Call 2021
Final Evaluation

QUANTERA
DECADE OF IMPACT 2016-2026

LEMAQUME

LEvitated MAgnets for QUantum MEtrology

Andrea Vinante

Website:
https://lemaqume.org

COLLABORATION (overview)

GEOGRAPHICAL BREADTH

Italy, France, Germany (3x), Israel, Latvia

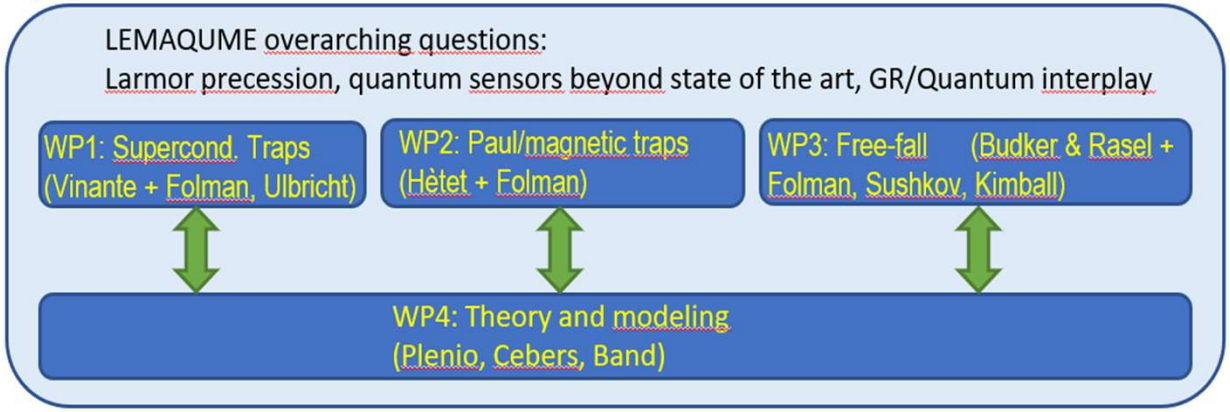
External non-funded: UK, US (2x)

VARIETY OF SECTORS, DISCIPLINES

3 main experimental sites (Trento, Paris, Mainz), **2 theory** partners (Uni Ulm, Riga)

1 big infrastructure (Einstein Elevator - Hannover), **1 microfabrication** partner (Ben Gurion Negev)

QUALITY OF COOPERATION



INFRASTRUCTURE SHARING within the project consortium

Einstein Elevator (Hannover): Hannover and Mainz

Ben Gurion University Microfabrication → Trento and Paris

SUCCESS STORY (highlights)

CHALLENGE – the aim of your research

Investigate and exploit rotational dynamics of a levitated nano/micro-ferromagnet

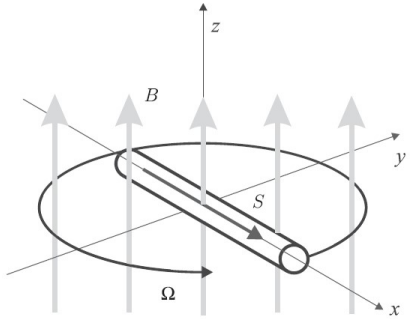
- Levitate a ferromagnet with various means (magnetic, electric, free-fall)
- Couple to a quantum system (NV, SQUIDs, optomechanics)
- Exploit torque sensitivity for extreme sensing (e.g. magnetometry)
- Demonstrate ″atomic-like″ gyroscopic dynamics in a macroscopic ferromagnet

Most spectacular demonstration would be the Macroscopic Larmor precession of a ferromagnet!

PRL 116, 190801 (2016) PHYSICAL REVIEW LETTERS week ending 13 MAY 2016

Precessing Ferromagnetic Needle Magnetometer

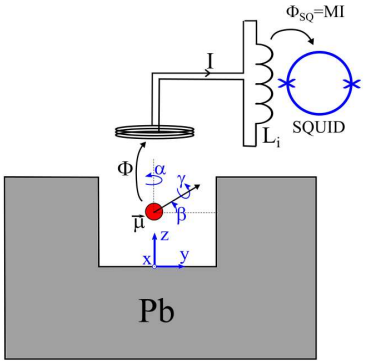
Derek F. Jackson Kimball,[1] Alexander O. Sushkov,[2] and Dmitry Budker[3,4,5]



SUCCESS STORY (highlights)

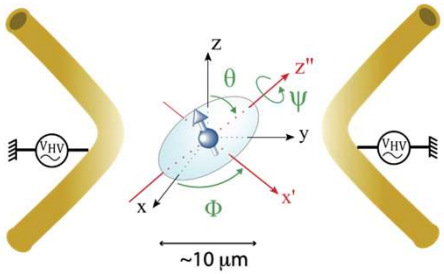
SOLUTION – research approach

Three Experimental Platforms (complementarity + risk mitigation)



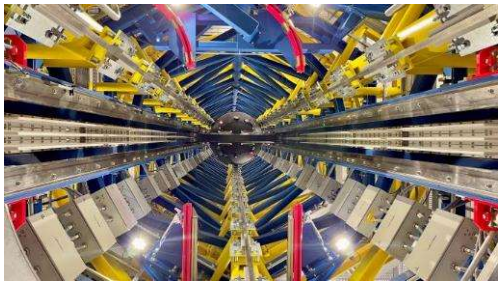
SUPERCONDUCTING TRAPS
+
SQUID & Low temperature
(Trento &Southampton)

- LOWEST NOISE



PAUL TRAPS &
CIRCUIT TRAPS
+
NV centers
(Paris)

- HIGHEST FLEXIBILITY
- COUPLING TO NVs



FREE-FALL (EINSTEIN ELEVATOR)
+
OPTICS
(Mainz & Hannover)

- NEAR-IDEAL 'LEVITATION'

SUCCESS STORY (highlights)

CNRIFN
Istituto di Fotonica e Nanotecnologie



Felix Ahrens

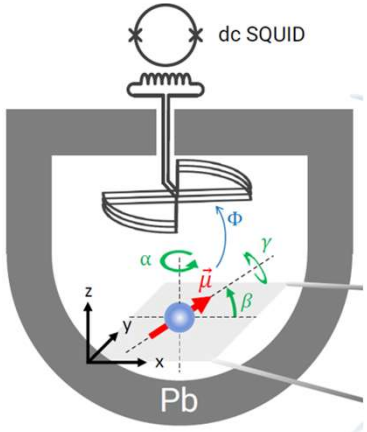
PLANNED OUTCOME

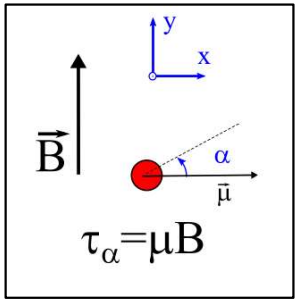
ULTRASENSITIVE TORQUE MAGNETOMETRY (SUPERCON PLATFORM)

PHYSICAL REVIEW LETTERS **134,** 110801 (2025)

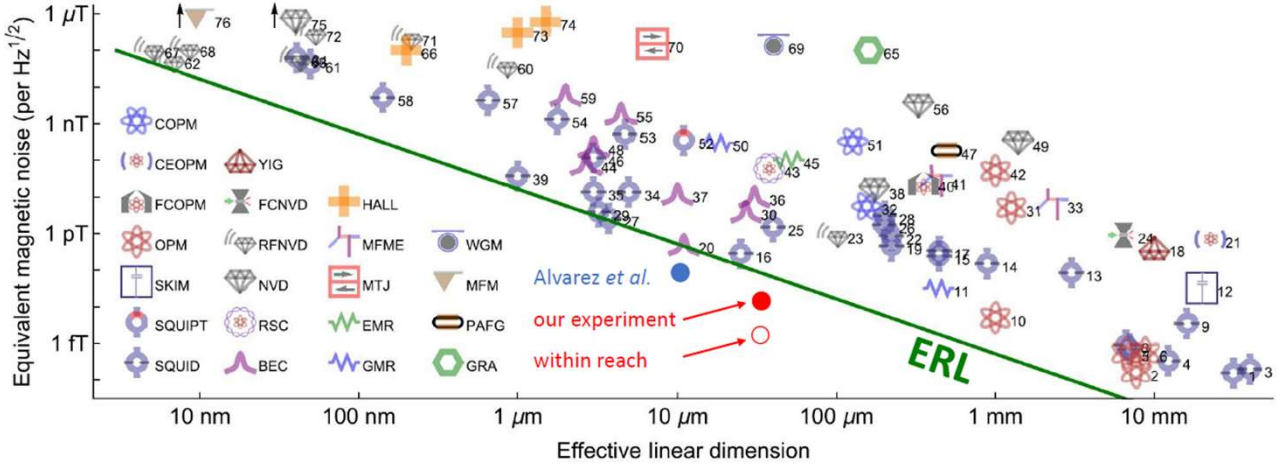
Levitated Ferromagnetic Magnetometer with Energy Resolution Well Below $\hbar$

Felix Ahrens,[1,2] Wei Ji,[3,4,5] Dmitry Budker,[3,4,6] Chris Timberlake,[7] Hendrik Ulbricht,[7] and Andrea Vinante[1,2,*]





PLOT ADAPTED FROM: M. Mitchell and S.P. Alvarez, Rev. Mod. Phys. 92, 021001 (2020)



Energy Resolution Limit (ERL)

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

$S_B^{1/2}$=(19.7 ±0.07) fT/Hz$^{1/2}$
E_R=(0.064±0.010) $\hbar$

SUCCESS STORY (highlights)

UNPLANNED OUTCOME

ULTRASENSITIVE MAGNETOMETRY (DIAMAGNETIC LEVITATION)



Prof. Wei Ji



Changhao Xu

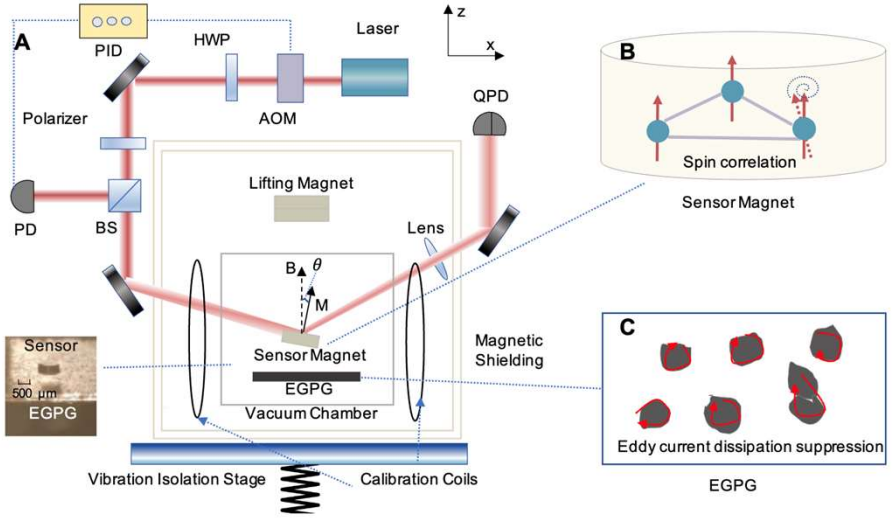
PEKING UNIVERSITY

JG|U HIM HELMHOLTZ Helmholtz-Institut Mainz

Levitated Sensor for Magnetometry in Ambient Environment

Science (2026): 32 fT/√Hz

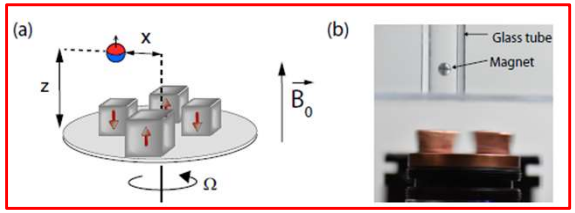
Wei Ji[1,2,3*†], Changhao Xu[2,3*†], Guofeng Qu[2,4], Dmitry Budker[2,3,5,6]



SUCCESS STORY (highlights)

PLANNED OUTCOMES

NEW DESIGNS AND SOLUTIONS

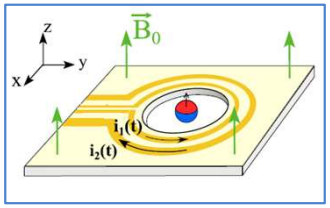


PROOF-OF-PRINCIPLE of a
MAGNETIC PAUL TRAP

M. Perdriat, C. Pellet-Mary, T. Copie and G. Hètet, Physical Review Research 5, L032045

LPENS
LABORATOIRE DE PHYSIQUE DE L'ÉCOLE NORMALE SUPÉRIEURE

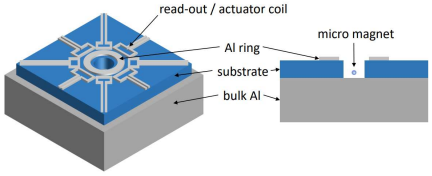
DESIGN AND FABRICATION
of a PLANAR CHIP FOR
MAGNETIC PAUL TRAP





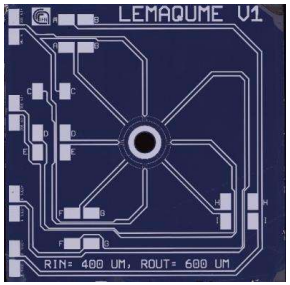
FABRICATED
IN BGU NEGEV

BGU
Ben-Gurion University of the Negev



FABRICATED
IN BGU NEGEV

BGU
Ben-Gurion University of the Negev



DESIGN AND FABRICATION
of a PLANAR CHIP TRAP
FOR SUPERCONDUCTING LEVITATION

SUCCESS STORY (highlights)

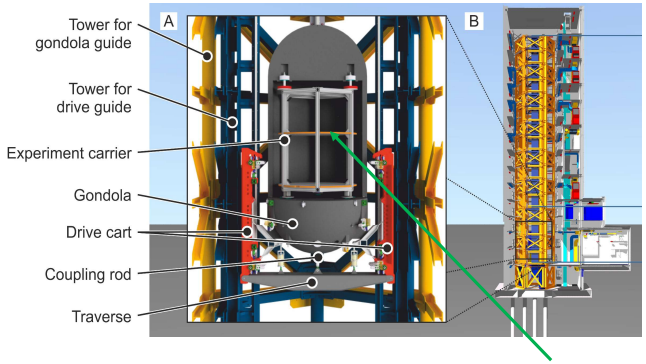
PLANNED OUTCOME

LAUNCH OF A MICROMAGNET IN FREE-FALL !

A tunable feedback-controlled magnetic trap for a magnet in free fall arXiv:2606.01056

Changhao Xu, Alexander Heidt, Mohammadreza Nematollahi, Christoph Lotz, Ernst Maria Rasel, Yan Liu, Wei Ji, Dmitry Budker

EINSTEIN ELEVATOR @HANNOVER



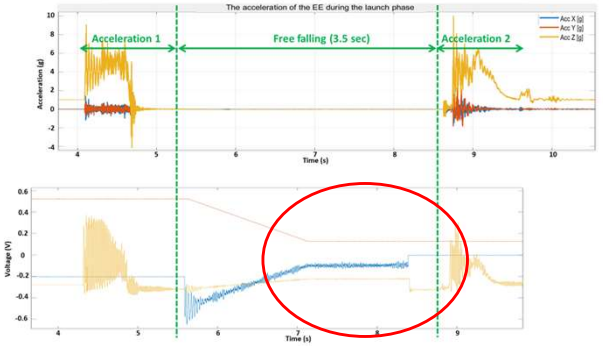

Alexander Heidt


Changhao Xu


Experiment Carrier

ACHIEVED IN THE PROJECT

- Launching platform based on PID-control trap
- Floating state with near-zero velocity (<2 mm/s)



FUTURE GOALS ENABLED

- Observe Larmor precession of a micromagnet in microgravity (Ferromagnetic GYROSCOPE)
- Enable space-based tests of QM+GR with ferromagnets in free-fall

SUCCESS STORY (highlights)

SURPRISING OUTCOME

GYROSCOPIC ATOMIC-LIKE BEHAVIOUR OF A FERROMAGNET (SUPERCONDUCTING PLATFORM)

PHYSICAL REVIEW LETTERS **136,** 146703 (2026)

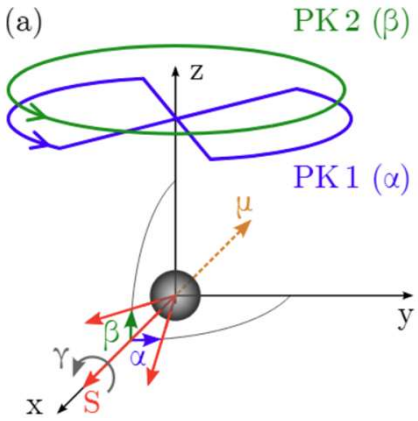
Editors' Suggestion | Featured in Physics

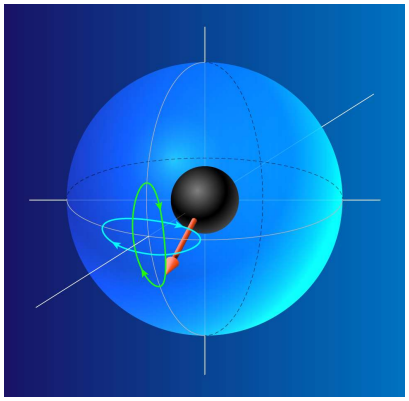
CNR IFN Istituto di Fotonica e Nanotecnologie

Observation of Gyroscopic Coupling in a Nonspinning Levitated Ferromagnet

Felix Ahrens and Andrea Vinante*

Istituto di Fotonica e Nanotecnologie IFN-CNR, 38123 Povo, Trento, Italy
and Fondazione Bruno Kessler, 38123 Povo, Trento, Italy







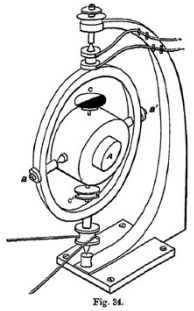


Fig. 34.

The apparatus shown 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

First experimental demonstration of Maxwell's intuition, after 160 years!

SUCCESS STORY (highlights)

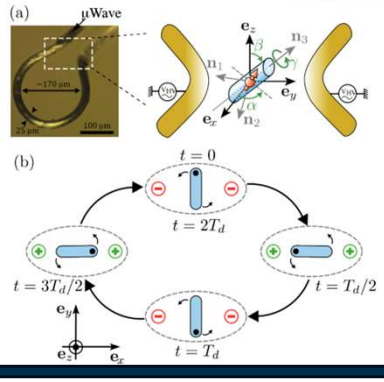
UNPLANNED OUTCOMES

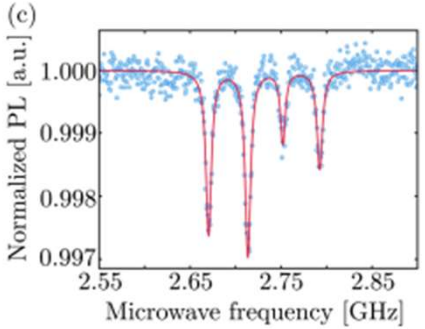
LEVITATED SPINNING ROTORS

Rotational Locking of Charged Microparticles in Quadrupole Ion Traps **PRL, 133, 253602 (2024)**

Maxime Perdriat,[1] Cosimo C. Rusconi,[2,3] Tom Delord,[4] Paul Huillery,[5] Clément Pellet-Mary,[6] Alrik Durand,[1] Benjamin A. Stickler,[7] and Gabriel Hétet[1]

LPENS LABORATOIRE DE PHYSIQUE DE L'ÉCOLE NORMALE SUPÉRIEURE





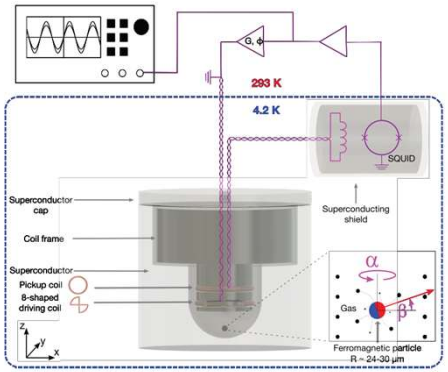
PAUL TRAP
(Synchronous spinning)

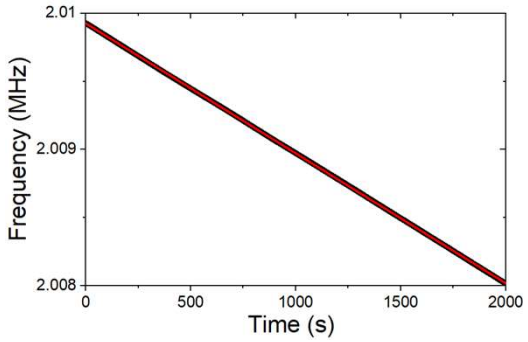
- Different types of particle (magnets, diamonds, …)
- Detect rotation of diamonds using NV center PL signal

J. Jose et al, arXiv:2509.24964

CNR IFN Istituto di Fotonica e Nanotecnologie

Magnētisku Mīkstu Materiālu Laboratorija LAB OF MAGNETIC SOFT MATERIALS





SUPERCONDUCTING TRAP
(Synchronous motor)

- Micromagnet spinning at > 2 MHz
- Exceptionally low damping $\gamma < 10^{-6}$ Hz , $Q > 10^{13}$

QuantERA Call 2021 Final Evaluation

SUCCESS STORY (highlights)

UNPLANNED OUTCOME

NEW APPROACH THEORETICALLY EXPLORED



Marit Steiner

universität ulm

Optically Hyperpolarized Materials for Levitated Optomechanics

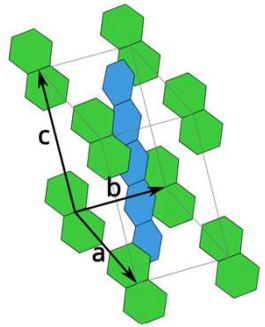
Quantum 9, 1928 (2025)

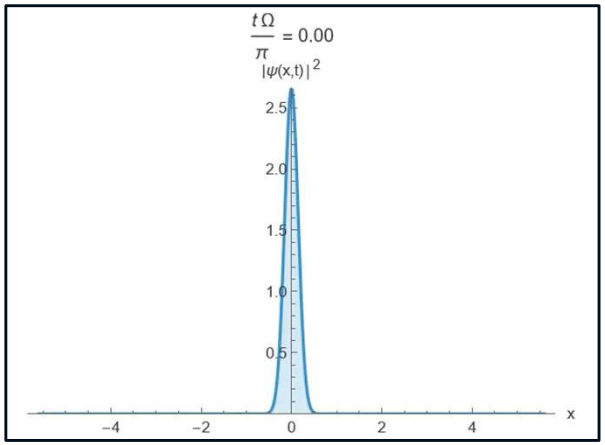
Marit O. E. Steiner[1,2], Julen S. Pedernales[1,2], and Martin B. Plenio[1,2]

IDEA: Replace a Ferromagnetic particle (electron-spin polarization) with a hyperpolarized particle (nuclear-spin polarization)

PROPOSED MATERIAL: Pentacene-doped Naphtalene

FEATURES: Ultralong relaxation & low decoherence





STERN-GERLACH NUCLEAR SPIN PROTOCOL

Coherent manipulation of 10^7 of polarised nuclei act collectively on the mechanical (center of mass) degree of freedom), creating a massive spatial superposition.

SUCCESS STORY (highlights)

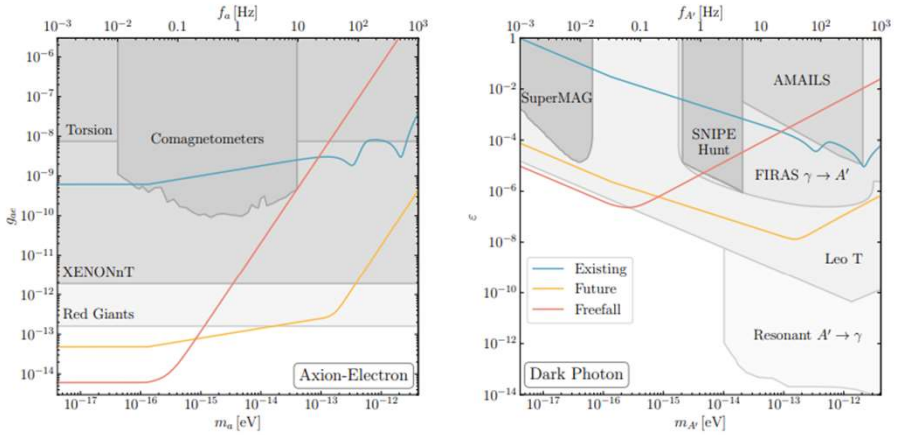
PLANNED OUTCOME

APPLICATIONS TO FUNDAMENTAL PHYSICS

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]



MORE RESULTS:

- X. Heng, Z. Xu, X. Huang, D. Gong, G. Tian, Wei Ji, J. Fang, D. Budker, and Kai Wei , Search for a parity-violating long-range spin-dependent interaction, PNAS 122, e2512538122 (2025)
- L. Cong et al, Spin-dependent exotic interactions, Rev. Mod. Phys. 97, 025005 (2025)
- Z. Xu et al, Constraints on Axion Mediated Dipole-Dipole Interactions, Phys. Rev. Lett. 134, 181801 (2025)

SCIENTIFIC OUTPUTS

PUBLICATIONS AND PRESENTATIONS (highlights)

35 SCIENTIFIC PAPERS
- 30 PUBLISHED
- 5 UNDER REVIEW

High Impact:
1 Science, 2 Science Advances, 1 PNAS, 7 PRL, 2 Nature Communications

~70 PRESENTATIONS AND COMMUNICATIONS AT INTERNATIONAL CONFERENCES

PATENTS

- 1 Pending

NUMBER OF BACHELOR, MASTER AND PhD THESES

- 5 PhD Theses
- 5 MSc Theses

IMPACT (potential users)

KEY COMMERCIALLY RELEVANT **APPLICATIONS**

1) **Ultrasensitive Magnetometry** with a Levitated Magnet.
   Applications to detection of ultralow magnetic fields from human brain activity

2) **Gravimetry** with a levitated magnet (UK partner, Southampton)
   Applications to geophysics, study of climate change relevant processes (ice melting), exploration of underground resources, defense

EXISTING/POTENTIAL **END USERS**

1) **Magnetometry**
   Biomagnetism companies

2) **Gravimetry**
   Space industry
   Oil Industry
   Defense

IMPACT (RRI aspects)

OPEN SCIENCE: promoting transparency and reproducibility of research, increasing and widening the diffusion of knowledge

Publications

30 papers published in International Peer-Reviewed Journals, all Open Access
19/30 Gold OA (63%)
11/30 Green OA (37%)

Organization of one scientific workshop

FONDAZIONE BRUNO KESSLER | ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

Quantum sensing and fundamental physics with levitated mechanical systems

- 2023 Jul 31th – Aug 3th, 2023 ECT* Trento (IT)
- Quantum levitodynamics community widened to space & dark matter
- > 50 attendants



IMPACT (RRI aspects)

PUBLIC ENGAGEMENT

Active participation to outreach events with talks and demonstrations related with the project and with quantum

- *Entanglement: intrecci di luce*
  Italian Quantum Weeks, Trento (April 2023), open to civil society
- *Circuiti quantistici superconduttori & levitazione magnetica*
  Italian Quantum Weeks, Trento (April 2024), open to civil society
- *The Levitron, a demonstration*
  Langer Abend der Wissenschaft, Ulm (July 2023 & June 2024), open to civil society
- *Meccanica quantistica: tra filosofia e tecnologie futuristiche*
  Italian Quantum Weeks, Trento (April 2025), open to civil society
- *Demonstrationen zur magnetischen Levitation*
  Academy Day, Ulm (September 2025), to students

WHAT'S NEXT

Continuation with/without members of the consortium

1) Several pathways opened by the project

- Fundamental aspects of quantum science
- Magnetometry with levitated magnets
- Applications to fundamental physics
- Applications to microgravity/space

2) Natural regrouping of the participants along different directions



QUANTERA

DECADE OF IMPACT 2016-2026



Co-funded by
the European Union