Quantum Metrology and Sensing with an

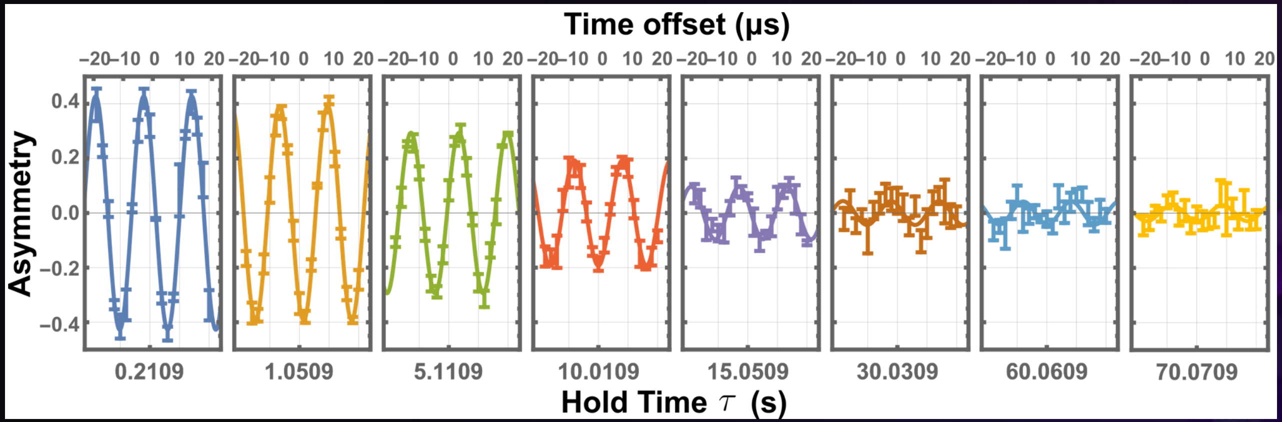
Atomic Spatial Superposition State Coherent for One Minute

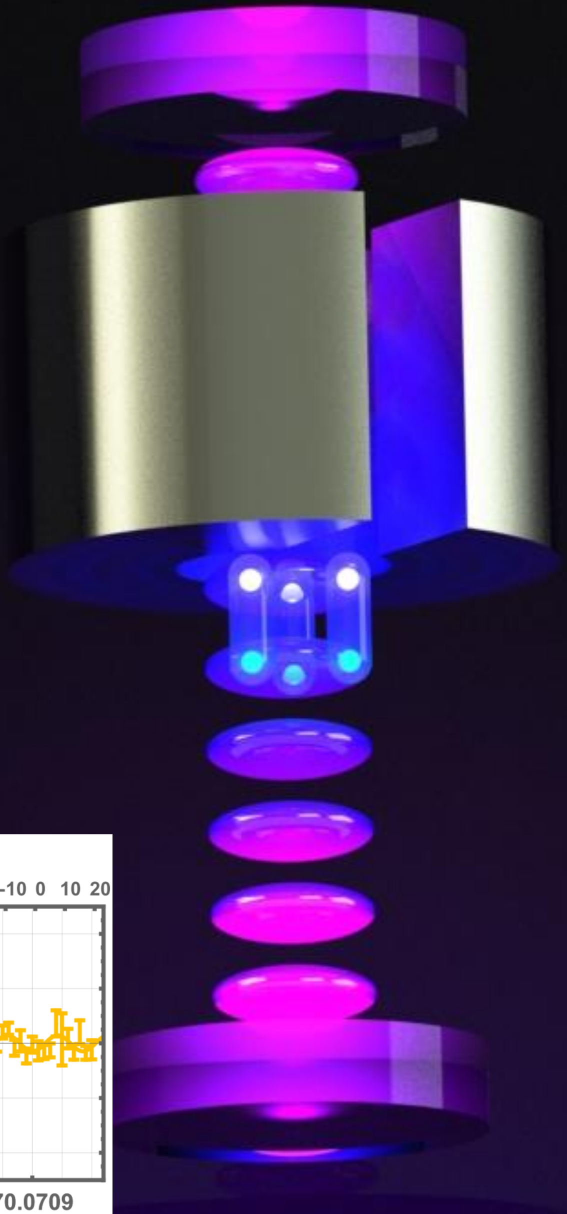
Cris Panda

University of Arizona

CLIVAR 2026

08/03/2026

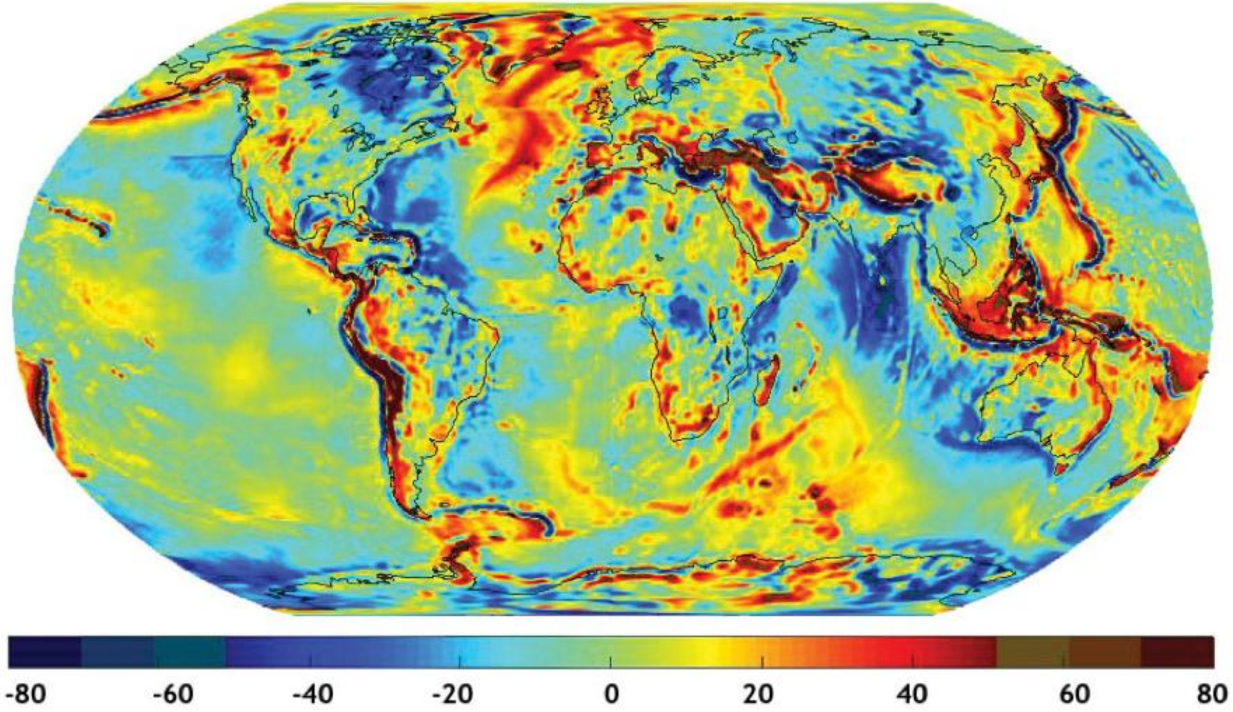




Gravity measurements from Space and on Earth

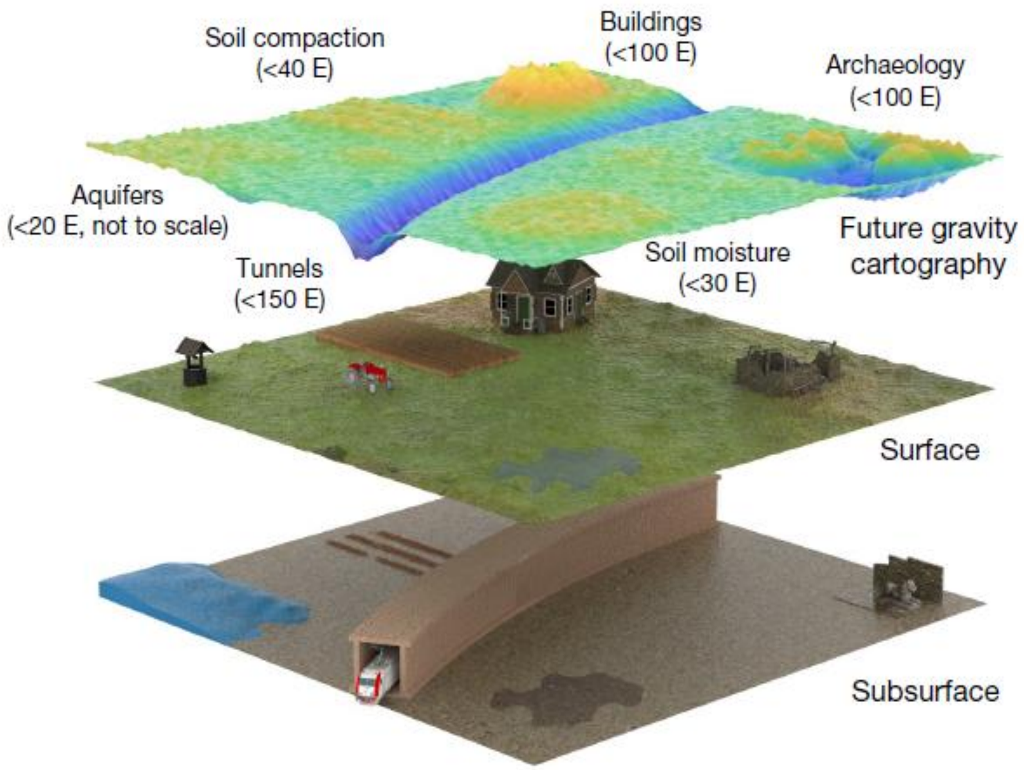
Gravimetry

Earth's gravity field measured by GRACE + GOCE



Gravity Anomaly. Units: 1 mGal = 1 µg = 10^{-5} m/s^2

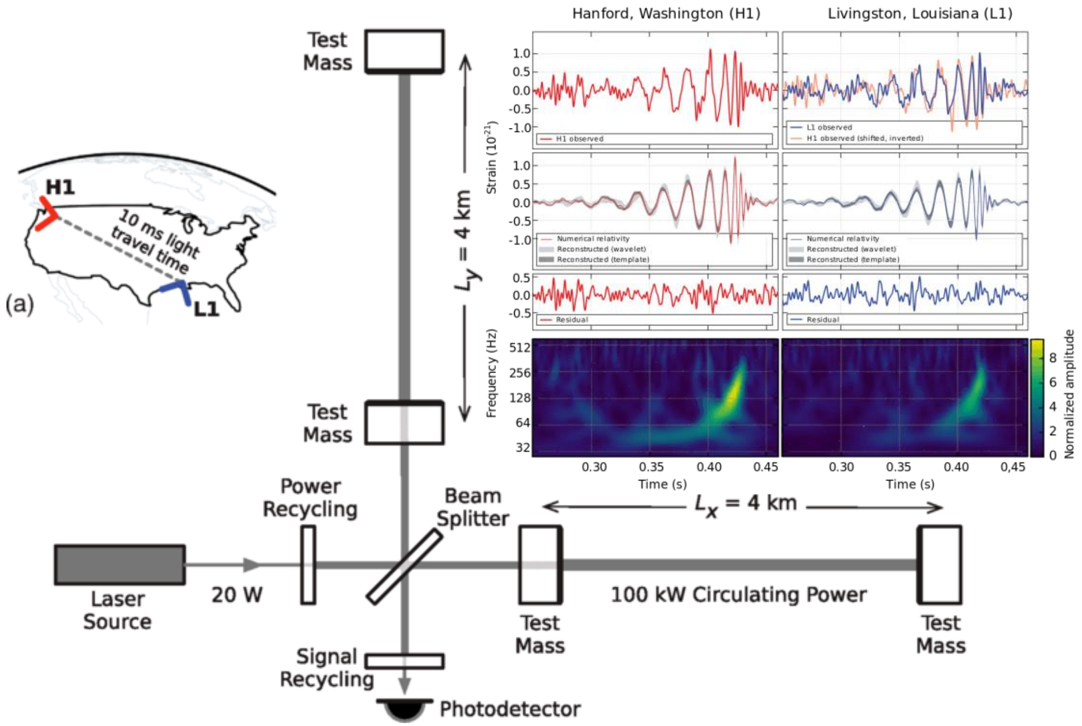
Gradiometry



Gravity Gradient. Units: 1 Eotvos = 10^{-9} /s^2

Interferometers

- Light (Laser) Interferometer
  - Use matter to control light



Interferometers

- Light (Laser) Interferometer
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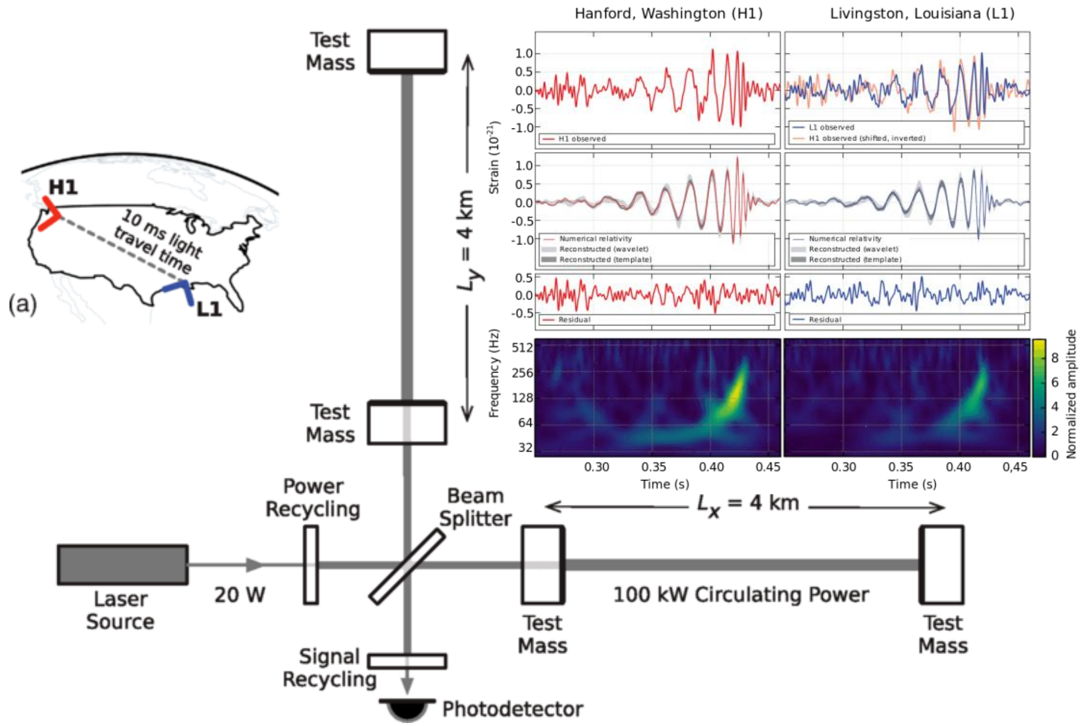
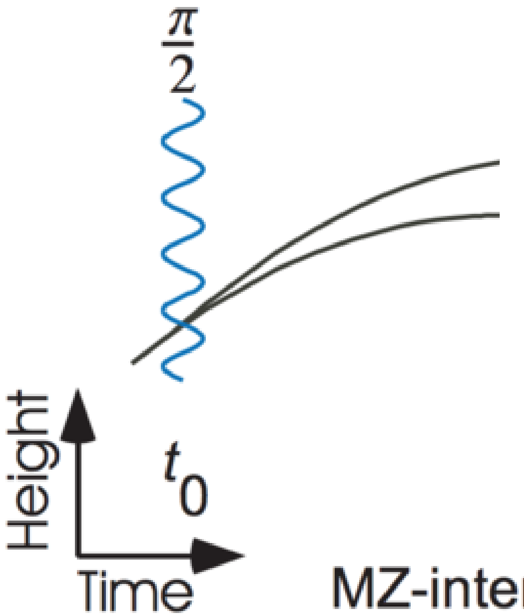
- Atom Interferometer
  - Use light to control atoms





MZ-interferometer

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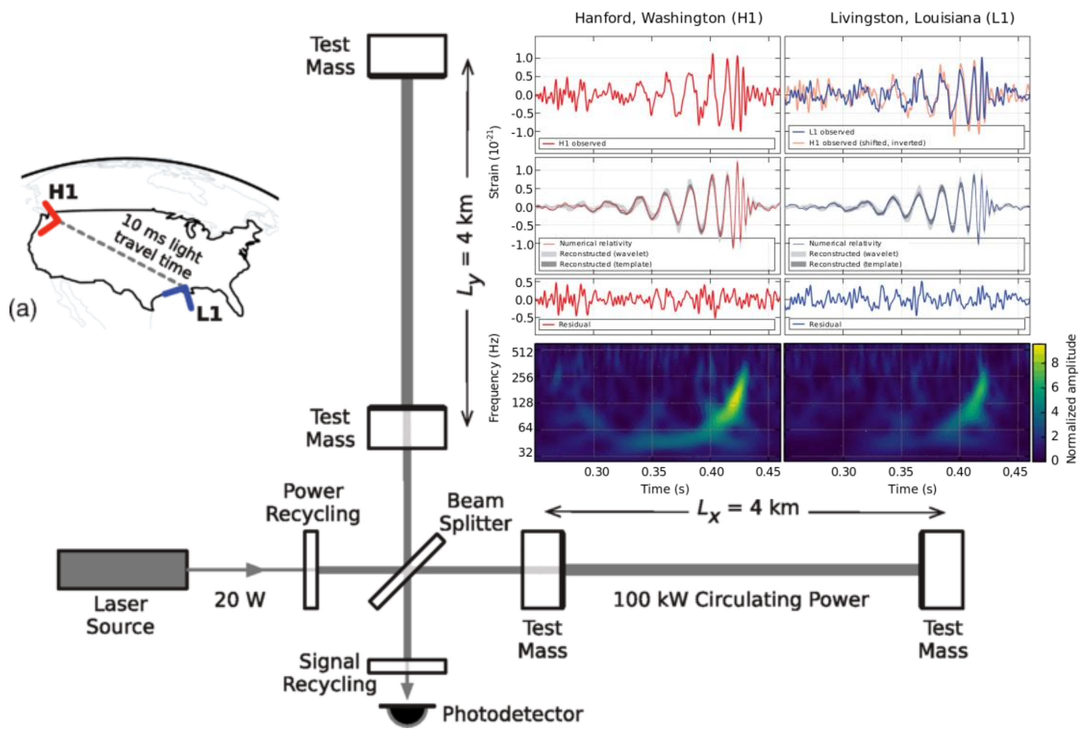

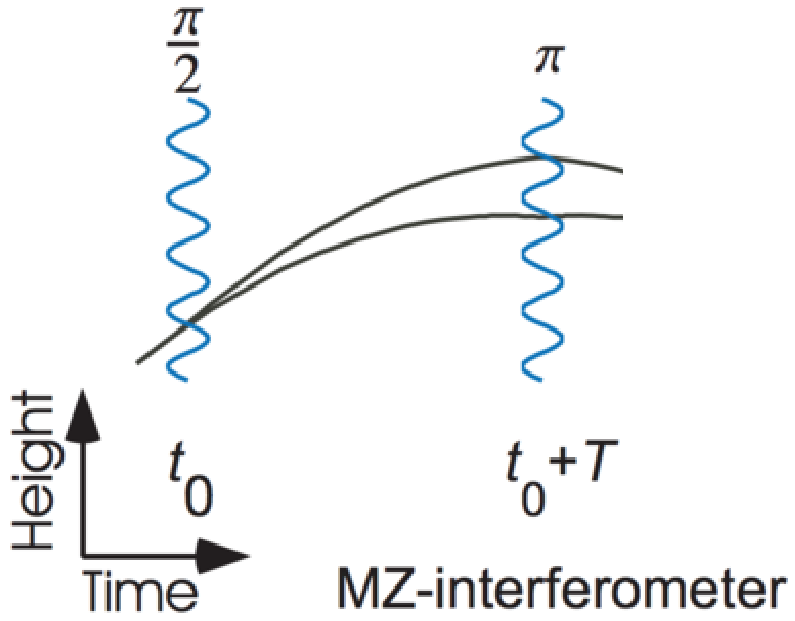

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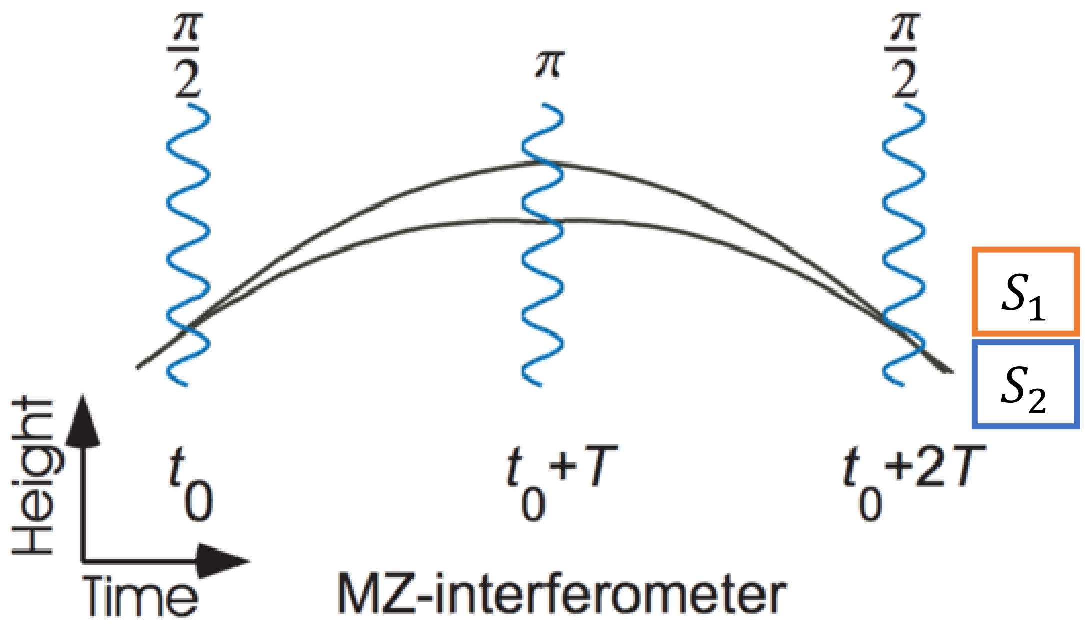

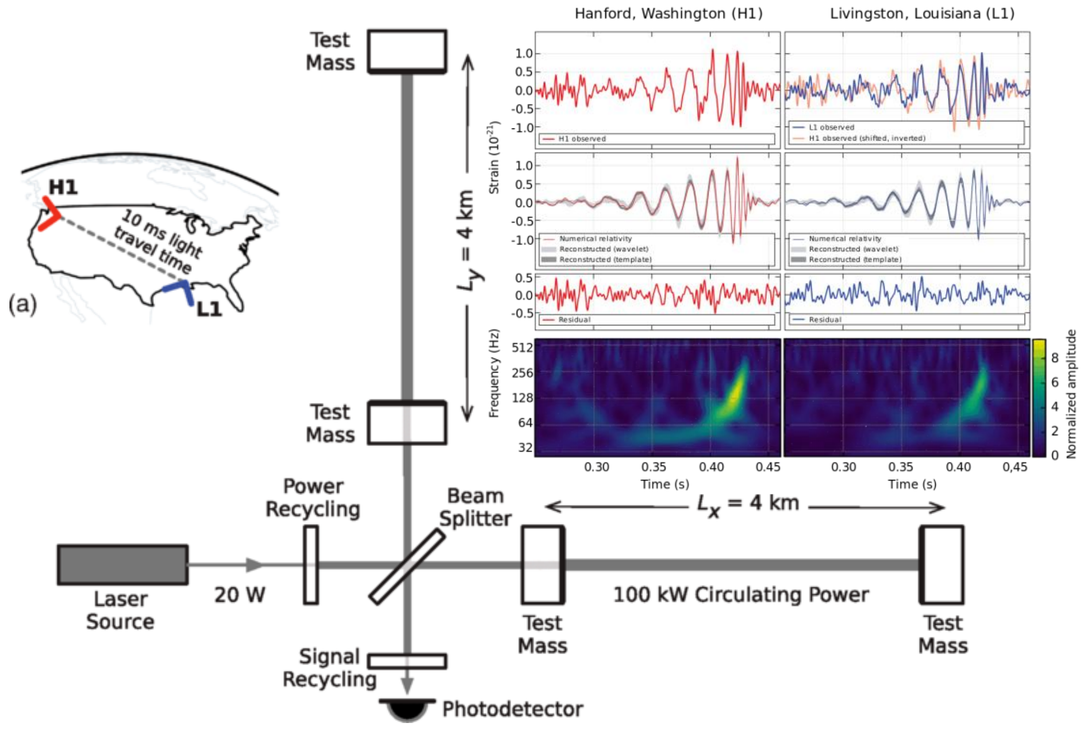

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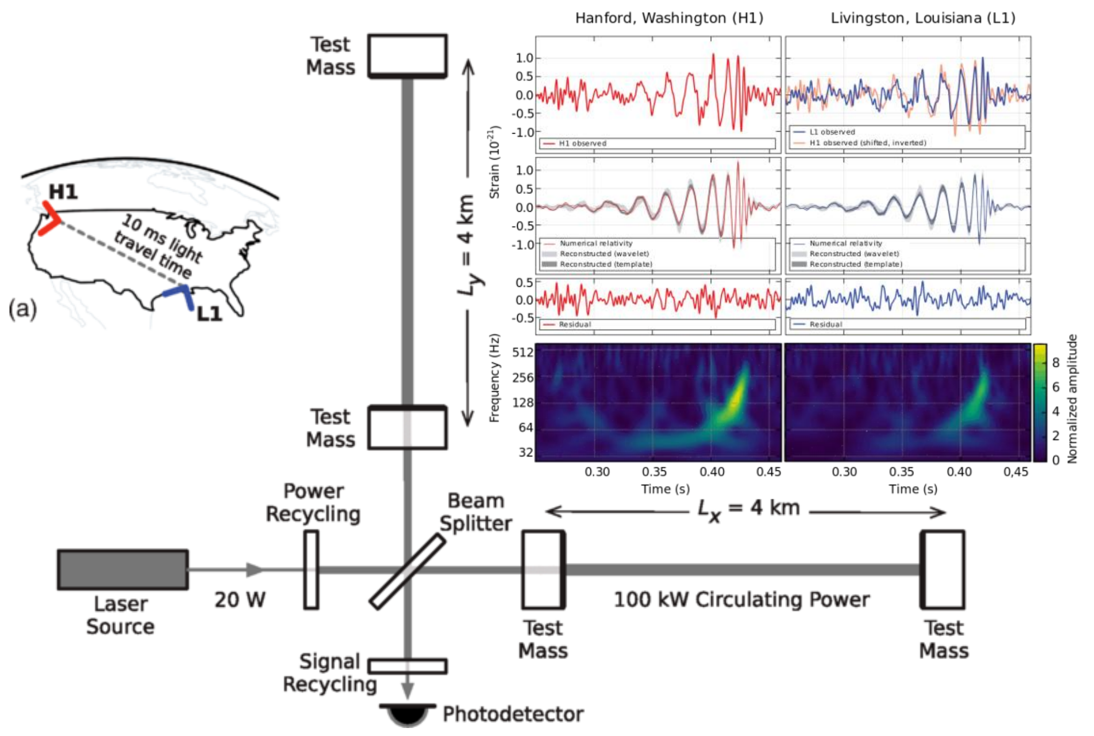
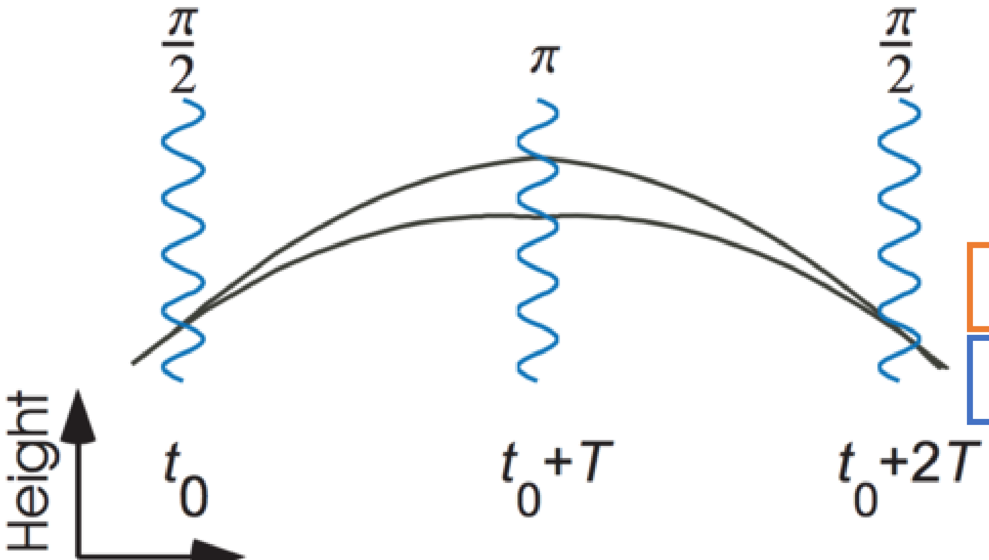




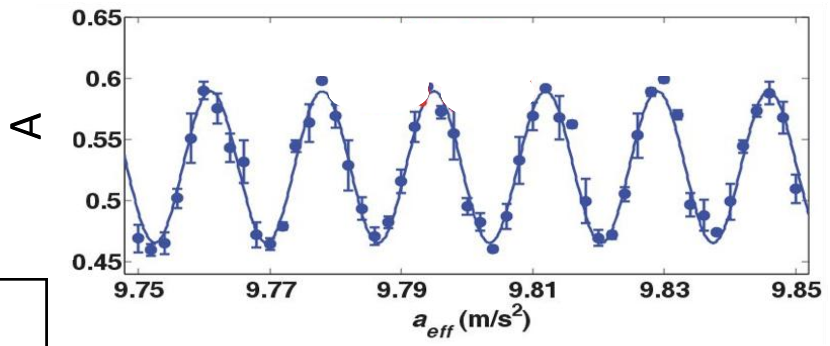
MZ-interferometer

$\boxed{S_1}$

$\boxed{S_2}$

$$A = \frac{\boxed{S_1} - \boxed{S_2}}{\boxed{S_1} + \boxed{S_2}}$$

$$A = C\sin(\Delta\phi)$$



Atom Interferometer Phase

- <u>Propagation phase</u>

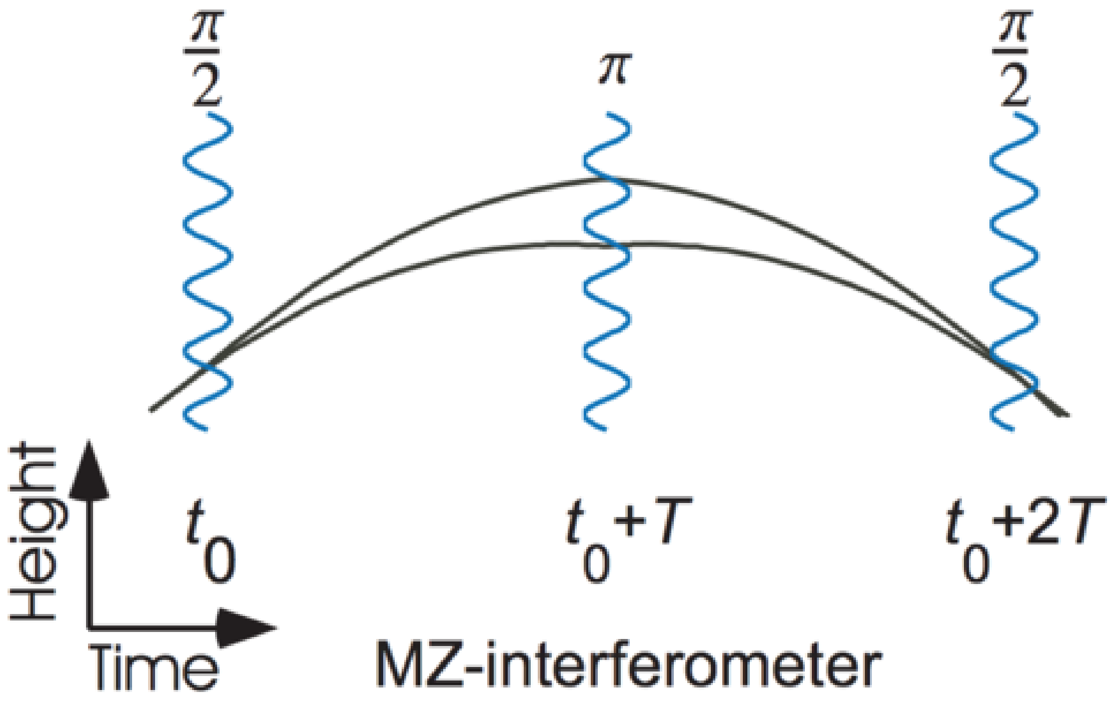
determined by Lagrangian

$\phi_{\text{prop}} = 1/\hbar \int L\, dt$

- <u>Atom-laser interaction phase</u>

laser acts as ruler

$\phi_{\text{laser}} = k\, z$



Atom Interferometer Phase

- <u>Propagation phase</u>

determined by Lagrangian

$\phi_{\text{prop}} = 1/\hbar \int L\, dt$

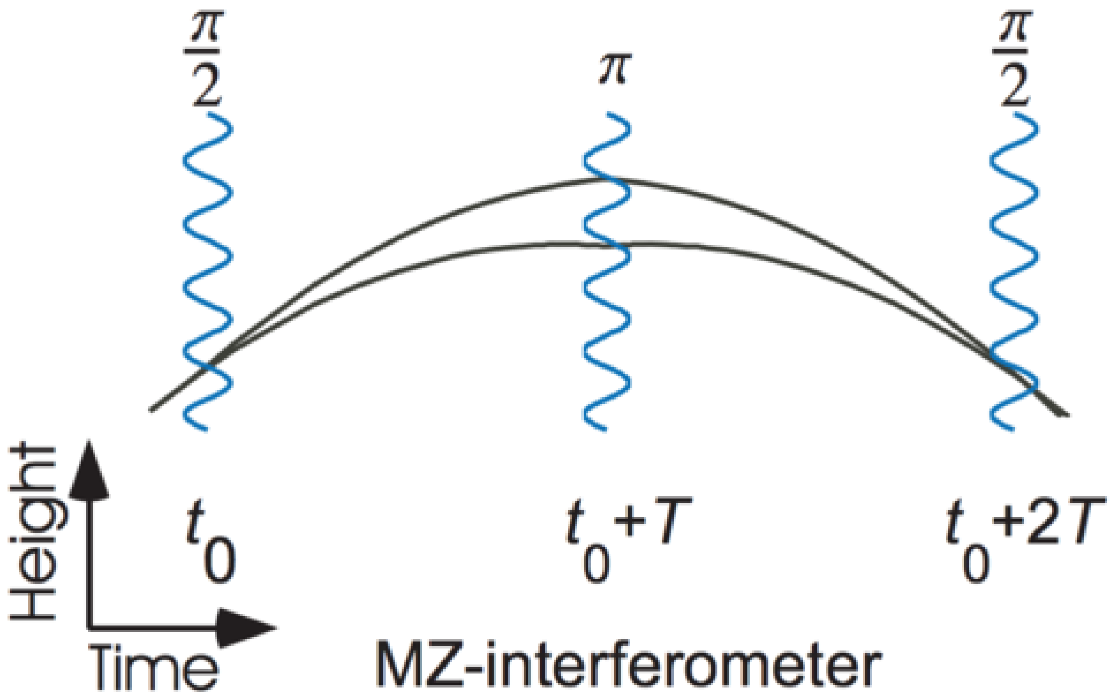
- <u>Atom-laser interaction phase</u>

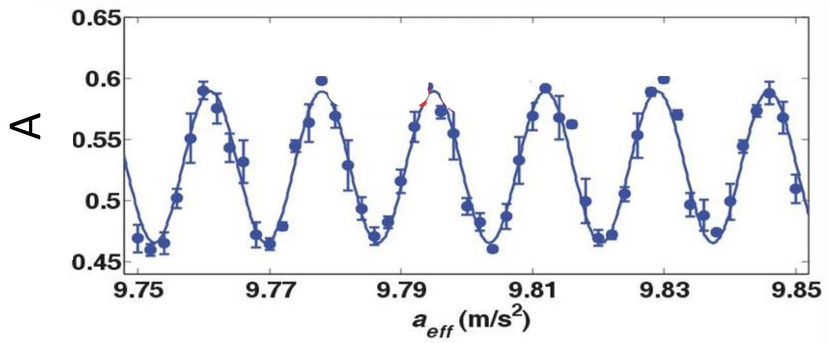
laser acts as ruler

$\phi_{\text{laser}} = k\, z$

- Total phase $> 10^9$ radians possible

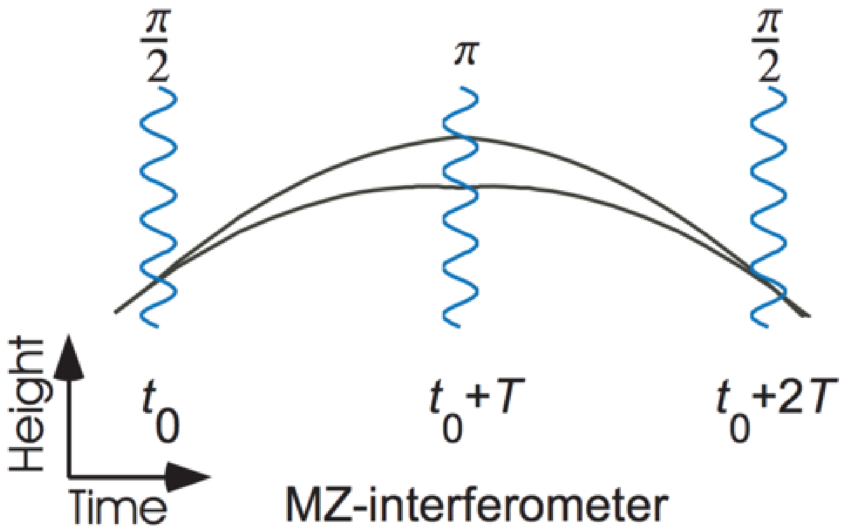
$$\boxed{\Delta\phi = k\, g\, T^2}$$

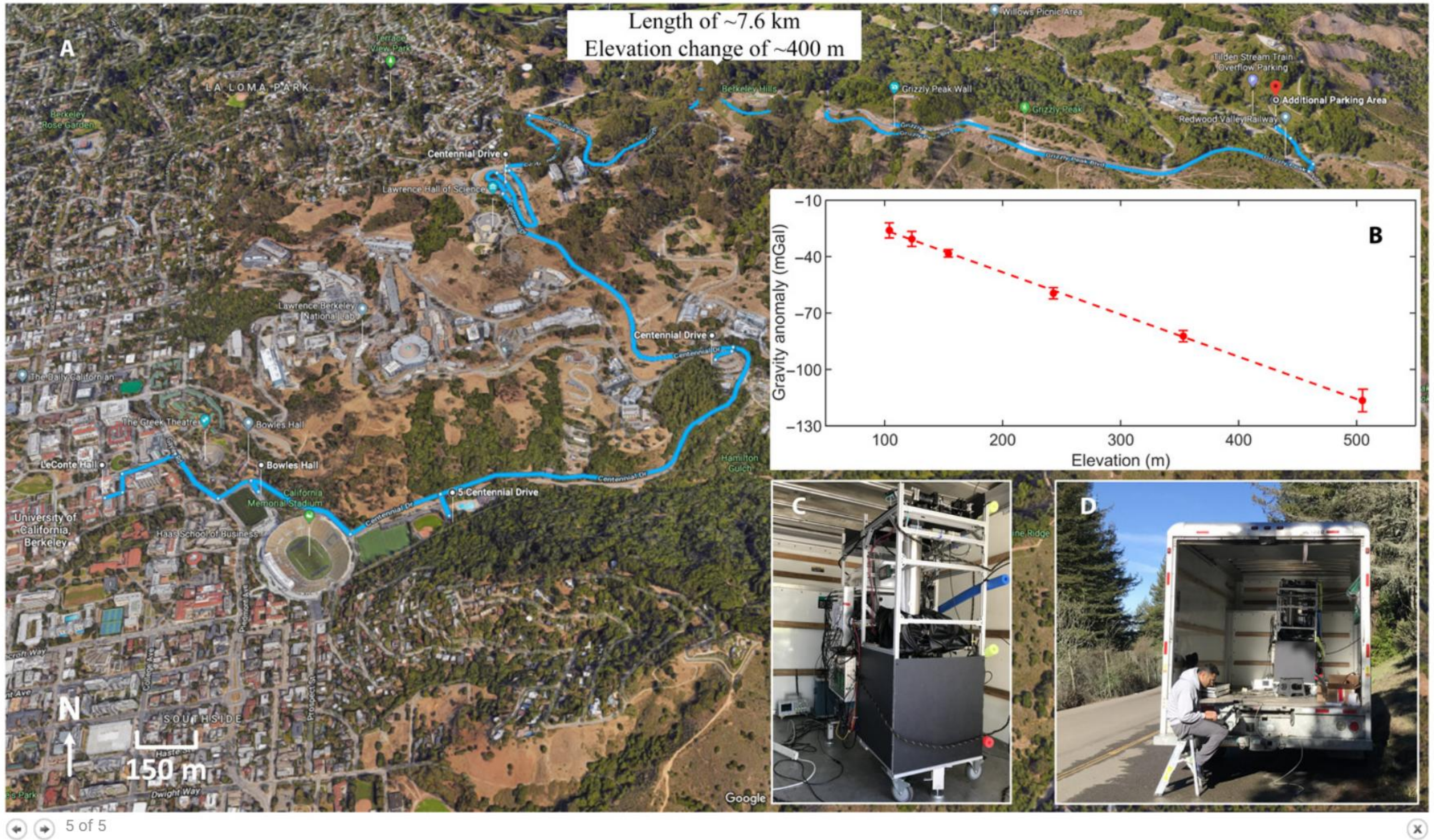




Quantum Sensing using Atom Interferometer

- Measure local gravity, geophysics, inertial sensing.





Commercial atomic gravimeters:

- VectorAtomic
- AOSense
- iXBlue

etc.

X. Wu, et. al., *Science Advances* 5(9), eaax0800 (2019)

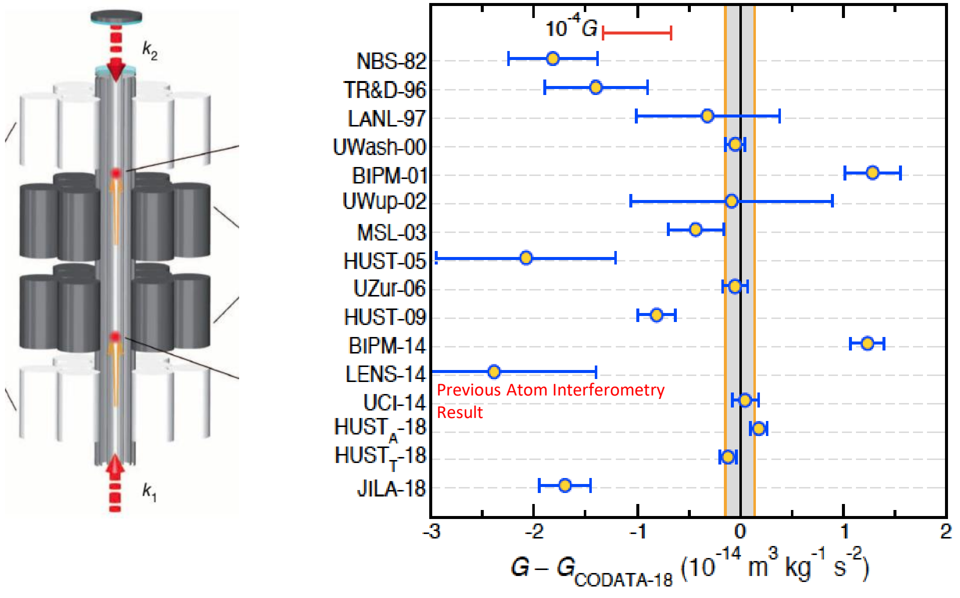
Precision Interferometry

- **The gravitational constant G**
- **Fifth force searches**

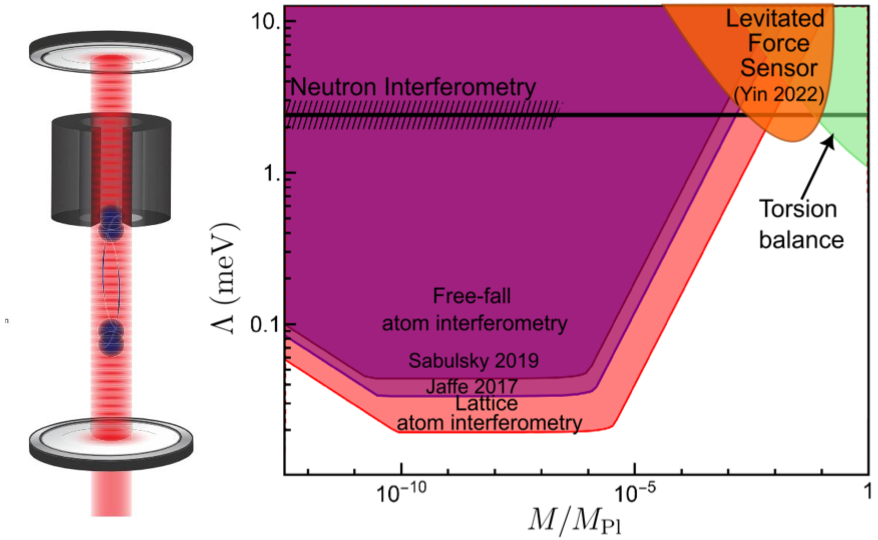
Many others

- The fine structure constant α
- Testing weak equivalence principle
- Quantum and gravity
- Proposed searches for gravitational waves
- Searches for dark matter

etc…



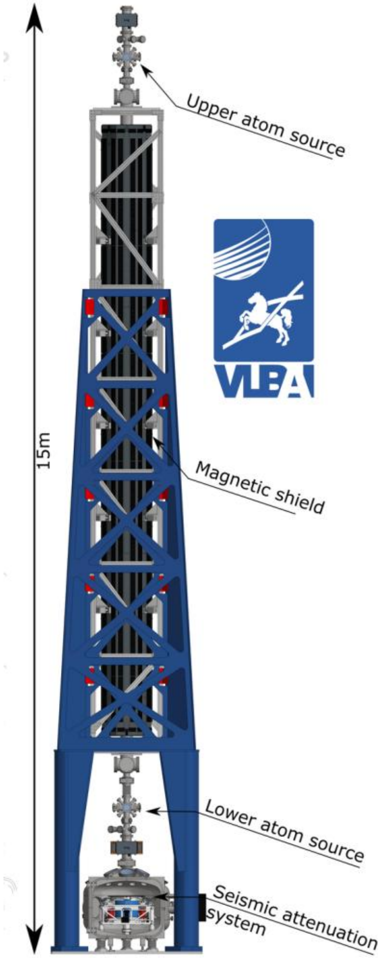
G. Rosi, et. al., Nature. 510, 518–521 (2014)



M. Jaffe et al., Nature Physics **14**, 257–260 (2017)
D. O. Sabulsky, et. al., PRL 123, 061102 (2019)

Interferometers Limited by Free-Fall Time

I. Atomic Fountains



Stanford, 10m fountain, T ~2 seconds

Hannover, VLBAI fountain

II. Zero-G planes, Drop towers, Sounding rockets

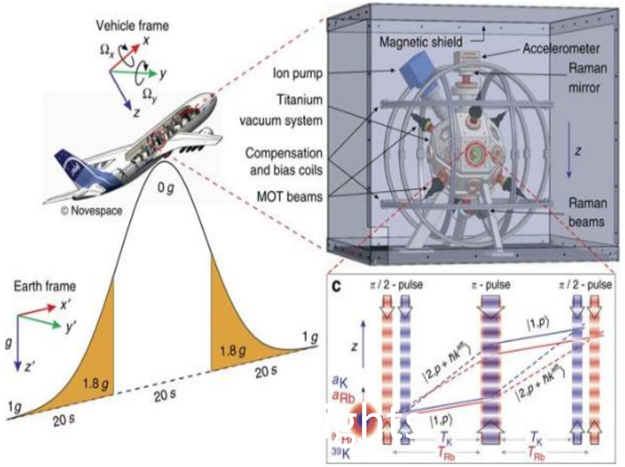
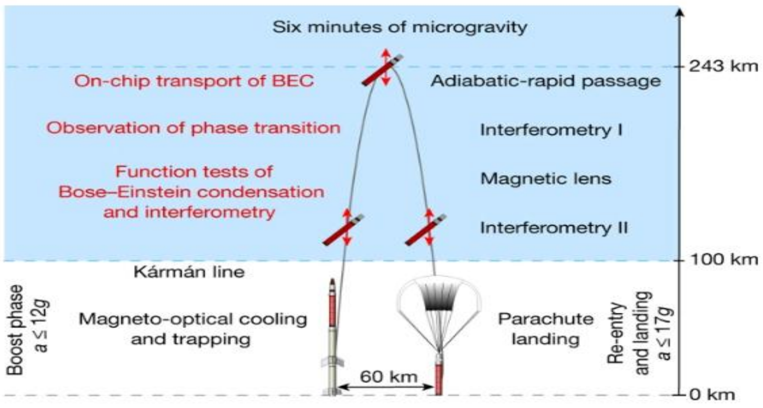
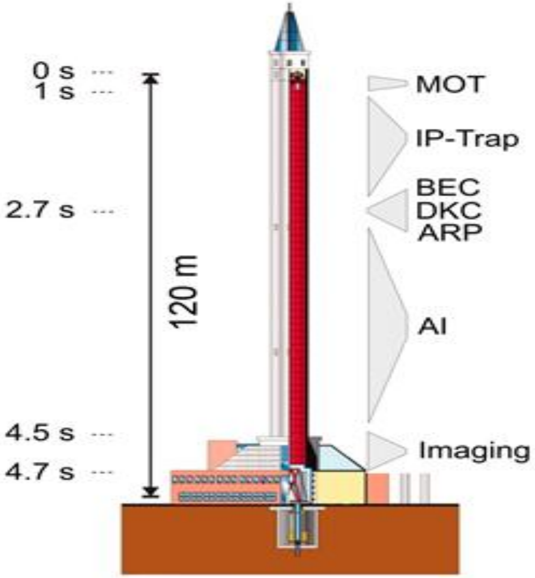
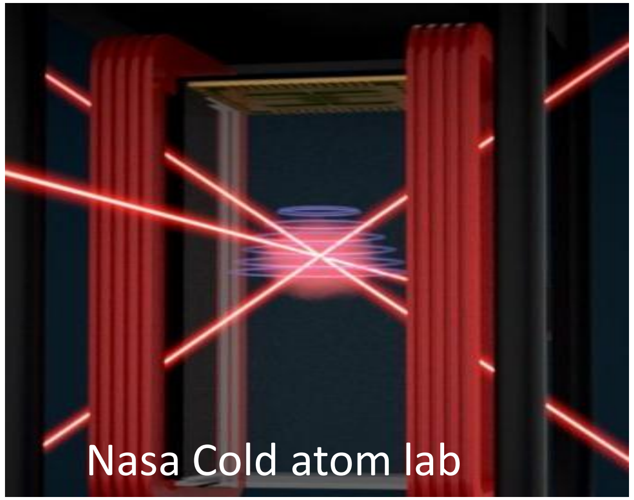


Fig. 2: Schedule for the MAIUS-1 sounding-rocket mission.





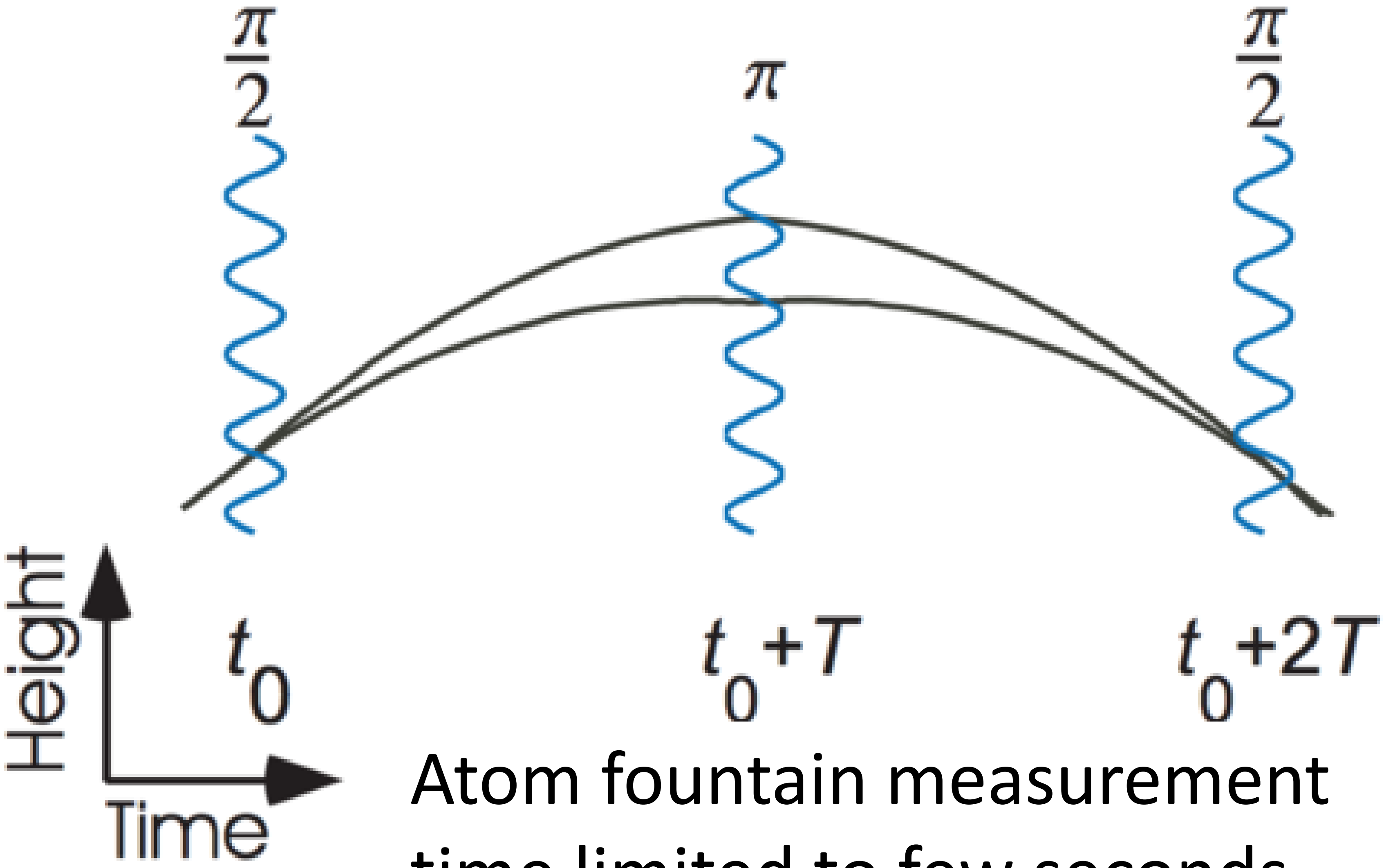
III. In space



Nasa Cold atom lab

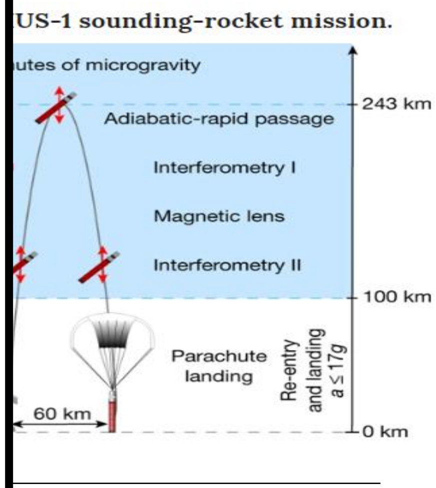
Interferometers Limited by Free-Fall Time

Stanford, 10r
fountain, T ~2 seconds fountain

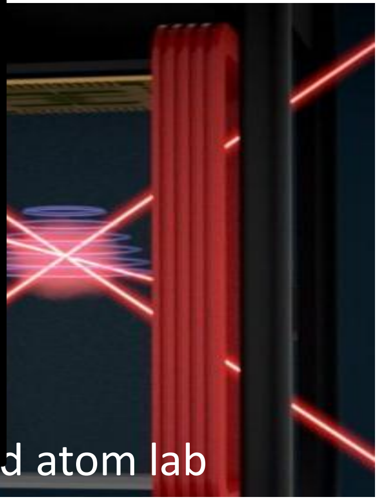


Atom fountain measurement time limited to few seconds

ockets

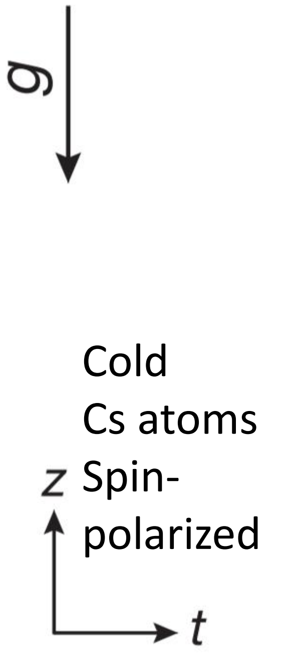


n space



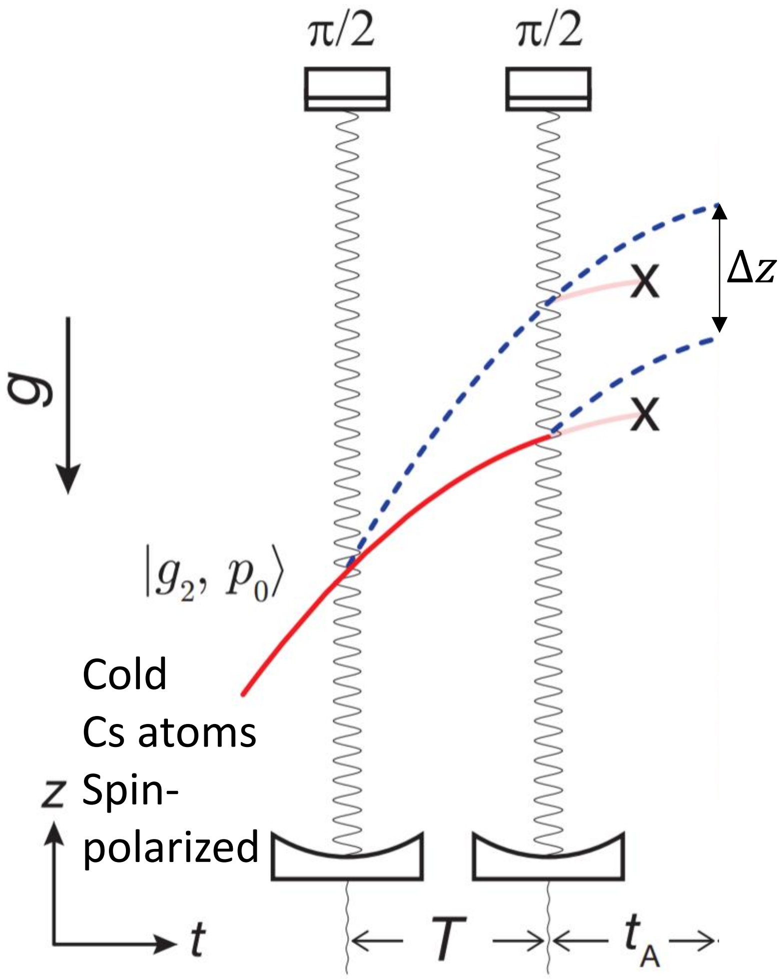
Nasa cold atom lab

Atom Interferometer in an Optical Lattice



0. Sample preparation

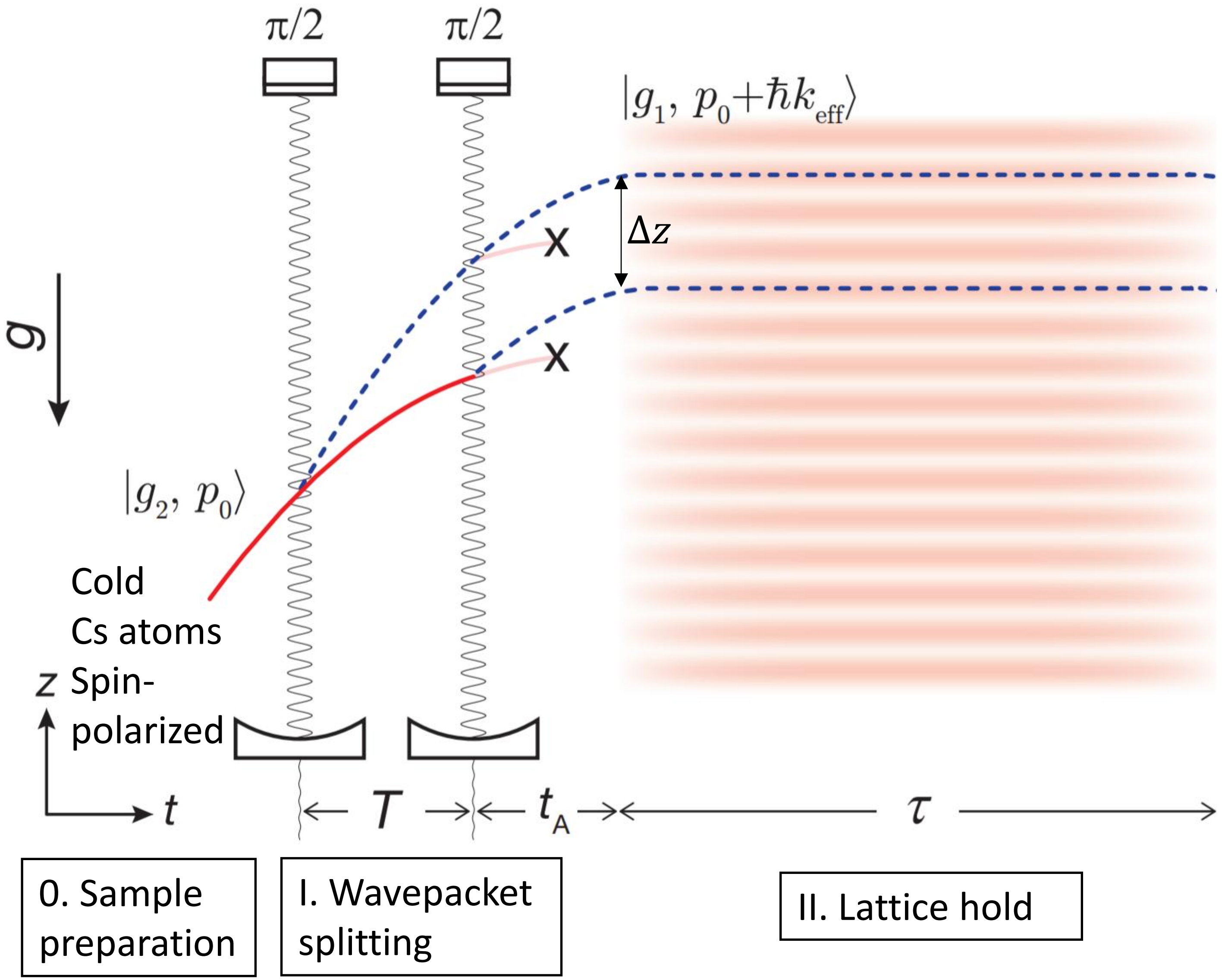
Atom Interferometer in an Optical Lattice



0. Sample preparation

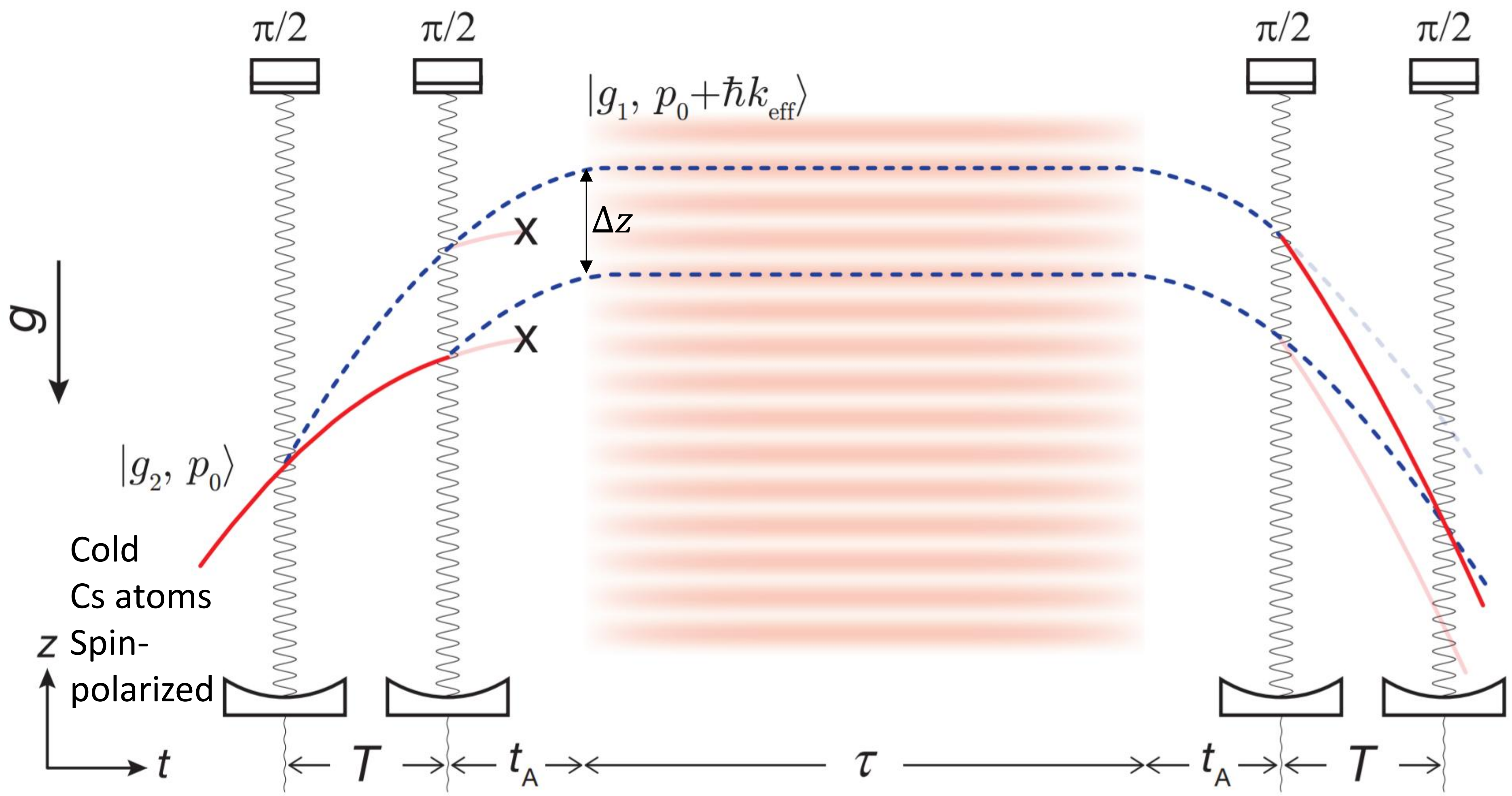
I. Wavepacket splitting

Atom Interferometer in an Optical Lattice



$$\Delta\phi_{\text{prop}} = \frac{1}{\hbar}\int L\,dt$$
$$= \frac{mg\Delta z}{\hbar}\tau$$

Atom Interferometer in an Optical Lattice



$$\Delta\phi_{\text{prop}} = \frac{1}{\hbar}\int L\,dt$$
$$= \frac{mg\Delta z}{\hbar}\tau$$

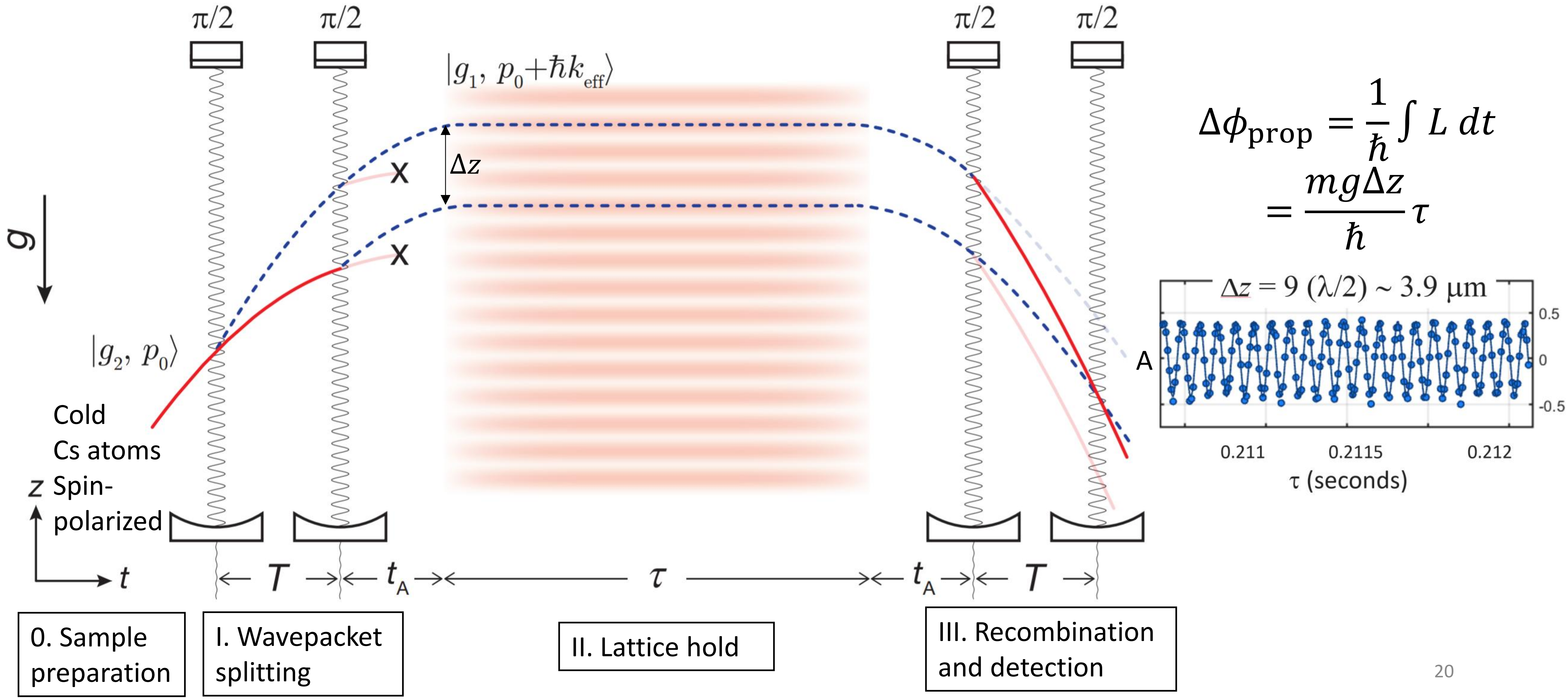
0. Sample preparation

I. Wavepacket splitting

II. Lattice hold

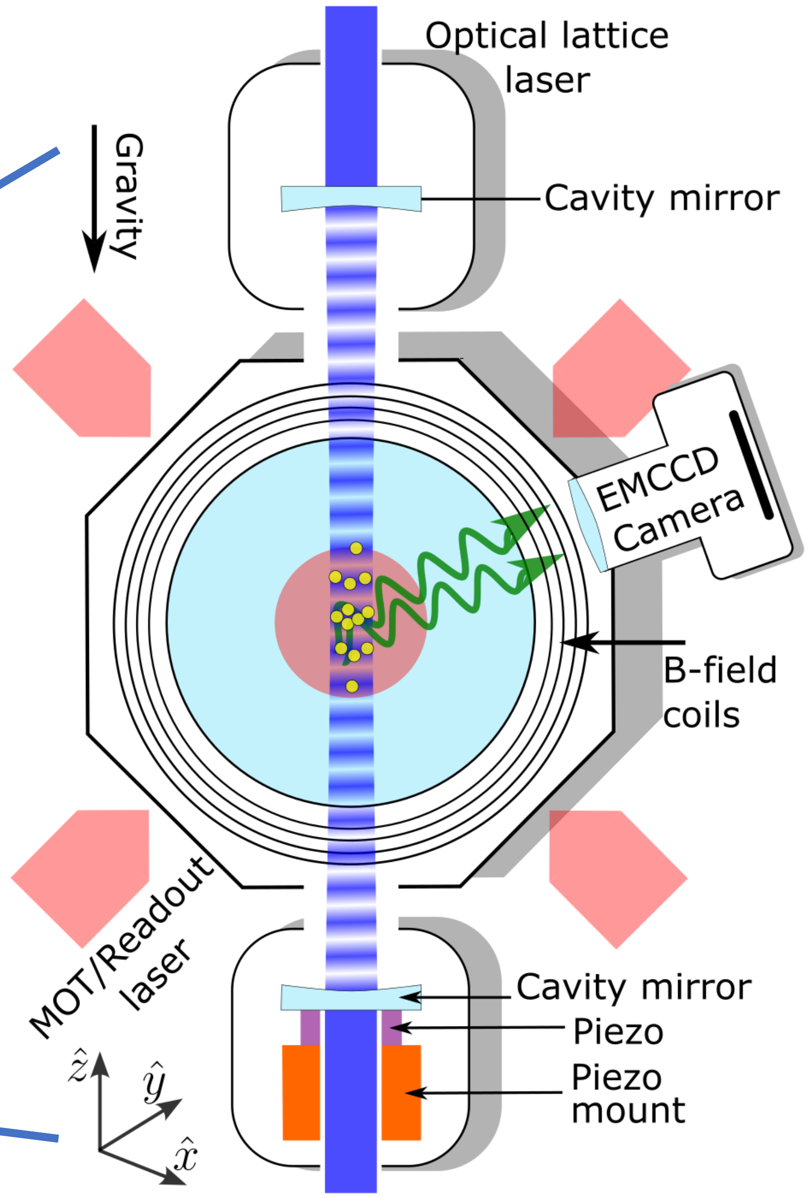
III. Recombination and detection

Atom Interferometer in an Optical Lattice



$$\Delta\phi_{\mathrm{prop}} = \frac{1}{\hbar}\int L\,dt = \frac{mg\Delta z}{\hbar}\tau$$

Experimental Apparatus

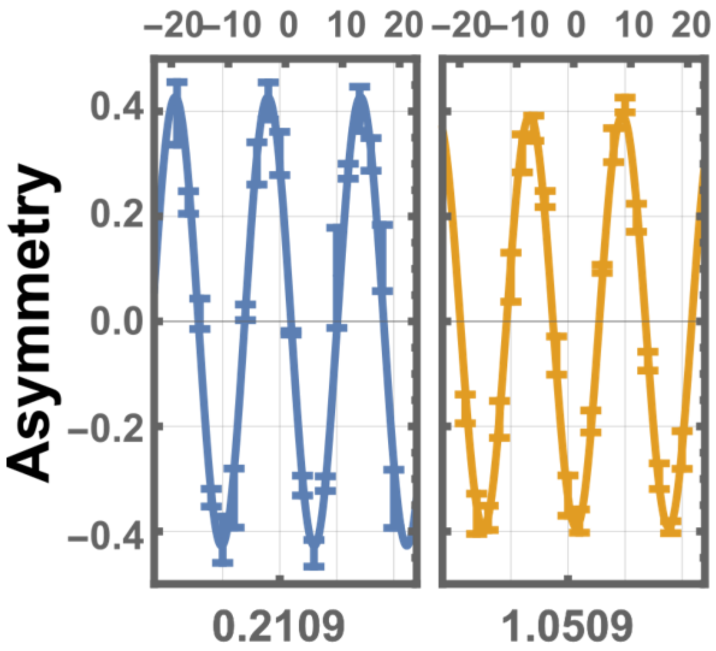


- Optical lattice filtered by in-vacuum Fabry Perot cavity

Long Coherence Times

Coherence limits in lattice atom interferometry at the one-minute scale,
CDP et al, *Nat. Phys.* **20**, *1234-1239* (2024)

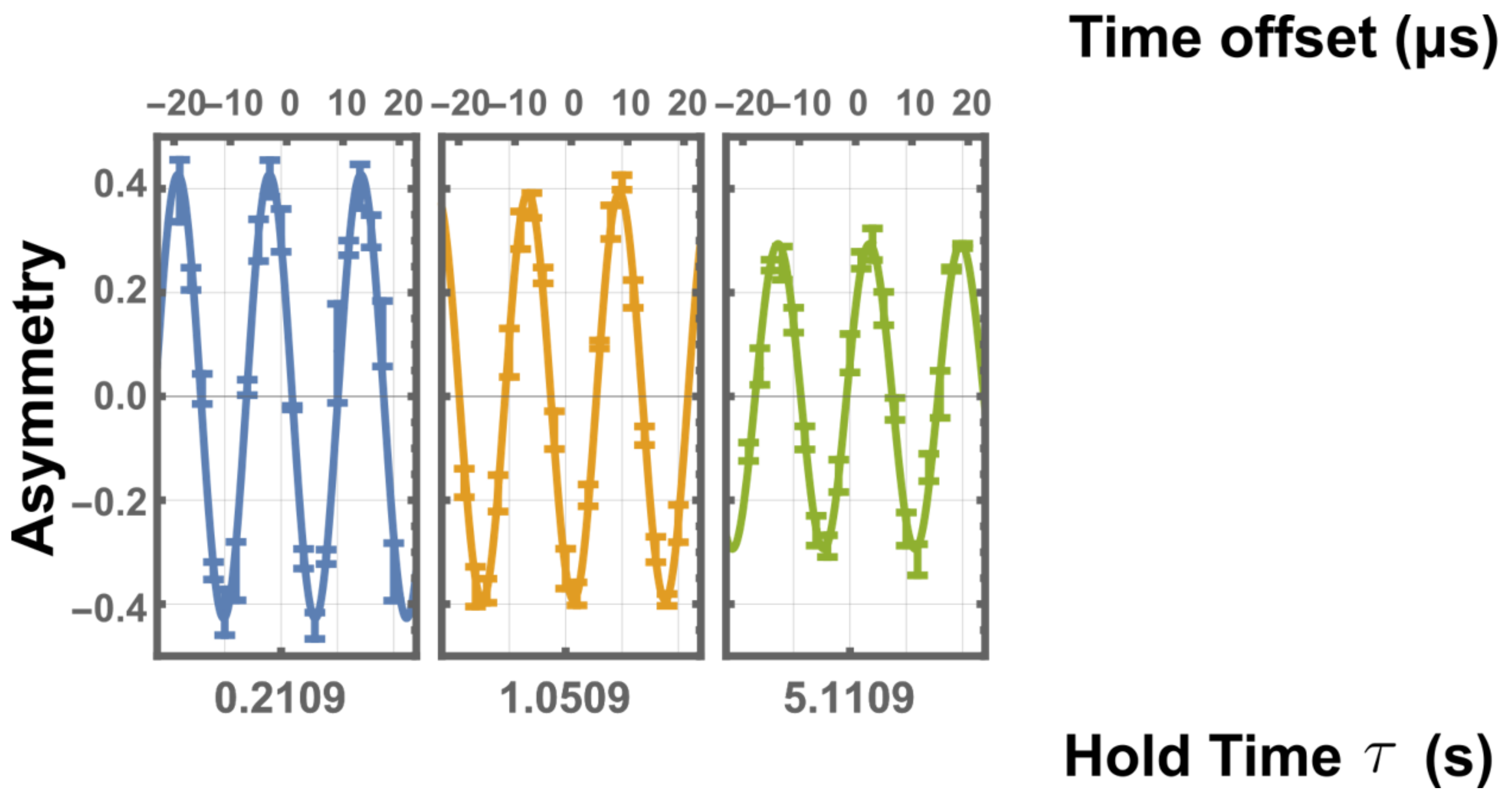
Time offset (μs)



Hold Time τ (s)

Long Coherence Times

Coherence limits in lattice atom interferometry at the one-minute scale,
CDP et al, *Nat. Phys.* **20**, *1234-1239* (2024)



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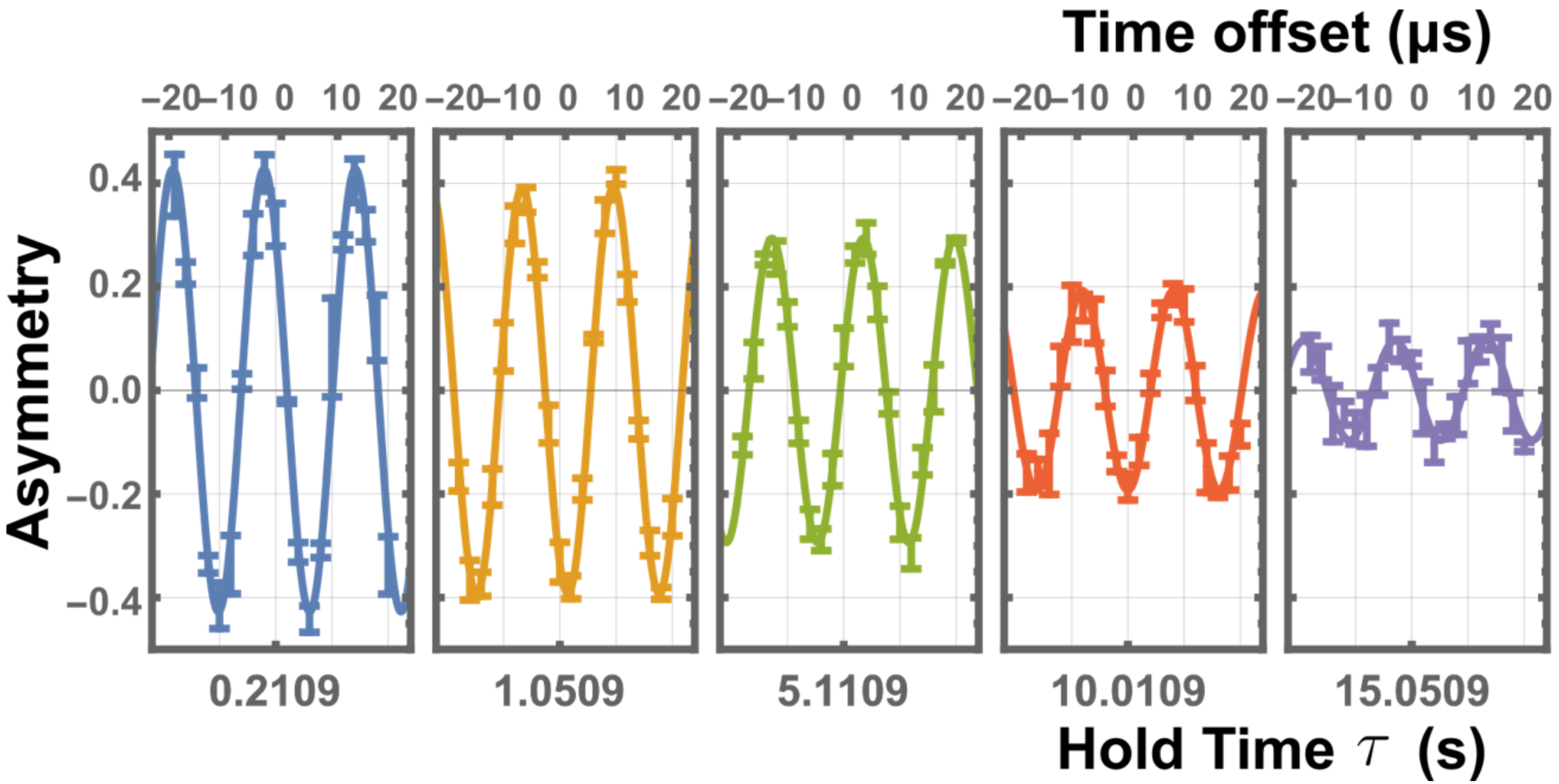

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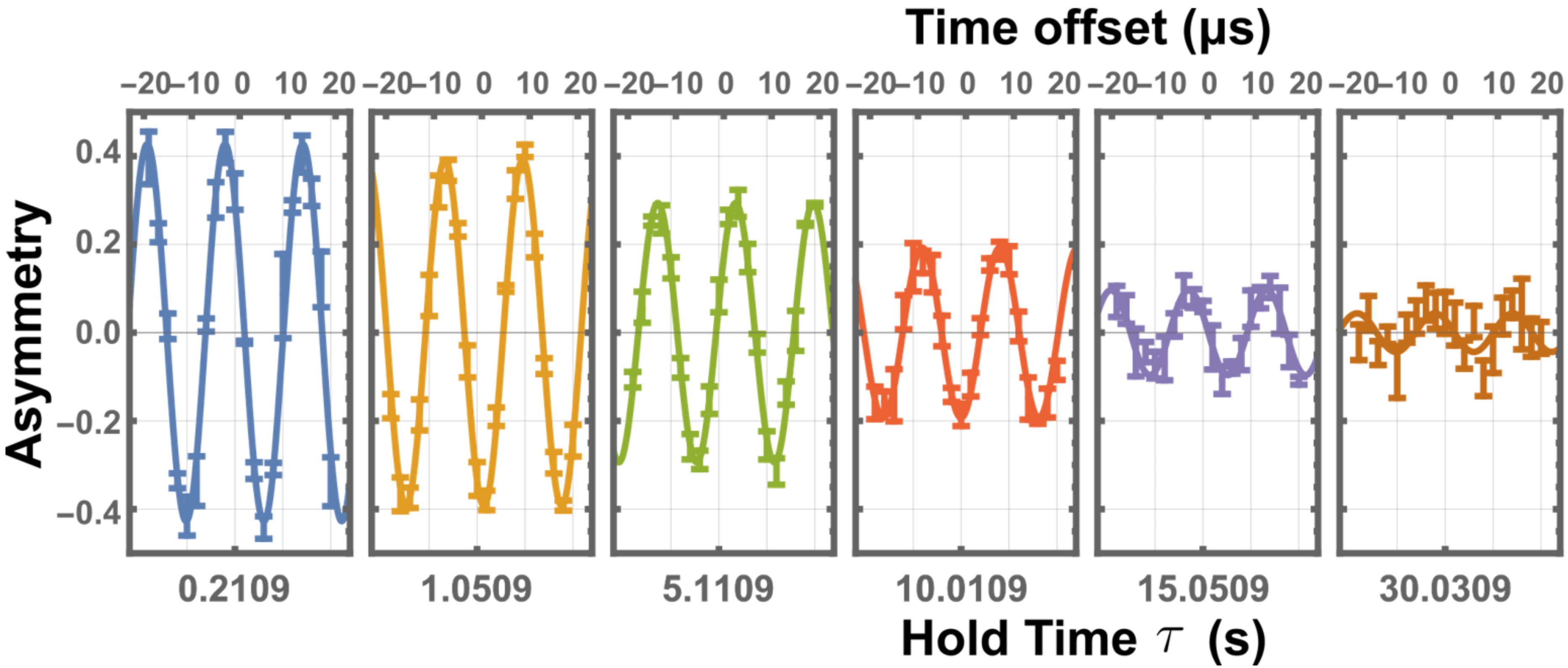
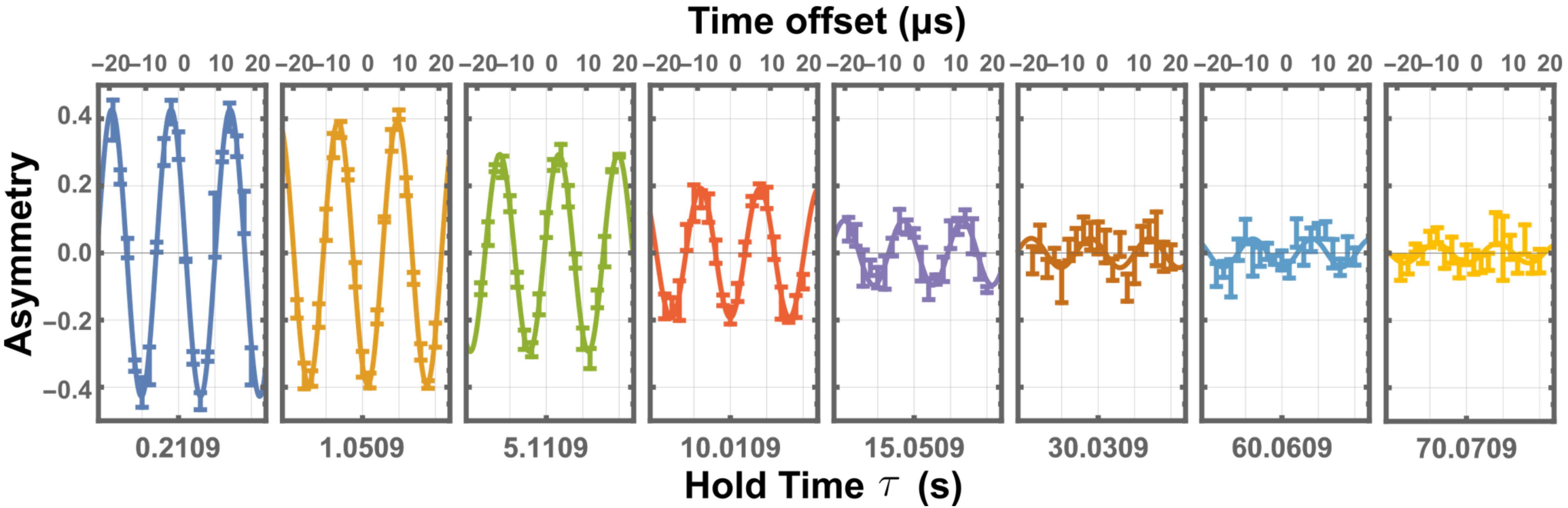


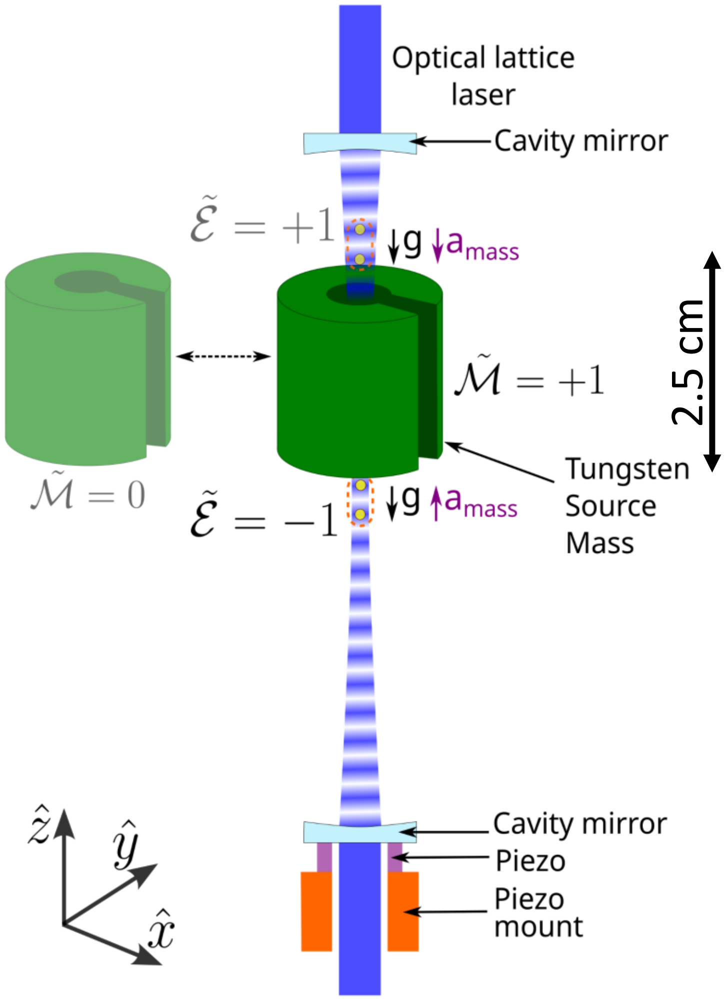
Coherent After 70 Seconds

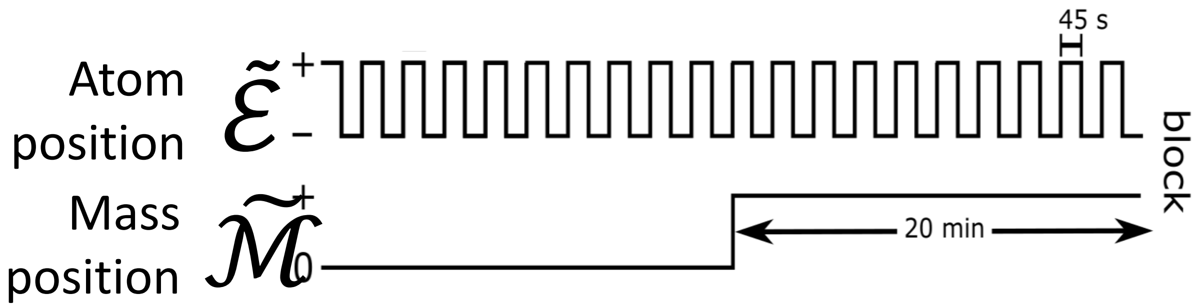
Coherence limits in lattice atom interferometry at the one-minute scale,
CDP et al, *Nat. Phys.* **20**, *1234-1239* (2024)

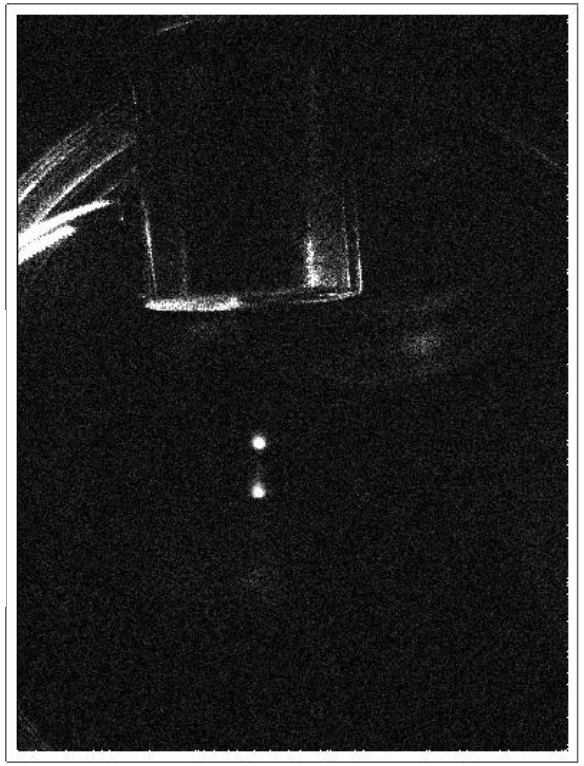


Searching for Fifth Forces by Measuring Gravity of Small Mass

- Measure acceleration from cm-sized tungsten mass.
  - Small signal – $35\ \mathrm{nm/s^2}$ - 3 parts per billion of Earth's gravity g
- Upgrades to lattice interferometer:
  - Better SNR - **10x increased precision**
  - Better precision than any previous measurements (atom fountains)
  - Quickly move atoms - use **atom elevator**
  - Differential measurement







Systematic Checks

- <u>Variation of over 40 parameters</u>. Systematics understood, under control

Parameter	Shift (nm/s^2)	Uncertainty (nm/s^2)
Black-body radiation gradient	0.05	1.30
$a^{\mathcal{E}}$(via $\partial B/\partial z$)		0.07
$\mathcal{M}$-correlated MOT position		1.86
$\mathcal{M}$-correlated trap depth		0.31
$\mathcal{M}$-correlated axial B-field		0.92
$\mathcal{M}$-correlated transverse B-field		0.84
DC Stark Shift		0.50
Total systematic	0.05	2.66
Statistical uncertainty		5.61
Total uncertainty		6.21
Source-mass calculated gravity	35.20	1.00

Table *1*. Systematic shifts and uncertainties in a_{mass}. All uncertainties are added in quadrature.

known

Lattice divergence -“expected”

Mass motion effects

known

5 times better than previous measurement

Results

- Result

$$a_{\text{mass}} = 33.3 \pm 5.6_{\text{stat}} \pm 2.7_{\text{syst}}\ \text{nm/s}^2$$

$$a_{\text{mass}}^{\text{Newton}} = 35.2 \pm 1.0\ \text{nm/s}^2$$

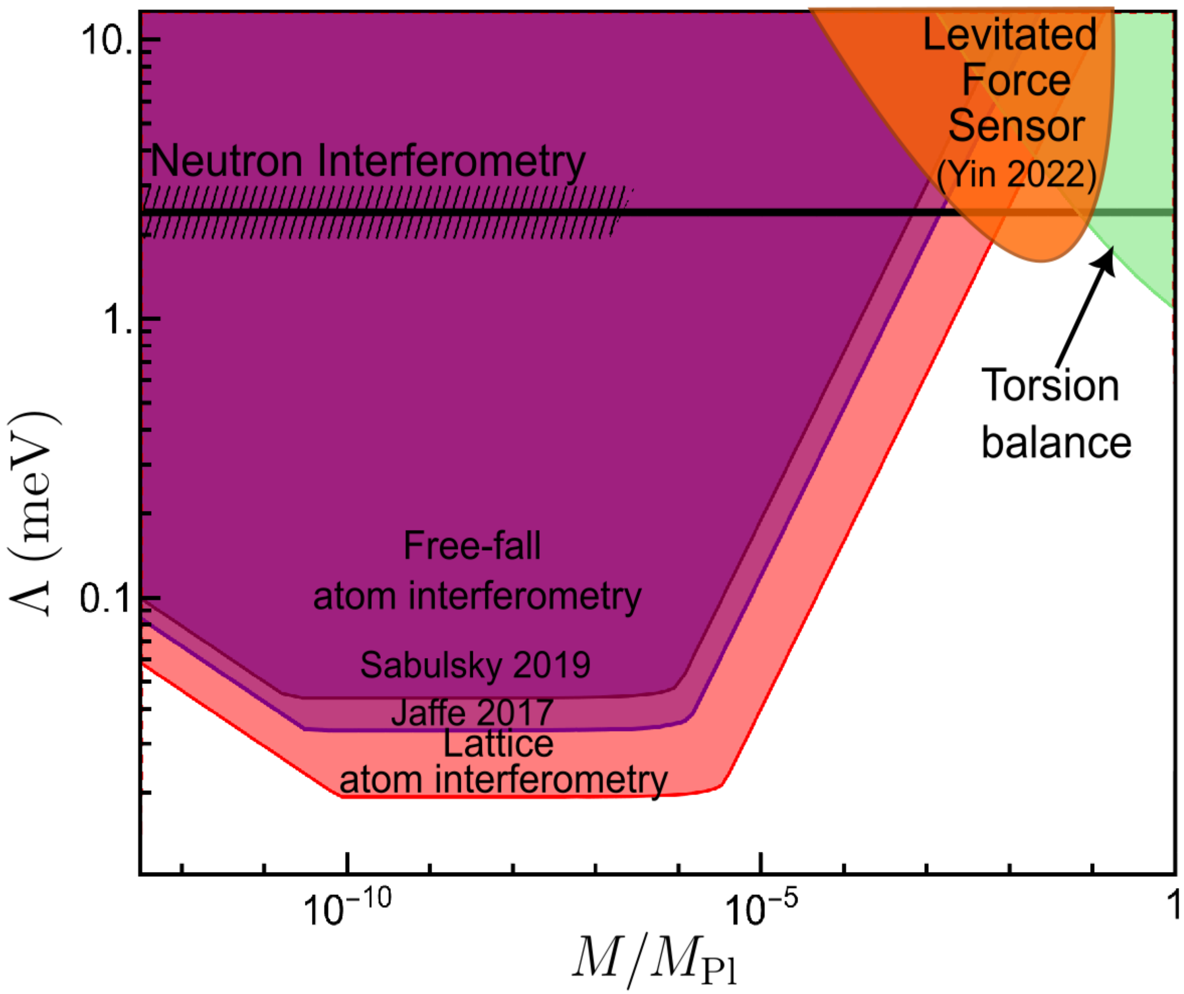
- Limit on deviation from Newtonian gravity

$$\left|a_{\text{mass}} - a_{\text{mass}}^{\text{Newton}}\right| < 13\ \text{nm/s}^2\ \text{(95\% confidence)}$$

Measuring gravitational attraction with a lattice atom interferometer, CDP et al, Nature **631**, 515-520 (2024)

Probing New Fifth Force Physics

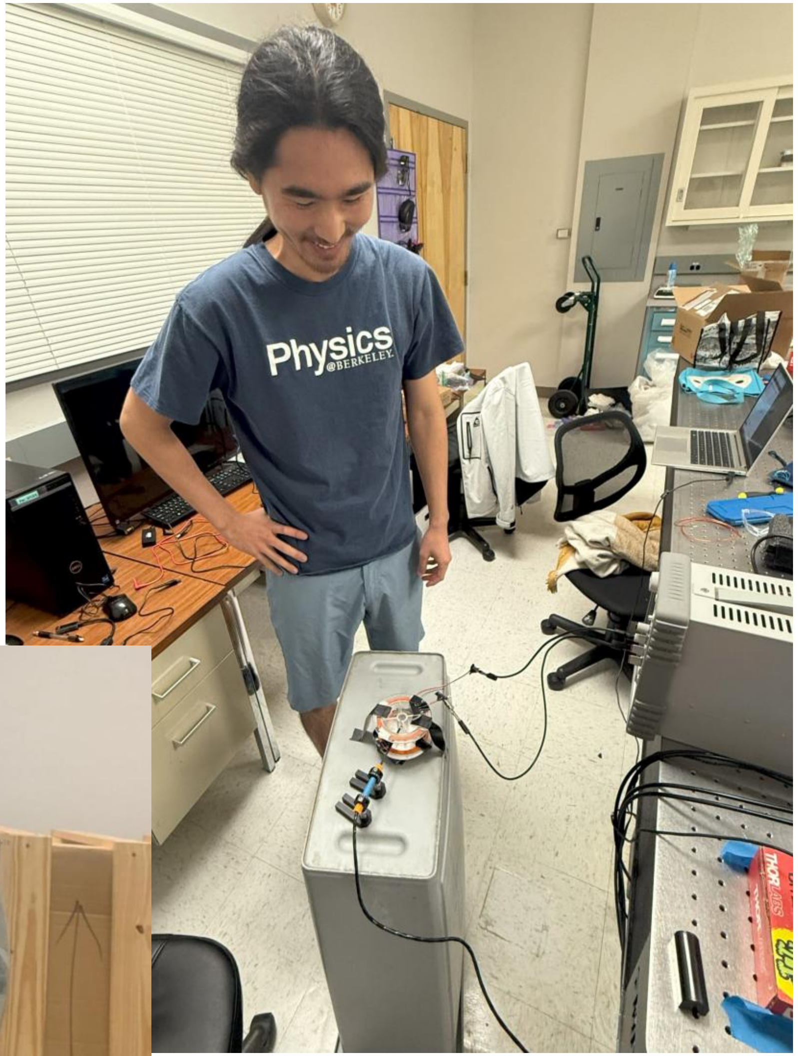
- <u>Particles (chameleon, symmetron)</u> => theories of *screened gravity*
- Help explain <u>dark energy</u> => why the Universe is expanding at an accelerated rate
- **First lattice interferometry result -** probes <u>parameter space that is 6 times larger than before</u>



Measuring gravitational attraction with a lattice atom interferometer, <u>CDP</u> et al, Nature **631**, 515-520 (2024)

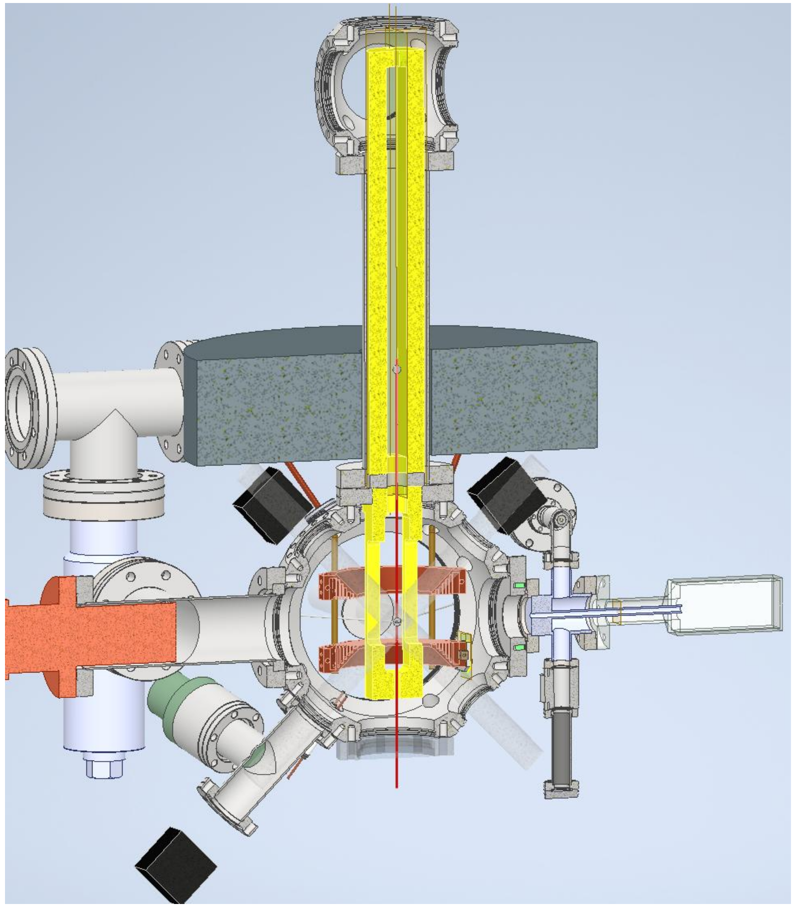
At University of Arizona since October 2024!

Group events and activities:

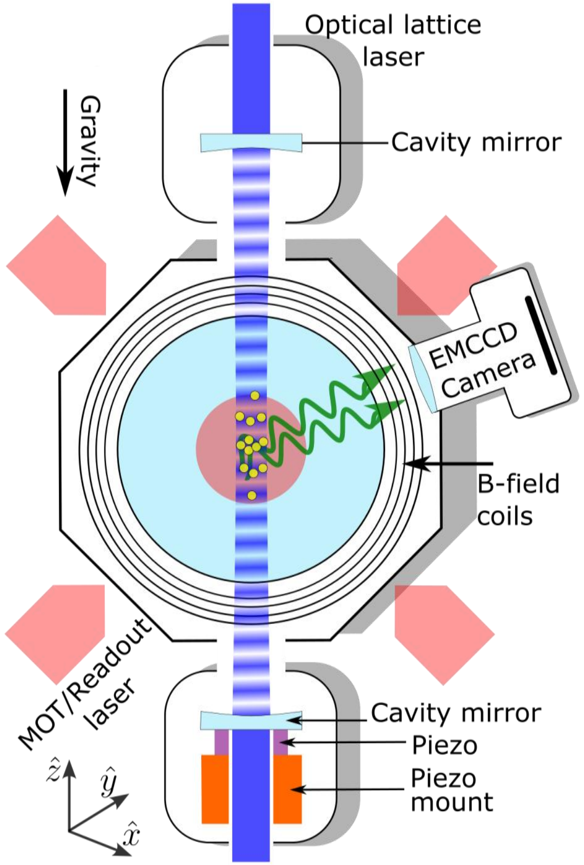


Research Program at U Arizona

Project 1: Next generation atom interferometer



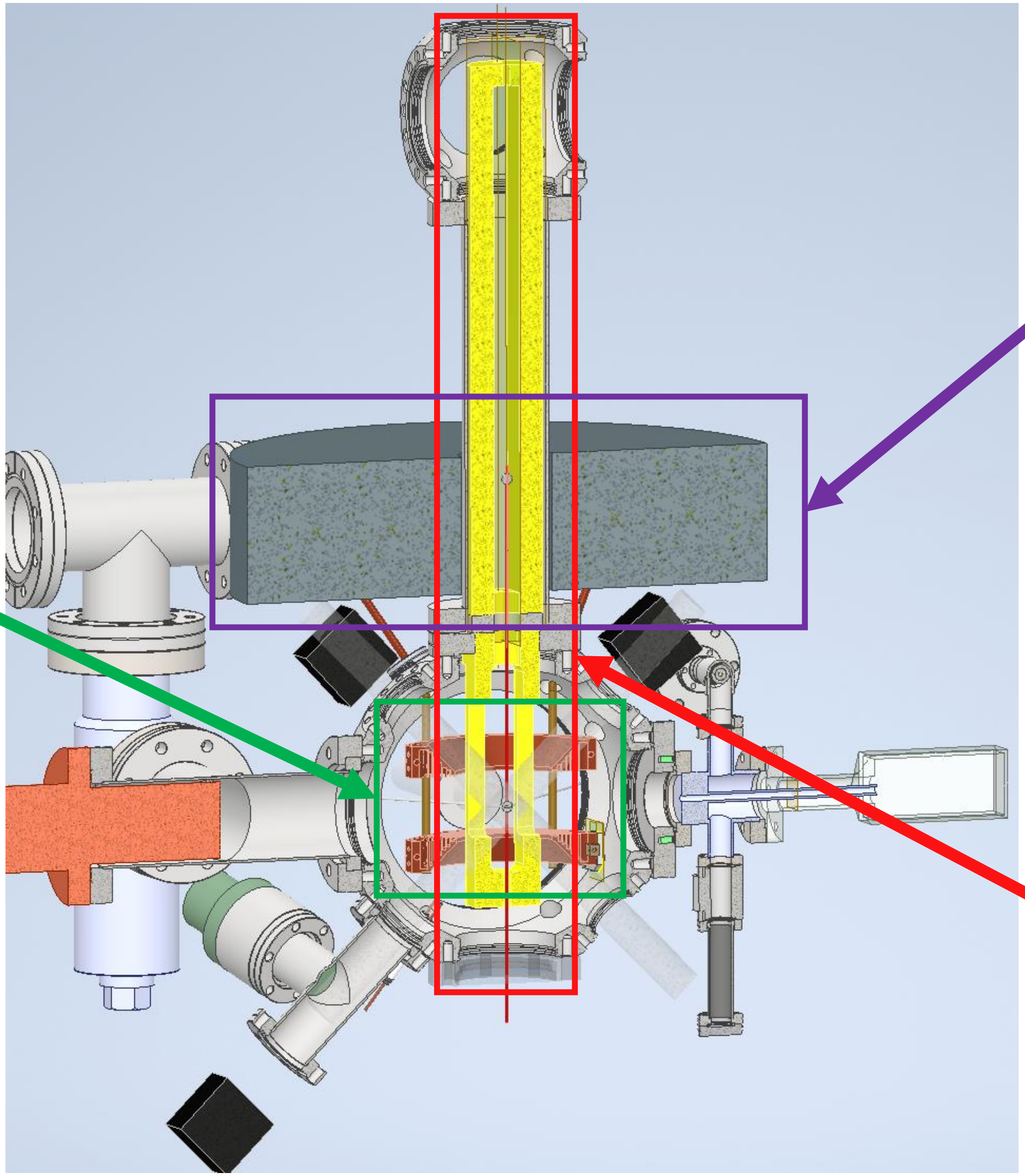
Project 2: Compact lattice interferometer gravimeter



Next Generation Atom Interferometer

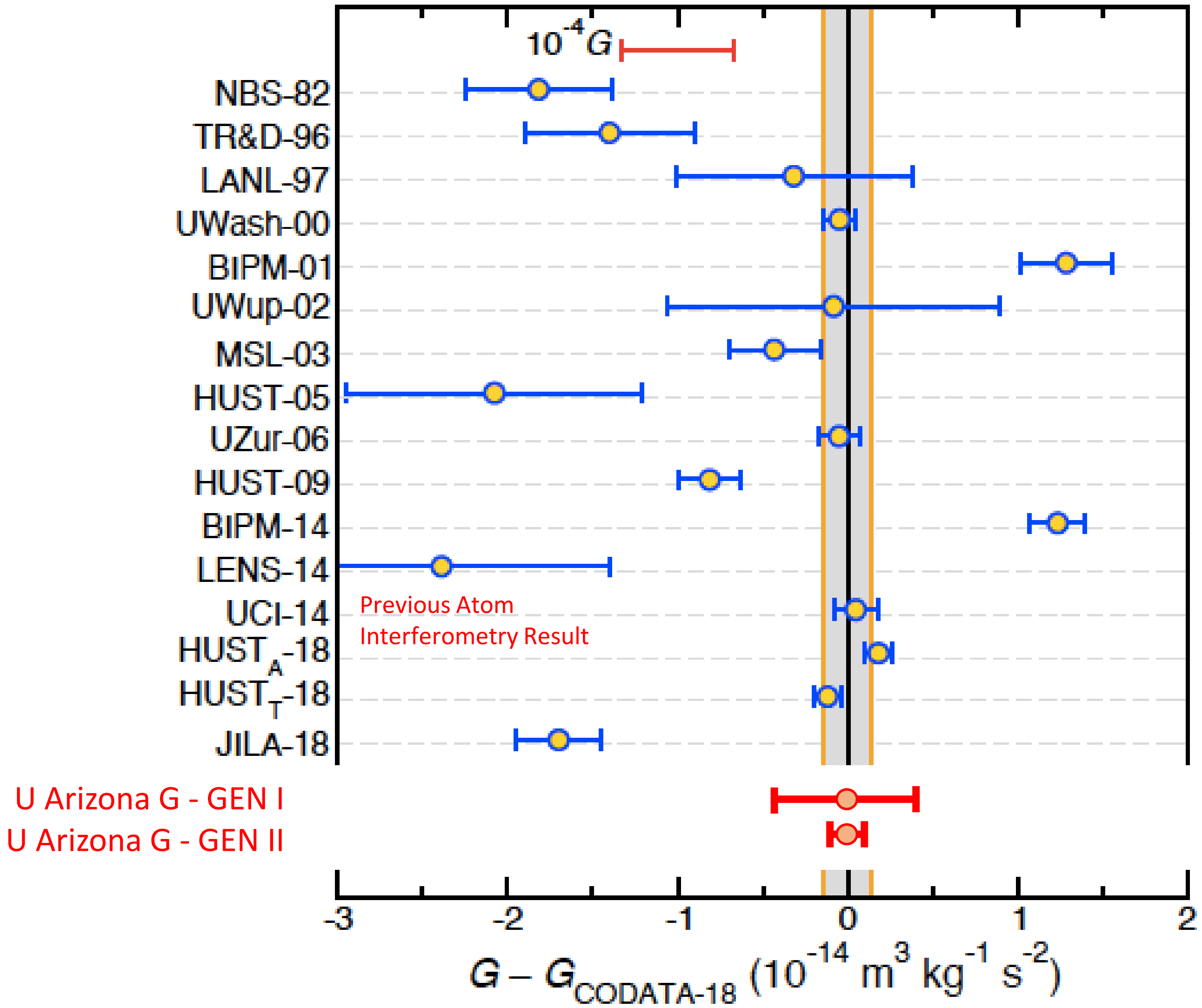
Source mass:
- Measure G
- Probe non-Netwonian gravity
  - Screened potentials
  - Inverse square law
  - Quantum mediated gravity

Evaporative cooling:
- In-vacuum electromagnet produces required field
- Lower temperature => Reduced decoherence



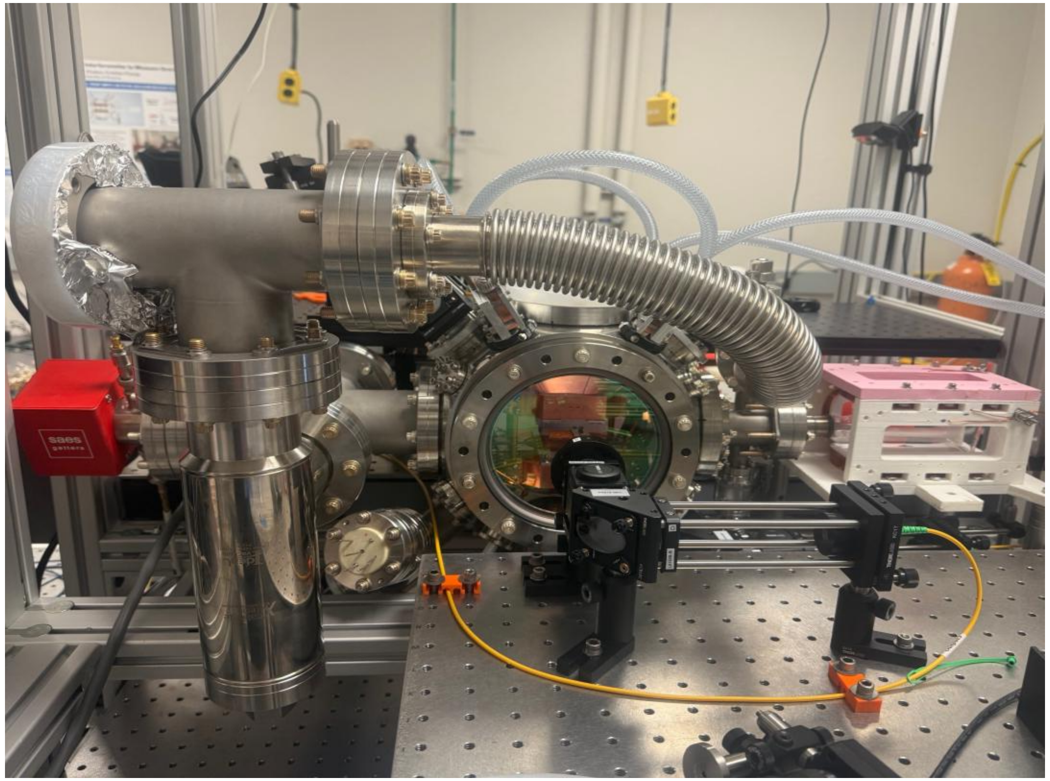
Monolithic optical cavity:
- Mirrors mounted on glass spacer
- Lower vibrations => Reduced decoherence + increased runtime

Projected Big G Results



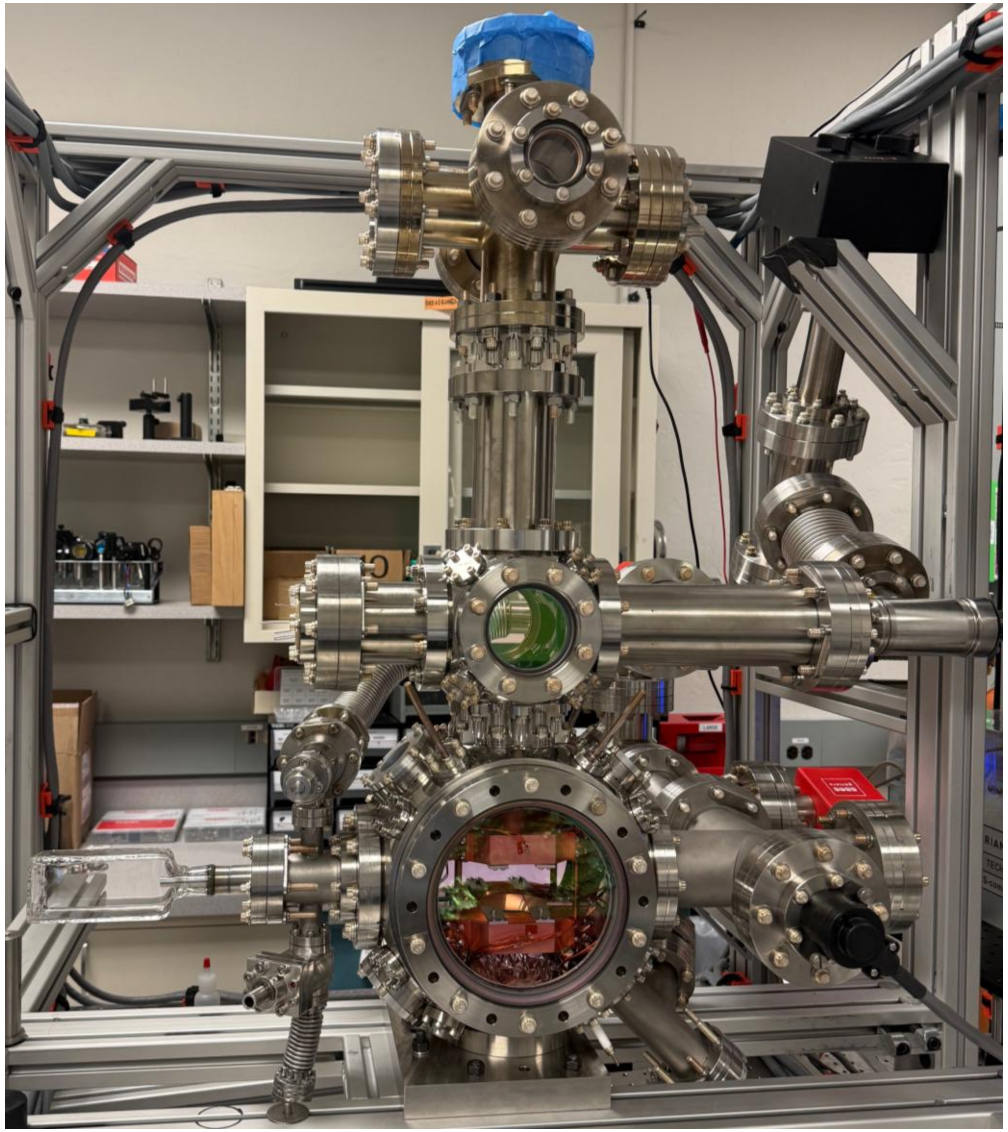
Building an optical lattice atom interferometer

May 2025

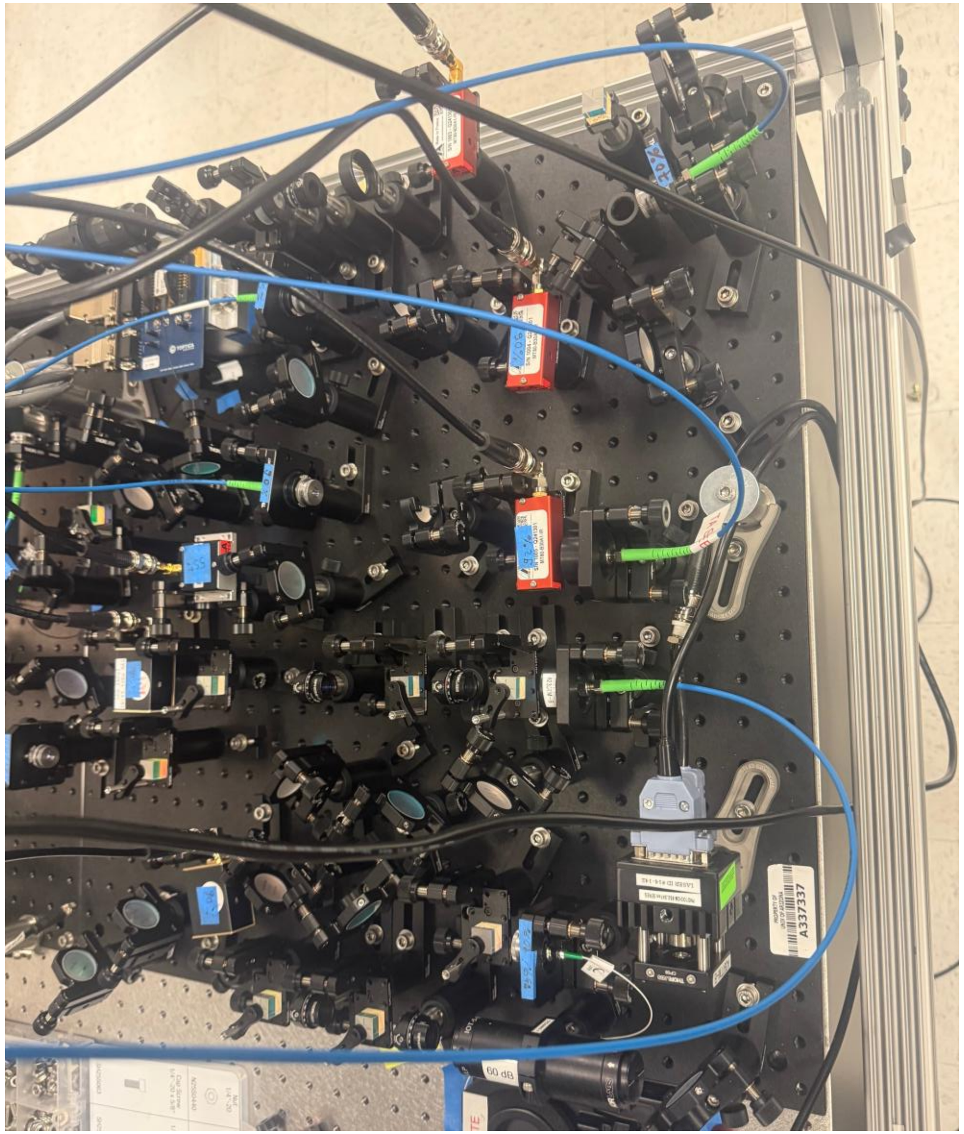


Ultra high-vacuum chamber fully operational

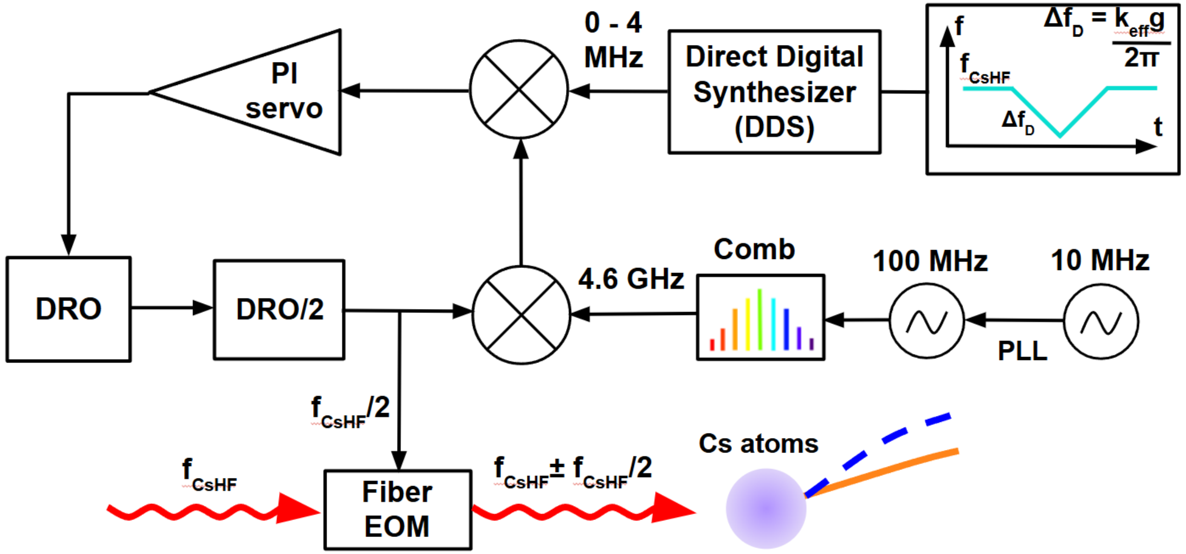
December 2025



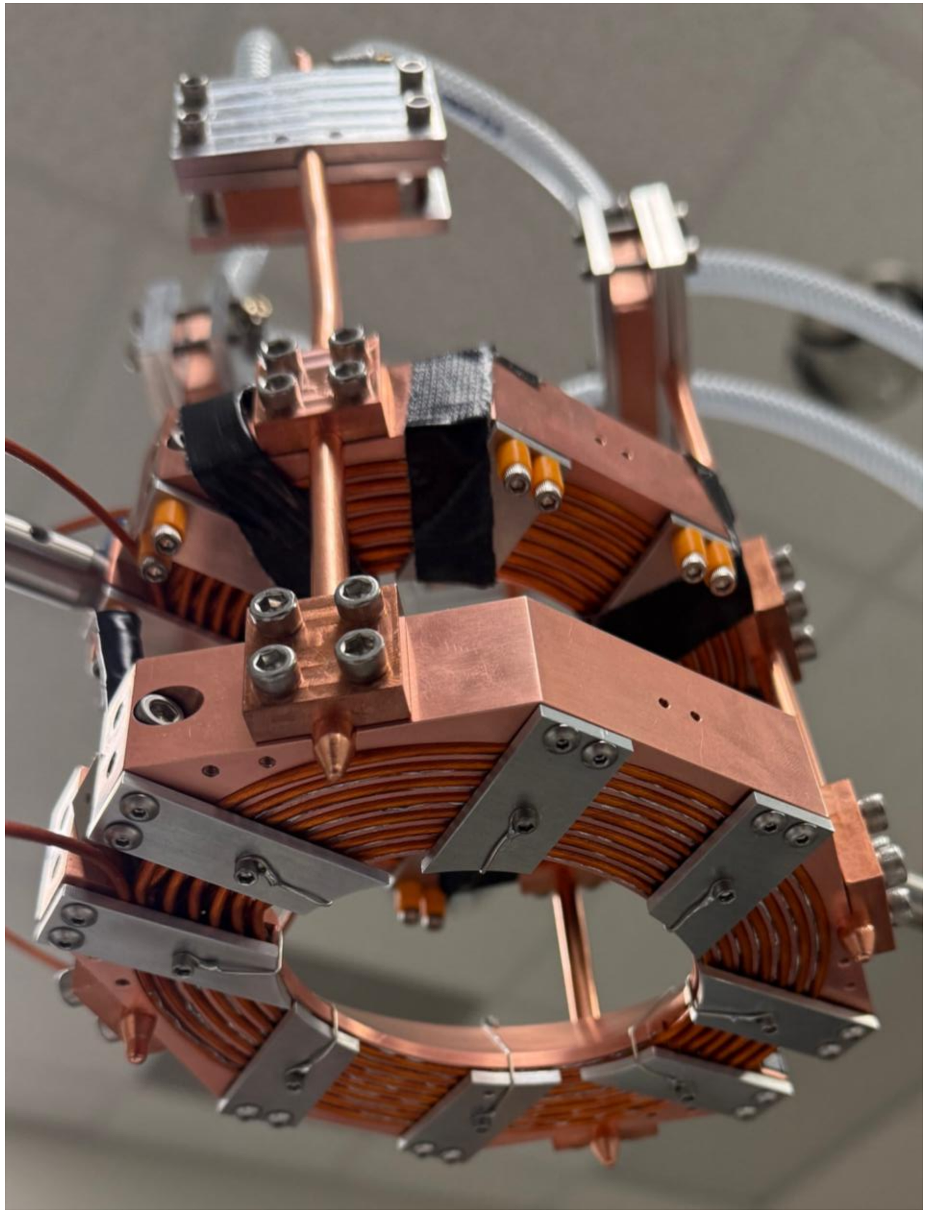
Building up capabilities for atomic quantum control



1. Laser systems complete
   - Narrow line, stable
   - Frequency, intensity, polarization are tunable, computer controlled
2. Low phase noise microwave system locked
3. Magnetic field control systems operational
4. Vacuum system complete
5. Zerodur optical cavity to ship soon => Installation by Fall 2026



Heatpipe cooled in-vacuum electromagnet



- >40 G/cm, >140 G fields with as little as 50 W dissipated power
- Quiet, low vibration
- <250 us magnetic field switching time
- Uses non-magnetic materials, compatible with vacuum operation

RESEARCH ARTICLE | AUGUST 21 2025

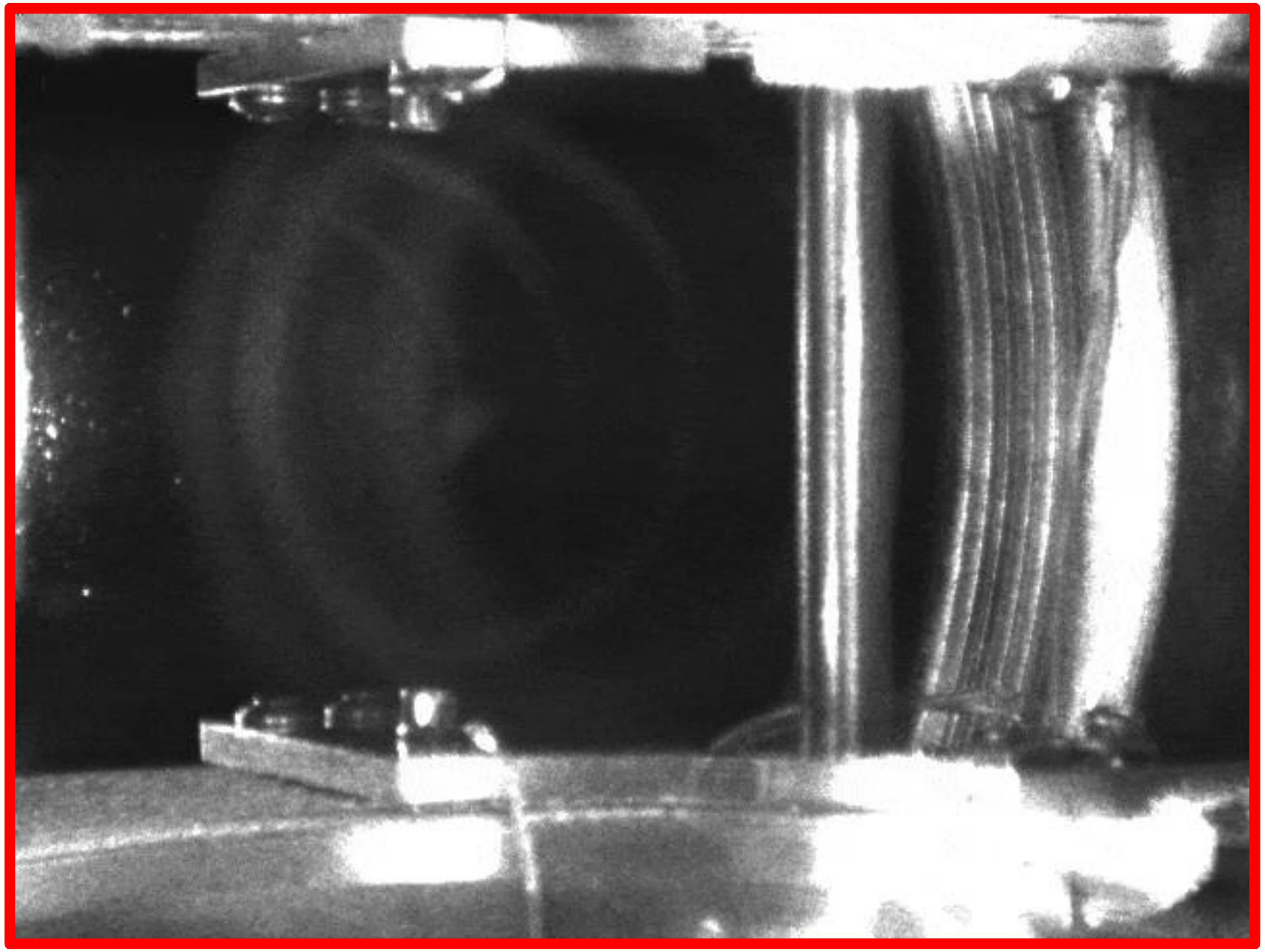
Heatpipe-cooled in-vacuum electromagnet for quantum science experiments

Kenneth Nakasone (中曽根ケネス); Paola Luna; Andrei Zhukov; Matthew Tao; Garrett Louie; Cristian D. Panda

Check for updates

Rev. Sci. Instrum. 96, 083201 (2025)
https://doi.org/10.1063/5.0277104

Ultracold atoms trapped in a MOT



May 2025 - First Cesium MOT – now 1 billion atoms, ~2 uK temperatures

MOT configuration

- Modular, adjustable optics cage system
- Diverging laser beams prevent light scattering from vacuum windows
- Confirmed polarization gradient cooling of atom sample to 2 uK with diverging laser beams
- Explored unconventional MOT geometries (diagonal laser beams).

MOT performance

- Operational for many months with minimal realignment
- Minimal fluctuations (<10%) in atom number and temperature.

Paola Luna et al., Robust and versatile Cs MOT configurations for quantum sensors and metrology, arXiv:2607.13145 (2026)

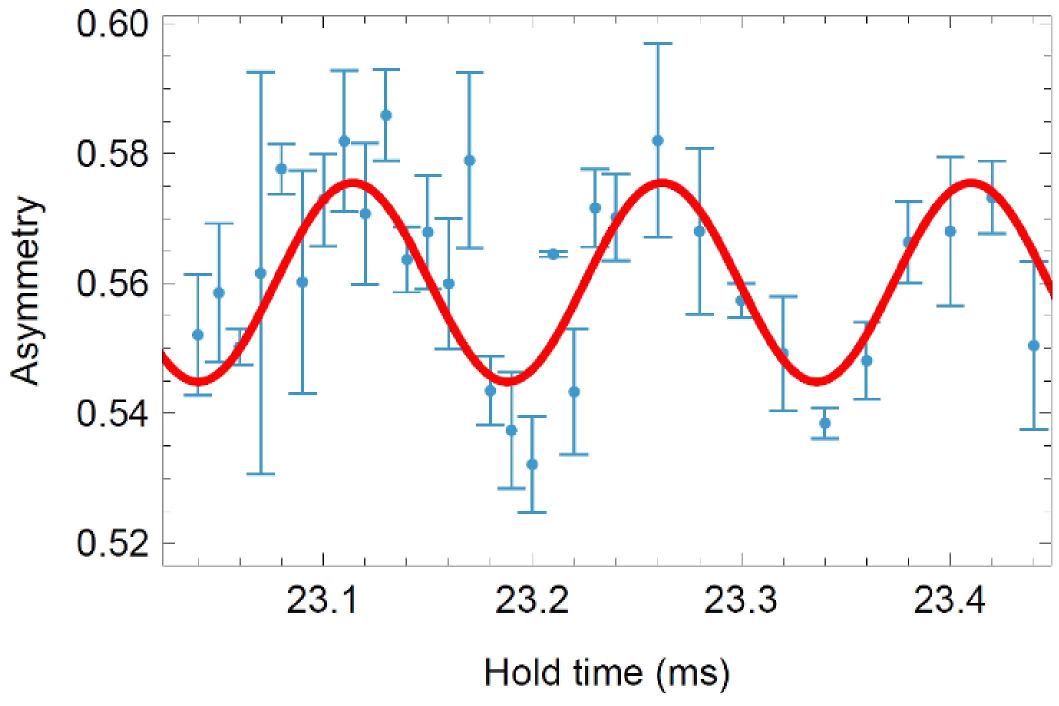
First optical lattice atom interferometer fringes

- All quantum control systems operational

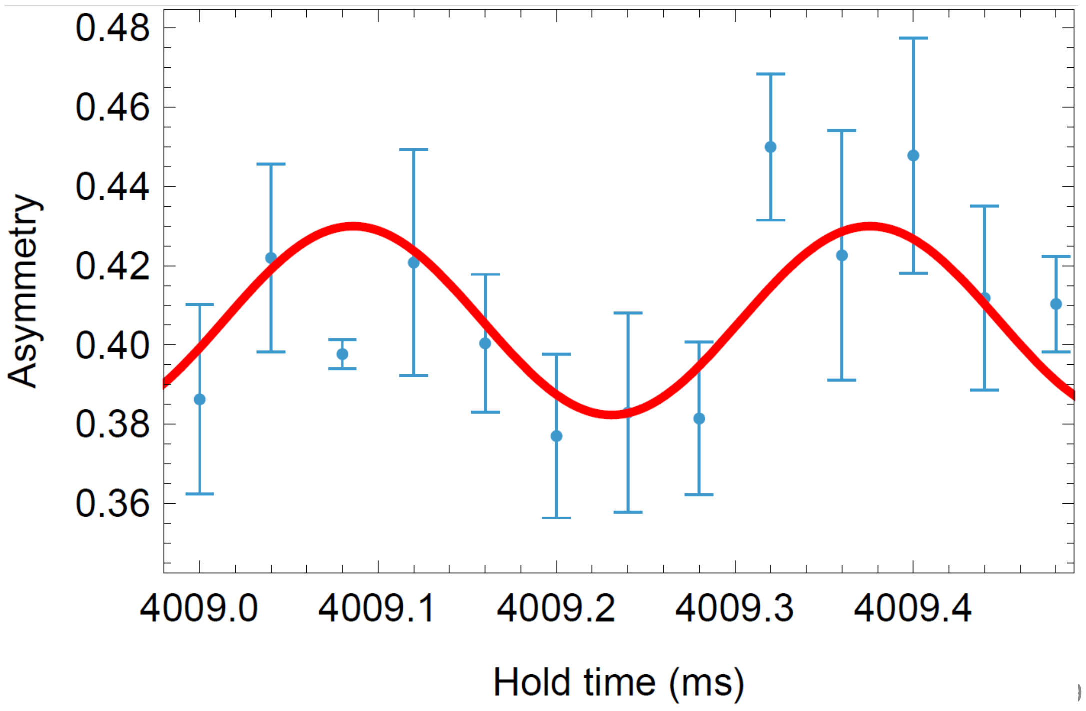
MOT => PGC => RSC => ARP => Launch => Raman BS => Optical Lattice Hold => Raman BS => Imaging

- Interferometer optimization in progress

May 21, 2026 - First fringe

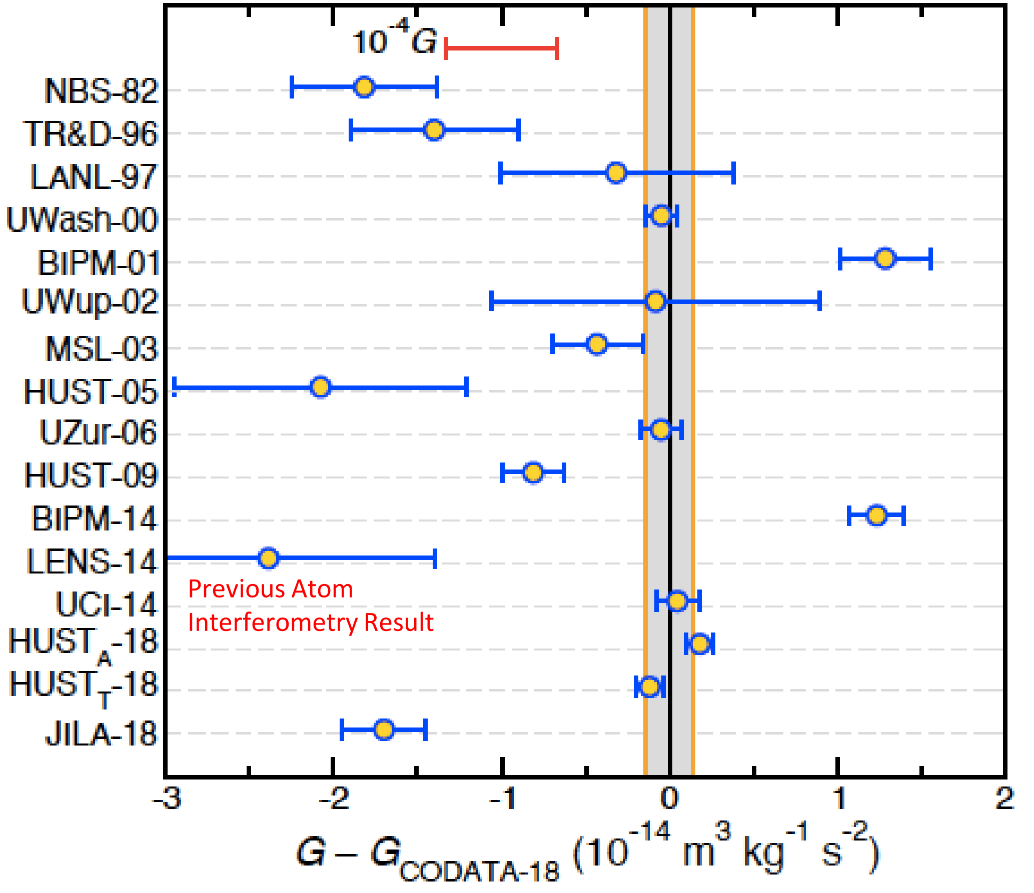


June 28, 2026 - Coherence at 4 seconds!

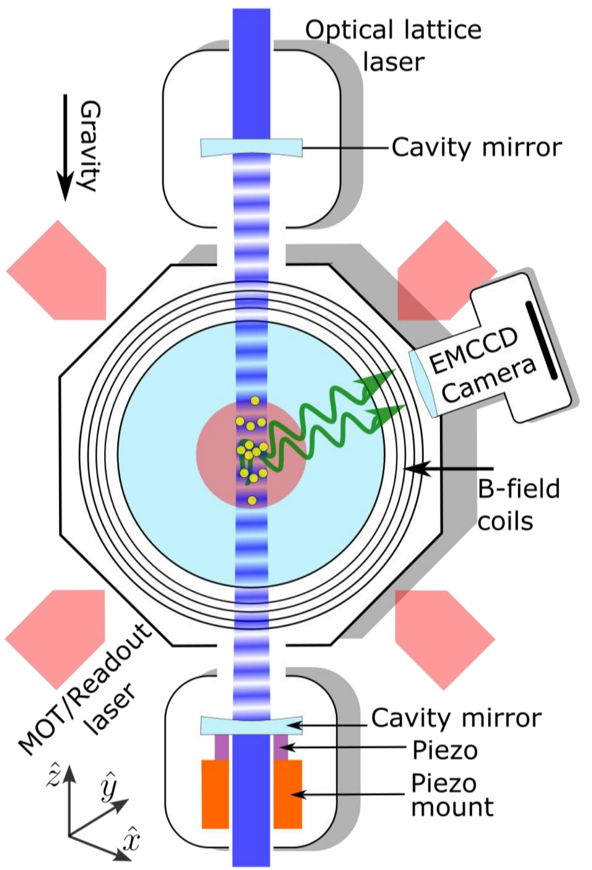


Research Program at U Arizona

Project 1: Next generation atom interferometer



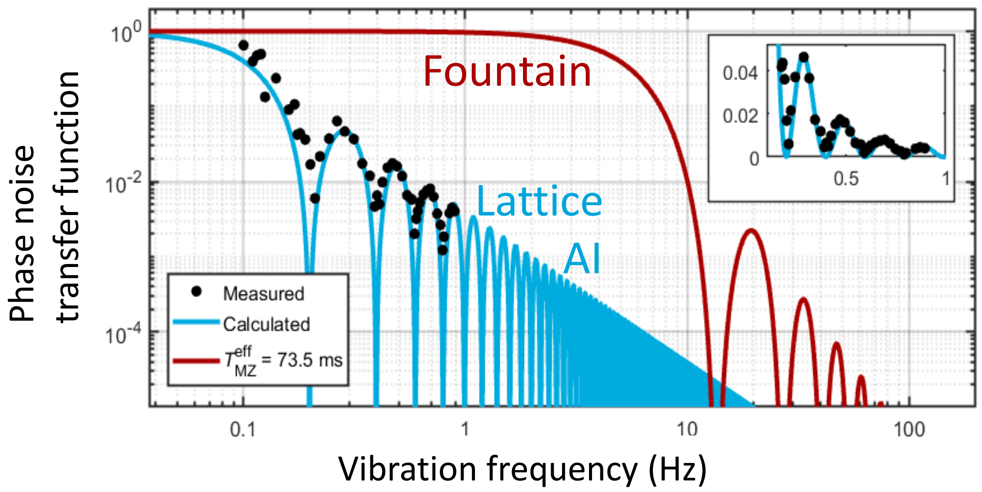
Project 2: Compact lattice interferometer gravimeter

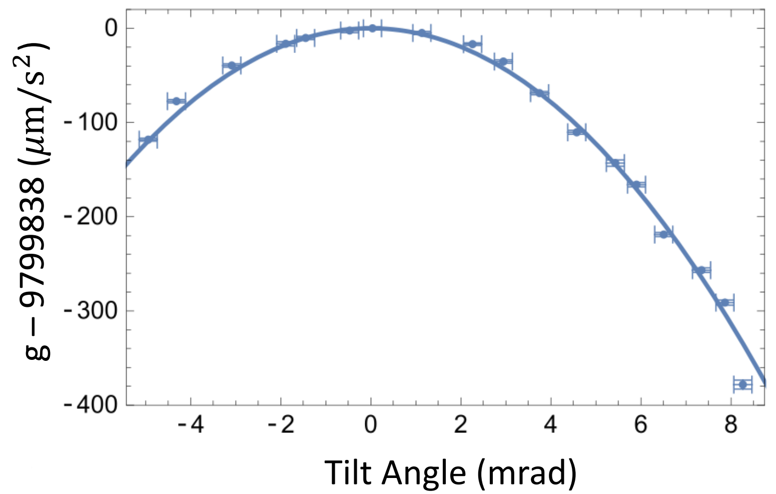


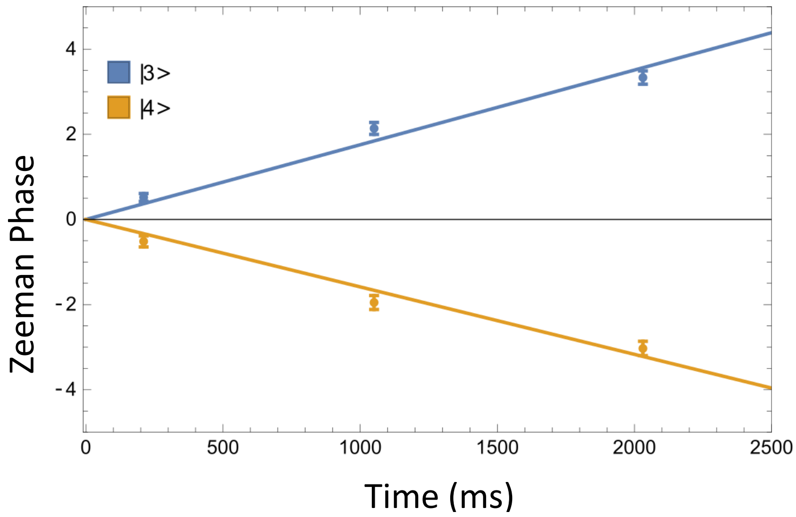
Mobile Gravimetry with the Lattice Interferometer

In comparison to atom fountains, robust to:

- Vibrations
- Apparatus tilts
- Environmental magnetic fields







Atomic gravimeter robust to environmental effects,
<u>CDP</u> *et al*, *Appl. Phys. Lett. 123*, 064001 (2023)

Compact Atom Interferometry

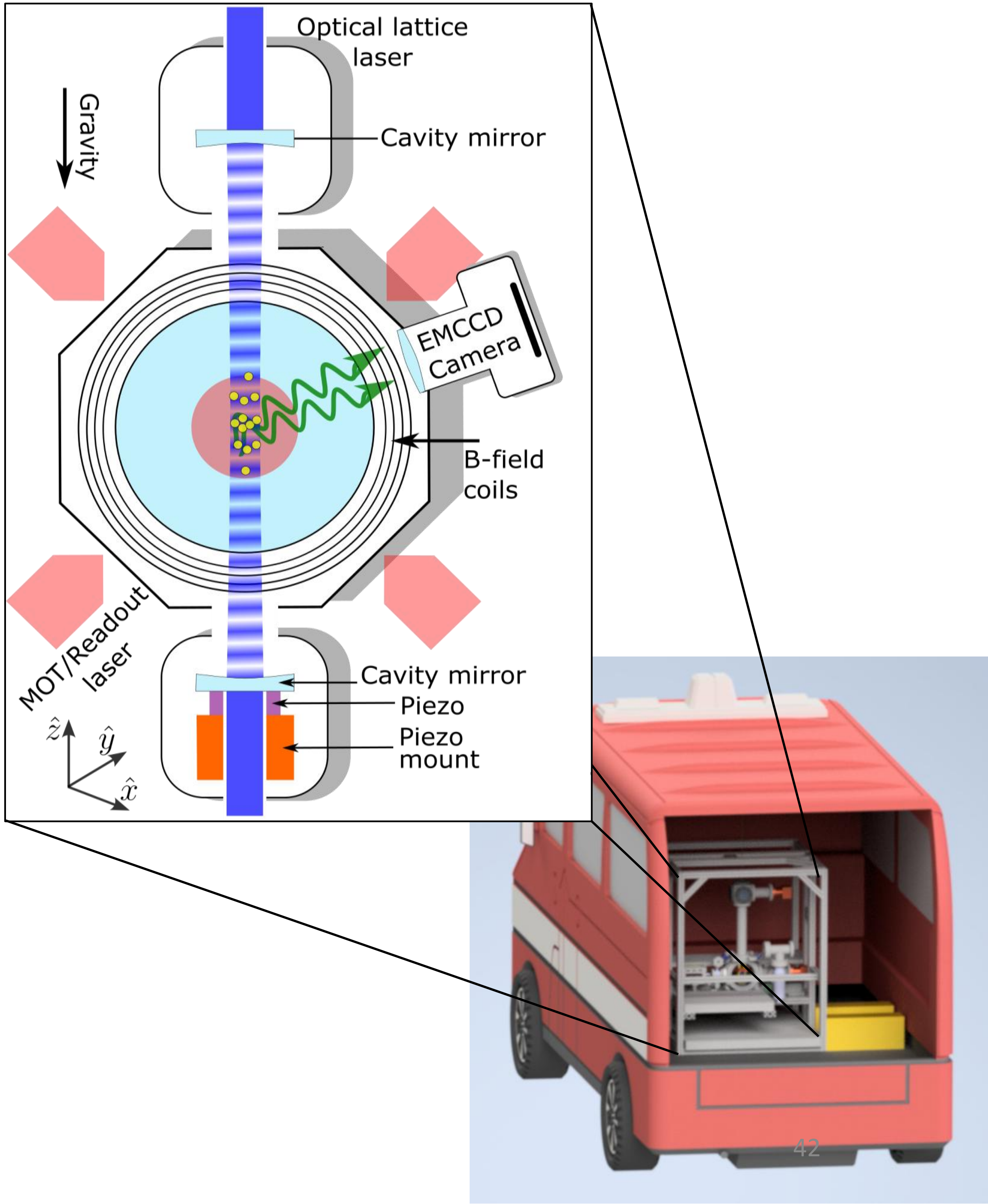
- Simple vacuum chamber + laser systems
- Compact, robust
- 1x1x1 m package
- On mobile platform, transportable

<u>Applications:</u>

Gravitational mapping on Earth

- Geology and geophysics
- Underground caves and structures
- Changes in underground water
- Mineral deposits discovery

Geodesy in space



Paola Luna
(grad)

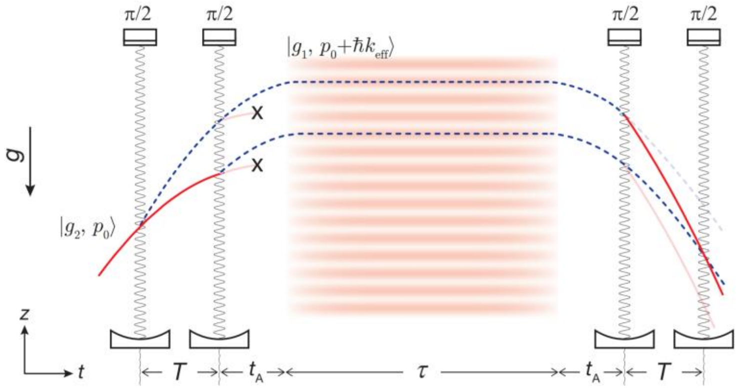
Andrei Zhukov
(grad)

Phillip Wondrak
(grad)

THE UNIVERSITY OF ARIZONA

Lattice Atom Interferometer with Minute Coherence

- Interferometry with atoms trapped in an optical lattice



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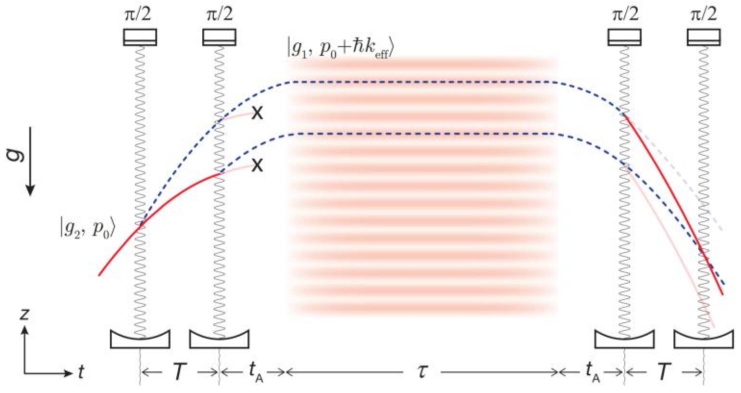
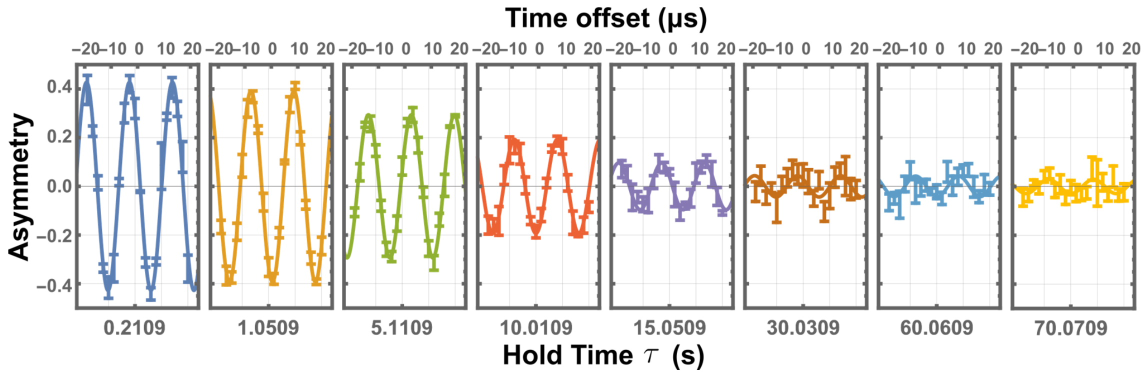


- Spatial superposition state coherent for 1 minute



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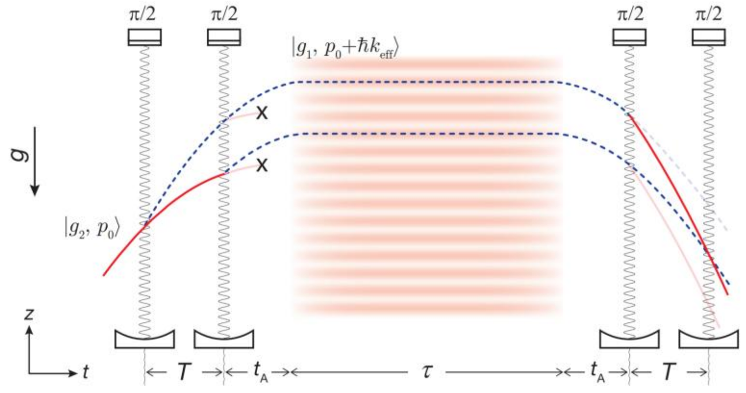
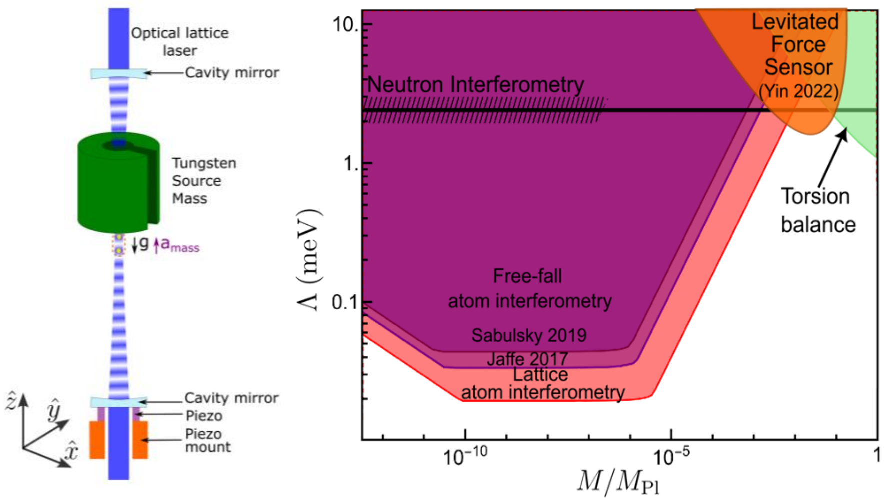


- New bounds on fifth forces



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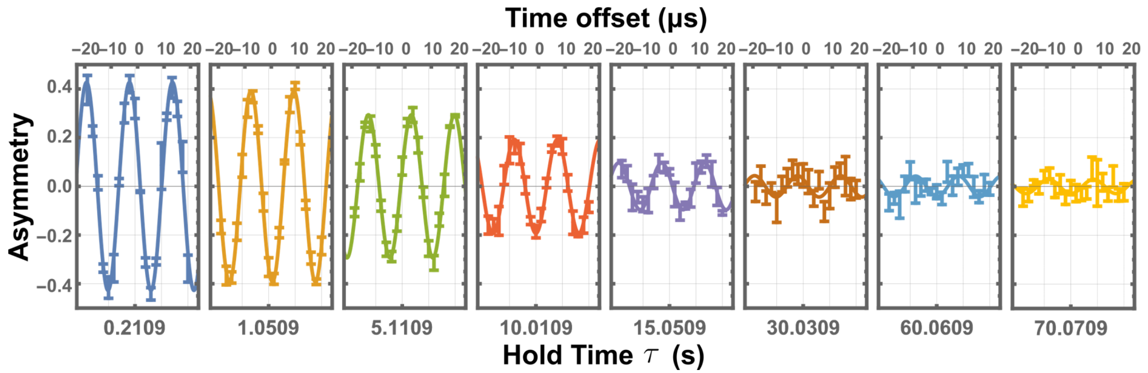

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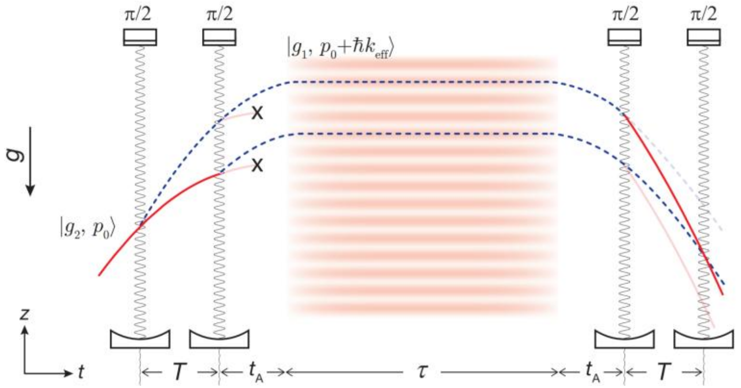

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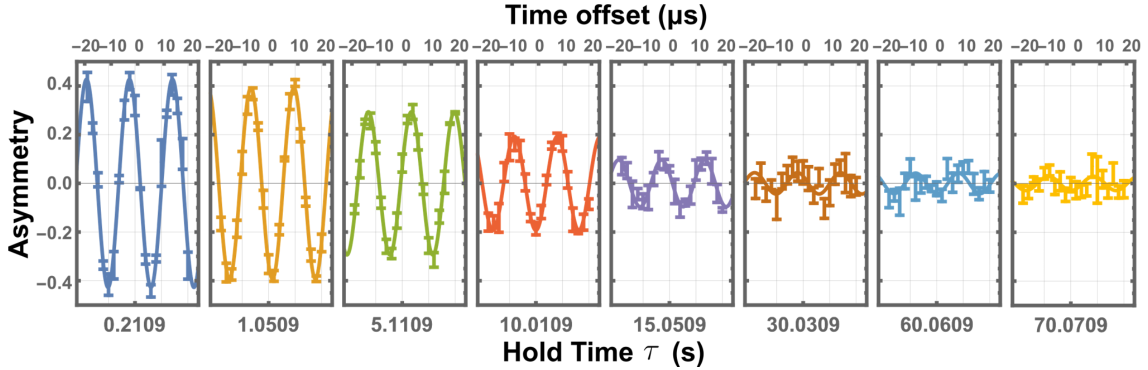

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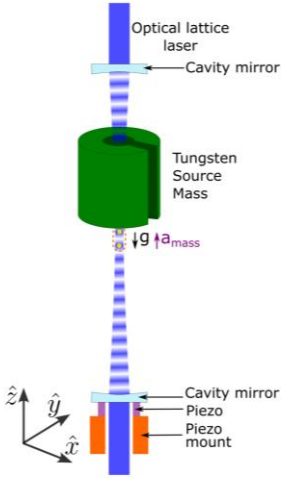

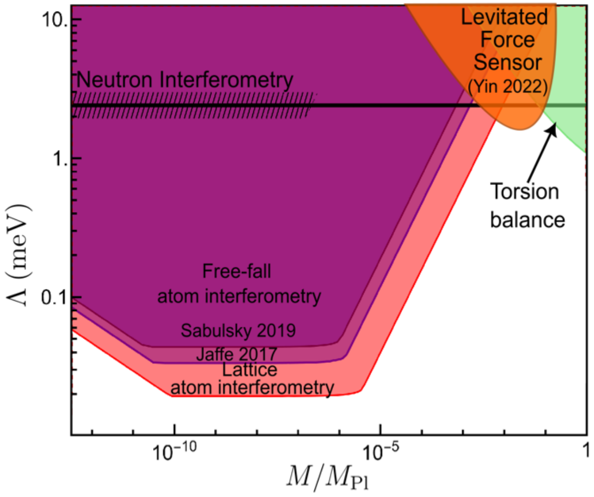

- First interferometer fringes in Arizona