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Soft Scattering Evaporation of Dark Matter Subhalos by Inner Galactic Gases

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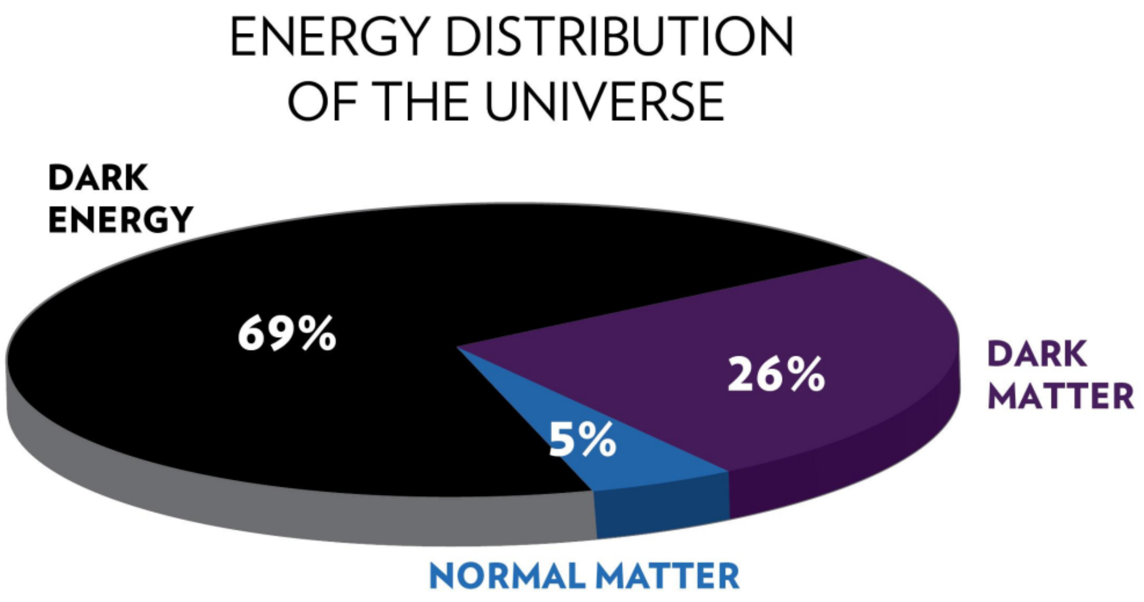
Introduction



Basic features of DM:

1. Electric neutrality
2. Don’t interact with baryon matter
3. Stable and long-life
4. moves slowly compared to the speed of light

Possible candidates of DM:

1. WIMP
2. Axion
3. Sterile neutrino
4. Primordial black hole
5. etc

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Dipole dark matter

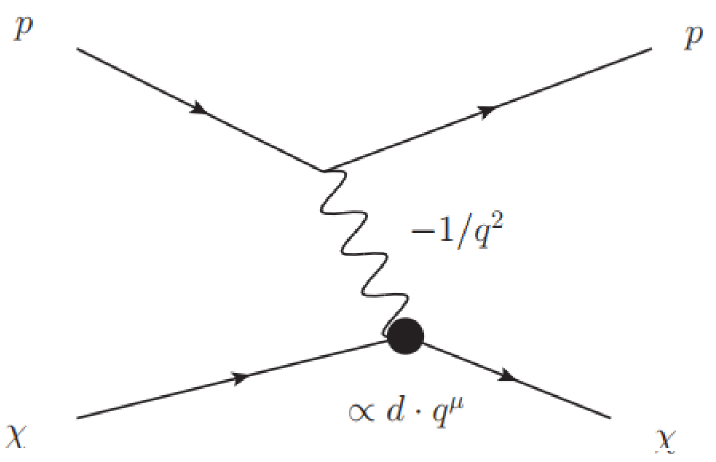
- Below the weak scale, electrically neutral WIMPs can acquire effective coupling to photons (via loop effects)

- The leading effective operator is the dimension-5 EM dipole operator

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

Where $\mathcal{D}$ and μ represents electric and magnetic dipole moments (EDM and MDM) which derive from loop corrections of high-scale UV physics.

Dipole-charge scattering



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

q^{-1} dependence in charge-dipole scattering amplitude and the cross-section has a well-known q^{-2} divergence

- At late universe after reionization, ionized hotspots re-emerge in inner galactic regions in the form of **heated gas** and **cosmic rays**
- For **small subhalos** located in such regions, through dipole-charge interaction, dark matter particles can escape these weakly bound subhalos
- By calculating soft dipole-scattering heating rate and assuming the survival of subhalos , we can place an upper limit on the DM's dipole form factor

Dipole-charge scattering differential cross-section

- Relativistic scattering (DM and cosmic ray)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}T_\chi} = \begin{cases} \frac{e^2\mathcal{D}^2}{8\pi T_\chi |\mathbf{p}_i|^2}(2E_i^2 - 2E_iT_\chi - m_\chi T_\chi), & \text{(EDM)} \\ \frac{e^2\mu^2}{8\pi T_\chi |\mathbf{p}_i|^2}(2|\mathbf{p}_i|^2 - 2E_iT_\chi + m_\chi T_\chi), & \text{(MDM)} \end{cases}$$

$\mathbf{p}_i$ is incident proton's 3-momentum
E_i is total energy of proton
T_χ is the kinetic energy of DM after collision

- Non-relativistic scattering (DM and hot gas)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} = \begin{cases} \alpha\mathcal{D}^2\frac{1}{v^2(1-\cos\theta)} & \text{(EDM)} \\ \alpha\mu^2\frac{3m_\chi^2+2m_\chi m_p+2m_p^2}{2(m_\chi+m_p)^2(1-\cos\theta)} & \text{(MDM)} \end{cases}$$

v is relative velocity between DM and gas
For **EDM**, there is a explicit v^{-2} **dependence**

Dipole-charge scattering transfer cross-section

The **transfer cross-section** for non-Relativistic and Relativistic case are respectively

$$\sigma_T(v) \equiv \int \mathrm{d}\cos\theta \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta}(1-\cos\theta)$$
$$= \begin{cases} 2\alpha\mathcal{D}^2 v^{-2} & \text{(EDM)} \\ \alpha\mu^2 \frac{3m_\chi^2+2m_\chi m_p+2m_p^2}{(m_\chi+m_p)^2} & \text{(MDM)} \end{cases}$$

For **EDM**, there is a explicit v^{-2} **dependence** in EDM induced non-relativsitic collisions

For **MDM**, the leading term is finite and not enhanced by v^{-2}

$$\sigma_T = \begin{cases} \alpha\mathcal{D}^2 \left[1 + m_p^2\left(\frac{1}{(m_\chi+m_p)^2+2m_\chi T_i} + \frac{2}{2m_p T_i + T_i^2}\right)\right] \\ \alpha\mu^2 \left[1 + \frac{2m_\chi^2+m_p^2}{(m_\chi+m_p)^2+2m_\chi T_i}\right] \end{cases}$$

Subhalo heating rate due to hot gas

$$\frac{\mathrm{d}\Delta E_p}{\mathrm{d}t} = \frac{m_\chi \rho_p}{(m_\chi + m_p)} \int d^3 v_p f_p(v_p) \int d^3 v_\chi f_\chi(v_\chi)$$
$$\times \bar{\sigma}\left(|\mathbf{v}_\chi - \mathbf{v}_p|\right) |\mathbf{v}_\chi - \mathbf{v}_p| \left[\mathbf{v}_{\mathrm{CM}} \cdot (\mathbf{v}_p - \mathbf{v}_\chi)\right],$$

$$f_\chi(\vec{v}_\chi) = \frac{1}{n} e^{-|\vec{v}_\chi - \vec{v}_0|^2/\sigma_v^2}$$

$$f_p(\vec{v}_p) = \frac{1}{n} e^{-m_p|\vec{v}_p - \vec{v}_{p0}|^2/2k_B T}$$

In the limit that energy transfer rate is dominated by their relative velocity v

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

- For EDM, the heating rate is proportional to relative veolocity v between DM and gas
- For MDM, the heating rate is proportional to v^3

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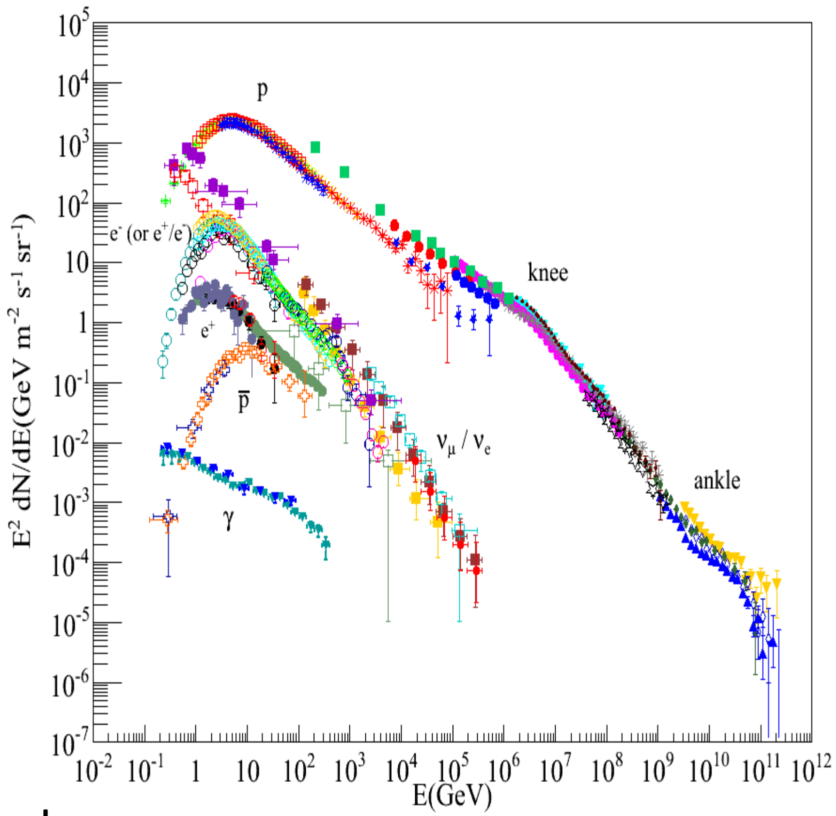
Subhalo heating rate due to cosmic ray

$$\frac{\mathrm{d}\Delta E_\chi}{\mathrm{d}t} = \int \Delta E_\chi n v \,\mathrm{d}\sigma$$
$$= \int \mathrm{d}T_i \mathrm{d}\Omega \left(\frac{\mathrm{d}\Phi}{\mathrm{d}T_i \mathrm{d}\Omega}\right) \int \frac{\mathrm{d}\sigma}{\mathrm{d}T_\chi} T_\chi \mathrm{d}T_\chi$$

- The proton energy spectrum is an approximate $E^{-2.7}$ powerlaw above the GeV scale.
- So far the cosmic ray energy spectrum has only been measured **locally at the Earth**.



The relative intensity distribution **in other location** can be modeled

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

r_{CR}~5.1kpc

z_{CR}~kpc

The volume-averaged proton flux within 1 kpc from the galactic center is about 2.1 times of that at the Sun's location

Galactic limits

- The time scale for an average DM particle to be heated to its host subhalo's escaped velocity can be estimated as

$$\tau_{\mathrm{esc.}} = \frac{1}{2} m_\chi \left(v_{\mathrm{esc.}}^2 - \bar{v}^2\right) \cdot \left(\frac{\mathrm{d}\Delta E_\chi}{\mathrm{d}t}\right)^{-1}$$

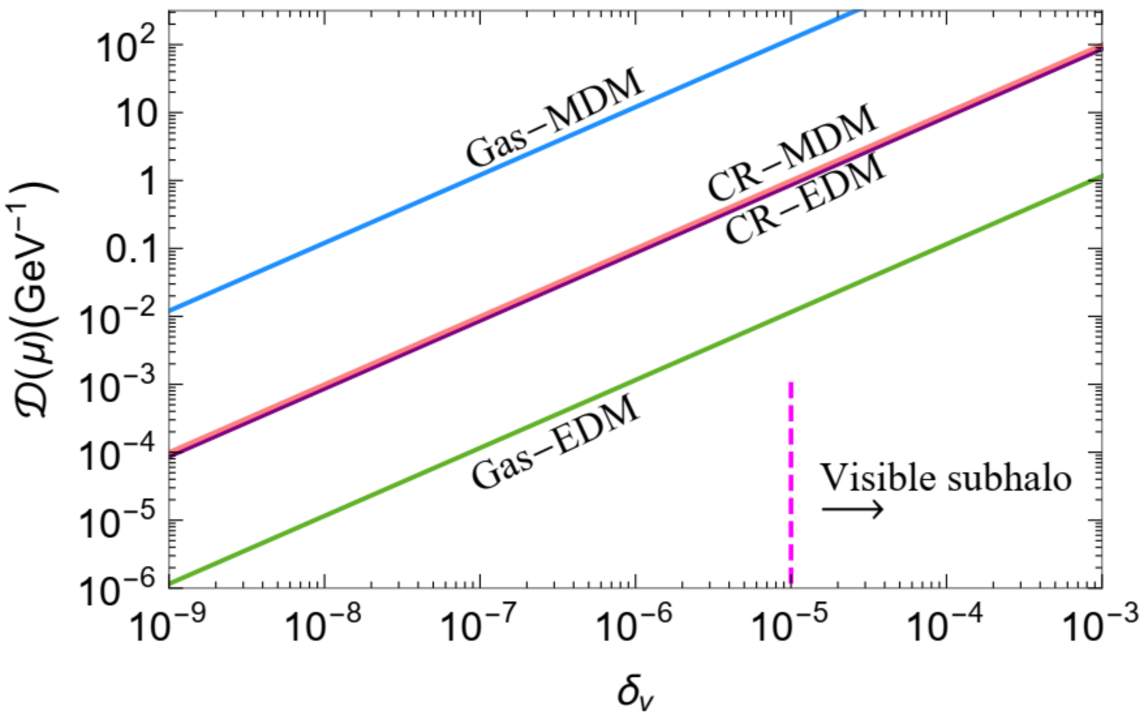
- Stability of subhalos would require $\tau_{esc} > 10^{10}$ yr by collision with either gas or cosmic rays.

- DM particle's velocity dispersion δ_v, root-mean-square velocity $\bar{v}$, escaped velocity v_{esc} would depend on the subhalo size. We use an empirical scaling relation

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

- For a Maxwellian distribution: $\bar{v}$=1.73 δ_v , v_{esc}=1.41 $\bar{v}$

Dipole moment limits



Dipole moment *D* and μ limits for different subhalo's velocity dispersion (corresponding to different subhalo size) that leads to over 10^{10}yr evaporation time

- Subhalo velocity assumes $v = 10^{-4}$ in the galactic frame.
- Cosmic ray collisions are insensitive to subhalo's velocity and their limits on EDM and MDM are comparable
- In non-relativistic gas-DM collision, The v^{-2}dependence in EDM σ_T leads to faster heating than MDM and a significantly more stringent limit

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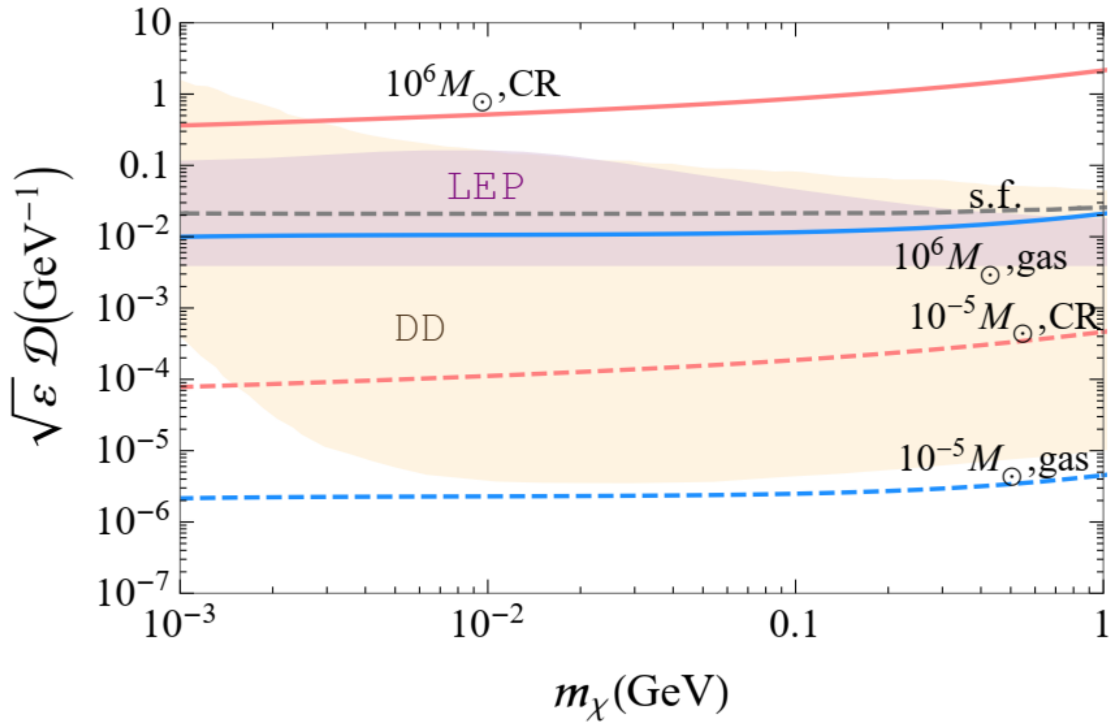
Dipole moment limits



Dark matter EDM limits for different mass of DM particle from soft collisional heating on gas and cosmic rays, with $v = 10^{-4}$

- Collider search constraint from LEP and direct detection exclusion limits on DM dipole moment are shown as color-shaped regions.
- The solid line represents large mass visible halo and dashed line represents lower mass invisible halo
- The invisible subhalo mass (around $10^{-5} M_\odot$) that allows the dipole-moment sensitivity dips below the current direct-search dipole limits.

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Summary

- The large gap between dark matter subhalo’s velocity and its own gravitational binding velocity creates the situation that dark matter soft-scattering on baryons can evaporate the subhalo, the survival of low-mass subhalos requires stringent limits on the photon-mediated soft scattering

- We have calculated the soft dipole-scattering heating 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

- To satisfying the current direct-detection limits on sub-GeV DM dipole interaction strength, the Milky Way’s hot ionized gas in the inner galactic region are capable of evaporating low-mass subhalo below $10^{-5}M_{\odot}$ over 10^{10} yr time span

THANKS！