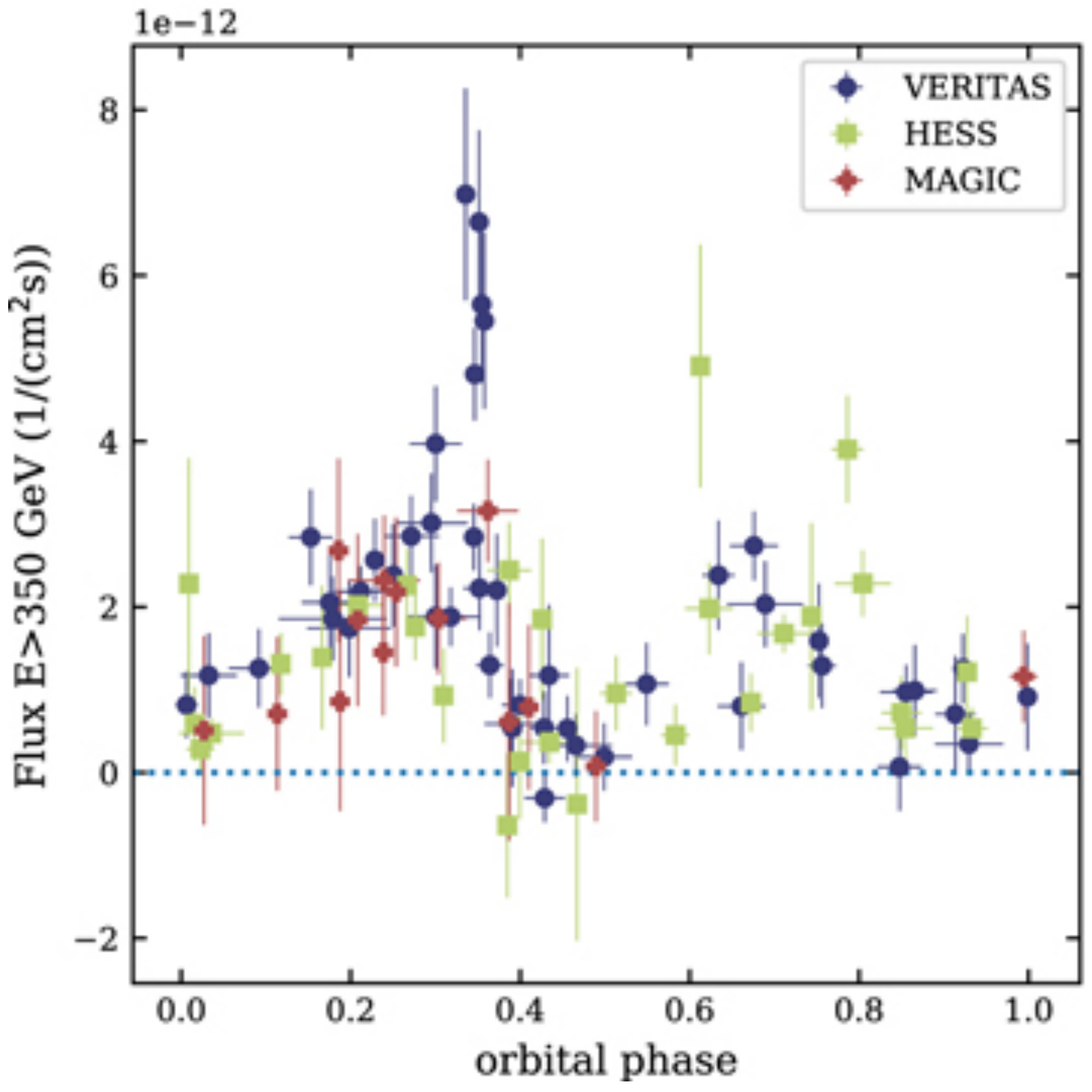
Gamma-ray binaries as population

How many are there ?

How many can we detect in HE/VHE ?

Impact of orbital modulation on detection

HESS J0632+057: 315 day orb. period



Assuming same lightcurve as HESS J0632, randomly placed in Galaxy, allow up to 200 HE « faint » gamma-ray binaries in the Galaxy. Strong constrains if none detected in CTA full survey (11% detection rate).

VERITAS+MAGIC+HESS coll. 2021

Galactic population estimate

1. distribute in Galaxy
2. model lightcurve
3. mock survey
4. get detection rates
5. infer population size

Galactic population estimate

How many are there ?

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

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

Combining both estimates, based on HE/VHE detections

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

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

updated from GD+ 2017

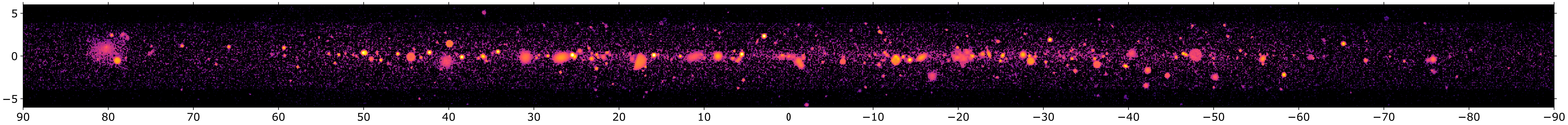
Future observations

How many can we see?

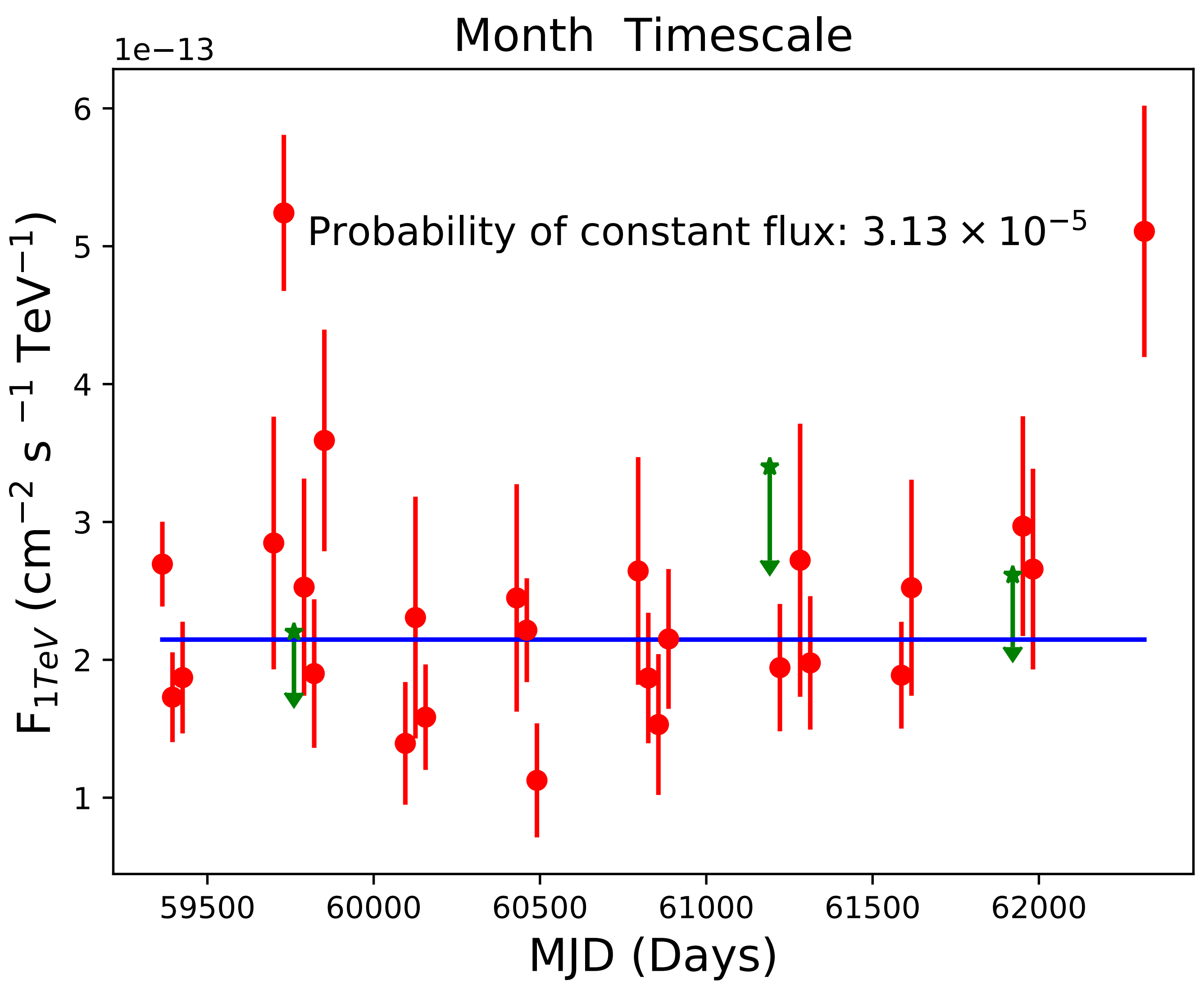
- up to 9 new detections in full *Fermi*-LAT (3 most likely)
- up to 10 new detections in full CTA GP survey (3 most likely)
- ≈ 15 with SKA1 (50 with SKA2)
- 100s-1000s NS + ★ with Gaia

⚠ detection ≠ identification!

Prospects for CTA Galactic Plane Survey



simulated binary lighcturve



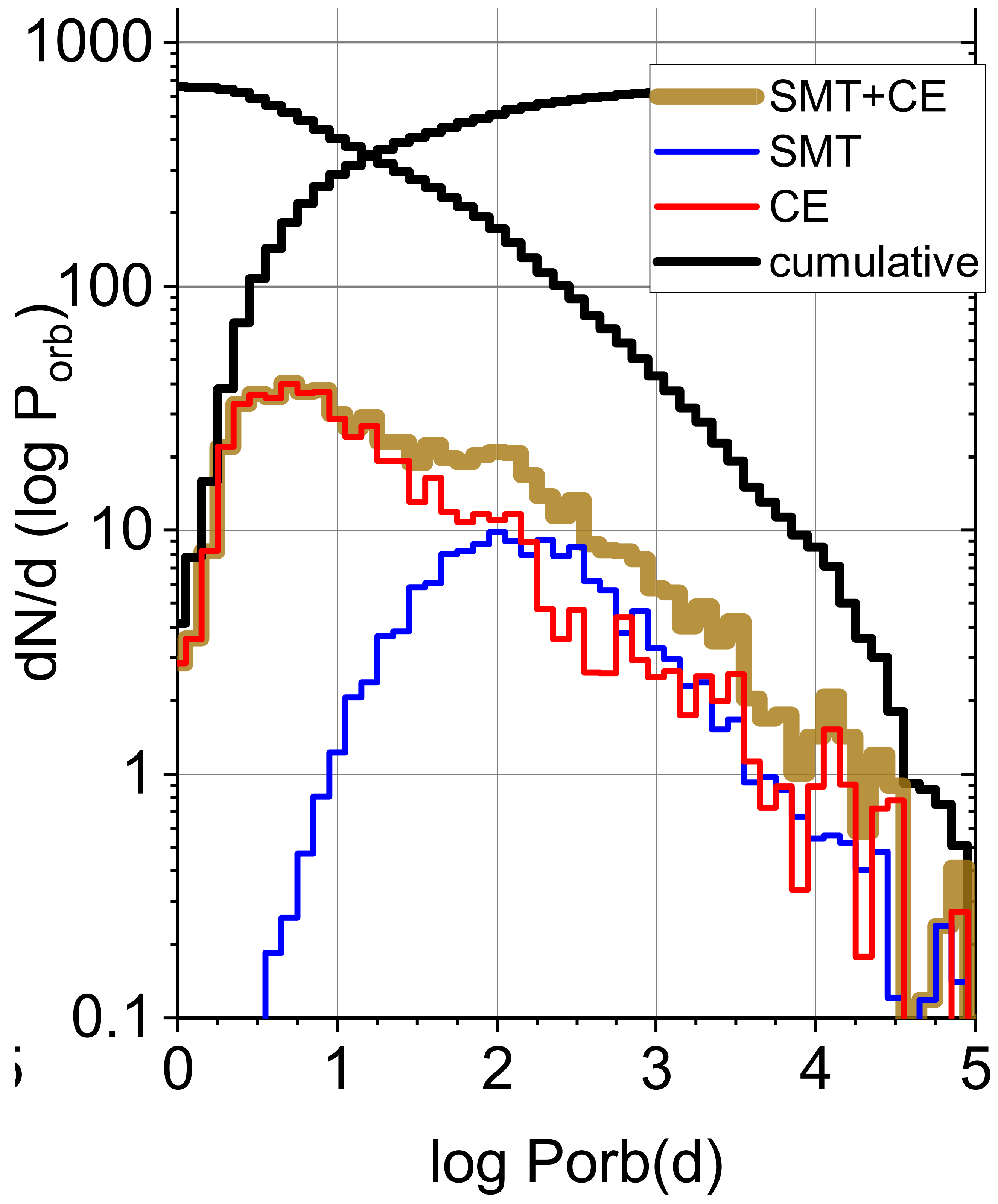
variable sources in mock survey

Source Name	σ_{obs}	F_{mean}	P_{Obs}	P_{Day}	P_{Week}	P_{Month}	P_{Year}	Period d
LS I +61° 303	15.6	0.97±0.03	**2×10^{-295}**	**8×10^{-302}**	**5×10^{-273}**	-	-	26.5
PSR B1259-63	11.1	0.33±0.01	**3×10^{-251}**	**4x10^{-121}**	**9×10^{-128}**	**10^{-288}**	**10^{-165}**	1241
bin040	5.3	0.06±0.01	6.5×10^{-1}	6.3×10^{-1}	1.6×10^{-1}	**5×10^{-3}**	**5.7×10^{-6}**	3358
1FGL J1018.6-5856	4.3	0.41±0.02	**9×10^{-22}**	**5×10^{-25}**	**7×10^{-29}**	-	-	16.6
LS5039	4.0	4.15±0.03	**10^{-37}**	**10^{-37}**	-	-	-	3.9
bin095	3.9	0.23±0.01	9.6×10^{-2}	**4.9×10^{-2}**	**1.8×10^{-3}**	**3.13×10^{-5}**	-	200
HESS J1832-093	3.5	2.28±0.02	**$6.6\ \times10^{-7}$**	**1.8×10^{-6}**	**1.5×10^{-5}**	**1.2×10^{-4}**	-	365
PSR J2032+4127	3.4	3.95±0.05	**$4.1\ \times10^{-26}$**	**1.2×10^{-26}**	**5.1×10^{-27}**	**8.23×10^{-29}**	**5.36×10^{-32}**	1.8×10^{4}
HESS J0632+057	3.0	0.30±0.06	**10^{-8}**	**10^{-8}**	**7×10^{-9}**	**6×10^{-10}**	-	315
bin074	2.8	0.05±0.01	9.9×10^{-1}	9.9×10^{-1}	9.3×10^{-1}	**6×10^{-3}**	4.9×10^{-1}	840
bin159	2.6	0.11±0.01	1.6×10^{-1}	**1.6×10^{-2}**	**4.7×10^{-2}**	-	-	5.2
bin123	2.3	0.09±0.01	3.9×10^{-1}	5×10^{-1}	3.7×10^{-1}	**1.8×10^{-2}**	**2×10^{-4}**	522
bin162	1.9	0.10±0.01	9.9×10^{-1}	9.9x10^{-1}	9.3×10^{-1}	6×10^{-2}	4.9×10^{-1}	1387
bin154	1.9	0.05±0.01	9.9×10^{-1}	9.7×10^{-1}	8.2×10^{-1}	6.1×10^{-1}	-	35.8
bin093	1.4	0.06±0.01	9.9×10^{-1}	9.9×10^{-1}	9.9×10^{-1}	-	-	7
bin146	1.0	0.07±0.01	9.9×10^{-1}	9.9×10^{-1}	-	-	-	1.5
pwn2059	2.5	2.30±0.17	**2.3×10^{-5}**	**4.8×10^{-3}**	**2.8×10^{-5}**	-	-	N/A
3FHL J1855.3+0751	1.1	1.55±0.37	9.9×10^{-1}	**10^{-5}**	**2.7×10^{-4}**	**1.1×10^{-3}**	-	N/A

CTA collaboration 2024

Direct estimate from population synthesis

Evolve a synthetic population of massive star binaries and identify young PSR + Be or O systems **Bykov+ 2026**



Bykov+ 2026

Orbital period	# Be+ # O	Obs
$P_{orb} > 10^4$ d	10+0	2
10^3 d < P < 10^4 d	30+0	2
10^2 d < P < 10^3 d	150+10	3
10 d < P < 10^2 d	200+30	6
1 d < P < 10 d	200+10	1

~1/3 chance of eclipse for 1 d < P_{orb} < 10 d

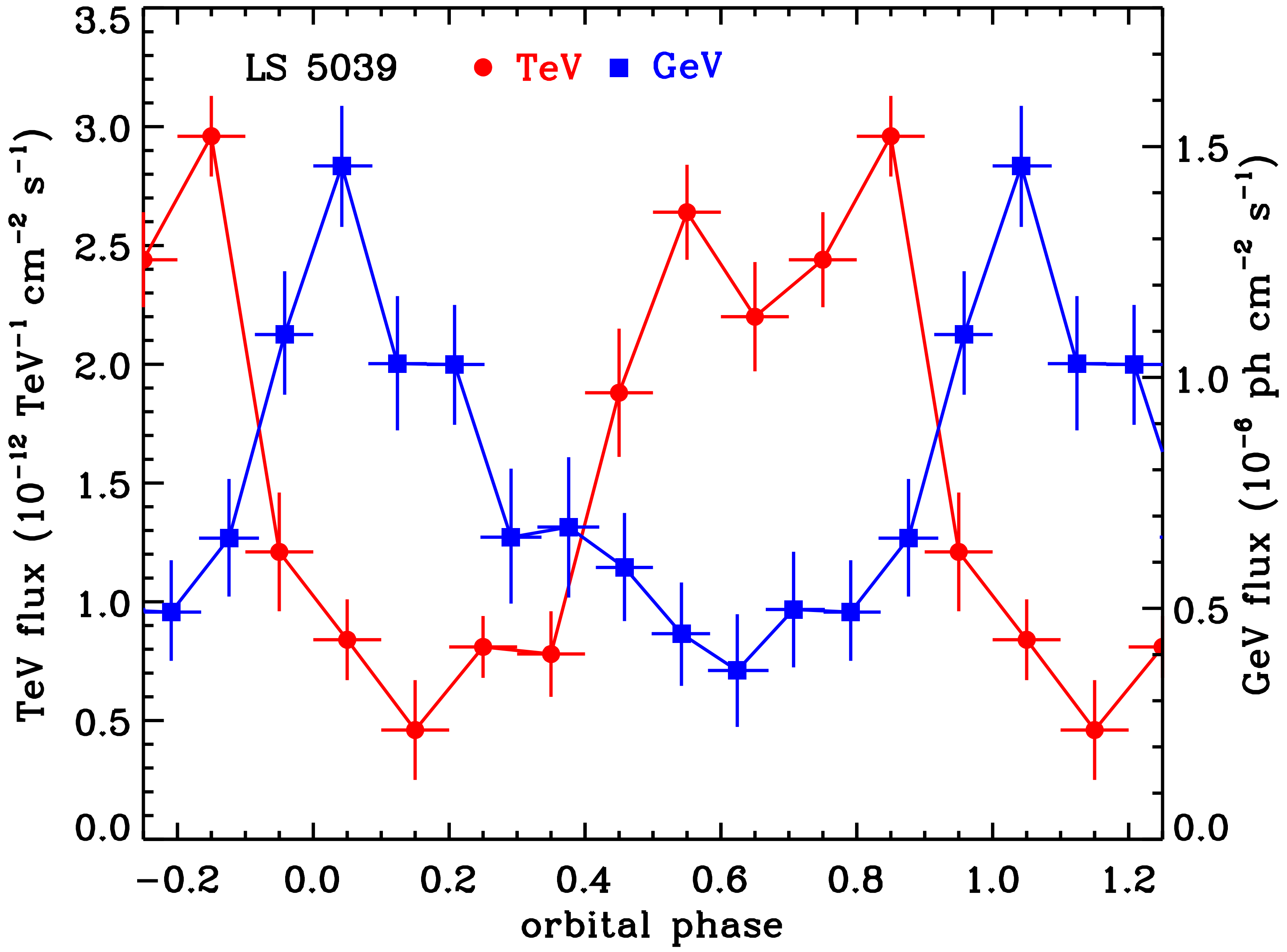
NB 20 yr Fermi-LAT and 10 yr CTA GP survey detect about 6% of the systems, typically at low P_{orb} and high power **GD+ 2017**

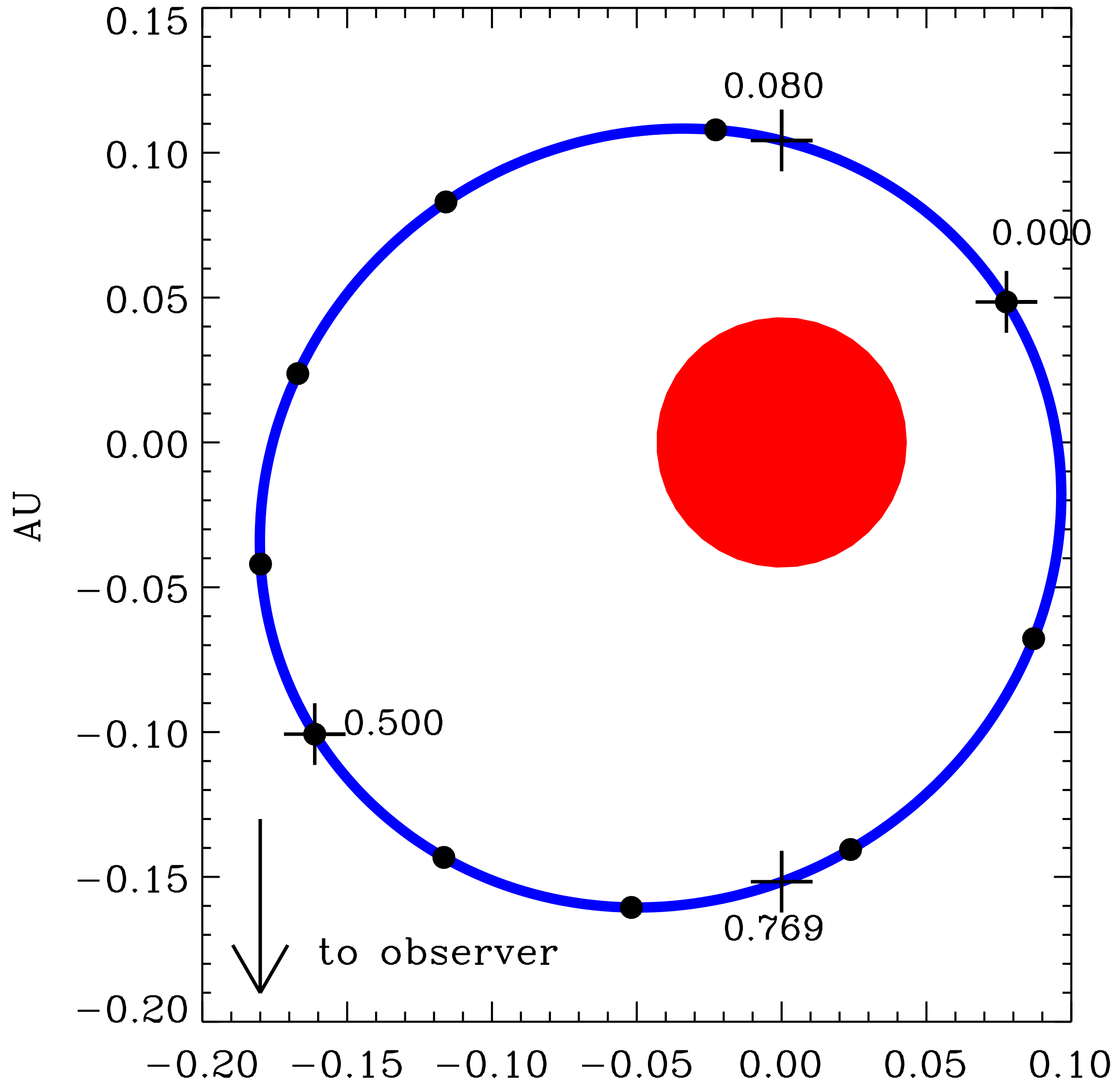
Gamma-ray orbital modulation

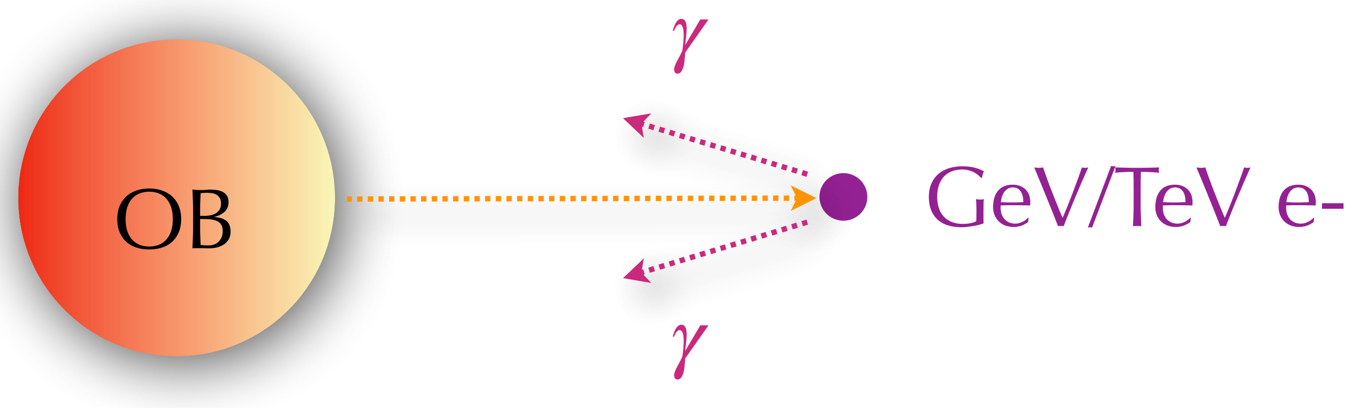
Anisotropic inverse Compton of ~10 eV star photons and VHE absorption by star photons produces “geometric” modulations

GD+ 2008, Khangulyan+ 2008

LS 5039

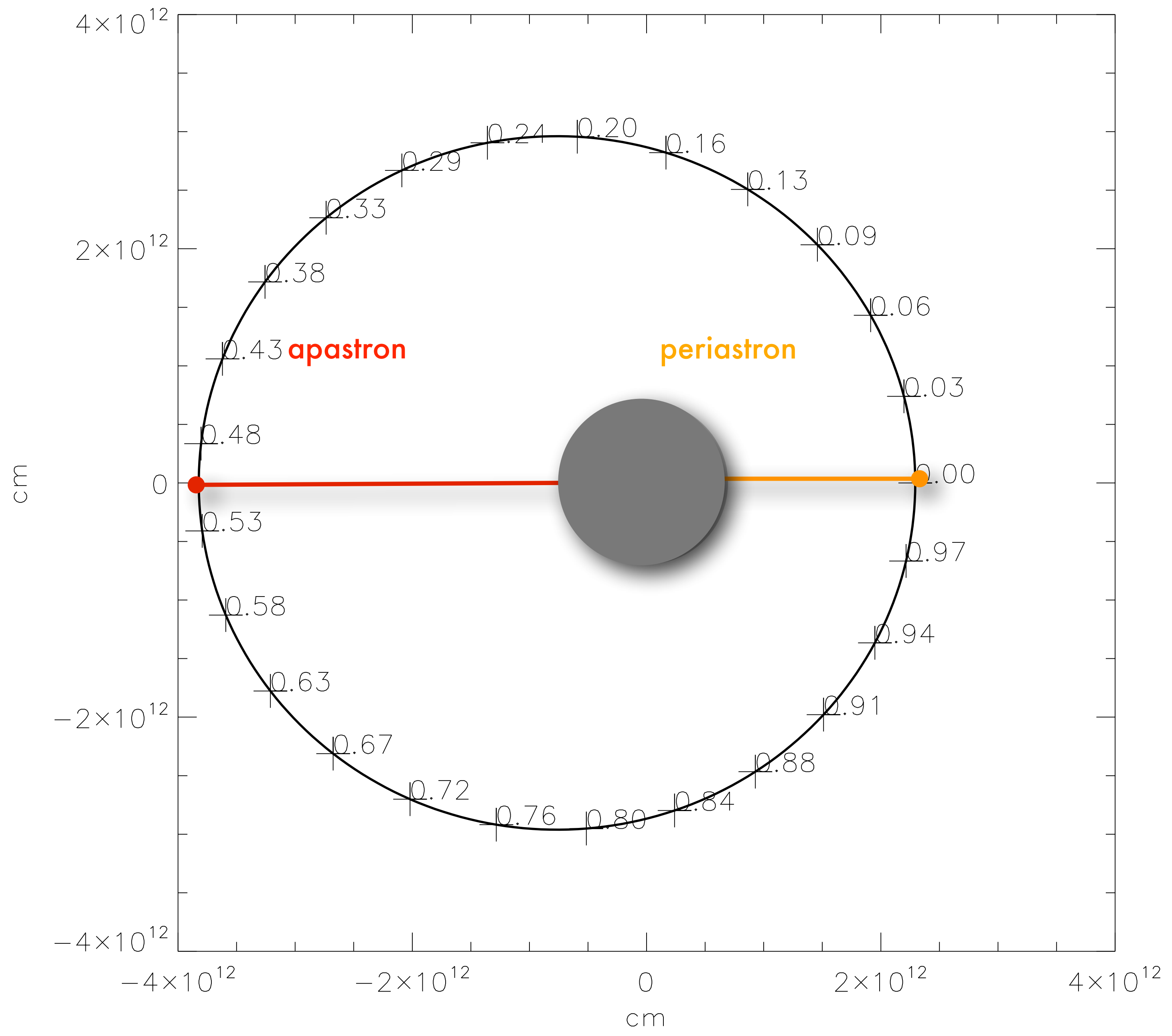




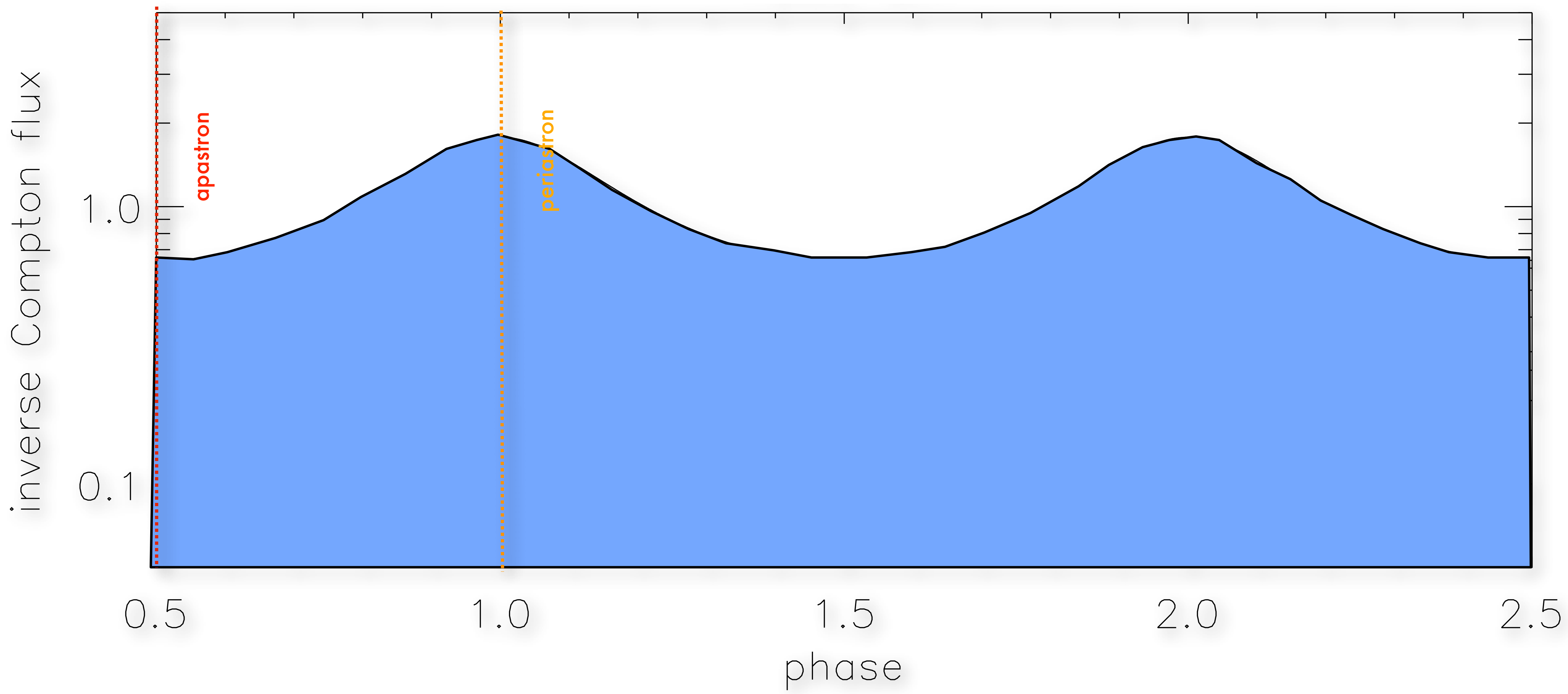


Orbital modulation constrains location of accelerator

Inverse Compton scattering of stellar photons

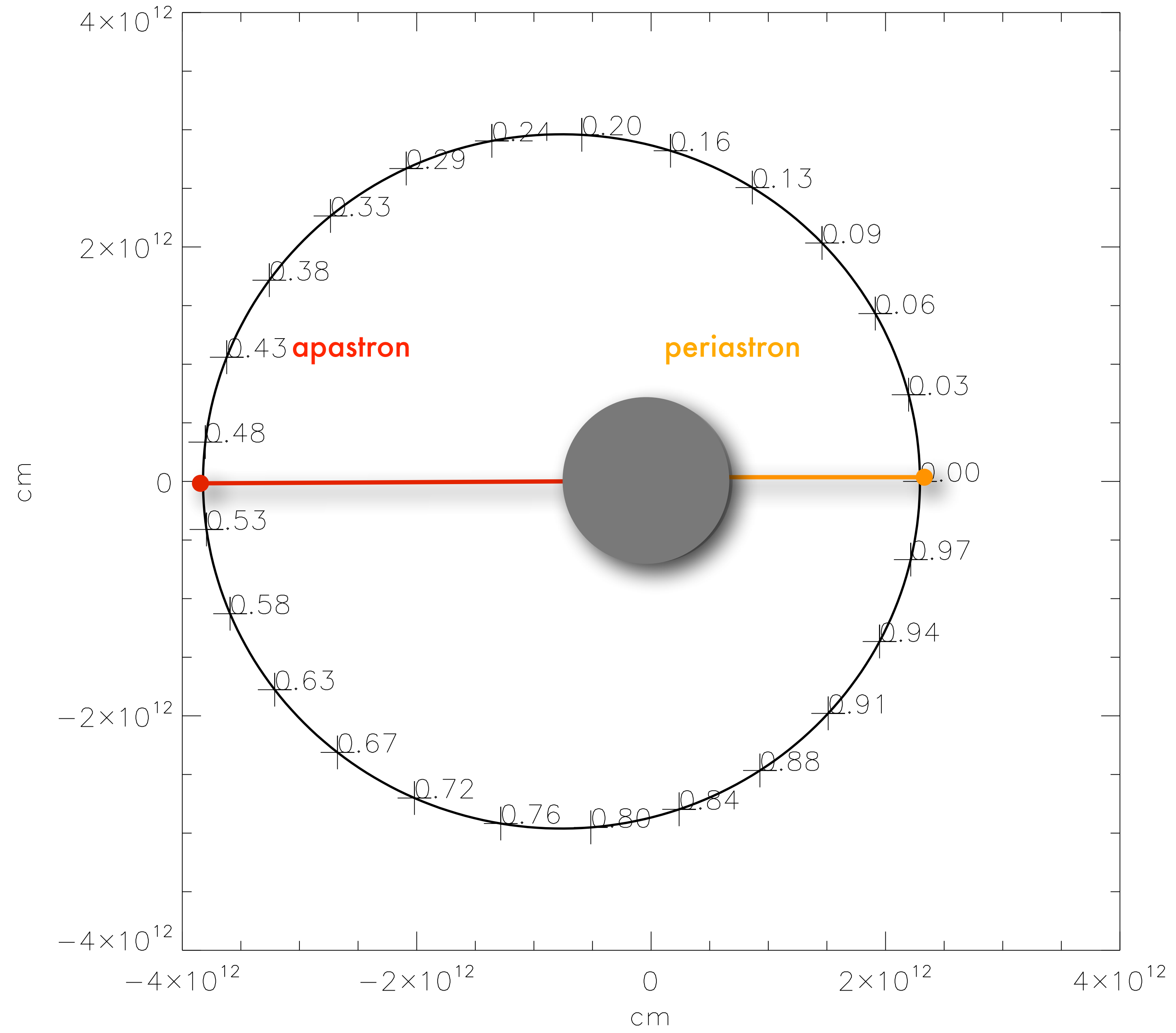


orbit seen face on

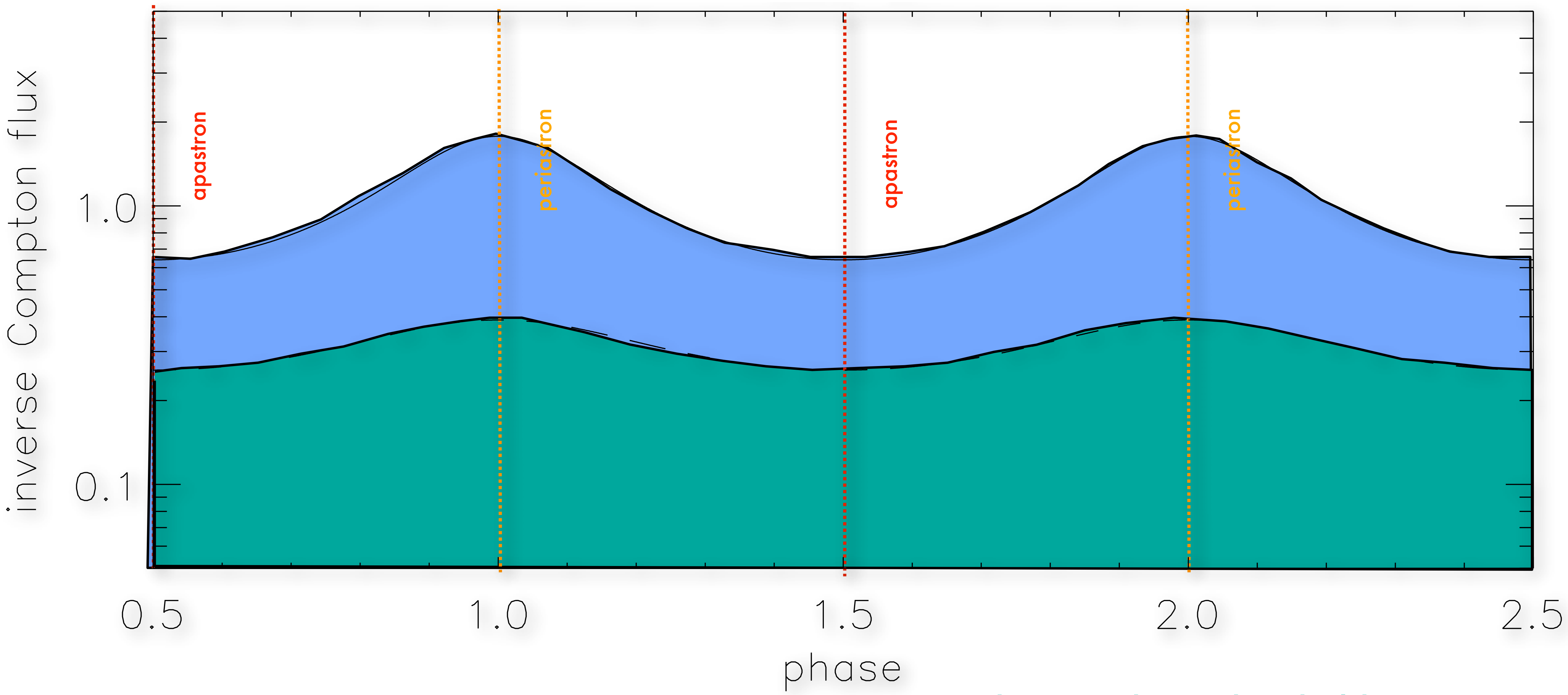


inverse Compton
(GeV)

Inverse Compton + pair production



orbit seen face on

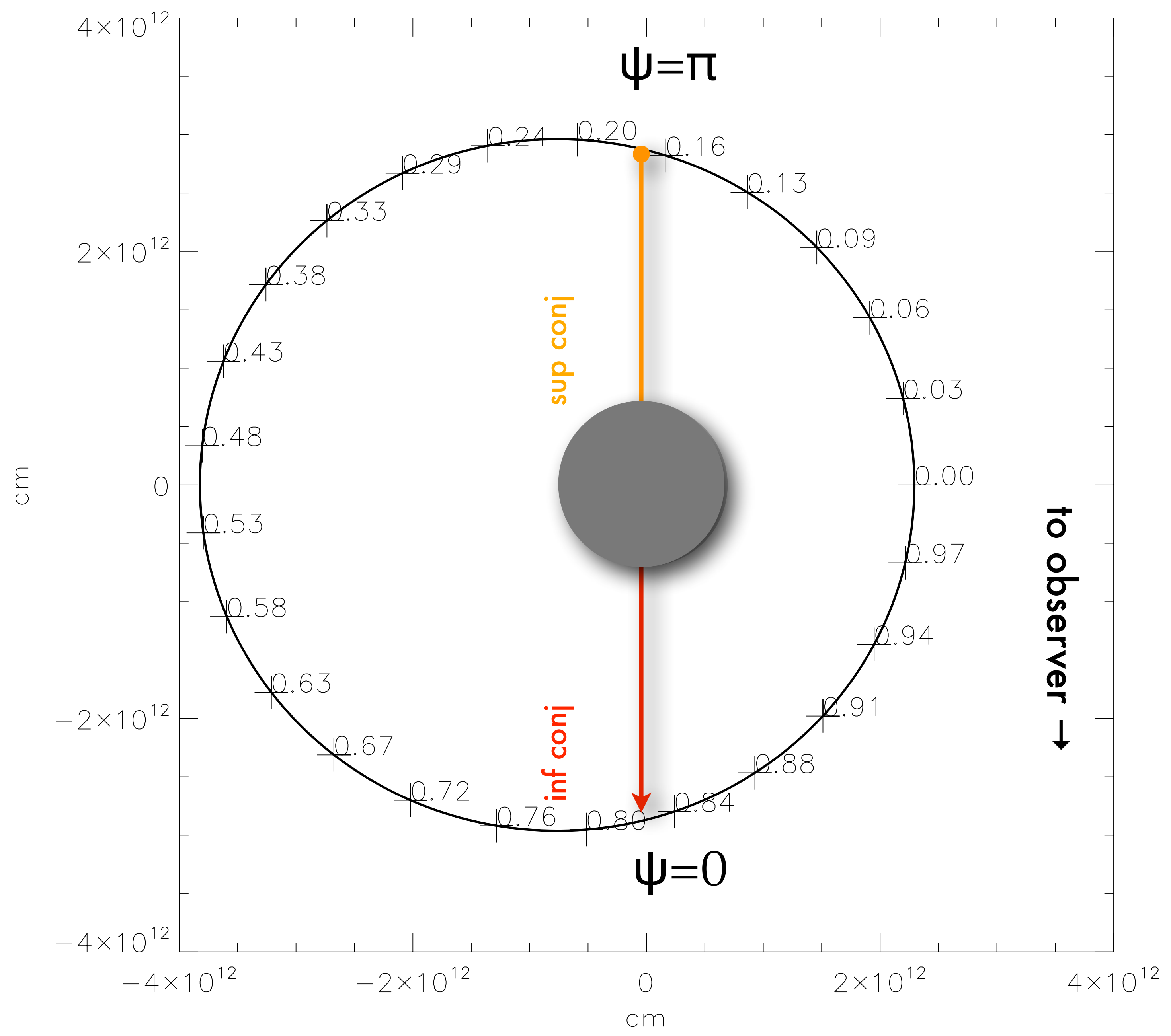


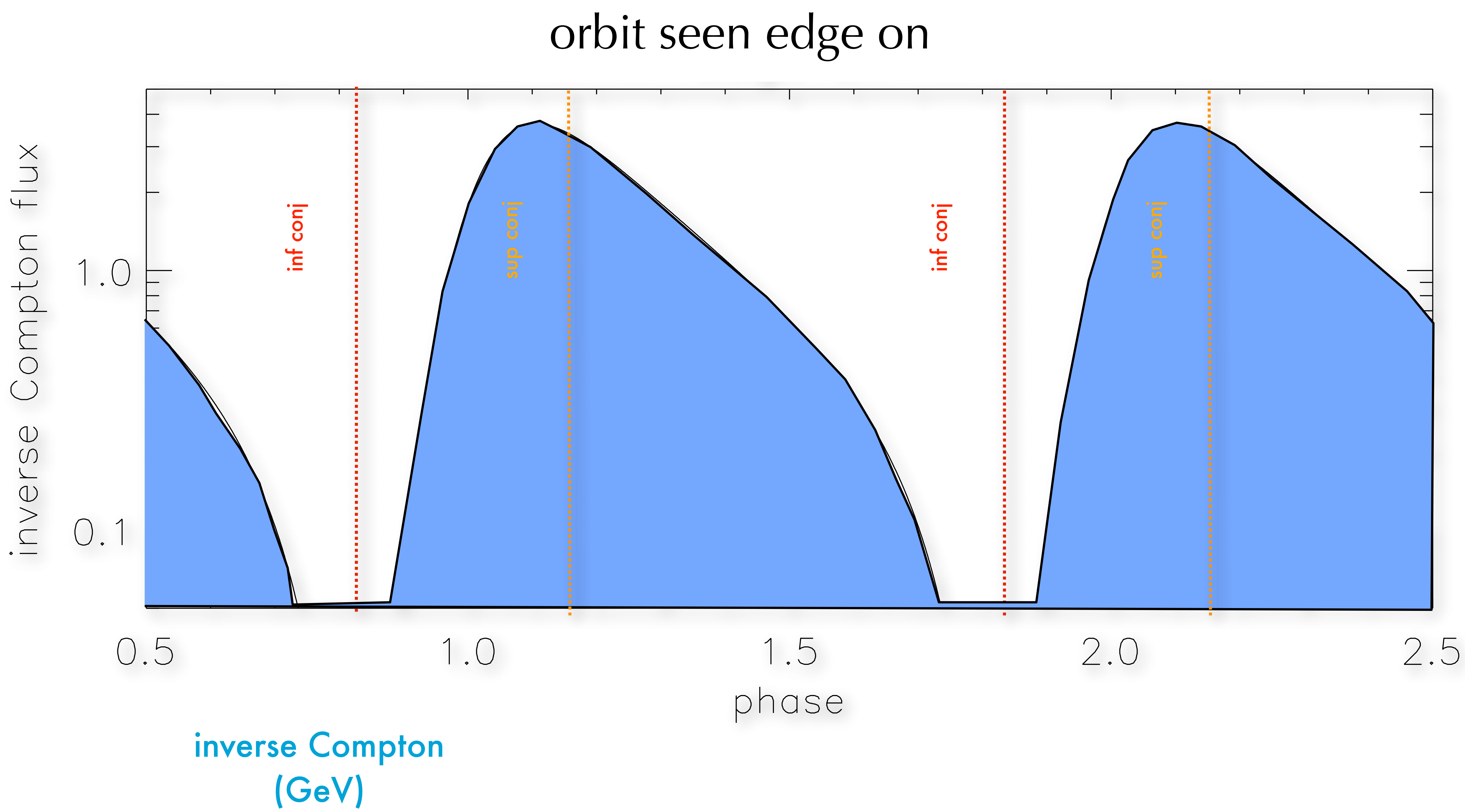
inverse Compton (GeV)

+ pair production above threshold (TeV)

$$\epsilon_{\rm min}\epsilon_\star \geq (511\,{\rm keV})^2$$

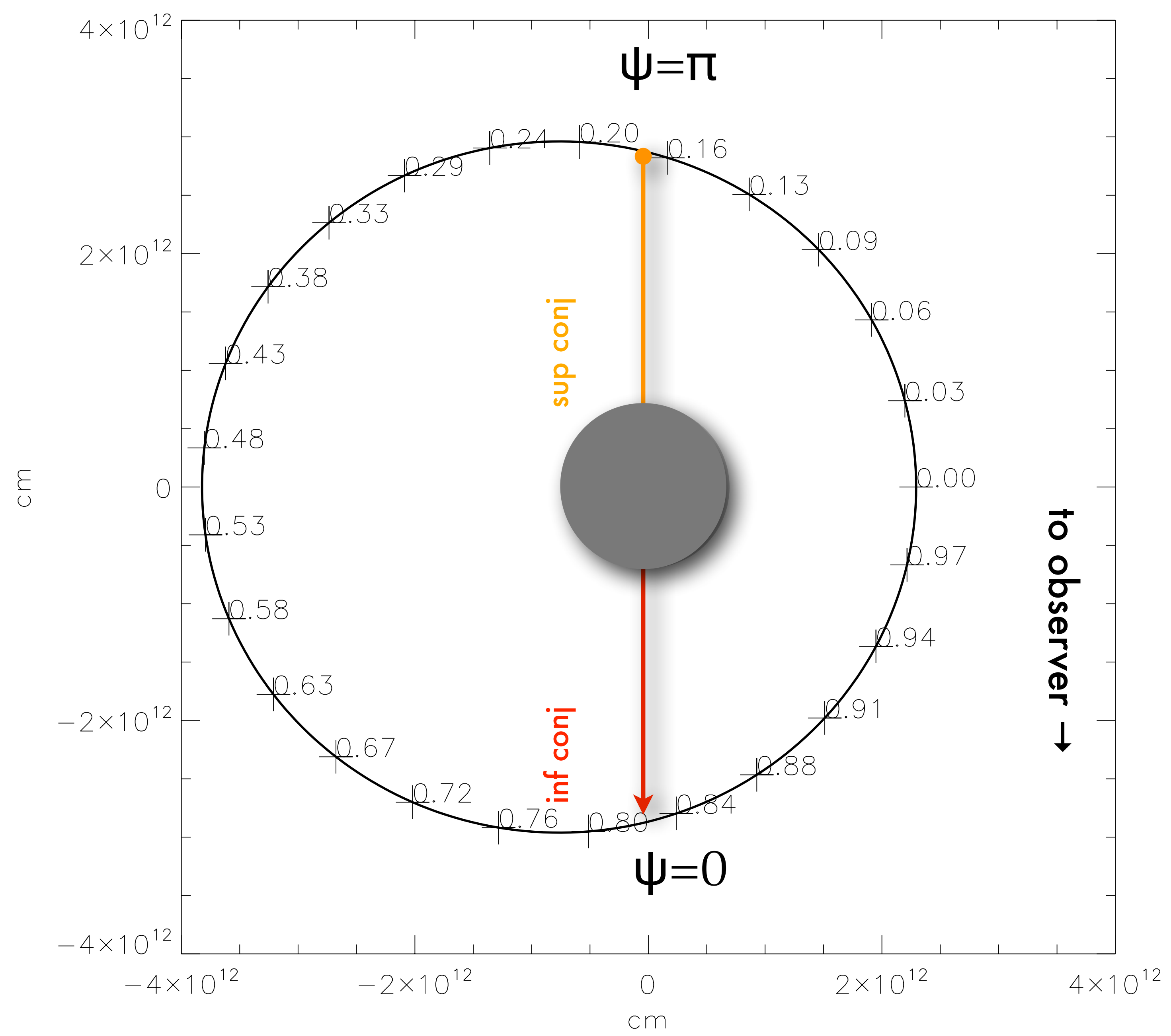
Edge-on orbit

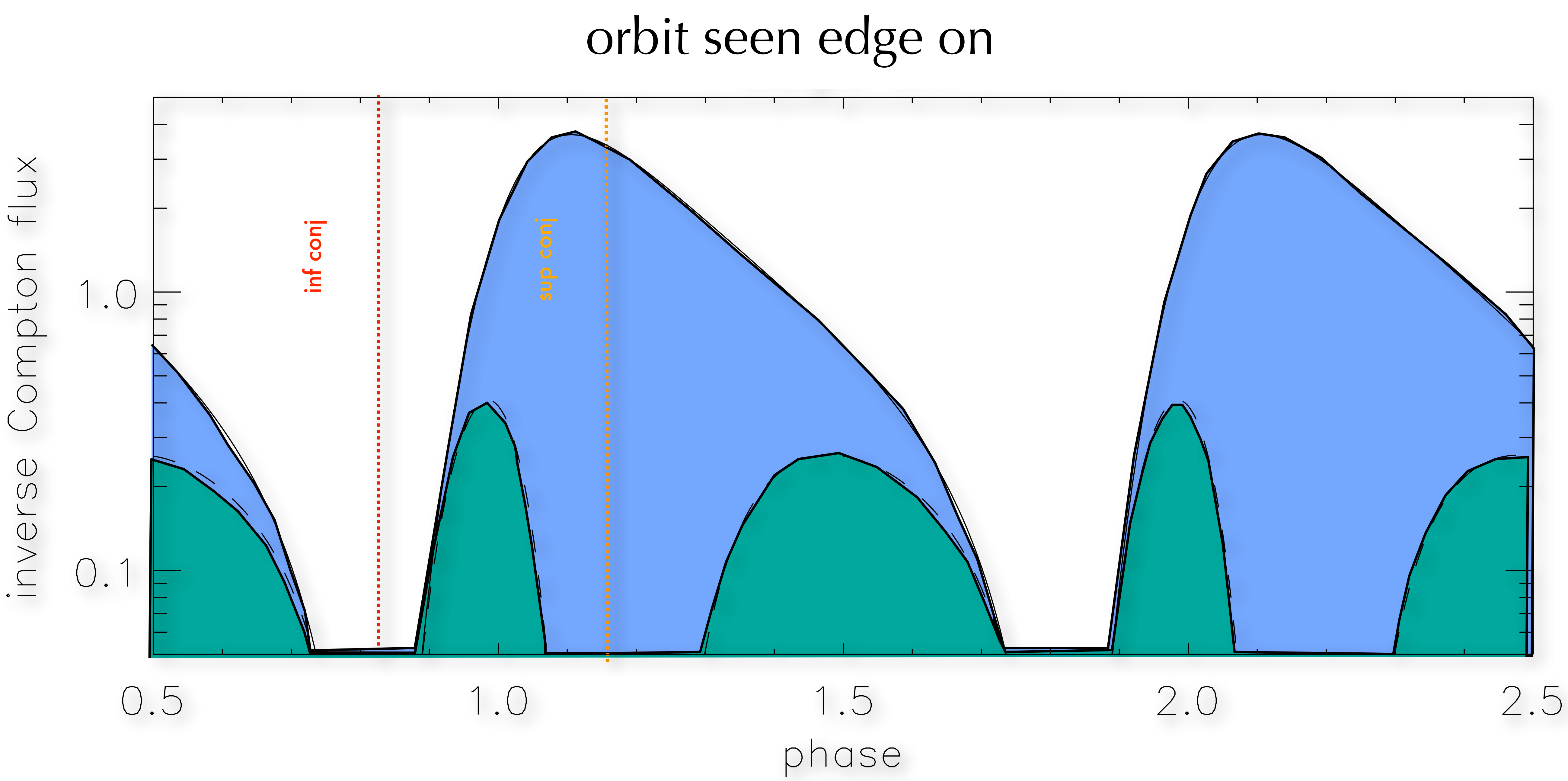




$$P_\star = \sigma_T c U_\star (1-\beta\cos\psi)\left[(1-\beta\cos\psi)\gamma^2 - 1\right]$$

Edge-on orbit





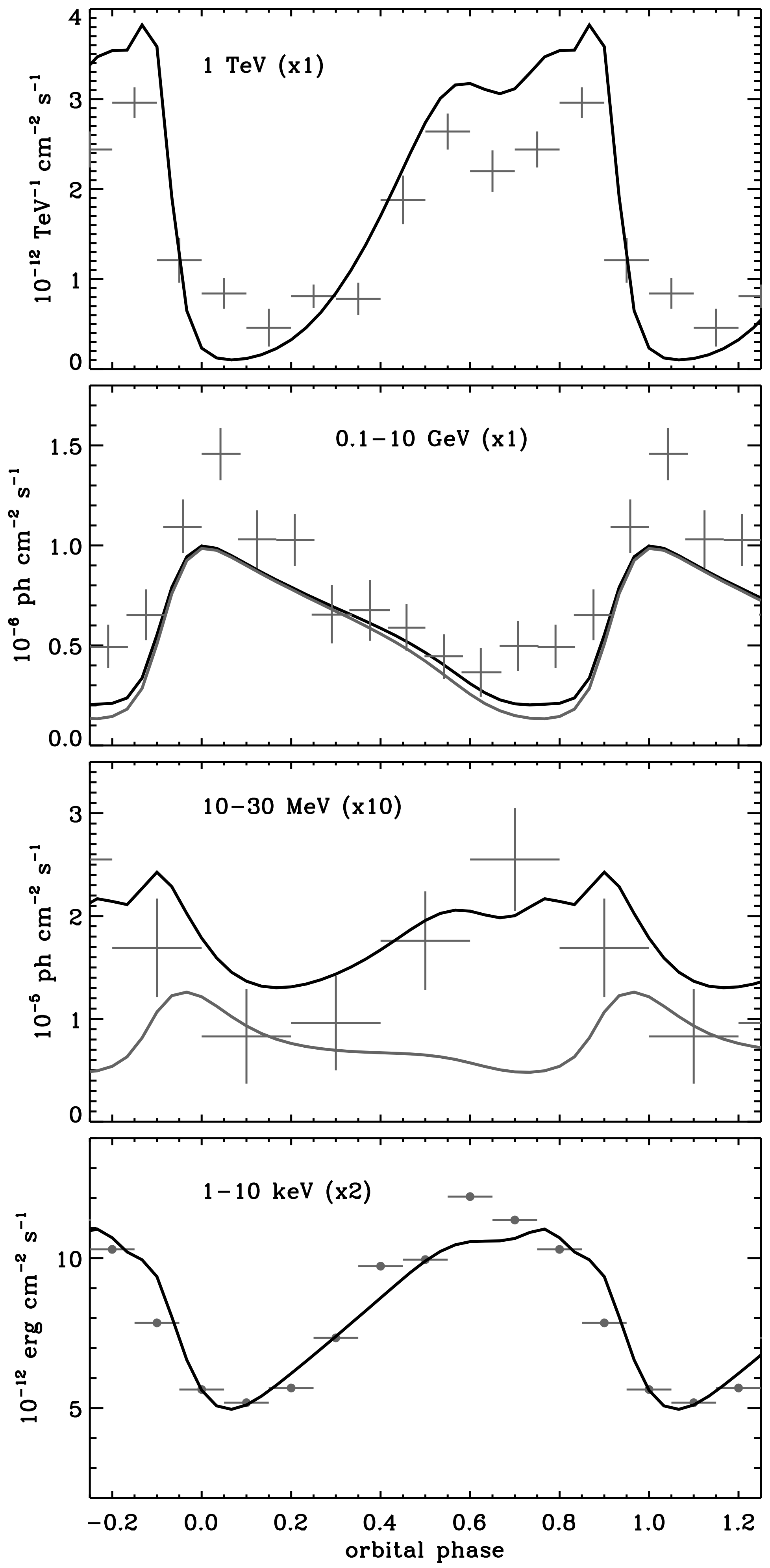
inverse Compton (GeV)

+ pair production above threshold (TeV)

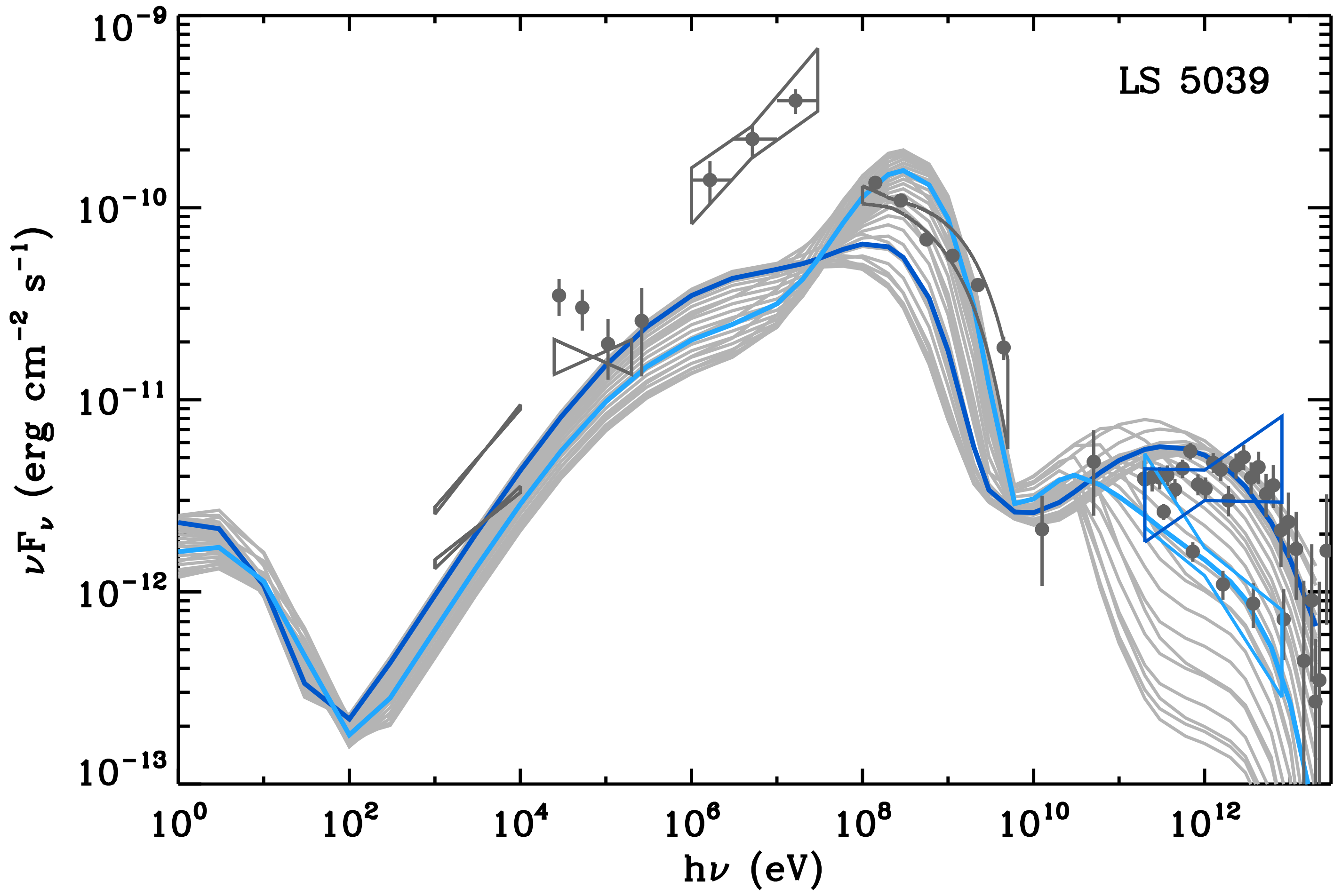
$$\epsilon_{\rm min} \approx 60 \frac{(10\,{\rm eV}/kT_\star)}{1-\cos\psi}\ {\rm GeV}$$

Linking radiative and dynamical models

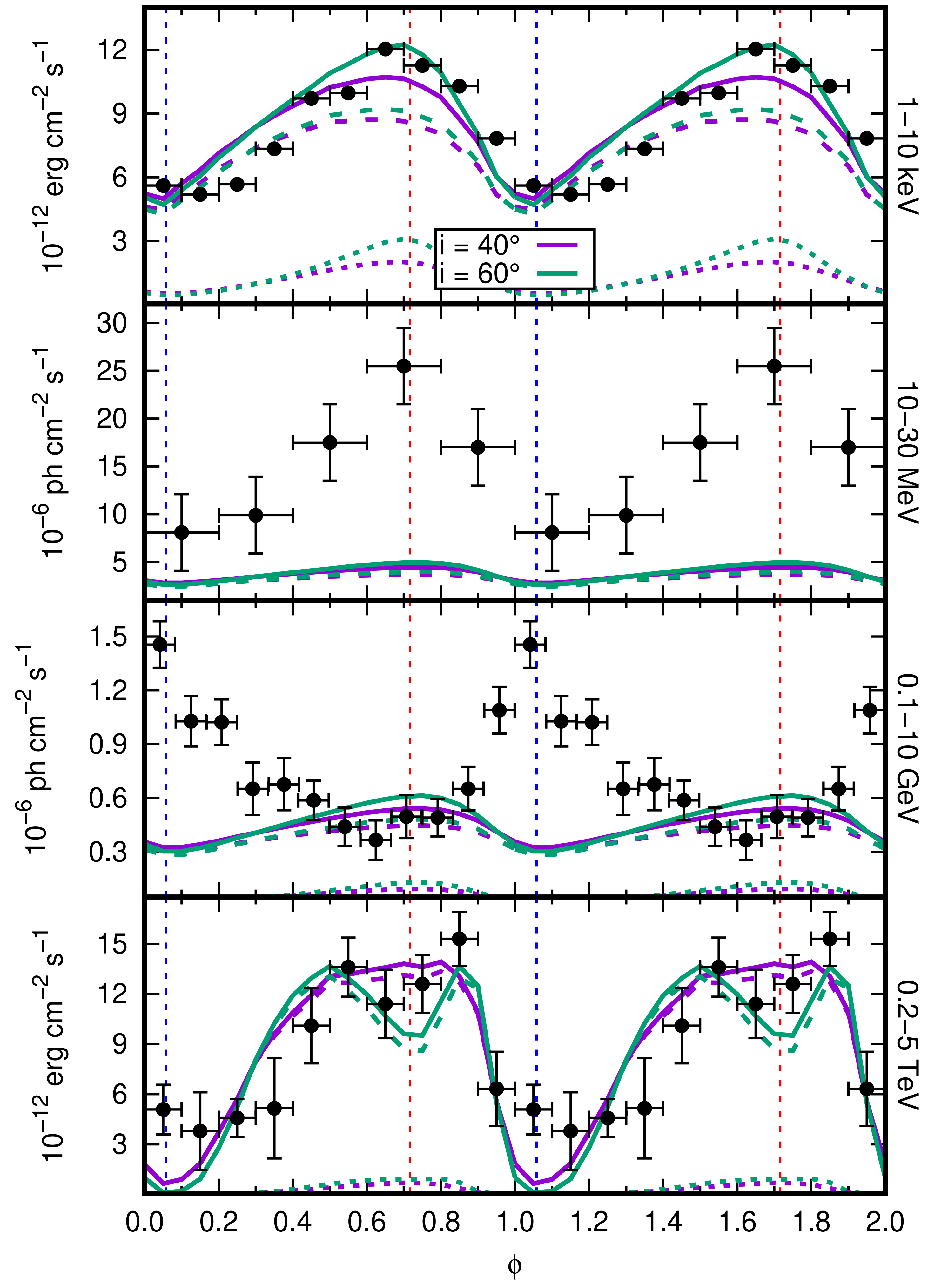
GD+ 2015



LS 5039

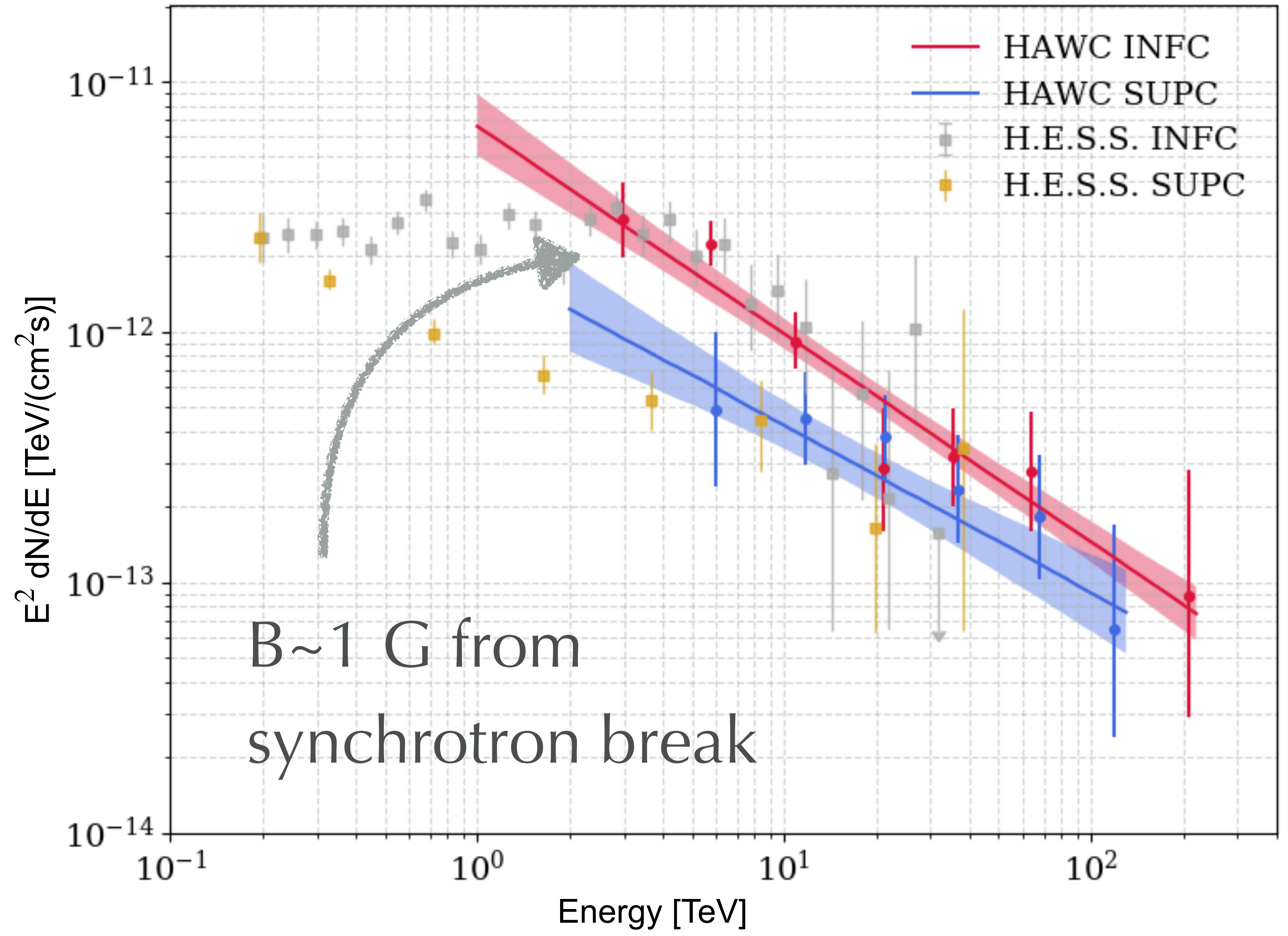


Molina & Bosch-Ramon 2020



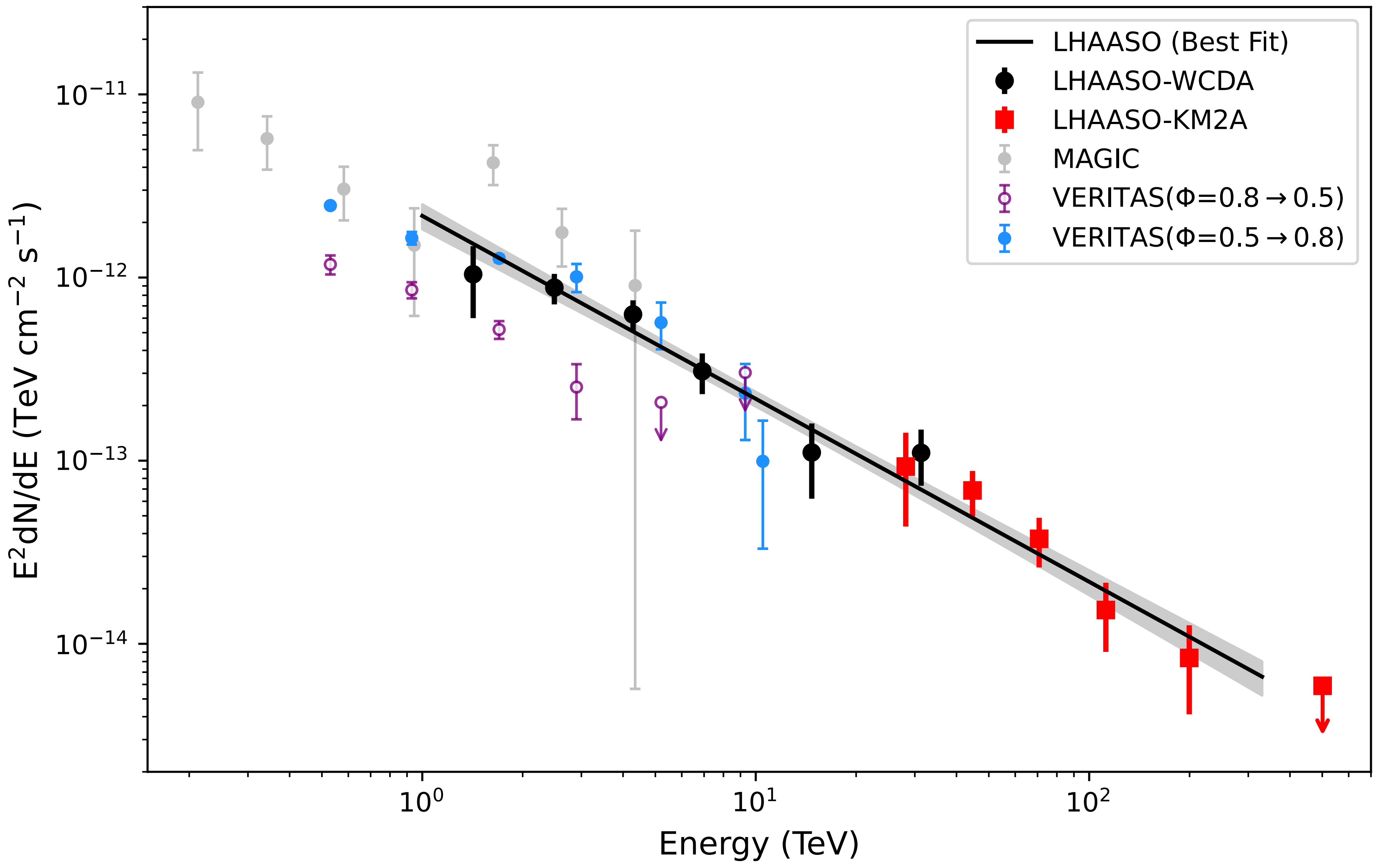
Recent detections at >100 TeV energies

LS 5039 (HAWC coll. 2025)



orbital modulation at 4.7σ confidence between 2 and 118 TeV

LS I+61 303 (LHAASO coll. 2025)



orbital modulation at 4.0σ confidence between 25 and 100 TeV

location of accelerator also constrained by spectrum

Extreme accelerators

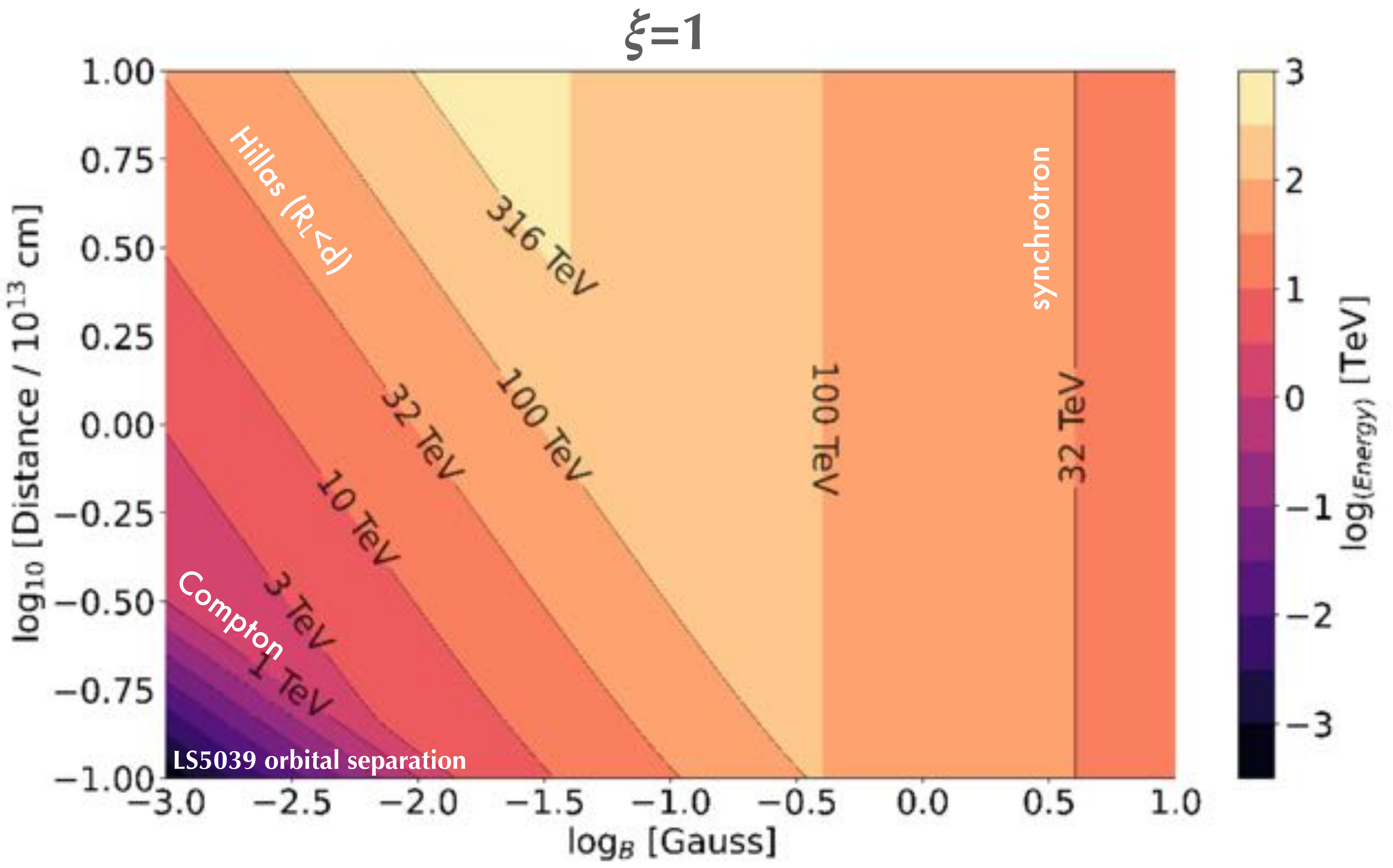
shock acceleration timescale $\tau_{\rm ac} \geq \xi \frac{R_L}{c} \approx 0.1\,\xi \left(\frac{E}{1\,{\rm TeV}}\right)\left(\frac{1\,{\rm G}}{B}\right)\,{\rm s}$

must be < synchrotron loss timescale

$$\tau_{\rm sync} \approx 400 \left(\frac{1\,{\rm TeV}}{E}\right)\left(\frac{1\,{\rm G}}{B}\right)^2\,{\rm s}$$

gives maximum energy

$$E_{\rm max} \approx 60\,\xi^{-1/2} B^{-1/2}\,{\rm TeV}$$



HAWC coll. 2025

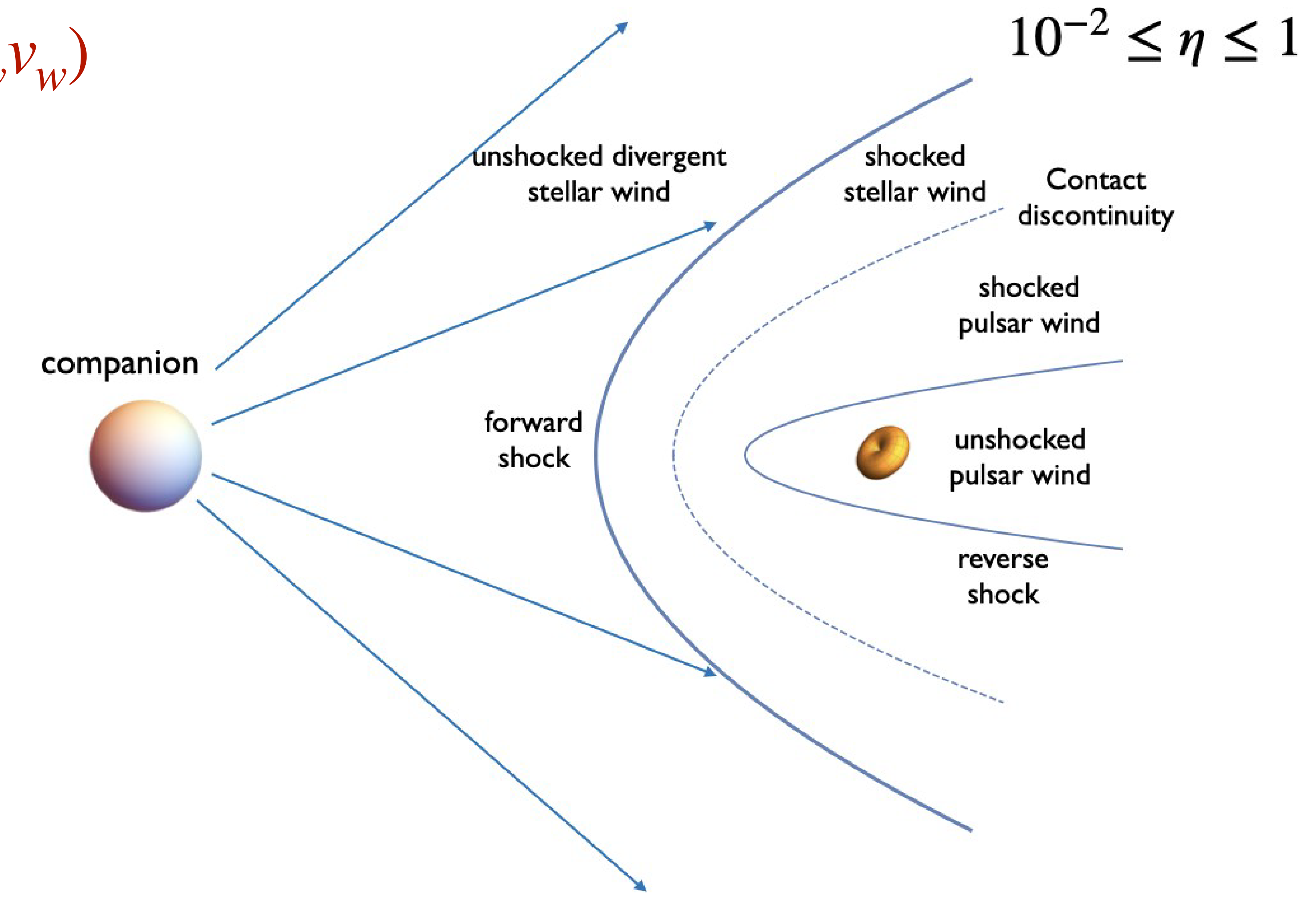
100 TeV photons with B~1 G ⇒ **ξ~1 extremely efficient acceleration**

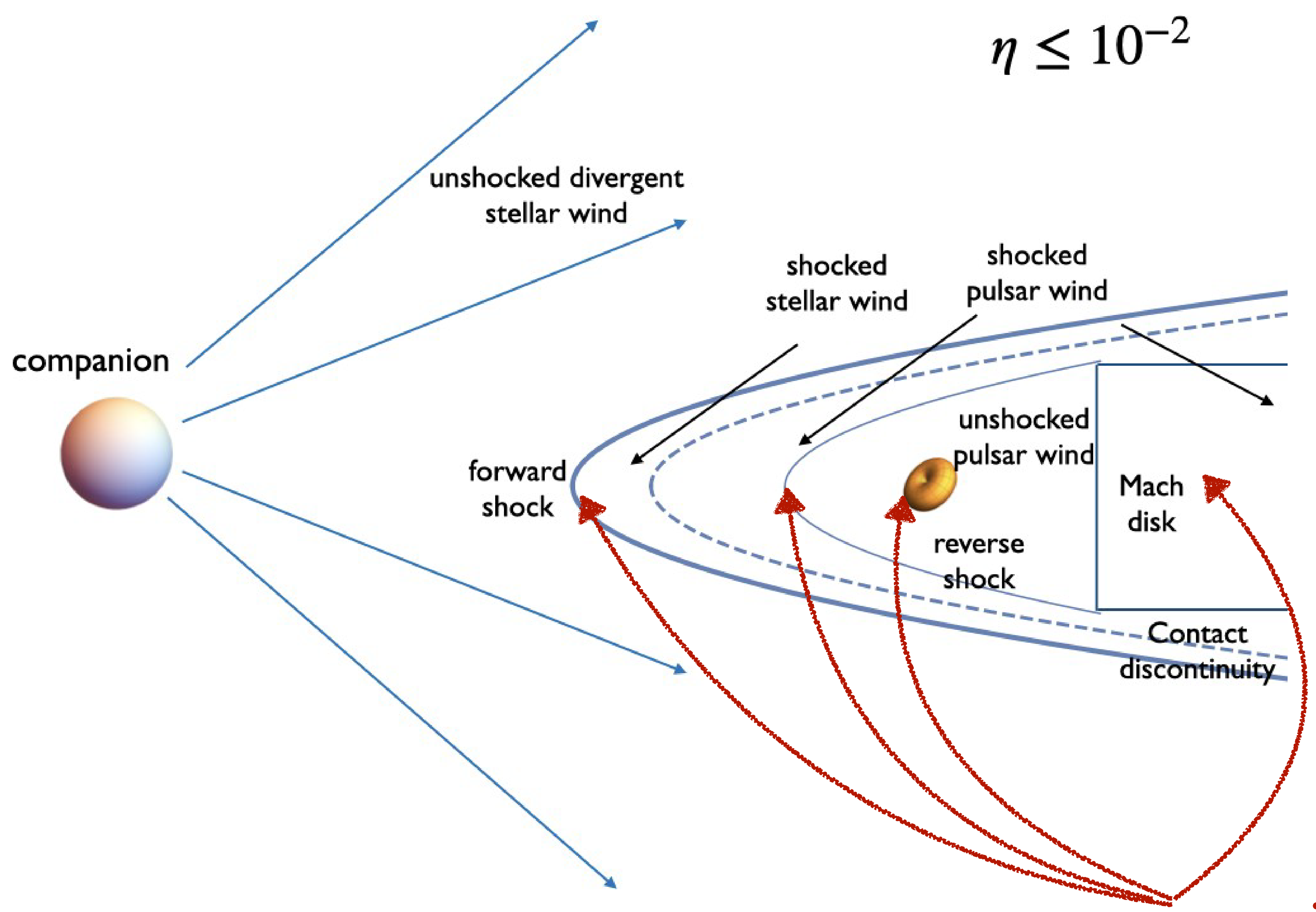
and, most likely, **several acceleration sites** (also supported by SED)

Several acceleration sites

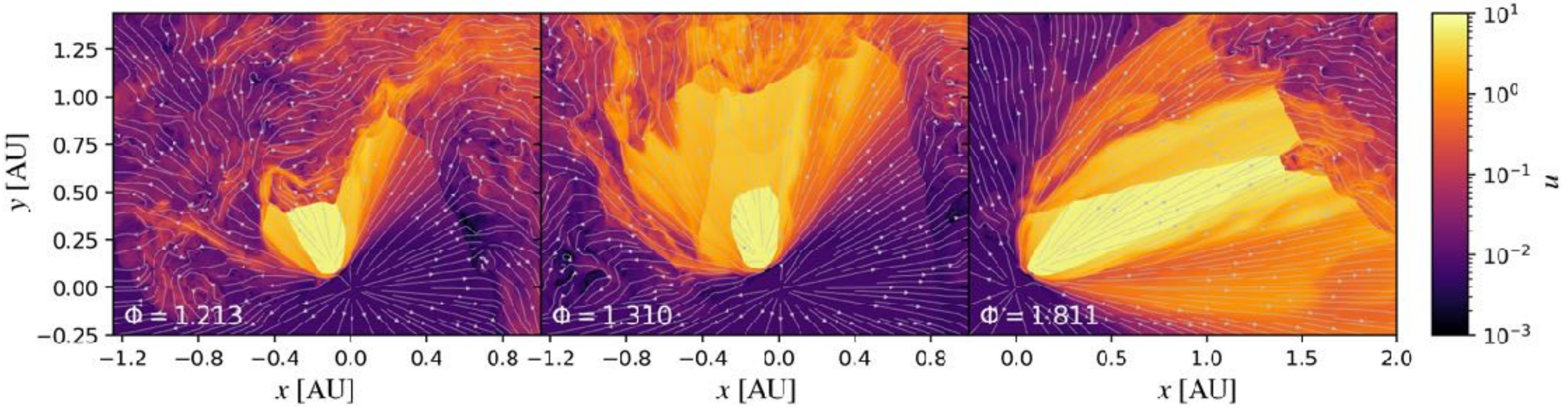
$\eta = (\dot{E}_p/c)/(\dot{M}_w v_w)$

Barkov+ 2023





+ morphological changes with orbital phase e.g. Kissmann+ 2023, Boch-Ramon+2015



Microquasars

from small scales to very large scales

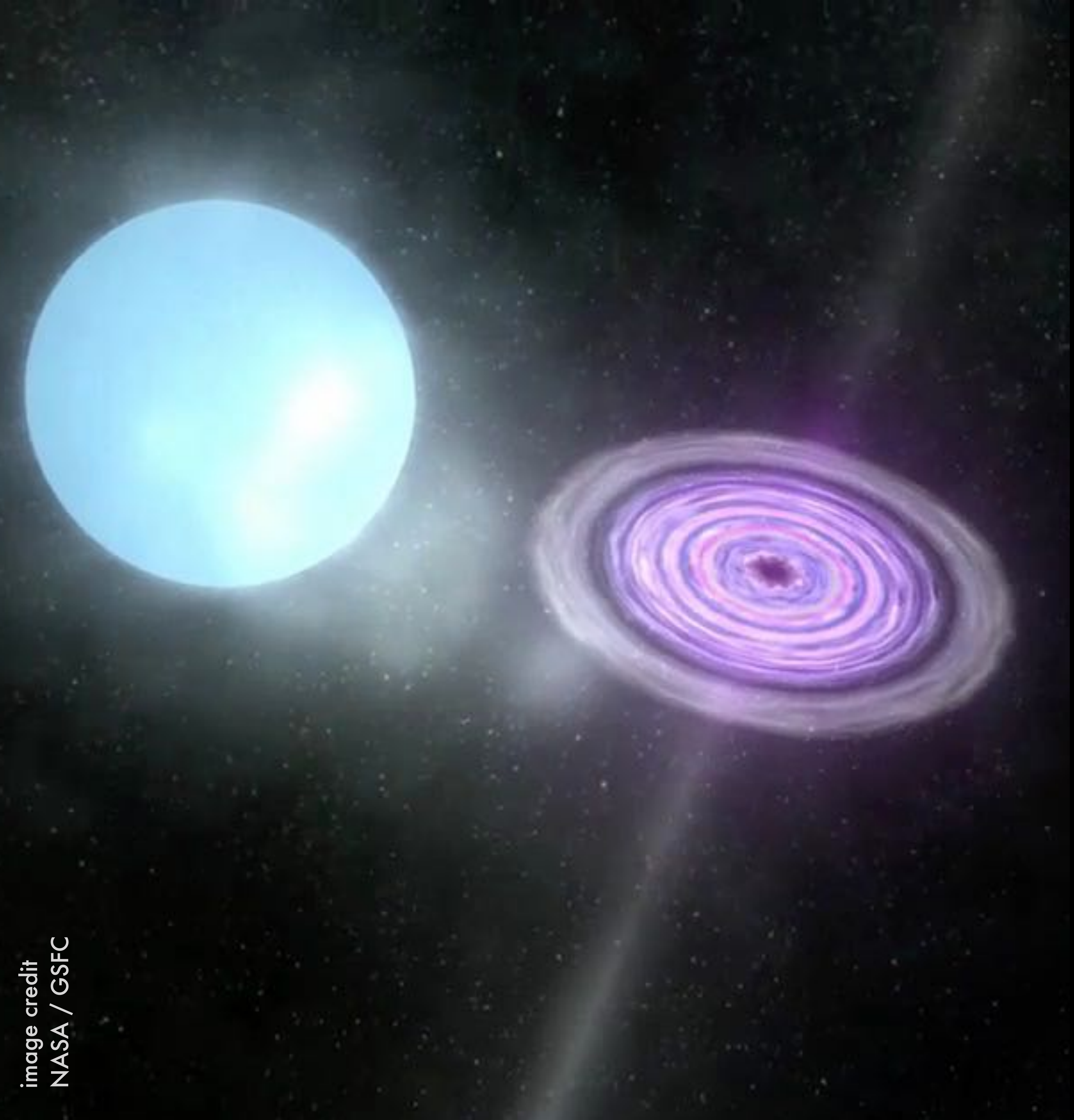


image credit
NASA / GSFC

Microquasars

Gamma-ray emission from particles associated with relativistic jet, powered by accretion or BH rotation

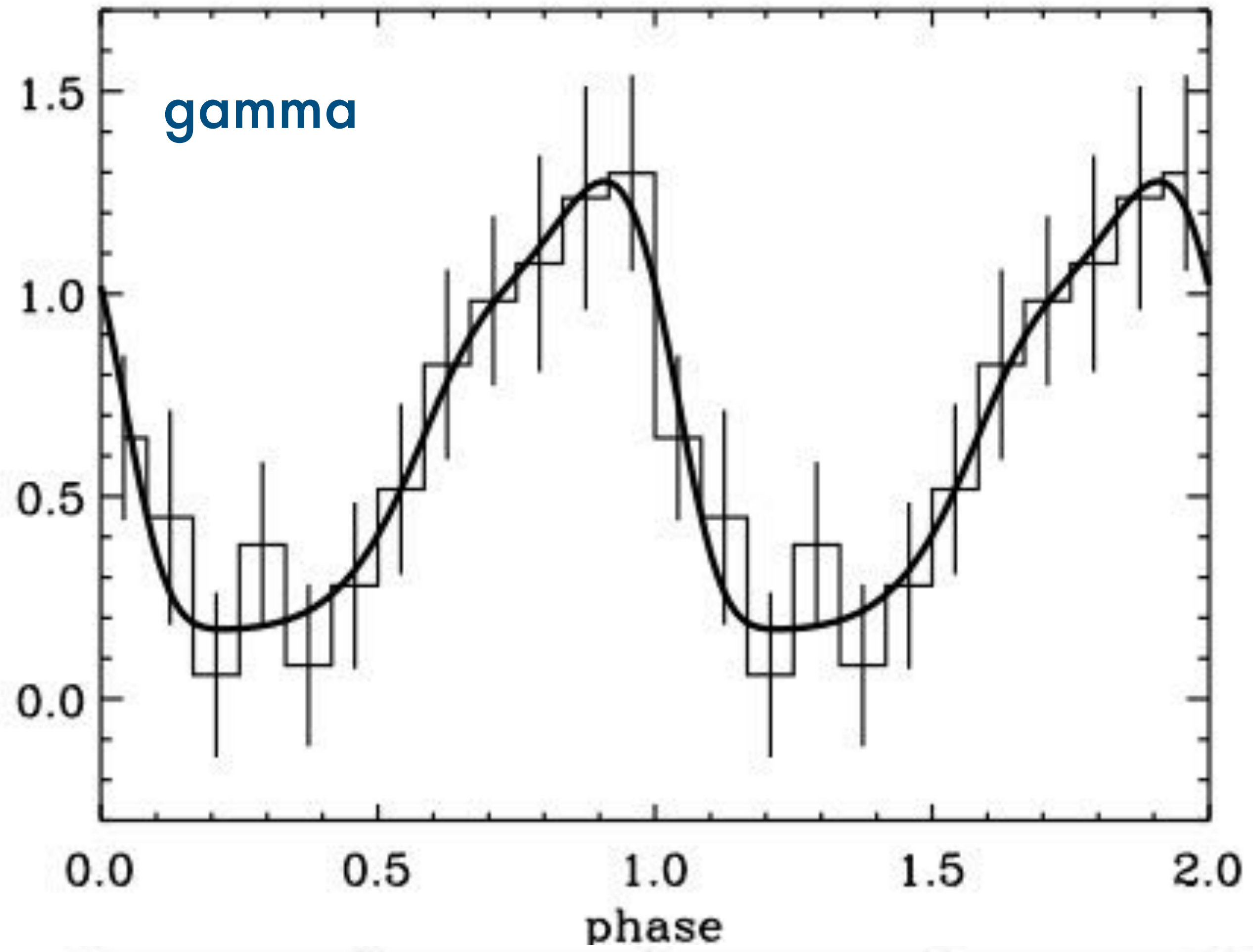
Only two microquasars confirmed in GeV
Cyg X-1, Cyg X-3

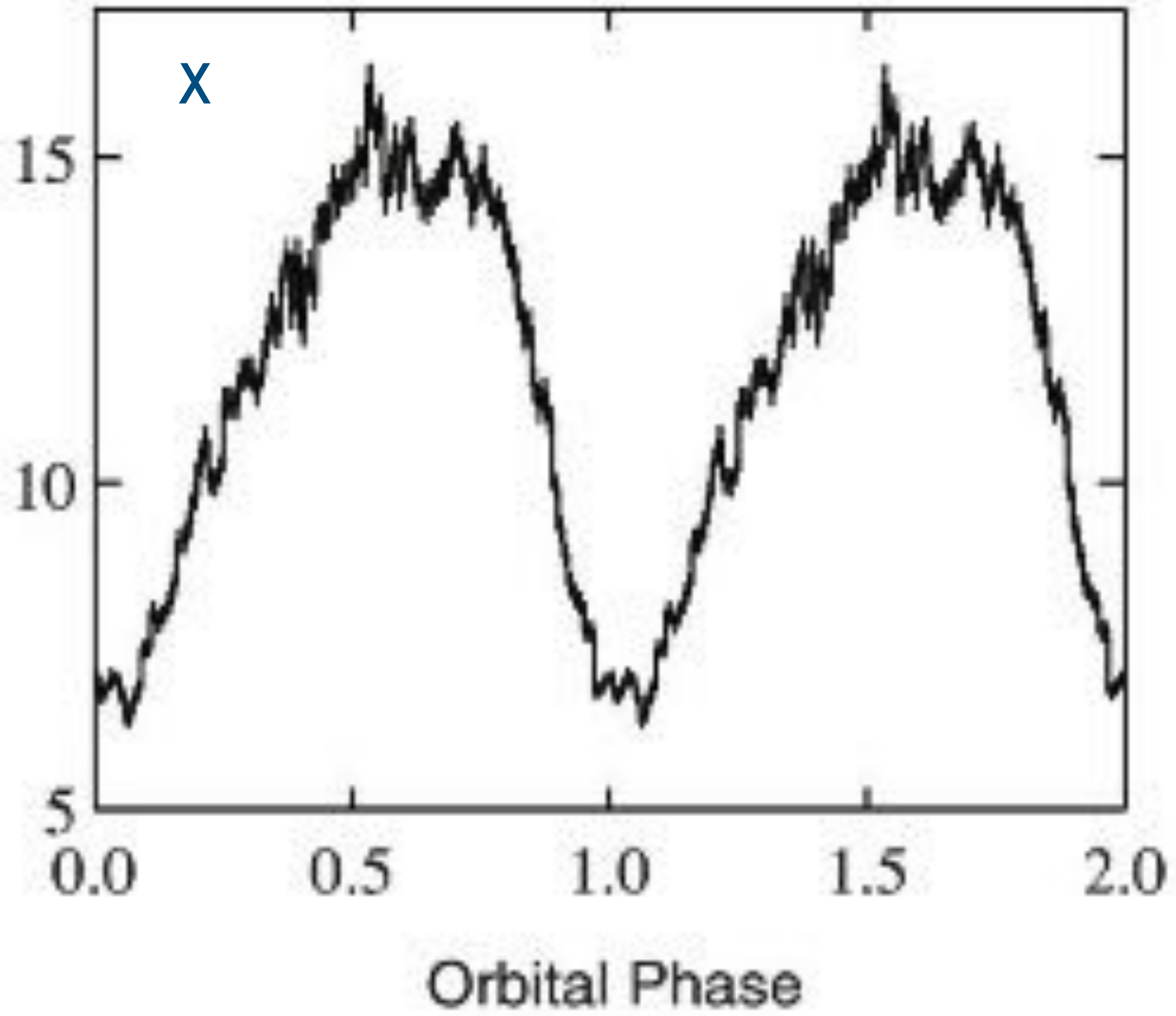
Gamma-ray orbital variability of Cyg X-3

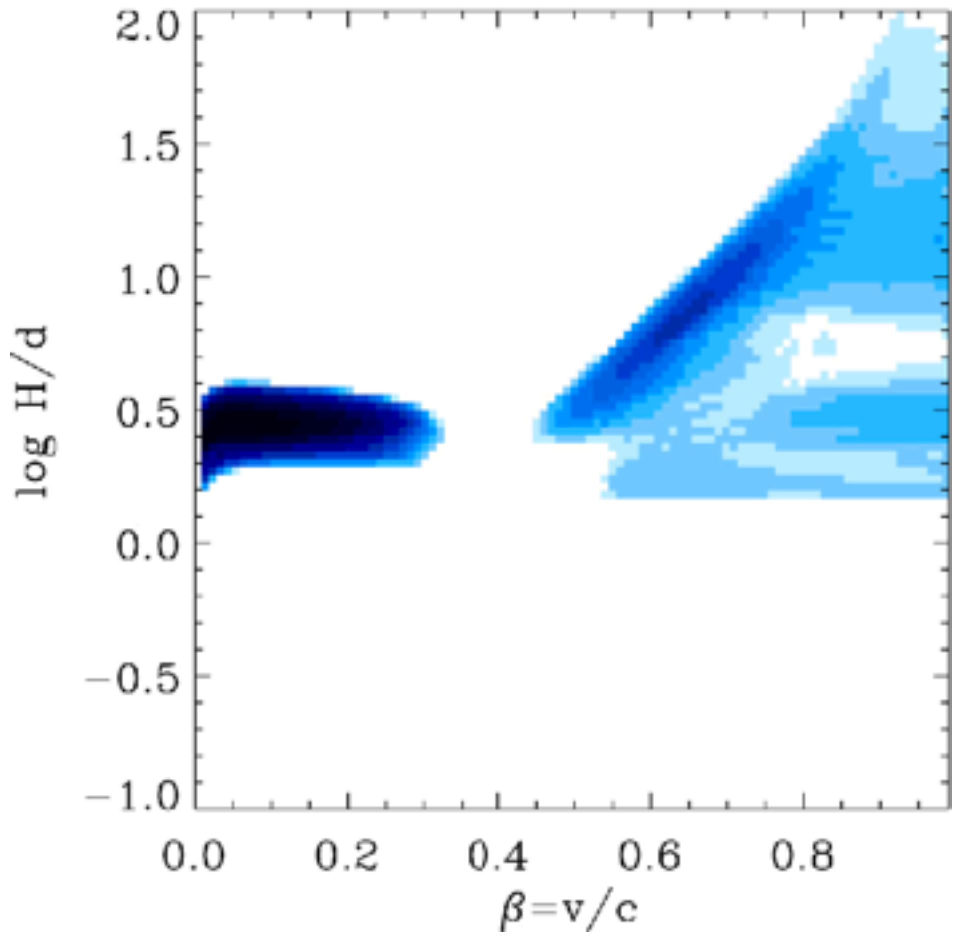
Cyg X-3

4.8 hour orbit

Fermi-LAT+ 2009

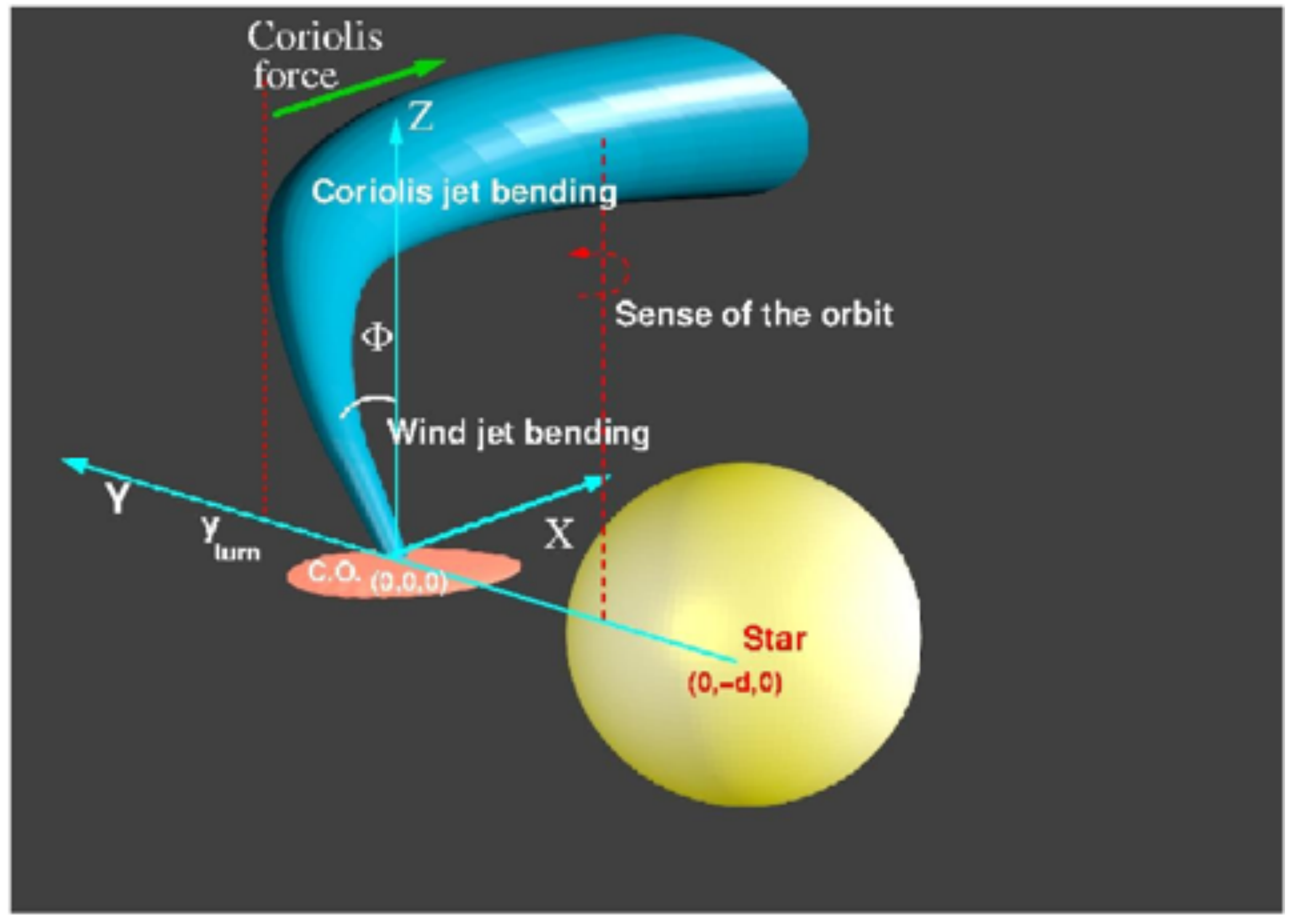






IC on star photons from particles located in relativistic jet

Zdziarski +2018



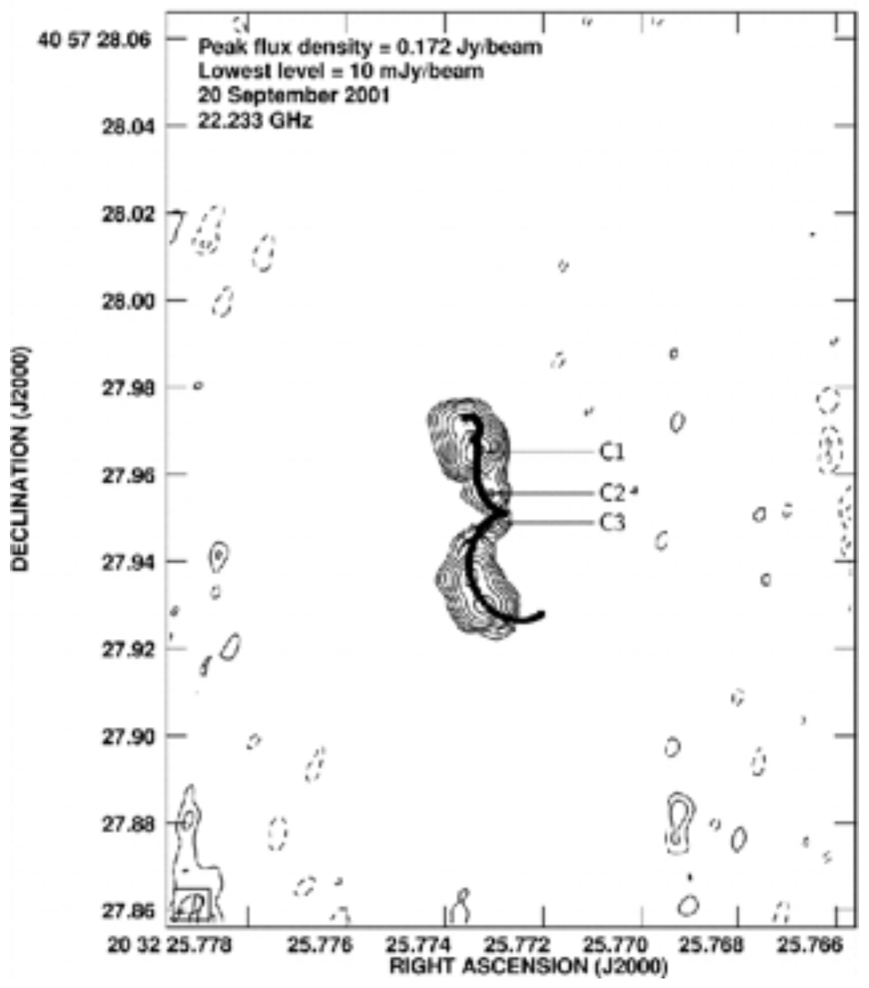
Bosch-Ramon & Barkov 2015, 2022

recollimation shock or jet bending ?

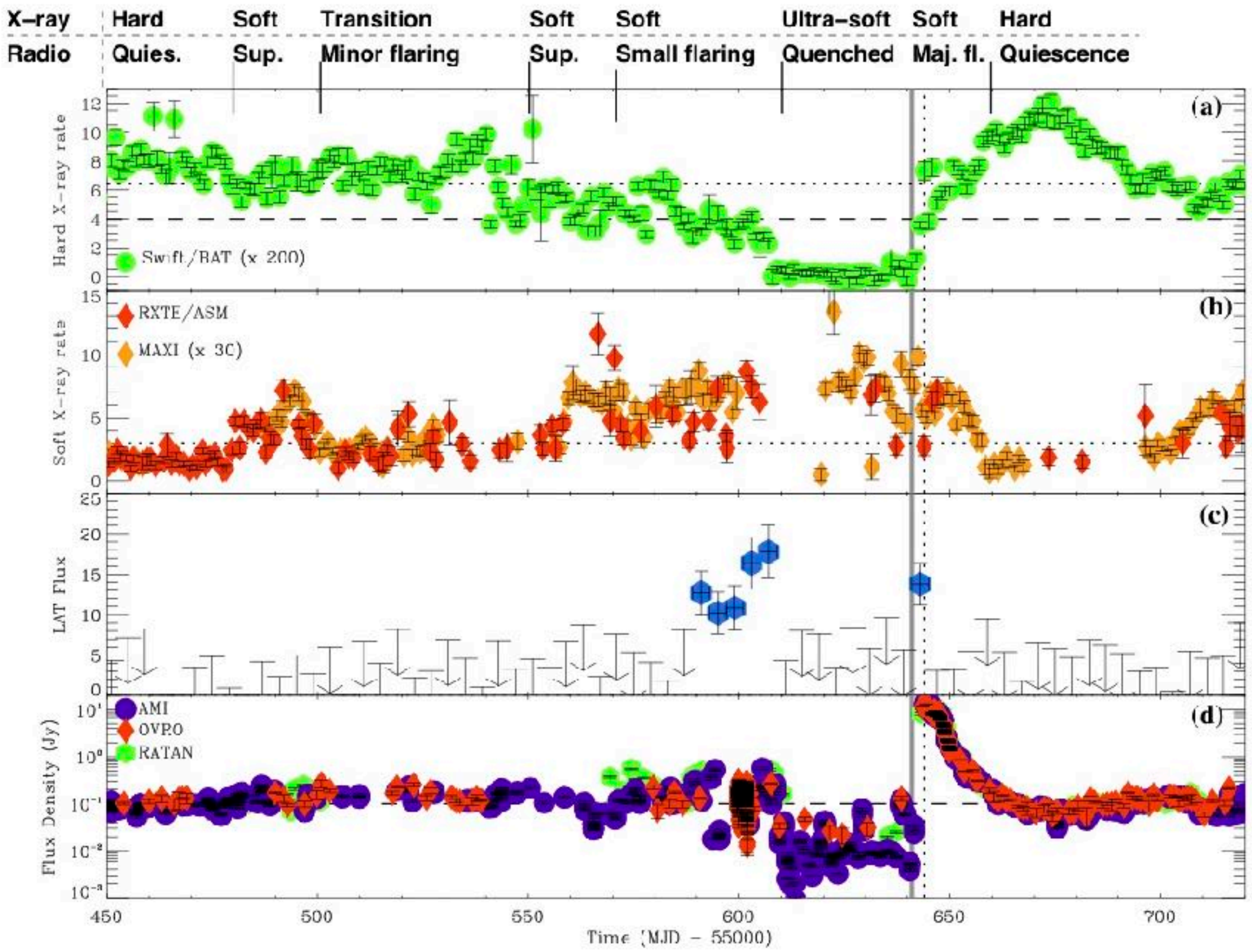
Dmytriiev+ 2024

Linking accretion, acceleration, jet launching

Cyg X-1 and Cyg X-3 detections clearly related to spectral state



Miller-Jones+ 2004



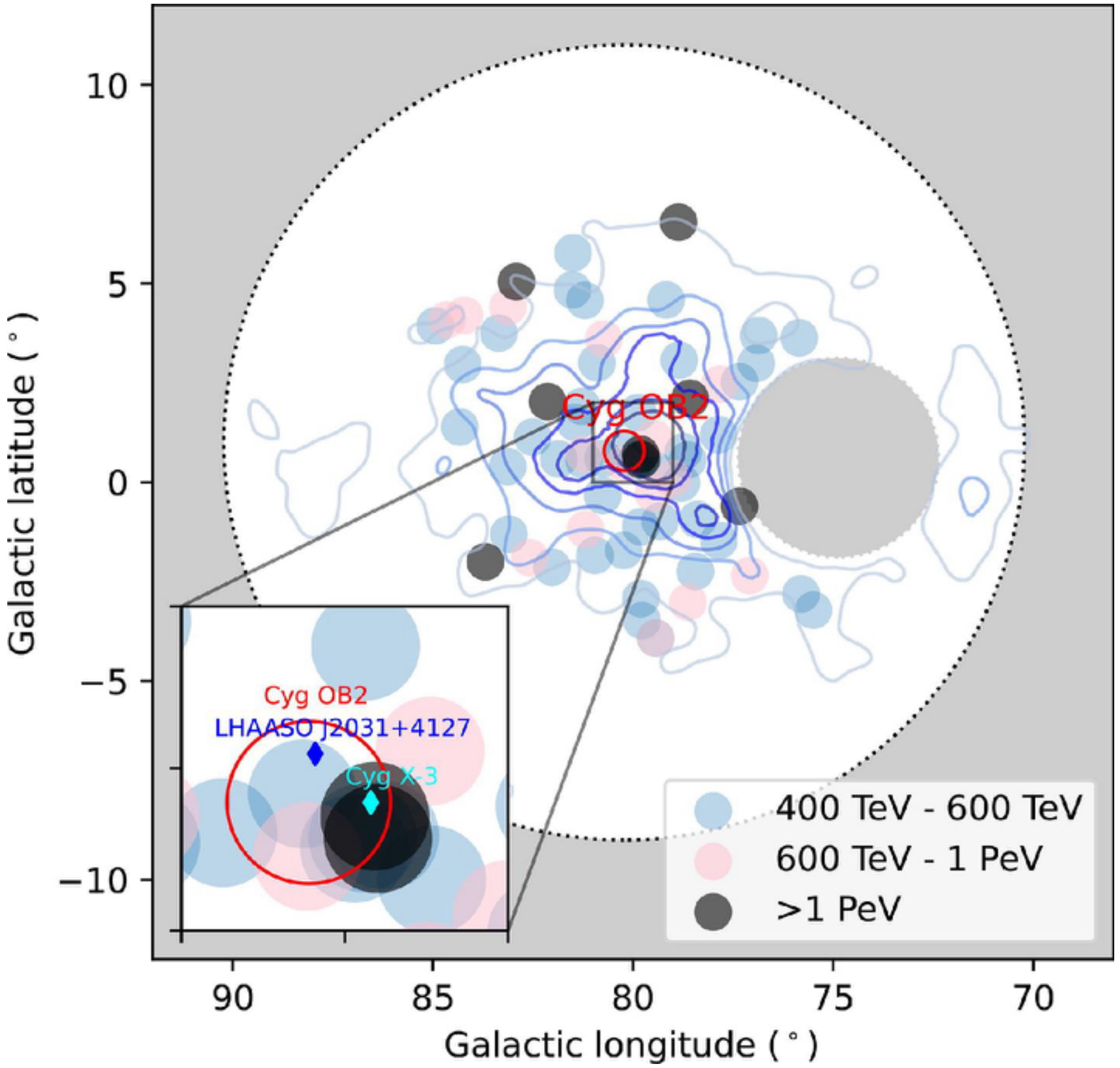
Corbel et al. 2012

Accretion

non-thermal / thermal

Ejection

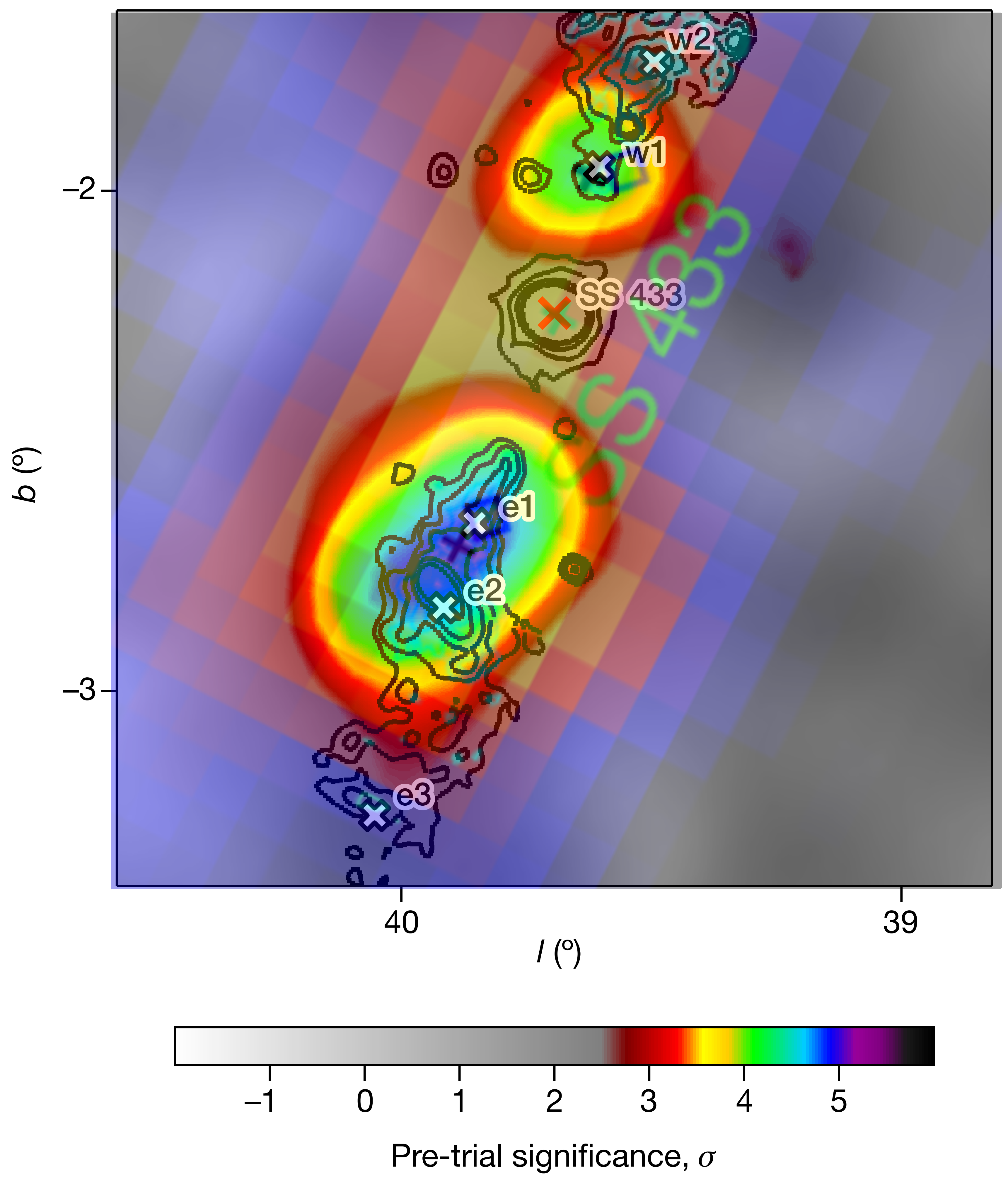
Cyg X-3 back as a PeV accelerator ?



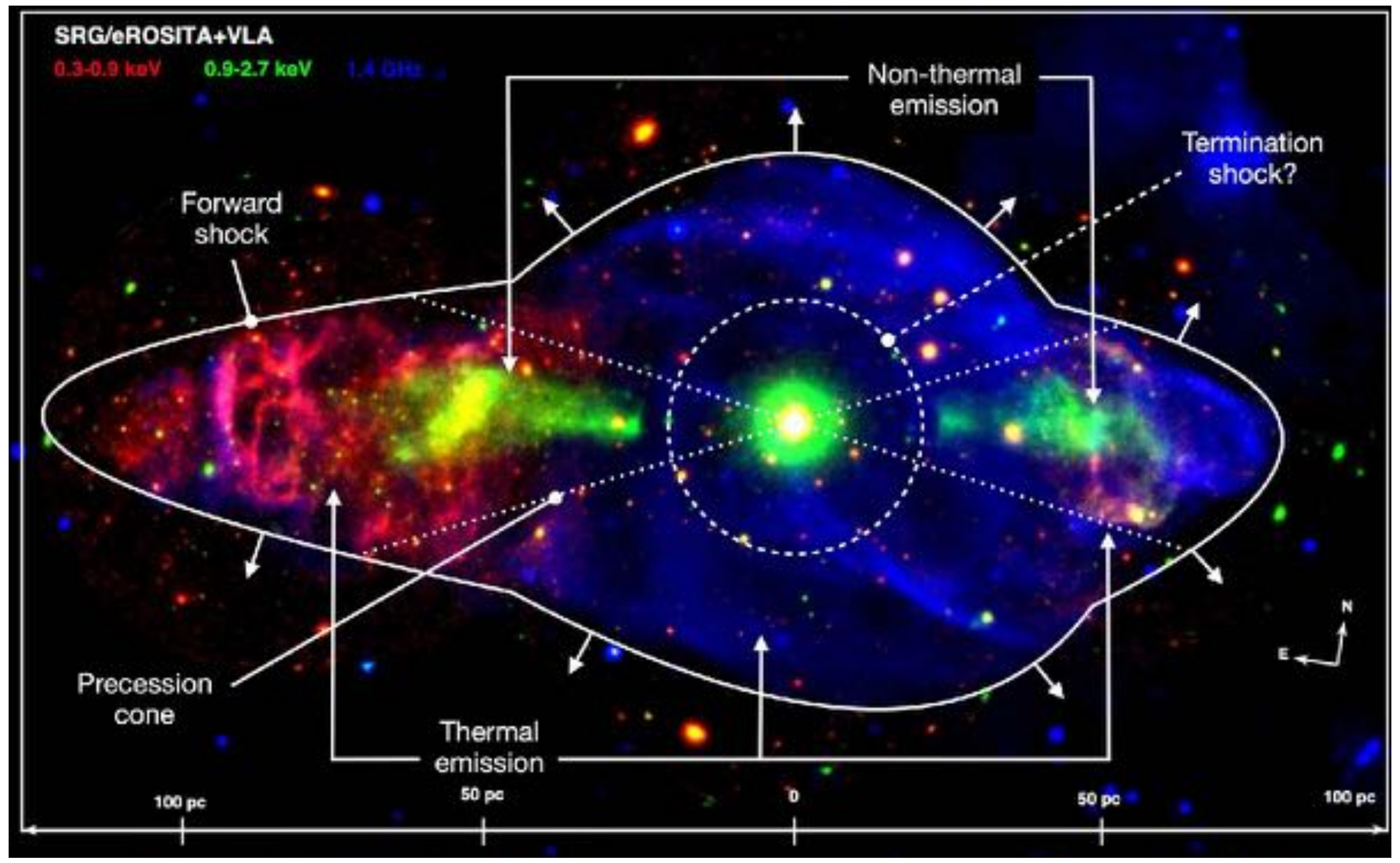
LHAASO coll. 2024

SS433 > TeV gamma rays on large scales

HAWC coll. 2018 & LHAASO 2024 superposed



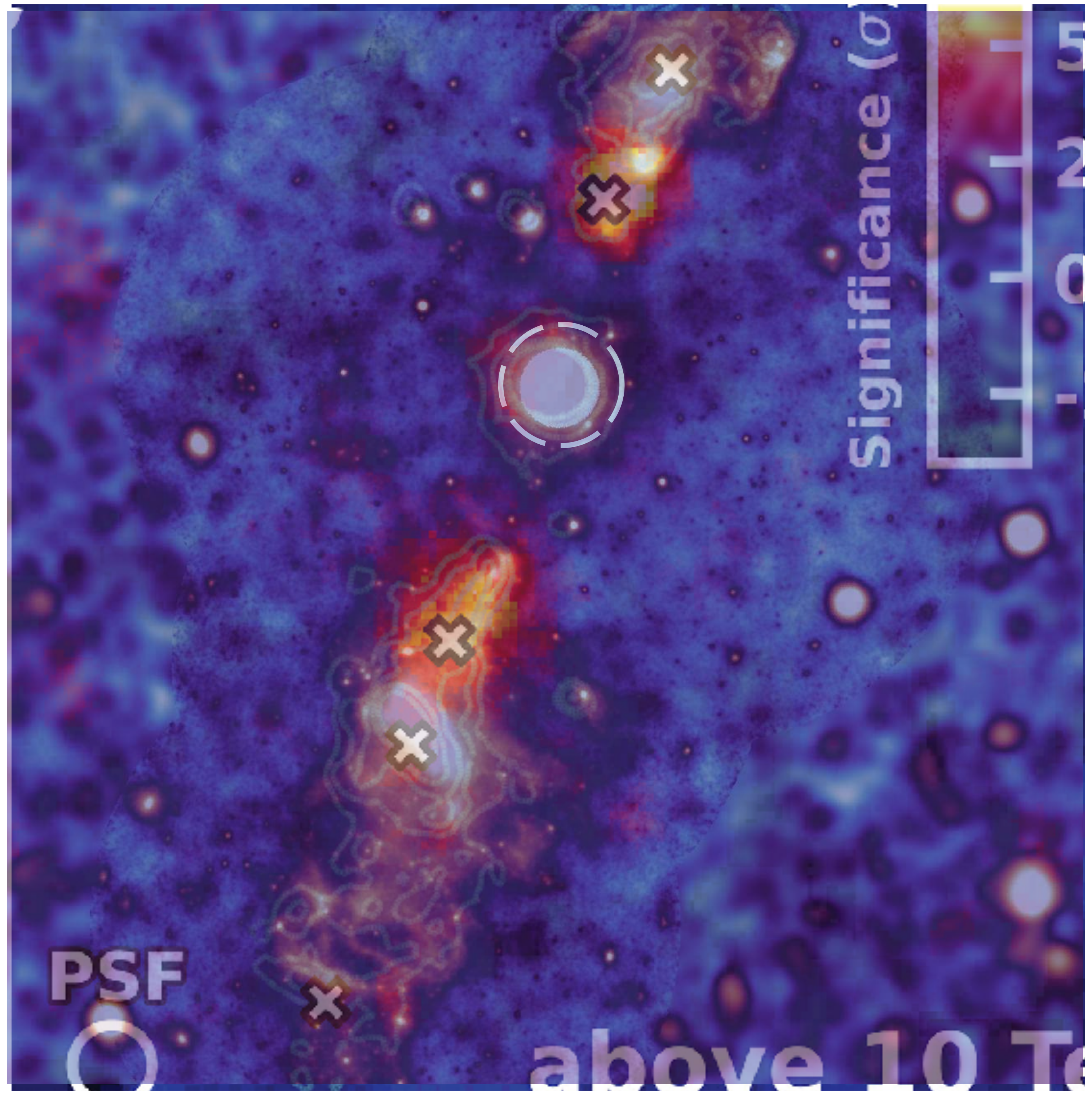
BH or NS in 13 day orbit with highly-evolved massive star, super Edddington, P_{jet}~10^{39} erg/s



Sunyaev+ 2025

SS433 > TeV gamma rays on large scales

HESS coll. 2024 & eROSITA Sunyaev+ 2025

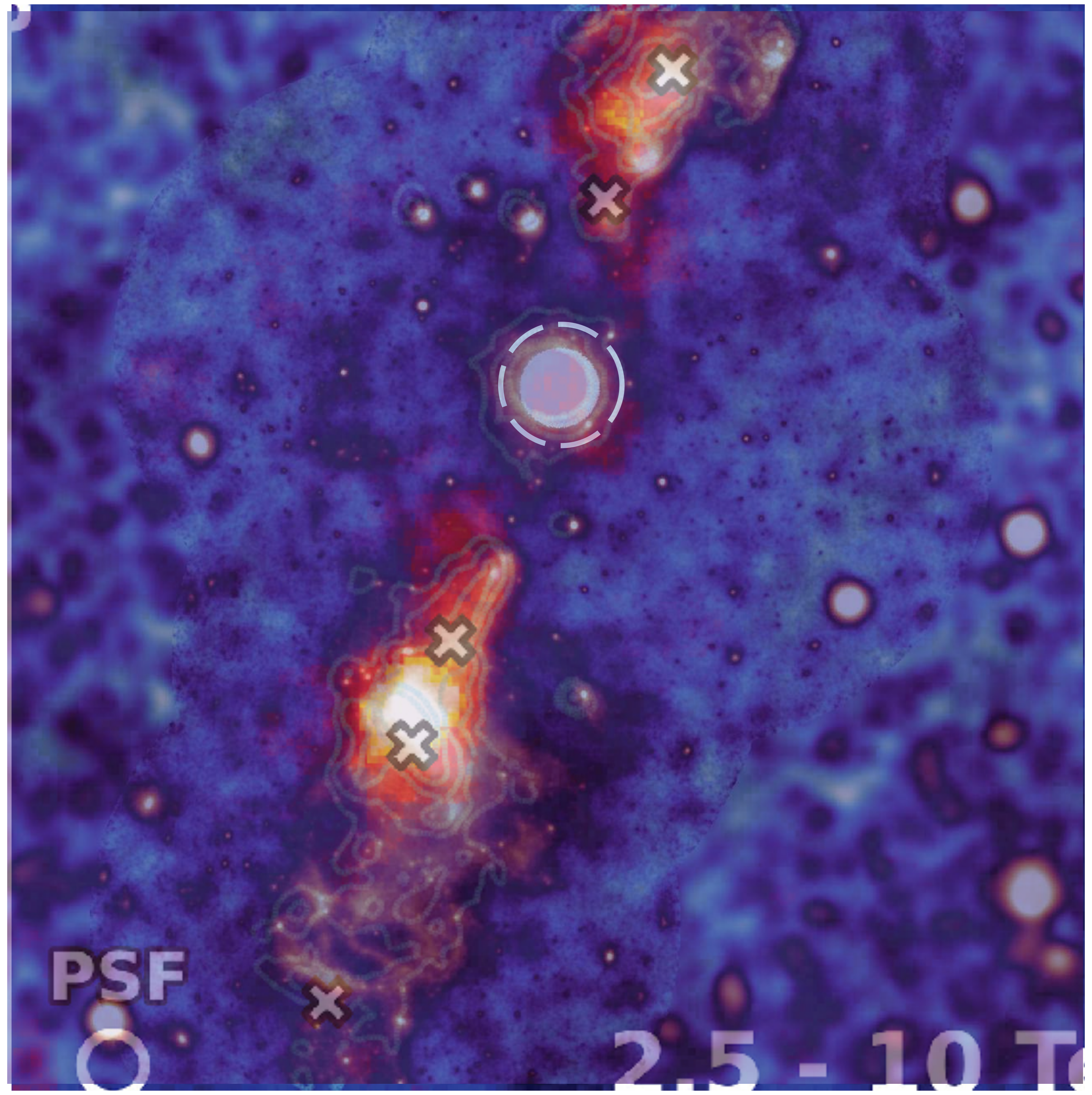


BH or NS in 13 day orbit with highly-evolved massive star, super Edddington, P_{jet}~10^{39} erg/s

- >100 TeV electrons upscattering CMB/IR (0.5% P_{jet}) and radiating synchrotron in X-rays
- pp emission requires ~ P_{jet}

SS433 > TeV gamma rays on large scales

HESS coll. 2024 & eROSITA Sunyaev+ 2025

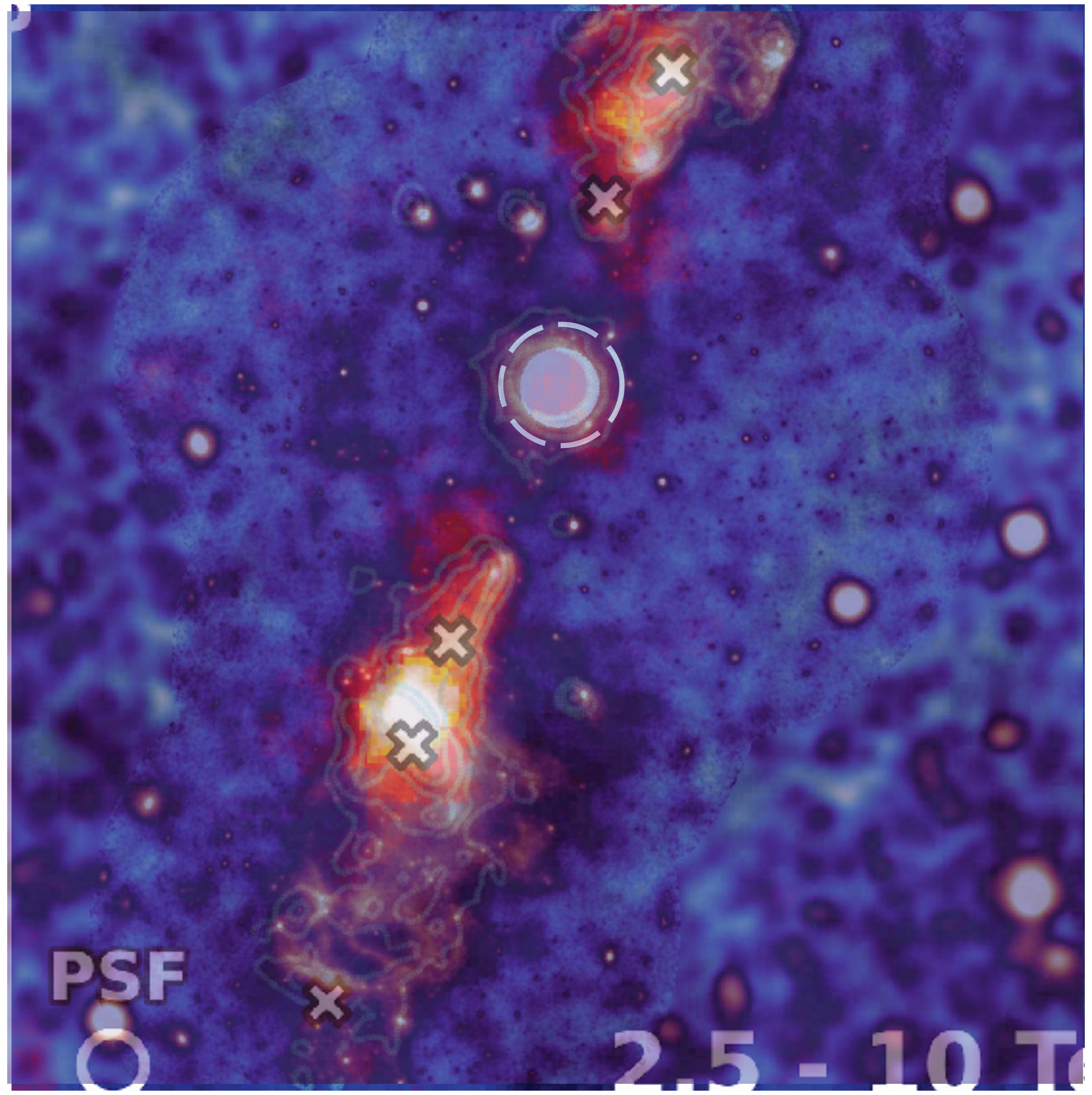


BH or NS in 13 day orbit with highly-evolved massive star, super Edddington, $P_{jet} \sim 10^{39}$ erg/s

- >100 TeV electrons upscattering CMB/IR (0.5% P_{jet}) and radiating synchrotron in X-rays
- pp emission requires ~ P_{jet}

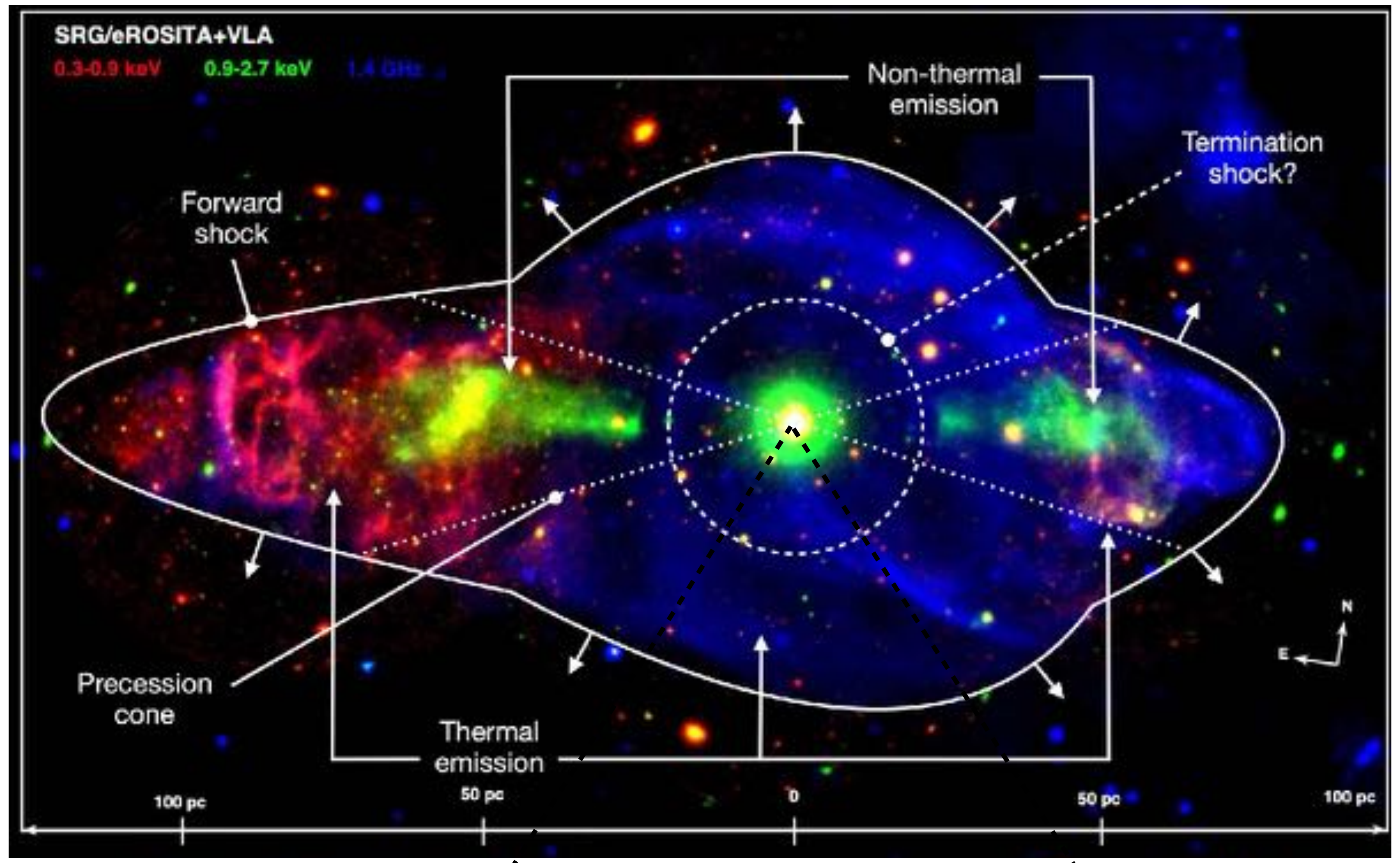
SS433 > TeV gamma rays on large scales

HESS coll. 2024 & eROSITA Sunyaev+ 2025



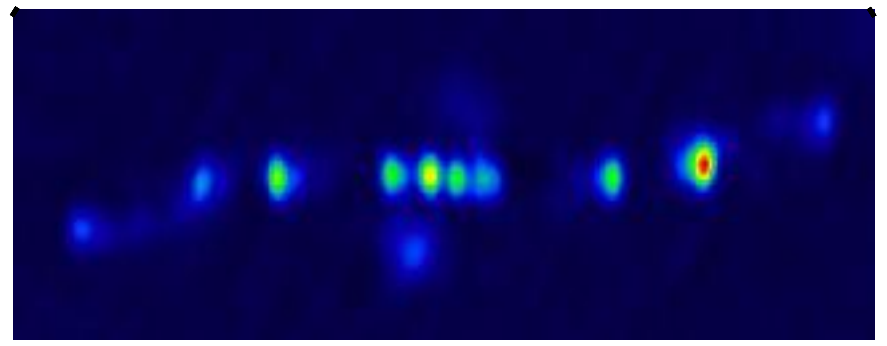
BH or NS in 13 day orbit with highly-evolved massive star, super Edddington, P_{jet}~10^{39} erg/s

- why does the jet reappear here ?



Sunyaev+ 2025

~100 pc

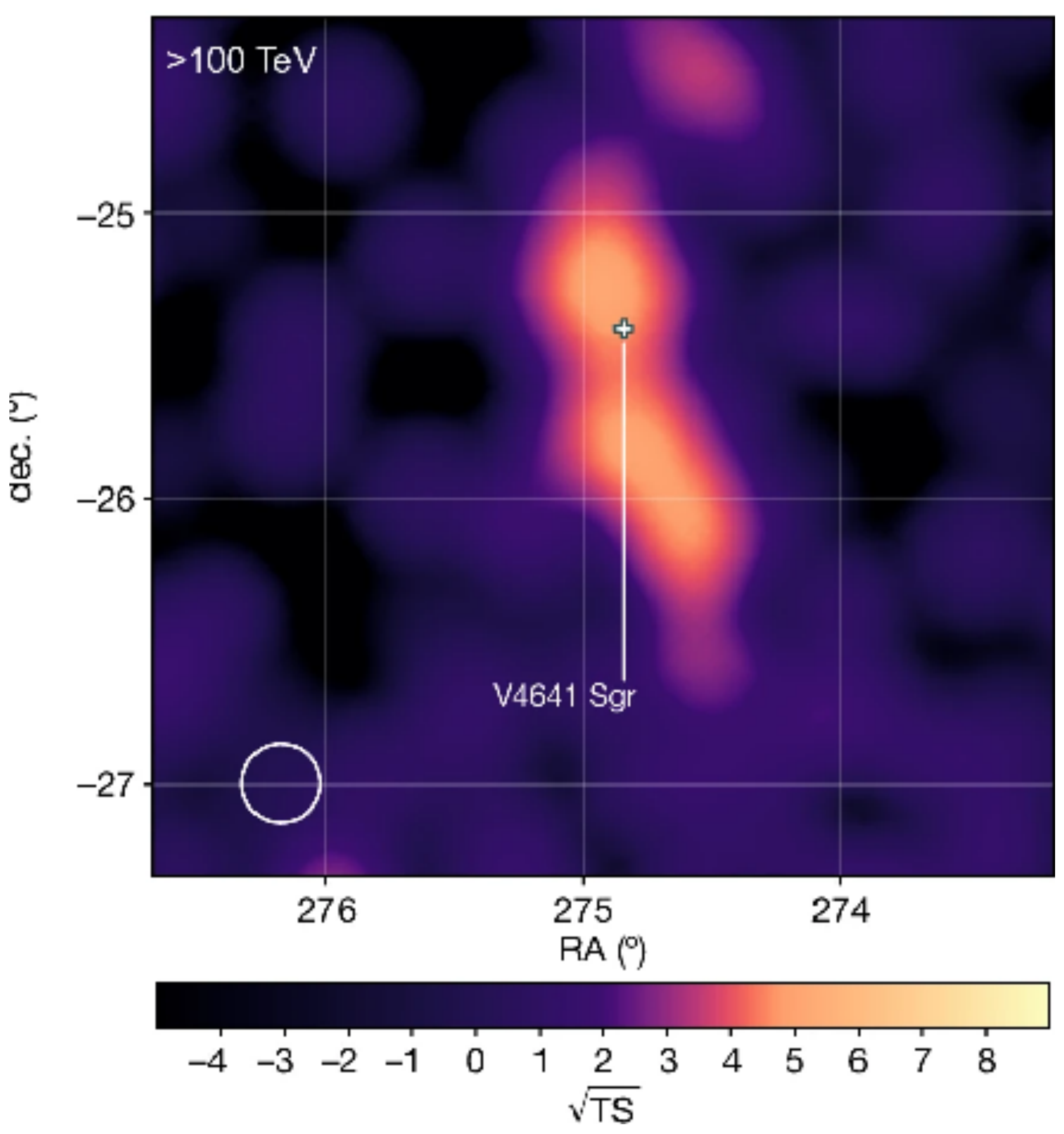


Mioduszewski+ 2004

~0.1 pc

Large scale UHE emission

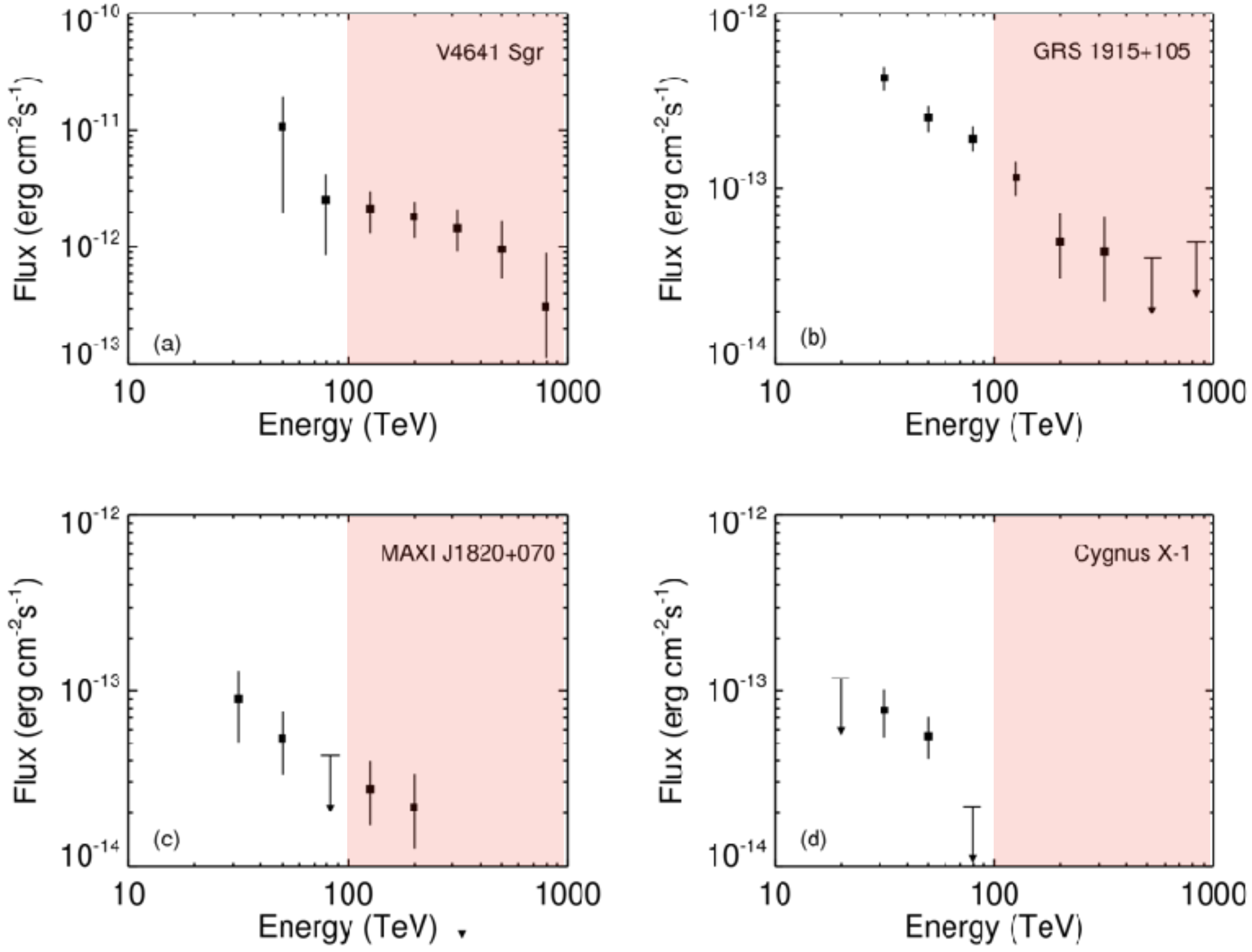
HAWC coll. 2024



V4641 Sgr, BH with L_j~10^{39} erg/s,

extended emission up to PeV

LHAASO coll. 2025

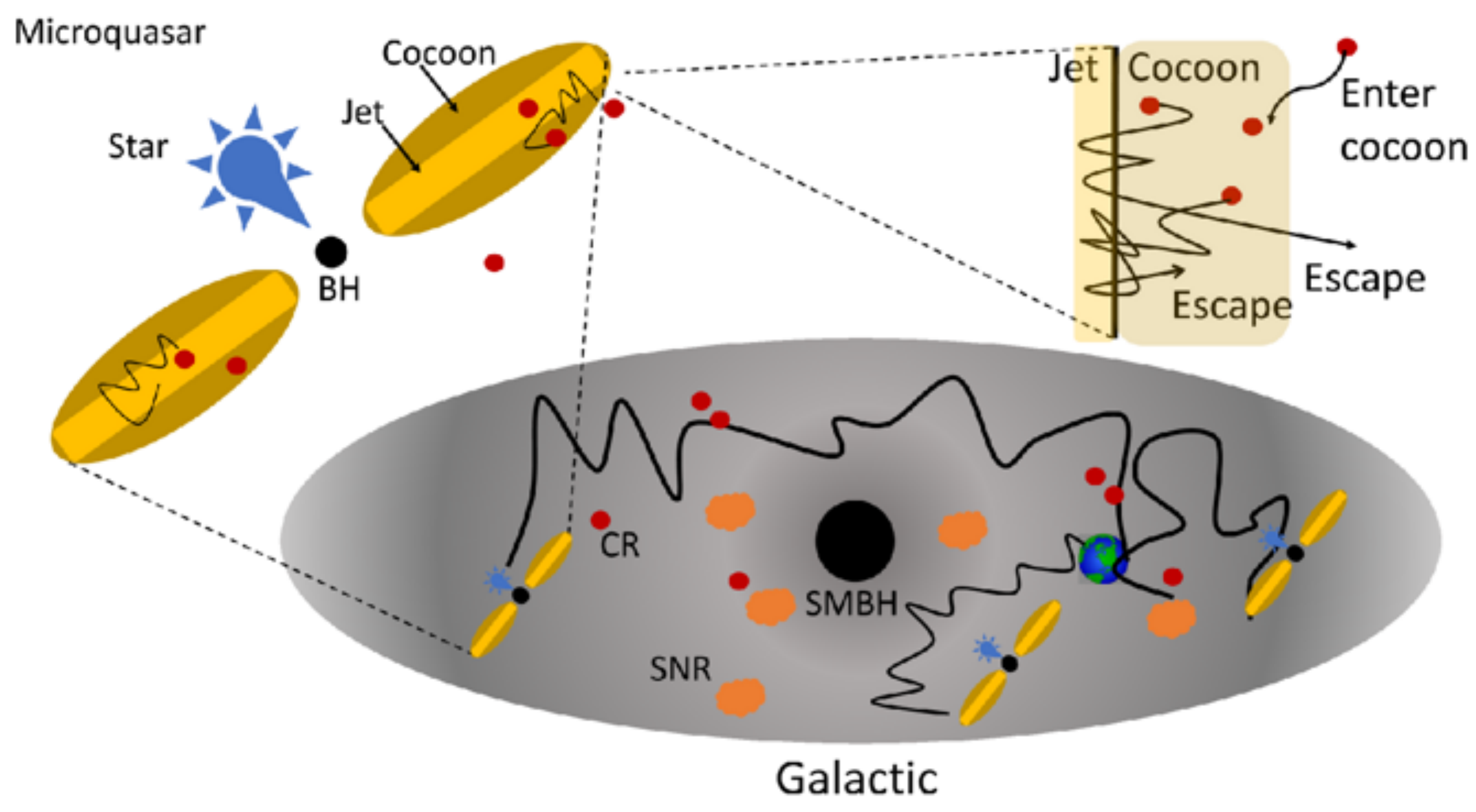


extended on ~50 pc scale in GRS1915, V4641 Sgr, SS433

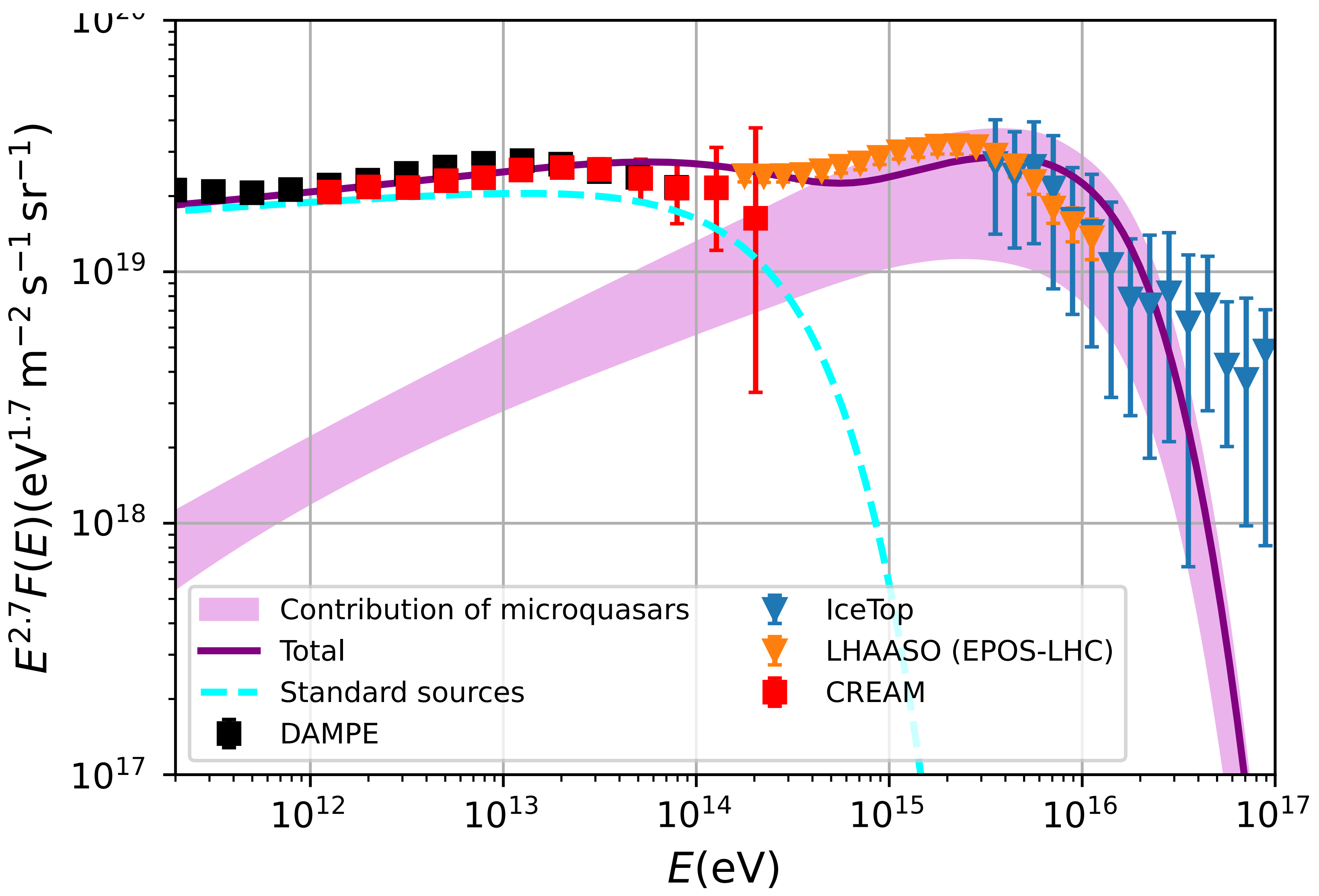
The missing PeVatrons ?

A handful of microquasars with (Hillas) $L_\mathrm{j} \geq 10^{38} \left(\frac{E}{10\,\mathrm{PeV}}\right)^2 \left(\frac{0.1}{\sigma}\right)$ erg/s **e.g. Wang+ 2025**

Zhang+ 2025



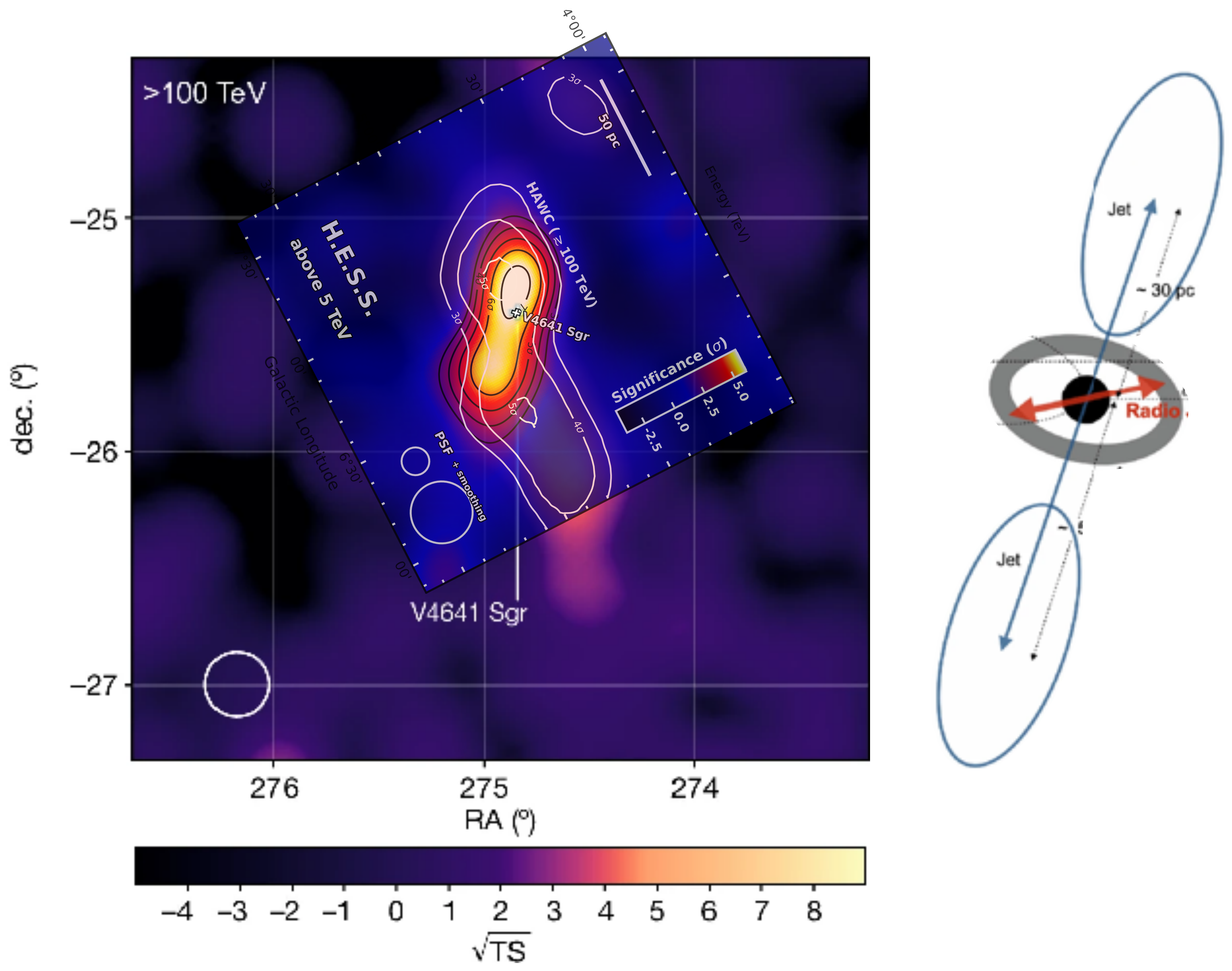
Kaci+ 2025



inflate jet bubbles (Sedov-Taylor) $R_\mathrm{b} = 100 \left(\frac{L_\mathrm{j}}{10^{39}\,\mathrm{erg/s}}\right)^{1/5} \left(\frac{1\,\mathrm{cm}^{-3}}{n}\right)^{1/5} \left(\frac{t}{10^6\,\mathrm{yr}}\right)^{3/5}$ pc **e.g. Ohira 2025**

Large scale UHE emission

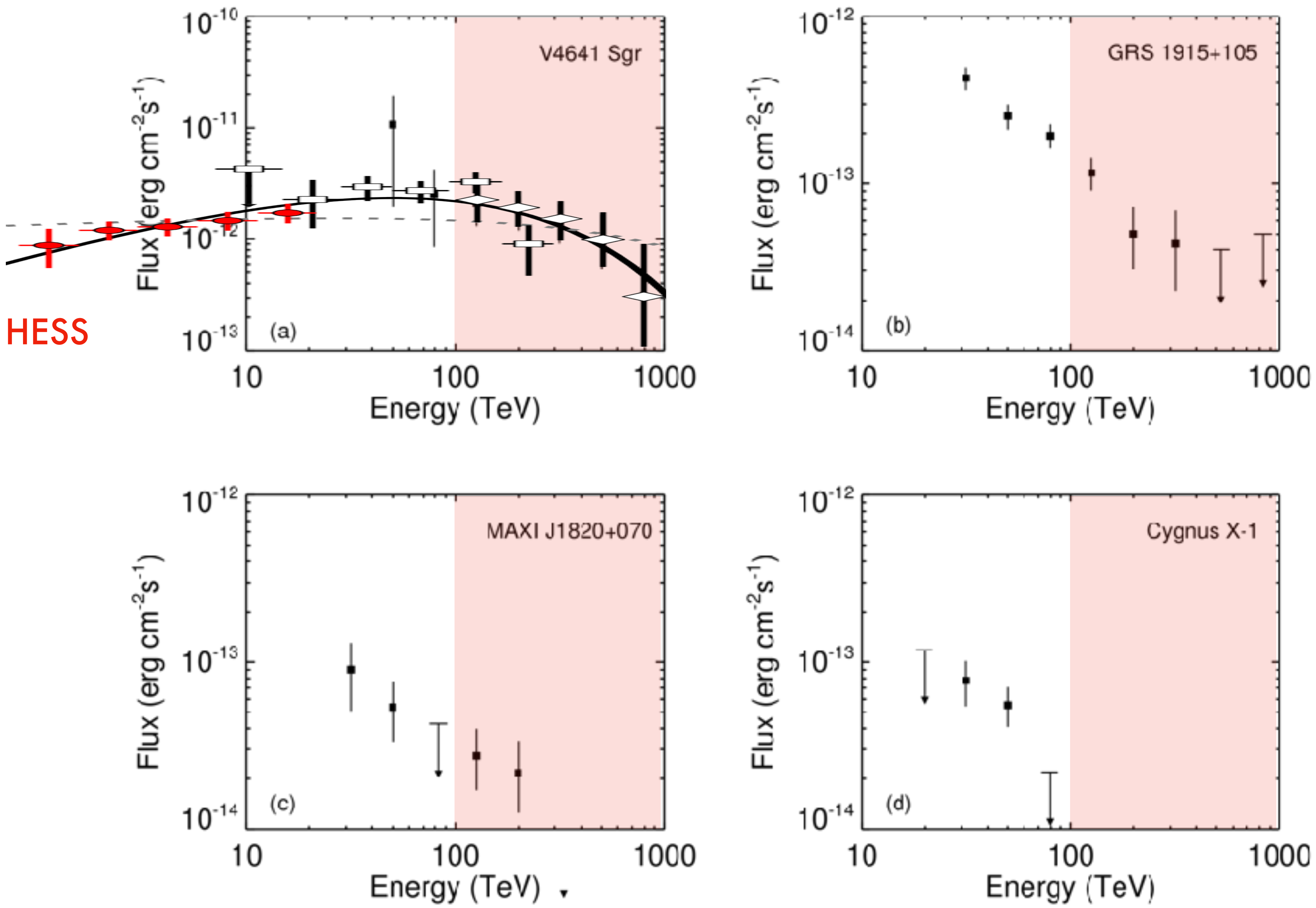
HAWC coll. 2024, HESS coll. 2025



V4641 Sgr, BH with $L_j \sim 10^{39}$ erg/s,

extended emission up to PeV

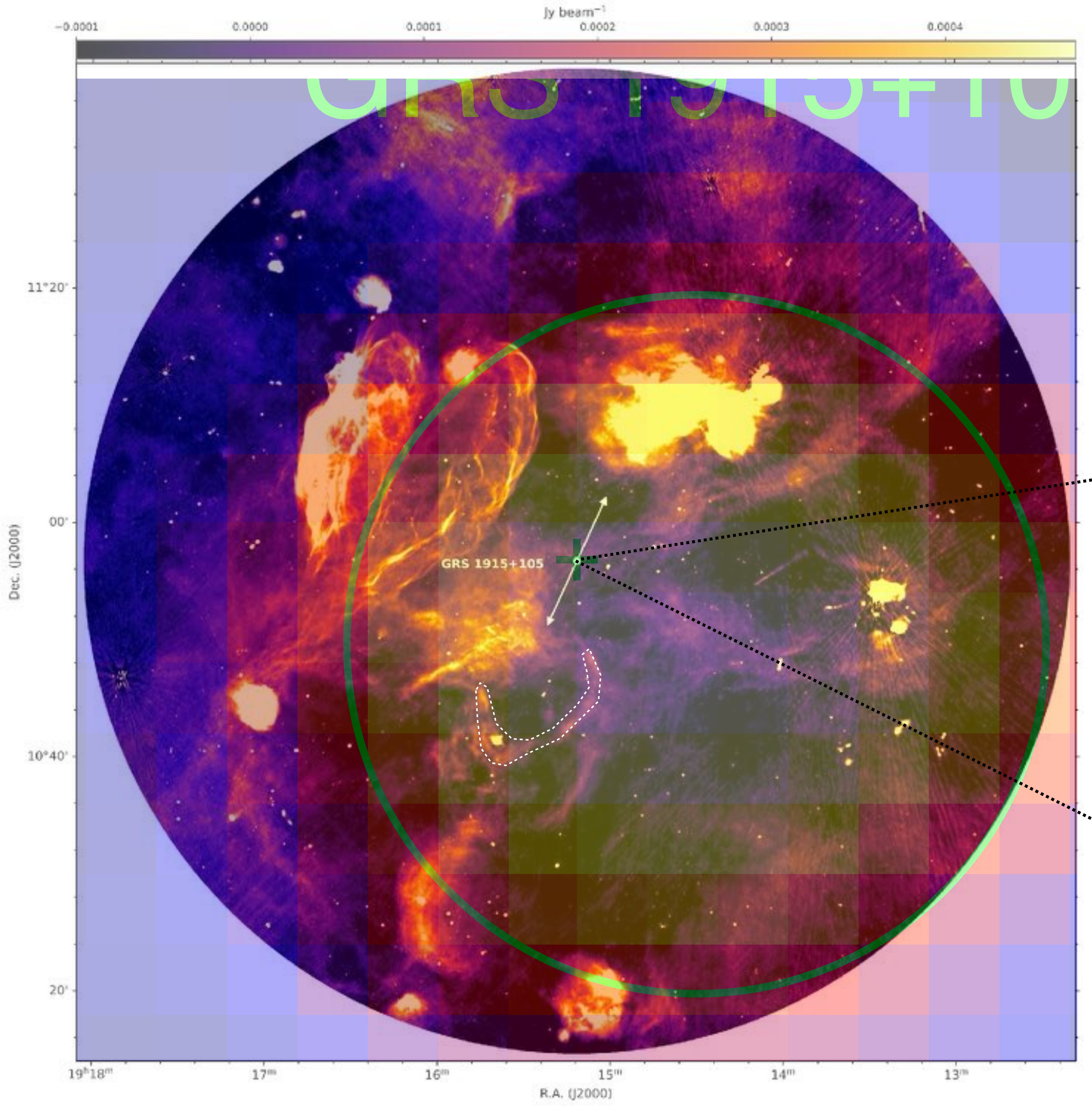
LHAASO coll. 2025



extended on ~50 pc scale in GRS1915, V4641 Sgr, SS433

Other evidence for jet interaction at large scales ?

Motta+ 2025 (MeerKAT+LHAASO)



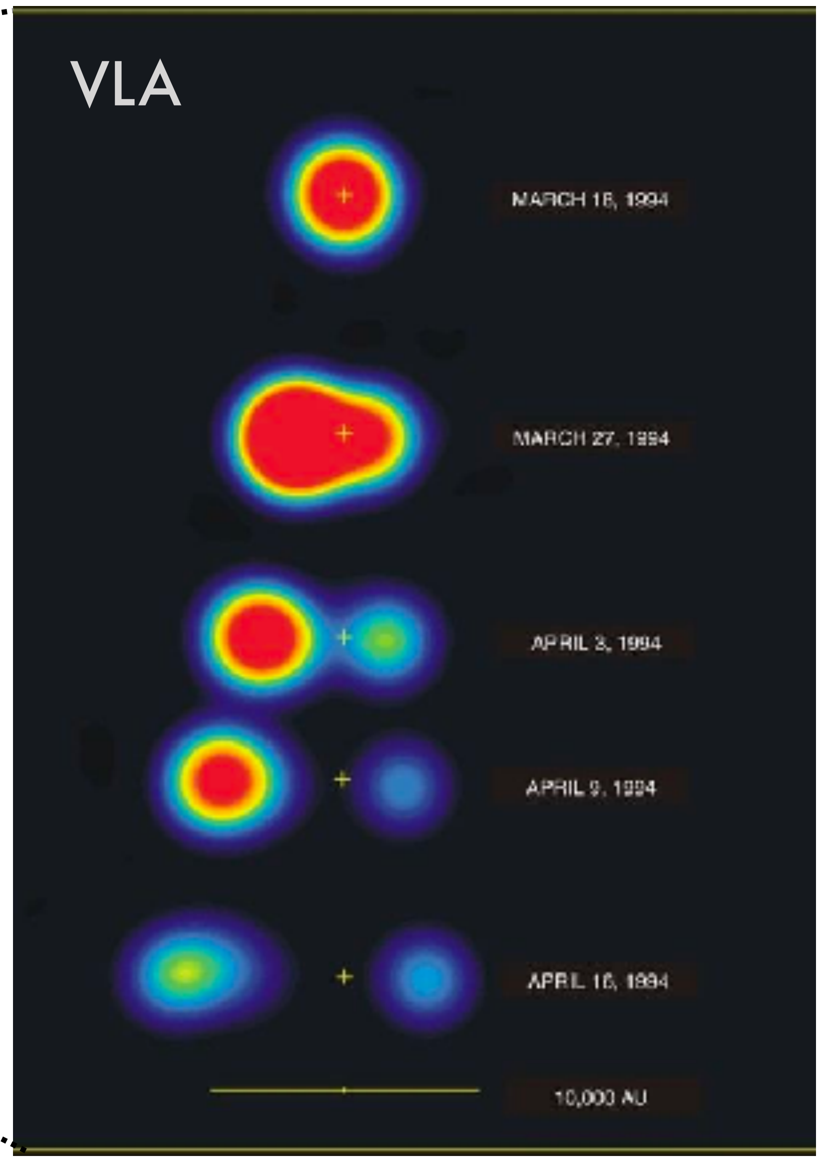
GRS 1915+105

jet calorimetry: $3 \times 10^{37} < L_j < 1.5 \times 10^{39}$ erg/s

jet age: $0.09 \times 10^6 < t < 0.22 \times 10^6$ yr

Motta+ 2025

(see Atri+2025 for Cyg X-1)



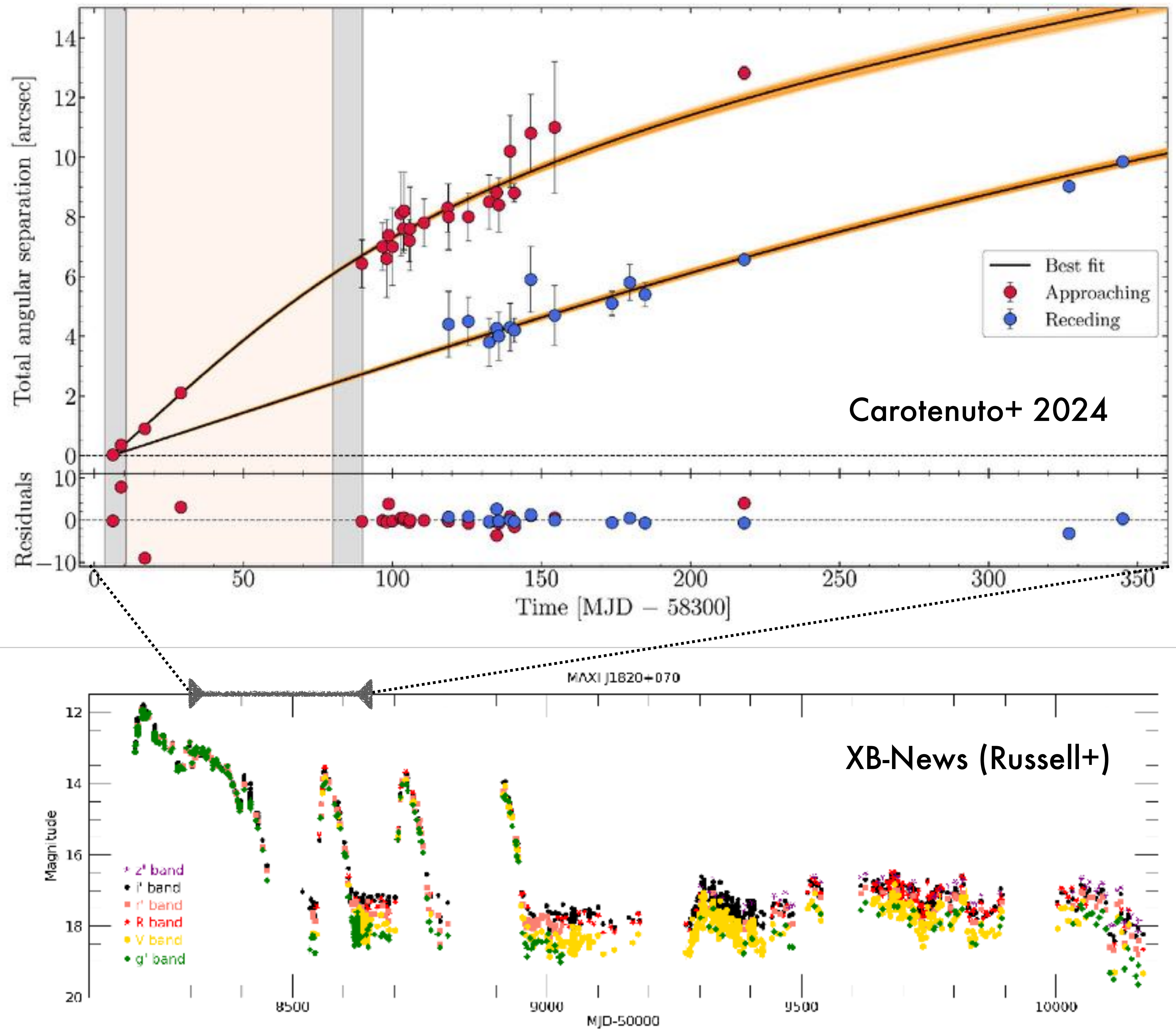
superluminal "blobs"

Mirabel & Rodríguez 1994

Jets at smaller scales

MAXI J1820+070 Deceleration of “blobs” as kinetic energy of jet is transferred to swept-up material at forward shock

~0.1pc



$$E_j \approx 3 \times 10^{46} \left(\frac{n}{1\ \mathrm{cm}^{-3}}\right) \left(\frac{\theta}{1^{\mathrm{o}}}\right)^2 \mathrm{erg} \lesssim 10^{43}\ \mathrm{erg}$$

At sub-pc scales, BH are in environments that are 2–4 orders of magnitude less dense than canonical ISM density unless jet is very narrowly collimated and/or very energetic.

Carotenuto+ 2024

How does this connect with acceleration, energetics, lifetime in large scale jets ?

Summary