DARK-MATTER RELAY FOR ULTRA-HIGH-ENERGY COSMIC RAYS

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19$^{\mathrm{th}}$ May 2026

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Estimate of the cross section

$$\sigma_c = \frac{1}{n\lambda} = \frac{m_{\rm DM}}{\rho\lambda}. \quad (1)$$

here n, ρ, $m_{\rm DM}$ denote the number density, mass density, and mass of dark-matter particle, respectively, while λ is the mean free path of the accelerated nucleus in the dark-matter medium.

Scales

Table 1. Interaction scales

Scale	λ, kpc	ρ, GeV/cm^3
Core	0.1	840
Galaxy	10	0.3
Galaxy cluster	10^3	10^{-3}

Estimate of the cross section

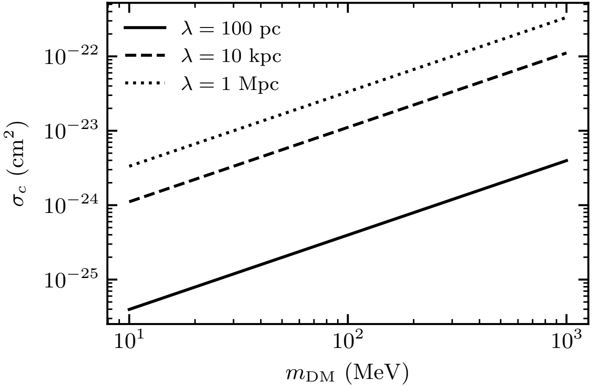


Рис.: Estimates of the required cross section σ_c versus mass $m_{\rm DM}$ calculated from Eq. (1). Three different spatial scales λ are considered.

Estimate of the cross section

We consider two cases:

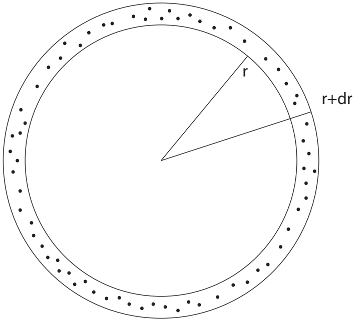
- Case A: $m_{\mathrm{DM}} = 50$ MeV, $\sigma = 10^{-25}$ cm^2, $\lambda = 100$ pc
- Case B: $m_{\mathrm{DM}} = 20$ MeV, $\sigma = 10^{-24}$ cm^2, $\lambda = 1$ Mpc

For case A, a more detailed estimate of the collision probability will be made.

Calculating the probability of the first collision

$$\mathrm{d}P(r) = \frac{\sigma}{m_{\mathrm{DM}}}\,\rho(r)\,\mathrm{d}r\,. \tag{2}$$

r is the distance from the center of the galaxy, $\mathrm{d}P(r)$ - the interaction probability in a spherical shell $(r; r + \mathrm{d}r)$, $\rho(r)$ is the density of dark matter



Burkert profile:

$$\rho(r) \equiv \rho_{\rm Bk}(r) = \frac{\rho_{\rm b}}{(1 + r/r_{\rm b})\left(1 + (r/r_{\rm b})^2\right)}, \tag{3}$$

We take $r_b = 8$ kpc, ρ_b is determined from the normalization:

$$4\pi \int_0^R \rho(r)\, r^2\, \mathrm{d}r = M \sim 10^{12} M_\odot. \tag{4}$$

Total probability:

$$P = \int_0^R \frac{\sigma}{m_{\rm DM}} \rho(r)\, \mathrm{d}r \tag{5}$$

For $m_{\rm DM} = 50$ MeV and $\sigma = 10^{-25}$ cm^2 we obtain $P \sim 0.1$

Calculating the probability of a repeat collision

$$\rho(R, z) = \frac{\Sigma_{\rm g}}{2z_{\rm gas}} \exp(-R/R_{\rm gas})\,\mathrm{sech}^2(z/z_{\rm gas}), \tag{6}$$

where $\Sigma_{\rm g} = 71.1\ M_\odot/\ \mathrm{pc}^2$, $R_{\rm gas} = 4.8$ kpc, $z_{\rm gas} = 130$ pc

$$\mathrm{d}P(z) = \frac{\sigma}{m_{\rm p}} \rho(z)\,\mathrm{d}z. \tag{7}$$

$R_\odot = 8.15$ kpc, $h \sim 100$ pc - half-thickness of the disc:

$$P = \int_0^h \frac{\sigma}{m_{\rm p}} \rho(R = R_\odot, z)\,\mathrm{d}z = \frac{\sigma}{m_{\rm p}} \frac{\Sigma_{\rm g}}{2\,z_{\rm gas}} \exp(-R_\odot/R_{\rm gas}) \int_0^h \mathrm{sech}^2(z/z_{\rm gas})\,\mathrm{d}z \sim 5 \cdot 10^{-5} \tag{8}$$

where we still take $\sigma = 10^{-25}$ см^2, and $m_{\rm p}$ is the proton mass.

Another scenario

$$P = \int_0^{R_\odot} \frac{\sigma}{m_\mathrm{p}} \rho(R, z = 0)\,\mathrm{d}R = \frac{\sigma}{m_\mathrm{p}} \frac{\Sigma_\mathrm{g}}{2z_\mathrm{gas}} \int_0^{R_\odot} \exp(-R/R_{gas})\,\mathrm{d}R \sim 0.01 \tag{9}$$

Interaction in filament

gas concentration in the filament $n \sim 10^{-4}$ cm^{-3} and the sizes of structures $\lambda \sim 30 - 100$ Mpc

$$\sigma = \frac{1}{n\,\lambda} \sim 10^{-23}\ \mathrm{cm}^2 \tag{10}$$

Model

Lagrangian:

$$\mathcal{L} = g_\chi \bar{\chi} \gamma^\mu \chi A'_\mu + \sum_q g_q \bar{q} \gamma^\mu q A'_\mu \tag{11}$$

$g_\chi = 0.1$, $g_q = Q_q e \epsilon$, the kinetic mixing parameter $\epsilon = 10^{-5}$. For definiteness, we take benchmark value $m_\chi = 50\mathrm{Mev}$ and $m_{A'} = 3m_\chi$

We consider the process

$$\chi(k) + q(xp) \longrightarrow \chi(k') + q(p') \tag{12}$$

Differential cross section

$$\frac{\mathrm{d}\sigma_{\chi\mathrm{p}}}{\mathrm{d}T_\chi} = \frac{|\vec{k'}|}{16\pi m_\chi Q^2 \sqrt{E_\mathrm{p}^2 - m_\mathrm{p}^2}} \times \sum_{\mathrm{q=u,d}} \int_{-1}^{\cos\theta_\mathrm{max}} f_\mathrm{q}(x, Q^2)\, \overline{|\mathcal{M}(x)|^2}\, \mathrm{d}\cos\theta \tag{13}$$

where $x = Q^2/(-2p\cdot q)$, the squared momentum transfer $Q^2 = -q^2 = 2m_\chi T_\chi$ and $-2p\cdot q = 2E_\mathrm{p}T_\chi - 2|\vec{p}||\vec{k'}|\cos\theta$, T_χ - kinetic energy of the final dark-matter particle, $q = p - p'$ (**arXiv**2308.02204)

$$\overline{|\mathcal{M}(x)|^2} = \frac{g_\chi^2 g_\mathrm{q}^2}{(Q^2 + m_{\mathrm{A'}}^2)^2}\big[16(xm_\chi E_\mathrm{p})^2 - 8xm_\chi E_p Q^2 - 4Q^2 m_\chi^2 - 4Q^2 x^2 m_\mathrm{p}^2 + 2(Q^2)^2\big] \tag{14}$$

Growth of the cross section

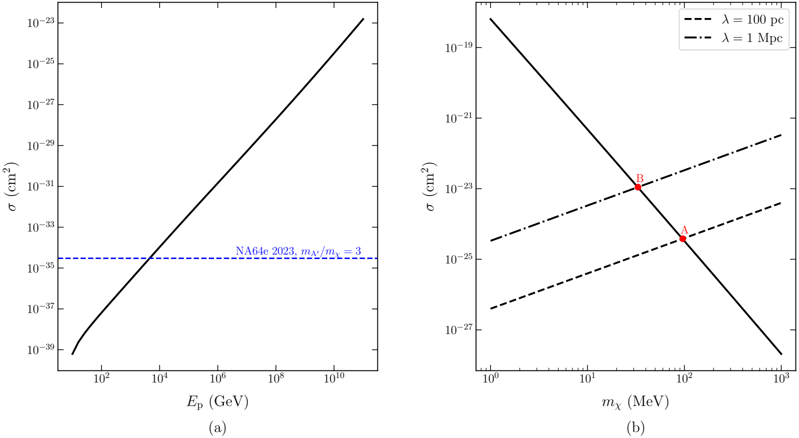


Рис.: (a) $m_{\rm DM} = 50$ MeV. The upper limit from NA64 (2023) are shown by the blue dashed line.
(b) $E_p = 10^{19}$ eV. The dashed lines show the estimates presented in Fig. 1

Growth of the cross section

For $E_\mathrm{p} \gtrsim 10^4$ GeV, the following asymptotic behavior holds:

$$\sigma \sim 10^{-40}\,\mathrm{cm}^2 \times \left(\frac{E_\mathrm{p}}{1\ \mathrm{GeV}}\right)^{1.5} \tag{15}$$

Conclusions

- Case A: $\sigma \sim 10^{-25}$ cm^2 and $m_{\mathrm{DM}} \sim 50$ MeV
  Significant probability, but there is anisotropy (poor for HiRes)
- Case B: $\sigma \sim 10^{-24}$ cm^2 and $m_{\mathrm{DM}} \sim 20$ MeV
  Estimated need to be clarified. Isotropically.
- Another models?

This work is supported in the framework of the State project "Science"by the Ministry of Science and Higher Education of the Russian Federation under the contract 075-15-2024-541.