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INAF ISTITUTO NAZIONALE DI ASTROFISICA

Extended PeVatron candidates with ASTRI Mini-Array and CTAO

Alan Sunny and Martina Cardillo

(IAPS-INAF, Rome)

with the CTAO and ASTRI Mini-Array collaborations

ASTRI CTAO Cherenkov Telescope Array Observatory TOR VERGATA UNIVERSITÀ DEGLI STUDI DI ROMA

From 9 to 40: the SST Telescopes and Gamma-ray science with ASTRI and CTAO

Picture Credits: NASA/JPL-Caltech The W51 Complex

Science Case

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

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

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)

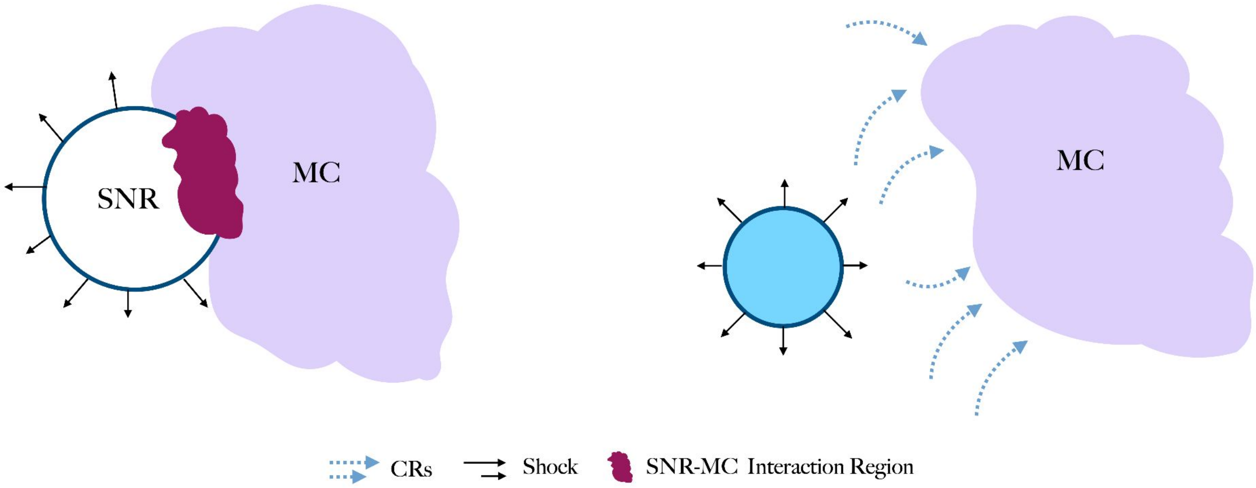
Role of interaction with surrounding medium!

MICROQUASARS (MQ)

YOUNG STAR CLUSTERS (YSC)

UNIDENTIFIED SOURCES

Types of interactions



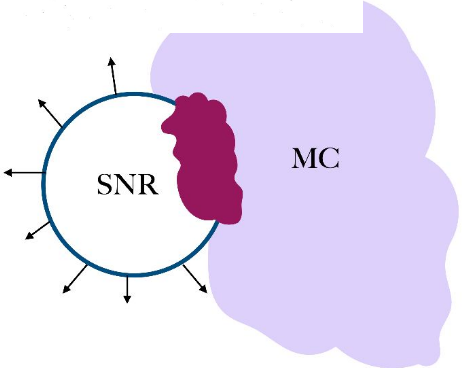
Types of interactions

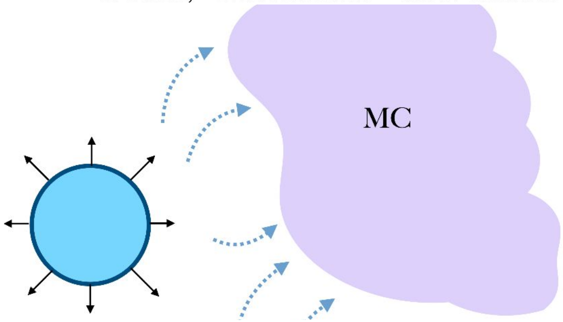
On the emissivity of π^0-decay gamma radiation in the vicinity of accelerators of galactic cosmic rays

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

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

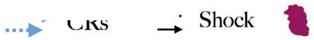
S. Gabici,[1★] F. A. Aharonian[1,2] and S. Casanova[2]





Supernova remnant W44: a case of cosmic-ray reacceleration

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



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

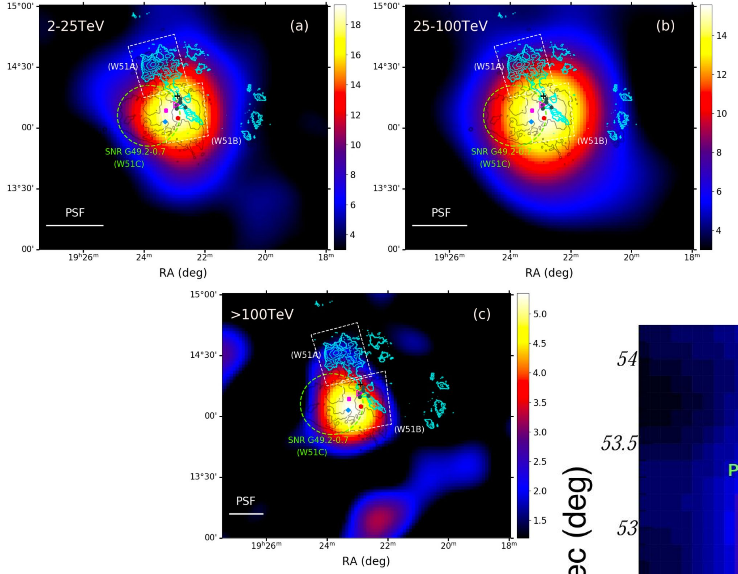
Leandro Abaroa[1,2★], Gustavo E. Romero[1,2], and Valentí Bosch-Ramon[3]

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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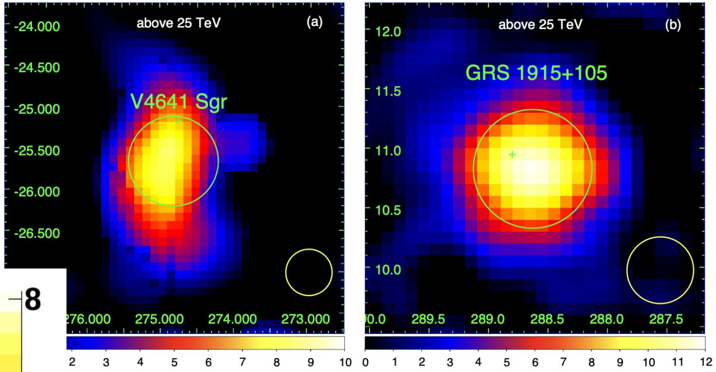
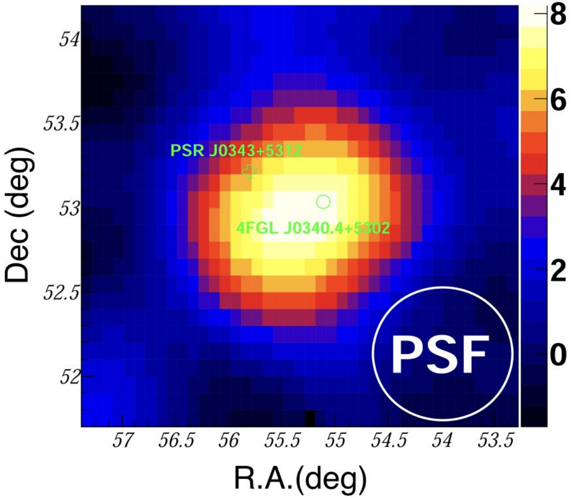




tion.

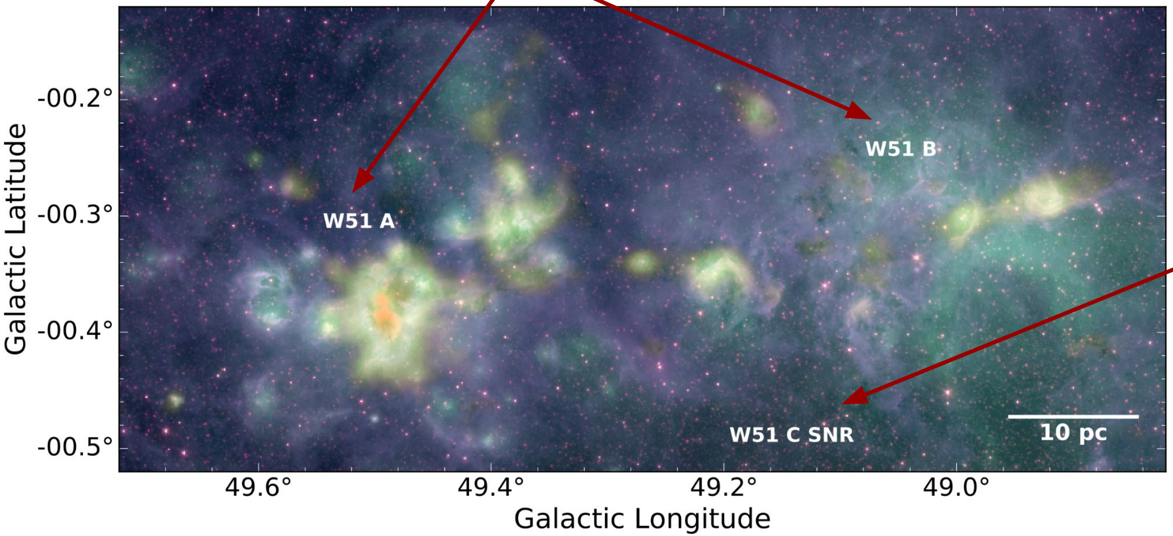
ded region

Story of W51

W51 is a giant complex within a diameter of ~ 100 pc, mass of 10^6 M at a distance of 5.5 kpc.

Two massive clouds

Credits Ginsburg et al 2015a



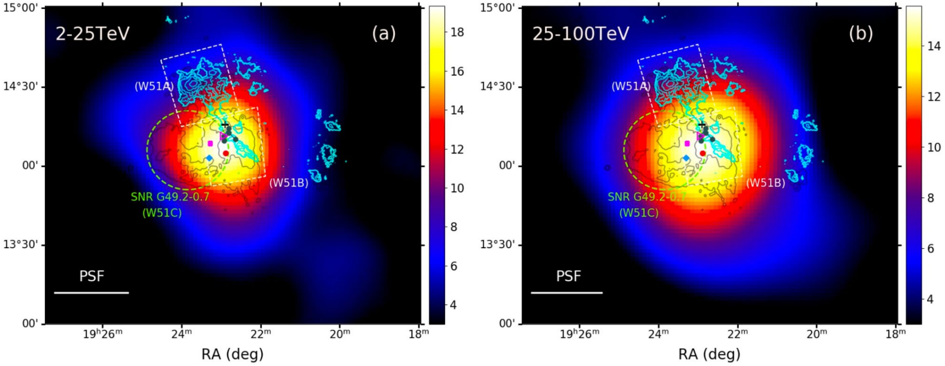
Supernova remnant (SNR), aka G49.2-0.7

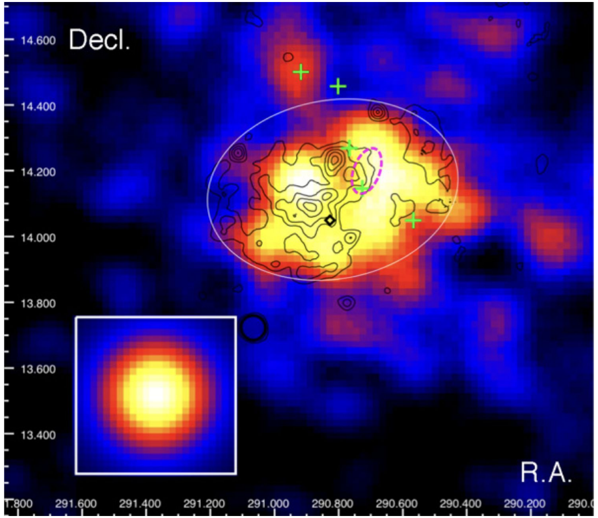
Story of W51

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

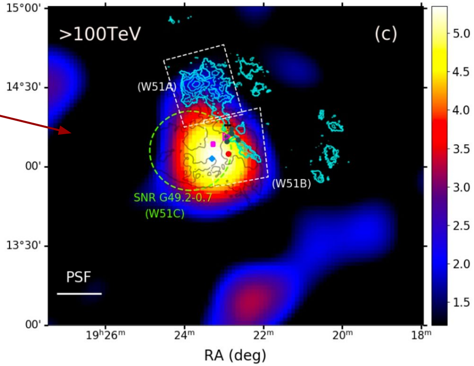
Theoretically an efficient CR accelerator





W51C with Fermi LAT
Credits A A Abdo et al 2009

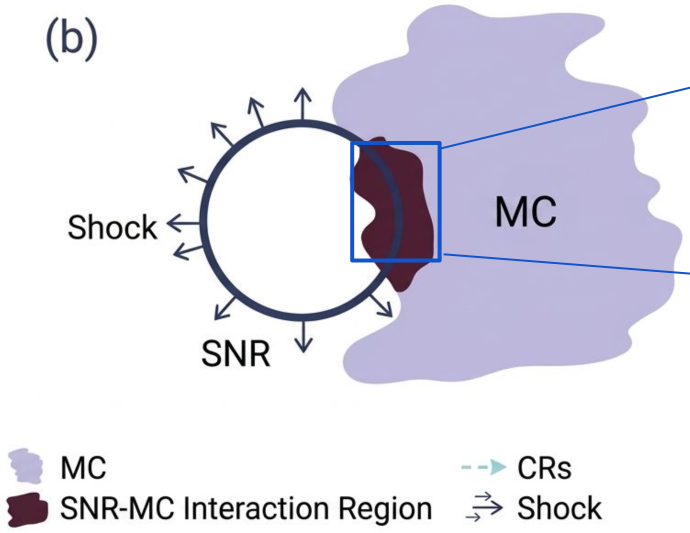
LHAASO reported ≈200 TeV from the Complex



W51 by LHAASO
Credits LHAASO Collab 2025

Direct interaction between W51 C and B

Case of Acceleration

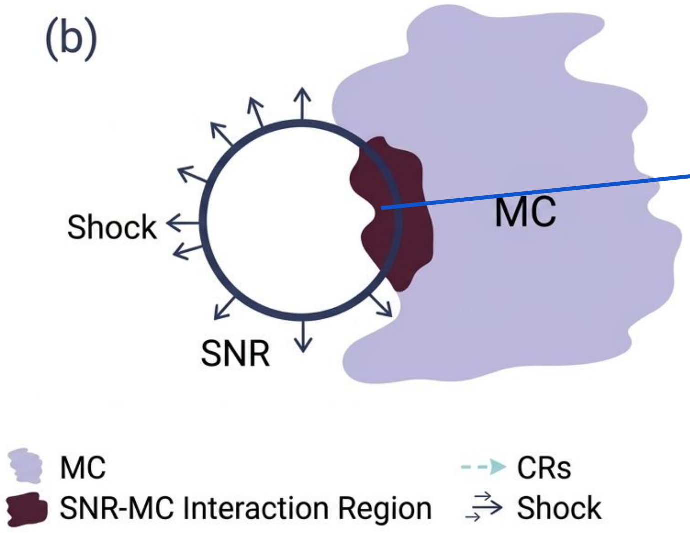


Contribution from fresh acceleration of particles at the shock.

Sunny and Cardillo in review with A&A

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.

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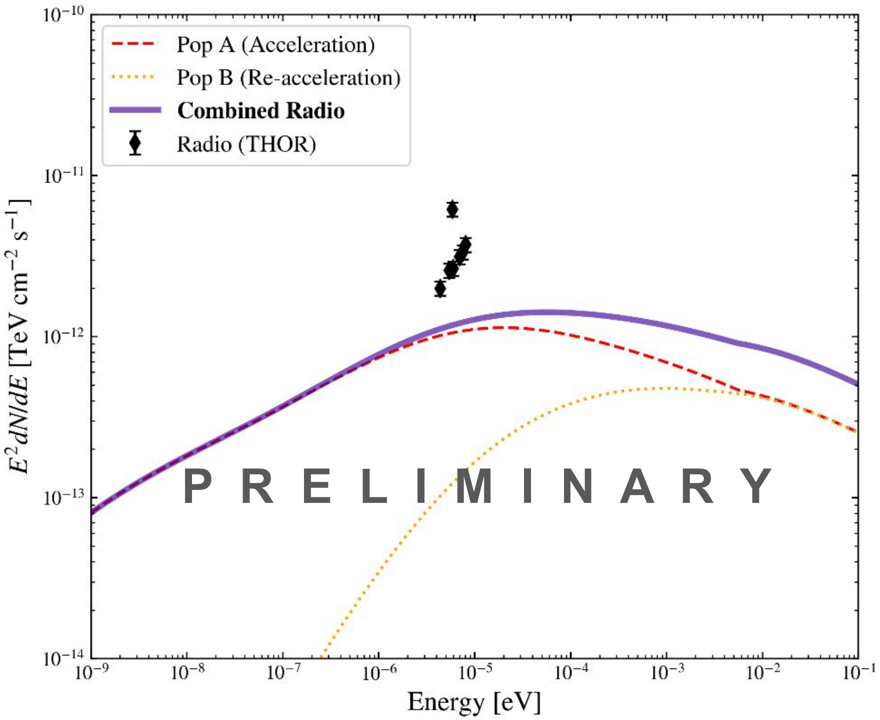
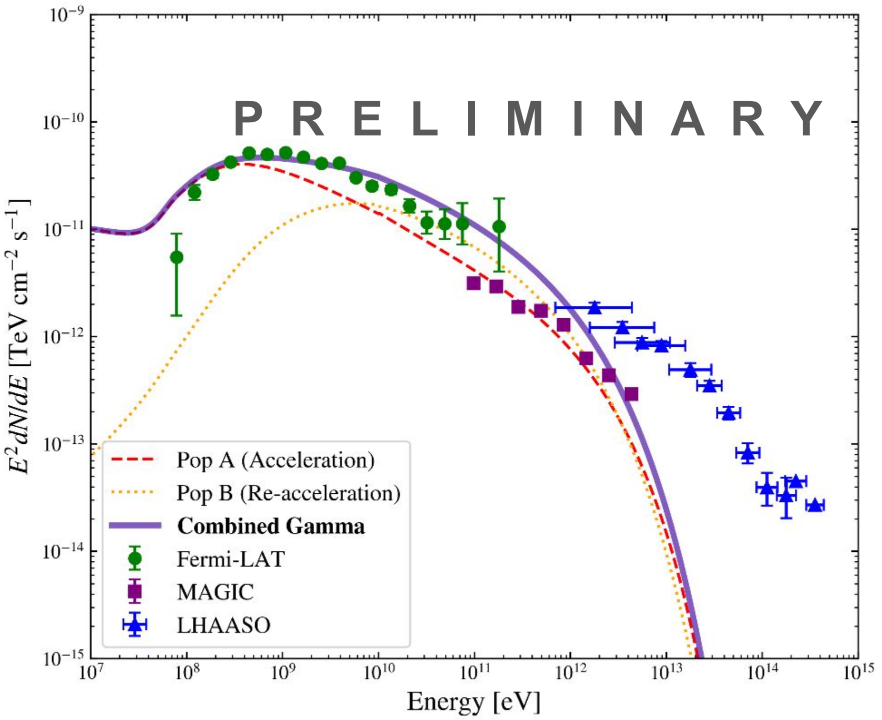
Direct interaction between W51 C and B





Pion-decay dominant scenarios

Model based on Cardillo et al 2016

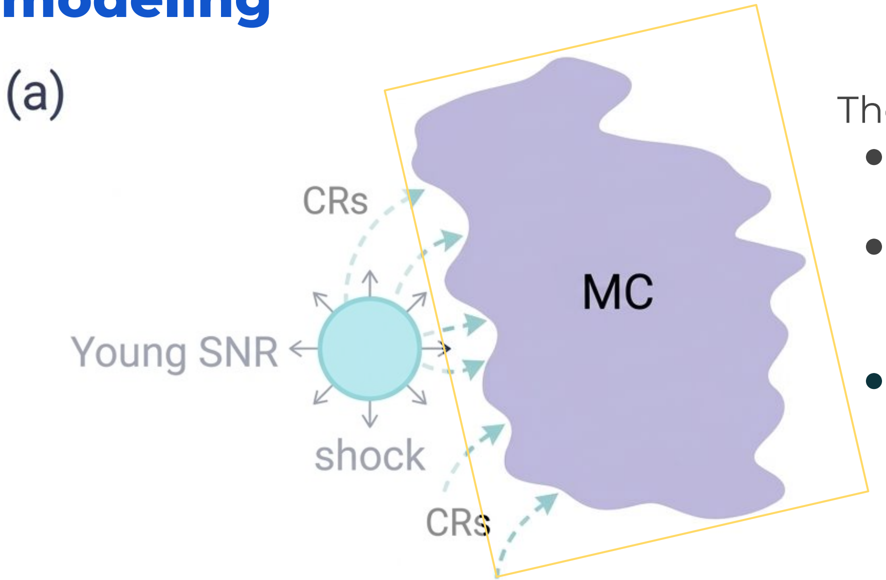
Sunny and Cardillo in review with A&A

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 in review with A&A

Cosmic ray illumination: accelerator independent modeling

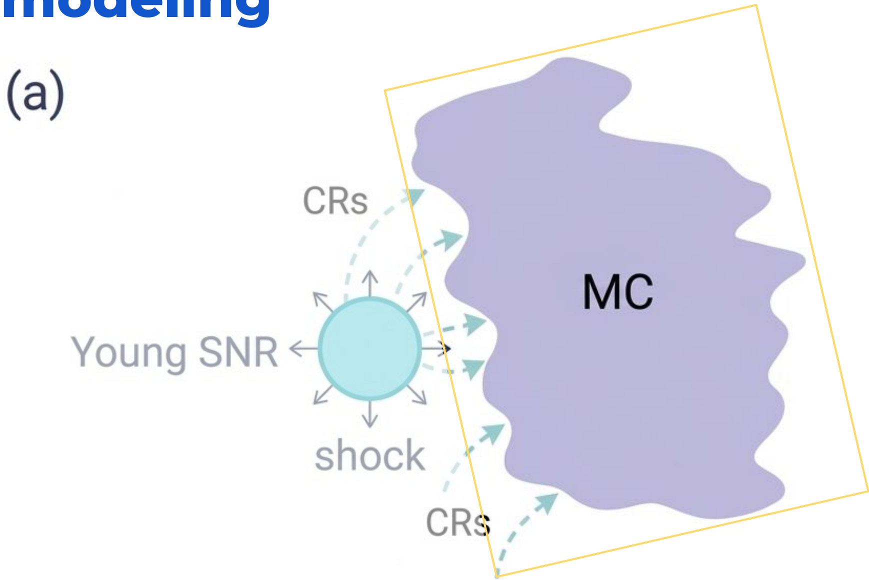


The W51B MC region:

- We know the mass (10^6 solar mass) and assume a uniform spherical 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 in review with A&A

Cosmic ray illumination: accelerator independent modeling



Diffusion coefficient:

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

[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:

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

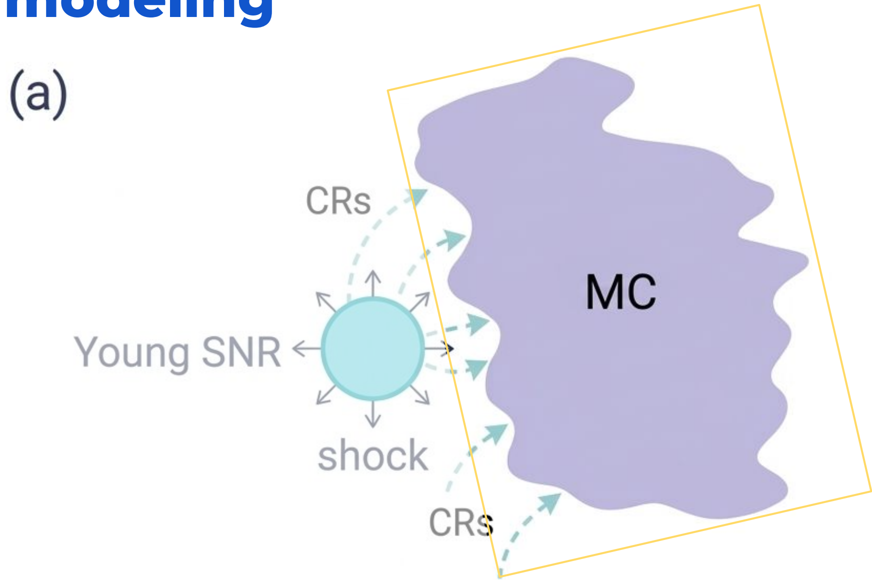
$$t_D = \frac{R^2}{D(E)}, \quad (2)$$

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

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

Sunny and Cardillo in review with A&A

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]

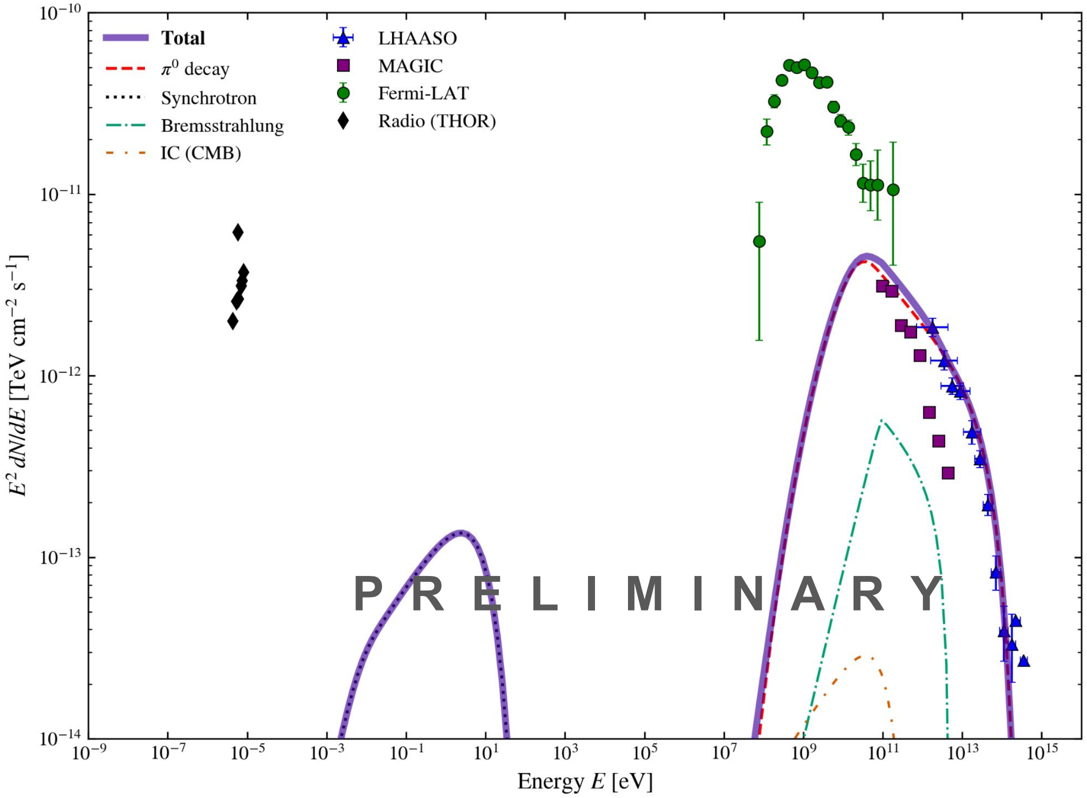
Lepto-hadronic

- $t_{inj} \approx 420$ 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

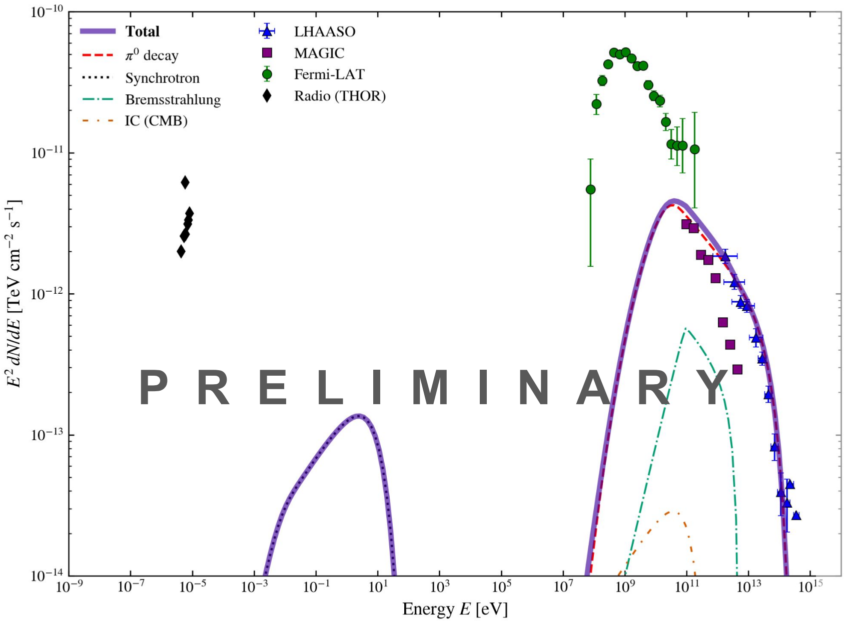
Sunny and Cardillo in review with A&A

Cosmic ray illumination: accelerator independent modeling



Sunny and Cardillo in review with A&A

Cosmic ray illumination: accelerator independent modeling



- Propagation from accelerator to cloud introduces:
  - diffusion effects
  - energy losses
  - environmental uncertainties

  Motivating the source independent treatment
- **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.

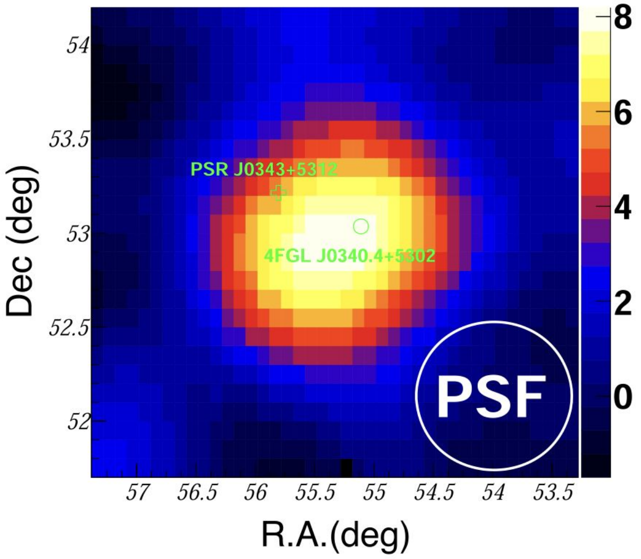
Sunny and Cardillo in review with A&A

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.

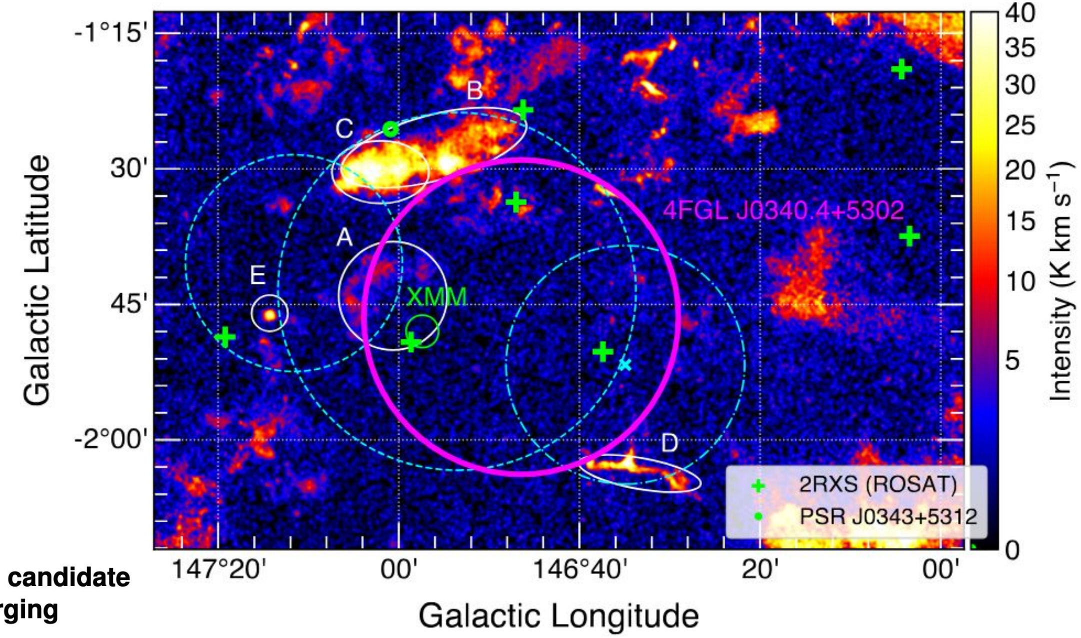
The main idea here will be “passive illumination”, where the accelerator is at an offset away from the cloud.

Passive illumination: LHAASO J0341+5258



Fermi source 4FGL

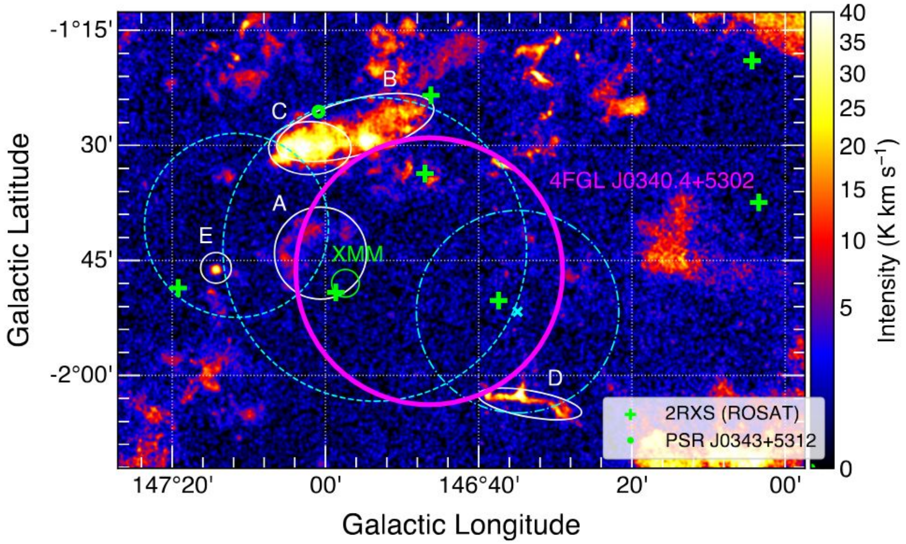
J0340.4+5302



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]

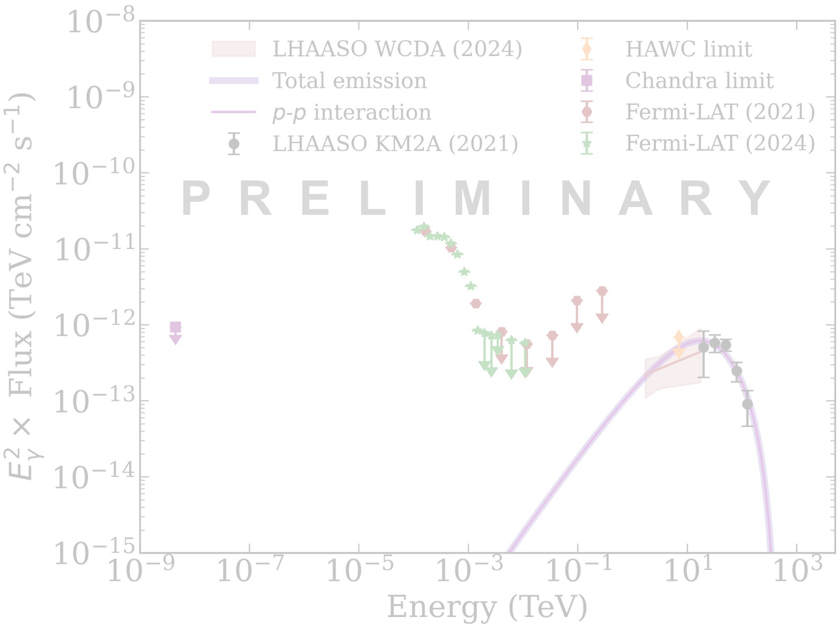
Passive illumination: LHAASO J0341+5258



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 Nobeyama found 5 MCs in the regions (with more in the 1 deg LHAASO region), we consider a uniform cloud, by averaging the properties, that spans the LHAASO extended emission.

Passive illumination: LHAASO J0341+5258



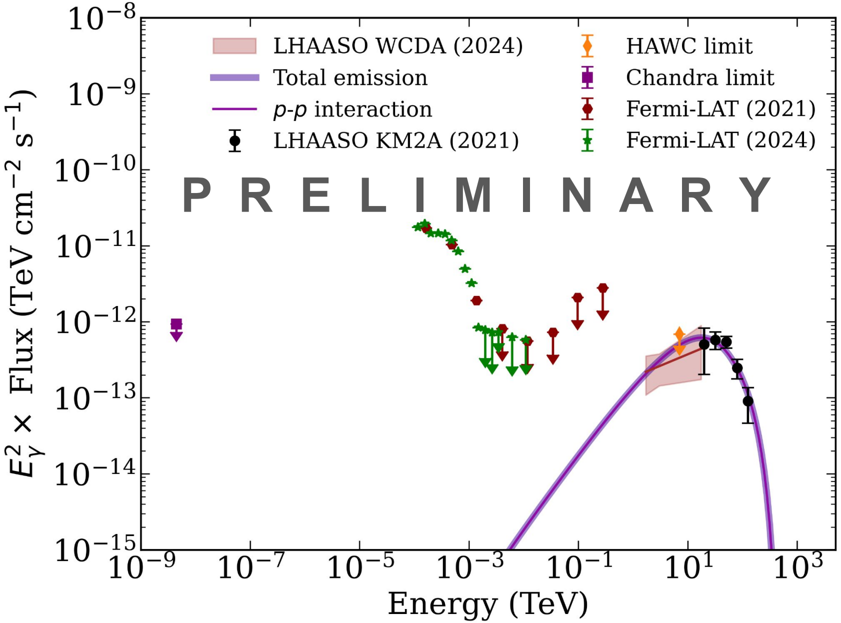
- GAMERA was used to account for the energy losses. But it's standard single-zone implementation does not include a spatially explicit (R-dependent) diffusion. We perform the spatial transport independently within our modeling framework.

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

- We then solve the transport equation with diffusion time scale as defined before.

A. Roy et al 2026

Passive illumination: LHAASO J0341+5258



- Conclusion:

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

We performed a detailed SNR scenario modeling to explain the GeV for this case - A. Roy et al 2026 *(ref: arxiv)*

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

Role of SSTs: ASTRI Mini-Array and CTAO

- Considering the molecular cloud population in our galaxy and the increasing number of unidentified UHE sources next generation IACTs are going to play a crucial role in understanding this scenarios.

- Illumination scenarios are bound to introduce extended emission regions and superior angular resolution and sensitivity will be required to resolve these emission regions.

We were introduced to CTAO and ASTRI Mini-Array yesterday
CTAO: D.Green
ASTRI: G. Tosti, S. Vercellone, C. Quartiroli

Role of SSTs: ASTRI Mini-Array and CTAO

To demonstrate this, we test our physically motivated emission model for W51 Complex:

- GeV component → W51C region
- Extended TeV/UHE component → W51 B molecular-cloud illumination by escaping CRs

ASTRI Mini Array with 9 SSTs **ref for IRFs[https://zenodo.org/records/6827882]**	**CTAO-South with 37 SSTs 14 MSTs** **ref for IRFshttps://zenodo.org/records/6827882**
Total Observation of 300 Hrs	**Total Observation of 200 Hrs**
Offset = 0.6 deg	**Offset = 0.6 deg**

https://gammapy.org/

Role of SSTs: ASTRI Mini-Array and CTAO

Gammapy considers:

Spectral model ➡ defines how the flux depends on energy.

Spatial model ➡ defines how the flux is distributed on the sky

Spatial model

We assume a spatial model, also referring to G Pirola PoS ICRC(2025)806,

Direct interaction → Gaussian distribution at 290.899, 14.085; Illumination → Disk distribution at 290.691, 14.216

Spectral model

We use the spectral model based on the simulation fit showed before

https://gammapy.org/

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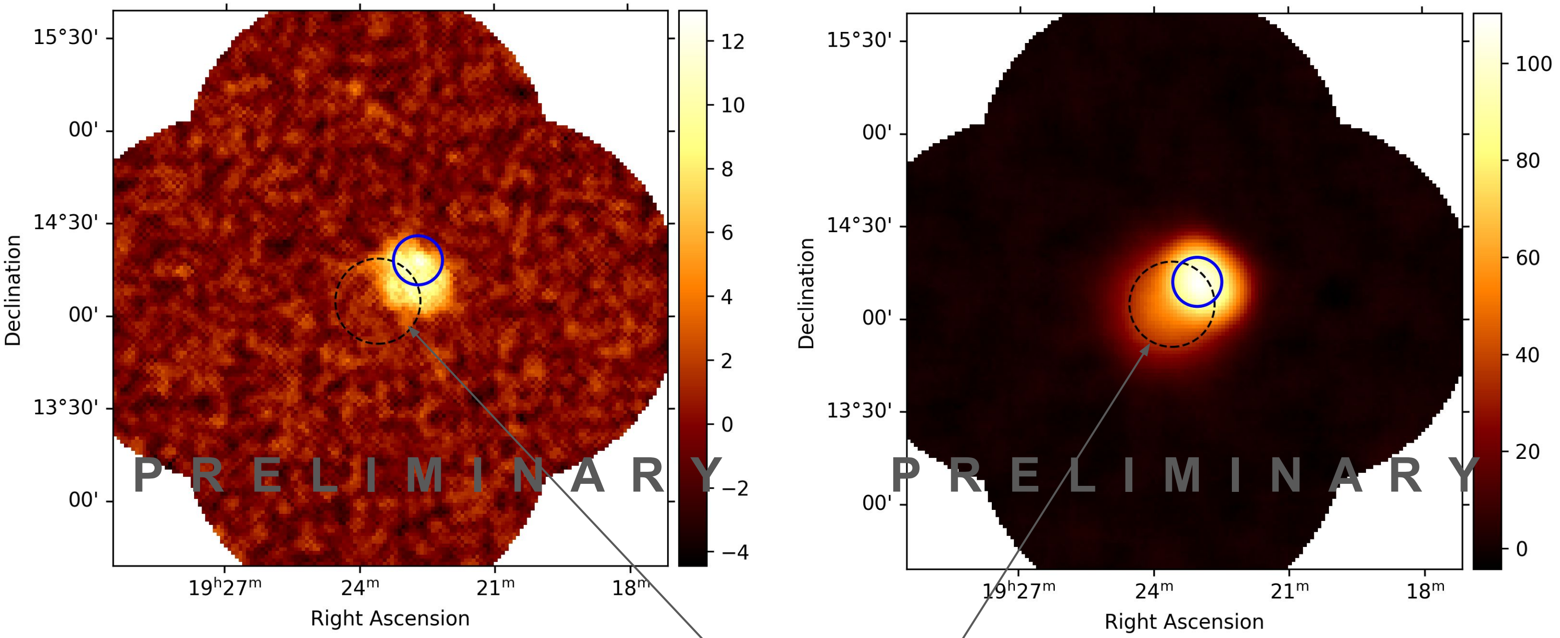


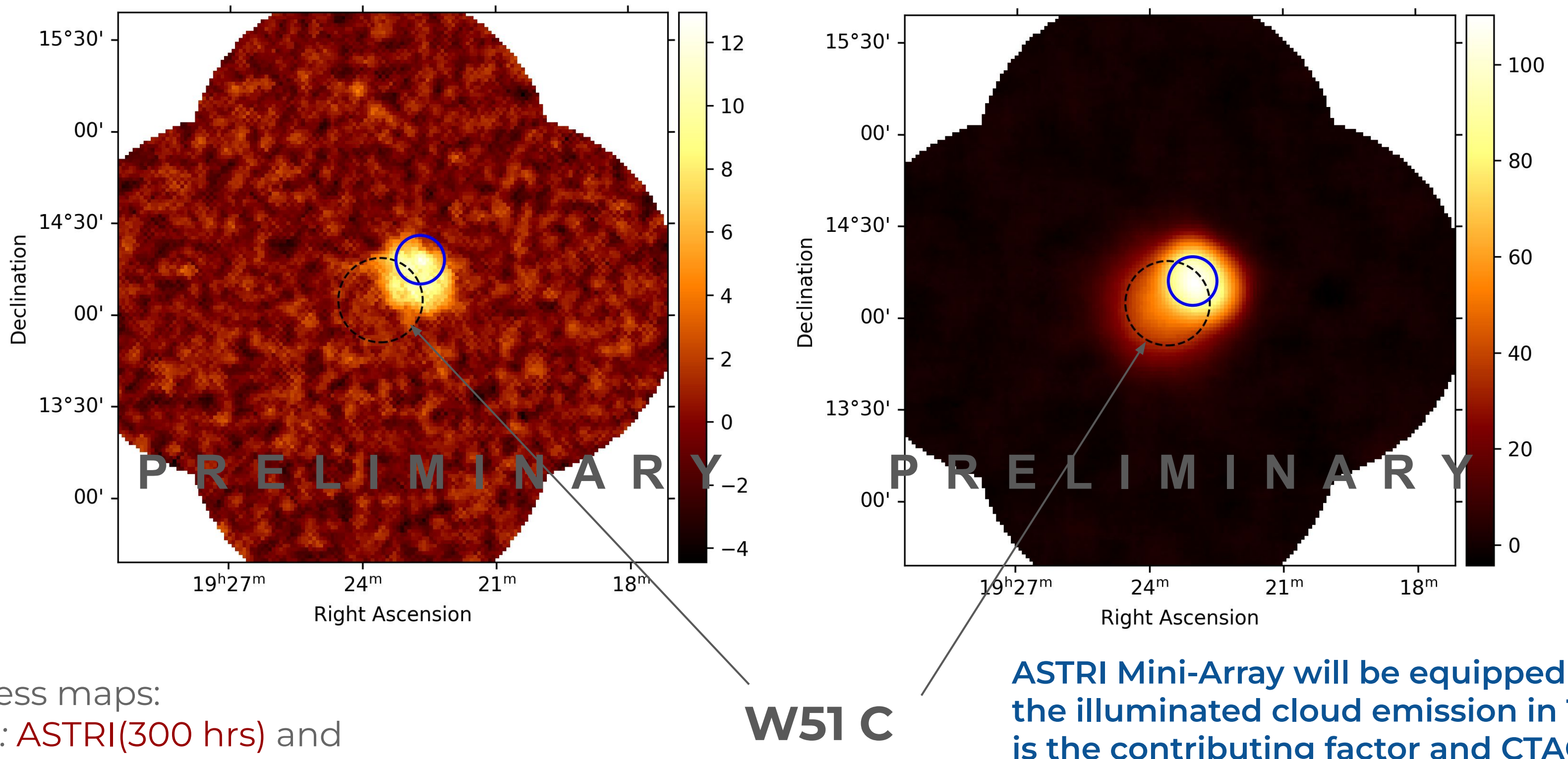
W51 C

The blue circle shows the 4 sigma significance peak found using find_peaks. Note that these are simulated observations with assumed morphological models.

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

https://gammapy.org/

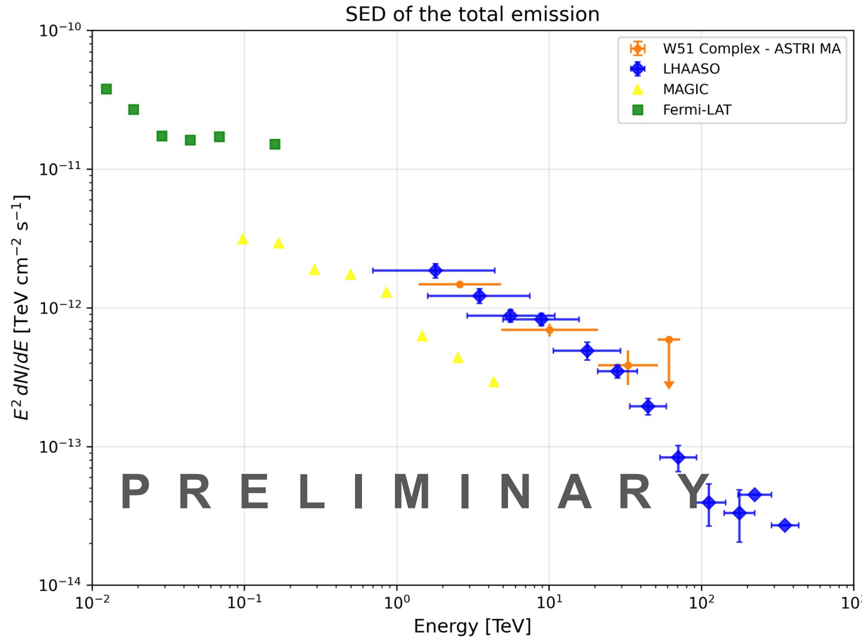
Role of SSTs: ASTRI Mini-Array and CTAO

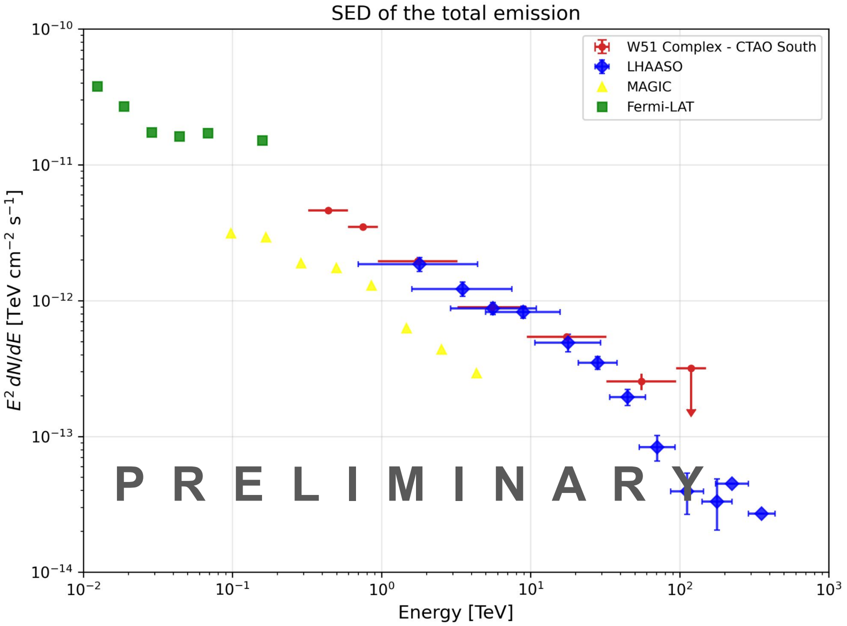


Excess maps:
Left: ASTRI(300 hrs) and
Right CTAO South (200 hrs)

ASTRI Mini-Array will be equipped to isolate the illuminated cloud emission in TeVs if that is the contributing factor and CTAO-South will help in disentangling each contribution.

Role of SSTs: ASTRI Mini-Array and CTAO

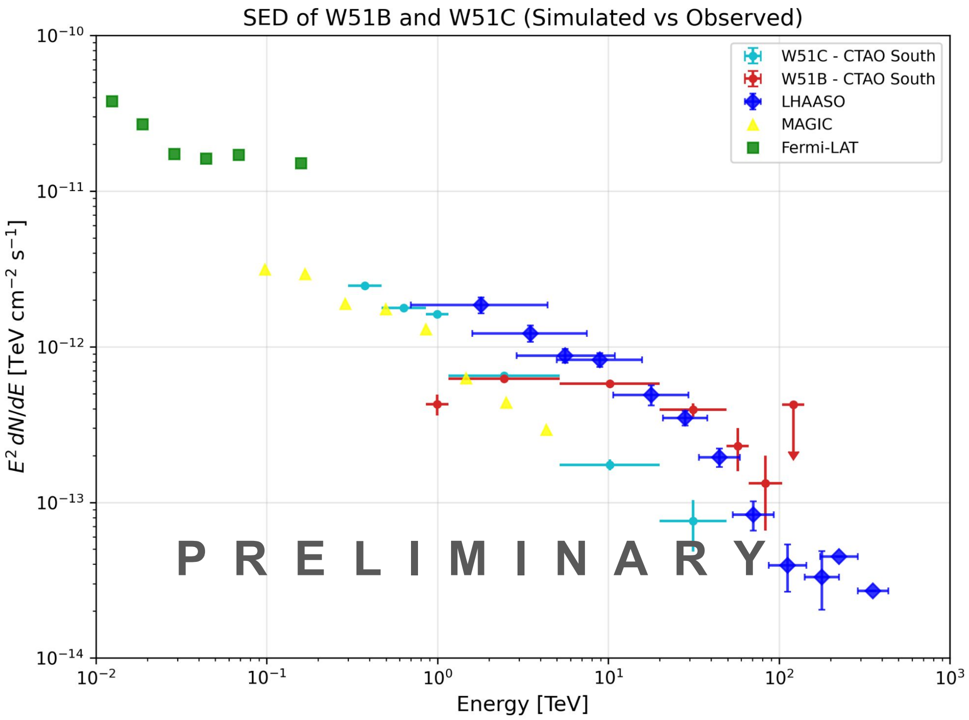




SED:
Left: ASTRI(300 hrs) and
Right CTAO South (200 hrs)

https://gammapy.org/

Role of SSTs: ASTRI Mini-Array and CTAO



Disentangled SED CTAO South (200 hrs)

https://gammapy.org/

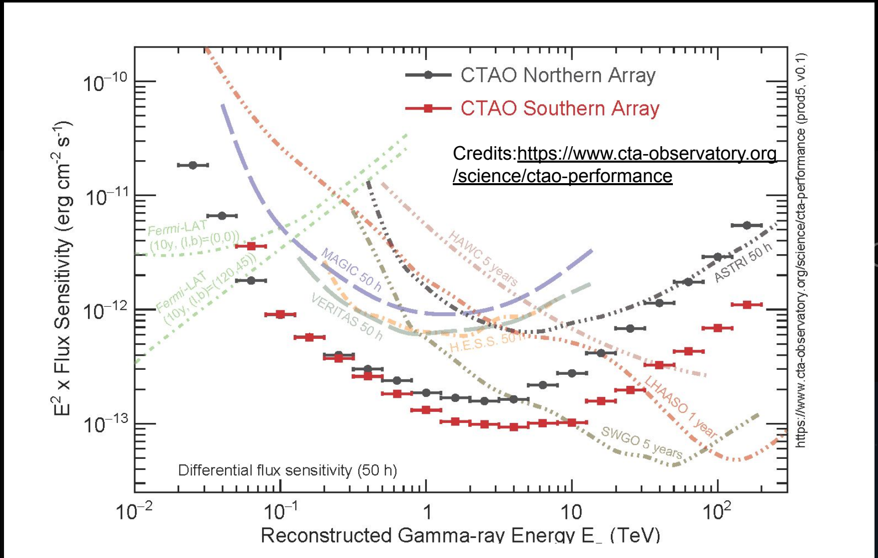
Takeaway points

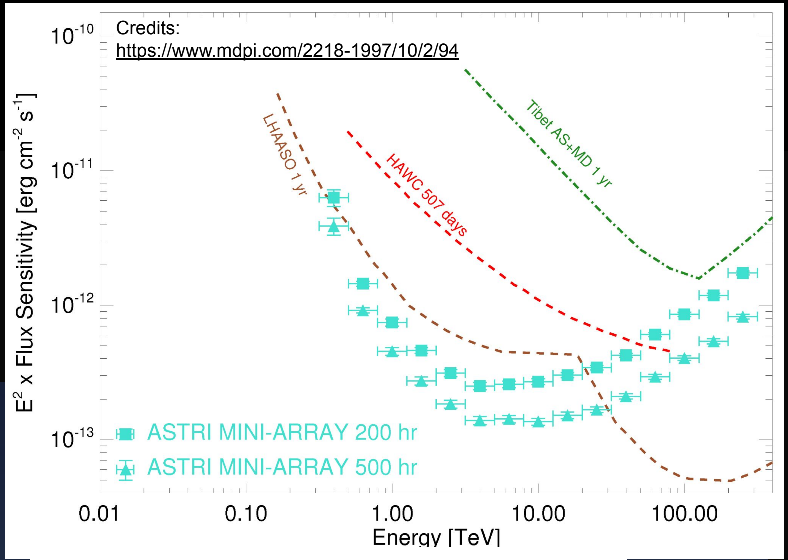
Dense molecular clouds may act as long-term cosmic-ray reservoirs, preserving historic PeVatron activity long after the accelerator's most powerful phase has ended.

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.

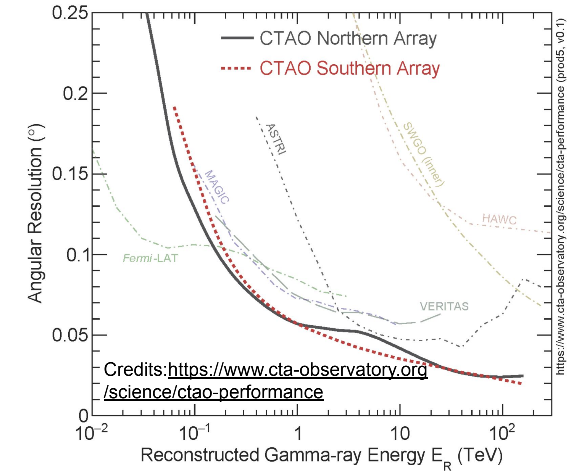
BONUS SLIDES



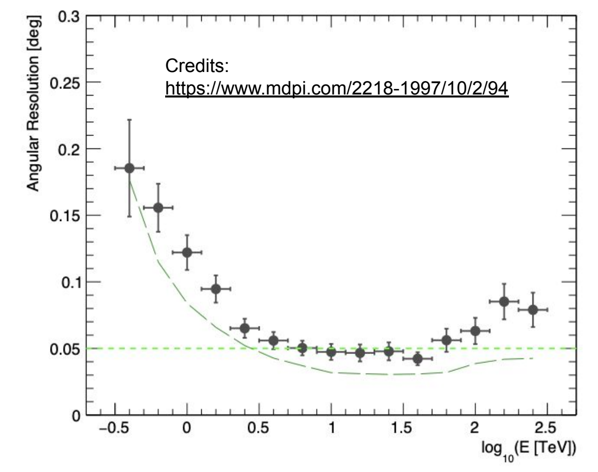


0 GeV

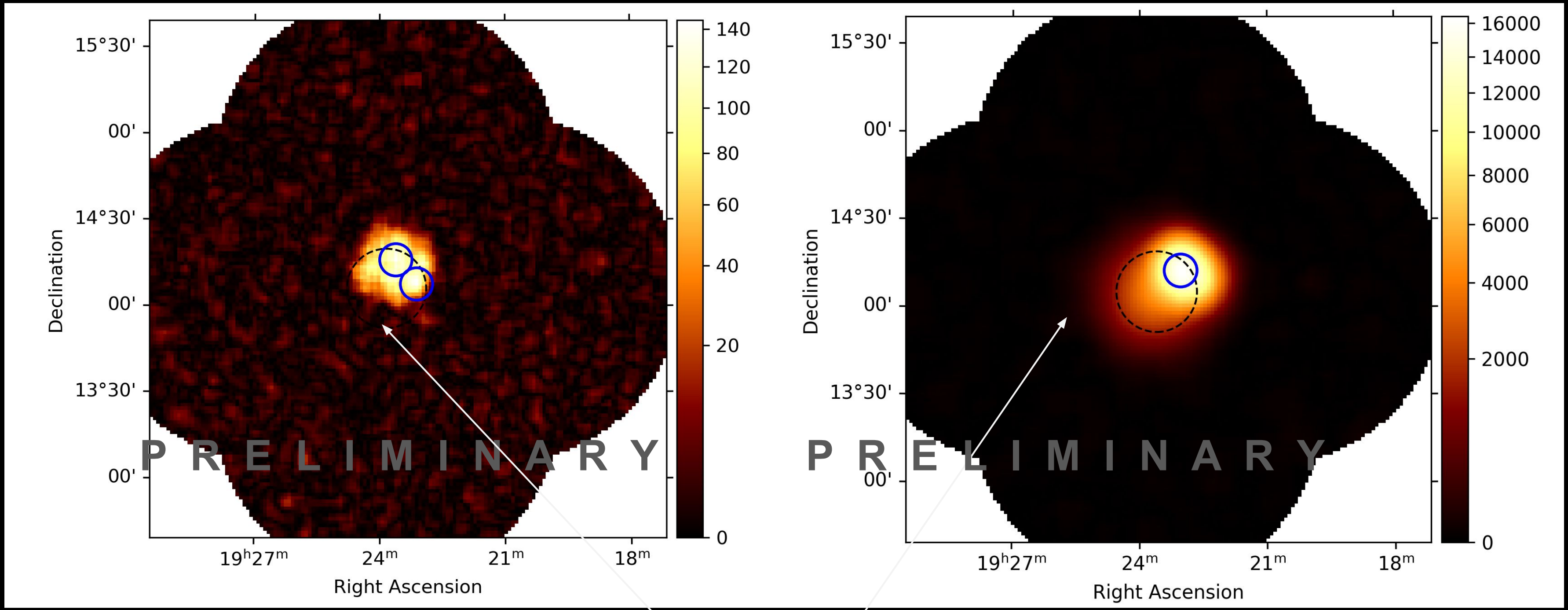
CTAO Telescopes (Cre



ASTRI-



Role of SSTs: TS Maps

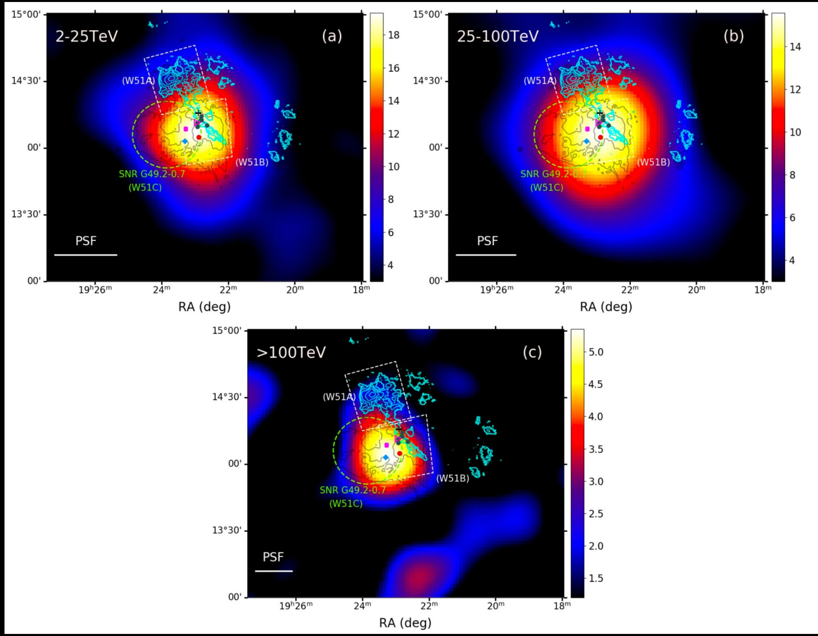


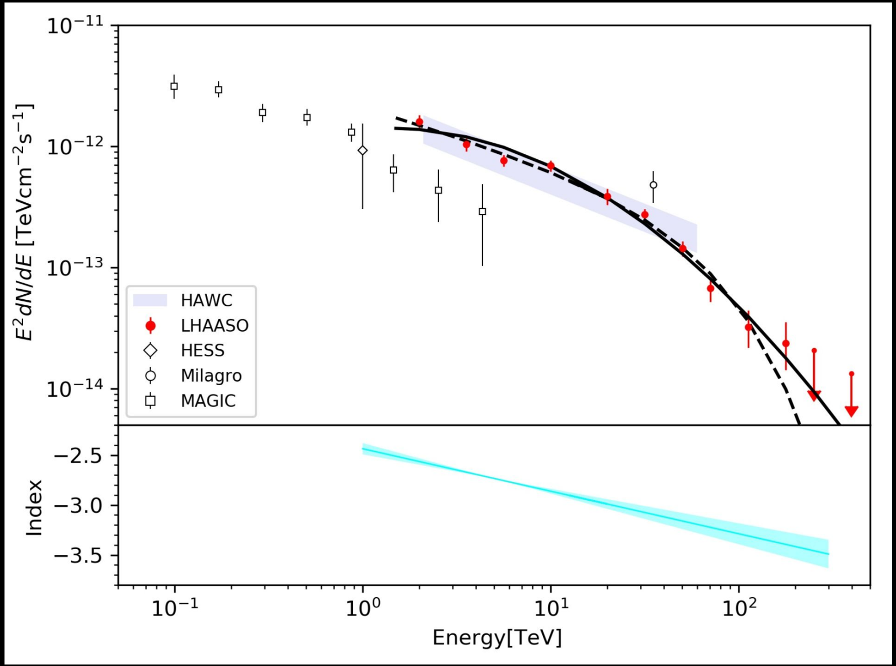
W51 C

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

https://gammapy.org/

W51 LHAASO Spectrum

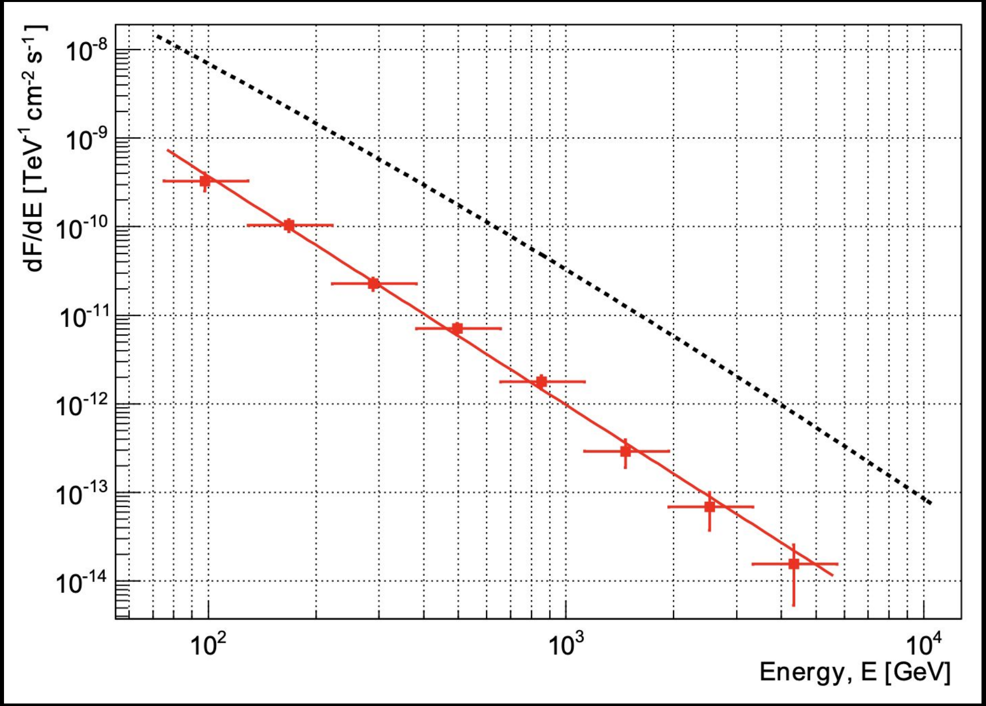




Spectral model - ***Exponential cutoff power law by LHAASO***

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

W51: MAGIC



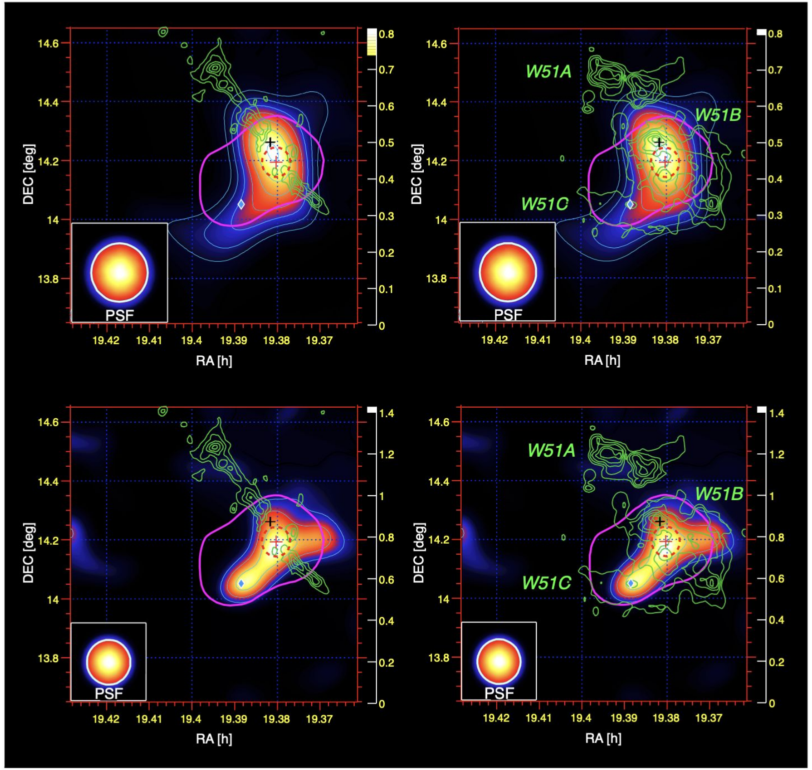
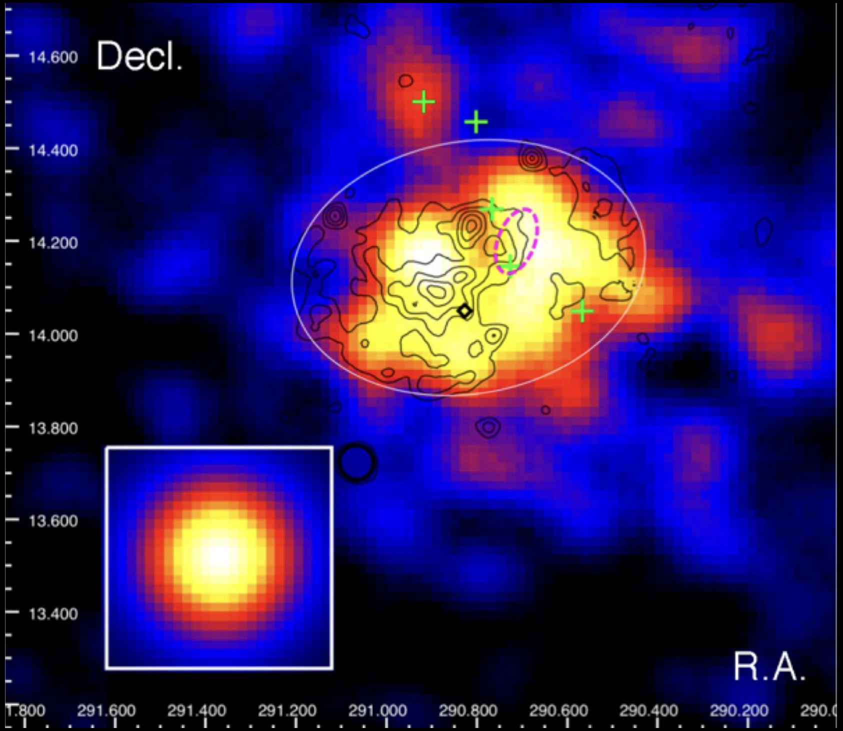


Fig. 4. Relative flux maps: from 300 GeV to 1000 GeV (*top*) and >1000 GeV (*bottom*). On the *left* hand side the MAGIC data are combined with the ^{13}CO (J = 1–0) intensity maps from the Galactic Ring Survey (see `http://www.bu.edu/galacticring/new_index.html`) integrated between 63 and 72 km s^{-1} 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

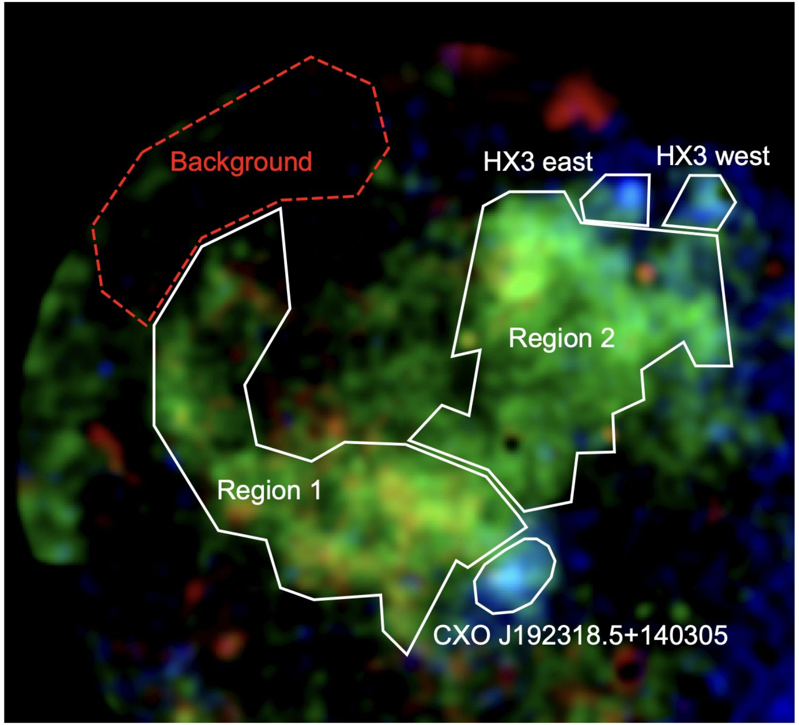


Fig. 2. Three-colour image of the mosaic images (red: 0.3–1.0 keV, green: 1.0–2.0 keV, blue: 2.0–8.0 keV). Extraction regions used for the spectral analysis are shown. Point sources are removed.

Credits: Sasaki et al 2014