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JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Search for ultralight new particles with spin-based sensors

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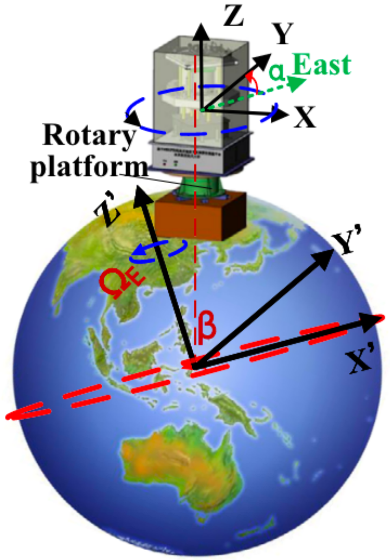
Matter AntiMater Section
Budker AG
2024.07.14
贵阳

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



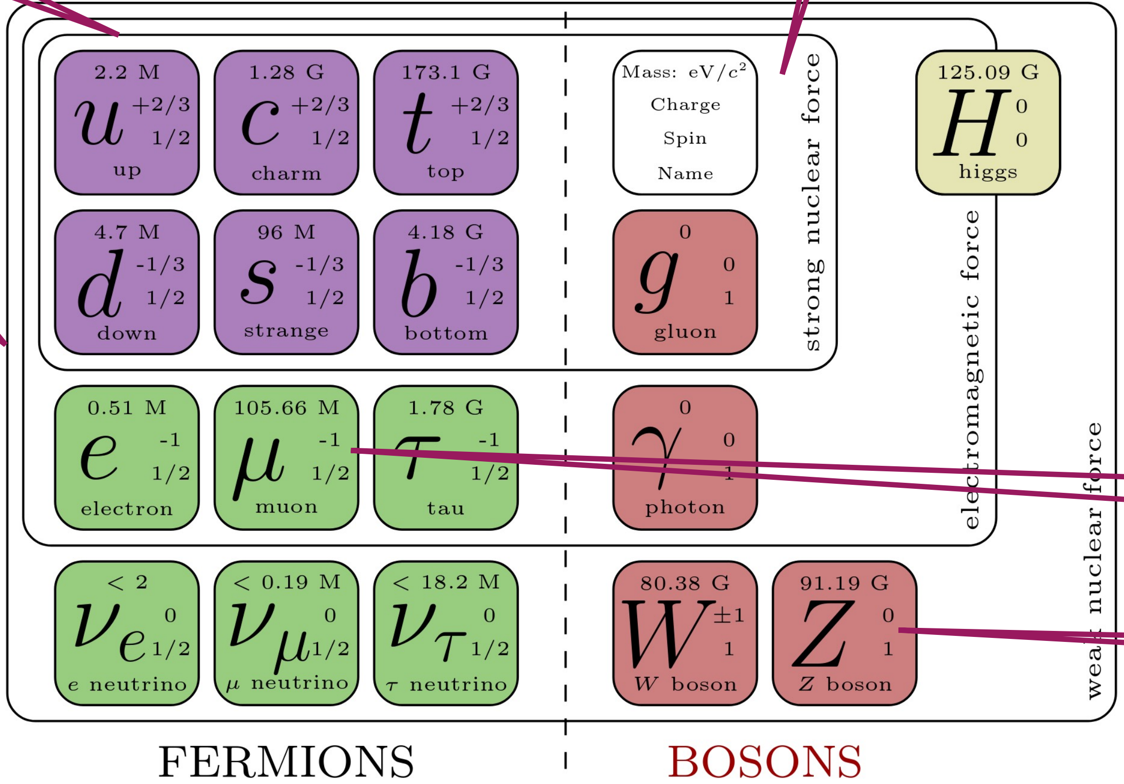
New Physics (Beyond the Standard Model)

Do spins couple to gravity?

How to include Gravity?

Dark Matter and Dark Energy

Why the universe look like this

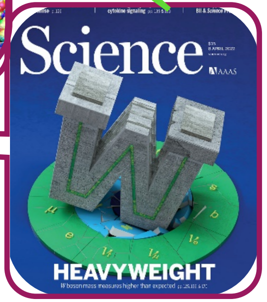


Strong CP problem

Why more matter than antimatter

Why do we exist?

Fifth force?

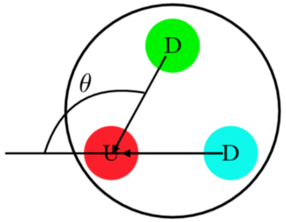


Axion: Peccei-Quinn-Weinberg-Wilczek (PQWW) Model

- 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

PRL 124, 081803 (2020)

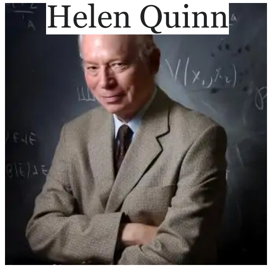
$$d_n = \left(0.0 \pm 1.1_{stat} \pm 0.2_{sys}\right) \times 10^{-26} e\,.\,\mathrm{cm}\,.$$

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

- Peccei-Quinn mechanism

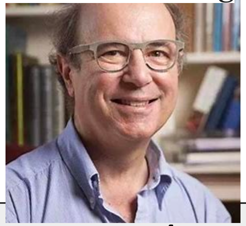
$a + \bar{\theta}f_a = \bar{a}$ The $\bar{\theta}$ term can be absorbed into the axion field and it can explain why $\bar{\theta}$ is so small.

Roberto Peccei



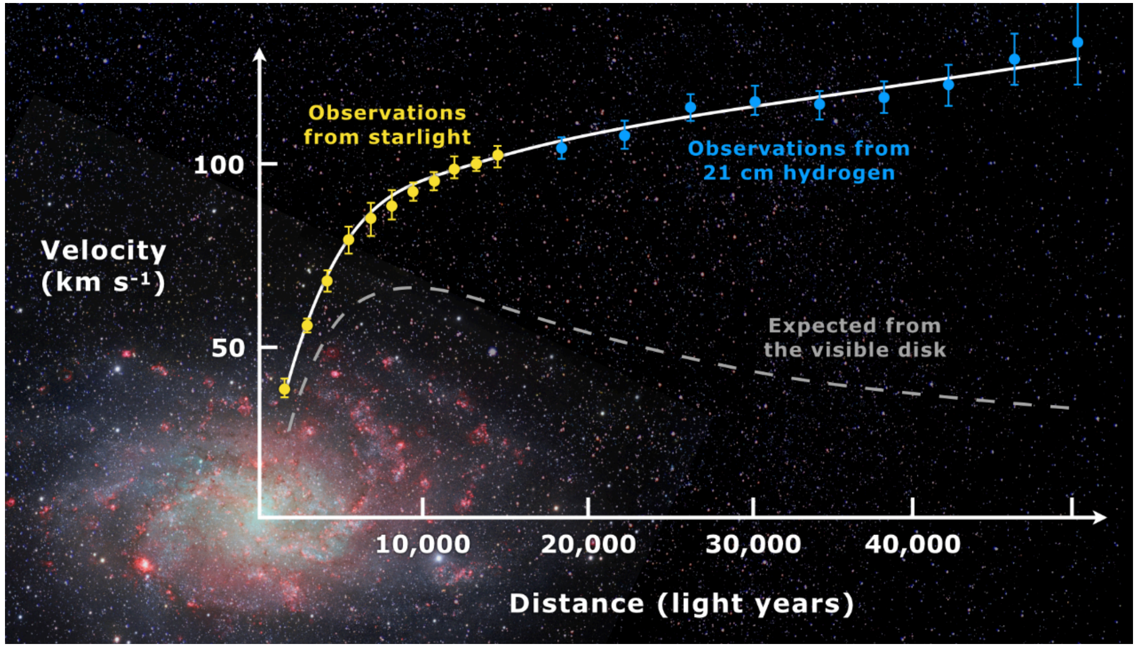
Helen Quinn

Steven Weinberg

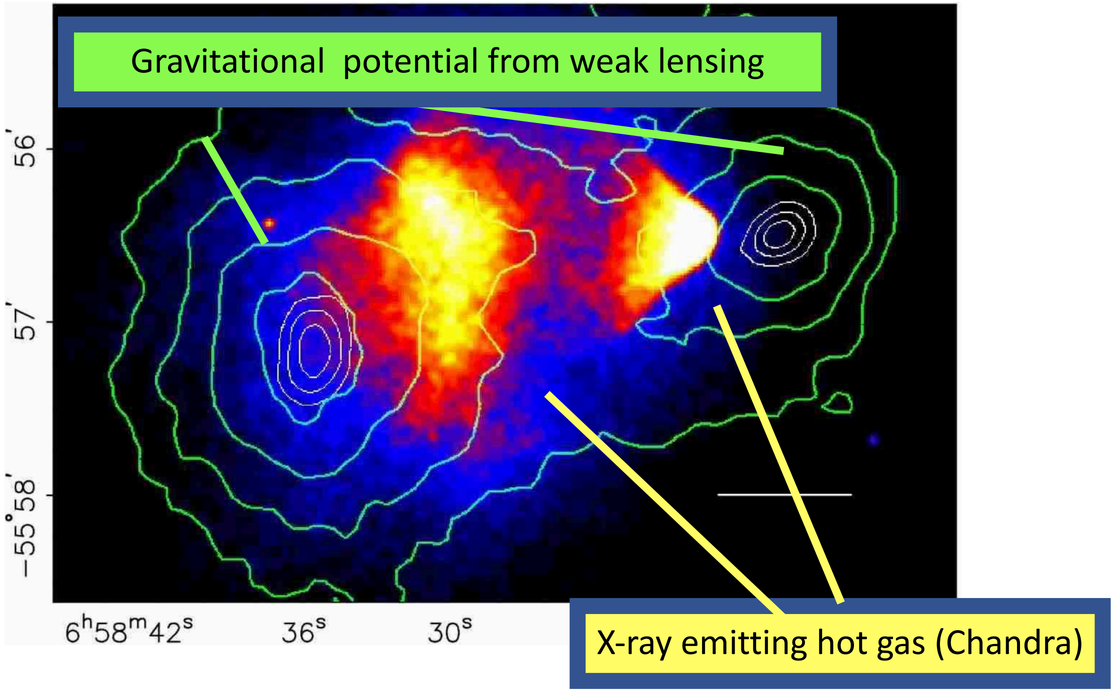


Frank Wilczek

Dark Matter



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



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

10^{-22}eV

Axion Window
μeV – 100 μeV

keV

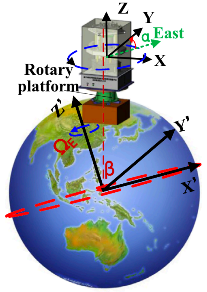
GeV

100 TeV

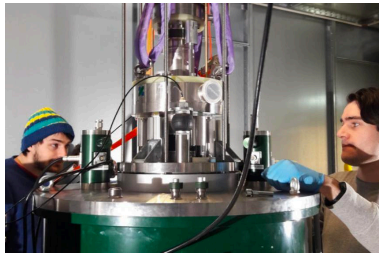
Ultralight Bosonic DM

Table-top Precision Measurement experiments

ChangE

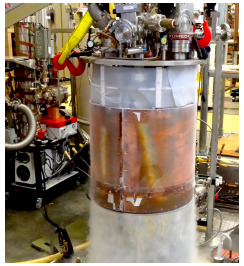


CASPEr



Cavity Experiments

ADMX

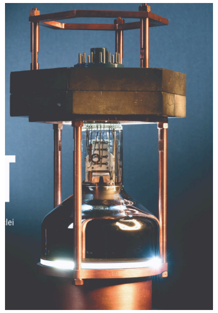


SRF

Light DM

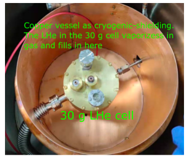
Sterile ν

COHERENT



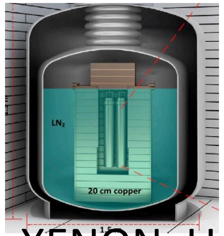
WIMPs

ALETHEIA

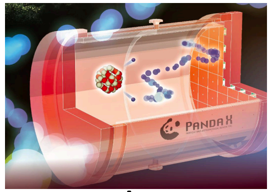


DOPMPE

CDEX



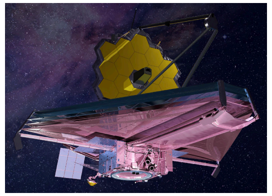
PandaX



XENON, LUX, ,Accelerator etc

Composite DMs & Primordial Black holes

James Webb Telescope



Axion (and Axionlike Particles) Dark Matter Detection

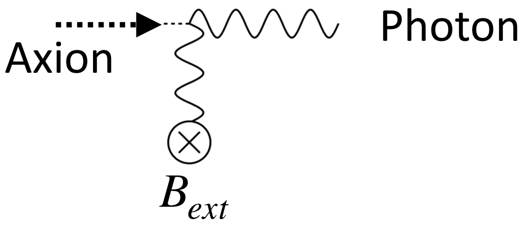
- Ultralight
- Weakly interacting
- Huge number density

Perfect DM candidate

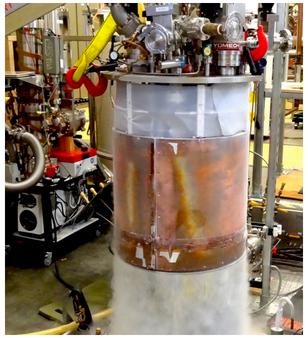
- Axion-Photon Coupling:

$$\mathscr{L}_{\mathrm{EM}} \approx g_{a\gamma\gamma} a(\vec{r}, t) F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Inverse Primakoff Effect

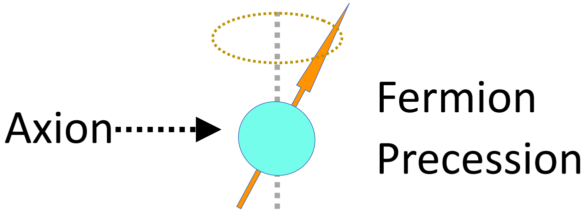


ADMX

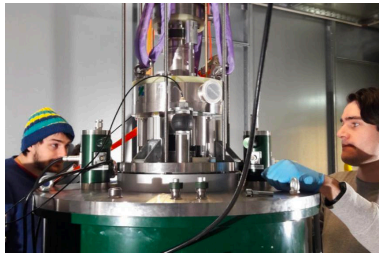


- **Axion-Fermion Coupling:**

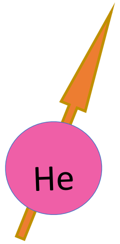
$$\mathscr{L}_{\mathrm{spin}} \approx g_{aNN} \left[\partial_\mu a(\vec{r}, t)\right] \bar{\Psi}_n \gamma^\mu \gamma_5 \Psi_n$$



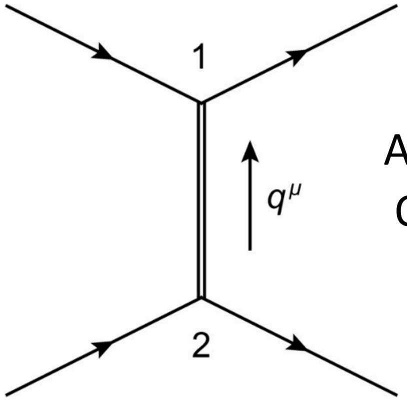
CASPEr



Exotic Spin-Dependent Force



New Interaction



Axion and ALPs
Or Z'

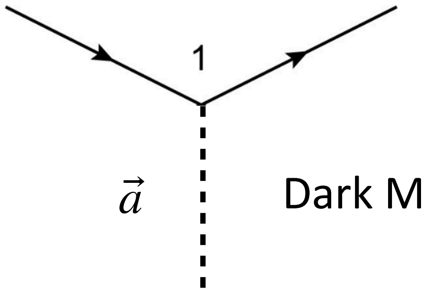
Spin-0

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

Spin-1

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

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)

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

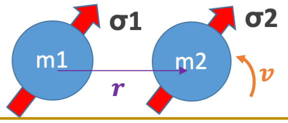
P Violation

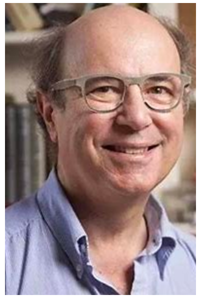
CP violation

Vector and Axial Vector Coupling

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

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





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)

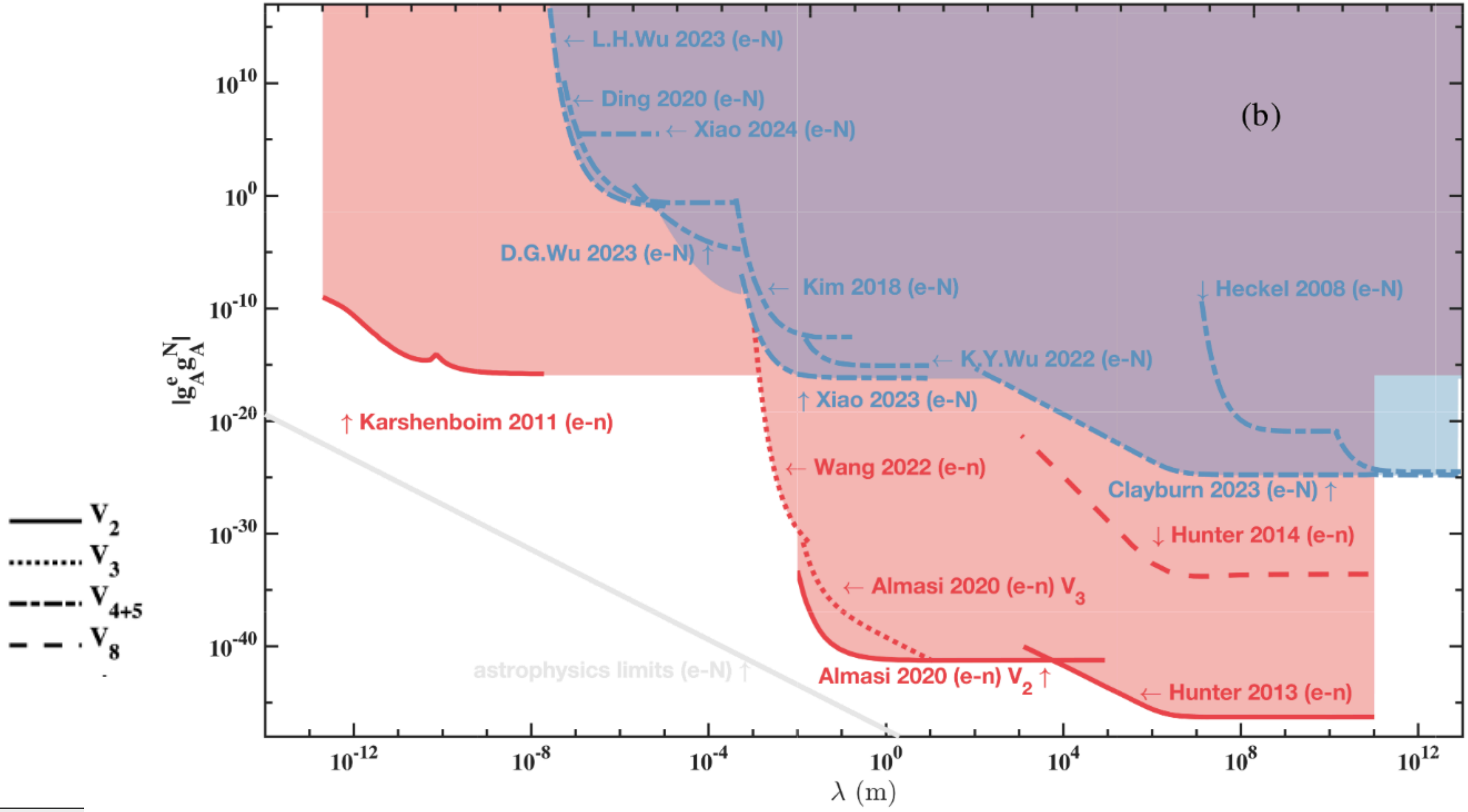
Spin-dependent macroscopic forces from new particle exchange

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

Preliminary Results (Invited by RMP)

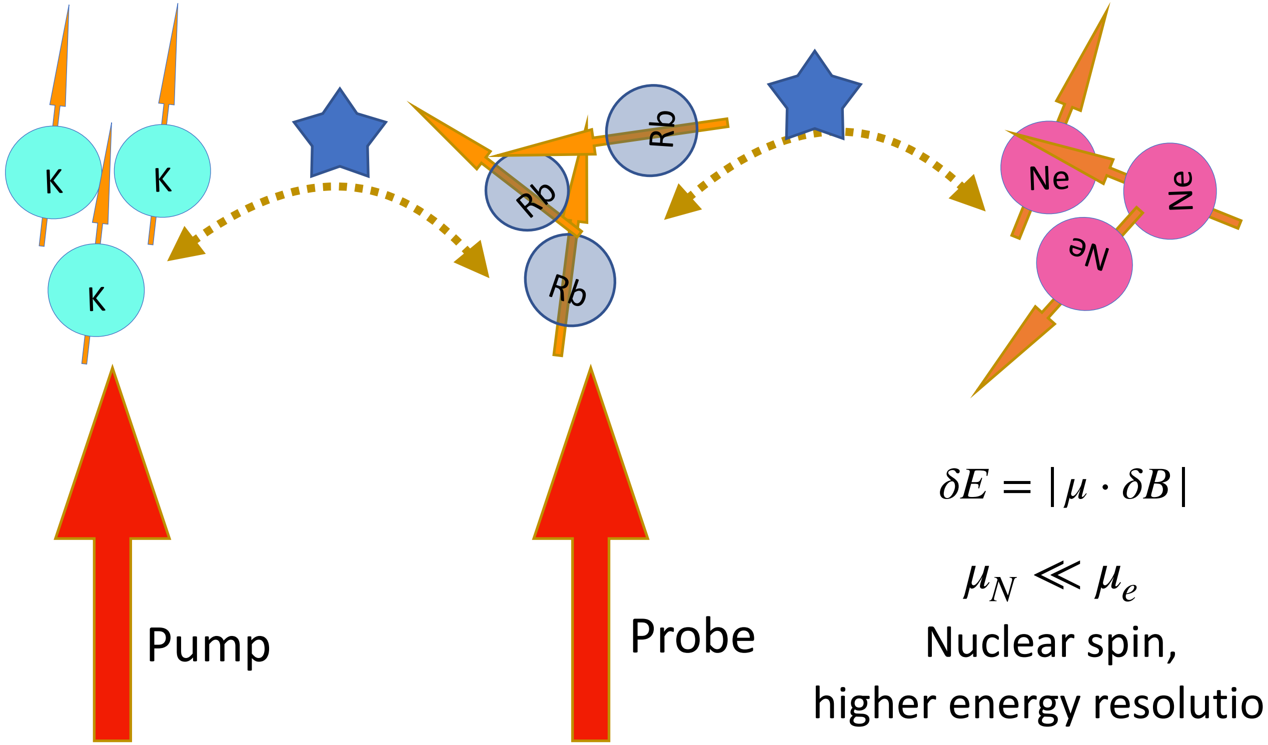
REVIEWS OF MODERN PHYSICS

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



Alkali-Noble Comagnetometer: Sword for New Physics

Hybrid Spin Exchange Pumping



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

$$\mu_N \ll \mu_e$$

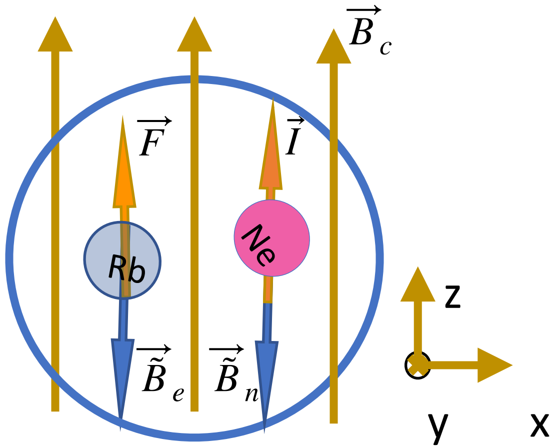
Nuclear spin,
higher energy resolution

Hybrid pumping enables the best nuclear polarisation and coherence time

Dynamics of the spins

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

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



Self-Compensation (SC) Regime

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

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

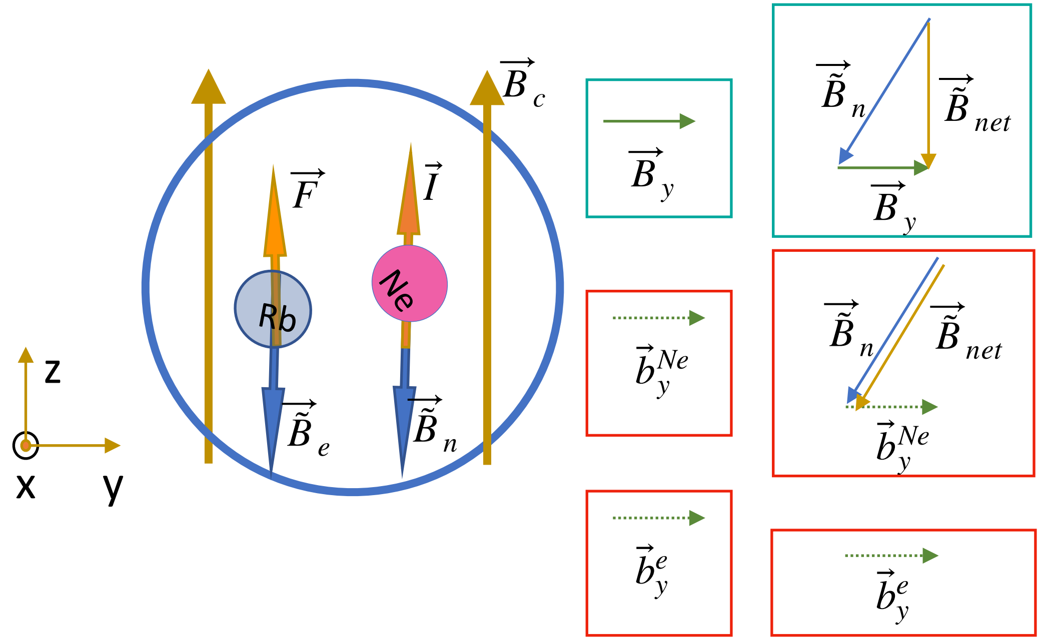
The SC can suppress normal magnetic field $\mathbf{B}$, rather than new physics field $\mathbf{b}^{e,n}$

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

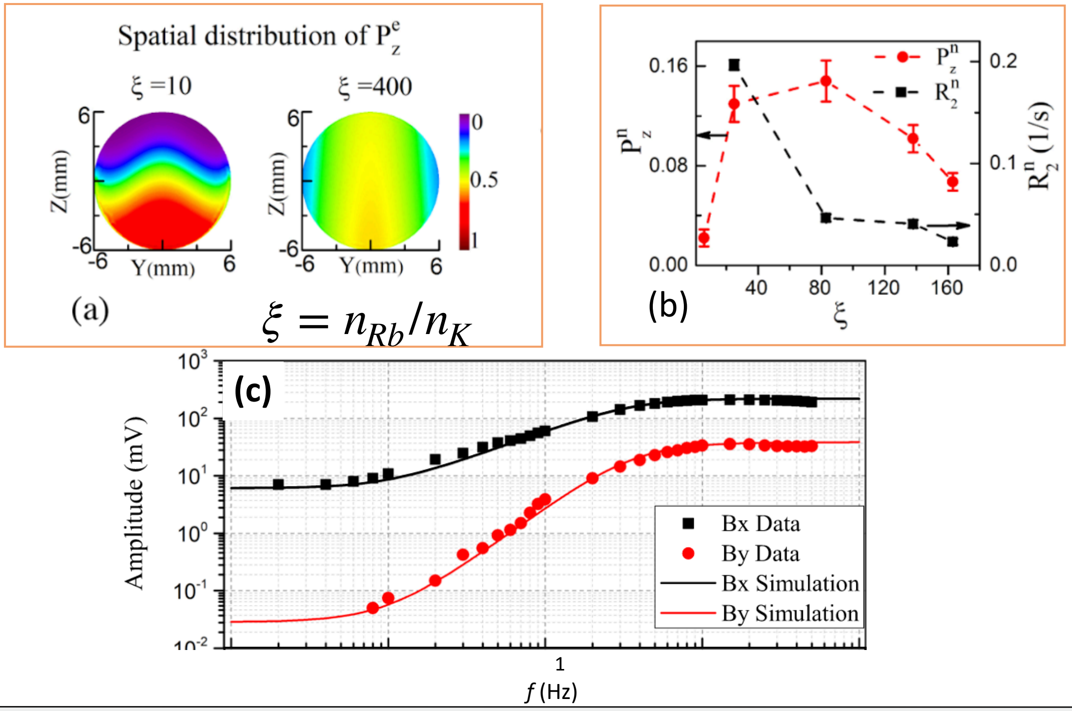
$$SF_y = \frac{(R_2^n)^2 + \omega^2}{\hat{\omega}_0^n\sqrt{(\hat{\omega}_0^n)^2 + (\hat{\omega}_0^e)^2\omega^2/R_2^{e\,2}}},$$

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

Reduce Alkali gradient ∇B_y^e to optimise suppression factor

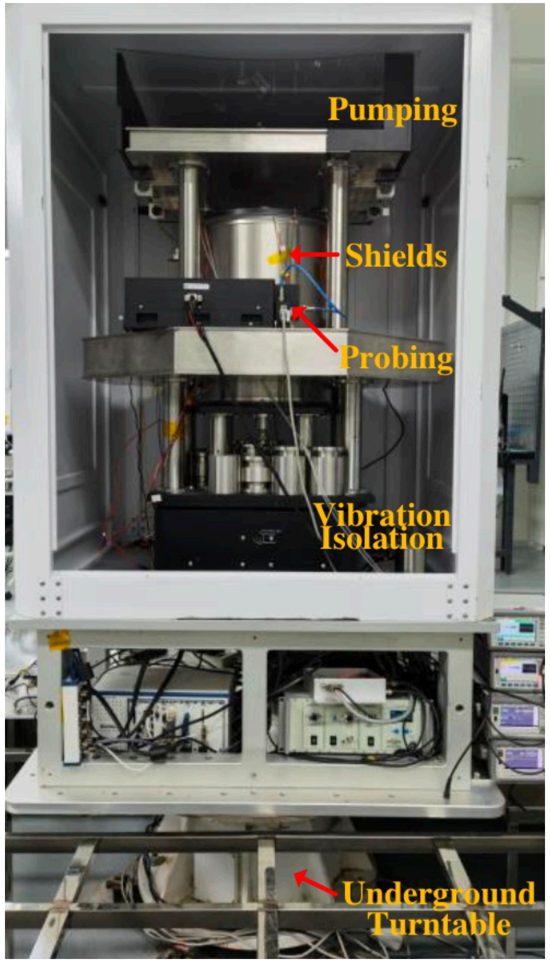


The y axis (sensitive axis) fields feel by Rb

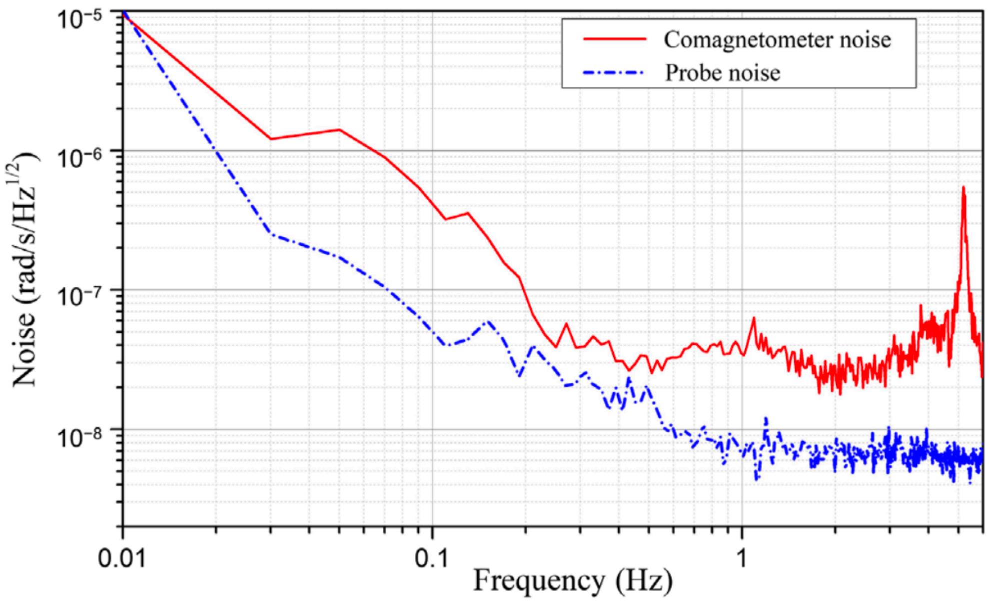


Ultrahigh sensitivity Self-Compensation Comagnetometry

Wei, et all. Physical Review Letters, 130(6), p.063201



K-Rb-^{21}Ne SERF Comagnetometer



$\delta\Omega = 3\times10^{-8}\mathrm{rad/s\,Hz^{-1/2}}$

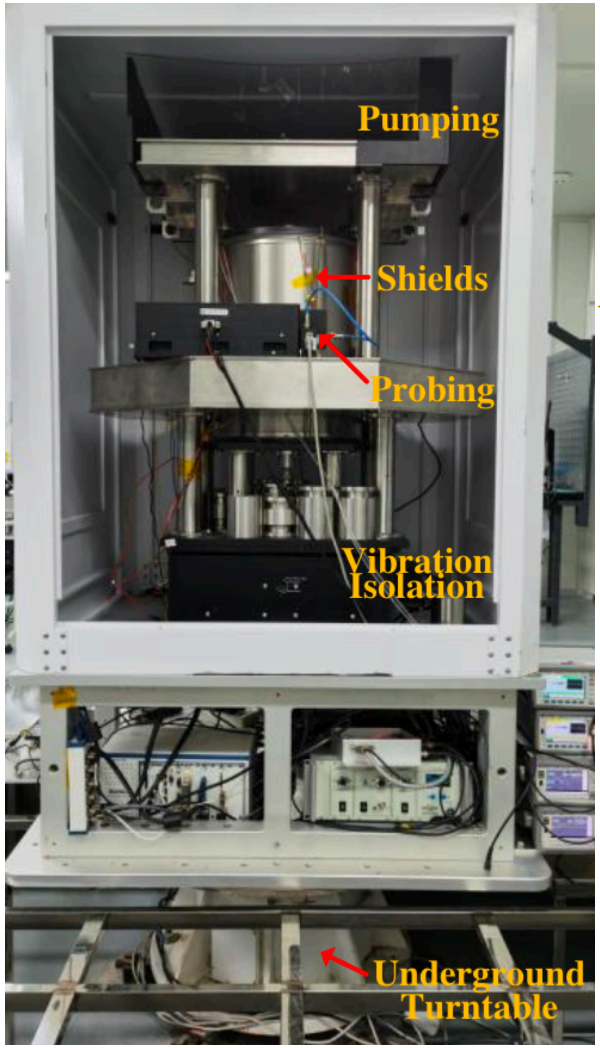
$\delta b^n = 1.5\,\mathrm{fT\,Hz^{-1/2}}$

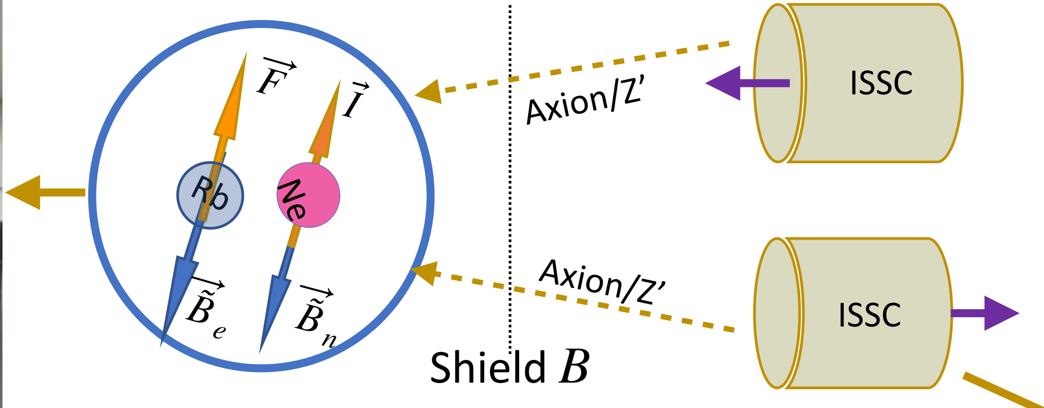
Highest Energy Resolution

$\delta E_{\mathrm{Ne}} = 3.1\times10^{-23}\mathrm{eV\,Hz^{-1/2}}$

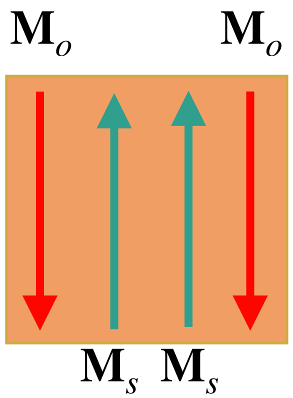
- **Recipe**
  - Magnetic Noise: Ferrite Shielding
  - Temperature gradient: Vacuum Isolation
  - Vibration Isolation: Additional foundation
  - Laser polarisation stability: Polarisation Modulation

Fifth Force Experiment



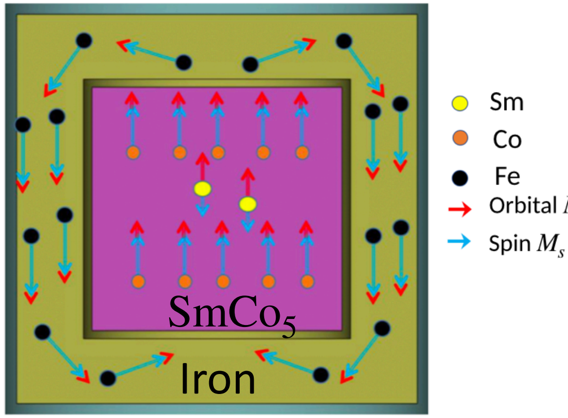


- Ji et al, PRL 130, 133202(2023).
- Wei et al, PRL130, 063201 (2023).
- Ji et al, PRL, 121(26): 261803, 2018.
- Ji et al, PRD, 95(7): 075014, 2017.
- Wei et al, NC 13, 7387, (2022)



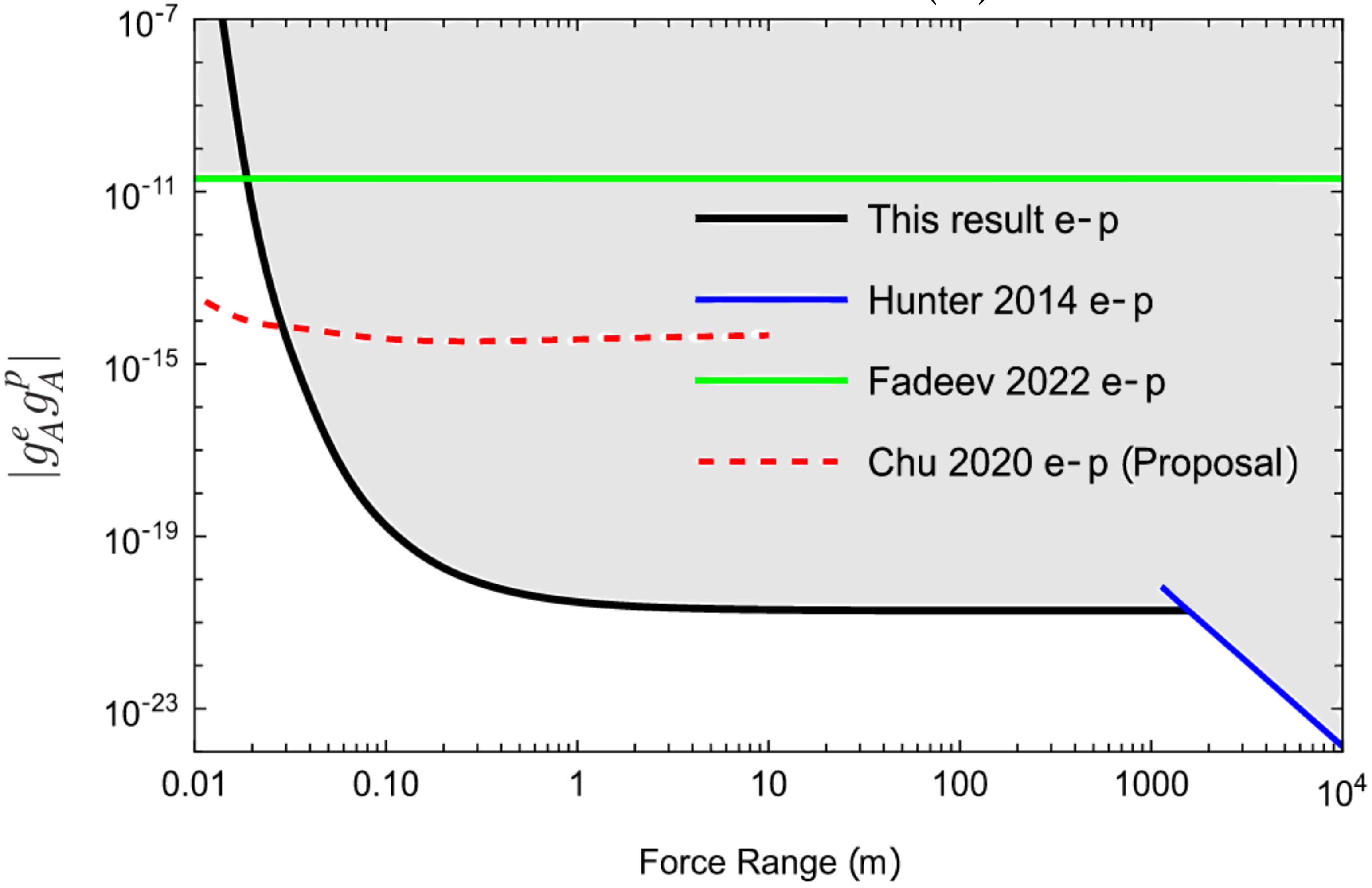
$$\mathbf{M} = \sum \mathbf{M}_s + \mathbf{M}_o = 0$$

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

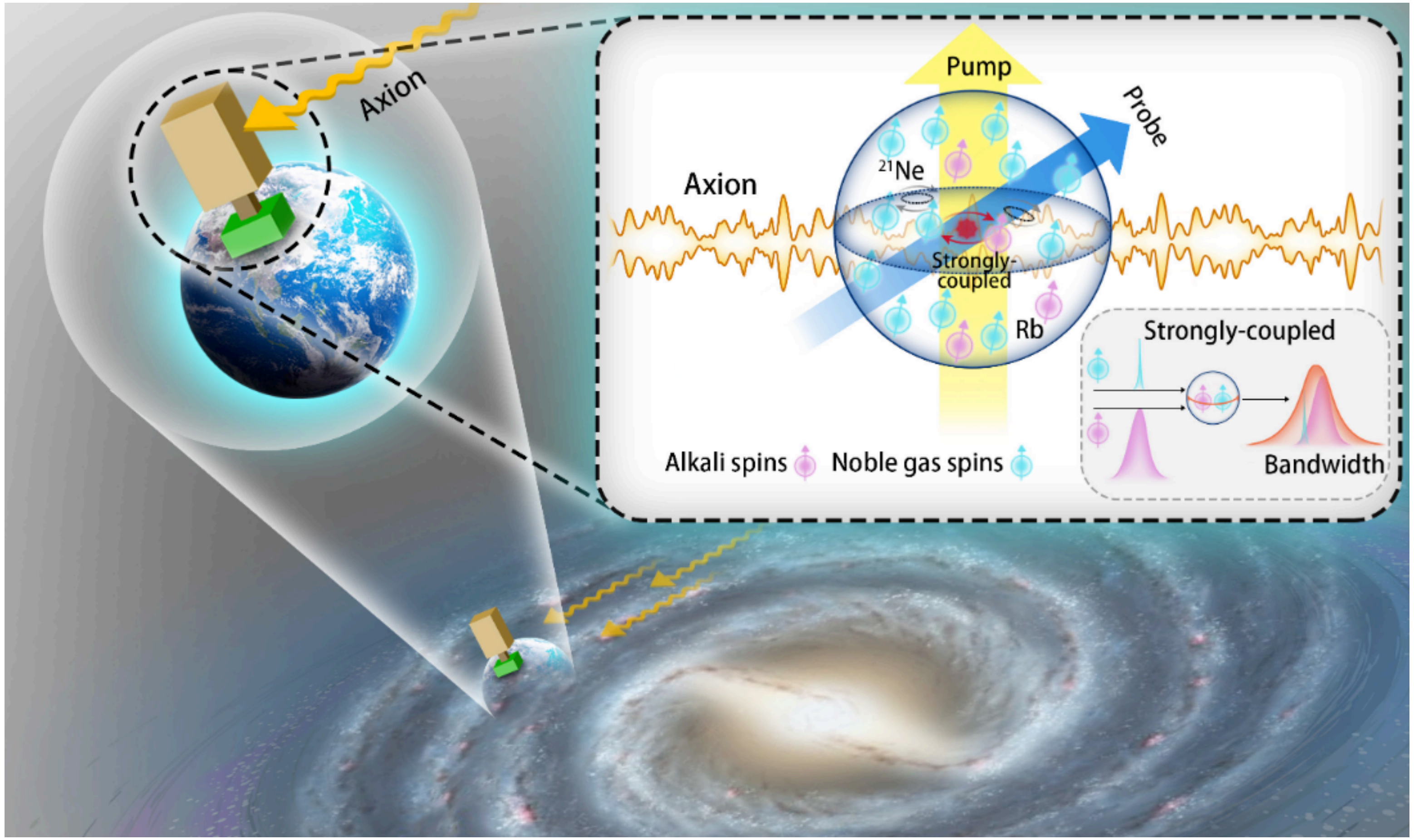


Fifth Force Experiment

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



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

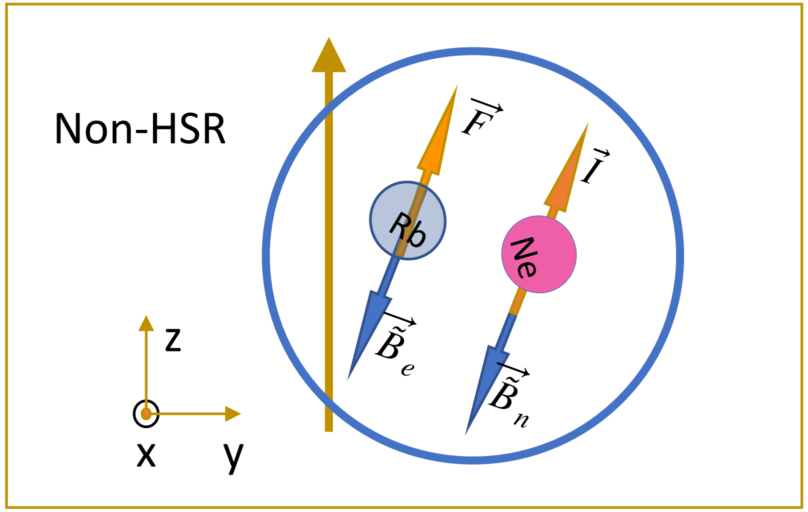
$$\beta_j = \frac{g_{aN}}{\gamma_N} \nabla a(j\Delta t) \cdot \hat{\mathbf{m}}(j\Delta t) ,$$

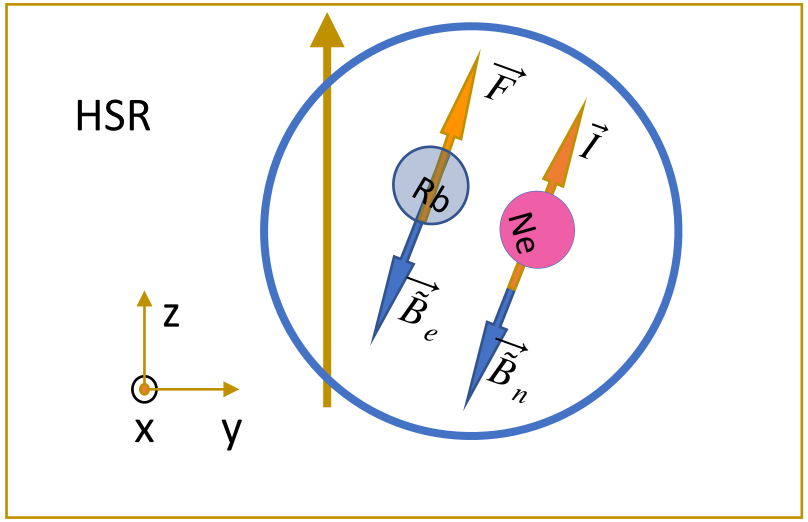
Daily Modulation

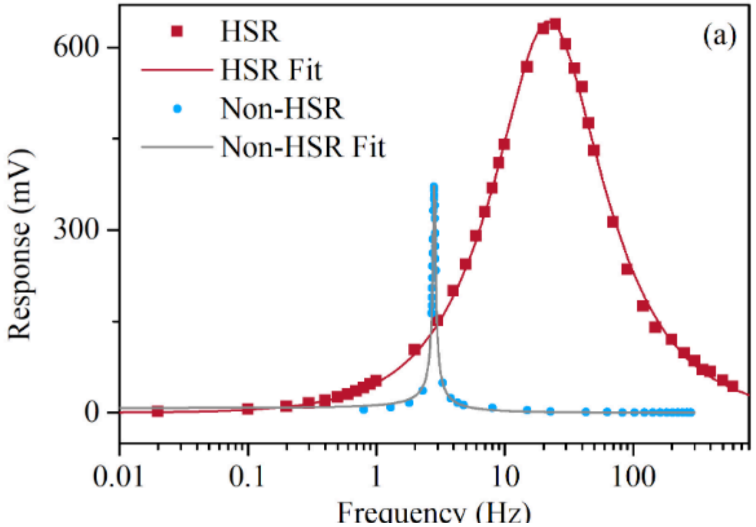
$$\hat{\mathbf{m}}_i(j\Delta t) \approx \mathbf{C}_i \cos(\omega_e j\Delta t + \theta_i) + \mathbf{D}_i ,$$

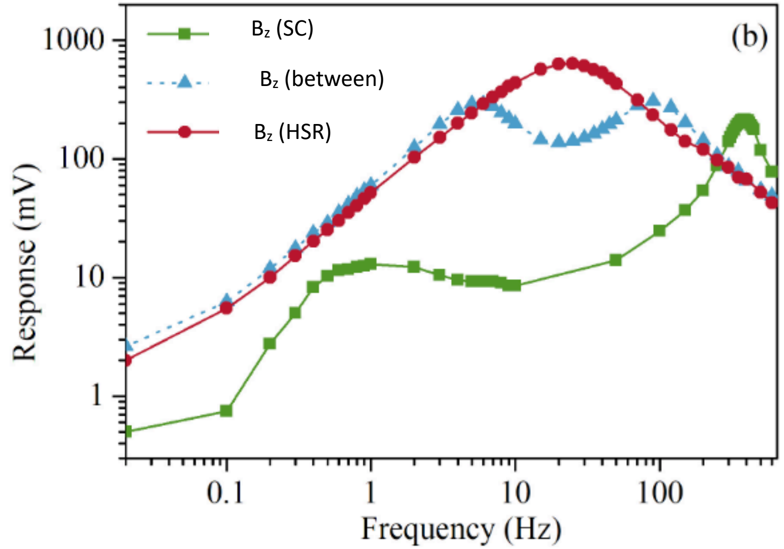
NMR resonance line width only 0.02 Hz, need broadband!

Hybrid Spin Resonance: High bandwidth



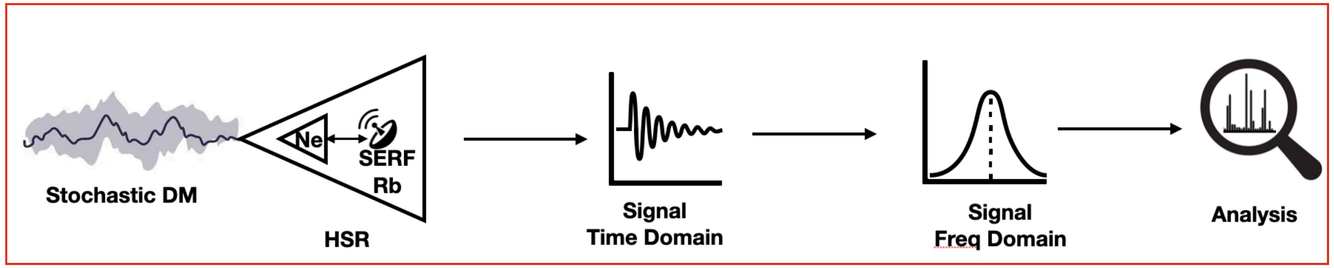


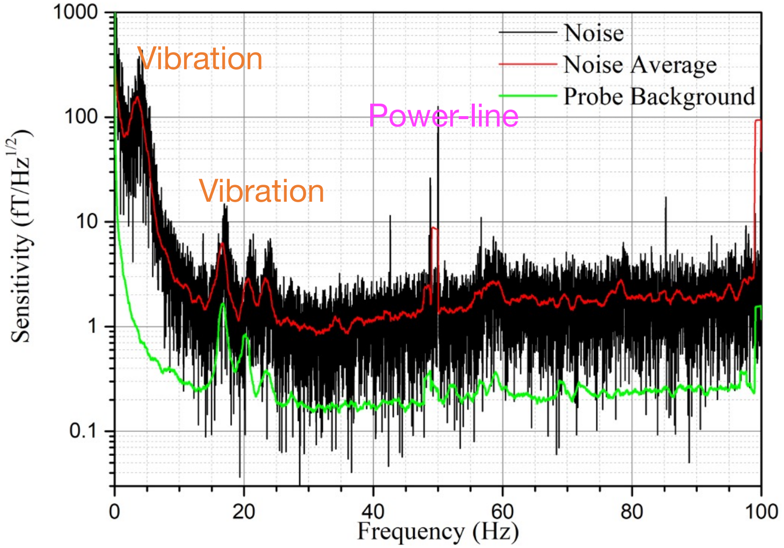


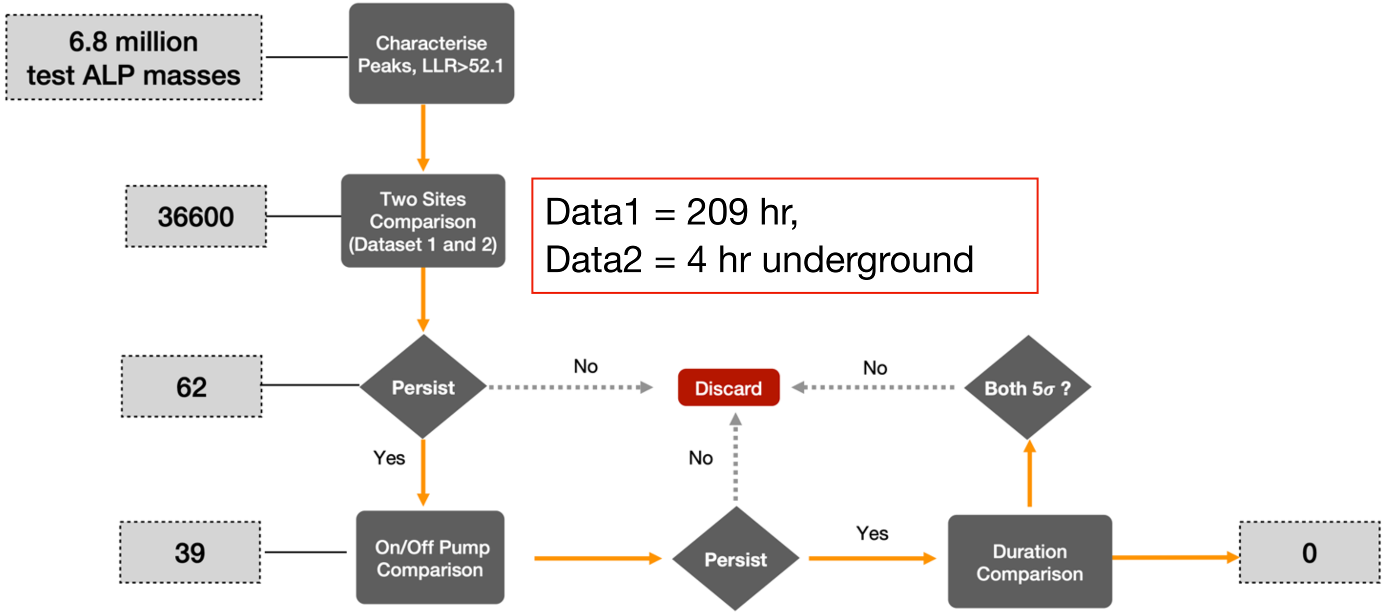


3 order of magnitude bandwidth improvement!

Broadband Axion Search





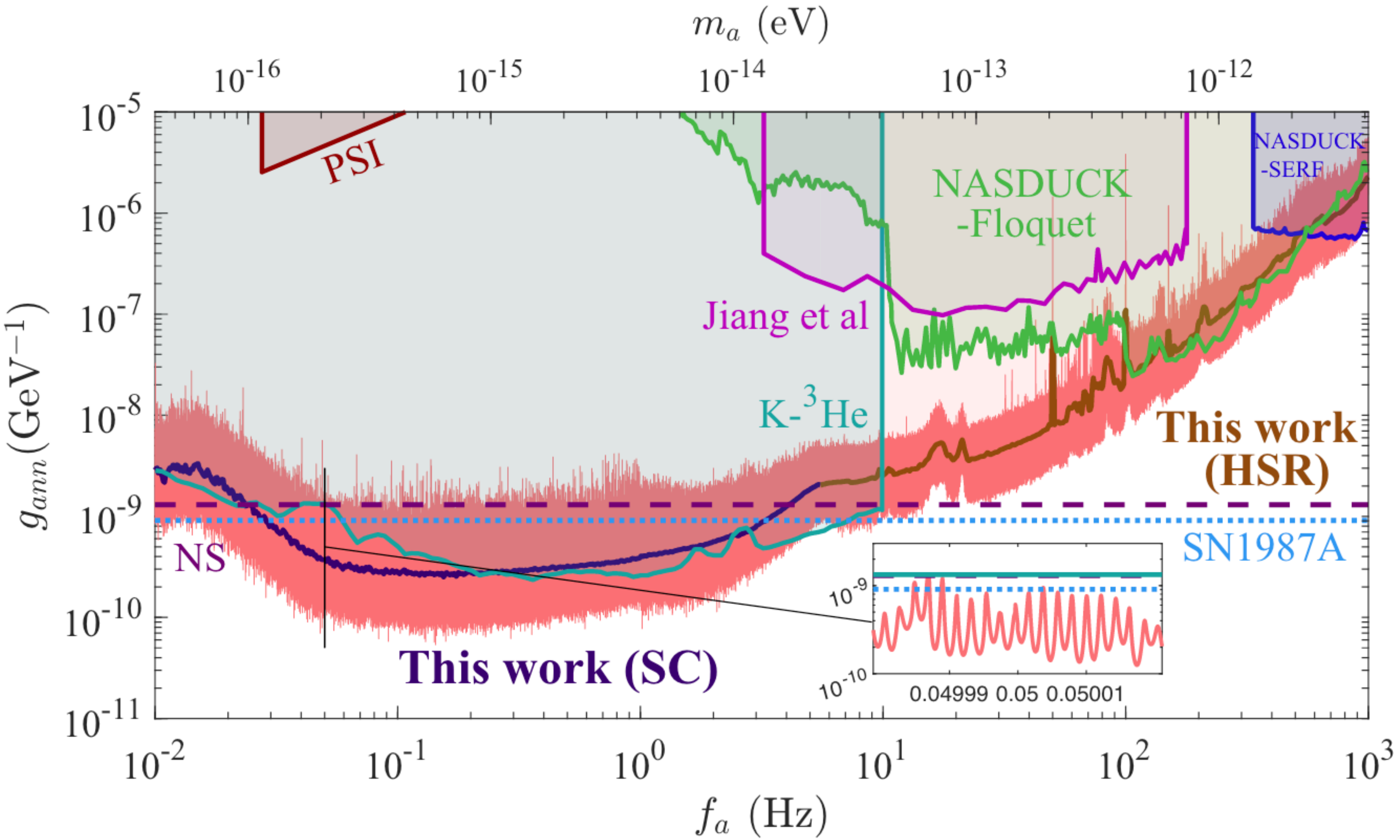


Data1 = 209 hr,
Data2 = 4 hr underground

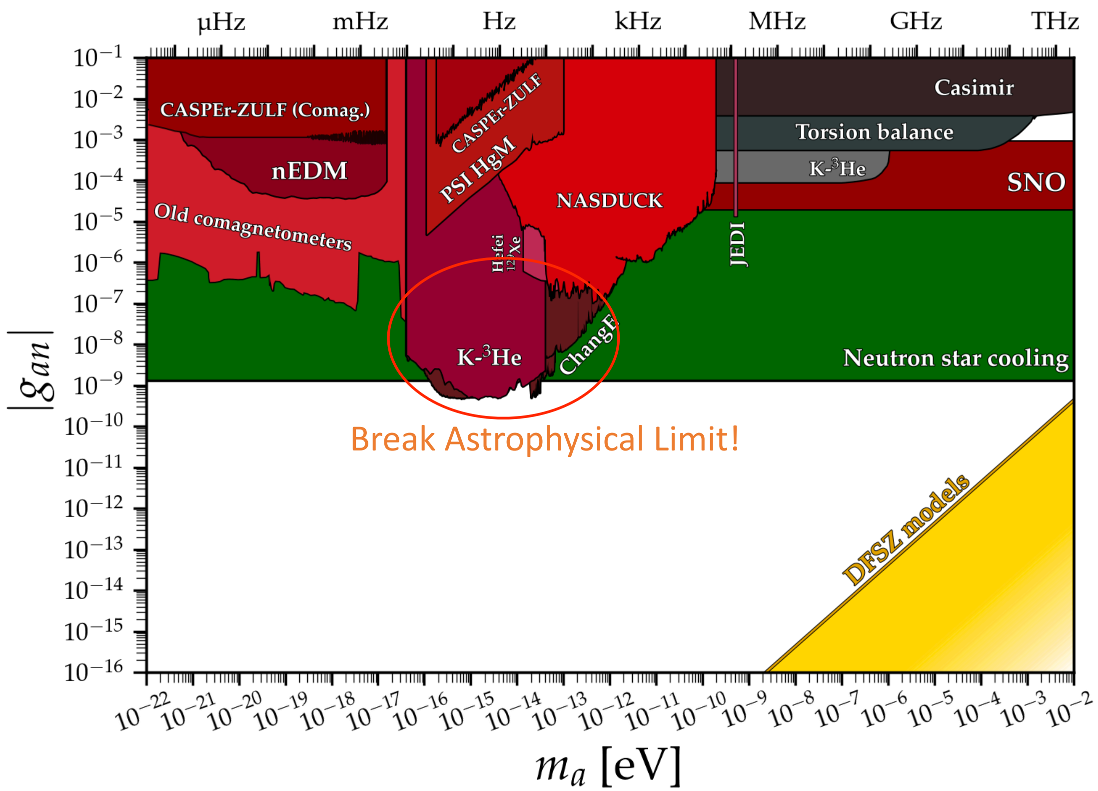
- Signal should be very narrow, $\frac{\delta f}{f} \approx 10^{-6}$
- Signal should persist
- Axion DM frequency unknown

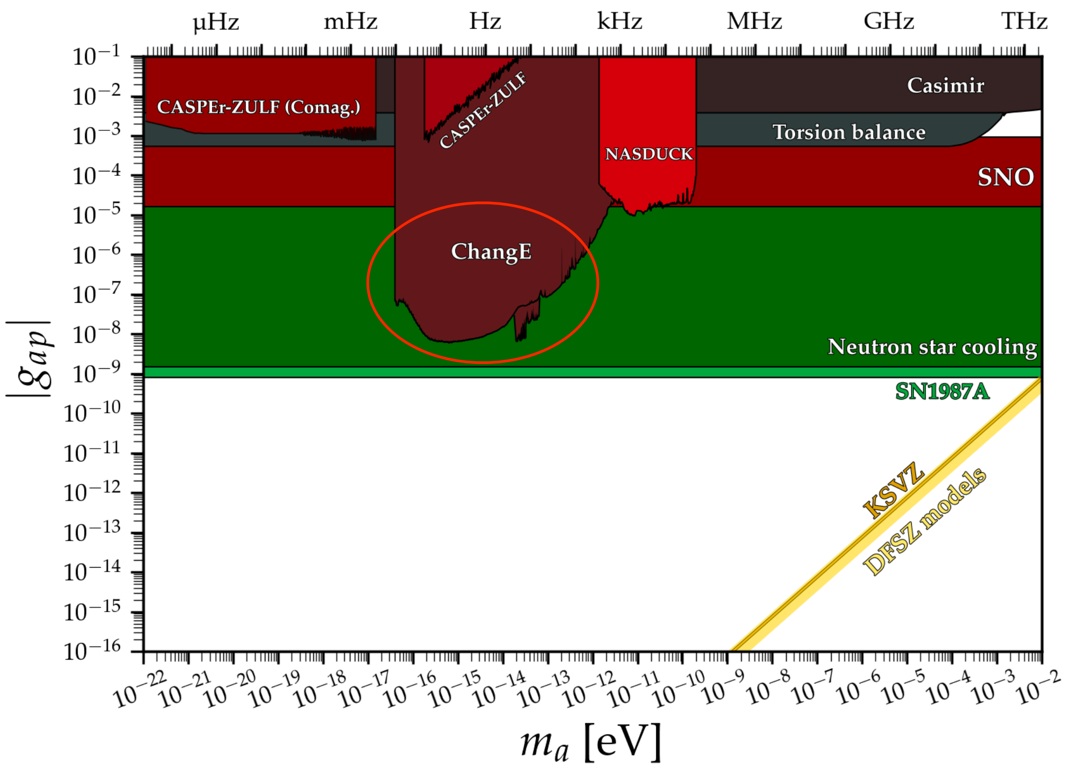
Axion Limits

Wei et al., arXiv:2306.08039



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





Xu et al, Commun. Phys. 7, 226, (2024)

Wei et al., arXiv:2306.08039

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

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

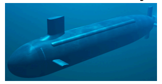
LEvitated MAgnets for QUantum MEtrology (LEMAQUME)

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

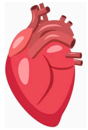
Equivalent magnetic noise (per $Hz^{1/2}$)

Earth

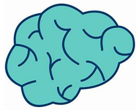
Submarine 1km away



Heart

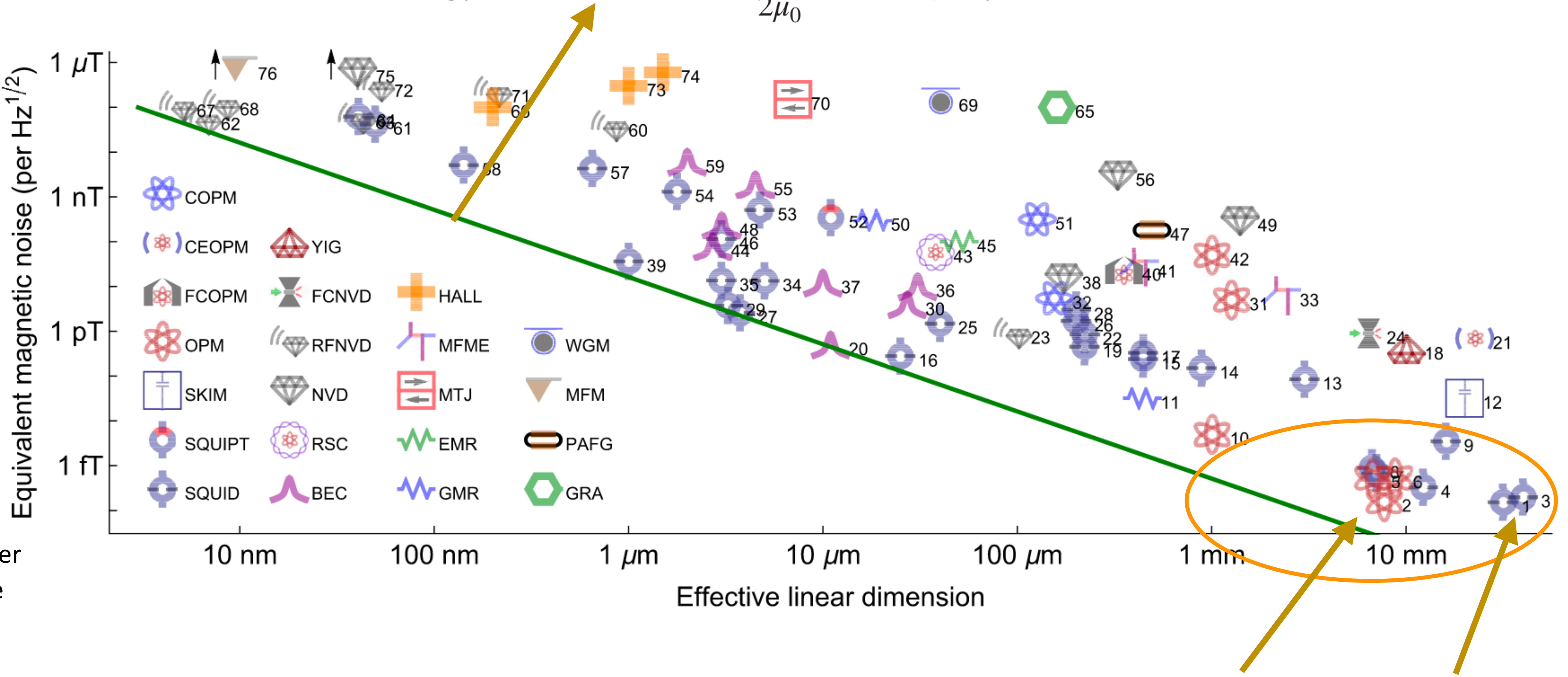


Brain



New Physics

Dark Matter
5th force



SERF OPMs SQUID

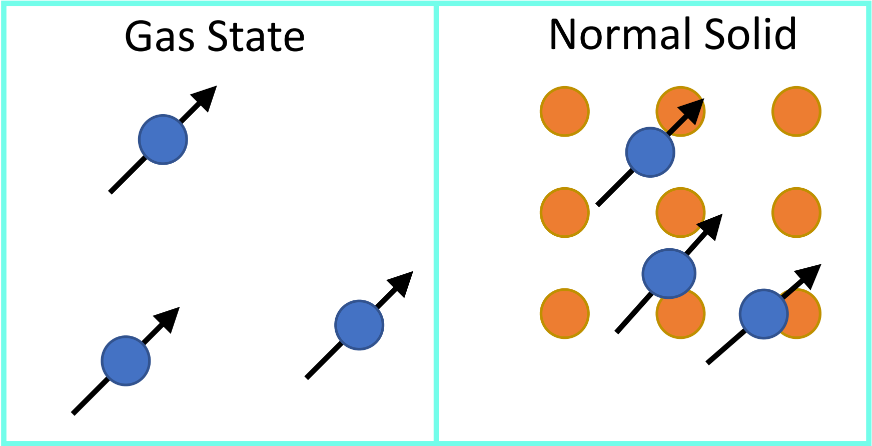
REVIEWS OF MODERN PHYSICS, VOLUME 92, APRIL–JUNE 2020

Ferromagnetism and Precession

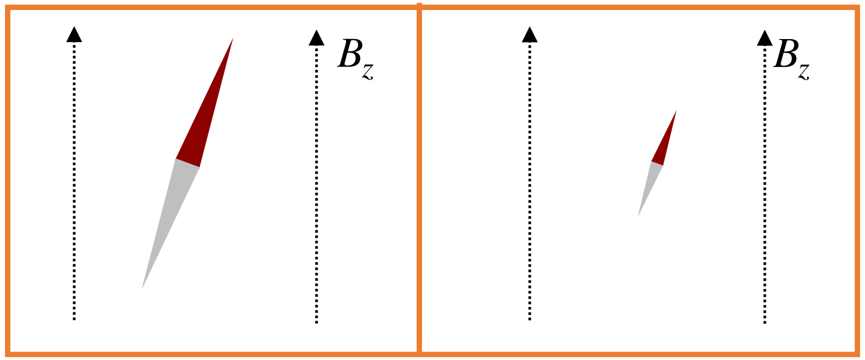
PRL 116, 190801 (2016) PHYSICAL REVIEW LET

Precessing Ferromagnetic Needle Magnetometer

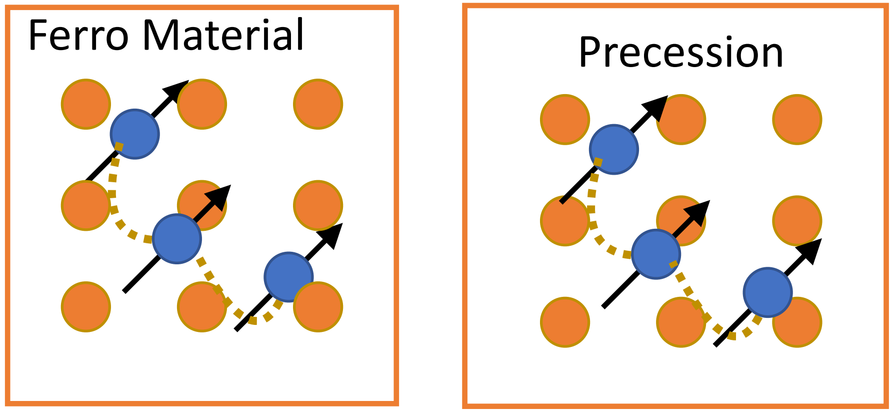
Derek F. Jackson Kimball,[1] Alexander O. Sushkov,[2] and Dmitry Budker[3,4,5]



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

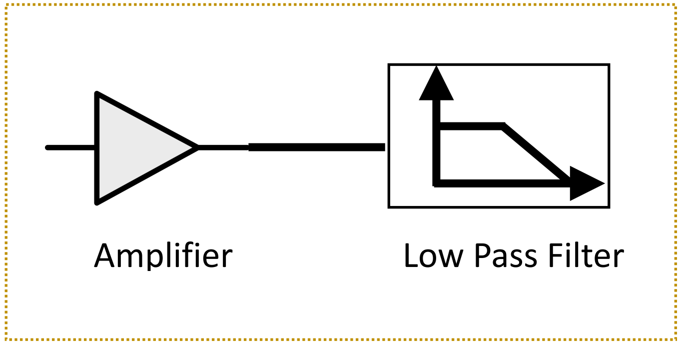


Libration v.s Precession

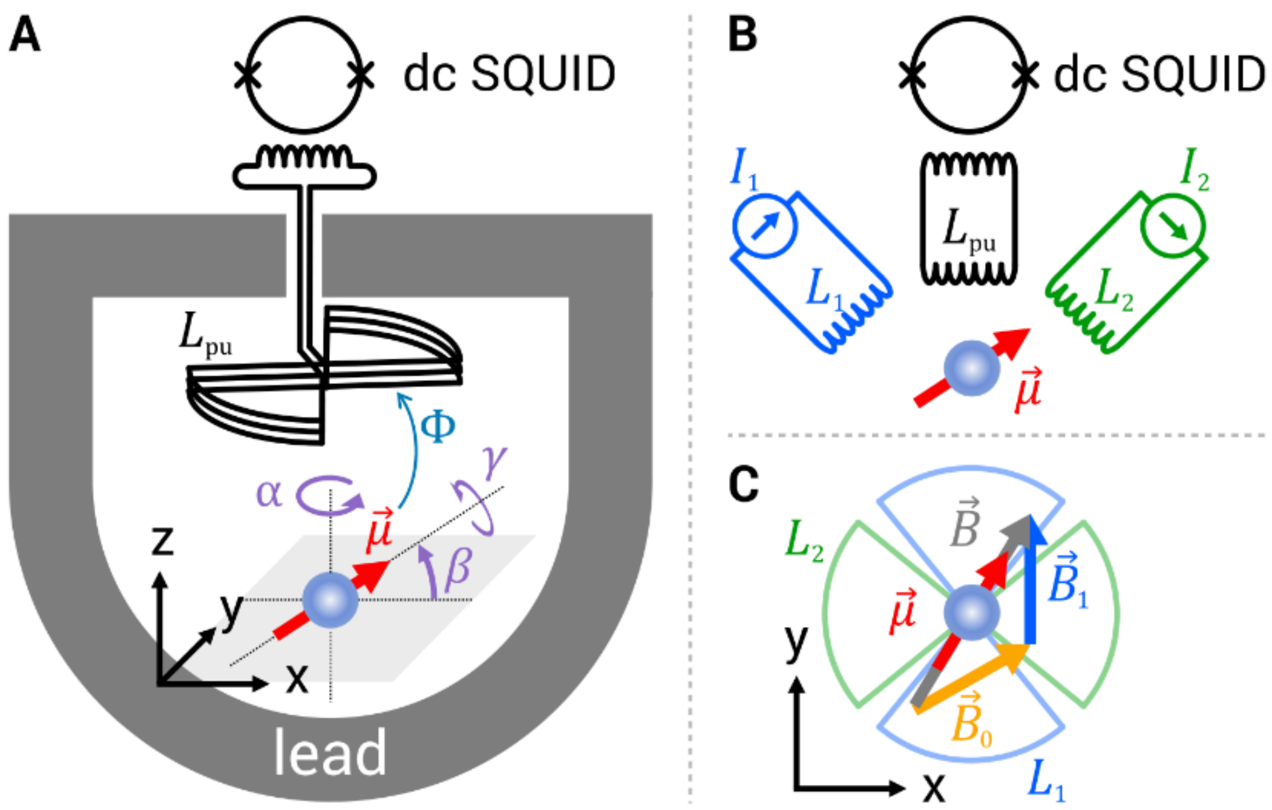


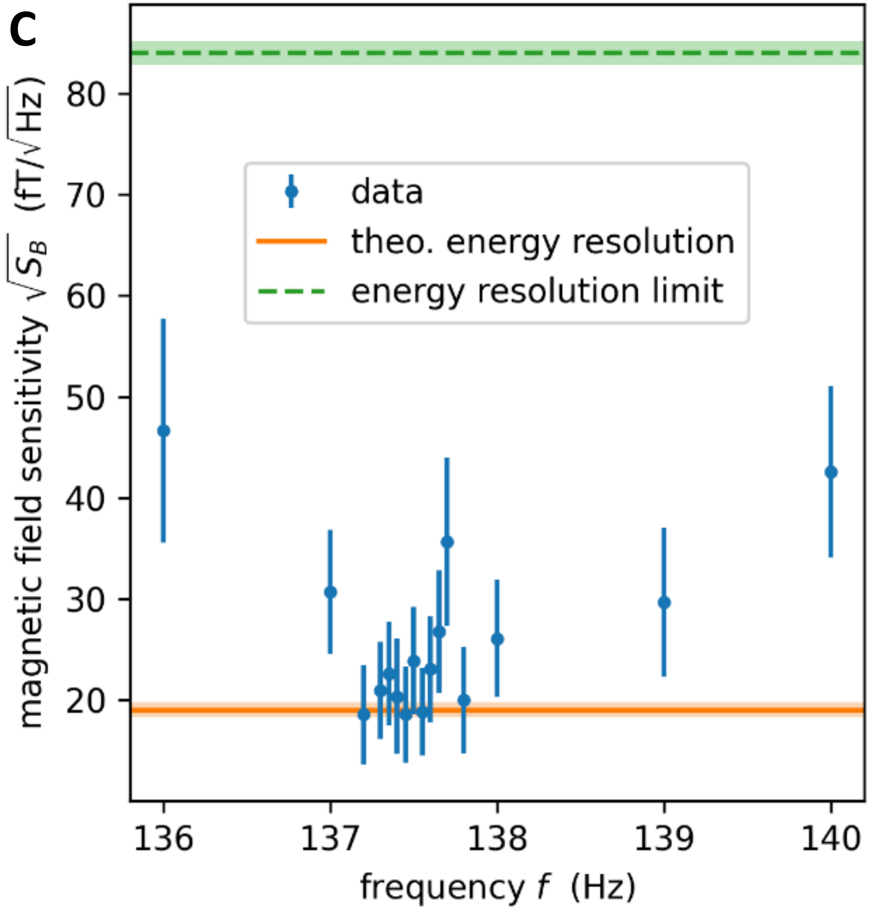
$$\Delta\phi = \frac{\Delta S_\perp}{S_\parallel}\frac{1}{\sqrt{t}} \approx \sqrt{\frac{2\alpha k_B T}{N\hbar\omega_0^2 t}}$$

Ferromagnetic Resonance (FMR) v.s Precession



LEMAQUME: Magnetometry

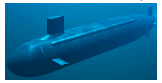




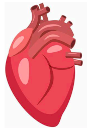
LEMAQUME: Magnetometry

Earth

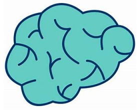
Submarine
1km away



Heart



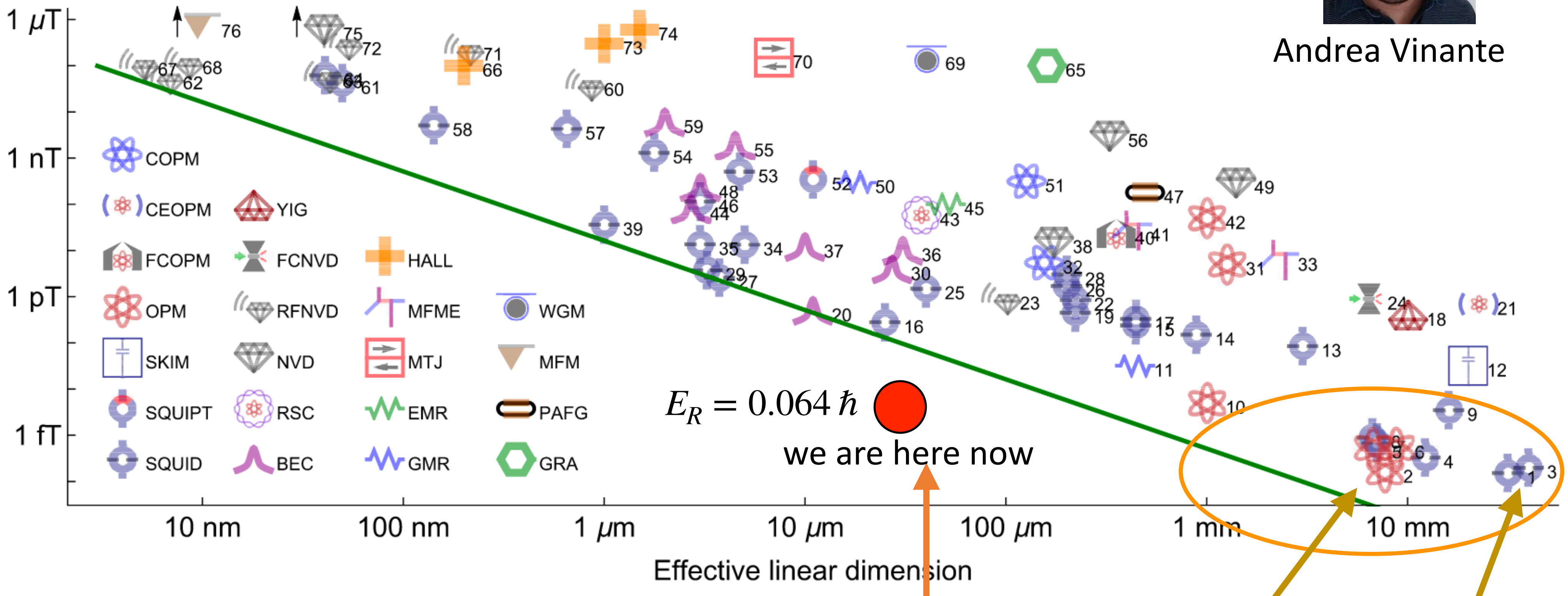
Brain



New Physics

Dark Matter
5th force

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

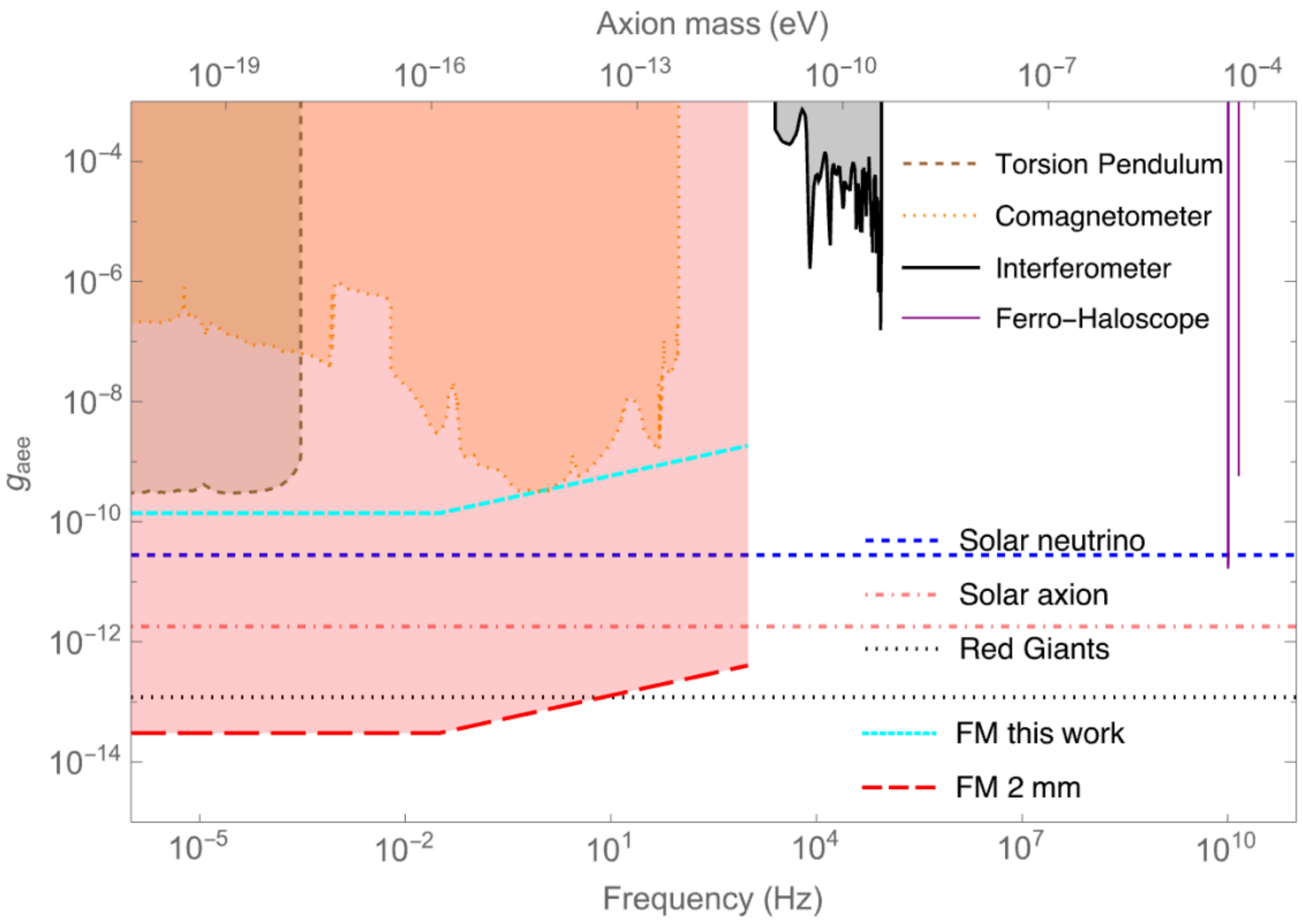


Andrea Vinante

arXiv:2401.03774 (2024).

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

LEMAQUME: Search For Axions



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

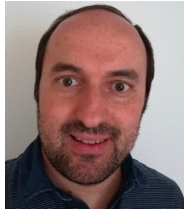
魏凯

王小平

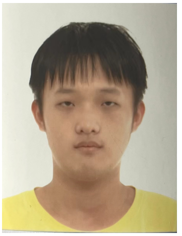
And many others

LEMAQUME

Dmitry Budker



Andrea Vinante



Changhao Xu

Guofeng Qu

Pavel Fadeev

Backup Slides

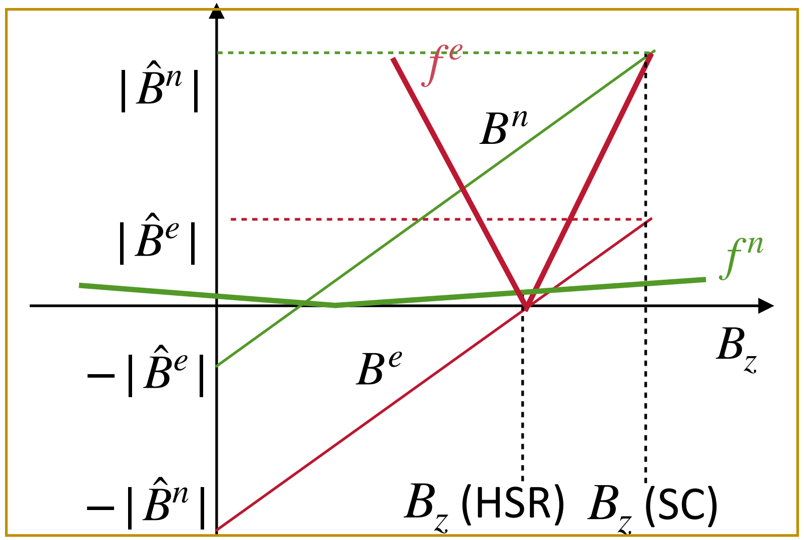
Screening Effect

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

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

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

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



Optically Pumped Magnetometer (OPM)

nature physics

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Published: April 2007

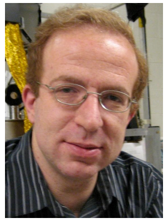
Optical magnetometry

Dmitry Budker & Michael Romalis

Nature Physics **3**, 227–234 (2007) | Cite this article

Dmitry Budker

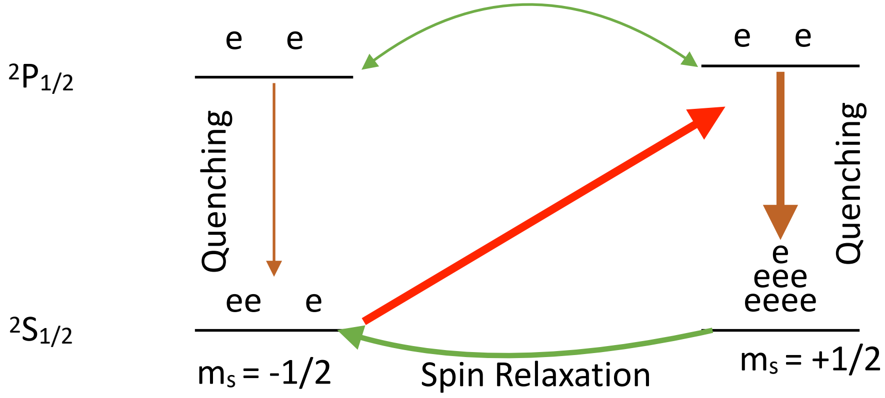
UC Berkeley and Mainz

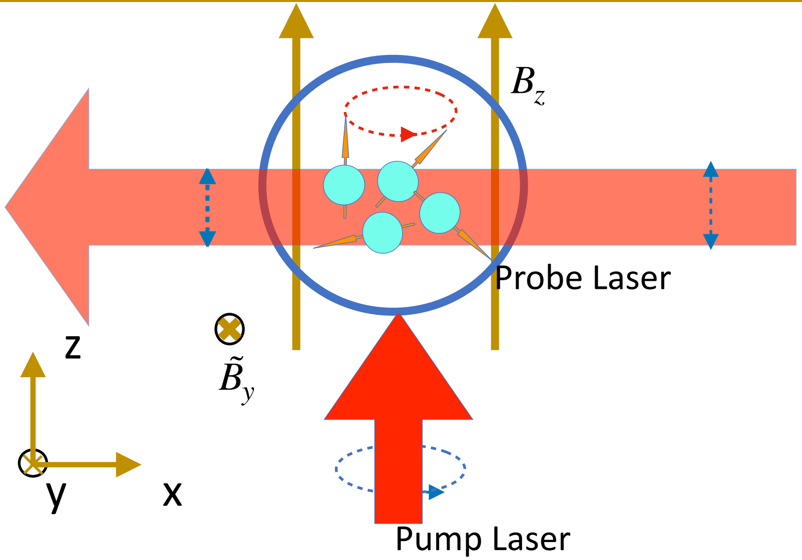


Michael Romalis

Princeton

- Optical Pumping
- Spin Precession
- Probe (Faraday Rotation)





OPM: Alkali Magnetometer

VOLUME 89, NUMBER 13 PHYSICAL REVIEW LETTERS 23 SEPTEMBER 2002

High-Sensitivity Atomic Magnetometer Unaffected by Spin-Exchange Relaxation

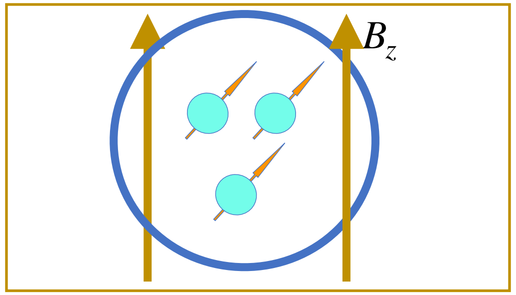
J. C. Allred and R. N. Lyman
Department of Physics, Univerisity of Washington, Seattle, Washington 98195

T. W. Kornack and M. V. Romalis*
Department of Physics, Princeton University, Princeton, New Jersey 08544

(Received 6 March 2002; published 9 September 2002)

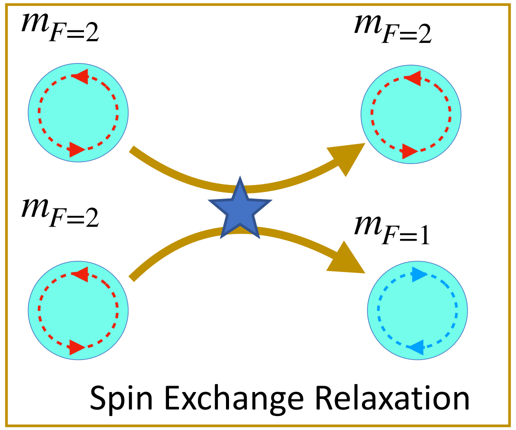
Budker's famous Equation 1:

$$\delta B = \frac{1}{\gamma\sqrt{nT_2Vt}}$$ (Spin Projection Noise)



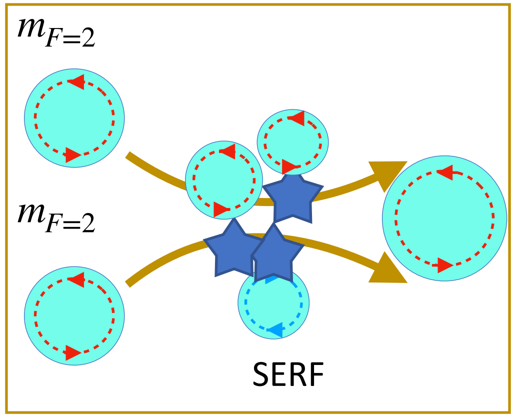
Spin Exchange Relaxation

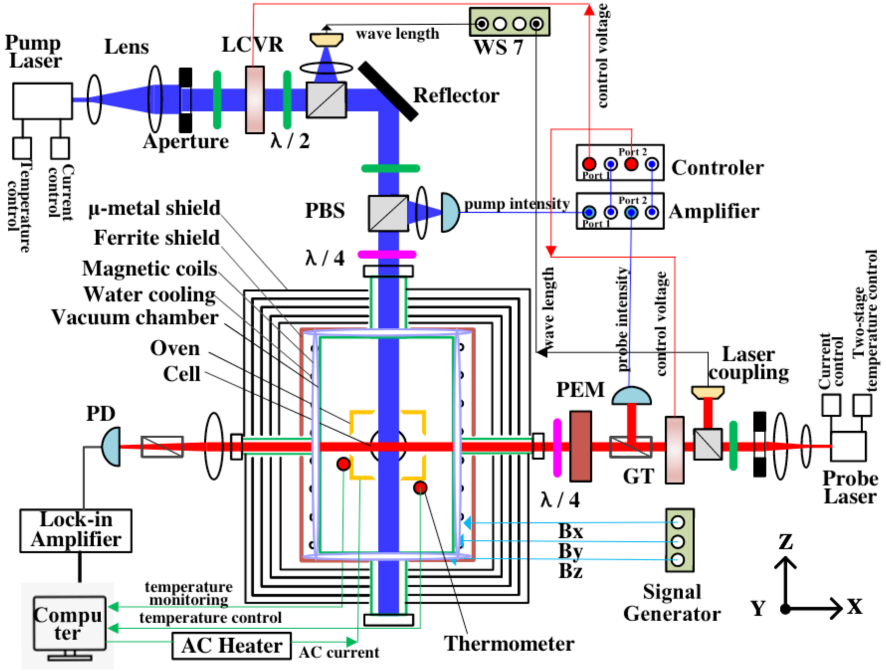
$$\frac{1}{T_2^{SE}} = \frac{\omega^2}{R_{SE}}\left[\frac{1}{2} - \frac{(2I+1)^2}{Q(P)^2}\right]Q(P)^2$$



SERF (Spin Exchange Relaxation Free):

$$R_{SE} \gg \omega^2 \quad \Rightarrow \quad T_2^{SE} \to \infty$$





$$V_2 = -g_A^X g_A^Y \frac{\hbar c}{4\pi} \boldsymbol{\sigma}_X \cdot \boldsymbol{\sigma}_Y \frac{1}{r} e^{-r/\lambda} . \qquad (46)$$

$$V_3|_{AA} = -\hbar c g_A^X g_A^Y \lambda^2 \left[\boldsymbol{\sigma}_X \cdot \boldsymbol{\sigma}_Y \left[\frac{1}{r^3} + \frac{1}{\lambda r^2} + \frac{4\pi}{3} \delta(\boldsymbol{r}) \right] - (\boldsymbol{\sigma}_X \cdot \hat{\boldsymbol{r}})(\boldsymbol{\sigma}_Y \cdot \hat{\boldsymbol{r}}) \left(\frac{3}{r^3} + \frac{3}{\lambda r^2} + \frac{1}{\lambda^2 r} \right) \right] \frac{e^{-r/\lambda}}{4\pi} , \qquad (47)$$

$$V_{4+5}|_{AA} = -\frac{g_A^X g_A^Y}{4} \frac{\hbar^2}{c} \left\{ \boldsymbol{\sigma}_X \cdot \left(\frac{\boldsymbol{p}_Y}{m_Y^2} \times \hat{\boldsymbol{r}} \right), \left(\frac{1}{r^2} + \frac{1}{\lambda r} \right) \frac{e^{-r/\lambda}}{8\pi} \right\} \Rightarrow g_A^X g_A^Y \frac{\hbar^2}{16\pi c} \frac{m_X}{m_Y (m_X + m_Y)} \boldsymbol{\sigma}_X \cdot (\boldsymbol{v} \times \hat{\boldsymbol{r}}) \left(\frac{1}{r^2} + \frac{1}{\lambda r} \right) e^{-r/\lambda} , \qquad (48)$$

$$V_8 = g_A^X g_A^Y \frac{\hbar}{c} \left[\left\{ \frac{\boldsymbol{\sigma}_X \cdot \boldsymbol{p}_X}{m_X}, \left\{ \frac{\boldsymbol{\sigma}_Y \cdot \boldsymbol{p}_Y}{m_Y}, \frac{e^{-r/\lambda}}{16\pi r} \right\} \right\} - \frac{1}{2} \left\{ \frac{\boldsymbol{\sigma}_X \cdot \boldsymbol{p}_Y}{m_Y}, \left\{ \frac{\boldsymbol{\sigma}_Y \cdot \boldsymbol{p}_Y}{m_Y}, \frac{e^{-r/\lambda}}{16\pi r} \right\} \right\} - \frac{1}{2} \left\{ \frac{\boldsymbol{\sigma}_X \cdot \boldsymbol{p}_X}{m_X}, \left\{ \frac{\boldsymbol{\sigma}_Y \cdot \boldsymbol{p}_X}{m_X}, \frac{e^{-r/\lambda}}{16\pi r} \right\} \right\} \right]$$
$$\Rightarrow -g_A^X g_A^Y \frac{\hbar}{8\pi c} (\boldsymbol{\sigma}_X \cdot \boldsymbol{v})(\boldsymbol{\sigma}_Y \cdot \boldsymbol{v}) \frac{1}{r} e^{-r/\lambda} . \qquad (49)$$