A novel constraint on ultralight dark matters

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Introduction

DM is the most rigid new physics

Target: Ultralight DM (10^{-22} eV $< m \ll$ eV)

$$\frac{\rho_{DM}}{T_1^3} \sim 10^{-9}\ \mathrm{GeV}, H(T_1) \sim m_{DM}, \rho_{DM} \sim m_{DM}^2 f^2$$

"A miracle": $\longrightarrow$ $m_{DM} \sim 10^{-14}\ \mathrm{eV} \left(\frac{f}{10^{15}\ \mathrm{GeV}}\right)^{-4}$

Let us consider **direct detection** for this DM

The recoil is not so small:

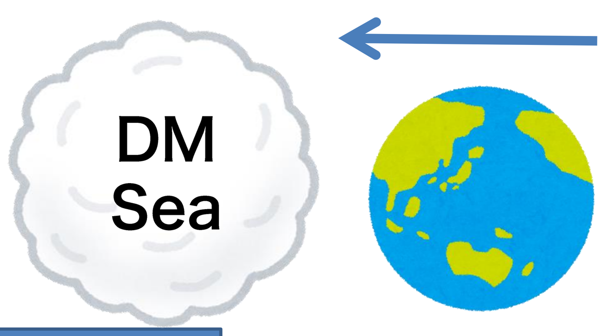
$$n = \frac{\rho_{DM}}{m_{DM}} \sim \frac{0.3\ \mathrm{GeV}}{m_{DM}} /cc \longrightarrow \Delta Q \sim np \propto \mathcal{O}({m_{DM}}^0)$$

The price is to choose the target properly:

- The greater the better (see below)
- The measurement is precise enough

Use planetary motions!

- Really huge target
- 10 orders magnitude precision

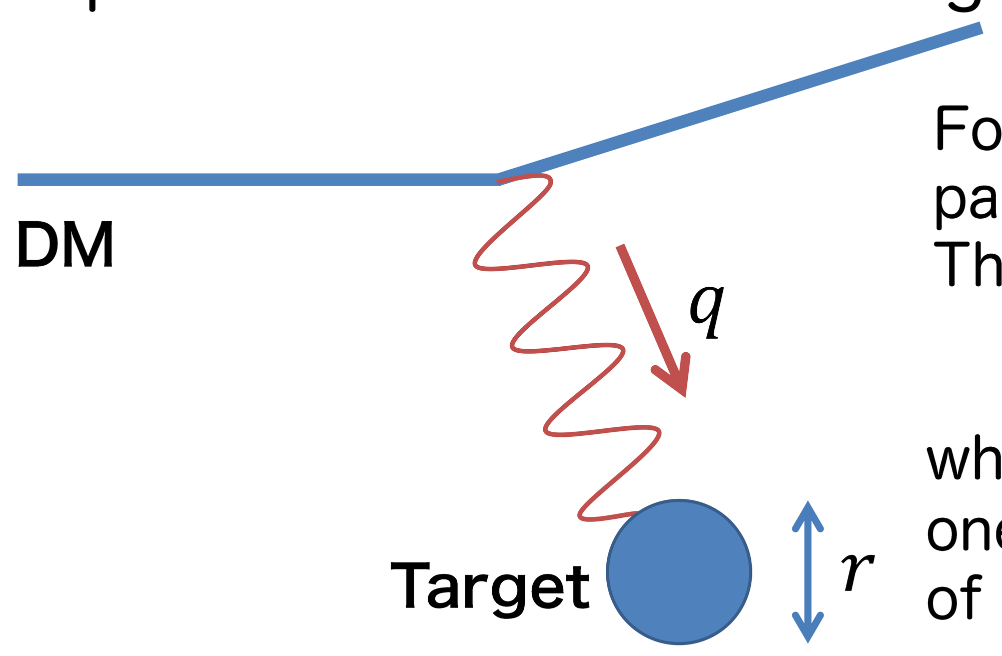


Enhancement Factor

Now, the problem is scattering b/w DM and planet. We correctly have to include enhancement effects.

- **Coherence effect**

DM can interact with the whole target if all the amplitudes have the same sign.



For $r < q^{-1}$, DM feels all particles simultaneously. The amplitude is:

$$\mathcal{A}_{tot} = \sum e^{iq\Delta r} \mathcal{A}_i \sim N\mathcal{A}_i$$

where $\mathcal{A}_i$ is the amplitude with one particle, N is the number of particles inside the target.

e.g.) Coulomb scattering with nucleus: $\mathcal{A} \propto Z, \sigma \propto Z^2$

As long as the momentum of DM is small enough, $\sigma \propto N^2$ and the larger target is better, which justifies to use planetary motion.

- **Stimulated emission**

Like LASER, the final state occupation number may enhance the amplitude:

$$\langle n+1 | a^+ | n \rangle \sim \sqrt{n+1} \longrightarrow \mathcal{A} \sim \sqrt{\mathcal{O}+1}, \sigma \sim \mathcal{O}+1$$

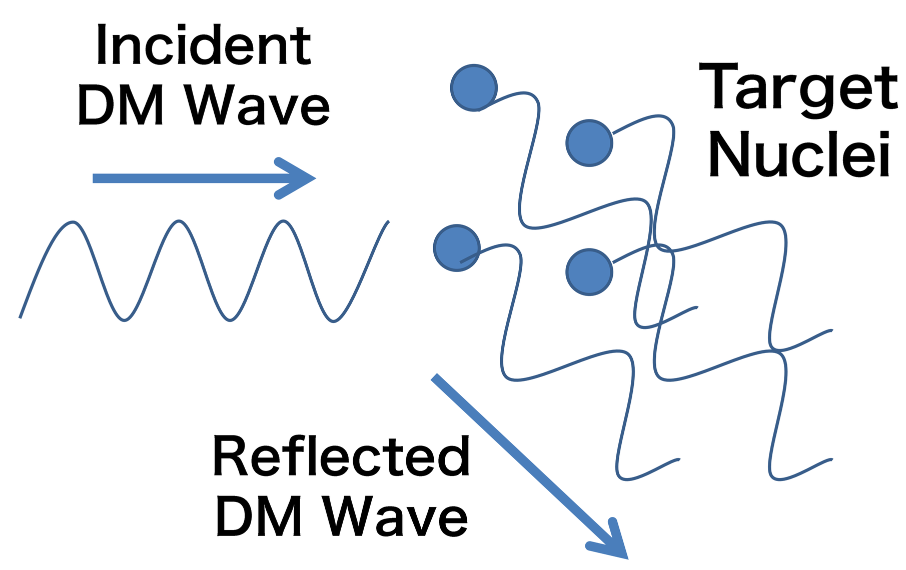
Here $\mathcal{O}$ is

$$\int d^3p\, \mathcal{O}(p,x) = n(x) \quad \therefore \mathcal{O} \sim \frac{\rho}{m} \frac{1}{(mv)^3} \sim 10^3 \left(\frac{1\ \mathrm{eV}}{m}\right)^4$$

Thus, the enhancement is huge for ultralight DM. However, this highly depends on the individual dark matter distribution in phase space, which nobody knows. Thus, we do not include it here.

Actual cross section

N^2 enhancement is too naïve!



For $\mathcal{A}_{tot} \sim N\mathcal{A}_i$, each scattering must be independent. However, if each amplitude is large enough, the initial wave is disturbed much and each process is no longer independent.

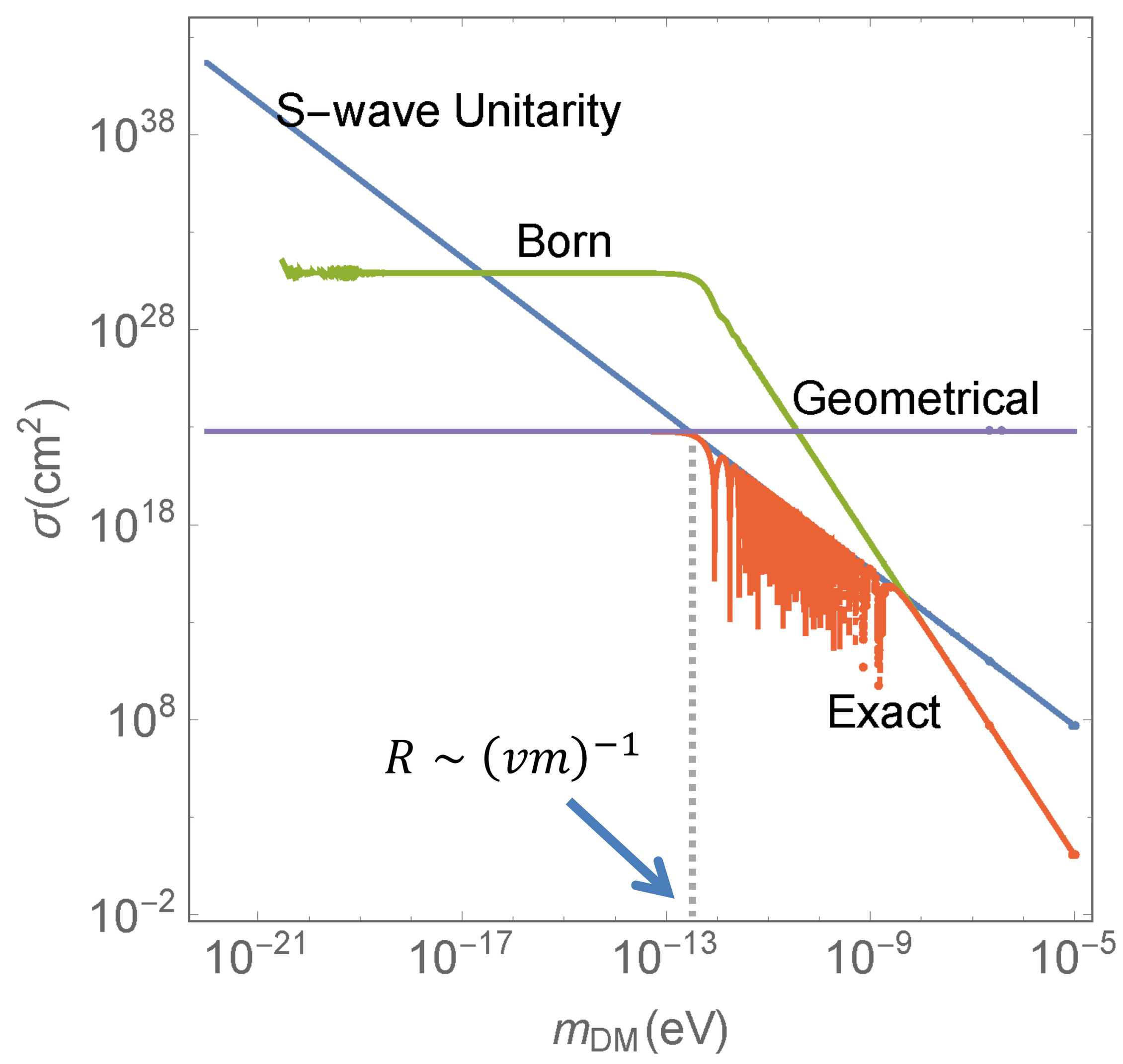
How can we get the correct amplitude?

> Use the Schrödinger equation with constant potential sphere: $V(r) = V_0 \Theta(r - R)$

The potential must be the function of the nucleus density, $V_0(\rho_A)$. For small enough target, $R = r_{small}$, we can employ:

- **Born approximation** for **QM**
- N^2 **enhancement** for **QFT**.

We can match both results obtaining V_0, which can be used for different r_0. Once V_0 is fixed, the Schrödinger equation can be solved exactly using the spherical wave expansion.



If the interaction is strong enough (here, $\Lambda < 10^{-5} M_{PL}$)

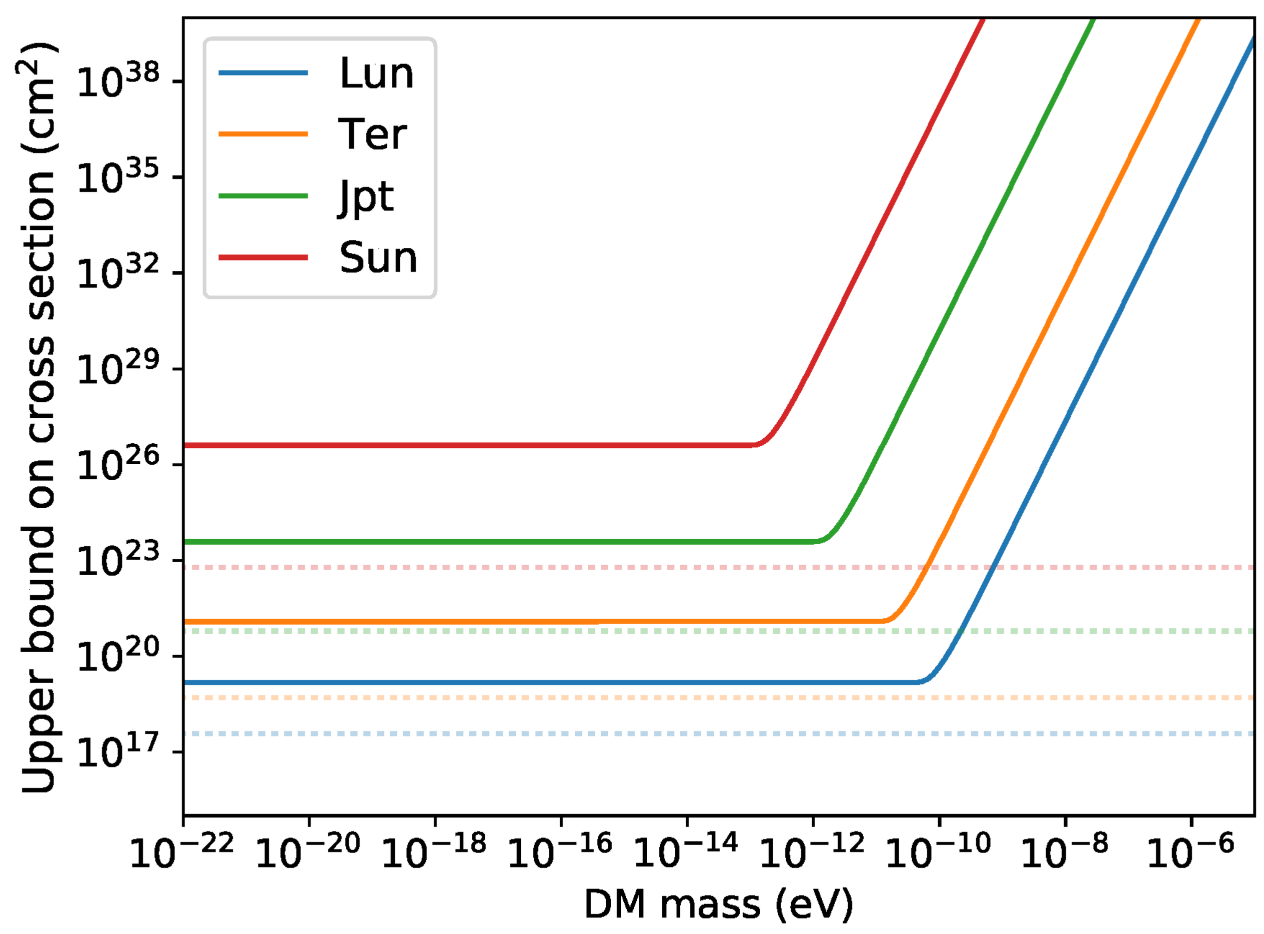
High E: Born approx.
Row E: Geom. Bounded

Intermediate region is a bit uncertain

> $\sigma \sim \pi R^2$, at most!

Result and Conclusion

The most severe constraint is one on moon. It roughly gives $\Delta v/v < 10^{-17}$-10^{-19} per second.



The region above the solid line is excluded for each heavenly bodies.

The cross sections are at most each dotted line.

It is still one order magnitude weaker, but it may be promising!