Soft Scattering Evaporation of Dark Matter Subhalos by Inner Galactic Gases

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Introduction

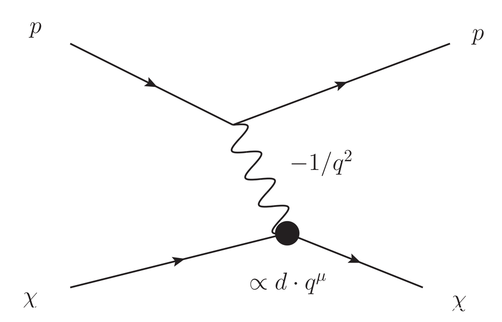
Electrically neutral WIMPs can acquire effective coupling to photons via loop effects. The leading effective operator is the dimension-5 EM dipole operator. Such effective electromagnetic (EM) operators allow for efficient soft scattering between dark matter and in particular ionized/charged environmental particles. We have studied dipole DM kinetic decoupling in the Early Universe and temperature evolution, then evaluate the corresponding smallest protohalo mass. At late time, ionized hotspots re-emerge in inner galactic regions, yielding a large ionized fraction in the form of heated gas and cosmic rays. For small subhalos located in such regions, they can be possibly evaporated by charged particles via dipole-charge soft scattering. We calculate the evaporation rate of DM by colliding with galactic hot gas and cosmic rays, and place an upper limit on the DM's dipole form factor by assuming the survival of subhalos in the ionized Galactic interior.

Dipole-charge soft scattering

For low-energy collisions, we adopt the dark matter χ acquires effective EM dipole interaction,

$$\Delta\mathcal{L} = -\frac{i}{2}\bar{\chi}\sigma_{\mu\nu}(\mu + \gamma_5\mathcal{D})\chi F^{\mu\nu} \tag{1}$$

where the electric and magnetic dipole moments (EDM and MDM) $\mathcal{D}$ and μ derive from loop corrections of high-scale UV physics. The scattering diagram of DM with a charged particle is shown below.



We calculate the following two cases, responding to non-relativistic and relativistic scattering. For the non-relativistic collision between DM and ionized gas, their relative velocity is represented by v and the corresponding transfer cross section is

$$\sigma_T(v) = \begin{cases} 2\alpha\mathcal{D}^2 v^{-2} & \text{(EDM)} \\ \alpha\mu^2 \frac{3m_\chi^2+2m_\chi m_p+2m_p^2}{(m_\chi+m_p)^2} & \text{(MDM)}. \end{cases} \tag{2}$$

There is a explicit v^{-2} dependence in EDM induced non-relativistic collisions. For the relativistic scattering between DM and cosmic ray proton, the corresponding transfer cross-section is

$$\sigma_T = \begin{cases} \alpha\mathcal{D}^2\left[1 + m_p^2\left(\frac{1}{(m_\chi+m_p)^2+2m_\chi T_p} + \frac{2}{2m_pT_p+T_p^2}\right)\right] & \text{(EDM)} \\ \alpha\mu^2\left[1 + \frac{2m_\chi^2+m_p^2}{(m_\chi+m_p)^2+2m_\chi T_p}\right] & \text{(MDM)}. \end{cases} \tag{3}$$

Dark matter kinetic decoupling and protohalo size

The DM kinetic decoupling temperature is related to the smallest protohalo size. To determine the time evolution of DM temperature, we consider the Boltzmann equation for a flat FRW metric

$$E\left(\partial_t - H\mathbf{p}\cdot\nabla_{\mathbf{p}}\right)f = C[f]. \tag{4}$$

In the above equation, $(E,\mathbf{p})$ represents the energy and 3-momentum of DM and f is the DM phase space density. $C[f]$ is the collision term that describes the changes of f between the scattering process of DM and SM particles

$$C[f] = \gamma(T)m_\chi\left[m_\chi T\nabla_{\mathbf{p}}^2 + \mathbf{p}\cdot\nabla_{\mathbf{p}} + 3\right]f(\mathbf{p}). \tag{5}$$

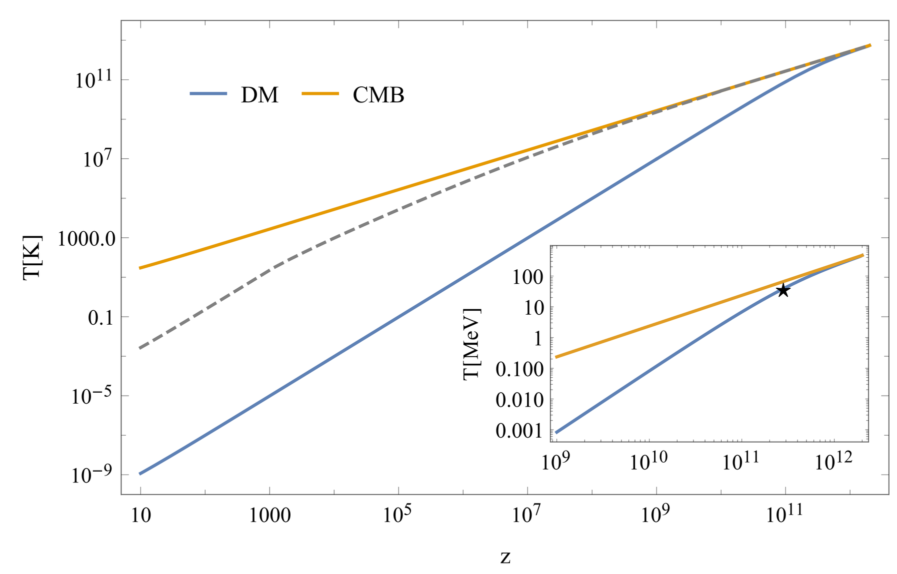
$\gamma(T)$ represents the momentum exchange rate between DM and SM particles, which can be written as (T is the plasma temperature)

$$\gamma(T) = \sum_i \frac{g_{\rm SM}}{6(2\pi)^3 m_\chi^3 T}\int dk k^5\omega^{-1}g^{\pm}\left(1 \mp g^{\pm}\right)\frac{1}{8k^4}\int_{-4k^2}^{0}dt(-t)\overline{|\mathcal{M}|}^2. \tag{6}$$

(ω,k) represent SM particles' energy and momentum. The evolution equation of DM temperature is

$$(1+z)\frac{dT_\chi}{dz} = 2T_\chi + \frac{\gamma(T)}{H(z)}\left(T_\chi - T\right), \tag{7}$$

numerically solve the equation and the DM temperature evolution result is shown below



The choice of parameter are $m_\chi = 1$ GeV, dipole moment 10^{-6} GeV^{-1} (blue solid) within current direct detection limits, and a larger dipole moment 10^{-3} GeV^{-1} (gray dashed). The kinetic decoupling temperature is around 30 MeV which is marked with an asterisk symbol. After T_{kd}, DM particles can stream freely and erase the perturbations on scales smaller than the free-streaming

$$\lambda_{fs} = a(t_0)\int_{t_{kd}}^{t_0}\frac{v(t)}{a(t)}dt. \tag{8}$$

The smallest protohalos from free-streaming effects can be estimated as the DM mass contained inside a sphere of radius $\lambda_{fs}/2$,

$$M_{fs} = \frac{4\pi}{3}\rho_m(t_0)\left(\frac{\lambda_{fs}}{2}\right)^3. \tag{9}$$

In our model, for GeV scale dark matter and a kinetic decoupling temperature around 30 MeV, the corresponding smallest protohalo mass is around $10^{-7}M_\odot$. Assuming such halos form, we would further study their evaporation in dense galactic areas at later times.

Subhalo heating by galactic gases and cosmic ray

For the non-relativistic case of DM and ionized gas scattering, the thermally averaged energy transfer rate of per unit time is given by,

$$\begin{aligned}\frac{\mathrm{d}\Delta E_p}{\mathrm{d}t} = &\frac{m_\chi\rho_p}{(m_\chi+m_p)}\int d^3v_p f_p(v_p)\int d^3v_\chi f_\chi(v_\chi) \\ &\times\sigma_T\left(|\boldsymbol{v}_\chi-\boldsymbol{v}_p|\right)|\boldsymbol{v}_\chi-\boldsymbol{v}_p|\left[\boldsymbol{v}_{\rm cm}\cdot(\boldsymbol{v}_p-\boldsymbol{v}_\chi)\right]\end{aligned} \tag{10}$$

For protons in hot gas and DM inside a subhalo, their velocity follows a Maxwellian-Boltzmann distribution. Substituting the distribution into Eq. 10 and integrating out the velocity distribution. The heating rate can be obtained

$$\frac{\mathrm{d}\Delta E_\chi}{\mathrm{d}t} = \begin{cases} \frac{2\alpha\mathcal{D}^2 m_p m_\chi\rho_p v}{(m_p+m_\chi)^2} & \text{(EDM)} \\ 3\alpha\mu^2\left[1 - \frac{m_p(m_p+4m_\chi)}{3(m_p+m_\chi)^2}\right]\frac{m_p m_\chi\rho_p v^3}{(m_p+m_\chi)^2} & \text{(MDM)} \end{cases} \tag{11}$$

where v represents their relative velocity. For the relativistic case of DM and cosmic ray scattering, the heating rate is obtained by integrating transfer cross-section σ_T with the cosmic ray flux intensity Φ

$$\begin{aligned}\frac{\mathrm{d}\Delta E_\chi}{\mathrm{d}t} &= \int \Delta E_\chi nv\,\mathrm{d}\sigma \\ &= \int \mathrm{d}T_i\mathrm{d}\Omega\left(\frac{\mathrm{d}\Phi}{\mathrm{d}T_i\mathrm{d}\Omega}\right)\int\frac{\mathrm{d}\sigma}{\mathrm{d}T_\chi}T_\chi\mathrm{d}T_\chi\end{aligned} \tag{12}$$

where n is the proton number density, $\Phi = nv$, $\Delta E_\chi = T_\chi$. Given this heating rate, the time scale for an average DM particle to be heated to its host subhalo's escaped velocity can be estimated as

$$\tau_{\rm esc.} = \frac{1}{2}m_\chi\left(v_{\rm esc}^2 - v_{\rm rms}^2\right)\cdot\left(\frac{\mathrm{d}\Delta E_\chi}{\mathrm{d}t}\right)^{-1}, \tag{13}$$

where $v_{\rm rms}$ is the root-mean-square velocity of DM inside the subhalo. Stability of subhalos would require $\tau_{\rm esc.} > 10^{10}$ yr by collision with either gas or cosmic rays. DM particle's root-mean-square velocity $v_{\rm rms}$, escaped velocity $v_{\rm esc}$ and velocity dispersion δ_v would depend on the subhalo size.

$$\delta_v \approx 3.9\ \mathrm{km/s}\left(\frac{M}{10^6 M_\odot}\right)^{1/3} \tag{14}$$

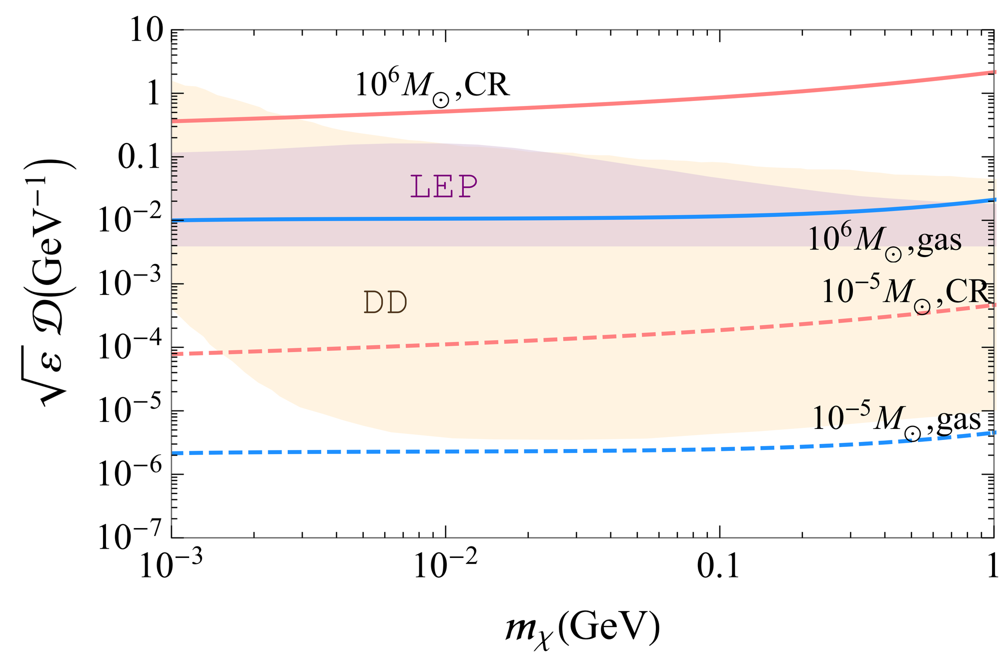
For a Maxwellian distribution, $v_{\rm rms} = 1.73\delta_v$ and $v_{\rm esc} = 2.44\delta_v$.

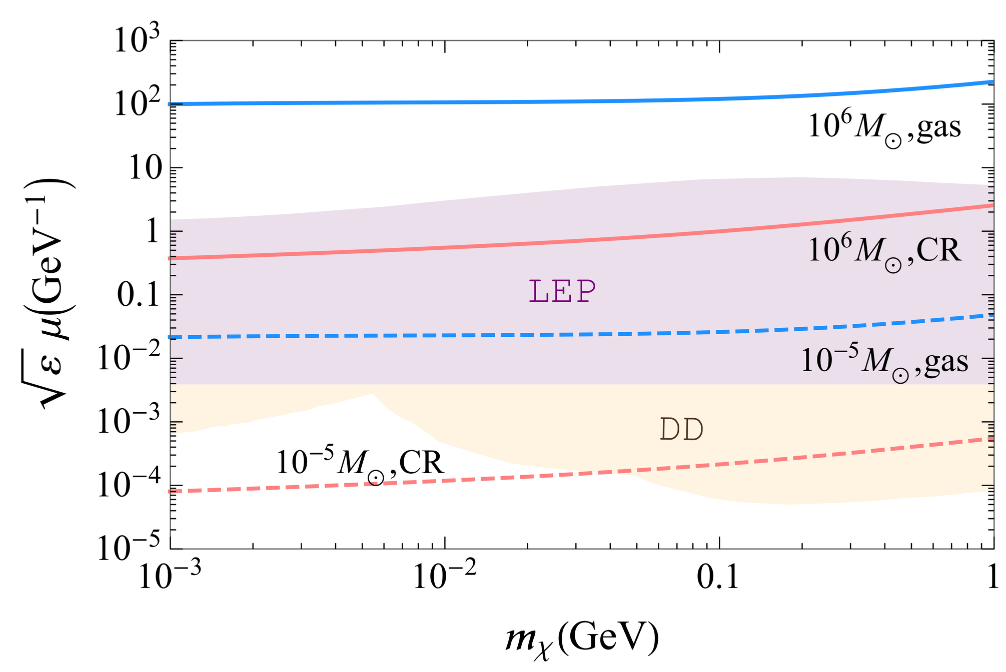
Galactic limits

For Galactic ionized clouds within 1 kpc from the disk, the number density is 0.5 cm^{-3}. The typical velocity of subhalos with $\mathcal{O}(kpc)$ orbit radius is $v \sim 10^{-4}$. For cosmic ray protons, the energy spectrum is an approximate $E^{-2.7}$ powerlaw above the GeV scale. So far the cosmic ray has only been measured 'locally' at the Earth. The relative intensity distribution in other location can be modeled as,

$$\frac{I(r,z)}{I(r_\odot,0)} = \frac{\mathrm{sech}(r/r_{\rm CR})}{\mathrm{sech}(r_\odot/r_{\rm CR})}\cdot\mathrm{sech}(z/z_{\rm CR}). \tag{15}$$

Using the above equation, the volume-averaged proton flux within 1 kpc from the galactic center is about 2.1 times of that at the Sun's location. Using Eq. 13, the dipole moment limits that lead to $\tau_{\rm esc.} = 10^{10}$ yr is shown below





The $\tau_{\rm esc.} = 10^{10}$ yr limits from collisional heating on gas(blue line) and cosmic rays(red line) are given for subhalo mass at $10^6 M_\odot$ (solid line) and $10^{-5}M_\odot$ (dashed line), which is respectively corresponding to the typical visible subhalo mass and a much lower invisible subhalo mass that allows the dipole-moment sensitivity dips below the current direct-search dipole limits.

Discussions

Satisfying the current sub-GeV direct-detection limits, the inner Galaxy's hot ionized gas and cosmic rays are capable of evaporating low-mass subhalo below $10^{-5}M_\odot$ over a 10^{10} yr time span. Evaporation by DM-gas collision potentially affects low-mass subhalo distribution around the galactic center, where DM is also abundant. Evaporation by cosmic rays would extend to a slightly larger region over a few kpc. In galaxies with an active core, higher amount of fully ionized gas and stronger cosmic ray outflow would further enhance the evaporation due to soft scattering.