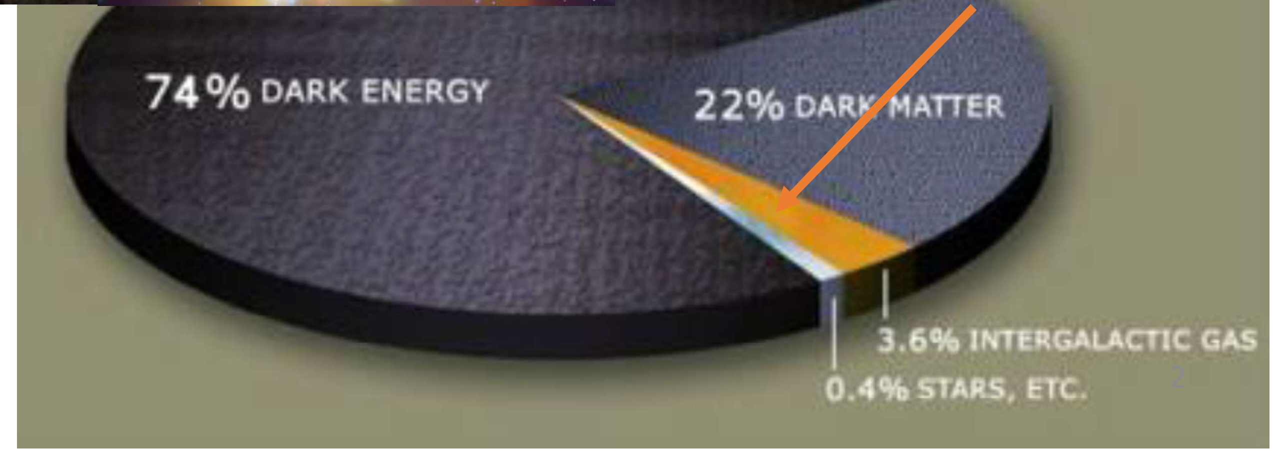
Atom Interferometry for Fundamental Physics

Cris Panda
UC Berkeley
DND 2020
11/05/2020

Questions that drive us



- Astrophysical observations tell us the Universe is mostly “dark”
    - Gravitational/inertial signals of dark matter and dark energy.

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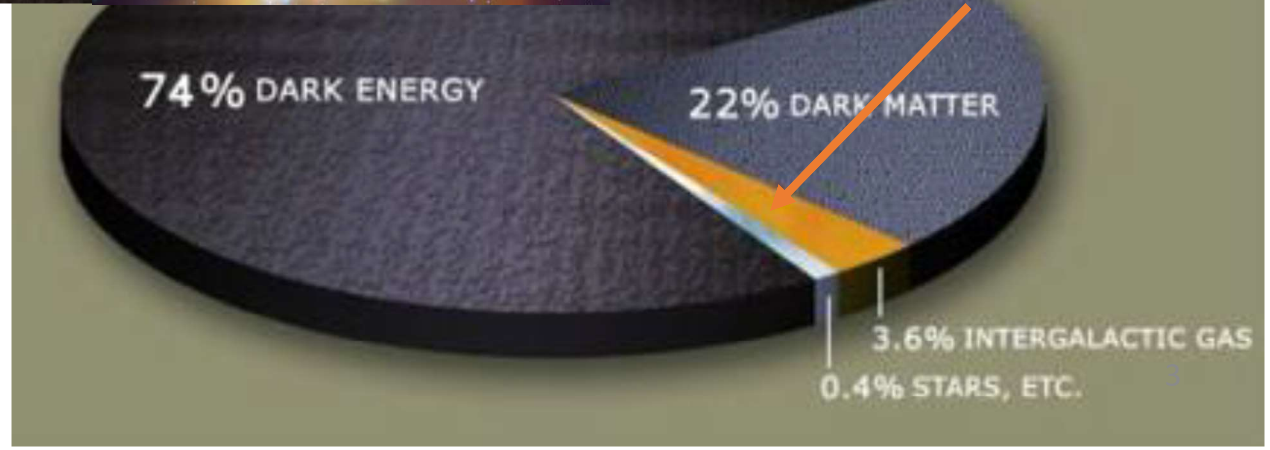

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- Quantum and gravity
  - How do they fit together?

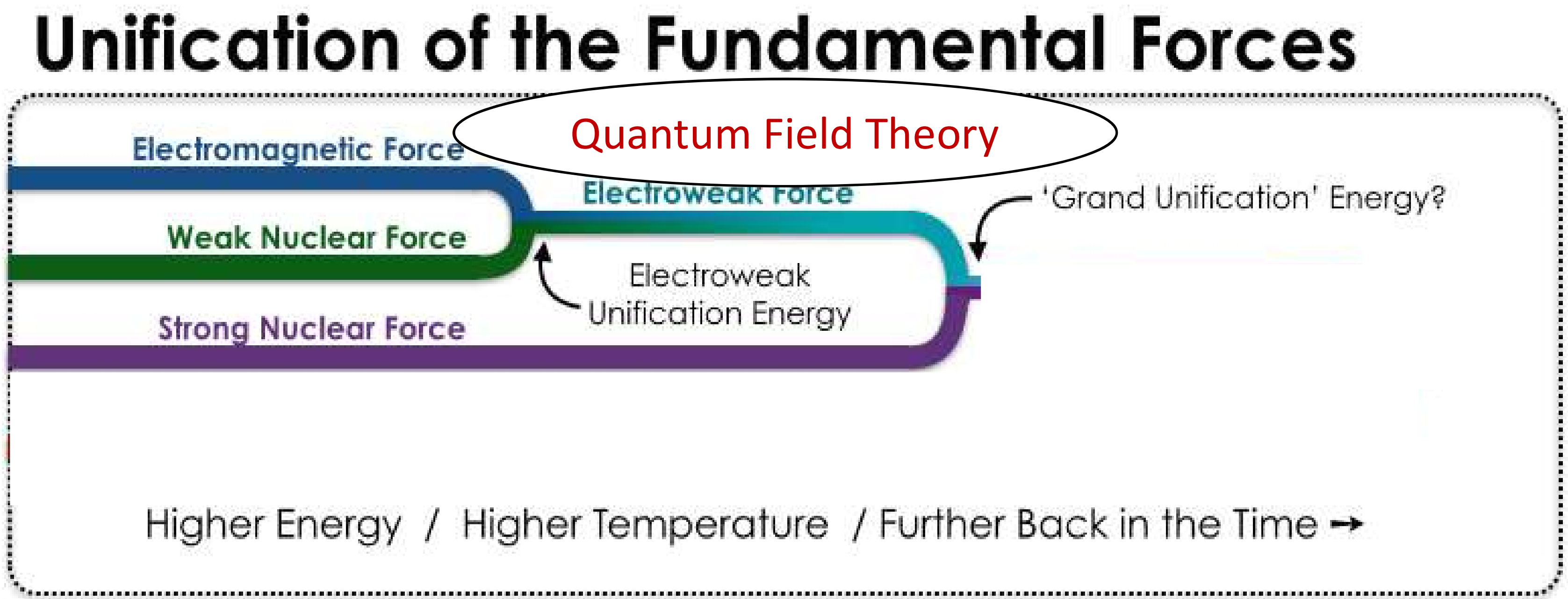

Image credit: Thomas G. McCarthy

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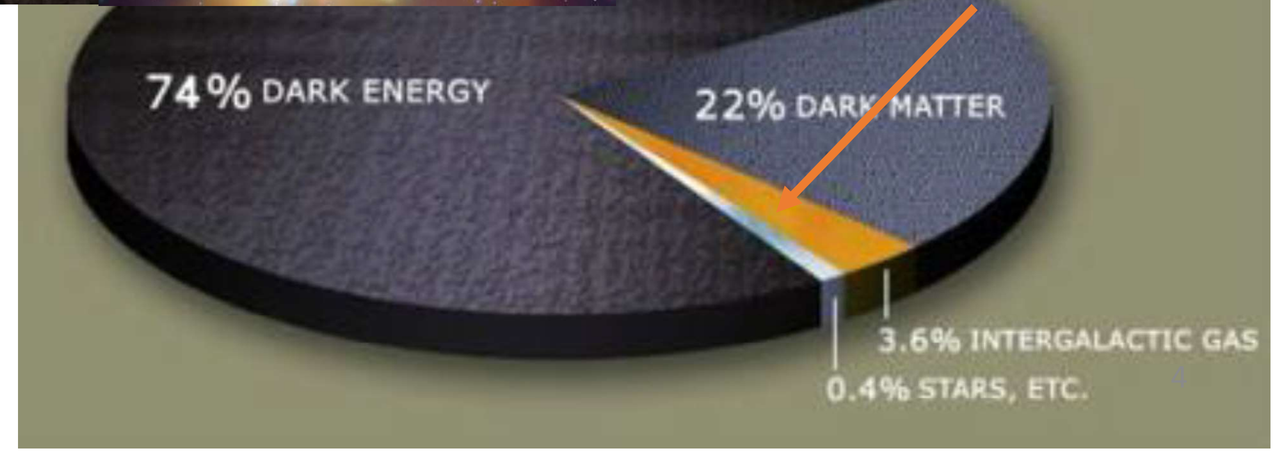

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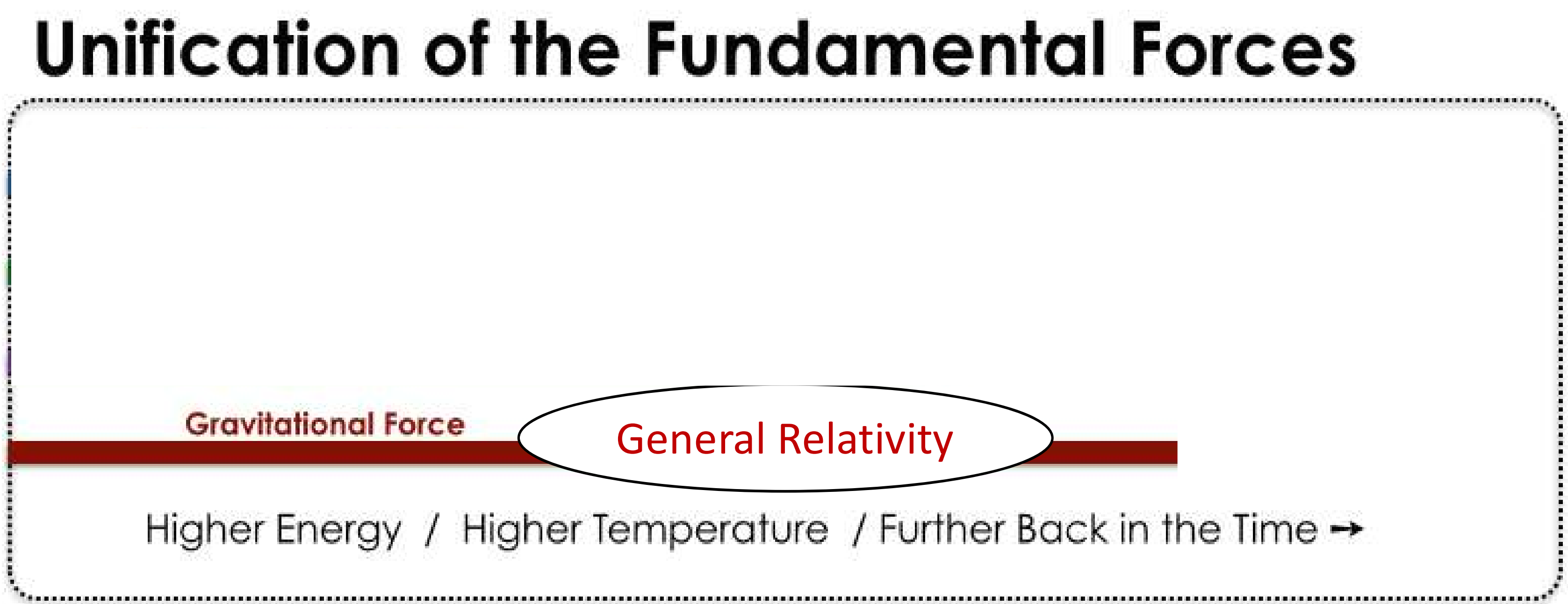

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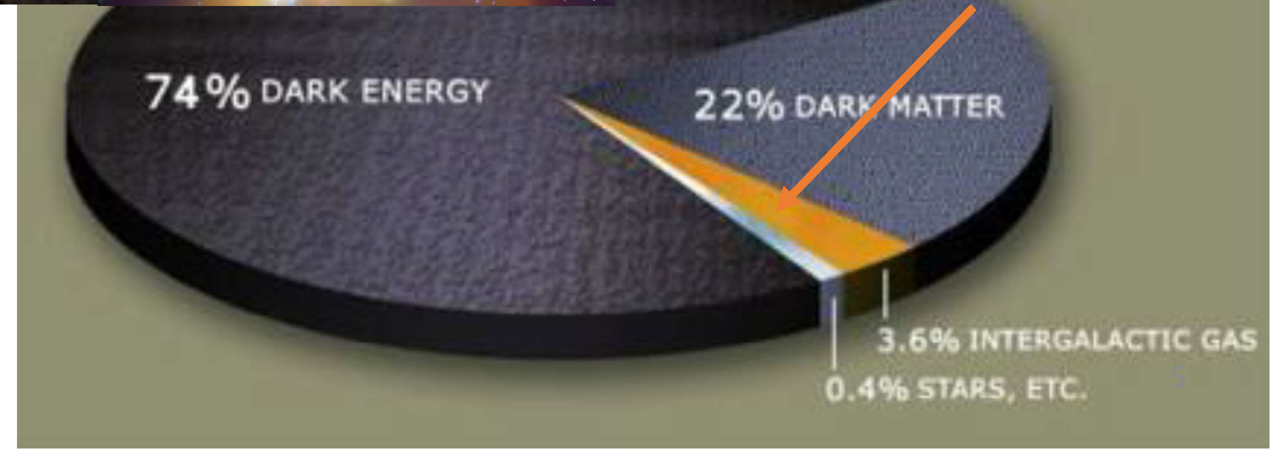

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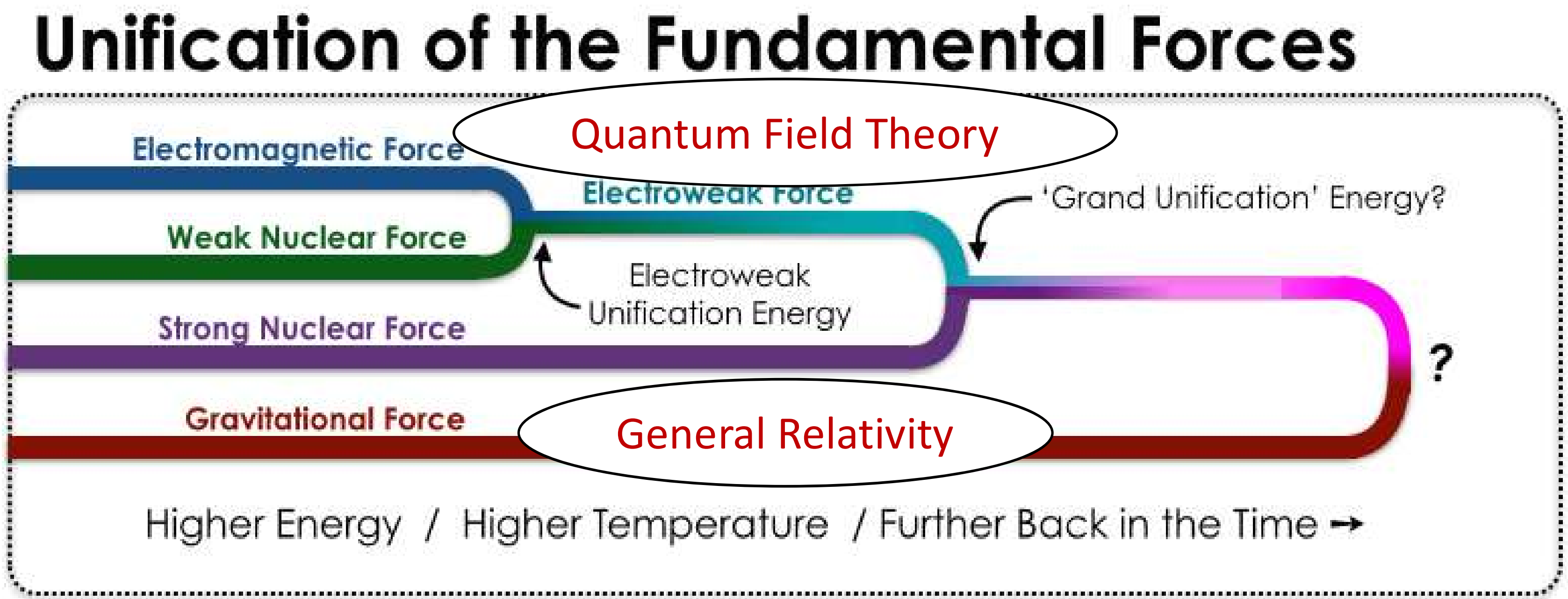

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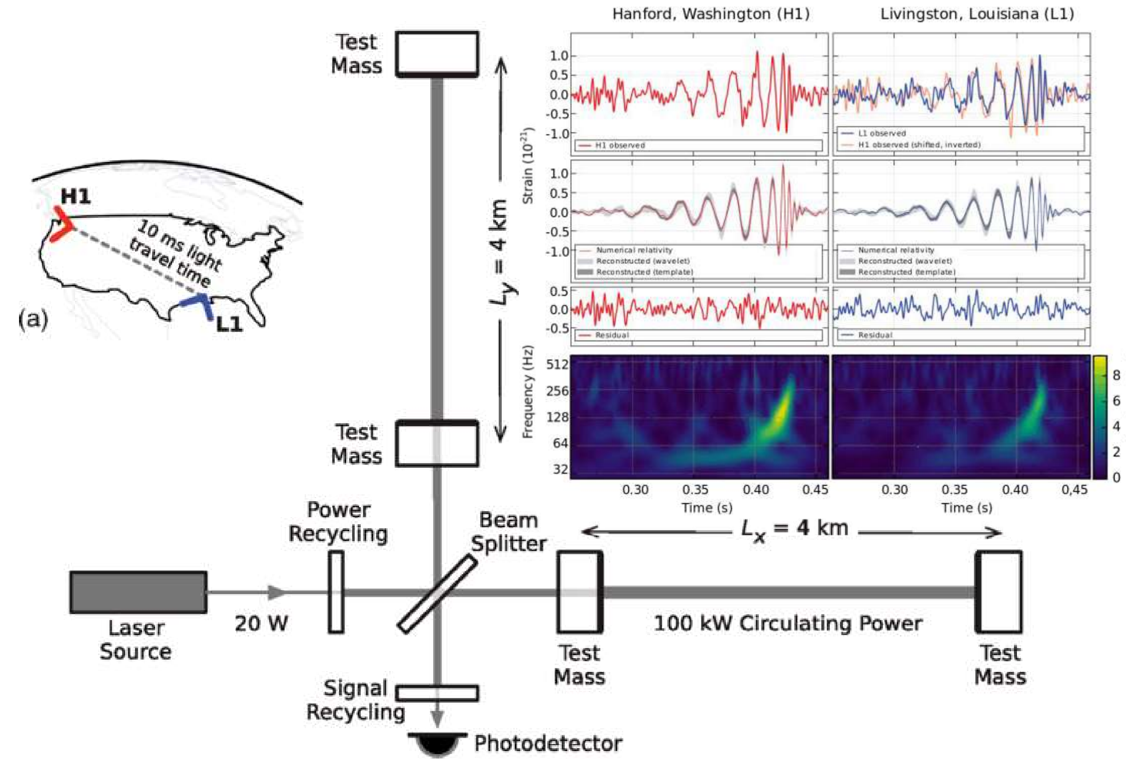
Interferometers

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



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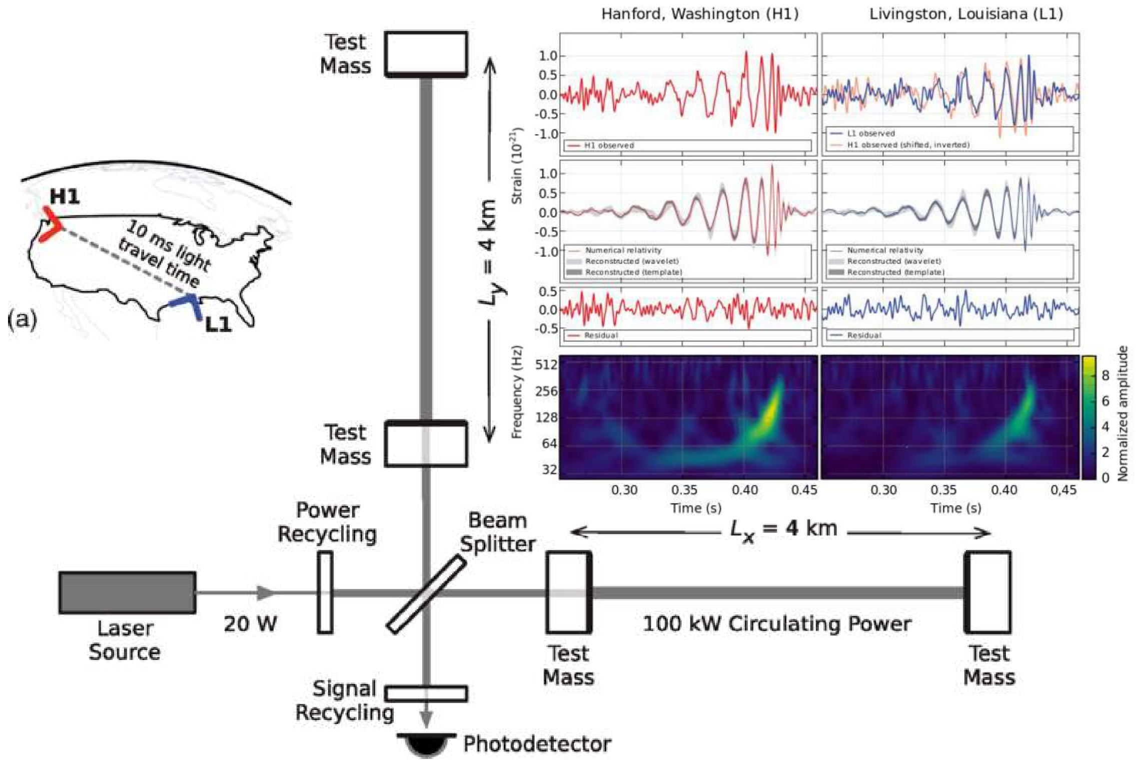

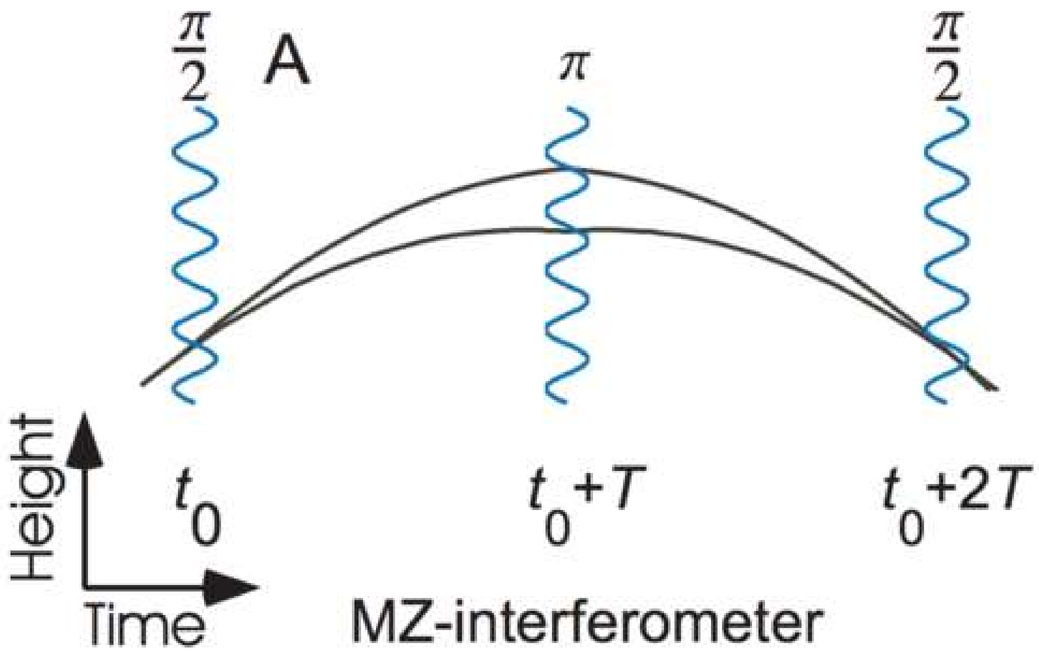

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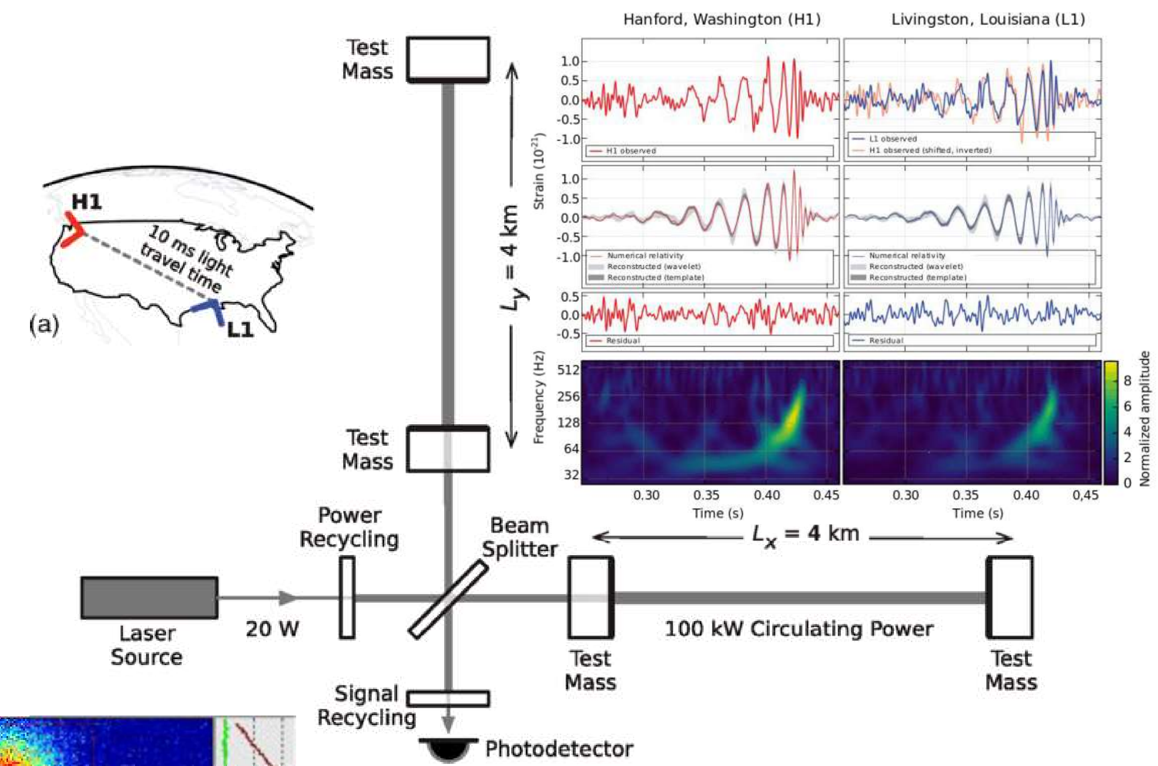

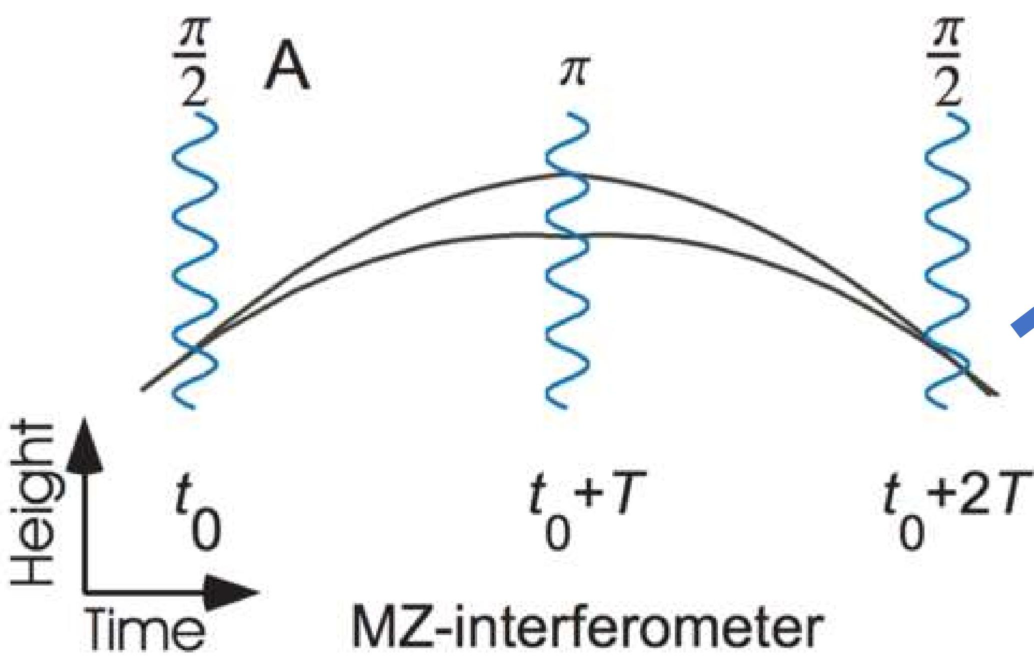

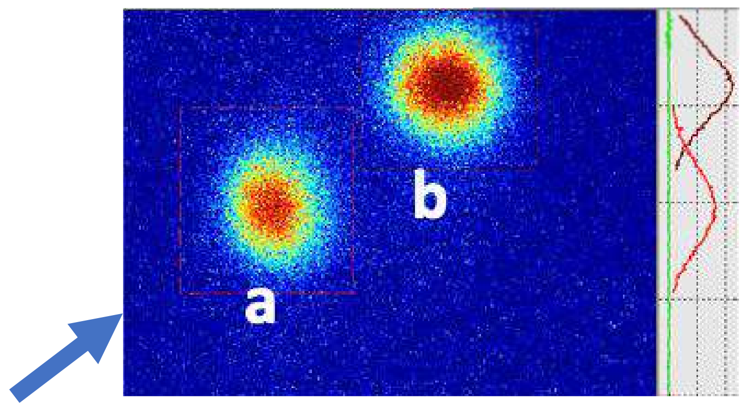

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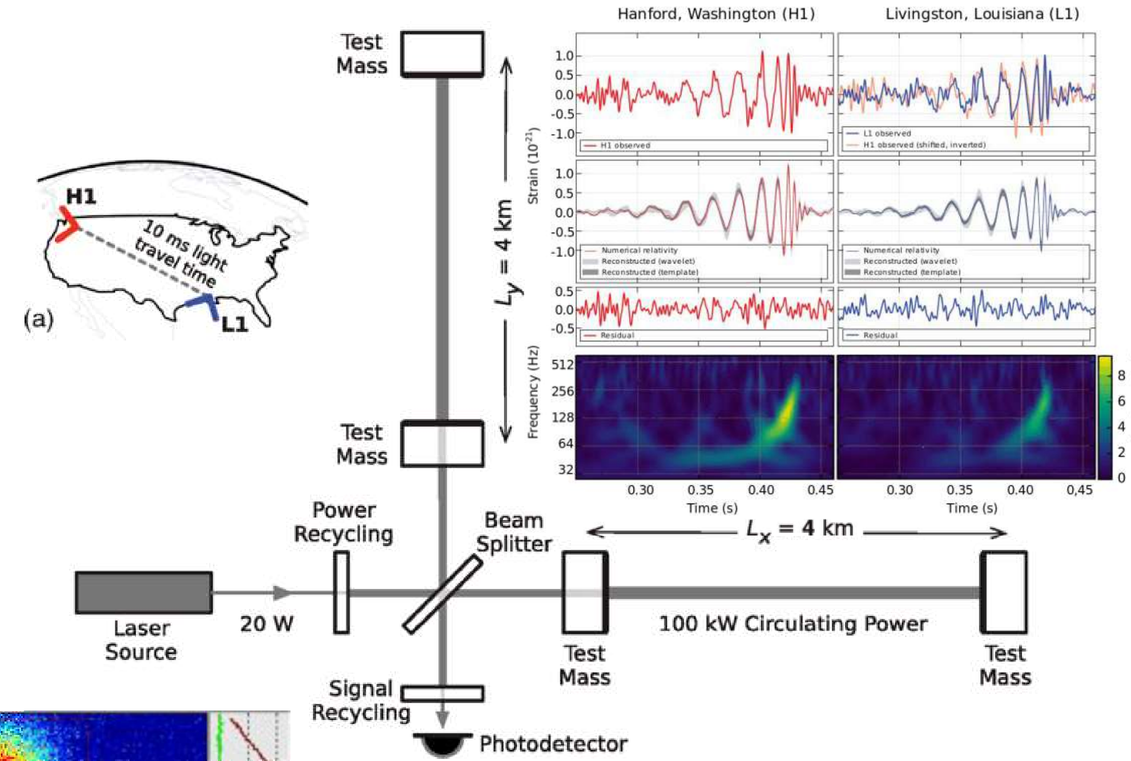
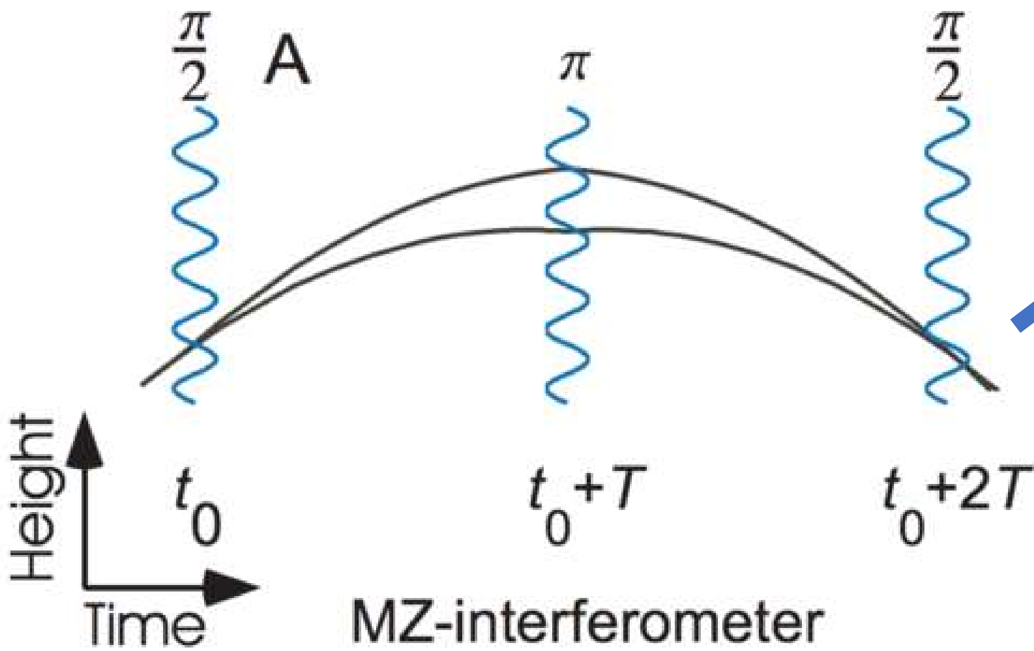
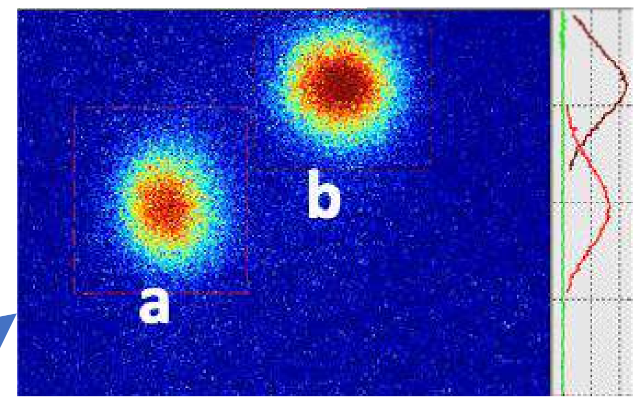
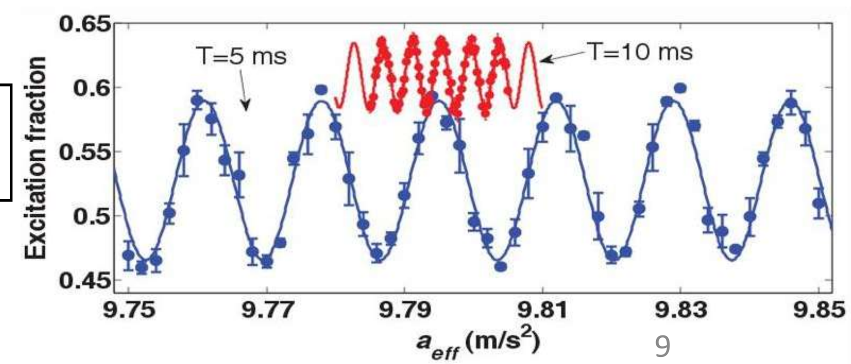






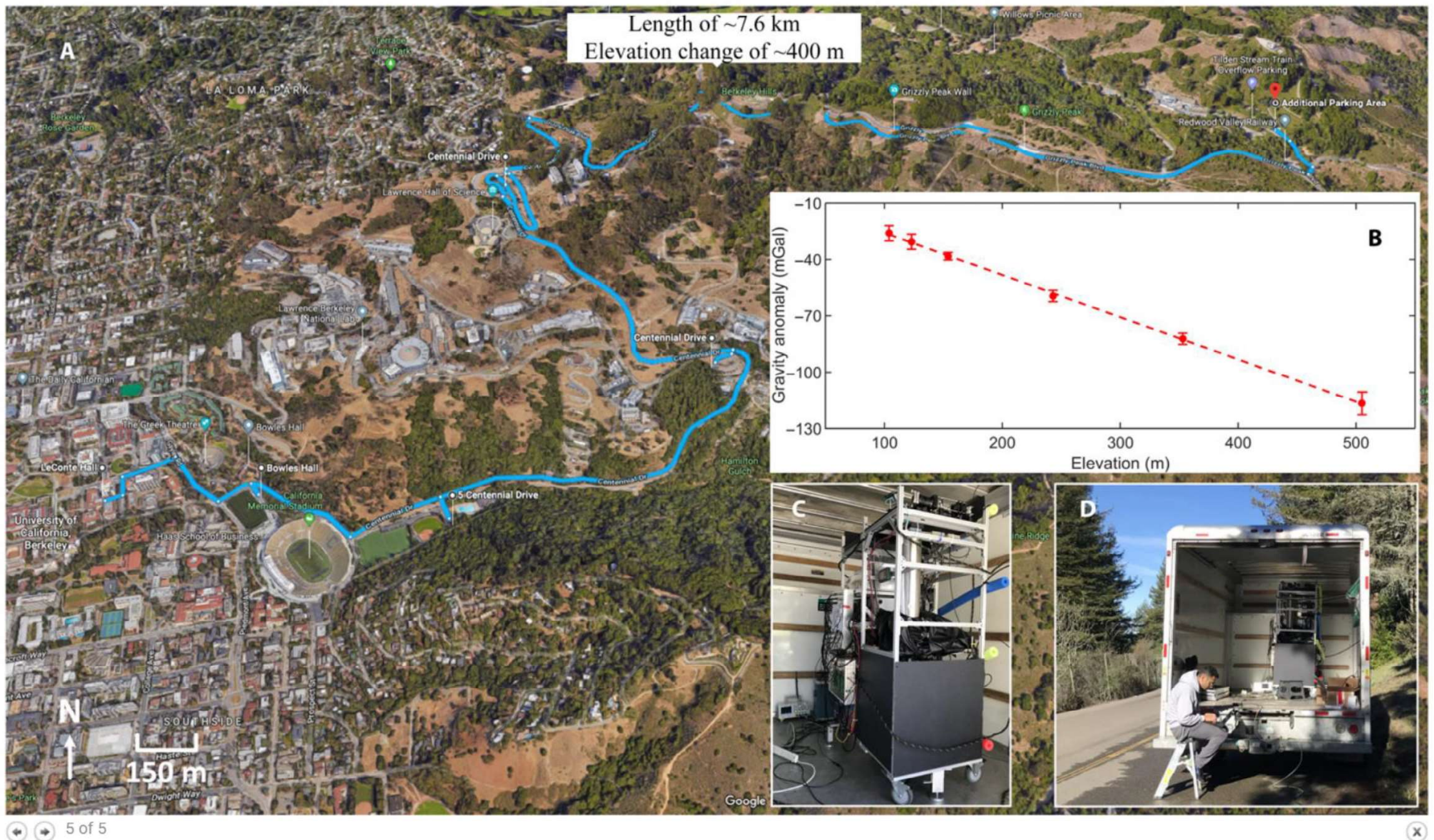
$$A = C \sin(\Delta\phi_{\text{laser}})$$

$$\Delta\phi_{\text{laser}} = \boldsymbol{k}\,\boldsymbol{g}\,T^2$$



Directions for atom interferometers

- **Measure local gravity,** geophysics, inertial sensing.



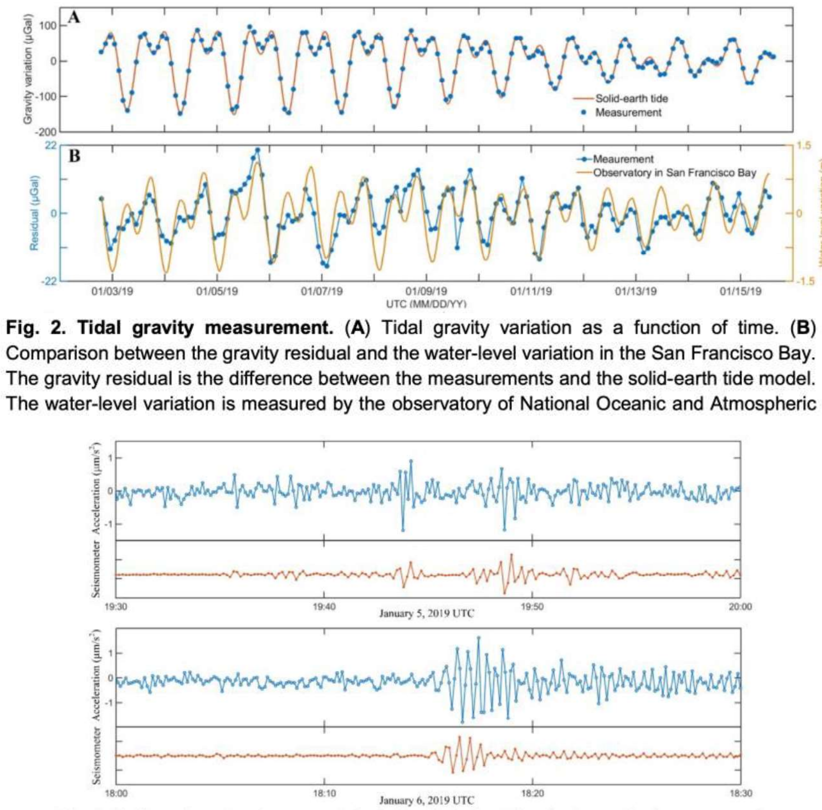
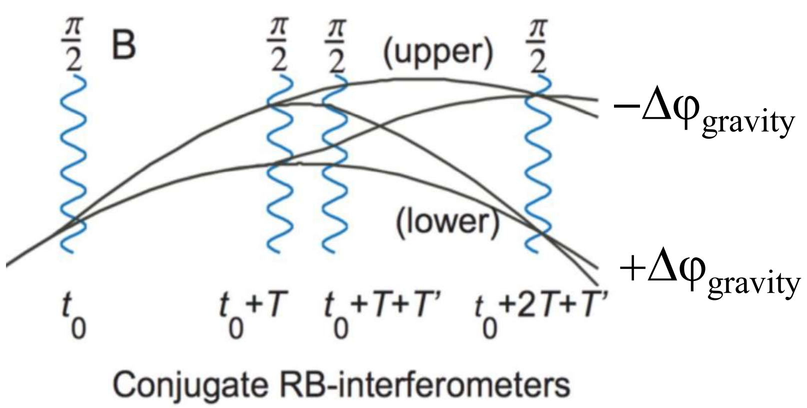


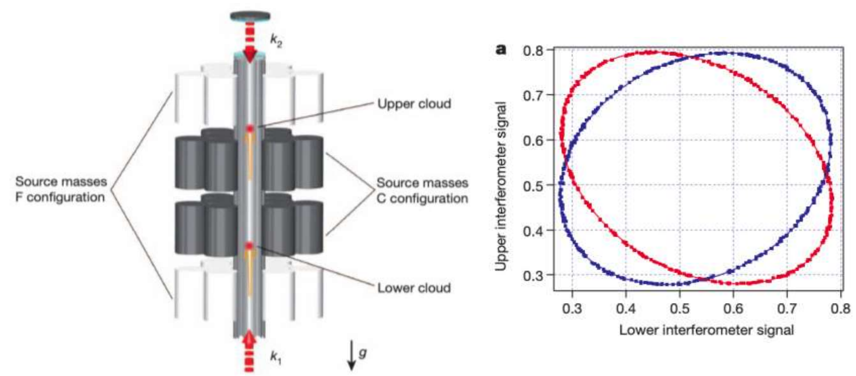
Fig. 2. Tidal gravity measurement. (**A**) Tidal gravity variation as a function of time. (**B**) Comparison between the gravity residual and the water-level variation in the San Francisco Bay. The gravity residual is the difference between the measurements and the solid-earth tide model. The water-level variation is measured by the observatory of National Oceanic and Atmospheric

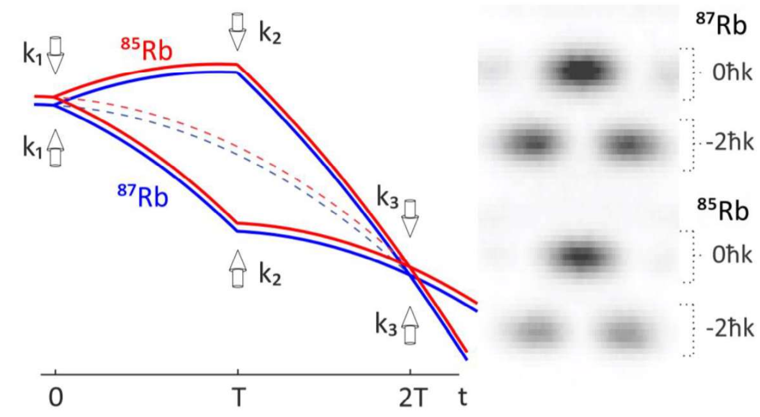
Fig. 3. Earthquake seismic waves detected in Berkeley. The atomic gravimeter measures the vertical acceleration of the seismic waves with an update rate of 0.13 Hz. The seismic signal is

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

Precision interferometry





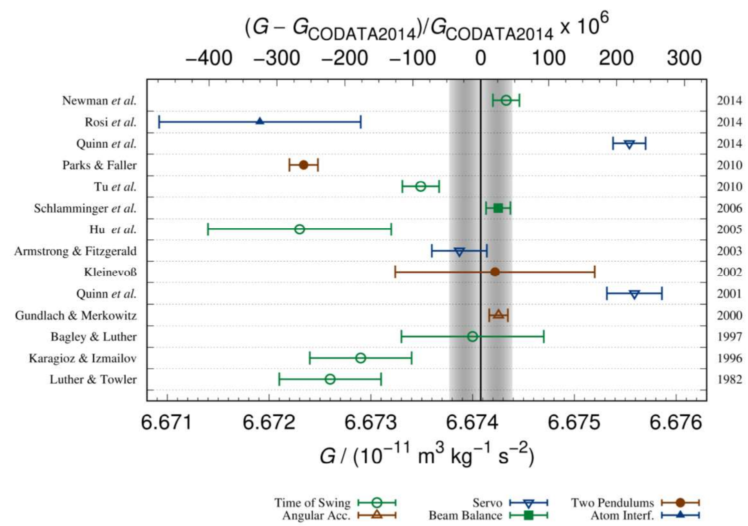


Measurement of the fine structure constant α

- Comparison between α and electron g-2 provides the most precise theory/experiment comparison in science at 0.2 ppb.

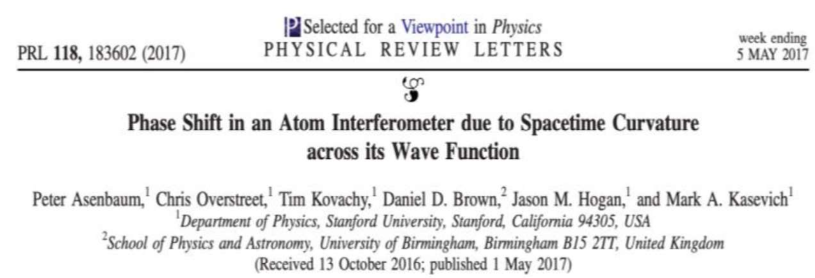
R. Parker, et. al., Science. 360, 191–195 (2018)

Measurement of the gravitational constant G



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

Testing GR and QM – equivalence principle


Selected for a Viewpoint in Physics

PRL 118, 183602 (2017) PHYSICAL REVIEW LETTERS week ending 5 MAY 2017

Phase Shift in an Atom Interferometer due to Spacetime Curvature across its Wave Function

Peter Asenbaum,[1] Chris Overstreet,[1] Tim Kovachy,[1] Daniel D. Brown,[2] Jason M. Hogan,[1] and Mark A. Kasevich[1]

[1]Department of Physics, Stanford University, Stanford, California 94305, USA

[2]School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, United Kingdom

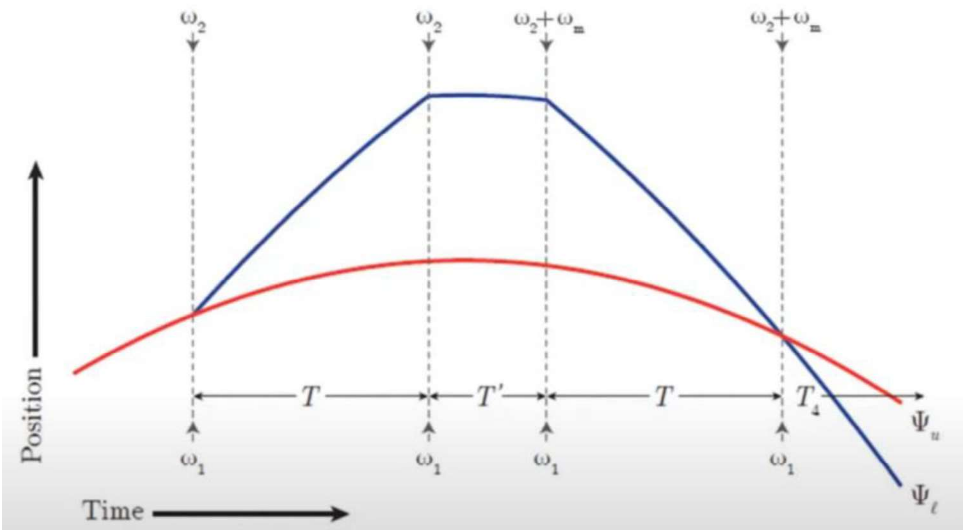
(Received 13 October 2016; published 1 May 2017)

P. Asenbaum, et. al., PRL. 118, 183602 (2017)
C. Overstreet, et. al., PRL. 120, 183604 (2018)
C. Overstreet, et. al., ARXIV:2005.11624V1 (2020)

Fine structure constant α

- Measure photon-kick momentum to extract "strength" of electromagnetic interaction.

$$\alpha^2 = \frac{2R_\infty}{c}\frac{m_{\rm At}}{m_e}\frac{h}{m_{\rm At}}$$



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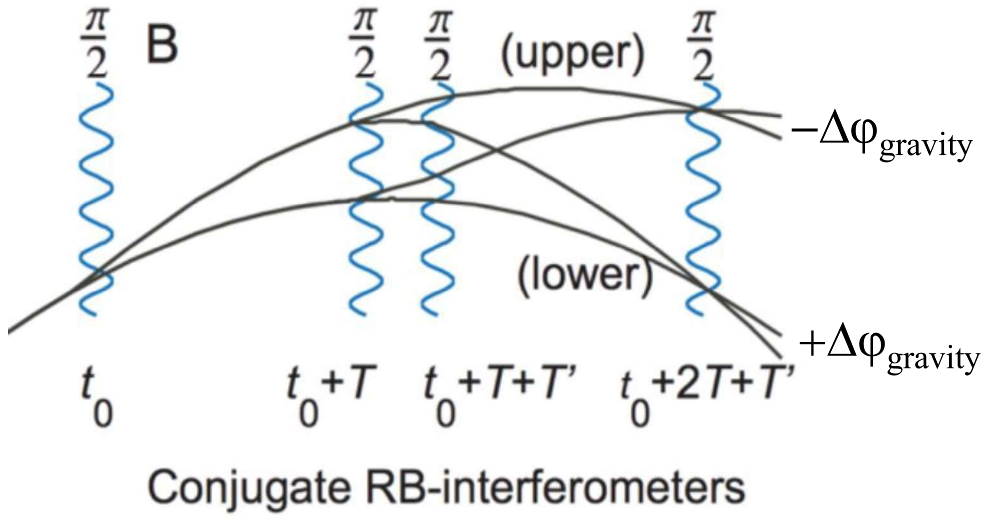

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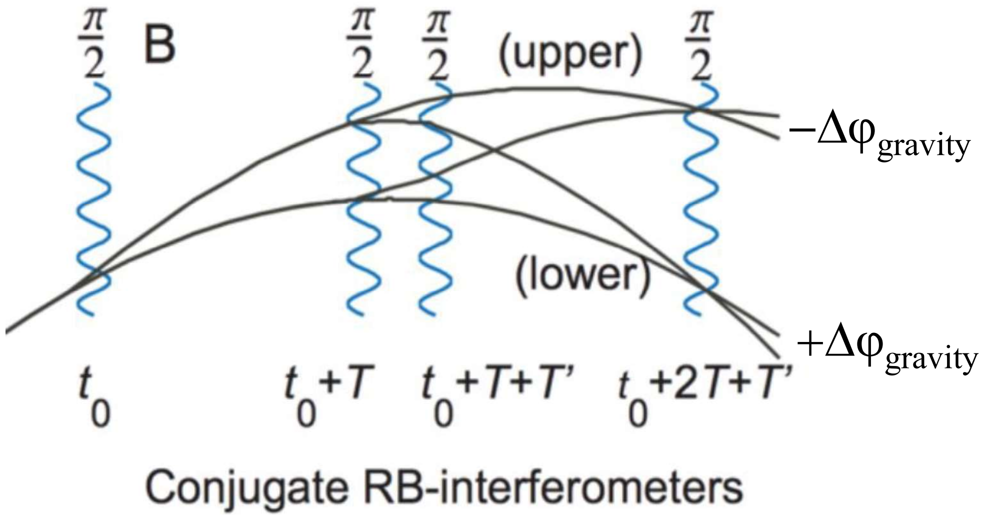

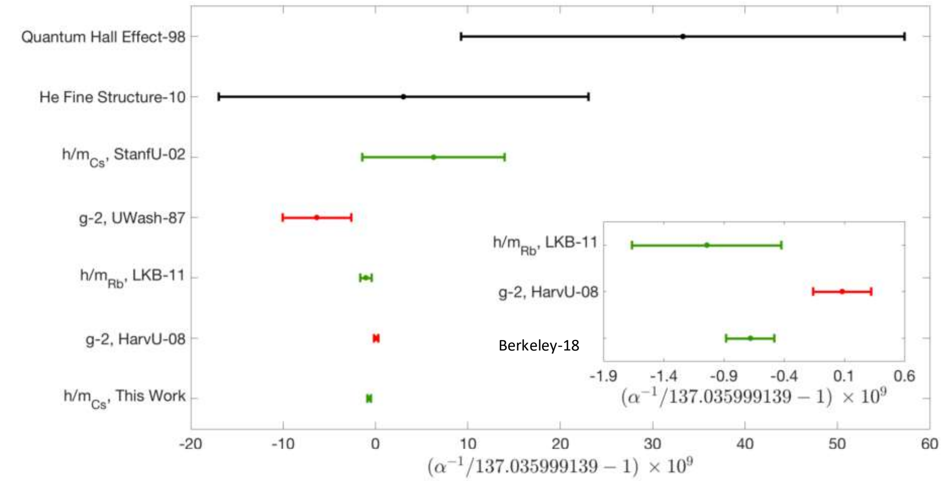

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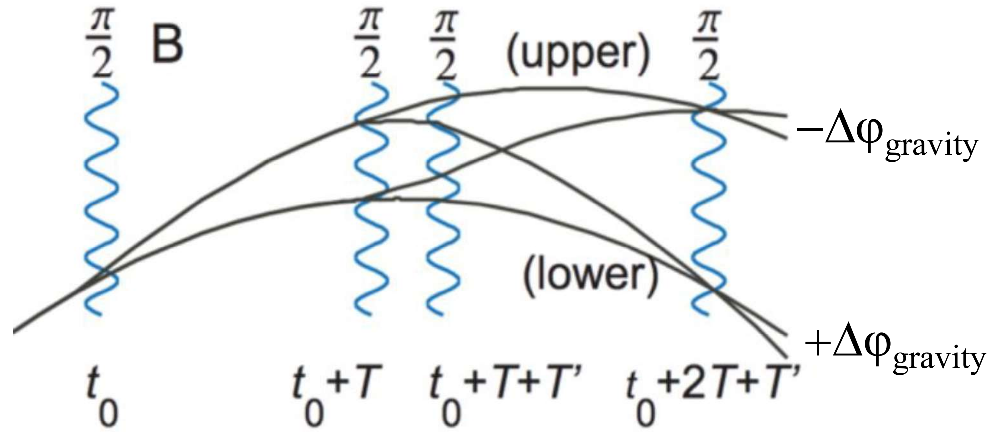
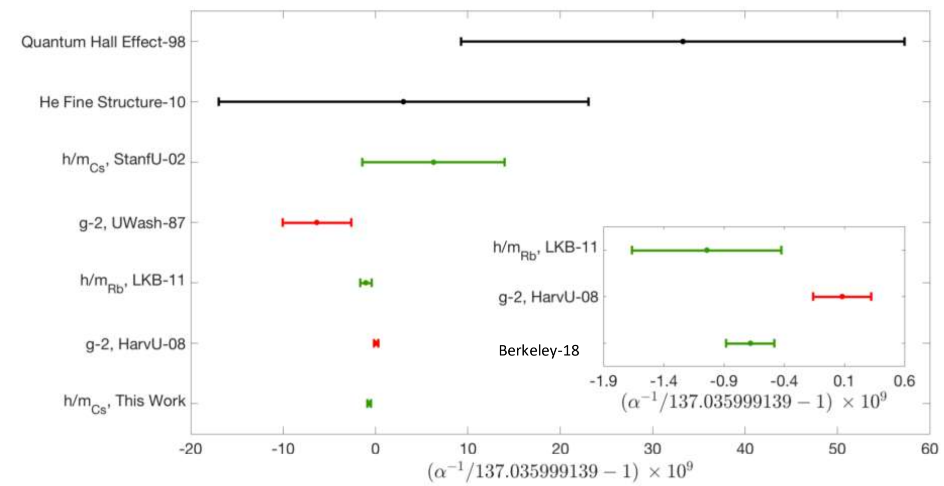
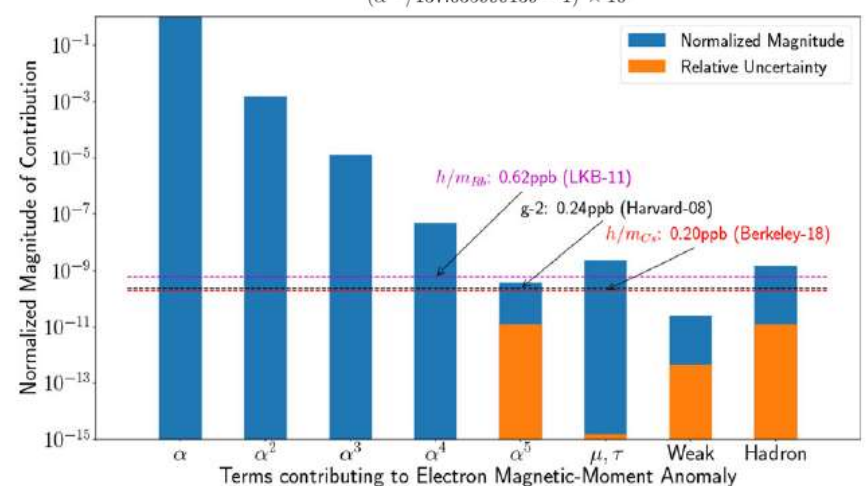
- Leading α measurements currently from atom interferometry (Berkeley, LKB Paris) -> 0.2 ppb.
- Comparison between α and electron g-2 provides the most precise theory/experiment test in science.
- Probing QED, weak, hadronic interactions, new particles.



Conjugate RB-interferometers





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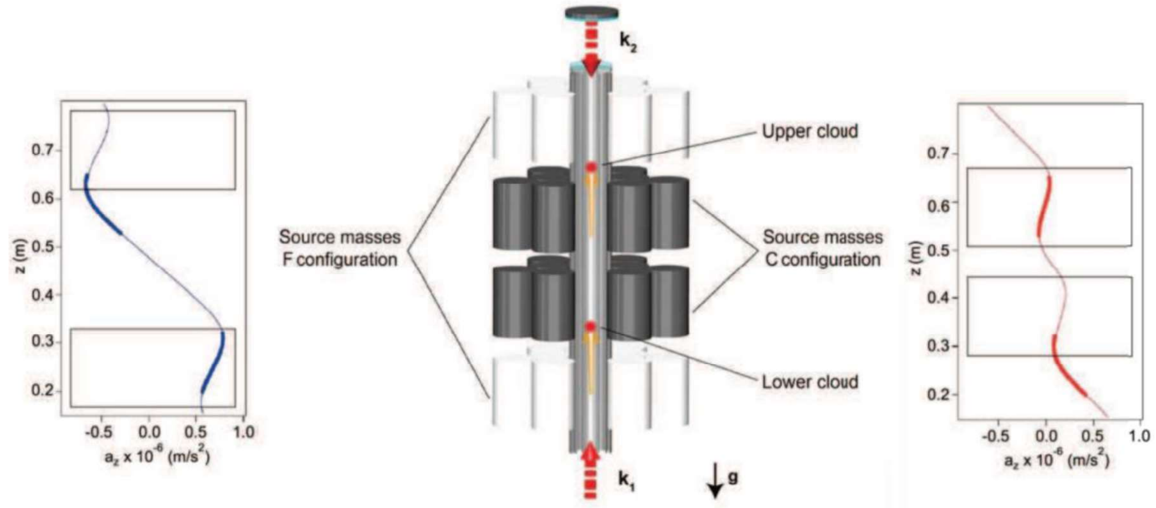
Gravitational constant G



- Experimental configuration of moving masses cancels Earth's gravity, other systematics. Requires precise knowledge of experiment geometry.

J. B. Fixler, et. al., Atom interferometer measurement of the Newtonian constant of gravity. Science, 315:74 (2007).
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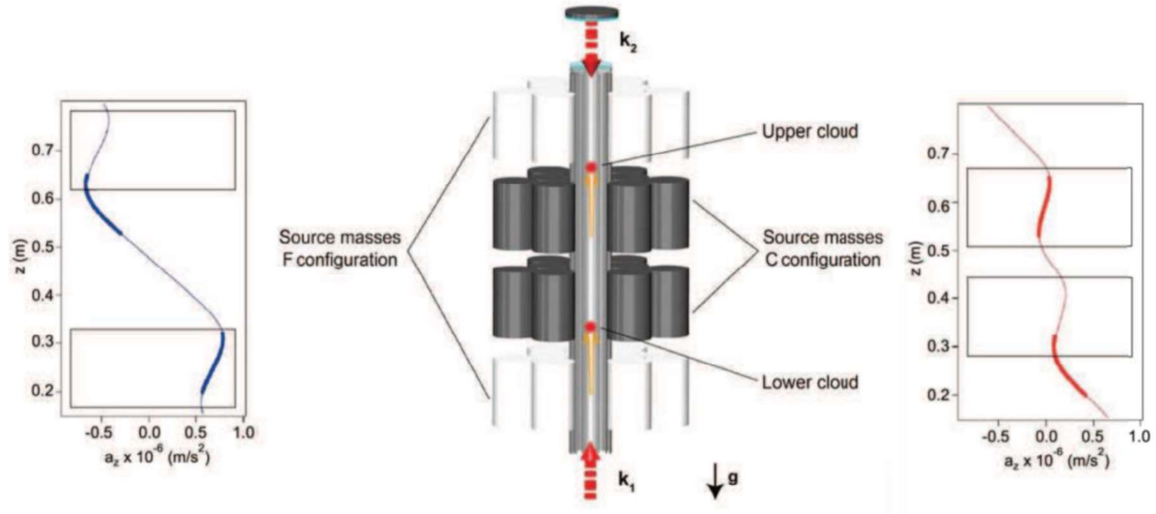
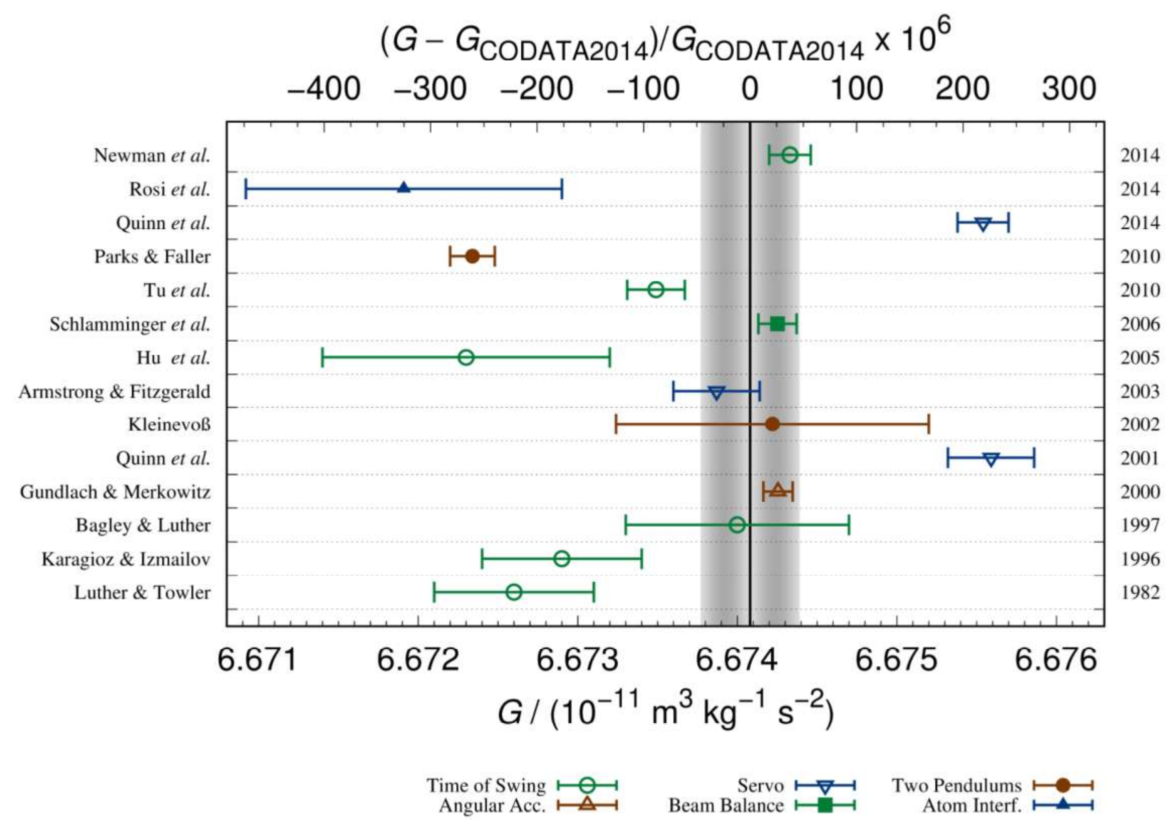
Gravitational constant G

- Experimental configuration of moving masses cancels Earth's gravity, other systematics. Requires precise knowledge of experiment geometry.
- 200 years of history, weakness of gravity in comparison to EM makes it challenging to probe experimentally.
- New method to measure an old constant important for controlling systematics.





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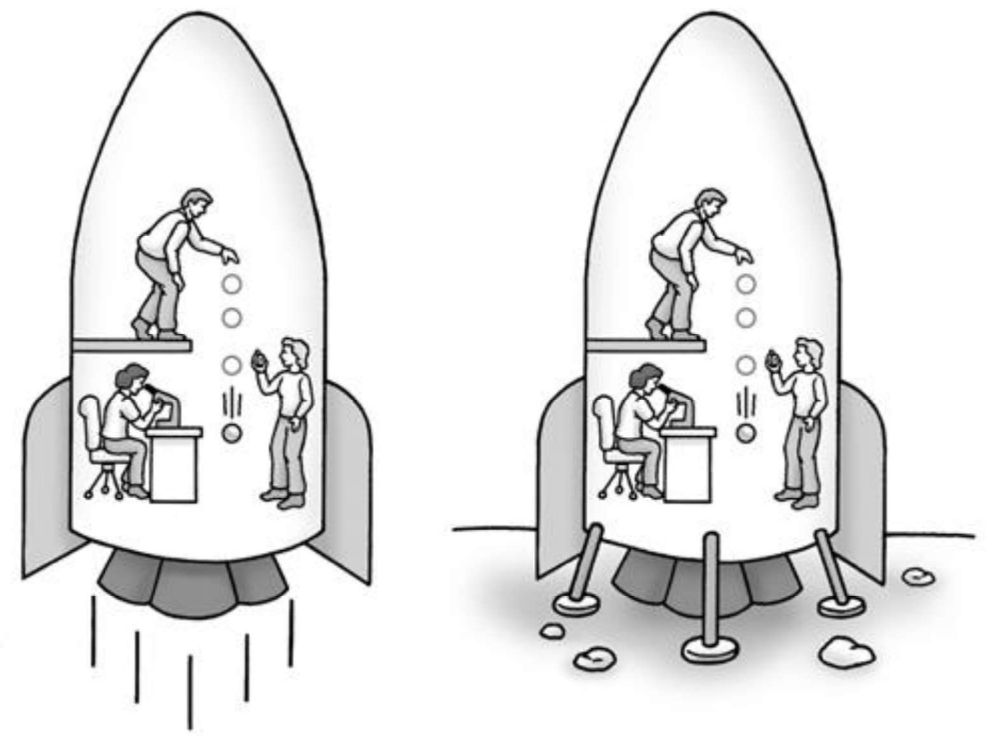
Weak equivalence principle

- Equivalence of gravitational and inertial mass.
- Measure the difference in free-fall acceleration between different species Eotvos parameter.

$$\eta = 2\left|\frac{a_1 - a_2}{a_1 + a_2}\right|.$$



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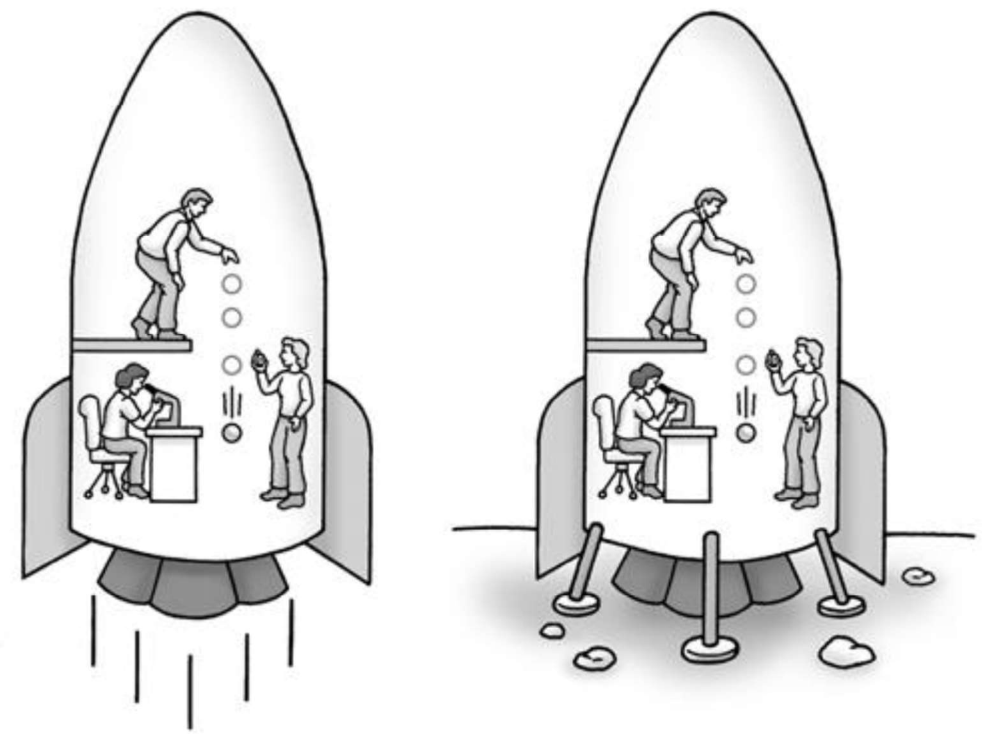
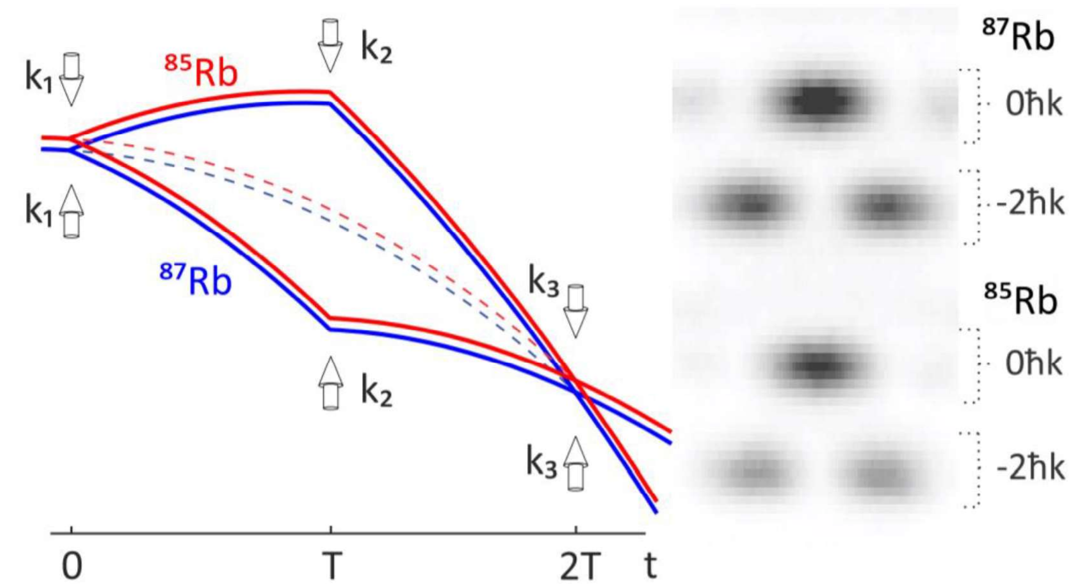
- Recently, experiments with different Rb isotopes reached 10^{-12} precision, getting competitive with classical Earth-based methods (torsion balance 10^{-13}) and space-based (MICROSCOPE mission 10^{-14}).
- Proposed tests with different atoms and anti-matter.

Peter Asenbaum et. al., Phys. Rev. Lett. 125, 191101 (2014)
Peter Asenbaum et. al., Phys. Rev. Lett. 125, 191101 (2020)
Paul Hamilton et. al., Phys. Rev. Lett., 112(12):121102–5, (2014).





Increasing free-fall time

$$z = \frac{1}{2} g\, T^2$$

Stanford 10m fountain, T ~2 seconds.

Hannover, 10m fountain (under construction)

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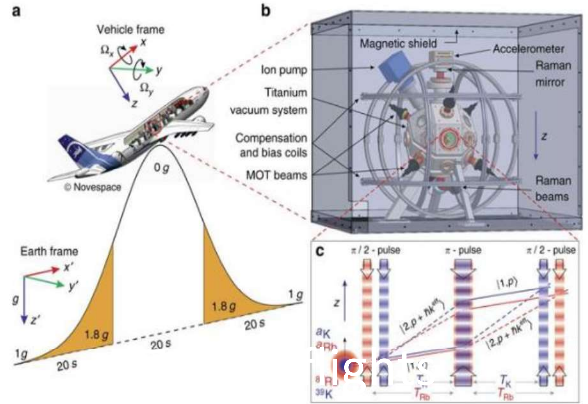
Dual matter-wave inertial sensors in weightlessness

Brynle Barrett, Laura Antoni-Micollier, Laure Chichet, Baptiste Battelier, Thomas Lévèque, Arnaud Landragin & Philippe Bouyer

Nature Communications 7, Article number: 13786 (2016) | Download Citation

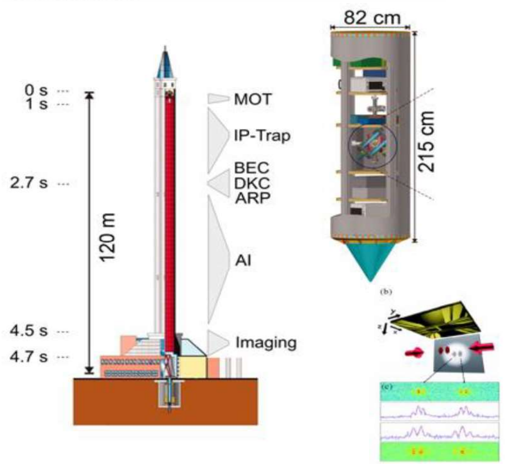
Figure 1: Dual matter-wave sensors onboard the Novespace Zero-G aircraft.



REPORT

Bose-Einstein Condensation in Microgravity

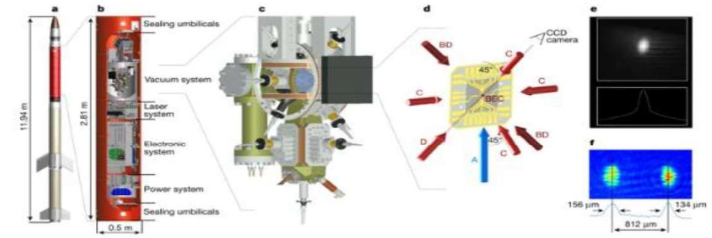
T. van Zoest, N. Gaaloul, Y. Singh, H. Ahlers, W. Herr, S. T. Seidel, W. Ertmer, E. Rasel, M. Eckart



Space-borne Bose–Einstein condensation for precision interferometry

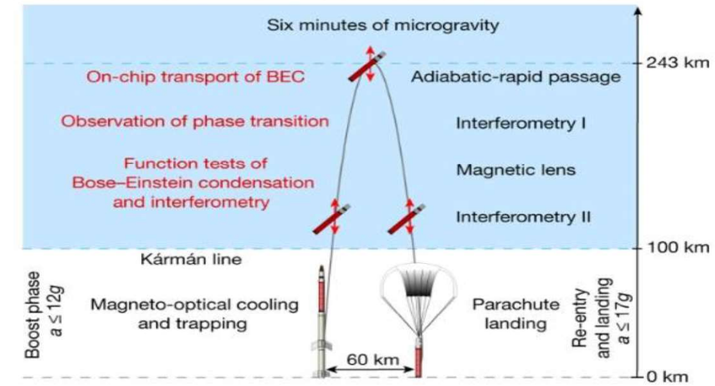
Dennis Becker, Maike D. Lachmann, [...] Ernst M. Rasel

Nature **562**, 391–395 (2018) | Download Citation



a–d, The rocket (**a**) carried the payload (**b**), including the vacuum system (**c**) that houses the atom chip (**d**), into space. On the atom chip, a magneto-optical trap

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



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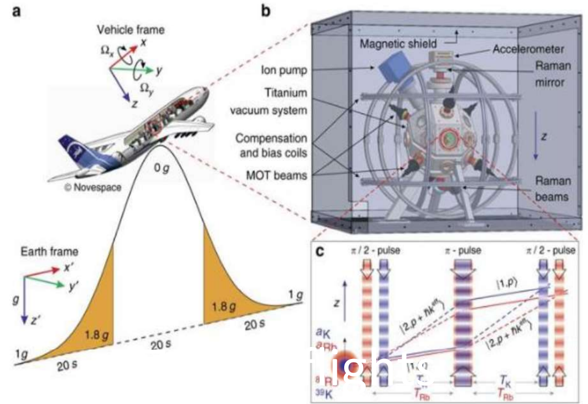

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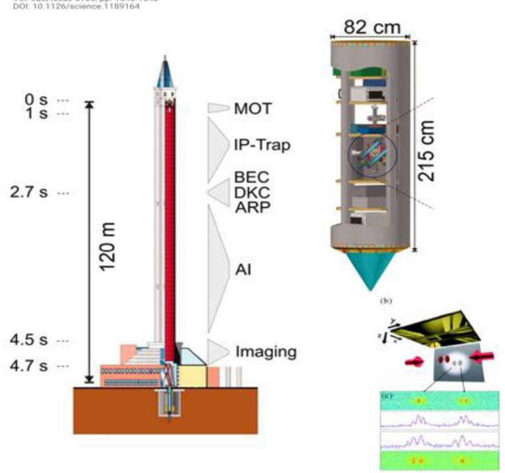

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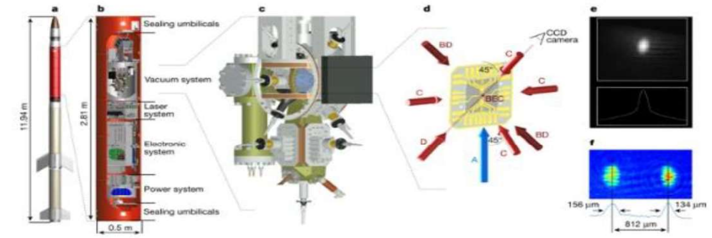

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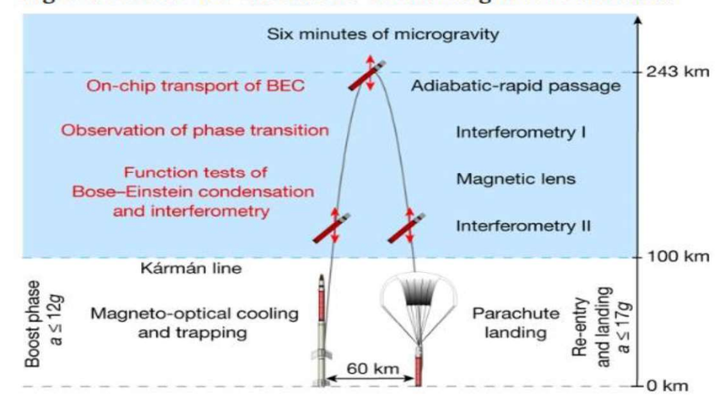
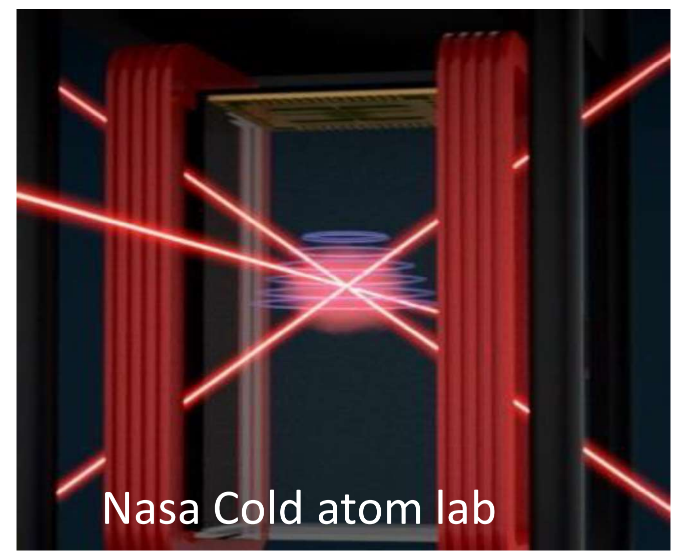
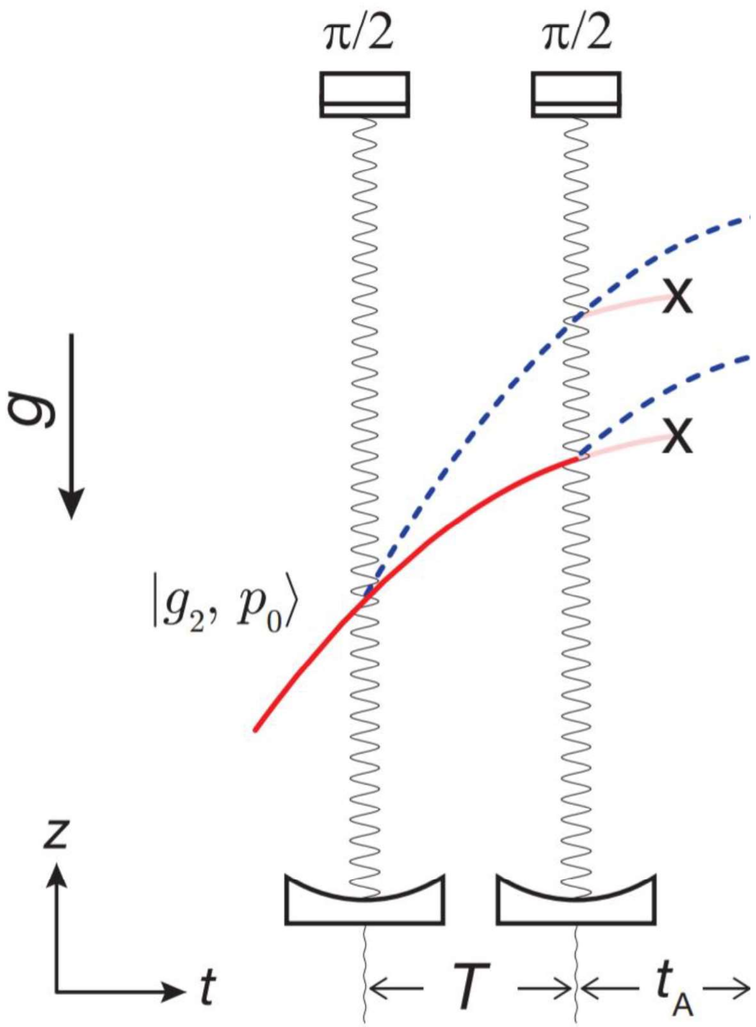




Atom interferometer in an optical lattice



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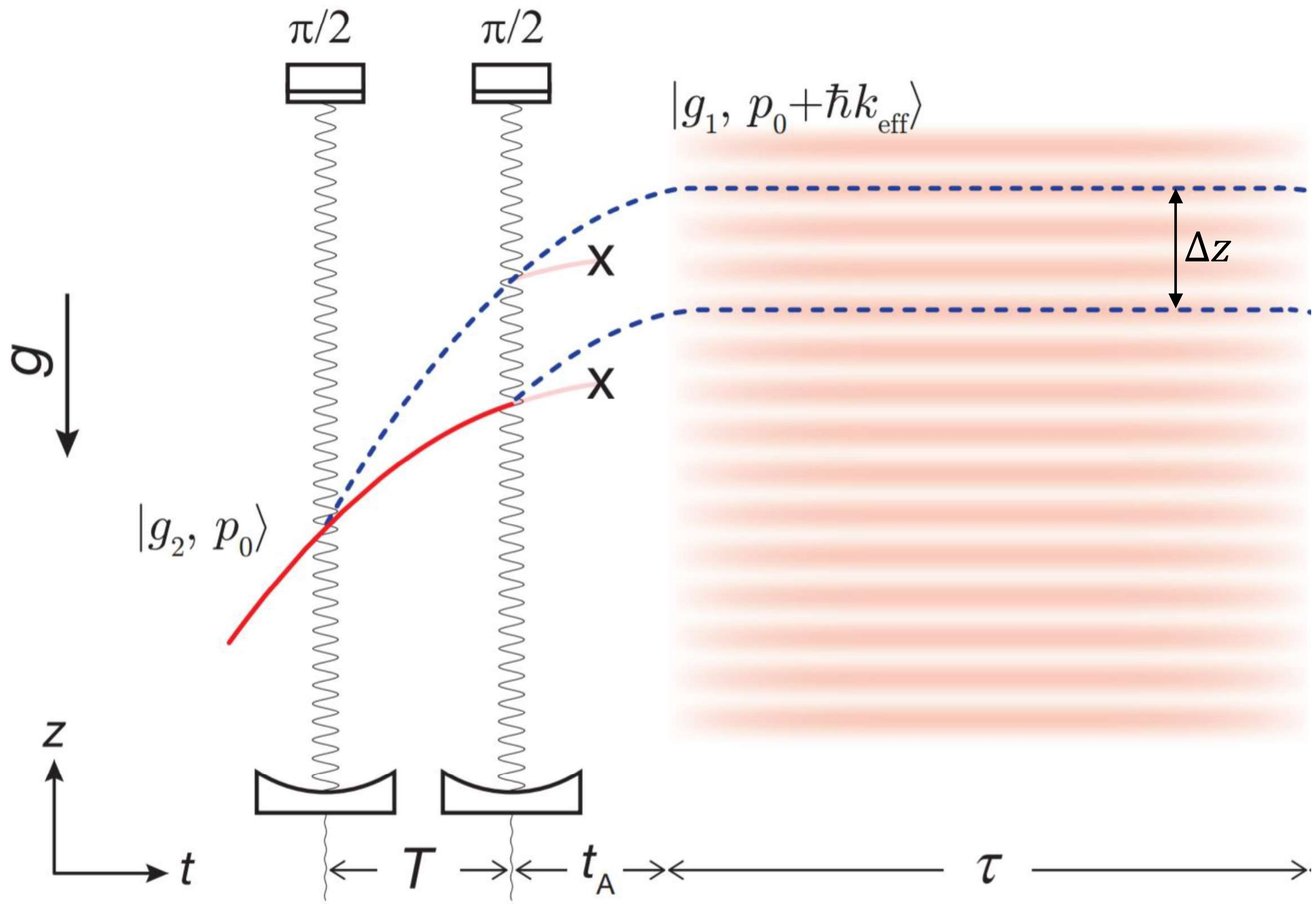

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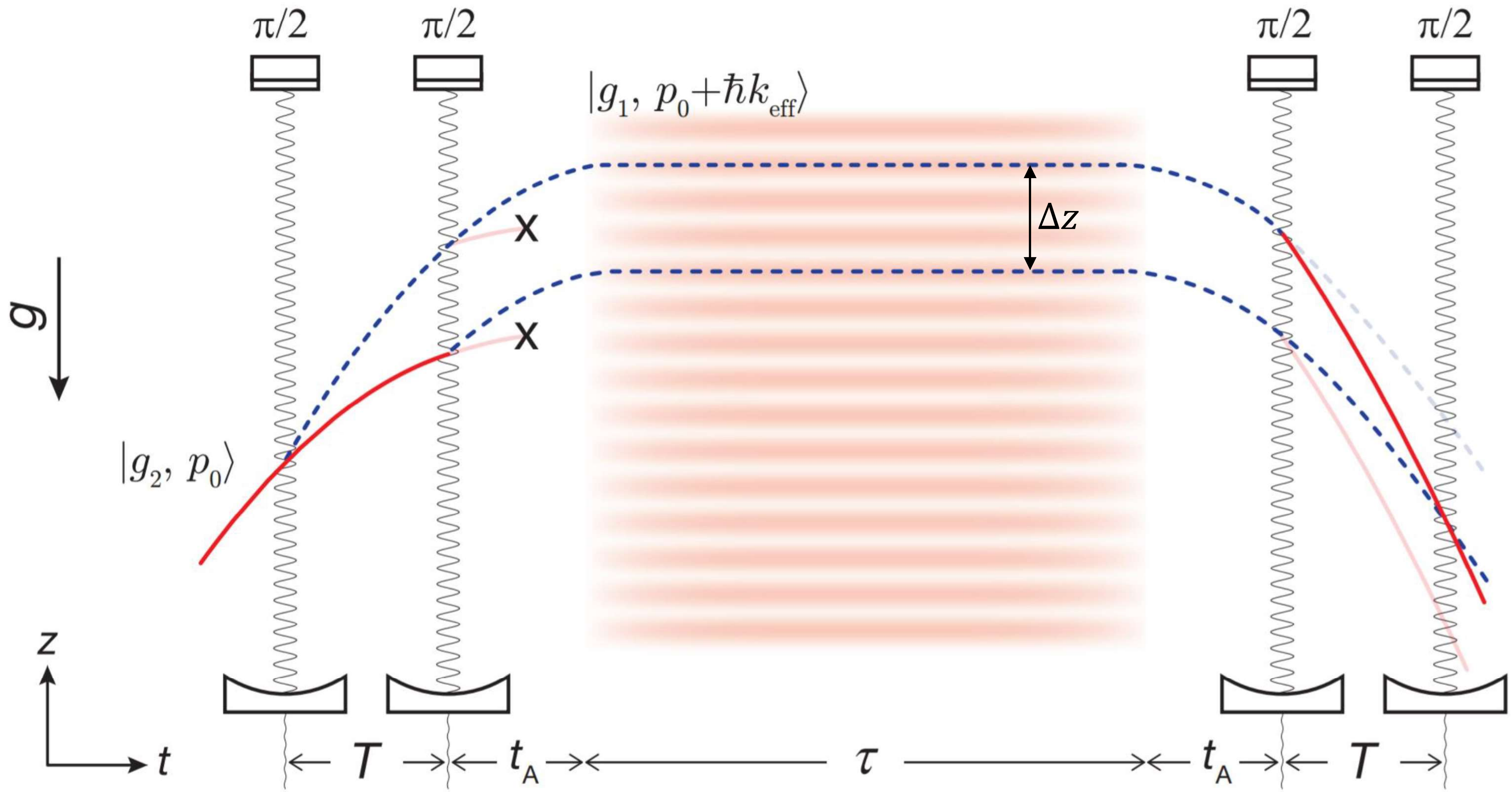

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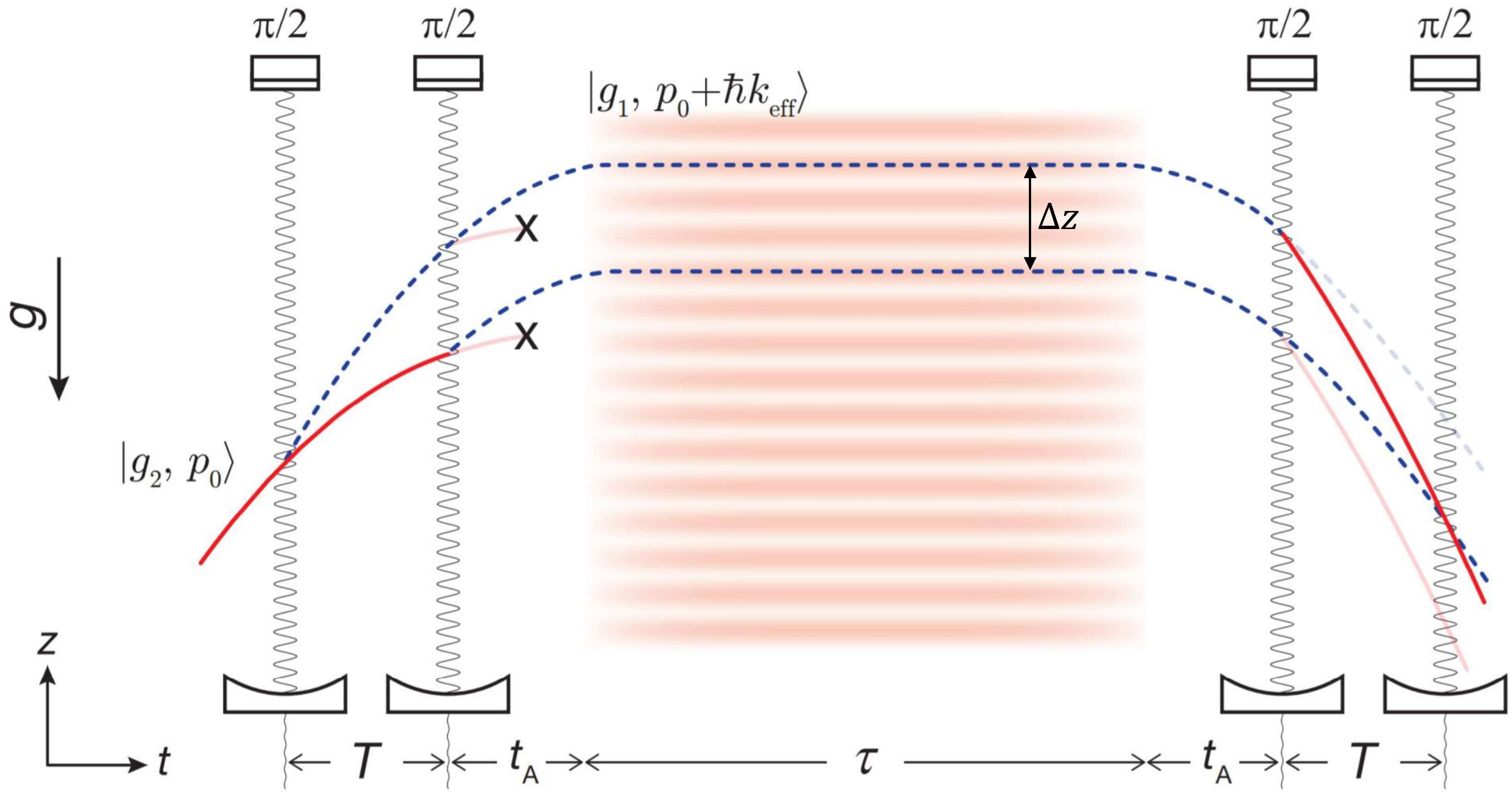
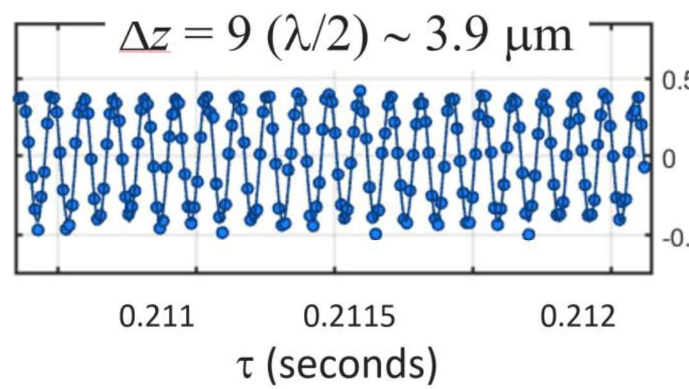
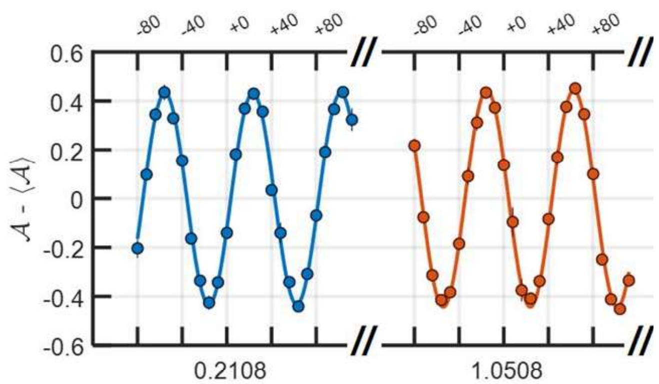


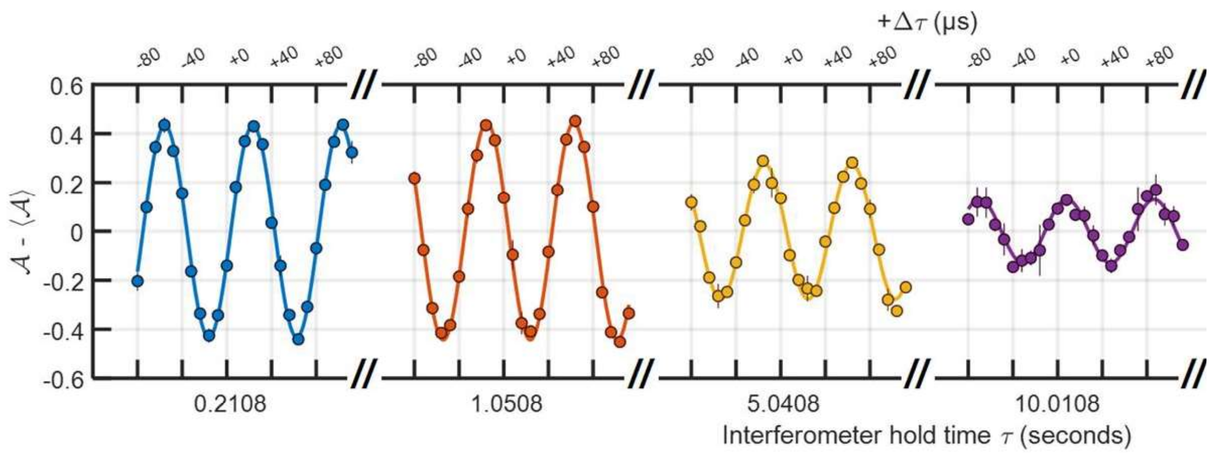
$$\Delta\phi_{\text{free}} = \frac{1}{\hbar}\int L\,dt$$
$$= \frac{mg\Delta z}{\hbar}\tau$$
$$\approx kgT\tau$$



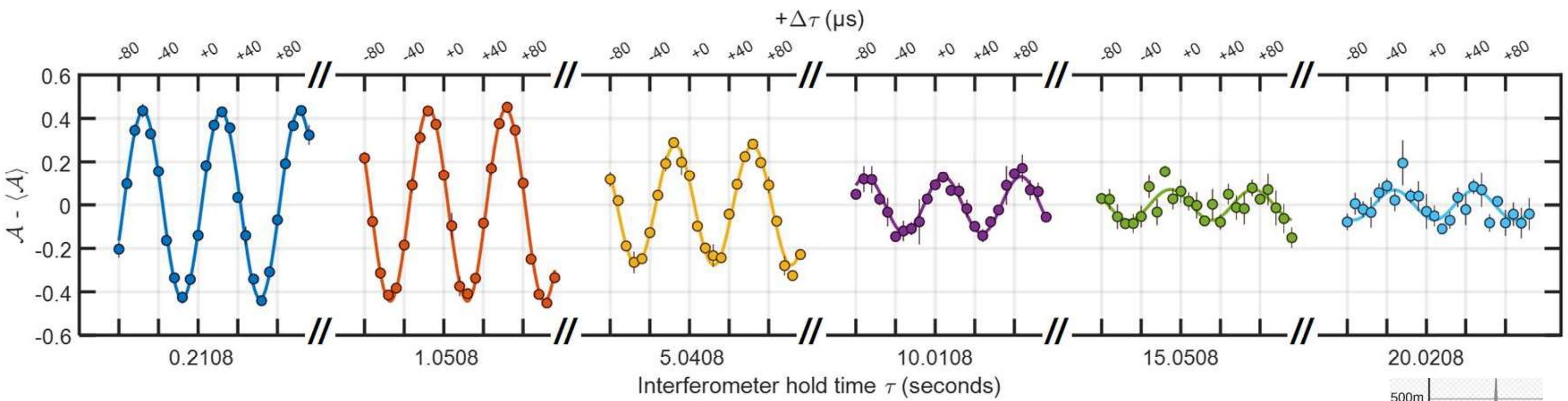
20 seconds coherence time



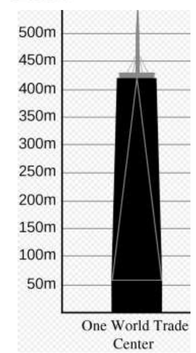
20 seconds coherence time



20 seconds coherence time



- In free-fall, would require 500 m tower.



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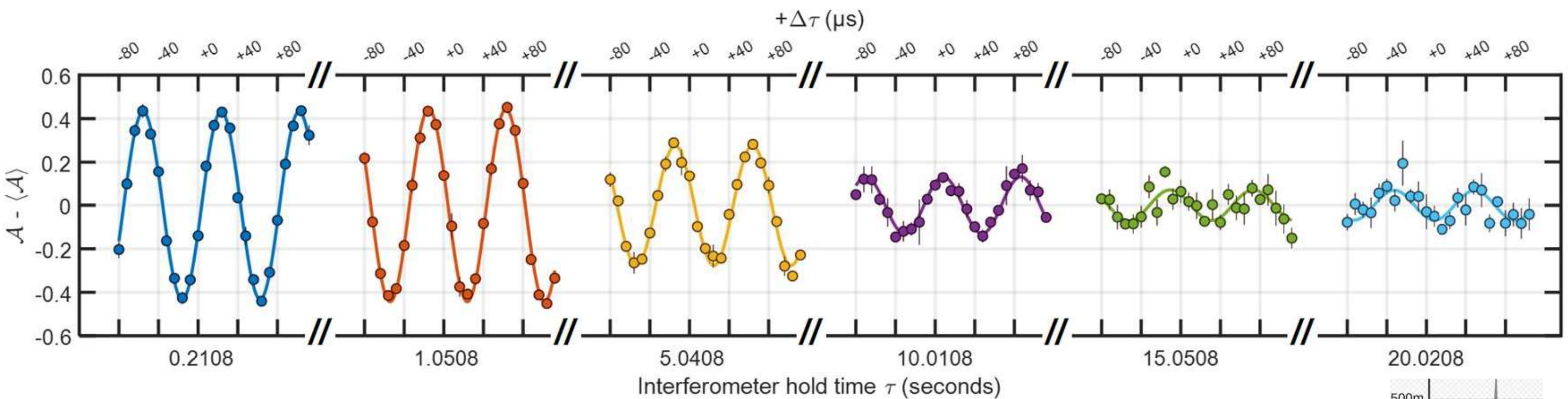

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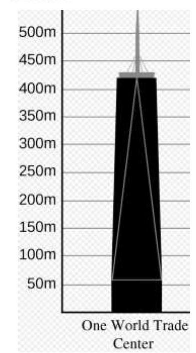
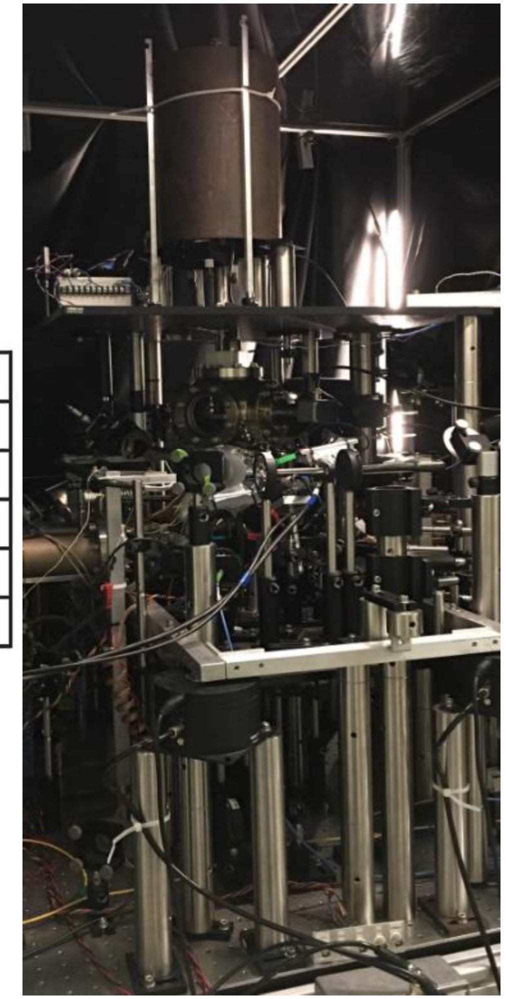
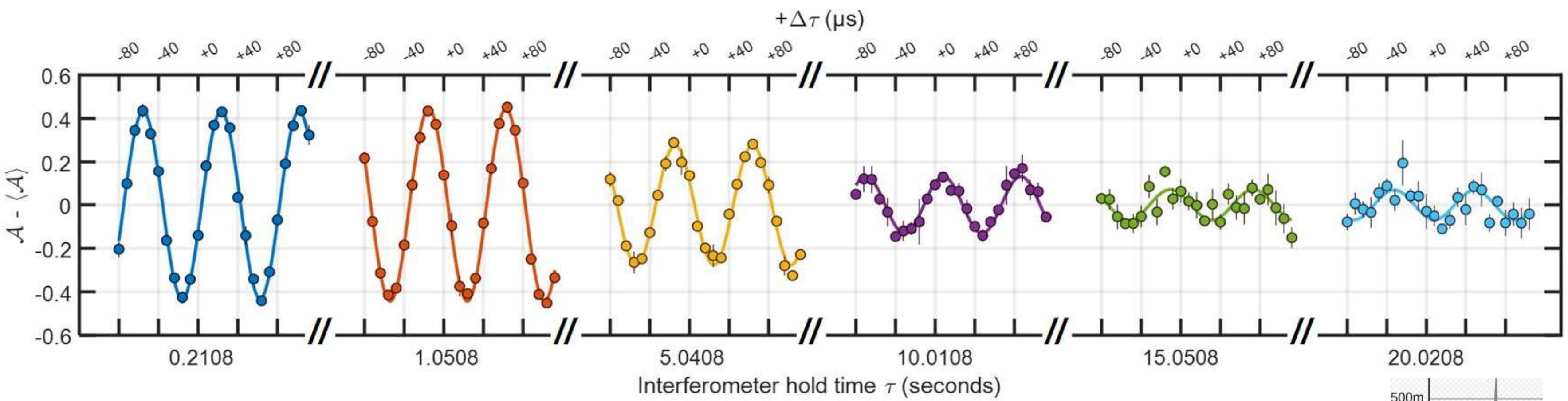




1 m

20 seconds coherence time

- Takes advantage of low-distortion wavefronts from optical cavity.



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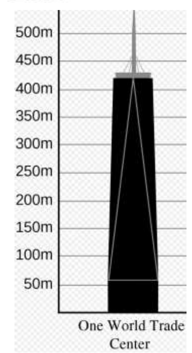

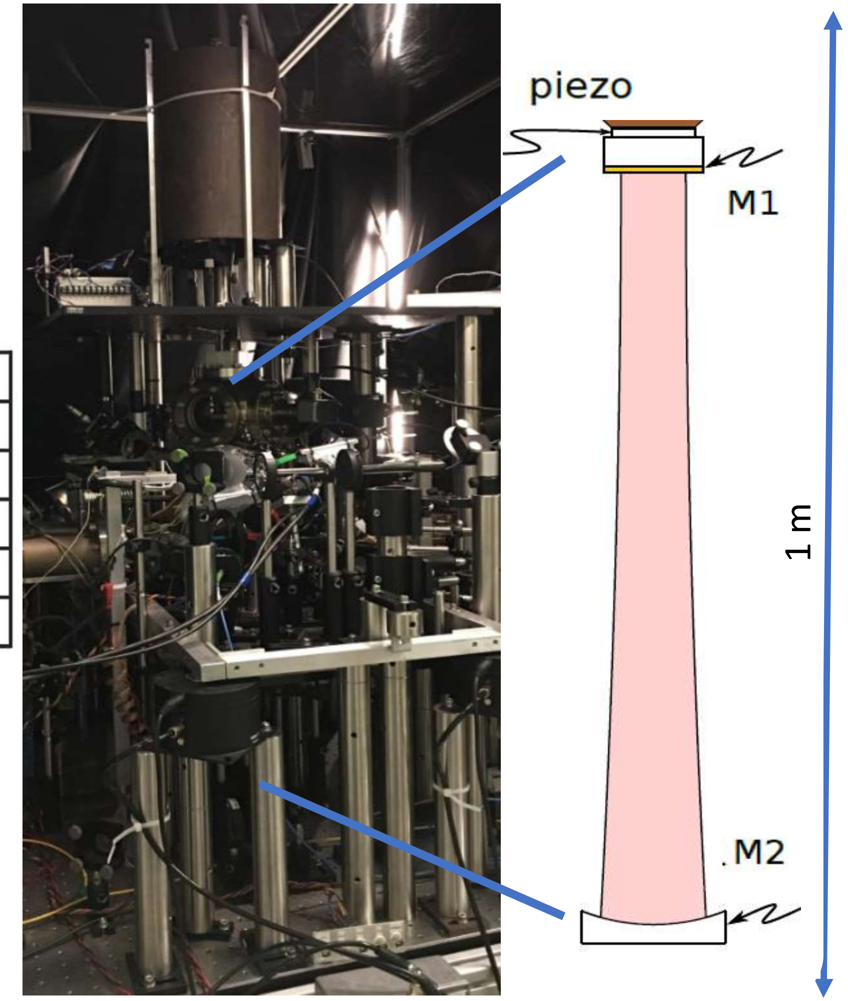

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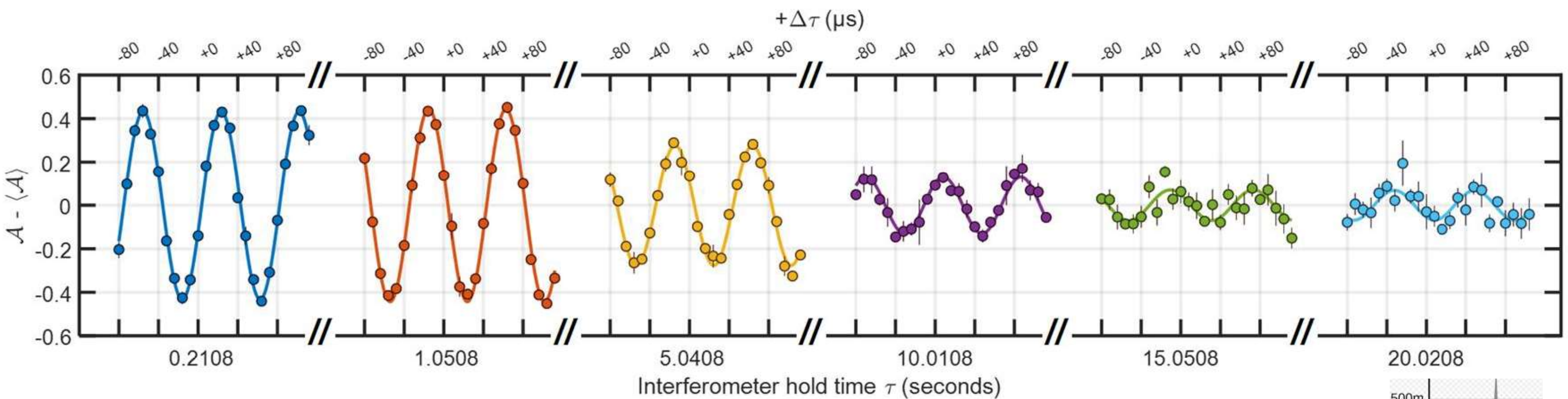

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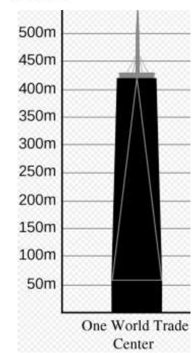
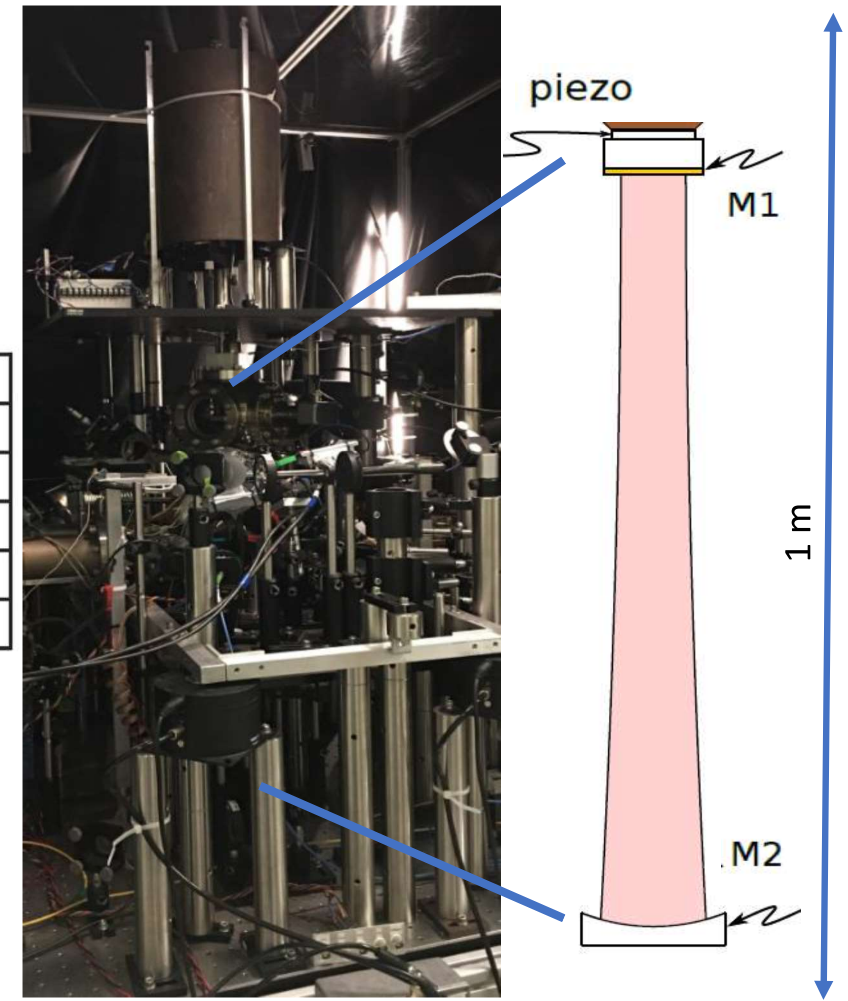
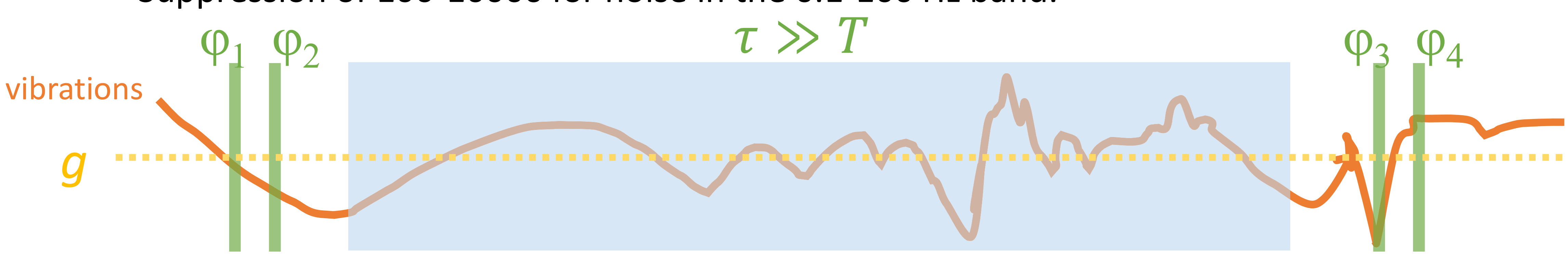




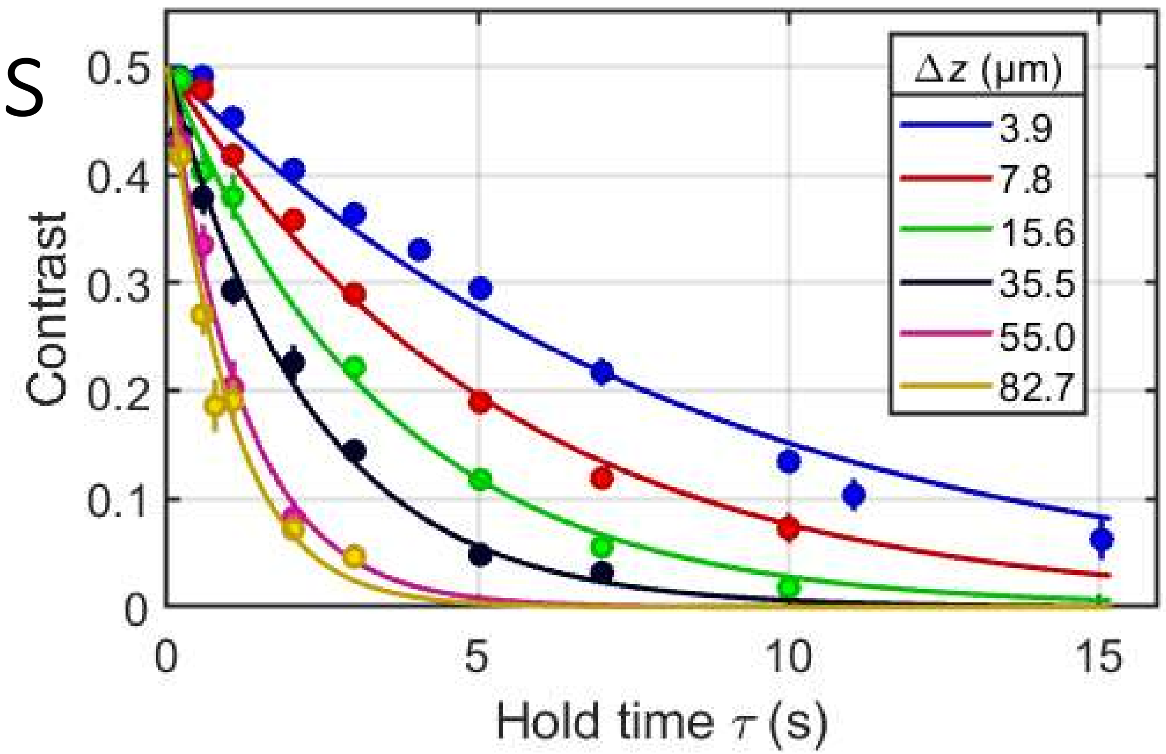
Vibration immunity

- Long hold time averages out vibration noise.
- Suppression of 100-10000 for noise in the 0.1-100 Hz band.



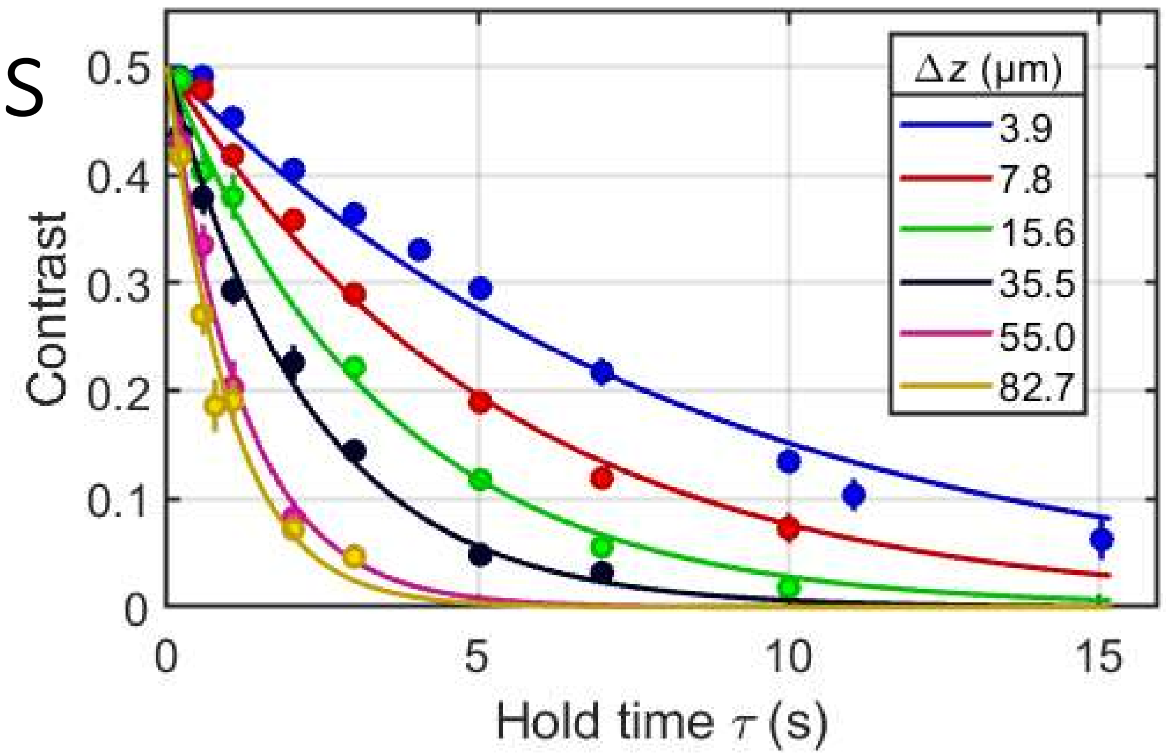
Contrast loss and solutions

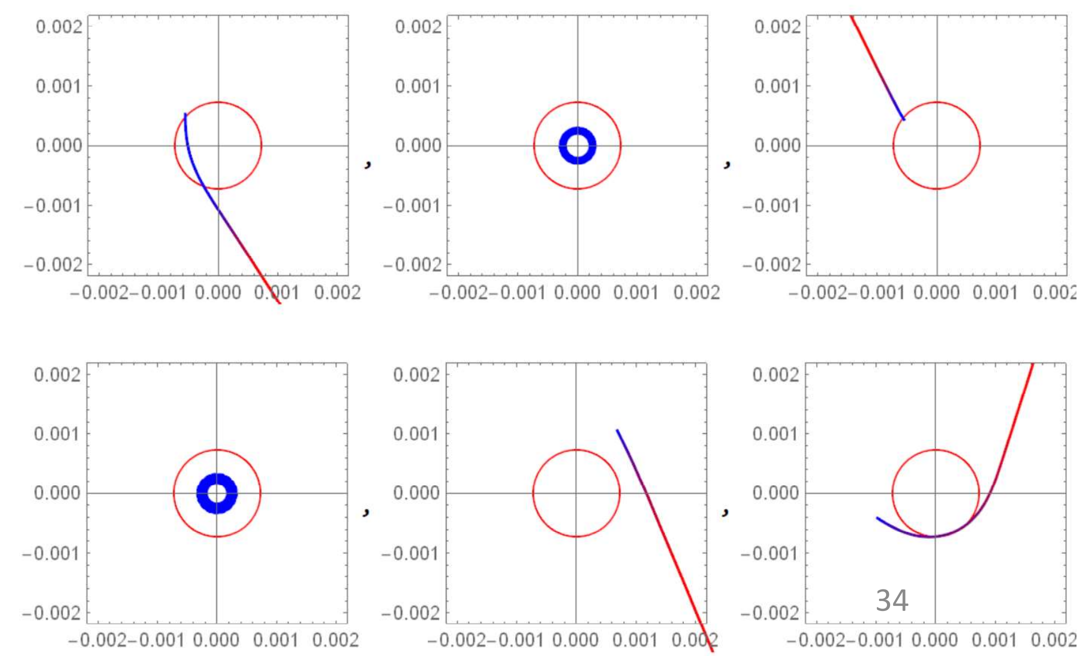
- Limited by contrast loss with increased arm separation.



Contrast loss and solutions

- Limited by contrast loss with increased arm separation.
- Simulations show contrast loss due to:
  - Imperfections in the holding potential
  - Difference in holding potential due to cavity wavefront curvature.
- Solutions:
  - Improved mirror surface.
  - Reduce wavefront curvature by holding atoms near cavity waist.





Future looks good

- Precision gravimetry.
  - Compact geometry.
  - Vibration free measurement.

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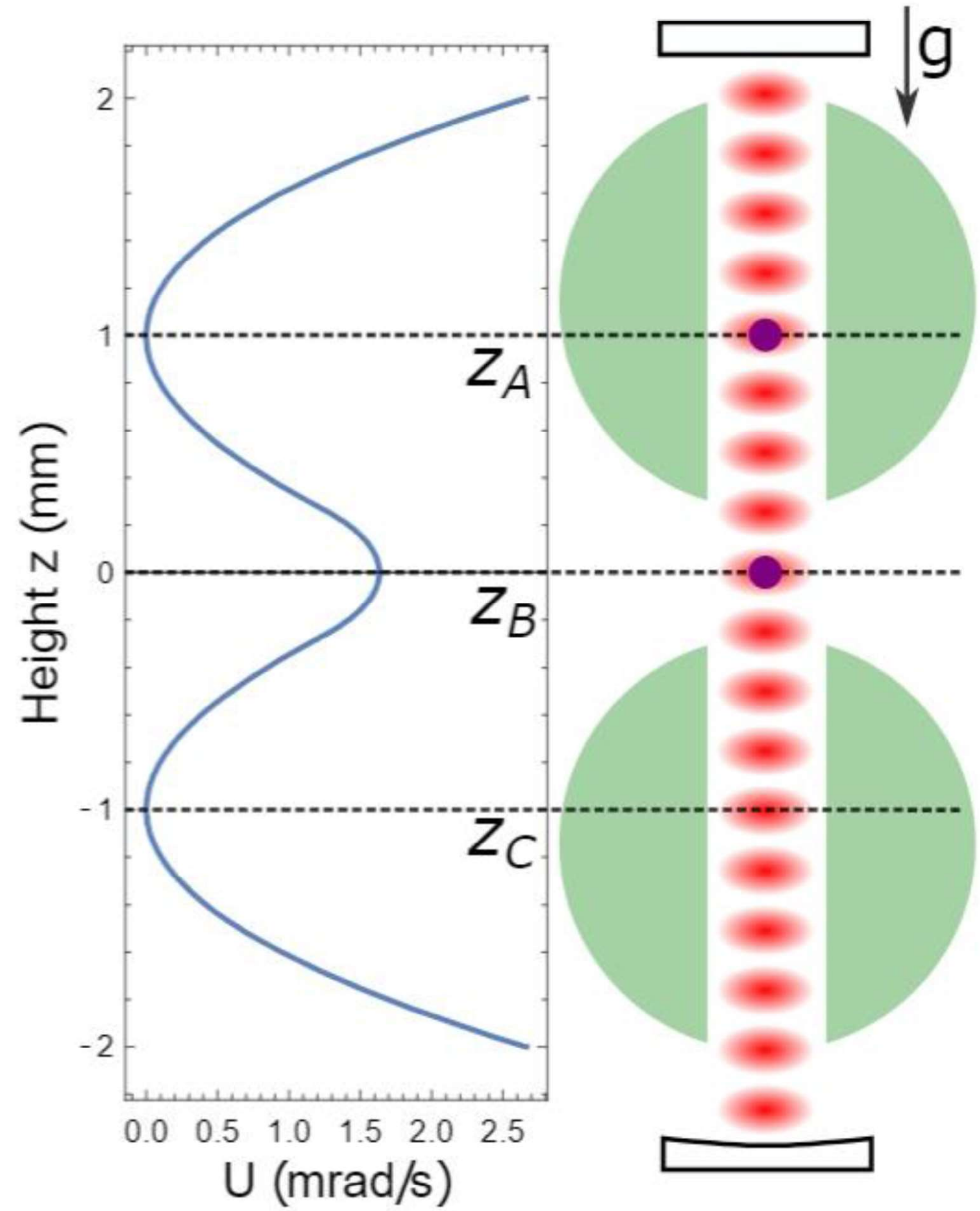
- Measurement of microscopic masses.
  - Improve our limits on dark energy candidates.
  - Probe gravity at smaller scales.
- Gravitational Aharonov-Bohm effect
  - Measure physical phase due to gravitational potential difference with no forces!
  - Probe non-classical effect of gravity.
  - New method to measure G.



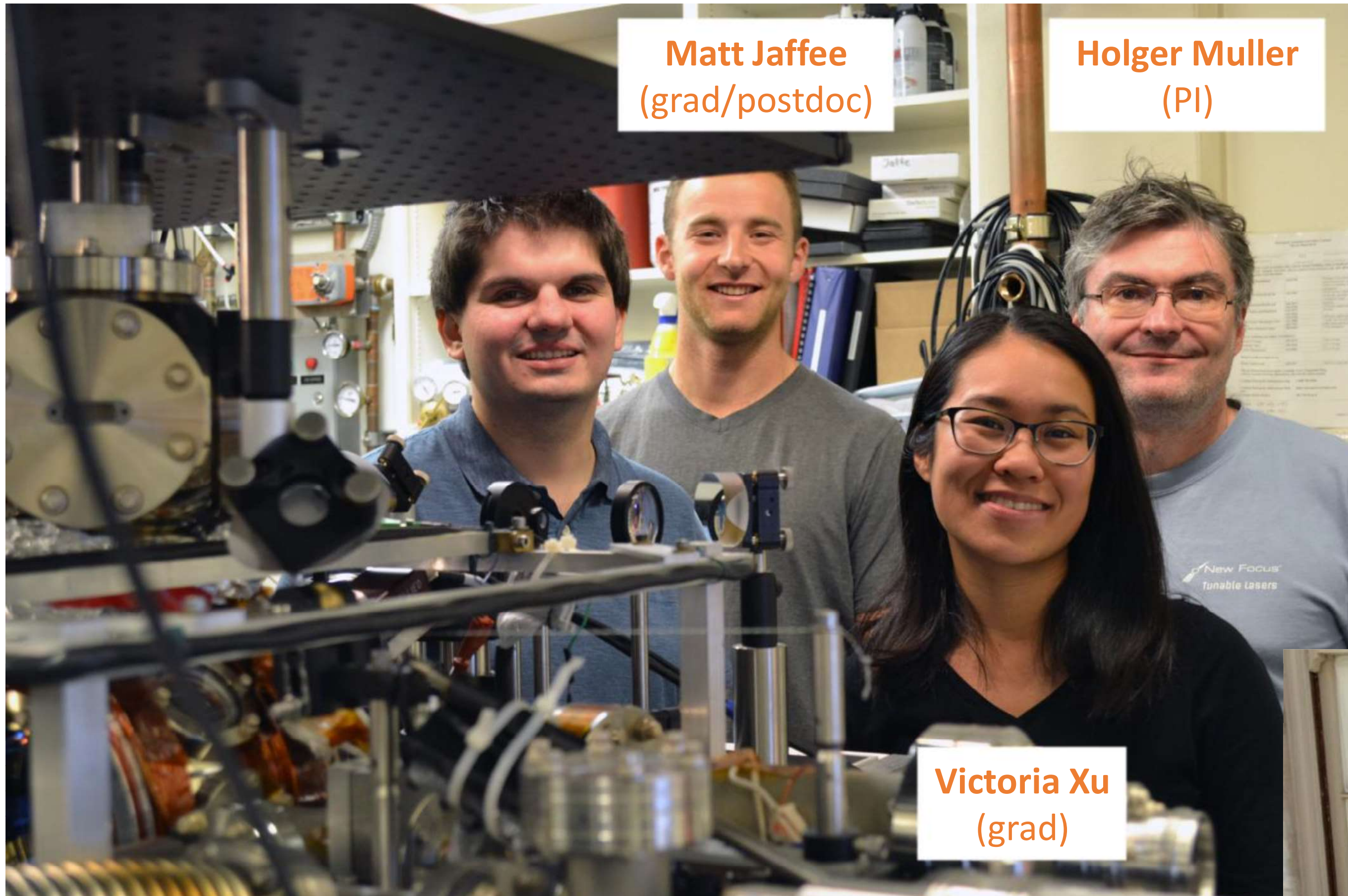
Directions for atom interferometers

Probe fundamental physics:

- Measurement of the fine structure constant: LKB Paris, UC Berkeley
- Measurement of gravitational constant G: Stanford, Florence, Wuhan
- Testing the equivalence principle, universality of free fall
  - Atoms: Stanford, Wuhan, Florence
  - Matter-antimatter
- Gravitational waves: MAGIS (Fermilab), ZAIGA (Wuhan), MAGIA (Sardinia)
- Space experiments: CAL – ISS, CACES, SAGE, AEDGE - ESAs
- Gravitational Aharanov Bohm effect
- Dark energy- chameleons, symmetrons: Berkeley, Imperial
- Quantum superpositions of many atom molecules: Vienna
- Interplay of gravity and quantum mechanics – interference of high precision clocks in gravitational potential, gravity decoherence, - Florence, Hannover
- Deviations from 1/r^2 at small r: Northwestern
- Many other ideas!

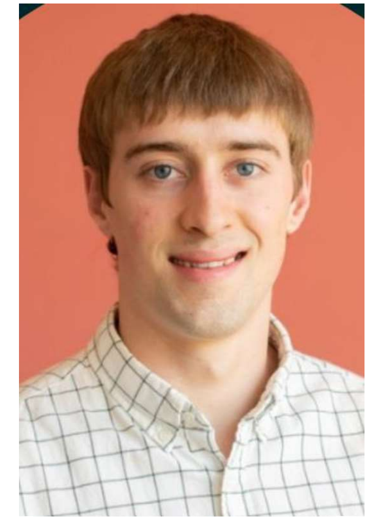
New techniques:

- Lattice interferometer: Berkeley
- Squeezed interferometers: JILA
- Clock interferometers: Hannover
- Large momentum: Stanford, Berkeley, Hannover, UW



Sofus Kristensen
(master)

Logan Clark
(postdoc)



James Egelhoff
(grad)

Thanks!