Direct Detection of Ultralight Dark Matter

In preparation

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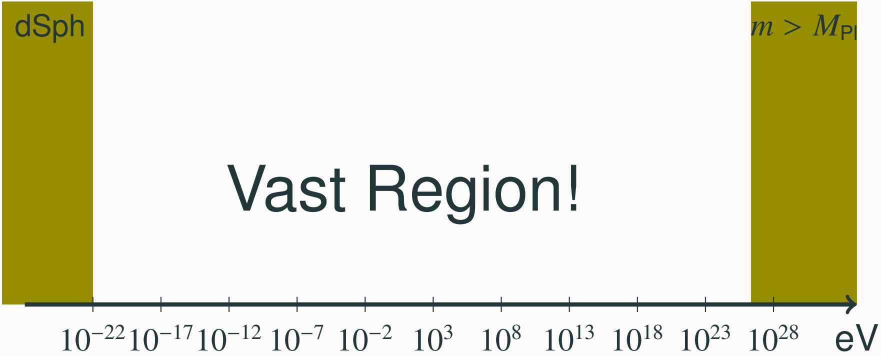
Introduction

- DM: one of the most established BSM
- How heavy is the mass?

Particle DM Mass Range



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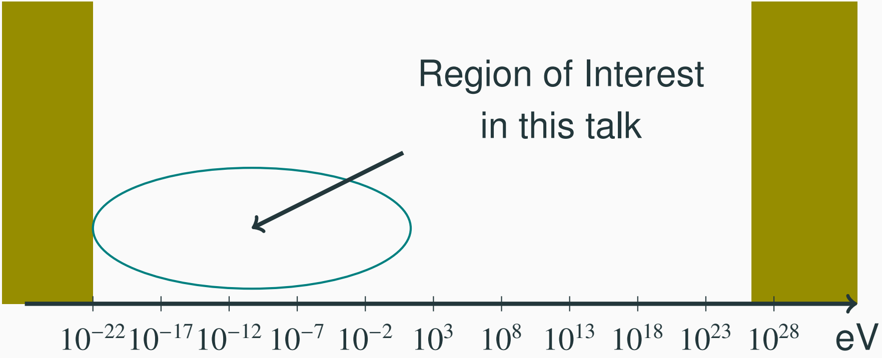


Ultralight DM

- (See L. Hui's plenary talk)
- DM for 10^{-22} eV $\lesssim m_{\text{DM}} \lesssim$ eV
- Must be Bosonic
- Behaves as CDM
  - Coherent oscillation/decay of defects/...
- Several interesting astrophysical signature
  - *e.g.* Hu, *et al.*, 2000
- Moduli? ALP?

Today’s topic

- How can we detect ultralight DM?
  - Indirect detection
  - Production
  - Direct detection
    - Assume DM and nucleons have non-gravitational interaction

Direct Detection

- One recoil, $q \sim p = mv$, is small
- However, $n_{\text{DM}} \sim \rho/m$ is quite large
- The total momentum transfer: $Q \propto qn \sim v\rho$
- **Quantum mechanical enhancement in XS**

Tasks

- What to be targets?
  - Measurement must be precise enough
  - Large enhancement
  - Our conclusion is *to use planets as targets*
- Enhancement factor?

Enhancement Effect

- Stimulated emission
- Coherent effect on the target

Stimulated Emission

- *e.g.* LASER

$$\mathcal{A} = \langle \gamma | a^{\dagger} | 0 \rangle$$

$$\rightarrow \mathcal{A}' = \langle (N+1)\gamma | a^{\dagger} | N\gamma \rangle = \sqrt{N+1}\,\mathcal{A}$$

- Because,

$$|N\gamma\rangle = \frac{1}{\sqrt{N!}} \left(a^{\dagger}\right)^{N} |0\rangle,$$

$$a^{\dagger}|N\gamma\rangle = \sqrt{N+1}\,|(N+1)\gamma\rangle$$

Stimulated Emission

- Given the phase space density $\mathcal{O}$, $\sigma \propto \mathcal{O} + 1$
    - Note that
$$\int \frac{\mathrm{d}^3 k}{(2\pi)^3} \mathcal{O}(k, x) = n(x)$$

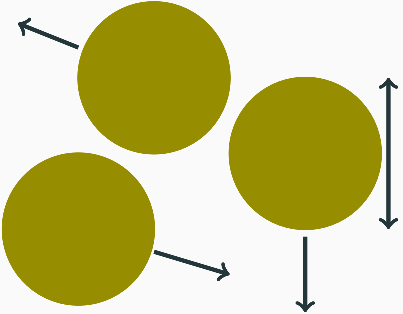
Enhancement

- DM: Gaussian distribution of $v \sim 10^{-3}$
- Assuming the distribution is uniform,

$$\mathcal{O} \sim \frac{\rho}{m}\frac{1}{(mv)^3} \sim 10^3\left(\frac{\text{eV}}{m}\right)^4$$

Loophole

- We need DM distribution around us
- Not the case for coherent oscillation?



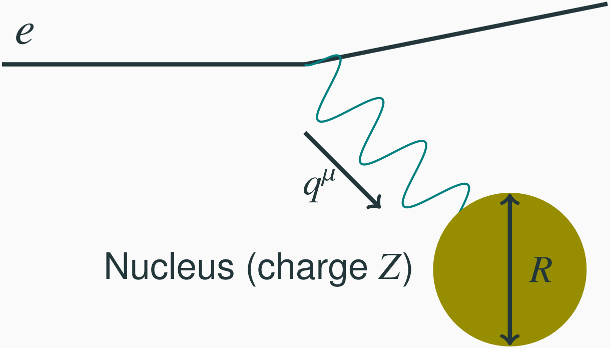
$$R_J \gtrsim r \gtrsim \frac{1}{mv}$$

Enhancement Effect

- Stimulated emission - $\times$ (or $\triangle$)
- Coherent effect on the target

Coherent Effect

- e.g. Coulomb scattering



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

Coherent Effect

- “With small q, we can’t see internal structures”
- Identical with “Spin-independent scattering”
    - $\sigma \sim [Z\sigma_p + (A - Z)\sigma_n]^2 |F(q)|^2$
    - DM must interact spin-independently also in this case

Coherence in Detail

- Easy to understand in 1st quantization
- Born Approximation: $\mathcal{A} \sim m\langle k'|V|k\rangle$
- For many targets:

$$V(x) = \sum_i V_i(x - x_i), \mathcal{A}_{\text{tot}} = \sum_i e^{iqx_i}\mathcal{A}_i$$

- $qx_i \to 0$ for all i, $\mathcal{A}_{\text{tot}} \simeq N\mathcal{A}$
- Amplitude scales as N, XS as N^2!
- The lighter the mass is, the smaller q is

Which Target?

- Enhancement depends on targets
- The bigger, the better
- **The celestial bodies in the solar system**, $N \sim 10^{50\text{-}58}$
    - Measurement is very accurate, $\Delta v / v \Delta t \lesssim 10^{-(17\text{-}19)}\,\mathrm{s}^{-1}$
- 10^{100} times larger σ?

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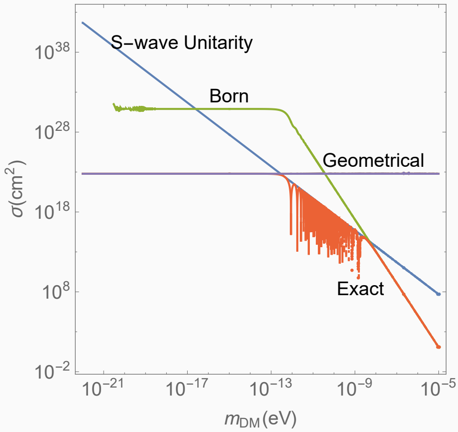
What's Wrong?

- $N^2|F(q)|^2$ enhance is valid only within Born app.
- Born app.: "Initial wave scatters only once"
  - High potential - $\times$
  - **Large object** - $\times$
- We need to solve Schrödinger eq. exactly

e.g. Sun-DM Scattering



- $\sigma \lesssim \mathcal{O}(1)\pi R^2$

Enhancement: in Summary

- Stimulated Emission - ?
- Coherent Effect - OK
- The larger the target is, the better
  - The celestial bodies in the solar system as targets
  - The cross section is at most geometrical

Constraint

- Constraints from the motion of the celestial bodies
- The solar system moves w.r.t. the DM
- DM-Star scattering $\rightarrow$ DM wind, *friction force*
- Periods and distances change

Actual constraints

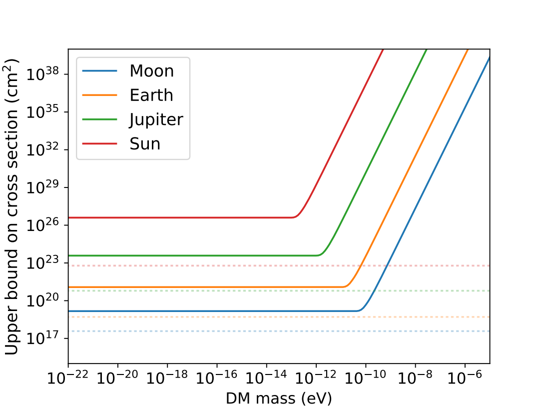
- Use Ephemeris
  - Ephemeris: A parameter fit for various quantities for celestial bodies in solar system from observations
- The latest one is numerical
  - Hard to reproduce :(
  - Naive estimation: $\Delta \ln v/\Delta t \sim \Delta L/T^2$

Cross section and the Size of the Object

- The weaker int. gets enhanced much for the heavier obj.
  - $\sigma_0 \sim {m_{\mathrm{DM}}}^2/\Lambda^4 \to \Lambda \lesssim 10^{13,14,15,16}$ GeV for Moon, Earth, Jupiter and Sun
- The lighter, the larger the effect is
  - EOM: $F = ma$
- Different region for different objects

Final Result

- For the best target, we need one order more



Summary

- Quantum mechanical enhancement for very light particles
- DM with $m \ll \text{eV}$ can be detectable with coherence enhancement