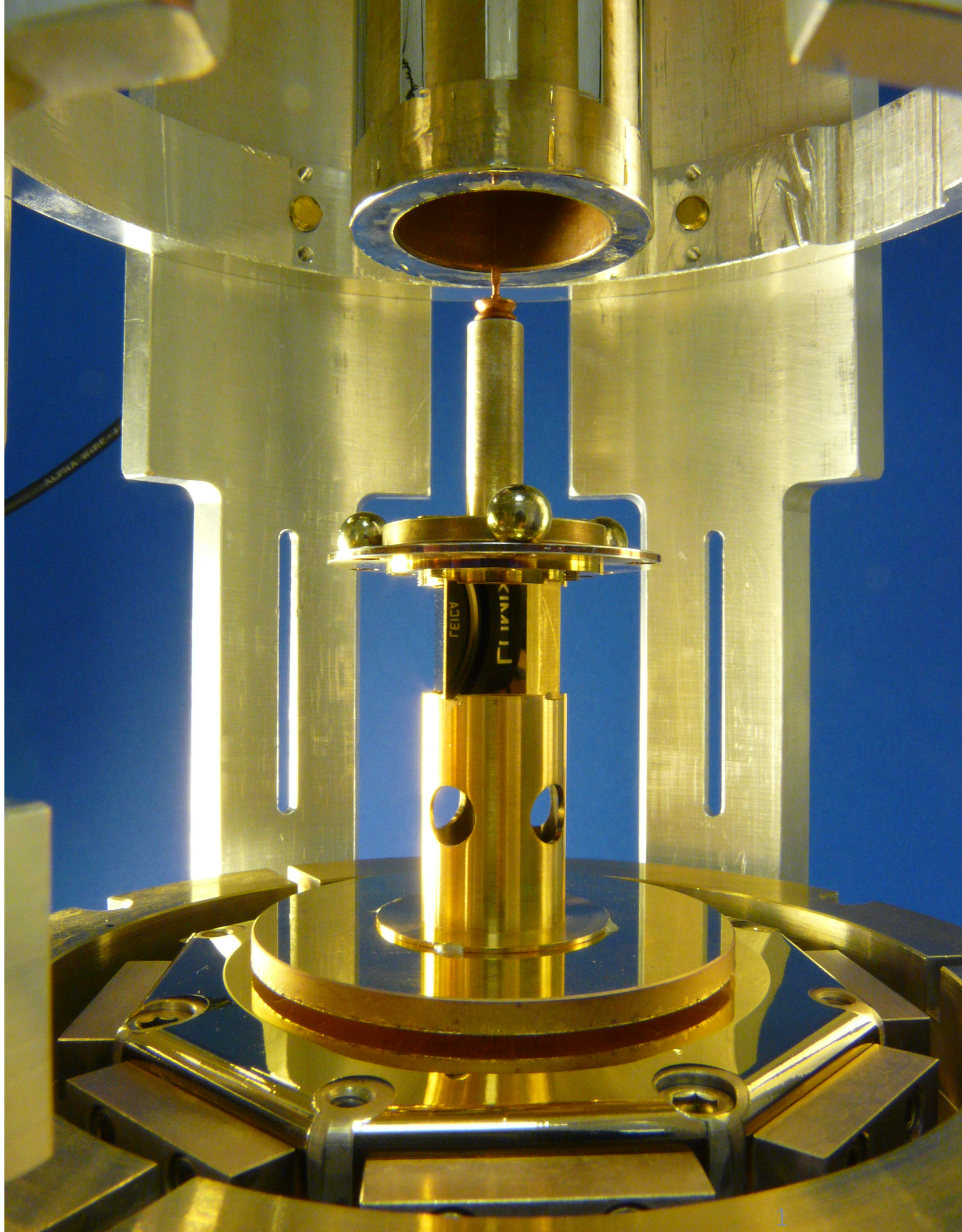
Gravity tests of all scales

David Moore, ***Yale University***

School on Table-Top Experiments for Fundamental Physics

September 22, 2022

PERIMETER INSTITUTE



https://www.npl.washington.edu/eotwash

Plan for these talks:

Lecture 1 (yesterday):

Overview of best current (lab) experiments and constraints

Lecture 2 (today):

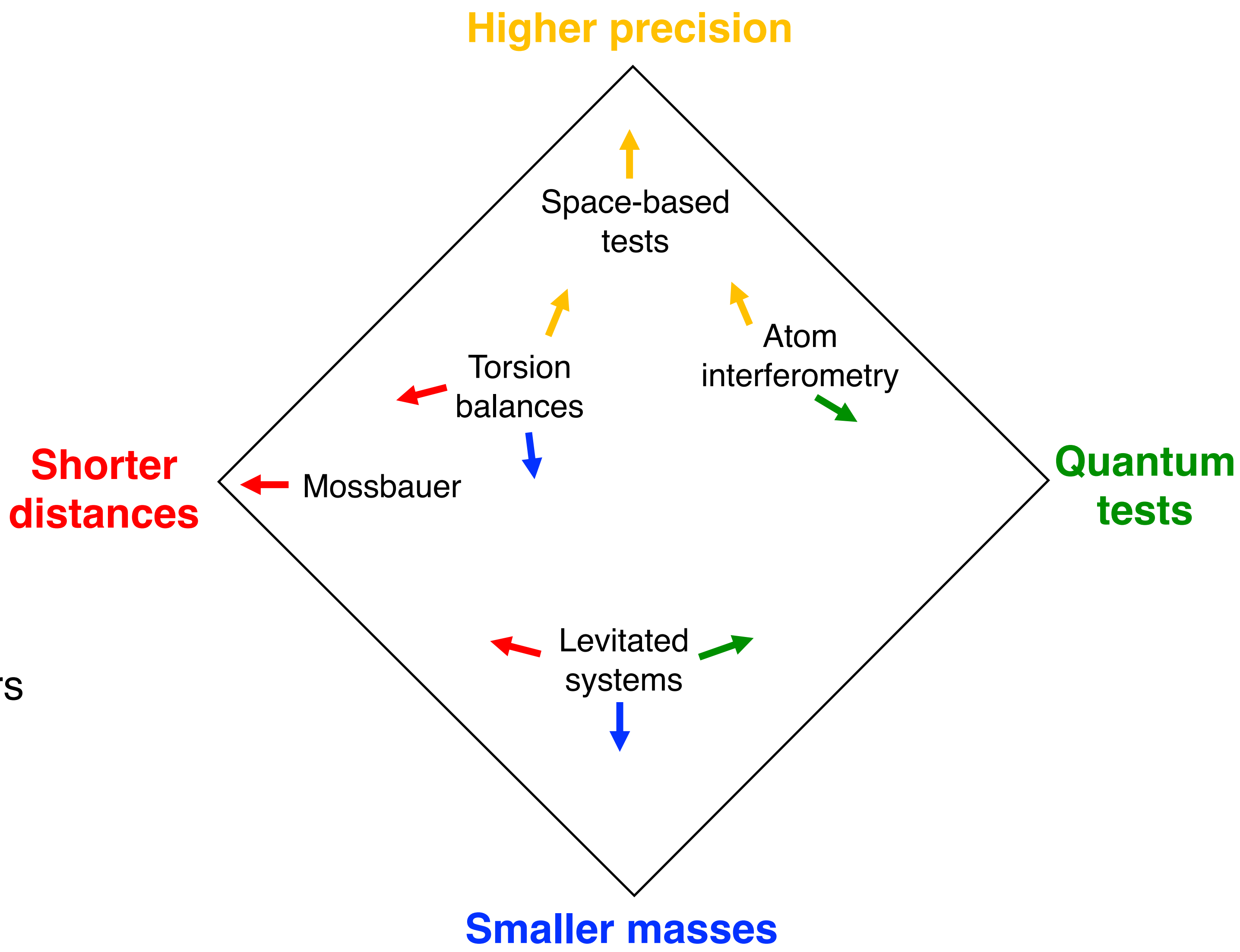
New experimental techniques and frontiers in the coming years

Current experimental frontiers

- Last lecture we summarized the existing constraints on gravity-like forces
- There are a number of new ideas to push the sensitivity of experiments towards:

  1. **Shorter Distances**
  2. **Smaller Masses**
  3. **Higher Precision**
  4. **Quantum tests**

- Many of the new techniques under development are aimed at multiple frontiers
- The first tests of gravity between quantum systems may also be on the horizon!



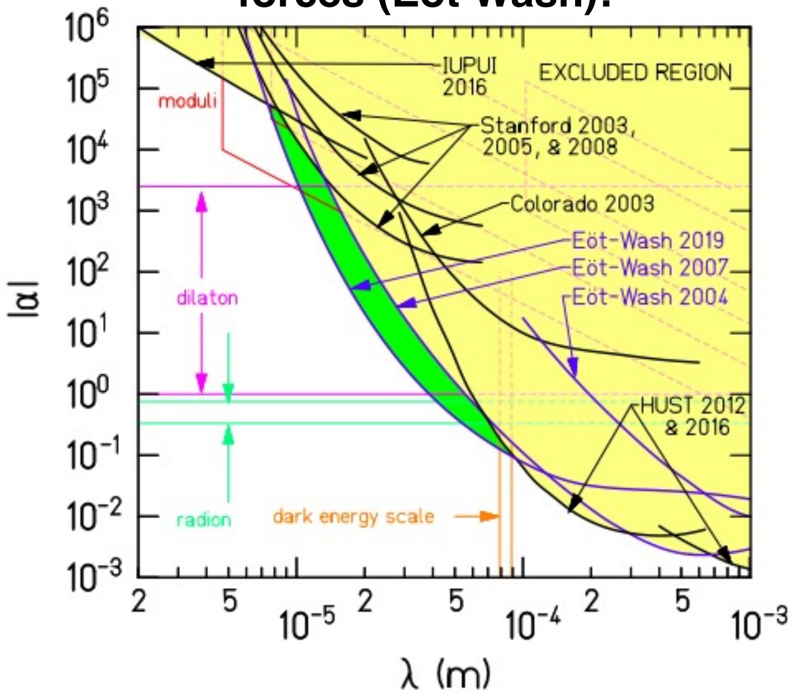
Experimental Frontiers:

1. Shorter Distances
2. Smaller Masses
3. Higher Precision
4. Quantum tests

Shorter distances

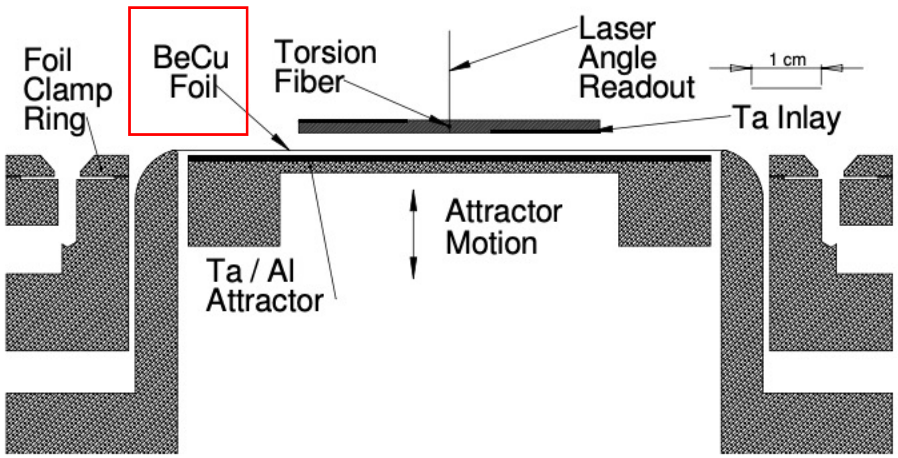
- Torsion balances (Eot-Wash) have now pushed measurements of gravitational strength interactions down to ~50 μm distances
- Measurements are not limited by intrinsic sensitivity, but instead by backgrounds
  - In particular, electrostatic "patch potentials" on shielding foil are extremely difficult to avoid

Constraints on short-range forces (Eot Wash):



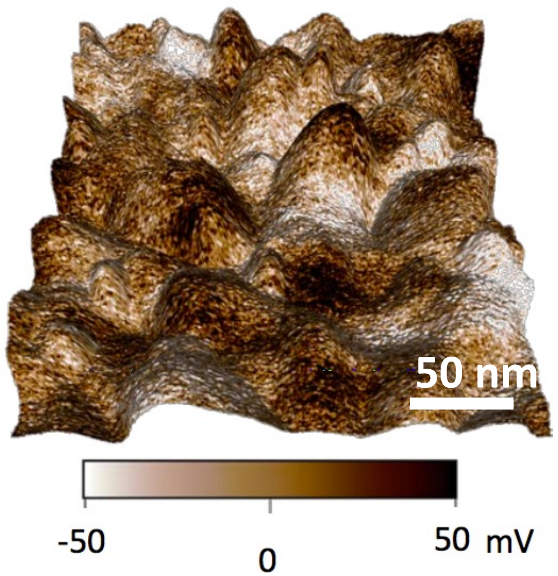
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.124.101101

Cross-section of Eot Wash ISL apparatus:



https://digital.lib.washington.edu/researchworks/bitstream/handle/1773/34135/Hagedorn_washington_0250E_14426.pdf

Topography and surface potential for sputtered Au film:

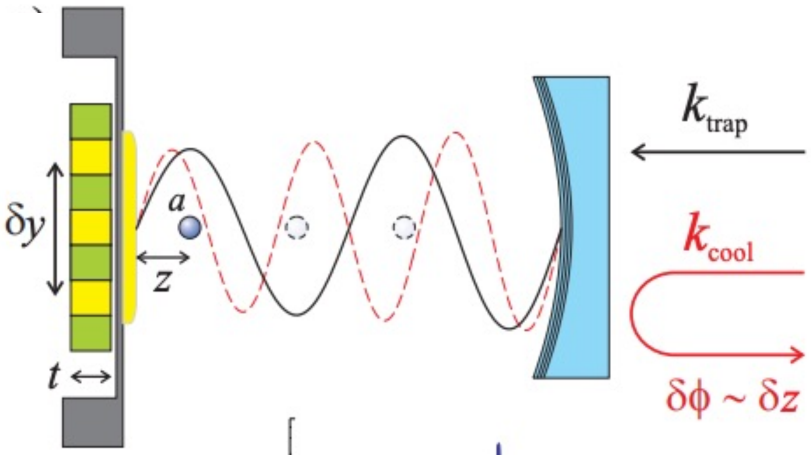


*Garrett et al., J. Phys. Condens. Matter **27**, 214012 (2015)*

Levitated optomechanical systems

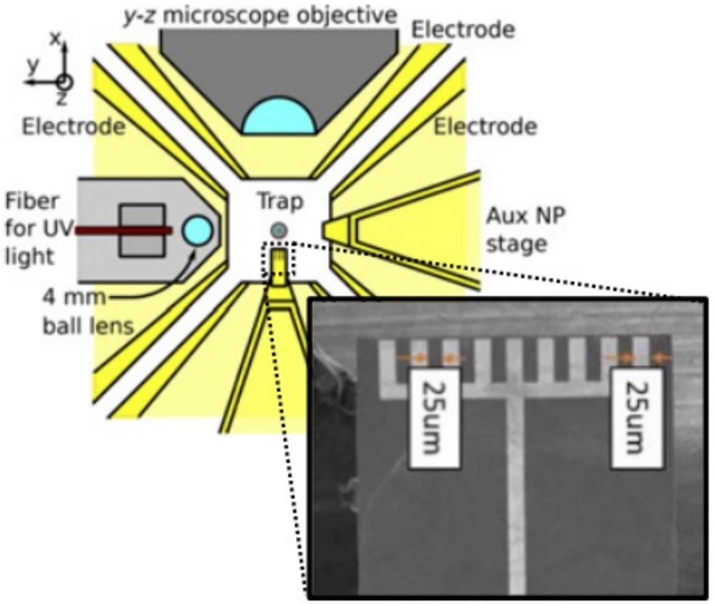
- New techniques using optically trapped particles (~100 nm to ~10 μm silica spheres) are being developed to probe shorter distances
- As with the torsion balance, existing systems are limited by backgrounds rather than sensitivity
  - Patch potentials, vibrations, scattered trapping light, …
- The key challenge is to design an attractor that modulates the mass at micron distances and is robust to these backgrounds ("lock-in measurement")

Northwestern (Geraci group):



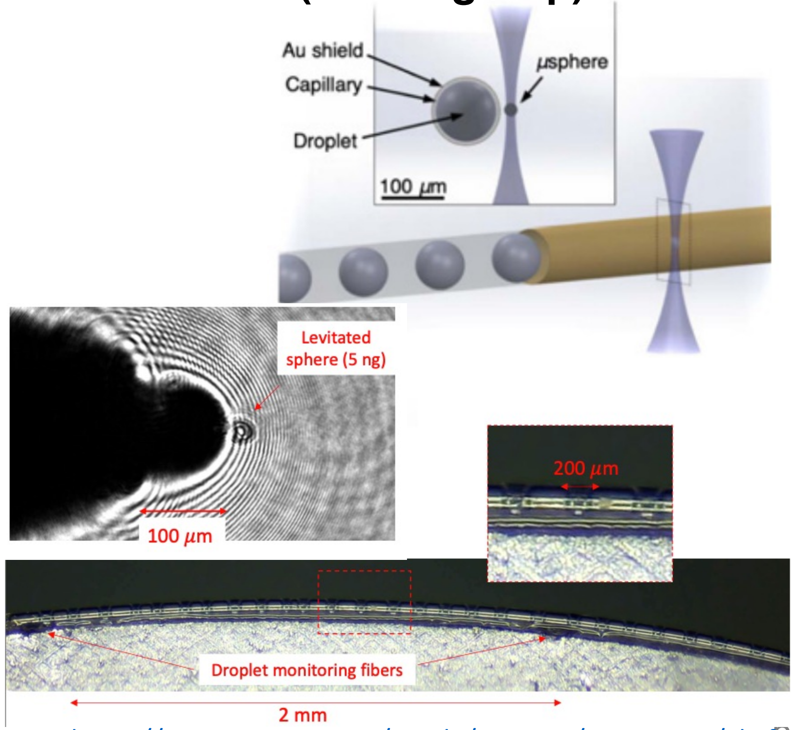
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.105.101101

Stanford (Gratta group):



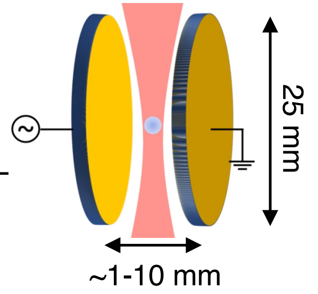
https://aip.scitation.org/doi/10.1063/5.0011759

Yale (Moore group):

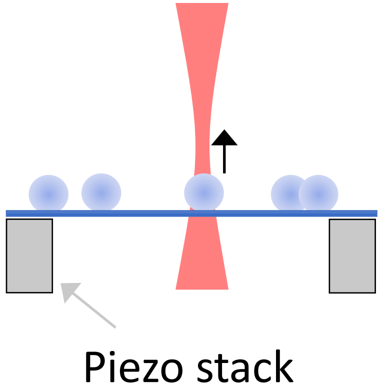


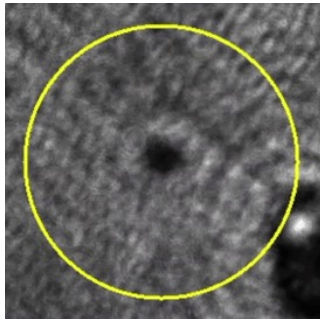
https://iopscience.iop.org/article/10.1088/2058-9565/abcf8a

Control of backgrounds/noise



Step 1: Trap sphere (~1 mbar)

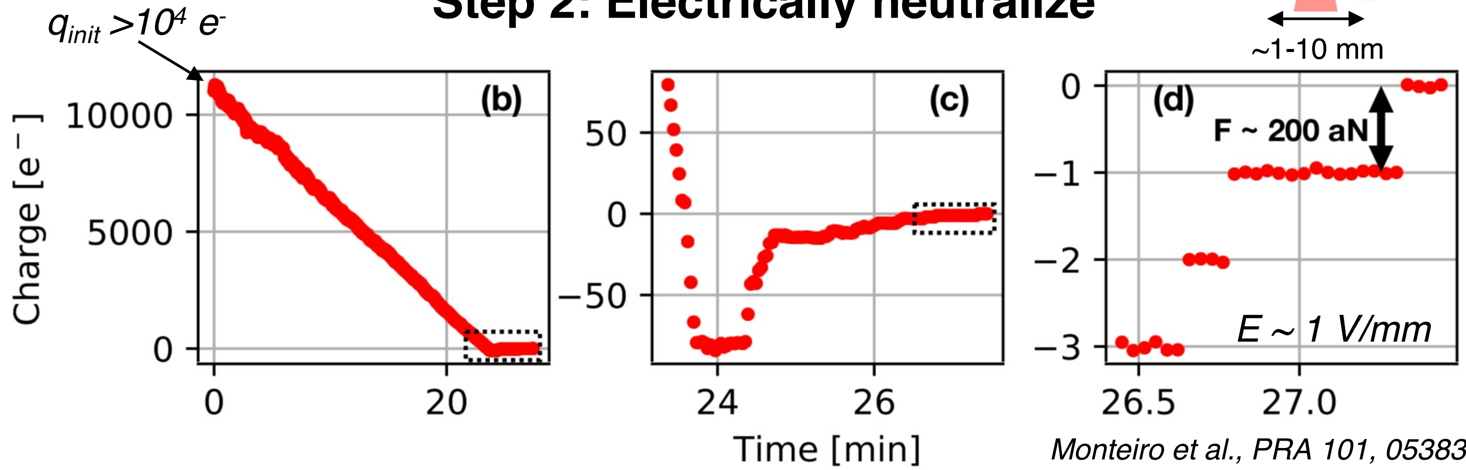




Monteiro et al., PRA 101, 053835, arXiv:2001.10931(2020)

Pump to ≲10^{-7} mbar

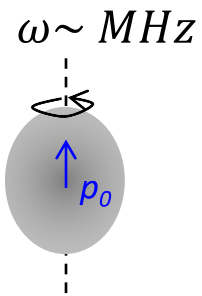
Step 2: Electrically neutralize

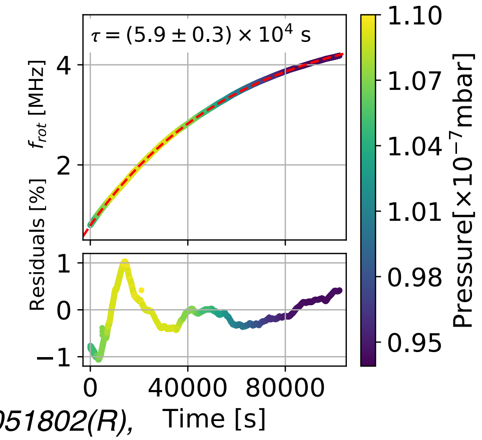


Monteiro et al., PRA 101, 053835, arXiv:2001.10931(2020)

Step 3: Stabilize spin

Optically spin to >MHz frequency

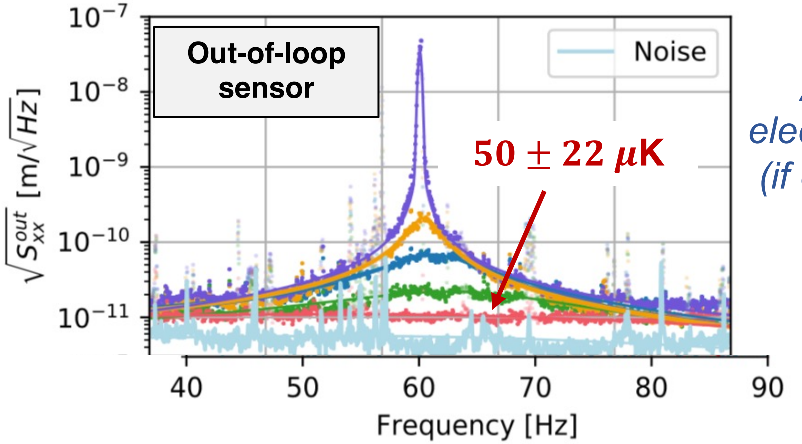




Monteiro et al., PRA 97, 051802(R), arXiv:1803.04297 (2018)

Active feedback cooling to <100 μK

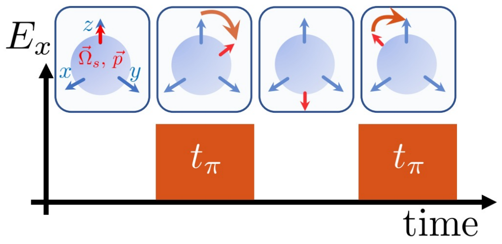
Step 4: Cool center-of-mass mode



Monteiro et al., PRA 101, 053835, arXiv:2001.10931(2020)
Monteiro et al., PRA 96, 063841, arXiv:1711.04675 (2017)

Step 5: Orient electric dipole moment

Apply electric field (if desired)

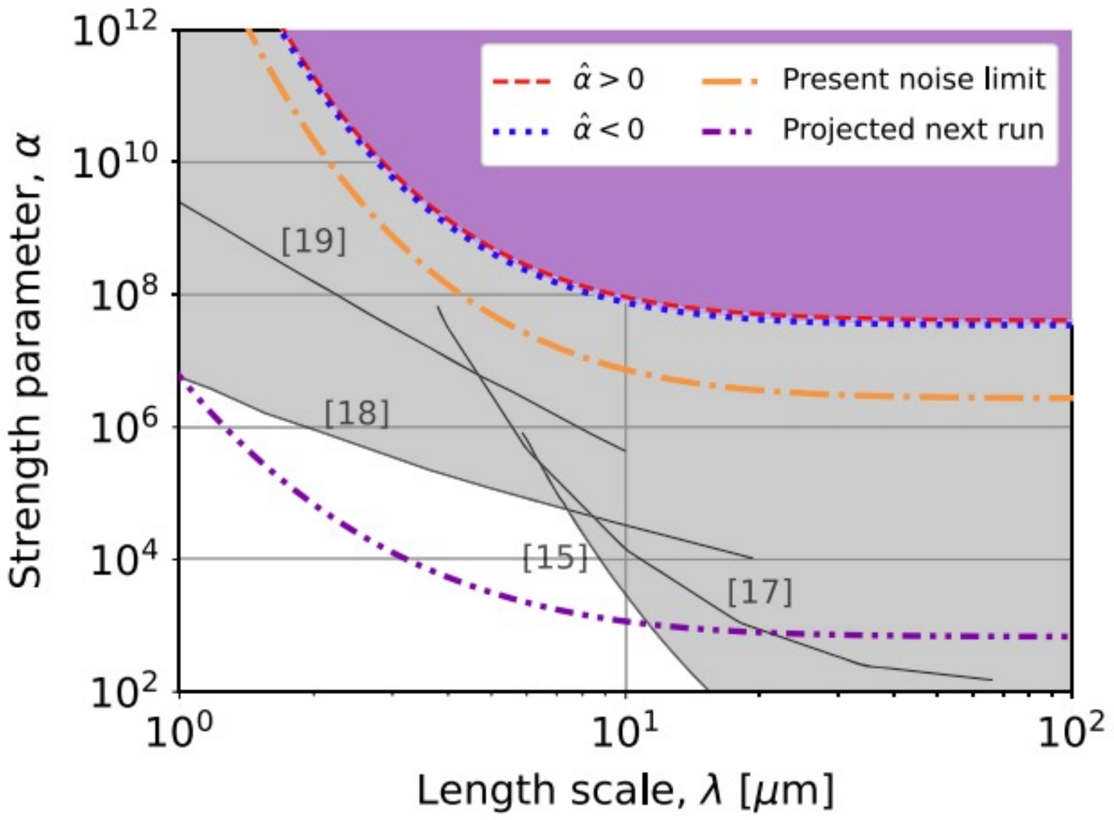


Afek et al., PRA 104, 053512, arXiv:2108.04406 (2021)

Current and future sensitivity (levitated systems)

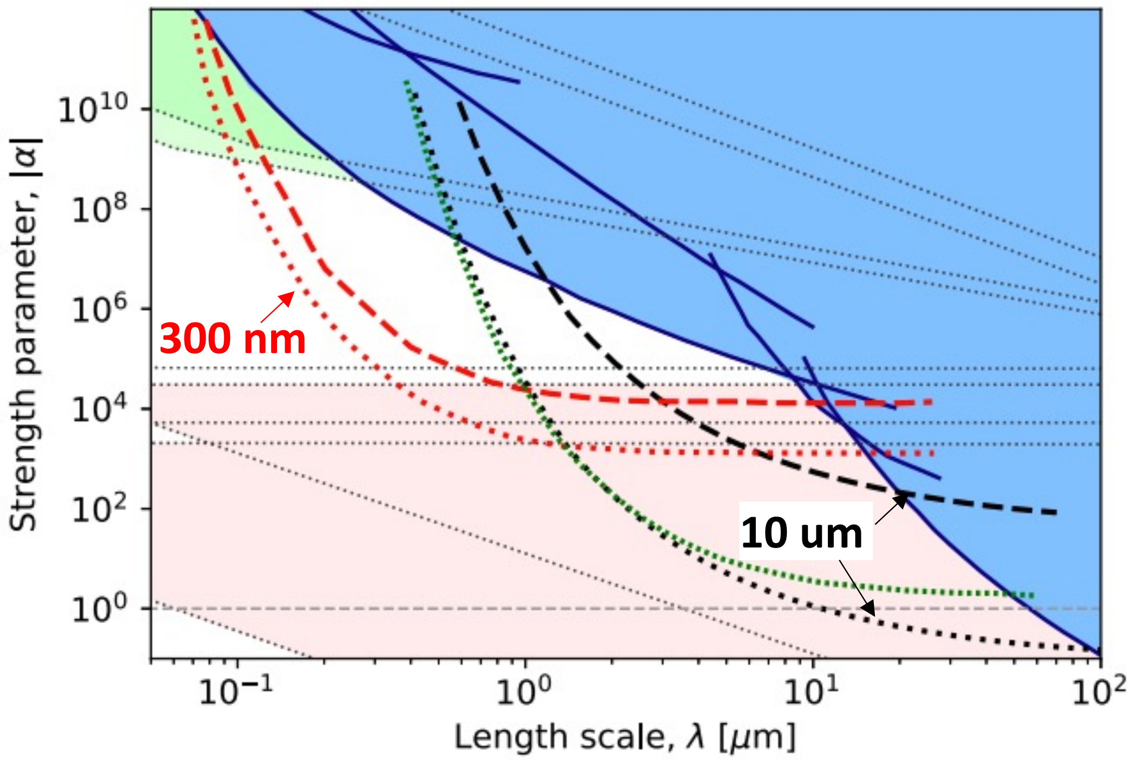
- First gravity test with a levitated system was recently performed by Stanford group (see talk by Giorgio)
- Further reducing backgrounds may allow gravity-strength interactions to be measured down to ~1-10 micron distances

First results from Stanford and near term sensitivity:



https://journals.aps.org/prd/abstract/10.1103/PhysRevD.104.L061101

Possible future sensitivity (~background free):

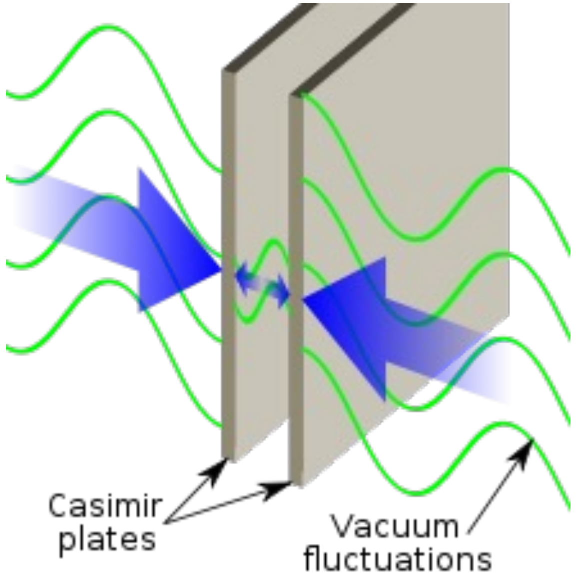


https://iopscience.iop.org/article/10.1088/2058-9565/abcf8a

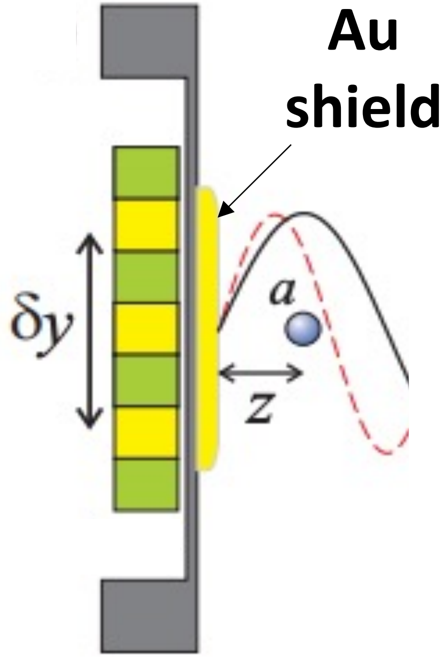
Casimir force

- Below ~micron distances, even a technically perfect experiment of the standard type (mass moving behind shield) would start to be limited by fundamental E&M backgrounds
- Shielding the Casimir force itself requires ~micron thick layers for real metals (e.g. Au)
- Further progress would require new ideas or accurate subtraction of Casimir force background

Schematic of Casimir force in vacuum fluctuation picture:



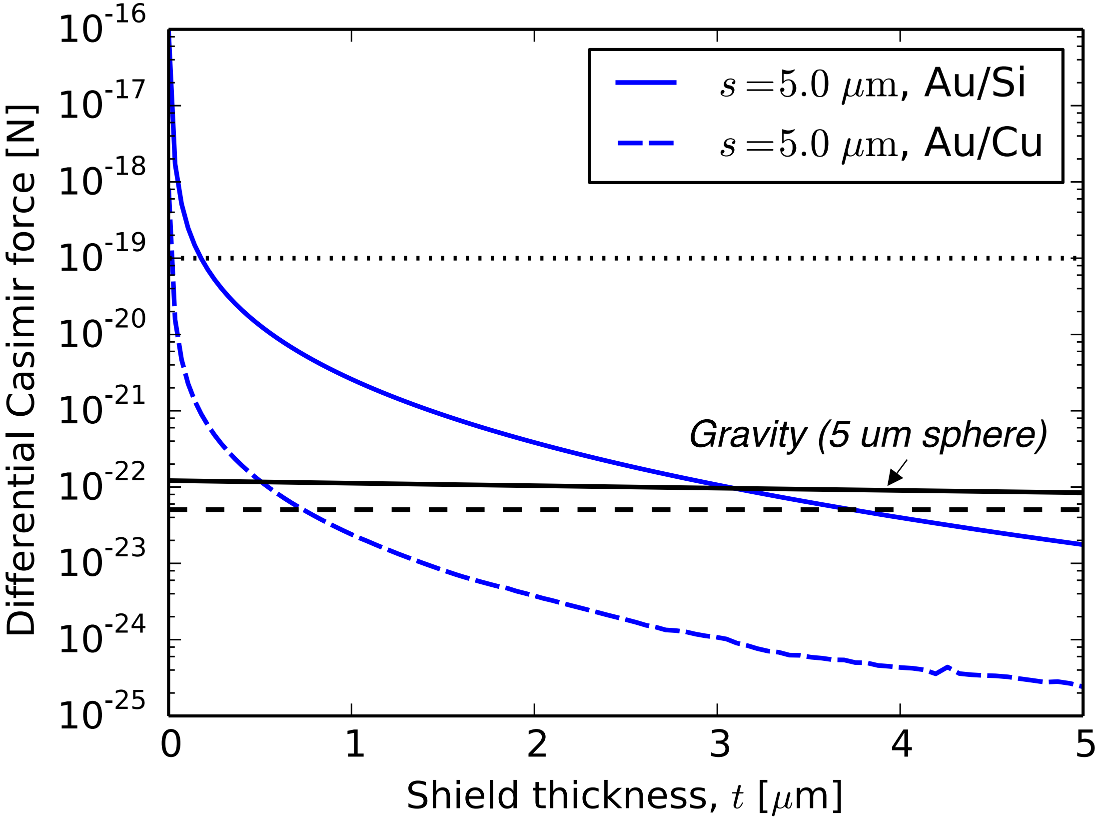
https://en.wikipedia.org/wiki/Casimir_effect



Note there is a completely equivalent description in terms of surface dipoles!

https://journals.aps.org/prd/abstract/10.1103/PhysRevD.72.021301

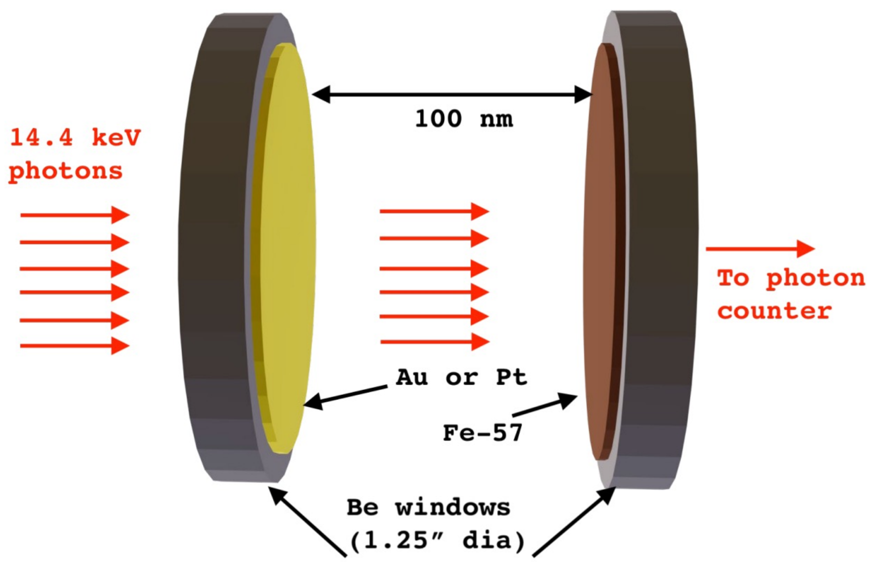
Calculation of differential Casimir force:



Mossbauer spectroscopy

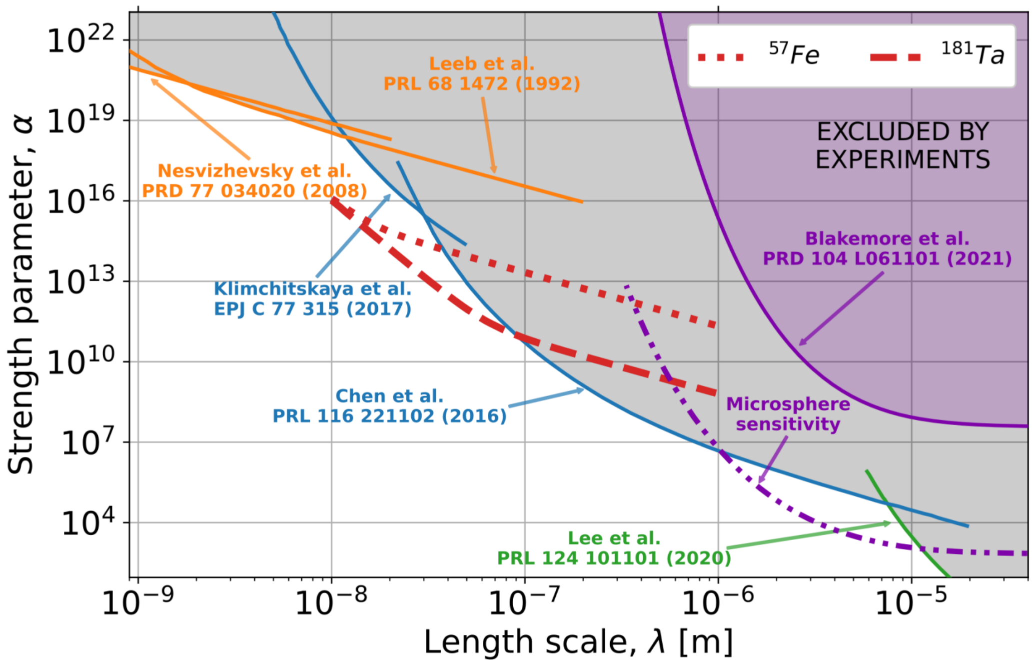
- Rather than shielding Casimir (and other E&M effects) with a conducting layer, use the electron cloud around a nucleus!
- Mossbauer effect allows absorption spectroscopy measurement of nuclear transitions
  - Similar to atomic absorption spectroscopy but at keV energies (with relative linewidths of 10^{-12} to 10^{-25}!)
- First experiments expected to be sensitivity rather than background limited!

Experimental schematic:



https://journals.aps.org/prd/abstract/10.1103/PhysRevD.102.115031

Projected sensitivity (Gratta group):



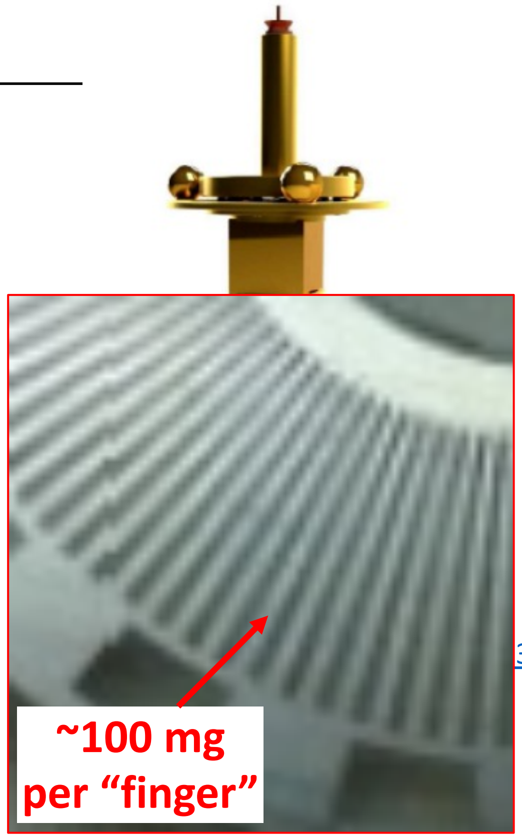
Use of synchrotron light sources to directly excite transitions may give further improvement!

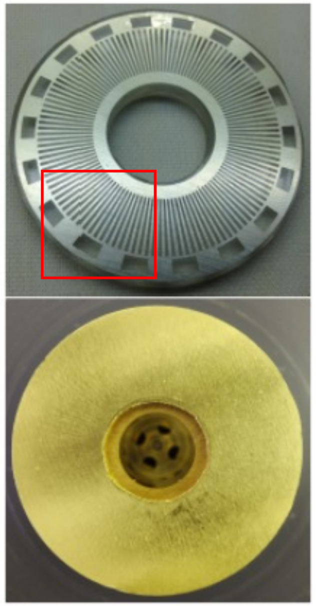
Experimental Frontiers:

1. Shorter Distances
2. Smaller Masses
3. Higher Precision
4. Quantum tests

Smaller masses

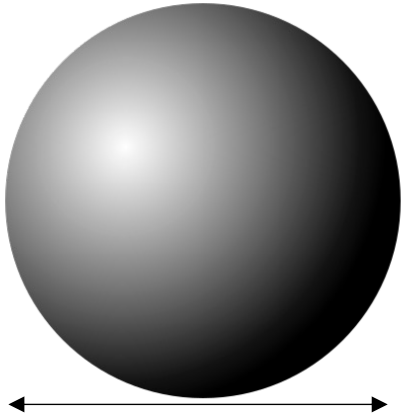
- Because there is a maximum practical density ($\rho \lesssim 20$ g/cm^3), smaller distances often correspond to smaller masses
- E.g., for Eot-Wash, divide attractor into 120-fold ”fingers”, each with mass ~100 mg
- For classical experiments, the optimal arrangement of mass is just a signal-to-background question
- However, single isolated masses are likely required for detecting gravity in experiments with “quantum” masses
- The smallest masses for which we can measure gravity to date are ~10^4 x larger than M_{Pl}, but may decrease quickly in near future!





3/PhysRevLett.124.101101

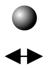
State-of-the-art (see next slide):



2 mm -> 100 mg

10^4 x lower mass

Planck Mass:

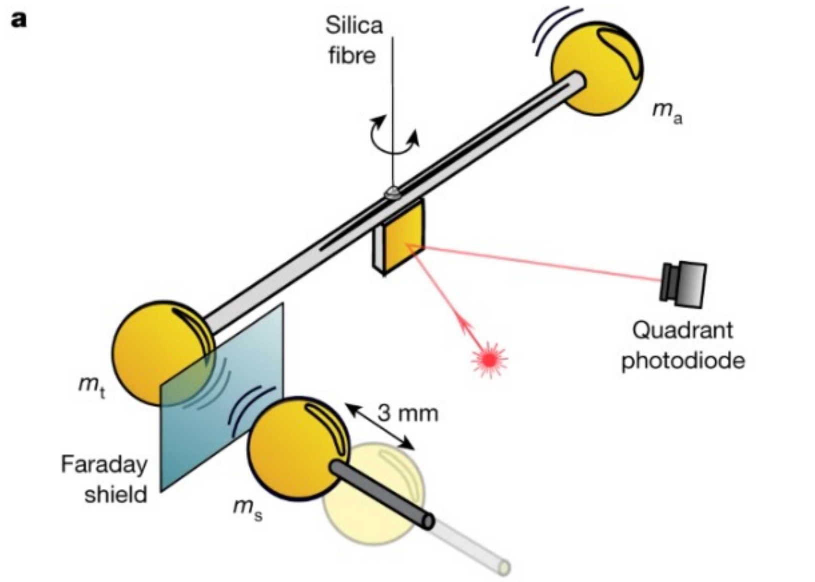


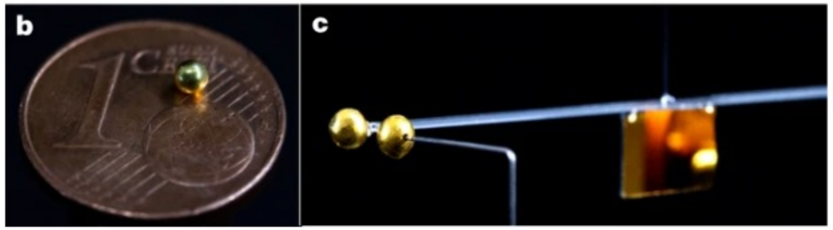
0.1 mm -> 20 μg

Smaller masses

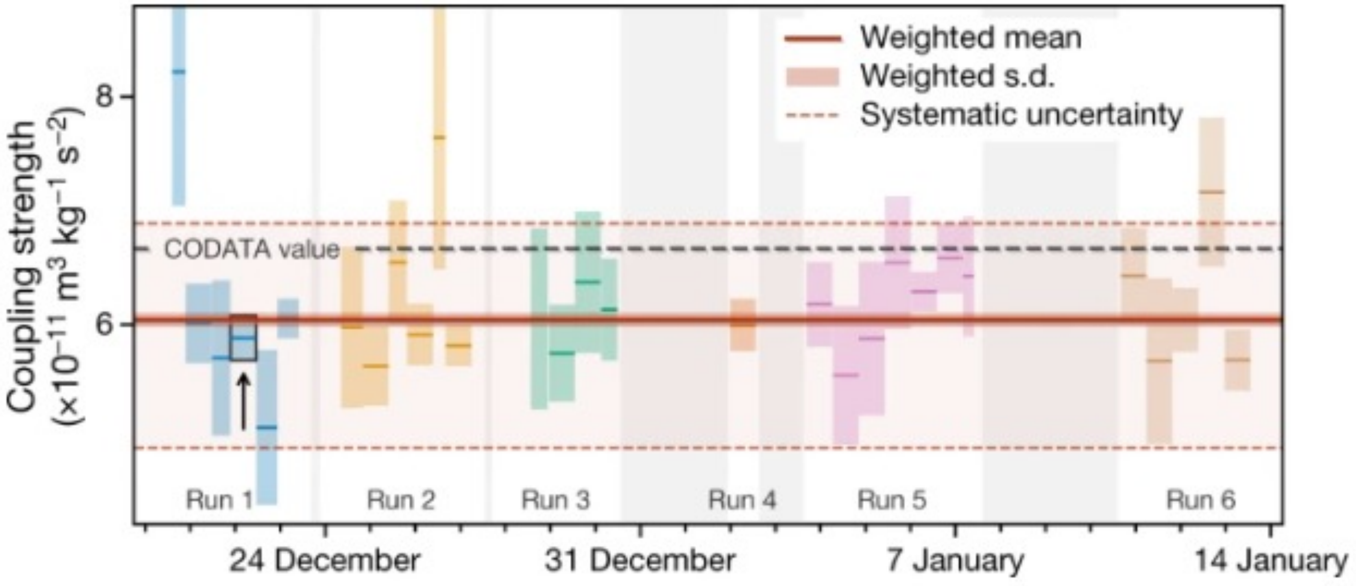
- The Vienna group (Aspelmeyer) has recently measured gravity between two isolated ~mm scale masses using a miniature torsion balance!
  - Working towards smaller masses using torsion balances, as well as levitated systems (magnetic, optical)

Schematic of experimental setup:





Measured coupling of 1/r² force:



Systematics dominated -> ~10% level accuracy measurement of G (~1% statistical precision)

https://www.nature.com/articles/s41586-021-03250-7

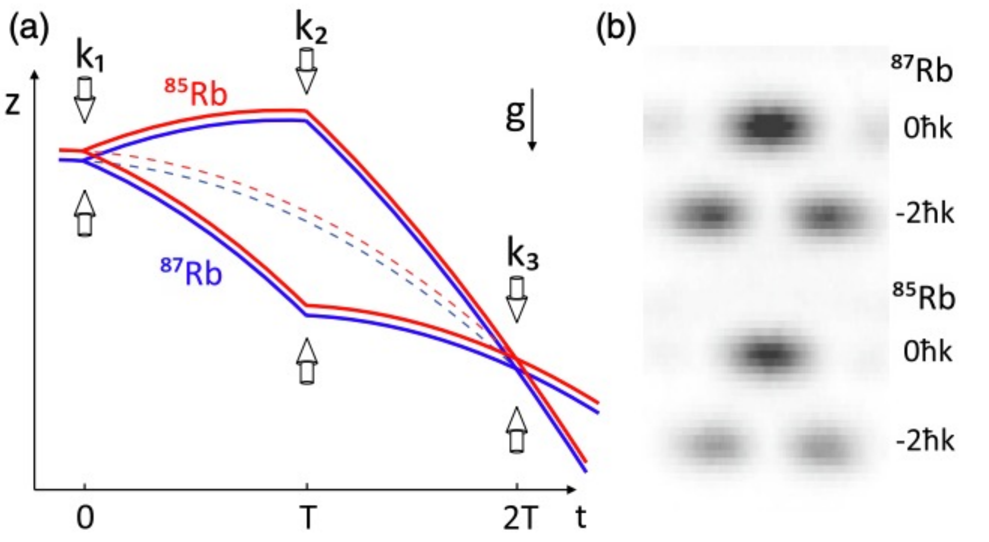
Experimental Frontiers:

1. Shorter Distances
2. Smaller Masses
3. Higher Precision
4. Quantum tests

Atom interferometry (equivalence principle)

- Atom interferometry provides an extremely sensitive tool for searching for weak interactions
- Dual-species atom interferometers (e.g. ^{85}Rb, ^{87}Rb) have long been envisioned for EP tests
- Current state of the art in Stanford interferometer (Kasevich group) is $\eta \sim 10^{-12}$

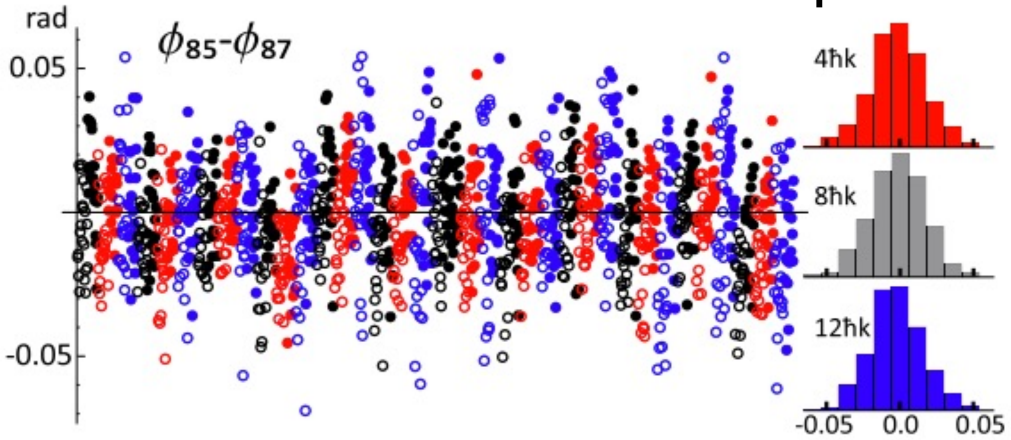
Experimental concept:



Current systematic uncertainties (Stanford):

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

Phase difference between isotopes:



https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.125.191101

See also: https://www.nature.com/articles/ncomms15529 (Firenze group [Tino])

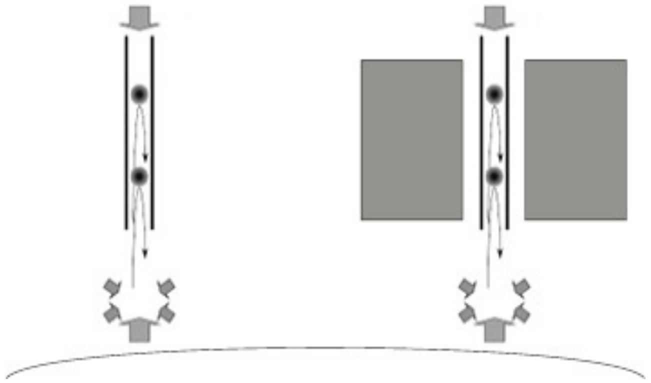
→ $\eta = [1.6 \pm 1.8(\mathrm{stat}) \pm 3.4(\mathrm{syst})] \times 10^{-12}$ (1.4×10^{-11} g per shot)

Atom interferometry (ISL)

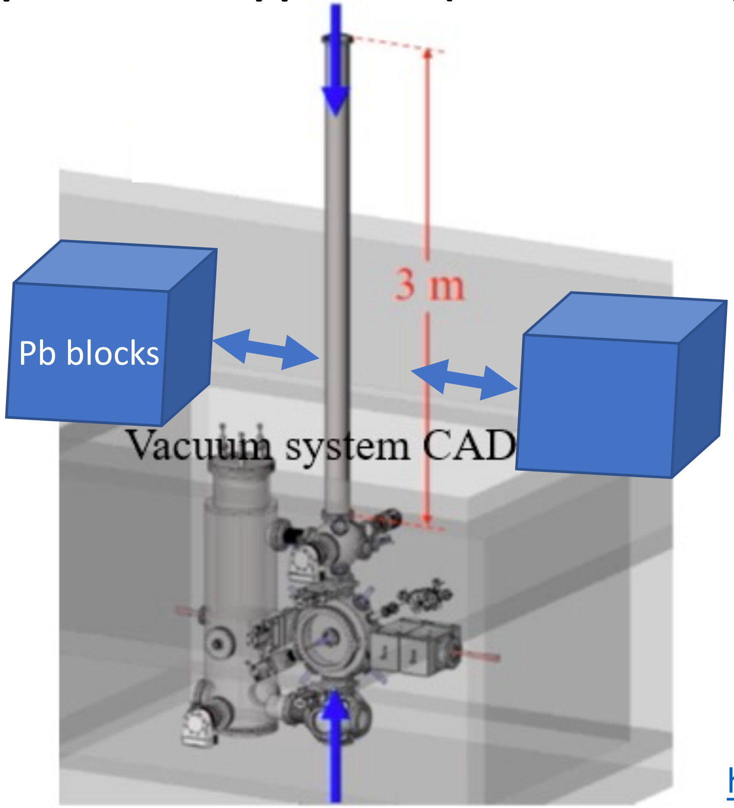
- Beyond EP tests, atom interferometry has also been proposed for inverse square law (ISL) tests
- New experiment under construction at Northwestern (Kovachy group) to search at 10 cm – 1 m length scales
  - Aims to probe below best torsion balance sensitivity at these distances ($\alpha \lesssim 10^{-3}$)

Experimental apparatus (Northwestern):

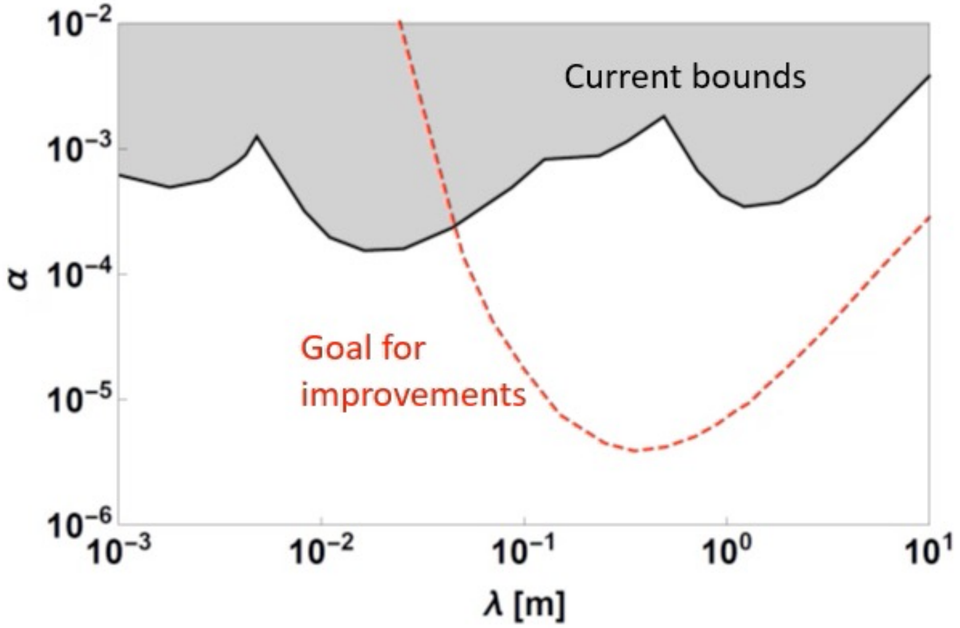
Recent proposal (Rosi, 2017):



https://iopscience.iop.org/article/10.1088/1681-7575/aa8fd8



Projected sensitivity:

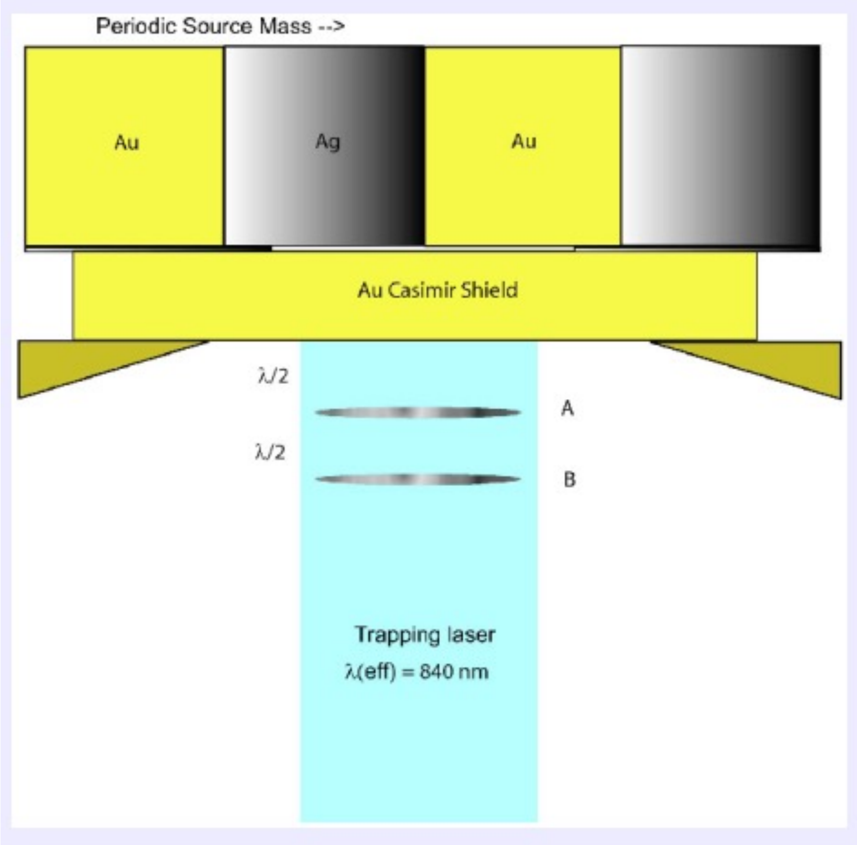


https://doi.org/10.1117/12.2595546

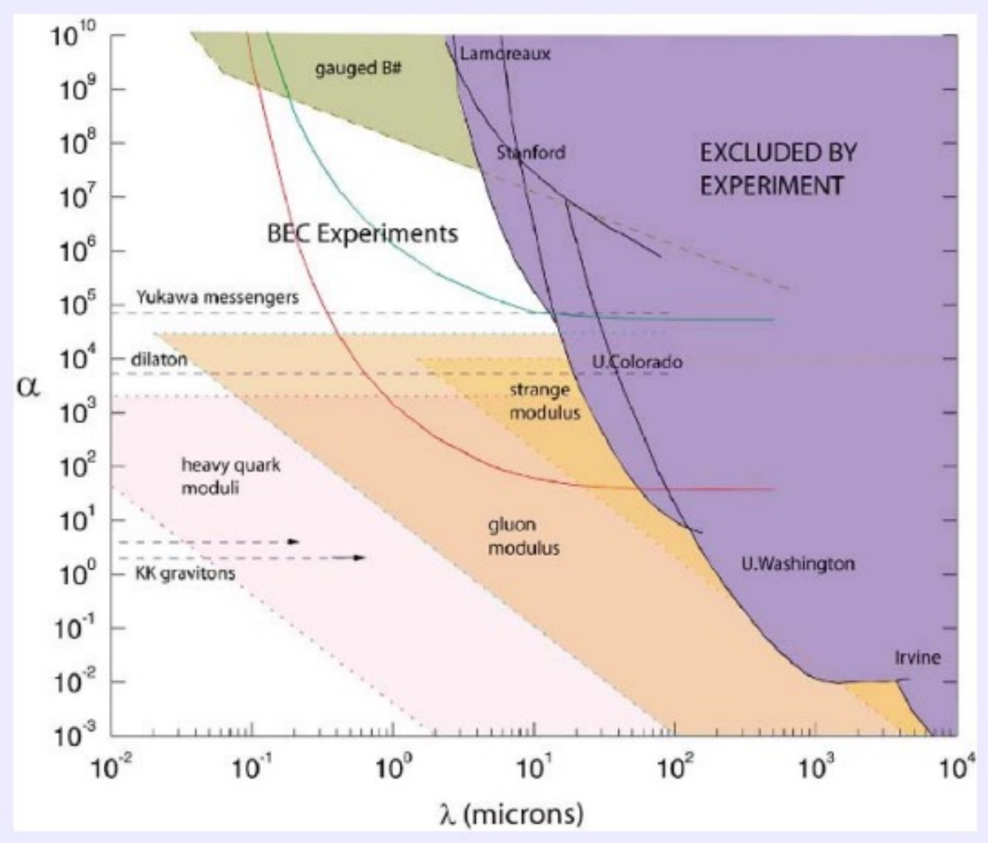
Atom interferometry (ISL)

- Micron distance ISL tests with atom interferometry have also been proposed
  - Similar to nanoparticle in standing wave trap (in particular, similar expected backgrounds!)

Schematic of short distance ISL test:



Projected (background free) sensitivity:

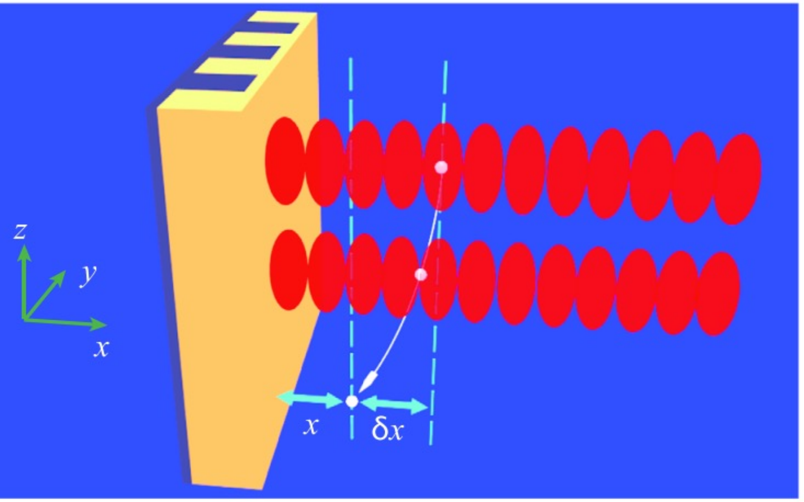


Review article: G.M Tino, https://iopscience.iop.org/article/10.1088/2058-9565/abd83e/pdf (2021)

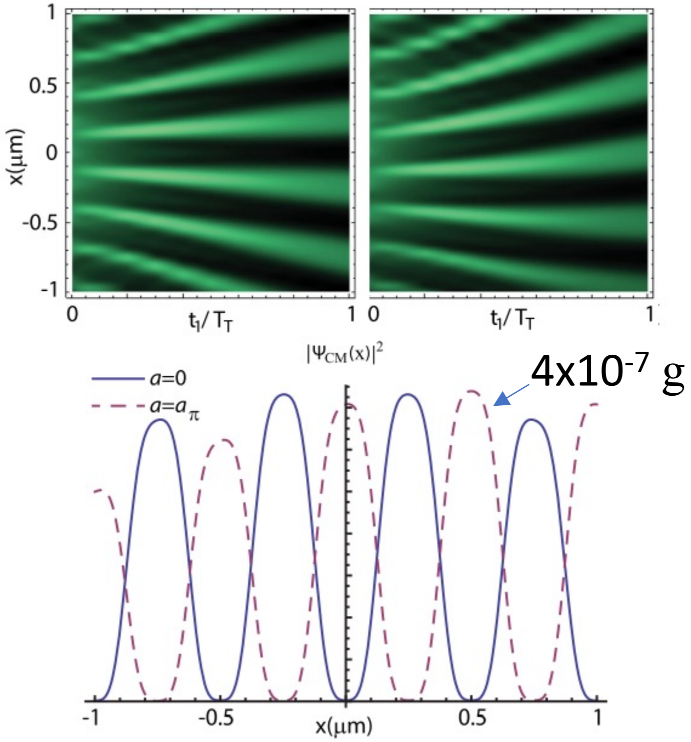
Matter waves with nanospheres

- For forces that couple to mass, making the interferometer out of a heavier particle than an atom may also beneficial (e.g. smaller wavepacket expansion -> sub-μm forces, high masses, …)
- Doesn't necessarily help with backgrounds, but extremely high sensitivity is in principle possible (to whatever forces are present)
- Would require technical developments beyond the state-of-the-art to realize this

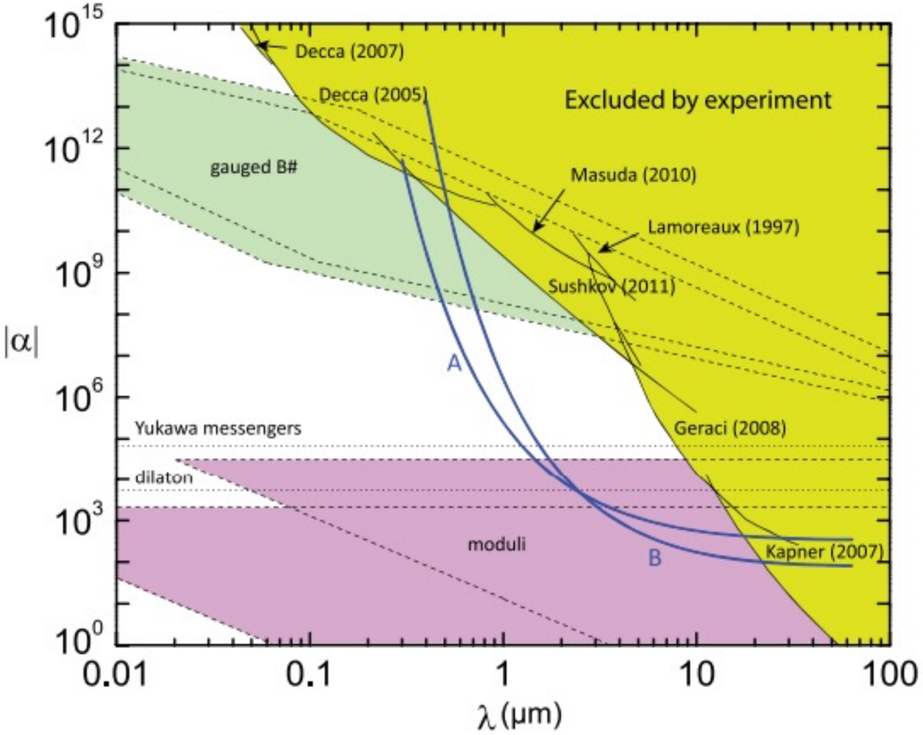
Near-field Talbot interferometer for a nanoparticle:



Predicted interference pattern:



Projected sensitivity (background free):



https://journals.aps.org/prd/abstract/10.1103/PhysRevD.92.062002

Cryogenic torsion balances

- University of Washington group is developing new generation of cryogenic torsion balances:
  - Lower thermal noise
  - Possibly lower patch potential backgrounds (?)
- However, additional complexity with cryogenics, need to control pulse tube vibrations, etc

Schematic of cryostat:

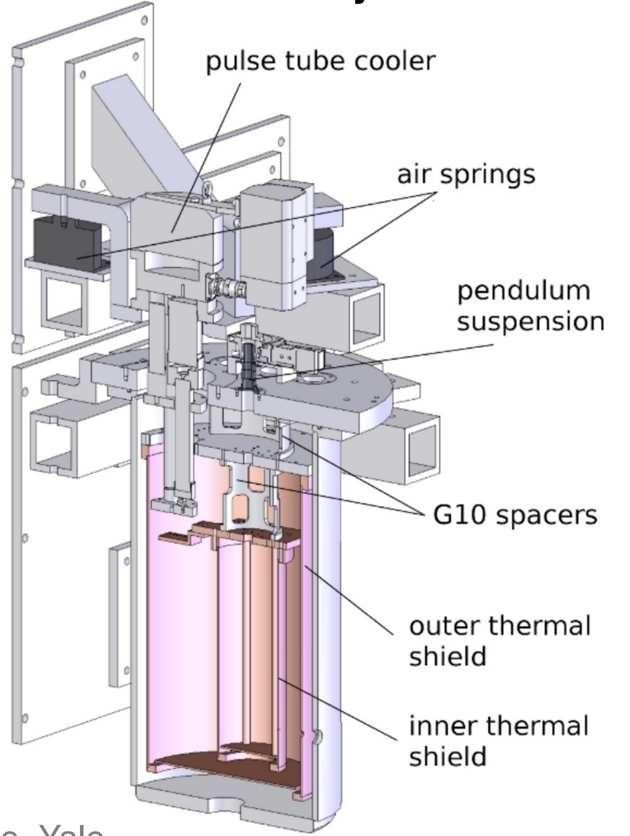
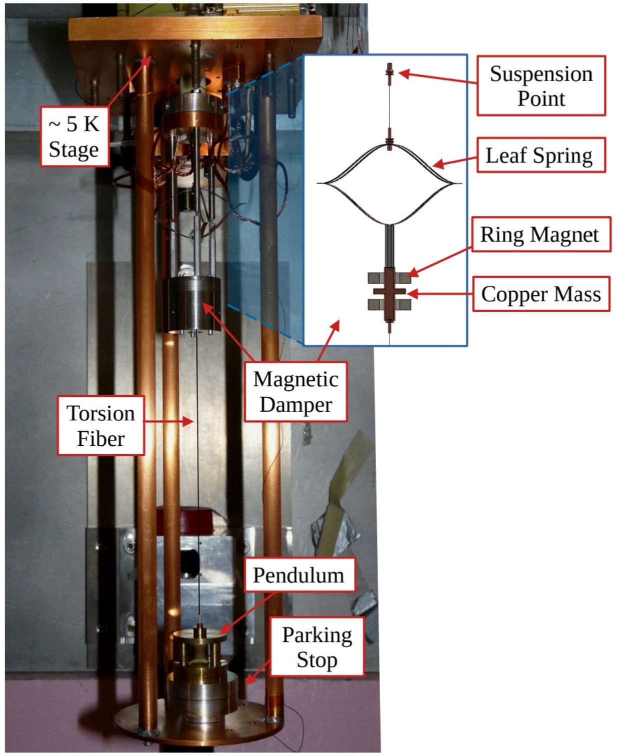
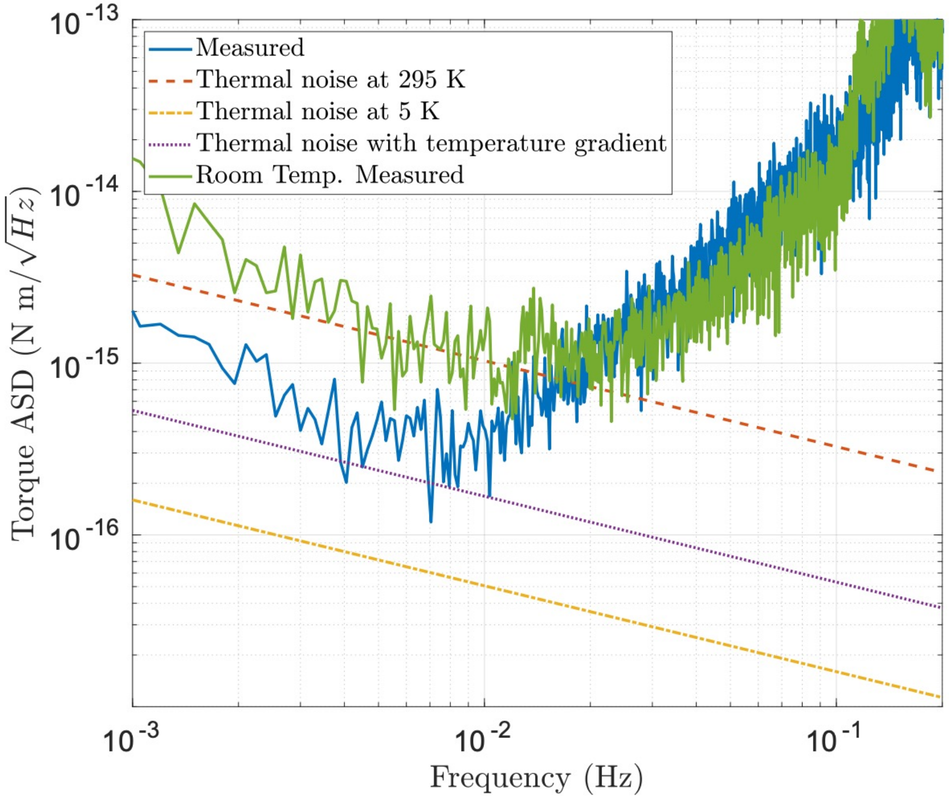


Photo of torsion balance prototype:



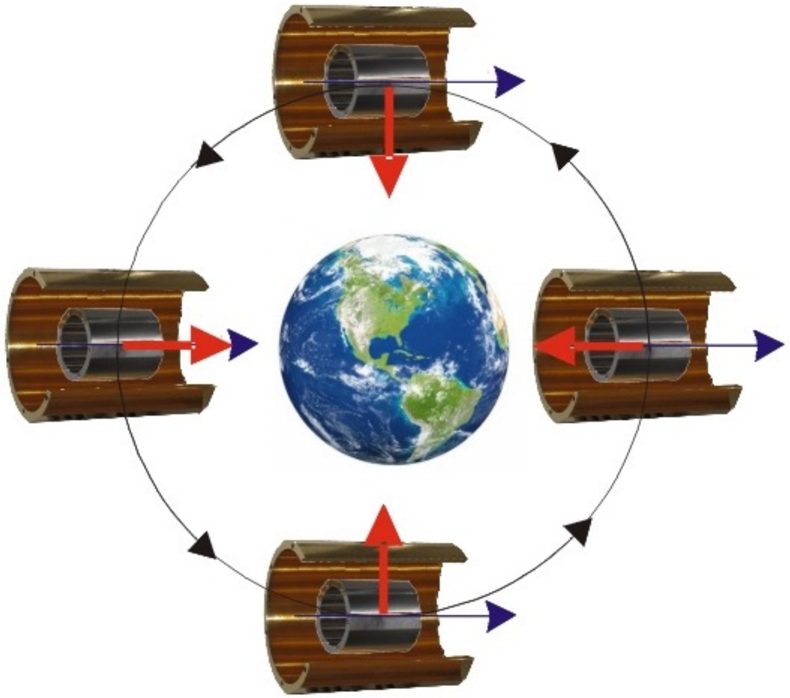
Measured torque noise spectrum:



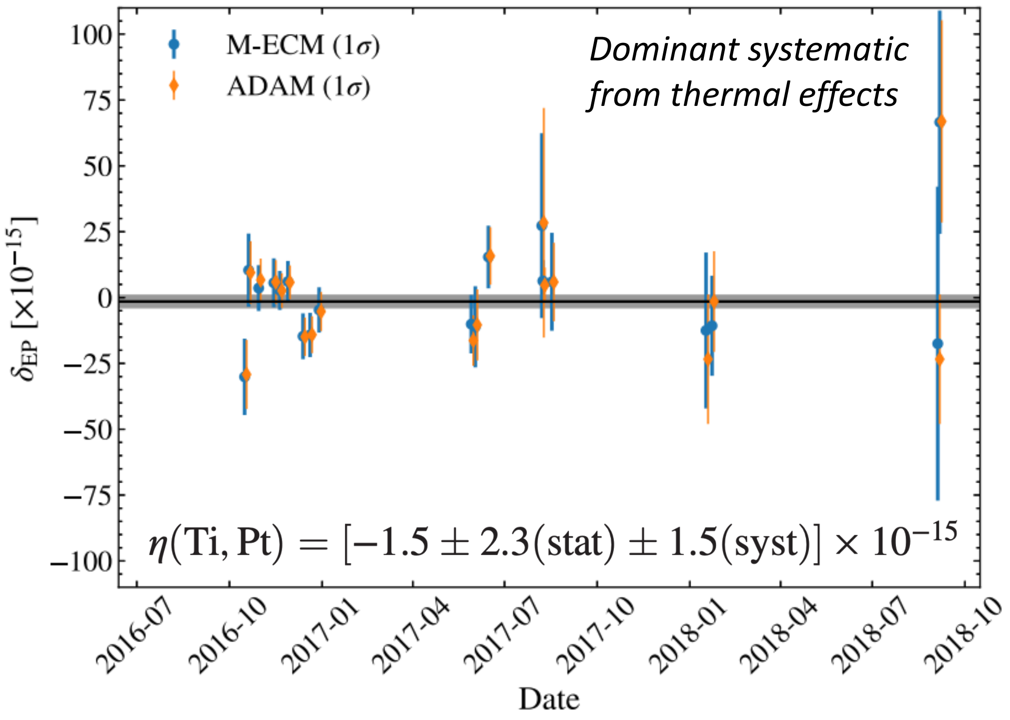
https://aip.scitation.org/doi/10.1063/5.0089933

Spaced based tests (MICROSCOPE)

- Very simple yet precise experiment to test the EP can be performed with drag free test masses orbiting the earth
  - Look at differential acceleration between Pt and Ti test masses in free fall
  - Data taken between 2016-2018 – final result in PRL last week



Measured differential accelerations:



Dominant systematic from thermal effects

Upgraded mission would aim to reach 10^{-17} scale

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.129.121102

Experimental Frontiers:

1. Shorter Distances
2. Smaller Masses
3. Higher Precision
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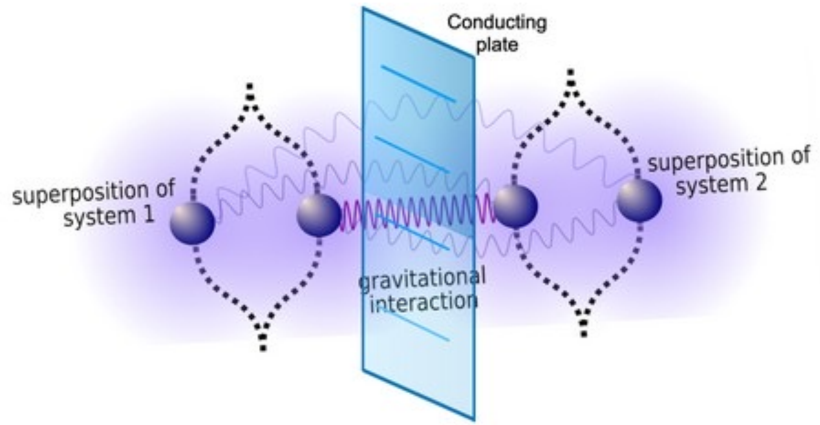
Gravitational entanglement of masses

- Thought experiment along these lines was famously proposed by Feynman at 1957 Chapel Hill Conference on “The Role of Gravitation in Physics”
  https://edition-open-sources.org/media/sources/5/Sources5.pdf
- While still well beyond current state-of-the-art, renewed interest in the possibility that levitated systems may allow realization of this sort of experiment
- Two general proposals:

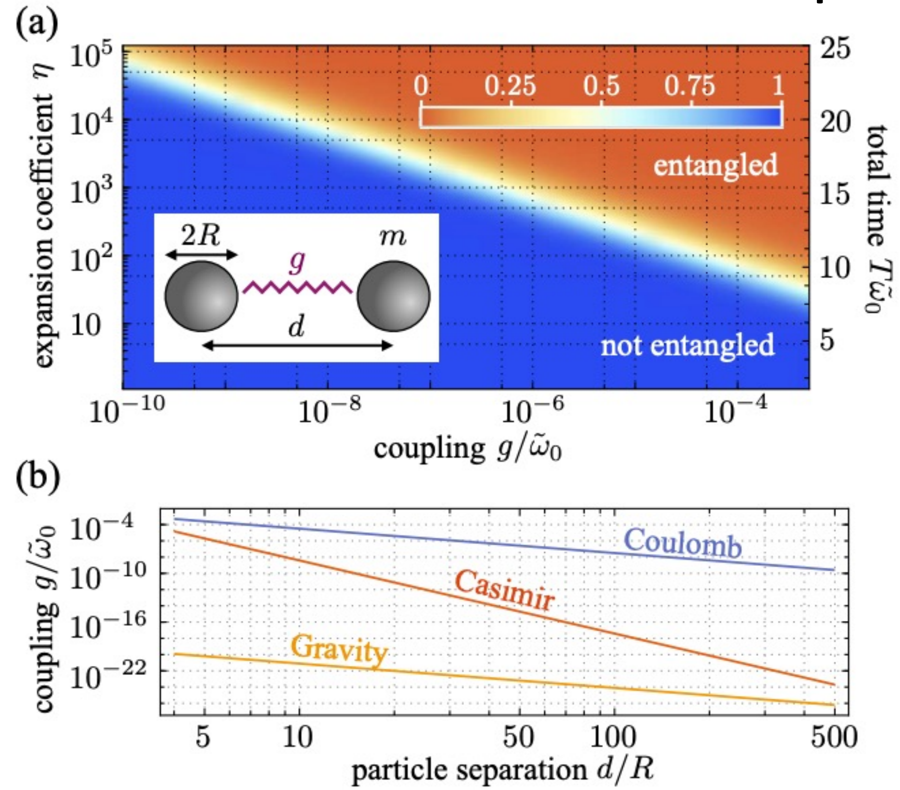
Gravitational interaction of two superpositions:



Anupam Mazumdar, University of Groningen

Bose et al. https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.119.240401 (2017)
Marletto and Vedral, https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.119.240402 (2017)

Gravitational interaction of two delocalized particles:



https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.127.023601

Gravitational entanglement of masses

- Thought experiment along these lines was famously proposed by Feynman at 1957 Chapel Hill Conference on “The Role of Gravitation in Physics”

  htt

- While ... may a
- Two g ... ticles:

Gr

See talks by Markus for full details

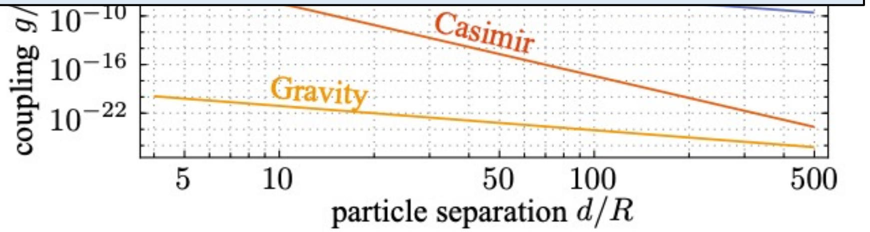
Many of the experimental challenges to shield non-gravitational interactions are similar to short distance tests of the inverse square law

Additional challenges:

- Create delocalized states
- Avoid decoherence

Beyond tests of gravitational entanglement, reaching these goals is likely to substantially advance tests of the ISL at short distance!

Anupam Mazumdar, University of Groningen



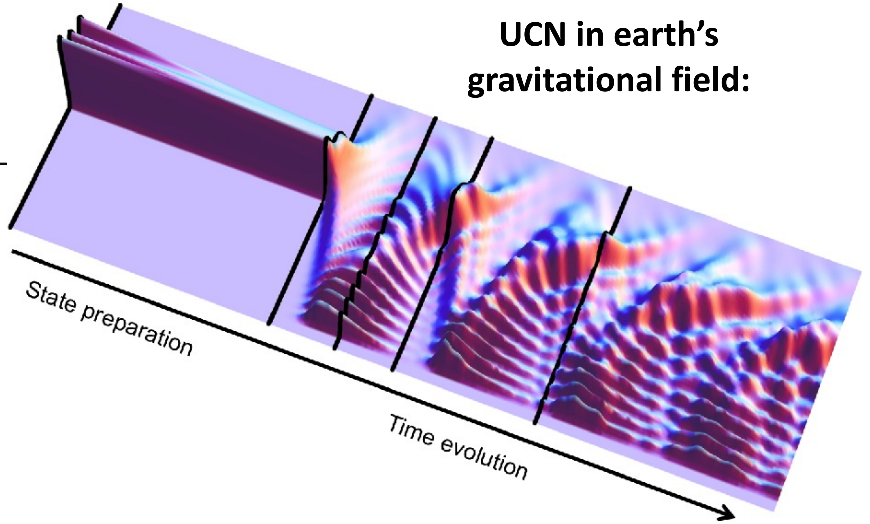
Bose et al. https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.119.240401 (2017)
Marletto and Vedral, https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.119.240402 (2017)

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.127.023601

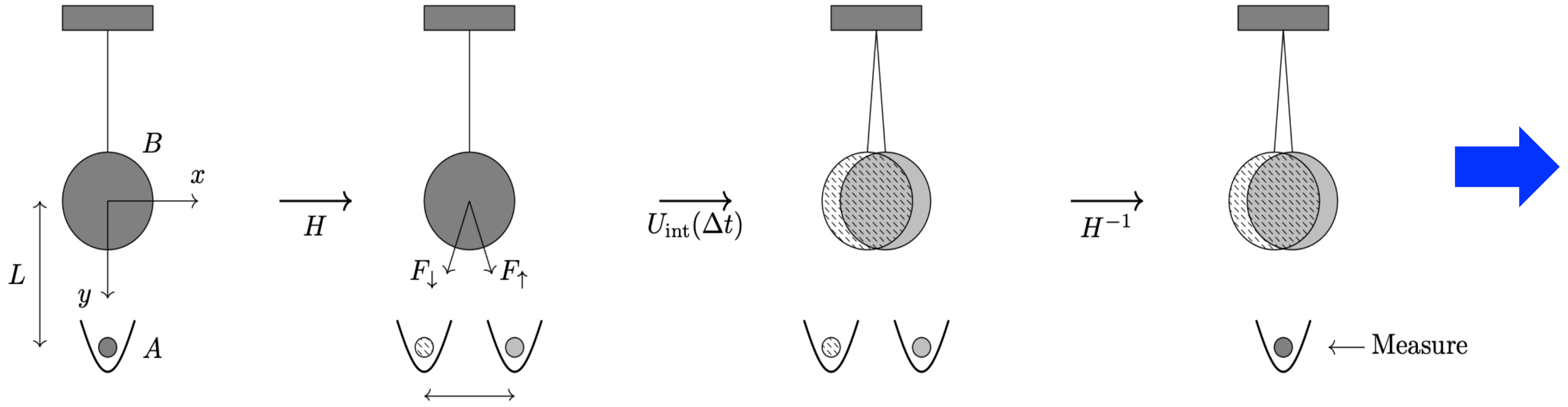
Interactions with classical masses

- We already heard this week about beautiful experiments with a quantum test mass and a classical attractor:
  - E.g., UCN bouncing in the earth's gravitational field
- Other recent proposals look at similar experimental signatures for an atom interferometer and a classical low frequency oscillator

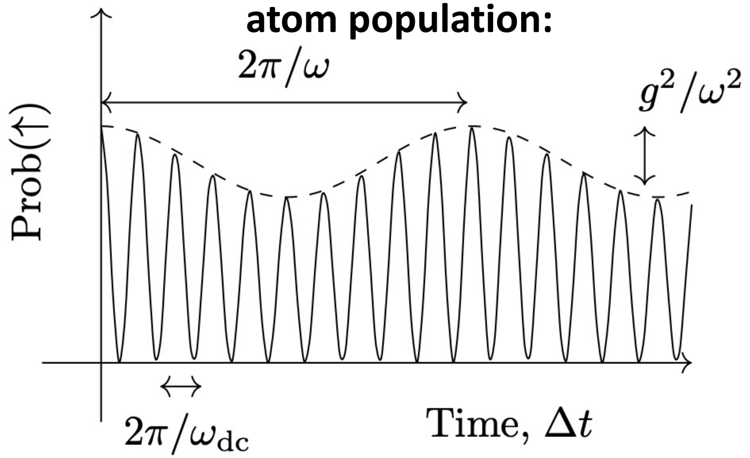
UCN in earth's gravitational field:



Proposal to entangle atoms with low frequency (classical) oscillator:



Predicted revivals in measurements of atom population:



https://journals.aps.org/prxquantum/pdf/10.1103/PRXQuantum.2.030330

- Revival phenomenon also possible semi-classically, and verification of entanglement appears to require the attractor to be in a pure quantum state

See e.g., https://journals.aps.org/prresearch/abstract/10.1103/PhysRevResearch.4.013023
https://journals.aps.org/prresearch/abstract/10.1103/PhysRevResearch.4.013024
https://www.mdpi.com/2218-1997/8/2/58

Summary

- Due to its weakness, gravity is extremely challenging to study in the lab and torsion balances remain the preferred experimental method at mm to meter length scales
- Frontiers in the coming years are:
  - Shorter distances
  - Higher precision
  - Smaller masses and quantum tests
- Huge number of new ideas – progress likely on all of these frontiers in the near term!