

Direct Detection of Ultralight Dark Matter via Astronomical Ephemeris

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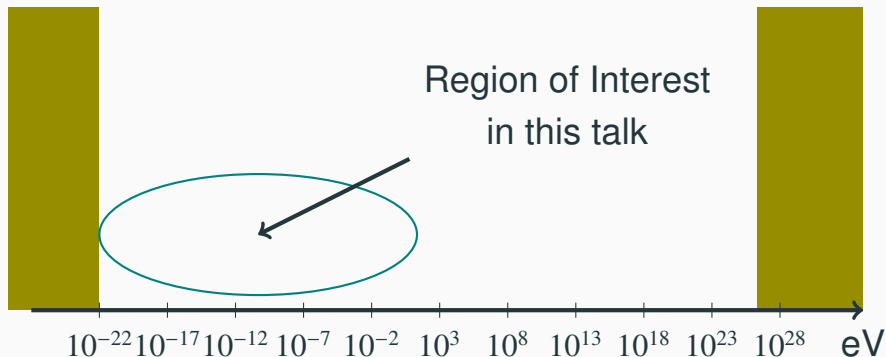
Introduction

- Dark matter is one of the most rigid new physics
- Which mass range?

Particle DM Mass Range



Particle DM Mass Range



Outline

- Introduction to Ultralight DM
- DM Collision Effects
- Cross Section Estimation
- Discussion and Summary

Introduction to Ultralight DM

Ultralight DM

- DM for $10^{-22} \text{ eV} \lesssim m_{\text{DM}} \lesssim \text{eV}$
- Must be Bosonic
- $m \sim 10^{-22} \text{ eV}$: “Fuzzy DM”
 - *e.g.* Hu, *et al.*, 2000
- Moduli d.o.f.?
- Non-thermally produced
 - Coherent oscillation
 - Decay of defects

Measure DM properties

- Suppose DM has non-gravitational interaction.
How could we detect them?
 - Production
 - Indirect Detection
 - **Direct Detection**

Direct Detection

- One recoil momentum: $\Delta p \propto m$
- Number density: $n_{\text{DM}} \propto m^{-1}$
 - Total recoil: $\Delta p_{\text{tot}} \propto n_{\text{DM}} \Delta p \propto m^0$
- The drawback is to choose a good target
- We propose to use the **celestial bodies** in the solar system

Why Celestial Bodies?

- The measurements are good enough
 - “Ephemeris”, $\Delta R/R \sim 10^{-10}$
- Large quantum mechanical enhancement

DM Collision Effects

Motion of Celestial Bodies

- The entire solar system moves w.r.t. the galaxy
 - $v_s \sim 10^{-3}$
- Each planets rotates
 - $v_p \sim 10^{-4}$

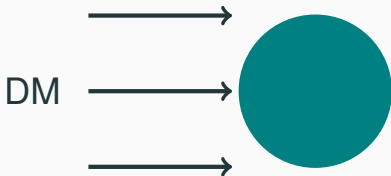


Motion of DM

- The DM velocity obeys Gaussian dist.
 - $v_0 \sim 10^{-3}$
- $v < v_{\text{esc}}$, $v_{\text{esc}} \simeq 600 \text{ km/s}$

DM Collision

- Consider the observer on the celestial body (e.g. us, on the Earth)



- The observer feels DM “wind” of $v \sim 10^{-3}$, which (de-)accelerate the object

Comparison with the Ephemeris

- Now, we know the position of each planets for decades by the ephemeris
- On the other hand,

$$M\vec{a} = \int d\Omega \frac{d\sigma}{d\Omega} n v \vec{q}(\Omega).$$

- We want to know the differential cross sect., $d\sigma/d\Omega$

Cross Section Estimation

Interaction

- Assume, between DM ϕ and nucleon N ,

$$\Delta\mathcal{L} = \frac{c_N}{2}\phi^2\bar{N}N,$$

where

$$c_N = \frac{f_N m_N}{\Lambda^2},$$

and Λ is the cutoff scale.

Naive Estimation - Starting Point

- Naively,

$$\frac{d\sigma}{d\Omega} = N \frac{c_N^2}{(4\pi)^2},$$

where $N = M/m_N \sim 10^{50-58}$

- Given $\Lambda \gg v_{EW}$, the momentum transfer is smaller than usual WIMPs
- However, Quantum mechanical effects enhance the cross section

Enhancement Effects

- The cross section gets enhanced by
 - Stimulated emission
 - Coherent effect

Enhancement Effects

- The cross section gets enhanced by
 - **Stimulated emission**
 - Coherent effect

Stimulated Emission

- e.g. LASER

$$\langle n+1 | a^\dagger | n \rangle \propto \sqrt{n+1}$$

- This is because of the state normalization

$$|n\rangle = \frac{1}{\sqrt{n!}} (a^\dagger)^n |0\rangle$$

- Producing a Boson in the Boson bg. gets enhanced

DM Scattering in the DM Background

- $T(P) + \text{DM}(p) \rightarrow T(P') + \text{DM}(p')$
- If there are already a number of $\text{DM}(p')$ s, the cross sect. becomes much larger

Most Naive Estimation

- The cross sect. gets $\mathcal{N} + 1$ times larger
 - \mathcal{N} is the number of DM per $d^3p d^3x / (2\pi)^3$
- Assuming specially uniform dist.,

$$\mathcal{N} \sim \frac{n}{p_0^3} \sim 10^{37} \left(\frac{10^{-10} \text{ eV}}{m} \right)^4 .$$

DM Distribution in the Galaxy

- DM obeys Gaussian dist., in the *galactic* scale
- Nobody knows how in the solar system scale
- Thus, we parameterized the effect by a factor B
 - $B \lesssim \mathcal{N} + 1$

Is this discussion correct?

- “Does really stim. emission effective?”
 - “It is just T-inversion of N particle scattering”
 - $\langle n + 1 | S | n \rangle = (\langle n | S | n + 1 \rangle)^*$
- However, the larger n is, the rarer it is that only 1 particle scatters
 - The cross sect. is not n times larger

How do we evaluate the effect?

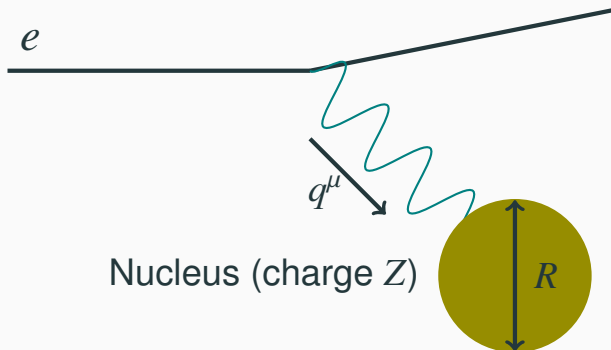
- At least, the cross section is smaller than the unitarity bound
- For $p = mv > R_{\text{targ}}$,
 - $\sigma < 4\pi/p^2$
- For $p < R_{\text{targ}}$,
 - Scattering occurs with $L < L_{\text{max}} = pR_{\text{targ}}$
 - $\sigma < \sum_L^{L_{\text{max}}} 4\pi(2L+1)/p^2 \sim \pi L_{\text{max}}^2/p^2 \sim \pi R_{\text{targ}}^2$

Enhancement Effects

- The cross section gets enhanced by
 - Stimulated emission
 - **Coherent effect**

Coherent Effect

- e.g. Coulomb scattering



- For $qR < 1$, $\sigma \propto Z^2$!

Coherent Effect

- Naively, $\sigma \propto N_{\text{targ}}^2$
 - (The interaction must be “spin-independent”)
- The larger, the better
- For $N \sim 10^{50-58}$, $> 10^{100}$ times enhancement?

N_{targ}^2 Scaling is Wrong

- What is coherence effect, in detail?



- If each scattering is nearly independent,
$$\mathcal{A}_{\text{tot}} = \sum e^{ik\Delta r_i} \mathcal{A}_i$$
 - This goes $\mathcal{A}_{\text{tot}} \sim N\mathcal{A}$ for $k\Delta r_i \ll 1$
 - e.g. “spin-independent scattering” for Xenon, ...

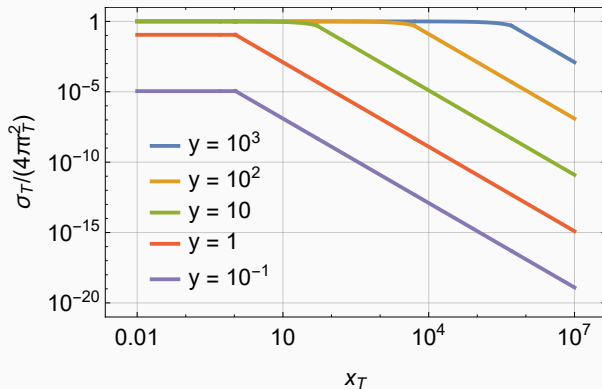
N_{targ}^2 Scaling is Wrong

- For weak enough interaction, each scattering is usually independent
 - “Born approximation”
- With very large N , “scattering” may occur multiple times
 - In other words, Born approximation fails

Real Cross Section

- How the planets look like to DM?
 - Uniform sphere → **Constant potential sphere**
- **Schrödinger eq. with $V(r) = V_0\Theta(R - r)$**
 - V_0 must be $V_0(\rho_{\text{targ}})$
 - Matching V_0 for small enough r with N^2 enhancement

Result of the Schrödinger Eq.



Short Summary

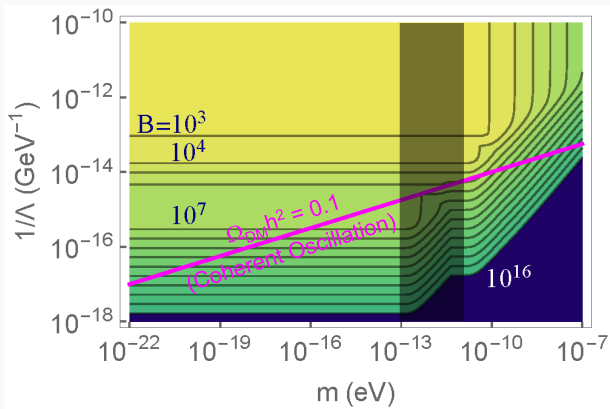
- The cross sect. gets enhanced by
- Stimulated emission
 - Parameterized by B , $B \lesssim 10^{37} (10^{-10} \text{ eV}/m)^4$
- Coherent effect
 - The cross section becomes as large as the geometrical one

Discussion and Summary

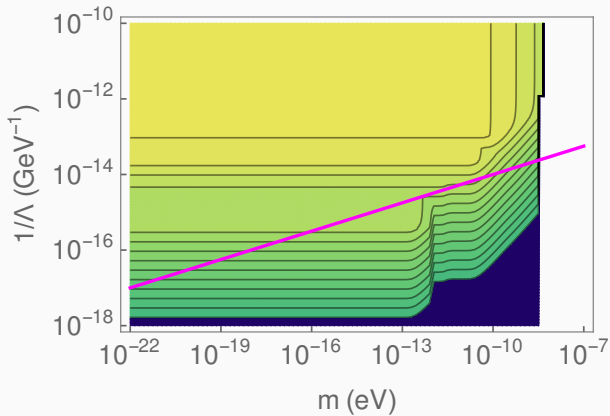
Result

- 3 Params: DM mass m , the cutoff Λ and B
- Given m and Λ , if B is too large, it is excluded
- We have shown the upper bound of B in terms of m and Λ
- Among the Earth, Sun, Saturn and Moon, the best one is used for each point

Result



Conservative Result



Discussion

- Is there any other target?
- Pseudoscalar DM?
 - No coherence, but stimulated emission is still there
- Inelastic scattering?

Summary

- For ultralight DM $m \ll \text{eV}$, the celestial bodies in the solar system can be good targets for the direct detection
- Depending on the DM distribution, it can be excluded