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INAF ISTITUTO NAZIONALE DI ASTROFISICA

Exploring PeVatrons with associated molecular clouds in the era of CTAO and ASTRI Mini-Array

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with Martina Cardillo (IAPS-INAF), Antonio Tutone (IASF-INAF)

ASTRI

CTAO Cherenkov Telescope Array Observatory

TOR VERGATA UNIVERSITÀ DEGLI STUDI DI ROMA

TeV Particle Astrophysics 2025, Valencia, Spain

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

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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 ≳ 100 TeV gamma ray detection from a range of sources including SNRs, PWNe, MQs, and also unidentified sources.

Picture Credits: NASA/JPL-Caltech The W51 Complex

SCIENCE CASE

SUPERNOVA REMNANT (SNR)

PULSAR WIND NEBULAE (PWNe)

MICROQUASARS (MQ)

YOUNG STAR CLUSTERS (YSC)

?

SCIENCE CASE

SUPERNOVA REMNANT (SNR)

PULSAR WIND NEBULAE (PWNe)

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YOUNG STAR CLUSTERS (YSC)

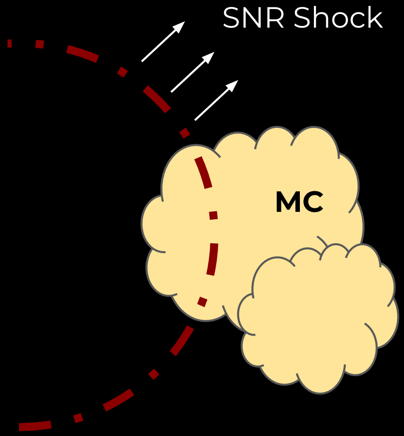
AMBIENT MEDIUM : Molecular Clouds / Atomic Gas

?

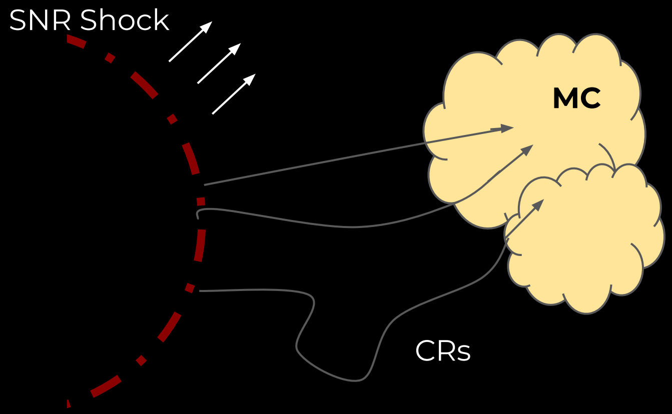
HOW DO THEY INTERACT?

SNRs and molecular clouds (MCs):

Scenario 1



Scenario 2



HOW DO THEY INTERACT?

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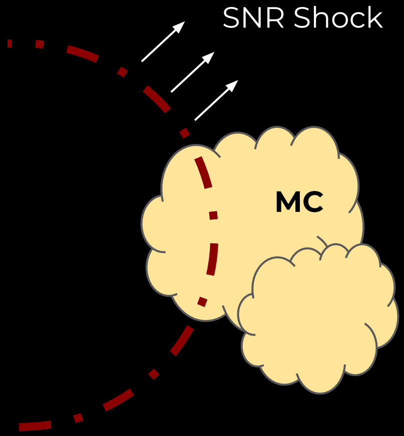
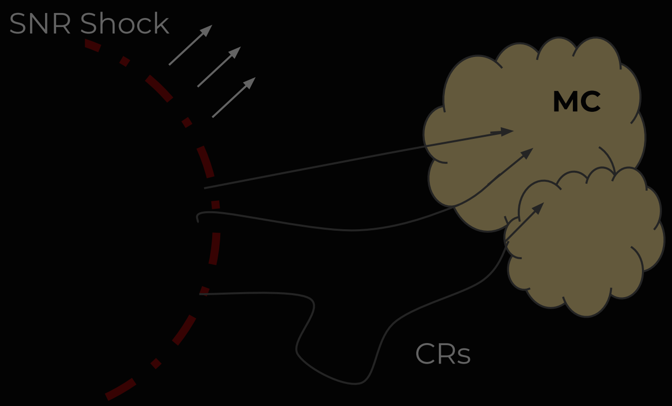


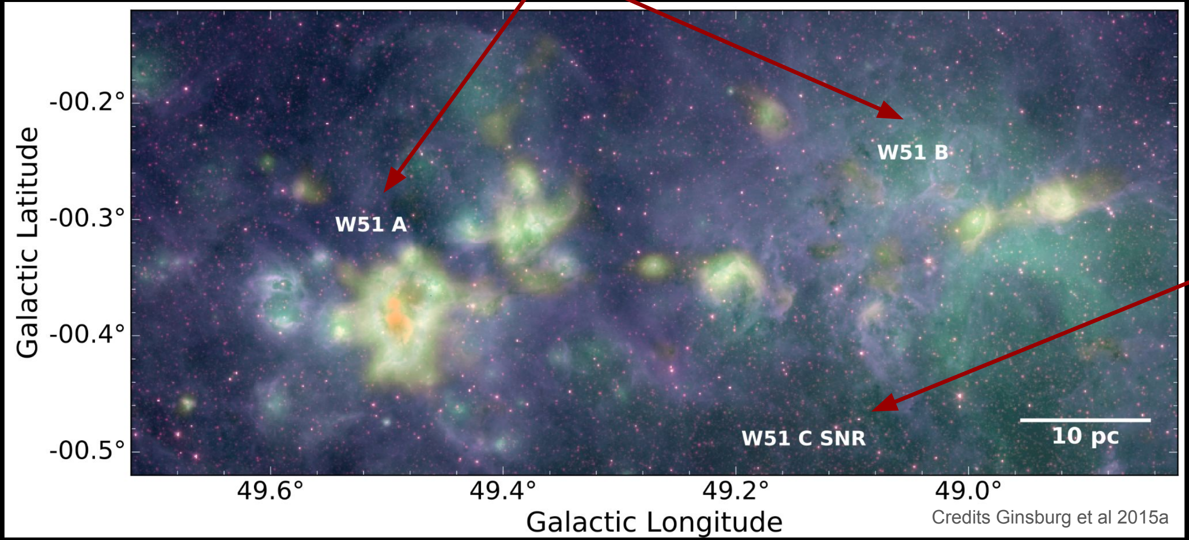
Scenario 2



TEST SOURCE : THE W51 COMPLEX

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



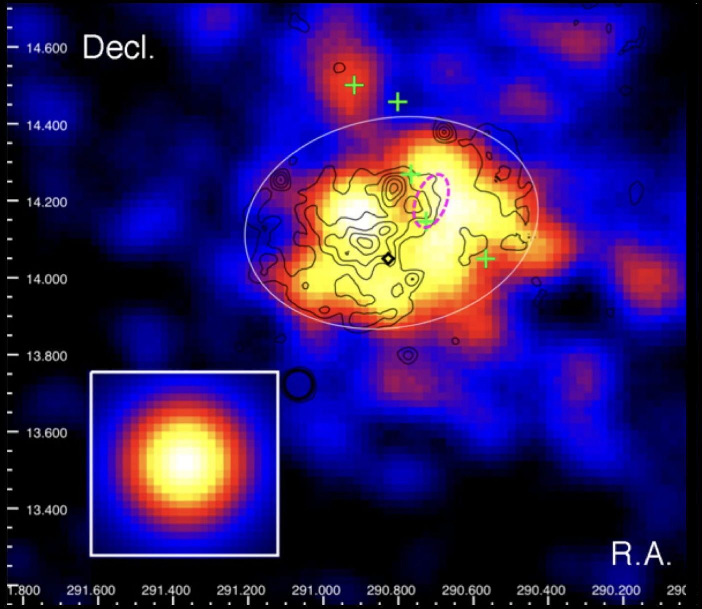
Supernova remnant (SNR), aka G49.2-0.7

TEST SOURCE : THE SNR W51C

W51C appears in radio as a shell type SNR:

- Middle aged: t ~ 30 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

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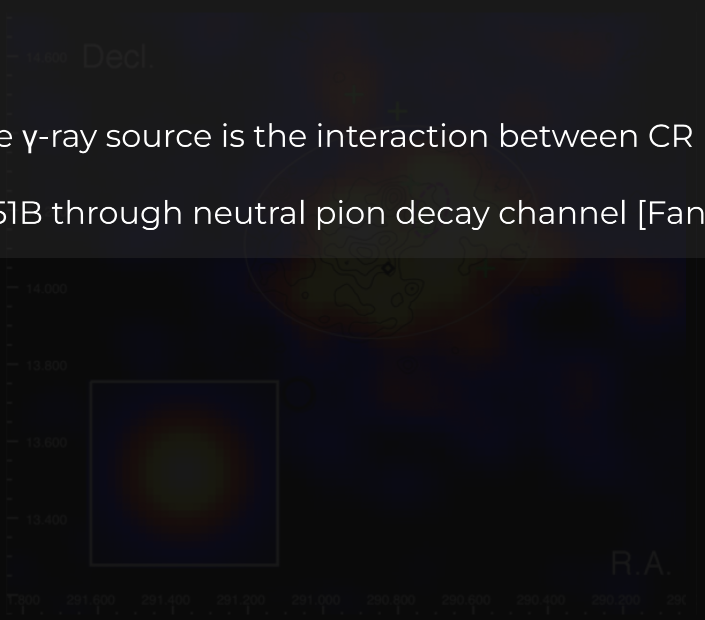
- Indication of a pion bump like feature - hadronic origin of low energy γ-rays [T. Jogler for LAT collaboration 2015].
- Leading hypothesis for the γ-ray source is the interaction between CR nuclei accelerated at the W51C shock and the nearby MCs in W51B through neutral pion decay channel [Fang et al 2010, Aharonian 2000].



W51C with Fermi LAT
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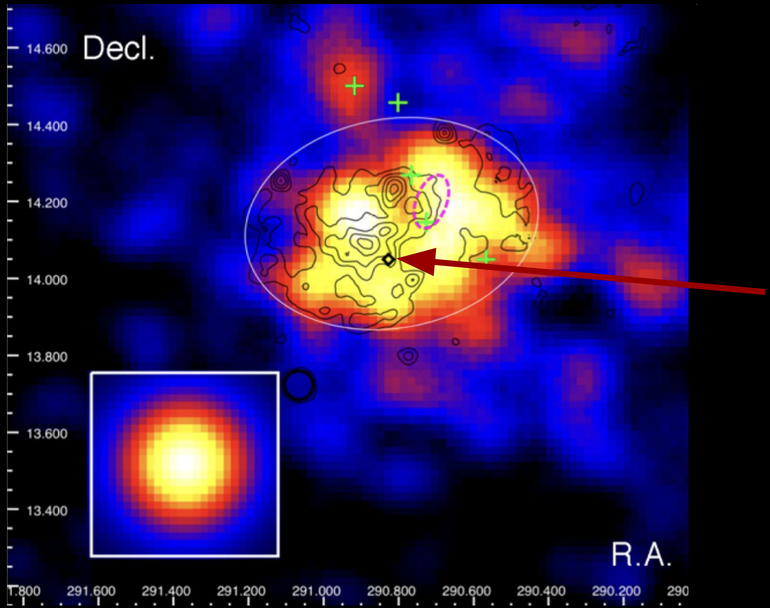
*More information in the bonus slides

W51 C : γ-RAY DETECTION



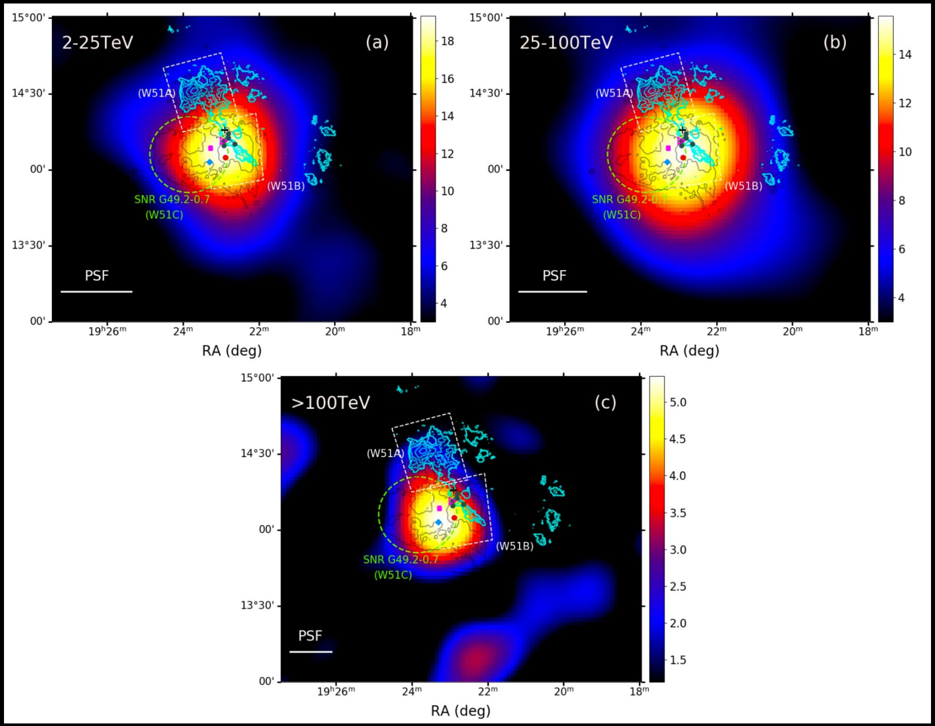
CXO J192318.5+140305

Also additional potential sources could be:

- ➔ Possible PWNe candidate CXO J192318.5+140305 associated to the SNR W51C.
- ➔ W51 complex hosts several young star clusters too.

W51 : LHAASO RESULTS

- (Dec,R.A) = (11 -19, 286.5 - 294.9) deg.
- γ-ray excess : 19.33σ, 15.58σ, 5.35σ across < 25 TeV, 25 - 100 TeV and > 100 TeV respectively.
- Upper limit of ≈ 200 TeV
- Flux measurement below 10 TeV is about 1.8 times higher than that reported by MAGIC.



Gamma ray map 2 TeV to > 100 TeV
Credits: LHAASO Collaboration 2024

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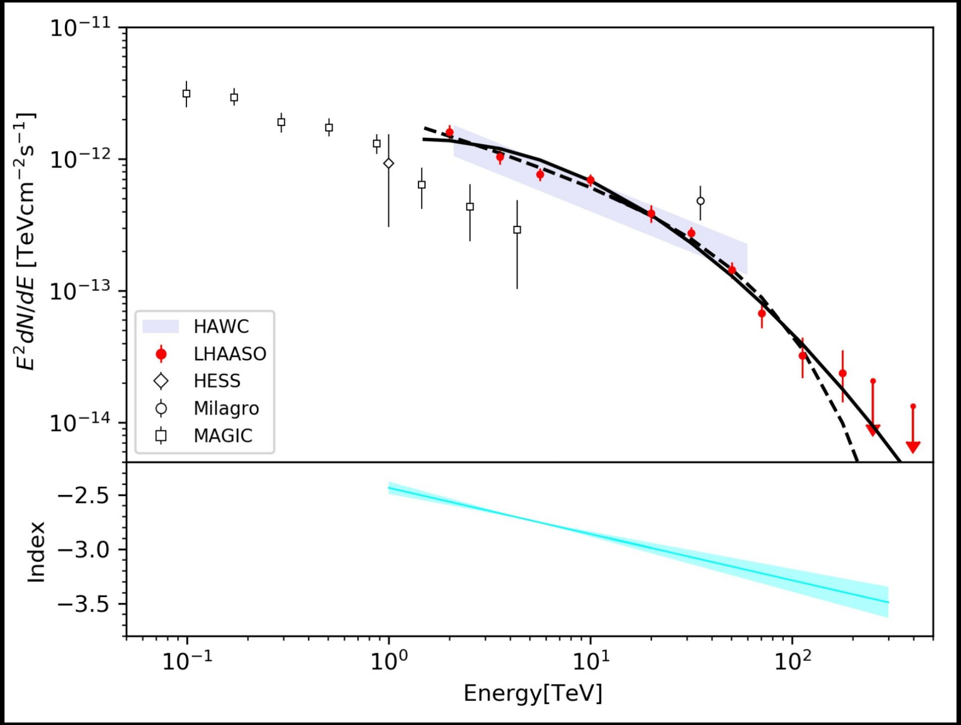

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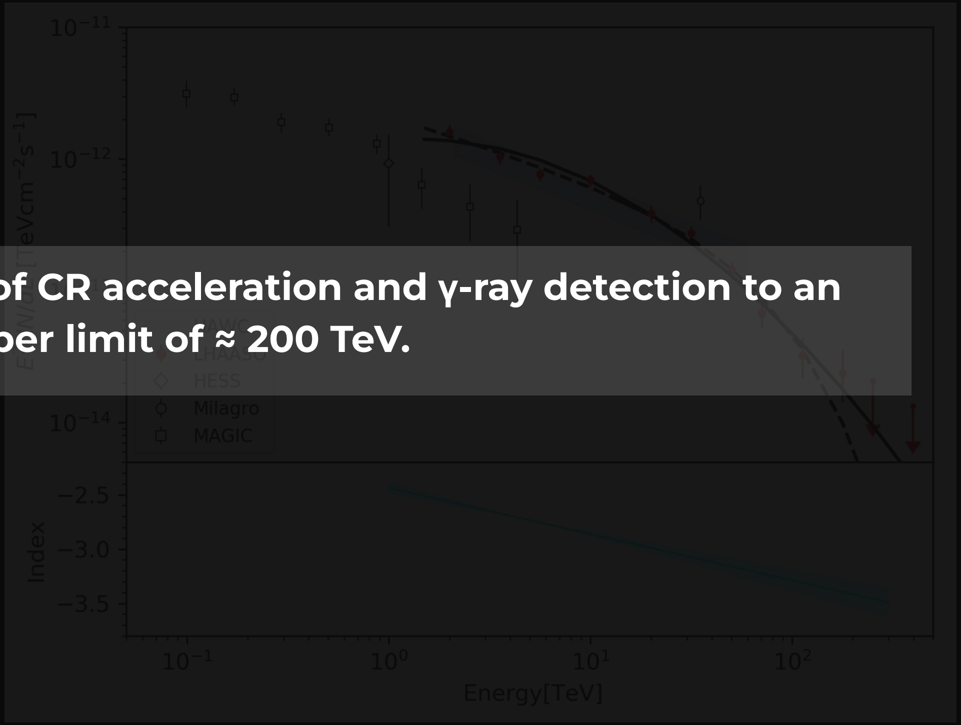

Credits: LHAASO Collaboration 2024

W51 is a unique source, marked by hints of CR acceleration and γ-ray detection to an unprecedented upper limit of ≈ 200 TeV.

TEST SOURCE W51 : AIM

- ➔ Test if the TeV emissions can be solely attributed to the the interaction between the supernova remnant and molecular cloud.
- ➔ In such complex regions extended emissions are inevitable - we test if CTAO and ASTRI Mini-Array can untangle their origins.

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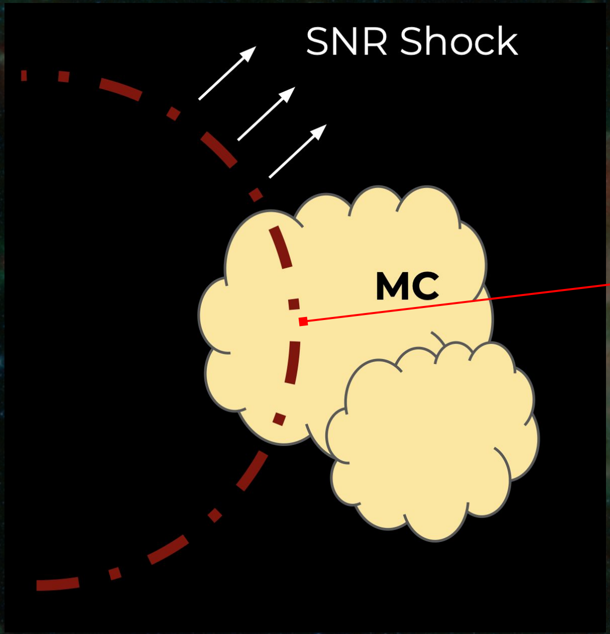
DIRECT INTERACTION : MODEL (Cardillo et al 2016, Cardillo et al 2019)

Case of Acceleration : Contribution from freshly acceleration of particles at the shock.



The shock converts a fraction of its energy into accelerating particles. Shock remains dynamically dominated by ram pressure, and acceleration is limited by that energy budget.

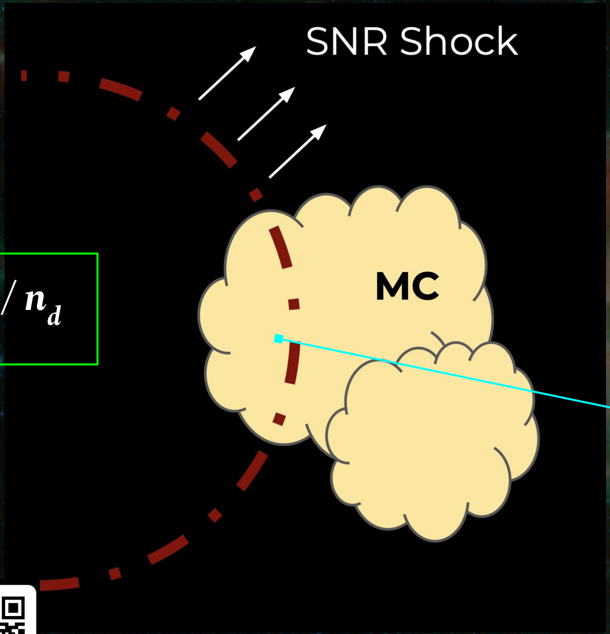
$$P_{CR} = \xi_{CR} \rho_0 v_{sh}^2$$

Picture Credits: NASA/JPL-Caltech The W51 Complex

DIRECT INTERACTION : MODEL (Cardillo et al 2016, Cardillo et al 2019)

Case of Compression : Compression due to radiative cooling, particles experiencing further energization.

$$s = n_{cc} / n_d$$



$$P_B \sim P_{ram}$$

No longer limited by ram pressure alone — the magnetic field controls CR acceleration and confinement, enabling higher-energy particle acceleration and stronger gamma-ray emission.

SCAN ME

Picture Credits: NASA/JPL-Caltech The W51 Complex

DIRECT INTERACTION: SIMULATION PARAMETERS

Age of the remnant = 18 kyrs [Zhang et al. 2017]

Age of interaction = 3600 yrs

Shock velocity = 480 km/s [Koo et al. 1995]

Ambient density = 20 cm^{-3} [Fang et al. 2010]

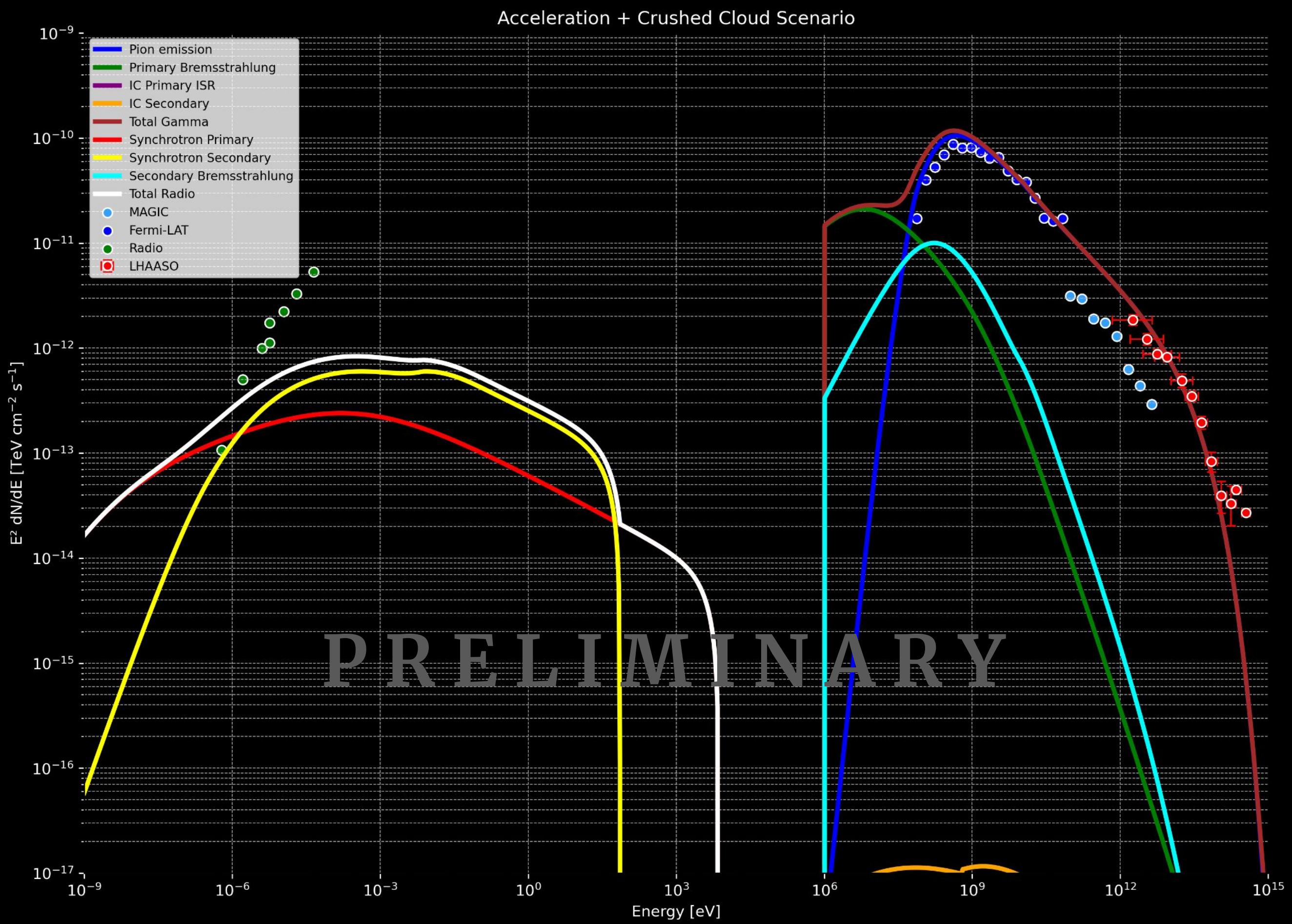
Distance = 4.3 kpc [Tian et al. 2013]

1% Filling factor

Kolmogorov turbulence

b = 0.3, where b determines the unperturbed mag. field upstream of the shock $B_0 = b \times \sqrt{(n_0/cm^{-3})}$

DIRECT INTERACTION: RESULTS



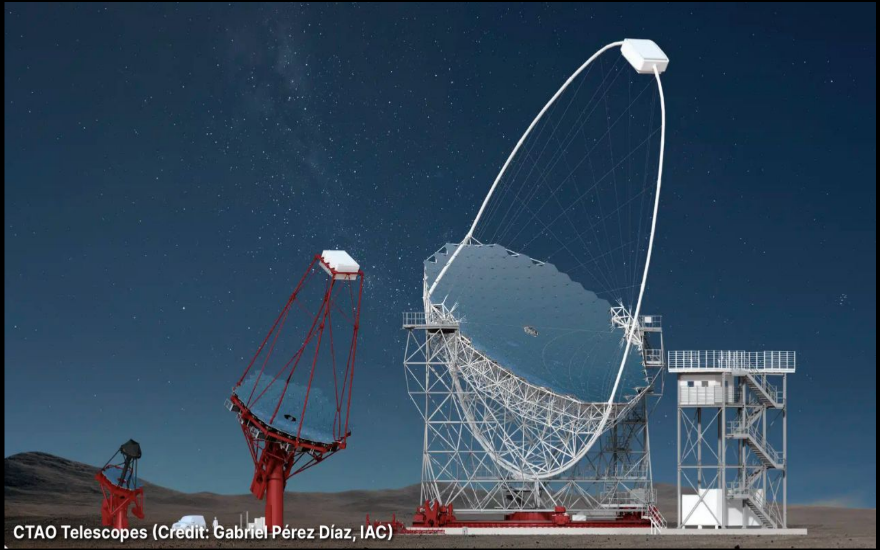
TEST CASE W51 : AIM

- ➔ Test if the TeV emissions can be solely attributed to the the interaction between the supernova remnant and molecular cloud.

- ➔ In such complex regions extended emissions are inevitable - we test if CTAO and ASTRI Mini-Array can untangle their origins.

W51C-B : GAMMAPY SIMULATIONS WITH IRFs

CTAO



ASTRI Mini Array

W51C-B : GAMMAPY SIMULATIONS WITH IRFs

CTAO	ASTRI Mini Array
Zenith 40deg, Averaged Azimuth for CTAO-N with 4 LSTs, 9 MSTs	Zenith 20deg, Averaged Azimuth for ASTRI MA with 9 SSTs
Total Observation of 200 Hrs	Total Observation of 300 Hrs
Offset = 0.7 deg	Offset = 0.7 deg

METHOD

The aim is to extract more morphological information. Treating the LHAASO model:

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

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

as the “expected total spectrum”, we treat W51 B and C as two sources and introduce two spatial models:

Spatial model for W51C = Template spatial model from known Fermi data

Spatial model for W51B = Disk spatial model

We now try to fit the spectral models of W51 B and C, so that it can be reasonable with the expected LHAASO spectral model being consistent with what we already got.

METHOD

Current best fit for W51C

Spectral_model - *Exponential cutoff power law spectral model considered by LHAASO*

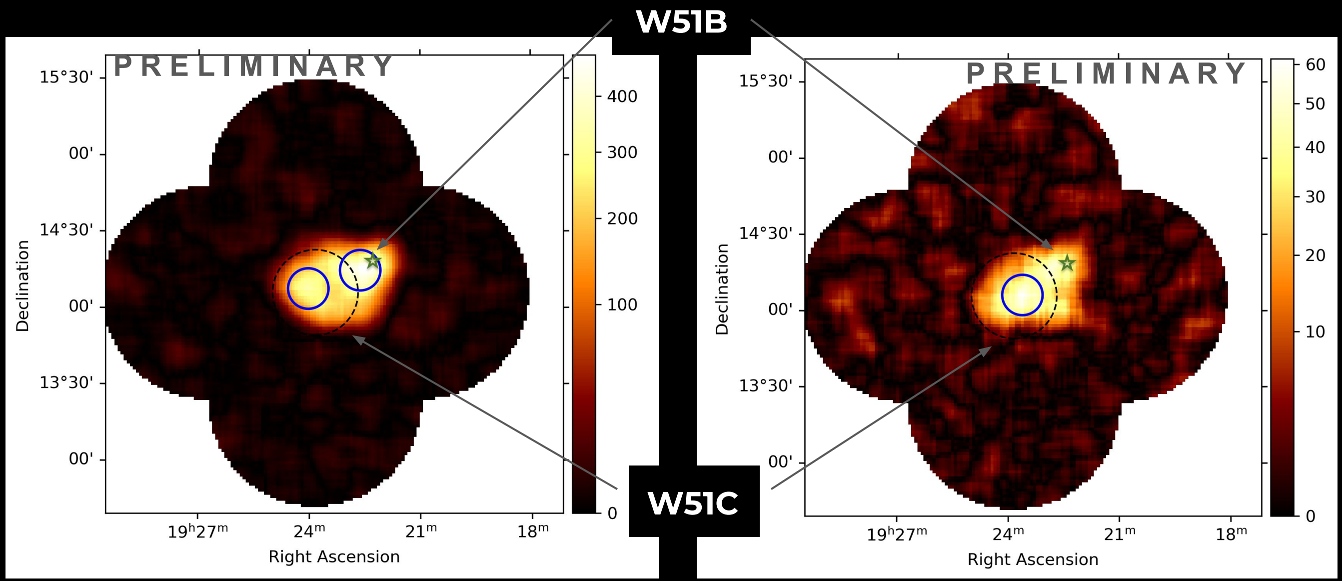
Amplitude=8.0×10^{-16} cm^{-2} s^{-1} TeV^{-1} ; index=2.6 ; Ecut at 75 TeV ; reference=20 TeV

Current best fit for W51 B:

Spectral Model - *Simple Power law spectral model*

Amplitude=1.1×10^{-16} cm^{-2} s^{-1} TeV^{-1} ; index=2.5 ; reference=20 TeV

SOURCE DETECTION: TS Maps with 4σ lower threshold

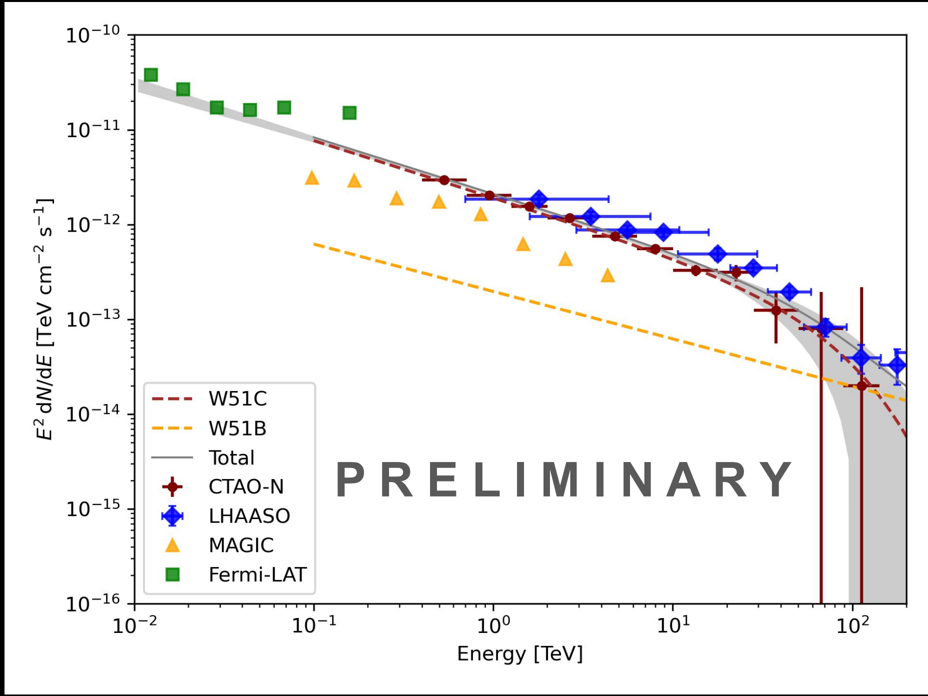


CTAO

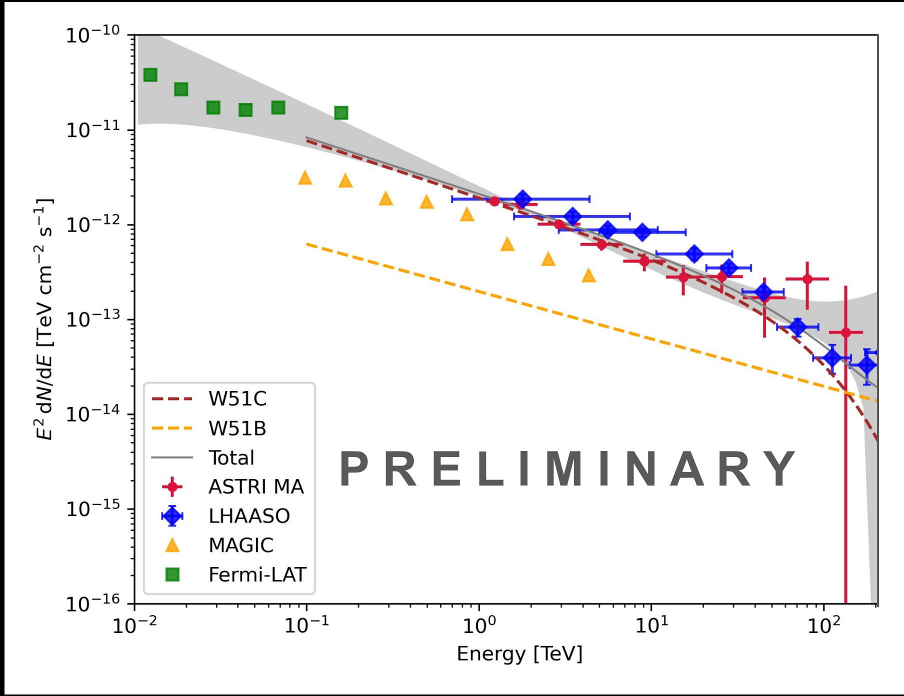
ASTRI Mini Array

Sunny et al. 2025 PoS(ICRC2025)853

ANALYSIS: S.E.D



CTAO



ASTRI Mini Array

Sunny et al. 2025 PoS(ICRC2025)853

Takeaway Points:

- CTAO and ASTRI Mini-Array can disentangle morphological information from complex emission regions like W51 Complex with sufficient observation time.
- The interaction between the SNR and MC, resulting in the compression or crushing of the clouds, could account for the observed UHE emission through the combined effects of shock-accelerated particles and enhanced radiation from compression.

Next steps:

- Using updated results with Fermi data from ICRC 2025, we aim to disentangle the individual spectral contributions of C and B.
- We aim for a unified model explaining both radio and gamma data, and is currently exploring re-acceleration mechanism at the shock [Cardillo et al. 2016]

Picture Credits: NASA/JPL-Caltech The W51 Complex

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BONUS SLIDES

Current best fit for W51C

Spectral_model - ***Exponential cutoff power law spectral model considered by LHAASO***

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