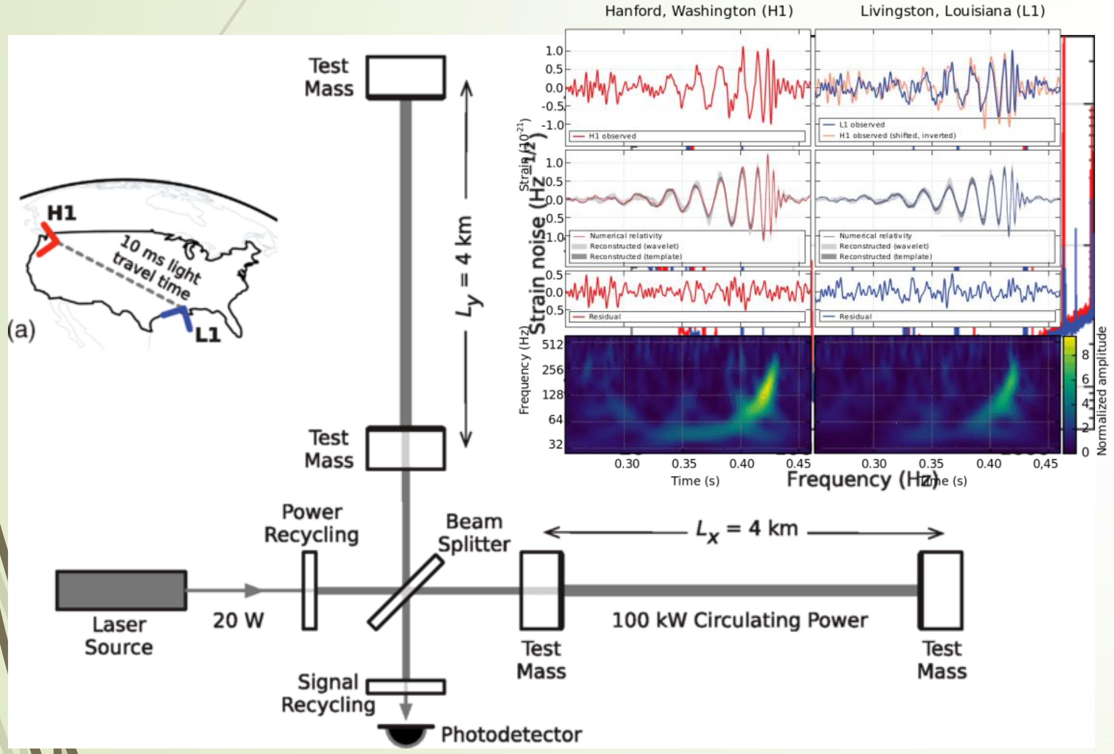
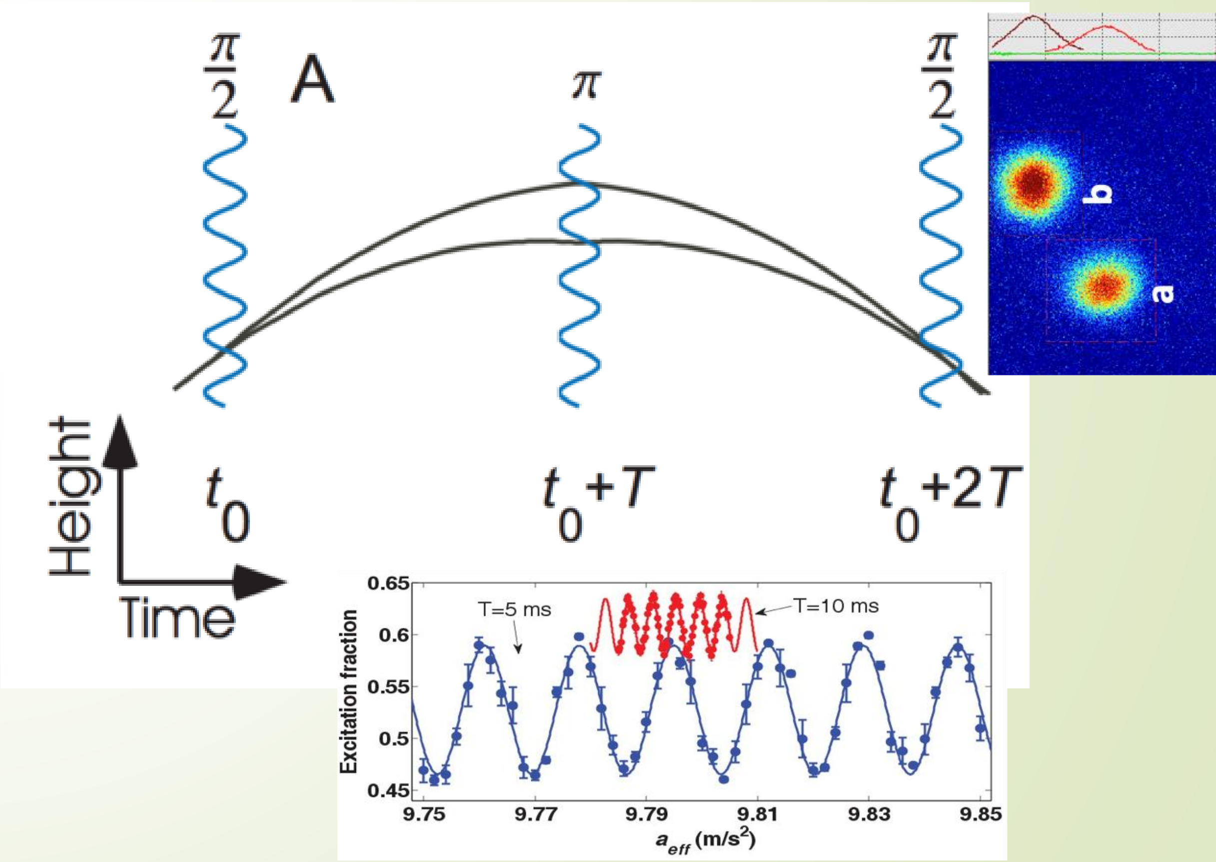
Minute-Scale Interference in an Atom Interferometer

Keep the Quantum State Alive!

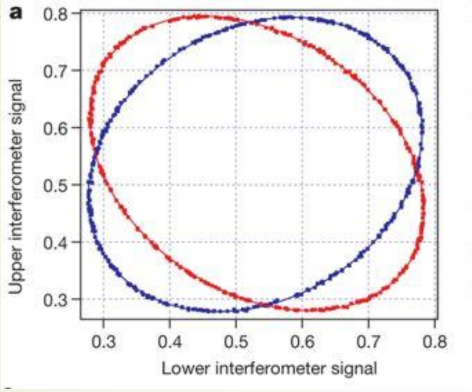
Interferometers

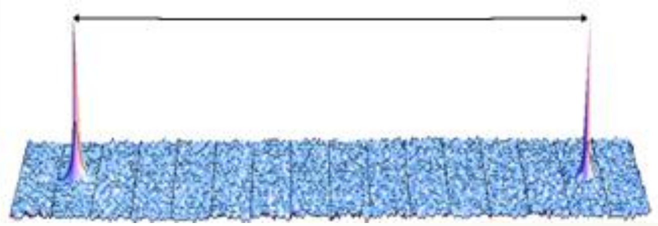
- Using matter to manipulate light
- Using light to manipulate matter

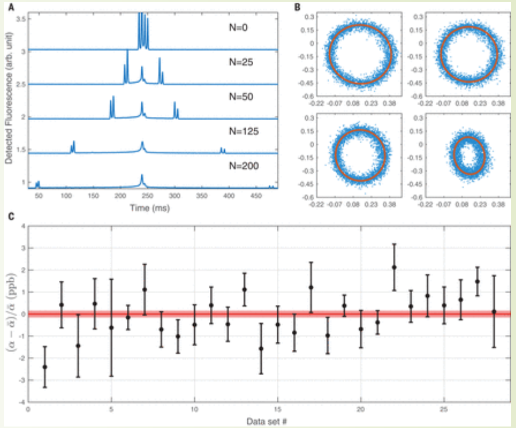




Dropping atoms for high precision…





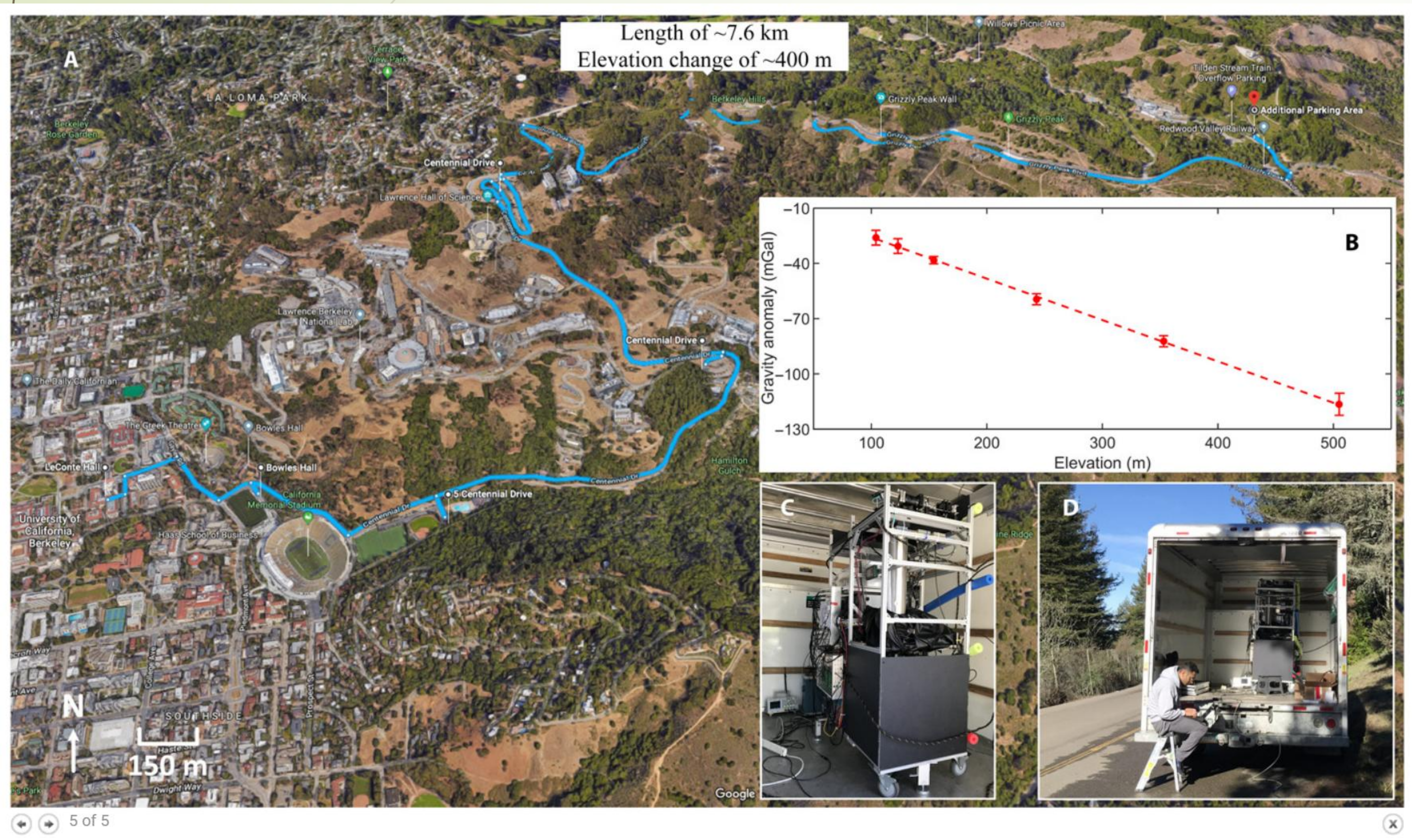


Measurement of G

Tests of GR and QM

Fine-structure constant

Applications: local gravity measurements, geophysics, inertial sensing



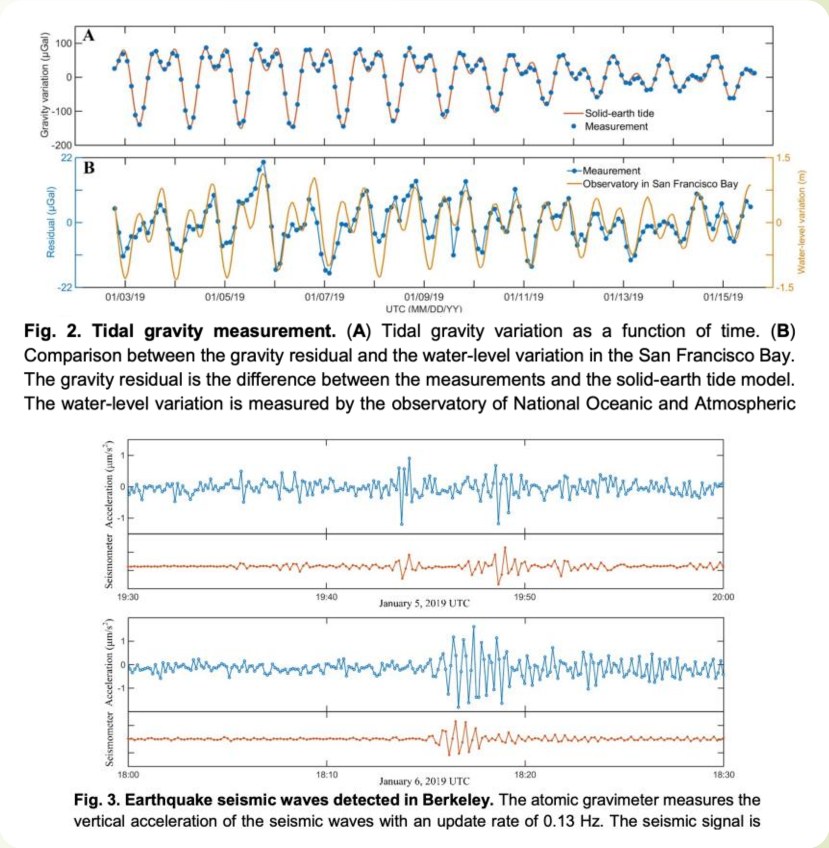


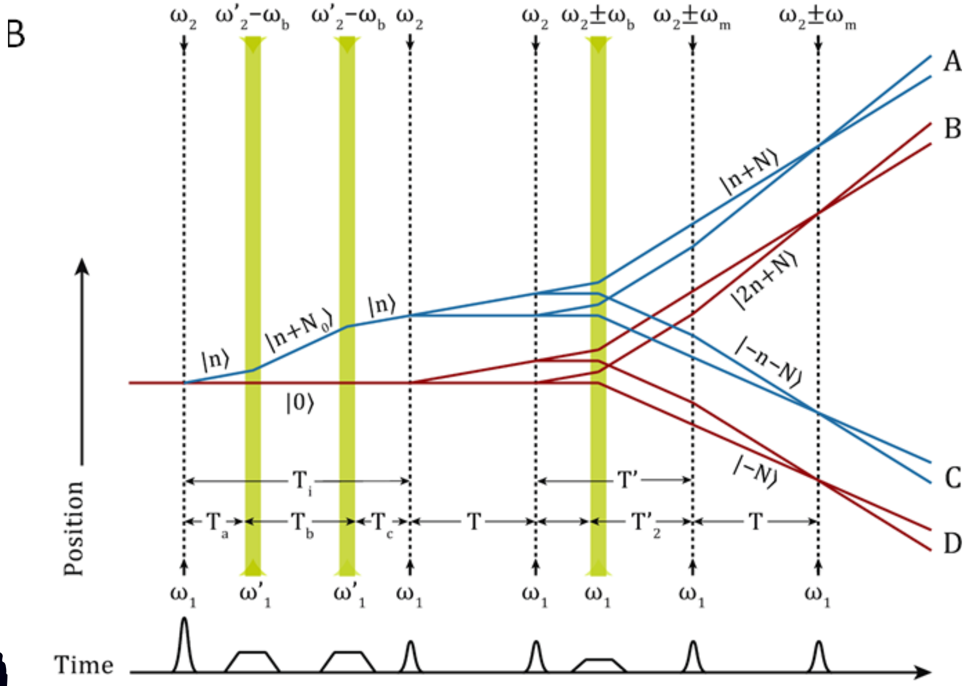
Fig. 2. Tidal gravity measurement. (**A**) Tidal gravity variation as a function of time. (**B**) Comparison between the gravity residual and the water-level variation in the San Francisco Bay. The gravity residual is the difference between the measurements and the solid-earth tide model. The water-level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

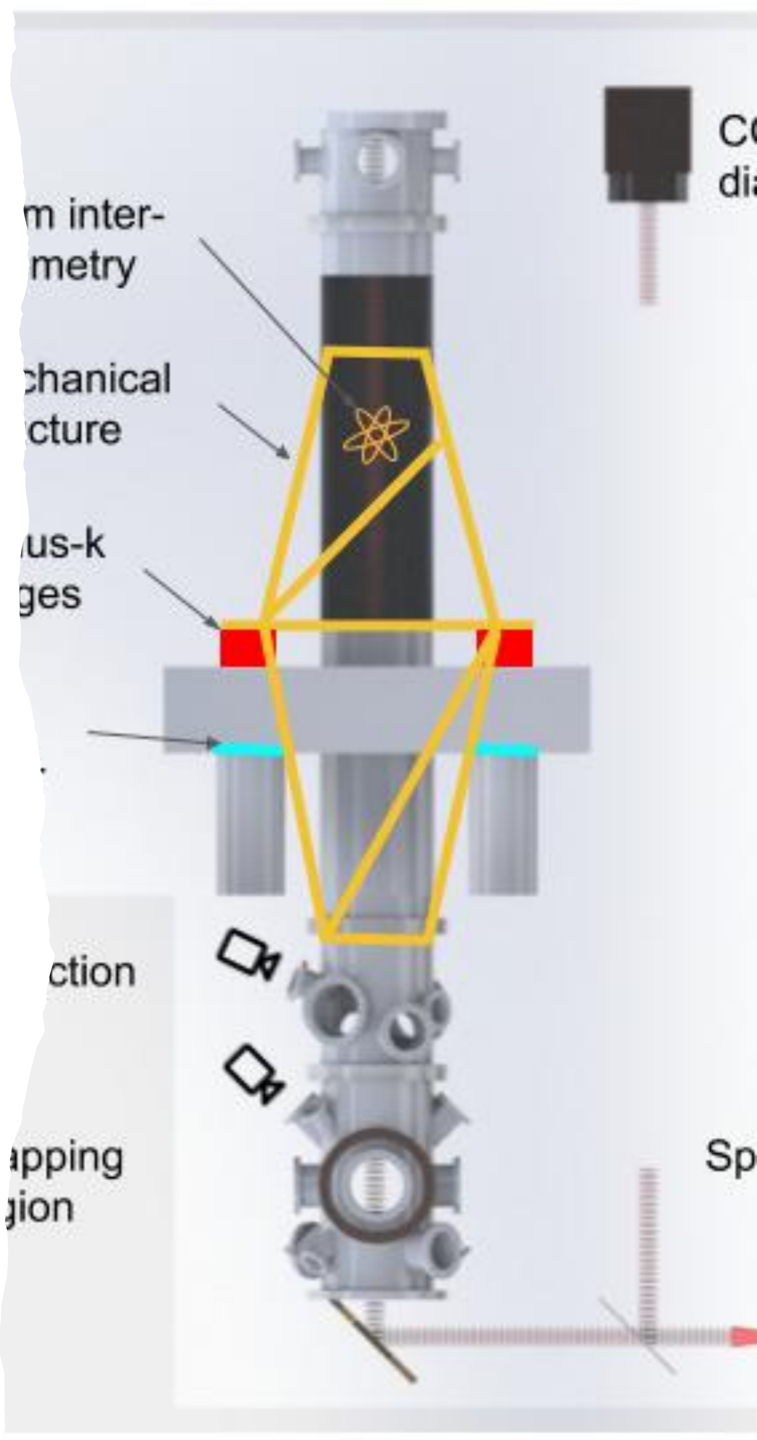
Fig. 3. Earthquake seismic waves detected in Berkeley. The atomic gravimeter measures the vertical acceleration of the seismic waves with an update rate of 0.13 Hz. The seismic signal is

X. Wu, et. al., *Science Advances* 2019

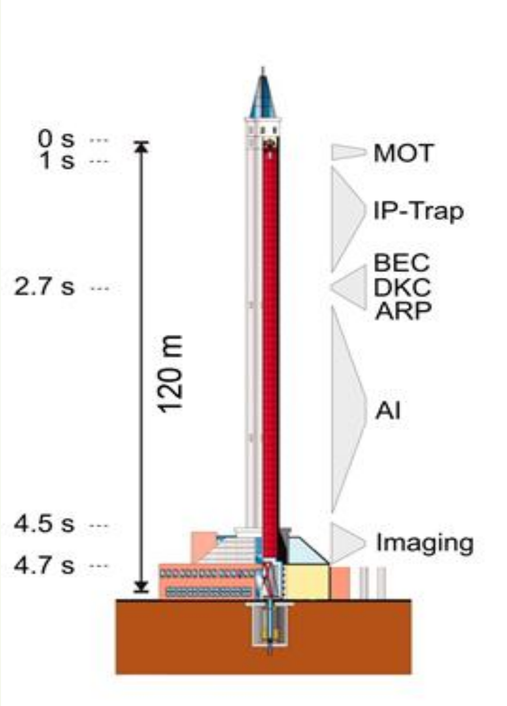
Extreme control over laser beam

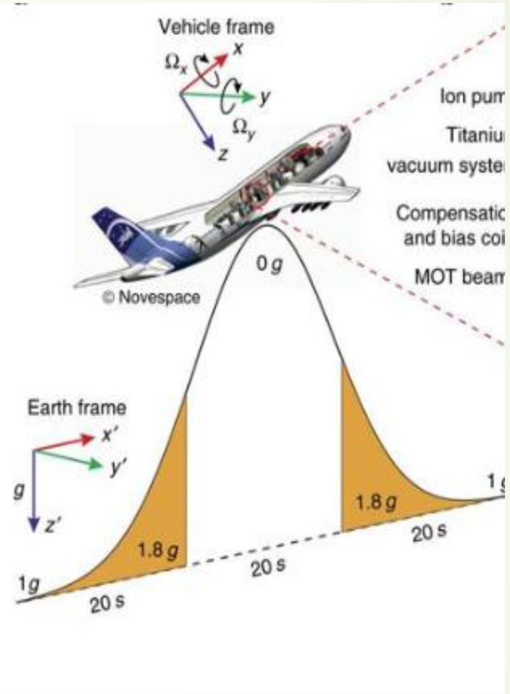
- Large clear aperture, catch stray beams, no polarization optics,..
- Gravity gradient cancellation
- Measuring effect of beam

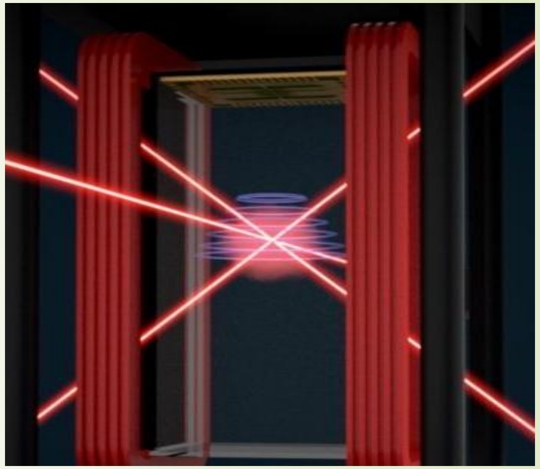




Limitations: free-fall time



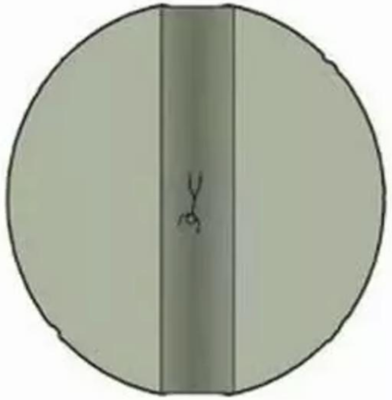




Stanford, Wuhan 10-m fountain	Bremen 100-m drop tower	French zero-g flights	NASA cold atom lab
2 -3 s (height)	<1 s (atom temp, vacuum, vibrations)	< 1s (atom temp, vacuum, vibrations)	<1 s (atom temp, vacuum, vibrations)

Why even longer coherence times?

Longer coherence times

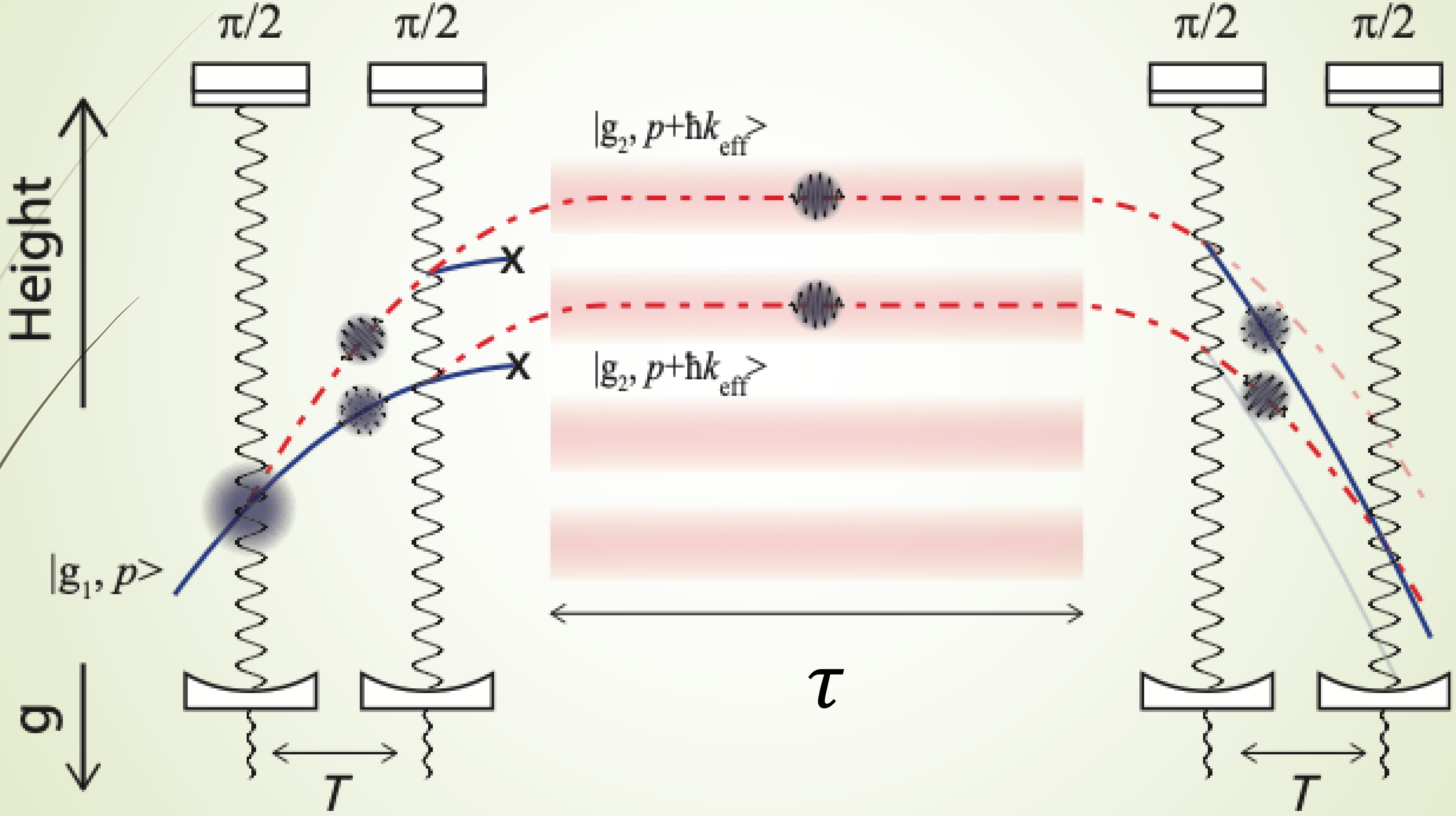


It takes at least $1/\sqrt{G\rho}$ ~ 15 minutes for gravity to dominate in an experiment!

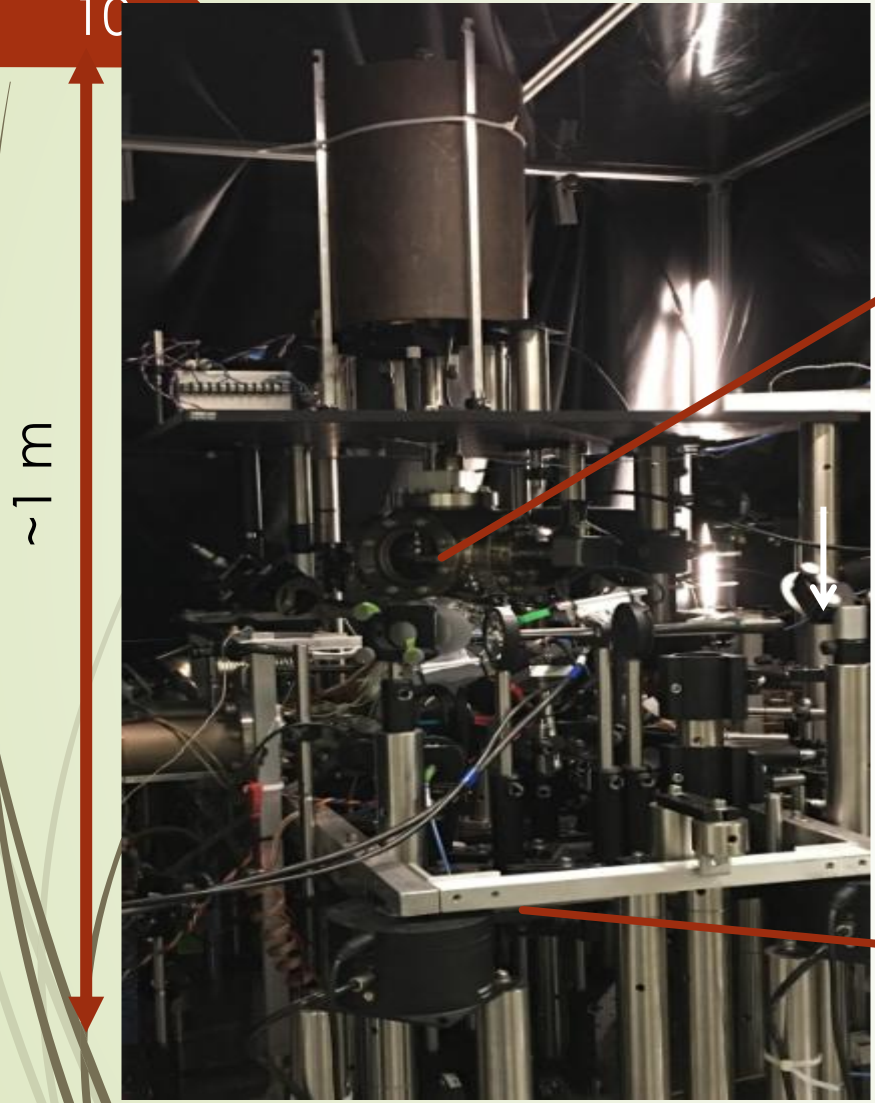
- E.g., gravitational harmonic oscillator

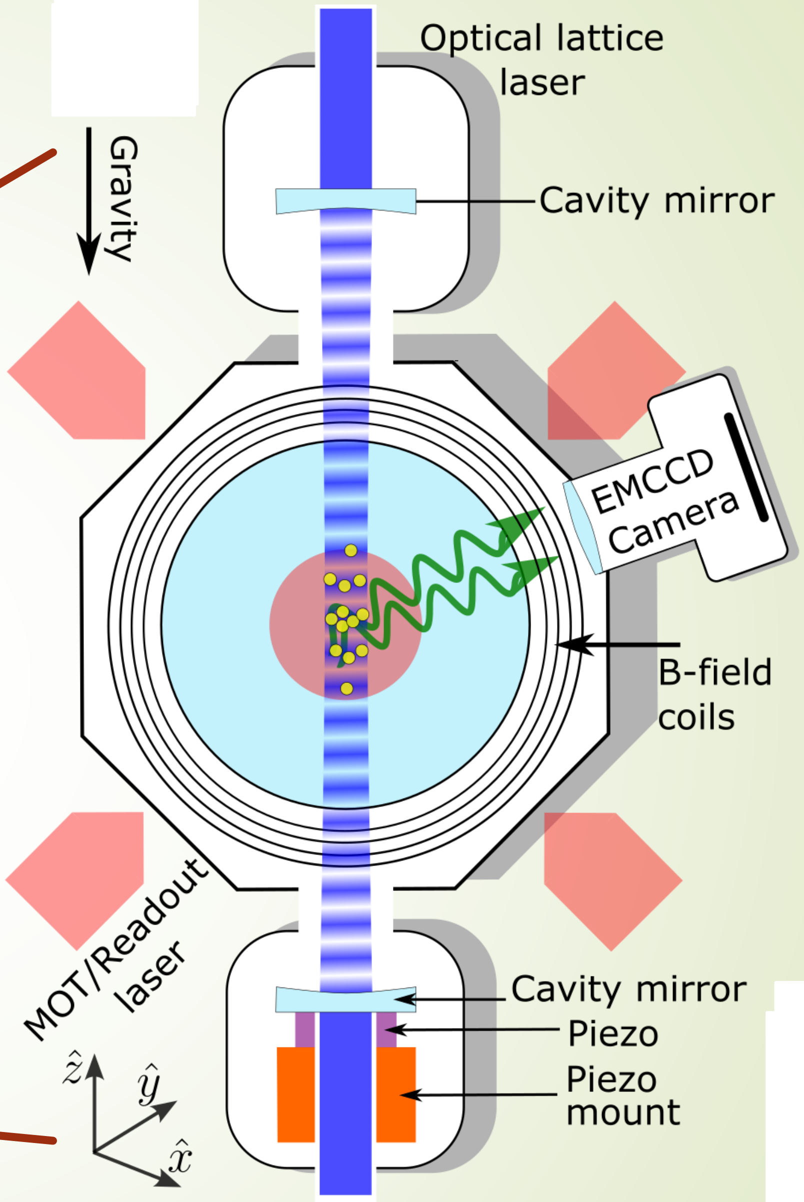
Minimum time scale on which quantum aspects of gravity can be expected to be noticeable

Lattice interferometer geometry



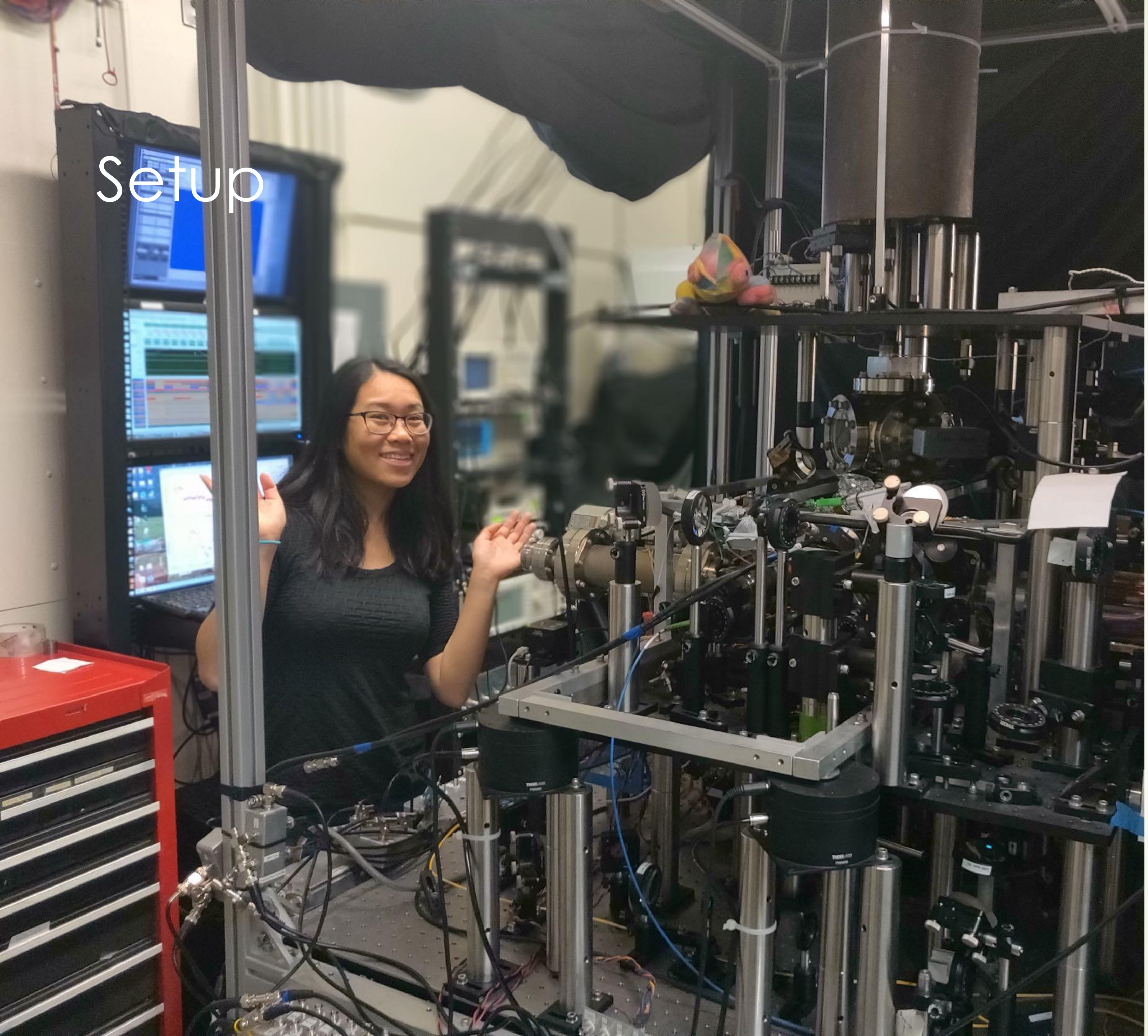
Apparatus





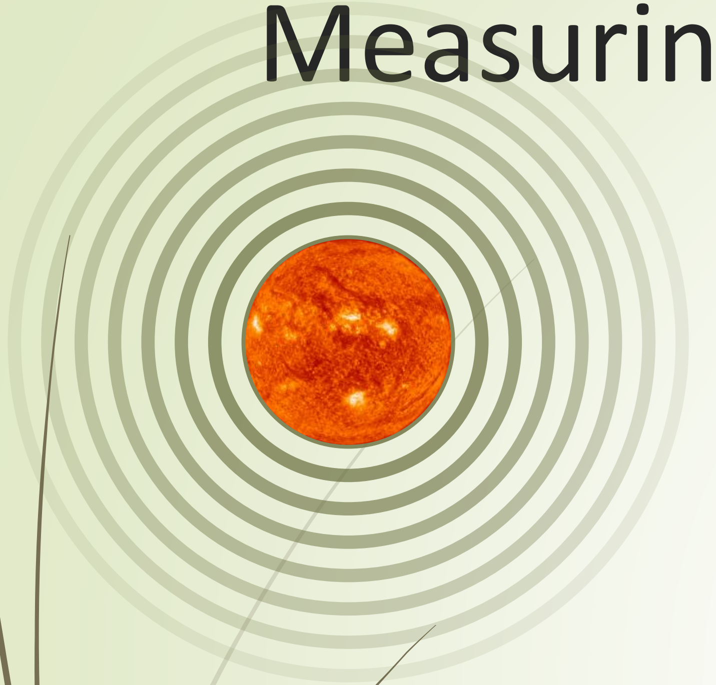
- Optical lattice filtered by in-vacuum Fabry Perot cavity.

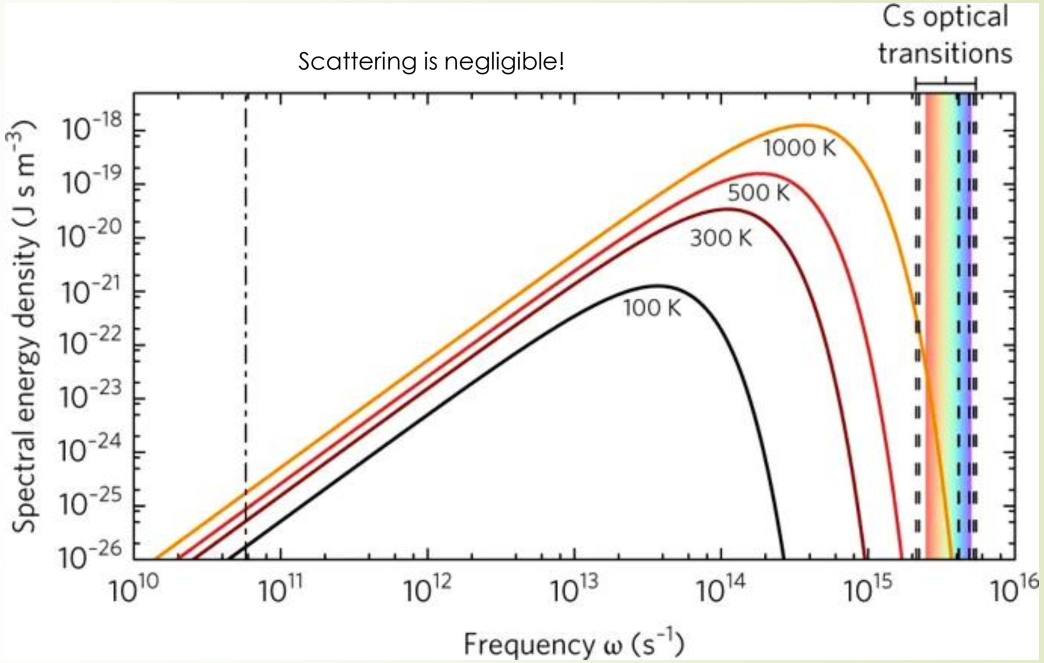
Setup



- 10^6 Cs atoms
- Cavity length 40 cm
- Beam waist 0.76 mm
- Finesse 130

Measuring the Force generated by blackbody radiation





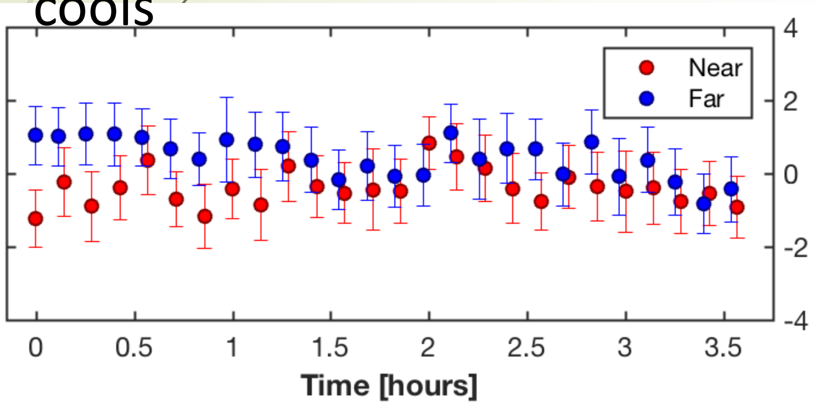
- Hot object creates a spatially inhomogeneous thermal radiation field
- Red-detuned thermal radiation leads to an attractive force on atoms

$$\Rightarrow \qquad \mathbf{F} = -\frac{\partial}{\partial \mathbf{r}} \boldsymbol{\Delta}\mathbf{E}_{\mathrm{BBR}}$$

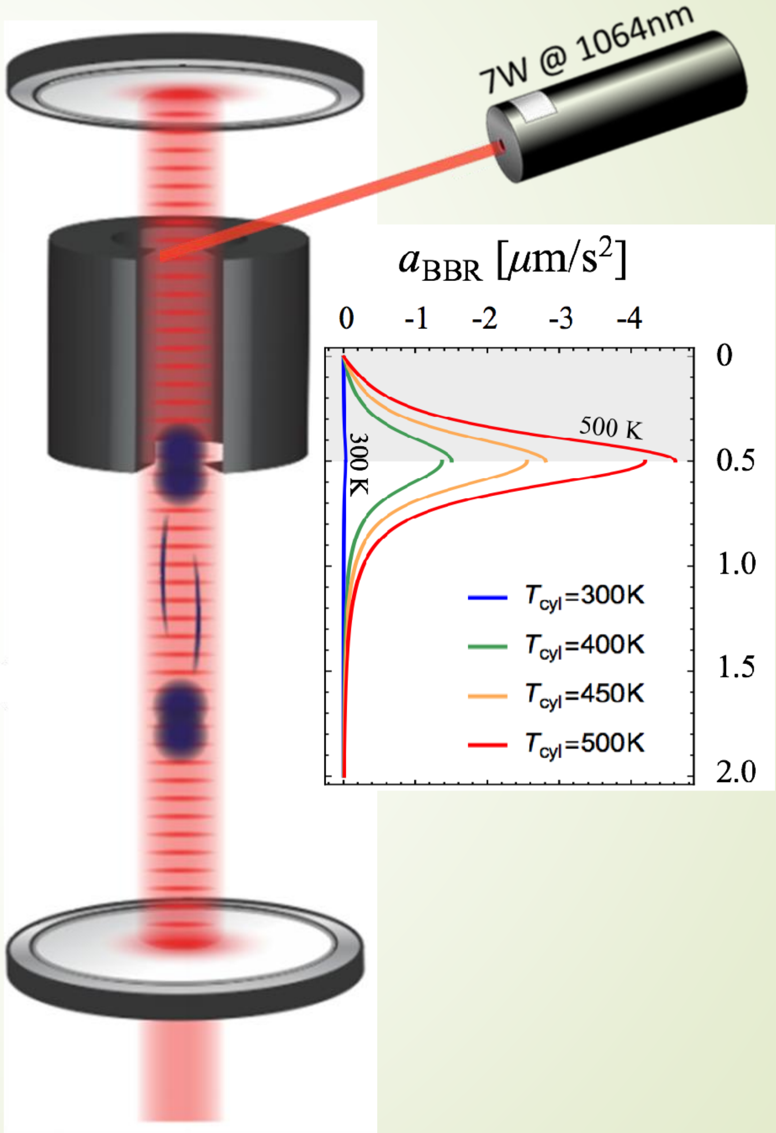
Sonnleitner et al., ***PRL*** *111, 023601 (2013)*

Is it measurable?

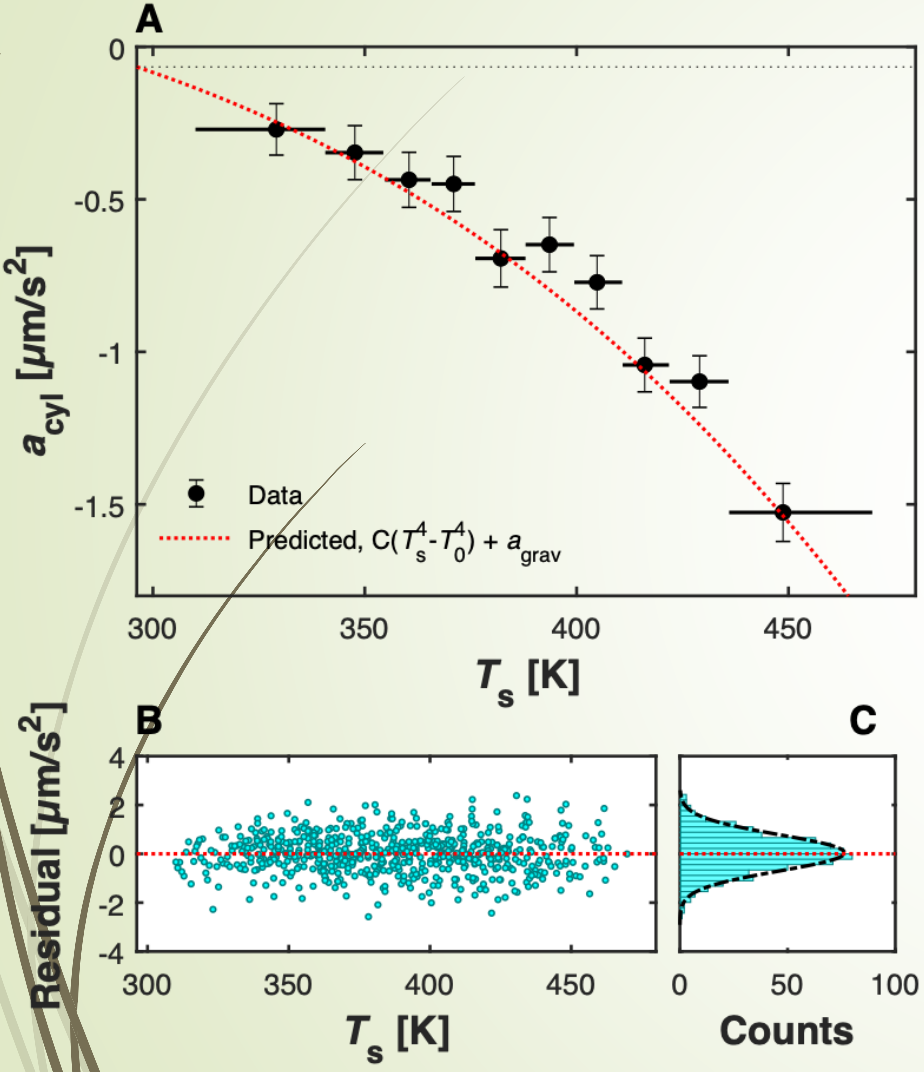
1. Heat up the source mass
2. Measure acceleration with(out) source mass as it cools

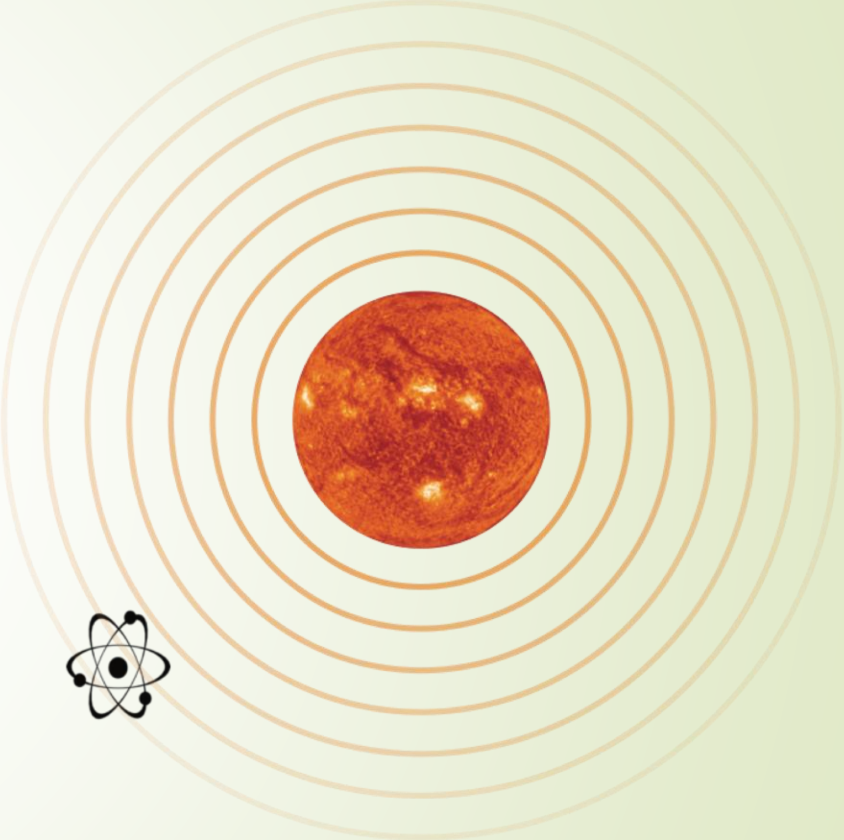


3. Repeat for many cooldowns



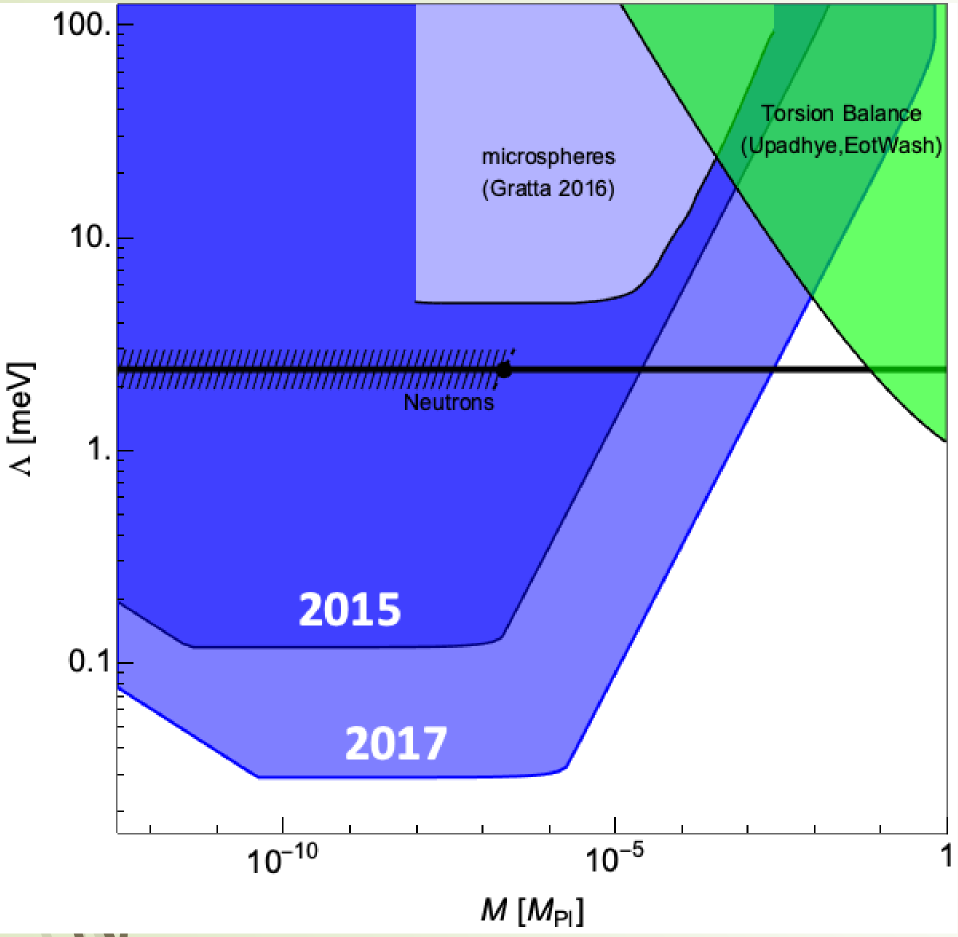
Blackbody-mediated force

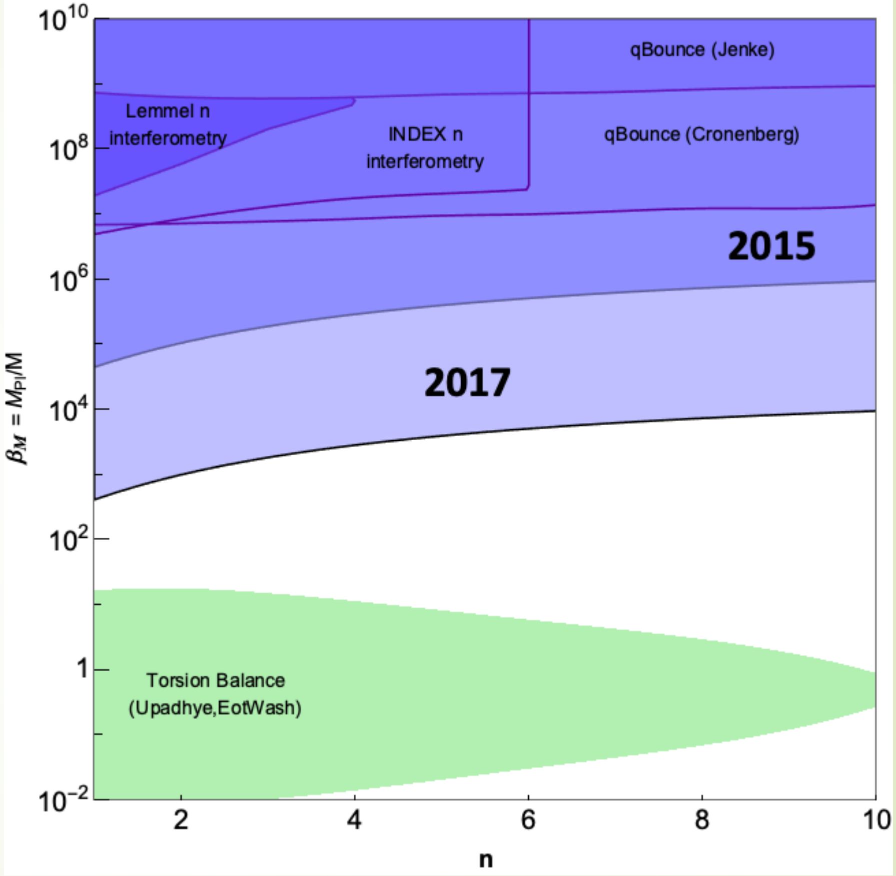




Haslinger, MJ et al., ***Nature Physics*** *14, 257–260 (2017)*

Testing a dark-energy candidate: Chameleons





$$V_{\text{eff}} = \Lambda^4 + \frac{\Lambda^{4+n}}{\phi^n} + \frac{\phi}{M}\rho$$

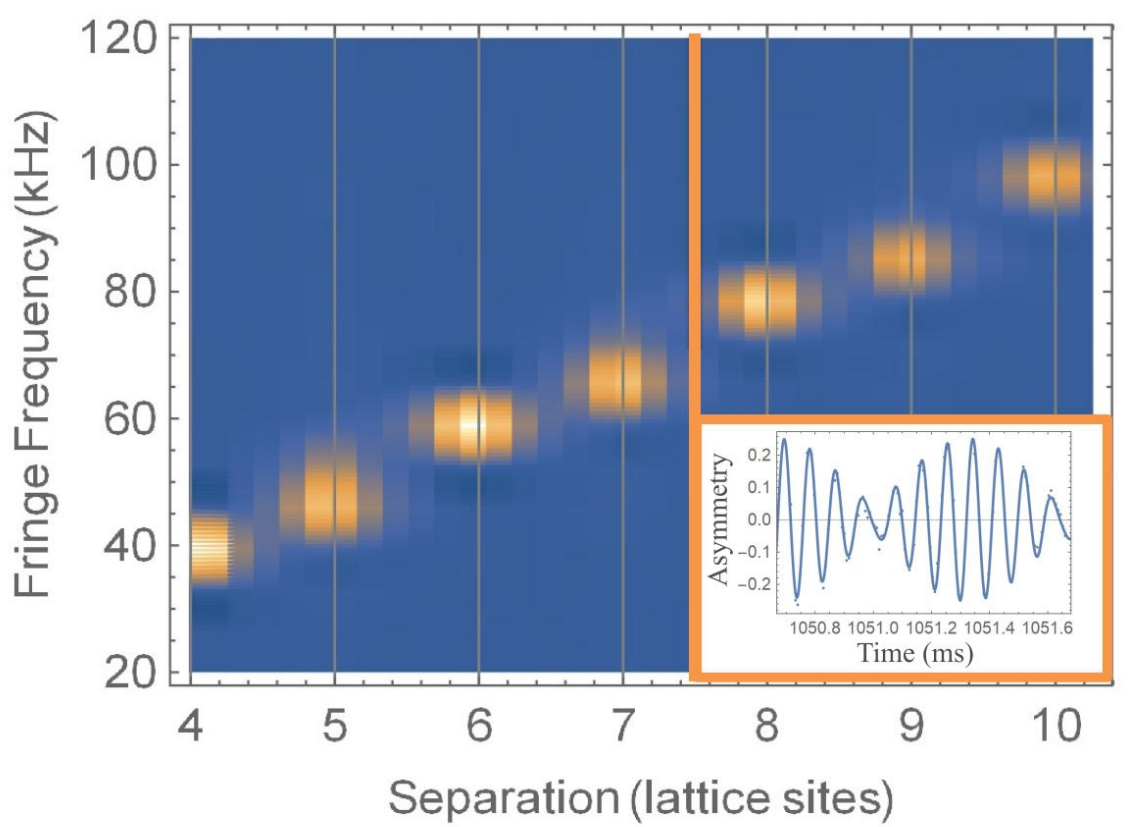
Self-potential

Coupling to
local density

*MJ et al., **Nature Physics** 13, 938–942 (2017)*
*Hamilton, MJ et al., **Science** 21, 849–851 (2015)*

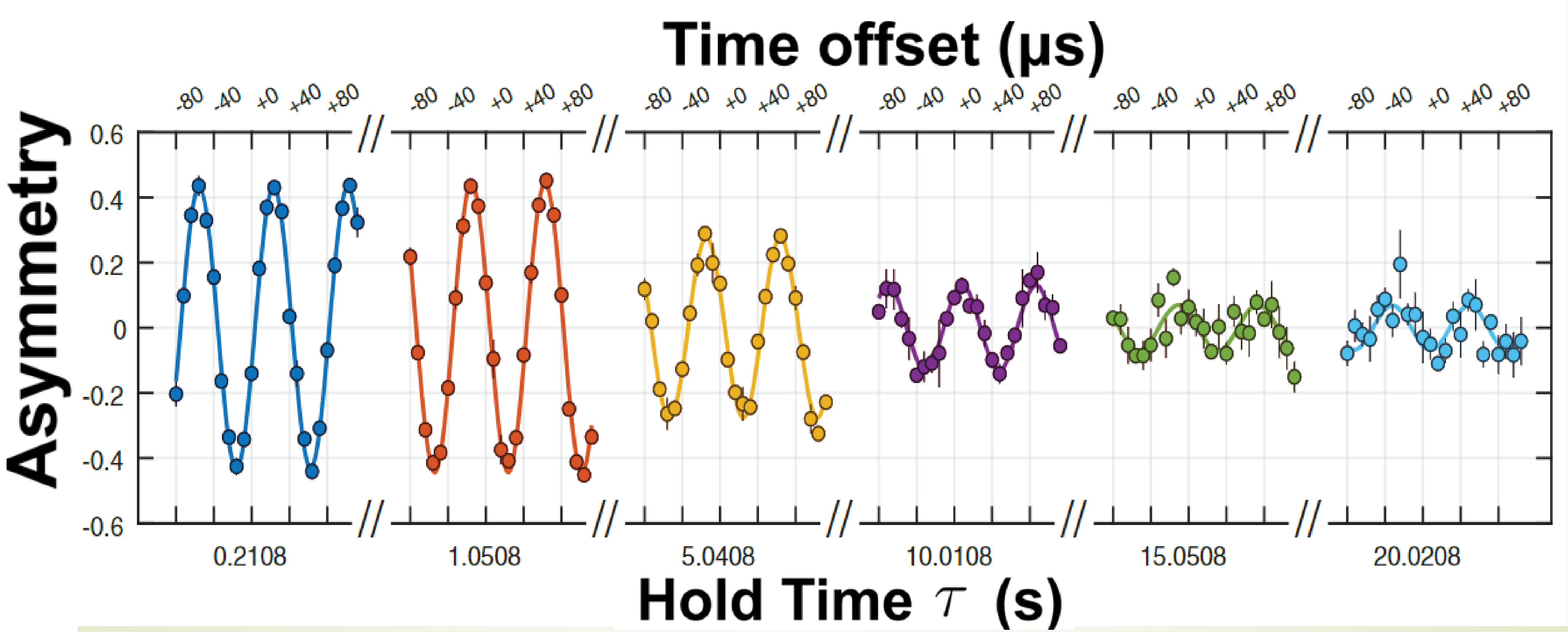
Quantization of the fringe spacing

- Wavepacket separation varied by varying the time of flight
- Fourier Transform of the fringe is plotted, color-coding the intensity of a component

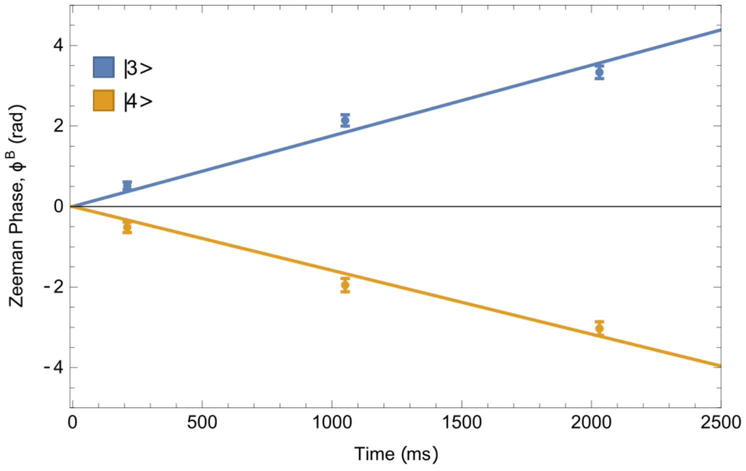


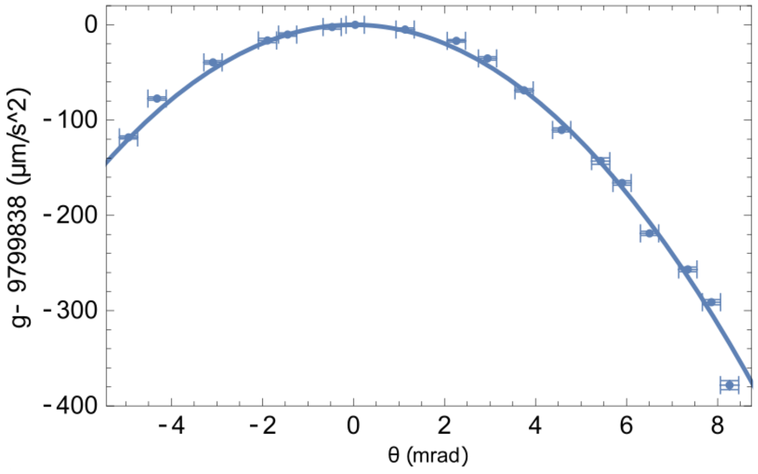
Long coherence times

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)



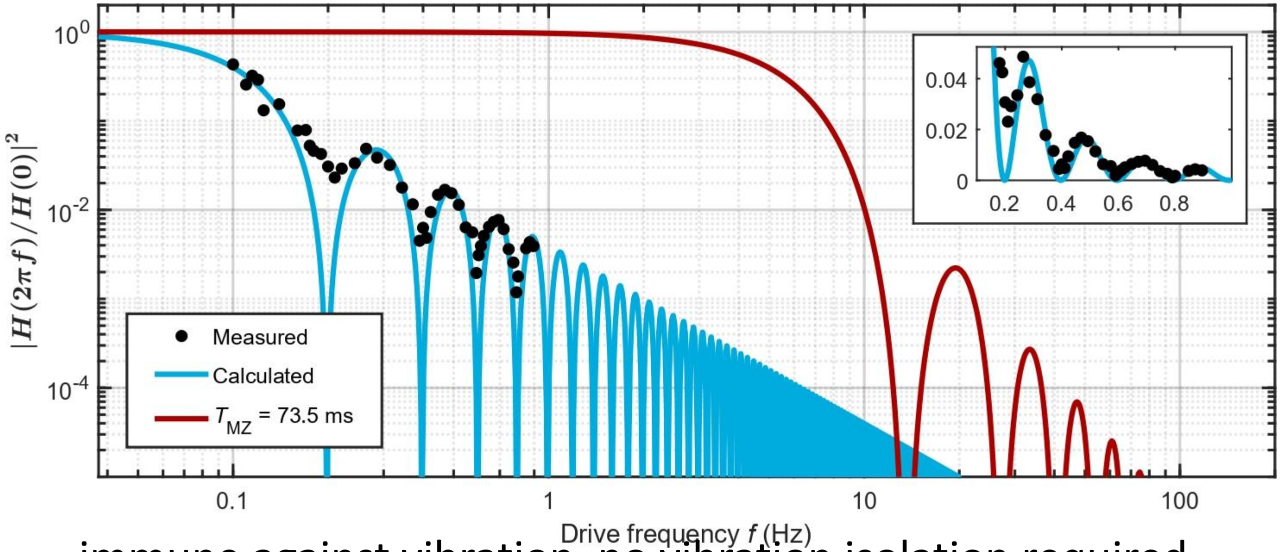
Suppression of vibrational noise, immune to tilt





Operation under strong B-field…

…tilt o…

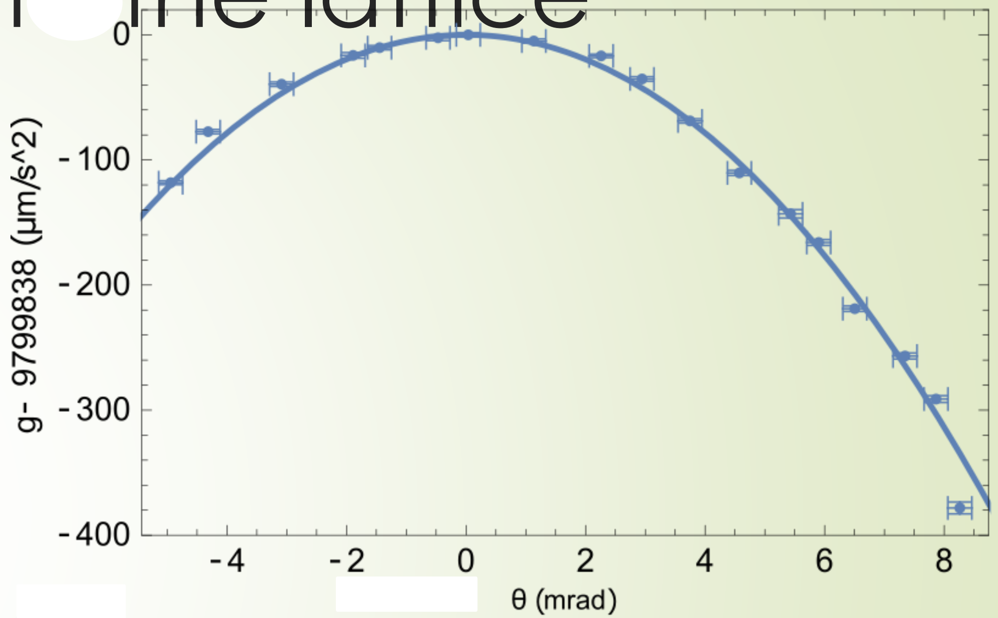


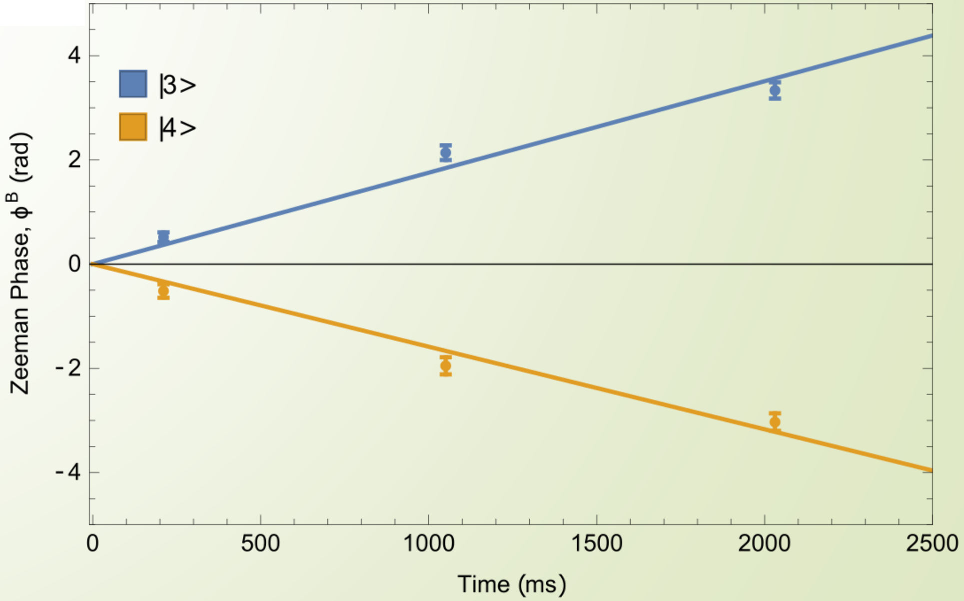
immune against vibration, no vibration isolation required

Atomic gravimeter robust to environmental effects, *Appl. Phys. Lett. 123*, 064001 (2023)

Mobile gravimetry with the lattice interferometer

- Robust:
  - Tilts: transverse confinement by lattice
  - B-fields: small volume means easy shielding =, less sensitivity
  - Vibrations: holding atoms averages, rather than aliases, vibrations.





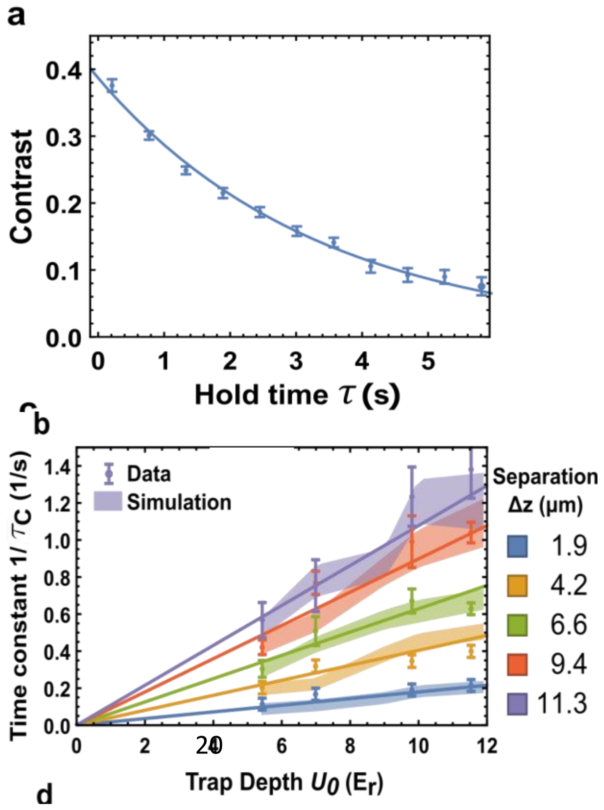
Atomic gravimeter robust to environmental effects,

Decoherence rate depends on splitting & lattice depth…

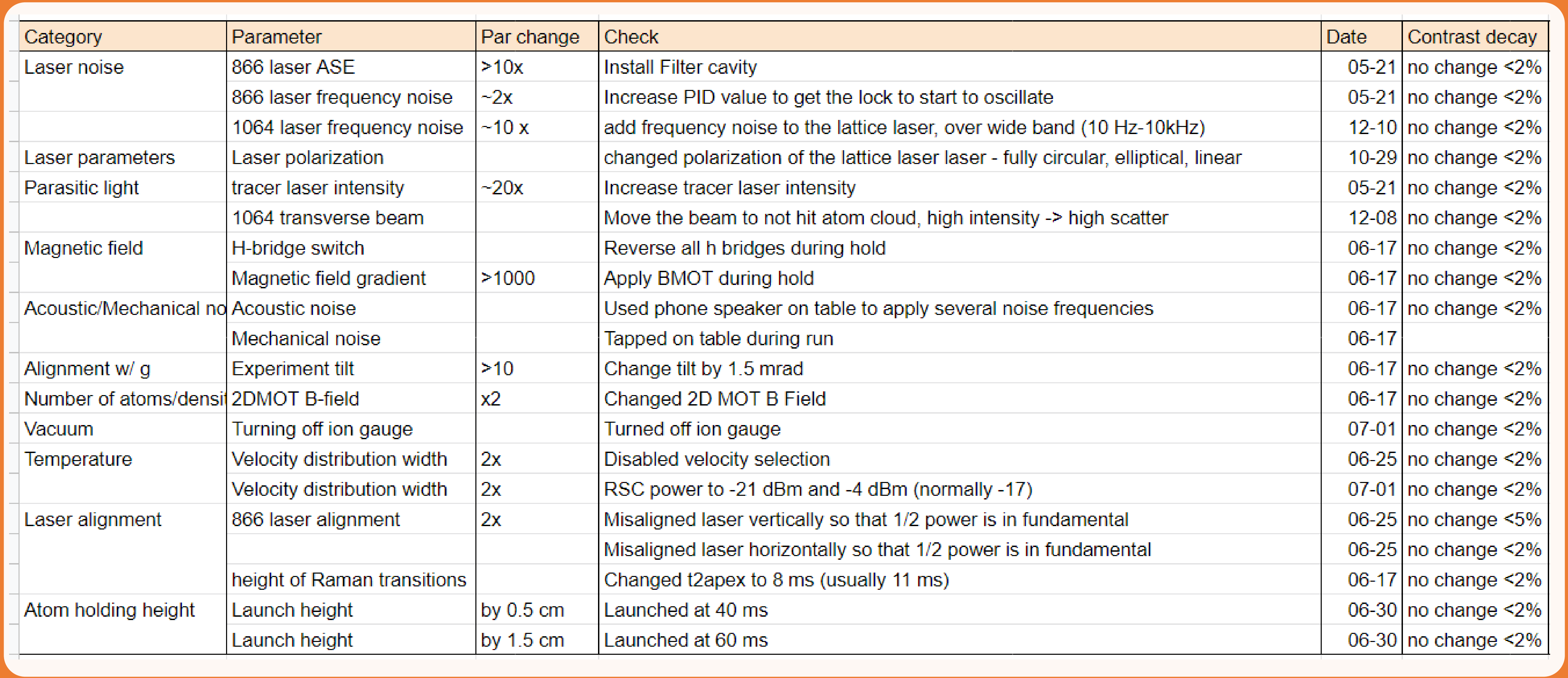
$$C = C_0 e^{-\tau/\tau_c},$$

$$\tau_c = \kappa/(U\,\Delta z)$$

C_0: initial contrast,
τ: hold time,
Δz: separation,
U: lattice depth,
$\kappa \sim 110\ \mu m\ E_r s$.



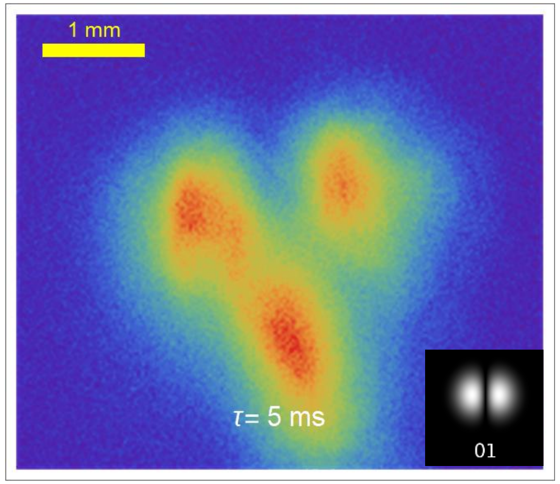
…but seem independent of almost everything else…

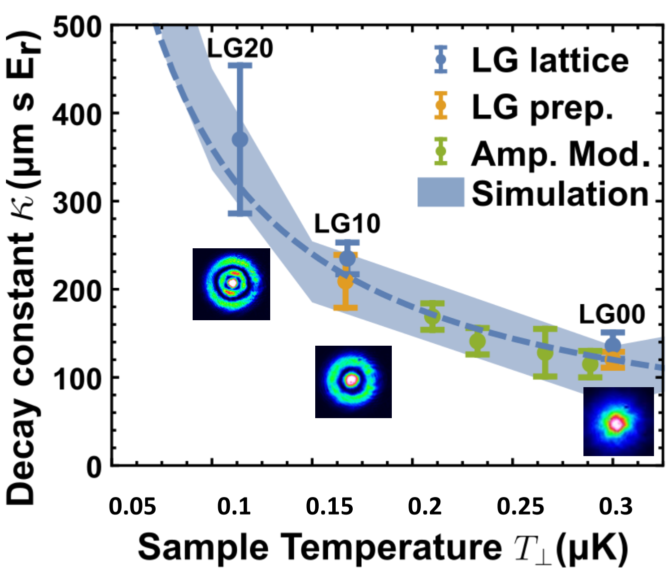


Category	Parameter	Par change	Check	Date	Contrast decay
Laser noise	866 laser ASE	>10x	Install Filter cavity	05-21	no change <2%
	866 laser frequency noise	~2x	Increase PID value to get the lock to start to oscillate	05-21	no change <2%
	1064 laser frequency noise	~10 x	add frequency noise to the lattice laser, over wide band (10 Hz-10kHz)	12-10	no change <2%
Laser parameters	Laser polarization		changed polarization of the lattice laser laser - fully circular, elliptical, linear	10-29	no change <2%
Parasitic light	tracer laser intensity	~20x	Increase tracer laser intensity	05-21	no change <2%
	1064 transverse beam		Move the beam to not hit atom cloud, high intensity -> high scatter	12-08	no change <2%
Magnetic field	H-bridge switch		Reverse all h bridges during hold	06-17	no change <2%
	Magnetic field gradient	>1000	Apply BMOT during hold	06-17	no change <2%
Acoustic/Mechanical no	Acoustic noise		Used phone speaker on table to apply several noise frequencies	06-17	no change <2%
	Mechanical noise		Tapped on table during run	06-17	
Alignment w/ g	Experiment tilt	>10	Change tilt by 1.5 mrad	06-17	no change <2%
Number of atoms/densi	2DMOT B-field	x2	Changed 2D MOT B Field	06-17	no change <2%
Vacuum	Turning off ion gauge		Turned off ion gauge	07-01	no change <2%
Temperature	Velocity distribution width	2x	Disabled velocity selection	06-25	no change <2%
	Velocity distribution width	2x	RSC power to -21 dBm and -4 dBm (normally -17)	07-01	no change <2%
Laser alignment	866 laser alignment	2x	Misaligned laser vertically so that 1/2 power is in fundamental	06-25	no change <5%
			Misaligned laser horizontally so that 1/2 power is in fundamental	06-25	no change <2%
	height of Raman transitions		Changed t2apex to 8 ms (usually 11 ms)	06-17	no change <2%
Atom holding height	Launch height	by 0.5 cm	Launched at 40 ms	06-30	no change <2%
	Launch height	by 1.5 cm	Launched at 60 ms	06-30	no change <2%

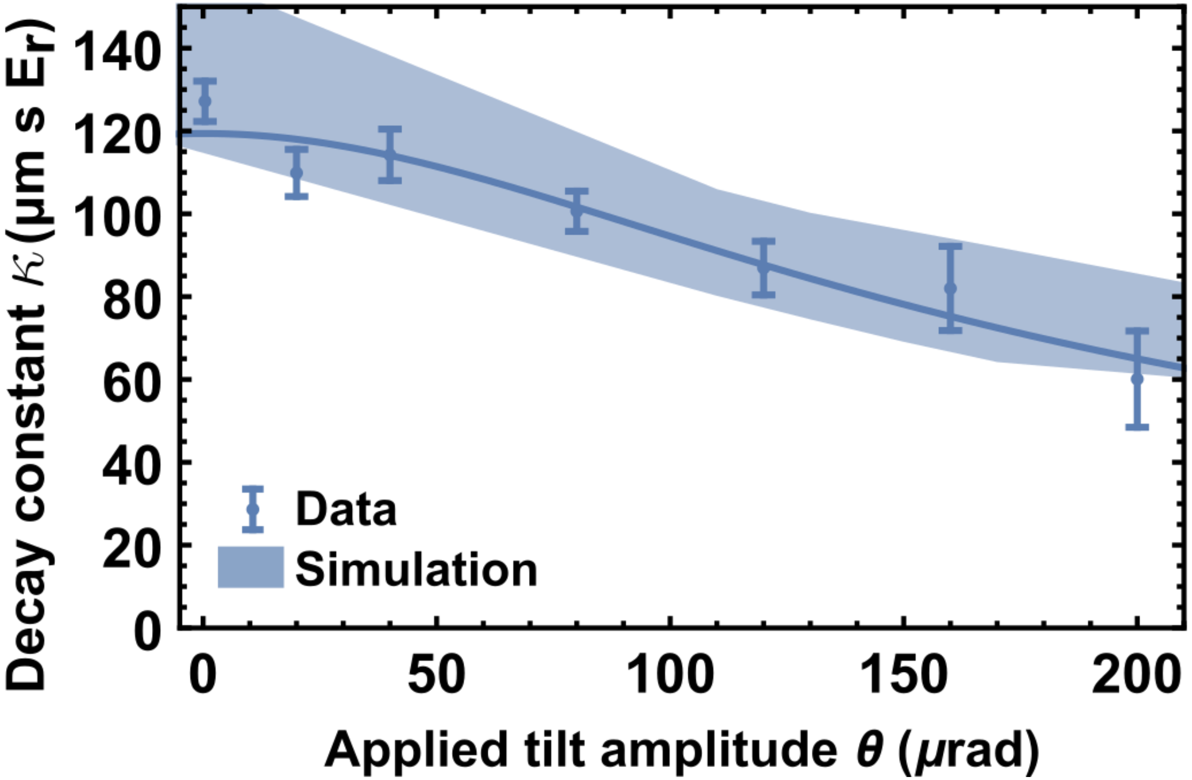
Years of work are summarized here

…except atom temperature…





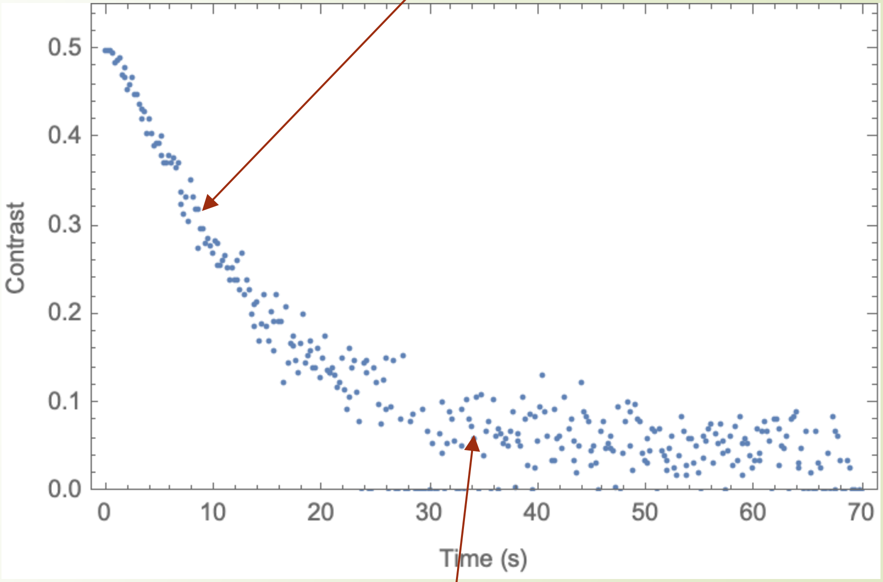
…and tilt noise!



Modeling predicts a new regime…

- Integrate motion for ~400 atoms
- Gaussian lattice potential
- LZ tunnelling rate $r = \exp\left(-\frac{\pi}{64}\frac{a_c}{g}\frac{U[x(t),y(t),t]}{E_r}\right)$
- Time-evolution $\phi = \frac{1}{\hbar}\int L[\left(\dot{x}(t), \dot{y}(t), x(t), y(t)\right]\, dt$
- Separation phase $\phi_s = [(x^t - x^b)(v_x^t + v_x^b) + (y^t - y^b)(v_y^t + v_y^b)]m_{Cs}/(2\hbar)$
- Lattice vibration $x_0 \rightarrow x_0(t) = 2z\,\theta \sin\omega t$

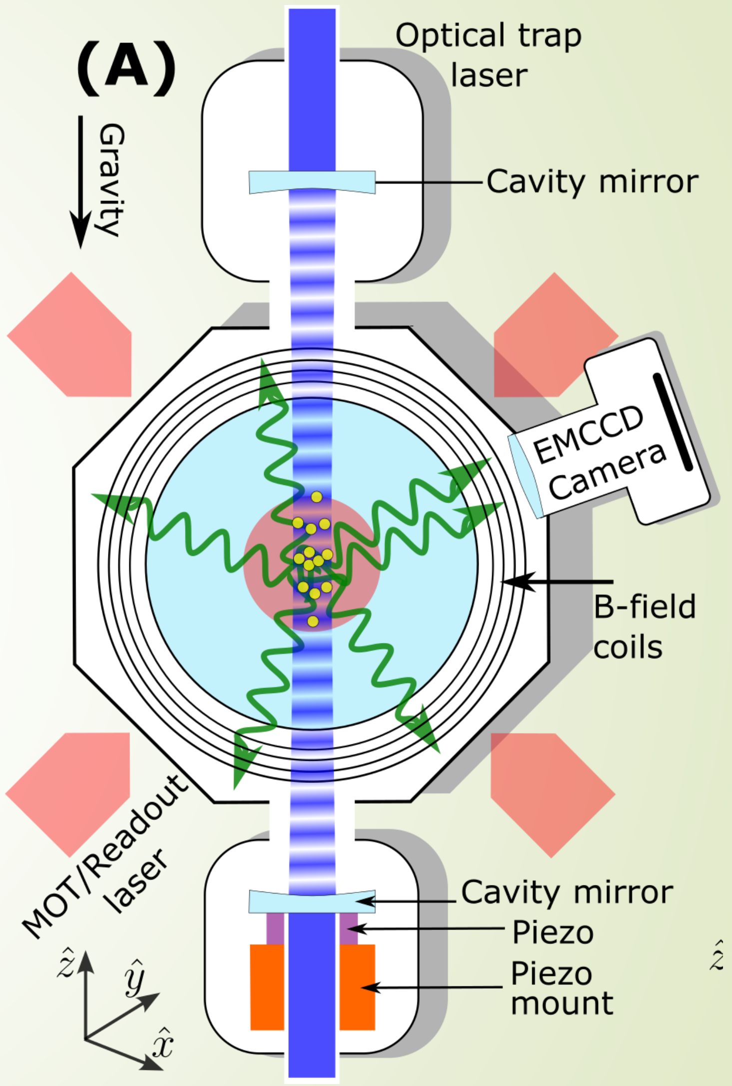
Roughly exponential decay for <20 s



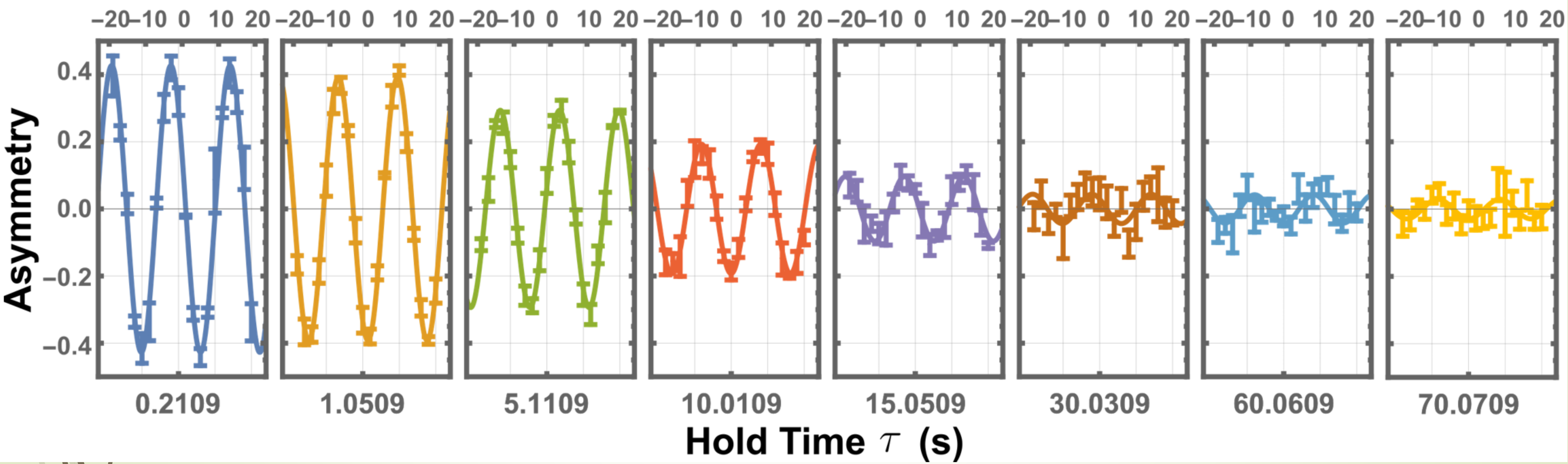
- Contrast persists at nonzero level after "hot" atoms have fallen away
- Tested by starting with only cold atoms

…but can we see it?

- 3x atom number by moving lattice launch
- Further detuned optical lattice (943 nm)
- Lattice amplitude stabilization increased atomic lifetime to 14 s, from 7
- Low-noise imaging: scatter reduction, EMCCD camera.
- Reduced Raman laser phase noise,
- => Measurement precision ~ 2 x SQL

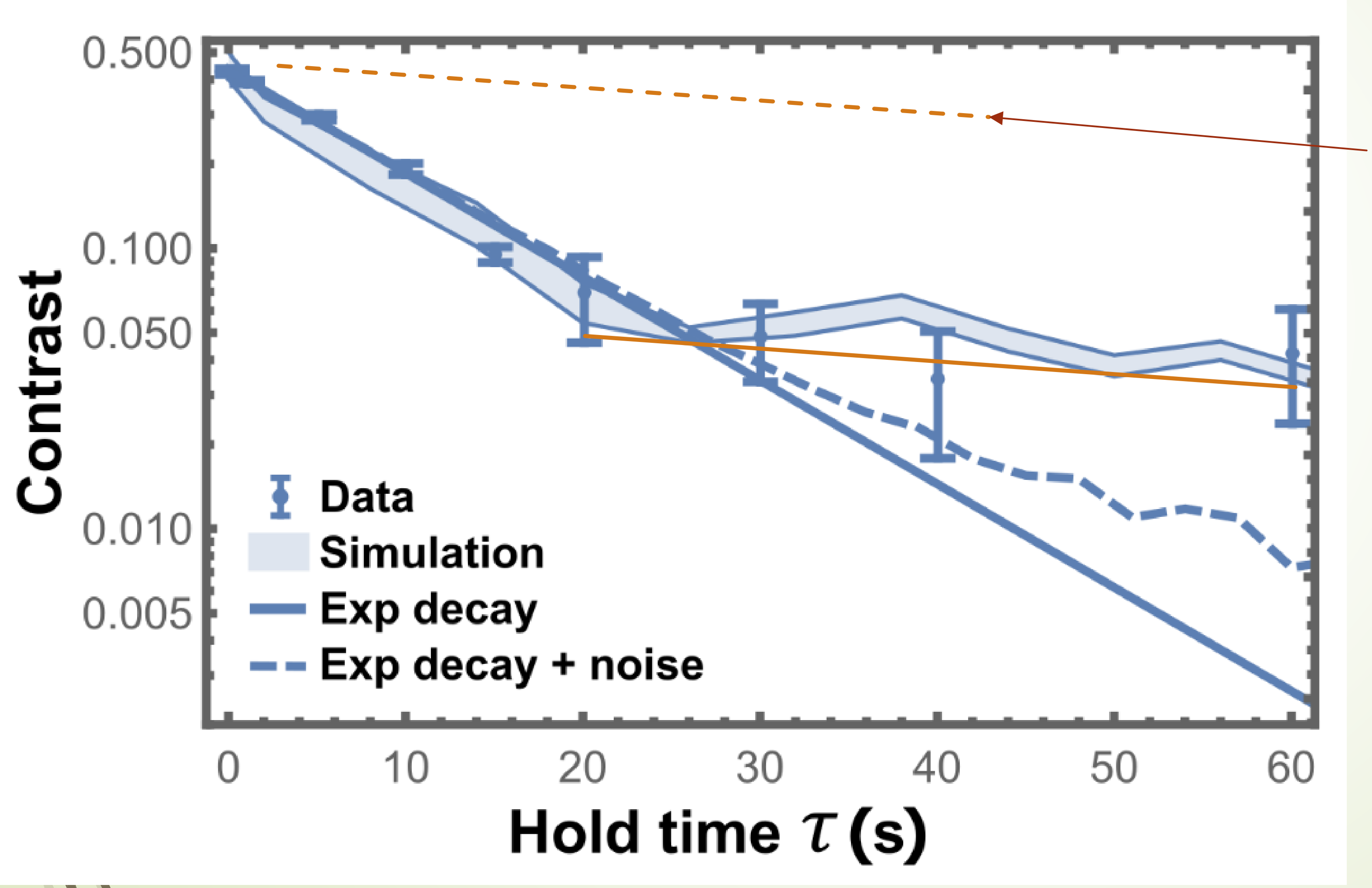


Coherent after 70 seconds!



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

Contrast decay confirms expectations



Prediction when starting with colder atoms

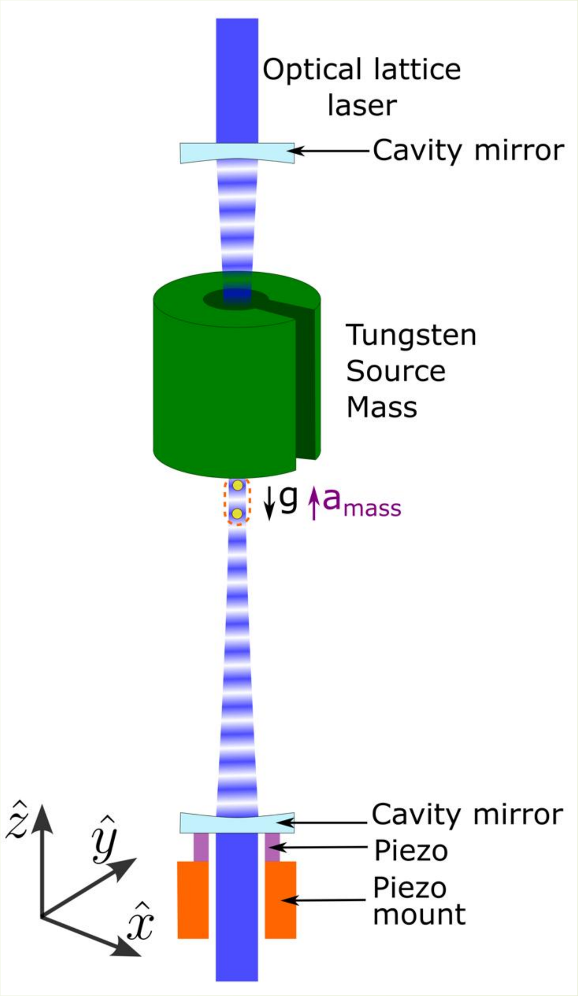
Contrast persists with >60 s decay time constant

But what about systematics?

- Light shift
  - May mimic position-dependent force
- Lattice imperfections
  - Clipping, excitation of higher order modes
  - 1 ppb of coherent stray light can give rise to radians of phase shift
- Drifts

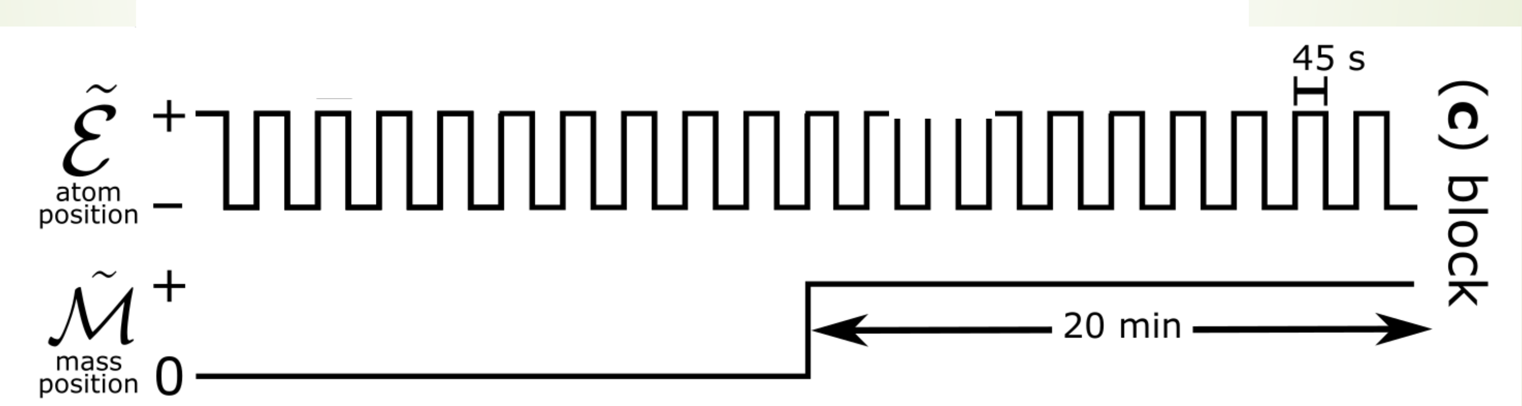
Let’s attempt a measurement of gravity of a small mass

- Tungsten mass, gravity 35 nm/s^2
- Atom elevator
- 10x increased precision:
  - Reduced laser noise
  - More efficient sample prep



From the ACME playbook: switches to suppress systematics

- Mass nearby ($\tilde{\mathcal{M}} = 1$) and mass far-away ($\tilde{\mathcal{M}} = 0$).
- Atoms above ($\tilde{\mathcal{E}} = +1$) and below source mass ($\tilde{\mathcal{E}} = +1$).

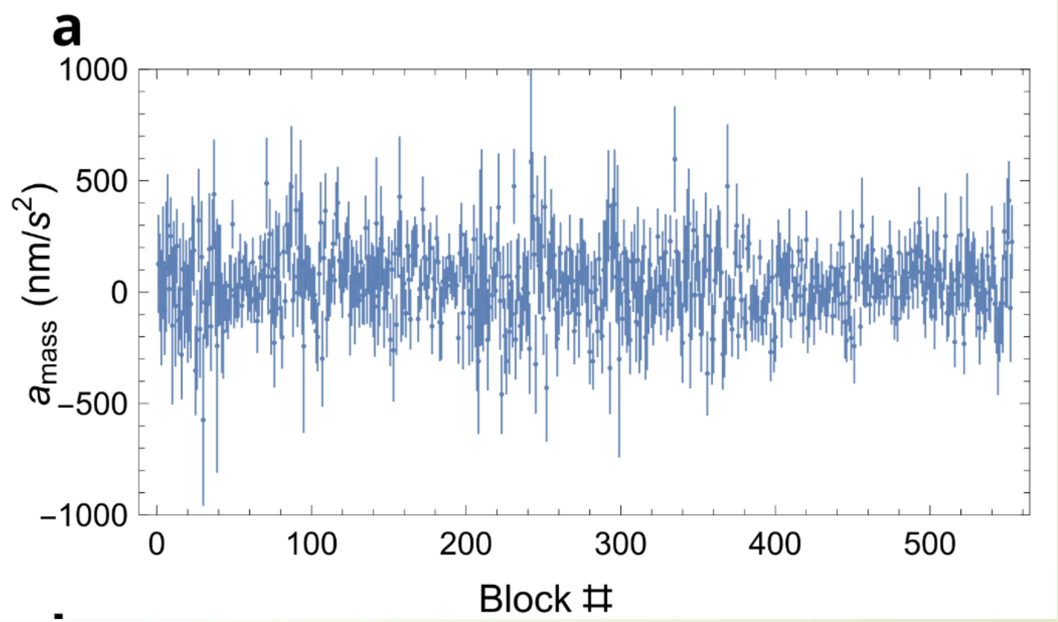


$$\boxed{a_{\text{mass}} = [a(1,1) - a(1,-1) - a(0,1) + a(0,-1)]/2}$$

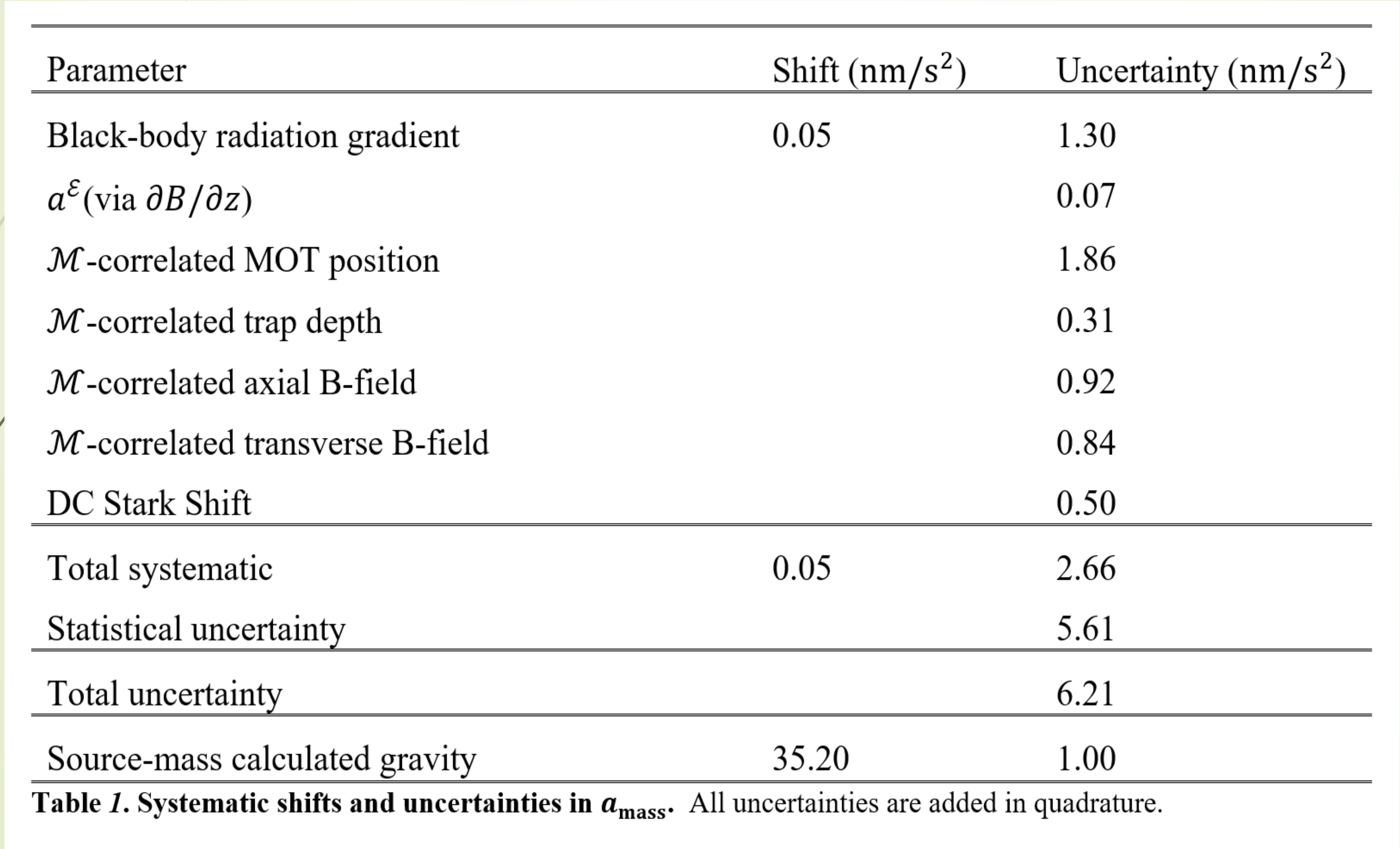
Measuring gravity by holding atoms,
CDP et al, arXiv:2310.01344 (2023)

Dataset

- 2 months of data
- Noise at the SQL, $\chi_r^2 = 1.06 \pm 0.04$.
- Systematic checks by varying over 40 parameters.
- Statistical uncertainty 5 times better than previous measurements
- $a_{\mathrm{mass}} = (*** \pm 5.6_{\mathrm{stat}} \pm 2.7_{\mathrm{syst}}) \ \mathrm{nm/s^2}$



Systematic error budget



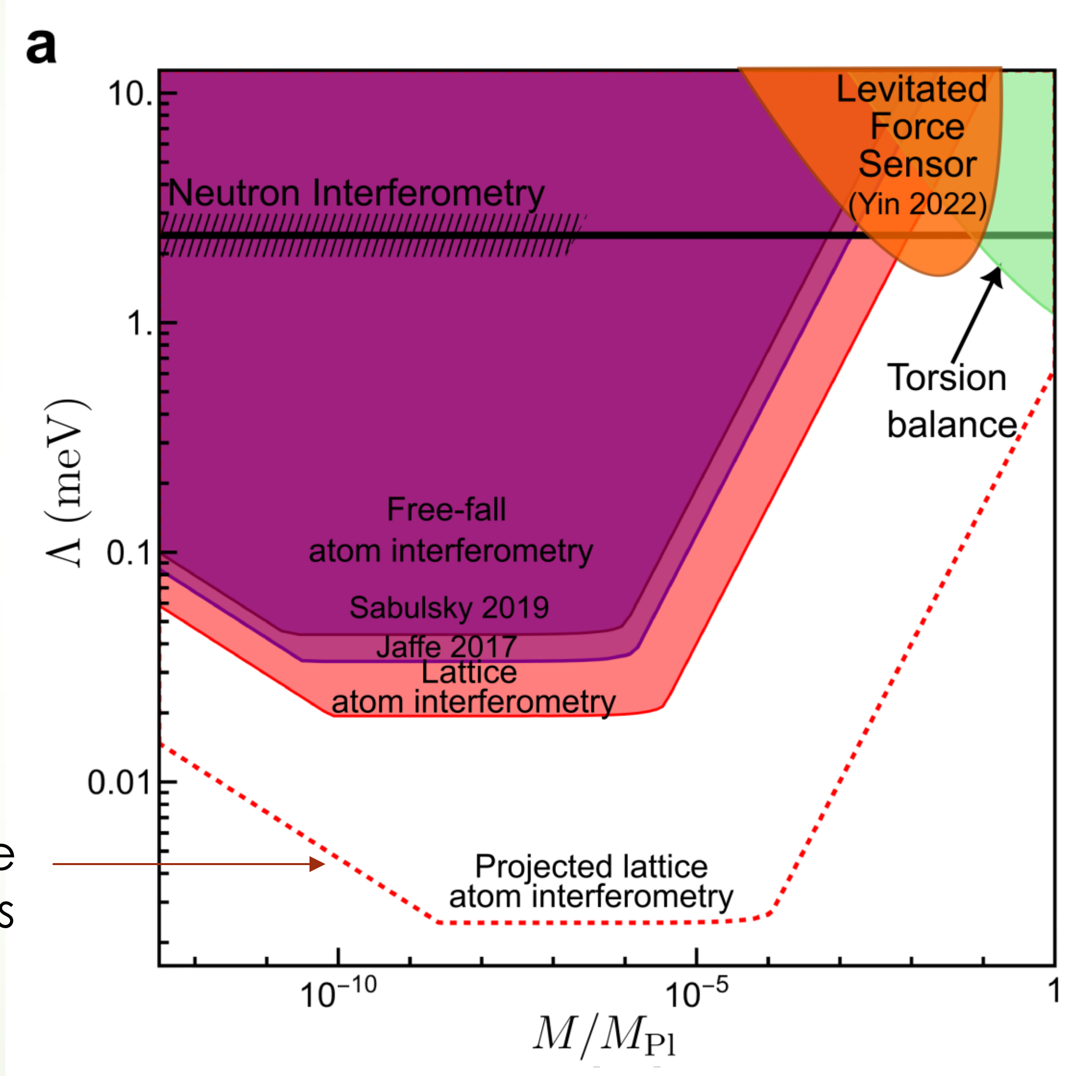
Parameter	Shift (nm/s^2)	Uncertainty (nm/s^2)
Black-body radiation gradient	0.05	1.30
$a^{\mathcal{E}}$(via $\partial B/\partial z$)		0.07
$\mathcal{M}$-correlated MOT position		1.86
$\mathcal{M}$-correlated trap depth		0.31
$\mathcal{M}$-correlated axial B-field		0.92
$\mathcal{M}$-correlated transverse 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 $\boldsymbol{a}_{\mathbf{mass}}$. All uncertainties are added in quadrature.

Unblinded result

- $a_{\mathrm{mass}} = 33.3 \pm 5.6_{\mathrm{stat}} \pm 2.7_{\mathrm{syst}} \mathrm{nm/s^2}$
- $\left|a_{\mathrm{mass}} - a_{\mathrm{mass}}^{\mathrm{calc}}\right| < 13\ \mathrm{nm/s^2}\ (95\%\ \mathrm{c.l.})$
- 6 x as sensitive as atomic fountain
- Rules out screened (chameleon) forces

New setup with better cooling, optimized source mass and lower vibrations



… 6 x as sensitive as atomic fountain

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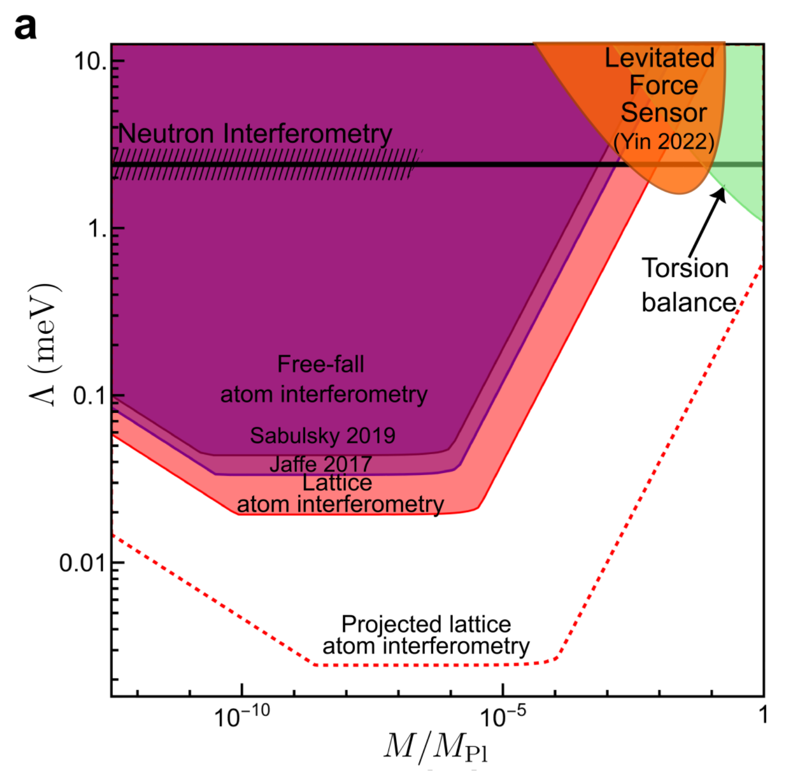
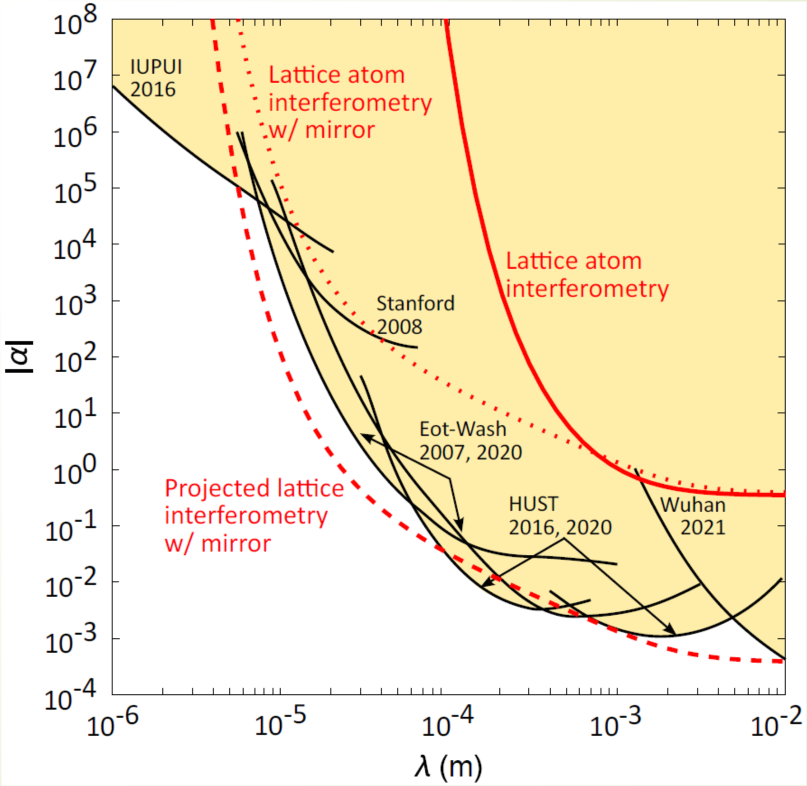
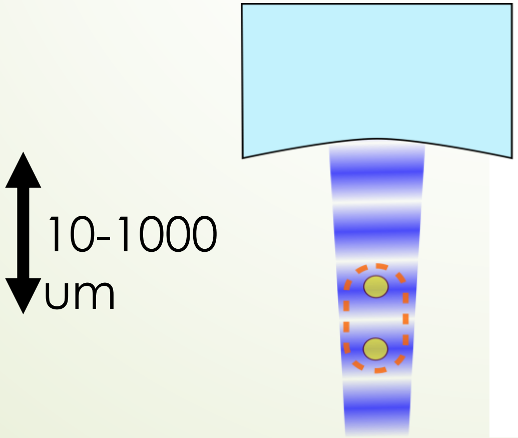


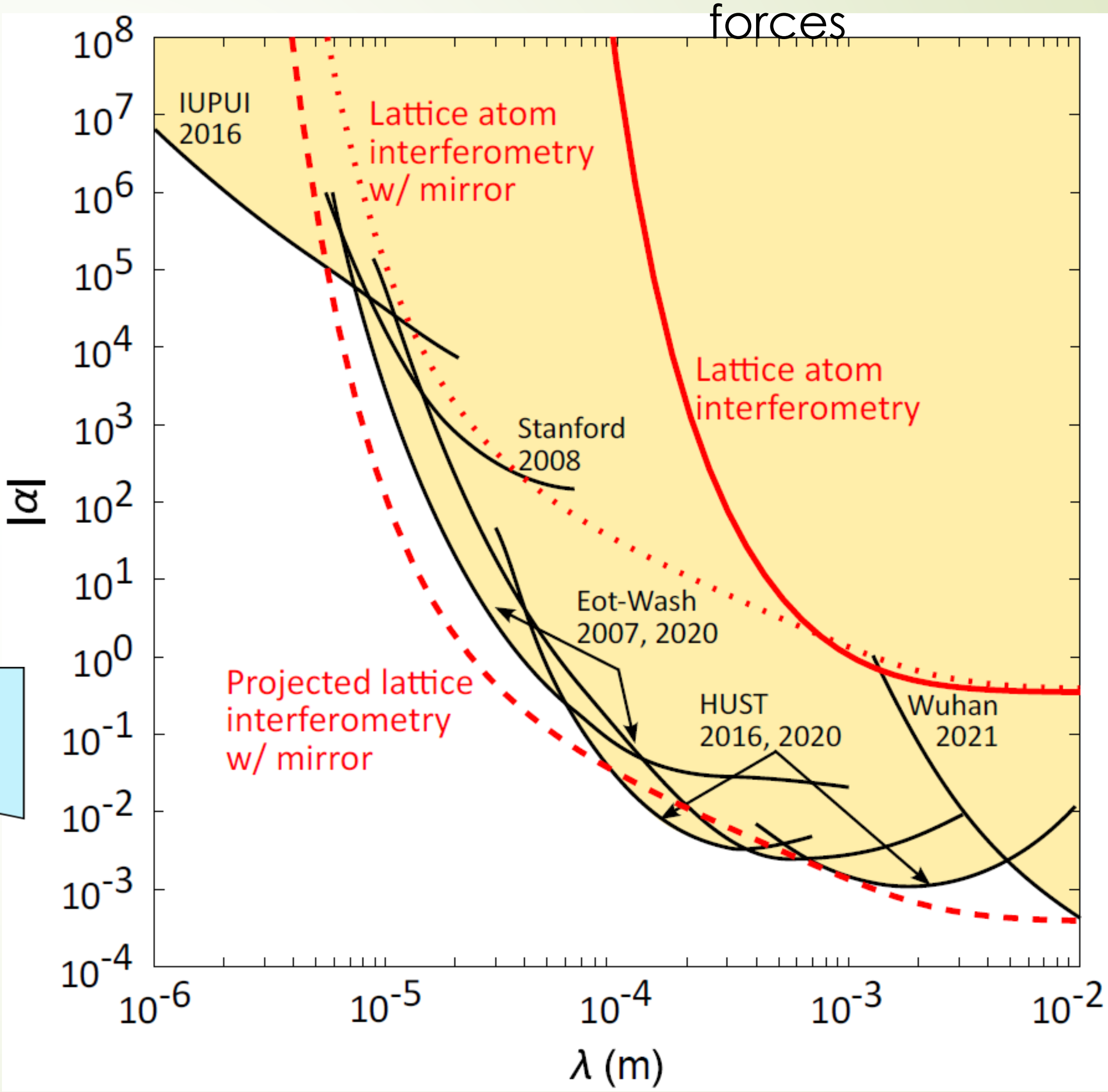


Future performance …

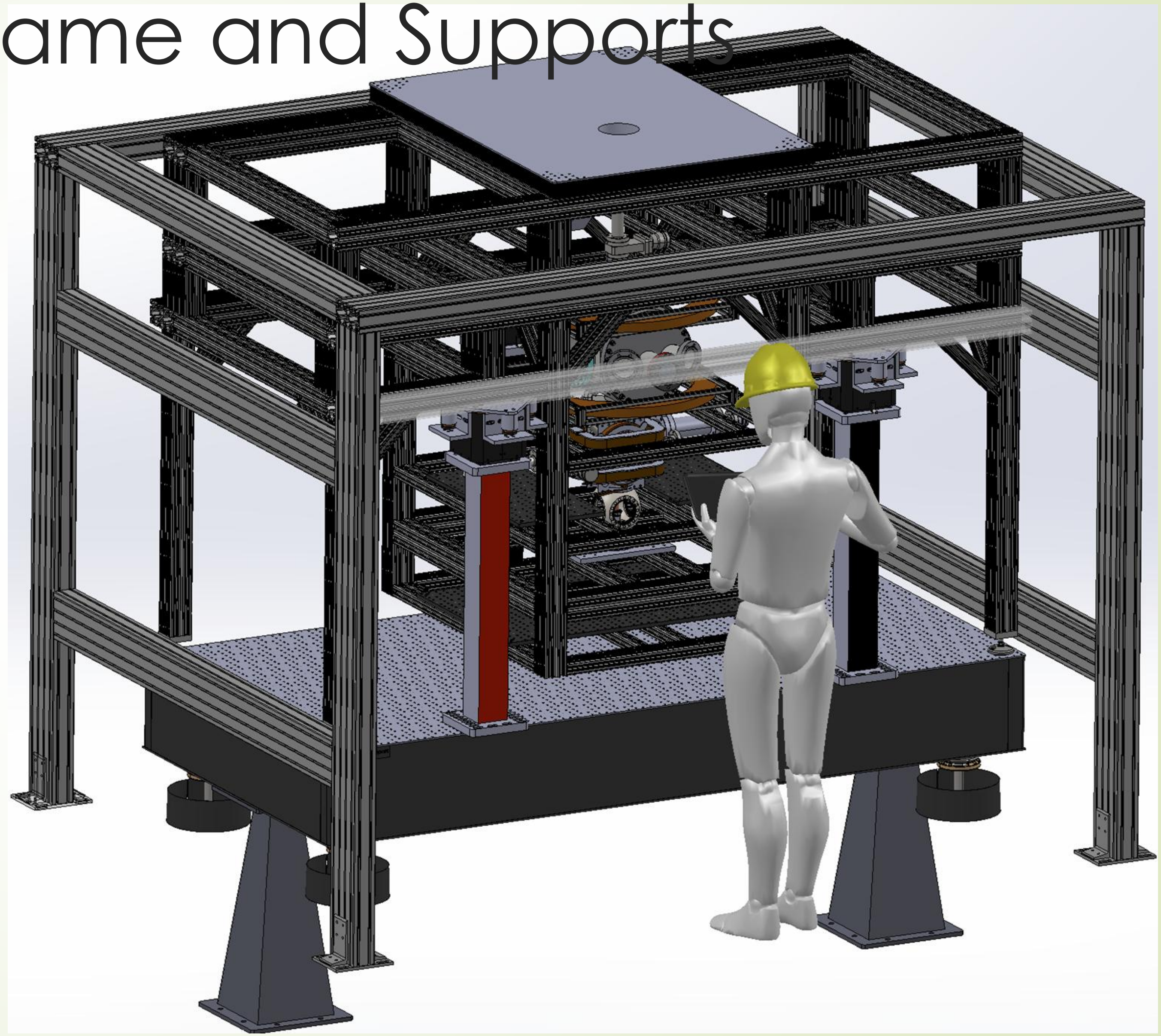
Rules out screened (chameleon) forces

- Optimized geometry
- Evaporative cooling to reduce temperature 5-fold
- ~15-fold active vibration isolation
- Newton’s G, fifth forces…





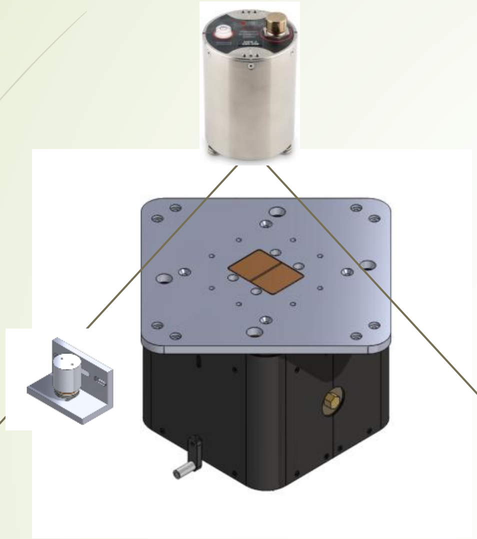
Experiment Frame and Supports

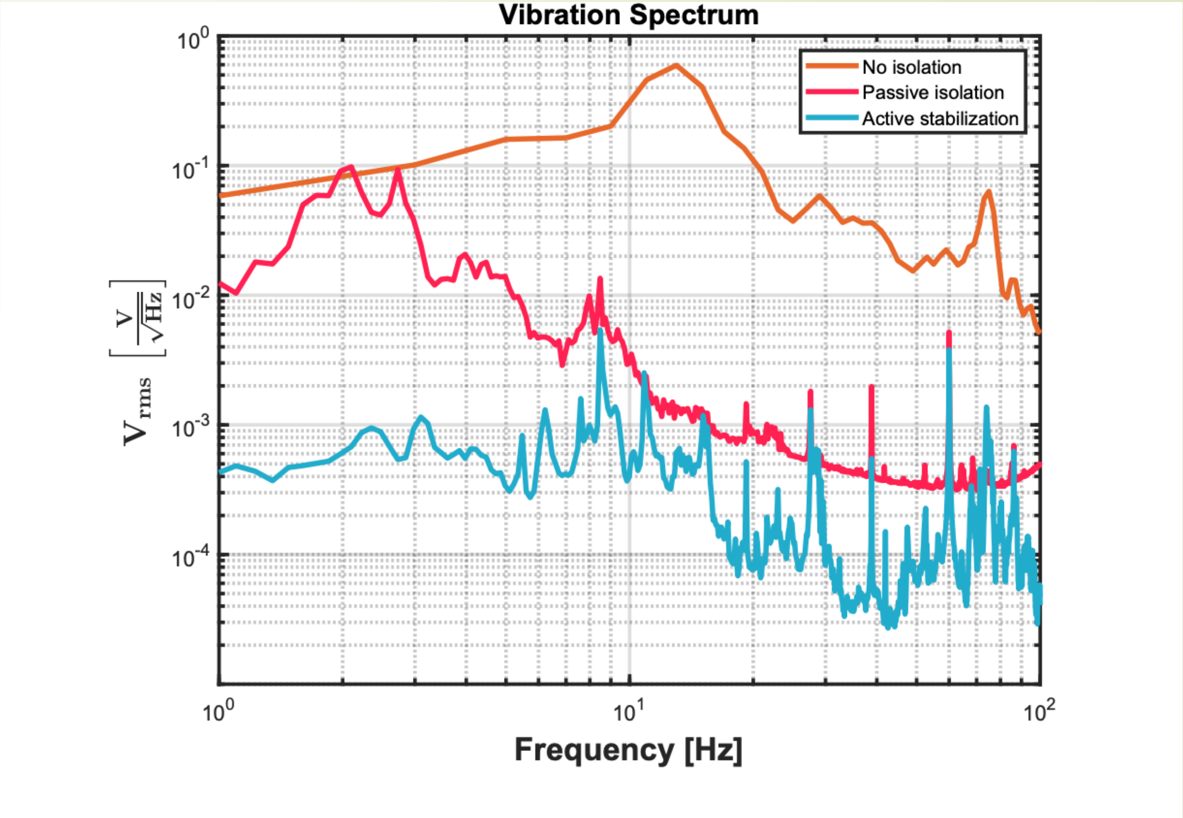


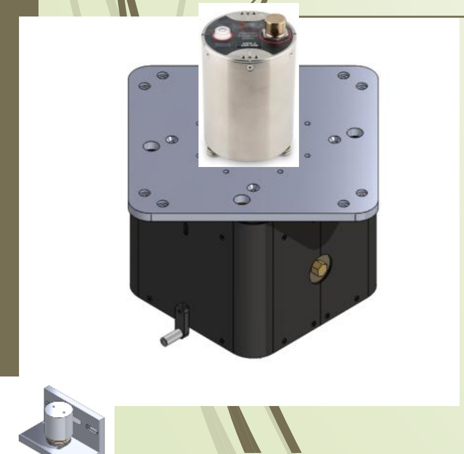
(Work in progress - feedback welcomed!)

- Outer floor-mounted support/safety structure
- Tiered inner frame floating on three minus K stages placed in an equilateral triangle

Active vibration/tilt isolation





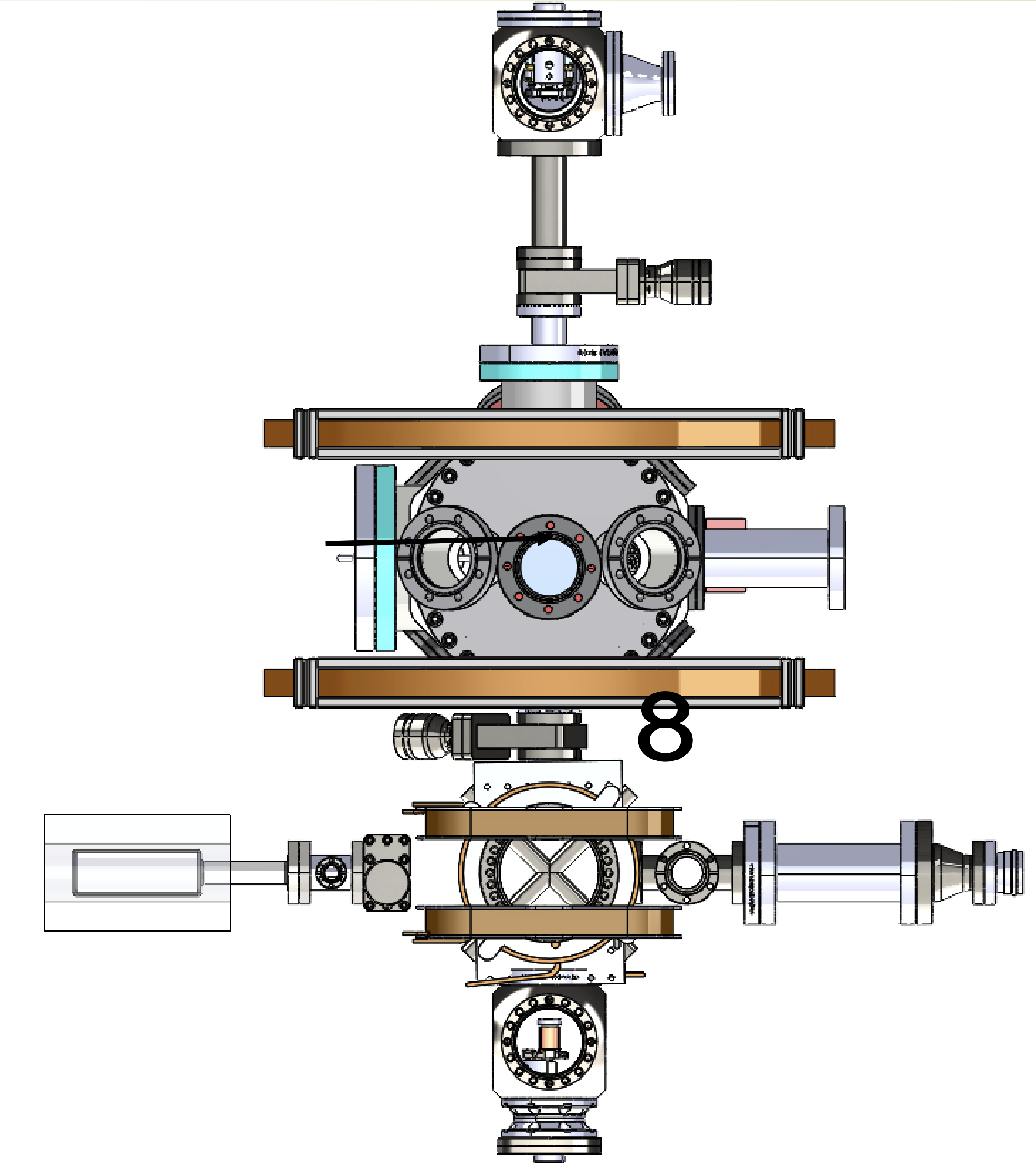


M. Jaffe, Ph. D. Thesis

Use seismometers and voice coils for active feedback

Experimental Sequence

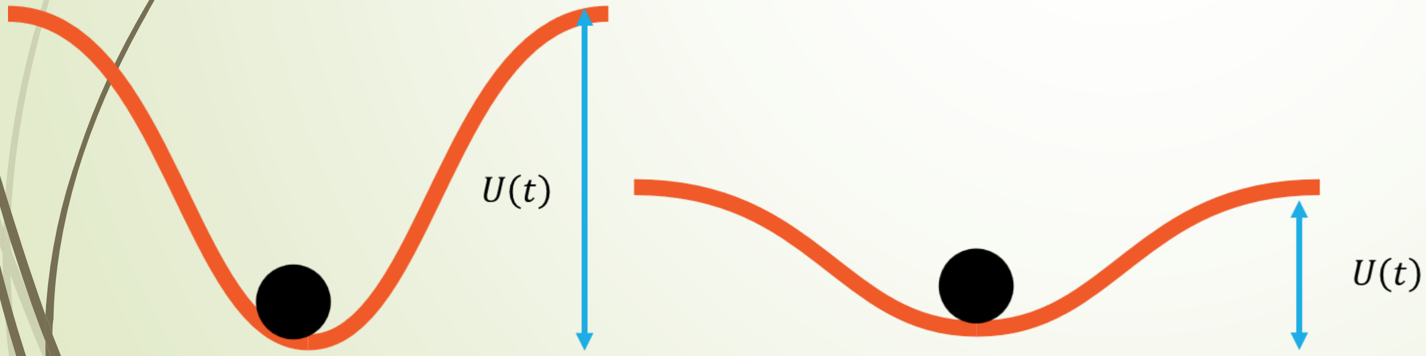
1. MOT
2. RSC/dipole trap load
3. Trap-tilt evaporation
4. State preparation & launch
5. Velocity selection
6. Elevator
7. Interferometry sequence
8. Magnetic field + pendulum interaction
9. Detection

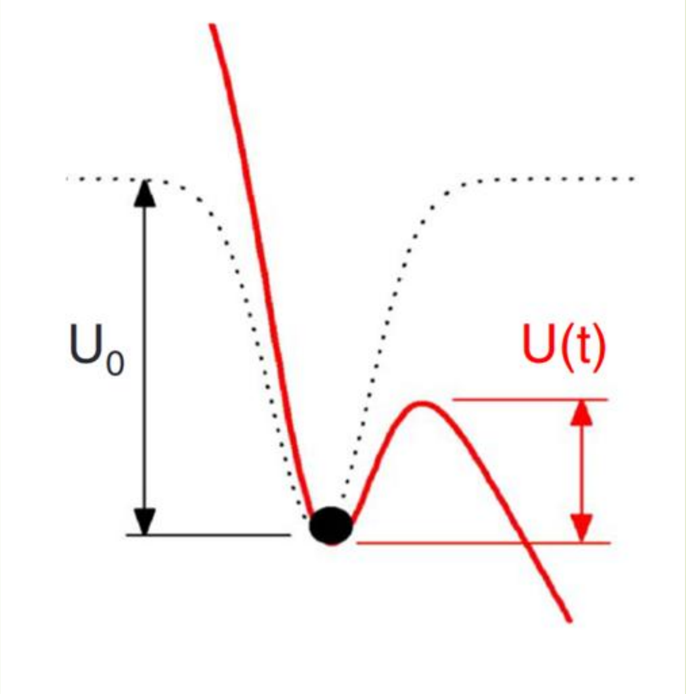


Lower atom temperatures with trap-tilt evaporation

Standard evaporation weakens confinement, slows thermalization down

…we can avoid this by applying a potential gradient via a magnetic field





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Holger Mueller
(PI)

CDP
(postdoc)

Matthew Tao
(grad)

Miguel Ceja
(undergrad)

Andrew Reynoso
(undergrad)

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Former members:
Victoria Xu
James Egelhoff
Matt Jaffee
Sofus L. Kristensen
Logan W. Clark
Philipp Haslinger
Paul Hamilton
Justin M. Brown
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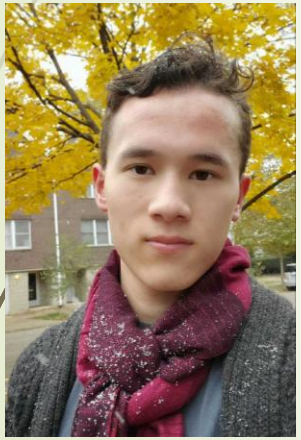
Brian Estey



Garrett Louie
(grad)

Pra Bhattacharyya
(postdoc)

Muller Group