Cosmic ray knee and diffuse $\gamma$, $e^+$ and $\bar{p}$ fluxes from collisions of cosmic rays with dark matter

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Abstract. In models with extra dimensions the fundamental scale of gravity $M_D$ could be of the order of TeV. In that case the interaction cross section between a cosmic proton of energy $E$ and a dark matter particle $\chi$ will grow fast with $E$ for center-of-mass energies $\sqrt{2m_\chi E}$ above $M_D$, and it could reach 1 mbarn at $E \approx 10^9$ GeV. We show that these gravity-mediated processes would break the proton and produce a diffuse flux of particles/antiparticles, while boosting $\chi$ with a fraction of the initial proton energy. We find that the expected cross sections and dark matter densities are not enough to produce an observable asymmetry in the flux of the most energetic (extragalactic) cosmic rays. However, we propose that unsuppressed TeV interactions may be the origin of the knee observed in the spectrum of galactic cosmic rays. The knee would appear at the energy threshold for the interaction of dark matter particles with cosmic protons trapped in the galaxy by $\mu$G magnetic fields, and it would imply a well-defined flux of secondary antiparticles and TeV gamma rays.

Keywords: cosmic rays, dark matter, extra dimensions
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1. Introduction

The gravitational interaction between two elementary particles is much weaker than the strong or electroweak ones at all the energies and distances explored until now in collider experiments. This is understood due to the large size of the Planck mass $M_P \approx 10^{19}$ GeV (in natural units, $M_P \equiv G_N^{-1/2}$) compared with the energy $E = \sqrt{s}$ in the collision, and suggests that gravity may have been only relevant in scatterings in the initial moments of the big bang (if the temperature was ever close to $M_P$). In recent years, however, it has become apparent that in models with extra dimensions this is no longer necessary: the fundamental scale of gravity $M_D$ could be much lower than $M_P$, and values close to the TeV scale would be natural in order to solve the hierarchy problem [1]. Center-of-mass energies above the TeV scale would then define a trans-Planckian regime where gravity dominates over the other interactions [4].

In particular, strong TeV gravity could affect the interactions of cosmic rays (mostly protons free or bound in nuclei [2]) that reach the Earth with energies of up to $10^{11}$ GeV. Notice that the relative effect of the new physics would be most relevant in processes with a weak cross section within the standard model (SM). In this paper we will focus on the interactions of ultra-high energy cosmic rays with dark matter particles $\chi$ in our galactic halo. We will assume that $\chi$ is a weakly interacting massive particle (WIMP) of mass $m_\chi \approx 100$ GeV, although $m_\chi$ could go from 10 MeV to 10 TeV if its interaction strength goes from gravitational to strong [3]. Being a WIMP, an anomalous $p-\chi$ interaction rate at high energies would be a clear signal of nonstandard physics. In addition, due to its possible large mass, the center-of-mass energy $\sqrt{s} = \sqrt{2m_\chi E}$ goes above the threshold $M_D$ for cosmic rays of $E \approx 10^5$ GeV, a region in the spectrum where the flux is still sizable.

First we briefly describe the gravity-mediated $p-\chi$ interactions in the trans-Planckian regime. Namely, we consider black hole production [5] and elastic (at the parton level) scatterings that can be calculated in the eikonal approximation [6]. We show that the
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The most important effect is due to the fact that these interactions break the incident proton, producing jets that fragment into hadrons and then shower into stable particles. We use the Monte Carlo jet code HERWIG [7] to determine and parameterize the flux of photons, neutrinos, electrons and protons, together with their antiparticles, produced in these collisions. Then we take a particular dark matter distribution and study the probability that an extragalactic cosmic ray of $E > 10^8$ GeV interacts with a galactic WIMP in its way to the Earth. This probability, and also the flux of secondaries from these interactions, depends on the galactic longitude, as protons reaching the Earth from different directions must cross a different dark matter column density (depth). Finally we consider the effect of the gravitational interactions on galactic cosmic rays of lower energy. The crucial difference with the more energetic ones is that the protons of energy below $10^8$ GeV are trapped by the $\mu$G magnetic fields [8] present in our galaxy (their Larmor radius is contained in a typical cell of the magnetic field). As a consequence, the dark matter depth that they face grows with time as they diffuse from the center of the galaxy, and a significant fraction of them may interact before reaching the Earth.

2. Interactions at trans-Planckian energies

The possibility of producing black holes (BHs) in the collision of two particles at $\sqrt{s} > M_D$ has been extensively discussed in the literature [5]. Basically, one expects that, for impact parameters smaller than the horizon $r_H$ of the system, they collapse into a BH of mass $M \approx \sqrt{s}$. Here we will assume that there are $n$ flat extra dimensions of common length where gravity propagates, that all matter fields are trapped on a four-dimensional brane and that $r_H$ is just the higher-dimensional Schwarzschild radius:

$$r_H = \left( \frac{2n \pi^{(n-3)/2} \Gamma((n+3)/2)}{n+2} \right)^{1/(n+1)} \left( \frac{M}{M_D} \right)^{1/(n+1)} \frac{1}{M_D}. \quad (1)$$

Therefore, for two point-like particles the cross section $\sigma_{BH} = \pi r_H^2$ to produce a BH (in figure 1) is of the order of $1/M_D^2$ and grows like $s^{1/(n+1)}$ with the center-of-mass energy.

Gravity-mediated interactions, however, are also important at impact parameters $b$ larger than $r_H$ [6]. In such processes an incident particle of energy $E$ will interact elastically with a target at rest and will lose a small fraction $y$ of its energy. The process can be calculated in the eikonal approximation, which provides a resummation of ladder and cross-ladder contributions. It has been shown [9] that effects like the dependence on the physics at the cutoff $M_D$ or the emission of gravitons during the collision are negligible if $\sqrt{s} \gg M_D$. For two point-like particles the eikonal amplitude can be written

$$A_{eik}(s, q) = 4\pi s b_c^2 F_n(b_c q), \quad (2)$$

where $q = \sqrt{-t} = \sqrt{2ymE}$ is the exchanged transverse momentum,

$$b_c = \left( \frac{(4\pi)^{n/2-1} \Gamma(n/2)}{2} \right)^{1/n} \left( \frac{\sqrt{s}}{M_D} \right)^{2/n} \frac{1}{M_D}, \quad (3)$$

and the functions

$$F_n(y) = -i \int_0^\infty dx x J_0(xy) \left( e^{ixy} - 1 \right) \quad (4)$$

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Figure 1. Cross section for gravitational interactions (eikonal and BH production) in a collision of two point-like particles for $n = 2, 6$, $M_D = 1$ TeV and $m_\chi = 200$ GeV.

are given in [10] in terms of Meijer’s $G$ functions. The eikonal cross section grows fast with the energy for low values of $n$, it goes like $s^{1+4/n}$. In figure 1 we plot the cross sections $\sigma_{\text{BH}}$ and $\sigma_{\text{eik}}$ between two point-like particles for $n = 2, 6$, $M_D = 1$ TeV, $m_\chi = 200$ GeV and values of the incident energy up to $10^{11}$ GeV. We have required that the transverse momentum is $q > 1$ GeV, which sets a minimum value of $y = (E - E')/E$ (notice that the eikonal amplitude diverges at $y = 0$ for $n \leq 2$).

When a cosmic proton of energy $E$ hits a dark matter particle $\chi$ initially at rest, the collision will be dominated by transverse distances ($r_H$ or $b_c$) much smaller than the proton radius. This indicates that $\chi$ sees the proton structure and interacts with a parton carrying a fraction $x$ of the proton momentum. The trans-Planckian regime requires then $\sqrt{s} = \sqrt{2x m_\chi E} > M_D$. In figure 2 we plot $\sigma_{\text{BH}}^{\text{PX}}$ and $\sigma_{\text{eik}}^{\text{PX}}$ for the same choice of parameters as in figure 1. We have used the CTEQ6M [11] parton distribution functions.

If the parton ($q$) and $\chi$ form a mini BH (in figure 3, left), after the collision we will have two jets: the BH, of mass $\sqrt{2x m_\chi E}$, energy $xE$ and the color of the parton involved in the collision, plus the proton remnant (qq, the spectator partons), with the opposite color and energy $(1 - x)E$.

On the other hand, if the collision of $q$ with $\chi$ is elastic (in figure 3, right), they will result in a boosted dark matter particle of energy $xyE$ plus two jets (indicated by dotted cones in figure 3): the one defined by the scattering parton, with energy $x(1 - y)E$ and transverse momentum $p_T = \sqrt{2xym_\chi E}$, and a proton remnant qq of opposite color and energy $(1 - x)E$.

3. Fragmentation and decay into stable species

To understand how the system evolves after the gravitational interaction, it is convenient to study the process in the center-of-mass frame of the two final jets. Let us start by
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Figure 2. Cross section for gravitational interactions in a $p-\chi$ collision for $n = 2, 6$, $M_D = 1$ TeV and $m_\chi = 200$ GeV.

Figure 3. Scheme of a $p-\chi$ collision giving a BH (left) or an eikonal process (right) in the lab (upper) and in the c.o.m. (lower) frames. In a BH process the final states are the proton remnant (qq) and the BH, whereas in the eikonal process we have the scattering parton ($q$), the proton remnant (qq) and the dark matter particle ($\chi$). The center-of-mass frame in the eikonal process refers to the two jets ($q$ and qq), not the $p-\chi$ system.

discussing the elastic (at the parton level) scattering of a dark matter particle $\chi$ with a parton $q$. The process will break the incident proton, since the typical transverse momentum exchanged is larger than 1 GeV. For $x, y \ll 1$ we go to that frame with a boost of

$$\gamma \approx \sqrt{\frac{E}{2ym_\chi}}.$$
There the energy of the two jets becomes
\[ E_q = E_{qq} \approx \sqrt{\frac{ym_\chi E}{2}}. \]  

The scattering parton and the proton remnant will then emit gluons and quarks, fragment into hadrons and shower into stable species. We evaluate this process using HERWIG \[7\]. In this center-of-mass frame we find that

(i) The scattering parton and the proton remnant define jets giving a very similar spectrum of stable particles. This spectrum is only mildly sensitive to the fact that the parton may be a quark or a gluon and the proton remnant may be, correspondingly, a diquark (color antitriplet) or a triquark (color octet). When the scattering parton is a gluon the jets tend to give a larger number of stable particles of smaller energy than when it is a quark. In the appendix we include two tables containing the spectrum (averaged over 100 HERWIG runs) of 100 GeV quark–diquark jets and gluon–triquark jets.

(ii) In this frame the final spectrum of stable particles is dominated by energies around 1 GeV, almost independently of the energy of the parton starting the shower. In table A.3 (also in the appendix) we include the spectrum from a 10 GeV di-jet.

(iii) The stable species (particle plus antiparticles) are produced with a frequency \( f_i \) that is mostly independent of the energy or the nature of the two jets. We obtain an approximate 55% of neutrinos, 20% of photons, 20% of electrons and 5% of protons.

We will then parameterize these fluxes in terms of functions \( g_i(E, E_{jet}) \) that indicate the number of particles of the species \( i \) coming from a jet of energy \( E_{jet} \):
\[ N_i = f_i N = \int dE \ g_i(E; E_{jet}). \]  

For photons, electrons and neutrinos we will use the ansatz
\[ g_i(E; E_{jet}) = \begin{cases} \frac{f_i N}{\Lambda} \left( \frac{\beta - 1}{\beta} \right)^{E < \Lambda} & E < \Lambda; \\ \frac{f_i N}{\Lambda} \left( \frac{\beta - 1}{\beta} \right) \left( \frac{E}{\Lambda} \right)^{-\beta} & E_{jet} > E > \Lambda, \end{cases} \]  

whereas for the proton
\[ g_p(E; E_{jet}) = \frac{f_p}{f_i} g_i(E - m_p; E_{jet}). \]  

In these expressions we take \( \Lambda = 0.2 \text{ GeV} \) and fix \( \beta \) by energy conservation:
\[ E_{jet} \approx N \Lambda \frac{\beta - 1}{2(\beta - 2)} + f_p N m_p. \]  

We plot in figure 4 the number of particles \( N \) and the parameter \( \beta \) that we obtain for the two types of jets (quark–diquark and gluon–triquark) of energy between 10 and \( 10^4 \) GeV.

In processes where a parton and \( \chi \) collapse into a BH (see figure 1, left) the situation is not too different. In the lab frame the mass and energy of the BH produced are

\[ f \text{ GeV and } df \text{ by energy conservation:} \]
\[ E_{jet} \approx N \Lambda \frac{\beta - 1}{2(\beta - 2)} + f_p N m_p. \]
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Figure 4. Value of the total number of stable particles $N$ (left) and of the spectral index $\beta$ (right) used in the parameterization of quark–diquark jets and gluon–triquark jets of energy $E_{\text{jet}} = E$ and of BHs of mass $M = E$.

$$M = \sqrt{2m_\chi E} \text{ and } \approx xE,$$

respectively, whereas the proton remnant has an energy $(1-x)E$. We go to the center-of-mass frame with a boost

$$\gamma \approx \sqrt{\frac{E}{2m_\chi}},$$

which leaves both jets with opposite momenta of order

$$E_{\text{BH}} = E_{qq} \approx \sqrt{m_\chi E/2}.$$

In this frame the proton remnant will produce a jet similar to the ones described above. The BH, however, follows a different path, as it emits radiation [12] and evaporates in a typical timescale much shorter than $\Lambda_{\text{QCD}}^{-1}$. The Hawking evaporation of these BHs has been analyzed in [13]. Very briefly, the results there can be summarized as follows.

(i) The spectrum of stable particles resulting from a mini-BH is very similar to the one obtained from the quark and gluon jets described before. It consists of approximately 55% of neutrinos, 20% of photons, 20% of electrons and 5% of protons. For $M_D = 1\text{ TeV}$ and $n = 2$, gravitons account for 1% of the total energy emitted by a BH of $M = 10^4\text{ GeV}$. If there are $n = 6$ extra dimensions graviton emission grows to 15%.

(ii) In the BH rest frame the spectrum of stable particles is dominated by energies below 1 GeV. In the lab frame this energy is boosted by a factor of $\gamma_{\text{BH}} \approx \sqrt{xe/(2m_\chi)}$.

Therefore, we will also use equation (8) to parameterize the spectrum of stable particles resulting from the evaporation of a BH in its rest frame. We substitute $E_{\text{jet}}$ for the BH mass $M$, discount from $M$ the energy taken by the emitted gravitons and include in figure 4 the total number of stable particles and the spectral index $\beta$ for light BHs of masses between 1 and 10 TeV.
4. Secondary flux from extragalactic cosmic rays

On their way to the Earth cosmic rays cross a medium full of dark matter particles. If the gravitational interaction becomes strong above the TeV scale, a fraction of them will collide, inducing a flux of secondary particles that might be observable in satellite- [15, 16] or ground-based [17] experiments. The probability that a cosmic ray interacts will depend on the cross section $\sigma$ and on the column density (depth $x$) of dark matter along its trajectory:

$$ p(x) \approx \frac{\sigma x}{m_\chi}, \quad (13) $$

where

$$ x = \int \rho \, dl \quad (14) $$

and $\rho$ is the dark matter density at each point of the trajectory. Throughout this paper we will assume $10^{69}$ GeV of galactic dark matter distributed in a sphere of 200 kpc with the density profile [18]

$$ \rho(r) \approx \rho_0 \frac{r_0}{(r/R)(1+r/R)^2}, \quad (15) $$

where $R = 20$ kpc (we are at 8 kpc from the center, 1 kpc = $3 \times 10^{19}$ m). This means that the depth $x$ of dark matter from the Earth to the border of our galaxy goes from 0.01 g cm$^{-2}$ for a galactic latitude $\theta = 180^\circ$ to 0.17 g cm$^{-2}$ for a trajectory crossing the galactic center with $\theta = 5^\circ$ (notice that the depth diverges at $\theta = 0$). For the dark matter particle we will take $m_\chi = 200$ GeV, although this value could oscillate within a wide range, depending on its annihilation and coannihilation cross sections.

In this section we will focus on cosmic rays of extragalactic origin and energy above $10^8$ GeV. Since their interaction probability grows with the dark matter depth, it may change by one order of magnitude depending on the angle $\theta$ of approach to the Earth. If this probability were sizable, it would deplete the flux of ultra-high energy protons and create an observable asymmetry. Taking $\theta = 90^\circ$ ($x \approx 0.02$ g cm$^{-2}$ from the border of the galaxy) and $\sigma = \sigma_{\text{BH}} + \sigma_{\text{eik}}$, we obtain interaction probabilities that go from $1.2 \times 10^{-3}$ for a proton of $E = 10^{11}$ GeV to $0.7 \times 10^{-5}$ for $E = 10^8$ GeV (with $n = 2$ and $M_D = 1$ TeV). This probability is dominated by $\sigma_{\text{eik}}$, where we only include exchanged momenta large enough to break the incident proton ($q_T > 1$ GeV). The one in a thousand depletion in the flux from interactions within the galaxy seems too small to be observable, although the effect would be larger for fluxes from distant sources crossing regions of large dark matter density.

To obtain the total flux of stable particles reaching the Earth we convolute the two processes under study (BH production and eikonal collisions) with the primary proton flux. We first define the event at the parton level. Then we go to the center-of-mass frame of the two jets (proton remnant–scattering parton or proton remnant–BH), where we get the spectrum of stable species using the parameterization discussed in the previous section (the BH evaporation is obtained in the BH rest frame). Finally, we boost these spectra to the lab frame. We also calculate the energy of the dark matter particle $\chi$ after the eikonal scattering with the proton.
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Figure 5. Photon flux from (eikonal and BH) collisions of extragalactic protons of $E > 10^8$ GeV with dark matter particles for $n = 2$, $M_D = 1$ TeV and $m_\chi = 200$ GeV. We take a galactic latitude of $\theta = 90^\circ$ (i.e. a dark matter depth of 0.02 g cm$^{-2}$). We also plot the flux of dark matter particles accelerated by the eikonal collision.

In figure 5 we plot the flux of photons and boosted dark matter particles for $n = 2$ and $M_D = 1$ TeV from interactions of cosmic rays of extragalactic origin and energy above $10^8$ GeV. The flux of the other species has basically the same spectrum (up to propagation effects) as the flux of photons. It is a factor of 2.7 larger for neutrinos, similar for electrons, and a factor of 4 smaller for protons. These fluxes include the same number of particles and antiparticles of any species. In figure 5 we separate the photons produced in eikonal and in BH events. It is apparent that the dominant source of secondaries is the elastic (eikonal) scattering of the partons in the proton with dark matter particles.

5. Flux from galactic cosmic rays

The effect of an anomalous proton–dark matter interaction rate could be most relevant for cosmic rays of $E < 10^8$ GeV of predominantly galactic origin. The reason is that a large fraction of them will be trapped by the random magnetic fields of order $\mu$G present in our galaxy (the Larmor radius of their trajectory, around 0.1 kpc for a $10^8$ GeV proton, would be contained in a typical cell of the magnetic field). From the moment they are produced, these protons may collide with $\chi$, their interaction length being around $L \approx m_\chi/(\sigma \rho)$. Now, a remarkable feature of the gravitational interaction that we are considering is that it grows fast above trans-Planckian energies, much faster than, for example, $Z$ boson exchange. In particular, if $m_\chi = 200$ GeV, $n = 2$ and $M_D = 5$ TeV, then at proton energies around $10^5$ GeV the gravitational interaction would be weak (with a pbarn cross section), whereas at $10^7$ GeV it would be four orders of magnitude larger (see figure 6). An increased collision rate of protons above the trans-Planckian threshold would reduce their abundance, producing an effect in the flux reaching the Earth that could explain the knee observed at $10^6$ GeV.
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Figure 6. Cross section for a gravitational interaction in a $p\chi$ collision for $n = 2$, $M_D = 5$ TeV and $m_\chi = 200$ GeV.

The cosmic ray flux up to energies around $10^6$ GeV is

$$\frac{d\Phi_N}{dE} \approx 1.8 \ E^{-2.7} \ \frac{\text{nucleons}}{\text{cm}^2 \ \text{s} \ \text{sr} \ \text{GeV}}.$$  \hspace{1cm} (16)

If gravitational interactions were responsible for the change in the differential spectral index from 2.7 to 3, then there would be a flux of secondary particles that could be readily estimated. Let us assume that, in the absence of gravitational interactions, the flux in (16) would have extended up to $10^8$ GeV. This means that the flux

$$\Phi_N \approx \int_{10^6 \text{ GeV}}^{10^8 \text{ GeV}} dE \ 1.8 \ (E^{-2.7} - 10^{1.8} E^{-3}) \ \frac{\text{nucleons}}{\text{cm}^2 \ \text{s} \ \text{sr}}$$ \hspace{1cm} (17)

had been processed by these interactions into secondary particles of less energy. We plot in figure 7 the proton and gamma-ray fluxes for $M_D = 5$ TeV, $m_\chi = 200$ GeV and $n = 6$ (the flux of neutrinos would be a factor of 2.7 more abundant than the $\gamma$-ray flux), together with the flux of dark matter particles boosted by the eikonalized scattering. The flux of $e = e^+ + e^-$ is similar to the photon flux, although the propagation effects (sintroton emission, etc) that may distort the spectrum have not been included. Recent data from PAMELA [19] signals an excess in the positron flux above 10 GeV, although the contribution that we find seems to be well below these data. We add in the plot the diffuse gamma-ray flux measured by MILAGRO [20] at energies around 15 TeV, which seems to indicate an excess versus the expected values from some regions in the galactic plane. Previous measurements of this flux have always indicated a TeV excess [21]–[23], while EGRET observations [24, 25] have also pointed to a harder spectrum than expected, with too many gamma rays in the 1–10 GeV region. The contribution that we find could explain anomalies in the gamma-ray flux above 10 GeV or in the positron and antiproton fluxes above 1 TeV.
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Figure 7. Secondary fluxes from $p$-$\chi$ gravitational collisions for $n = 6$, $M_D = 5$ TeV and $m_\chi = 200$ GeV. The fluxes include the same amount of particles and antiparticles. The point at 15 TeV indicates the gamma-ray flux measured by MILAGRO.

Figure 8. Flux of secondary photons from $p$-$\chi$ gravitational collisions for $M_D = 5$ TeV, $n = 2, 6$, and $m_\chi = 100$ GeV (solid) or $m_\chi = 500$ GeV (dashes). For $n = 2$ 80% of the flux comes from eikonal interactions, whereas for $n = 6$ BH production dominates and is the origin of 85% of the secondaries.

In figure 8 we give the gamma-ray flux for different values of the dark matter mass and the number of extra dimensions. We observe that the spectrum changes only slightly with these parameters, while the frequency of the different species in the flux of secondaries is model-independent.
6. Summary and discussion

Strong gravity at the TeV scale could affect the propagation of the most energetic cosmic rays through the galactic and intergalactic media. In particular, cosmic protons could interact with the WIMP $\chi$ that constitutes the dark matter of our universe. These interactions would be in addition to the standard ones with nucleons in the interstellar medium, where the effect is negligible [26]. Basically, there are three consequences from such processes.

(i) Since the interaction breaks the incident proton, if a sizable fraction of them interacts we would observe a reduced flux reaching the Earth. At energies around $10^{10}$ GeV (i.e. for cosmic rays not trapped by the galactic magnetic fields) this reduction would be stronger from directions crossing regions with a larger dark matter density, whereas at lower energies (trapped protons) it increases with the length of the proton trajectory. In both cases the suppression measures the product of the dark matter column density faced by the flux on its way to the Earth and the $p-\chi$ cross section, which increases with the energy of the cosmic ray.

(ii) The interactions would produce a flux of secondary particles. This flux includes basically the same amount of particles and antiparticles, and it grows with the flux of primaries (they should have similar angular dependence) and with the dark matter depth to reach the Earth. Its origin would be the jets defined by the proton remnant (the spectator partons) and the scattering parton in gravitational interactions with $\chi$, and also the BH decay products.

(iii) The third generic effect would be a flux of dark matter particles boosted by the eikonal interactions with cosmic protons. This flux, also proportional to the flux of primaries and to the dark matter depth, would only depend on the mass of $\chi$, not on its electroweak interactions.

For very energetic extragalactic protons, we have shown that the gravitational interaction and the dark matter density are not large enough to produce an asymmetry in the cosmic ray flux reaching the Earth, as only one in a thousand of the $10^{10}$ GeV protons could experience a BH or an eikonal interaction (an asymmetry would require cross sections or dark matter densities 100 times larger). The flux of secondary antiparticles or gamma rays that we obtain (in figure 5) is also negligible.

We have argued, however, that these interactions could have an observable effect on the less energetic ($E < 10^8$ GeV) protons of galactic origin. The reason is that a large fraction of them are trapped by the random magnetic fields of order $\mu$G present in our galaxy. The dark matter column density that these protons face grows with time, and eventually a gravitational interaction could break them before they reach the Earth. We have speculated that this may be the origin of the knee in the cosmic ray flux at energies around $10^6$ GeV. If that were the case, then the secondaries would define a TeV flux of antiprotons, positrons and gamma rays that could be observable at GLAST [16], MILAGRO [17] or PAMELA [15]. Notice that the energy dependence of these fluxes (to be measured in the near future) is clearly different from the one obtained from dark matter annihilation [27]–[30] or pulsars [31].
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A proof that the knee has anything to do with strong TeV gravity or with other new physics producing an anomalous proton–dark matter interaction rate would require an elaborate model for the production of galactic cosmic rays together with a simulation of the effects caused by the galactic magnetic fields on the propagation of primary and secondary cosmic rays. In any case, it is puzzling that the change in the spectral index in the flux appears at center-of-mass energies $\sqrt{2m_\chi E_{\text{knee}}} \approx 10$ TeV, where the new physics is expected. The knee could be more related to the destruction of cosmic rays in collisions with dark matter than to the production mechanisms at energies around $10^6$ GeV. We think that the experimental observation of a flux of gamma rays and antiparticles with the spectrum in figure 7 would provide strong support for this hypothesis.

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Appendix. Stable particles from jets

In this appendix we include several tables with the spectrum of stable species resulting from di-jets of different natures, in the center-of-mass frame of the two jets. They have been obtained by simulating elastic collisions with the HERWIG code, averaging over 100 runs in each case. The scattering parton may be a quark (q) or a gluon (g), whereas the proton remnant would be, correspondingly, a diquark (qq) or a triquark (qqq). The spectra include particles and antiparticles (for $\nu$, $e$ and $p$), and for $\nu$ it also includes the three neutrino flavors.

| Table A.1. Spectrum of stable species from quark and diquark jets of 100 GeV. |
|---------------------------------------------------------------|
| Energy (GeV) | $\nu$ | $e$ | $p$ | $\gamma$ | Total |
| From q-jet (100 GeV) | $10^{-2}$–$10^{-1.5}$ | 8.8 | 3.3 | 0 | 1.6 | 13.8 |
| | $10^{-1.5}$–$10^{-1}$ | 11.5 | 4.2 | 0 | 3.4 | 19.3 |
| | $10^{-1}$–$10^{-0.5}$ | 9.9 | 3.6 | 0 | 4.3 | 17.8 |
| | $10^{-0.5}$–1 | 6.3 | 2.1 | 0.74 | 3.4 | 12.6 |
| | 1–$10^{0.5}$ | 2.3 | 0.84 | 0.94 | 1.7 | 5.8 |
| | $10^{0.5}$–10 | 0.55 | 0.21 | 0.53 | 0.54 | 1.8 |
| | Total | 39.5 | 14.3 | 2.2 | 15.1 | 71.2 |
| From qq-jet (100 GeV) | $10^{-2}$–$10^{-1.5}$ | 7.4 | 5.1 | 0 | 1.3 | 13.8 |
| | $10^{-1.5}$–$10^{-1}$ | 9.8 | 5.5 | 0 | 2.9 | 18.2 |
| | $10^{-1}$–$10^{-0.5}$ | 8.9 | 5.2 | 0 | 4.0 | 18.1 |
| | $10^{-0.5}$–1 | 4.8 | 2.8 | 0.75 | 2.9 | 11.3 |
| | 1–$10^{0.5}$ | 1.8 | 0.71 | 0.76 | 1.52 | 4.8 |
| | $10^{0.5}$–10 | 0.28 | 0 | 0.50 | 0.64 | 1.4 |
| | 10–$10^{1.5}$ | 0 | 0 | 0.15 | 0 | 0.15 |
| | Total | 33.0 | 19.4 | 2.2 | 13.3 | 67.8 |
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Table A.2. Spectrum of stable species from gluon and triquark jets of 100 GeV.

| Energy (GeV)          | $\nu$  | $e$  | $p$  | $\gamma$ | Total |
|----------------------|-------|------|------|----------|-------|
| From g-jet (100 GeV) | $10^{-2}$–$10^{-1.5}$ | 14.7 | 5.6  | 0        | 2.5   | 22.8  |
|                      | $10^{-1.5}$–$10^{-1}$ | 18.5 | 6.5  | 0        | 5.9   | 30.9  |
|                      | $10^{-1}$–$10^{-0.5}$ | 16.6 | 5.7  | 0        | 7.2   | 29.6  |
|                      | $10^{-0.5}$–1       | 8.4  | 3.0  | 0.1      | 5.0   | 17.8  |
|                      | $10^{0.5}$–1       | 2.3  | 0.75 | 1.5      | 2.2   | 6.7   |
|                      | $10^{0.5}$–10      | 0.20 | 0.09 | 0.42     | 0.41  | 1.1   |
| Total                | 60.6            | 21.7 | 3.4  | 23.2     | 108.9 |
| From qqq-jet (100 GeV)| $10^{-2}$–$10^{-1.5}$ | 15.2 | 5.7  | 0        | 2.7   | 23.6  |
|                      | $10^{-1.5}$–$10^{-1}$ | 18.6 | 6.3  | 0        | 5.9   | 30.7  |
|                      | $10^{-1}$–$10^{-0.5}$ | 16.2 | 5.9  | 0        | 7.2   | 29.3  |
|                      | $10^{-0.5}$–1       | 8.6  | 3.2  | 1.5      | 8.9   | 18.3  |
|                      | $10^{0.5}$–1       | 2.1  | 0.80 | 1.3      | 2.2   | 6.4   |
|                      | $10^{0.5}$–10      | 0.09 | 0.09 | 0.49     | 0.40  | 0.98  |
| Total                | 60.7            | 21.9 | 3.3  | 23.4     | 109.3 |

Table A.3. Spectrum of stable species from quark and diquark jets of 10 GeV.

| Energy (GeV)          | $\nu$  | $e$  | $p$  | $\gamma$ | Total |
|----------------------|-------|------|------|----------|-------|
| From q-jet (10 GeV)  | $10^{-2}$–$10^{-1.5}$ | 5.5  | 1.9  | 0        | 0.91  | 8.3   |
|                      | $10^{-1.5}$–$10^{-1}$ | 5.2  | 1.8  | 0        | 2.0   | 9.0   |
|                      | $10^{-1}$–$10^{-0.5}$ | 2.9  | 1.2  | 0        | 1.7   | 5.9   |
|                      | $10^{-0.5}$–1       | 0.57 | 0.26 | 0.67     | 0.72  | 2.2   |
|                      | $10^{0.5}$–1       | 0    | 0    | 0.18     | 0.20  | 0.38  |
| Total                | 14.2            | 5.2  | 0.85 | 5.5      | 25.8  |
| From qq-jet (10 GeV) | $10^{-2}$–$10^{-1.5}$ | 4.8  | 2.0  | 0        | 1.0   | 7.8   |
|                      | $10^{-1.5}$–$10^{-1}$ | 5.0  | 1.7  | 0        | 1.6   | 8.3   |
|                      | $10^{-1}$–$10^{-0.5}$ | 2.9  | 1.0  | 0        | 1.7   | 5.6   |
|                      | $10^{-0.5}$–1       | 0.85 | 0.34 | 0.59     | 0.74  | 2.5   |
|                      | $10^{0.5}$–1       | 0    | 0    | 0.20     | 0.14  | 0.34  |
| Total                | 13.6            | 5.1  | 0.79 | 5.2      | 24.7  |

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