Cosmic ray knee and new physics at the TeV scale

Roberto Barceló¹, Manuel Masip¹, Iacopo Mastromatteo²

¹CAFPE and Departamento de Física Teórica y del Cosmos
Universidad de Granada, E-18071 Granada, Spain

²International School for Advanced Studies (SISSA)
Via Beirut 2-4, I-34014 Trieste, Italy

rbarcelo@ugr.es, masip@ugr.es, mastroma@sissa.it

Abstract

We analyze the possibility that the cosmic ray knee appears at an energy threshold where the proton–dark matter cross section becomes large due to new TeV physics. It has been shown that such interactions could break the proton and produce a diffuse gamma ray flux consistent with MILAGRO observations. We argue that this hypothesis implies knees that scale with the atomic mass for the different nuclei, as KASKADE data seem to indicate. We find that to explain the change in the spectral index in the flux from $E^{-2.7}$ to $E^{-3.1}$ the cross section must grow like $E^{0.4+\beta}$ above the knee, where $\beta = 0.3–0.6$ parametrizes the energy dependence of the age ($\tau \propto E^{-\beta}$) of the cosmic rays reaching the Earth. The hypothesis also requires mbarn cross sections (that could be modelled with TeV gravity) and large densities of dark matter (that could be clumped around the sources of cosmic rays). We argue that neutrinos would also exhibit a threshold at $E = (m_\chi/m_p) E_{\text{knee}} \approx 10^8$ GeV where their interaction with a nucleon becomes strong. Therefore, the observation at ICECUBE or ANITA of standard neutrino events above this threshold would disprove the scenario.
1 Introduction

The observed cosmic ray flux reaching the Earth extends up to energies around $10^{11}$ GeV. It seems remarkable that over 10 decades of energy this flux can be described in very simple terms \[1\]. Between 10 and $10^6$ GeV (the knee) it is given by

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

At $E_{knee}$ the spectral index changes to $-3.1$ and stays constant up to $\approx 10^{9.5}$ GeV (the ankle). There it goes back to $-2.7$ until (arguably) hits the GZK suppression a decade later (see \[2, 3\] for a review).

The ankle is generally explained as the overtaking in the cosmic ray flux of a new component of extragalactic origin. These ultra-high energy particles arrive from all regions in the sky, which excludes the possibility that they are produced only in the galactic disc. For less energetic particles, $E \leq 10^8$ GeV, one can assume production in the disc despite the fact that the observed flux is also isotropic. The reason is that their Larmor radius is smaller, so the trajectory is isotropized by the random magnetic fields present in our galaxy ($r_L \approx 0.1$ kpc for a $E = 10^8$ GeV proton inside a $B = 1 \mu$G magnetic field).

The other main feature in the spectrum, the knee, seems more involved. It is usually thought that $E_{knee}$ reflects the maximum energy reached by the dominant cosmic accelerators in our galaxy. In that case, however, one would expect a transition regime (not seen) between $E_{knee}$ and the energy $E$ where the new acceleration mechanism dominates. Propagation and confinement within the galaxy could also play an important role. In particular, the knee could correspond to a critical energy where a large fraction of cosmic rays escapes the galactic disc before reaching the Earth \[4\]. Again, it seems difficult to obtain a sustained spectrum $\propto E^{-3.1}$ from that energy up to $E_{ankle}$ \[5\].

In this paper we explore a different possibility recently proposed in \[6\]. Namely, the knee could be caused by new interactions with dark matter particles ($\chi$) in our galaxy. This hypothesis requires that the cross section $\sigma_{p\chi}$ becomes strong and breaks the cosmic protons of energy above the threshold $E_{knee}$ in their way to the Earth. It is supported by the possible excess in the diffuse gamma-ray flux observed by MILAGRO \[7\]. Here we study other possible implications and also the conditions (on the cross section and the dark matter distribution) that have to be satisfied for this scenario to really work.
2 Other knees and the change in the spectral index

In addition to protons, the cosmic ray flux contains atomic nuclei (He, C, Fe, etc.). The abundance of the different species at energies around $10^6$ GeV has been measured in extensive air-shower experiments. In particular, KASCADE \[8, 9\] has observed that these fluxes also seem to exhibit a knee at an energy that increases with the atomic number. It is obvious that if there is an energy threshold $E_{knee}$ where the $p-\chi$ cross section becomes strong and produces the proton knee, also a nucleus $N$ will experience a similar effect.

As a first approximation, if $\sigma_{p\chi}$ is negligible at energies below $E_{knee}$ then the nucleus will start interacting when the energy per nucleon reaches that same threshold. This implies that the knee scales linearly with the atomic mass $A$:

$$E_{knee}^N \approx A E_{knee}.$$  \hspace{1cm} (2)

One can take into account, however, that $\sigma_{p\chi}$ is not zero at $E < E_{knee}$ (a step function), and that its raise with the energy may be better described by the power law

$$\sigma_{p\chi}(E) \propto E^\alpha \quad (E < E_{knee}).$$  \hspace{1cm} (3)

In that case the atomic knee is moved towards the proton knee $E_{knee}$ by two factors. First, the electric charge $Z > 1$ of a nucleus increases its interaction strength with the turbulent magnetic fields in our galaxy \[10\]. This implies that the average time $\tau$ (and distance $L = c\tau$) that it is travelling from the source to the Earth also increases \[11\]:

$$\tau \propto R^{-\beta},$$  \hspace{1cm} (4)

where $R = E/Z$ is the rigidity and the index $\beta$ at these energies may take values between 0.3 (typical for a Kolmogorov spectrum of magnetic fluctuations) and 0.6 (as deduced from the study of fluxes of stable and unstable nuclei of energy below the TeV). The probability that a cosmic ray interacts along its trajectory grows with $\tau$,

$$p_{int} \approx 1 - e^{-\sigma_{N\chi} n_{\chi} L} \approx \sigma_{N\chi} n_{\chi} c\tau,$$  \hspace{1cm} (5)

where $n_{\chi} = \rho_{\chi}/m_{\chi}$ is the number density of dark matter particles (the average depth $x$ of a trajectory is $\rho L$, and the nucleus interaction length is $1/(\sigma_{N\chi} n_{\chi})$). Therefore, a larger $\tau$ requires a smaller $\sigma_{N\chi}$ to obtain the same probability of interaction. The second factor is that the nucleus-dark matter cross section is larger than $\sigma_{p\chi}$. One can estimate that

$$\sigma_{N\chi}(E) \approx \begin{cases} A \sigma_{p\chi}(E/A) & \sigma_{p\chi} \leq 1 \text{ mbarn} ; \\ A^{2/3} \sigma_{p\chi}(E/A) & \sigma_{p\chi} \gg 1 \text{ mbarn} . \end{cases}$$  \hspace{1cm} (6)
Therefore, the interaction probability at the nucleus knee will coincide with the one at the proton knee if

\[ E_{\text{knee}}^N \approx E_{\text{knee}} A^{\frac{\alpha-1}{2}} Z^{-\beta}. \]  

(7)

For large values of \( \alpha \) we recover the linear scaling with the mass number, whereas taking \( \alpha = 2 \) and \( \beta = 0.5 \), the helium, carbon, and iron knees would move from \( 4E_{\text{knee}} \), \( 12E_{\text{knee}} \) and \( 55E_{\text{knee}} \) to \( 2E_{\text{knee}} \), \( 3E_{\text{knee}} \) and \( 5E_{\text{knee}} \), respectively. Therefore, we conclude that the hypothesis under study here seems able to explain the knees for the different nuclei observed by KASKADE.

Another important point to address is whether these interactions could also explain the constant spectral index \( -3.1 \) in the flux between the knee and the ankle. Let us suppose that with no dark matter perturbing its propagation the cosmic ray flux would have followed a \( E^{-2.7} \) dependence up to \( E_{\text{ankle}} \). This implies that the probability of interaction changing the spectral index from \( -2.7 \) to \( -3.1 \) must be

\[ p_{\text{int}}(E > E_{\text{knee}}) \approx 1 - \left( \frac{E}{E_{\text{knee}}} \right)^{-0.4}. \]  

(8)

We will show that this probability can be obtained if above \( E_{\text{knee}} \) the proton-dark matter cross section keeps growing with a given exponent \( \alpha' \):

\[ \sigma_{p\chi} \propto E^{\alpha'} (E > E_{\text{knee}}). \]  

(9)

The probability of interaction for a cosmic ray along a trajectory of length \( l \) is

\[ p_{\text{int}}(l, E) = 1 - e^{-\sigma_{p\chi} n_\chi l}. \]  

(10)

Now let us assume that \( l \) is a random variable with an exponential probability distribution \( w(l) \) and an average value \( \langle l \rangle = L \):

\[ w(l) = \frac{1}{L} e^{-l/L}. \]  

(11)

This is justified if the cosmic ray propagation can be modelled by a diffusive process driven by irregularities in the galactic magnetic field [1]. The diffusion coefficient is \( D \sim L^{-1} \propto E^\beta \) and lengths larger than \( L \) will be suppressed exponentially. The probability of interaction is then

\[ p_{\text{int}}(E) = \int dl \, p_{\text{int}}(l, E) \, w(l) = 1 - \frac{1}{\sigma_{p\chi} n_\chi L + 1}. \]  

(12)

Since at energies above \( E_{\text{knee}} \) \( \sigma_{p\chi} n_\chi L \) grows fast larger than 1, a constant spectral index needs that

\[ \left( \frac{E}{E_{\text{knee}}} \right)^{-0.4} \approx \sigma_{p\chi} n_\chi L \propto E^{\alpha'-\beta}. \]  

(13)

\[ \text{IIntermediate values in the position of the knee would be obtained for larger values of } \alpha \]
If \( \sigma_{p\chi} \) grows between the knee and the ankle like \( E^{0.4+\beta} \), with \( \beta = 0.3-0.6 \), then we can explain a sustained spectral index of \(-3.1\) in the cosmic ray flux.

### 3 Constraints and predictions at neutrino telescopes

The large probability of interaction required to produce the knee means that

\[
\sigma_{p\chi} n_\chi L = \frac{\sigma_{p\chi} x_\chi}{m_\chi} \approx 1 .
\]

(14)

It is easy to see that this can only be achieved with very large values of the cross section \( \sigma_{p\chi} \) and of the dark matter density \( \rho_\chi \). In particular, we know that as cosmic rays propagate from the source a significant fraction of them interact with interstellar matter. Since they collide with a hadronic cross section, the amount of matter that they cross must be a few \( g/cm^2 \) (a hadronic interaction length is around \( 50 \text{ g/cm}^2 [1] \)). Therefore, on dimensional grounds \( \chi \) may have an impact on the cosmic ray propagation if \( \sigma_{p\chi} \) grows above the mbarn and \( \rho_\chi \) is larger than the density of interstellar gas.

Let us first discuss the cross section. A possibility that has been extensively discussed during the past years is strong TeV gravity in models with extra dimensions [12]. If the fundamental scale is \( M_D \approx 1 \text{ TeV} \), at larger center of mass energies the gravitational cross section will dominate over gauge boson exchange due to the spin 2 of the graviton. At lower energies (below the mass \( M_c \) of the first Kaluza-Klein mode) 4-dimensional gravity is unchanged, whereas between \( M_c \) and \( M_D \) Newton’s constant grows like a power law. An analysis of the proton–dark matter cross section at center if mass energies \( s > M_D^2 \) in these models can be found in [13]. The scattering is dominated by eikonal processes where a parton carrying a fraction \( x \) of the proton momentum transfers a small fraction \( y \) of energy to \( \chi \). The cross section at the parton level grows like \( s^{1+4/n} \), so it is larger and softer (involves larger distances and smaller energy transfer) for lower values of the number \( n \) of extra dimensions. This is easily understood because gravity dilutes faster with the distance for larger \( n \), if \( n < 2 \) it is a long distance interaction with a divergent total cross section.

We find that if \( M_D \geq 1 \text{ TeV} \) only \( n = 1 \) seems to give the large values of \( \sigma_{p\chi} \) required to explain the cosmic ray knee. Of course, we need in that case a mechanism to avoid bounds from supernova and from macroscopic gravity. For example, Giudice et al [14] build a model where a warp factor adds a mass of \( \approx 10 \text{ MeV} \) to the Kaluza-Klein excitations of the graviton without changing the basic properties of the 5-dimensional model at high energies. The effective model has a TeV fundamental scale and only one extra dimension up

\[ \text{Notice that growth of } \sigma_{p\chi} \text{ with the energy will also be determined by the parton distribution functions.} \]
to distances of \( \approx (10 \text{ MeV})^{-1} \). In Fig. 1 we plot the cross section in this setup. The average fraction of energy transferred by a \( E = 10^6 \) GeV proton to the dark matter particle in an interaction is \( \langle y \rangle = 10^{-5} \). We have required a minimum \( q^2 \) of 1 GeV\(^2\), since the collision must break the incident proton.

Let us now comment on the dark matter density that is required. Although it is thought that the total amount of dark matter in the galaxy is much larger than the amount of baryonic interstellar matter, the former would be distributed inside a spherical halo of \( \approx 200 \) kpc \cite{15}, whereas the latter would be mainly within a disc of thickness \( \approx 6 \) kpc. As a consequence, the depth \( x_\chi \) of dark matter crossed by a cosmic ray from the source (in the galactic disc) to the Earth would be similar or even smaller than that of baryonic gas \( (x_{IM}) \). For example, if we assume a constant \( \rho_\chi \approx 0.3 \) g/cm\(^3\) (the local density near the solar system) then \( x_\chi \approx 0.1x_{IM} \). This value is clearly insufficient to explain the cosmic ray knee.

We think, however, that one may consider scenarios where the density \( \rho_\chi \) that cosmic rays face in their way to the Earth is substantially larger \( (x_\chi \approx 100 \ x_{IM}) \). In particular, the dark matter could be more clumped locally, in the regions where the cosmic rays are produced. It is also possible that cosmic rays spend a significant fraction of time inside local clouds of dark matter, trapped by stronger magnetic fields. They would also face a larger depth if the distribution of dark matter were more flattened towards the galactic plane (a non-spherical halo) \cite{16}. This third possibility might be better accommodated if the galactic dark matter has two components (a \textit{heavier} and a \textit{lighter} one \cite{17}), as the proximity of the

![Figure 1: Cross section for an eikonal gravitational interaction in \( p-\chi \) collisions.](image)

\[ \sigma [\text{mb}] \]

\[ n = 1 \]

\[ M_D = 1 \text{ TeV} \]

\[ m_\chi = 300 \text{ GeV} \]

\[ E [\text{GeV}] \]

\[ 10^5 \]

\[ 10^6 \]

\[ 10^7 \]

\[ 10^8 \]

\[ 10^9 \]
heavier component to the fundamental scale in these models would imply a larger $\chi-\chi$ elastic cross section justifying an anomalous distribution. Notice that although the total amount of dark matter in the galaxy is well established, its distribution is underconstrained (the rotation curves can be fitted with different distributions [18, 19], and magnetic fields could also play a role [20]).

We would like to discuss a last consequence that could be used to disregard the scenario under study in a model independent way. If gravity produces an increase in the dark matter interactions, it will also imply a large cross section for neutrinos above a certain energy threshold. More precisely, the center of mass energy when a neutrino of energy $E_\nu$ hits a proton at rest is

$$\sqrt{s} = \sqrt{2m_p E_\nu}.$$  \hspace{1cm} (15)

This coincides with the $\sqrt{s}$ in the collision of a proton at the knee with a dark matter particle if

$$E_\nu^{th} = \frac{m_\chi}{m_p} E_{knee} \approx 10^8 \text{ GeV}.$$ \hspace{1cm} (16)

Therefore, in this framework we would not observe any neutrino events above $E_\nu^{th}$ at $\nu$-telescopes. Such a neutrino would have an interaction length of 1–10 m in rock, losing a $y \approx 10^{-5}$ fraction of its energy in each collision. In Fig. 2 we plot the distribution of $y$ in

Figure 2: Differential cross section $d\sigma/dy$ (mbarn) in a $\nu-p$ (or $p-\chi$) gravitational interaction, where $y = (E_\nu - E'_\nu)/E_\nu$ is the fraction of energy lost by the incident neutrino (or transferred to $\chi$).
neutrino–proton interactions.

For example, a cosmogenic neutrino [21] of $10^9$ GeV would interact with a mbarn cross section and lose around 1 TeV of energy ($y \approx 10^{-6}$) in each interaction with matter. Energy loss, however, is dominated by the (less frequent) collisions of larger $y$. We estimate that such neutrino could deposit a 10% of its energy every 1–10 km. This means that it would never reach a telescope from up-going directions. One would have, however, other possible signals there. The neutrino could reach the center of IceCube (2 km under the ice) [22] from large (inclined) zenith angles. It would start there a TeV hadronic shower every 1–10 meters of ice, an event that would be clearly different from the muon bundle produced by an extensive air shower.

Notice also that bounds on the $\nu-p$ cross section from the non-observation of quasi-horizontal extended air showers [23] produced by cosmogenic neutrinos do not apply here. The reason is that in the interaction the neutrino will deposit just a small fraction $y$ of energy, starting an air shower below the $\approx 10^8$ GeV threshold in these experiments.

4 Summary and discussion

Cosmic rays may be affected by new physics at the TeV scale. In particular, their interaction with dark matter seems interesting because of two generic reasons: i) the dark matter particle is expected to be heavy, which provides larger center of mass energies ($\sqrt{2m_\chi E}$) than in cosmic ray collisions with a nucleon, and ii) the standard interactions are expected to be weak, which makes the relative effect of new physics easier to detect.

We have studied the possibility that the knee observed in the cosmic ray flux at energies around $10^6$ GeV may be caused by these interactions. In particular, models with extra dimensions and a TeV fundamental scale of gravity predict cross sections that grow very fast in the trans-Planckian regime. In [6] it is shown that these interactions could break the protons and produce a diffuse flux of secondary gamma rays consistent with MILAGRO observations. Here we have found that the knee would also imply knees that scale with the atomic number for the other nuclei present in the cosmic ray flux. We have shown that the constant power law $E^{-3.1}$ for the flux between the knee and the ankle could be correlated with a sustained growth $\sigma_{p\chi} \propto E^{\alpha'}$ in the proton–dark matter cross section.

We have also found, however, that the cross sections and the dark matter densities which are required are very large (mbarn and 100 times over the expected value, respectively). In particular, the size and the scaling of $\sigma_{p\chi}$ seem possible only in models with one extra
dimension. Such a model should be completed with a mechanism increasing the Kaluza-Klein masses like the one discussed in [14] to be consistent with observations. As for the dark matter, it may require a large local concentration near the sources of cosmic rays, or a flattened galactic distribution. We have speculated that this could be justified in a 2-component model (see, for example, [17]) where the heavier one may not be completely collisionless (the elastic scattering with another dark matter particle could have a center of mass energy just below the fundamental scale $M_D$).

Notice also that the presence of a possible second knee in the cosmic ray spectrum at $10^{8.5}$ GeV would not alter or invalidate the proposed mechanism. This second knee would have a different origin, the dominance in the spectrum of extragalactic protons [24, 25]. The extragalactic cosmic ray flux would not be affected by the interactions producing the first knee because dark matter densities are smaller outside the galaxy and the trajectories at these energies are not a random walk [6].

In any case, the scenario that we have discussed has what we think is a model independent implication in neutrino physics that could prove it wrong: the absence of standard neutrino interactions above a threshold energy around $10^8$ GeV. Neutrinos above this energy would interact with protons with a mbarn cross section, losing a small amount of energy (around 1 TeV) in each interaction. When a cosmogenic neutrino enters the atmosphere horizontally, the penetrating shower that it starts would contain an energy below the triggers in extended air shower experiments. However, in $\nu$-telescopes one could observe inclined events (down-going but from large zenith angles) where a very energetic neutrino starts a continuous of showers spaced by 1–10 m, a signal with no background within the standard model. The correlation between dark matter and neutrino physics is a generic feature in TeV gravity models. We find very appealing that a possible observational effect, the knee from cosmic ray–dark matter collisions, can be disproved (or supported) in the near future by another one, the observation of cosmogenic neutrino interactions at ICECUBE or ANITA [26].

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References

[1] C. Amsler et al. [Particle Data Group], Phys. Lett. B 667 (2008) 1.

[2] A. M. Hillas, arXiv:astro-ph/0607109.

[3] A. Dar and A. De Rujula, Phys. Rept. 466 (2008) 179.

[4] M. Prouza and R. Smida, Astron. Astrophys. 410 (2003) 1.

[5] R. Aloisio, V. Berezinsky, P. Blasi, A. Gazizov, S. Grigorieva and B. Hnatyk, Astropart. Phys. 27 (2007) 76.

[6] M. Masip and I. Mastromatteo, JCAP 0812 (2008) 003.

[7] A. A. Abdo et al., “A Measurement of the Spatial Distribution of Diffuse TeV Gamma Ray Emission from the Galactic Plane with Milagro,” arXiv:0805.0417 [astro-ph].

[8] T. Antoni et al. [The KASCADE Collaboration], Astropart. Phys. 24 (2005) 1.

[9] M. Aglietta et al. [EAS-TOP Collaboration], Astropart. Phys. 21 (2004) 583.

[10] J. L. Han, arXiv:0901.1165 [astro-ph].

[11] A. W. Strong, I. V. Moskalenko and V. S. Ptuskin, Ann. Rev. Nucl. Part. Sci. 57 (2007) 285.

[12] N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B 429 (1998) 263; I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B 436 (1998) 257; L. Randall and R. Sundrum, Phys. Rev. Lett. 83 (1999) 3370.

[13] G. F. Giudice, R. Rattazzi and J. D. Wells, Nucl. Phys. B 630 (2002) 293; J. I. Illana, M. Masip and D. Meloni, Phys. Rev. D 72 (2005) 024003; E. M. Sessolo and D. W. McKay, Phys. Lett. B 668 (2008) 396; P. Draggiotis, M. Masip and I. Mastromatteo, JCAP 07 (2008) 014.

[14] G. F. Giudice, T. Plehn and A. Strumia, Nucl. Phys. B 706 (2005) 455.

[15] J. F. Navarro, C. S. Frenk and S. D. M. White, Astrophys. J. 462 (1996) 563.

[16] P. D. Sackett, H. W. Rix, B. J. Jarvis and K. C. Freeman, Astrophys. J. 436 (1994) 629.

[17] K. Hsieh, R. N. Mohapatra and S. Nasri, JHEP 0612 (2006) 067.
[18] E. Battaner and E. Florido, Fund. Cosmic Phys. 21 (2000) 1.

[19] C. F. Martins, “The distribution of the dark matter in galaxies as the imprint of its Nature,” arXiv:0903.4588 [astro-ph.CO].

[20] E. Battaner, J.L. Garrido, M. Membrado and E. Florido, Nature 360 (1992) 652; E. Battaner and E. Florido, Astron. Nachr. 328 (2007) 92.

[21] D. V. Semikoz and G. Sigl, JCAP 0404 (2004) 003.

[22] A. Achterberg et al. [IceCube Collaboration], Astropart. Phys. 26 (2006) 155.

[23] L. A. Anchordoqui, Z. Fodor, S. D. Katz, A. Ringwald and H. Tu, JCAP 0506 (2005) 013.

[24] V. Berezinsky, A. Gazizov and M. Kachelriess, Phys. Rev. Lett. 97 (2006) 231101.

[25] R. Aloisio, V. Berezinsky, P. Blasi and S. Ostapchenko, Phys. Rev. D 77 (2008) 025007.

[26] P. W. Gorham et al. [ANITA collaboration], “New Limits on the Ultra-high Energy Cosmic Neutrino Flux from the ANITA Experiment,” arXiv:0812.2715 [astro-ph].