

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);***

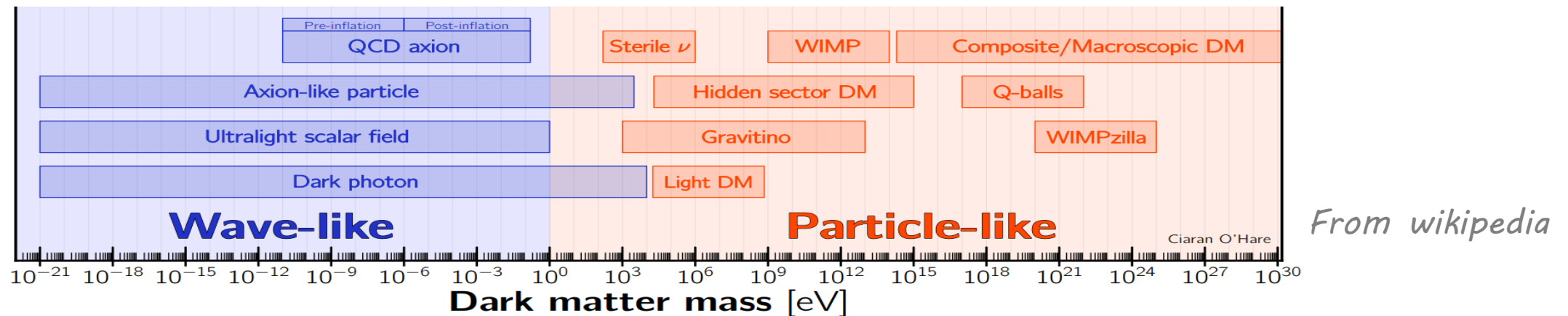
*S. Matsumoto, J. S., C. Y. Xing, L. Zhu, **PRL136, 121803 (2026).***

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

Introduction to DM

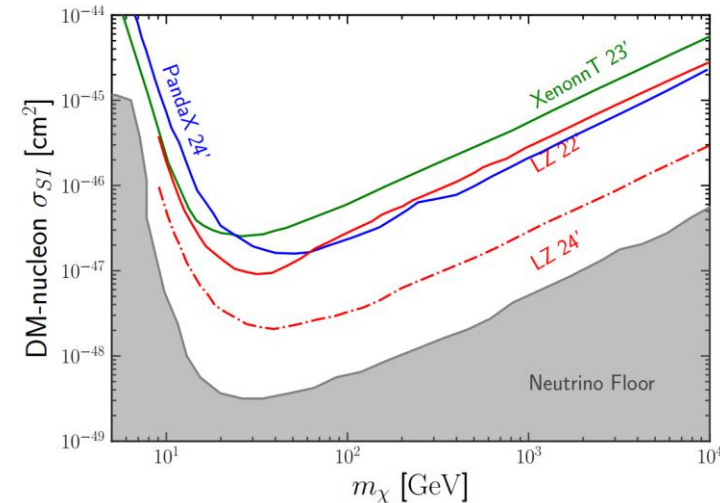
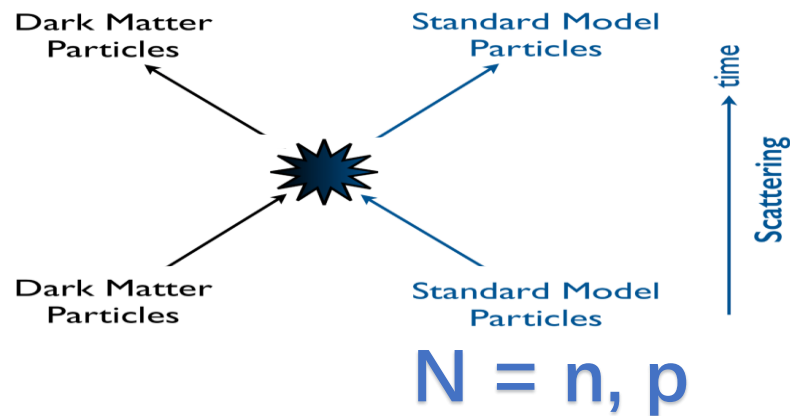
- We know that more than 80 percent of the matter in our Universe today is dark matter (DM) from astro and cosmic observations.
- Answering “**what dark matter is**” has become one of the most important questions in physics.



- **Physics is fundamentally an experimental science.**
- Therefore, the more urgent question may be: “**How can we detect dark matter?**”, especially **in the laboratory.**

Direct Detection of DM

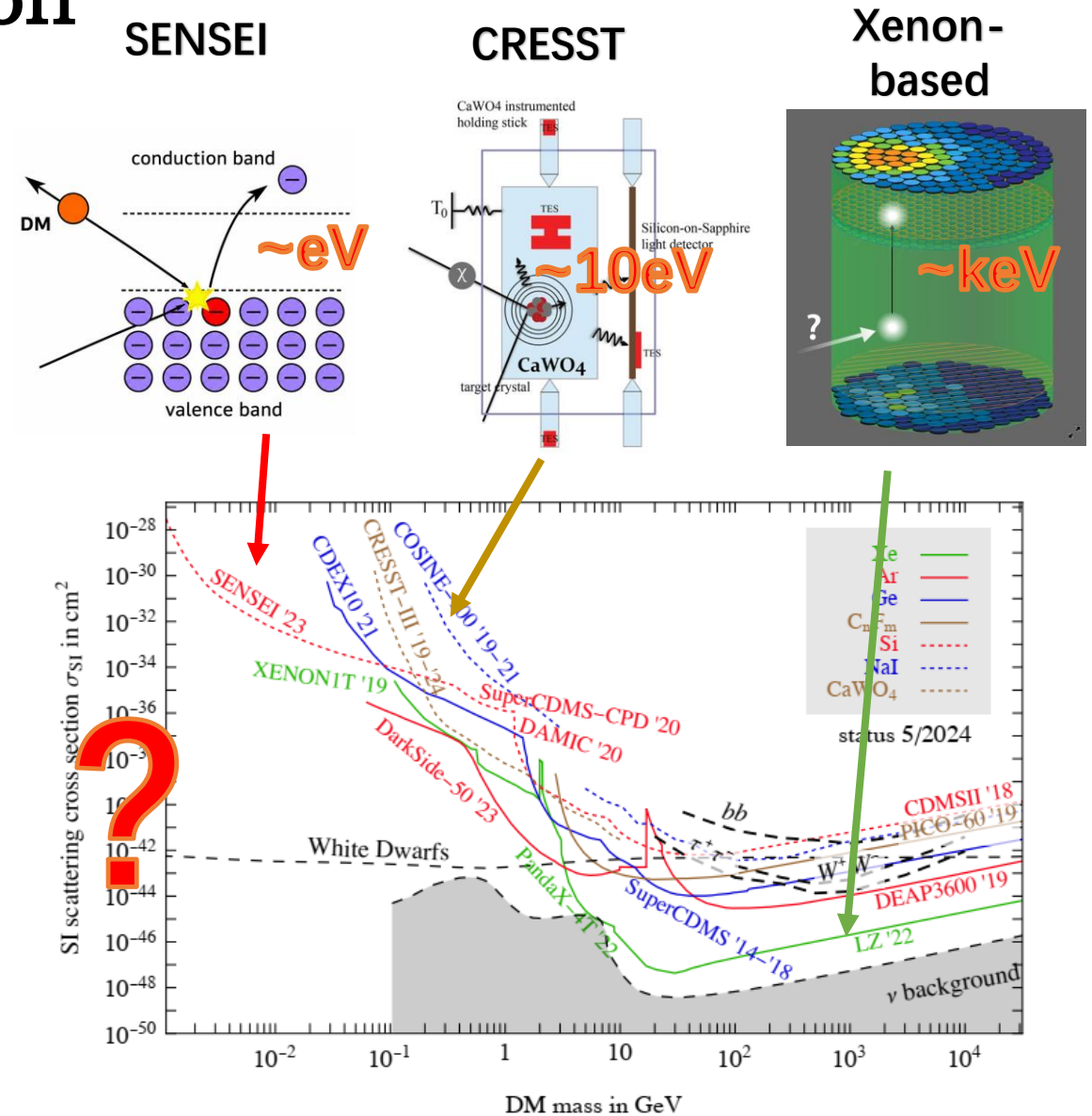
- Detection of DM in laboratory is the so called “**Direct Detection**” based on **DM-SM particle Scattering**.
- Goodman & Witten proposed DM-Heavy nuclei scattering for WIMP DM [**Tone-scale Xenon experiments**].



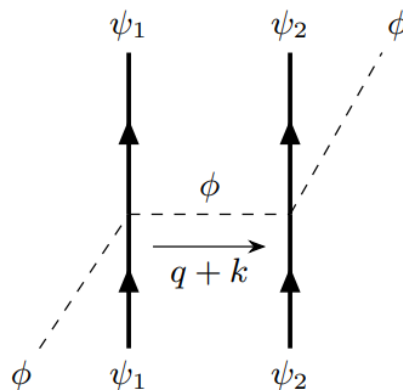
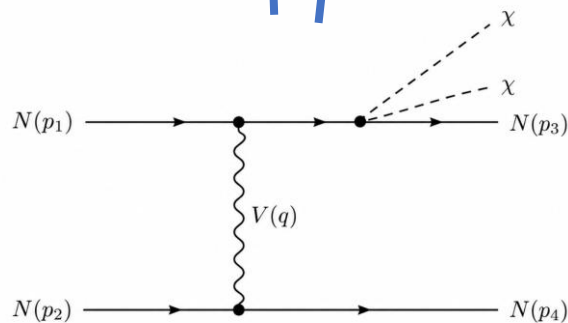
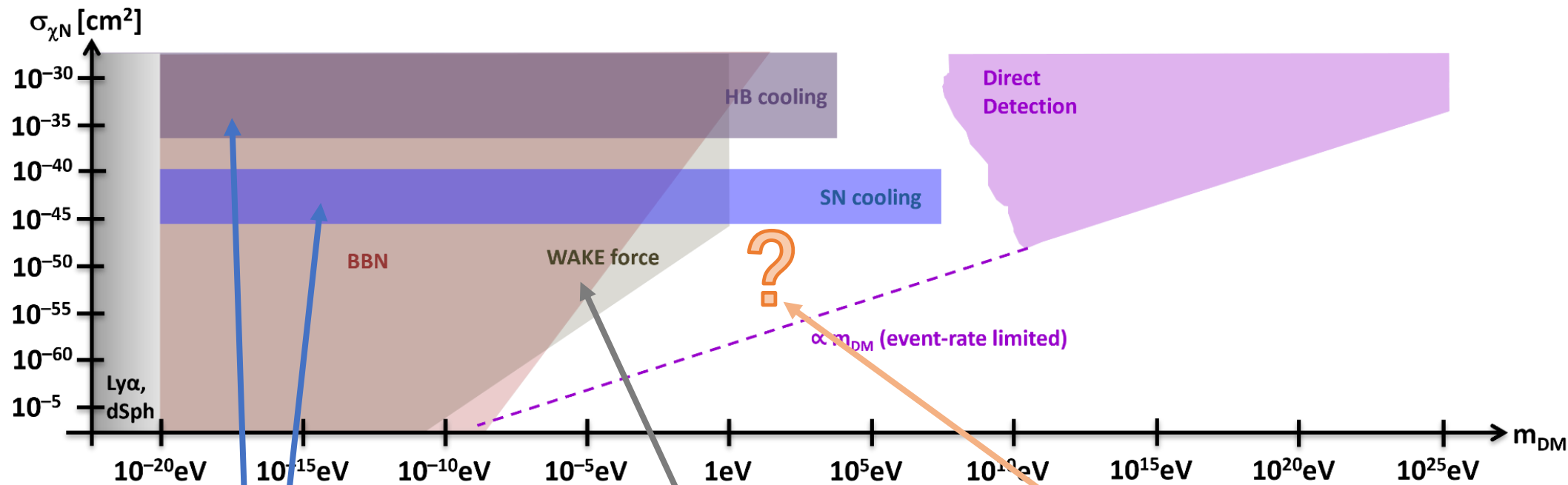
- Currently, **DM-nucleon/nuclei elastic scattering**, $\chi + N \rightarrow \chi + N$, becomes one of the most general and **benchmark** processes when we talk about direct detection.
- **Quadratical** coupling: $\frac{m_N \chi^2 \bar{N} N}{\Lambda^2}$ [scalar] or $\frac{\bar{\chi} \chi \bar{N} N}{\Lambda^2}$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



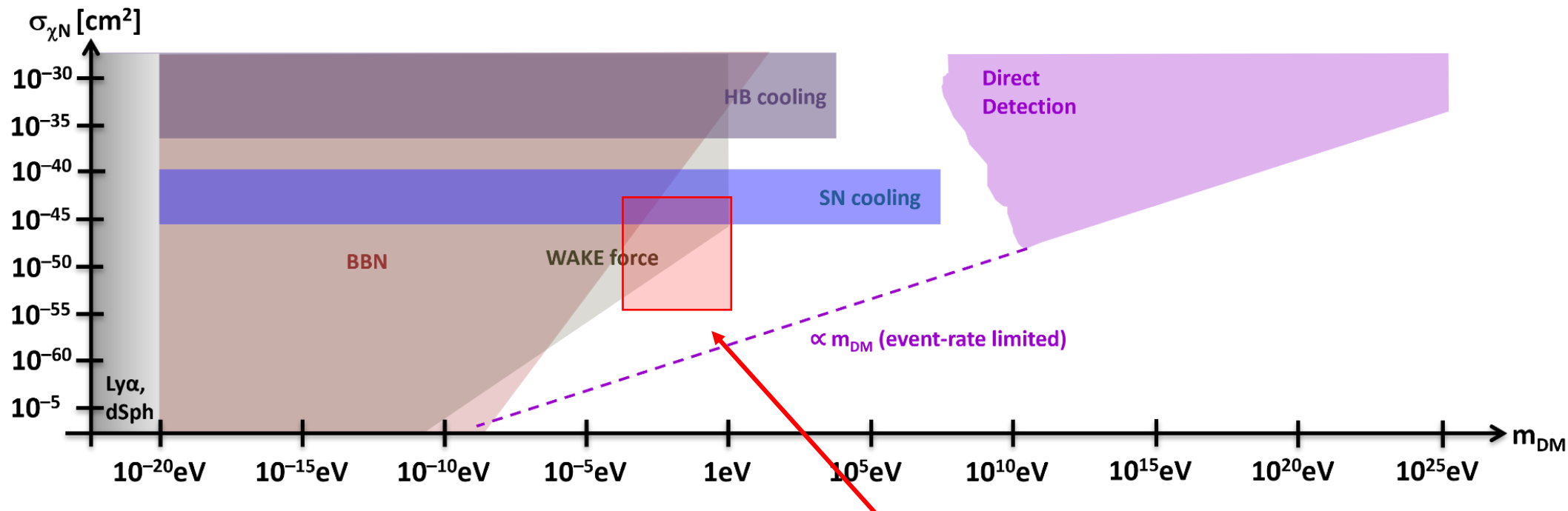
Summarizes of DM-nuclei SI cross section limits



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.

Outline

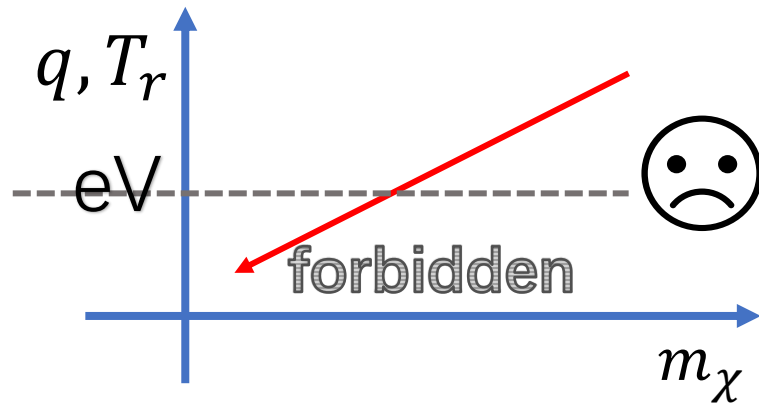
1. Introduction and target
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Merits of lighter DM

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

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

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



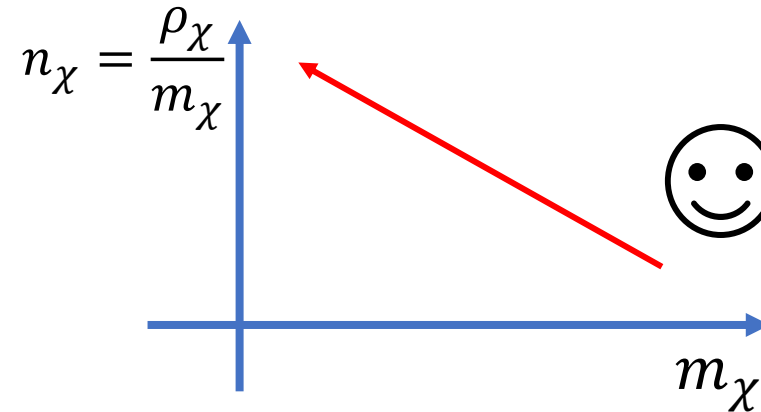
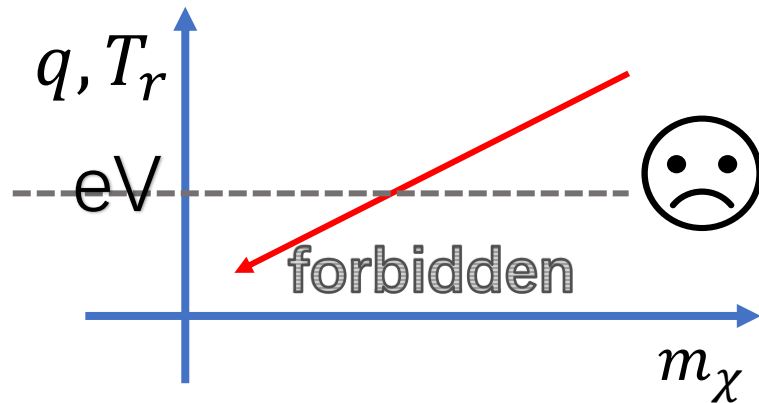
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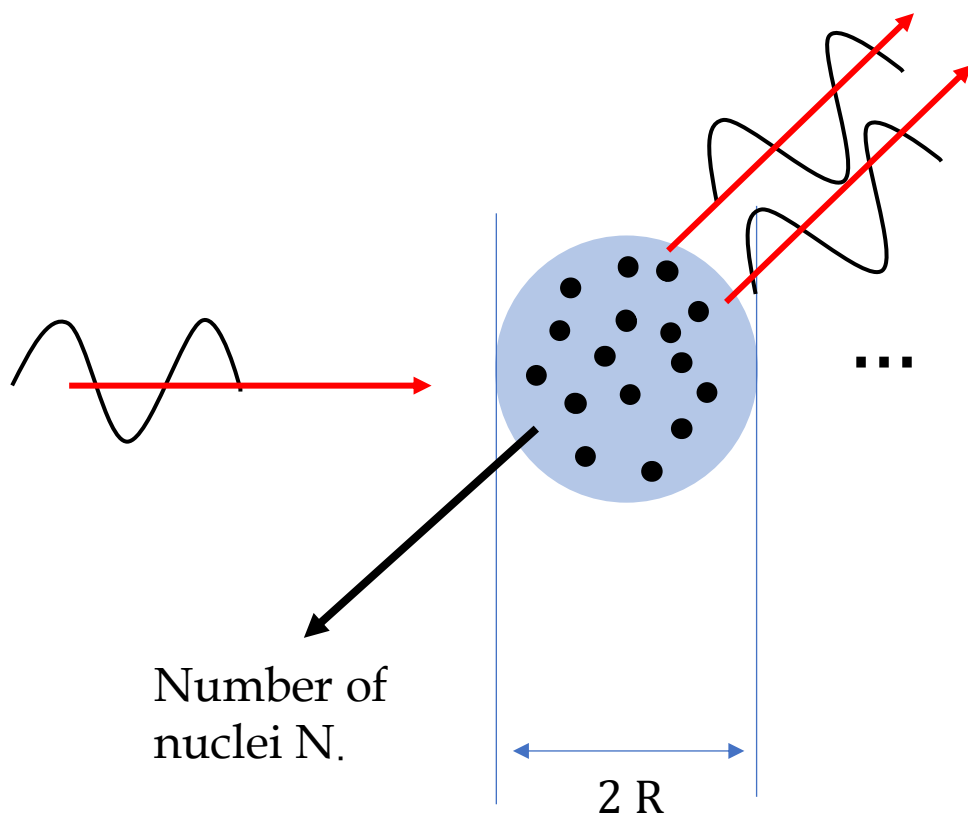
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What, then, are its merits?

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

Coherent scattering enhancement



- Light DM have a relative long de Broglie wavelength:

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

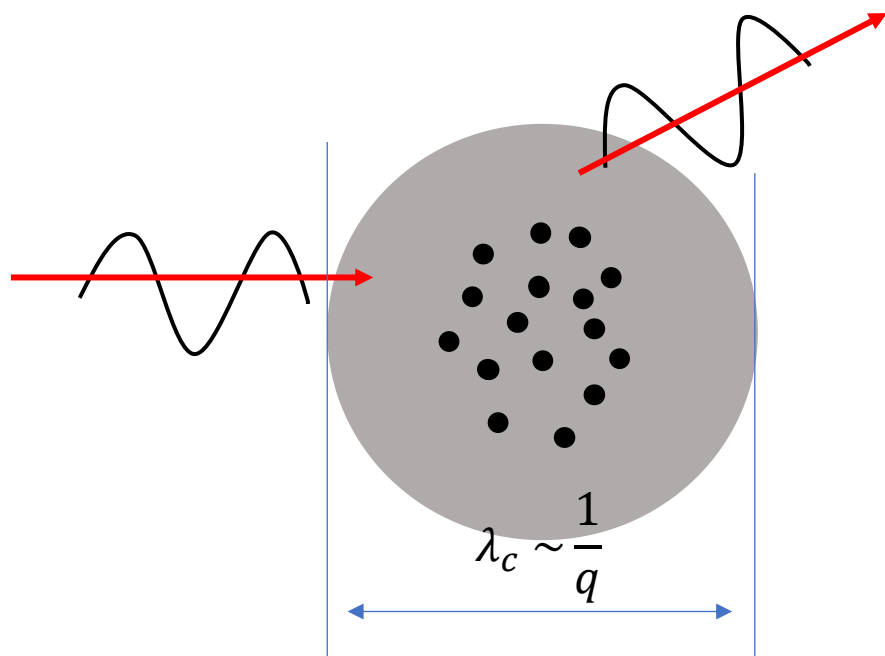
- $0.01\text{eV DM} \sim 1\text{cm}$
- Coherent Scattering: If the DM wavelength is larger than the size of the target, the scattering cross section is enhanced by N^2 .**

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

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

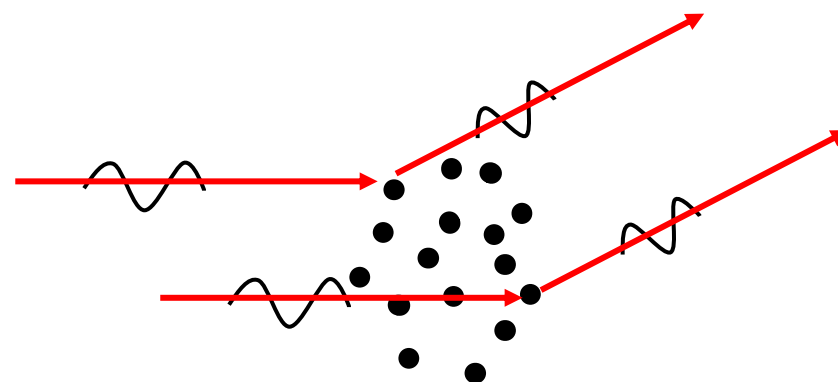
Uncertainty principle: $\delta p * \delta x \sim 1$, coherence scattering length/interacting region: $\lambda_c \sim \frac{1}{q}$



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

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

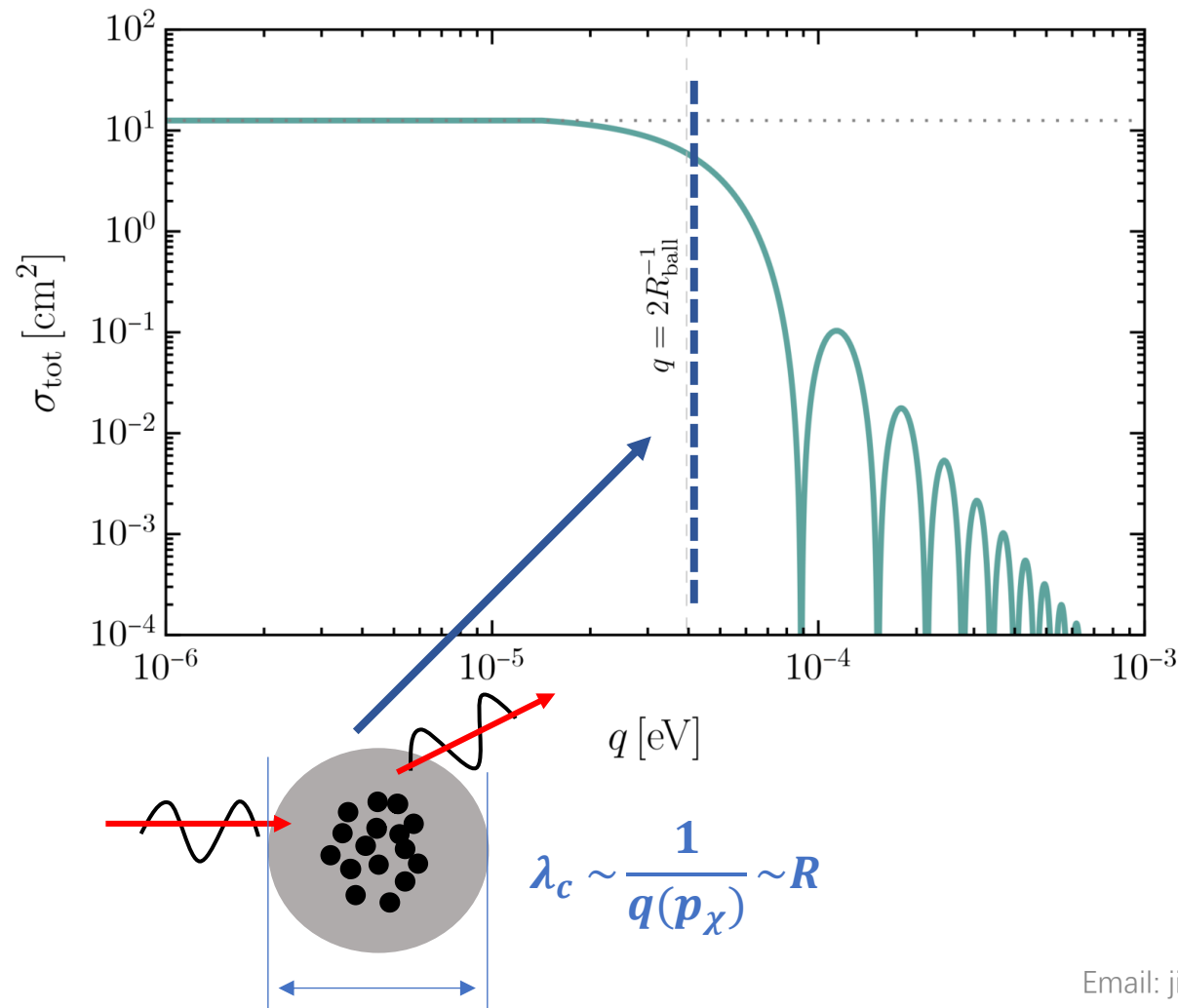
It is also the DM de Broglie wavelength $\frac{1}{q} \sim \frac{1}{p_\chi}$.



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



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

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

Check the limits:

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

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

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

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

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



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



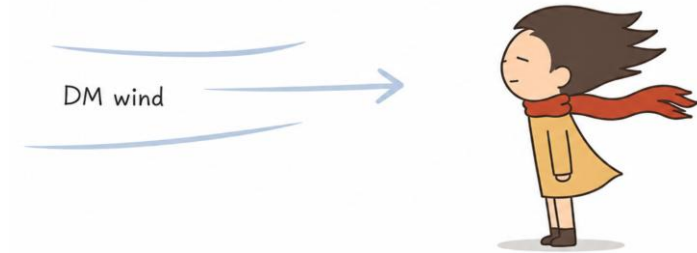
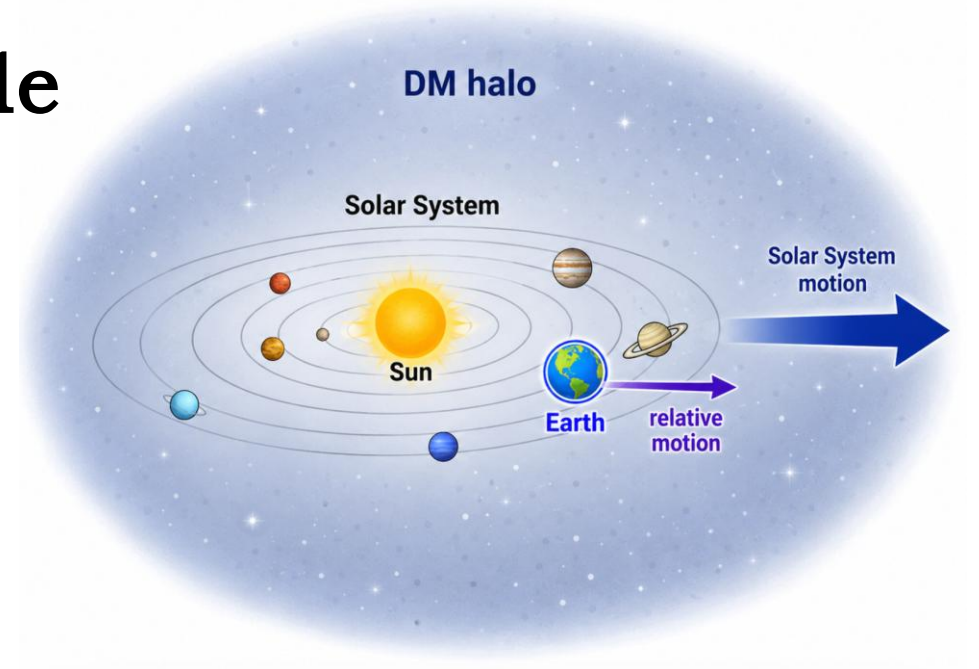
What it is?



Observable: Some collective effects enhanced by the scattering rate

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.



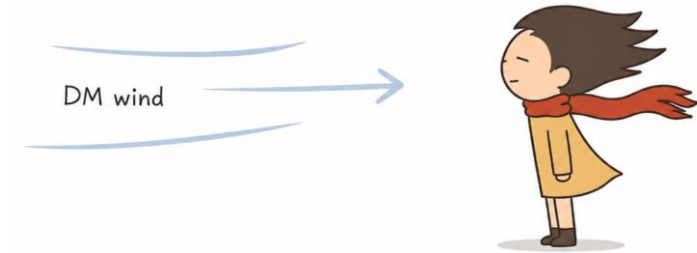
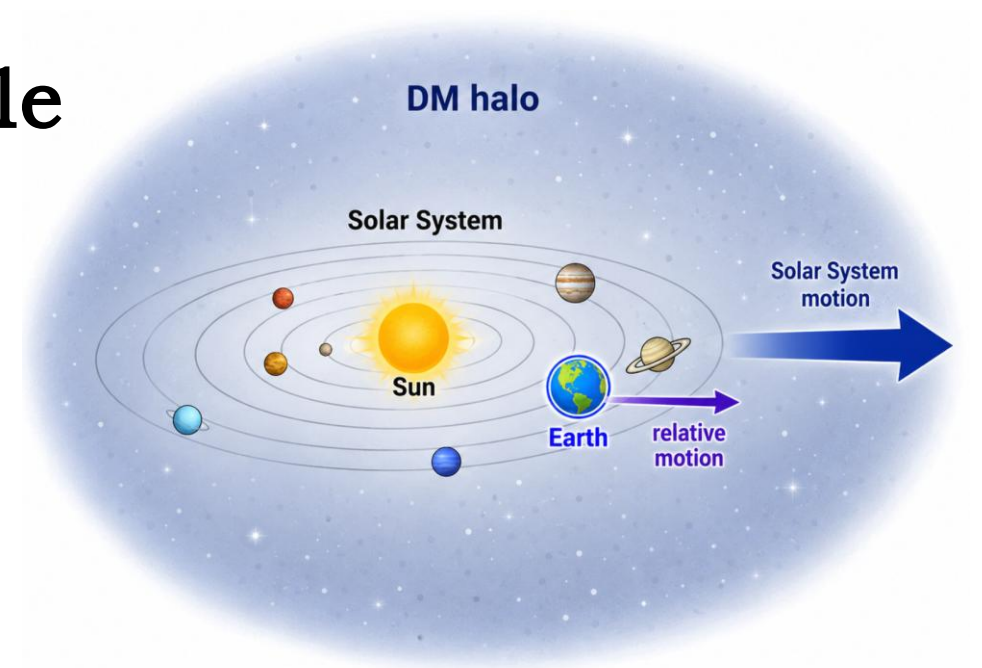
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$$F = n_{\chi} \sigma_{tot} v q = \frac{\rho_{\chi}}{m_{\chi}} \sigma_{tot} v_{\chi} m_{\chi} v_{\chi} = \rho_{\chi} \sigma_{tot} v_{\chi}^2.$$

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

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



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

$$\rho_{\chi} = 0.4 \text{ GeV/cm}^3$$

$$N = 10^{24}$$

$$\sigma_{\chi N} = 10^{-50} \text{ cm}^2$$

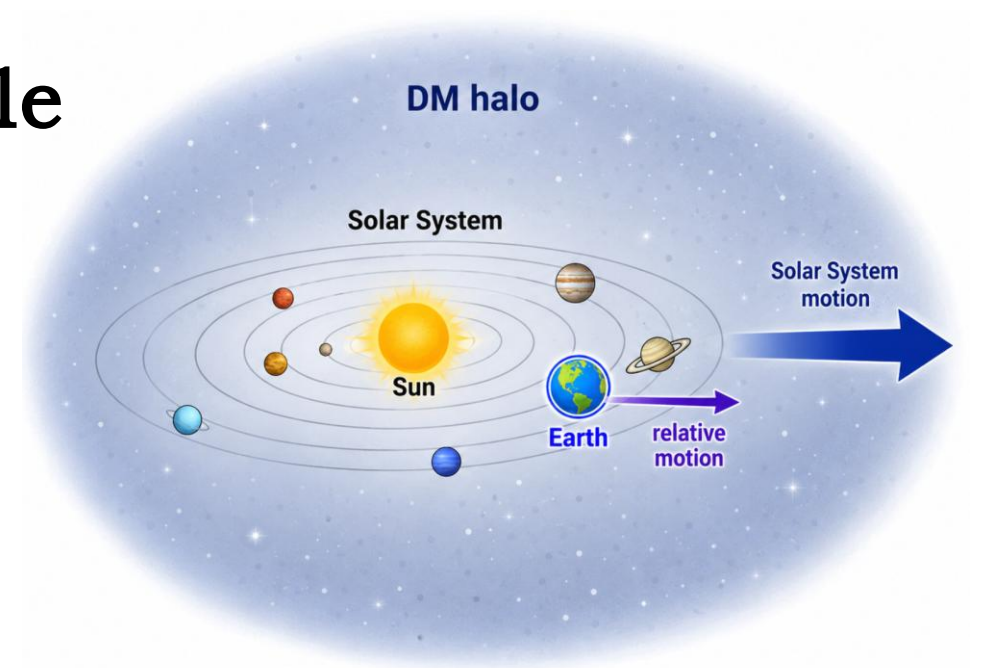
$$v_{\chi}^2 = 10^{-6}$$

$$m_N = 1 \text{ GeV}$$



$$a \sim 4 \times 10^{-12} \text{ cm/s}^2$$

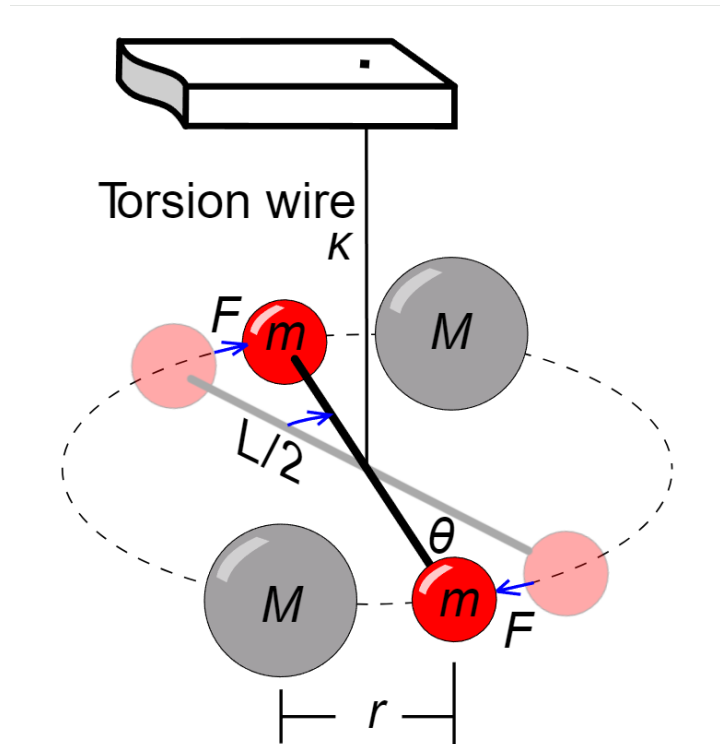
Not bad!



Outline

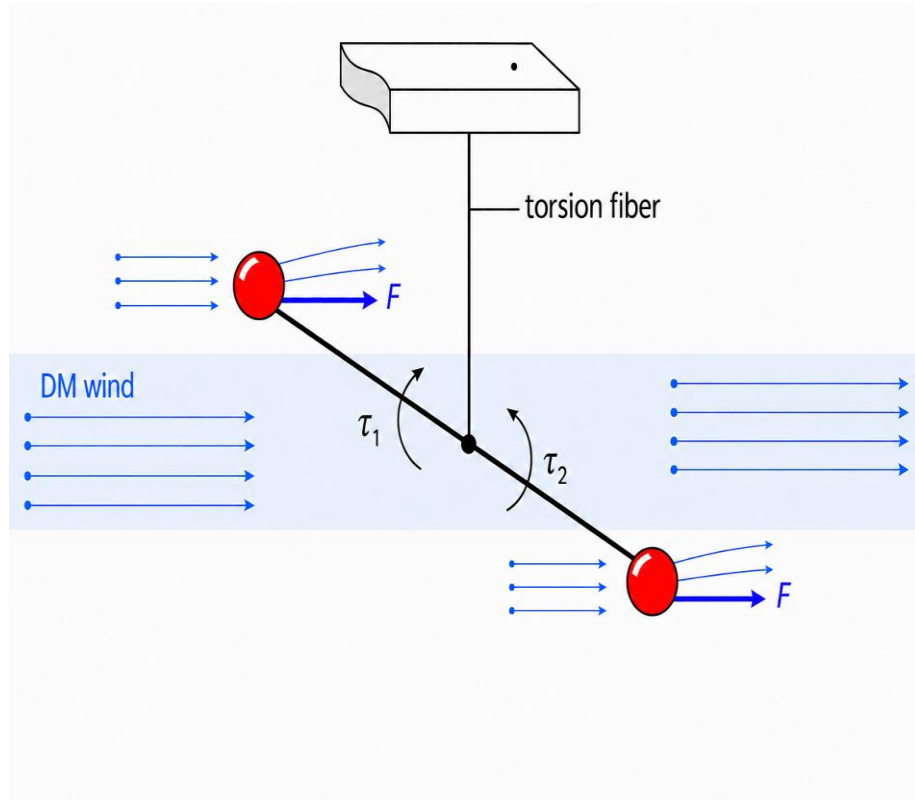
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How to detect such a small acceleration?



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

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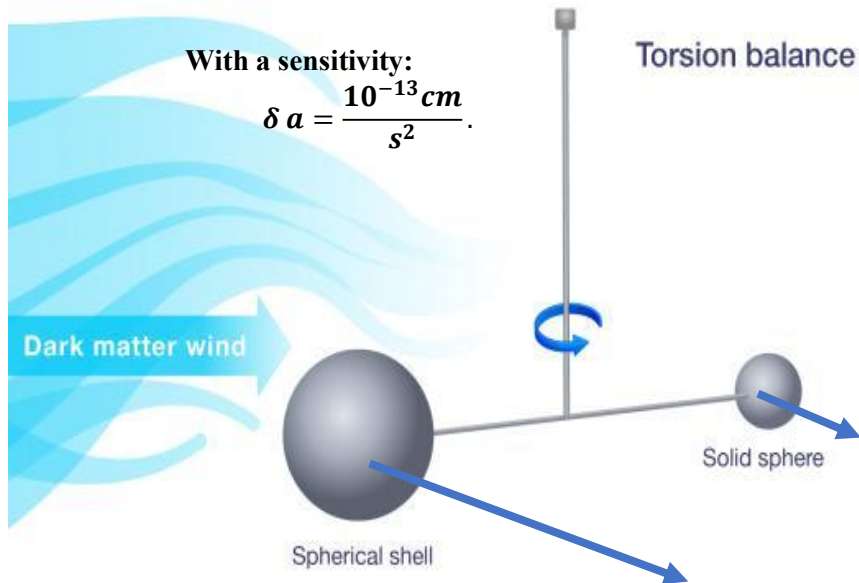


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- However, the usual **symmetric** torsion balance with **same masses and same sizes** does not work.

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

(Note: In the original image, the term $\Delta \sigma_{tot}$ is circled in red with a red '0' above it, indicating it is zero.)

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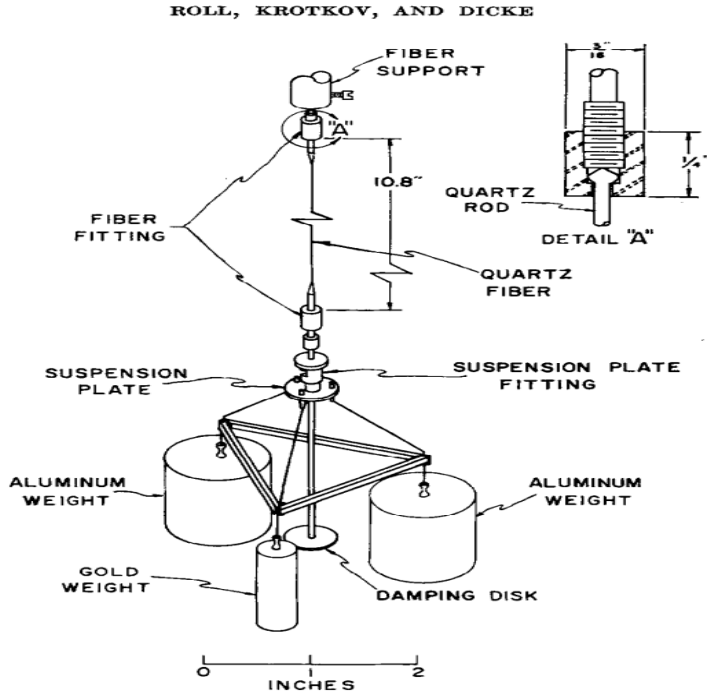
$$\Delta a = \frac{\rho_\chi \Delta \sigma_{tot} v_\chi^2}{m_{target}} \neq 0$$

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

$$m = \rho * V$$



Early stage:

- I. Same shape but different outer-sizes
- II. Daily modulation due to the earth rotation



Current stage:

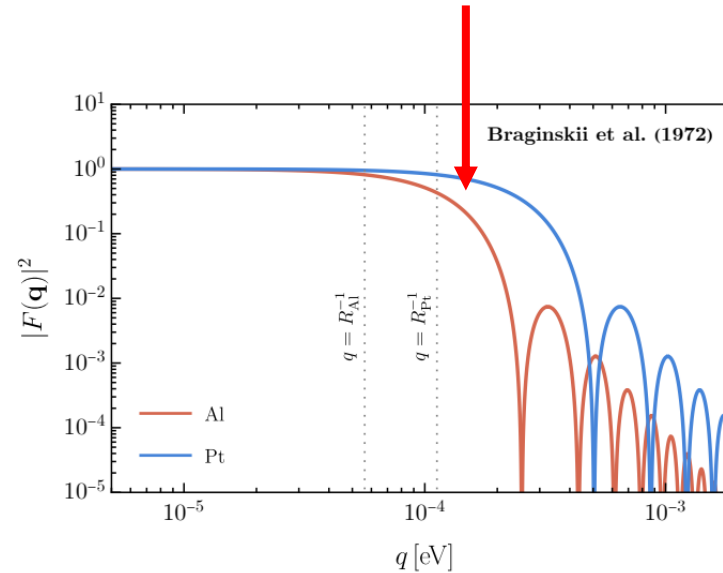
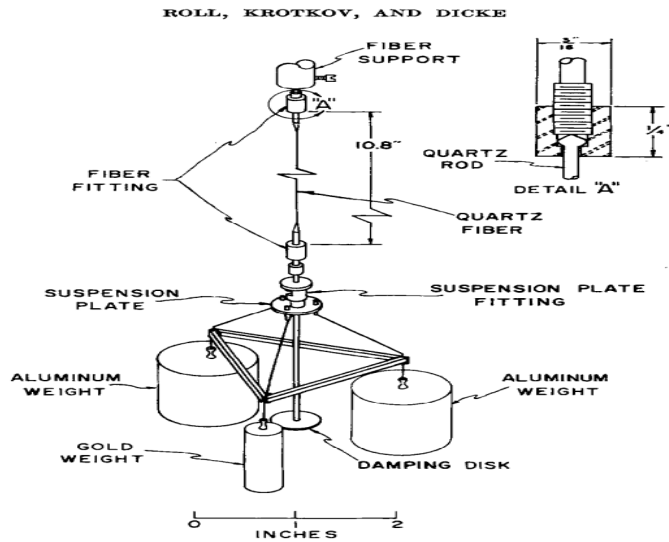
- I. Same outer-size but different inner structures
- II. Self-rotation[mHz] with a mHz frequency

Higher sensitivity

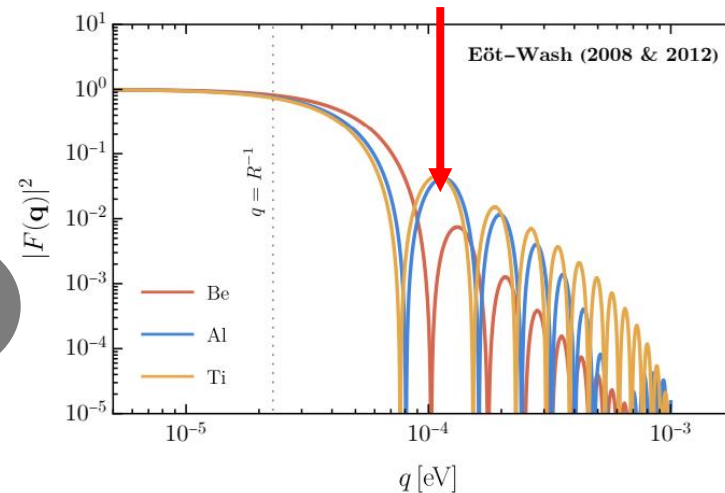
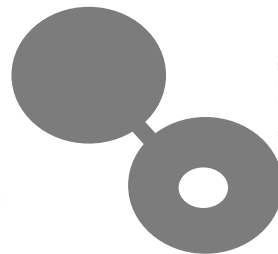
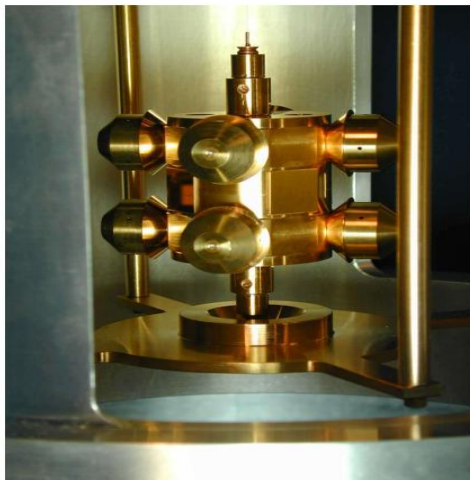
Cross-section difference

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

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:

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

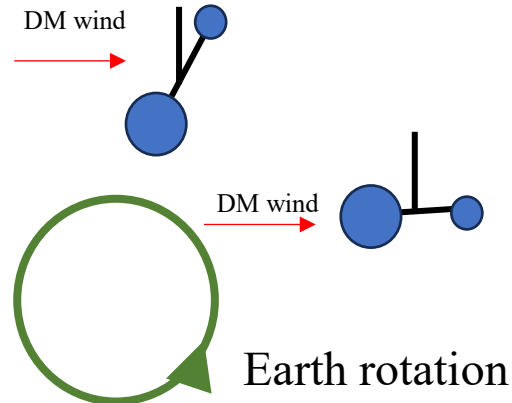
$$\langle a_z \rangle = \frac{1}{m_{\text{tot}}} \frac{\rho_\chi}{m_\chi} \int d^3 \mathbf{v}_\chi d\Omega'_\chi q_z |\mathbf{v}_\chi| f(\mathbf{v}_\chi) \frac{d\sigma_{\text{tot}}(\mathbf{q})}{d\Omega'_\chi}.$$

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

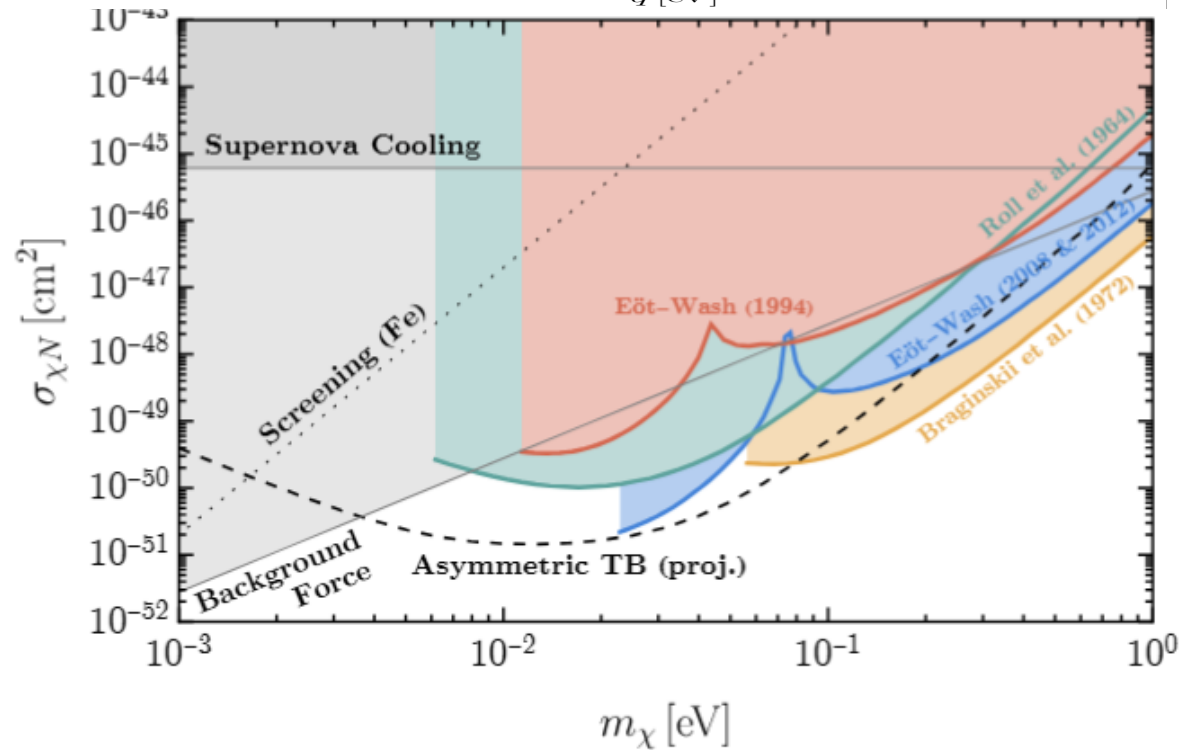
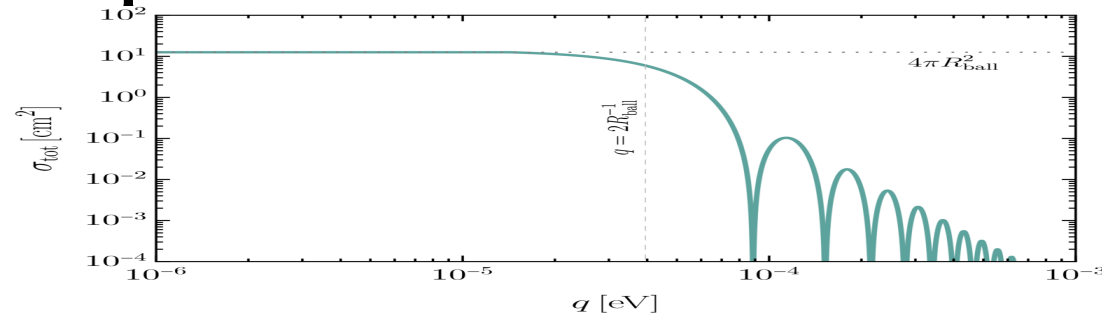
Sensitivity:

DM signal frequency =
TB rotating frequency

Sensitivity of WEP
testing can be directly
used here in this case.



Limits: **signal < sensitivity**

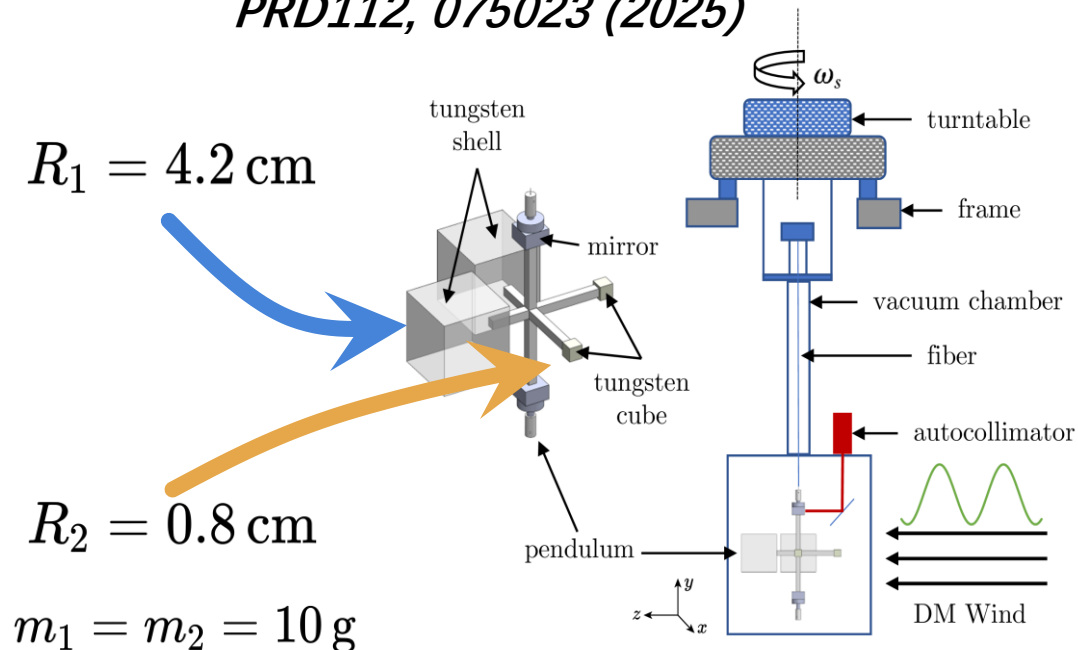


A reminder: $q \sim p_\chi \sim m_\chi v_\chi \sim 10^{-3} m_\chi$

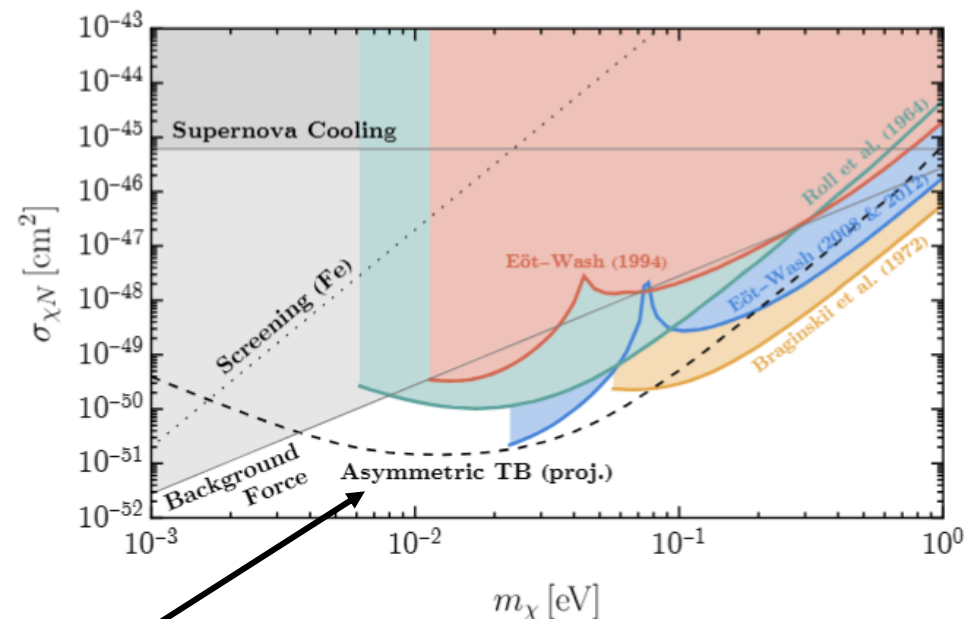
PRL136, 121803 (2026)

A new proposal

PRD112, 075023 (2025)



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

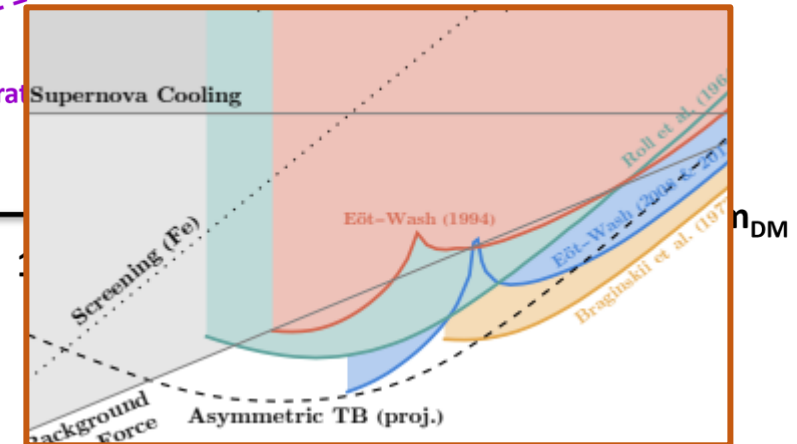
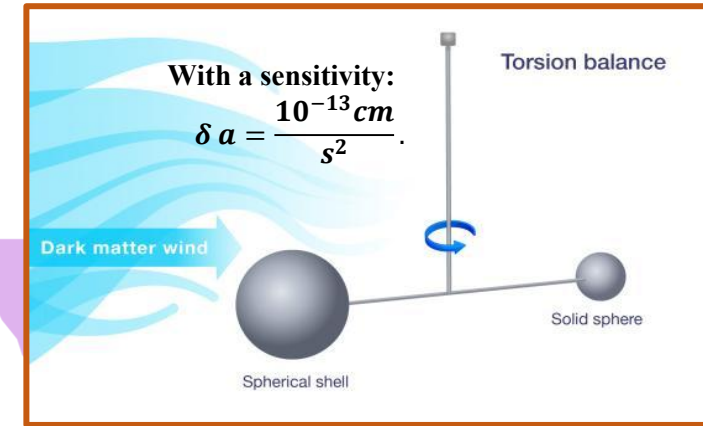
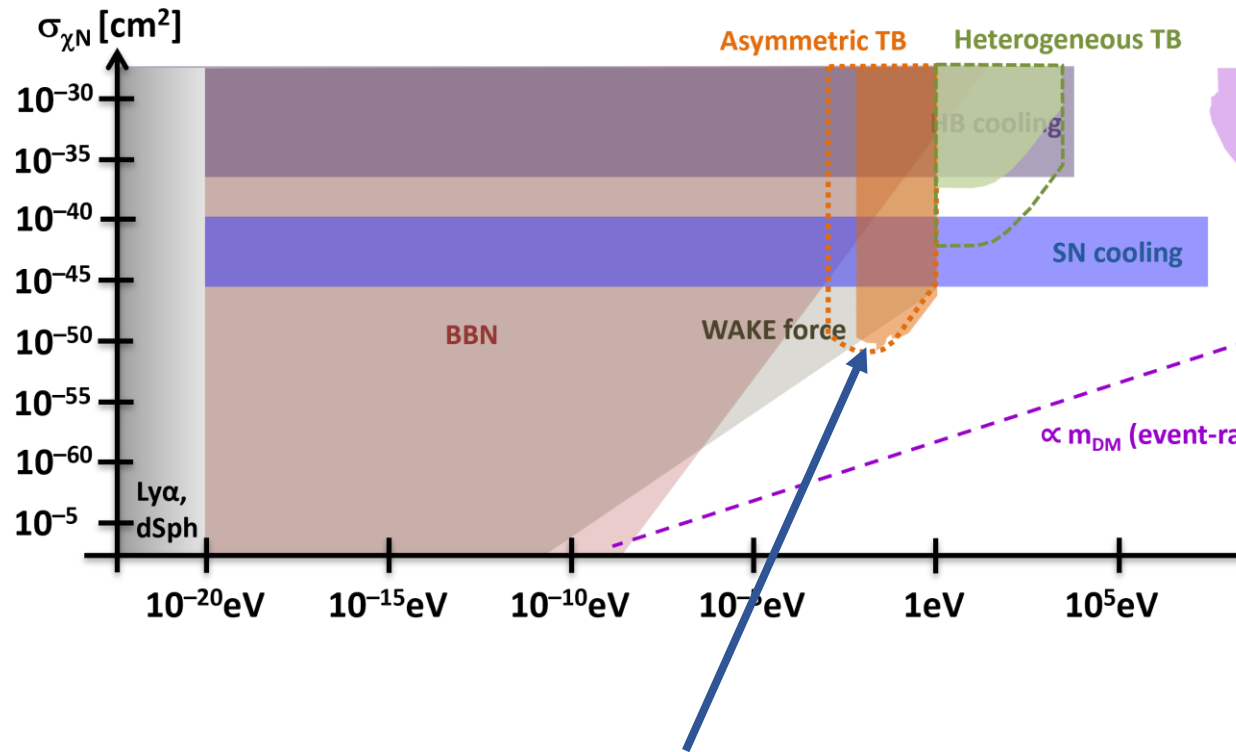


Expected to be completed around 2027.05 by HUST

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

Thank you!