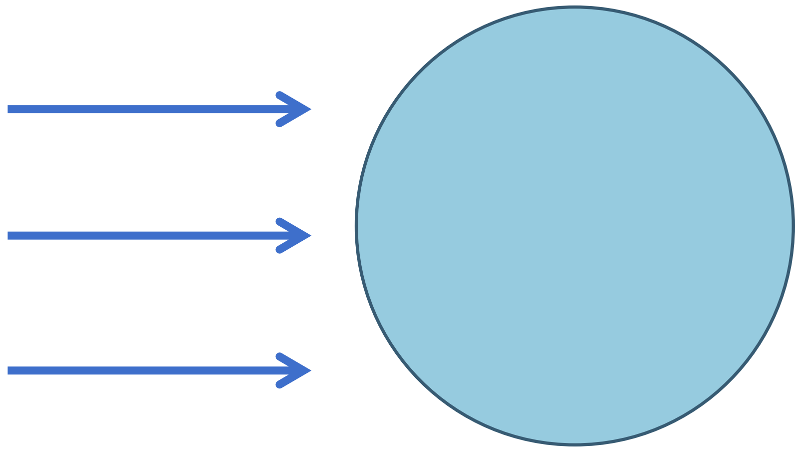
Macroscopic Quantum Interference in Dark Matter Wave Scattering with MICROSCOPE

Chengtao Fu/符承涛

National Gravitational Laboratory
Huazhong University of Science and Technology

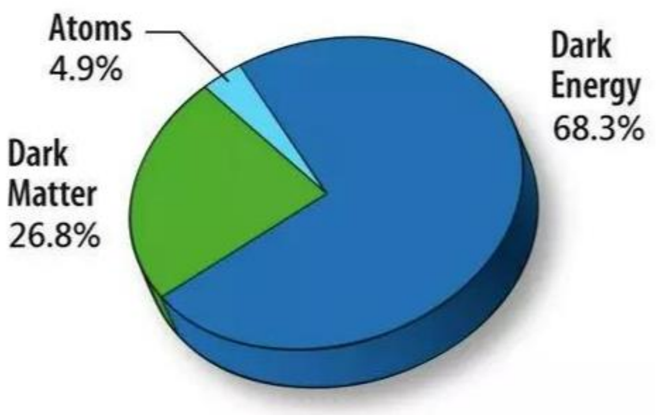


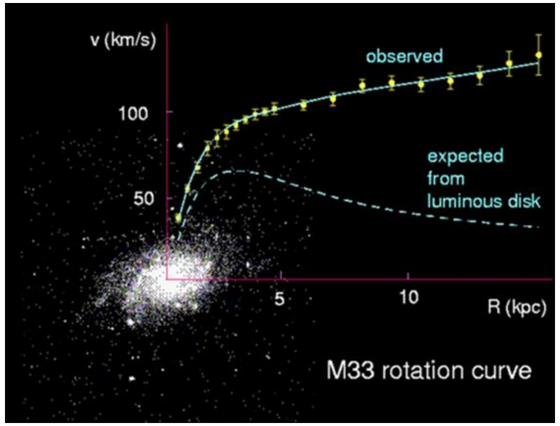
July 23, 2026

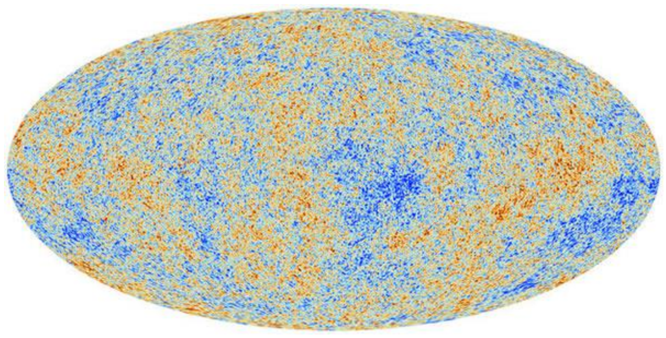
Chengtao Fu, Pengshun Luo, Rui Luo, Jie Sheng, and Chuan-Yang Xing, arXiv:2606.07008 (2026)

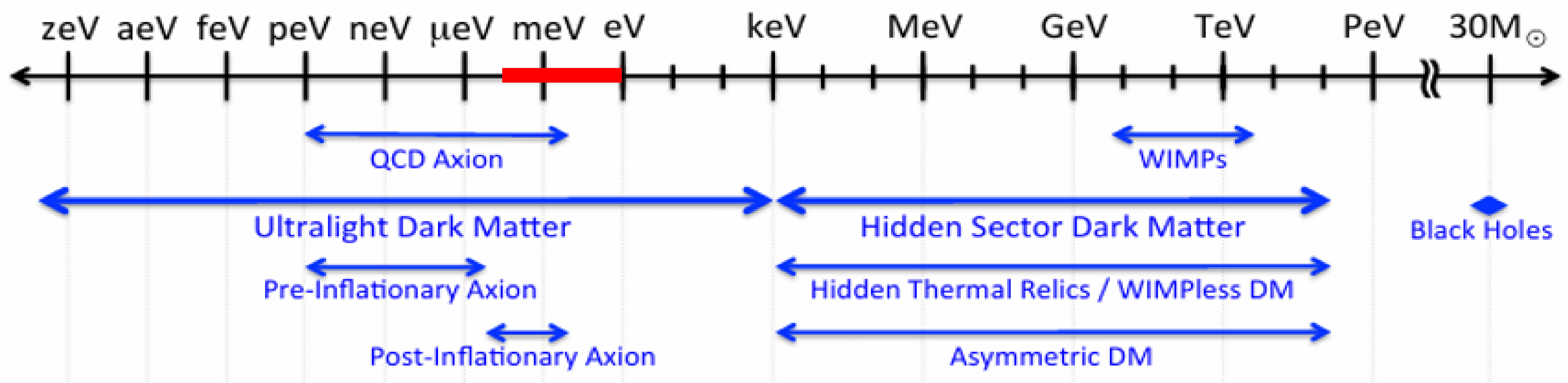
Motivation: Why Dark Matter Matters

Strong gravitational evidence, yet particle identity remains a mystery





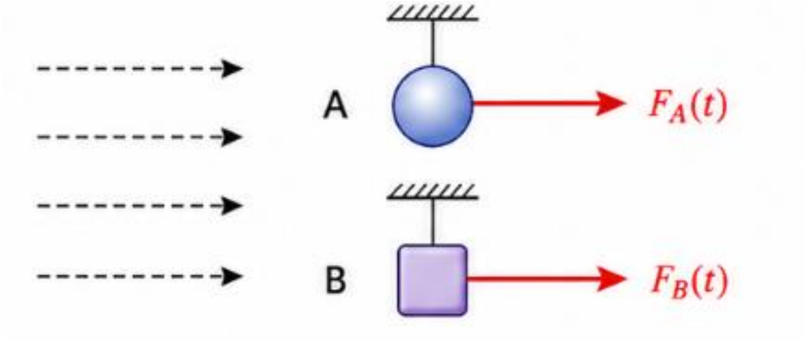




How DM couples to ordinary matter?

Mechanical Signatures of Sub-eV Dark Matter

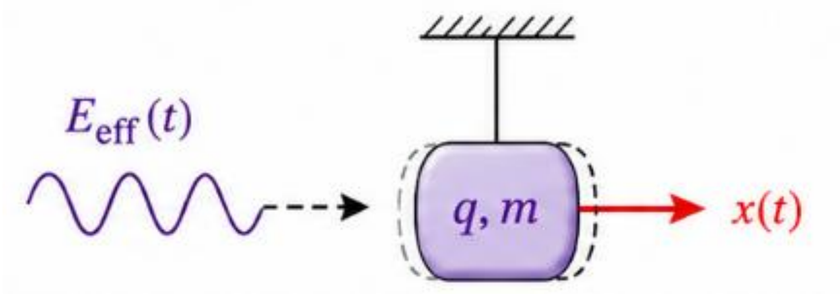
B−L Vector DM



$$F_{B-L} = g_{B-L} Q_{B-L} E_X$$

Phys. Rev. Lett. 134, 251001 (2025)

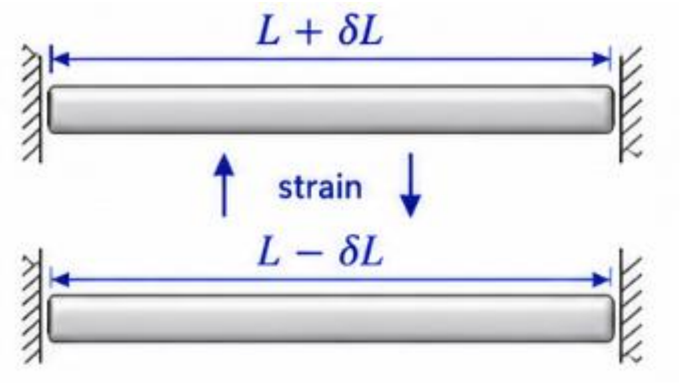
Dark Photon



$$F = qE_{eff}$$

Phys. Rev. Lett. 130, 181001 (2023)

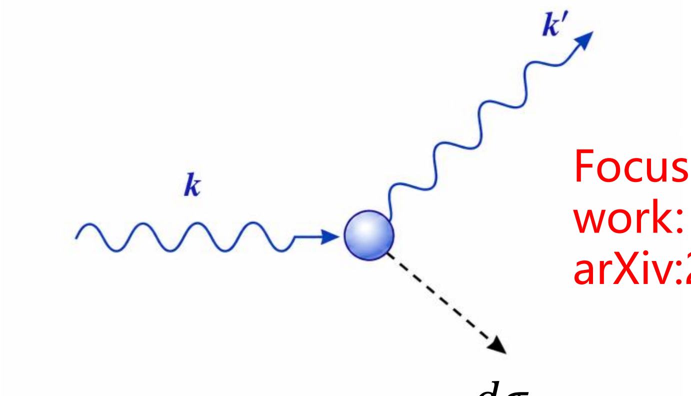
Scalar DM: Linear Coupling



$$h = \delta L / L$$

Phys. Rev. Lett. 134, 031001 (2025)

Scalar DM: Quadratic Coupling



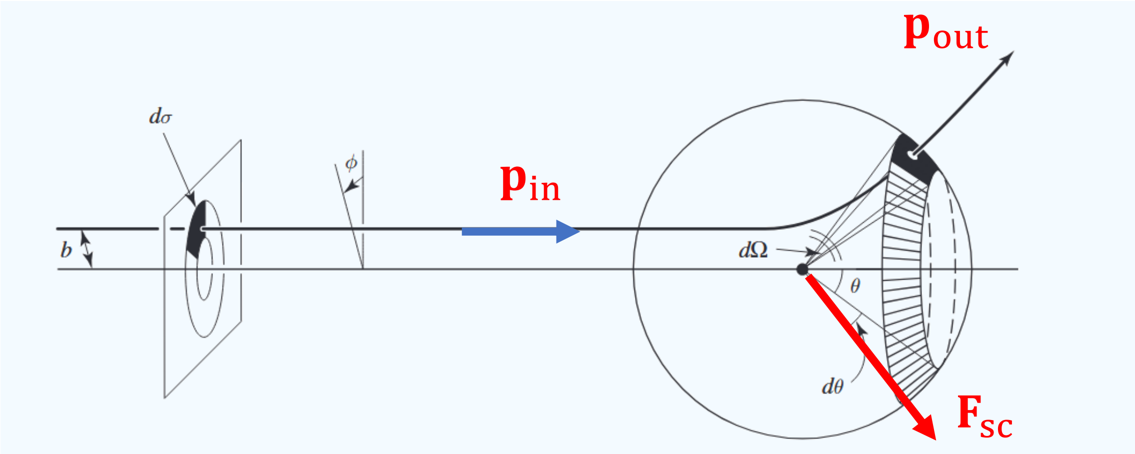
Focus of this work: Fu et al., arXiv:2606.07008

$$F = n_\chi v \int d\Omega \, q \frac{d\sigma}{d\Omega}$$

Phys. Rev. Lett. 136, 121803 (2026)

Dark Matter Scattering off Single Object

Scattering Process



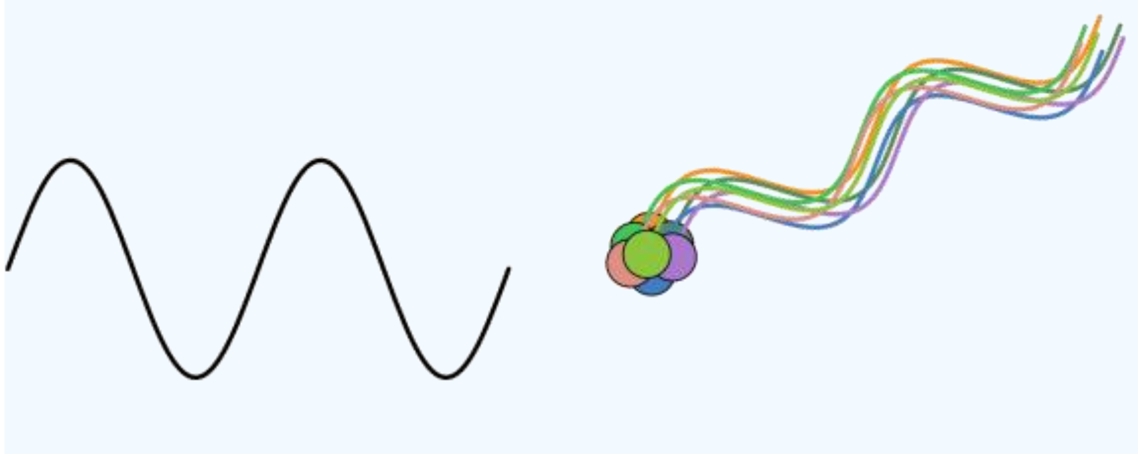
➢ Momentum transfer

$$\mathbf{q} = \mathbf{p}_{\text{in}} - \mathbf{p}_{\text{out}}$$

➢ Force

$$\mathbf{F}_{sc} = n_\chi \int d^3 v f(\mathbf{v})\, v \int d\Omega\, \mathbf{q} \frac{d\sigma}{d\Omega}$$

Coherent Scattering



➢ Wave Function and Form Factor

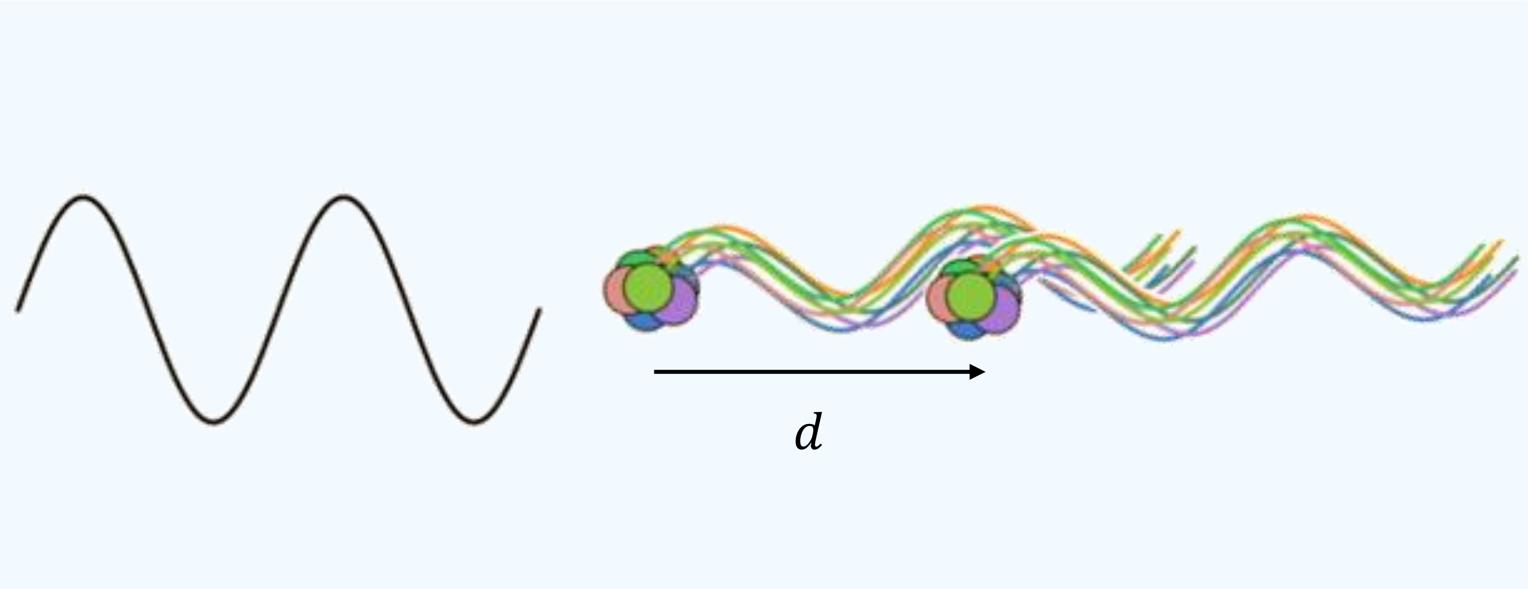
$$\psi_{\text{T}} = e^{i\mathbf{kr}} + f(\mathbf{q}) \sum^{N} e^{i\mathbf{q}\cdot\mathbf{r}_\text{j}} \frac{e^{ikr}}{r} \qquad F(\mathbf{q}) = \frac{1}{N}\sum^{N} e^{i\mathbf{q}\cdot\mathbf{r}_\text{j}}$$

➢ Cross Section

$$\frac{d\sigma_{\text{T}}}{d\Omega} = N^2 |F(\mathbf{q})|^2 |f(\mathbf{q})|^2 \qquad qR \ll 1 \rightarrow F(\mathbf{q}) \simeq 1$$

Long wavelength ➡ $\boldsymbol{f_N \propto N}$ **and** $\boldsymbol{\sigma_T \propto N^2}$

Dark Matter Scattering off Multiple Objects



- Wave Function

$$\psi_{\text{tot}} = e^{i\mathbf{kr}} + \left(f_1 + f_2 e^{i\mathbf{kd}}\right)\frac{e^{ikr}}{r}$$

- Cross Section

$$\frac{d\sigma_{\text{tot}}}{d\Omega} = \left(f_1 + f_2 e^{i\mathbf{kd}}\right)^2$$
$$= |f_1|^2 + |f_2|^2 + 2\mathrm{Re}\left(f_1 f_2^* e^{-i\mathbf{kd}}\right)$$

- Total Force

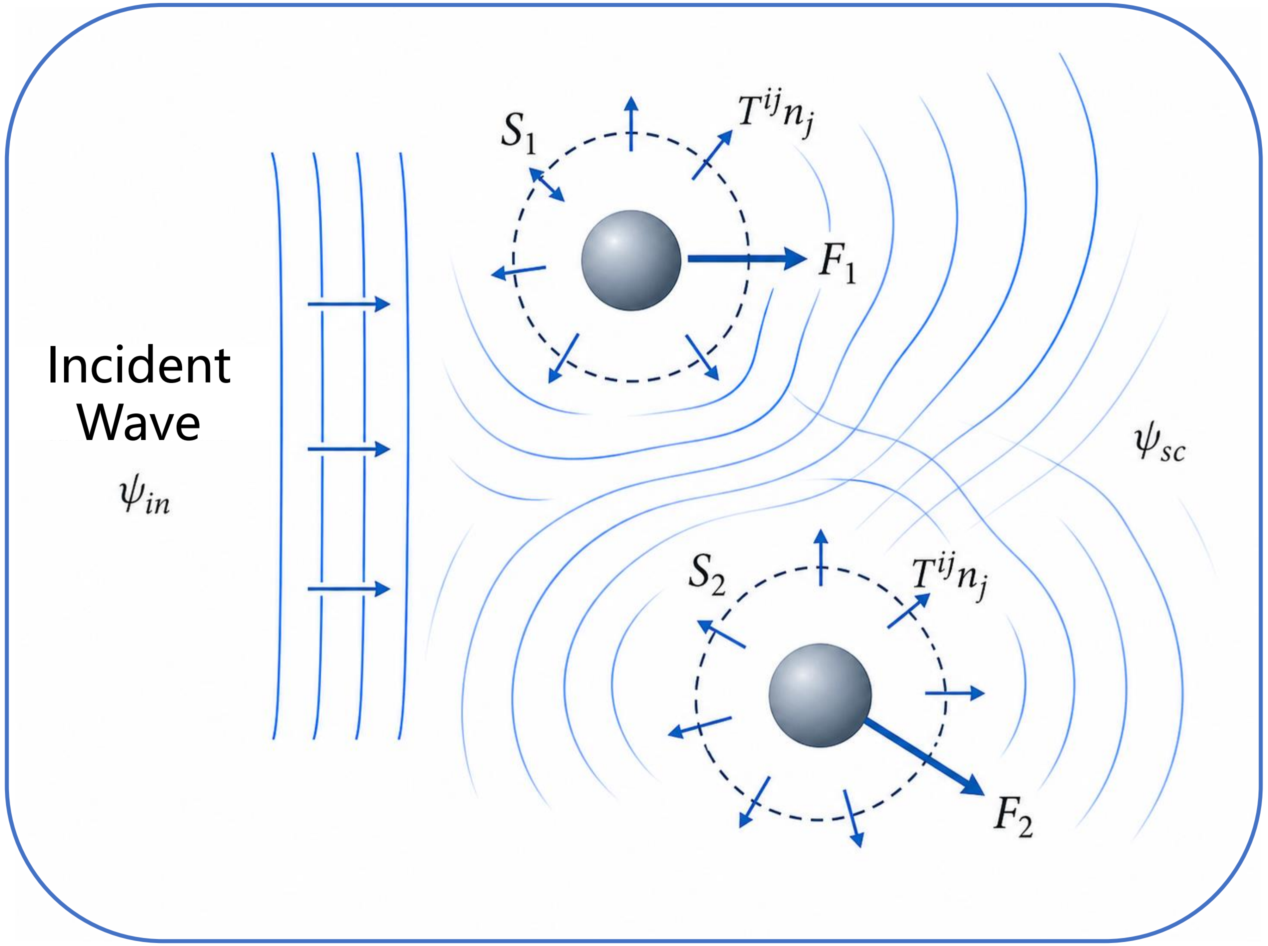
$$\mathbf{F}_{\text{tot}} = n_\chi v \int \mathbf{q}\frac{d\sigma_{\text{tot}}}{d\Omega} d\Omega$$

How to determine F_1 and F_2 ?

$$F_1 = F_2 \quad \text{or} \quad \frac{F_1}{F_2} = \frac{N_1}{N_2}$$

Force Evaluation of Single Object via Momentum Flux

Enclose each object and integrate the local momentum flux



Ø DM Wavefunction

$$\psi(\mathbf{r}) = \psi_{in}(\mathbf{r}) + \psi_{sc}(\mathbf{r})$$

Ø Energy-Momentum Tensor

$$T^{\mu\nu} = \partial^\mu\psi^*\partial^\nu\psi + \partial^\mu\psi\partial^\nu\psi^* - g^{\mu\nu}[(\partial_\rho\psi)(\partial^\rho\psi^*) - m^2|\psi|^2]$$

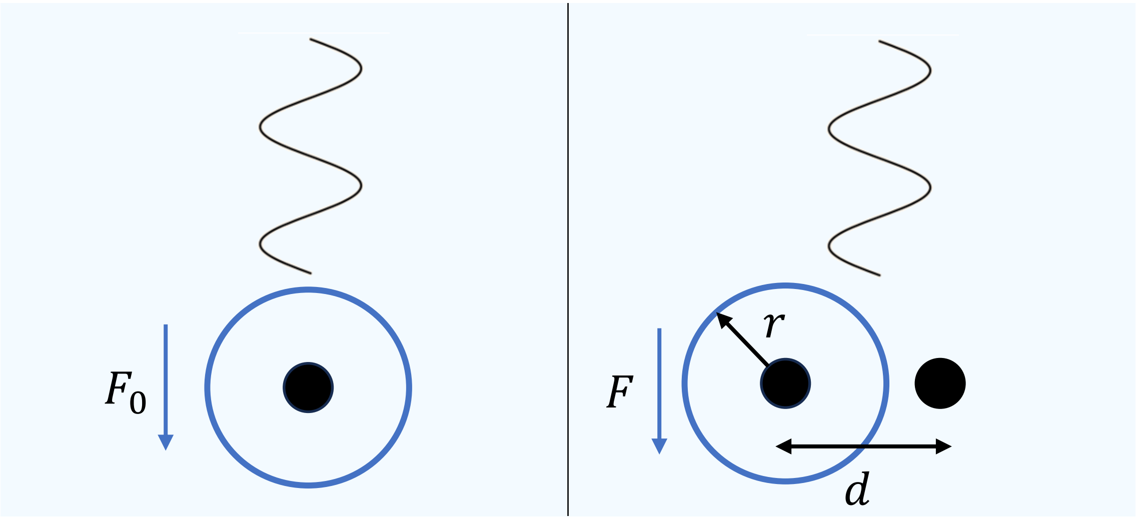
Ø Surface Integral for the Force

$$F_n^i = -\oint_{S_n} T^{ij} n_j \, dS$$

Toy Model: Delta Scattering Potential

- Force Calculation

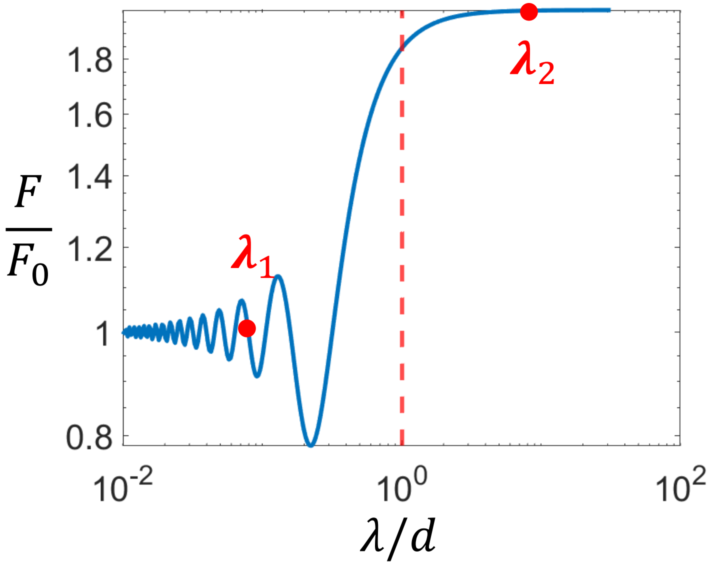
$$F_n^i = -\oint_{S_n} T^{ij} n_j \, dS$$



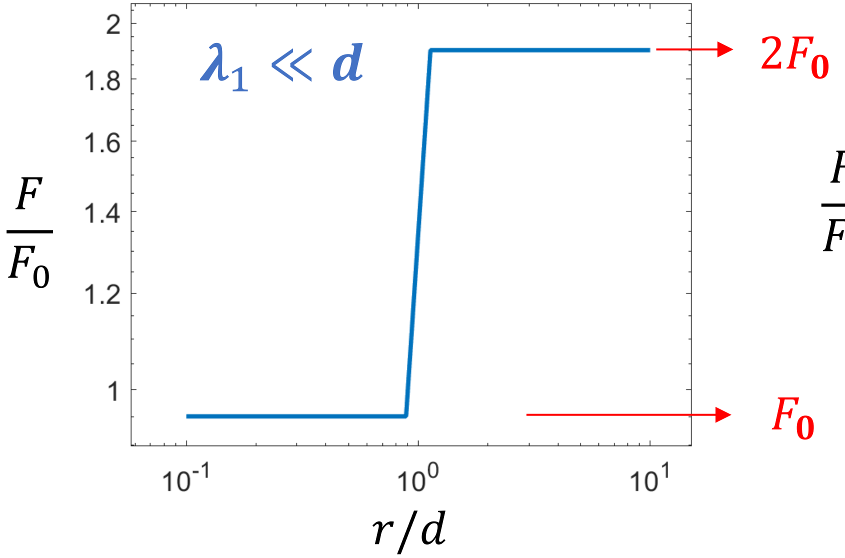
- Axial Incidence

$$F(r<d) = \frac{F(r>d)}{2}$$

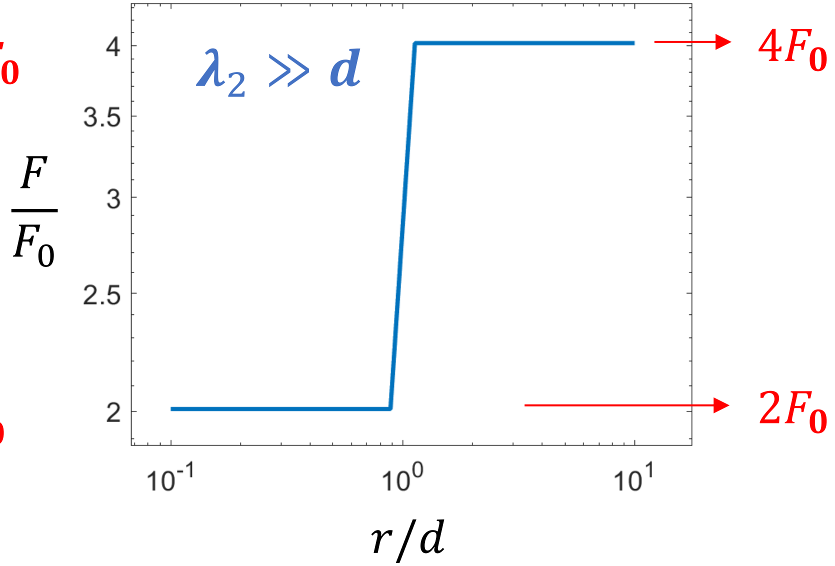
Force on target 1



Short wavelength limit

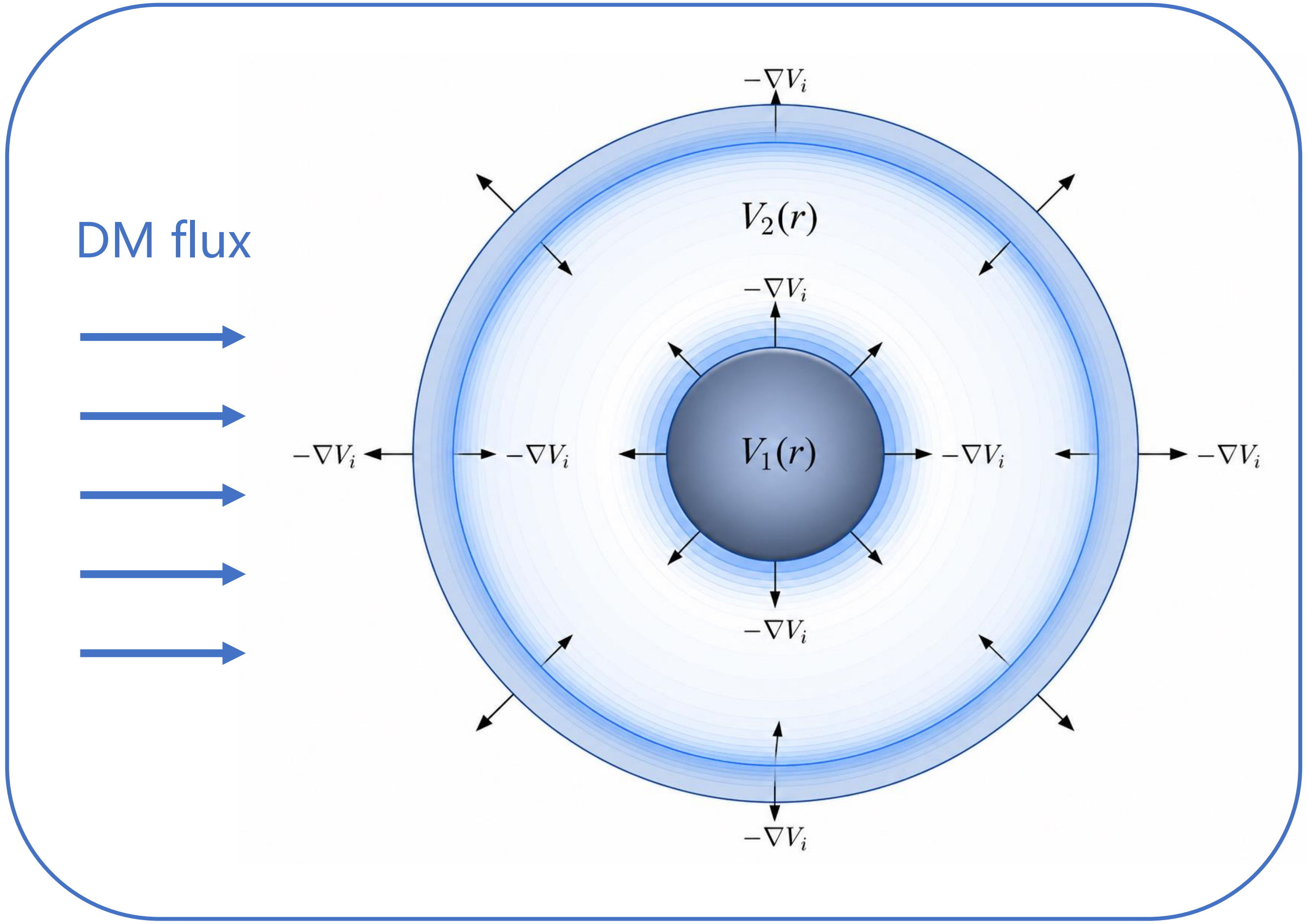


Long wavelength limit



Force Evaluation of Single Object via Ehrenfest theorem

Integration of the interaction force over the DM density distribution



Ø Ehrenfest Theorem

$$F_i = -\int d^3r|\psi(r)|^2\nabla V_i(r)$$

$\psi(r)$ DM wavefunction

$V_i(r)$ Potential of scatterer i

Ø For Concentric Targets

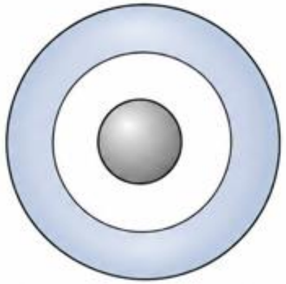
$$F_i = n_\chi \int d^3v f(\mathbf{v}) v \int d\Omega\, f_{\text{tot}} f_i \mathbf{q}$$

Cross-section-like formula :

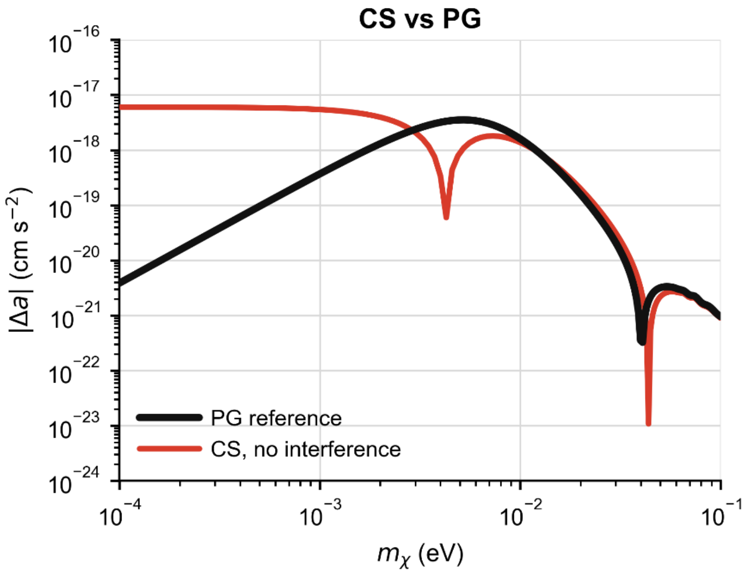
$$F_{\text{tot}} = n_\chi \int d^3v f(\mathbf{v}) v \int d\Omega\, f_{\text{tot}}^2 \mathbf{q}$$

Comparison of Force-Calculation Methods

Model: concentric sphere + shell; Observable: $|\Delta a|$

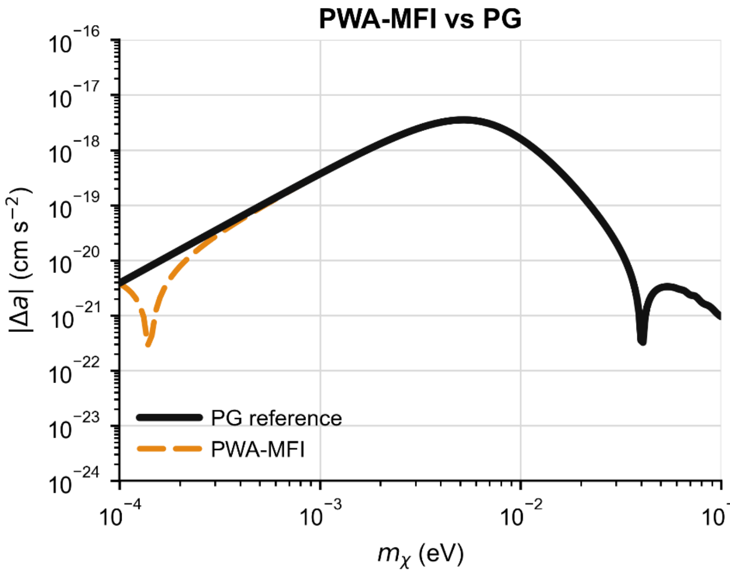


cross section



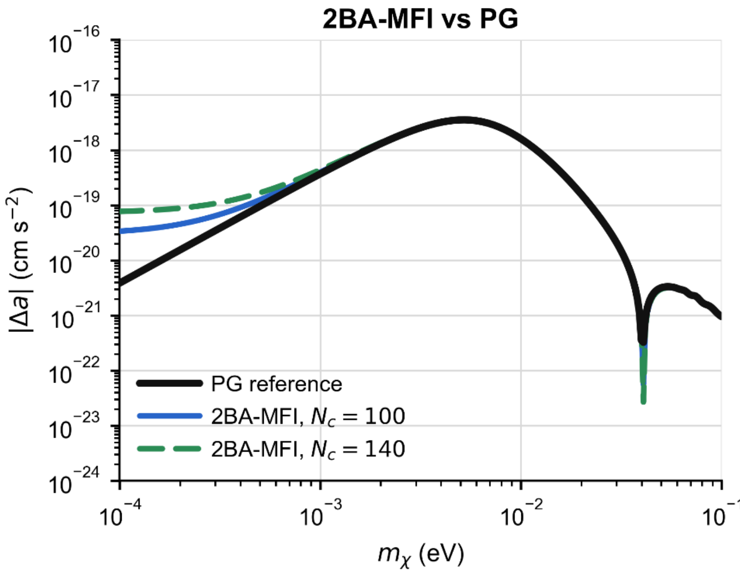
Fails when inter-body interference is neglected

PWA + momentum flux



Numerically unstable in the low-mass regime

2nd BA + momentum flux

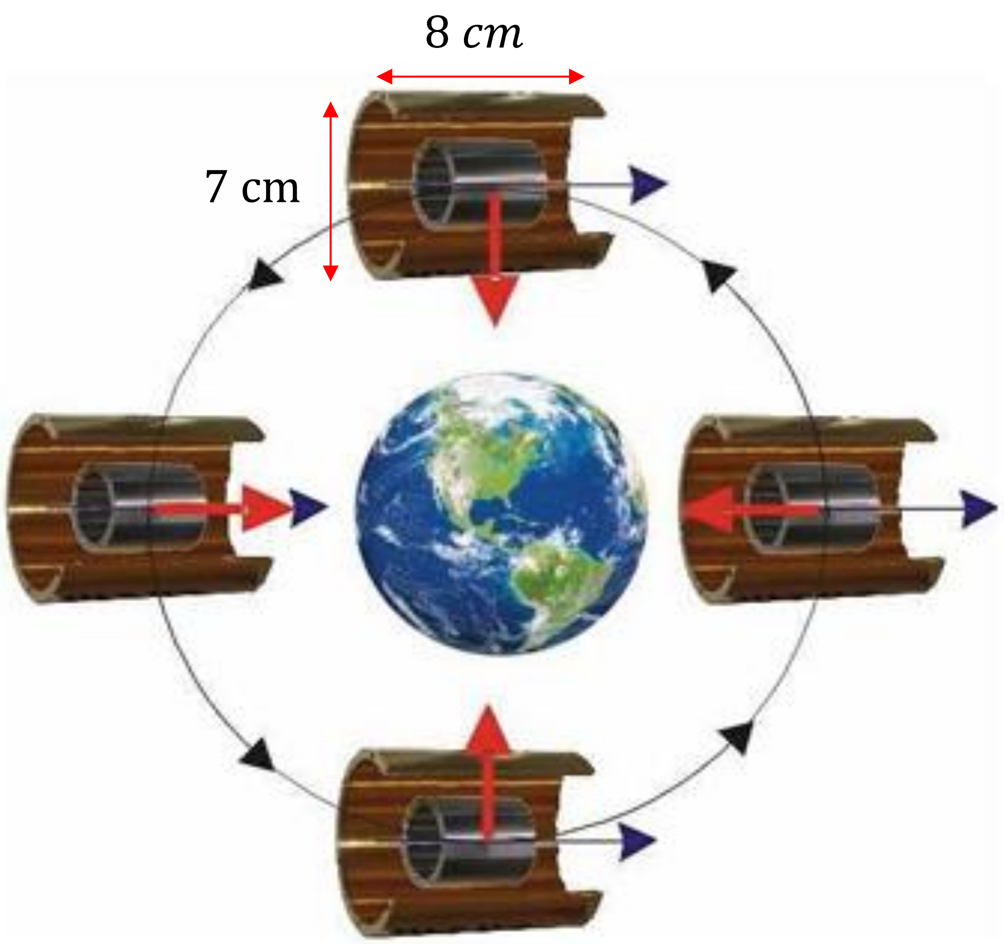


Converges to the reference under grid refinement

The method base on Ehrenfest theorem is adopted for subsequent calculations

Constraints from MICROSCOPE Experiment

MICROSCOPE experiment



- Objective

  Test the Weak Equivalence Principle (WEP)

- Core Components

  Concentric cylindrical test masses

- Key Feature

  Satellite spin modulates the signal at the spin frequency

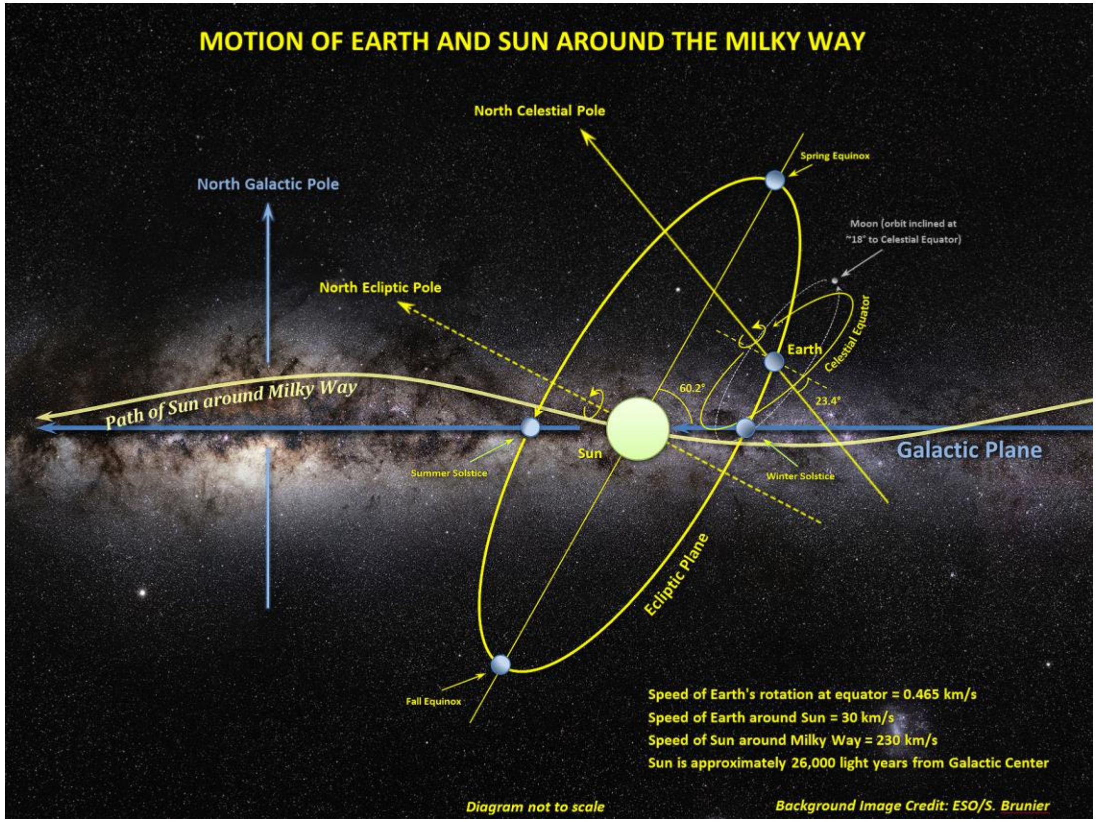
- Measurement Precision

  Precision at the $10^{-14}\ \mathrm{m/s^2}$ level

Detects dark matter through induced differential acceleration

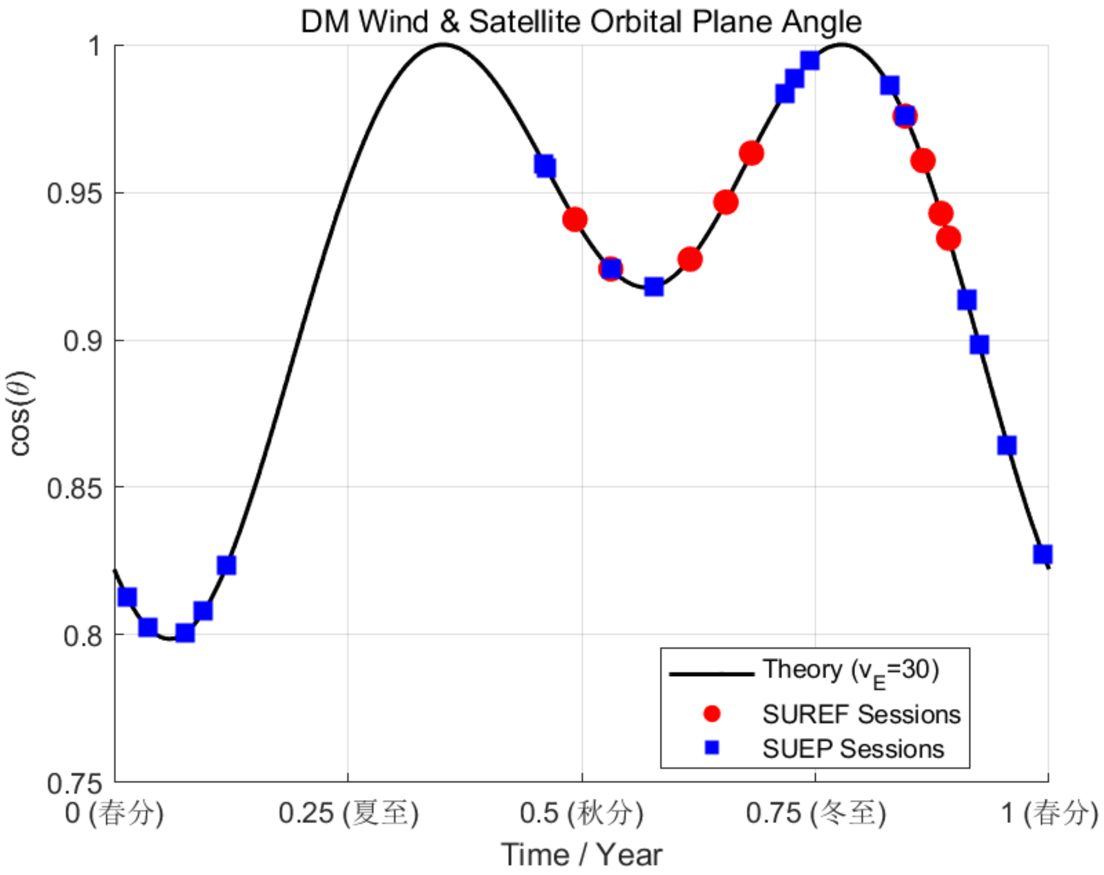
DM Wind Direction During MICROSCOPE Sessions

DM wind in galactic frame



$$\vec{v}_{\text{sat}}(t) = \mathbf{V}_{\bigcirc} + \mathbf{V}_{\oplus} + \mathbf{V}_{sat}$$

DM wind in satellite frame

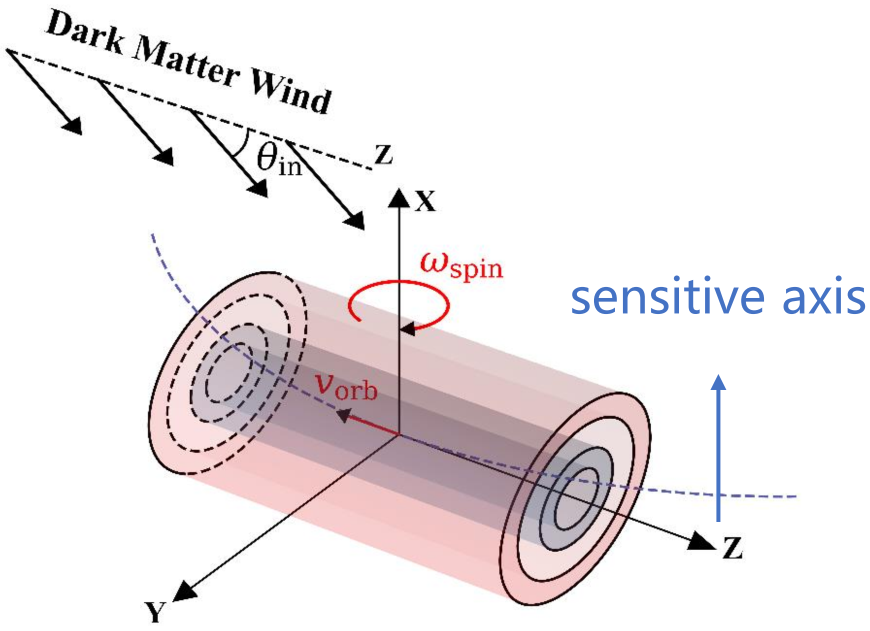


Within each scientific session

$\vec{v}_{\text{sat}}(\text{t})\sim$constant

Modulation of the DM Signal

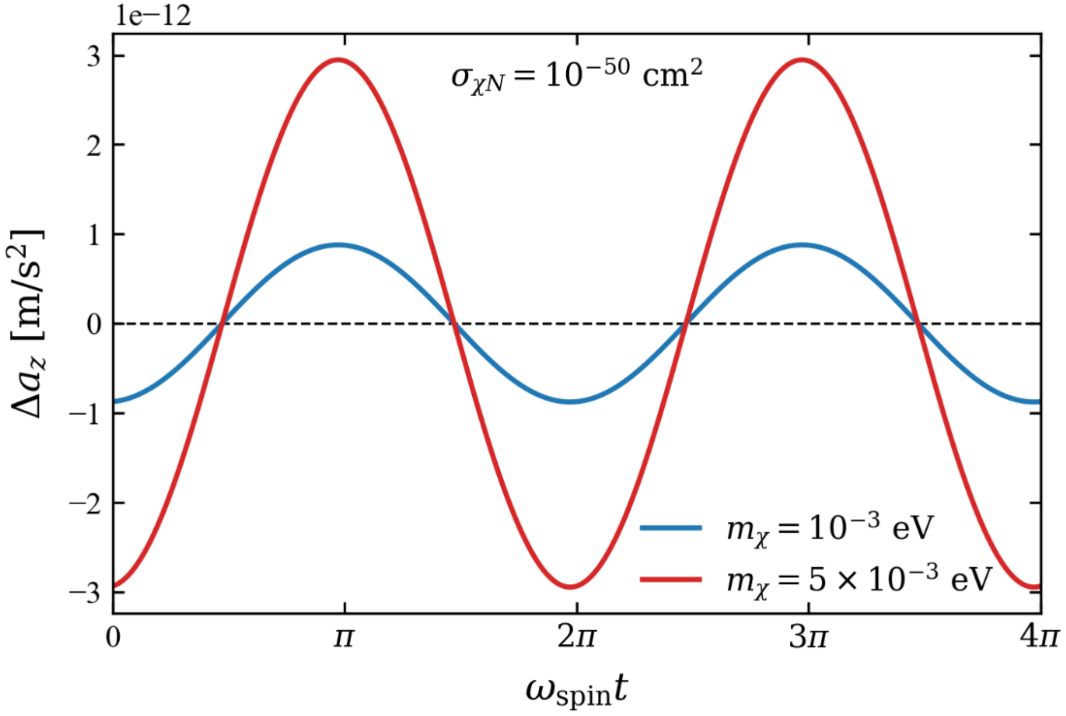
Incidence angle



$$\cos\theta_{in}(t) = \hat{\boldsymbol{v}}_{\rm sat}(\mathrm{t}) \cdot \hat{\boldsymbol{Z}}(t)$$

$$\hat{\boldsymbol{Z}}(t) = \mathbf{R}_{\rm spin}(\omega_{\rm spin} t)\hat{\boldsymbol{Z}}_0$$

DM theory signal



$$\Delta a_z(t; m_\chi, \sigma_{\chi N}) = \sigma_{\chi N} \Delta\tilde{a}_z[m_\chi, \theta_{\rm in}(t)]$$

Data Analysis

Sensors

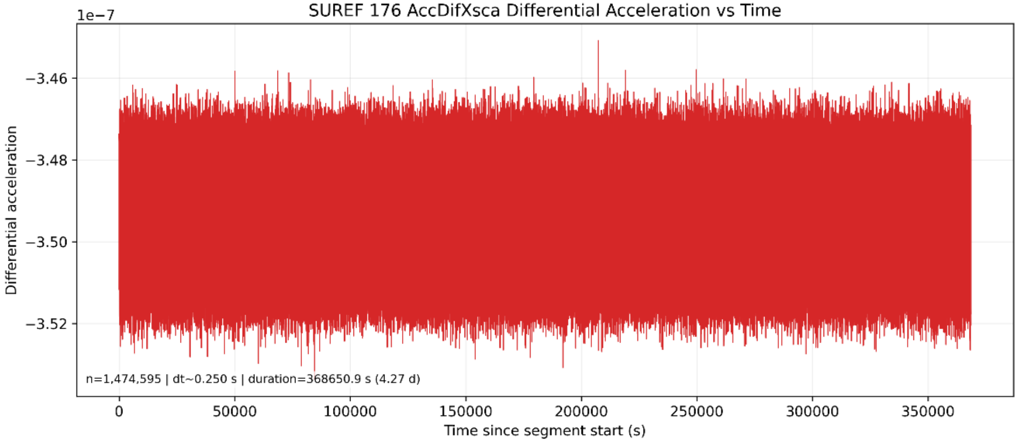
SUREF

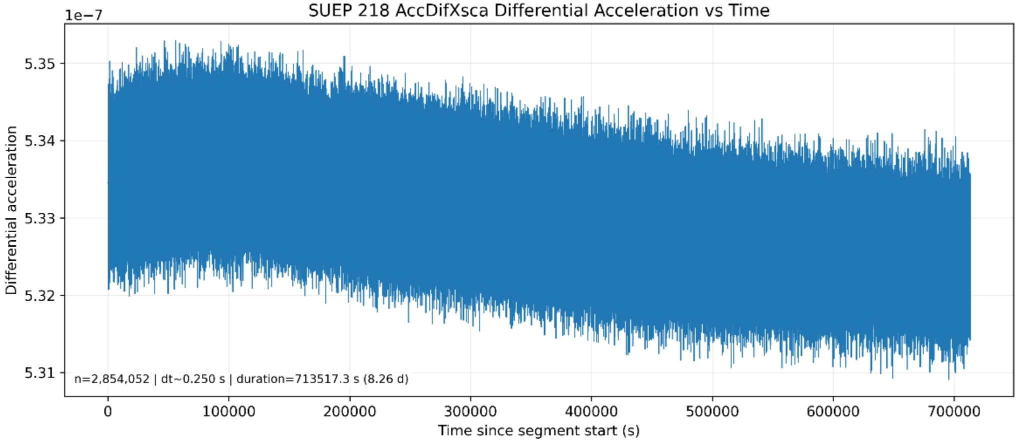
Same composition

SUEP

Different compositions

MICROSCOPE time series





Session-level estimates

TABLE II: Session-level fitted cross section for SUREF w/o OH at $m_\chi = 5 \times 10^{-3}$ eV.

Session	$\hat{\sigma}_{\chi N}$ [10^{-52} cm^2]	$\Delta\sigma^{\rm stat}_{\chi N}$ [10^{-52} cm^2]	$\Delta\sigma^{\rm sys}_{\chi N}$ [10^{-52} cm^2]
120-1	−1.68	2.24	1.05
120-2	0.83	1.13	1.05
174	−0.07	0.69	0.91
176	0.23	0.67	1.09
294	0.87	0.40	0.49
376-1	1.15	1.02	0.71
376-2	0.52	0.72	0.71
380-1	−1.88	0.33	0.16
380-2	−2.37	0.30	0.16
452	1.57	0.97	0.49
454	0.35	0.53	0.63
778-1	−0.82	0.73	0.64
778-2	0.40	0.83	0.64

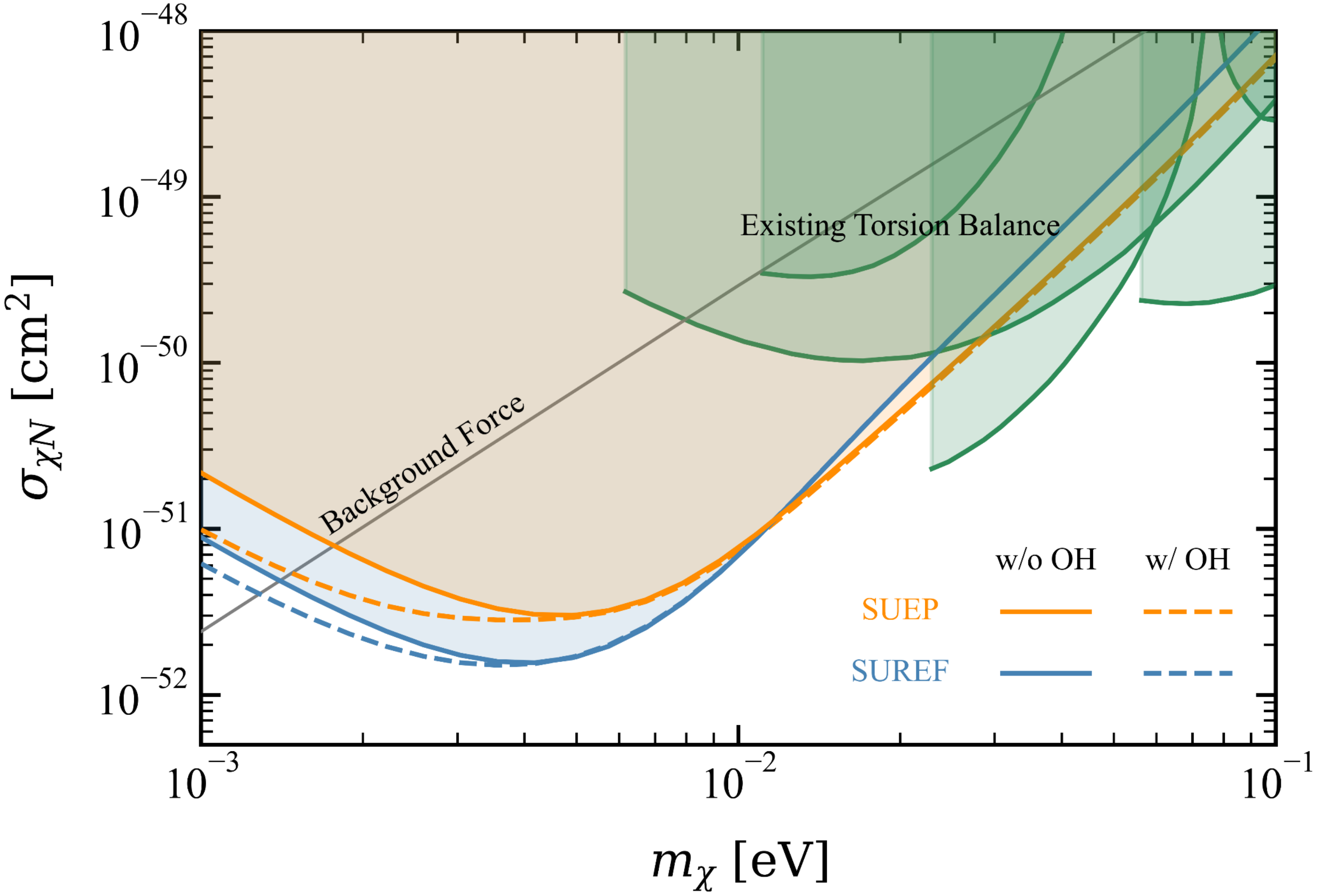
TABLE III: Session-level fitted cross section for SUEP w/o OH at $m_\chi = 5 \times 10^{-3}$ eV.

Session	$\hat{\sigma}_{\chi N}$ [10^{-52} cm^2]	$\Delta\sigma^{\rm stat}_{\chi N}$ [10^{-52} cm^2]	$\Delta\sigma^{\rm sys}_{\chi N}$ [10^{-52} cm^2]
210	11.78	3.80	0.77
212	1.71	3.44	0.43
218	−1.90	2.27	0.46
234	1.89	2.13	0.39
236	2.69	1.53	0.46
238	0.22	1.42	0.45
252	1.70	1.76	0.39
254	1.66	1.46	0.53
256	−0.52	1.86	0.39
326-1	3.63	2.23	0.65
326-2	−1.79	4.02	0.59
358	0.85	2.36	0.40
402	12.66	10.83	2.65
404	2.63	1.54	0.37
406	−0.35	4.48	1.20
438	−4.20	7.06	2.25
442	2.65	5.95	3.05
748	26.93	17.99	3.43
750	5.46	11.16	3.36

Weighted Combination:

$$\bar{\sigma}_{\chi N}(m_\chi) = \frac{\sum_l w_l(m_\chi)\hat{\sigma}_{\chi N,l}(m_\chi)}{\sum_l w_l(m_\chi)}, w_l(m_\chi) = [\sigma^{stat}_{\chi N,l}(m_\chi)]^{-2}$$

Constraints on DM–Nucleon Scattering from MICROSCOPE



- Contribution of the Outer Housing(OH)

When $\lambda_{\mathrm{DM}} \sim R_{\mathrm{OH}}$, coherent interference further strengthens the constraint.

Fu et al., arXiv:2606.07008 (2026)

Summary

- We resolve the individual-force problem in long-wavelength coherent scattering involving multiple macroscopic objects

$$F_i = -\int d^3r|\psi(r)|^2\nabla V_i(r)$$

- Applying the formalism to MICROSCOPE data, we derive leading constraints on quadratic DM–nucleon coupling

$$m_\chi \sim 10^{-3} - 10^{-2}\ \mathrm{eV} \qquad \sigma_{\chi N} \sim 10^{-52}\ \mathrm{cm}^2$$

Thank you