

Multiwavelength Observations of PeVatrons and Microquasars

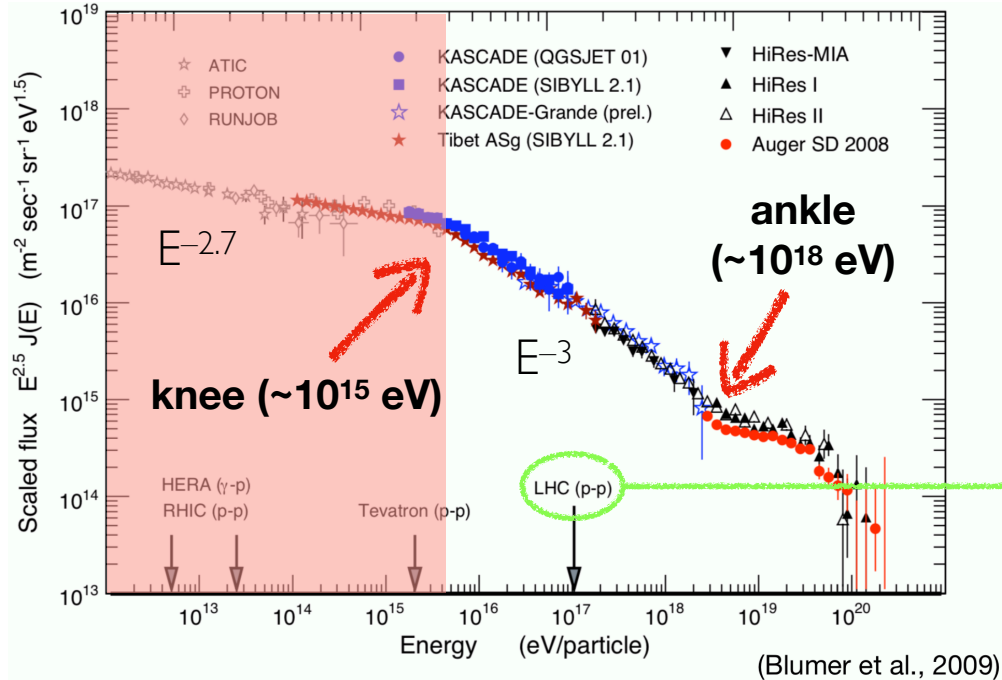
**“MeV–PeV Frontiers: New Perspectives in Gamma-Ray Astronomy and Particle Acceleration”
at Kavli IPMU**

December 16–18, 2025

Naomi Tsuji (ICRR / University of Tokyo)

Cosmic Ray (CR)

- ✓ High-energy particles in space
- ✓ Protons (~90%), He nuclei (~10%), electrons, and heavy nucleon
- ✓ ~600 events/m²/yr@10¹⁵ eV and ~2 events/100 km²/yr@10²⁰ eV
- ✓ CR spectrum has two breaks; knee and ankle



Where do CRs come from?
(=What is acceleration site?)

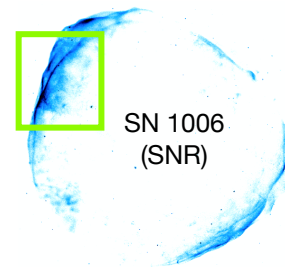
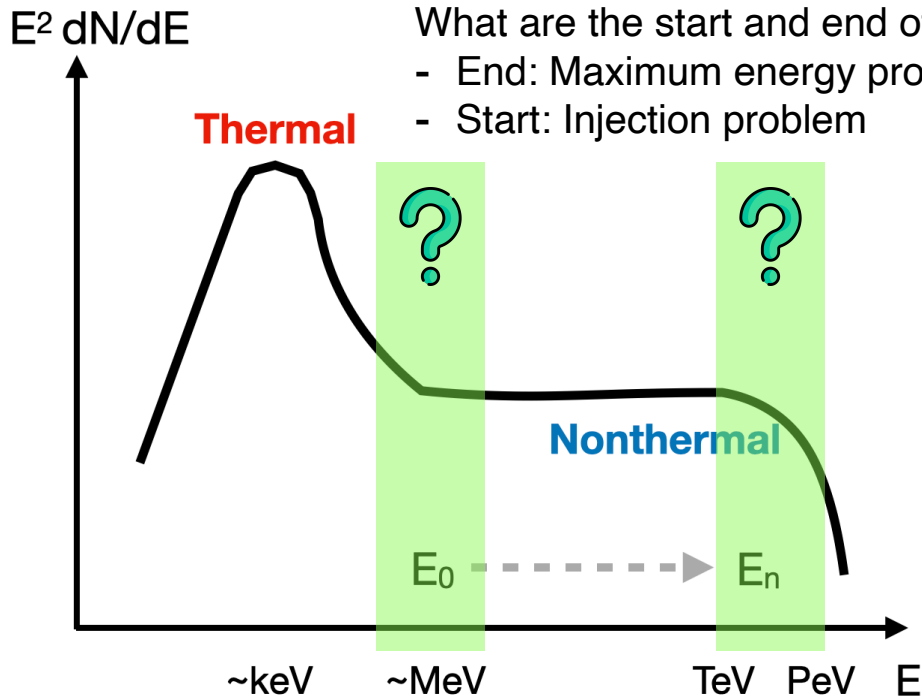
< knee → **Galactic SNRs**
 knee—ankle → Unknown
 > ankle → Extragalactic?

The most powerful accelerator at Earth (LHC)

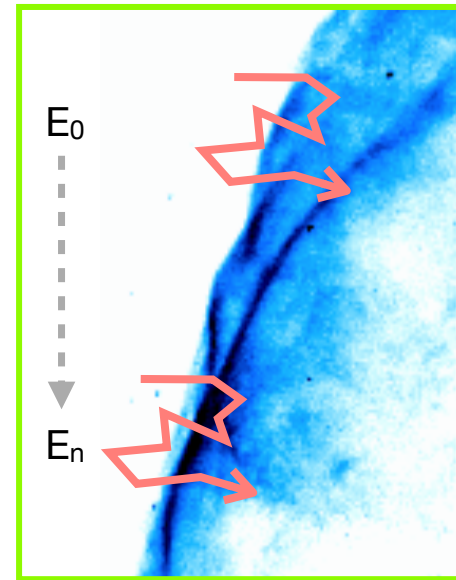


Particle acceleration

Diffusive shock acceleration



Shock wave at SNR surface



1. Introduction
2. Maximum energy problem: search for PeVatrons
 - A. Microquasars
 - B. Dark PeVatrons
 - C. X-ray to probe for CR protons
3. Injection problem: prospects for hard X-ray and MeV
4. Summary

1. Introduction

2. Maximum energy problem: search for PeVatrons

A. Microquasars

B. Dark PeVatrons

C. X-ray to probe for CR protons

3. Injection problem: prospects for hard X-ray and MeV

4. Summary

Gamma rays to find PeVatrons

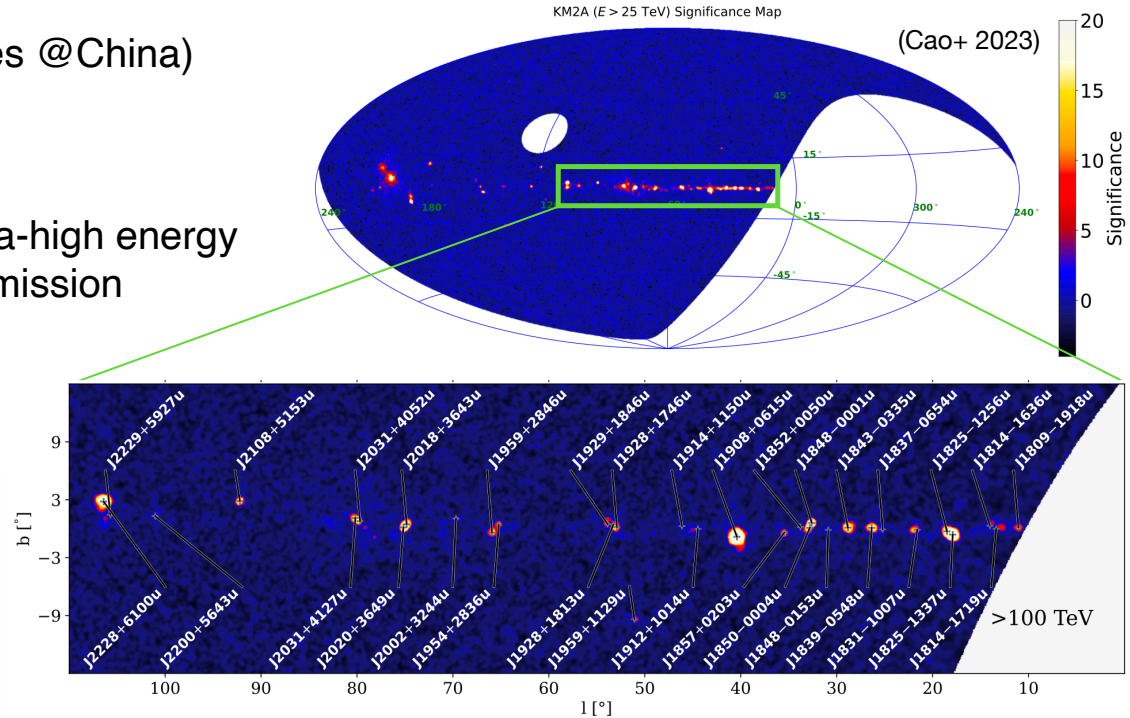
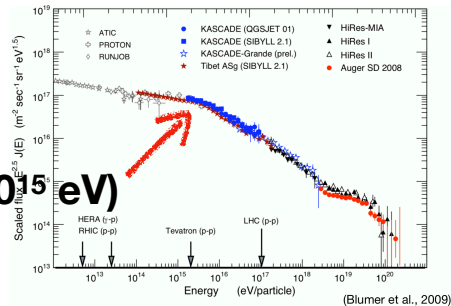
LHAASO (ground-base telescopes @China)
in operation since 2019

43 sources are detected with ultra-high energy
($E_\gamma > 100$ TeV, thus $E_p > 1$ PeV) emission



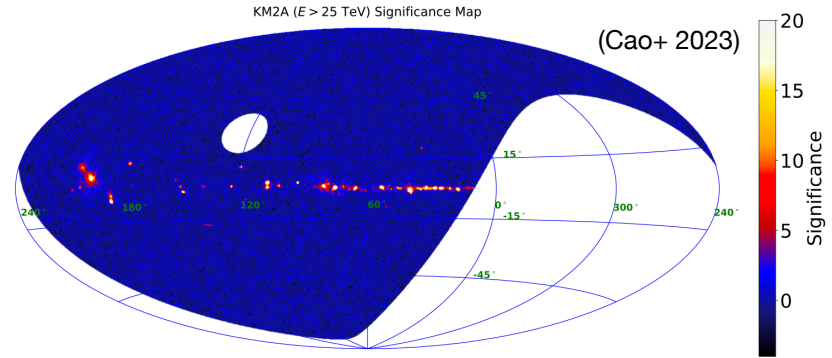
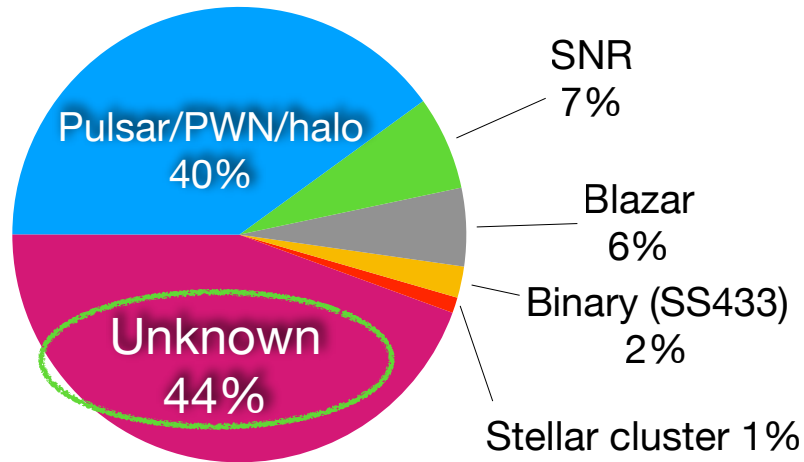
Contribution to CR knee!

knee ($\sim 10^{15}$ eV)



Gamma rays to find PeVatrons

Source breakdown of LHAASO catalog



- New type PeV CR accelerators: stellar cluster and binary
- Many unknown sources
→ Should be investigated at different wavelengths

Microquasars

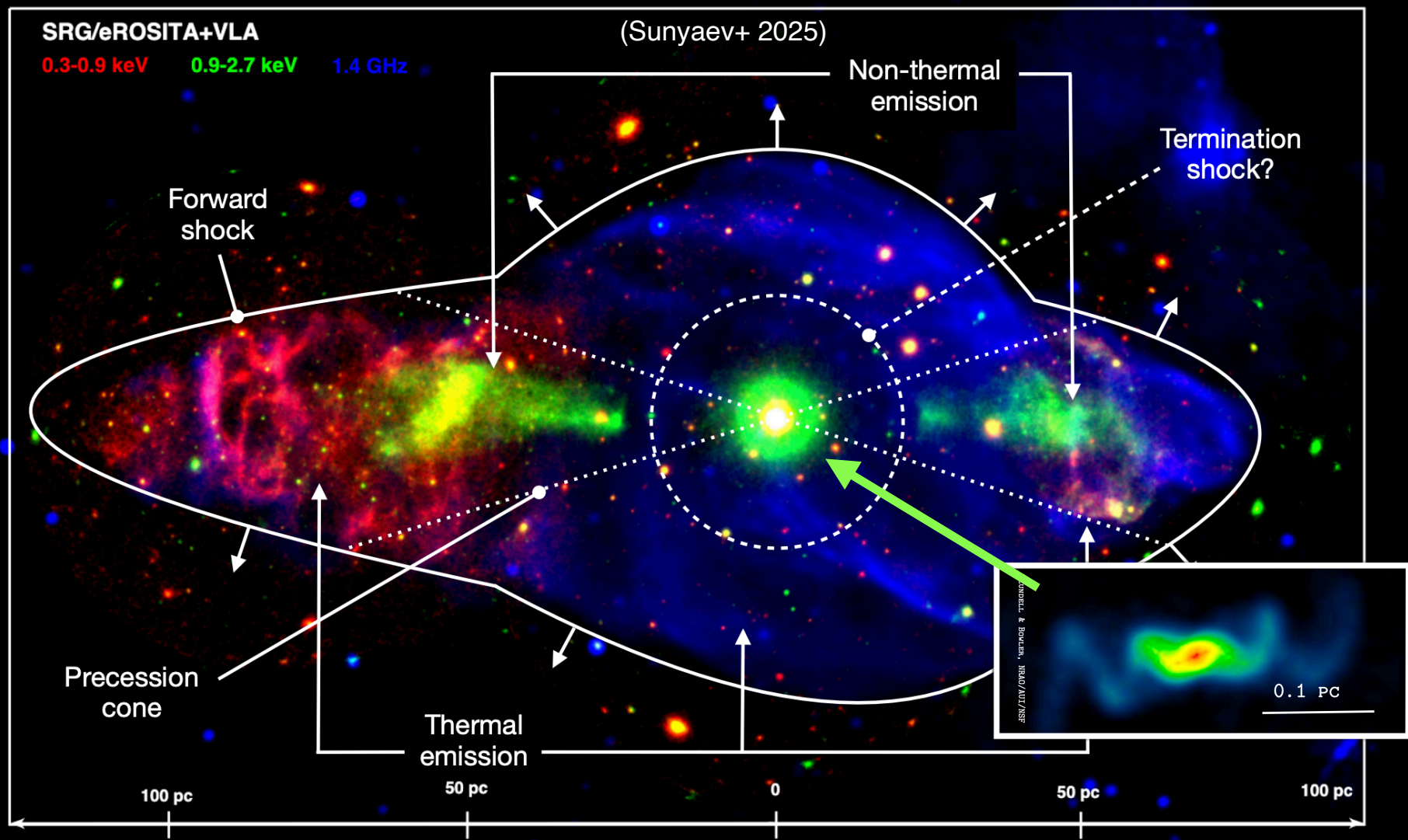
SRG/eROSITA+VLA

(Sunyaev+ 2025)

0.3-0.9 keV

0.9-2.7 keV

1.4 GHz



SRG/eROSITA+VLA

(Sunyaev+ 2025)

0 9-2.7 keV 1.4 GHz

Non-thermal
emission

Termination
shock?

EAST

Gamma rays

WEST

Gamma rays

e1

e2

e3

w1

w2

Precession
cone

Thermal
emission

100 pc

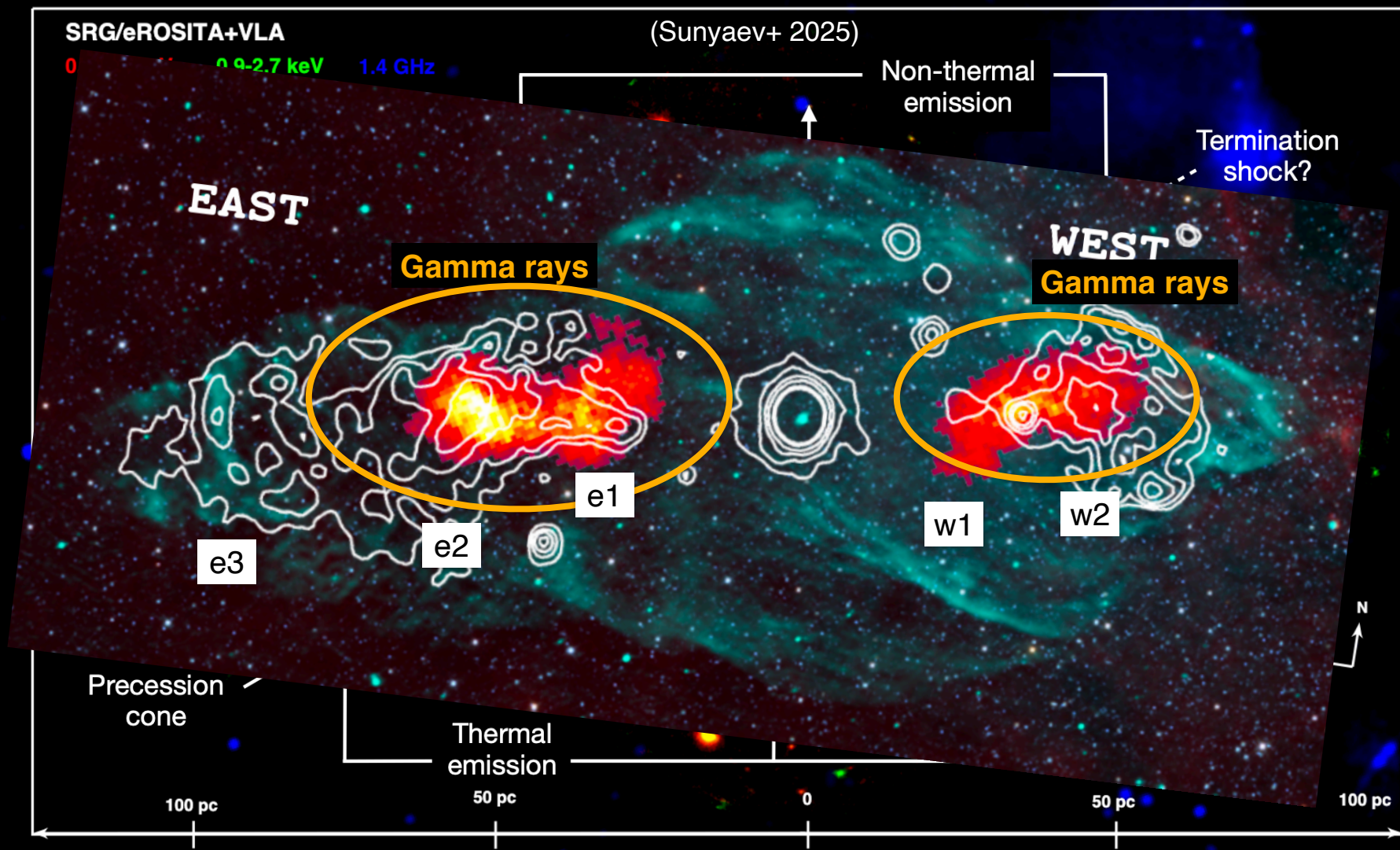
50 pc

0

50 pc

100 pc

N



eROSITA in 0.5-6 keV

XMM in 2004

Chandra in 2003

e3

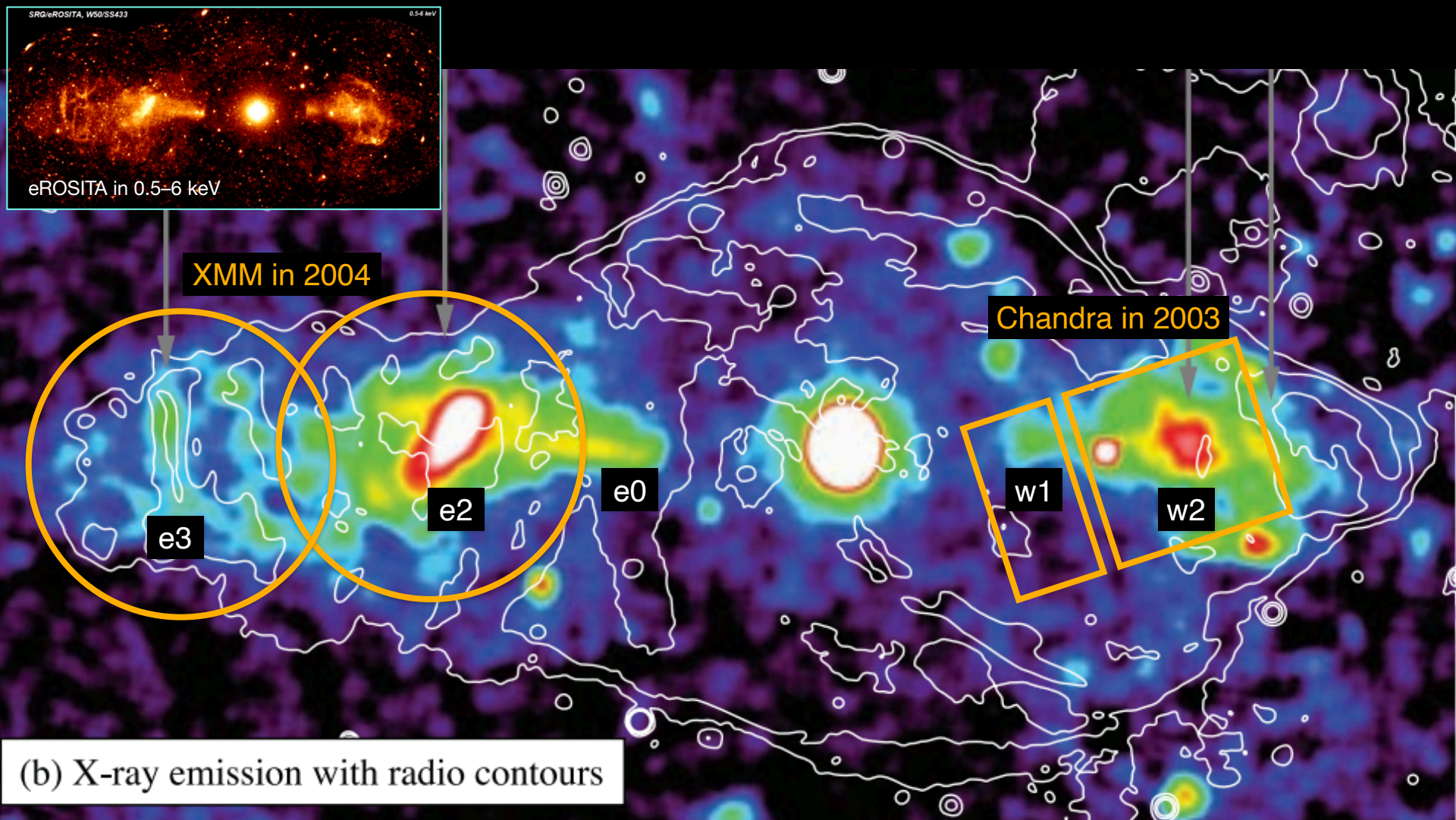
e2

e0

w1

w2

(b) X-ray emission with radio contours



eROSITA in 0.5–6 keV

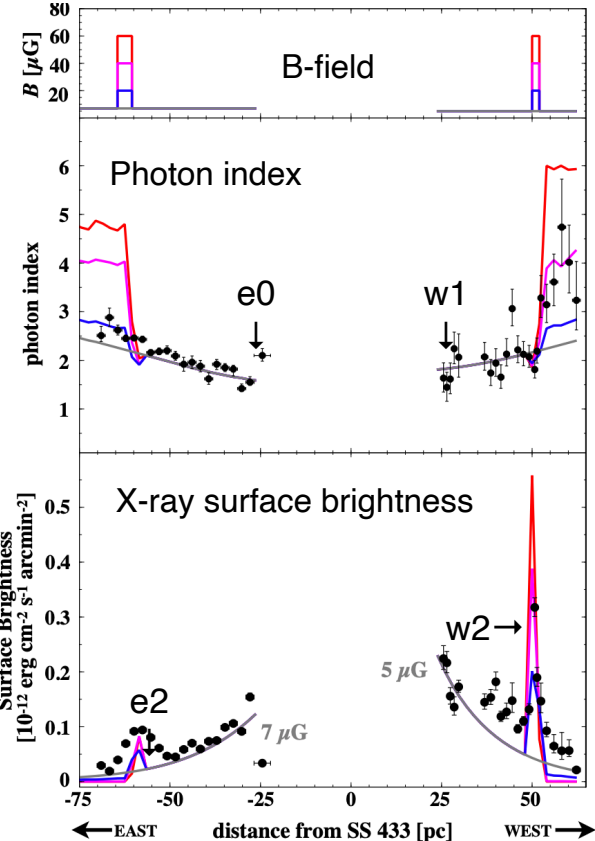
XMMThermal ($kT \sim 1$ keV) emission
SNR or jet/wind?

Clump

Shell

XMM + NuSTAREastern head knot with $\Gamma \sim 1.6$
up to 30 keV without cutoff

(Safi-Harb+ 2022)

IXPEPolarization degree 38–77%
B-field parallel to the jet axis
(Kaaret+ 2024)X-ray spectral profile along the lobes
(Kayama+ 2022; 2025)

(b) X-ray emission with radio contours

SRG/eROSITA+VLA

0.3-0.9 keV

0.9-2.7 keV

Forward
shock

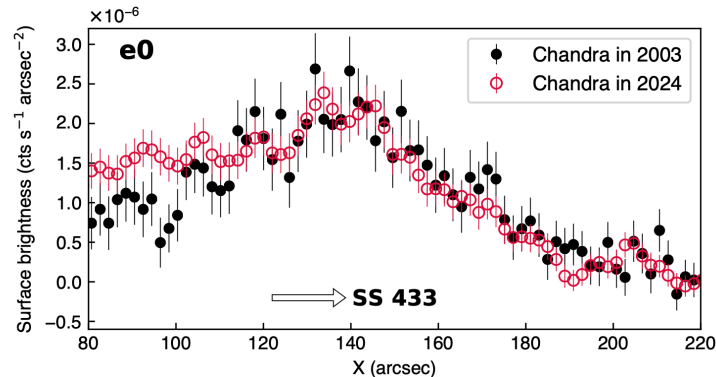
Precession
cone

Thermal
emission

100 pc

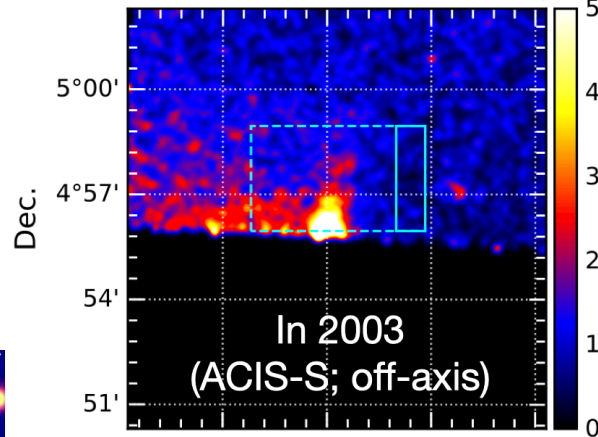
50 pc

0



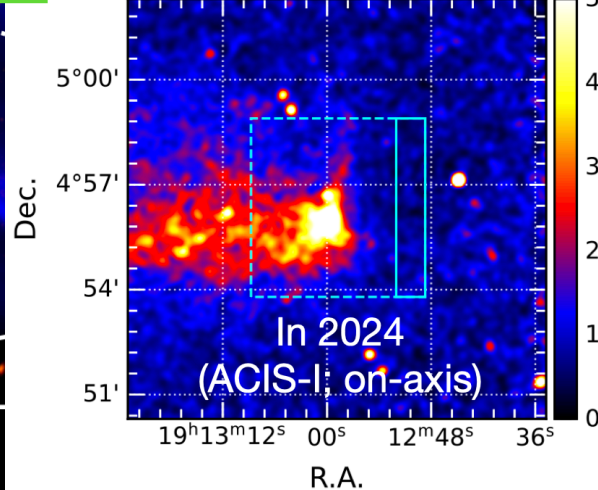
e0 in 2003 (Chandra)

× 10⁻⁶



e0 in 2024 (Chandra)

× 10⁻⁶



Comparison of 2003–2024 data
Apparent velocity < 0.02c
Shock velocity ~ 10⁴ km/s
→ Efficient particle acceleration
(Tsuji+ 2025)

Stay tuned—more exciting X-ray results ahead!



AXIS

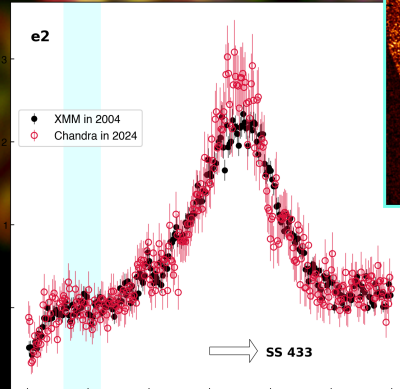
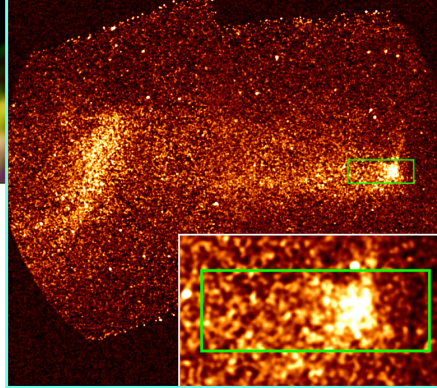
NASA's Probe mission
(Reynolds+2023; Safi-Harb+ 2023)

XRISM

Resolve on SS 433 + Xtend on diffuse
184 ks in PV phase and 80 ks in AO-2
(Shidatsu, Suzuki, et al.)

Xtend 4–7 keV

AXIS 50-ks simulation



XMM and Chandra

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

IXPE

Polarization at w1
AO-2 observation underway
(Kaaret et al.)

XMM

NuSTAR

XM

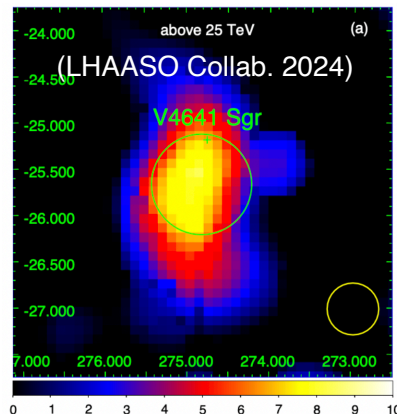
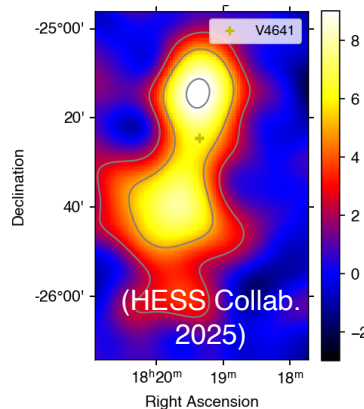
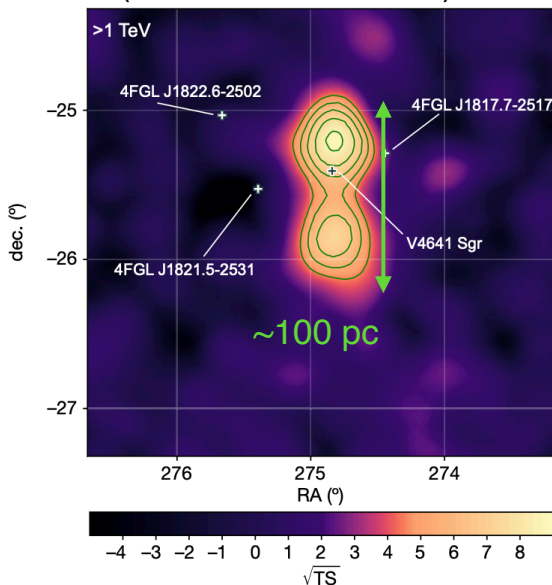
NuSTAR + XMM

New w3 or w2-north/w2-south?
(kT ~ 0.27 keV; enhanced Mg and Si)
(Mac Intyre+ in prep.)

V4641 Sgr

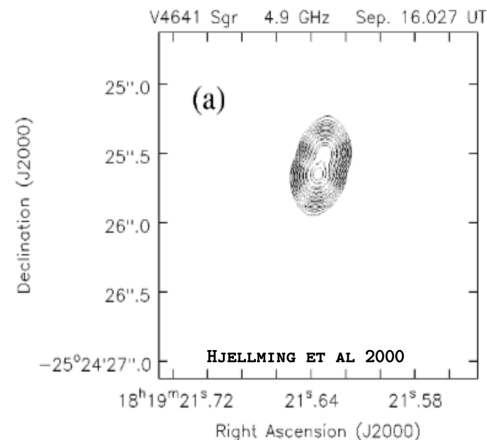
2nd example of VHE gamma-ray microquasar: V4641 Sgr

(HAWC Collab. 2024)



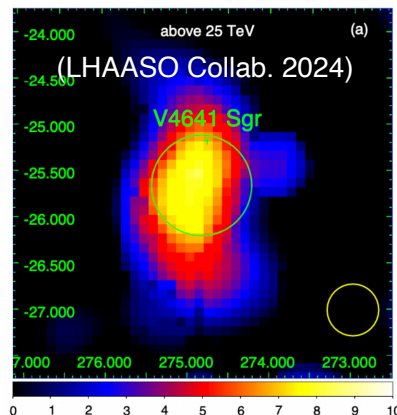
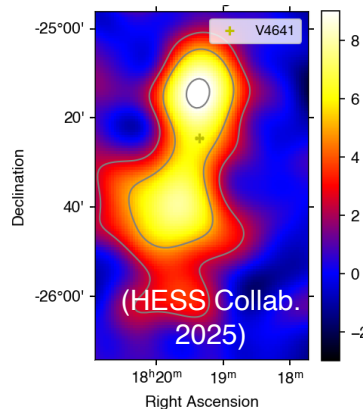
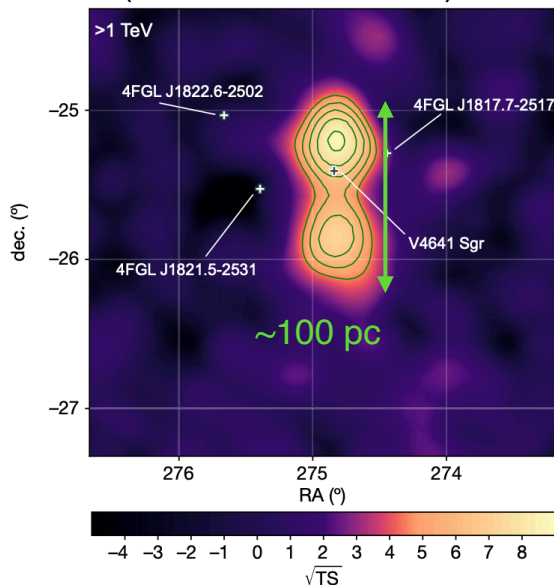
V4641 Sgr

- 6.4 M_{sun} BH and 2.9 M_{sun} B9III star
- Discovered in 1999 during outburst ($L_X \sim 10^{39}$ erg/s)
- Super-luminal proper motions $\rightarrow$ relativistic jet with low inclination angle (“microblazar”)



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

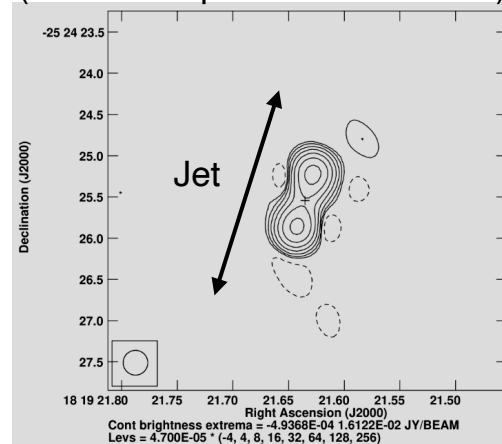
(HAWC Collab. 2024)



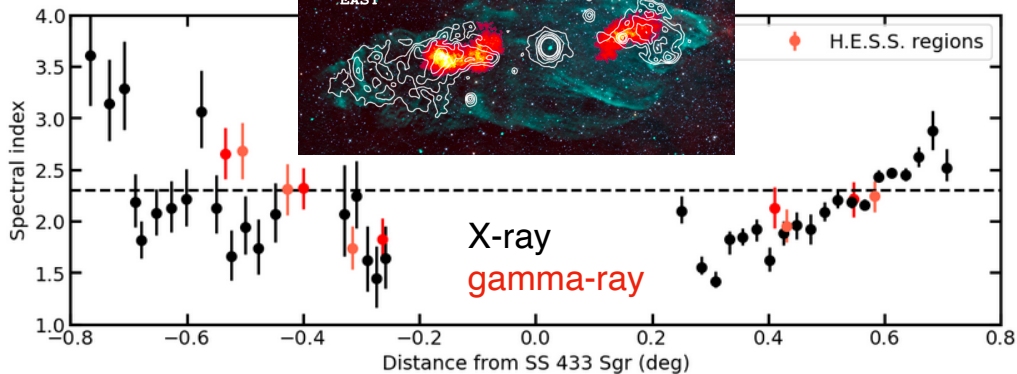
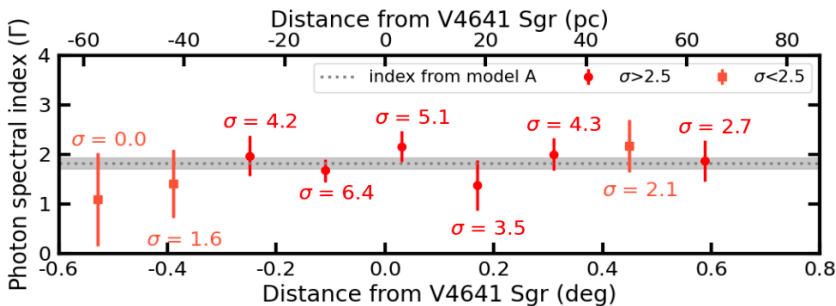
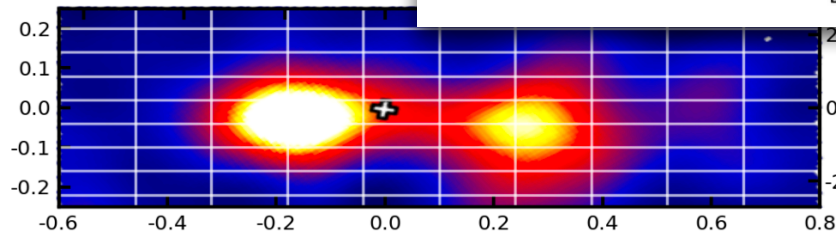
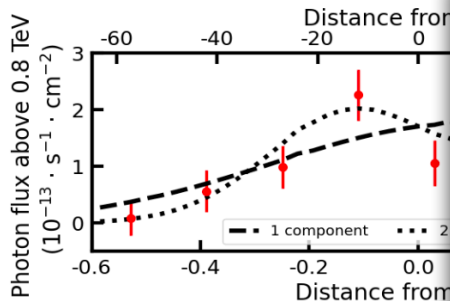
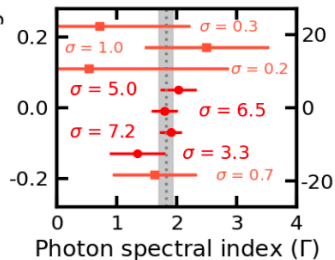
V4641 Sgr

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

Reanalysis of VLA data revealed jets aligned the gamma-ray emission (Marti & Luque-Escamilla 2025)



Distance from V4641 Sgr (deg)

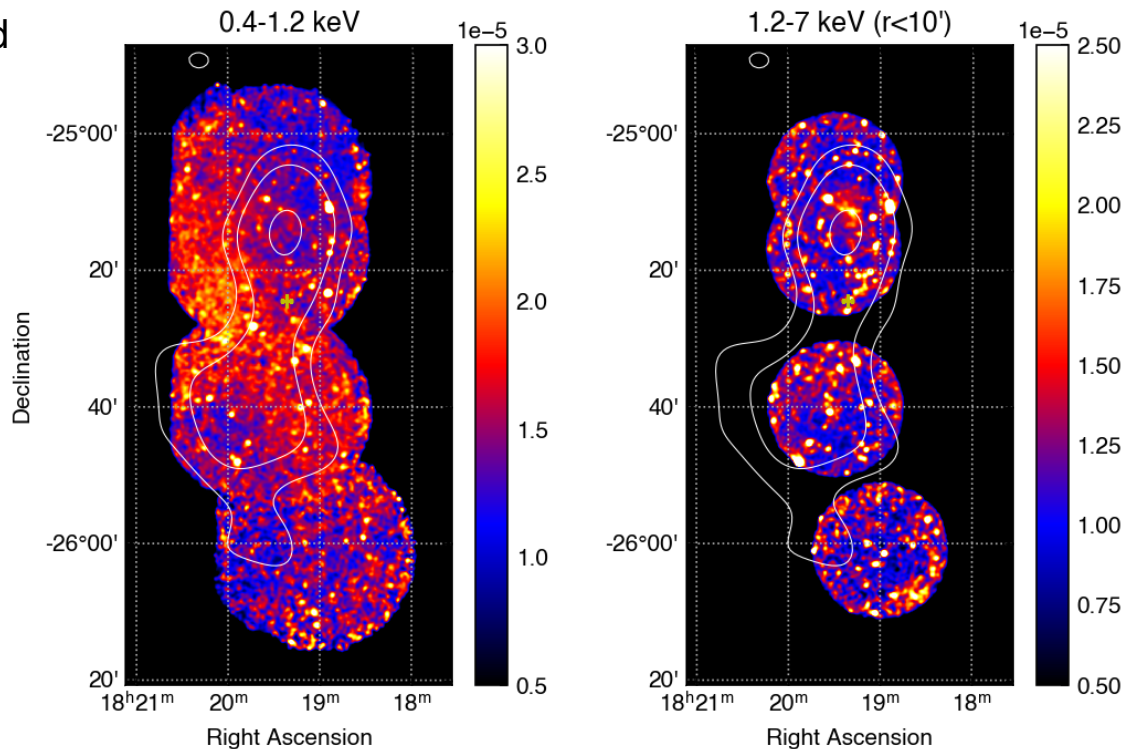


- Photon index ~ 2 across the entire gamma-ray region
- Fast advection and slow cooling

XMM-Newton observation

- Some structures in soft/thermal band
(Probably not related to V4641)
- No clear X-ray counterparts of the gamma-ray emission
- Many point-like sources
 - Too many at $b = -5$ degree?
 - XRISM/Xtend diffuse $\rightarrow$ unresolved point sources?
 - Some might be molecular cores?

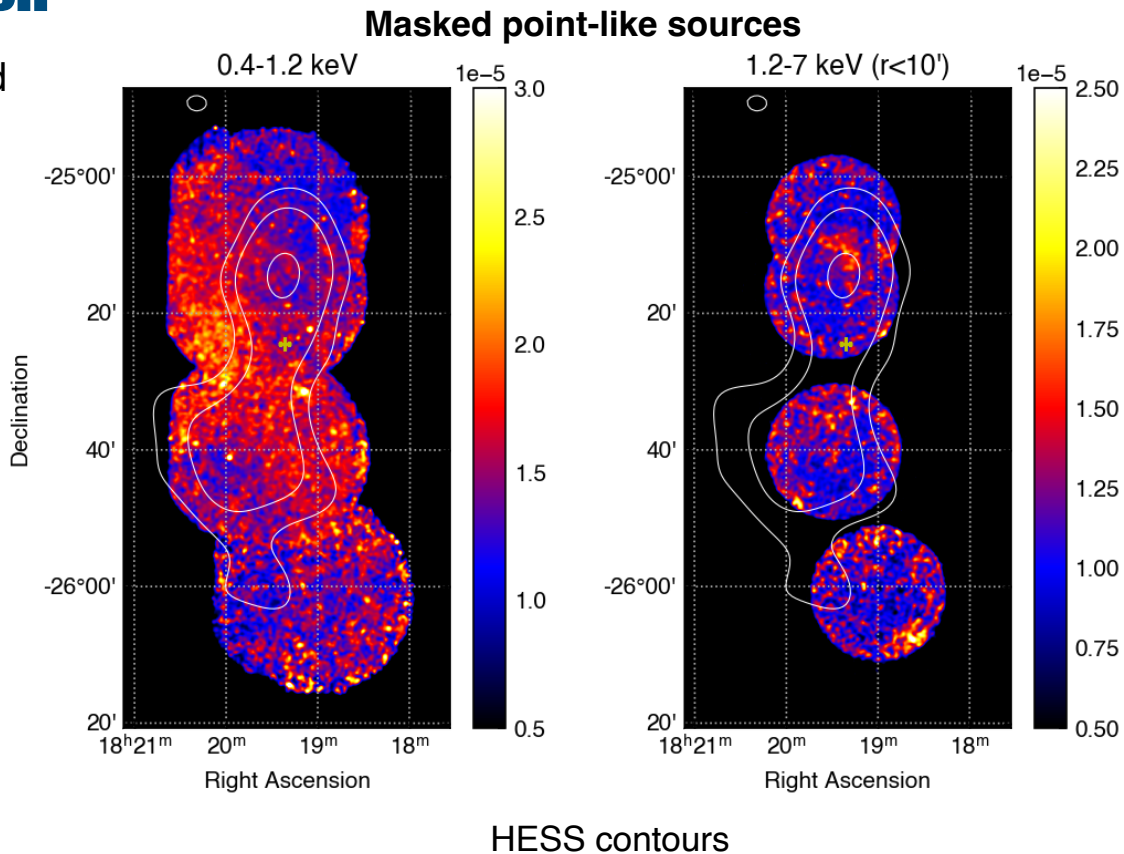
Observed on September, 2025
First X-ray view of the entire gamma-ray region



HESS contours

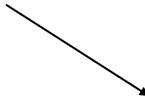
XMM-Newton observation

- Some structures in soft/thermal band (Probably not related to V4641)
- No clear X-ray counterparts of the gamma-ray emission
- Many point-like sources
 - Too many at $b = -5$ degree?
 - XRISM/Xtend diffuse $\rightarrow$ unresolved point sources?
 - Some might be molecular cores?
- Faint diffuse emission around north gamma-ray peak?
- Future work: detailed analysis (spectra, diffuse, point-like sources)



MWL view of V4641 Sgr

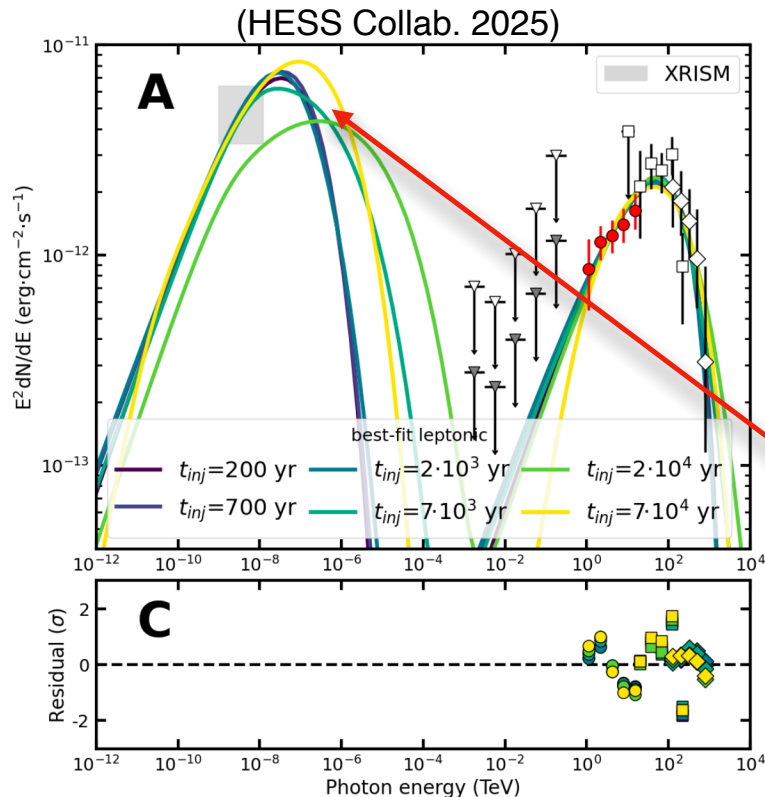
Very recent MeerKAT observation
(Grollimund+ submitted)



MWL observation (...a mess!)

- (Likely) two lobes in TeV
- No detection in GeV
- No clear counterparts in X-ray
- “Bow-tie” structure in radio continuum
- No molecular clouds nor gas

Particle acceleration in V4641 Sgr?



Hadronic scenario

- $n < 0.2 \text{ cm}^{-3}$
- A lot in proton energetics ($L_{\text{source}} \sim L_{\text{edd}}$ for millions of years/entire age of source)

Leptonic scenario

- $B < 2\text{--}3 \text{ uG}$
- Fast advection ($>0.1c$) and slow cooling

E_{max} reaches $\sim \text{PeV}$

Synchrotron peaked at MeV
(Same for SS 433)

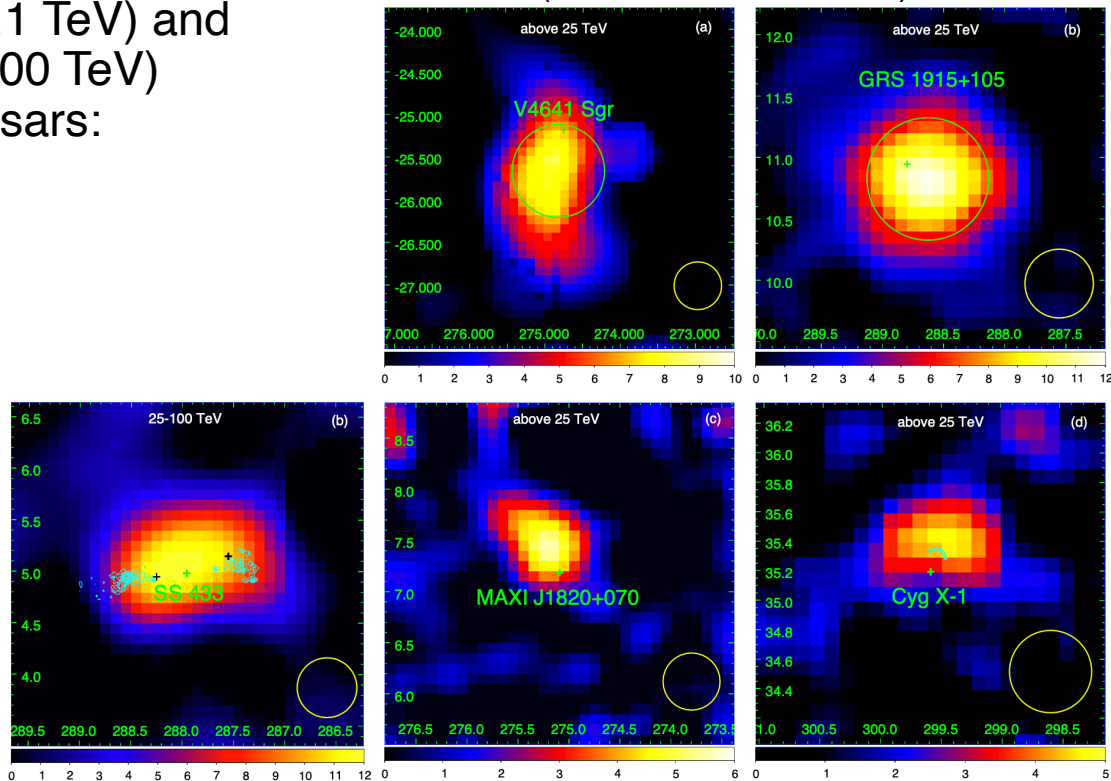
Microquasars at VHE-UHE gamma rays

(LHAASO Collab. 2024)

- Very-high-energy (VHE; >0.1 TeV) and Ultra-high-energy (UHE; >100 TeV) gamma rays from microquasars:
 - SS 433
 - V4641 Sgr
 - GRS 1915+105
 - MAXI J1820+070
 - Cyg X-1

→ Particle accelerated up to $> \text{PeV}$

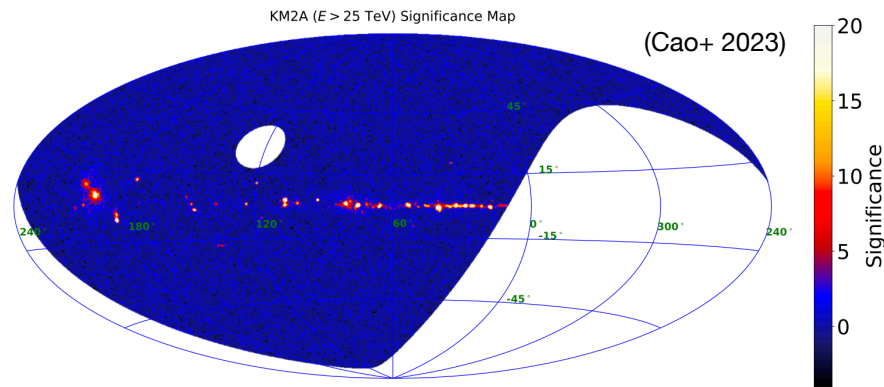
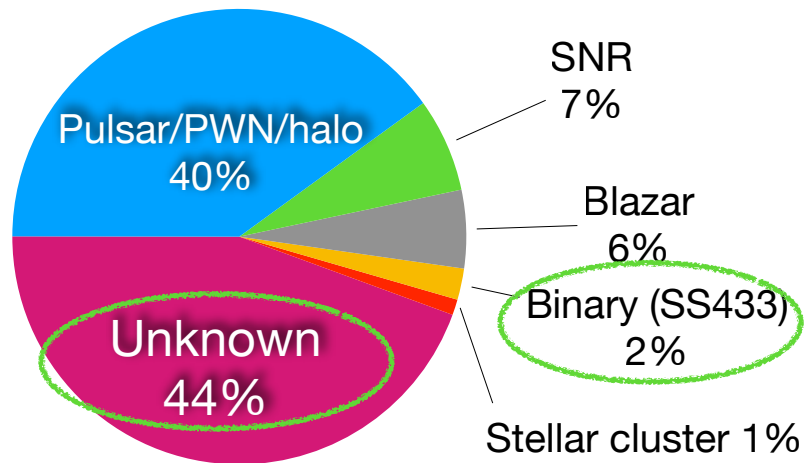
→ Microquasars (substantially) contribute to PeV cosmic rays?



Dark PeVatrons

Gamma rays to find PeVatrons

Source breakdown of LHAASO catalog



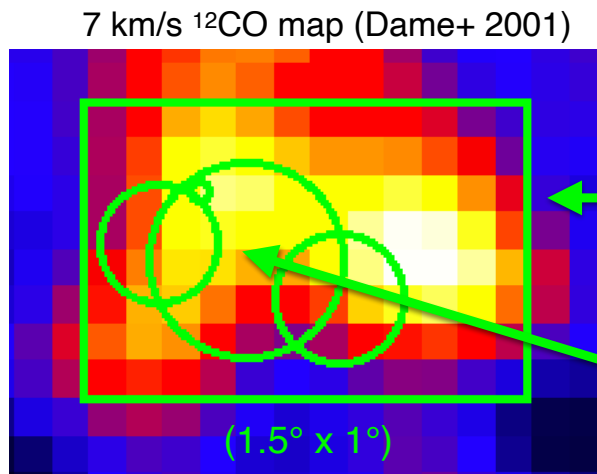
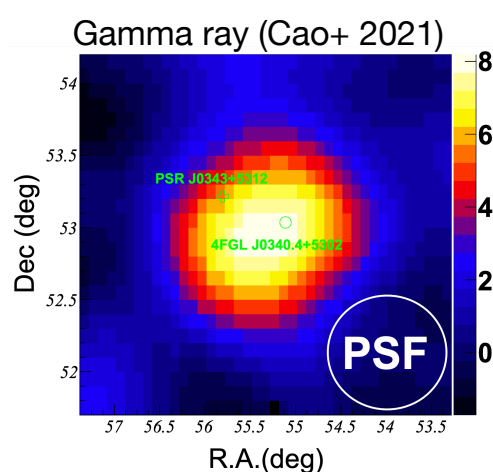
- New type PeV CR accelerators: stellar cluster and binary
- Many unknown sources
→ Should be investigated at different wavelengths

LHAASO J0341 + 5258: X-ray and CO observations

■ 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

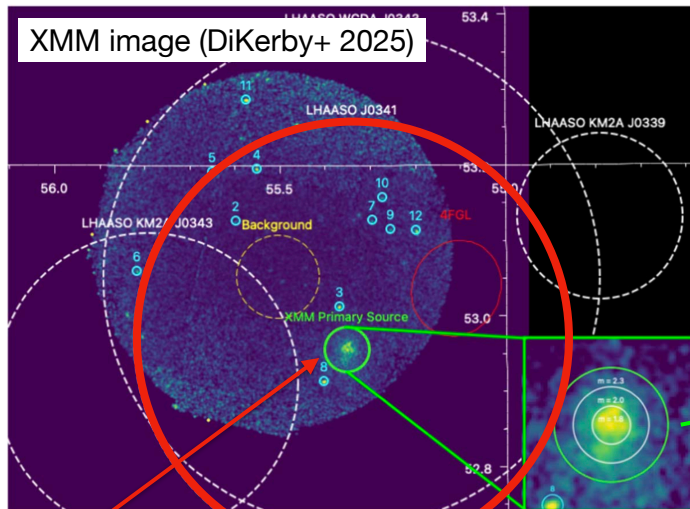
Observations of ^{12}CO , ^{13}CO , and C^{18}O lines ($J=1-0$)



XMM-Newton



LHAASO J0341 + 5258



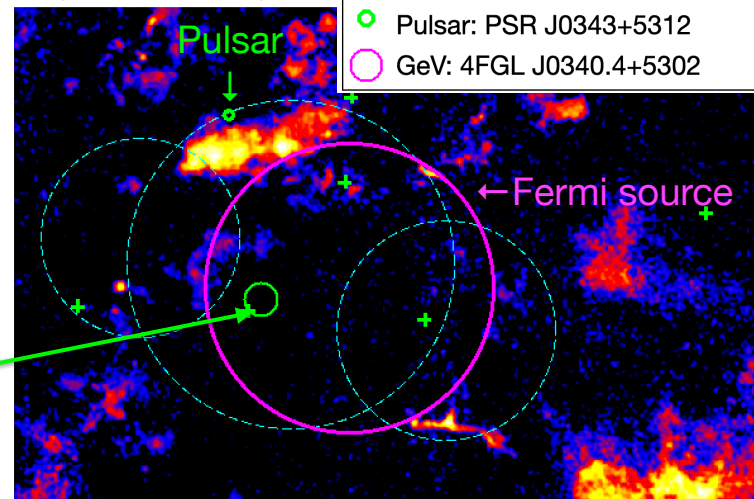
At the very center of firstly reported LHAASO emission

■ **Leptonic: pulsar/PWN + halo**

Extended X-ray emission (likely PWN) in new XMM data

→ Follow-up Chandra + NuSTAR in 2026

Nobeyama ^{12}CO image
(-40 to 10 km/s)



- + X-ray: 4 ROSAT sources (Boller et al. 2016)
- Pulsar: PSR J0343+5312
- GeV: 4FGL J0340.4+5302

■ **Hadronic: CR + clouds**

Molecular clouds (Tsuji+ 2025)

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

$$W_p \sim 3 \times 10^{45} \left(\frac{d}{1 \text{ kpc}} \right)^2 \left(\frac{n}{100 \text{ cm}^{-3}} \right)^{-1} \text{ erg}$$

CO and X-ray studies of PeVatron candidates

nature First 12 UHE sources

Explore content ▾ About the journal ▾ Publish with us ▾ Subscribe

[nature](#) > [articles](#) > [article](#)

Article | Published: 17 May 2021

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

First LHAASO catalog

THE ASTROPHYSICAL JOURNAL

SUPPLEMENT SERIES

OPEN ACCESS

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](#)

Published 2024 February 27 • © 2024. The Author(s). Published by the American Astronomical Society.

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

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

Source name	X-ray	CO
LHAASO J0341+5258	Extended (PWN-like)	Yes
LHAASO J2108+5157	No	Yes
1LHAASO J0622+3754	Point-like (Pulsar)	—
1LHAASO J1956+2921	No	Yes

Second round “high-b dark sources”

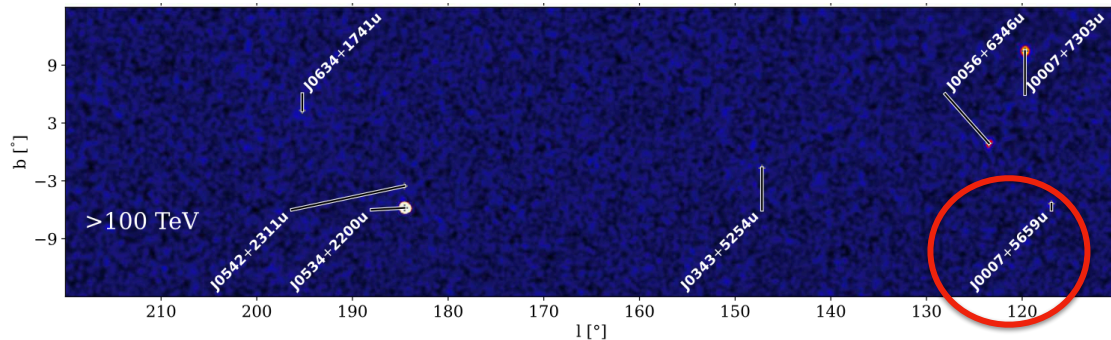
Source name	X-ray	CO
1LHAASO J0216+4237u (peanut)	?	No
1LHAASO J0007+5659	?	Yes
1LHAASO J1959+1129	Binary?	No
SWIFT J1727.8-1613	Microquasar	Scheduled in 2026

Collaboration with

K. Mori, S. Takekawa, A. Mitchell, S. Zhang, P. Bangale, J. Gelfand, J. Alford, J. Woo, S. Safi-Harb, I. Sander, L. Olivera-Nieto, and E. de la Fuente

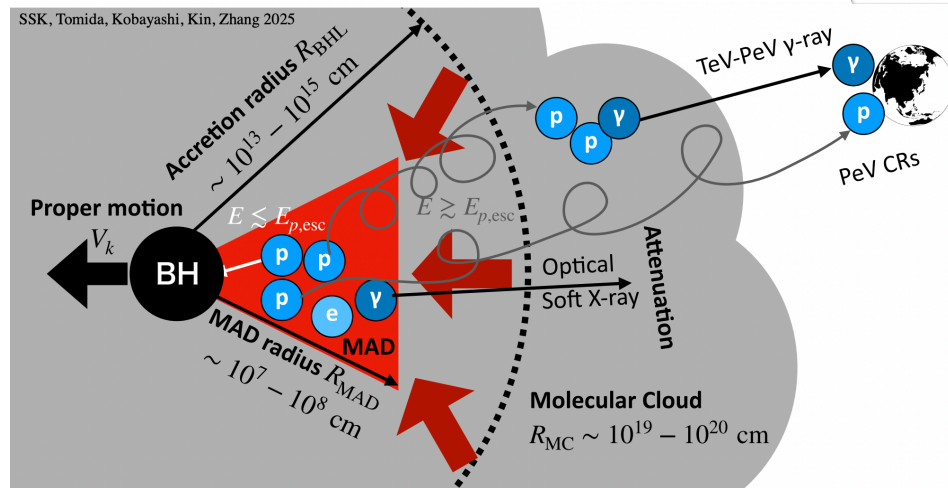
1LHAASO J0007 + 5659

- High-latitude with $b = -5$ deg
- Detected by only KM2A
 - $\Gamma = 3.10 \pm 0.20$
 - $r_{39} < 0.18$ deg
- No known source

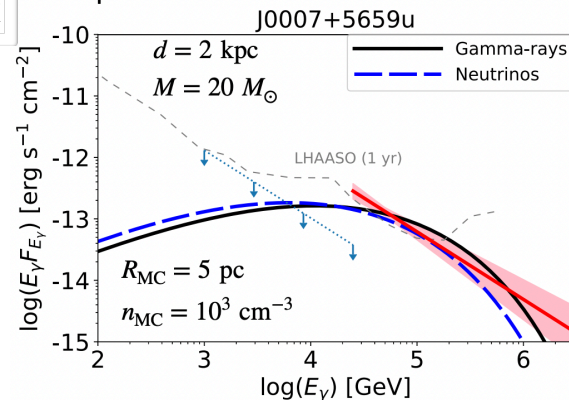


“Isolated black holes in MCs as dark PeVatrons”

Kimura-san's talk



• Optimistic environment



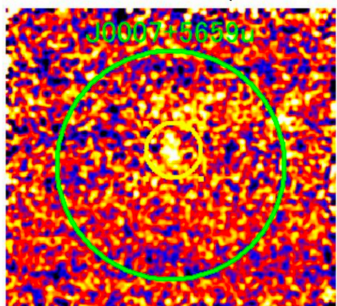
- Our scenario can explain LHAASO data
- Future detectors may be able to detect neutrinos from “dark” sources

Nobeyama observation of 1LHAASO J0007 + 5659

Preliminary results of Nobeyama CO observation

- Scanned $0.5 \times 0.5 \text{ deg}^2$ region
- Observed on Dec 8–15 with ~ 6 hours

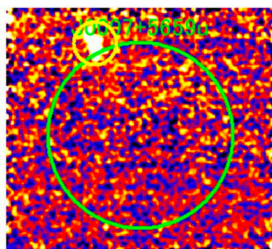
-3.5 km/s



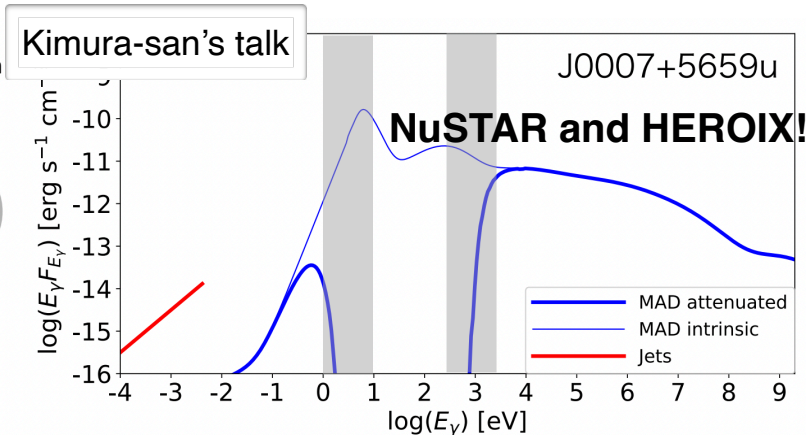
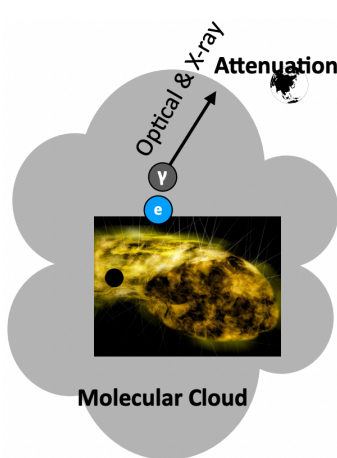
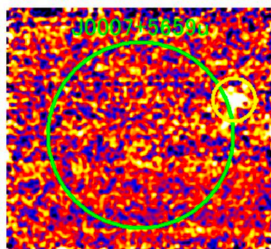
Three MCs (one at the very center of gamma rays)

Detailed analysis led by Ryohei Kanazashi from Kanagawa U

-36.1 km/s

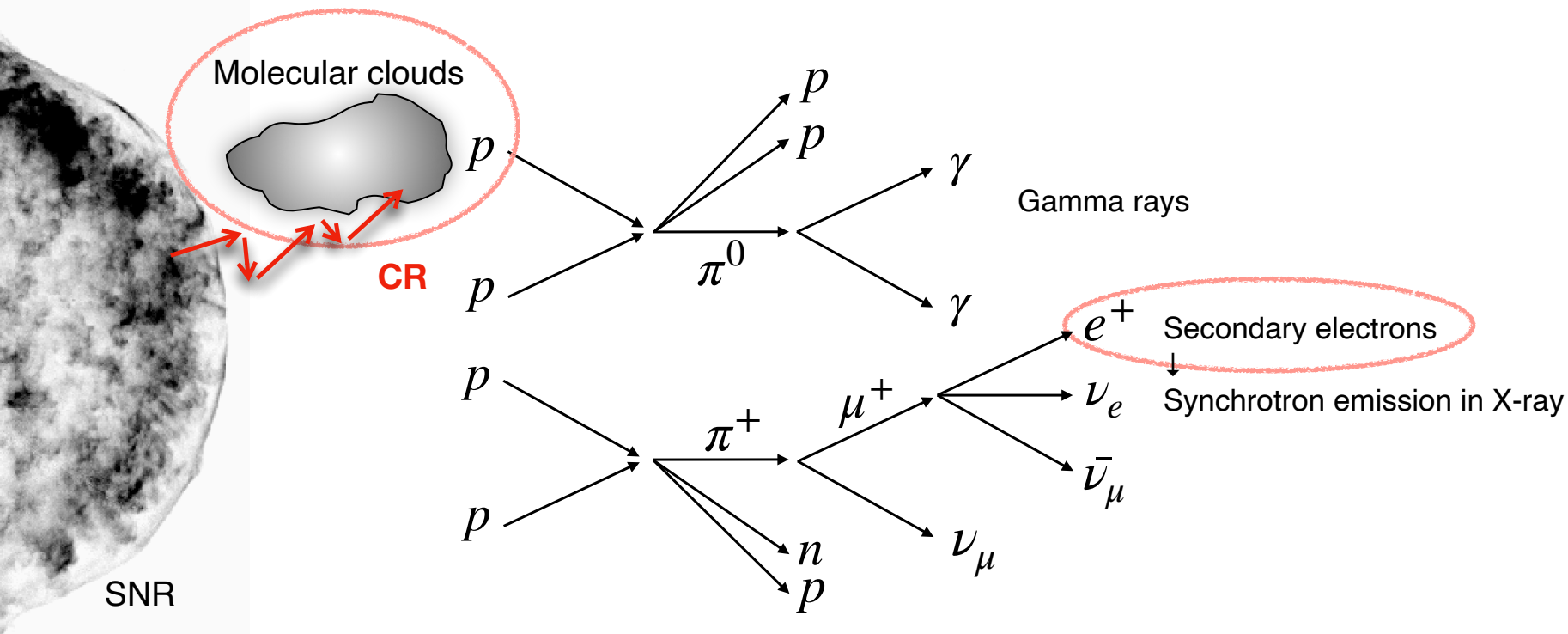


-2.9 km/s



X-ray to probe for (PeV) protons

Hadronic gamma-ray emission

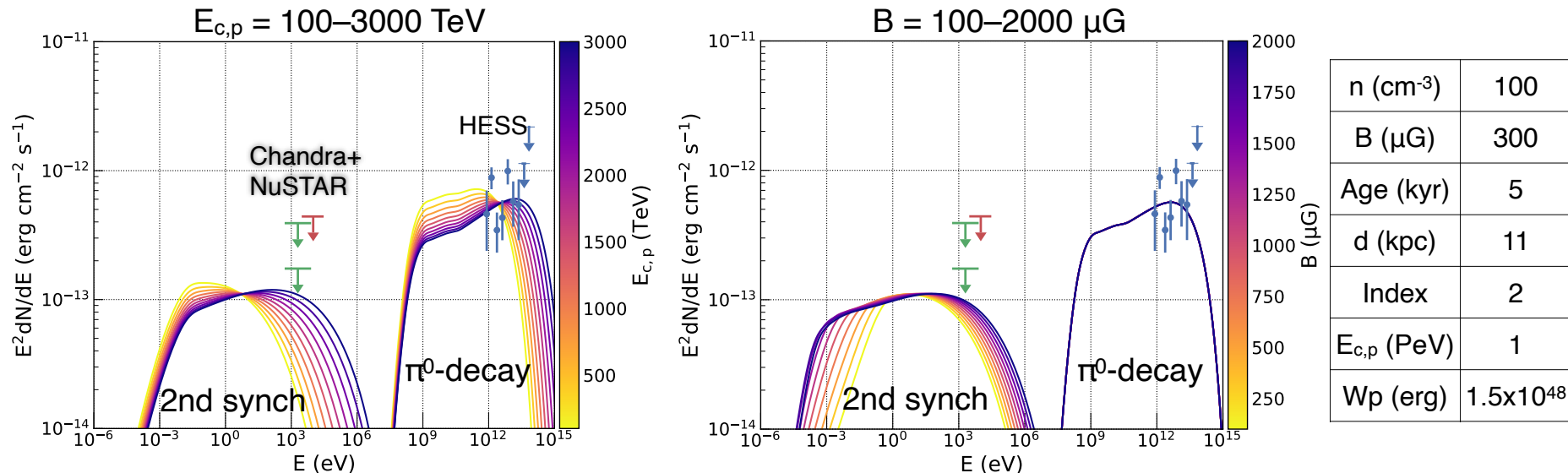


[this talk] search for secondary synchrotron emission (X-ray observation) and molecular clouds (CO observation)

HESS J1641-463

Tsuji et al 2024 *ApJ* 967 138

Synchrotron X-ray from secondary $e^\pm$ in pp interaction

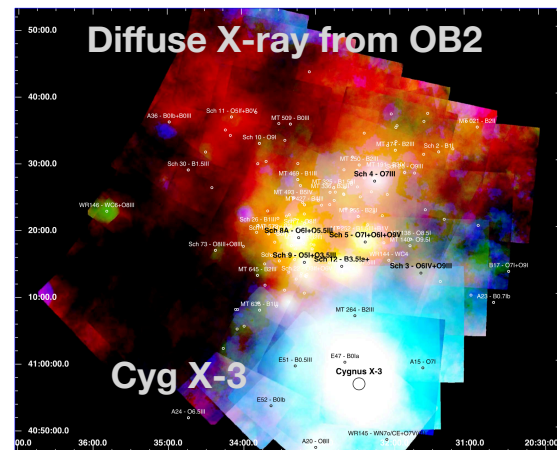
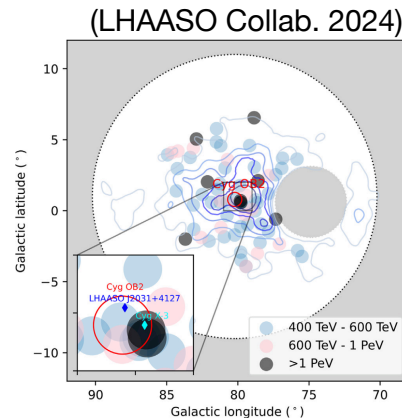
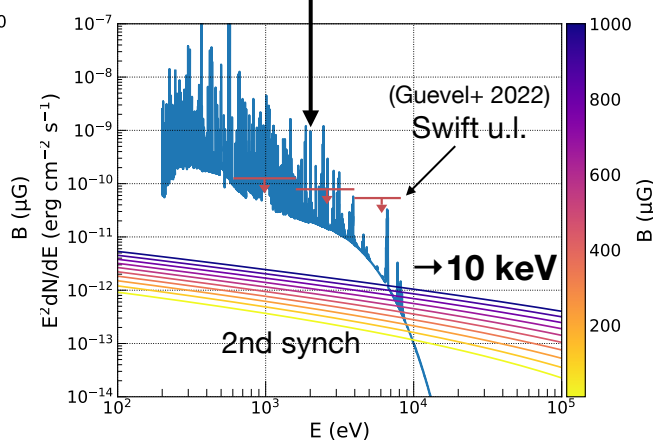
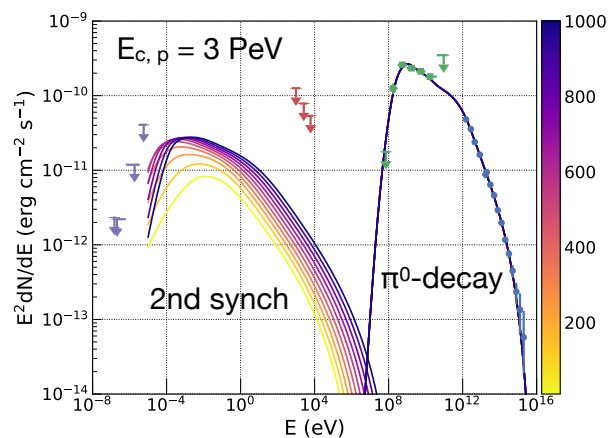


- X-ray upper limits (this work) cannot place tight constraint
- X-ray emission, if detected, might be able to determine $E_{\text{max}, p}$

Detectability of 2nd electrons

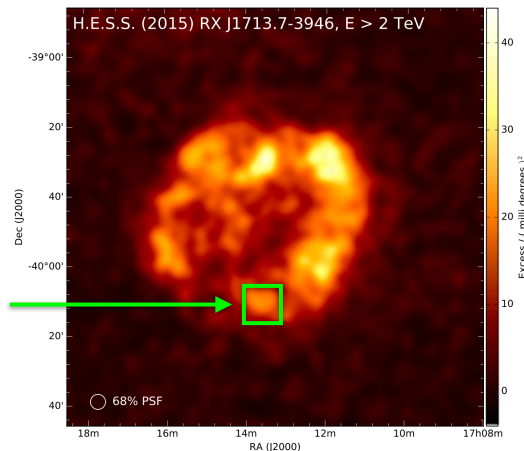
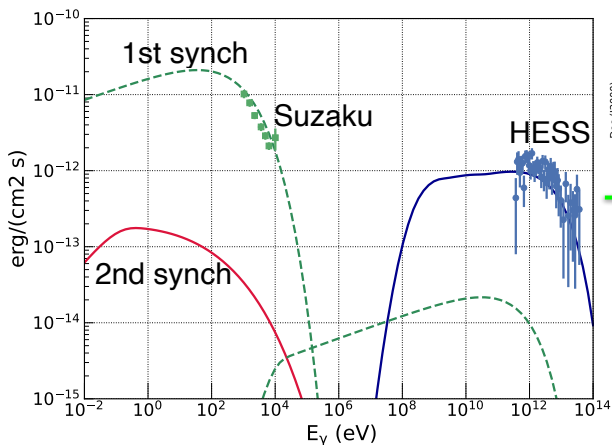
Cygnus cocoon/OB2

- $> \text{PeV}$ emission
 - ~ 6 deg bubble and ~ 0.3 deg core (including OB2 and Cyg X-3)
 - Hadronic origin $\rightarrow$ 2nd synchrotron depends on only B-field
- Thermal diffuse emission ($kT = 0.1 - 1$ keV) from OB2 region
 - 2nd synch becomes dominant at > 10 keV

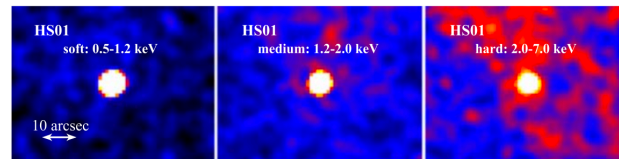


Detectability of 2nd electrons

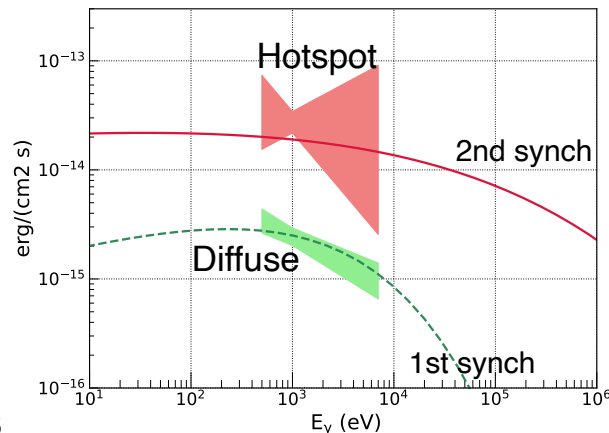
SNR RX J1713.7-3946



Many X-ray “hotspots” in NW shell:
cores of molecular clouds?



(Higurashi, NT, Uchiyama, 2020)



■ South region

- $\sim 5 \times 5$ arcmin² (HESS Collab. 2018)
- Hadronic fraction $> 70\%$ (Fukui+ 2021)
- Primary synchrotron component is dominant

■ Hotspots

- ~ 5 arcsec in radius
- 2nd synchrotron component ($\sim 10^{-14}$ cgs)
- Angular resolution should be < 15 arcsec
 - Otherwise, 1st synchrotron dominates

Detectability of secondary electrons

Future prospect

- What is the best target?
 - Hard TeV gamma-ray spectrum and low thermal/synchrotron X-ray flux

	Example	Size	Notes
1. UnID gamma-ray source	HESS J1641-463	3 arcmin	△ Needs deep observation
2. Star forming region	Cygnus bubble	~6 deg	✗ Too largely extended
	Cygnus OB2	~0.3 deg	○ Detectable at >10 keV
3. SNR	RX J1713's diffuse	~5 arcmin	✗ 1st synchrotron dominant
	RX J1713's hotspot	~5 arcsec	○ Requires <15" resolution

- Detectable by future hard X-ray telescope with good angular resolution (e.g., HEROIX)
- If detected, X-rays can be used to probe for CR protons

Chien-Ting's talk

1. Introduction

2. Maximum energy problem: search for PeVatrons

- A. Microquasars

- B. Dark PeVatrons

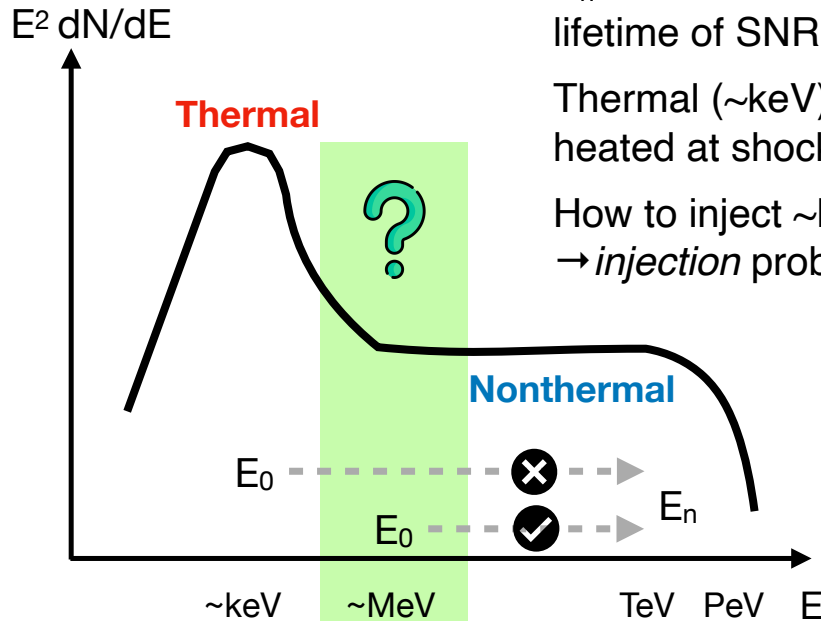
- C. X-ray to probe for CR protons

3. Injection problem: prospects for hard X-ray and MeV

4. Summary

Between thermal and nonthermal particles

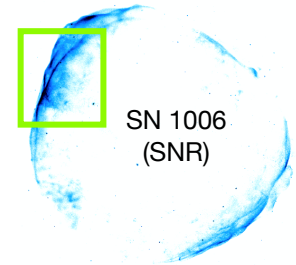
“Injection problem”



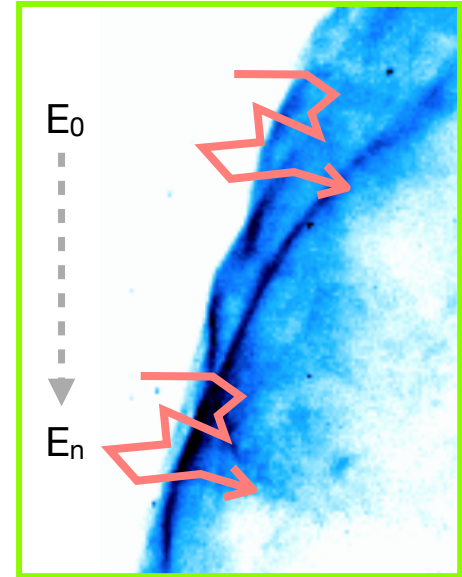
If acceleration starts from $E_0 \sim \text{MeV}$,
 $E_n \sim \text{TeV-PeV}$ can be achieved in a
lifetime of SNR

Thermal ($\sim \text{keV}$) particles can be
heated at shock

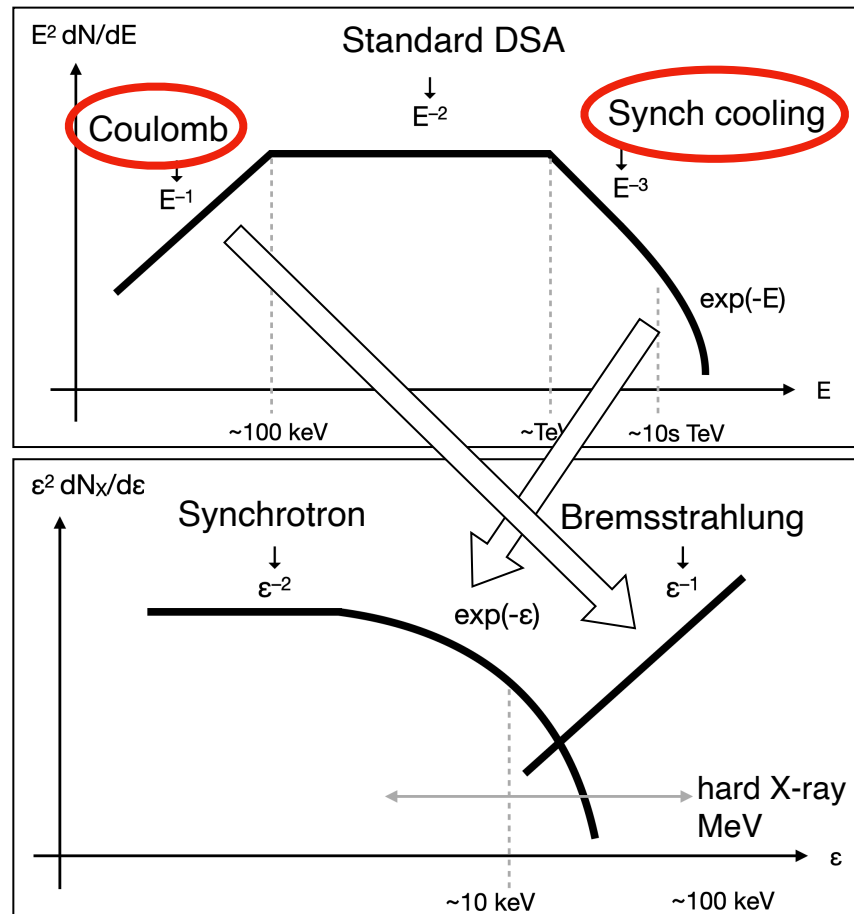
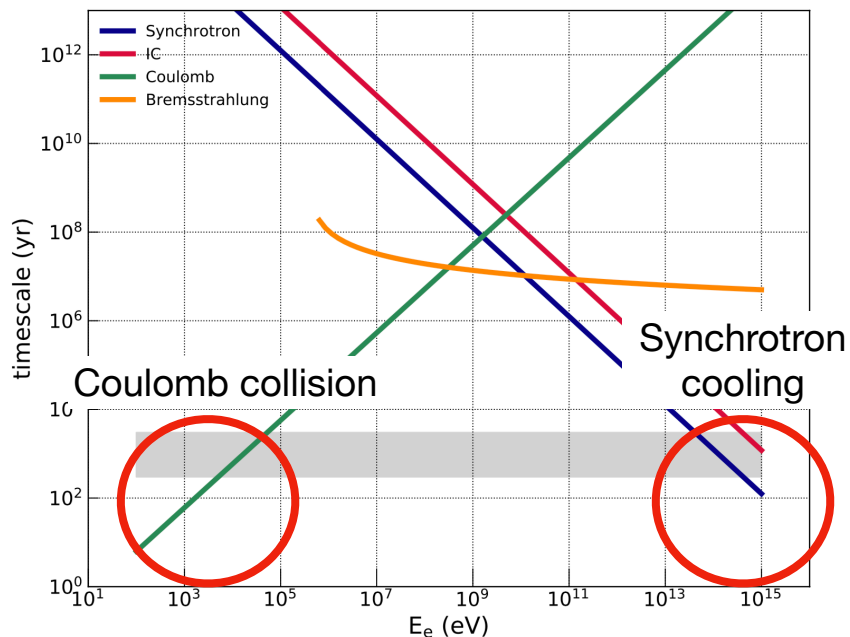
How to inject $\sim \text{MeV}$ particles?
→ *injection problem*



Shock wave at SNR surface



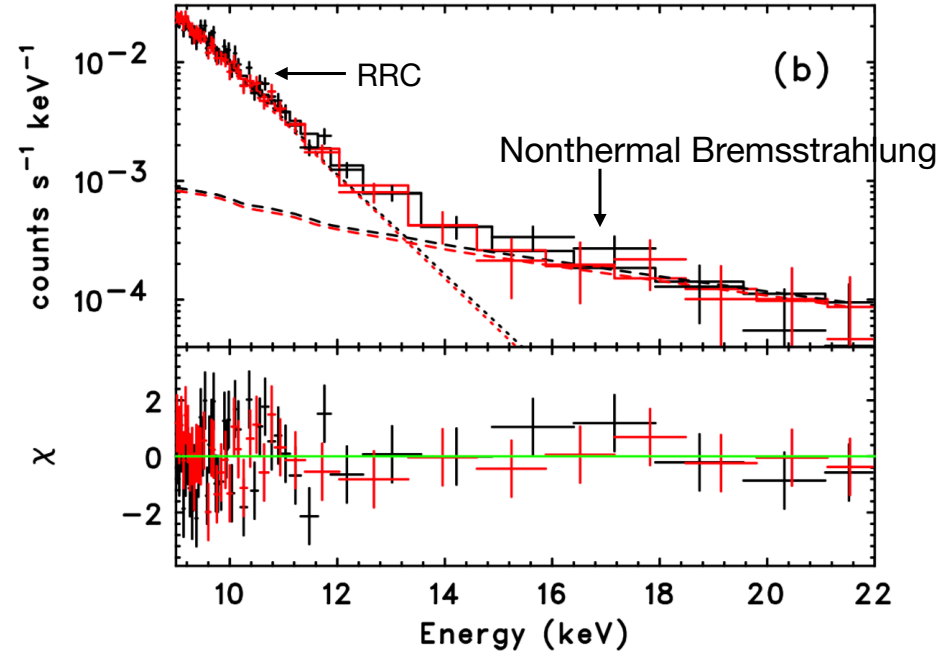
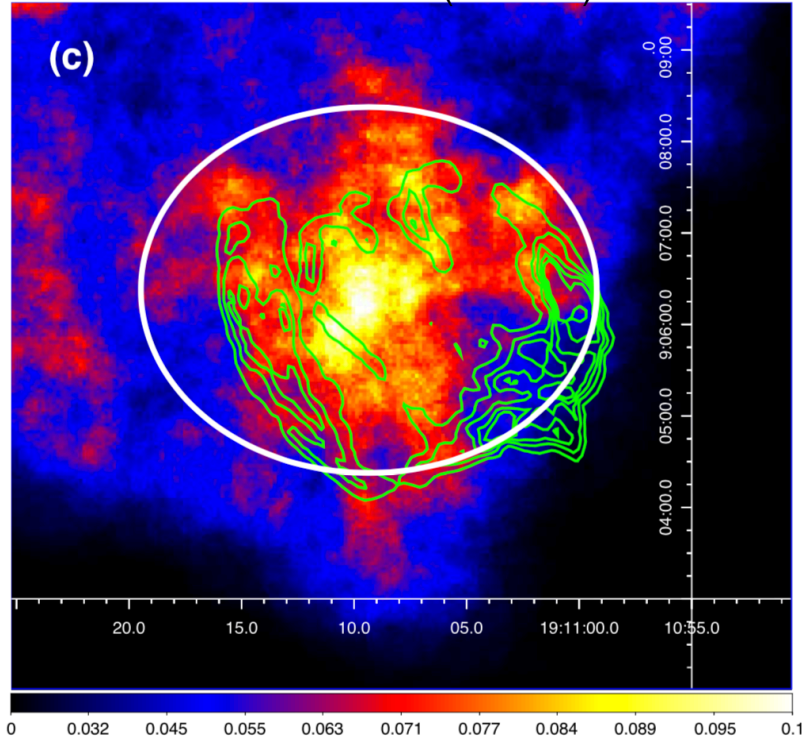
How to find low-energy CR?



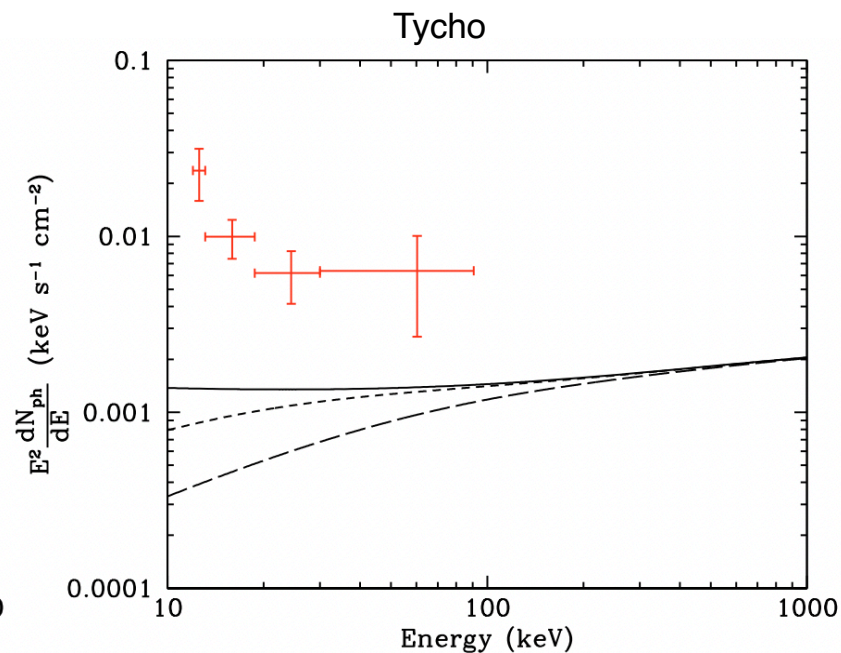
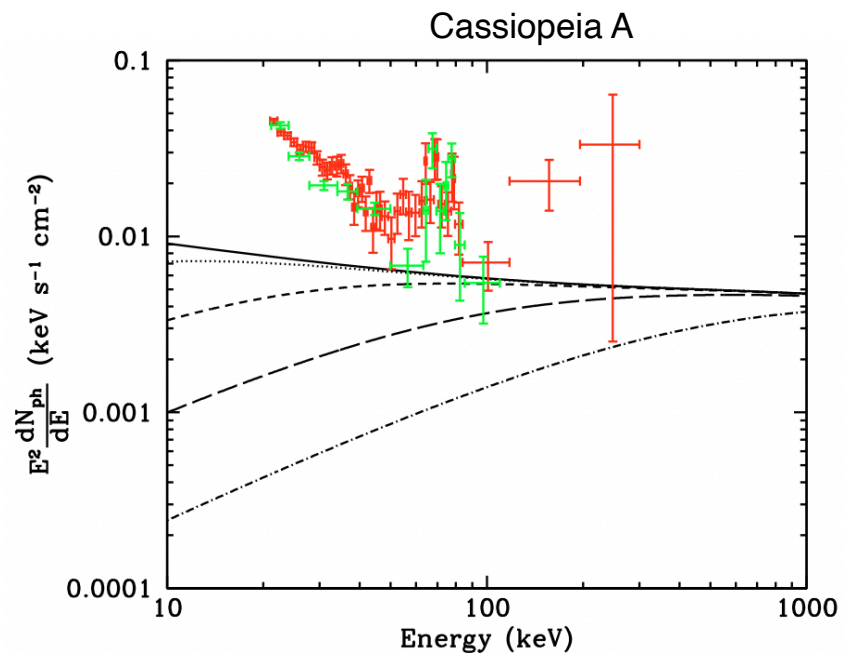
Nonthermal Bremsstrahlung in W49B

(Tanaka et al. 2018)

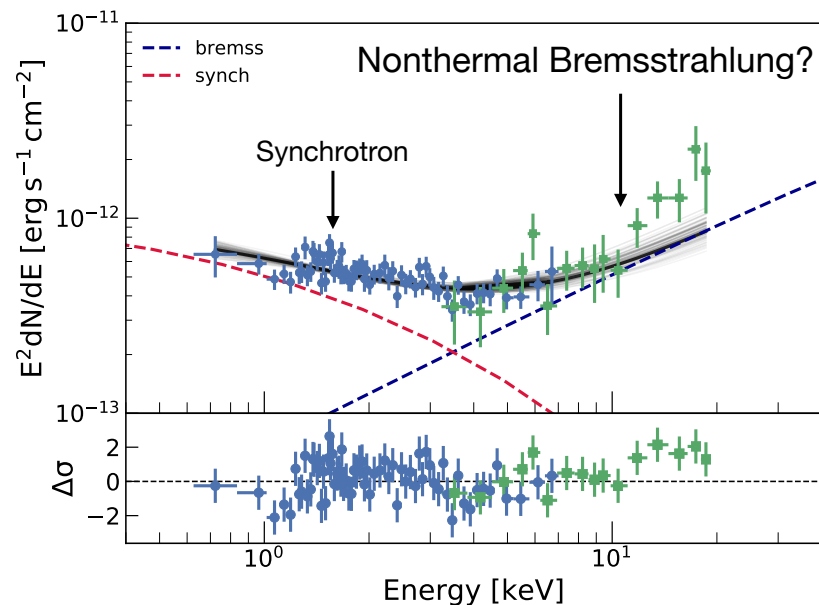
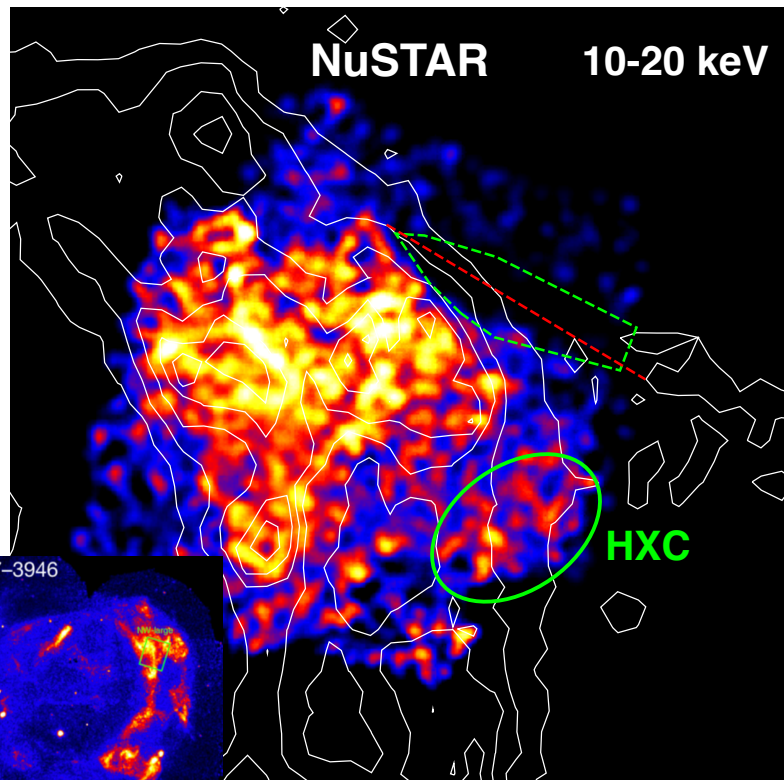
NuSTAR (15–20 keV)
Contours: VLA (1.4 GHz)



Nonthermal Bremsstrahlung in Casiopeia A and Tycho?



Nonthermal Bremsstrahlung in RX J1713.7-3946?



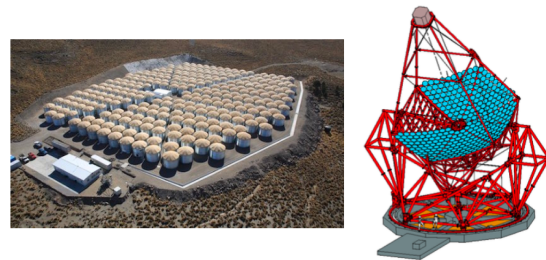
Not confirmed due to stray light issue in NuSTAR data...

- Needs hard X-ray
- Could peaked at MeV

Summary

- Microquasars
 - Extensive X-ray (and other wavelength) observation campaign of SS 433/W50 and V4641 Sgr
 - Synchrotron peak in $\sim$ MeV?
- Unidentified LHAASO sources
 - X-ray (PI Kaya Mori) and CO observations
 - Completed for 4 sources so far
 - New X-ray extended emission only in LHAASO J0341+5258
 - Continued in future
- X-ray could be new tool via secondary synchrotron emission
- Hard X-ray and MeV needed for the injection problem

TeV gamma-ray telescope
(angular resolution $\sim 0.05\text{--}1^\circ$)



Multiwavelength observation

Radio telescope
(<15 arcsec)



X-ray telescope
($\sim 0.5\text{--}15$ arcsec)

