Detecting Light DM via a Novel Torsion Balance

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Based on: *Detection of Dark Matter Coherent Scattering via Torsion Balance with Test Bodies of Different Sizes [arXiv: 2409.09950]* by Shigeki Matsumoto, **J.S.,** Chuan-Yang Xing

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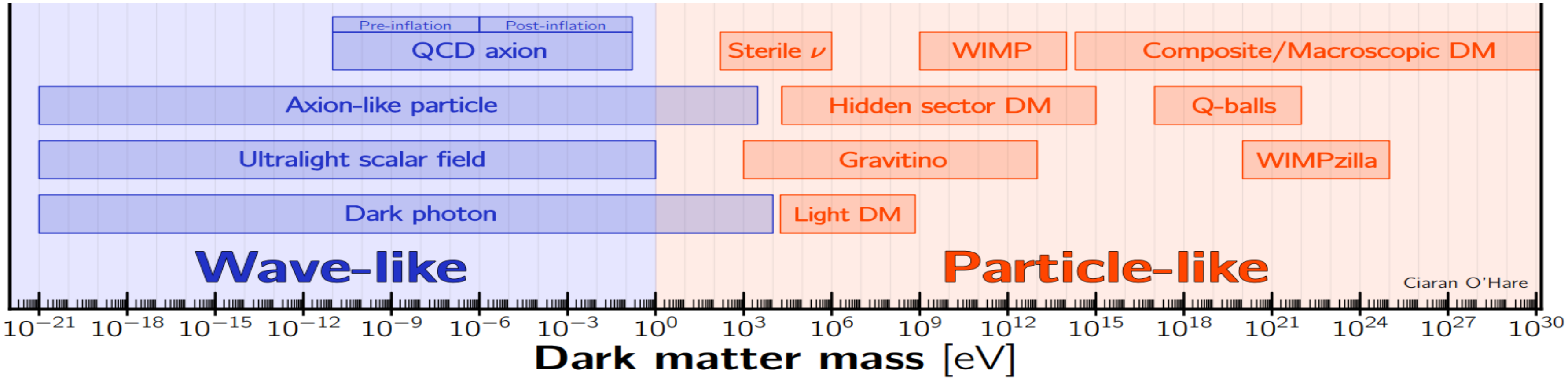

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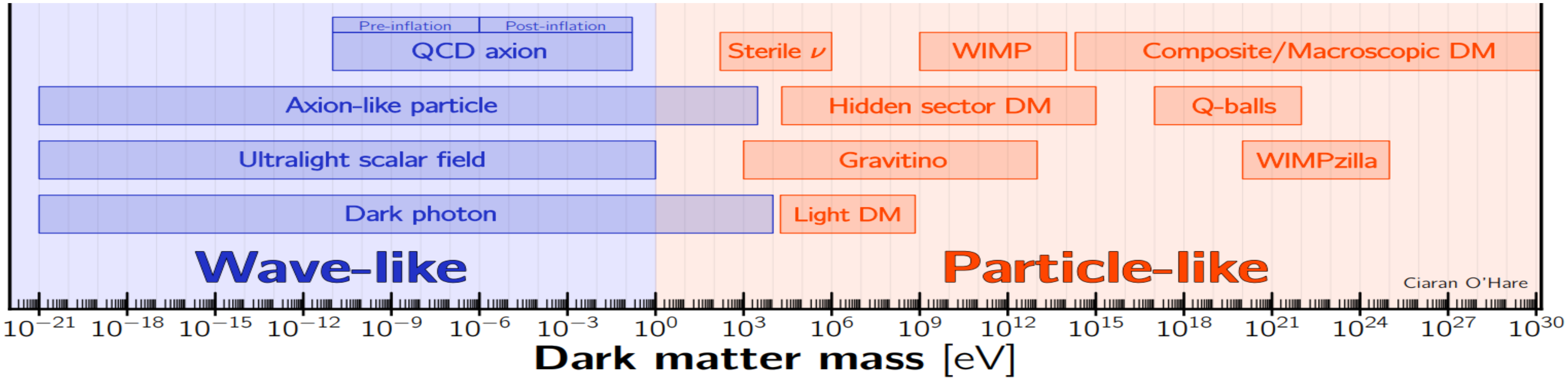

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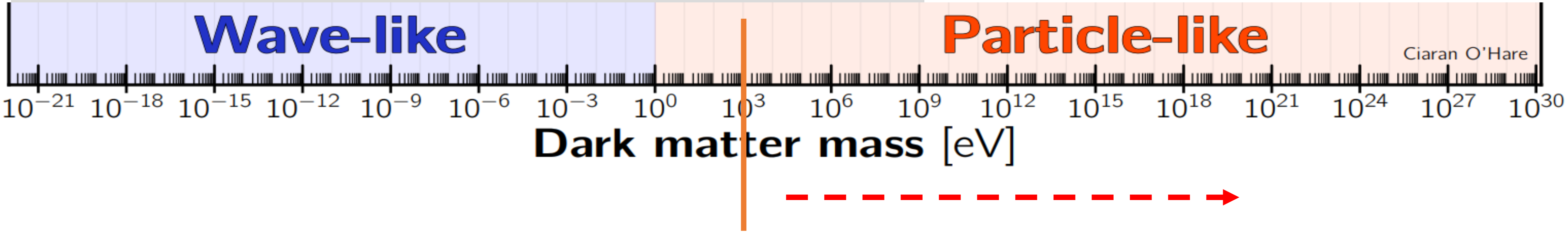
- Although the question is generic, we don't have a generic answer to it.
- The detection of DM highly depends on the DM mass and its interaction with SM particles.
- In the same mass range, there can still be some common rules.

1.1 DM mass above keV



1) DM mass $m_\chi > O(10GeV)$, (WIMP-like). — **Kinetic energy $T_\chi \sim m_\chi v^2$ >keV.**

DM-nucleon elastic scattering

2) DM mass MeV $< m_\chi < O(10GeV)$, — **Kinetic energy $T_\chi \sim m_\chi v^2 > 1\text{eV}$.**

DM-electron elastic scattering

3) DM mass keV $< m_\chi < MeV$, — **Kinetic energy $T_\chi \sim m_\chi v^2 < 1\text{eV}$.**

Further lower the threshold:

Scattering with optical trapped atoms, superconductors;

Boosted DM;

DM absorption:

Hidden photon and Fermionic DM absorption

[2203.08084, 2203.07492, 2201.11497, 2111.03597v3…]

Single Scattering Event Beyond the Detection Threshold

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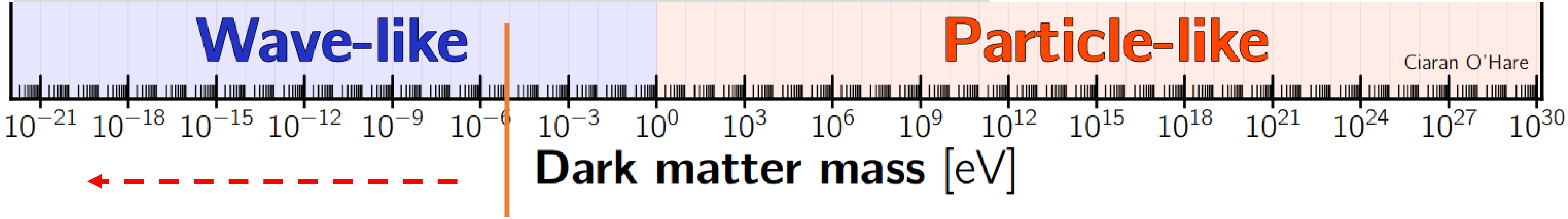
1.2 DM mass below 10^{-5} eV



1) Pseudo-Scalar DM (axion, ALP).
[a-neutron: CASPEr, Comagnetometer…]; [a-electron: NV center…]; [a-photon: ADMX (Haloscope)…]

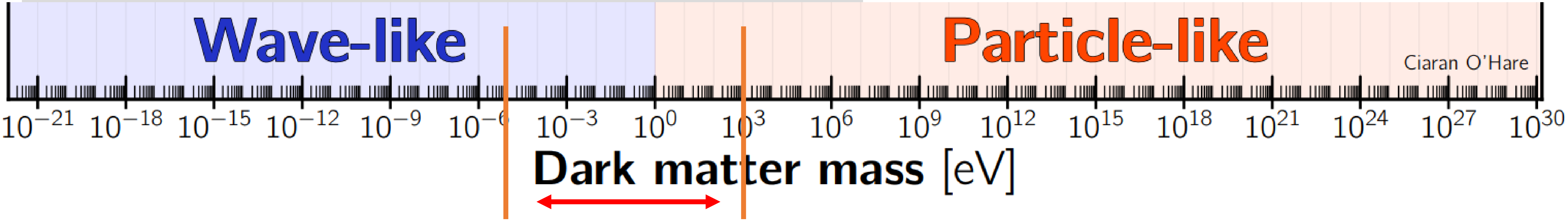
2) Scalar DM.
Atomic clock; Atom interferometers…

2) Vector DM (without Z2 symmetry).
[B-L gauge boson: Fifth force, Ligo…]; [dark photon: Haloscope…]

[2203.14915v1]

Coherent DM states as a background perturbation to affect the fundamental constants…

1.3 DM mass in between



- States begin to overlap: $n\, V_{dB} \geq 1$. DM number density is $n = \frac{\rho_\chi}{m_\chi}$ and the de Broglie volume of a particle is $V_{dB} = (m_\chi v_\chi)^{-3}$.
- Once $m_\chi < 1$ eV, the quantum wave of DM particle starts to overlap. Thus, we call ~1eV a **crossover mass range between wave and particle DM**.
- The recoil energy from single DM scattering event is not enough. **Not particle-like enough.**
- The DM can not form coherent modes. **Not wave-like enough either.**
- **There are currently few sensitive detection methods particularly targeting it.**

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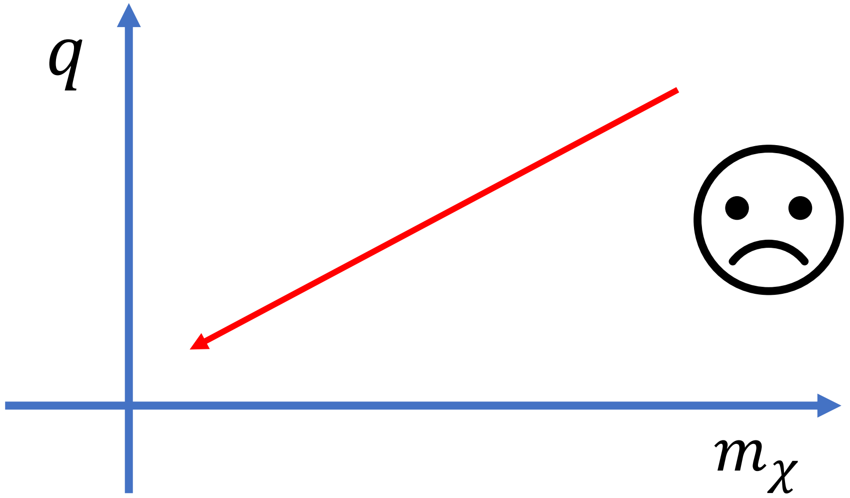

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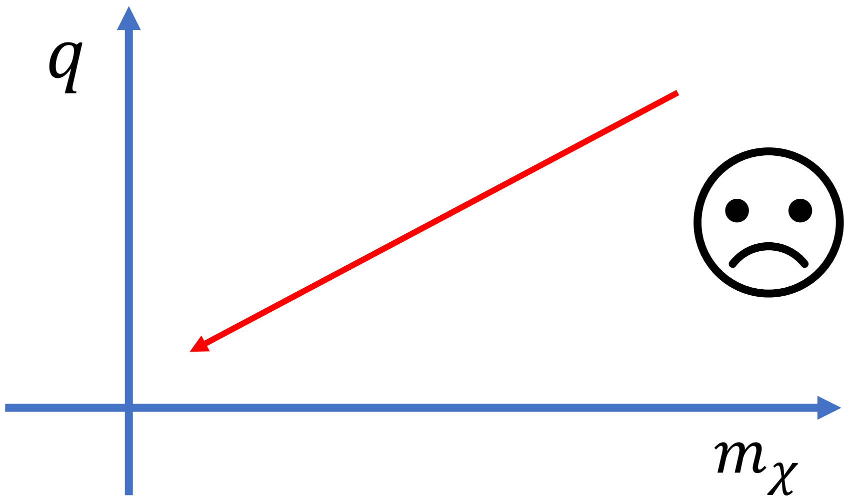

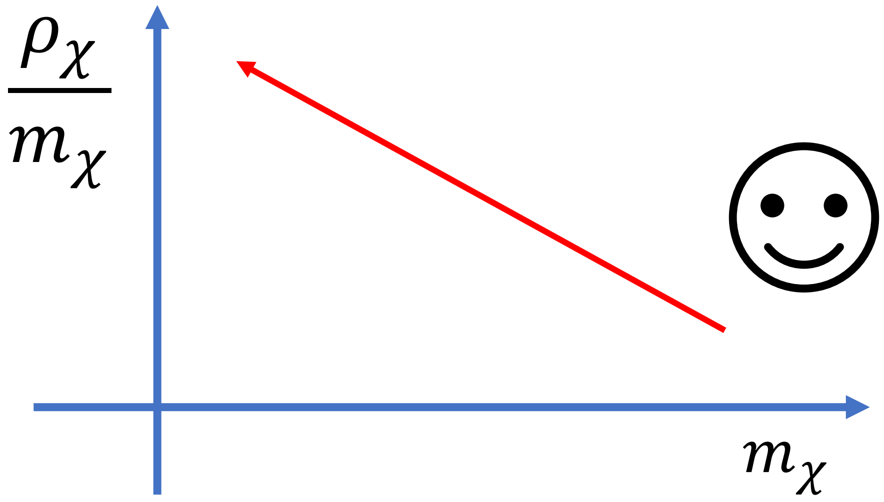

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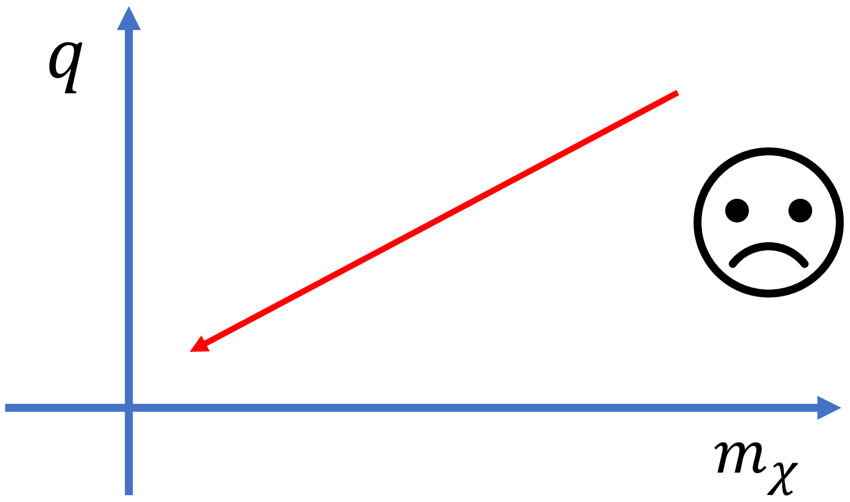

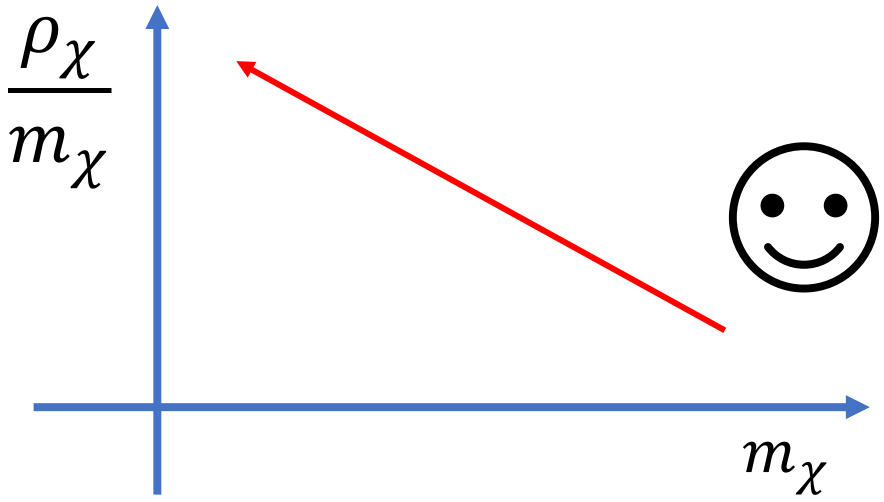

Since individual event cannot be detected, we need some collective effects.

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2.1 Acceleration (Force)

DM has a relative velocity with the earth. As a result the continuous scattering will induce some force and acceleration to the targets.

$$F = \frac{\rho_\chi}{m_\chi} \sigma_{tot} \, v \, q = \frac{\rho_\chi}{m_\chi} \sigma_{tot} \, v_\chi \, m_\chi \, v_\chi = \rho_\chi \, \sigma_{tot} \, v_\chi^2.$$

$$a = \frac{F}{m_{target}} = \frac{\rho_\chi \sigma_{tot} \, v_\chi^2}{m_{target}}$$

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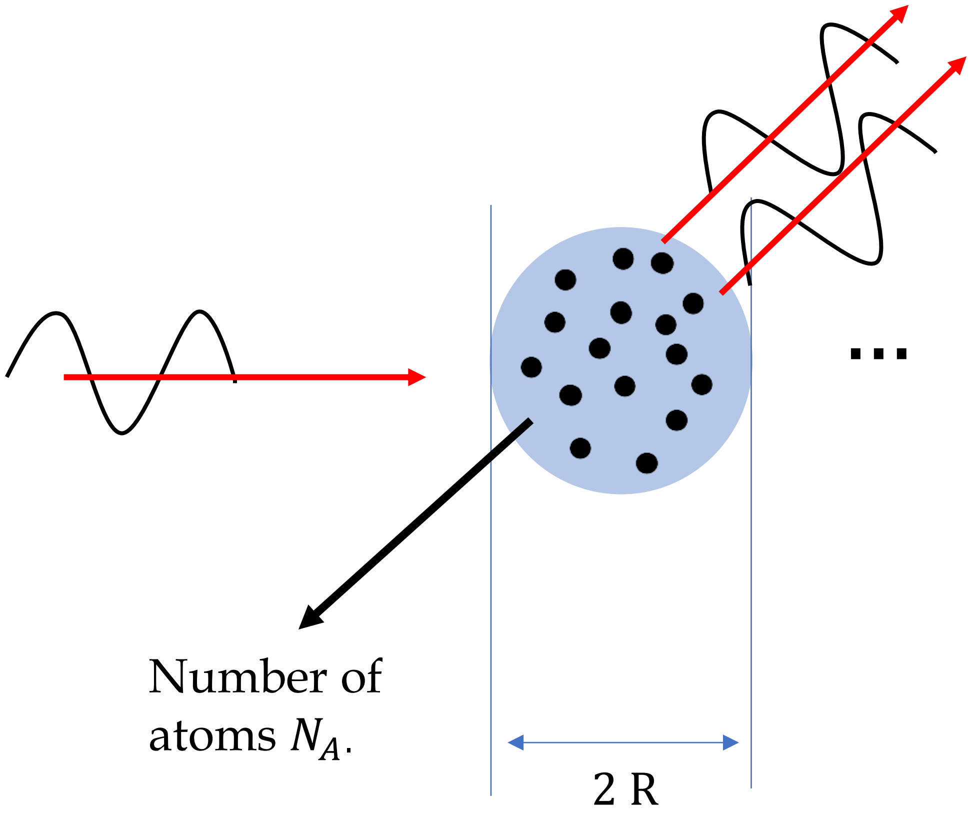
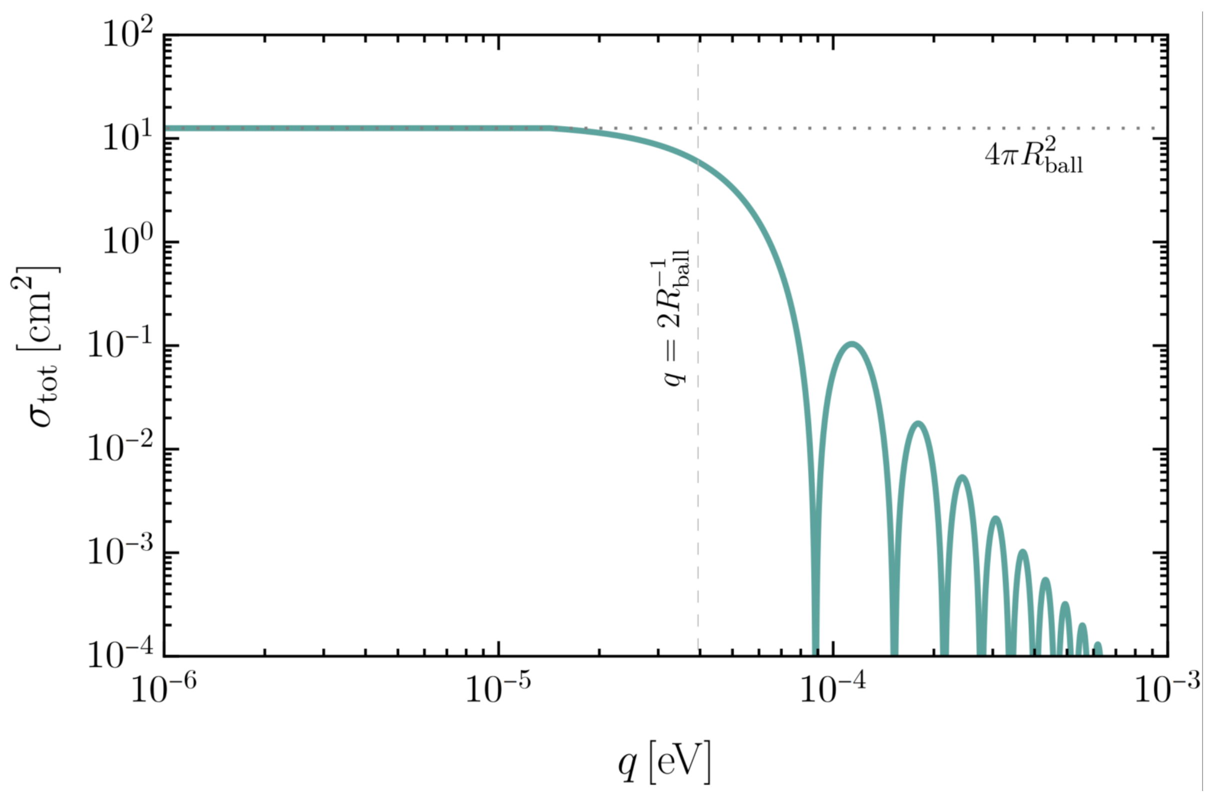
- The mass of DM seems to be cancelled in the formalism.
- To enhance the signal, the only possibilities lies in the cross section.
- Fortunately, we **have coherent scattering effects** for light DM with a macroscopic wave length.

2.2 Coherent Scattering



- If we receive the outgoing wave at infinite far with initial and final momentum fixed, the only difference of these waves is the phase factor e^{iqr_j} .
- In the amplitude level, $Amp \to Amp \sum e^{iqr_i}$.
- In the cross section level, $\sigma_{tot} = \sigma_{\chi A} \sum_{ij} e^{iq\Delta r_{ij}}$.
- If $q\Delta r_{ij} \ll 1, e^{iq\Delta r_{ij}} = 1$. The enhancement of total cross section is N_A^2 as we expected. [This N square coherent factor is verified by neutrino scattering in CEνNS.]
- If $q\Delta r_{ij} \gg 1$, all the phases cancel each other except for the cases $i = j, \Delta r_{ii} = 0$. The enhancement factor is simply N_A.

2.2 Coherent Scattering



- Assuming N_A atoms in a ball-like body with radius R_{ball}, the cross section dependence on momentum transfer is shown as the green line.
- The coherent effects start to disappear when the momentum transfer roughly corresponds to the geometric size of the body $\frac{1}{q} \sim R_{ball}$.
- Naively, the larges cross section for the small q limit should be $N_A^2\ \sigma_{\chi A}$. However, the cross section will saturate to the geometric area of the body $4\ \pi\ R_{ball}^2$ due to the unitarity of quantum mechanics.
- As a result, $\sigma_{tot} = Min\ [N_A^2 \sigma_{\chi A}, 4\ \pi\ R_{ball}^2]$.

2.3 Enhancement of Acceleration

$$F = \frac{\rho_\chi}{m_\chi}\,\sigma\, v\, q = \frac{\rho_\chi}{m_\chi}\,\sigma_{tot}\, v_\chi\, m_\chi\, v_\chi = \rho_\chi\, \sigma\, v_\chi^2.$$

$$a = \frac{F}{m_{target}} = \frac{\rho_\chi \sigma_{tot}\, v_\chi^2}{m_{target}} = \frac{\rho_\chi N_A^2\, \sigma_{\chi A}\, v_\chi^2}{N_A\, m_A} = \frac{\rho_\chi N_A\, \sigma_{\chi A}\, v_\chi^2}{m_A}.$$

The force or acceleration is now only proportional to the total cross section!

This rough derivation shows that, with coherent scattering effect, the acceleration can be enhanced by a factor an atom number, which is of order 10^{23} in macro-objects.

3. Q: How to detect an Acceleration?

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3.1 A: Torsion Balance

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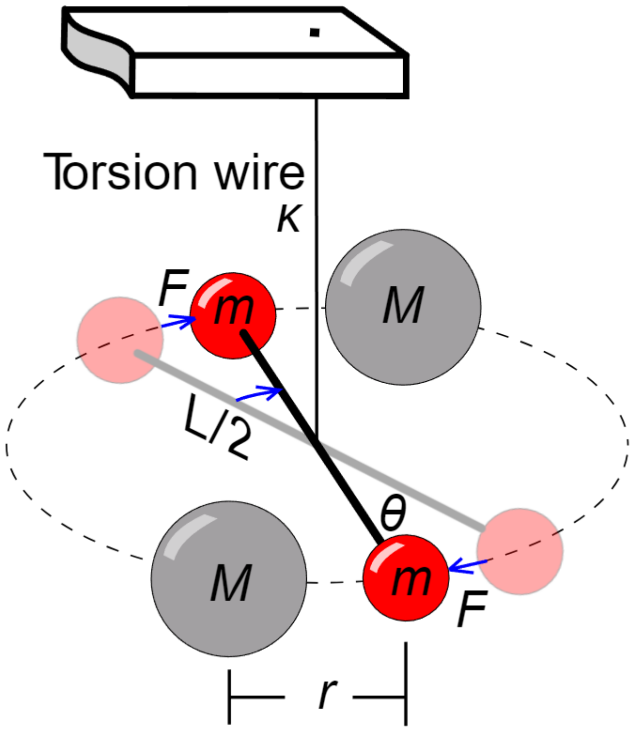


[Cavendish Experiment (1797)]

With a sensitivity:

$$\delta a = \frac{10^{-13} cm}{s^2}.$$

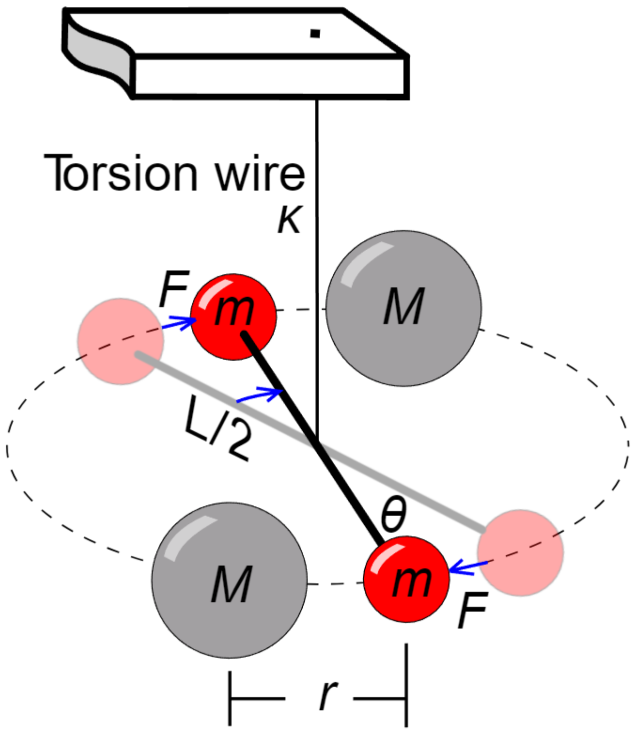
3.2 Asymmetry is needed

- The current torsion balance setup using to measure the weak gravity and test equivalence principle contains two balls with same masses and same sizes.

- The entire device has rotational symmetry around the central wire.

- As a result, the DM wind induces same forces on both sides. No signal can be detected.

- *Asymmetry is needed!*



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- To make the torsion in balance, the two targes should have the same mass (If the arm lengths are the same).
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- To have different coherent form factor, the two targets should have different geometric sizes.
- *Targets with equal masses but different sizes.*

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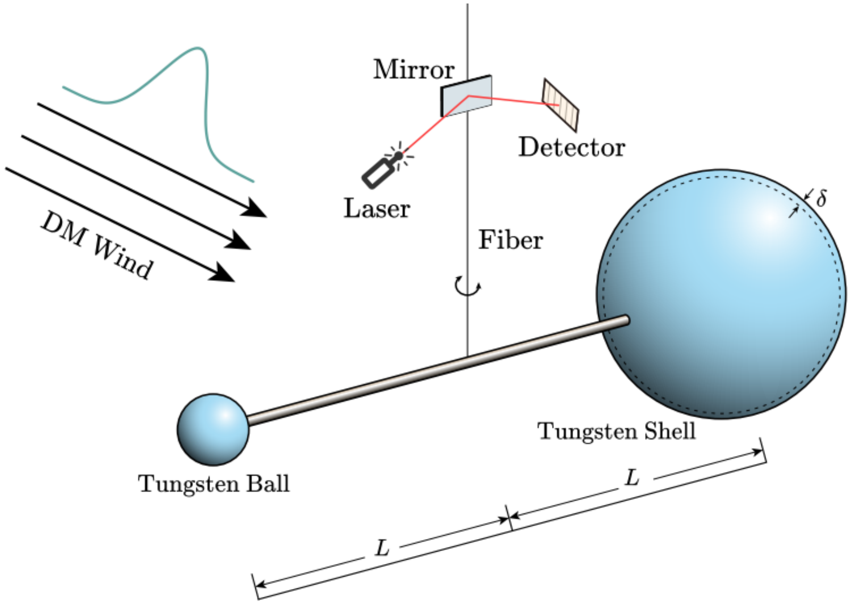
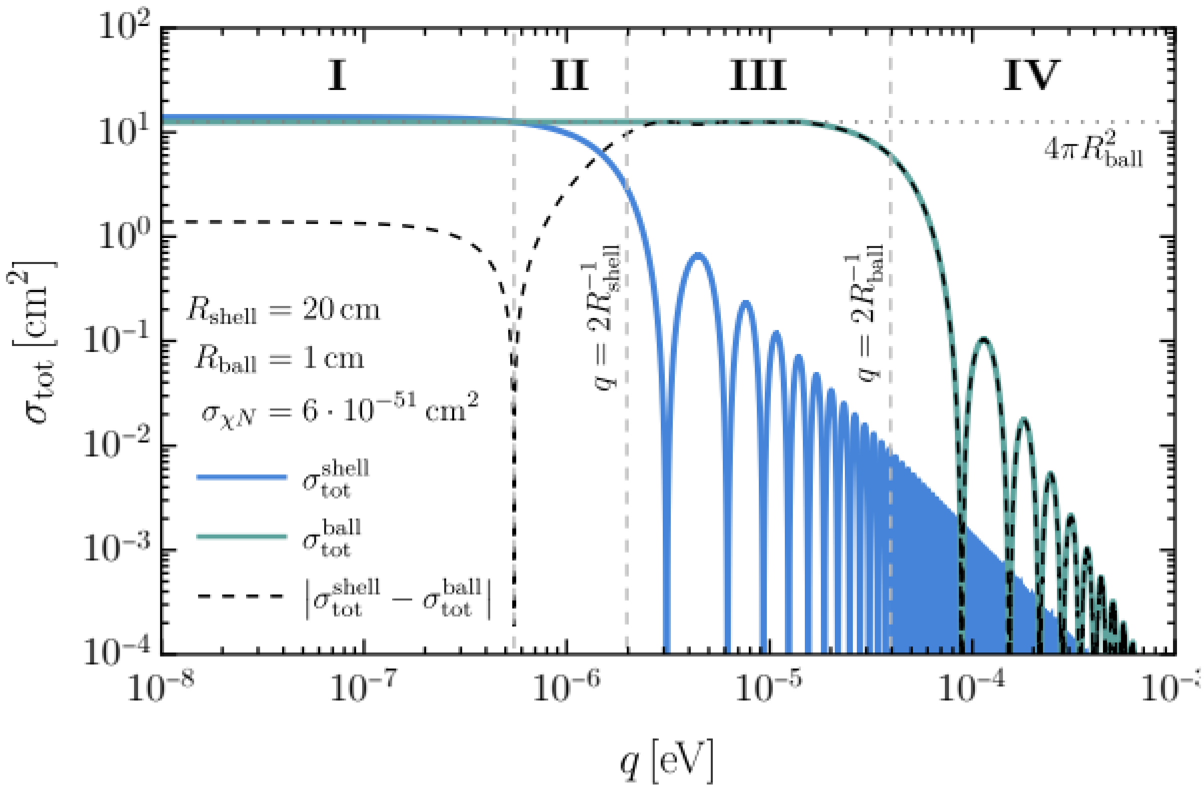


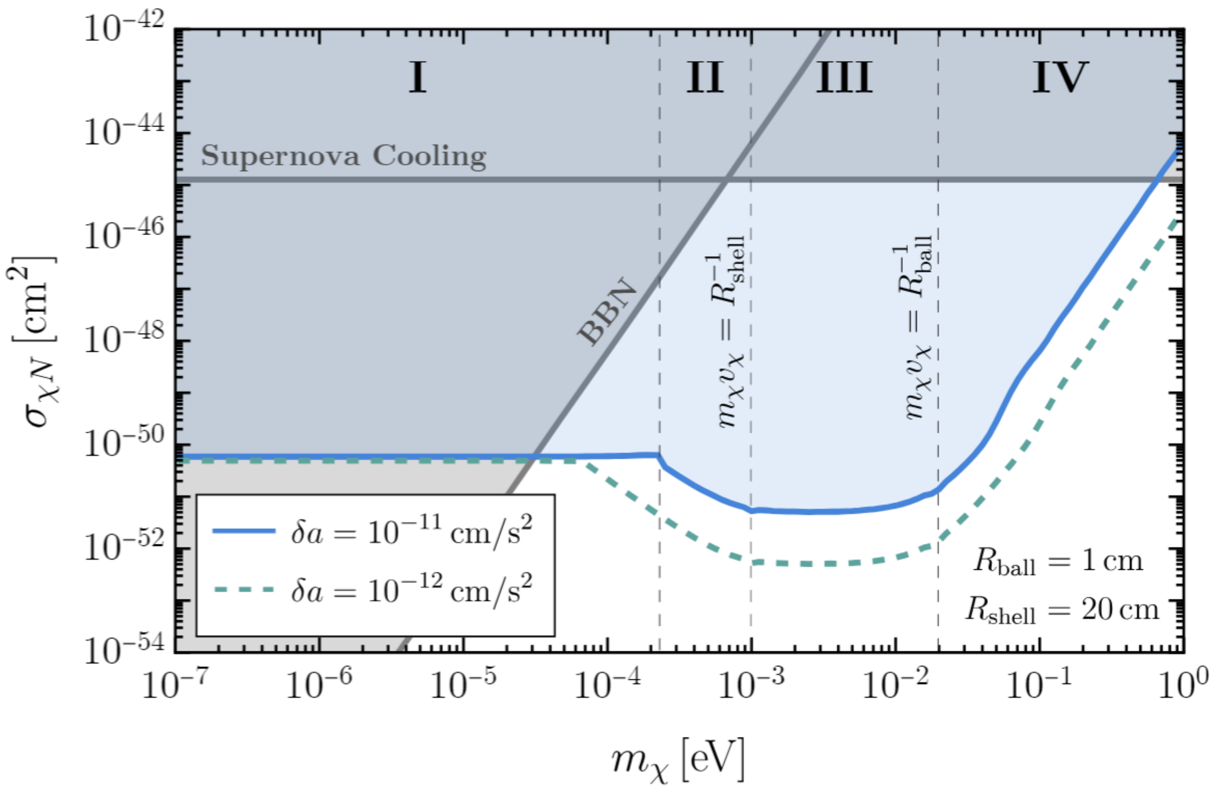
	Material	Density	Radius	Thickness	Mass
Ball	Tungsten	19.25 g/cm^3	1 cm	-	80.6 g
Shell	Tungsten	19.25 g/cm^3	20 cm	8.3 μm	80.6 g

5 Results



- Region I: DM wavelength much larger than both the radii of the ball and the shell. $\sigma_{shell} = N_A^2\ \sigma_{\chi A}; \sigma_{ball} = 4\ \pi\ R_{ball}^2$.
- Region II: DM wavelength ~ R_{shell}; Coherent effects of the shell starts to decrease.
- Region III: R_{ball}<DM wavelength< R_{shell}; Coherent scattering only with the ball.
- Region IV: DM wavelength< R_{ball}; Coherent effects gradually disappear.

5 Results



A reminder: $q \sim p_\chi \sim m_\chi v_\chi \sim 10^{-3} m_\chi$

- The detection sensitivity of a stationary torsion with different test bodies is $\delta\, a \sim 10^{-11} cm/s^2$. [Annals Phys. 26(1964) 442-517]
- Assume general models, such as $\frac{\chi^2 G_{\mu\nu} G^{\mu\nu}}{\Lambda^2}$, $\frac{m_i\, \chi^2 \overline{\psi_i} \psi_i}{\Lambda^2}$ with ψ_i the SM quarks.
- Constraint-1: supernova cooling due to the DM emission.
- Constraint-2: the DM will change the nucleon mass and affect the BBN.

5. Conclusion and Discussion

- How to detect DM?

  The gap in the DM mass region in the crossover range of particle- and wave-DM

- How to detect DM in the above mass range?

  Collective signals like force or acceleration.

- How to enhance the signal?

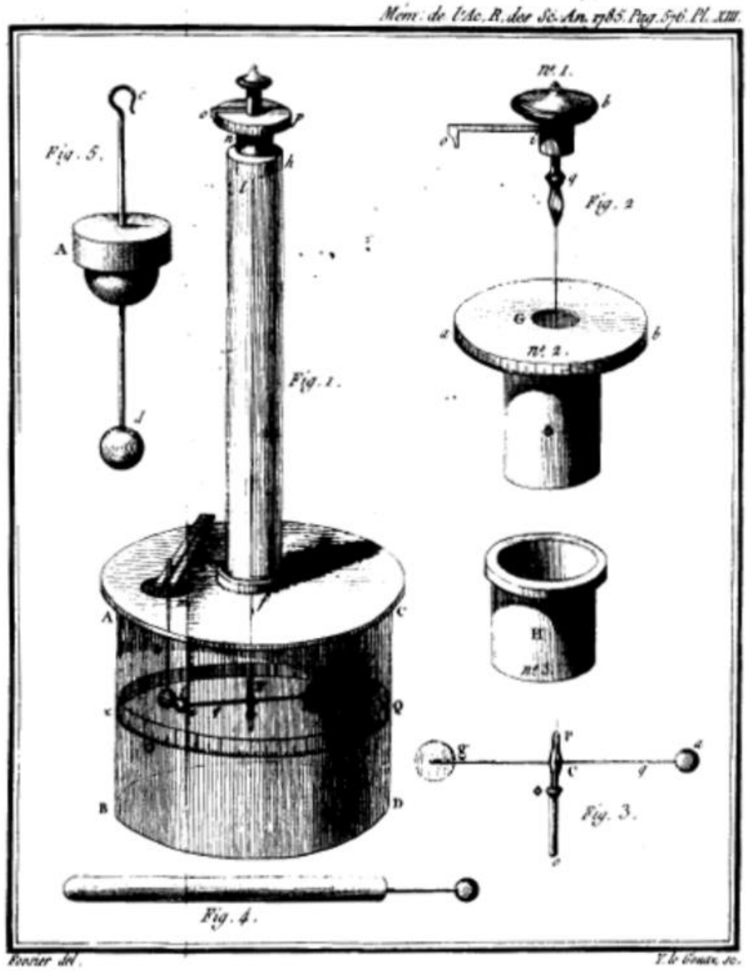
  Coherent scattering of light DM.

- How to detect the DM-induced acceleration?

  Torsion balance with test-bodies of equal massed but different sizes.

An Interesting Discussion

- In 1785 (even earlier than Cavendish), Coulomb design **the exact same setup (a ball and a shell)** to measure the electric force.
- This is called as Coulomb's Torsion Balance[1785]!
- Since we are focus on the measurement of gravity over hundreds of years. Coulomb's torsion balance did not progress further.
- **Old devices, new purpose!**
- It is the time to develop Coulomb-type torsion balance again for DM detection!



Backup: References

[1] In early studies, similar ideas were used for cosmic neutrino background ($C\nu B$) detection [28, 32–35]. Unfortunately, due to the diffuse flux of cosmic neutrinos and their small scattering cross-section with nucleons, the resulting acceleration of the objects is far below the detectability threshold of current technologies.

Although the energy transfer of such a DM is insufficient to detect, their continuous momentum transfer can induce acceleration on macro-objects [28–31].[1]

Backup: Unitarity

It is interesting that there is a maximum possible value for the cross section for each partial wave. From Eq. (20), the cross section for a given partial wave l is

$$\sigma_l = \frac{4\pi}{k^2}(2l+1)\sin^2\delta_l \leq \frac{4\pi}{k^2}(2l+1). \tag{22}$$

This limit can be qualitatively understood in the following semi-classical argument. If you inject a particle with momentum p at the impact parameter b, it has angular momentum $L = pb$. On the other hand, the angular momentum is quantized in quantum mechanics, $L = \hbar l$. Let us say that the quantized angular momentum l corresponds roughly to the impact parameter $b = L/p$ for $\hbar l < L < \hbar(l+1)$, *i.e.*,

$$\frac{l}{k} \leq b \leq \frac{l+1}{k}. \tag{23}$$

Assuming that the particle gets scattered with 100% probability when entering this ring, the classical cross section would be

$$\pi\left(\frac{l+1}{k}\right)^2 - \pi\left(\frac{l}{k}\right)^2 = \pi\frac{2l+1}{k^2}. \tag{24}$$

The unitarity limit is roughly the same as this semi-classical argument except for a factor of four.

Backup: UV completion

As one would expect for a model of a light scalar with non-derivative couplings, the mass m_ϕ is very fine-tuned. The dark matter relic abundance depends sensitively on m_ϕ (for example through the misalignment mechanism [18–20]), so this tuning may have an anthropic origin [21]. On the other hand, a coupling of the form

$$\Delta\mathcal{L} = -\frac{\lambda_\phi}{4!}\phi^4 \tag{B.1}$$

is allowed by all symmetries and is also UV sensitive.[6] This coupling is tightly constrained by constraints from structure formation [22]

$$\lambda_\phi \lesssim 3\times 10^{-7}\left(\frac{m_\phi}{\text{eV}}\right)^4 . \tag{B.2}$$

$$\Delta\mathcal{L}_{\text{SM}} = -\tfrac{1}{2}m_\phi^2\phi^2 - \frac{\lambda_\phi}{4!}\phi^4 - \tfrac{1}{2}\epsilon\phi^2 H^\dagger H. \tag{B.3}$$

This gives a ϕ dependent shift in the Higgs VEV:

$$\frac{\delta v}{v} = \frac{\epsilon\phi^2}{2m_h^2}, \tag{B.4}$$

where $m_h = 125$ GeV is the physical Higgs mass. Below the electroweak symmetry breaking scale, this induces various couplings of ϕ^2 to standard model fields. For example, the coupling to SM fermions ψ is given by

$$\Delta\mathcal{L}_{\text{eff}} = -\sum_\psi \frac{1}{2f_\psi}\phi^2\bar{\psi}\psi \qquad \frac{1}{f_\psi} = \frac{\epsilon m_\psi}{m_h^2}. \tag{B.5}$$

[arXiv: 2312.13345v1]