北京大学物理学院
SCHOOL OF PHYSICS,PEKING UNIVERSITY

核物理与核技术全国重点实验室
State Key Laboratory of Nuclear Physics and Technology

Search for Dark Matter with Levitated Ferromagnetic Spin Sensor

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Xichang, 2025.08.26

TAUP XICHANG

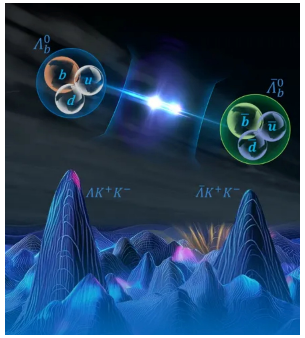
New Physics

Do spins couple to gravity?

How to include Gravity?

Dark Matter
and
Dark Energy

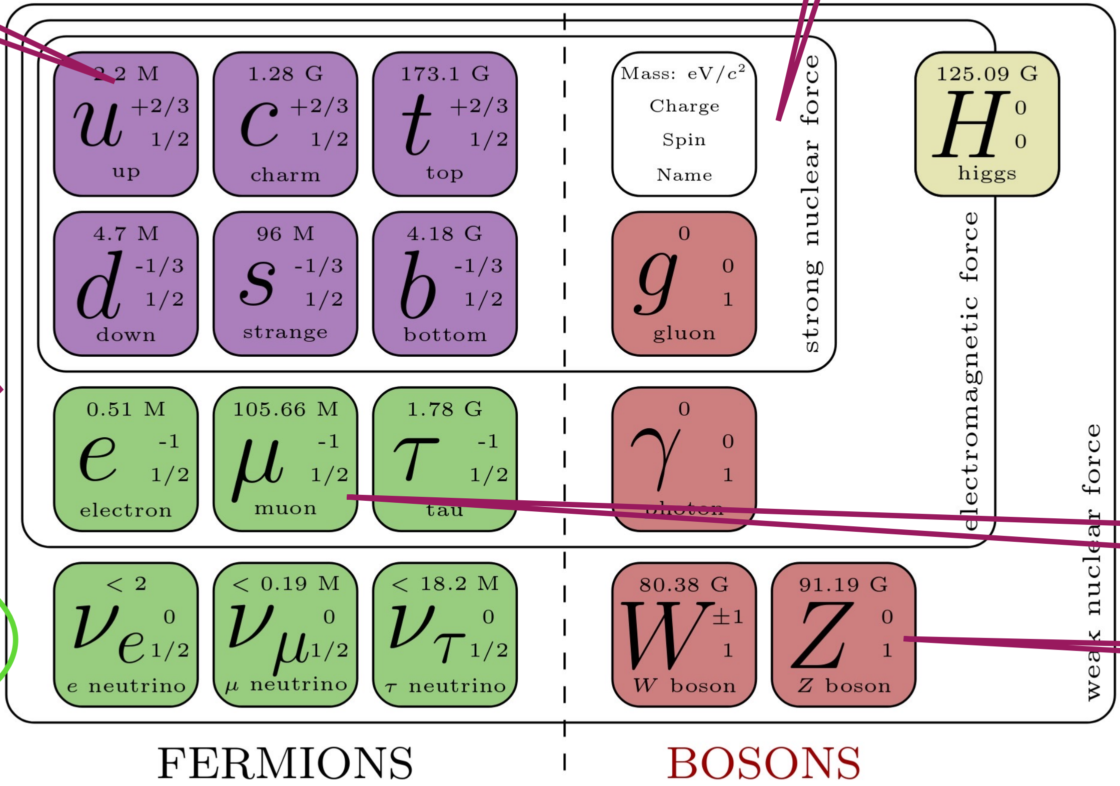
Why does the universe look like this?



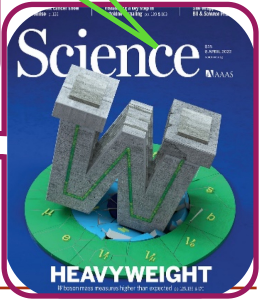
Strong CP problem

Why more matter than antimatter

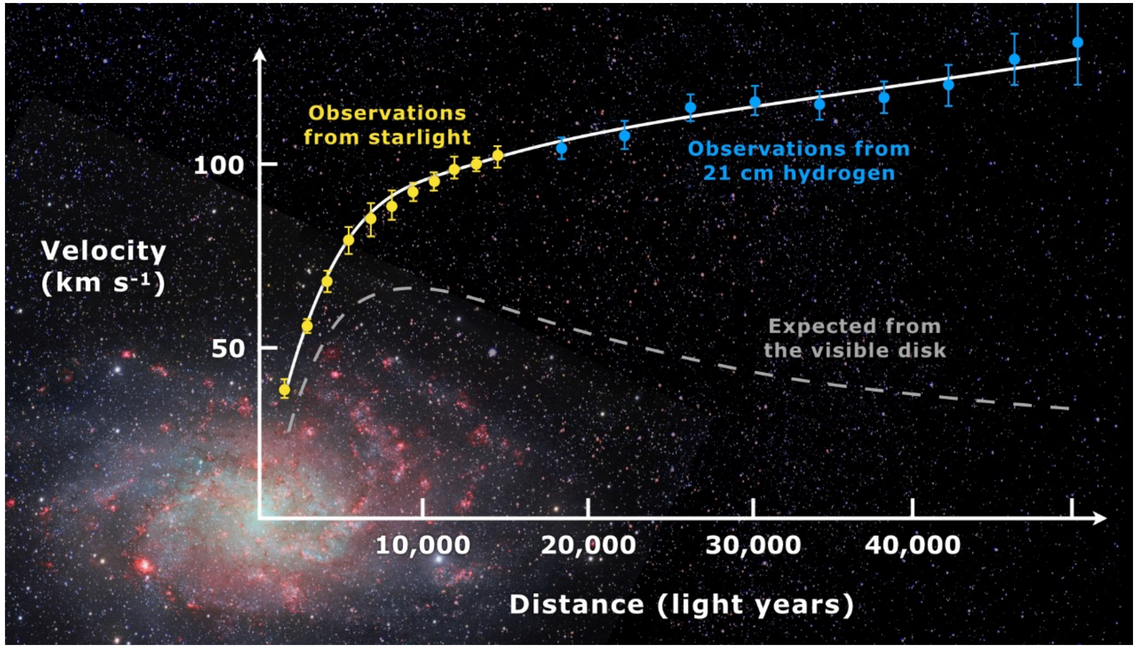
Why do we exist?



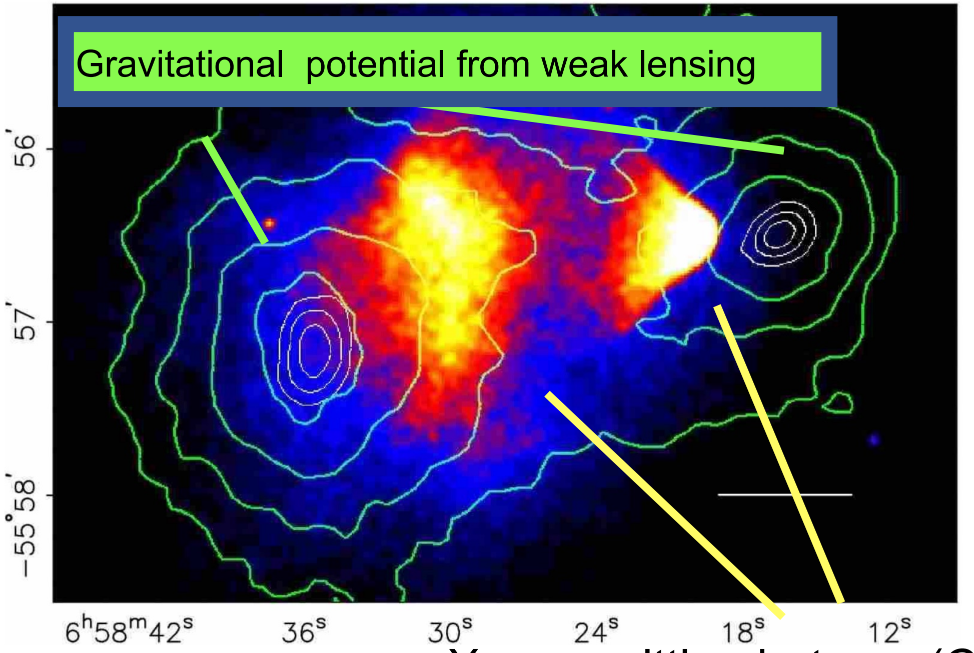
Fifth force?



Dark Matter



M33 Galaxy, Velocity v.s. Distance from the center



X-ray emitting hot gas (Chandra)

D. Clowe, et al. Astrophys. J. Lett. 648, L109 (2006)

Fritz Zwicky

Coma Cluster

1930s

5 times more than normal matter!

Dark Matter Mass Range

Wave-Like — Particle-Like

Axion Window

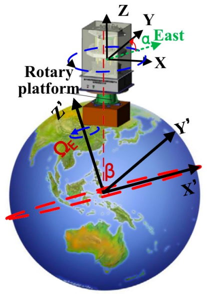
10^{-22}eV | 10μeV $- 1meV$ | keV | GeV | 100TeV

Ultralight Bosonic DM

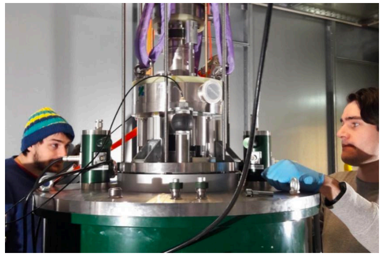
Table-top Experiments

Cavity Experiments

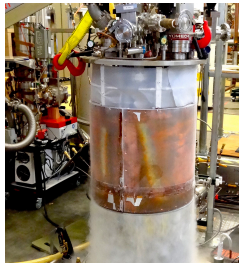
ChangE



CASPEr



ADMX, CAPP

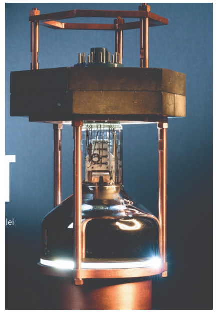


SRF

Light DM

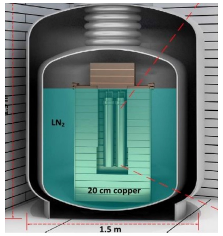
Sterile ν

COHERENT



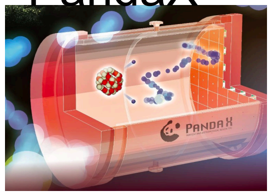
WIMPs

CDEX



DOPMPE

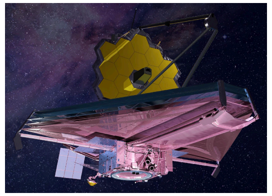
PandaX



XENON, LUX, Accelerator etc

Composite DMs & Primordial Black holes

James Webb Telescope



Exotic Spin-Dependent Force

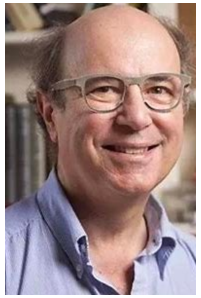
Scalar and Pseudoscalar Coupling (Axion)

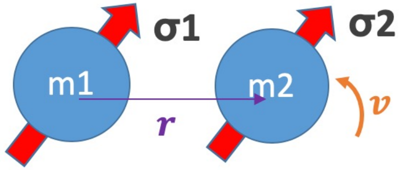
$$V_3 = \frac{g_p g_p \hbar^3}{16\pi c m_1 m_2}\left[(\hat{\boldsymbol{\sigma}}_1 \cdot \hat{\boldsymbol{\sigma}}_2)\left(\frac{1}{\lambda r^2}+\frac{1}{r^3}+\frac{4\pi}{3}\delta(r)\right) - (\hat{\boldsymbol{\sigma}}_1 \cdot \hat{\boldsymbol{r}})(\hat{\boldsymbol{\sigma}}_2 \cdot \hat{\boldsymbol{r}})\left(\frac{3}{\lambda r^2}+\frac{3}{r^3}+\frac{1}{r\lambda^2}\right)\right] e^{-r/\lambda},$$

Vector and Axial Vector Coupling (Z')

$$V_{4+5} = \frac{(g_A^2 - 3g_V^2)\hbar^2}{16\pi m c}\left[(\hat{\boldsymbol{\sigma}} \cdot (\boldsymbol{v} \times \hat{\boldsymbol{r}})\right]\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right) e^{-r/\lambda},$$

$$V_8 = \frac{g_A g_A \hbar}{4\pi c}\left[(\hat{\boldsymbol{\sigma}}_1 \cdot \mathbf{v})(\hat{\boldsymbol{\sigma}}_2 \cdot \mathbf{v})\right]\left(\frac{1}{r}\right) e^{-\frac{r}{\lambda}}$$





New macroscopic forces?

Phys. Rev. D 30, 130 (1984).

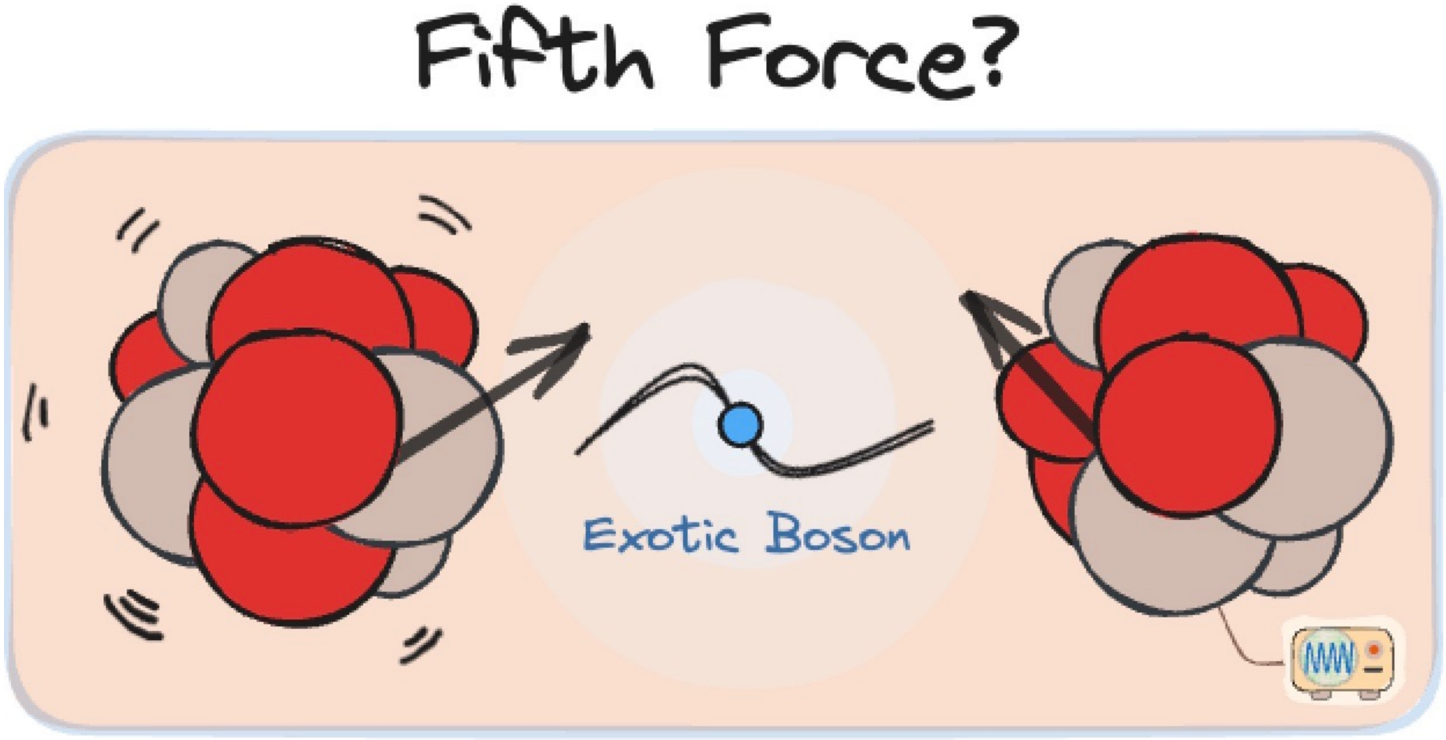
J. E. Moody* and Frank Wilczek
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106

(Received 17 January 1984)

Spin-dependent macroscopic forces from new particle exchange

B. A. Dobrescu and I. Mocioiu, J. High Energy Phys. 11 (2006) 005

Review



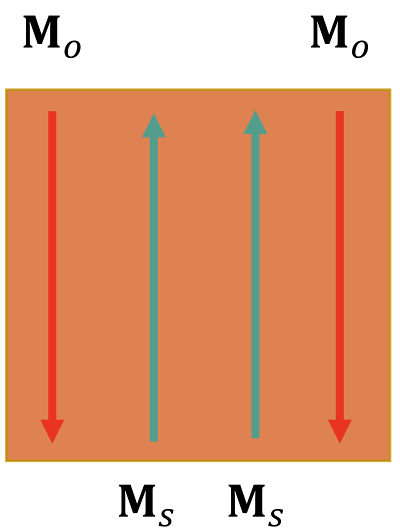
Lei Cong, **Wei Ji** et al, Rev. of Mod. Phys. 97,April-June,(2025)

Electron Spin Source

^{87}Rb (Wang *et al.*, 2022)	$\eta_e = 0.06$, $\eta_p = 0.31$ low polarisation limit (Jackson Kimball, 2015)	$n_A \approx 3.8 \times 10^{14}$ (Wang *et al.*, 2022)
$SmCo_5$ (Heckel *et al.*, 2008; Ji *et al.*, 2017)	$\eta'_e = 0.51$ (Heckel *et al.*, 2008)	$n_e \approx 4.2 \times 10^{22}$ @ 0.96 T (Heckel *et al.*, 2008)
Alnico 5 (Heckel *et al.*, 2008)	$\eta'_e = 0.95$(Heckel *et al.*, 2008)	$n_e \approx 7.8 \times 10^{22}$ @0.96 T (Heckel *et al.*, 2008)
Iron (Heckel *et al.*, 2013; Ji *et al.*, 2017; Almasi *et al.*, 2020)	$\eta'_e = 0.96$ (Ji *et al.*, 2017)	$n_e \approx 8.2 \times 10^{22}$ @ 1 T (Ji *et al.*, 2017)
Dy-Fe alloys (Chui and Ni, 1993; Ritter *et al.*, 1990)	—	$n_e \approx 1.5 \times 10^{22}$ (Chui and Ni, 1993)
DyIG (Leslie *et al.*, 2014)	—	$n_e \approx 8 \times 10^{20}$ (Leslie *et al.*, 2014)
pentacene (Rong *et al.*, 2018a)	—	$n_e \approx 1.62 \times 10^{18}$ (Rong *et al.*, 2018a)

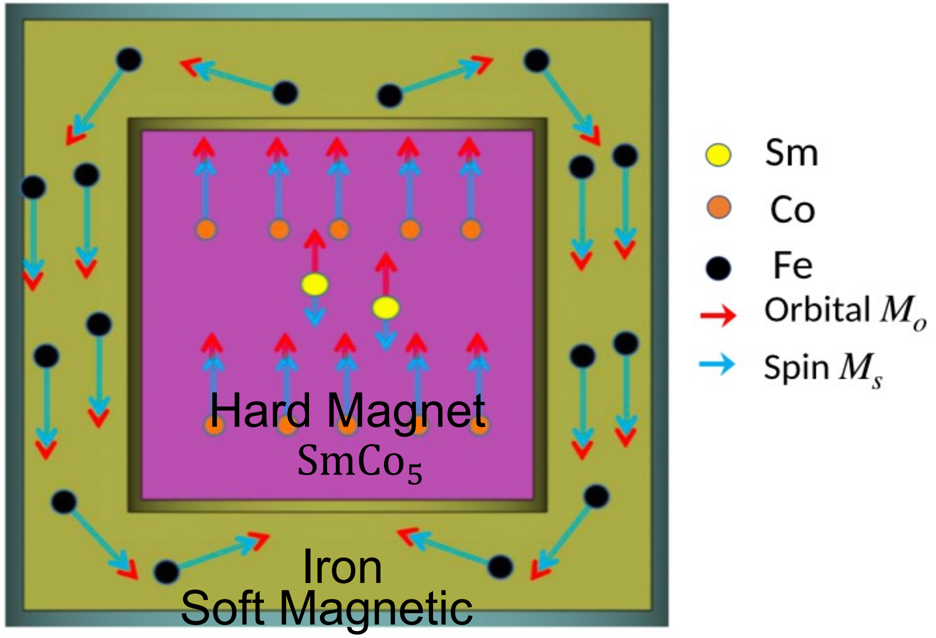
Lei Cong, **Wei Ji** et al, Rev. of Mod. Phys. 97,April-June,(2025)

Iron Shielded SmCo5 (ISSC)



$$\mathbf{M} = \sum \mathbf{M}_s + \mathbf{M}_o = 0$$

$$\mathbf{M_s} = \sum \mathbf{M}_s \neq 0$$

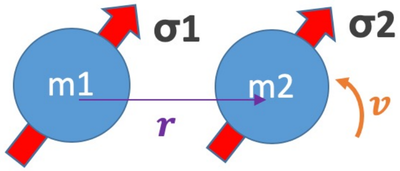


Ultra-low magnetic leakage! ($< \mu T$)
Ultra-high spin density! ($10^{22}/cm^3$)

Wei Ji et al, PRD, 95(7):075014,(2017)

Works that used ISSC source

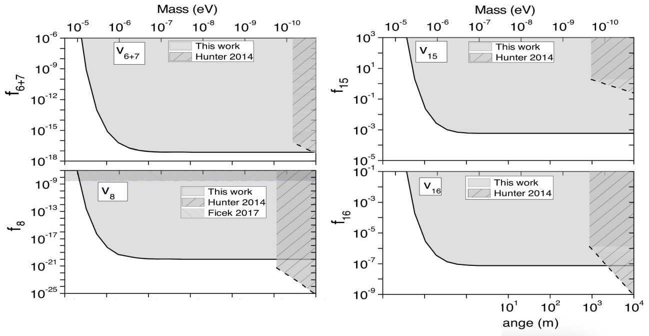
Our Team 2018



Wei Ji et al, PRD, 95(7):075014,(2017)

Wei Ji et al, PRL, 121: 261803,(2018)

e-e coupling

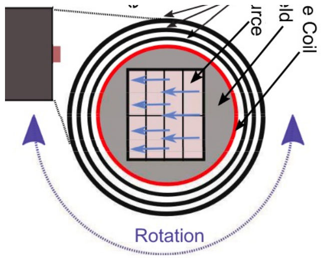


Princeton 2020

M. Romalis Group

PHYSICAL REVIEW LETTERS **125,** 201802 (2020)

e-n coupling



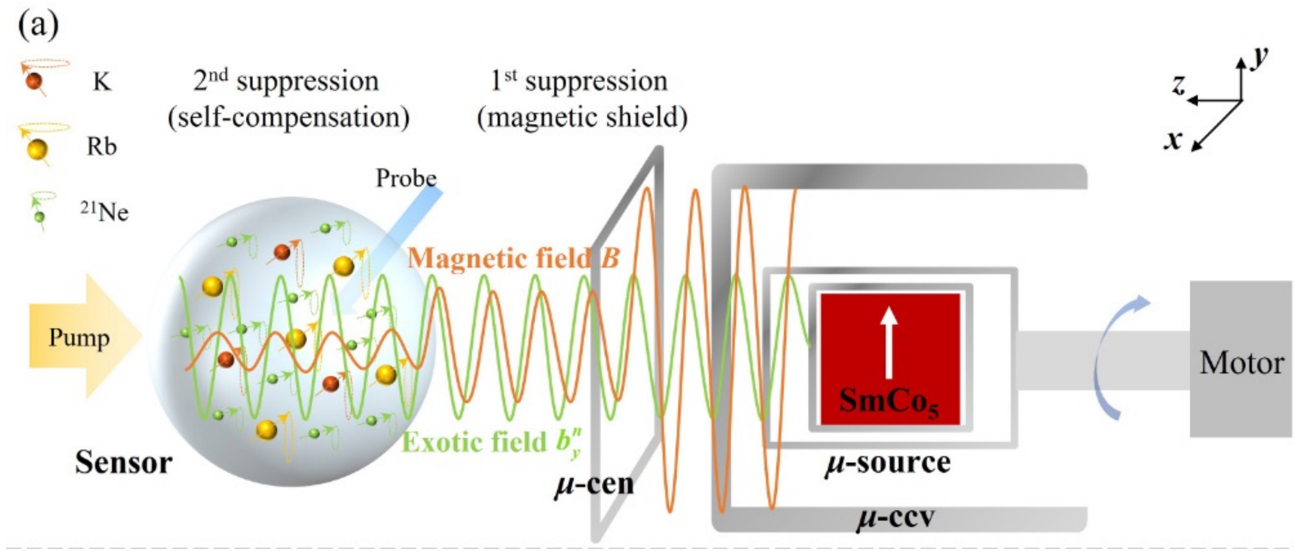
Our Team 2023

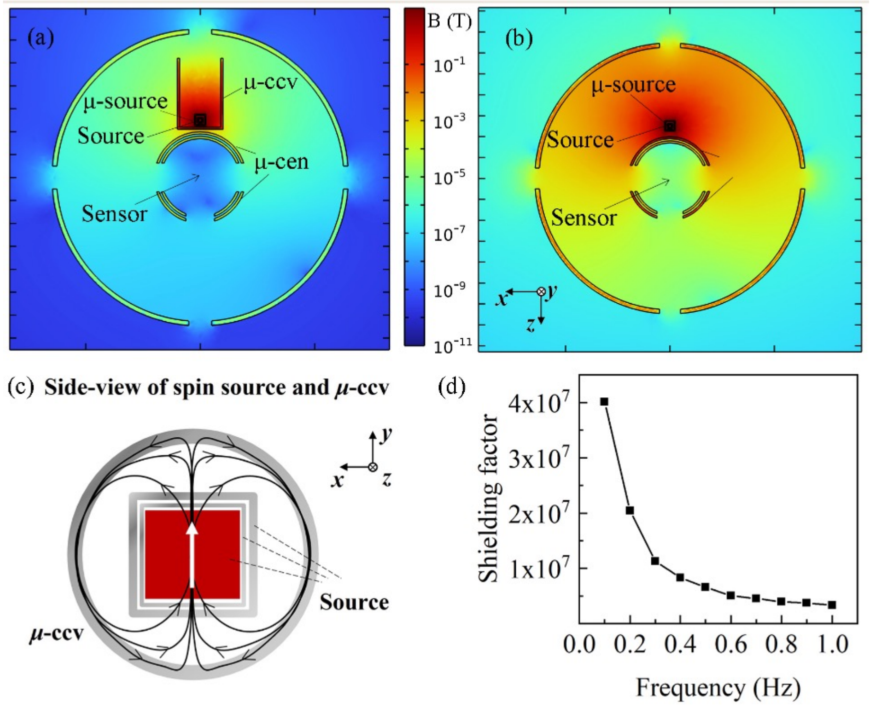
Wei Ji et al, PRL, 130:133202,(2023)

e-p coupling

Dipole-Dipole in Axion window

Axion Window (10μeV – 1meV)

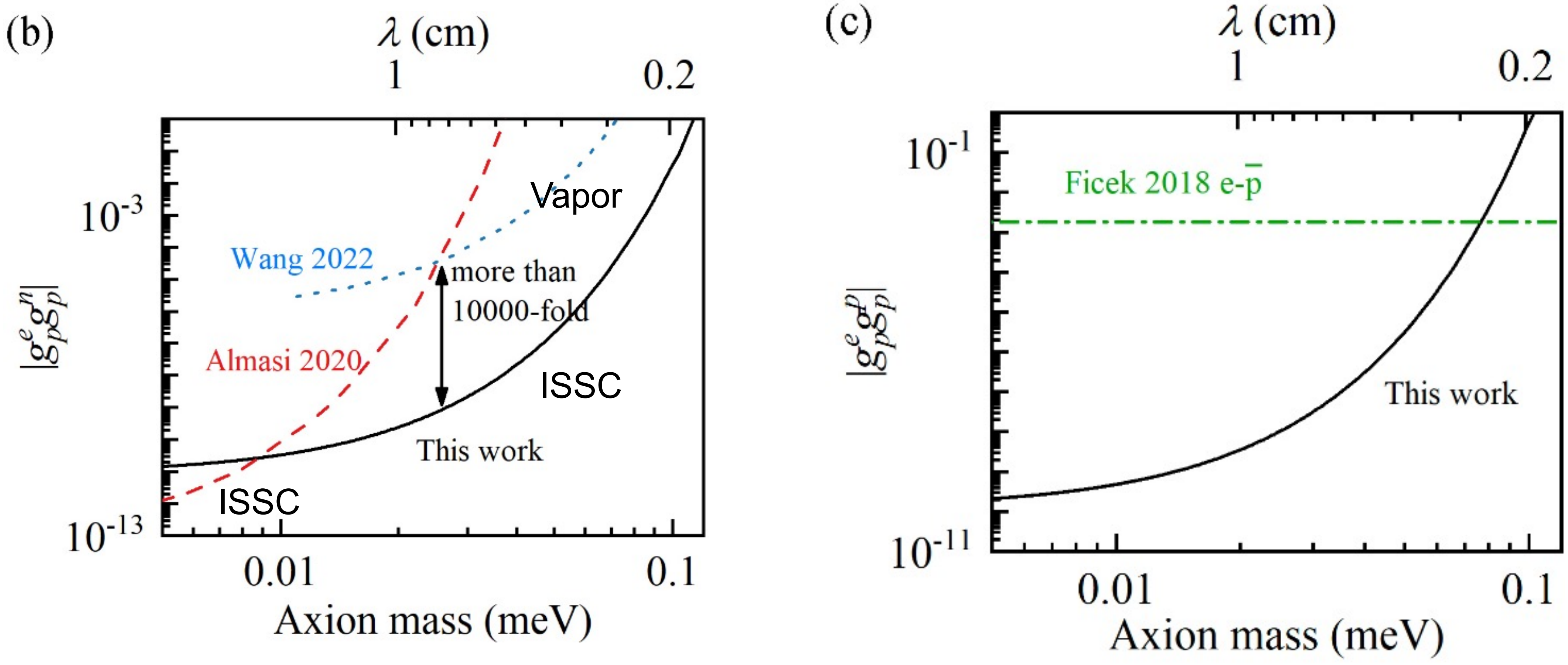




Z. Xu et al, Phys. Rev. Lett. 134, 181801 (2025)

Fifth Force Experiment

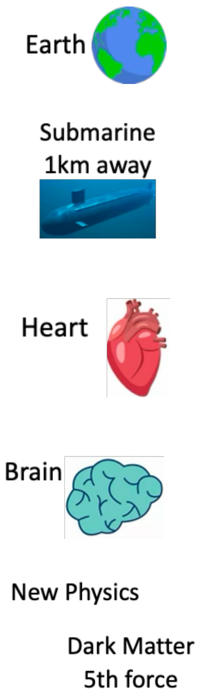
Z. Xu et al, Phys. Rev. Lett. 134, 181801 (2025)

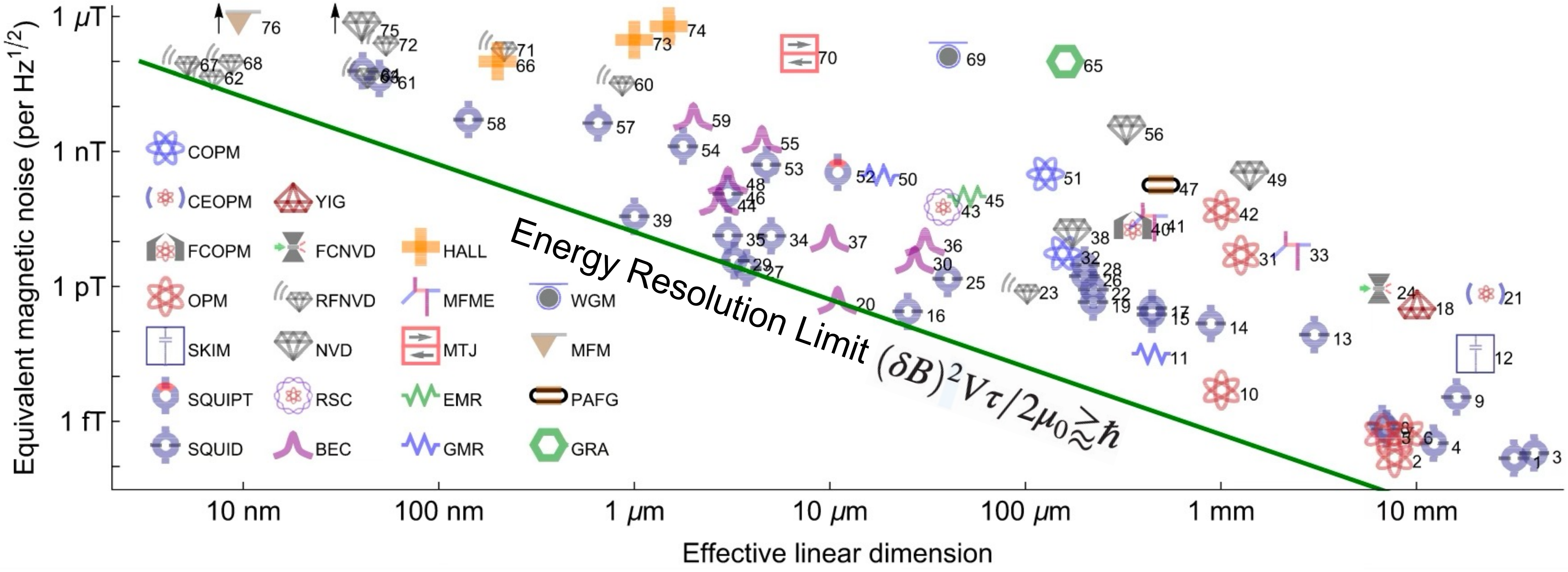


$$V_3 = \frac{g_p g_p \hbar^3}{16\pi c m_1 m_2}[(\hat{\boldsymbol{\sigma}}_1 \cdot \hat{\boldsymbol{\sigma}}_2)\left(\frac{1}{\lambda r^2} + \frac{1}{r^3} + \frac{4\pi}{3}\delta(r)\right) - (\hat{\boldsymbol{\sigma}}_1 \cdot \hat{\boldsymbol{r}})(\hat{\boldsymbol{\sigma}}_2 \cdot \hat{\boldsymbol{r}})\left(\frac{3}{\lambda r^2} + \frac{3}{r^3} + \frac{1}{r\lambda^2}\right)]e^{-r/\lambda},$$

Magnetic field Sensors

Morgan W. Mitchell et al, RMP,92, 2020



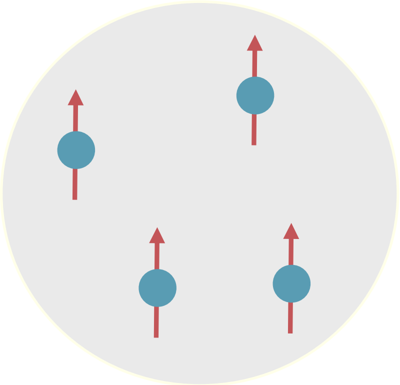


Dynamics of Ferromagnet

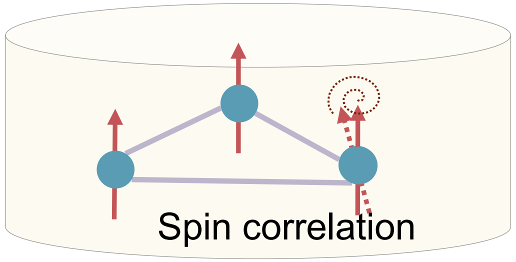


D. Budker DF Kimball Alex Sushkov

Atomic Vapor Cell



Ferromagnetic Magnet



- $t^{3/2}$ vs $t^{1/2}$ internal noise for correlated system, but external noise for uncorrelated one .
- Larger N number for solid system.

Spin Projection Noise

$$\delta B = \frac{\hbar}{g\mu_B}\frac{1}{\sqrt{NT_2 t}}$$

T_2 coherence time
N number of spins
$\gamma = \frac{\hbar}{g\mu_B}$ gyromagnetic ratio

$$\delta B = \frac{\hbar}{g\mu_B}\sqrt{\frac{2\alpha k_B T}{\hbar{\omega_0}^2}}\frac{1}{\sqrt{Nt^3}}$$

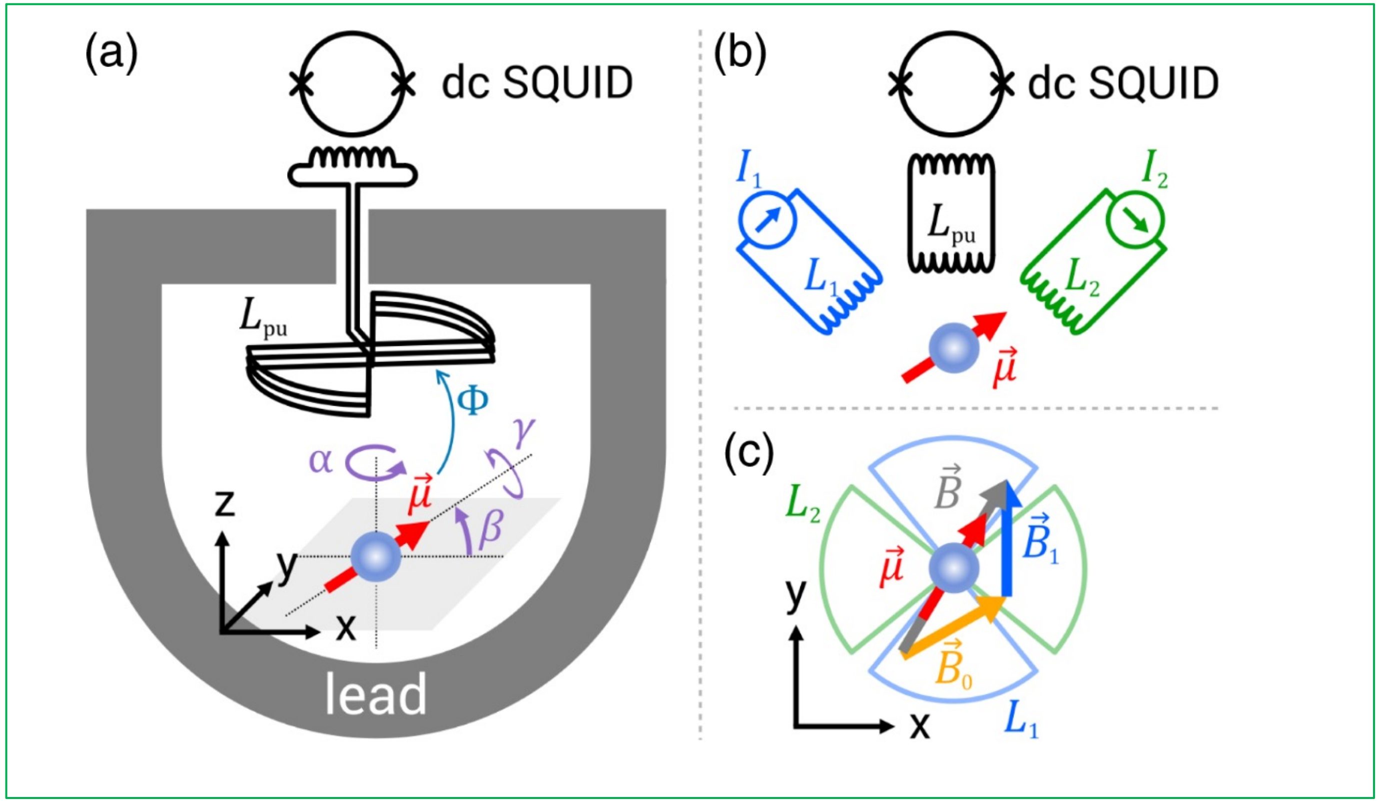
α Gilbert damping rate.

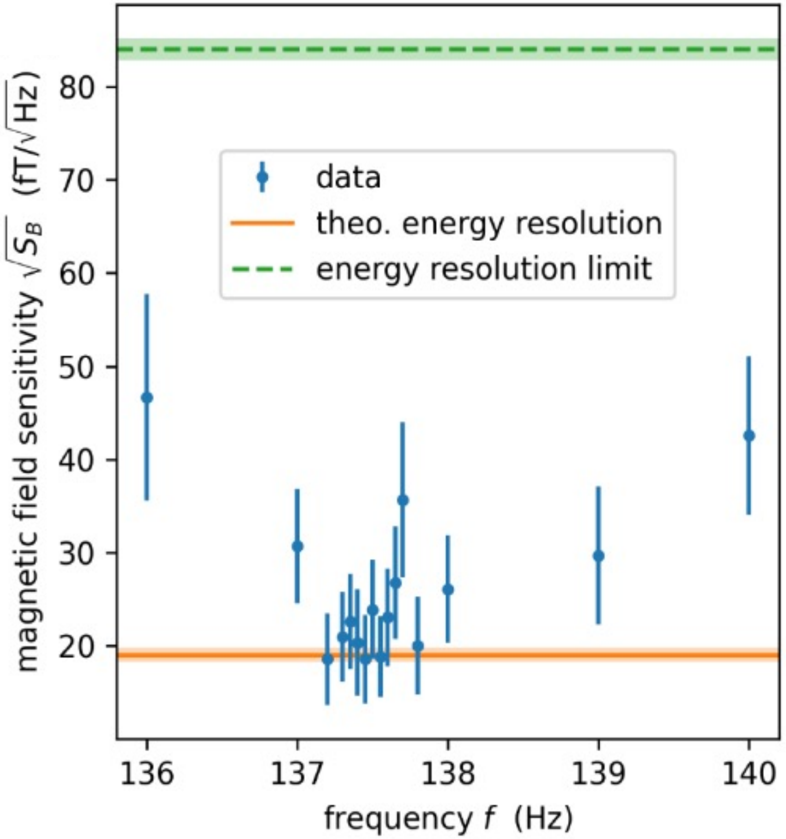
- 7 orders of magnitude smaller noise for same spin numbers!
- Much smaller size!

Kimball et al, PRL 116, 190801 (2016)

LeMaMa – Superconducting Levitation

LeMaMa: Levitated Magnet Magnetometer “悬铁”磁强计

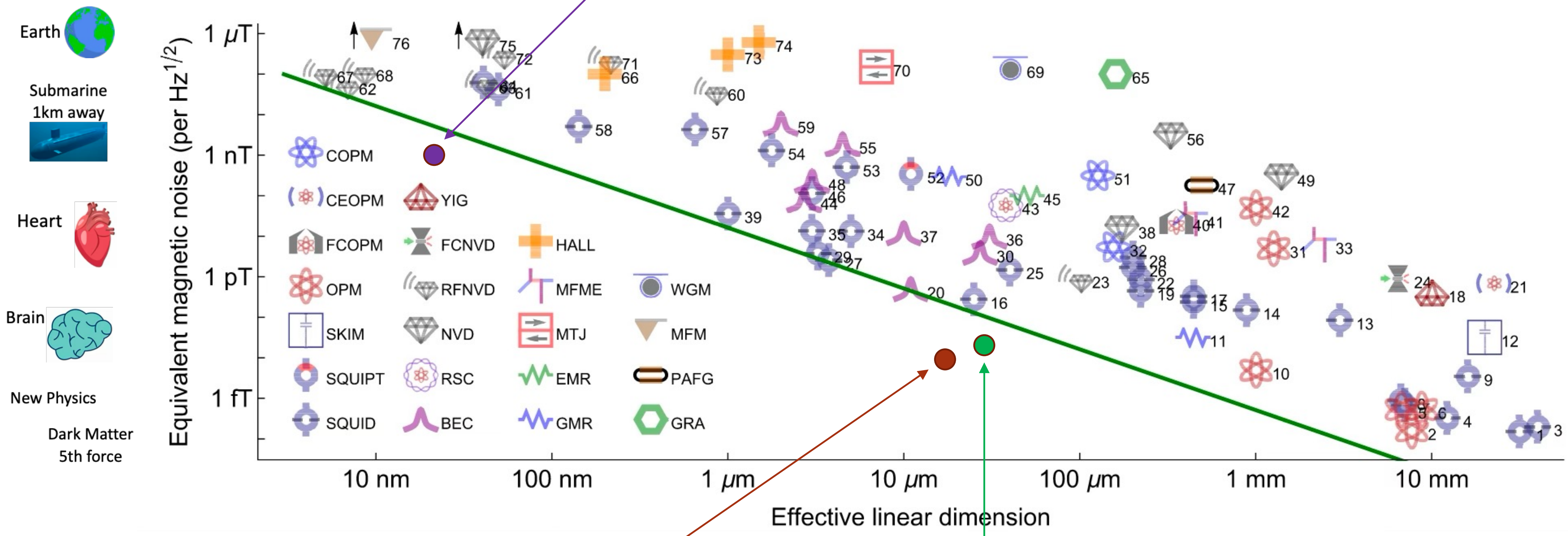




F. Ahrens, W. Ji et al,PRL, 134, 110801 (2025)

Magnetic Sensors

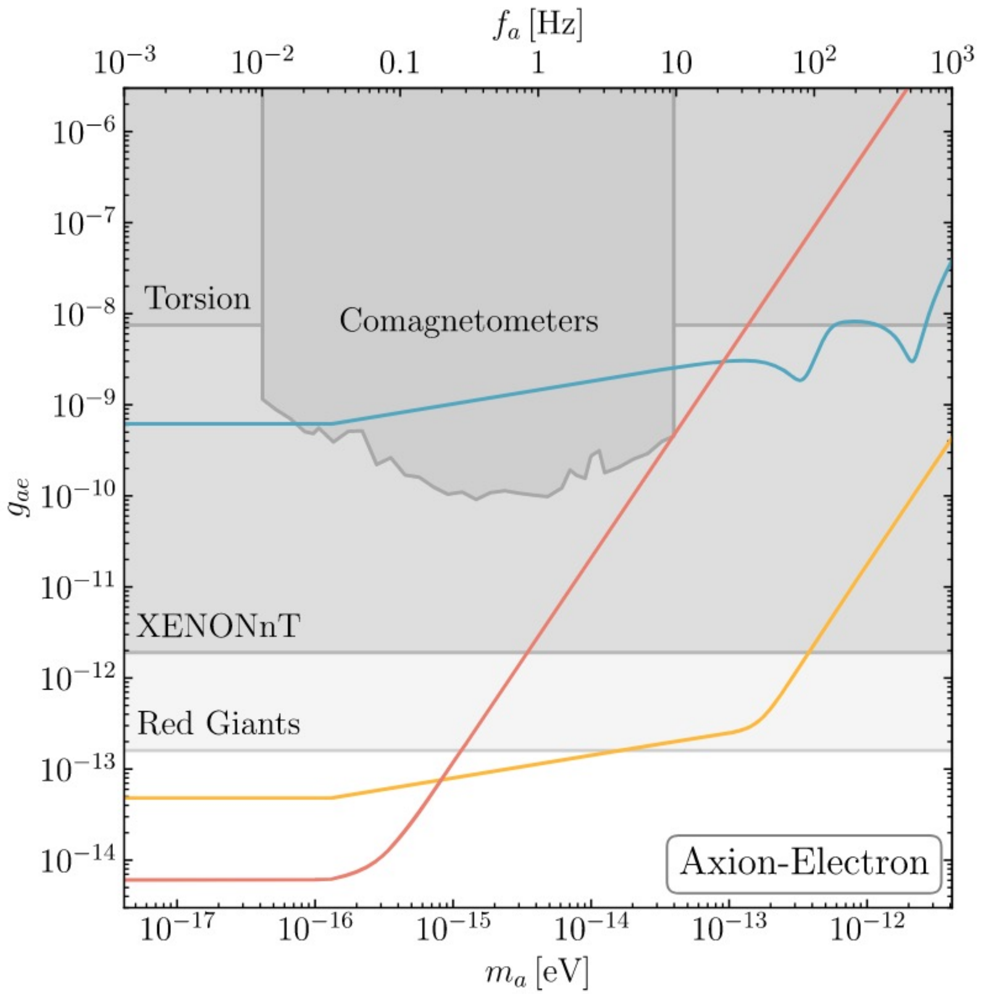
Z. Zhao et al, Nat. Sci. Rev. 10, nwad100 (2023). Nitrogen Vacancy in diamond

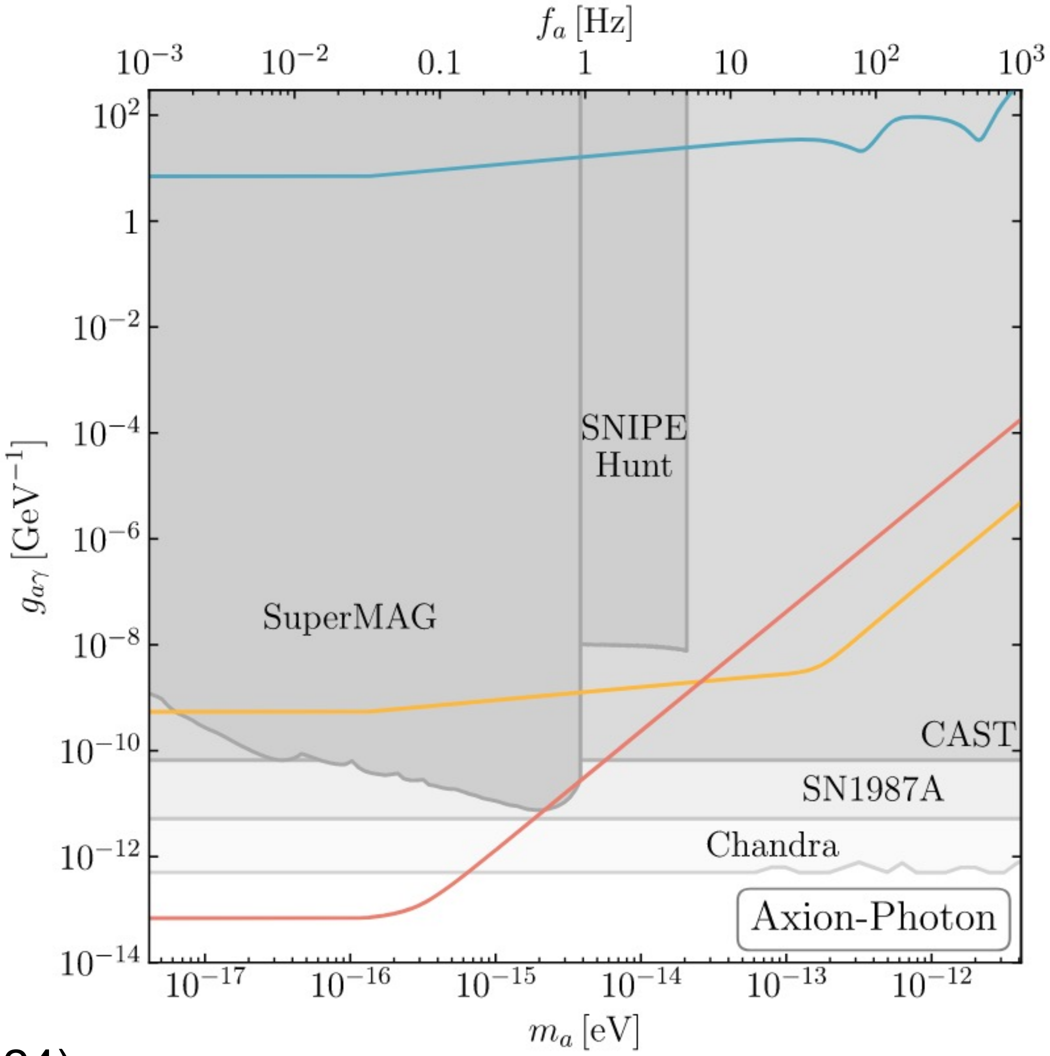


F. Ahrens, W. Ji et al,PRL, 134, 110801 (2025)

S. P. Alvarez et al, PNAS 119,6,2115339119 (2022) Cold atom spinor

Applications in New Physics





S. Kalia et. al, Phys. Rev. D 110, 115029 (2024)

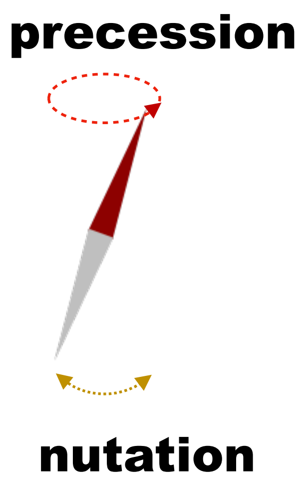
Thanks!

wei.ji@pku.edu.cn

Backup Slides

Parameter	Existing	Future	Freefall
Ferromagnet radius R	20 μm	2 mm	2 cm
Ferromagnet magnetization M		7×10^5 A/m	
Ferromagnet density ρ		7400 kg/m^3	
Temperature T	4 K	50 mK	300 K
Dissipation rate γ	10^{-2} Hz	2×10^{-6} Hz	10^{-10} Hz
Azimuthal trapping $V_{\phi\phi}$	10^{-14} J	$10^{-3} V_{\theta\theta}$	7×10^{-9} J
Energy resolution $\kappa_\theta = \kappa_\phi$	$1000\hbar$	$\hbar$	$\hbar$
Polar coupling $\tilde{\eta}_\theta$	$1.1 \times 10^{-7}\ \sqrt{\mathrm{J}}$	$3.7 \times 10^{-3}\ \sqrt{\mathrm{J}}$	$10^{-5}\ \sqrt{\mathrm{J}}$
Azimuthal coupling $\tilde{\eta}_\phi$	$5 \times 10^{-9}\ \sqrt{\mathrm{J}}$	$3.7 \times 10^{-3}\ \sqrt{\mathrm{J}}$	$10^{-5}\ \sqrt{\mathrm{J}}$
$\tilde{\eta}_\theta^{(\mathrm{res})} = \tilde{\eta}_\phi^{(\mathrm{res})}$	$9.1 \times 10^{-7}\ \sqrt{\mathrm{J}}$	$4.6 \times 10^{-3}\ \sqrt{\mathrm{J}}$	$2.5\ \sqrt{\mathrm{J}}$
$\tilde{\eta}_\theta^{(\mathrm{broad})}$	$6.4 \times 10^{-7}\ \sqrt{\mathrm{J}}$	$3.6 \times 10^{-3}\ \sqrt{\mathrm{J}}$	$10^{-5}\ \sqrt{\mathrm{J}}$
$\tilde{\eta}_\phi^{(\mathrm{broad})}$	$10^{-7}\ \sqrt{\mathrm{J}}$	$1.1 \times 10^{-4}\ \sqrt{\mathrm{J}}$	$10^{-5}\ \sqrt{\mathrm{J}}$
ω_I	$2\pi \times 0.53$ Hz	$2\pi \times 5.3 \times 10^{-5}$ Hz	$2\pi \times 5.3 \times 10^{-7}$ Hz
$v_{\theta\theta}$	$2\pi \times 4.9 \times 10^5$ Hz	$2\pi \times 1.6 \times 10^7$ Hz	$2\pi \times 0.12$ Hz
$v_{\phi\phi}$	$2\pi \times 1.2 \times 10^4$ Hz	$2\pi \times 1.6 \times 10^4$ Hz	$2\pi \times 0.12$ Hz

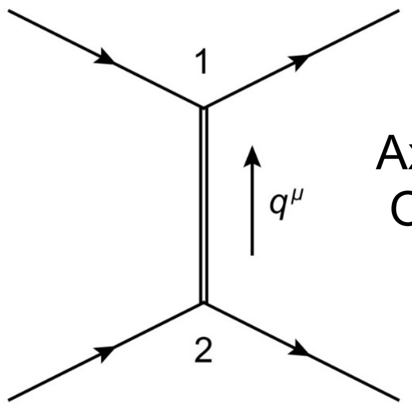
Ferromagneic Gyroscope



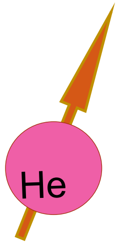
- Einstein Elevator (@ Hannover)
  - Test duration: 4 s
  - Total height: 40 m
  - Repetition rate: 300 tests per day
  - Pay load: 1 t
  - Size of experiments: Ø 1.7 m x 2 m
  - Residual acceleration: 1e-6 *g*

Exotic Spin-Dependent Force

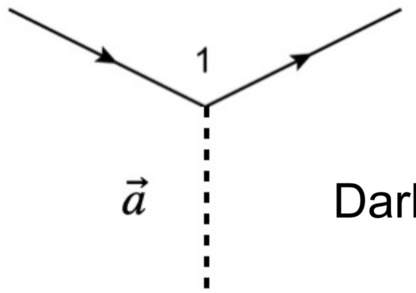
New Interaction



Axion and ALPs
Or Z'



Axion and ALPs



Dark Matter Halo

Spin-0 $$\mathcal{L}_\phi = \phi \sum_\psi \overline{\psi} \left(g_\psi^s + i\gamma_5 g_\psi^p \right) \psi,$$

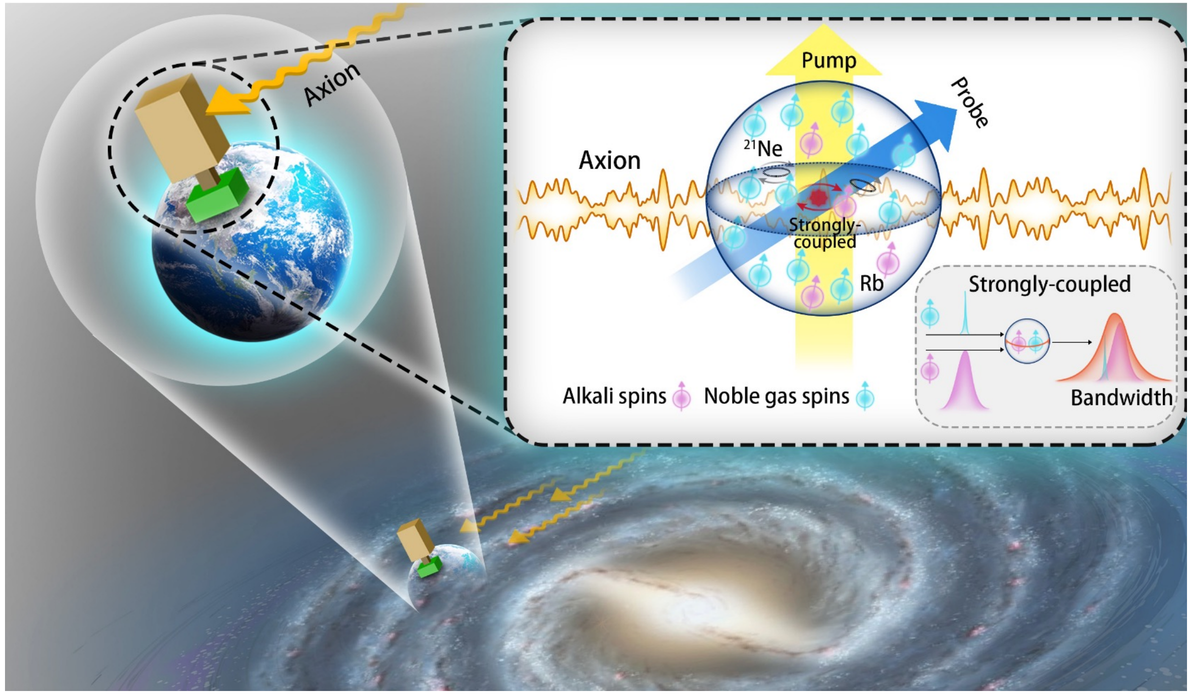
Spin-1 $$\mathcal{L}_{Z'} = Z'_\mu \sum_\psi^\psi \overline{\psi} \gamma^\mu (g_\psi^V + \gamma_5 g_\psi^A) \psi,$$

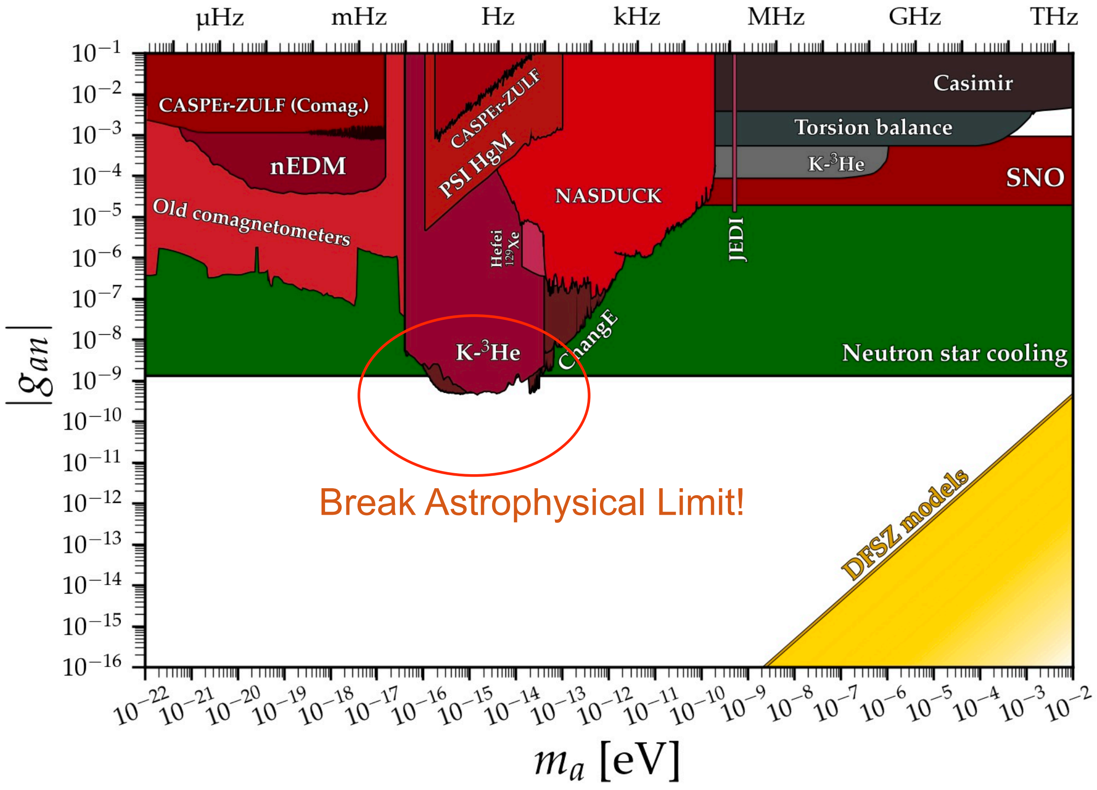
Axion Gradient coupling

$$\mathcal{L}_a = (\partial_\mu a) \overline{\psi} \gamma^\mu \gamma_5 \psi,$$

ChangE Experiment: Dark Matter

(Coupled Hot Atom eNsembles to search for liGht dark mattEr)





Wei et al, Rep. Prog. Phys. 88 (2025) 057801 (16pp)

https://github.com/cajohare/AxionLimits/blob/master/docs/app.md