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& FBK & INFN-TIFPA

Fundamental physics with levitated micromagnets

INFN-LNF Workshop on The Low Energy Frontiera of Physics. Frascati 10-12/2/2025

Outline

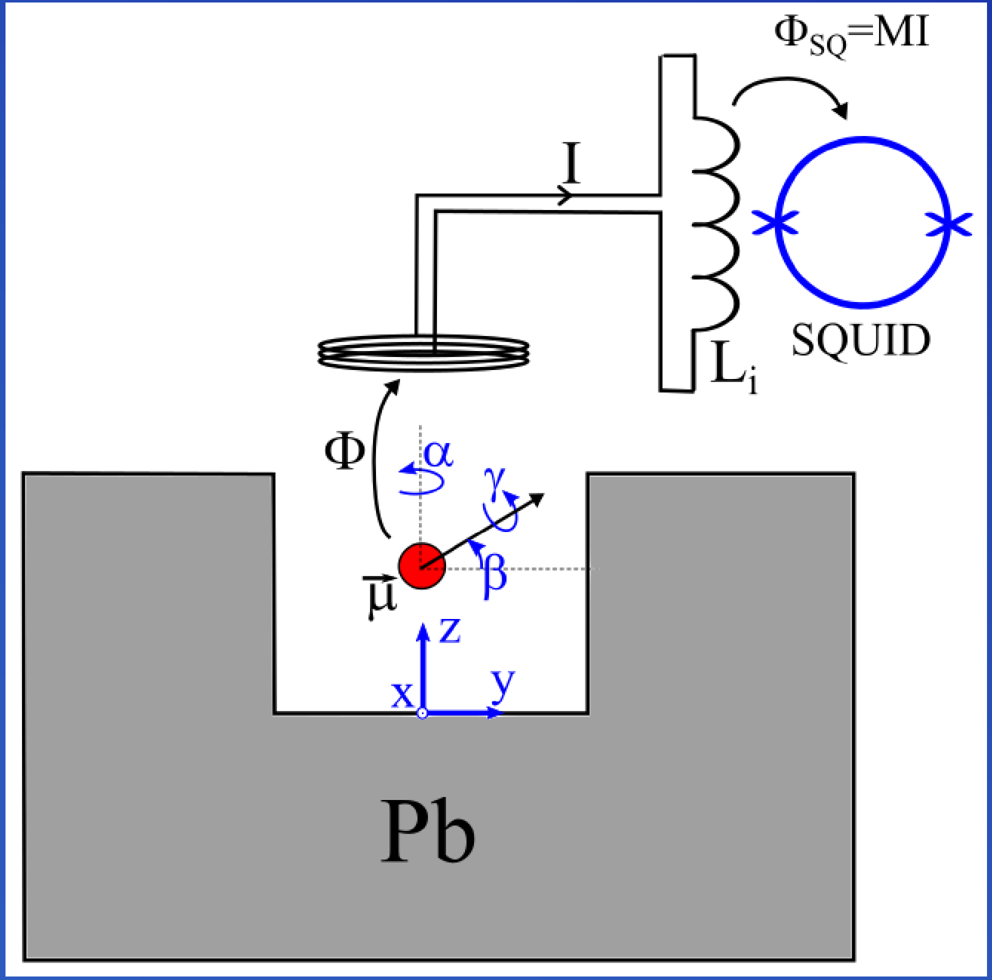
- Levitated ferromagnets
    - Motivations & Experimental setup

- Magnetometry
    - Beyond the (quantum) energy resolution limit
    - Search for ultralight dark matter in the mHz-kHz

- Ultrafast spinning
    - Experimental results
    - Prospects (two-mass experiments)

- Macroscopic quantum physics & quantum gravity

Basic scheme and motivations



- Hard (permanent) micromagnet
- Type I superconductor ⇒ Meissner effect
- Magnetic detection (SQUID)

+

- Low Temperature T
- Vacuum
- Frequency tunabilility

⇓

Mechanical modes (translation & rotations) with very low dissipation = ultrahigh Q

- Low thermal force/torque noise (good for sensing)

$$S_F \propto \frac{T}{\tau} = \frac{\omega T}{Q}$$

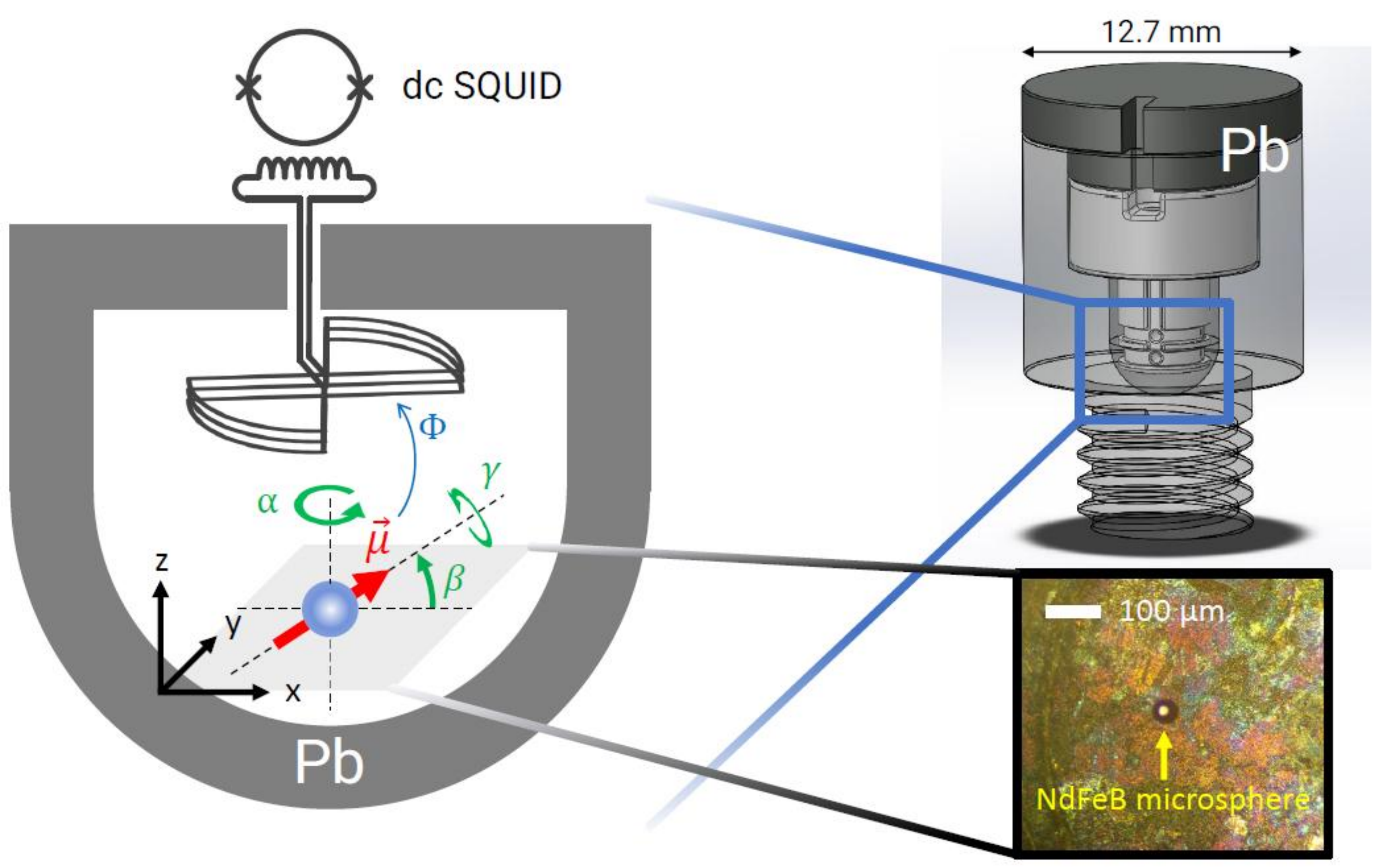
- Low environmental decoherence (good for macroscopic quantum physics/ delocalized states / quantum gravity…)

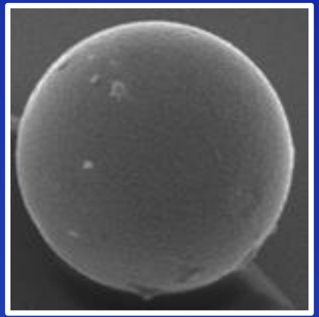
Why levitate ferromagnets?

Some advantages compared to nonmagnetic particles

- Easy to levitate and passive: compatible with low temperature
- High coupling to external magnetic fields
  Magnetometry → Axion dark matter
- High coupling to superconducting circuits
  SQUID linear detection
  Flux-tunable resonators & qubits (delocalized quantum states)
- Unique features: gyroscopic effects
- Internal degrees of freedom as extraresources (magnons)

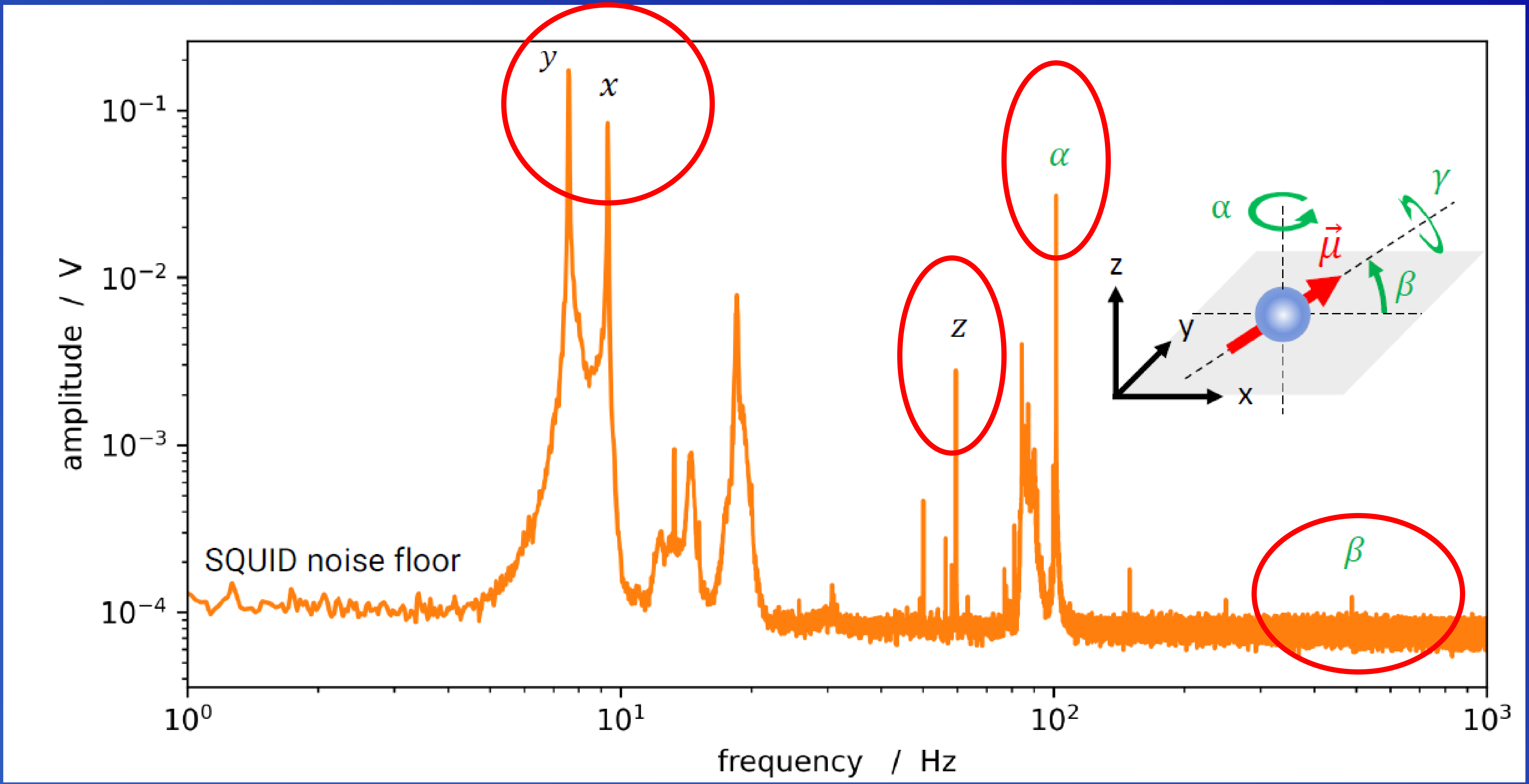
Experimental setup ($P=10^{-5} – 10^{0}$ mbar, $T=4.2$ K)



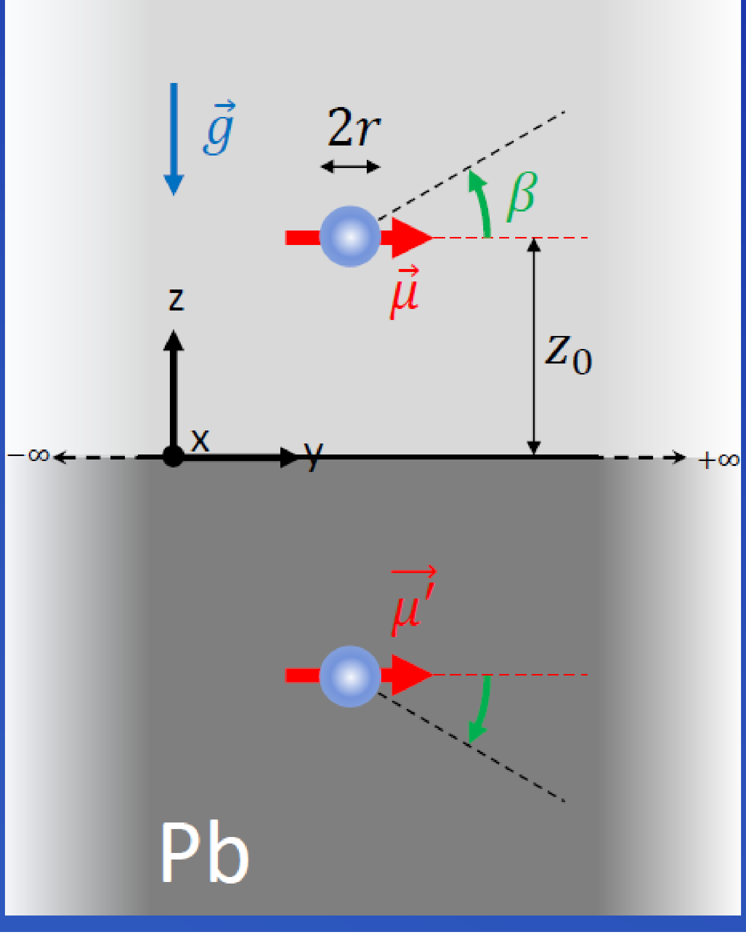


Nearly spherical shape

Mode identification



Modelling: image method (z and β)



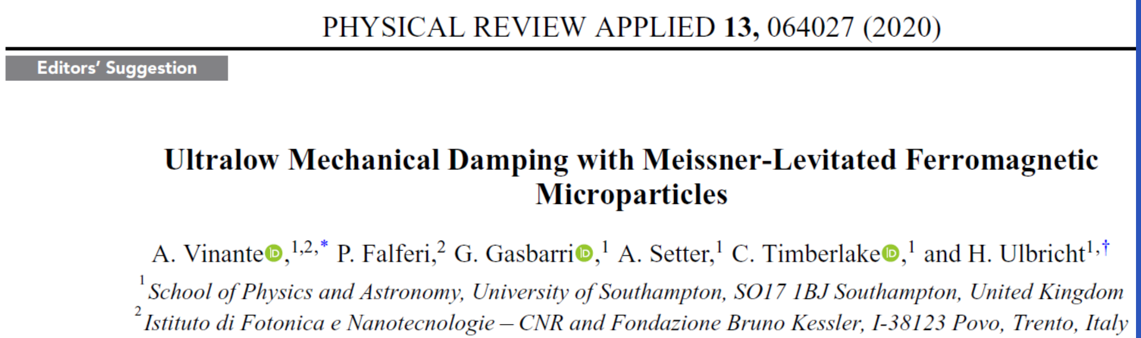
$$U = \frac{\mu_0 \mu^2}{64\pi z^3}\left(1+\sin^2\beta\right) + mgz$$

$$z_0 = \left(\frac{3\mu_0\mu^2}{64\pi m g}\right)^{\frac{1}{4}}$$

$$\beta_0 = 0$$

$$\omega_z = \sqrt{\frac{4g}{z_0}}$$

$$\omega_\beta = \sqrt{\frac{5 z_0 g}{3R^2}}$$



PHYSICAL REVIEW APPLIED **13,** 064027 (2020)

Editors' Suggestion

Ultralow Mechanical Damping with Meissner-Levitated Ferromagnetic Microparticles

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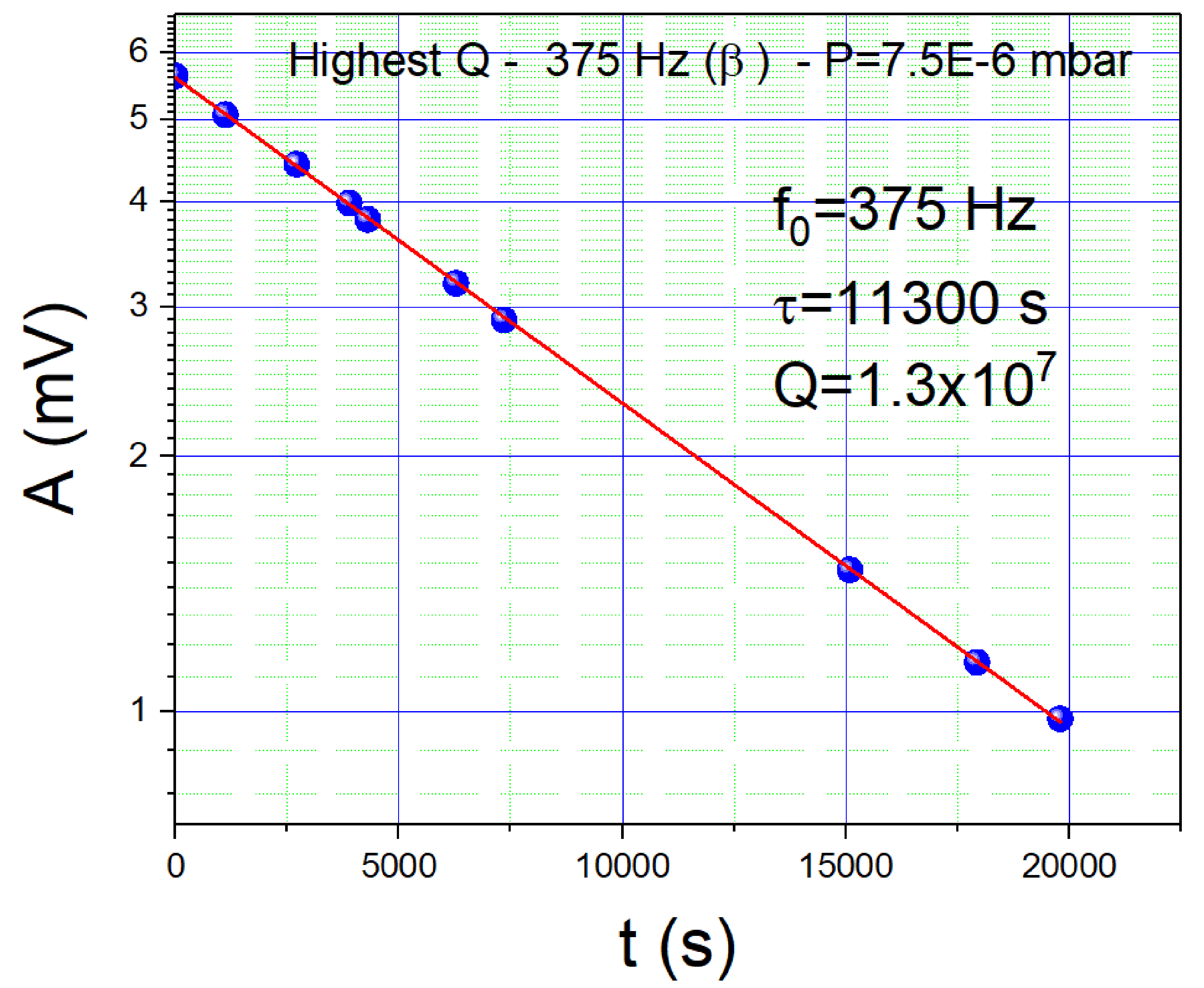
$$\boxed{\omega_z\,, \omega_\beta \quad \Leftrightarrow \quad \mu\,, m\,(R, M)}$$

Mechanical damping - Q factor

RINGDOWN

Measurement for librational β-mode and translational z-mode

τ > 3 hours



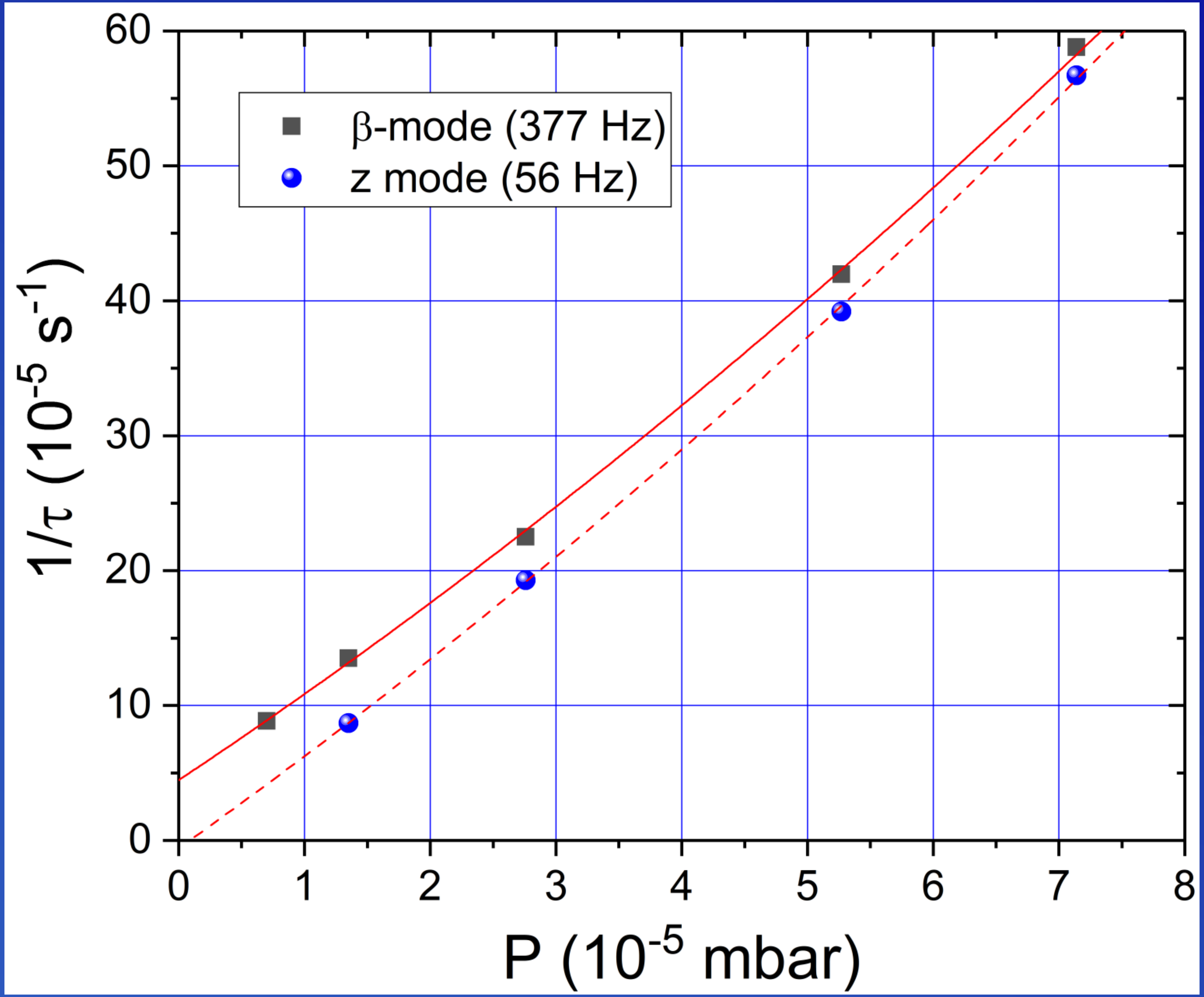
Damping vs Pressure

$$\frac{1}{\tau_t} = \frac{1}{2}\left(1+\frac{8}{\pi}\right)\frac{P}{\rho R v_{\mathrm{th}}}$$

$$\frac{1}{\tau_r} = \frac{5}{\pi}\frac{P}{\rho R v_{\mathrm{th}}}$$

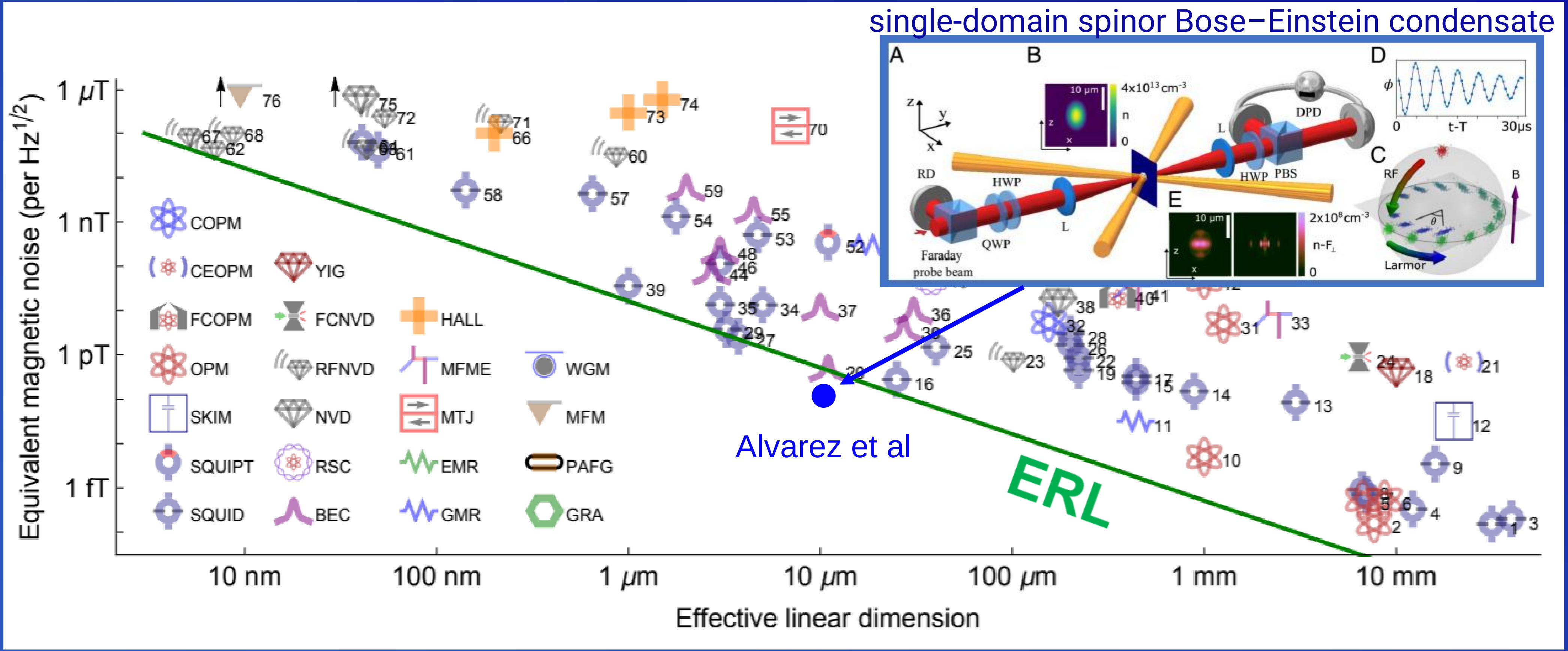
Epstein, Phys Rev. 23, 710 (1924)

SLOPE AGREES WITH MODEL WITHIN 10%



Magnetometry: librational regime

Magnetometry beyond the Energy Resolution Limit



single-domain spinor Bose−Einstein condensate

Alvarez et al

M. Mitchell and S.P. Alvarez, Review Modern Physics 92, 021001 (2020)

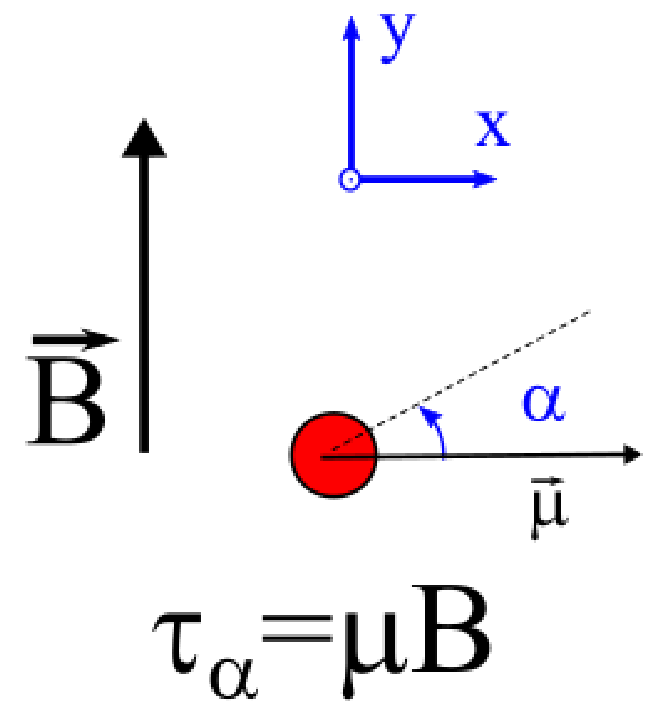
Alvarez *et al.*, PNAS 119, e2115339119 (2022)

ERL

$$\boxed{E = \frac{S_B}{2\mu_0} V = \hbar}$$

ERL IS NOT A FUNDAMENTAL LIMIT !
CAN BE BEATEN by HIGHLY CORRELATED SPIN SYSTEMS

Torque Magnetometry in levitated magnet



Magnetic Field → Torque

$$S_{\tau,\mathrm{thermal}} = 4k_\mathrm{B}TI\frac{\omega_\alpha}{Q_\alpha}$$

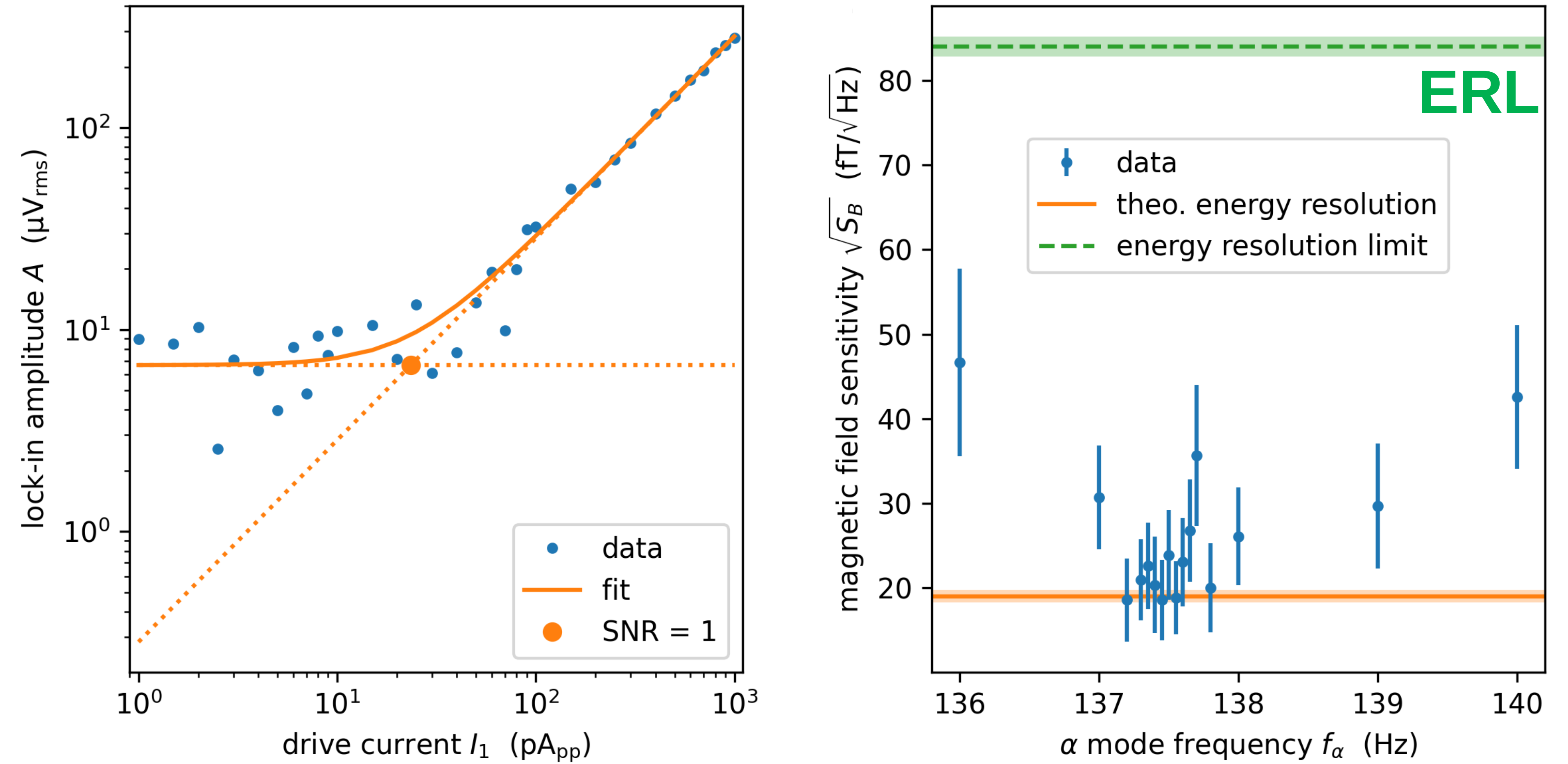
CALCULATED FOR OUR SETUP

$$S_{B,\mathrm{thermal}} = \frac{S_{\tau,\mathrm{thermal}}}{\mu^2} = \frac{12k_\mathrm{B}T\rho f_\alpha}{5M^2rQ_\alpha} \ll S_{B,\mathrm{ERL}}$$

Minimum detectable B in the experiment

- Apply a weak sinusoidal signal around resonance
- Synchronous detection of the output signal (lock-in)

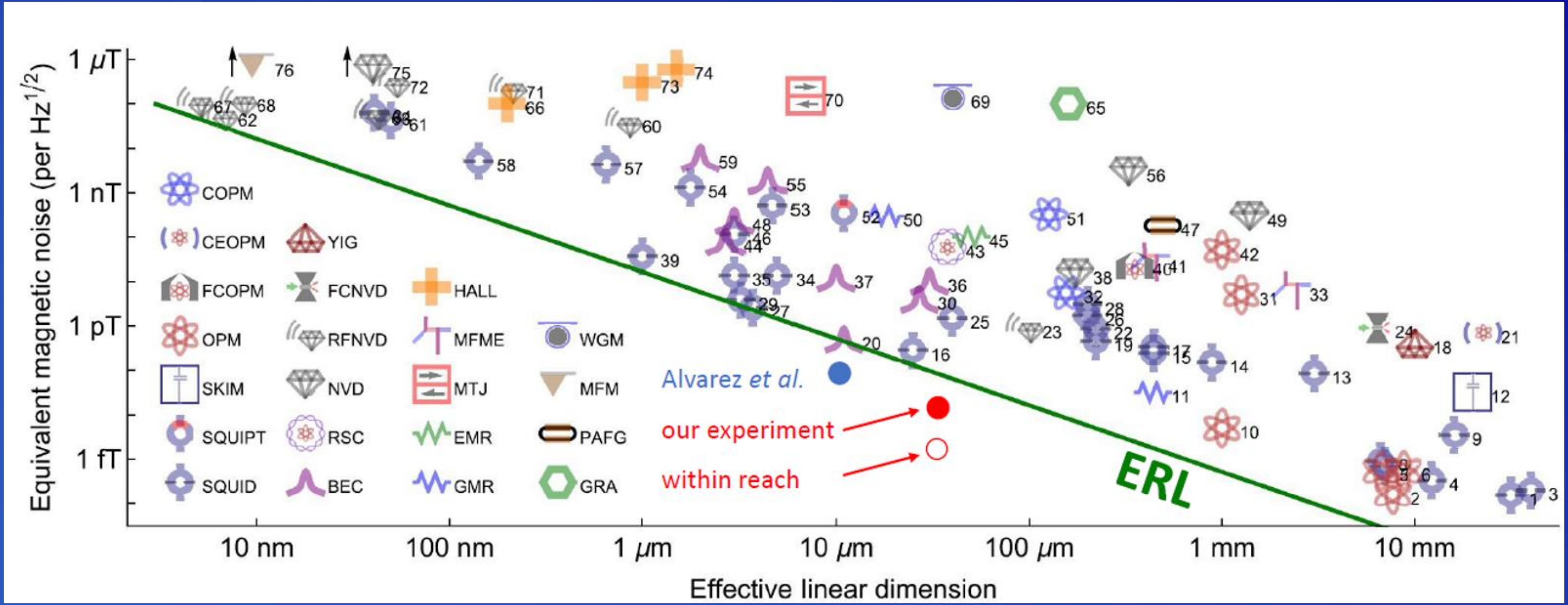
$$E_R = \frac{S_B}{2\mu_0} V = \hbar$$



Magnetic field noise: 20 fT/Hz$^{1/2}$

Measured Energy resolution: E_R=(0.064±0.010) $\hbar$

Magnetometry well beyond the Energy Resolution Limit

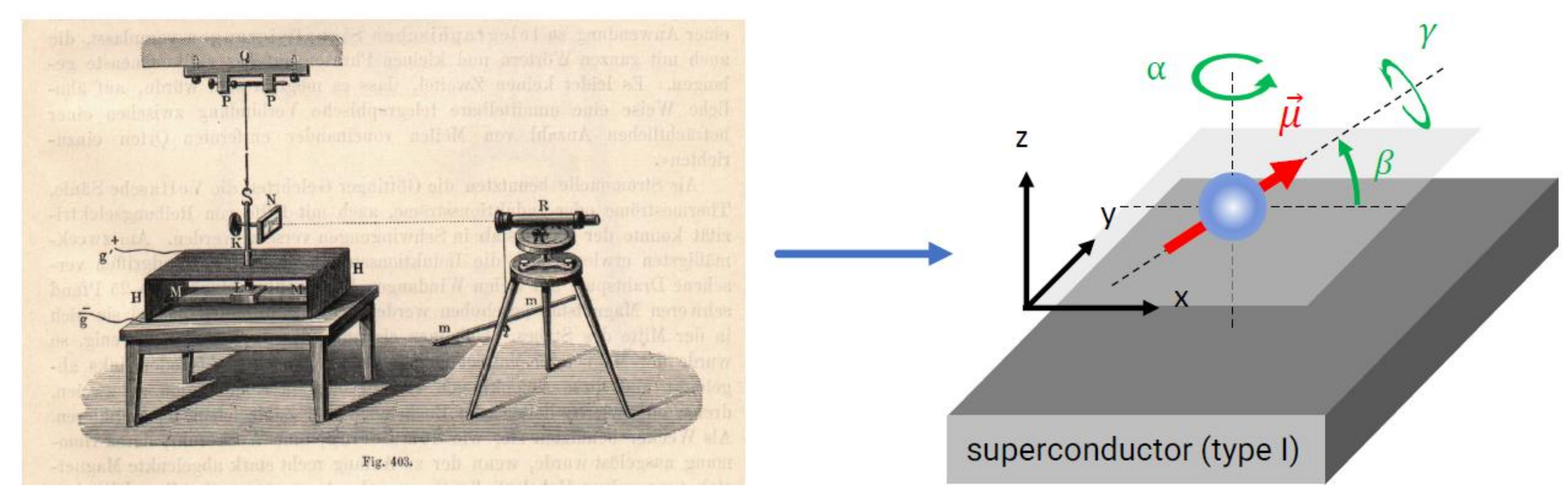


F. Ahrens, W. Ji, D. Budker, C. Timberlake, H. Ulbricht, A. Vinante, arXiv 2401:03774

Damping can be reduced by at least factor > 10^2 at lower pressure (measured!)

Projected Energy Resolution < $10^{-3}\,\hbar$

Credits



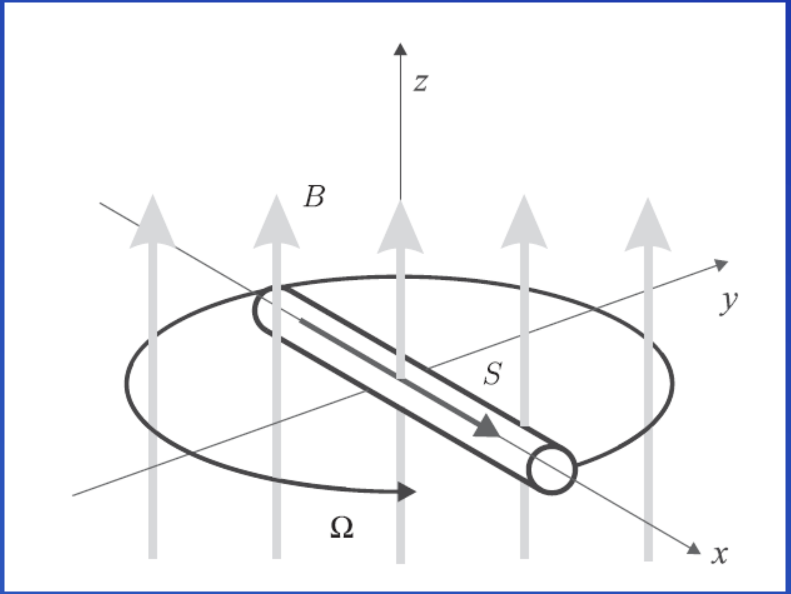
C.F. Gauss, *Intensitas vis magnetica et terrestris ad mensuram absolutam revocata*, Göttingen,1833

First magnetometer of history!

Magnetometry: ferromagnetic gyroscope

Ferromagnetic spin-gyroscope

Derek Jackson Kimball et al, PRL 16, 190801 (2016)



For sufficiently small magnetic field a ferromagnetic needle behaves as an atomic spin magnetometer

$$\Omega = \gamma B$$

Macroscopic Larmor precession!

(spins transfer precessional motion to the lattice)

Predicted to beat quantum limits on magnetometry (by orders of mag) !

Naïve explanation: atom-like dynamics it is a system of N highly correlated spins

Hard to observe:

$$\boxed{\gamma B = \Omega \ll \omega_I = \frac{S}{I} = \frac{N\hbar/2}{I}}$$

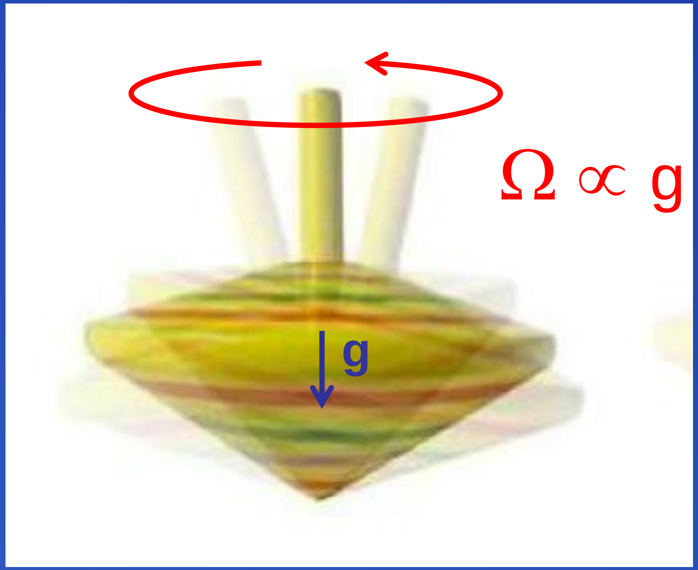
$\omega_I/2\pi \approx 200$ μHz → B ≈ 5 fT (R = 1 mm sphere FM)

$\omega_I/2\pi \approx 2$ Hz → B ≈ 0.5 nT (R = 10 μm sphere FM)

Classical gyroscope

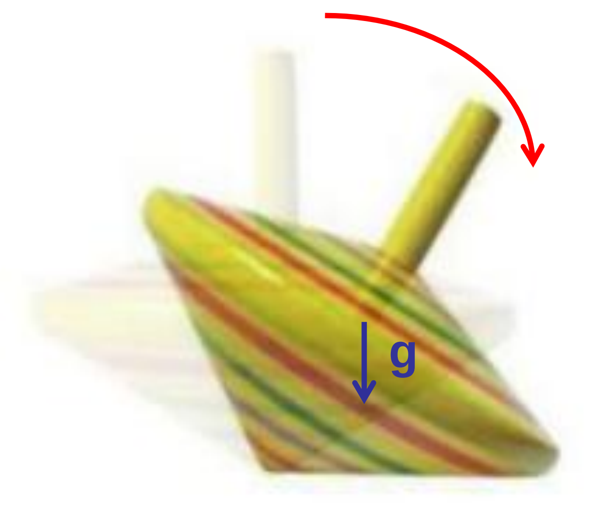
Spinning top under effect of gravity torque

Gyroscopic (atomic-like)



$S \gg L = I\Omega$

Librational (compass-like)

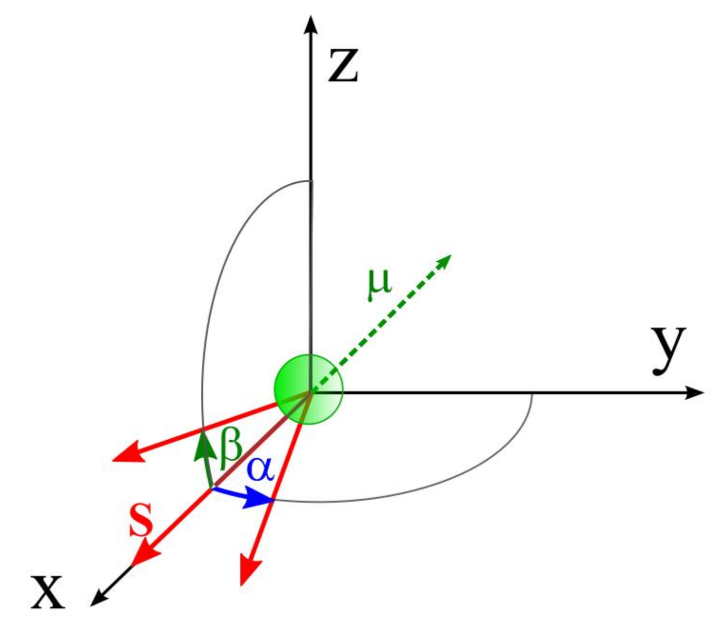


$S < L$

Condition to observe gyroscopic behaviour:

$$\Omega \ll \omega_I = \frac{S}{I}$$

Gyromagnetic effects under librational confinement



$$\dot{\boldsymbol{J}} = \boldsymbol{T}$$
$$\dot{\boldsymbol{S}} = \boldsymbol{\Omega} \times \boldsymbol{S}$$

GYROSCOPIC COUPLING

$$\ddot{\alpha} + \omega_\alpha^2 \alpha \boxed{+ \omega_I \dot{\beta}} = 0$$
$$\ddot{\beta} + \omega_\beta^2 \beta \boxed{- \omega_I \dot{\alpha}} = 0$$

Neglecting dissipation and γ motion:

Quasi-β mode

$$\beta = \beta_0 \sin(\omega_\beta t)$$
$$\alpha = \alpha_0 \cos(\omega_\beta t)$$
$$\alpha_0 = \beta_0 \frac{\omega_\beta \omega_I}{\omega_\beta^2 - \omega_\alpha^2}$$

Quasi-α mode

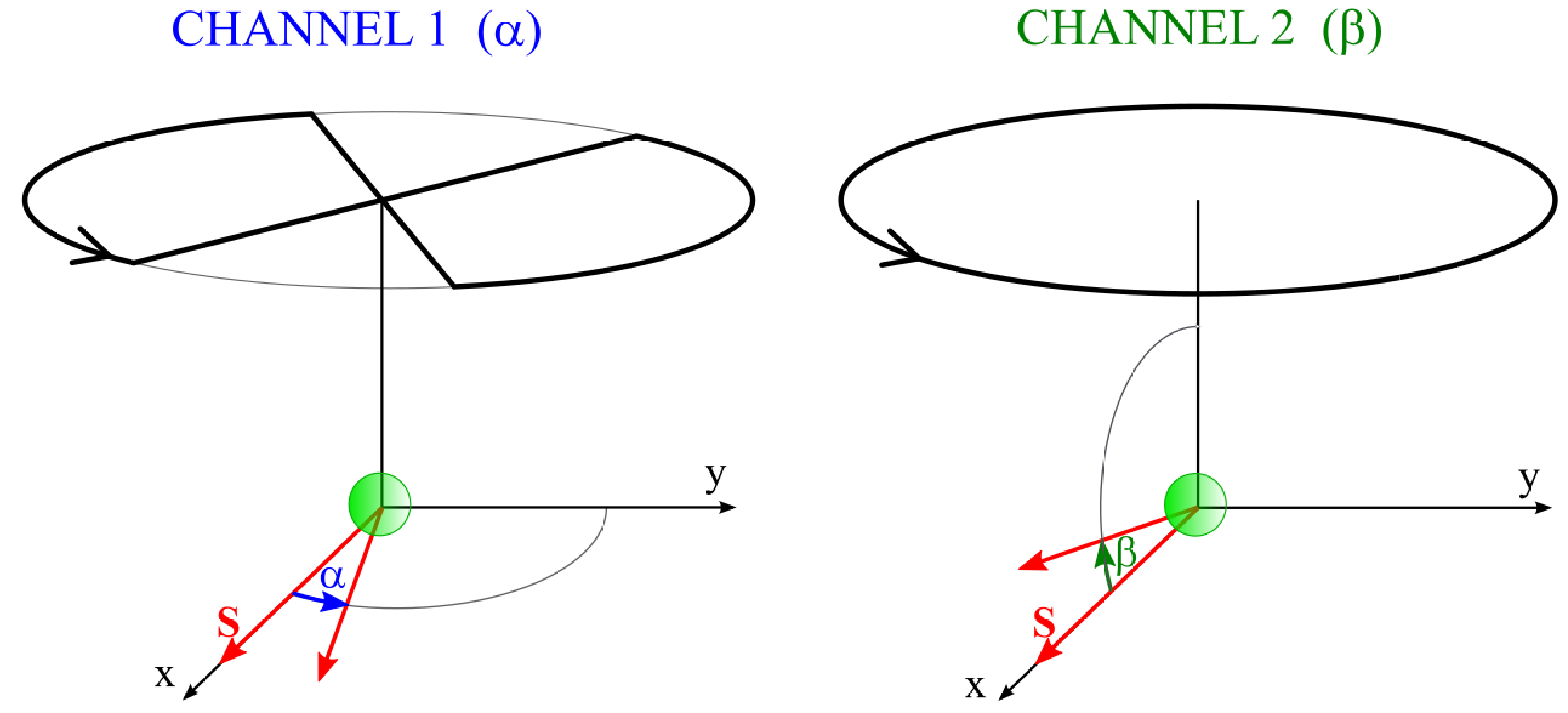
$$\alpha = \alpha_0 \sin(\omega_\alpha t)$$
$$\beta = \beta_0 \cos(\omega_\alpha t)$$
$$\beta_0 = \alpha_0 \frac{\omega_\alpha \omega_I}{\omega_\beta^2 - \omega_\alpha^2}$$

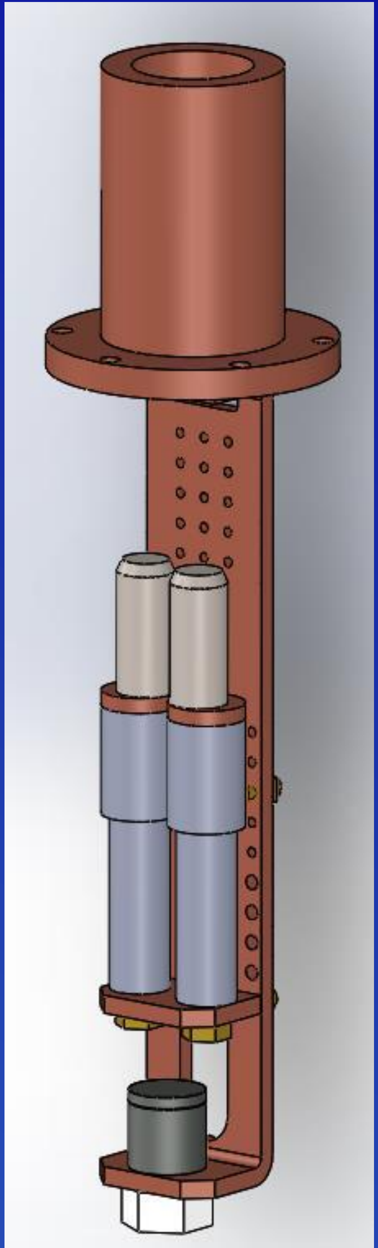
→ Elliptical motion on (α,β) plane

How to detect? Two-channel setup

Effect is small in our setup but in principle detectable

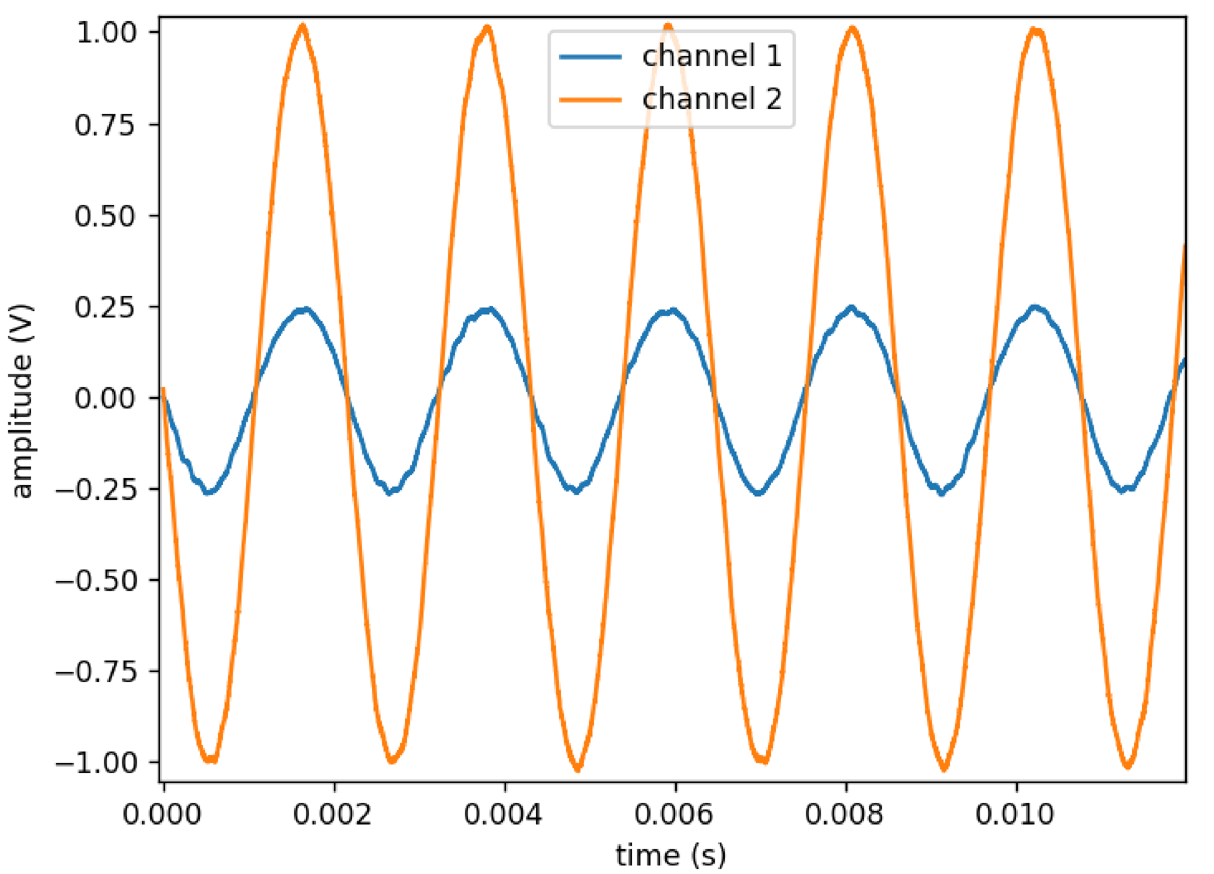
$$\boxed{\frac{\alpha_0}{\beta_0} \approx 3 \times 10^{-3}}$$



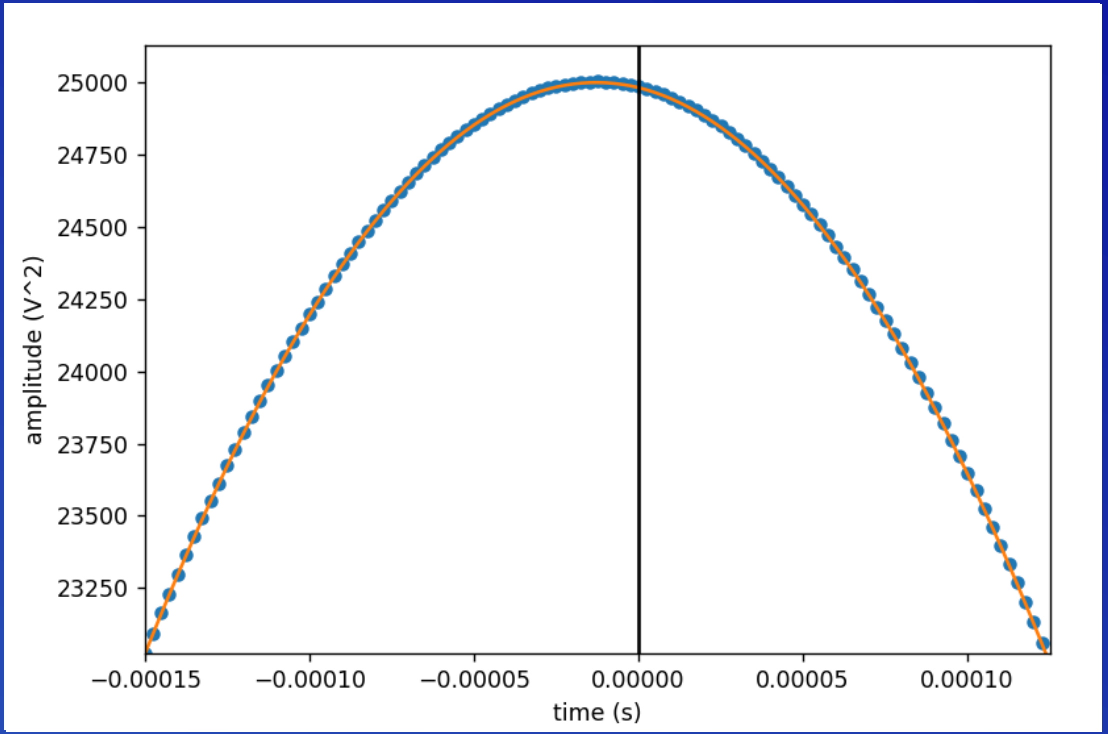


Example of data (magnet radius ~24 μm)

quasi-β MODE excited



Crosscorrelation ch1 – ch 2



$\delta = -0.038$ rad $\neq 0$

⇩

SIGNATURE OF ELLIPTICAL MOTION

Preliminary results

radius R (μm)	$B_S = \mu_0 M$ (T)	$\omega_I/2\pi$ (Hz)	g
31.2	0.75	0.33±0.04	1.13 ±0.14
23.6	0.85	0.624±0.018	1.18 ±0.05
18.9	0.72	0.89±0.06	1.10±0.08
18.9*	0.72	0.86±0.03	1.14±0.05

- Magnetic moment and size derived from resonance frequencies:

$$\omega_z\,,\omega_\beta \;\Rightarrow\; \mu\,,m\;\;(M,R)$$

- If moment of inertia I is known (and isotropic), a measurement of ω_I is an absolute measurement of the intrinsic angular momentum

$$S = I\omega_I$$

- If magnetic moment $\mu = MV$ is known, we can infer the gyromagnetic factor:

$$g = \frac{\mu/\mu_B}{S/\hbar}$$

Magnetometry: applications to fundamental physics

Search for ultralight dark matter

Ultralight dark matter often appears as an effective magnetic field:

1) <u>Axion – electron spin</u>

Quasimonocromatic signal

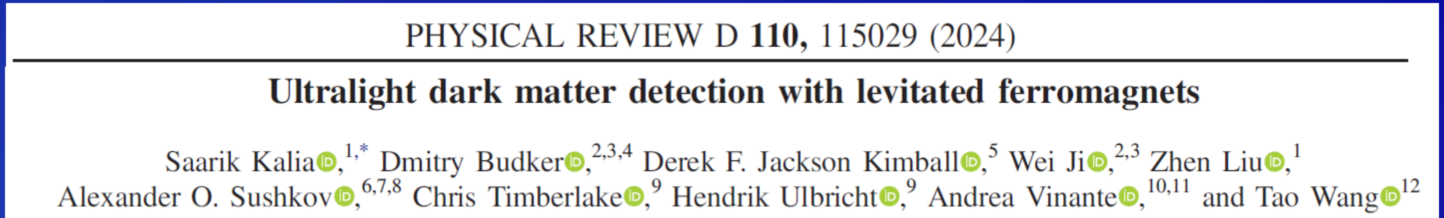
$$B_{ae} \sim g_{ae} \cdot 4 \times 10^{-8}\ \mathrm{T}$$

$$t_{\mathrm{coh}} \sim c^2/f_a v_{\mathrm{DM}}^2$$

2) <u>Dark Photon</u> (close to inner wall of conductive box with size L)

$$B_{A'} \sim 7 \times 10^{-21}\ \mathrm{T} \left(\frac{\varepsilon}{10^{-8}}\right)\left(\frac{f_{A'}}{30\ \mathrm{Hz}}\right)\left(\frac{L}{10\ \mathrm{cm}}\right)$$

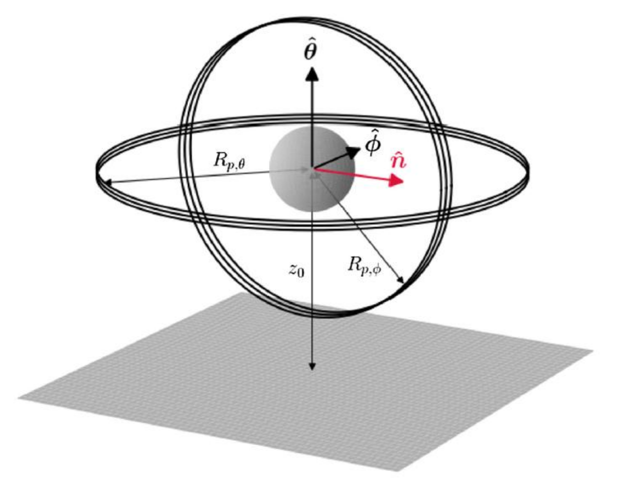
Concrete proposal

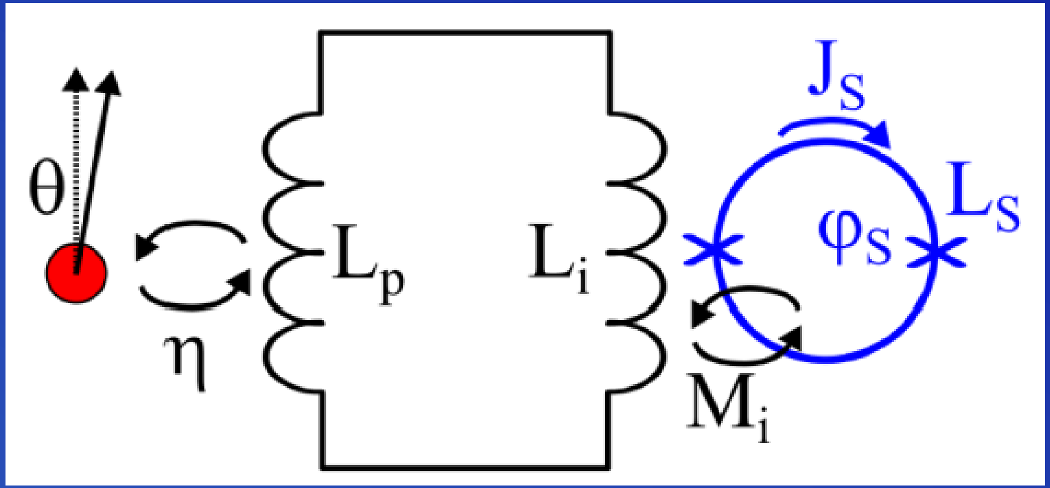

PHYSICAL REVIEW D **110,** 115029 (2024)

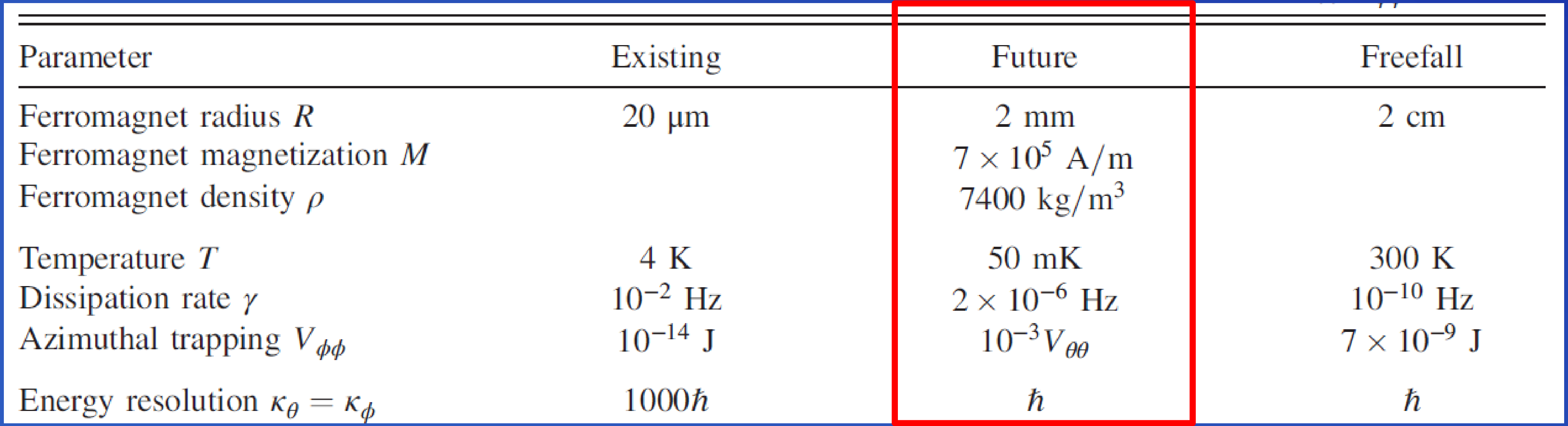
Ultralight dark matter detection with levitated ferromagnets

Saarik Kalia[1,*] Dmitry Budker[2,3,4] Derek F. Jackson Kimball[5] Wei Ji[2,3] Zhen Liu[1]
Alexander O. Sushkov[6,7,8] Chris Timberlake[9] Hendrik Ulbricht[9] Andrea Vinante[10,11] and Tao Wang[12]

Two channel (pickup coil + SQUID)
Two librational modes

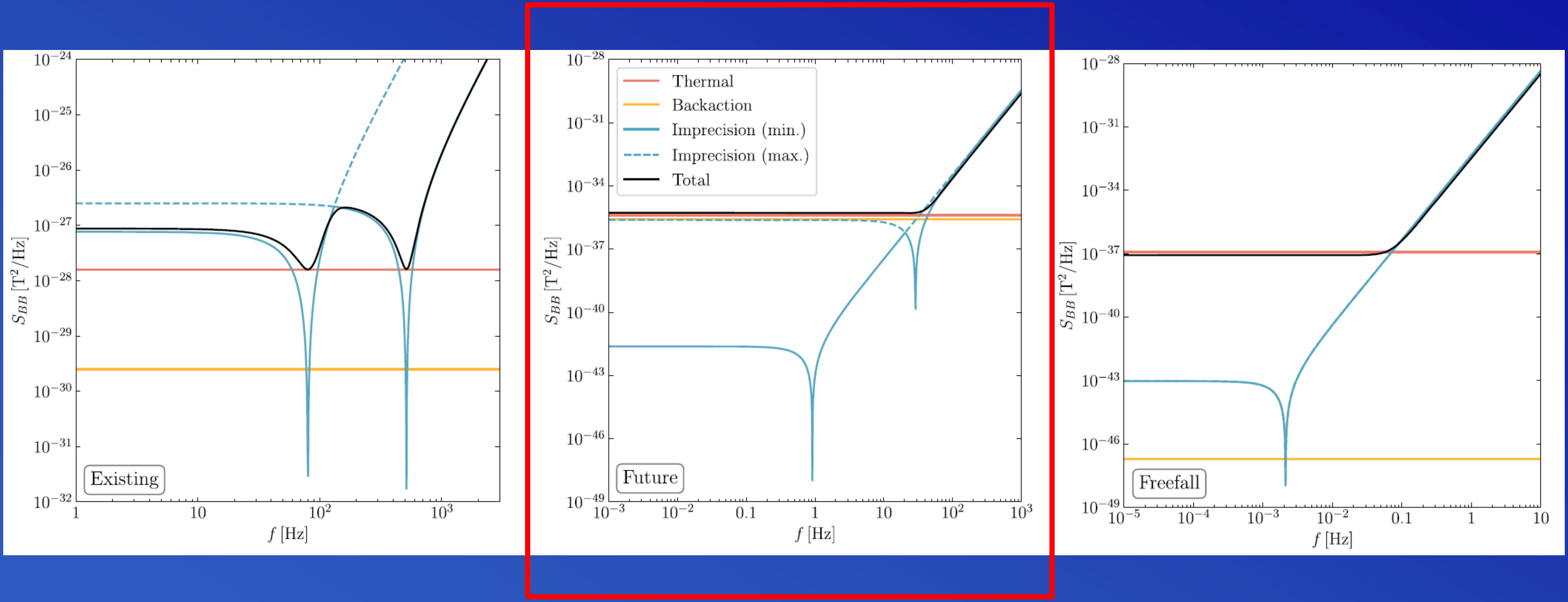






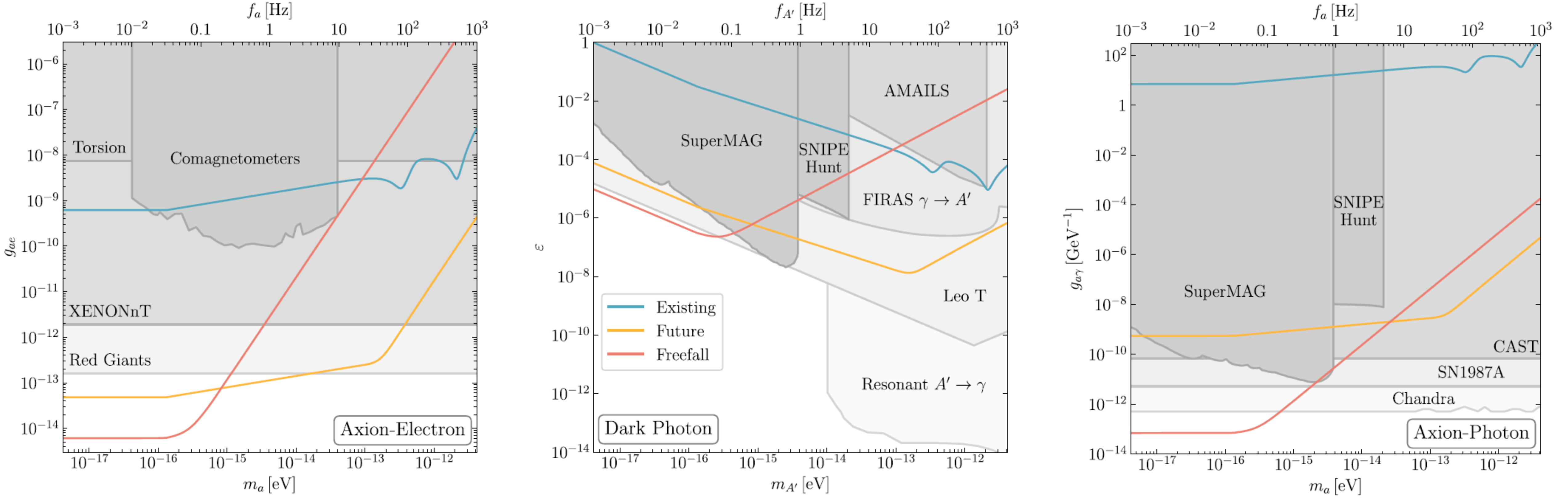
Parameter	Existing	Future	Freefall
Ferromagnet radius R	20 μm	2 mm	2 cm
Ferromagnet magnetization M		7×10^5 A/m	
Ferromagnet density ρ		7400 kg/m^3	
Temperature T	4 K	50 mK	300 K
Dissipation rate γ	10^{-2} Hz	2×10^{-6} Hz	10^{-10} Hz
Azimuthal trapping $V_{\phi\phi}$	10^{-14} J	$10^{-3} V_{\theta\theta}$	7×10^{-9} J
Energy resolution $\kappa_\theta = \kappa_\phi$	$1000\hbar$	$\hbar$	$\hbar$

Magnetic field resolution



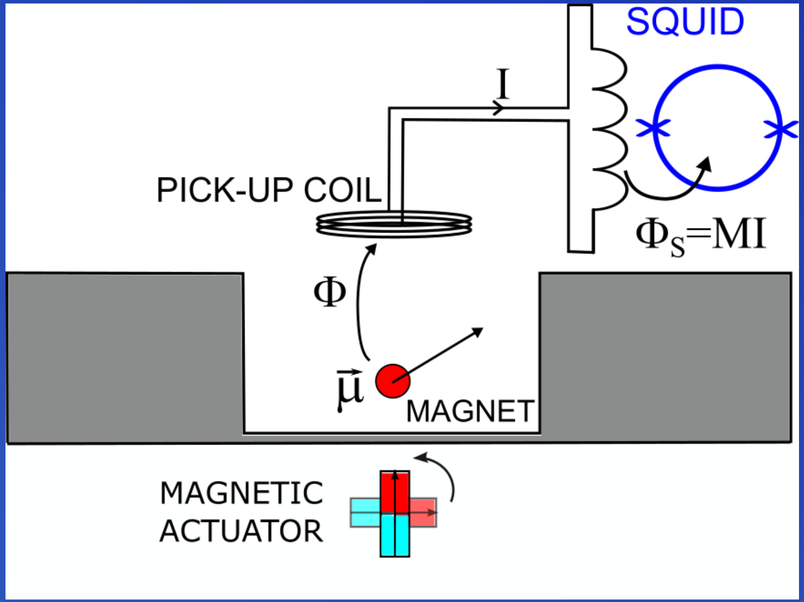
Projected upper limits

(integration time 1 yr, SNR=3)



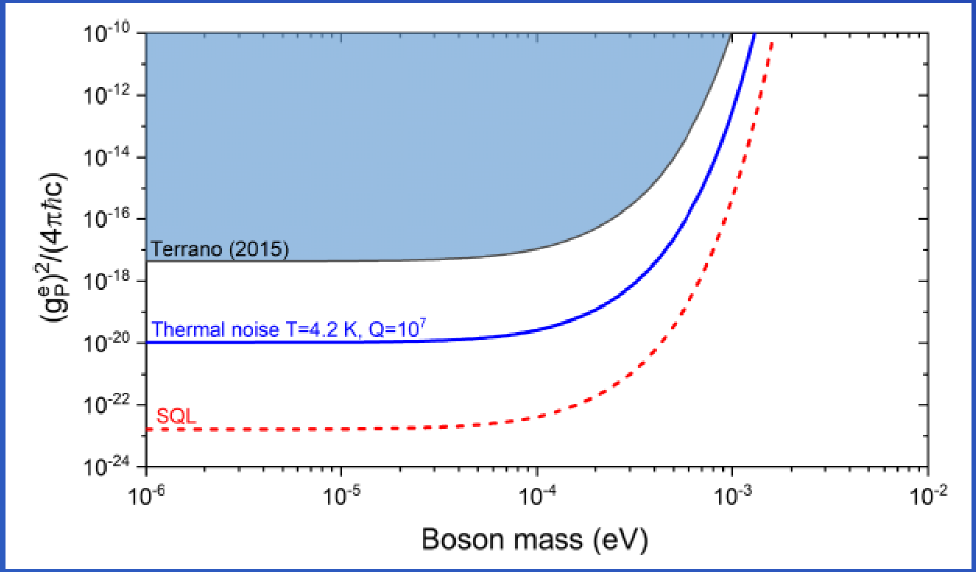
Exotic spin-spin interactions / fifth force

Predicted by several ″beyond standard model″ proposals (e.g. axion-like particles)



$$\mathcal{V}_{PP}(\mathcal{R}) = \boxed{\frac{(g_P^e)^2}{4\pi\hbar c}}\frac{\hbar^3}{4m_e^2 c}\left[S_1\cdot S_2\left(\frac{m_b c}{\hbar\mathcal{R}^2}+\frac{1}{\mathcal{R}^3}+\frac{4\pi}{3}\delta^3(\mathcal{R})\right) - \left(S_1\cdot\hat{\mathcal{R}}\right)\left(S_2\cdot\hat{\mathcal{R}}\right)\left(\frac{m_b^2c^2}{\hbar^2\mathcal{R}}+\frac{3m_b c}{\hbar\mathcal{R}^2}+\frac{3}{\mathcal{R}^3}\right)\right]e^{-m_b c\mathcal{R}/\hbar}$$

- Spin-spin pseudomagnetic interaction + Yukawa cutoff
- Not shielded by the superconductor layer (unlike the true magnetic one)



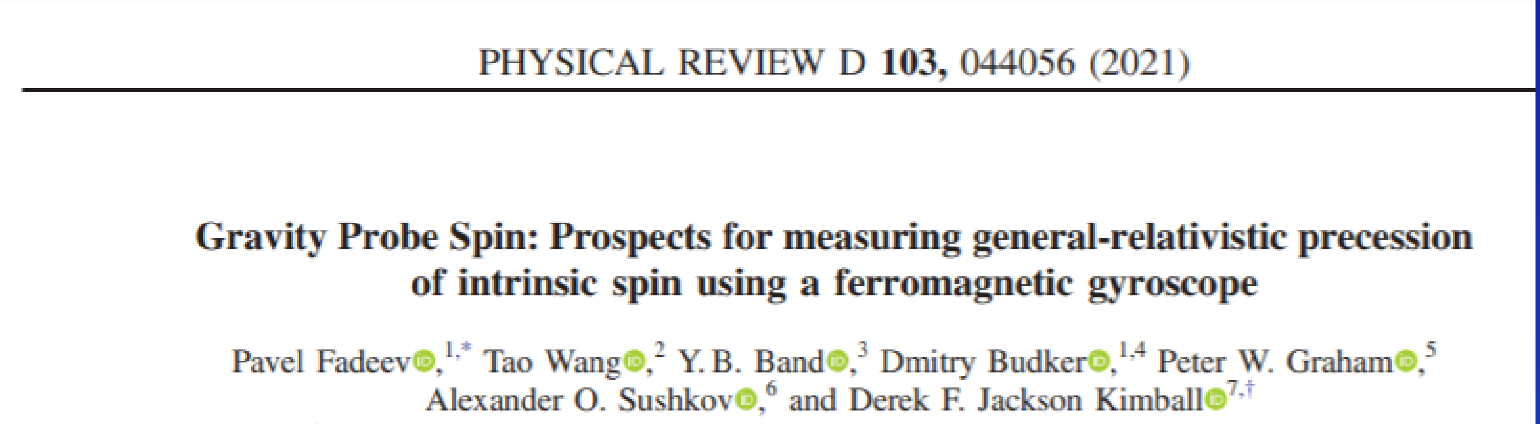
Predicted bounds for:

- Sensing magnetic sphere, radius 0.2 mm
- Actuator sphere, radius 20 mm
- Distance 24 mm

A. Vinante et al, PRL 127, 070801 (2021)

Testing GR dragging effects with a ferromagnet

TEST of GR (Lense-Thirring) using quantum spin angular momentum (Quantum + Gravity !)

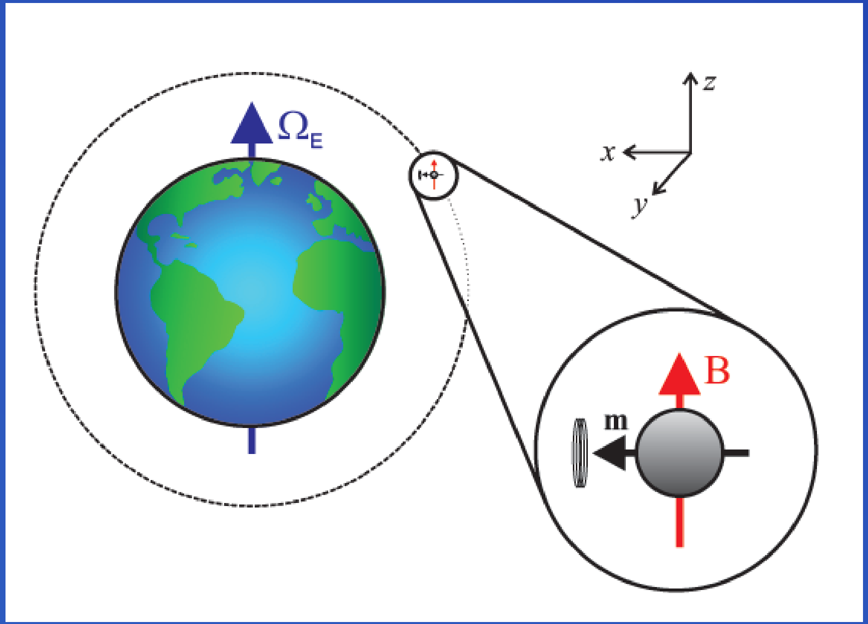


PHYSICAL REVIEW D **103,** 044056 (2021)

Gravity Probe Spin: Prospects for measuring general-relativistic precession of intrinsic spin using a ferromagnetic gyroscope

Pavel Fadeev,[1,*] Tao Wang,[2] Y. B. Band,[3] Dmitry Budker,[1,4] Peter W. Graham,[5]
Alexander O. Sushkov,[6] and Derek F. Jackson Kimball[7,†]

Ferromagnetic gyroscope

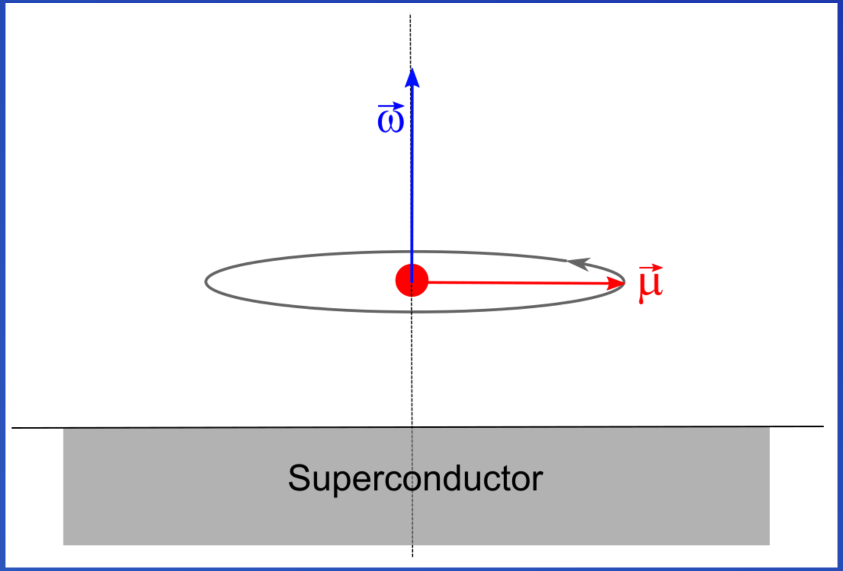


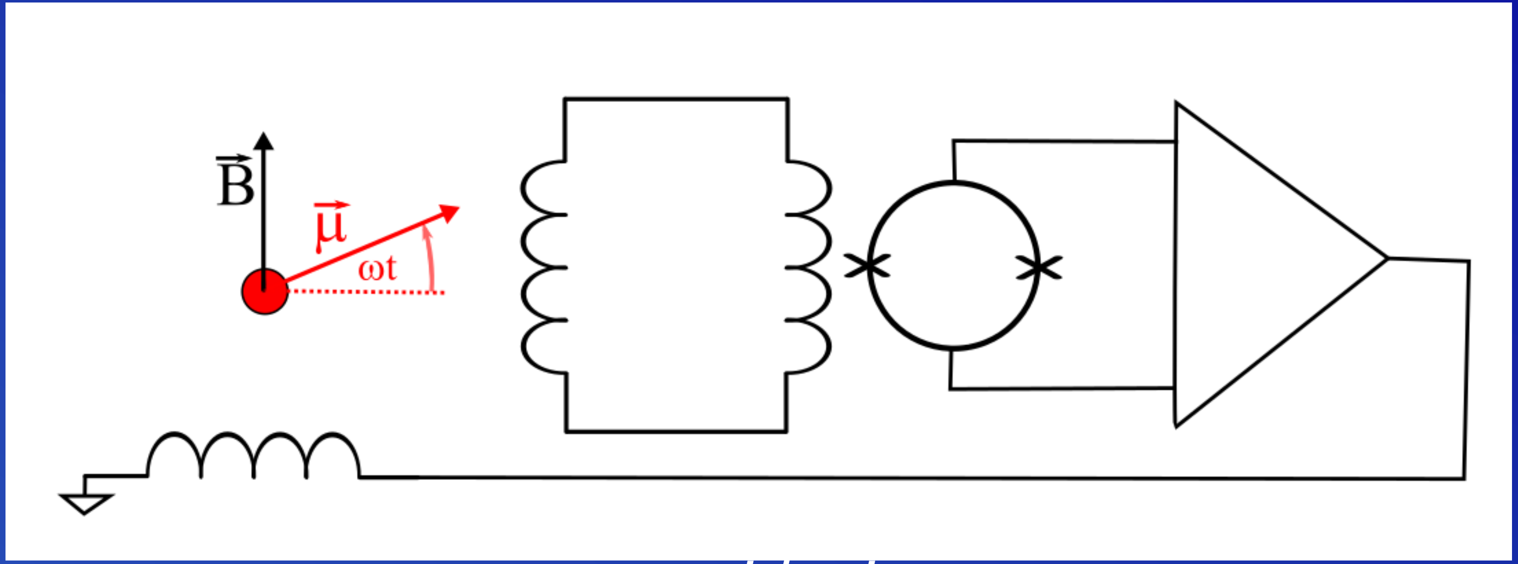
- Precession of local inertial frame
- For electron spin, rotational motion is equivalent to a magnetic field

$$B=\Omega/\gamma \sim 10^{-25}\ \mathrm{T}\ \ !!$$

Spinning a levitated ferromagnet

Measurement/feedback synchronous driving





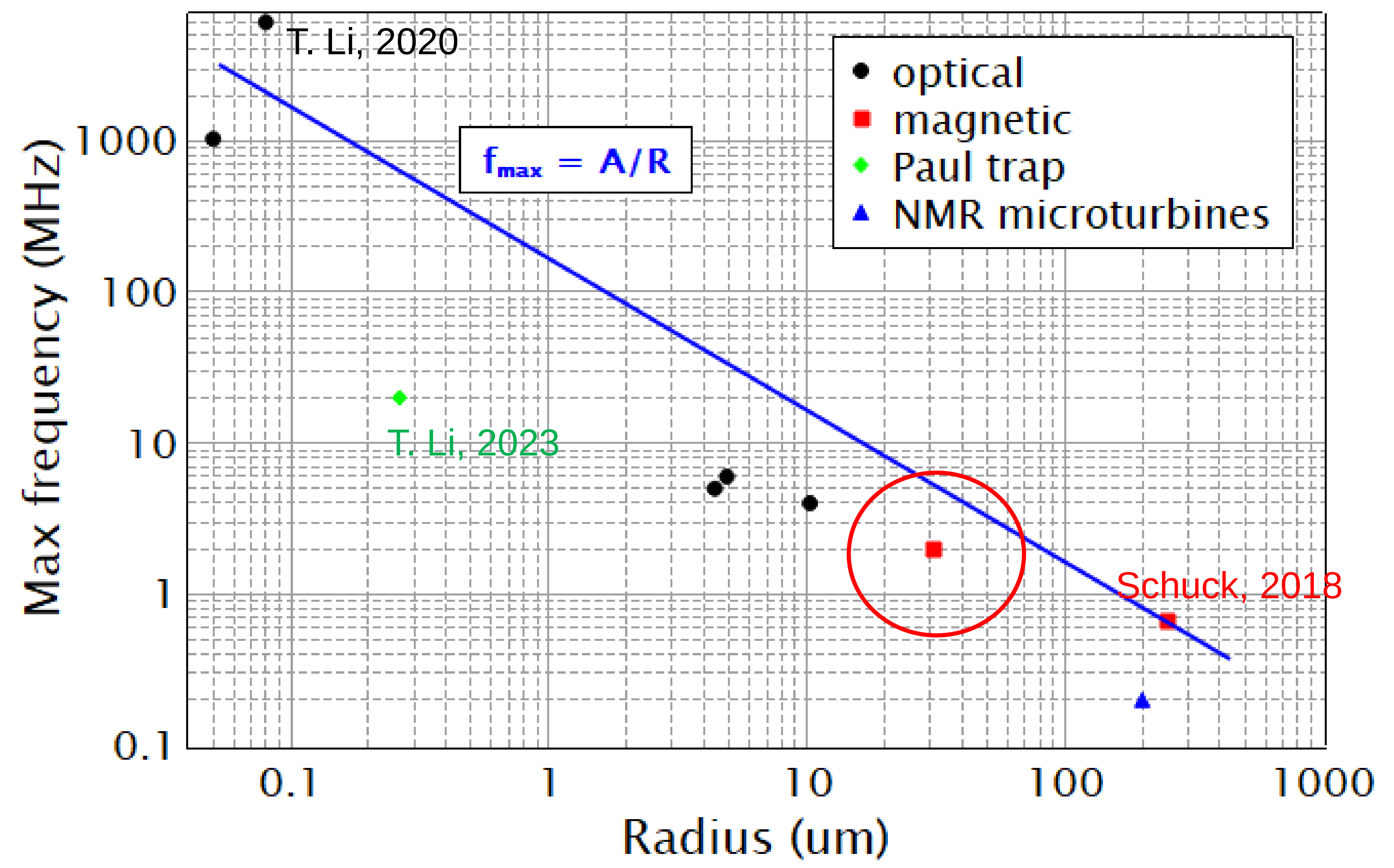
$$B = Ge^{i\phi}e^{i\omega t}$$

- Net torque dependent on ϕ
- Limited by SQUID bandwidth (~ 10 MHz)
- Low heat dissipation (works well at cryogenic T !)

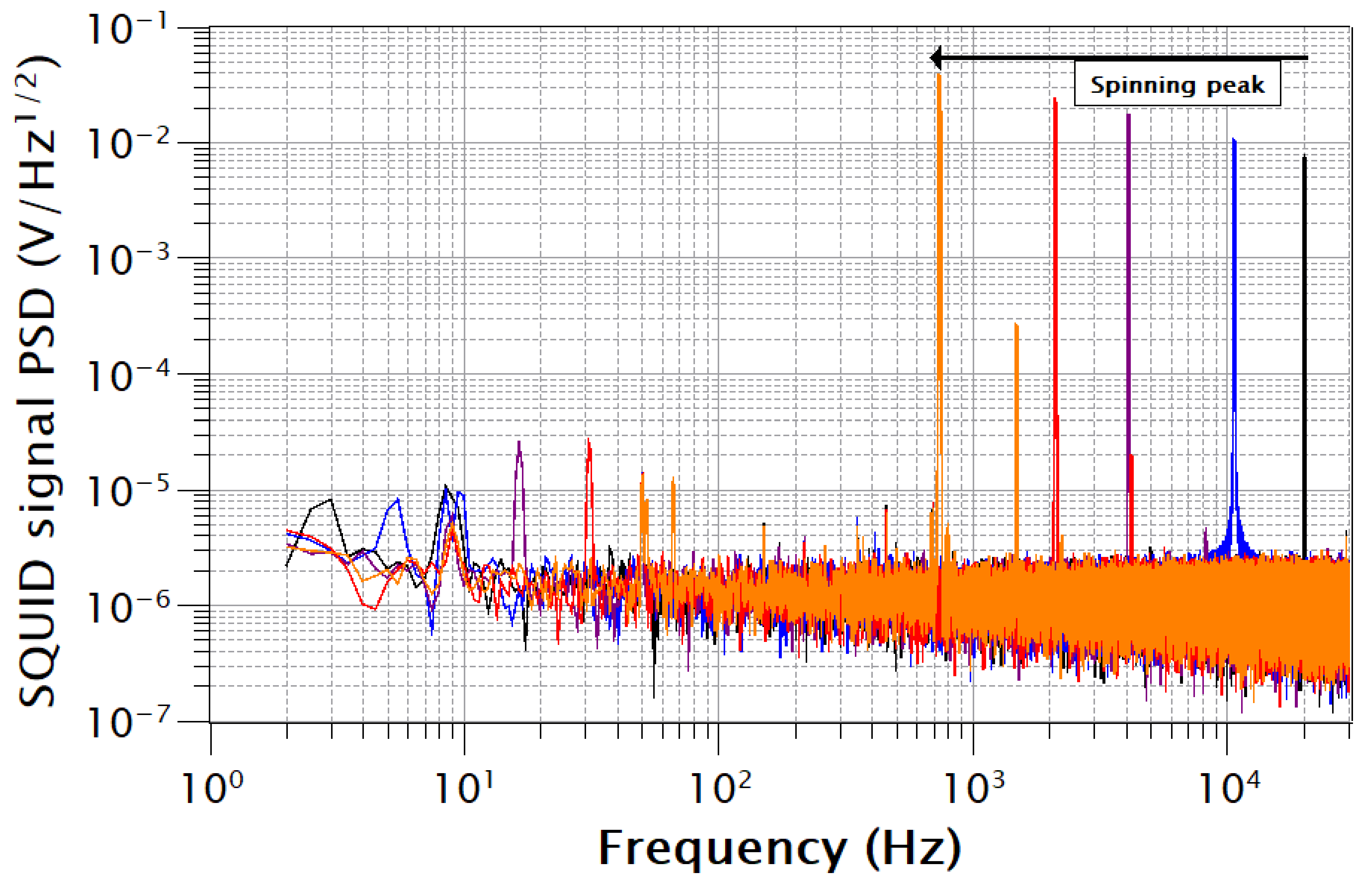
Ultrafast spinning of a levitated magnet

Maximum spinning limit:
Material breaking

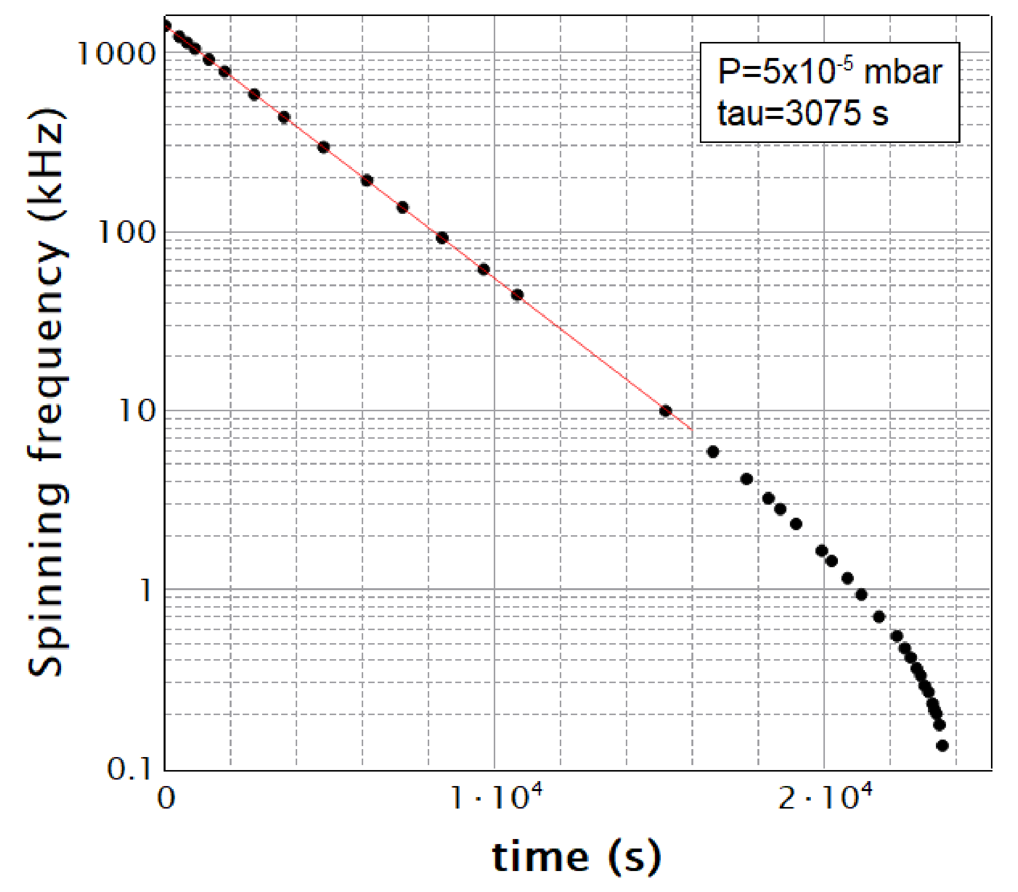
$$f_{max} \propto \frac{1}{R}$$

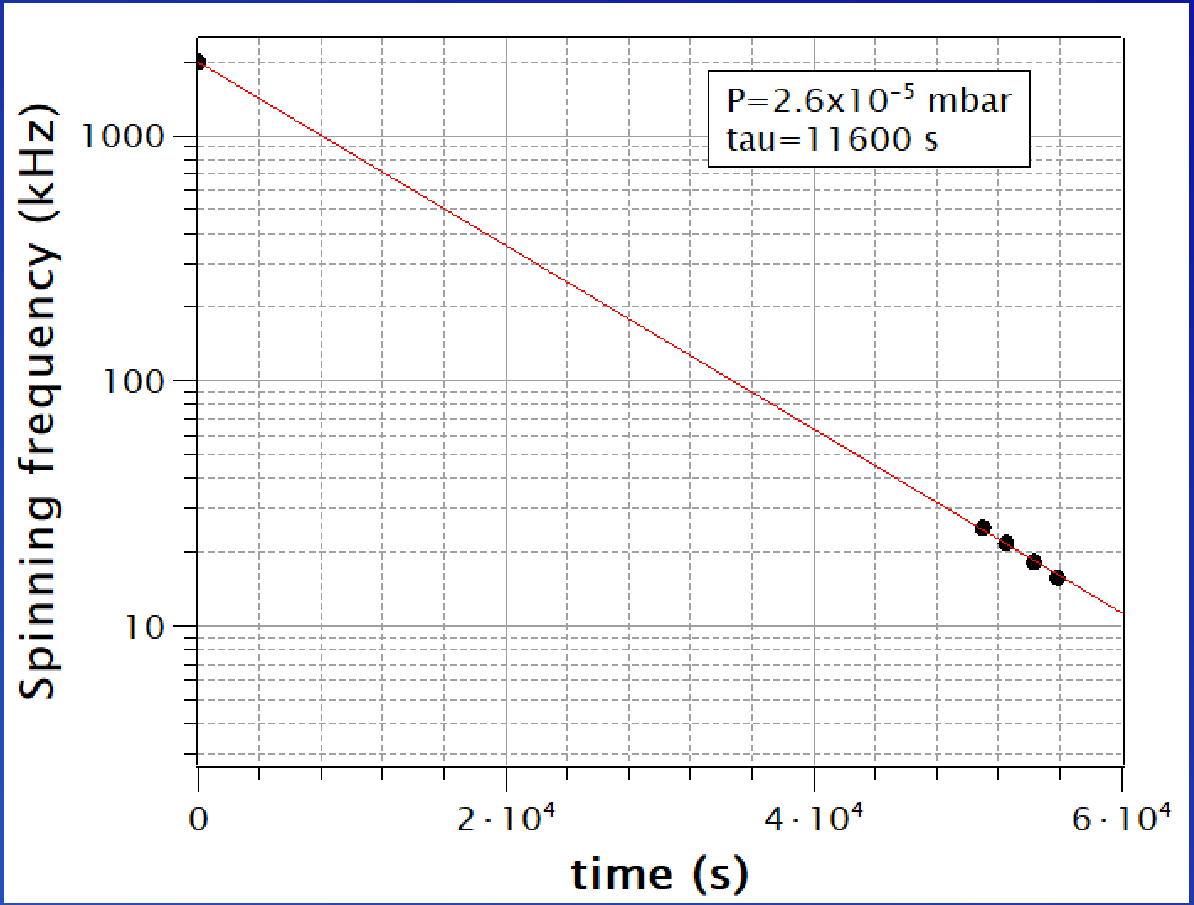


Spindown


Spinning peak
SQUID signal PSD (V/Hz$^{1/2}$)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Frequency (Hz)

Spindown

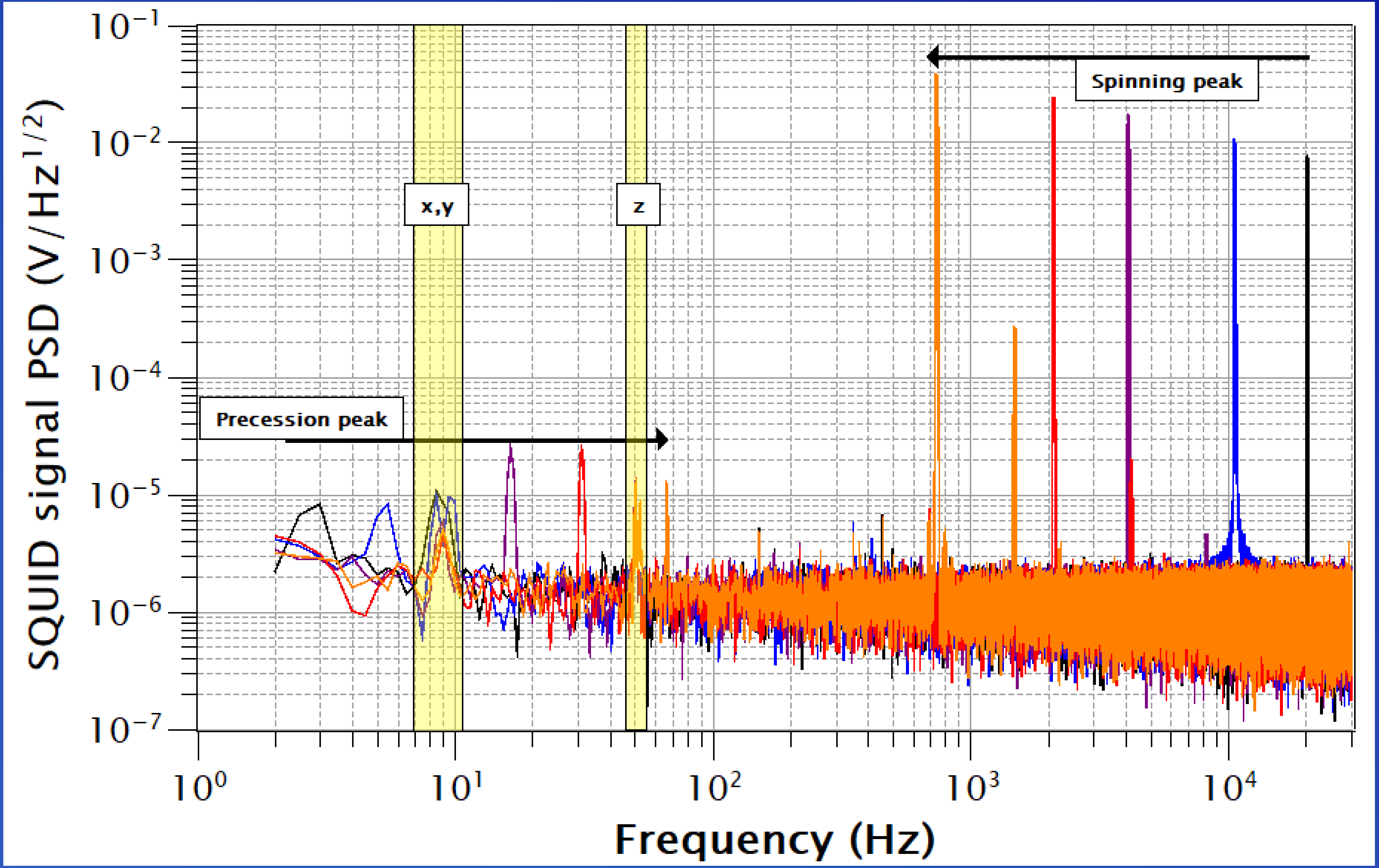




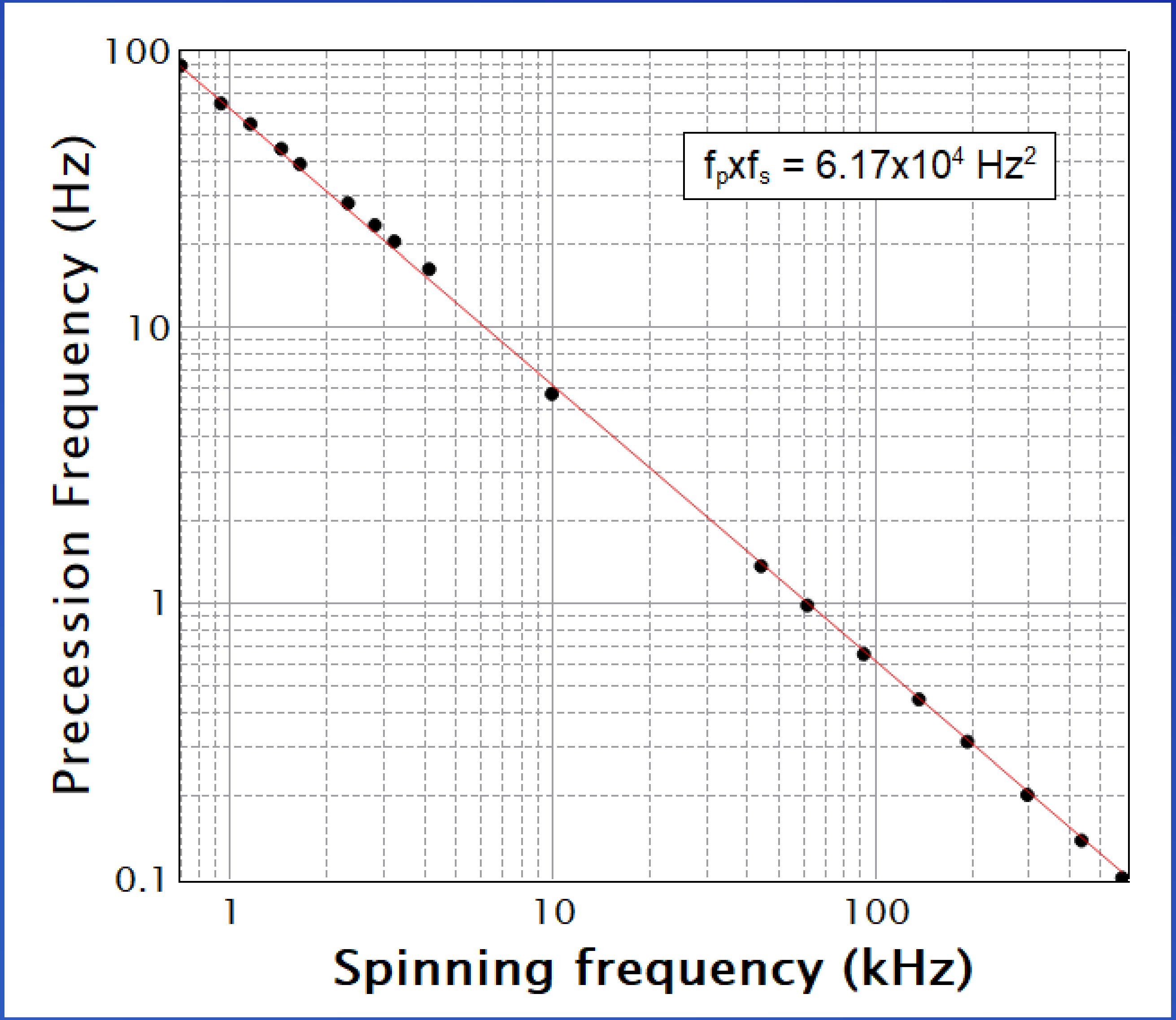
Consistent with gas collision damping (preliminary)

Rotational Q factor ~ 10^{11} $\left(Q = \frac{Stored\ energy}{\omega * Power\ dissipation} \right)$

(spinning-top) precession

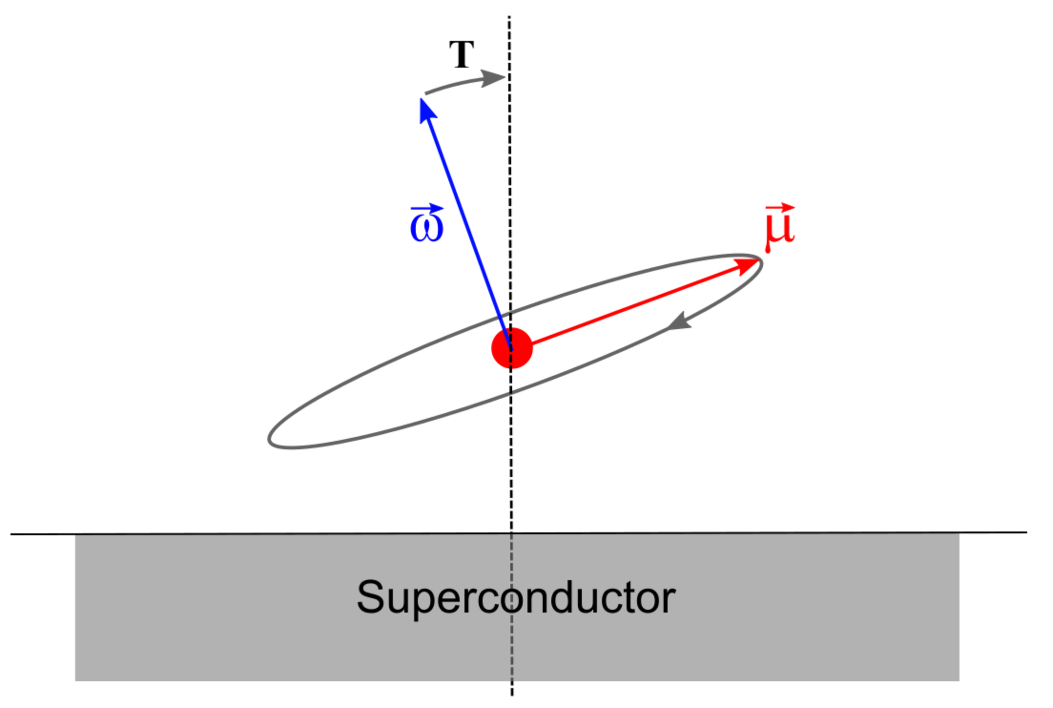


(spinning-top) precession



PRELIMINARY

Consistent with the stabilizing torque from superconductor image field (quasi-equivalent to gravity torque in spinning-top)



Prospects

- Cryogenic pressure sensors, gyroscopes, gravimeters …

- Magnetism and materials at ultrastrong stress!
  (@2 MHz acceleration at surface ~10^9 g !)

- Sources/actuators for two-mass experiments

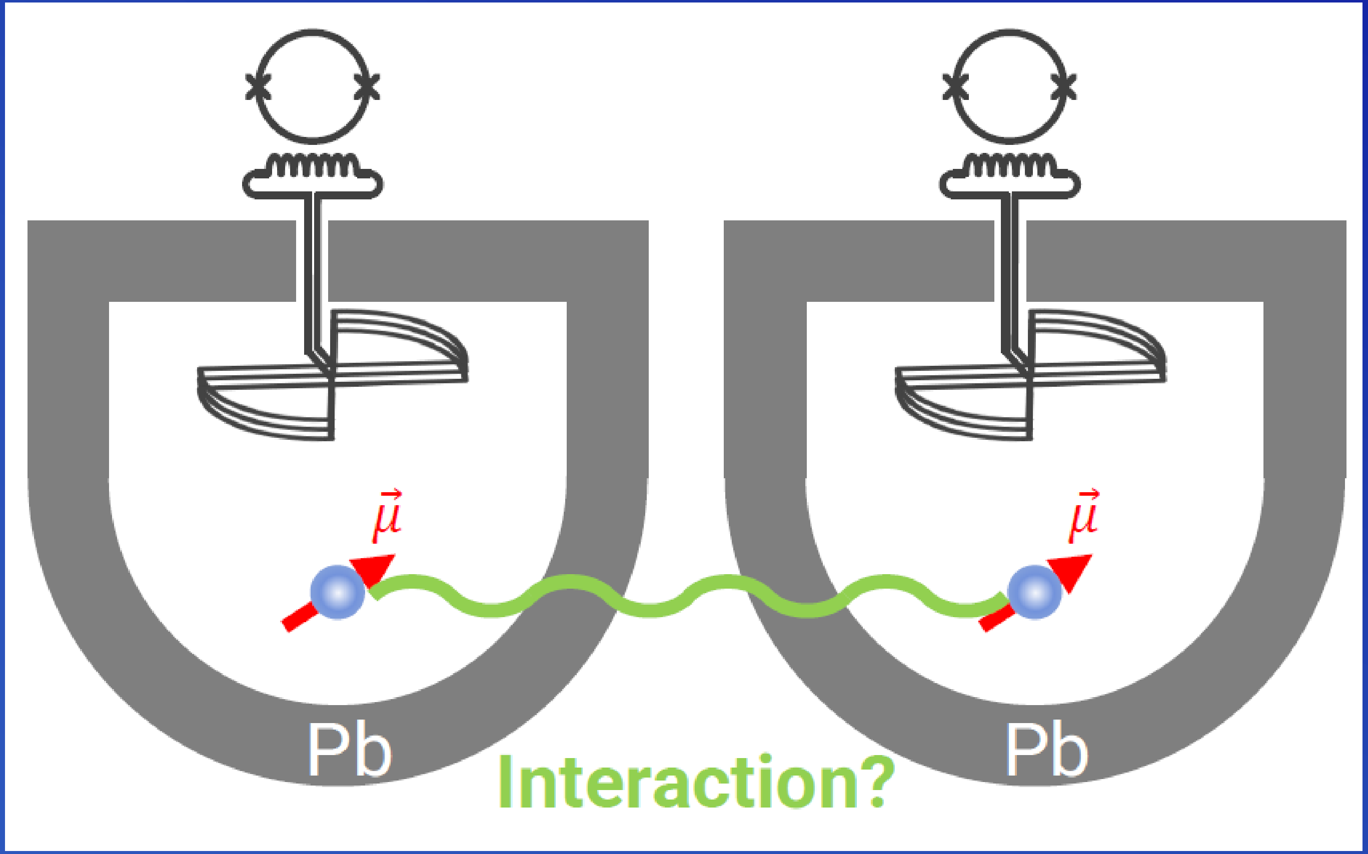
- Towards rotational quantum friction / photon emission from rotation ?

  MC Braidotti, A Vinante, G Gasbarri, D Faccio, H Ulbricht, PRL 14, 125 (2020)

- Towards detecting non-inertial quantum effects (rotational Unruh) ?

  K Lochan, H Ulbricht, A Vinante, SK Goyal, PRL 125, 241301 (2020)

Double trap for two-mass experiments



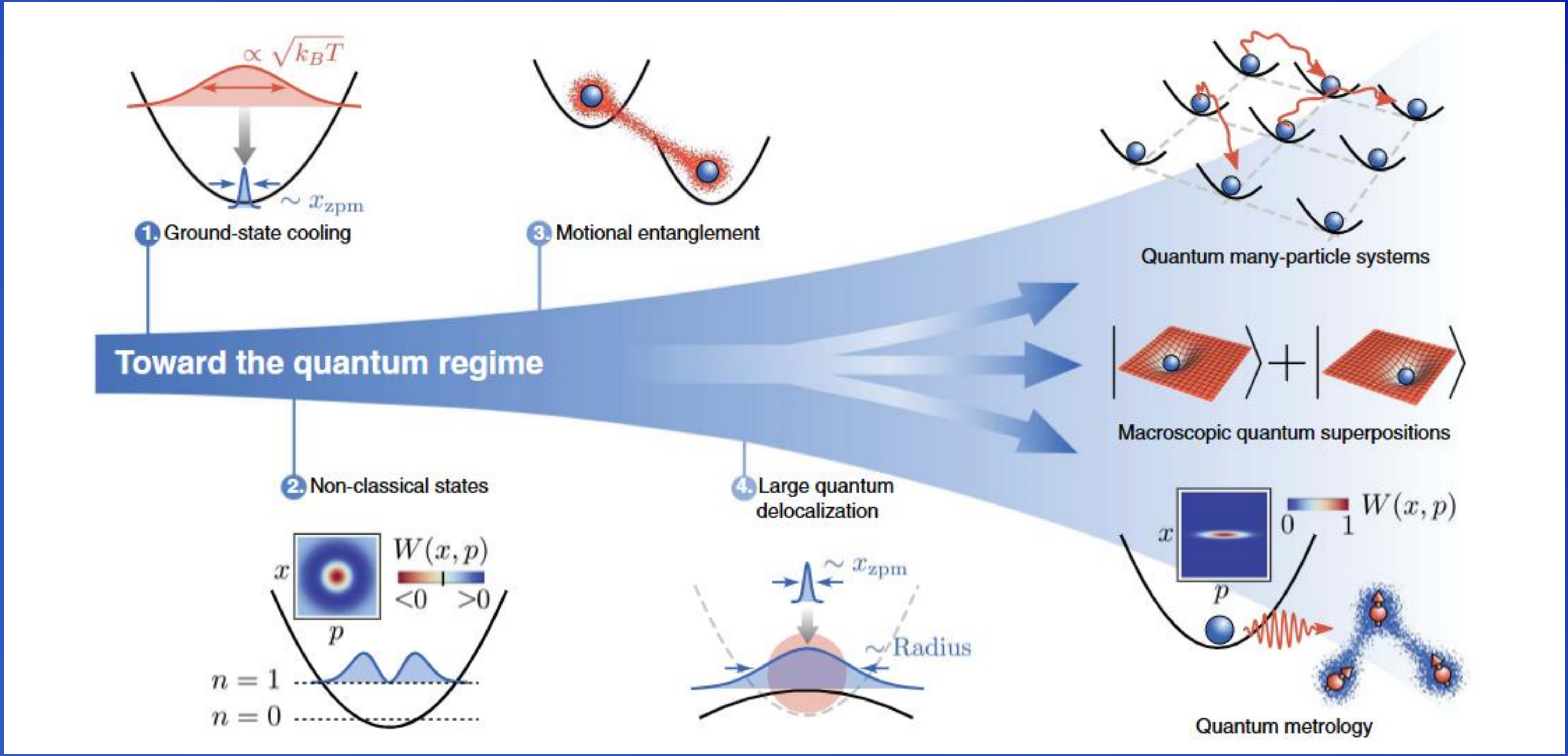
- Exotic spin-spin interactions beyond standard model (5th force)
- Gravity: needs a rotor with quadrupole moment (no sphere)

towards tests of
macroscopic quantum mechanics?

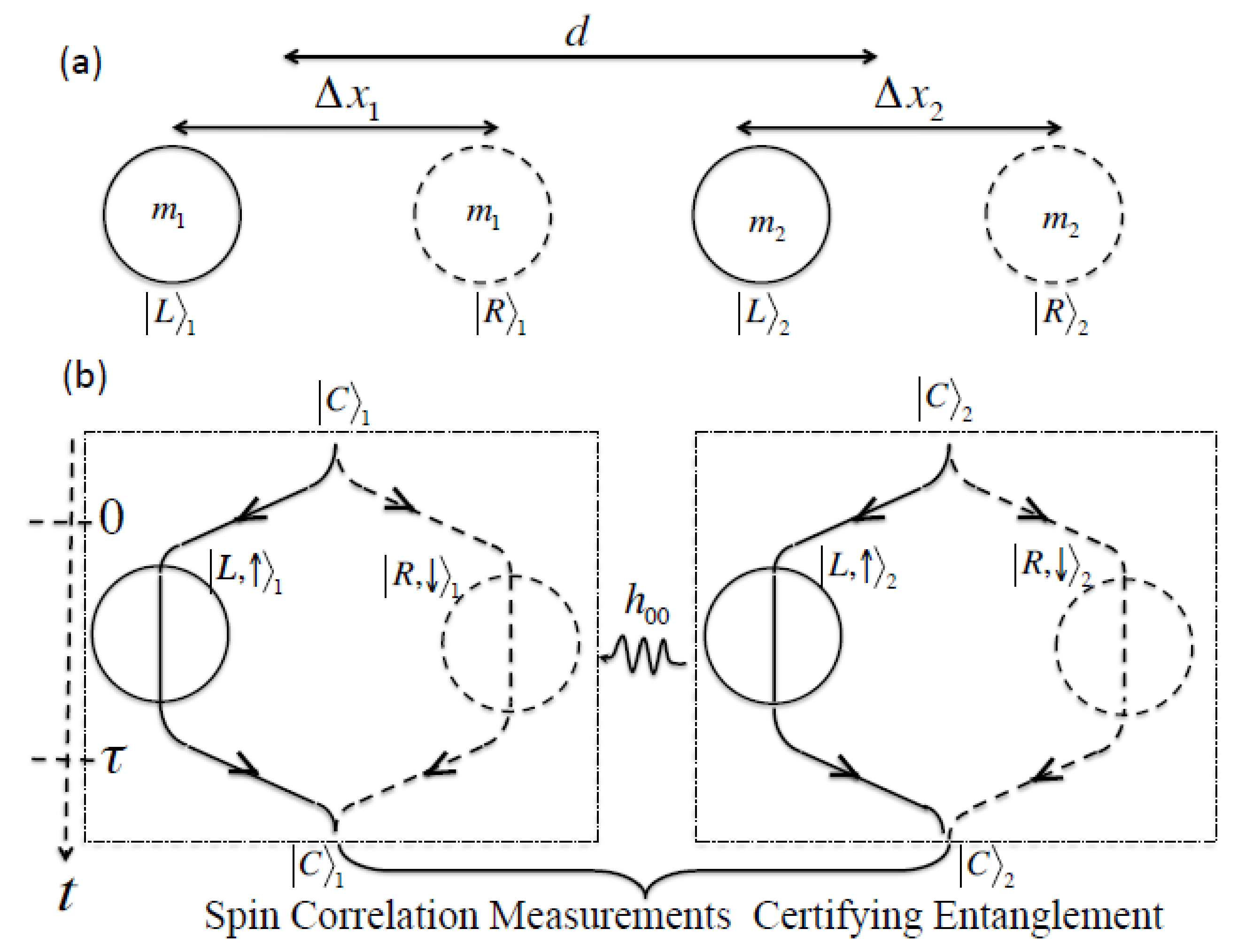
Levitodynamics: Levitation and control of microscopic objects in vacuum

C. Gonzalez-Ballestero[1,2], M. Aspelmeyer[3,4], L. Novotny[5,6], R. Quidant[6,7], O. Romero-Isart[1,2]*

Science 374, 6564 (2021)



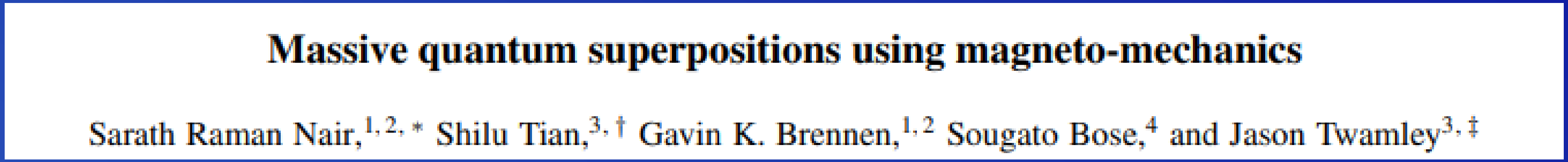
Gravitationally induced entanglement



S. Bose et al, PRL 2017
Marletto, Vedral, PRL 2017

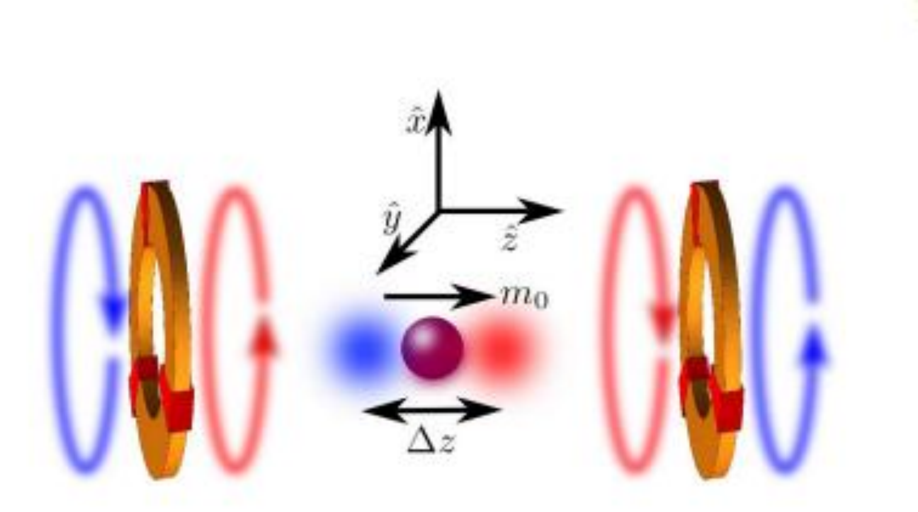
Positive result would imply gravity is quantum interaction

Cat states with a levitated magnet



Massive quantum superpositions using magneto-mechanics

Sarath Raman Nair,[1,2,*] Shilu Tian,[3,†] Gavin K. Brennen,[1,2] Sougato Bose,[4] and Jason Twamley[3,‡]

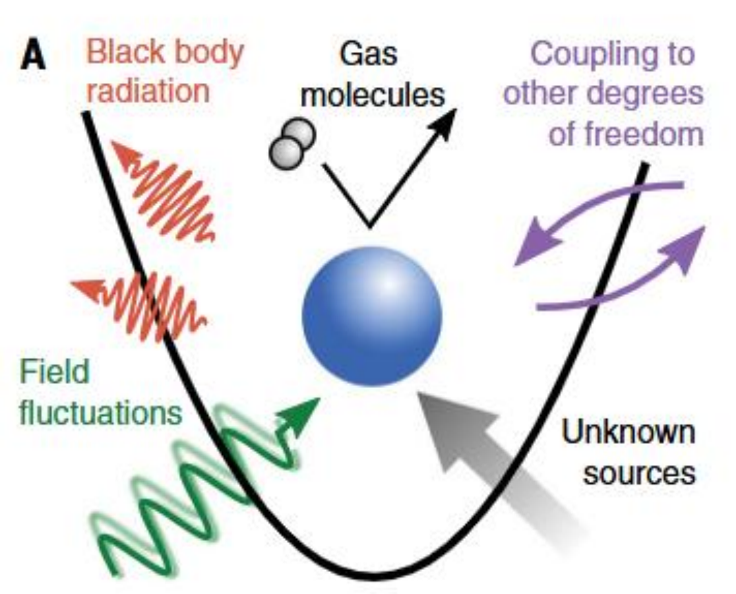


High magnetic moment

Large magnetomechanical coupling

Looks great for creating
large massive superpositions
in short time

Problem: decoherence and noise



PROS (of magnets):

- at low T, blackbody & gas negligible (unlike optical lev)
- Large mass range

CONS:

- Losses in magnet and superconductor
- Coupling to spins/defects on surfaces
- Vibrational noise

Repeatibility: one needs to repeat N times the experiment (preparation, expansion and measurement) with same initial conditions!

First step: create a pure state (ground state cooling)

Already achieved in optical levitation!   (Aspelmeyer et al, Novotny et al, Marin et al …)

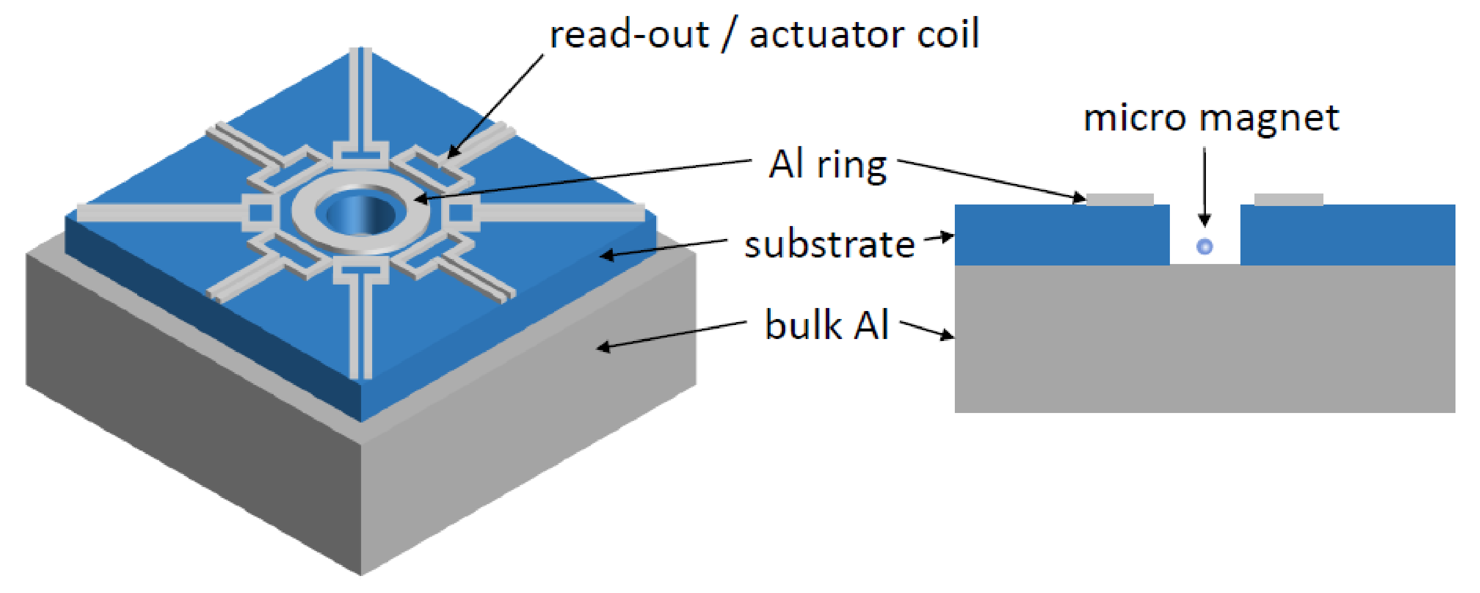
Yet to be achieved in magnetic levitation

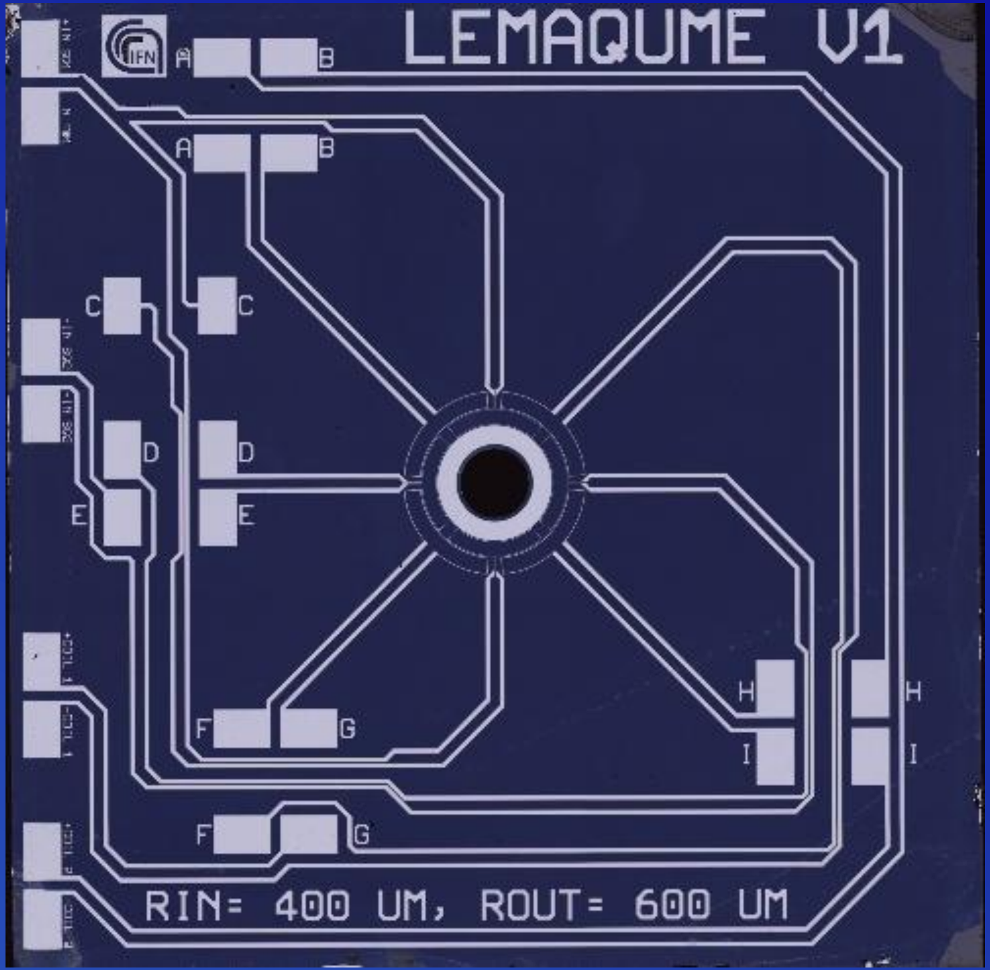
- Frequency 1000 x lower (100s Hz instead of 100s kHz)
- Larger vibrational noise

In principle achievable with

- f = 0.5-1 kHz, T=0.1 K, $Q=10^7$
- quantum limited SQUID / microwave SQUID with large coupling

Towards a chip trap experiment



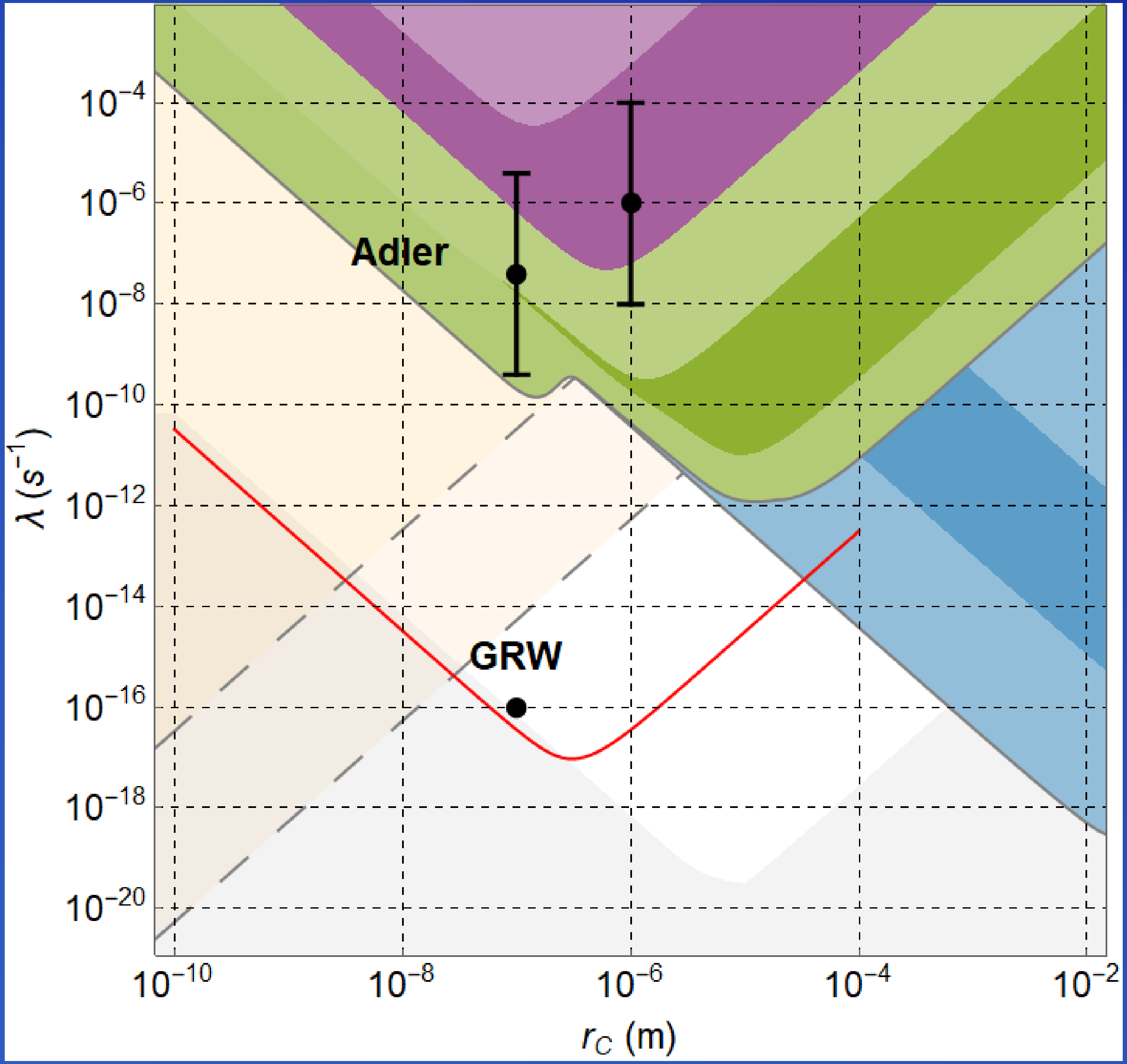


Advantages

- Higher coupling to SQUID
- Scalability
- Smaller size
- Coupling to microwave SQUID / JPA

Chip fabricated (R. Folman, BGU Israel), recently delivered

Noninterferometric testing collapse models



CSL parameter space

(plot from Matteo Carlesso)

- Merge unitary + collapse dynamics
- Decoherence + diffusion
- Just need measure classical noise

Simulated for:

2-sphere dumbbell,
R=0.5 μm
Librational mode

Thermal noise
T=10 mK
f=100 Hz
Q=10^{12}

Conclusion – Take home

Levitated ferromagnets are an interesting experimental platform

- Very good magnetometers + spinning magnets
  - Ultralight dark matter (axions)
  - Exotic spin-mediated interactions (fifth force)
  - Gravity at small masses/short distance

Prospects towards macroscopic quantum physics (gravity and quantum …)

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D. Budker et al
R. Folman et al
T. Wang et al
G.Carugno et al
C. Gatti et al

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