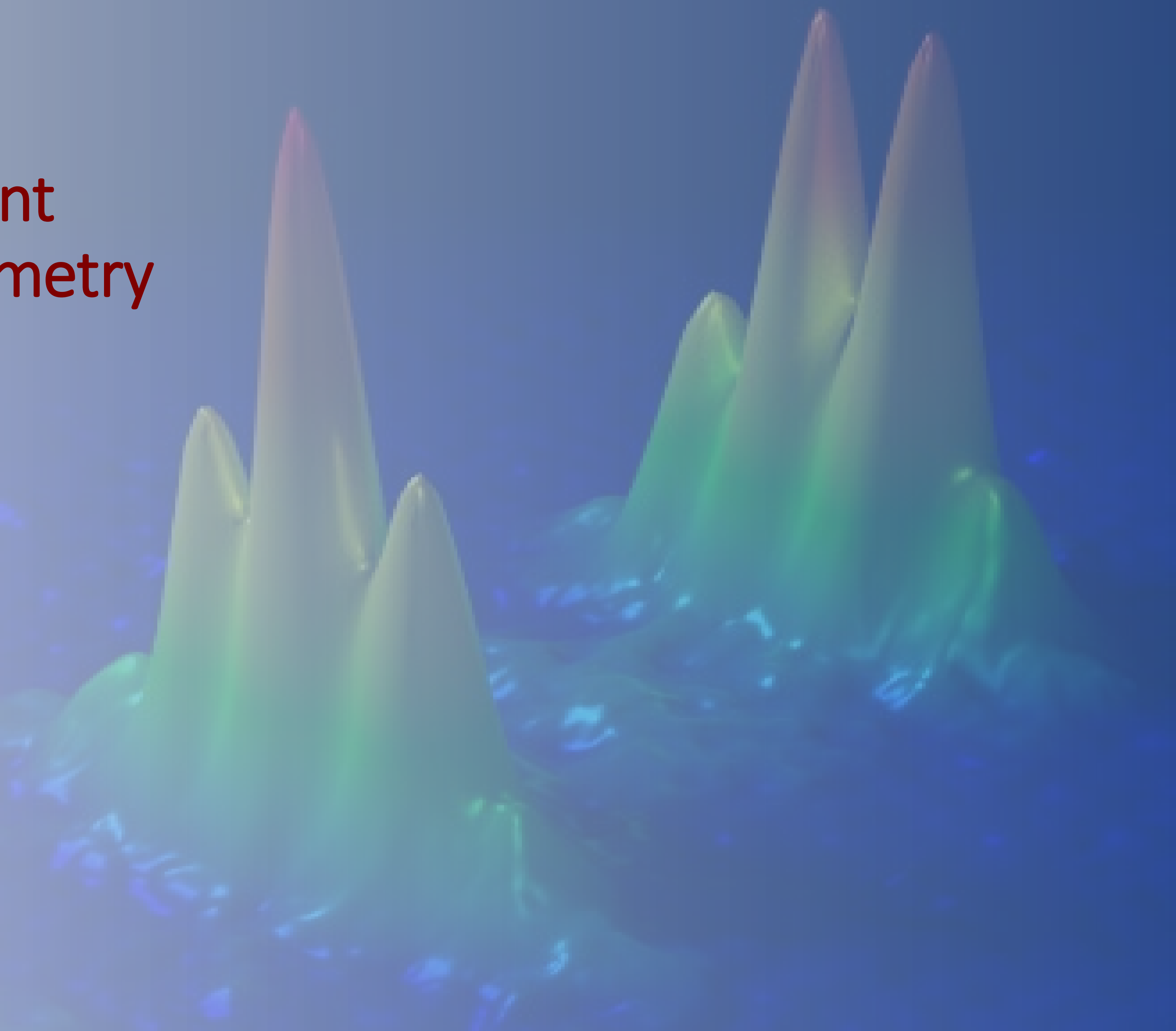
Precision measurement with atom interferometry



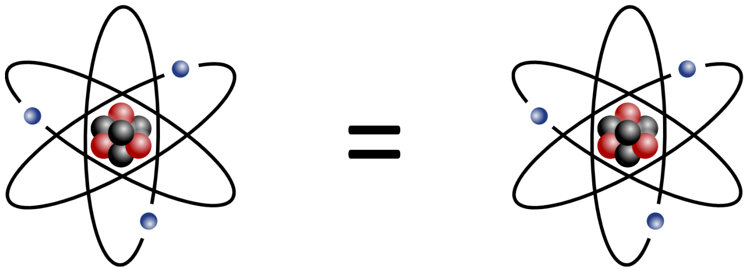
MITP
November 21, 2024

Chris Overstreet
Johns Hopkins University

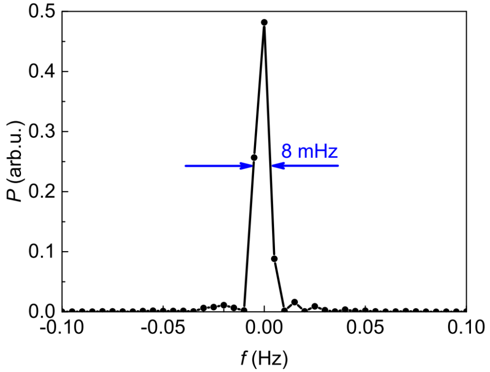
Why atomic, molecular, and optical (AMO) systems?

Atoms are good test objects:

- -simple
- -identical
- -time-independent
- -sensitive to new physics



Lasers are good measuring devices (very precise).



D. G. Matei, T. Legero, S. Häfner, et al., *Phys. Rev. Lett.* **118**, 263202 (2017)

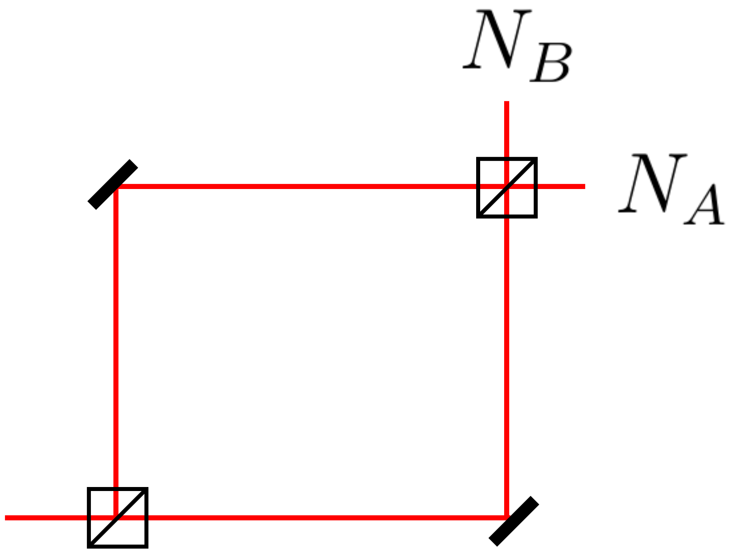
Atom-light interactions are well-understood and controllable.

Outline

1. Introduction to atom interferometry
2. Equivalence principle test
3. Quantum sensing applications
4. Dark matter searches

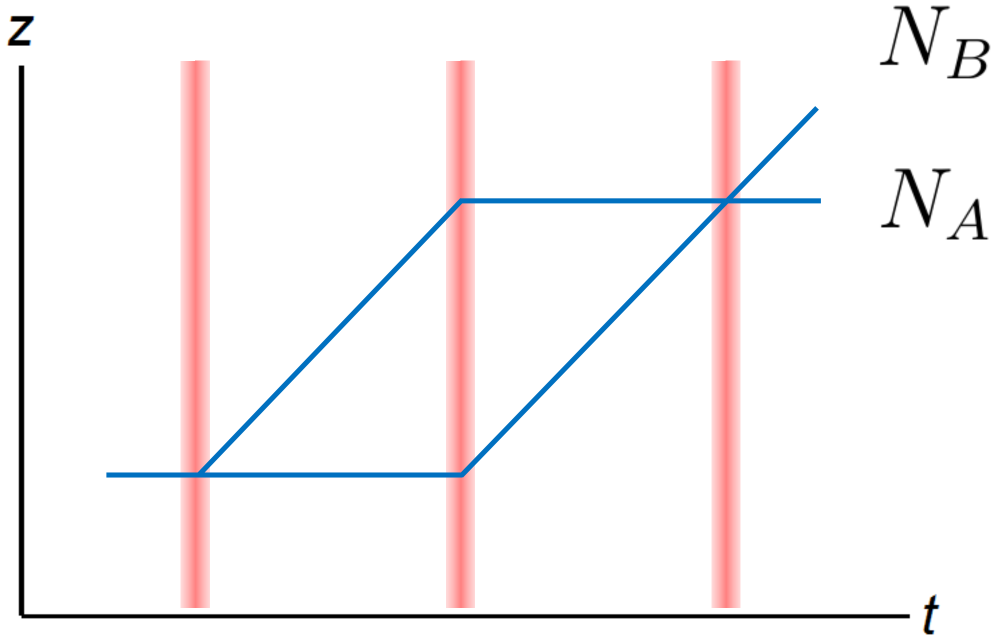
Introduction to atom interferometry

Optical interferometer



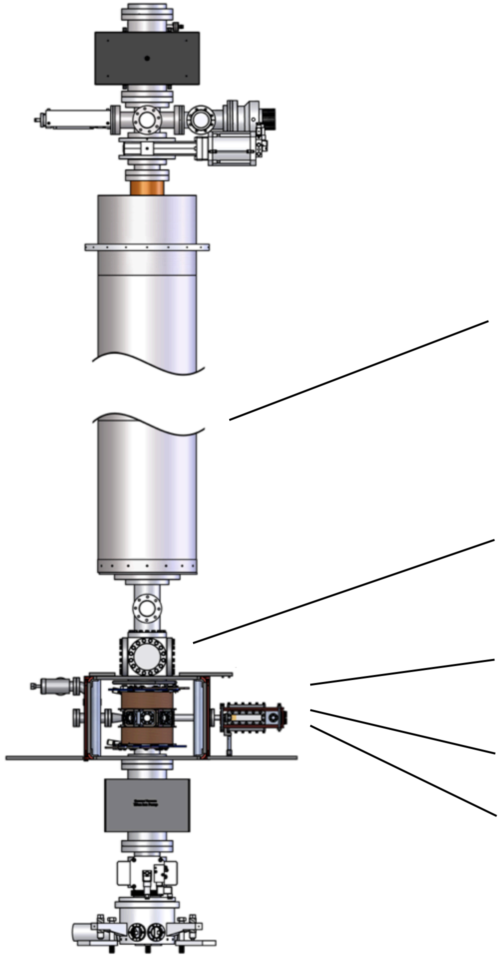
$$\frac{N_A}{N_A+N_B}=\frac{1}{2}+\frac{1}{2}\cos\phi$$

Atom interferometer



$$\frac{N_A}{N_A+N_B}=\frac{1}{2}+\frac{1}{2}\cos\phi$$

Apparatus



4. Atom interferometry

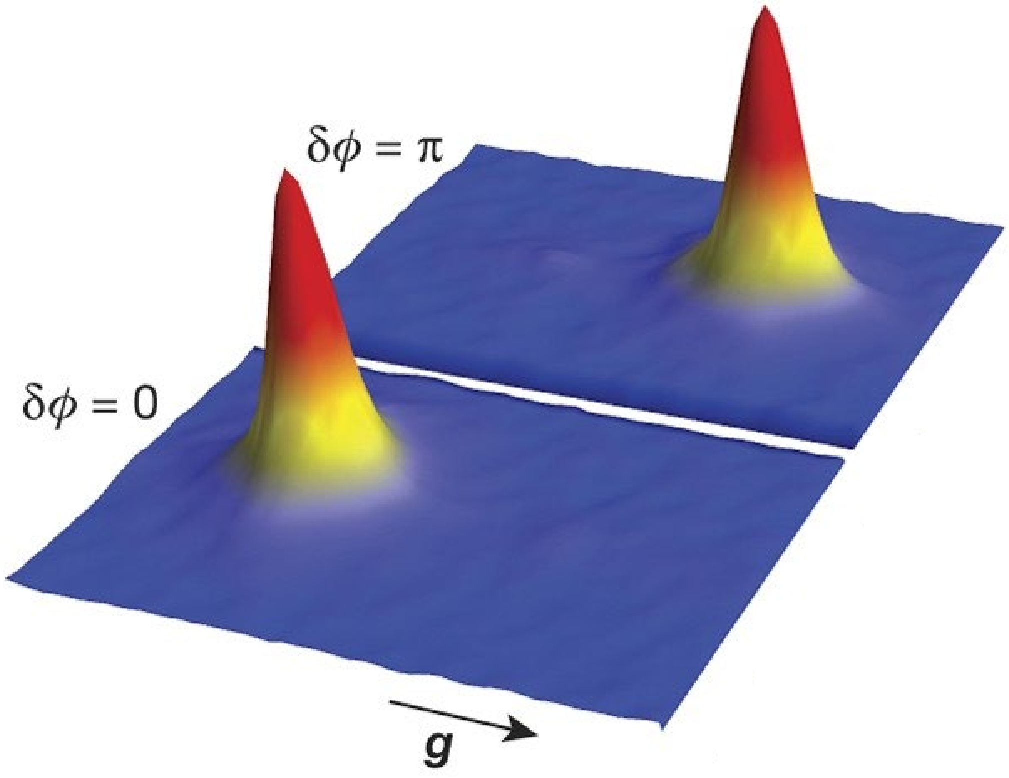
5. Fluorescence imaging

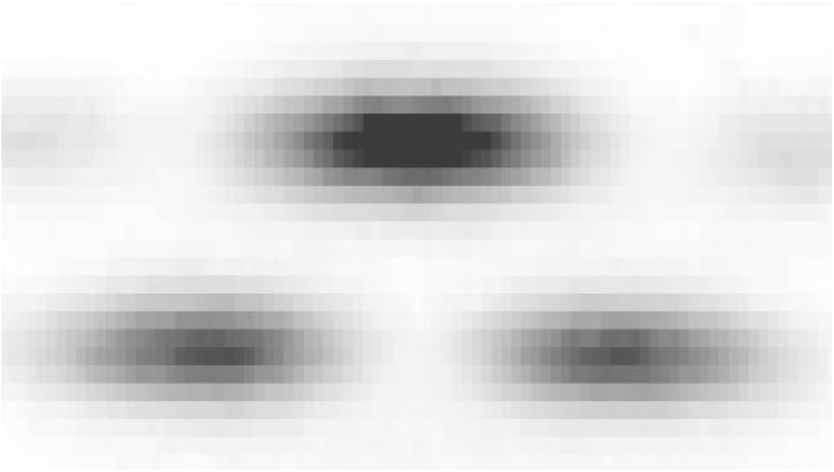
3. Lattice launch

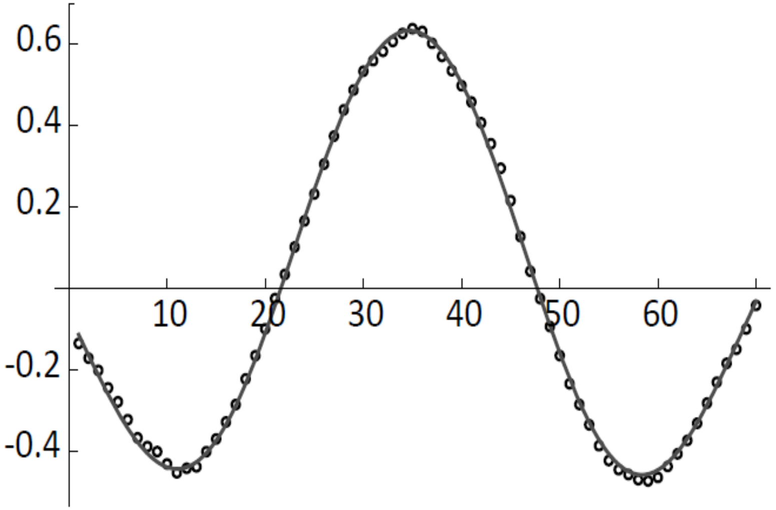
2. Magnetic lens

1. MOT and evaporation

Data







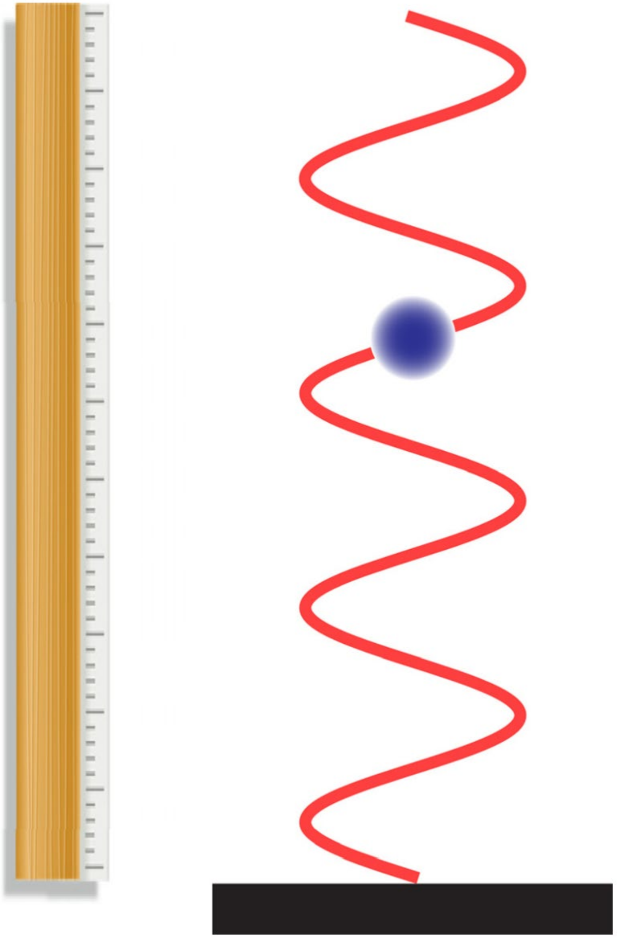
P. Asenbaum, C.O., et al., *Phys. Rev. Lett.* **125**, 191101 (2020)

Atom interferometer phase

Midpoint theorem: $\phi = \sum_i (k_{1,i} - k_{2,i}) \frac{z_{1,i} + z_{2,i}}{2}$

Mach-Zehnder geometry:

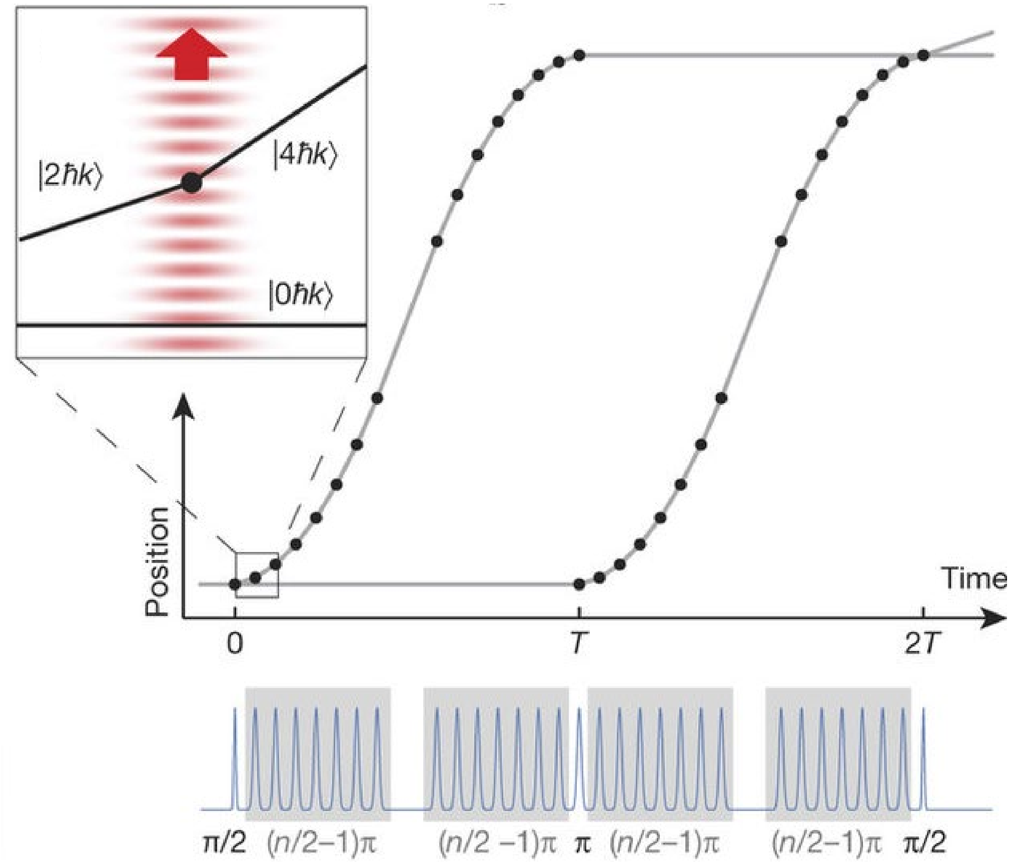
$$= k \left[\int_T^{2T} \int_0^t \ddot{z}(t')\, dt'\, dt - \int_0^T \int_0^t \ddot{z}(t')\, dt'\, dt \right]$$



C. Antoine and C. J. Bordé, *J. Opt. B* **5**, S199 (2003)
C.O., P. Asenbaum, and M. A. Kasevich, *Am. J. Phys.* **89**, 324 (2021)

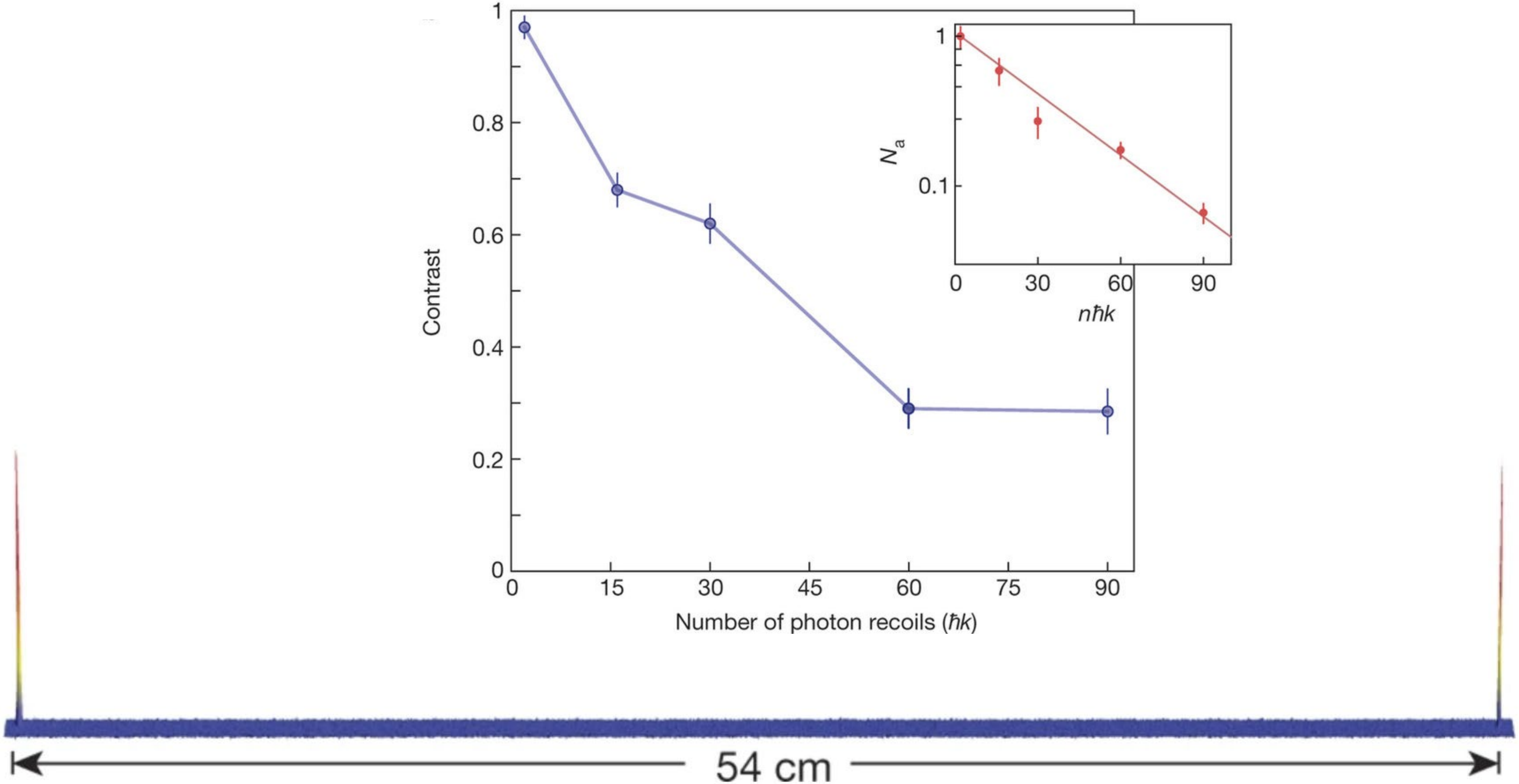
Large momentum transfer (LMT) interferometry

-Sequential two-photon Bragg transitions



T. Kovachy, P. Asenbaum, C.O., et al., *Nature* **528**, 530 (2015)

LMT in action



T. Kovachy, P. Asenbaum, C.O., et al., *Nature* **528**, 530 (2015)

Outline

1. Introduction to atom interferometry
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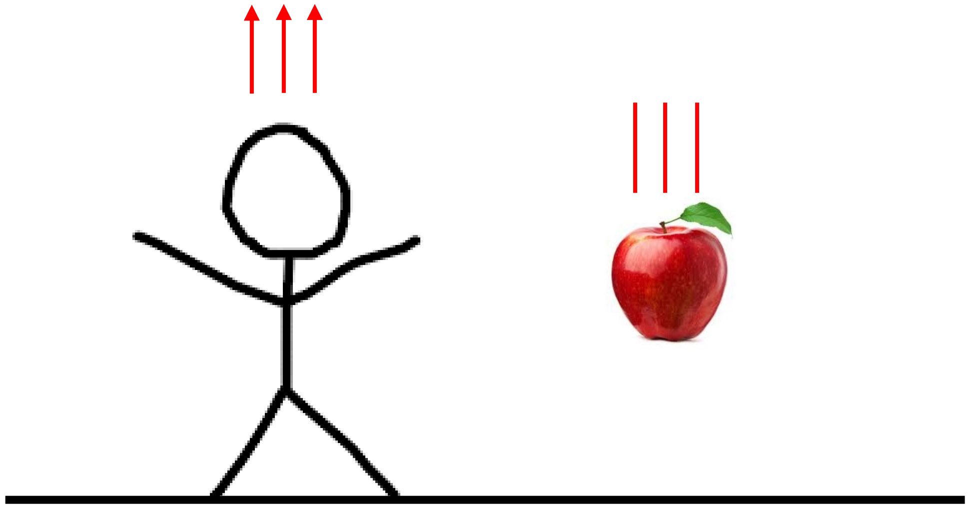
The equivalence principle

Gravity is a purely nonlocal phenomenon

Gravity cannot be observed in any local measurement



P. Asenbaum, C.O., and M. A. Kasevich, *Phys. Scr.* **99**, 046103 (2024)

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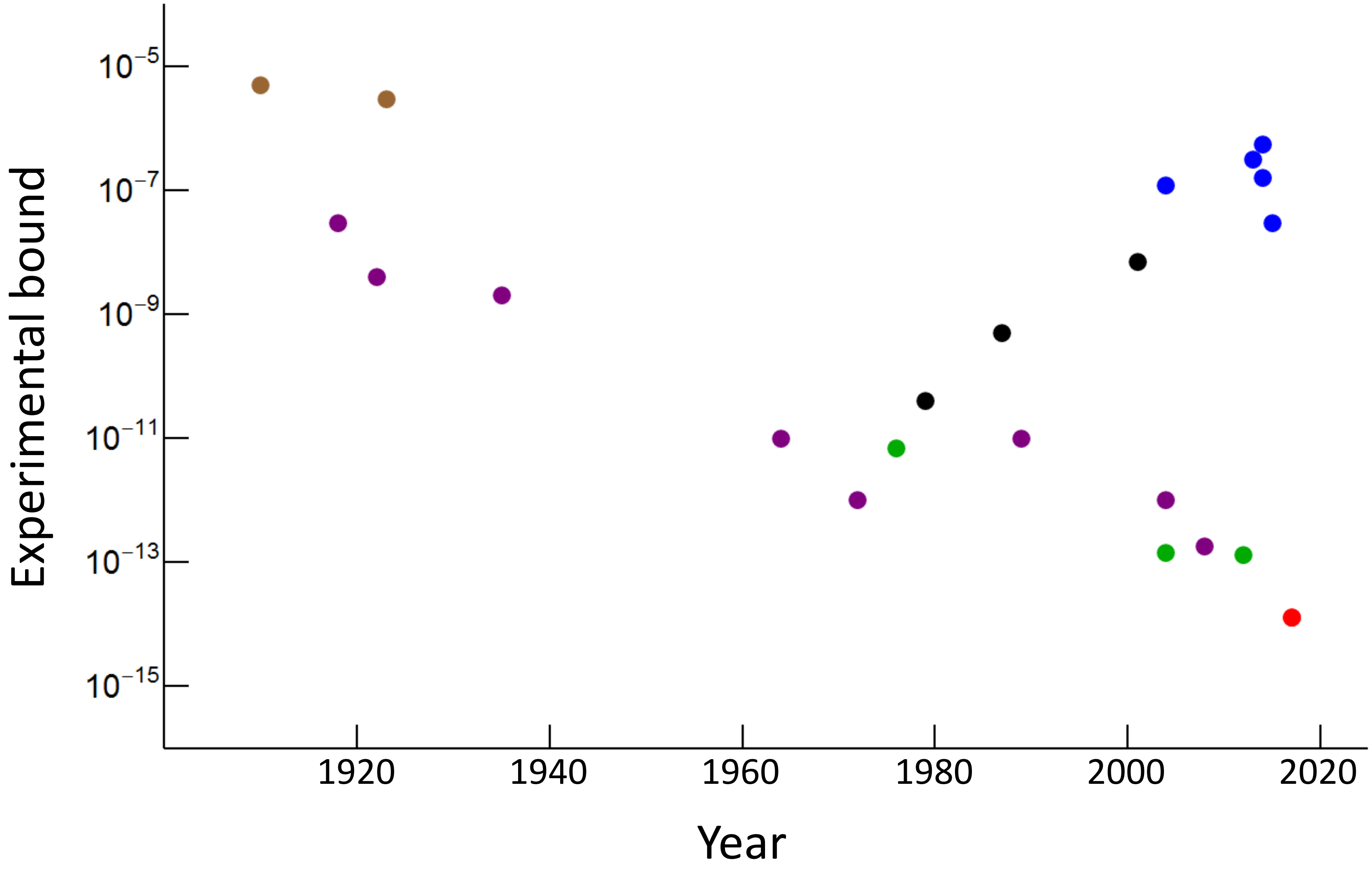
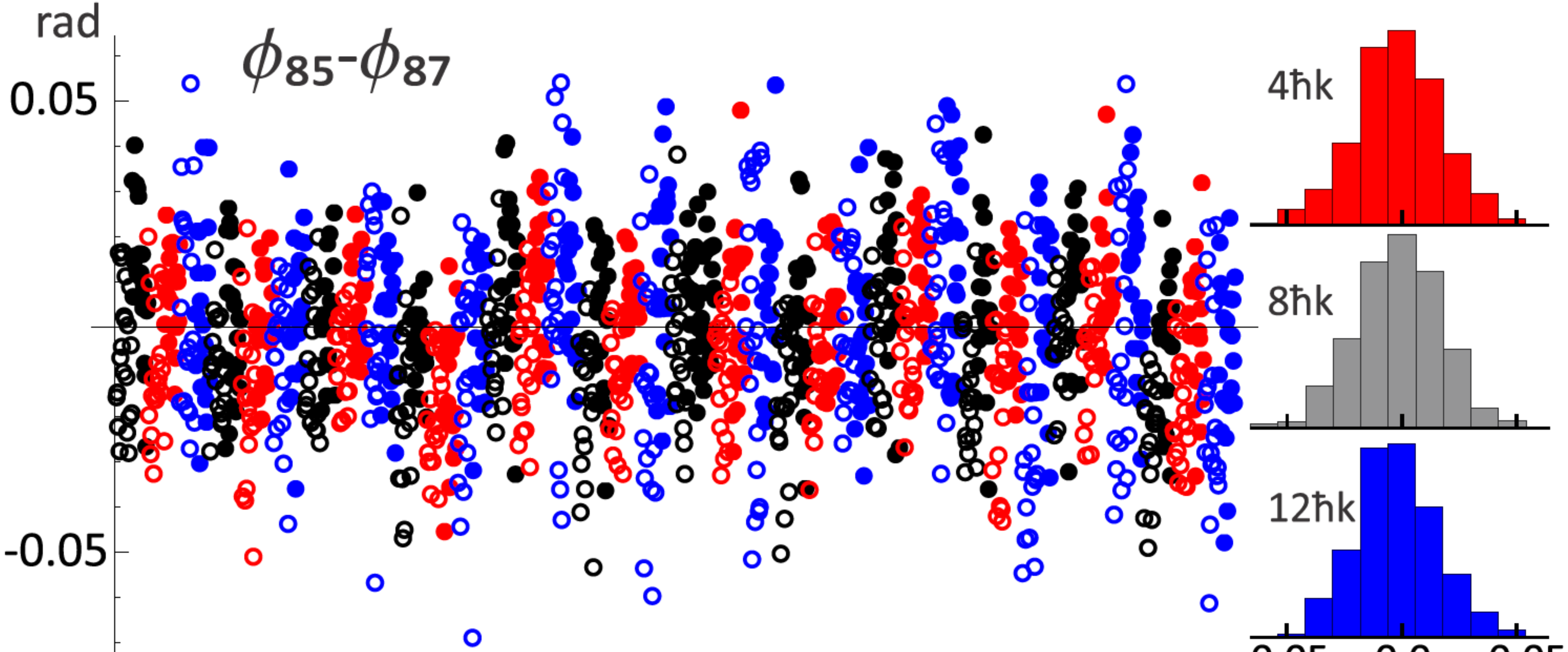
History of equivalence principle (EP) tests

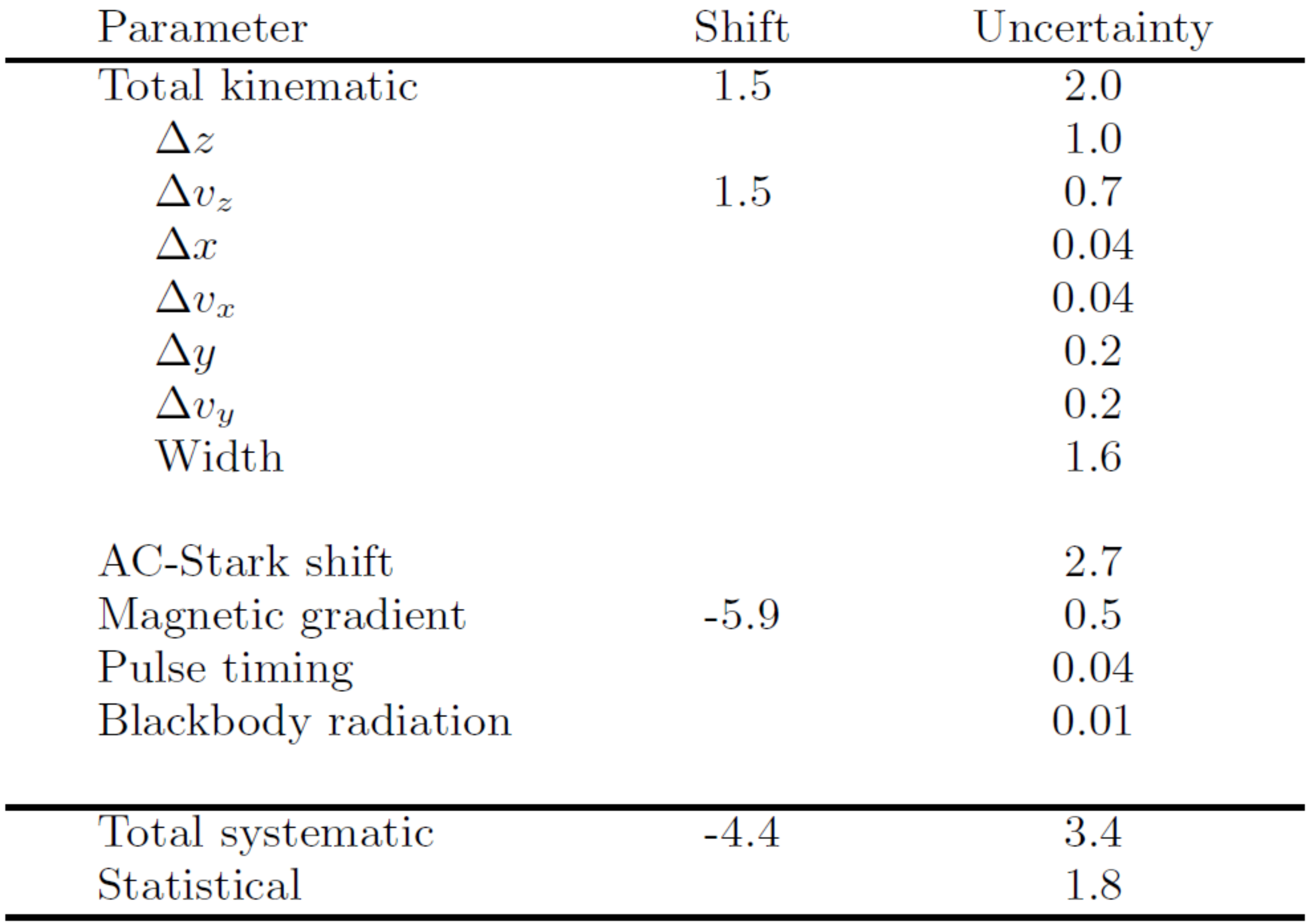


EP sensitivity



P. Asenbaum, C.O., et al., *Phys. Rev. Lett.* **125**, 191101 (2020)

Error table

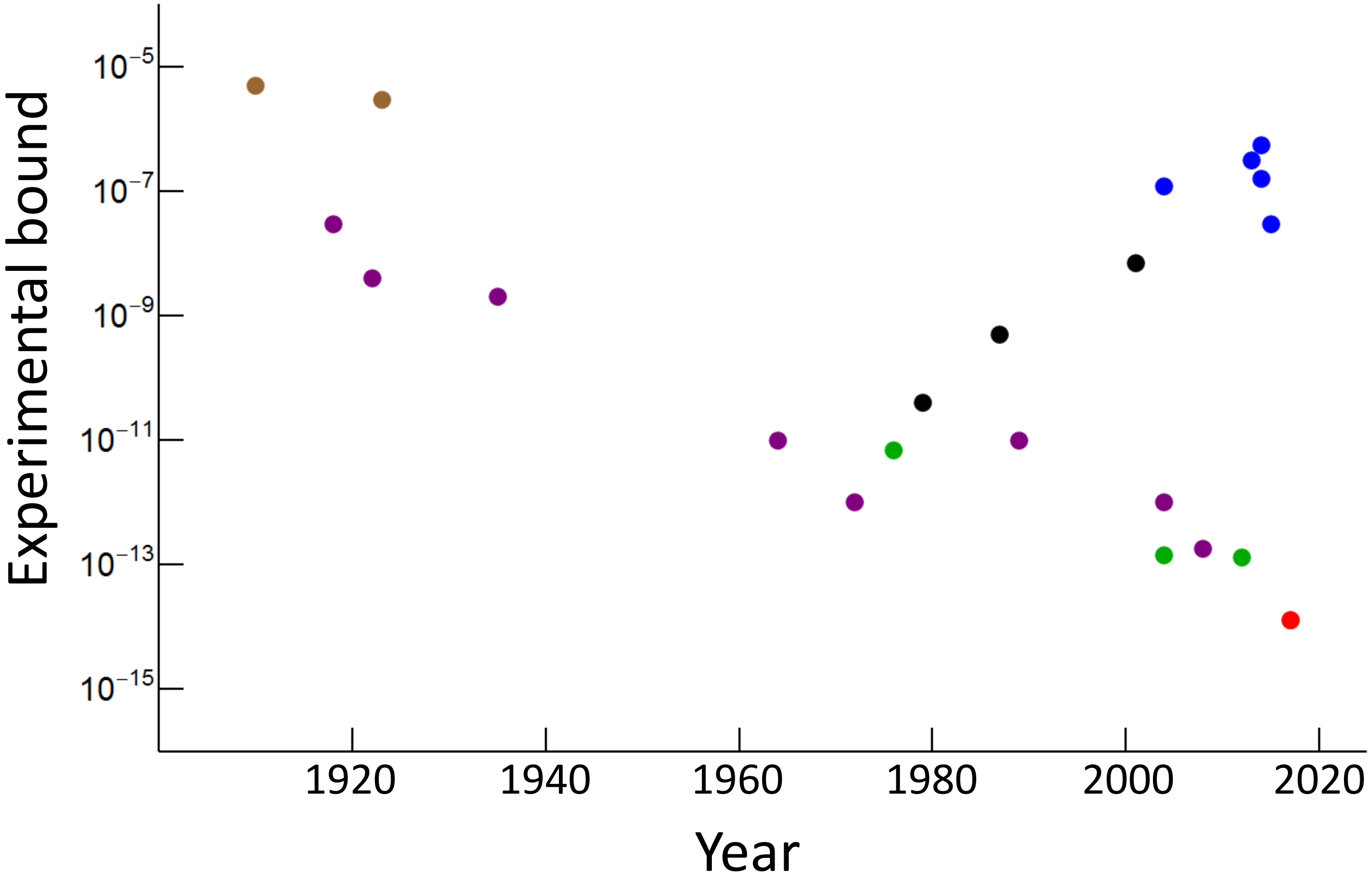


Parameter	Shift	Uncertainty
Total kinematic	1.5	2.0
Δz		1.0
Δv_z	1.5	0.7
Δx		0.04
Δv_x		0.04
Δy		0.2
Δv_y		0.2
Width		1.6
AC-Stark shift		2.7
Magnetic gradient	-5.9	0.5
Pulse timing		0.04
Blackbody radiation		0.01
Total systematic	-4.4	3.4
Statistical		1.8

P. Asenbaum, C.O., et al., *Phys. Rev. Lett.* **125**, 191101 (2020)

Result

$$\eta = [\qquad \pm 1.8\ (\text{stat}) \pm 3.4\ (\text{sys})] \times 10^{-12}$$



P. Asenbaum, C.O., et al., *Phys. Rev. Lett.* **125**, 191101 (2020)

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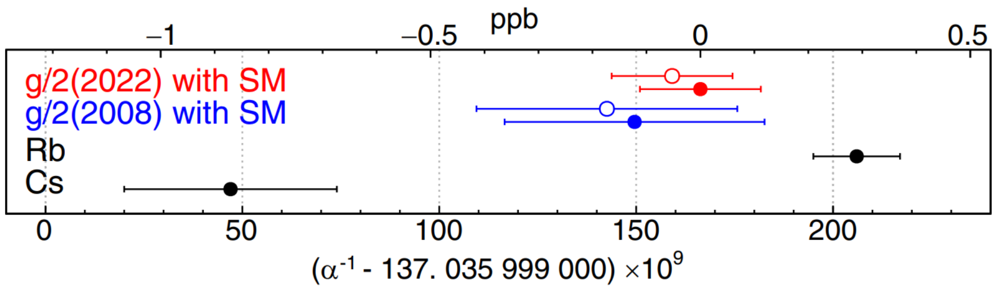
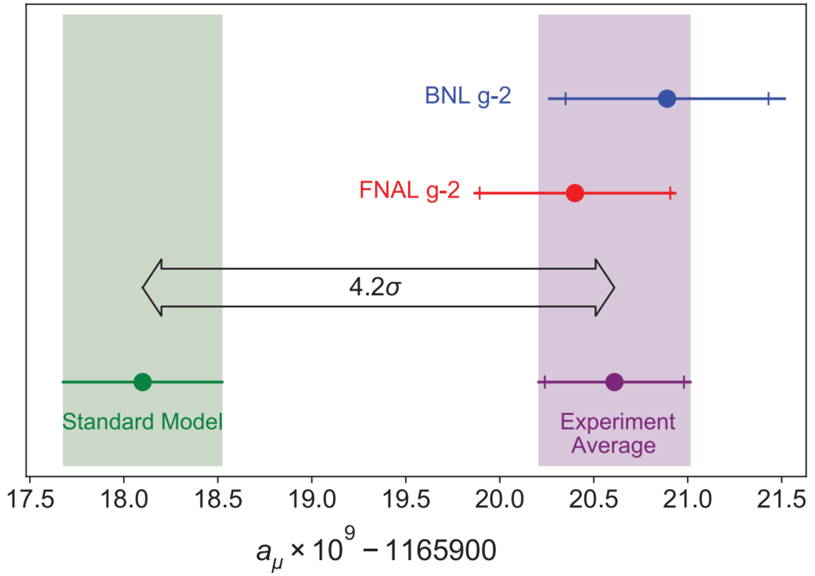
Measuring the fine-structure constant

The fine-structure constant α sets the strength of EM interactions.
-Measure with different systems -> test QED



X. Fan et al., *Phys. Rev. Lett.* **130**, 071801 (2023)



B. Abi et al., *Phys. Rev. Lett.* **126**, 141801 (2021)

$$\alpha^2 = \frac{2R_\infty}{c} \times \frac{m}{m_e} \times \frac{h}{m}$$

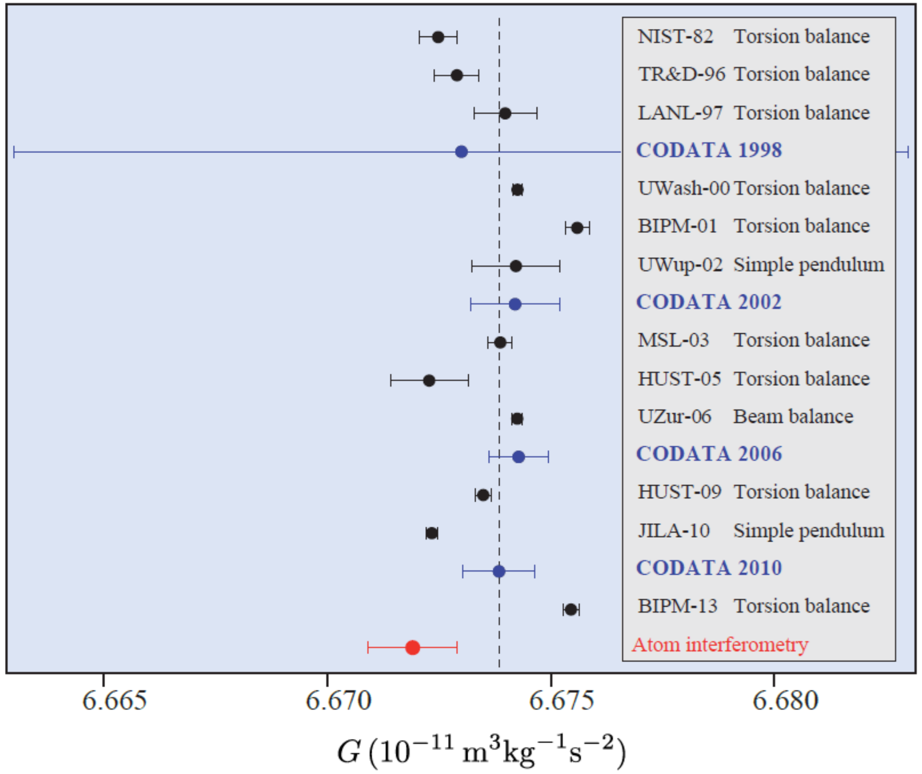
New physics should affect electron's magnetic moment!

Need 10x more accurate measurement of α to check

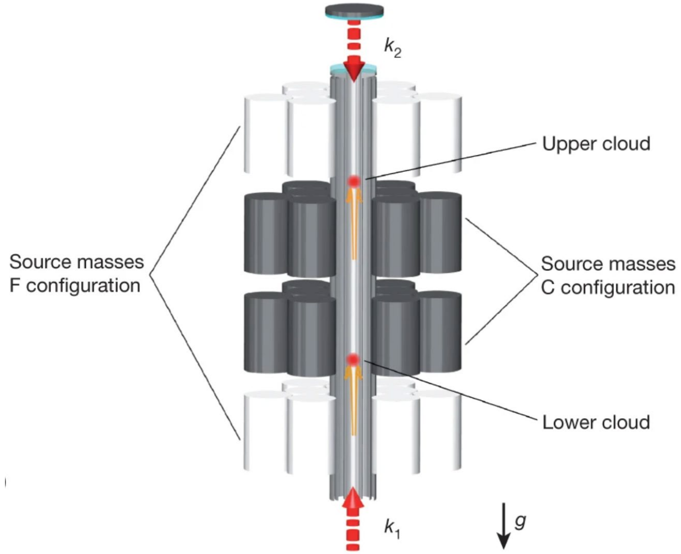
Measuring G

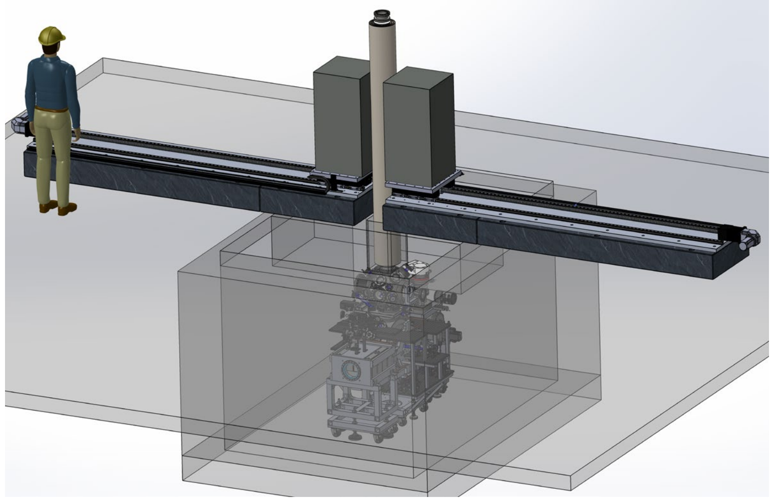
-Newton's constant G sets the strength of gravity

-Known with comparatively low precision (~20 ppm); prior measurements inconsistent



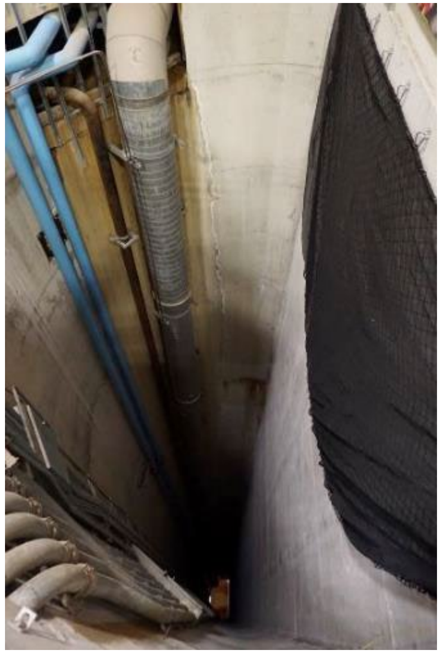
G. Rosi et al., *Nature* **510**, 514 (2014)

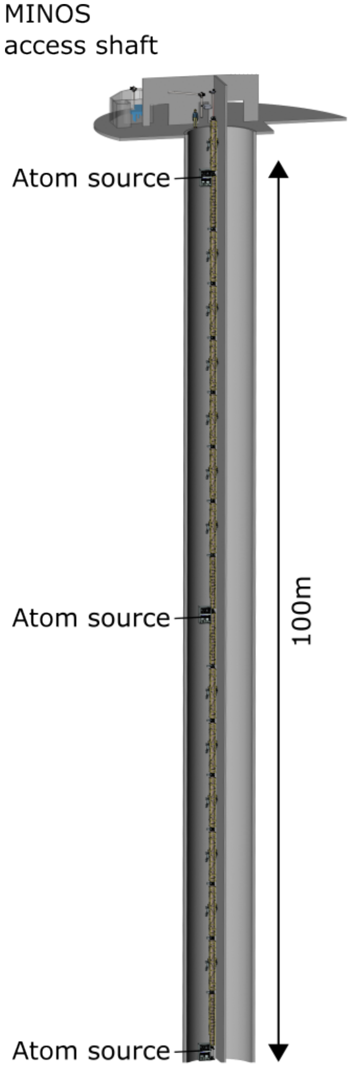


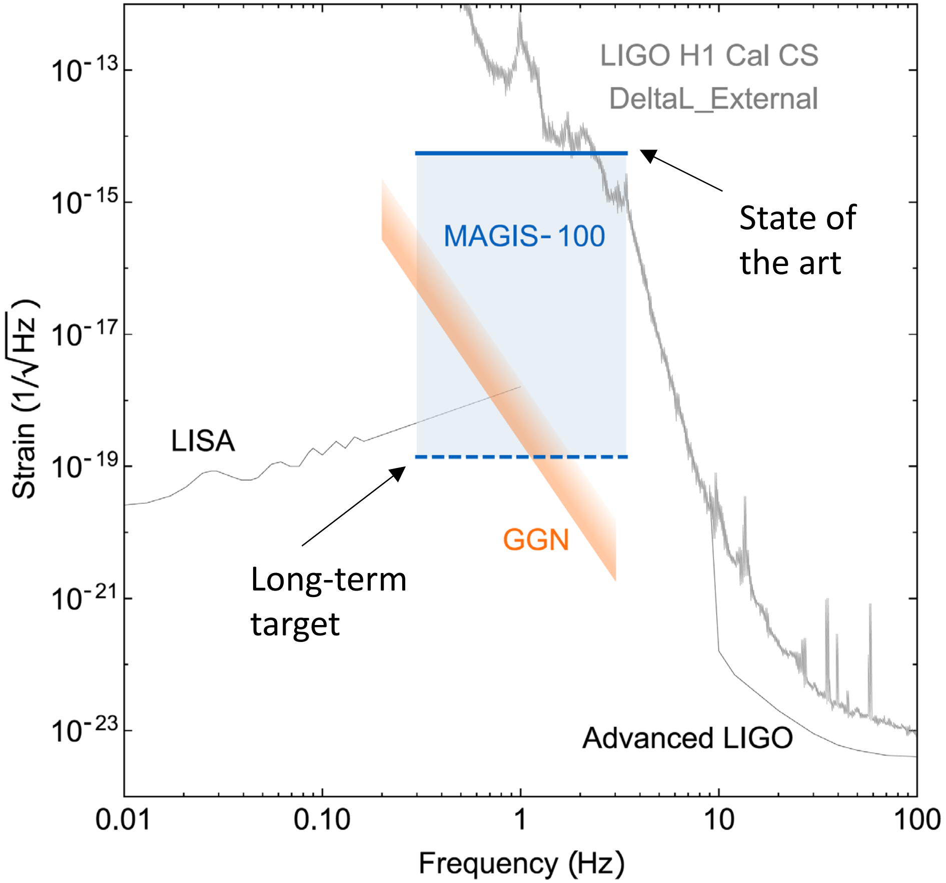


Kovachy lab, Northwestern

Gravitational wave detection and long-baseline interferometry







M. Abe et al., *Quantum Sci. Technol.* **6**, 044003 (2021)

Future EP tests with atom interferometry

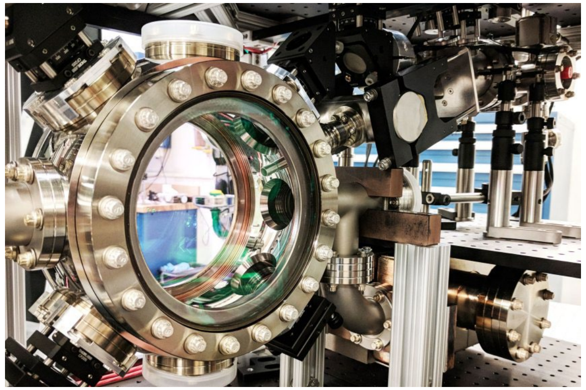
Systematic error reduction

- -Improved laser systems
- -Alkaline-earth atoms

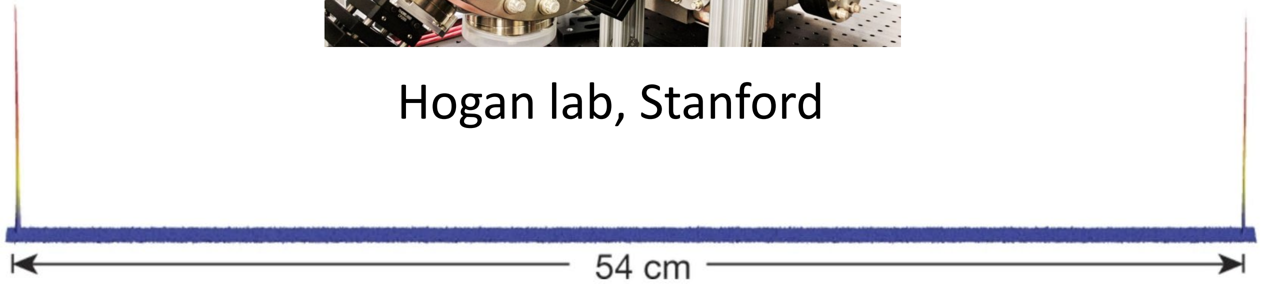
Sensitivity improvement:

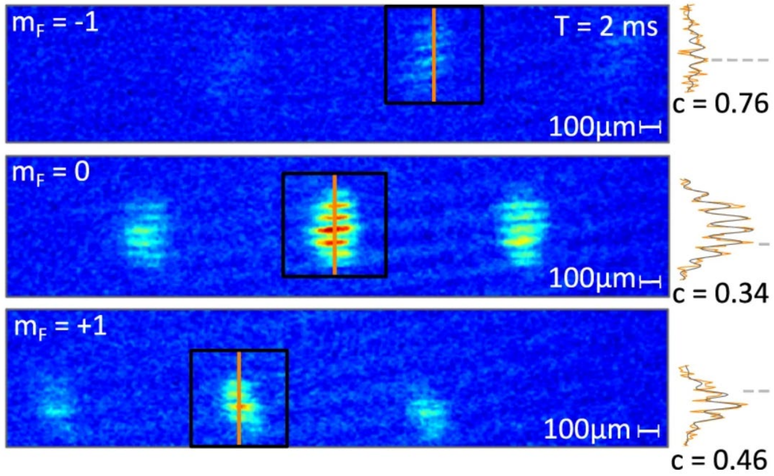
10^{-13} /(Hz)$^{1/2}$ and beyond

- -Higher LMT order
- -Increased interferometer time
- -Heavier test masses
- -Squeezed sources



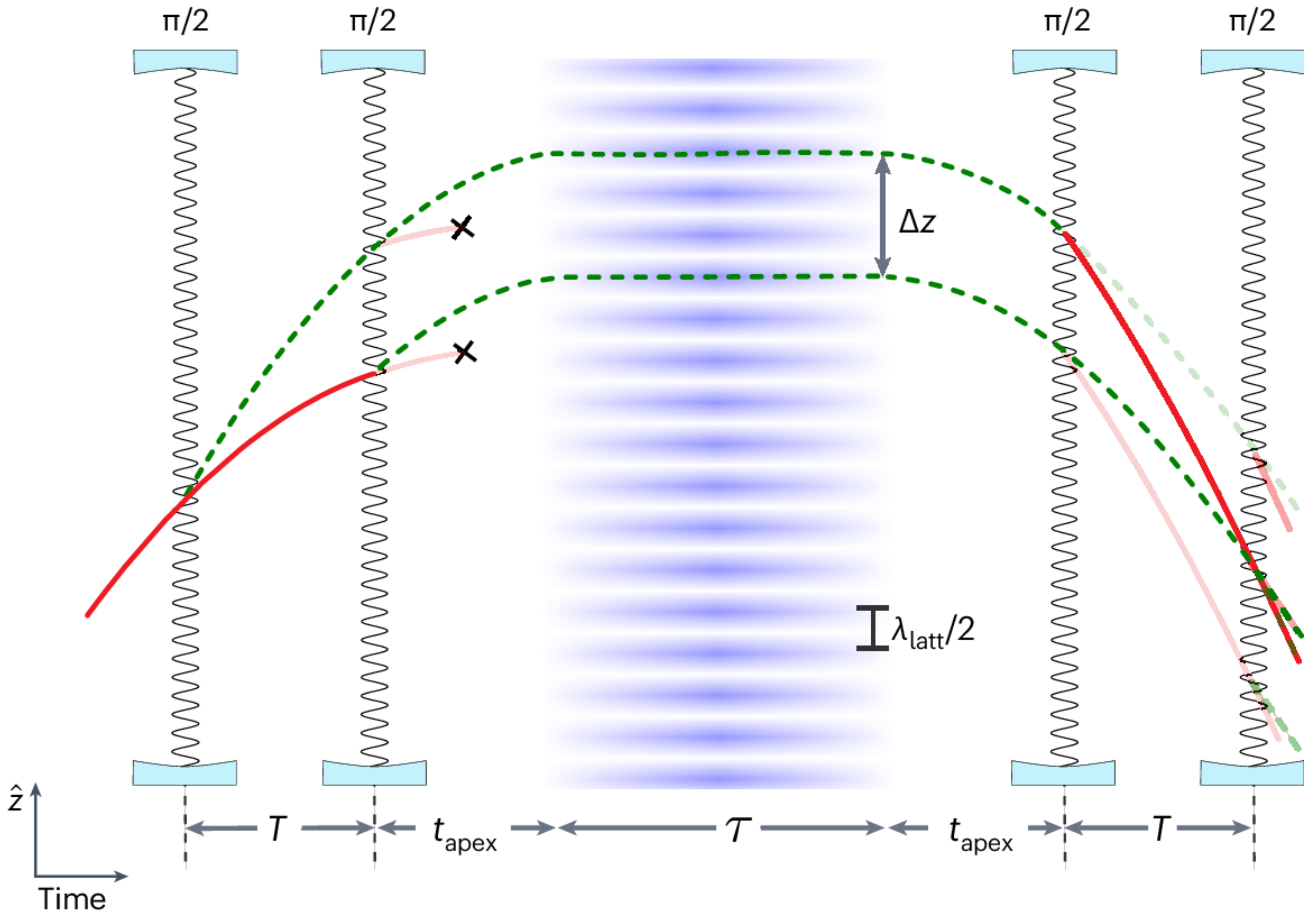
Hogan lab, Stanford





M. D. Lachmann et al., *Nat. Commun.* **12**, 1317 (2021)

New architecture: lattice atom interferometry



C. D. Panda et al., *Nat. Phys.* **20**, 1234 (2024)
C. D. Panda et al., *Nature* **631**, 515 (2024)

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Searching for dark matter

Energy density: 0.4 GeV/cm^3 in the lab

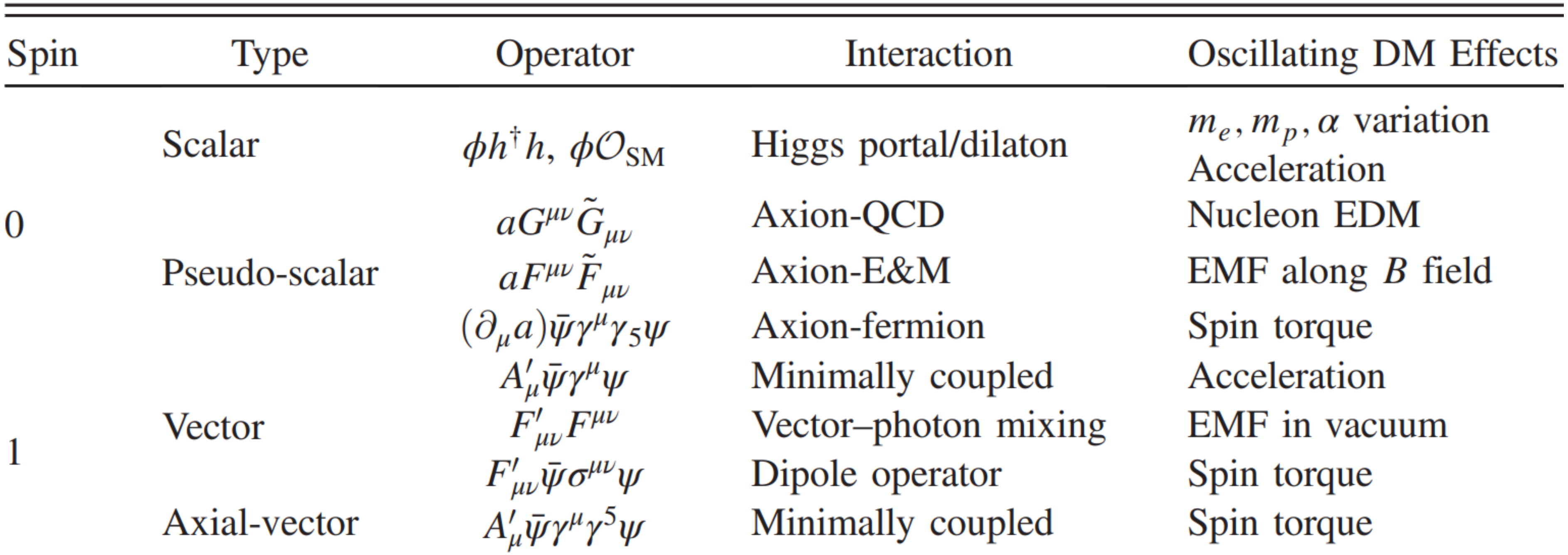
DM particle mass: unknown, between 10^{-22} eV and 10^{28} eV

Below 1 eV: DM phase space density > 1, behaves like a classical field

Lowest-order coupling of DM field to Standard Model:

all signals oscillate at DM Compton frequency

Ultralight dark matter couplings



Spin	Type	Operator	Interaction	Oscillating DM Effects
0	Scalar	$\phi h^\dagger h$, $\phi\mathcal{O}_{\mathrm{SM}}$	Higgs portal/dilaton	m_e, m_p, α variation Acceleration
	Pseudo-scalar	$aG^{\mu\nu}\tilde{G}_{\mu\nu}$	Axion-QCD	Nucleon EDM
		$aF^{\mu\nu}\tilde{F}_{\mu\nu}$	Axion-E&M	EMF along B field
		$(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi$	Axion-fermion	Spin torque
1	Vector	$A'_\mu\bar{\psi}\gamma^\mu\psi$	Minimally coupled	Acceleration
		$F'_{\mu\nu}F^{\mu\nu}$	Vector–photon mixing	EMF in vacuum
		$F'_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi$	Dipole operator	Spin torque
	Axial-vector	$A'_\mu\bar{\psi}\gamma^\mu\gamma^5\psi$	Minimally coupled	Spin torque

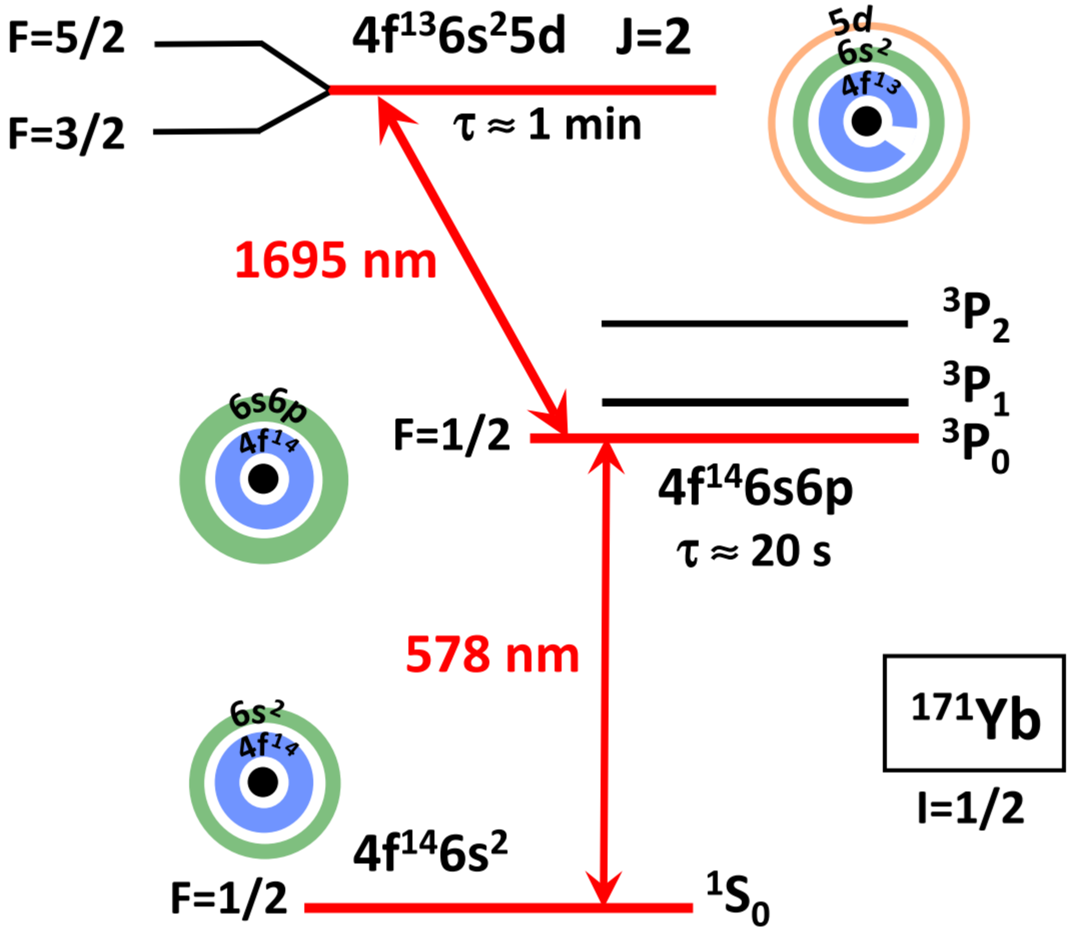
P. W. Graham et al., *Phys. Rev. D* **93**, 075029 (2016)

JHU experiment: Yb atomic fountain

Parameters:

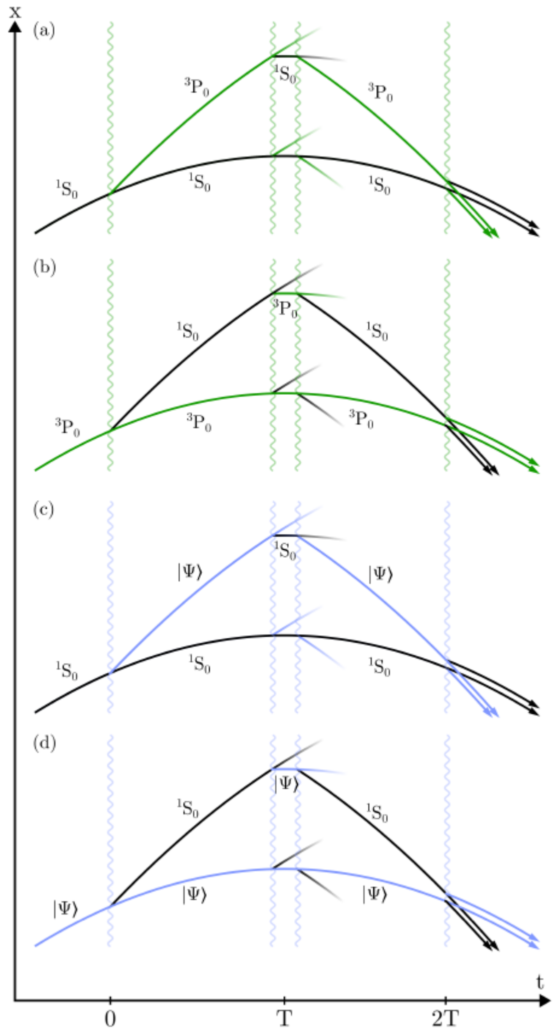
- 10^5 atoms per shot
- 2 meter interferometry region
- Interferometer time T = 0.6 seconds
- 10 second cycle time
- Up to 1000 photon beam splitters

Sensitivity: 10^{-8} Hz to 10 Hz
(10^{-22} eV to 10^{-13} eV)

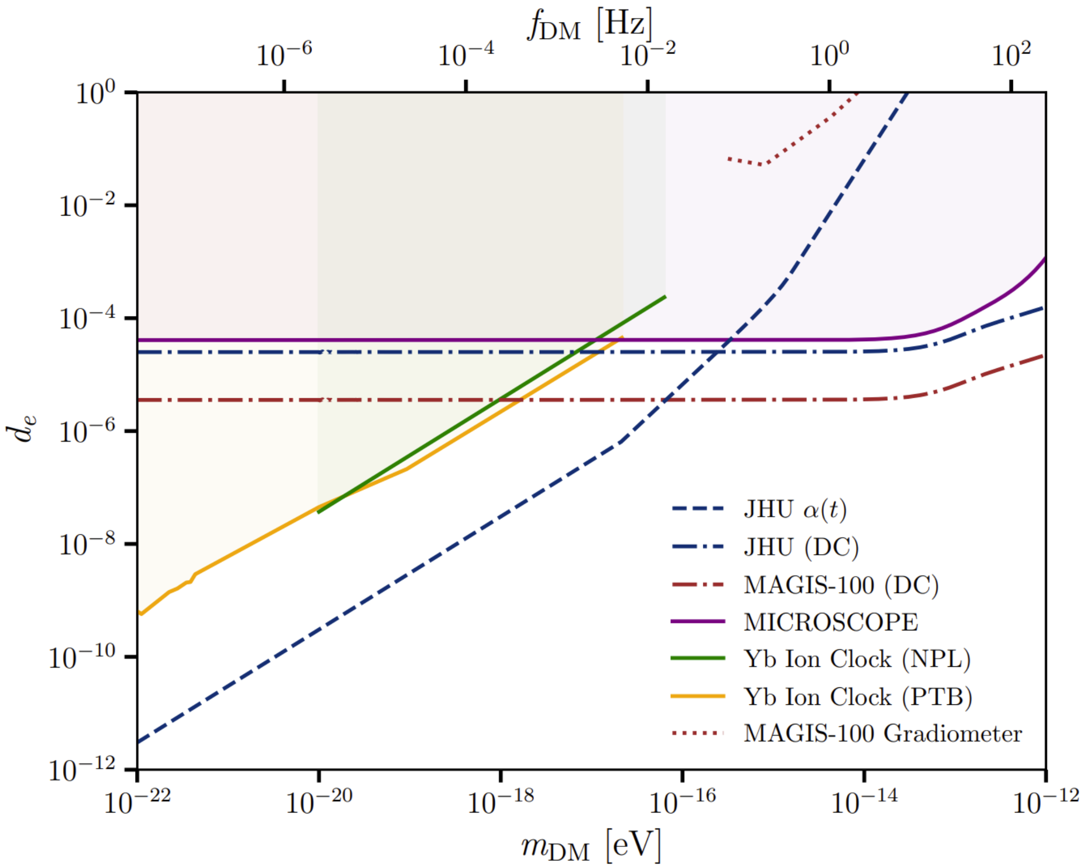


M. S. Safronova et al., *Phys. Rev. Lett* **120**, 173001 (2018)

Measurement 1: differential spectroscopy



Y. Zhou et al., *Phys. Rev. A* **110**, 033313 (2024)



P. Touboul et al., *Phys. Rev. Lett.* **129**, 121102 (2022)
M. Filzinger et al., *Phys. Rev. Lett.* **130**, 253001 (2023)
N. Sherrill et al., *New J. Phys.* **25**, 093012 (2023)

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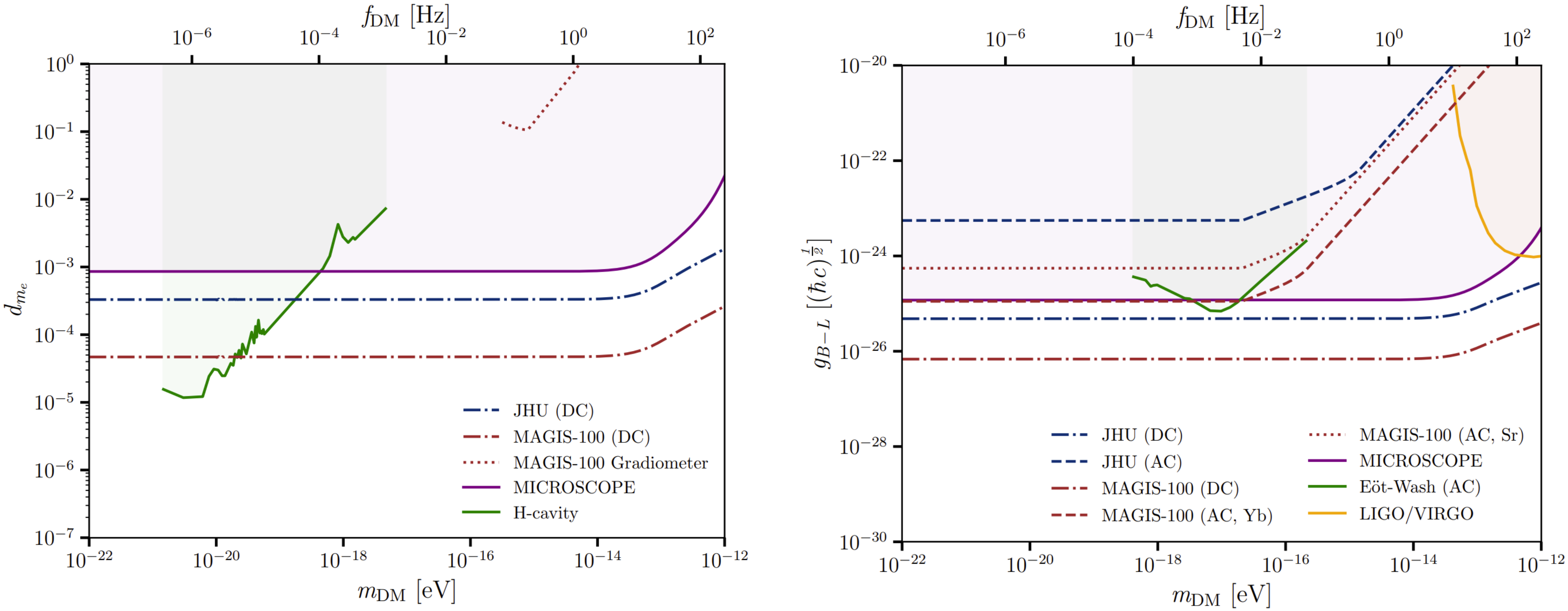
Measurement 2: differential acceleration



P. Touboul et al., *Phys. Rev. Lett.* **129**, 121102 (2022)
E. A. Shaw et al., *Phys. Rev. D* **105**, 042007 (2022)
LIGO Scientific Collaboration et al., *Phys. Rev. D* **105**, 063030 (2022)
C. J. Kennedy et al., *Phys. Rev. Lett.* **125**, 201302 (2020)

Y. Zhou et al., *Phys. Rev. A* **110**, 033313 (2024)

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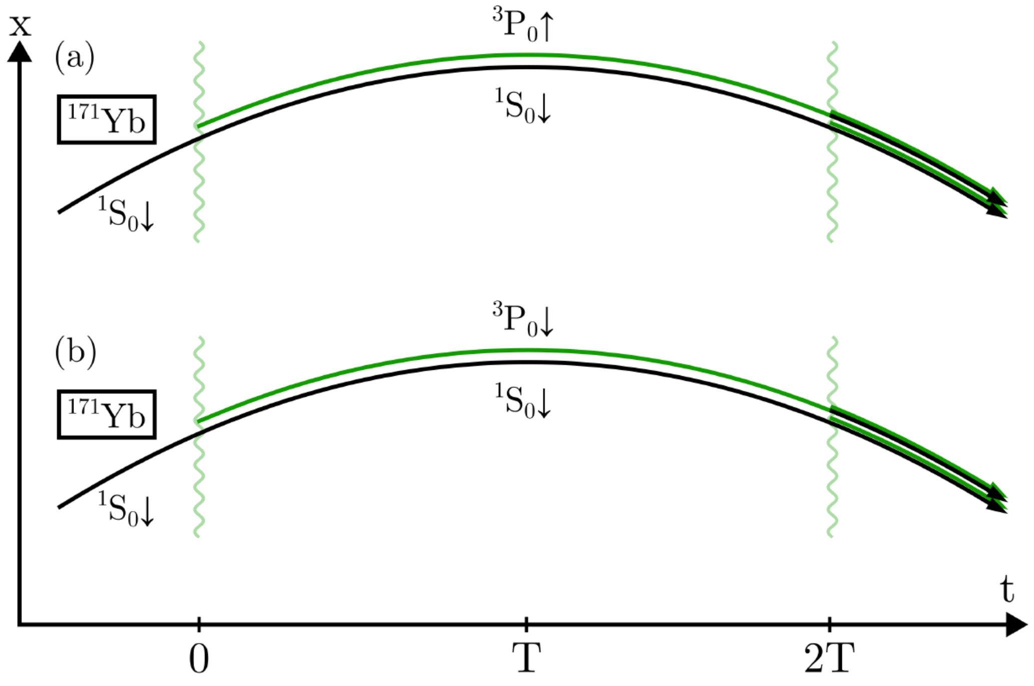
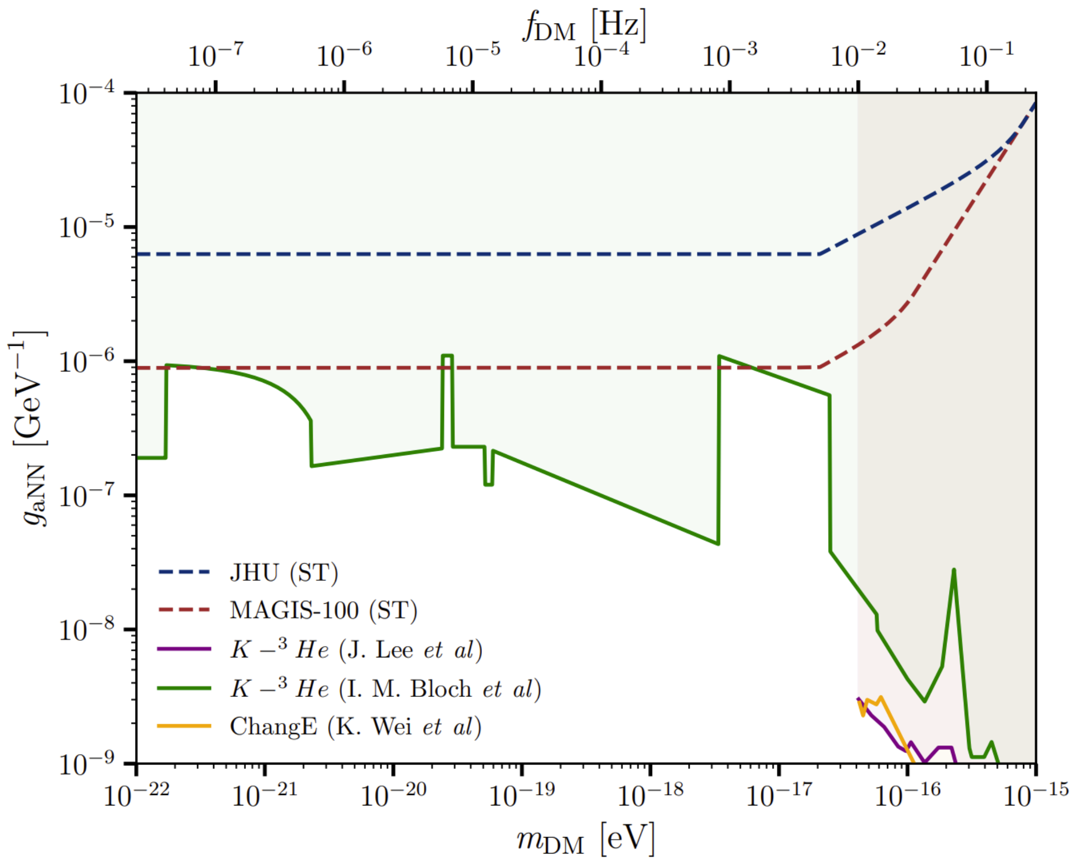
Measurement 3: spin torque



Y. Zhou et al., *Phys. Rev. A* **110**, 033313 (2024)



I. M. Bloch et al., *JHEP* **167** (2020)
J. Lee et al., *Phys. Rev. X* **13**, 011050 (2022)
K. Wei et al., arXiv:2306.08039 (2024)

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Summary

Atom interferometers have been used to:

-test the equivalence principle at the 10^{-12} level

-measure the fine-structure constant and Newton’s constant G

Future experiments seek to:

-detect gravitational waves

-search for dark matter

For a wide class of “inertial measurements,” atoms are ideal.

Acknowledgments

EP team: Minjeong Kim, Joseph Curti, Mark Kasevich

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JHU team: Rose Ranson, Yifan Zhou, Michalis Panagiotou

Looking for postdocs!

c.overstreet@jhu.edu

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