



## Article

## Evidence for particle acceleration approaching PeV energies in the W51 complex

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## ABSTRACT

The  $\gamma$ -ray emission from the W51 complex is widely acknowledged to be attributed to the interaction between the cosmic rays (CRs) accelerated by the shock of supernova remnant (SNR) W51C and the dense molecular clouds in the adjacent star-forming region, W51B. However, the maximum acceleration capability of W51C for CRs remains elusive. Based on observations conducted with the Large High Altitude Air Shower Observatory (LHAASO), we report a significant detection of  $\gamma$  rays emanating from the W51 complex, with energies from 2 to 200 TeV. The LHAASO measurements, for the first time, extend the  $\gamma$ -ray emission from the W51 complex beyond 100 TeV and reveal a significant spectrum bending at tens of TeV. By combining the “ $\pi^0$ -decay bump” featured data from Fermi-LAT, the broadband  $\gamma$ -ray spectrum of the W51 region can be well-characterized by a simple pp-collision model. The observed spectral bending feature suggests an exponential cutoff at  $\sim 400$  TeV or a power-law break at  $\sim 200$  TeV in the CR proton spectrum, most likely providing the first evidence of SNRs serving as CR accelerators approaching the PeV regime. Additionally, two young star clusters within W51B could also be theoretically viable to produce the most energetic  $\gamma$  rays observed by LHAASO. Our findings strongly support the presence of extreme CR accelerators within the W51 complex and provide new insights into the origin of Galactic CRs.

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## 1. Introduction

The W51 giant cloud stands out as one of the most massive and active star-forming regions in the Galaxy [1]. This cloud boasts an impressive diameter of  $\sim 100$  pc and mass of  $10^6 M_\odot$  [2]. Within this expansive complex lie two primary clumps, W51A in the north and W51B to the west. Also located in this region, at a distance of  $d = 5.4 - 5.7$  kpc [3,4], is the middle-aged supernova remnant (SNR) W51C (G49.2 – 0.7), most likely remnant of a very energetic core-collapse supernova explosion [5]. W51C appears in radio as a shell-type SNR, with an estimated age of  $t \sim 30$  kyr [6], a kinetic energy release as high as  $3.6 \times 10^{51}$  erg [6], and a radius of 24 pc if  $d = 5.5$  kpc is assumed<sup>2</sup> [9].

The detection of  $\gamma$ -ray radiation emanating from the W51 complex has been successively reported by a series of experiments, including H.E.S.S. [10], Milagro [11], Fermi-LAT [12], MAGIC [13], and HAWC [14]. These observations span an energy range of nearly six orders of magnitude, from  $\sim 50$  MeV up to  $\sim 30$  TeV. The prevailing hypothesis for the source of these  $\gamma$  rays is the interaction between cosmic-ray (CR) nuclei accelerated at the W51C shock and the nearby molecular clouds (MCs) in W51B, through the neutral pion ( $\pi^0$ ) decay channel. Support for this scenario is multifaceted, including extensive evidence of SNR-MC interactions observable in radio bands [15–18] and the identification of the spectral feature “ $\pi^0$ -decay bump” [19]. The latter is considered a distinctive signature of CR-MC interactions, representing a crucial piece of evidence for probing CR acceleration in SNR-driven shocks. In log – log coordinates, the  $\gamma$ -ray energy spectrum exhibits a symmetry relative to half the rest mass of  $\pi^0$ , thereby creating such a sub-GeV bump structure. W51C is one of the few SNRs with a clear  $\pi^0$ -decay bump detected [19–21].

SNRs have long been considered the major factories of Galactic CRs [22], owing to the fact that supernova explosions can provide sufficient energy to maintain the observed CR intensity, with a required conversion efficiency of  $\approx 10\%$ , and to the presence of

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<sup>2</sup> There are still debates on the distance and age measurement of W51C. Some studies indicate that W51C is possibly located at a closer distance of 4.3 kpc [7] and at a younger age of 18 kyr [8].

shock regions as reliable sites for accelerating CRs [23]. However, because  $\gamma$ -ray spectral measurements of SNRs have been constrained to energies well below 100 TeV until recently, there has been a lack of definitive evidence to establish SNRs as accelerators CRs with energies of PeV, where the knee of the CR energy spectrum is located [24], a feature that may represent the upper limit of acceleration by Galactic sources. Therefore, the detection of ultra-high-energy (UHE,  $> 100$  TeV)  $\gamma$  rays from SNRs, particularly from those like W51C with established CR acceleration evidence, presents an excellent opportunity to study the acceleration potential of SNRs and the origin of Galactic CRs [25].

On the other hand, the intricate environment of W51 harbors additional potential sources of UHE  $\gamma$  rays. Among these is the pulsar wind nebula (PWN) candidate, CXO J192318.5+140305 [5], which has possibly originated from the same explosion that produced W51C. Its hard X-ray emission [5,26,27] suggests that it has the potential to accelerate high-energy leptons. These leptons, in turn, could be responsible for generating TeV  $\gamma$  rays through the inverse Compton (IC) scattering process. Furthermore, the W51 complex hosts several young star clusters (YSCs) [28]. They have been suggested as alternative contributors to SNRs recently [29], which is supported by the detection of several PeV photons in the Cygnus region by LHAASO [30].

In this work, we report the Large High Altitude Air Shower Observatory (LHAASO) measurements of the  $\gamma$ -ray spectrum of the W51 complex, covering an impressive energy range from 2 TeV to the UHE domain of 200 TeV. We first detail the LHAASO observations and the corresponding analytical outcomes. Subsequently, we deliberate on the discussion of physical scenarios that aim to interpret the broadband  $\gamma$ -ray spectrum of this astrophysically rich region.

## 2. Observation

### 2.1. Experiment

LHAASO is a ground-based experiment located high on the edge of the Tibetan Plateau at an average altitude of 4410 m. It has broken through the limited energy range of space-borne instruments and sensitively extended the measured energy beyond sub-TeV to PeV [31]. This hybrid array consists of the Kilometer Square Array (KM2A), the Water Cherenkov Detector Array (WCDA), and the Wide Field of View Cherenkov Telescope Array (WFCTA) [32]. With a large field of view and continuous exposure, WCDA and KM2A provide full-duty monitoring of  $\gamma$ -ray emissions from almost 60% of the sky each day [33]. The  $\gamma$ /hadron separation capability of KM2A in the UHE band is better than  $4 \times 10^3$  to reject the contamination of CR-induced showers [33]. Performance study of KM2A indicates the energy resolution is better than 20% and angular resolution is smaller than  $0.25^\circ$  at 100 TeV [33]. All these features allow KM2A to achieve 1% sensitivity above 100 TeV for Crab-like sources in one year [34], and to precisely determine the  $\gamma$ -ray spectral characteristics of SNRs with unprecedented sensitivity beyond 100 TeV [25].

We conducted measurements with LHAASO, including both WCDA and KM2A in the W51 region over effective exposure times of 795.96 days (from March 5, 2021, to July 31, 2023) and 1216.24 days (from December 27, 2019, to July 31, 2023), respectively. Analogous data-processing criteria were adopted as previous works [33,35], including the detector trigger model, noise filter method, event direction selection,  $\gamma$ /hadron separation efficiency, and detector response simulation. For background estimation, we employed the Direct Integration method [36], which has been widely used in  $\gamma$ -ray source surveying with LHAASO [33,37].

### 2.2. Morphology

The spatial and spectral distribution of radiation from the W51 region was estimated by employing a conservative approach by fitting a relatively large region of interest (ROI), with declination (Dec.) from  $11^\circ$  to  $19^\circ$  and Right ascension (R.A.) from  $286.5^\circ$  to  $294.9^\circ$ , covering the entire complex and the ambient diffuse regions. We modeled the contamination due to the Galactic diffuse emission (GDE) consistently with the spatial distribution of Planck dust observations [38,39], applying the same flux treatment as established in previous works [35]. We further considered two significant spatially extended nearby sources, LHAASO J1919+1556 ( $1\sigma$  extent  $\sigma_{\text{ext}} = 0.11^\circ \pm 0.04^\circ_{\text{stat}}$ ) and LHAASO J1924+1609 ( $1\sigma$  extent  $\sigma_{\text{ext}} = 1.47^\circ \pm 0.06^\circ_{\text{stat}}$ ), and subtracted their contributions. Other sources located at larger distances from the W51 region were subtracted using the same source parameters as provided in the LHAASO catalog [30].

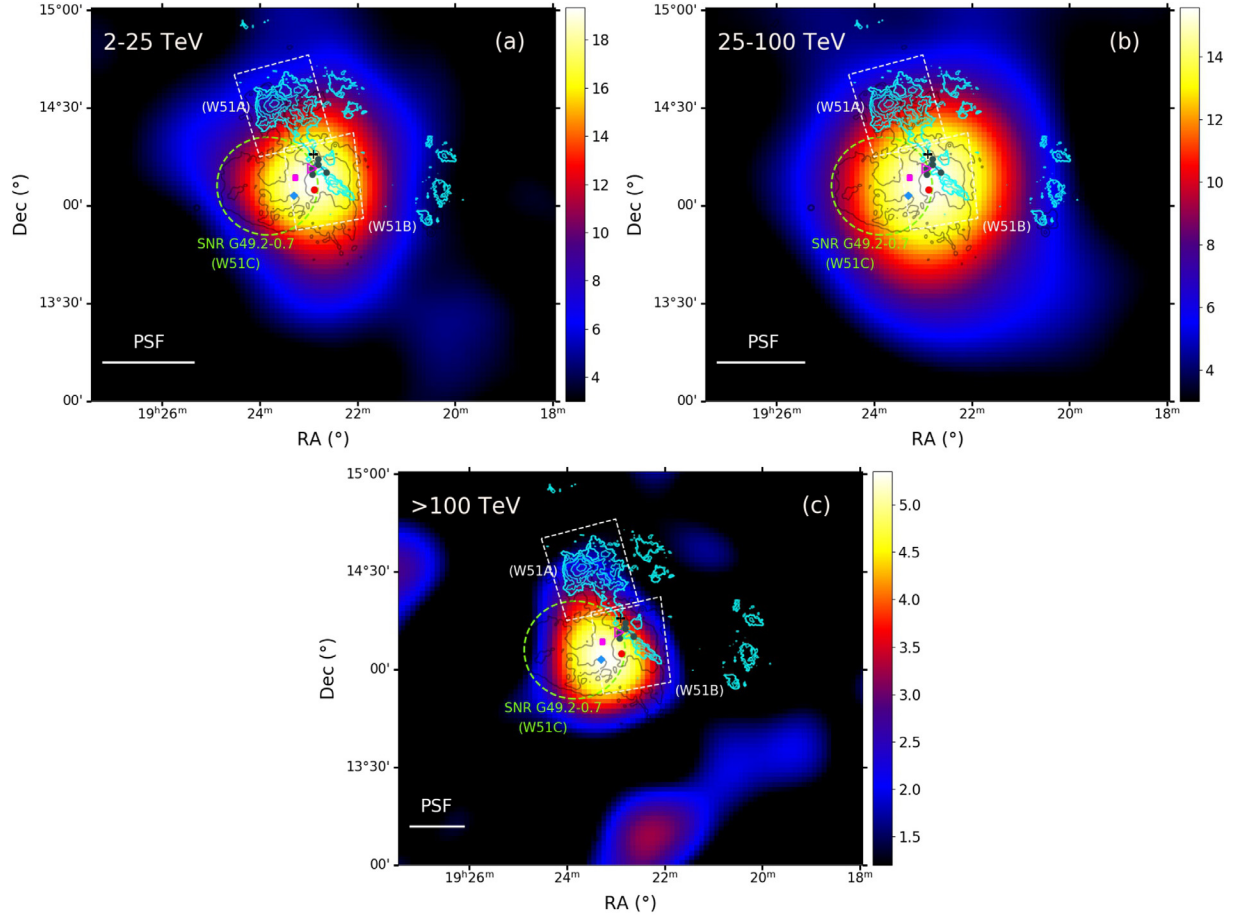
The spatial distribution and energy spectrum of the W51 complex are simultaneously measured by means of a binned maximum 3D-likelihood analysis method [35]. Gamma-ray excesses with statistical significances of  $19.33\sigma$ ,  $15.58\sigma$ , and  $5.35\sigma$  are revealed across three energy regimes of  $< 25$  TeV,  $25 - 100$  TeV, and  $> 100$  TeV, respectively. Gamma-ray significance maps of these three energy bins are illustrated in Fig. 1. By adopting a 2D Gaussian distribution template for the  $\gamma$ -ray emission, the overall centroid was found at (R.A., Dec.) =  $(290.72^\circ \pm 0.02^\circ_{\text{stat}}, 14.08^\circ \pm 0.02^\circ_{\text{stat}})$ , which is shown in Fig. 1 with a red dot. The overall  $\gamma$ -ray emission exhibits an extension with  $\sigma_{\text{ext}} = 0.17^\circ \pm 0.02^\circ_{\text{stat}}$  after removing the Point Spread Function (PSF), consistent with previous findings from Fermi-LAT and MAGIC considering statistical uncertainties [12,13].

The radio continuum map at 1.4 GHz, which delineates the components of the W51 complex, is also illustrated in Fig. 1 [40]. It is evident that the  $\gamma$ -ray emission region observed by LHAASO coincides with W51C and W51B, whereas no significant emission is detected from W51A. There are two compelling pieces of evidence for the interaction between the shock driven by W51C and the molecular cloud associated with W51B. One is the detection of OH masers at 1720 MHz [17,41], and the other is the detection of shocked CO clumps and atomic gas in the adjacent region between W51C and W51B [15,16], both of which are spatially consistent with the centroid of the  $\gamma$ -ray emission measured by LHAASO. In addition, we superimposed the high-resolution  $^{12}\text{CO}$  contour provided by the Milky Way Imaging Scroll Painting (MWISP) survey [42] onto the  $\gamma$ -ray map to provide a more detailed context of the MC environment.

According to LHAASO observations and analysis, the PSF sizes at energy intervals of  $2 - 25$  TeV,  $25 - 100$  TeV, and above 100 TeV are  $0.46^\circ$ ,  $0.44^\circ$ , and  $0.27^\circ$ , respectively. Given that these values significantly exceed the angular separation between the SNR-MC interaction region and the putative PWN mentioned above, morphological analysis alone is insufficient to distinctly attribute  $\gamma$ -ray emission to these sources independently. Nonetheless, a detailed physical assessment of the potential contribution of the PWN candidate to the UHE  $\gamma$ -ray emission is provided in Appendix B in Supplementary materials.

### 2.3. Spectrum

In the estimation of the  $\gamma$ -ray spectrum, our initial 3D-likelihood fitting approach consists of adopting a simulated detector response to convert the observed number of excess events ( $N_s$ ) into differential flux points [35], based on an assumed spectrum model such as pure power-law function, power-law with exponential cutoff (PLEXPcut), or log-parabola



**Fig. 1.** (Color online) Gamma-ray maps in the intervals [2 – 25] (a), [25 – 100] TeV (b) and > 100 TeV (c) of the W51 region presented in equatorial coordinates. The color scale indicates the statistical significance of the excess  $\gamma$ -ray counts after subtracting the Galactic diffuse emission. Maps have been smoothed with a Gaussian kernel of 1.58 times the PSF. The central position determined by the all-energy-range fit to the LHAASO data is marked by a red dot. The  $\gamma$ -ray centroids given by Fermi-LAT [12] and MAGIC [13] observations are marked with a magenta square and a magenta triangle, respectively. Cyan contours show the MWISP [42] measurement of the  $^{12}\text{CO}$  emission integrated the velocity from 54 to 70  $\text{km s}^{-1}$ . Black contours overlay the 1.4 GHz continuum emission as observed by the Very Large Array [40]. The blue diamond marks the position of a PWN candidate CXO J192318.5+140305 [5]. The black cross shows where 1720 MHz OH masers are emitted from Ref. [41], while six dark-green marked points localize shocked CO clumps [15,16]. Two white dashed rectangles define the two star-forming regions, W51A and W51B [43]. The radio shell of SNR W51C is indicated with a green dashed circle [41].

(LOG). Energy resolution and the energy bias of both WCDA and KM2A thus have to be taken into account by unfolding the spectrum [33].

The  $\gamma$ -ray spectrum of the W51 complex, as depicted in Fig. 2, extends from  $\approx 2$  TeV to an unprecedented upper limit of  $\approx 200$  TeV, marking the first observation of this astrophysical object in the UHE band. The spectrum below 25 TeV has been precisely measured by WCDA and is consistent with the result from HAWC [44], another Extensive Air Shower (EAS) facility. Notably, the flux measured by LHAASO below 10 TeV is about 1.8 times higher than that reported by MAGIC [13]. When the different spatial extensions observed by MAGIC and LHAASO are accounted for, the flux should exhibit an increase by a factor of 1.3 relative to the MAGIC data. Systematic biases between imaging telescopes and EAS arrays for point-like sources may also be a factor contributing to this difference, as indicated by the spectrum measurements of the Crab Nebula [45]. Additionally, flux points from H.E.S.S. and Milagro also exhibit slight differences while remaining statistically consistent with the current measurements.

The  $\gamma$ -ray spectrum above tens of TeV is characterized by a significant curvature: as such, to quantify the spectral index variation as a function of photon energy, we employed the LOG function in our 3D likelihood estimation. The spectral model is expressed as follows:

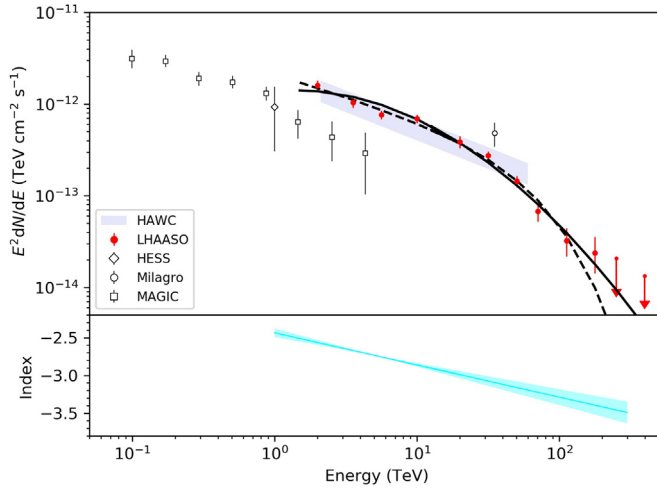
$$\frac{dN_\gamma}{dE_\gamma} = J_0 (E_\gamma/20 \text{ TeV})^{-[a+b\log_{10}(E_\gamma/20 \text{ TeV})]} \quad (1)$$

The estimated parameters are  $J_0 = (0.94 \pm 0.06_{\text{stat}}) \times 10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$ ,  $a = 2.98 \pm 0.04_{\text{stat}}$ , and  $b = 0.43 \pm 0.08_{\text{stat}}$ . The goodness of fit of the model to the corresponding flux points yields  $\chi^2/\text{ndf} = 10.43/7$ . The confidence interval of  $b$  indicates that the  $\gamma$ -ray spectrum deviates from a power-law function with a  $5.4\sigma$  significance, exhibiting a very pronounced spectral bending. It is important to note that the best-fit spectrum obtained from the 3D likelihood approach may not coincide precisely with the spectrum that would result from a direct fit to the flux points depicted in Fig. 2.

If the UHE emission is attributed to proton-proton collisions, the detection of photons with energies of a few hundred TeV may imply the responsible source to be a PeVatron [30]. The maximum acceleration limit for protons may manifest in the  $\gamma$ -ray spectrum as a characteristic exponential cut-off feature. Thus, we also adopt a PLEXP function to describe the  $\gamma$ -ray spectrum, which is expressed as

$$\frac{dN_\gamma}{dE_\gamma} = J_0 (E_\gamma/20 \text{ TeV})^{-\Gamma} \exp(-E_\gamma/E_{\gamma,\text{cut}}) \quad (2)$$

The parameters estimated by the 3D-likelihood method are  $J_0 = (1.29 \pm 0.18_{\text{stat}}) \times 10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$ ,  $\Gamma = 2.48 \pm 0.08_{\text{stat}}$ , and



**Fig. 2.** (Color online) Spectral energy distribution of W51C plotted as  $E^2 dN_\gamma / dE_\gamma$ . Top panel: Red flux points, covered an energy band from  $2.24^{+0.01}_{-0.01}$  TeV to  $177.83^{+46.04}_{-36.57}$  TeV, are the measured fluxes from LHAASO by performing a 3D-likelihood method assuming a PLEXPcut spectrum in the simulation. The error bars for all points are given at 1 times standard deviation. The statistical significance at the highest detection point is  $3.33\sigma$ . The last two flux upper limits are given at  $\approx 281.84^{+72.98}_{-57.97}$  and  $\approx 446.68^{+102.86}_{-83.61}$  TeV, respectively. Previous observation results from MAGIC [13], H.E.S.S. [21], Milagro [11], and HAWC [44] are also depicted. The solid black line is the fitting result with a LOG function, while the dashed black line represents the fitting result with a PLEXPcut function. Bottom panel: Energy-dependent  $\gamma$ -ray slope as derived by the LOG model. The cyan band represents the  $1\sigma$  confidence interval.

$E_{\gamma, \text{cut}} = (61.05 \pm 15.28_{\text{stat}})$  TeV. The goodness of fit characterized by the chi-square statistic is  $\chi^2 / \text{ndf} = 7.94/7$ . The PLEXPcut function marginally underestimates the flux around 200 TeV, suggesting that a model with a smoother cutoff may yield a better representation [46].

Owing to the unprecedented sensitivity of LHAASO at the UHE band, the bending of the  $\gamma$ -ray spectrum in the W51 complex is detected for the first time. The cutoff energy  $E_{\gamma, \text{cut}}$  derived from the PLEXPcut fitting clearly indicates the spectral bending at tens of TeV, corresponding to the spectral softening revealed by the LOG model. The bending feature is a clear deviation from the pure power-law spectrum, suggesting that we have detected a signature of either the maximum acceleration or the confinement capability of the source in this region.

The systematic uncertainties in the  $\gamma$ -ray spectrum measurements of the LHAASO experiment have been thoroughly investigated in Refs. [33,47], leading to 7% and  $^{+8\%}_{-24\%}$  for the KM2A and WCDA measurements, respectively. The primary uncertainty arises from the atmospheric model used in the Monte Carlo simulations. Furthermore, we have evaluated the uncertainties arising from the GDE and the influence of nearby sources, determining that the flux may vary by 13% at maximum. Variations in the initial spectral models used for simulation, which in turn influence the generated detector response, can induce a fluctuation of about 1%–9% in the final flux estimation. The positional accuracy of our results is subject to a systematic pointing uncertainty of  $\approx 0.04^\circ$ , as established by targeting point-like sources such as the Crab Nebula, Mrk 421, and Mrk 501 [35]. Similarly, the systematic uncertainty of the source extension was estimated to be  $\approx 0.05^\circ$  [35].

#### 2.4. Joint fitting of LHAASO and Fermi-LAT data with a simple hadronic model

The presence of the  $\pi^0$ -decay bump unambiguously signifies a hadronic mechanism behind the  $\gamma$ -ray emission observed by

Fermi-LAT [19]. Considering that the  $\gamma$ -ray emission detected by LHAASO is spatially consistent with that reported by Fermi-LAT, and the energy spectrum measurements of the two instruments can be smoothly bridged with a power-law form (as will be illustrated in Fig. 3), it is reasonable to ascribe the broadband  $\gamma$ -ray energy spectrum to a unified  $\pi^0$ -decay framework.

Computation is performed using the Python package Naima [48]. The  $\gamma$ -ray flux generated by  $\pi^0$  decay is dependent on the proton incident flux, the target gas density, and the  $\pi^0$ -production cross-section. We adopt for the energy spectrum of the incident protons a power law function with an exponential cut-off (ECPL), described as

$$\frac{dN_p}{dE_p} \propto E_p^{-\alpha} \cdot \exp\left(-\frac{E_p}{E_{p, \text{cut}}}\right), \quad (3)$$

where  $E_p$  is the proton energy, and  $dN_p/dE_p$  is the energy differential number density of protons. Alternatively, broken power law (BPL) could also be a plausible form for the proton spectrum, expressed as

$$\frac{dN_p}{dE_p} \propto \begin{cases} E_p^{-\alpha_1}, & E_p < E_{p, \text{br}}, \\ E_{p, \text{br}}^{\alpha_2 - \alpha_1} E_p^{-\alpha_2}, & E_p > E_{p, \text{br}}. \end{cases} \quad (4)$$

The gas in the interaction region is predominantly atomic hydrogen that has been dissociated from molecular hydrogen [15]. As the density of the expanding atomic hydrogen gas pushed by the SNR shock is estimated to be  $\approx 30 - 160 \text{ cm}^{-3}$  (derived from the scale and column density of the expanding gas [15]), we set the average of this range as the default value, which is  $n_H \approx 100 \text{ cm}^{-3}$ . The Pythia 8 option embedded in the Naima package [49] is used for the  $\pi^0$ -production cross section. The free parameters for the ECPL scenario are  $\alpha$ ,  $E_{p, \text{cut}}$ , and the total energy of the proton incident spectrum above 1 GeV, denoted by  $W_p$ , while those for the BPL scenario are  $\alpha_1$ ,  $\alpha_2$ ,  $E_{p, \text{br}}$ , and  $W_p$ . Markov Chain Monte Carlo fitting [50] is applied for parameter estimation.

The fitting results are depicted in Fig. 3. The reduced  $\chi^2$  statistic of the best-fit model is 32.4/25 for the scenario of the ECPL proton spectrum while 31.8/24 for the BPL case. The difference in the Bayesian information criterion<sup>3</sup> between the former and the latter is  $\approx -3$ , indicating that neither model demonstrates significant superiority over the other.

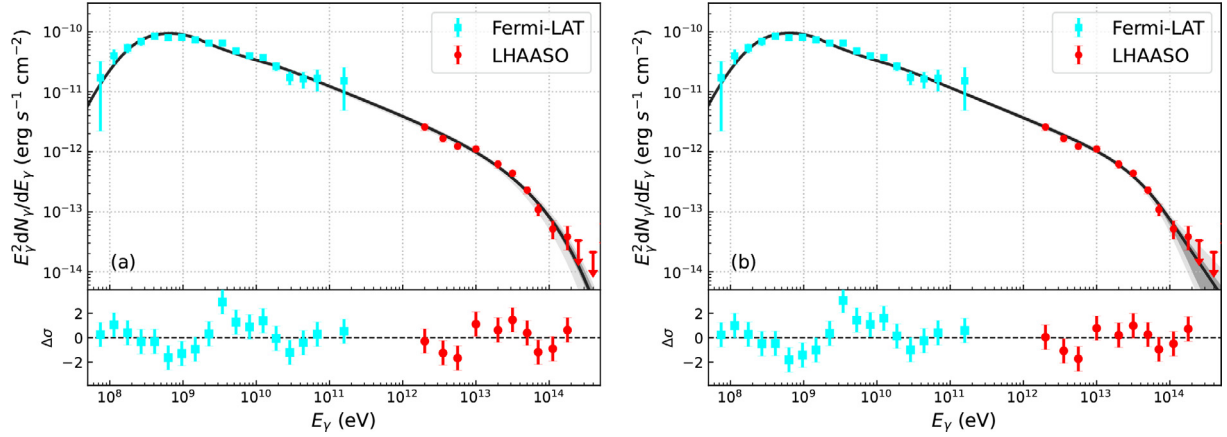
The estimated parameters are  $\alpha = 2.55 \pm 0.01$  and  $E_{p, \text{cut}} = 385^{+65}_{-55}$  TeV for the scenario of the ECPL proton spectrum, and  $\alpha_1 = 2.56 \pm 0.01$ ,  $\alpha_2 = 4.07^{+0.55}_{-0.44}$ , and  $E_{p, \text{br}} = (180 \pm 45)$  TeV for the BPL proton spectrum. In both cases, the total energy of the proton spectrum is  $W_p = (1.30 \pm 0.05) \times 10^{50} (d/5.5 \text{ kpc})^2 (n_H/100 \text{ cm}^{-3})^{-1}$  erg. These results are summarized in Table 1 and 2. Remarkably, the values of  $E_{p, \text{cut}}$  and  $E_{p, \text{br}}$  indicate that a considerable number of CRs have been accelerated beyond 100 TeV. With the default values of  $d$  and  $n_H$ , the required total proton energy amounts to a mere 4% of the kinetic energy of SNR W51C. This energy proportion is well within a feasible supply range for SNRs. Additionally, we have checked that the results of parameter estimation are slightly affected by the choice of different hadronic interaction models while remaining consistent within the range of error.

### 3. Interpreting the origin of the radiation

The W51 complex is quite rich in candidate particle accelerators, possibly producing radiation extending in the UHE domain, among which are the SNR W51C, the putative PWN from the same

<sup>3</sup> The definition is  $-2 \ln L + k \ln n$ , where  $L$  is the likelihood,  $k$  is the number of free parameters, and  $n$  is the number of data points.





**Fig. 3.** (Color online) Fitting results of the  $\pi^0$ -decay model to the  $\gamma$ -ray spectrum measurements of W51C. The LHAASO spectrum reported by the present work and the Fermi-LAT spectrum [19] are used in the fitting processes. The proton incident spectrum takes the form of ECPL (BPL) in the left (right) panel. For each panel, the main plot presents the differential energy spectrum of  $\gamma$  rays, denoted by  $dN_\gamma/dE_\gamma$ . The black line is the best-fit curve, while the dark and light grey bands are the  $2\sigma$  and  $3\sigma$  confidence intervals of the model, respectively. Directly beneath, a subplot details the standardized residuals between the best-fit curve and the data.

**Table 1**

Parameter estimation results obtained by fitting LHAASO and Fermi-LAT data with a simple hadronic model. The incident proton spectrum is assumed to be an ECPL. For each parameter, the table lists both the maximum a posteriori (MAP) estimate and the median of the posterior distribution (accompanied by the 16th and 84th percentile confidence interval). The reduced  $\chi^2$  is calculated using the MAP parameters.

$\alpha$		$E_{\text{cut}} \text{ (TeV)}$		$W_{p,0}^a \text{ (} 10^{50} \text{ erg)}$		$\chi^2/\text{ndf}$
Best	Median	Best	Median	Best	Median	
2.55	$2.55^{+0.01}_{-0.01}$	382	$383^{+66}_{-54}$	1.30	$1.30^{+0.04}_{-0.04}$	32.4/25

<sup>a</sup>  $W_{p,0}$  is the total proton energy when the default values of  $d$  and  $n_H$  are adopted, that is,  $W_p = W_{p,0}(d/5.5 \text{ kpc})^2(n_H/100 \text{ cm}^{-3})^{-1}$ .

**Table 2**

Same as Table 1, but the incident proton spectrum takes the form of a BPL.

$\alpha_1$		$\alpha_2$		$E_{\text{br}} \text{ (TeV)}$		$W_{p,0} \text{ (} 10^{50} \text{ erg)}$		$\chi^2/\text{ndf}$
Best	Median	Best	Median	Best	Median	Best	Median	
2.56	$2.56^{+0.01}_{-0.01}$	3.86	$4.07^{+0.55}_{-0.44}$	161	$179^{+42}_{-45}$	1.32	$1.33^{+0.04}_{-0.04}$	31.8/24

explosion, and several YSCs. We present a detailed investigation of each scenario in the following.

### 3.1. The supernova remnant W51C

The middle-aged SNR W51C is a well-known  $\gamma$ -ray emitter, belonging to one of the few cases where the hadronic origin of its low-energy radiation could be ascertained thanks to the clear detection of the  $\pi^0$ -bump. The hadronic scenario is supported by the presence of massive nearby MCs providing a dense enough target for hadronic collisions to occur, such that the resulting secondary  $\gamma$ -ray flux is enhanced. Indeed, strong and multiple pieces of evidence indicate the ongoing collision between the W51C shock and massive clouds within the surrounding giant MC. As such, the most likely origin of the observed  $\gamma$ -ray emission up to the highest energies can be realized in the scenario of the interaction between the shock-accelerated particles and the nuclei in the clouds, either in direct collisions [51] or after their nominal escape from the acceleration cycles [52–54].

In the direct interaction scenario, namely among freshly accelerated particles and target clouds, the slope of the incident proton spectrum inferred from the data would correspond to the acceleration stage: Its value of  $\alpha \approx 2.5$  may correspond to a low Mach number shock ( $M \approx 3$ ), consistently with the expectation for a middle-aged SNR like W51C [51]. However, the observed  $\gamma$ -ray spectrum extending to the highest observed energies among SNRs

is unexpected for the low-speed shock of a middle-aged system. The current maximum energy of accelerated protons can be estimated as  $160 v_{s,8}^2 (B/10 \mu\text{G})(t_{\text{age}}/10^5 \text{ yr}) \text{ TeV}$  [55], where  $v_{s,8}$  is the shock velocity in units of  $10^8 \text{ cm s}^{-1}$ ,  $B$  is the magnetic field strength, and  $t_{\text{age}}$  is the SNR age. The Sedov expansion of the SNR shock yields a current shock velocity of  $\sim 300 \text{ km s}^{-1}$  for W51C, further reproducing the radius of W51C under the same evolutionary assumption [56]. The average  $B$  of W51C should be of the order of  $\sim 50 \mu\text{G}$  to account for the non-thermal radio emission of the whole SNR shell [13]. Taking  $v_{s,8} = 0.3$ ,  $B = 50 \mu\text{G}$ , and  $t_{\text{age}} = 30 \text{ kyr}$ , the current maximum proton energy is only  $\approx 22 \text{ TeV}$ , insufficient to account for LHAASO observation. This implies that the direct interaction model is disfavored by the LHAASO measurements.

An alternative scenario is that the highest-energy  $\gamma$  rays observed in W51C are generated by PeV CRs that escaped from the SNR shock at early stages and are now encountering the MC associated with W51B. Depending on the diffusion conditions occurring near the SNR shock, a significant number of high-energy CRs could still be distributed nearby and capable of illuminating the MCs at a sufficient level for detection [57]. The escaped CRs themselves may induce magnetic turbulence and suppress the diffusion coefficient through streaming instability [58]. In this context, this remnant was previously proposed as a potential PeVatron candidate [59]: The steepness of the proton slope could then be reasonably interpreted by the spectral softening effect owing to

the energy-dependent diffusion of protons [54]. In terms of conversion efficiency from bulk motion into non-thermal particles, the combination between the estimated explosion energy of W51C and the aforementioned proton energetics requires a  $\approx 3.6\%$  level, when the default  $d$  and  $n_H$  are used, in agreement with the standards SNR paradigm for the origin of Galactic CRs, that in turn needs for a 10% efficiency. If  $n_H$  were substantially higher, a smaller conversion efficiency would be expected.

Electrons are accelerated alongside protons at the shock front of W51C and are also able to generate  $\gamma$  rays through bremsstrahlung radiation and IC scattering of background photons. However, the detection of the  $\pi^0$ -decay bump suggests that the GeV emission from W51C primarily arises from hadronic interactions [19]. Furthermore, the maximum energy attainable by electrons is severely restricted by the synchrotron energy loss, which can be estimated by  $14\nu_{s,8}(B/10\ \mu\text{G})^{-1/2}\ \text{TeV}$  [55]. Taking the current shock velocity of  $v_{s,8} = 0.3$  and  $B = 50\ \mu\text{G}$ , a cutoff energy of only  $\approx 2\ \text{TeV}$  is derived for electrons. Although electrons may be accelerated to higher energies during the early evolutionary stages of the SNR, the synchrotron energy loss prevents them from surviving to the present day [60]. E.g., electrons with energy of 100 TeV have a lifetime of only  $\approx 30$  years in a magnetic field of  $50\ \mu\text{G}$ . Therefore, leptonic radiation from the SNR is unlikely to provide a significant contribution to the high-energy  $\gamma$ -ray spectrum observed by LHAASO.

### 3.2. The young star clusters

Besides the SNR W51C, it is not possible to exclude a contribution to the  $\gamma$  radiation from other powerful accelerators, e.g., the nearby massive star clusters. These systems could enable particle acceleration either at the collective Wind Termination Shocks (WTSs) developed in young compact systems or at the multiple supernova shocks occurring there. The W51 region hosts at least four young embedded stellar clusters observed as bright radio-continuum and far-infrared sources, namely G48.9–0.3, G49.2–0.3, G49.4–0.3, and G49.5–0.4 [28]. All are young enough that their evolution is expected to be powered mainly by strong WTSs [61]. In fact, within the first 3 Myr of their lifetime, the geometry and energetics of a compact star cluster are dominated by the action of the collective WTS. This is the case of all the YSCs observed in the W51 complex, for which we hence proceed to the determination of the system physical parameters, including the hadron acceleration efficiency, by following the models of Refs. [62,63], respectively. In particular, starting from the mass values obtained in Ref. [28], we apply the approach defined by Ref. [64] for the computation of wind speed and kinetic energy of each cluster. We report in Table A.1 (online) expected values for each system, including WTS radius  $R_{\text{TS}}$  and bubble size  $R_b$ , both computed with a circumstellar density of 10 protons per cc, wind mechanical power  $L_w$  and proton maximum energy  $E_{\text{max}}$ , in the assumption that 10% of efficiency is achieved in converting wind pressure into magnetic energy density and MHD-like turbulence (i.e., Kraichnan, a scenario in between the most effective Bohm and the Galactic observed Kolmogorov). We also provide sky maps in Appendix A together with the observed LHAASO emission.

Interestingly, we find that the star clusters G48.9–0.3 and G49.2–0.3 are alternative viable accelerators to reproduce observations in the UHE domain, both morphologically and in terms of maximum energy. We further compute the total energetics so far injected by the collective winds of these two systems, accounting for the mass-dependent lifetime of main sequence stars [65], obtaining respectively values of  $E_w \simeq 6.1 \times 10^{51}\ \text{erg}$  and  $E_w \simeq 4.8 \times 10^{51}\ \text{erg}$  for G48.9–0.3 and G49.2–0.3, implying reason-

able conversion efficiencies into protons at the level of 2%–3% to explain the observed radiation in hadronic scenarios.

### 3.3. The nearby PWN

The presence of a putative nearby PWN radiating  $\gamma$  rays through IC scattering was previously discussed in Ref. [13]. This PWN candidate, discovered by X-ray observations, is located southwest of the interaction region between W51C and W51B and might be the leftover of the supernova explosion associated with W51C. Its  $\gamma$ -ray emission has even been tentatively identified by MAGIC, mostly in sub-TeV data, as an additional source, distinct from the dominant emission arising at the shock-cloud interaction region [13], despite the significance of this observation is not enough for a conclusive assertion. Such a feature is, however, absent in current LHAASO data.

Further investigations were conducted with LHAASO data to determine whether the  $\gamma$ -ray morphology exhibits variations across the three energy bins presented in Fig. 1, which would serve to evaluate leptonic scenarios for the origin of the radiation. We find that, for energies above 100 TeV, the centroid of the emission is located at  $(\text{R.A., Dec.})_{100\text{TeV}} = (290.80^\circ \pm 0.06^\circ_{\text{stat}}, 14.06^\circ \pm 0.07^\circ_{\text{stat}})$ , closer to the PWN candidate; however, this shift is less than a  $2\sigma$  deviation from the overall fit result, and it is not statistically significant. Additionally, the source extent at the highest energy bin has been measured to amount to  $\sigma_{\text{ext}} = 0.07^\circ \pm 0.10^\circ_{\text{stat}}$ . However, due to the measurement uncertainty, it is not possible to conclusively determine whether there is a significant shrinking in size with increasing energy. These arguments, together with discussions that we further elaborate upon in Appendix B in Supplementary materials, suggest that the  $\gamma$ -ray contribution from the PWN candidate to the LHAASO observed radiation is marginal.

## 4. Conclusion

With over two years of data collection and highly sensitive observations, LHAASO has significantly detected  $\gamma$ -ray events covering 2 TeV up to 200 TeV emanating from the W51 complex. The observed spectrum, for the first time, reveals the presence of radiation extending beyond 100 TeV with a significance above  $5\sigma$  and exhibits a pronounced spectral bending at tens of TeV, deviating from a power-law form with a  $> 5\sigma$  significance. Morphological analyses indicate the centroid of the  $\gamma$ -ray source is close to the interaction region between the SNR W51C and the dense MCs in W51B, consistent with the lower-energy observations. Incorporating the Fermi-LAT spectral data, we find that the broadband  $\gamma$ -ray emission from 60 MeV to 200 TeV can be naturally interpreted by the interaction between the CRs accelerated by W51C and the MCs, using a straightforward pp-collision model. The notable spectral bending suggests an exponential cutoff at  $\sim 400\ \text{TeV}$  or a power-law break at  $\sim 200\ \text{TeV}$  in the CR proton spectrum, most likely providing the first evidence of SNRs serving as CR accelerators approaching the PeV regime.

Regarding other potential accelerators within the W51 complex, we point out that  $\gamma$ -rays possibly emitted by the candidate PWN CXO J192318.5+140305 are unlikely to impact our conclusions. Two YSCs embedded within W51B (G48.9–0.3 and G49.2–0.3) may be theoretically viable to account for the most energetic  $\gamma$  rays observed by LHAASO, while the relatively coarse angular resolution of LHAASO precludes precise source identification through morphological analysis. Instruments with a significantly improved angular resolution are required to definitively identify the main contributor of these photons; future imaging atmospheric Cherenkov telescopes, such as LACT [66], ASTRI Mini-Array [67], and CTAO

[68], are poised to play a crucial role in this domain. Moreover, should LHAASO be capable of conducting spectral measurements at even higher energies for the W51 complex in the future, it would also provide further valuable insights into the origin of the UHE photons.

### Conflict of interest

The authors declare that they have no conflict of interest.

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### Author contributions

Zhe Li is the convener of this study and leading the observation data analysis. Kun Fang led the manuscript preparation and performed the hadronic model fitting, as well as the SNR and PWN interpretations. Cheng Liu analyzed the WCDA data and performed the cross-check. Silvia Celli discussed the young star cluster scenario. Felix Aharonian made crucial contributions to the theoretical interpretation. Yinxue Chai (supervised by Shaoru Zhang and Zhe Li) initially analyzed the data part from KM2A. Hui Zhu provided multi-wavelength data on the W51 region. Songzhan Chen, Shaoqiang Xi, and Shicong Hu gave useful suggestions on the background and diffusion analysis procedure. Yang Su helped provide the MWISP data covering a region of  $2^\circ \times 2^\circ$  centered at SNR W51C. The whole LHAASO collaboration contributed to the publication, with involvement at various stages ranging from the design, construction, and operation of the instrument, to the development and maintenance of all software for data calibration, data reconstruction, and data analysis. All authors reviewed, discussed, and commented on the present results and the manuscript.

### Appendix A. Supplementary materials

Supplementary materials to this article can be found online at <https://doi.org/10.1016/j.scib.2024.07.017>.

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