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PARTICLES AND FIELDS

A Tale of Cosmic Rays Narrated in γ Rays by *Fermi*

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Abstract Because cosmic rays are charged particles scrambled by magnetic fields, combining direct measurements with other observations is crucial to understanding their origin and propagation. As energetic particles traverse matter and electromagnetic fields, they leave marks in the form of neutral interaction products. Among those, γ rays trace interactions of nuclei that inelastically collide with interstellar gas, as well as of leptons that undergo Bremsstrahlung and inverse-Compton scattering. Data collected by the *Fermi* large area telescope (LAT) are therefore telling us the story of cosmic rays along their journey from sources through their home galaxies. Supernova remnants emerge as a notable γ-ray source population, and older remnants interacting with interstellar matter finally show strong evidence of the presence of accelerated nuclei. Yet the maximum energy attained by shock accelerators is poorly constrained by observations. Cygnus X, a massive star-forming region established by the LAT as housing cosmic-ray sources, provides a test case to study the impact of wind-driven turbulence on the early propagation. Interstellar emission resulting from the large-scale propagation of cosmic rays in the Milky Way is revealed in unprecedented detail that challenges some of the simple assumptions used for the modeling. Moreover, the cosmic-ray induced γ-ray luminosities of galaxies-scale quasi-linearly with their massive-star formation rates: the overall normalization of that relation below the calorimetric limit suggests that for most systems, a substantial fraction of energy in cosmic rays escapes into the intergalactic medium. The nuclear production models and the distribution of target gas and radiation fields, not determined precisely enough yet, are key to exploiting the full potential of γ-ray data. Nevertheless, data being collected by *Fermi* and complementary multiwavelength/multimessenger observations are bringing us ever closer to solving the cosmic-ray mystery.

Keywords Cosmic rays · Diffuse emission · Galaxies · Gamma rays: observations · Gamma rays: production · Interstellar medium · Milky Way · Superbubbles · Supernova remnants

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1 Introduction: on the Connection Between Cosmic Rays and γ Rays

Cosmic rays (CRs), high-energy particles filling the interstellar space in galaxies, are a product of the most energetic processes in the Universe, and also a fundamental constituent of the interstellar medium (ISM) [1]. Despite more than one century of investigation in this field, we are still struggling to understand which processes accelerate particles over more than ten decades in energy, which mechanisms rule their propagation, how they interact with the ISM and influence its evolution, and if they carry any traces of still unknown physical phenomena such as dark matter annihilation or decay.

The vast majority of CRs are charged particles, mostly nuclei. Disordered magnetic fields scramble their trajectories, so that direct measurements of CRs in the proximity of the Earth cannot directly identify their production sites. However, interactions of charged particles with gas and electromagnetic fields produce neutral secondaries that we can detect and use to trace them from the point of interaction.

Among neutral secondaries, γ rays play a crucial role because they trace the most energetic interactions and are relatively easy to detect, as opposed, e.g., to neutrinos. The most important processes to produce γ rays are (1) inelastic collisions between high-energy nucleons and gas nuclei that yield in the final states γ rays mostly due to the production and decay of neutral mesons (notably π^0), (2) Bremsstrahlung of high-energy electrons in the Coulomb fields of gas nuclei, and (3) inverse-Compton (IC) scattering of low-energy photons (cosmic microwave background, thermal emission from dust, and stellar radiation) by high-energy electrons.

The γ-ray sky at energies between 20 MeV and hundreds of GeV has been surveyed with unprecedented sensitivity and angular resolution over the past 5 years by the large area telescope (LAT) aboard the *Fermi Gamma-ray Space Telescope* [2, 3]. In this paper, I will review how LAT observations are complementing other multiwavelength and multimessenger data to tell us the story of CRs along their journey through the galaxies they originate from. I will focus on CRs with energies up to hundreds of TeV that are traced by γ rays detected by the LAT. I will summarize the main lessons learned from LAT observations and challenges for the coming years concerning CR acceleration in supernova remnants (SNRs), the early phases of CR life in massive-star forming regions, and the large-scale propagation of CRs in the Milky Way as well as in external galaxies.

2 Cosmic-Ray Acceleration in Supernova Remnants

SNRs are strongly advocated to be the most likely sources of CRs at least up to the *knee* in their overall spectrum at $\sim 3 \times 10^{15}$ eV (e.g., [4]). This was initially motivated by the fact that the observed rate of supernovae in the Milky Way of $\sim 1/50$ year^{-1} and their characteristic energy of 10^{44} J yields, on the assumption of 10 % conversion efficiency into accelerated particles, a power of a few 10^{33} W, i.e., the CR injection power inferred from the local CR density of 10^{-13} J m^{-3} and the propagation volume of 10^{62} m^3 and escape time of 10^8 years necessary to explain the elemental/isotopic abundances in the local CRs [5].

This fact turned into the so-called *SNR paradigm* thanks to the development of a comprehensive theory of nonlinear diffusive shock acceleration (NDSA) that explains quite successfully how SNRs can accelerate particles that subsequently undergo diffusive propagation in the Milky Way to reproduce the observed CR phenomenology (e.g., [6]).

Multiwavelength spectra of SNRs undoubtedly show the presence of accelerated electrons. The acceleration of nuclei was more elusive. It was unambiguously demonstrated only very recently for two middle-aged SNRs interacting with molecular clouds, W44 and IC443, thanks to the detection of the characteristic γ-ray spectral signature from π^0 decay by AGILE [7] and the LAT [8].

However, a question that remains to be answered is the maximum particle energy that SNRs can provide. This is important to connect NDSA theory with direct CR measurement, since the CR spectrum does not show any sizable features up to the *knee*. Hence, we expect a single acceleration mechanism and source class to dominate. The γ-ray spectrum of the Tycho SNR measured by the LAT [9], in addition to other multiwavelength observations, convincingly points to the presence of accelerated nuclei up to energies of $\sim 0.5 \times 10^{15}$ eV [10]. Indeed, NDSA theory predicts SNRs to be able to produce the bulk of CRs up to the knee (e.g., [11]). This prediction needs to be further investigated from the observational point of view using LAT data and data from TeV γ-ray telescopes to pinpoint PeV nuclei in or close to SNRs, and constrain the poorly understood process of escape from the shock (e.g., [12]).

Another major achievement by *Fermi* is the possibility to study SNRs as a γ-ray source population thanks to the detection of a large number of these objects. Thanks to its superior angular resolution, the LAT is also the first instrument in the GeV band able to clearly show in some objects the association between γ-ray emission (i.e., accelerated particles) and the shock region (e.g., [13]). Figure 1 shows some examples of broad-band γ-ray spectra of SNRs obtained by combining results from the LAT and data from various imaging atmospheric Cerenkov telescopes (IACTs).

Middle-aged ($\gtrsim 10^4$ year) SNRs interacting with dense interstellar material (e.g., IC443 and W44) are the brightest SNR class in the LAT energy range, while same-age objects interacting with lower-density matter have lower

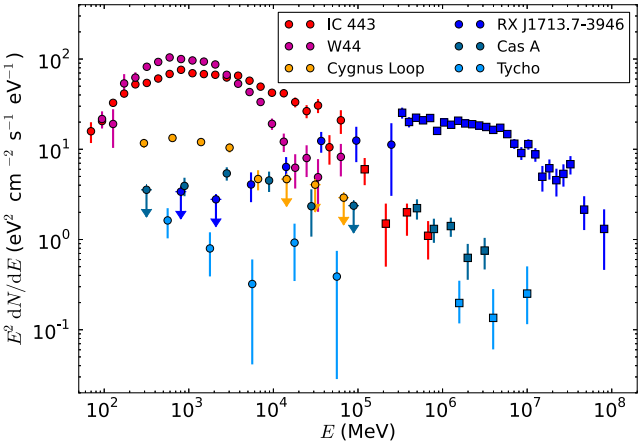

Fig. 1 Examples of broad-band γ-ray spectral energy distributions for some SNRs. *Circle points* are derived from LAT data, *square points* from IACT data (from H.E.S.S., VERITAS, or MAGIC). The SNRs are IC443 [8, 14], W44 [8], the Cygnus Loop [13], RX J1713.7−3946 [15, 16], Cas A [17, 18], and Tycho [9, 19]

γ-ray luminosities (e.g., the Cygnus Loop). Middle-aged SNRs show curved γ-ray spectra, indicative of a break or cutoff in the underlying particle spectrum at a few GeV, and the multiwavelength modeling favors the origin of the bulk of γ-ray emission from interactions of accelerated nuclei. The origin of the spectral curvature is not clear yet and may be attributed to the aging of the shockwave and evolution of properties of escaping particles (e.g., [12]), or to interactions of the shockwave with the surrounding neutral medium (e.g., [20, 21]).

Younger SNRs (with ages of centuries to a few 10^3 year), still expanding in relatively low-density environments, show γ-ray spectra extending as power laws to TeV energies (e.g., Cas A, Tycho, and RX J1713.7−3946), with weak evidence for harder spectra relative to older objects [22]. This may be tentatively explained by the prediction of NDSA theory that the maximum acceleration efficiency occurs toward the end of the initial free-expansion phase (lasting for $\sim 10^3$ years). Some of these young SNRs are more easily described by models in which γ-ray emission is predominantly produced by IC interactions of energetic electrons (e.g., RX J1713.7−3946).

So far, we are relying on a limited sample of cases well-studied individually. Progressing in understanding SNRs as a CR-source class and disentangling evolutionary and environmental effects affecting their γ-ray emission properties will require a comprehensive study of SNRs as a γ-ray source population. This is the objective of the forthcoming first LAT SNR Catalog [23, 24].

Preliminary results yield the identification of 12 γ-ray emitting SNRs, and the detection of > 40 SNR candidates. The aggregate properties of γ-ray SNRs already begin to challenge some of the simple assumptions used for the multiwavelength modeling. For instance, while for young SNRs, there is a correlation between γ-ray and radio spectral indices consistent with expectations for γ-ray and radio emission produced by particle populations with the same spectra, for older SNRs interacting with interstellar material, there is a different correlation pointing to two emitting particle populations with different properties.

3 Cosmic Rays in Massive-Star Forming Regions

The isotopic abundances in CRs show deviations from those in the solar system, e.g., a ratio ^{22}Ne/^{20}Ne larger by a factor of 5 than in the solar system, and similar deviations for trans-iron elements. This points to $\sim$ 20 % of CRs being accelerated in regions of massive-star formation (e.g., [25, 26]). Moreover, $\sim$ 80 % of supernovae are produced by the collapse of cores of massive stars, thus often in massive-star clusters, as opposed to thermonuclear explosions in isolated binary systems.

These indications gave credence to the hypothesis that some of the CRs may be accelerated in massive-star forming regions by the repeated action of SNR and stellar-wind shockwaves in *superbubbles* (e.g., [27]). Regardless of the acceleration mechanism, if CRs are produced in massive-star forming regions, their early propagation may be significantly influenced by the turbulent environment characterized by supersonic winds, ionization fronts, and enhanced radiation fields.

*Fermi*observations enabled us to image for the first time the early phases of CR life in the massive-star forming region of Cygnus X [28]. Cygnus X, located at 1.5 kpc from the solar system in the Local Arm of the Milky Way, hosts more than 100 O stars and several hundred B stars grouped in numerous clusters formed out of a reservoir of millions of solar masses of gas.

The LAT revealed an extended excess of γ-ray emission with a hard spectrum over the diffuse emission produced by CRs with a spectrum compatible with that of quiet local interstellar clouds near the solar system [29]. The morphology of this excess γ-ray emission closely follows that of the 50-pc interstellar cavities carved in the Cygnus complex by the activity of the stellar clusters and bounded by the photon-dominated regions visible at 8 ∝m [28].

This strongly suggests an interstellar origin for the excess, that, however, cannot be explained under the assumption that it is produced by interactions of CRs with a spectrum similar to that near the solar system, neither via nucleon-nucleon interactions (the measured spectrum is too hard) nor via IC scattering even in the enhanced radiation field in Cygnus X (the excess is too intense by a factor $\sim$ 50 and too hard). The hard spectrum points to CRs that recently underwent acceleration processes. Therefore, we concluded that the Cygnus X cavities form a cocoon of young CRs [28]. On the other hand, the CR population averaged over the whole Cygnus complex on a scale of $\sim$ 400 pc, as traced by *Fermi* measurements, is consistent with that in the local interstellar space [29] (see Fig. 2), suggesting an efficient confinement of the particles in the cocoon.

The observations were not sufficient to identify the source of the freshly accelerated particles. They may have been accelerated by a SNR, notably by G78.2 + 2.1, that lies in the same direction as the cocoon, even if their mutual relationship is not clear. Alternatively, they may have been accelerated in a distributed process by the multiple stellar wind shocks that are energetic enough and could effectively confine CRs in the region over timescales of $\sim 10^5$ years.

More data to look for possible spectral variations across the cocoon and theoretical advances in the modeling of particle transport in superbubble-like environments are required in order to achieve a deeper understanding of this phenomenon. However, the results so far confirm the long-standing hypothesis that massive-star forming regions

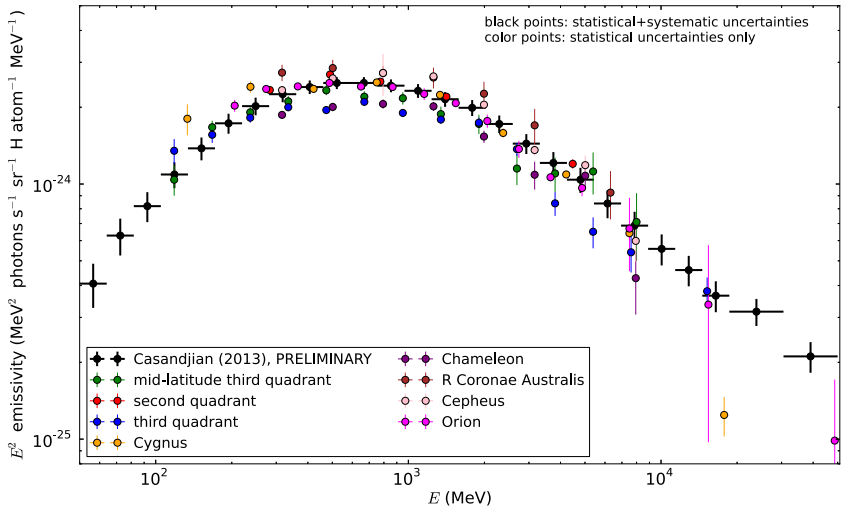

Fig. 2 Gamma-ray emissivity per H atom in the local interstellar space as measured for the whole sky at intermediate Galactic latitudes [49], a mid-latitude region in the third Galactic quadrant [45], nearby clouds in the Galactic plane in the second [44] and third [46] Galactic quadrants, the Cygnus complex [29], the R Coronae Australis and Cepheus clouds [47], and the Orion complex [48]

shelter CR acceleration, and provide a test case to advance understanding of CR propagation in the presence of wind-driven turbulence.

Milagro detected potentially extended >TeV emission from Cygnus X [30, 31], and ARGO extended the measurement down to $\sim$ 600 GeV [32]. The angular resolution of these two telescopes was not sufficient to establish whether there is a more extended diffuse contribution in addition to emission from the 0.2° source TeV J2032+4130, but they both measured a flux significantly higher than what IACTs reported for the latter [33]. Therefore, this excess emission may be the TeV counterpart to the *Fermi* cocoon. The upcoming survey of the northern sky by HAWC [34], thanks to its improved angular resolution, may shed light on the nature of TeV emission from Cygnus X. If a TeV counterpart to the *Fermi* cocoon is detected, this will help us to locate the particle acceleration site(s), disentangle whether the accelerated particles are electrons or nuclei, and constrain their maximum energies.

Other large massive-star clusters exist in the Milky Way and in nearby galaxies like the Large Magellanic Cloud. GeV and TeV emission was detected toward a few of them (e.g., [35–38]). Over the coming years, studies of diffuse emission from massive star forming regions by *Fermi* and present and future TeV telescopes, such as HAWC [34] and the Cerenkov telescope array (CTA) [39], will be key to understanding the acceleration and early propagation of CRs in such a turbulent environment.

4 Large-Scale Propagation of Cosmic Rays in the Milky Way

The history of large-scale CR propagation in the Milky Way is encoded in their composition that we can measure directly in the proximity of the solar system. Ratios of unstable to stable isotopes, such as ^{10}Be/^{9}Be, serve as radioactive clocks that constrain the residency time of CRs in the Milky Way to $\sim 10^7$ years. Ratios such as B/C show an overabundance of secondaries produced in inelastic nuclear interactions over primaries with respect to typical abundances in the solar system, pointing to interactions of CRs with a few g cm^{-2} of traversed interstellar material. These data are interpreted by assuming that CRs propagate in a halo surrounding the Milky Way occasionally interacting with the denser material in its disk (e.g., [41]).

It is widely accepted that large-scale CR propagation in the ISM is dominated by diffusion on disordered magnetic fields, with the possible inclusion of convection. Over the past years, this problem has been treated preferentially with numerical codes based on simplified yet realistic models of the Milky Way, such as GALPROP [40–42]. However, the inputs to such models, for instance the exact value and dependence on particle rigidity of the diffusion coefficient or the size of the propagation halo, are highly uncertain (e.g., [41, 43]). Interstellar γ-ray emission produced by CRs during their propagation can be used to characterize the properties of CRs (densities and spectra) throughout the Milky Way, and therefore constrain their origin and transport.

The interstellar space within $\sim$ 1 kpc of the solar system is a region uniquely suitable to study the interactions of CRs with well-resolved gas complexes in the Gould Belt and the local arm. Figure 2 shows the γ-ray emissivity, i.e., the γ-ray emission rate per H atom, derived by comparing LAT intensity maps with maps of the multiwavelength tracers of the ISM, including the column densities of atomic hydrogen derived from observations of its 21-cm line (see, e.g., [44]).

The emissivity traces the densities of CRs and encodes information about their spectrum. Taking into account the effect of solar modulation, the emissivity of local interstellar gas is consistent with predictions based on the CR spectra

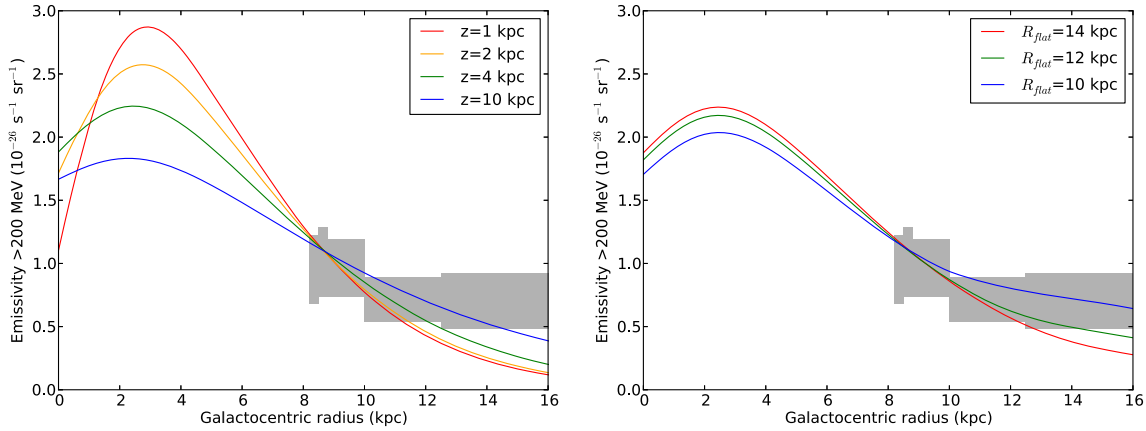

Fig. 3 The *gray band* shows the envelope of the measurements of the γ-ray emissivity at energies > 200 MeV as a function of Galactocentric radius from [29, 44, 46]. The *curves* show model predictions from [46] based on different values of the height of the CR propagation halo z (*left*, assuming a CR source distribution from SNR observations) and on the assumption that the CR source density is constant as a function of radius beyond R_{flat} (*right*, assuming $z = 4$ kpc)

directly measured near the Earth, and show that CR densities are uniform within $\lesssim 30$ % in the proximity of the solar system[1]. In fact, the local emissivity can be used to infer the local interstellar spectrum of CRs [49, 50] and serve as a "Rosetta stone" to interpret γ-ray measurements in terms of the underlying CR properties.

For protons, the interstellar spectrum can be determined independently from direct measurements, and used to constrain solar modulation in conjunction with the first direct measurements at the border of the heliosphere that are now becoming available [51]. Preliminary results [50] indicate good spectral agreement with direct measurements in the heliosphere above 10 GeV, with a modest $\lesssim 30$ % excess in absolute fluxes that may have various origins, including uncertainties in the cross sections and the gas tracers, as discussed later, and/or hidden systematic errors in the direct measurements themselves. This work shows evidence for deviations from a simple power law in particle momentum at energies of a few GeV, where direct measurements are more complicated to interpret due to solar modulation, confirming previous clues from elemental abundances (e.g., [41]).

The large-scale properties of diffuse γ-ray emission from the Milky Way were recently compared to a suite of GALPROP models [52], showing an approximate agreement between LAT data and model predictions within $\lesssim 30$ % over the whole sky. From this study, a range of source and propagation parameters consistent with data was established, but the level of degeneracy is high. In spite of the overall good agreement, deviations with respect to the models appear both on intermediate scales due to local peculiarities, such as the Cygnus X cocoon where freshly-accelerated particles are injected, and on large scales, highlighting limitations of the current models.

The most remarkable example is the "*Fermi* bubbles" [53], giant lobed structures apparently emanating from the Galactic center filled by energetic particles emitting in γ rays. The bubbles are probably powered by activity in or near the central region of the Milky Way, such as due to a past active state of the central black hole or to enhanced massive star formation. Substantial uncertainties in the morphological and spectral properties of the bubbles due to foreground emission from the Milky Way need to be taken into account in characterizing the properties of the underlying particle population [54].

Another remarkable example is given by an excess in emission from gas observed toward the outer region of the Milky Way [44, 46], where the density of putative CR sources, SNRs, or regions of massive-star formation, is greatly reduced. Figure 3 shows the profile of γ-ray emissivity as a function of Galactocentric radius. We used the Doppler shift or radio lines tracing interstellar gas to separate different cloud complexes along the line of sight, and, subsequently, to evaluate their γ-ray emissivity thanks to the morphological resemblance to the radio maps (e.g., [44]).

Figure 3 shows two possible solutions to the *gradient problem* in the outer Galaxy, i.e., the flat emissivity profile: a thick CR propagation halo with a height of ~ 10 kpc (at the upper limit of the range allowed by the ^{10}Be/^{9}Be ratio), or a flat CR source density in the outer Galaxy, at odds with multiwavelength observations of the putative sources. This issue may point again to the inadequacies

[1]The emissivity spectrum of the Chameleon cloud in [47] shows a larger deviation, that, however, was found to be due to analysis issues. An *erratum* has been accepted for publication.

of simplified propagation models to reproduce the detailed structures of the γ-ray sky, e.g., in this case, due to spatial variations of the diffusion coefficient possibly related to the dynamical coupling between CRs and interstellar turbulence [55, 56].

5 Cosmic Rays in External Galaxies and Beyond

Interstellar γ-ray emission is produced in external galaxies in the same way as in the Milky Way. Observations of external galaxies are very useful because they are free from the complications of viewing the Milky Way from inside and are well-suited to study the properties of the galaxies' aggregate emission. On the other hand, the limited angular resolution of the γ-ray instruments makes it difficult to separate interstellar emission from individual objects within galaxies, and especially from active galactic nuclei that are the largest known class of γ-ray sources.

Historically, observations of nearby galaxies by EGRET [57] demonstrated from the observational point of view that CRs below the *knee* are galactic in origin, since galaxies' γ-ray fluxes are not consistent with particle densities constant over the local group, as confirmed later by *Fermi* [58, 59].

The LAT brought a new quality to the subject, first of all making spatially resolved studies of nearby galaxies possible thanks to the improved angular resolution [58, 59]. Studies of the Large Magellanic Cloud based on LAT data [37, 58] showed how diffuse γ-ray emission intensities peak toward 30 Doradus, a conspicuous region of massive-star formation. Moreover, the γ-ray intensities from the Large Magellanic Cloud do not correlate well on a global scale with its neutral gas densities [58].

The LAT, with the detection of a few nearby galaxies, and more distant starbust galaxies, also enabled us to perform the first population studies in γ rays [60], and look for correlations with their luminosities at other wavelengths. LAT detections and upper limits on the fluxes from a sample of galaxies selected based on their star-formation rates [60] revealed a quasi-linear scaling between γ-ray luminosities and either radio or infrared (IR) luminosity in the 8–1,000-∝m band. The correlation is robust against the inclusion or not in the analysis of galaxies with known active nuclei.

This resembles the well-known IR-radio correlation (e.g., [61]). The latter is interpreted based on the idea that galaxies are electromagnetic *calorimeters*, which means that all the energy injected in the form of leptonic CRs is dissipated within galaxies and reemitted in the form of electromagnetic radiation, including radio synchrotron emission. Therefore, if CR acceleration is related to massive stars and/or the aftermaths of their final explosions, SNRs, the radio luminosity is expected to be proportional to IR luminosity, a proxy for star-formation rate due to dust heating by stellar radiation.

On the other hand, the quasi-linear relation between γ-ray and IR luminosity lies below the calorimetric limit derived assuming that all the energy injected in the form of hadronic CRs[2] is dissipated within galaxies and reemitted in the γ-ray domain. This possibly indicates that the final fate of most of CR nuclei is escaping from galaxies into the intergalactic medium, as formerly inferred from CR propagation models for the Milky Way [62]. Observational evidence based on 4 years of LAT data for the presence of CR nuclei in the intergalactic medium of galaxy clusters, injected by either member galaxies or intergalactic processes, is still very weak [63].

Starbust galaxies, with high rates of massive-star formation, are the only ones found to be close to the calorimetric limit in γ rays. In contrast to more quiet local galaxies, they also have γ-ray spectra harder than the Milky Way, extending in some cases to TeV energies (e.g., [64]). These facts suggest that in starbust galaxies, energy losses of CR nuclei may not be dominated by diffusive transport, as in the Milky Way, but rather by energy-independent mechanisms.

6 What else Do We Need to Get the Most Out of γ-Ray Observations?

The LAT brought high-energy γ-ray astronomy from a science still dominated by limited photon statistics to a point where systematic uncertainties often play the dominant role. In addition to uncertainties inherent to the γ-ray measurements, like those in the instrument effective areas or backgrounds, there are some that depend from other measurements. I will summarize here the most relevant ones that we could improve on in the near future in order to exploit the full potential of γ-ray measurements to learn about CR physics.

Uncertainties can be attributed to the targets for γ-ray production, both gas and interstellar radiation fields. While substantial progress in the interpretation of γ-ray observations for individual objects, such as SNRs, can be often achieved only on a case-by-case basis, some general properties of ISM tracers may soon be better constrained by observations and advances in theory/simulations, helping us to better understand CR nuclei using γ-ray data.

Interstellar gas is most often traced by combining the 21-cm line of H I to trace the neutral atomic gas, the 2.6-mm line of CO as a surrogate of neutral molecular gas, and different dust tracers that serve to account for gas invisible to the two lines (either opaque or self-absorbed H I or CO-dark

[2]The estimate requires assumptions on the relation between IR/radio luminosity and star-formation rate, and also assumes the canonical supernova energy of 10^{44} J converted with 10 % efficiency into accelerated particles. See [60] for details.

H_2). All of these tracers have known limitations. Forthcoming high-resolution H I data [65] and improved dust maps obtained from the *Planck* survey (e.g., [66]) for the whole sky are going to be of great use for γ-ray astronomers.

A major source of uncertainty in the determination of the CR content of the Milky Way at large scale currently is the determination of H I column densities from the 21-cm line, subject to approximations in the analytic handling of the radiative transfer equation (e.g., [46, 67]). There is no clear path to improve on this issue, but it may profit from the combination of the aforementioned survey releases and numerical simulations of the ISM (e.g., [68]) to set the treatment of H I opacity on a more physical ground than the current assumptions of effective optical thickness of the neutral medium or of a uniform spin temperature.

Molecular clouds provide more localized targets for CR interactions that could be useful, in principle, to identify intermediate-scale enhancements of particles. Unfortunately, the column densities of H_2 present larger uncertainties, of a factor of a few on average, since we rely on CO as a surrogate tracer. Figure 4 shows X_{CO}, the ratio between H_2 column densities and the intensities of the CO line, as a function of Galactocentric radius in the Milky Way, combining results from LAT observations with other values/models from the literature.

Indeed, γ-ray measurements can be used to derive X_{CO} as the emissivity per CO intensity unit divided by twice the emissivity per H atom for atomic clouds at approximately the same locations. This assumes that CRs can penetrate molecular clouds uniformly to their cores and that the variations of CR densities are small over the scales of interstellar complexes. Note that the green band in Figure 4 from [52], on the other hand, represents a range of values used to model LAT data based on some *a priori* assumptions on the CR distribution in the Milky Way; thus it will be possible to extract more stringent constraints on X_{CO} from LAT data.

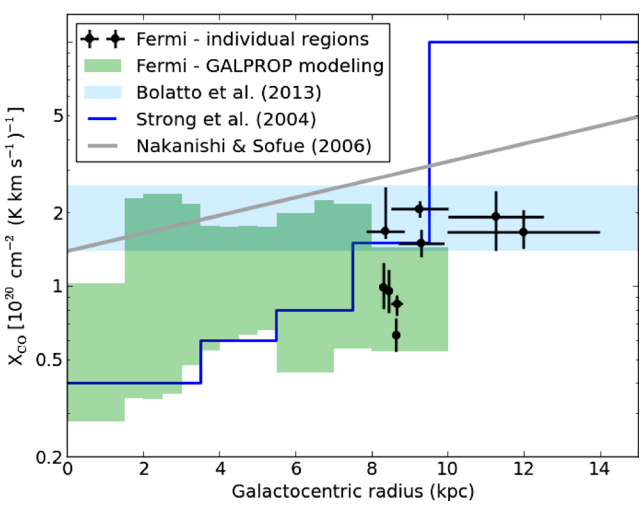

Fig. 4 X_{CO} as a function of Galactocentric radius in the Milky Way. *Black points* are derived from LAT observations of selected clouds and complexes [29, 44, 46, 47]. The *green band* shows the range of X_{CO} values used to model large-scale diffuse γ-ray emission as observed by the LAT using GALPROP [52]. The *light blue band* represents the value for X_{CO} in the Milky Way and its uncertainty recently recommended by [69]. The *blue* [70] and *gray* [71] *lines* are two models not based on γ-ray data used in the literature to study diffuse γ-ray emission

LAT observations are consistent with a constant X_{CO} for clouds in the disk of the Milky Way within a few kpc of the solar system [69]. However, the X_{CO} values inferred from LAT data for well-resolved nearby clouds are lower by a factor $\sim$ 2 [44, 47]. The origin of this difference is still under investigation. There is an indication from γ rays that X_{CO} drops by about one order of magnitude in the innermost region of the Milky Way, in agreement with infrared observations of external galaxies [72]. Figure 4 also illustrates how estimates of X_{CO} based on observations at other wavelengths (like those from virial masses inferred from the 2.6-mm CO line, or from infrared emission from dust as a mass tracer) need to be critically evaluated in relation to γ-ray observations.

Targets, however, are not the only issue we need to deal with. While the γ-ray yield from electromagnetic interactions can be calculated with high precision, there exist significant uncertainties related to nucleon-nucleon interactions, that are, in some cases, comparable to uncertainties in the γ-ray measurements by the LAT [49, 50].

Nuclear production models rely on a set of measurements that are limited in energy coverage, angular coverage around the interaction point, and bullet/target elements. Theoretical frameworks bridging those limited sets of measurements are used to predict γ-ray yields over all energies, directions and from interactions of all elements in CRs and the ISM. Yet differences between alternative nuclear production models in some cases turn out to be larger than the uncertainties intrinsic to the γ-ray measurements (e.g., [73, 74]).

Recent accelerator-based measurements are helping to constrain nuclear production models at the highest energies accessible [75]. Those measurements are very helpful to interpret TeV γ-ray data. Nuclear production models for lower energies of interest to interpret LAT data, however, depend mostly on accelerator measurements from the 60s and the 70s [76, 77]. In order to fully exploit the potential of *Fermi* data to understand CR physics, nuclear production models need to be critically evaluated against the existing accelerator data, and the relative uncertainties need to be taken into account in γ-ray analyses and propagated to the final results. Accelerator experiments dedicated to reduce these uncertainties in the energy range most relevant for *Fermi* would also be highly beneficial to the γ-ray community.

7 Looking Forward: a γ-Ray Bright Future

Despite all the uncertainties, as I discussed in this article data from the LAT, together with other multiwavelength and multimessenger observations, are illuminating several aspects of CR life, and are going to continue being a treasure trove in the coming years.

This will be facilitated by continued accumulation of γ-ray data by the LAT, especially in the energy range $>$ 10 GeV where skymaps are still photon starved, bridging satellite-based observations to those by current and future ground-based instruments such as CTA and HAWC. The highest-energy end of the LAT energy range is interesting both to study CR electrons through IC emission from the Milky Way that becomes dominant over the emission from gas, and to search for further evidence of freshly accelerated CRs in selected regions following the detection in Cygnus X.

The ongoing revision of the LAT event-level analysis and subsequent event selection based on the experience with data gained in the prime phase of the mission [78] is going to bring a new quality to LAT data, providing increased acceptance for γ rays, and a better control of backgrounds and instrumental systematics. The anticipated improvements in the angular resolution at low energies will also be key to disentangling sources and diffuse emission in the Milky Way disk, especially toward massive-star forming regions and the inner Galaxy.

This will be most useful in the energy range $<$ 100 MeV to bridge LAT observations with those by Compton telescopes such as COMPTEL [79] and potential future missions such as GRIPS [80]. This will enable us to study in more detail the spectral roll off of the π^0 decay component due to nucleon-nucleon interactions, both in discrete sources such as SNRs and in diffuse emission from the ISM. Diffuse emission produced by Bremsstrahlung is going to be a probe of the CR electron population complementary to IC and synchrotron emission observed in radio to microwaves (e.g., [81]).

In conclusion, with the many facets of CR acceleration in SNRs, the recent observations of freshly-accelerated CRs in massive-star forming regions, interstellar emission from the Milky Way revealed in unprecedented detail, a growing population of star-forming galaxies detected in γ rays, and possibly new phenomena related to CRs awaiting discovery thanks to the ongoing survey by *Fermi* and complementary surveys by the current generation of ground-based γ-ray telescopes, as well as the forthcoming surveys by HAWC and CTA, the future of γ-ray astronomy looks bright and promises to bring us ever closer to understand the mysteries of CRs.

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References

1. K. M. Ferrière, Rev. Mod. Phys. **73**, 1031–1066 (2001)
2. M. Ackermann et al., ApJS. **203**, 4 (2012)
3. W. B. Atwood et al., ApJ. **697**, 1071–1102 (2009)
4. L. O. Drury, Astropart. Phys. **39**, 52–60 (2012)
5. V. L. Ginzburg, S. I. Syrovatskii, *The Origin of Cosmic Rays*, (1964)
6. P. Blasi, Nuc. Phys. B - Proc. Suppl. **239–240**, 140–147 (2013)
7. A. Giuliani et al., ApJL. **742**, L30 (2011)
8. M. Ackermann et al., Sci. **339**, 807–811 (2013)
9. F. Giordano et al., ApJL. **744**, L2 (2012)
10. G. Morlino, D. Caprioli, A&A. **538**, A81 (2012)
11. P. Blasi, E. Amato, JCAP. **1**, 010 (2012)
12. S. Gabici, F. A. Aharonian, S. Casanova, MNRAS. **396**, 1629–1639 (2009)
13. H. Katagiri et al., ApJ. **741**, 44 (2011)
14. J. Albert et al., ApJL. **664**, L87–L90 (2007)
15. A. A. Abdo et al., ApJ. **734**, 28 (2011)
16. F. Aharonian et al., A&A. **464**, 235–243 (2007)
17. A. A. Abdo et al., ApJL. **710**, L92–L97 (2010)
18. T. B. Humensky, Vol. 1085, ed. by F. A. Aharonian, W. Hofmann, F. Rieger, *American Institute of Physics Conference Series*, (2008), pp. 357–360
19. V. A. Acciari et al., ApJ. **714**, 163–169 (2010)
20. Y. Uchiyama, R. D. Blandford, S. Funk, H. Tajima, T. Tanaka, ApJL. **723**, L122–L126 (2010)
21. M. A. Malkov, P. H. Diamond, R. Z. Sagdeev, Nat. Commun. **2**, 194 (2011)
22. C. D. Dermer, G. Powale, A&A. **553**, A34 (2013)
23. J. W. Hewitt et al. this conference, 0785, arXiv:1307.6570
24. T. J. Brandt et al. this conference, 0786, arXiv:1307.6571
25. W. R. Binns et al., SSRv. **130**, 439–449 (2007)
26. W. R. Binns et al. this conference, 0646
27. A. M. Bykov, G. D. Fleishman, MNRAS. **255**, 269–275 (1992)
28. M. Ackermann et al., Sci. **334**, 1103 (2011)
29. M. Ackermann, others., A&A. **538**, A71 (2012)
30. A. A. Abdo et al., ApJL. **658**, L33–L36 (2007)
31. A. A. Abdo et al., ApJ. **753**, 159 (2012)
32. S. Vernetto et al. this conference, 0758
33. J. Albert et al., ApJL. **675**, L25–L28 (2008)
34. J. A. Goodman, Vol. 1516, ed. by J. F. Ormes, *American Institute of Physics Conference Series*, (2013), pp. 265–268
35. F. Aharonian et al., Nat. **439**, 695–698 (2006)
36. F. Aharonian et al., A&A. **467**, 1075–1080 (2007)
37. E. J. Murphy, T. A. Porter, I. V. Moskalenko, G. Helou, A. W. Strong, ApJ. **750**, 126 (2012)
38. A. Abramowski, otehrs, A&A. **537**, A114 (2012)
39. M. Actis, otehrs, Exp. Astron. **32**, 193–316 (2011)
40. I. V. Moskalenko, A. W. Strong, O. Reimer, A&A. **338**, L75–L78 (1998)
41. A. W. Strong, I. V. Moskalenko, V. S. Ptuskin, Annu. Rev. Nucl. Part S. **57**, 285–327 (2007)

42. I. V. Moskalenko et al. this conferece, 0822
43. D. Maurin, A. Putze, L. Derome, A&A. **516**, A67 (2010)
44. A. A. Abdo et al., ApJ. **710**, 133–149 (2010)
45. A. A. Abdo et al., ApJ. **703**, 1249–1256 (2009)
46. M. Ackermann et al., ApJ. **726**, 81 (2011)
47. M. Ackermann et al., ApJ. **755**, 22 (2012)
48. M. Ackermann et al., ApJ. **756**, 4 (2012)
49. J.-M. Casandjian. this conference, 0966
50. C. D. Dermer et al. this conference, 1165, arXiv:1307.0497
51. E. Stone et al., Sci. **341**, 150–153 (2013)
52. M. Ackermann et al., ApJ. **750**, 3 (2012)
53. M. Su, T. R. Slatyer, D. P. Finkbeiner, ApJ. **724**, 1044–1082 (2010)
54. A. Franckowiak et al. this conference, 0996
55. D. Breitschwerdt, V. A. Dogiel, H. J. Völk, A&A. **385**, 216–238 (2002)
56. C. Evoli, D. Gaggero, D. Grasso, L. Maccione, Phys. Rev. Lett. **21, 211102** (2012)
57. Y. C. Lin et al., ApJS. **105**, 331 (1996)
58. A. A. Abdo et al., A&A. **512**, A7 (2010)
59. A. A. Abdo et al., A&A. **523**, A46 (2010)
60. M. Ackermann et al., ApJ. **755**, 164 (2012)
61. M. J. Jarvis et al., MNRAS. **409**, 92–101 (2010)
62. A. W. Strong et al., ApJL. **722**, L58–L63 (2010)
63. M. Ackermann et al. arXiv:1308.5654 (2013)
64. V. A. Acciari et al., Nat. **462**, 770–772 (2009)
65. P. M. W. Kalberla et al., A&A. **521**, A17 (2010)
66. P. A. R. Ade et al., A&A. **536**, A19 (2011)
67. L. Tibaldo et al., Nuovo Cimento. **C 24**, 3 (2011). arXiv:1012.0455
68. E. Saury, M.-A. Miville-Deschênes, P. Hennebelle, E. Audit, W. Schmidt. arXiv:1301.3446 (2013)
69. A. D. Bolatto, M. Wolfire, A. K. Leroy, ARAA. **51**, 207–268 (2013)
70. A. W. Strong, I. V. Moskalenko, O. Reimer, S. Digel, R. Diehl, A&A. **422**, L47–L50 (2004)
71. H. Nakanishi, Y. Sofue, PASJ. **58**, 847–860 (2006)
72. K. M. Sandstrom et al., ApJ (2013). arXiv:1212.1208
73. M. Kachelrieß, S. Ostapchenko, PRD. **86**, 4, 043004 (2012)
74. C. D. Dermer, otehrs, ed. by N. Omodei, T. J. Brandt, C. Wilson-Hodge, *Proceedings of 2012 Fermi Symposium eConf C121028*, (2013). arXiv:1303.6482
75. H. Sato, T. Shibata, R. Yamazaki, Astropar. Phys. **36**, 83–92 (2012)
76. F. W. Stecker, ApJ. **185**, 499–504 (1973)
77. C. D. Dermer, A&A. **157**, 223–229 (1986)
78. W. Atwood et al., ed. by N. Omodei, T. J. Brandt, C. Wilson-Hodge, *Proceedings of 2012 Fermi Symposium eConf C121028*, (2013). arXiv:1303.3514
79. V. Schönfelder, NewAR. **48**, 193–198 (2004)
80. J. Greiner, otehrs, Exp. Astron. **34**, 551–582 (2012)
81. E. Orlando, A. W. Strong, MNRAS (2013). arXiv:2974.1309