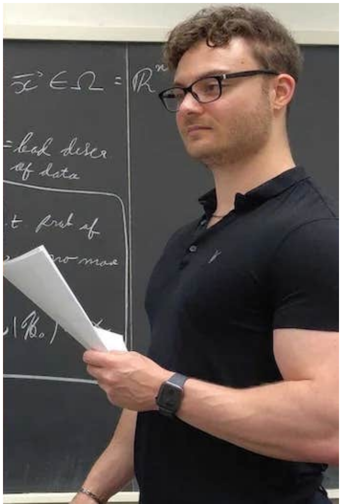
First Dark Matter Search using Magnetic Levitation
and more…

Prof Christopher Tunnell

TAUP 2025

Xichang/西昌市/ꀒꎂꏃ

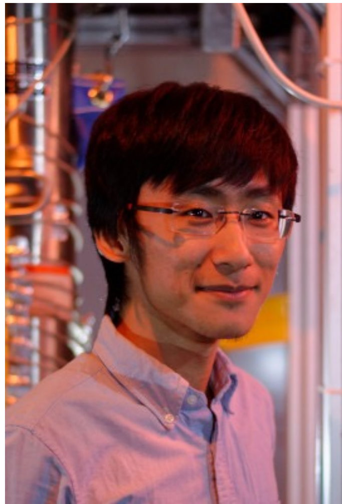
POLONAISE



Dr Dorian do Amaral

Windchime

Dr Juehang Qin



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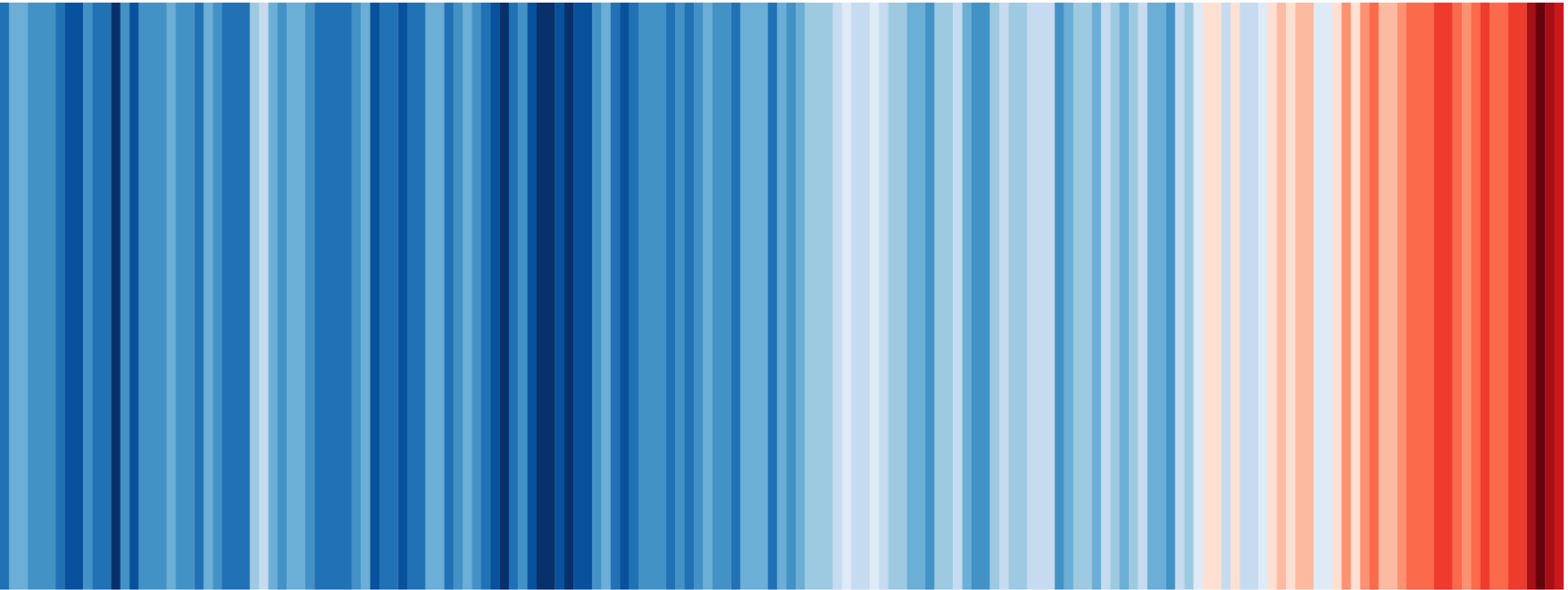
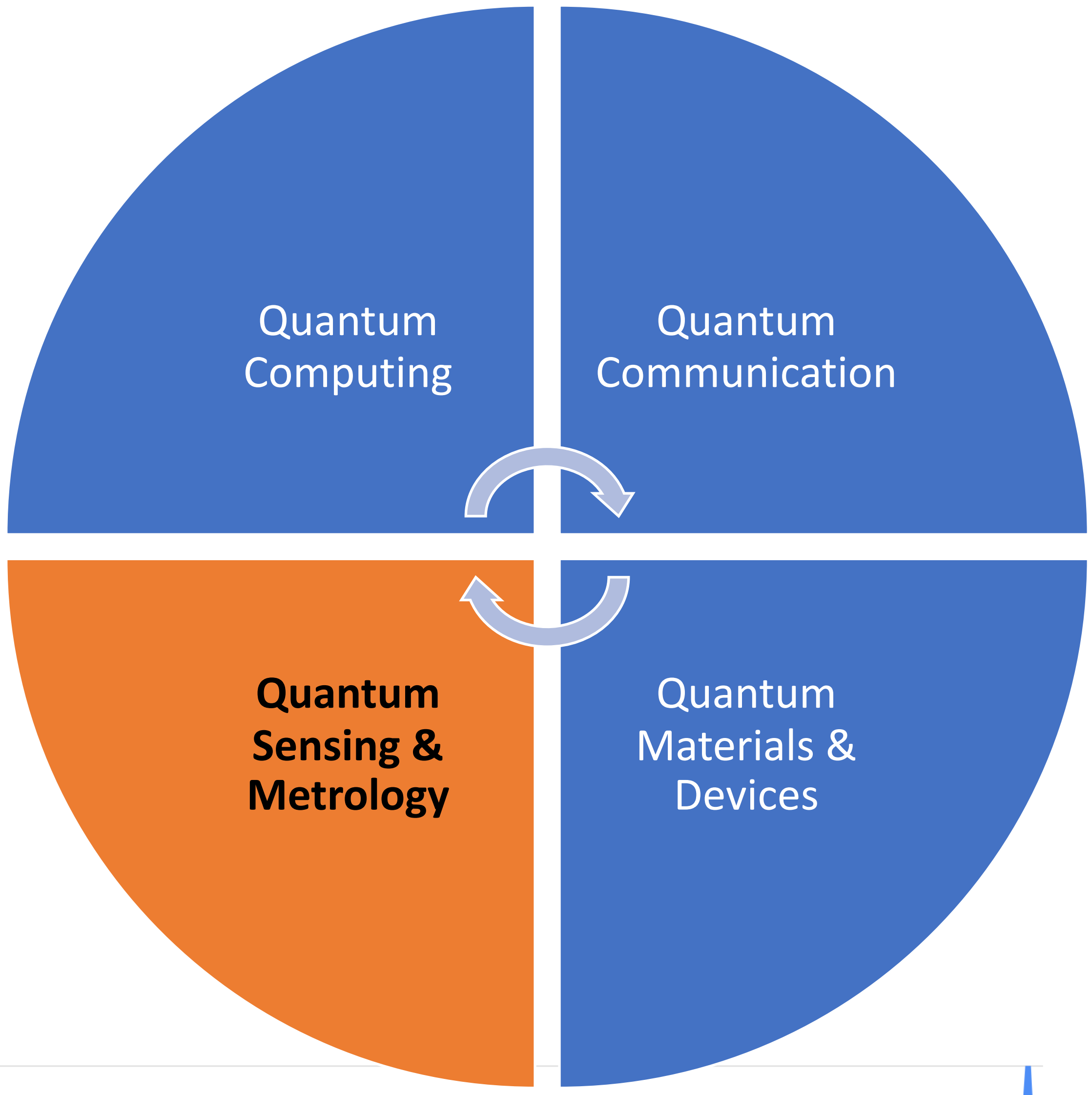
Can table-top experiments lead searches?

- Due to climate crisis, my personal goal is less carbon intensive experimentation.
- Bonding with other concerned scientists from other fields made me realize their table-top experiments could teach us about particle physics.
- New promising technological path forward for particle physics.



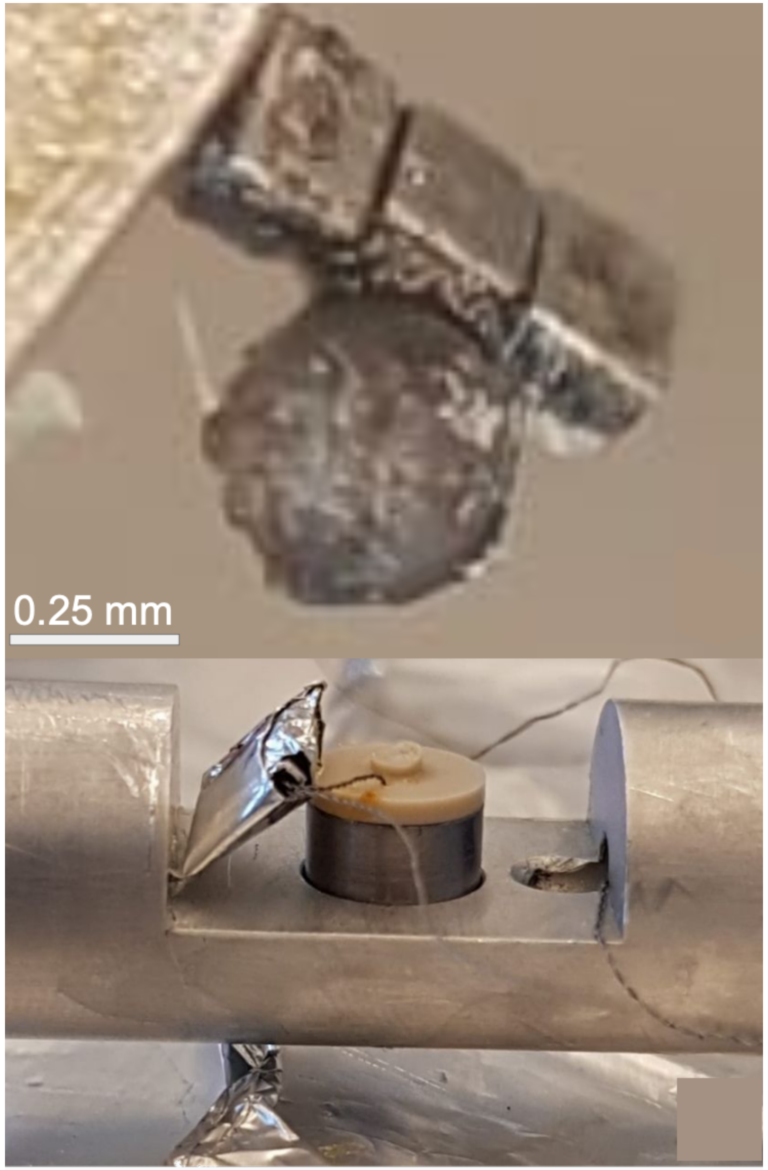
Many new technologies.

- Quantum technologies outpace technology development in HEP.
- E.g. quantum sensors even ‘beat’ the uncertainty principle (i.e. SQL)
- What can we learn about particle physics and cosmology?
- Today’s talk is on European magnetic levitation (‘maglev’) technologies.



Maglev

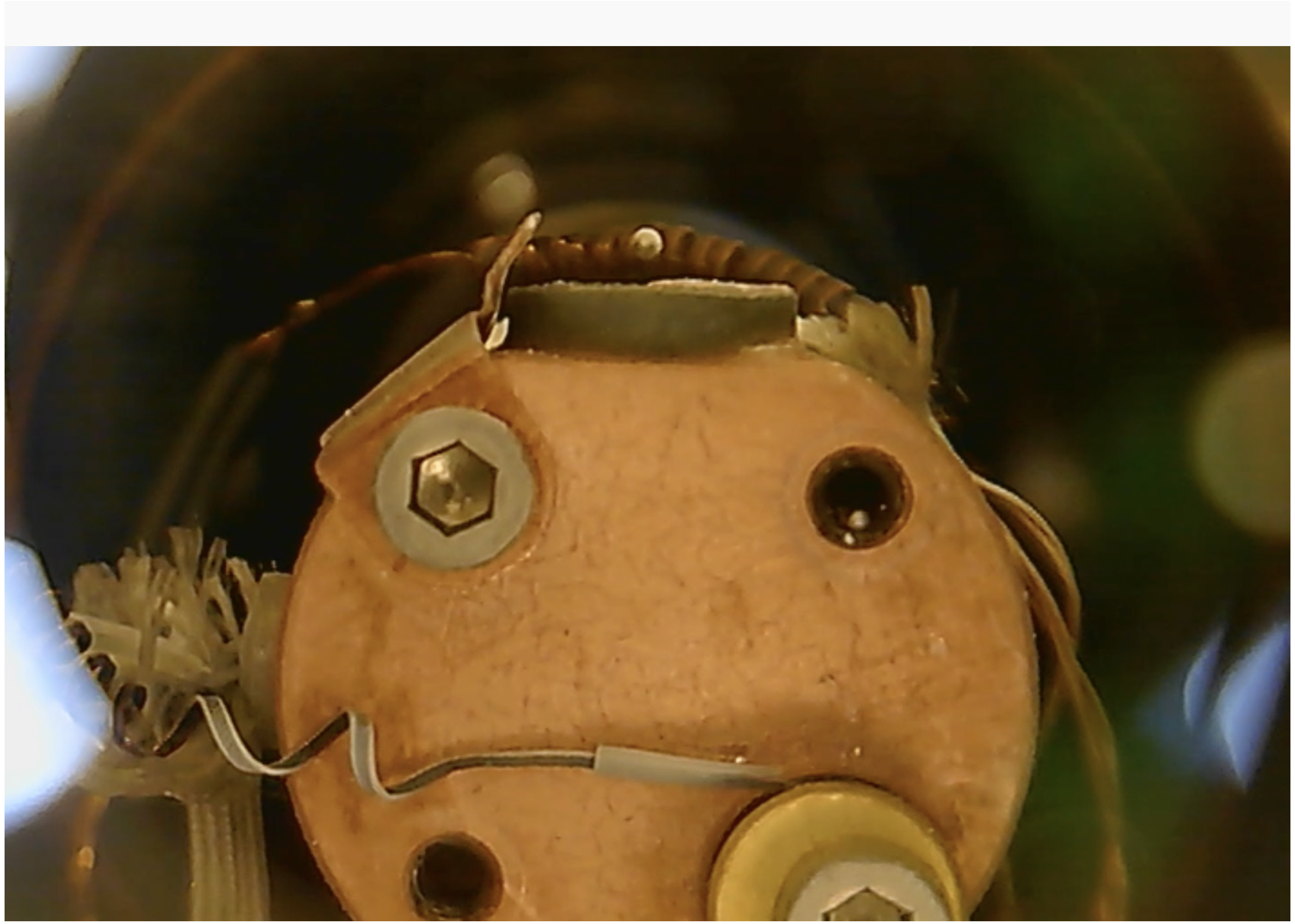
Maglev



Universiteit Leiden

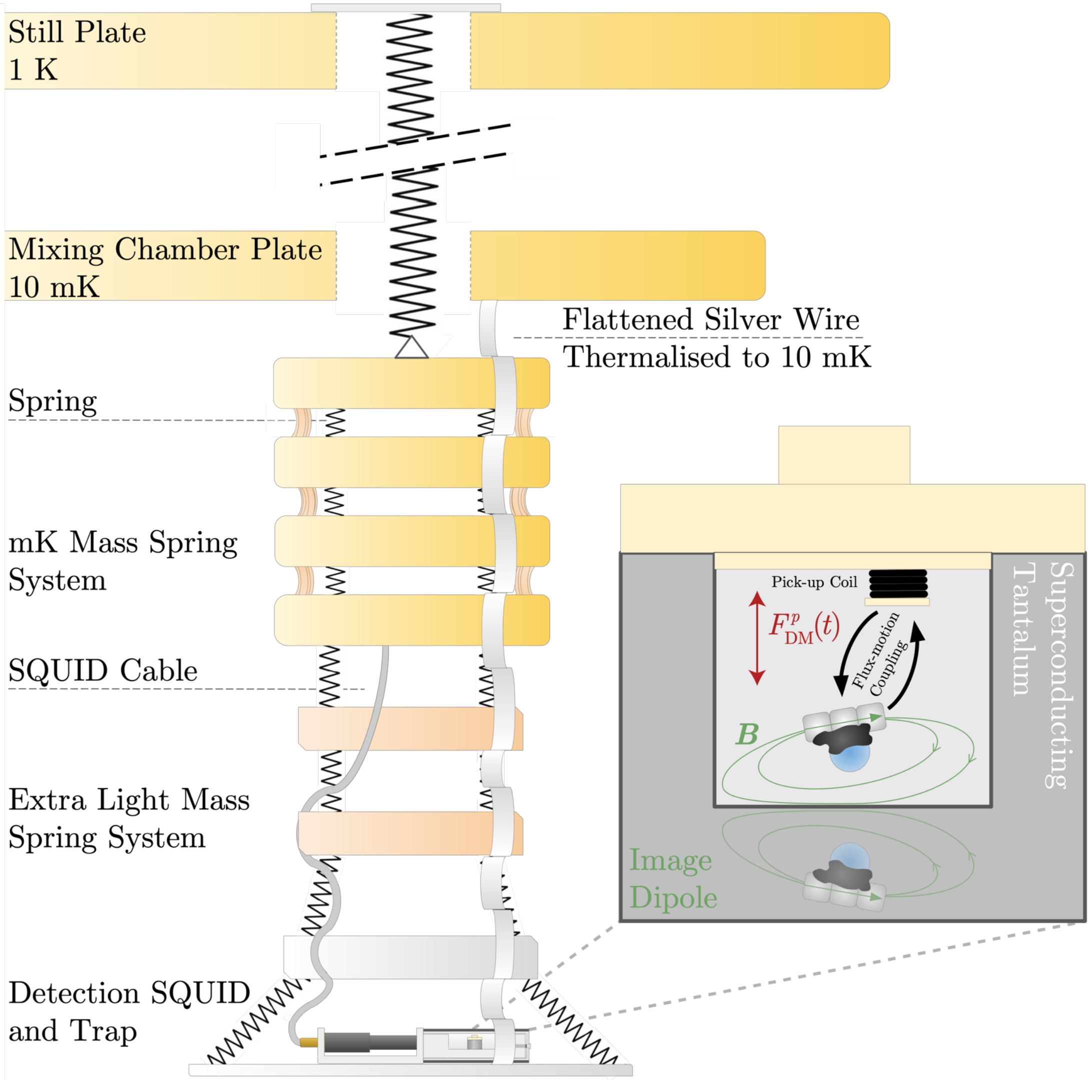
T. M. Fuchs et al. **2303.03545** *Sci. Adv.*

Maglev



Courtsey of T. M. Fuchs

Maglev



- Test mass: three Nd2Fe14B magnetic cubes with glass ball ($m_p \lesssim$ mg)
- Levitated over cooled superconducting tantalum ($T \lesssim 1$ K)
- A force F^p can push the levitated particle around
- Force sensitivity: $S_{FF} \sim 10^{-16}$ N Hz$^{-1/2}$

D. Amaral, D. Uitenbroek, T. Oosterkamp, CT **2409.03814** *PRL*

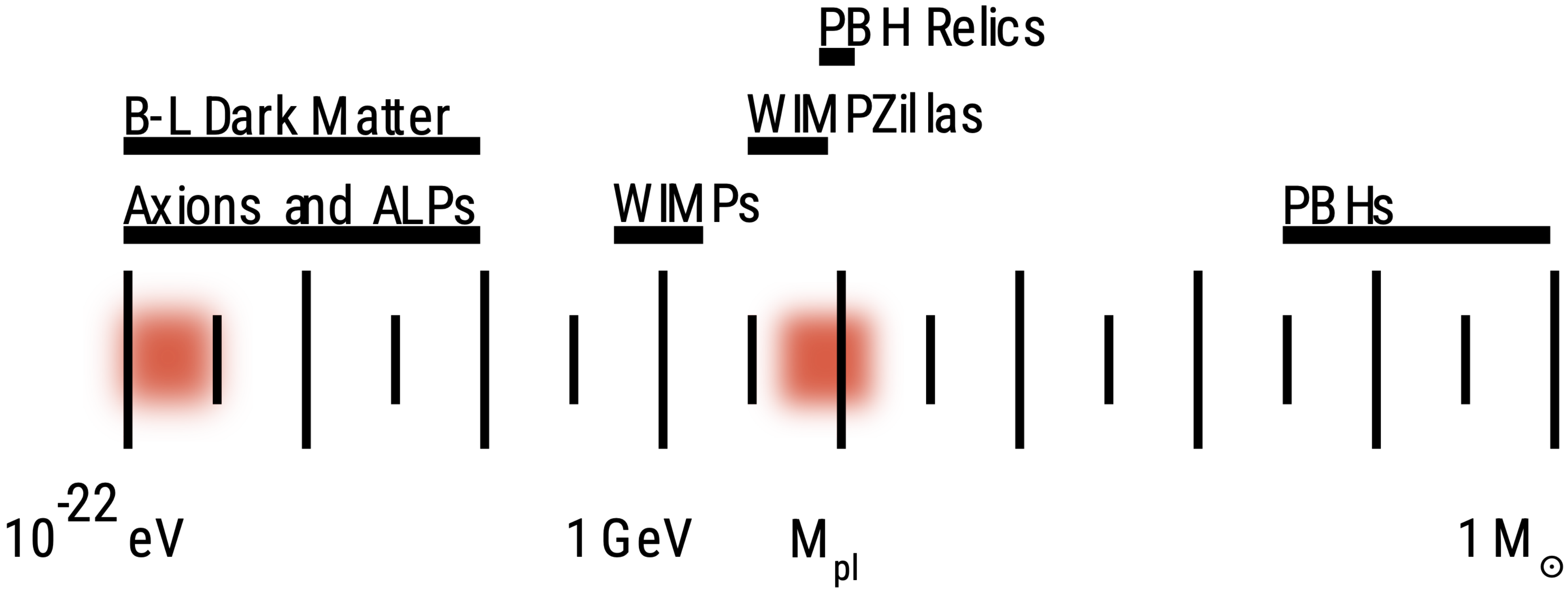
Our papers

Collaboration	Title	Reference	arXiv
Windchime	The Windchime Project	Snowmass 2021	2203.07242
(Theory)	Vector wave dark matter and terrestrial quantum sensors	JCAP 06 (2024) 050	2403.02381
POLONAISE	**First Search for Ultralight Dark Matter Using a Magnetically Levitated Particle**	**Phys. Rev. Lett. 134, 251001 (2025)**	**2409.03814**
Windchime	Mechanical Sensors for Ultraheavy Dark Matter Searches via Long-range Forces	Accepted PRD	2503.11645
MORRIS	The MORRIS Experiment: Magnetic Levitation as a New Probe of Non-Newtonian Gravity	(Under review)	2506.17385

Other papers

Title	Reference	arXiv
Dark-photon and axion dark matter sensing with levitated superconductors	Phys. Rev. D 109, 055024 (2024)	2310.18398
Ultralight dark matter detection with levitated ferromagnets	Phys. Rev. D 110, 115029 (2024)	2408.15330
Superconducting Levitated Detector of Gravitational Waves	Phys. Rev. Lett. 134, 181402 (2025)	2408.01583

Many places dark matter can be.



Adapted J.Q.

Ultralight dark photons

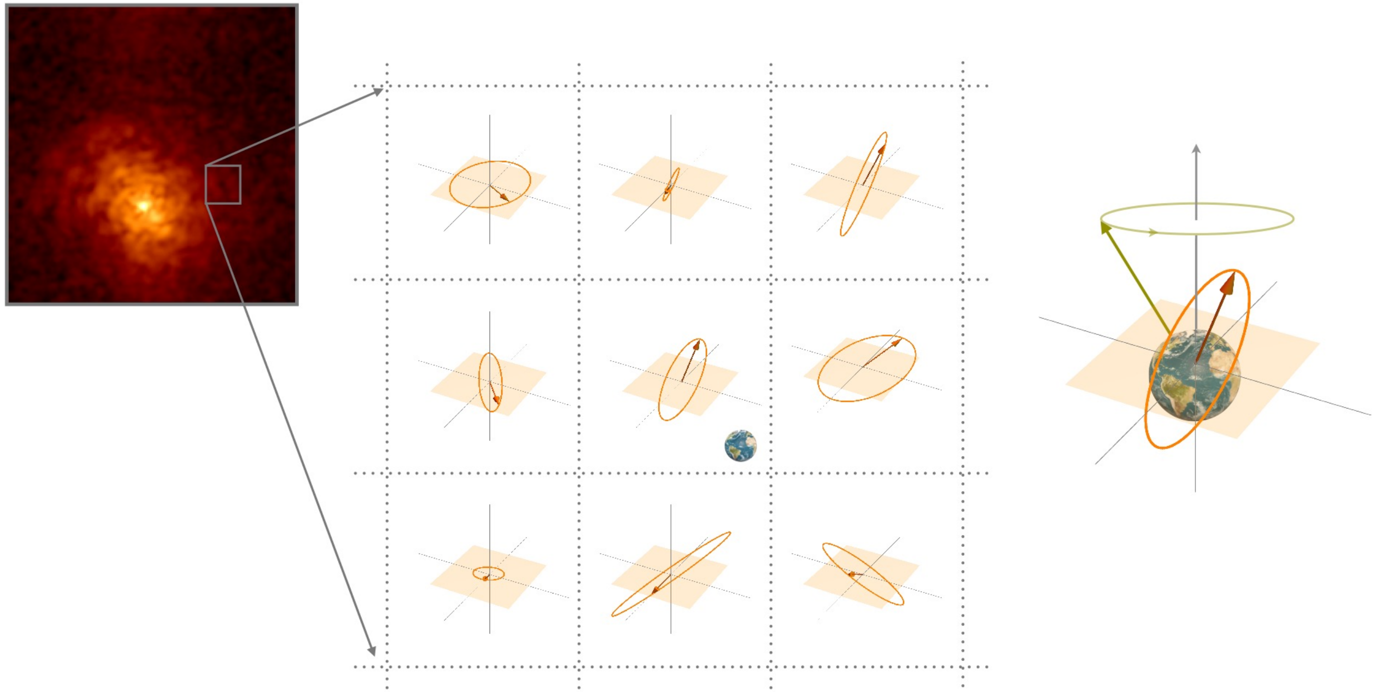
Vector Wave Dark Matter and Terrestrial Quantum Sensors

Dorian W. P. Amaral[a*], Mudit Jain[a,b*]
Mustafa A. Amin[a], and Christopher Tunnell[a]

- For ultralight, occupation number macroscopic

$$N = n_{\rm DM}\lambda_{\rm dB}^3 \sim 10^{58}\left(\frac{10^{-13}\,{\rm eV}}{m_{\rm DM}}\right)^4$$

- Bosonic polarized wave
- Joint theory project for signal model:
  - Model polarized field
  - Formalism for direct detection (including polarization)
- The scale of force on test mass is:



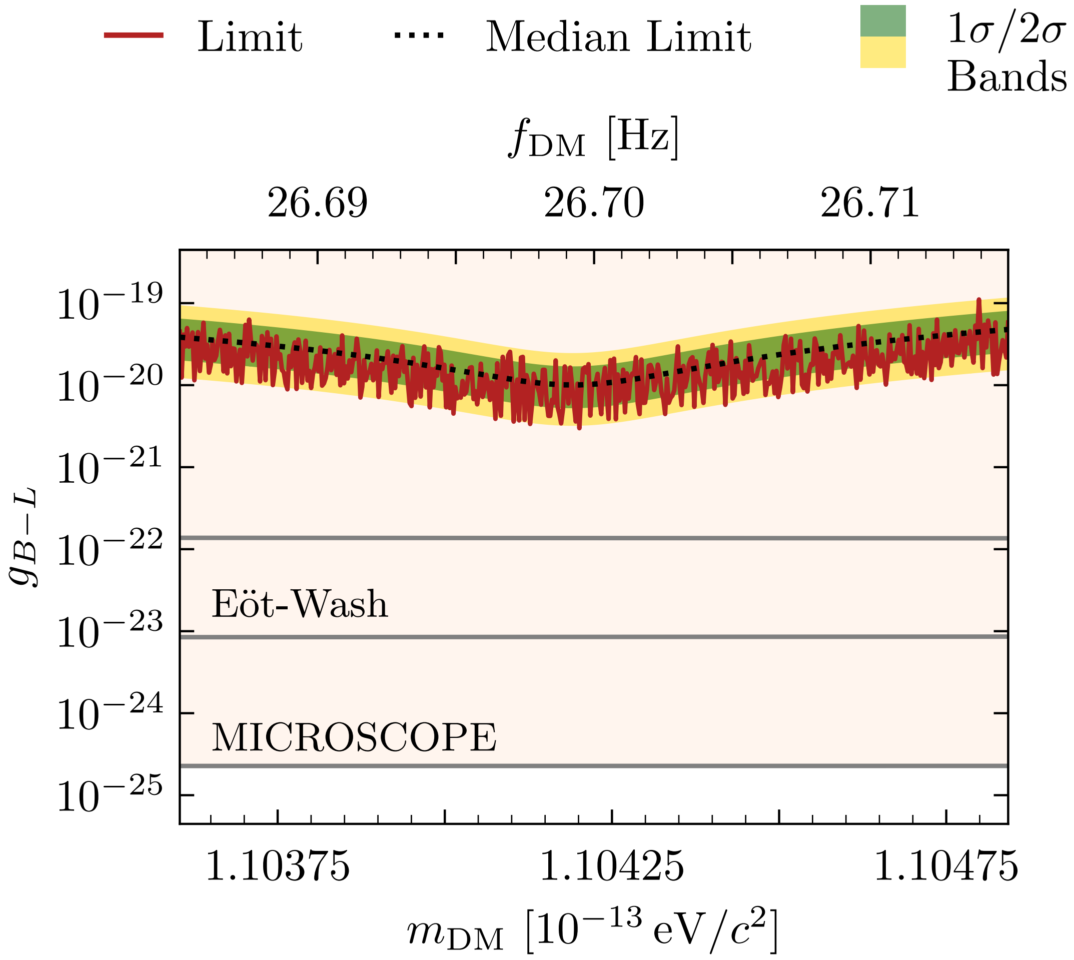
$$\mathcal{F} \equiv g_{B-L}\left(\mathcal{R}_p - \frac{\omega_0^2}{\omega_{\rm DM}^2}\mathcal{R}_t\right) m_p a_0$$

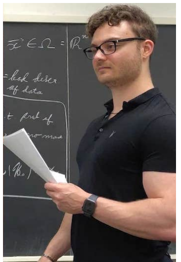
with $\mathcal{R}_p$ and $\mathcal{R}_t$ the averaged neutron-to-atomic-weight ratios of the particle and trap, respectively, ω_0 the resonance angular frequency of the particle, m_p the total mass of the particle, and $a_0 \approx 2.12 \times 10^{11}\,{\rm m\,s^{-2}}$ a characteristic acceleration imparted by the ULDM field [68].

First Search for Ultralight Dark Matter Using a Magnetically Levitated Particle

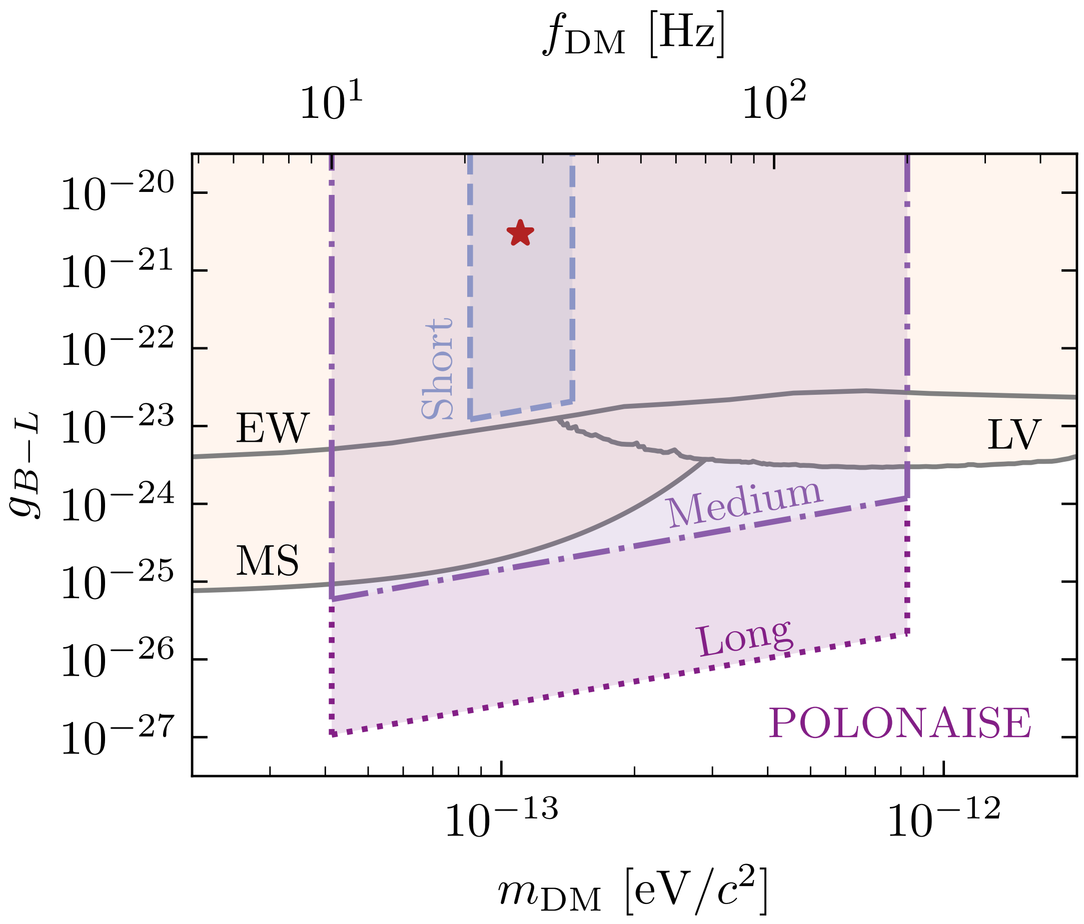
Dorian W. P. Amaral [1,*] Dennis G. Uitenbroek [2] Tjerk H. Oosterkamp [2] and Christopher D. Tunnell [1]
[1] Department of Physics and Astronomy, Rice University, MS-315, Houston, TX, 77005, U.S.A.
[2] Leiden Institute of Physics, Leiden University, P.O. Box 9504, 2300 RA Leiden, The Netherlands.

- Developed first statistical and analysis pipeline, connecting theorists and experimentalists (details in paper)
- Why an exciting PRL:
  - First time using *data*
  - Not so far from torsion balances given:
    - Experiment not tuned for this measurement (giant spinning wheel!)
    - Only 4 hours of data
- We now have machinery to improve things



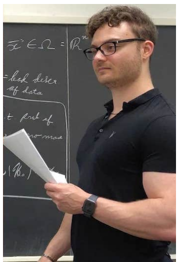


POLONAISE experiment
Probing Oscillations using Levitated Objects for Novel Accelerometry In Search of Exotic-physics



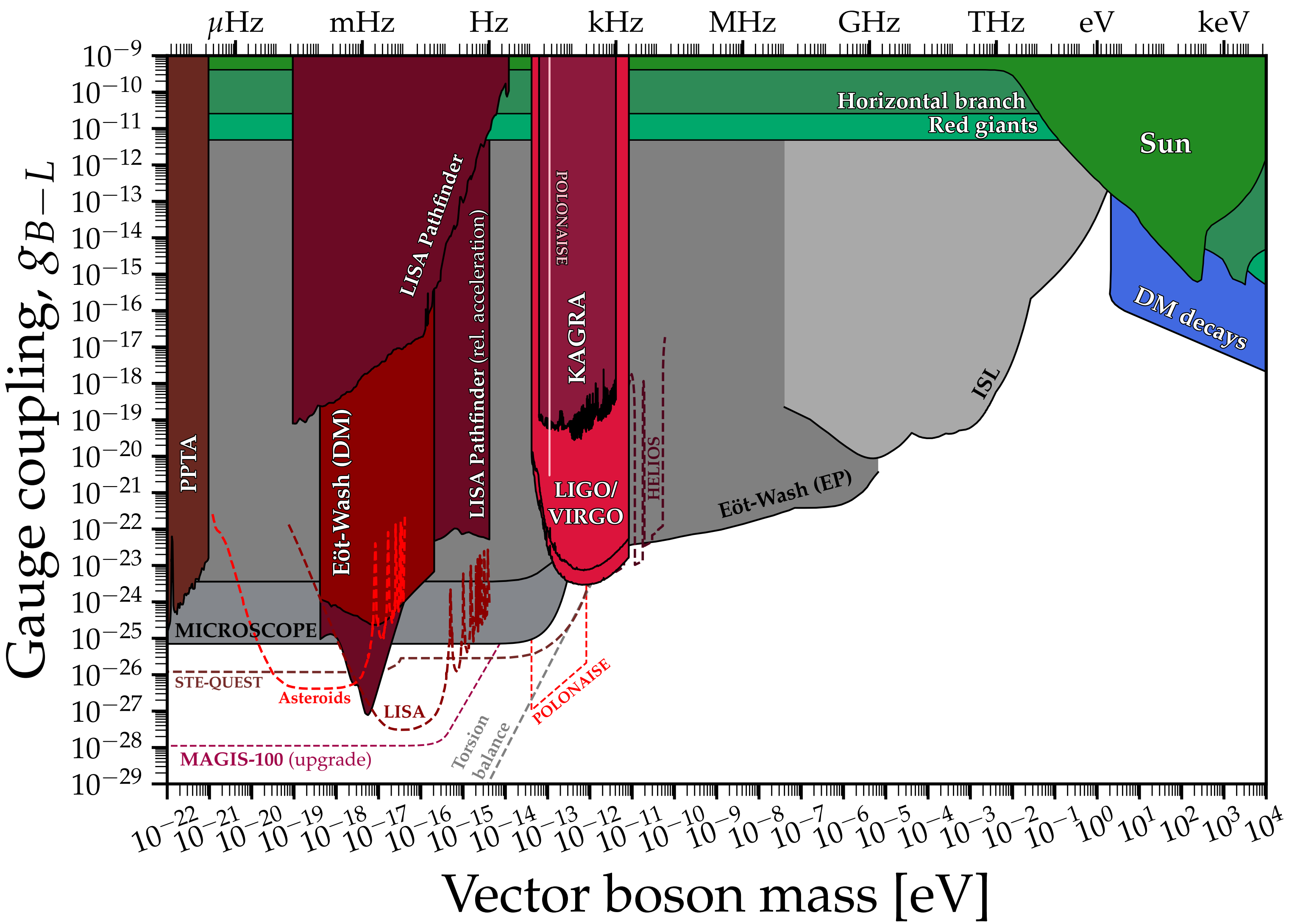
	Short	Medium	Long
T [mK]	20	20	2
m_p [mg]	0.43	430	430
n_{SQ} [$\hbar$]	10^3	10^2	10^1
$\sqrt{S_{FF}}$ [N/$\sqrt{\mathrm{Hz}}$]	$10^{-19} f_0^{1/2}$	$10^{-18} f_0^{1/2}$	$10^{-19} f_0^{1/2}$
Δf_{opt} [mHz]	3.4	3.4	0.34
Q	10^8	10^9	10^{10}
$\lvert\mathcal{R}_p - \mathcal{R}_t\rvert$	0.039	0.039	0.213
N_p	1	10	100

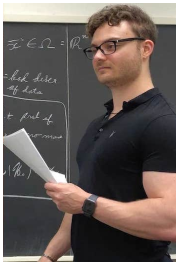
- Two years of data taking
- Synergy Einstein Telescope R&D



POLONAISE **2409.03814** *PRL*

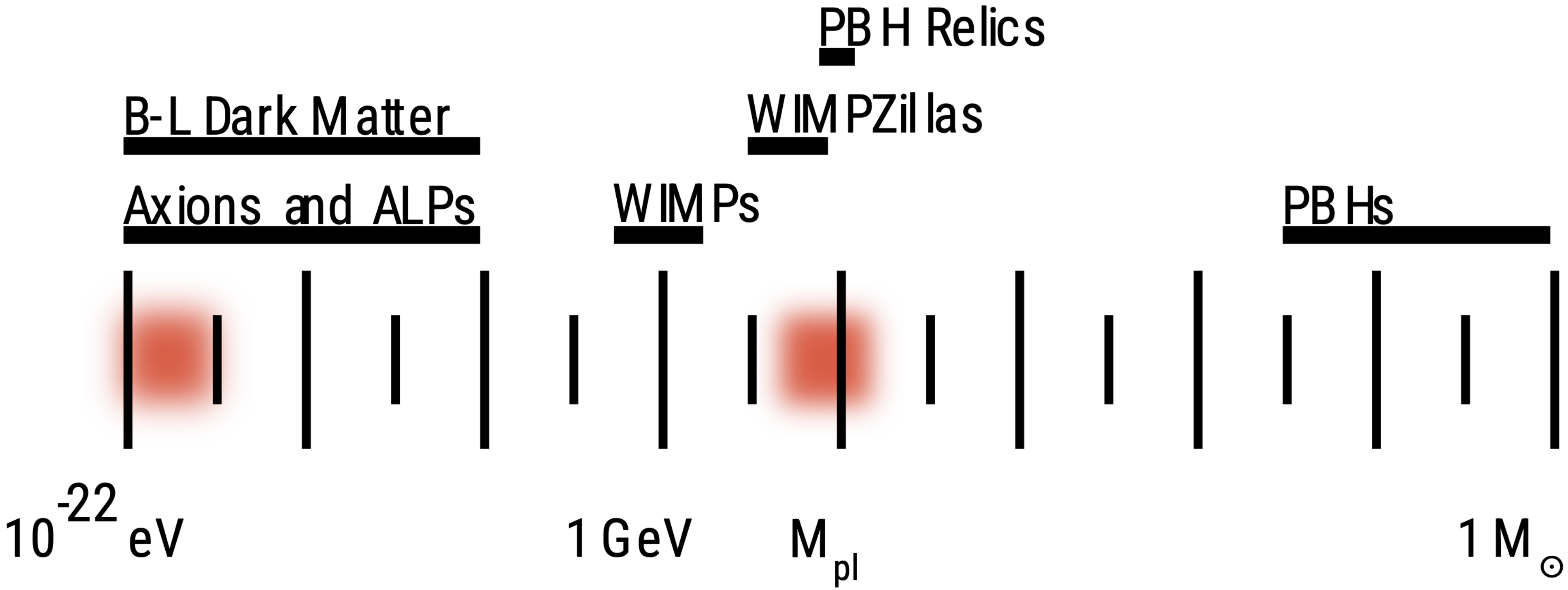
We made it to the summary plot

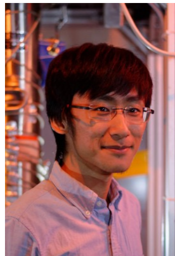




O'Hare Axion Limit Plotter, https://doi.org/10.5281/zenodo.3932430

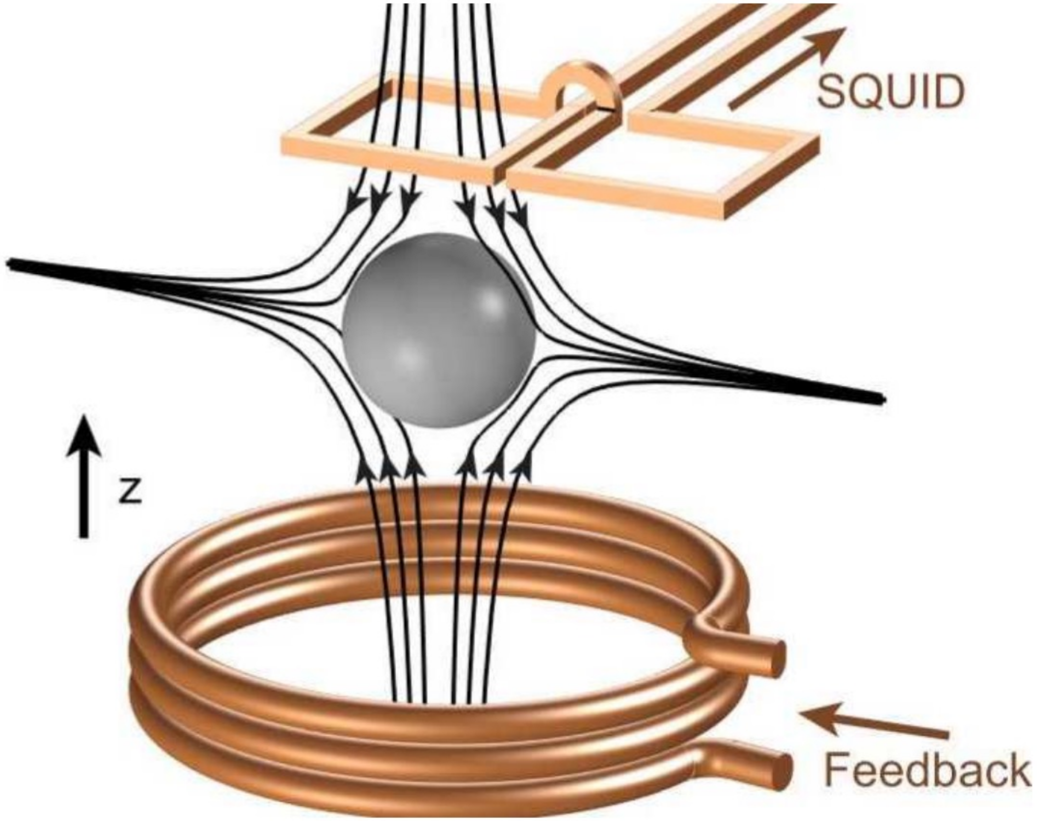
Many places dark matter can be.

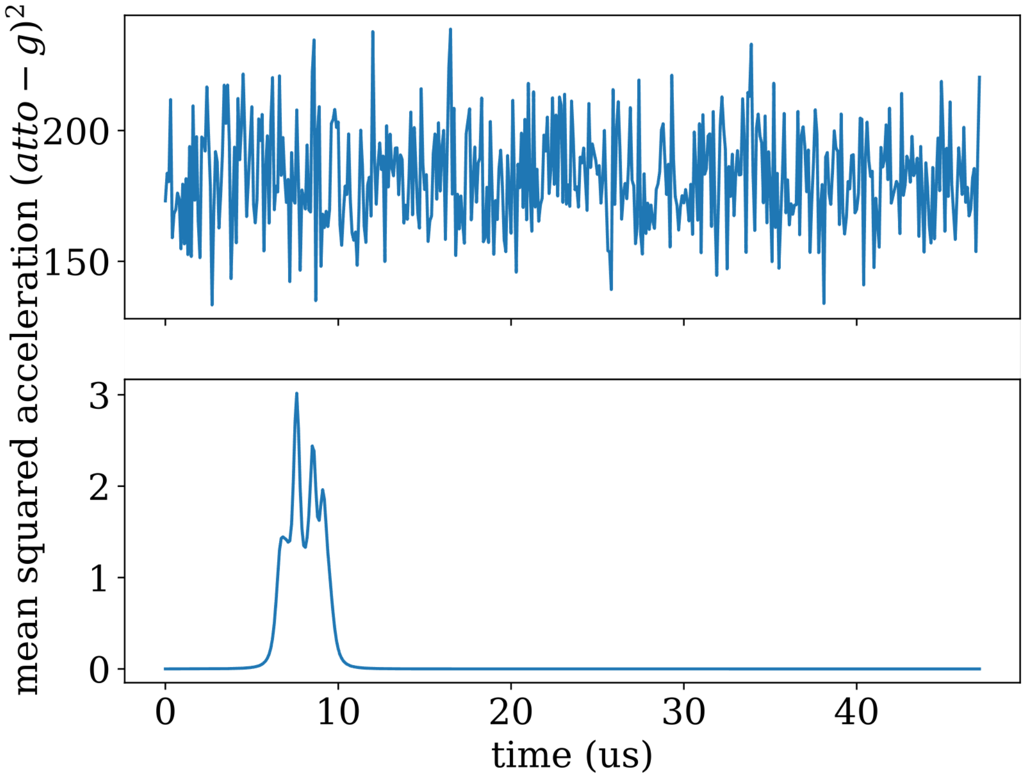


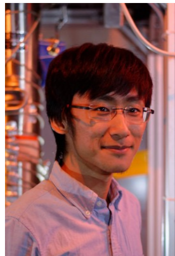


Windchime

Planck-scale dark matter



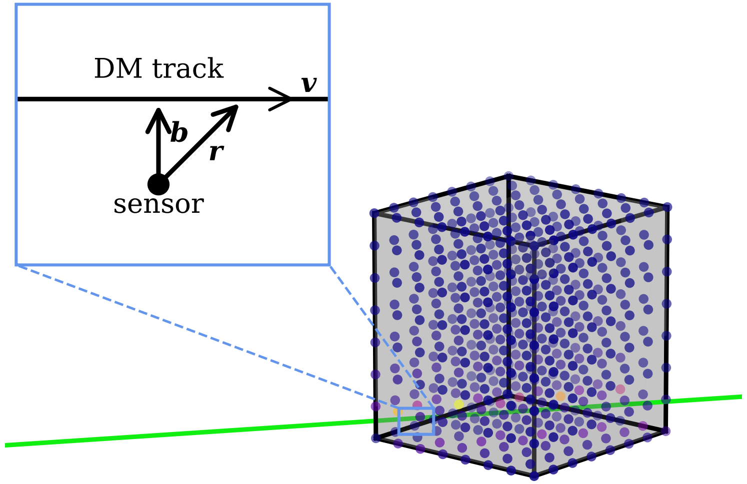


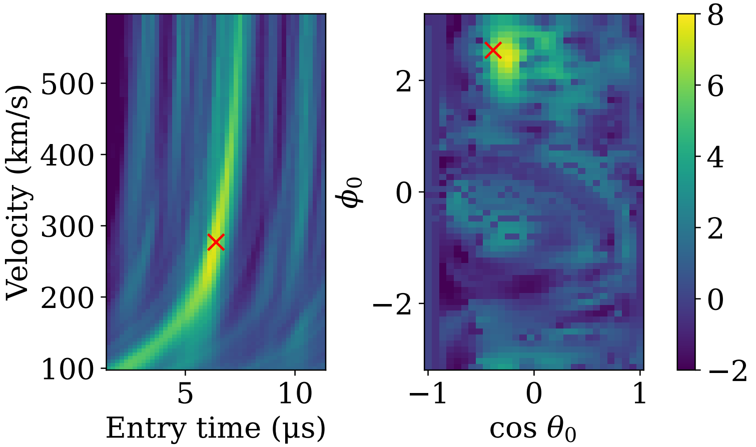


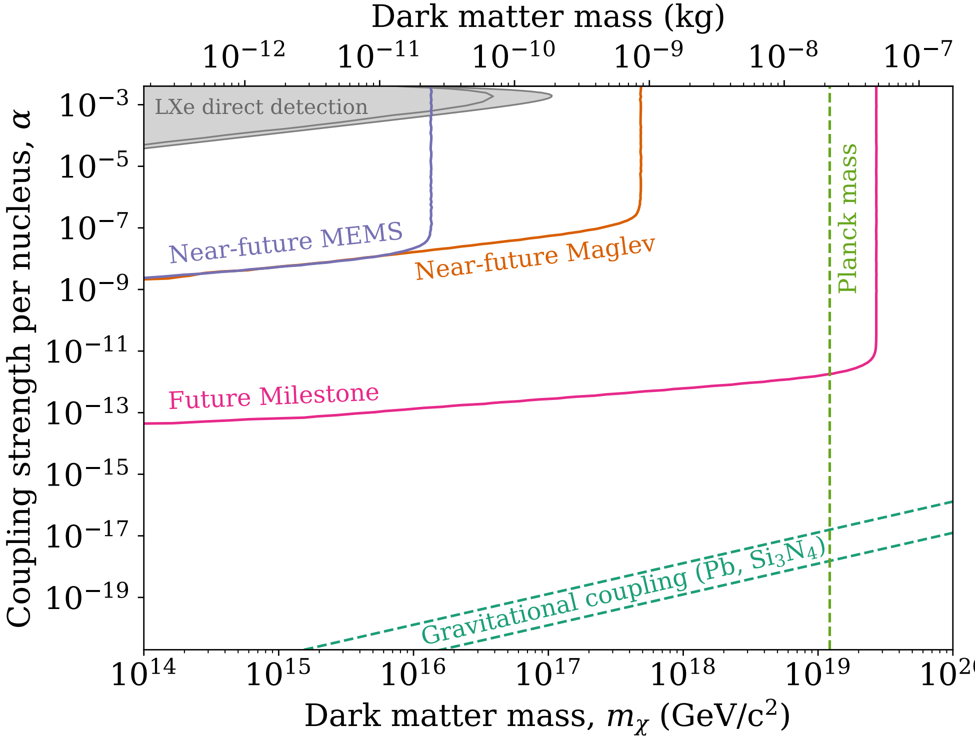
Windchime **2503.11645** *PRD*

Mechanical Sensors for Ultraheavy Dark Matter Searches via Long-range Forces

Juehang Qin,[1,2,*] Dorian W. P. Amaral,[1] Sunil A. Bhave,[3,2] Erqian Cai,[1]
Daniel Carney,[4] Rafael F. Lang,[5,2] Shengchao Li,[5,†] Alberto M. Marino,[6,2]
Claire Marvinney,[6,2,‡] Jared R. Newton,[5,2] Jacob M. Taylor,[7,8] and Christopher Tunnell[9,1]







Parameter	Near-term MEMS	Near-term maglev	Future milestone
Mechanical quality factor Q_m	10^7	10^7	10^{10}
Resonance frequency ω_m	20 kHz	1 Hz	20 mHz
Sensor mass m_s	20 mg	100 mg	100 g
Sensor density	3.2×10^3 kg/m^3	1.13×10^4 kg/m^3	1.13×10^4 kg/m^3
Temperature T	15 mK	15 mK	15 mK
Quantum noise reduction ξ	10 dB	0 dB	15 dB
Sensor count	$10 \times 10 \times 2$	$2 \times 2 \times 1$	$20 \times 20 \times 20$
Sensor array size	0.1 m	0.6 m	2 m
Exposure	1 year	1 year	5 years

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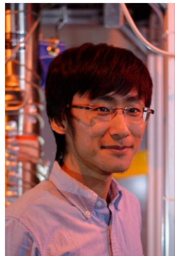
Windchime **2503.11645** *PRD*



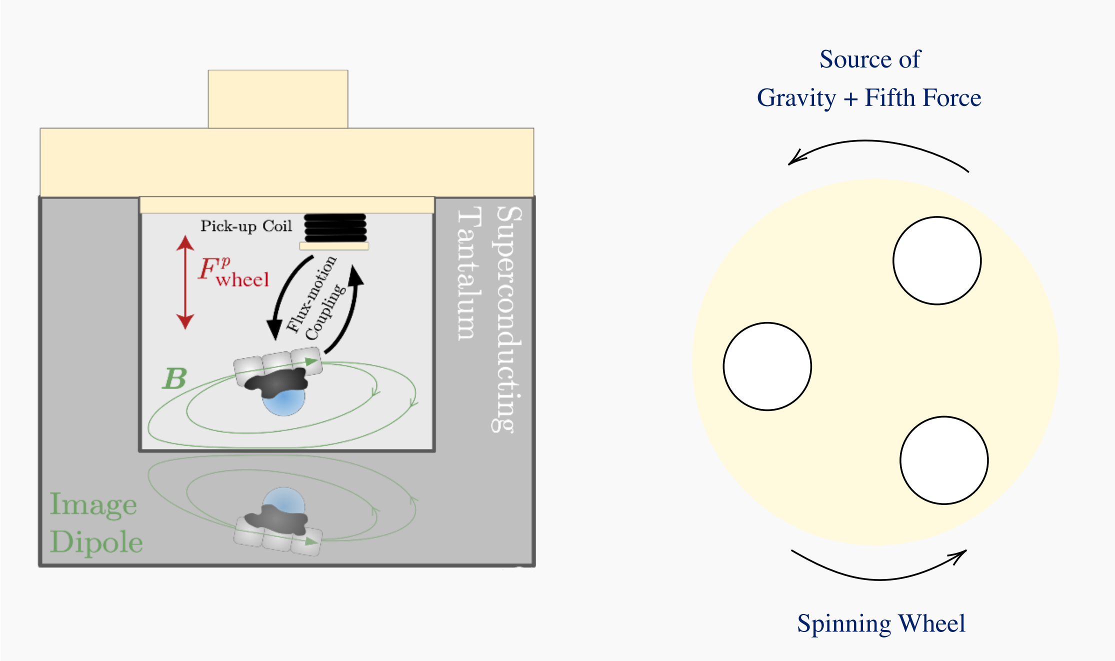
The MORRIS Experiment:
Magnetic Levitation as a New Probe of Non-Newtonian Gravity

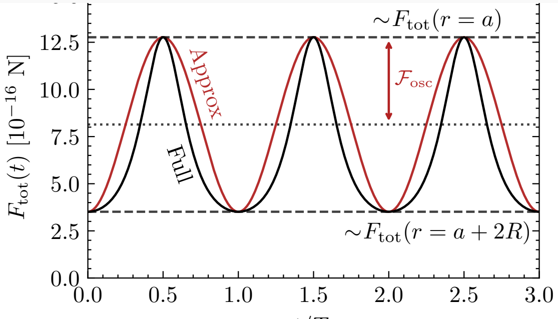
Dorian W. P. Amaral,[1,*] Tim M. Fuchs,[2] Hendrik Ulbricht,[2] and Christopher D. Tunnell[1]

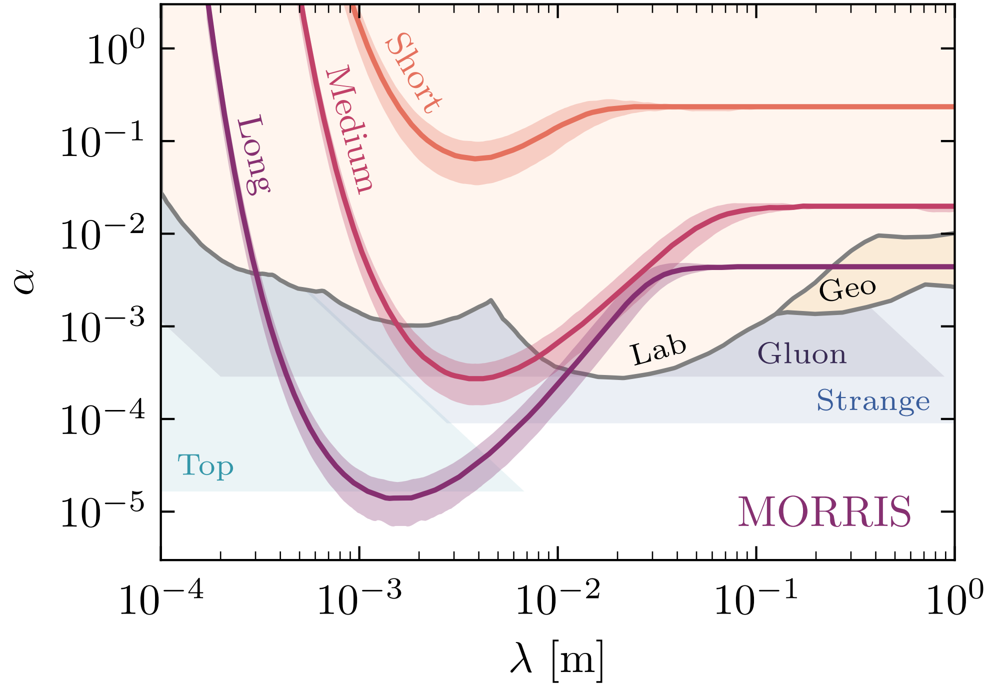
$$U(r;\alpha,\lambda) \equiv -\frac{G_\infty m_s m_p}{r}\left(1+\alpha\, e^{-r/\lambda}\right)$$

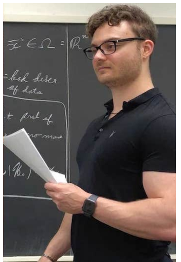
Length Scale (λ)

Coupling (α)









Building setup now, data later this Fall.

MORRIS **2506.17385** (Under review)

What to remember

- **Magnetic levitation** offers force sensing at the quantum frontier
- New detector technology informs particle physics:
  - Ultralight: made analysis pipeline for the first analysis with data
    - Projected leading sensitives [10^{-12}, 10^{-13}] eV
  - Heavy: appears competitive near Planck scale compared to our previous LXe results
  - Gravity: we working with gravity experiments to interpret their soon leading data in particle physics frameworks
- **Want more beyond papers?**
  - Workshop: Planning workshop, email me tunnell@rice.edu or talk to me after if interested.
  - Seminars: Temporarily based in Netherlands.
  - Impatient?: Please talk today with me over food and/or drinks.