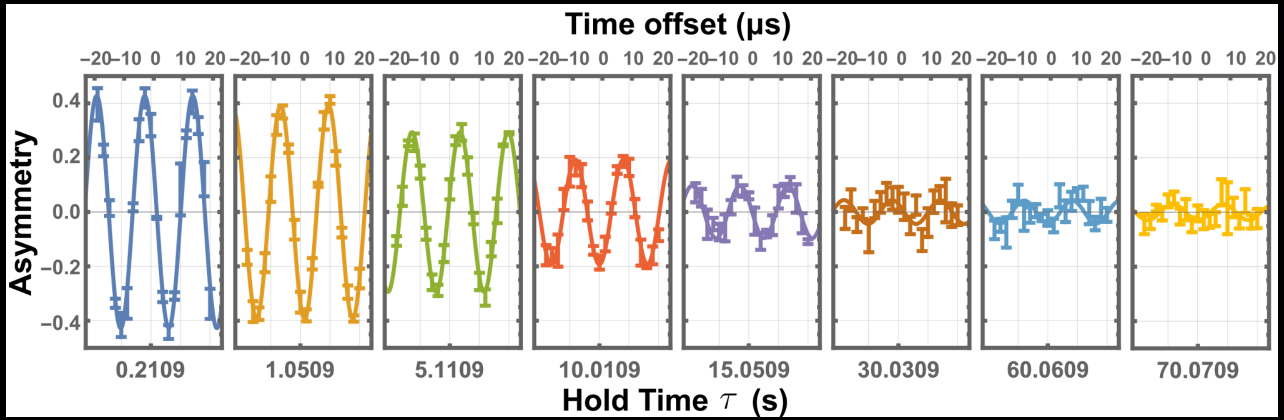
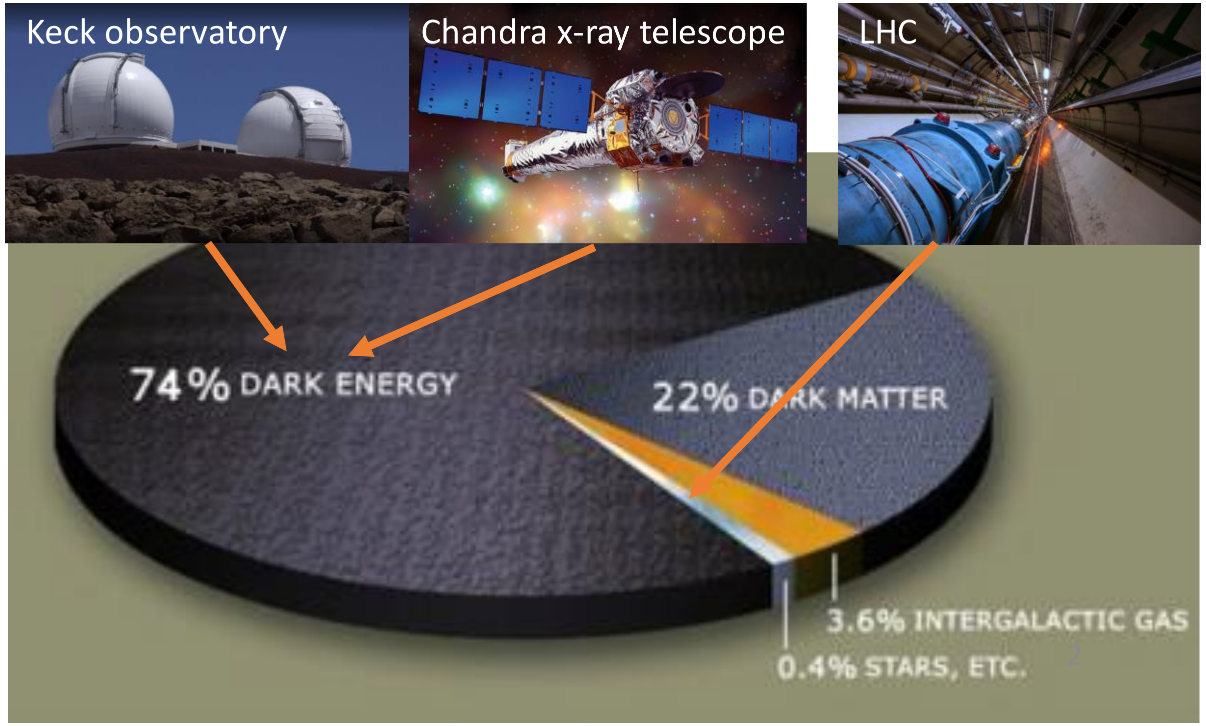
Fundamental physics with atoms and molecules

Measuring gravity by holding atoms

Cris Panda
UC Berkeley Department of Physics
Lake Louise Winter Institute
02/23/2024



Questions that Drive Us



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  - What is the microscopic composition of dark matter/energy?

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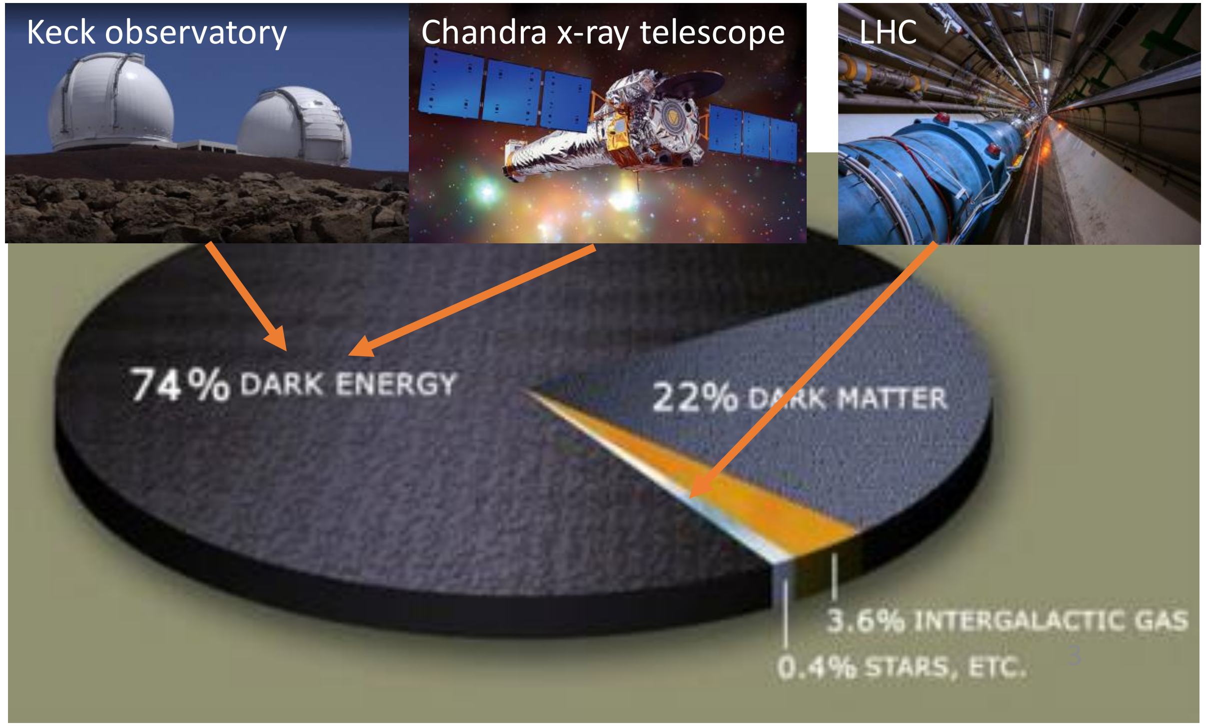


- Quantum and gravity
  - How do they fit together?

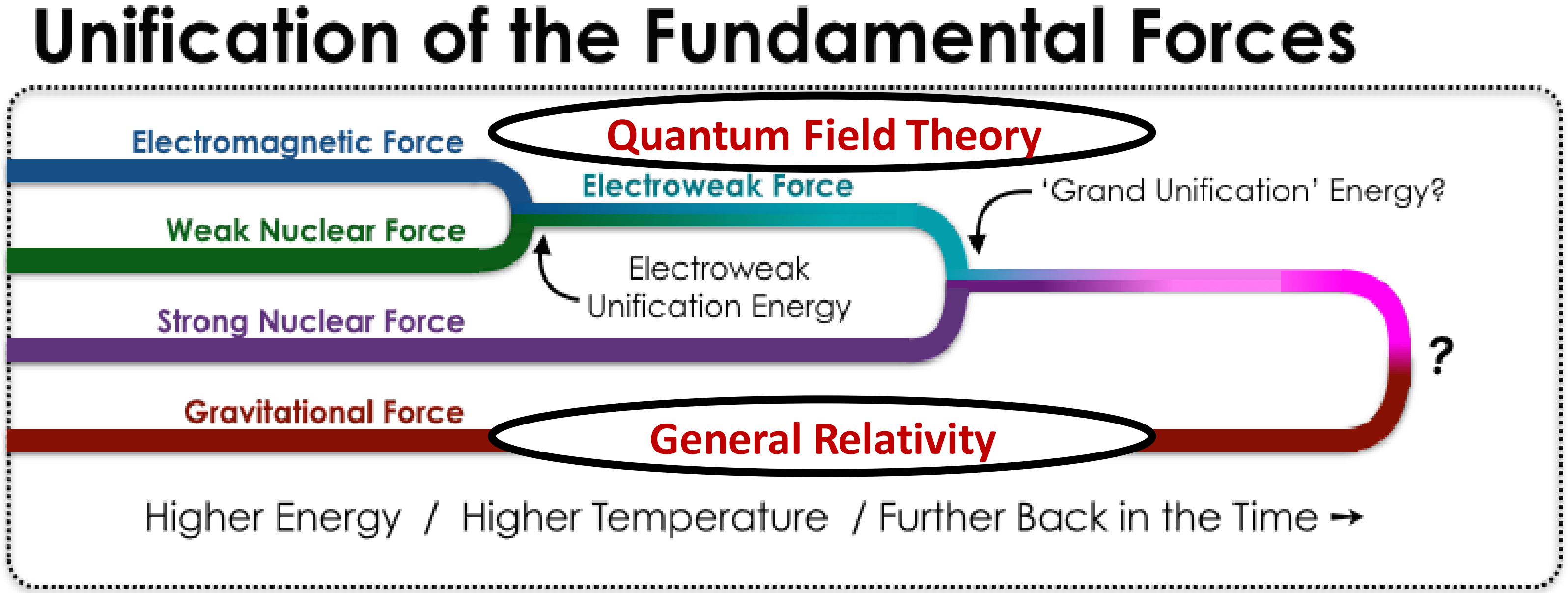
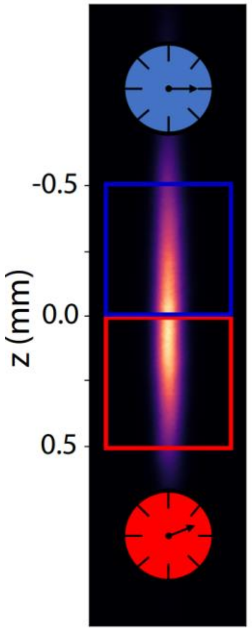


Image credit: Thomas G. McCarthy

Precision Quantum Metrology with Atoms and Molecules

Clocks

- Variation of fundamental constants
- Gravitational redshift



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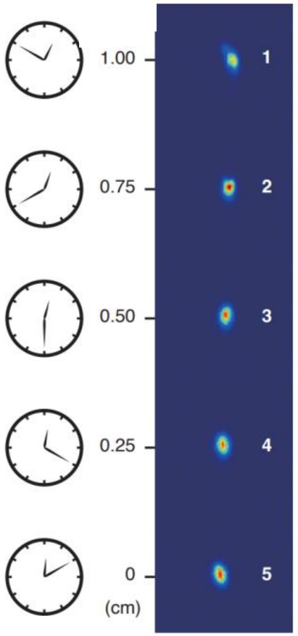
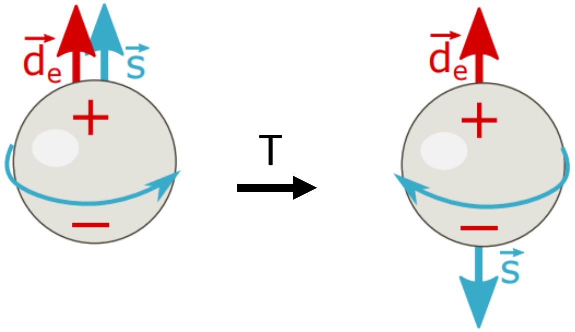


Zheng, X. et al, *Nat Commun* **14**, 4886 (2023).

Magnetometers

- Dark matter (Axions)
- Lorentz symmetry
- Parity violation
- CP-violation – searches for EDMs



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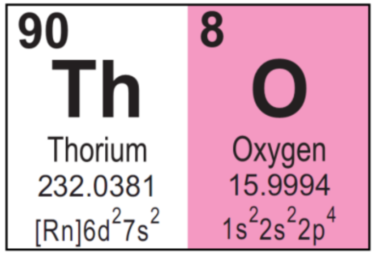
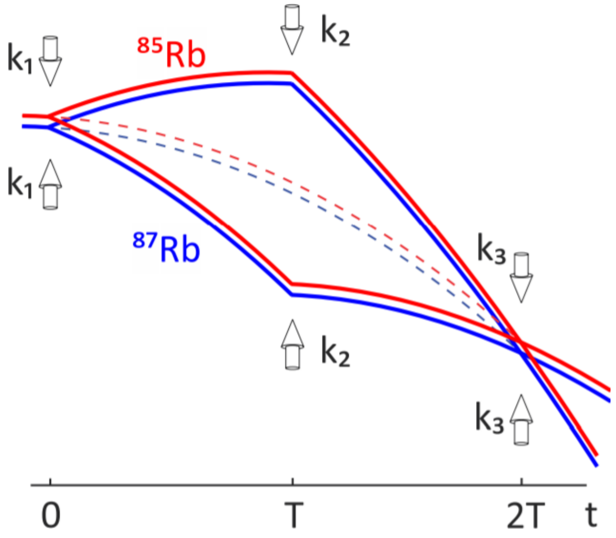


Atom Interferometers

- Fundamental constants: Alpha, G
- Universality of free fall



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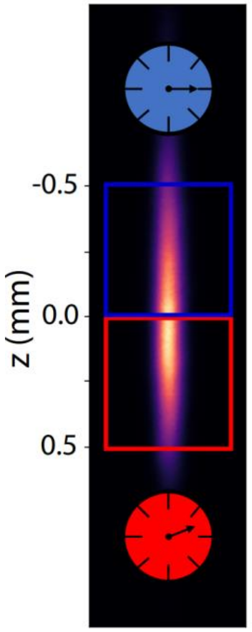

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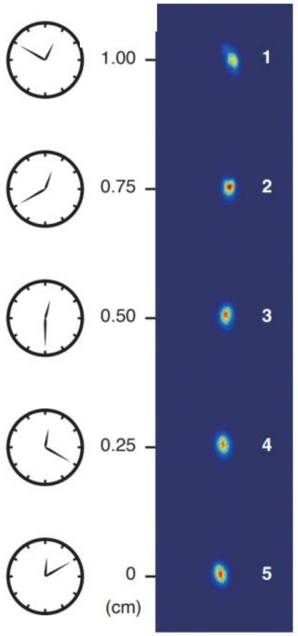

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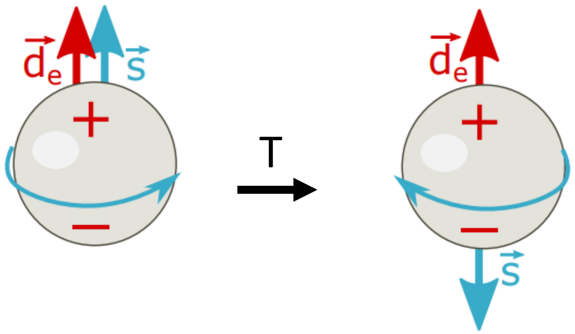

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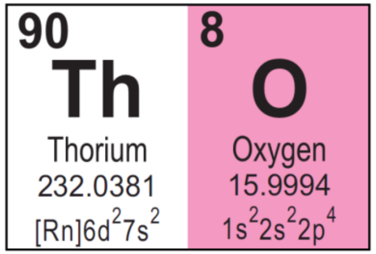

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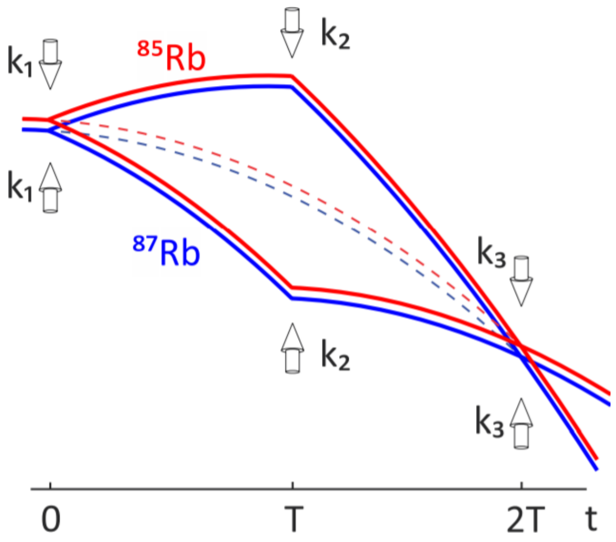

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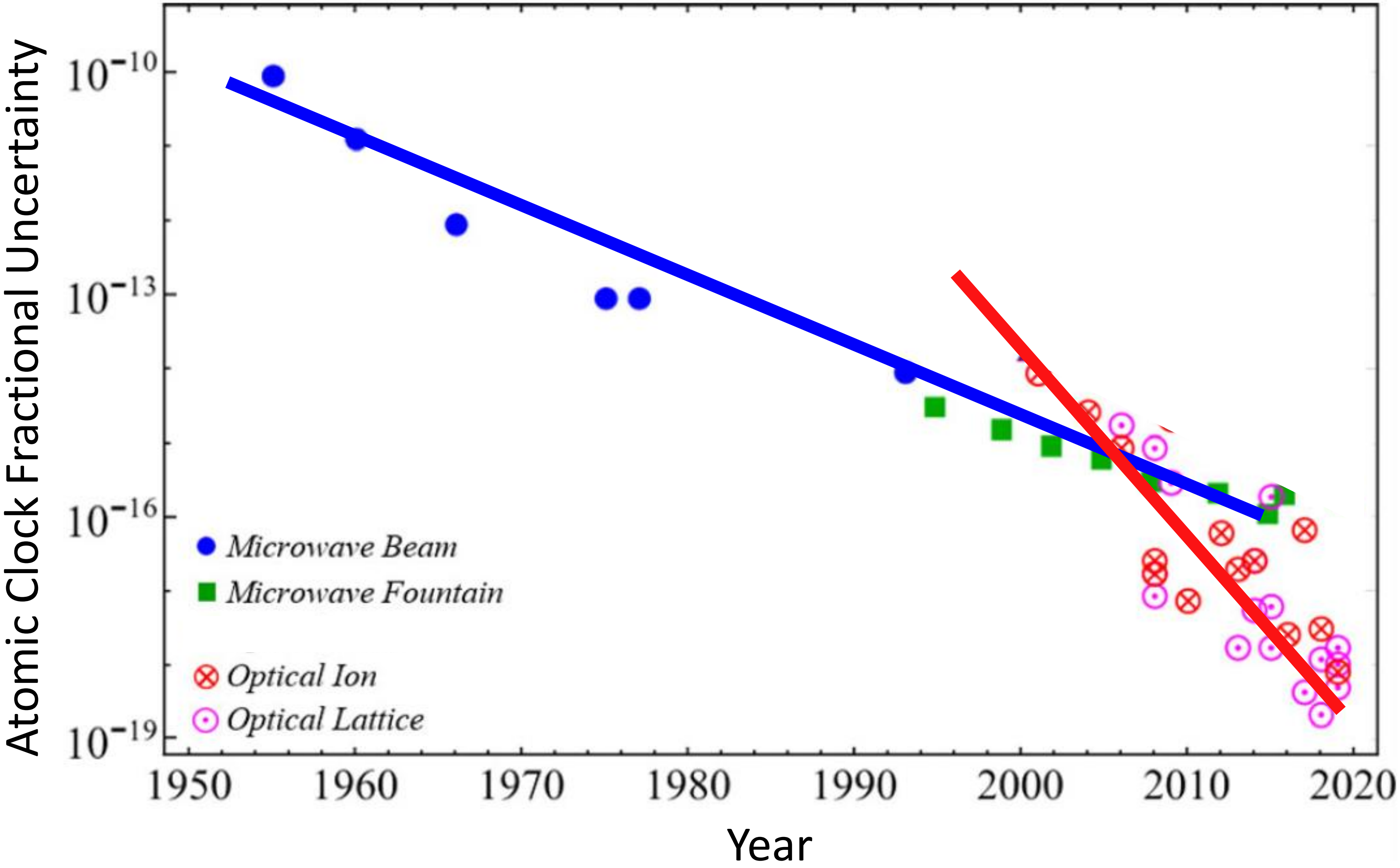
New Technologies can be Disruptive



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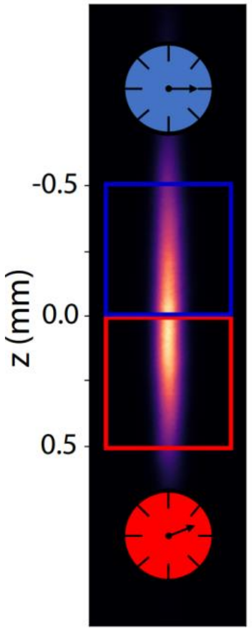

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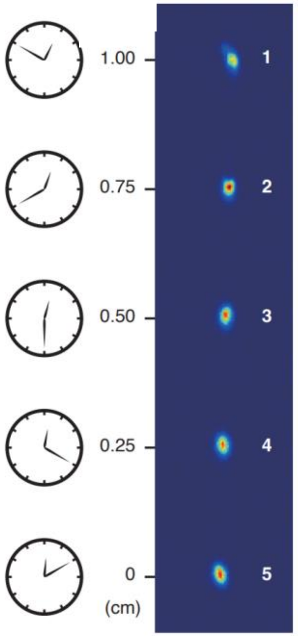

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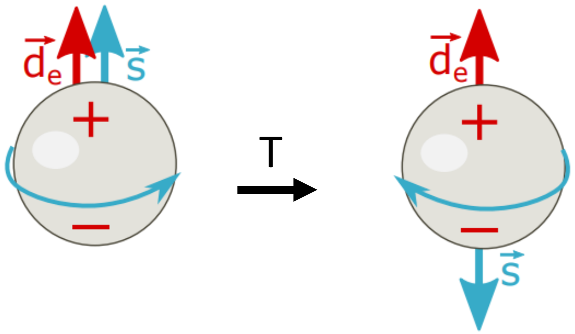

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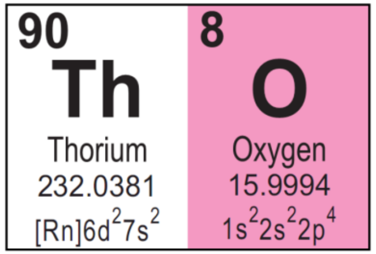

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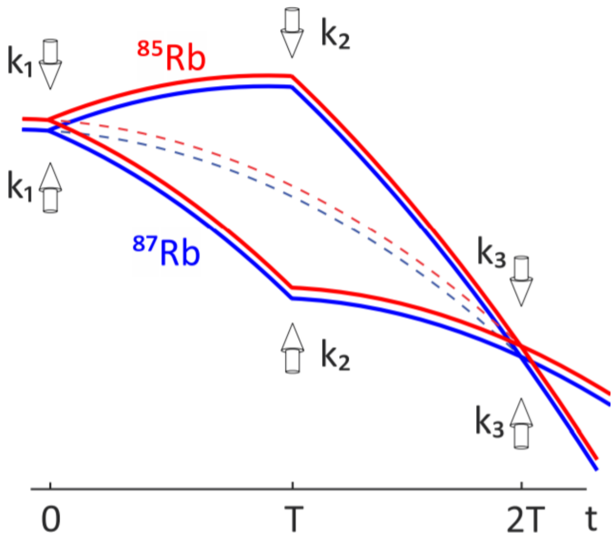

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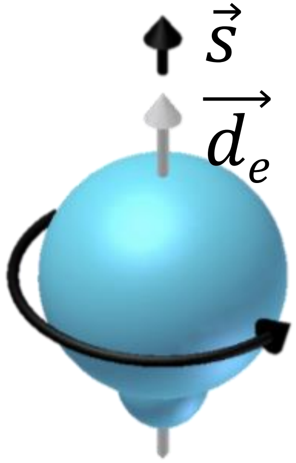
Electric dipole moments probe new physics



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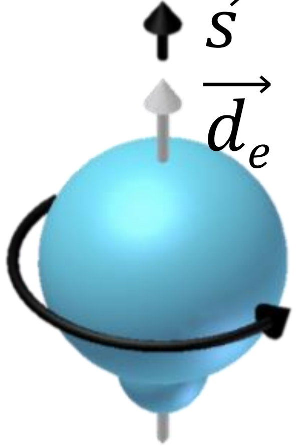

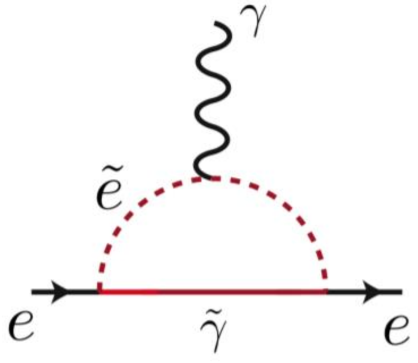

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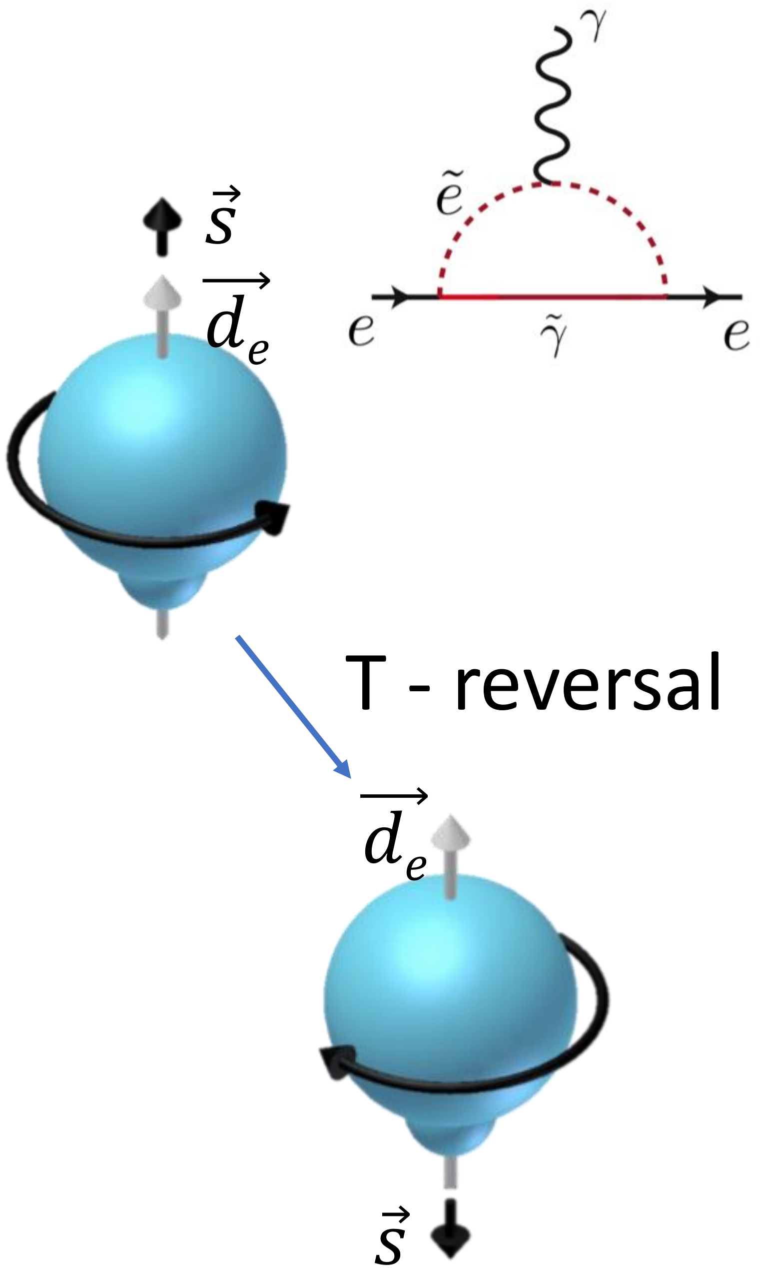
- Permanent EDMs of fundamental particles violate T-symmetry.



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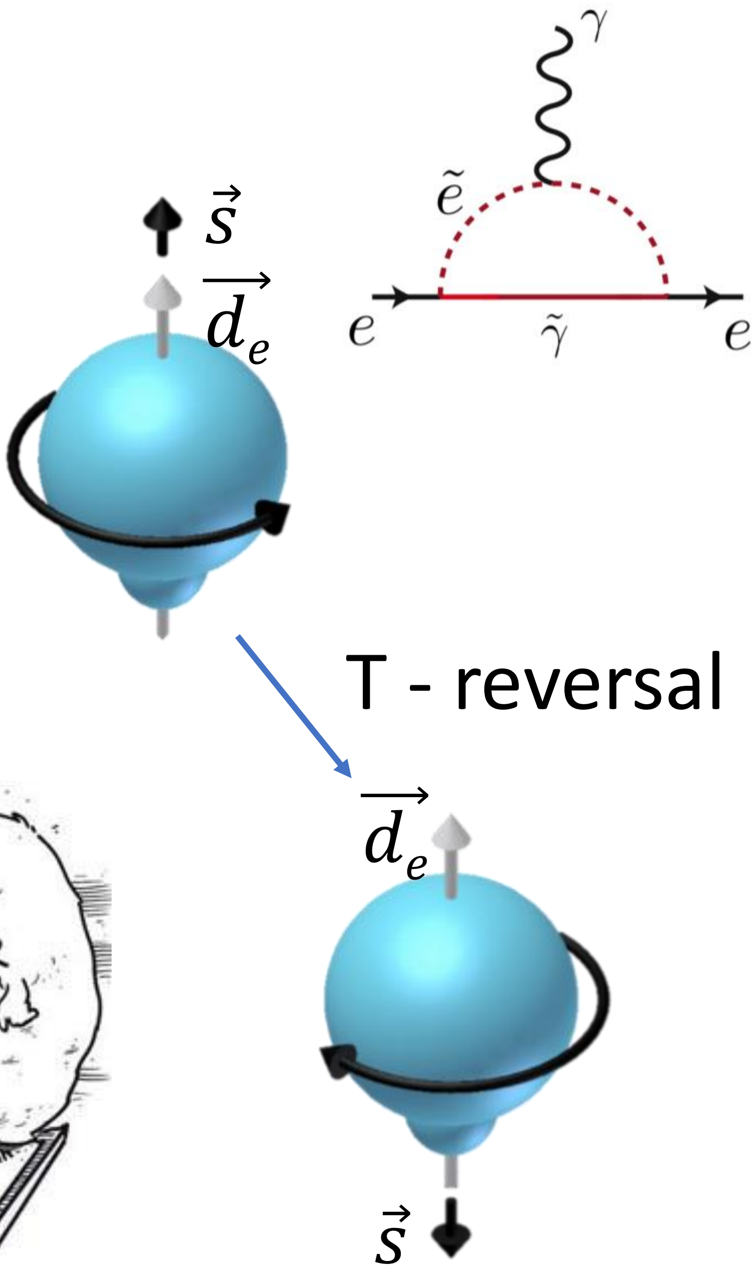
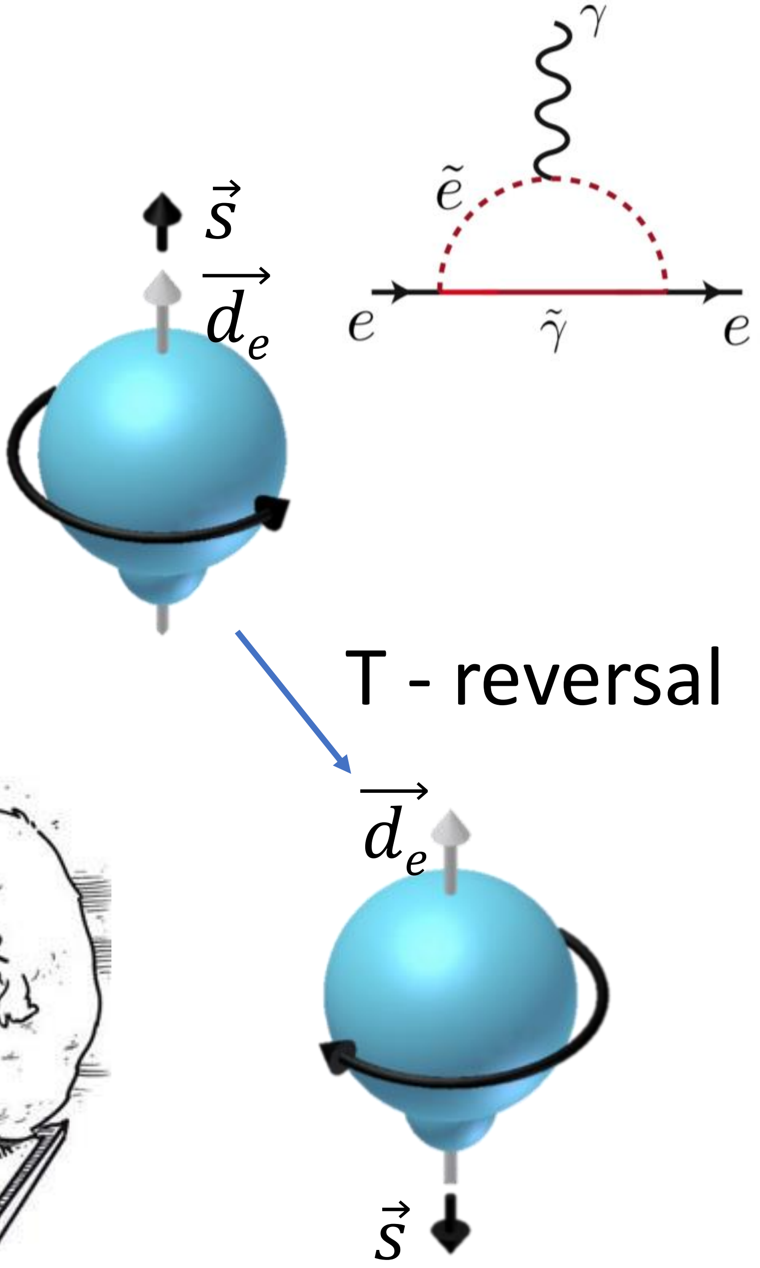


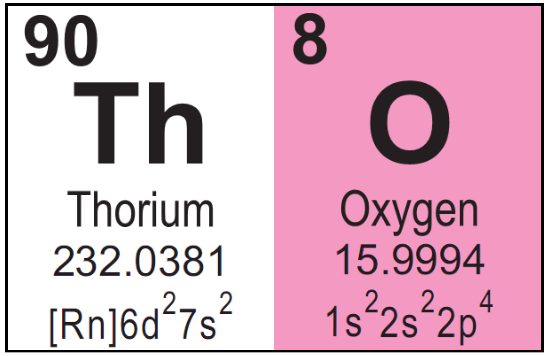
Electric dipole moments probe new physics

- Permanent EDMs of fundamental particles violate T-symmetry.
- CPT Theorem <-> EDMs are also CP-violating <-> baryogenesis.
- No permanent EDMs observed, despite 70 years of searches[1].



[1] Purcell, E. & Ramsey, N., *Phys. Rev.*, *78*(6), 807 (1950)

Why use a molecule?



"A diatomic molecule is a molecule with one atom too many."

- Arthur Schawlow, Nobel Prize winner

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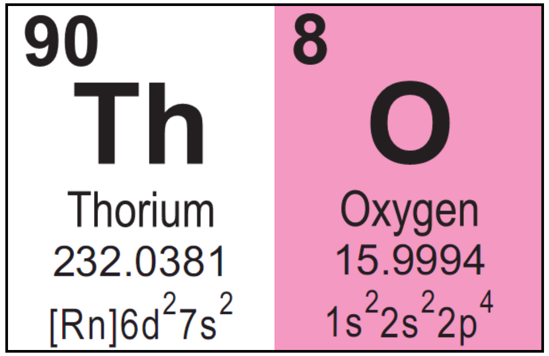

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$$H = -d_e \cdot \mathcal{E}_{\text{eff}}.$$

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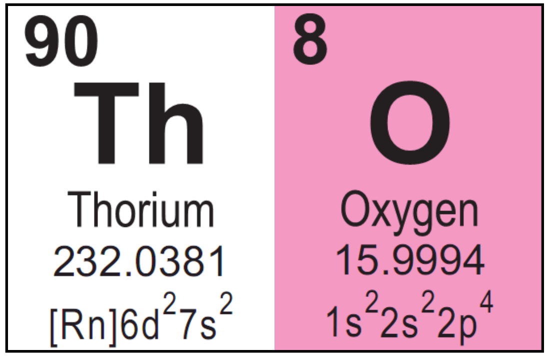

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  - >1,000,000 larger than in lab.

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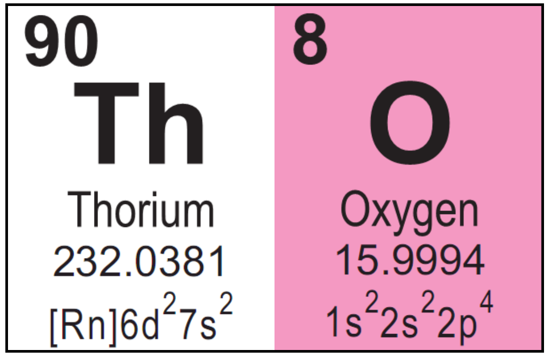
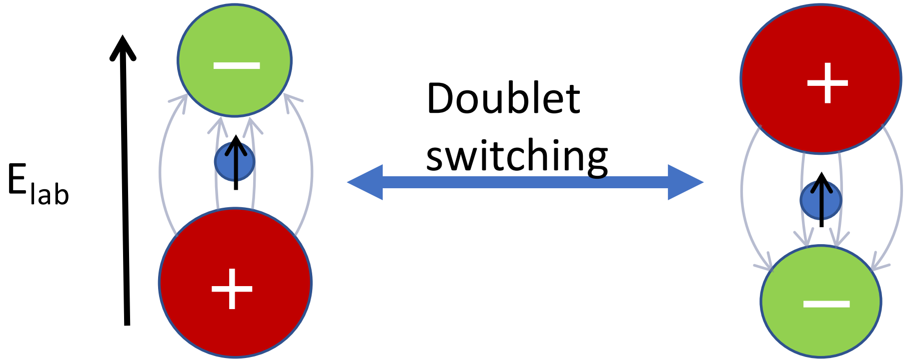
  - Reverse $\mathcal{E}_{\text{eff}}$ by tuning our laser, without switching the lab electric field.





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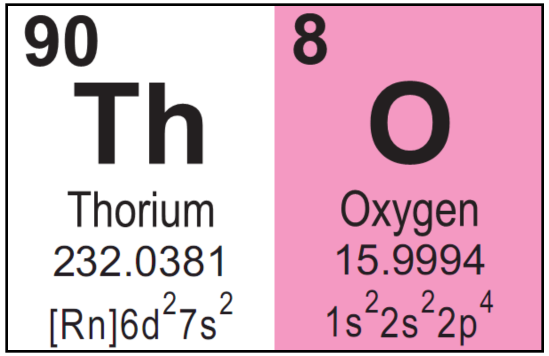
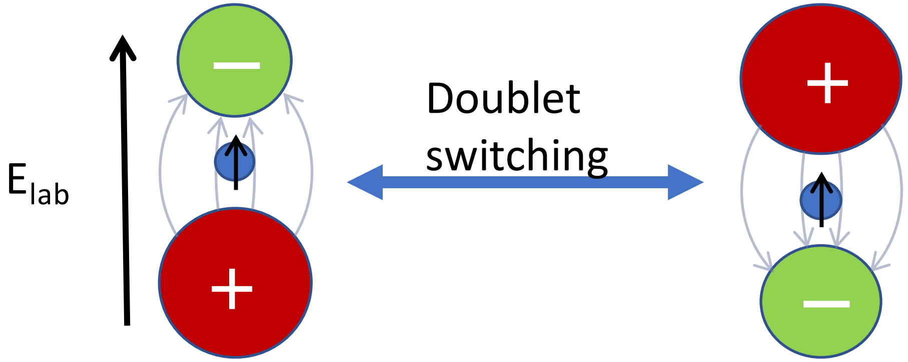
- Magnetically insensitive, reduces B field systematics
  - Magnetic moment is 0.004 μ_B.





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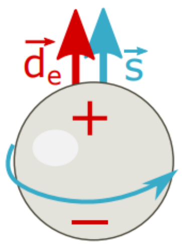
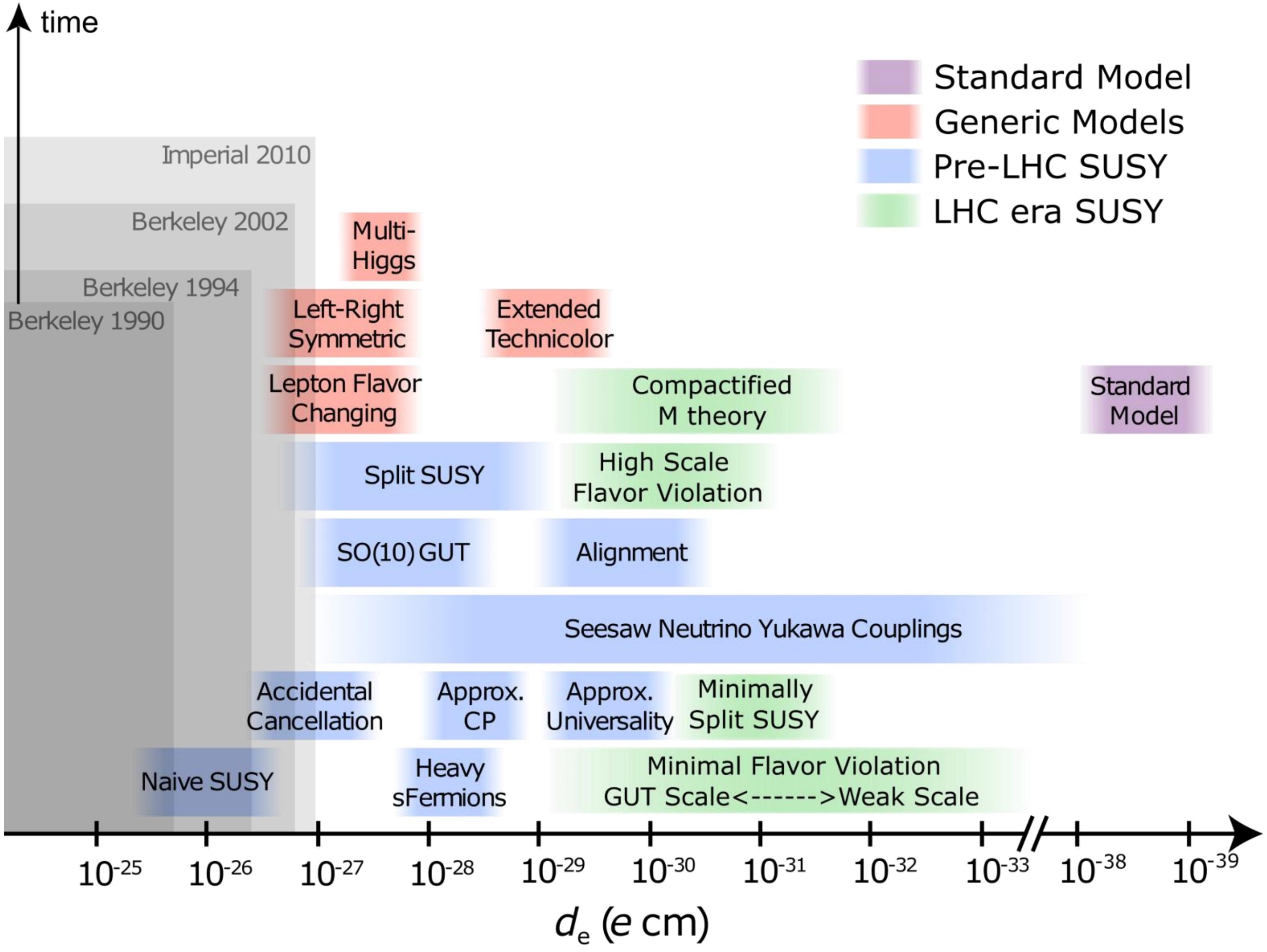
Measurements of the Electron EDM





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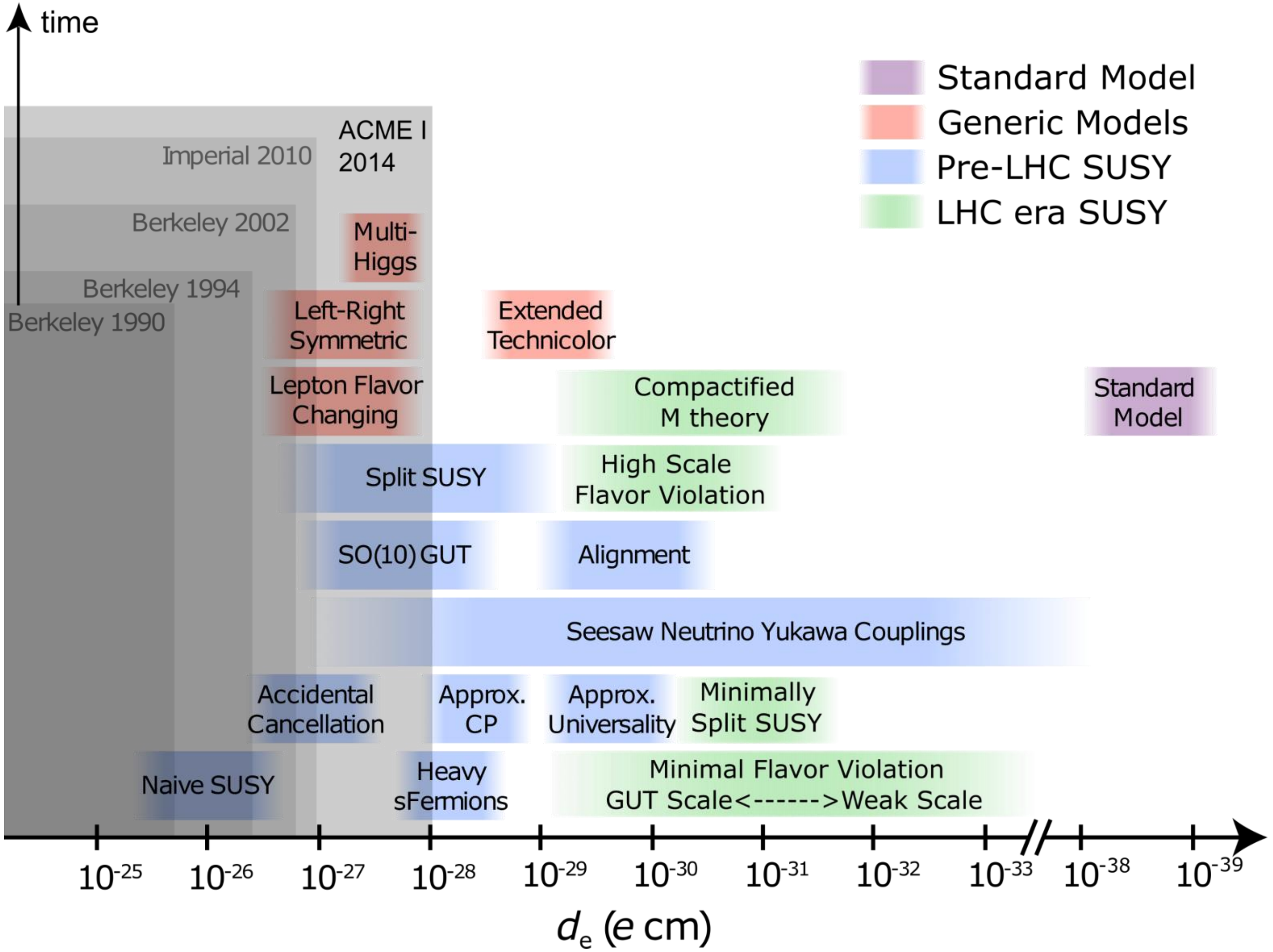

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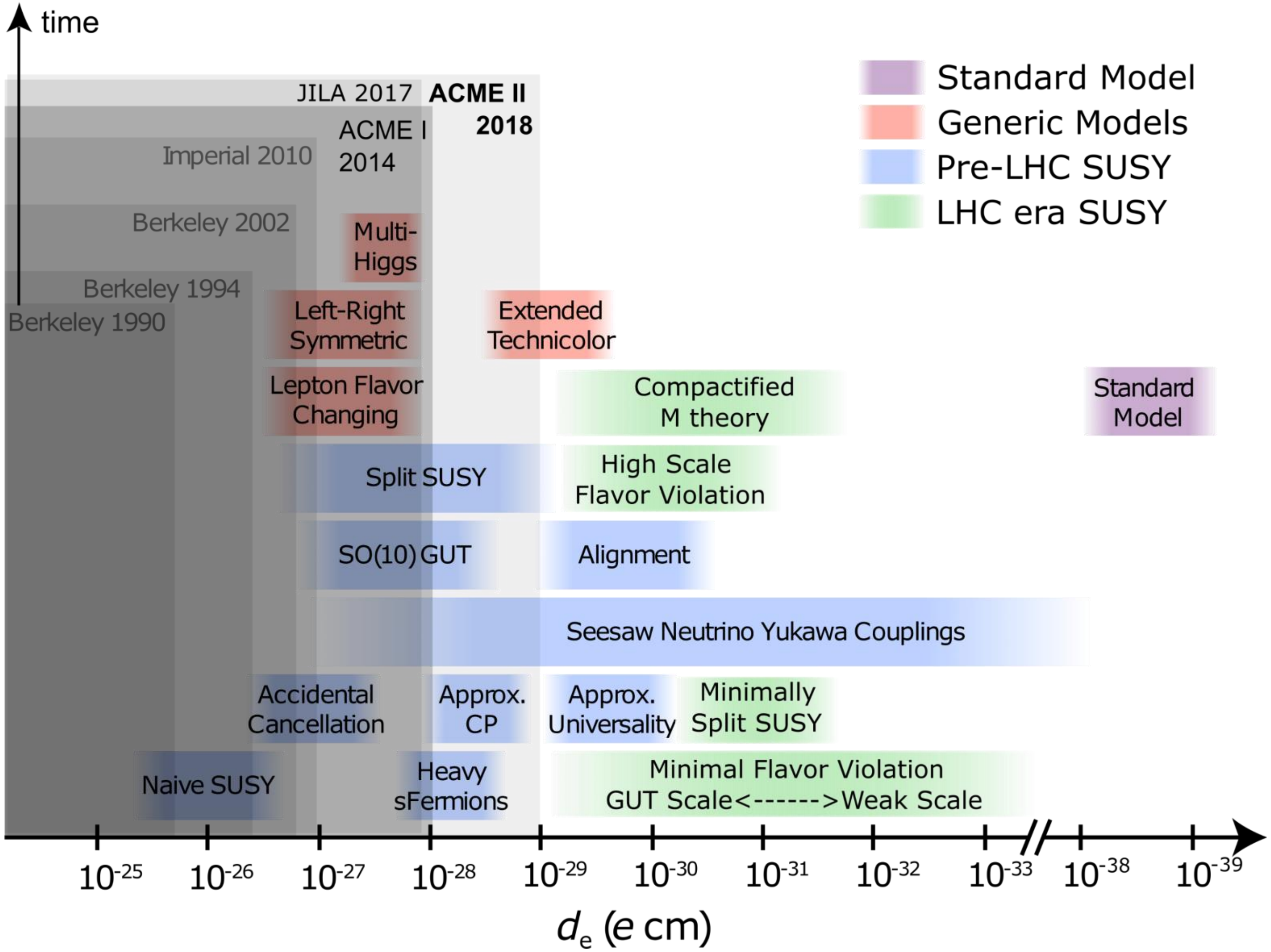

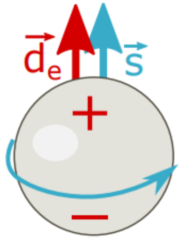

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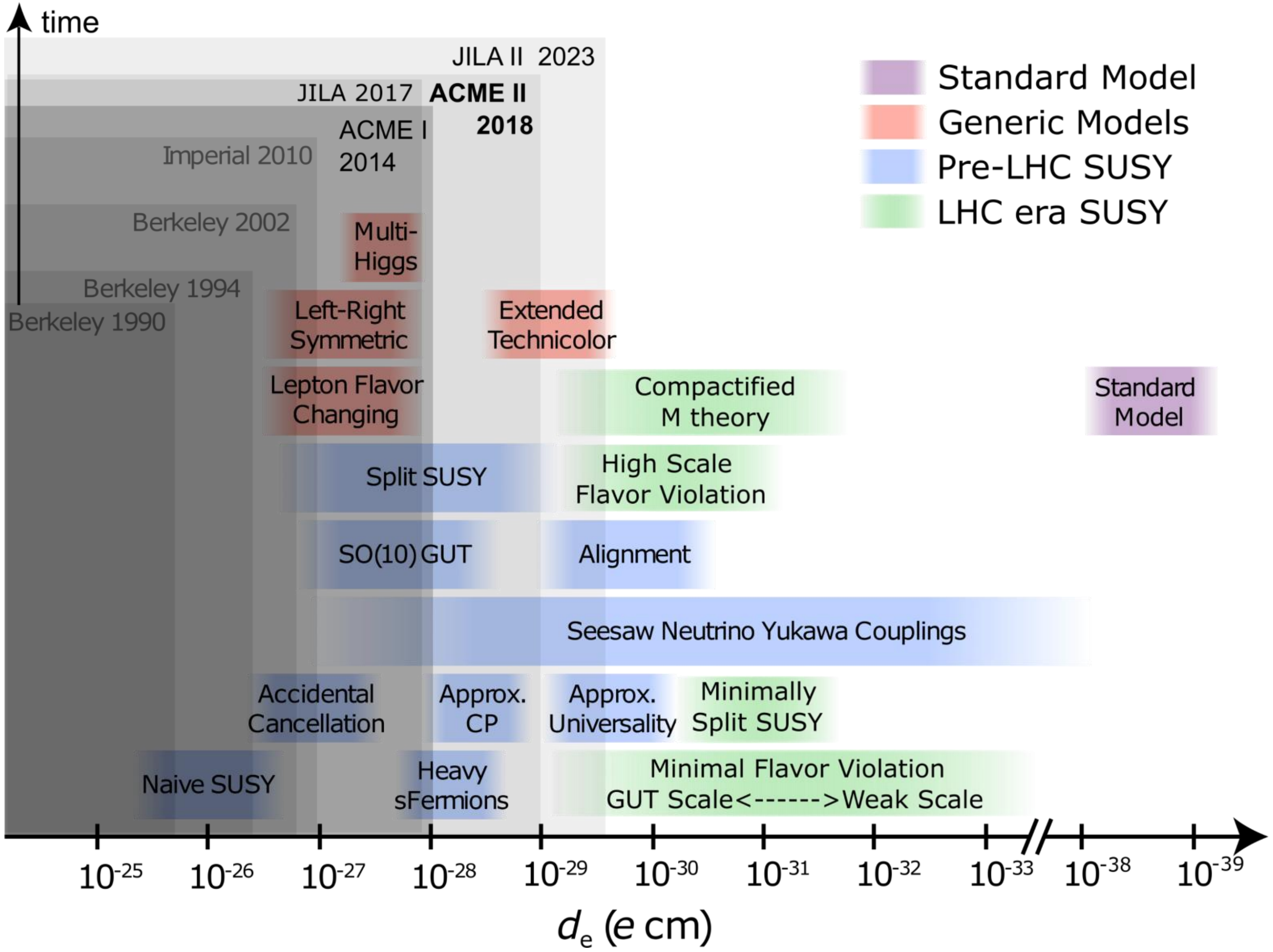

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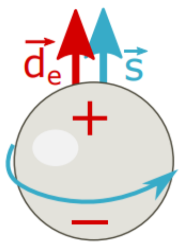

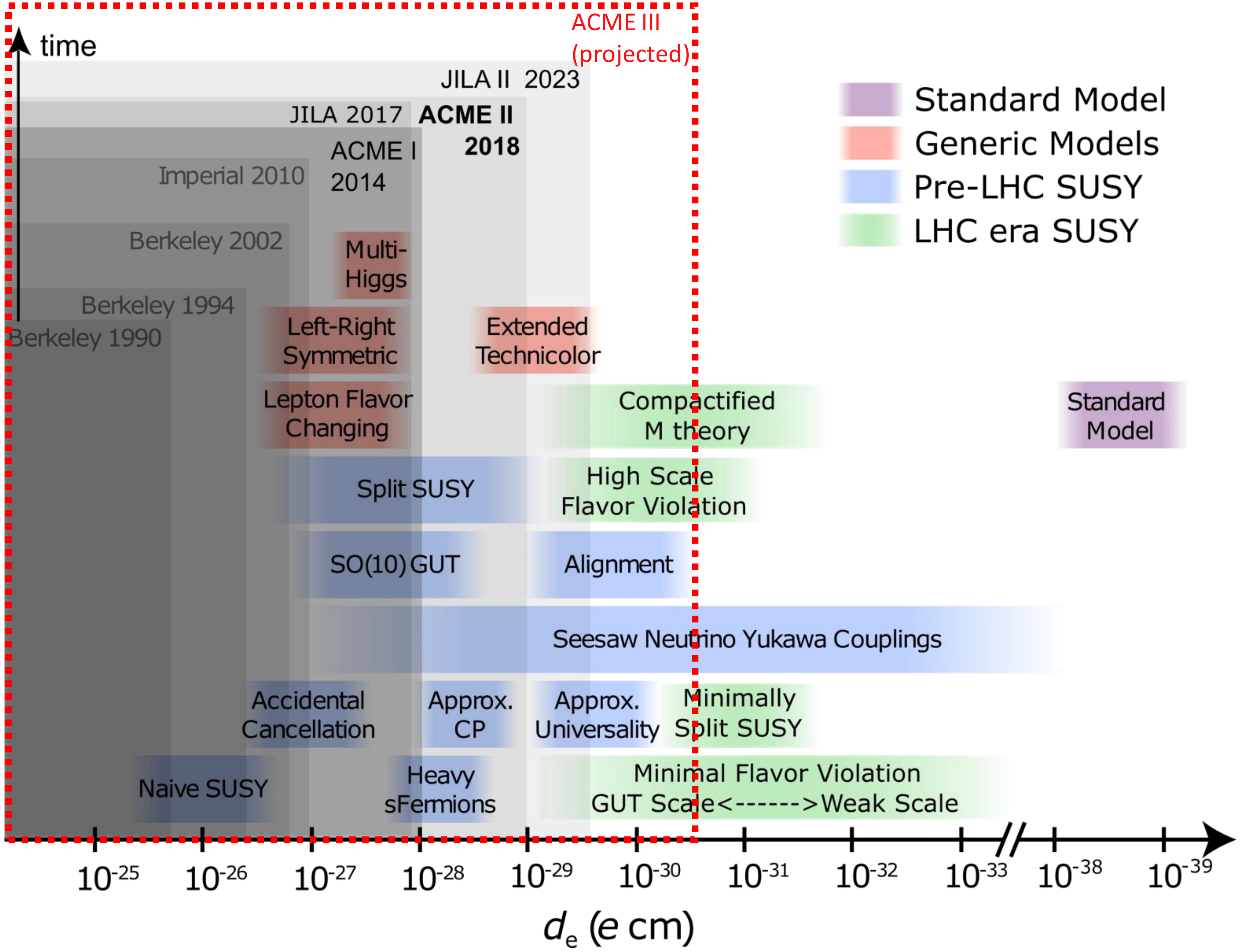

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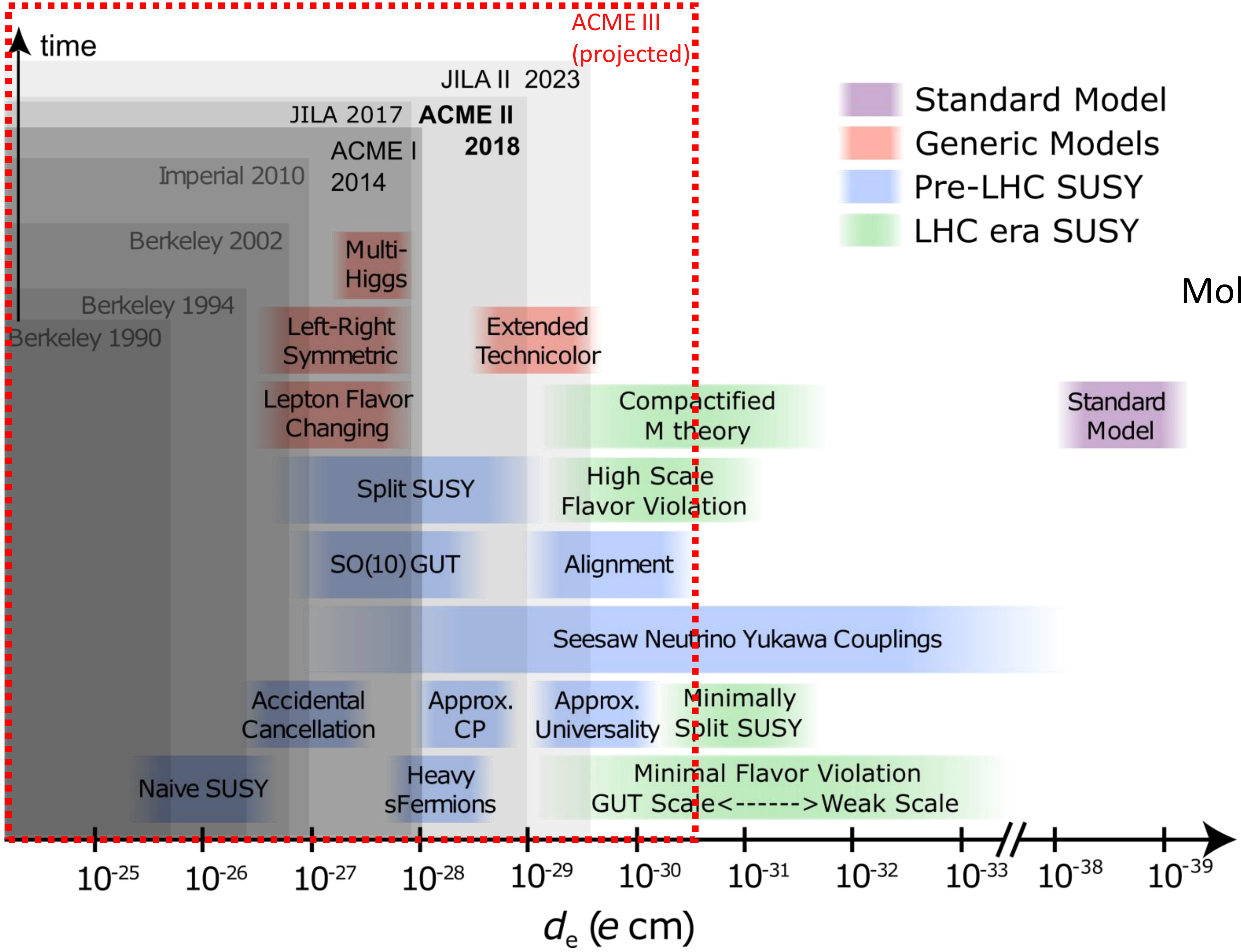
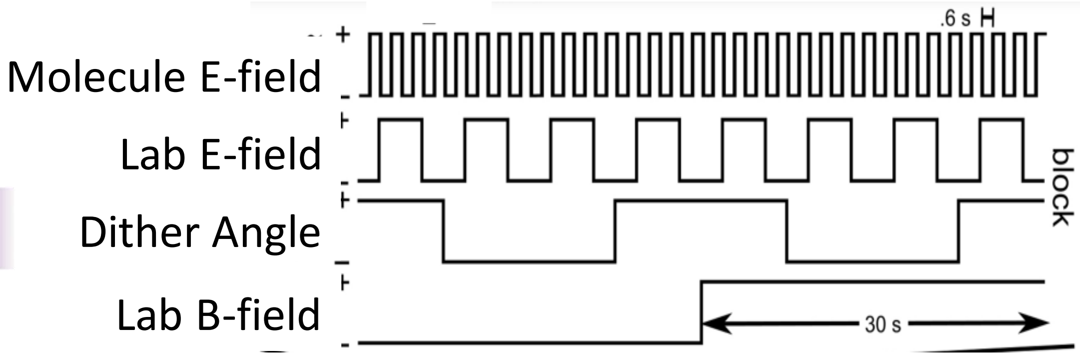


Switches!



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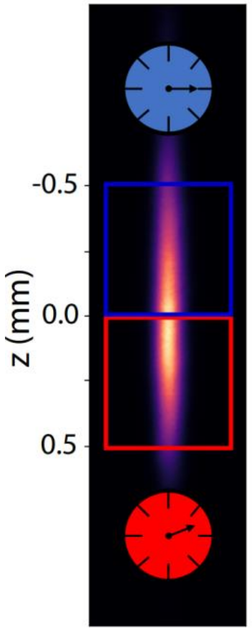

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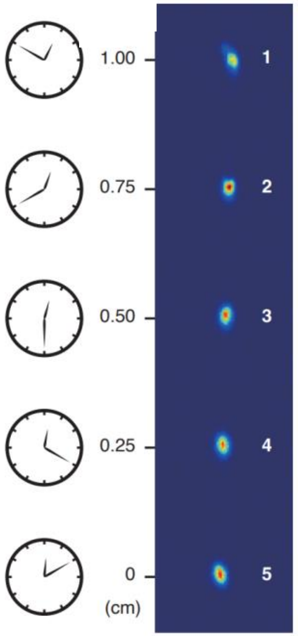

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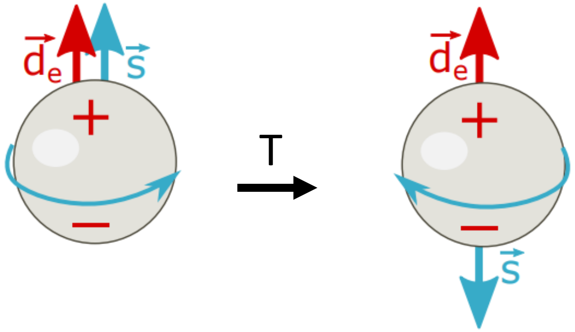

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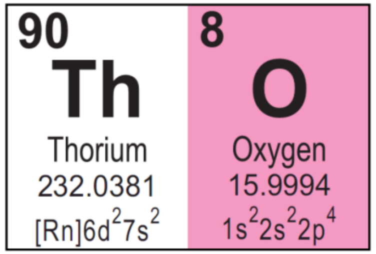

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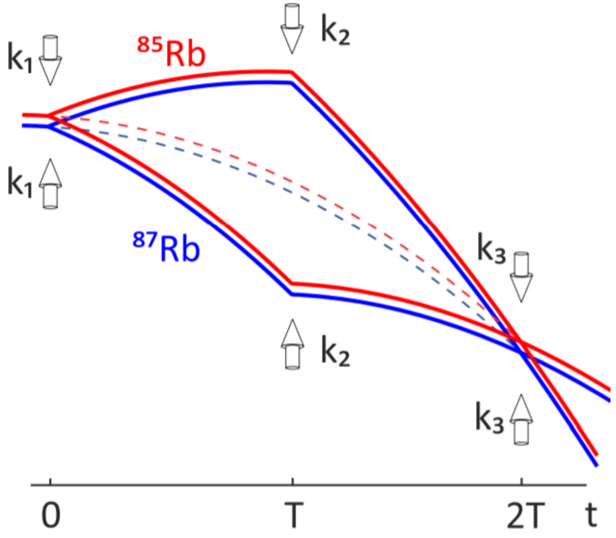

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Outline

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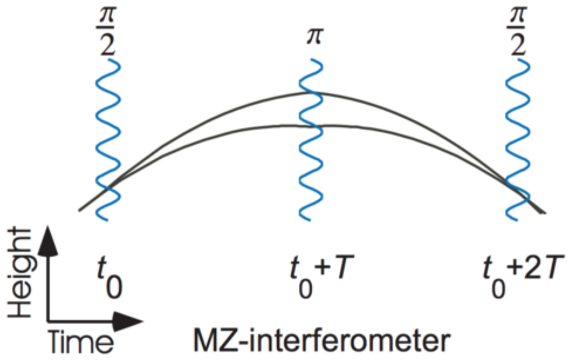
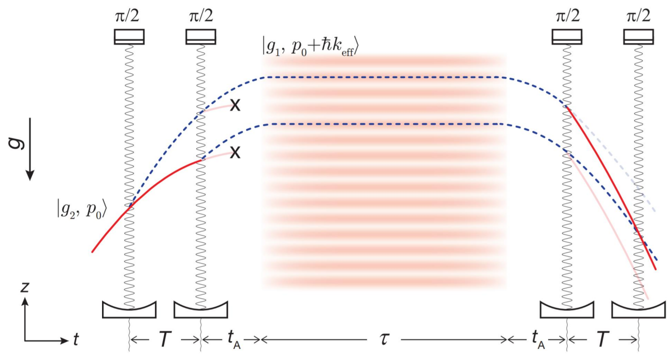
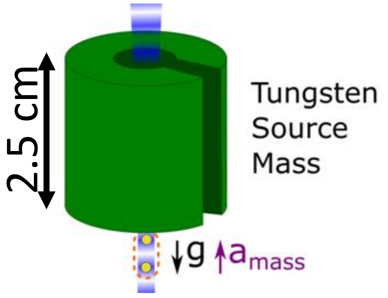


- Optical lattice atom interferometer

- theory and experiment



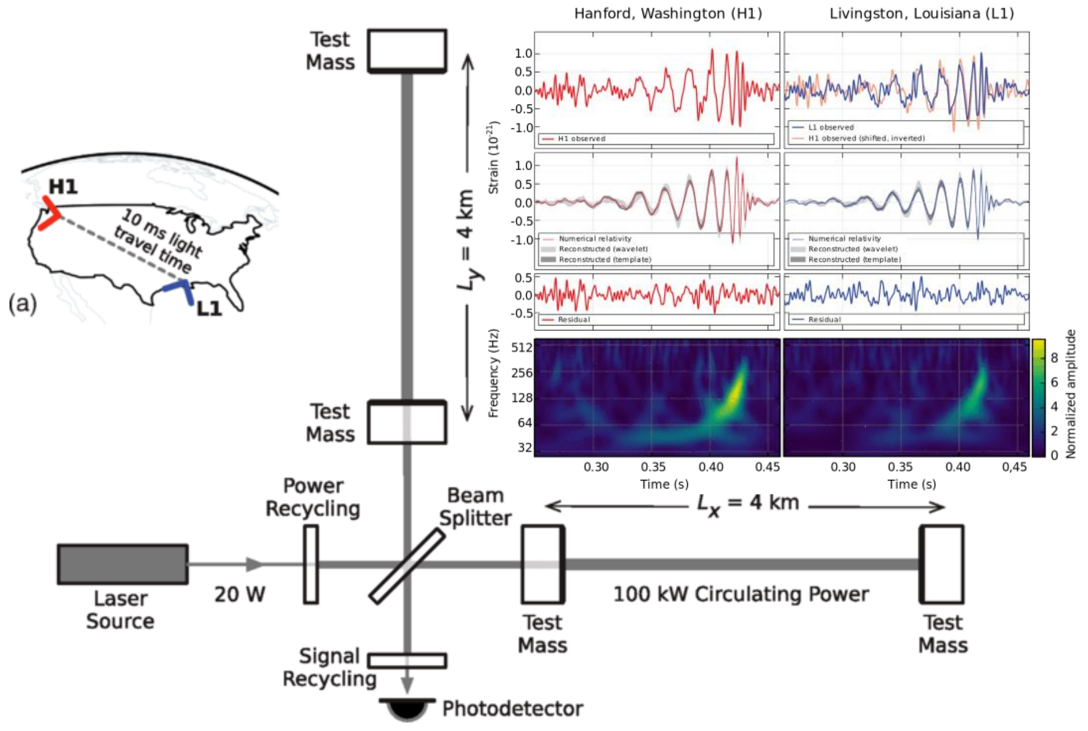
- Precise measurement of gravity and fifth forces



- Future directions

Interferometers Review

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



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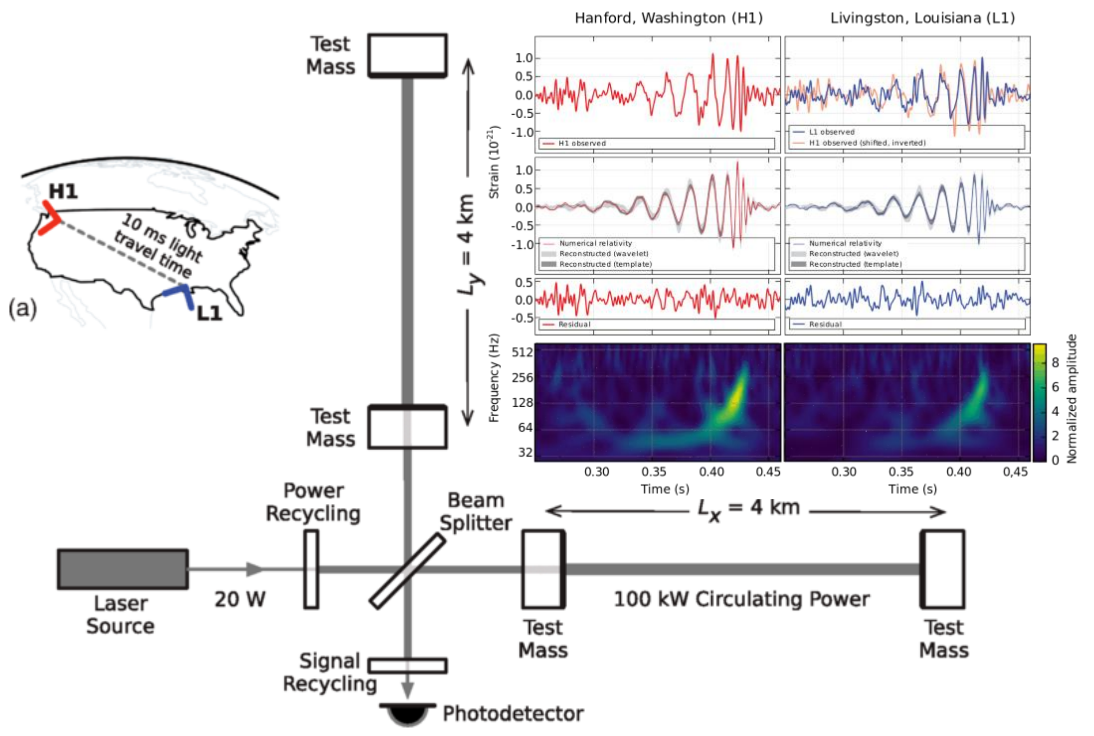
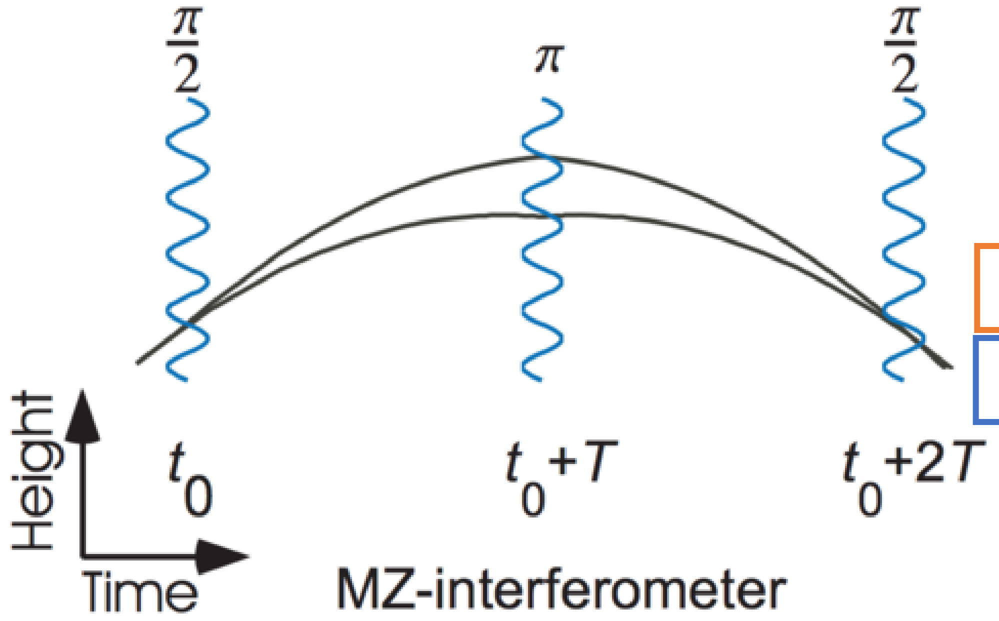
  - Use matter to manipulate light
- Atom Interferometer
  - Use lasers to manipulate atoms



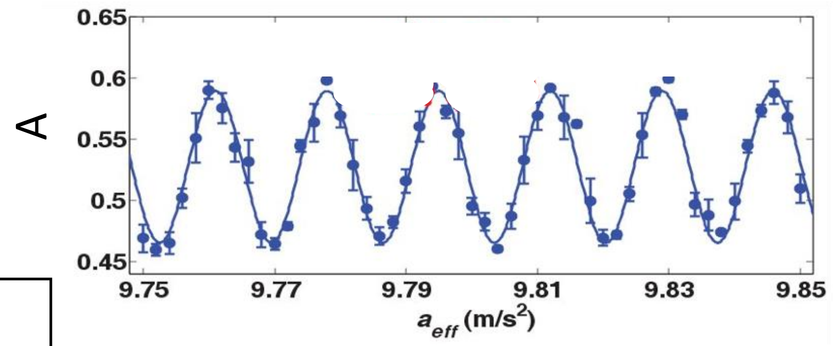


S_1

S_2

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

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



Atom Interferometer Phase

- <u>Propagation phase</u>

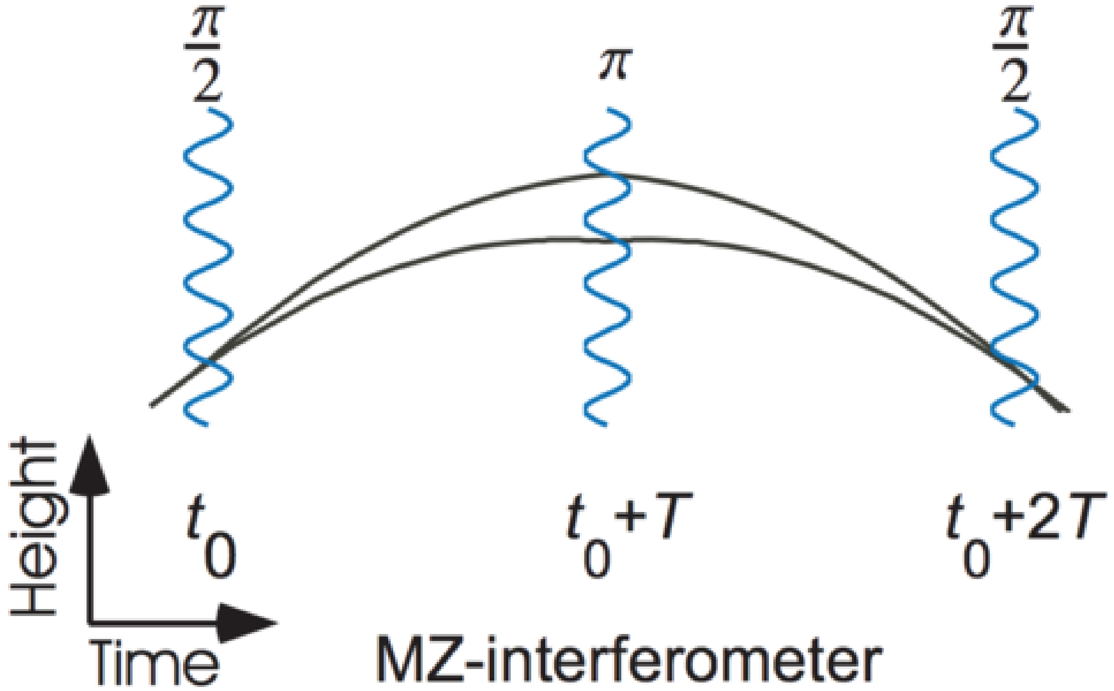
determined by Lagrangian

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

- <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

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

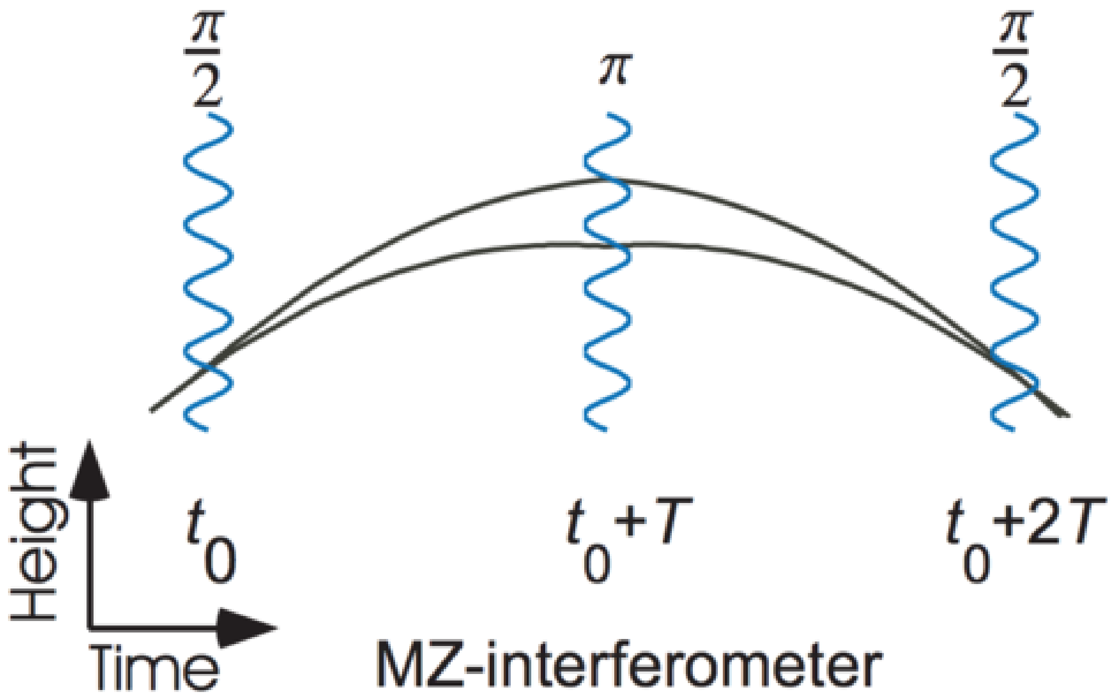
- <u>Atom-laser interaction phase</u>

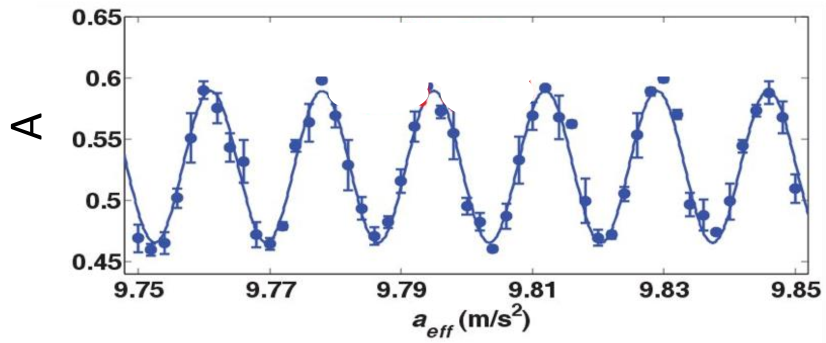
laser acts as ruler

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

- Total phase $> 10^9$ radians possible

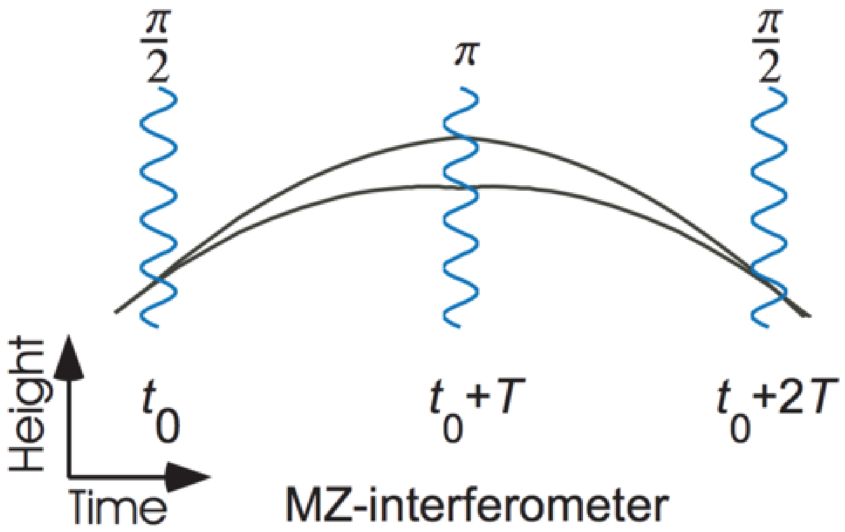
$$\Delta\phi = k\, g\, T^2$$

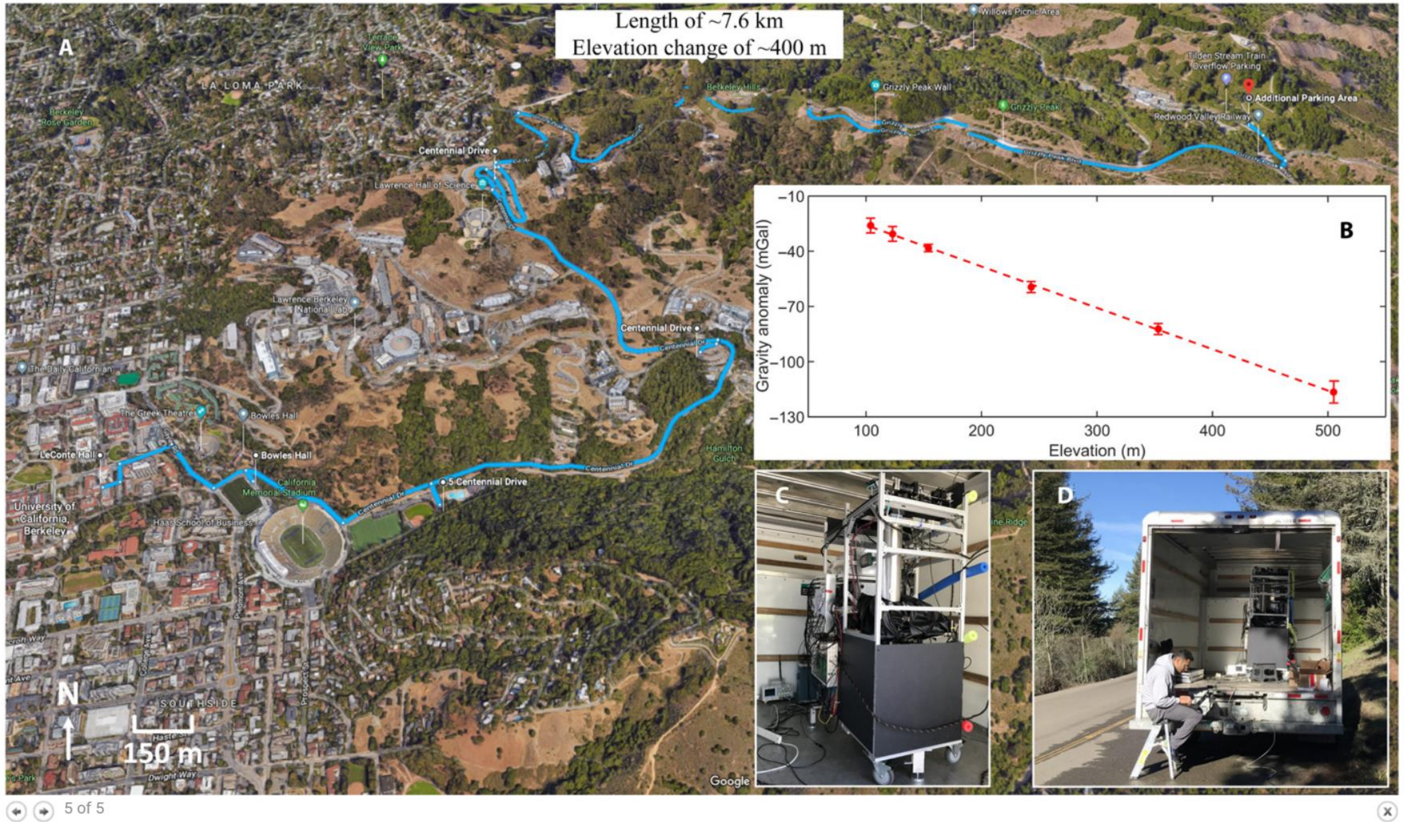




Quantum Sensing using Atom Interferometer

- Measure local gravity, geophysics, inertial sensing.





Commercial atomic gravimeters:

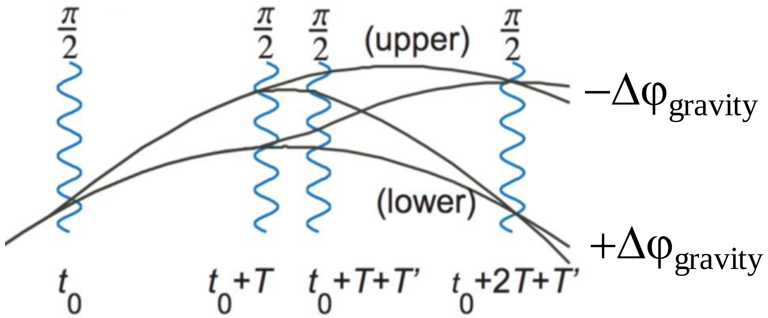
- VectorAtomic
- AOSense
- iXBlue

etc.

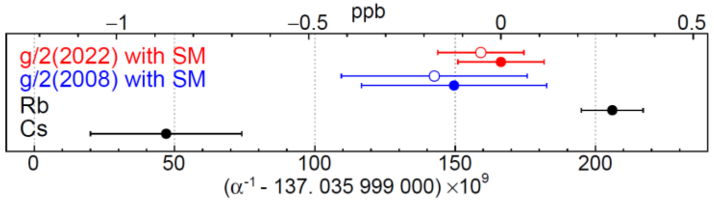
X. Wu, et. al., *Science Advances* 5(9), eaax0800 (2019)

Precision Interferometry

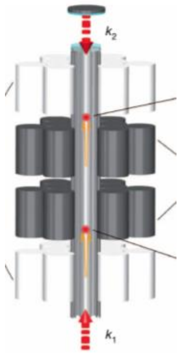
The fine structure constant α

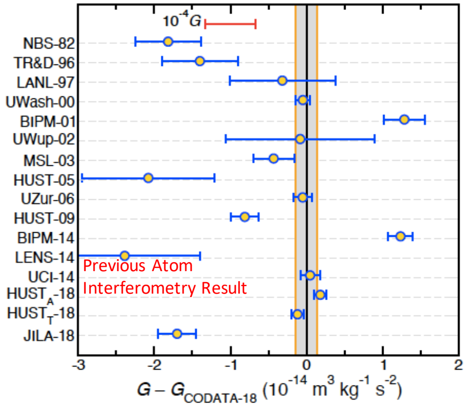


R. Parker, et. al., Science. 360, 191–195 (2018)

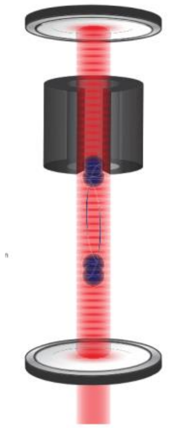


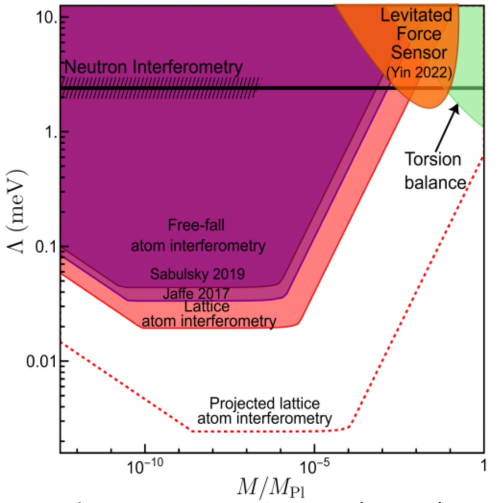
The gravitational constant G





Fifth-force searches





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

Many others

- Testing weak equivalence principle
- Quantum and gravity
- Proposed searches for gravitational waves
- Searches for dark matter

etc…

Precision Interferometry

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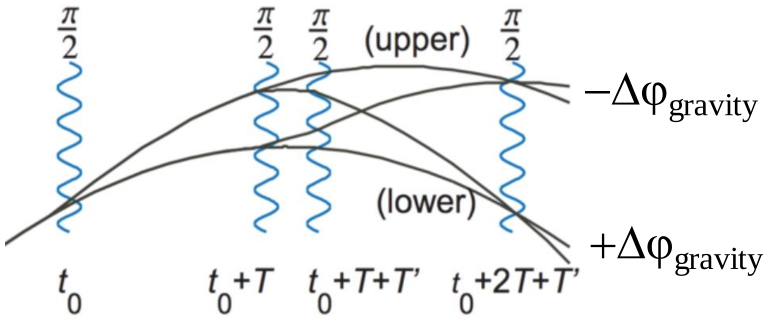

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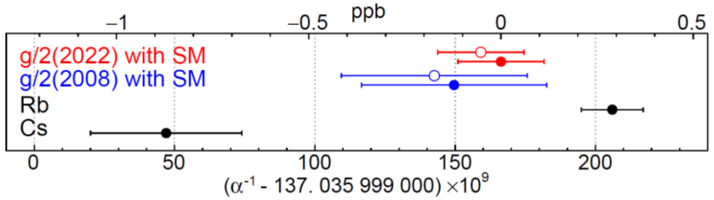

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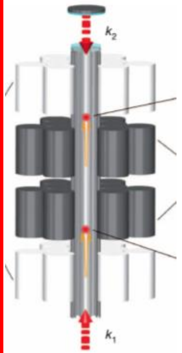

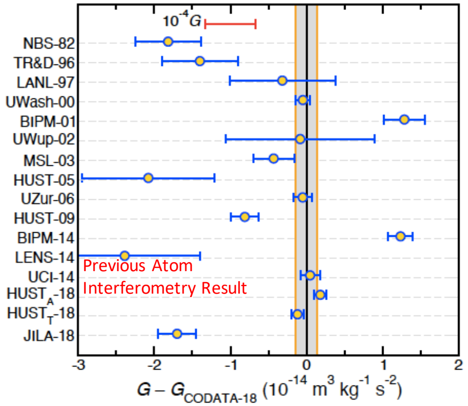

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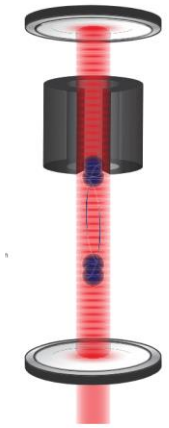

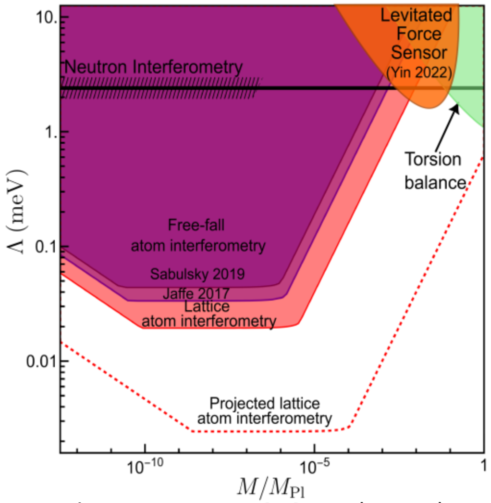

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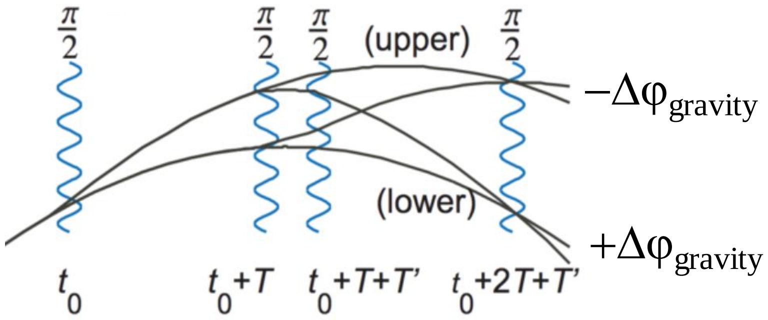

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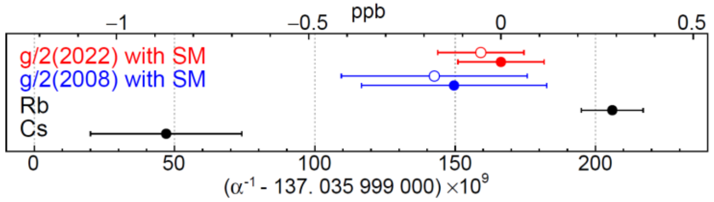

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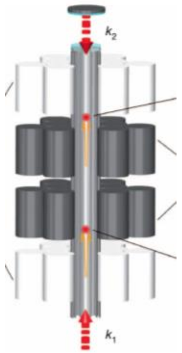

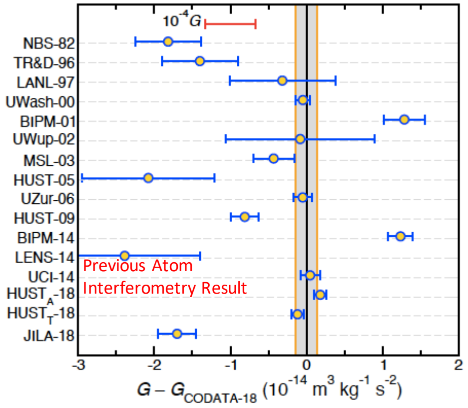

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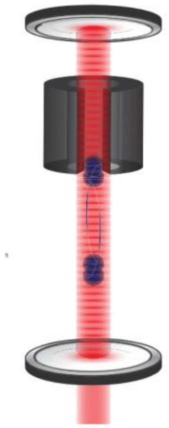

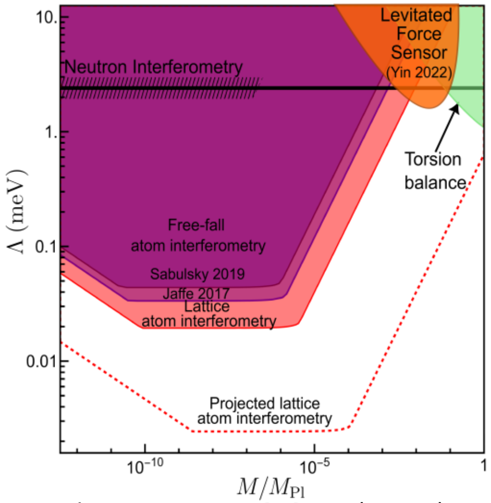

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Many others

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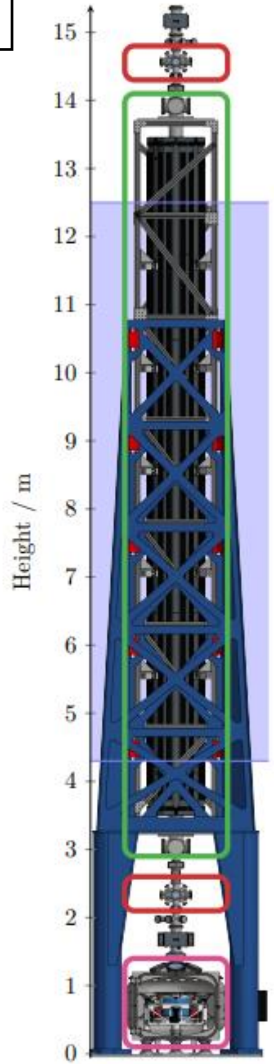
etc…

Interferometers Limited by Free-Fall Time

I. Atomic Fountains

Stanford, 10m fountain, T ~2 seconds



Hannover, 10m fountain

Interferometers Limited by Free-Fall Time

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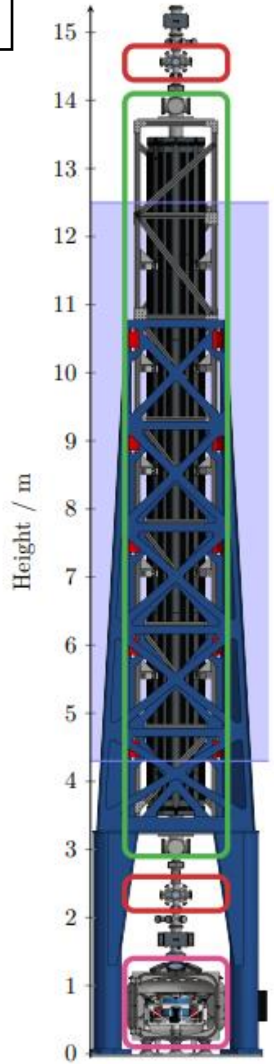
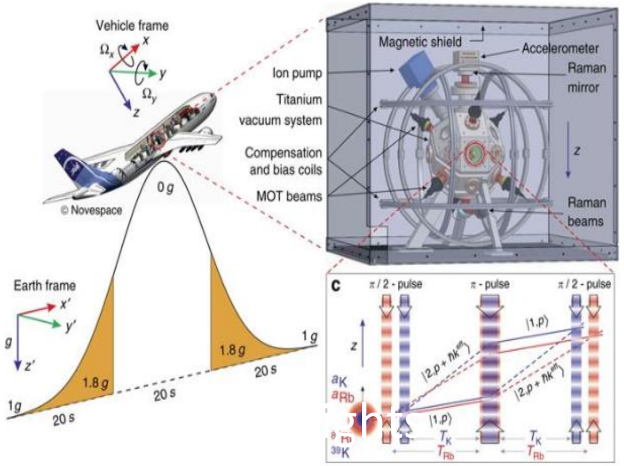
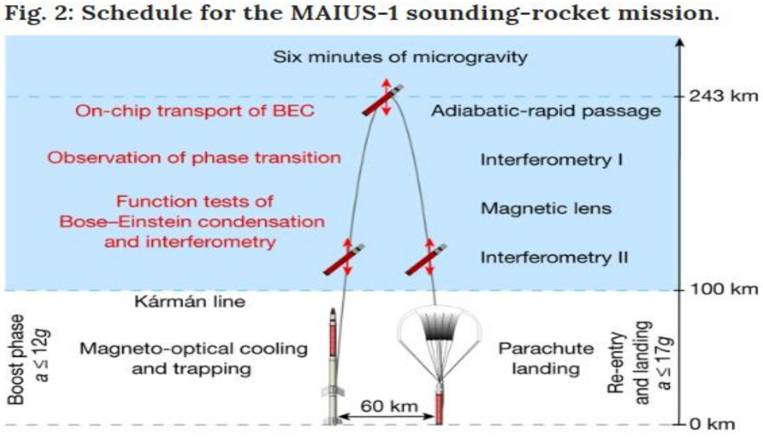


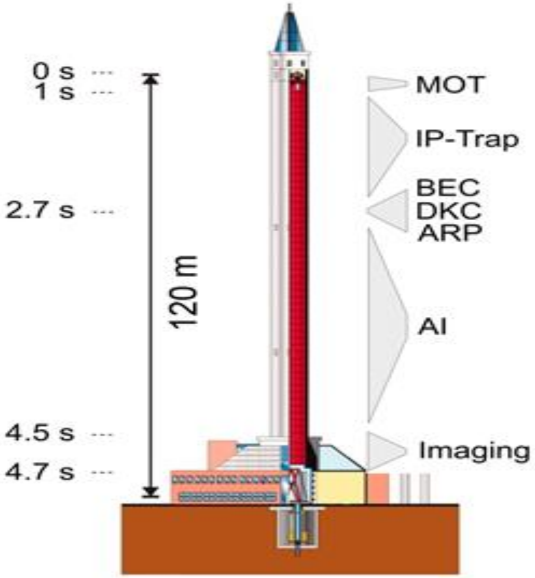
Stanford, 10m fountain, T ~2 seconds

Hannover, 10m fountain

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







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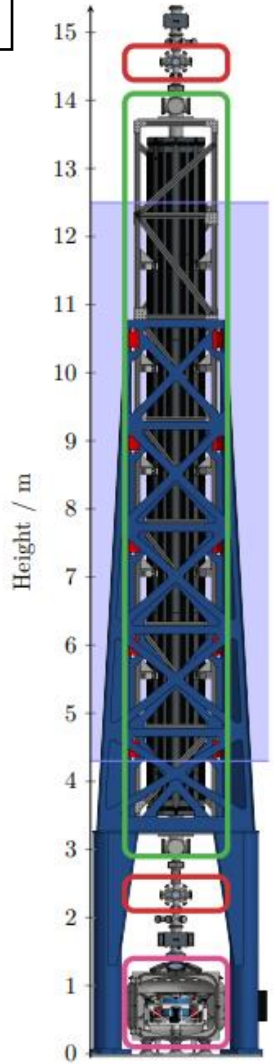

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Hannover, 10m fountain

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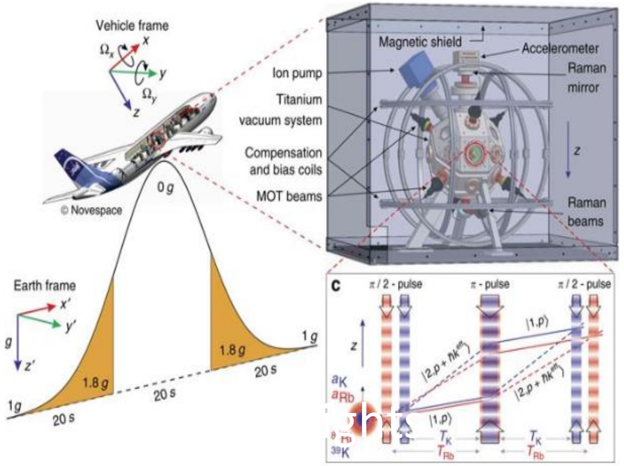
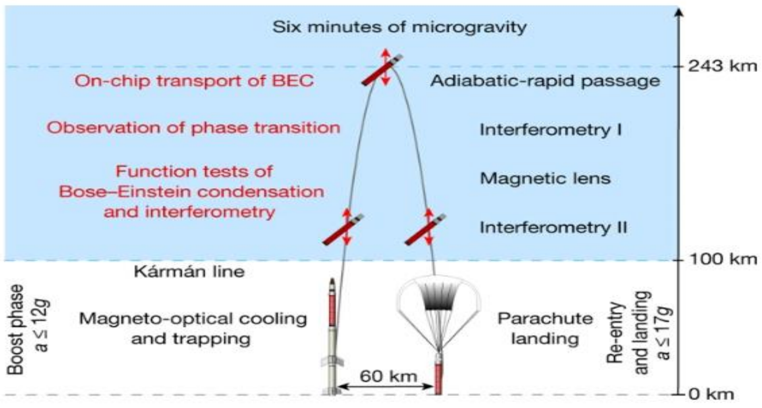
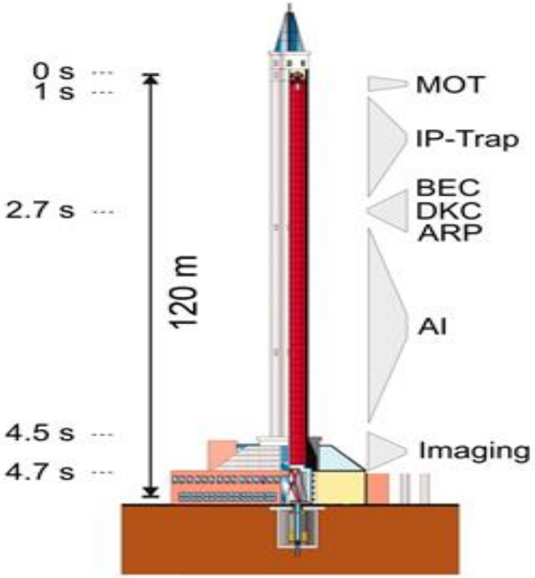
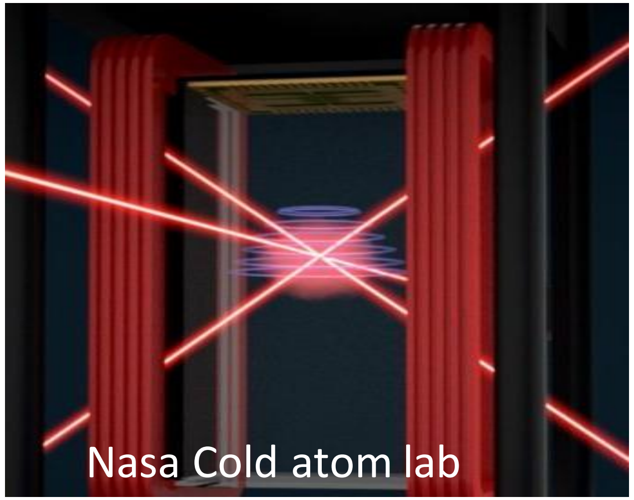


Fig. 2: Schedule for the MAIUS-1 sounding-rocket mission.





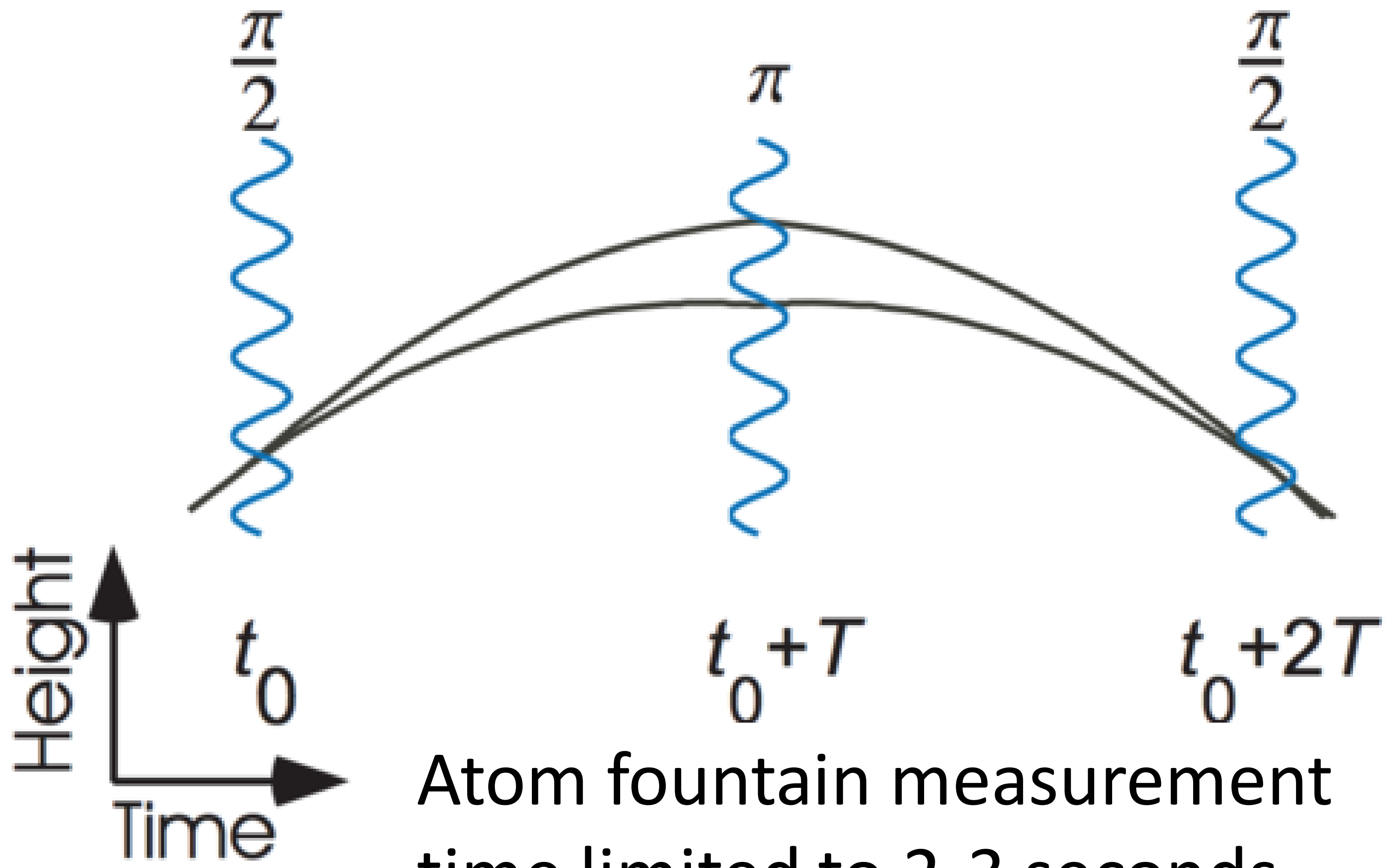
III. In space



Nasa Cold atom lab

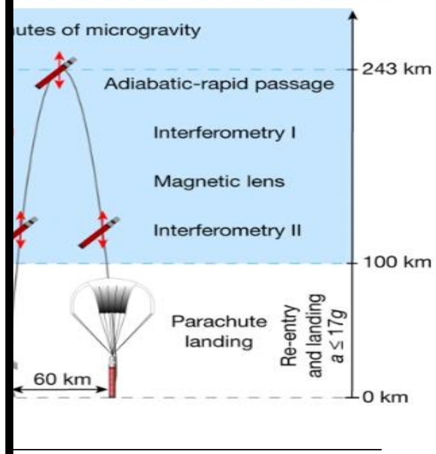
Interferometers Limited by Free-Fall Time

Stanford, 10r
fountain, T ~2



Atom fountain measurement time limited to 2-3 seconds

ockets



n space

d atom lab

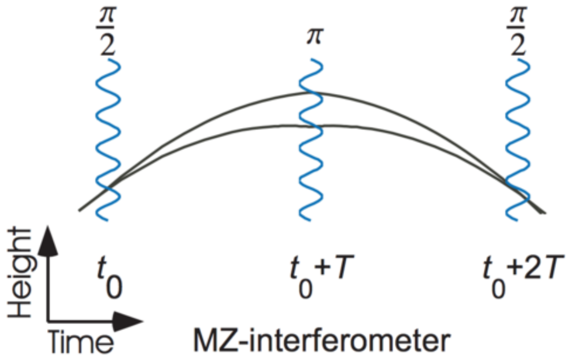
Outline

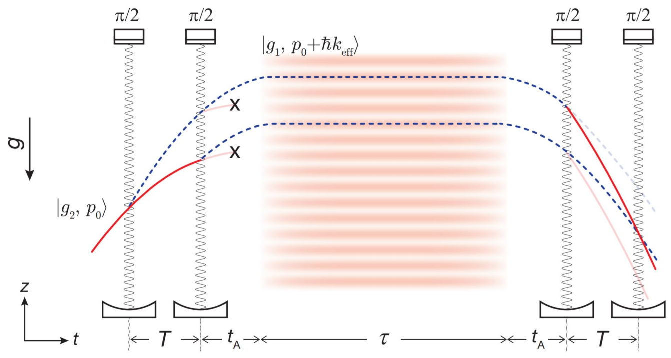
- Atom interferometry review

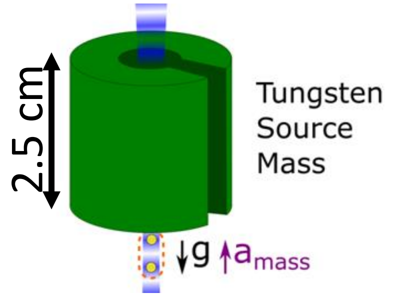
- Optical lattice atom interferometer
- theory and experiment

- Precise measurement of gravity and fifth forces

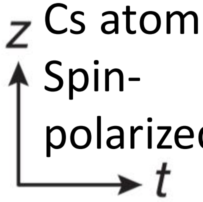
- Future directions







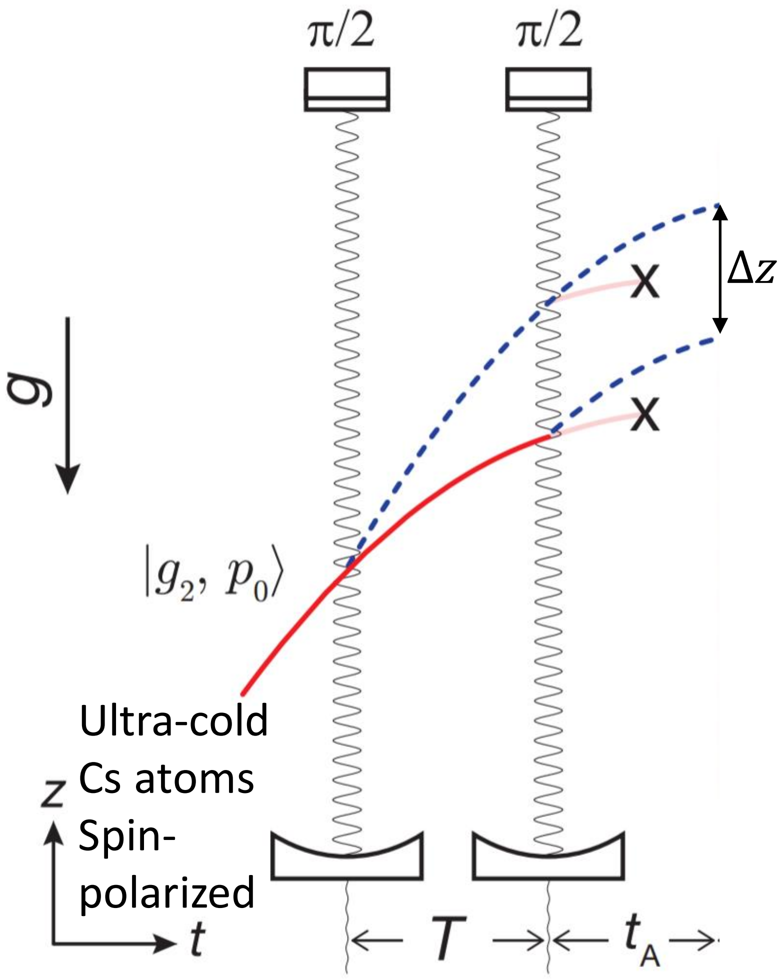
Atom Interferometer in an Optical Lattice



Ultra-cold
Cs atoms
Spin-
polarized

0. Sample
preparation

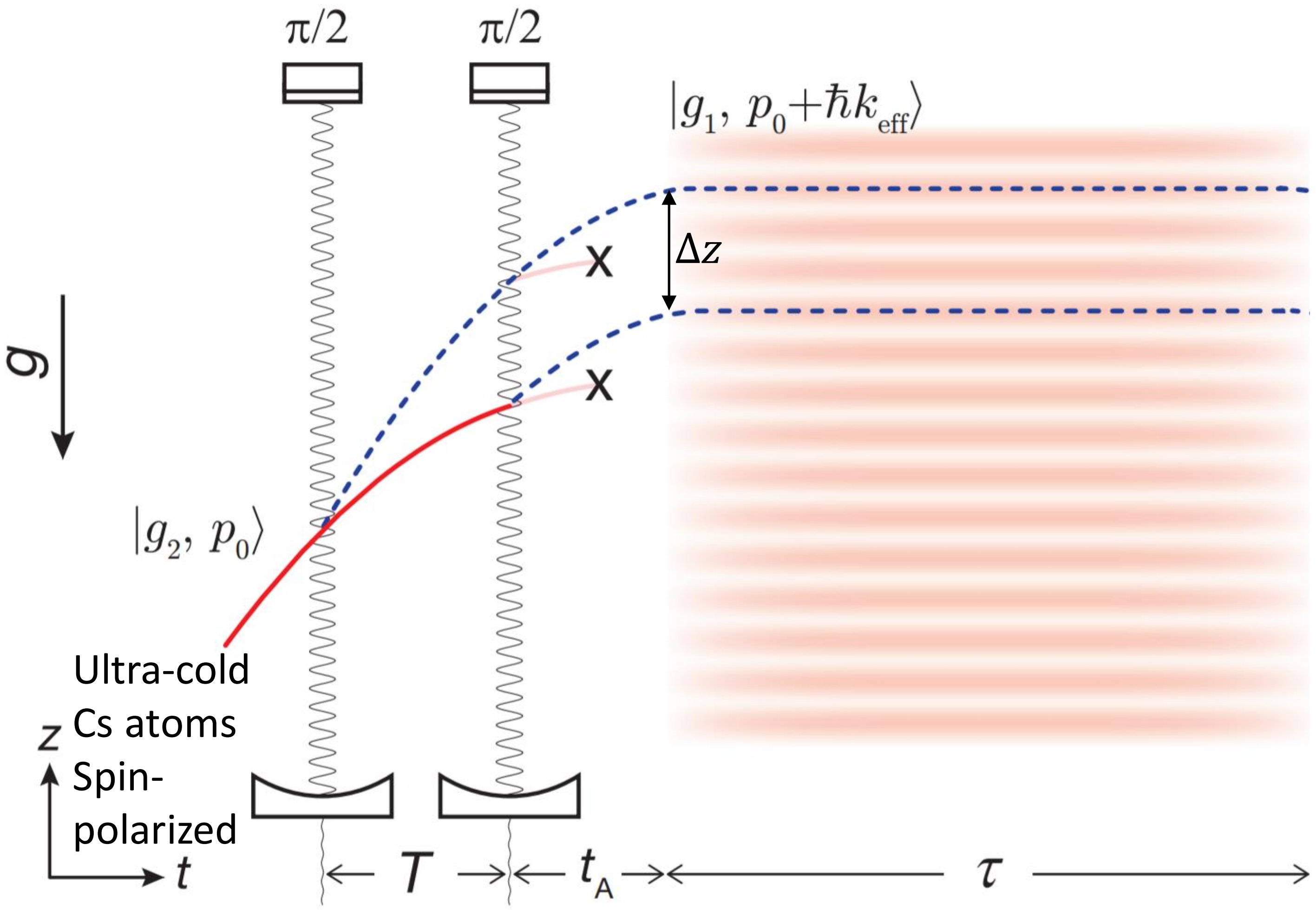
Atom Interferometer in an Optical Lattice



0. Sample preparation

I. Wavepacket splitting

Atom Interferometer in an Optical Lattice

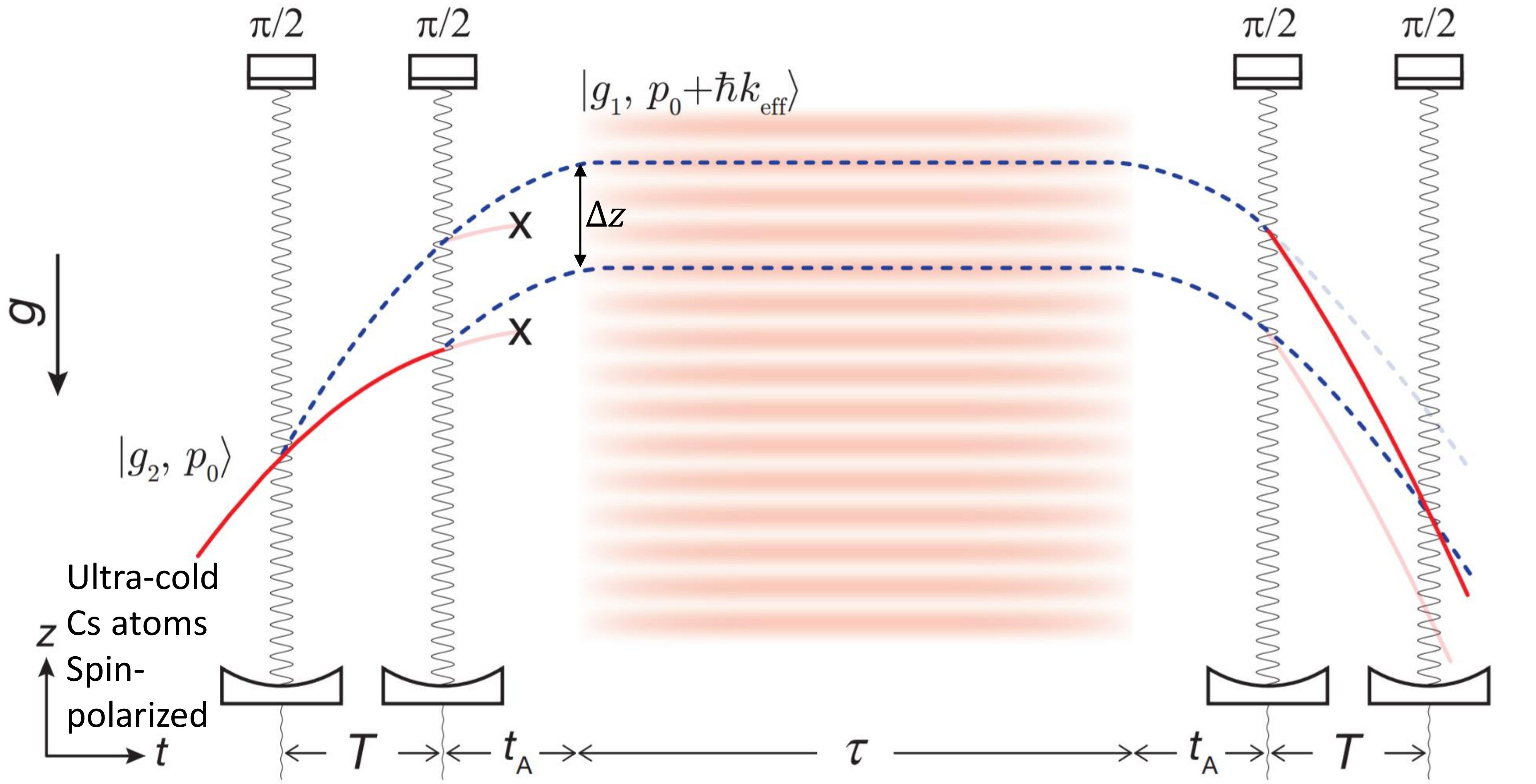


0. Sample preparation

I. Wavepacket splitting

II. Lattice hold

Atom Interferometer in an Optical Lattice



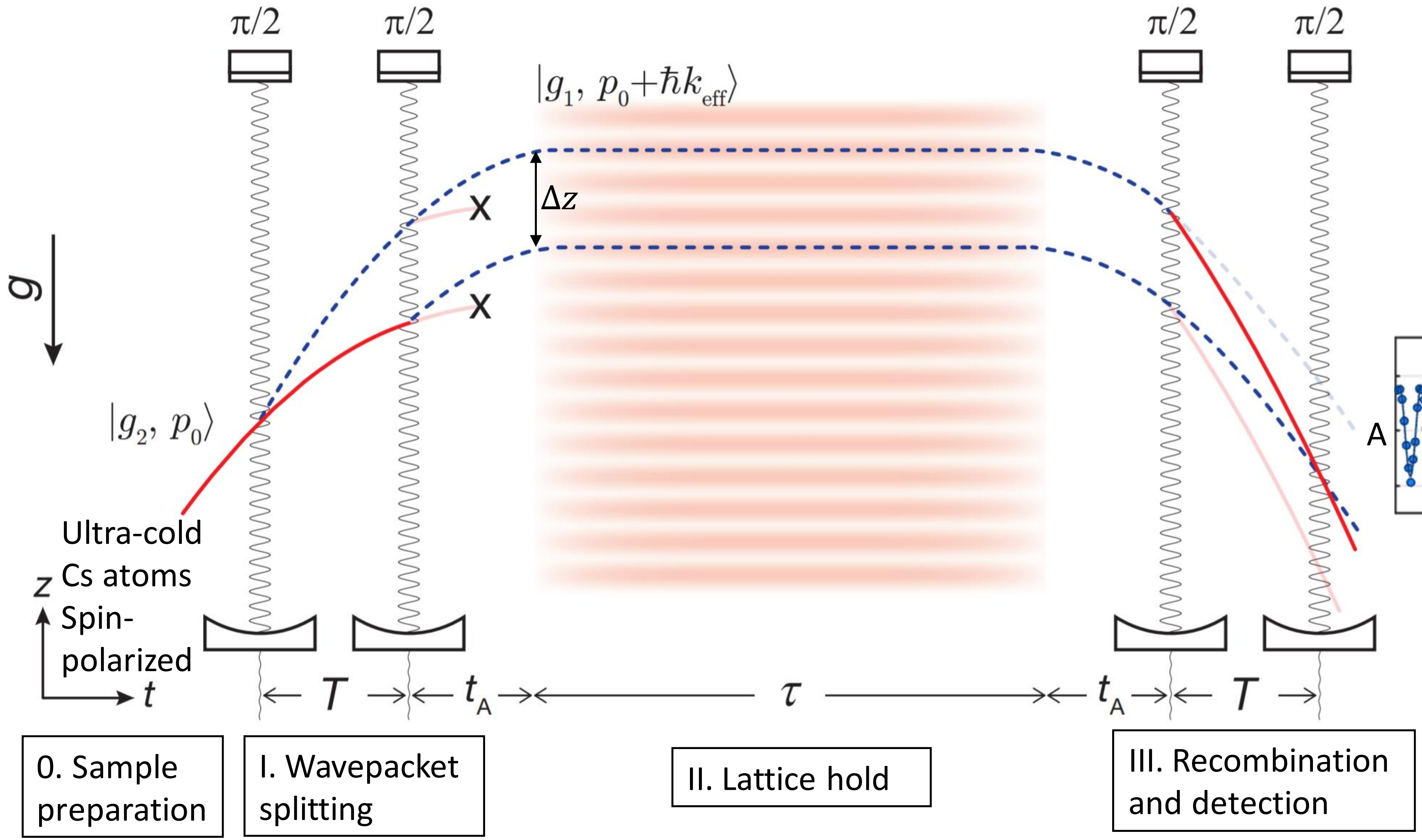
0. Sample preparation

I. Wavepacket splitting

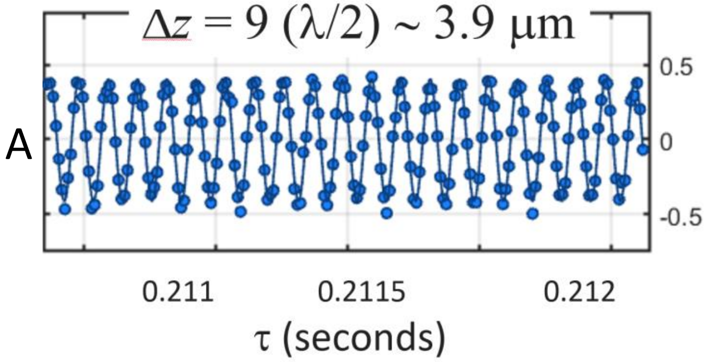
II. Lattice hold

III. Recombination and detection

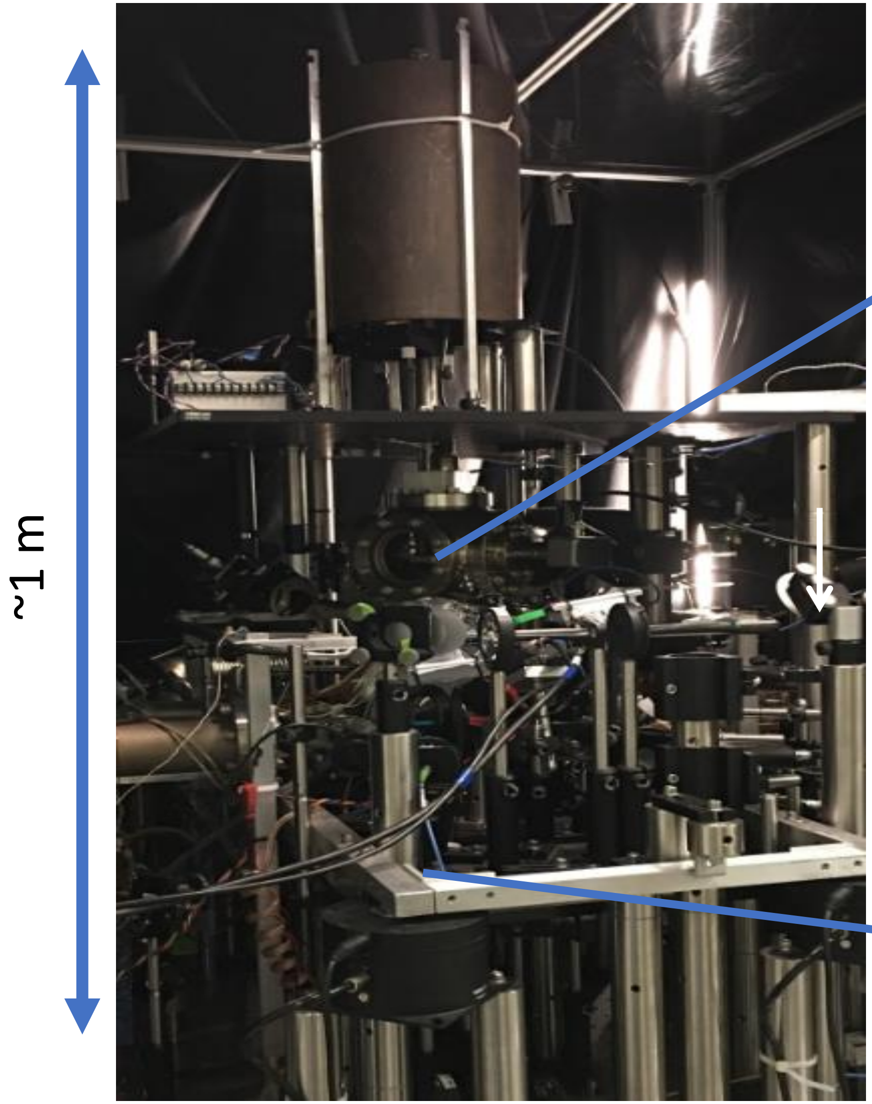
Atom Interferometer in an Optical Lattice

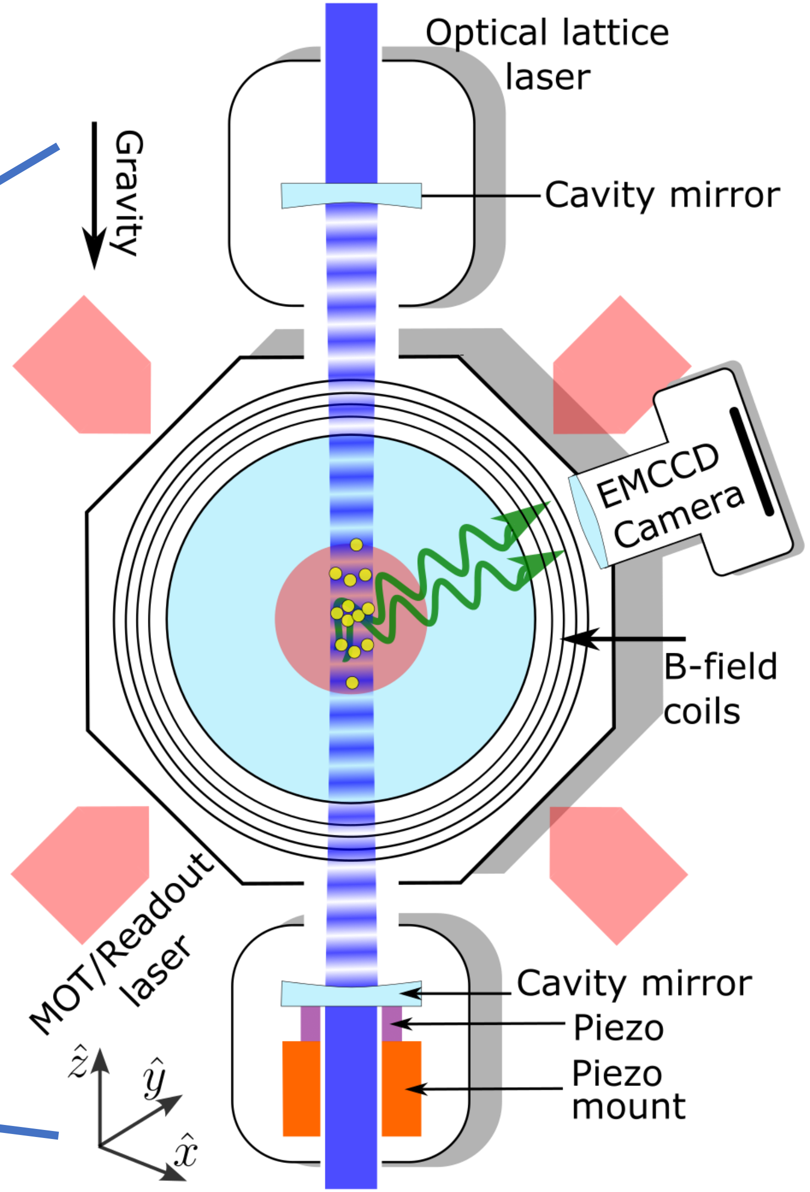


$$\Delta\phi_{\text{prop}} = \frac{1}{\hbar}\int L\,dt$$
$$= \frac{mg\Delta z}{\hbar}\tau$$



Experimental Apparatus

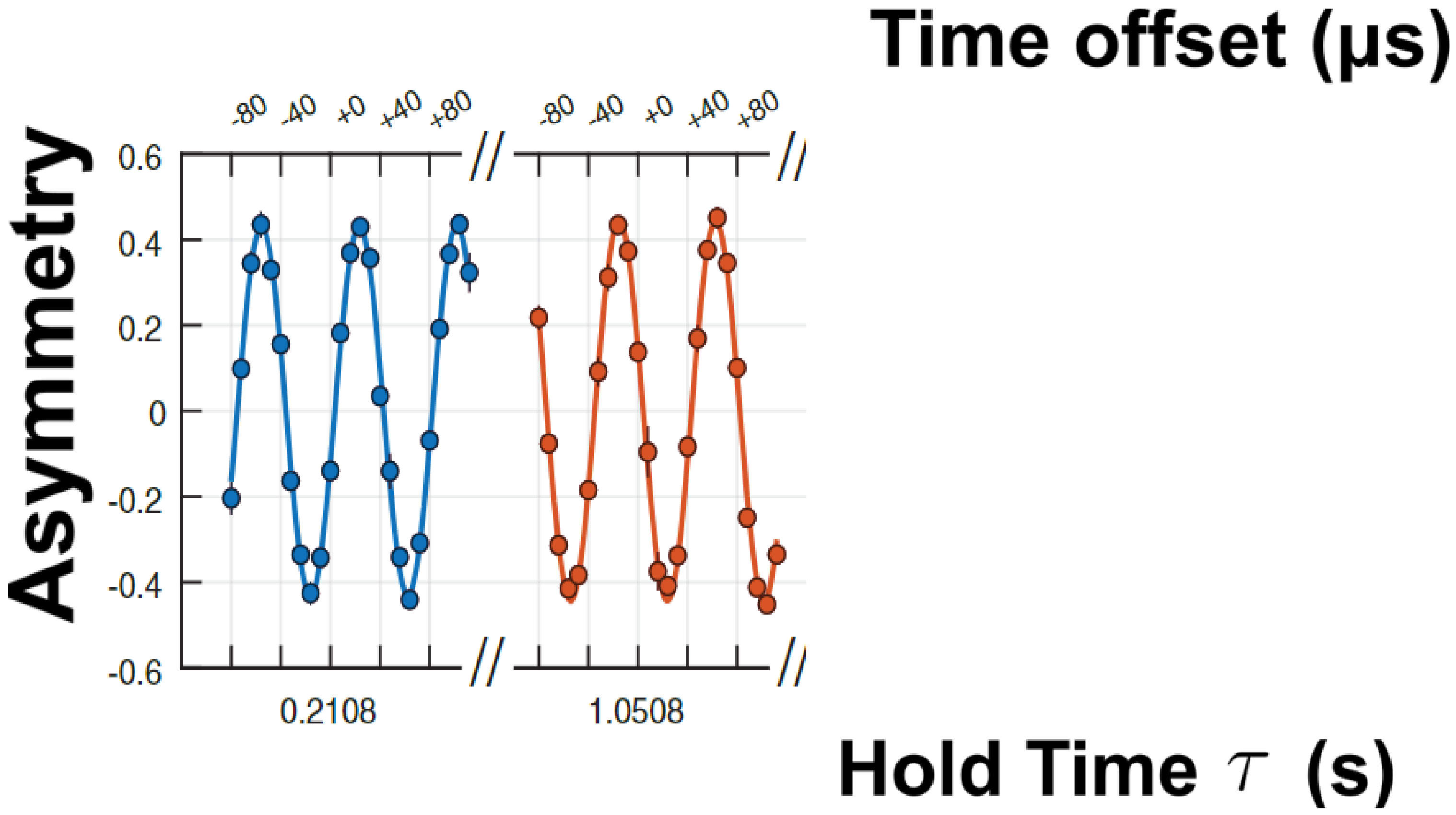




- Optical lattice filtered by in-vacuum Fabry Perot cavity

Long Coherence Times

Probing gravity by holding atoms for 20 seconds. Victoria Xu, Matt Jaffe, CDP, Sofus L. Kristensen, Logan W. Clark, Holger Müller, [Science **366**, 745-749 (2019)]



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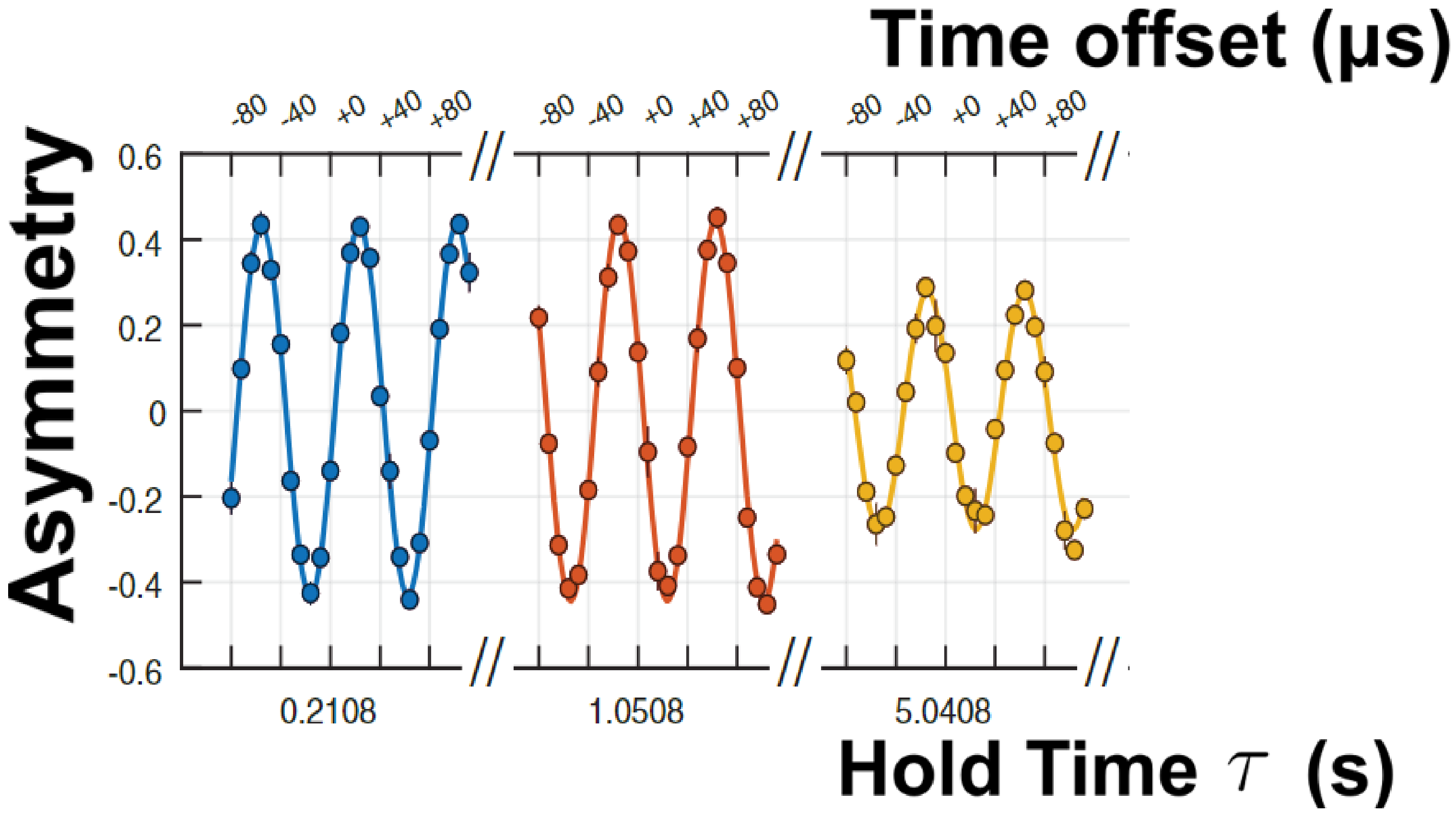

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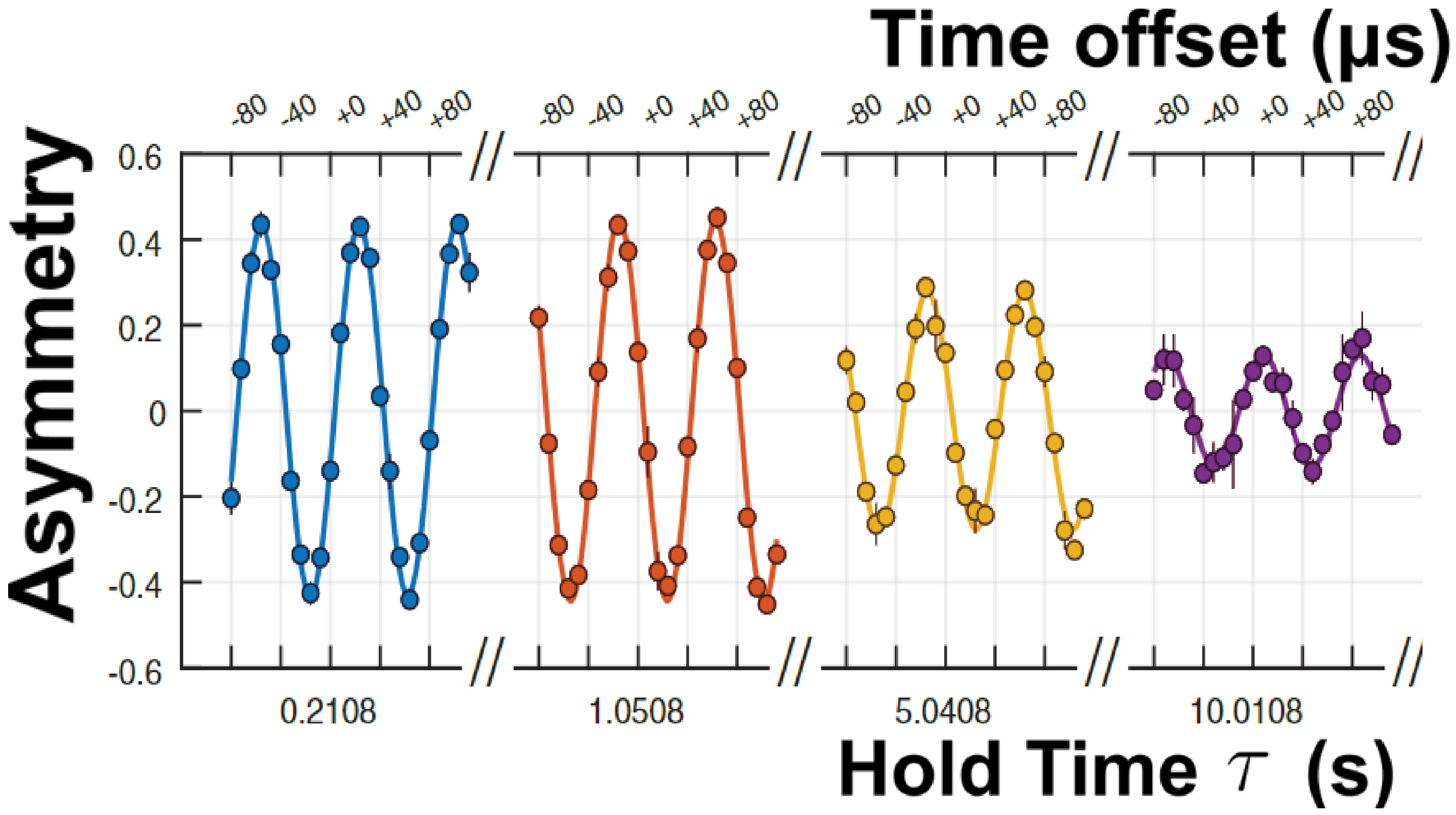

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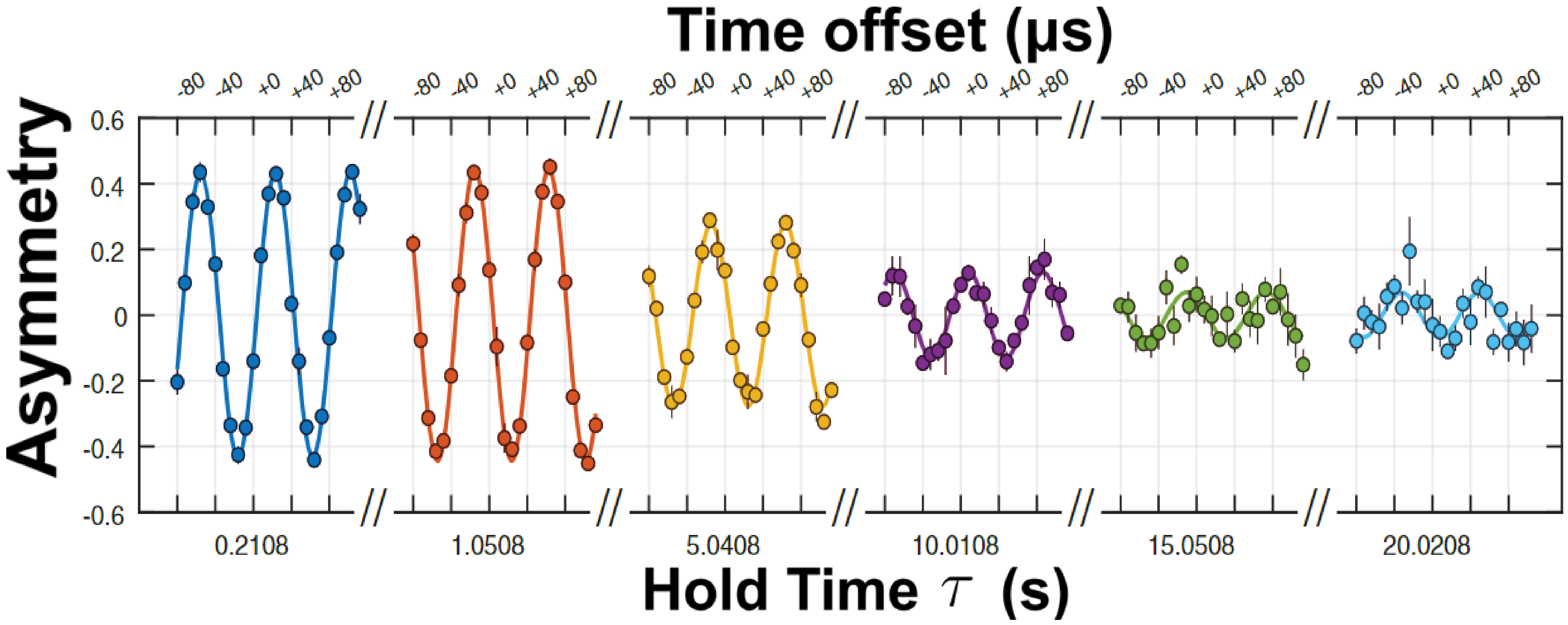

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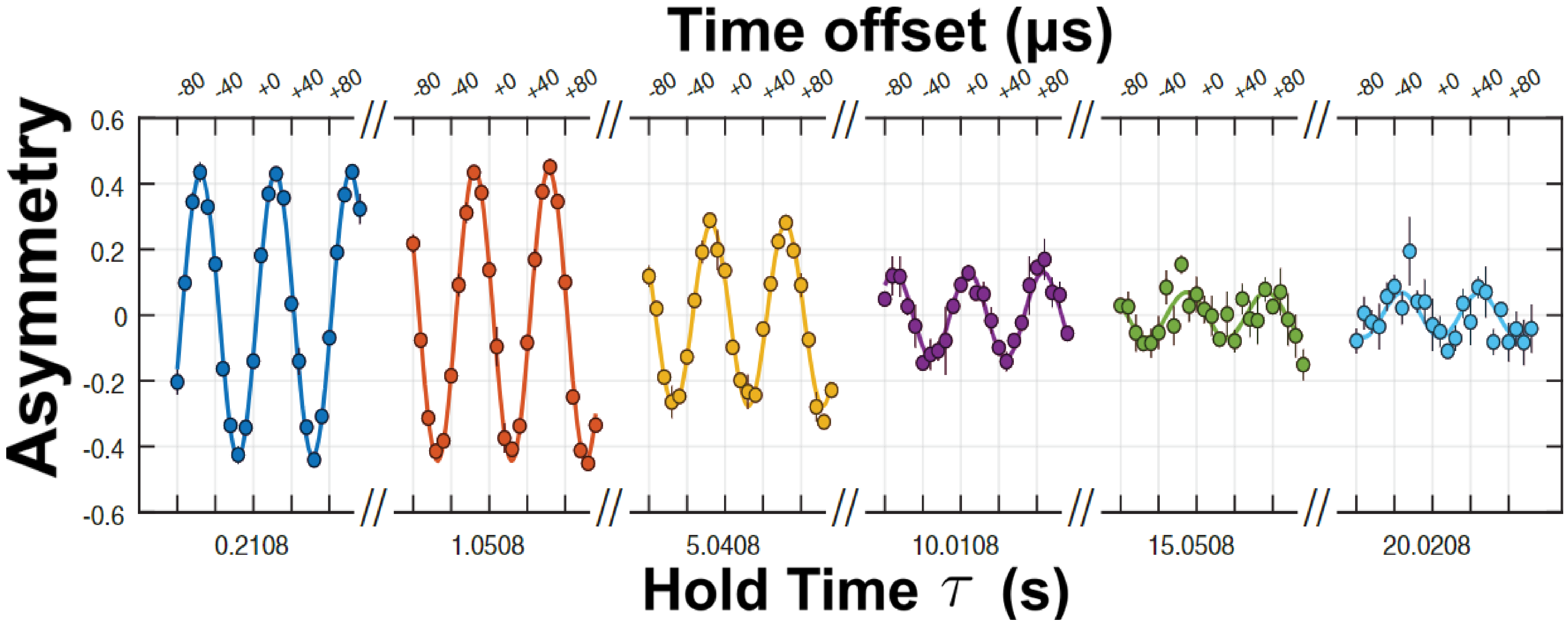


But… sensitivity not sufficient for measuring gravity of localized mass

Investigating Decoherence Mechanisms

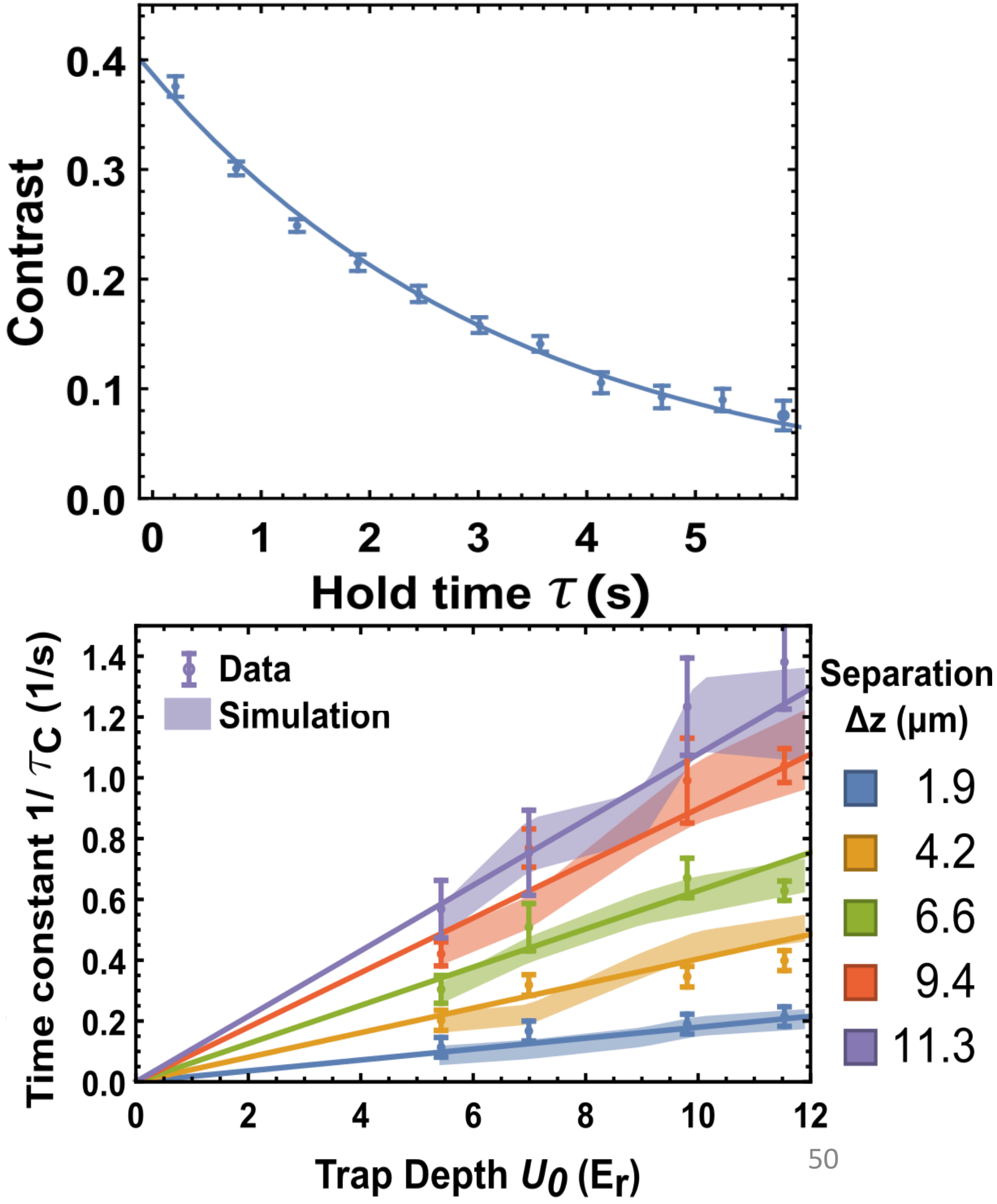
- Decoherence (contrast loss)

$$C(\tau) = C_0 e^{-\tau/\tau_C}$$
$$1/\tau_C = U\Delta z/\ \kappa$$

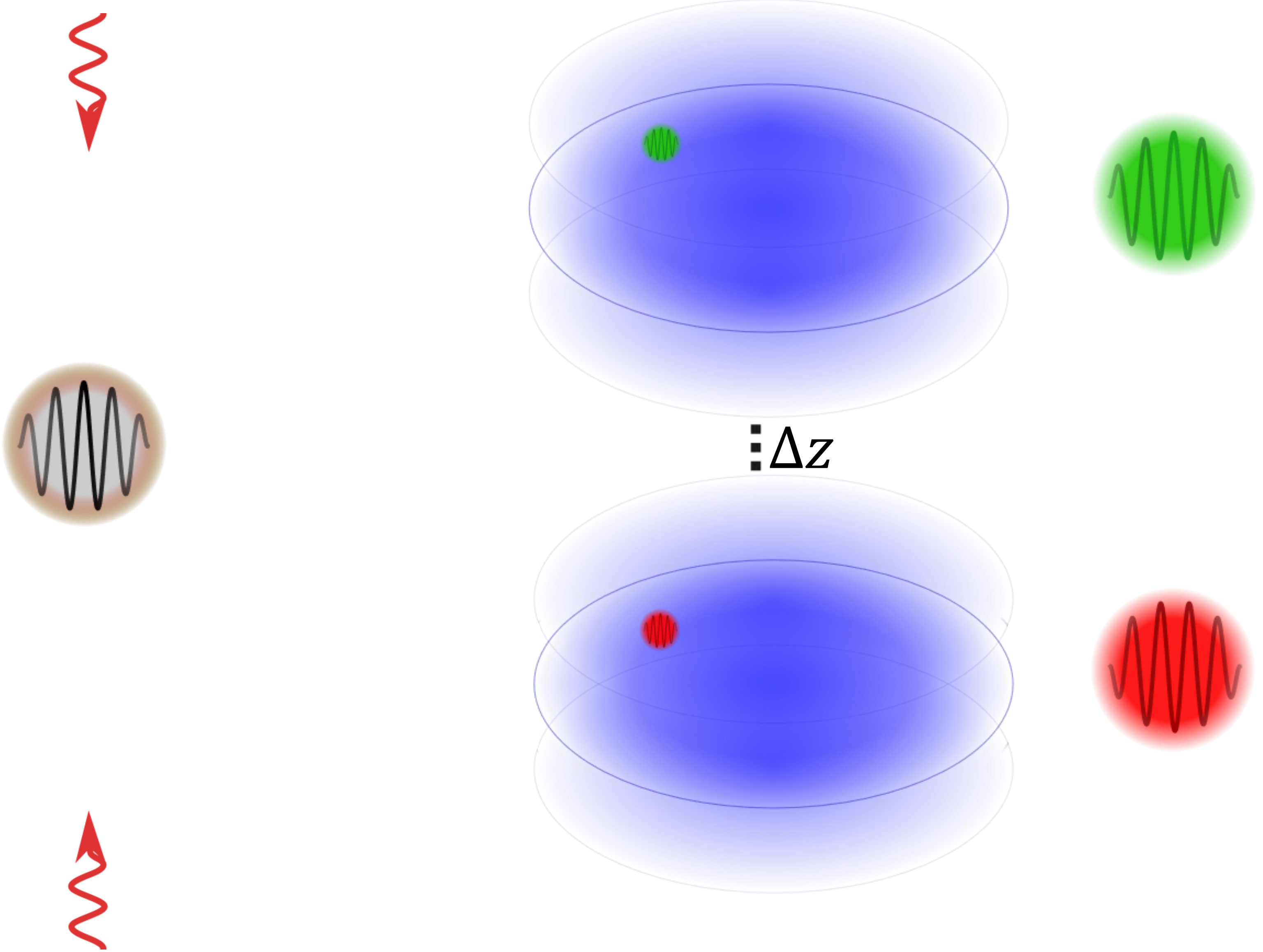
where

  - C_0 is initial contrast,
  - U is the lattice trap depth

- <u>Why is $\kappa \sim 110\ \mu\mathrm{m}\ E_{\mathrm{r}}\ s$?</u>
- Depends on U, Δz => spatial variation in lattice potential?



Simplified Ideal Lattice Atom Interferometer



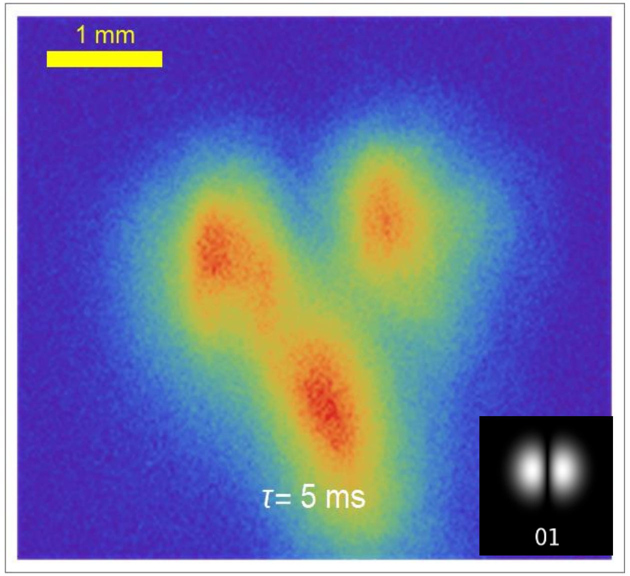
$$\Delta\phi^{\text{prop}} = \frac{1}{\hbar}\int L\, dt$$
$$= \frac{mg\Delta z}{\hbar}\tau + ???$$

Spatial variation of lattice potential

κ is Robust to Changing Many Parameters

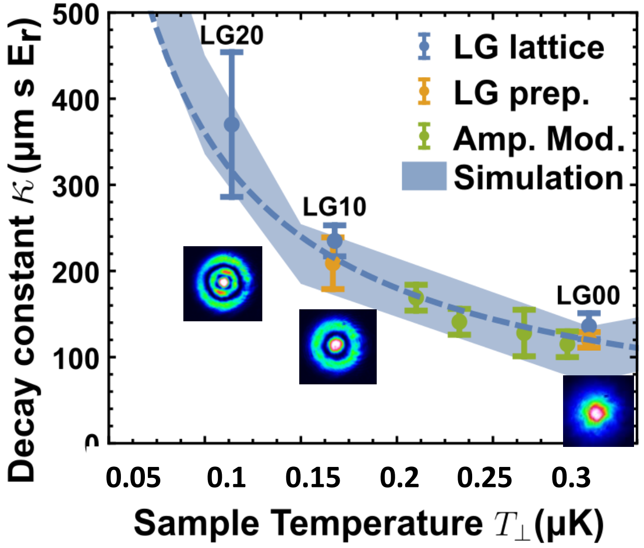
Parameters Varied	Experimental Test Performed	Observed Outcome
Radial lattice uniformity	Installed new superpolished cavity mirrors (surface rms <1 Å)	Same κ
Axial lattice uniformity	Replaced planar- concave cavity with symmetric concave-concave cavity (mirrors have equal radii of curvature)	Same κ
Vacuum pressure	New pumps, reduced outgassing	Same κ
Lattice laser frequency noise	2x higher with tuning PID lock	Same κ
	Narrower laser linewidth by locking to a high-finesse (F=20,000) cavity	
Raman beamsplitter symmetry	Symmetric beamsplitters using microwave $\frac{\pi}{2}$ pulse followed by optical π pulse (32)	Same κ
Laser lattice broadband emission	Suppressed >10x with filter cavity	Same κ
Lattice intensity noise	10x reduced by intensity stabilization using transmitted light as a monitor	Same κ
Background scatter	Increased 20x by shining mode-mismatched light at cavity mirror and/or experiment vacuum window	Same κ
Acoustic noise	Phone speaker, tapping the optical table	Same κ
Alignment with gravity	Tilted optical table by 1.5 mrad	Same κ
Changing atom number and density	2x reduction by lowering state selection efficiency	Same κ
Axial atom temperature selection	Reduced 3x by increasing the length of velocity selection pulse	Same κ
Misaligned lattice laser, coupling light to high order cavity modes	Reduced cavity coupling efficiency 2x by misaligning and changing beam diameter	Same κ
Lattice laser detuning	Replaced lattice laser with 866 nm ECDL (14 nm det.) and 1064 nm fiber laser (212 nm det.)	Same κ
Environmental field gradients	Varied the vertical atom position by up to 1.5 cm	Same κ
Magnetic field gradients	Increased 1000x by turning on MOT coils during interferometer	Same κ
Position within the atomic sample	Analyzed horizontal and vertical slices of fluorescence image	Same κ

High Order Lattice Modes Reduce Decoherence

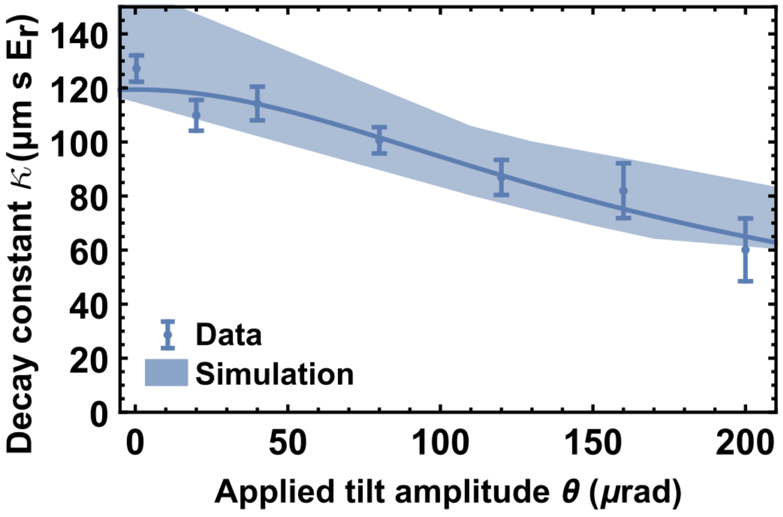


- Observed <u>3-fold higher κ</u> when loading into symmetric Laguerre Gauss higher order modes

- Transverse sample temperature

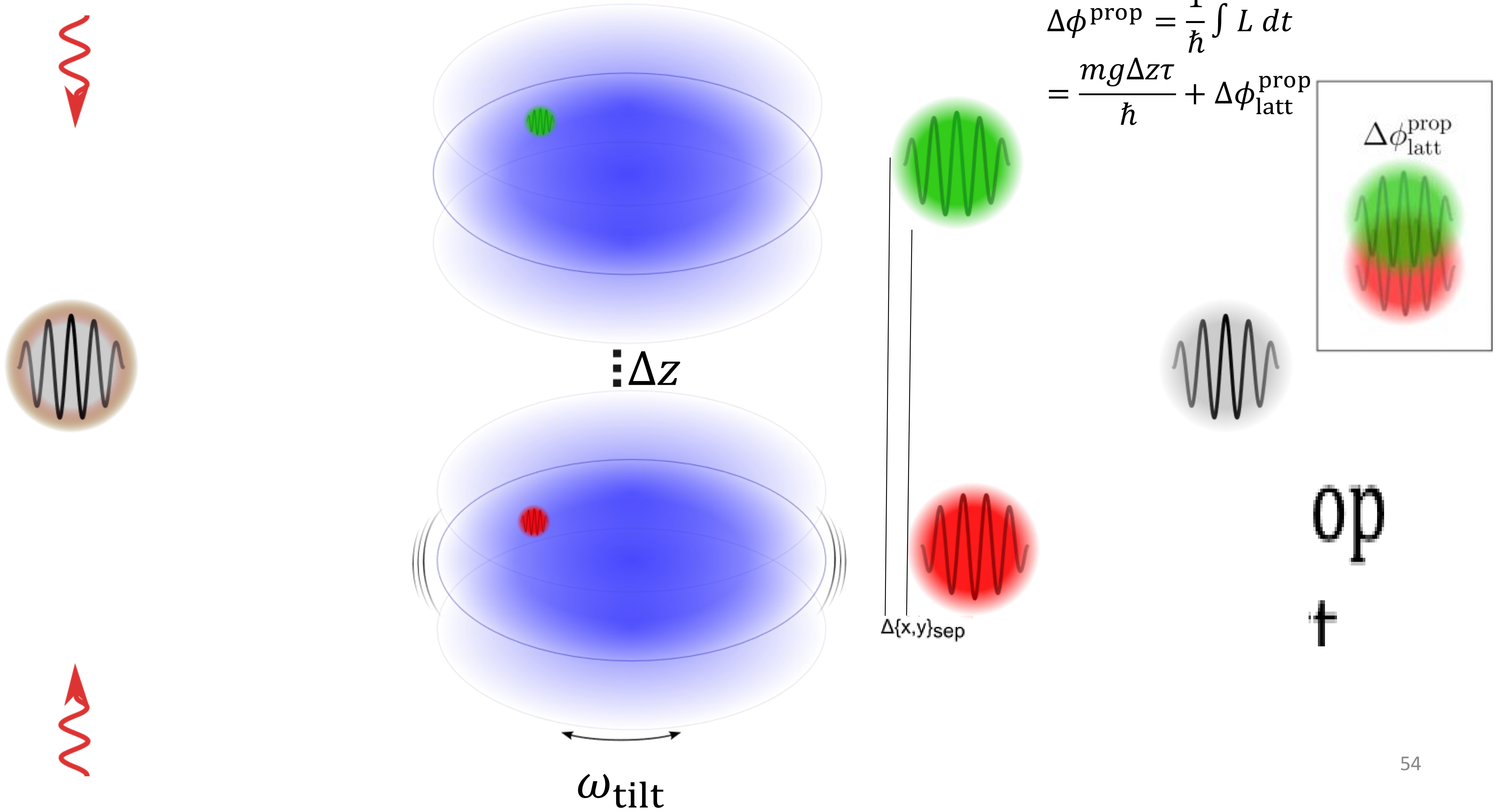


- Apparatus tilt-noise



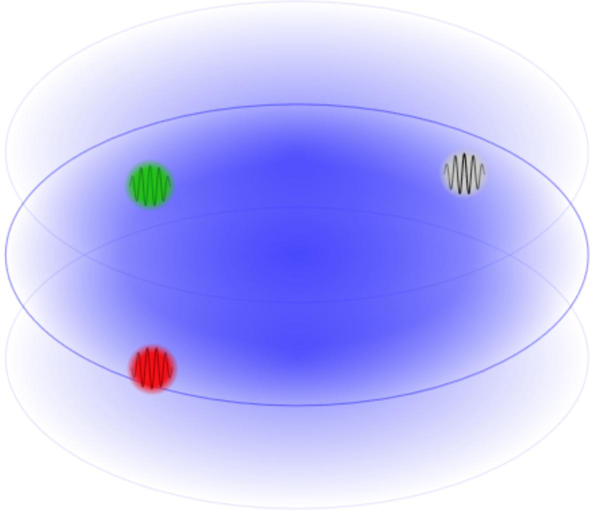
Ingredient 1: Phase Shifts due to Tilt-Noise

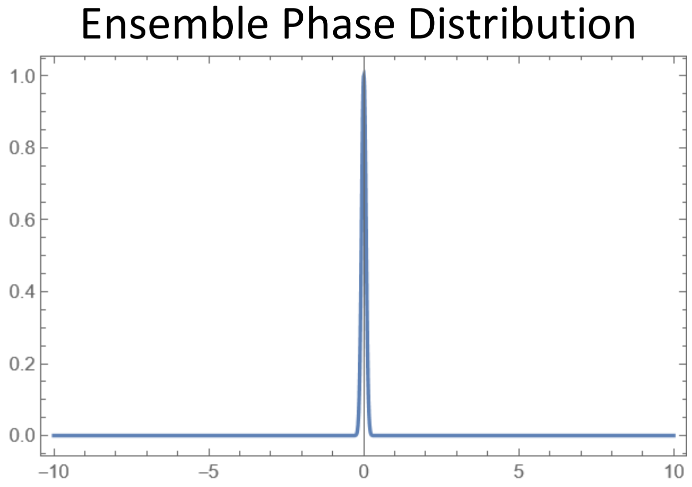
$$\Delta\phi^{\text{prop}} = \frac{1}{\hbar}\int L\, dt$$
$$= \frac{mg\Delta z\tau}{\hbar} + \Delta\phi^{\text{prop}}_{\text{latt}}$$



Ingredient 2: Thermal Motion of Atoms

Position and
velocity distribution
in thermal cloud
=> Phase dispersion

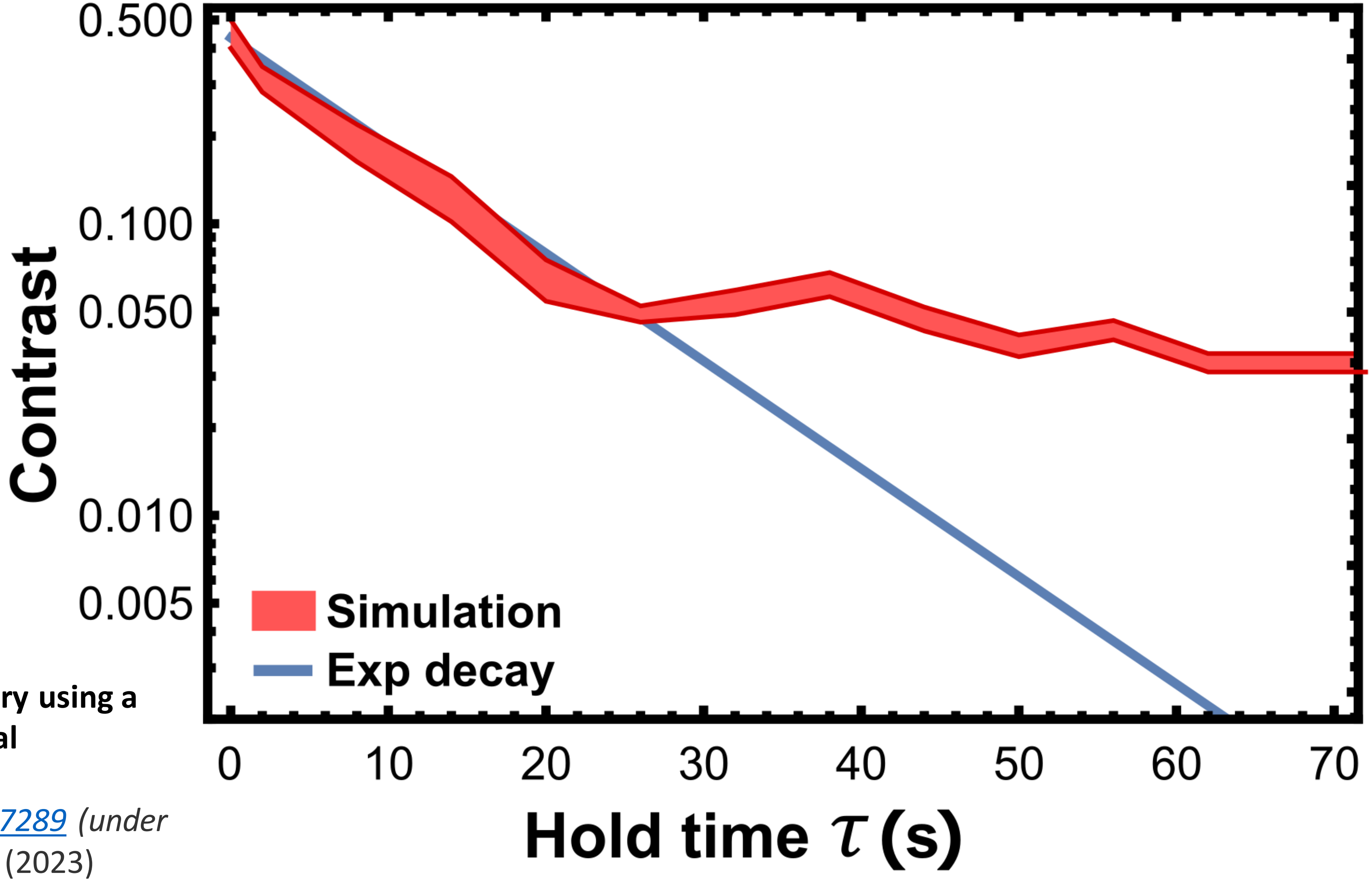




Quantitative agreement of ensemble dephasing model and experimental data

Minute-scale gravimetry using a coherent atomic spatial superposition,
CDP et al, arXiv:2210.07289, (under review Nature Physics) (2023)

Enduring Coherence at Ultra-Long Hold Time



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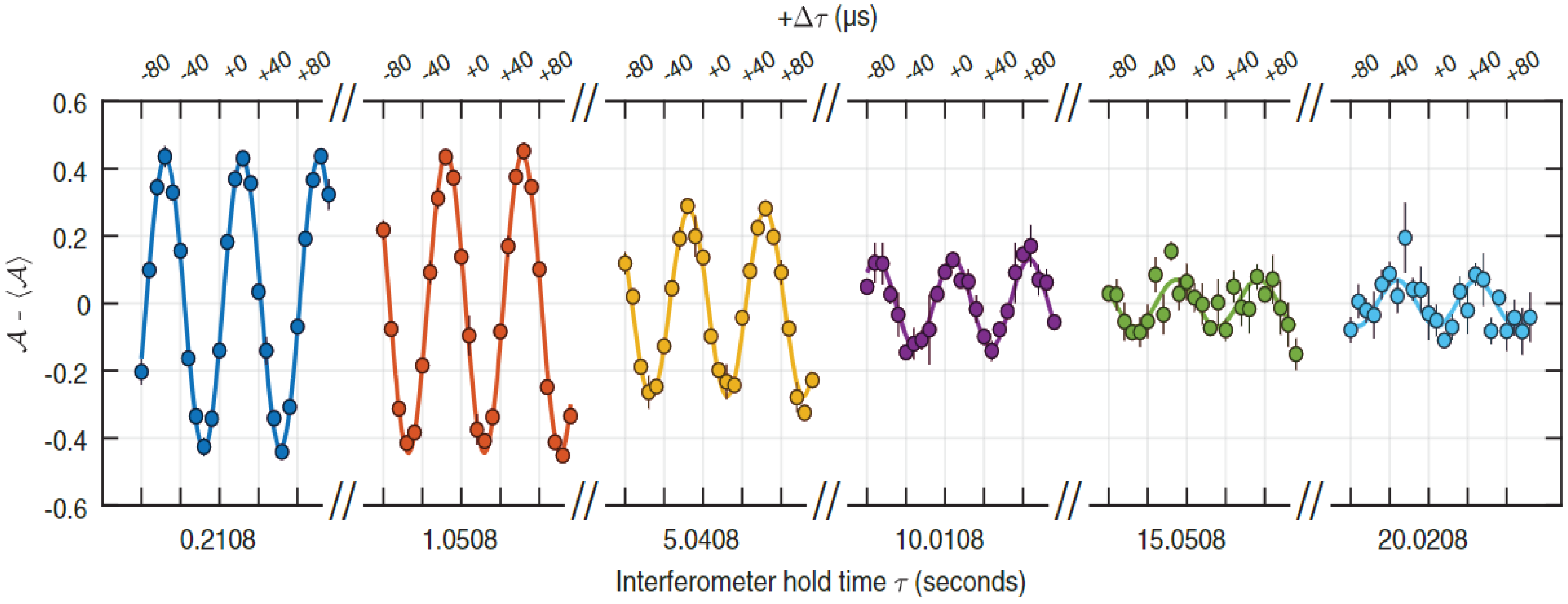

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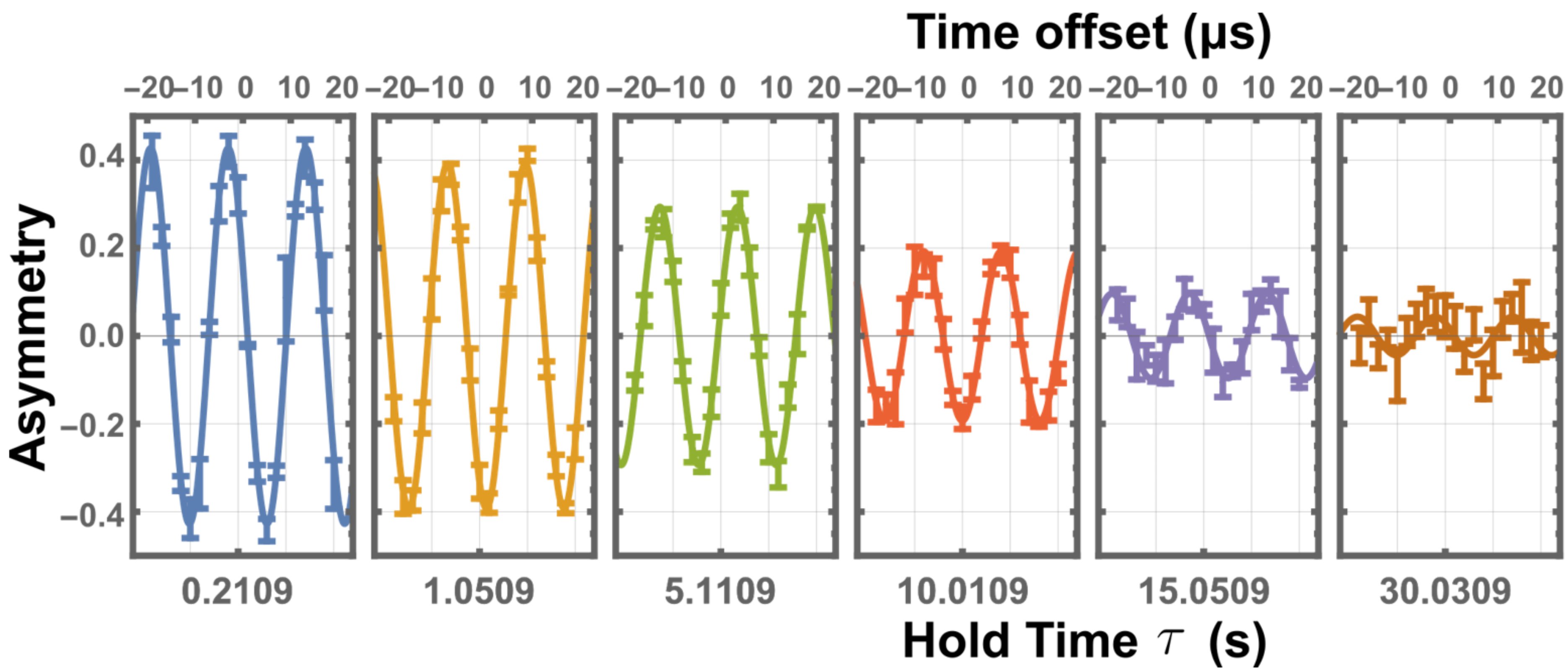

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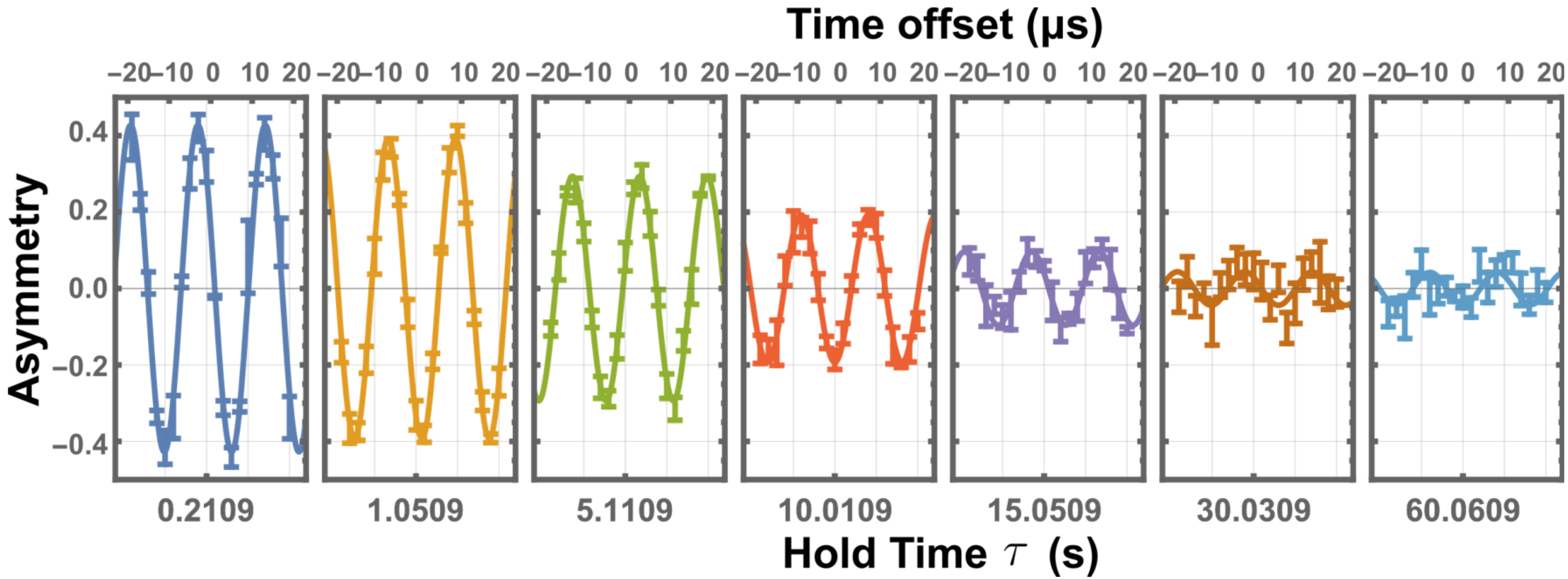
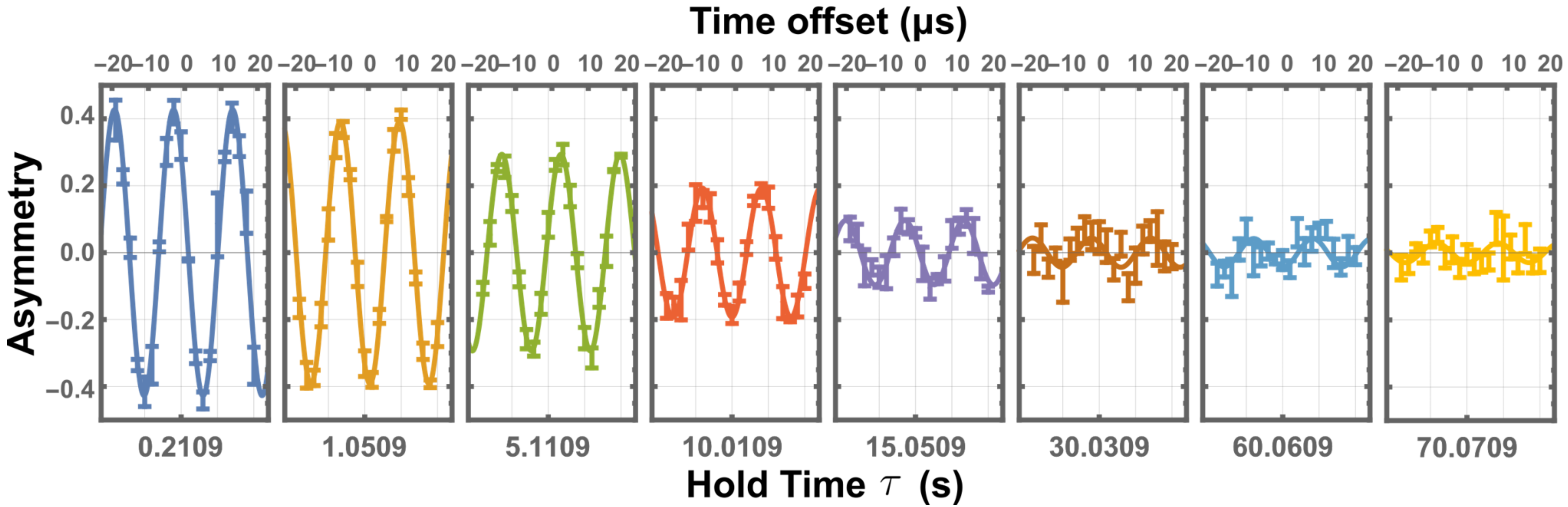


Coherent After 70 Seconds

Minute-scale gravimetry using a coherent atomic spatial superposition,
CDP et al, *arXiv:2210.07289 (under review Nature Physics)* (2023)



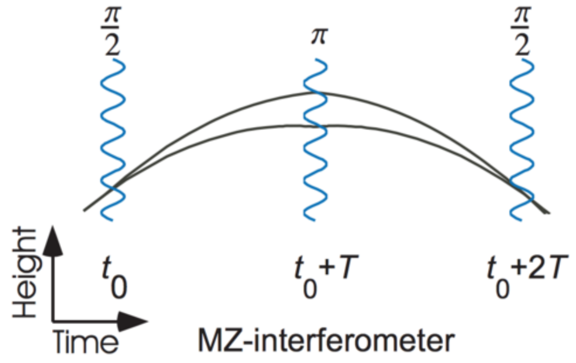
Outline

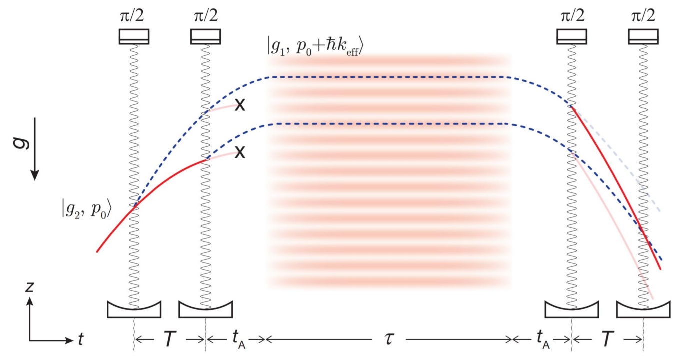
- Atom interferometry review

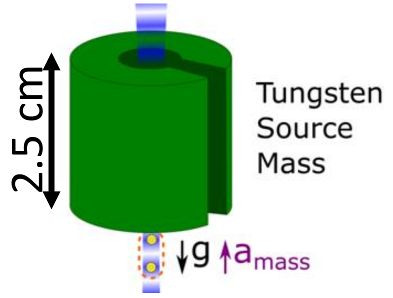
- Optical lattice atom interferometer
- theory and experiment

- Precise measurement of gravity and fifth forces

- Future directions

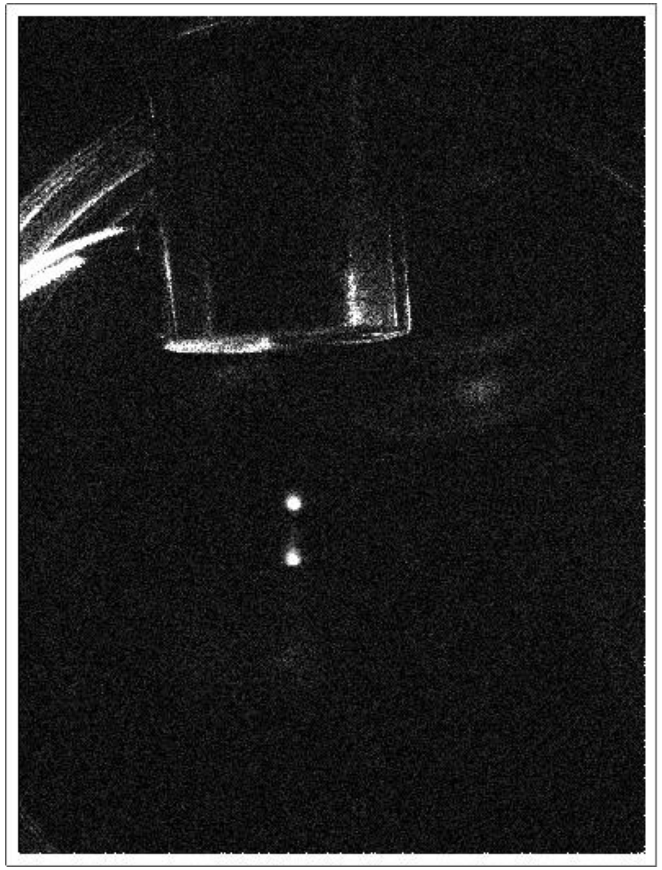






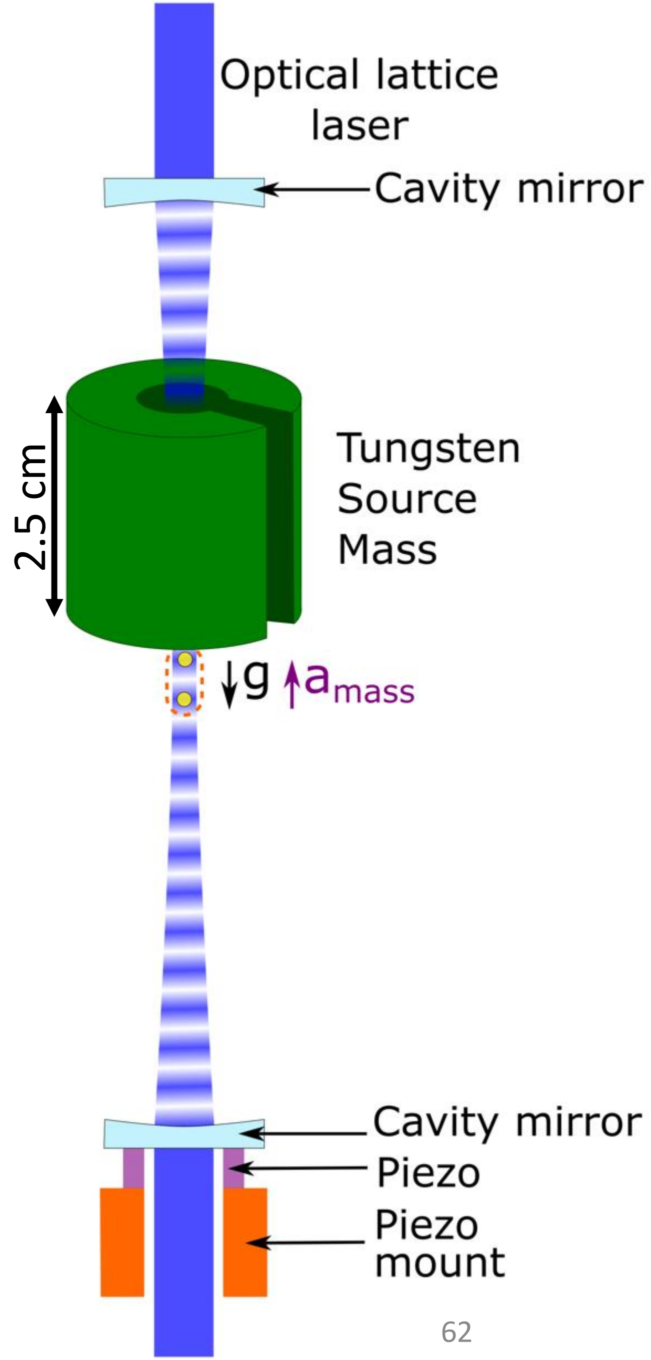
Searching for Fifth Forces by Measuring Gravity of Small Mass

- 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:
  - Quickly move atoms - use **atom elevator**
  - Better SNR - **10x increased precision**
  - Better precision than any previous measurements (atom fountains)



- But...

  Drifts and systematics unexplored



Measuring gravity by holding atoms,
CDP et al, arXiv:2310.01344 (under review Nature) (2023)

Drifts and Systematics

Possible causes for drift/noise

- Tides
- Perturbations in gravitational field (seismic, local noise)
- Tilt drift
- Cavity thermal drift
- Next door magnet ON/OFF

etc…

Possible systematic effects

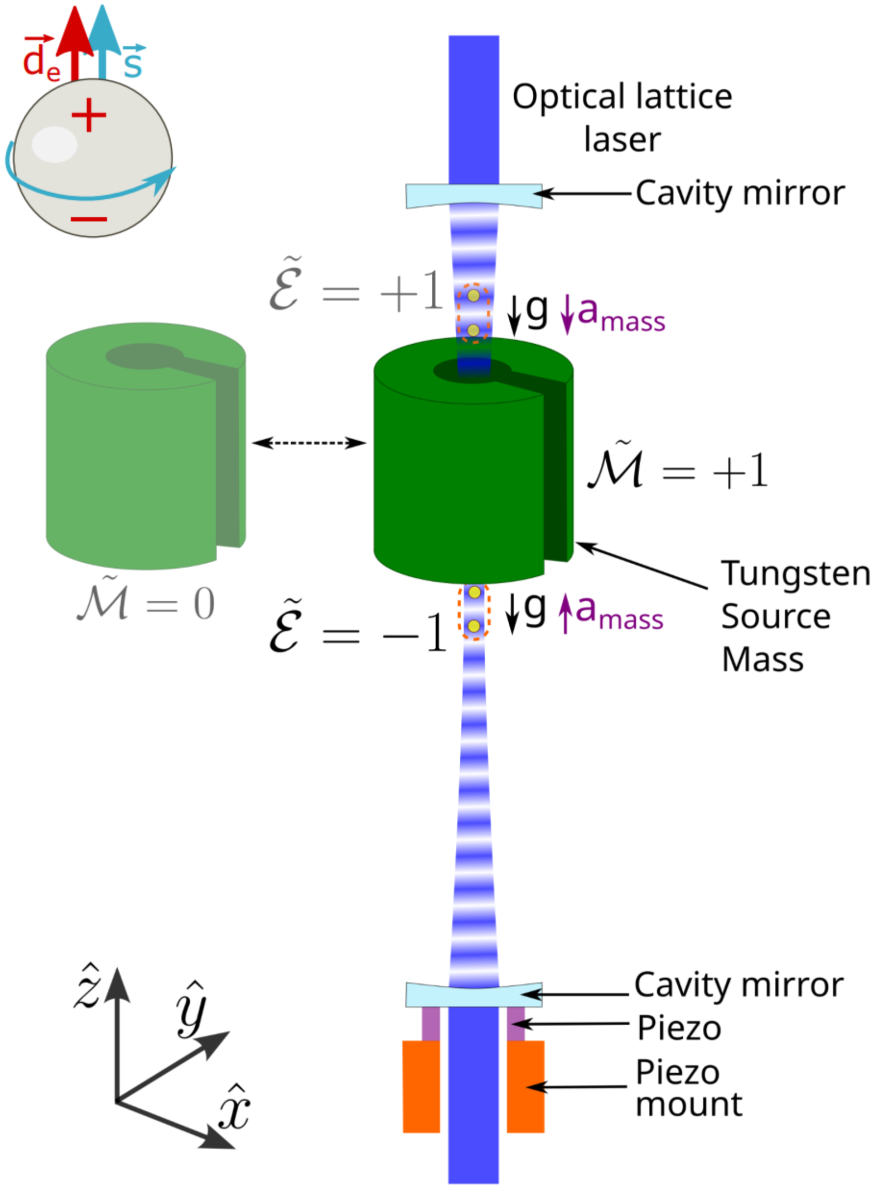
- Strong interactions with the lattice
- Field gradients
- Source mass effects

etc…

Measuring gravity by holding atoms,
CDP et al, arXiv:2310.01344 (under review Nature) (2023)

Switches

- Suppress experiment drifts and systematic effects by **differential measurement** (ACME inspired)



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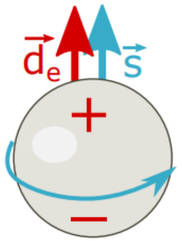
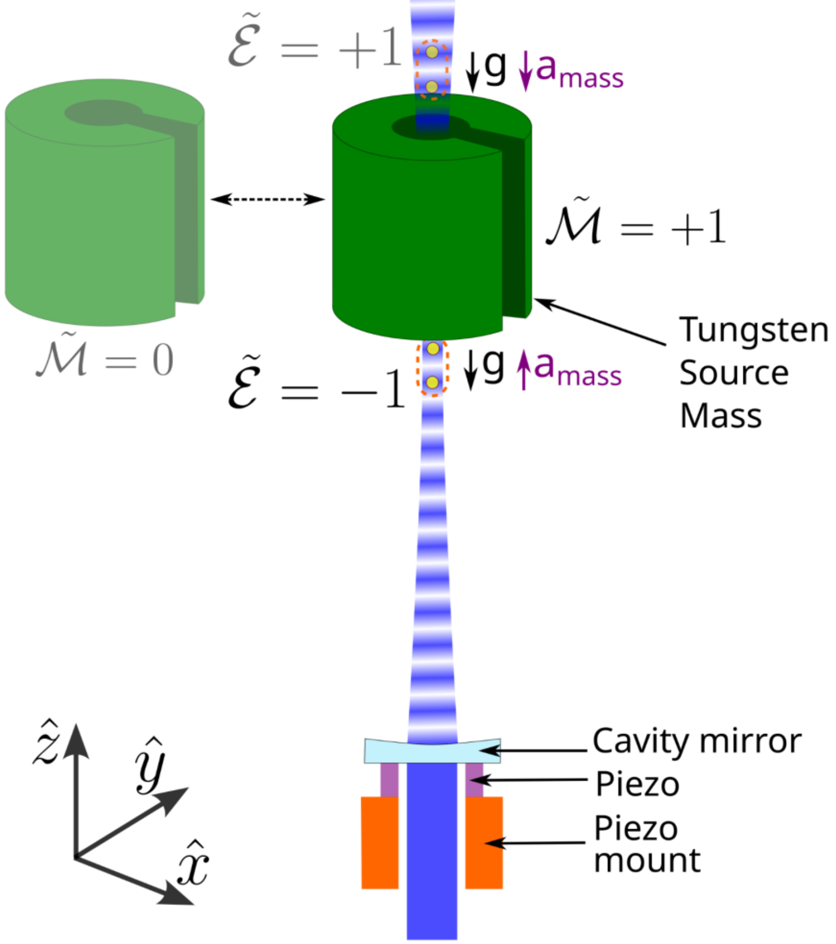
Switches

- Suppress experiment drifts and systematic effects by **differential measurement** (ACME inspired)
- Four experiment configurations
  - Mass nearby ($\widetilde{\mathcal{M}} = 1$) and mass far-away ($\widetilde{\mathcal{M}} = 0$).
  - Atoms positioned above ($\tilde{\mathcal{E}} = +1$) and below source mass ($\tilde{\mathcal{E}} = -1$).





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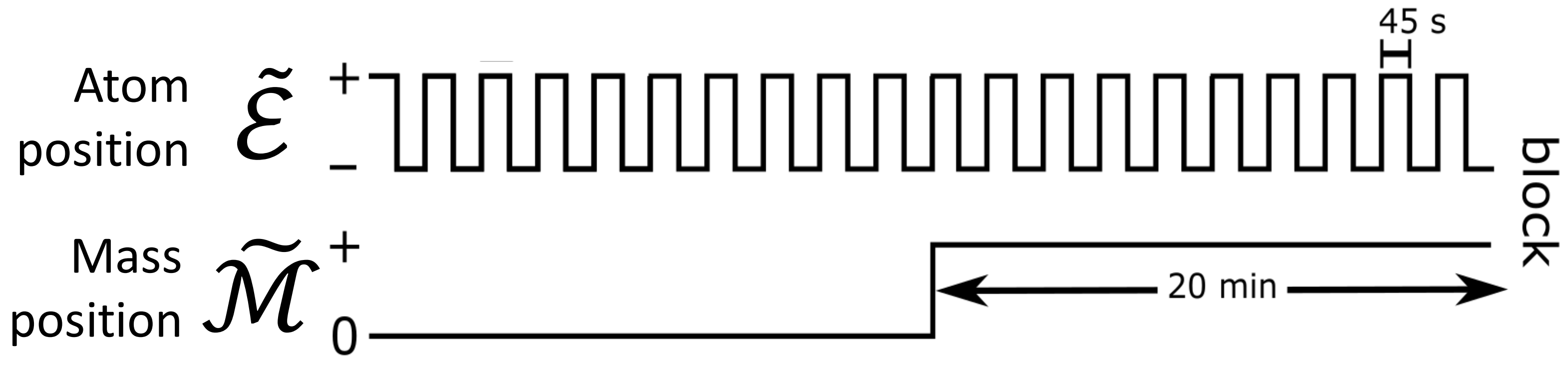
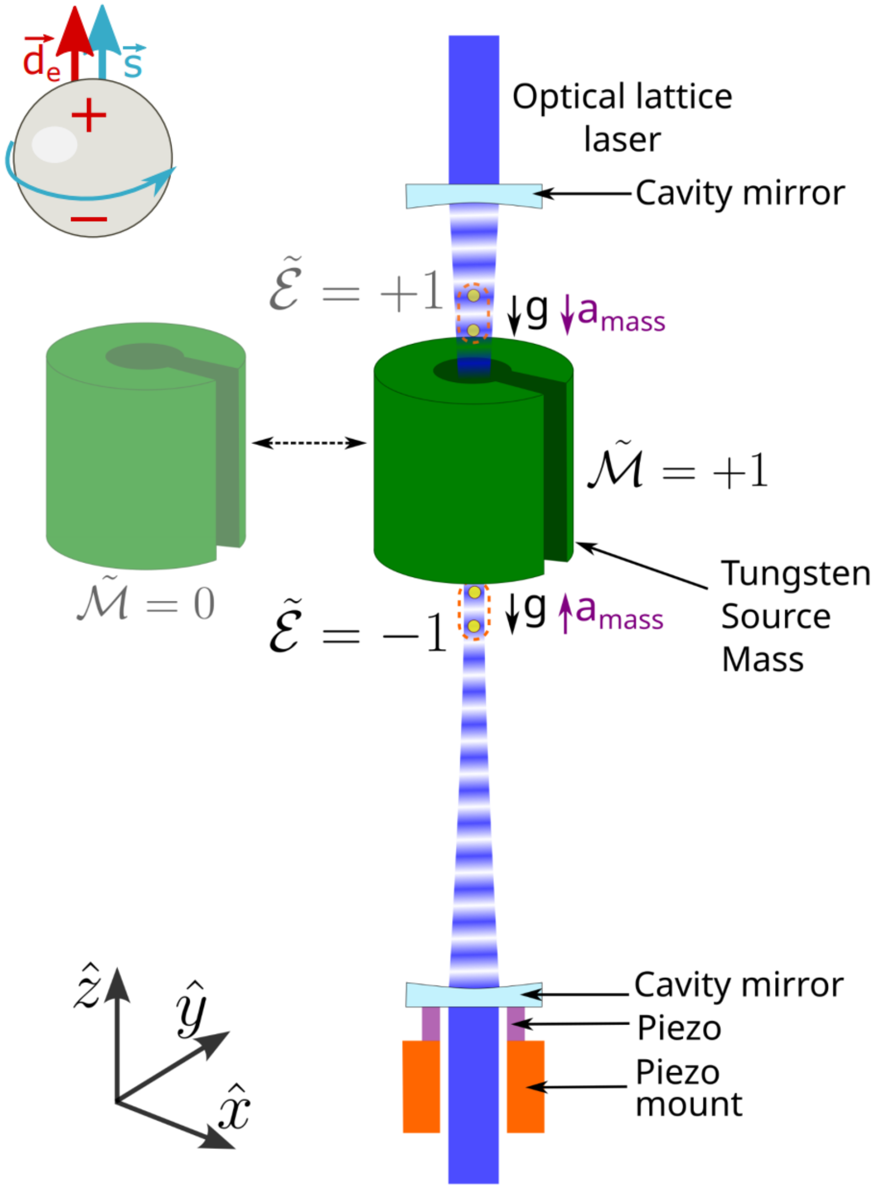


- 4 measurements: $a\left(\tilde{\mathcal{E}} = \pm 1, \widetilde{\mathcal{M}} = \{0, +1\}\right)$



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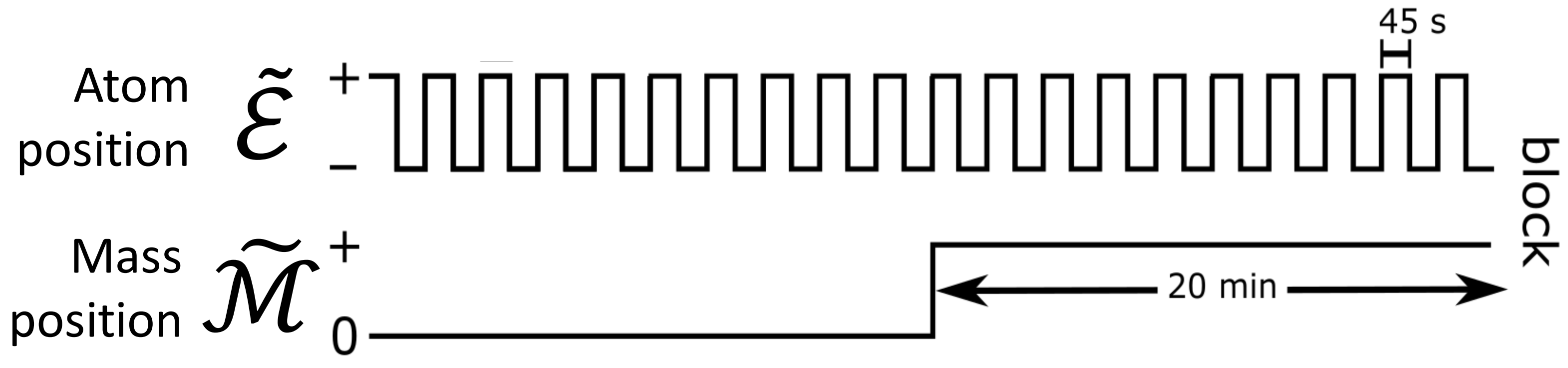
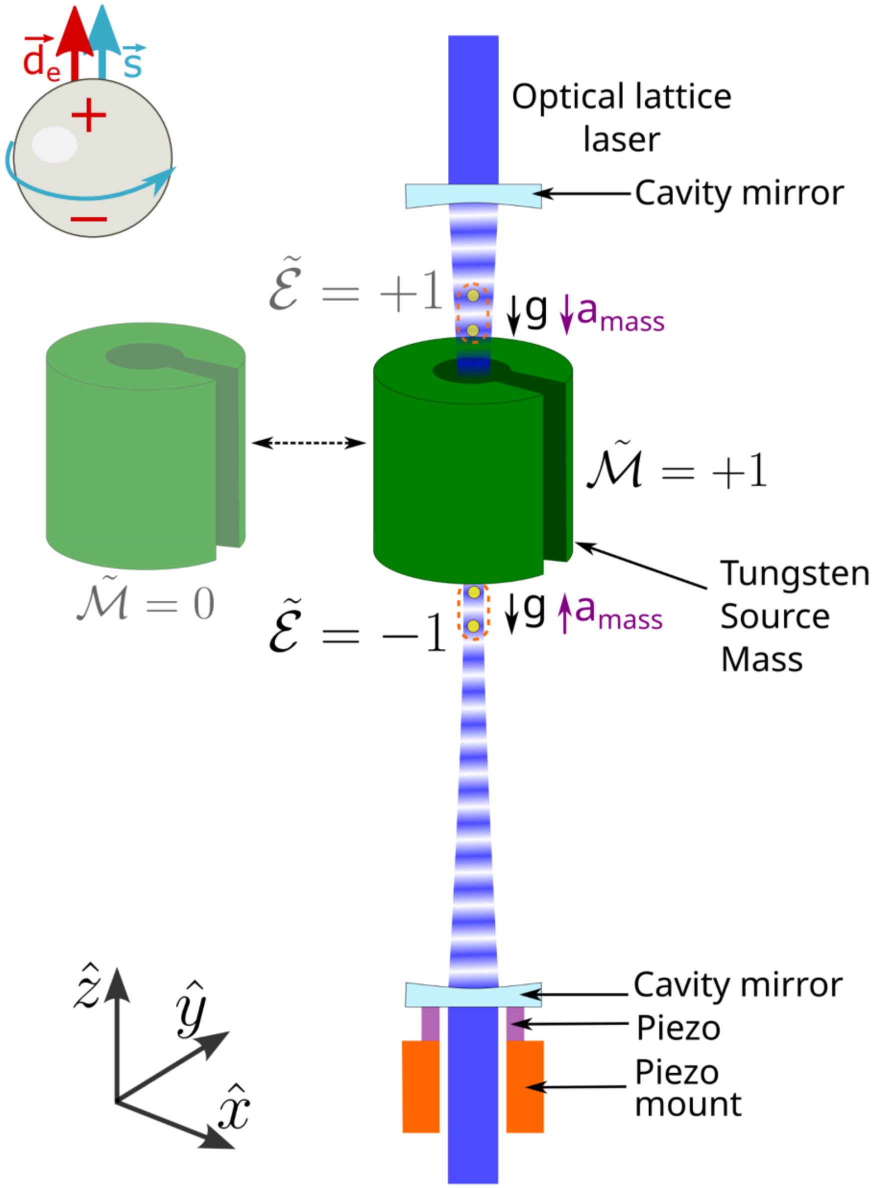


  - 4 measurements: $a\left(\tilde{\mathcal{E}} = \pm 1, \tilde{\mathcal{M}} = \{0, +1\}\right)$

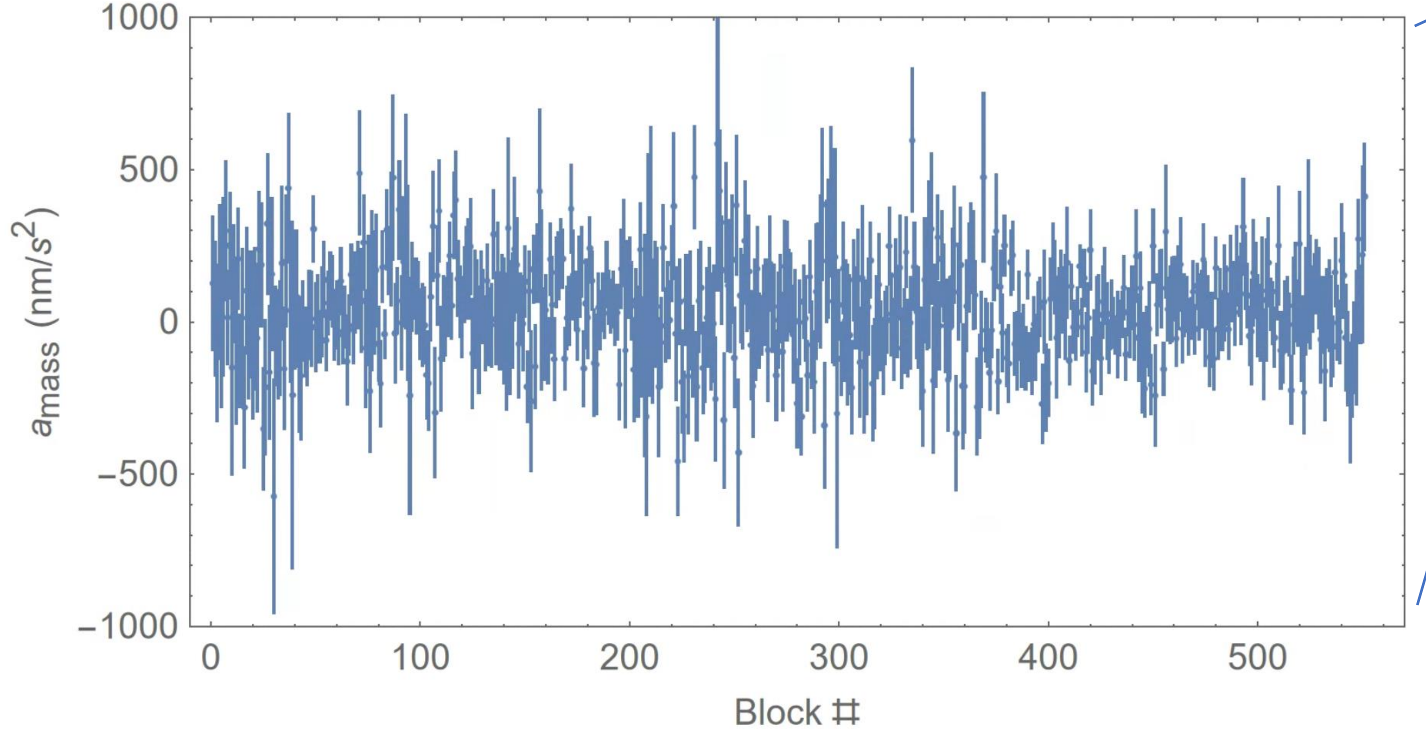
$$a_{\text{mass}} \equiv a^{\mathcal{M}\mathcal{E}} = [a(1,1) - a(1,-1) - a(0,1) + a(0,-1)]/2$$

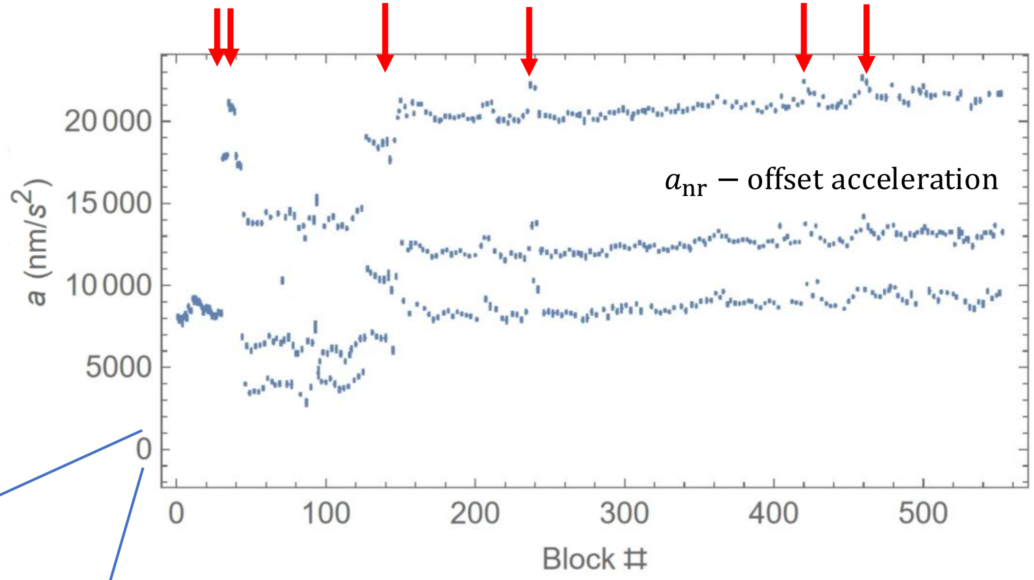


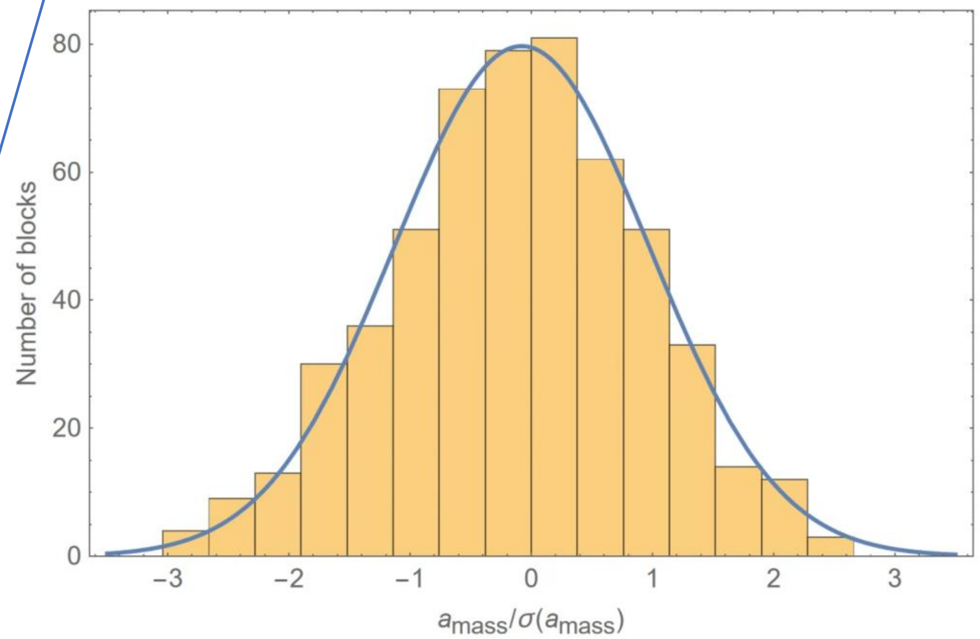
Measuring gravity by holding atoms,
CDP et al, arXiv:2310.01344 (under review Nature) (2023)

Dataset Statistics

- 2 months of data, ~45 days, 400 hours
- Noise near the standard quantum limit and $\chi_r^2 = 1.06 \pm 0.04$







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Systematic Checks

- Variation of over 40 parameters. 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 (Black-body radiation gradient)

Lattice divergence -“expected” ($a^{\mathcal{E}}$)

Mass motion effects ($\mathcal{M}$-correlated rows)

known (DC Stark Shift)

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CDP et al, arXiv:2310.01344 (under review Nature) (2023)

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- Black-body radiation gradient: known
- $a^{\mathcal{E}}$: Lattice divergence -"expected"
- $\mathcal{M}$-correlated rows: Mass motion effects
- DC Stark Shift: known
- Total uncertainty 6.21: 5 times better than previous measurement

Results

- Blinded result

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

Measuring gravity by holding atoms,
CDP et al, arXiv:2310.01344 (under review Nature) (2023)

Results

- Unblinded result

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

Measuring gravity by holding atoms,
CDP et al, arXiv:2310.01344 (under review Nature) (2023)

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- Unblinded result

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

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

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CDP et al, arXiv:2310.01344 (under review Nature) (2023)

Results

- Unblinded result

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

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

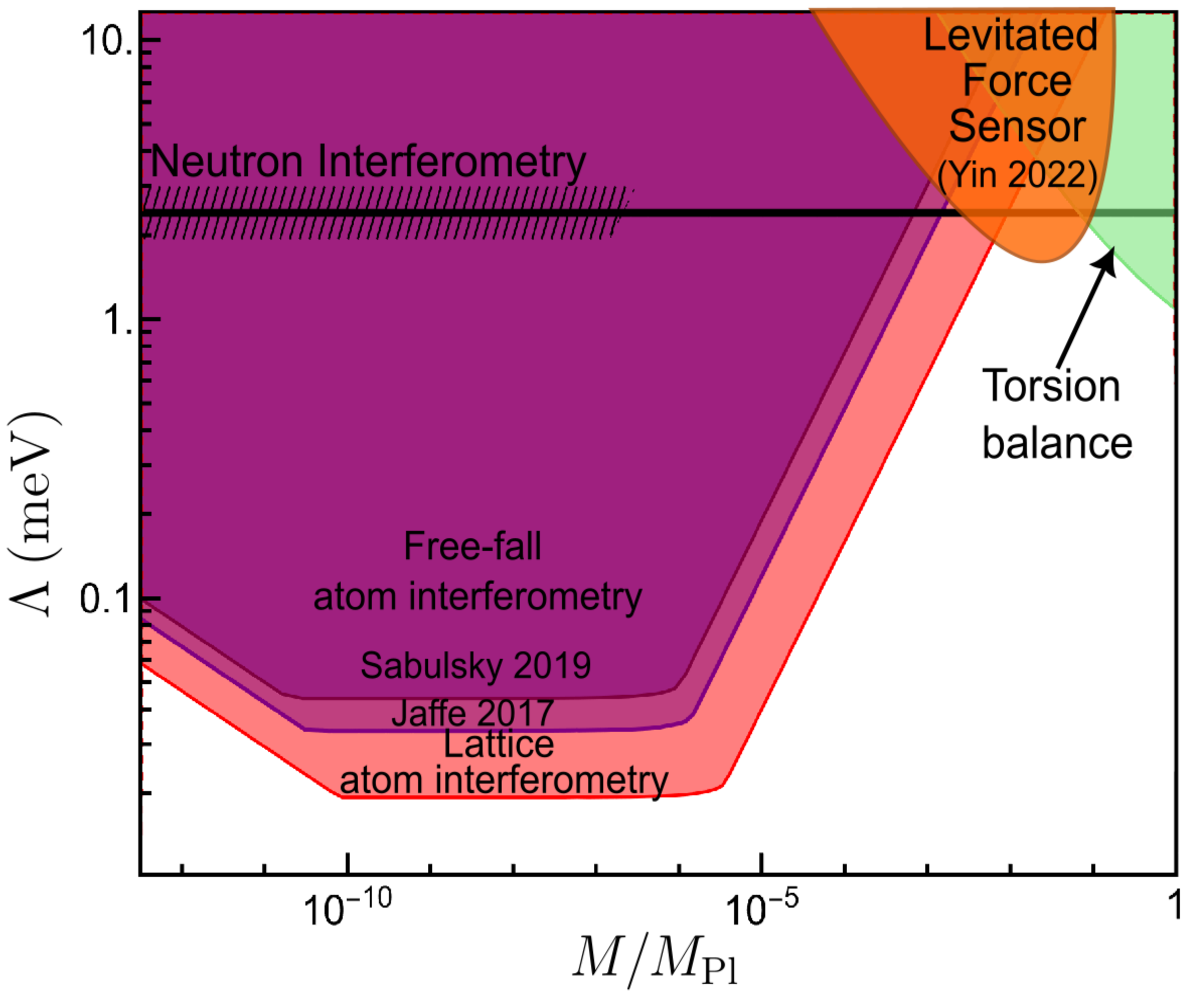
- Limit on deviation from Newtonian gravity

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

Measuring gravity by holding atoms,
CDP et al, arXiv:2310.01344 (under review Nature) (2023)

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



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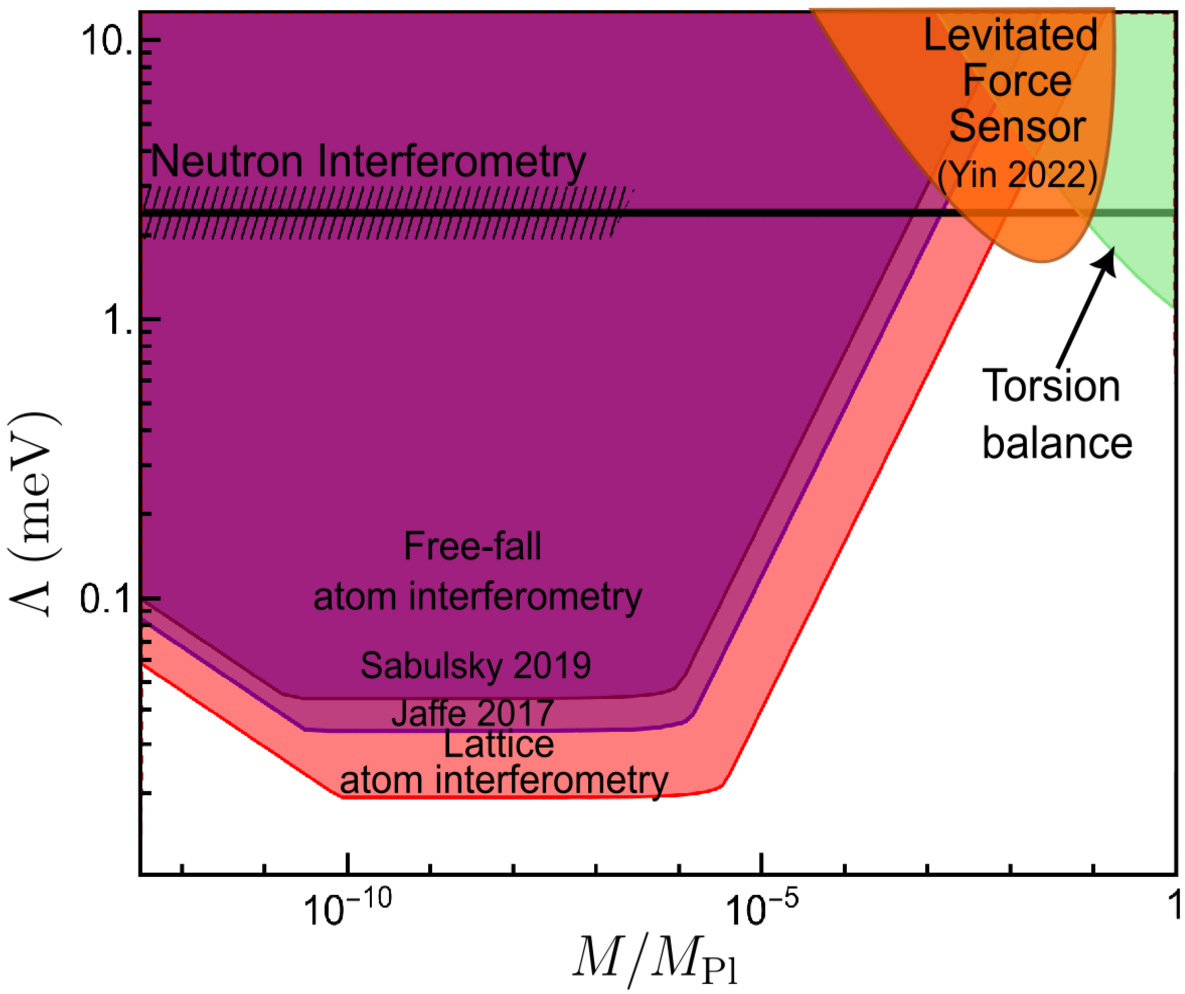
Probing New Fifth Force Physics

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



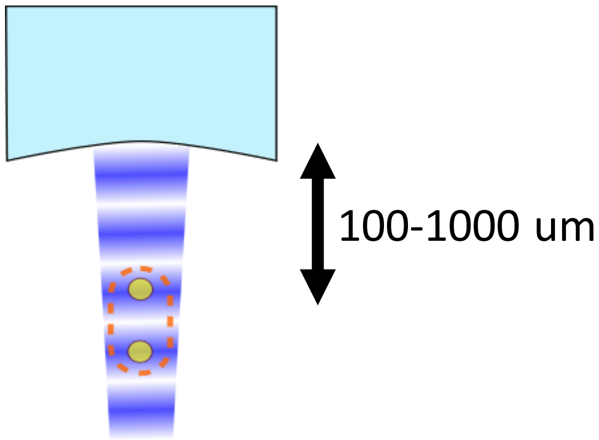
Measuring gravity by holding atoms,
CDP et al, arXiv:2310.01344 (under review Nature) (2023)

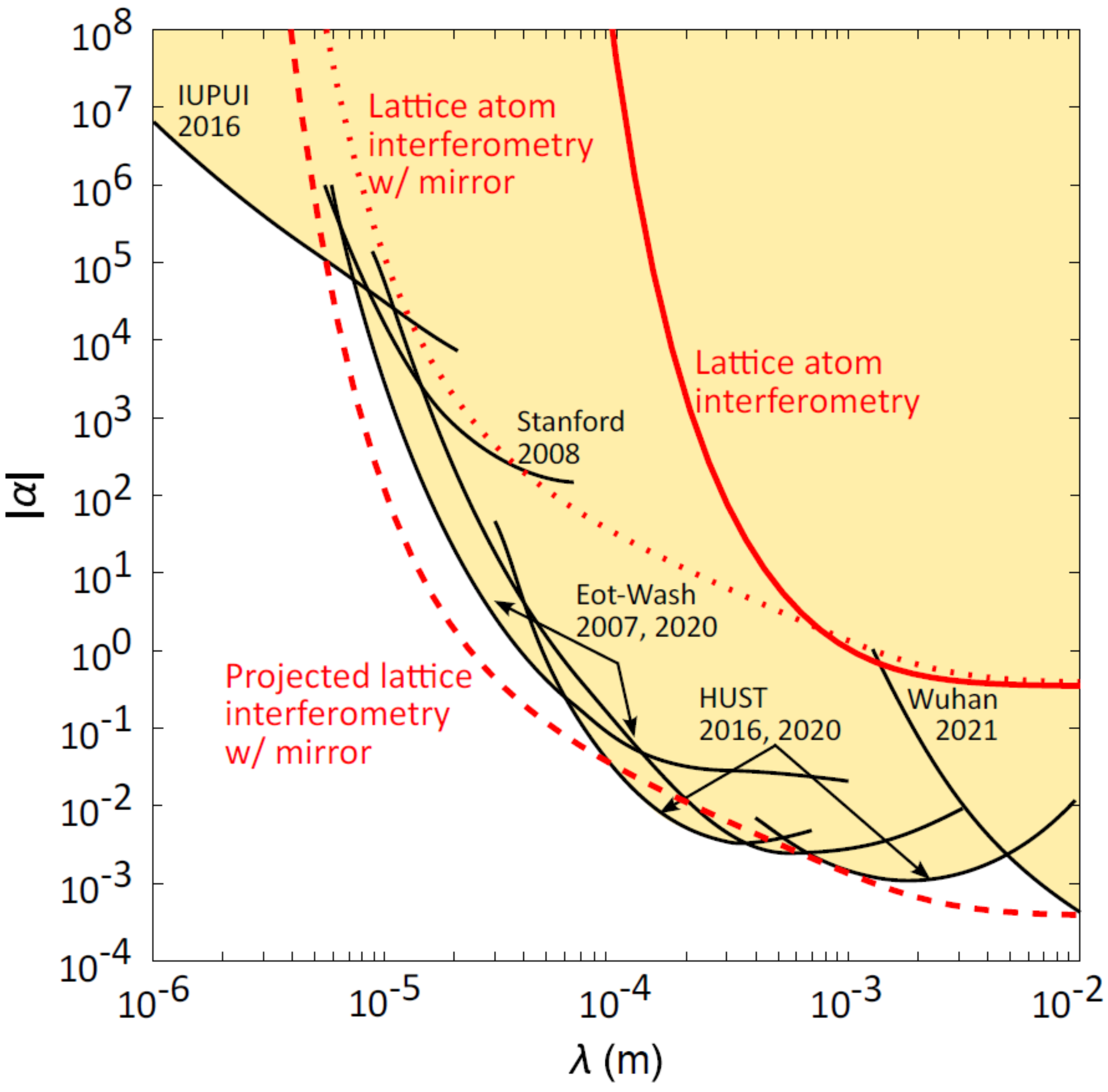
Beyond "Screened Potentials"

- Modified 1/r Newtonian potential with Yukawa term:

$$V(r) = -G_N \frac{m_1 m_2}{r}(1 + \alpha e^{-r/\lambda})$$

- Sensitive at short ranges <1 cm
- New experiment geometry => atoms near a mirror that acts as a source mass





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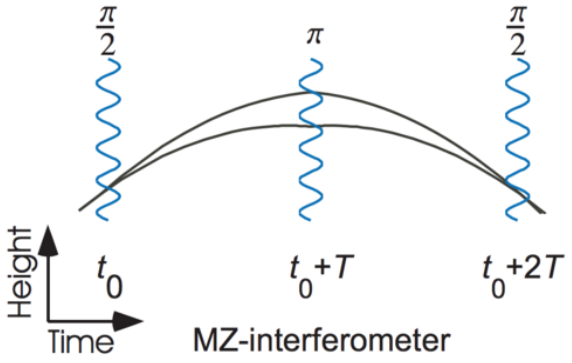
Outline

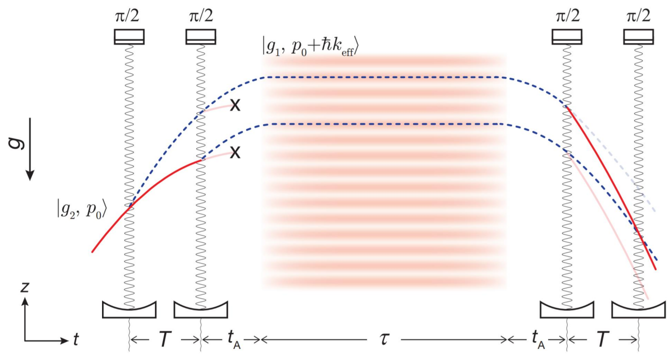
- Atom interferometry review

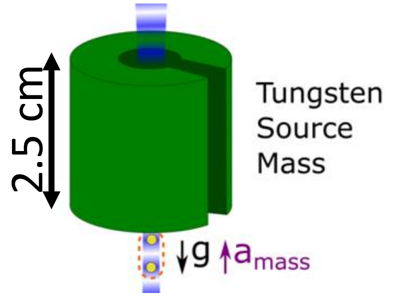
- Optical lattice atom interferometer
- theory and experiment

- Precise measurement of gravity and fifth forces

- Future directions

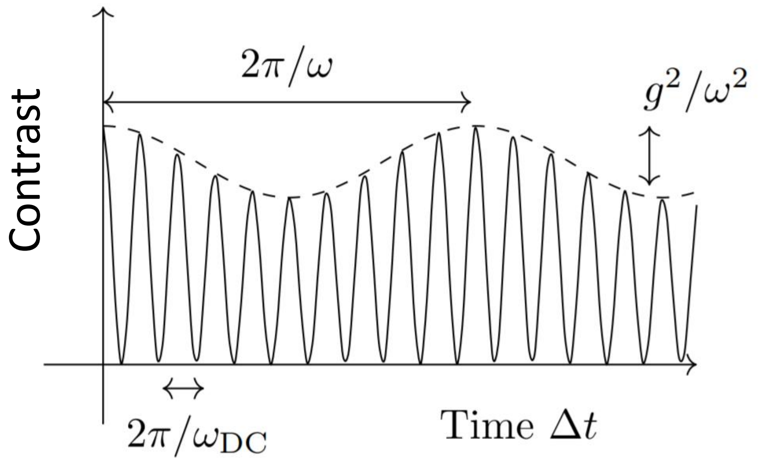


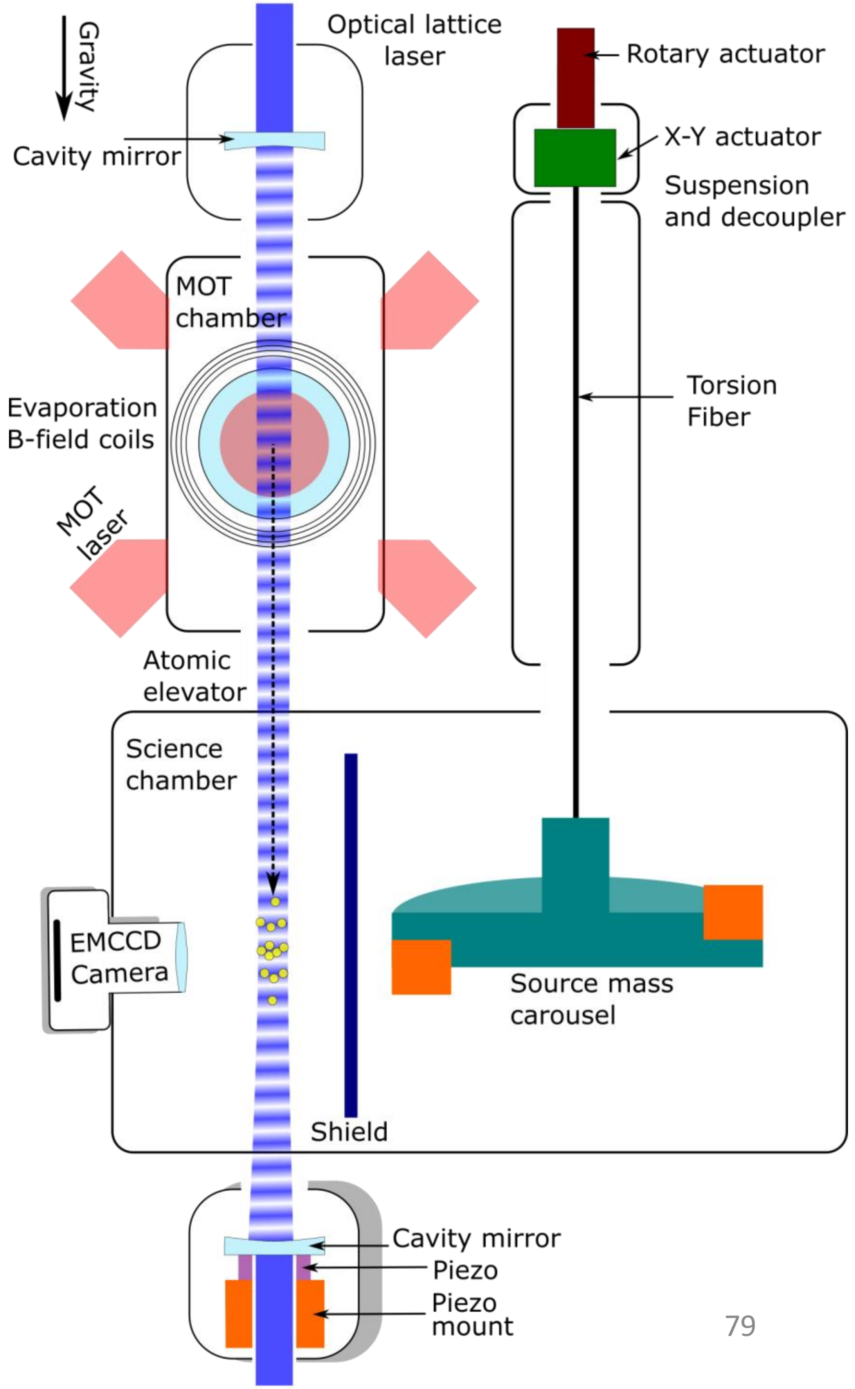




Probe gravity-mediated entanglement

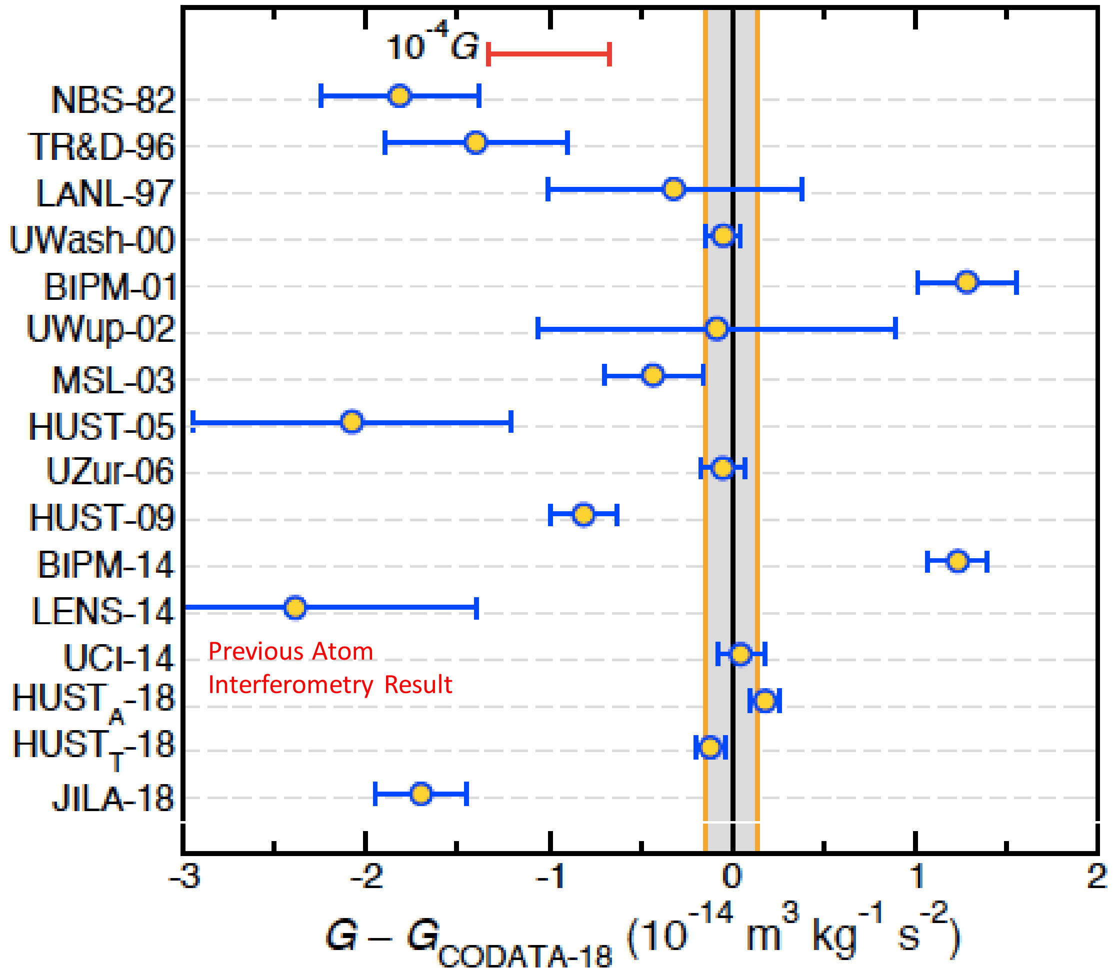
- Probe quantum interactions between atom interferometer (Cesium) and torsion balance pendulum
- Requires:
  - Non-gravitational pre-entanglement
  - Shielding to reduce other interactions



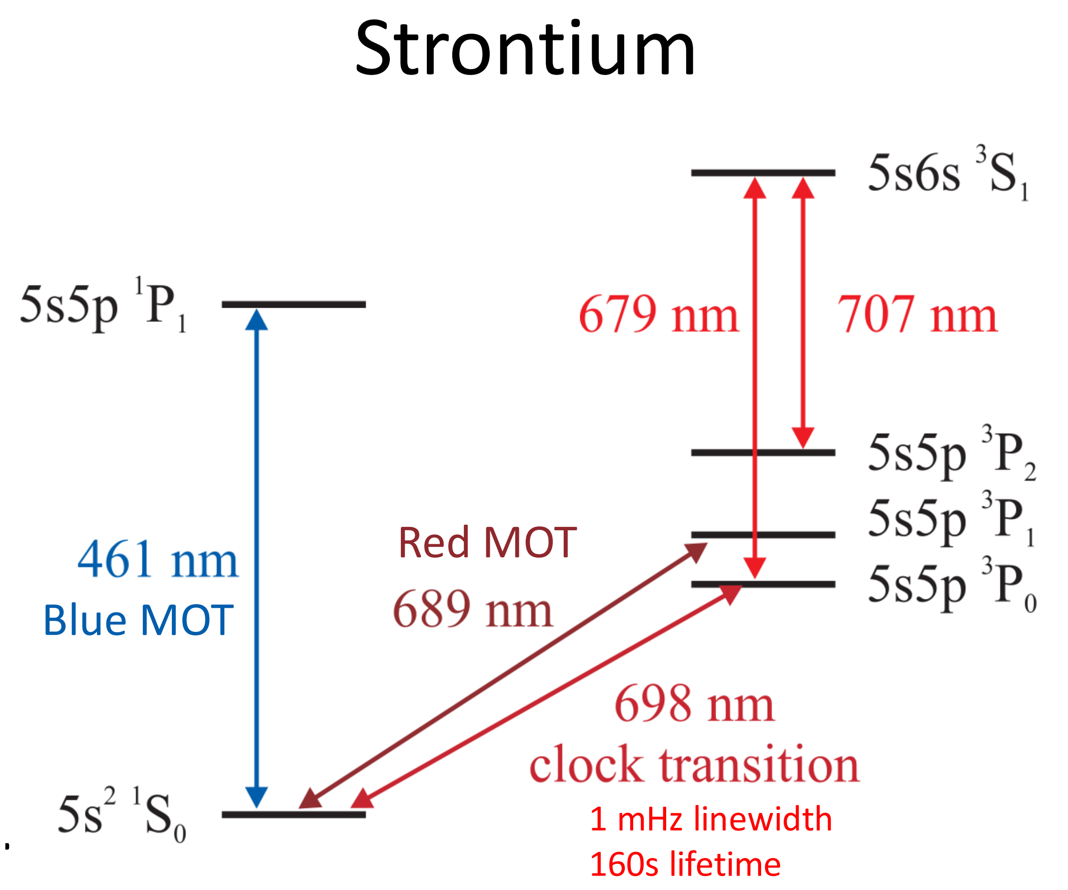


Using an Atom Interferometer to Infer Gravitational Entanglement Generation.
Daniel Carney et al., PRX Quantum 2, 3, 030330 (2021).

Measuring Big G



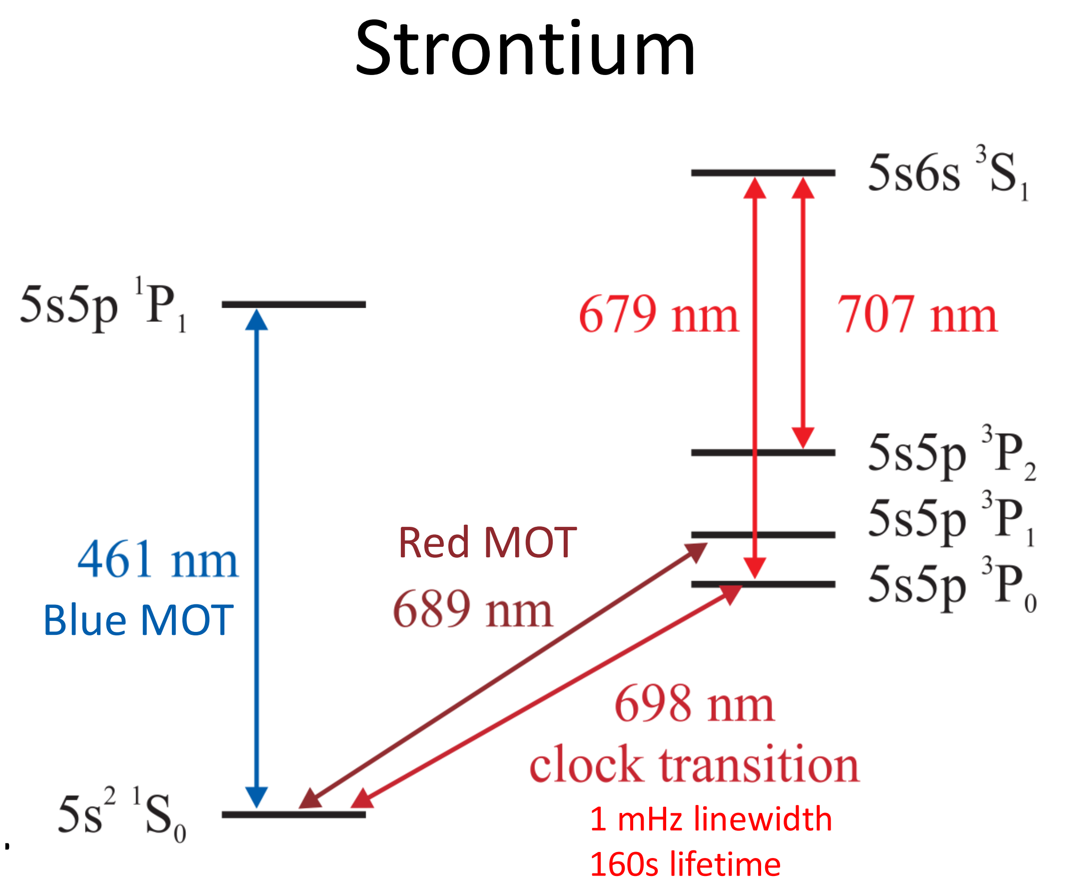
Next Generation Atom Interferometer



Next Generation Atom Interferometer

Advantages of Strontium (vs Cesium)

- Lower atom temperatures (10-100 times) possible with easy cooling => reduced decoherence
- Reduced collisions (1000-fold) => no decoherence
- Clock states
  - Single-photon large momentum transfer
  - Insensitive to background fields
- Fermionic and bosonic isotopes -> Quantum enhanced precision and accuracy via entanglement



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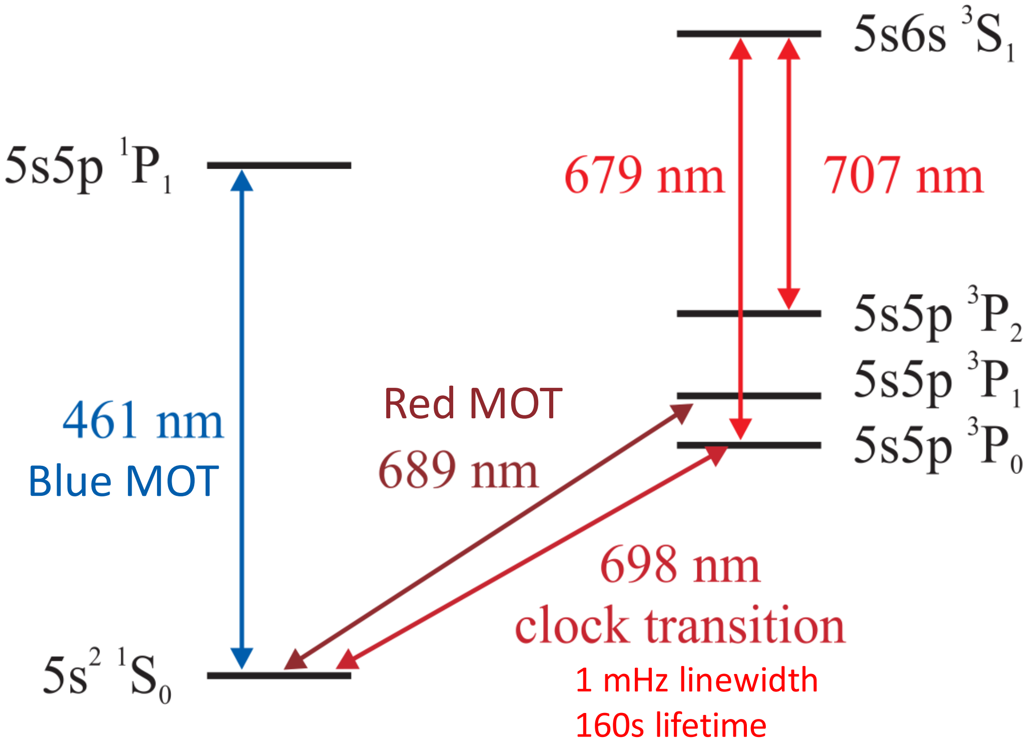
Lower temperature + improved lattice uniformity => **Sensitivity gains of 10^2-10^3 possible in table-top setup.**

- Sufficient for 10^{-4}-10^{-5} big G precision

Strontium



Reduced Systematics when Measuring G

Effect	Uncertainty	Correction to G (ppm)	Relative uncertainty $\Delta G/G$ (ppm)
Air density	10 %	60	6
Apogee time	30 μs		6
Atomic clouds horizontal size	0.5 mm		24
Atomic clouds vertical size	0.1 mm		56
Atomic clouds horizontal position	1 mm		37
Atomic clouds vertical position	0.1 mm		5
Atoms launch direction change C/F	8 μrad		36
Cylinders density inhomogeneity	10^{-4}	91	18
Cylinders radial position	10 μm		38
Ellipse fitting		-13	4
Size of detection region	1 mm		13
Support platforms mass	10 g		5
Translation stages position	0.5 mm		6
Other effects		<2	1
Systematic uncertainty			92 ppm

Fountain Interf.	Lattice Interf.
Atom position accuracy	Determined by optical lattice
Source mass properties	Smaller mass - easy to characterize
Analysis and Imaging	Small detection region

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

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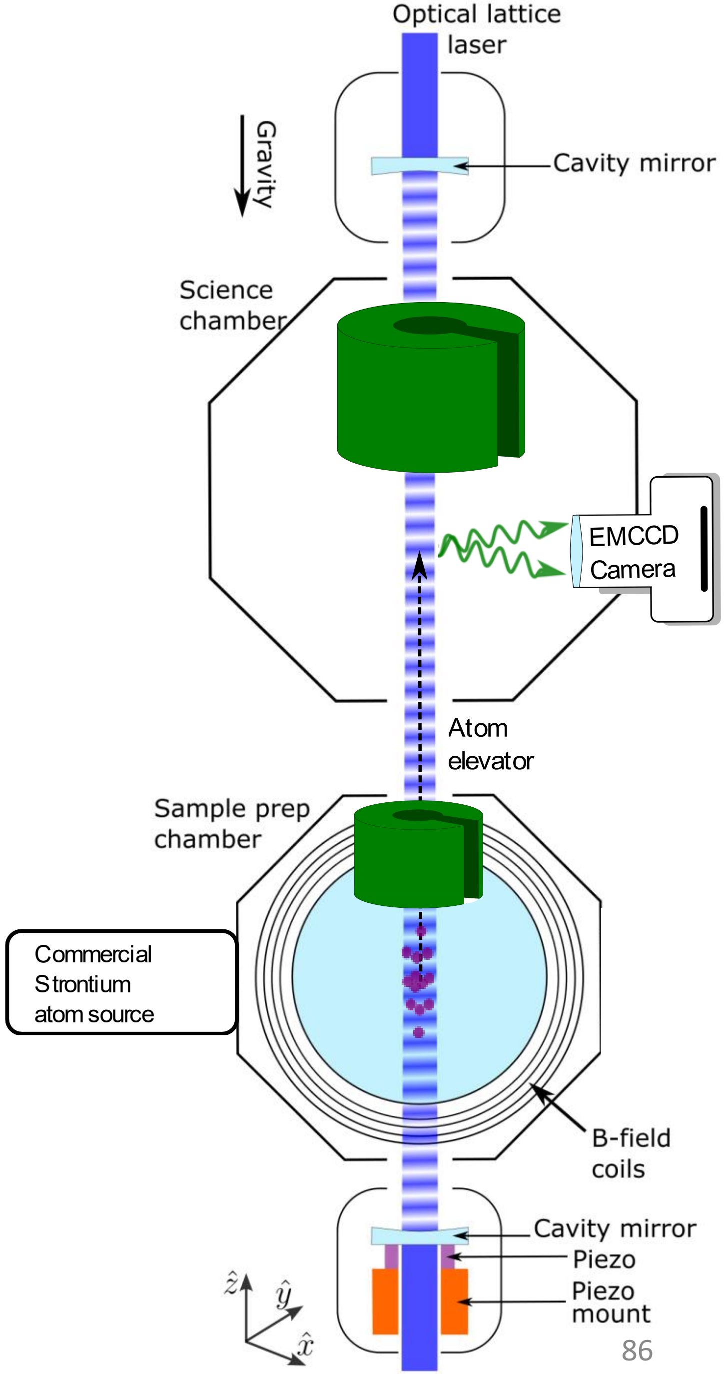
→ Lattice Interf. **<10 ppm**

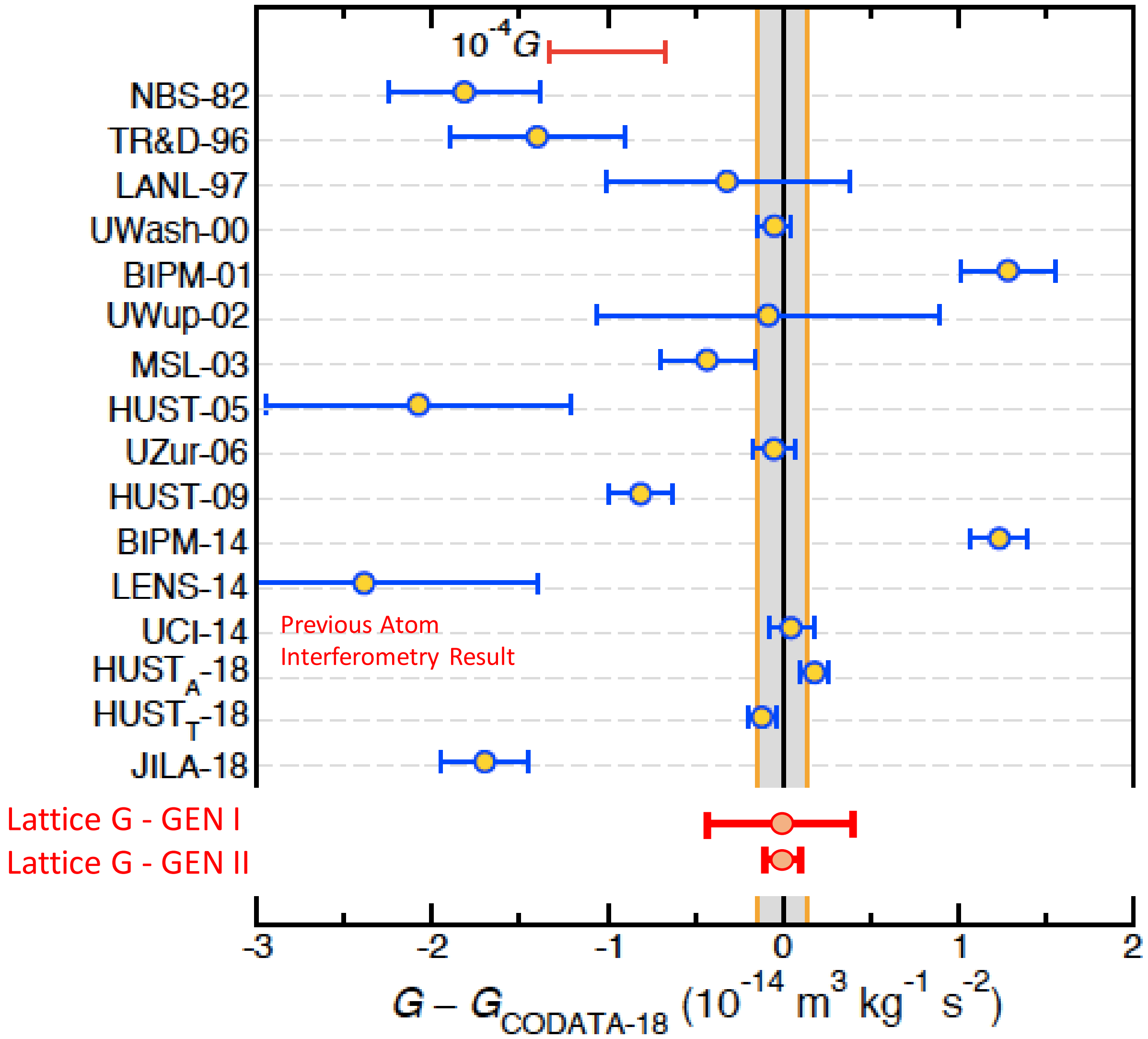
G. Rosi, et. al., Nature. 510, 518–521 (2014)

Next Generation Atom Interferometer

- New Science vacuum chamber – houses larger source mass + detection.



Projected Big G Results

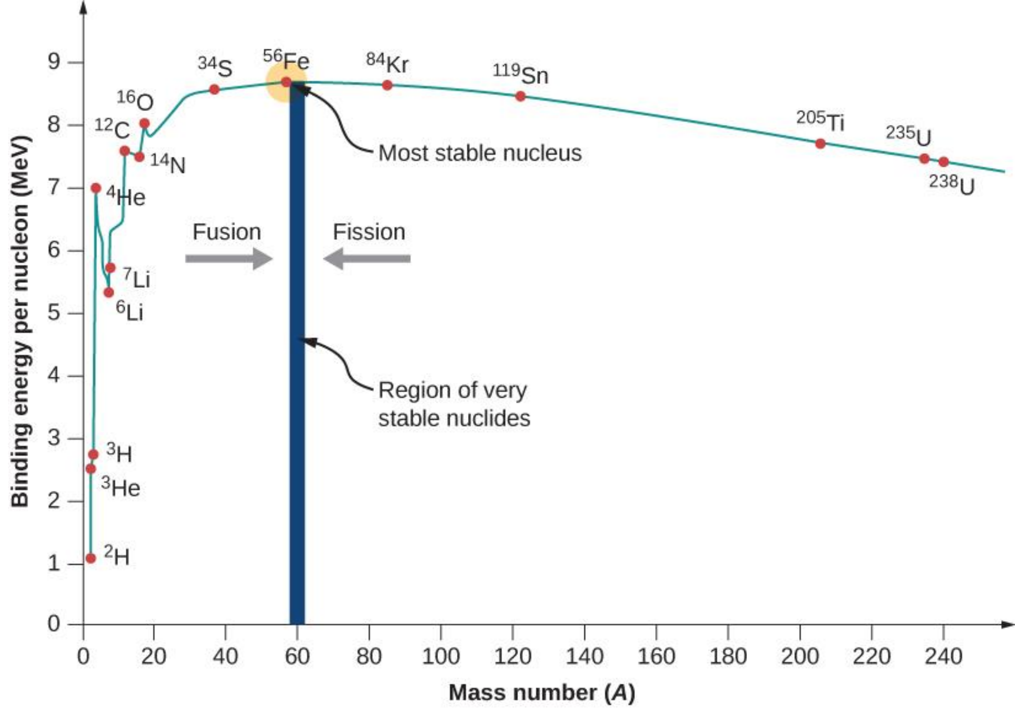


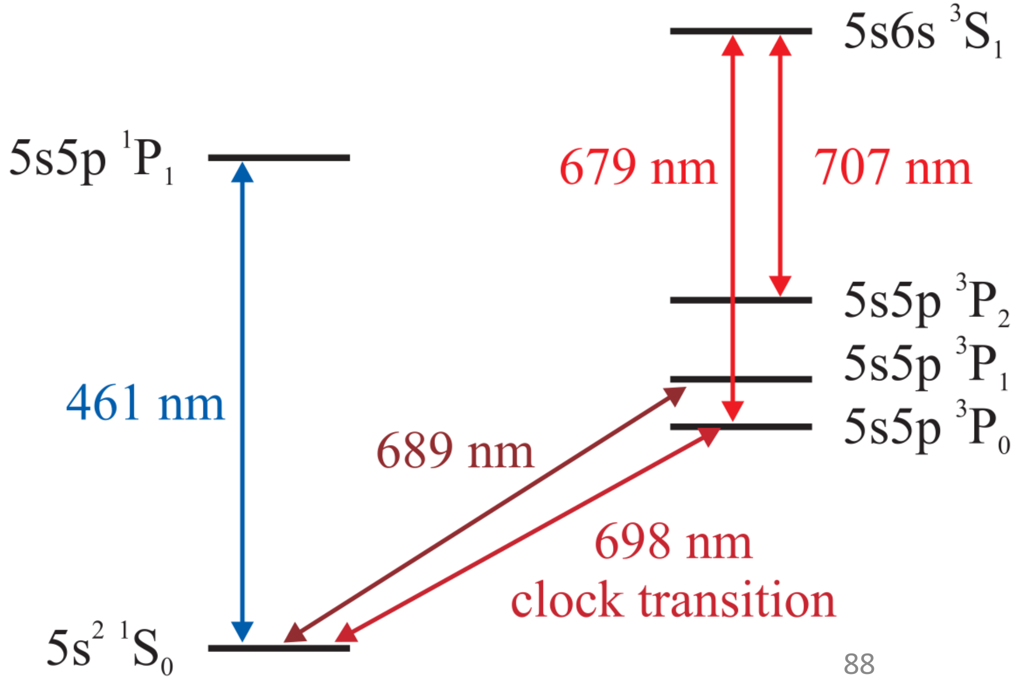
Measuring Atomic Mass Defect

- Nuclear mass defect: mass of the atomic nucleus is **less** than the sum of its nucleons (protons + neutrons) => **binding energy**
- Analogous change in “mass of excited atom”
- Extract “mass defect” Δm from phase difference between ground and excited states

$$\frac{\Delta m}{m_{\mathrm{Sr}}} = \frac{\phi^e - \phi^g}{\phi^g}$$

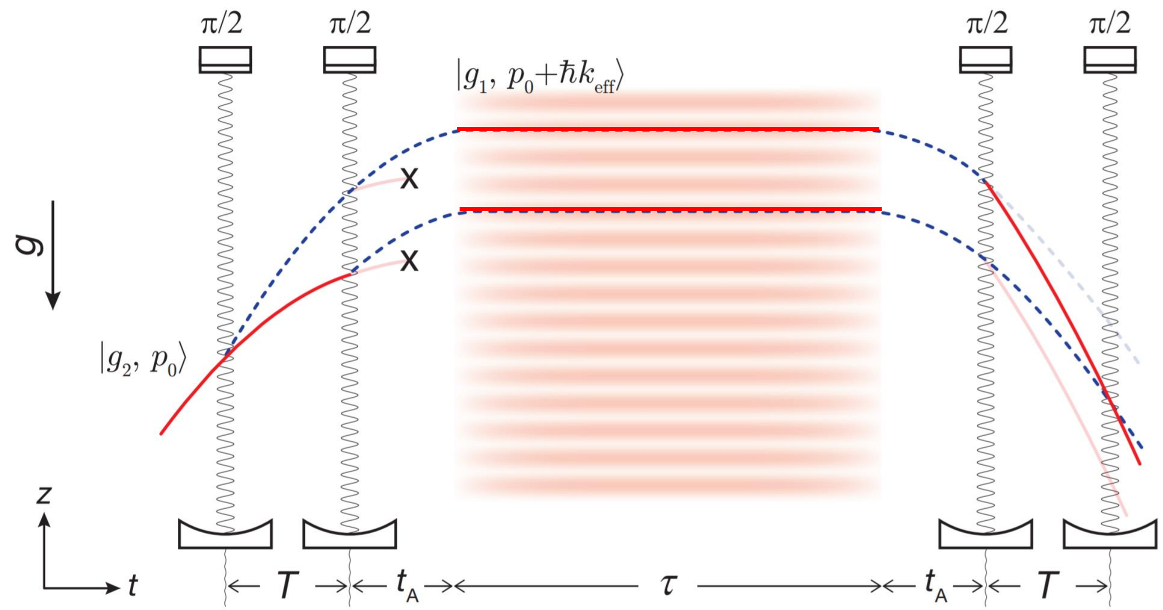
- Precise atomic weight balance: 10^{-33} grams.

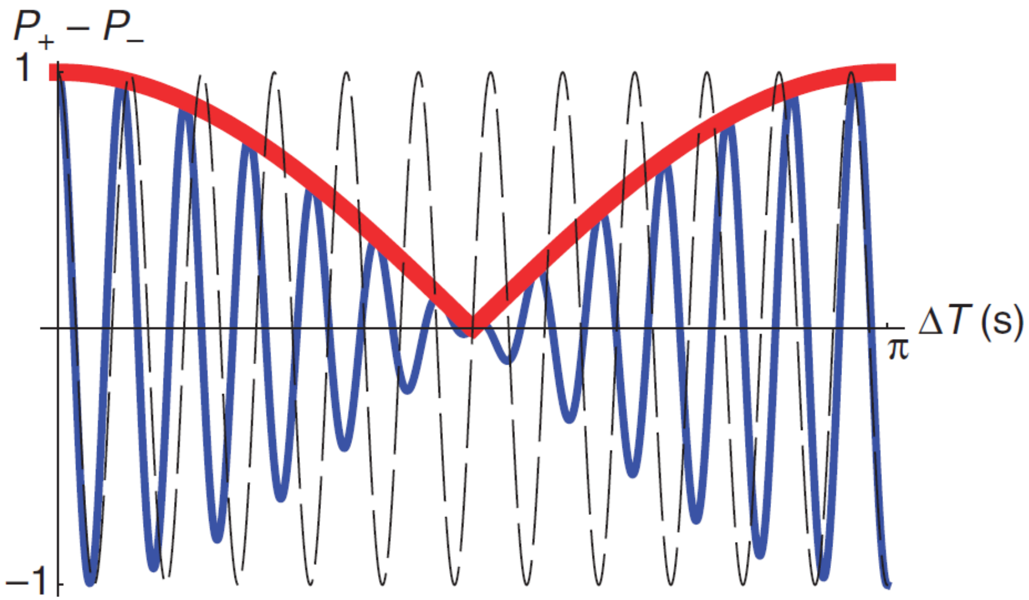




Testing GR Proper Time in QM

- Sr atoms in superposition of ground and excited states.



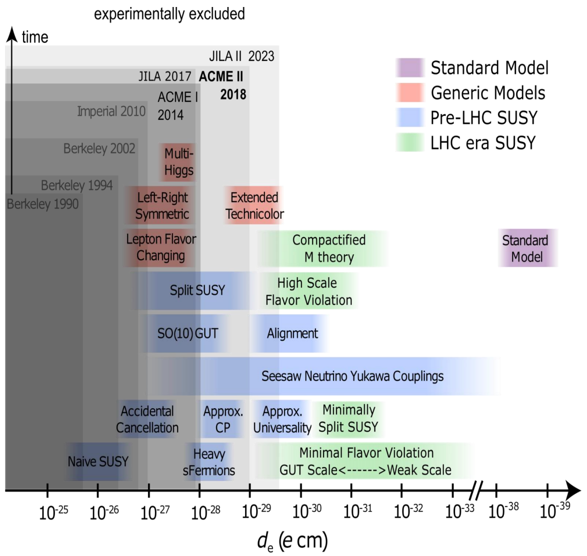


- Correspondence principle: contrast loss when which-way information becomes available from reading out general relativistic proper time.

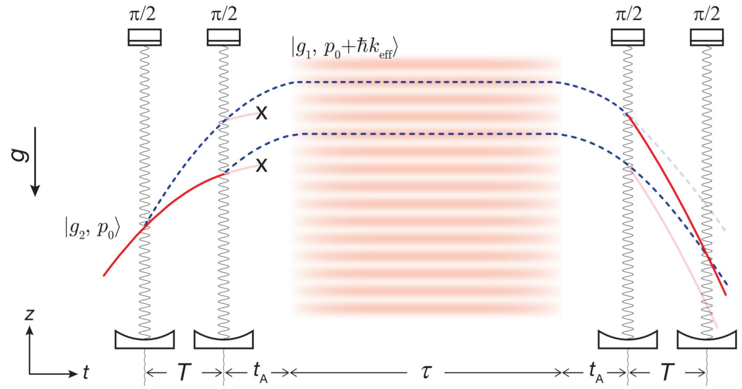
Zych, M *et al.* **Quantum interferometric visibility as a witness of general relativistic proper time.** *Nat Commun* **2**, 505 (2011).

Fundamental Physics with Atoms and Molecules

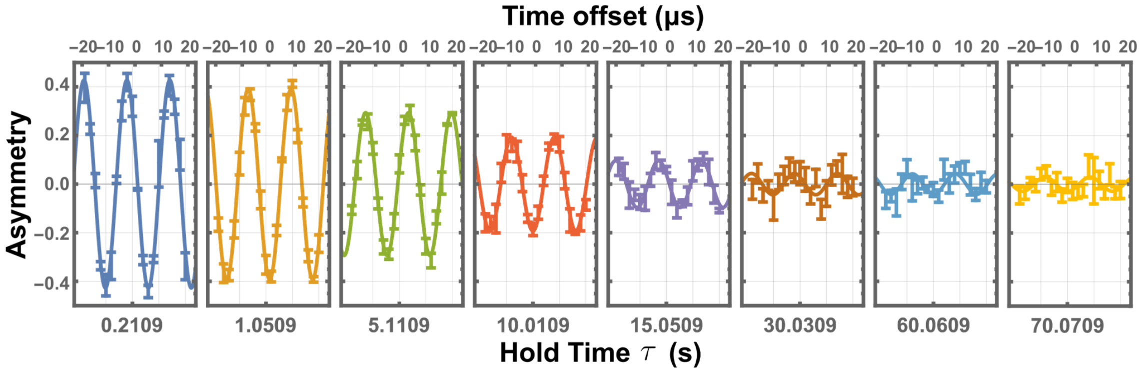
- Searches for eEDMs with molecules



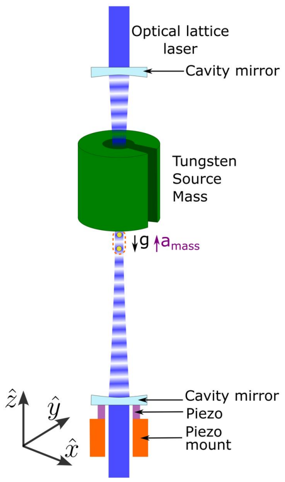
- Interferometry with atoms trapped in an optical lattice

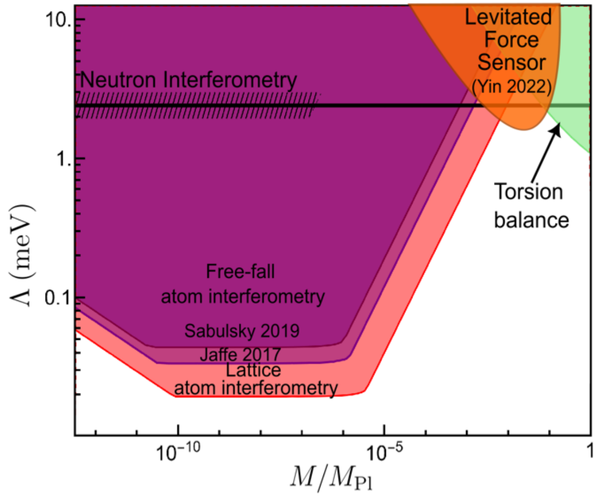


- Spatial superposition state coherent for 1 minute



- New bounds on fifth forces





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CDP
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(grad)

Miguel Ceja
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Andrew Reynoso
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Logan W. Clark
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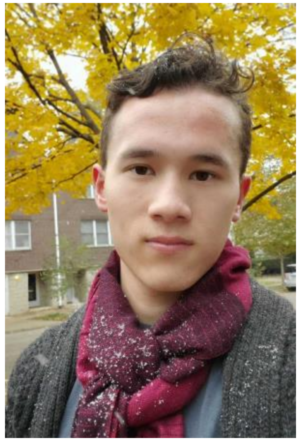

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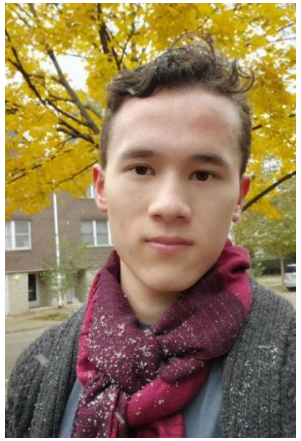

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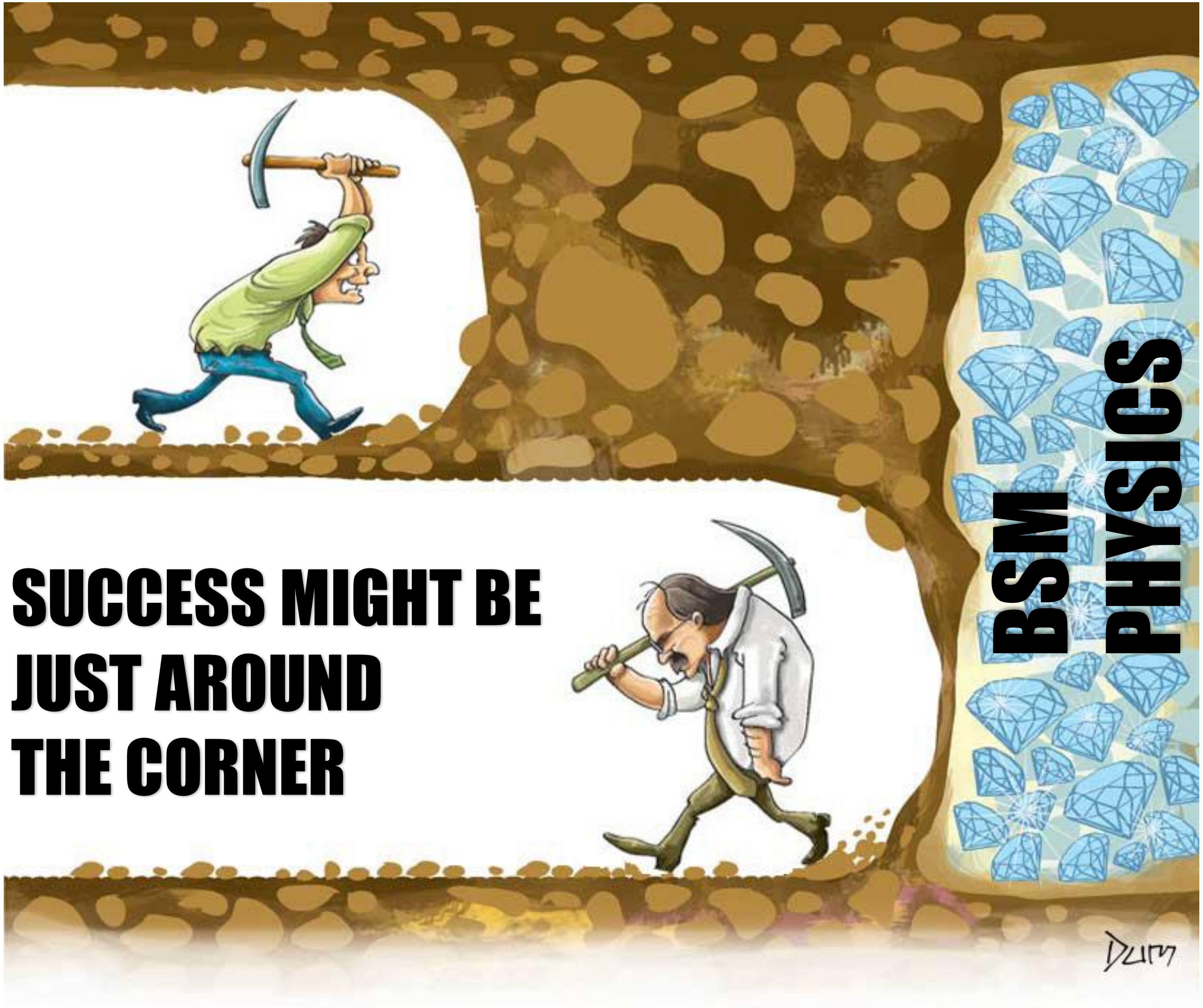
SUCCESS MIGHT BE
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THE CORNER
BSM
PHYSICS

Credit Seyda Ipek

Fundamental Physics with Atoms and Molecules

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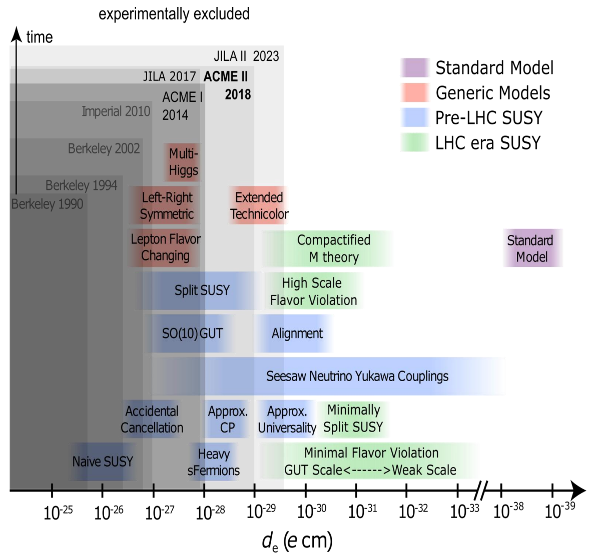

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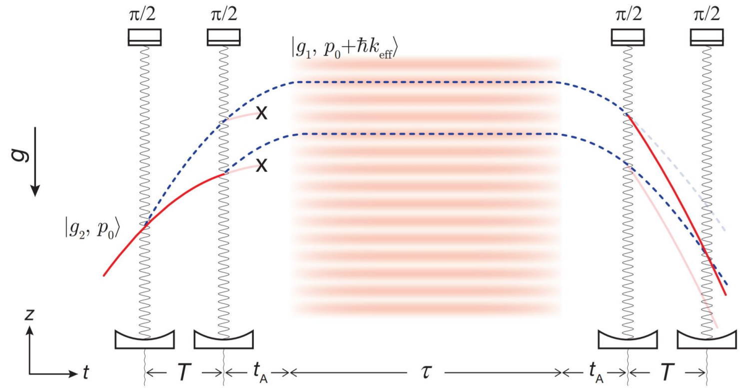

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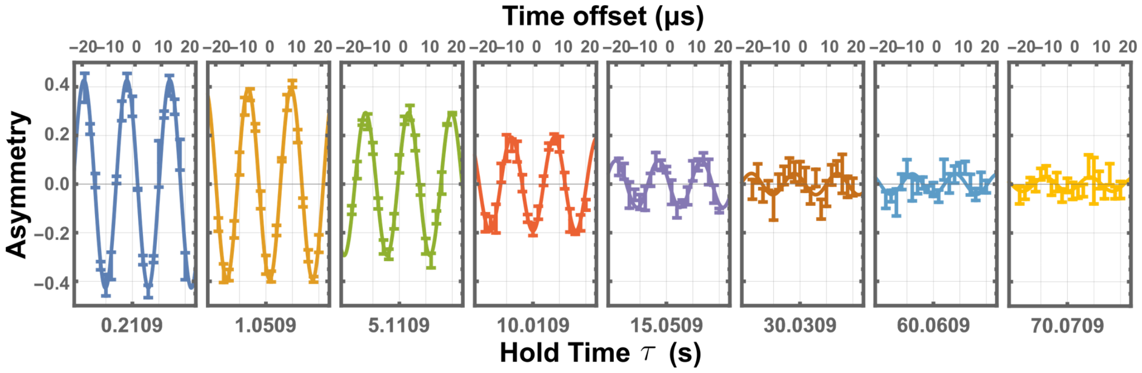

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