Overview of Work Group 4: Low-energy high-precision experiments bridging Quantum and Gravity

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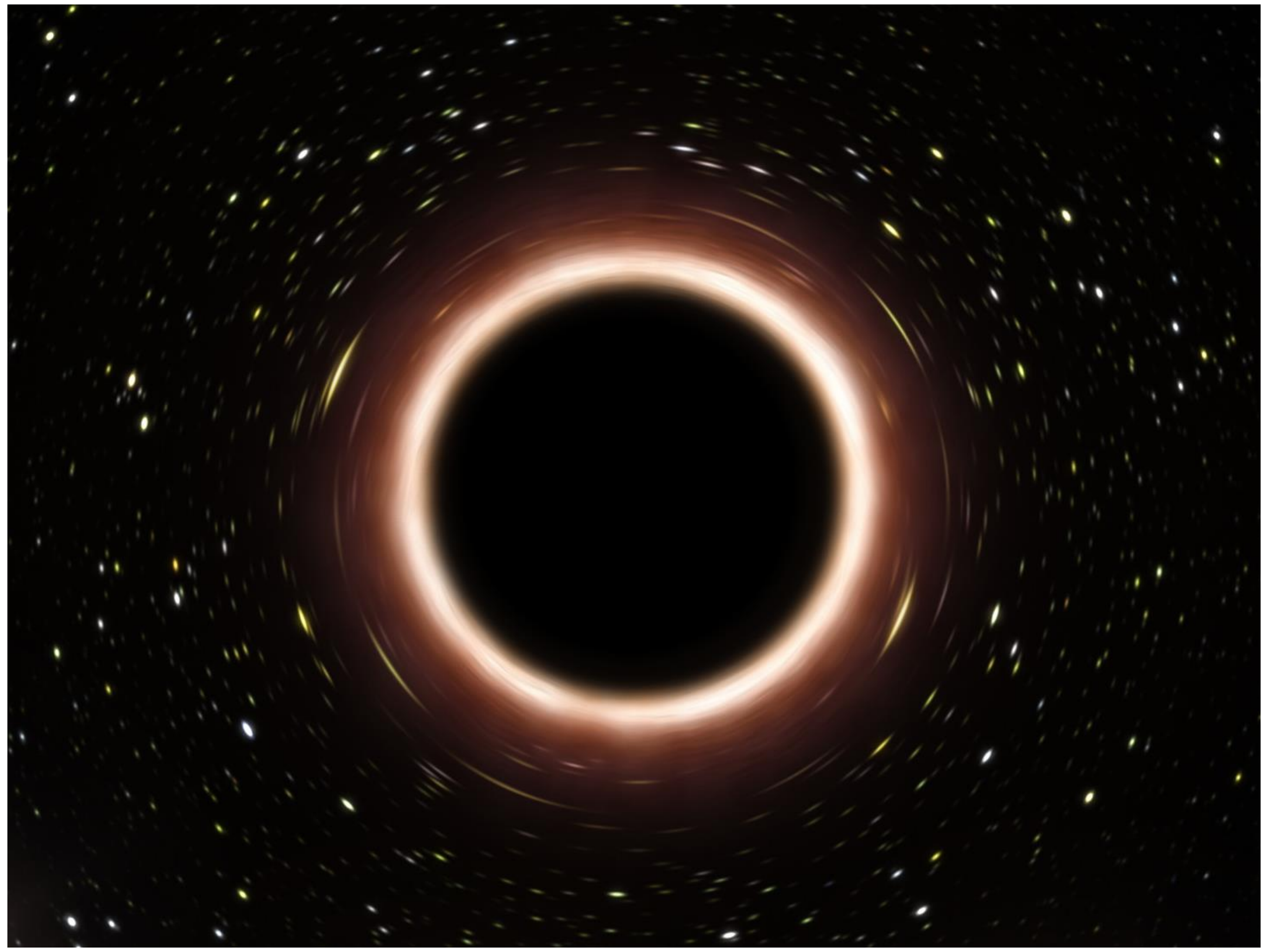
Matteo Fadel, ETH Zurich, Switzerland

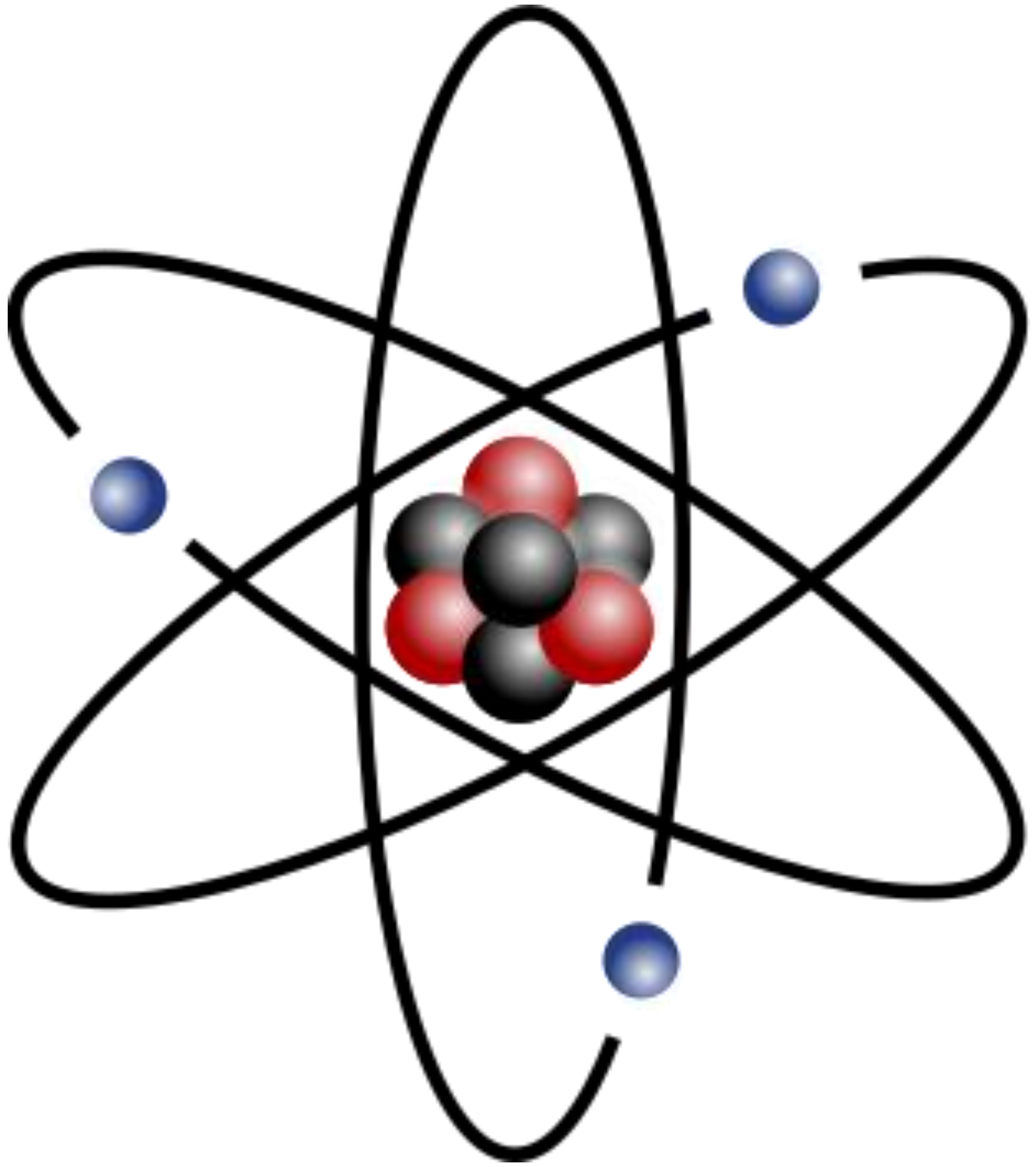
Bridging high and low energies in search of quantum gravity - 2025
Cost Action CA23130 First Annual Conference
7-11 July 2025, Paris

Quantum gravity?



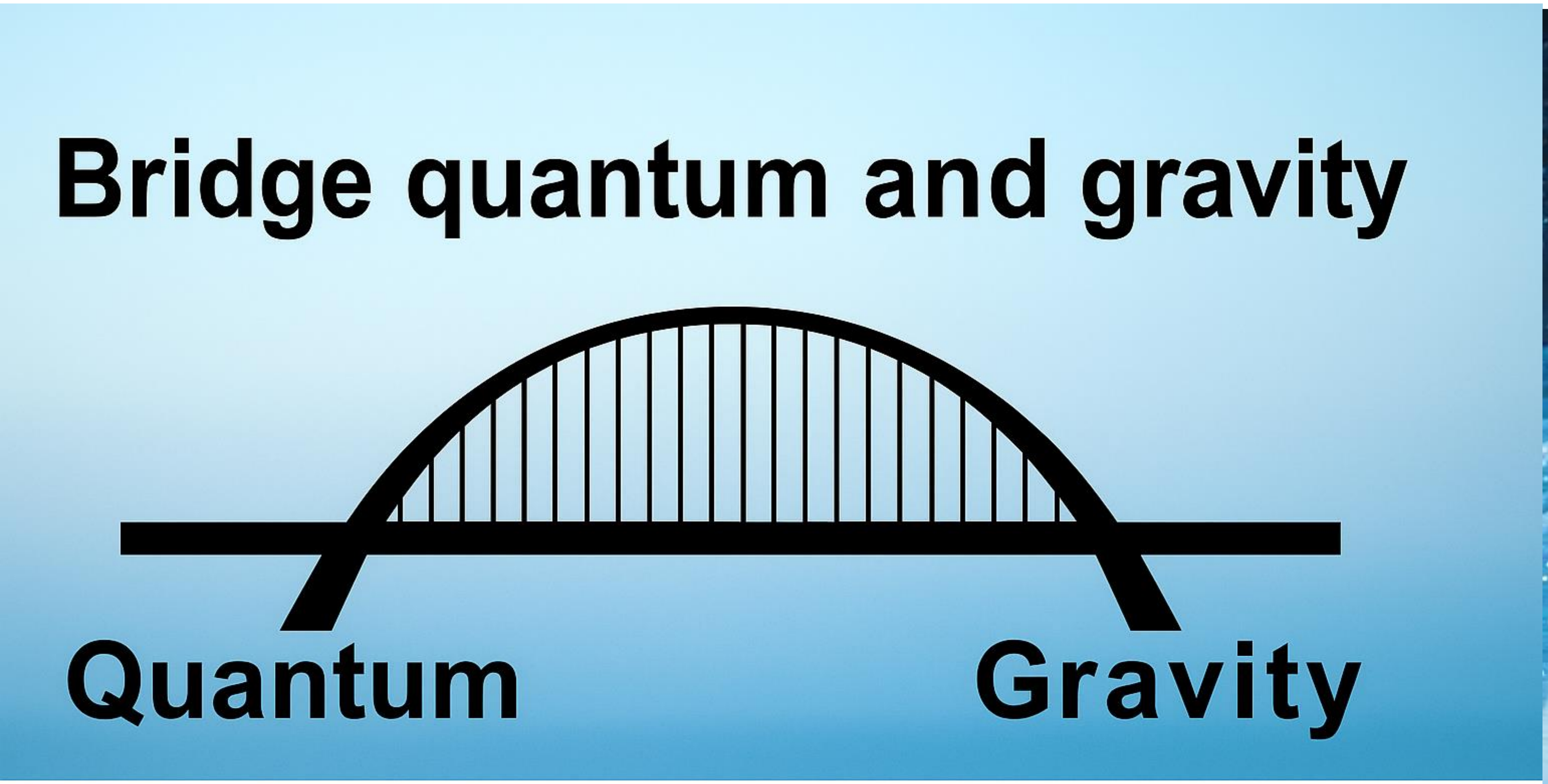
Einstein’s field equations

?

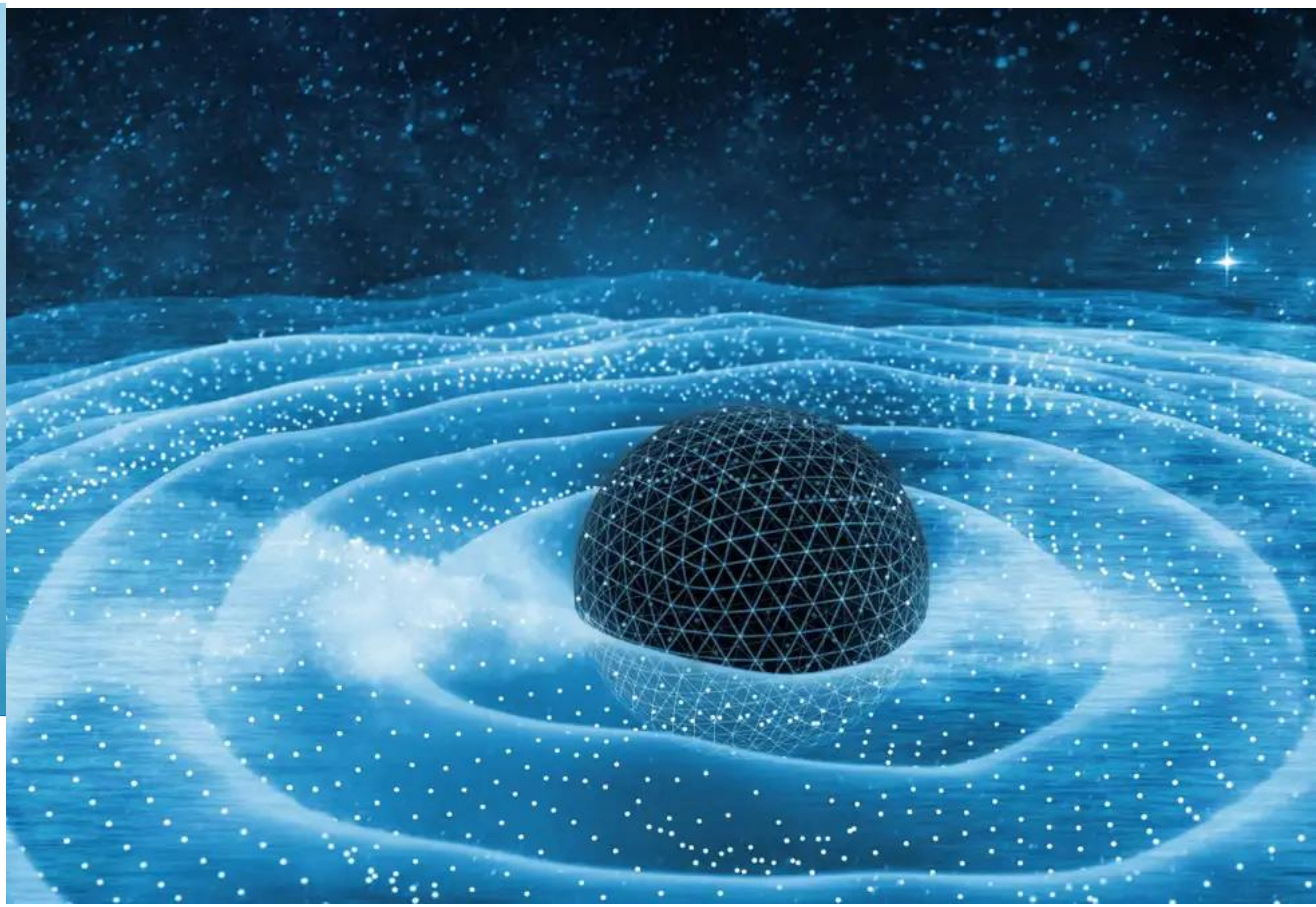


Schrödinger’s equation

Which are the type of experiments ay low-energy investigate the relation between Quantum and Gravity?



Low-energy high-precision experiments bridging Quantum and Gravity



Getty Images/iStockphoto Source: iStockphoto

Experimental approaches to test QG

high-energy

accelerators

gamma-rays

gravitational waves

compact objects

neutrinos

cosmic rays

black-hole physics

....

WG 2

Experimental approaches to test QG

WG 4

low-energy

precision spectroscopy

underground experiments

atomic clocks

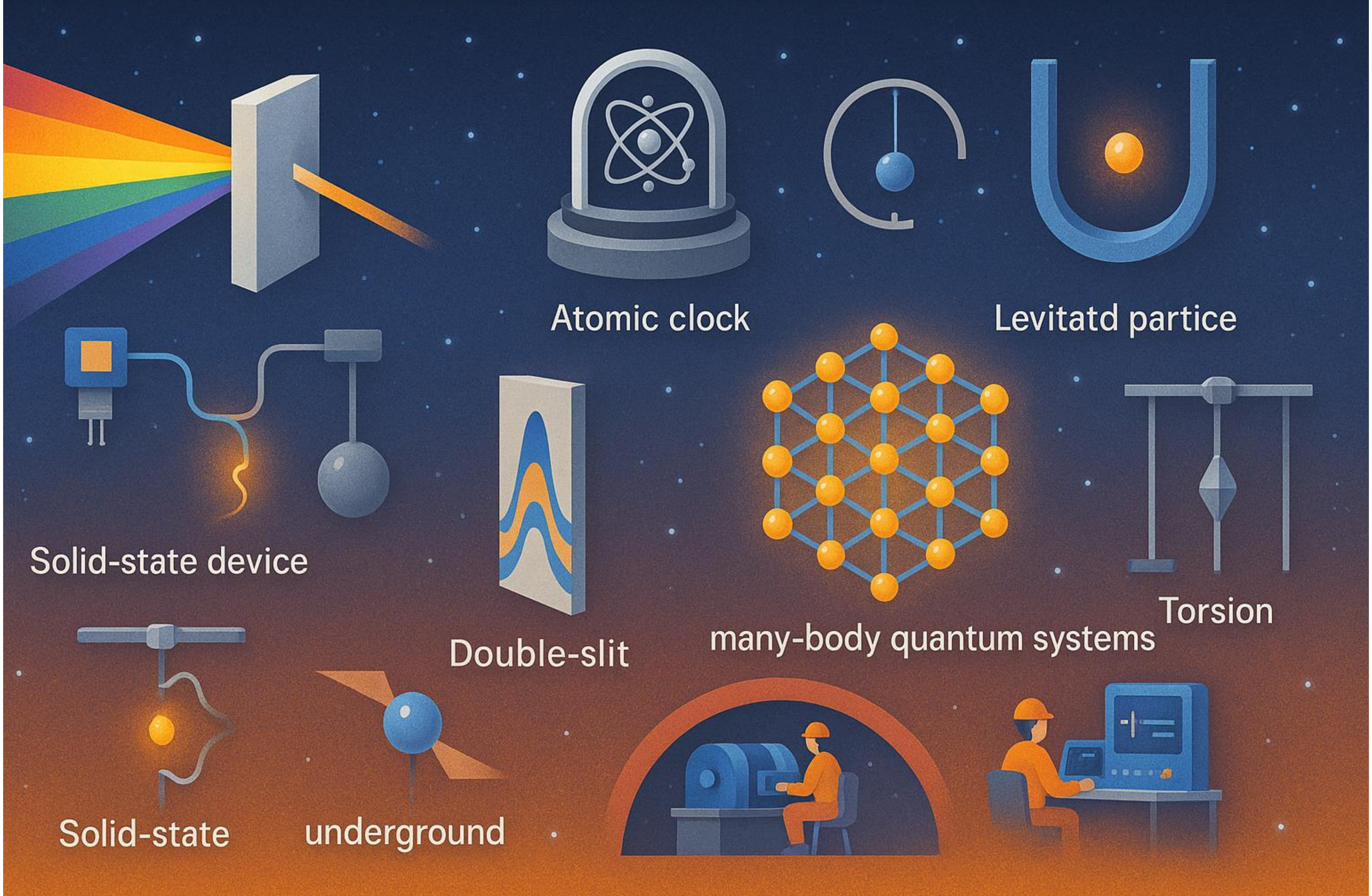
levitated particles

many-body quantum systems

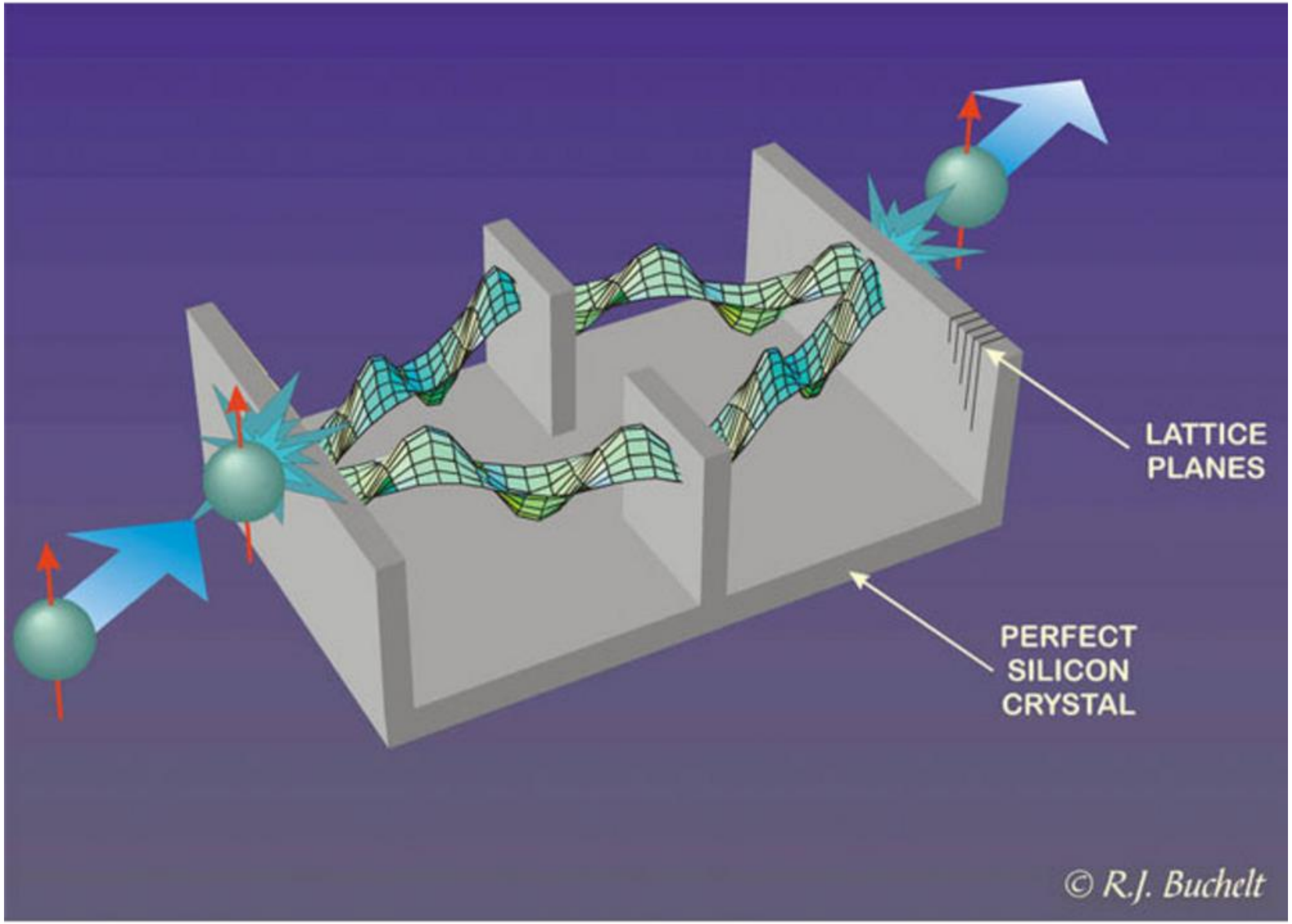
double-slit exp.

torsion balances

solid-state devices

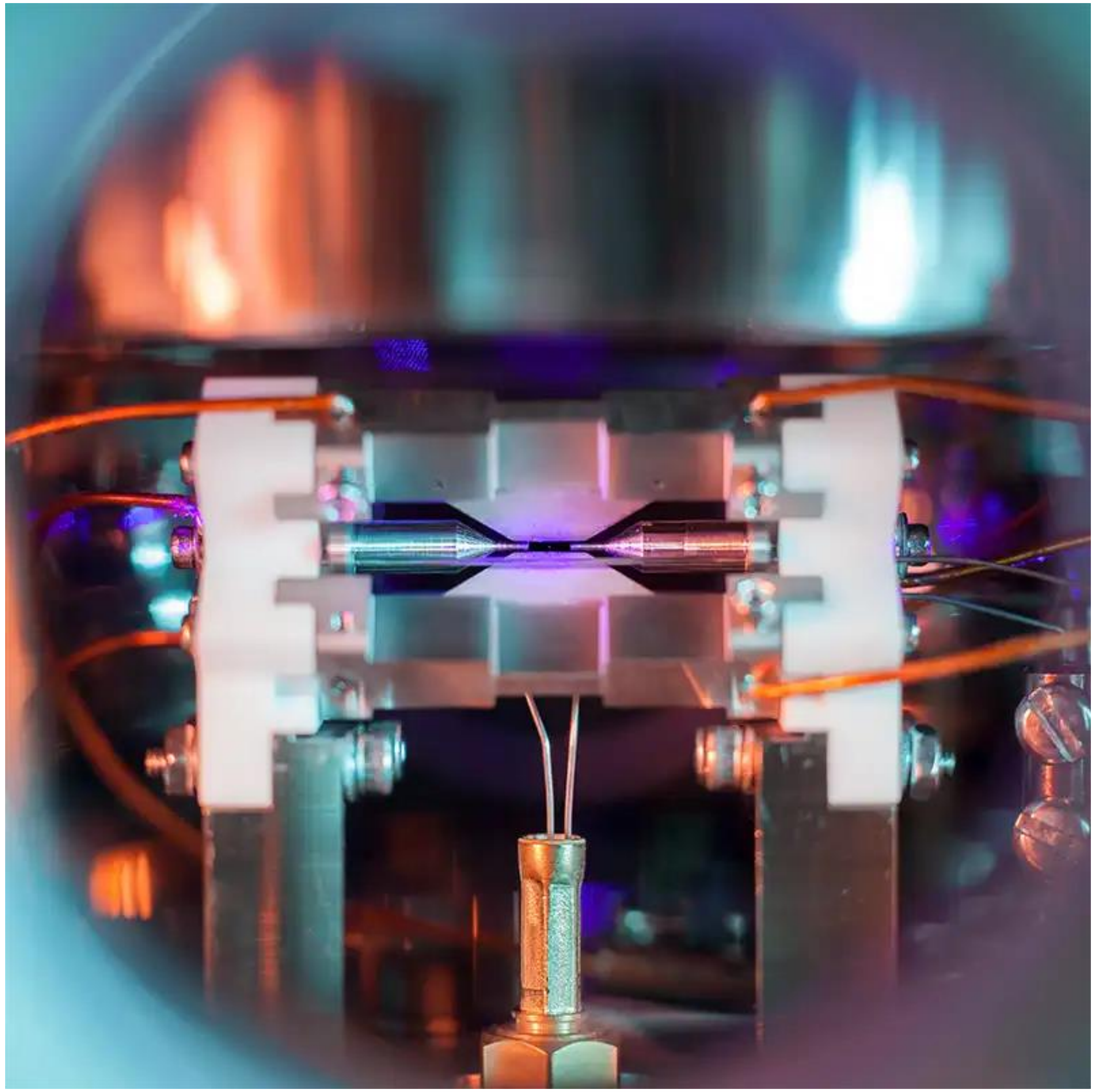

Atomic clock
Levitatd partice
Solid-state device
Double-slit
many-body quantum systems
Torsion
Solid-state
underground

Experiments with quantum systems!



neutron interferometry

Experiments with quantum systems!

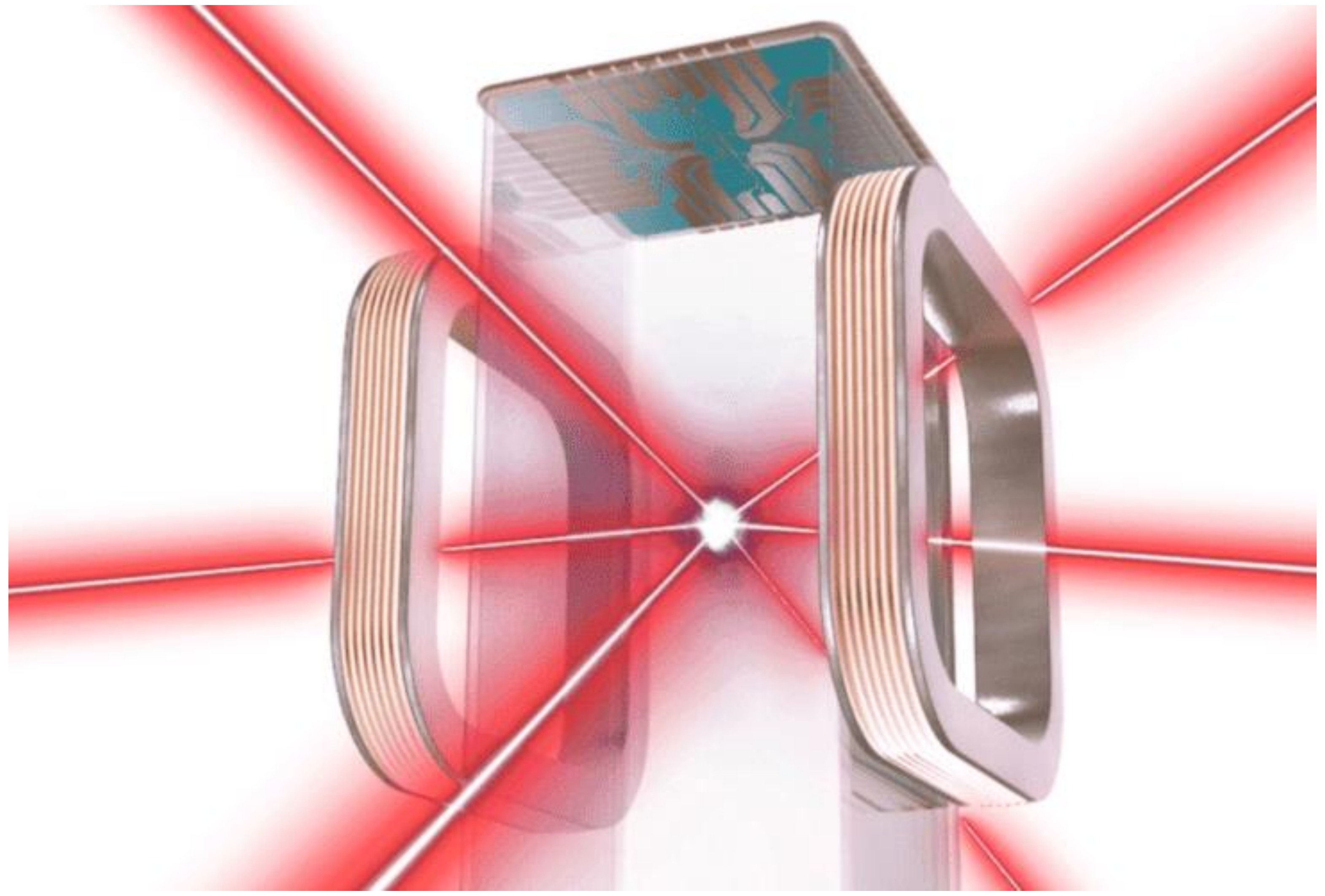


single trapped ion

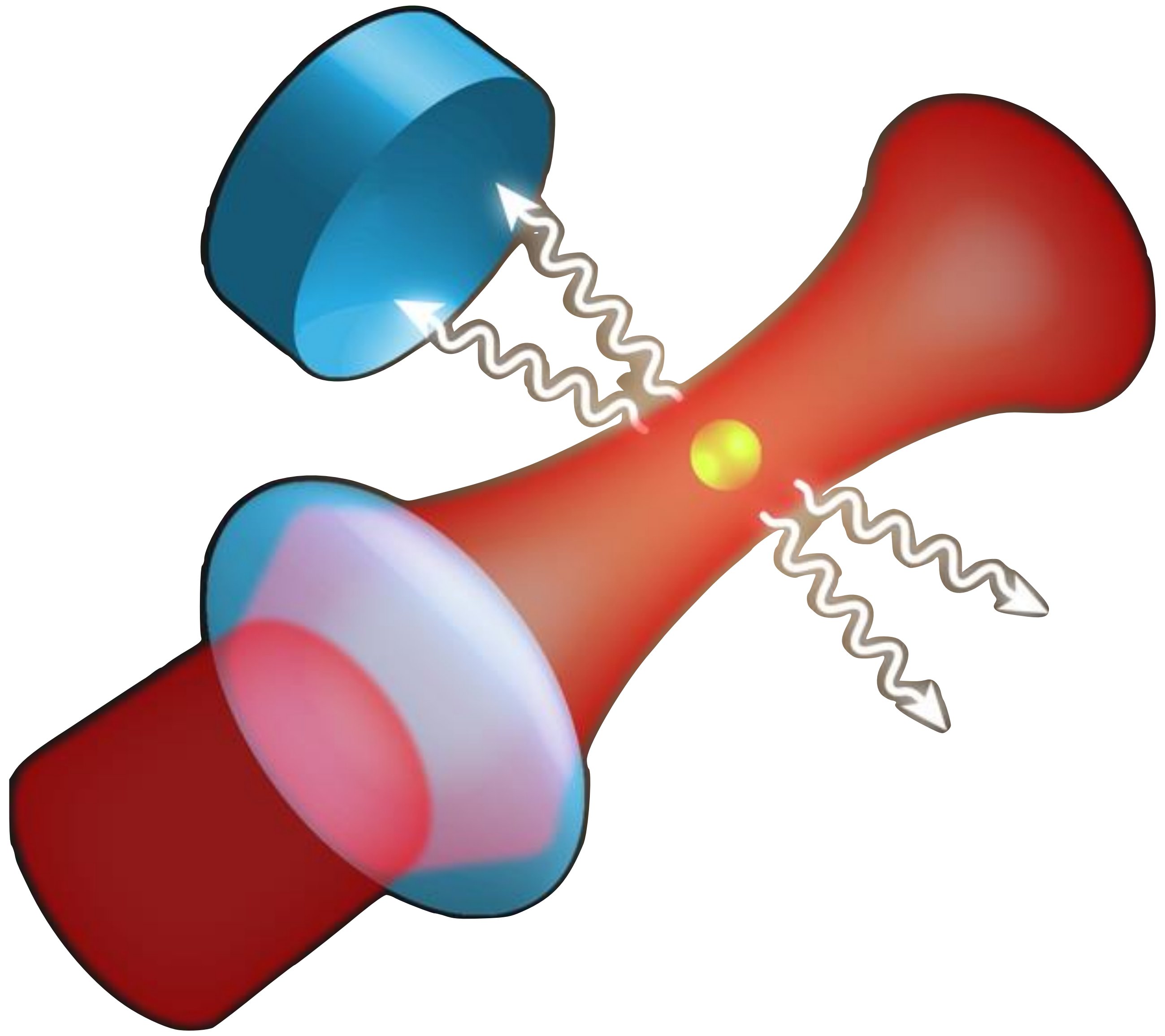
An ion trap in an ultra-high vacuum vessel. In the centre of the picture, as small bright dot is visible – a single trapped $^{88}Sr^{+}$ ion.

(Overall 1st in the EPSRC 2018 Science Photography Competition; crop slightly changed here.) Image by David Nadlinger/University of Oxford

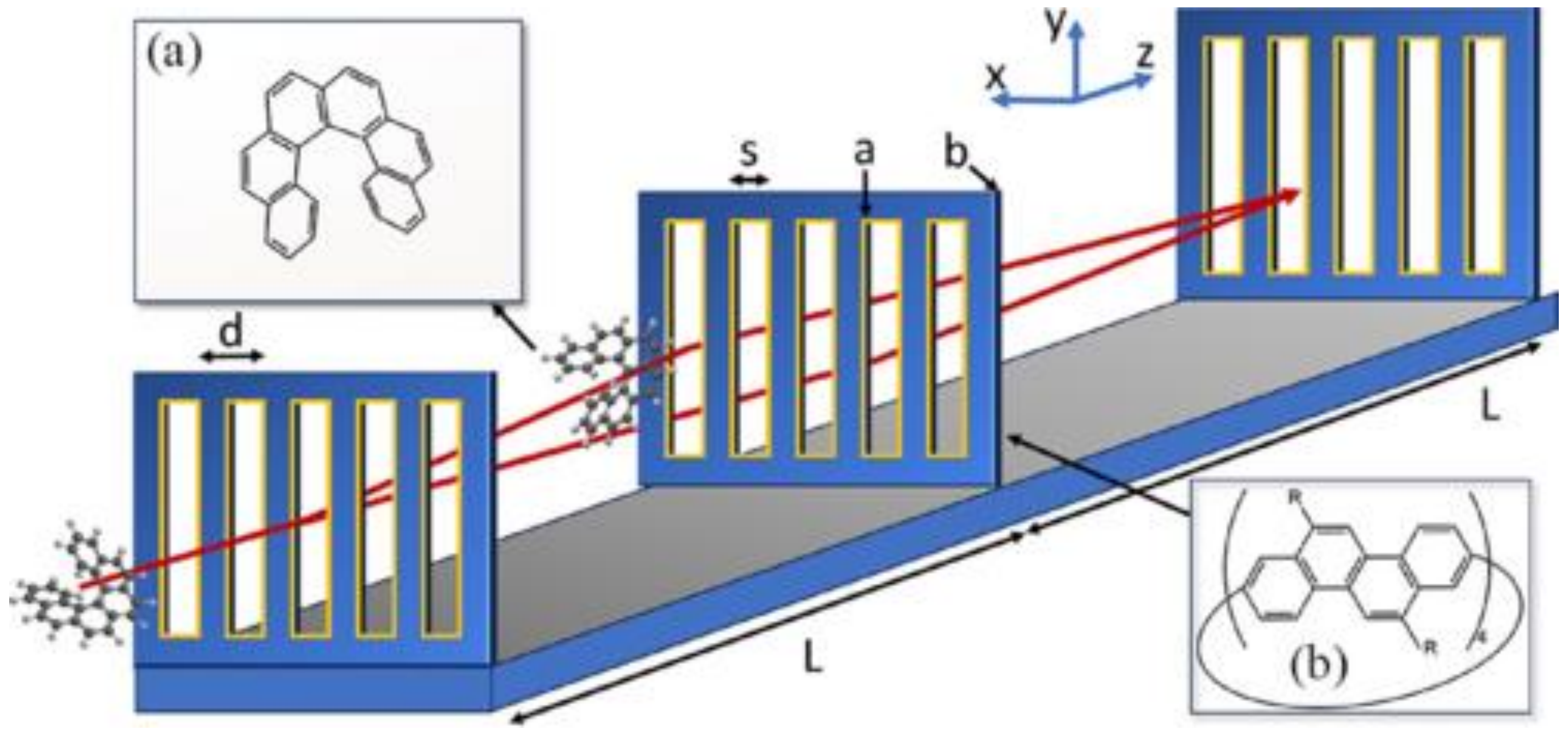
Not only single particles or atoms



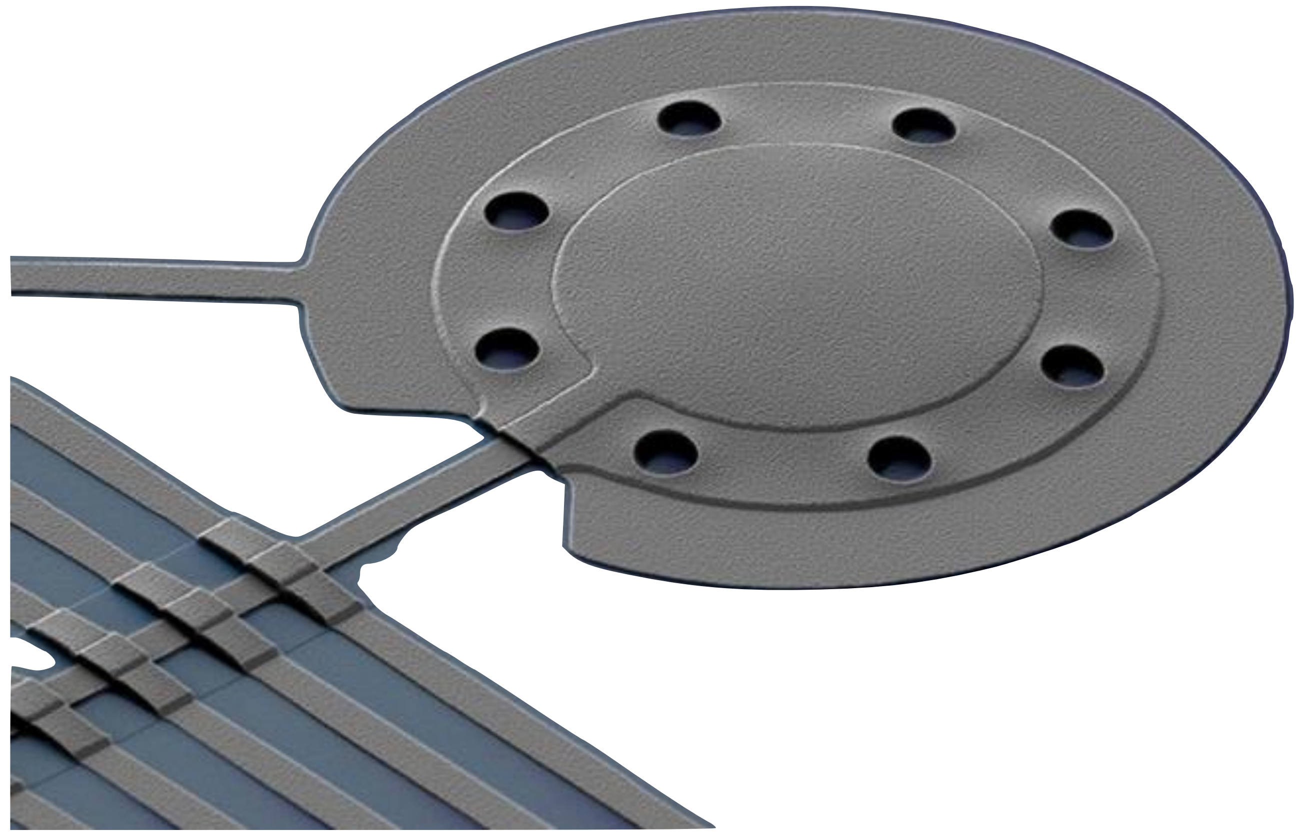
Bose-Einstein condensates (10^2-10^5 atoms)



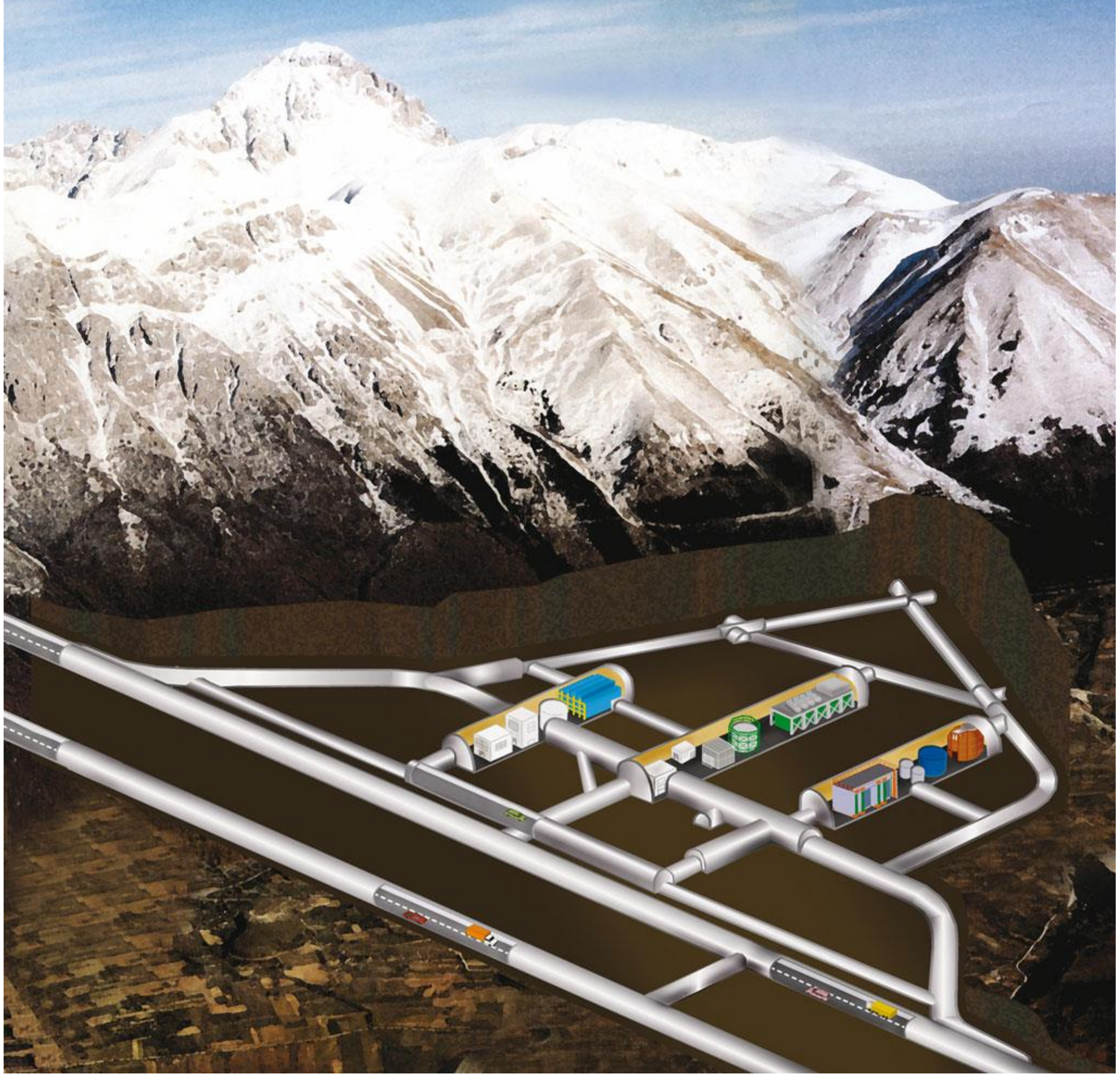
levitated particles (10^7-10^{10} atoms)



molecule interferometry (10^3 atoms)



nano-mechanical oscillators (10^7-10^{17} atoms)



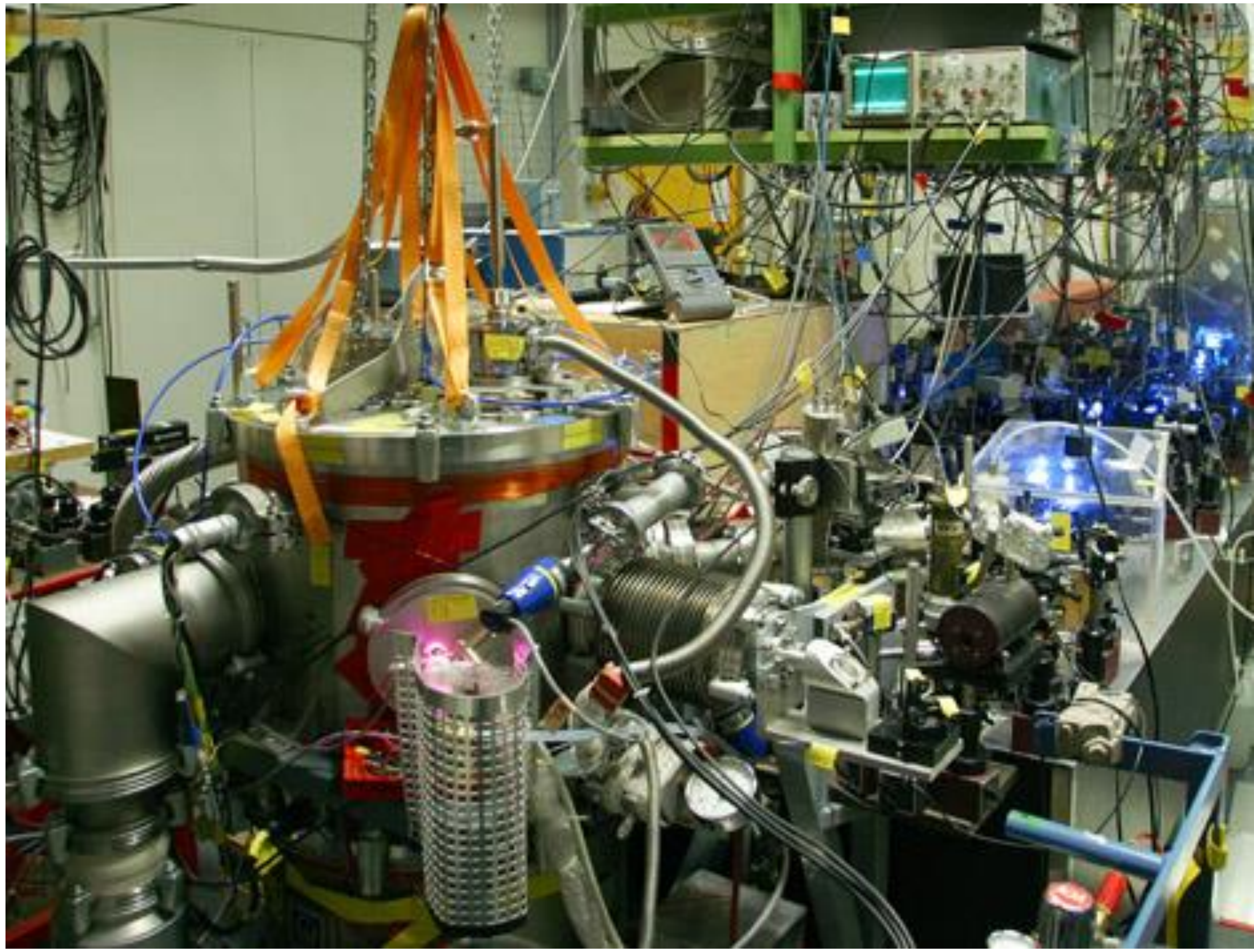
Gran Sasso

Experiments underground

Extreme precision experiments in underground laboratories – also relationship between DM and QG

Precision Spectroscopy

- **Status:** Among the most mature approaches.
- **Focus:** Measuring tiny shifts in atomic and molecular energy levels (e.g., hydrogen spectroscopy, antihydrogen spectroscopy).
- **Quantum Gravity Connection:** Tests of Lorentz invariance, limits on spacetime discreteness, and searching for effects predicted by quantum gravity models (like Planck-scale modifications).
- **Example:** Hydrogen 1S–2S transition measured at the 10^{-15} relative uncertainty; no deviation from QED so far.



The 1S-2S hydrogen lab in 2010

http://www2.mpq.mpg.de/~haensch/1s2s/1s2s.html

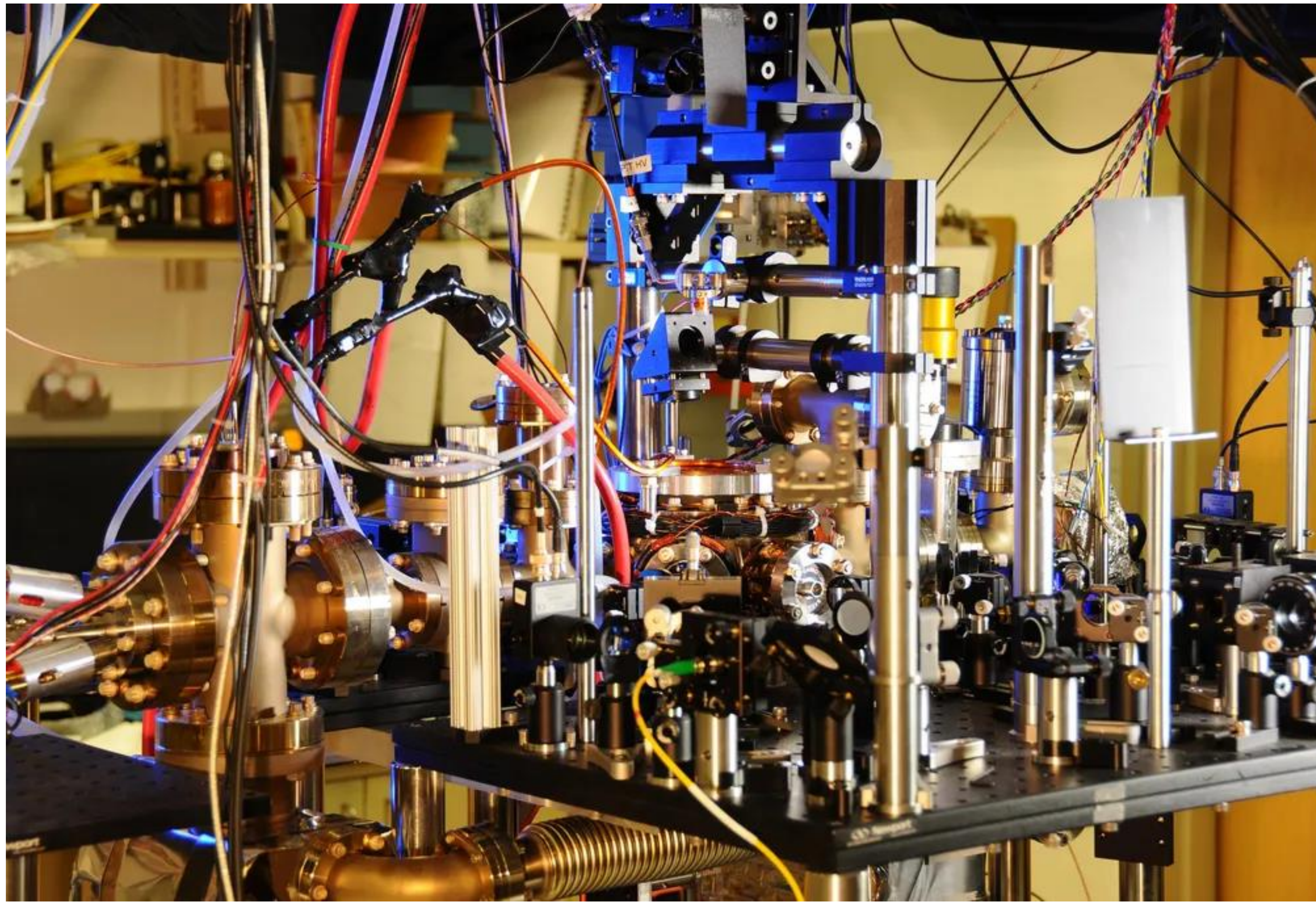
Atomic Clocks

Status: World-leading precision in time measurement.

Focus: Testing time dilation, gravitational redshift, and potential time-varying constants.

Quantum Gravity Connection: Constraining models of temporal decoherence, searching for Planck-scale noise.

Example: achieving stability at $\sim 10^{-18}$; no evidence yet of quantum gravity noise.



This is an atomic clock that uses the predictable frequency of ytterbium atoms absorbing and emitting light to tell time. A new experiment paired a ytterbium-based atomic clock with two others that used aluminum and strontium atoms, respectively, to create an even more accurate measure of time. Burrus / NIST

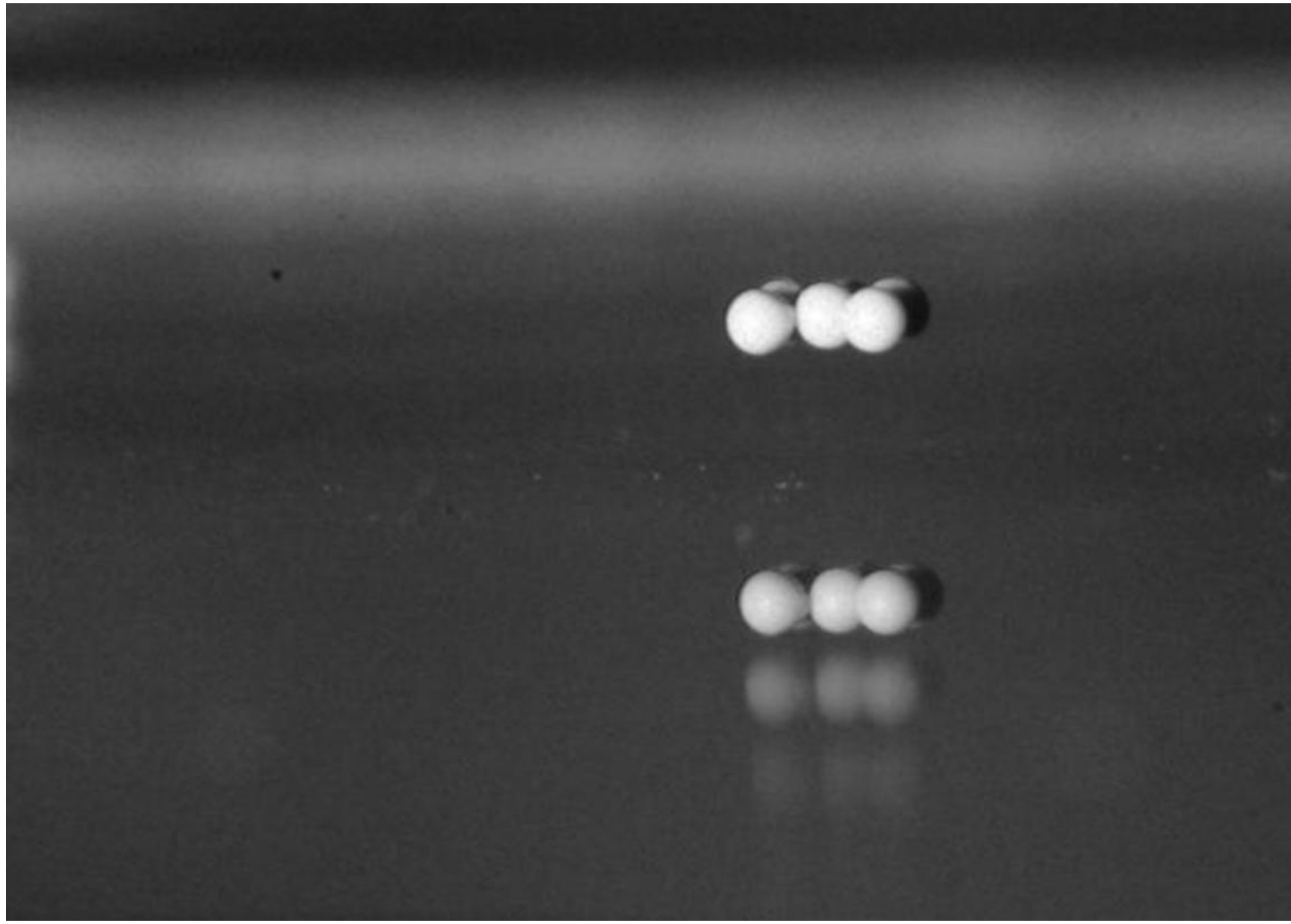
Levitated Particles

Status: Rapidly developing field.

Focus: Controlling the motion of optically or magnetically levitated nanoparticles in ultra-high vacuum.

Quantum Gravity Connection: Proposals to detect minimal length scales or spacetime fluctuations, probe wavefunction collapse…..

Example: Experiments have reached the quantum ground state of motion; searches for gravitational decoherence ongoing.



Univ.of Chicago and the University of Bath scientists revealed new insights about how materials cluster together in the absence of gravity. Courtesy of Melody Lim

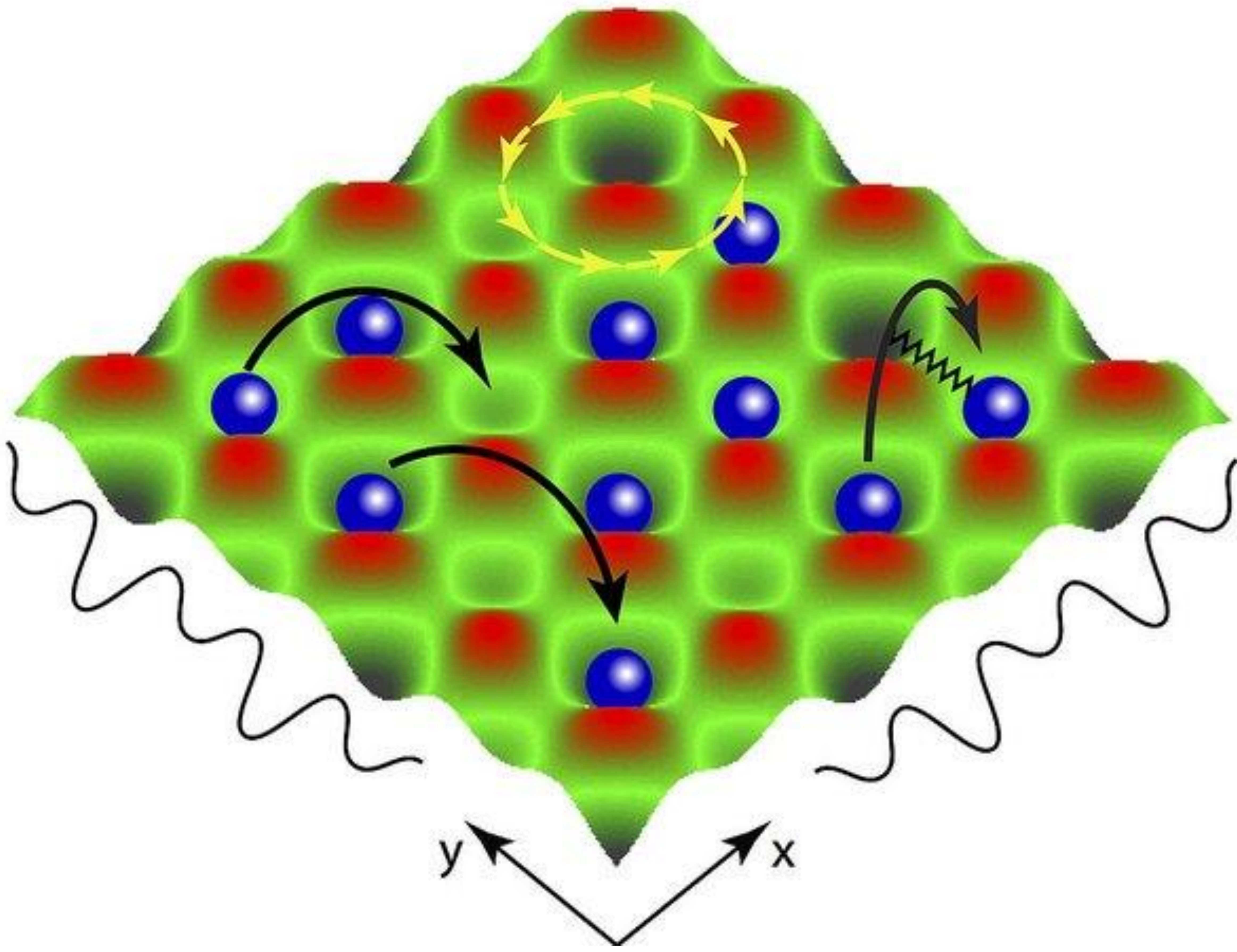
Many-Body Quantum Systems

Status: Emerging.

Focus: Entanglement and coherence in ultracold atoms and condensed matter.

Quantum Gravity Connection: Studying whether gravitational interactions can entangle spatially separated masses (testing models like semiclassical gravity vs. quantized gravity).

Example: Early experiments with Bose-Einstein condensates coupled to massive objects.



https://www.pks.mpg.de/nqd

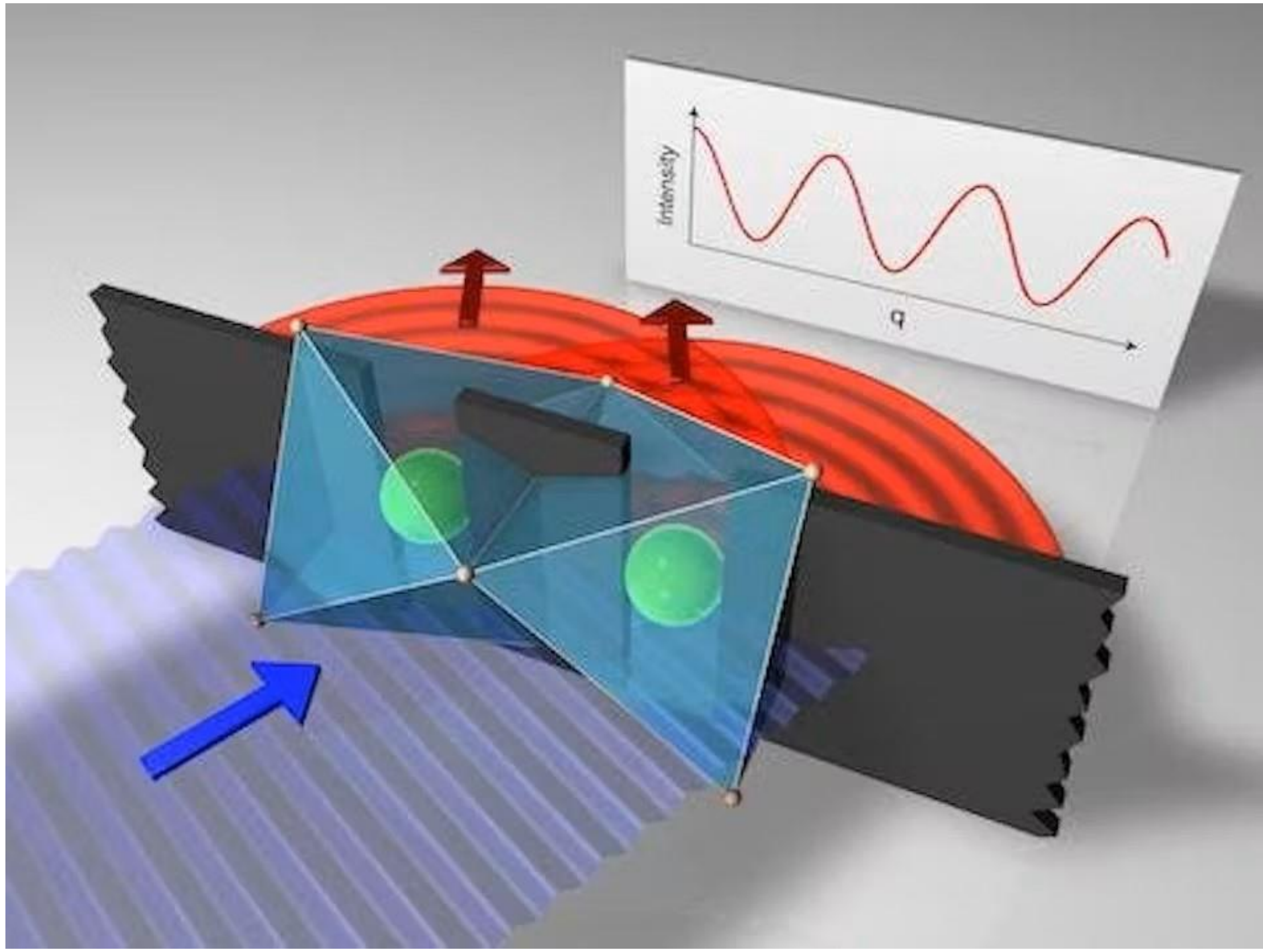
Double-Slit Experiments

Status: Classic but scaling up.

Focus: Interference of ever-larger particles.

Quantum Gravity Connection: Seeing whether interference disappears for large masses due to gravitational effects (e.g., spontaneous localization).

Example: Molecule interference up to ~10,000 amu; proposals for interferometry with nanoparticles.



https://www.laserfocusworld.com/test-measurement/test-measurement/article/16566907/classic-double-slit-experiment-redone-with-x-rays-and-two-adjacent-iridium-atoms

Torsion Balances

Status: Established.

Focus: Detecting tiny forces and torques.

Quantum Gravity Connection: Tests of inverse square law violations at short distances; probing extra dimensions.

Example: search of new forces down to micrometer scales.

Figure 4. Central apparatus of Colorado-Indiana experiment. The distance from the base plate to the top plate is about 50 cm.

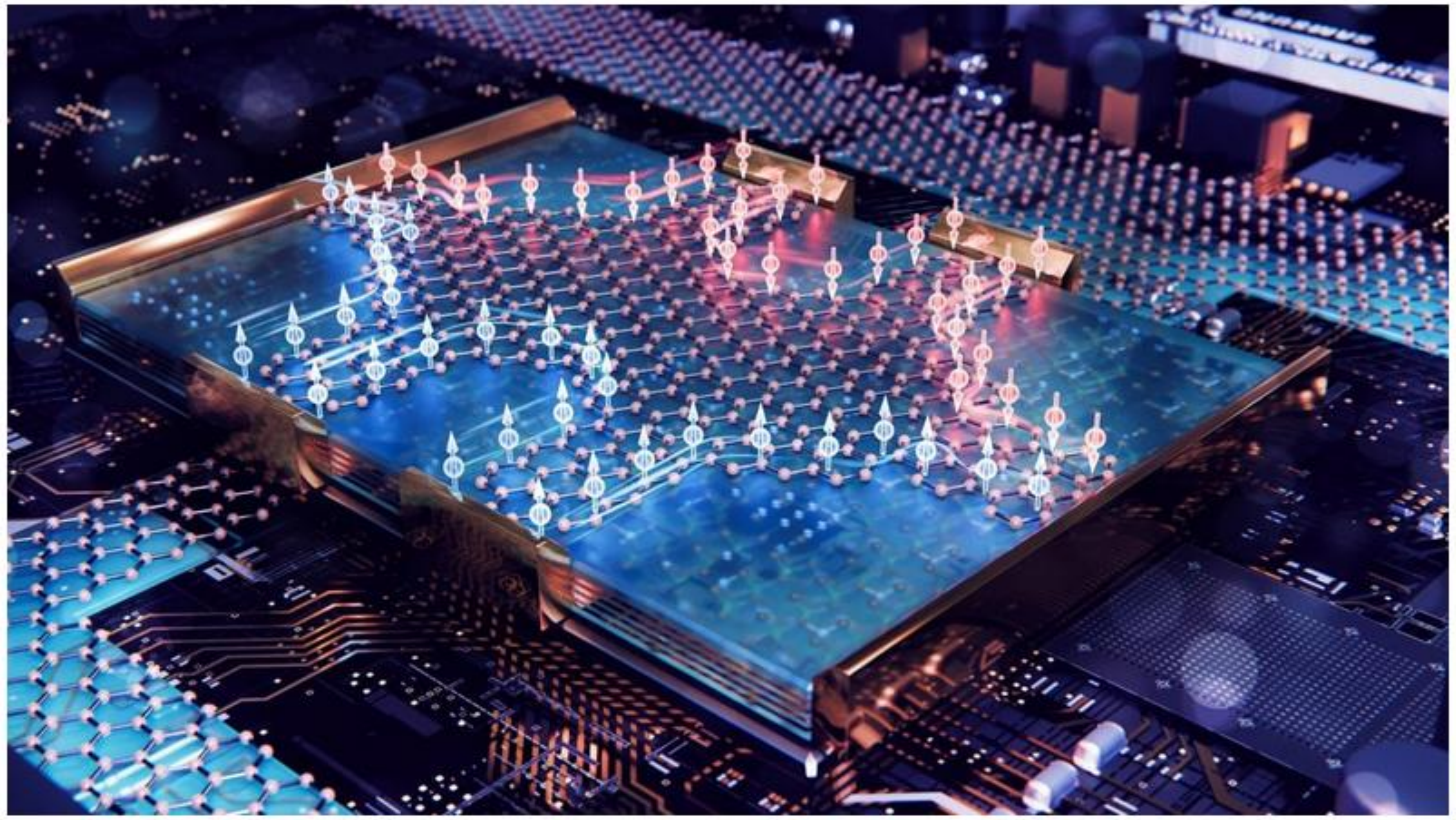
Solid-State Devices

Status: Growing.

Focus: Josephson junctions, SQUIDs, resonators.

Quantum Gravity Connection: Searching for quantum spacetime noise, minimal length effects, and decoherence.

Example: No conclusive detection; sensitivity improving.



Artist's impression of the quantum spin Hall effect in a graphene-based spintronic device, integrated in a chip. The blue and red spheres are spin-up and spin-down electrons traveling along the edge of the graphene. Underneath the graphene lies the layered magnetic material CrPS4. Credit: ScienceBrush, Talieh Ghiasi

Underground Experiments

Status: Mature in dark matter and neutrino physics; beginning for quantum gravity.

Focus: Low-background environments.

Quantum Gravity Connection: Potential tests of Planck-scale effects, rare decays, and energy deposition from spacetime granularity.

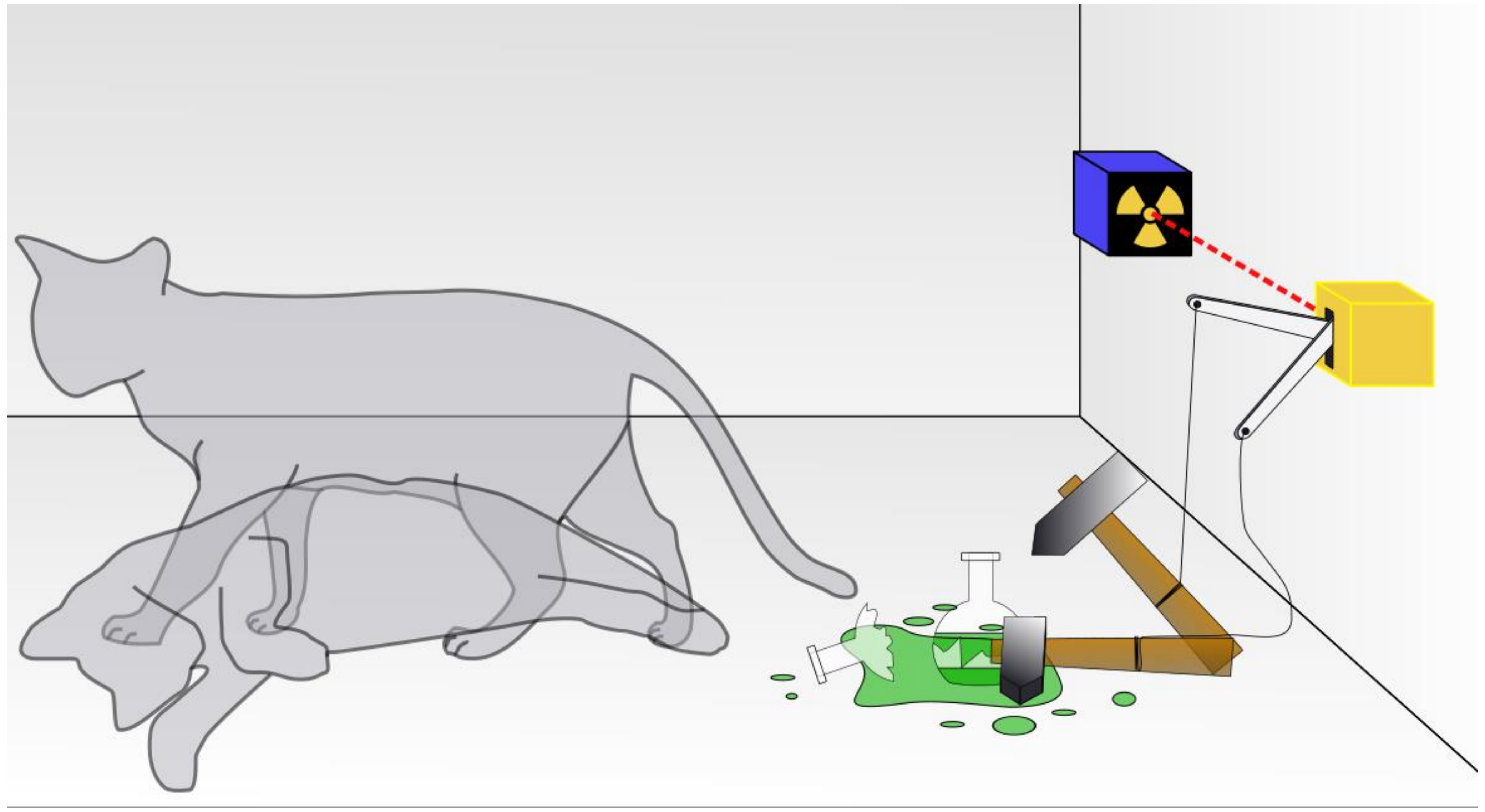
Example: No signal yet; facilities like Gran Sasso provide ideal environments.

LNGS

Challenges

many atoms = large mass ☺
= many degrees of freedom available ☺

many atoms = many degrees of freedom to control ☹
= many decoherence channels ☹



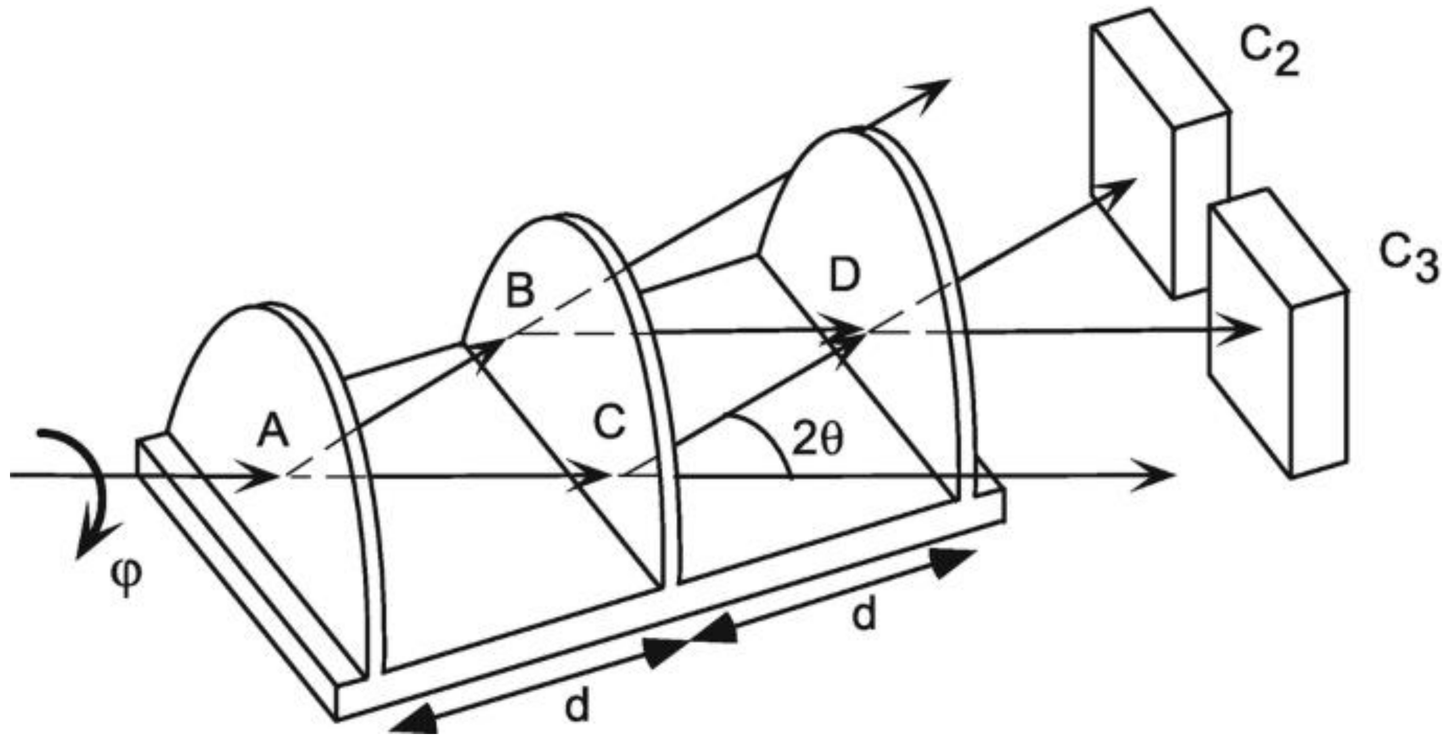
many atoms = macroscopic?

number of particles, mass, energy difference, delocalization distance, coherence time, …

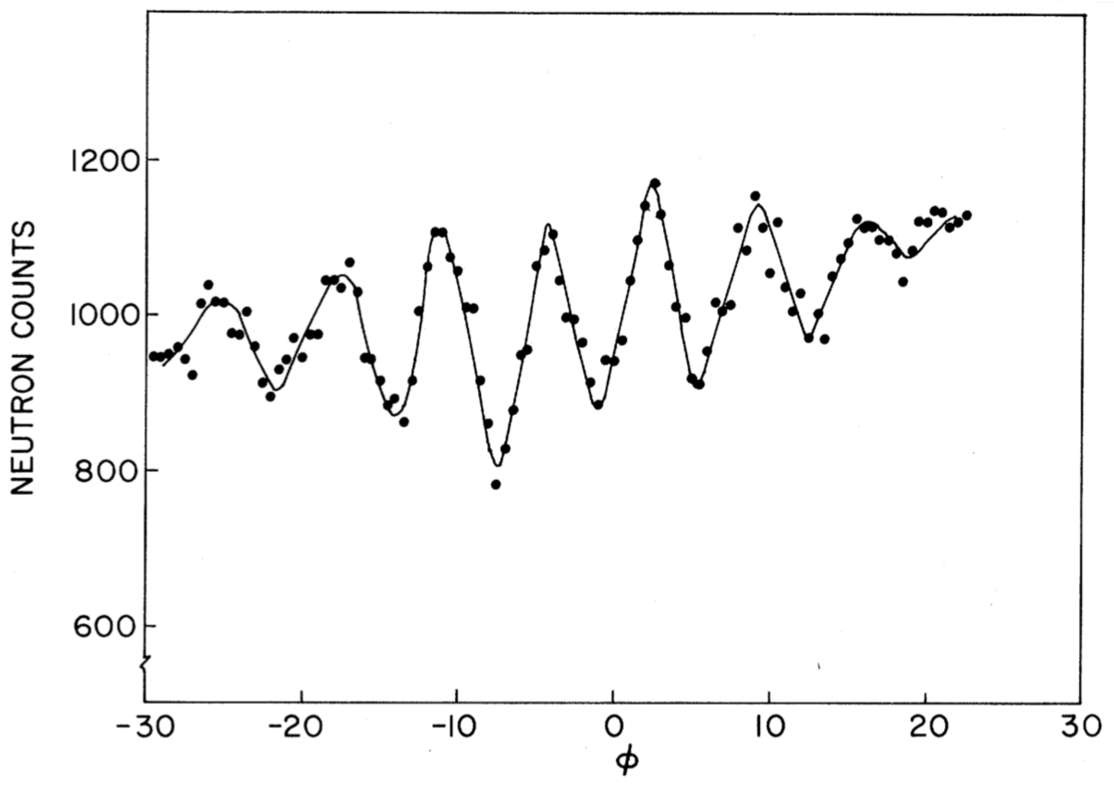
Schrinski et at. PRL 130, 133604 (2023)
Yadin and Fadel, arXiv:2503.08324 (2025)

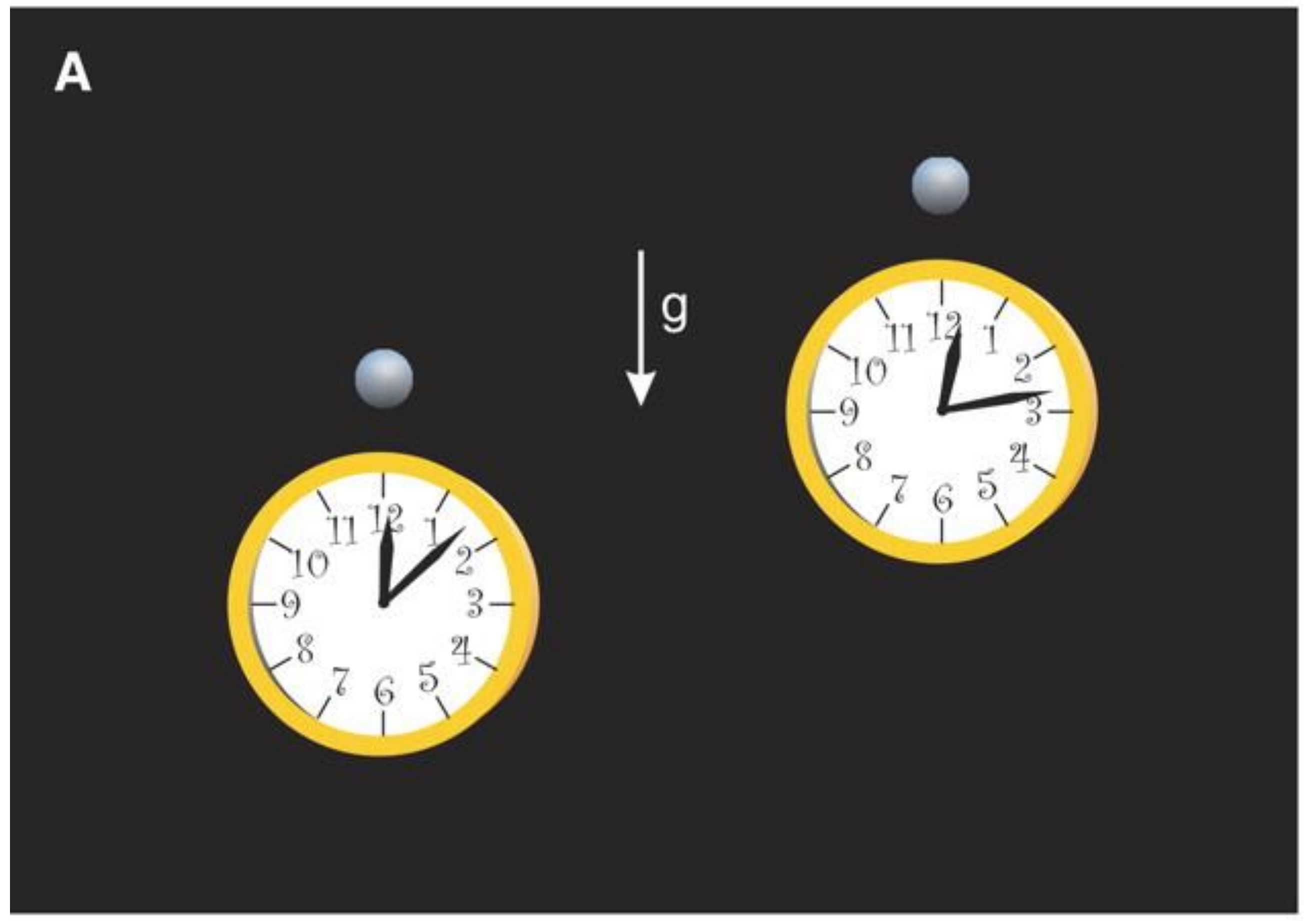
	Experiment	Year	μ
Mechanical resonators	*Bulk acoustic waves*	*2022*	*11.3*
	Phononic crystal resonator [13]	2022	~9.0*
	Surface acoustic waves [12]	2018	~8.6*
Matter-wave interference	Molecule interferometry [8]	2019	14.0
	Atom interferometry [6]	2019	11.8
	BEC interferometry [5]	2017	12.4

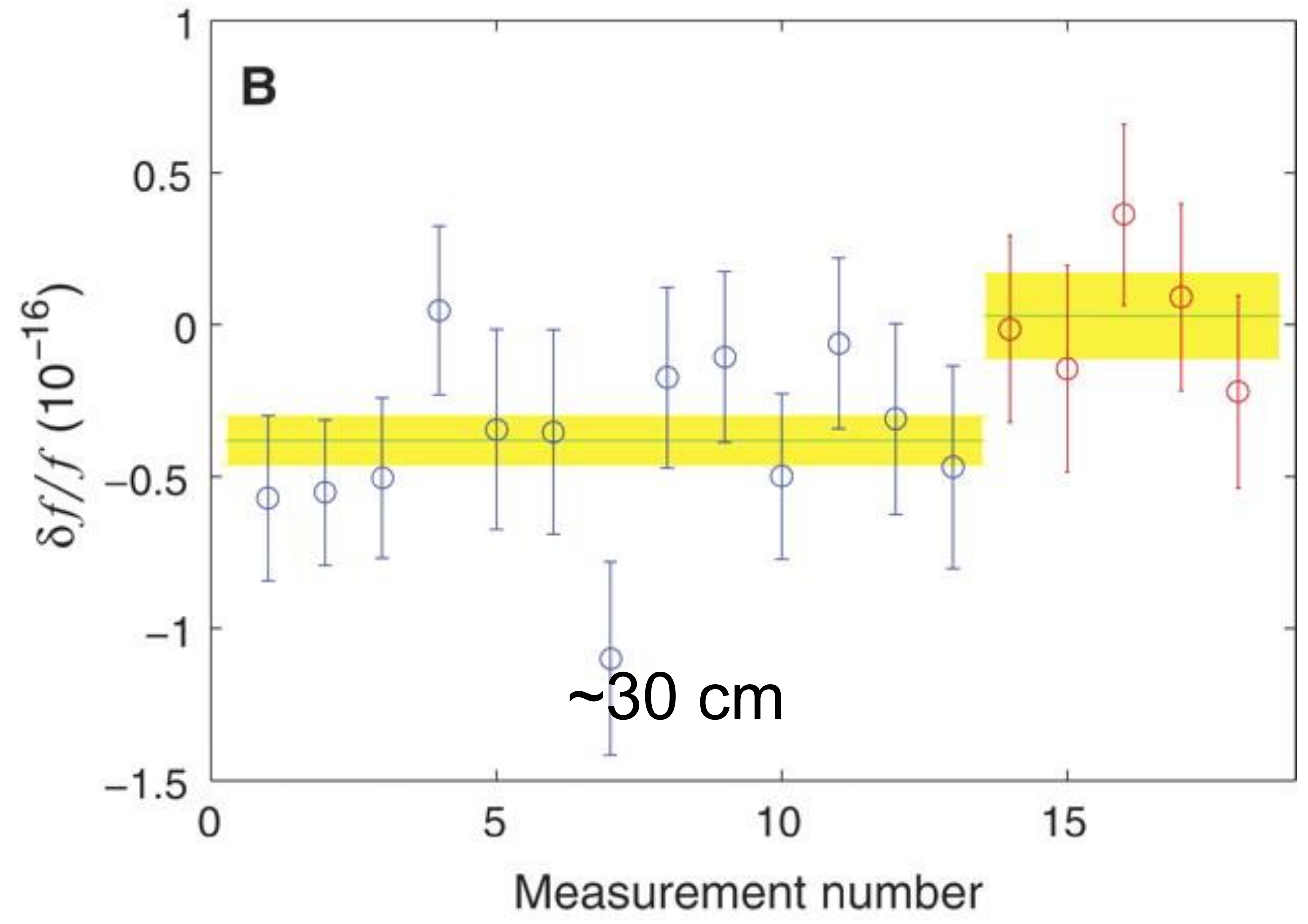
Interaction with gravity

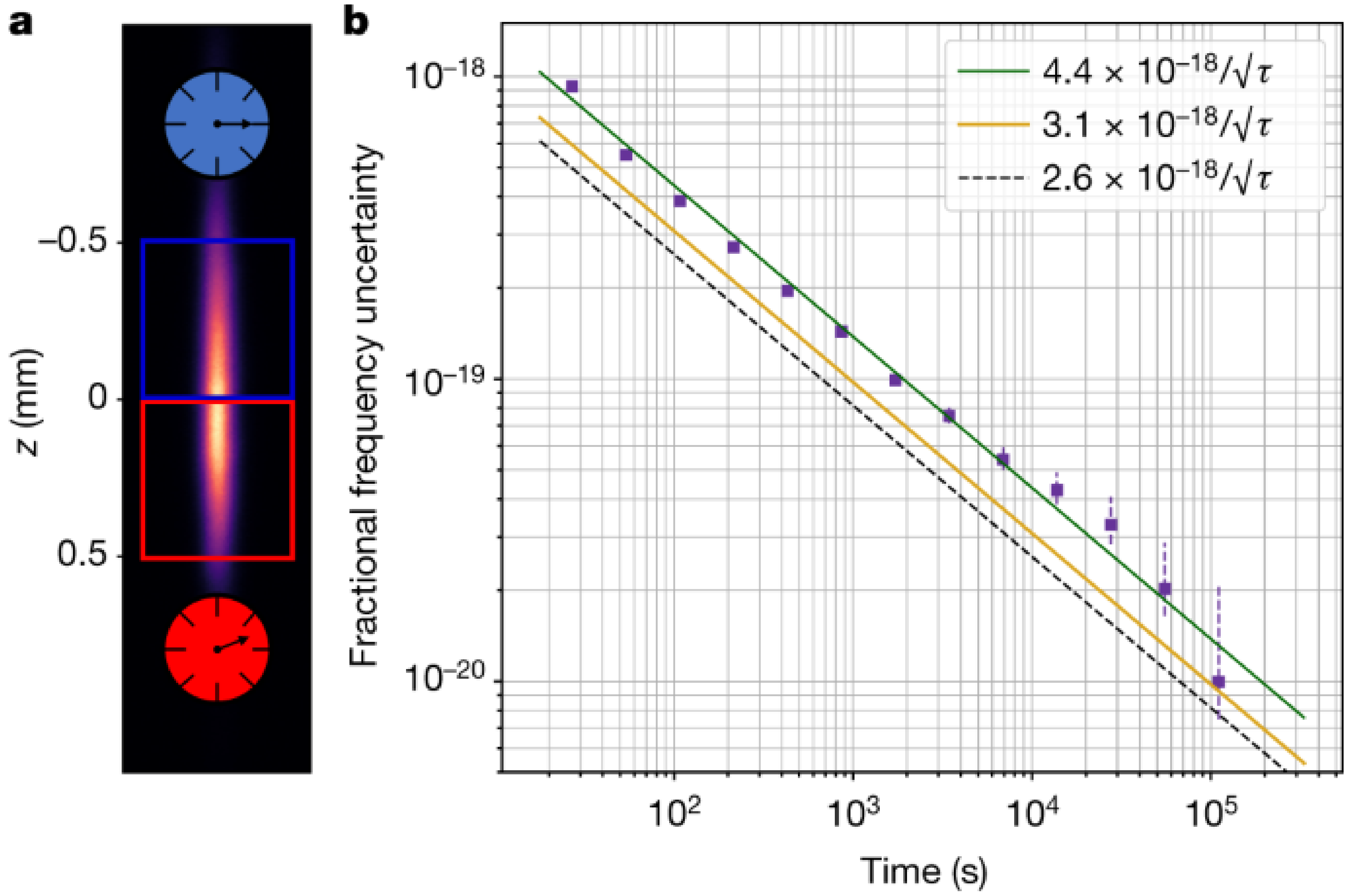


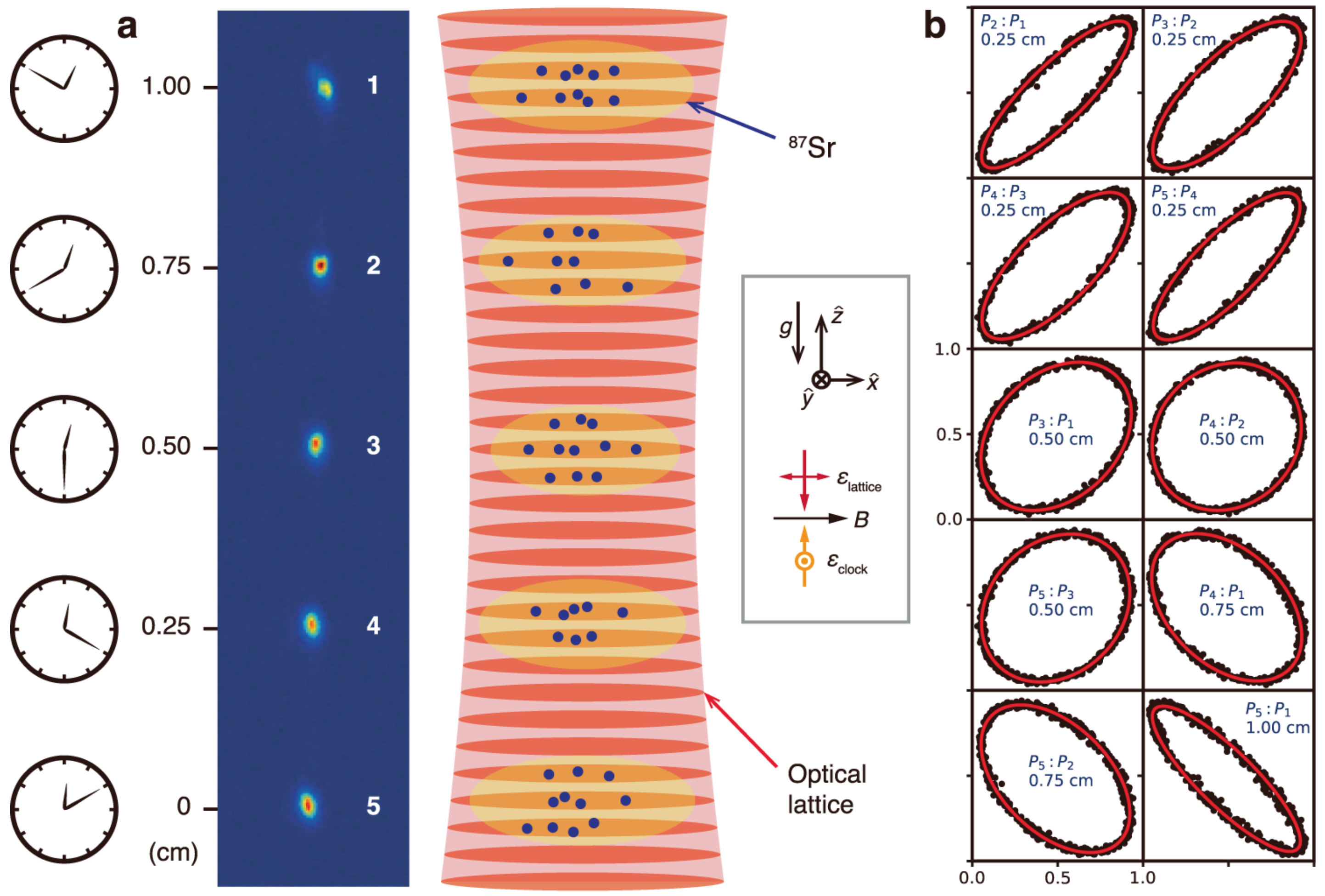
Colella et al. Phys. Rev. Lett. 34, 1472 (1975)











Chou et al. Science 329, 1630 (2010)
Zheng et al. Nat. Comm. 14, 4886 (2023)
Bothwell et al. Nature 602, 420 (2022)

Testing modifications to QM

standard QM

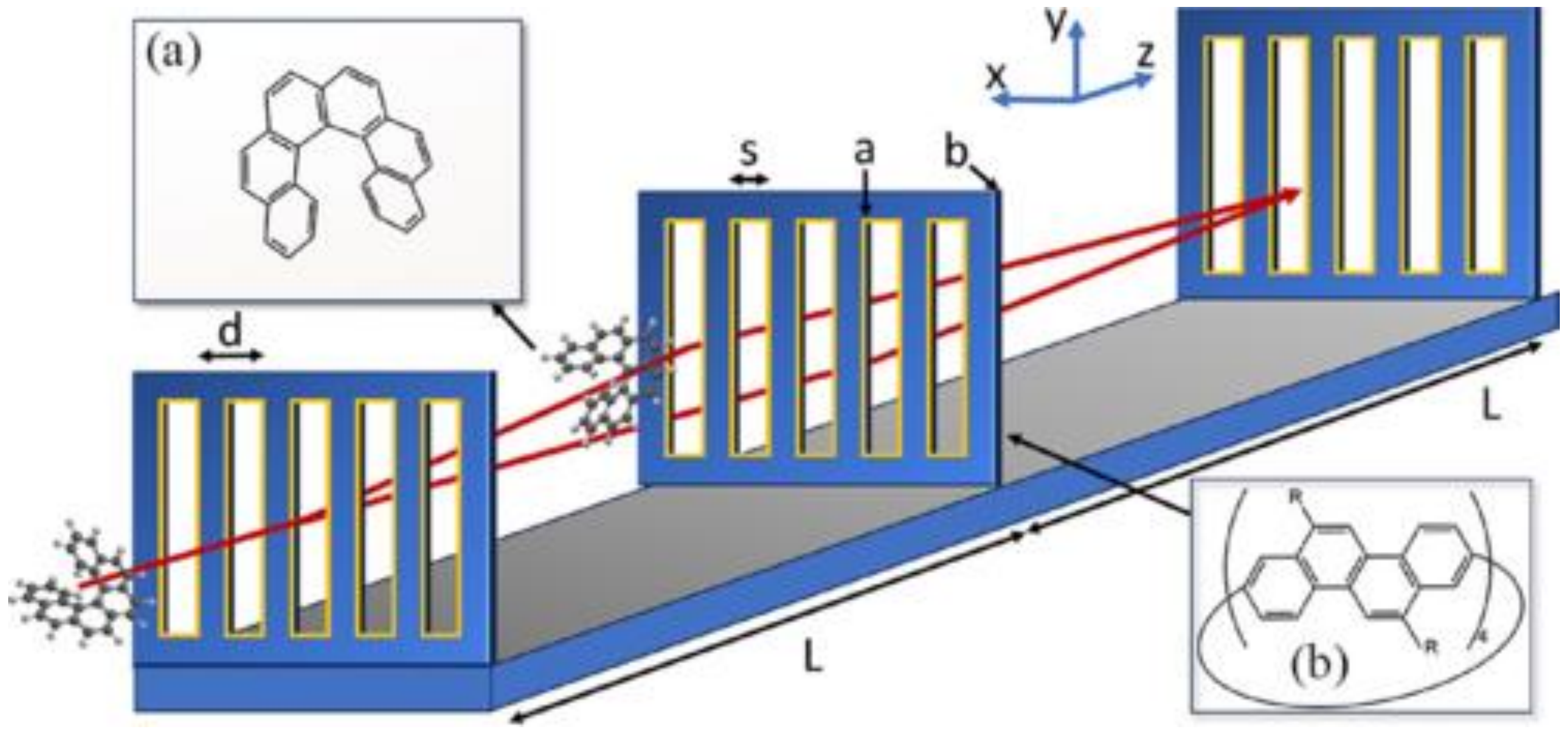
modification

$$\partial_t \rho_t = \mathcal{L}\rho_t + \frac{1}{\tau_e}\mathcal{M}_\sigma \rho_t$$

Testing modifications to QM

interferometric tests

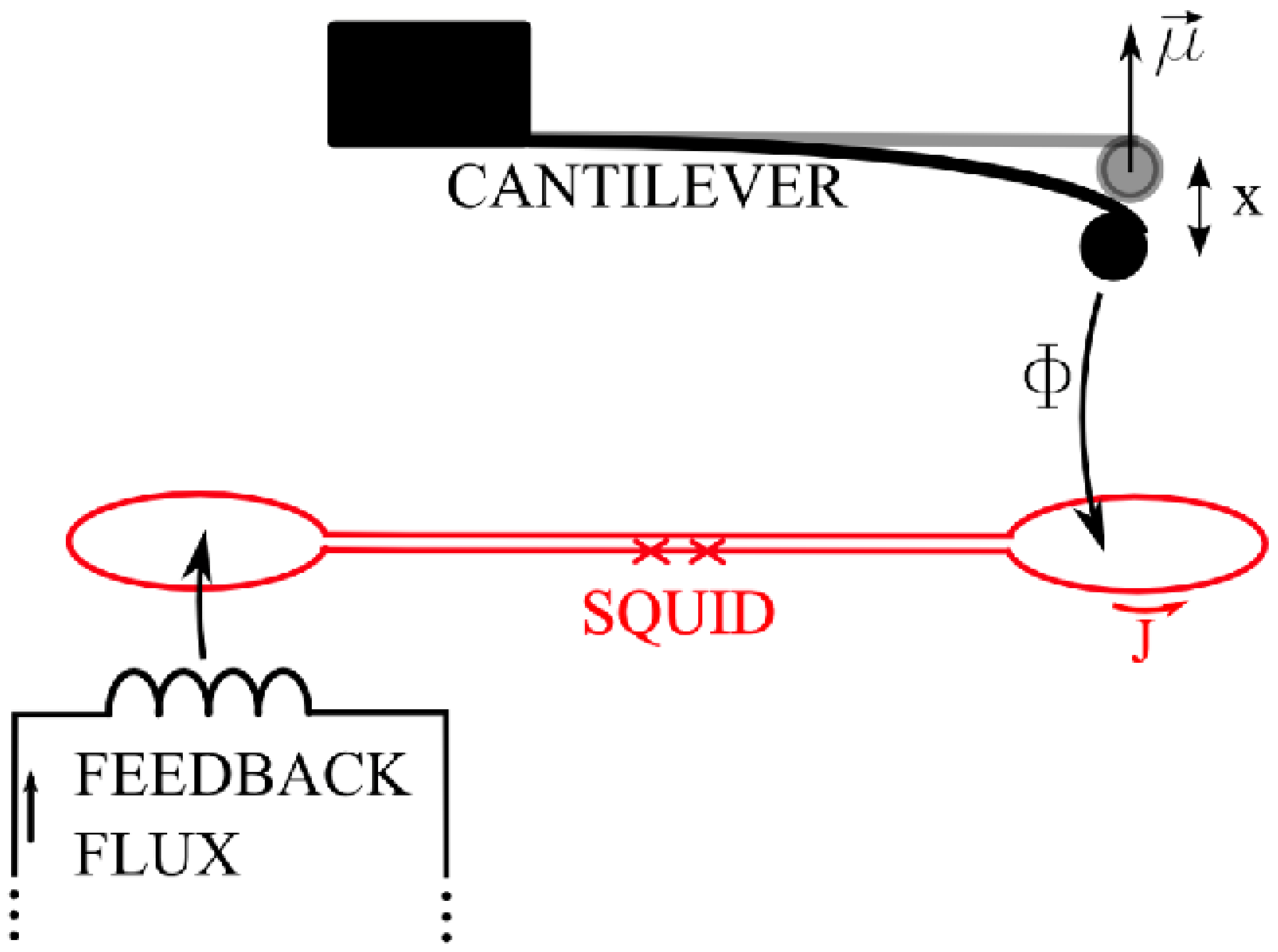
direct measurement of the decoherence
of a quantum (superposition) state



see also: precision spectroscopy,
mechanical oscillators,
atom interferometers, …

non-interferometric tests

indirect decoherence measurement
through e.g. heating or emission effects

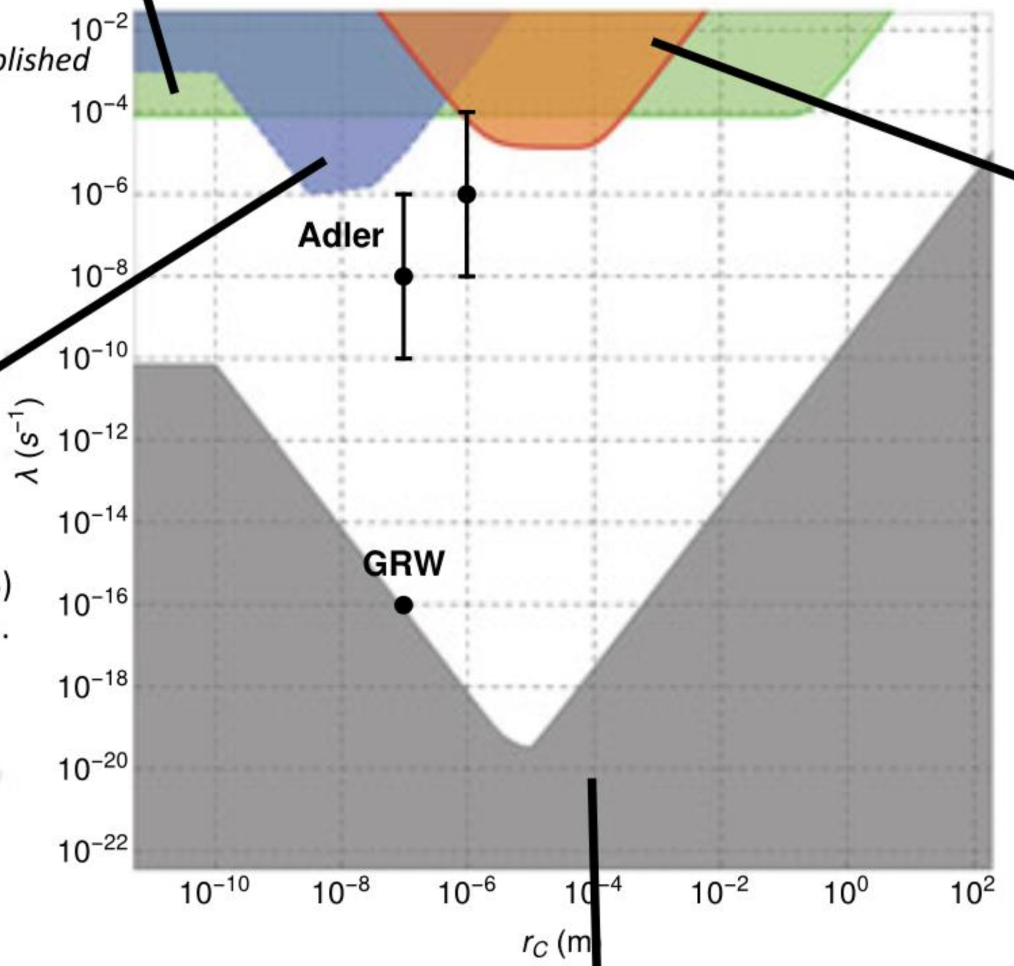


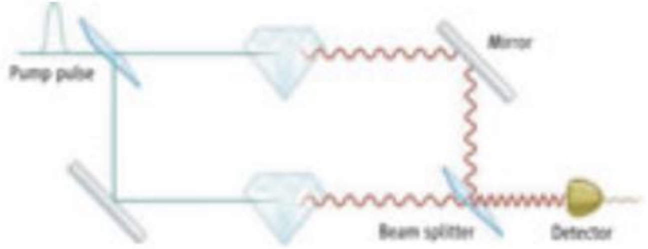
see also: levitated particles, bulk matter,
cold atoms, gravitational waves, …

Testing modifications to QM

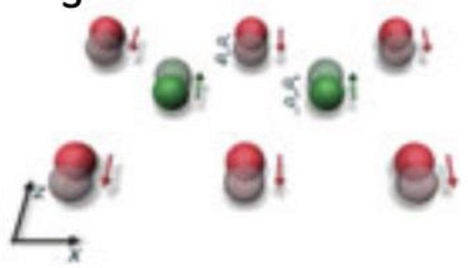
interferometric tests

Atom Interferometry
T. Kovachy *et al.*, Nature 528, 530 (2015)
M. Carlesso *et al.*, to be published
M = 87 amu
d = 0.54 m
T = 1 s

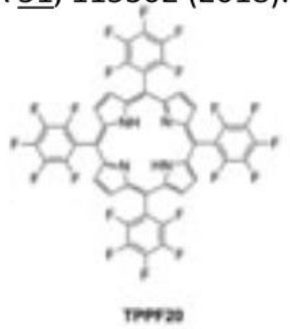




Entangling Diamonds
K. C. Lee *et al.*, Science. 334, 1253 (2011).
S. Belli *et al*, Phys. Rev. A 94, 012108 (2016).
M = 10^{16} amu
d = 10^{-11} m
T = 10^{-12} s



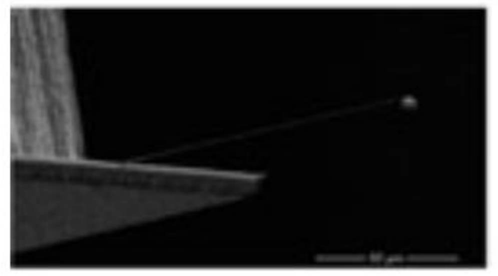
Molecular Interferometry
S. Eibenberger *et al.* PCCP 15, 14696 (2013)
M. Toros *et al.*, J. Phys. A 51, 115302 (2018).
M = 10^4 amu
d = 10^{-7} m
T = 10^{-3} s



M. Toros *et al.*, Phys. Lett. A 381, 3921 (2017).
Lower bound: Collapse effective at the macroscopic level
Graphene disk: N = 10^{11} amu, d = 10^{-5} m, T = 10^{-2} s

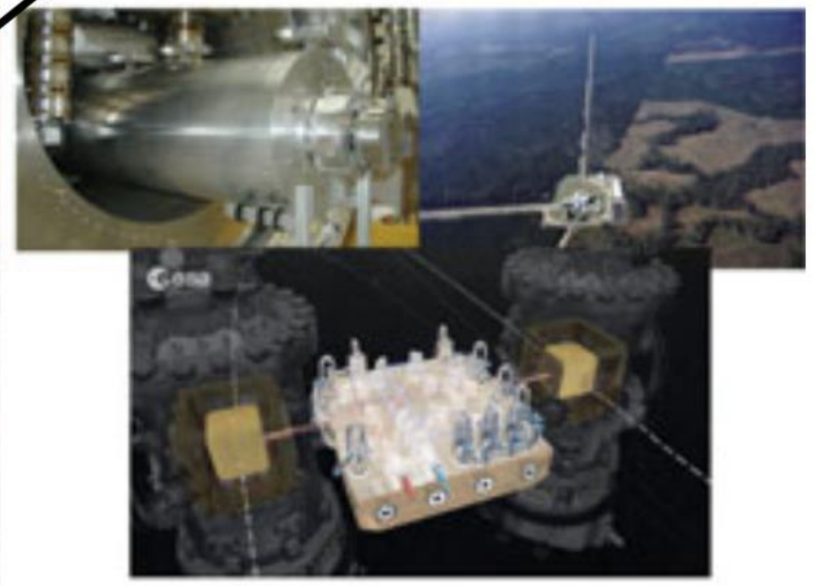
non-interferometric tests

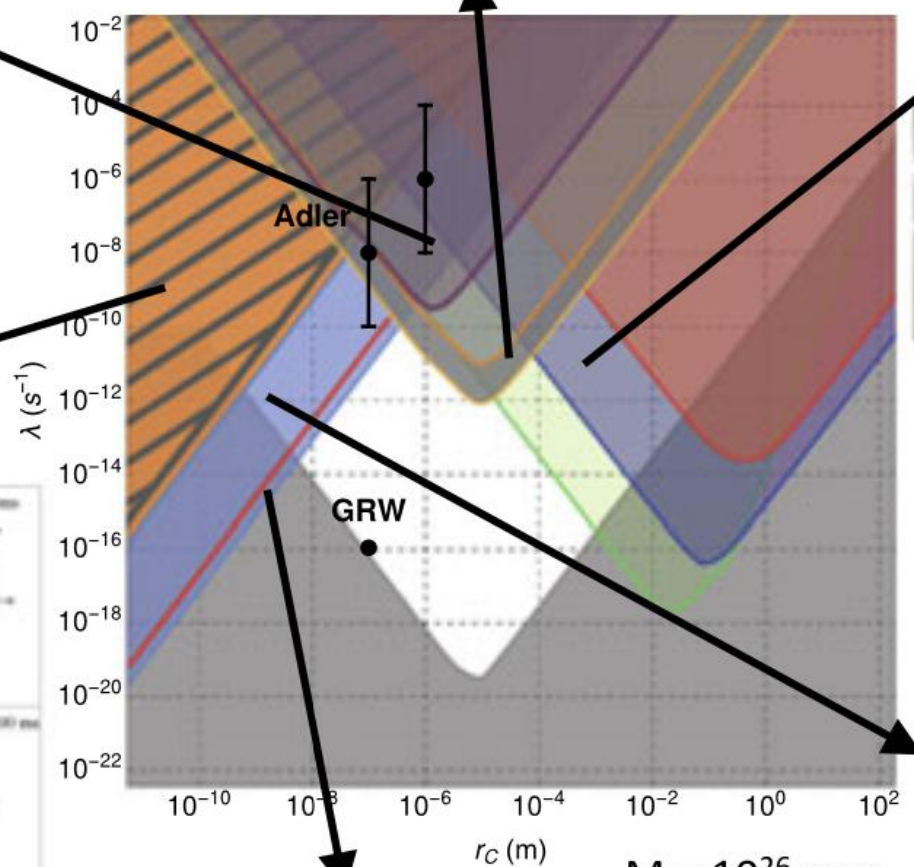
Nanomechanical Cantilever
Vinante *et al.*, Phys. Rev. Lett. 116, 090402 (2016).
M = 10^{14} amu
T = ∞



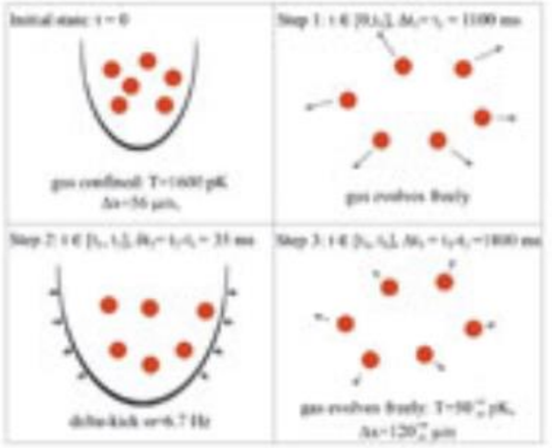
Improved Nanomechanical Cantilever
Vinante *et al.*, Phys. Rev. Lett. 119, 110401 (2017).

Gravitational wave detectors
Carlesso *et al.*, Phys. Rev. D 94, 124036 (2016).
M = $10^{26\text{-}30}$ amu
T = ∞



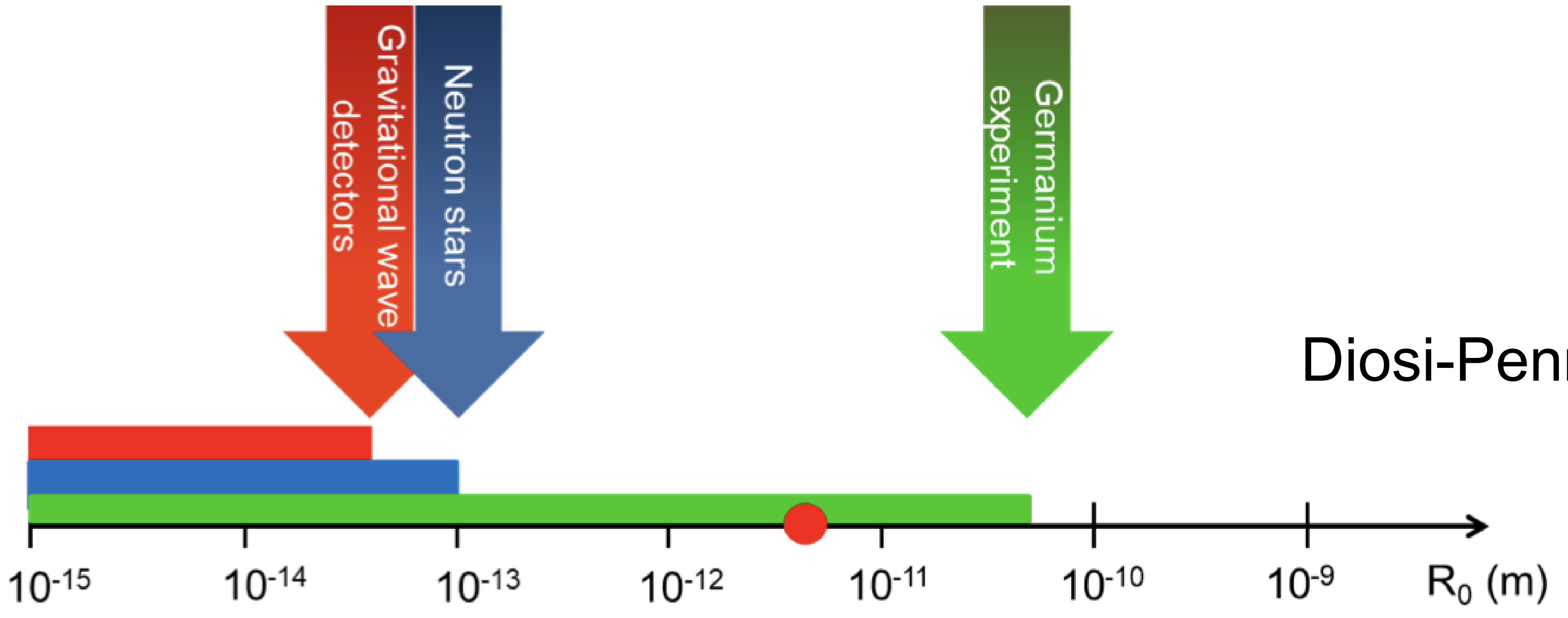


Cold Atoms
Bilardello *et al.*, Physica A, 462:764-782 (2016).
M = 87 amu
T = 1 s



X-rays emission
Piscicchia *et al*, Entropy 19(7), 319 (2017)
M = 10^{26} amu
T = days / months

Phonon Spectrum
Adler *et al.*, Phys. Rev. A 97, 052119 (2018).
Bahrami, Phys. Rev. A 97, 052118 (2018).



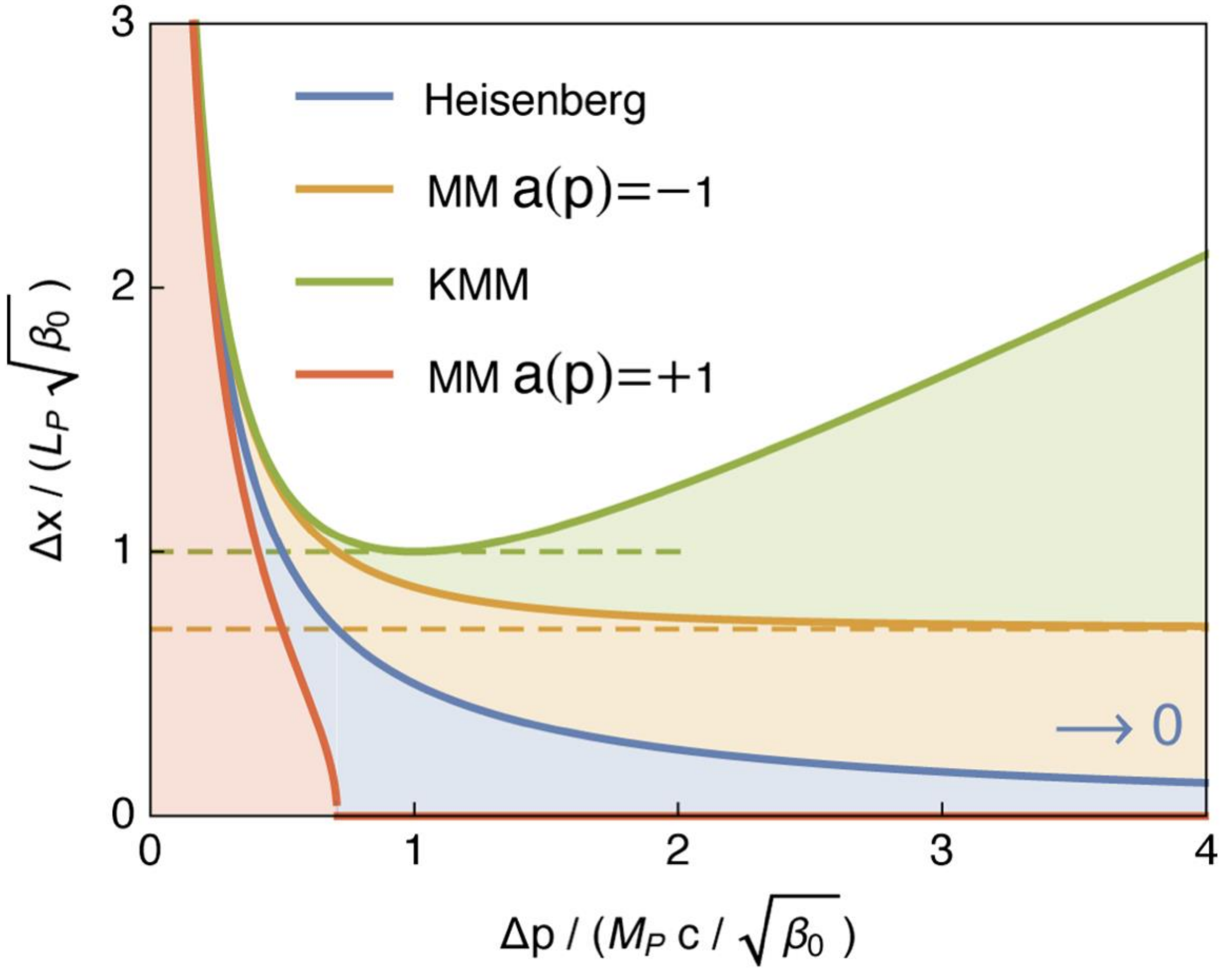
Carlesso and Donadi, Springer (2019)
Donadi et al. Nature Physics 17, 74 (2021)

Spacetime structure tests

GUP

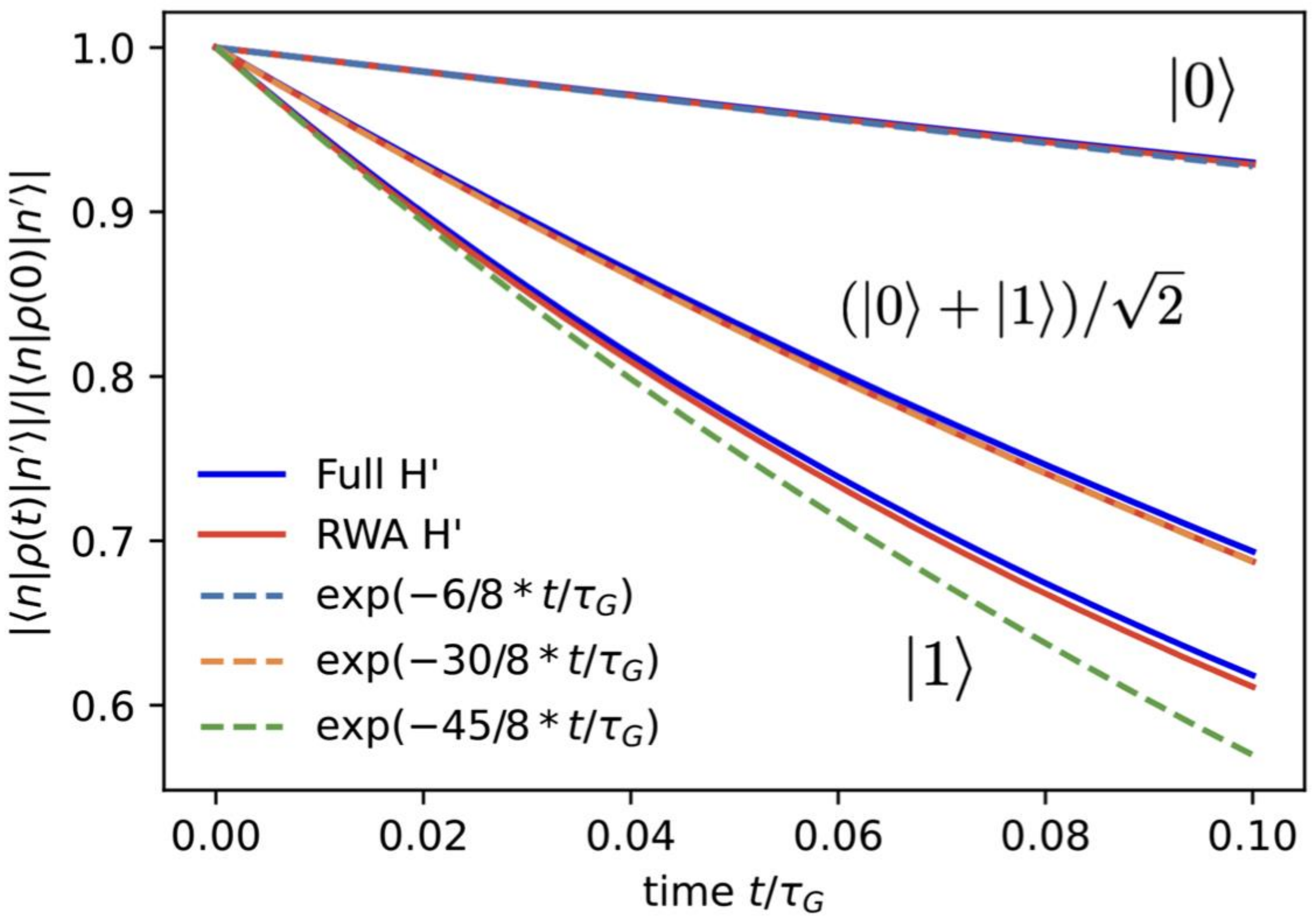
$$\Delta x \geq \frac{\hbar}{2\Delta p}\left[1+\beta_0\left(\frac{\Delta p}{M_P c}\right)^2+\mathcal{O}\left(\frac{\Delta p}{M_P c}\right)^4\right]$$

Fadel and Maggiore PRD 105, 106017 (2022)

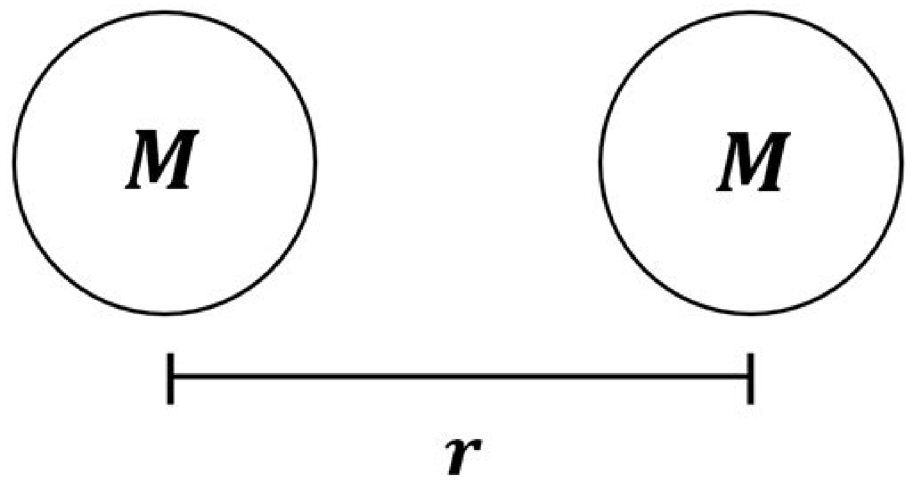


stochastic spacetime fluctuations or foaminess

Breuer et al., Quant. Grav. 26, 105012 (2009).
Petruzziello and Illuminati, Nat. Comm. 12 (2021)
Arzano et al., Comm. Phys. 6 (2023)
Donadi and Fadel PRD 111, 026009 (2025) ← experiment

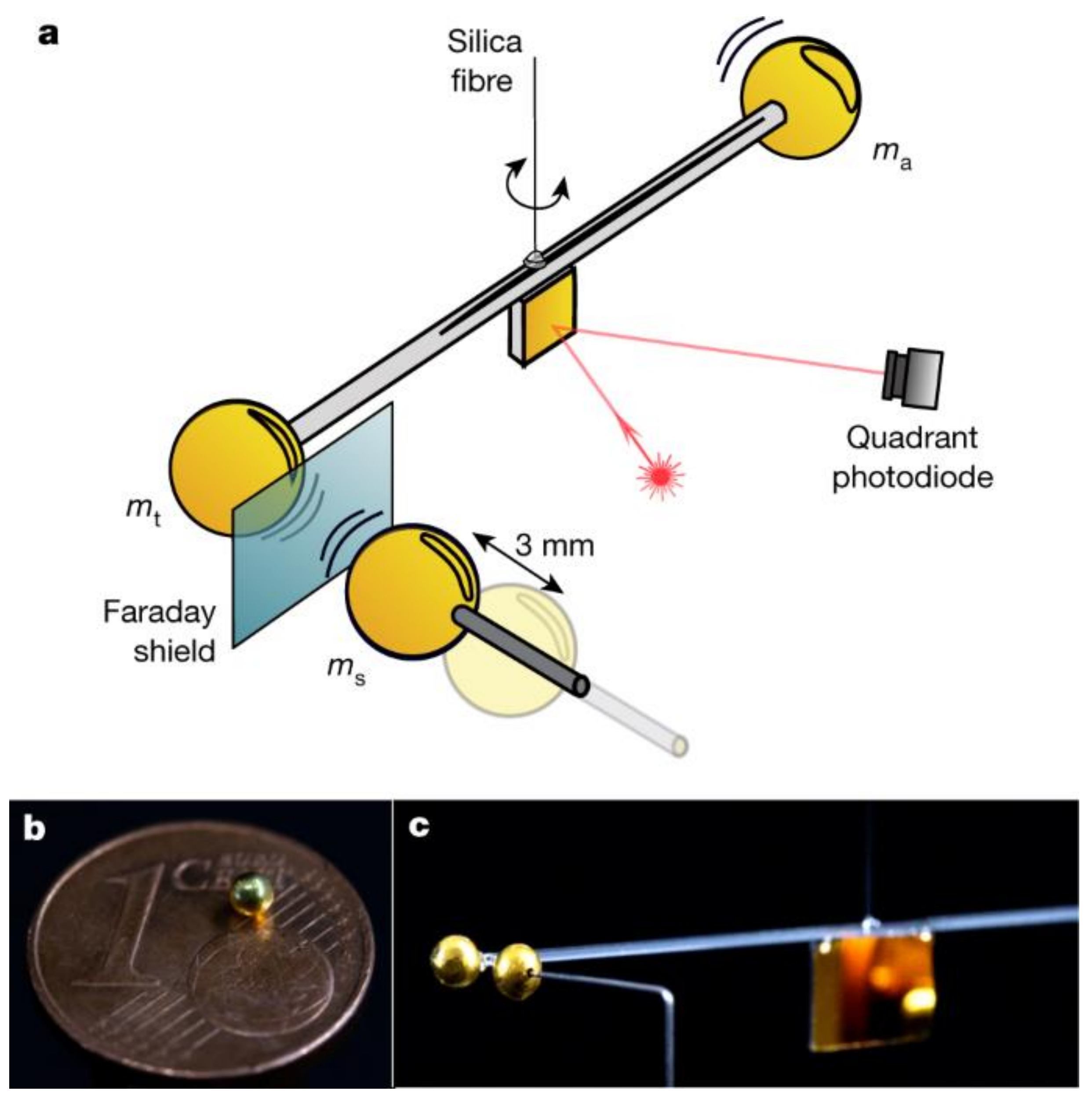


Gravity at short distances

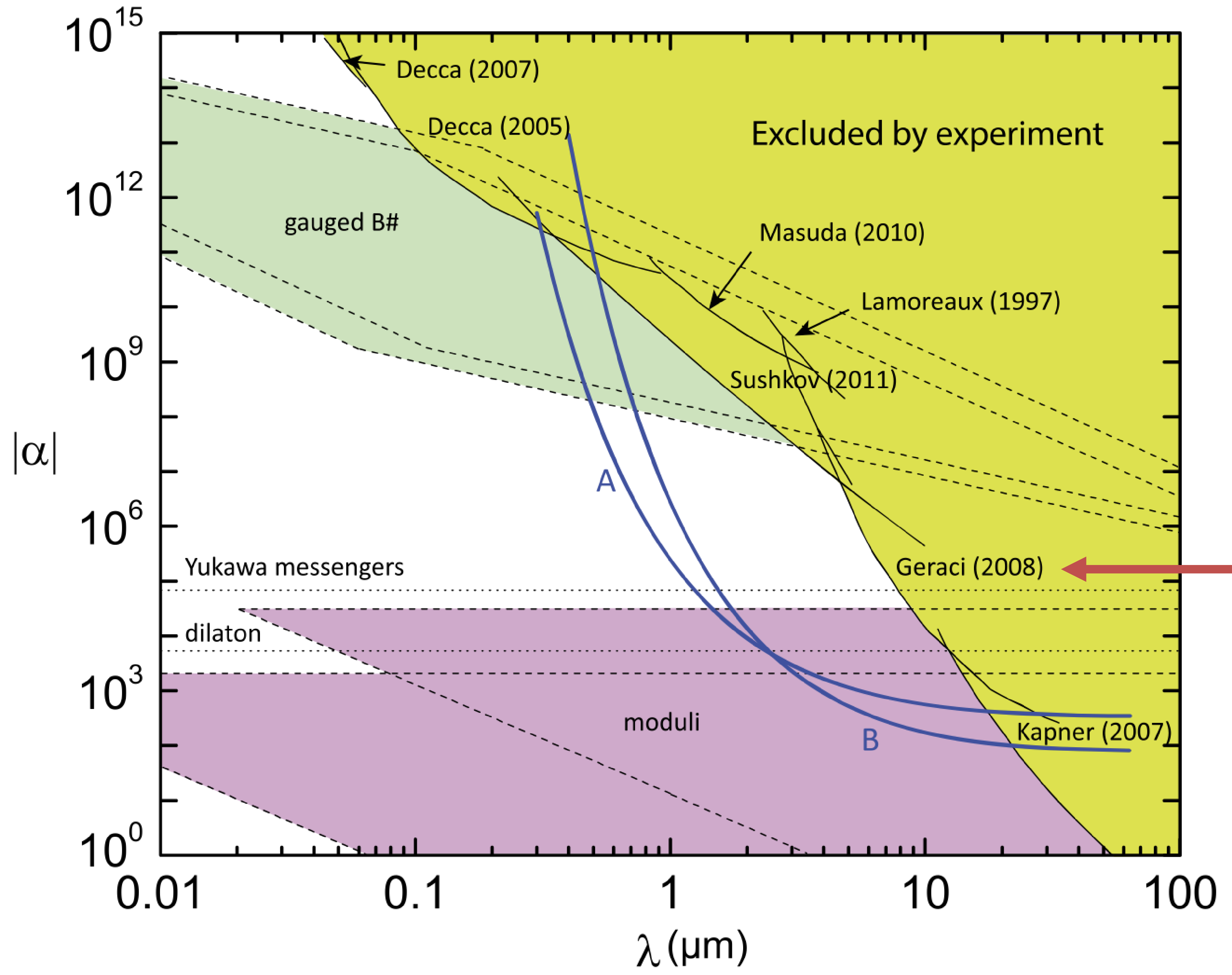


$$U_G = -G\frac{M_1 M_2}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$

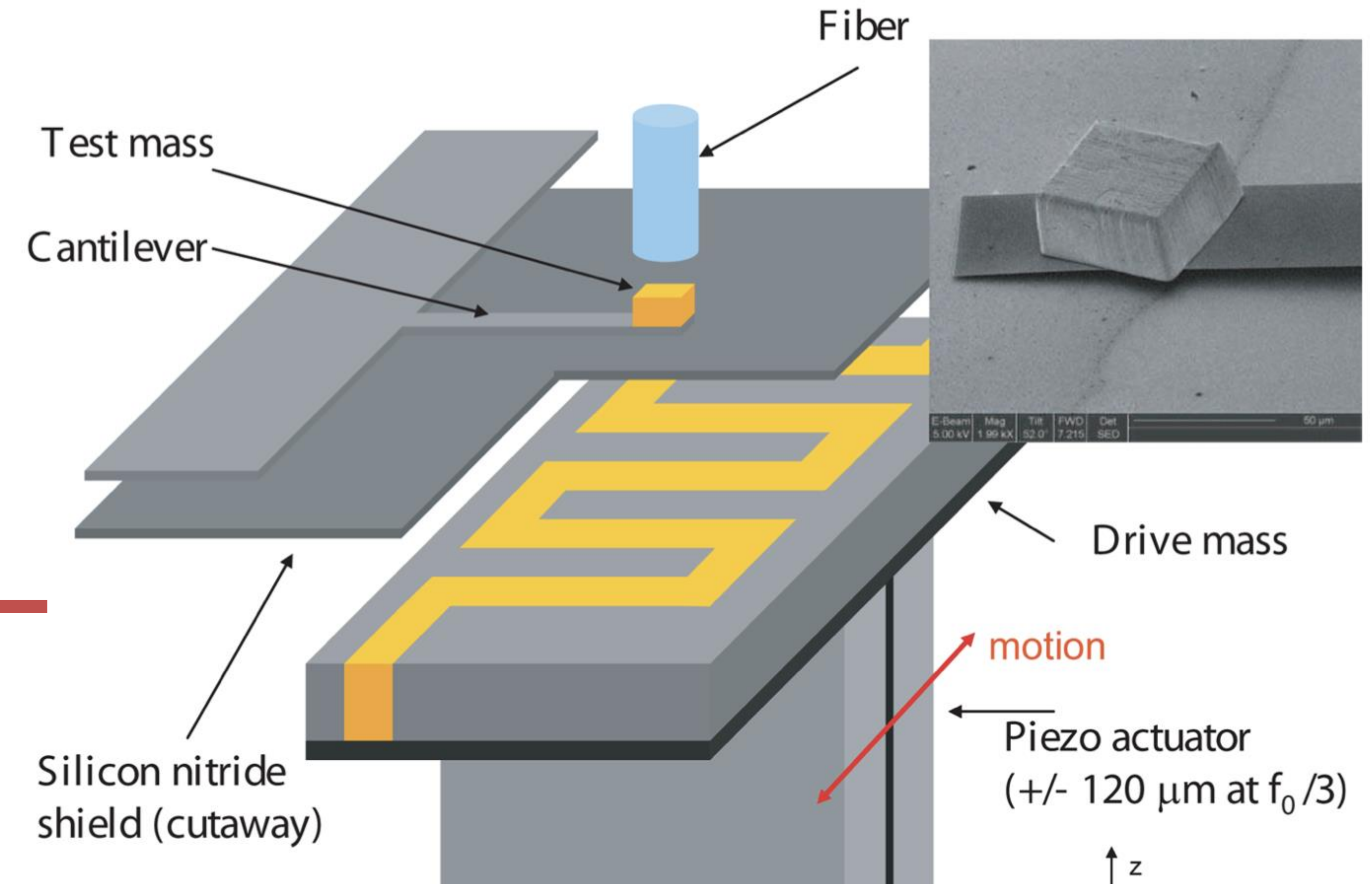
Westphal et al., Nature 591, 225 (2021)



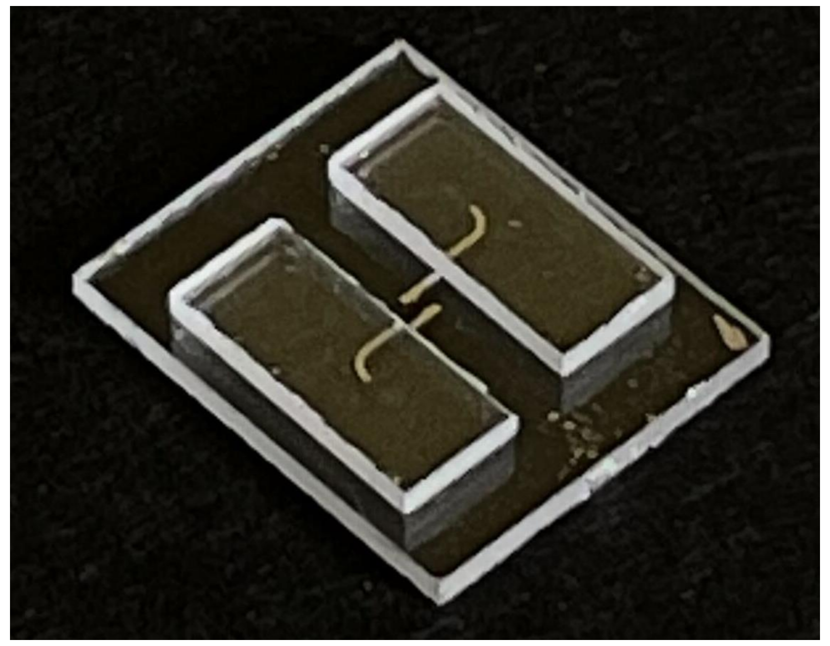
Geraci and Goldman, PRD 92, 062002 (2015)



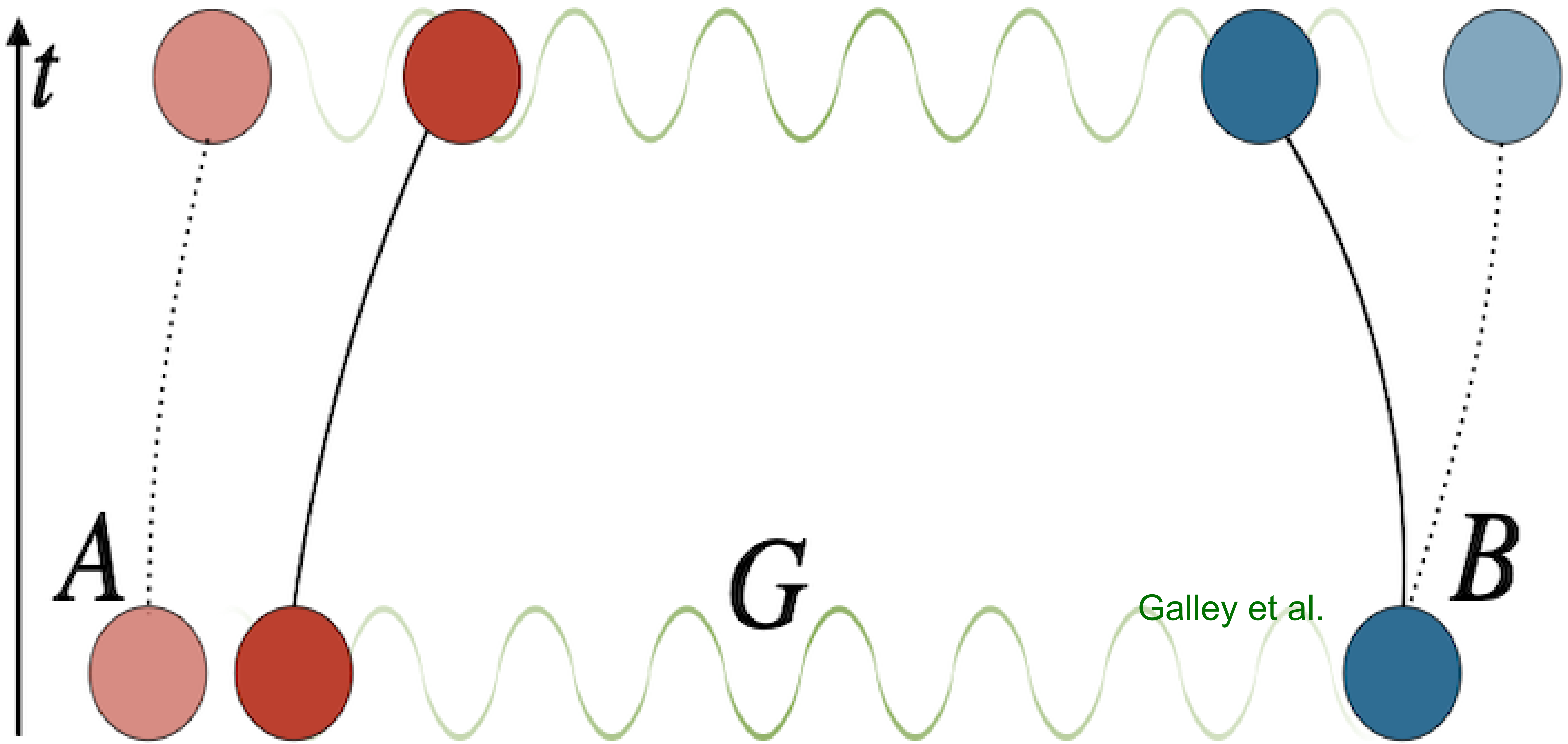
Geraci et al., PRD 78, 022002 (2008)



Long term goal



can gravity mediate entanglement?
i.e. is gravity quantum?



Marletto ad Vedral PRL 119 (2017)
Bose et al. PRL 119 (2017)

Summary

No confirmed experimental evidence of quantum gravity yet.

Precision keeps improving by orders of magnitude every decade.

Next milestones:

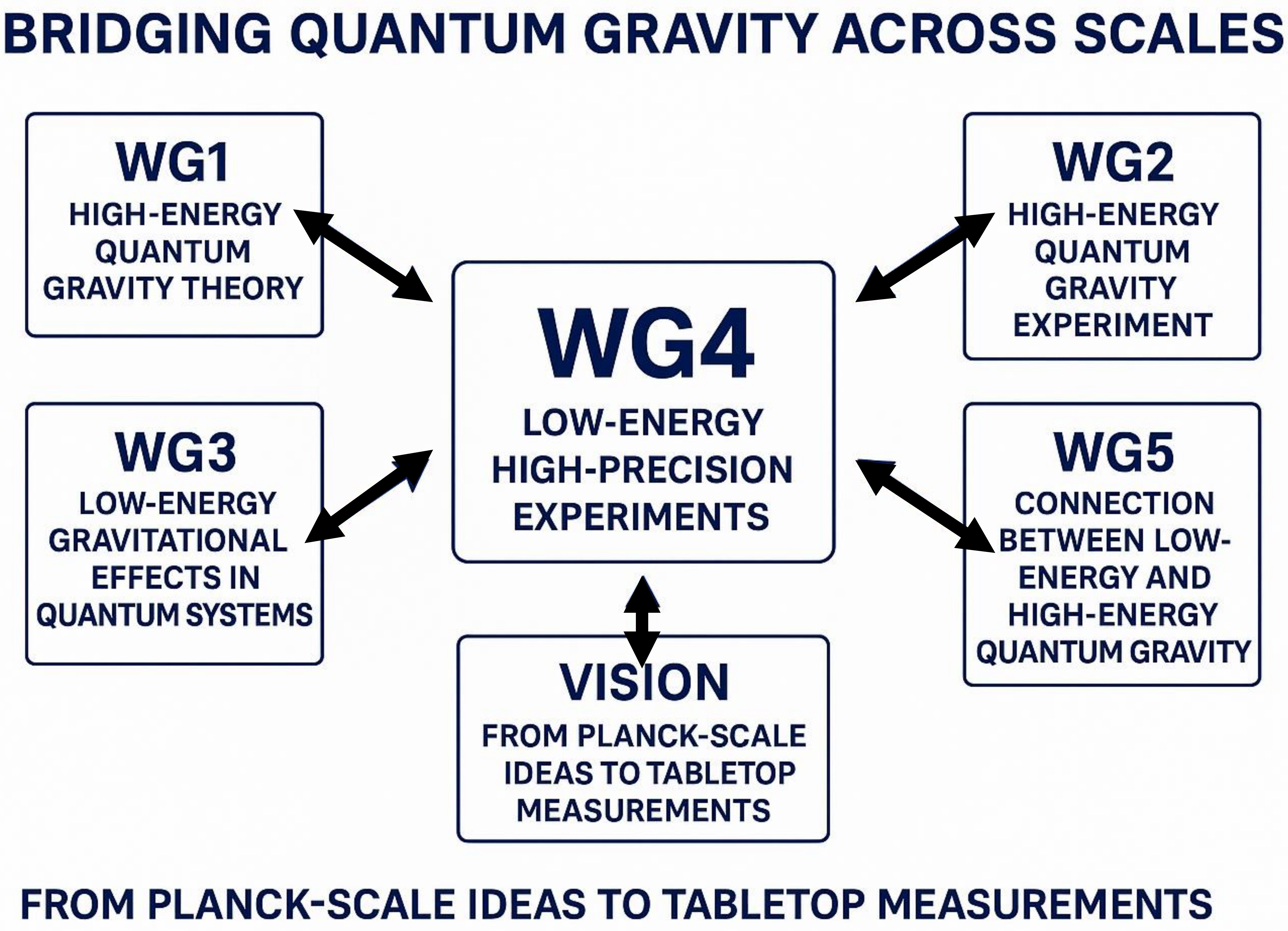
Entanglement experiments with mesoscopic masses.

Interference of levitated particles $>10^9$ amu.

Better torsion balance sensitivity below microns.

Clock comparisons over gravitational gradients

Underground experiments – more precision


BRIDGING QUANTUM GRAVITY ACROSS SCALES
WG1
HIGH-ENERGY QUANTUM GRAVITY THEORY
WG2
HIGH-ENERGY QUANTUM GRAVITY EXPERIMENT
WG4
LOW-ENERGY HIGH-PRECISION EXPERIMENTS
WG3
LOW-ENERGY GRAVITATIONAL EFFECTS IN QUANTUM SYSTEMS
WG5
CONNECTION BETWEEN LOW-ENERGY AND HIGH-ENERGY QUANTUM GRAVITY
VISION
FROM PLANCK-SCALE IDEAS TO TABLETOP MEASUREMENTS
FROM PLANCK-SCALE IDEAS TO TABLETOP MEASUREMENTS