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The Galactic diffuse gamma ray emission in the energy range 30 TeV - 3 PeV

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The new generation gamma ray telescopes, such as LHAASO, HISCORE and CTA will have a much larger sensitivity at energies above 30 TeV with respect to the current instruments, allowing the study of the gamma ray sky in an energy range almost completely unexplored. The observations will focus both on individual gamma ray sources and (in case of large field of view detectors like air shower arrays) on diffuse emissions, such as the radiation generated by cosmic ray interactions in the interstellar medium. In this energy range the absorption effects due to pair production, when the gamma rays interact with the radiation fields present in space, effectively prevent the observations of extragalactic sources, but are also significant for Galactic photons. In this paper we describe different predictions for the diffuse Galactic emission in the energy range [30 TeV, 3 PeV], that are based on extrapolations of the observations at lower energy, and also include the possibility that a non negligible fraction of the IceCube signal of astrophysical neutrinos is of Galactic origin, and has a gamma ray counterpart. A detailed modeling of the effects of gamma ray absorption is required for a correct interpretation of the observations, because the absorption, that strongly depends on the distance and direction of the emission point, modifies the spectral shape, and distorts the angular distribution of the observed flux. In this work we discuss the potential of the future observatories for the study of the Galactic gamma ray diffuse emission, and the importance of these studies for our understanding the properties of Galactic cosmic rays.

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The ground based gamma ray detectors currently under construction, as LHAASO [1], HISCORE [2] and CTA [3], are expected to have a larger sensitivity at energies above 30 TeV than current instruments, allowing the observation of gamma ray sources in an energy range so far poorly studied. Among them, air shower arrays, with a field of view of ∼2 sr, will also have the possibility to detect diffuse gamma ray fluxes, as those produced by the interactions of cosmic rays travelling in the interstellar medium or originating in other processes inside our Galaxy and halo.

The observation of the Galactic diffuse gamma ray emission is a fundamental tool to study the space and energy distribution of cosmic rays (CR) and their propagation properties. So far only upper limit exists on the diffuse flux above 30 TeV and the extension of data to higher energies would be of great value to investigate this problem.

An additional reason for the study of the diffuse emission at high energy comes from the results of the IceCube detector [4, 5] that observed a signal of astrophysical neutrinos emerging above the atmospheric foreground in the energy range $E_\nu \simeq$ 30–2000 TeV. The IceCube signal is consistent with an isotropic flux, suggesting an extragalactic origin of neutrinos, however several authors suggest that a fraction of events could be produced in our Galaxy or halo. At present, the low statistics and the large errors in the arrival direction of most events prevent a definite conclusion.

The production of high energy neutrinos in astrophysical sources is usually accompanied by a gamma ray emission with a similar spectral shape and intensity, since both neutrinos and gamma rays originate in the decay of pions produced in hadronic interactions of relativistic protons and nuclei. During propagation, gamma rays undergo pair production with low energy photon fields and their flux can be significantly reduced. At energies above 30 TeV, in particular, pair production can also affect gamma rays inside our Galaxy. If the IceCube neutrinos source are extragalactic, the associated gamma ray emission is in good approximation entirely absorbed during propagation and is not observable. On the other hand if neutrinos are generated in our Galaxy, the associated gamma rays are only partially absorbed, and the Galactic models on neutrino production can be tested experimentally with gamma ray observations. These studies require a detailed calculation of the absorption effects, that can significantly reduce the observable fluxes and modify the spectra with an absorption pattern that depends on the source position inside the Galaxy.

In this paper we describe the effects of the absorption on Galactic diffuse gamma ray fluxes assuming different space distributions of the emission regions, from the "standard" Galactic disk distribution expected for gamma rays produced by cosmic rays, to more "exotic" Galactic models proposed in the literature for the possible origin of the IceCube neutrinos.

1. Attenuation of gamma rays

The gamma ray energy threshold for pair production is $E_\gamma^{th} = 0.52/[\varepsilon(1-cos\theta)]$ TeV, where ε is the target photon energy (in eV) and θ is the angle between the two interacting photons. The maximum absorption occurs when the gamma ray energy is $\sim 2 \times E_\gamma^{th}$. Given this relation between the energy of the two photons, the shape of the spectrum of the target photons produces well defined absorption features in the spectrum of gamma rays. The survival probability of gamma rays can be evaluated by knowing the number density, energy spectrum and angular distribution of the target photons in all points of the trajectory connecting the source to the observer.

The radiation field in our Galaxy has four major components: two of extragalactic origin, having a uniform and isotropic flux, and two originating in our Galaxy, anisotropic, with a larger flux from the direction of the Galactic center. The extragalactic field with the largest number density of photons is the Cosmic Microwave Background Radiation (CMBR), a blackbody radiation of temperature 2.725°K, that affects mostly gamma rays in the PeV range. The intensity of the CMBR is known with high accuracy, hence it is possible to evaluate precisely its contribution to absorption. A much weaker component is the Extragalactic Background Light (EBL), due to the emission of stars and dust integrated over all galaxies during the history of the universe. The absorption by the EBL is significant for extragalactic gamma rays, but almost negligible in our Galaxy.

The two radiation fields of Galactic origin are intrinsically linked. The most relevant, for density of photons, is the infrared light emitted by the dust heated by stars. The spectrum peaks around 0.01 eV and mostly affects gamma rays with energy of order 100 TeV. The second component is the starlight, that peaks around 1 eV. It mostly interacts with gamma rays of energy of order 1 TeV, but the absorption effect is almost negligible due to the small photon density. The flux of the radiation emitted by stars and dust have been measured locally, but a model is necessary to evaluate the spectrum and angular distribution in other locations in the Galaxy.

Starting from a parametrization of the infrared radiation made by Misiriotis et al. [6] we developed a simplified emission model that gives the spectrum of the *emitted* radiation of energy between 10^{-4} and 100 eV for any point of the Galaxy [7]. Integrating the emission over the whole Galaxy, the spectrum and angular distribution of the radiation *arriving* in any point of the Galaxy are obtained, being consistent with previous estimates [8]. Fig.1 shows the number density of photons for all the radiation components. For the EBL spectrum, we used the parametrization by Franceschini et al. [9]. The Galactic radiation, evaluated according to our model, is given for points on the Galactic equator at different distances from the Galactic center. The curve for a distance of 8 kpc (corresponding to the solar neighborhood) agrees well with the infrared data by COBE-FIRAS [10] and IRAS [11].

Given the radiation field in any location of the Galaxy, it is possible to evaluate the amount of absorption for any gamma ray trajectory. Fig.2 show the gamma ray survival probability for three source positions in the Galactic plane. Up to $\sim$20 TeV the flux attenuation is less than 3% for any position. Above $\sim$20-30 TeV the absorption increases due to the interaction with infrared photons, with a maximum effect at $\sim$150 TeV. At this energy $\sim$30-50% of photons from sources located beyond the Galactic center, are absorbed. Above $\sim$200 TeV the CMBR becomes the major cause of absorption, whose amount only depends on the source distance. At these energies, the absorption can be a severe obstacle to observations of sources at distances larger than a few kiloparsecs.

2. Diffuse gamma ray flux from the Galactic disk

Cosmic rays propagating in the Galaxy generate gamma rays and neutrinos when they interact with the gas and radiation fields in interstellar space. The Galactic gamma ray diffuse flux has been measured over the entire sky by the *Fermi* LAT detector in the energy range from 0.1 to 100 GeV [12]. The dominant contribution above 10 GeV is the production and decay of neutral pions in hadronic interactions of protons and nuclei. An additional contribution is from cosmic ray electrons via Inverse Compton scattering and bremsstrahlung. The measured spectrum for $E_\gamma \gtrsim 10$ GeV has

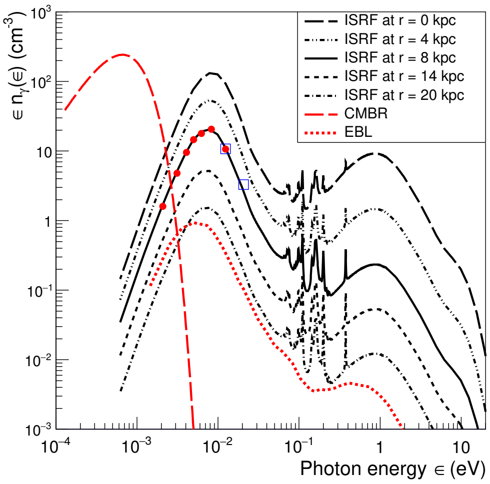

Figure 1: Photon number density for CMBR, EBL and Interstellar Radiation field (sum of star and dust emission). The ISRF is given for points on the Galactic plane at different distances from the center. Red dots (blue squares) indicate the COBE-FIRAS (IRAS) data.

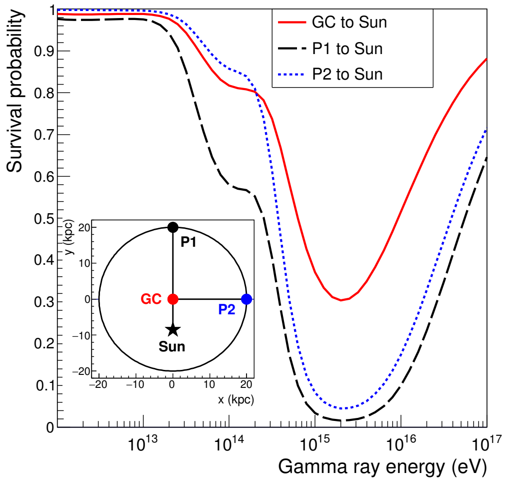

Figure 2: Survival probability of gamma rays for three different trajectories in the Galactic plane, as a function of the gamma ray energy. The inset shows a top view of the three sources positions in the Galaxy.

in good approximation a power law form with a spectral index of order $\alpha \simeq 2.76 \pm 0.05$ that reflects the spectral shape of CR protons and nuclei in interstellar space. It has to be noted that a fraction, not trivial to evaluate, of the measured diffuse flux could be due to the ensemble of unresolved Galactic gamma ray sources. The diffuse flux is concentrated in a narrow region in Galactic latitude around the equator (50% of the emission above 10 GeV is contained in the region $|b| \lesssim 5.2^\circ$), and is higher from the direction of the inner Galaxy (the flux from the Galactic center is about four times larger than the flux from the anticenter).

To estimate the Galactic diffuse flux at higher energies, we extrapolate the *Fermi* data with the following assumptions: (i) π° decay is the dominant emission mechanism; and (ii) the spectral shapes of CR p and nuclei are approximately equal in all Galaxy points and the same as observed at the Sun position, hence the energy and angular distribution of the flux *neglecting absorption* factorize into an angle independent spectral shape and an energy independent angular distribution.

The predicted energy distribution of the emission reflects the spectral shape of the interacting CR and therefore follows the power law behaviour measured at $E_\gamma \simeq 10$ GeV, with a softening at 100 TeV due to the presence of the "knee" in CR spectra. The effects of the knee have been calculated using a simple model of π° production in hadronic interactions and the model [13] for the CR spectra.

To evaluate the gamma ray absorption one should know the space distribution of the emission. The form of this distribution can be estimated from the angular distribution of the diffuse flux measured by *Fermi* at energies where the absorption is negligible. The main features of this distribution can be reproduced by a simple axysimmetric, exponential form for the source density $q(r,z) \propto \exp(-r/r_0 - |z|/z_0)$ with r and z cylindrical coordinates. The parameters r_0 and z_0 can be estimated by fitting the observed angular distribution for $E_\gamma \simeq 10$ GeV with the result $r_0 \simeq 3.9$ kpc and $z_0 \simeq 0.27$ kpc.

Summing the contributions of the whole Galaxy, it is straightforward to compute the angular and energy distribution of the gamma ray flux at Earth, taking into account the absorption for each trajectory. Fig.3 (red curve) shows the effect of the absorption on the total flux (i.e. integrated over the whole solid angle) as a function of the gamma ray energy. The maximum absorption is for energy ∼2 PeV, where the average flux is reduced to ∼ 70%. The absorption at 100 TeV, due to the infrared radiation, depends on the direction, with the maximum effect (survival probability ∼0.8) towards the Galactic center.

Is is interesting to compare these expectation with the available data at energies higher than the *Fermi* range. At energies from ∼ 300 GeV to ∼30 TeV, measurements exist from ARGO-YBJ [14] and Milagro [15, 16] air shower detectors in the angular region of the Galactic disk $|b| \leq 5^\circ$ and $20^\circ \leq \ell \leq 100^\circ$. There is no positive detection above 30 TeV, where the best upper limits have been obtained by the CASA-MIA air shower array in the energy range 0.14–3 PeV, in a different Galactic region (of lower gamma ray emission) [17]. Fig. 4 shows that all data are consistent with the extrapolation of the FERMI data (calculated for the Galactic region observed by ARGO-YBJ). The band width of the extrapolated spectrum is determined by the uncertainties of the *Fermi* spectrum slope and normalization.

The figure also shows the neutrino spectrum obtained by IceCube, under the assumption of an isotropic flux. If a fraction f of the measured flux was produced in a region of the Galactic plane of solid angle Ω, the associated gamma ray flux (per unit solid angle) would be larger by a factor of order $f \times 4\pi/\Omega$ with respect to the isotropic neutrino flux. Future measurements of the gamma ray flux above 30 TeV could constraint the neutrino flux from the Galactic plane.

Among the new projects of gamma ray detectors, LHAASO will have the highest sensitivity at ∼100 TeV. A rough evaluation of its sensitivity to a diffuse flux can be obtained by multiplying the LHAASO point source sensitivity given in [18] by the factor $f_c = (\Omega_{PSF}\Omega_{GP})^{-1/2}$, where Ω_{PSF} is the solid angle of the observational window used for point sources and Ω_{GP} in the solid angle of the Galactic plane region to be studied. This estimation is based on an ON/OFF comparison of regions in the sky where gamma rays are present/absent. According to this calculation the minimum flux detectable at 5 sigma by LHAASO in one year at 100 TeV in the same region observed by ARGO-YBJ is a factor ∼5 smaller than the CASA-MIA upper limits at a median energy of 140 TeV, and below the expected flux produced by cosmic ray interactions in the same energy region.

3. Galactic models for IceCube neutrinos

Several authors have proposed Galactic models for the Icecube neutrino signal with new source mechanisms, able to produce an angular distribution close to isotropic, in agreement with observations. This neutrino emission could be associated to an observable gamma ray flux. In this section we describe the absorption effects on these hypotetical gamma rays, according to 3 models of neutrino origin, assuming that gamma rays and neutrinos have the same spatial distribution and spectrum at the emission. Actually, if gamma rays and neutrinos are generated by pion decay in hadronic interactions, their spectral shape is equal to that of parent particles and the ratio of the fluxes F_γ/F_ν ranges between 0.65 and 1.2 when the spectral index is between 2.0 and 3.0.

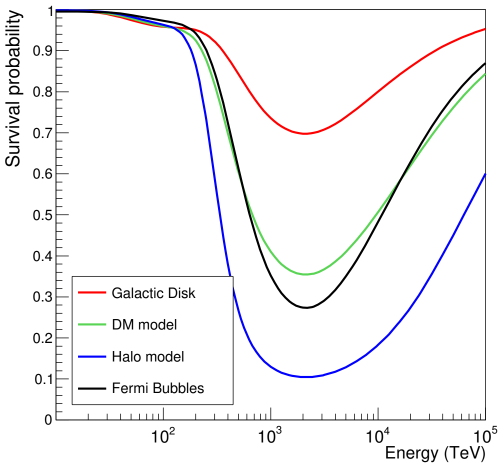

Figure 3: Average survival probability of gamma rays as a function of energy, for the different emission models described in the text. The disk model represents the emission from the Galactic disk via conventional production by cosmic rays interacting with interstellar matter. The other models describe possible gamma rays emission associated to IceCube neutrinos.

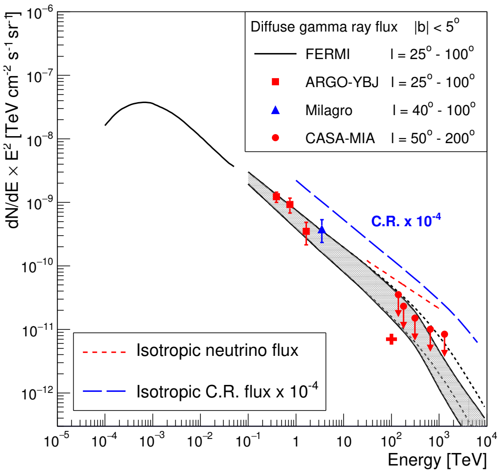

Figure 4: Galactic gamma ray diffuse flux measurements by different experiments. The shaded band shows the predicted flux in the 100 GeV–1 PeV energy range for the angular region observed by ARGO-YBJ. The dotted lines delimit the unabsorbed spectrum. The approximate LHAASO sensitivity is indicated by a red cross. The CR spectrum and the isotropic neutrino flux are also shown.

1) The first model, by Esmaili and Serpico [19], assumes that high energy neutrinos are generated in the decay of a very massive, unstable Dark Matter (DM) particle. The space distribution of the emission corresponds to the mass density of the Galactic DM, and can be modeled with the (spherically symmetric) Navarro-Frenk-White [20] form $\rho_{DM}(r) = \rho_0/(r/r_c(1+r/r_c)^2)$ with $r_c \simeq 20$ kpc.

2) The second model, by Taylor, Gabici and Aharonian [21], hypothesizes that neutrinos are produced by cosmic rays escaping from the Galactic disk, interacting in a large halo of gas extending at distances of order 100 kpc. In the following we will describe this halo emission as a simple Gaussian function $q(r) \propto \exp(-r^2/2r_0^2)$ with $r_0 = 57$ kpc, so that $\sqrt{\langle r^2 \rangle} = 100$ kpc.

3) The third model, by Lunardini et al. [22], assumes that neutrinos (likely a fraction of the observed flux) are produced in the *Fermi* Bubbles (FB) [23]. We describe the *Fermi* Bubbles as two spheres of radius $R = 3.9$ kpc, whose centers are symmetric with respect to the Galactic center, at a height +5.5 kpc (-5.5) Kpc above (below) the Galactic plane. The emission from each bubble has been modeled with the radial dependence $q(r) \propto 1/\sqrt{1-(r/R)^2}$, that results in a flux independent from the direction with a sharp drop at the boundary.

The absorption effects (averaged over the whole solid angle) as a function of the gamma ray energy, are shown in Fig.3, for the 3 models. For all models the largest absorption occurs in the PeV region, due to the CMBR contribution. In the 100 TeV region, the average absorption is only a few percent of the flux for all models, but the absorption in particular directions can be much larger. It is interesting to apply the absorption to the possible spectra of gamma rays emitted according to

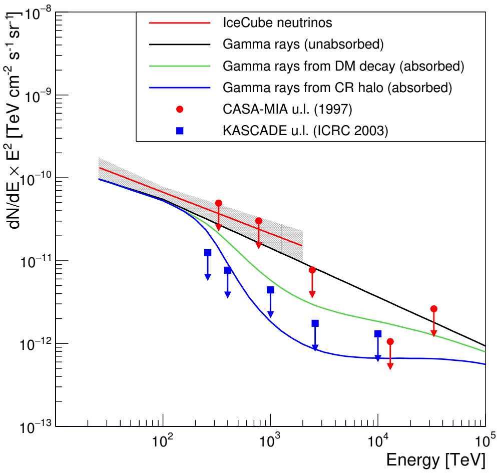

Figure 5: Effect of absorption on gamma rays emitted with a spatial distribution according to the DM model and the extended halo model. The shaded band indicates the IceCube neutrino spectrum with one sigma error. The arrows represent the upper limits for the isotropic gamma ray flux measured by CASA-MIA and KASCADE.

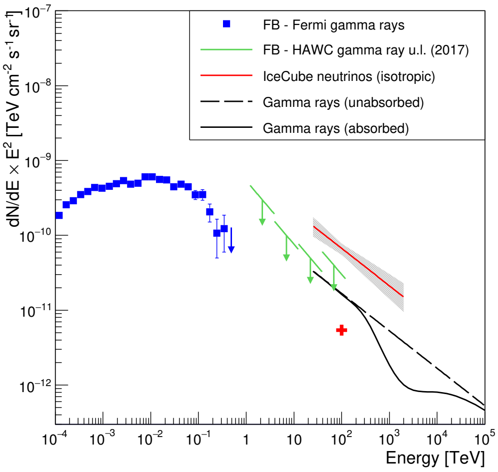

Figure 6: Fermi Bubbles: gamma rays data by Fermi and HAWC. The black dashed curve represents the unabsorbed gamma ray flux associated to an hypotetical neutrino flux equal to 1/4 of the isotropic neutrino flux. The black solid curve shows the effects of absorption. The red cross is an approximate evaluation of the LHAASO sensitivity to detect the Northern Fermi Bubble.

the 3 models, and compare the expectations with available (and future) data.

For model 1 and 2 we assume the unabsorbed gamma ray spectrum to be equal to the lower limit of the neutrino spectrum measured by IceCube [5]. This assumption is valid when gamma rays and neutrino are produced by pion decay. Note that for the DM model the relation between ν and γ emission depends of the branching ratios into different decay channels, and therefore on the assumed properties of the DM particle. Fig.5 shows the absorbed gamma ray spectra, compared with the 90% C.L. upper limits on the isotropic flux obtained by KASCADE [24] and CASA-MIA [25]. It should be stressed that in case of isotropic (or quasi isotropic) flux, the ON/OFF technique cannot be applied and the sensitivity is reduced. The KASCADE upper limits (published on conference proceedings) are in tension with the DM model. It has to be noted however that both sets of upper limits has been obtained with observations from the northern hemisphere. Since the Sun has an offset of $\sim$8 kpc from the Galactic center, a halo distribution will produce an anisotropic flux, higher from the direction of the Galactic center, not visible from the locations of KASCADE and CASA-MIA. Since the absorption too will be larger for gamma rays from the direction of the Galactic center, the anisotropy will be in some measure reduced. All these effects must be accurately taken into account to make a correct comparison between models and data.

Concerning the third model, it is difficult to estimate a possible neutrino flux originating from the *Fermi* Bubbles. So far no neutrino excess has been measured from the region, and given the low statistics the upper limit is of order of the isotropic flux. Fig.6 reports the gamma ray flux measured by *Fermi* at energies > 100 MeV [23] and the 90% C.L. upper limits obtained by HAWC in the 1-100 TeV region [26]. The HAWC limits are below the neutrino isotropic flux in the range 30-100 TeV, setting a constrain on neutrinos from the Fermi Bubbles (assuming a common hadronic origin). To be consistent with HAWC data, we assume a neutrino flux from FB equal to 1/4 of the measured neutrino isotropic flux, and evaluate the absorption effect on a gamma ray spectrum of equal shape and normalization. The resulting gamma ray flux is reported in Fig.6.

Future experiments, like LHAASO (whose approximate sensitivity for the detection of the Northern Fermi Bubble is reported in the same figure) will likely probe the existence of a high energy gamma ray flux from the *Fermi* Bubbles and consequently could set stronger constraints on the associated neutrino flux.

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