Probing the galactic cosmic-ray density with current and future γ-ray instruments

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ABSTRACT

Context. Cosmic Rays (CRs) propagating through dense molecular clouds (MCs) produce gamma-rays which carry direct information about the CR distribution throughout the Galaxy. Observations of gamma-rays in different energy bands allow exploration of the average CR density in the Galactic Disk, the so-called level of the "CR Sea". Fermi-LAT observations have demonstrated the method’s feasibility based on two dozen MCs in our Galaxy. However, the potential of Fermi-LAT is limited by the most massive and relatively nearby MCs; thus, the current observations cover only a tiny fraction of the Milky Way.

Aims. In this paper, we study the prospects of expanding the CR measurements to very and ultra-high energies and remote parts of the Galaxy with the current and next-generation detectors.

Methods. Based on calculations of fluxes expected from MCs, we formulate the requirements to the sensitivity of the post-Fermi-LAT detectors to map GeV-TeV CRs in the Galactic Disk. We also explore the potential of the current and future air-shower and atmospheric Cherenkov telescope arrays for the extension of CR studies to multi-TeV and PeV energy bands.

Results. We demonstrate that the improvement of the Fermi-LAT sensitivity by a factor of a few would allow a dramatic increase in the number of detectable MCs covering almost the entire Galaxy. The recently completed LHAASO should be able to take the first CR probes at PeV energies in the coming five years or so.

Key words. cosmic rays, Gamma rays: ISM, ISM: clouds

1. Introduction

The paradigm of Galactic cosmic rays (CRs) assumes that the locally measured CR density (ρ\textsubscript{CR}(1GeV) \simeq 1 eV/cm\textsuperscript{3}), represents the average level of CRs in the Galactic Disk (GD) (see, e.g. Amato & Casanova (2021)). During their confinement in the GD, CRs mix and lose track of their production sites, creating the so-called "CR sea". The spatial distribution of CRs in the Milky Way depends on the distributions of CR sources and the diffusion coefficient characterizing the CR propagation in GD. It is believed that the mixture of CRs caused by diffusion is so effective that one should expect uniform distribution of CRs throughout the Galaxy with almost constant level of the "CR sea". However, significant deviations of the density cannot be excluded both on small (tens of parsecs) scales because of the concentration of active or recent CR accelerators and on large (kiloparsec) scales due to the spatial variations of the CR diffusion coefficient.

The locally measured CR fluxes give direct information about the "CR sea level" only in a single point in the Milky Way. Meanwhile the measurements of the "CR sea level" throughout the Galaxy is of paramount importance. Low-energy (MeV/GeV) CRs play a significant role in the regulation of the ionization, chemistry, and the dynamics of the gas and dust, and consequently on the star and planet formation (Padovani et al. 2020). Moreover, CRs might have a non-negligible impact on the habitability of planets around other stars (Atri et al. 2014). At very high energies, the influence of CRs on these processes is less pronounced. However, the information about the distribution of highest energy CRs in the GD is essential for searching for CR TeVatrons and PeVatrons in the Milky Way.

Gamma-ray astronomy provides a unique channel for investigating the distribution of CRs far from the Solar System. Of particular interest is the gamma-ray emission produced at interactions of CRs with the interstellar medium (ISM) which provide straightforward information on the CR content at the location of the interaction. The observations with the Fermi-Large Area Telescope (LAT) demonstrated the feasibility of this method: CR densities have been extracted both from studies of the diffuse gamma-ray emission (Acero et al. 2016; Yang et al. 2016; Pothast et al. 2018) and from giant molecular clouds (GMCs) (Yang et al. 2015; Neronov et al. 2017; Aharonian et al. 2020; Peron et al. 2021). The latter, being small regions of enhanced gas density, provide localized information on the CR content with accuracy better than 100 pc.

Fermi-LAT is the only instrument that succeeded in extensively measuring the γ-ray flux from "passive", i.e. a cloud without having in the proximity of currently operating CR sources, GMCs. Yet, the detection is limited to exceptionally massive (\geq 10\textsuperscript{6} M\textsubscript{☉}) or nearby (d \leq 1 kpc) clouds, if the illuminating CR flux coincides with the local flux of cosmic rays, J\textsubscript{⊙}. The soft power-law spectrum of the "CR sea" (α\textsubscript{⊙} \sim 2.7) makes the studies at TeV and higher energies very difficult. The HAWC Collaboration reported upper flux limits from local molecular clouds (Abeysekara et al. 2021) which agree with the above assessment. Meanwhile, the H.E.S.S. Collaboration reported the detection at TeV energies of a GMC located in the galactic plane that shows
enhanced emission at GeV energies (Sinha et al. 2021). The advent of new and improved γ-ray instruments opens up new possibilities for the exploration of the sea of galactic cosmic rays in the near future. The Cherenkov Telescope Array (CTA) is designed to reach a sensitivity 10 times better than H.E.S.S., which is promising for detection of at least a few "passive" molecular clouds. Even more optimistic assessment can be applied to ultra-high-energy (UHE) gamma-rays thanks to the dramatic improvement of the flux sensitivity above 100 TeV by the Large High Altitude Air Shower Observatory (LHAASO) (Cao 2021).

Below we discuss the perspectives of detection of gamma-rays from GMCs in high, very-high and ultra-high energy bands.

2. Cosmic Ray interaction in molecular clouds

The inelastic interaction of CRs with the interstellar gas result in production of secondary unstable products, first of all "heavier"; consequently the nuclear enhancement factor \( \xi_N \) increases with energy. The significant uncertainty in the CR composition in the knee region introduces non-negligible uncertainty in \( \xi_N \). The calculations based on the available CR data show that \( \xi_N \) progressively increases from 1.8 at 10 GeV to \( \approx 2.6 \) at 1 PeV.

The third parameter that determines the cloud’s flux is \( A = M_5/d_{\text{kp}} \), which is the measure of the column density of the gas embedded in the cloud. Indeed, given that \( M = N_{\text{col}} \theta \), we have \( A \propto N_{\text{col}} \theta \) where \( \theta \) is the angular area of the considered region. It can be presented in the form:

\[
A = 8 \times 10^{-20} \left( \frac{N_{\text{col}}(l, \theta)}{\text{cm}^{-2}} \right) \left( \frac{d\theta}{180} \right)^2
\]

where \( dl \) and \( db \) are the pixel size of the gas tracer map. Remarkably, \( A \) is independent of uncertainties both in the mass of the cloud and the distance. The only relevant uncertainty is related to the column density and comes from the tracers of molecular gas. The most commonly employed tracers are the \(^{12}\text{CO} (J=1\rightarrow0)\) line that brings an uncertainty of the order of 30% (Bolatto et al. 2013) in the gas density and the dust opacity with an uncertainty that amounts to ~20% (Ade et al. 2011).

3. Molecular Clouds in the Milky Way

From the recent analysis of the all-Galaxy CO survey of Dame, Hartmann and Thaddeus (Dame et al. 2000), Miville-Deschênes et al. (2016) identified more than 8000 MCs distributed all throughout the galactic plane. When inspecting the clouds of Miville-Deschênes et al. (2016), hereafter MD16, we see that most of the clouds have a low A parameter (see Fig 2), below 0.4, which was determined in Aharonian et al. (2020) to be a safe threshold for spectral measurements of clouds of different extensions, located both in the inner and outer parts of the Galaxy. These considerations were based on the assumption that the level of CRs that illuminates the cloud is coincident with the local level of CR, \( J_0 \), which was taken as a reference value. Among the M16 catalog clouds, less than 1% is above the detection threshold of Fermi-LAT; the fraction is even lower when considering...
only the inner ($|l| < 60^\circ$) Galactic regions (~0.3%). For the outer Galaxy, the threshold can be lowered by a factor of 2. However this part of the Galaxy hosts less dense clouds, with $A$ parameters in most cases lower than 0.6 and which overcomes the detection threshold only for the ~1% of the cases, even when lowering the threshold to $A = 0.2$. This means that most of the "CR Sea" cannot be explored by Fermi-LAT. In particular, ~15% of the molecular clouds, corresponding to more than 1000 MCs, have an $A$ factor between 0.1 and 0.4, just below the Fermi-LAT detection threshold.

In addition to emissivity, source confusion affects the detectability of clouds in $\gamma$-rays. Confusion can arise both due to the proximity of known $\gamma$-ray sources, and due to other clouds located on the same line of sight.

### 3.1. Overlaps with other gamma ray sources

We included into consideration all reported GeV and TeV $\gamma$-ray sources from the 4FGL (Fermi-LAT; The Fermi-LAT collaboration (2019)), HGPS (HESS Galactic Plane Survey, Abdalla et al. (2018)) and the 3HWC (HAWC; Albert et al. (2020)) catalogs which lie within the radius of 1.1 $\theta$, where $\theta$ is the angular size of the cloud:

- 75% of clouds do not have an overlapping source
- 3% of clouds have at least one overlapping known source
- 22% of clouds have only unidentified overlapping sources
- 63% of the clouds do not have nearby sources within 0.5$^\circ$.

Clouds without nearby sources are ideal to test the "CR Sea", even though this does not exclude possible contributions of yet unresolved gamma-ray sources.

### 3.2. Fraction of gas on the line of sight

Differently from the smoothly distributed atomic gas, the molecular component of the interstellar medium (ISM) is clumpy and mostly concentrated in dense clouds. Miville-Deschênes et al. (2016) pointed out that the line of sight column densities in most (~60%) directions are contributed by three or fewer molecular clouds; in the 20% of cases, the column density is dominated by a single cloud. Following the approach proposed by Peron et al. (2021), one can derive a relation between the maximum fraction of back- and fore-ground gas ($X$) which can be on the line of sight of a cloud and the level of excess ($N$) with respect to the local $\gamma$-ray emissivity ($\phi_0(J_0)$), which can be detected:

$$X < \frac{0.7N}{0.7N + 1.3}$$

For example, if a cloud has an emissivity larger than the nominal value, by a factor of $N = 4$, it would be detected if the fraction of background gas is $X < 0.68$ or, in other words, if the fraction of column density belonging to the cloud is at least 32%. For detection of the local CR Sea in molecular clouds ($N = 1$), the fraction of gas in the cloud has to be at least 65%. This guarantees the distinction of the cloud above the background gas, even without subtracting the contribution of the latter. Otherwise, the flux of the cloud, even if enhanced, would be masked by the $\gamma$-ray flux of the back- and foreground gas. To avoid this, it is necessary to model the back- and fore-ground gas as a separate source, as done for example in Aharonian et al. (2020). This approach, however, is subject to large uncertainties of the CO and HI measurements, which are the only tracers that can be used for 3-dimensional decomposition. Notice nevertheless that, even without a 3-dimensional decomposition, measuring a flux similar to $J_0$ coming from a column of gas, is a strong indication that the entire column is emitting at a similar level as the local CR sea. The local flux can be considered a minimum level, as no lower flux has been recorded so far, except for the outermost part of the Galaxy, which are far from the highest concentration of Supernova Remnants (SNRs) and Pulsar Wind Nebulae (PWNe).

We calculated the fraction of gas belonging to each cloud of the MD16 catalog relative to the total gas in the l.o.s. included in the area of the cloud from the brightness of the CO, $W_{CO}$:

$$\rho = \frac{\int_{-\theta/2}^{+\theta/2} d\theta \int_{\phi_{-\theta/2}}^{\phi_{+\theta/2}} db \int_{-\theta/2}^{\theta/2} dv W_{CO}(l, b, c)}{\int_{-\theta/2}^{+\theta/2} d\theta \int_{\phi_{-\theta/2}}^{\phi_{+\theta/2}} db \int_{-\theta/2}^{\theta/2} dv W_{CO}(l, b, c)}.$$
The potential of current gamma-ray instruments

Fermi-LAT is a powerful large field-of-view gamma-ray detector with the best performance at GeV energies. It is well designed to explore extended galactic sources, particularly SNRs and PWNe. This also concerns GMCs; however, the sensitivity of Fermi-LAT is at the margin of detection of gamma-rays from only a handful GMCs unless the CR density in the vicinity of the clouds does not substantially exceed the local level. Another problem is the energy coverage. Because of the steep spectrum and the limited detection area of Fermi-LAT, the detection of gamma-rays even from the most favorable "passive" GMCs with \( A \sim 1 \) cannot be extended beyond 0.1 TeV. The range of TeV energies is the domain of ground-based detectors - Imaging Atmospheric Cherenkov Telescopes (IACTs) and air shower particle arrays. However, for the current detectors, particularly HESS and HAWC, GMCs illuminated by \( J_0 \) are not accessible.

This can be seen in Fig. 4 where the flux sensitivities of the currently operating detectors are shown together with the flux induced by the local CR Sea on a cloud with \( A = 1 \), calculated with Eq.(1). In the plot are displayed: the sensitivity achieved after 10 years observations with Fermi-LAT for the inner \( (l, b = (0, 0); \text{dark red}) \) and outer \( (l, b = (0, 30); \text{light red}) \) Galaxy (Maldera et al. 2019); the H.E.S.S. sensitivity for 100 hours observation with the 4-telescopes configuration (solid yellow) (Funk & Hinton 2013) and the preliminary calculation of the sensitivity for the 5-telescopes configuration (yellow dashed; Holler et al. (2015)); the HAWC sensitivity for 5 years of observations (green;HAWC (2020)); and the LHAASO sensitivity for 1-year observations (magenta; Di Sciascio (2016)). The γ-ray flux of the given cloud exceeds the sensitivity of current instruments only at GeV energies.

The condition for visibility of a molecular cloud can be determined by imposing that the flux of a cloud is higher or equal than the sensitivity, \( S(t, E) \), calculated for a certain exposure time, \( t \):

\[
F(E) \geq S(t, E)
\]

\[
A \phi_t(E) \geq \sqrt{\frac{t_0}{t}} S_0(E)
\]

\[
A \sqrt{\frac{t}{t_0}} \geq \frac{S(E)}{\phi_t(E)} = R_0(E)
\]

here \( S_0 \) is the sensitivity calculated at a specific exposure \( t_0 \). In this sense \( R_0 \) represents a condition for visibility as it is the minimum ratio to detect a cloud of \( A \sim 1 \), which is characterized by a emissivity \( \phi_t \) with an instrument of sensitivity \( S_0(E) \) calculated for a \( t_0 \)-long exposure.

The values for \( R_0 \) for the current γ-ray instruments are plotted (dotted curves) in Fig 6, for the assumption of the local gamma-ray emissivity \( \phi_t = \phi_t(10^3) \). One can see that in order to measure a similar emissivity as the local one with the current TeV instruments, at least a \( R_0 \) of ~ 3 should be obtained. No single cloud in the Galaxy is characterized by \( A \sim 3 \), except for some of the Gould Belt’s clouds. However, these nearby clouds are very extended, thus the sensitivity is significantly reduced. The sensitivity for a source of extension \( \theta \) compared to the point-like source is worsened by the factor:

\[
\omega(E, \theta) = \sqrt{\theta^2 + \sigma_{PSF}^2(E)}
\]

\[
\sigma_{PSF} = \frac{\sigma_{PSF}(E)}{\epsilon(E)}
\]

where \( \sigma_{PSF} \) is the instrument’s point spread function. This results in a stricter condition on the visibility factor:

\[
R(E, \theta) = \omega(\theta, E) R_0 = \omega(\theta, E) \frac{S_0(E)}{F_0(E)}
\]

The worsening is especially significant for Imaging air Cherenkov telescopes (IACTs) having the best angular resolution of 0.05-0.1° or better (see the top panel of Fig 7). The effect is less dramatic for water Cherenkov (WC) detectors, which have a point spread function (PSF) of 0.1-0.3°, comparable to
the Fermi-LAT one and to the typical angular extensions of most of the clouds in the Galactic plane.

The exposure time is another important factor for the detectability of GMCs. IACTs are pointed telescopes with a small (a few degrees) FoV, while WC detectors cover simultaneously a significant fraction of the sky. The typical exposure time for specific segments of the Galactic Plane during the survey of the latter by IACTs over several years could be as large as 100 hours, which however is not sufficient to detect TeV gamma-rays from "passive" GMCs if illuminated by the local CR flux.

The exposure time of a large fraction of clouds in the Galaxy by large FoV ground-based air shower particle detectors is much larger; it can be as large as 2000 hours per year (approximately 6 hours per night). Nevertheless, to observe passive clouds with HAWC, at least a factor $R = 10$ is needed, which is too large to be reached only with the exposure time increase.

The recently completed Water Cherenkov Detector Array (WCDA) of LHAASO will be able to detect a limited number of passive GMCs between 1 and 10 TeV. A breakthrough is expected at higher energies, thanks to the superior sensitivity of the KM2A (square km array) of LHAASO. For KM2A, $R \lesssim 1$ after five years of observations, making the ultrahigh energies as expected at higher energies, thanks to the superior sensitivity of KM2A (square km array) of LHAASO.

The detectability of a cloud in $\gamma$-rays is significantly improved in the case of location of the cloud in the environment with enhanced CR density caused by the presence in the proximity of recent and currently operating accelerator(s). Runaway CRs, i.e. particles which already have left the accelerator and injected into the circumstellar medium have been registered both at GeV and TeV energies in the vicinity of some middle-aged supernova remnants, (e.g. W44 (Peron et al. 2020), W28 (Aharonian et al. 2008)). The spectrum of runaway particles close/inside the clouds is hard to predict as it depends on different conditions such as the age of the accelerator, the distance of the clouds and of the diffusion coefficient Aharonian & Atoyan (1996). Meanwhile, the flux can be enhanced, e.g. in the surroundings of W44 (Peron et al. 2020), by order of magnitude compared to the local CR flux. If the injection occurs in a continuous regime, as in the case of massive star clusters, the CR density is expected to be strongly peaked towards the the accelerator, therefore could be enhanced around the latter by orders of magnitude (Aharonian et al. 2019). Observations of the escaped particles are fundamental to understand the entire acceleration power of a source (Gabici et al. 2007) and new and future $\gamma$-ray instruments will help in constraining the spectrum of escaped particles at the highest energies.

5. The prospects

The next generation of instruments will include the Cherenkov telescope array (CTA) and the Southern wide-field gamma-ray observatory (SWGO). The first will reach a sensitivity 10 times better than H.E.S.S., with an angular resolution close to 3 arcmins. Such an improved sensitivity would be promising to detect passive molecular clouds because in the case of CTA $R \sim 0.5$ at 1 TeV. The improved sensitivity, together with the better angular resolution, make CTA an ideal instrument to study not only the spectral energy distribution but also to investigate the spatial distribution of CRs inside the cloud itself. SWGO as well will reach a sensitivity an order of magnitude better than HAWC; therefore it could be a valid counterpart of WCDA-LHAASO in the southern hemisphere, where the most massive clouds are located. Nevertheless, even with the improved sensitivity of the forthcoming gamma-ray telescopes, the measurements will remain limited to a handful of clouds in the VHE regime.

Meanwhile, even a relatively moderate (by a factor of 2-3) improvement of the Fermi-LAT sensitivity at GeV energies would dramatically increase the number of clouds and thus provide a probe of the CR pressure (energy density) throughout the substantial fraction of the Galactic Disk. Achieving such an improvement in sensitivity is not a trivial task. Given that GeV $\gamma$-rays are detected in the background-dominated regime, the minimum detectable flux (sensitivity) decreases with the exposure time as $t^{-1/2}$. Therefore, the resource of 12-year old Fermi-LAT in this regard is rather limited. Even assuming that Fermi-LAT will continue observations for another decade, the gain in the sensitivity cannot exceed 40%. Clearly, one needs a new, more sensitive detector of GeV $\gamma$-rays. The improvement of sensitivity for the specific task of detection of $\gamma$-rays from extended GMCs cannot be realized by improving the angular resolution. Taking Fermi-LAT 10-yr sensitivity as reference, Fig. 7 shows how enlarging the exposure time by a factor $r$ or the size of the detector by a factor $a$ affects the sensitivity. A breakthrough can be achieved only through an order of magnitude ($\Sigma > 3$) increase of the detection area. Thus, we will need a new Very large area telescope (VLAT) to achieve our goals. This is a challenging but still feasible task for the space-based instruments; see, e.g. the recent proposal for the Advanced Particle-astrophysics Telescope (APT) (Buckley et al. 2019). An improvement of the sensitivity of a factor $\Sigma \sim 3$ can already be achieved by observing for 15 years with a Fermi-like instrument of size $(3 \times 3) \text{m}^2$. The APT aims at having a $\sim 10$ times larger effective area compared to the Fermi-LAT. Two designs have been proposed: a $(3 \times 3) \text{m}^2$ instrument and a $(3 \times 6) \text{m}^2$ one. It is clear that, if this project will be approved, it will be an ideal instrument for our scopes.

5.1. Probing the CR sea

With its current sensitivity, the Fermi-LAT can map at most 1% of the molecular clouds identified in the MD16-catalog. This corresponds to 40 objects, of which only 10 belong to the inner Galaxy. Lowering the sensitivity of a factor $\Sigma = 3$ would increase the detectable sources to more than 1300 in total, of
which ∼200 in the inner Galaxy (< 4 kpc). The spatial distribution of the detectable MCs from the MD16-catalog is plotted in Fig. 8. With a factor Σ = 3 improvement, all galactic rings will be sampled with sufficient clouds, especially the 2–4 kpc ring, which is the most difficult to analyze because it is projected in a small range of longitudes, and therefore several sources may overlap.

Finally, while Fermi-LAT is limited to the observation of molecular clouds relatively close to the galactic plane, an advanced detector with improved sensitivity would allow access to several locations up to 400 parsecs above the plane (see the lower panel of Fig. 8). The combined knowledge of the cosmic-ray density at different distances from the Galactic Centre and at different heights from the Galactic plane would improve the knowledge regarding the propagation properties of these high-energy particles in the radial and perpendicular directions.

6. Conclusions

Gamma-ray emitting GMCs play a unique role of CR barometers allowing deep probes of the pressure (energy density) of CRs throughout the Galactic Disk with far-going astrophysical implications.

The γ-rays fluxes from GMCs are faint and extended, which makes their detection difficult. Yet, the analysis of Fermi-LAT observations of the Galactic Disc revealed γ-ray spectra from a limited number of GMC in the energy interval between 1–100 GeV (Aharonian et al. 2020; Peron et al. 2021; Baghmanyan et al. 2020). These results convincingly demonstrate the power of the method. At the same time, they indicate that the potential of Fermi-LAT concerning the studies of GMCs is almost saturated. For deeply probing CRs in different, including remote parts of the Galactic Disk, we need a new advanced γ-ray detector in the GeV band (a “V-LAT”) with sensitivity improved, compared to Fermi-LAT, by a factor of few. Hopefully, such a detector will appear in the foreseeable future. Such an instrument will be beneficial not only for effectively probing the CR “Sea” but also for searching of dark matter, investigating the nature of gamma-ray bursts and resolving other faint sources.

Although with the increase of energy, the detection of GMCs in γ-rays becomes more challenging, the CTA, as well as the water Cherenkov detectors like the proposed SWGO and currently operating WCDA-LHAASO, should be able to detect γ-rays in the energy interval between 1 to 10 TeV from GMCs characterised by the parameter A > 0.5. The domain of ultra-high energy γ-rays from 30 TeV up to 1 PeV looks even more promising. One may predict that the recently completed and presently working in its full power KM2A-LHAASO in the coming years will detect GMCs in ultra-high energies and thus contribute significantly to uncovering the origin of highest energy CRs around the knee and beyond.

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Fig. 5. Point source sensitivity which will be obtained with future γ-ray instruments. We included: the sensitivity for an hypothetical Fermi Very Large Area Telescope (VLAT) with a 3 times larger effective area (blue curves). The expected sensitivity of CTA from the Northern (light orange) and Southern (orange) site, for 50 hours observations; the sensitivity of SWGO (cyan) after 5 years of observations; and the sensitivity of LHAASO (magenta) for 5-years of observations.

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Fig. 6. $R$ values calculated for the current instruments (upper panel): Fermi-LAT (red), H.E.S.S. (yellow), HAWC (green), LHAASO (1-year; violet) and next-generation instruments (lower panel): VLAT (blue), CTA (orange), SWGO (cyan), LHAASO (5-years; violet). The exposure times are the same as in Figs 4 and 5. The curves refer to the point source hypothesis (dotted lines) and to a 0.5°-wide source (solid lines).

Fig. 7. Uppermost panel: the worsening factor of the sensitivity due to the source extension as a function of the extension for different angular resolutions. The middle and the lowermost panel show the combined effect of an extension, $\Lambda$, of the size and of an increase $\tau$ of the observation time on the total improvement, $\Sigma$, of the sensitivity.
Fig. 8. Spatial distribution of the clouds from the MD16-catalog in the \((X_{\text{gal}}, Y_{\text{gal}})\) plane (upper panel) and in the \((R_{\text{gal}}, Z_{\text{gal}})\) plane (lower panel). In the left, the molecular clouds that overcome the detection threshold of Fermi-LAT and of an advanced detector with improved sensitivity \(\Sigma = 3\) are indicated in dark-red, and blue, respectively. In the right, the clouds visible by LHAASO after 5 (light purple) and 10 (dark purple) years of observations are indicated. In the latter we assumed the same performance in the entire Galaxy, even though the sensitivity in the inner Galaxy should be worse. The size of the clouds is considered and an average angular resolution of 0.5° and 0.3° are assumed for Fermi-LAT and LHAASO, respectively.