Direct Detection of Light Dark Matter at Torsion Balance

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In collaboration with **Shigeki Matsumoto, Chuan-Yang Xing, and gravity experimental group in HUST**

Based on:

*P. Luo, S. Matsumoto, J. S., C. Y. Xing, L. Zhu, Z. J. Zhuge, **PRD112, 075023 (2025);***

*S. Matsumoto, J. S., C. Y. Xing, L. Zhu, **PRL136, 121803 (2026).***

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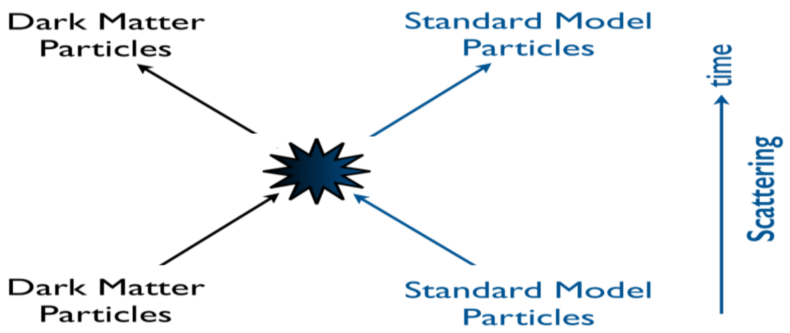
Outline

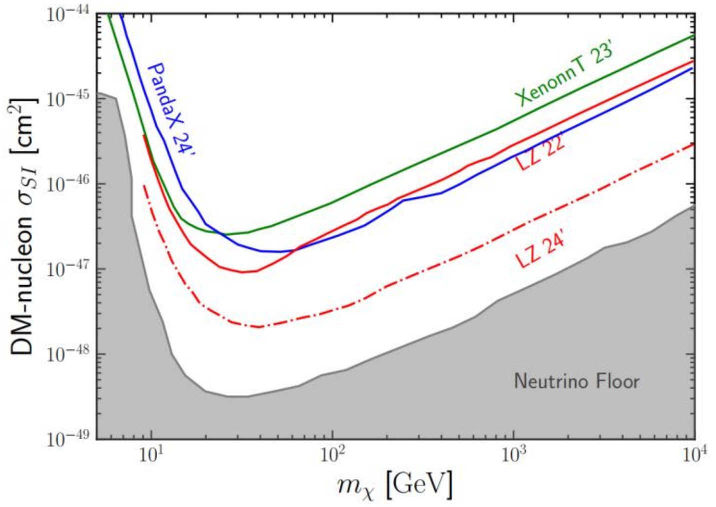
1. Introduction and target
2. Coherent-scattering-induced acceleration as an observable
3. Torsion-balance probe of sub-eV DM
4. Conclusion and Discussion

Direct Detection of DM

- Detection of DM in laboratory is the so called "Direct Detection" based on DM-SM particle Scattering.
- Goodman & Witten proposed DM-Heavy nuclei scattering for WIMP DM [Tone-scale Xenon experiments].



N = n, p



- Currently, DM-nucleon/nuclei elastic scattering, χ+N→χ+N, becomes one of the most general and benchmark processes when we talk about direct detection.
- Quadratical coupling: $\frac{m_N\,\chi^2\bar{N}N}{\Lambda^2}$ [scalar] or $\frac{\bar{\chi}\chi\bar{N}N}{\Lambda^2}$ [fermion]

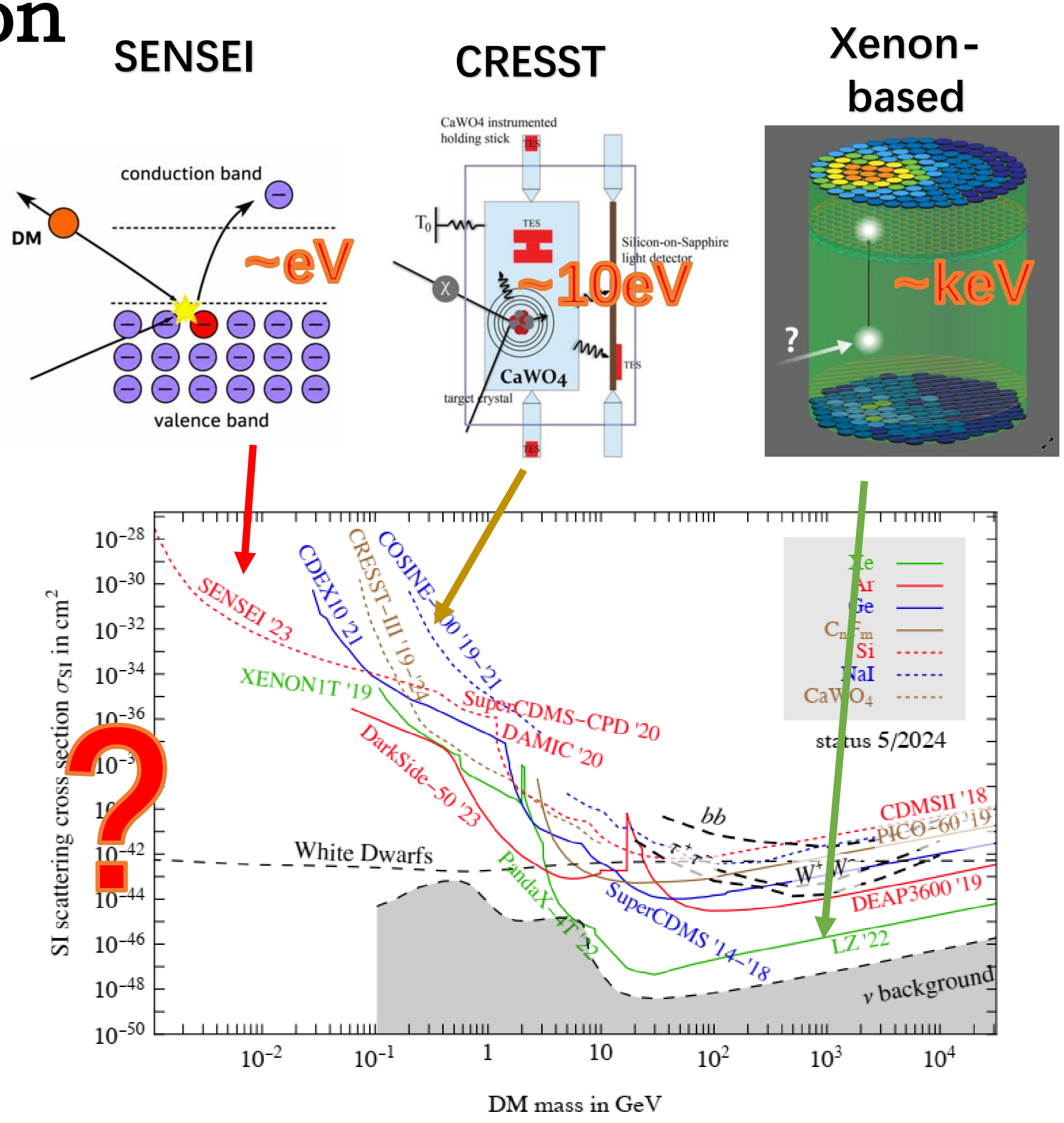
Difficulty of Light DM Detection

- **People have built different DD experiments to probe wide mass and interaction strength ranges. They essentially rely on the same underlying principle:**

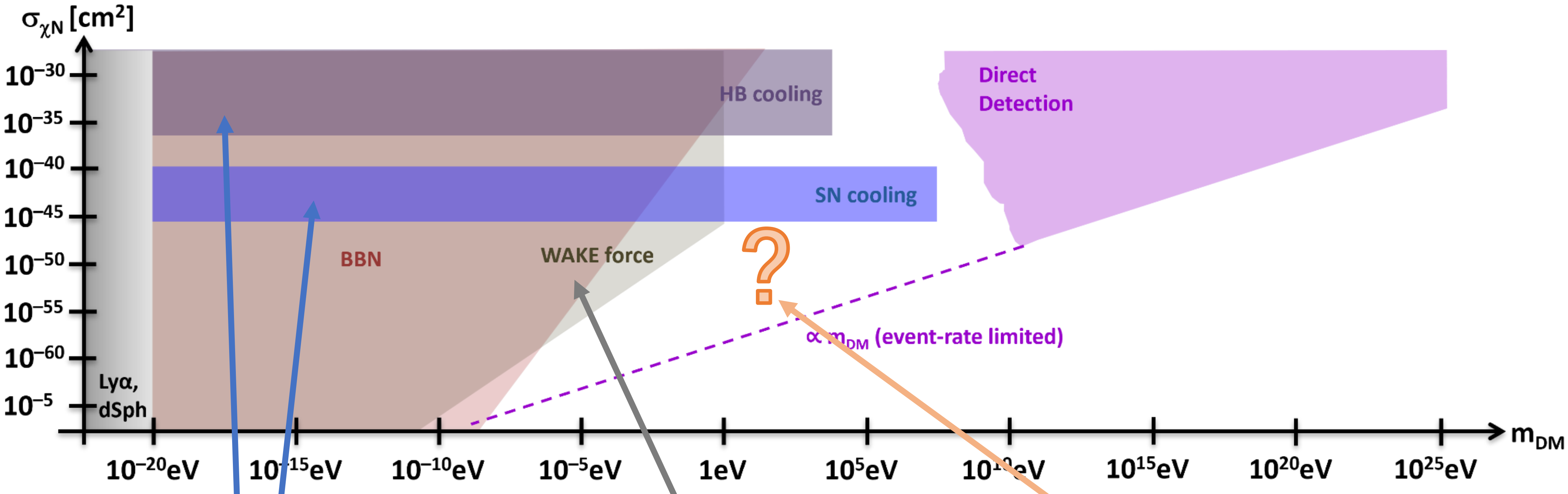
- **Searching for scattering events with energy transfers above the experimental threshold.**

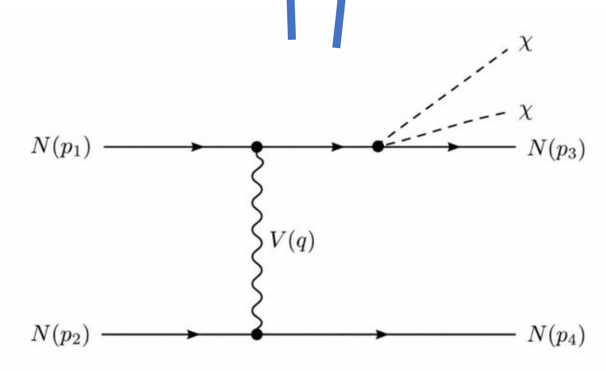
- **However, lighter dark matter particles carry less kinetic energy [$T_\chi \sim \frac{1}{2} m_\chi v_\chi^2 \sim 10^{-6} m_\chi$] and therefore deposit less energy transfer.**

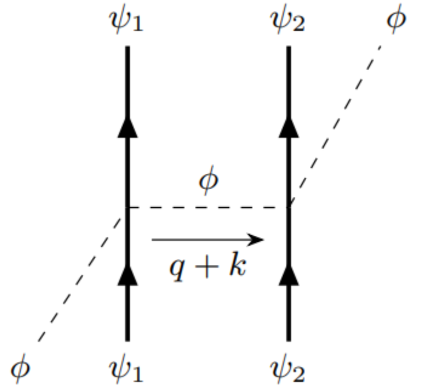
- **The detection of lighter [sub-MeV] DM is still an experimental challenge!**



Summarizes of DM-nuclei SI cross section limits



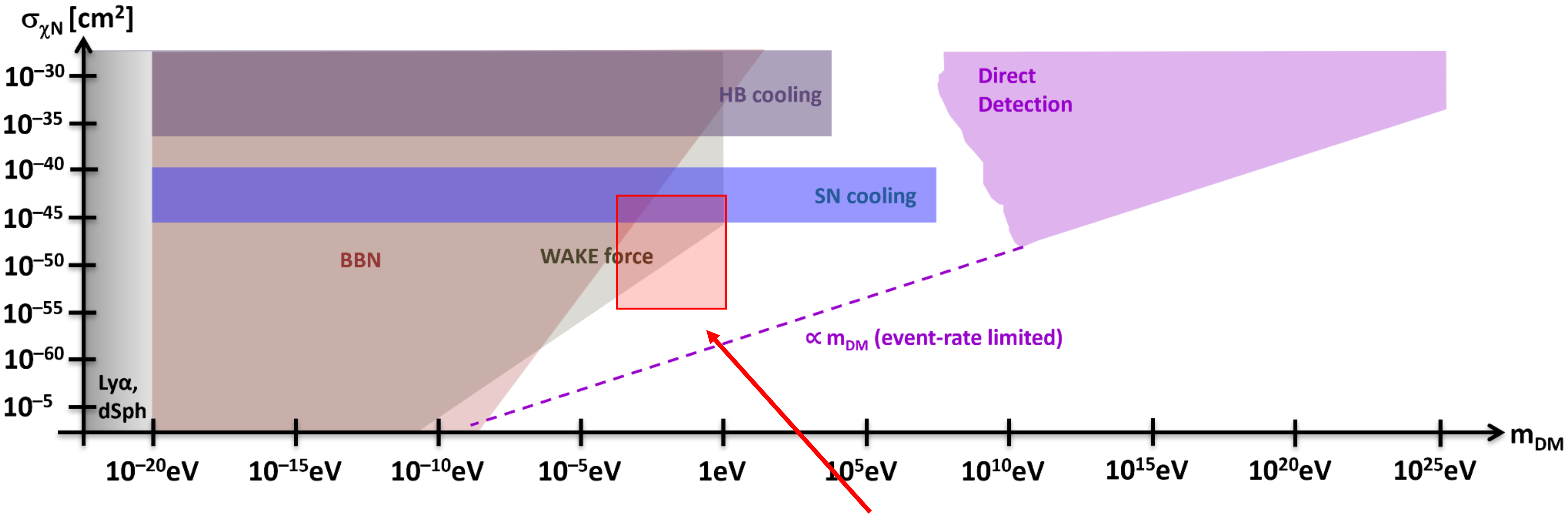




Detection gap of DM-nucleon elastic scattering

Our Target

We want to propose a new detecting mechanism for light DM



Target this sub-eV mass range and place stronger direct-detection limits.

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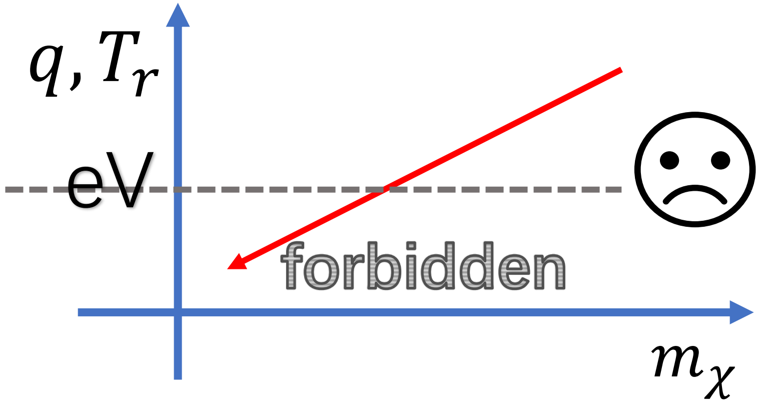
Merits of lighter DM

We know: The drawback of light dark matter is the *insufficient energy transfer*.

For nuclei [GeV] and light DM [< MeV] scattering, we have:

$$q \sim p_\chi = m_\chi v_\chi = 10^{-3}\, m_\chi, \qquad \Delta E = T_r = \frac{q^2}{m_T}.$$



What, then, are its merits?

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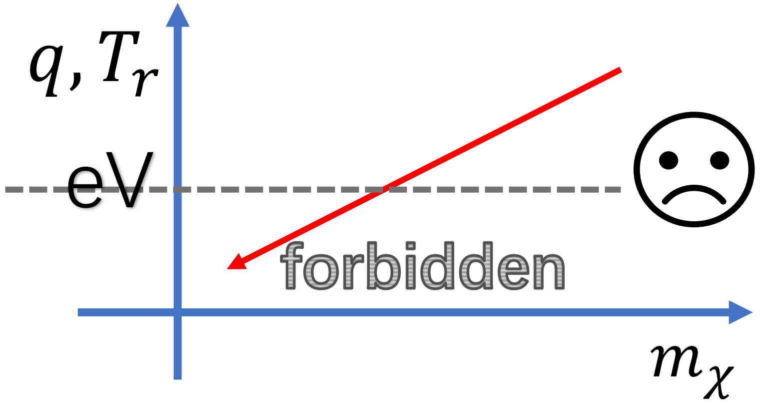

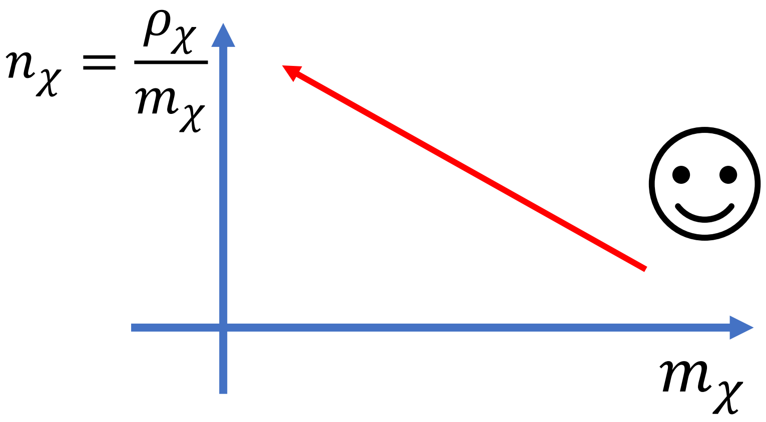

What, then, are its merits?

I. Large Number Density II. Large Scattering Cross Section!!!

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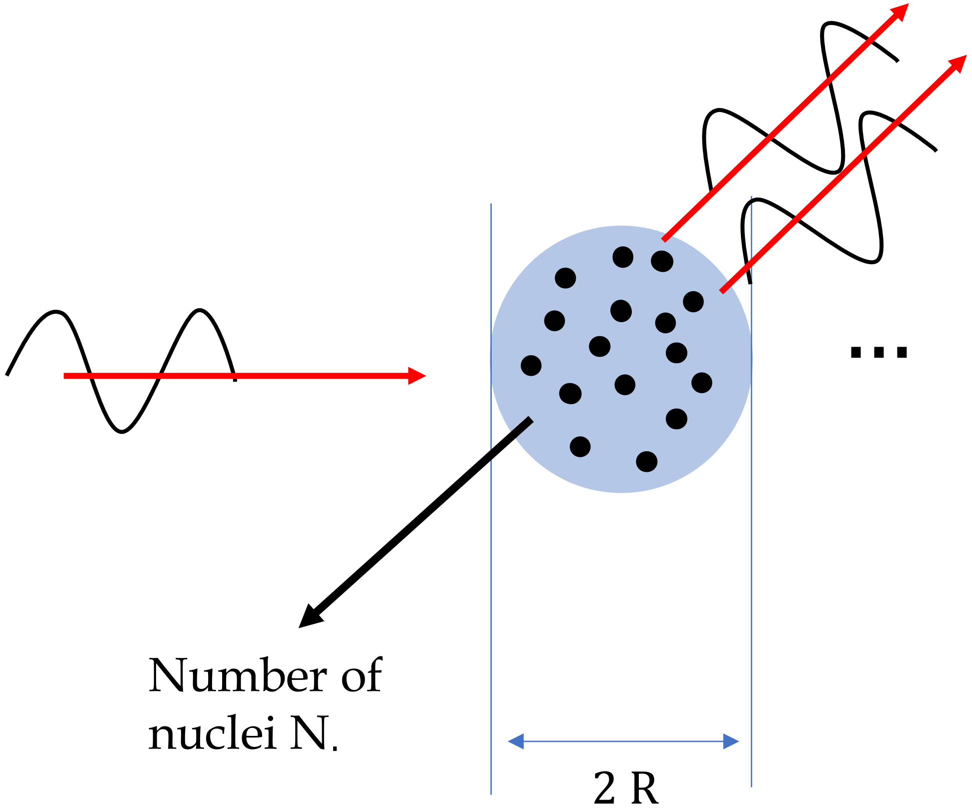
Coherent scattering enhancement



- Light DM have a relative long de Broglie wavelength:

$$\lambda_{DM} \sim \frac{1}{p_\chi} \sim \frac{1}{q} \sim \frac{10^{-3}}{m_\chi}$$

- 0.01eV DM ~ 1cm

- ***Coherent Scattering: If the DM wavelength is larger than the size of the target, the scattering cross section is enhanced by N^2.***

$$\sigma_{tot} = N^2\, \sigma_{\chi N}$$

- This N^2 coherent factor is verified by neutrino scattering in CEνNS.

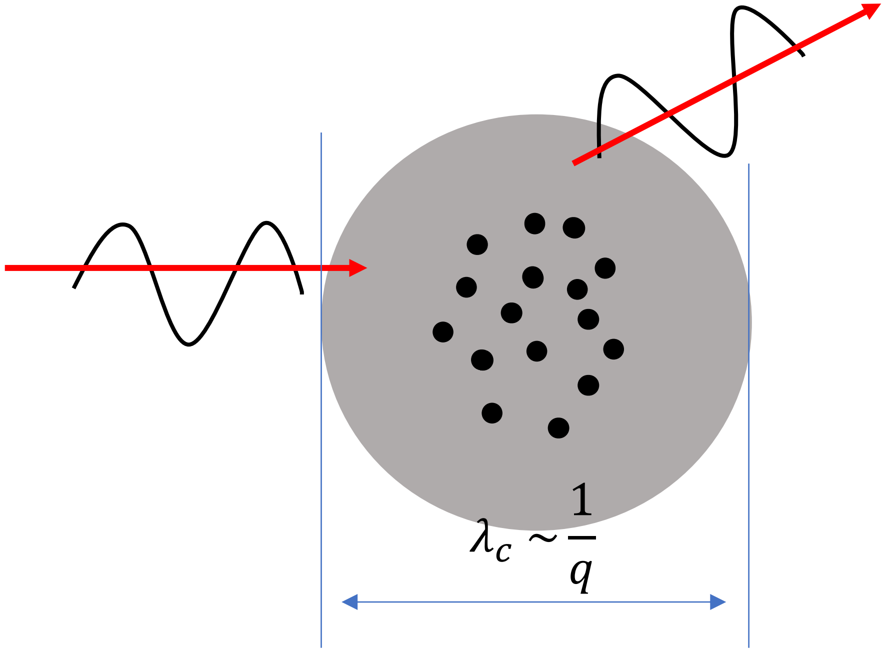
- **Incoherent [$q(p_\chi)$R $\gg$ 1, heavy DM]:** $\sigma_{tot} = N\, \sigma_{\chi N}$

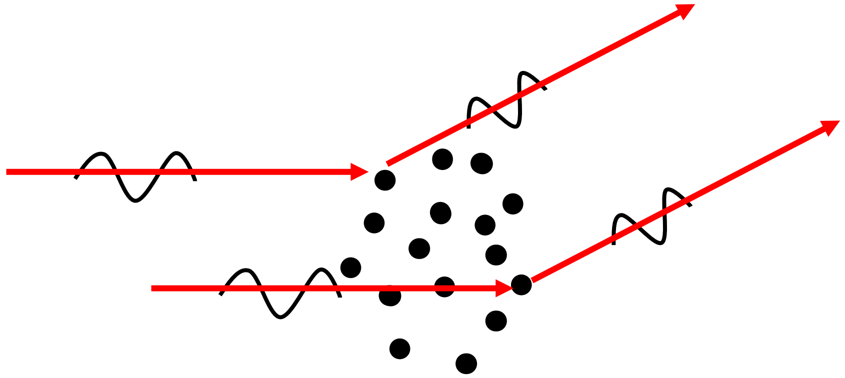
- For macro object, $N \sim 10^{23}$ **[Avogadro constant]**

Intuitive picture of coherent scattering

Uncertainty principle: $\delta p * \delta x \sim 1$, coherence scattering length/interacting region: $\lambda_c \sim \frac{1}{q}$

It is also the DM de Broglie wavelength $\frac{1}{q} \sim \frac{1}{p_\chi}$.





1) Small-q limit ($qR \ll 1$) $P_{tot} = |\sum A_i|^2$

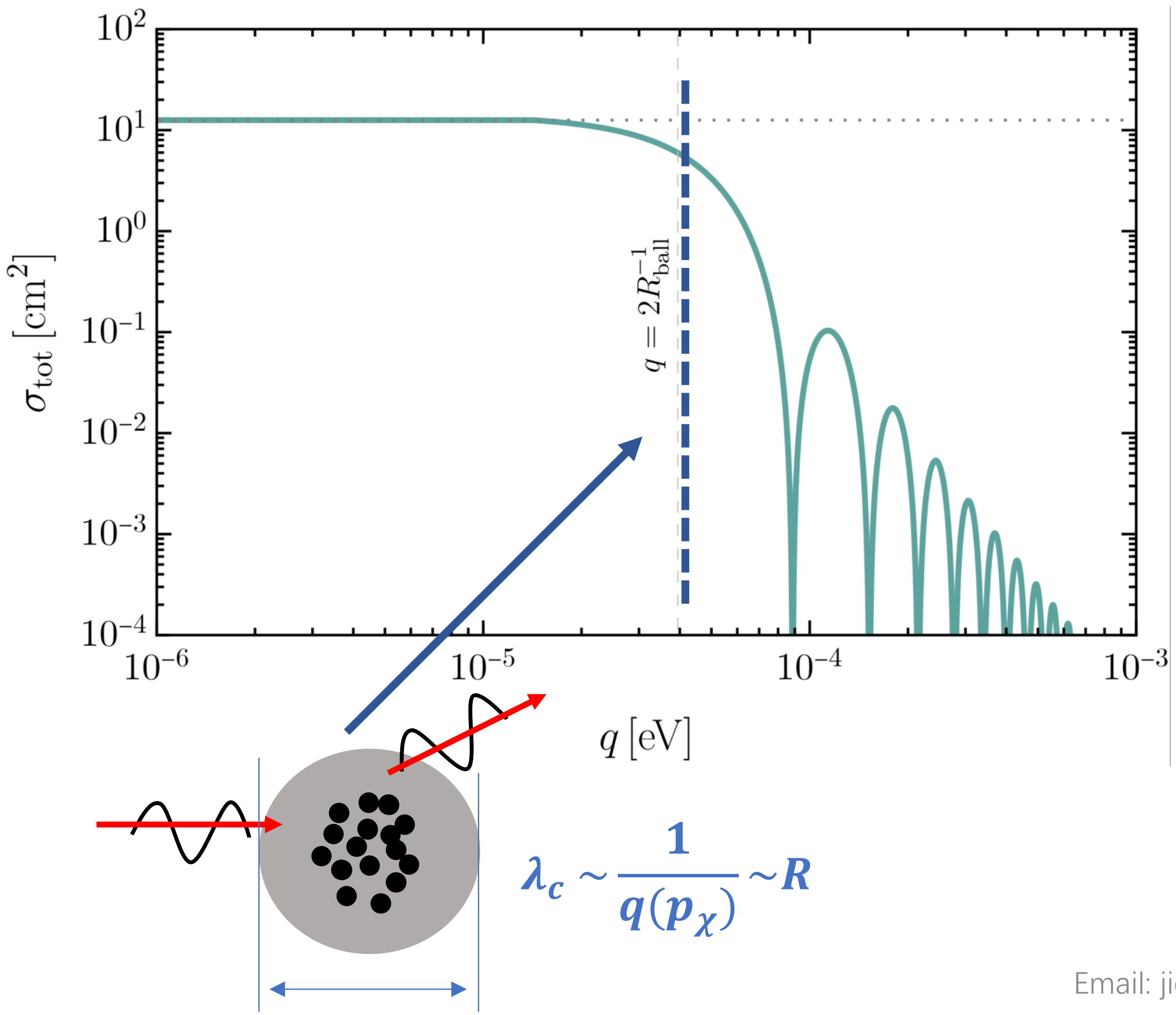
$$\sigma_{tot} = N^2 \, \sigma_{\chi N}$$

2) Large-q limit ($qR \gg 1$) $P_{tot} = \sum |A_i|^2$

$$\sigma_{tot} = N \, \sigma_{\chi N}$$

Form factor description of coherent scattering

$$\sigma_{tot} \simeq N^2 |F(q)|^2 \sigma_{\chi N} \qquad |F(\mathbf{q})|^2 = \frac{1}{V^2}\int d^3\mathbf{r}_i\, d^3\mathbf{r}_j\, e^{i\mathbf{q}\cdot\Delta\mathbf{r}_{ij}}.$$



For a sphere: $$F_S(\mathbf{q}) = \frac{3}{(qR)^3}\left[\sin(qR) - qR\cos(qR)\right].$$

Check the limits:

1) Small-q limit ($qR \ll 1$)

$$F_S(q) = 1 - \frac{x^2}{10} + O(x^4) = 1 - \frac{(qR)^2}{10} + O((qR)^4). \rightarrow \sigma_{tot} = N^2\,\sigma_{\chi N}$$

2) Large-q limit ($qR \gg 1$)

$$F_S(q) \simeq -\frac{3\cos(qR)}{(qR)^2} \rightarrow \sigma_{tot} \propto 1/q^4$$

The shape and size of target determines the scattering form factor.

Merits of light DM imply……

Merits:

1. Number density becomes large
2. Scattering cross section can be super-enhanced

$\rightarrow$

$\boldsymbol{Scattering\ Rate \sim n_\chi v_\chi \sigma_{tot}}$

$\downarrow$

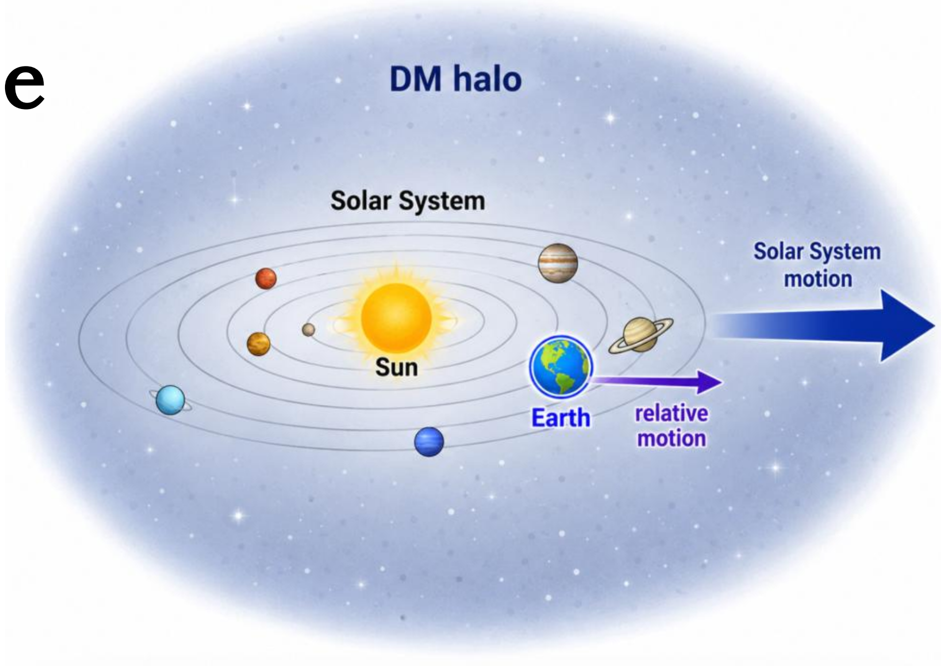
Observable: Some collective effects enhanced by the scattering rate

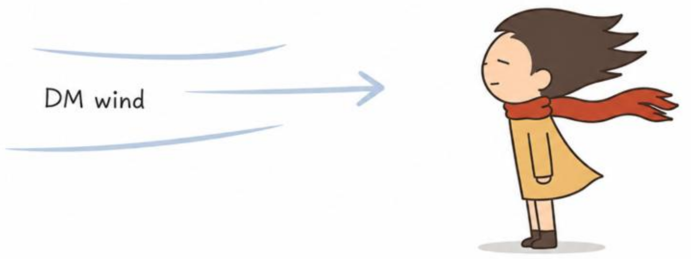
$\leftarrow$

What it is?

Force/Acceleration as observable

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





Force/Acceleration as observable

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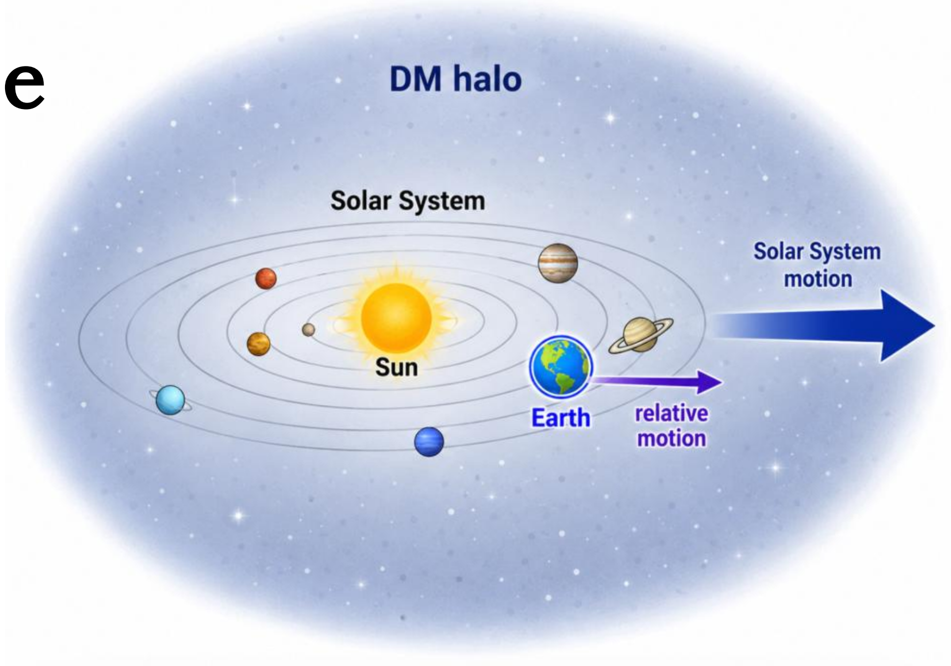
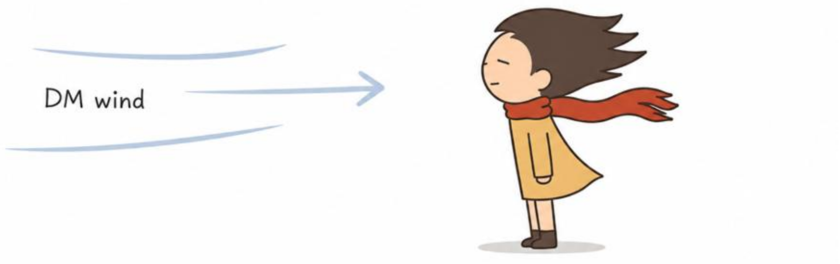
$$F = n_\chi\, \sigma_{tot}\, v\, q = \frac{\rho_\chi}{m_\chi}\, \sigma_{tot}\, v_\chi\, m_\chi\, v_\chi = \rho_\chi\, \sigma_{tot}\, v_\chi^2.$$

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

It can be enhanced by a factor an atom number, which is of order 10^{23} in macro-objects.





Force/Acceleration as observable

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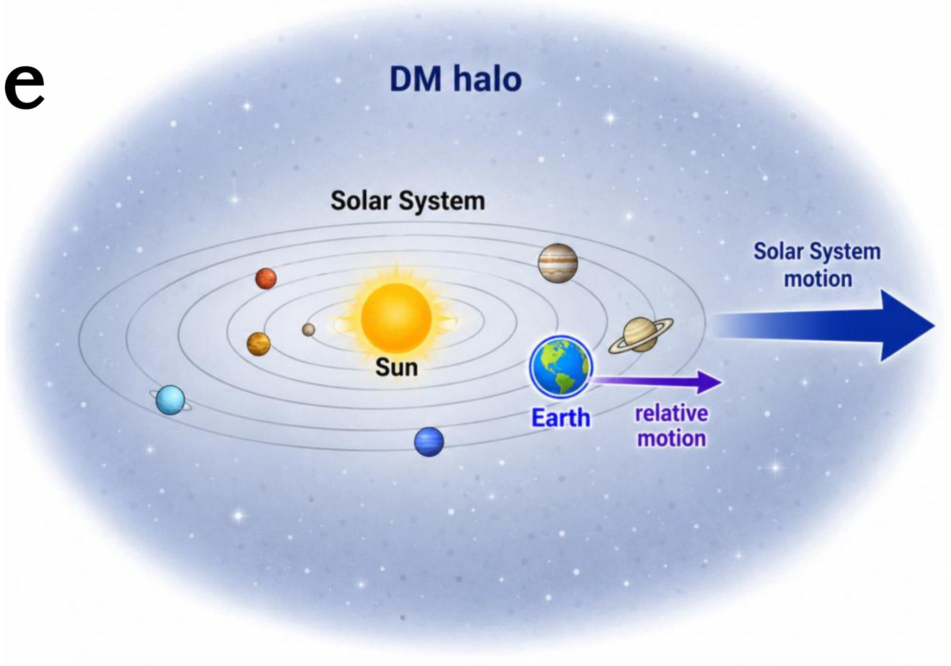
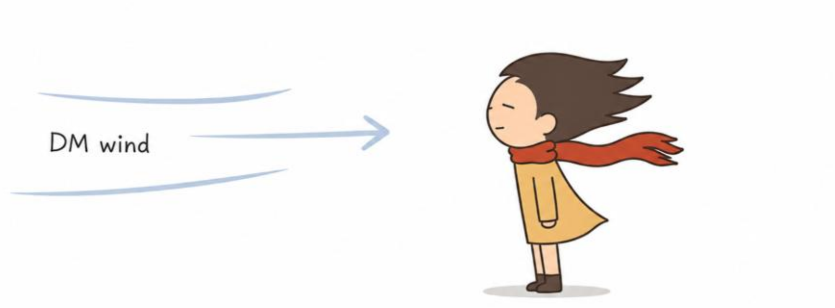
Please always do a conservative order estimation before doing the project!

$$\rho_\chi = 0.4\ \mathrm{GeV/cm^3}$$
$$N = 10^{24}$$
$$\sigma_{\chi N} = 10^{-50}\ \mathrm{cm^2}$$
$$v_\chi^2 = 10^{-6}$$
$$m_N = 1\ \mathrm{GeV}$$

$$\rightarrow \quad \boxed{a \sim 4 \times 10^{-12}\ \mathrm{cm/s^2}}$$

Not bad!





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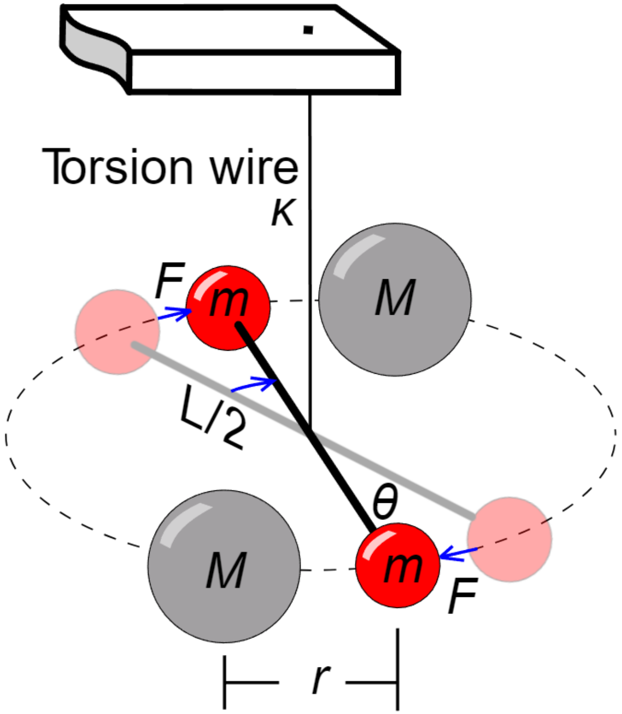
How to detect such a small acceleration?



- **Torsion balance was first invented for the detection of gravity and determination of Newton constant G [Cavendish Experiment (1797)].**

- **With more than two centuries of development, it now reaches a sensitivity: $\delta a = \frac{10^{-13} cm}{s^2}$.** ☺

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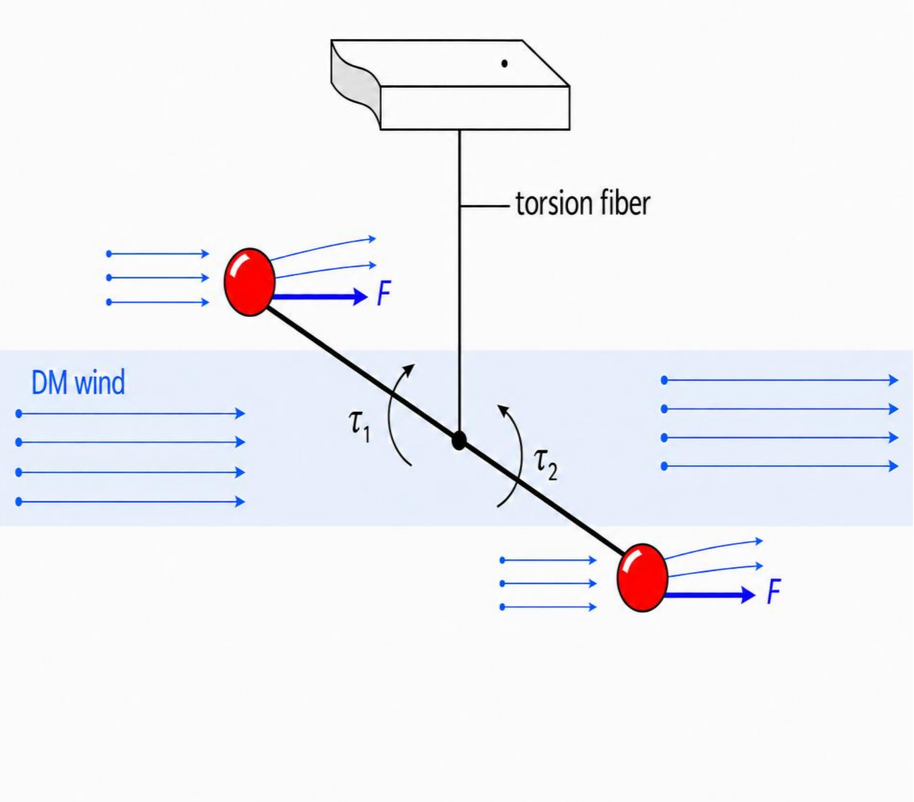

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- With more than two centuries of development, it now reaches a sensitivity: $\delta a = \frac{10^{-13} cm}{s^2}$.
- However, the usual symmetric torsion balance with same masses and same sizes does not work.

$$\Delta a = \frac{\rho_\chi \overbrace{\Delta\sigma_{tot}}^{=0} v_\chi^2}{m_{target}}$$

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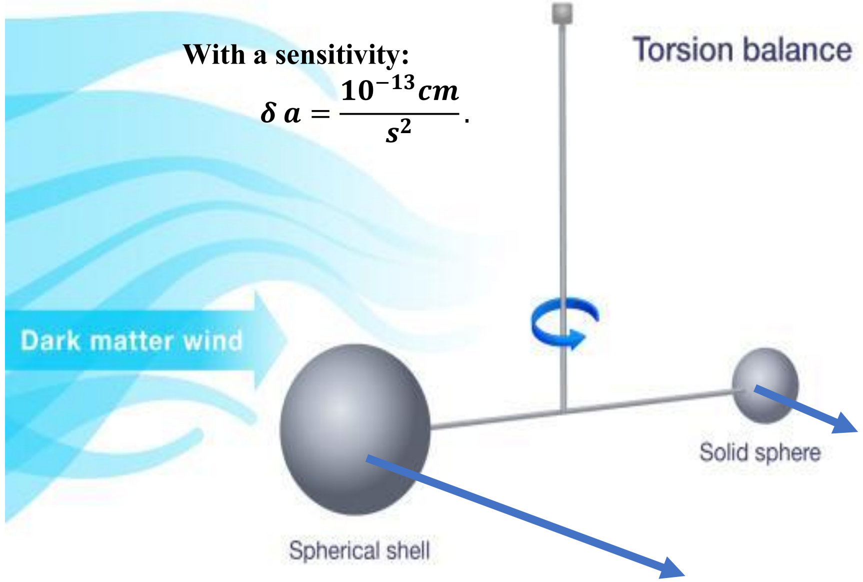
How to detect such a small acceleration?



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- With more than two centuries of development, it now reaches a sensitivity: $\delta\, a = \frac{10^{-13} cm}{s^2}$.
- However, the usual symmetric torsion balance with same masses and same sizes does not work.

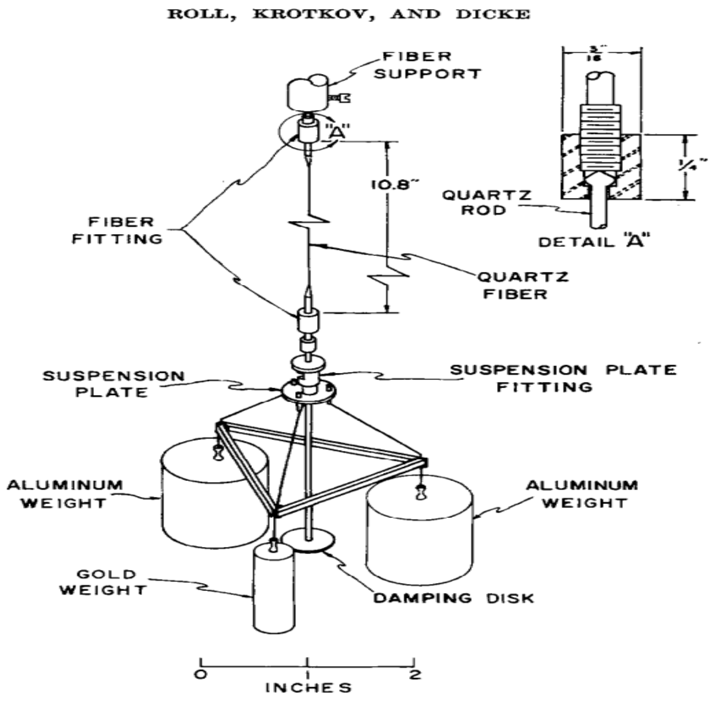
$$\Delta a = \frac{\rho_\chi \overset{\neq 0}{\Delta\sigma_{tot}} v_\chi^2}{m_{target}}$$

- If we want to detect DM wind, some asymmetry is needed! The two targets have different scattering cross section with DM.

WEP-testing torsion balance [WEP: weak equivalence principle]

Experiment	Materials	Mass	Shape	Structure	Outer Diameter	Height	$\lvert\Delta a\rvert$
Roll et al. (1964) [55]	Al/Au	30 g	cylinder	solid/solid	2.1 cm/0.78 cm	3.2 cm	$< 1.8 \cdot 10^{-11}$ cm/s^2
Braginskii et al. (1972) [56]	Al/Pt	0.49 g	sphere	solid/solid	0.70 cm/0.35 cm	-	$< 1.1 \cdot 10^{-12}$ cm/s^2
Eöt-Wash (1994) [57]	Be/Al	10 g	cylinder	solid/hollow	2.0 cm/2.0 cm	1.7 cm	$< 1.0 \cdot 10^{-11}$ cm/s$^{2\,a}$
	Be/Cu	10 g	cylinder	solid/hollow	2.0 cm/2.0 cm	1.7 cm	$< 1.0 \cdot 10^{-11}$ cm/s$^{2\,a}$
Eöt-Wash (2008 & 2012) [58, 59]	Be/Al	5 g	sphere^b	solid/hollow	1.7 cm/1.7 cm	-	$< 4.9 \cdot 10^{-13}$ cm/s$^{2\,a}$
	Be/Ti	5 g	sphere^b	solid/hollow	1.7 cm/1.7 cm	-	$< 8.3 \cdot 10^{-13}$ cm/s$^{2\,a}$

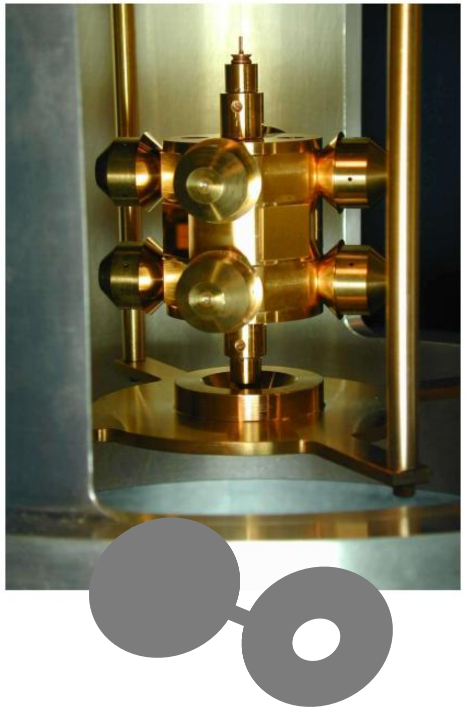
$$m = \rho * V$$



Early stage:

I. Same shape but different outer-sizes

II. Daily modulation due to the earth rotation



Current stage:

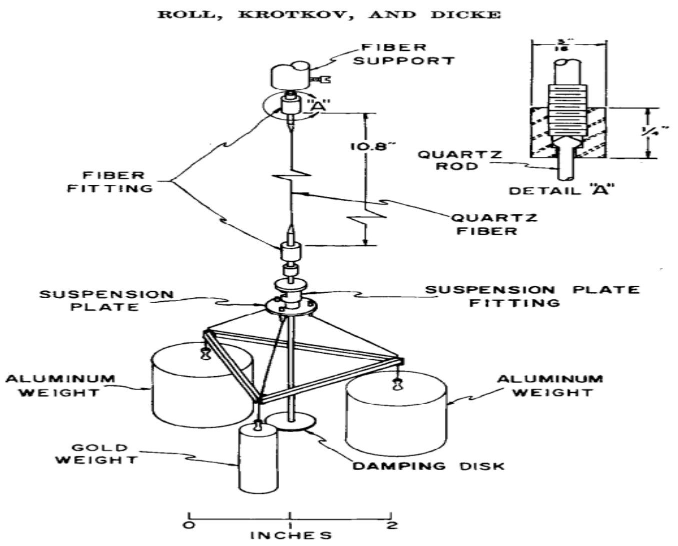
I. Same outer-size but different inner structures

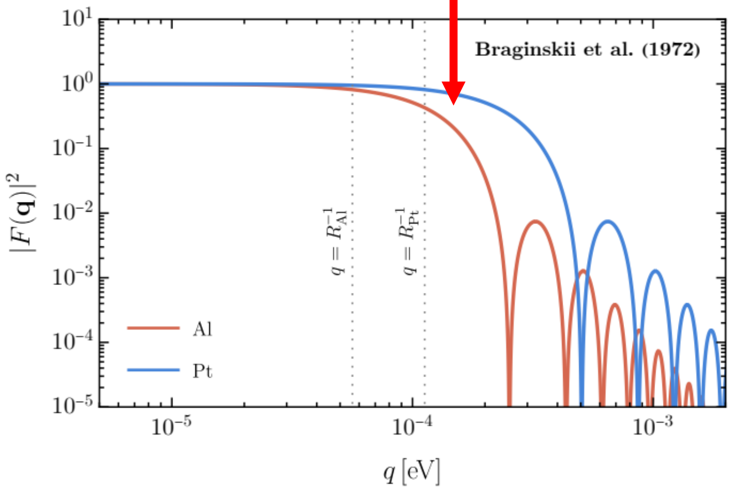
II. Self-rotation[mHz] with a mHz frequency

Cross-section difference

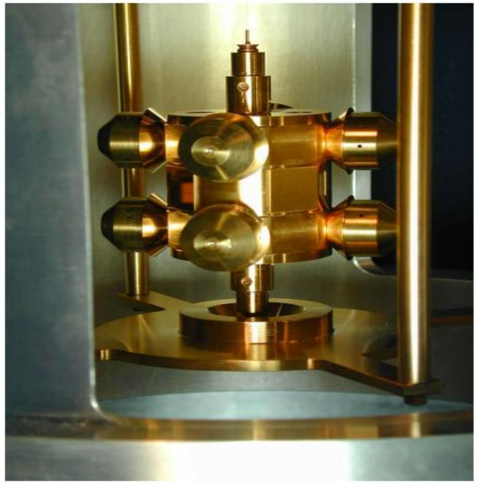
$$\Delta a = \frac{\rho_\chi \Delta\sigma_{tot} v_\chi^2}{m_{target}}$$

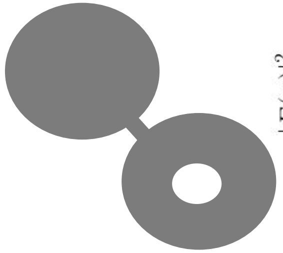
The shape and size of target determines the scattering form factor.

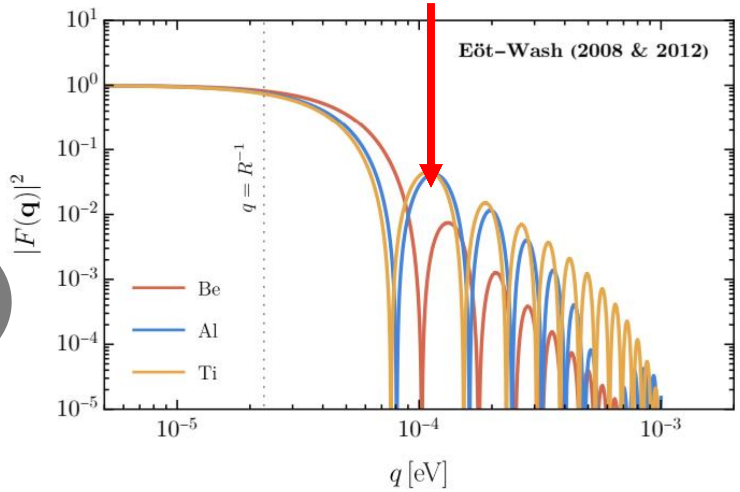




The largest difference occurs when the dark matter wavelength lies between the sizes of the large and small objects. In this case, it can coherently scatter only with the smaller test mass.







The largest difference occurs when the dark matter wavelength is smaller than the size of the test mass, so that it can "resolve" or "see" the internal structure.

DM limits from existing WEP experiments

Signal:

$$a \sim \frac{1}{m_{\rm tot}}\frac{\rho_\chi}{m_\chi}\sigma_{\rm tot} v_\chi q \simeq \frac{\rho_\chi \sigma_{\rm tot} v_\chi^2}{m_{\rm tot}}$$

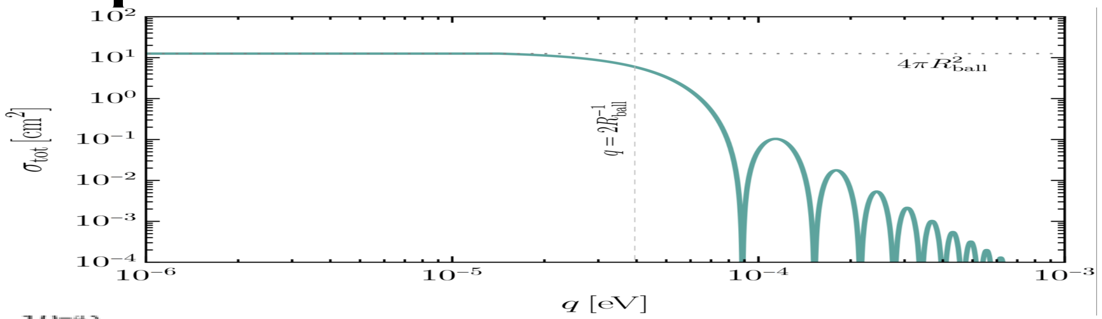
$$\langle a_z \rangle = \frac{1}{m_{\rm tot}}\frac{\rho_\chi}{m_\chi}\int d^3\mathbf{v}_\chi\, d\Omega'_\chi\, q_z\, |\mathbf{v}_\chi|\, f(\mathbf{v}_\chi)\, \frac{d\sigma_{\rm tot}(\mathbf{q})}{d\Omega'_\chi}.$$

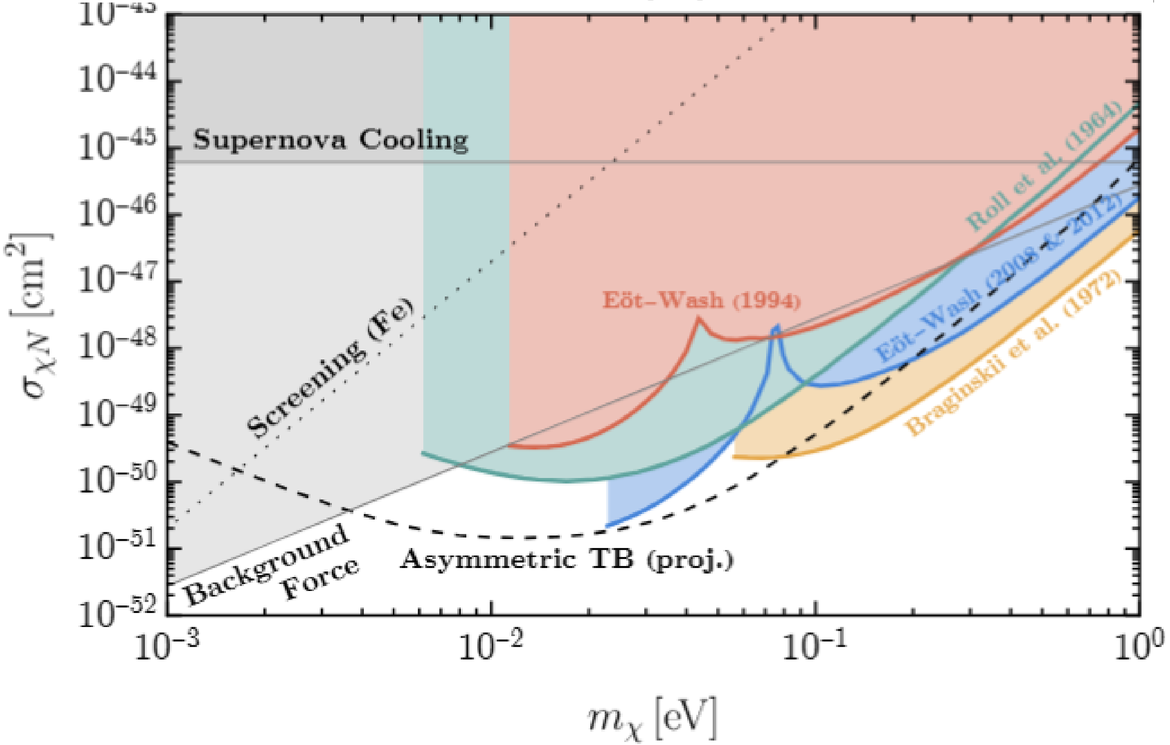
$$f_\chi(\mathbf{v}) \propto \exp\left(-\frac{|\mathbf{v}|^2}{v_0^2}\right)\Theta\left(v_{\rm esc} - |\mathbf{v}|\right),$$ with $v = v_\chi + v_{solar}$

Limits: signal < sensitivity

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

$\lvert\Delta a\rvert$
$< 1.8 \cdot 10^{-11}$ cm/s^2
$< 1.1 \cdot 10^{-12}$ cm/s^2
$< 1.0 \cdot 10^{-11}$ cm/s$^{2\,a}$
$< 1.0 \cdot 10^{-11}$ cm/s$^{2\,a}$
$< 4.9 \cdot 10^{-13}$ cm/s$^{2\,a}$
$< 8.3 \cdot 10^{-13}$ cm/s$^{2\,a}$





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

PRL136, 121803 (2026)

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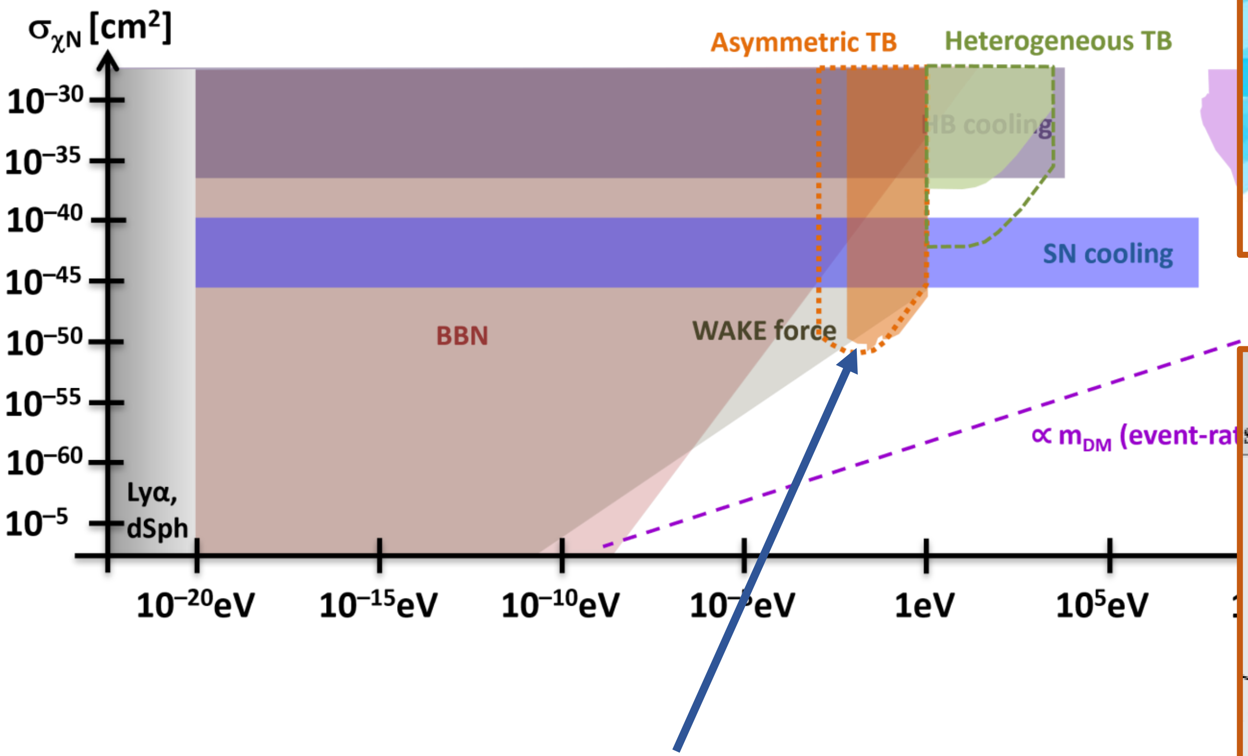
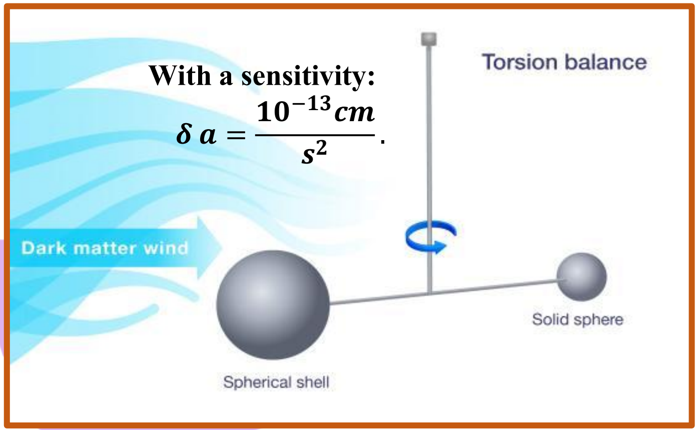
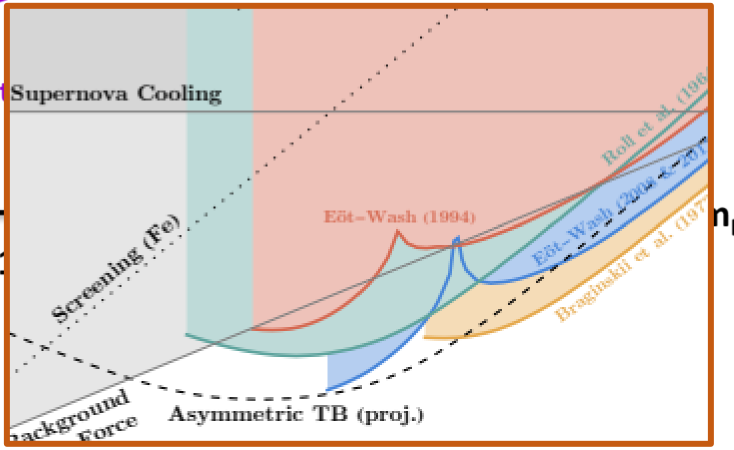
Conclusion







Conclusion: Through our studies of coherent dark matter scattering and accelerometer-based constraints, we have made some contributions here in this plot.

Thank you!

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]

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

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

This gives a ϕ dependent shift in the Higgs VEV:

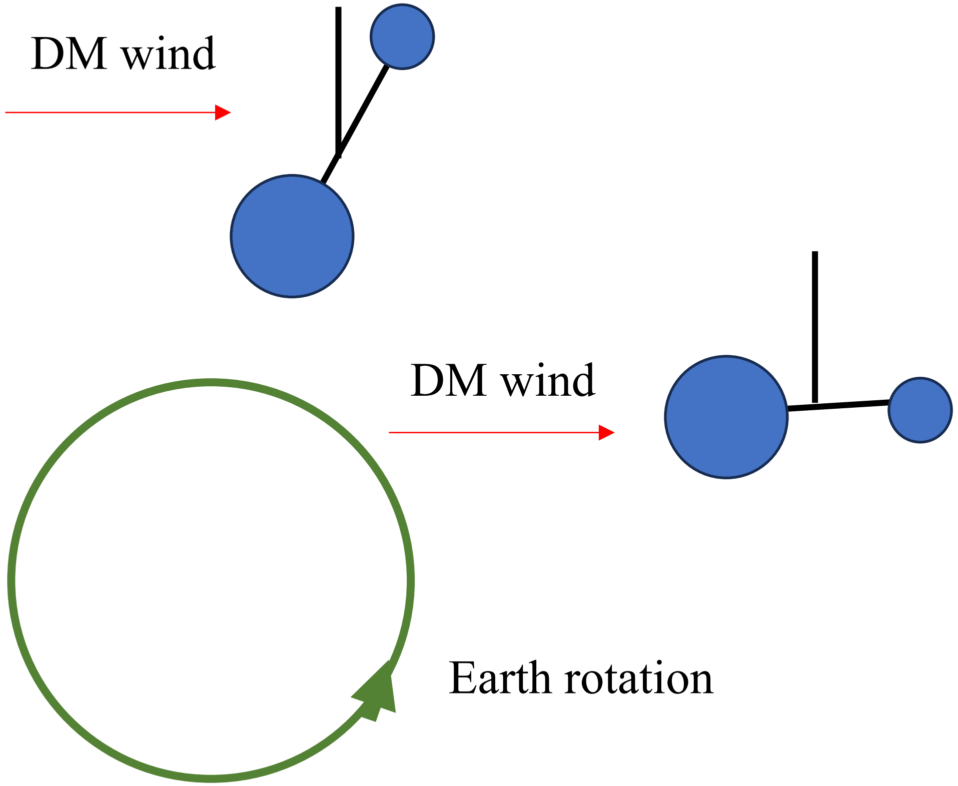
$$\frac{\delta v}{v} = \frac{\epsilon\phi^2}{2m_h^2}, \tag{B.4}$$

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

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

[arXiv: 2312.13345v1]

5. Signal



- Because of the earth rotation, we can observe a time-dependent signal with a period of one day.
- When the setup is parallel to the DM wind, the signal is at its minimum
- When the setup is perpendicular to the DM wind, the signal is at its maximum

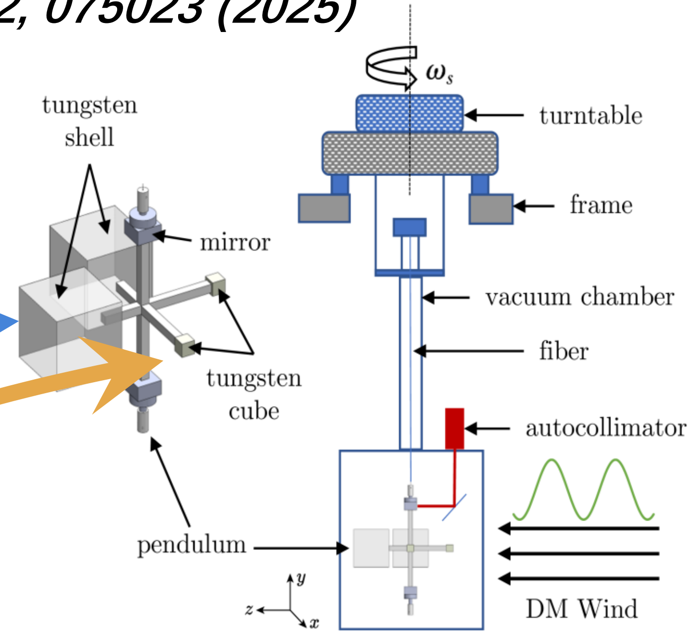
A new proposal

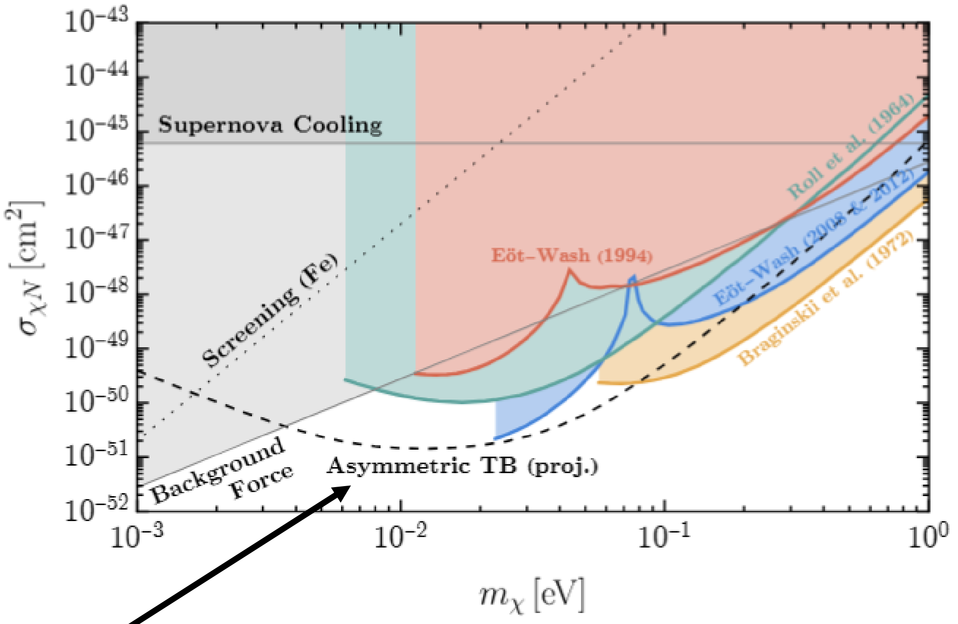
PRD112, 075023 (2025)

$R_1 = 4.2\,\mathrm{cm}$

$R_2 = 0.8\,\mathrm{cm}$

$m_1 = m_2 = 10\,\mathrm{g}$





- Self-rotating, High Sensitivity
- Large Form Factor Difference
- Large Mass & N-Enhancement

Expected to be completed around 2027.05 by HUST