Supernova Remnants and their role in shaping TeV emission from PeVatrons Candidates

Alan Sunny and Martina Cardillo

(IAPS-INAF, Rome)

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TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA

Picture Credits: NASA/JPL-Caltech The W51 Complex

TeV Particle Astrophysics Conference 2026, Tendo, Japan

The social life of Molecular Clouds and Supernova Remnants

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Picture Credits: NASA/JPL-Caltech The W51 Complex

Science Case

LHAASO, in the past few years (and months), has reported UHE gamma ray detection from a range of sources.

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

Nature **594**, 33–36 (2021) | Cite this article

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

Evidence for particle acceleration approaching PeV energies in the W51 complex

LHAASO Collaboration*,[1]

Peta–electron volt gamma-ray emission from the Crab Nebula

THE LHAASO COLLABORATION, ZHEN CAO, F. AHARONIAN, Q. AN, AXIKEGU, L. X. BAI, Y. X. BAI, Y. W. BAO, D. BASTIERI, [...], AND X. ZUO +265 authors

Ultrahigh-Energy Gamma-ray Emission Associated with Black Hole-Jet Systems

LHAASO Collaboration

Picture Credits: NASA/JPL-Caltech The W51 Complex

Source classes

SUPERNOVA REMNANT (SNR)

PULSAR WIND NEBULAE (PWNe)

?

MICROQUASARS (MQ)

YOUNG STAR CLUSTERS (YSC)

UNIDENTIFIED SOURCES

Source classes

SUPERNOVA REMNANT (SNR)

PULSAR WIND NEBULAE (PWNe)

Role of interaction with surrounding medium!

MICROQUASARS (MQ)

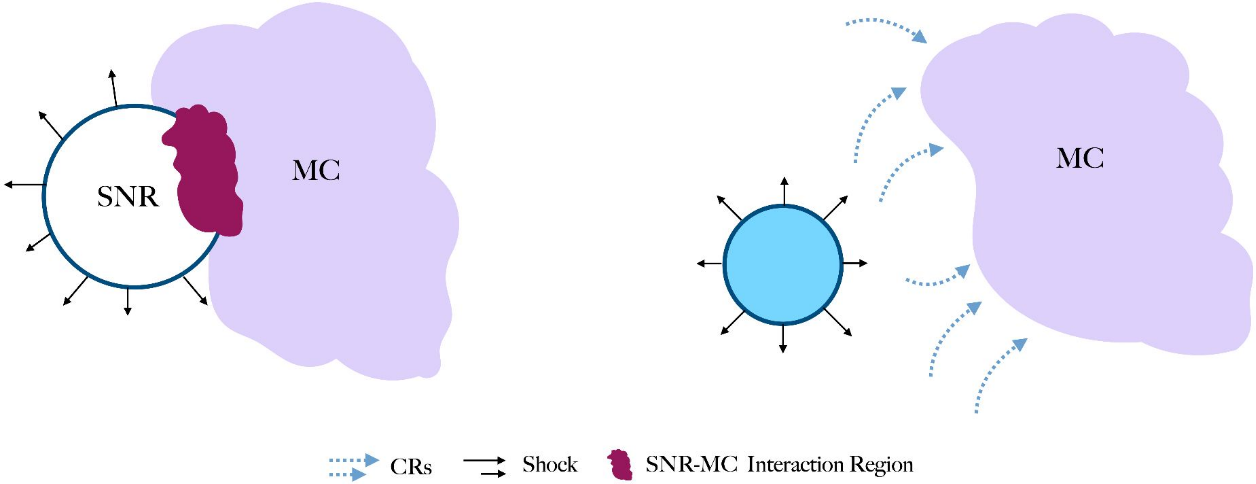
YOUNG STAR CLUSTERS (YSC)

UNIDENTIFIED SOURCES

Types of interactions

Scenario 1:

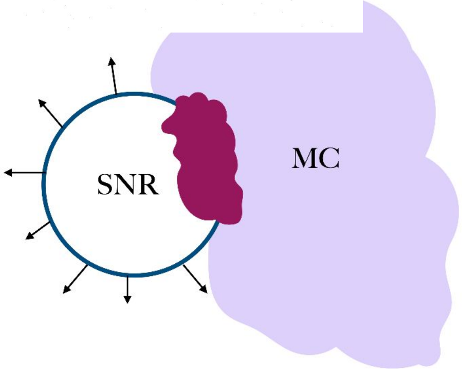
Scenario 2:



Types of interactions

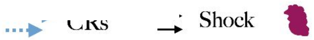
On the emissivity of π^0-decay gamma radiation in the vicinity of accelerators of galactic cosmic rays

F.A. Aharonian[1] and A.M. Atoyan[1,2]



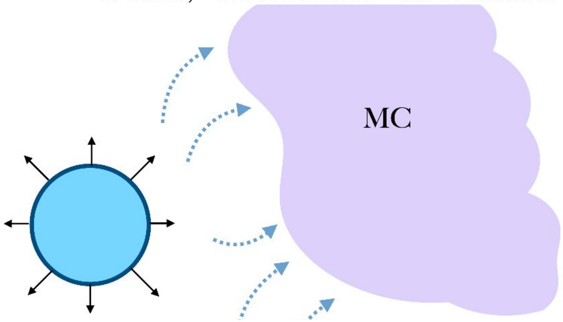
Supernova remnant W44: a case of cosmic-ray reacceleration

M. Cardillo[1], E. Amato[1], and P. Blasi[1,2]



Broad-band non-thermal emission from molecular clouds illuminated by cosmic rays from nearby supernova remnants

S. Gabici,[1★] F. A. Aharonian[1,2] and S. Casanova[2]



Exploring the supernova remnant contribution to the first LHAASO source catalog via passively illuminated interstellar clouds

Alison M.W. Mitchell[a], Silvia Celli[b]

LHAASO J2108+5157 as a Molecular Cloud Illuminated by a Supernova Remnant

A.M.W. Mitchell[1 ★]

Microquasar remnants as hidden PeVatrons

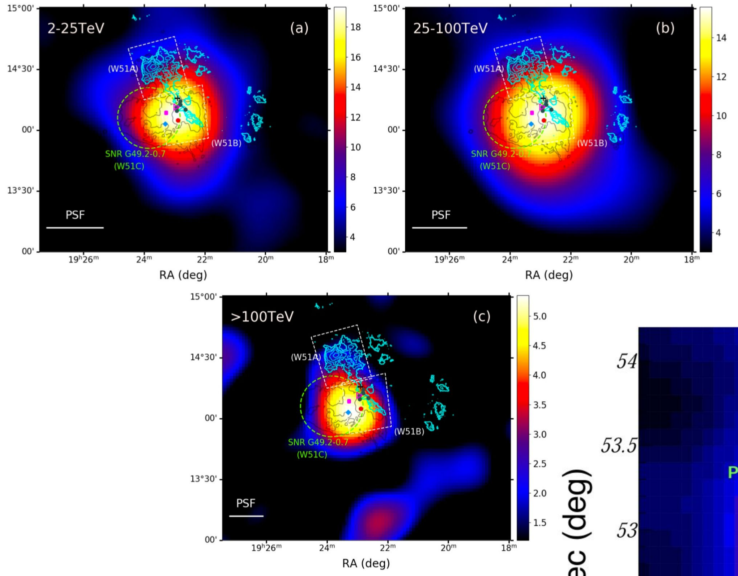
Leandro Abaroa[1,2★], Gustavo E. Romero[1,2], and Valentí Bosch-Ramon[3]

LHAASO sources we target

- **UHE gamma-ray sources lacking a currently active PeVatron but has spatial association with dense environments**
    - No known accelerator capable of sustaining the observed TeV-PeV emission, examples include old SNRs.
    - Strong spatial association with molecular clouds and dense gas structures.
    - Favorable conditions for cosmic-ray confinement and hadronic interactions.
- **Unidentified and dark PeVatron candidates**
    - No confirmed counterpart at other wavelengths.
    - Extended UHE emission with no obvious accelerator association.
    - Has dense structures like molecular clouds within the extended region

LHAASO sources we target

Poor angular resolution and large PSF of LHAASO → poor morphological information!



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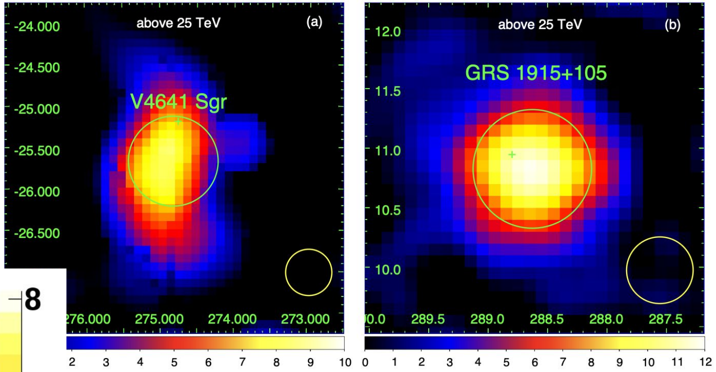
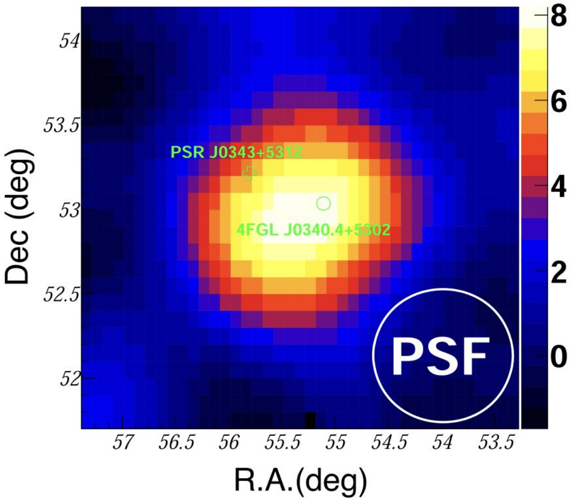




tion.

ded region

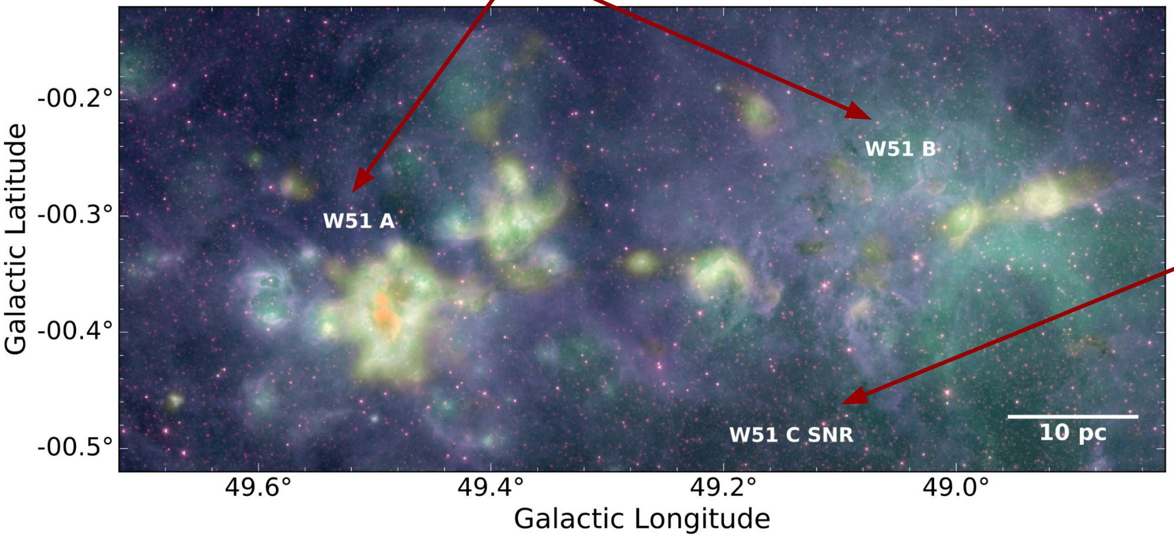
Credits LHAASO Collaboration

Story of W51

W51 is a giant complex within a diameter of ~ 100 pc, mass of 10^6 $M_{\odot}$ at a distance of 5.5 kpc.

Two massive clouds

Credits Ginsburg et al 2015a



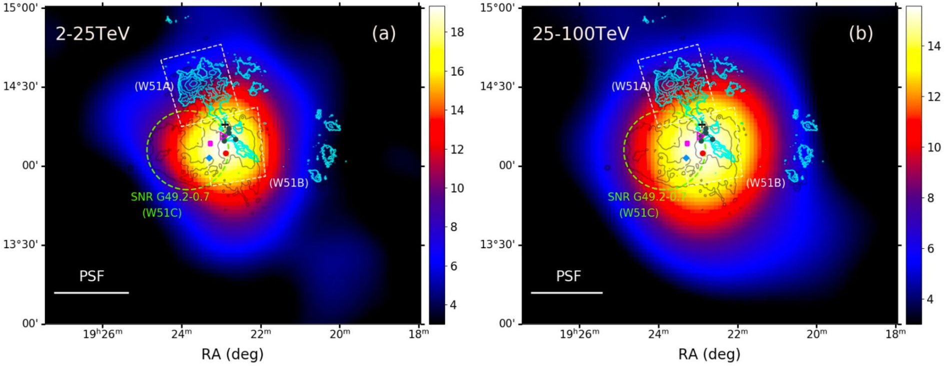
Supernova remnant (SNR), aka G49.2-0.7

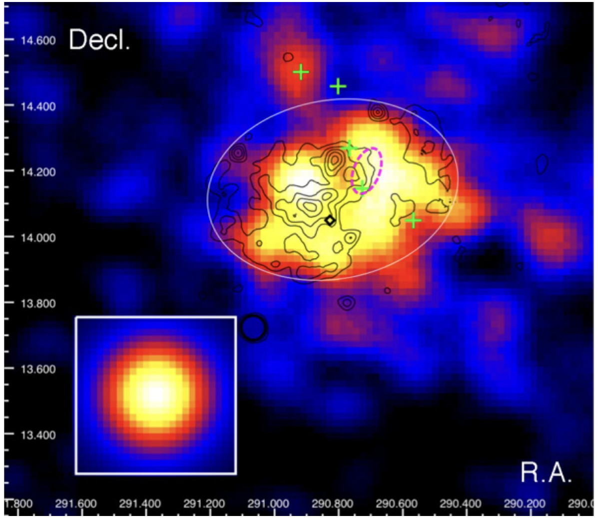
Story of W51

W51C appears in radio as a shell type SNR where Fermi-LAT has reported a pion-bump like feature [Jogler et al 2016]:

- Middle aged: t ~ 18 kyr
- KE = 3.6 x 10^{51} erg
- Radius = 24 pc

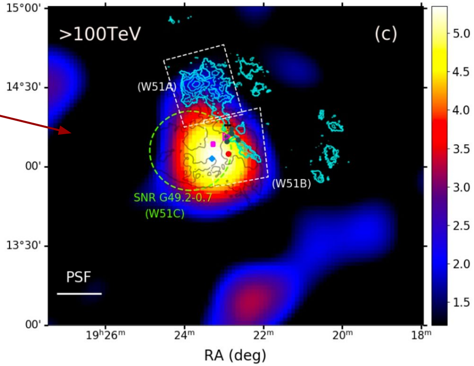
Theoretically an efficient CR accelerator





W51C with Fermi LAT
Credits A A Abdo et al 2009

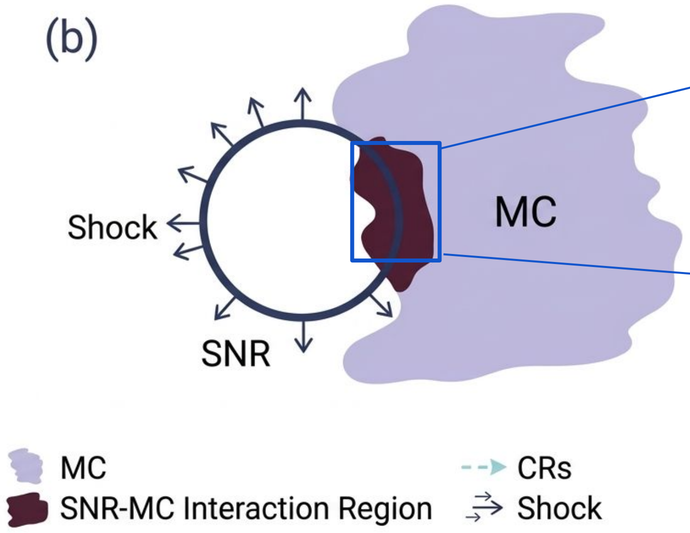
LHAASO reported ≈200 TeV from the Complex



W51 by LHAASO
Credits LHAASO Collab 2025

Direct interaction between W51 C and B

Case of Acceleration

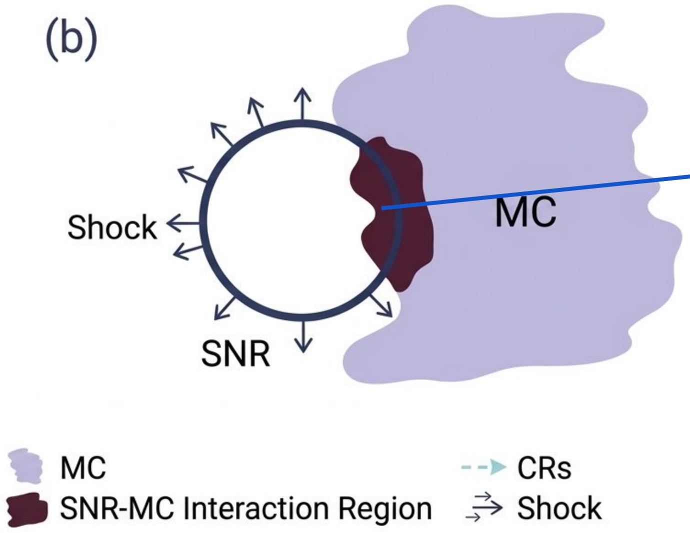


Contribution from fresh acceleration of particles at the shock.

Sunny and Cardillo 2026 accepted in A&A (arXiv)

Direct interaction between W51 C and B

Case of Compression and Reacceleration

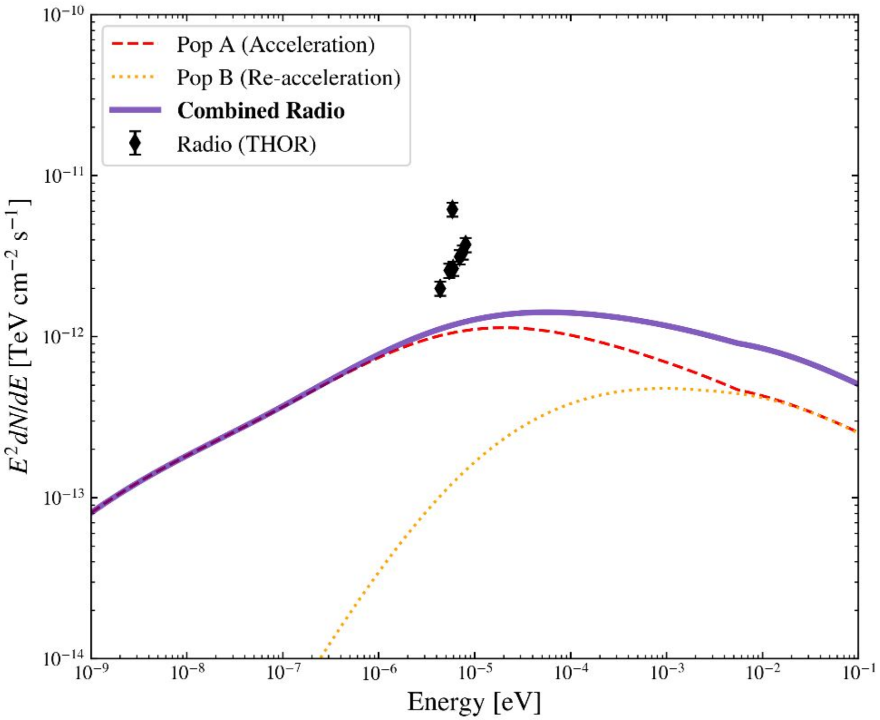


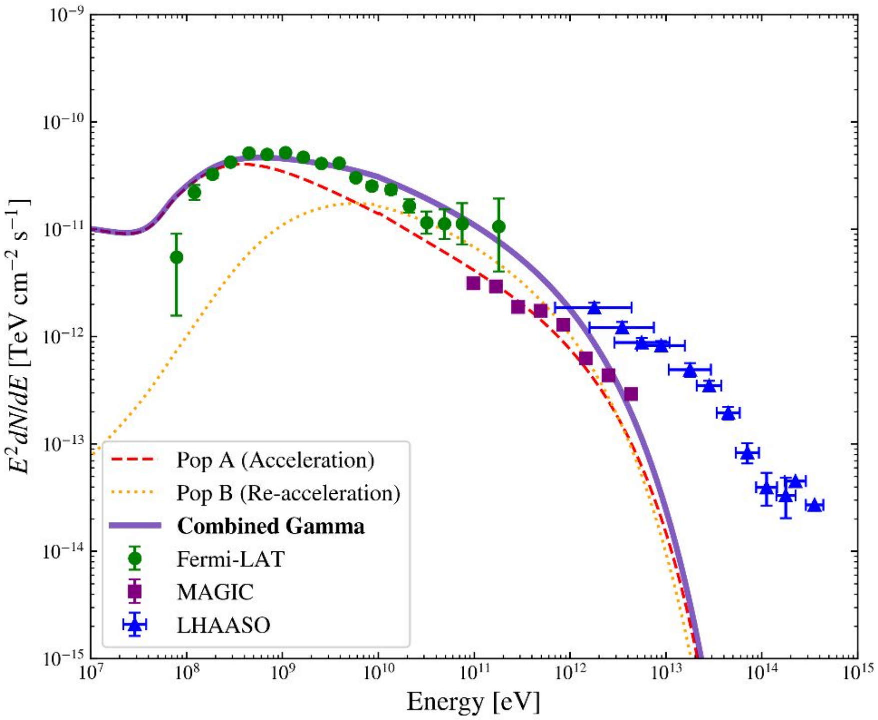
Compression due to radiative cooling - particles experiencing further energization.

Already existing sea of Galactic CRs go through re-acceleration.

Sunny and Cardillo 2026 accepted in A&A (arXiv)

Direct interaction between W51 C and B





Pion-decay dominant scenarios

Model based on Cardillo et al 2016

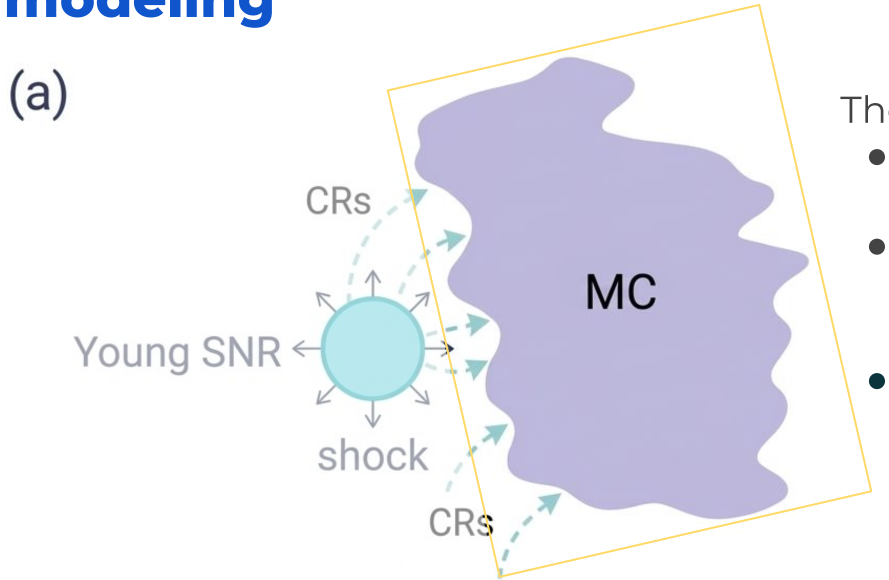
Sunny and Cardillo 2026 accepted in A&A ([arXiv])

Cosmic ray illumination

- W51C SNR, in a relatively early evolutionary stage, may have injected UHE particles into the MC
- Particle escape from stellar clusters in W51B
- The massive star-forming regions and associated stellar winds in W51A
- The PWNe candidate CXO J192318.5+140305

Sunny and Cardillo 2026 accepted in A&A (arXiv)

Cosmic ray illumination: accelerator independent modeling

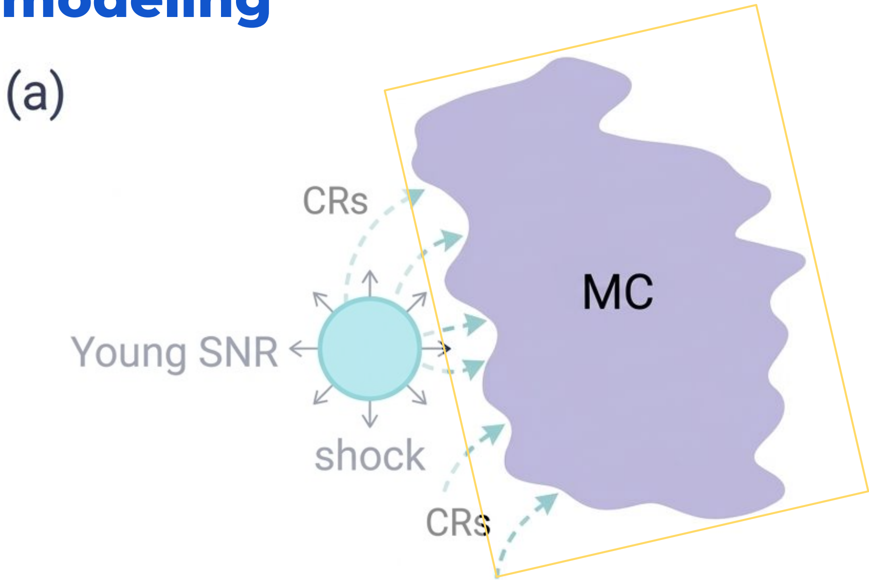


The W51B MC region:

- We know the mass (10^6 solar mass) and assume a uniform cloud.
- Assuming a distance of 5.5 kpc, the physical extension of ∼ 30 pc. We derive an average density of ∼ 120 cm^{-3}
- We assume a mag. field value ~ 7μG, ideal for a giant MC [Crutcher 2012] .

Sunny and Cardillo 2026 accepted in A&A (arXiv)

Cosmic ray illumination: accelerator independent modeling



Diffusion coefficient:

D_0= 10^{26} cm^2/s ; E_0= 4 GeV ; δ = 0.33

[Kar et al 2022; Cui et al 2016, Gabici et al 2010]

We start from the particle injection into the cloud and try to constraint the parameters that agrees with the observational data the most.

Using GAMERA we solve the transport equation:

$$\frac{\partial N}{\partial t} = Q(E,t) - \frac{\partial}{\partial E}\left[b(E,t), N(E,t)\right] - \frac{N(E,t)}{t_D},$$

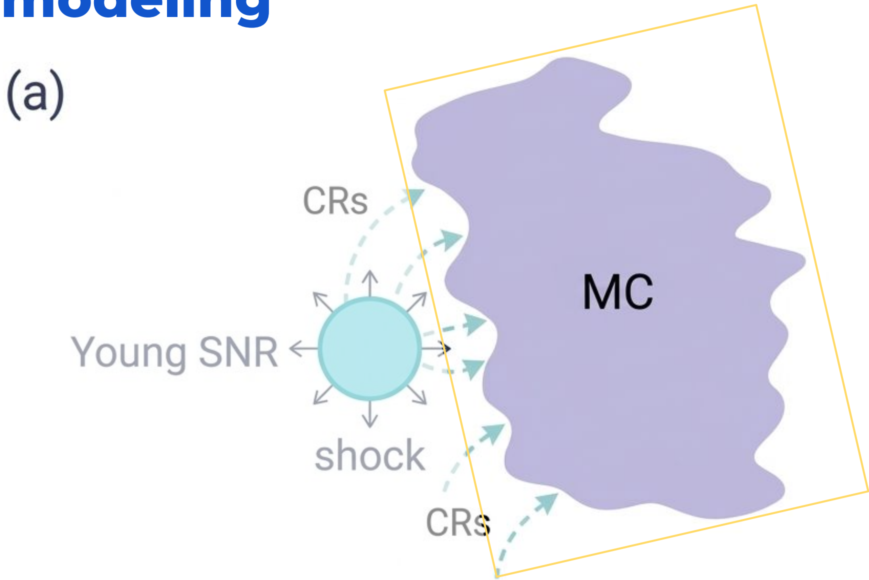
$$t_D = \frac{R^2}{D(E)}, \tag{2}$$

where R is the characteristic spatial scale of the system, in this case the height of the cloud. The diffusion is modeled as,

$$D(E) = D_0 \left(\frac{E}{E_0}\right)^{\delta}, \tag{3}$$

Sunny and Cardillo 2026 accepted in A&A (arXiv)

Cosmic ray illumination: accelerator independent modeling



Suppressed diffusion in the cloud:

$D_0 = 10^{26}$ cm^2/s

[Kar et al 2022; Cui et al 2016, Gabici et al 2010]

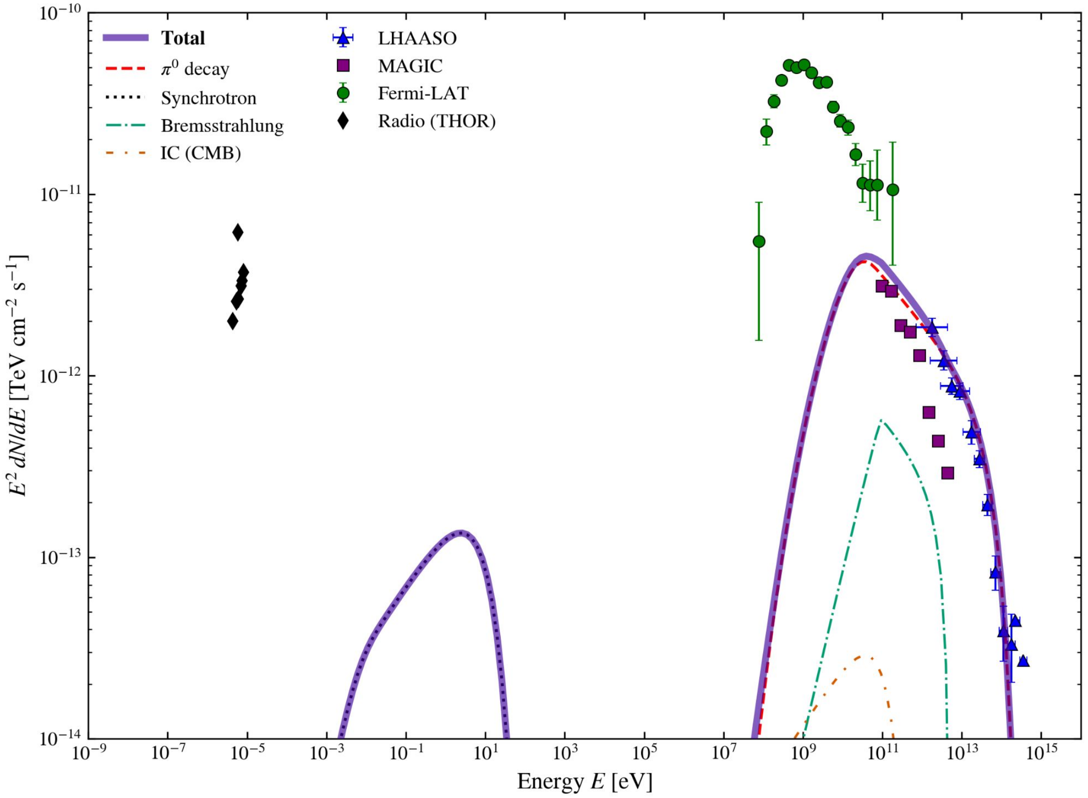
Lepto-hadronic

- $t_{inj} \approx 420$ yr → very brief injection phenomena.
- Evolved in the clouds for 18000 years.

Parameters	Protons	Electrons
Max. energy of particles injected into the MC (TeV)	400	10
Min. energy of particles injected into the MC (TeV)	0.1	0.1
Luminosity (erg/s)	4.5×10^{38}	4.5×10^{36}
Spectral index	2.3	2.3

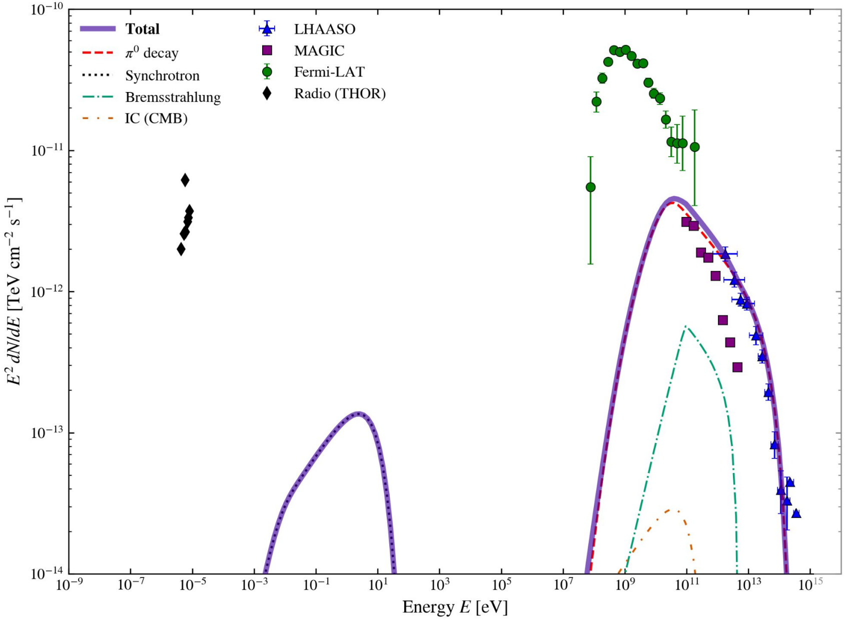
Sunny and Cardillo 2026 accepted in A&A (arXiv)

Cosmic ray illumination: accelerator independent modeling



Sunny and Cardillo 2026 accepted in A&A (arXiv)

Cosmic ray illumination: accelerator independent modeling



Conclusion:

- CRs confined in a dense molecular cloud can explain the UHE emission through pp interactions, while the GeV can be explained with direct interaction between the shock and cloud.

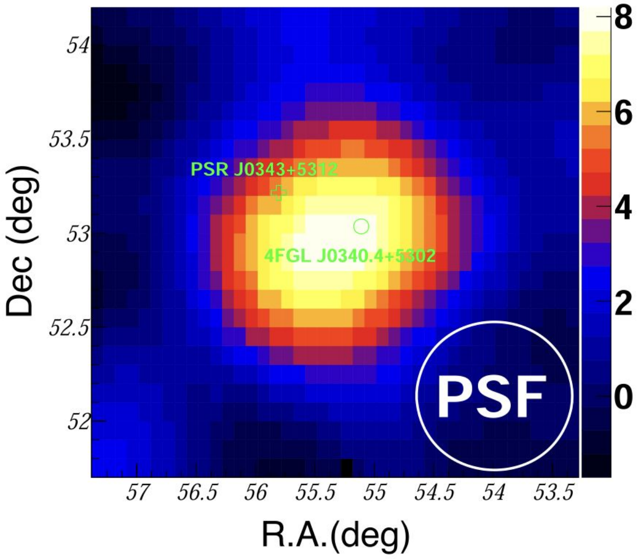
Sunny and Cardillo 2026 accepted in A&A (arXiv)

Cosmic ray illumination: accelerator independent modeling

The framework can be readily extended to unidentified LHAASO sources, similar to the studies of Mitchell et al., Kar et al., and De Sarkar et al. Unlike these works, which typically assume a specific SNR origin, our approach can be accelerator-independent and instead constrains the properties of the injected hadronic particle population and its interaction with the surrounding environment.

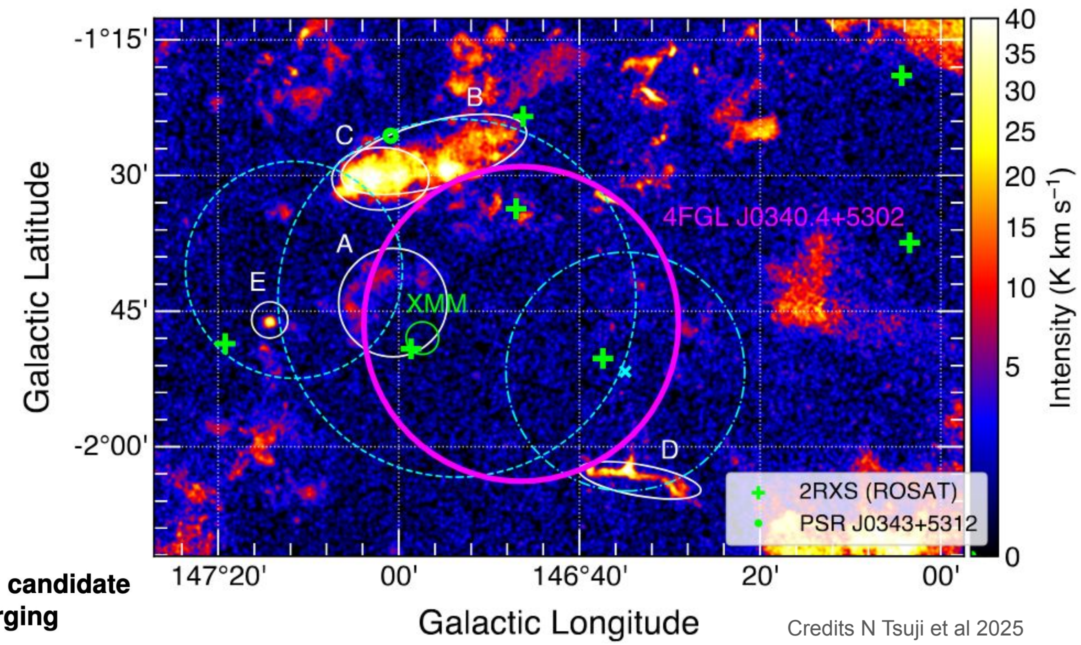
The main idea here will be “passive illumination”, where the accelerator is at an offset away from the cloud.

Passive illumination: LHAASO J0341+5258



Fermi source 4FGL

J0340.4+5302

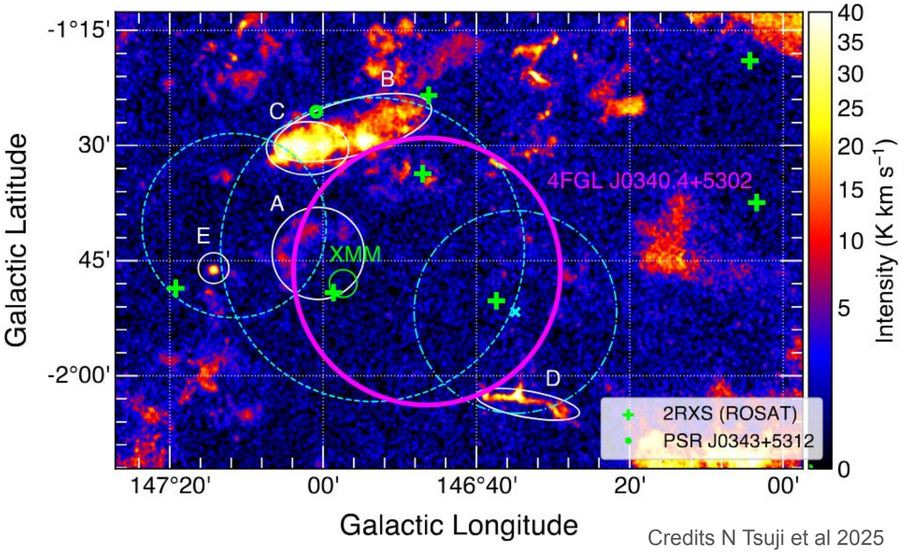


Multiwavelength insights into the pulsar wind nebula candidate near 1LHAASO J0343+5254u: An obscured merging galaxy cluster?

H. W. Edler[1,★], M. Arias[1], A. Botteon[2], and C. G. Bassa[1]

Credits N Tsuji et al 2025

Passive illumination: LHAASO J0341+5258

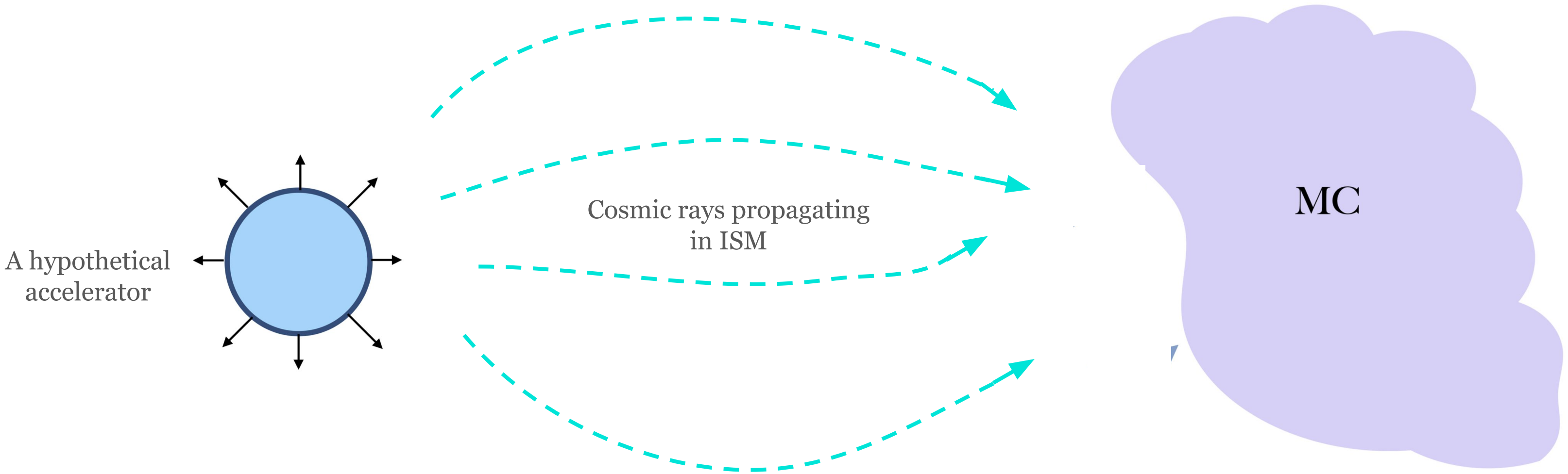


Credits N Tsuji et al 2025

Our assumptions:

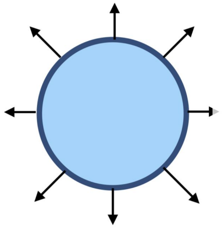
- The accelerator is 50 pc away from the cloud.
- A hadronic accelerator governed by DSA.
- The protons propagate through standard ISM like medium but with slow diffusion (for ref Oka 2025, Gabici 2009, Schroer 2022).
- Based on the propagation time (t_{prop}), we can calculate which particles escape the ISM region into the MC ⇒ $t_{prop} > t_D$.
- Even though Tsuji et al 2025 reported 5 MCs in the regions, we consider a uniform cloud, by averaging the properties, that spans the LHAASO extended emission, due to numerical limitations.

Passive illumination: LHAASO J0341+5258



An accelerator is 50 pc away from the cloud → Propagation losses within ISM

Passive illumination: LHAASO J0341+5258

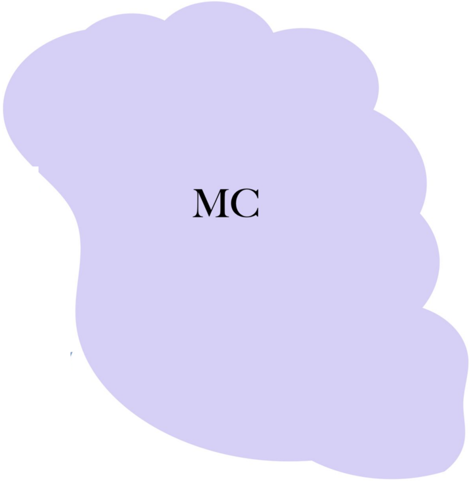


For an injected particle population, the spatial probability density after a time

$t_{prop,}$,

given a diffusion radius $R_D = 2\sqrt{D(E)t_D}$

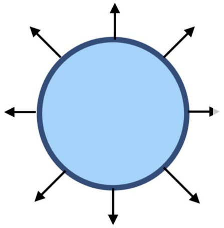
$$G(R_D, E, t_{\text{prop}}) = \frac{1}{\left(4\pi D(E) t_{\text{prop}}\right)^{3/2}} \exp\left(-\frac{R_D^2}{4D(E)t_{\text{prop}}}\right)$$



An accelerator is 50 pc away from the cloud → Propagation losses within ISM

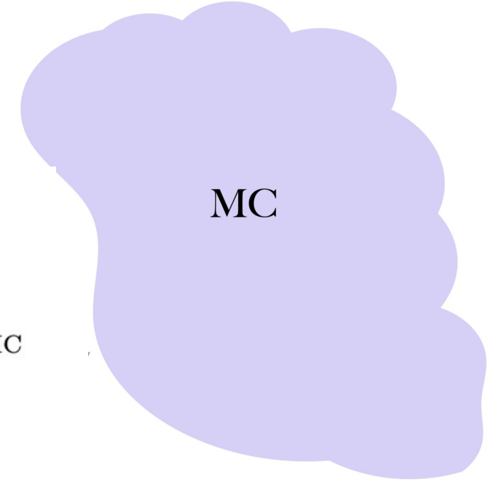
A. Roy et al 2026 (arXiv)

Passive illumination: LHAASO J0341+5258



After modelling the spatial propagation, we derive the particle population that escape the ISM that eventually gets injected into the MC

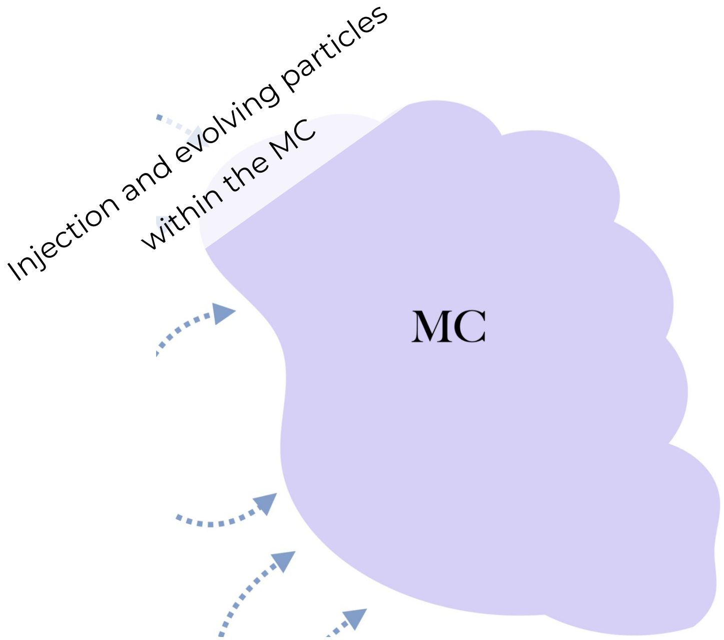
$$\left.\frac{dN}{dE}\right|_{\text{MC, inj}} = N_{\text{total}}(E) \times G(R, E, t_{\text{prop}}) \times V_{\text{MC}}$$



Note: Based on the propagation time (t_{prop}), we can calculate which particles escape the ISM region into the MC ⇒ $t_{prop} > t_D$.

A. Roy et al 2026 (arXiv)

Passive illumination: LHAASO J0341+5258

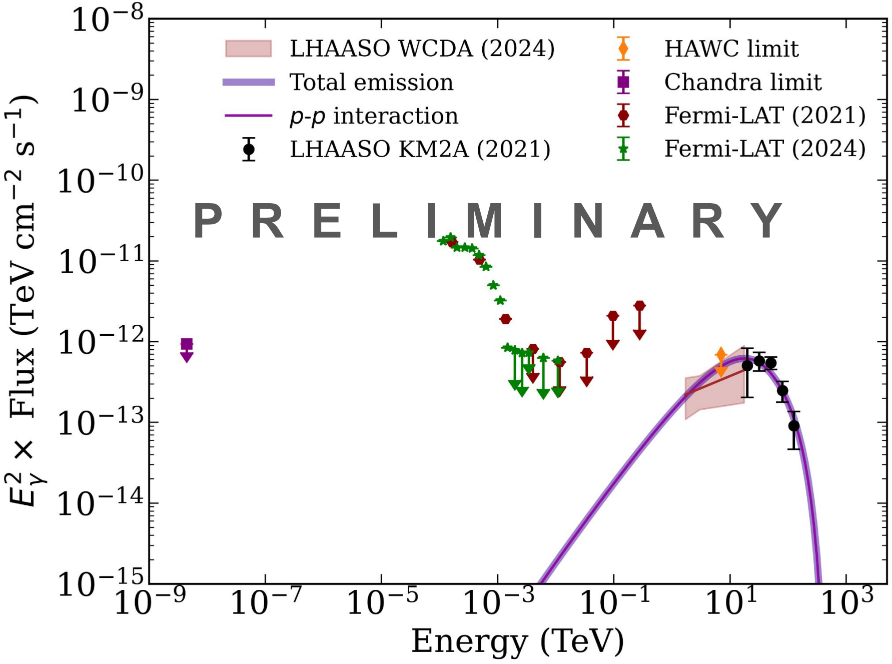


- After we get the particle population that is being injected into the MC, we solve the transport equation with diffusion time scale as defined before using GAMERA.

Parameters	ISM	MC
Density (cm^{-3})	0.1	30
Magnetic field (μG)	2	6
Characteristic distance R_D (cm)	1.543×10^{20}	1.67×10^{19}
Constant D_0 ($cm^2\ s^{-1}$)	5×10^{26}	10^{26}

A. Roy et al 2026 (arXiv)

Passive illumination: LHAASO J0341+5258



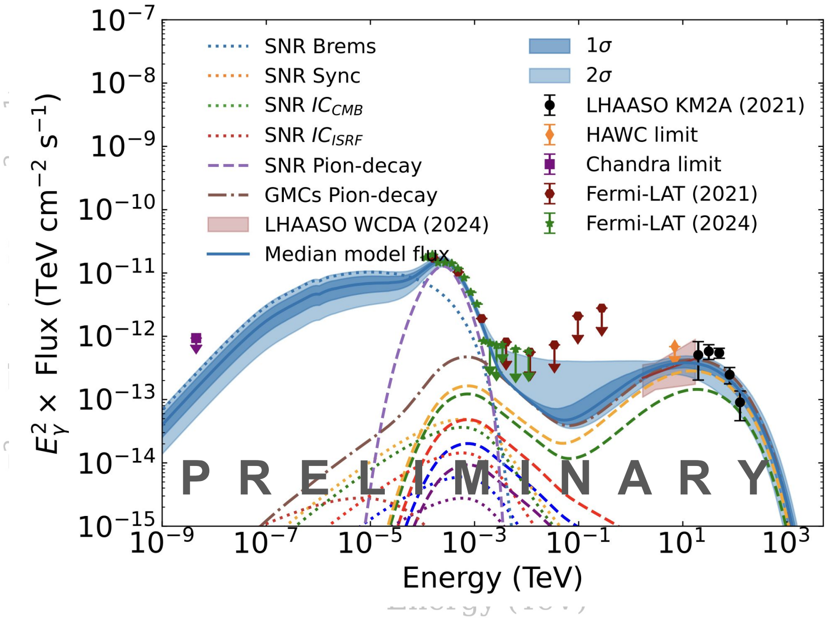
- Conclusion:

  An accelerator offset from the clouds illuminating can explain the TeV emission too.

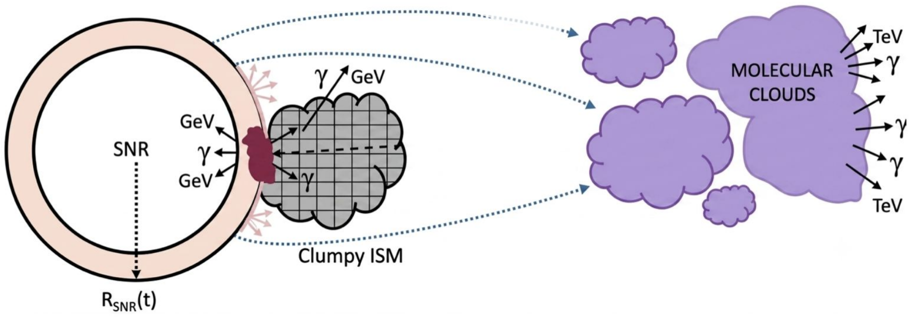
But we still don't know what is the source of the GeV emission!!!

External collaborators: A. Roy (GSSI) and J. Joshi (ARIES)

Passive illumination: LHAASO J0341+5258



SNEAK PEAK :)

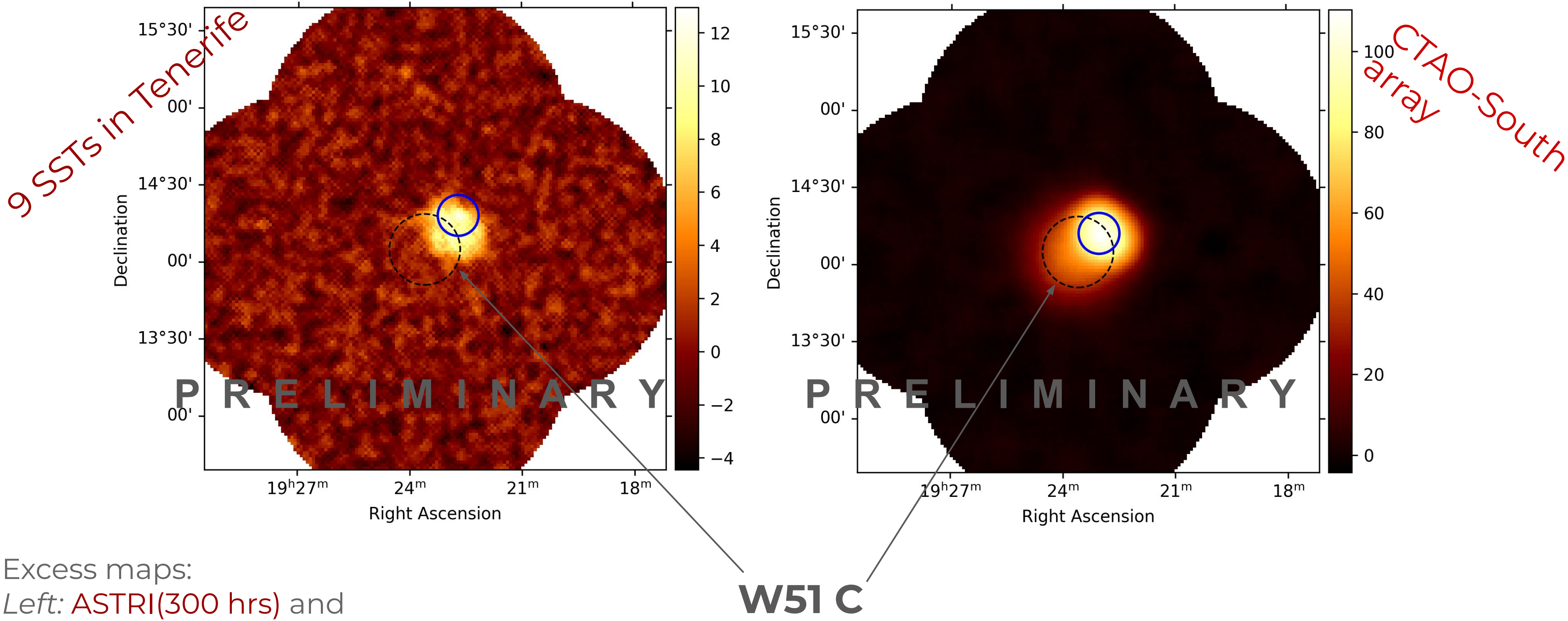


For detailed discussion refer- A. Roy et al 2026

(submitted to A &A: ref: arxiv)

External collaborators: A. Roy (GSSI) and J. Joshi (ARIES)

W51 Complex through future missions:
ASTRI Mini-Array and CTAO

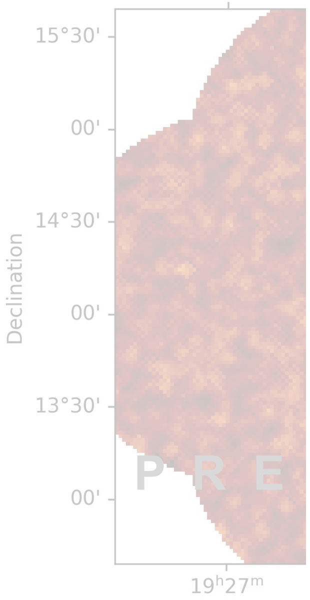


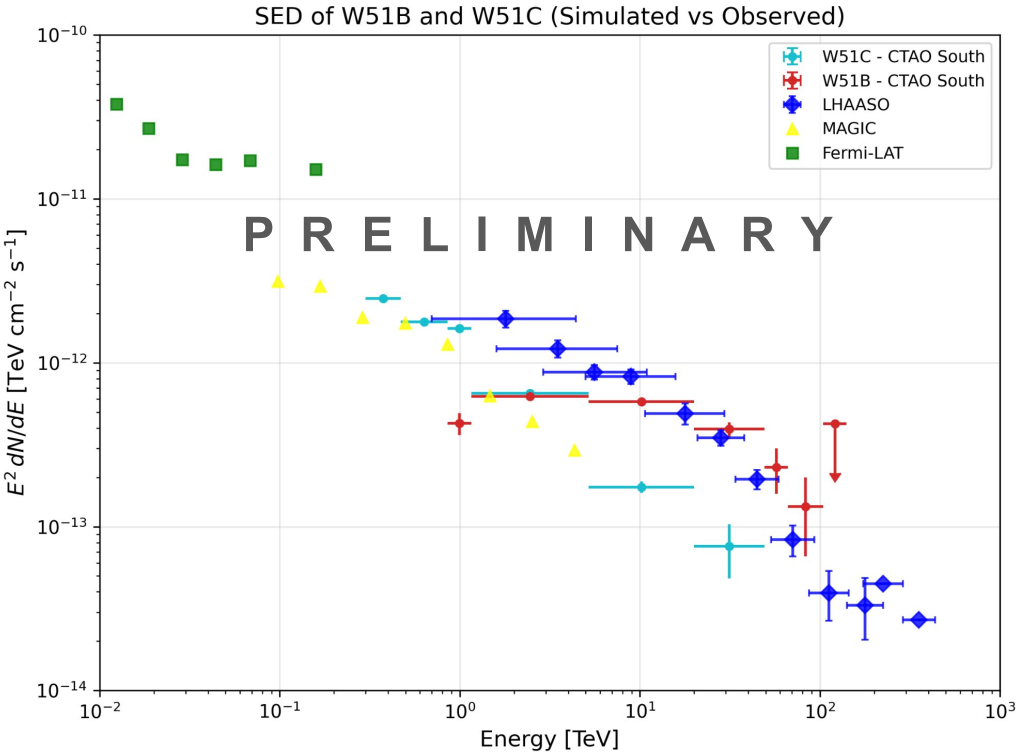
Excess maps:
Left: ASTRI(300 hrs) and
Right CTAO South (200 hrs)

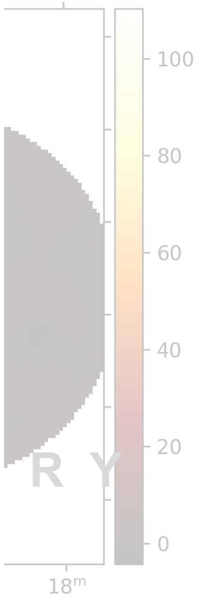
Note: The blue circle shows the 4 sigma significance peak. These are simulated observations with assumed morphological models.

https://gammapy.org/

W51 Complex through future missions:
ASTRI Mini-Array and CTAO







Excess maps:
Left: ASTRI(300 hrs) ar
Right CTAO South (20

gma significance peak found using
re simulated observations with
els.

https://gammapy.org/

For more discussions on the simulations see:
https://indico.ict.inaf.it/event/3571/contributions/26935/

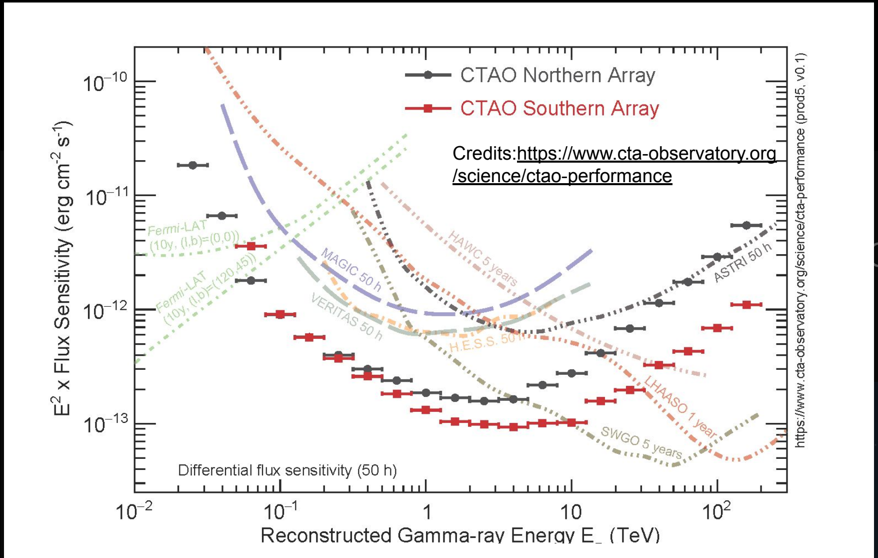
Takeaway points

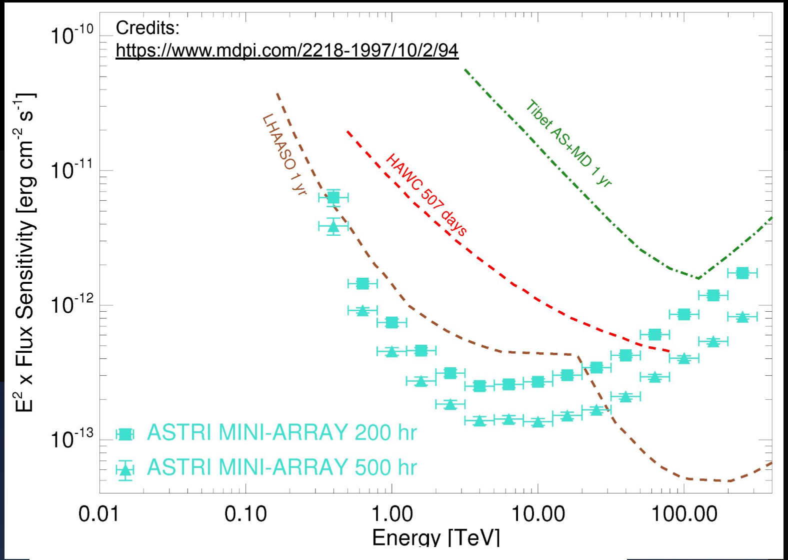
Dense molecular clouds may act as long-term cosmic-ray reservoirs, preserving historic PeVatron activity long after the accelerator's most powerful phase has ended.

With their angular resolution and sensitivity in the multi-TeV regime, **ASTRI Mini-Array and CTAO will be uniquely positioned to test this scenario.**

MC illumination could offer a natural explanation for a fraction of the currently UNID and dark PeVatron candidates, where no obvious accelerator is directly observed.

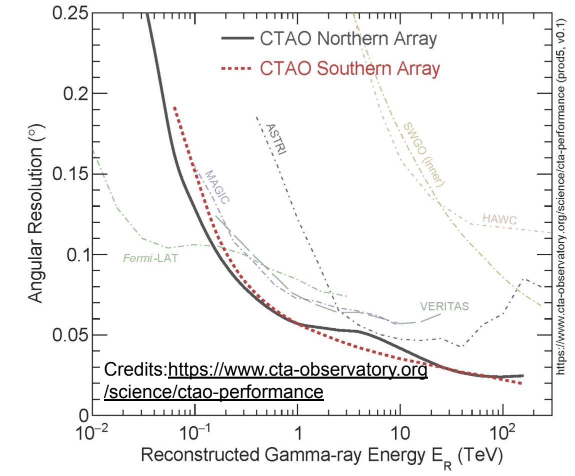
BONUS SLIDES



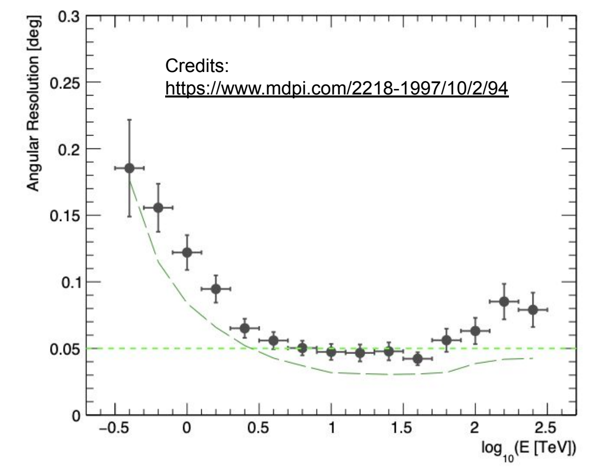


0 GeV

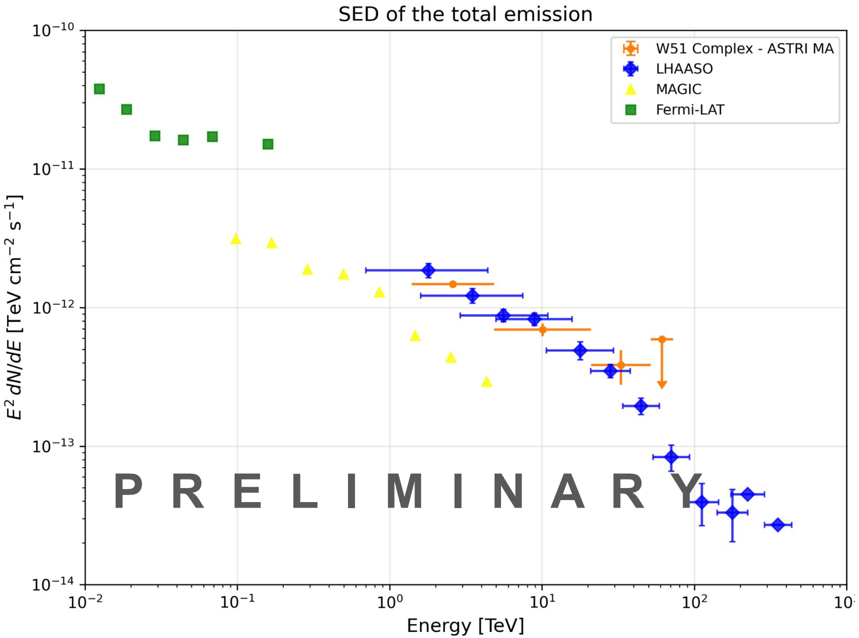
CTAO Telescopes (Cre

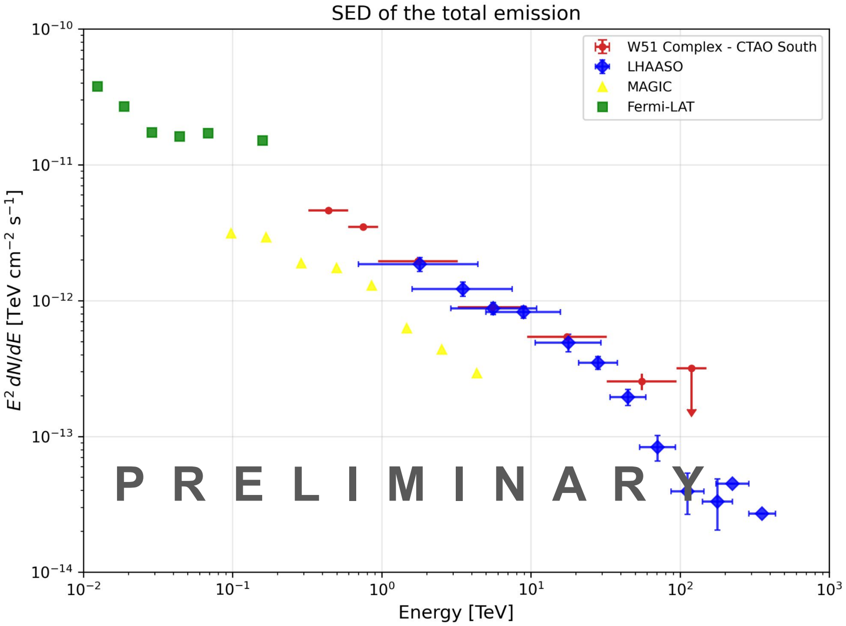


ASTRI-



MC illuminated cases through future missions:
CTAO and ASTRI Mini-Array

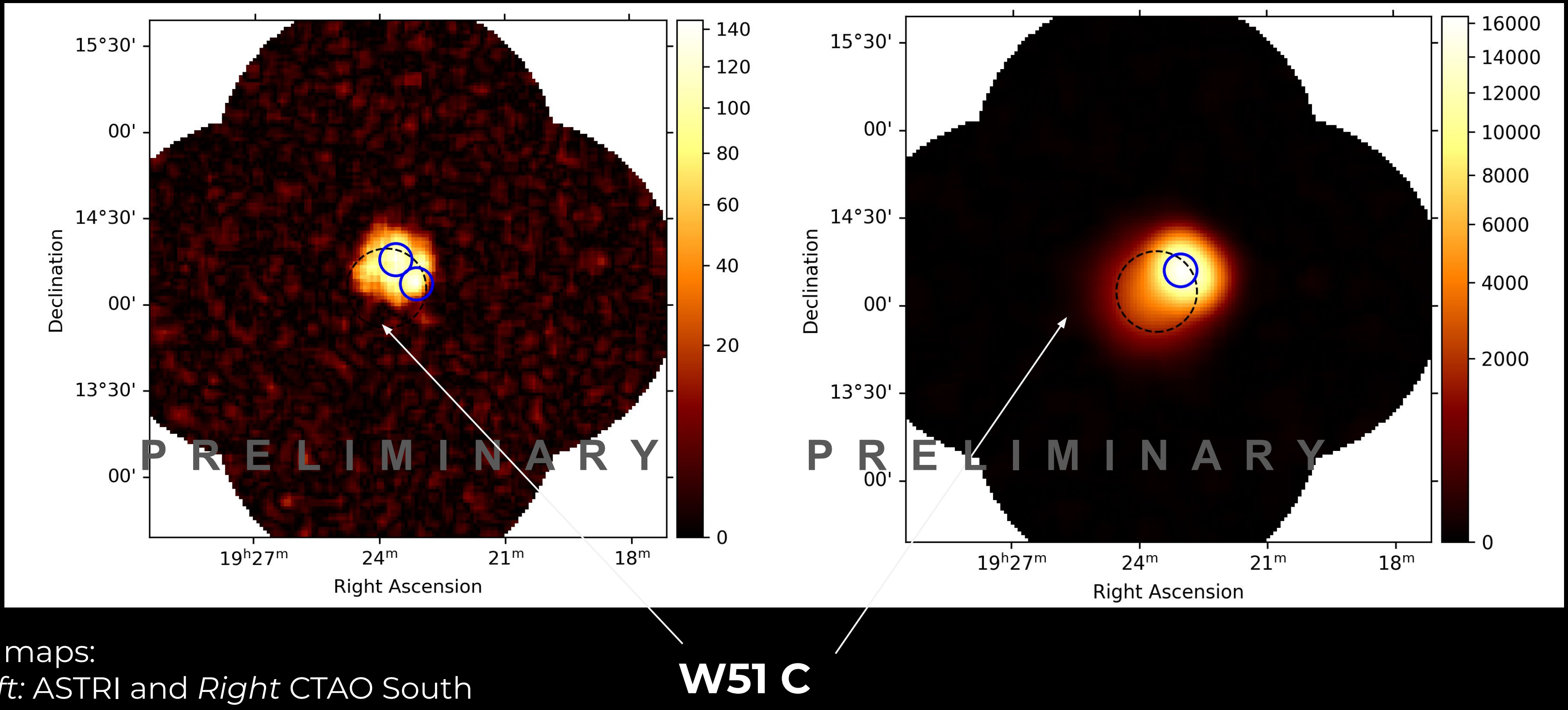




SED:
Left: ASTRI(300 hrs) and
Right CTAO South (200 hrs)

https://gammapy.org/

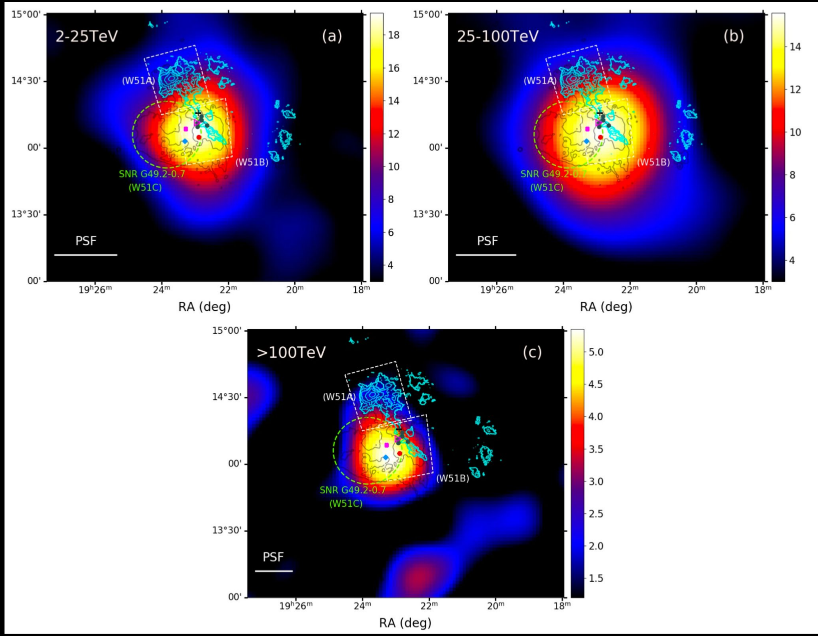
Role of SSTs: TS Maps

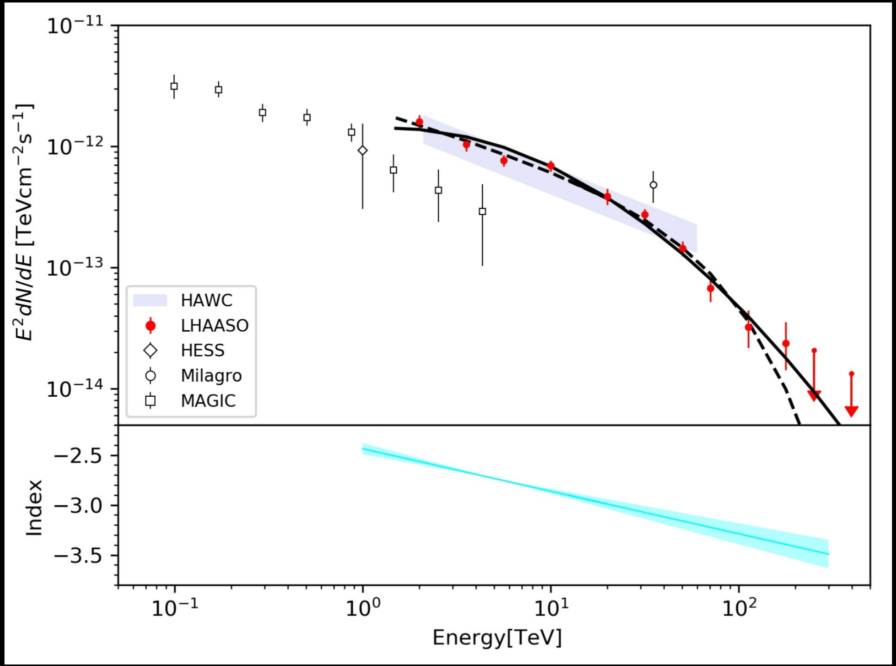


TS maps:
Left: ASTRI and *Right* CTAO South

https://gammapy.org/

W51 LHAASO Spectrum

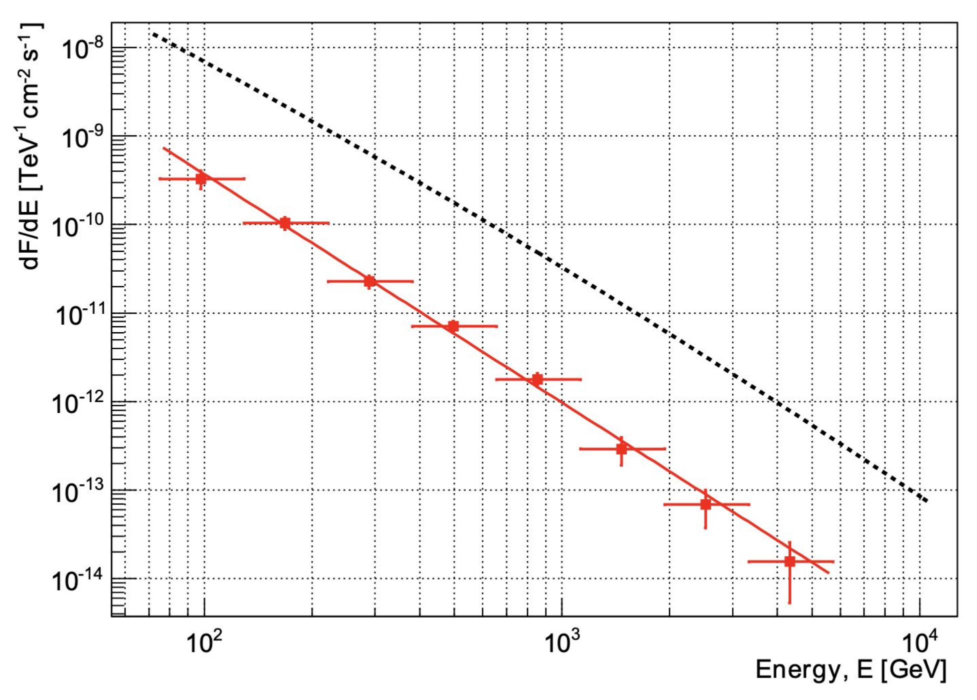




Spectral model - *Exponential cutoff power law by LHAASO*

Amplitude=1.30 x10^{-15} cm^{-2} s^{-1} TeV^{-1} ; **index**=2.6 ;
Ecut at 75 TeV ; **reference**=20 TeV

W51: MAGIC



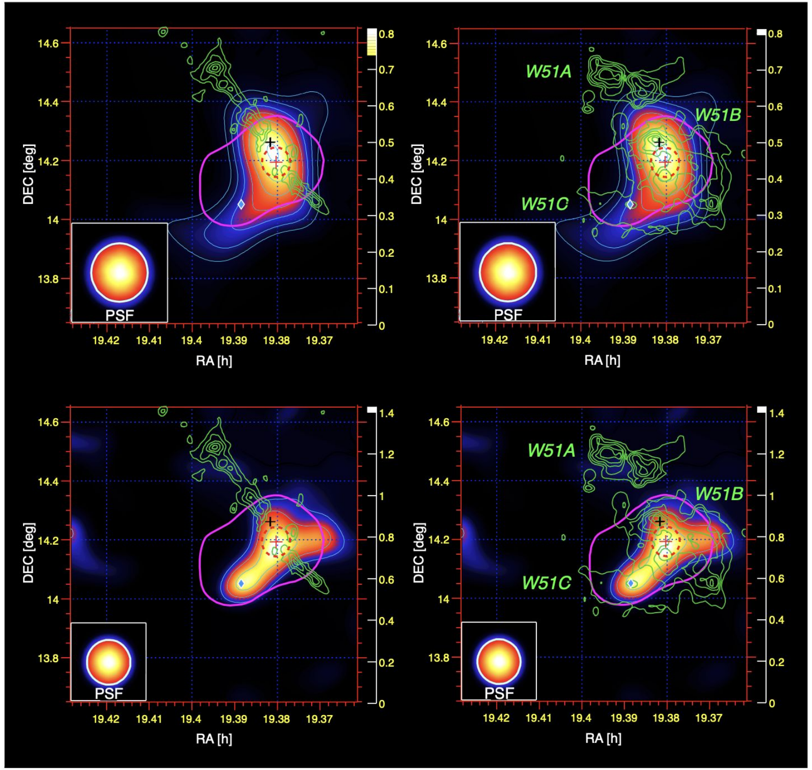
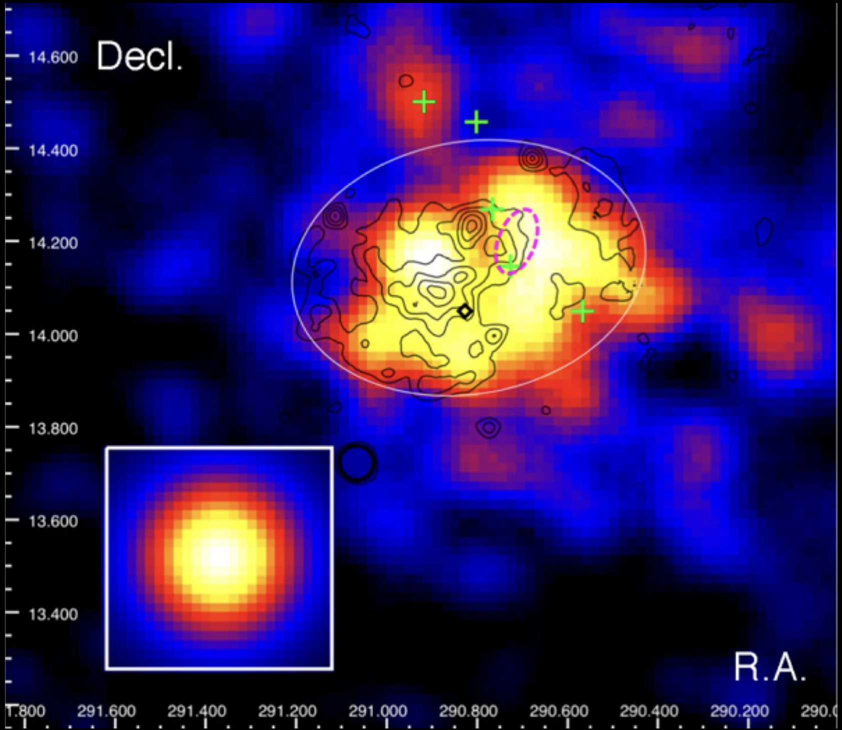


Fig. 4. Relative flux maps: from 300 GeV to 1000 GeV (*top*) and >1000 GeV (*bottom*). On the *left* hand side the MAGIC data are combined with the ^{13}CO (J = 1–0) intensity maps from the Galactic Ring Survey (see `http://www.bu.edu/galacticring/new_index.html`) integrated between 63 and 72 km s^{-1} shown as green countours. On the *right* hand side the green contours represent the 21 cm radio continuum emission is shown from (Koo & Moon 1997a). In all maps the blue diamond represents the position of CXO J192318.5+140305 and the black cross the position of the OH maser emission (Koo et al. 2005; Green et al. 1997). The red dashed ellipse represents the region of shocked atomic and molecular gas (Koo & Moon 1997b,a). The 3 counts contour above 1 GeV determined by *Fermi*/LAT is displayed by the pink contour. In each picture the Gaussian sigma of a point-like source (PSF) after the applied smearing is shown. The color scale (blue to red) represents the relative flux as measured with MAGIC. In addition the TS contours (cyan) are shown starting at 3 and increasing by one per contour.

Credits: J Aleksic et al for MAGIC (2012)

W51: FERMI-LAT



- Outer boundary of W51C is indicated in a white ellipse.
- The contours are ROSAT x-ray map from Koo et al 2009.
- The dashed magenta ellipse is the region where shocked CO clumps where found.
- Diamond near the SNR centroid is the Pulsar.
- Green crosses are the HII region positions [Carpenter & Sanders 1998]

W51: XMM- NEWTON

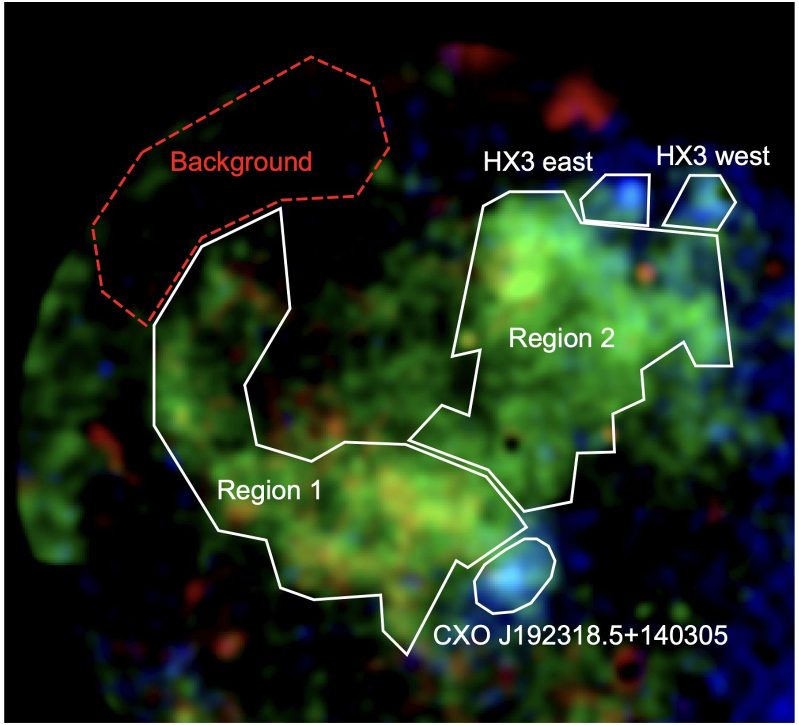


Fig. 2. Three-colour image of the mosaic images (red: 0.3–1.0 keV, green: 1.0–2.0 keV, blue: 2.0–8.0 keV). Extraction regions used for the spectral analysis are shown. Point sources are removed.

Credits: Sasaki et al 2014