# Search for ultralight new particle with spin-based sensors

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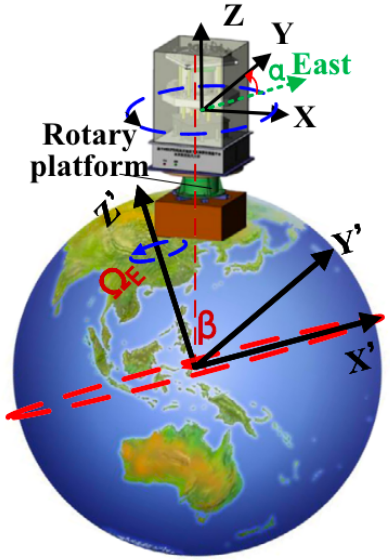
Matter AntiMater Section
2024.05.09

西昌

# Outline

- Motivation: New Physics (Exotic Fields that Couple to Spins. )
  - Dark Matter
  - Exotic Spin-Dependent Force

- Spin-based Magnetometry Techniques:
  - Optically Pumped Magnetometer (OPM)
  - Alkali-Noble Gas Comagnetometer
  - LEvitated MAgnets for QUantum MEtrology (LEMAQUME)




- Experimental Results and Outlook

# New Physics (Beyond the Standard Model)

Do spins couple to gravity?

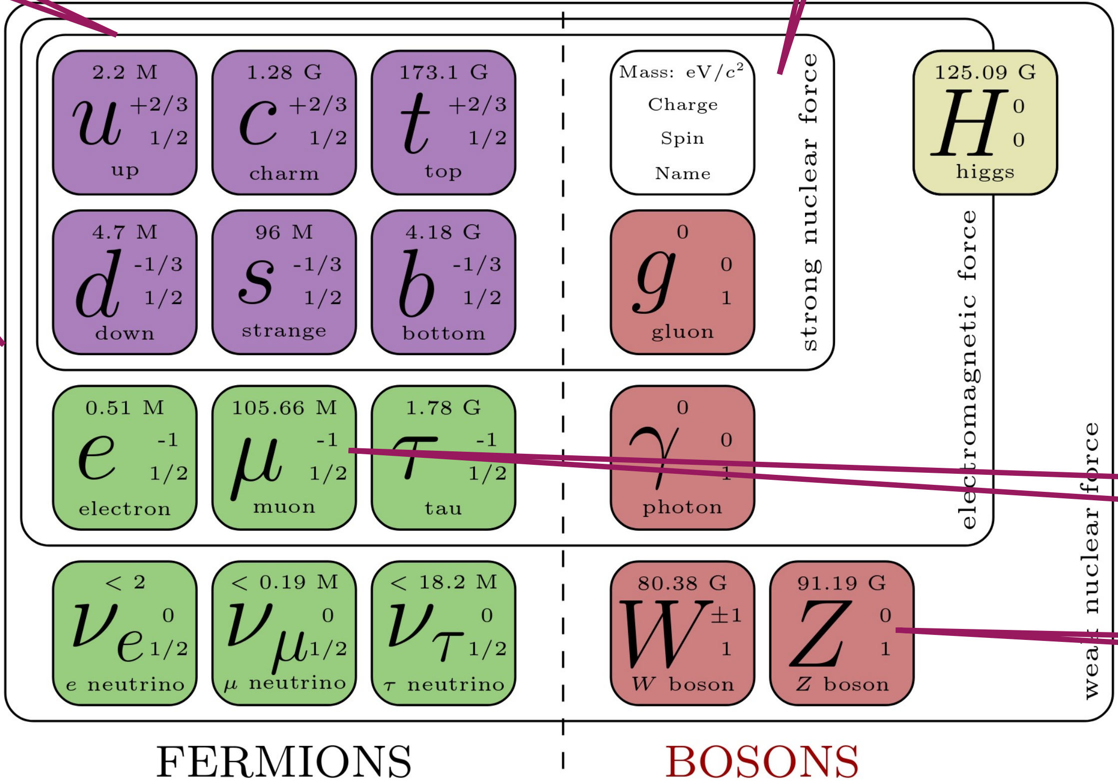
How to include Gravity?

Strong CP problem

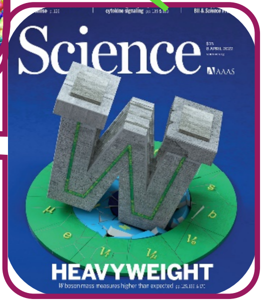
Why more matter than antimatter

Why do we exist?


Dark Matter and Dark Energy




Fifth force?

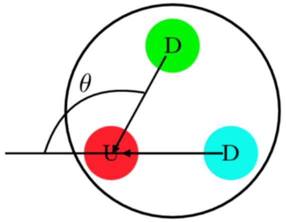

Why the universe look like this

# Axion: Peccei-Quinn-Weinberg-Wilczek (PQWW) Model

- Strong CP problem.

$$L_{CP_{vio}} = \frac{\alpha_s}{8\pi}\theta tr(G_{\mu\nu}\tilde{G}^{\mu\nu}) \qquad \bar{\theta} = \theta + \arg\det M_q$$

- Neutron EDM




Prediction

$$d_n(\bar{\theta}) \approx \frac{e\bar{\theta}m_u m_d}{(m_u + m_d)\, m_n^2} \approx 6 \times 10^{-17}\bar{\theta} e \cdot \mathrm{cm}$$

Experiment

$$d_n = \left(0.0 \pm 1.1_{stat} \pm 0.2_{sys}\right) \times 10^{-26} e\,.\,\mathrm{cm}\,.$$

*PRL 124, 081803 (2020)*

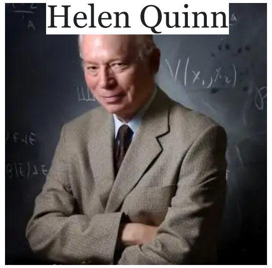
$$|\bar{\theta}| < 10^{-9}$$

- Peccei-Quinn mechanism

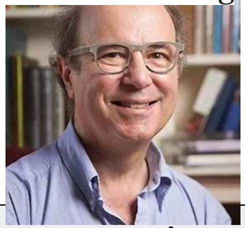
$a + \bar{\theta} f_a = \bar{a}$ The $\bar{\theta}$ term can be absorbed into the axion field and it can explain why $\bar{\theta}$ is so small.

Roberto Peccei

Helen Quinn

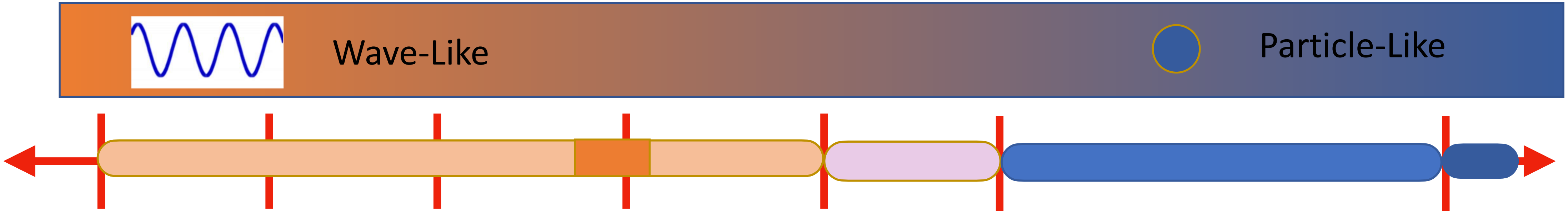


Steven Weinberg



Frank Wilczek

# Dark Matter Mass Range




$10^{-22}$eV

Axion Window
$\mu$eV – 100 $\mu$eV

keV

GeV

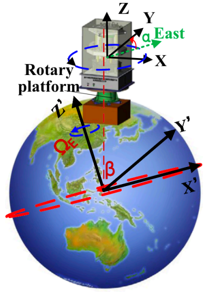
100 TeV

## Ultralight Bosonic DM

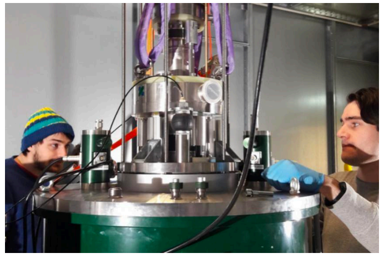
Table-top Precision Measurement experiments

Cavity Experiments

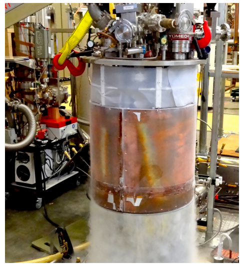
ChangE




CASPEr



ADMX

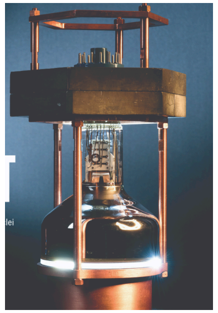


SRF

## Light DM

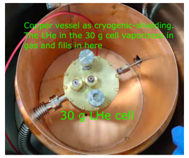
Sterile $\nu$

COHERENT



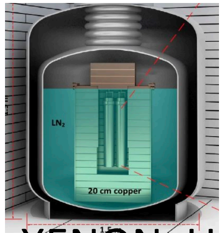
## WIMPs

ALETHEIA

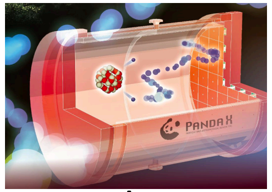


DOPMPE

CDEX



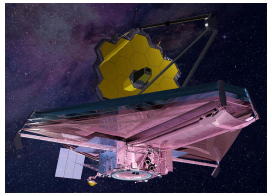

PandaX



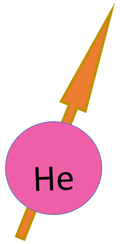

XENON, LUX, ,Accelerator etc

## Composite DMs & Primordial Black holes

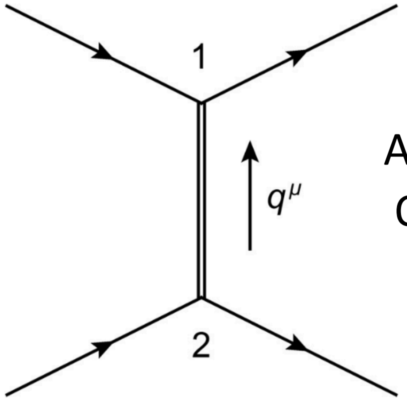
James Webb Telescope



# Exotic Spin-Dependent Force




New Interaction

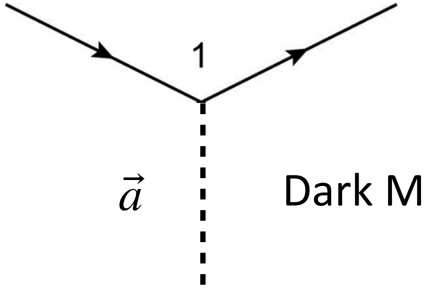



Axion and ALPs
Or Z'

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

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

Axion and ALPs



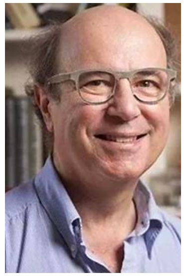

Dark Matter Halo

Axion Gradient coupling

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

# Exotic Spin-Dependent Force

## Scalar and Pseudoscalar Coupling (Axion)



$$V_{9+10} = \frac{g_s g_p \hbar^2}{8\pi m_1}(\hat{\boldsymbol{\sigma}}_1 \cdot \hat{\boldsymbol{r}})\left(\frac{1}{r\lambda} + \frac{1}{r^2}\right) e^{-r/\lambda},$$

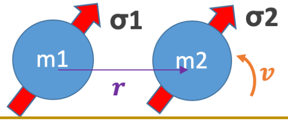
P Violation

**CP** violation

## Vector and Axial Vector Coupling

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

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




REVIEWS OF MODERN PHYSICS

On 4/17/23, 8:05 AM, "rmp@aps.org" <rmp@aps.org> wrote:

Re: RC10141
Spin-dependent exotic interactions
by Lei Cong, Wei Ji, Pavel Fadeev, et al.

Dear Prof. Dr. Budker,

I was happy to learn from our associate editor, Dr. Klaus Molmer, that you have agreed to write for Reviews of Modern Physics the above article, following your proposal. We look forward to receiving from you an article of no more than 50,000 words (roughly 50 journal pages) by 17 April 2024. Our standard honorarium for reviews is $750.00, payable shortly after publication. Authors pay for their own reprints.

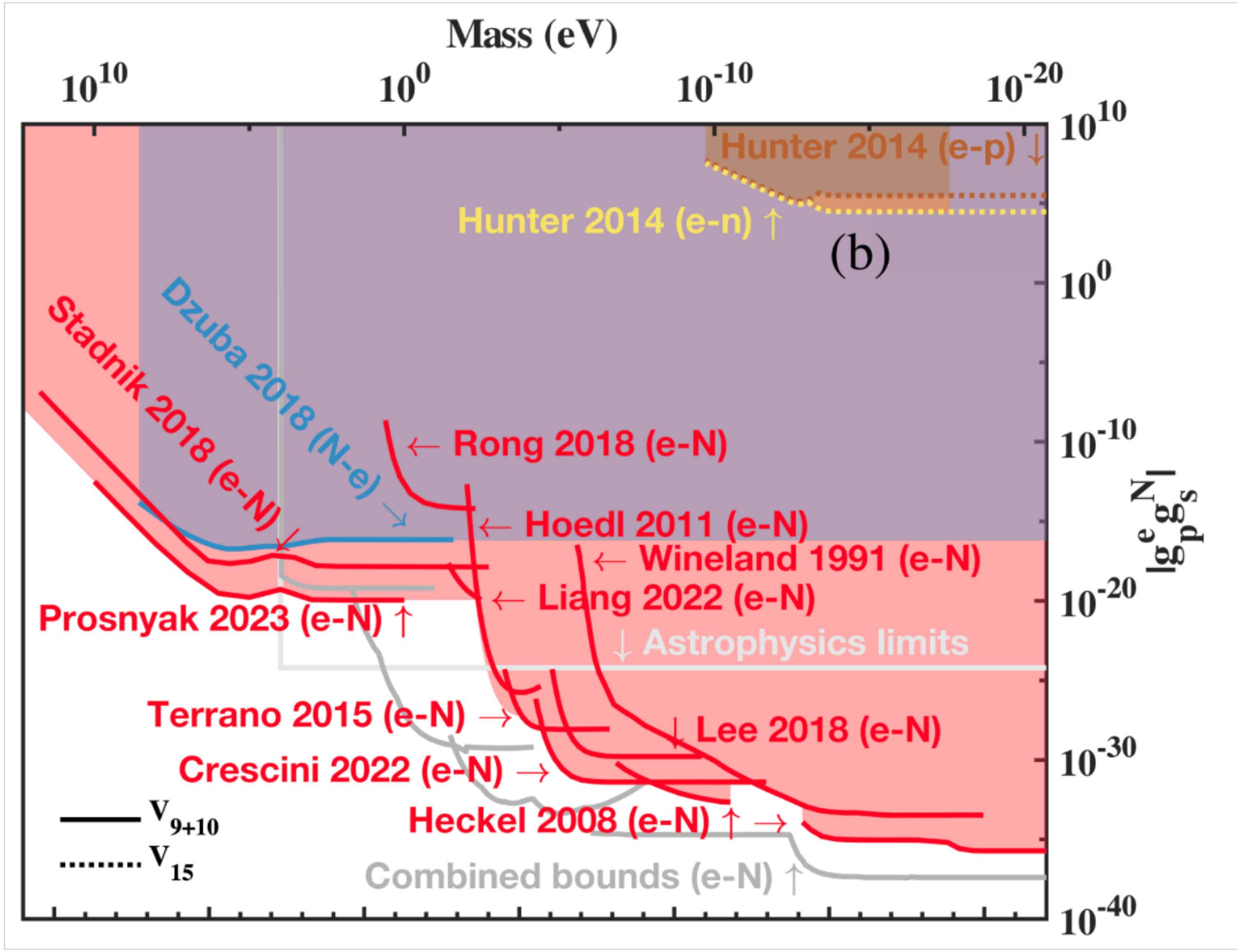
**New macroscopic forces?** Phys. Rev. D 30, 130

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**

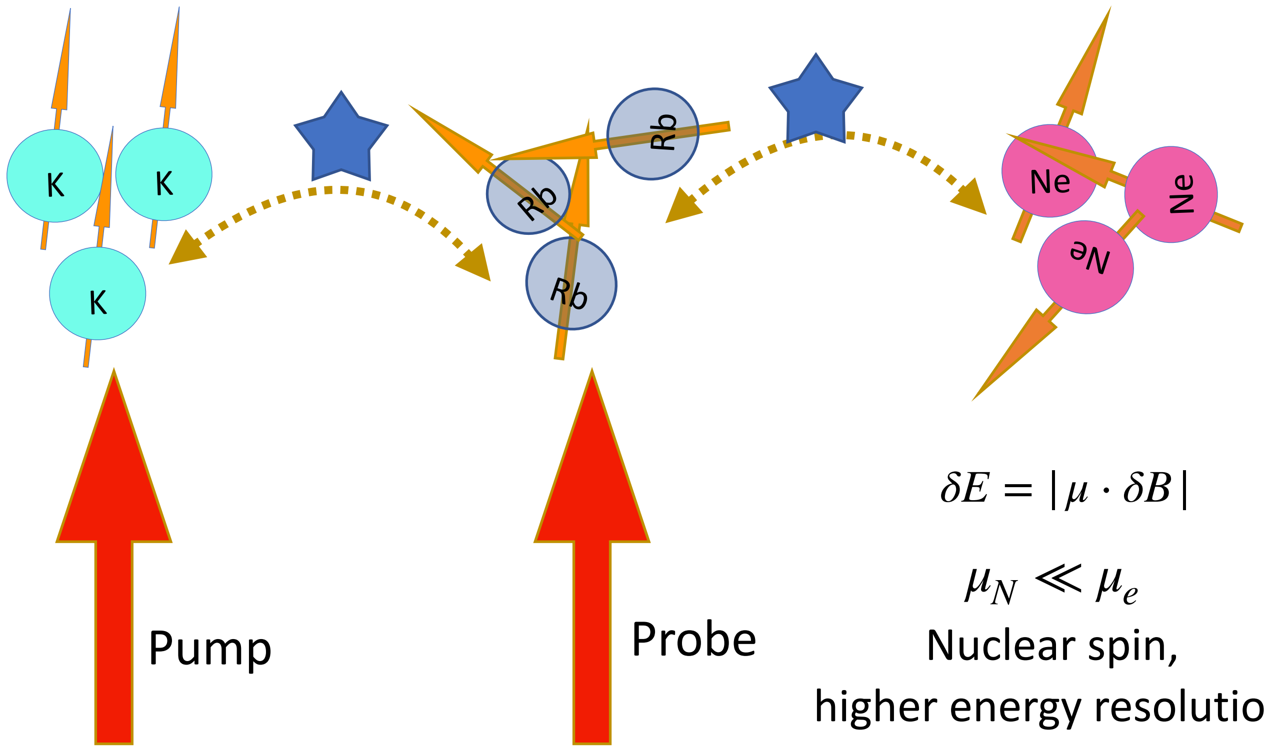
B. A. Dobrescu and I. Mocioiu, J. High Energy Phys. 11 (2006) 005.

# Preliminary Results



# Alkali-Noble Comagnetometer: Sword for New Physics

Hybrid Spin Exchange Pumping




$\delta E = |\mu \cdot \delta B|$

$\mu_N \ll \mu_e$

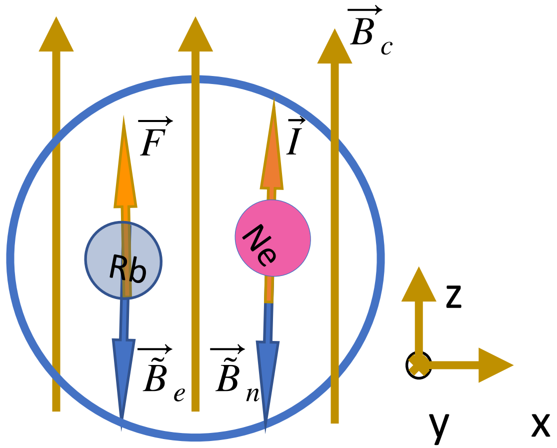
Nuclear spin, higher energy resolution

Hybrid pumping enables the best nuclear polarisation and coherence time

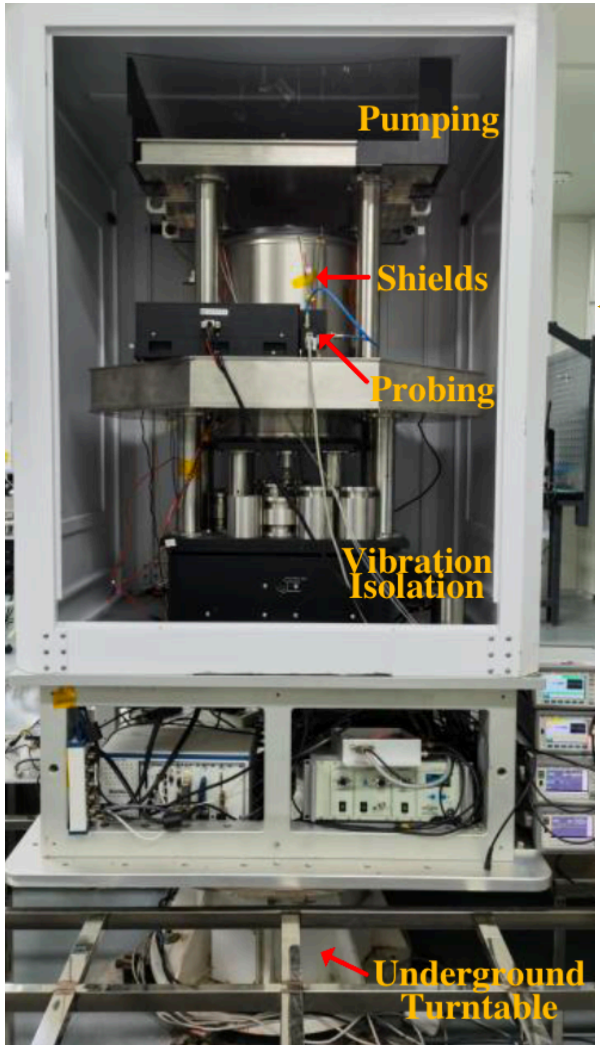
Dynamics of the spins

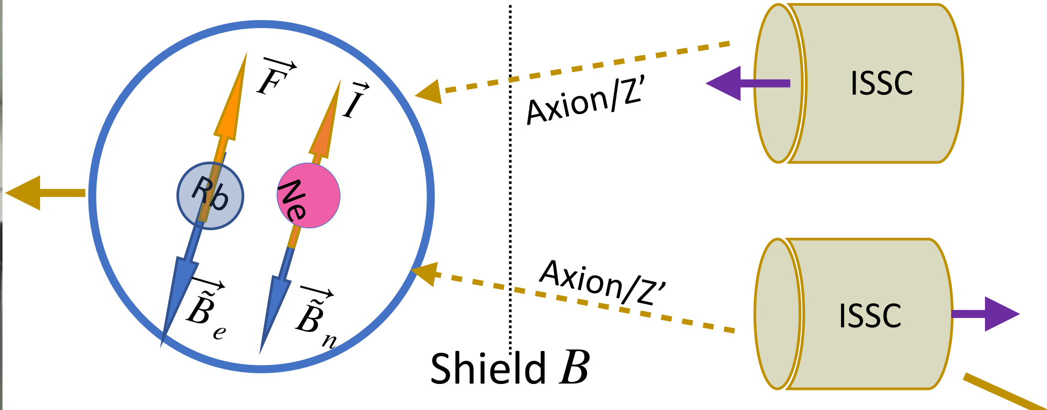
$$\frac{\partial \boldsymbol{P}^e}{\partial t} = \frac{\gamma_e}{Q(P^e)}\left[\boldsymbol{b}^e + \boldsymbol{B} + \lambda M^n \boldsymbol{P}^n + \boldsymbol{L}\right] \times \boldsymbol{P}^e + \frac{P_0^e \hat{z} - \boldsymbol{P}^e}{T_e Q(P^e)}$$

$$\frac{\partial \boldsymbol{P}^n}{\partial t} = \gamma_n \left[\boldsymbol{b}^n + \boldsymbol{B} + \lambda M^e \boldsymbol{P}^e\right] \times \boldsymbol{P}^n + \frac{P_0^n \hat{z} - \boldsymbol{P}^n}{\{T_{2n}, T_{2n}, T_{1n}\}}$$

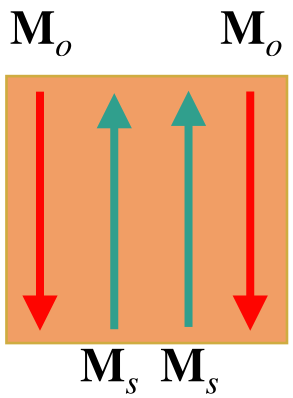


# Fifth Force Experiment



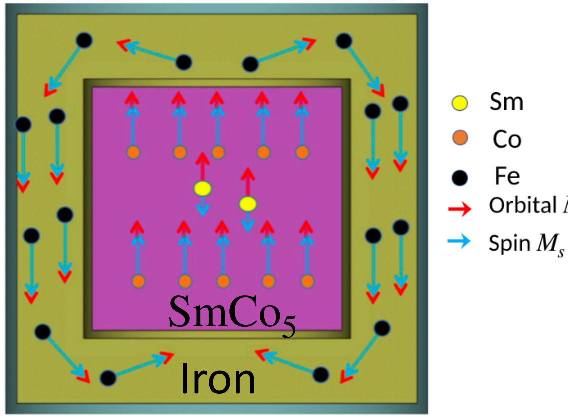




- Ji et al, PRL 130, 133202(2023).
- Wei et al, PRL130, 063201 (2023).
- Ji et al, PRL, 121(26): 261803, 2018.
- Ji et al, PRD, 95(7): 075014, 2017.
- Wei et al, NC 13, 7387, (2022)

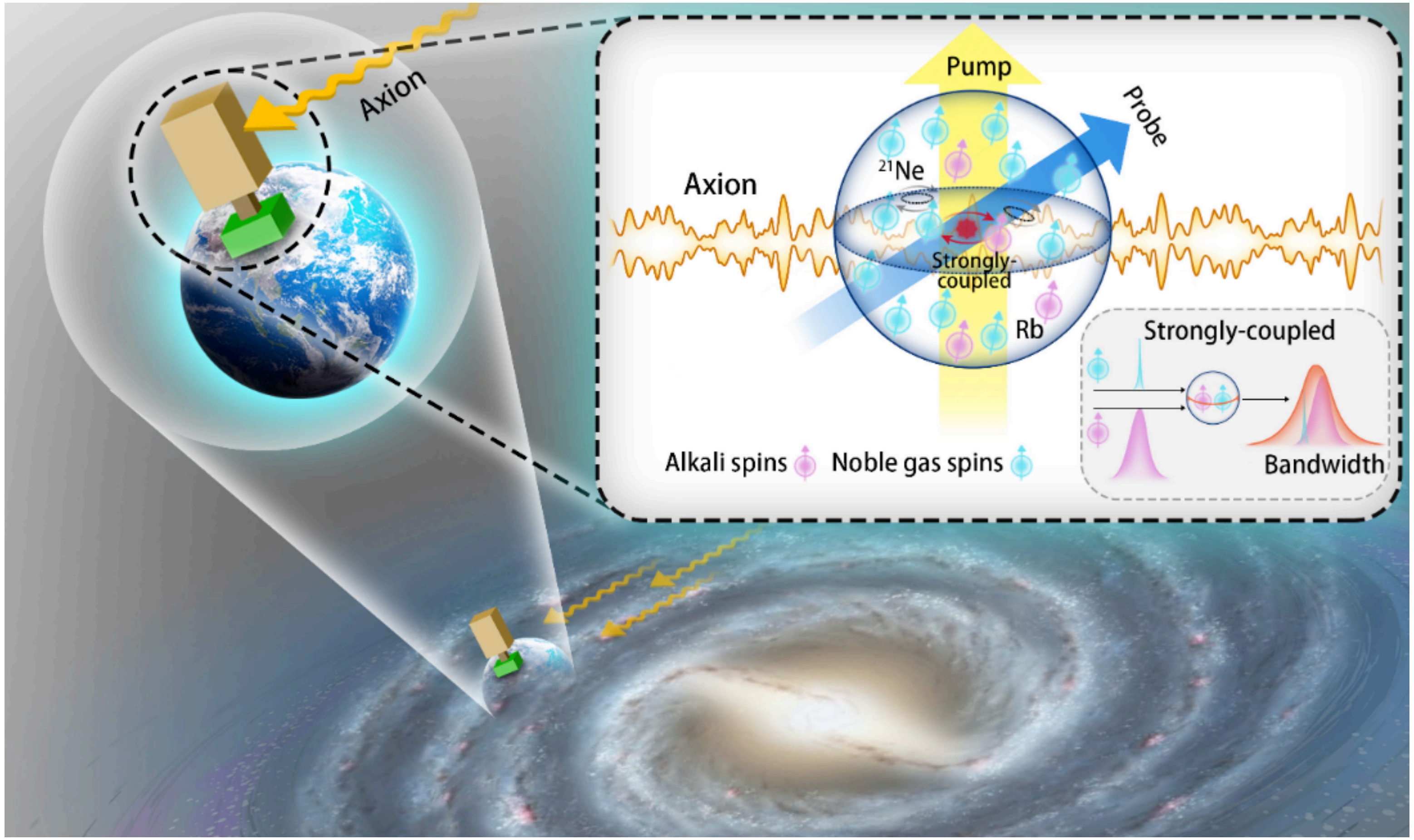



$$\mathbf{M} = \sum \mathbf{M}_s + \mathbf{M}_o = 0$$

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



# Axion Dark Matter Wind




**Axion wave**

$$\nabla a(x) = \sum_{\boldsymbol{p}} \sqrt{\frac{2N_{\boldsymbol{p}}}{V\omega_{\boldsymbol{p}}}} \cos(\omega_{\boldsymbol{p}} t - \boldsymbol{p}\cdot\boldsymbol{x} + \phi_{\boldsymbol{p}})\boldsymbol{p}$$

**Axion-Nucleon spin coupling**

$$\mathscr{H} = g_{aNN}\nabla a \cdot \boldsymbol{\sigma}_N,$$

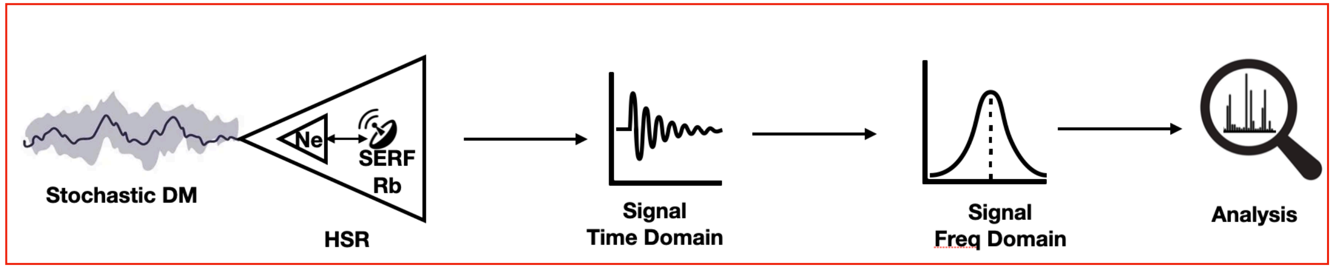
**Signal**

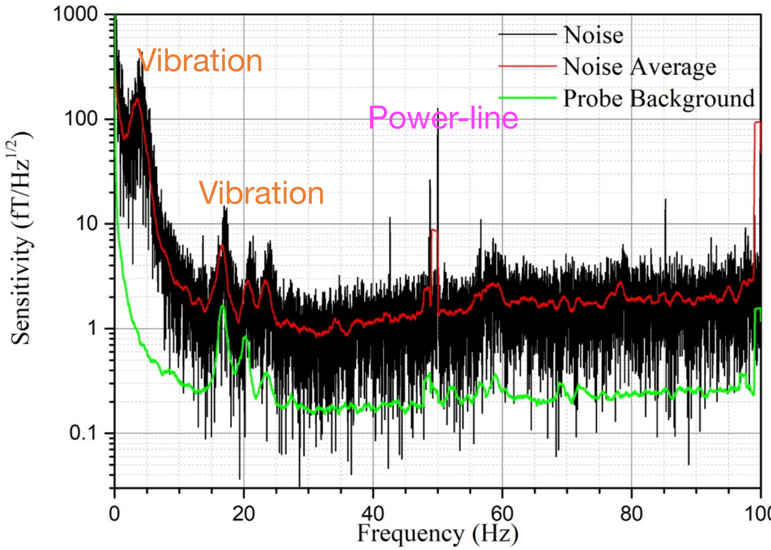
$$\beta_j = \frac{g_{aN}}{\gamma_N} \nabla a(j\Delta t)\cdot \hat{\mathbf{m}}(j\Delta t),$$

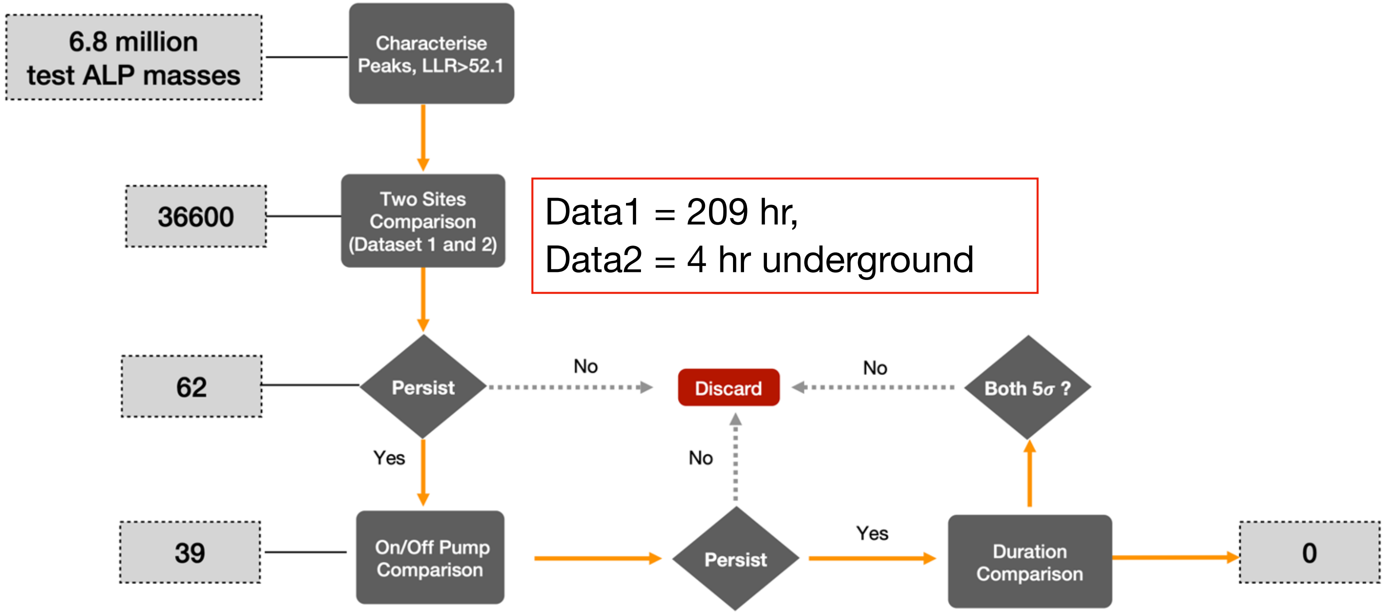
**Daily Modulation**

$$\hat{\mathbf{m}}_i(j\Delta t) \approx \mathbf{C}_i \cos(\omega_e j\Delta t + \theta_i) + \mathbf{D}_i,$$

# Broadband Axion Search



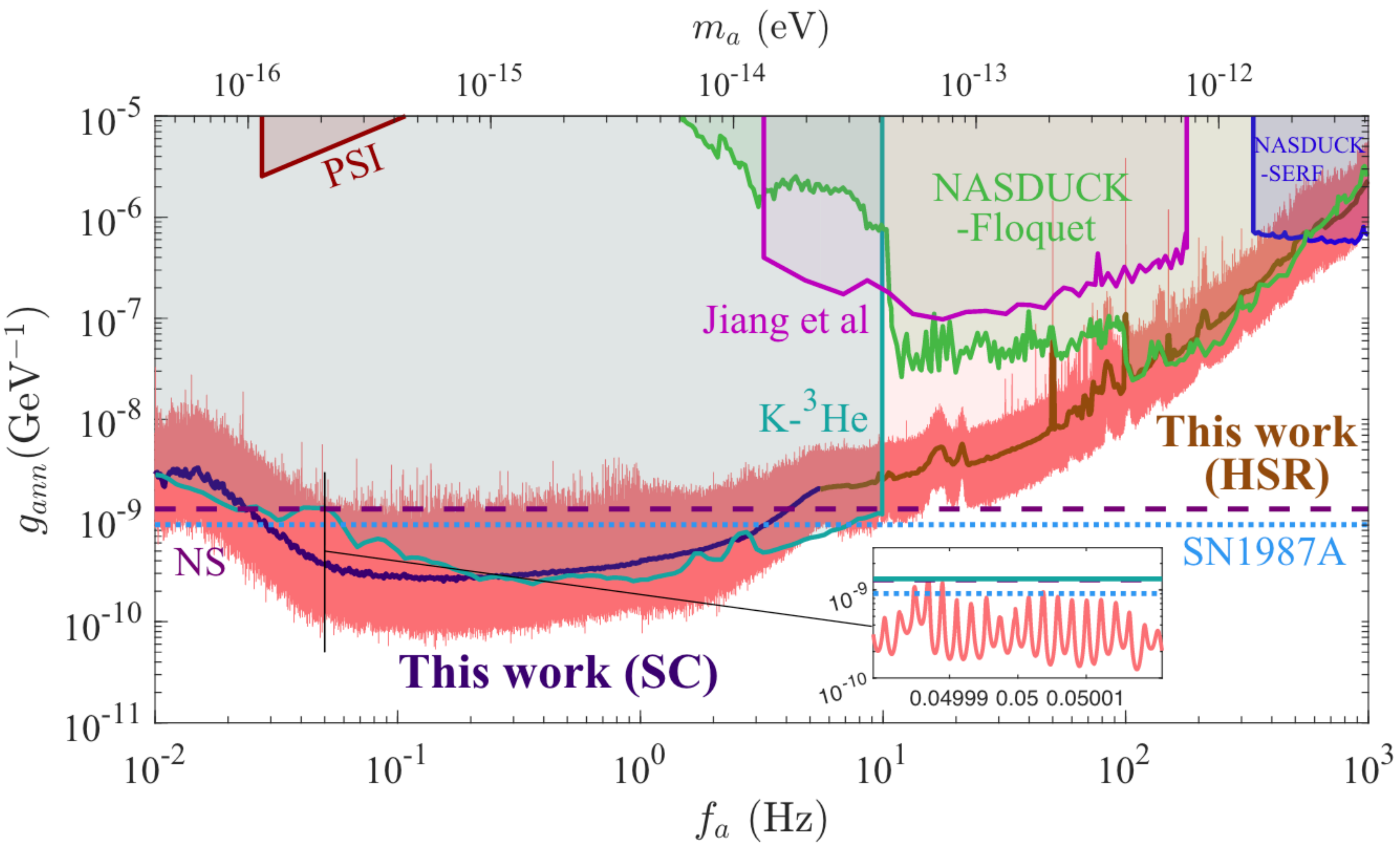




Data1 = 209 hr,
Data2 = 4 hr underground

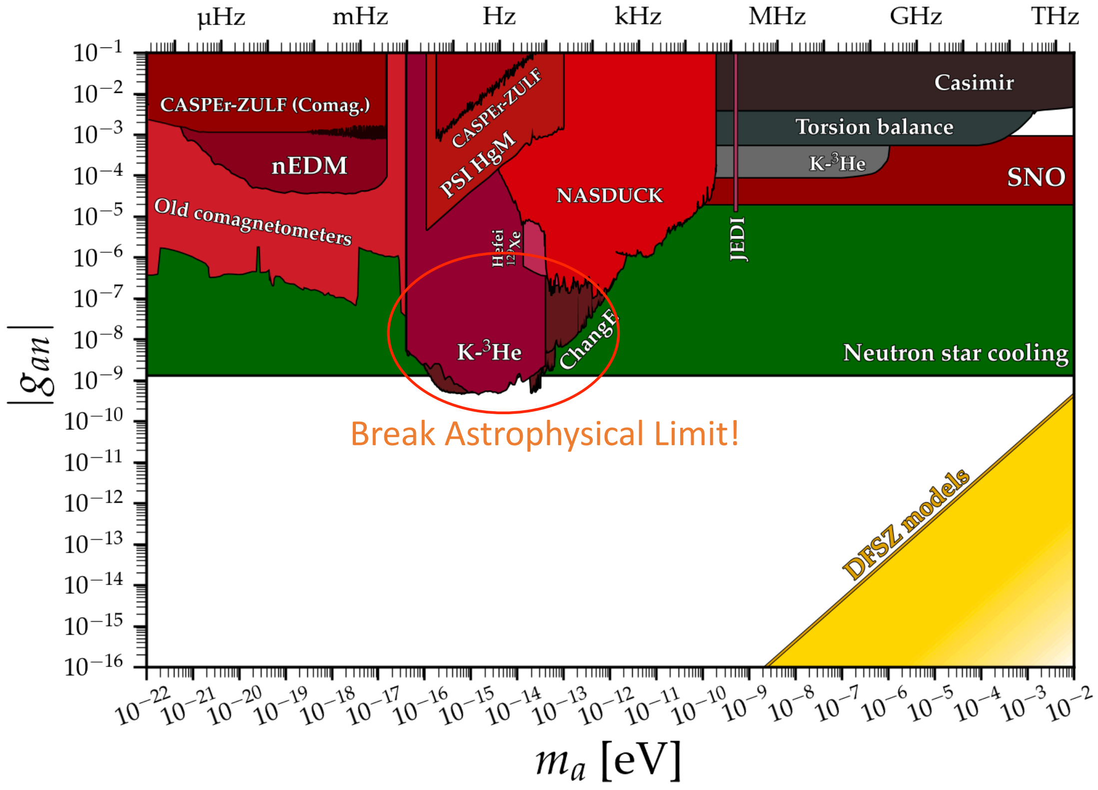
- Signal should be very narrow, $\frac{\delta f}{f} \approx 10^{-6}$
- Signal should persist
- Axion DM frequency unknown

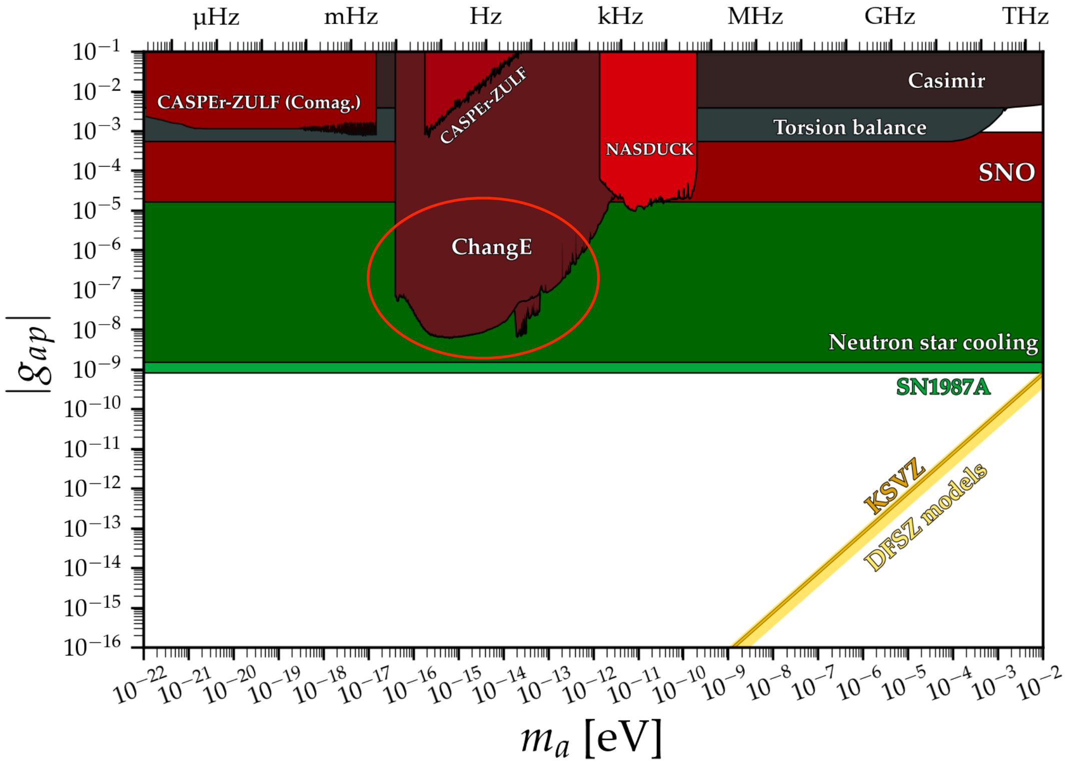
# Axion Limits

*Wei et al., arXiv:2306.08039*



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




$$b^{Ne} = b^n \zeta^n + b^p \zeta^p$$

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

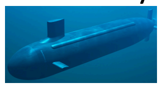
# LEvitated MAgnets for QUantum MEtrology (LEMAQUME)

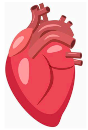
Energy Resolution Limit $\frac{S_B}{2\mu_0} V \geq \hbar,$ (empirical)

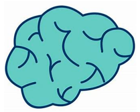
Equivalent magnetic noise (per Hz$^{1/2}$)

Earth 

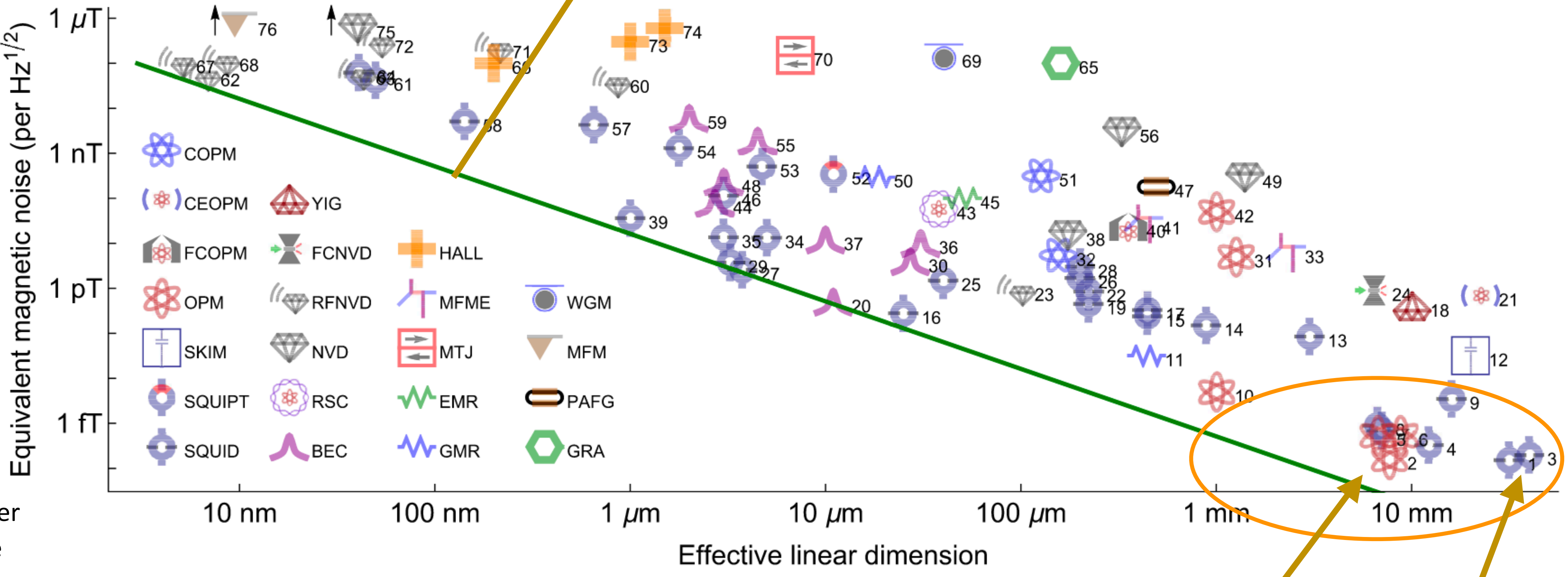
Submarine 1km away



Heart 

Brain 

New Physics




Dark Matter
5th force

SERF OPMs SQUID

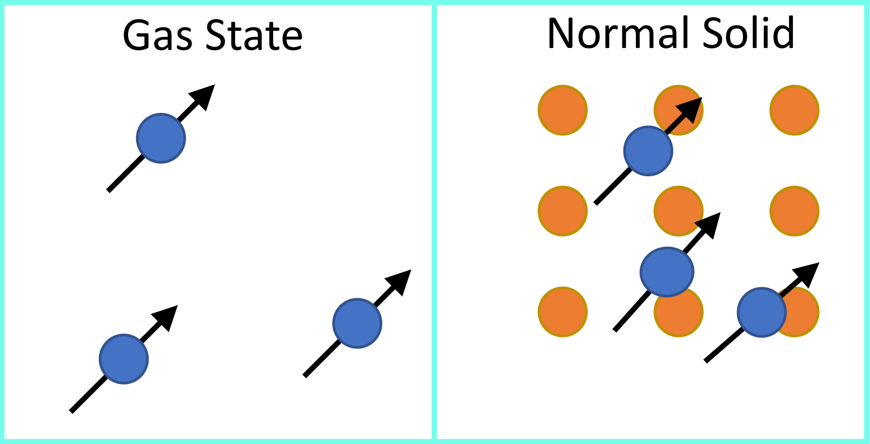
REVIEWS OF MODERN PHYSICS, VOLUME 92, APRIL–JUNE 2020

# Ferromagnetism and Precession

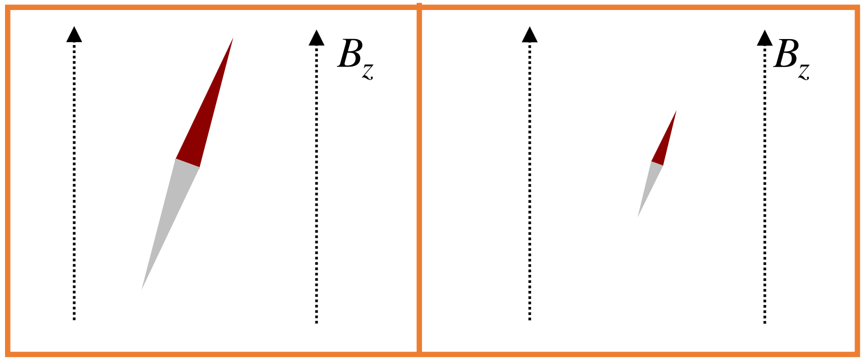
PRL 116, 190801 (2016) PHYSICAL REVIEW LET

**Precessing Ferromagnetic Needle Magnetometer**

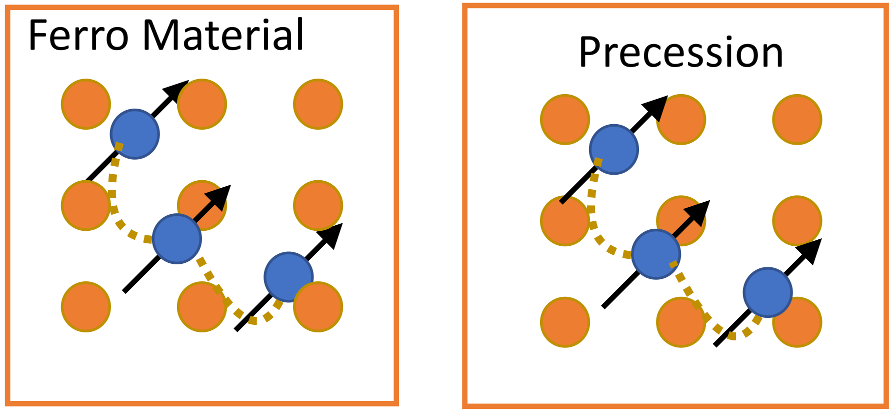
Derek F. Jackson Kimball,[1] Alexander O. Sushkov,[2] and Dmitry Budker[3,4,5]




$$\Delta\phi = \frac{\Delta S_\perp}{S_\parallel} \approx \sqrt{\frac{R_{rel}}{Nt}}$$

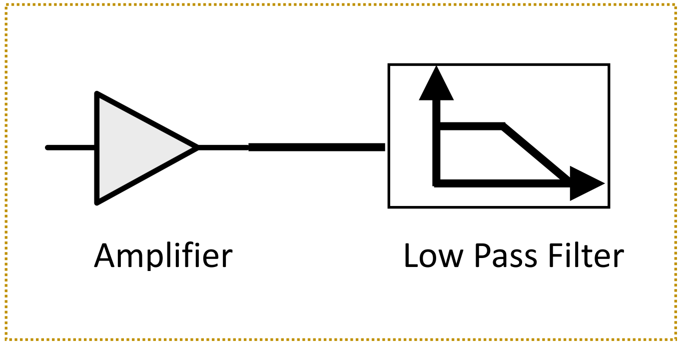



Libration v.s Precession

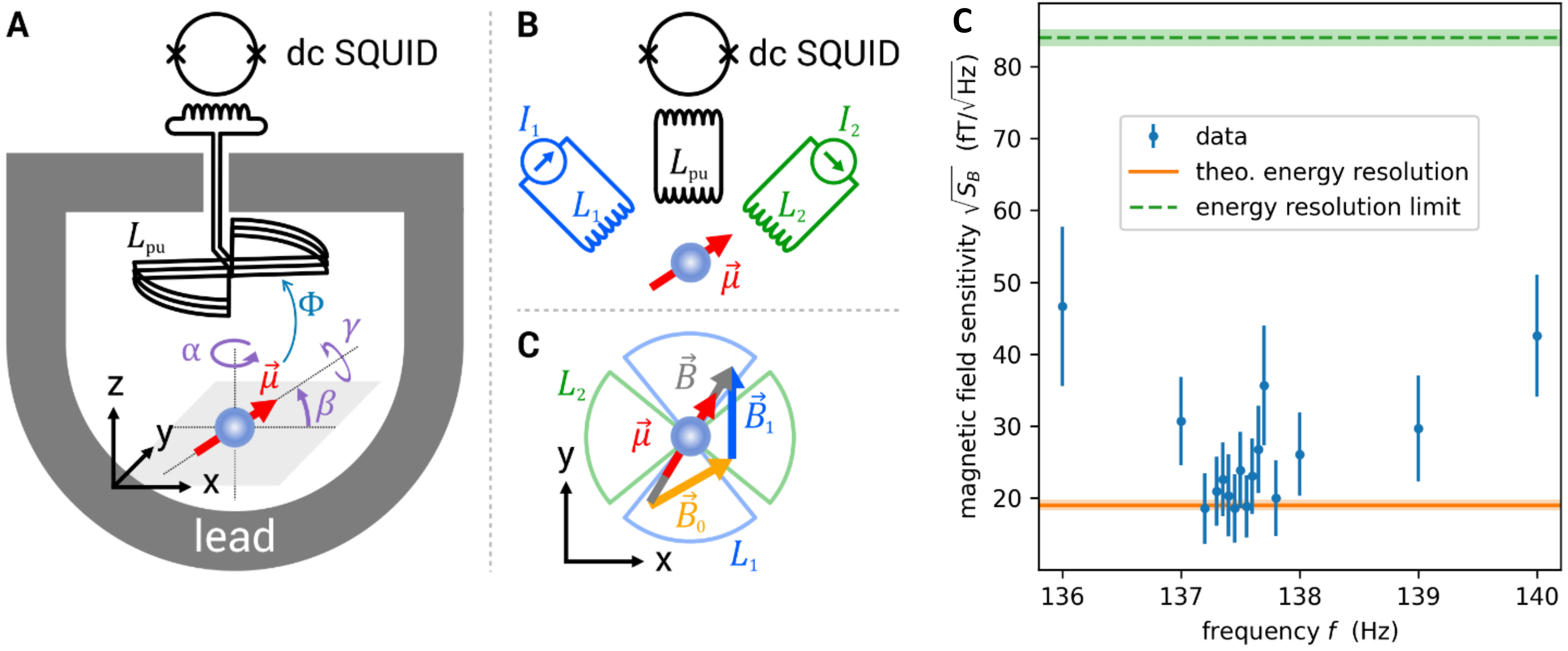



$$\Delta\phi = \frac{\Delta S_\perp}{S_\parallel}\frac{1}{\sqrt{t}} \approx \sqrt{\frac{2\alpha k_B T}{N\hbar\omega_0^2 t}}$$

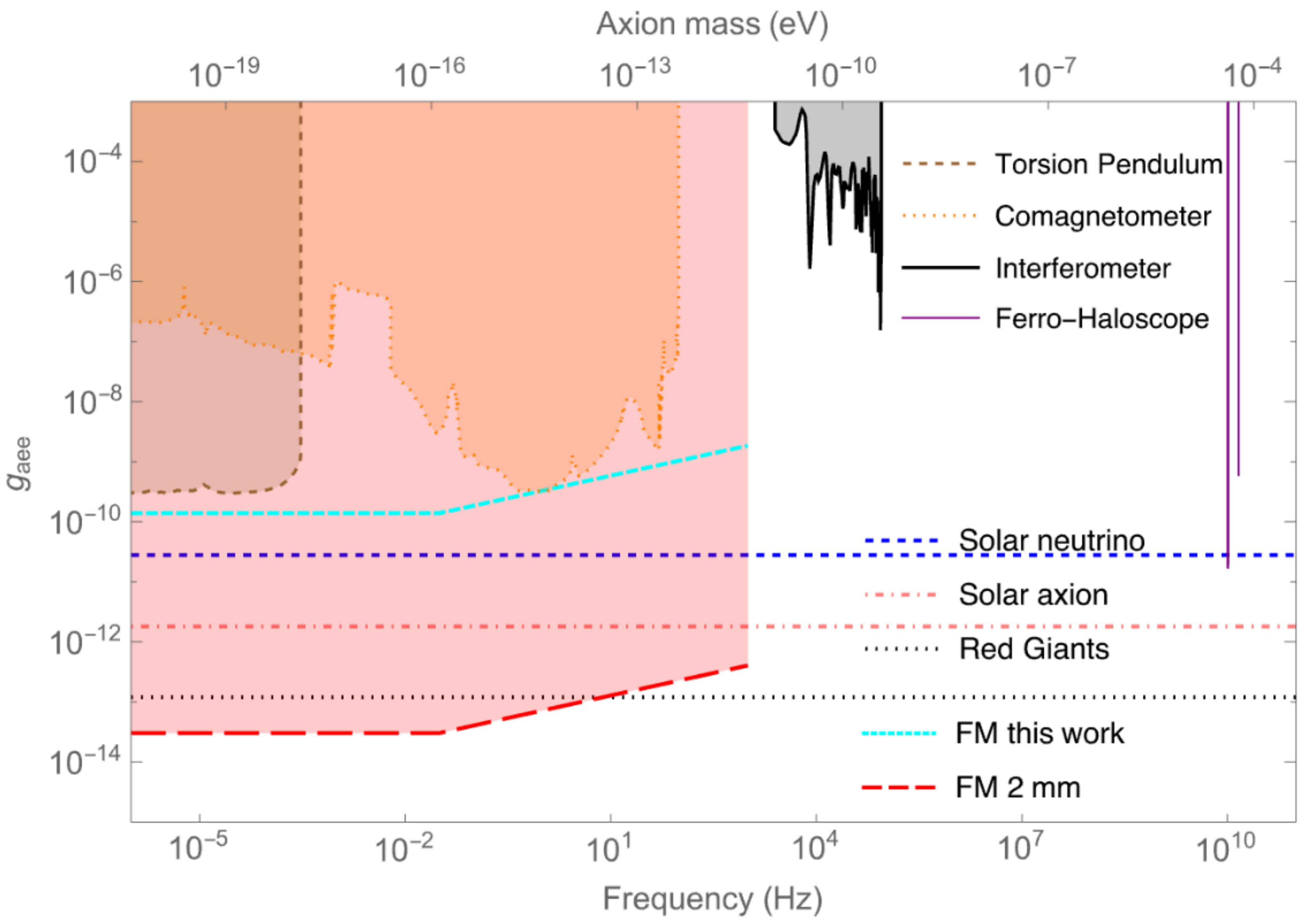
Ferromagnetic Resonance (FMR) v.s Precession



# LEMAQUME: Magnetometry



# LEMAQUME: Search For Axions



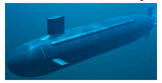
# LEMAQUME: Magnetometry

Andrea Vinante

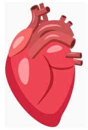
Equivalent magnetic noise (per $Hz^{1/2}$)

Earth

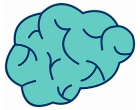
Submarine
1km away



Heart

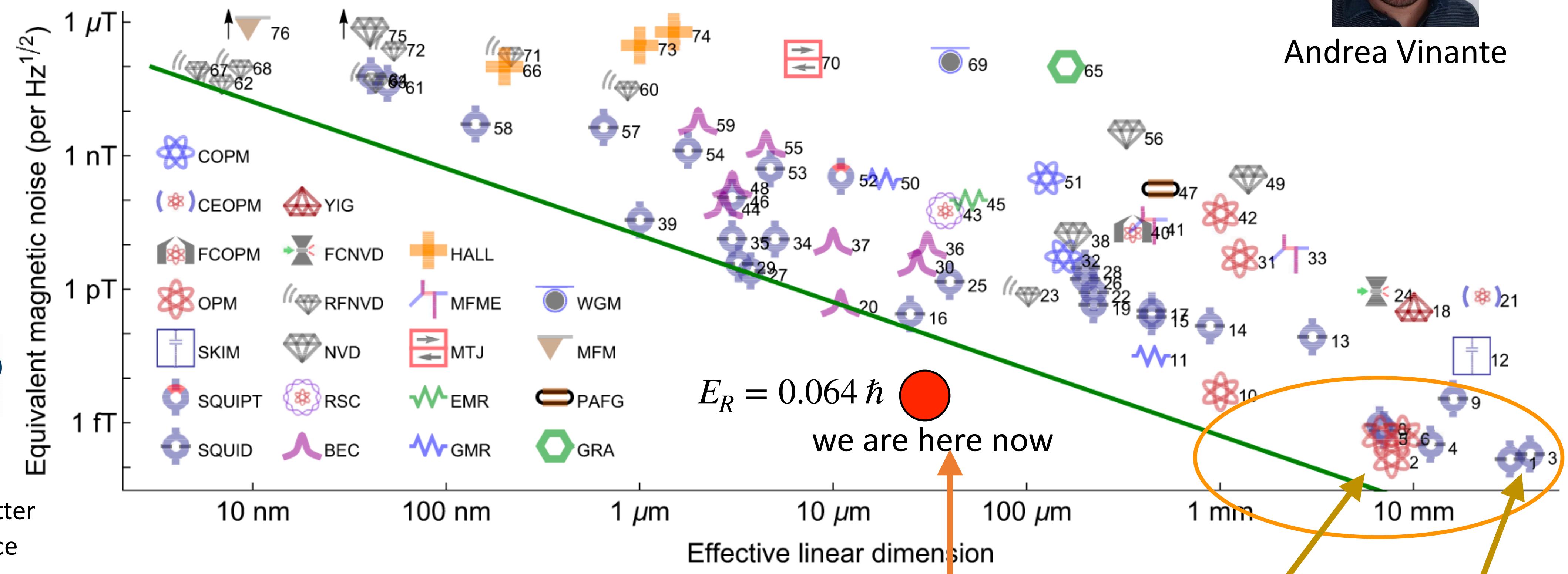


Brain



New Physics

Dark Matter
5th force




SERF OPMs

SQUID

REVIEWS OF MODERN PHYSICS, VOLUME 92, APRIL–JUNE 2020

*arXiv:2401.03774* (2024).

# Thanks!

New Interaction Collaboration


Dmitry Budker
Mainz
& UC Berkeley


高海燕
Duke
& BNL


房建成
北航


魏凯
北航


彭新华
中科大


符长波
复旦


刘永椿
清华


丛磊
Mainz

Dark Matter Collaboration


Dmitry Budker


刘佳


房建成

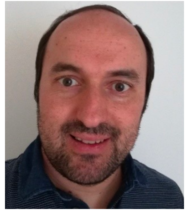

魏凯

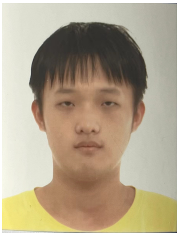

王小平

And many others

LEMAQUME


Dmitry Budker


Andrea Vinante

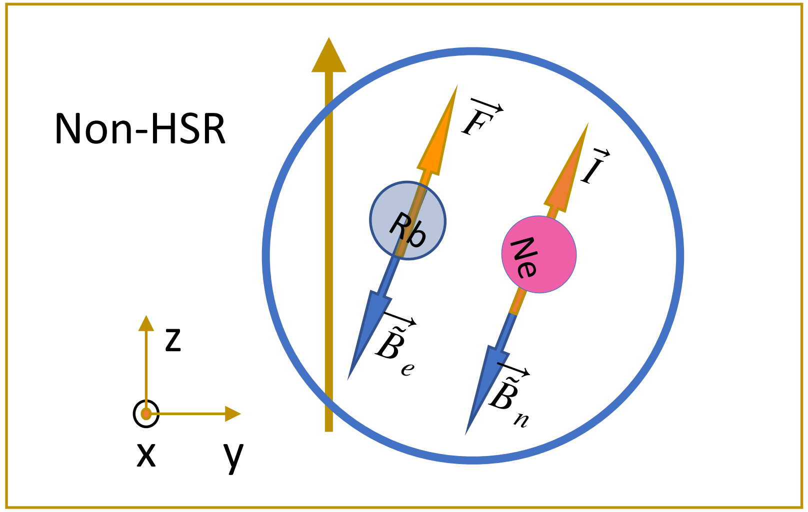

Changhao Xu

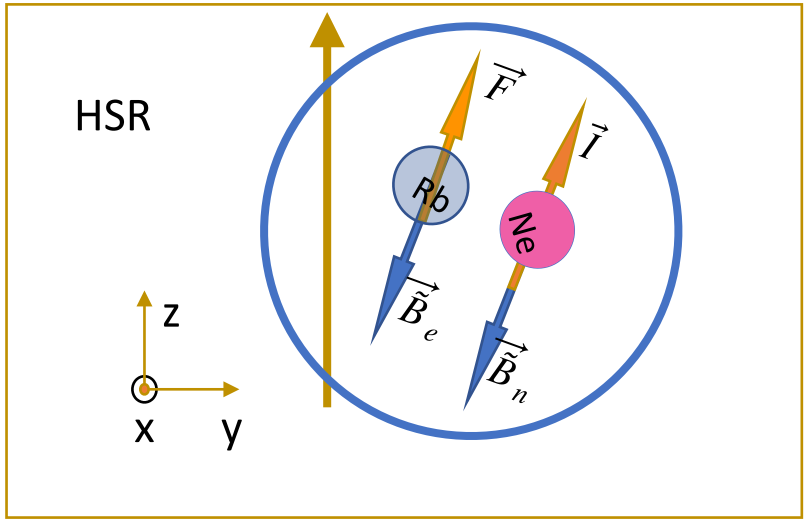

Guofeng Qu


Pavel Fadeev

# Backup Slides

# Hybrid Spin Resonance: High bandwidth




Screening Effect

$$B^e = \hat{B}^n + B_z$$

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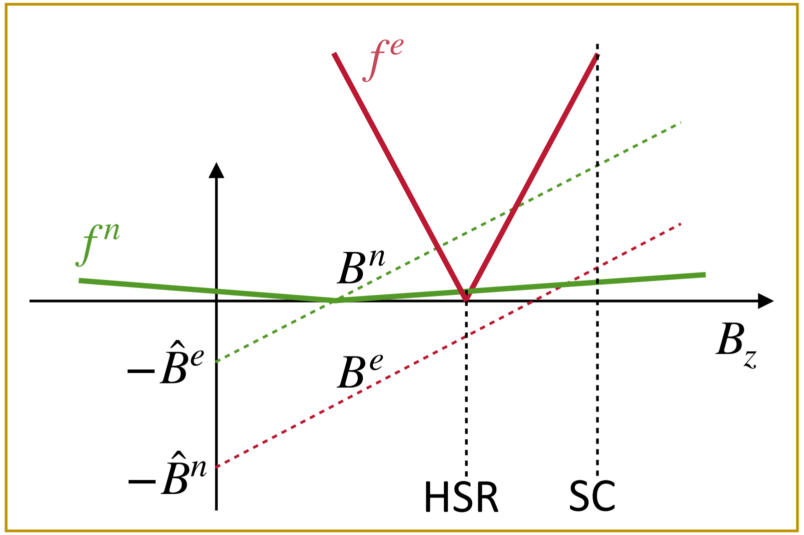
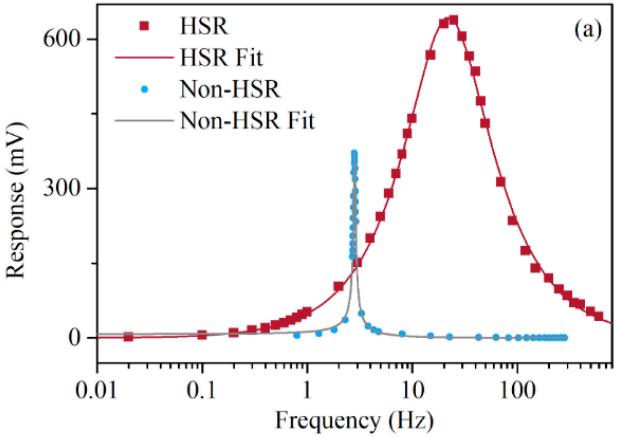
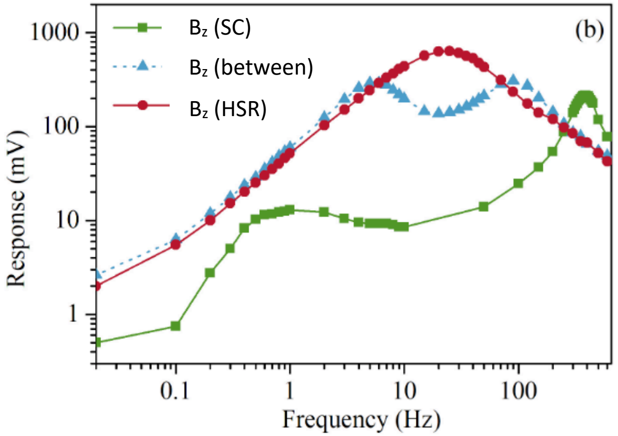
$$B_z(\text{HSR}) \approx \hat{B}^n$$

$$B_z(\text{SC}) \approx \hat{B}^n + \hat{B}^e$$



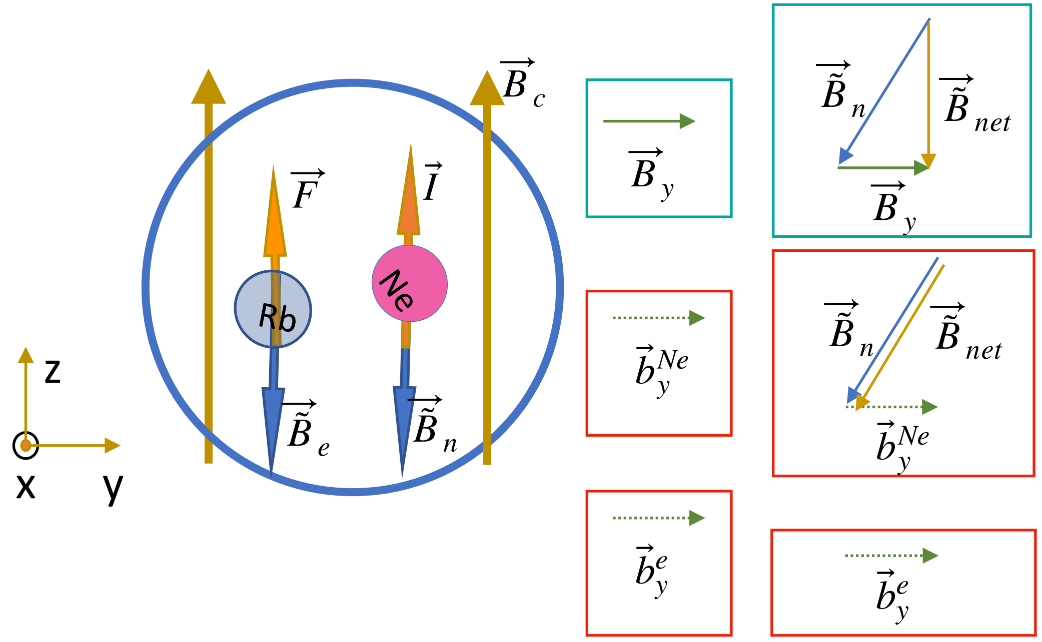

3 order of magnitude bandwidth improvement!

# Self-Compensation (SC) Regime

Wei et al, Phys Rev Lett.130.063201 (2023)

$$S = K\frac{\gamma_e P_z^e}{R_{\mathrm{tot}}^e}\left((B_y^{\mathrm{Ne}} - B_y^e) + (b_y^{\mathrm{Ne}} - b_y^e) + \frac{\Omega_y}{\gamma_{\mathrm{Ne}}}\right),$$

The SC can suppress normal magnetic field $\mathbf{B}$, rather than new physics field $\mathbf{b}^{e,n}$




The y axis (sensitive axis) fields feel by Rb

$$SF_x = \frac{R_2^n + \omega/2 + \omega^2\hat{\omega}_0^e/(R_2^e\hat{\omega}_0^n)}{\sqrt{(\hat{\omega}_0^n)^2 + (\hat{\omega}_0^e)^2\omega^2/R_2^{e\,2}}},$$

$$SF_y = \frac{(R_2^n)^2 + \omega^2}{\hat{\omega}_0^n\sqrt{(\hat{\omega}_0^n)^2 + (\hat{\omega}_0^e)^2\omega^2/R_2^{e\,2}}},$$

Suppression Factor $SF_{x,y} \propto R_2 \propto \nabla B$ (smaller the better)

Reduce Alkali gradient $\nabla B_y^e$ to optimise suppression factor