Direct Detection of Ultralight Dark Matter via Astronomical Ephemeris

1801.02807

Hajime Fukuda, S. Matsumoto, T. T. Yanagida

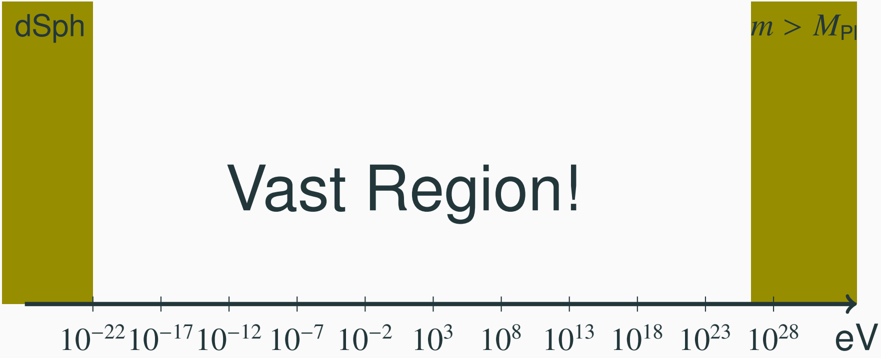
September 4, 2018

Kavli IPMU, U. Tokyo

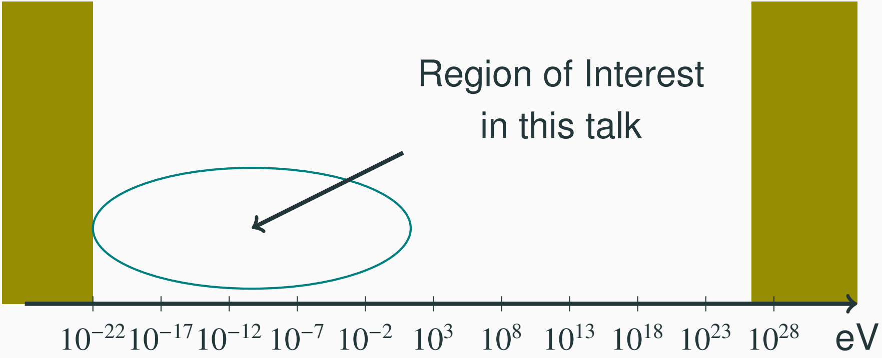
Introduction

- 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} eV $\lesssim m_{\mathrm{DM}} \lesssim$ eV
- Must be Bosonic
- $m \sim 10^{-22}$ 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: $n_{\mathrm{DM}} \propto m^{-1}$
    - Total recoil: $\Delta p_{\mathrm{tot}} \propto n_{\mathrm{DM}} \Delta p \propto m^{0}$
- The drawback is to choose a good target
- We propose to use the **celestial bodies** in the solar system

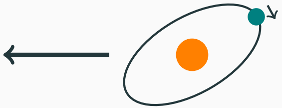
Why Celestial Bodies?

- 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
  - $v_p \sim 10^{-4}$

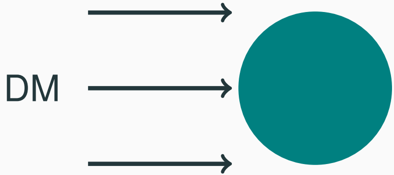


Motion of DM

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

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,

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

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

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,

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

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

- Given $\Lambda \gg v_{\mathrm{EW}}$, the momentum transfer is smaller than usual WIMPs
- However, Quantum mechenical 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 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 $\mathrm{d}^3 p \mathrm{d}^3 x/(2\pi)^3$
- Assuming specially uniform dist.,

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

DM Distribution in the Galaxy

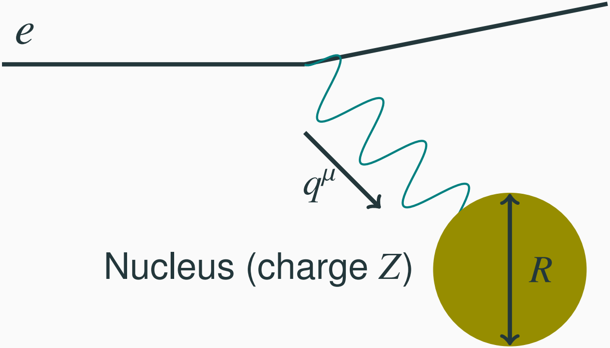
- DM obeys Gaussian dist., in the *galactic* scale
- Nobody knows how in the solar system scale
- Thus, we parameterized the effect by a factor B
    - $B \lesssim \mathcal{N} + 1$

Enhancement Effects

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

Coherent Effect

- *e.g.* Coulomb scattering



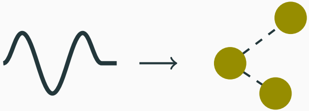
- For $qR < 1$, $\sigma \propto Z^2$!

Coherent Effect

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

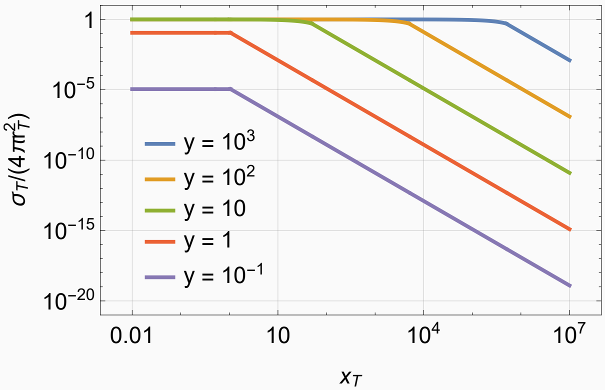
$N_{\textbf{targ}}^2$ Scaling is Wrong

- 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

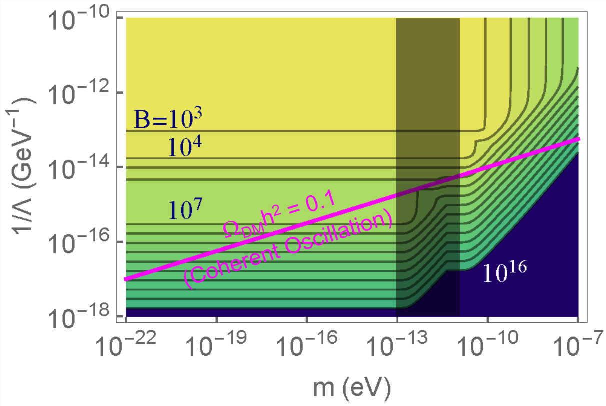
- The cross sect. gets enhanced by
- Stimulated emission
  - Parameterized by B, $B \lesssim 10^{37}(10^{-10}\,\text{eV}/m)^4$
- Coherent effect
  - The cross section becomes as large as the geometrical one

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



B=10^3
10^4
10^7
10^16
Ω_DM h^2 = 0.1
(Coherent Oscillation)
1/Λ (GeV^-1)
10^-10
10^-12
10^-14
10^-16
10^-18
10^-22
10^-19
10^-16
10^-13
10^-10
10^-7
m (eV)

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