基于旋转扭秤的暗物质散射截面探测

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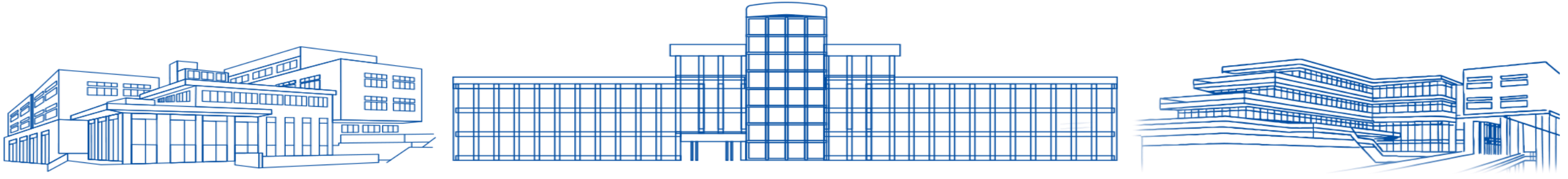
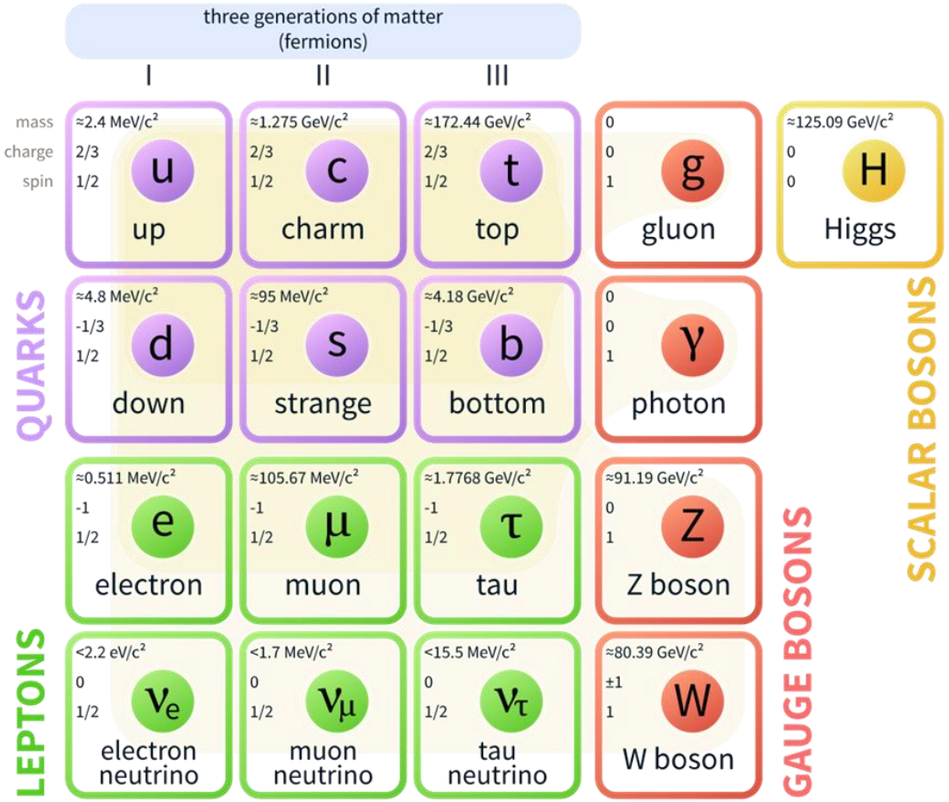
2026.07.22



报告内容

粒子物理标准模型



待解答的问题：

- 暗物质

  标准模型中没有合适的候选者

- 强CP破坏问题

  QCD轴子axion

- 正反物质不对称

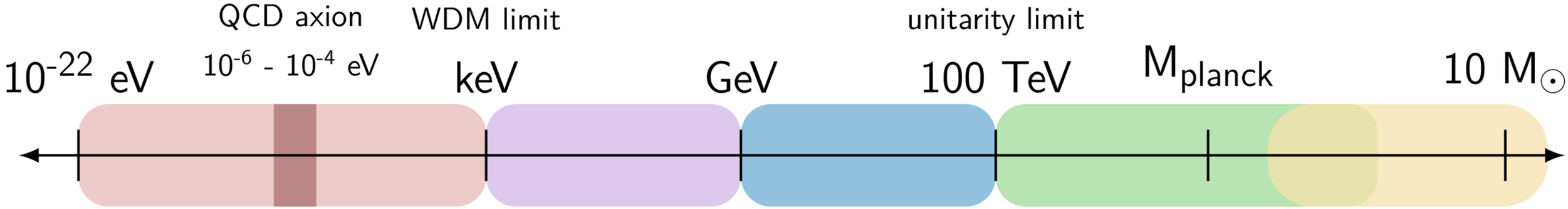
- …

新的粒子？新的相互作用？

Frank Wilczek. *et al*., PRD, 1984, 30(1):130
Paul Langacker, RevModPhys.81.1199
Lotty Ackerman. *et al*., PRD 79, 023519(2009)

暗物质的质量标度

(未按比例)



"Ultralight" DM
non-thermal
bosonic fields
(dark photon, Axion-like particle)

"Light" DM
dark sectors
sterile ν
can be thermal

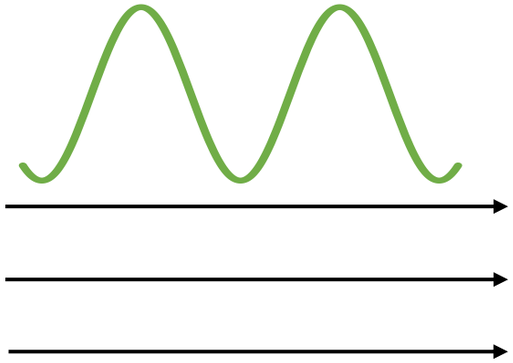
WIMP

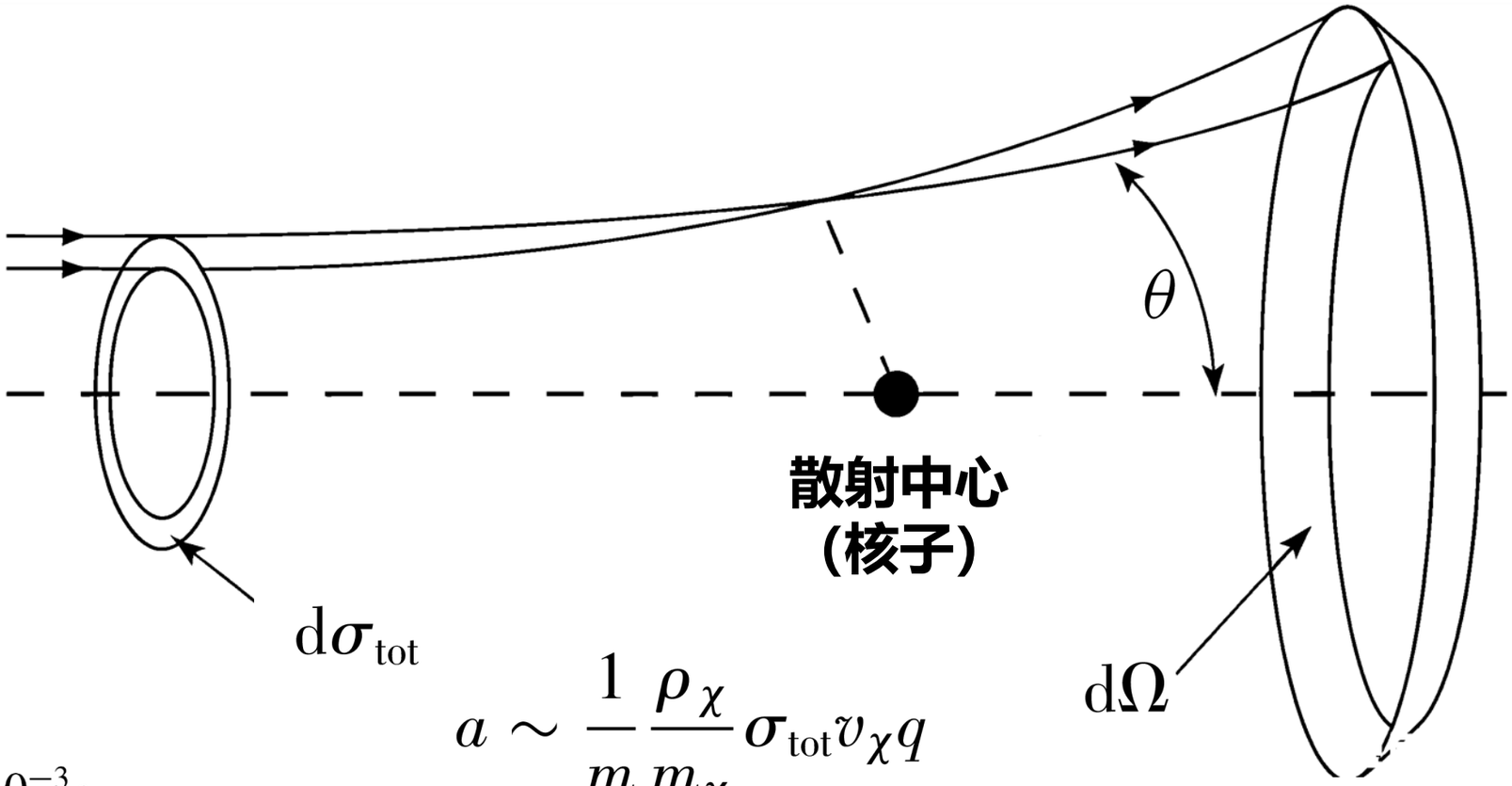
Composite DM
(Q-balls, nuggets, etc)

Primordial
black holes

Tongyan Lin, arXiv: 1904.07915 (2019)

1 研究背景——暗物质散射动量转移





$$\mathscr{L}_{\text{eff}} = \pm\frac{\bar{N}N\phi^2}{2f}$$

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

速度：$v_\chi \simeq 10^{-3}c$

密度：$\rho_\chi \simeq 0.4\,\text{GeV/cm}^3$

粒子入射动量：$q \simeq m_\chi v_\chi$

粒子质量：$m_\chi \ll m_N$

若 $1/q$ 远大于靶尺寸　$\sigma_{\chi A}^{\text{tot}} = A^2\sigma_{\chi N}(\cdot N_A^2)$

靶尺寸 $\simeq 1\,\text{mm}, m_\chi \lesssim 0.1\text{eV}$

Luo. *et al.*, PRD 112 (2025) 075023

1 研究背景——扭秤技术灵敏度

国家精密重力测量科学中心
NATIONAL GRAVITATION LABORATORY

等效原理检验

TABLE I. Error budgets of the experiments, unit: 10^{-17} N m. Uncertainties are 1-σ.

	$\phi_0 = \pi/4$	
Error sources	$\tau_{\sin}$	$\tau_{\cos}$
Measurement and statistical uncertainty	5.32 ± 0.42	-8.33 ± 0.39
Tilt	-5.21 ± 0.06	-16.57 ± 0.06
Wobble	-0.50 ± 0.03	0.29 ± 0.03
Rotation rate variation	5.63 ± 0.11	5.98 ± 0.12
Magnetic field	-0.84 ± 0.04	0.12 ± 0.04
$q_{21}Q_{21}$ coupling	6.55 ± 0.13	-1.31 ± 0.13
$q_{31}Q_{31}$ coupling	-0.57 ± 0.05	-0.16 ± 0.05
$q_{41}Q_{41}$ coupling	1.86 ± 0.17	4.78 ± 0.17
Temperature gradient	0.00 ± 0.06	0.00 ± 0.06
Corrected [a]	$-1.60 \pm 0.42 \pm 0.26$	$-1.46 \pm 0.39 \pm 0.27$

[a]The first uncertainty is the statistical shown in Fig. 4, and the second is systematic.

$$u(\tau) \sim 10^{-18}\ \mathrm{N\,m}$$

L. Zhu *et al.*, PRL 121, 261101 (2018)

2018年弱等效原理检验实验装置

报告内容

1 背景介绍

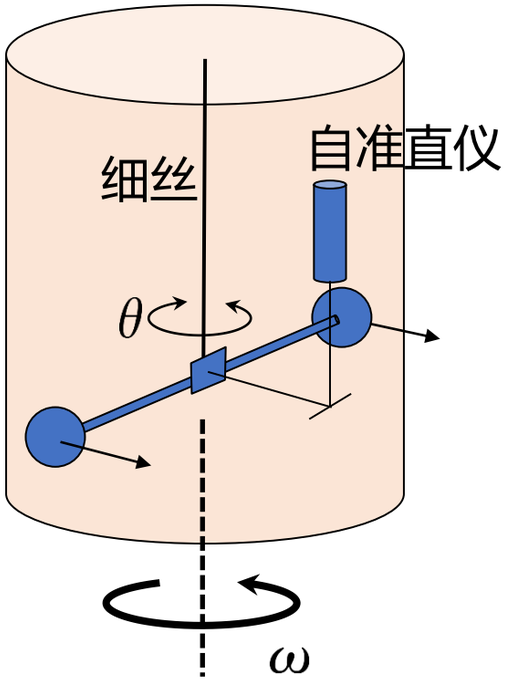
2 方案设计

3 扭摆设计

4 预期结果

2 旋转扭秤测量原理

基本结构



匀速旋转
(~1000s/rev)

待测力矩信号：

转台旋转

$$\tau_0 \Longrightarrow \tau = \tau_0 \sin(\omega t + \phi_0)$$

引起的偏转角：

$$\theta(\omega) = \tau(\omega) \cdot H(\omega)$$

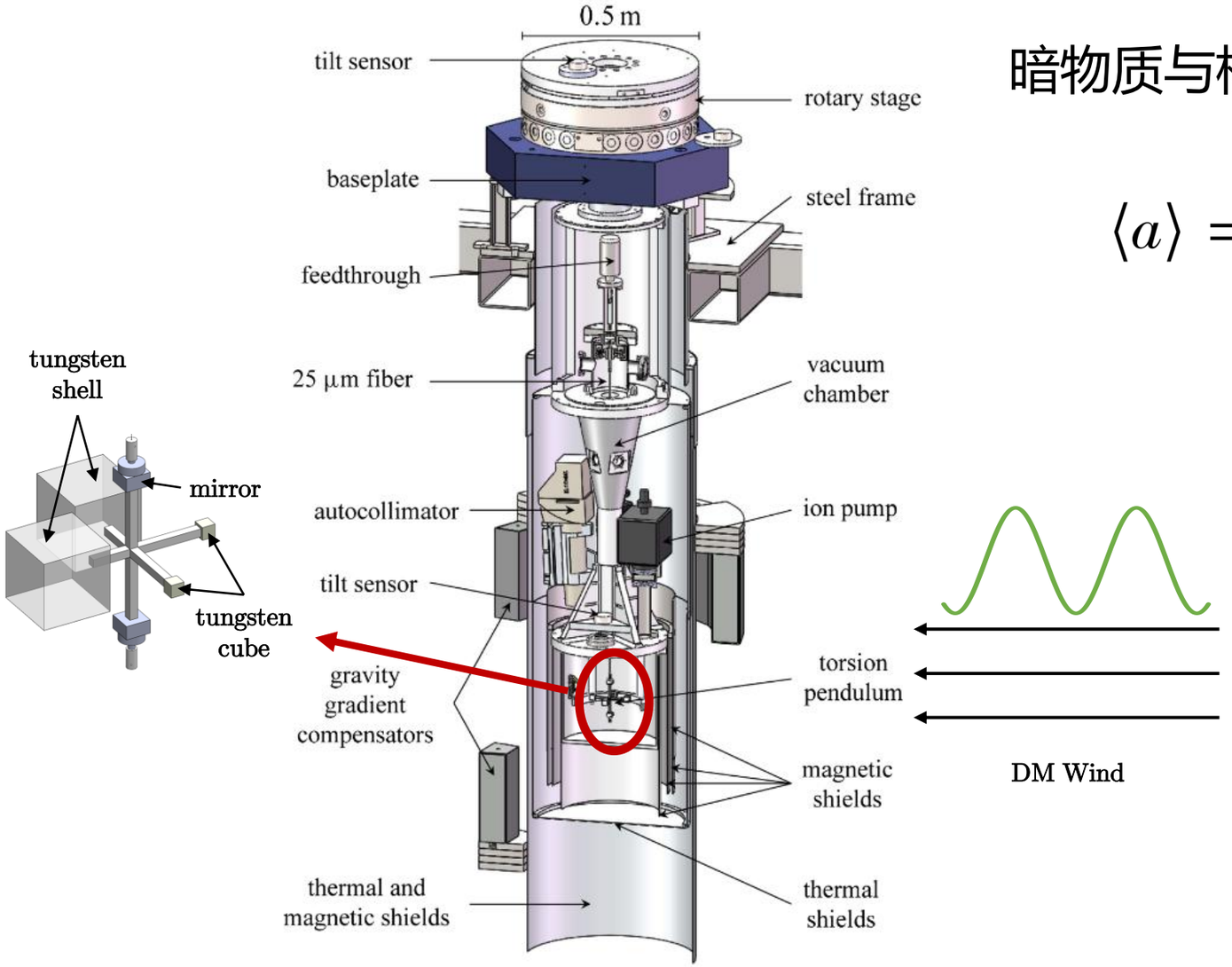
其中传递函数：

$$H(\omega) = \frac{1}{k} \frac{\omega_0^2}{(\omega_0^2 - \omega^2) + i(2\gamma\omega + \epsilon\omega_0^2)}$$

k：弹性系数　　ϵ：耗散角　　I：转动惯量

$$\omega_0 = \sqrt{k/I}$$　　γ：气体阻尼系数

2 方案设计



暗物质与核子相干散射产生的平均加速度：

$$\langle a \rangle = \frac{n_\chi}{m_{\rm tot}} \int \mathrm{d}^3\vec{v}_\chi \, \mathrm{d}\Omega'_\chi q_z |\vec{v}_\chi| f(\vec{v}_\chi) \frac{\mathrm{d}\sigma_{\rm tot}(q)}{\mathrm{d}\Omega'_\chi}$$

$$q_z = m_\chi |\vec{v}_\chi - \vec{v}'_\chi|$$

暗物质动量转移量

$f(\vec{v}_\chi)$ 暗物质的动量分布 (Maxwell-Boltzmann)

$\frac{\mathrm{d}\sigma_{\rm tot}(q)}{\mathrm{d}\Omega'_\chi}$ 微分散射截面

$$\Delta a \equiv |\langle a \rangle_{块} - \langle a \rangle_{壳}|$$

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扭摆设计

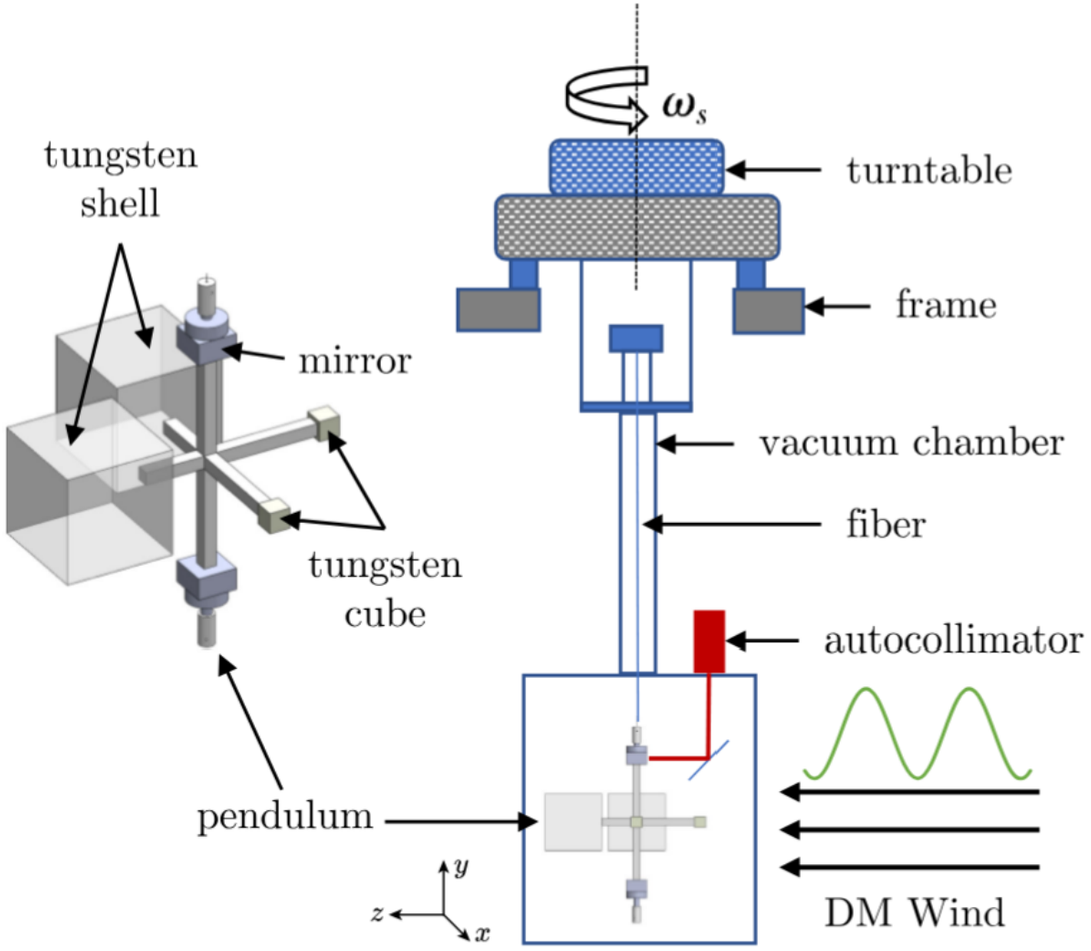
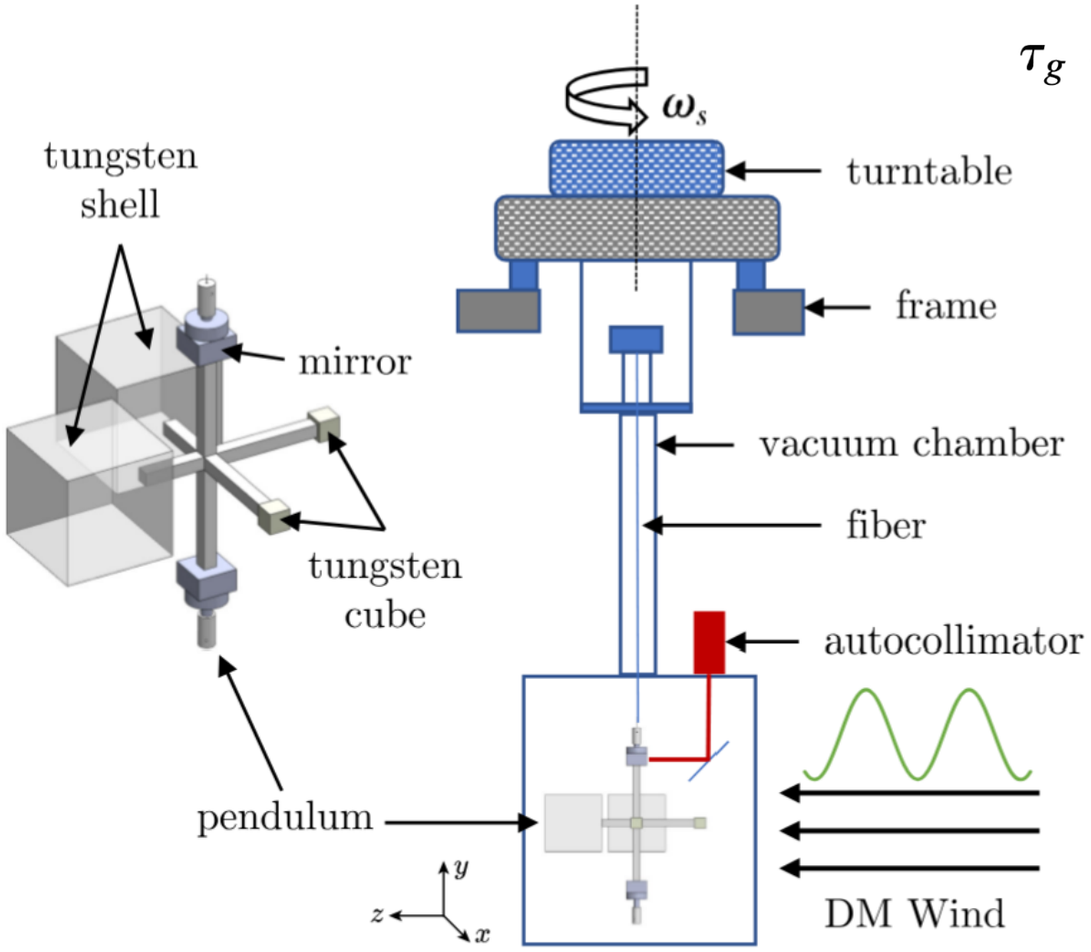


TABLE I. Parameters of the test bodies: their edge lengths (L_{cube} and L_{shell}), the thickness of the shell (δ), and their masses (m_{tot}). The density of the tungsten is 19.25 g/cm^3.

	Material	Edge length	Thickness	Mass
Cube	Tungsten	0.804 cm	···	10.0 g
Shell	Tungsten	4.166 cm	50 μm	10.0 g

钨块	边长：8.039mm		
钨壳	外边长：41.663mm，厚0.05mm		
反射镜	15mm	15mm	8.5mm
短杆	40/23.188mm	5/5mm	5/13.769mm
长杆	5mm	5mm	85mm

扭摆设计



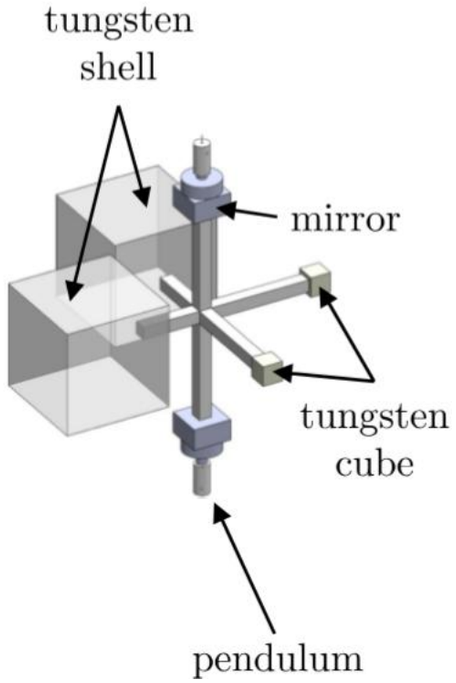
$$\tau_g = 8\pi G \sum_{\ell=1}^{\infty} \frac{1}{2\ell+1} \sum_{m=0}^{\ell} m|\tilde{q}_{\ell m}|\cdot|Q_{\ell m}| \sin\left(\phi_{\tilde{q}_{\ell m}} + \phi_{Q_{\ell m}} - m\omega_s t\right)$$

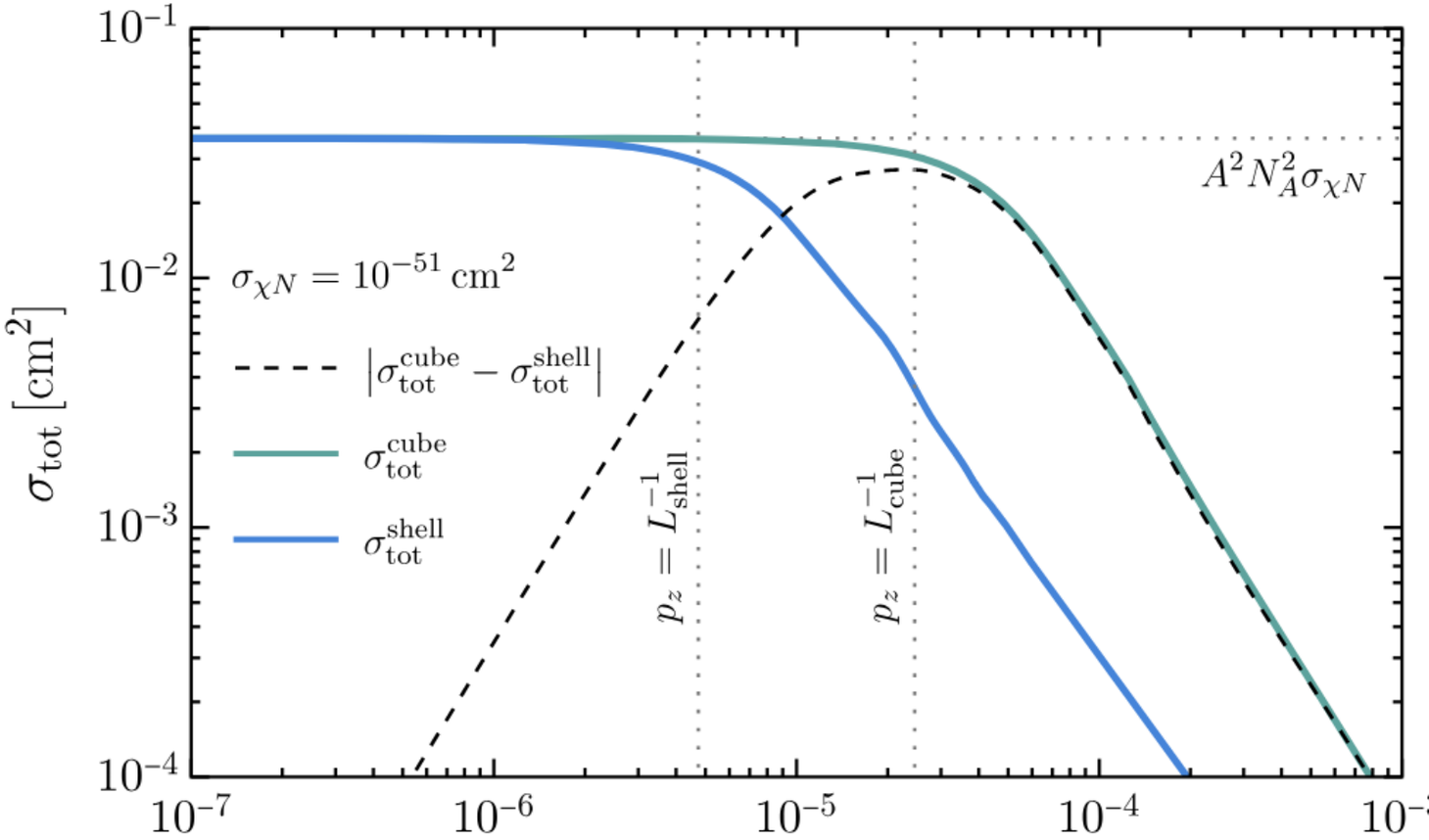
$$\tilde{q}_{\ell m} = \iiint \rho_p(r_p, \vartheta_p, \varphi_p) r_p^{\ell} \, Y^*_{\ell m}(\vartheta_p, \varphi_p) \, \mathrm{d}V_p,$$

$$Q_{\ell m} = \iiint \rho_s(r_s, \vartheta_p, \varphi_p) \frac{1}{r_s^{\ell+1}} \, Y_{\ell m}(\vartheta_s, \varphi_s) \, \mathrm{d}V_s.$$

	m=1	2	3	4	单位
l=1	-0.000+0.000i	-	-	-	g cm
2	0	0	-	-	g cm^2
3	10.06-10.06i	0	-11.84-11.86i	-	g cm^3
4	0	0	0	8349	g cm^4

暗物质散射信号





$$\sigma_{\chi N} \simeq 10^{-51}\,{\rm cm}^2$$

报告内容

1 背景介绍

2 方案设计

3 扭摆设计

4 预期结果

4 测量不确定度——统计

TABLE I. Error budgets of the experiments, unit: 10^{-17} N m. Uncertainties are 1-σ.

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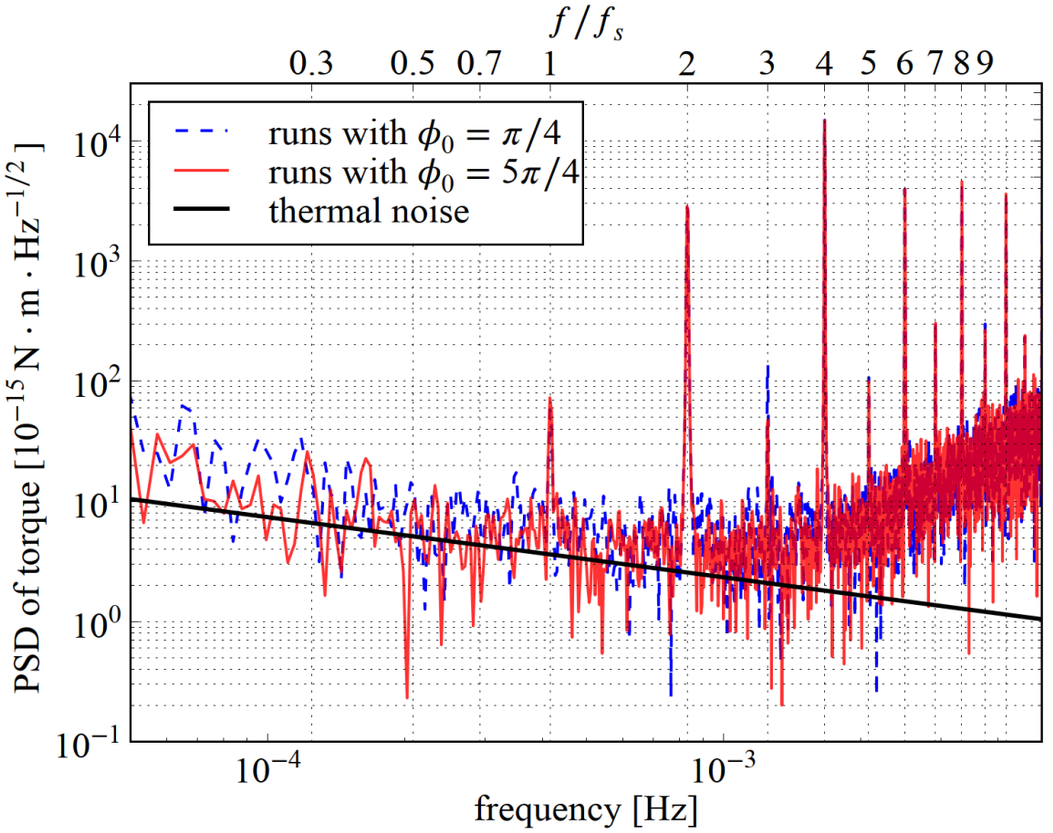

统计不确定度（81天）：

$$u_{\mathrm{sta}}(\tau) = 2.6 \times 10^{-18}\mathrm{N \cdot m}$$

L. Zhu *et al.*, PRL 121, 261101 (2018)

4 测量不确定度——系统效应

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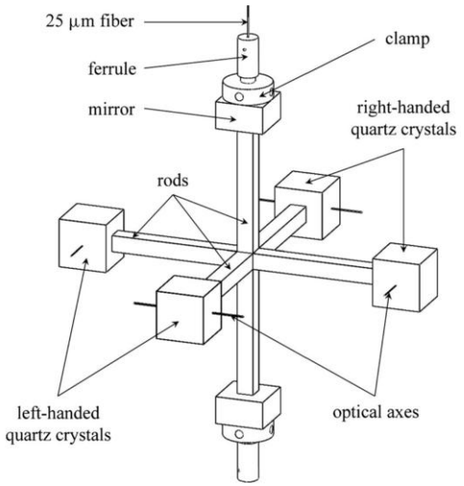
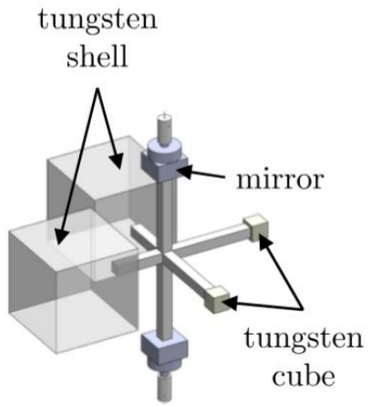
	不确定度（N m）
转轴倾斜	0.6×10^{-18}
转轴晃动	0.3×10^{-18}
磁场	0.4×10^{-18}
引力梯度	5.0×10^{-18}
温度梯度	6.0×10^{-18}
合计	7.9×10^{-18}





4 预期结果

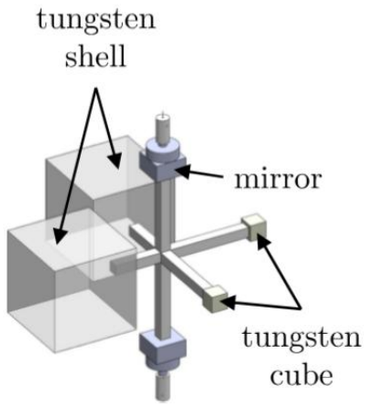
$$u_{\mathrm{sta}}(\tau) = 2.6 \times 10^{-18}\,\mathrm{N \cdot m}$$

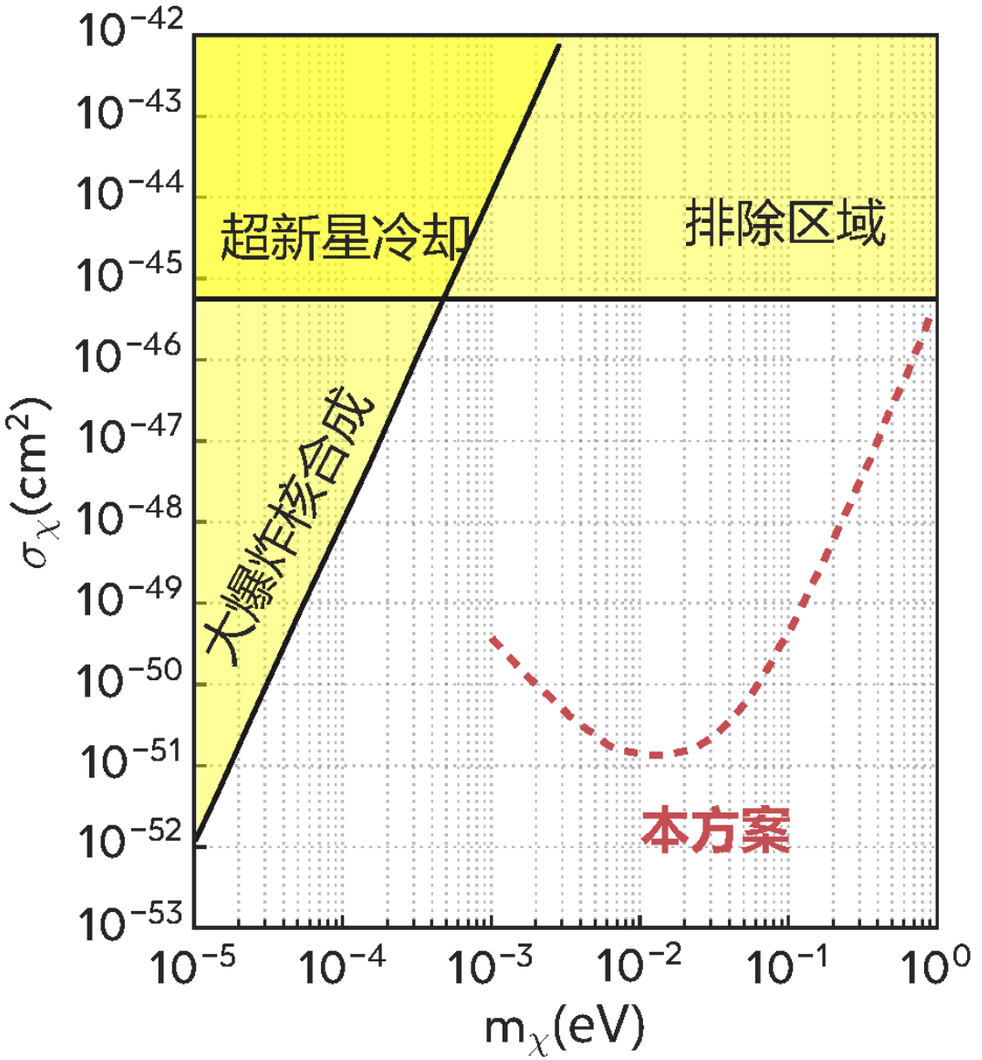
合成不确定度：

$$u(\tau) = \sqrt{u_{\mathrm{sta}}^2(\tau) + u_{\mathrm{sys}}^2(\tau)}$$

$$= 8.3 \times 10^{-18}\,\mathrm{N \cdot m}$$

$$\Delta a_z = 1.4 \times 10^{-14}\,\mathrm{m/s^2}$$





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