

Weak-Equivalence-Principle Tests as Detectors for Coherent Dark Matter Scattering

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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);***

*Z. H. Liu, S. Matsumoto, J. S., C. Y. Xing, **arXiv:2512.16451.***

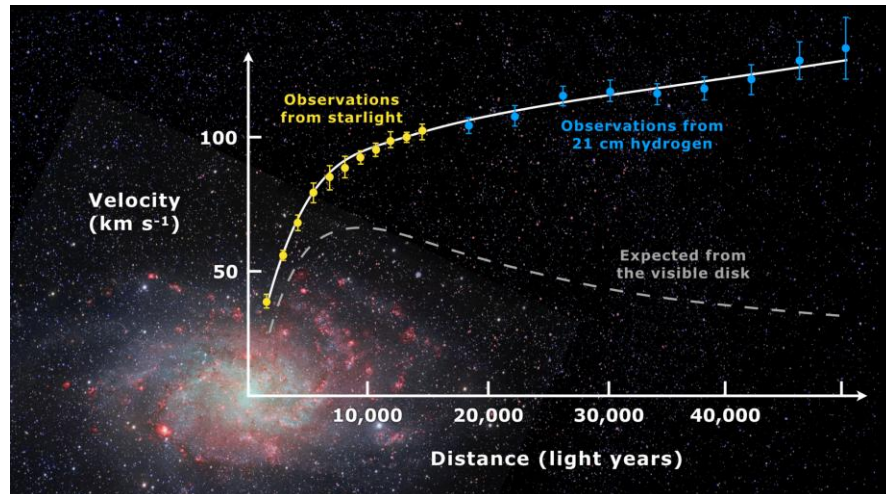
Outline

1. Introduction and targets
2. Coherent-scattering-induced acceleration as an observable
3. Torsion-balance probe of sub-eV DM
4. Random material for sub-keV DM
5. Conclusion and discussion

Introduction to DM

Existence:

wikipedia

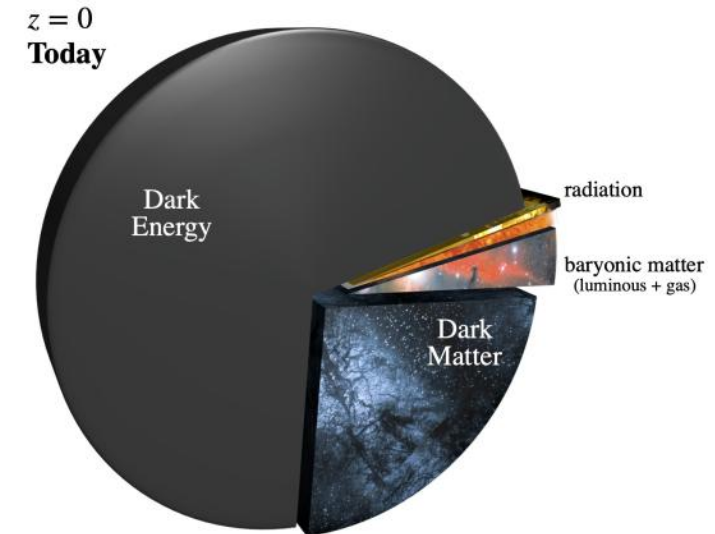


$$m \frac{v_{\text{circ}}^2(r)}{r} = \frac{G m \mathcal{M}(r)}{r^2} \Rightarrow v_{\text{circ}}(r) = \sqrt{\frac{G \mathcal{M}(r)}{r}}.$$

Many astronomical and cosmological observations have proved the existence of dark matter (DM).

Amount:

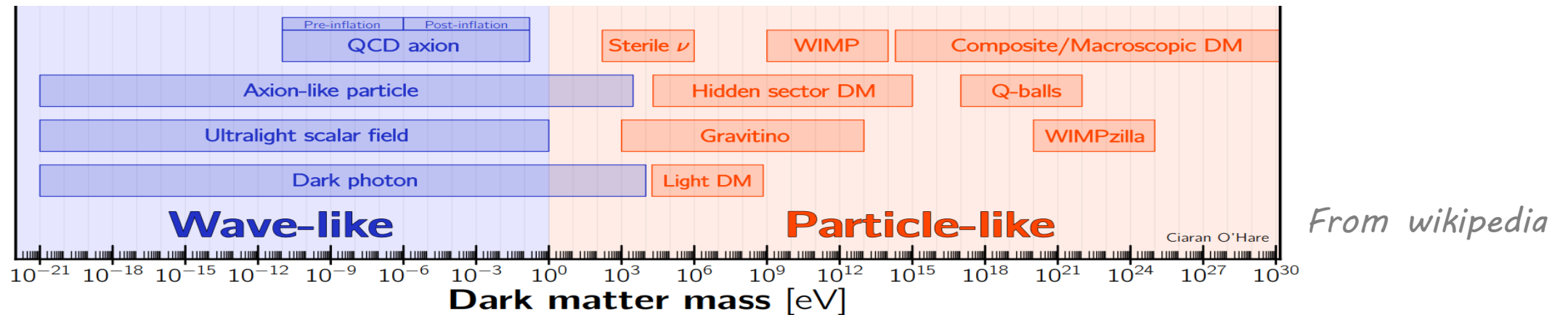
[arXiv:2406.01705]



CMB reveals that DM constitutes approximately 27% of the total energy of the universe (6 times of that of baryon).

Introduction to DM

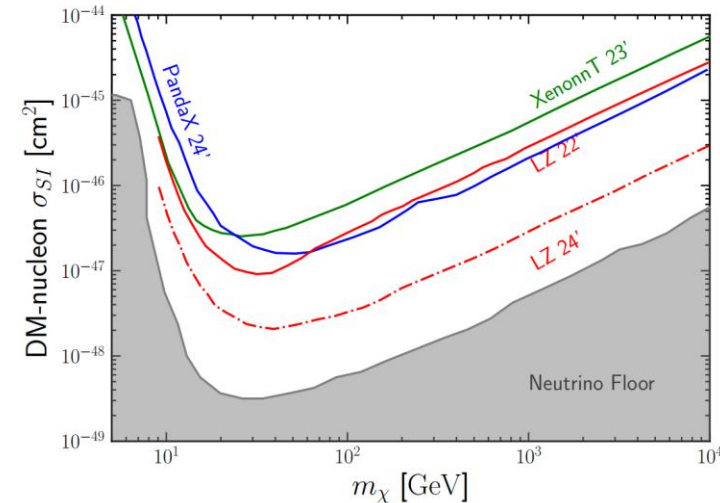
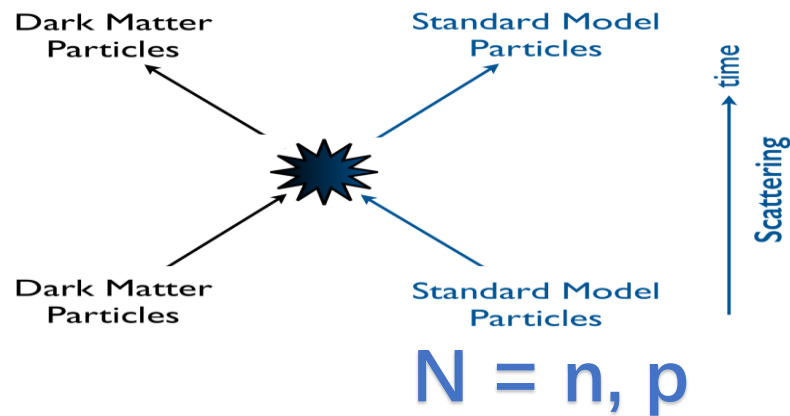
- We know that more than 80 percent of the matter in our Universe today is dark matter (DM) from astro and cosmic observations.
- Answering “**what dark matter is**” has become one of the most important questions in physics.



- **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

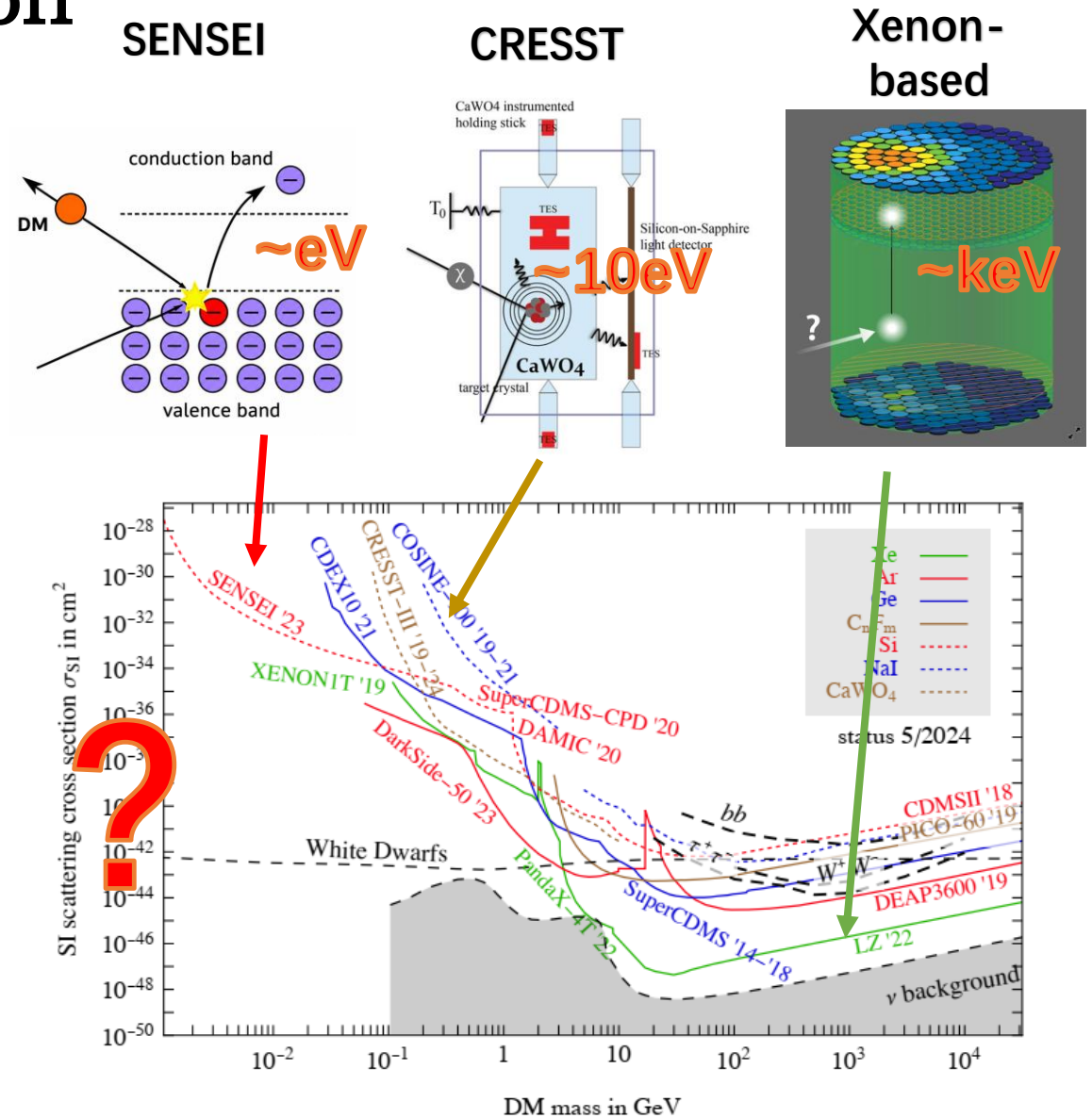
- Detection of DM in laboratory is the so called “**Direct Detection**” based on **DM-SM particle Scattering**.
- Goodman & Witten proposed DM-Heavy nuclei scattering for WIMP DM [**Tone-scale Xenon experiments**].



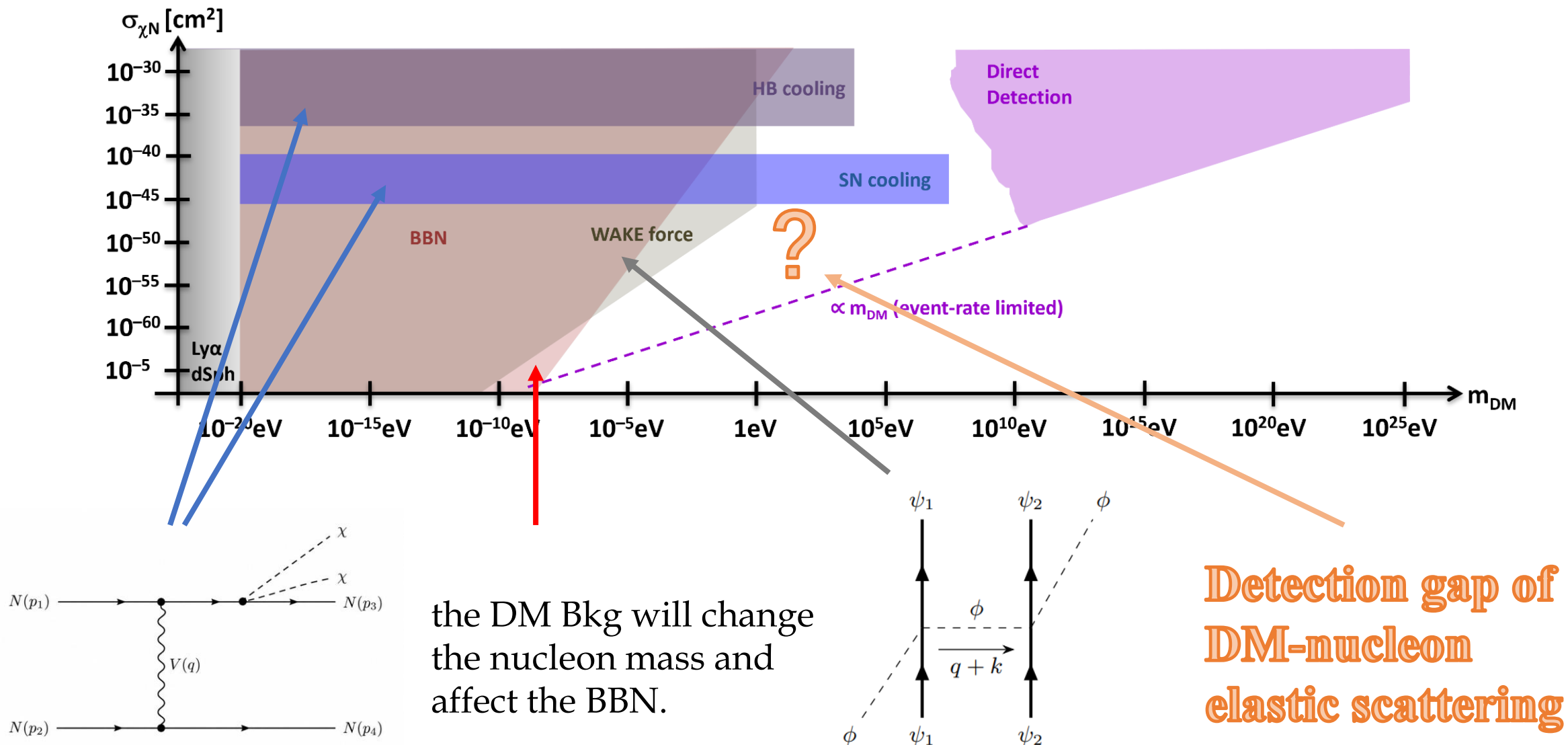
- Currently, **DM-nucleon/nuclei elastic scattering**, $\chi + N \rightarrow \chi + N$, becomes one of the most general and **benchmark** processes when we talk about direct detection.
- **Quadratical** coupling: $\frac{m_N \chi^2 \bar{N} N}{\Lambda^2}$ [scalar] or $\frac{\bar{\chi} \chi \bar{N} N}{\Lambda^2}$ [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.
- $T_\chi \sim 10^{-6} m_\chi (1\text{MeV}) > \Delta E (1\text{eV})$
- **The detection of lighter [sub-MeV] DM is still an experimental challenge!**

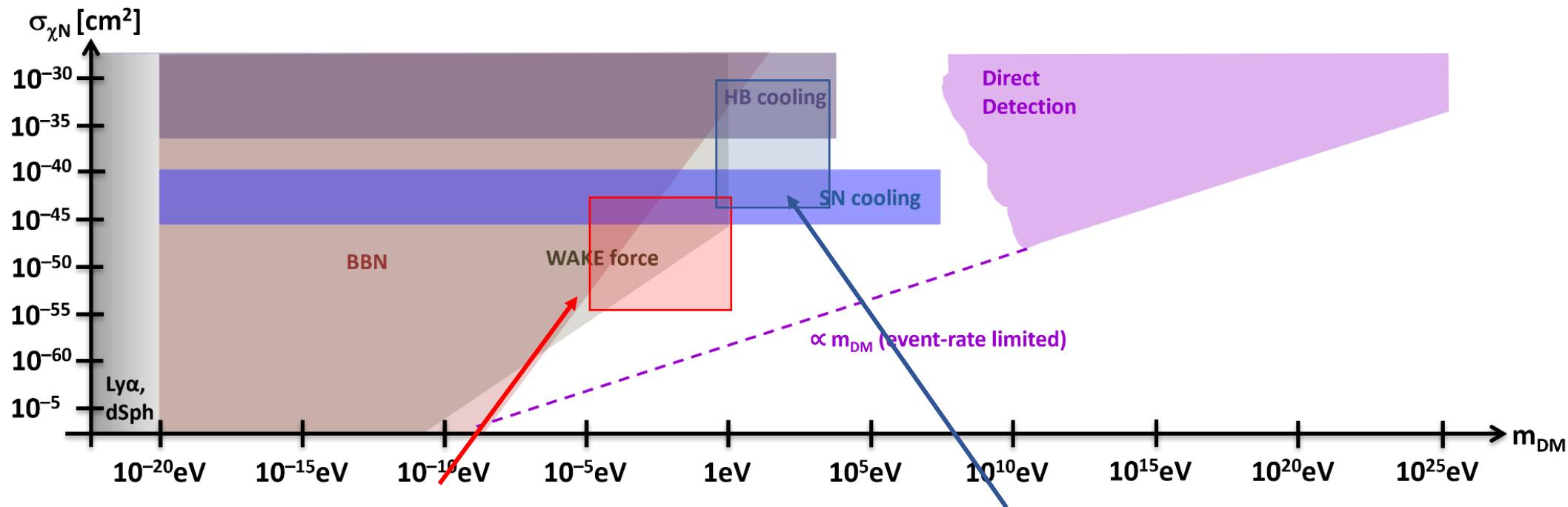


Summarizes of DM-nuclei SI cross section limits



Our Target

We want to propose a new detecting mechanism for light DM



I. Place stronger direct-detection limits on sub-eV DM–nucleon elastic scattering.

II. Direct detection of keV-scale DM–nucleon elastic scattering.

Outline

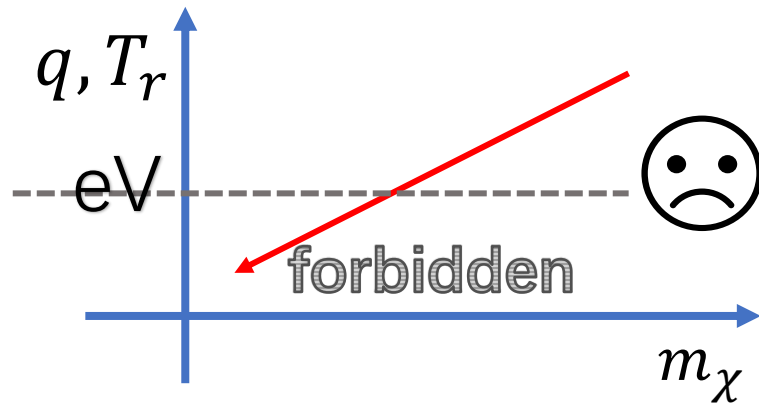
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Merits of lighter DM

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

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

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



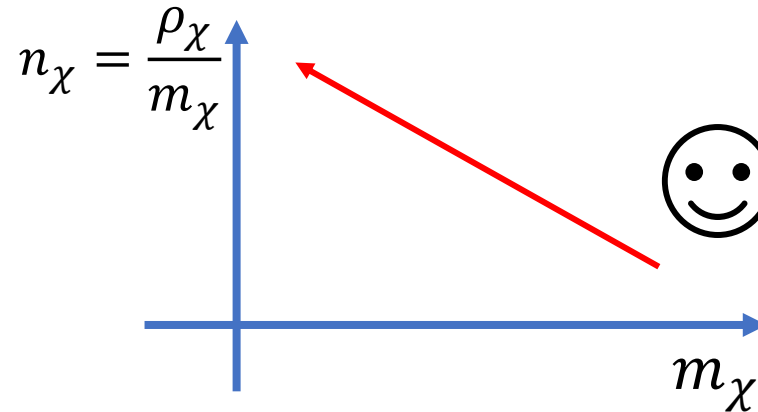
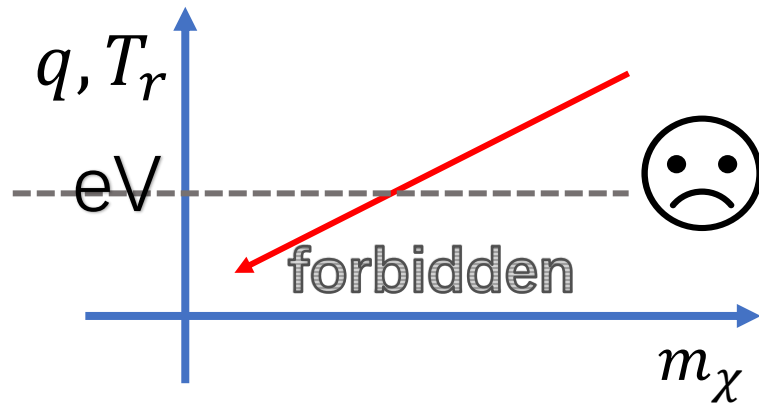
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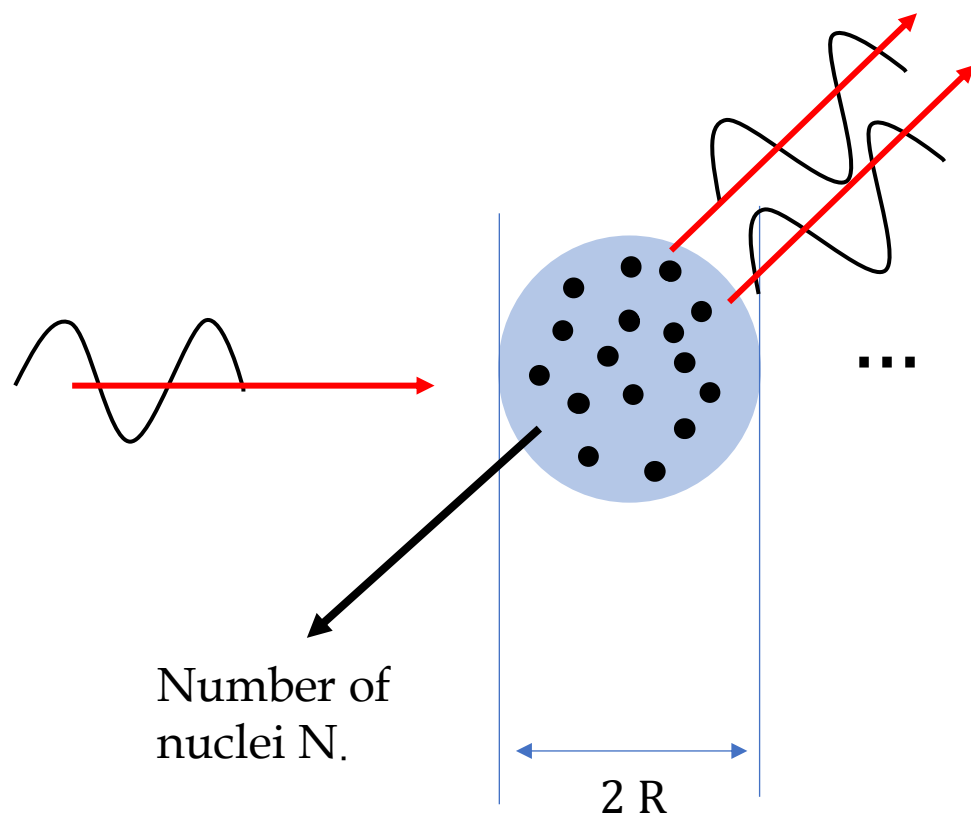
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What, then, are its merits?

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

Coherent scattering enhancement



- Light DM have a relative long de Broglie wavelength:

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

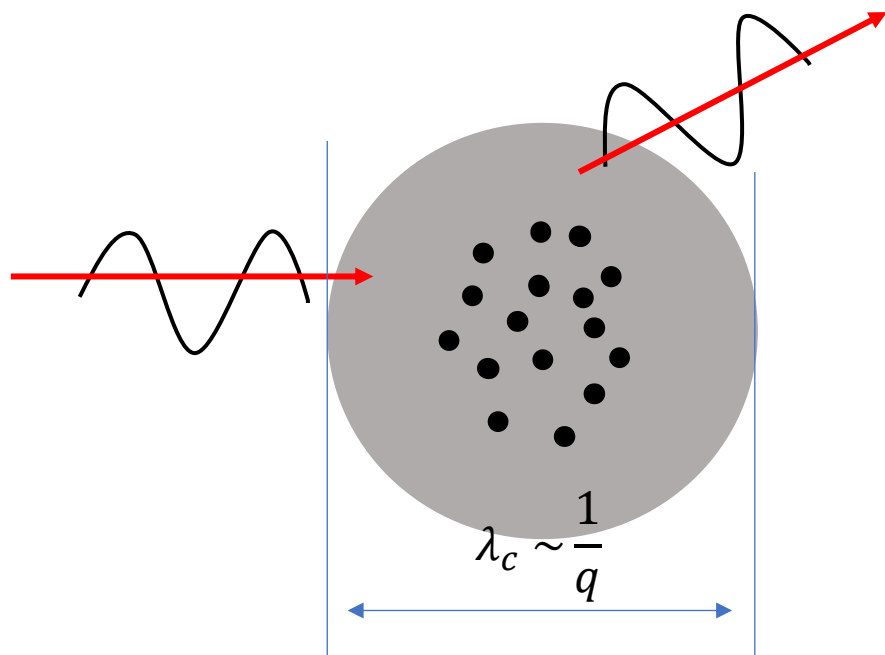
- $0.01\text{eV DM} \sim 1\text{cm}$
- Coherent Scattering: If the DM wavelength is larger than the size of the target, the scattering cross section is enhanced by N^2 .**

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

- This N^2 coherent factor is verified by neutrino-nuclei 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]

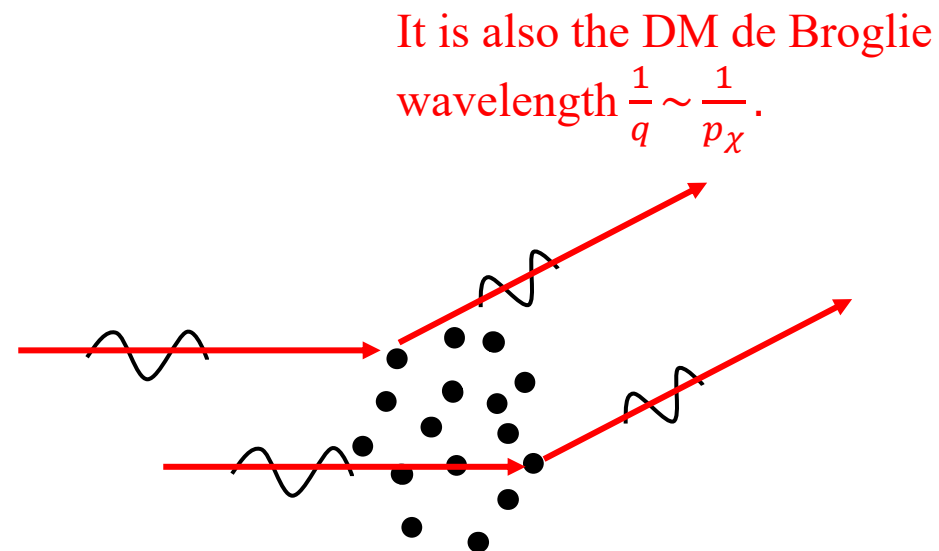
Intuitive picture of coherent scattering

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



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

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

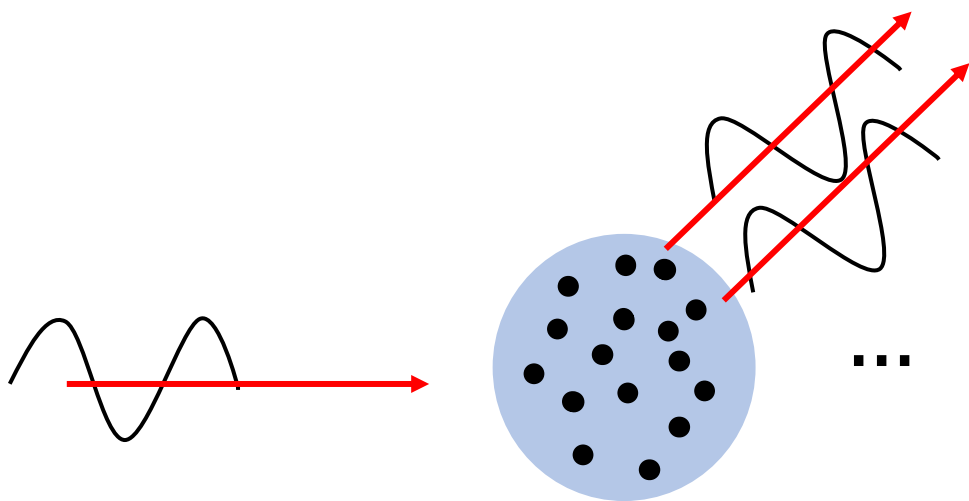


2) Large- q limit ($qR \gg 1$) $P_{tot} = \sum |A_i|^2$

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

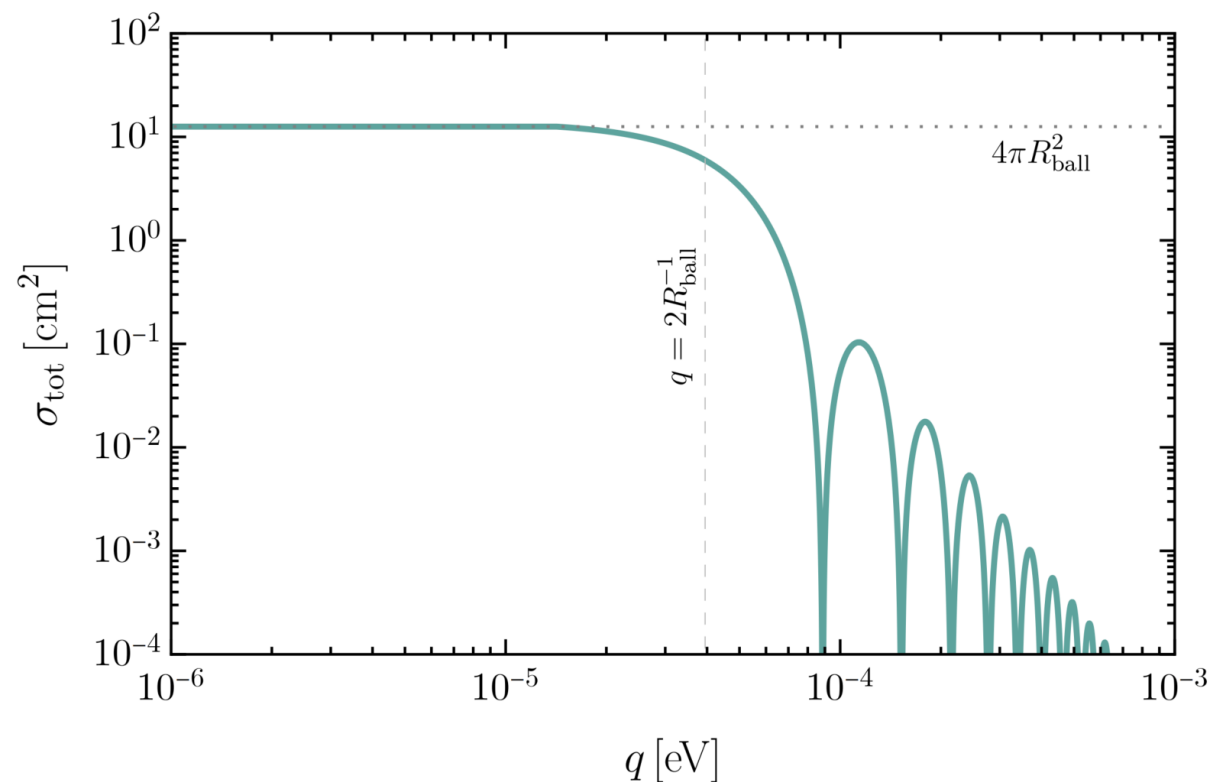
Form factor description of coherent scattering

- If we receive the outgoing wave at infinite far with momentum transfer q , initial and final momentum fixed, the only difference of these waves is the **phase factor** e^{iqr_j} .
- At the amplitude level, $Amp \rightarrow Amp \sum e^{iqr_i}$.
- At the cross section level, $\sigma_{tot} = \sigma_{\chi N} \sum_{ij} e^{iq\Delta r_{ij}}$.

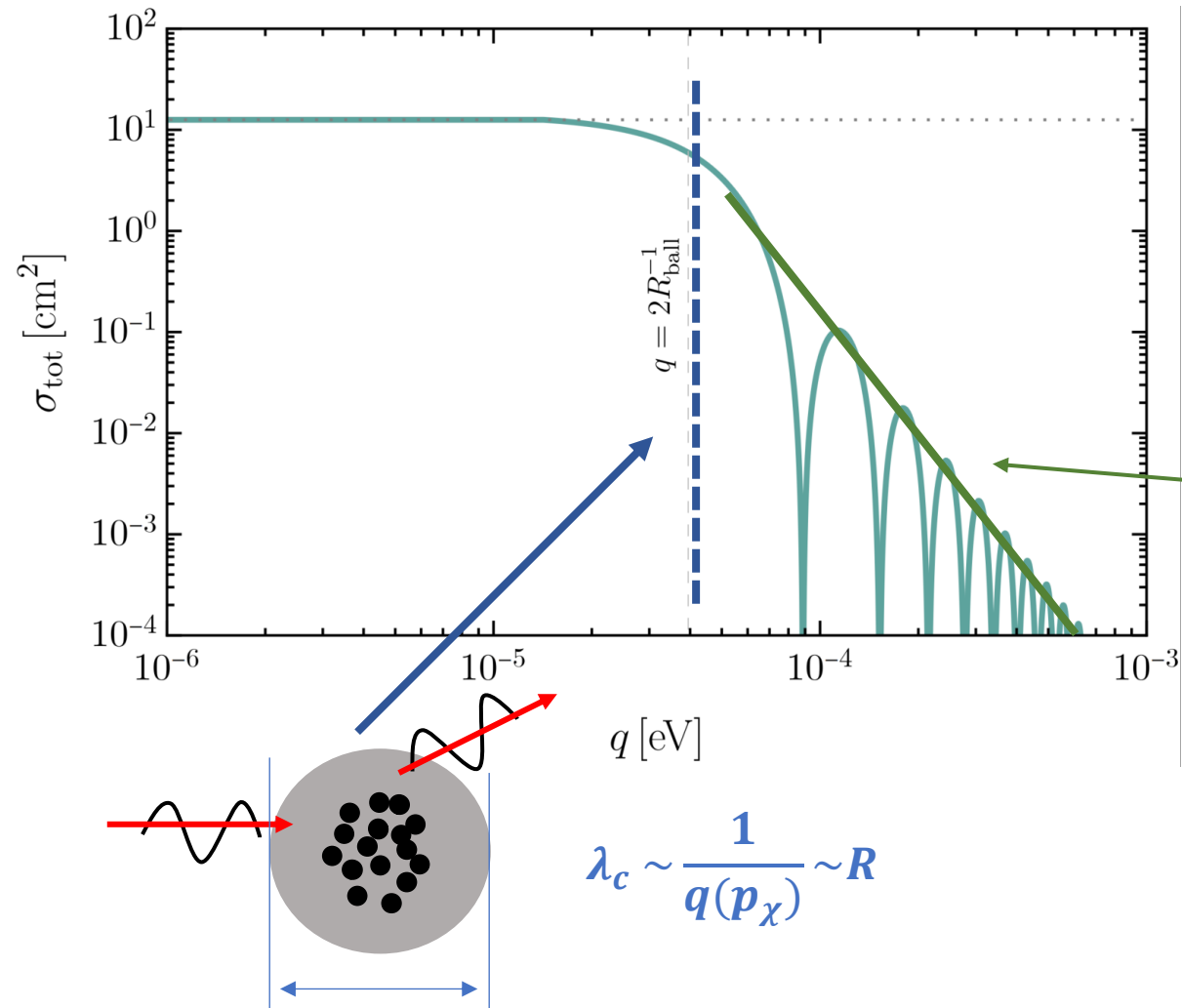


$$\sigma_{tot} \simeq N^2 |F(q)|^2 \sigma_{\chi N} \quad |F(\mathbf{q})|^2 = \frac{1}{V^2} \int d^3\mathbf{r}_i d^3\mathbf{r}_j e^{i\mathbf{q} \cdot \Delta \mathbf{r}_{ij}}.$$

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



Form factor description of coherent scattering



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

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.....

Demerit:

The momentum/energy transfer is highly suppressed



~~Observable: Single scattering event beyond the detection threshold~~

Merits:

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

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

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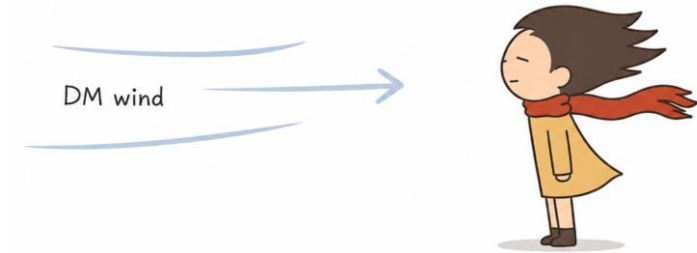
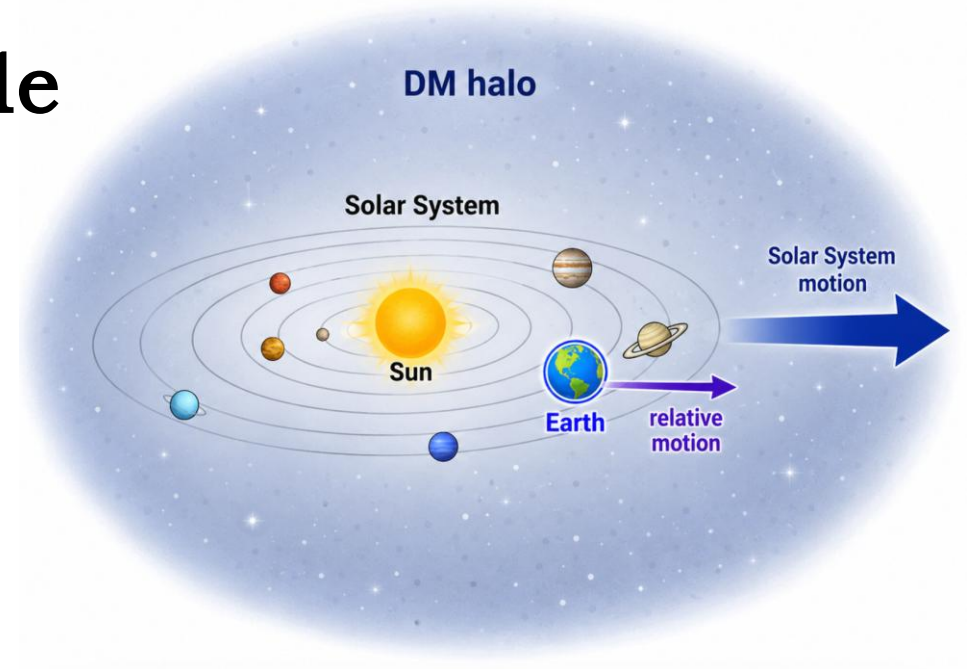
Observable: Some collective effects enhanced by the scattering rate

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

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.



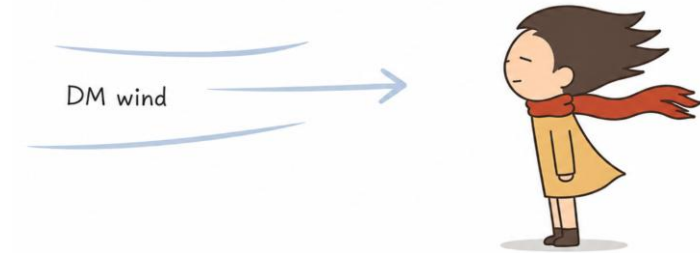
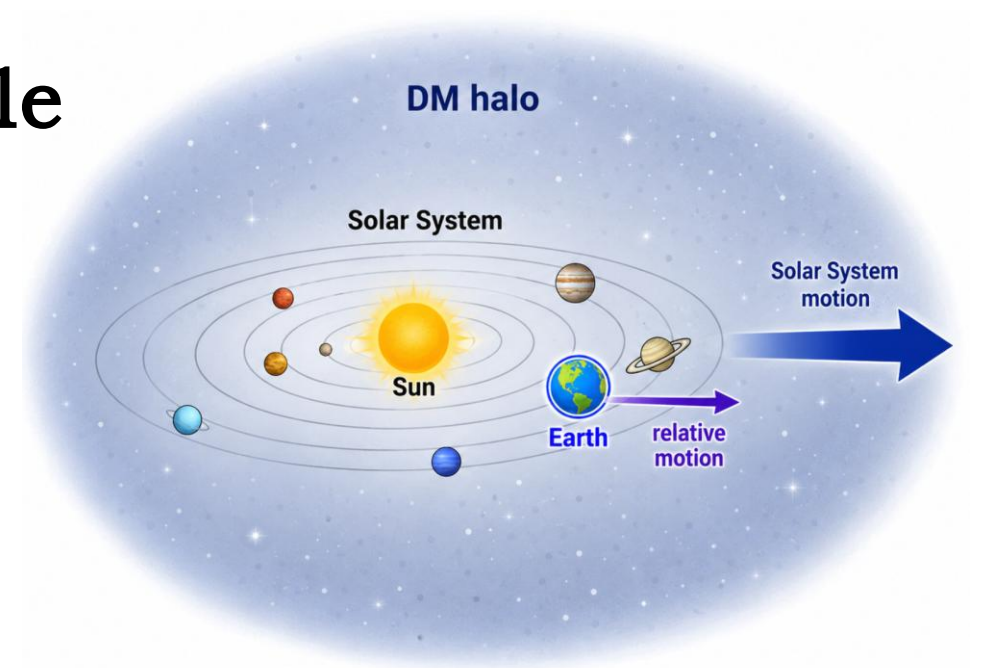
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$$F = n_{\chi} \sigma_{tot} v q = \frac{\rho_{\chi}}{m_{\chi}} \sigma_{tot} v_{\chi} m_{\chi} v_{\chi} = \rho_{\chi} \sigma_{tot} v_{\chi}^2.$$

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

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!

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

$$N = 10^{24}$$

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

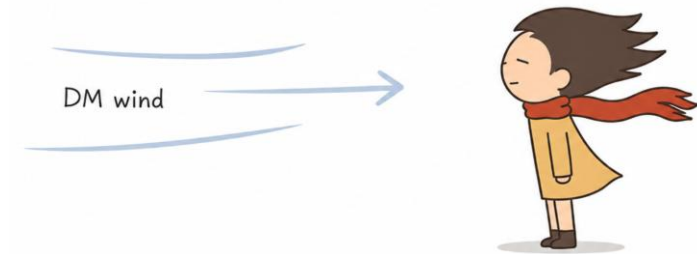
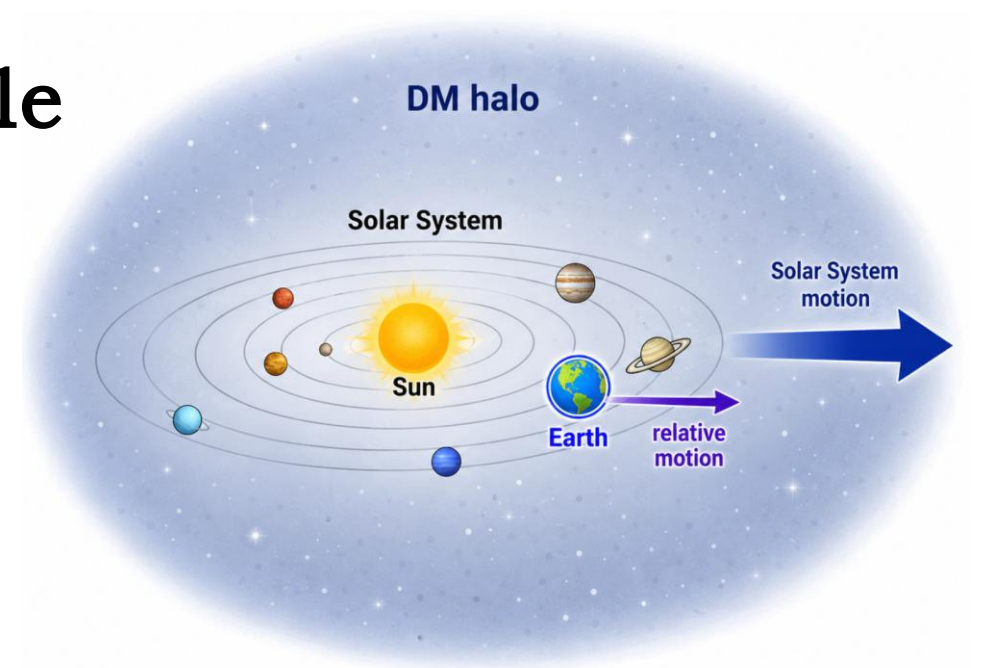
$$v_{\chi}^2 = 10^{-6}$$

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



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

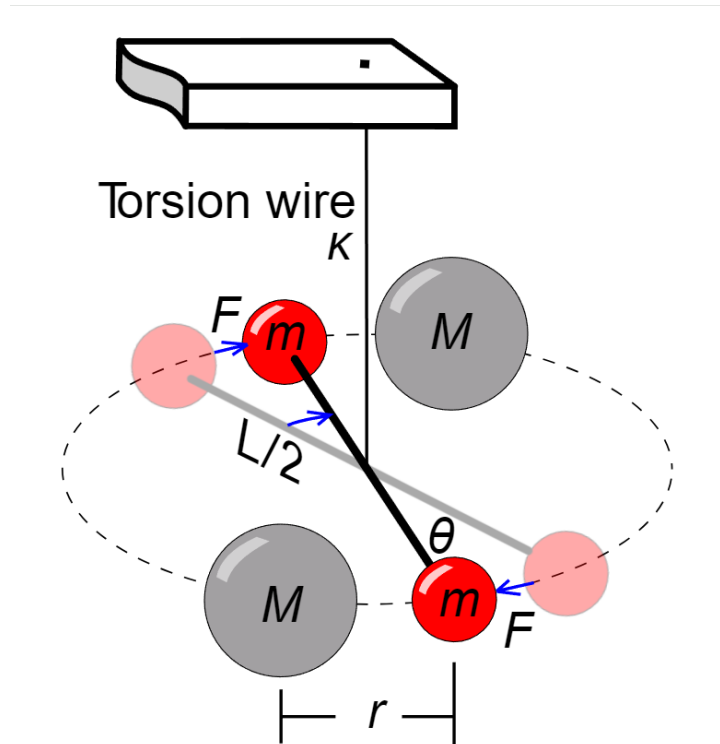
Not bad!



Outline

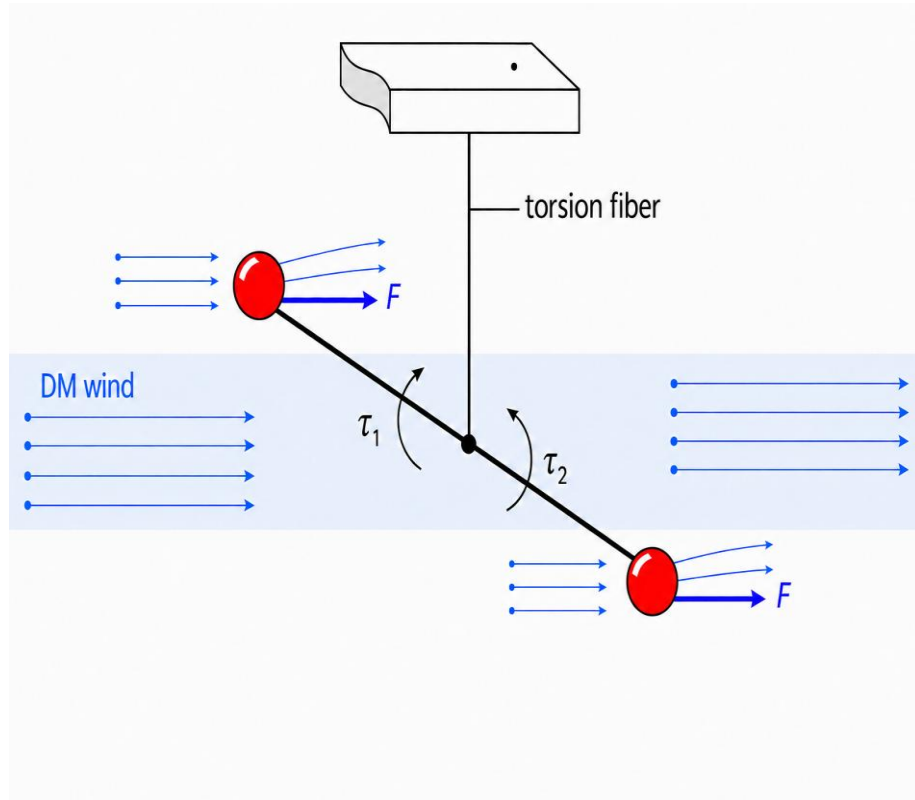
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How to detect such a small acceleration?



- 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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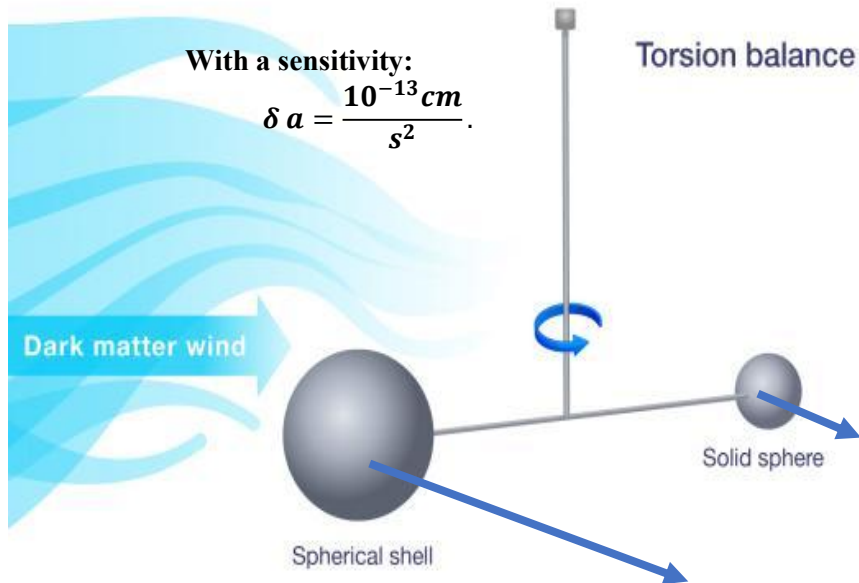


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- However, the usual **symmetric** torsion balance with **same masses and same sizes** does not work.

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

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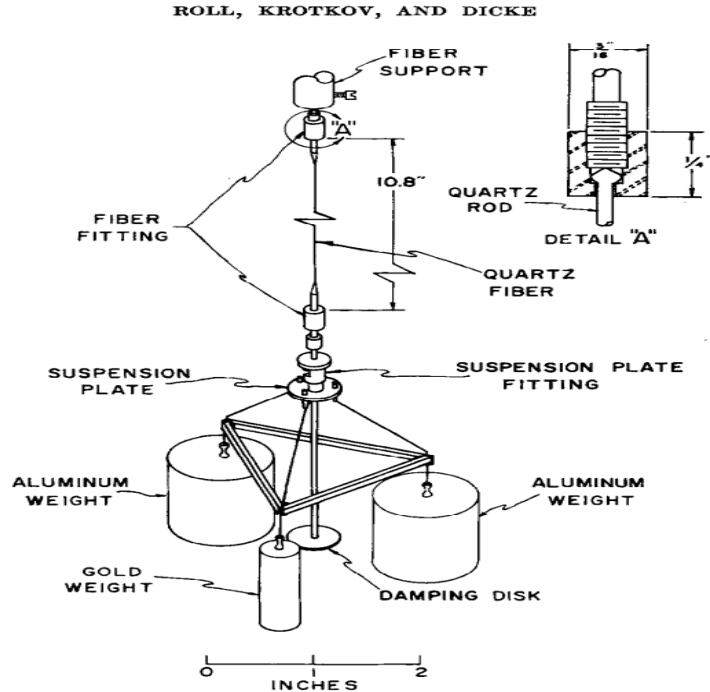
$$\Delta a = \frac{\rho_\chi \Delta \sigma_{tot} v_\chi^2}{m_{target}} \neq 0$$

- **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:

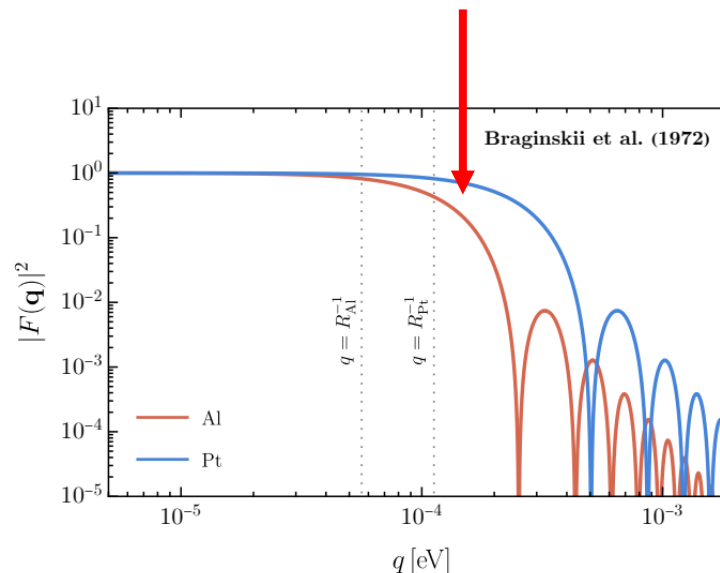
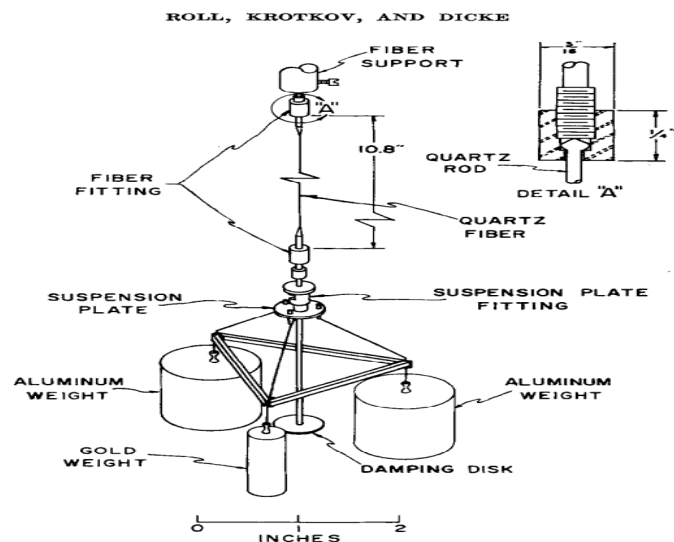
- I. Same outer-size but different inner structures
- II. Self-rotation[mHz] with a mHz frequency

Higher sensitivity

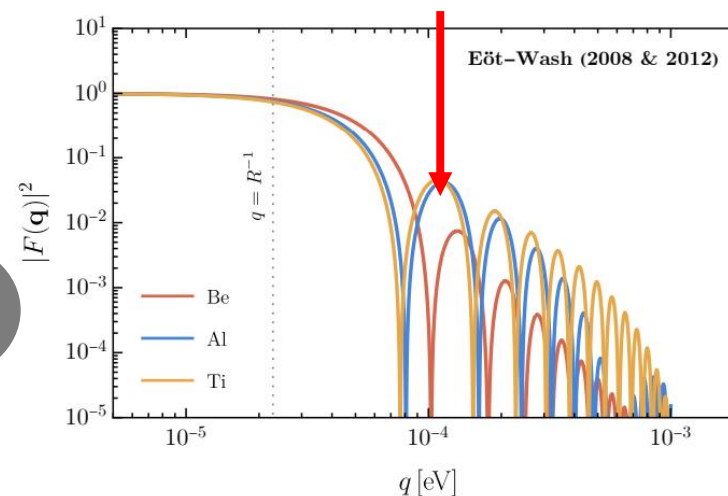
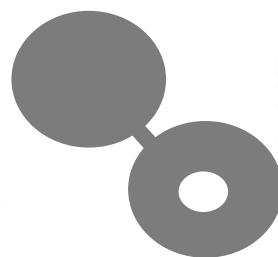
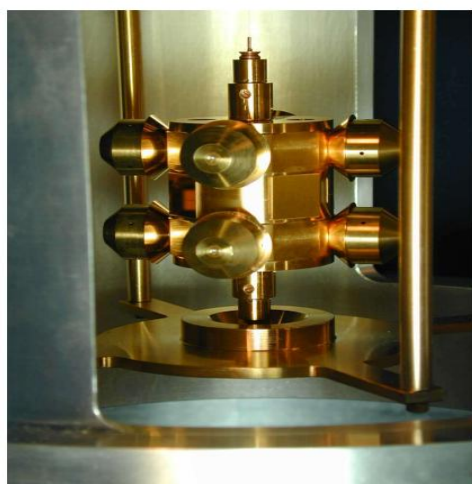
Cross-section difference

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

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:

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

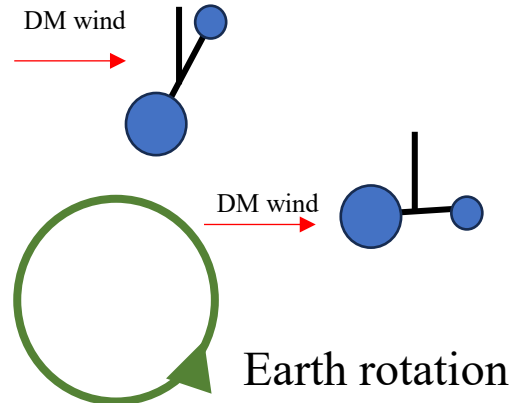
$$\langle a_z \rangle = \frac{1}{m_{\text{tot}}} \frac{\rho_\chi}{m_\chi} \int d^3 \mathbf{v}_\chi d\Omega'_\chi q_z |\mathbf{v}_\chi| f(\mathbf{v}_\chi) \frac{d\sigma_{\text{tot}}(\mathbf{q})}{d\Omega'_\chi}.$$

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

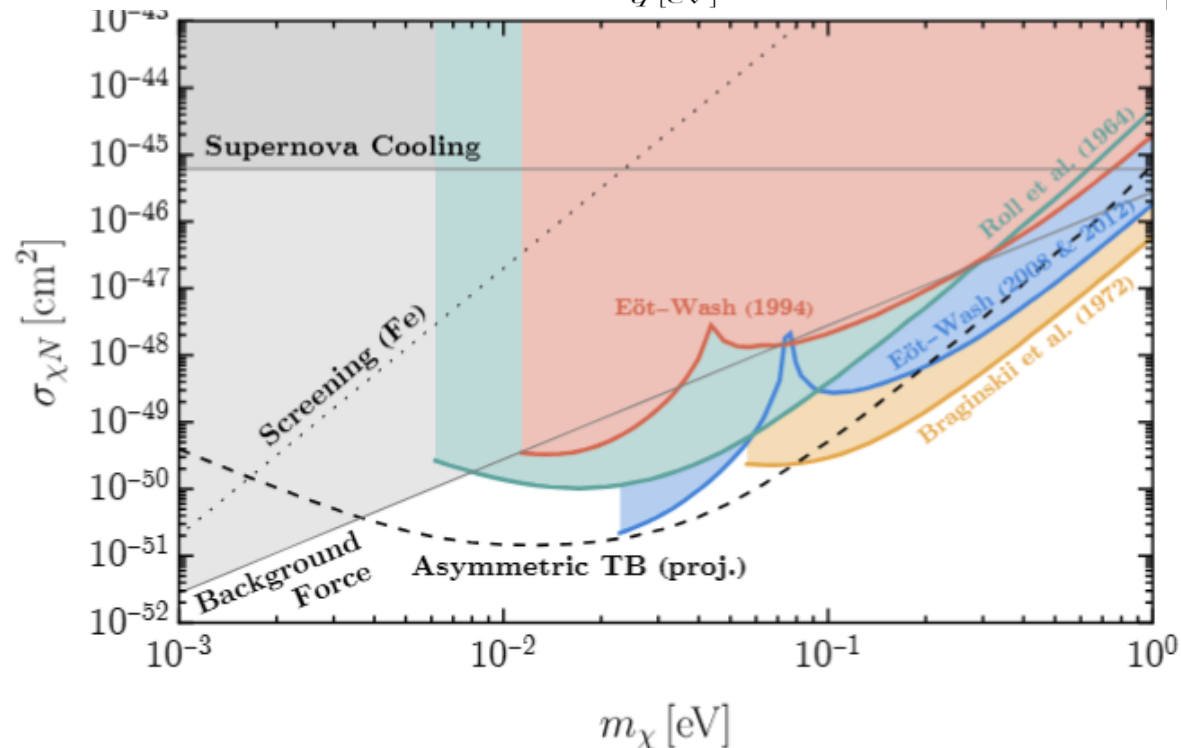
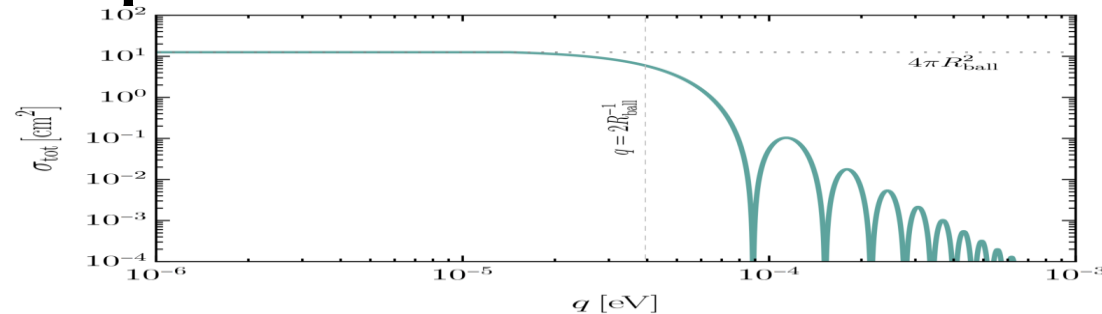
Sensitivity:

DM signal frequency =
TB rotating frequency

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



Limits: **signal < sensitivity**

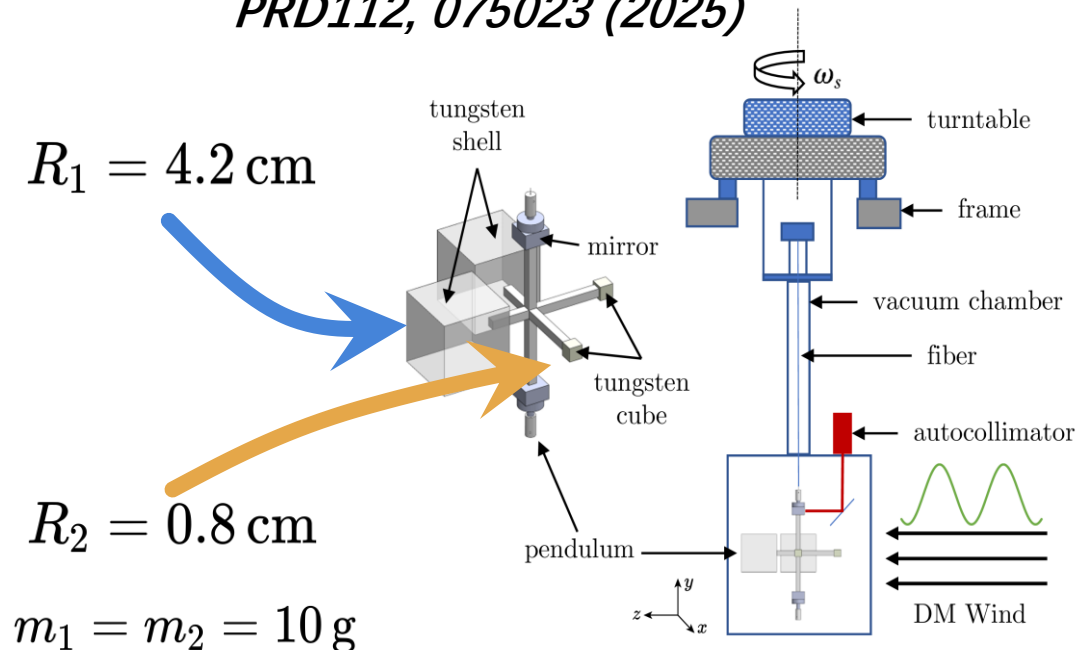


A reminder: $q \sim p_\chi \sim m_\chi v_\chi \sim 10^{-3} m_\chi$

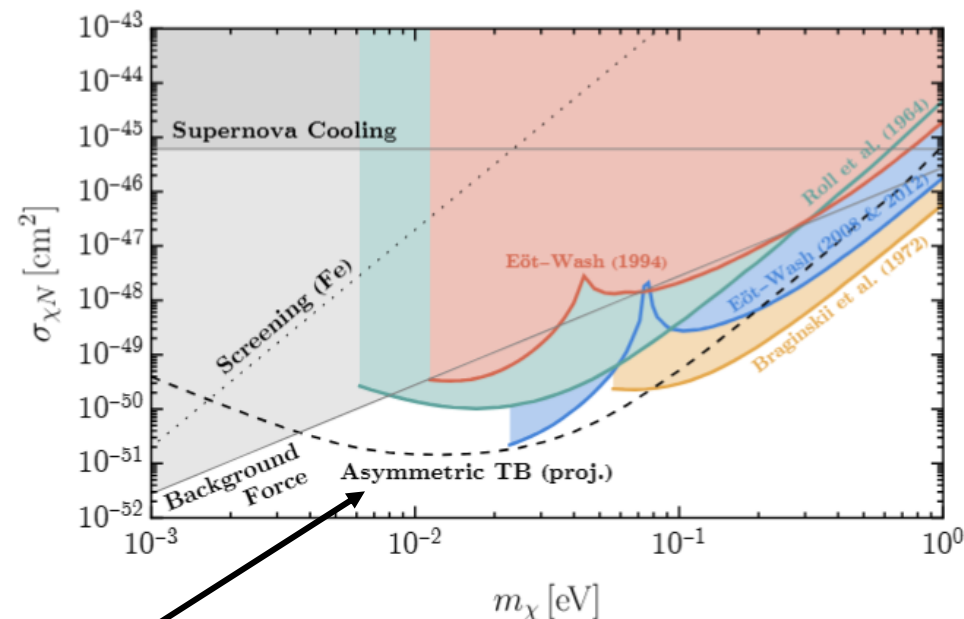
PRL136, 121803 (2026)

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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What we are not satisfied...

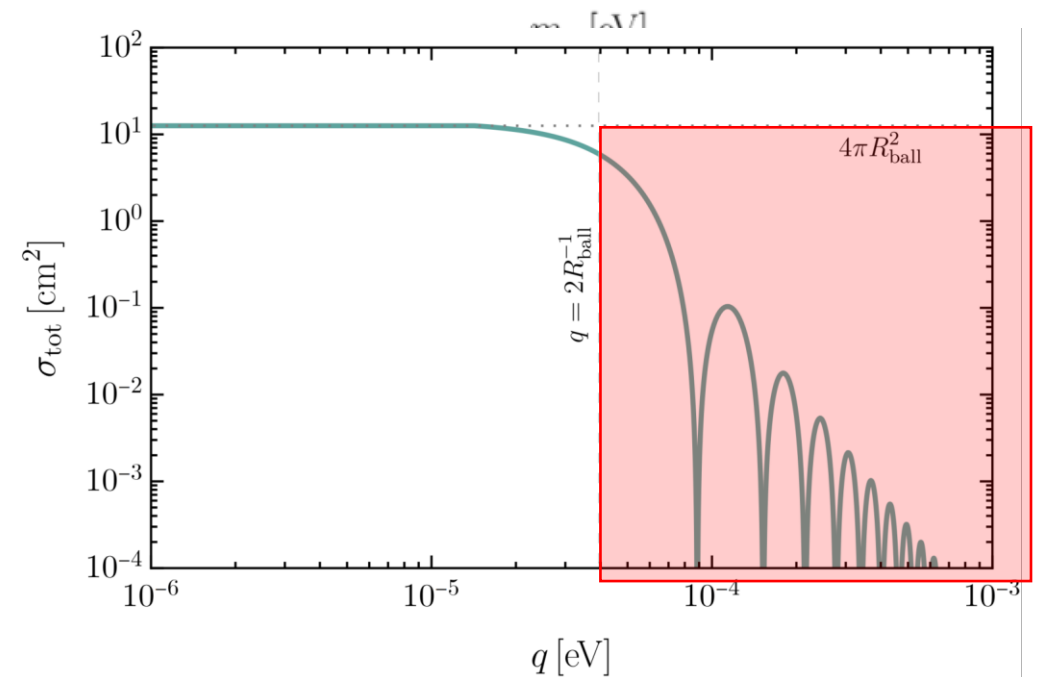
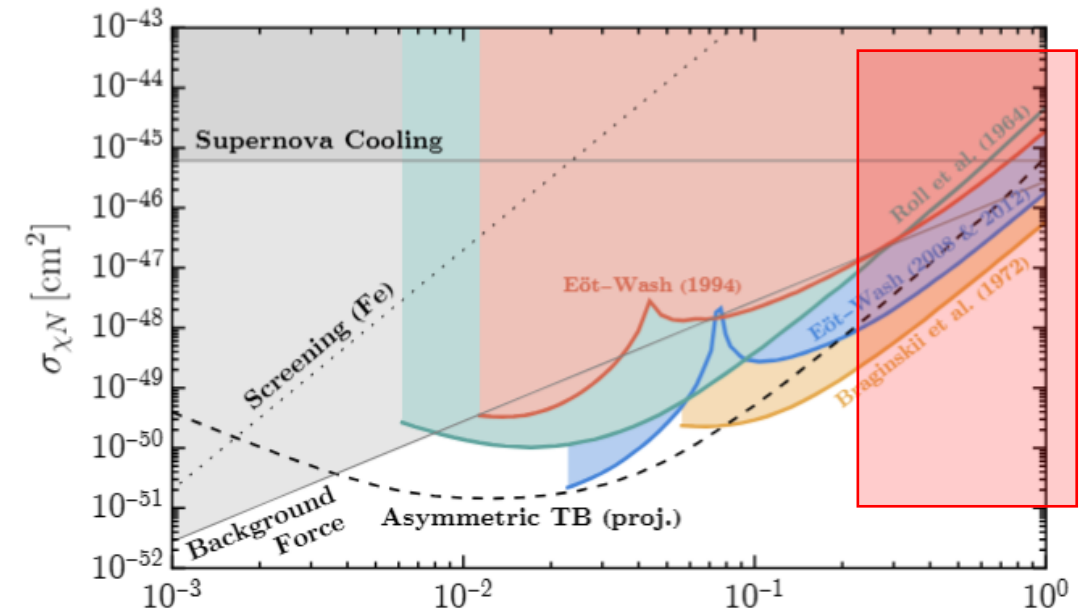
$$\sigma_{tot} \simeq N^2 F(q)^2 \sigma_{\chi N}$$

For a sphere:

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

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

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



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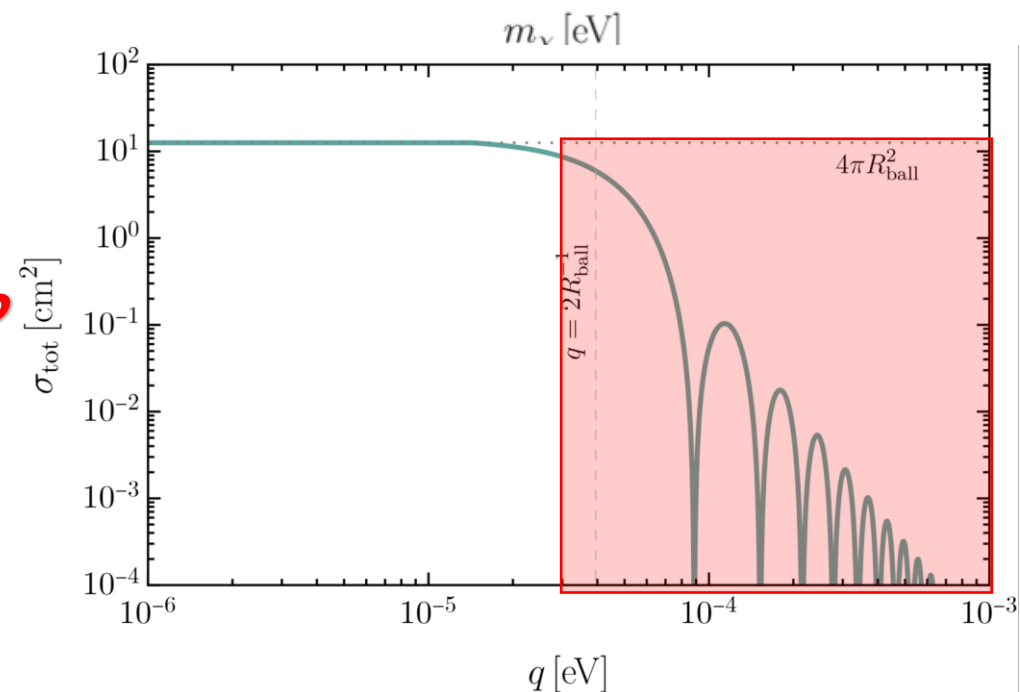
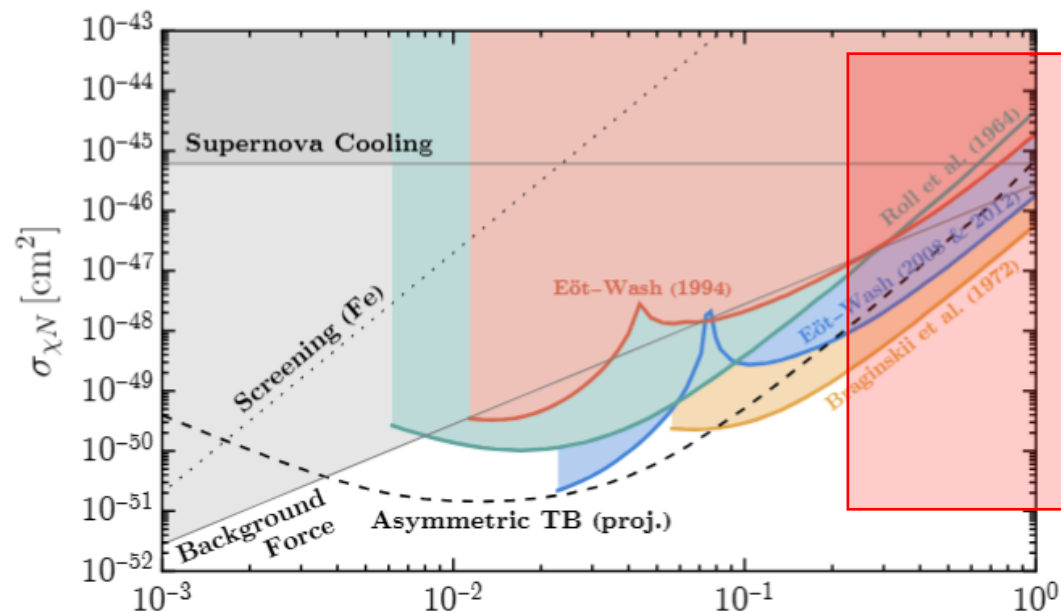
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Is it possible to enhance sensitivity?

Our intuition is that it can, which motivates the following thought experiment.



A scaling estimation

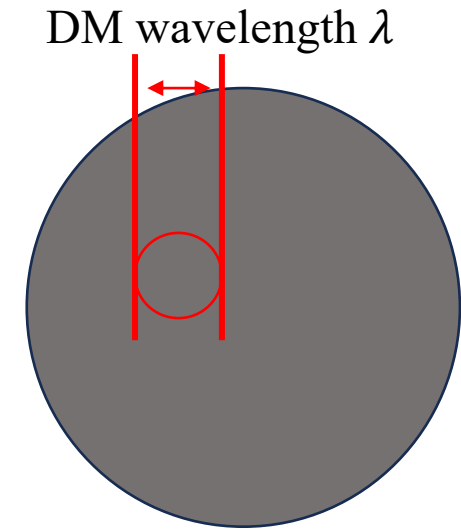
$$\sigma_{tot} \simeq N^2 F^2 \sigma_{\chi N}, [N = n * V]$$

Case I: large sphere with radius $R > \lambda \sim \frac{1}{q}$

$$N = n * V \sim n * R^3$$

2) Large- q limit ($qR \gg 1$) $F_S(q) \simeq -\frac{3 \cos(qR)}{(qR)^2} \rightarrow F_S \sim \left(\frac{\lambda}{R}\right)^2$

$$\sigma_{tot} \sim (nR^3)^2 \left[\left(\frac{\lambda}{R}\right)^2 \right]^2 \sigma_{\chi N} = n^2 R^6 \left(\frac{\lambda}{R}\right)^4 \sigma_{\chi N} \sim n^2 R^2 \lambda^4 \sigma_{\chi N}$$



A scaling estimation

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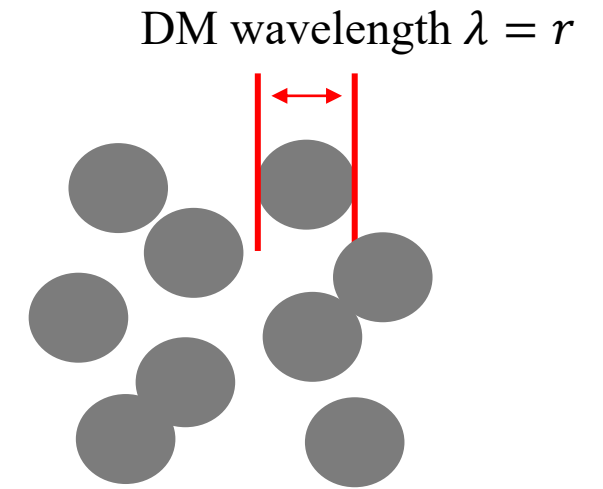
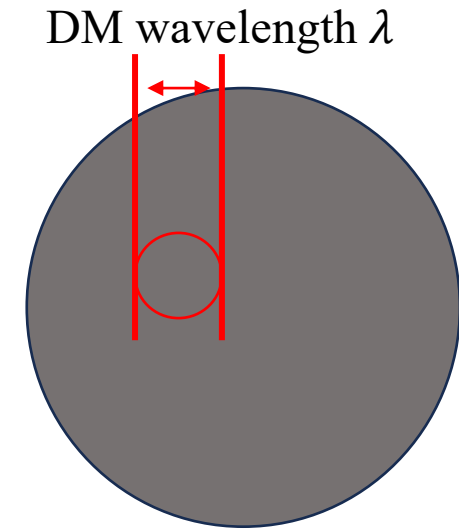
$$\sigma_{tot} \sim n^2 R^6 \left(\frac{\lambda}{R}\right)^4 \sigma_{\chi N} \sim n^2 R^2 \lambda^4 \sigma_{\chi N}$$

Case II: small spheres with radius $r = \lambda \sim \frac{1}{q}$

$$\sigma_s \sim (n \lambda^3)^2 \sigma_{\chi N} = n^2 \lambda^6 \sigma_{\chi N}$$

How many spheres: $N_s = \left(\frac{R}{\lambda}\right)^3$

$$\sigma'_{tot} \sim N_s \sigma_s = \left(\frac{R}{\lambda}\right)^3 n^2 \lambda^6 \sigma_{\chi N} = n^2 R^3 \lambda^3 \sigma_{\chi N}$$



A scaling estimation

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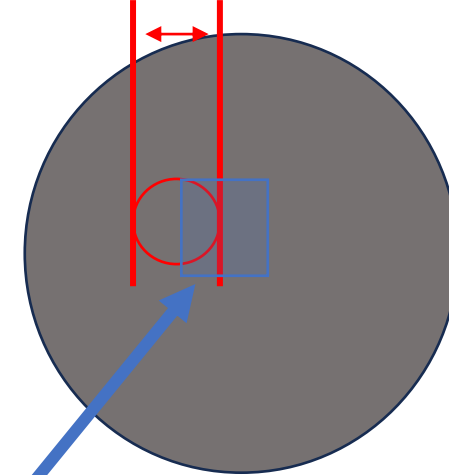
$$\sigma'_{tot} \sim N_s \sigma_s = \left(\frac{R}{\lambda}\right)^3 n^2 \lambda^6 \sigma_{\chi N} = n^2 R^3 \lambda^3 \sigma_{\chi N}$$

$$\frac{\sigma'_{tot}}{\sigma_{tot}} = \frac{R}{\lambda} \gg 1$$

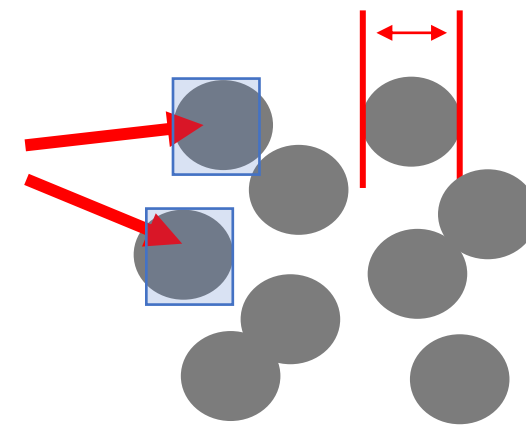
With interference

Independent patches

DM wavelength λ



DM wavelength $\lambda = r$

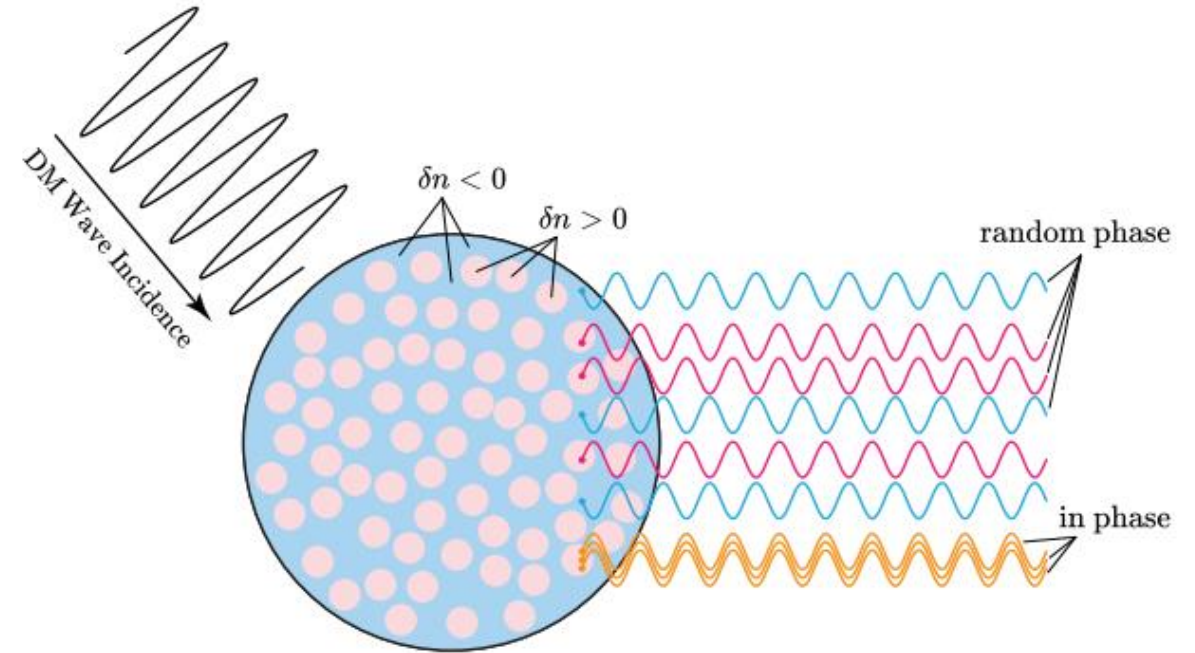


Random, heterogeneous material

For $m_\chi \sim keV, q \sim 1eV, \lambda \sim \mu m$ scale.

From experimental side, it would be difficult to maintain the acceleration sensitivity and keep the size of target so small.

We need some **macro targets with micro fluctuations**, which is **Random, Heterogeneous Materials**



Cross section for random, heterogeneous material

For $q \sim 1\text{eV}, \lambda \sim \mu\text{m}$ scale.

We need some **macro targets with micro fluctuations**, which is **Random, Heterogeneous Materials**

$$\langle \delta n(\mathbf{r}_1) \delta n(\mathbf{r}_2) \rangle = \overline{\delta n^2} e^{-|\mathbf{r}_2 - \mathbf{r}_1|/\xi}$$

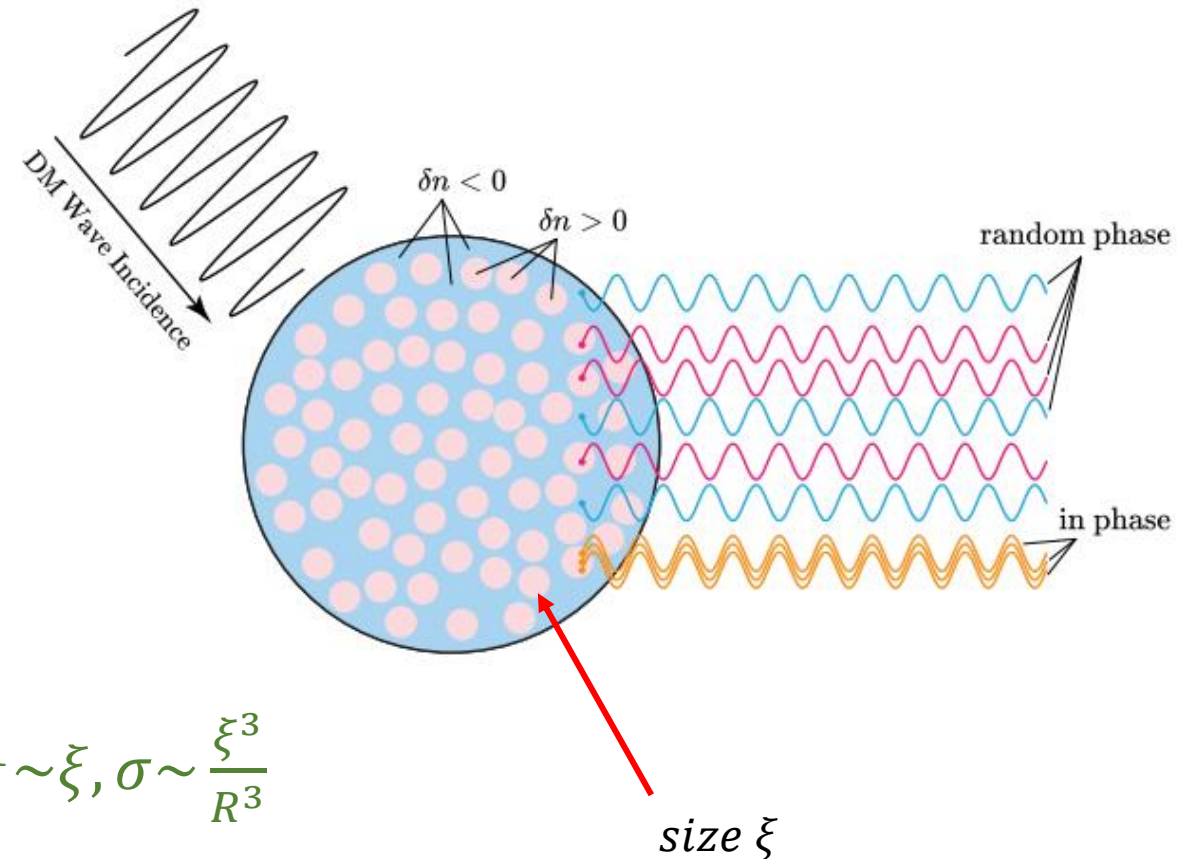
$$\left\langle \frac{d\sigma_{\text{tot}}}{d\Omega} \right\rangle = N_{\text{tot}}^2 |F(\mathbf{q})|^2 \frac{d\sigma_{\chi N}}{d\Omega}.$$

$$|F_{\text{fluc}}(\mathbf{q})|^2 = \frac{\overline{\delta n^2}}{n_0^2} \frac{6\xi^3}{R^3 (1 + q^2 \xi^2)^2}.$$

Density fluctuation

Coherence length

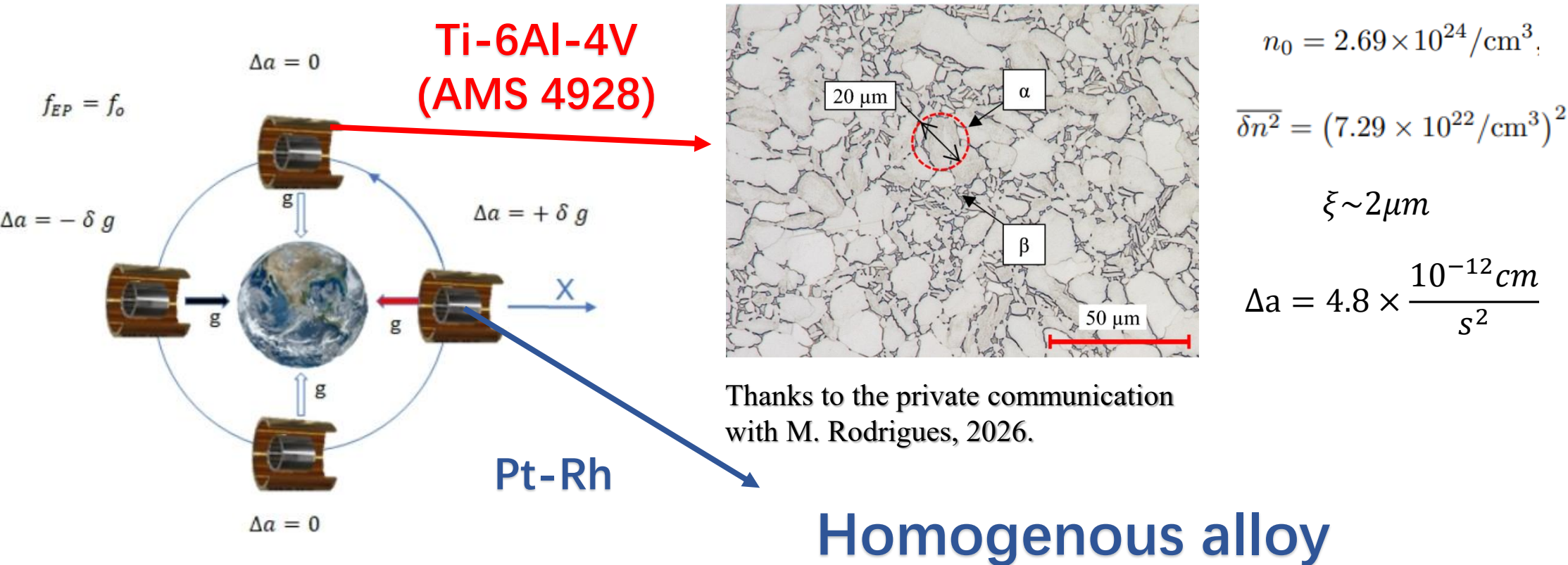
$$\text{If } q^{-1} \sim \xi, \sigma \sim \frac{\xi^3}{R^3}$$



MICROSCOPE, accelerometer made of random materials

Phase	Structure	Lattice Parameter (Å)	Weight Frac. (Ti/Al/V)	Volume Frac.	Nucleon Number Density (cm ⁻³)
α	HCP	$a = 2.9228, c = 4.6692$	92.05/6.30/1.66	74.39 %	2.65×10^{24}
β	BCC	$a = 3.2001$	88.44/5.50/6.05	25.61 %	2.81×10^{24}

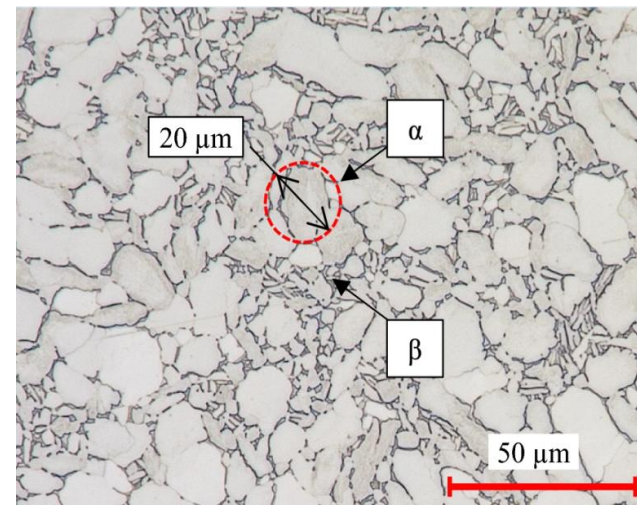
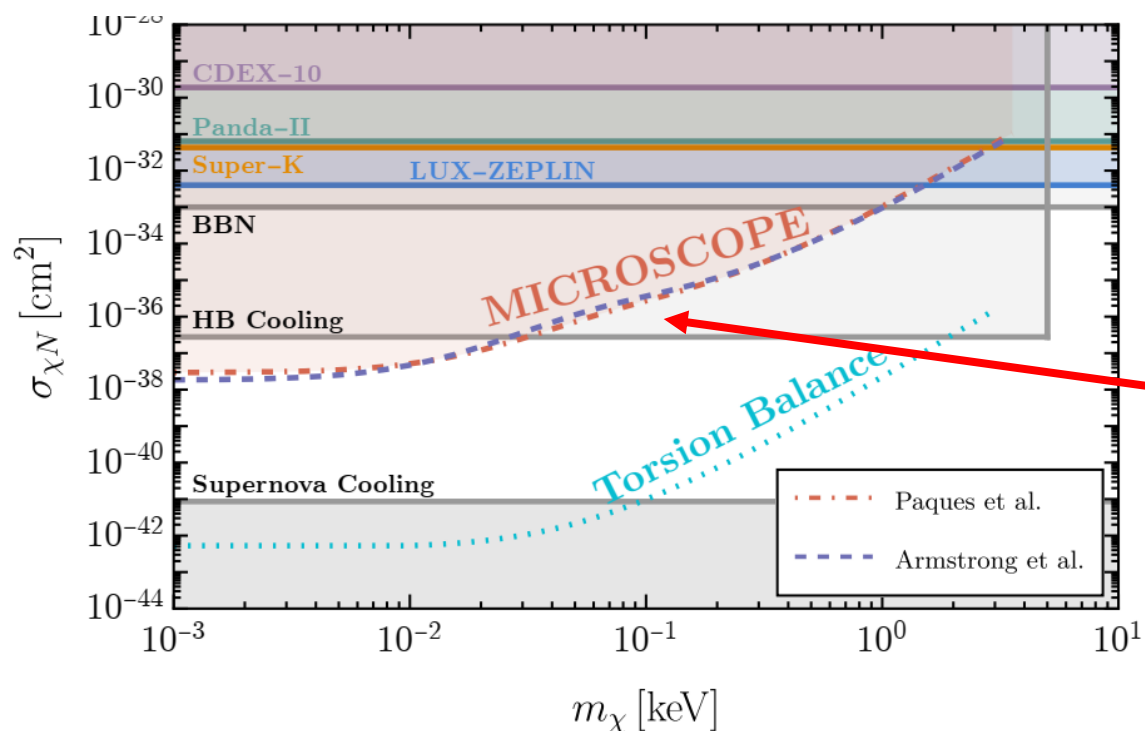
TABLE I: Summary of the microstructural properties of the α and β phases in the Ti-6Al-4V alloy.



Limits from MICROSCOPE

Phase	Structure	Lattice Parameter (Å)	Weight Frac. (Ti/Al/V)	Volume Frac.	Nucleon Number Density (cm ⁻³)
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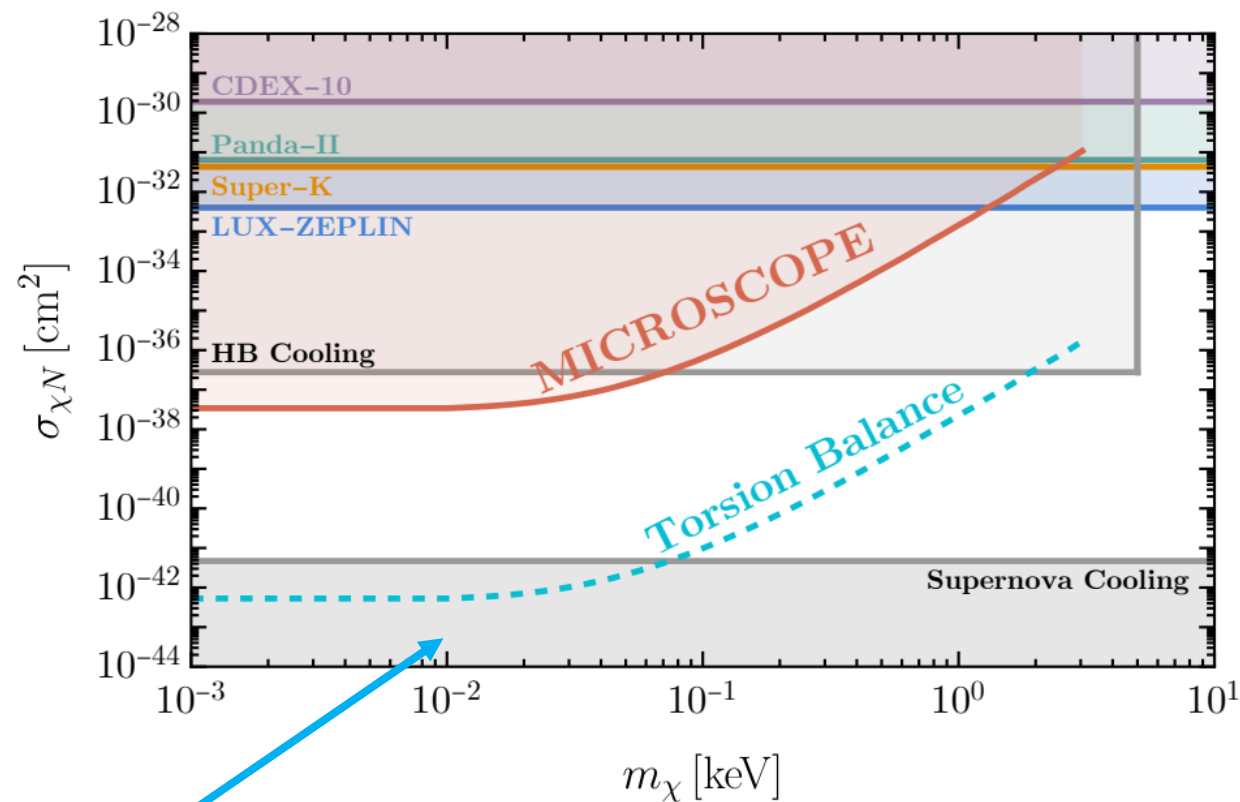
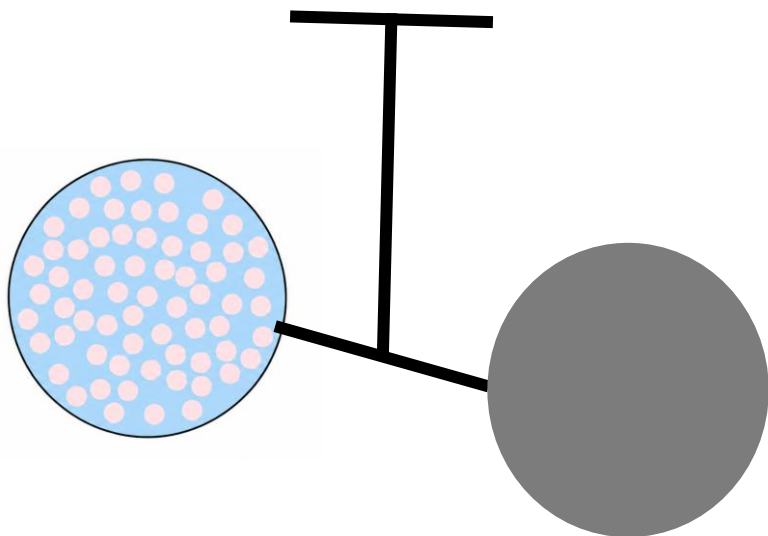
$$n_0 = 2.69 \times 10^{24} / \text{cm}^3,$$

$$\overline{\delta n^2} = (7.29 \times 10^{22} / \text{cm}^3)^2$$

$$\xi \sim 5 \mu\text{m}$$

$$\Delta a = 4.8 \times \frac{10^{-12} \text{cm}}{s^2}$$

A new proposal

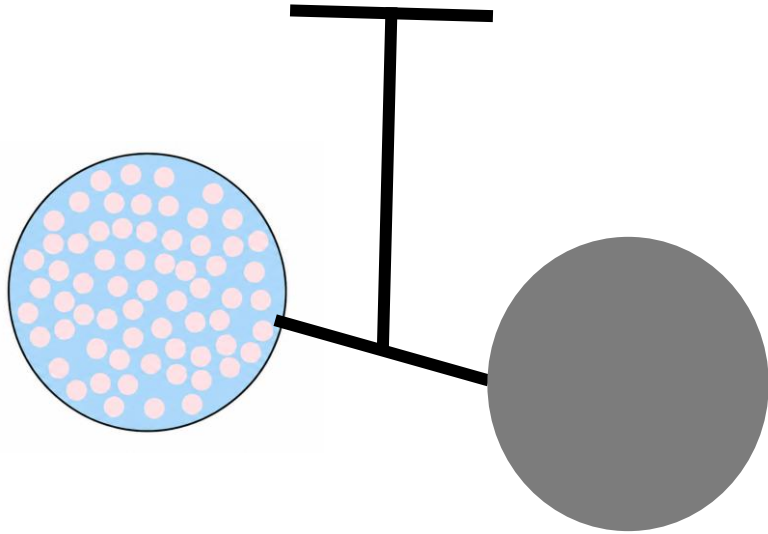


$$\overline{\delta n^2} = n_0^2 = (5.80 \times 10^{24} \text{ cm}^{-3})^2 \quad \text{2 orders}$$

$$\xi \sim 2 \mu\text{m}$$

$$\Delta a = \frac{10^{-13} \text{ cm}}{s^2} \quad \text{1 order}$$

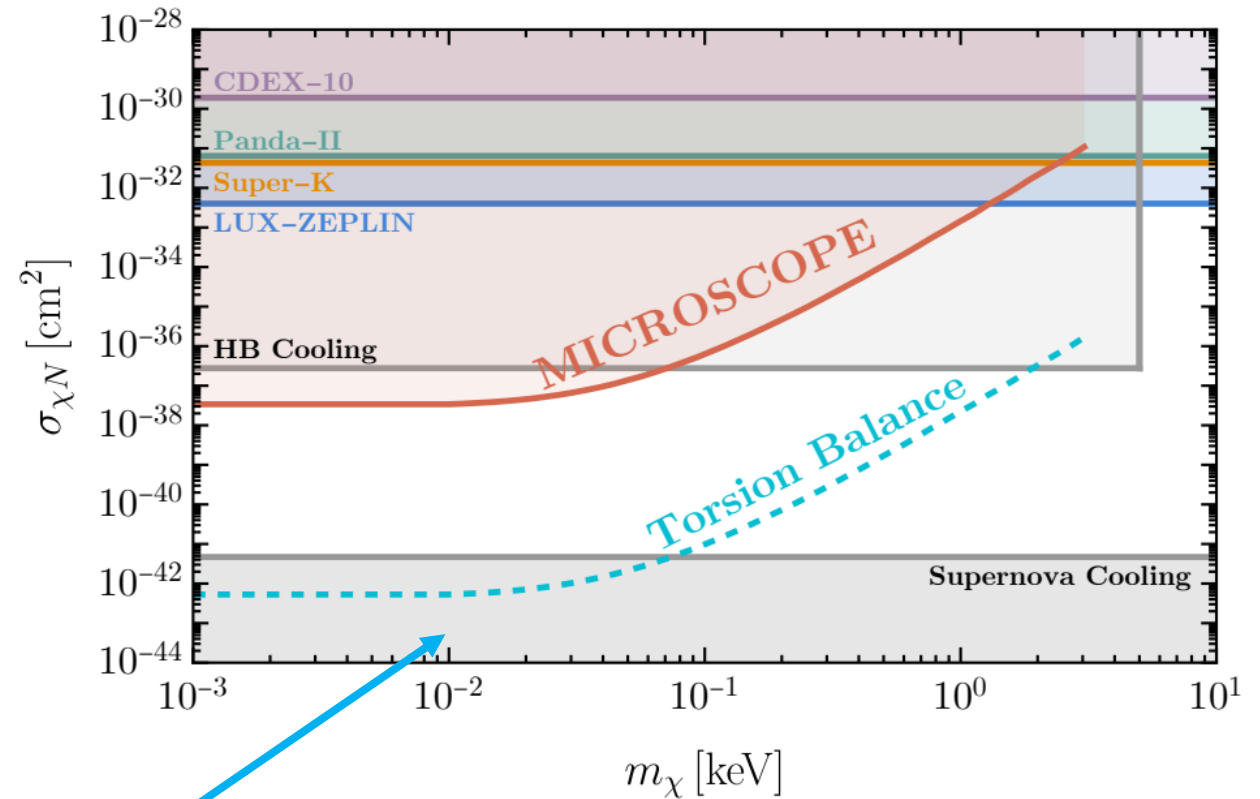
A new proposal



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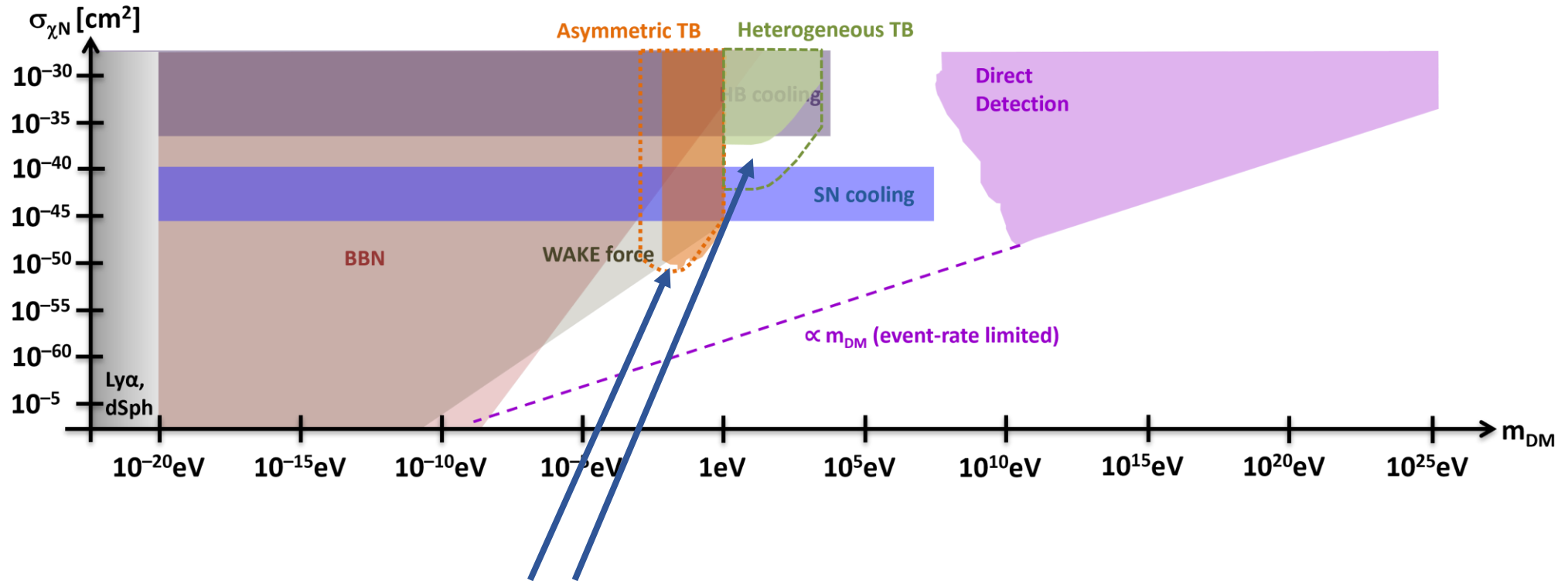


For the **same mass, size, and shape**, the backgrounds should be well controlled. The key challenge is how to fabricate **a material with large density fluctuations**.

Outline

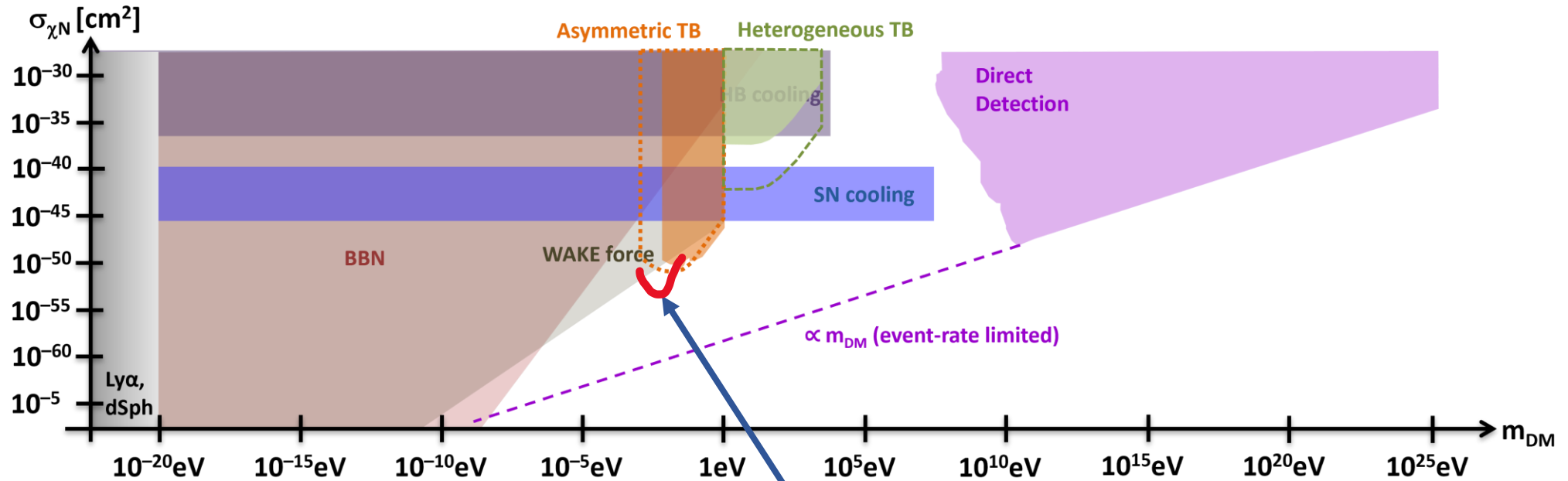
1. Introduction and targets
2. Coherent-scattering-induced acceleration as an observable
3. Torsion-balance probe of sub-eV DM
4. Random material for sub-keV DM
5. Conclusion and discussion

Conclusion and discussions



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

Conclusion and discussions



arXiv: 2606.07008

Discussion: We recently wrote a paper discussing interference effects in the scattering of light dark matter off the MICROSCOPE test masses.

Thank you for your attention!

Special thanks to Salva and everyone at the institute for your warm hospitality during my visit.

I am having a lovely and productive week here!

Backup: References

¹ In early studies, similar ideas were used for cosmic neutrino background (C ν 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: 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

$$\Delta\mathcal{L} = -\frac{\lambda_\phi}{4!}\phi^4 \quad (\text{B.1})$$

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

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

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

This gives a ϕ dependent shift in the Higgs VEV:

$$\frac{\delta v}{v} = \frac{\epsilon\phi^2}{2m_h^2}, \quad (\text{B.4})$$

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

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

[arXiv: 2312.13345v1]

Backup: coherent scattering formalism

In standard potential scattering, an incoming plane wave incident on a radially symmetric potential evolves to the outgoing state

$$|\mathbf{p}\rangle \rightarrow S |\mathbf{p}\rangle = |\mathbf{p}\rangle + \int d^3\mathbf{p}' \delta(E_{\mathbf{p}} - E_{\mathbf{p}'}) f(\mathbf{p}, \mathbf{p}') |\mathbf{p}'\rangle .$$

from the origin to some location $\mathbf{x} \neq 0$, we would replace $S \rightarrow USU^\dagger$ where $U = \exp(-i\mathbf{x} \cdot \mathbf{p})$ is the translation operator. Using this instead, the plane wave scatters to

$$\begin{aligned} |\mathbf{p}\rangle &\rightarrow USU^\dagger |\mathbf{p}\rangle \\ &= |\mathbf{p}\rangle + \int d^3\mathbf{p}' \delta(E_{\mathbf{p}} - E_{\mathbf{p}'}) e^{-i\mathbf{x} \cdot \mathbf{q}} f(\mathbf{p}, \mathbf{p}') |\mathbf{p}'\rangle \end{aligned} \quad (3)$$

where the momentum transfer is $\mathbf{q} = \mathbf{p}' - \mathbf{p}$.

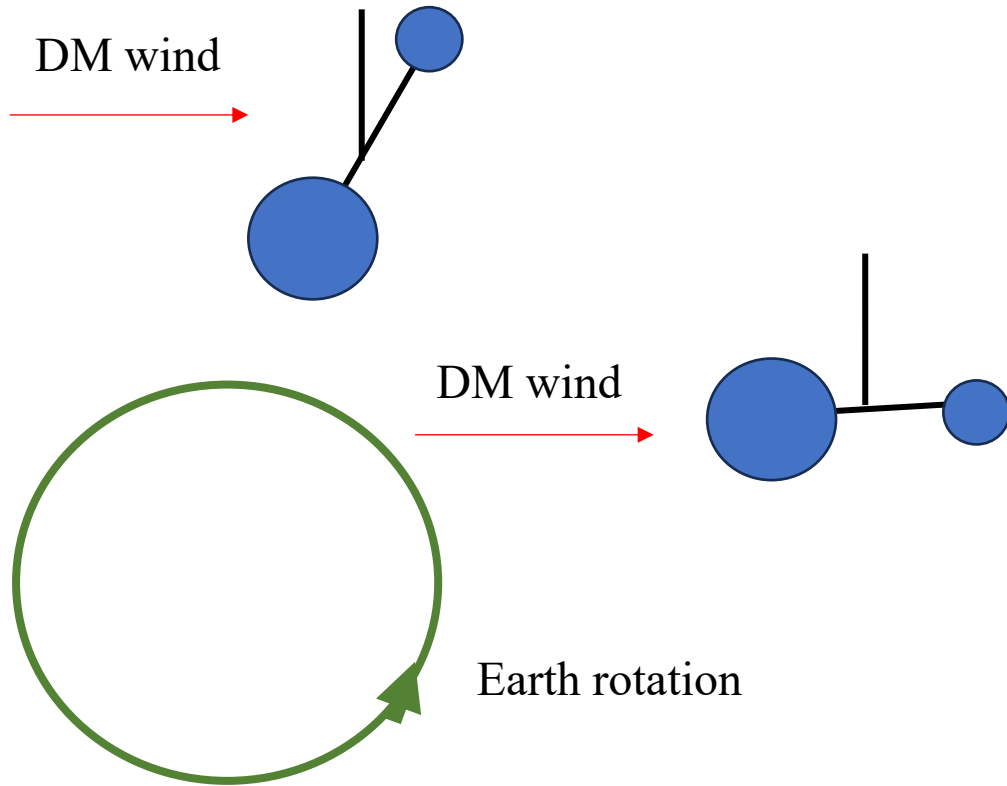
$\mathbf{x}_i$. To lowest order in perturbation theory, the amplitude adds coherently, and the scattering process produces

$$|\mathbf{p}\rangle \rightarrow |\mathbf{p}\rangle + \sum_{i=1}^N \int d^3\mathbf{p}' \delta(E_{\mathbf{p}} - E_{\mathbf{p}'}) e^{-i\mathbf{x}_i \cdot \mathbf{q}} f(\mathbf{p}, \mathbf{p}') |\mathbf{p}'\rangle .$$

$$P(\mathbf{p}') \propto |\langle \mathbf{p}' | \psi \rangle|^2 \propto \sum_{ij} \langle e^{-i\Delta\mathbf{x}_{ij} \cdot \mathbf{q}} \rangle_{\text{target}} |f(\mathbf{p}, \mathbf{p}')|^2 \quad (5)$$

[arXiv: 2111.03597v3]

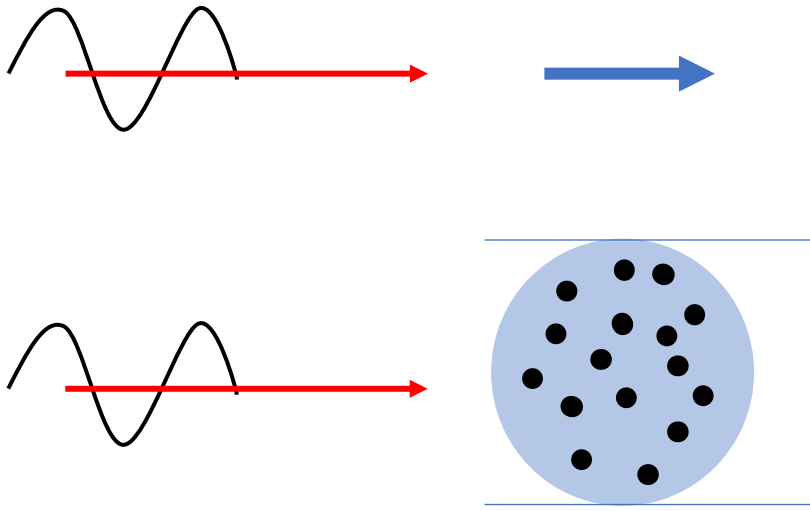
Backup: Frequency



- 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

Backup: unitarity limit

Strong-interaction-limit



$$\sigma_{max} \sim S = 4 \pi r^2$$

- From partial wave method,
$$\sigma_l = \frac{4\pi}{p^2} (2l + 1) \sin^2 \delta \leq \frac{4\pi}{p^2} (2l + 1)$$
- If the incoming particle's energy is low, usually its s-wave scattering, $l = 0$. The maximum cross-section is $\sigma = \frac{4\pi}{p^2} \sin^2 \delta$.
- In the strong interaction limit, the incoming wave will be backwards at the surface of the ball, $\delta \sim -pR$.
- The maximum cross section is then, $\sigma_{max} \simeq 4\pi R^2$.

Backup: materials

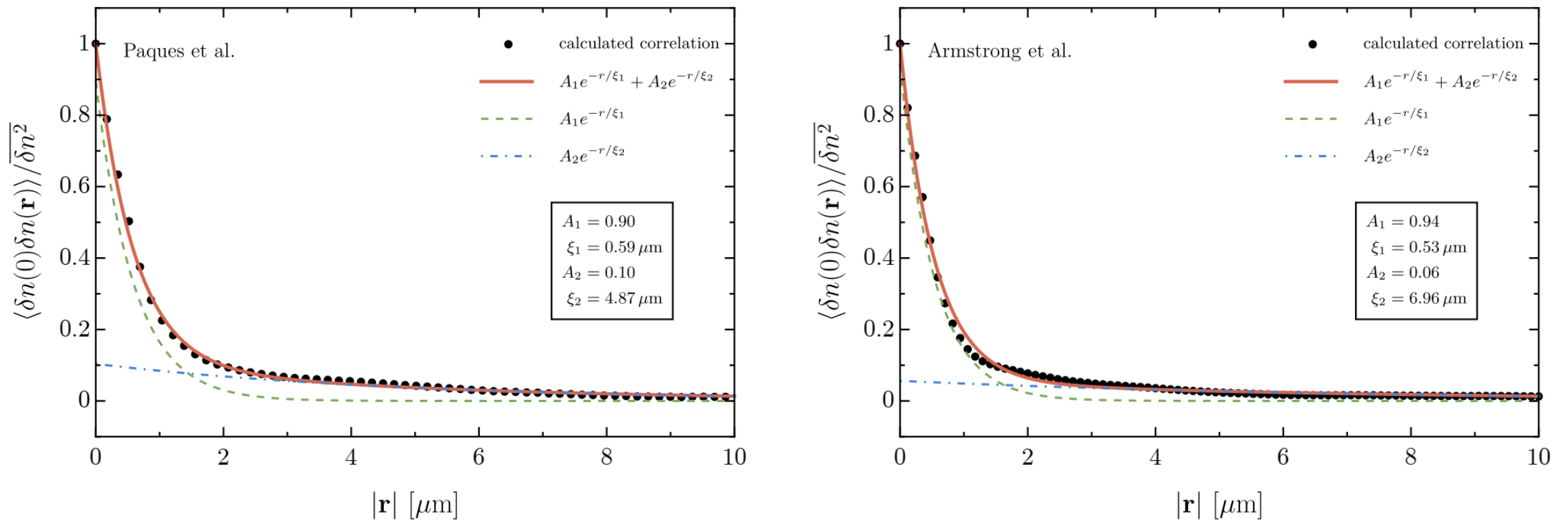


FIG. 4: Normalized two-point correlation functions obtained from representative AMS 4928 Ti-6Al-4V micrographs, together with the corresponding constrained fits to a sum of two exponentials. Left: Paques et al. [48]; right: Armstrong et al. [49].

Backup: Cosmological constraint (BBN)

The key issue in the BBN-era rate estimate is the number density of nucleon targets. The estimate $\Gamma/H \sim \sigma T M_{\text{Pl}}$ corresponds to a target density of order T^3 , as appropriate for a relativistic species. At $T \sim 1$ MeV, however, nucleons are non-relativistic and nucleon–antinucleon pairs are Boltzmann suppressed. The relevant target density is the residual baryon density,

$$n_B(T) = \eta_B n_\gamma(T), \quad n_\gamma(T) = \frac{2\zeta(3)}{\pi^2} T^3, \quad (8)$$

with $\eta_B \simeq 1.7 \times 10^{-9}$ at $T \sim 1$ MeV [13]. This gives the nucleon scattering rate

$$\Gamma_{\chi N} = n_B \langle \sigma_{\chi N} v \rangle = \eta_B \frac{2\zeta(3)}{\pi^2} T^3 \langle \sigma_{\chi N} v \rangle, \quad (9)$$

and hence

$$\frac{\Gamma_{\chi N}}{H} = \frac{\eta_B}{1.66\sqrt{g_*}} \frac{2\zeta(3)}{\pi^2} \sigma_{\chi N} v T M_{\text{Pl}}. \quad (10)$$

For $\sigma_{\chi N} \simeq 4 \times 10^{-38} \text{ cm}^2 \simeq 1.0 \times 10^{-10} \text{ GeV}^{-2}$, $g_* = 10.75$, and $v \simeq 1$, this gives

$$\left. \frac{\Gamma_{\chi N}}{H} \right|_{T=1 \text{ MeV}} \simeq 9.3 \times 10^{-5} \left(\frac{\sigma_{\chi N}}{10^{-10} \text{ GeV}^{-2}} \right) \left(\frac{T}{1 \text{ MeV}} \right) \left(\frac{10.75}{g_*} \right)^{1/2}. \quad (11)$$

The nucleon elastic scattering rate is therefore far below the Hubble rate at BBN temperatures. Therefore, the dark matter in the parameter space considered in this work is not in thermal equilibrium during the BBN epoch.

Backup: Cosmological constraint (BBN)

decoupling. Since scattering off residual baryons is suppressed by their small abundance, the dominant low-temperature energy-transfer channel is typically photon scattering induced by a proton loop. In the absence of an additional UV contribution that cancels the loop-induced amplitude, the χ -proton interaction generically generates an effective coupling of χ to photons of the form,

$$\mathcal{L}_{\chi\gamma}^{\text{eff}} \sim \frac{\alpha}{6\pi} \frac{\chi^2}{\Lambda^2} F_{\mu\nu} F^{\mu\nu}. \quad (12)$$

For relativistic particles this gives a photon scattering cross section of order

$$\sigma_{\chi\gamma} \sim \frac{1}{16\pi} \left(\frac{\alpha}{6\pi}\right)^2 \frac{s}{\Lambda^4} \sim \left(\frac{\alpha}{6\pi}\right)^2 \frac{T^2}{m_N^2} \sigma_{\chi N}, \quad (13)$$

where the last expression uses $s \sim (4T)^2$ and $\sigma_{\chi N} \simeq m_N^2/(\pi\Lambda^4)$. Evaluating the corresponding interaction rate at the decoupling temperature gives

$$\left. \frac{\Gamma_{\chi\gamma}}{H} \right|_{T=T_{\text{dec}}} \sim \left(\frac{T_{\text{dec}}}{10 \text{ MeV}} \right)^3 \left(\frac{\sigma_{\chi N}}{4 \times 10^{-33} \text{ cm}^2} \right) \left(\frac{10.75}{g_*} \right)^{1/2}. \quad (14)$$

Requiring $\Gamma_{\chi\gamma}/H \lesssim 1$ at $T_{\text{dec}} \sim 10 \text{ MeV}$ therefore gives

$$\sigma_{\chi N} \lesssim 4 \times 10^{-33} \text{ cm}^2 \left(\frac{10 \text{ MeV}}{T_{\text{dec}}} \right)^3 \left(\frac{g_*}{10.75} \right)^{1/2}. \quad (15)$$