MICROQUASARS AND PULSAR WIND NEBULAE AS PeVATRONS

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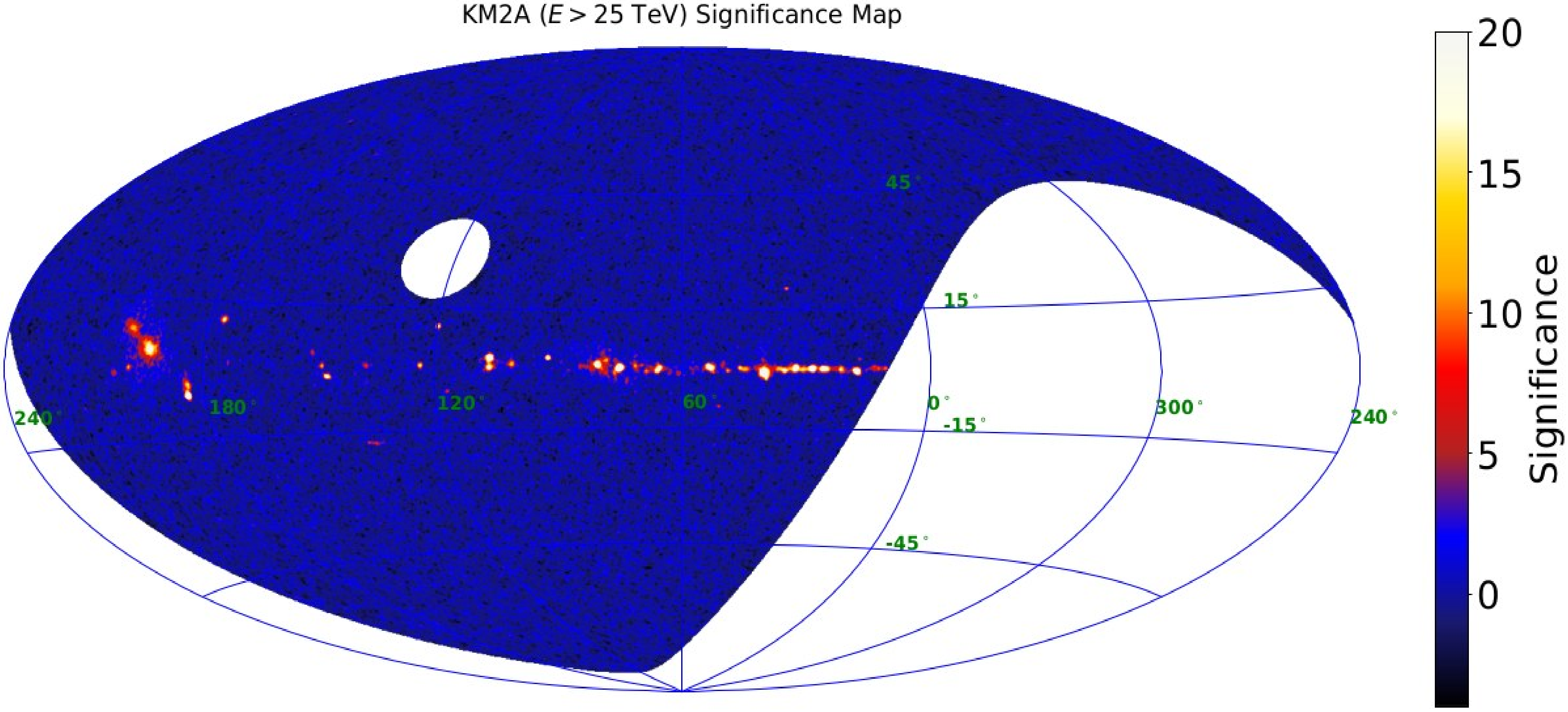
Sky at 25 TeV – 1 PeV with LHAASO

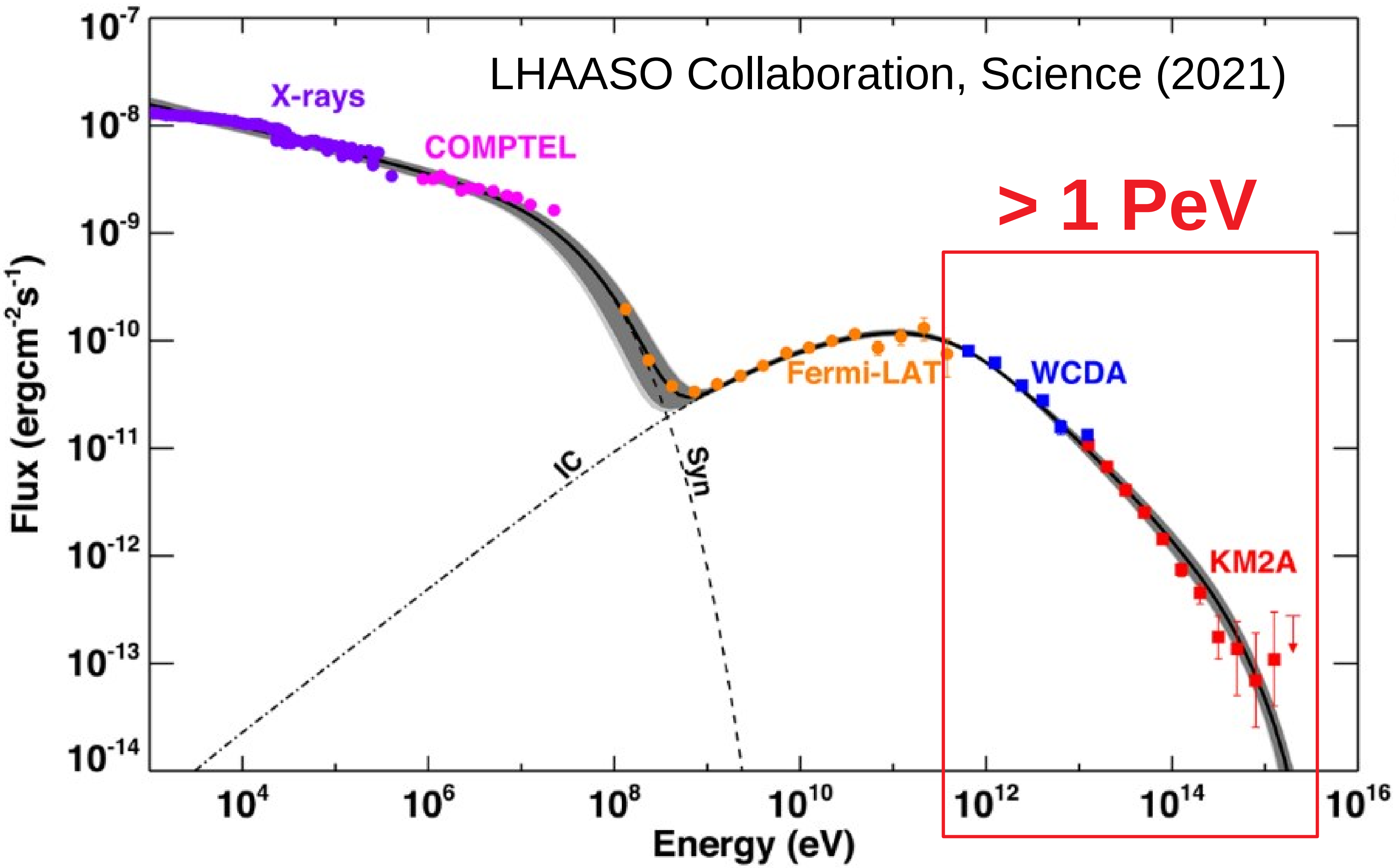
LHAASO Collaboration



> Dozen of PeVatrons:

Many **PWNe and TeV halos** (leptonic) ; **Microquasars** (Hadronic?)

Crab Nebula observed by LHAASO



… and dozens of other PWNe

PWNe & Potential TeV Halos in LHAASO Catalogue

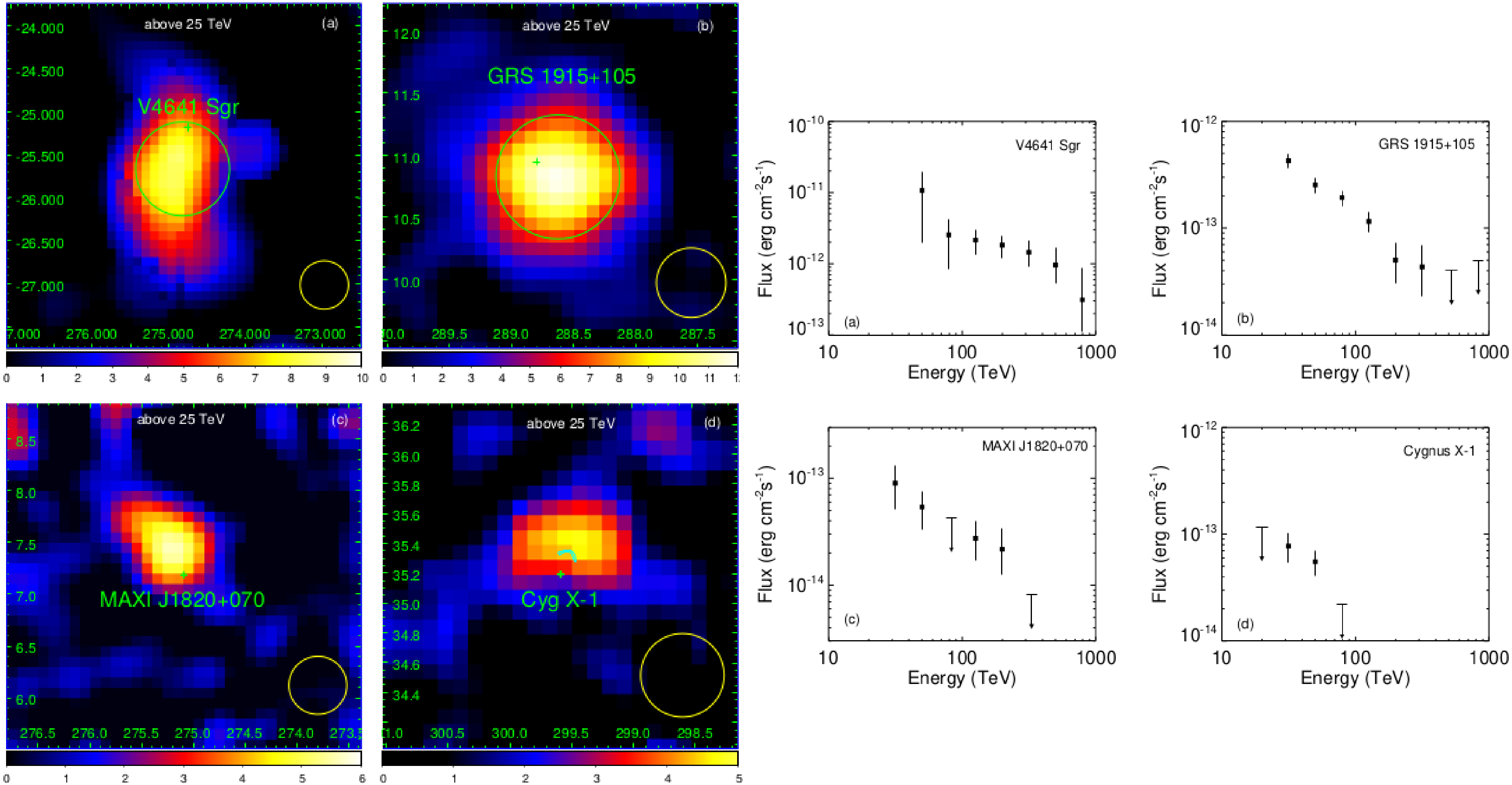
Table 4. 1LHAASO sources associated pulsars

Source name	PSR name	Sep.(°)	d (kpc)	τ_c (kyr)	$\dot{E}$ (erg s^{-1})	P_c	Identified type in TeVCat
1LHAASO J0007+7303u	PSR J0007+7303	0.05	1.40	14	4.5e+35	7.3e-05	PWN
1LHAASO J0216+4237u	PSR J0218+4232	0.33	3.15	476000	2.4e+35	3.6e-03	
1LHAASO J0249+6022	PSR J0248+6021	0.16	2.00	62	2.1e+35	1.5e-03	
1LHAASO J0359+5406	PSR J0359+5414	0.15	-	75	1.3e+36	7.2e-04	
1LHAASO J0534+2200u	PSR J0534+2200	0.01	2.00	1	4.5e+38	3.2e-06	PWN
1LHAASO J0542+2311u	PSR J0543+2329	0.30	1.56	253	4.1e+34	8.3e-03	
1LHAASO J0622+3754	PSR J0622+3749	0.09	-	208	2.7e+34	2.5e-04	PWN/TeV Halo
1LHAASO J0631+1040	PSR J0631+1037	0.11	2.10	44	1.7e+35	3.5e-04	PWN
1LHAASO J0634+1741u	PSR J0633+1746	0.12	0.19	342	3.3e+34	1.3e-03	PWN/TeV Halo
1LHAASO J0635+0619	PSR J0633+0632	0.39	1.35	59	1.2e+35	9.4e-03	
1LHAASO J1740+0948u	PSR J1740+1000	0.21	1.23	114	2.3e+35	1.4e-03	
1LHAASO J1809-1918u	PSR J1809-1917	0.05	3.27	51	1.8e+36	6.2e-04	
1LHAASO J1813-1245	PSR J1813-1245	0.01	2.63	43	6.2e+36	6.3e-06	
1LHAASO J1825-1256u	PSR J1826-1256	0.09	1.55	14	3.6e+36	1.6e-03	
1LHAASO J1825-1337u	PSR J1826-1334	0.11	3.61	21	2.8e+36	2.8e-03	PWN/TeV Halo
1LHAASO J1837-0654u	PSR J1838-0655	0.12	6.60	23	5.6e+36	2.2e-03	PWN
1LHAASO J1839-0548u	PSR J1838-0537	0.20	-	5	6.0e+36	6.1e-03	
1LHAASO J1848-0001u	PSR J1849-0001	0.06	-	43	9.8e+36	1.2e-04	PWN
1LHAASO J1857+0245	PSR J1856+0245	0.16	6.32	21	4.6e+36	3.1e-03	PWN
1LHAASO J1906+0712	PSR J1906+0722	0.19	-	49	1.0e+36	5.9e-03	
1LHAASO J1908+0615u	PSR J1907+0602	0.23	2.37	20	2.8e+36	6.8e-03	
1LHAASO J1912+1014u	PSR J1913+1011	0.13	4.61	169	2.9e+36	1.5e-03	
1LHAASO J1914+1150u	PSR J1915+1150	0.09	14.01	116	5.4e+35	1.8e-03	
1LHAASO J1928+1746u	PSR J1928+1746	0.04	4.34	83	1.6e+36	1.6e-04	
1LHAASO J1929+1846u	PSR J1930+1852	0.29	7.00	3	1.2e+37	2.6e-03	PWN
1LHAASO J1954+2836u	PSR J1954+2836	0.01	1.96	69	1.1e+36	1.6e-05	PWN
1LHAASO J1954+3253	PSR J1952+3252	0.33	3.00	107	3.7e+36	6.7e-03	
1LHAASO J1959+2846u	PSR J1958+2845	0.10	1.95	22	3.4e+35	2.8e-03	PWN
1LHAASO J2005+3415	PSR J2004+3429	0.25	10.78	18	5.8e+35	9.9e-03	
1LHAASO J2005+3050	PSR J2006+3102	0.20	6.04	104	2.2e+35	9.2e-03	
1LHAASO J2020+3649u	PSR J2021+3651	0.05	1.80	17	3.4e+36	1.5e-04	PWN
1LHAASO J2028+3352	PSR J2028+3332	0.36	-	576	3.5e+34	8.0e-03	
1LHAASO J2031+4127u	PSR J2032+4127	0.08	1.33	201	1.5e+35	1.0e-03	PWN
1LHAASO J2228+6100u	PSR J2229+6114	0.27	3.00	10	2.2e+37	2.2e-03	PWN
1LHAASO J2238+5900	PSR J2238+5903	0.07	2.83	27	8.9e+35	3.0e-04	

LHAASO Collaboration, ApJS 271, 25 (2024)

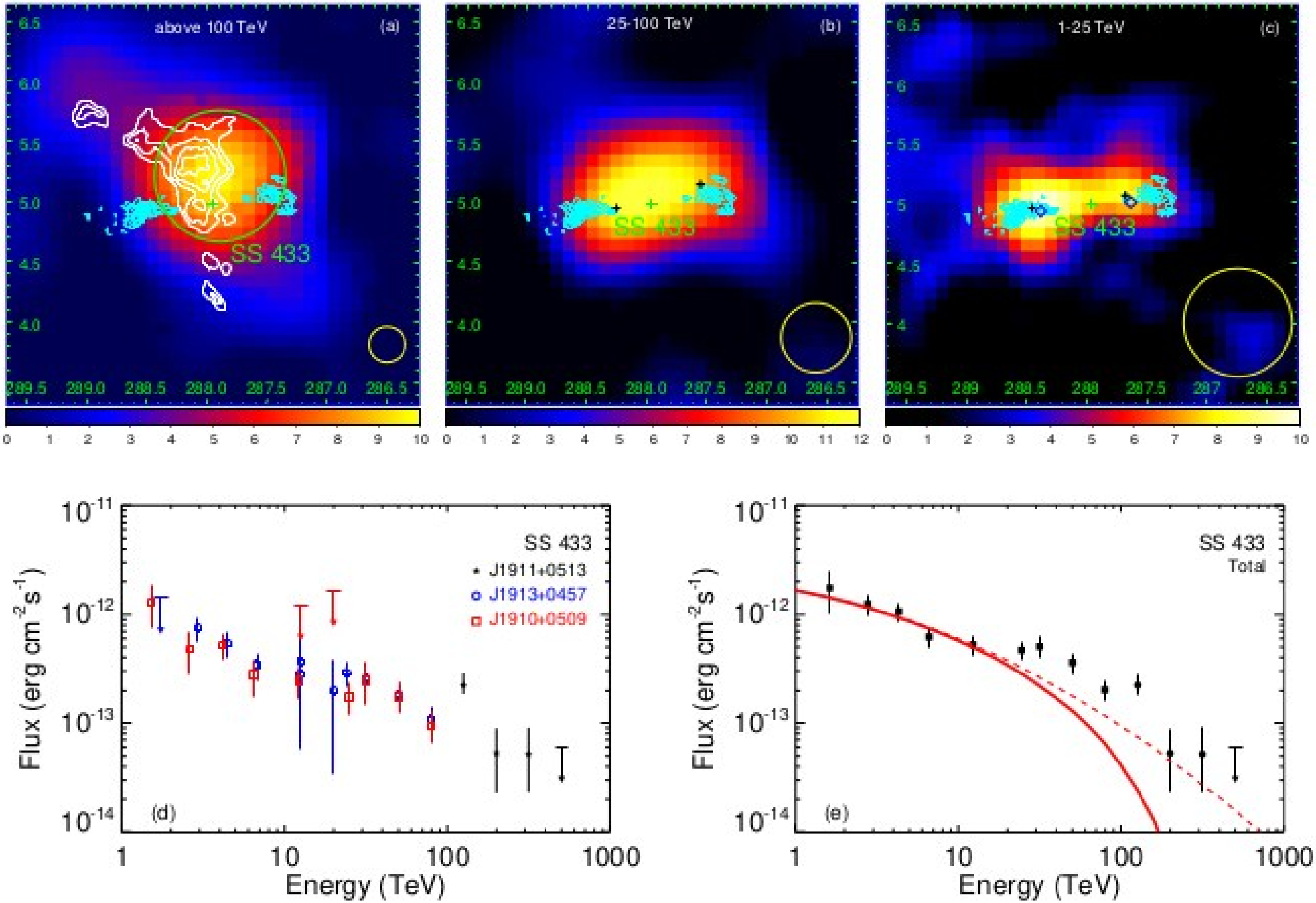
LHAASO's PeVatron microquasars

LHAASO Collaboration, arXiv:2410.08988



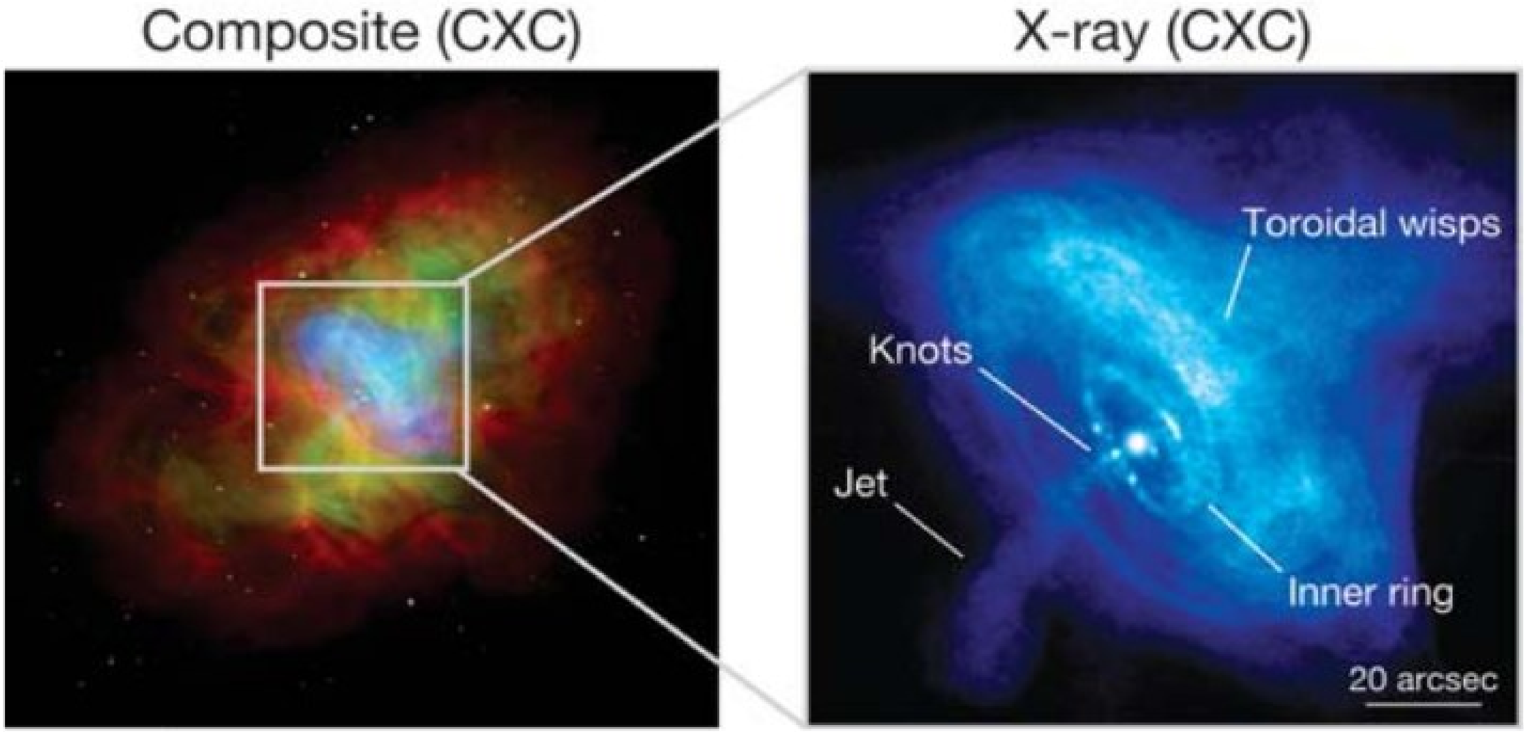
LHAASO’s PeVatron microquasars

LHAASO Collaboration, arXiv:2410.08988



1 – Particle acceleration to PeV at Pulsar Wind Nebulae and jet termination shocks

Synchrotron from the Crab Nebula

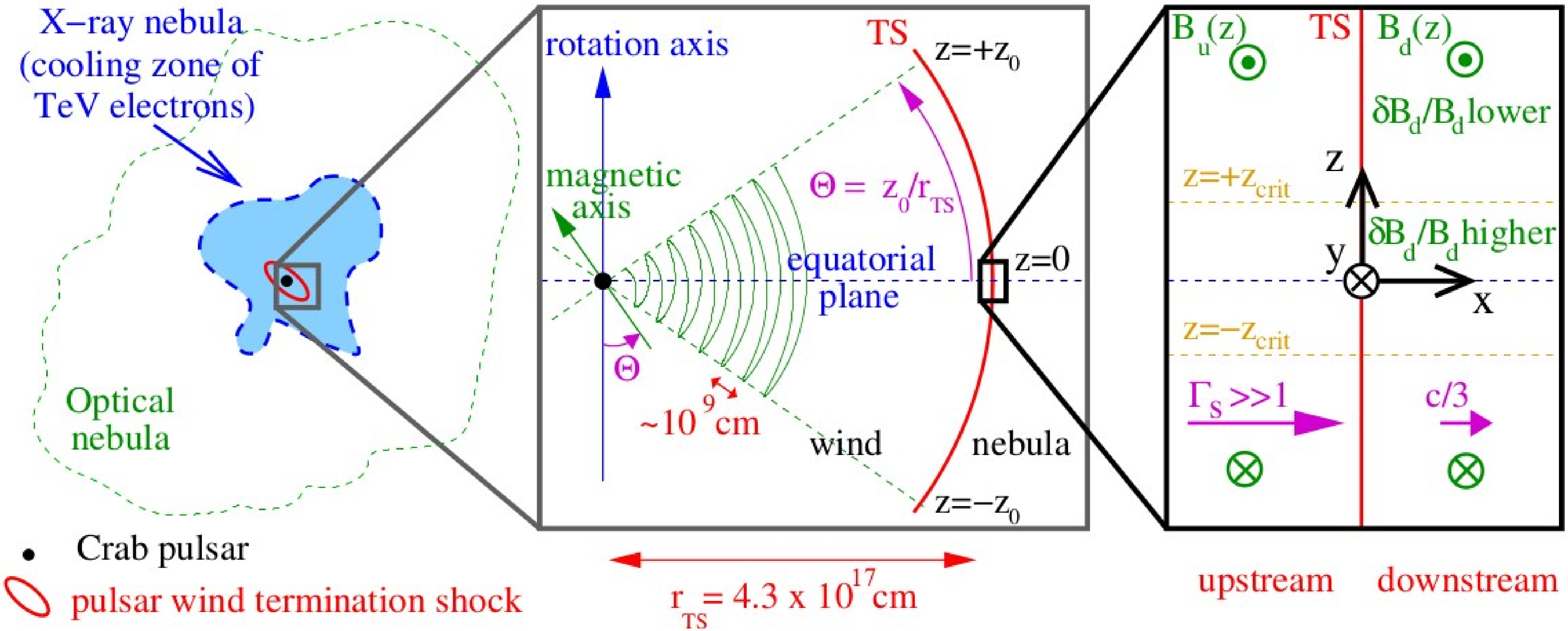


BUT perpendicular shock

=> 1st order Fermi
should NOT work !

Model

Giacinti & Kirk, ApJ **863**, 18 (2018), arXiv:1804.05056



→ **INJECTION :** e.g. Giacchè & Kirk (2017):

$$\boxed{E_{\rm inj,d} = 1\,\mathrm{TeV}}$$

→ Komissarov profile for the B field,

→ Add synthetic turbulence,

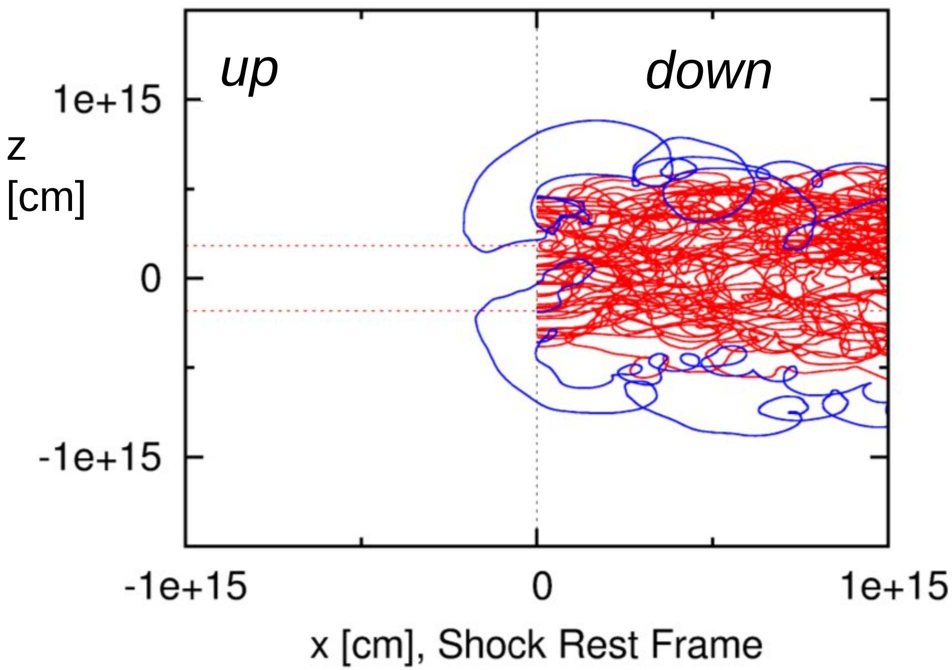
→ Integrate the **trajectories** of **individual particules** in **3D** (**test particle limit**).

Numerical simulations

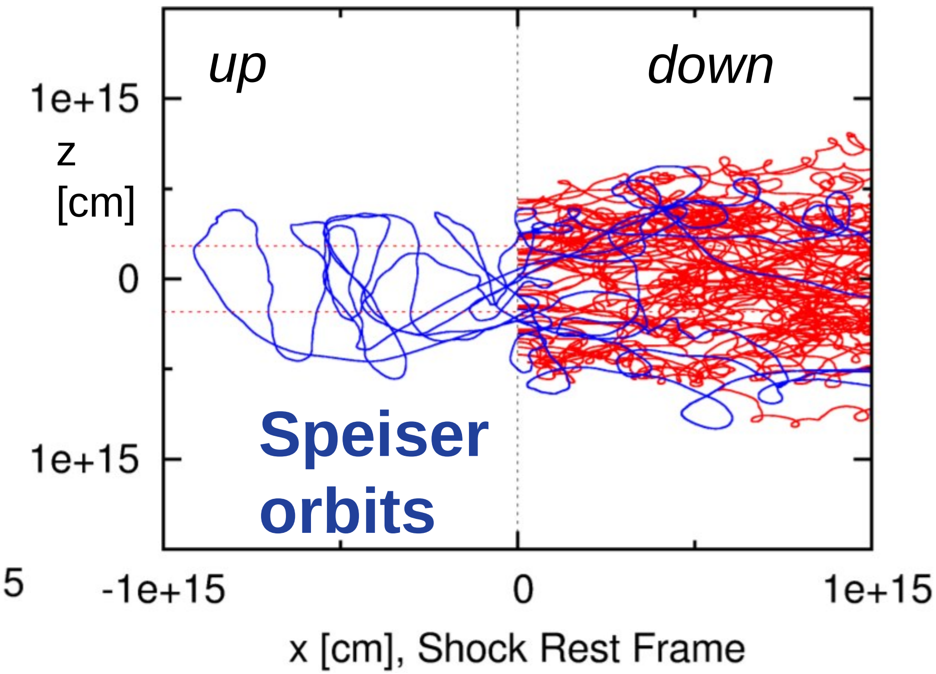
POSITRONS: **ELECTRONS:**

(roles exchanged with opposite pulsar polarity)

No/little acceleration



Efficient acceleration to VHE



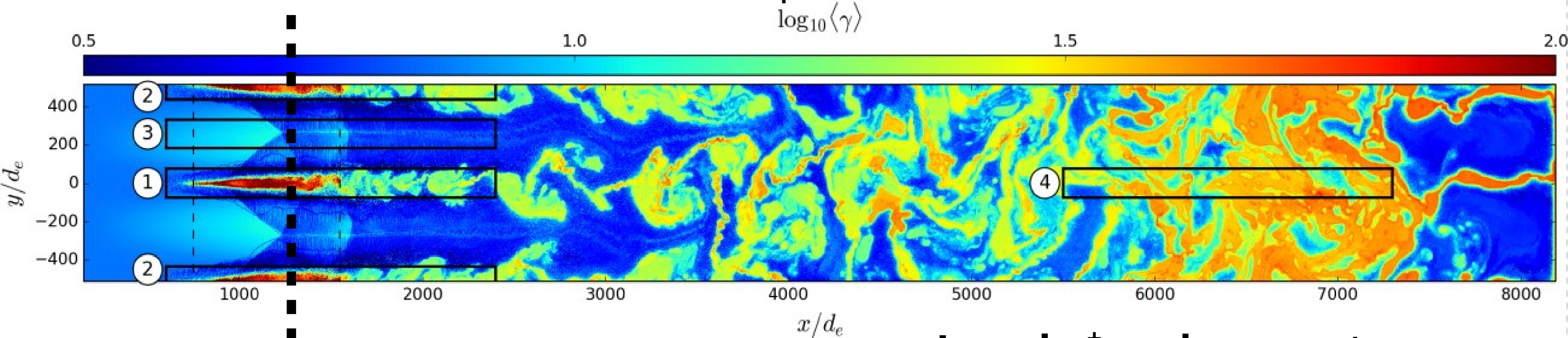
Drift motions on the shock surface eject the positrons...

...and **confine the electrons in the equatorial region**

Particle-In-Cell simulations

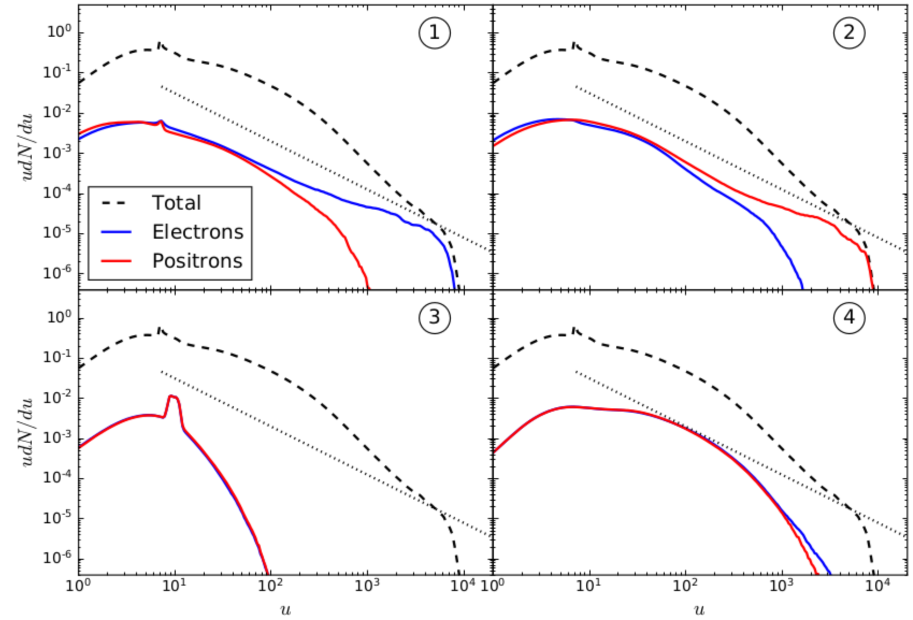
Cerutti & Giacinti, A&A **642**, A123 (2020)

Mean particle Lorentz factor at $\omega_{pe}t$ = 7840 for σ_0 = 30 :

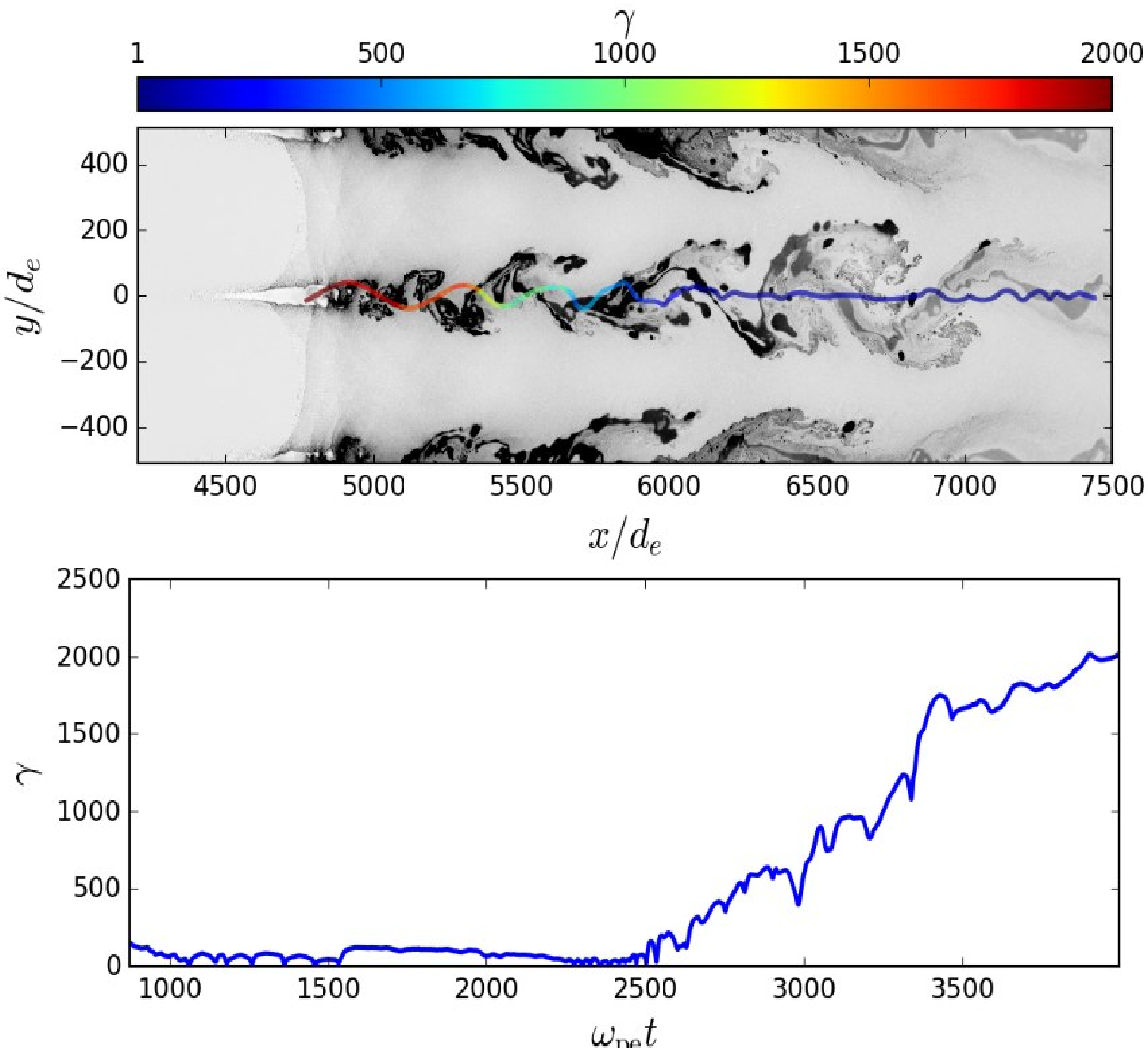


Shock

Local e^+ and e^- spectra :



Particle trajectories / acc. mechanisms:

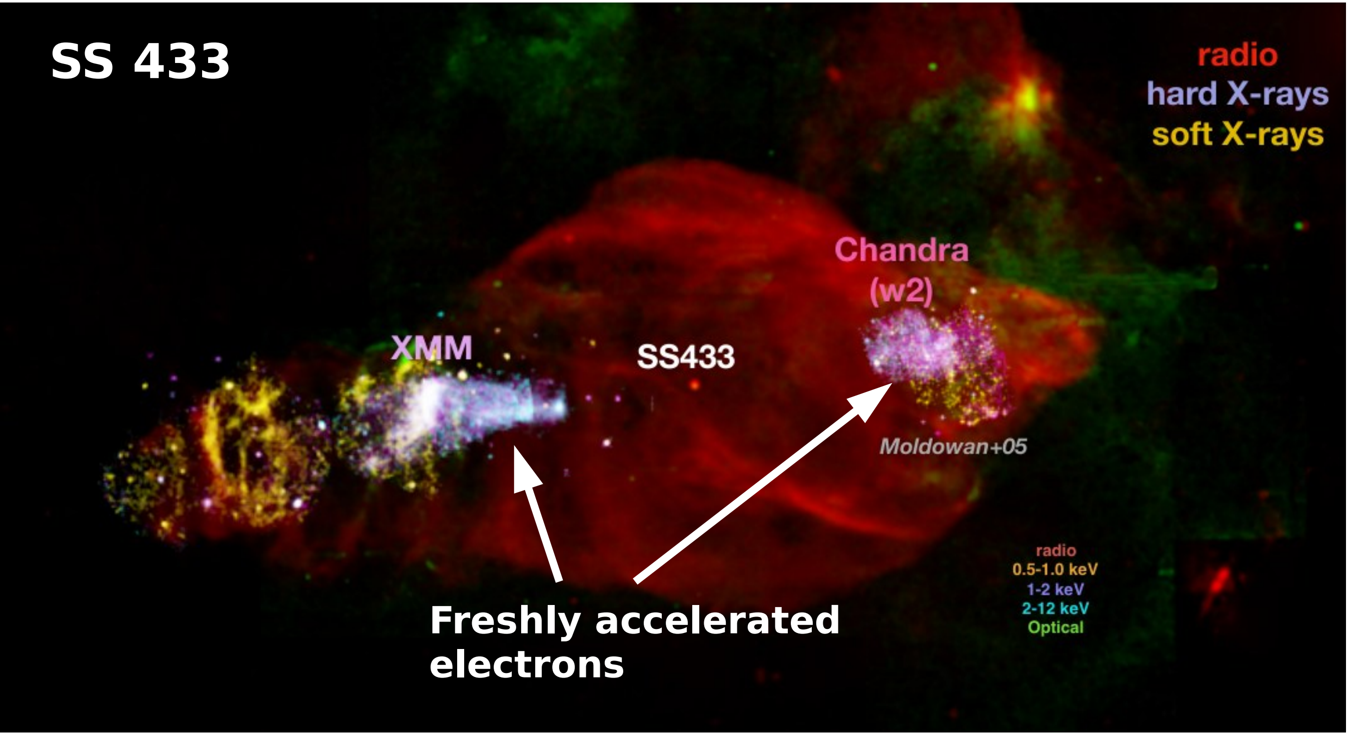


→ Particles on **Speiser orbits** in the **equatorial cavity**

→ **Shear-flow acceleration**

→ Variable, Doppler-boosted synchrotron emission → **Crab flares?**

e^- acceleration at microquasar jet termination shocks?



Safi-Harb et al. (2022)

Detected by H.E.S.S. and HAWC.

In-situ particle acceleration, to > 100 TeV.

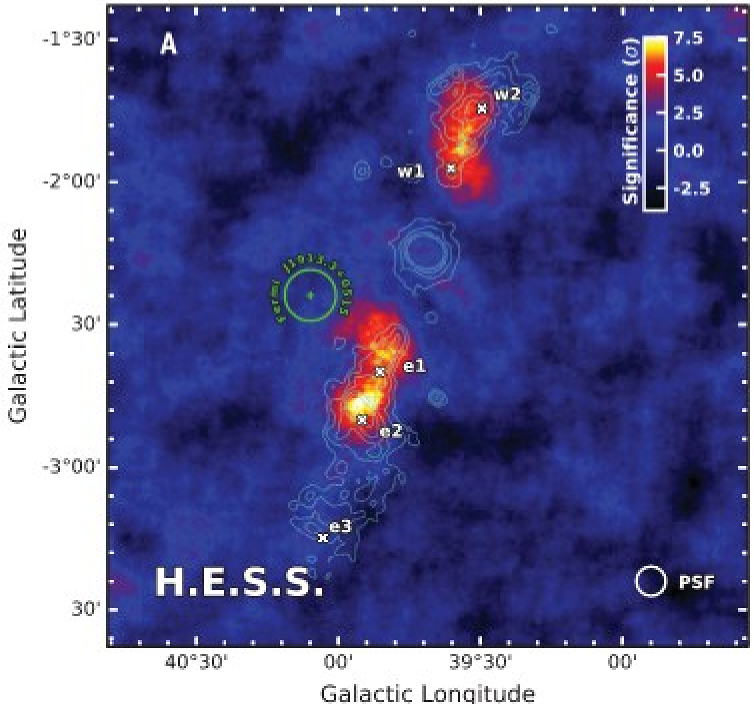
e⁻ acceleration at microquasar jet termination shocks?

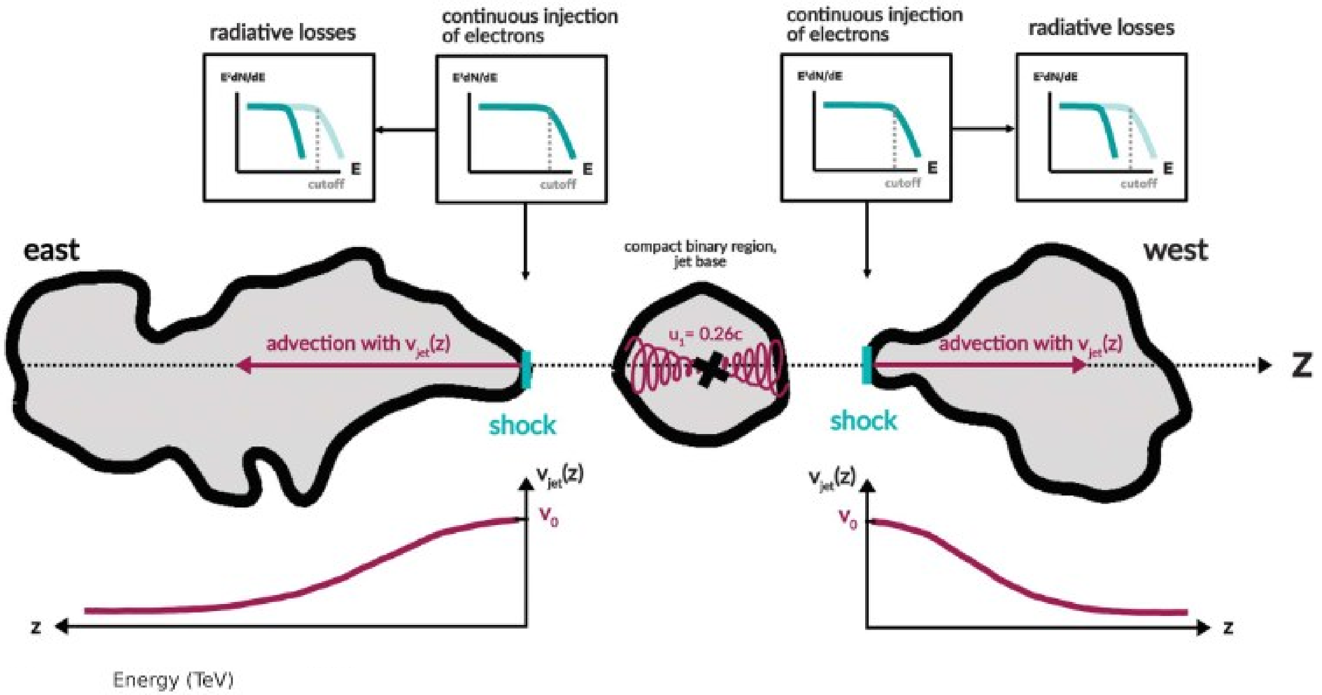
RESEARCH

GAMMA-RAY ASTRONOMY

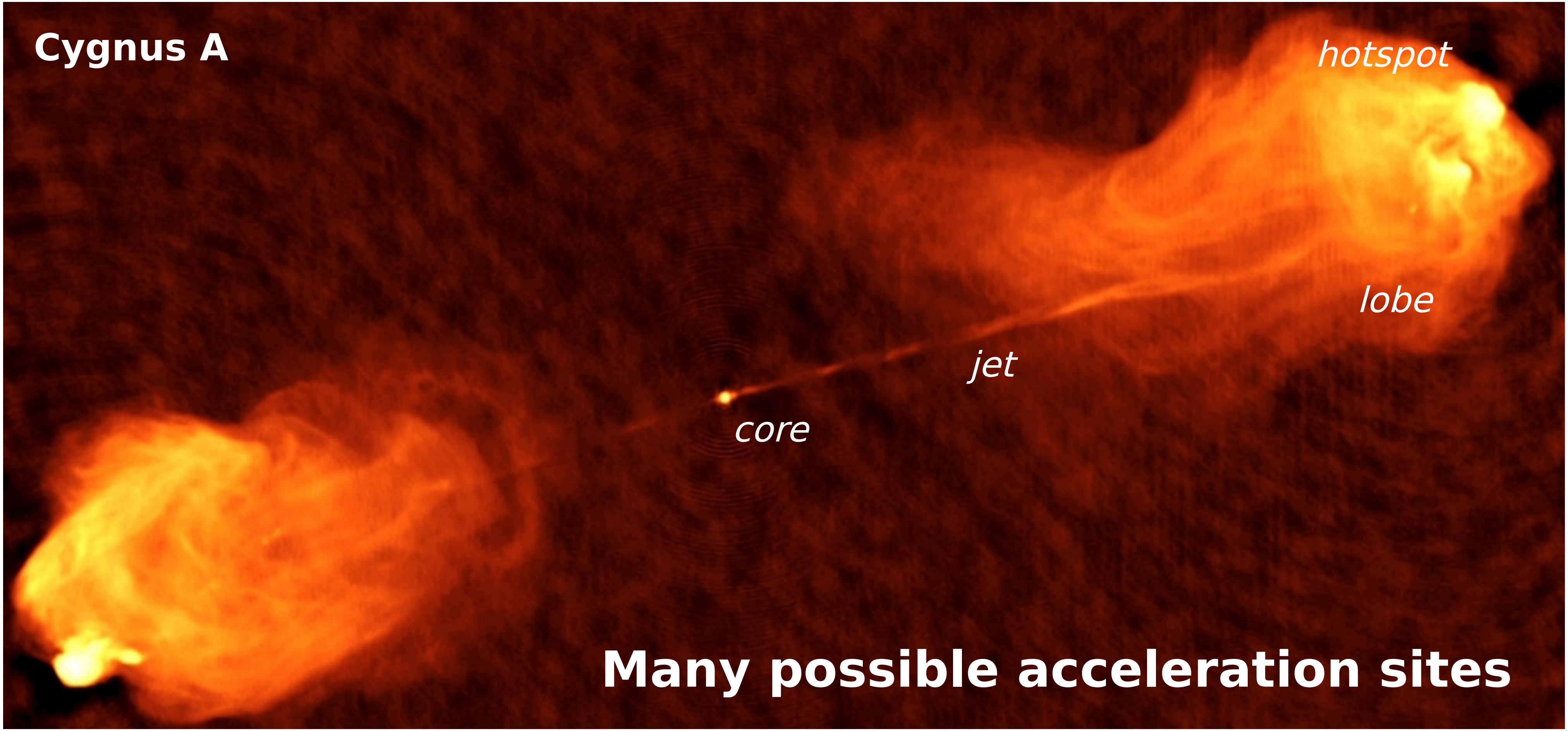
Acceleration and transport of relativistic electrons in the jets of the microquasar SS 433

H.E.S.S. Collaboration,
Science **383**, 402–406 (2024)



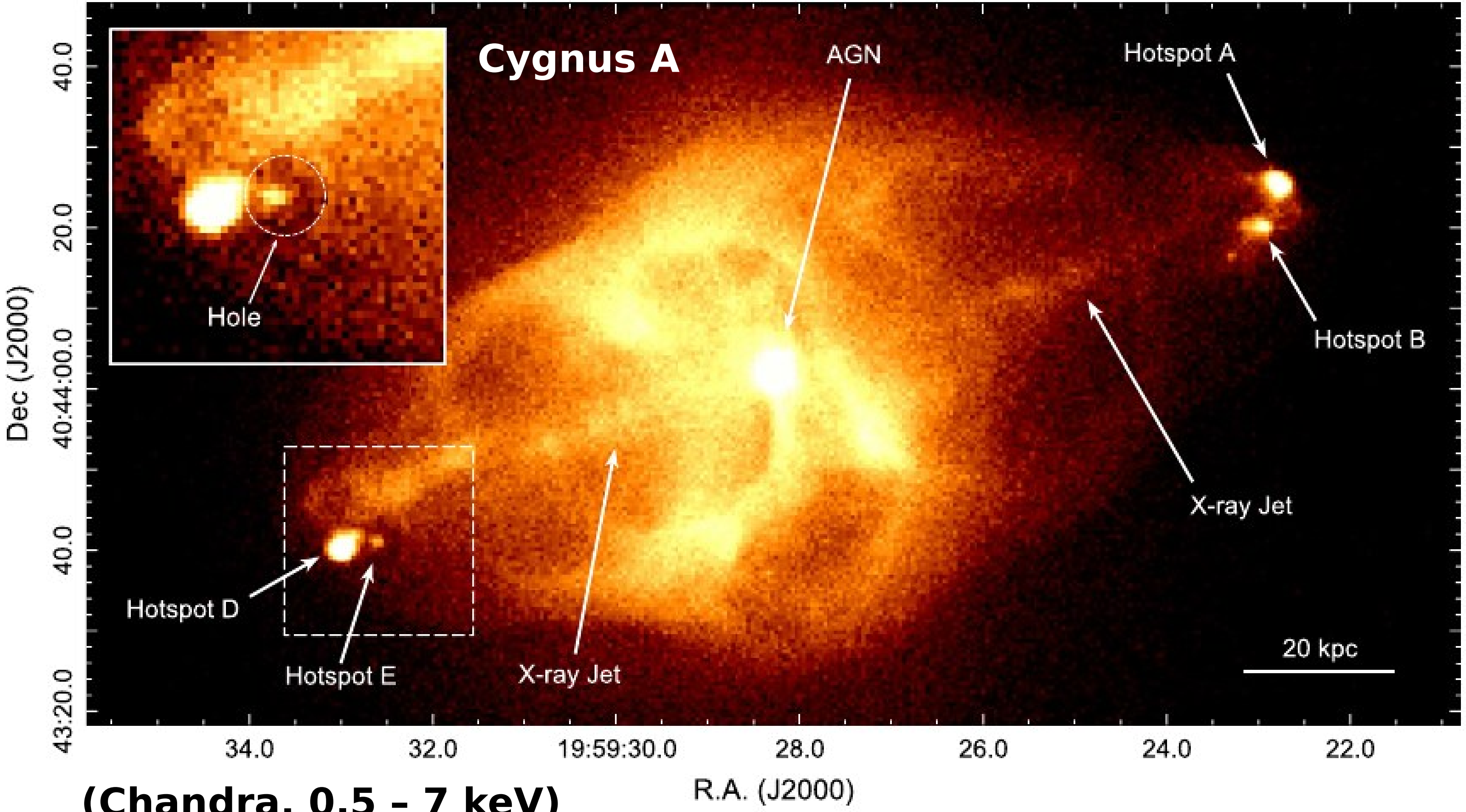


FR II jets


Cygnus A
hotspot
lobe
jet
core
Many possible acceleration sites

In-situ part. acceleration: Cygnus A hotspots

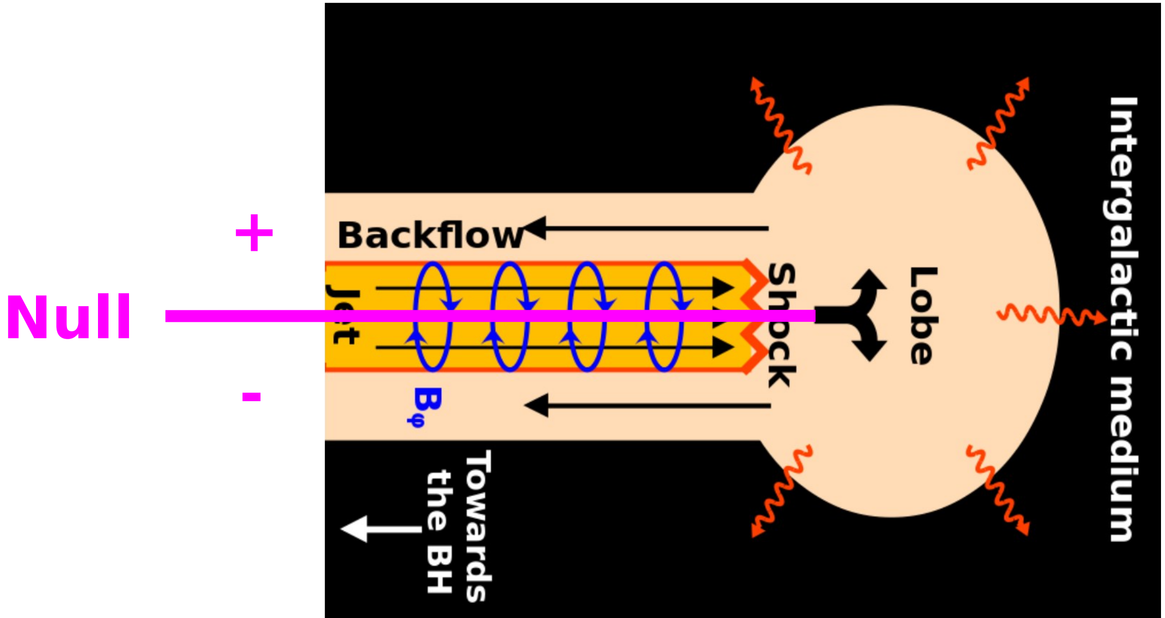
THE ASTROPHYSICAL JOURNAL, 891:173 (10pp), 2020 March 10 Snios et al.



(Chandra, 0.5 – 7 keV)

Solution: Global B field geometry

LARGE-SCALE GEOMETRY OF THE B FIELD MAY SOLVE THE PROBLEM!



Cerutti & Giacinti, A&A (2023)

Particle-In-Cell (PIC) setup

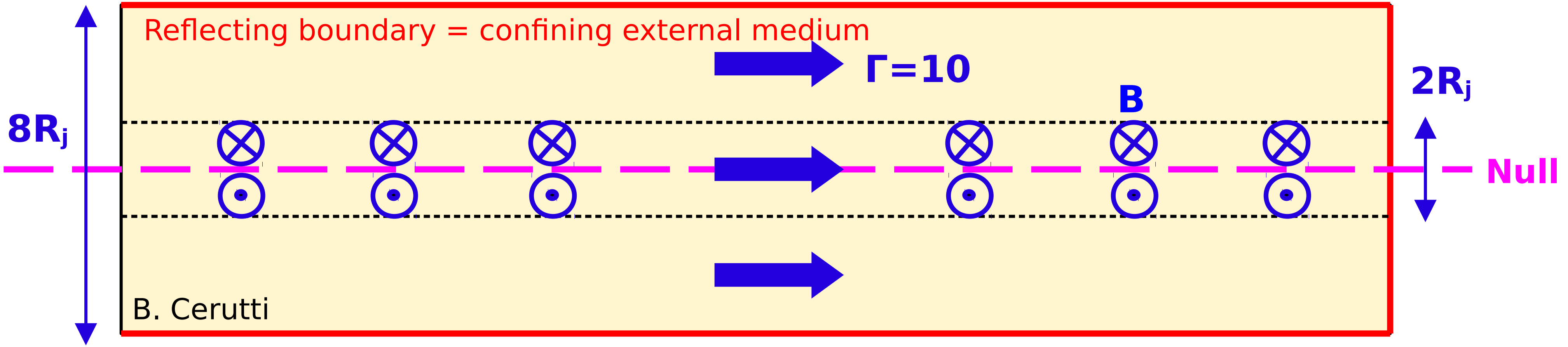
2D Cartesian box (xz-plane), **262,144×16,384 cells, or 6554x410 d_i (ion skin depth)**

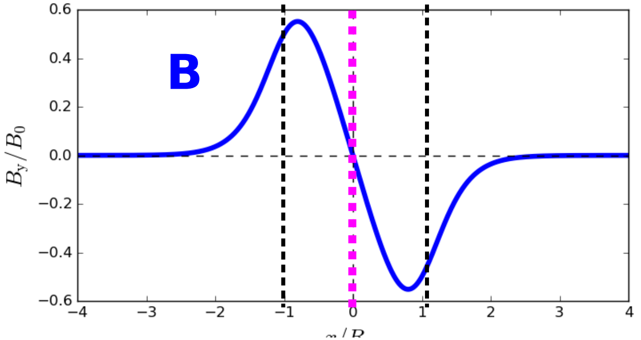
Electron-ion plasma with **m_i/m_e=25**

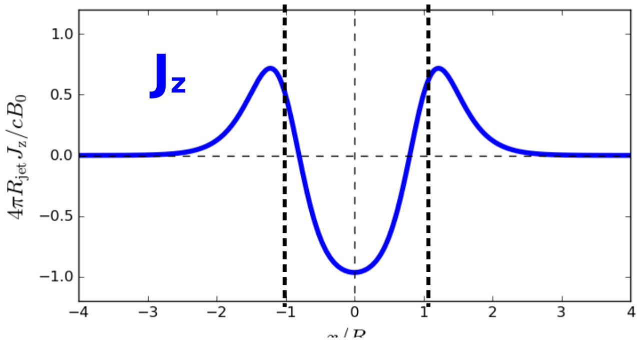
Magnetization : **σ=0.1, 1**

Cerutti & Giacinti, A&A (2023)

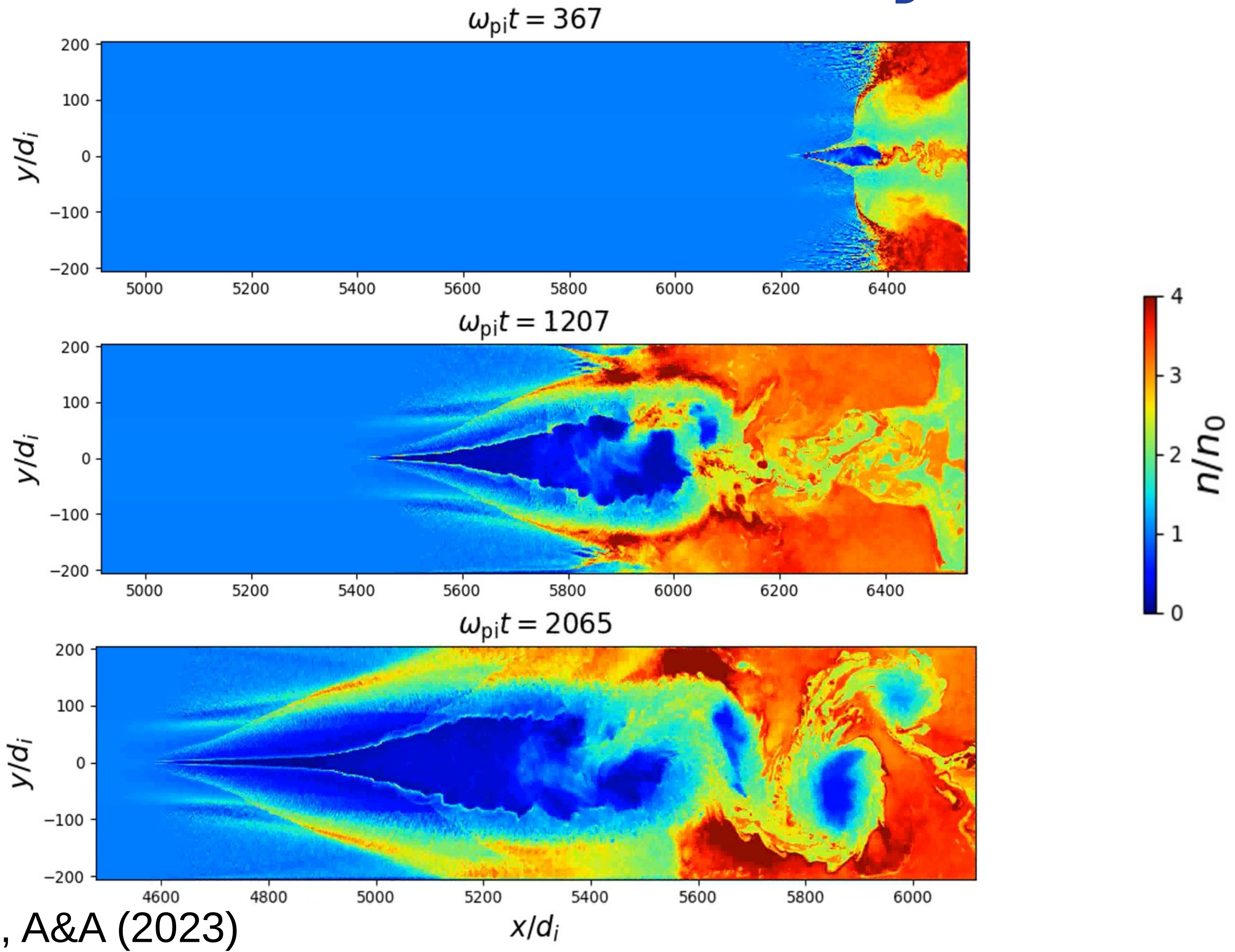
Reflecting boundary
= contact discontinuity







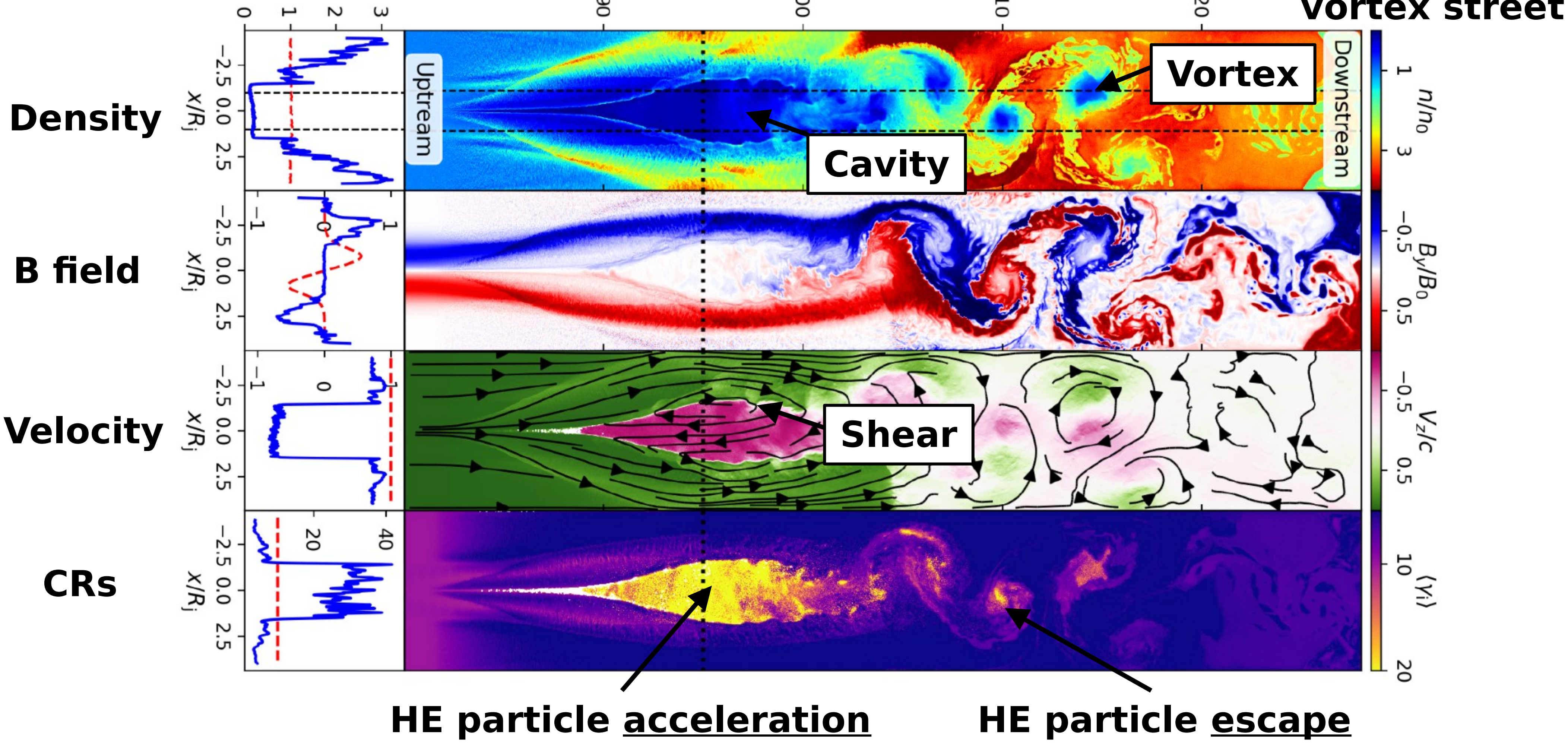
Results PIC Sim.: Density evolution



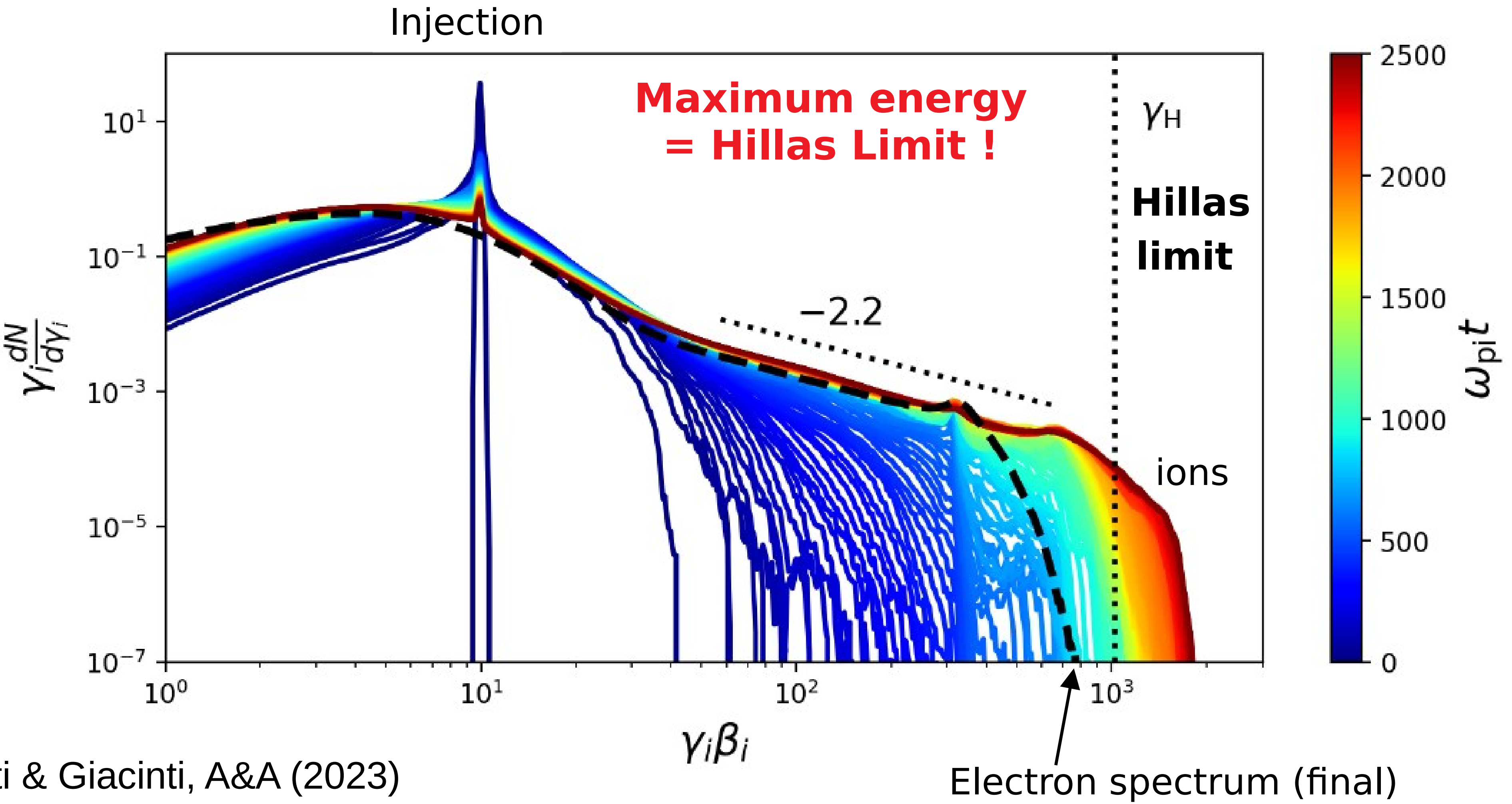
Cerutti & Giacinti, A&A (2023)

Results – PIC Simulations

Cerutti & Giacinti, A&A (2023)

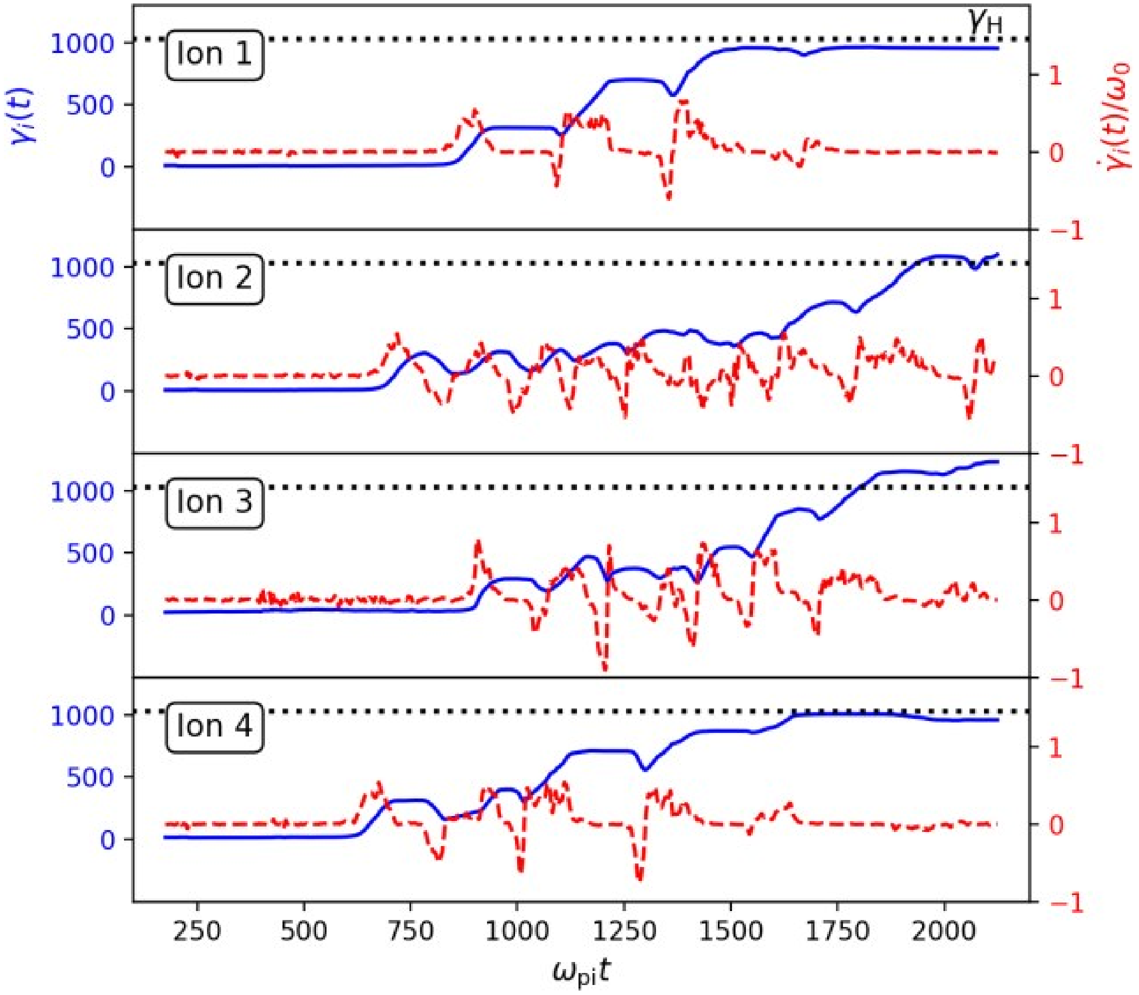


Ion spectrum: Time Evolution & E_{max}



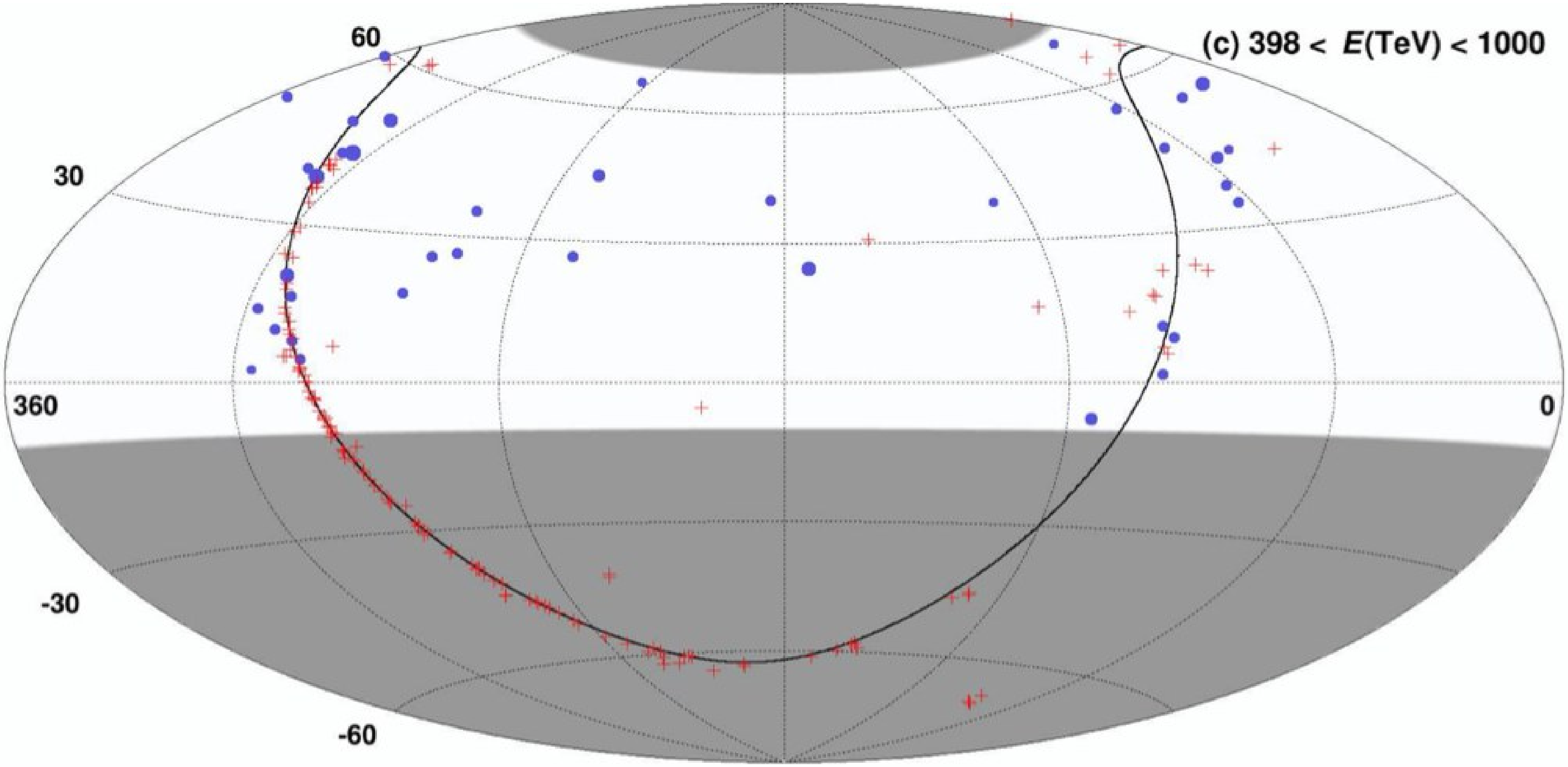
Cerutti & Giacinti, A&A (2023)

Particle acceleration mechanism



2 – Diffuse γ-ray emission: Pulsar wind nebulae & microquasars

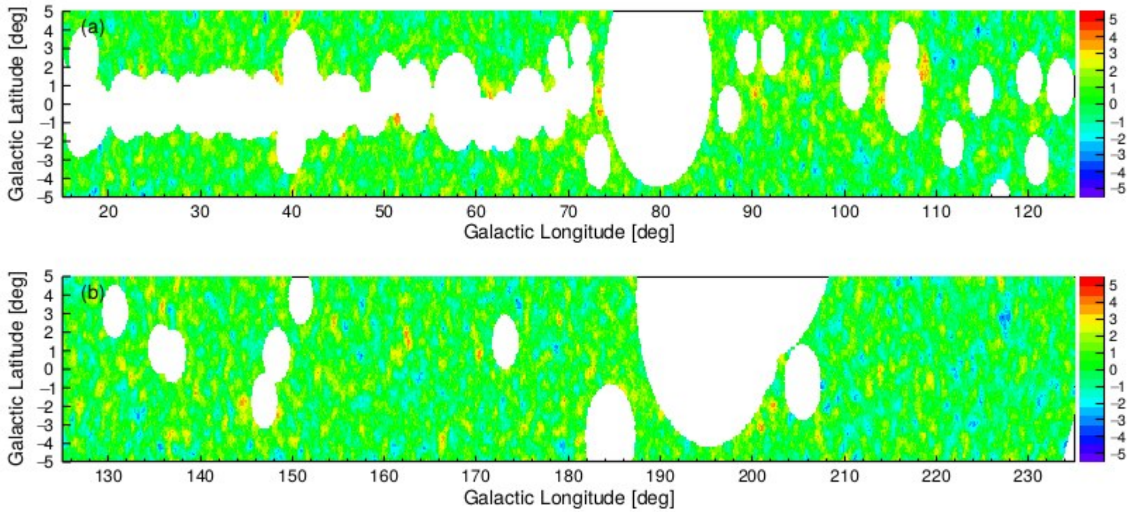
The sky at ~ 400 TeV – 1 PeV: Diffuse emission from AS-γ

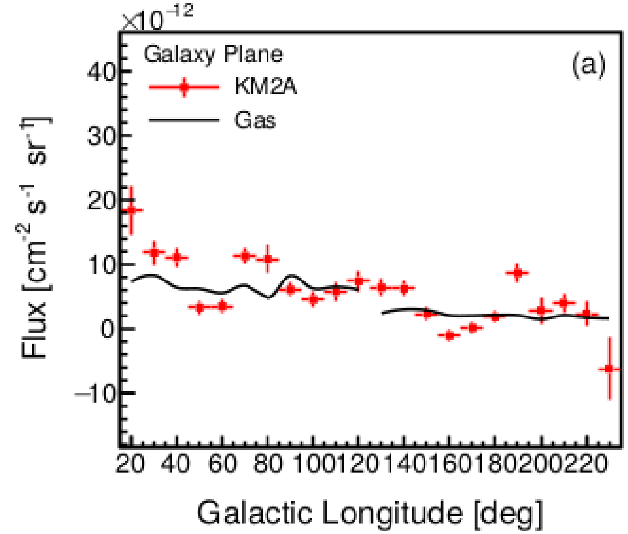


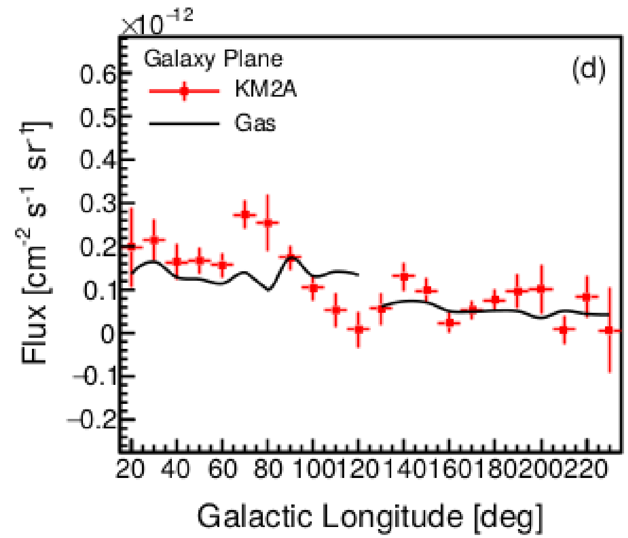
AS-γ Collaboration,
arXiv:2104.05181

The sky at ~ 10 TeV – 1 PeV: Diffuse emission from LHAASO

LHAASO Collaboration, arXiv:2305.05372







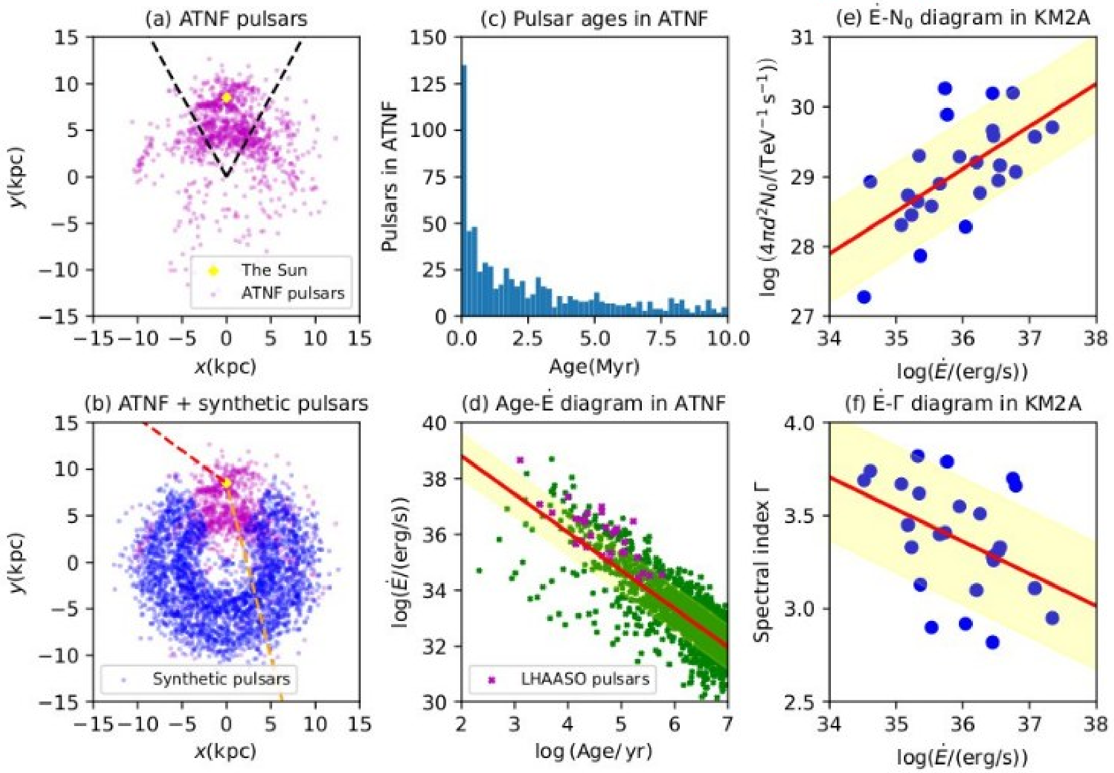
Emission in Galactic longitude does not follow target gas…

→ Leptonic origin?

→ Stochasticity of CR injection?

Impact of unresolved sources (PWNe)

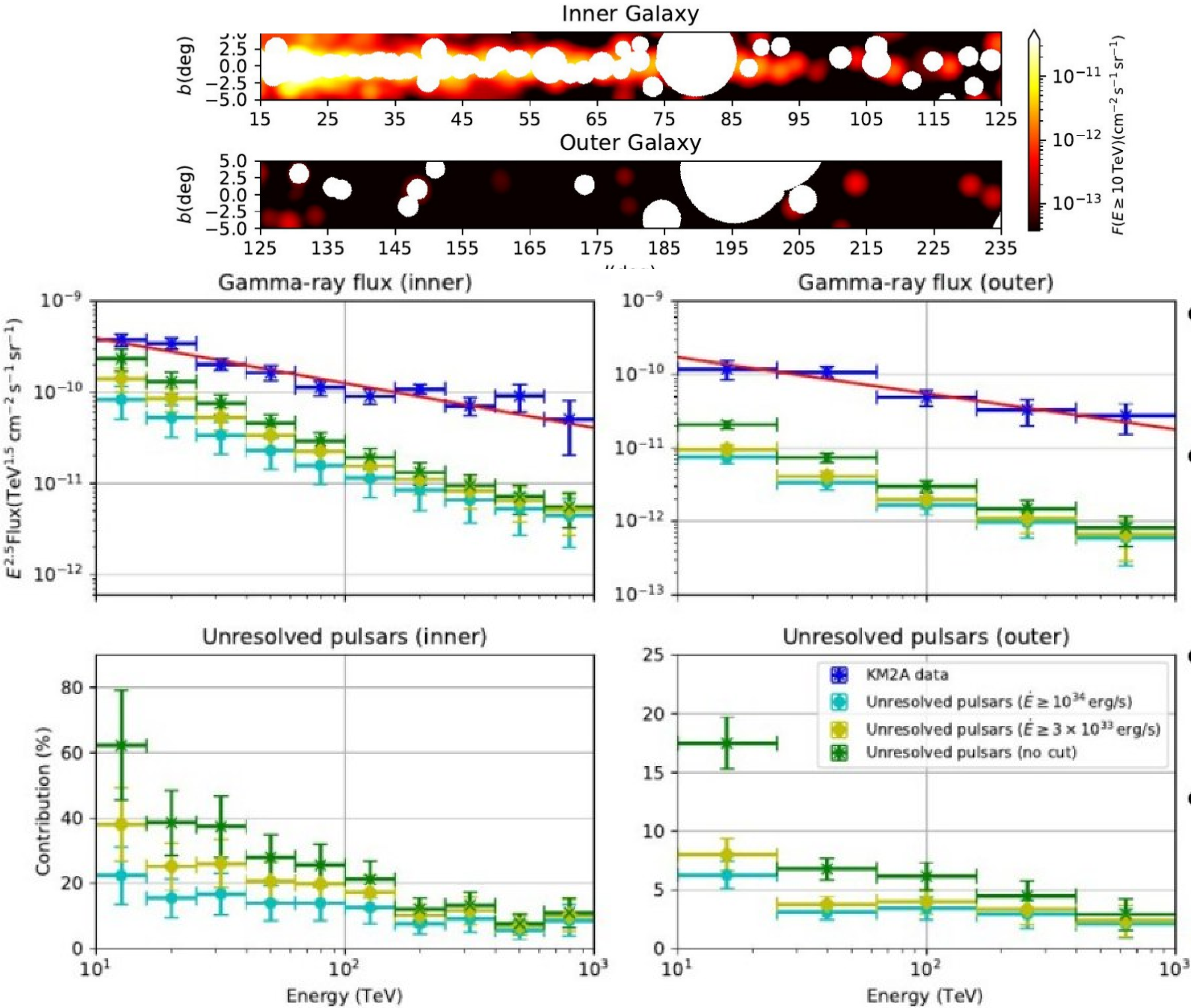
Kaci, Giacinti, Semikoz, ApJ Lett. 975, L6 (2024)



- Use ATNF catalog and complete it.
- Generate a VHE gamma-ray emission similar to that measured by KM2A for each source.
- Constrain the gamma-ray emission to be below KM2A sensitivity.
- Use the same masks as LHAASO.
- Compare the contribution of unresolved sources to the total flux measured by KM2A.

Upper Limits unresolved PWNe/halos

Kaci, Giacinti, Semikoz, ApJ Lett. 975, L6 (2024)



Diffuse VHE γ-ray emission from discrete sources

SIMULATION:

Kaci & Giacinti, JCAP 01, 049 (2025)

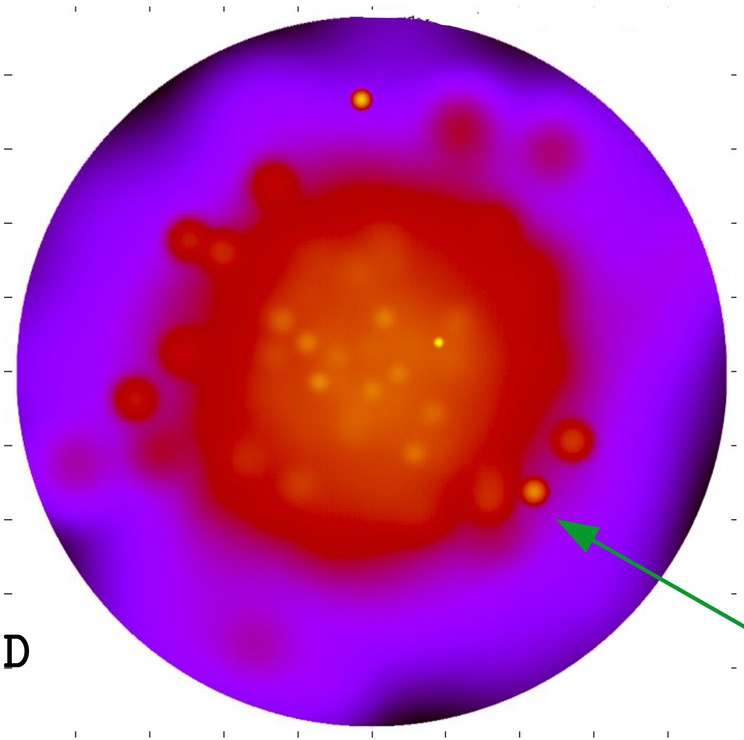
Isotropic and homogeneous diffusion

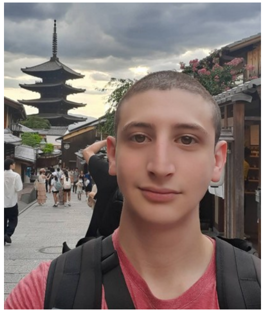
1) GALPROP-like (d=1/3) :

$$D(E) = 10^{28} D_{28} \left(\frac{R}{3GV} \right)^{\delta} cm^2/s$$

$$D_{28} = 1.33 \times \frac{H}{kpc}$$

2) Time-dependent (mimics self-confinement): 1/100 x D around sources for 10 kyr.





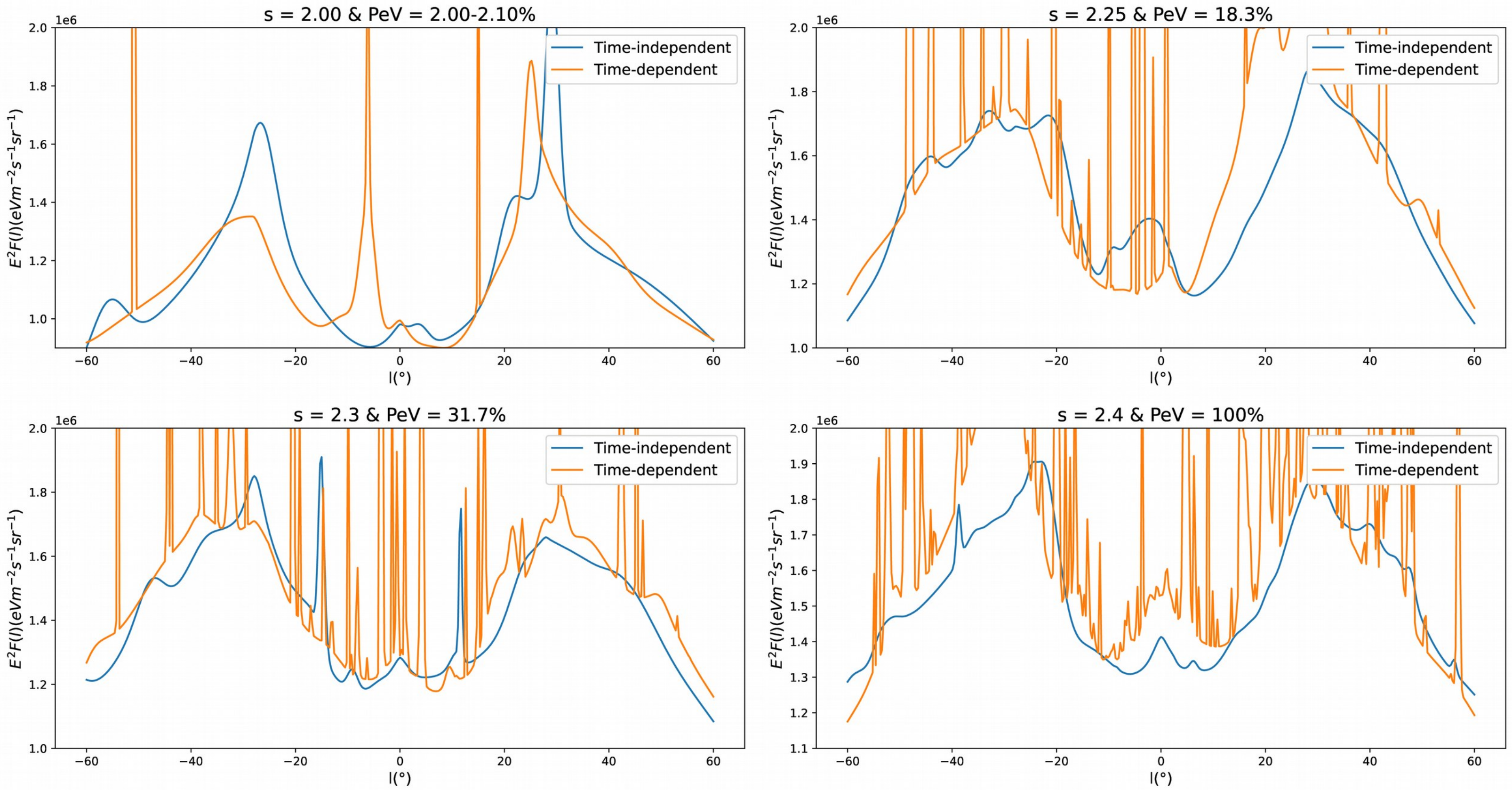
Samy Kaci

Cosmic-ray flux at Earth and B/C ratio satisfied

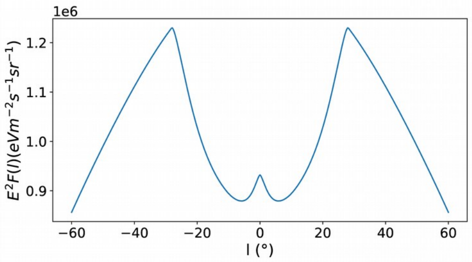
Discrete injection of cosmic rays

Clumps in the gamma-ray flux

Kaci & Giacinti, JCAP 01, 049 (2025)



Vs shape from Lipari & Vernetto(2018):



Diffuse gamma-ray flux clumpy at VHE

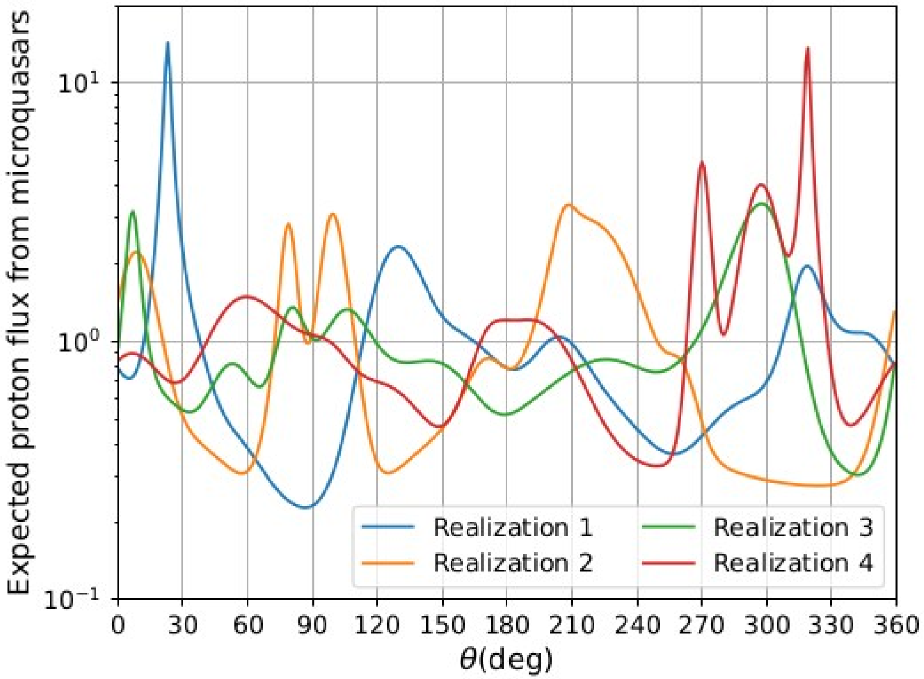
Microquasars as Galactic super-PeVatrons

Kaci, Giacinti et al., Submitted (2025), arXiv:2510.01369

Microquasars: inj. -2 spectrum, cutoff at 10 PeV, 100 kyr lifetime, 0.1/kyr rate, power $10^{39\text{-}40}$ erg/s.

→ **Much more clumpy than the 2.1% SNR case**

CR proton flux at 3.5 PeV over a circle of radius 8.5 kpc centered around the Galactic center. Angle θ for different positions on the circle.



Microquasars as Galactic super-PeVatrons

Kaci, Giacinti et al., Submitted (2025), arXiv:2510.01369

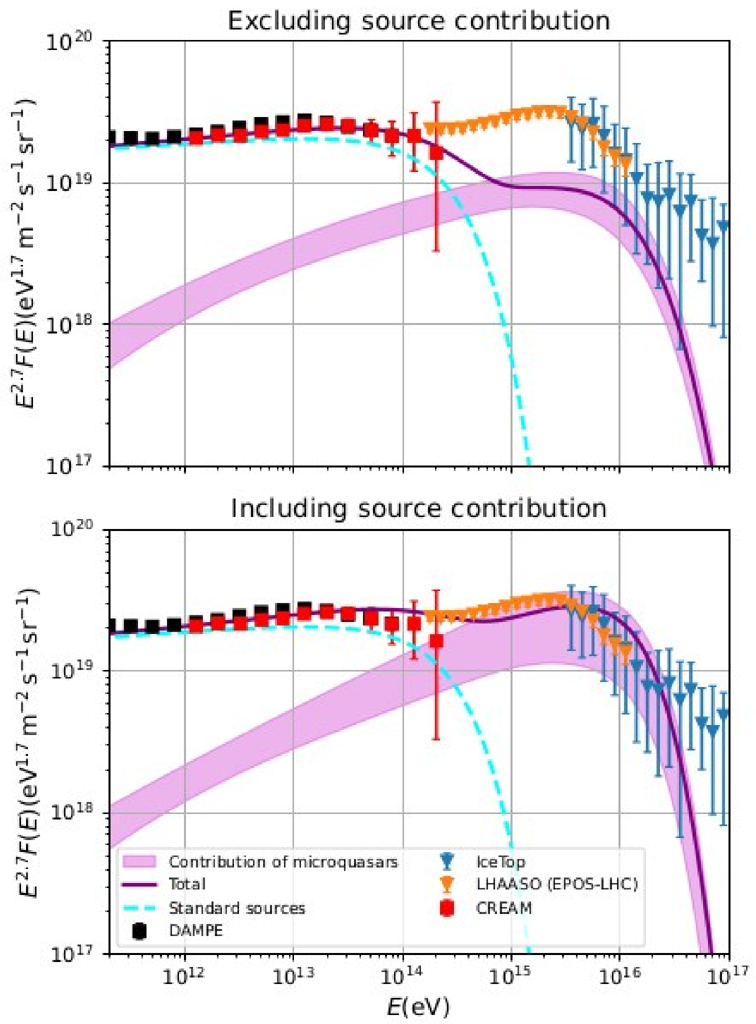
Microquasars: inj. -2 spectrum, cutoff at 10 PeV, 100 kyr lifetime, 0.1/kyr rate, power $10^{39\text{-}40}$ erg/s.

(Standard/SNR sources: -2.7 Power-law & exponential cutoff at 260TeV.)

-Up: Lower limit by excluding the existence of any active source within 4 kpc in the last 500 kyr.

- Down: All sources included. Shaded band: 68% containment region.

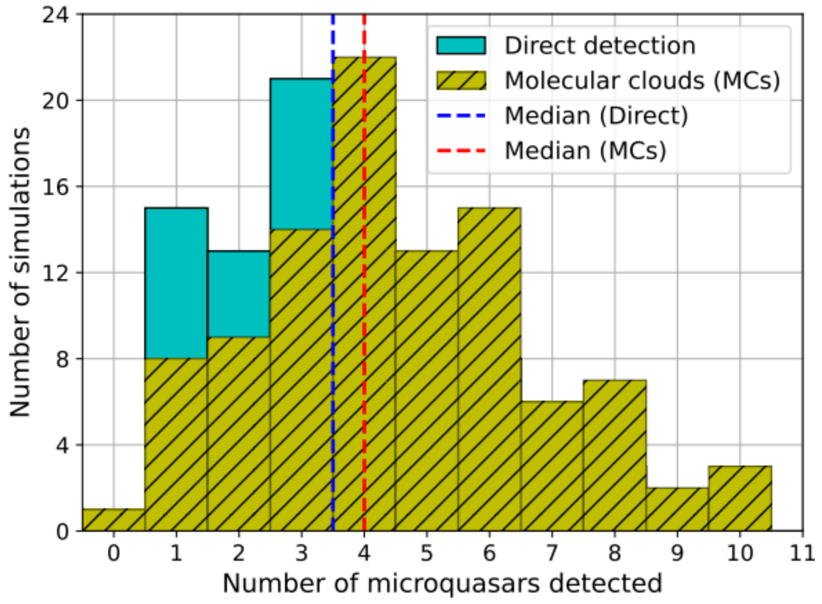
→ **Fits the knee and the 10TeV bump.**



Microquasars as Galactic super-PeVatrons

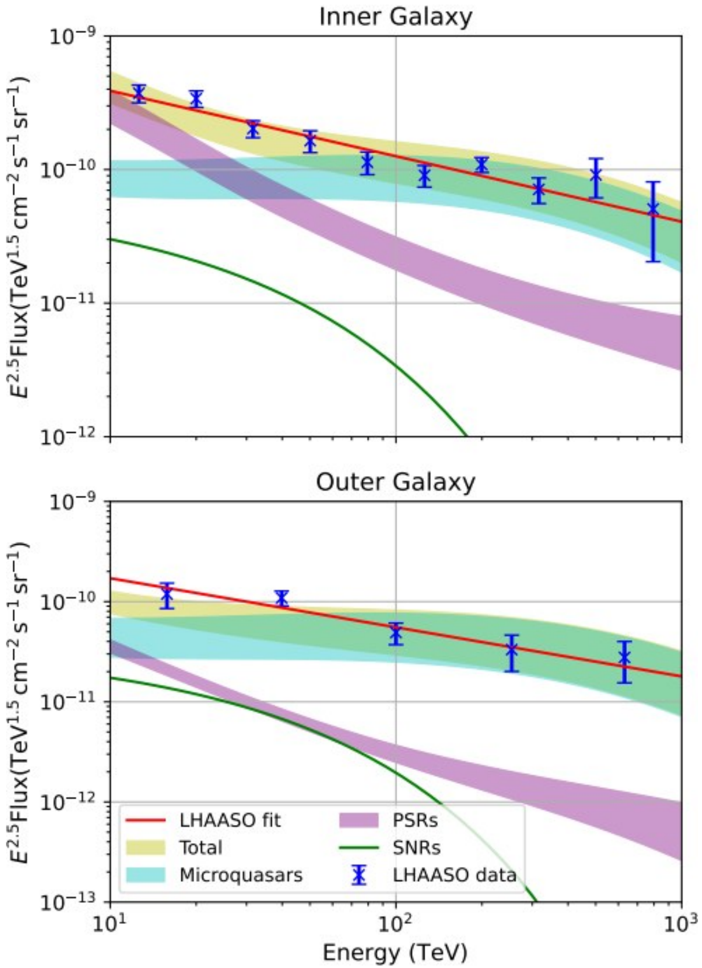
Kaci, Giacinti et al., Submitted (2025), arXiv:2510.01369

On average 3-4 sources detectable:



molecular clouds similar to that around SS433
(uniform sphere with r = 20pc and n=30cm^{-3})

Contribution to the diffuse emission:



Conclusions

→ **Particle acceleration possible in equatorial region of pulsar wind termination shocks**

→ **Similar mechanism possible at microquasar jet termination shocks**
→ **Particle acceleration around the middle axis of the jet**

→ **Clumpy diffuse γ-ray background at VHE**

→ **Unresolved PWNe/halos**: Minor contribution to LHAASO diffuse emission at > a few 10 TeV

→ ~ 10 powerful **microquasars can fit CR spectrum and LHAASO diffuse γ-ray emission.**