Andrea Vinante

CNR - Istituto di Fotonica e Nanotecnologie, Trento

Levitodynamics

Quantum Optics Course, 29-5-2026

Who we are

- Part of CNR - IFN (CNR as Iacopo, but different Institute)
- Experimentalists
- Lab hosted by FBK & UNITN
- Strong collaboration with F. Mantegazzini, I. Carusotto, G. Rastelli

Topics

- Superconducting devices
- Hybrid mechanical/superconducting systems & microwave optomechanics
- Levitodynamics
- Fundamental and quantum physics

Cryo Quantum Lab

In our laboratory we develop and investigate several types of ultrasensitive superconducting and micromechanical devices, with special interest in the application to quantum technologies and fundamental physics. We have available a large dry dilution refrigerator with base temperature 20 mK, equipped with microwave and SQUID instrumentation, a wet dilution refrigerator and several liquid helium cryostats.

Superconducting quantum sensors and devices

We have recently started several projects in the field of superconducting quantum technologies. In particular, we are currently investigating superconducting quantum devices operated in the microwave domain, with focus on parametric amplifiers and single photon detectors.

https://www.tn.ifn.cnr.it/research/cryo-quantum-lab

email: anvinante@fbk.eu

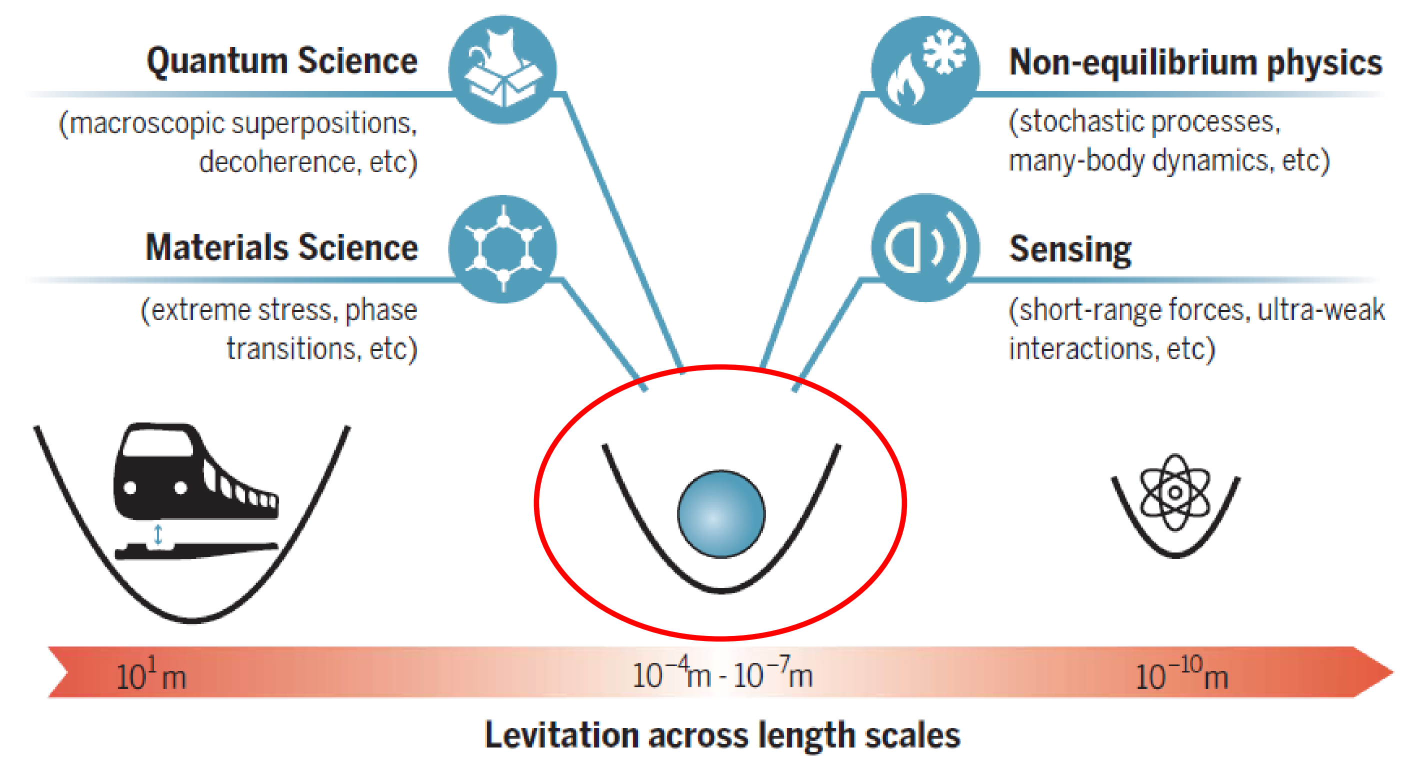
Outline

- Overview of the field worldwide
  - Motivations
  - State of the art

- Overview of our experiment in Trento
  - Meissner-levitated micromagnets
  - Applications

- An unexpected result: gyroscopic effects in a macroscopic ferromagnet

Levitodynamics: trapping & control of micro/nano-objects in vacuum



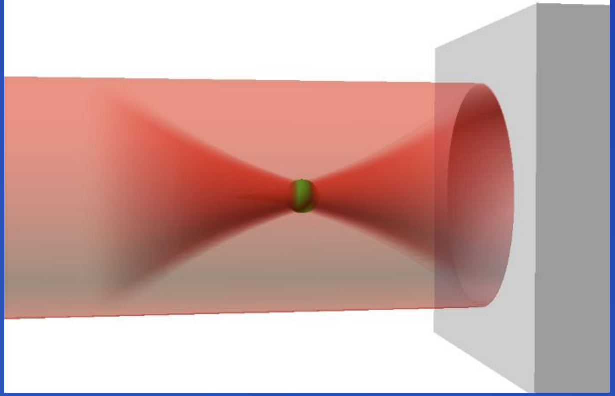
C. Gonzalez-Ballestero, M. Aspelmeyer, L. Novotny, R. Quidant, O. Romero-Isart, Science 374, 168 (2021)

Convergence from many fields
- Optomechanics
- Micro/nanomechanics
- Atomic physics

Many ways of levitating

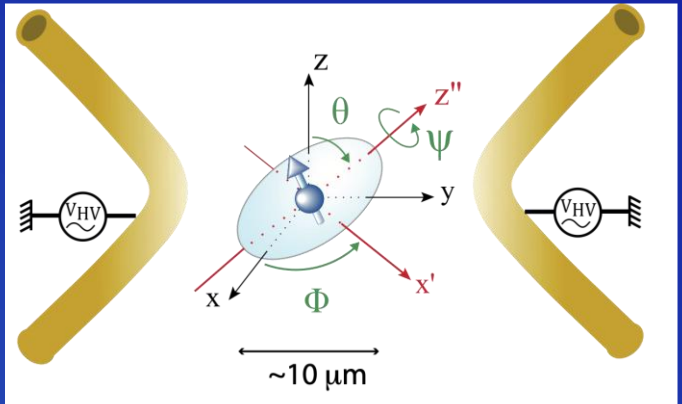
ACTIVE TECHNIQUES: external dynamical fields required !

Optical (optical tweezer)



Novotny, ETH Zurich
Aspelmeyer, Vienna
Marin, Firenze
….

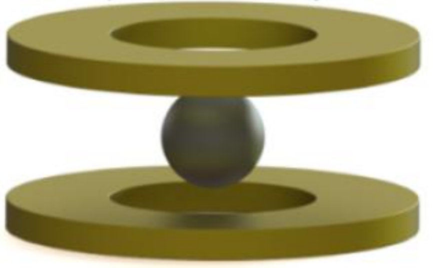
Electrodynamical (Paul traps)



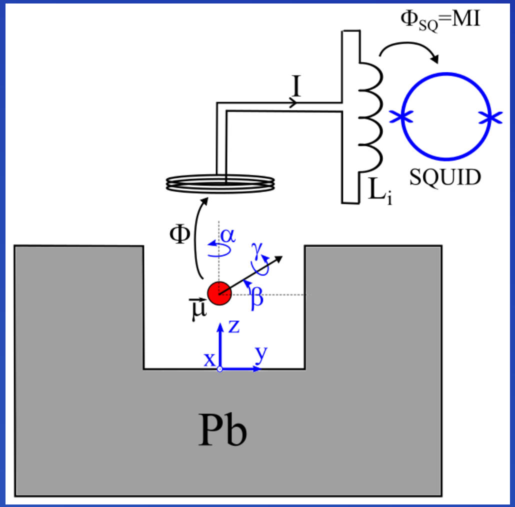
Northup, Innsbruck
Hetet, Paris
…

PASSIVE (MAGNETIC)

Superconducting particles + coils



Wieczorek, Chalmers
Aspelmeyer, Vienna



Lukin, Harvard
..
Us

Main good features of levitodynamical systems

6 Mechanical modes (3 translational + 3 rotational modes) highly decoupled from internal modes

1) Very low mechanical losses (NO CLAMPING)

VERY LOW THERMAL MECHANICAL NOISE
(& DECOHERENCE)

$$S_F = 2m\gamma\hbar\omega\coth\left(\frac{\hbar\omega}{2k_BT}\right) \approx 4k_BTm\gamma$$

Fluctuation-Dissipation theorem

Power spectral density of stochastic force on Resonator mass m, freq ω, temperature T

Energy Dissipation rate
($E = E_0 e^{-\gamma t}$)

2) Large degree of control on trapping potentials

Unlike conventional mechanical resonators, the frequency of the modes can be controlled (for instance, switched on and off)

Motivations: Sensing

Very low dissipation → Very low thermal (mechanical) noise

No clamping losses

$$S_F = 4k_BTm\gamma$$

Mechanical systems are universal

Can measure virtually anything…

Forces, acceleration, gravity

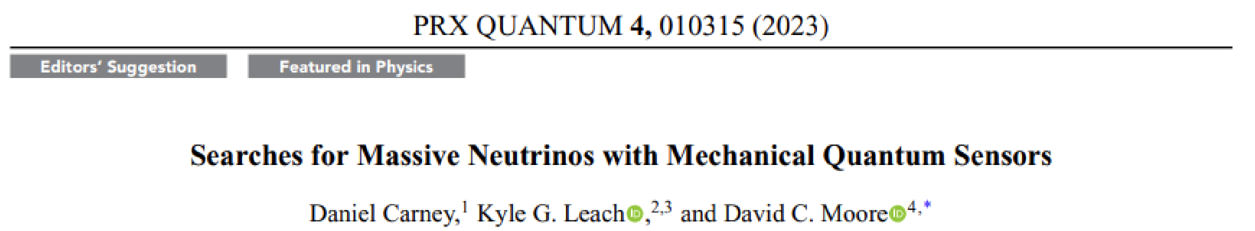
Magnetic fields, pressure

Gyroscopes

Particle detectors →

Dark matter

Gravitational waves



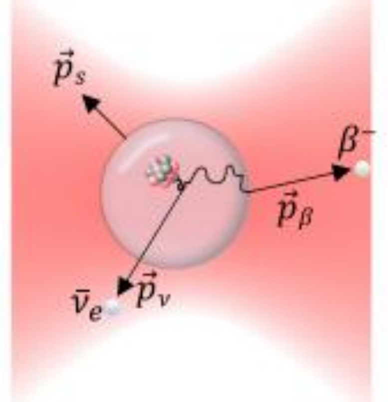
PRX QUANTUM **4,** 010315 (2023)

Editors' Suggestion

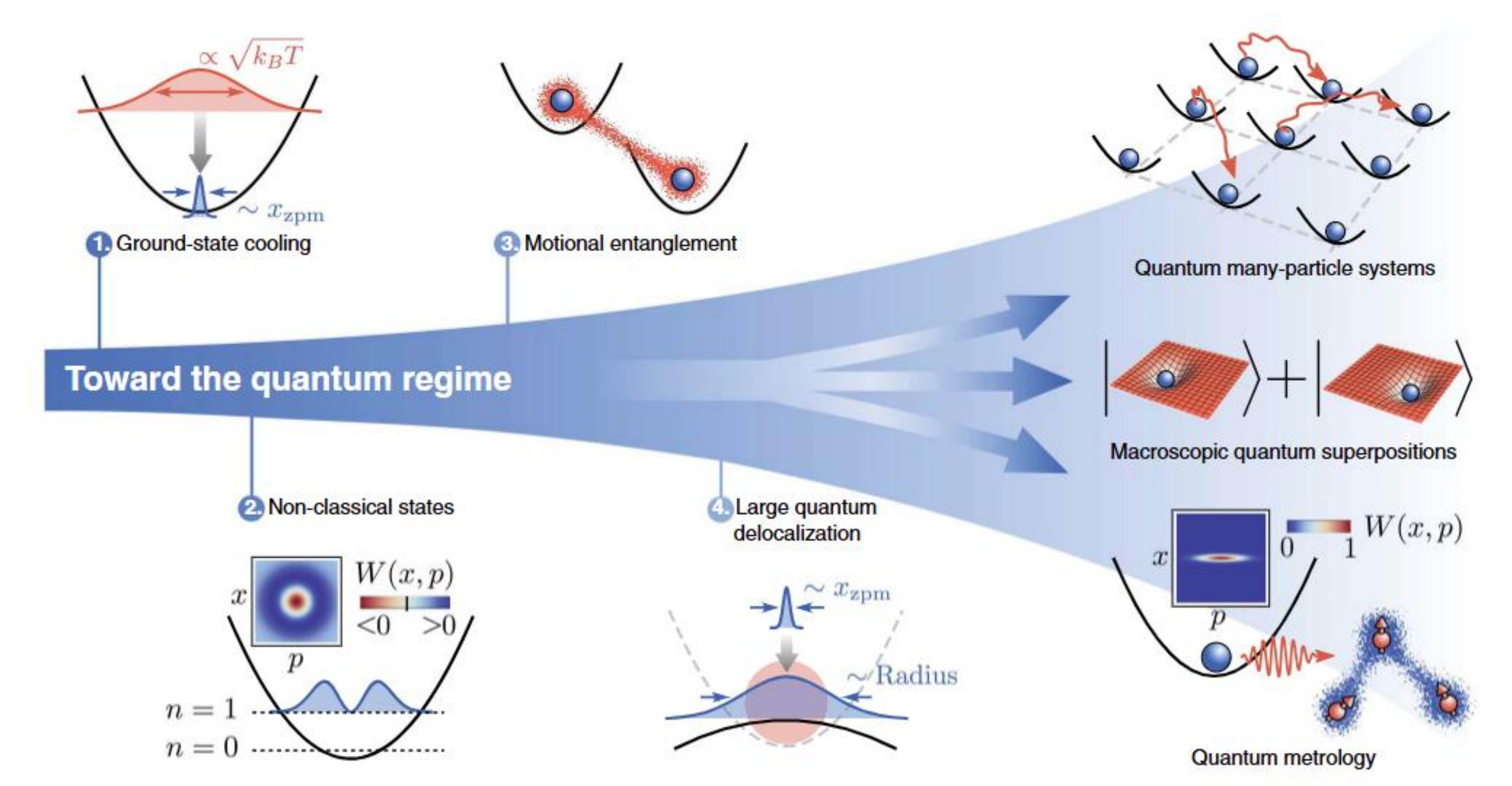
Featured in Physics

Searches for Massive Neutrinos with Mechanical Quantum Sensors

Daniel Carney,[1] Kyle G. Leach,[2,3] and David C. Moore[4,*]



Motivations: quantum regime of massive objects



C. Gonzalez-Ballestero et al, Science 374, 168 (2021)

The first milestone: ground state cooling

Article

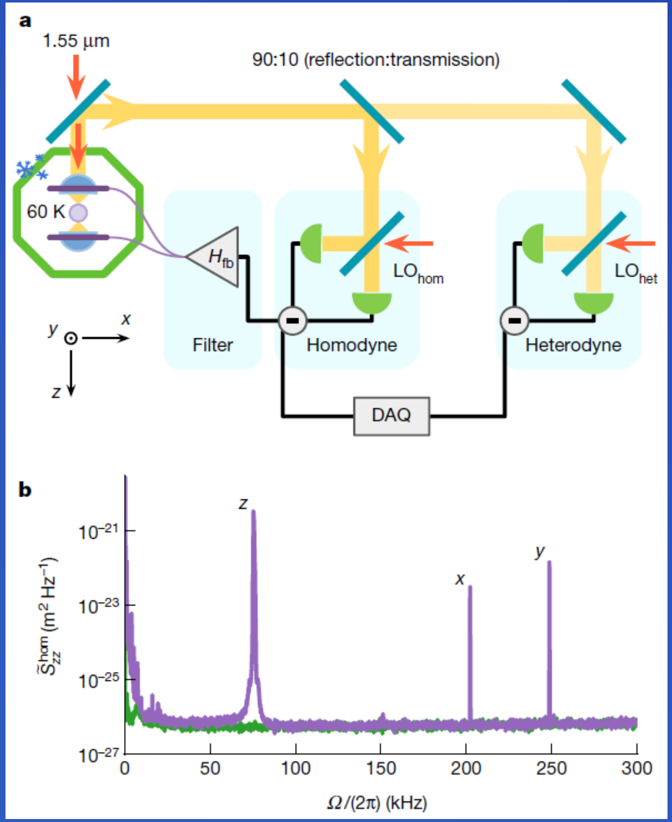
Quantum control of a nanoparticle optically levitated in cryogenic free space

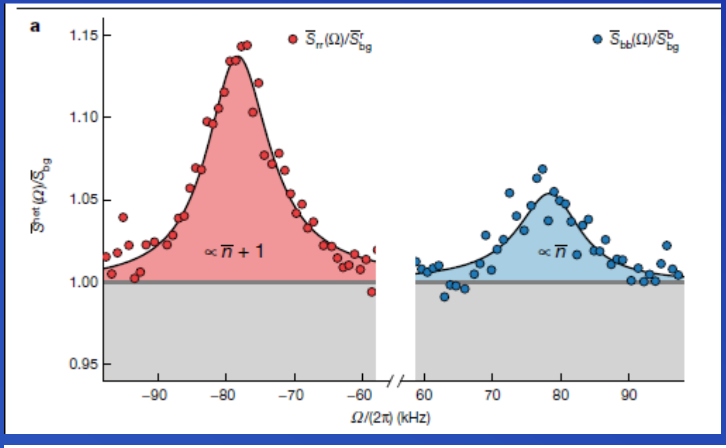
https://doi.org/10.1038/s41586-021-03617-w

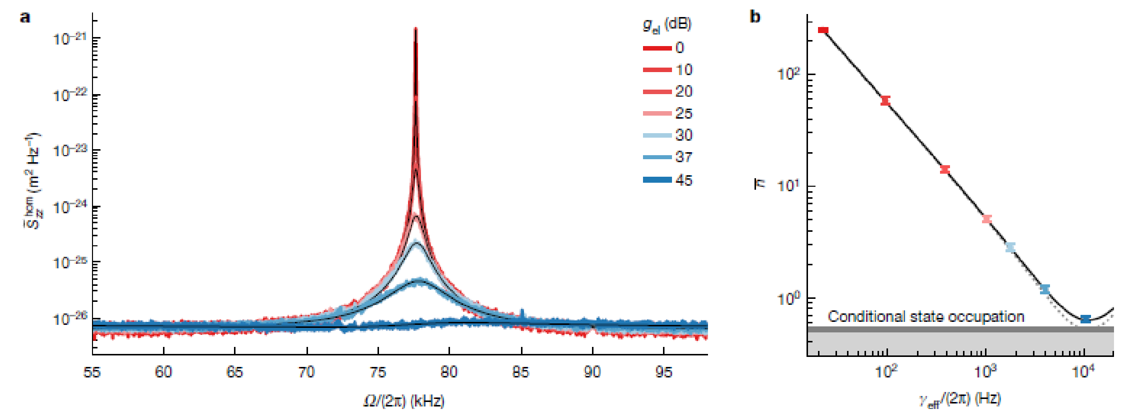
Received: 4 March 2021

Felix Tebbenjohanns[1,3], M. Luisa Mattana[1,3], Massimiliano Rossi[1,3], Martin Frimmer[1] & Lukas Novotny[1,2]✉

- Achieved by other groups worldwide
- Achieved via different protocols (feedback, cavity-based)







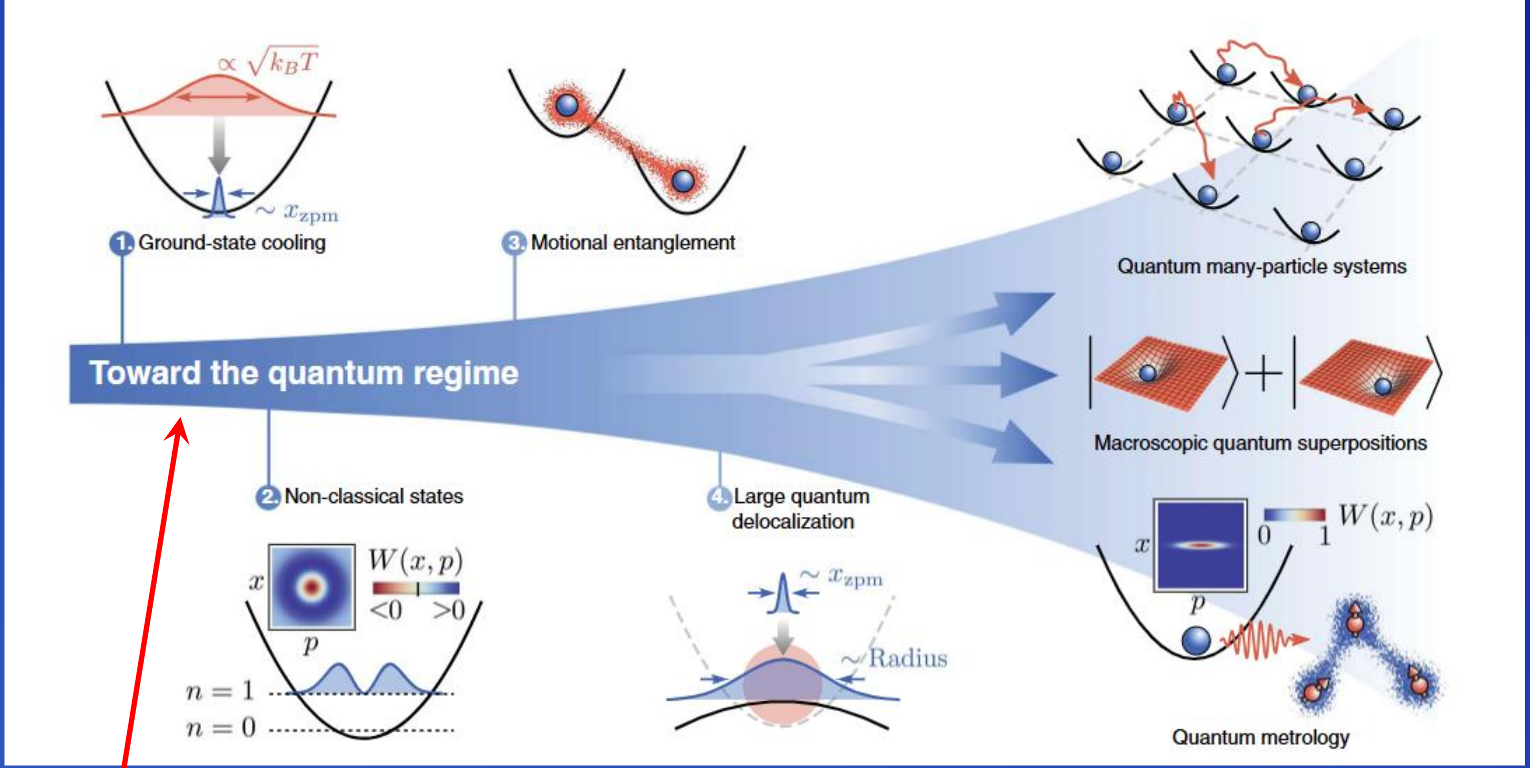
$$k_B T \gg \hbar\omega$$

BUT

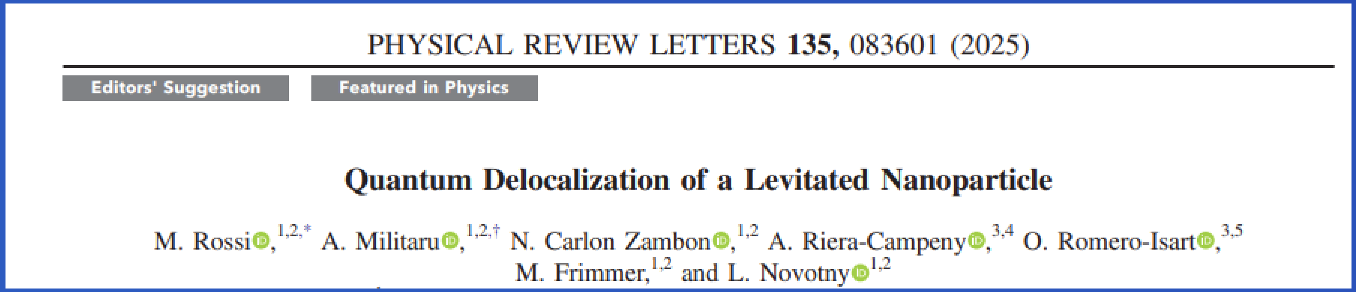
$$\frac{k_B T}{Q} < \hbar\omega$$

$$Q = \frac{\omega}{\gamma}$$ Quality factor

Current state of the art



C. Gonzalez-Ballestero et al, Science 374, 168 (2021)



PHYSICAL REVIEW LETTERS **135,** 083601 (2025)

Editors' Suggestion   Featured in Physics

Quantum Delocalization of a Levitated Nanoparticle

M. Rossi,[1,2,*] A. Militaru,[1,2,†] N. Carlon Zambon,[1,2] A. Riera-Campeny,[3,4] O. Romero-Isart,[3,5]
M. Frimmer,[1,2] and L. Novotny[1,2]

1) Optomechanical ground state cooling
2) Switch-off the trapping laser:
   expansion of the «pure» wave function

Why is it interesting to create massive nonclassical (= delocalized) states

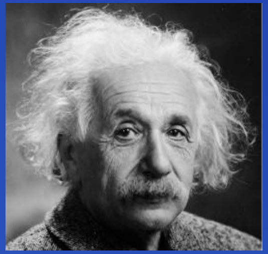
1) We don’t know if quantum mechanics is valid up to arbitrary mass scale
   - Quantum mechanics interpretations?
   - Wave function collapse models (QM can be modified !)

2) At sufficiently large mass, gravity will play a role
   - How does the gravitational field of a delocalized state look?
   - Can spacetime be in «quantum superposition» ?
   - We don’t know (no theory quantum gravity yet)

Is gravity quantum?

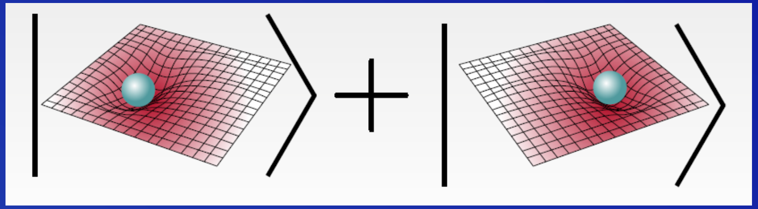
WE DON'T KNOW!

QUANTUM MECHANICS IS INCOMPATIBLE WITH GENERAL RELATIVITY



$$\boxed{G_{\mu\nu} + \Lambda g_{\mu\nu}} = \boxed{\kappa T_{\mu\nu}}$$

SPACETIME GEOMETRY QUANTUM MATTER



= ?

TWO OPTIONS:

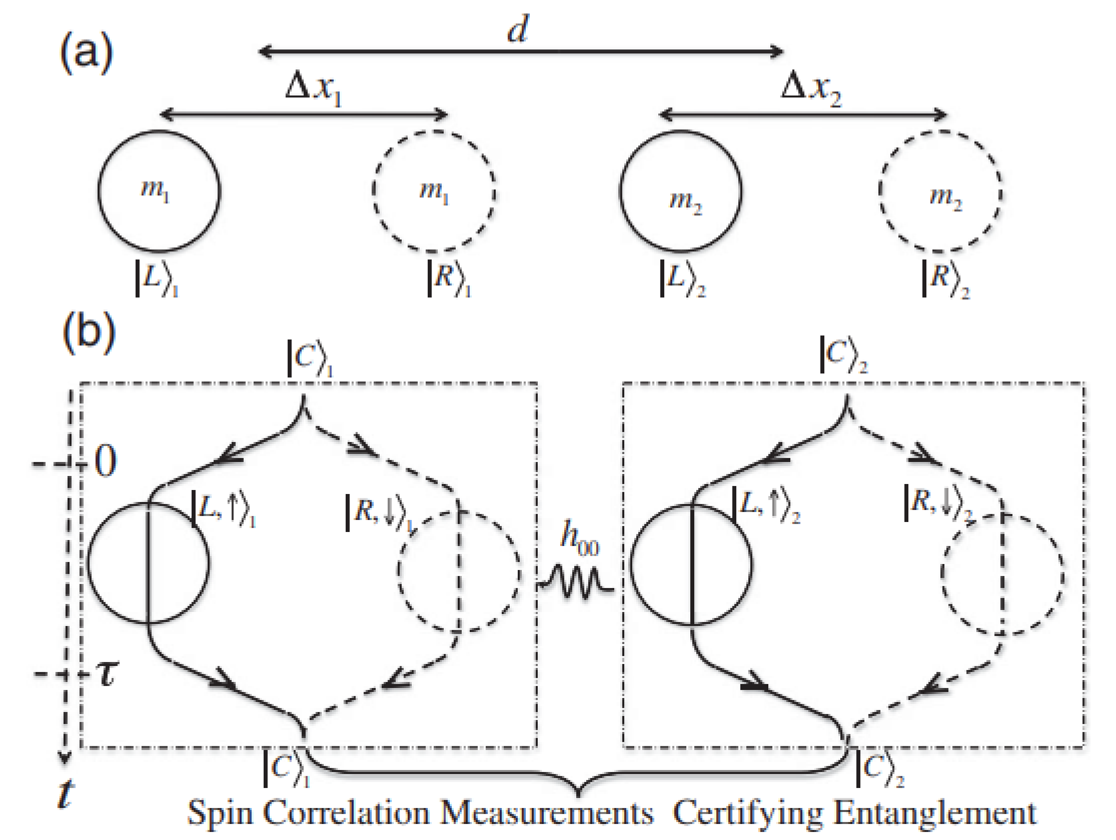
- Gravity must be «quantized». Then we need a theory of quantum gravity. So far all attempts to build a fully consistent theory failed
- Quantum mechanics has to be «gravitized». Also hard to find a consistent solution

BUT THE BIGGEST PROBLEM ACTUALLY IS:

There is no experiment to date that can help answering this question

Is gravity quantum? Or may it be classical?

S. Bose et al, Phys Rev Lett 240401 (2017)
C. Marletto, V. Vedral, Phys Rev Lett 240402 (2017)

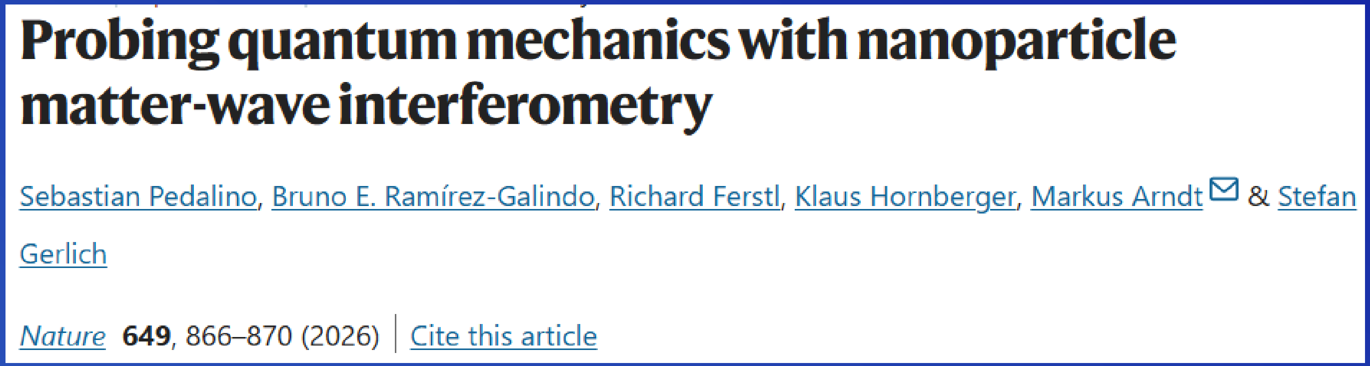


NO NEED FOR ULTRA HIGH ENERGY ACCELERATORS

Instead need for ultralow energy experiments

IDEA: If gravity is quantum, it will generate entanglement in a pair of masses each one in quantum superposition of two positions in space

Massive superpositions (1): current record

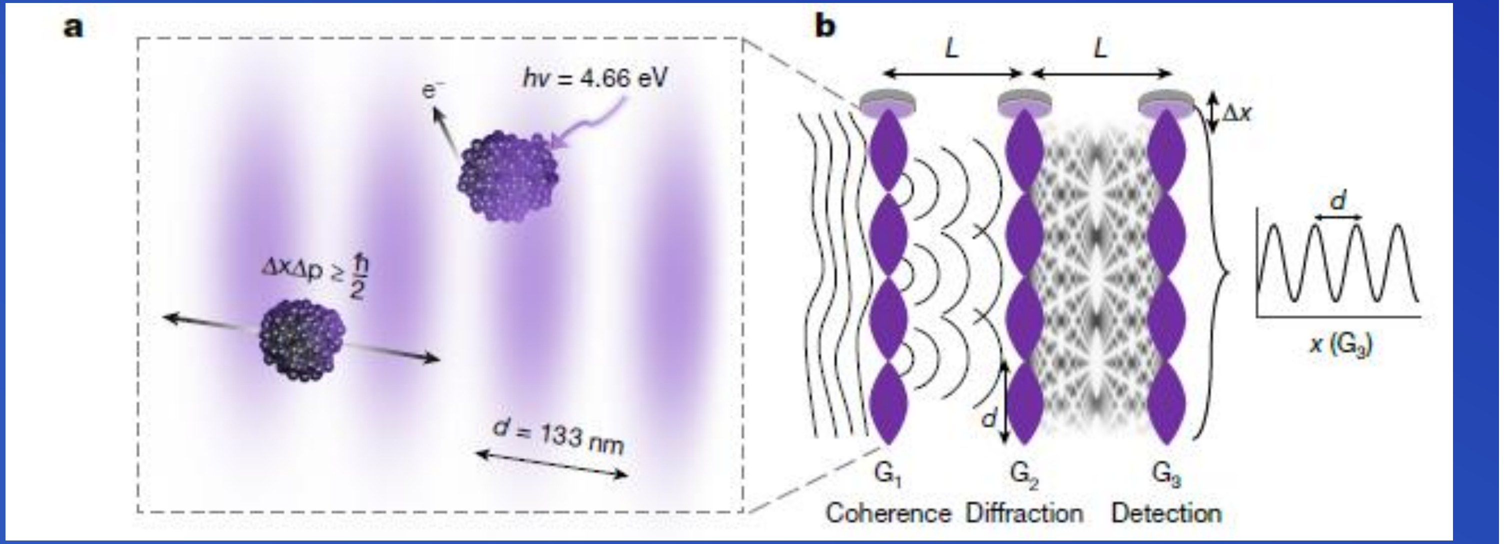


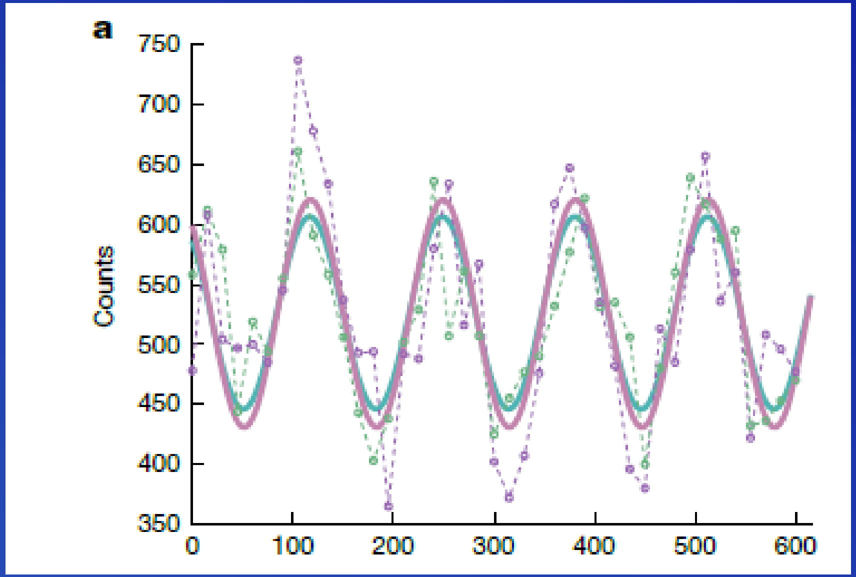
Probing quantum mechanics with nanoparticle matter-wave interferometry

Sebastian Pedalino, Bruno E. Ramírez-Galindo, Richard Ferstl, Klaus Hornberger, Markus Arndt & Stefan Gerlich

Nature **649**, 866–870 (2026) | Cite this article

Markus Arndt, Vienna

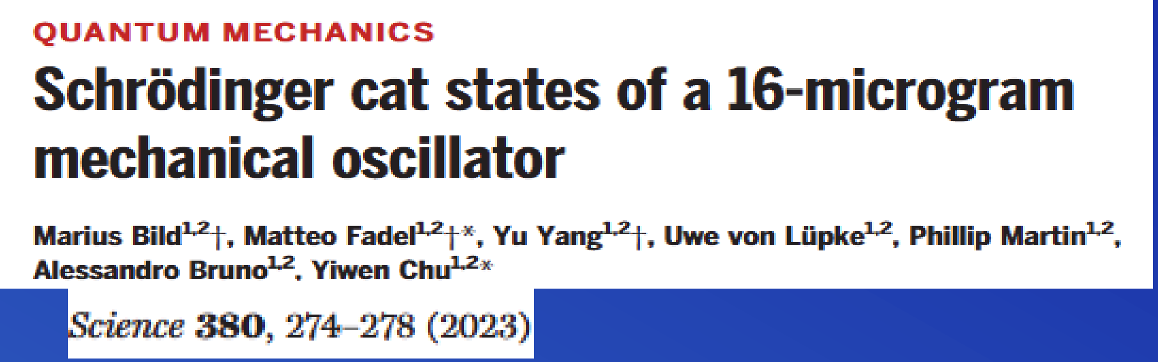




~7000 sodium atoms
Nanoparticle Mass ~ 200000 x proton mass

Massive but still very «nano»

Massive superpositions (2)

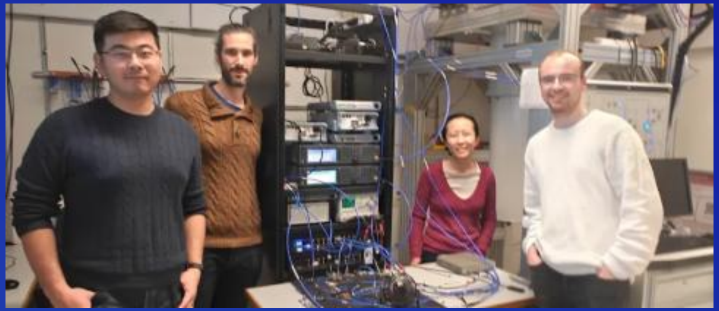


QUANTUM MECHANICS

Schrödinger cat states of a 16-microgram mechanical oscillator

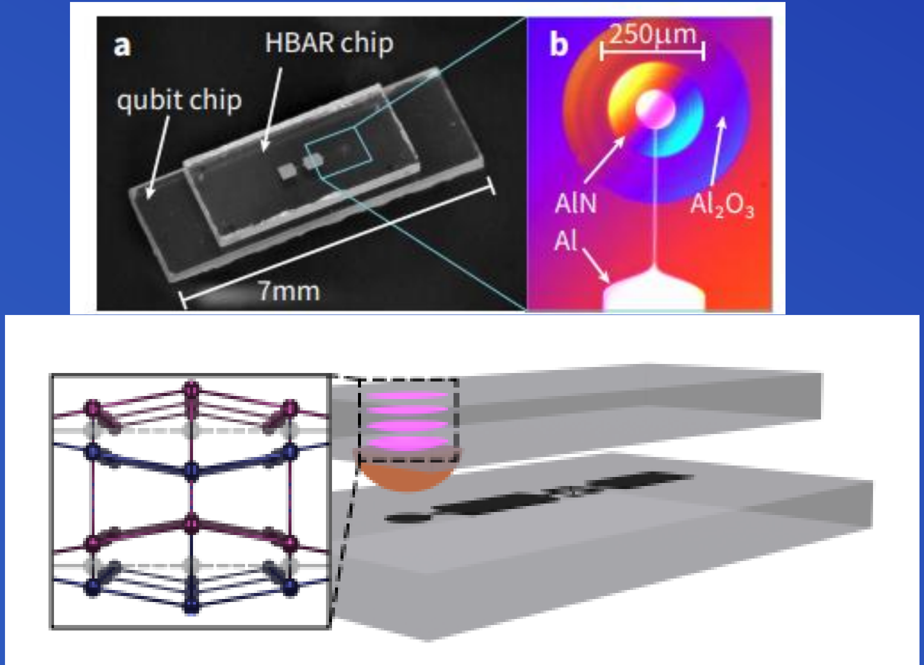
Marius Bild[1,2]†, Matteo Fadel[1,2]†*, Yu Yang[1,2]†, Uwe von Lüpke[1,2], Phillip Martin[1,2], Alessandro Bruno[1,2], Yiwen Chu[1,2]*

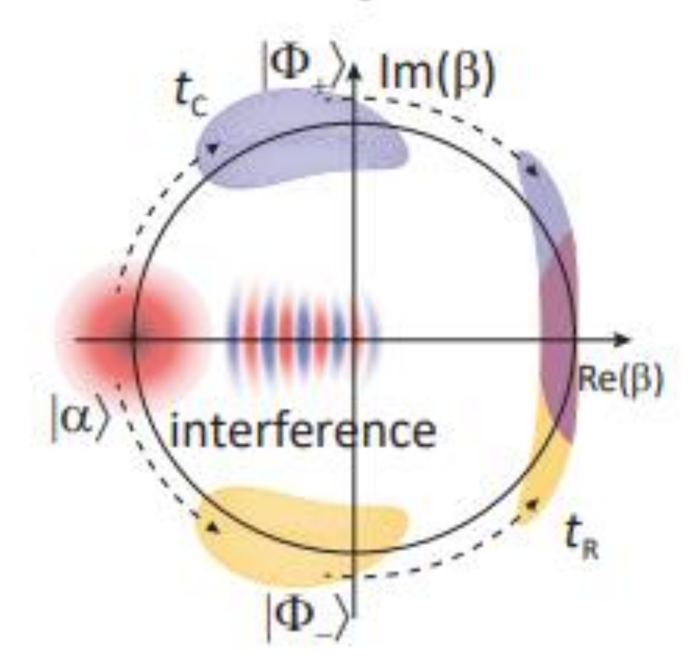
Science **380**, 274–278 (2023)



Yiwen Chu group, ETH Zurich

SUPERCONDUCTING QUBIT + ACOUSTIC VIBRATION





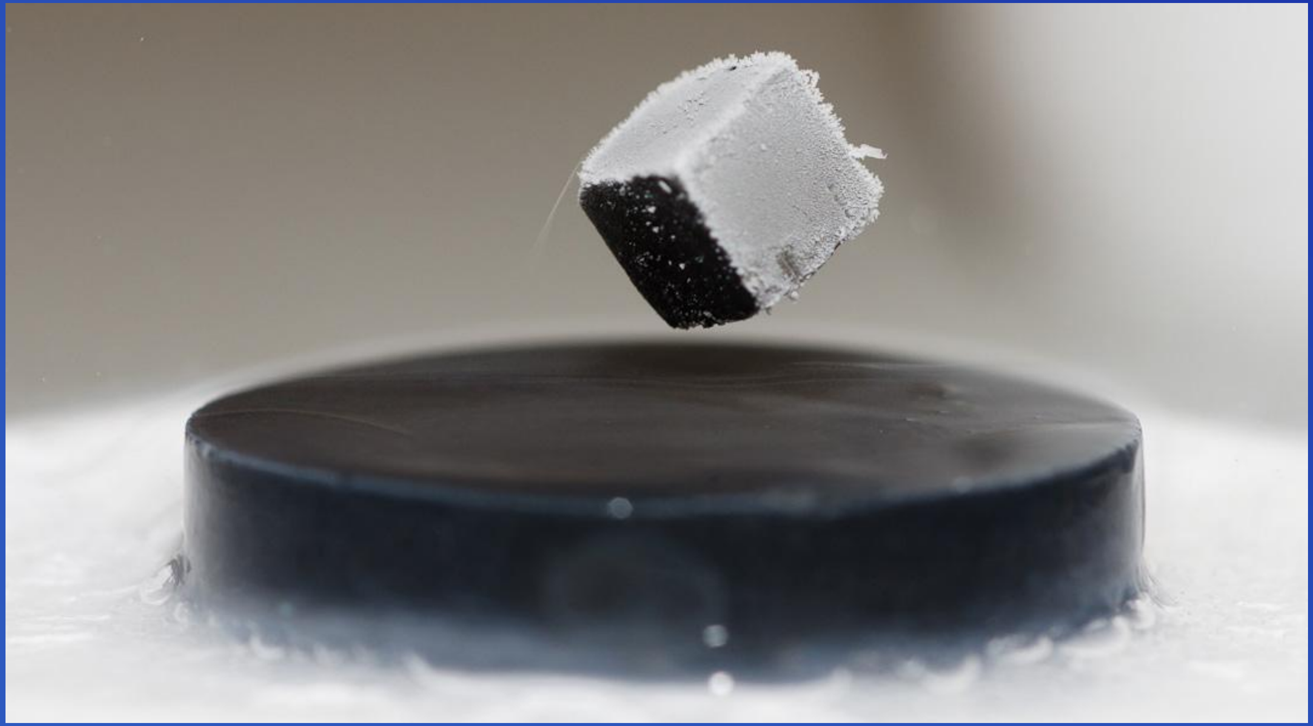
- Very large effective mass in quantum superposition = 16 micrograms !!
- Very tiny separation of the superposition = 2×10^{-18} meters

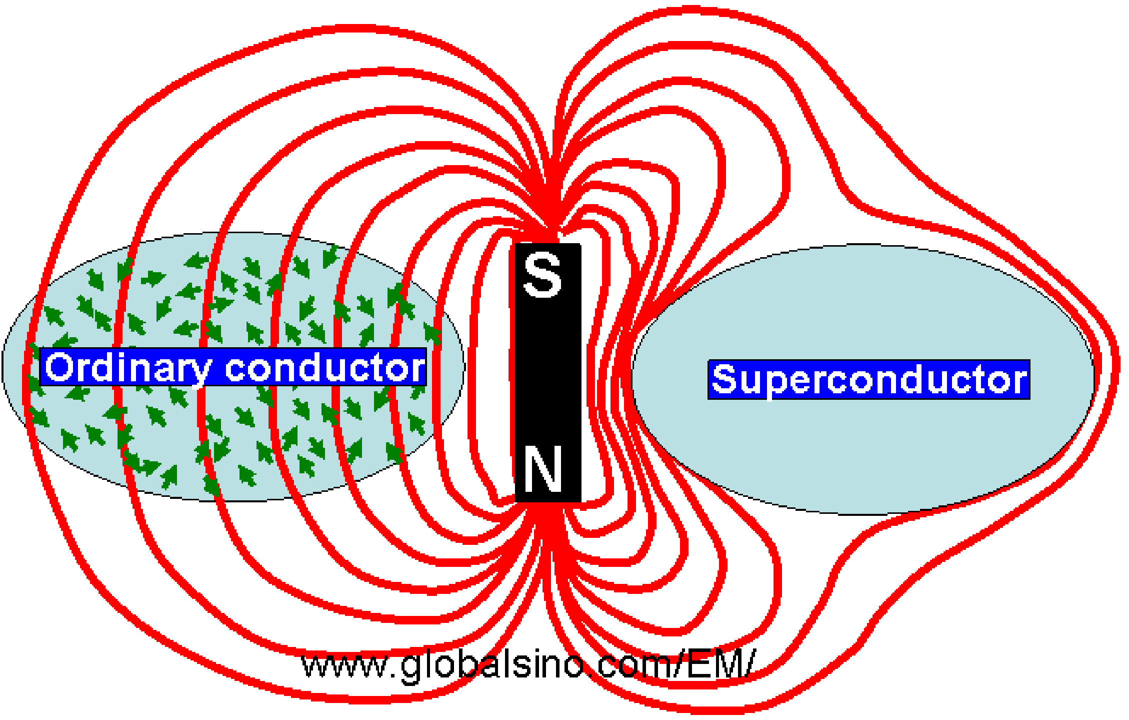
The ideal system

- Large mass (Gravity plays a role)
- Large delocalization (Large quantumness)
- Long duration (High isolation from environment)

Levitated particles in the cleanest possible environment:
Possibly at lowest possible temperature to avoid decoherence

Meissner-based Levitation





Levitated micromagnets: what's special?

Hard ferromagnets + Type I superconductors

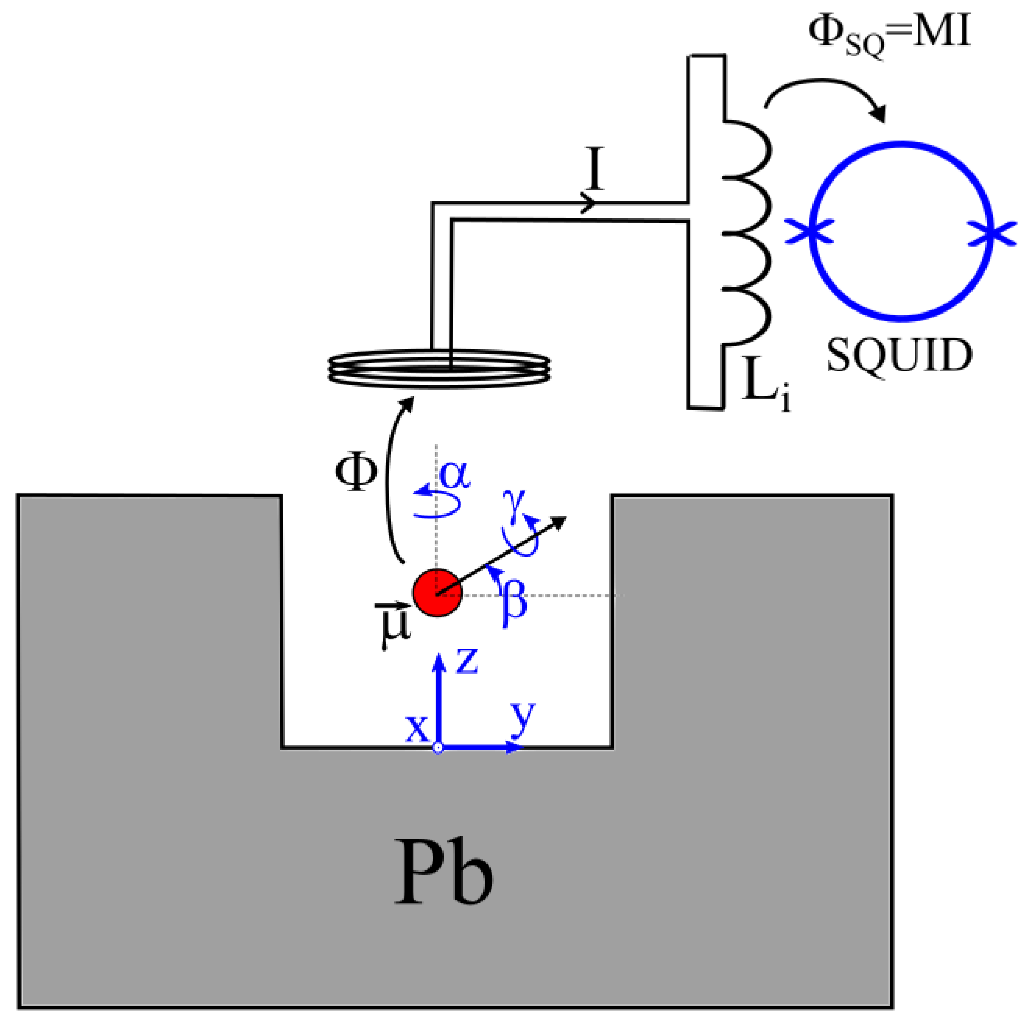
Very clean mechanical modes
(translation/rotations)

1) very low losses (NO CLAMPING)
works at low temperature (passive, NO HEATING)

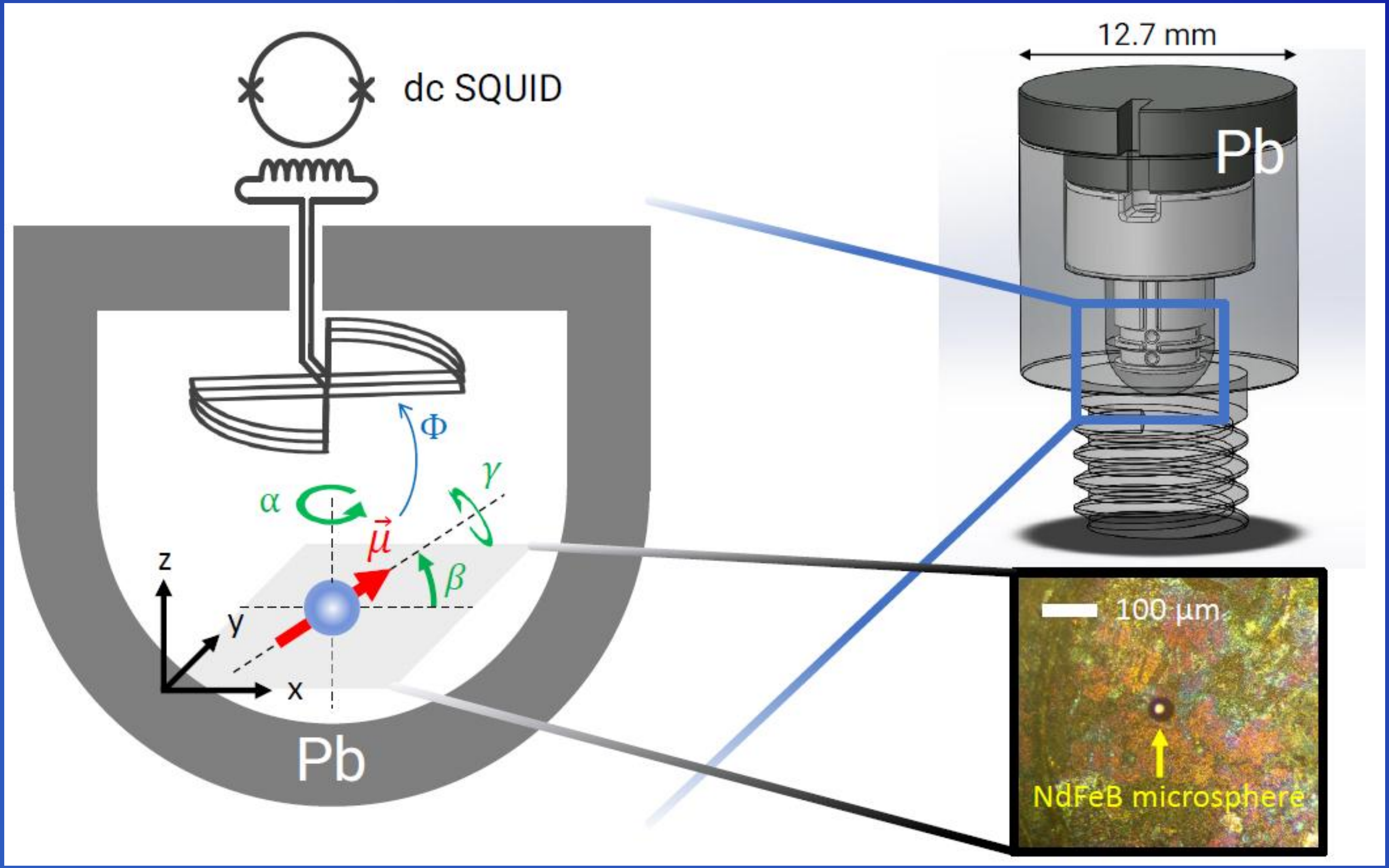
$$\boxed{S_F = 4k_B T m\gamma}$$

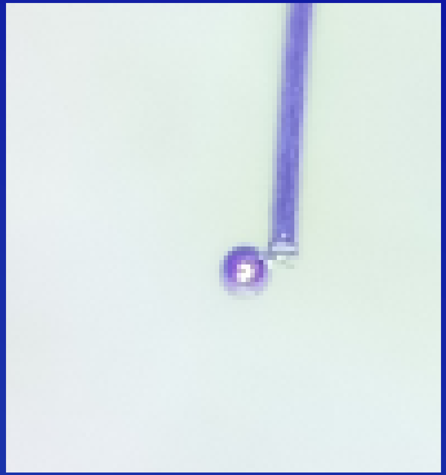
LOW FORCE/TORQUE NOISE
LOW DECOHERENCE

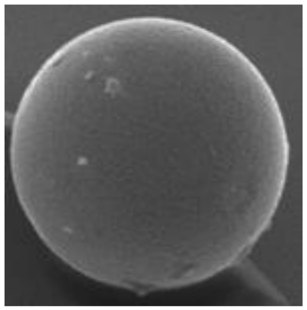
2) sensitive to magnetic fields
EXCEPTIONAL MAGNETOMETERS



Bulk trap (P=10^{-6} – 10^{-1} mbar, T=4.2 K)

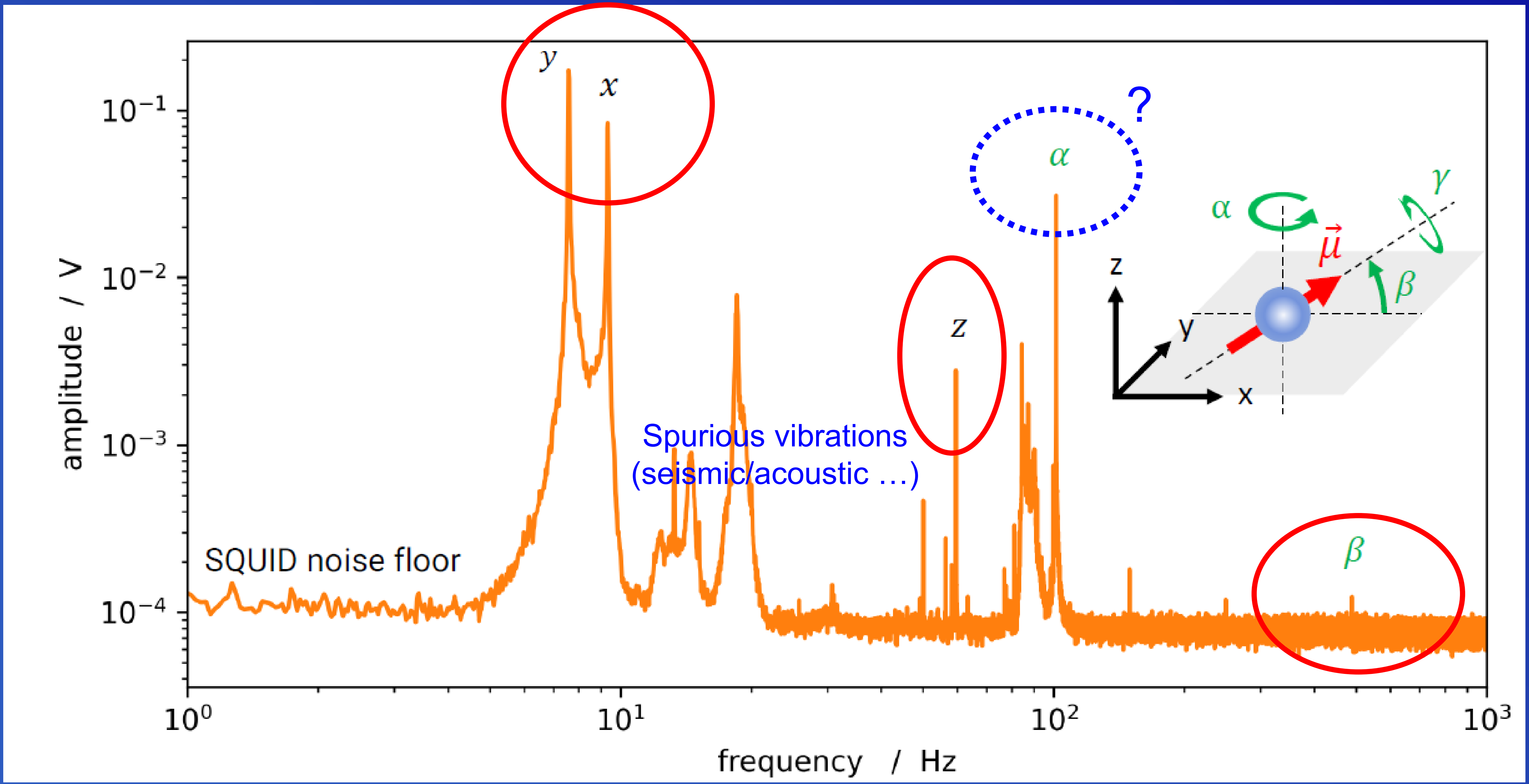




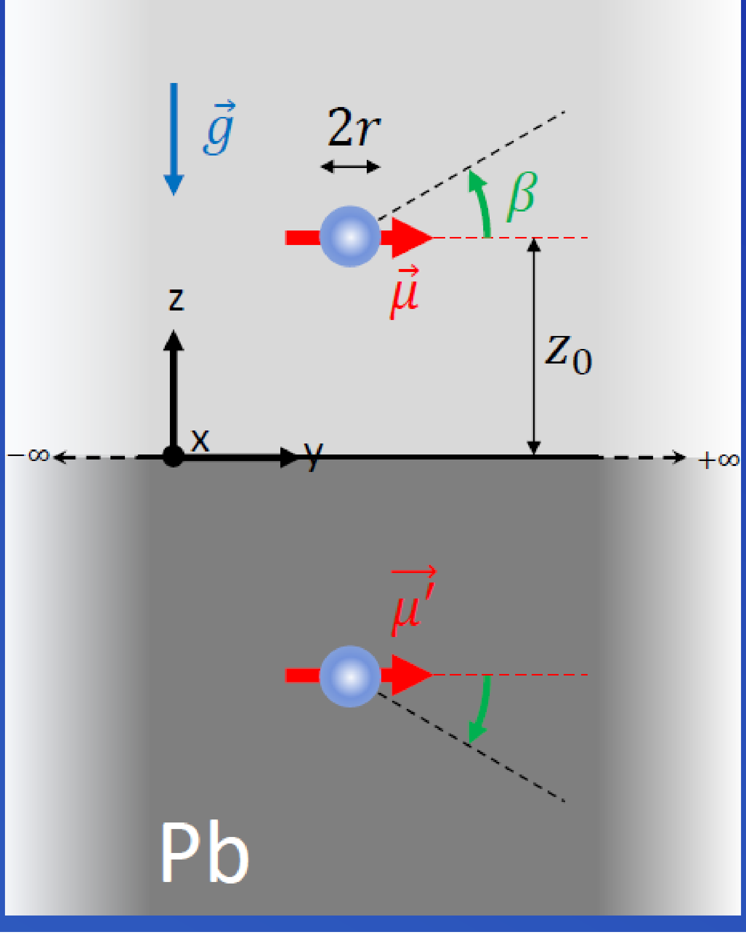


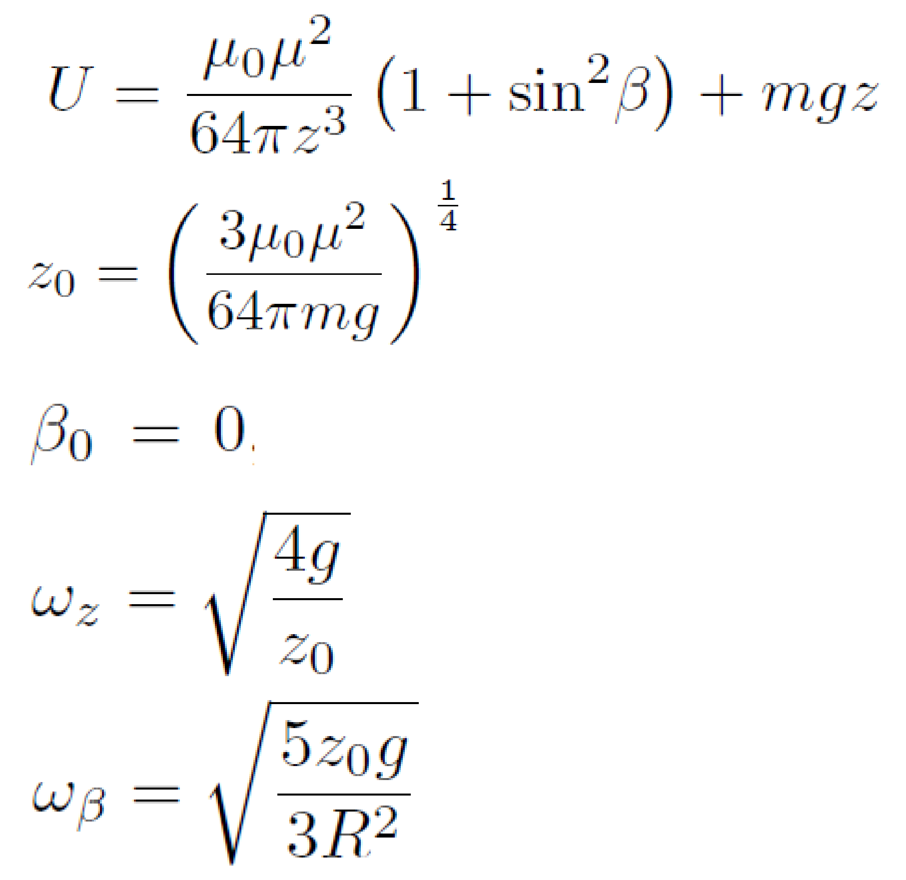
Nearly spherical shape

Mode identification: Translations & Librations



Modelling: image method (z and β)





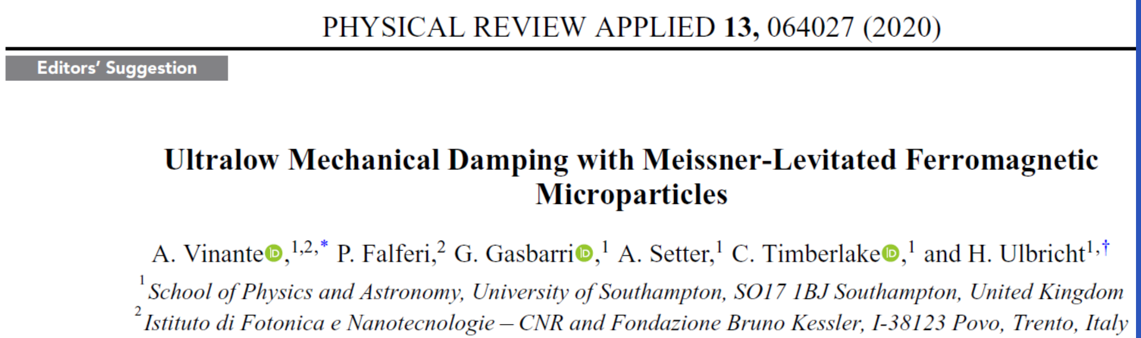
$$U = \frac{\mu_0 \mu^2}{64\pi z^3}\left(1+\sin^2\beta\right) + mgz$$

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

$$\beta_0 = 0,$$

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

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



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

Editors' Suggestion

Ultralow Mechanical Damping with Meissner-Levitated Ferromagnetic Microparticles

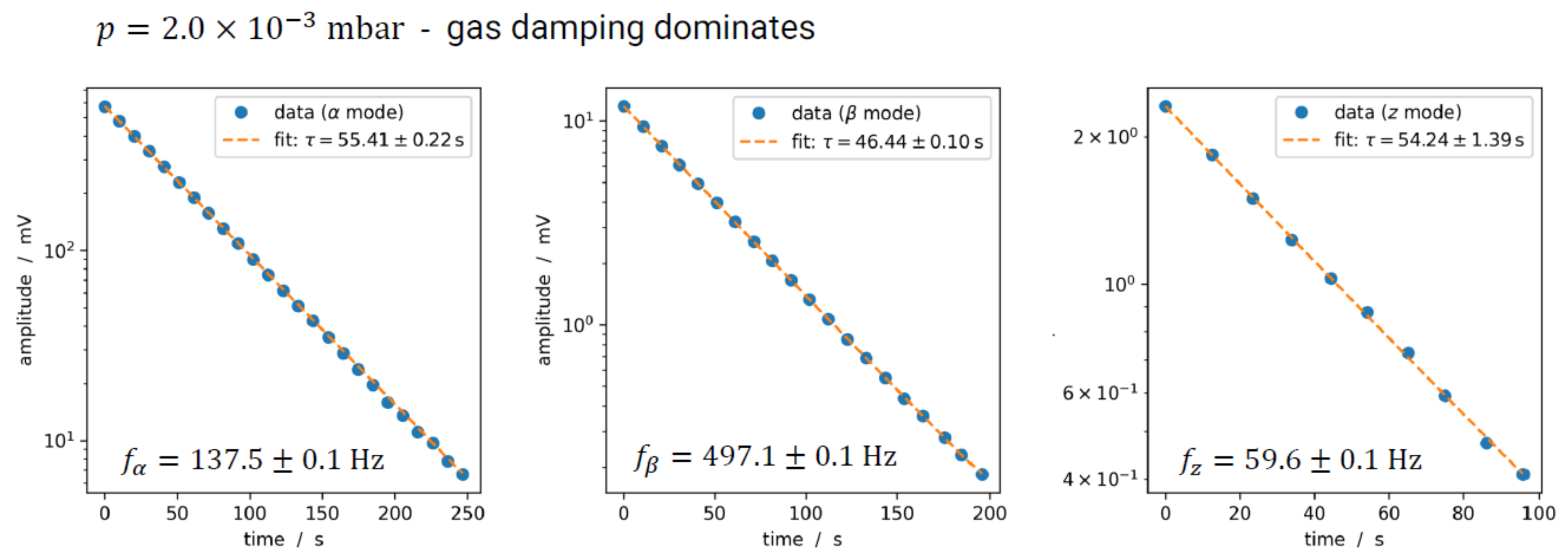
A. Vinante,[1,2,*] P. Falferi,[2] G. Gasbarri,[1] A. Setter,[1] C. Timberlake,[1] and H. Ulbricht[1,†]

[1] *School of Physics and Astronomy, University of Southampton, SO17 1BJ Southampton, United Kingdom*

[2] *Istituto di Fotonica e Nanotecnologie – CNR and Fondazione Bruno Kessler, I-38123 Povo, Trento, Italy*

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

Dissipation - High Q



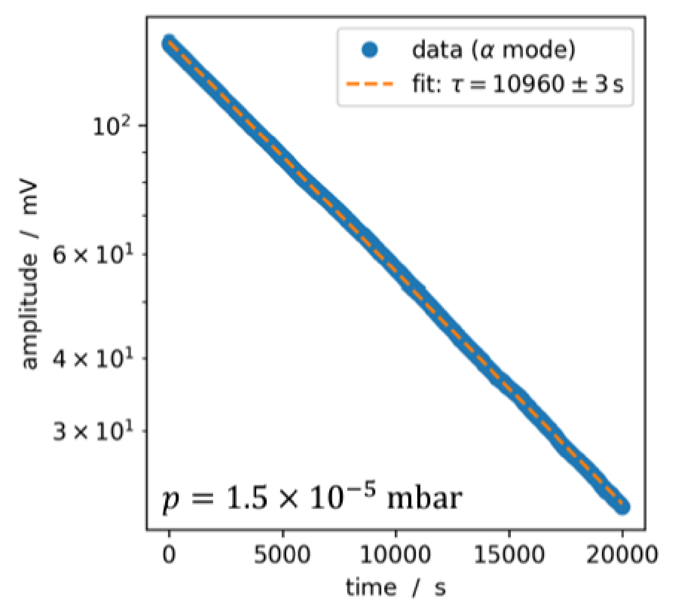
$p = 2.0 \times 10^{-3}$ mbar - gas damping dominates

High Pressure

$\tau \approx 50\ s$

For all modes

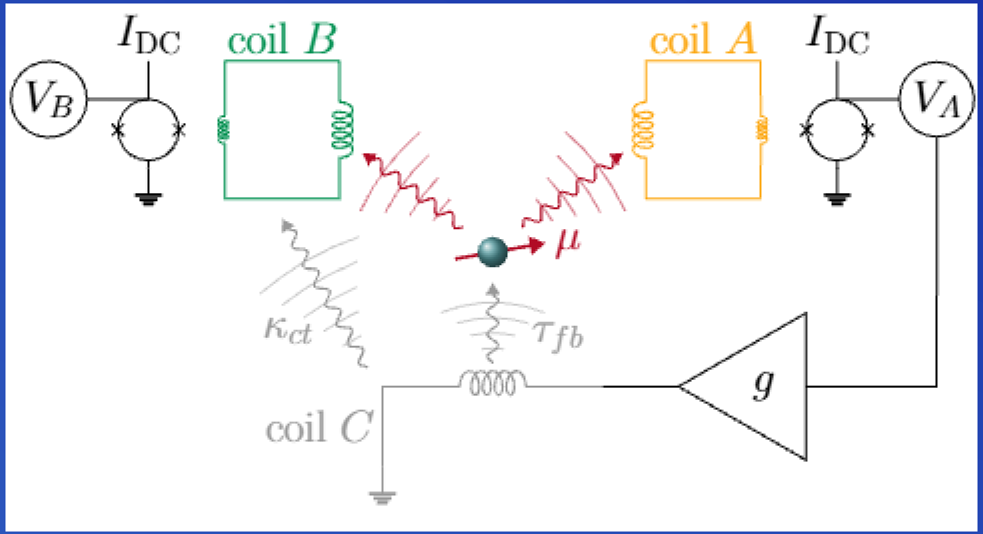
Lower pressure



$\tau \approx 3$ hours

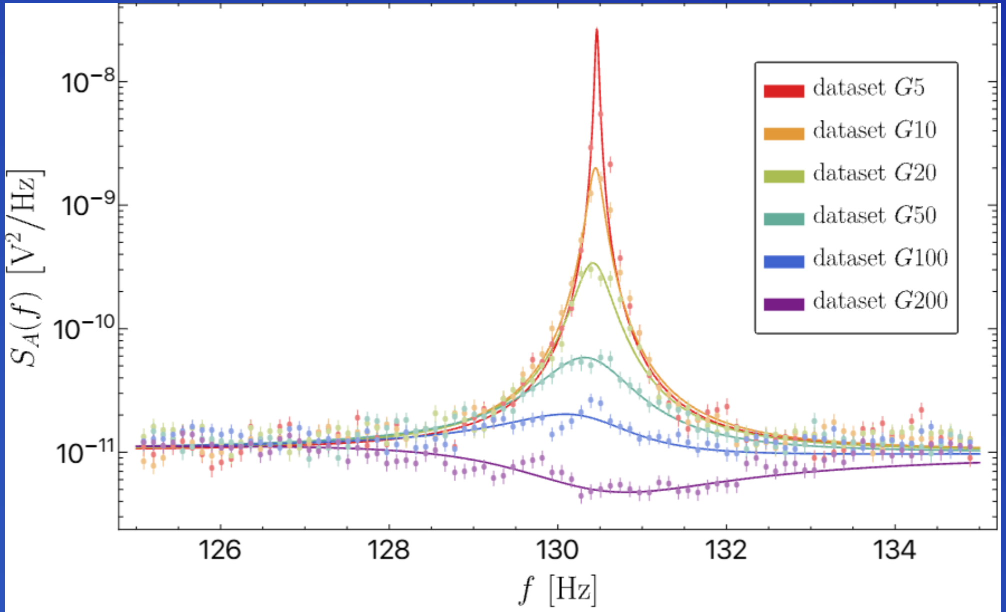
Q=4.7x10^6

Feedback-cooling (still far from ground state)



- Detection with a Superconducting Quantum Interference Device (dc SQUID)
- Magnetic feedback-cooling of a librational mode via a coil
- Cooling from 4.2 K down to ~ 2 mK

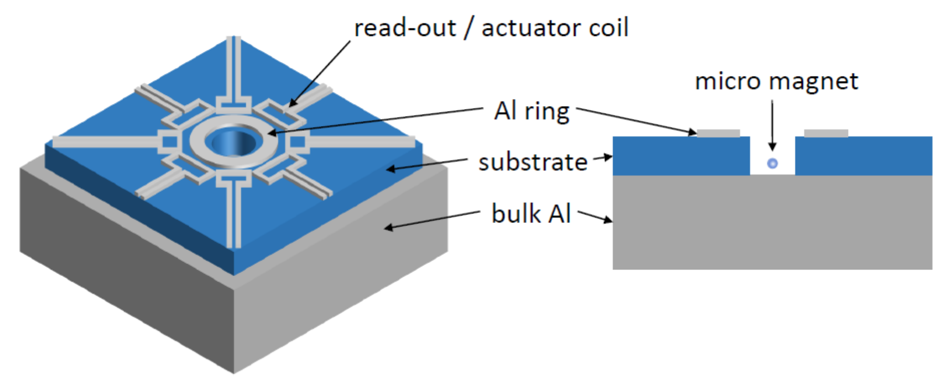
Ground state at $f = 130$ Hz corresponds to $T = \frac{hf}{k_B} \approx 6$ nK !



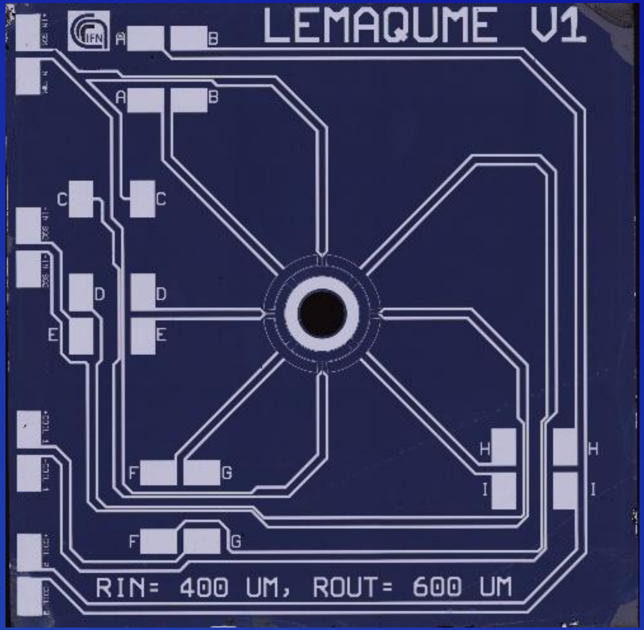
Current limitations

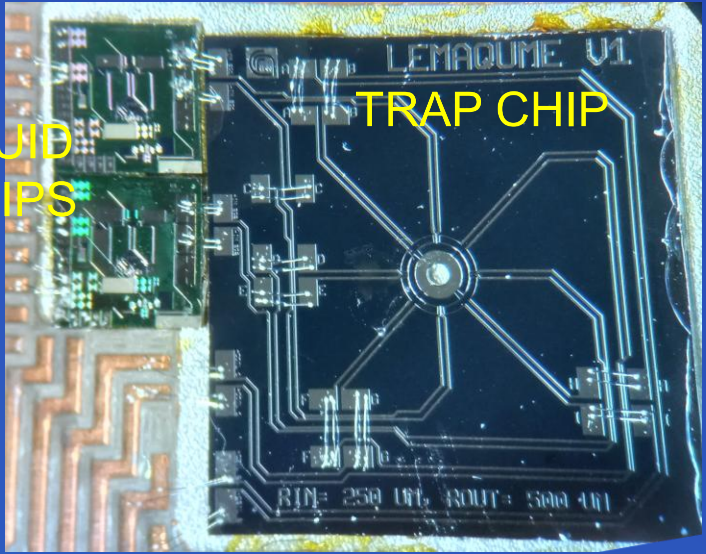
- Started from relatively low Q factor ~ 1×10^5
- Magnetomechanical coupling to SQUID is too low (= we need to get closer)
- dc SQUIDs are not limited by quantum noise (need for a quantum limite device)

Chip-trap (fab by Ron Folman, BGU Negev)



FABRICATION

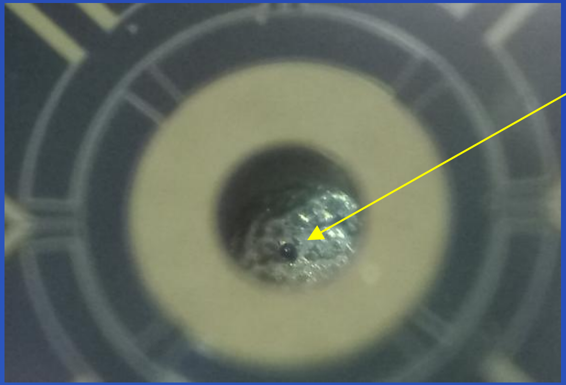




SQUID CHIPS

TRAP CHIP

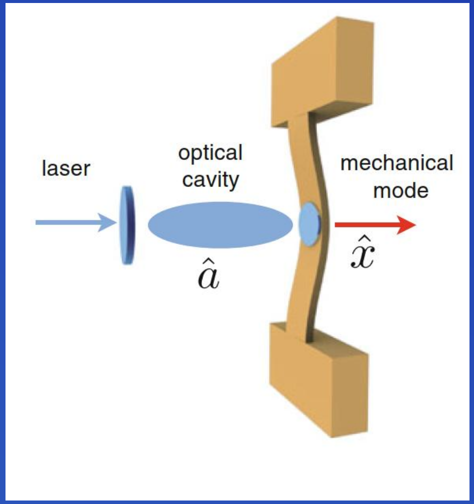
- Circuit + SQUIDs work as expected



Micromagnet placed inside the hole

- First levitation attempts failed (no spontaneous levitation)
- Problems with piezo excitation

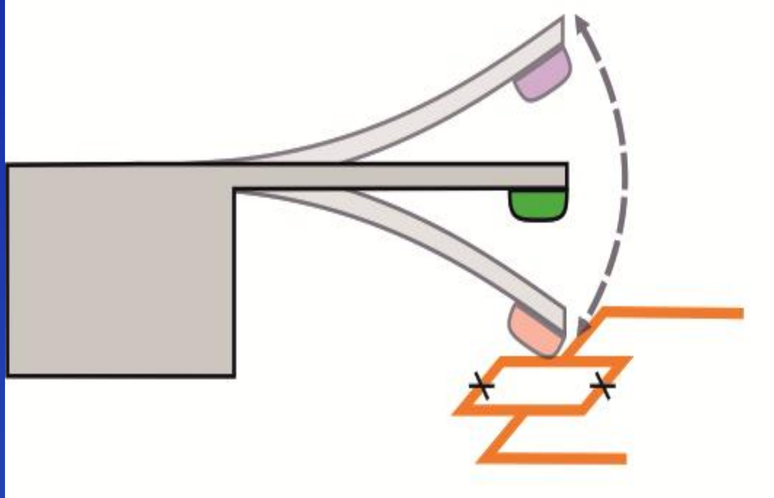
Microwave Optomechanics with Tunable Resonators

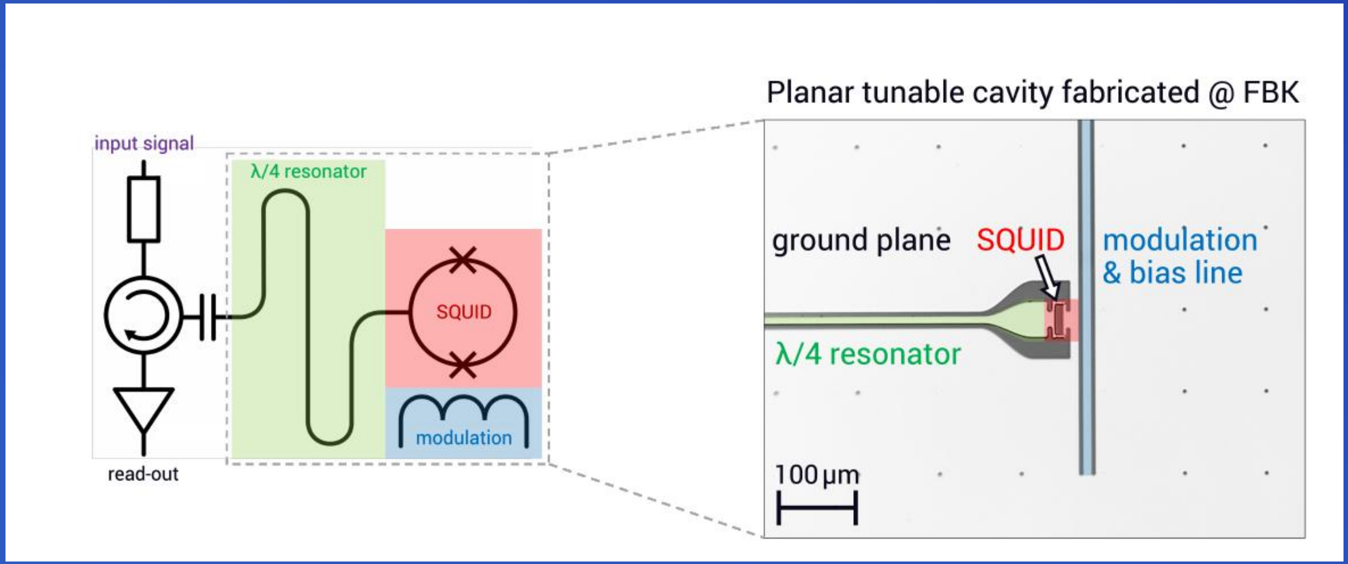


$$\omega_c(x) = \omega_c + x\,\frac{d\omega_c}{dx} + \cdots$$

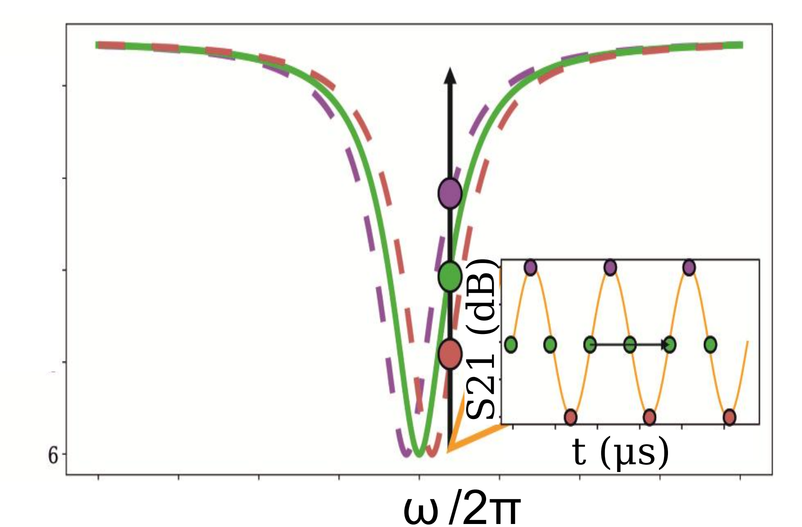
$$\hat{H} = \hbar\omega_c \hat{a}^\dagger\hat{a} + \hbar\Omega_m\, \hat{b}^\dagger\hat{b} - \hbar g_0\, \hat{a}^\dagger\hat{a}\left(\hat{b}^\dagger + \hat{b}\right)$$

(Lecture by G. Rastelli)



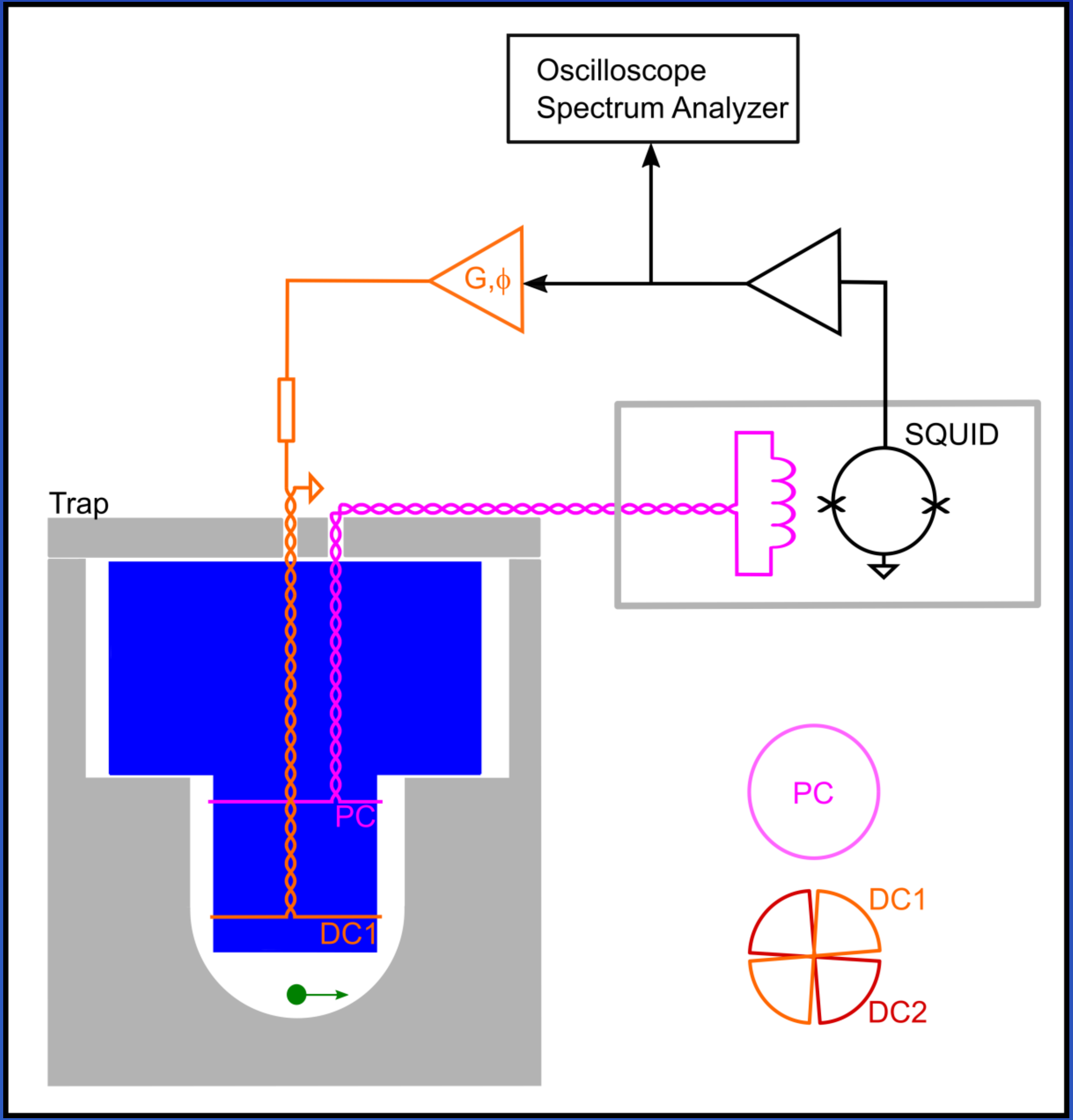


(Lecture by F. Mantegazzini)

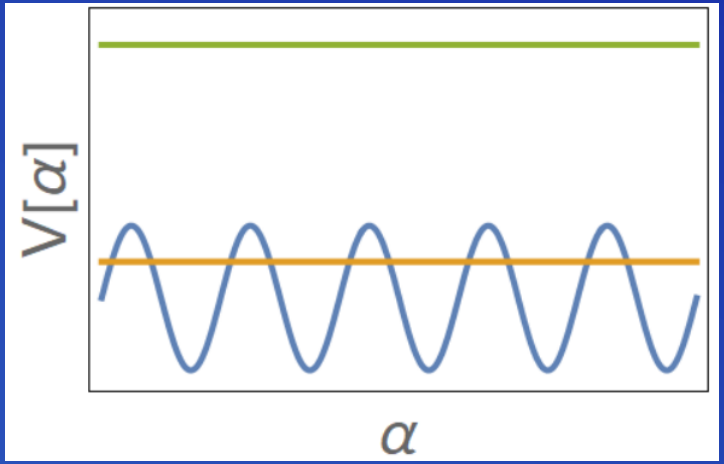


Meissner-levitated rotor

Setup



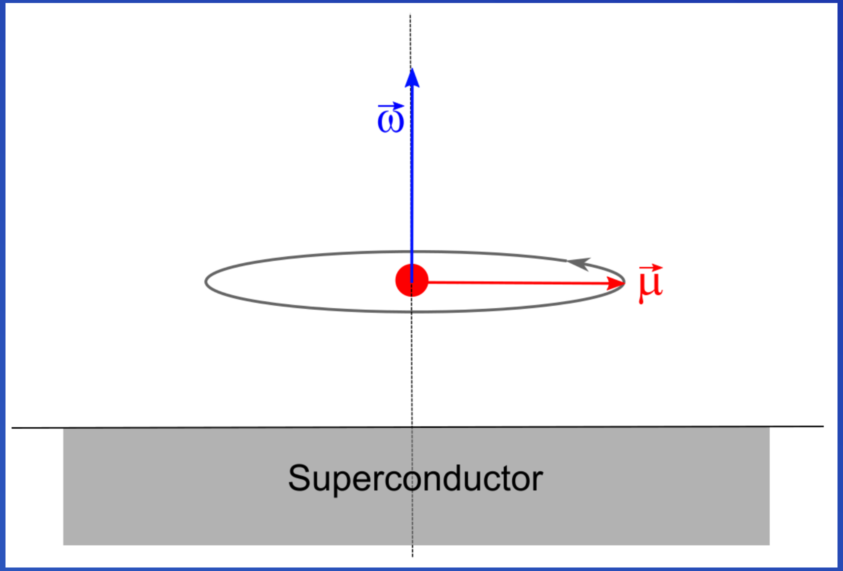
- TRAPPED MODES
  Feedback-cooling OR self-oscillation via measurement & feedback
- FREE ROTATIONS
  Driving up or down

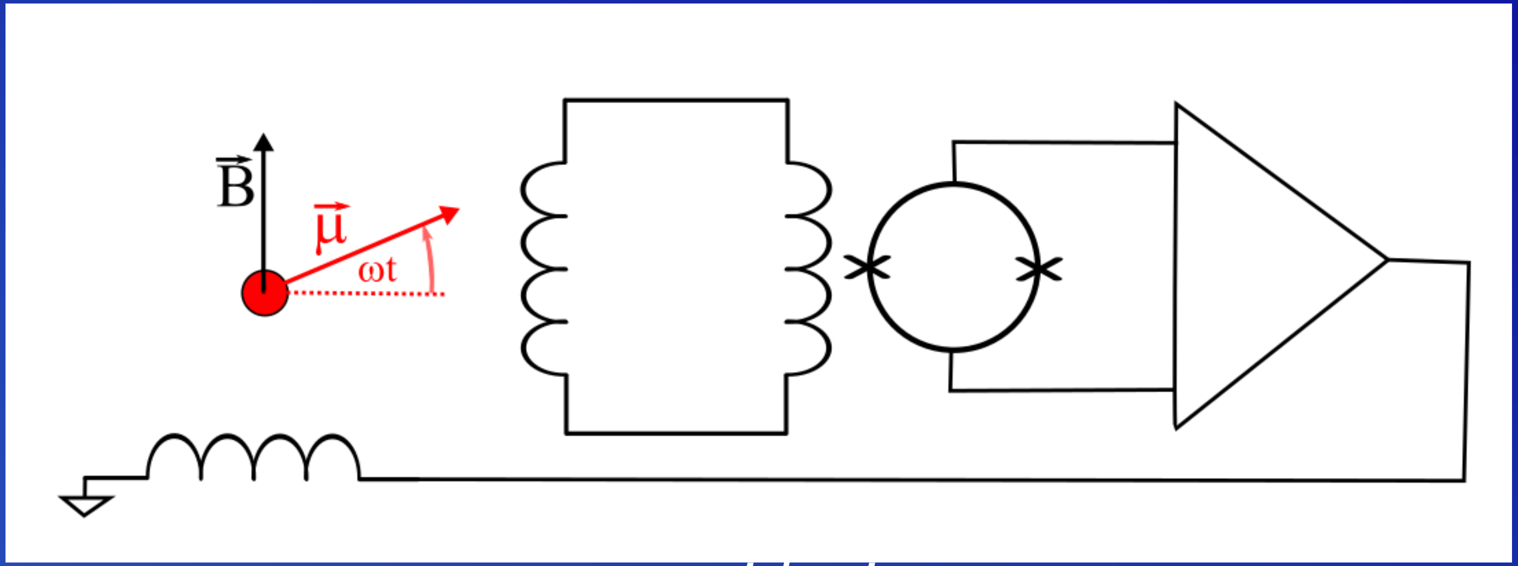


$V = -\boldsymbol{\mu} \cdot \boldsymbol{B} = -\mu B cos(\alpha)$

$\boldsymbol{B}$: residual field

Measurement/feedback synchronous driving

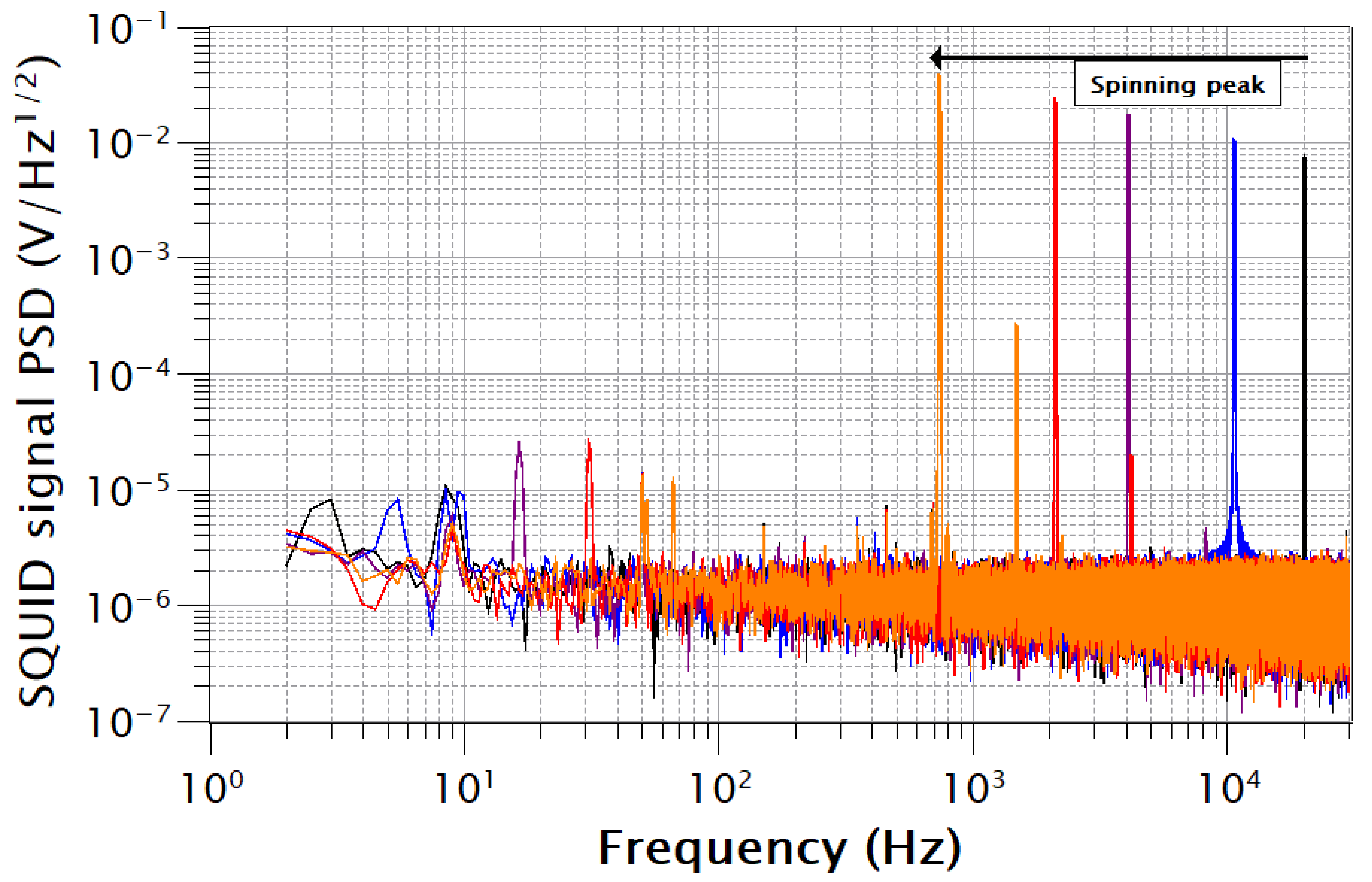




$$B = Ge^{i\phi}e^{i\omega t}$$

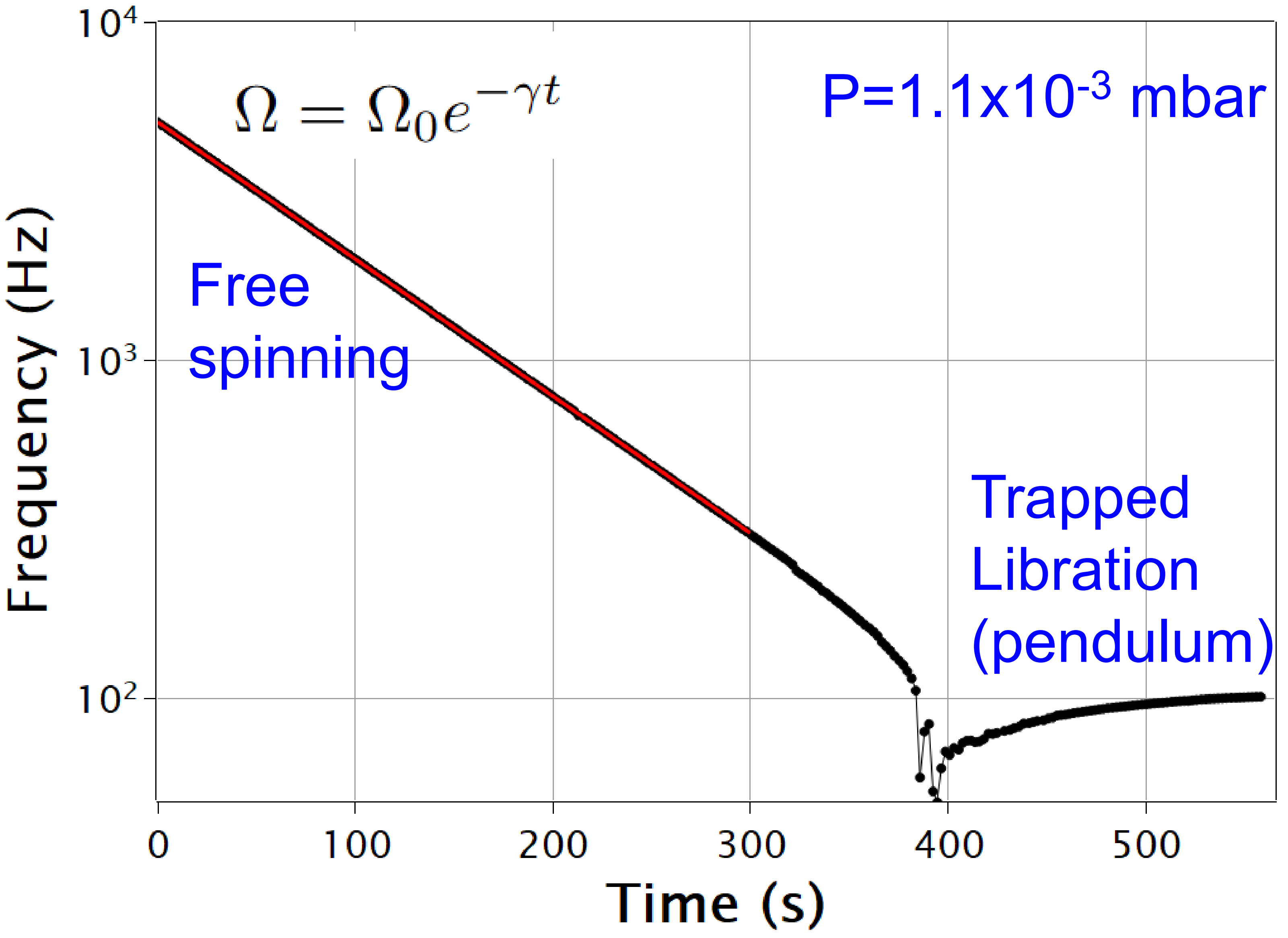
- Net torque dependent on ϕ
- Low heat dissipation, unlike induction motors! (works well at cryogenic T)

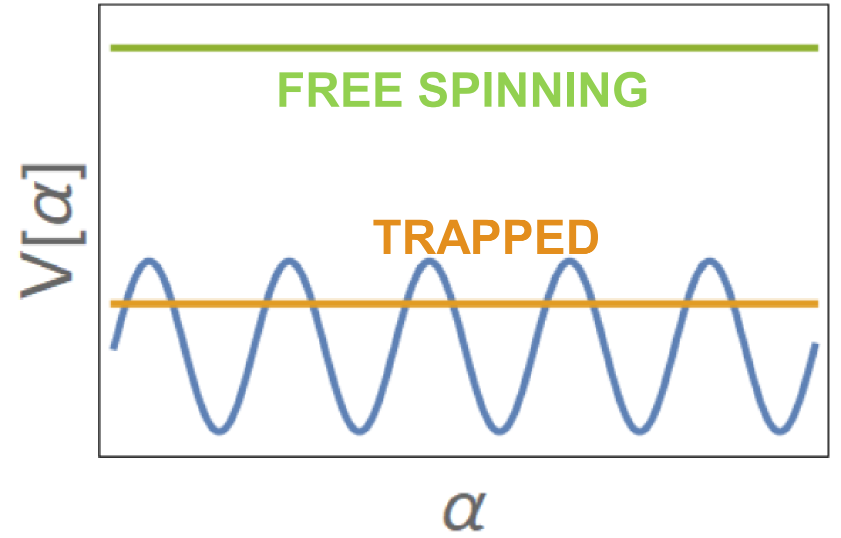
Spindown



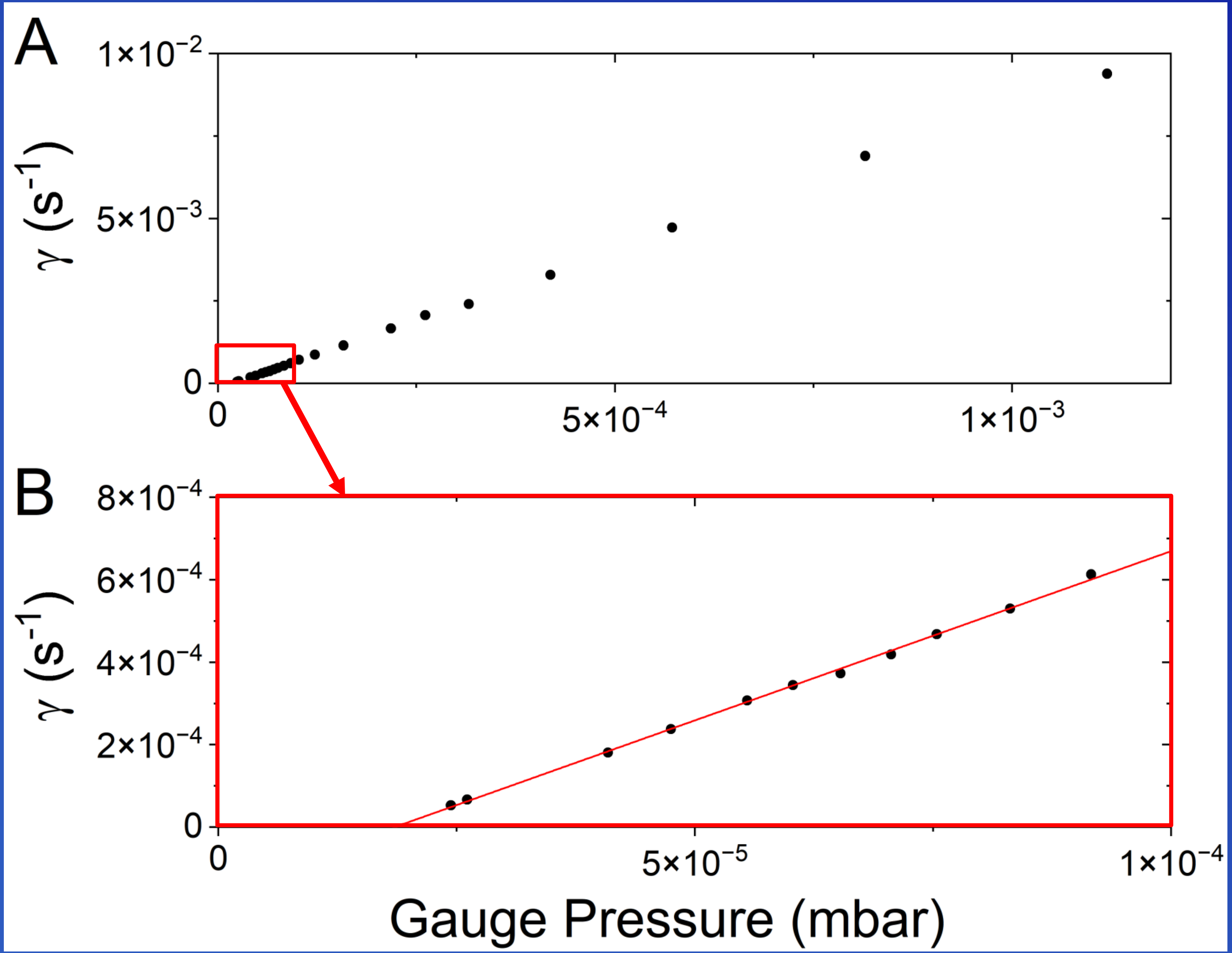
SQUID signal PSD (V/Hz$^{1/2}$)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Spinning peak
10^0
10^1
10^2
10^3
10^4
Frequency (Hz)

Spindown (high pressure/damping)





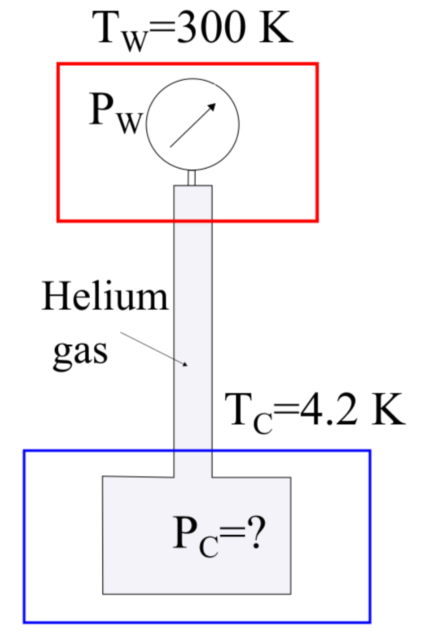
Gas damping (pressure sensor)



$$\Omega = \Omega_0 e^{-\gamma t}$$

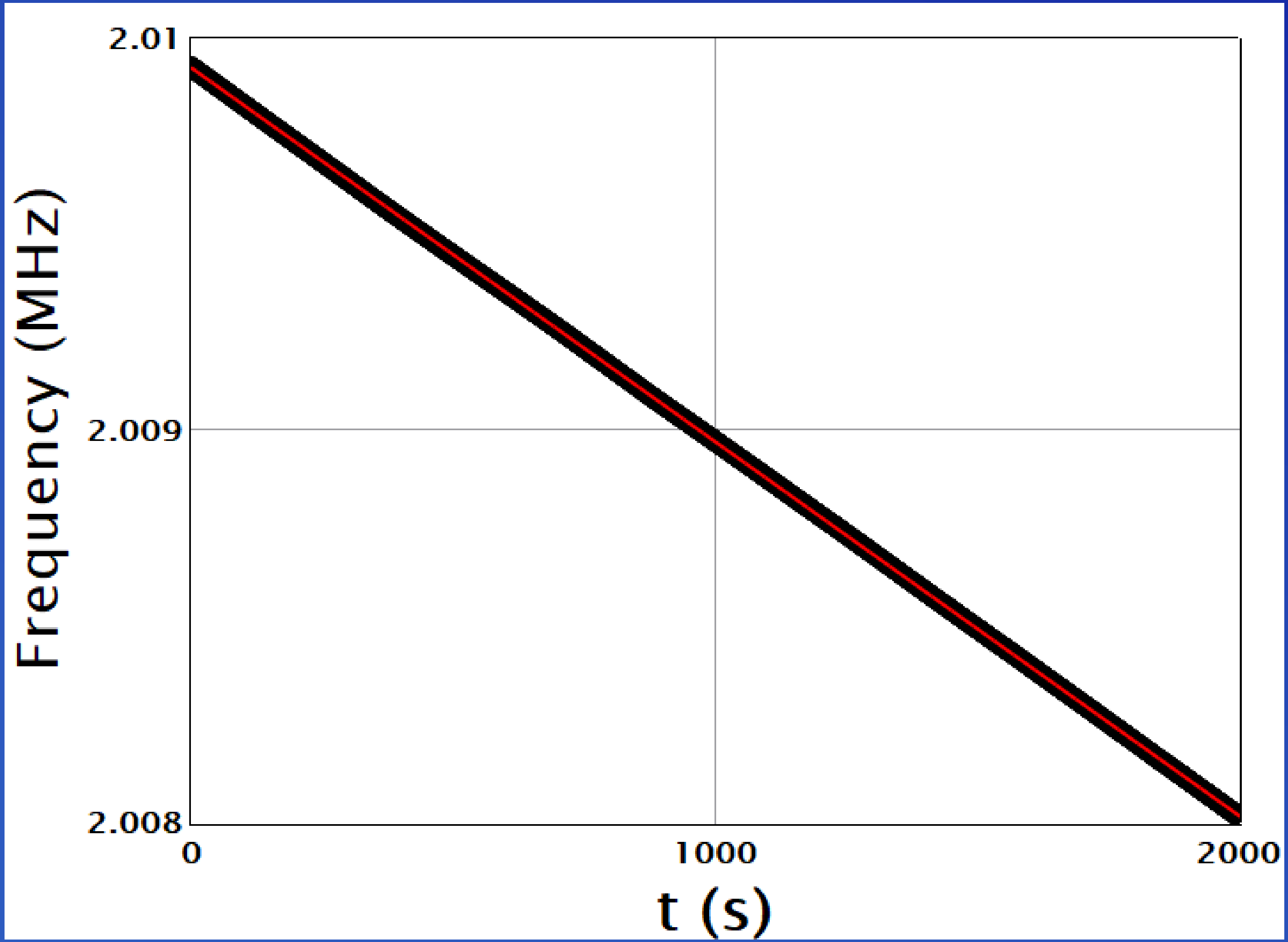
$$\gamma = \frac{10}{\pi} \frac{P}{\rho \bar{v} R}$$

Thermomolecular effect



$$\frac{P_W}{P_C} = \left(\frac{T_W}{T_C}\right)^{\frac{1}{2}}$$

Ultralow damping (no exchange He gas)



$$\boxed{\gamma = 4.75 \times 10^{-7}\ s^{-1}}$$

$$\tau = \frac{1}{\gamma} = 2.11 \times 10^{6}\ s$$

(~24 days)

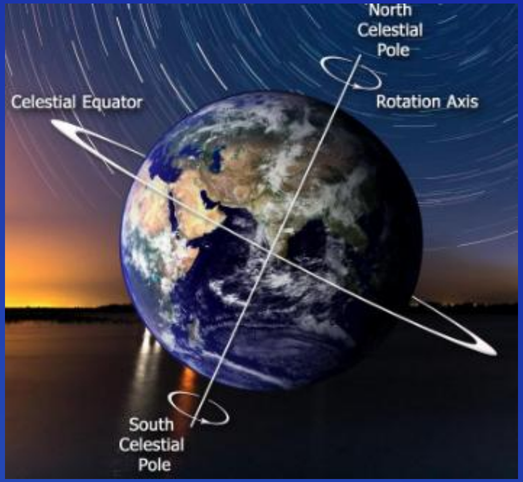
$$Q = \pi f \tau = 1.3 \times 10^{13}\ \ !!$$

if gas damping limited,
$\mathrm{P} = 4 \times 10^{-8}$ mbar

BUT other effects could play a role!

Comparisons

- A natural rotor: the Earth!



$\tau = 5 \times 10^9\ yrs$

$f = 1\ \mathrm{day}^{-1}$

$Q = 5.7 \times 10^{12}$

- Gravity Probe B

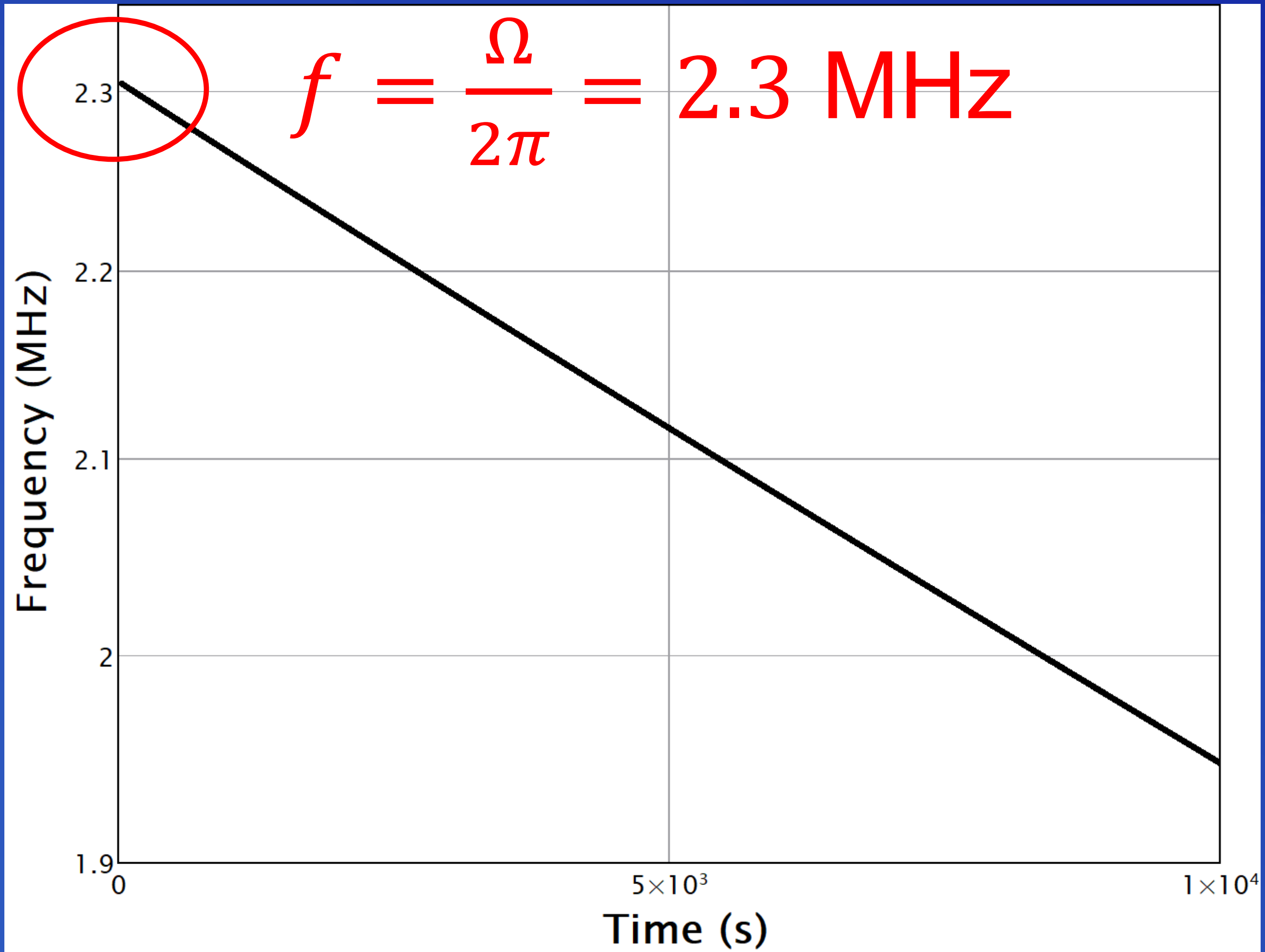
cm-size Nb-coated quartz sphere
$P = 10^{-14}$ mbar, in space

$\tau = 15000\ yrs$!!!

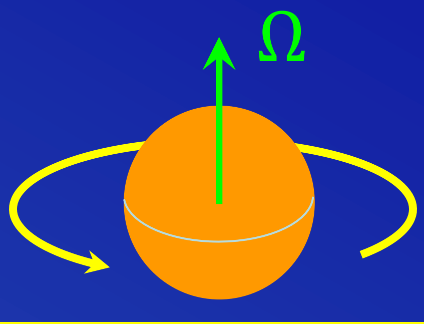
$f = 60\ \mathrm{Hz}$

$Q = 9 \times 10^{13}$

Highest frequency (achieved)



$$f = \frac{\Omega}{2\pi} = 2.3\ \text{MHz}$$



Radius: $R \approx 30\ \mu$m

Tangential speed

$$v = \Omega R = 466\ \frac{m}{s}$$

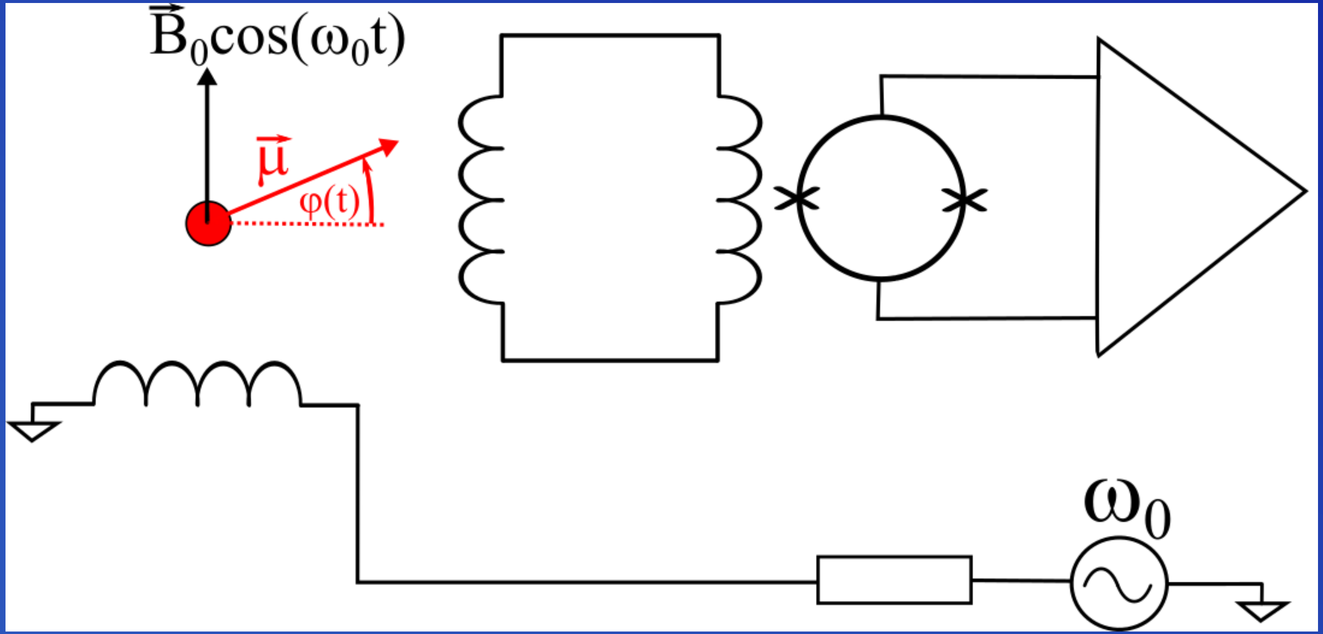
Centrifugal acceleration

$$a = \Omega^2 R = 0.7 \times 10^{10}\ \frac{m}{s^2}$$

Ultimate limits:

- SQUID measurement bandwidth (5-10 MHz for current setup)
- Material disintegration by centrifugal forces (~5 MHz for current setup)

Rotor Synchronization

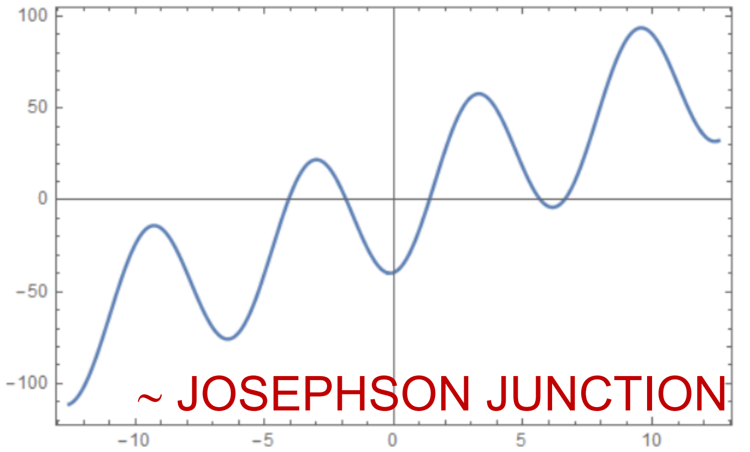


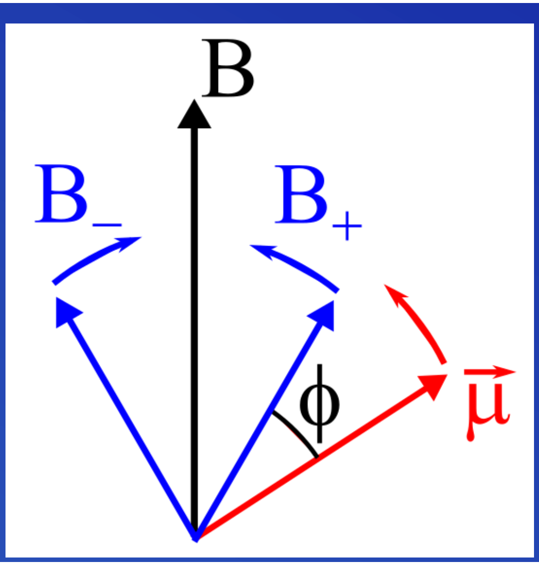
$$\phi(t) = \varphi(t) - \omega_0 t$$

$$\ddot{\phi} + \gamma\dot{\phi} + \omega_L^2 \sin\phi + \gamma\omega_0 = 0$$

$$\omega_L^2 = \frac{\mu B_0}{2I}$$

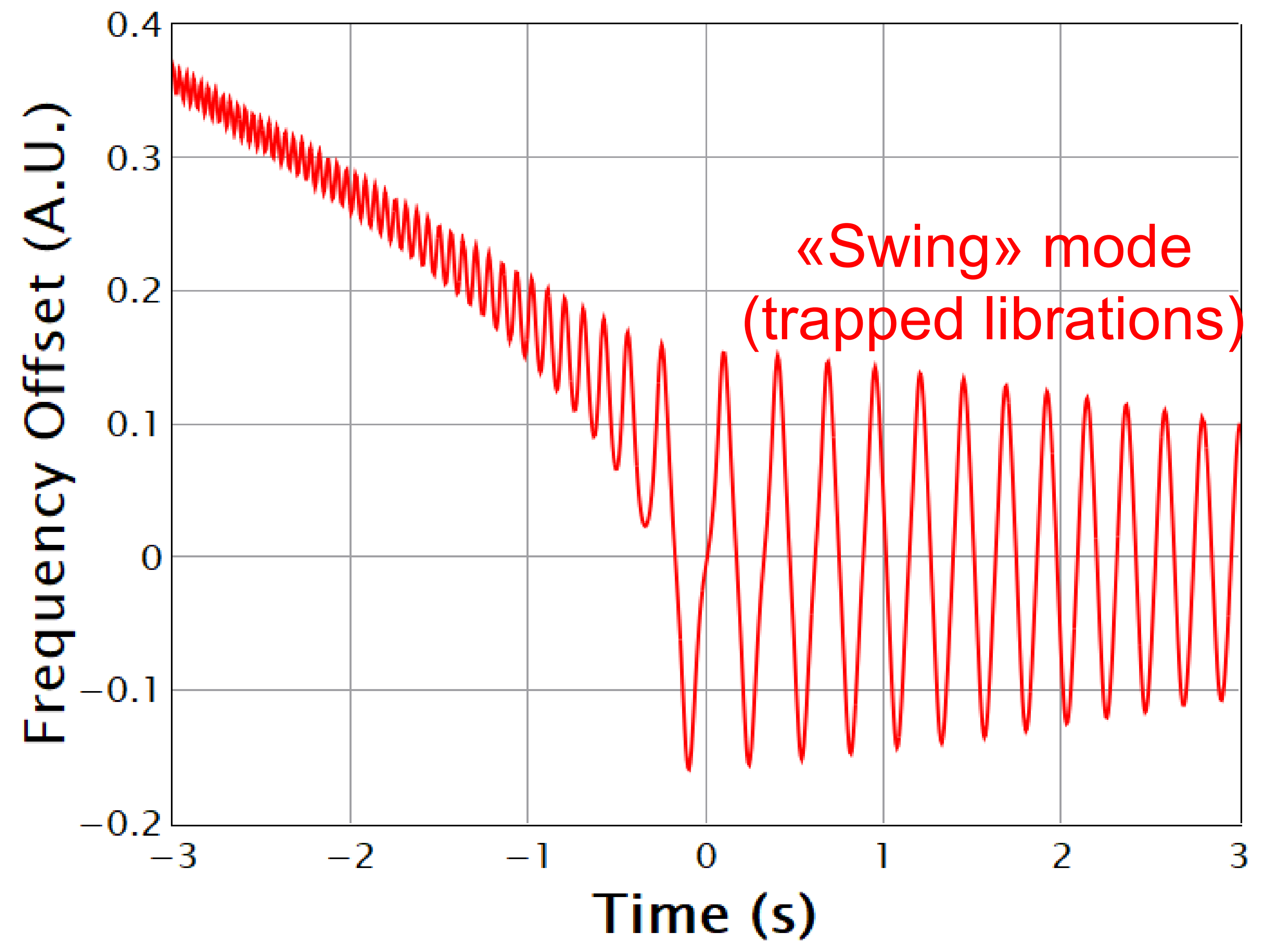
$$U = -\omega_L^2 \cos\phi + \gamma\omega_0\phi$$



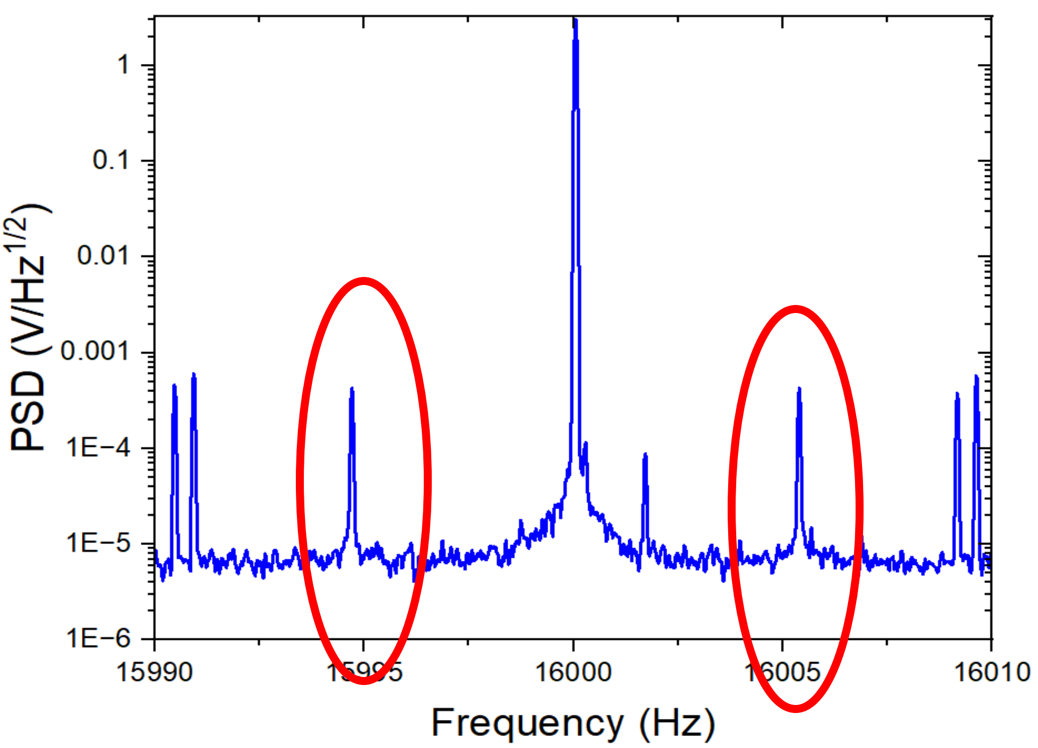


$$B\cos\omega_0 t = B_+ e^{i\omega_0 t} + B_- e^{-i\omega_0 t}$$

Trapping into the synchronized regime



A low frequency resonator at high frequency!



Very Preliminary!
SWING MODE IS CLOSE TO THERMAL NOISE

@ γ=5x10^{-4} s T=4.2 K

$$S_\tau = 4k_B T I \gamma$$

Multiple Advantages:

Low frequency mode ➡ soft and very sensitive

Move away from vibrational noise at low frequency

Get rid of 1/f noise & drifts

Easily tunable

Prospects in applied physics

- Pressure sensor
- Magnetometers
- Gravimeter
- Gyroscopes

Prospects in fundamental physics

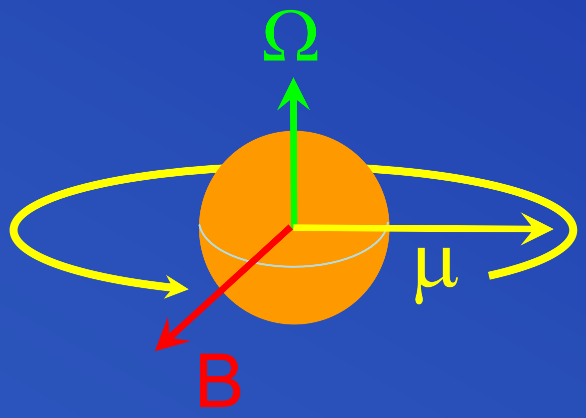
- Sensing weak torques
  - Axion-like Dark matter
  - Gravitational Waves
  - Tests of spontaneous collapse models
  - Classical vs Quantum gravity

- Sources/actuators in two-mass experiments:
  - Gravity (at MHz?)
  - Exotic interactions beyond standard model

- Noninertial quantum effects
  - Zeldovich effect (rotational superradiance)
  - Unruh effect (radiation emission in accelerated frame)

Torque from axion-like dark matter

TORQUE FROM A MAGNETIC FIELD oscillating close to Ω



Resolution in magnetic field with
current parameters
at thermal noise limit

$B_n \sim 10^{-17}$ T/Hz$^{1/2}$

Axion-like particles: Hypothetical light spin-0 particles from various SM extensions

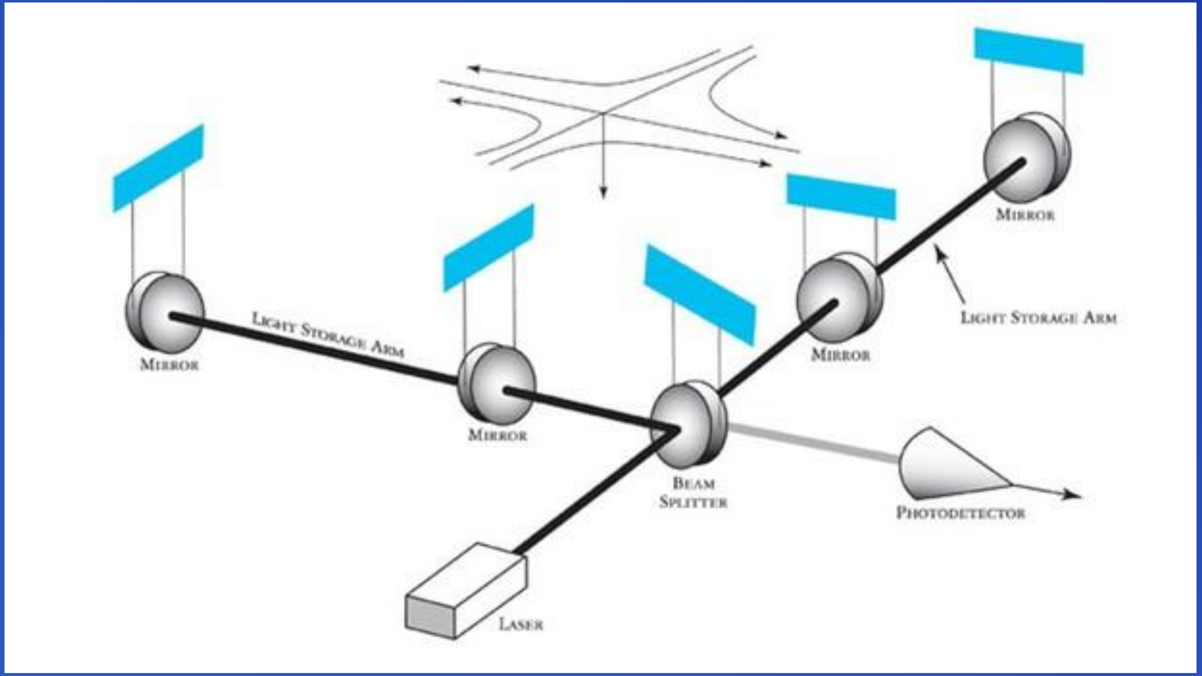
Axion-like dark matter: behaves as a classical field
Appears to electron spins as an effective magnetic field !

$$f = \frac{m_a c^2}{h} \qquad \frac{\delta f}{f} \sim 10^{-6} \qquad B_a \sim \boxed{g_{ae}} \cdot 4 \times 10^{-8} T$$

Torque from a gravitational tidal field

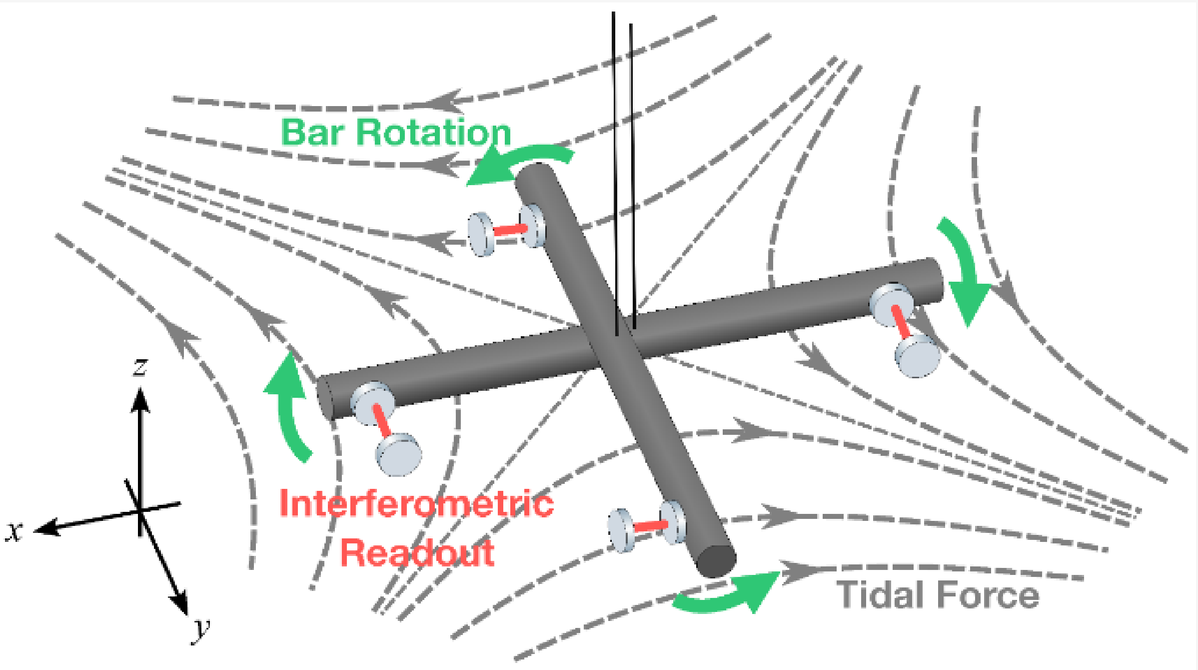
Two possible schemes to detect gravitational waves

TIDAL LONGITUDINAL DEFORMATION (LIGO-Virgo)



(from LIGO website)

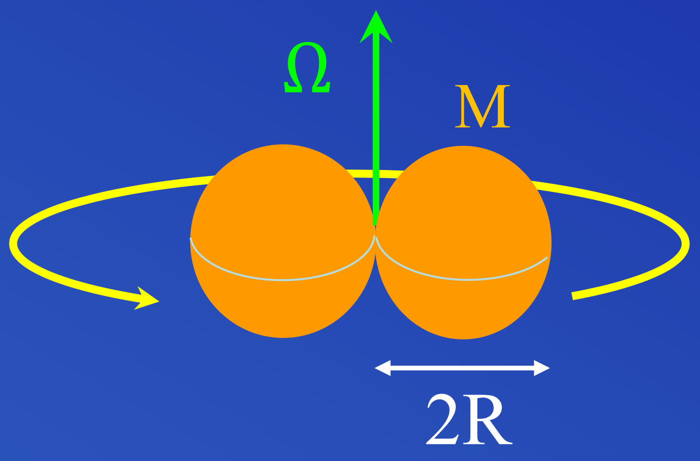
TIDAL «TRANVERSE» (TOBA)



S. Takano et al, 10.3390/galaxies12060078

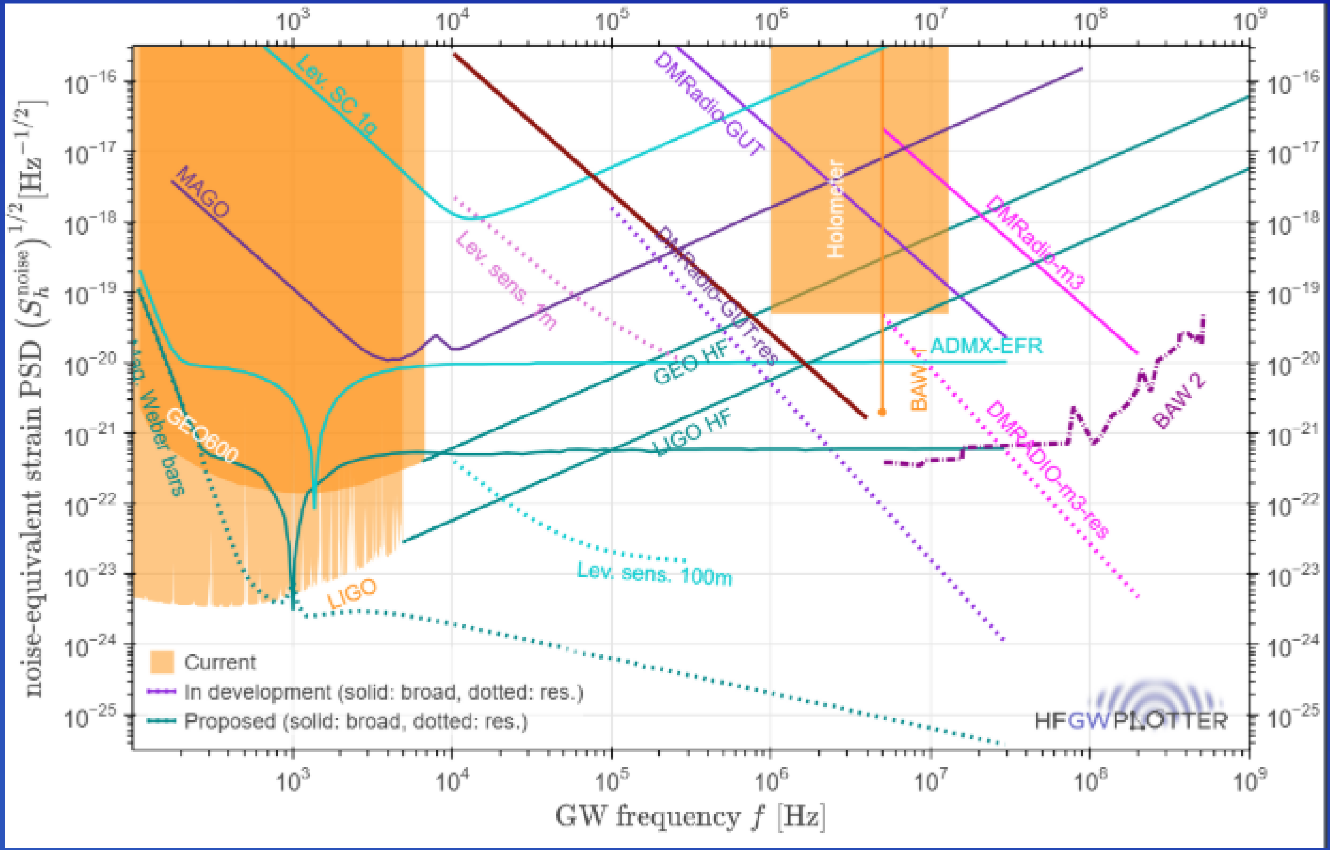
FIRST IDEA (FOR ROTORS)
Braginsky, Zel'dovich, Rudenko, JETP 10, 280 (1969)

Torque on a rotor from a gravitational tidal field



With current parameters & thermal noise narrowband resolution in spacetime metric deformation

$h_n \sim 10^{-20}$ Hz$^{-1/2}$ @4MHz



Max Torque from GW (optimal orientation/phase)

$$\tau(\Omega) = MR^2(2\Omega)^2h^2$$

- COMPACT
- CHEAP
- FULLY TUNABLE
- MULTIPLE DETECTORS (CROSSCORRELATION)

Serendipity in action: Gyroscopic effects in a nonspinning levitated ferromagnet

Quick history of gyromagnetism

Magnetization ⇔ Angular Momentum

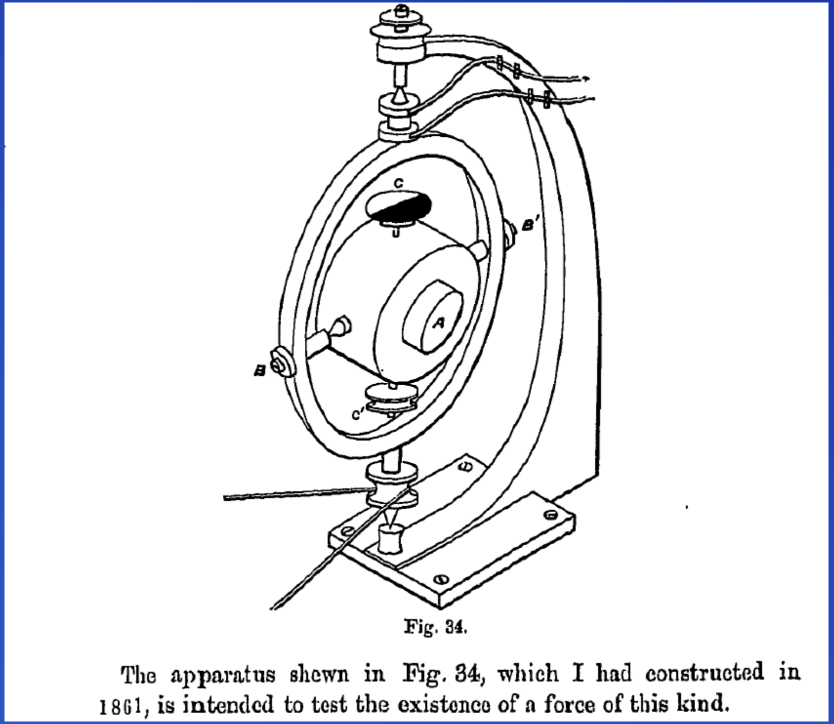


Fig. 34.

The apparatus shewn in Fig. 34, which I had constructed in 1861, is intended to test the existence of a force of this kind.

James Clerk Maxwell, *Treatise on Electricity and Magnetism* §575

1861: Very first experiment by Maxwell to test the gyroscopic nature of a ferromagnet
(null result)

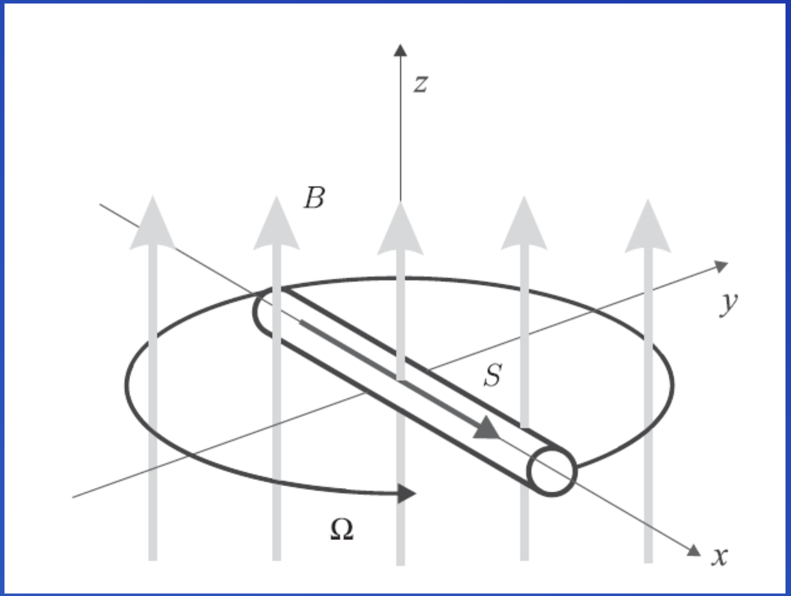
AMAZING: Nothing was known yet about the microscopic nature of electricity!

1915: Barnett & Einstein-de Haas experiments (DIFFERENT PRINCIPLE: magnetization change in a soft ferromagnet)

Surprisingly, the brilliant experimental scheme conceived by Maxwell has never been demonstrated in lab!

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)

Hard to observe:

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

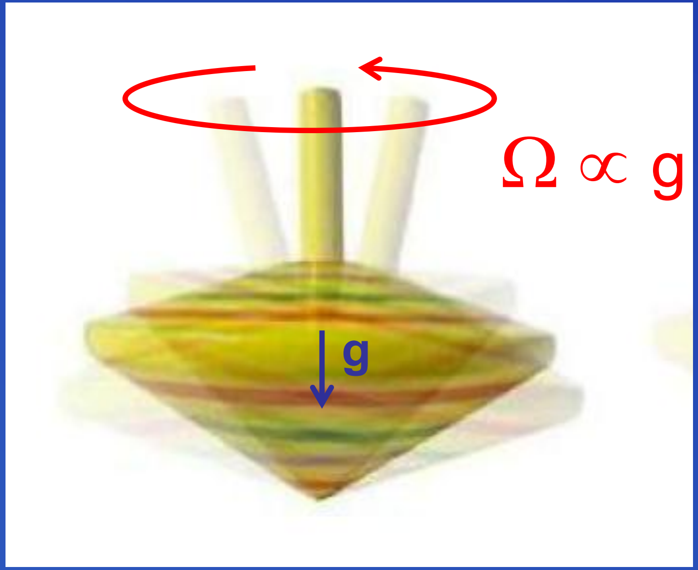
$\omega_I/2\pi \approx$ 200 μHz → B ≈ 5 fT (R = 1 mm sphere FM)

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

Classical spinning top

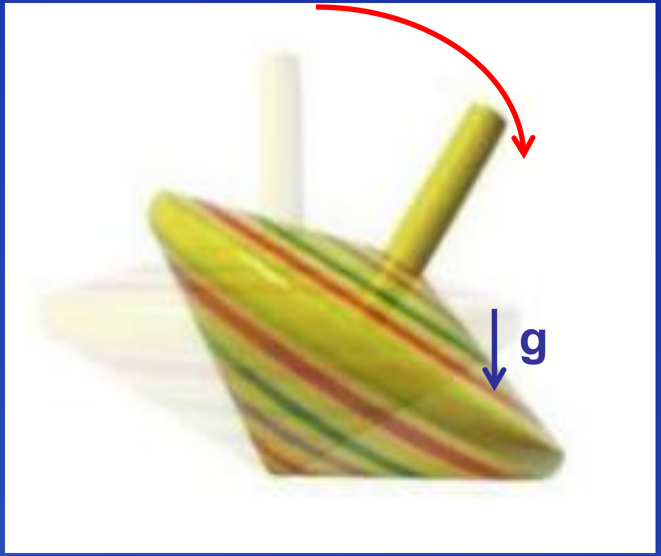
Spinning top under effect of gravity torque

Gyroscopic



$S \gg L = I\Omega$

Librational



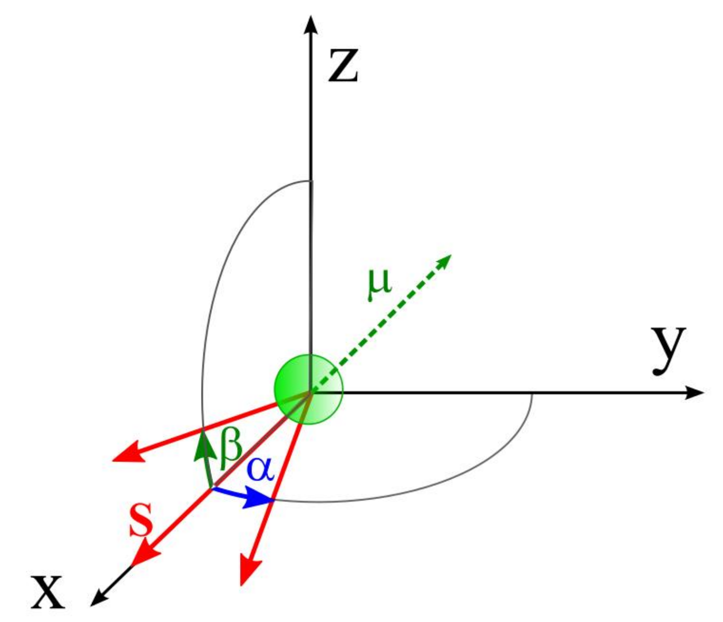
$S < L$

Condition to observe gyroscopic behaviour:

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

For a ferromagnet, ω_I is the Einstein-de Haas frequency

Gyromagnetic effects under librational confinement



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

GYROSCOPIC
SPIN-ROTATION
COUPLING

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

Coupling via $\dot{\gamma}$ measured in Zielinska et al, PRL **132**, 253601

Neglecting dissipation and γ motion:

Quasi-β mode

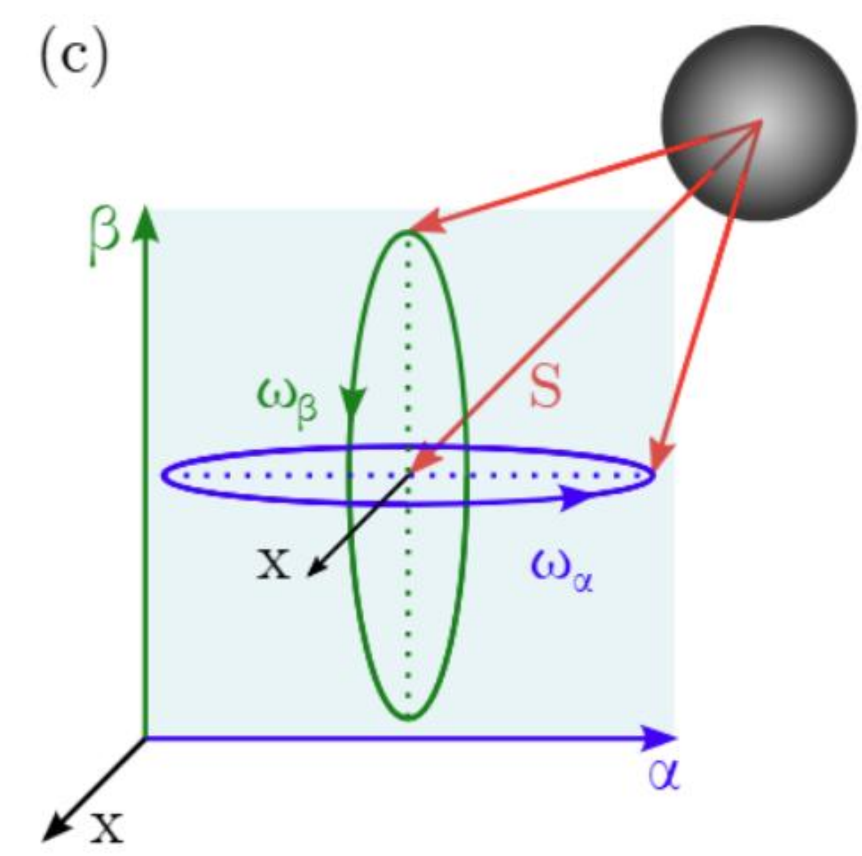
$$\beta = \beta_0 \sin(\omega_\beta t)$$
$$\alpha = \alpha_0 \cos(\omega_\beta t)$$
$$\alpha_0 = \beta_0 \frac{\omega_\beta \omega_I}{\omega_\beta^2 - \omega_\alpha^2}$$

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

Trajectories



F. Ahrens and A. Vinante Phys Rev Lett 136, 146703 (2026)

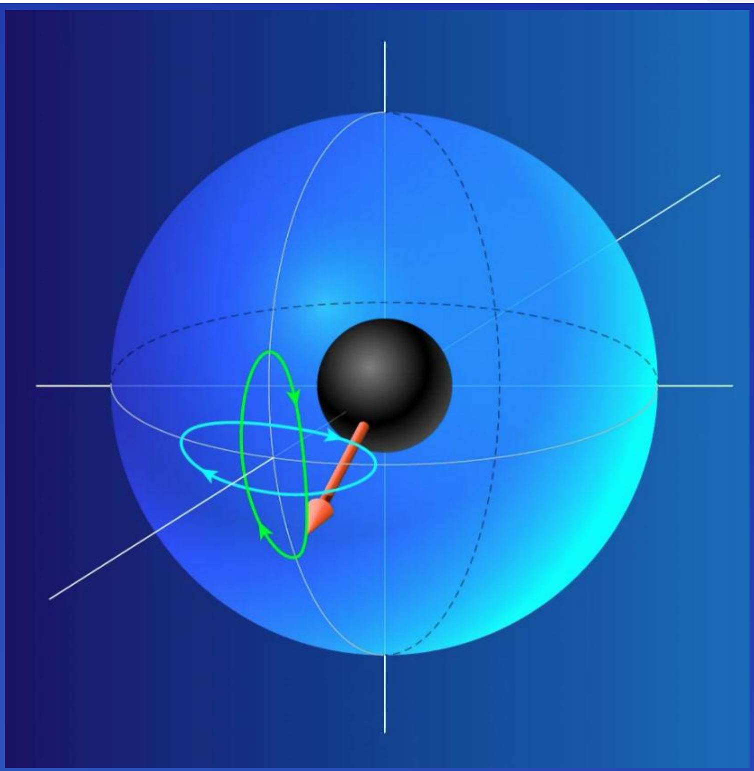
Featured on Physics «A Macroscopic magnet precesses»

A Macroscopic Magnet Precesses

April 10, 2026 • *Physics* 19, 51

An isolated magnet's intrinsic angular momentum induces gyroscopic motion, an observation that could lead to ultrasensitive magnetometers.

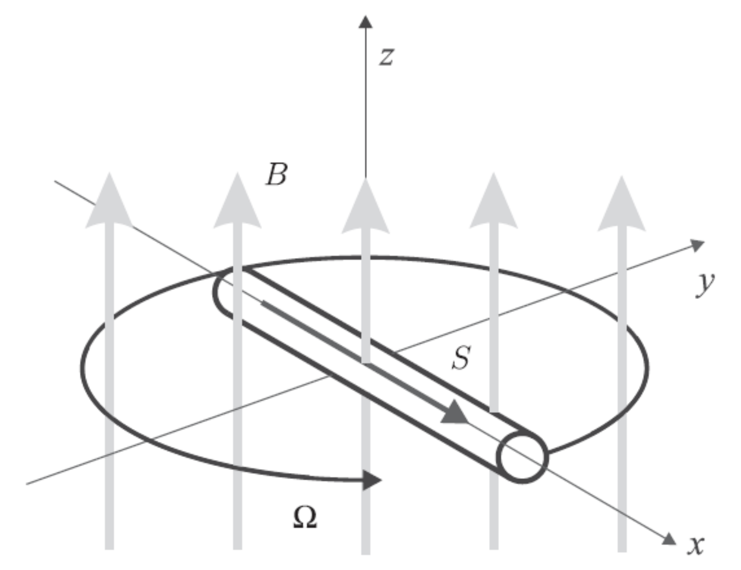
Observation of Gyroscopic Coupling in a Nonspinning Levitated Ferromagnet
Felix Ahrens and Andrea Vinante
Phys. Rev. Lett. 136, 146703 (2026)
Published April 10, 2026



adapted by APS/**Alan Stonebraker**

Librational to gyroscopic transition (compass-like to atomic-like dynamics)

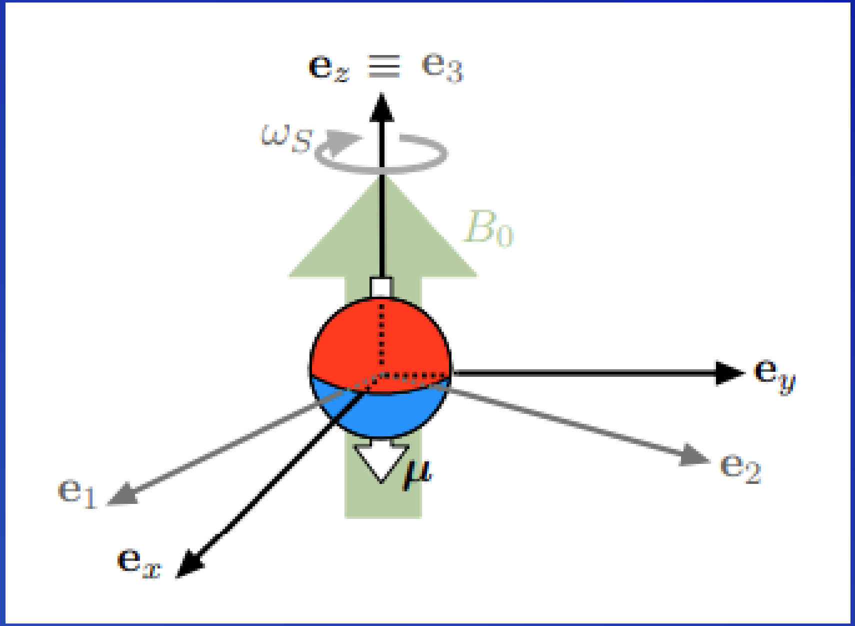
Derek Jackson Kimball et al, PRL 16, 190801 (2016)



Larmor Precession of a magnetic needle

(*atomic magnetometry* with a macroscopic magnet)

C. Rusconi et al, PRL 119, 167202 (2017)



Quantum stabilized trapping of a nanomagnet in a static magnetic trap

(*atomic-like* trapping of a macroscopic magnet)

If you are interested in any of these topics

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