

Microquasars as PeV accelerators: the mounting observational evidence

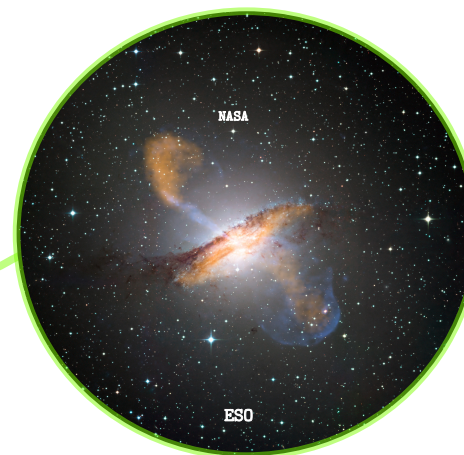
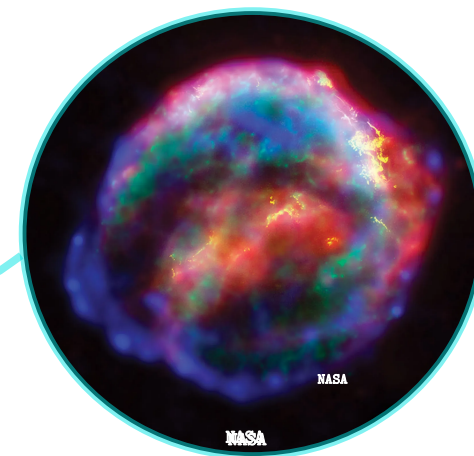
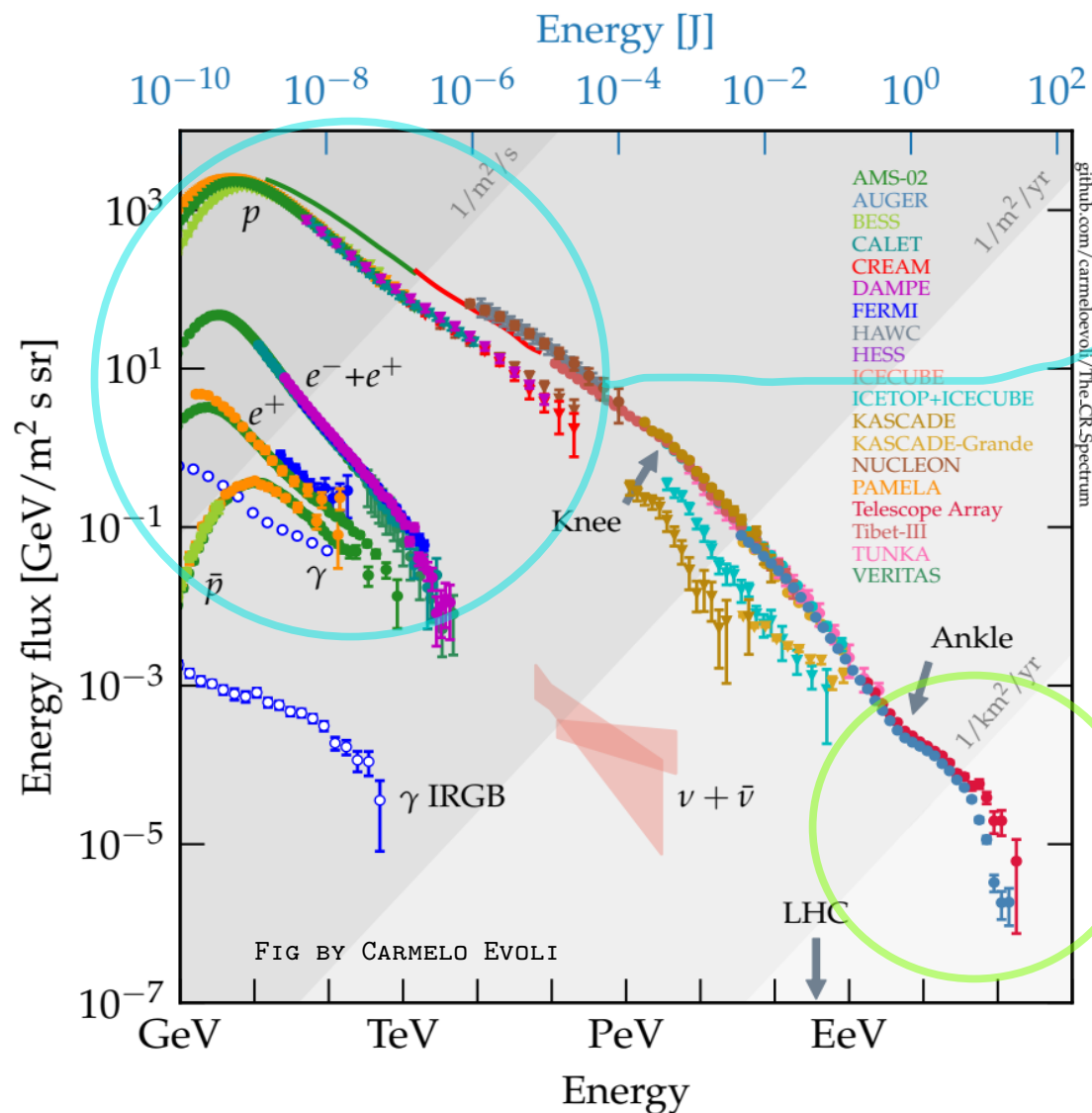
The background of the slide is a composite image. On the left, a bright, glowing accretion disk surrounds a black hole, with a powerful jet of light blue and white energy extending upwards. On the right, a large, bright yellow-orange star, identified as a type A supergiant, is shown. The overall scene is set against a dark, cosmic background.

black hole

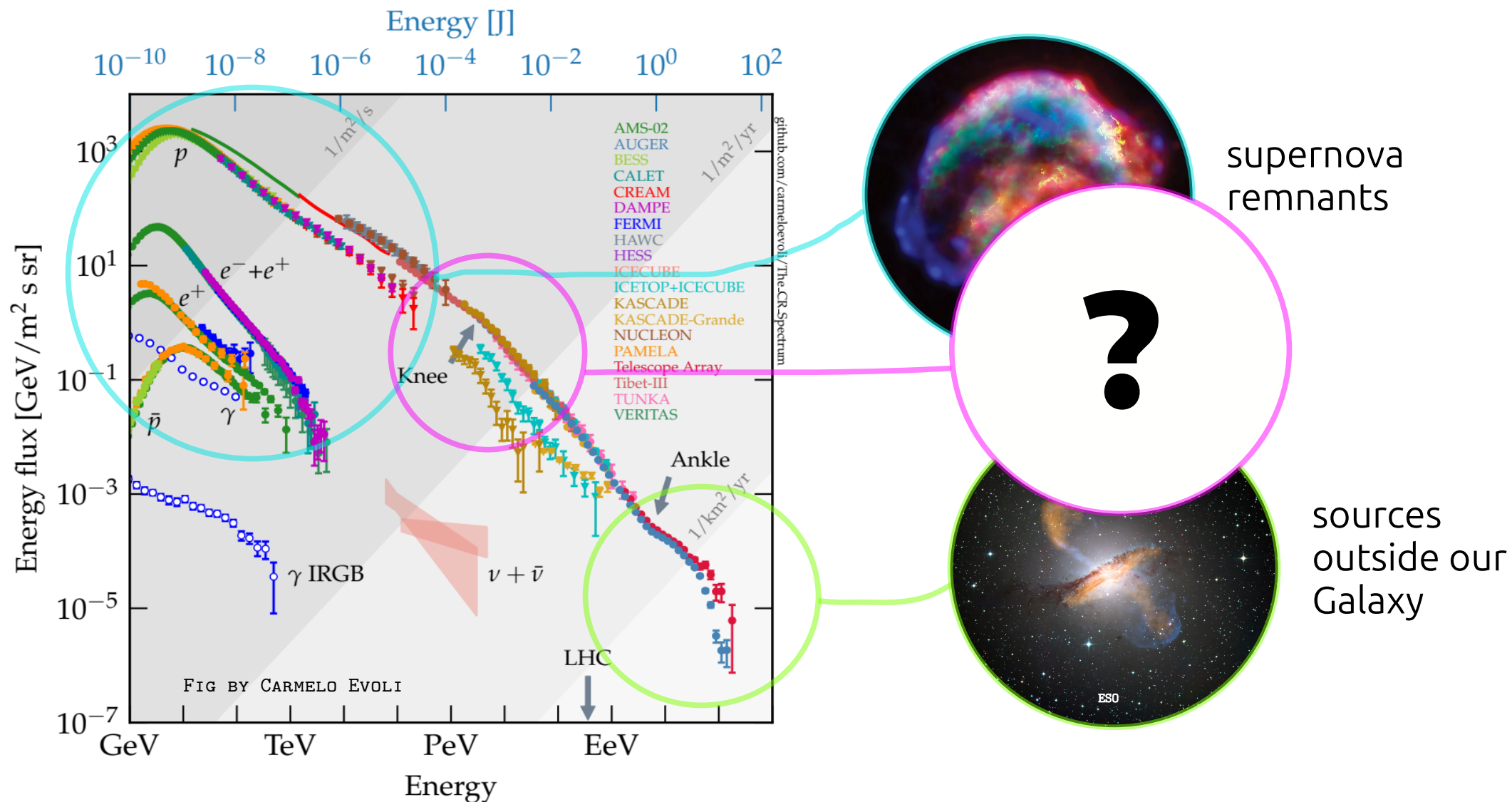
type A supergiant

CDHY PeVatron Workshop
October 9th 2025
Laura Olivera-Nieto

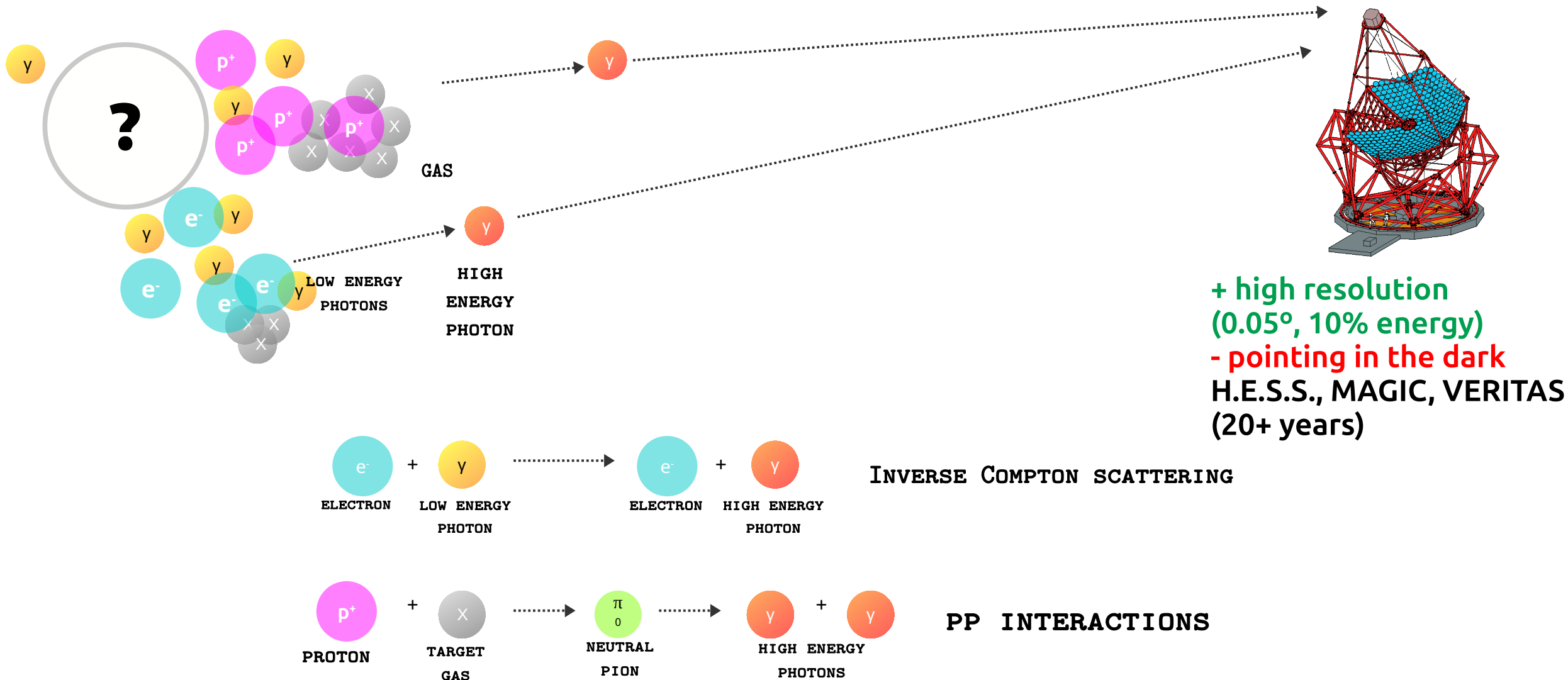
The origin of cosmic rays



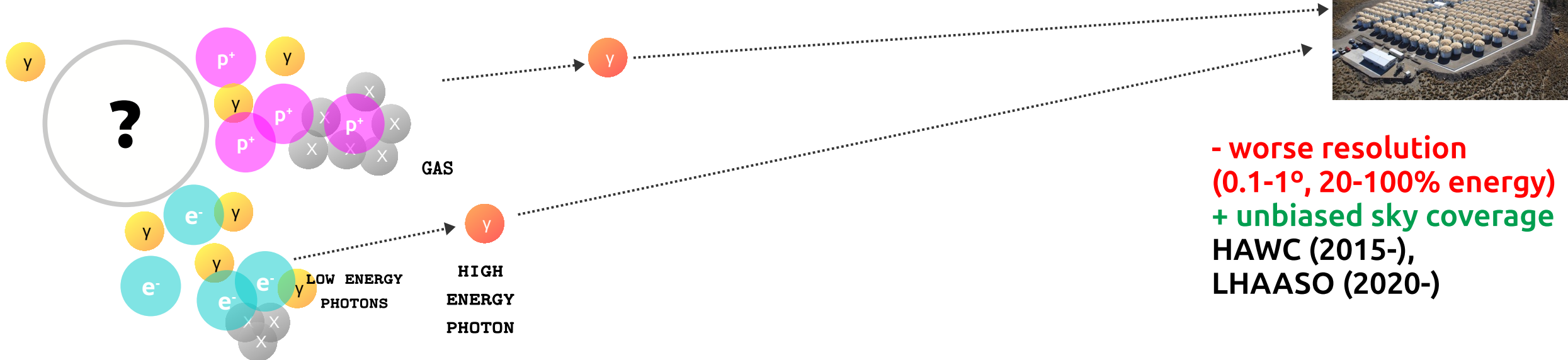
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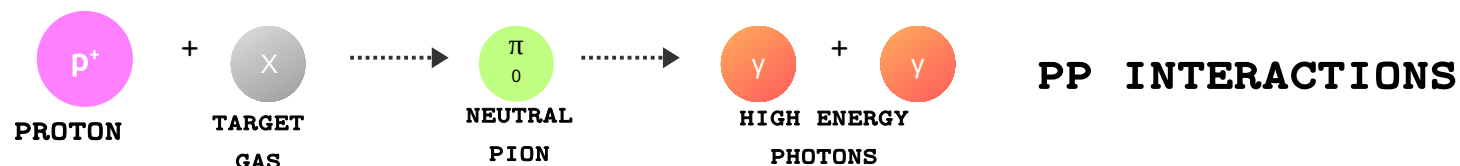
How to find a cosmic ray source



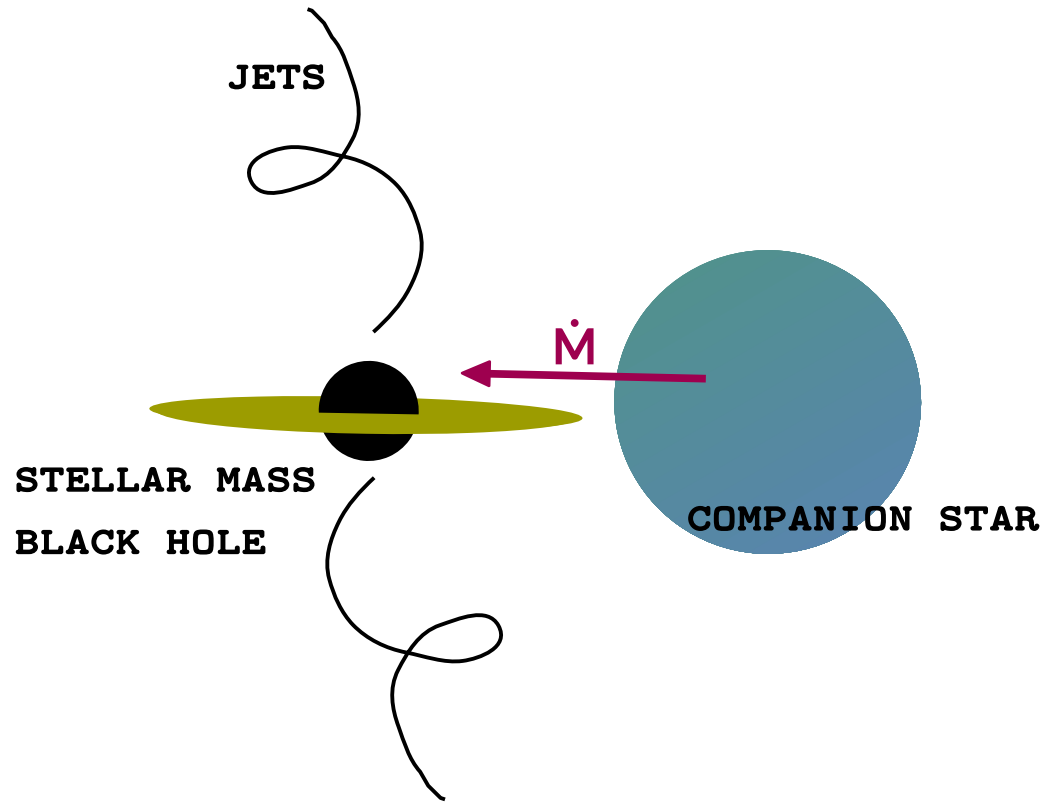
How to find a cosmic ray source



- worse resolution
(0.1-1°, 20-100% energy)
+ unbiased sky coverage
HAWC (2015-),
LHAASO (2020-)



Microquasars



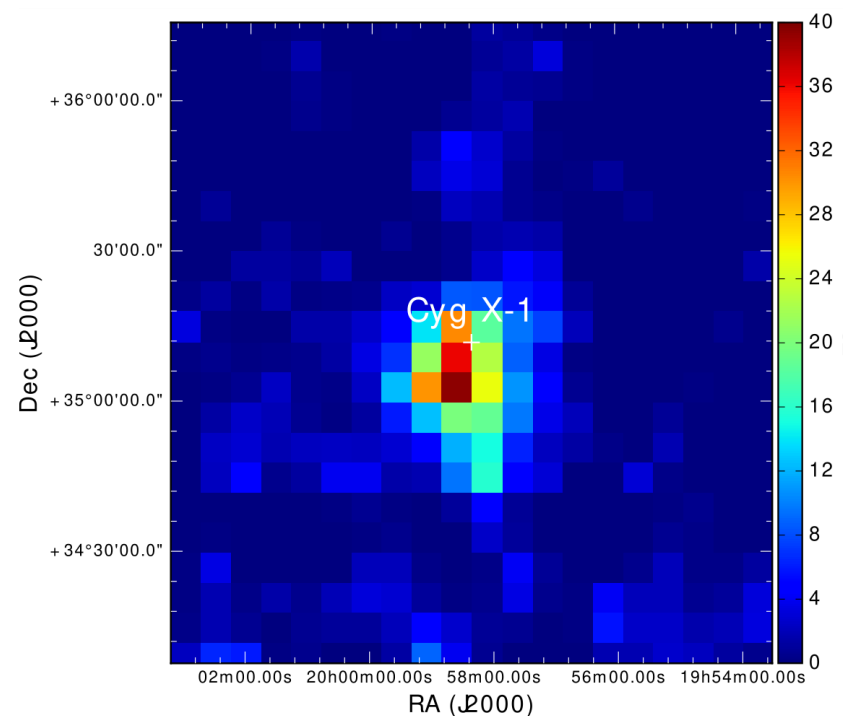
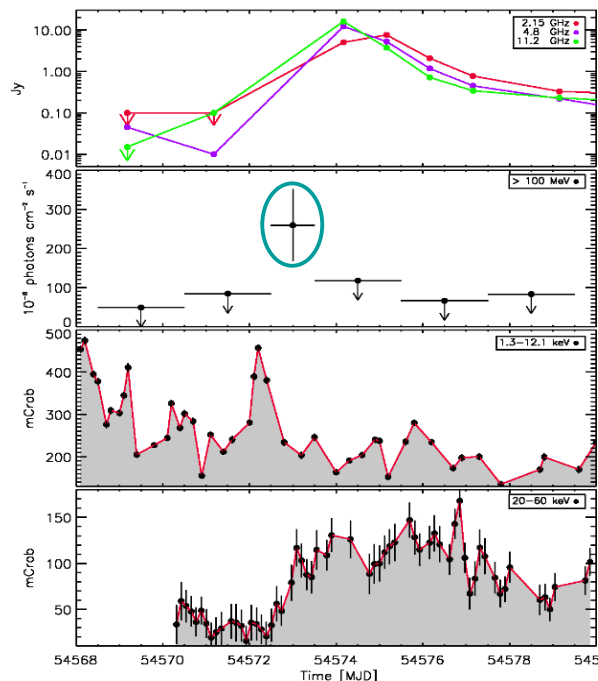
- ▶ X-ray binaries launching a (semi-)relativistic jet.
- ▶ Much less powerful than AGN ($L_{\text{edd}} \sim 10^{39}$ erg/s), but also much closer!
- ▶ Highly variable: generally go through short-lived phases of high activity.
- ▶ Proposed as particle accelerators since a long time, but elusive in the gamma-ray band since decades.
- ▶ Jets known/expected to contain **hadronic material**

Clues from the GeV band

- Pointed TeV instruments rely on GeV satellites heavily: a GeV detection is promising when looking for TeV signal

AGILE Coll 2009

>100 MeV photons from Cyg X-3 during a flare



Zanin et al 2016

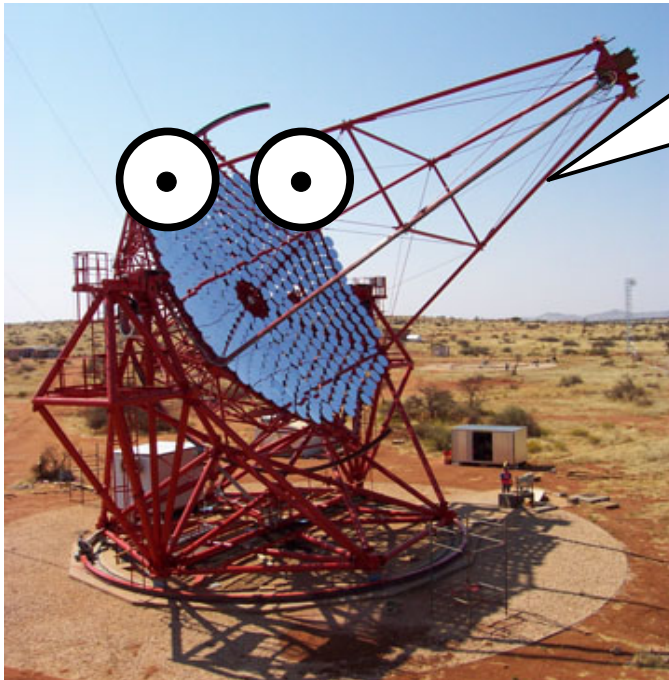
Cyg X-1 detected in the hard state with Fermi-LAT

(also Zdziarski et al 2017)

Seems like: GeV emission is variable and correlates with transit flares or spectral changes

Clues from the GeV band

let's point at microquasars
during flares/special times!



A search for very high-energy flares from the microquasars GRS 1915+105, Circinus X-1, and V4641 Sgr using contemporaneous H.E.S.S. and RXTE observations

H.E.S.S. Collaboration

JOURNAL ARTICLE

MAGIC observations of the microquasar V404 Cygni during the 2015 outburst FREE

M. L. Ahnen, S. Ansoldi, L. A. Antonelli, C. Arcaro, A. Babić, B. Banerjee, P. Bangale, U. Barres de Almeida, J. A. Barrio, J. Becerra González ... [Show more](#)

Monthly Notices of the Royal Astronomical Society, Volume 471, Issue 2, October 2017, Pages 1688–1693, <https://doi.org/10.1093/mnras/stx1690>

Published: 08 July 2017 **Article history** ▼

Advance Access publication 2022 September 23

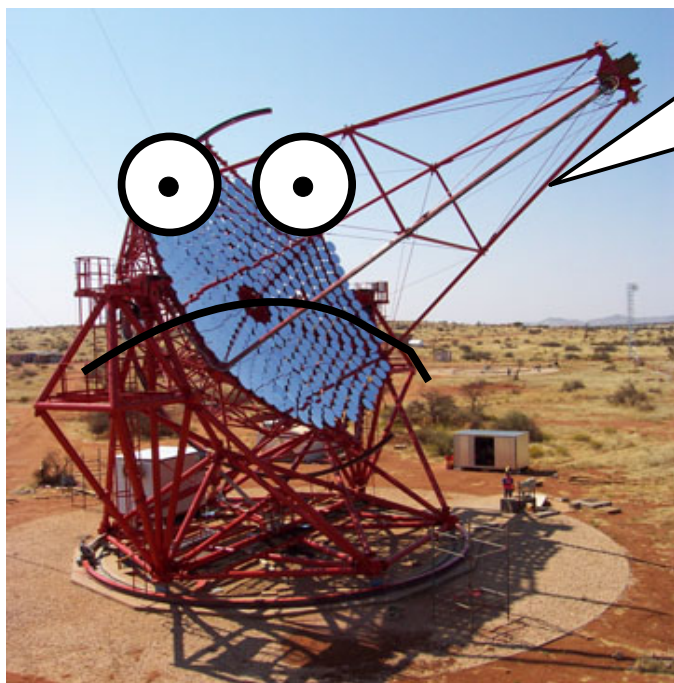
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Gamma-ray observations of MAXI J1820+070 during the 2018 outburst

H. Abe,¹ S. Abe,¹ V. A. Acciari,² T. Aniello,³ S. Ansoldi,^{4*} L. A. Antonelli,³ A. Arbet Engels,⁵ C. Arcaro,⁶ M. Artero,⁷ K. Asano,¹ D. Baack,⁸ A. Babić,⁹ A. Bagnato,¹⁰ U. Barres de Almeida,¹¹

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No detections (yet!)

<https://doi.org/10.1093/mnras/stac268>

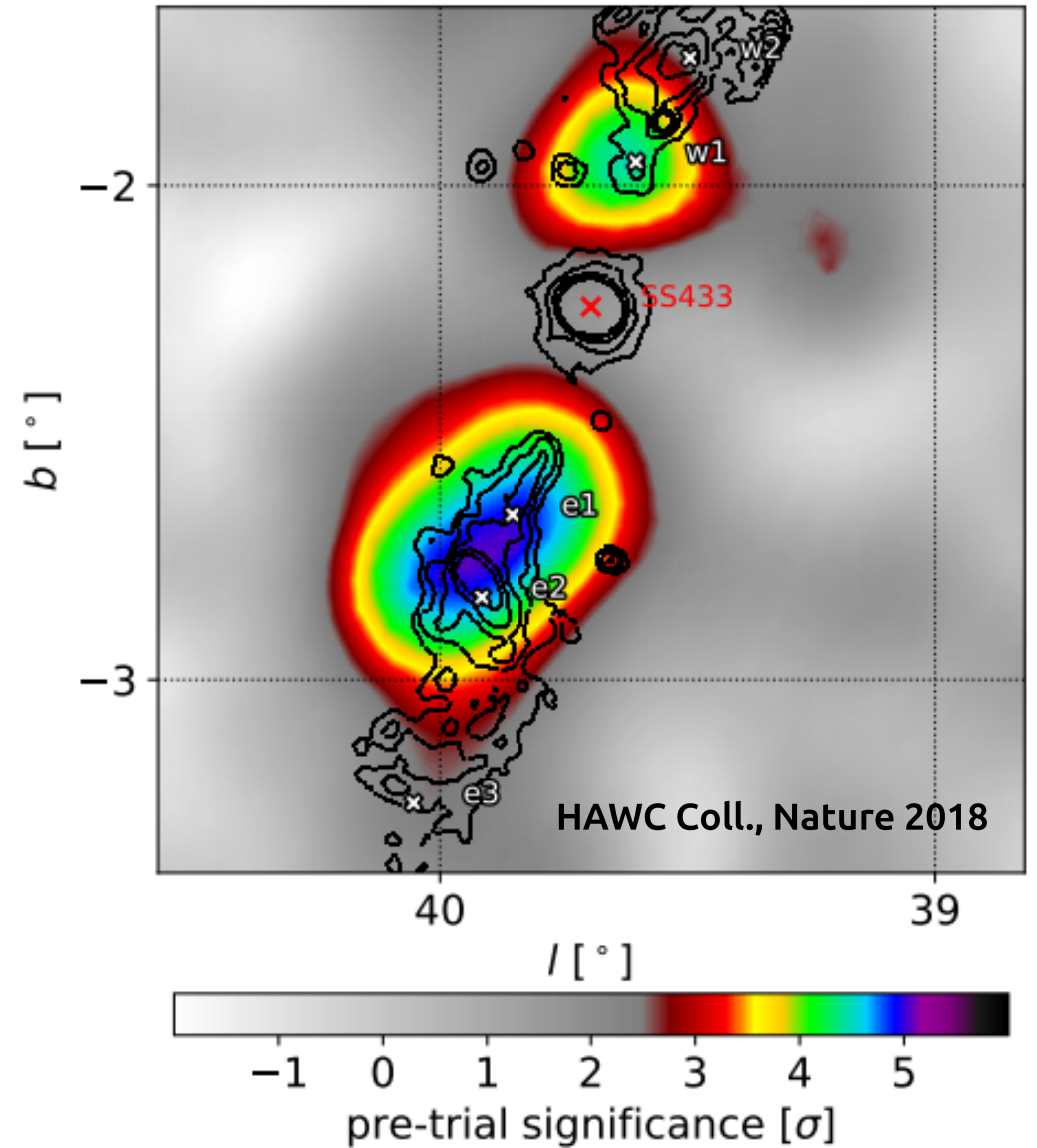
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surprise!

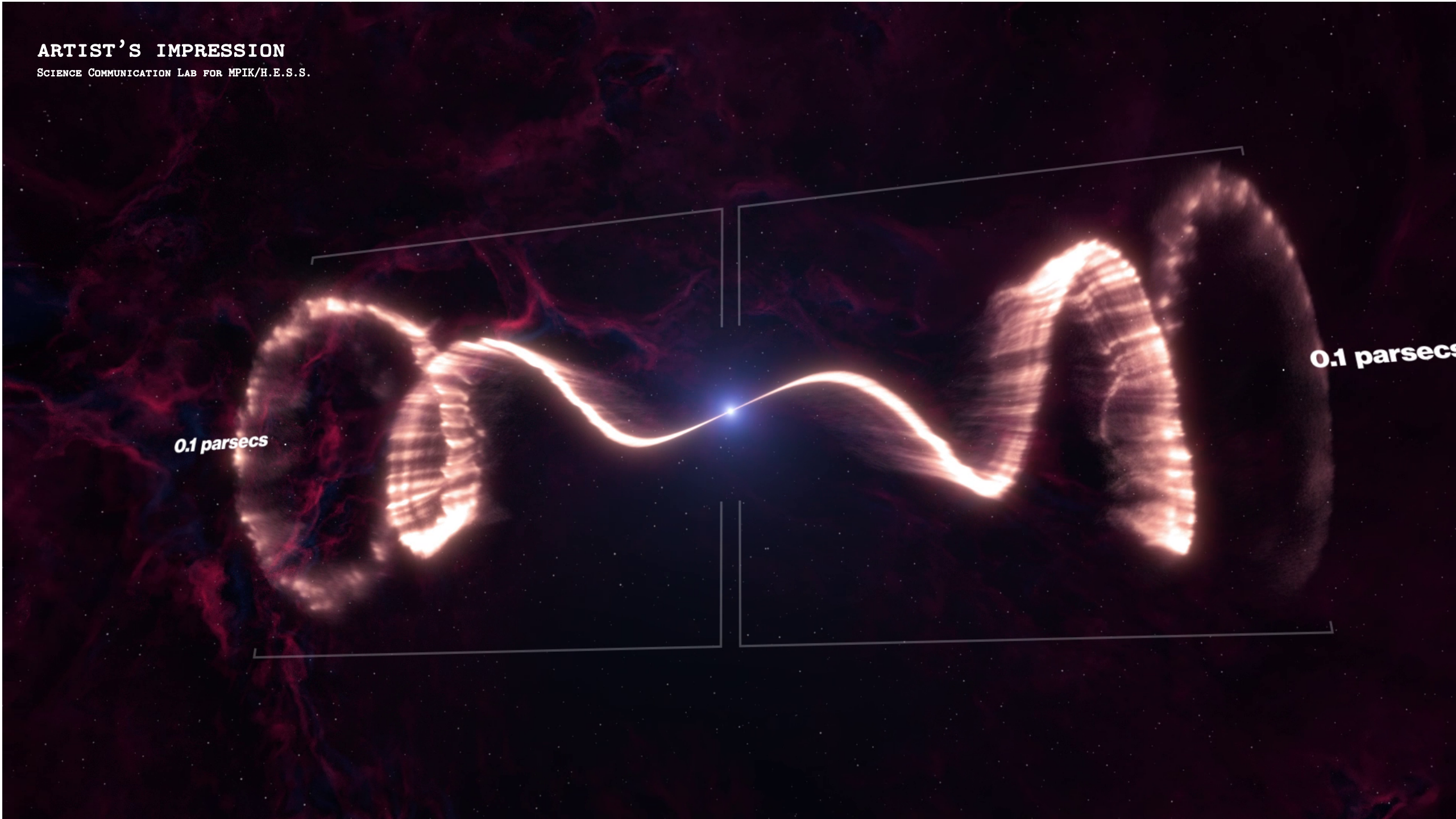
- ▶ In 2018, HAWC detected persistent TeV emission from the jets of the microquasar SS 433
- ▶ Emission not spatially resolved (two point sources), coincident with extended x-ray structures located tens of pc away from binary

HAWC Observatory



0.1 parsecs

0.1 parsecs



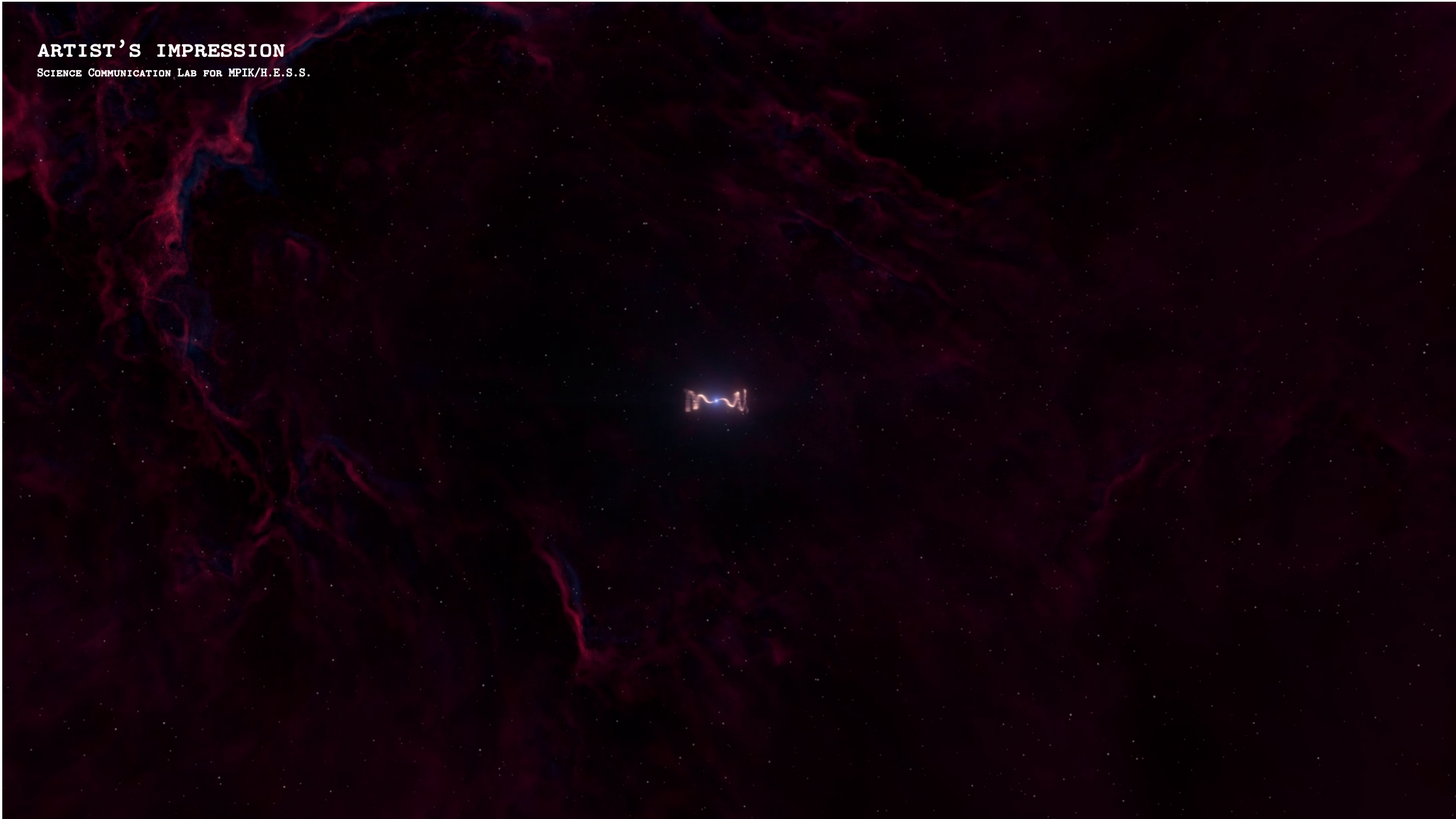
ARTIST'S IMPRESSION

SCIENCE COMMUNICATION LAB FOR MPIK/H.E.S.S.



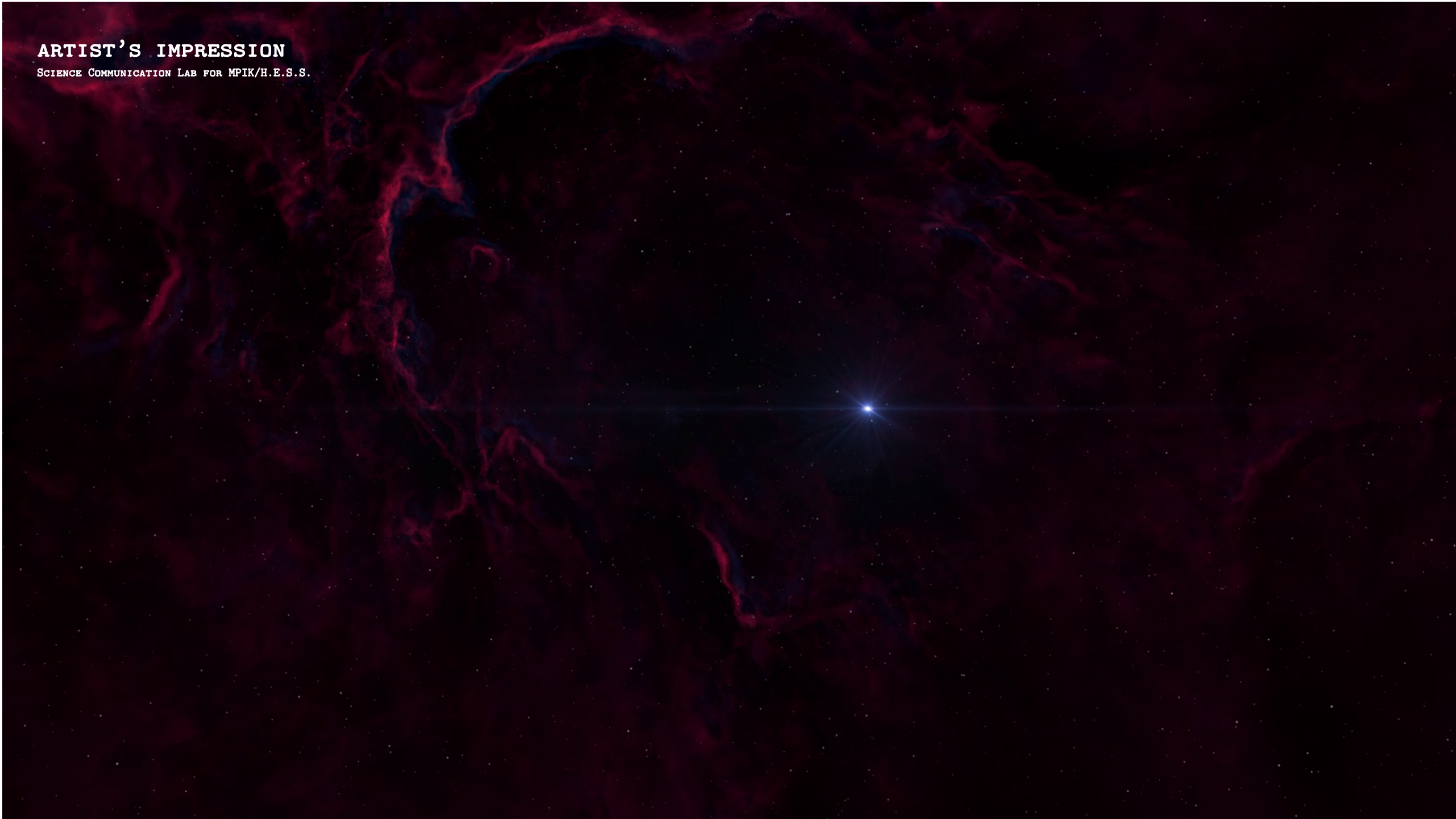
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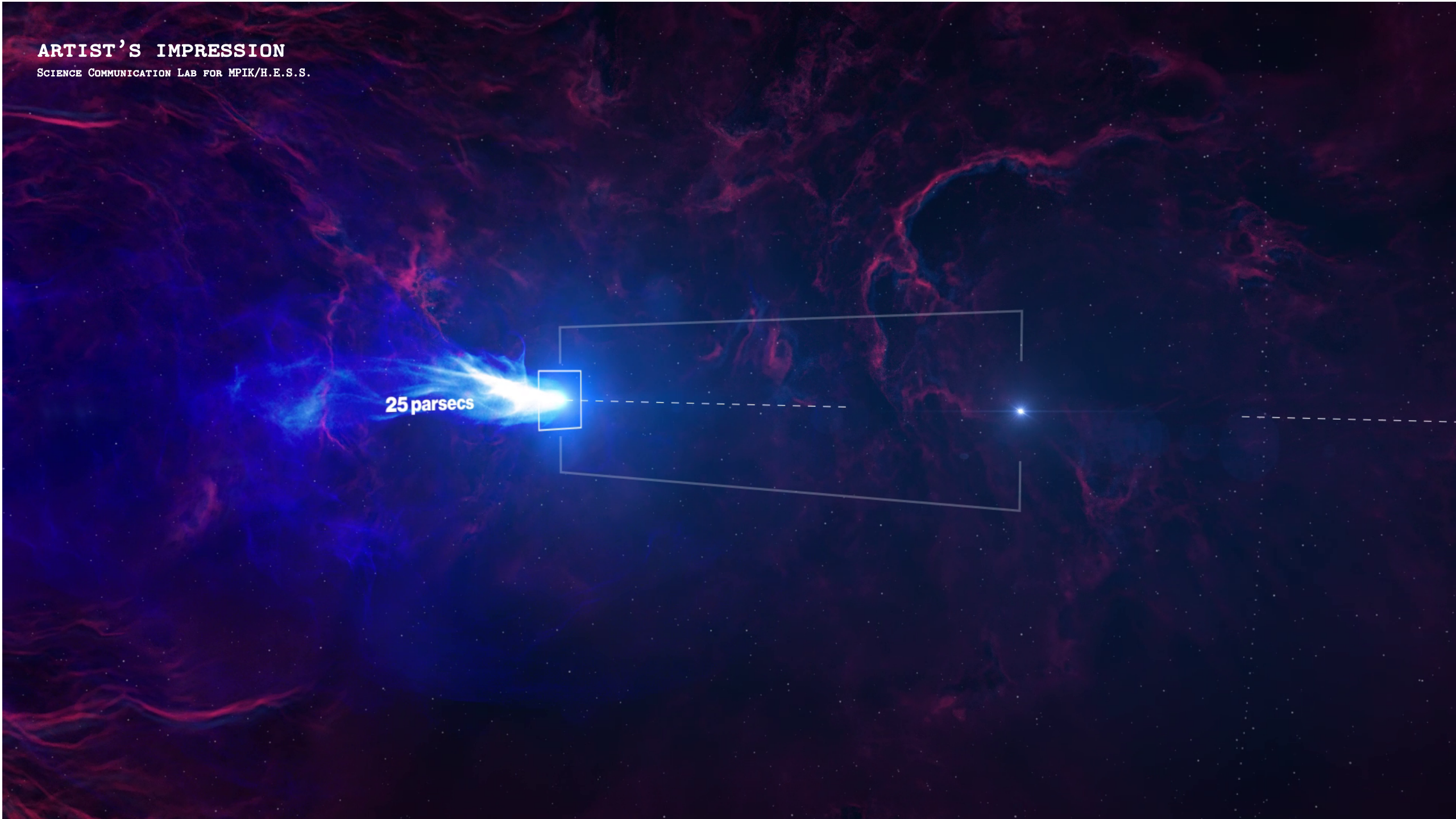
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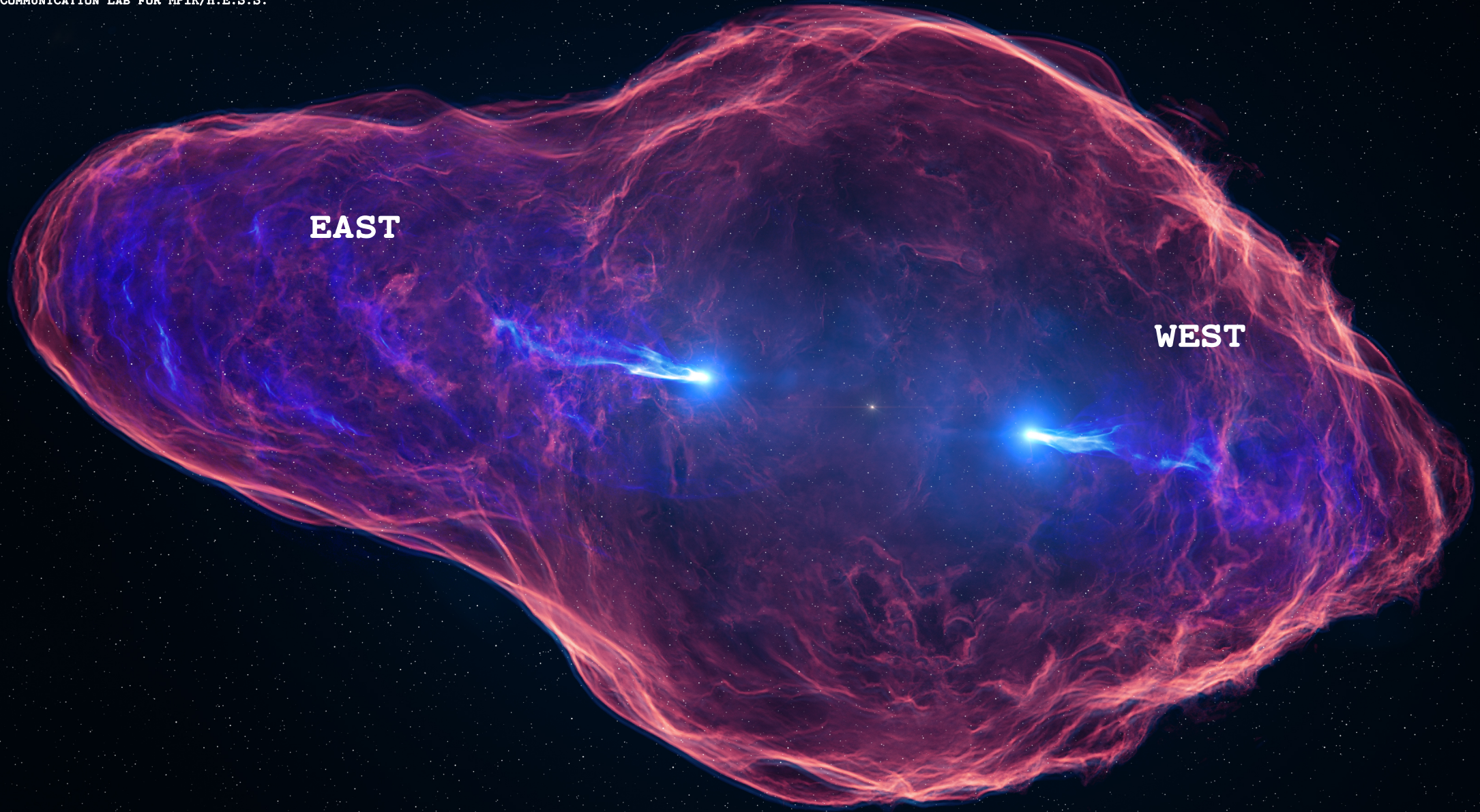
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ACTUAL DATA

BLUE: RADIO EMISSION FROM NEBULA

WHITE: OUTLINE OF JETS IN X-RAY



EAST

WEST

~200 PC

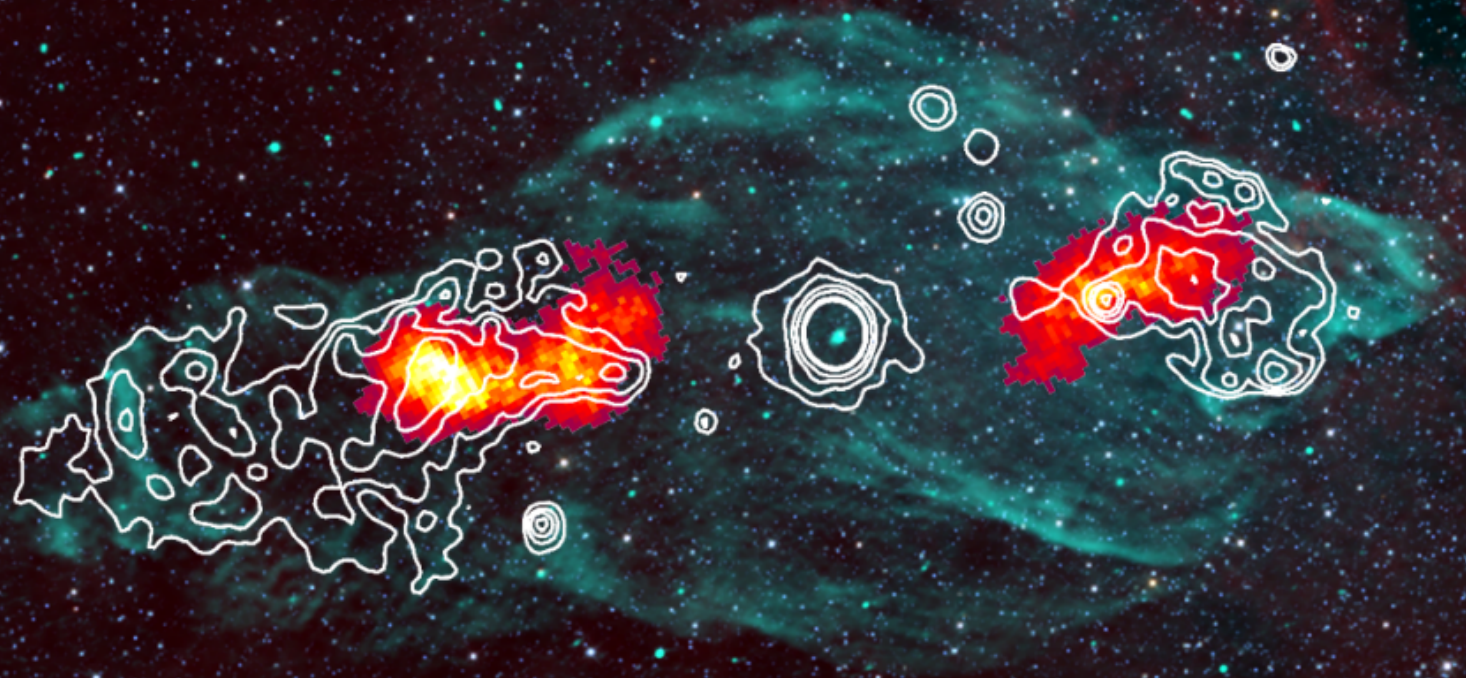
$(6 \cdot 10^{18} \text{ m})$

BACKGROUND: NRAO/AUI/NSF, K.
GOLAP, M. GOSS; NASA'S WIDE FIELD
SURVEY EXPLORER (WISE); X-RAY
(GREEN CONTOURS): ROSAT/W.
BRINKMANN; TEV (RED COLORS):

ACTUAL DATA

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H.E.S.S. COLLABORATION SCIENCE 383 6681, 2024 (LON LEADING AUTHOR)

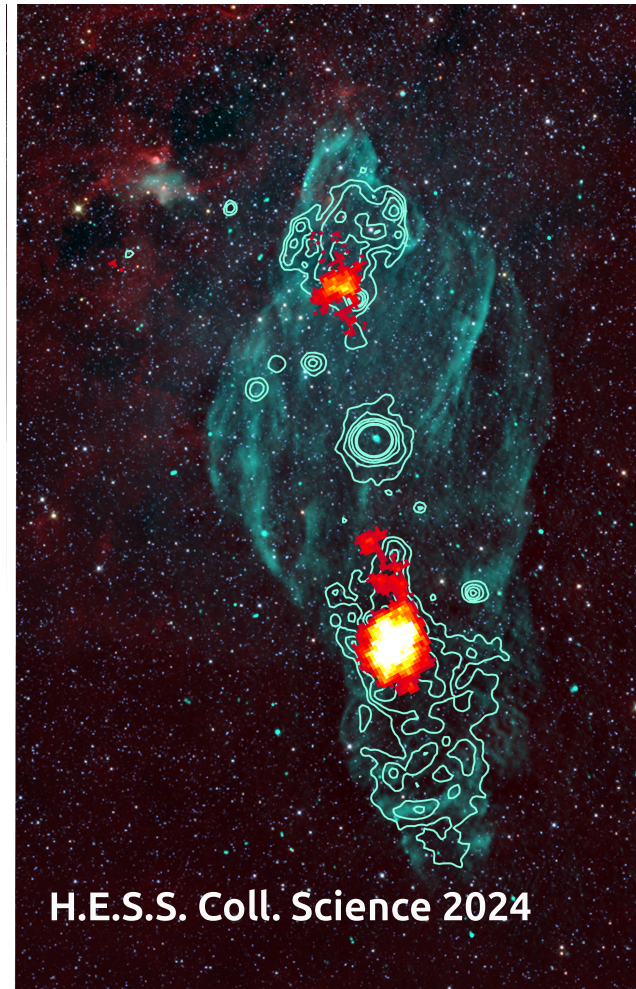


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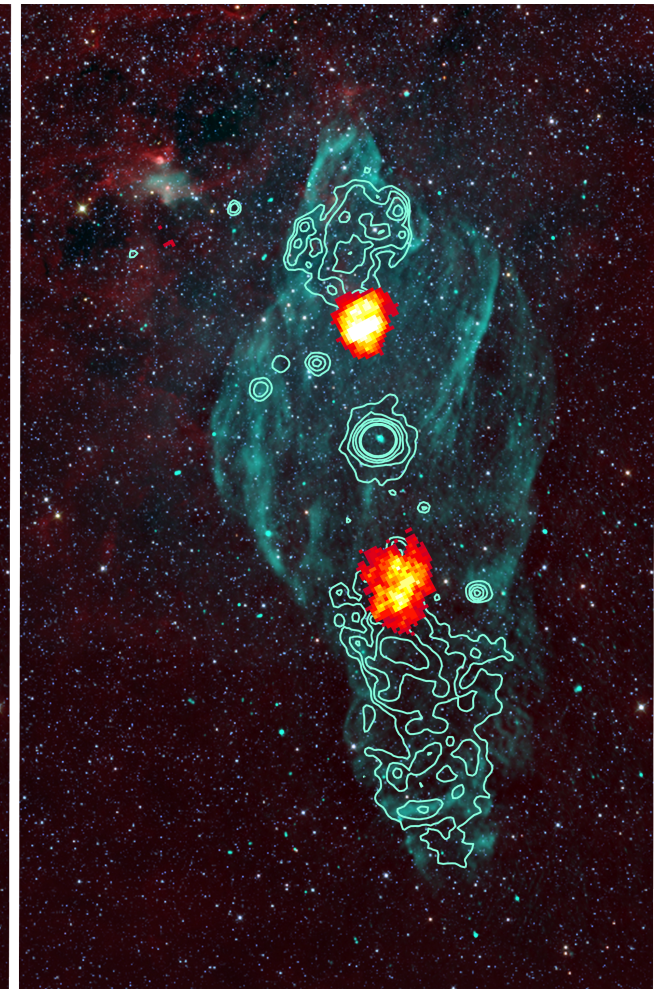
more surprises!

- ▶ Follow-up study with H.E.S.S. revealed energy-dependent morphology in the emission of the jets, closely following x-ray morphology
- ▶ Means TeV **emission** likely made by electrons
- ▶ Acceleration site identified
- ▶ Bulk speed of electrons $\sim 0.08c$
- ▶ **Likely a shock!**
- ▶ **SS 433 can accelerate particles to >100 TeV energies**
- ▶ But SS 433 hardly “normal”...

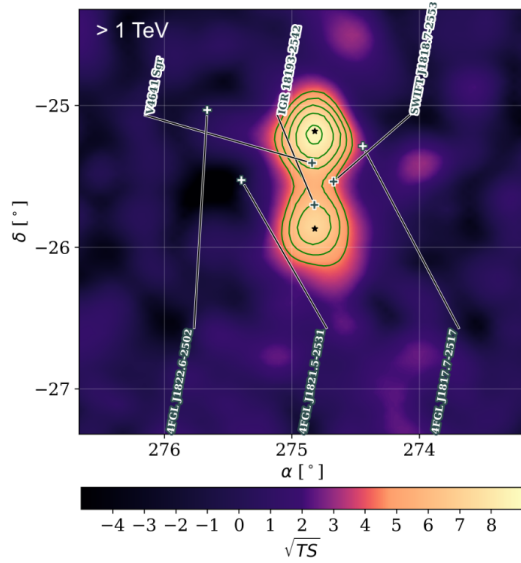
below 10 TeV



above 10 TeV

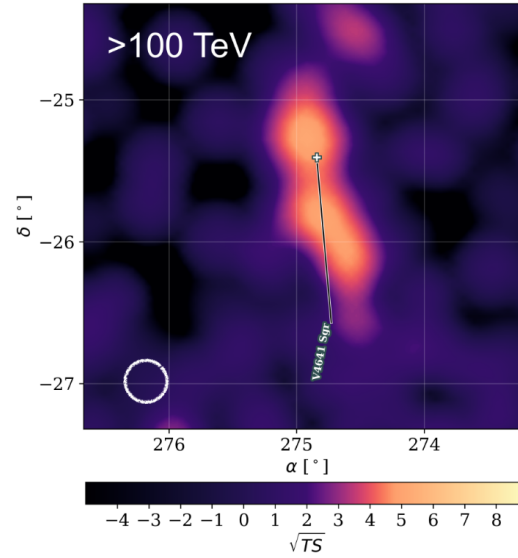


... maybe it is!

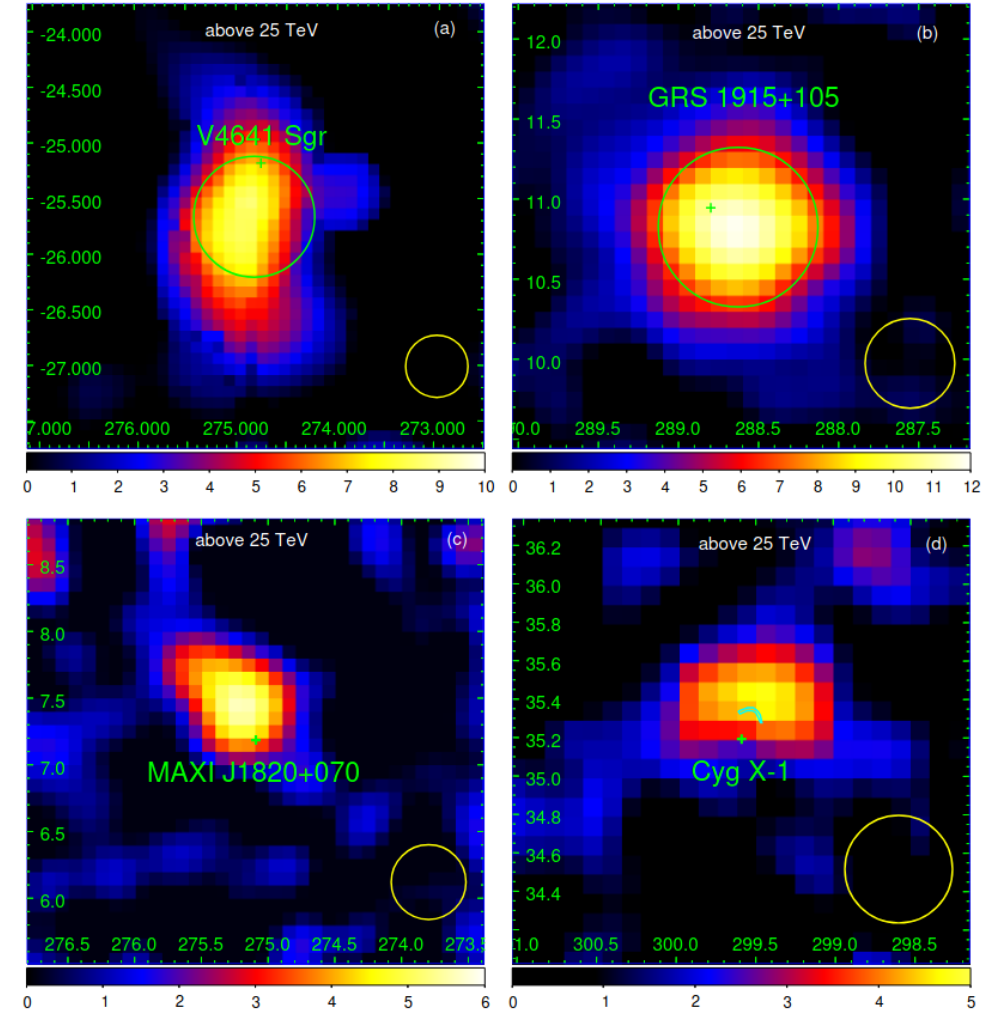


HAWC Coll., Nature 2024

- ▶ >25 TeV emission detected around 4 more sources!
- ▶ Emission is **spatially extended** and **persistent**
- ▶ Spatial scales correspond to several 10s of pc
- ▶ Very large scales! (either extension or **offset**)

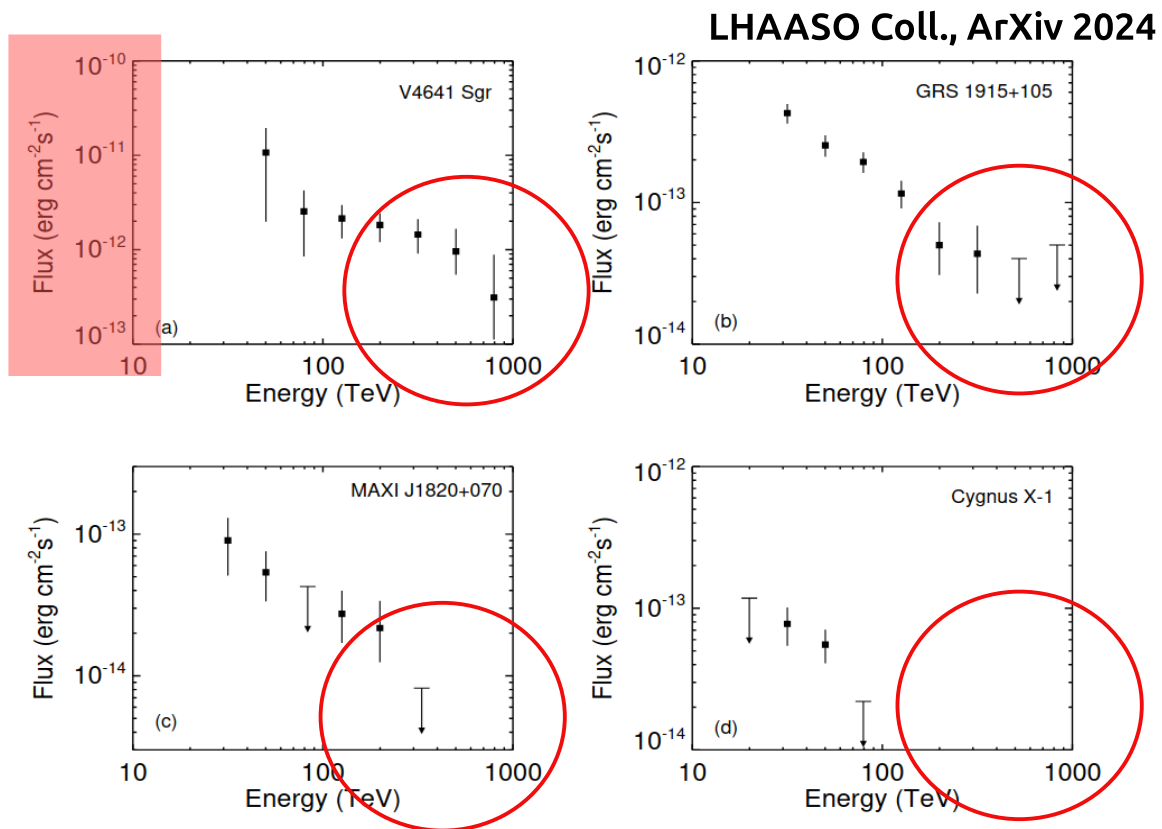


LHAASO Coll., ArXiv 2024

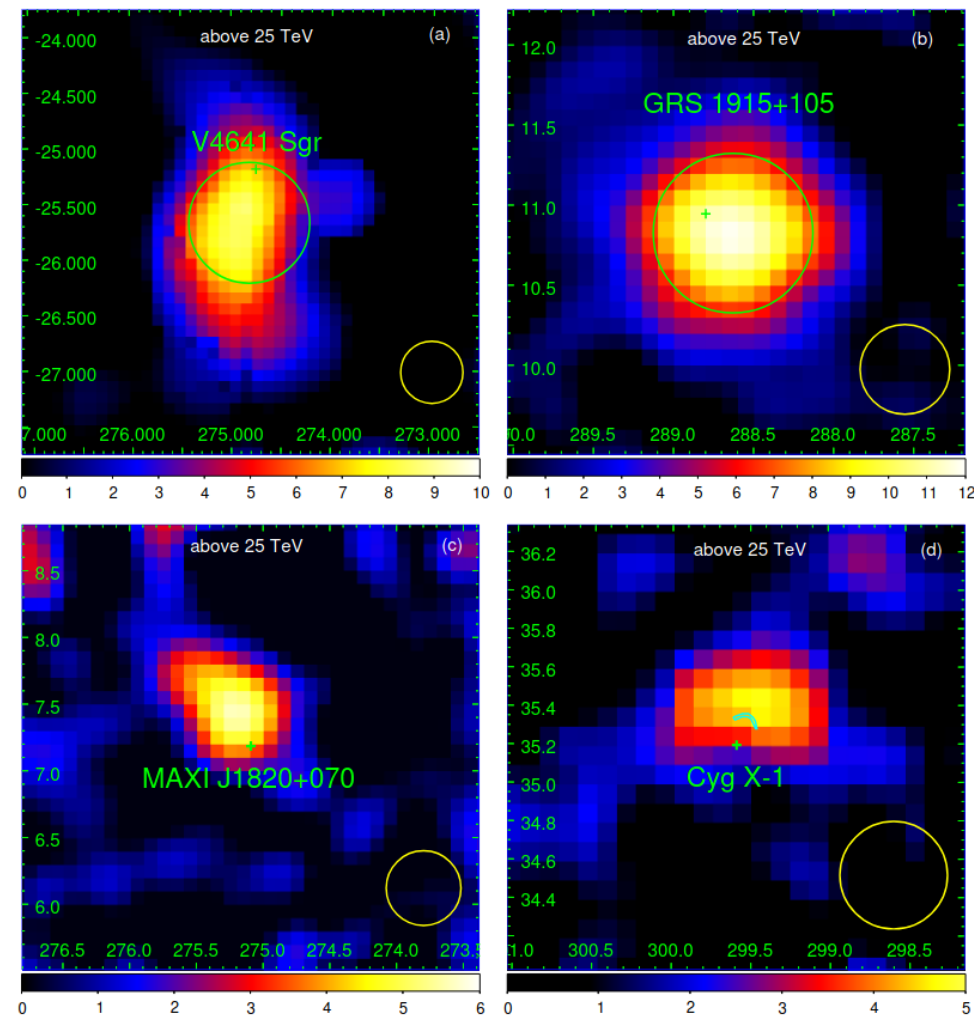


something stands out

- ▶ V4641 Sgr is the brightest (by an order of magnitude)
- ▶ Photons detected out to 800 TeV
- ▶ Requires PeV particles!

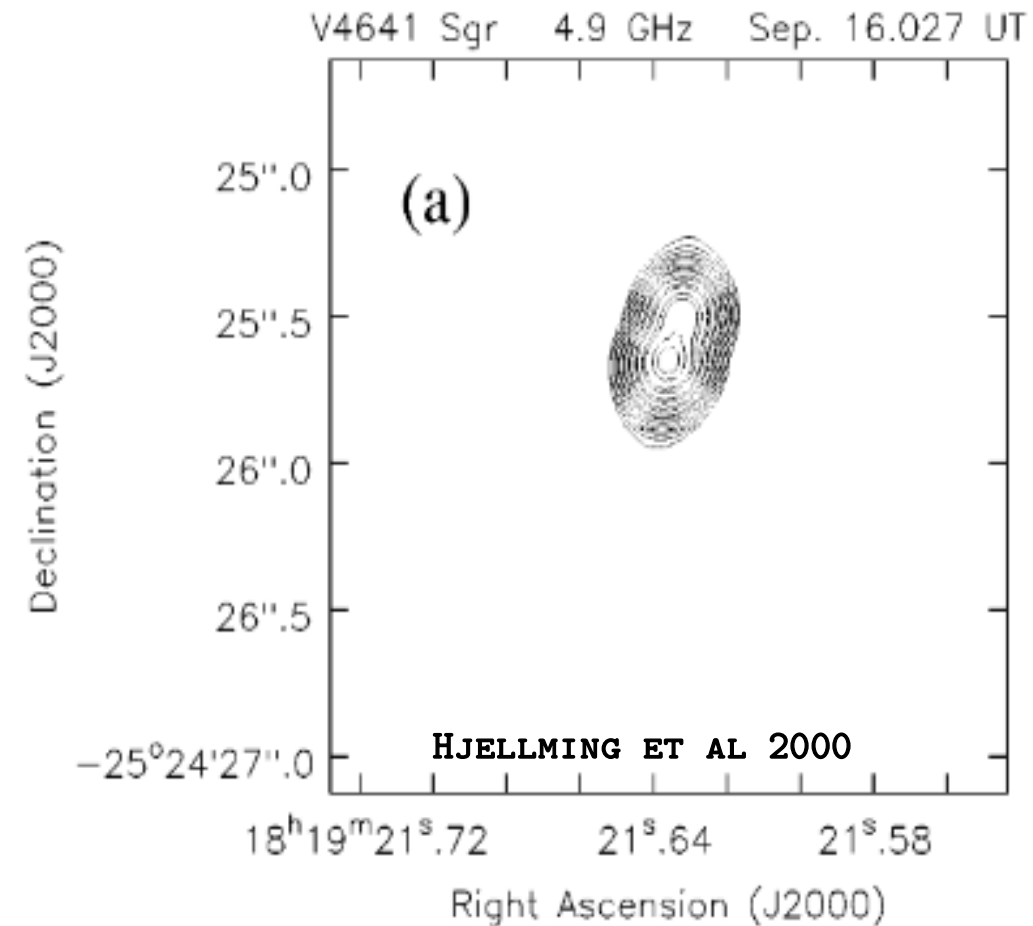


LHAASO Coll., ArXiv 2024



V4641 Sgr

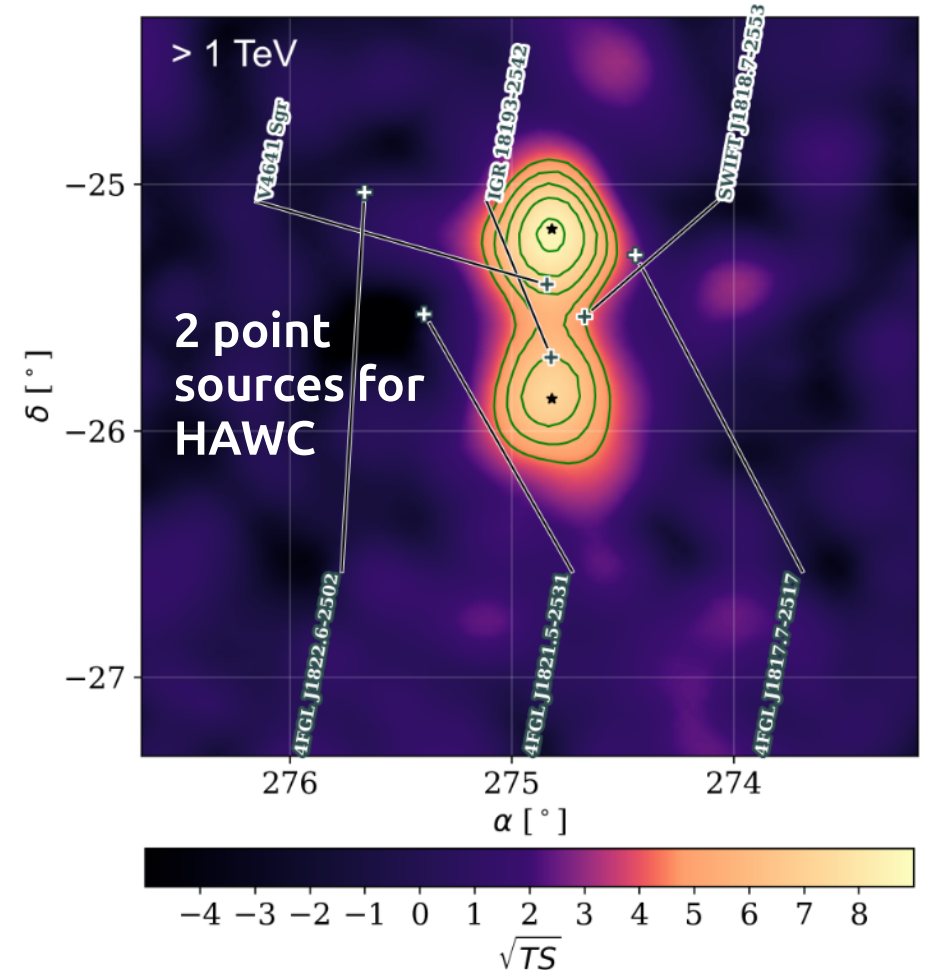
- ▶ Discovered in 1999 during extremely bright outburst
- ▶ Relatively “quiet” since: most of the time in quiescence + small ($\sim 10^{36}$ erg/s) outbursts.
- ▶ During 1999 outburst, detection of a compact radio source, interpreted as a jet
- ▶ **Inferred** super-luminal proper motions $\rightarrow$ relativistic jet with low inclination angle (“microblazar”)
- ▶ **BUT** TeV emission is ~ 100 pc long! and elongated
- ▶ No known x-ray or radio counterpart to the extended emission...



V4641 Sgr

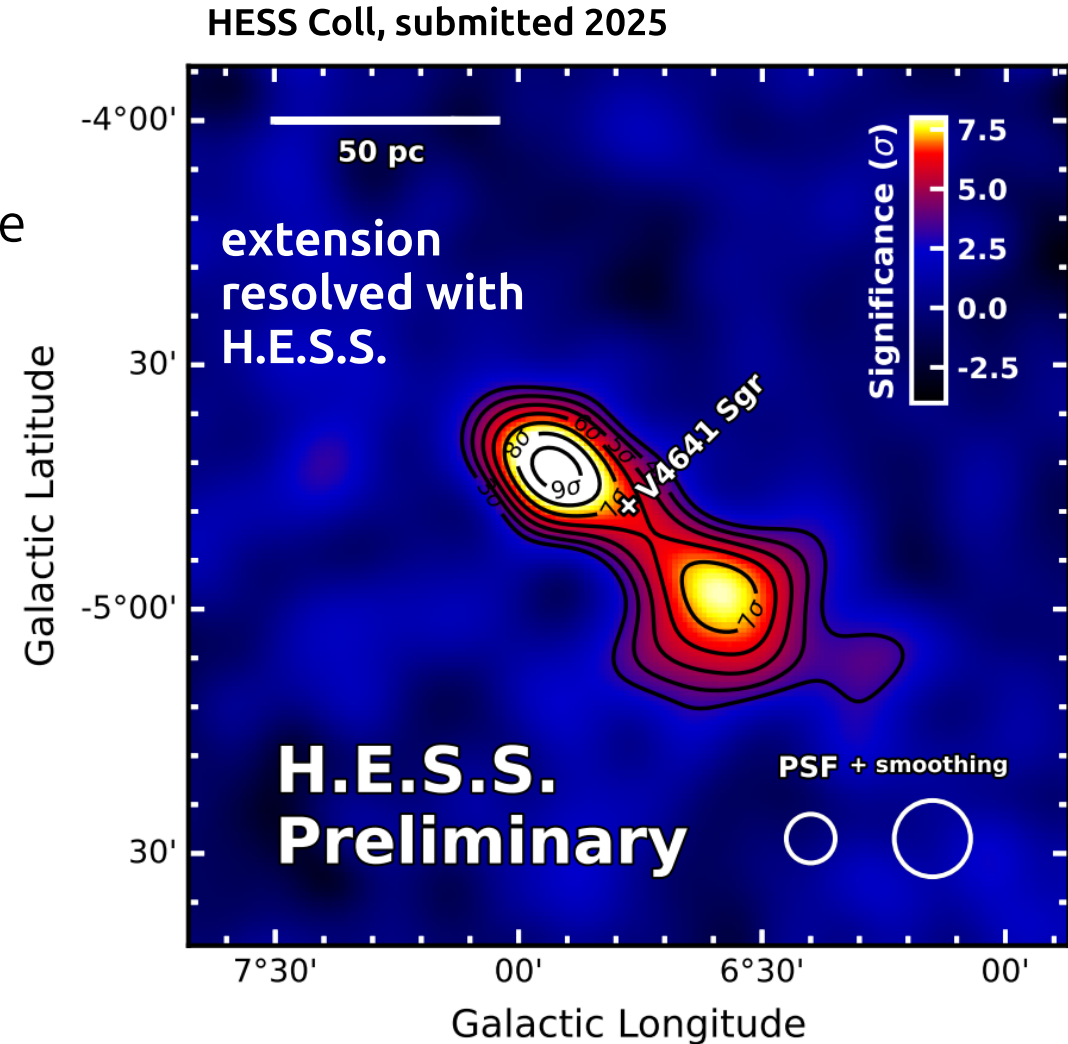
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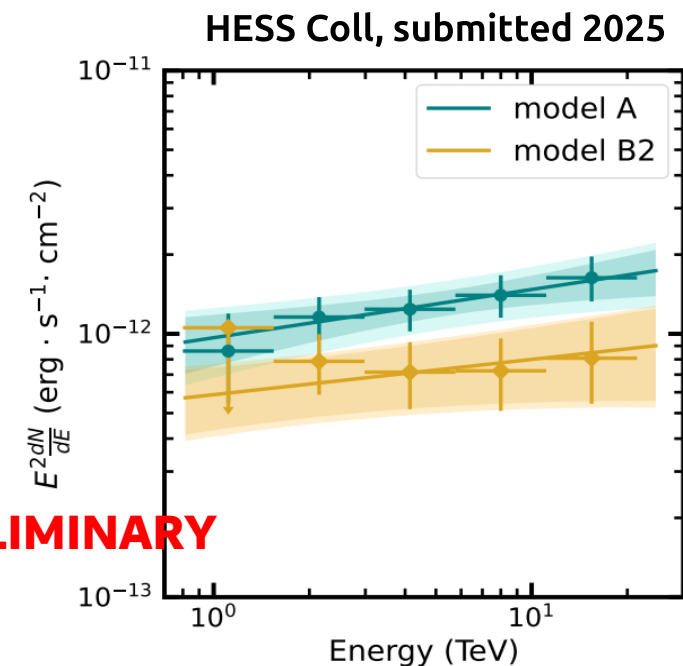
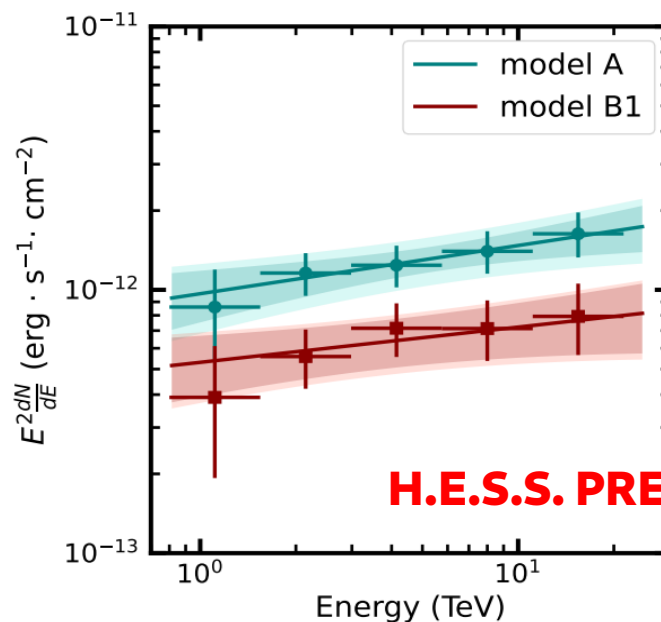
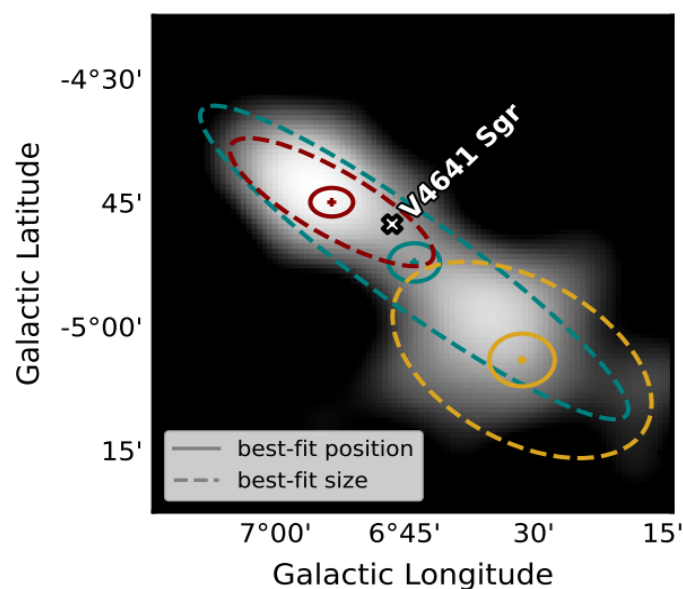
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V4641 Sgr – detailed TeV morphology

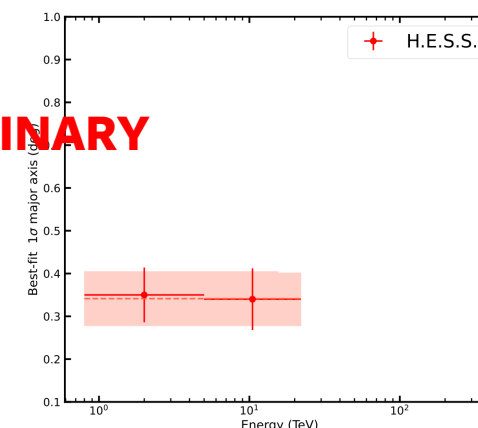
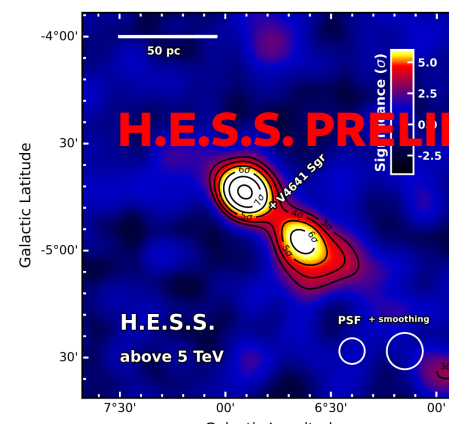
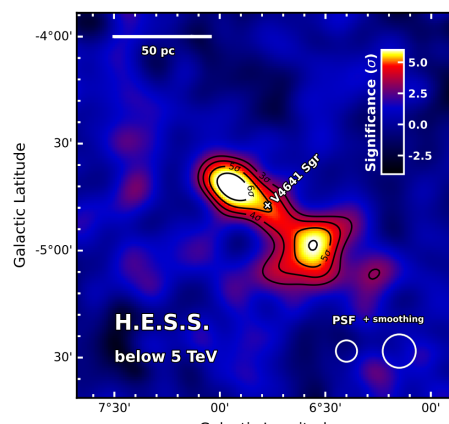
- ▶ Single elliptical Gaussian + PL: 13σ . Significantly (5σ) elongated in both directions.
- ▶ No curvature or cutoff in spectrum, index = $1.82 \pm 0.27 \pm 0.07$ -> hard!
- ▶ Model with two extended elliptical components weakly (3σ) preferred, spectral properties between both components undistinguishable.



V4641 Sgr – energy-dependent morphology

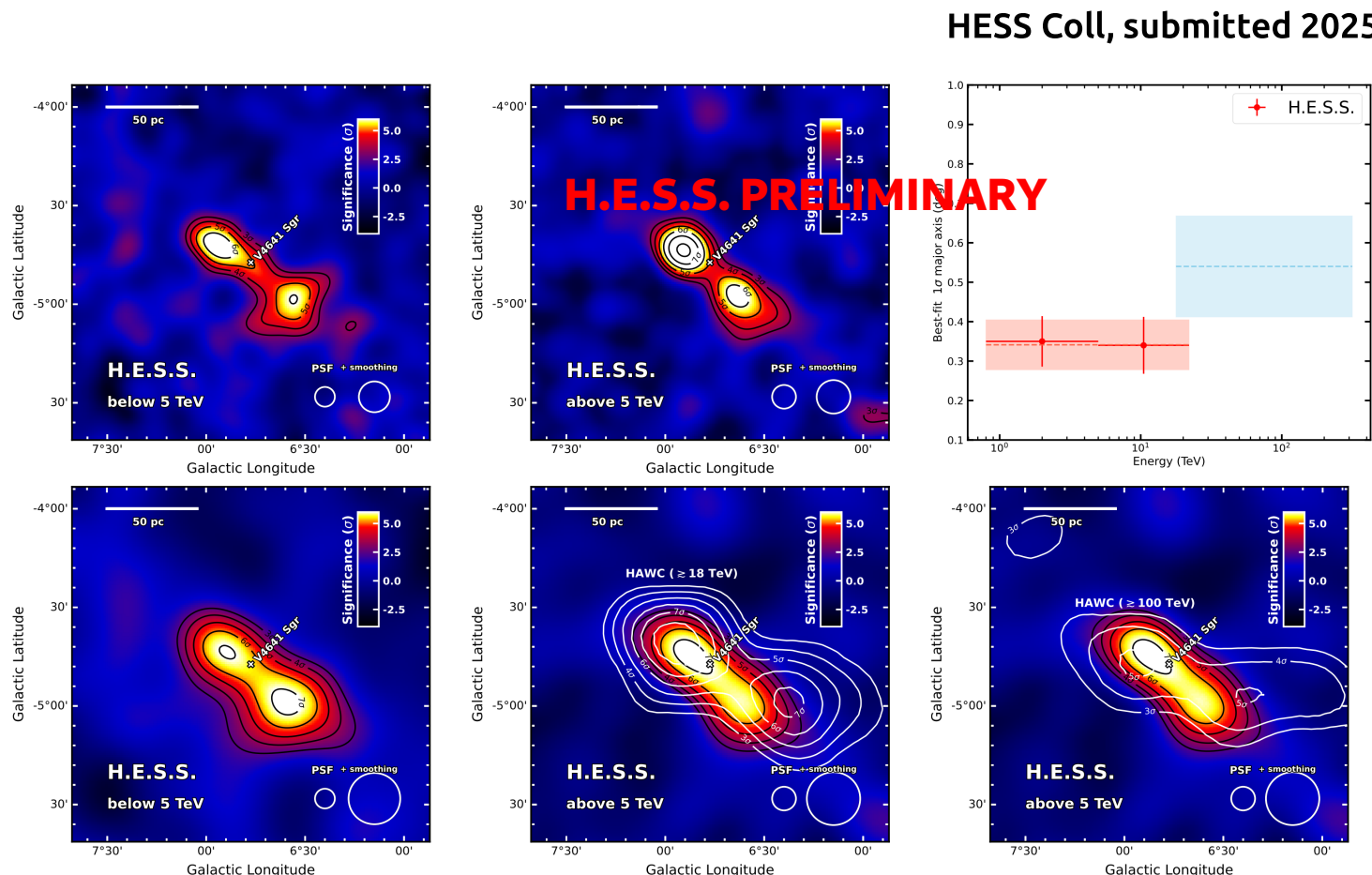
- Split energy range into two bands and repeat fits. Overall size completely consistent, hint that ellipticity of 2 components change but statistics don't allow statement.

HESS Coll, submitted 2025



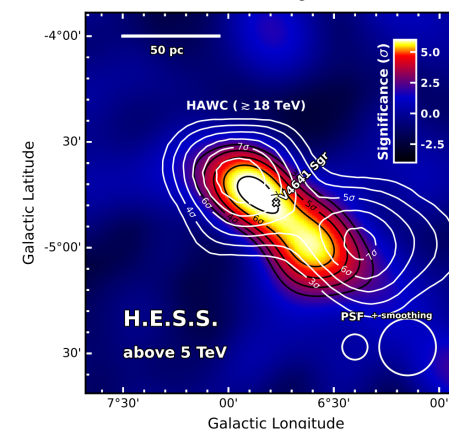
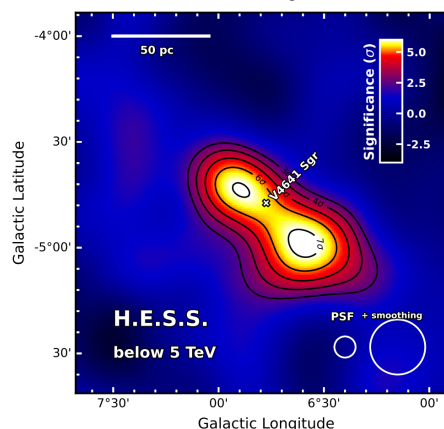
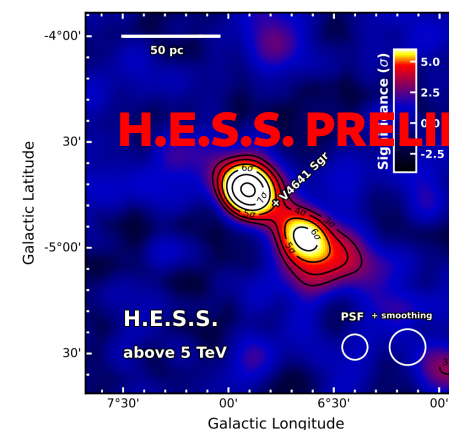
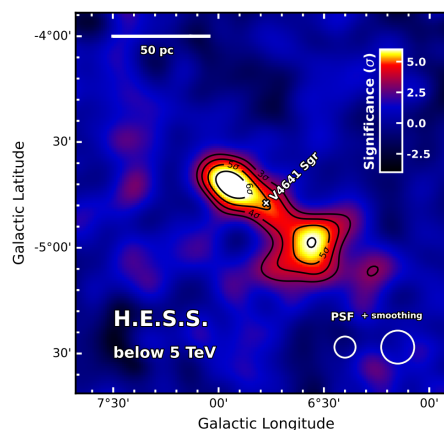
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- ▶ Energy-averaged size consistent within 1.5σ (incl syst)

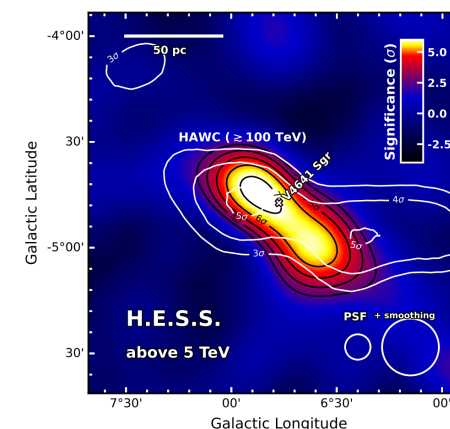
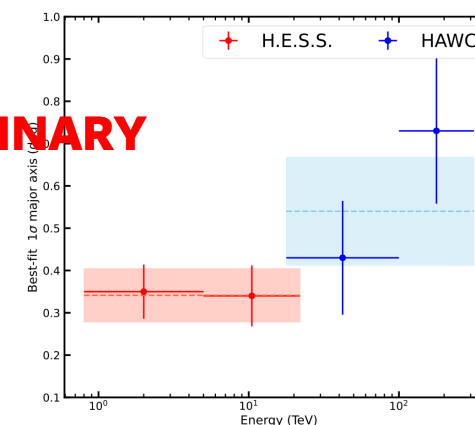


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- ▶ What about comparing to HAWC?
- ▶ Energy-averaged size consistent within 1.5σ (incl syst)
- ▶ HAWC data and scripts are public -> fit below and above 100 TeV
- ▶ Below 100 TeV H.E.S.S. and HAWC are consistent well within 1σ
- ▶ 2σ jump above. Real? Can't tell. LHAASO might!
- ▶ **No evidence** (as far as we can tell)

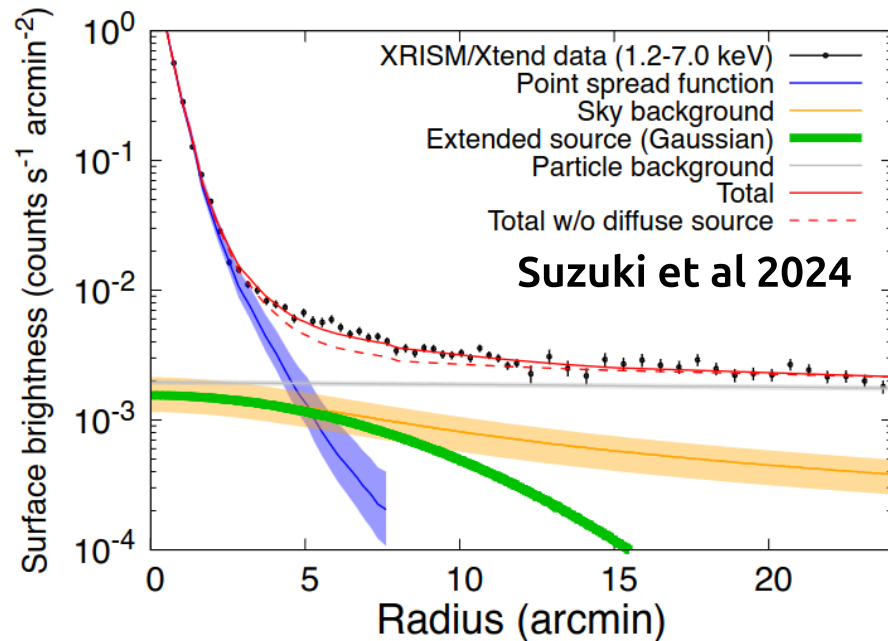


HESS Coll, submitted 2025



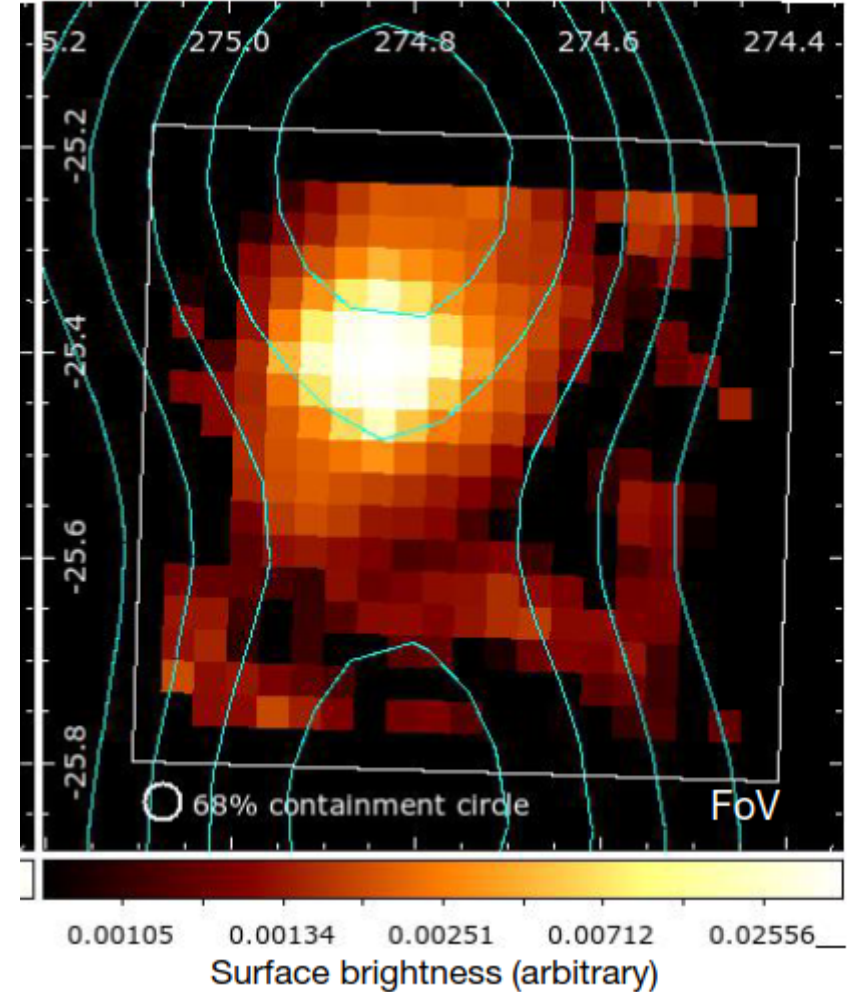
V4641 Sgr with XRISM

- ▶ ToO XRISM observations in September 2024 during an outburst of the source
- ▶ Detection of previously unknown extended (~ 10 pc) emission
- ▶ Thermal/non-thermal origin unclear
- ▶ Much smaller than TeV region but promising start!



Suzuki et al 2024

(c) NXB-subtracted, vignetting-corrected
1.2–7.0 keV image with HAWC contours



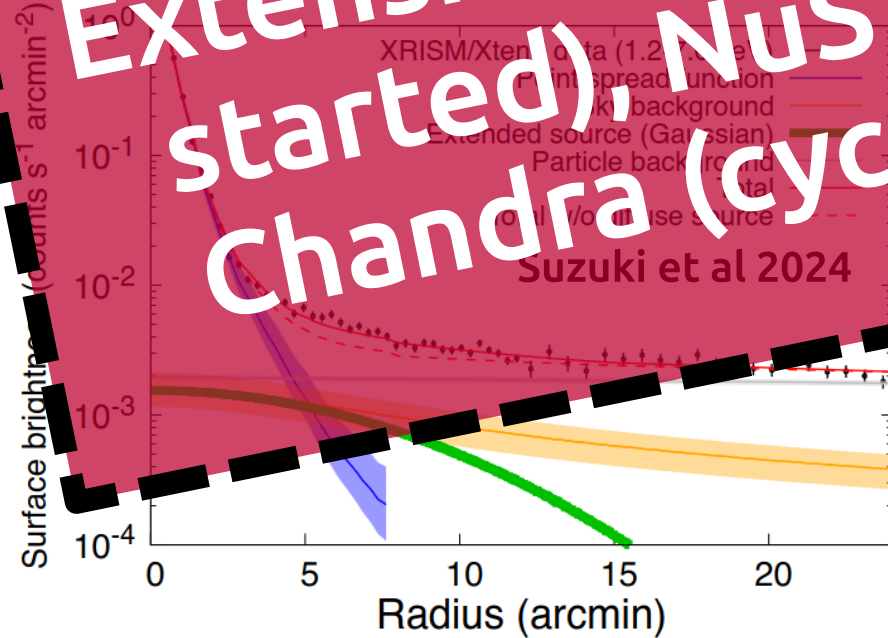
V4641 Sgr with XRISM

Suzuki et al 2024

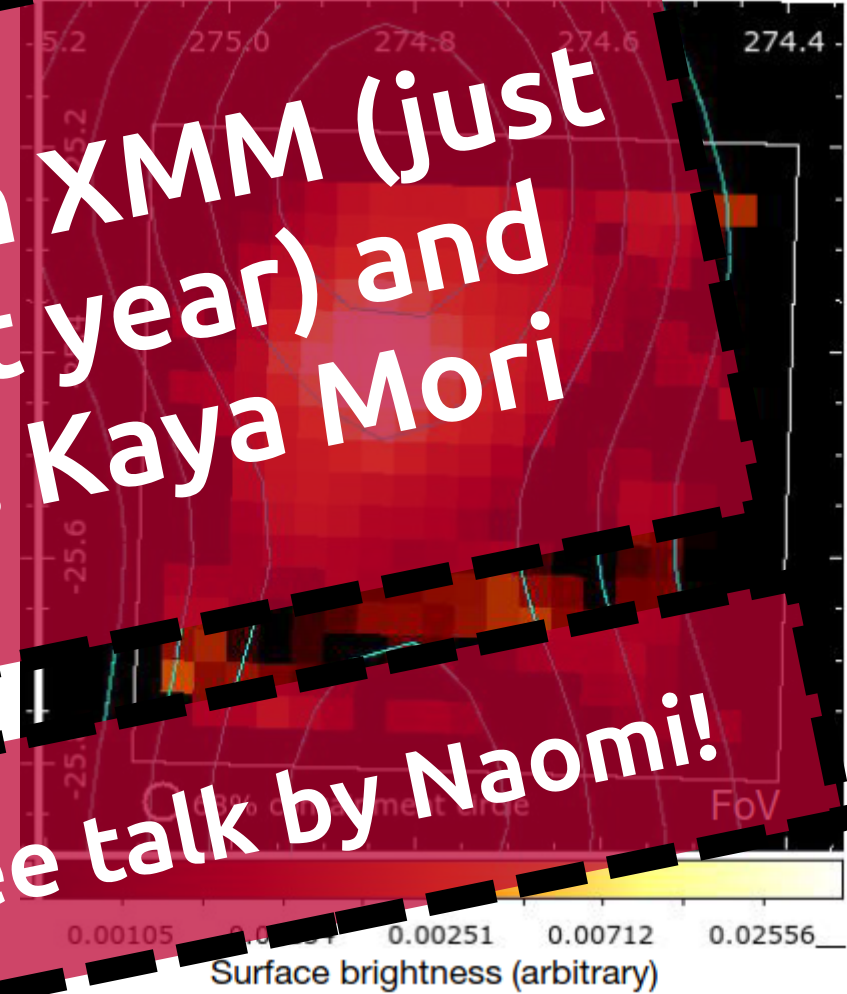
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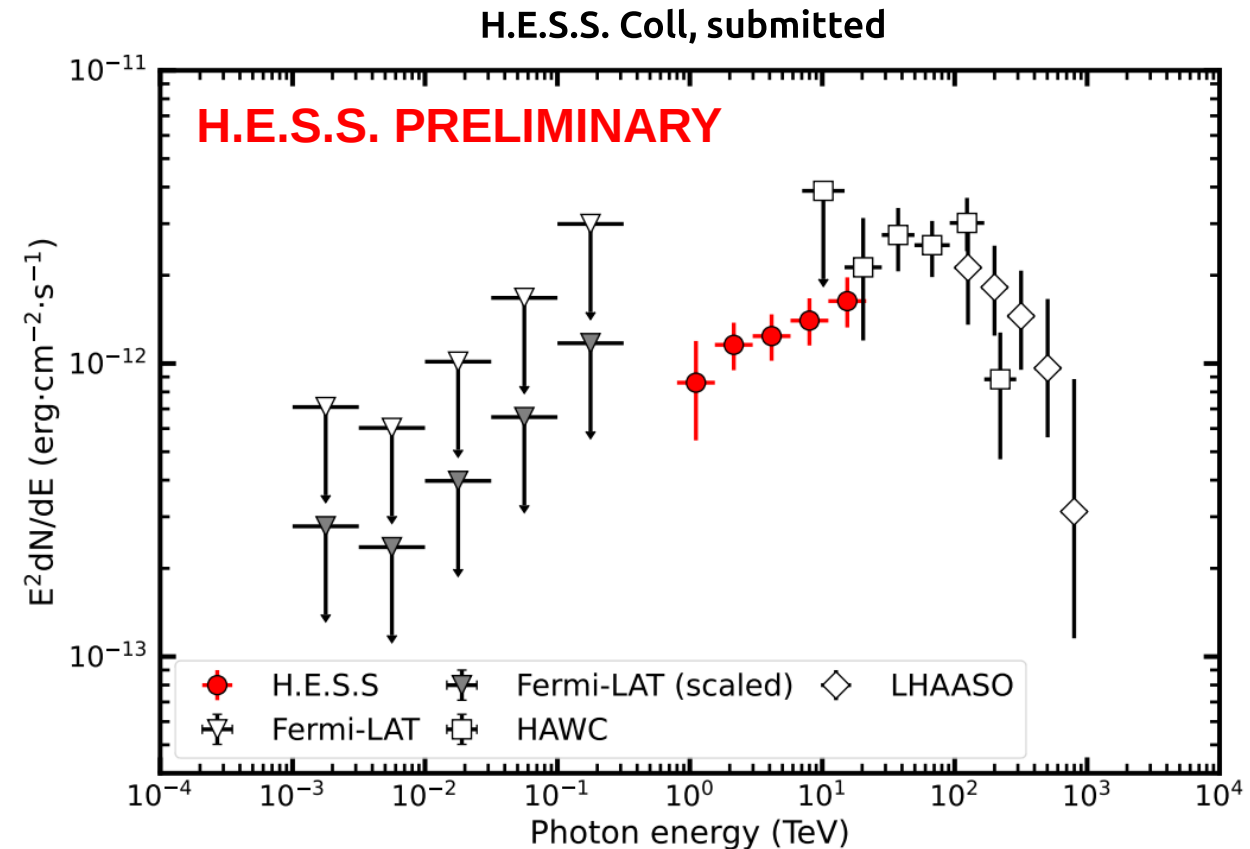


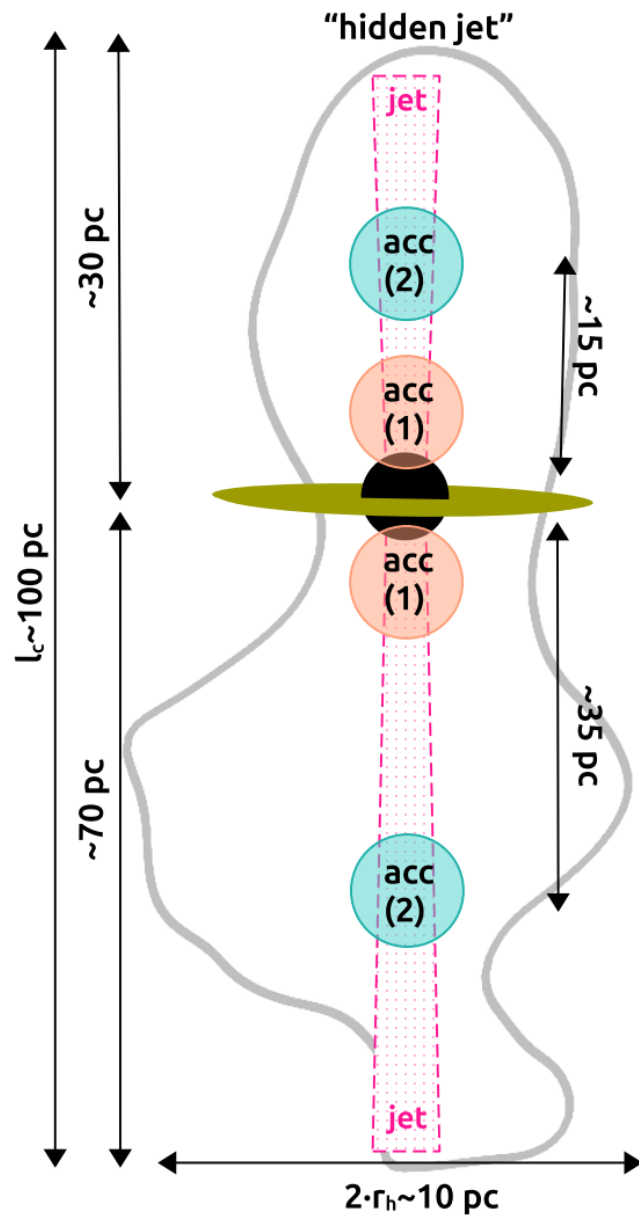
Extensive campaign with XMM (just started), NuSTAR (next year) and Chandra (cycle 27), PI: Kaya Mori

see talk by Naomi!

An impressive particle accelerator

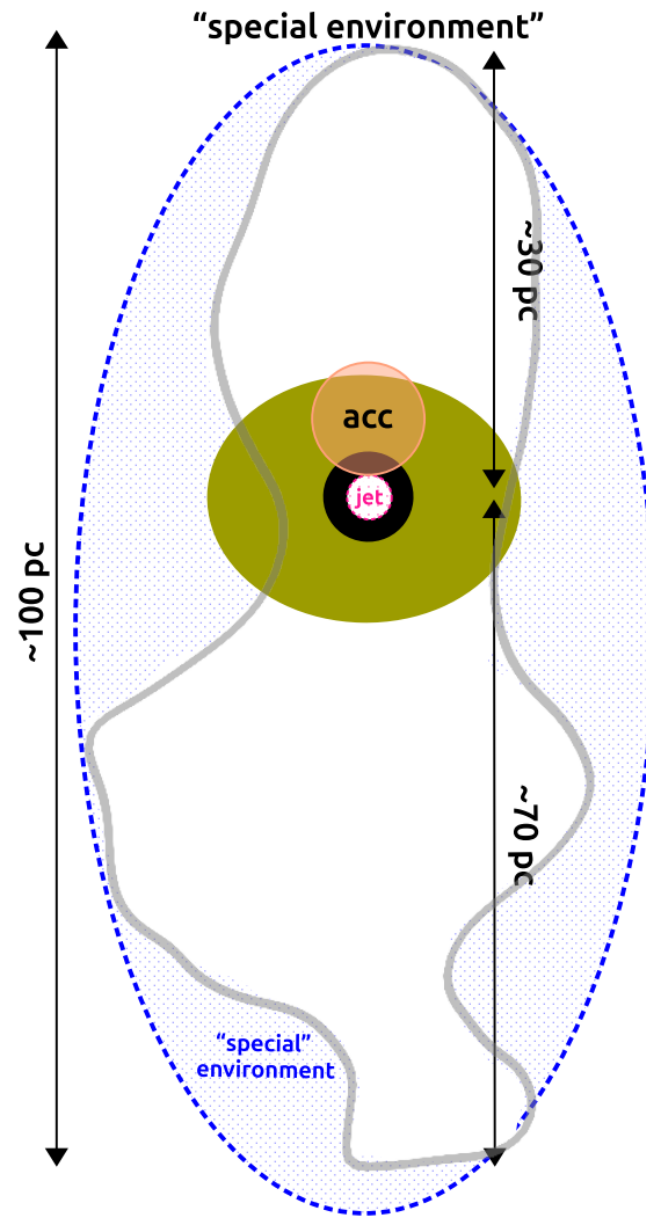
- ▶ “Normal” x-ray binary - extraordinary gamma-ray source
- ▶ **First source spectra with peak at 100 TeV**
- ▶ 4 times brighter than Crab Nebula at 100 TeV
- ▶ 1-2 orders of magnitude brighter than SS 433
- ▶ Unexpected morphology
- ▶ What is happening here???





Perpendicular jet

- Morphology easy
- No other evidence?

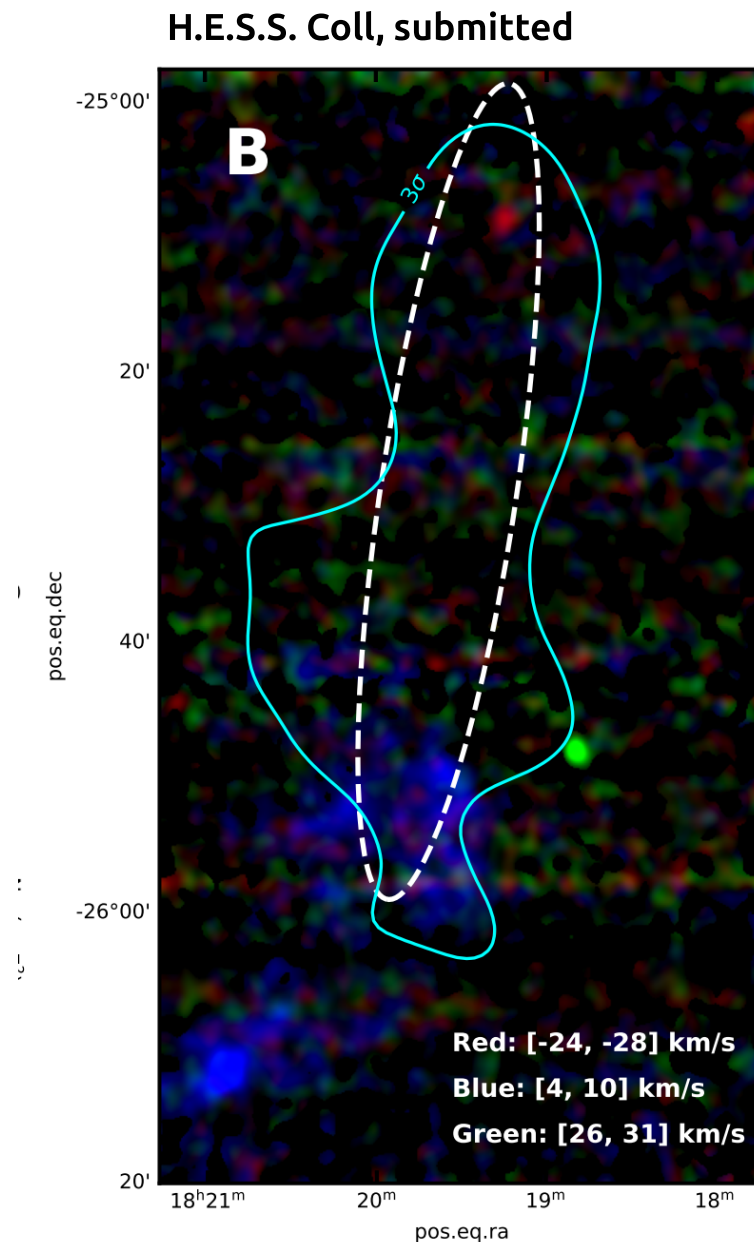


Low inclination jet

- Morphology must be product of environment
- Molecular cloud?
- Magnetic field structure? (Neronov et al)

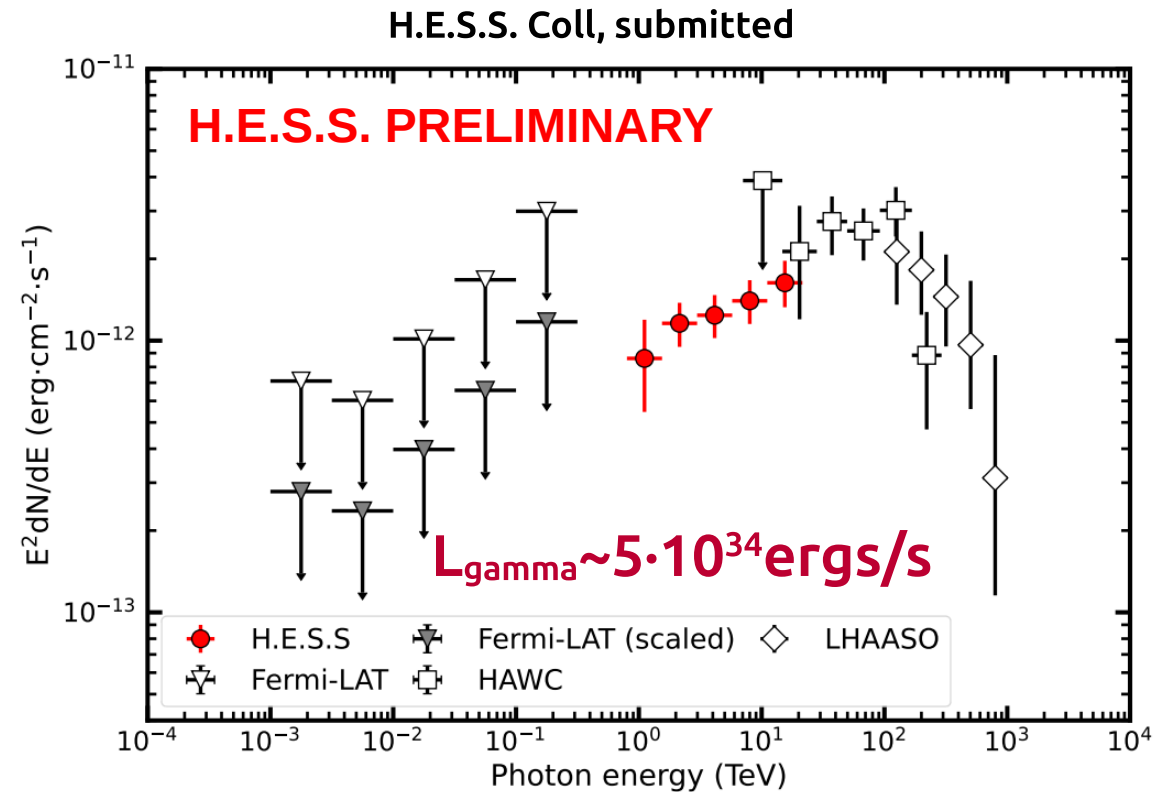
Molecular cloud?

- ▶ Nope :-)
- ▶ V4641 Sgr is located ~ 500 pc below Galactic plane
- ▶ CO observations (Nobeyama Radio Observatory, PI: Naomi Tsuji) confirm $n \ll 1 \text{ cm}^{-3}$
- ▶ Clouds at velocities consistent with either very close or very far distances
- ▶ No gas (remotely) consistent with distance of V4641 Sgr (6.2 kpc, Macdonald et al 2014)
- ▶ **No gas consistent with gamma-ray morphology**
- ▶ Aligned jet requires fine-tuning of the environment properties
- ▶ Scenario with perpendicular jet more natural?



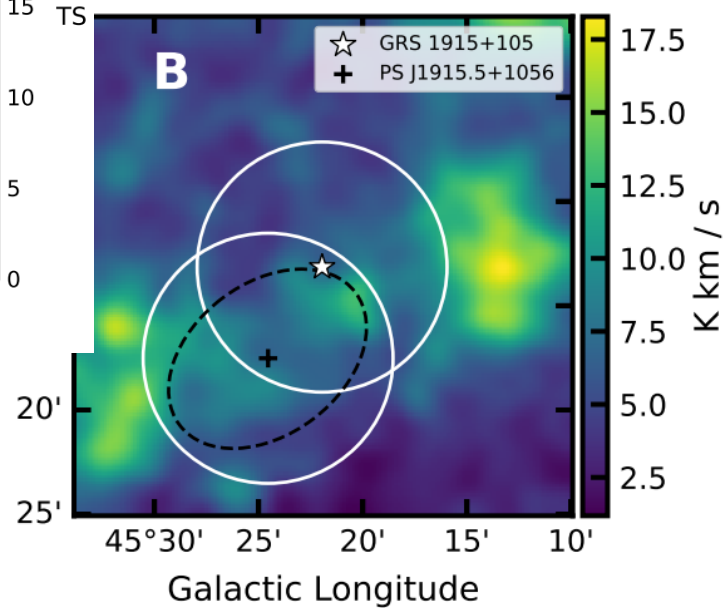
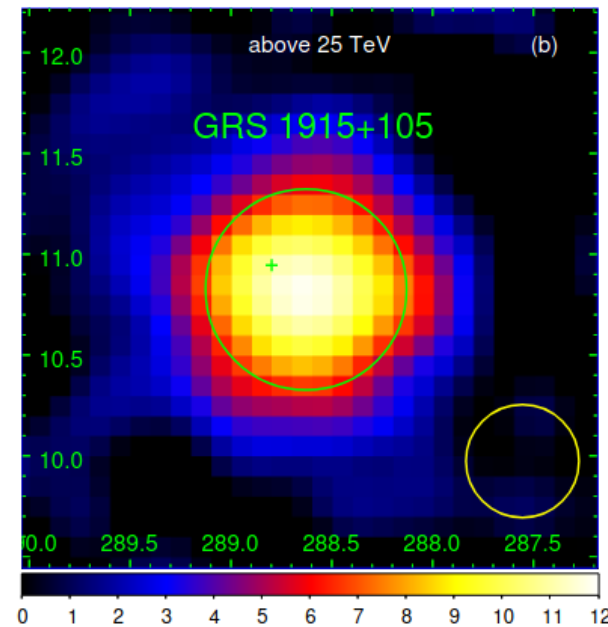
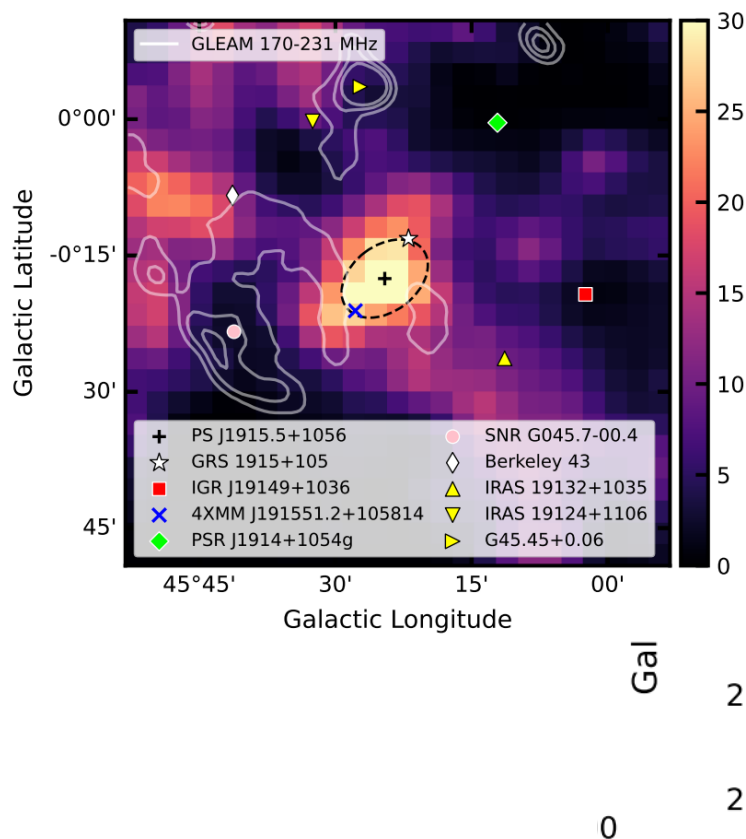
Tracing past activity

- ▶ No gas = extreme constraints to energetics in hadronic case
 - ▷ gamma-ray luminosity + low density require $L_{\text{source}} \sim L_{\text{edd}}$ for millions of years (entire age of source)
- ▶ A leptonic scenario faces significantly less constraints, as long as $B < 3\text{uG}$
 - ▷ advection in $>0.1c$ outflow fast enough to beat cooling
 - ▷ but still requires $L_{\text{electrons}} \sim 10^{36} \text{erg/s}$ for $\sim 10^3 \text{yr}$!
- ▶ V4641 Sgr must have been significantly more active in the past



Looking for hadronic emission

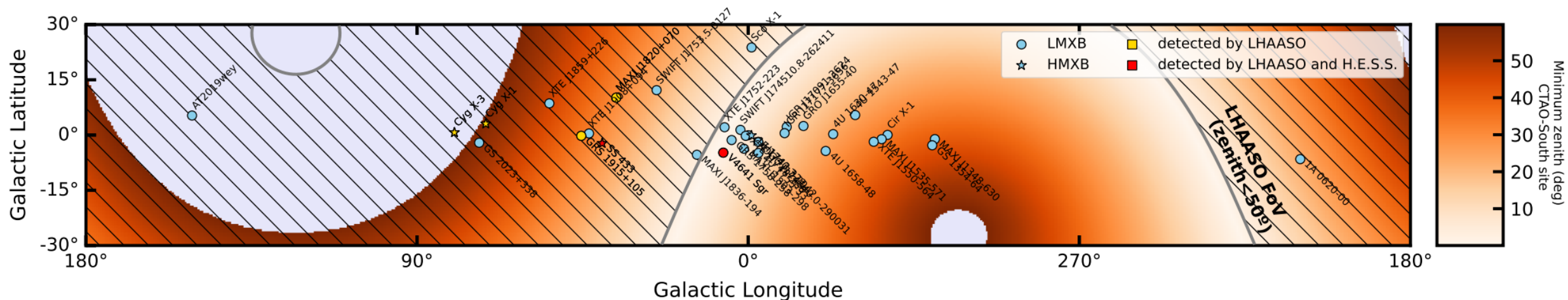
- ▶ Particle acceleration in microquasar systems + evidence of heavy jets in some systems = plausible cosmic ray accelerators
- ▶ It would be nice to find detect evidence!
 - ▷ Neutrino flux too low for current experiments (unless a purely hadronic V4641 Sgr “twin”)
 - ▷ Microquasars which have nearby gas?
- ▶ Issue: dense gas usually concentrated near the Plane. So usually, nearby gas also means crowded region!
- ▶ Harder to identify microquasar as sole responsible!
- ▶ E.g. GRS 1915+105



The population

- ▶ All detected microquasars are on the Northern half of the sky.
- ▶ Simply because that is where the unbiased instruments (HAWC, LHAASO) observe
- ▶ H.E.S.S. only looking for point-like sources during flares for decades (but no longer ;-)
- ▶ More detections almost guaranteed once the right observations are carried out.
- ▶ How rare is V4641 Sgr? Is this a phase “normal” sources can go through?

H.E.S.S. Coll. 2024 (SS 433)

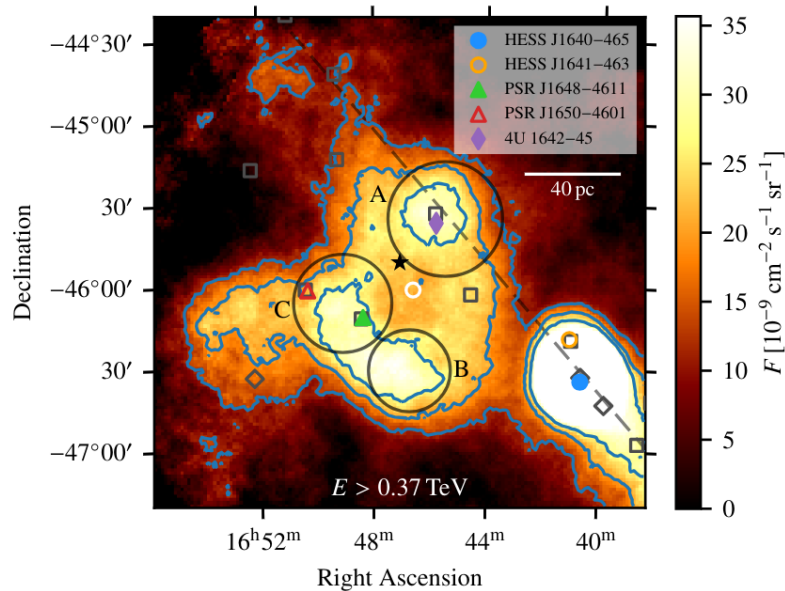


The population

- ▶ Distinction between x-ray binary/microquasar is **not so well defined!!!**
- ▶ Any BH binary (and some NS binaries) could be a microquasar (i.e. host jets) at some point
- ▶ Our microquasar list is heavily biased by
 - ▶ sources which are powerful **now**
 - ▶ sources for which the **right kind of data** was taken at the **right time** (e.g. radio outburst)
- ▶ But the presence of TeV/PeV gamma-rays in the scale of several pc can be completely unrelated to what the compact object is doing today (see V4641 Sgr)
- ▶ Good and bad news:
 - ▶ Arguing that microquasars are responsible for knee+ becomes easier
 - ▶ Evidence becomes weaker (“any” x-ray binary is enough, how to decide?)
- ▶ Opposite problem: there are **lots** of x-ray binaries: clearly not all are PeVatrons!

Unidentified sources?

- ▶ Spatial coincidence of TeV emission with X-ray binaries disregarded in the past
- ▶ “normal” X-ray binaries not expected to make persistent TeV emission
- ▶ **Paradigm change thanks to LHAASO result!**
- ▶ There could be many, including some “unremarkable” binaries which were more active in the past



(a) Smoothing kernel: 0.22° top hat

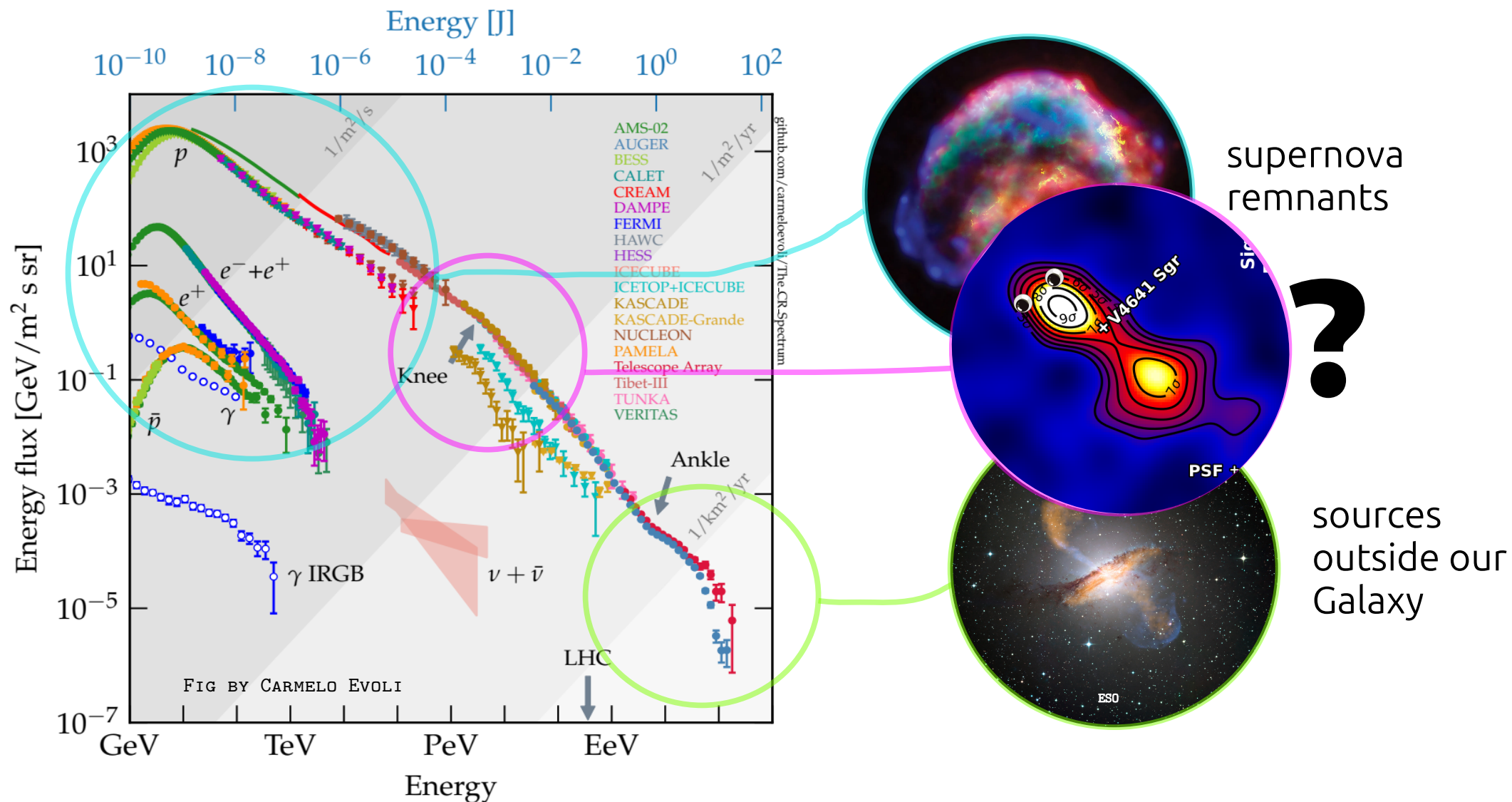
3.1.1. 4U 1642–45

H.E.S.S. Coll, A&A 2022

The LMXB 4U 1642–45 lies close to the peak in γ -ray emission observed in region A (cf. Fig. 3). However, despite this positional coincidence, we consider an association of 4U 1642–45 with HESS J1646–458 – or even the emission observed just in region A – highly unlikely: LMXBs are not known emitters of γ rays in the TeV energy range, in fact, Kantzas et al.

(Kantzas et al. 2019, 2020; Kargaltsev et al. 2000; Kargaltsev & Pavlov 2001; Kargaltsev et al. 2002; Kargaltsev & Pavlov 2003; Kargaltsev et al. 2004; Kargaltsev et al. 2005; Kargaltsev et al. 2006; Kargaltsev et al. 2007; Kargaltsev et al. 2008; Kargaltsev et al. 2009; Kargaltsev et al. 2010; Kargaltsev et al. 2011; Kargaltsev et al. 2012; Kargaltsev et al. 2013; Kargaltsev et al. 2014; Kargaltsev et al. 2015; Kargaltsev et al. 2016; Kargaltsev et al. 2017; Kargaltsev et al. 2018; Kargaltsev et al. 2019; Kargaltsev et al. 2020; Kargaltsev et al. 2021; Kargaltsev et al. 2022; Kargaltsev et al. 2023; Kargaltsev et al. 2024; Kargaltsev et al. 2025)

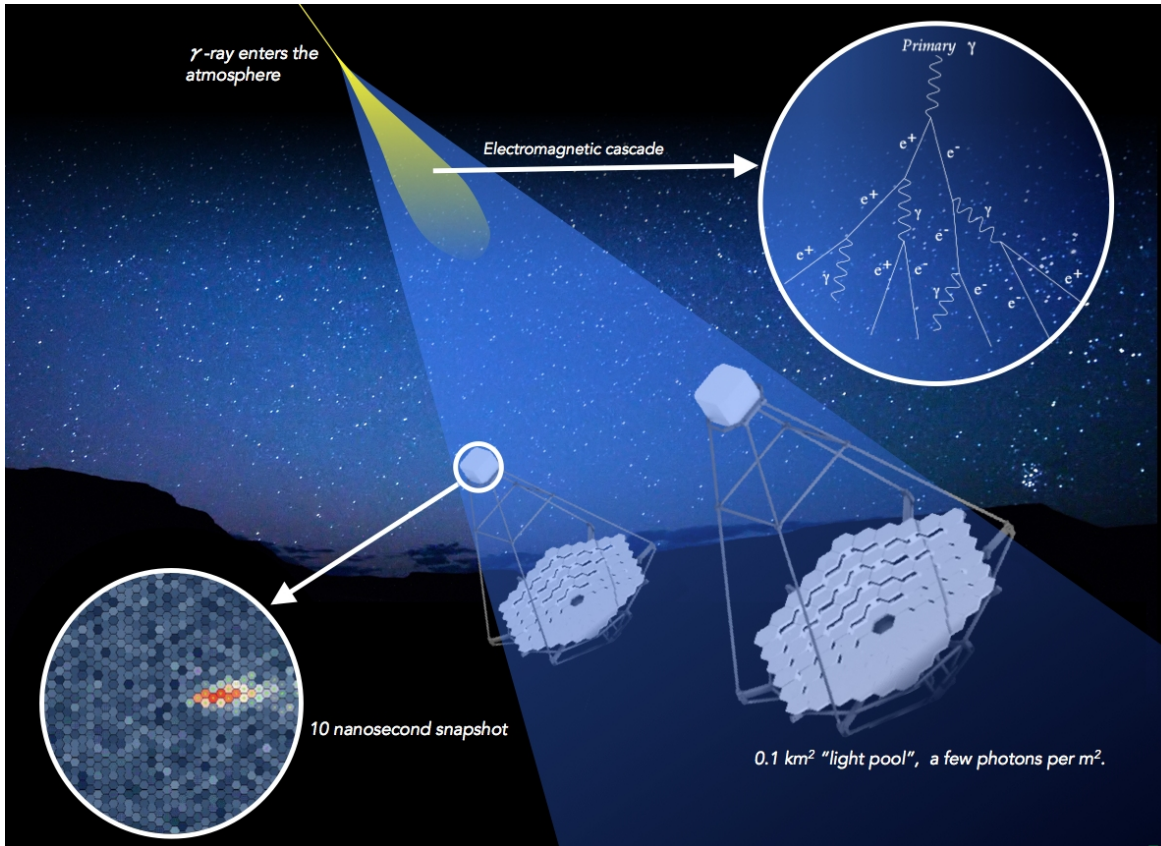
The origin of cosmic rays



Thanks!

DETECTING TEV GAMMA-RAYS

IACT TECHNIQUE



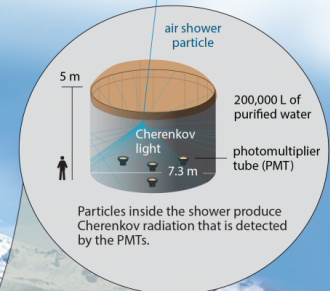
WCD TECHNIQUE



Mapping the Northern Sky in High-Energy Gamma Rays

Water Cherenkov tank

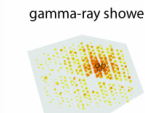
HAWC comprises an array of 300 tanks that record the particles created in gamma-ray and cosmic-ray showers.



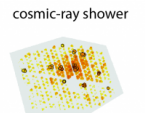
Particles inside the shower produce Cherenkov radiation that is detected by the PMTs.

Gamma rays vs cosmic rays

HAWC selects gamma rays from among a much more abundant background of cosmic rays.



"hot" spots concentrate around the core



"hot" spots are more dispersed

HAWC Observatory

HAWC operates day and night, providing a large field of view for the observation of the highest energy gamma rays.

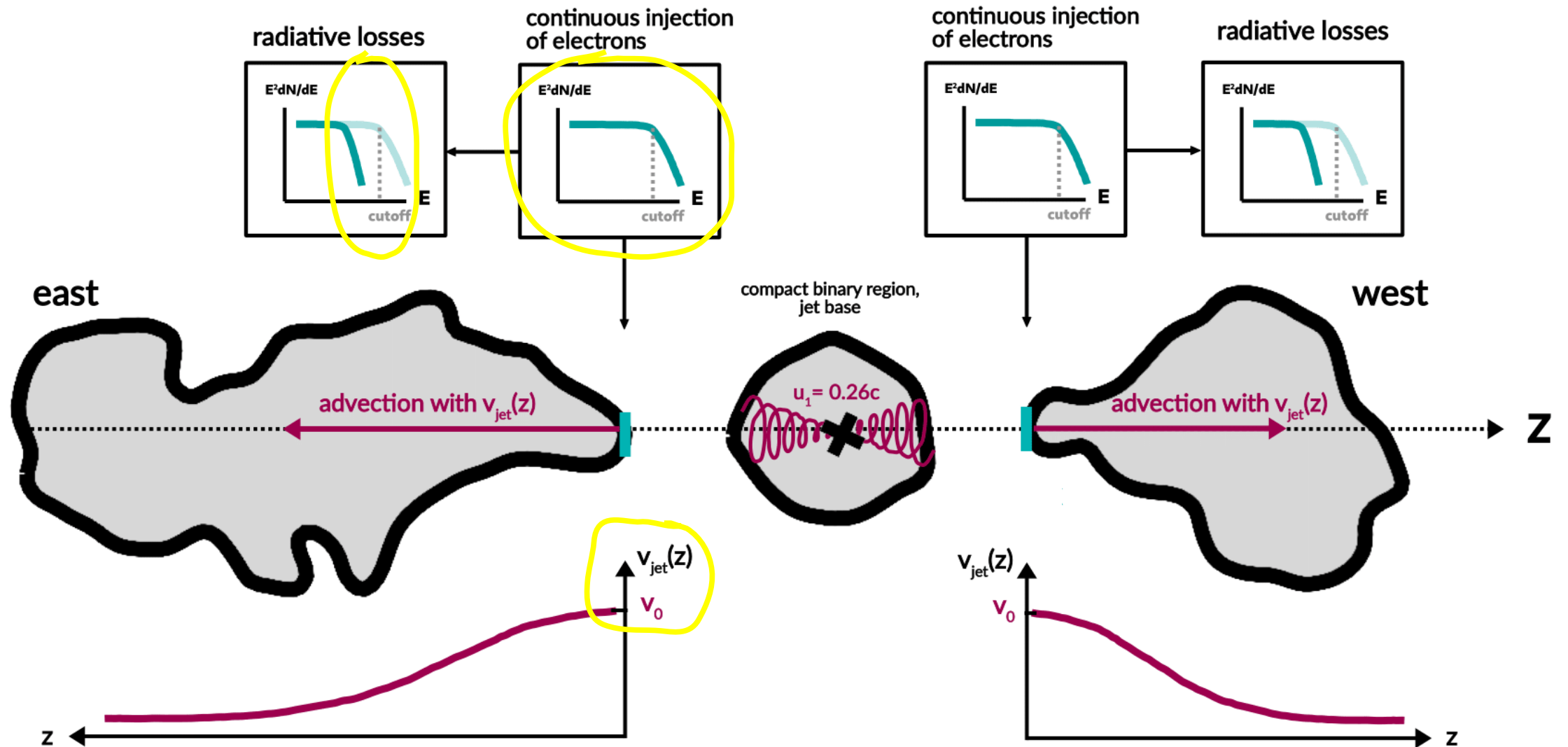


Pico de Orizaba
(5,626 m)

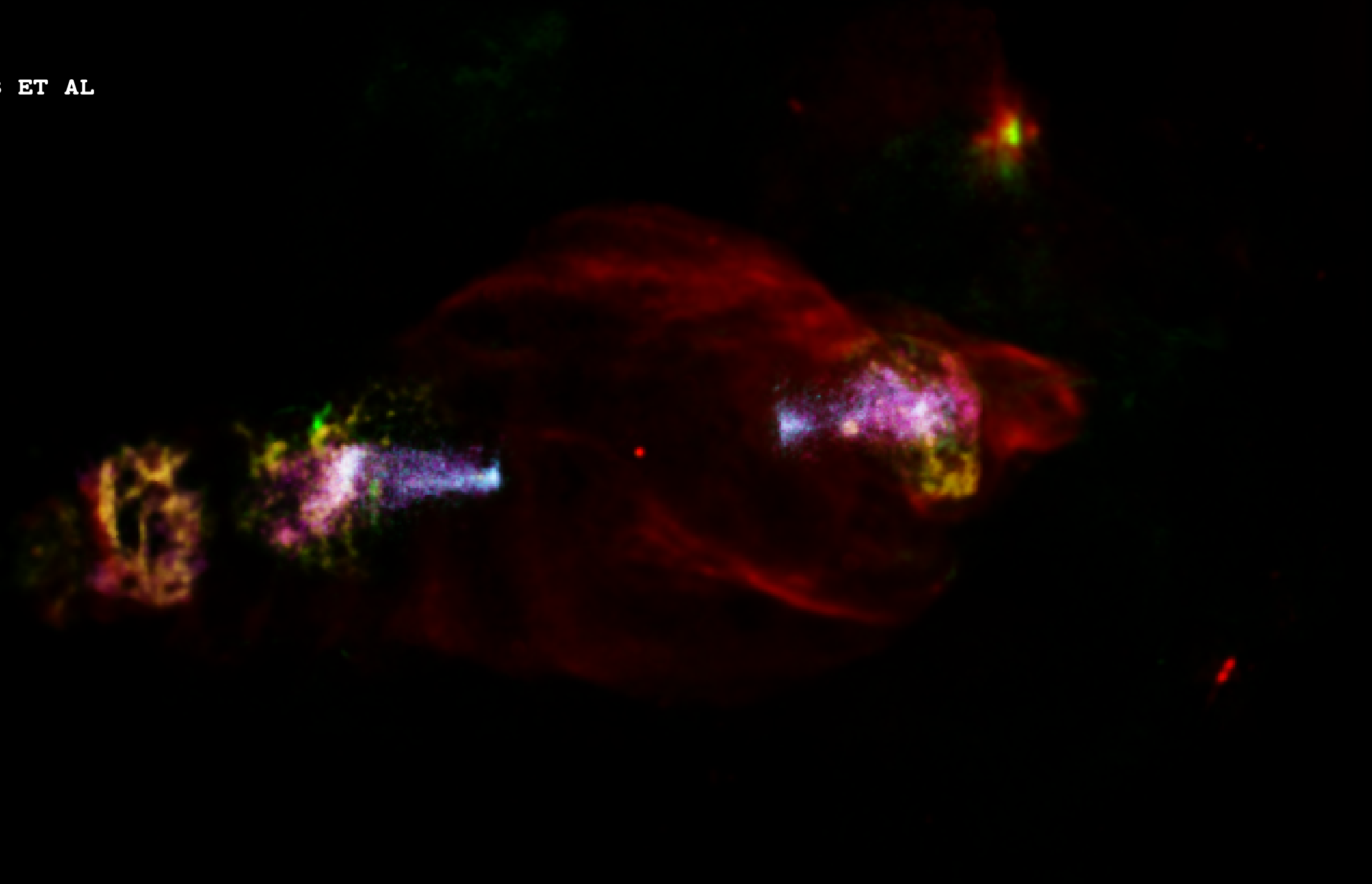
HAWC is located at 4,100 m above sea level, covering an area of 20,000 m².

150 m

SIMULATING TRANSPORT AND RADIATION OF ELECTRONS

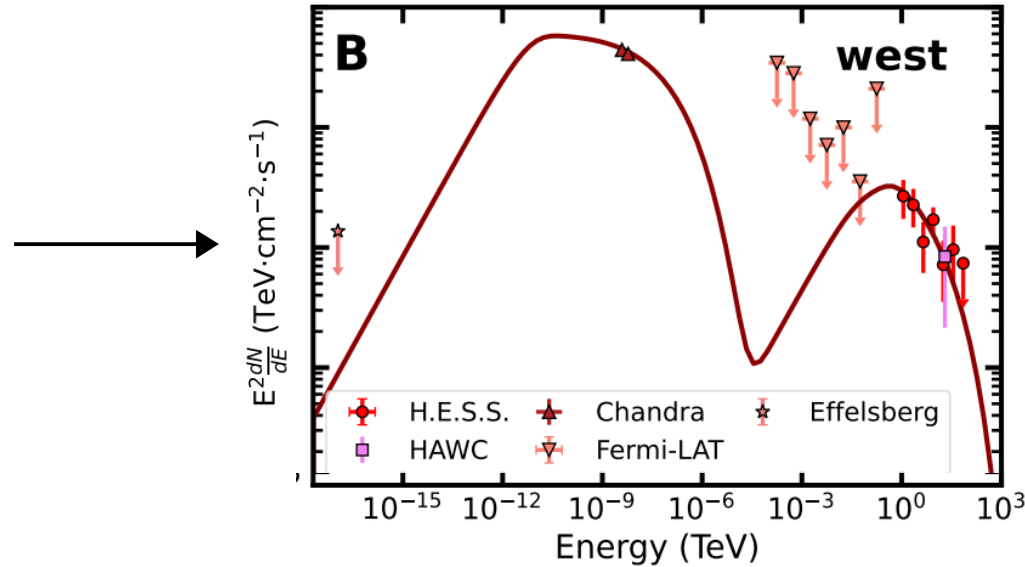
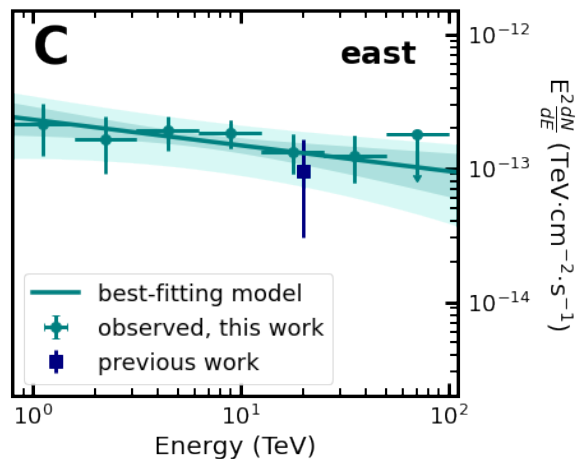
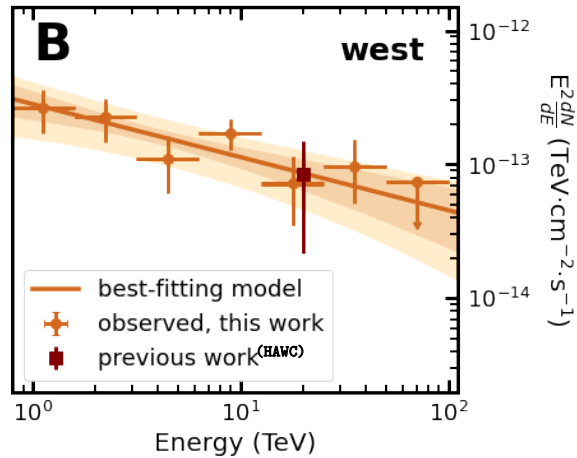


SAFI-HARB ET AL



HOW FAST DO ELECTRONS LOSE ENERGY?

MEASURED GAMMA-RAY SPECTRUM

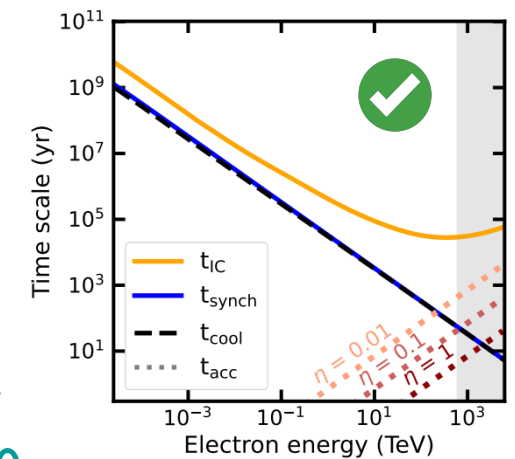


ELECTRONS RADIATE DUE TO:

- ▶ INVERSE COMPTON
- ▶ SYNCHROTRON

ESTIMATED:

- ▶ MAGNETIC FIELD (B) ~ 20 μG
- ▶ INJECTED ELECTRON SPECTRUM:
 - ▷ NORMALIZATION: 0.1% OF JET KINETIC POWER
 - ▷ SPECTRAL SHAPE: E^{-2} WITH **NO CUTOFF ($E_c > 200 \text{ TeV}$)**

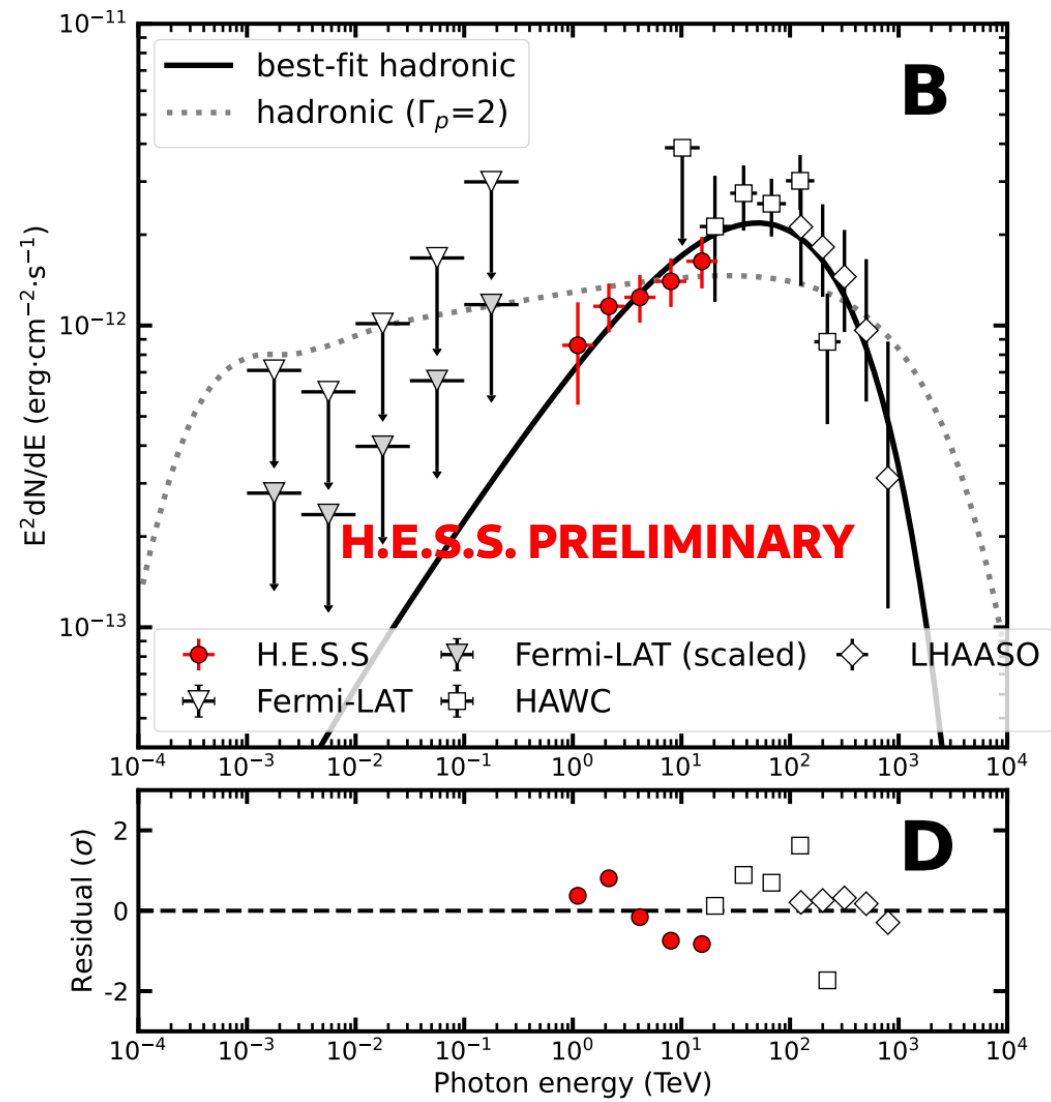


Hadronic scenario

- ▶ H.E.S.S. spectral index requires $\Gamma_p \sim 1.5$
- ▶ Lack of dense gas requires extreme energetics: proton energy density in the order of $\text{keV}/\text{cm}^{-3}$.
- ▶ Matching that density in low-n environment requires $T_{\text{ISM}} \sim 10^7$
- ▶ If 1% of L_{edd} goes to protons, matching gamma-ray flux takes **2.5 Myr**
- ▶ Proper motion: **source has only been there for ~2 Myr!**

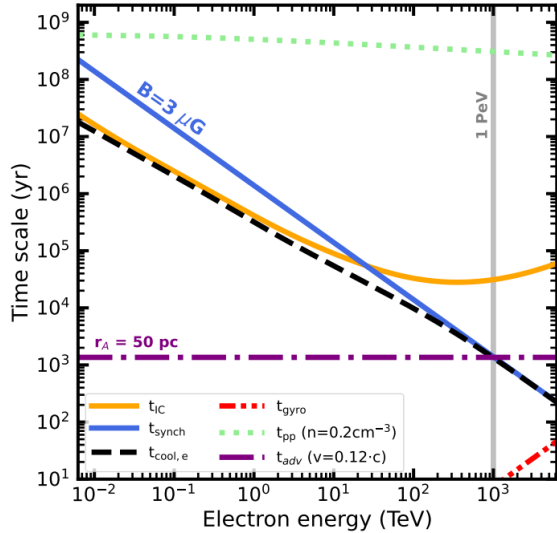
	hadronic model		
Γ_p	1.49	(1.24, 1.64)	(1.04, 1.79)
$E_{\text{tot}}^p (10^{50} \cdot n_{0.2}^{-1} \text{ cm}^{-3} \text{ erg})$	8.0	(7.17, 8.76)	(6.57, 10.31)
$u_{\text{tot}}^p (n_{0.2}^{-1} \text{ cm}^{-3} \text{ keV} \cdot \text{cm}^{-3})$	0.49	(0.44, 0.54)	(0.40, 0.63)
$E_{\text{cut}}^p (\text{PeV})$	1.74	(1.00, 2.69)	(0.72, 4.99)

Fit using GAMERA and bayesian sampling implemented in Gammapy 1.3



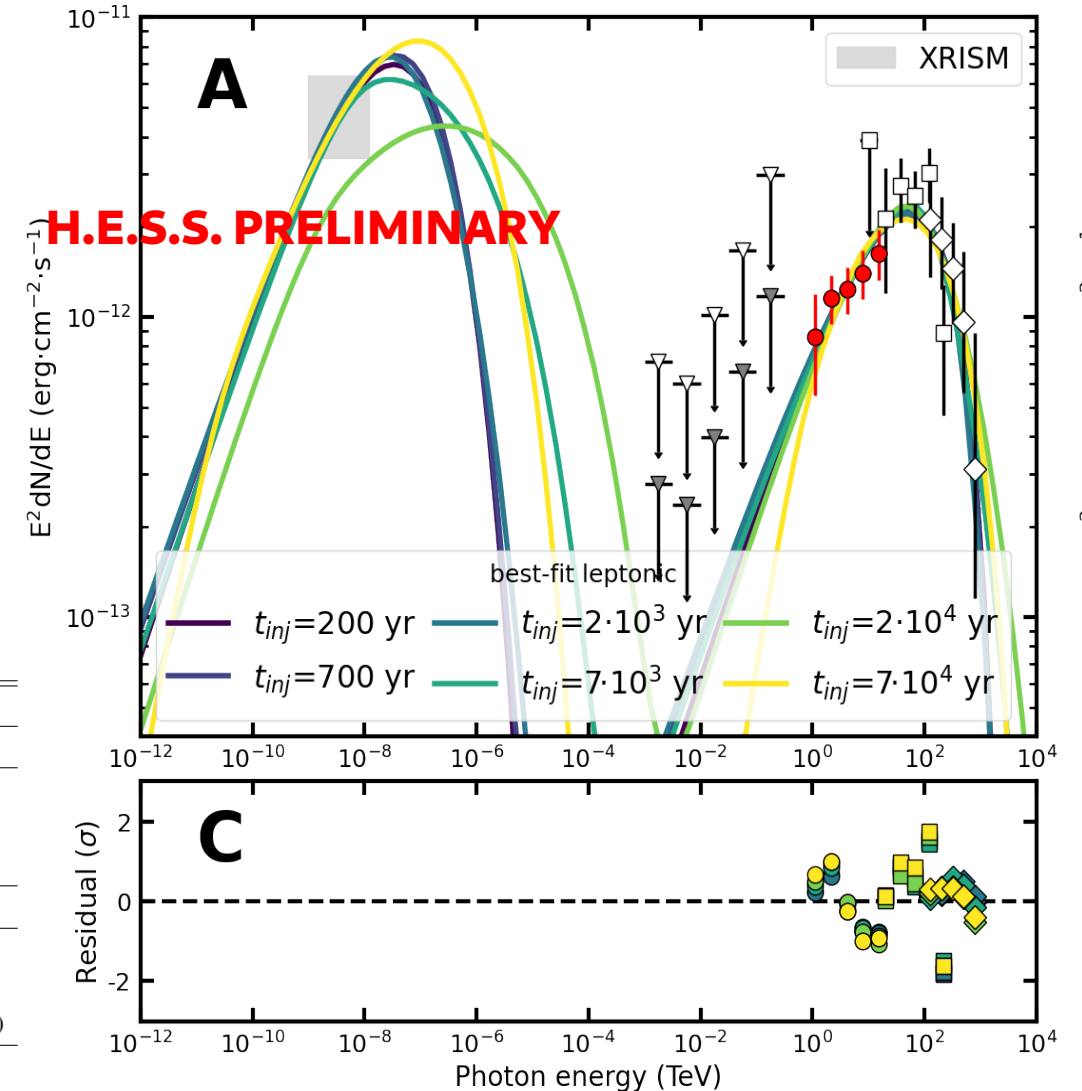
Leptonic scenario

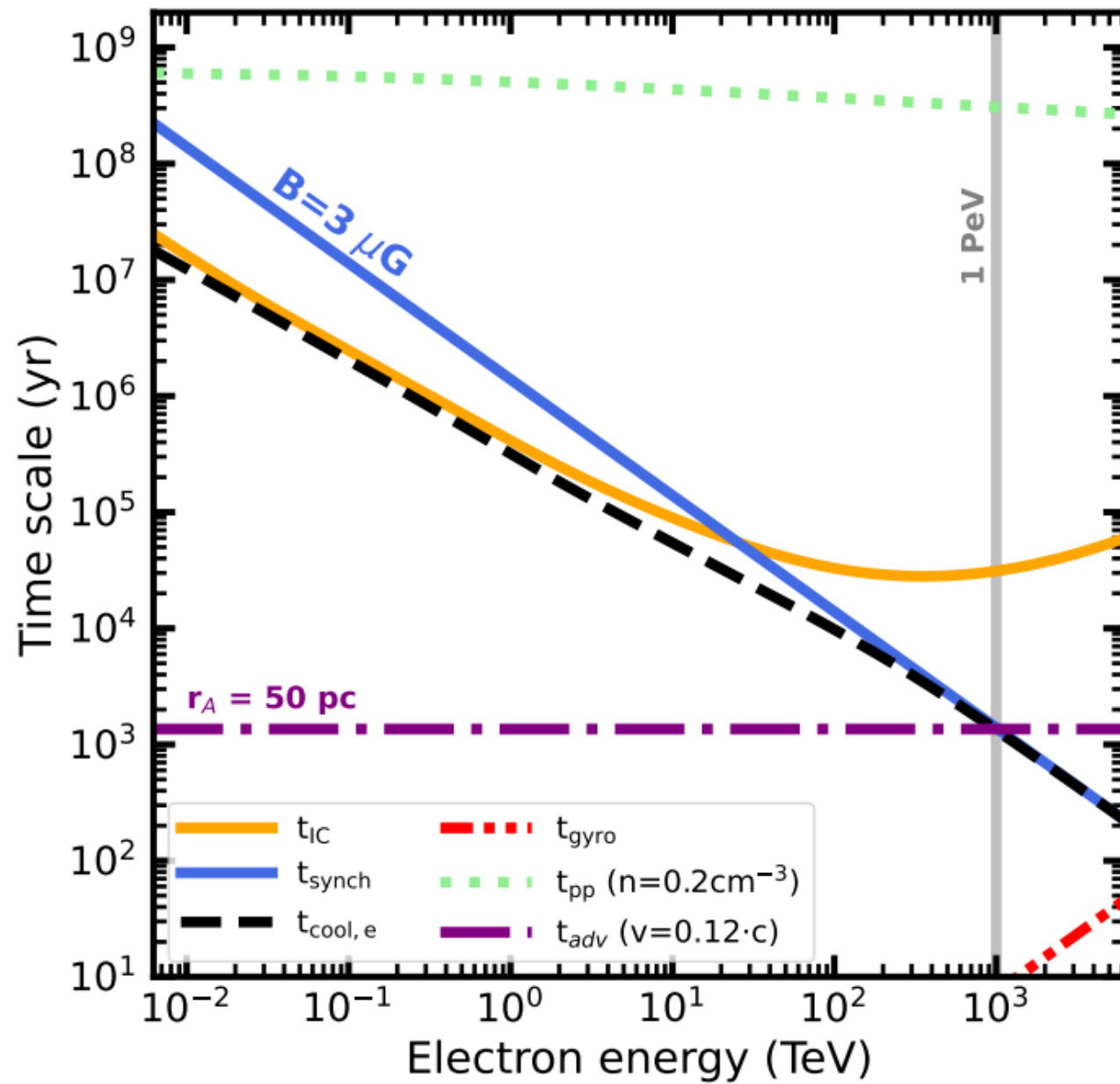
- ▶ Relative flux of X-ray and gamma-ray components require $B < 3\mu\text{G}$
- ▶ Best-fit parameters suggest electrons are injected for 1-10 kyr range
- ▶ A jet would only need to be mildly relativistic (0.05-0.1c) for transport to be faster than cooling!
- ▶ (Some) Diffusion scenarios also work



Parameter	Best-fit value	68.3% C.I.	95.3% C.I.
leptonic model, $t_{\text{inj}} = 2 \cdot 10^2$ yr			
B (μG)	2.72	(2.11, 3.26)	(1.31, 3.82)
α (% of L_{Edd})	2.13	(1.45, 5.13)	(1.10, 8.59)
Γ_e	1.85	(1.70, 2.01)	(1.47, 2.07)
E_{cut}^e (PeV)	0.49	(0.33, 0.86)	(0.21, 1.46)
leptonic model, $t_{\text{inj}} = 2 \cdot 10^3$ yr			
B (μG)	2.87	(2.26, 3.45)	(1.48, 3.96)
α (% of L_{Edd})	0.33	(0.20, 1.41)	(0.13, 3.52)
Γ_e	1.93	(1.82, 2.12)	(1.59, 2.19)
E_{cut}^e (PeV)	0.99	(0.59, 11.59)	(0.31, 68.41)

Fit using GAMERA and bayesian sampling implemented in Gammapy 1.3





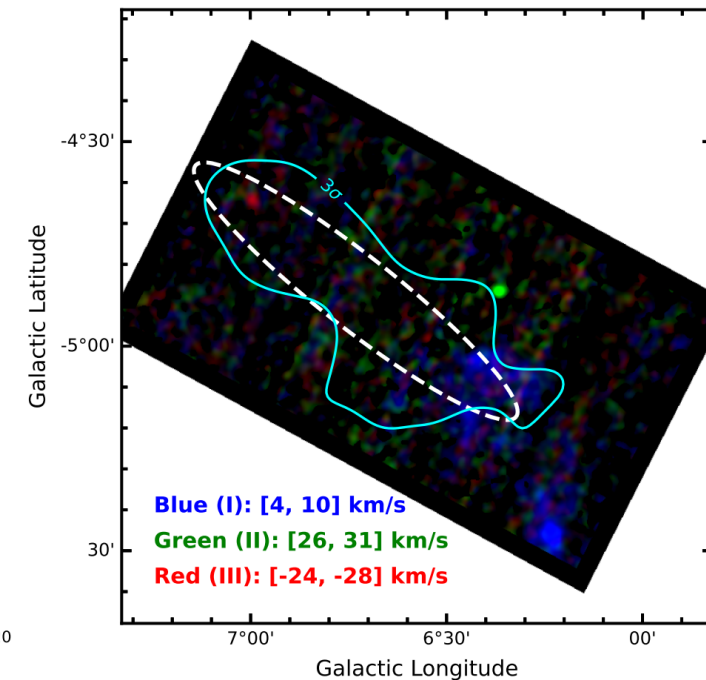
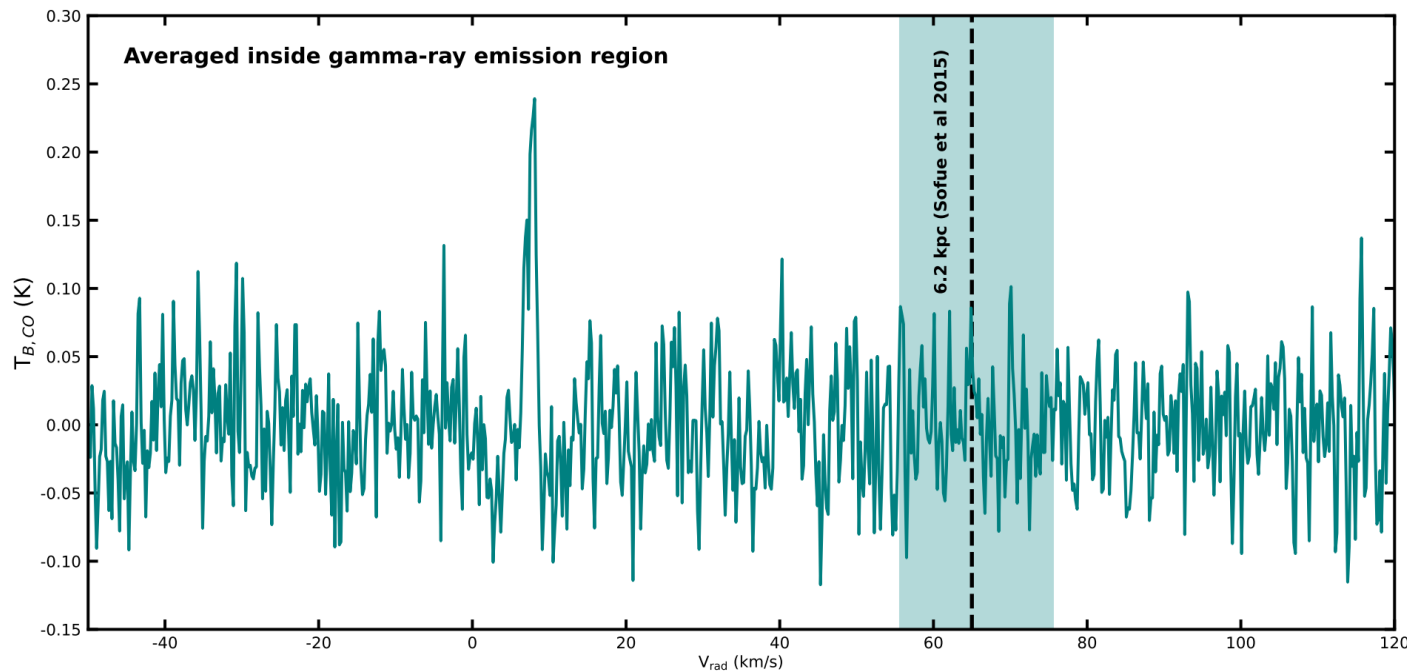
Distance to the source

Constraints on the binary system's distance are less ambiguous. While [Hjellming et al. \(2000\)](#) assumed a modest distance of 0.5 kpc, the earliest quantitative estimate of the distance to V4641 Sgr was made by [Orosz et al. \(2001\)](#) by determining the spectral type of the companion star during X-ray quiescence and comparing it to the observed magnitude accounting for extinction, finding $d = 9.6 \pm 2.5$ kpc. This calculation was updated in [MacDonald et al. \(2014\)](#), which accounts for optical variability during the X-ray quiescence period and finds $d = 6.2 \pm 0.7$ kpc. Measurements of proper motion with the Gaia satellite ([Bailer-Jones et al. 2018](#)) provide an independent distance estimate, and a dedicated analysis of the Gaia data, taking into account the proper motion of the binary ([Gandhi et al. 2019](#)), results in $d = 6.62 \pm 1.81$ kpc. For simplicity we will adopt $d = 6.2$ kpc throughout this work unless specified otherwise but note that the distance could plausibly lie somewhere between 5 and 8 kpc.



Gas around V4641 Sgr

- ▶ Dedicated Nobeyama Radio Observatory (NRO; PI: Naomi Tsuji) observations the region
- ▶ No gas that matches morphology regardless of distance. No gas at V4641 Sgr distance.
- ▶ **Upper limit $n < 0.2 \text{ cm}^{-3}$ averaged over the gamma-ray emission region**
- ▶ Consistent with $n \sim 0.3 \text{ cm}^{-3}$ from XRISM modeling (under thermal interpretation).



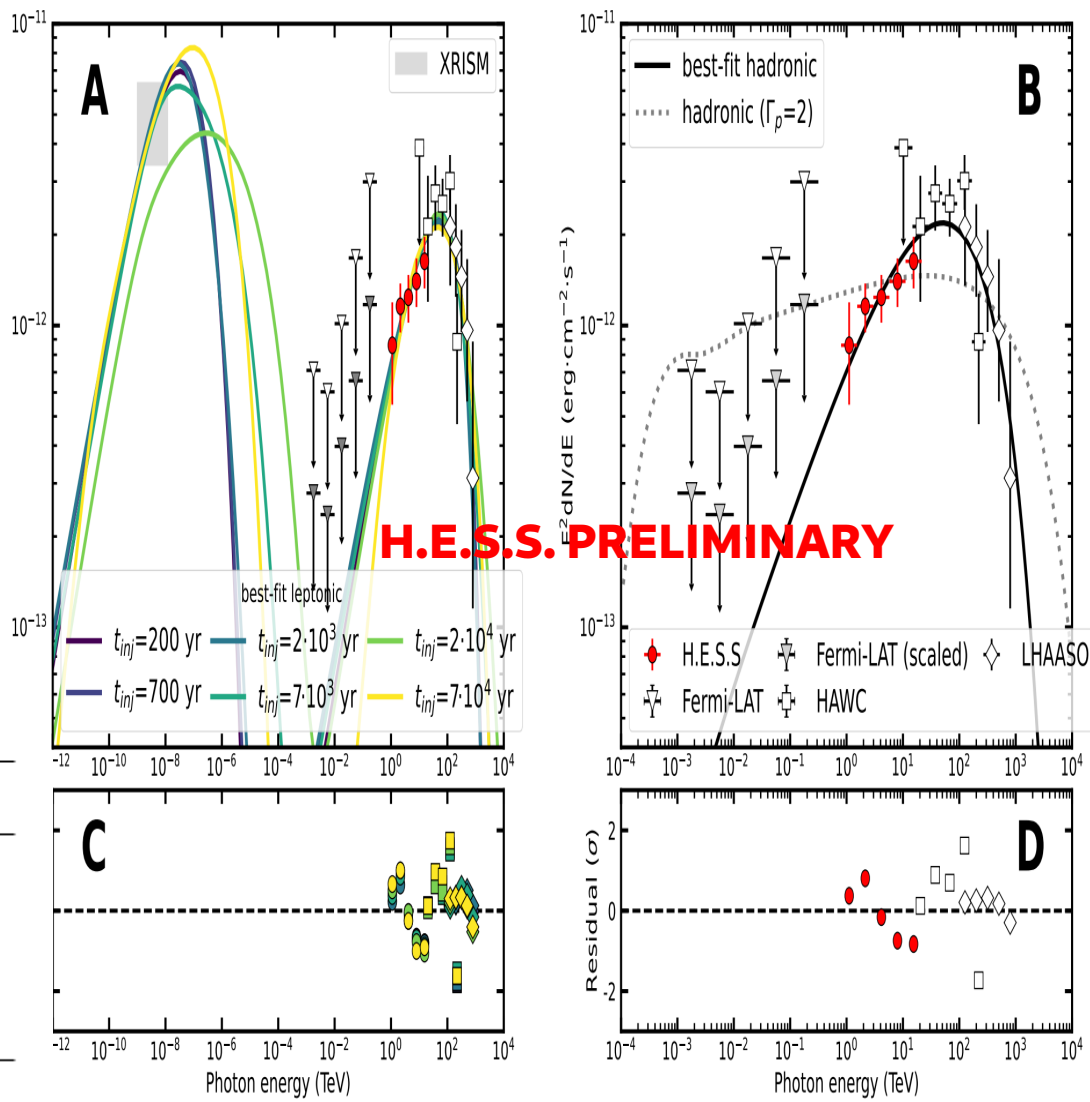
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E_{cut}^e (PeV)	0.99	(0.59, 11.59)	(0.31, 68.41)
leptonic model, $t_{\text{inj}} = 2 \cdot 10^4$ yr			
B (μG)	1.91	(1.54, 2.66)	(1.1, 3.5)
α (% of L_{Edd})	0.04	(0.03, 0.06)	(0.02, 0.1)
Γ_e	1.81	(1.59, 1.87)	(1.39, 1.98)
E_{cut}^e (PeV)	20.31	(2.58, 49.09)	(0.88, 90.95)
leptonic model, $t_{\text{inj}} = 7 \cdot 10^4$ yr			
B (μG)	2.84	(2.11, 3.42)	(1.4, 3.99)
α (% of L_{Edd})	0.03	(0.02, 0.09)	(0.01, 0.19)
Γ_e	1.0	(1.09, 1.43)	(1.01, 1.62)
E_{cut}^e (PeV)	1.74	(2.03, 28.2)	(1.16, 78.09)

Hadronic scenario

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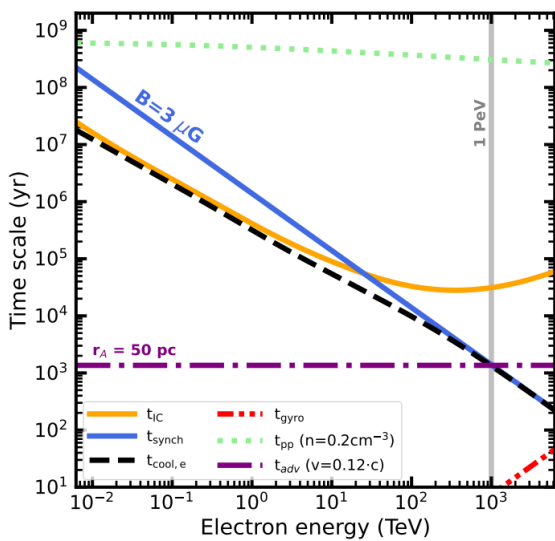
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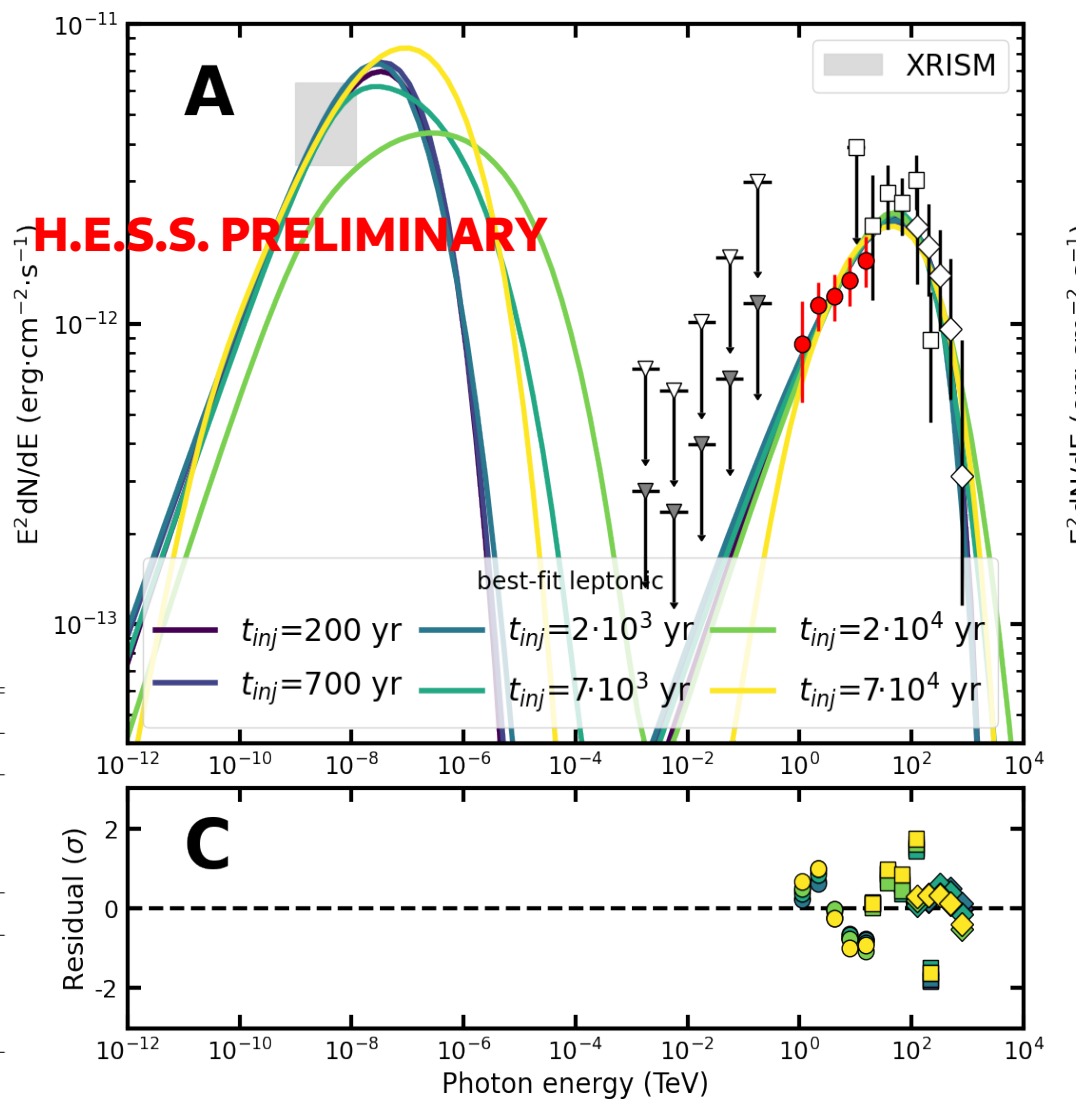
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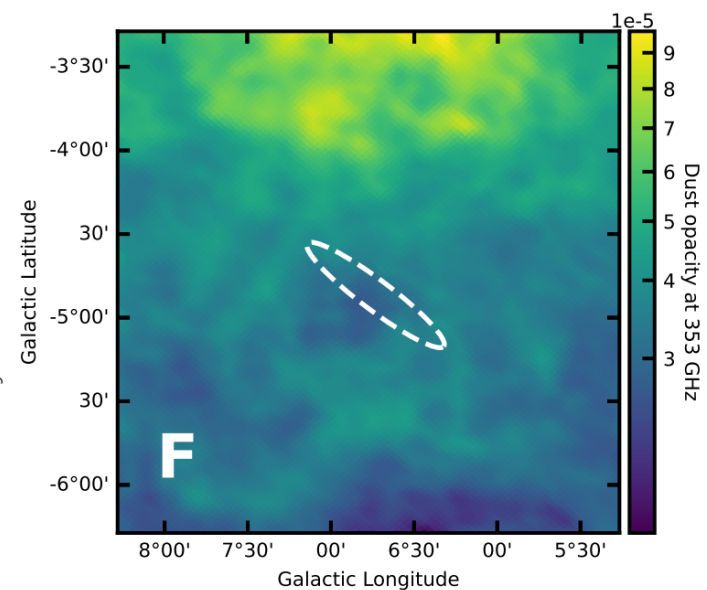
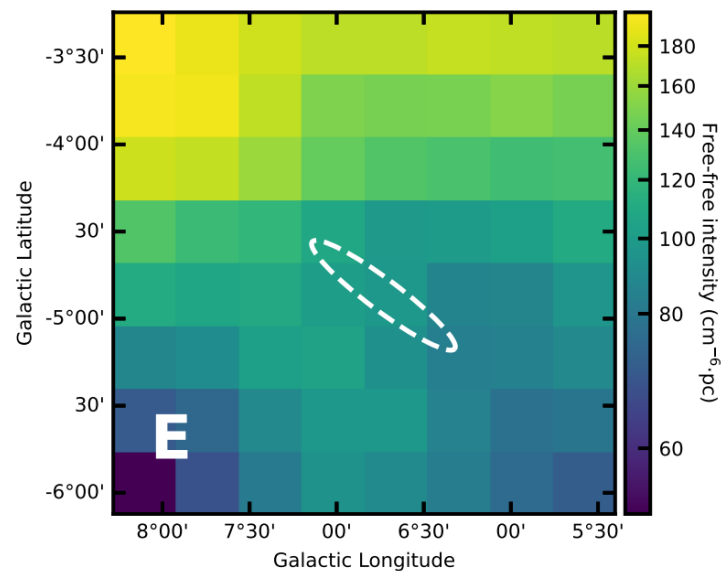
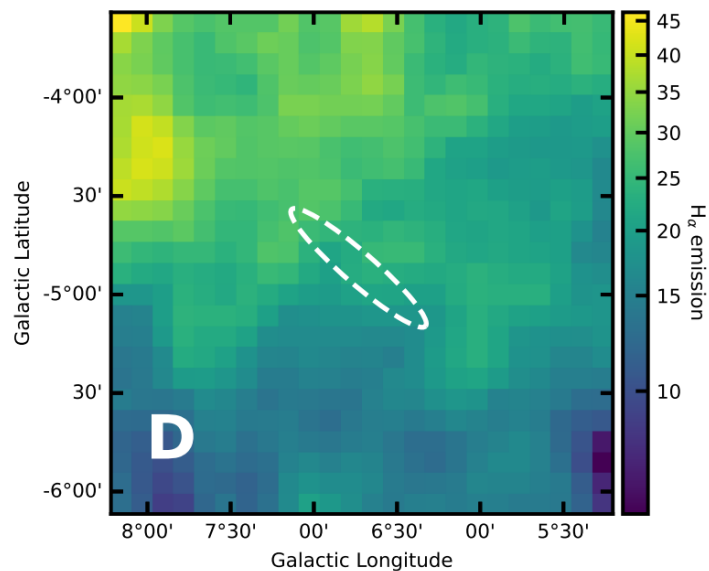
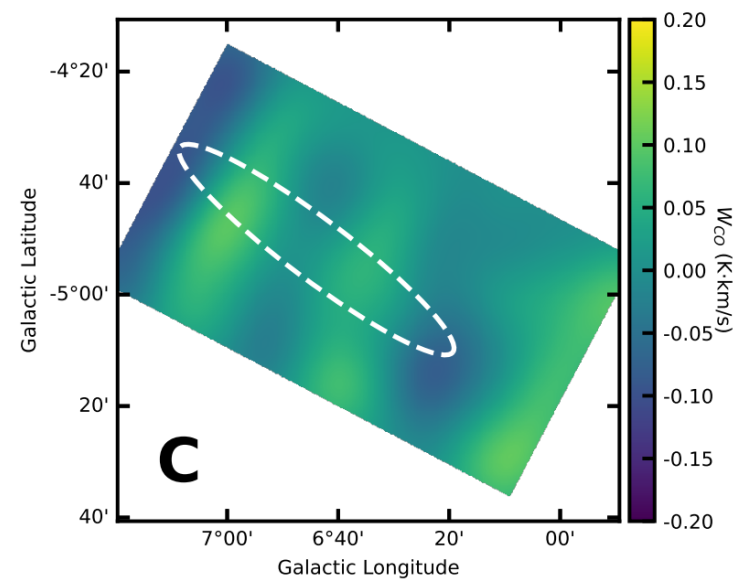
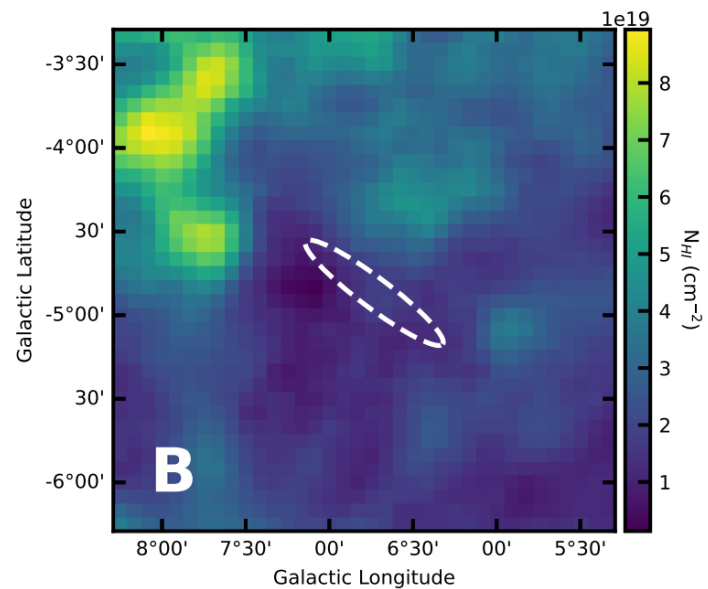
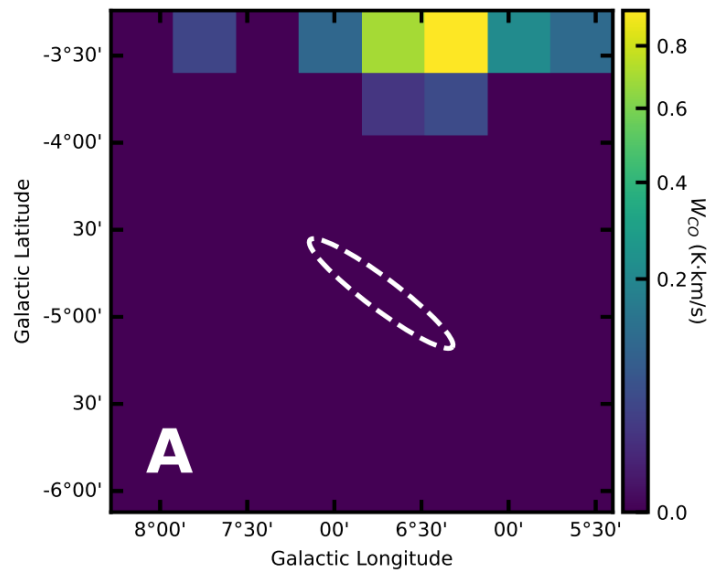
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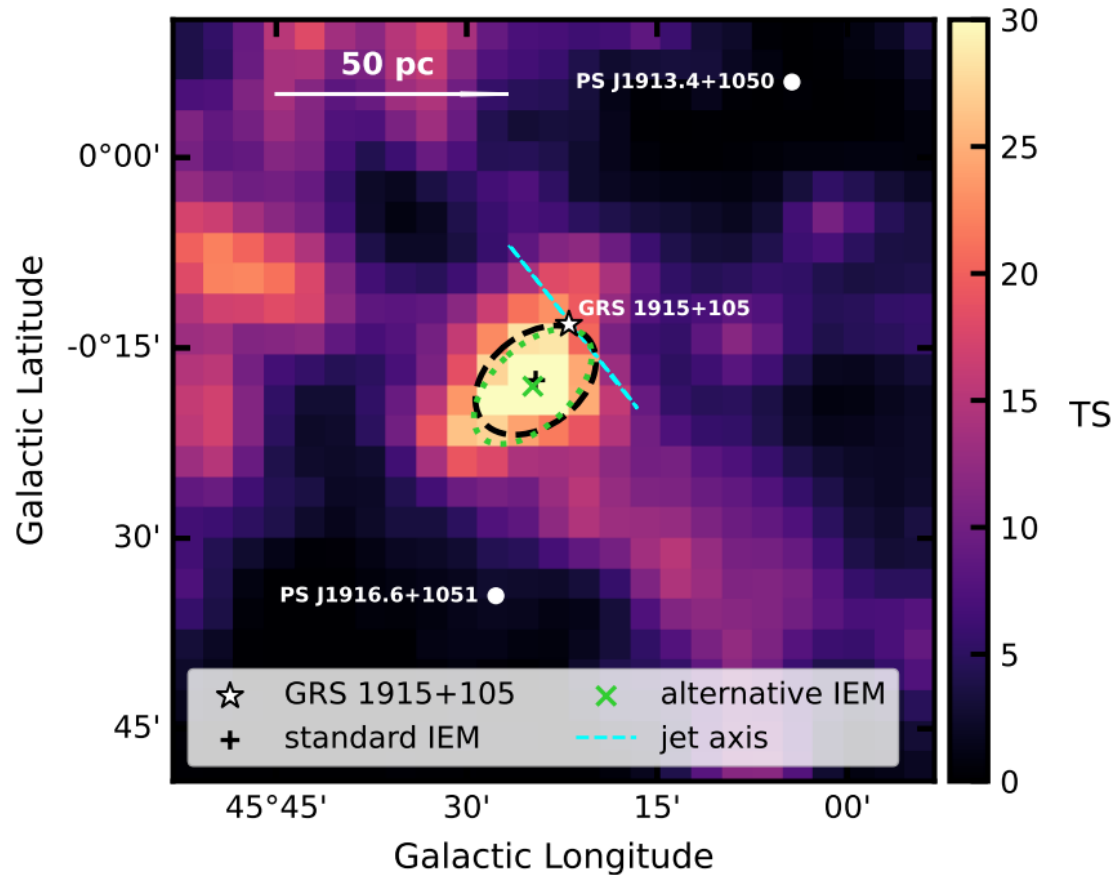
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GRS 1915+105: NOT EVERYTHING IS TRANSIENT IN THE GEV!



MARTI-DEVESA & LON 2025

- ▶ FERMI-LAT DATA AROUND GRS 1915+105
- ▶ PERSISTENT NEW SOURCE, BEST COUNTERPART IS THE MICROQUASAR
- ▶ LIKELY HADRONIC ORIGIN: THIS TIME THERE IS GAS!

