

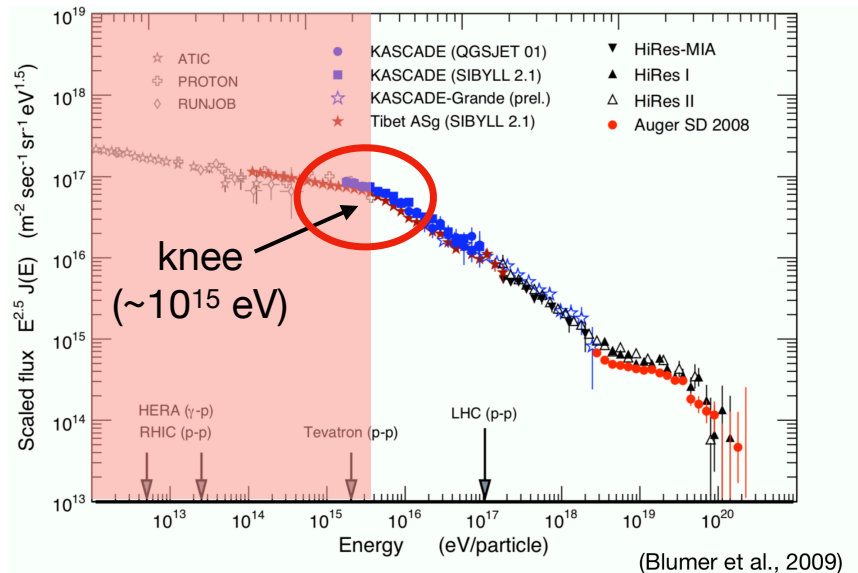
X-ray observation campaigns of Galactic PeVatron candidates

**TeVPA 2026 @Tendo, Yamagata
August 30–September 4, 2026**

Naomi Tsuji (ICRR / University of Tokyo)

**Collaborators: K. Mori, S. Takekawa, A. Mitchell, J. Gelfand, J. Alford, M. Abdelmaguid,
J. Woo, S. Safi-Harb, I. Sander, J. Park, H. An, L. Olivera-Nieto, E. de la Fuente, C.
Tresoldi, G. Ponti, H. Suzuki, M. Lundy, H. Sakemi, R. Kanazashi**

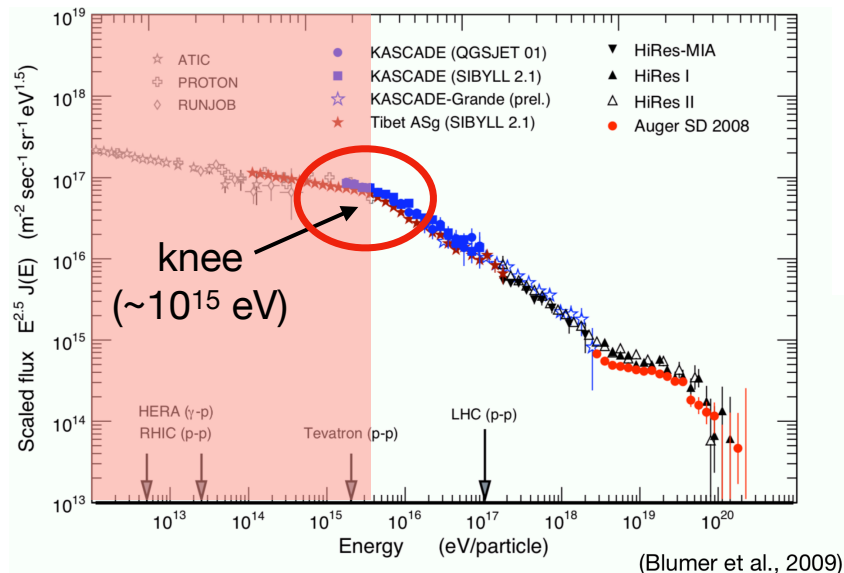
Galactic cosmic rays



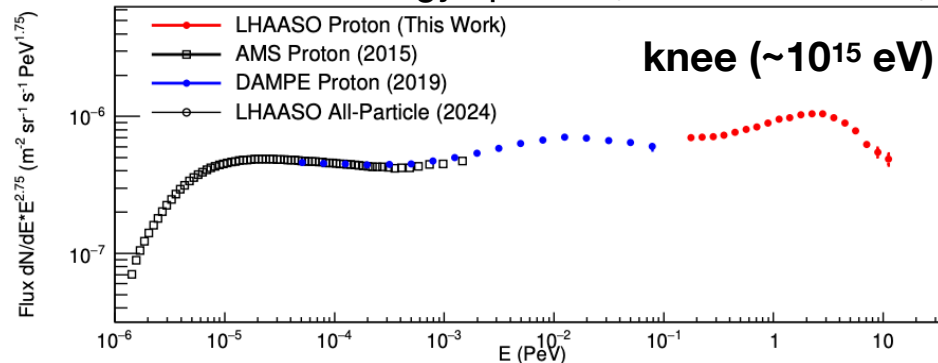
SNRs = primary candidate of Galactic
cosmic-ray accelerators

What about PeVatrons?
Microquasar? Stellar cluster?

Galactic cosmic rays



Latest CR energy spectra (LHAASO Collab. 2025)

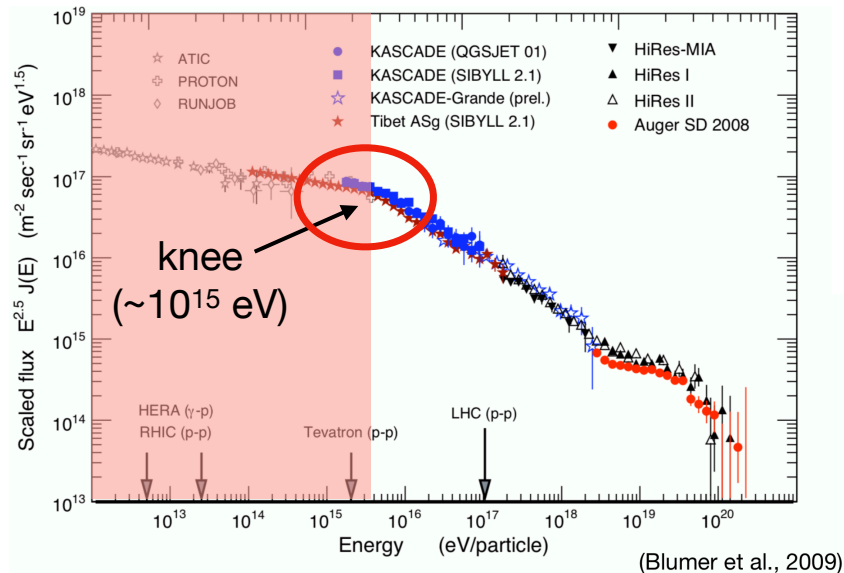


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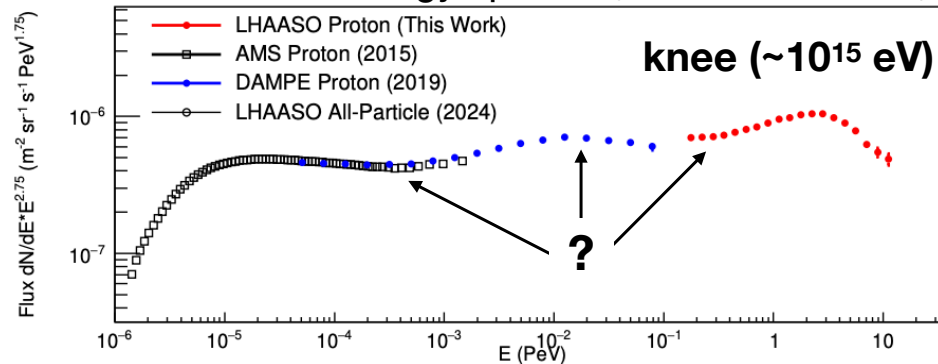
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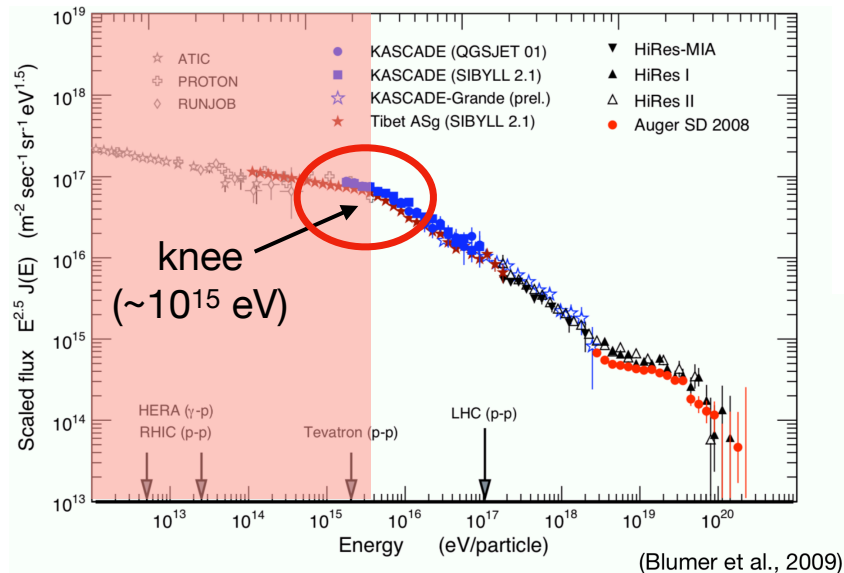


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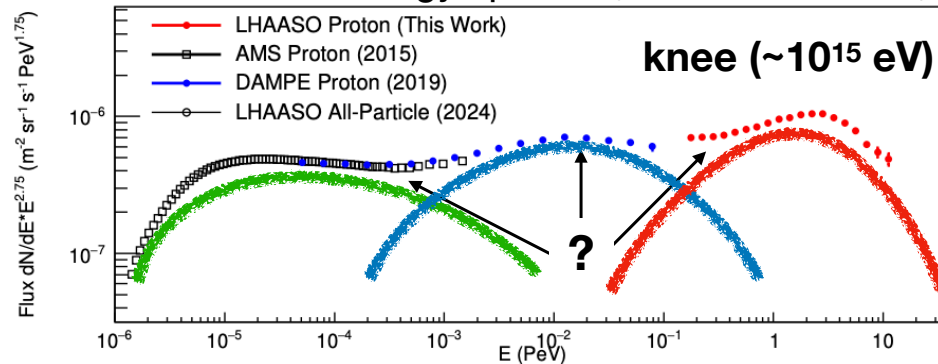
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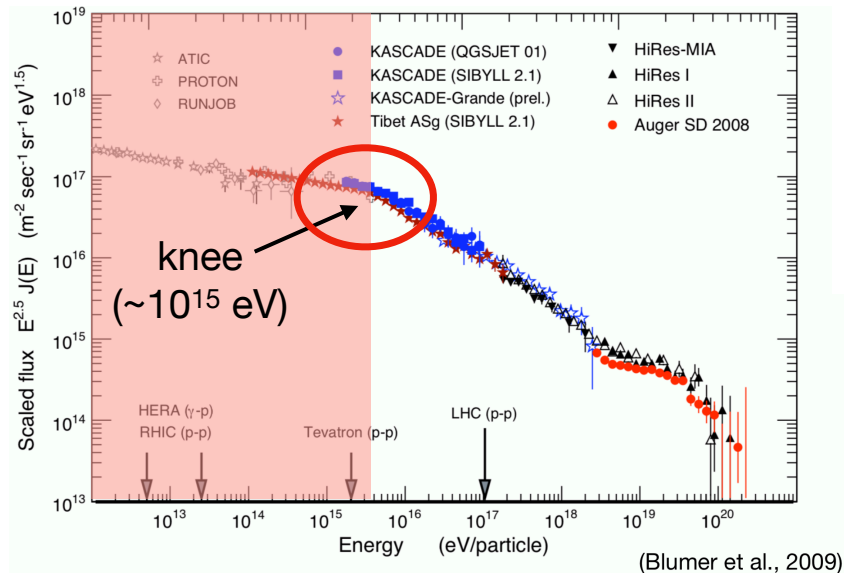


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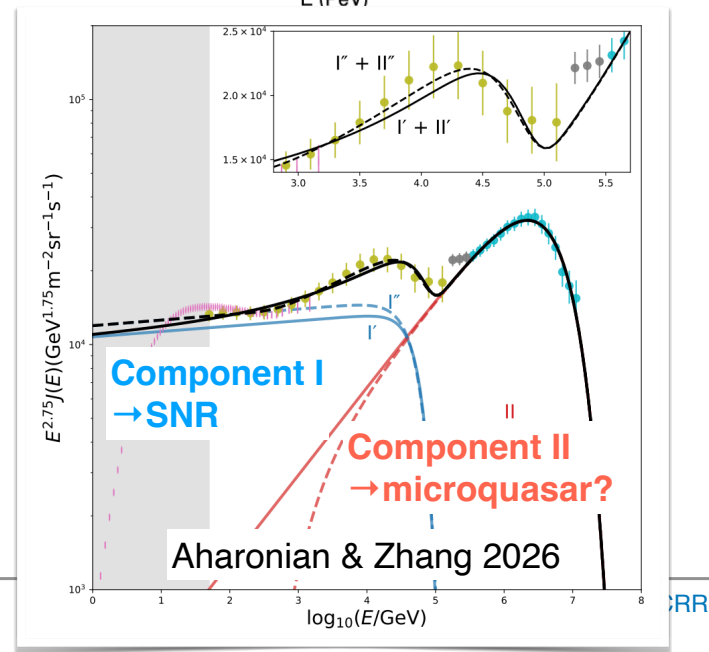
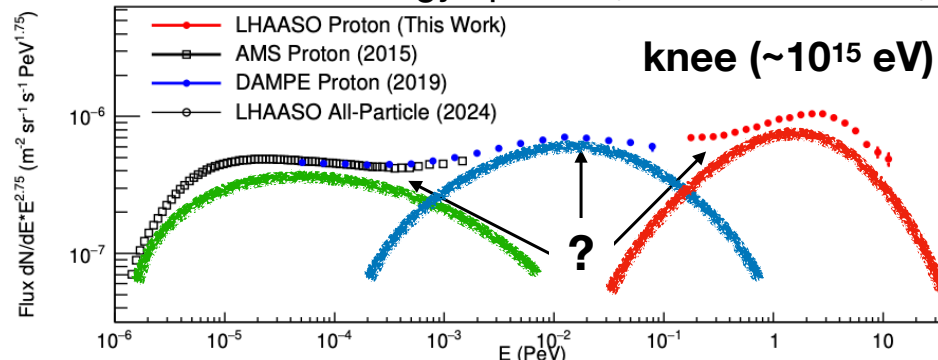
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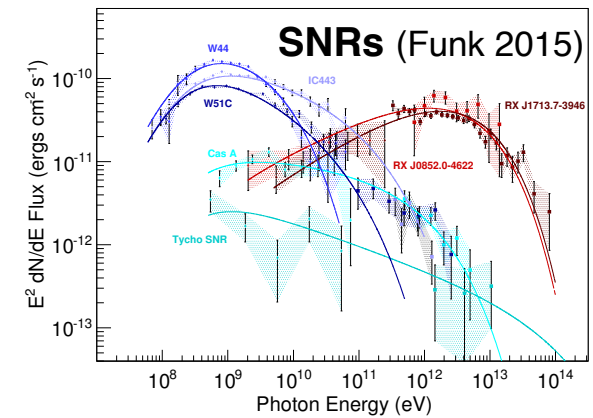
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The study of PeVatrons

TeV gamma-ray astronomy by IACTs

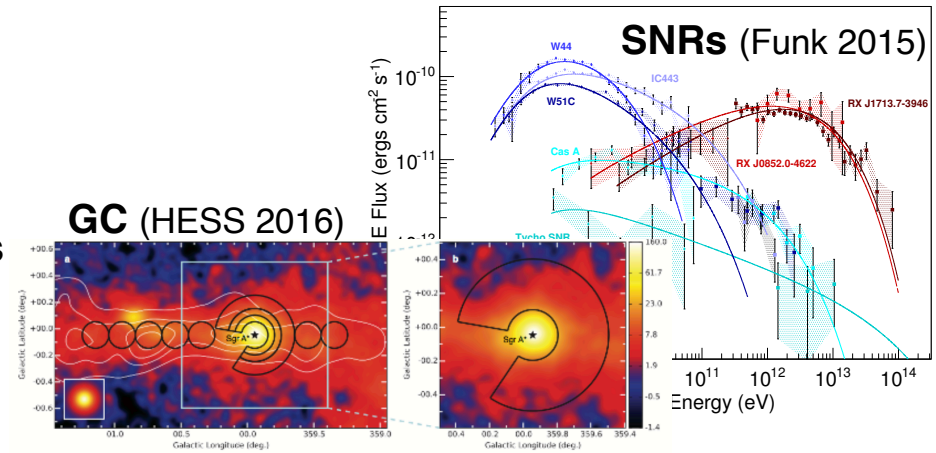
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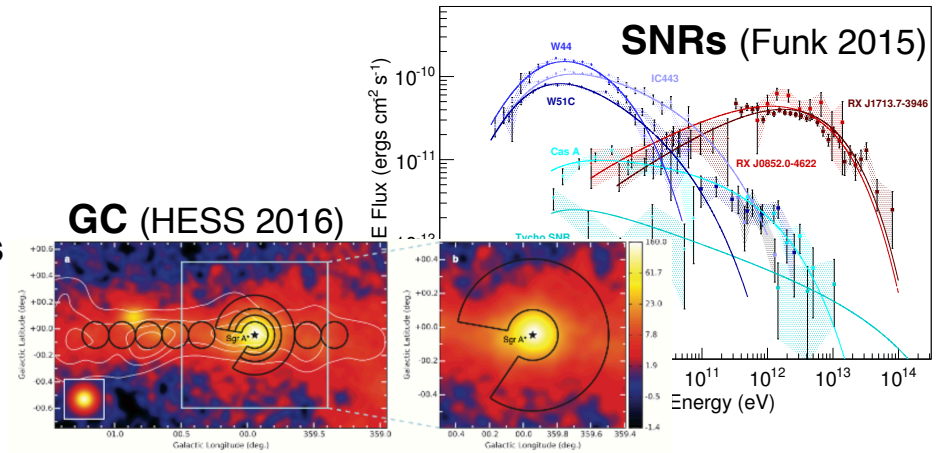


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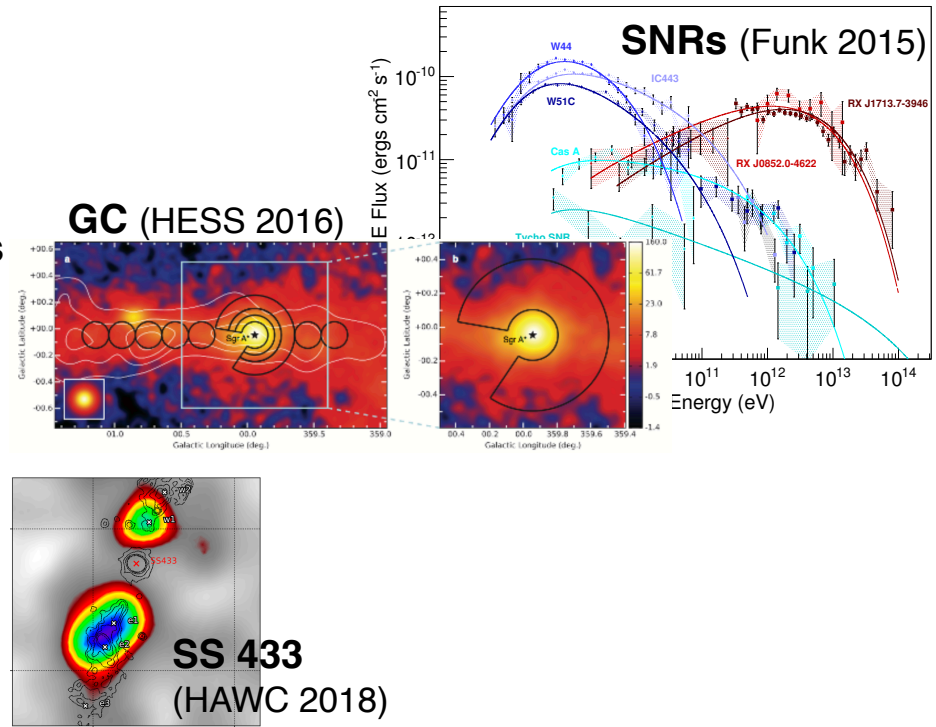
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- >25 TeV gamma rays from microquasar SS 433 (HAWC Collab. 2018)



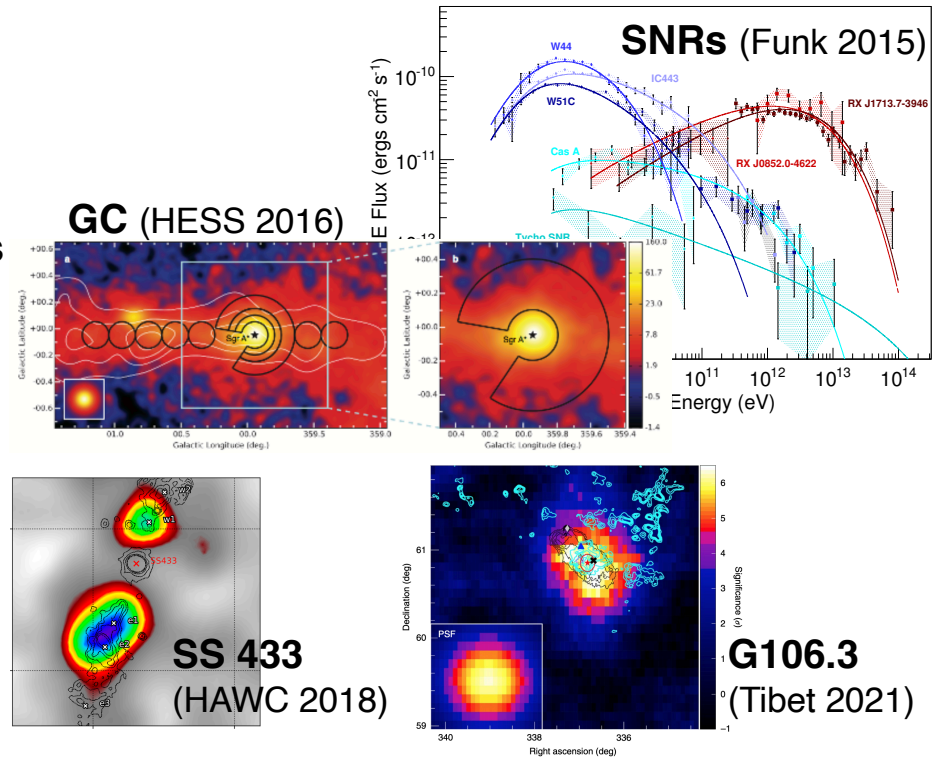
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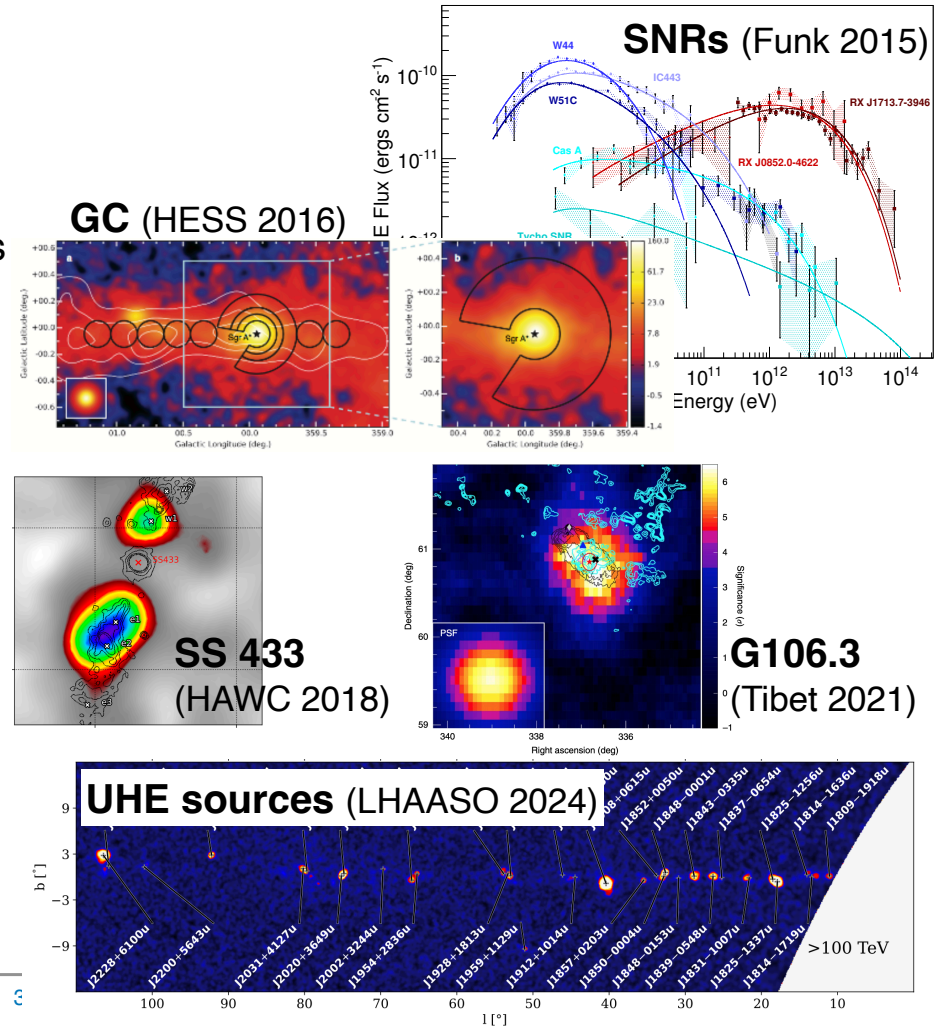
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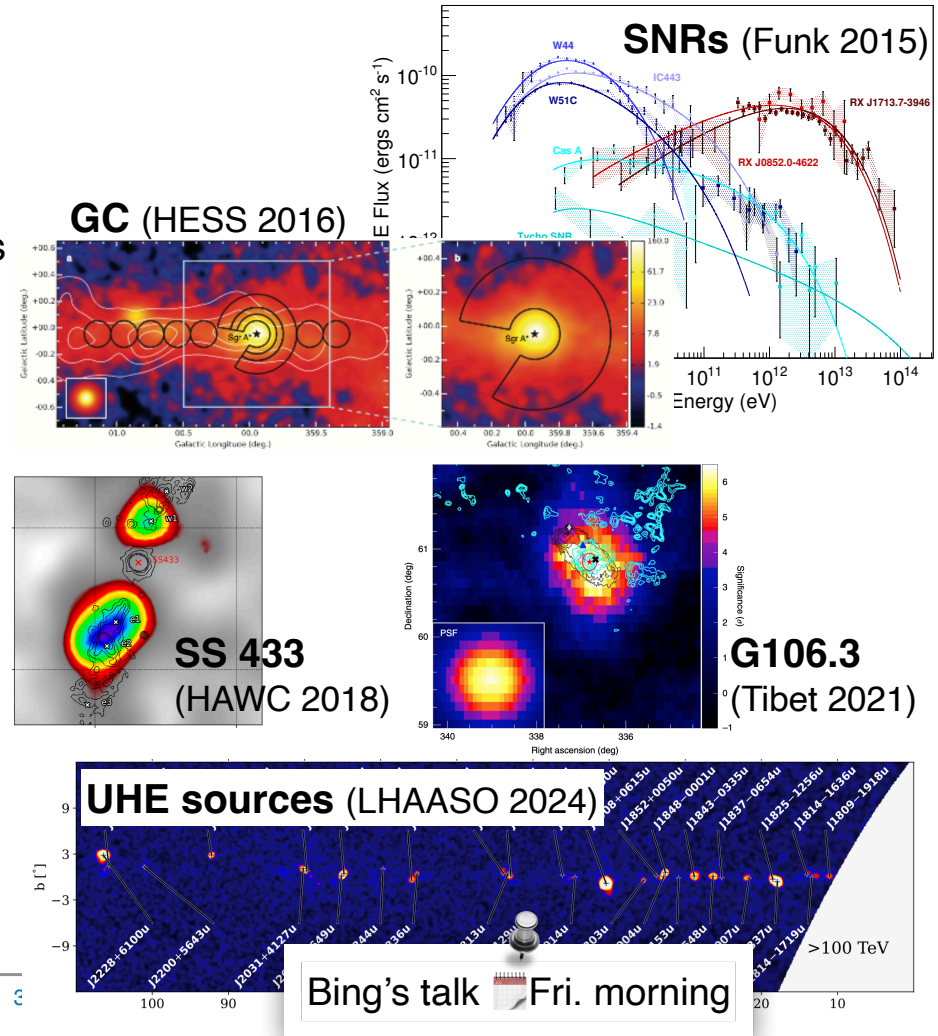
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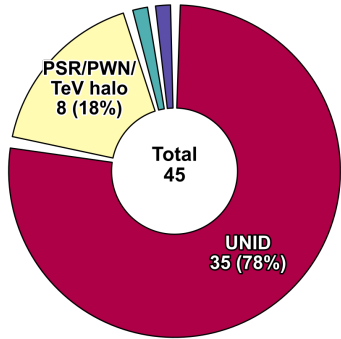
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Current status of the PeVatron study

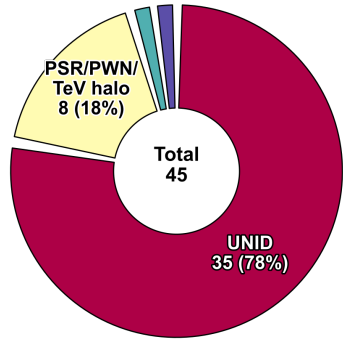
Source breakdown of
LHAASO's UHE sources



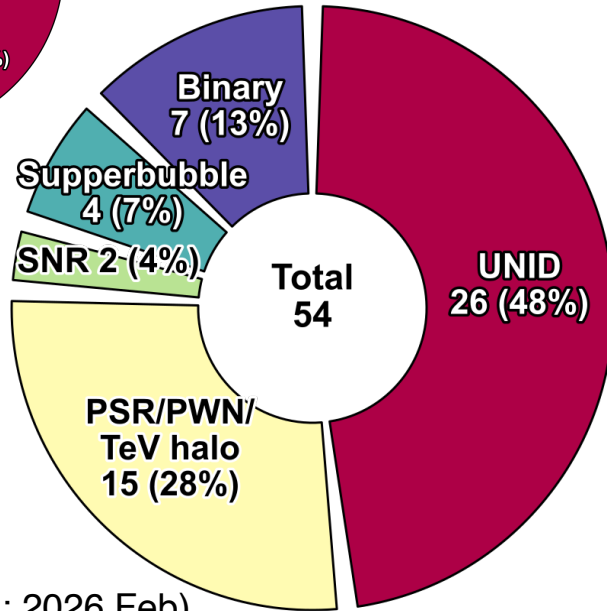
(43 sources;
2023 May)

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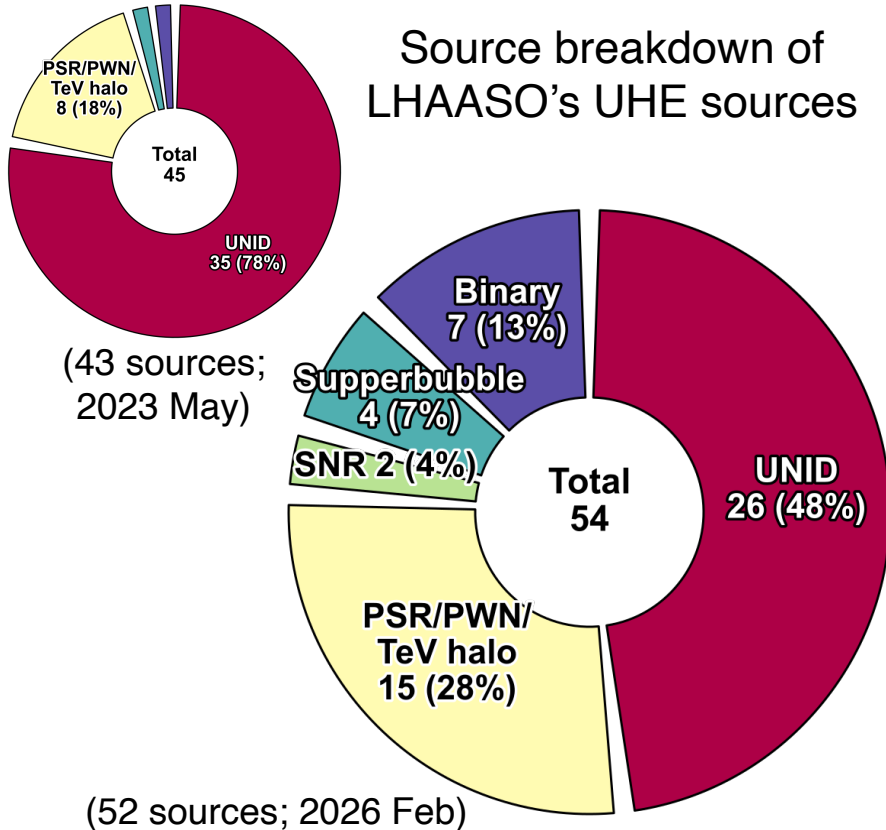
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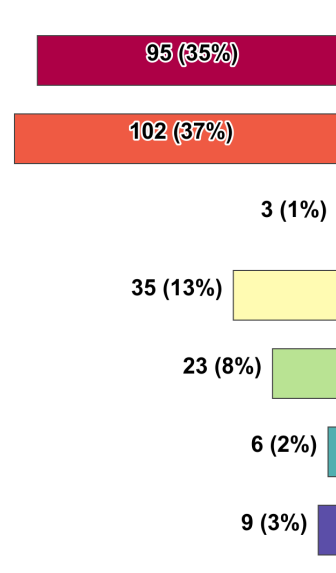
(52 sources; 2026 Feb)

Current status of the PeVatron study

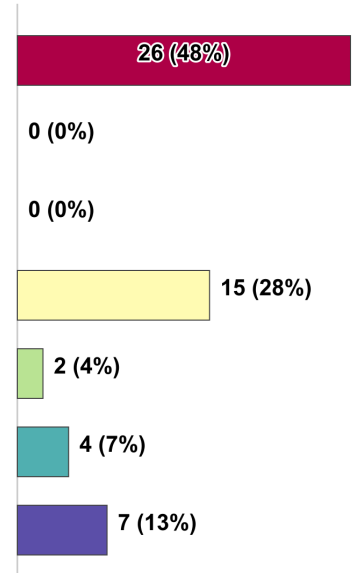
Source breakdown of LHAASO's UHE sources



TeVatron (273)

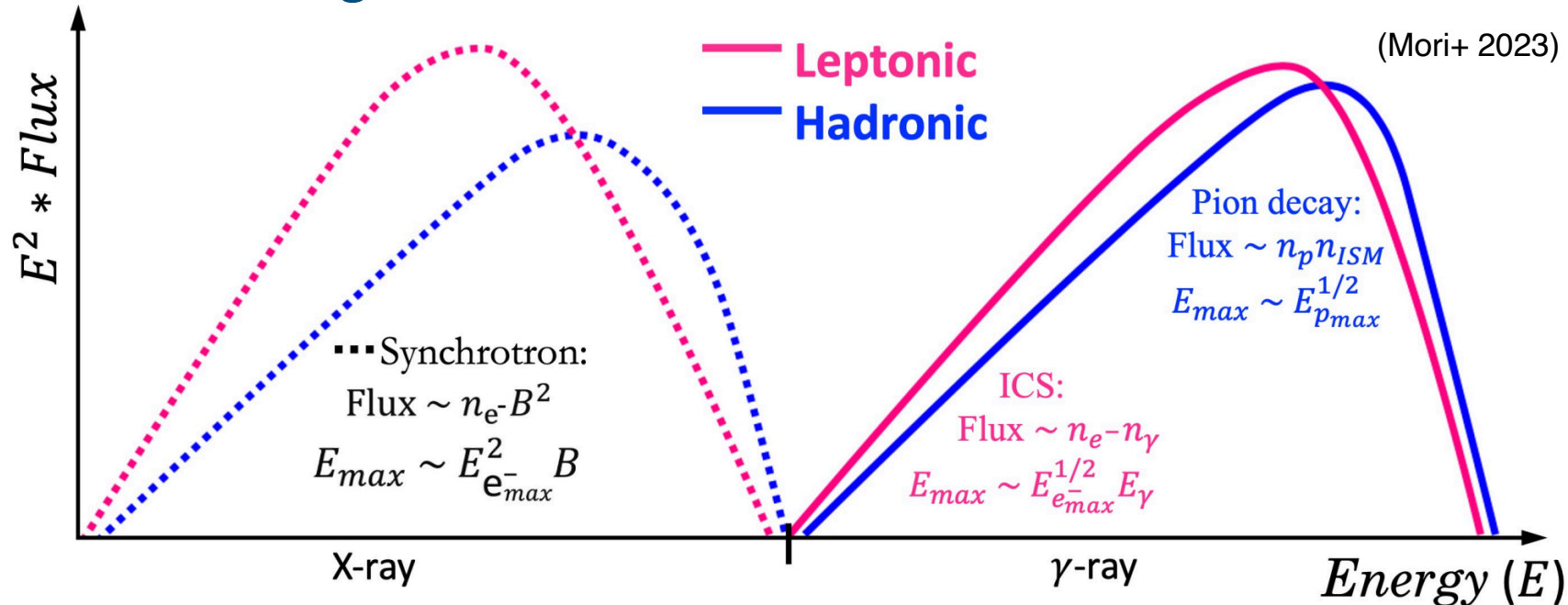


PeVatron (54)



I will cover microquasars and unIDs in this talk
(SNRs and PWNe if I have time...)

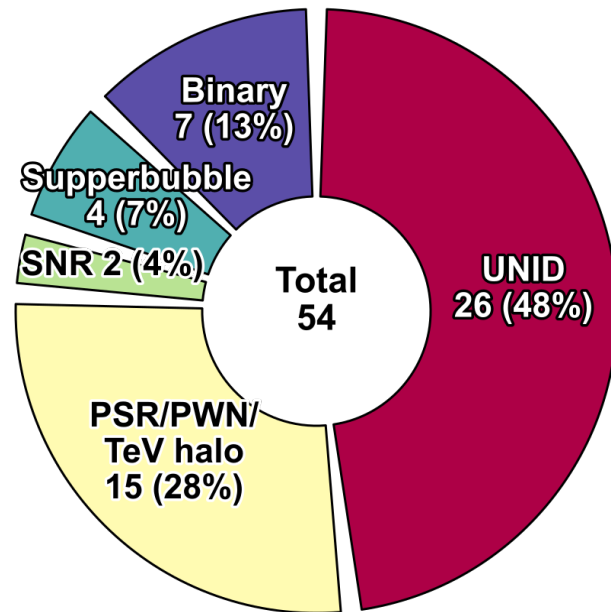
Multiwavelength observation



Radio and X-ray observations

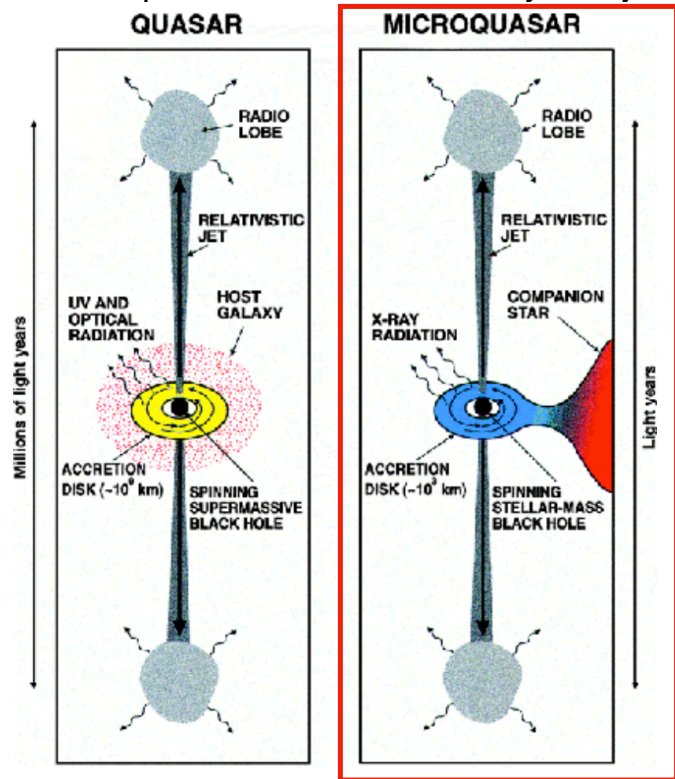
- Distinguish leptonic vs hadronic
- Constrain E_{max} and B-field
- Identify acceleration sites with better angular resolution

Microquasars

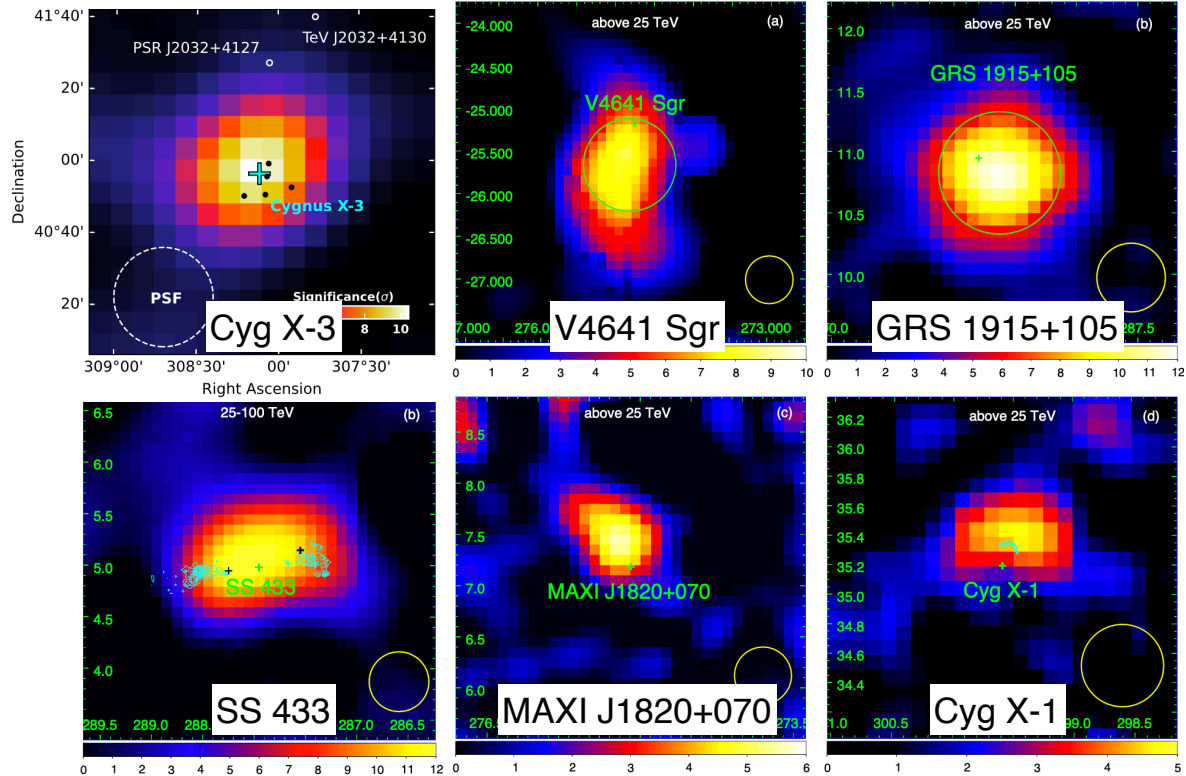


Microquasars at VHE-UHE gamma rays

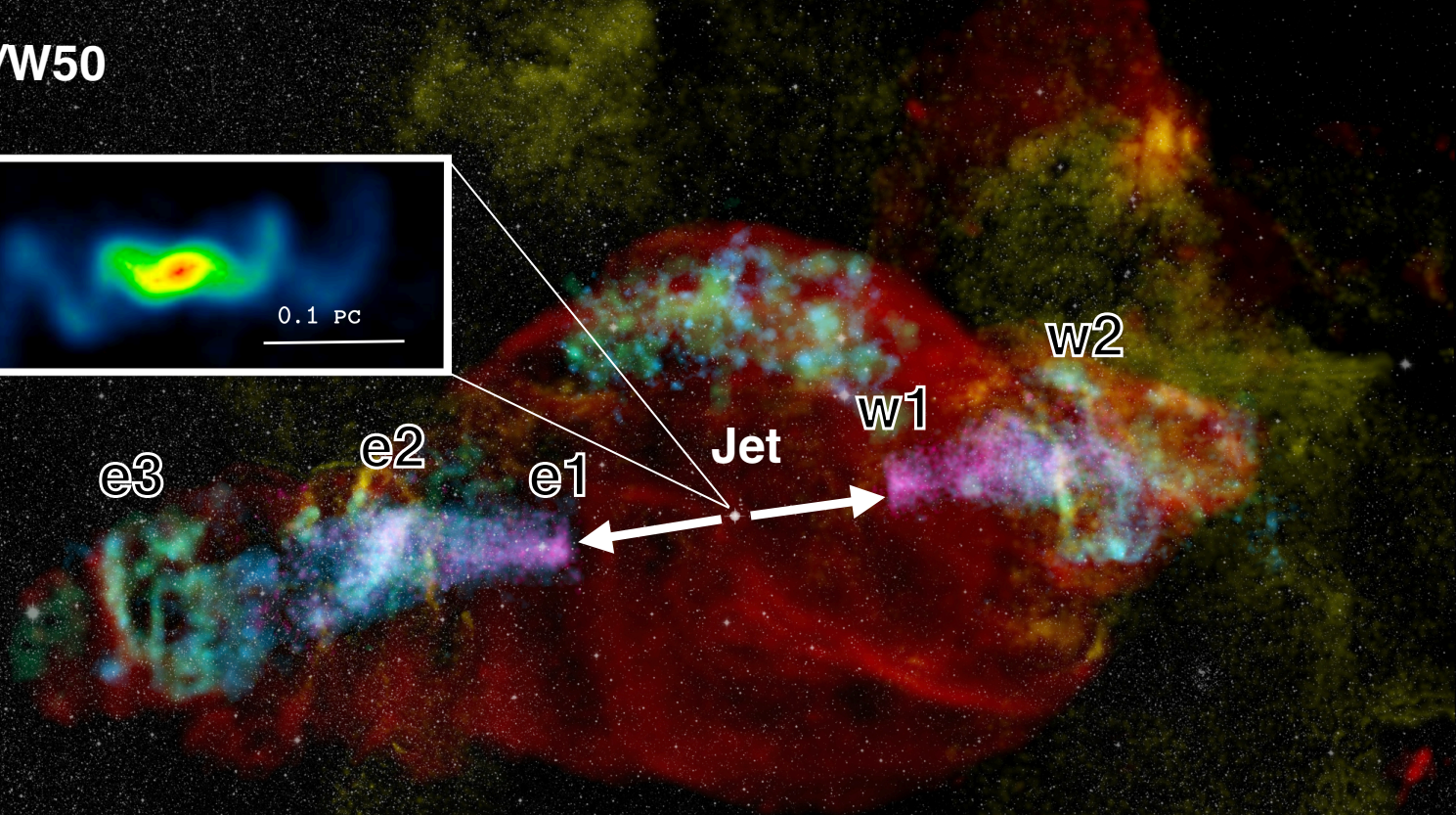
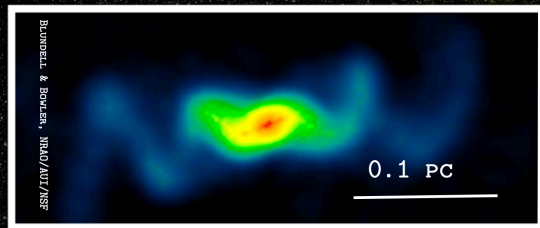
Microquasar = “BH or NS binary with jet”



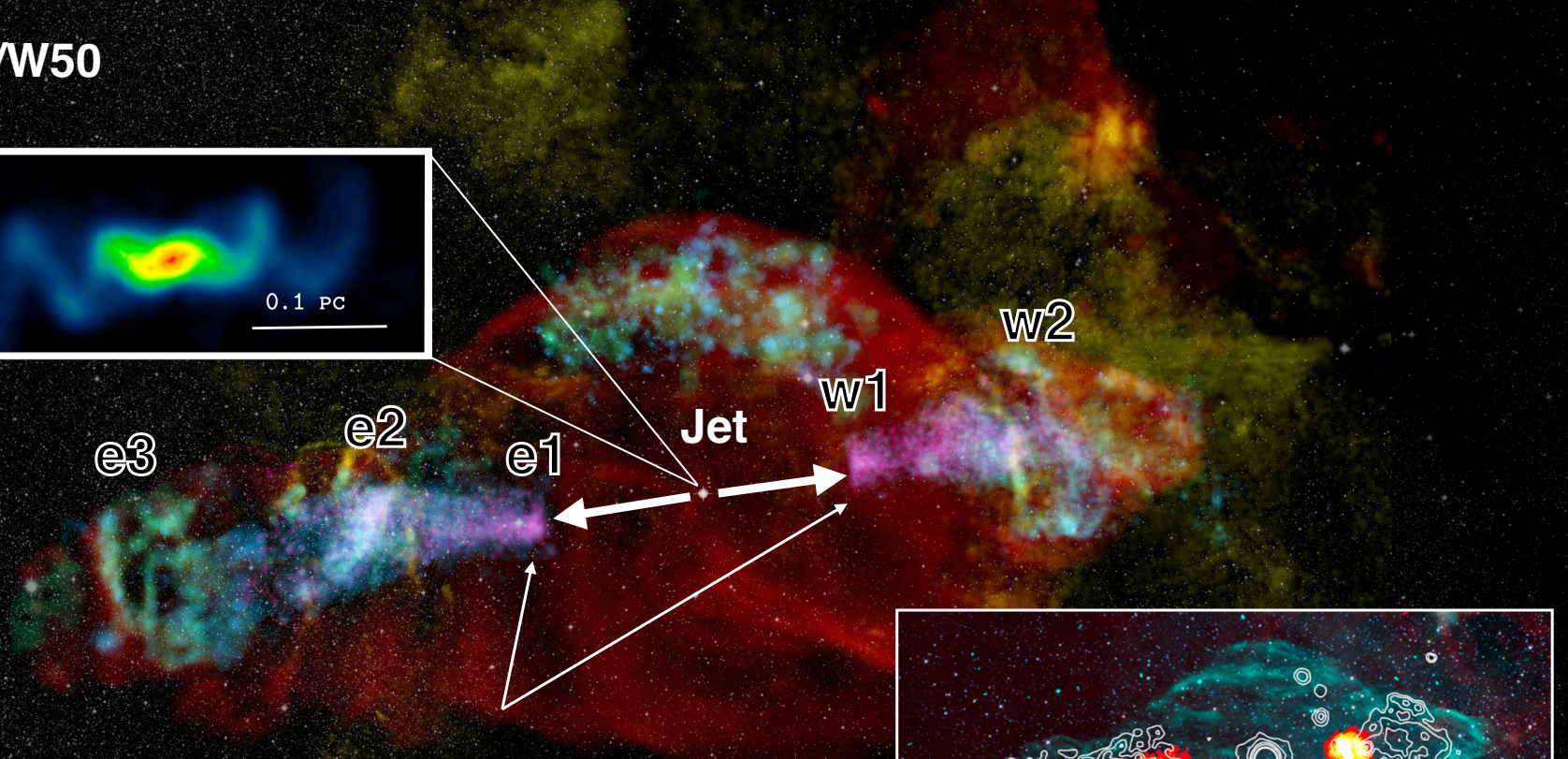
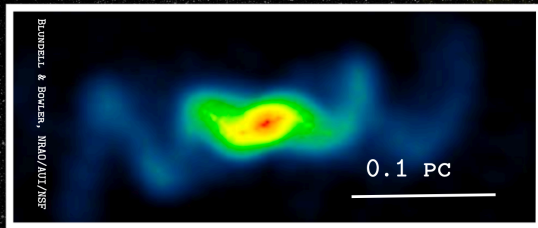
(LHAASO Collab. 2024, 2025)



SS 433/W50

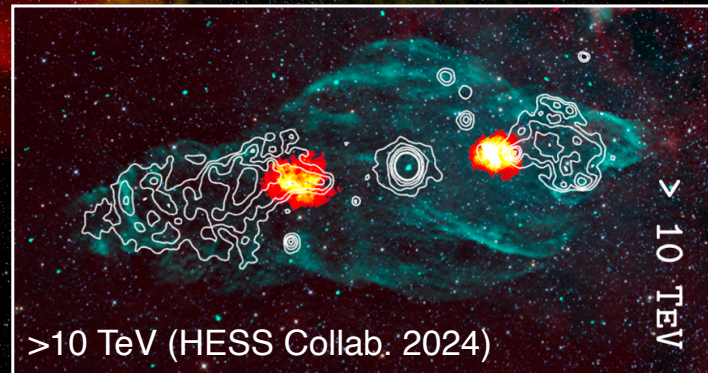


SS 433/W50

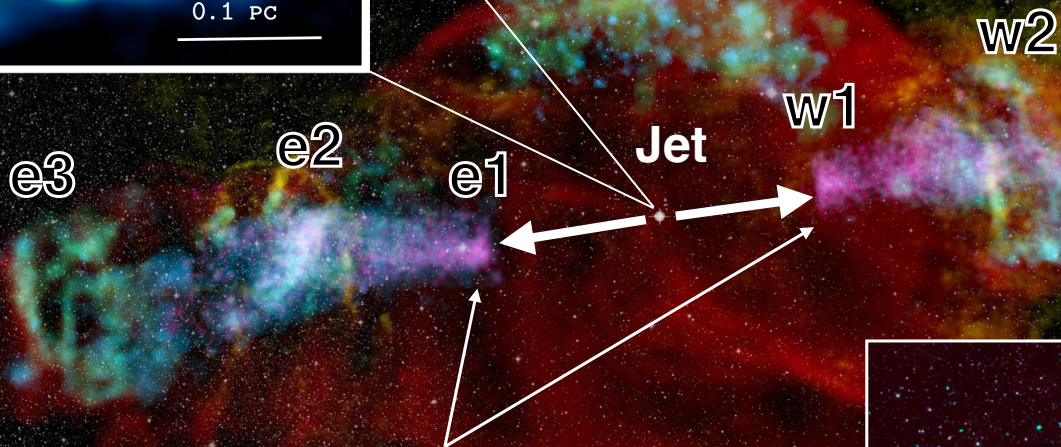
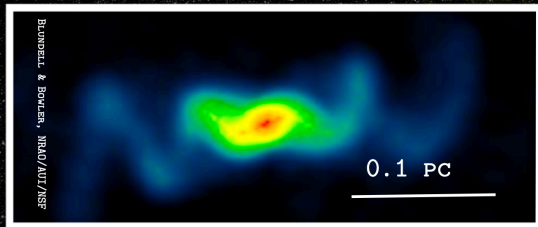


Particle acceleration sites
(re-collimation/termination region?)

- ✓ Nonthermal hard X-rays
- ✓ Higher-energy gamma rays



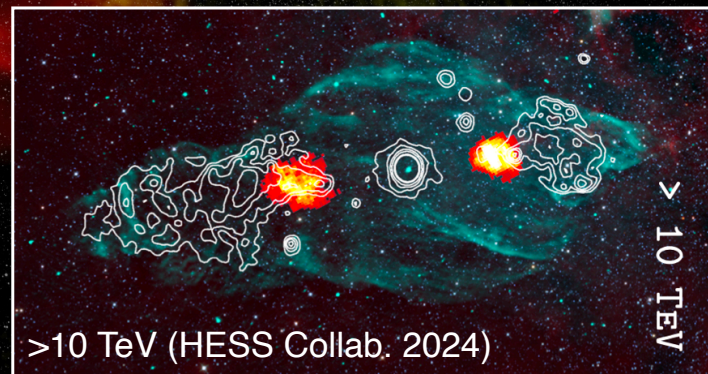
SS 433/W50



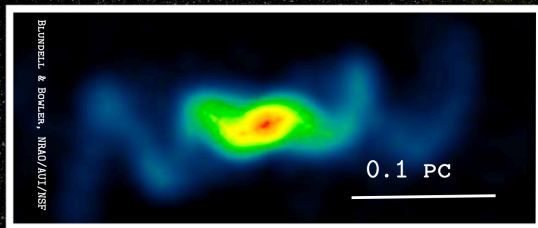
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Jet-MC interaction
(Sakemi+ 2026)



SS 433/W50



Advection & cooling

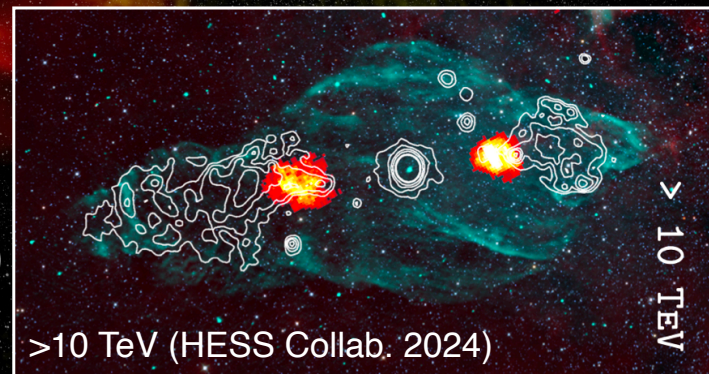
- ✓ X-ray and gamma-ray spectral softening

Jet-MC interaction
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Particle acceleration sites

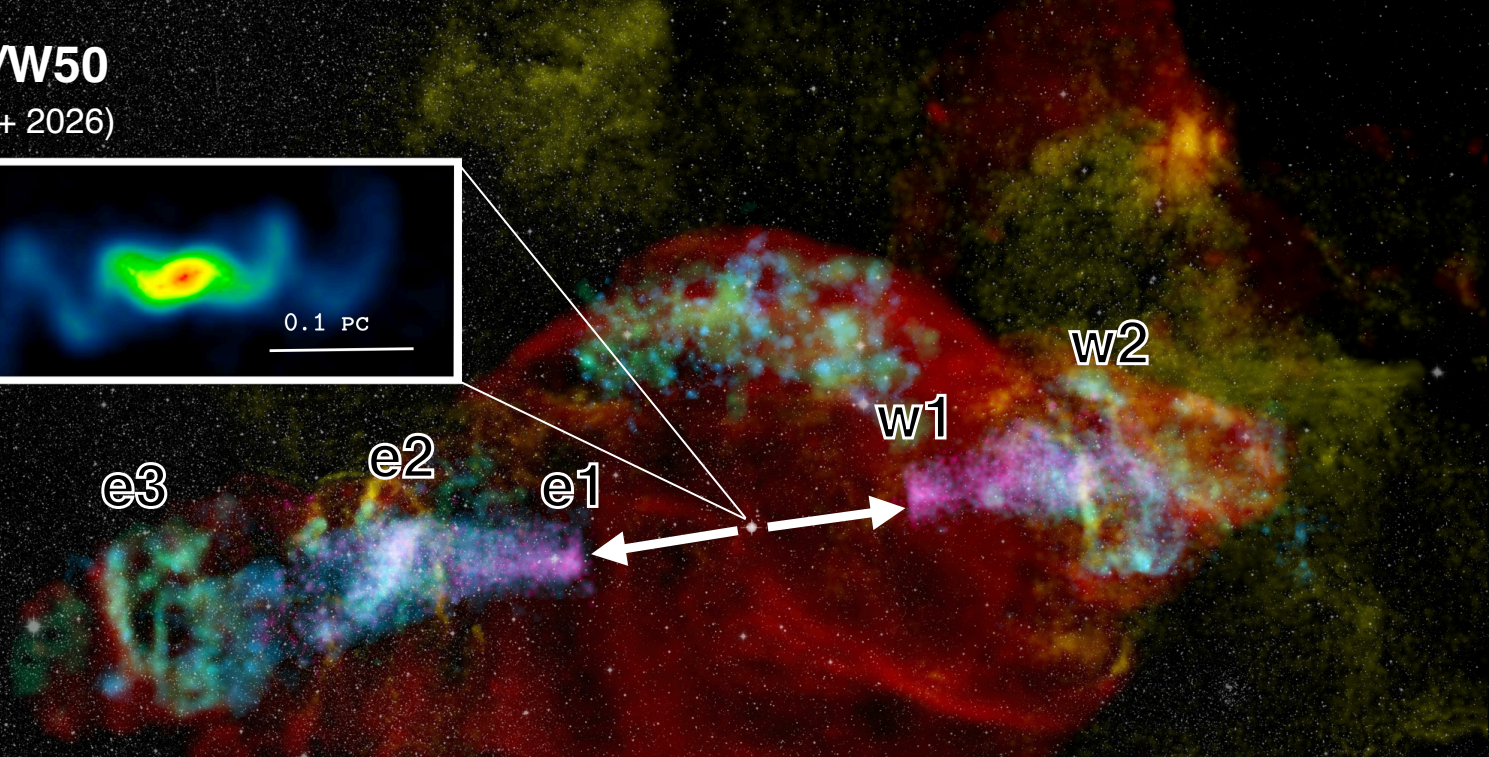
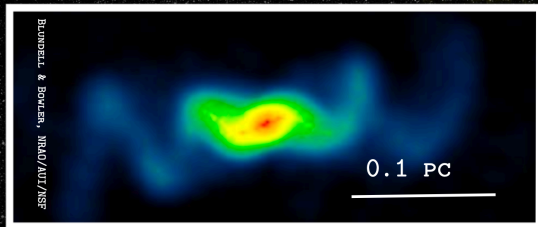
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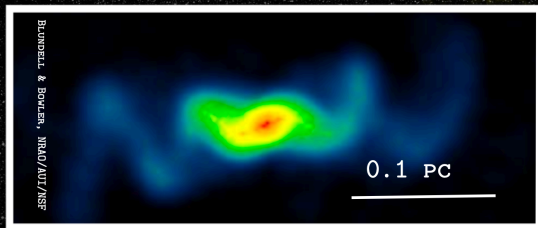
(Mac Intyre+ 2026)



- NuSTAR: no cutoff up to 30 keV at e1/w1 (Safi-Harb+ 2022)
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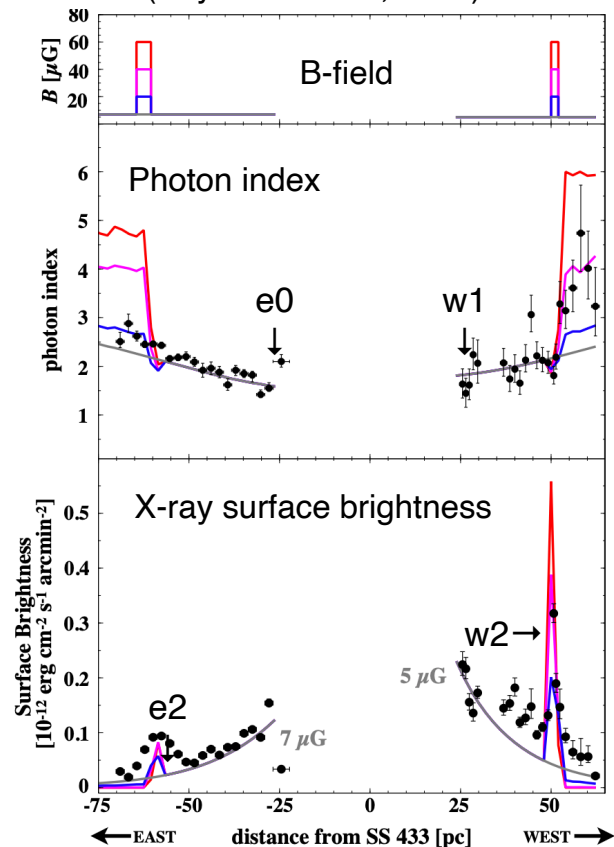
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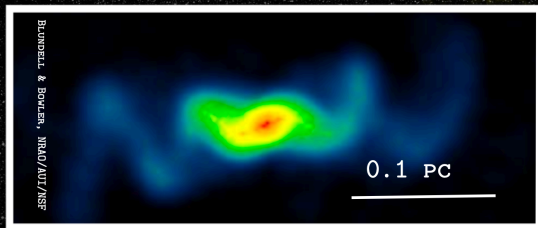
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X-ray spectral profile along the lobes (Kayama+ 2022; 2025)



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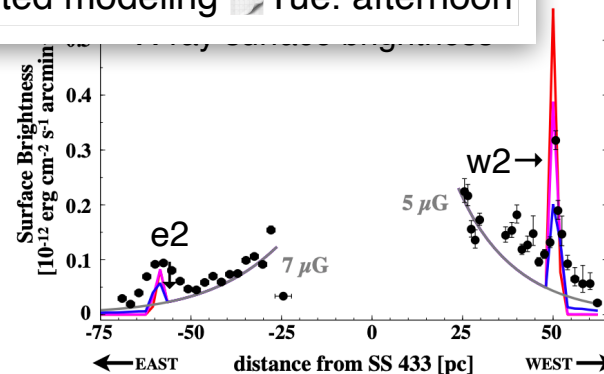
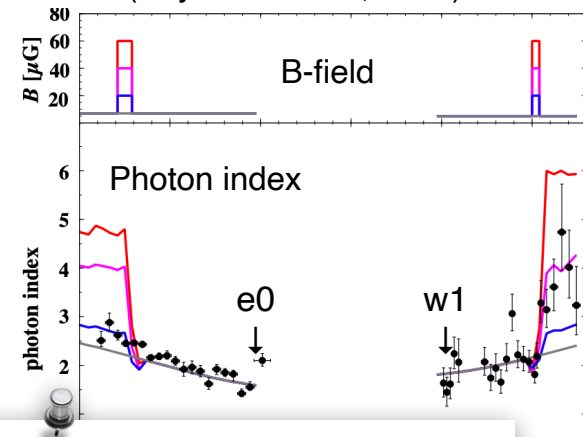
(Mac Intyre+ 2026)



Tatsuki's talk for updated modeling 📅 Tue. afternoon

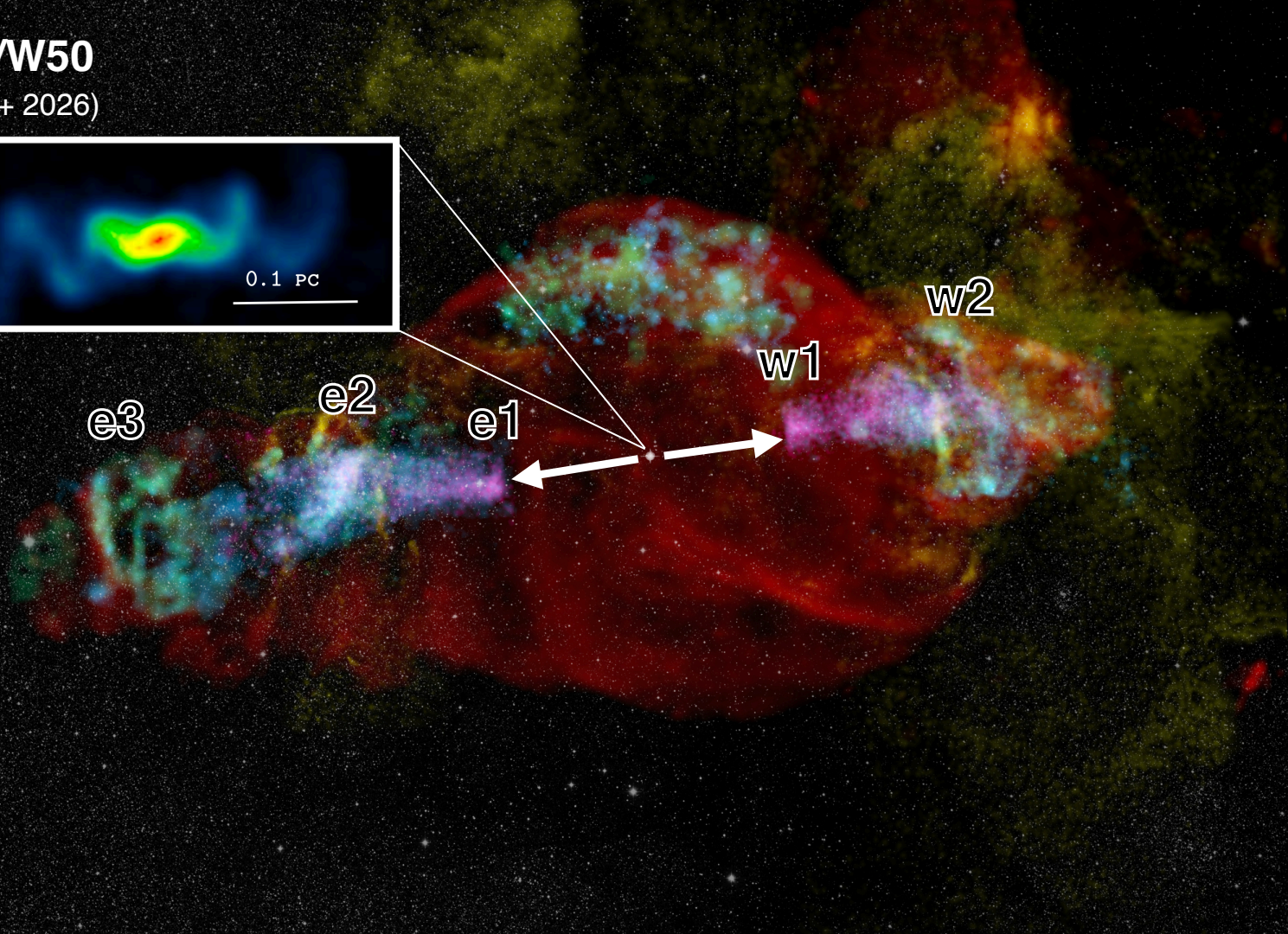
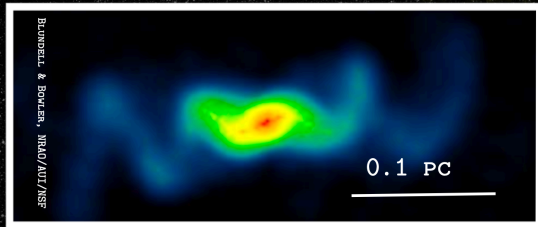
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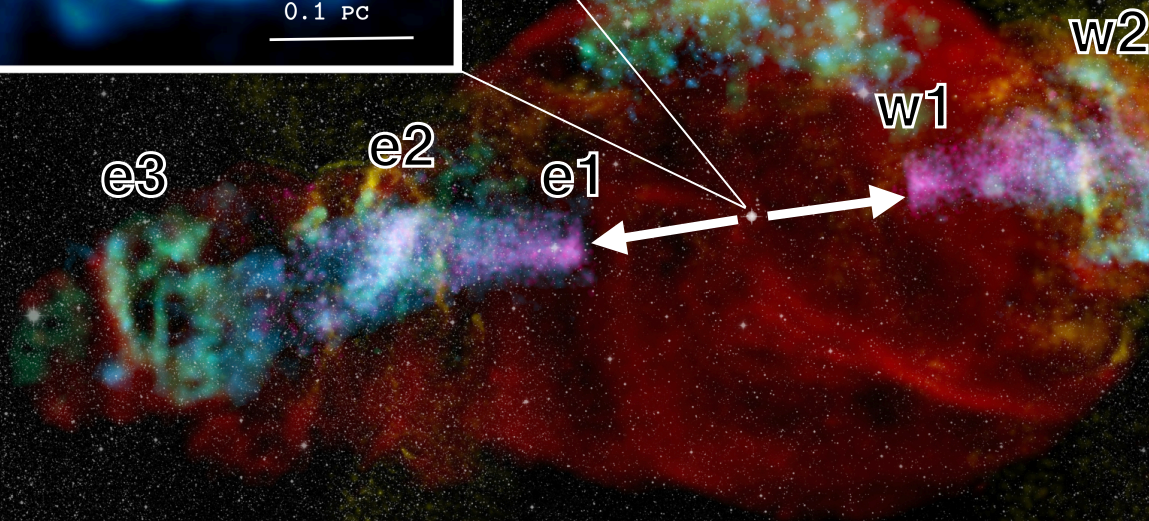
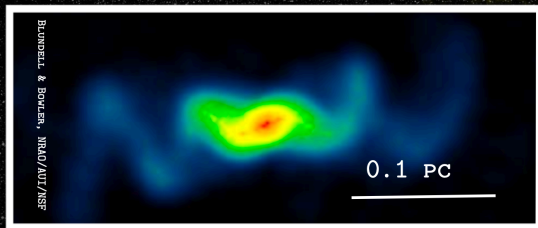
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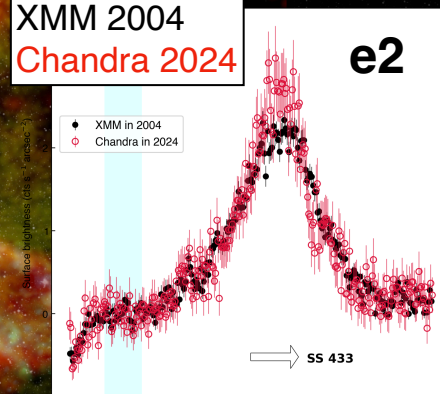
(Mac Intyre+ 2026)

- ~30% flux decrease over 20 yrs at w1-w2
- ~30% flux **increase** over 20 yrs at e2



XMM 2004

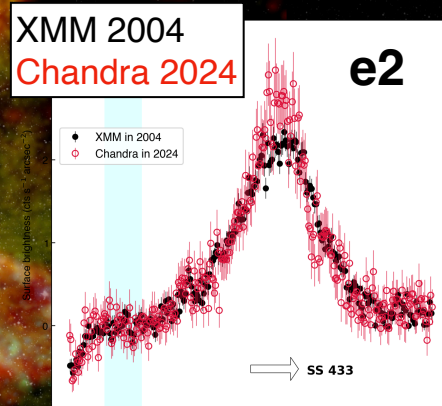
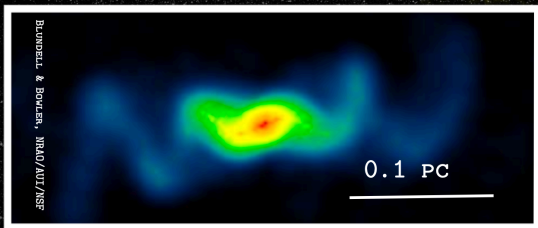
Chandra 2024



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(Mac Intyre+ 2026)

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Our extensive X-ray survey:

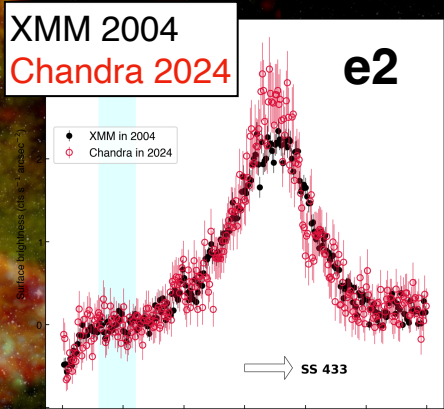
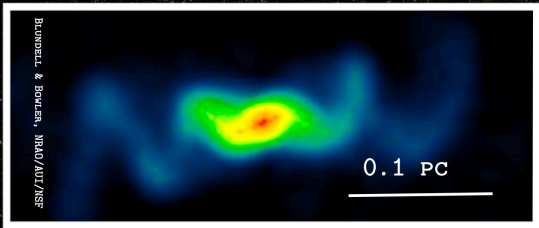
5D data will be obtained
(X, Y, E, t, polarization)

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IXPE	—	2026 new	Kaaret+ 2024	2025 new	—
XRISM/Xtend	—	—	Suzuki+ in prep. new		—

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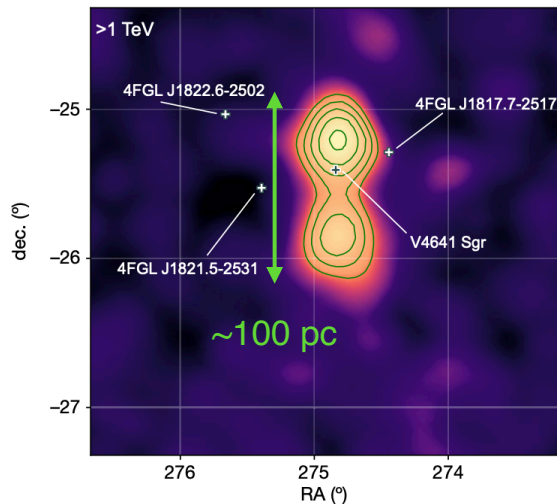
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IXPE	Hiromasa's talk for the study with Xtend Tue. afternoon				
XRISM/Xtend	—	—	Suzuki+ in prep. new		—

2nd example of VHE gamma-ray microquasar: V4641 Sgr

V4641 Sgr

- 6.4 M_{sun} BH and 2.9 M_{sun} B9III star
- Discovered in 1999 during outburst ($L_X \sim 10^{39}$ erg/s)

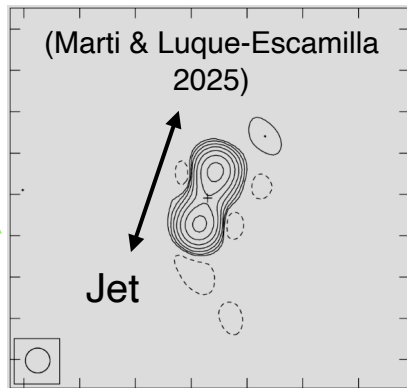
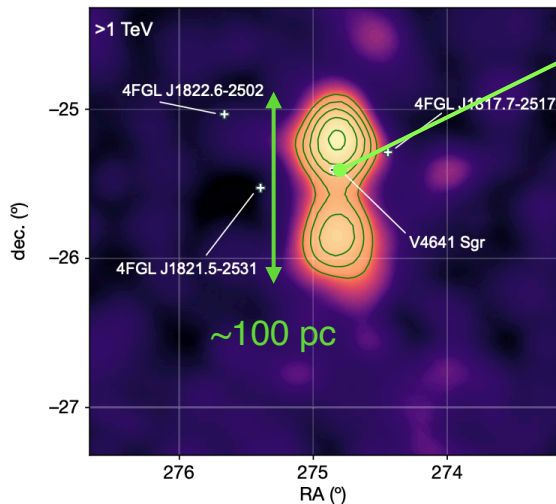


(HAWC Collab. 2024; LHAASO
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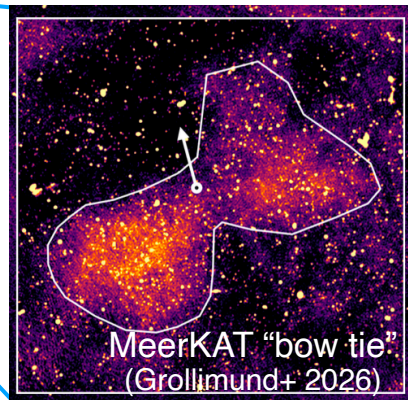
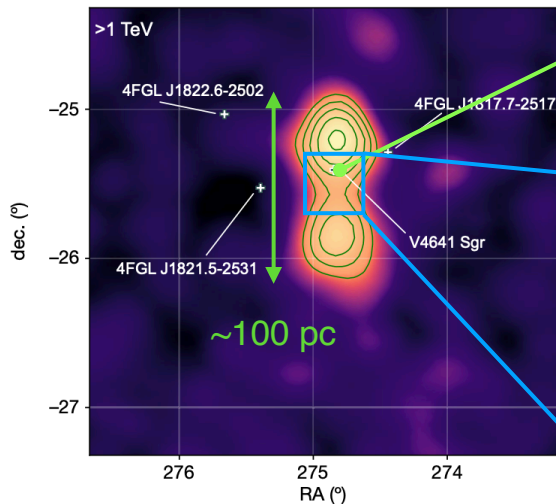
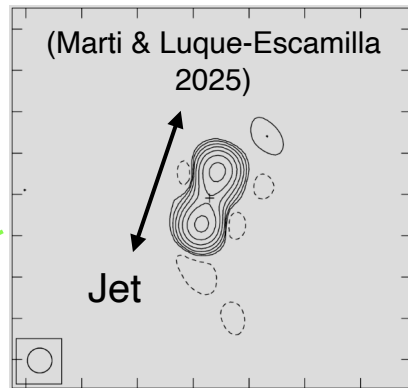


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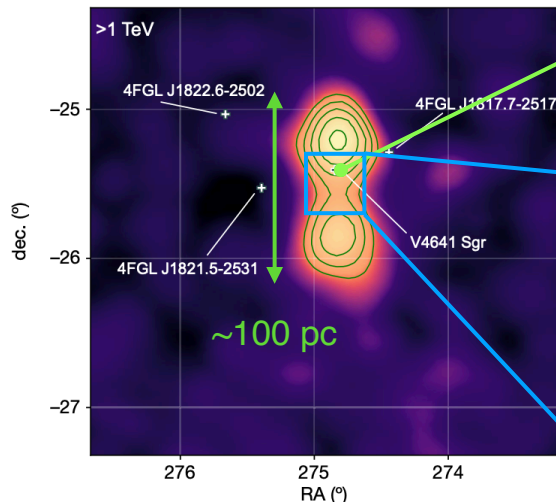
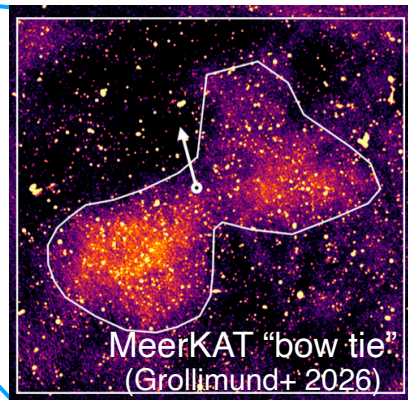
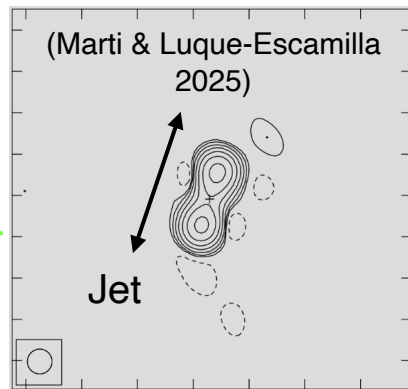


(HAWC Collab. 2024; LHAASO Collab. 2025; HESS Collab. 2026)

2nd example of VHE gamma-ray microquasar: V4641 Sgr

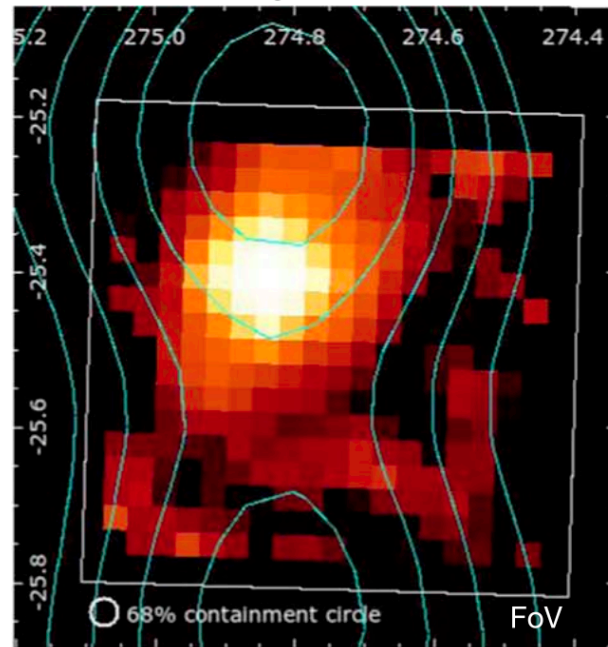
V4641 Sgr

- 6.4 M_{sun} BH and 2.9 M_{sun} B9III star
- Discovered in 1999 during outburst ($L_X \sim 10^{39}$ erg/s)



(HAWC Collab. 2024; LHAASO Collab. 2025; HESS Collab. 2026)

XRISM/Xtend 1.2–7 keV image
(Suzuki+ 2025)

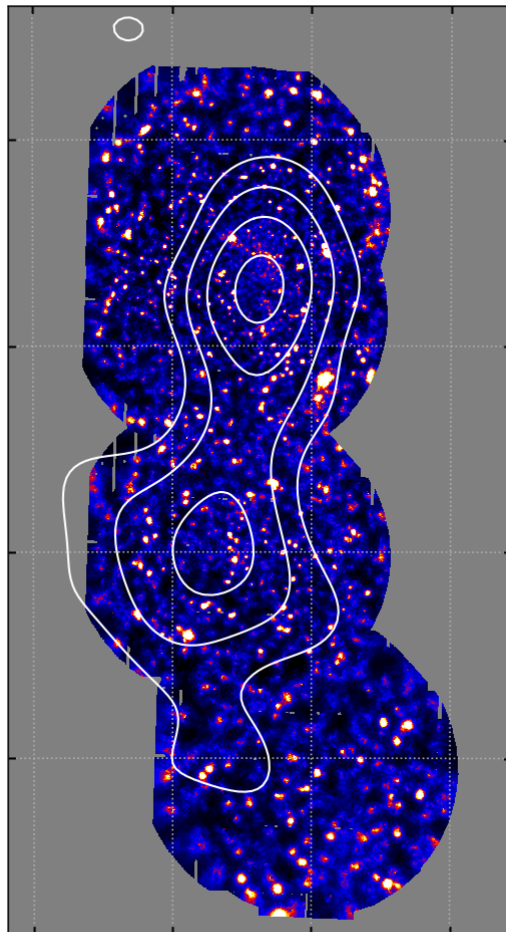


XMM image

(NT, Tresoldi, Mori et al.,
submitted)

- XMM 40 ks x 4
pointings in 2025
- 2–5 keV
- QPB background
subtracted and
exposure-corrected

Contours:
HESS (3, 5, 7, 9 sigma)

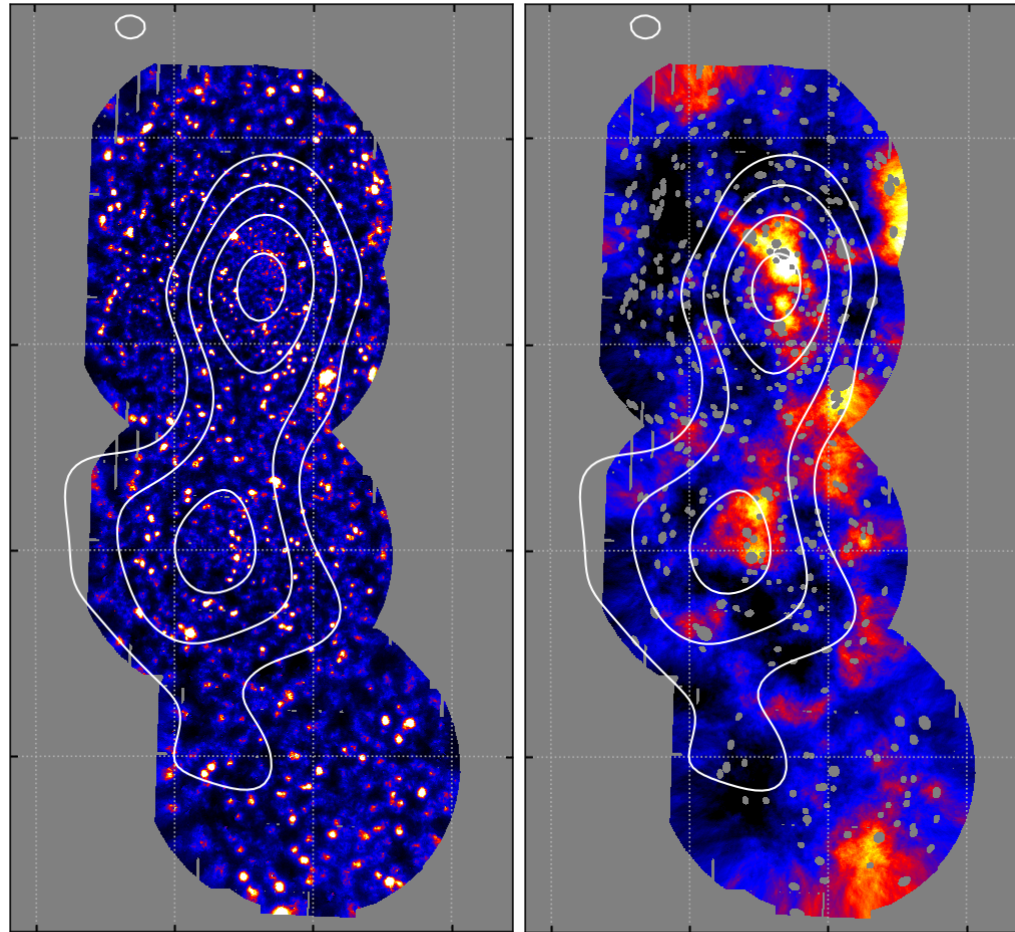


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submitted)

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pointings in 2025
- 2–5 keV
- QPB background
subtracted and
exposure-corrected
- **Masked point-like
sources**
- **Adaptive smoothing**

Contours:
HESS (3, 5, 7, 9 sigma)

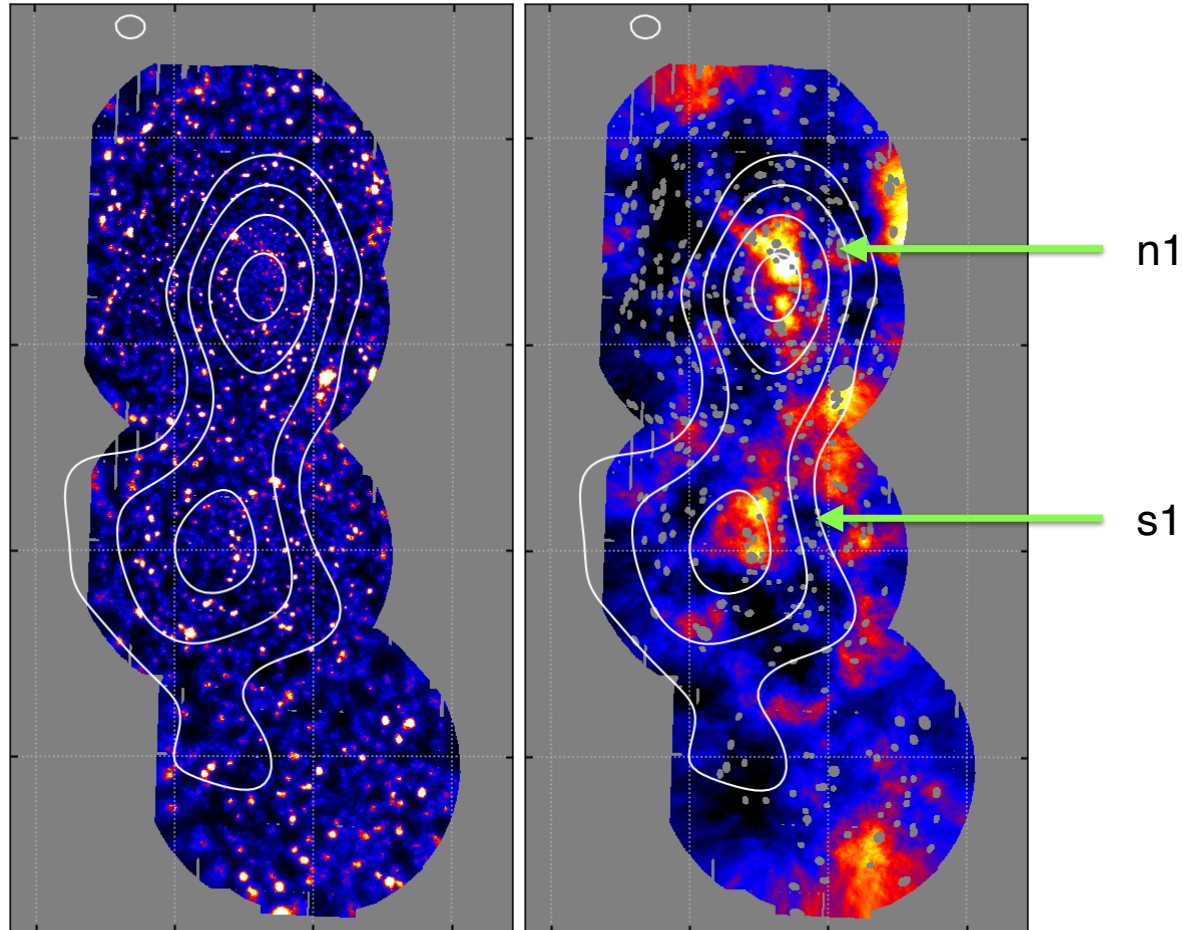


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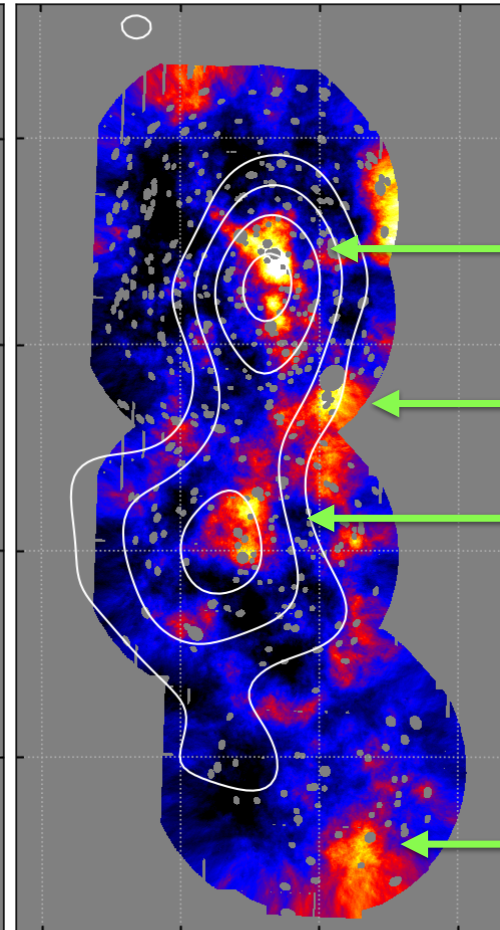
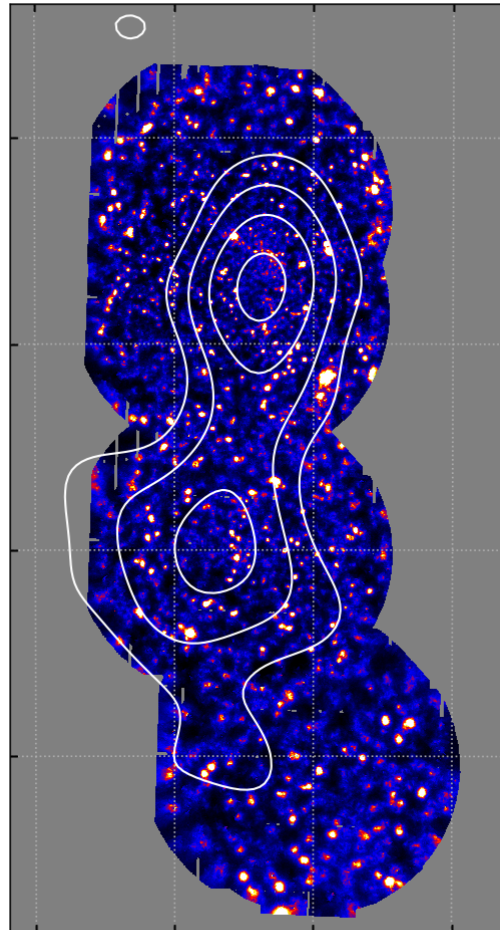


XMM image

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Contours:
HESS (3, 5, 7, 9 sigma)



n1

w1?

s1

s2?

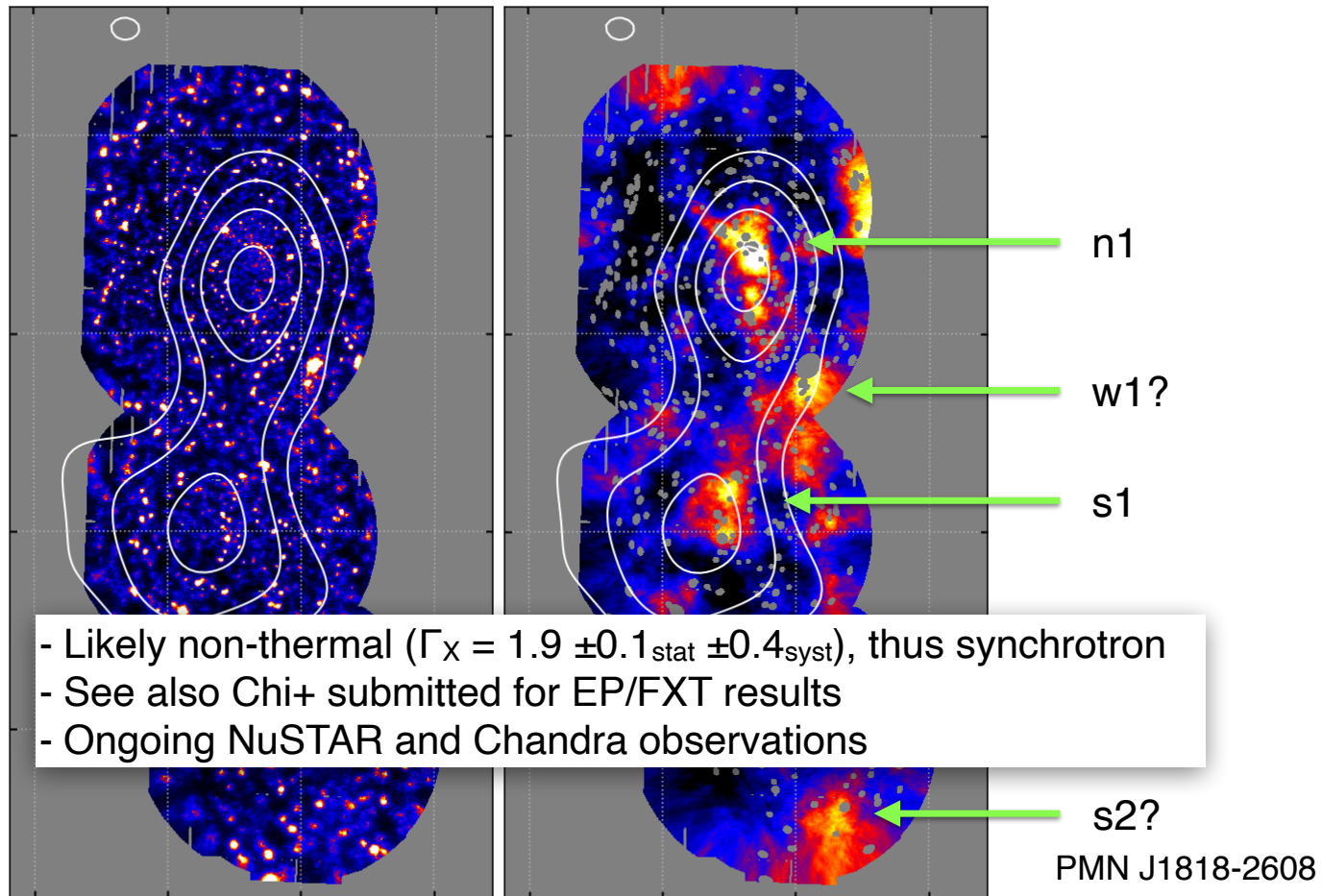
PMN J1818-2608

XMM image

(NT, Tresoldi, Mori et al.,
submitted)

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pointings in 2025
- 2–5 keV
- QPB background
subtracted and
exposure-corrected
- **Masked point-like
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Contours:
HESS (3, 5, 7, 9 sigma)



XMM image

Comparison with Xtend

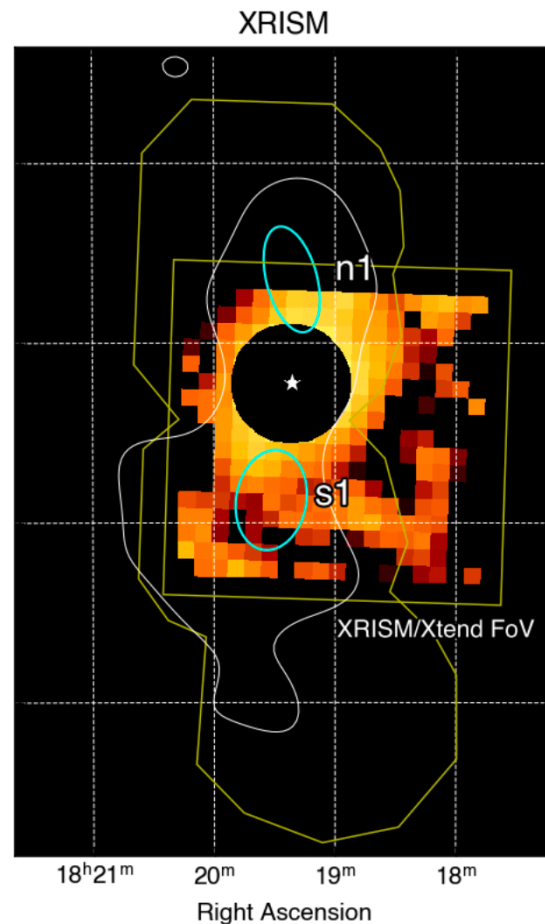
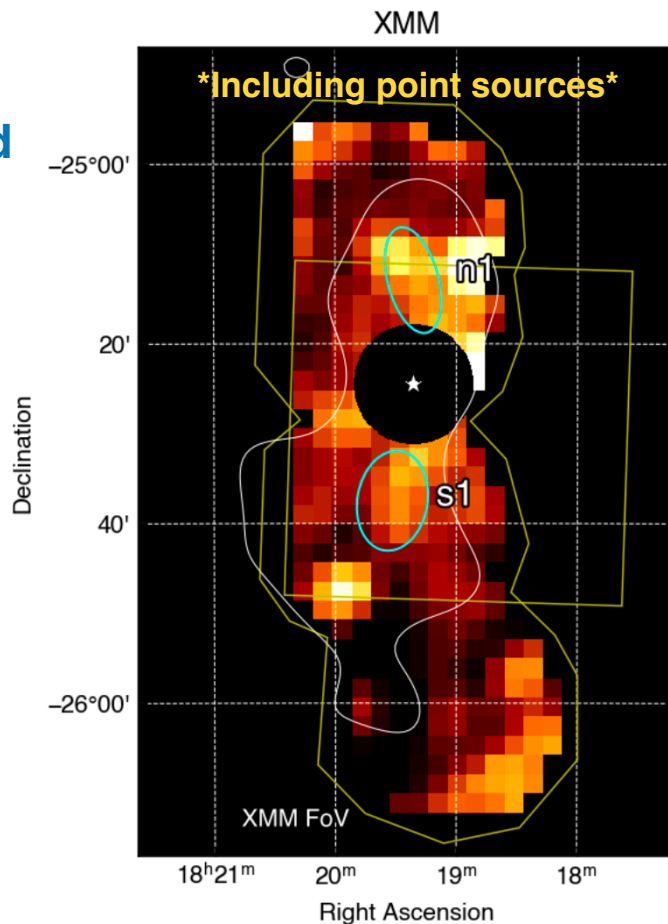
Extended emission by Xtend
(Suzuki+ 2025)

= BH

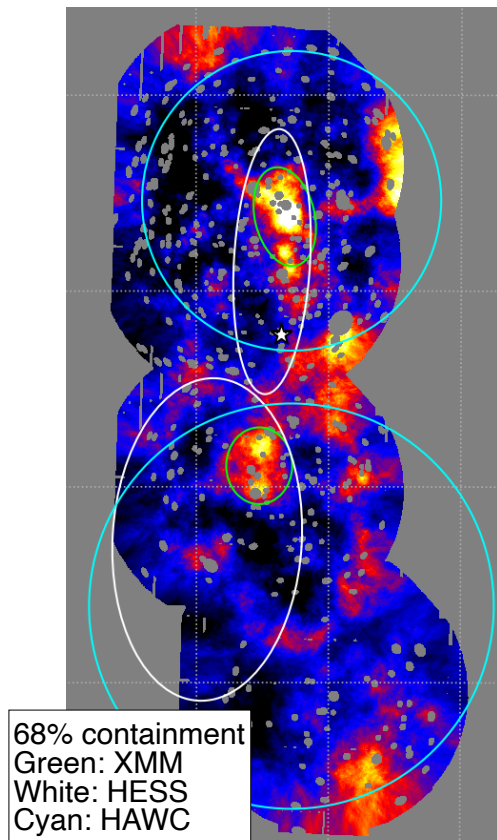
+ unresolved point sources

+ n1 + s1

Xtend's flux is roughly
consistent with n1 and s1.

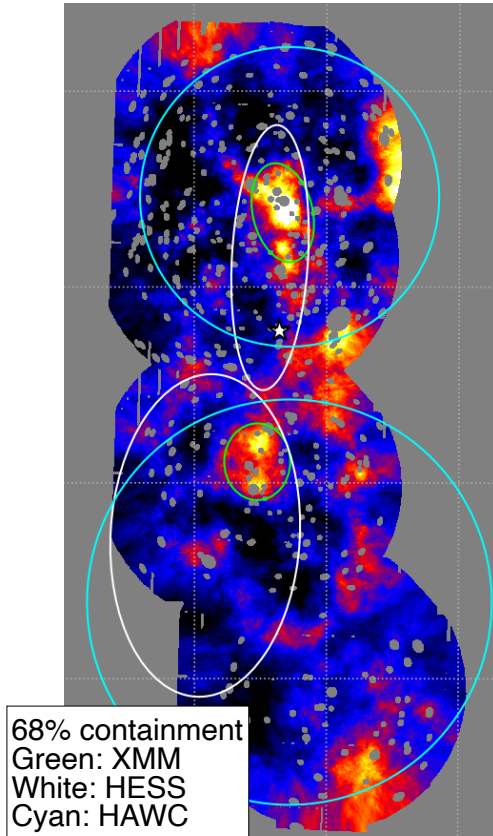


Discussion

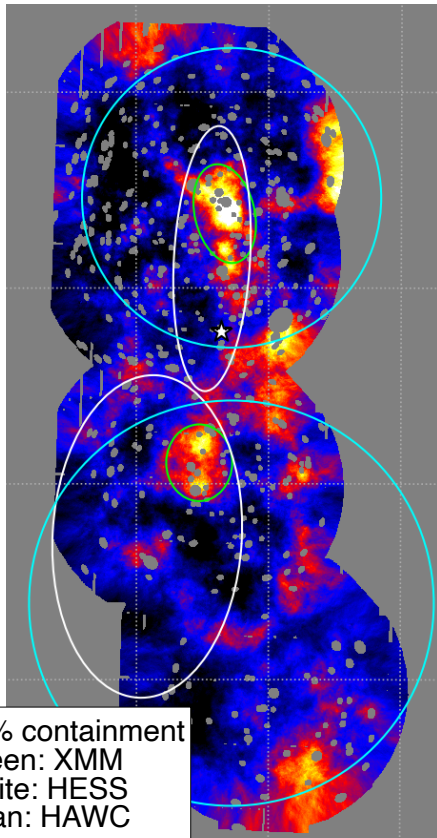


Discussion

Similar X-ray and gamma-ray morphologies => favors **leptonic** origin



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X-ray knots ($3' \times 2'$) are smaller than the TeV lobes ($9\text{--}11' \times 2\text{--}7'$)

Volume fitting factor: 0.03–1

Enhanced magnetic field region?

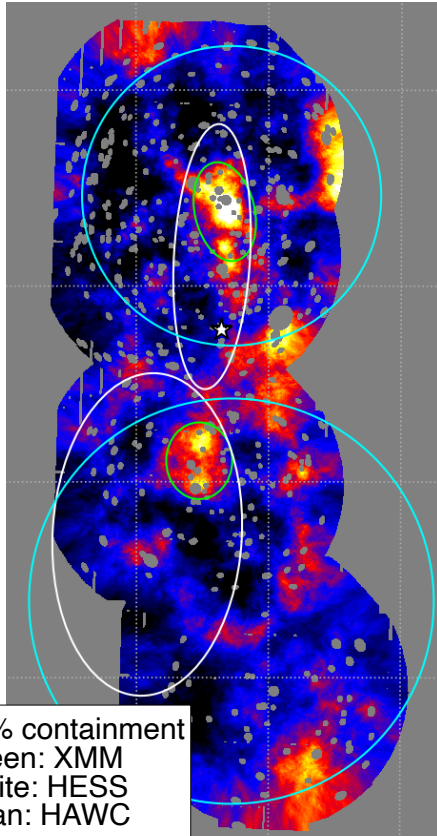
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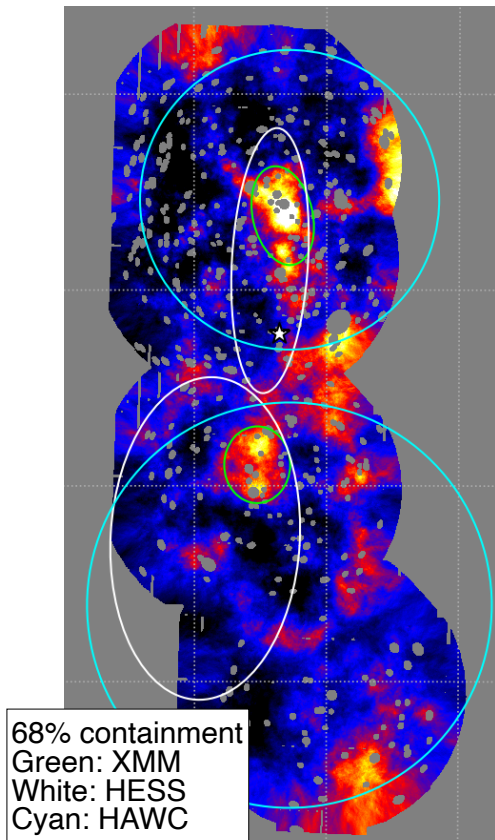
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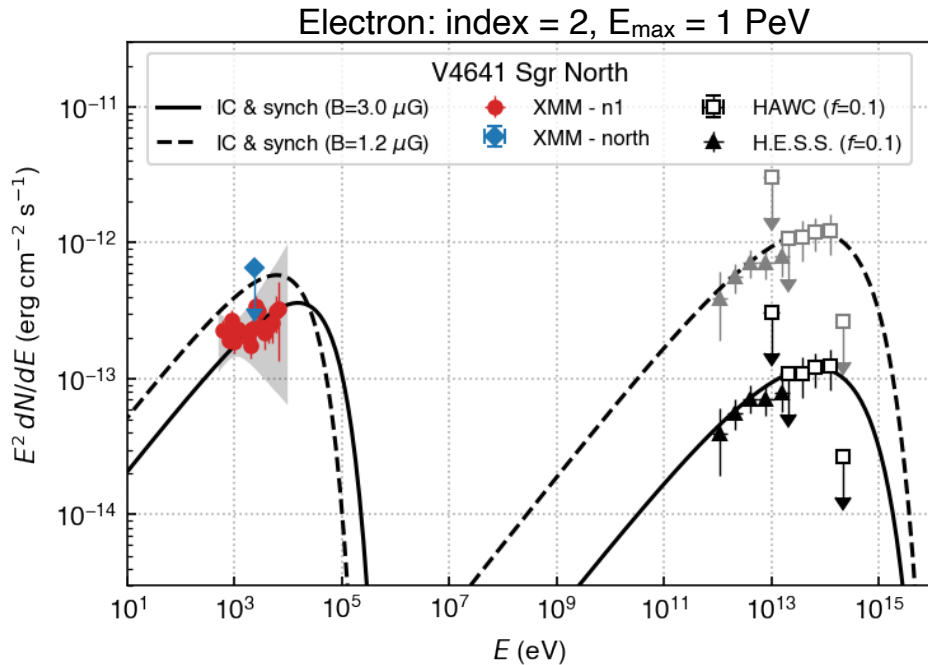
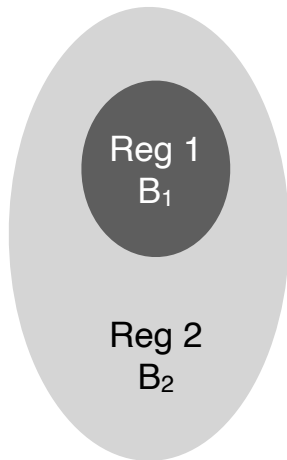


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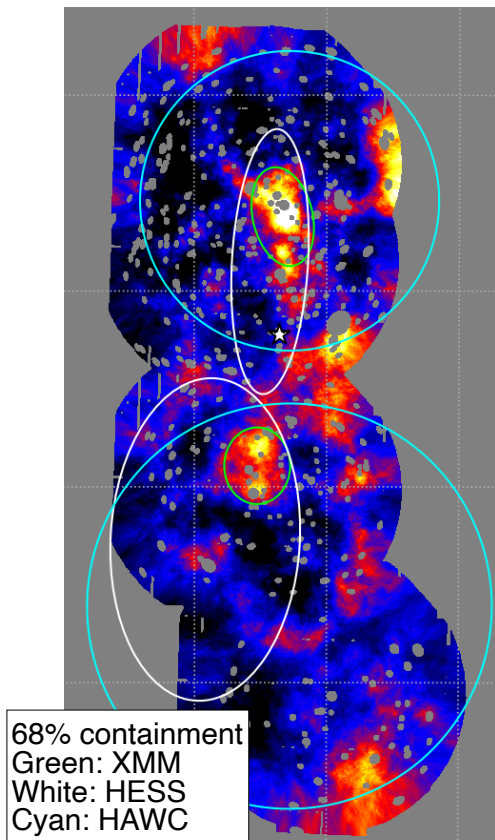
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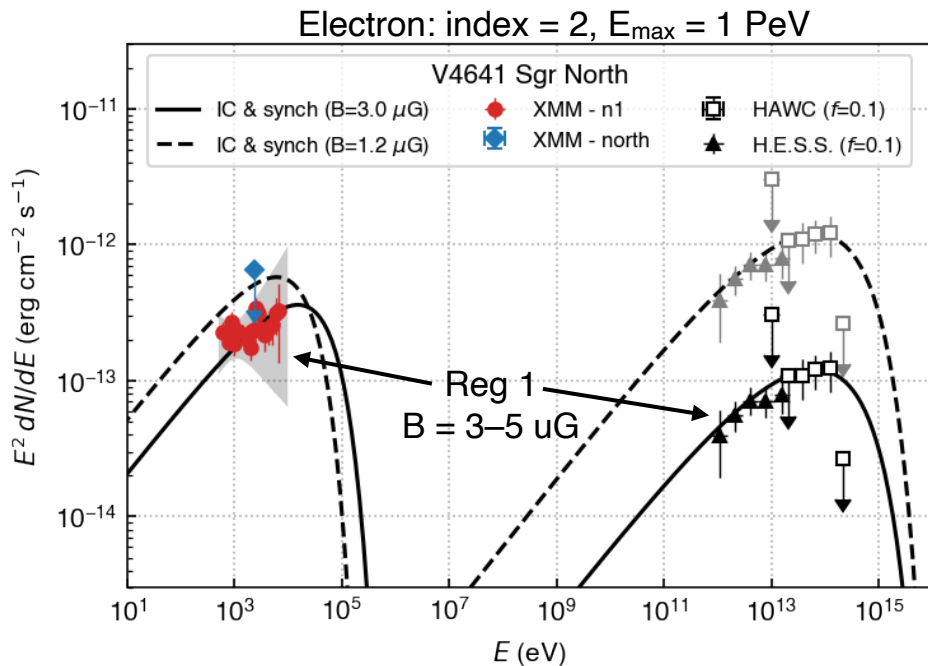
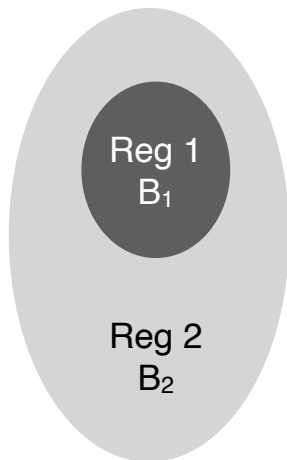


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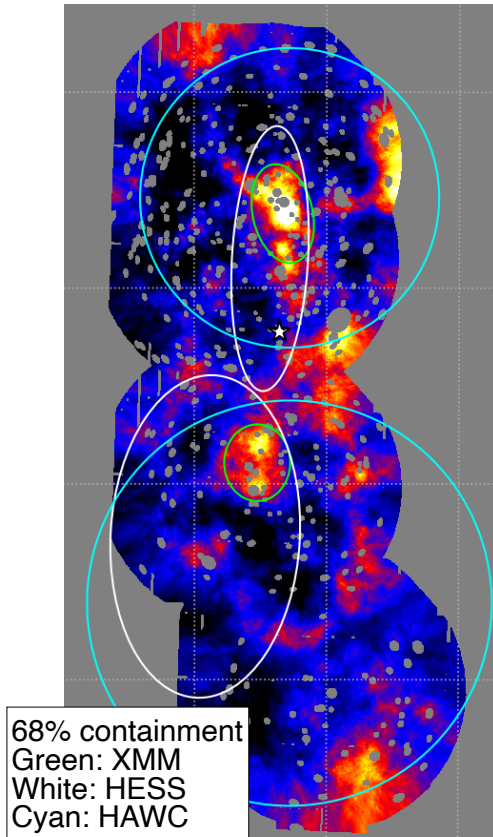
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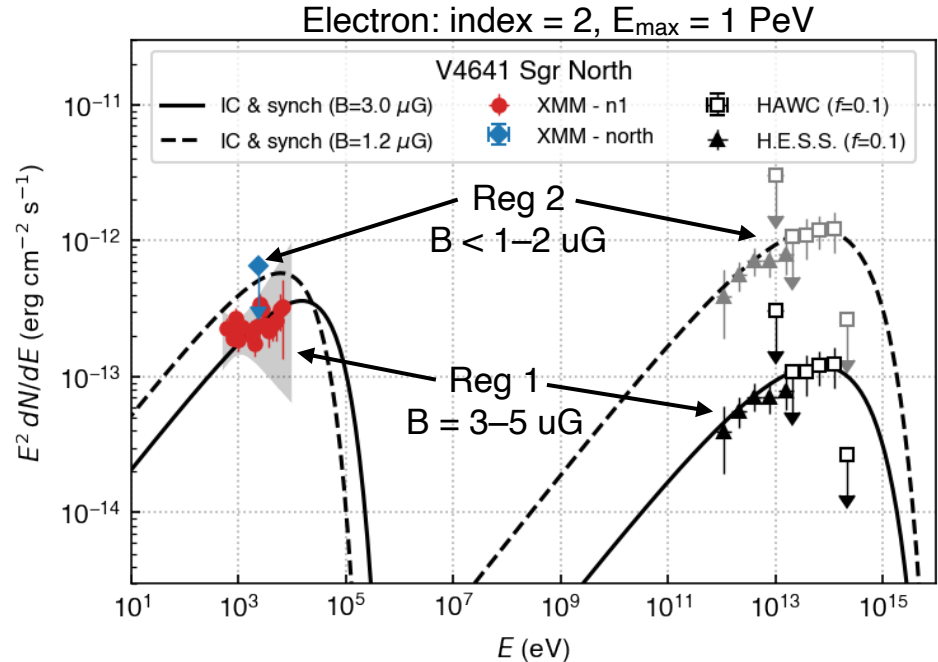


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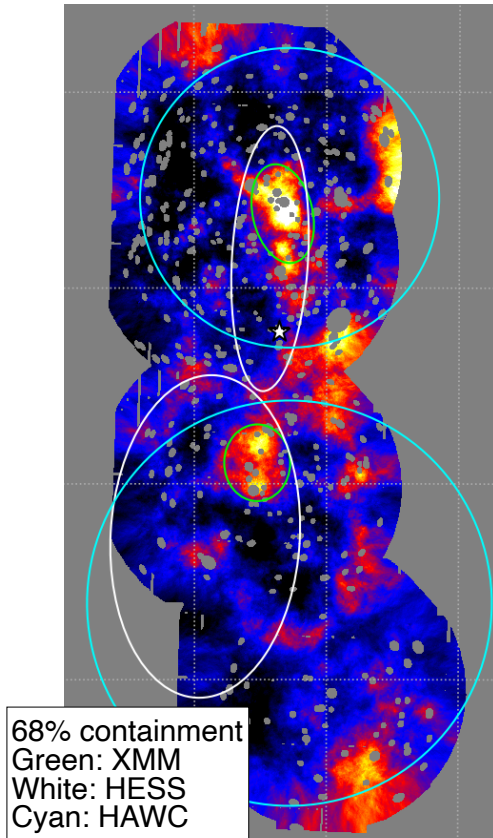
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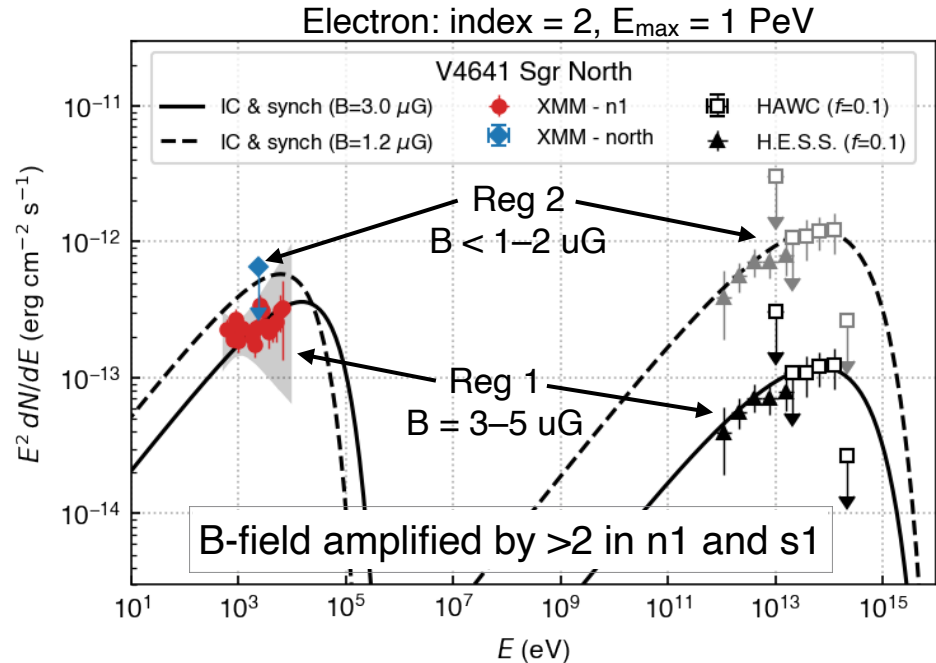


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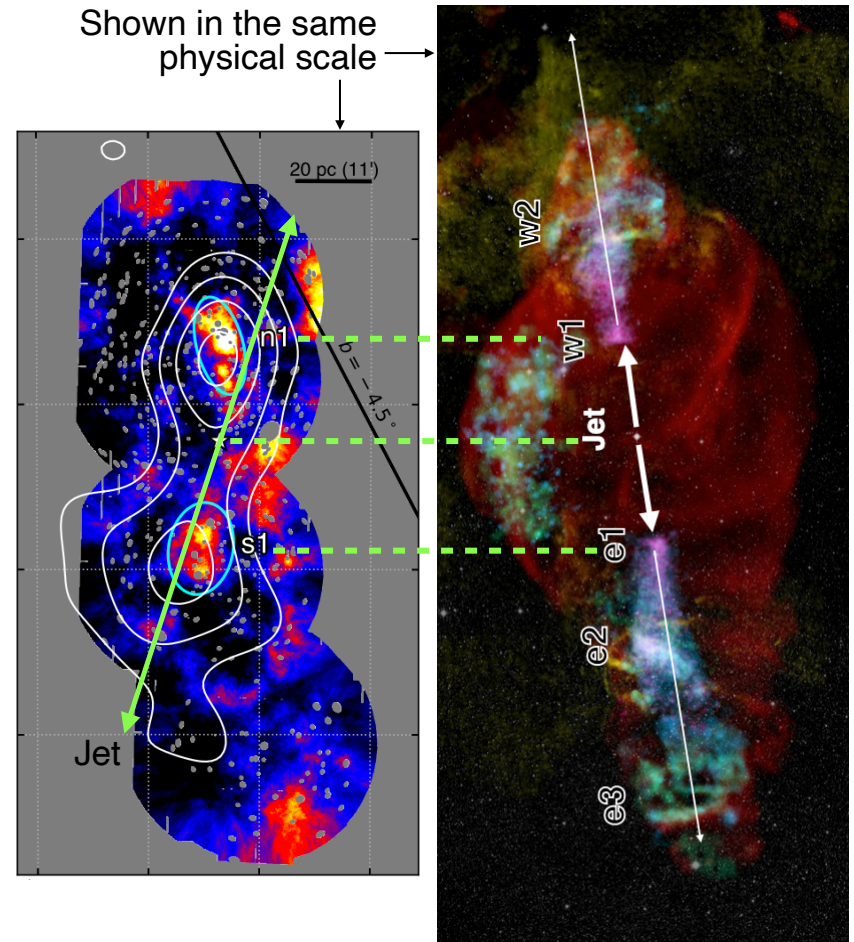
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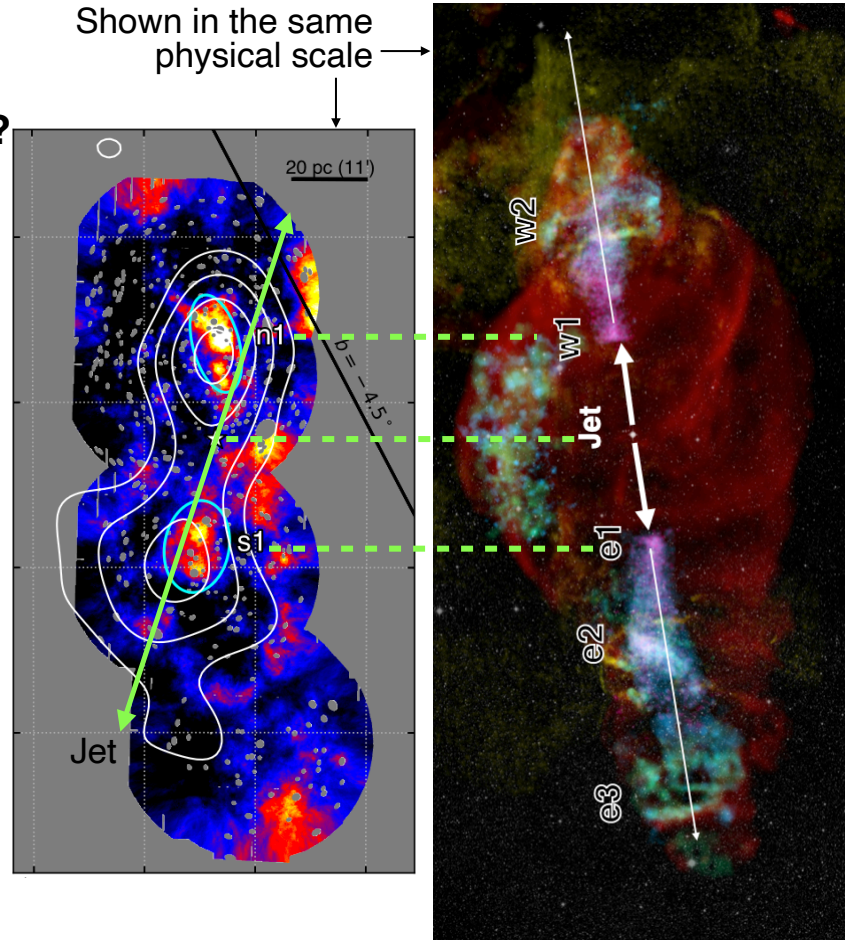
V4641 Sgr vs SS 433



V4641 Sgr vs SS 433

X-rays have ~ 20 pc offsets $\rightarrow$ acceleration site?

- Both in V4641 and SS 433
- Same physical origin, such as jet collimation
- Accidentally same? / Hidden inner knots in V4641?

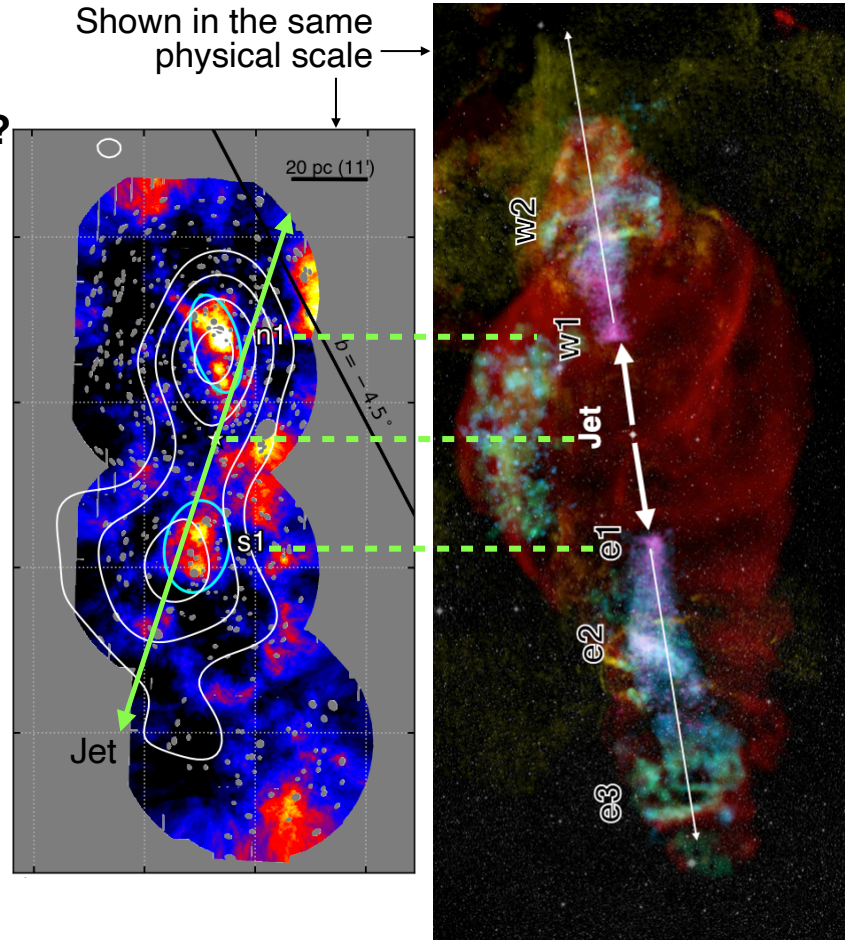
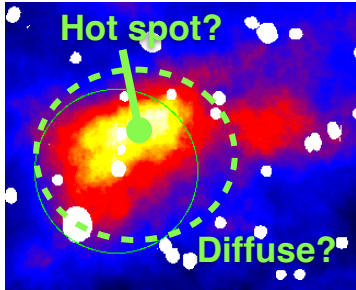


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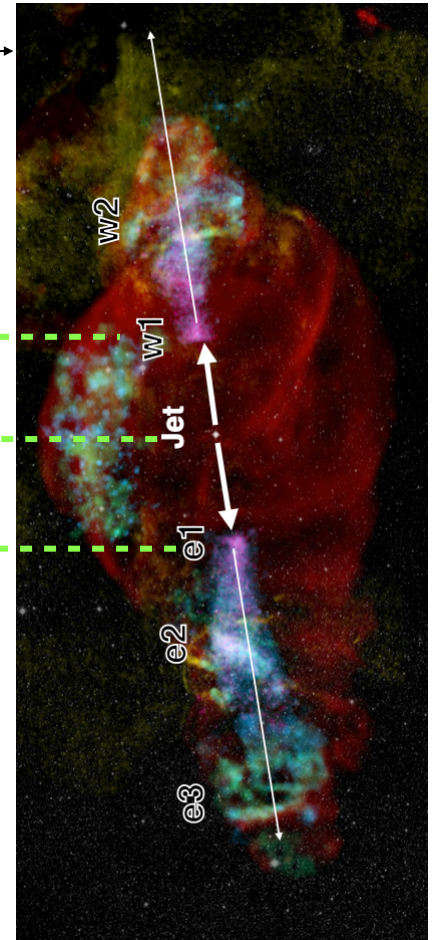
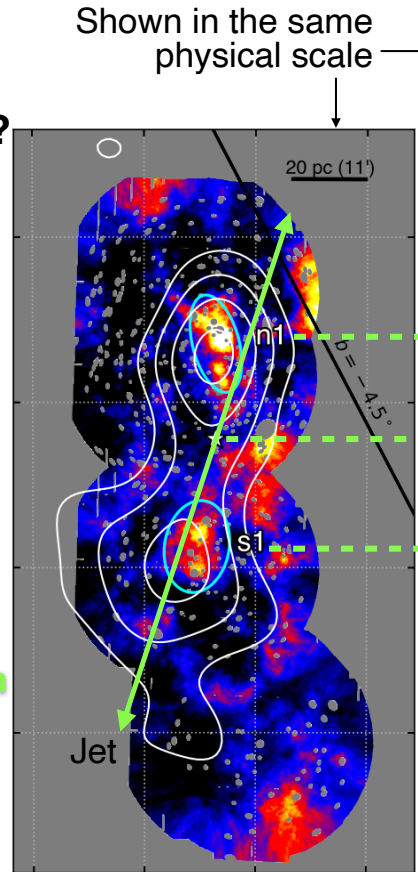
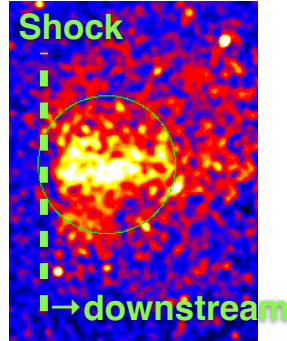
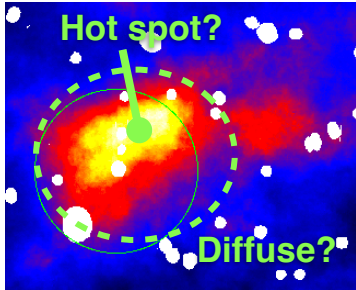
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sharp edge?



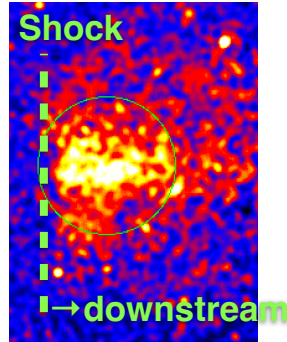
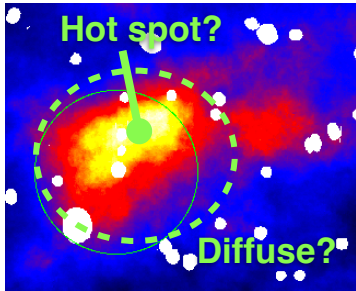
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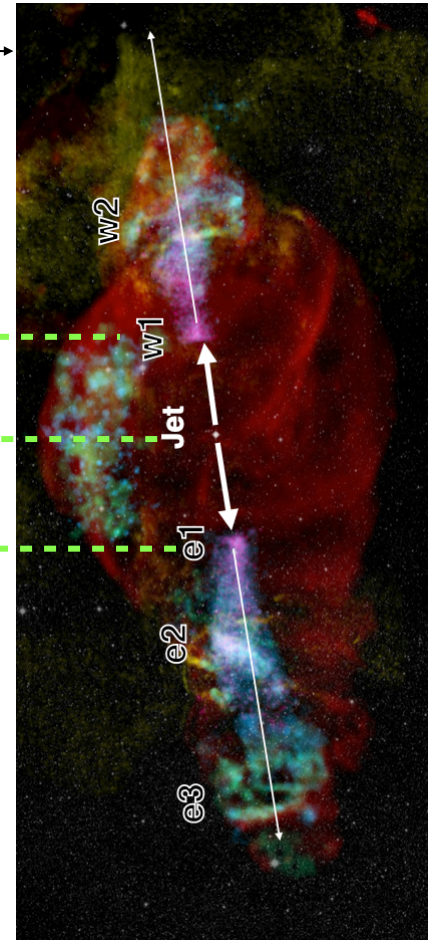
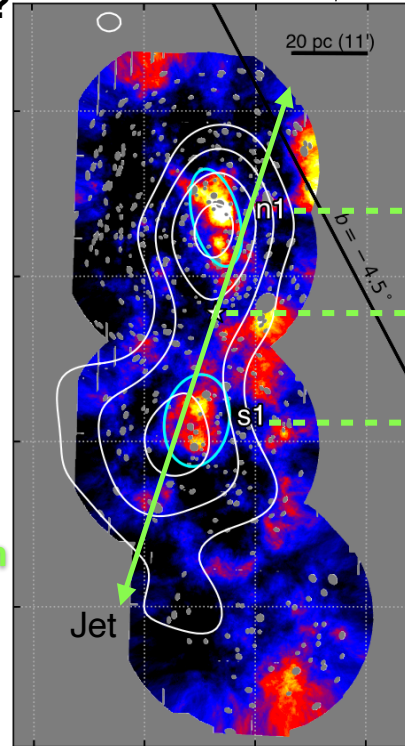
SS 433's w1: shock-like
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Jet-knot misalignment in V4641

- Aligned in SS 433

Shown in the same
physical scale $\rightarrow$



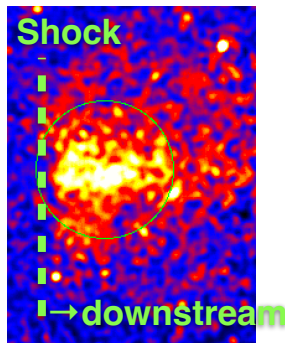
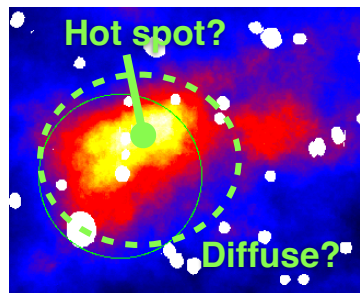
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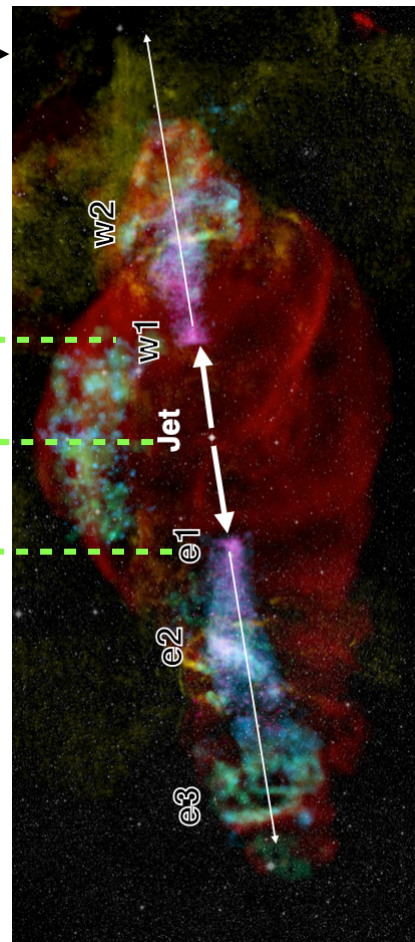
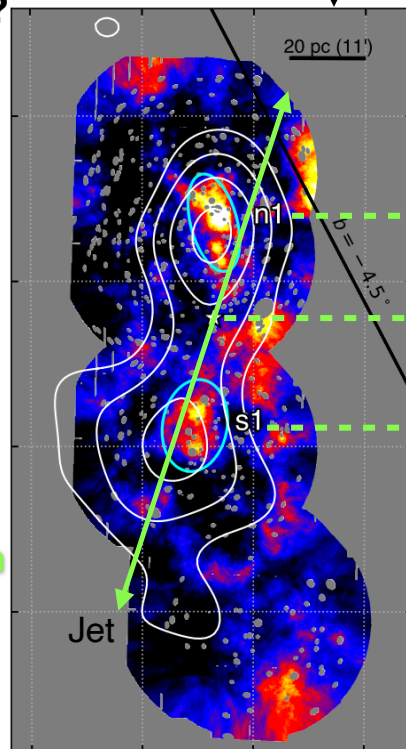
Jet-knot misalignment in V4641

- Aligned in SS 433

No outer and thermal knots in V4641?

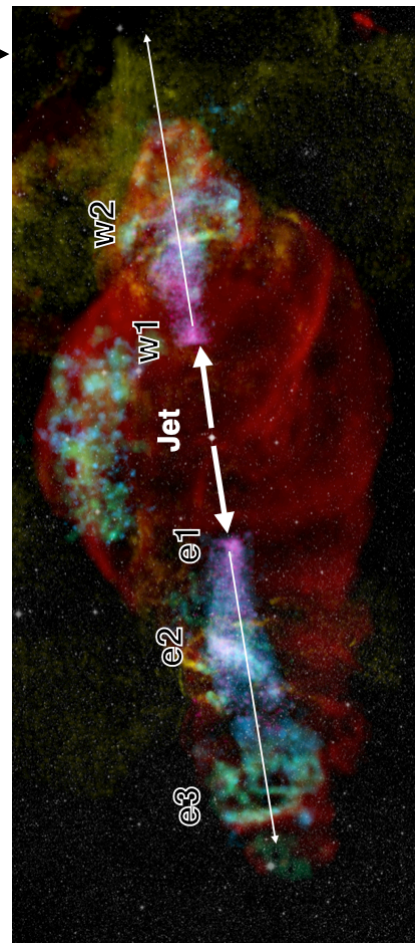
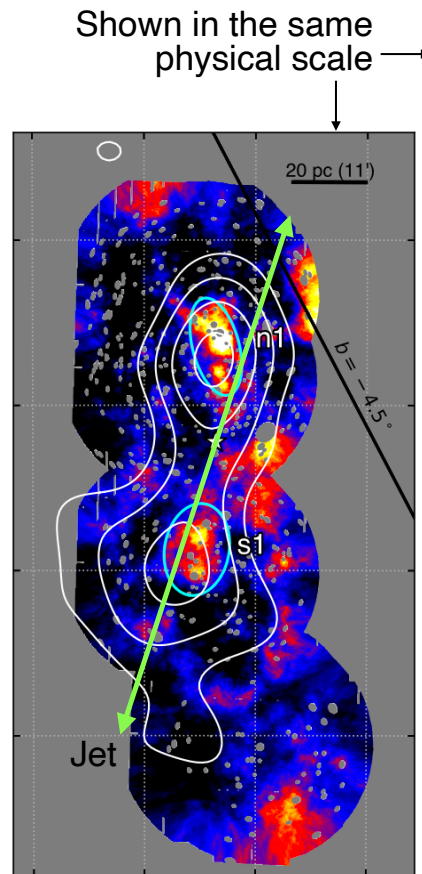
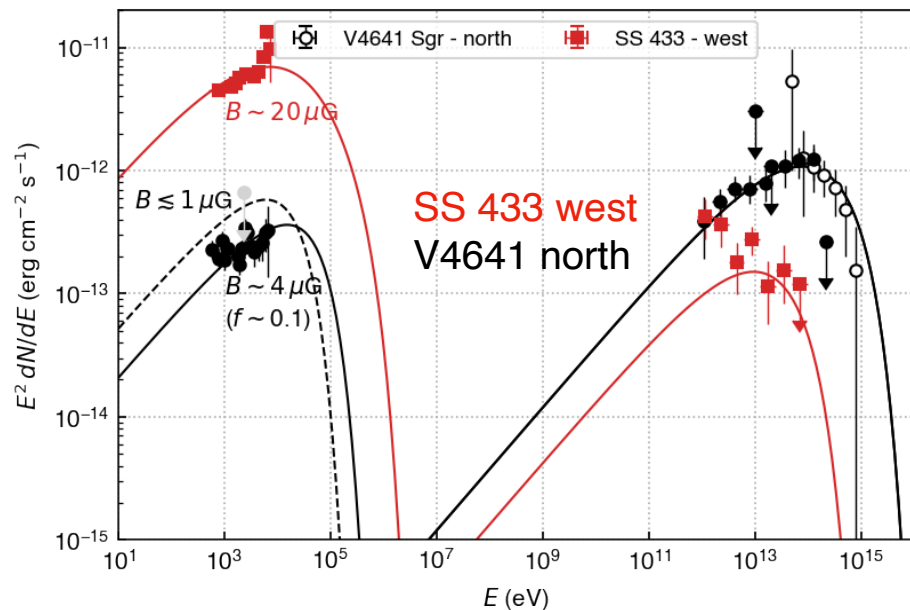
- For future/deeper observations

Shown in the same physical scale $\rightarrow$



V4641 Sgr vs SS 433

- X-ray dominant SED in SS 433
- Gamma-ray dominant SED in SS 433
- Difference of B-field, surroundings, etc?



Are X-ray knots common in PeVatron microquasars?

SS 433 and V4641

- X-ray knots in gamma-ray lobes

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- Contamination from too bright central objects...

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GRS 1915+105

- Quiescent phase after 2018
- Chandra observation on radio bow shock (Motta+ 2025)
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- XMM + NuSTAR observation in 2026 (led by Caterina Tresoldi)

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What about non-PeVatron (yet detected?) microquasars?

- Ongoing search for X-ray extended emission (with Suzuki, Shidatsu+)
- Radio data also help (Sakemi, Takekawa+)

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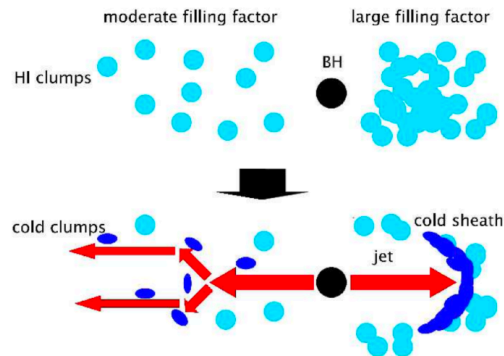
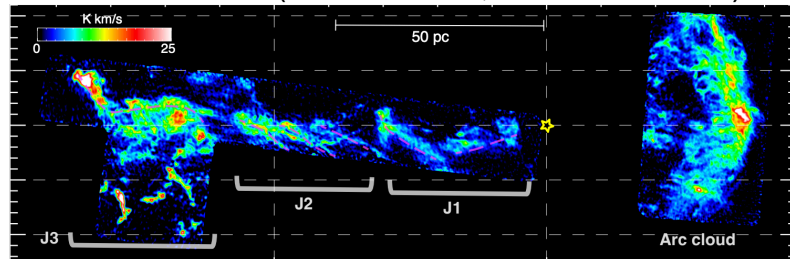
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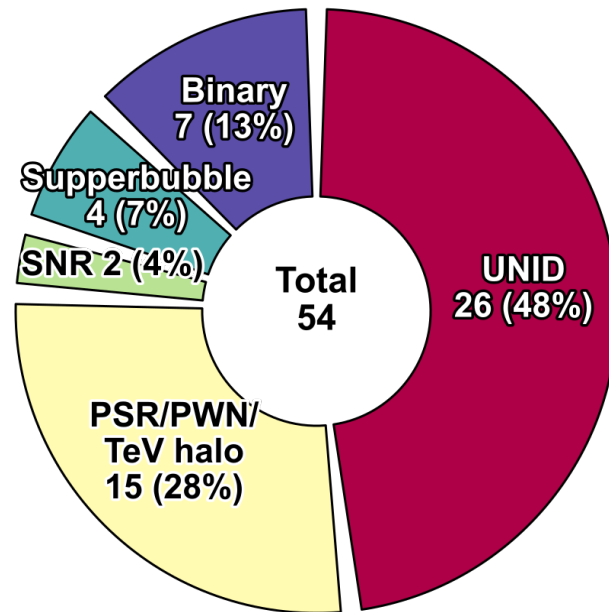
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Footprints of past jet activities in surrounding medium
Westerlund 2 (Fukui+ 2026; Asahina+ 2017)



Unidentified UHE sources

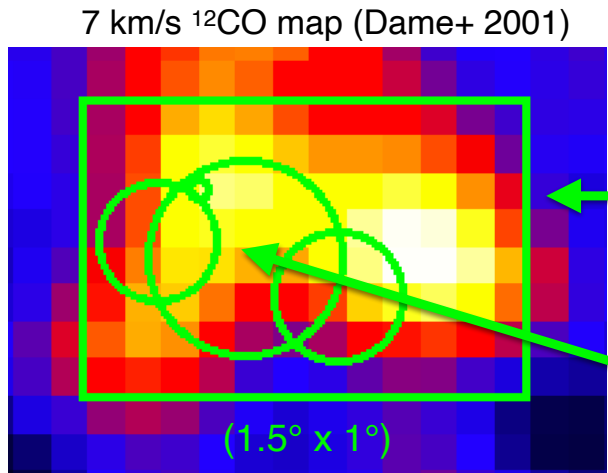
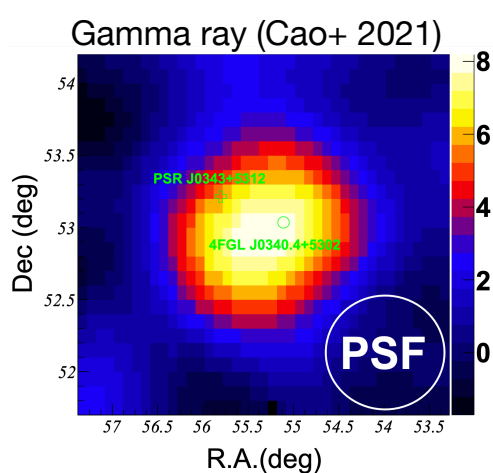


LHAASO J0341 + 5258

■ LHAASO J0341+5258

- Extended, unidentified source up to >100 TeV
- $E_{\text{max}} \sim 200$ TeV (Cao+ 2021; Kar and Gupta 2022)

Name	Size (deg)		Γ	
	KM2A	WCDA	KM2A	WCDA
LHAASO J0341+5258	0.29	—	2.98	—
1LHAASO J0339+5307	<0.22	—	3.64	—
1LHAASO J0343+5254u	0.20	0.33	3.53	1.70



45-m Nobeyama radio telescope

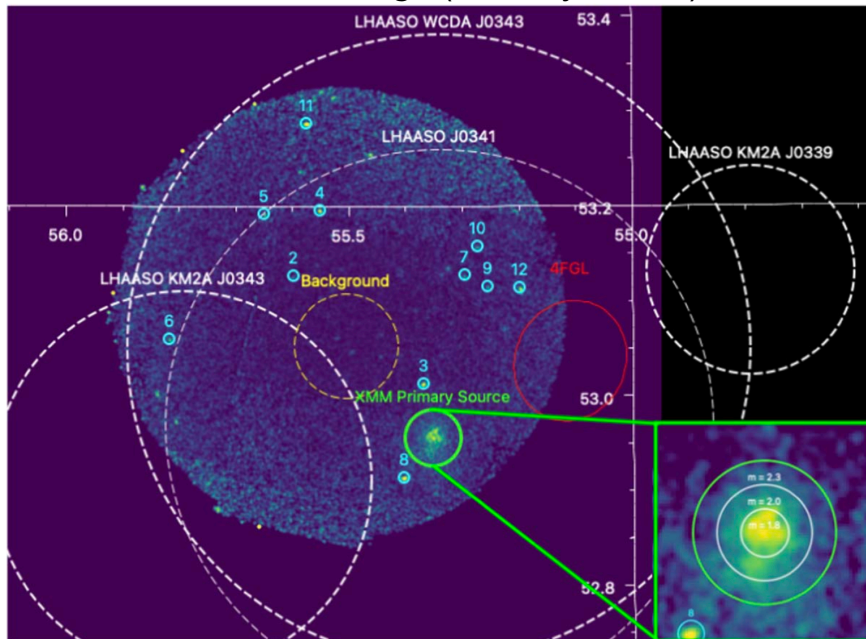
Observations of ^{12}CO , ^{13}CO , and C^{18}O lines ($J=1-0$)

XMM-Newton



LHAASO J0341 + 5258: X-ray observations

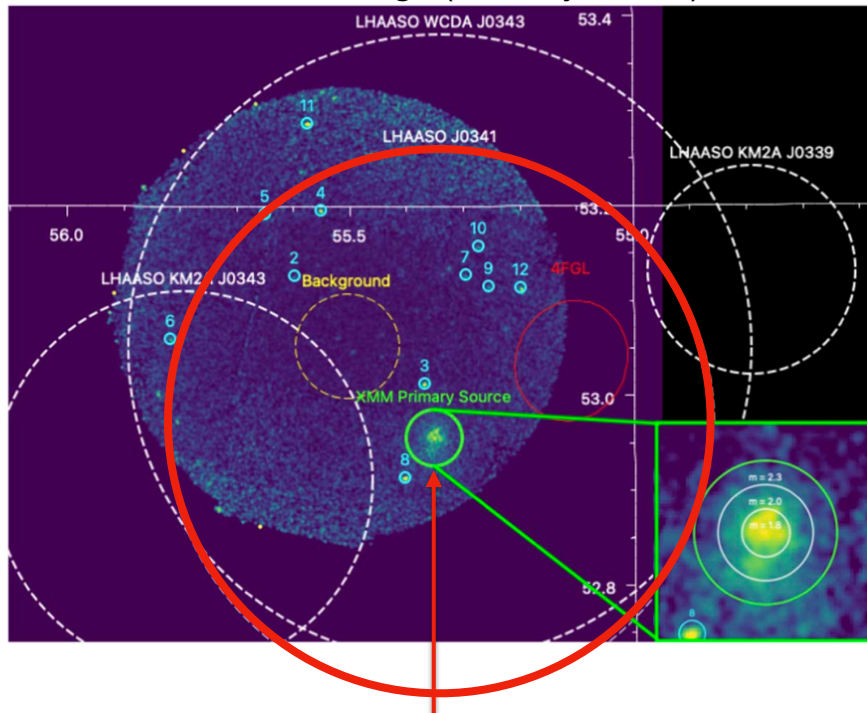
XMM image (DiKerby+ 2025)



New XMM observation with ~ 90 ks

LHAASO J0341 + 5258: X-ray observations

XMM image (DiKerby+ 2025)

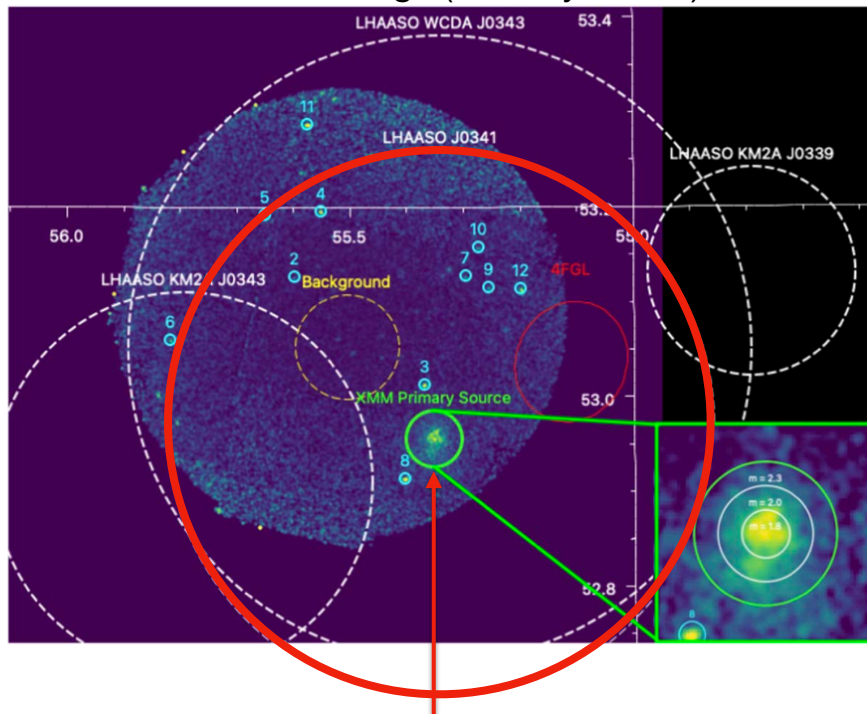


At the very center of firstly reported LHAASO emission

New XMM observation with ~ 90 ks

LHAASO J0341 + 5258: X-ray observations

XMM image (DiKerby+ 2025)



At the very center of firstly reported LHAASO emission

New XMM observation with ~ 90 ks

Newly discovered extended X-ray emission

Power-law with no cutoff

$$NH = (1.7 \pm 0.1) \times 10^{22} \text{ cm}^{-2}$$

$$\Gamma = 1.9 \pm 0.1$$

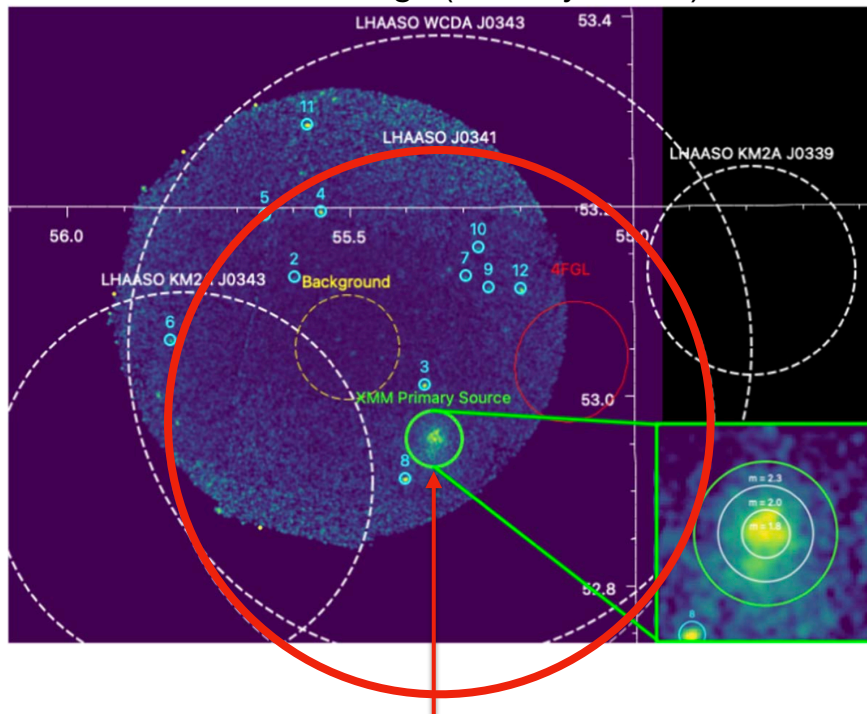
$$F = (1.29 \pm 0.05) \times 10^{-12} \text{ cgs (in 0.2–12 keV)}$$

Softening ($\Gamma = 1.8$ to 2.3) toward the outer region

→ Likely PWN

LHAASO J0341 + 5258: X-ray observations

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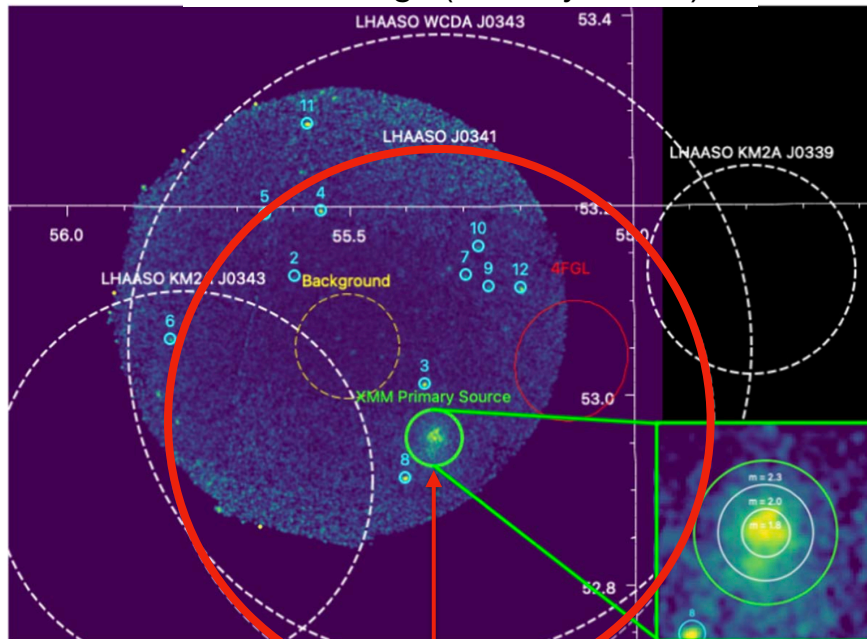
Softening ($\Gamma = 1.8$ to 2.3) toward the outer region

→ Likely PWN

→ Follow-up Chandra + NuSTAR observations in 2026

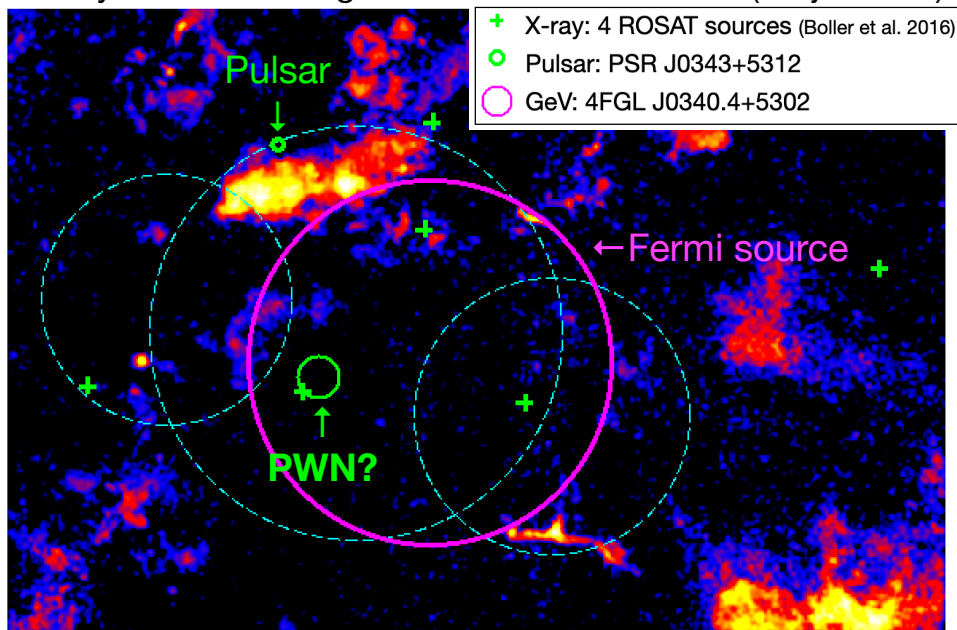
LHAASO J0341 + 5258: X-ray and CO observations

XMM image (DiKerby+ 2025)



At the very center of firstly reported LHAASO emission

Nobeyama ^{12}CO image with $V = -40$ to 10 km/s (Tsuji+ 2025)



Molecular clouds

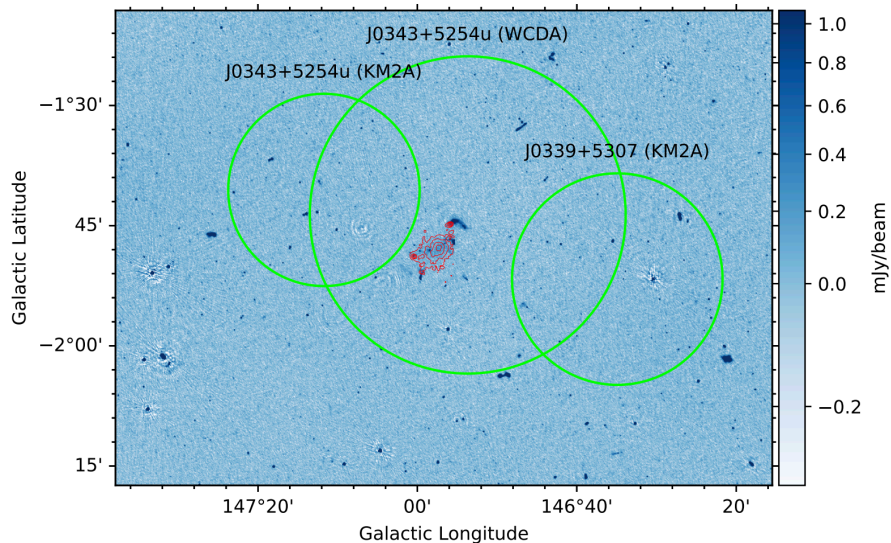
- $d < \sim 1$ kpc
- $n = 100\text{--}1000$ cm $^{-3}$

$$W_p \sim 10^{44}\text{--}10^{45} \text{ erg}$$

LHAASO J0341 + 5258: LOFAR observations

(Edler+ 2026)

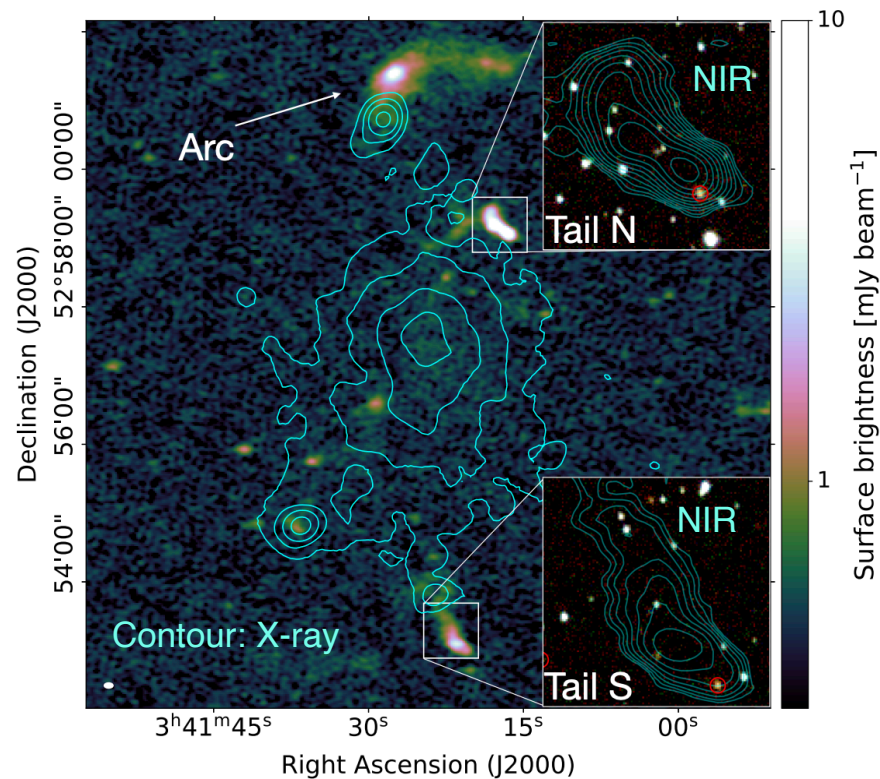
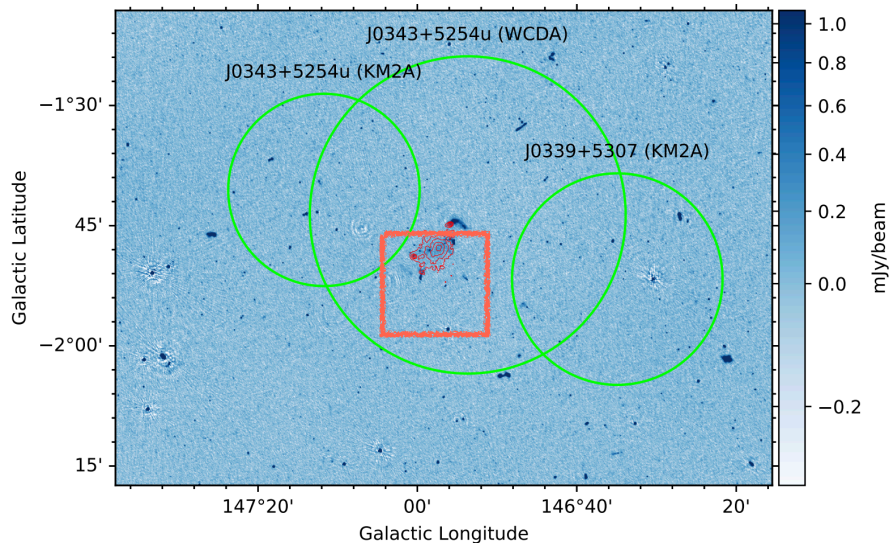
144 MHz map by LOFAR



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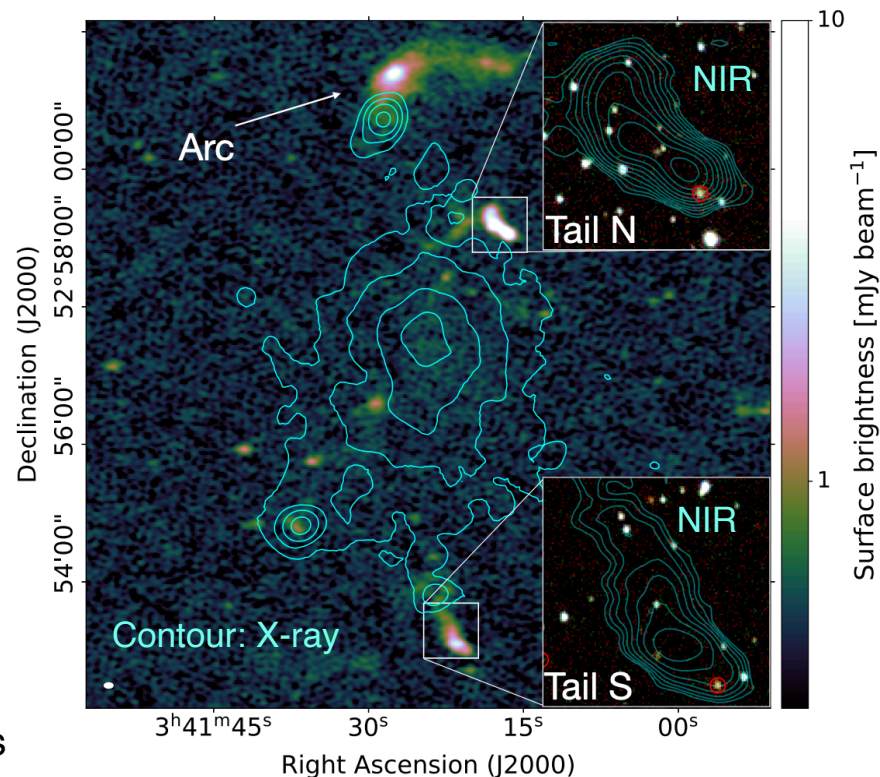
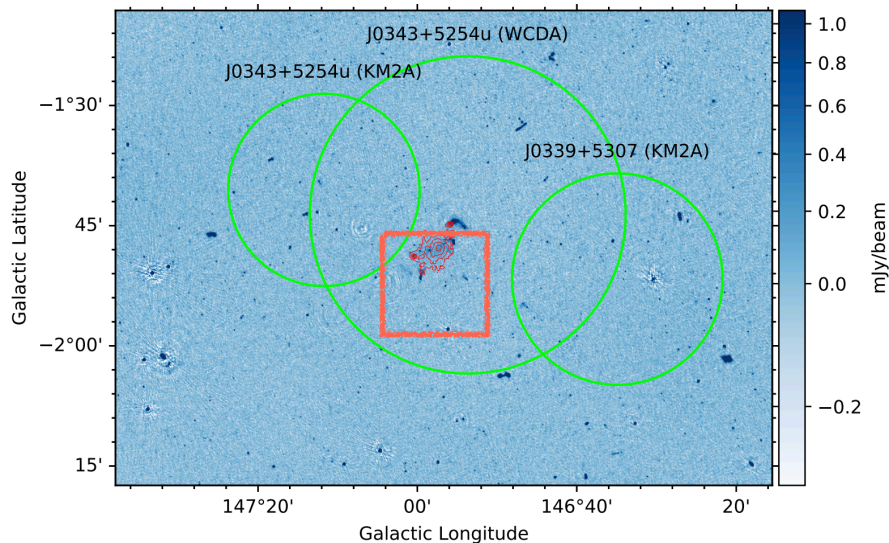
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144 MHz map by LOFAR



Background galaxy cluster? (Edler+ 2026)

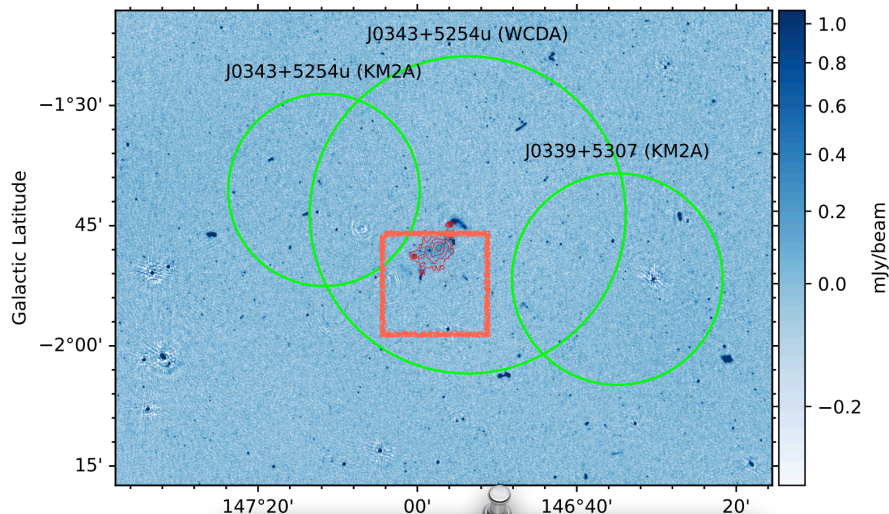
→ If so, not associated with the gamma rays

SNR-MC interaction (Roy+ 2026)

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144 MHz map by LOFAR

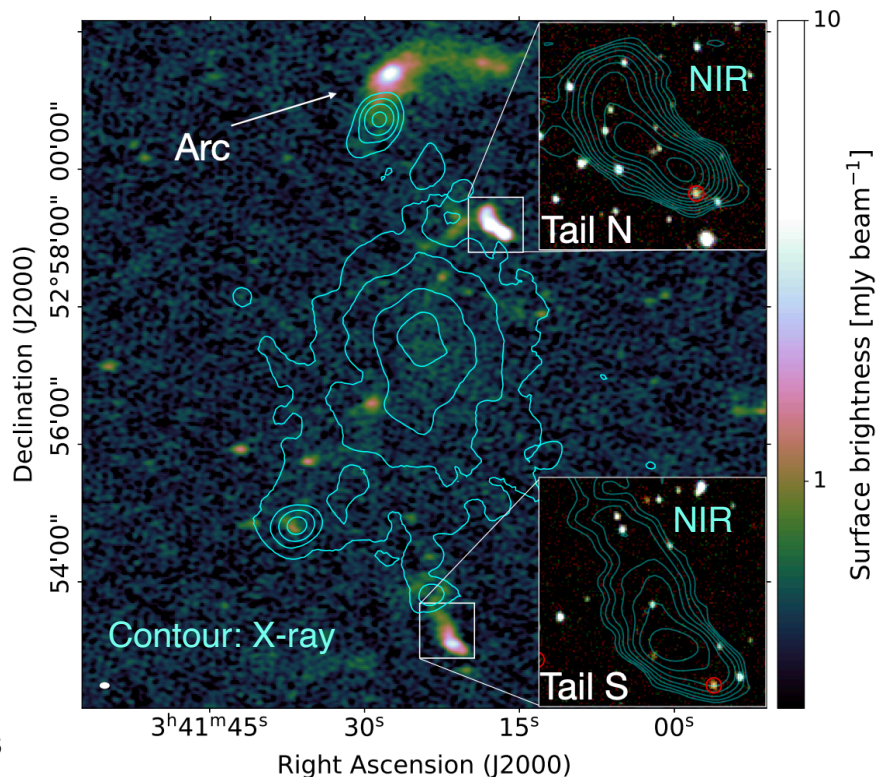


Maria's talk  Mon. afternoon

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X-ray and CO studies of PeVatron candidates

First round “dark sources” (X-ray PI: Kaya Mori)

nature First 12 UHE sources

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Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ -ray Galactic sources

[Zhen Cao](#) , [F. A. Aharonian](#) , [Q. An](#), [Axikegu](#), [L. X. Bai](#), [Y. X. Bai](#), [Y. W. Bao](#), [D. Bastieri](#), [X. J. Bi](#), [Y. J. Bi](#), [H. Cai](#), [J. T. Cai](#), [Zhe Cao](#), [J. Chang](#), [J. F. Chang](#), [X. C. Chang](#), [B. M. Chen](#), [J. Chen](#), [L. Chen](#), [Liang Chen](#), [Long Chen](#), [M. J. Chen](#), [M. L. Chen](#), [Q. H. Chen](#), ... [X. Zuo](#)  Show authors

Source name	Source type	X-ray	CO
LHAASO J0341+5258	PWN-like?	Extended	Yes
LHAASO J2108+5157	?	No	Yes
1LHAASO J0622+3754	Pulsar + halo	Point-like	Nobeyama 2026
1LHAASO J1956+2921	PWN?	Likely extended	Yes

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Second round “off-plane and dark sources” (PI: Jooyun Woo)

First LHAASO catalog

THE ASTROPHYSICAL JOURNAL
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The First LHAASO Catalog of Gamma-Ray Sources

Zhen Cao, F. Aharonian, Q. An, Axikegu, Y. X. Bai, Y. W. Bao, D. Bastieri, X. J. Bi, Y. J. Bi, J. T. Cai
[Show full author list](#)

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[The Astrophysical Journal Supplement Series, Volume 271, Number 1](#)

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1LHAASO J0007+5659	Dark	XMM+ NuSTAR in 2026-2027	Yes
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1LHAASO J1839–0548u	Young PWN?		Yes
1LHAASO J1954+3253	Bow-shock PWN?		Yes
Penut region	Dark	—	No
1LHAASO J1959+1129u	LMXB?	—	No
1LHAASO J1740+0948u	PWN	Extended	No

X-ray and CO studies of PeVatron candidates

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nature First 12 UHE sources

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First LHAASO catalog

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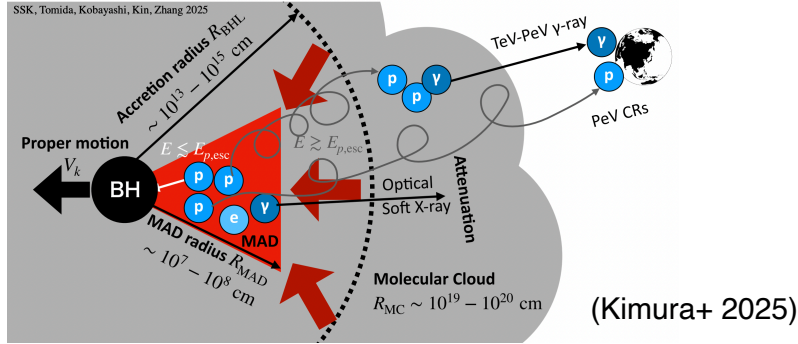
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1LHAASO J1740+0948u	PWN	Extended	No

Ryohei's talk for CO studies  Mon. afternoon

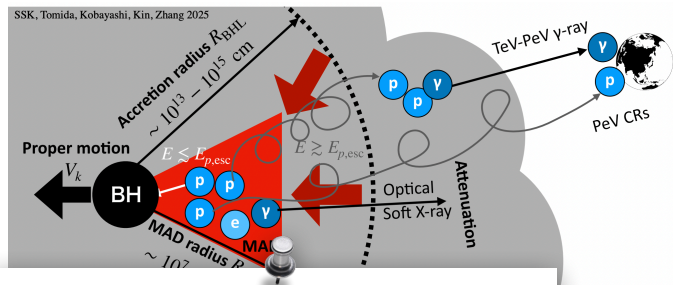
Unassociated gamma-ray sources = X-ray binaries?

“Isolated black holes in MCs as dark PeVatrons”



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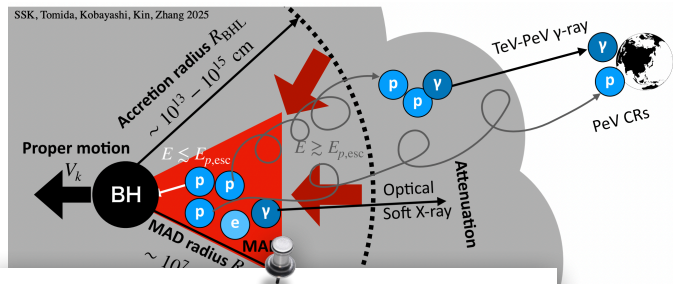


Shigeo's talk  Mon. afternoon

(Kimura+ 2025)

Unassociated gamma-ray sources = X-ray binaries?

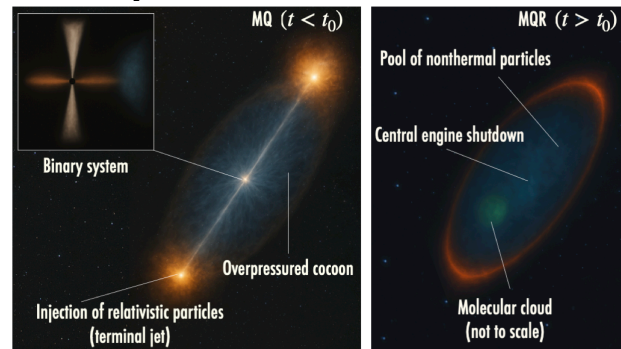
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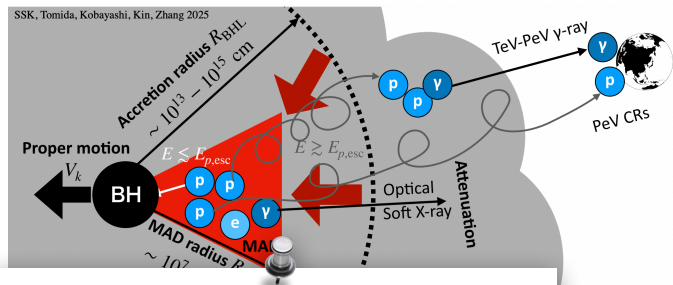
“Microquasar remnants as hidden PeVatrons”



(Abaroa+ 2025)

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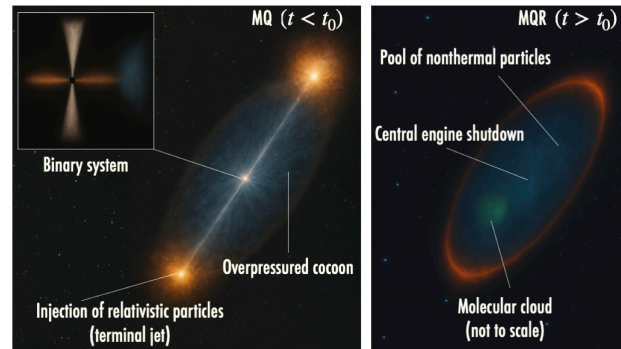
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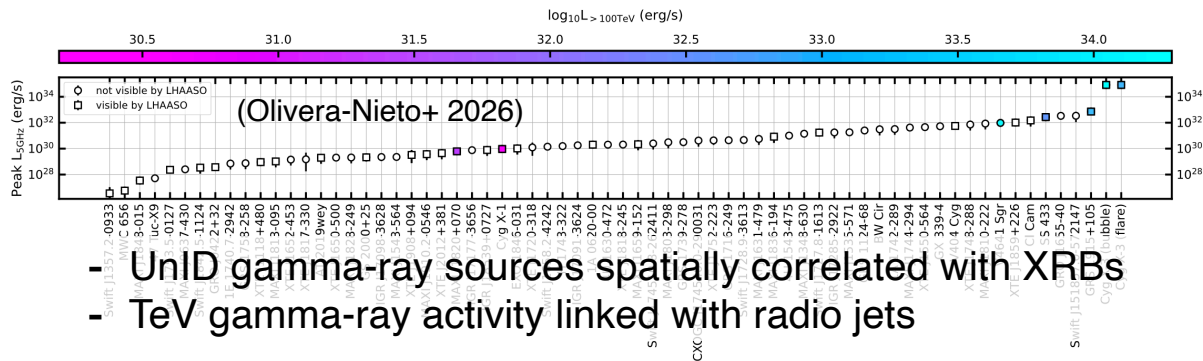
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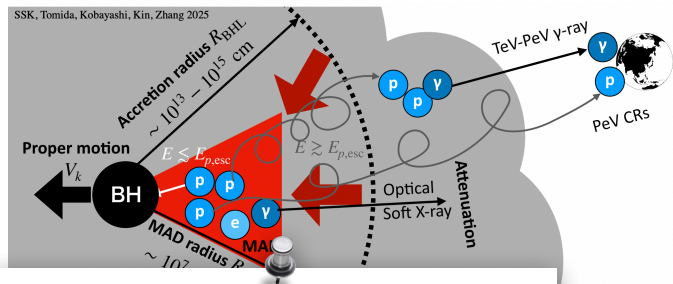
(Abaroa+ 2025)



- UnID gamma-ray sources spatially correlated with XRBs
- TeV gamma-ray activity linked with radio jets

Unassociated gamma-ray sources = X-ray binaries?

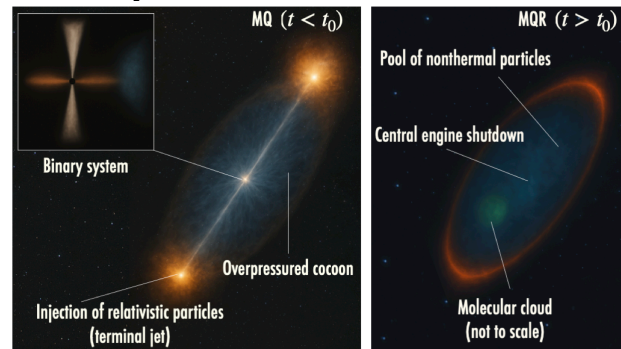
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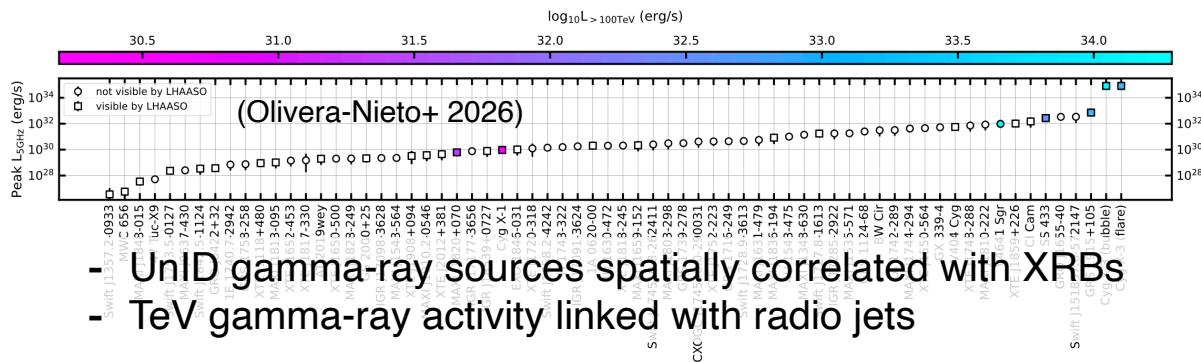
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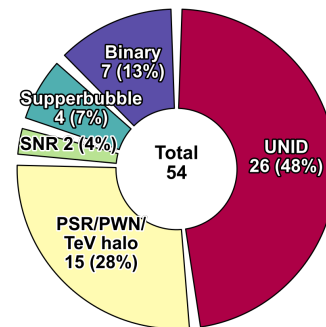
“Microquasar remnants as hidden PeVatrons”



(Abaroa+ 2025)



- UNID gamma-ray sources spatially correlated with XRBs
- TeV gamma-ray activity linked with radio jets



What's true fraction of PeVatrons, including the southern sources?

Summary

■ (Sub-)PeV gamma-ray astronomy

=> Diverse classes of Galactic PeVatron candidates

- Microquasars and Dark/unID sources
- SNRs, PWNe, Star clusters, and GC (not covered in this talk)

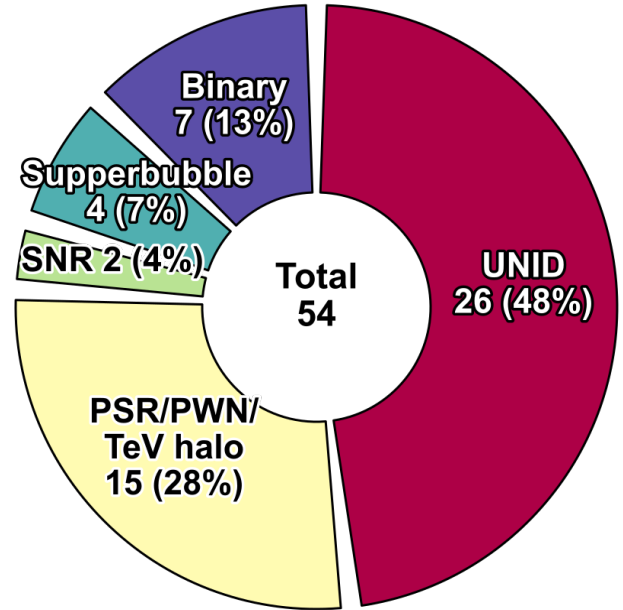
■ Microquasars

- Extensive X-ray survey of SS 433 and V4641 Sgr with Chandra, XMM, NuSTAR, IXPE, XRISM, and EP/FXT
- X-ray knot-like emission both in SS 433 and V4641
 - Acceleration sites?
 - Common key features in PeVatron microquasars?

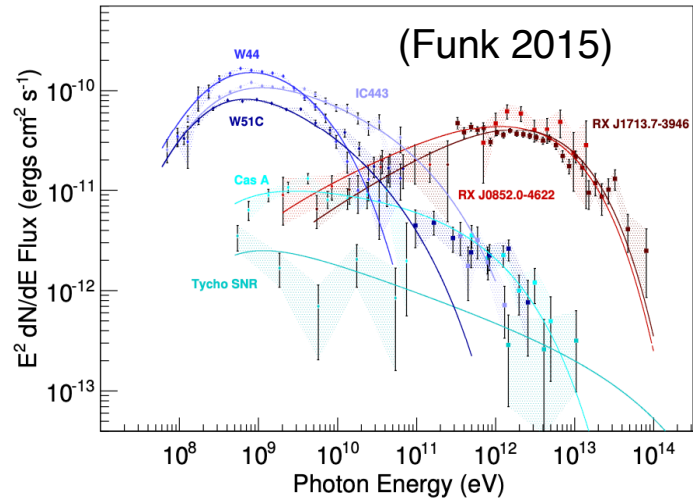
■ Dark/unID sources

- Our X-ray survey revealed PWN-like emission in a few LHAASO unID sources
- Are unID gamma-ray sources microquasars?
- → Ongoing MWL studies

Supernova remnants

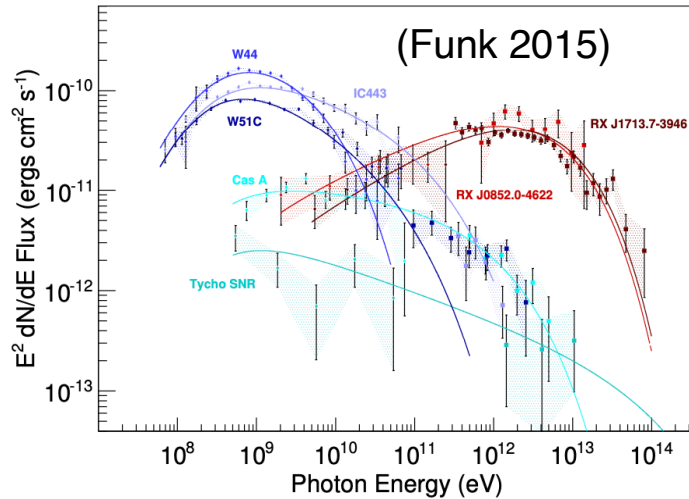


PeVatron SNRs?



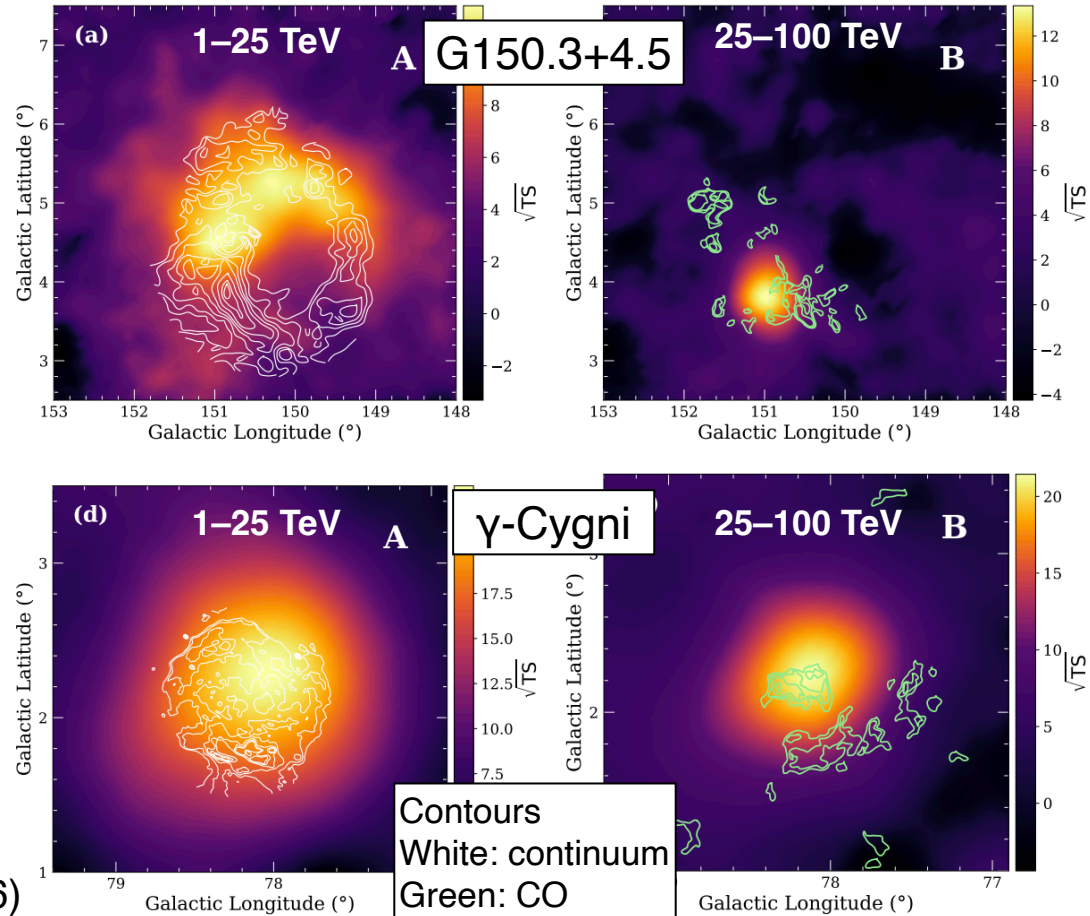
SNRs have cutoffs at 10s TeV
→ Challenging to be PeVatrons

PeVatron SNRs?

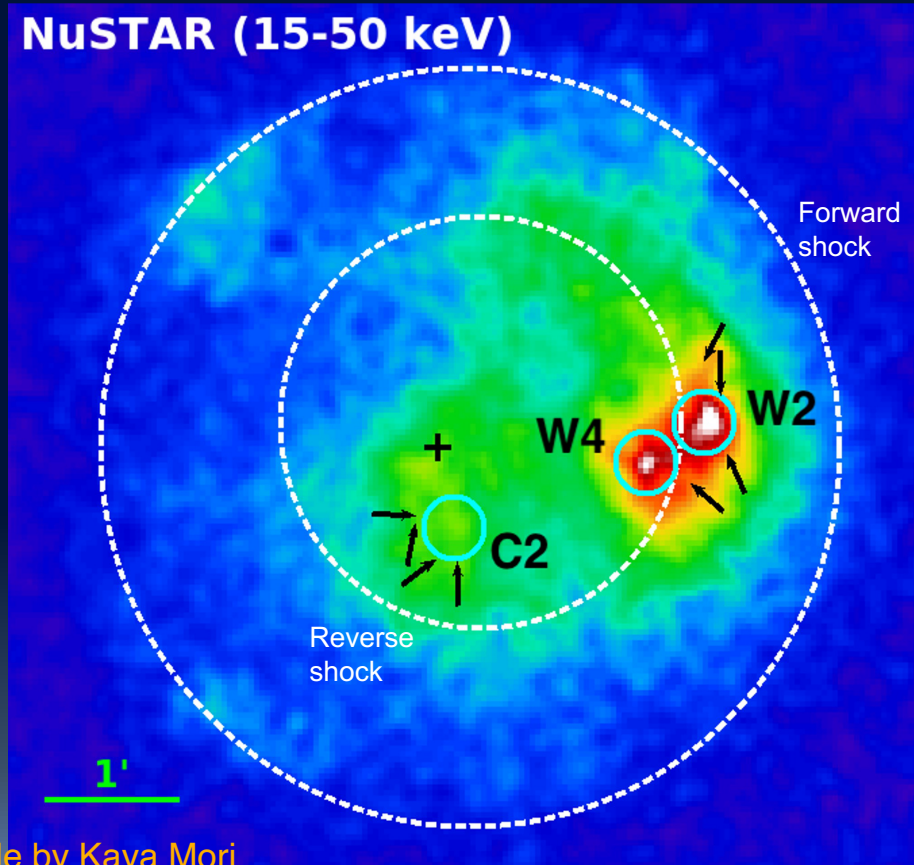


SNRs have cutoffs at 10s TeV
 → Challenging to be PeVatrons

The latest >100 TeV detection from several SNRs revived the interest of PeVatron SNRs (LHAASO Collab. 2026)



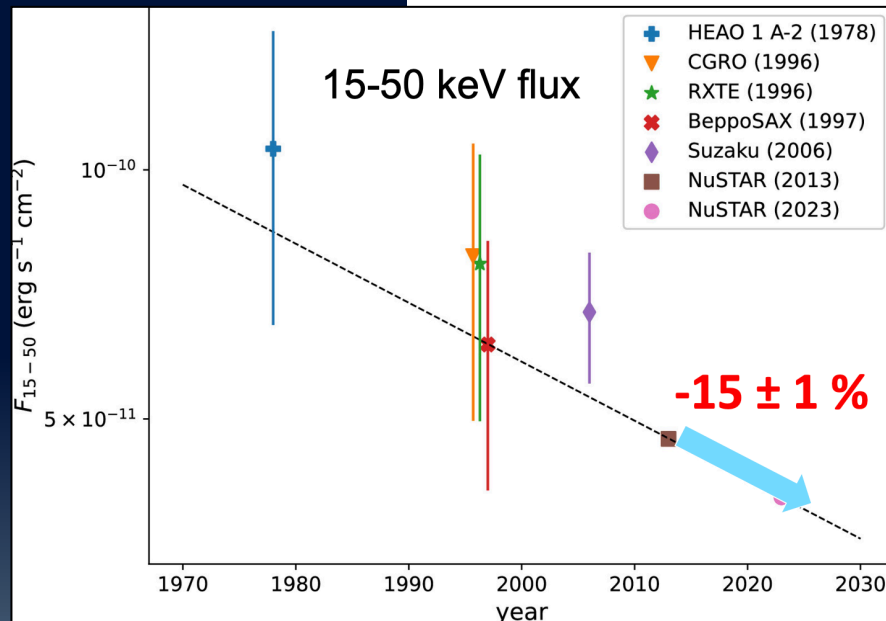
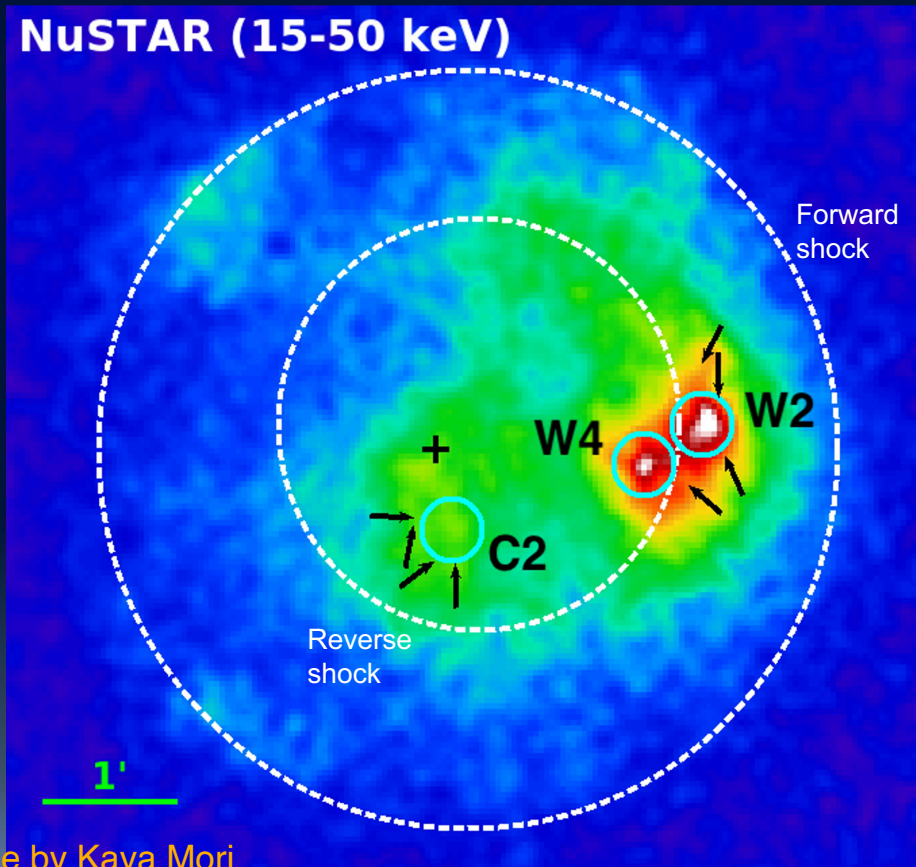
Cas A: NuSTAR located the most energetic electrons



2.4 Ms NuSTAR
observation in 2012
(Grefenstette+ 2015)

Cas A: NuSTAR located the most energetic electrons

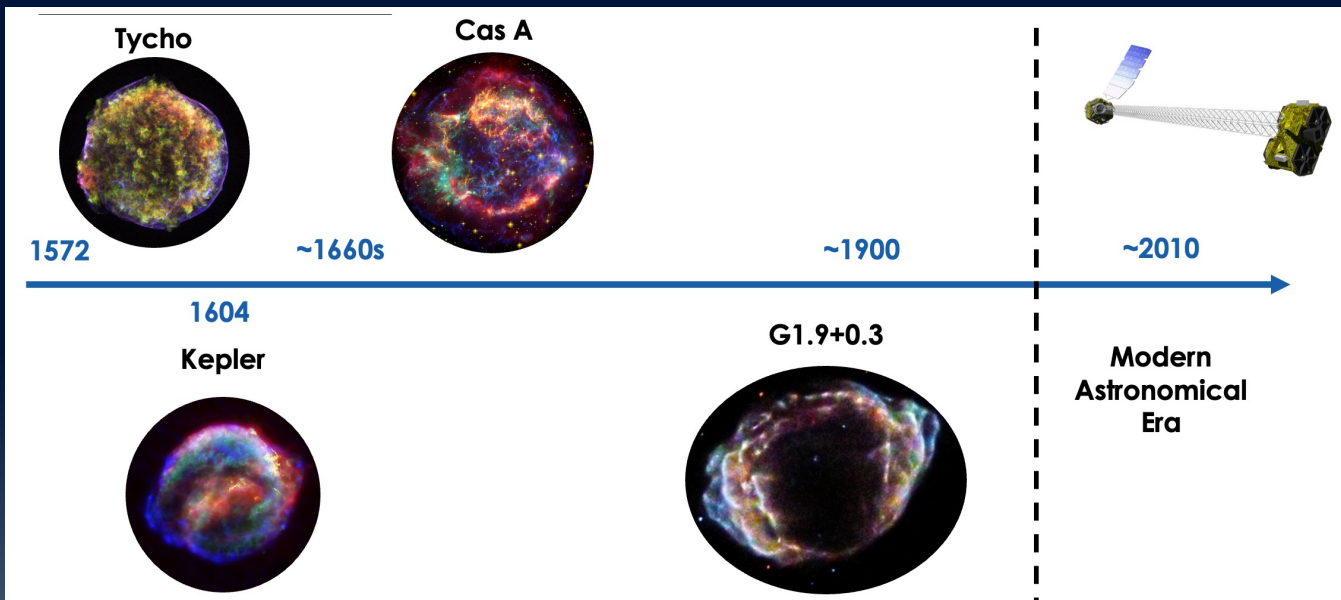
Hard X-ray flux *decreased* by 15% over 10 years
→ requires freshly injected accelerated particles
(Woo+ 2025)



Multi-epoch NuSTAR observations of young SNRs

- 1) NuSTAR spent mega-seconds to look for Ti44 nuclear lines
- 2) We can search for hard X-ray variability (synchrotron) over ~ 10 yrs

Analyses done by
Ceaser Stringfield, Lain
Brewer, Matthew Lundy
at Columbia U

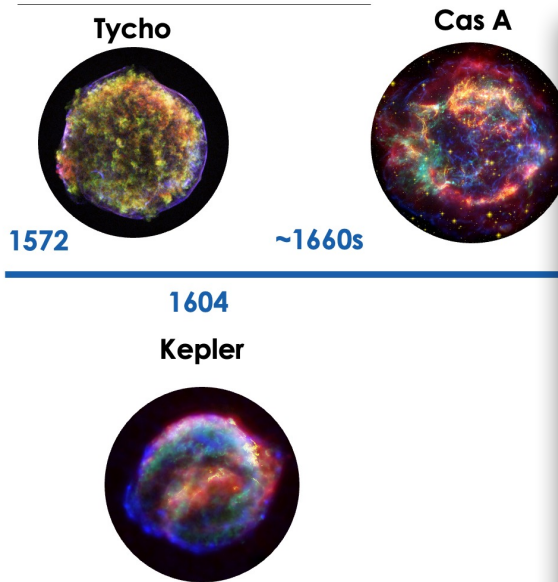


Presented by M. Lundy

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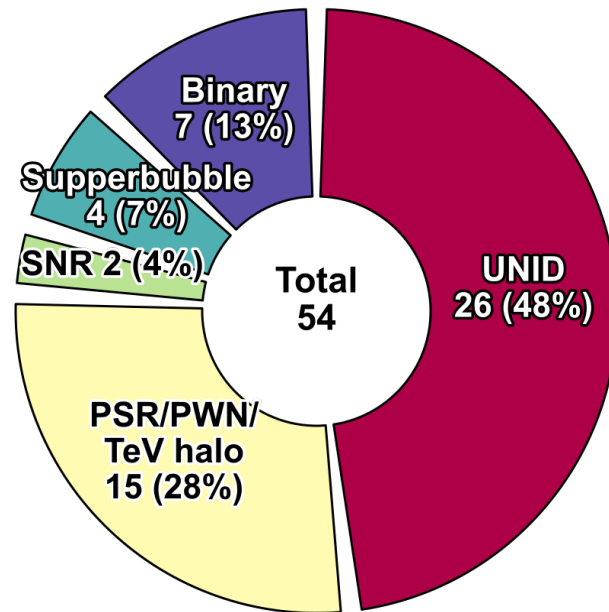


-1.5 to +1.5%/yr changes in young SNRs

	Cas A	G1.9+0.3	Kepler	Tycho
Supernova type	IIb	Ia	Ia	Ia
Age (yr)	350	100	420	450
Distance (kpc)	3.4	8.5	6	2.5
Flux change	-15% / 10 yr (15 – 50 keV)	+12% / 8 yr (3 – 20 keV)	0% / 10 yr (15 – 25 keV)	
Preexisting Electron spectrum	$\Gamma = 2.4$ $E_{cut} < 4 \text{ TeV}$	$\Gamma = 2.2$ $E_{cut} < 10 \text{ TeV}$		
Injection spectrum	$\Gamma < 2.2$ $E_{cut} < 36 \text{ TeV}$	$\Gamma < 2.2$ $E_{cut} < 32 \text{ TeV}$		

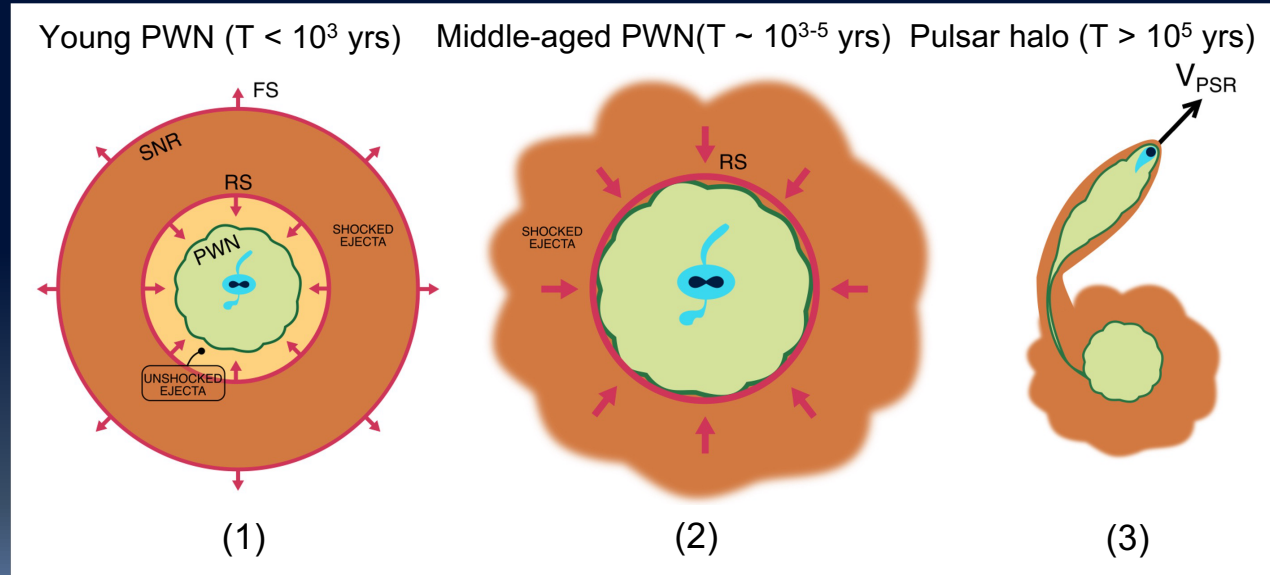
(c) Jooyun Woo

Pulsar, PWN, TeV halo



Three PWN evolution stages

- Many PWNe are associated with Galactic TeV sources.
- PWNe are powered by pulsar's rotational energy: $\dot{E} = I\Omega\dot{\Omega}$ [erg/s]
- Particle injection, propagation and cooling => complex MW morphology



Some of the middle-aged PWNe are PeVatrons

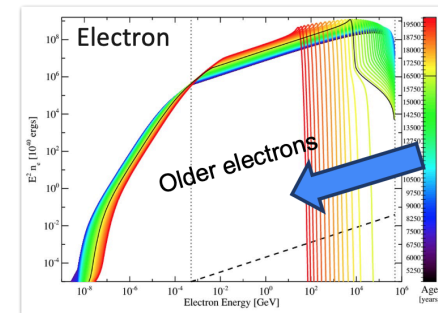
- NuSTAR LP program of 8 TeV-detected PWNe (PI: K. Mori)
- Fit two different PWN SED models
 - One-zone time evolution (VIPER; Gelfand group)
 - Multi-zone and Monte-Carlo simulation (An group)
- $E_{\text{max}} \sim 1\text{-}2 \text{ PeV} \Rightarrow \text{PeVatron PWNe}$

PWN name	LHAASO source	Edot [erg/s]	Spin-down age [kyr]	E_{max} [PeV]	B [uG]
Eel	J1825-1256u	3.6×10^{36}	14	2	1
Dragonfly	J2020+3649u	3.4×10^{36}	17	1	3
Boomerang	J2228+6100u	2.2×10^{37}	10	1	3
G32.6+0.53	1848-0001u	9.8×10^{36}	43	0.4	7
Kookaburra	NA	1×10^{37}	13	0.9	5
Rabbit	NA	5×10^{36}	10	1	12
G0.9+0.1	NA	5×10^{37}	5.3	2	20

PWN evolution models

(Gelfand+ 2009, Torres+ 2014, Park+ 2023)

- (1) Inject pulsar's spin-down energy into PWNe
- (2) Evolve with cooling



(3) Fit

