Fundamental physics applications of atom interferometry

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London, 9 December 2020

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Institute of Quantum Technologies
(Ulm)

PARTS I–V

I. *Long-time* atom interferometry for *precision measurements*

II. *Fine-structure constant* and *atomic mass* measurements

III. *Gravitational* measurements

IV. Searching for *dark energy* and *dark matter*

V. *Gravitational time-dilation* in macroscopically *delocalized quantum superpositions*

PART I

Long-time atom interferometry for precision measurements

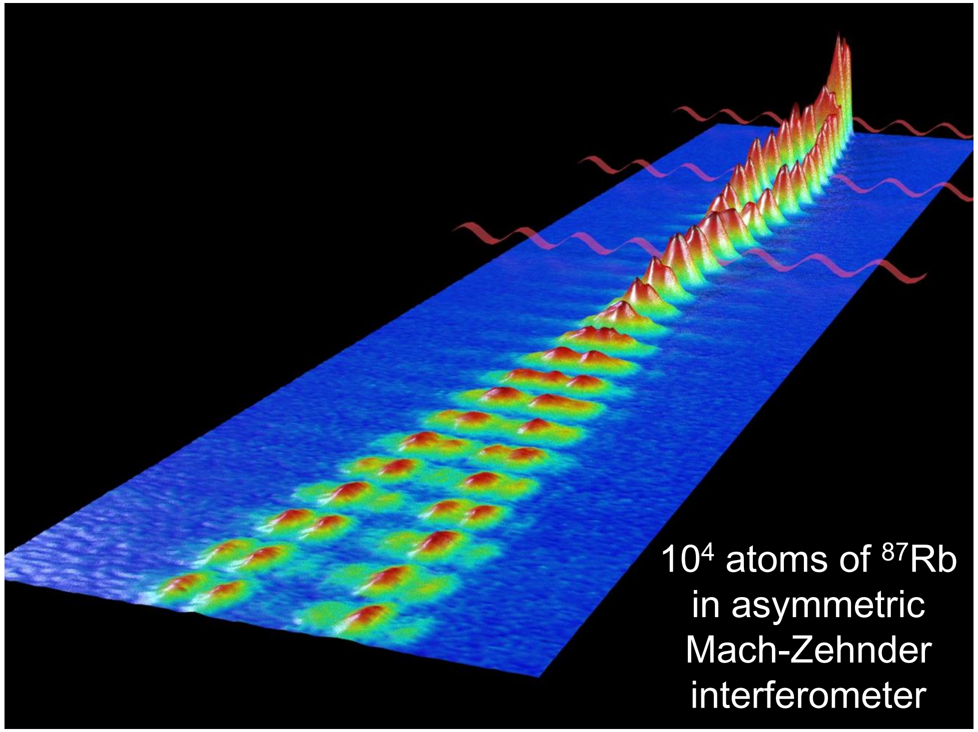
Outline

1. *Quantum sensors* based on atom interferometry
    - atom interferometers as accelerometers
    - long-time interferometry
    - microgravity platforms
2. Atomic *lensing*
3. Experiments with ultracold atoms in microgravity

Quantum sensors based on atom interferometry

- Exploit quantum features of atomic systems
- Interferometry with matter waves diffracted by laser beams (*reversed roles* of matter and light)

Louis de Broglie



10^4 atoms of ^{87}Rb in asymmetric Mach-Zehnder interferometer

H. Ahlers

- *Appealing properties* of atomic sensors:
  - atoms of the same element & isotope are identical (definition of *metrological standards*)
  - *neutral* atoms in *magnetically insensitive* states
    → excellent inertial references
  - superb control and manipulation capabilities using lasers

Applications to precision measurements:

- Atomic clocks (*internal degrees of freedom*)
  - *microwave* transitions → $\Delta\nu/\nu \sim 10^{-16}$
  - *optical* transitions → $\Delta\nu/\nu \sim 10^{-18}$

- Inertial sensors (*geophysics, geodesy, navigation*)
  - accelerometers / gravimeters $\Delta g/g \sim 10^{-9}$

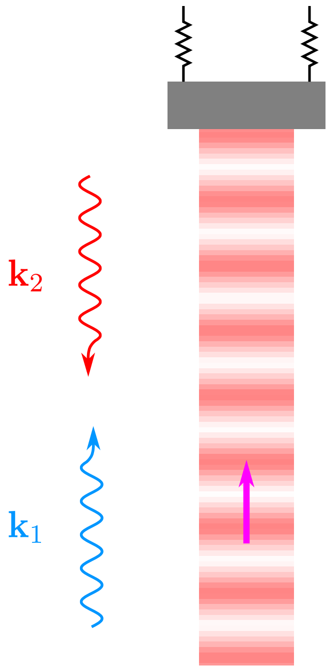
    ↳ gradiometers
  - gyroscopes (*Coriolis*) $\Delta\Omega \approx 3 \times 10^{-10}\,\mathrm{rad/s}$

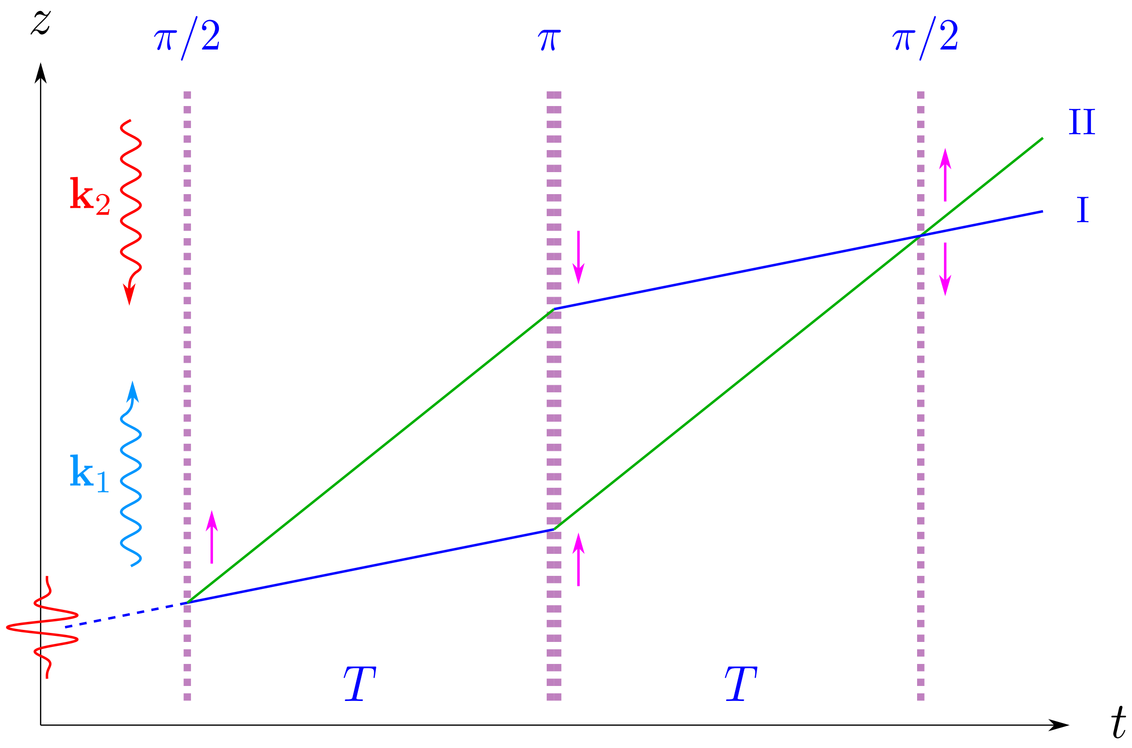
- Measurement of fundamental constants:
  - fine-structure constant α $\Delta\alpha/\alpha \approx 2 \times 10^{-10}$
  - Newtonian gravitational constant G $\Delta G/G \sim 10^{-4}$

- Fundamental tests:
  - *universality of free fall* (UFF) (weak equivalence principle) $\eta_{AB} = 2\,\frac{|g_A - g_B|}{g_A + g_B} \lesssim 10^{-12} \ldots\ 10^{-14}$
  - *local Lorentz invariance* (LLI)

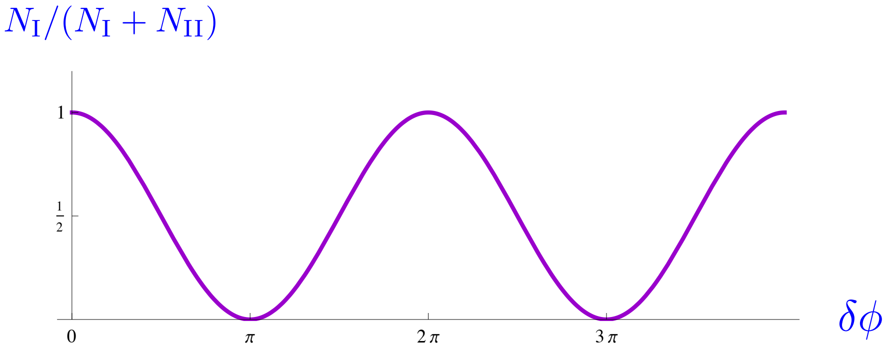
- Searching for dark energy and dark matter.

Atom interferometers as accelerometers





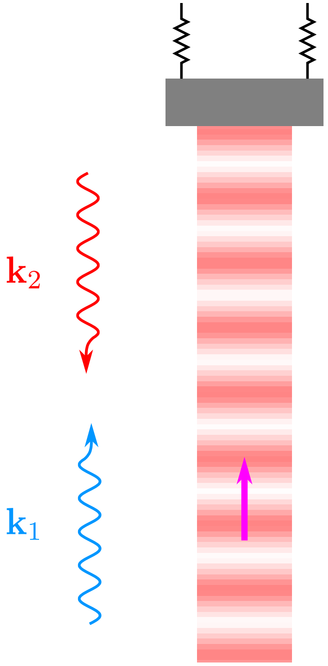
$$\mathbf{k}_{\text{eff}} = \mathbf{k}_1 - \mathbf{k}_2$$

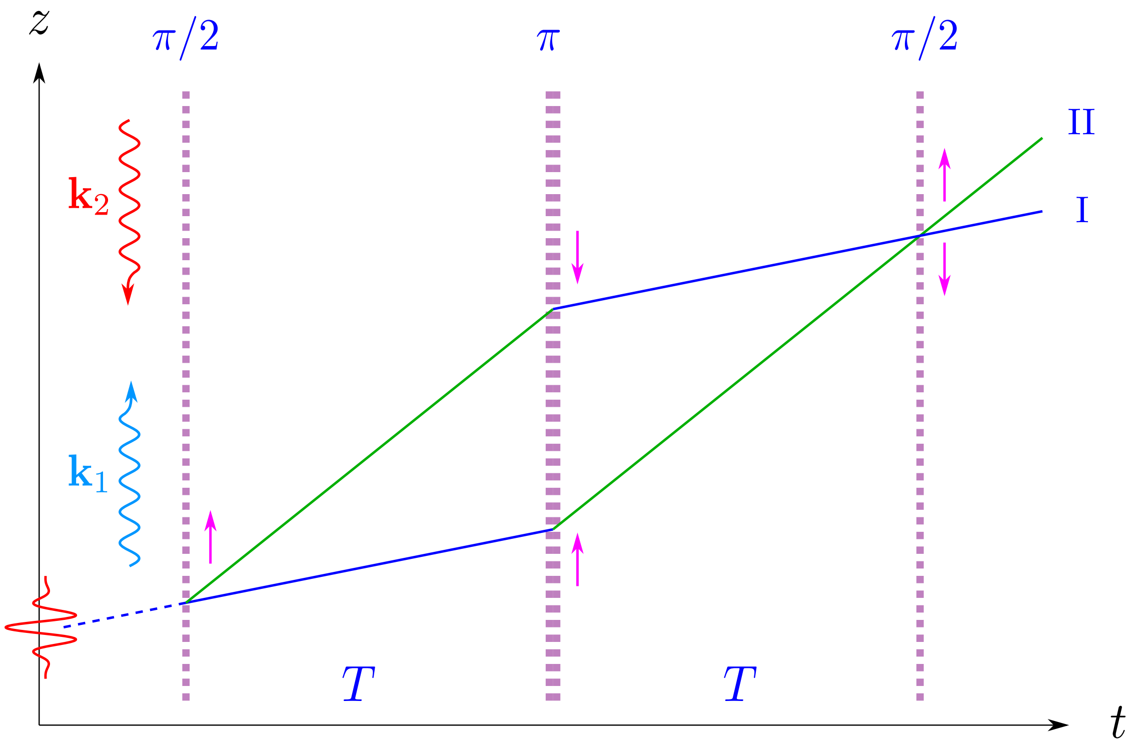


The evolution of the wave packets can be decomposed into two independent aspects:

- expansion dynamics of a *centered* wave packet
- central position and momentum which follow *classical trajectories* including the kicks from the laser pulses

Atom interferometers as accelerometers





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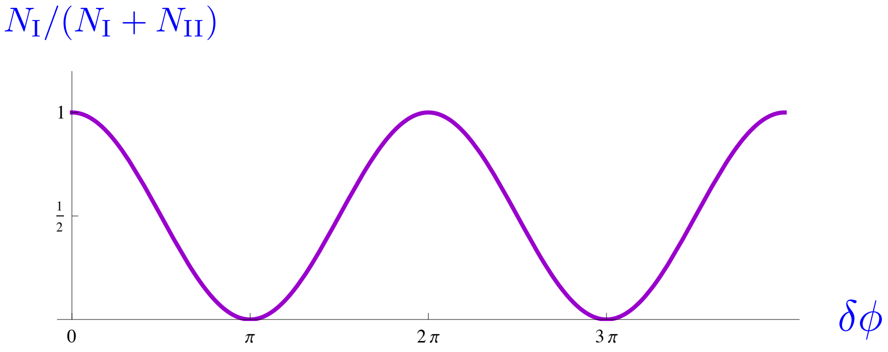
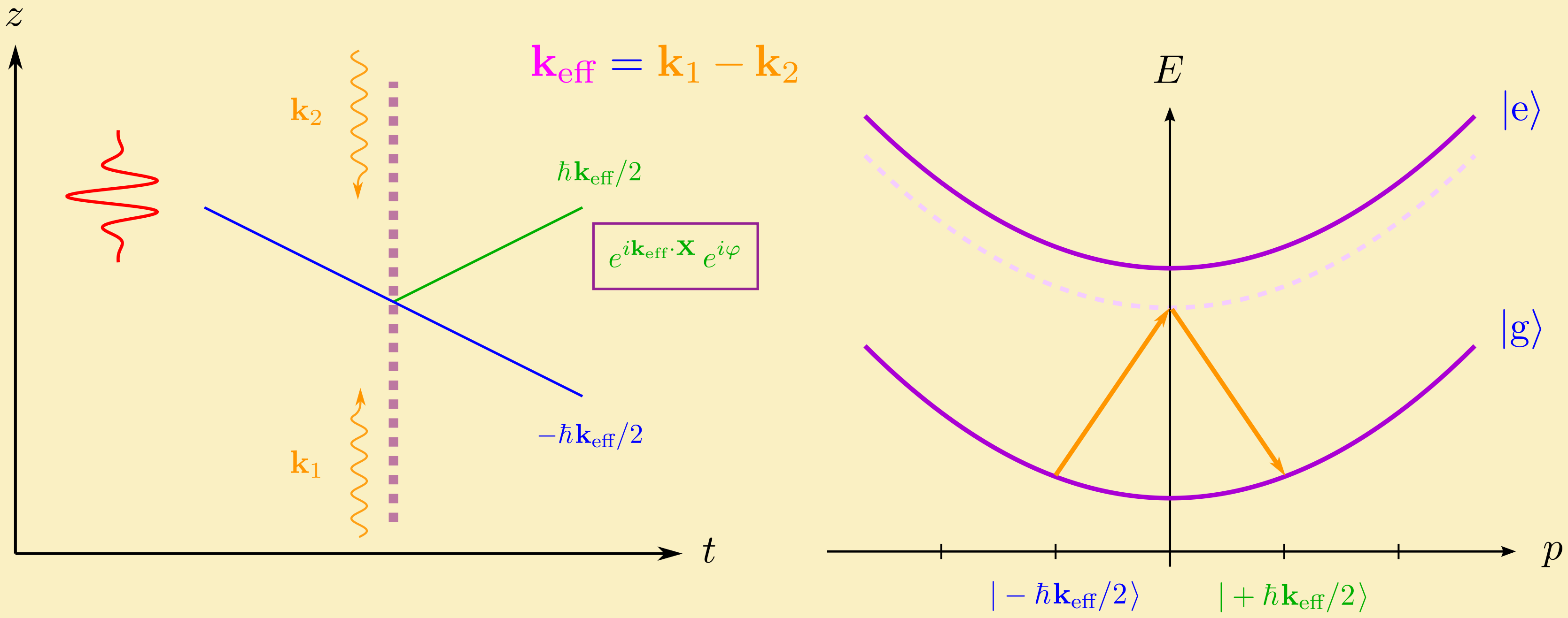


Bragg diffraction

standing e.m. wave → periodic optical potential

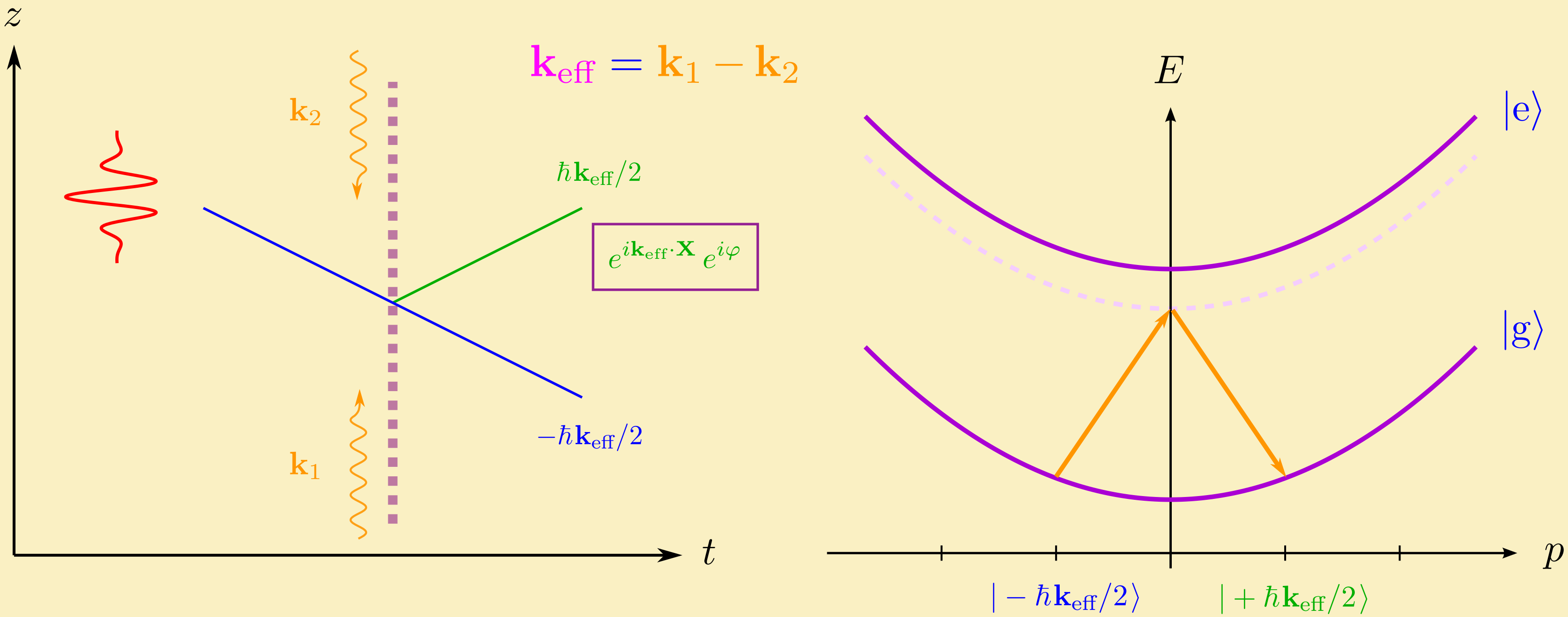


analogous to Bragg diffraction of *X rays* off a *crystal*

roles of *light* and *matter* exchanged

Bragg diffraction

standing e.m. wave → periodic optical potential



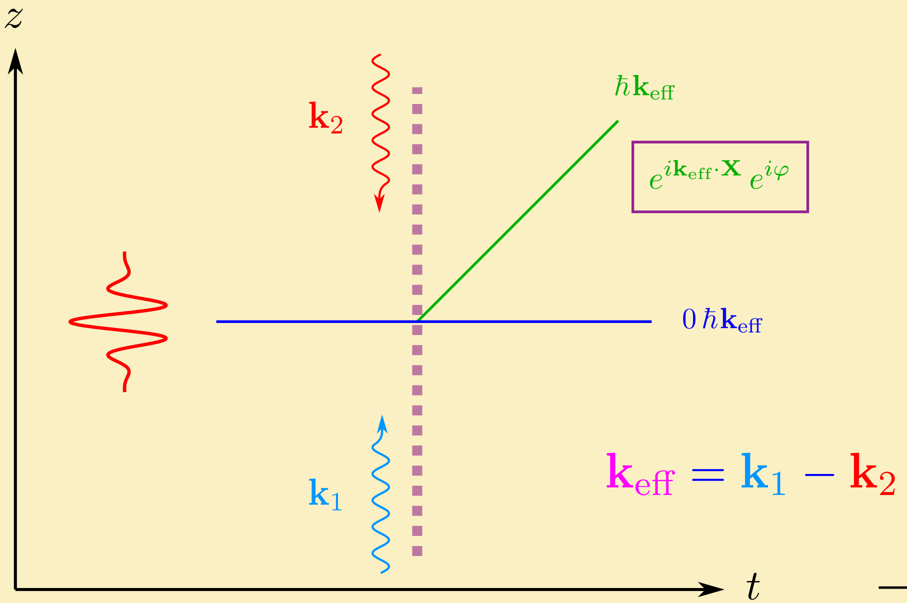
$$\mathbf{k}_{\text{eff}} = \mathbf{k}_1 - \mathbf{k}_2$$

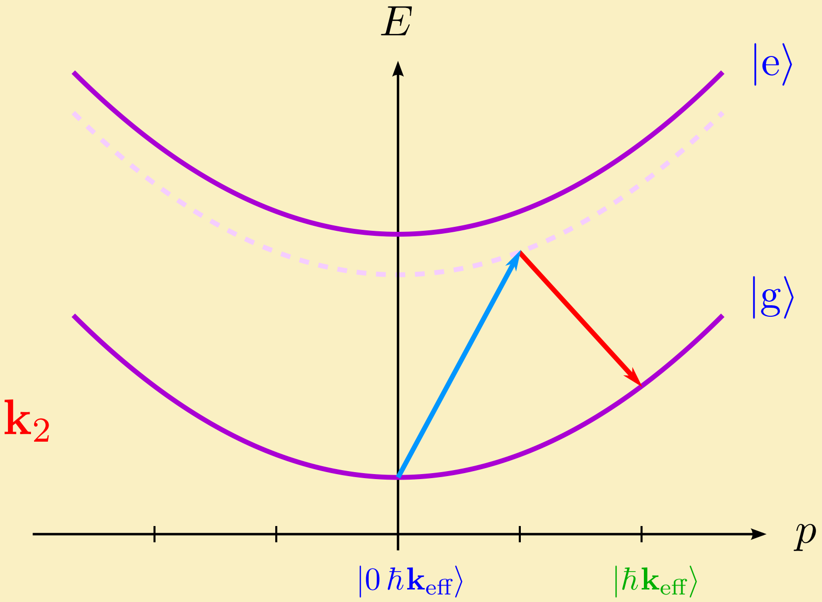
useful description in terms of *Rabi oscillations*
in an effectively *two-state* system

(*adiabatic elimination* of the excited internal state)

Bragg diffraction

different frame where the *initial* wave packet is *at rest*





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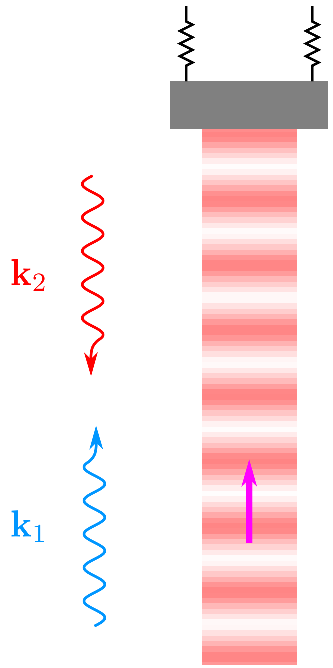
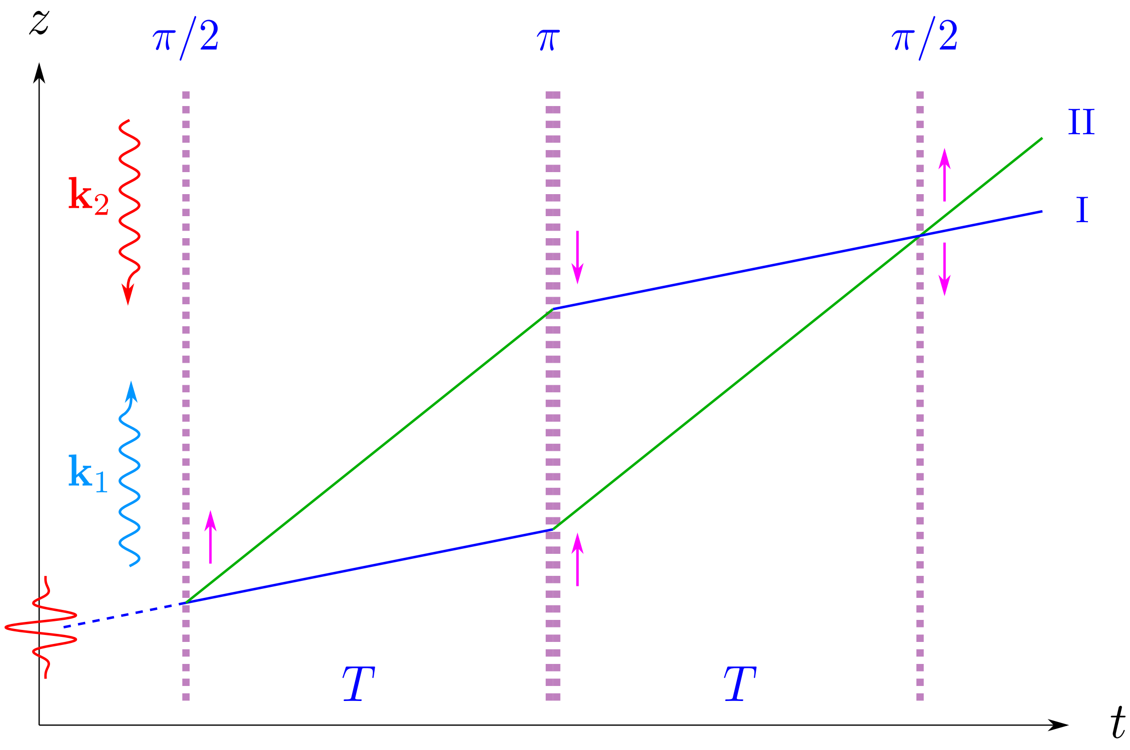
Atom interferometers as accelerometers





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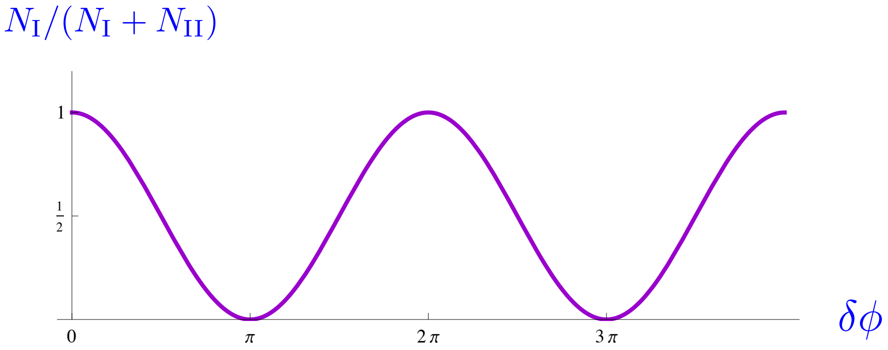

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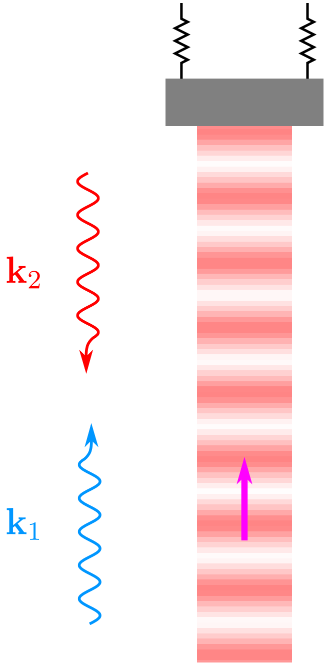

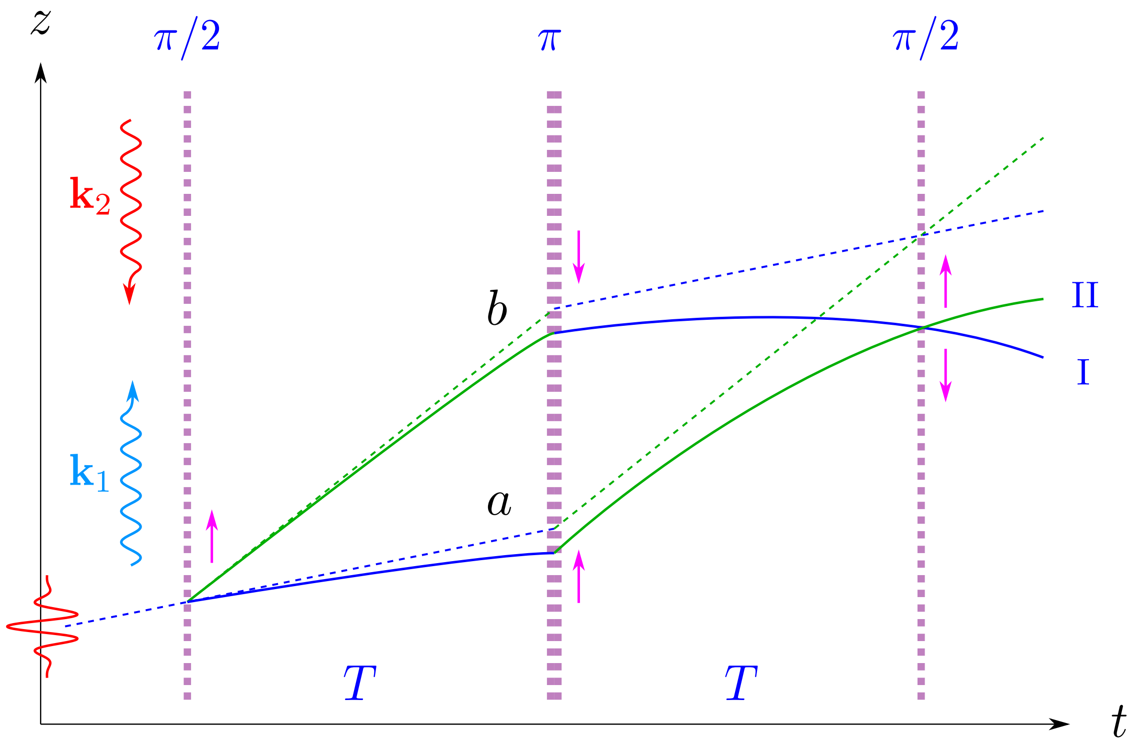

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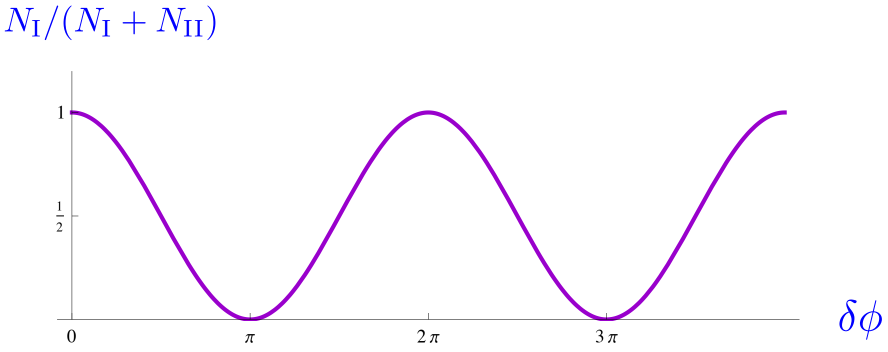
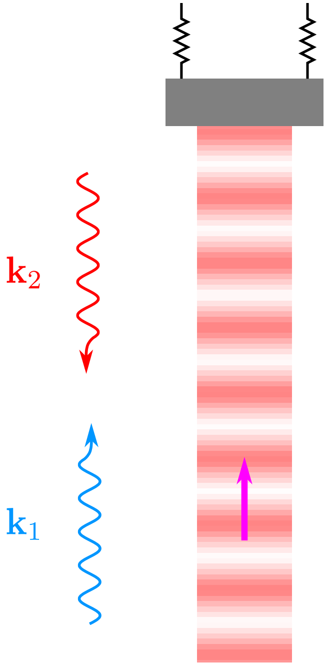
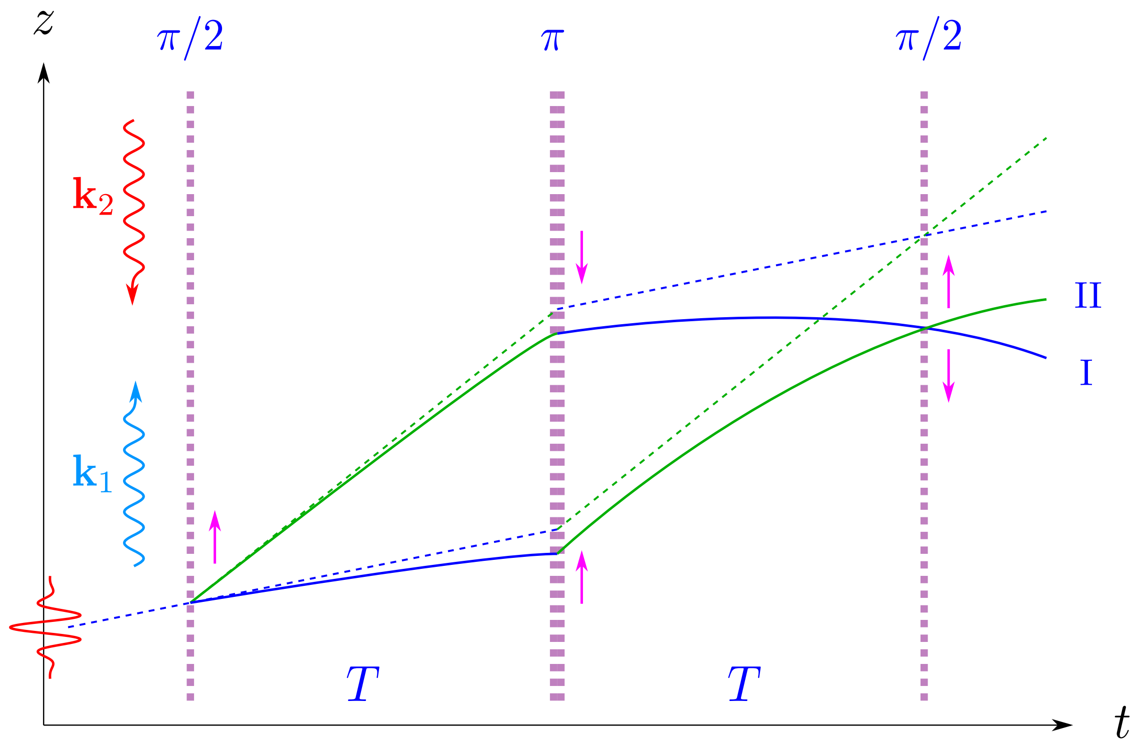


$$\begin{aligned}\delta\phi &= k_{\text{eff}}\left[\left(z_3^{(a)} - z_2^{(a)}\right) - \left(z_2^{(b)} - z_1^{(b)}\right)\right] \\ &= -\,k_{\text{eff}}\,g\,T^2\end{aligned}$$

Atom interferometers as accelerometers





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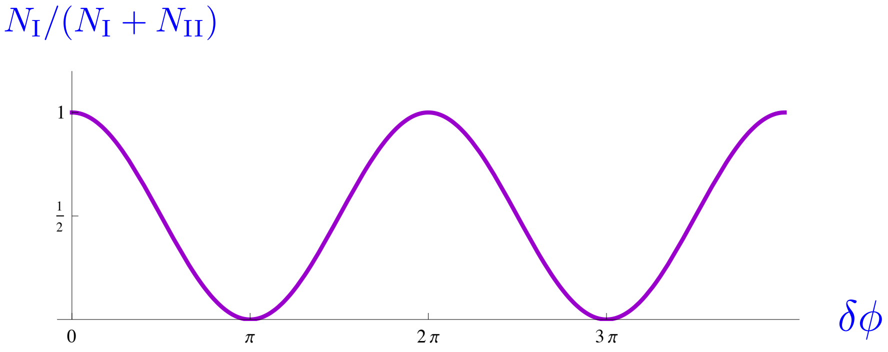


$$\boxed{\delta\phi = -\,k_{\text{eff}}\; g\, T^2}$$

Long-time interferometry

- Higher sensitivity → long-time interferometry

$$\delta\phi = k_{\text{eff}}\, a\, T^2$$

- Natural compact set-ups in microgravity platforms (*freely falling frame*)

- Challenges:
  - *growing size of atom cloud* → *BECs, atomic lensing*
  - *rotations*
  - *gravity gradients* (effects grow cubically with time)

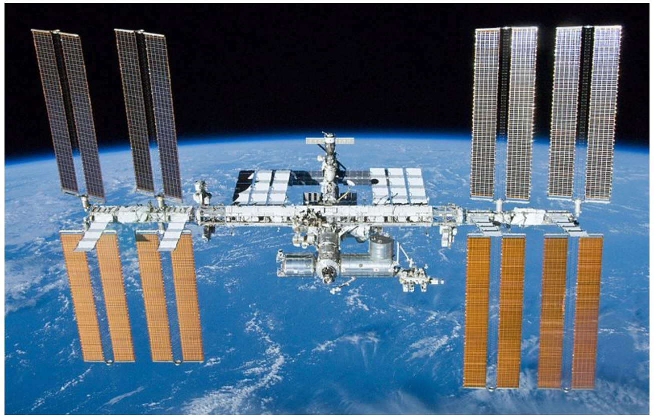
Microgravity platforms

$$\delta g \sim 10^{-5} g – 10^{-6} g$$

drop tower in Bremen
(> 500 drops)

sounding rocket
(23 Jan 2017)

International Space Station
(2018–)



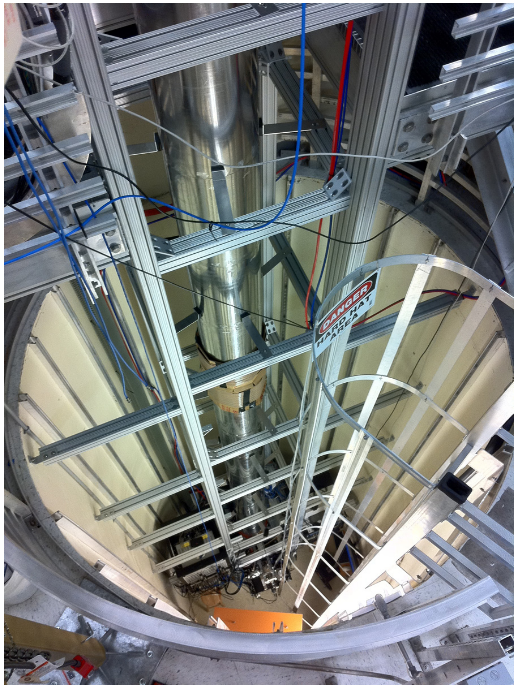
QUANTUS (5-10 s)

MAIUS (6 min)

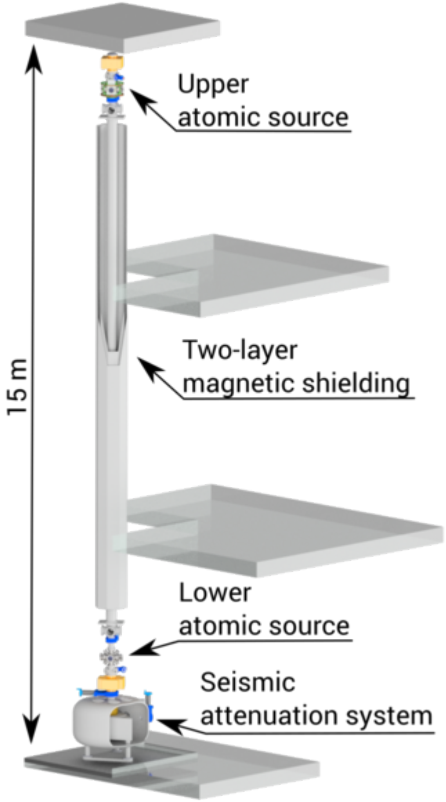
CAL / BECCAL
(several years)

Large atomic fountains

- Large atomic fountains ($10\,\mathrm{m}$ high) → $2.5\,\mathrm{s}$ free-fall time



Stanford (USA)



HITec, Hannover (Germany)

Wuhan (China)

Long-time interferometry

- Higher sensitivity → long-time interferometry

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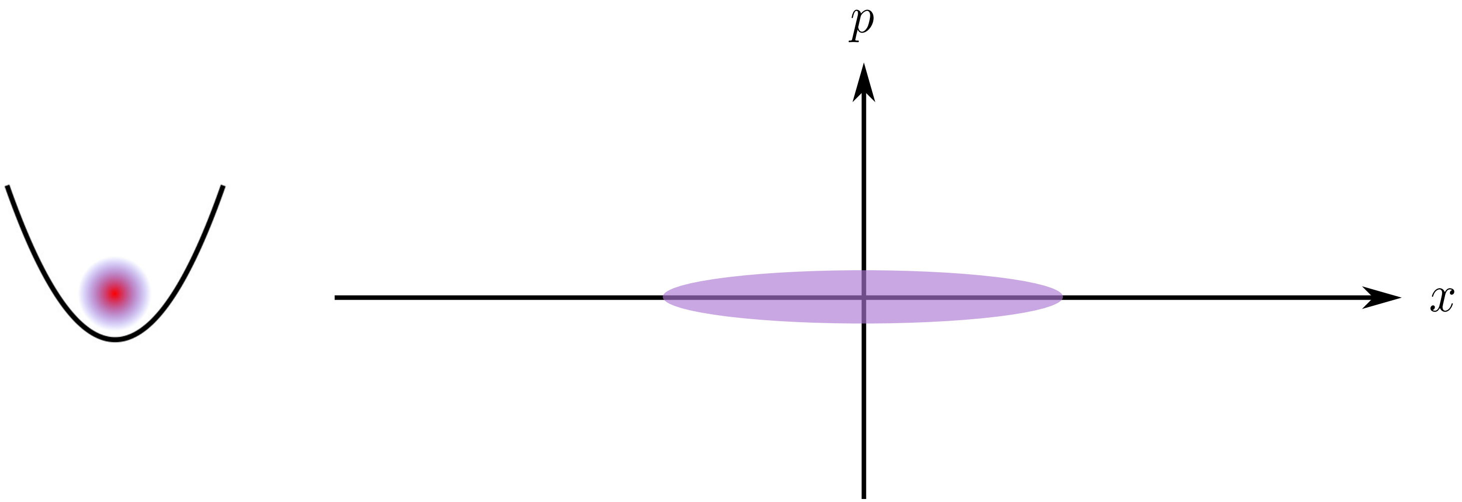
Atomic lensing

- Need to minimize growing size of atom cloud (signal-to-noise at detection, systematics, noise, contrast loss)

- BECs have *narrow momentum width,* but nonlinear interaction energy converted into kinetic energy after release



- Atomic lensing → $T_{\text{eff}} \approx 1\,\text{nK} \quad (0.3\,\text{mm/s})$
  $T_{\text{eff}} \approx 50\,\text{pK} \quad (0.1\,\text{mm/s})$ (2D)

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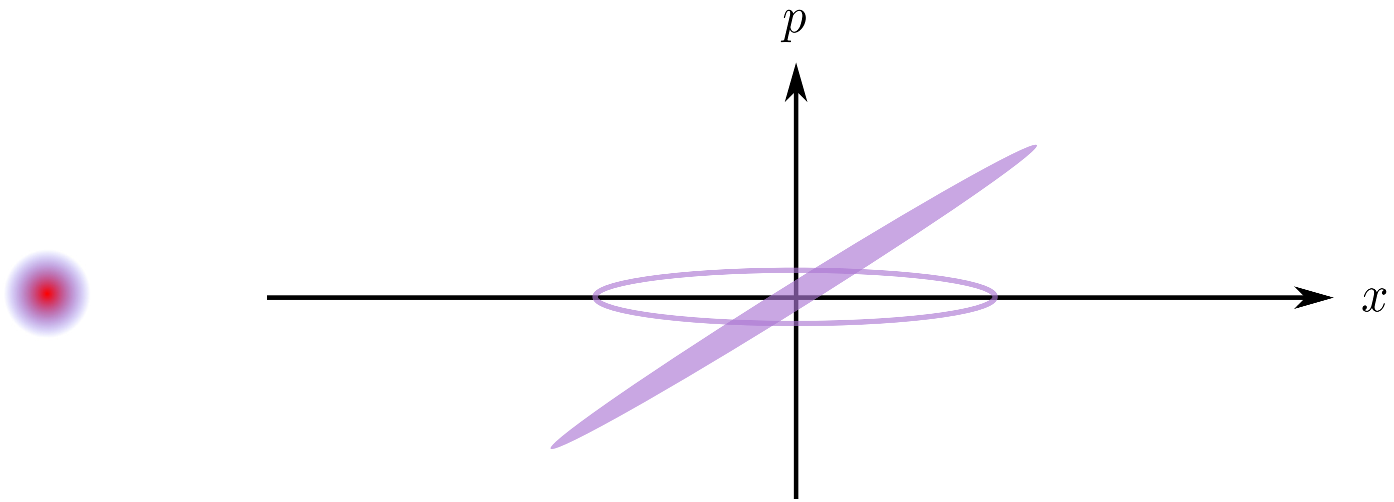

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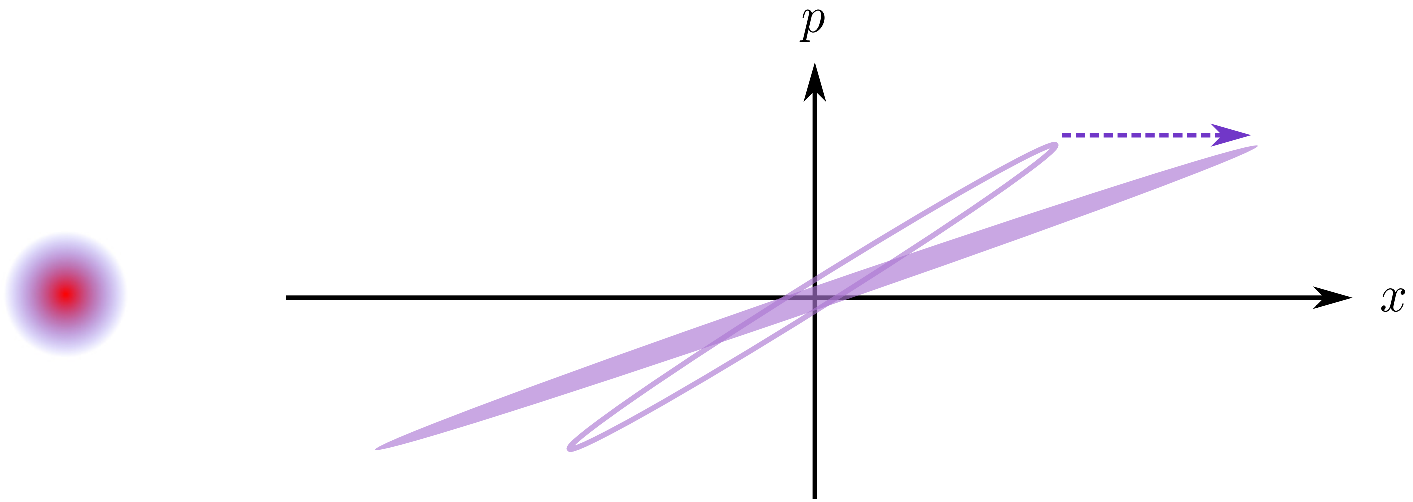

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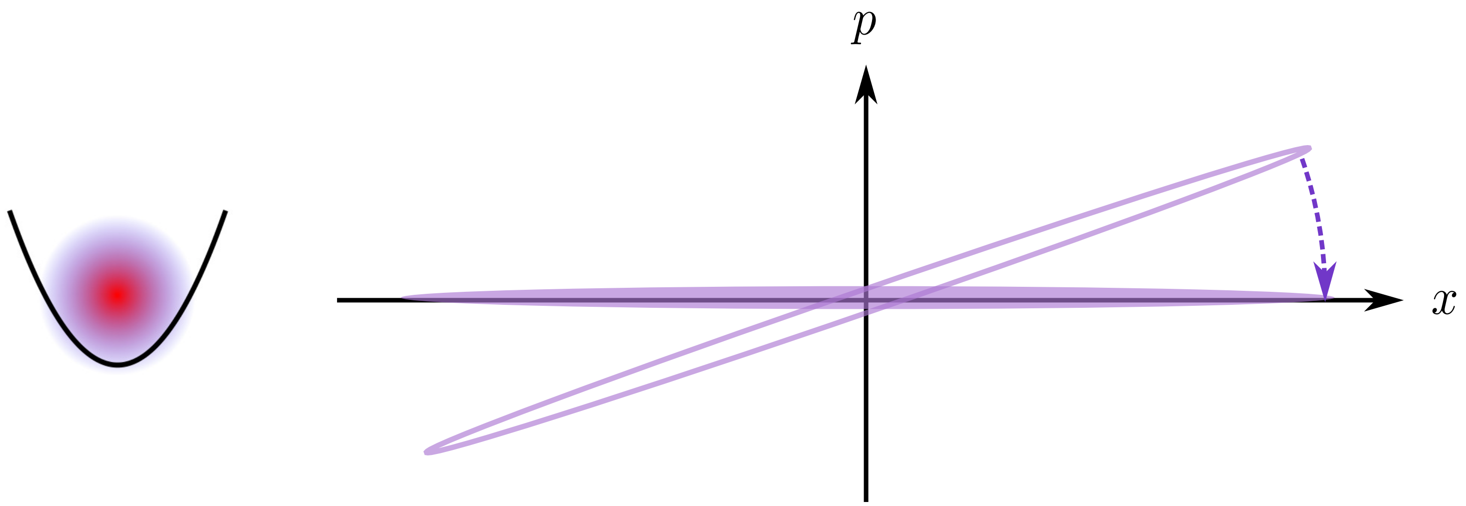

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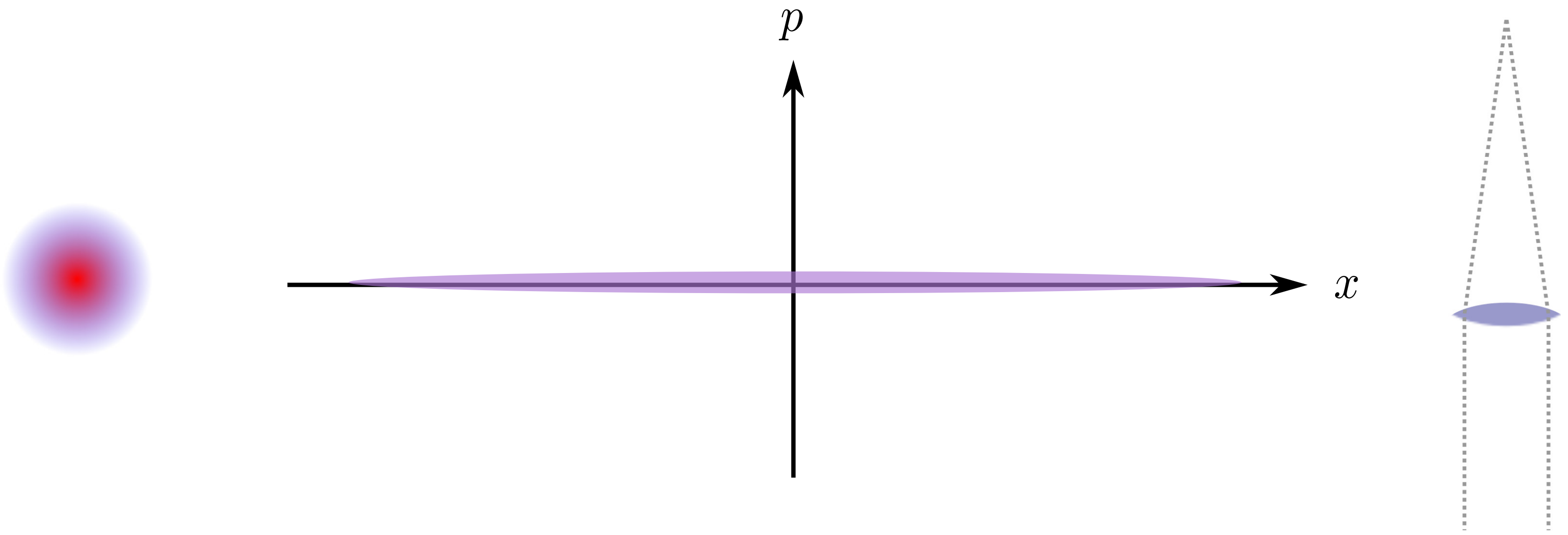

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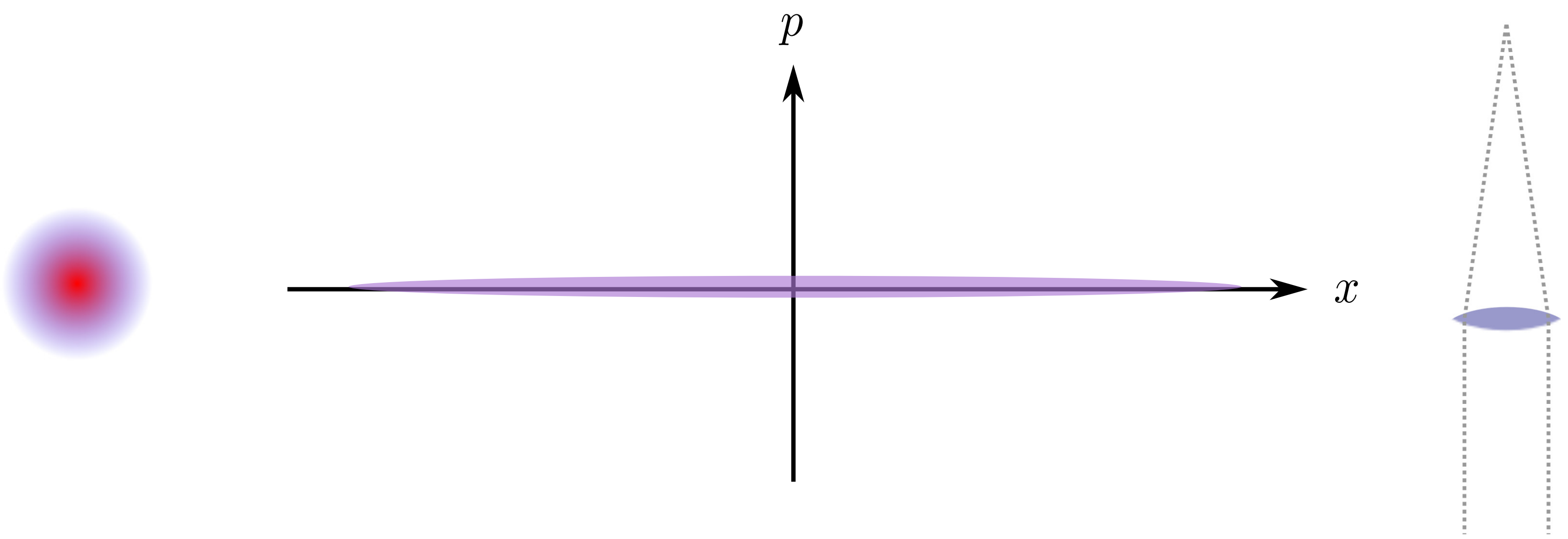

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Müntinga *et al.*, *PRL* (2013) Kovachy *et al.*, *PRL* (2015)

PART II

Fine-structure constant and atomic mass measurements in the new SI units

Recoil measurements and the fine-structure constant

Fine structure constant & QED tests

- The most precise measurement of the *fine structure constant* is based on atom interferometry:

$$\Delta\alpha/\alpha \approx 2 \times 10^{-10}$$

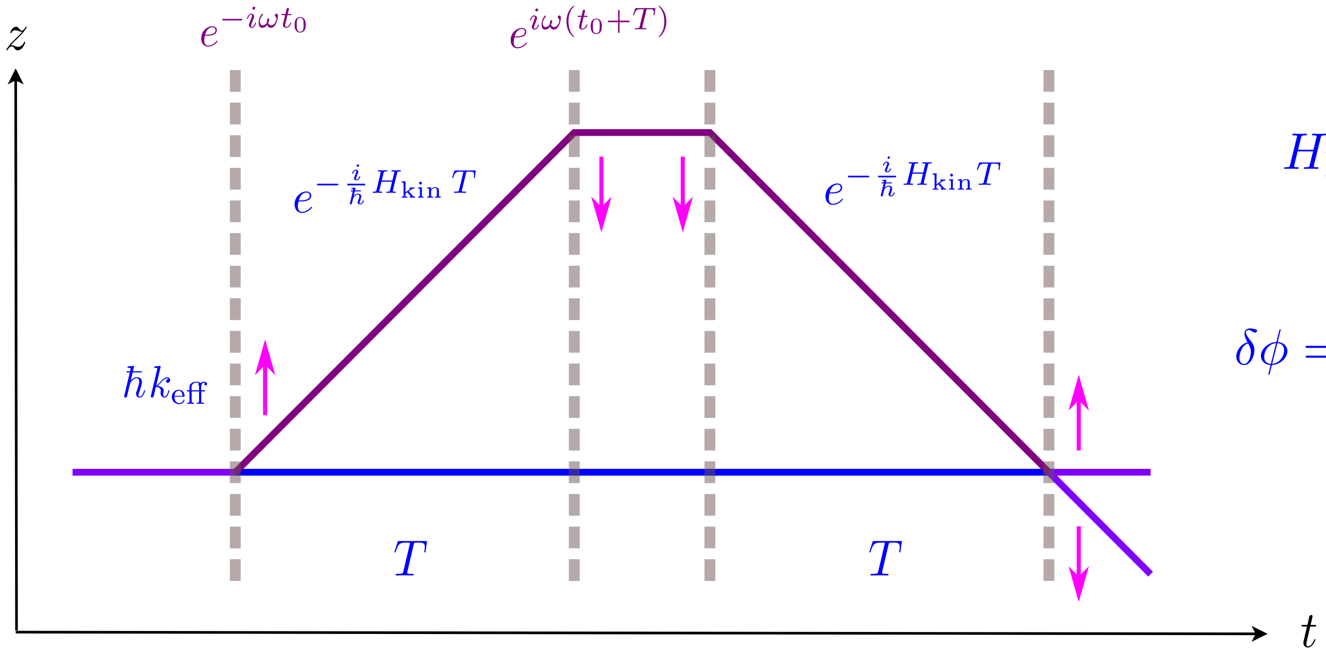
R.H. Parker, C. Yu, W. Zhong, B. Estey, H. Müller, *Science* (2018)

- Comparison with $g_e - 2$ *measurement + theoretical calculation*

  → *highly precise tests of QED.*

Recoil measurements and fine-structure constant

- Different kinetic energy along the two branches:



$$H_{\mathrm{kin}} = \frac{(\hbar\, k_{\mathrm{eff}})^2}{2\, m_{\mathrm{Rb}}}$$

$$\delta\phi = \left[\omega - \frac{\hbar}{m_{\mathrm{Rb}}}\,(k_{\mathrm{eff}})^2\right] T$$

Bouchendira *et al.*, *PRL* **106** 080801 (2011)

Lan *et al.*, *Science* **339** 554 *(2013)*

- k_{eff} very well known in terms of the laser wavelengths

→ accurate determination of $\hbar/m_{\mathrm{Rb}}$

- Kilogram definition within *revised S.I. of units* (fixed $\hbar$)
  $\hbar/m_{\mathrm{Rb}}$ ⟶ accurate measurement of microscopic masses

- Determination of the fine-structure constant:

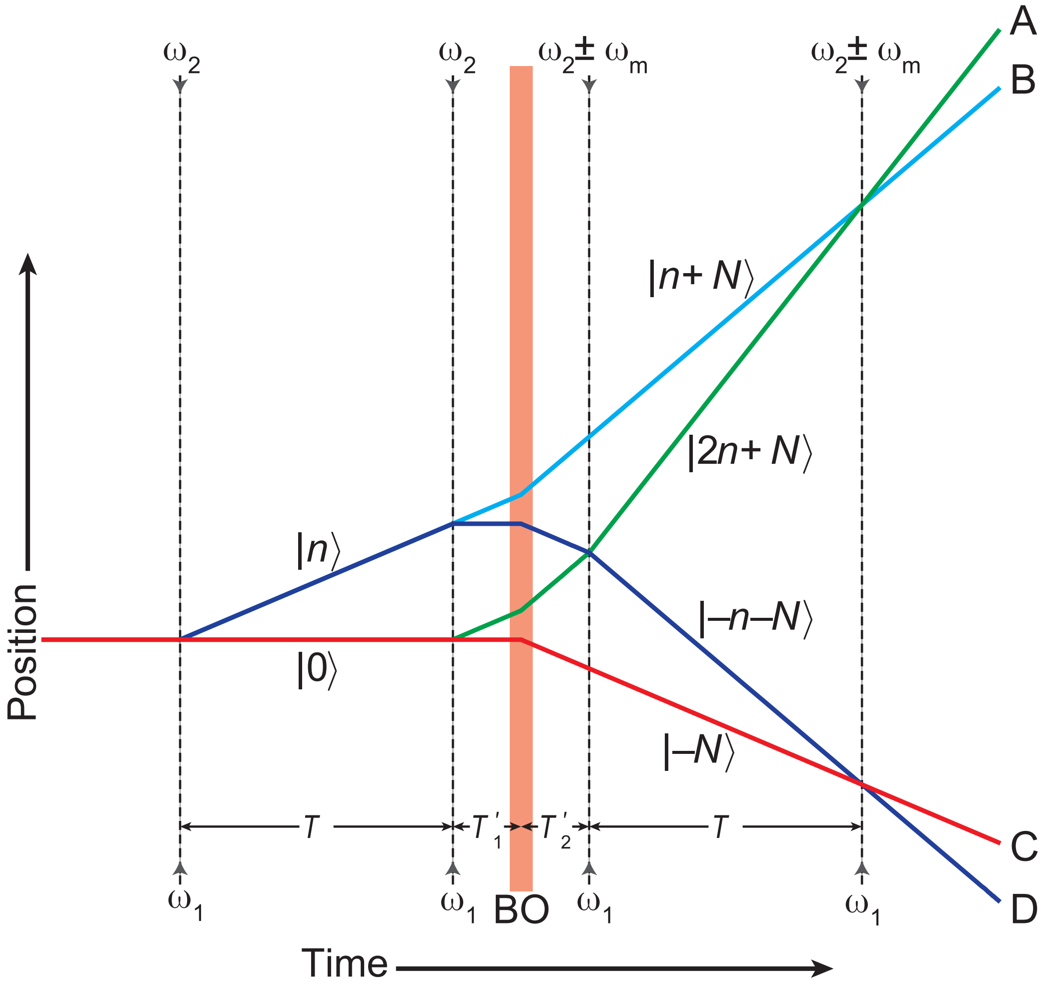
$$\alpha^2 = \frac{2R_\infty}{c}\frac{m_{\mathrm{Rb}}}{m_e}\frac{h}{m_{\mathrm{Rb}}} \qquad \Delta\alpha/\alpha \approx 7\times 10^{-10}$$

Bouchendira *et al.*, *PRL* **106** 080801 (2011)

Comparable to results from e^- anomalous magnetic moment:
depolarization measurements + *QED calculations*

⟶ *high-precision* test of QED with atomic systems

- *Large momentum transfer* + subtraction of *conjugate interferometers* for suppression of *vibration noise*.



$$\Delta\alpha/\alpha \approx 2 \times 10^{-10}$$

R.H. Parker, C. Yu, W. Zhong, B. Estey, H. Müller, *Science* (2018)

The new SI units

On the revision of the International System of Units (SI)

Resolution 1

The General Conference on Weights and Measures (CGPM), at its 26th meeting,

considering

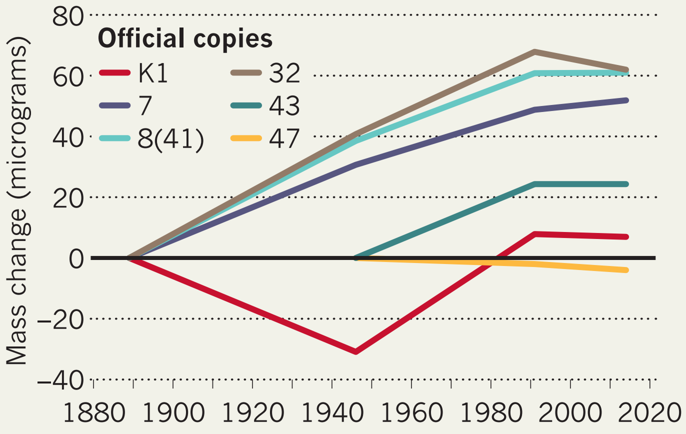
decides that, effective from 20 May 2019, the International System of Units, the SI, is the system of units in which:

- the unperturbed ground state hyperfine transition frequency of the caesium 133 atom $\Delta \nu_{\mathrm{Cs}}$ is 9 192 631 770 Hz,
- the speed of light in vacuum c is 299 792 458 m/s,
- the Planck constant h is $6.626\,070\,15 \times 10^{-34}$ J s,
- the elementary charge e is $1.602\,176\,634 \times 10^{-19}$ C,
- the Boltzmann constant k is $1.380\,649 \times 10^{-23}$ J/K,
- the Avogadro constant N_{A} is $6.022\,140\,76 \times 10^{23}$ mol^{-1},
- the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, K_{cd}, is 683 lm/W,


kg
m
s
A
K
mol
cd
h
c
$\Delta\nu_{Cs}$
e
k
N_A
K_{cd}
SI

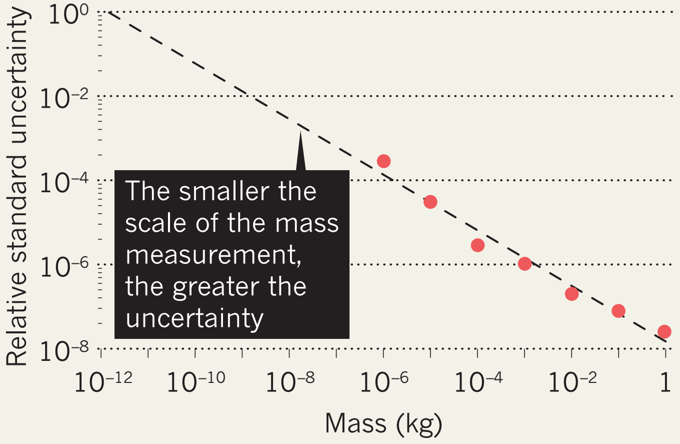
THE UNSTABLE KILOGRAM

The kilogram is currently defined by a lump of platinum-iridium, stored in a vault near Paris. Because objects can easily lose atoms or absorb molecules from the air, using one to define an SI unit is problematic. Compared to the prototype, some official copies have gained at least 50 micrograms over a century.



A QUESTION OF SCALE

When a unit is defined on a fixed scale, uncertainties grow larger the further scientists move away from that point. Currently, for example, measurements in milligrams have a minimum relative uncertainty 2,500 times that associated with the kilogram. The problem disappears under the proposed system, which relies on constants to define units.

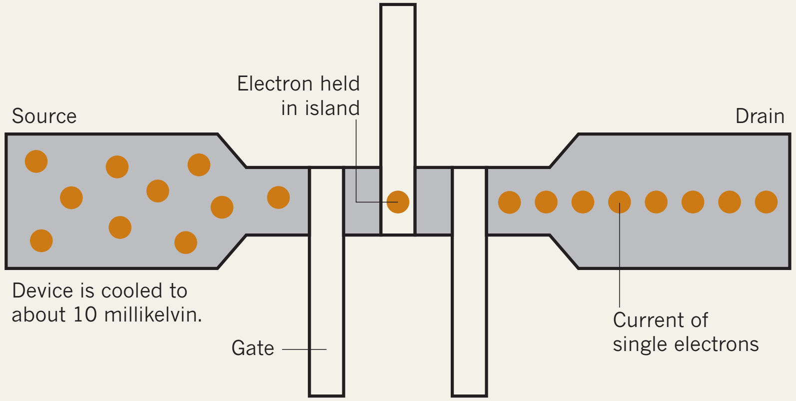


The smaller the scale of the mass measurement, the greater the uncertainty

SOURCE: SHAW, G. *ET AL.* *METROLOGIA* **53**, A86–A94 (2016).

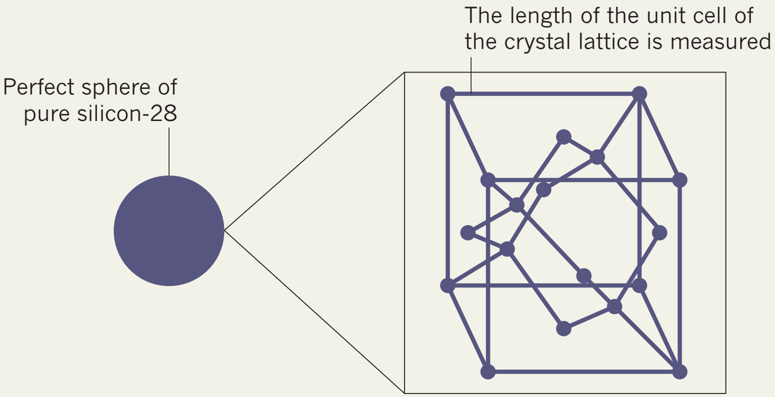
AMPERE: THE SINGLE-ELECTRON PUMP

Used to measure the charge of an electron, an electron pump could become one tool for determining the ampere. By trapping individual electrons as they travel rapidly across a conductor, the pump can generate a measureable current by counting single electrons.



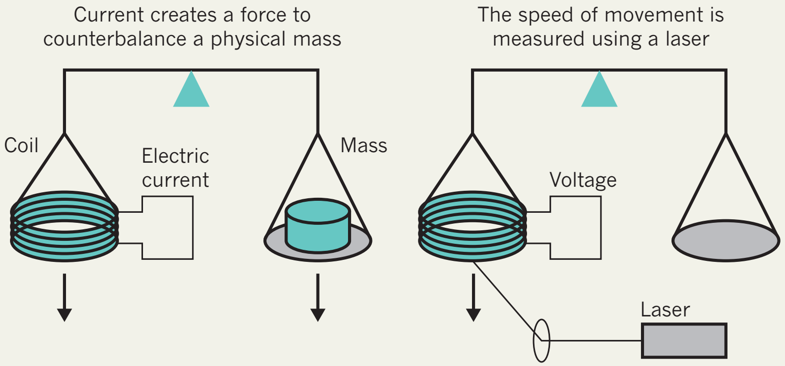
MOLE: THE SILICON SPHERE

As the device that gives scientists Avogadro's constant, this silicon sphere offers a state-of-the-art way to measure a mole. It would determine the precise number of atoms in a perfect sphere of pure silicon-28. Researchers do this by using lasers to measure the length of a unit of the sphere's crystal lattice, and its mean diameter.



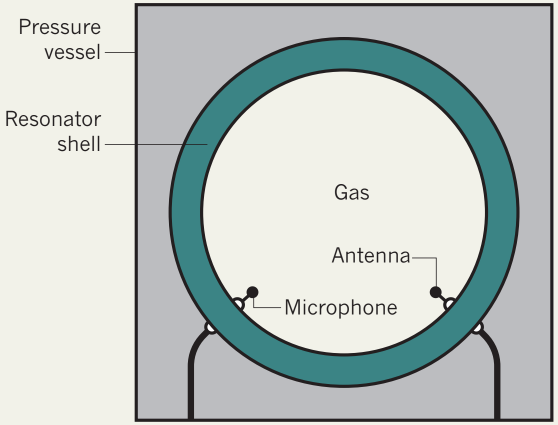
KILOGRAM: THE WATT BALANCE

The Watt balance compares mechanical power with electromagnetic power using two separate experiments. First, a current is run through a coil in a magnetic field to create a force that counterbalances a known physical mass. Then, the coil is moved through the field to create a voltage. By measuring the speed as well as experimental values that relate the voltage and current to Planck's constant, scientists can precisely determine the weight of a mass in kilograms.

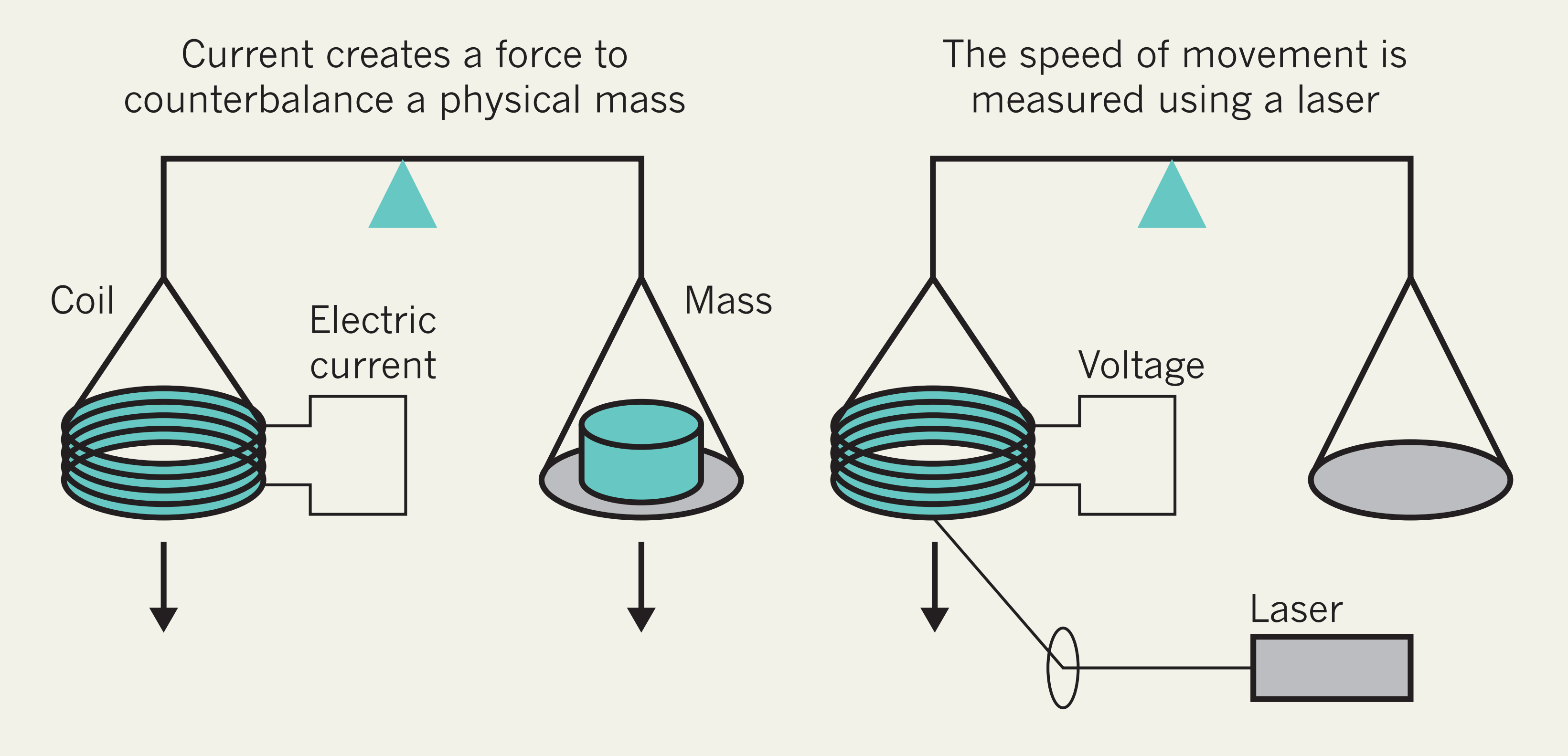


KELVIN: ACOUSTIC THERMOMETRY

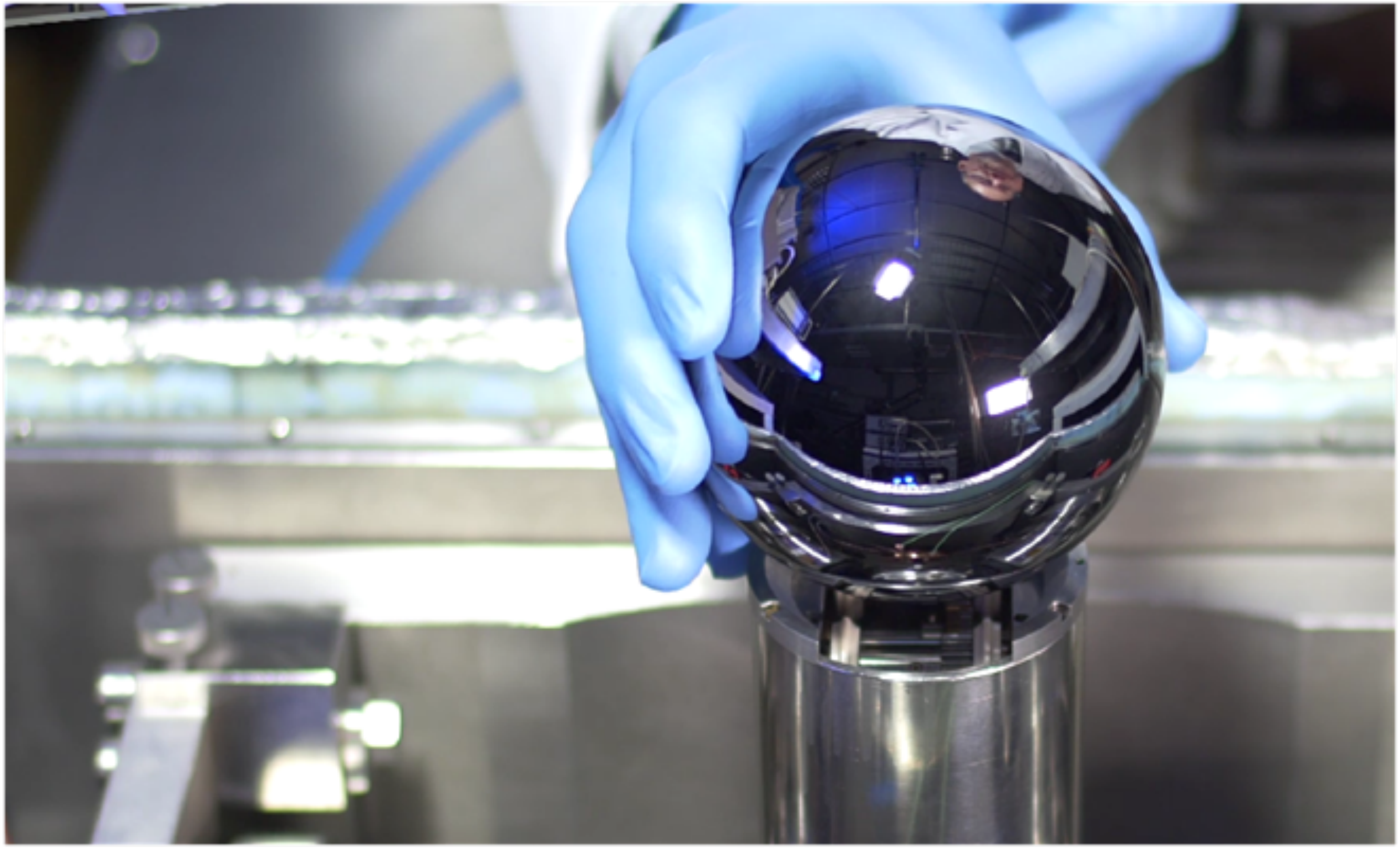
This technique could be used to derive precise temperature measurements. The speed of sound in a gas-filled sphere (which is proportional to the average speed of the atoms in it) can be determined at a fixed temperature, by analysing the frequency of sound waves that resonate within in it and measuring the sphere's volume.



Kibble balance



Avogadro project



PART III

Gravitational measurements based on atom interferometry

Outline

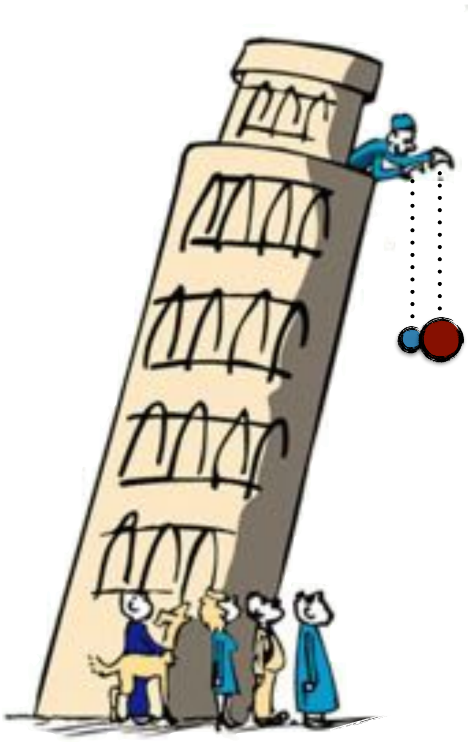
1. Testing the universality of free fall
2. Measurement of the gravitational constant G
3. Recent breakthroughs

Testing the universality of free fall

Tests of *universality of free fall* (UFF)

- Universal gravitational acceleration of test masses, independent of the composition.

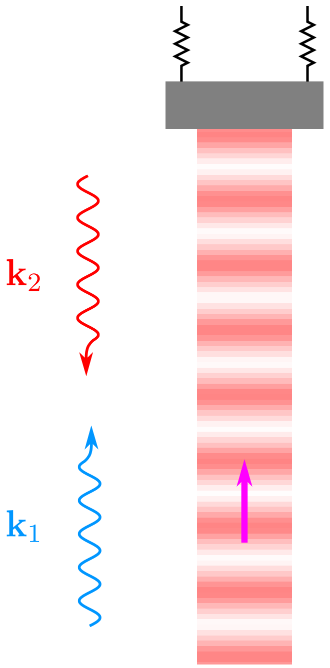
Tests of *universality of free fall* (UFF)

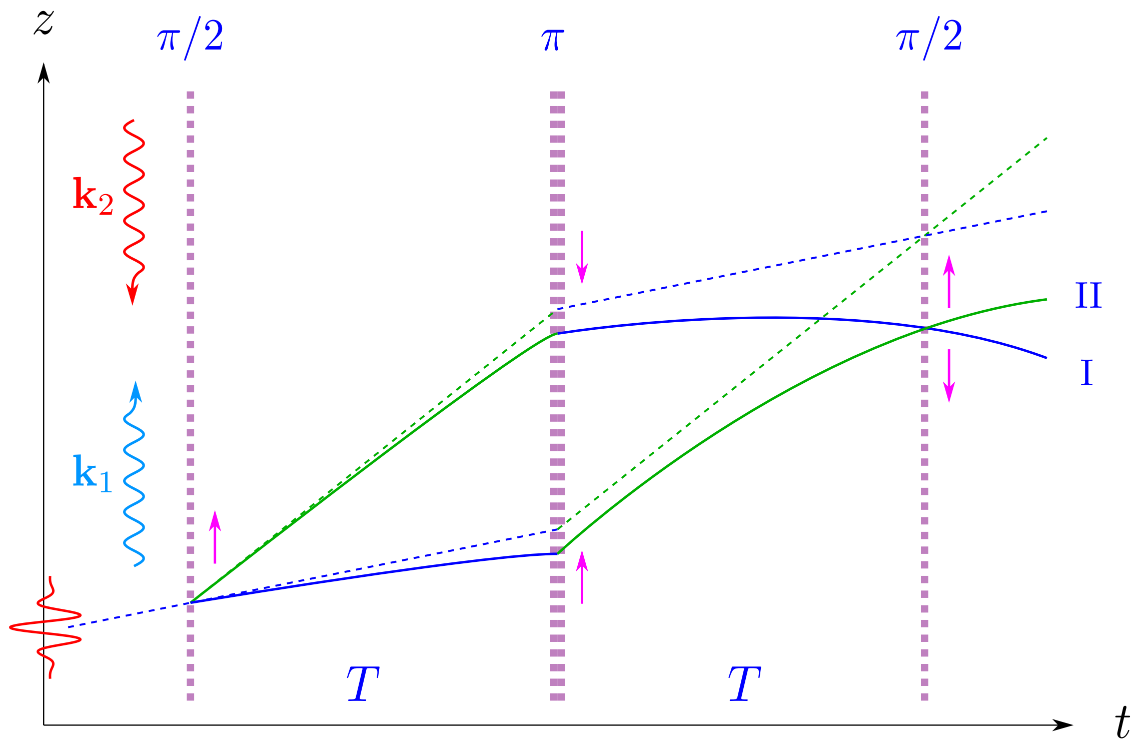


- Central to Einstein's equivalence principle.
- Tests of UFF with macroscopic masses:
  - free fall, *lunar laser ranging* (LLR)
  - *torsion balance* (Ëotvös)

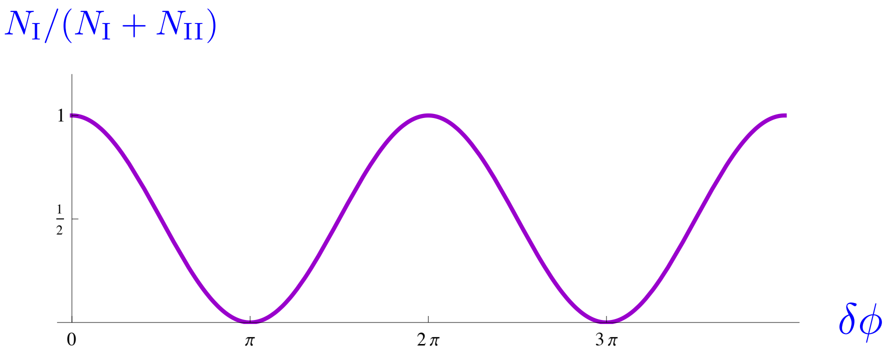
$$\eta_{AB} = 2\,\frac{|g_A - g_B|}{g_A + g_B} \lesssim 10^{-13} \ldots\ 10^{-14}$$

(atom interferometers as accelerometers)

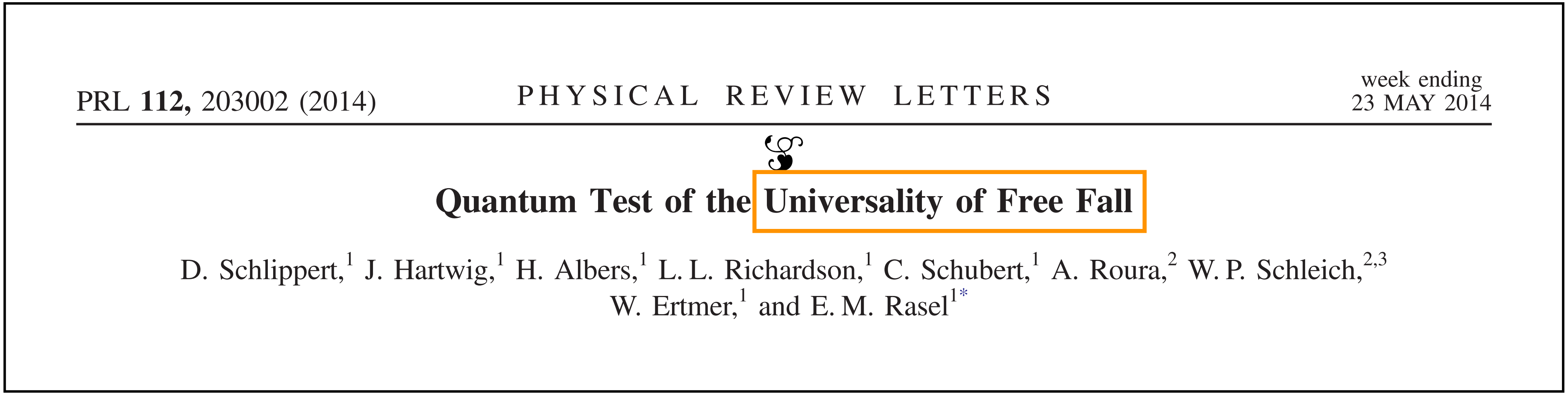




$$\mathbf{k}_{\rm eff} = \mathbf{k}_1 - \mathbf{k}_2$$



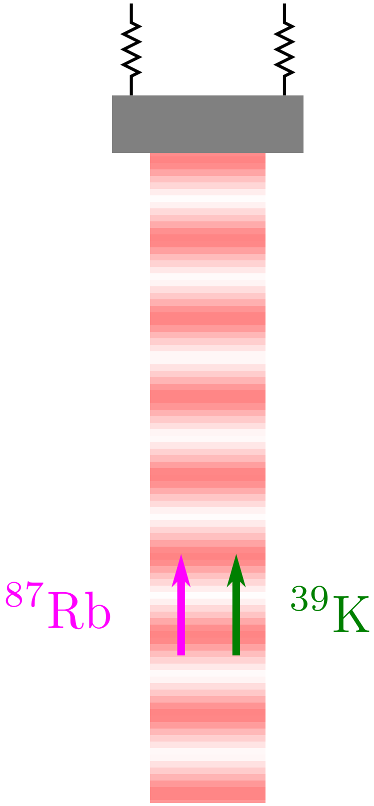
$$\boxed{\delta\phi = -\,k_{\rm eff}\; g\, T^2}$$



PRL **112,** 203002 (2014) PHYSICAL REVIEW LETTERS week ending 23 MAY 2014

Quantum Test of the Universality of Free Fall

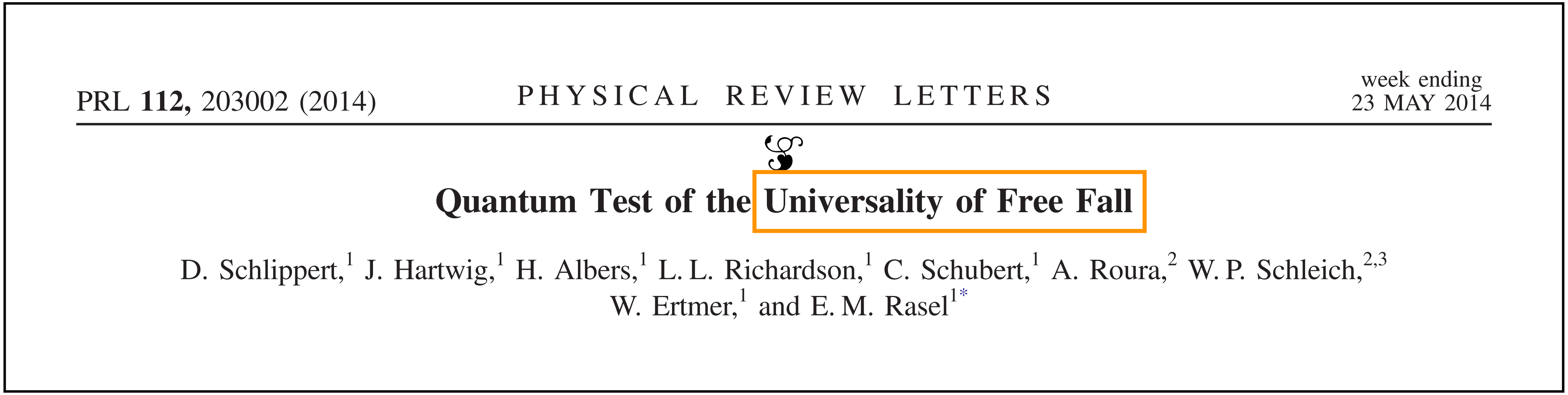
D. Schlippert,[1] J. Hartwig,[1] H. Albers,[1] L. L. Richardson,[1] C. Schubert,[1] A. Roura,[2] W. P. Schleich,[2,3]
W. Ertmer,[1] and E. M. Rasel[1*]



- simultaneous differential measurement
- *common* mirror → effect of *vibration noise* highly suppressed
- Eötvös parameter: $\eta_{\mathrm{Rb,K}} < 5 \cdot 10^{-7}$

  improved bounds for *dilaton models* and *SME*
- Future plans on ground and in space:

$$\eta_{AB} \lesssim 10^{-14} \ldots\ 10^{-17}$$



PRL **112,** 203002 (2014) PHYSICAL REVIEW LETTERS week ending 23 MAY 2014

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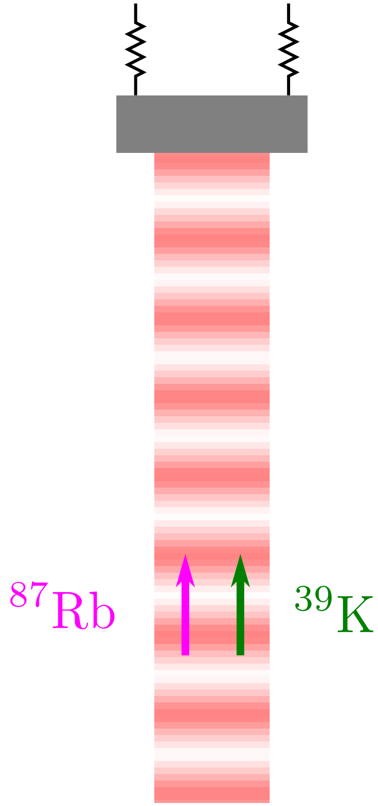


- simultaneous differential measurement
- *common* mirror → effect of *vibration noise* highly suppressed
- Eötvös parameter: $\eta_{^{87}\mathrm{Rb},^{85}\mathrm{Rb}} < 3 \cdot 10^{-12}$

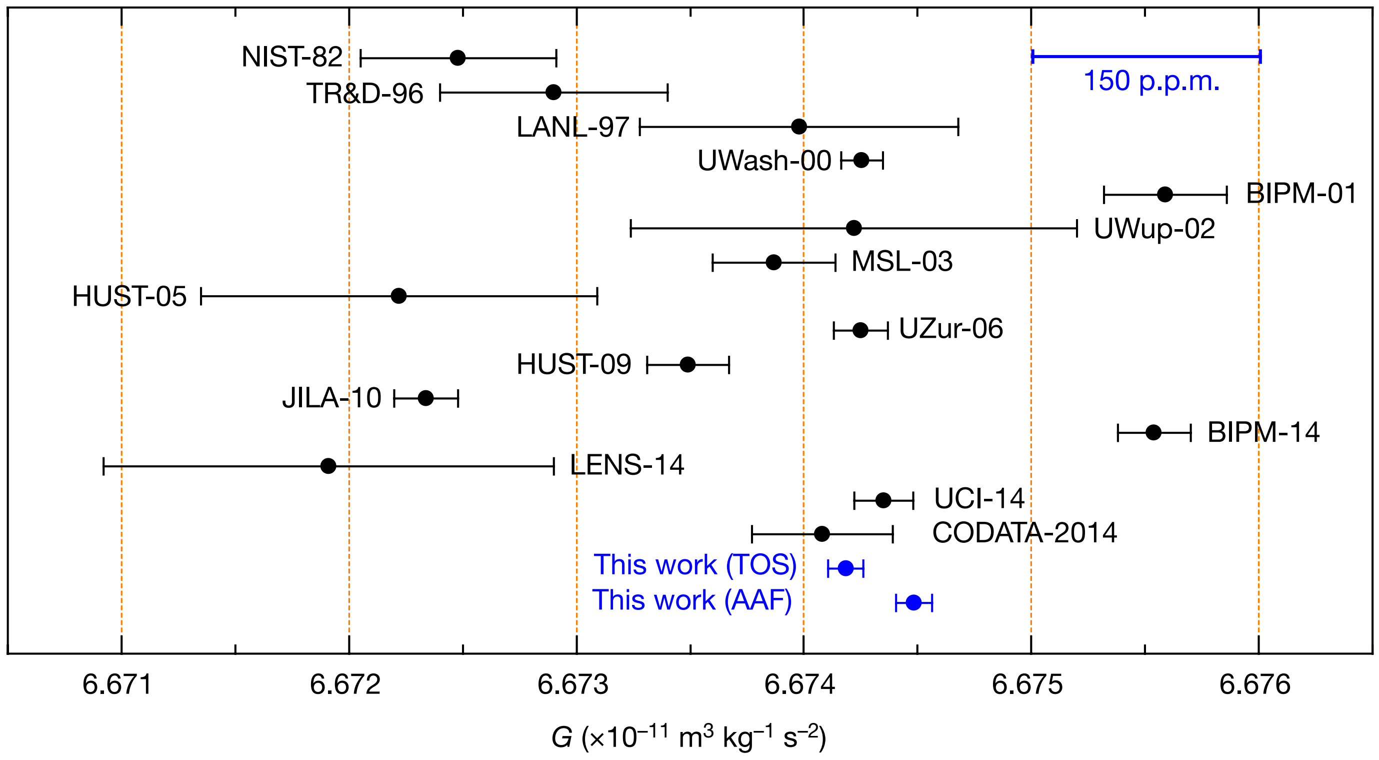
  improved bounds for *dilaton models* and *SME*
- Future plans on ground and in space:

$$\eta_{AB} \lesssim 10^{-14} \ldots\ 10^{-17}$$

Measurement of the gravitational constant *G*

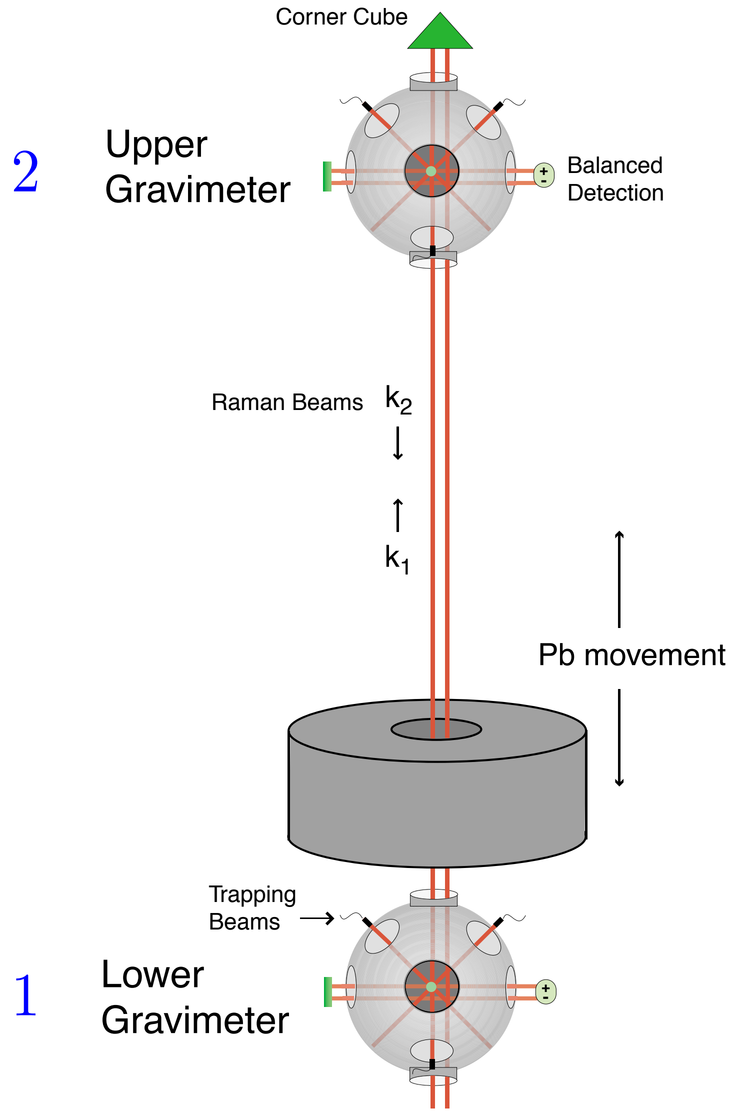
Measurement of Newton's gravitational constant *G*

- By far the less accurately determined of all fundamental constants (using *macroscopic* masses).



Li *et al.*, *Nature* **560**, 582 (2018)

Gradiometry and measurements of G



Fixler *et al.*, *Science* ***315****, 74 (2007)*

- differential measurement
- *common-mode* noise suppression
- determination of the gravity gradient

$$\Gamma_{zz} = -\frac{\partial^2 U}{\partial z\,\partial z} \approx -\frac{g_2 - g_1}{z_2 - z_1}$$

- *changing position* of well-characterized source mass → measurement of G

$$\Delta G/G \approx 1.5 \times 10^{-4}$$

Rosi *et al.*, *Nature* ***510****, 518 (2014)*

Recent breakthroughs

- Tests of *universality of free fall* with atom interferometry.

  Recently demonstrated capability of reaching

$$\eta_{AB} = 2\,\frac{|g_A - g_B|}{g_A + g_B} \lesssim 10^{-14}$$

  and *surpassing* best bounds on ground with *macroscopic masses.*

  C. Overstreet *et al.*, *Phys. Rev. Lett.* (2018)

  P. Asenbaum *et al.*, *Phys. Rev. Lett.* (2020)

- Alternative determination of *Newton's* *gravitational constant* G based on atom interferometry.

  G. Rosi *et al.*, *Nature (2014)*

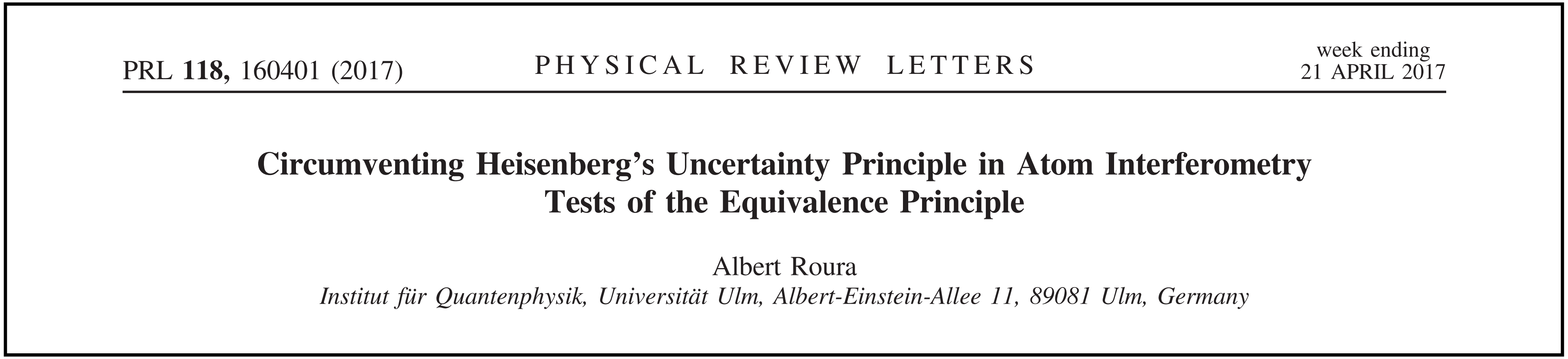
  New approach that can potentially *outperform* currently best results with *macroscopic test masses.*

  G. Rosi, *Metrologia*, (2018)

  G. D'Amico *et al.*, *Phys. Rev. Lett.* (2017)

- Major challenge associated with *gravity gradients:* phase-shift dependence on the wave packet's *initial position* and *velocity.*

- These recent breakthroughs relied on a very effective technique for overcoming this problem (*gravity gradient compensation*).



PRL **118,** 160401 (2017) PHYSICAL REVIEW LETTERS week ending 21 APRIL 2017

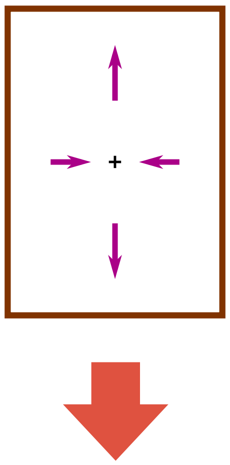
Circumventing Heisenberg's Uncertainty Principle in Atom Interferometry Tests of the Equivalence Principle

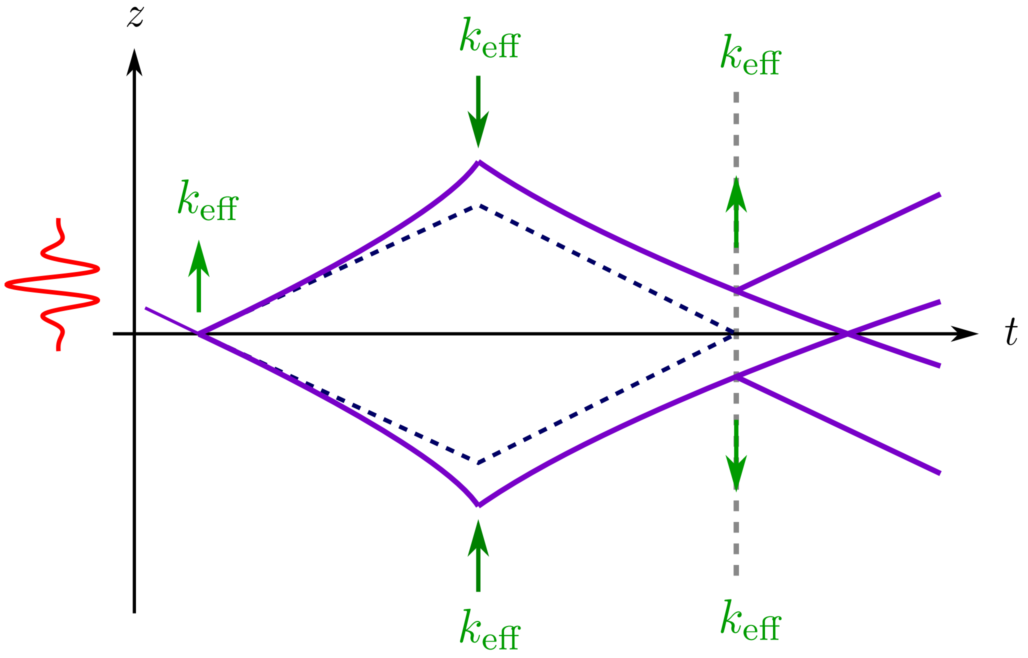
Albert Roura
Institut für Quantenphysik, Universität Ulm, Albert-Einstein-Allee 11, 89081 Ulm, Germany

- *Gravity gradients* lead to open interferometers

→ *loss* of contrast and *sensitivity* to initial conditions

freely falling frame
(*Einstein elevator*)





$$\delta z = \left(\Gamma_{zz}\, T^2\right) v_{\rm rec}\, T$$

$$\delta p = \left(\Gamma_{zz}\, T^2\right) m\, v_{\rm rec}$$

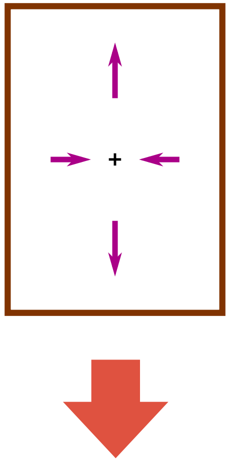
$$\boxed{\delta\phi = \frac{1}{\hbar}\,\delta\mathbf{p}\cdot\left(\mathbf{x}_0 + 2\,\mathbf{v}_0 T\right) - \frac{1}{\hbar}\,\delta\mathbf{x}\cdot m\mathbf{v}_0 + \ \dots}$$

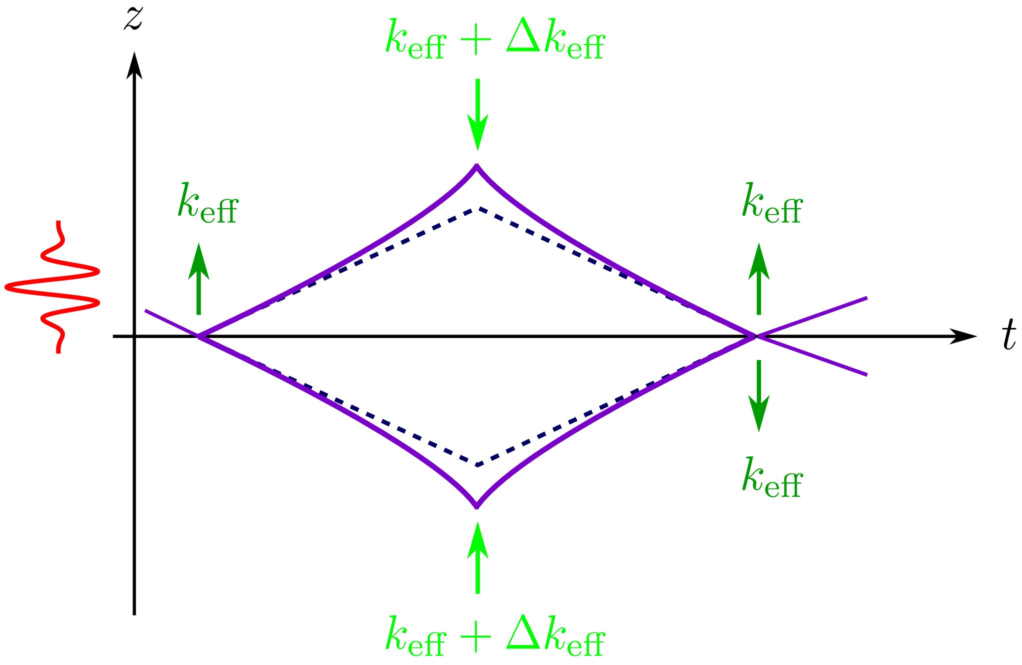
- Suitable adjustment of laser wavelength of *2nd pulse*

  → compensation of unwanted gravity gradient effects

freely falling frame

(*Einstein elevator*)





$$\boxed{\Delta k_{\mathrm{eff}} = \left(\Gamma_{zz}\, T^2/2\right) k_{\mathrm{eff}}}$$

Tests of universality of free fall (UFF)

- Atomic fountain experiments in *Stanford's 10-meter tower:*

- *gravity-gradient compensation* scheme successfully implemented
- very effective in overcoming the *initial-colocation* problem
- key ingredient in efforts to test UFF with *atom interferometry* at 10^{-14} level

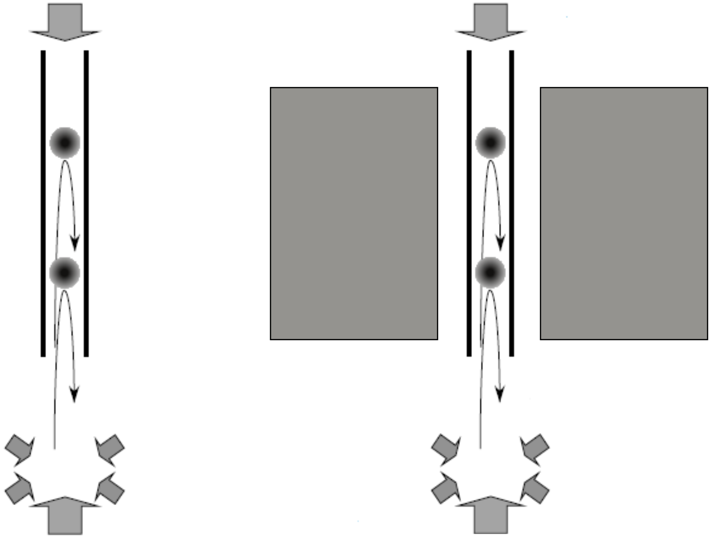
Overstreet *et al.*, *Phys. Rev. Lett.* **120**, 183604 (2018)

P. Asenbaum *et al.*, *Phys. Rev. Lett.* **125**, 191101 (2020)

Gradiometry & determination of G

- One can use the technique to cancel the effect of *static* gravity gradients in measurement of *time-dependent* ones.
- Also for measurements of *static gravity gradients insensitive* to *initial position & velocity*:

G. Rosi, *Metrologia* **55**, 50 (2018)



vanishing *gradiometry phase* for

$$\boxed{\Delta\nu = \frac{c}{4\pi}\left(\Gamma_{zz}\, T^2/2\right) k_{\mathrm{eff}}}$$

G. D'Amico *et al.*, *Phys. Rev. Lett.* **119**, 253201 (2017)

(application to determination of G)

PART IV

Searching for dark energy and dark matter with atom interferometry

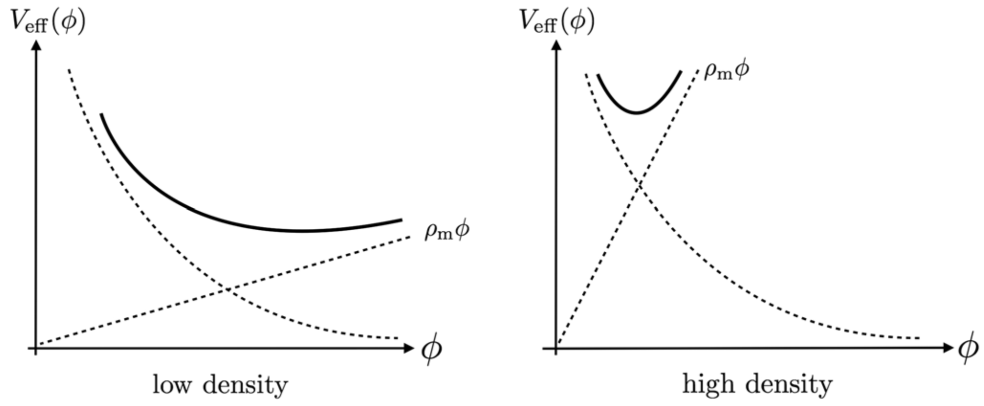
Search for certain kinds of dark energy fields

Chameleon and symmetron fields

- Candidate *dark-energy fields* that become screened in presence of non-negligible matter density (*avoid* standard *tests of UFF*):

e.g. *chameleon* field

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



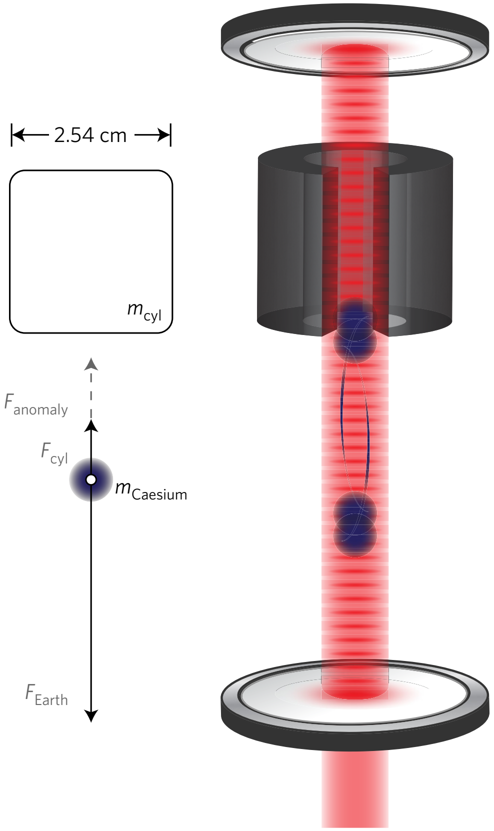
low density

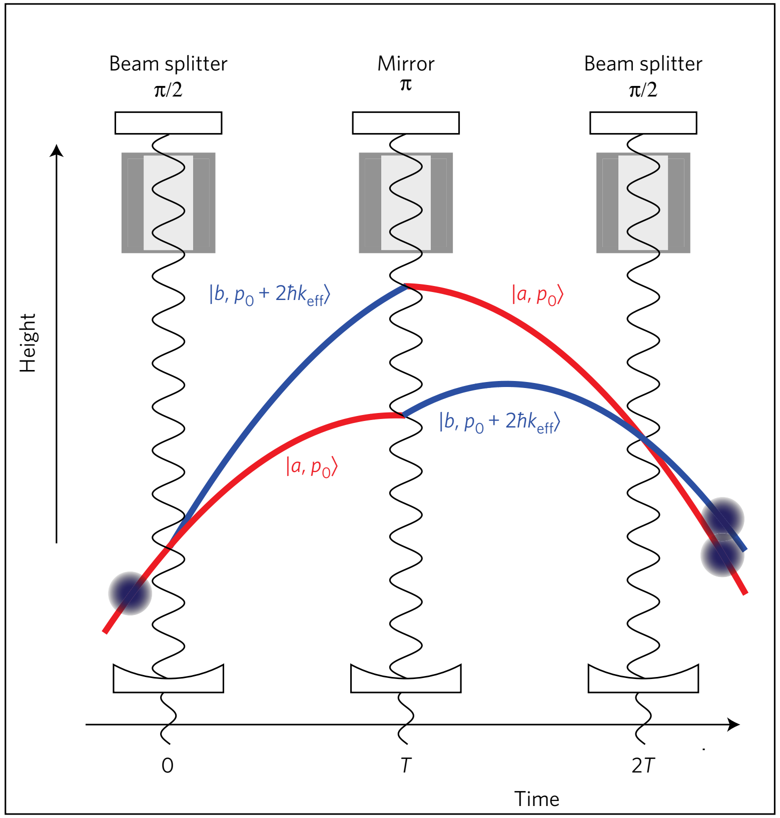
high density

Elder *et al.*, *Phys. Rev. D* **94**, 044051 (2016)

- Atomic *test mass* in *vacuum* chamber → hardly screened

Hamilton *et al.*, *Science* **349**, 849 (2015)

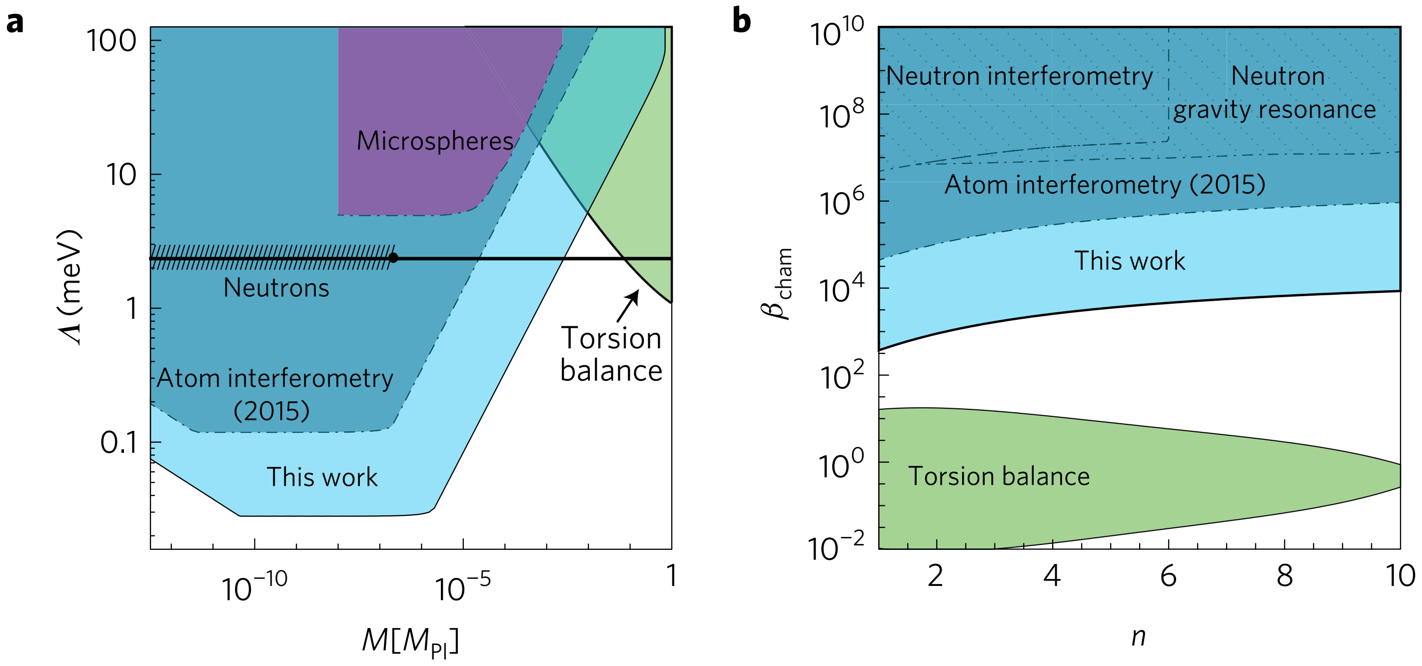




Jaffe *et al.*, *Nature Phys.* **13**, 938 (2017)

[See also Sabulsky *et al.*, *Phys. Rev. Lett.* **123**, 061102 (2019)]

- Substantial improvement of the parameter bounds for this kind of models:



Jaffe *et al.*, *Nature Phys.* **13**, 938 (2017)

Detection of ultralight dark matter fields

Detection of ultralight dark matter fields

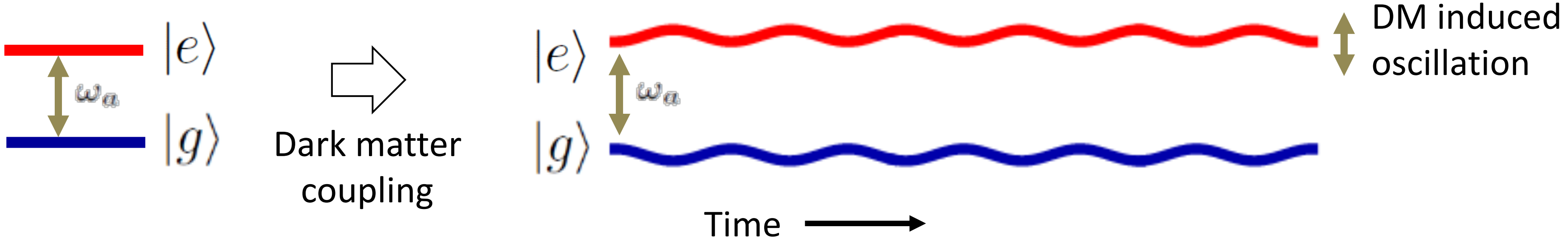
- Coupling of ultralight scalar field to the Standard Model sector leads to small *oscillations* of the *energy* of internal *atomic states*:

$$\mathcal{L} = \underbrace{+\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2}_{\text{DM scalar field}} - \sqrt{4\pi G_N}\,\phi\left[\underbrace{d_{m_e}m_e\bar{e}e}_{\text{Electron coupling}} - \underbrace{\frac{d_e}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{Photon coupling}}\right] \underbrace{+\ \ldots}_{\text{e.g., QCD}}$$

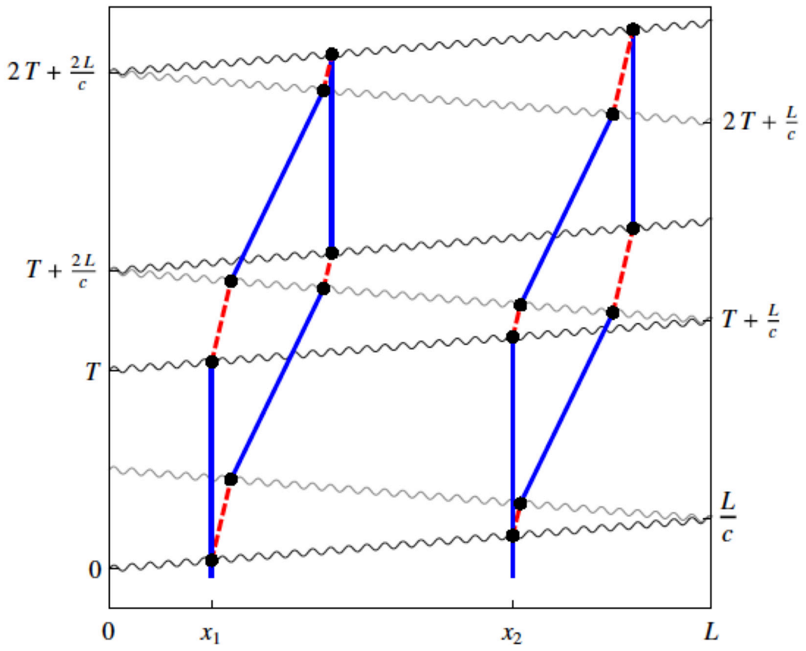
$$\phi\left(t,\mathbf{x}\right) = \phi_0\cos\left[m_\phi(t-\mathbf{v}\cdot\mathbf{x})+\beta\right] + \mathcal{O}\left(|\mathbf{v}|^2\right)$$

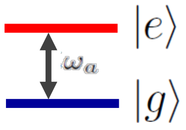
$$\phi_0 \propto \sqrt{\rho_{\mathrm{DM}}}$$ DM mass density

Jason Hogan, AION Workshop



- Oscillations of *transition energies* at *Compton* frequency.

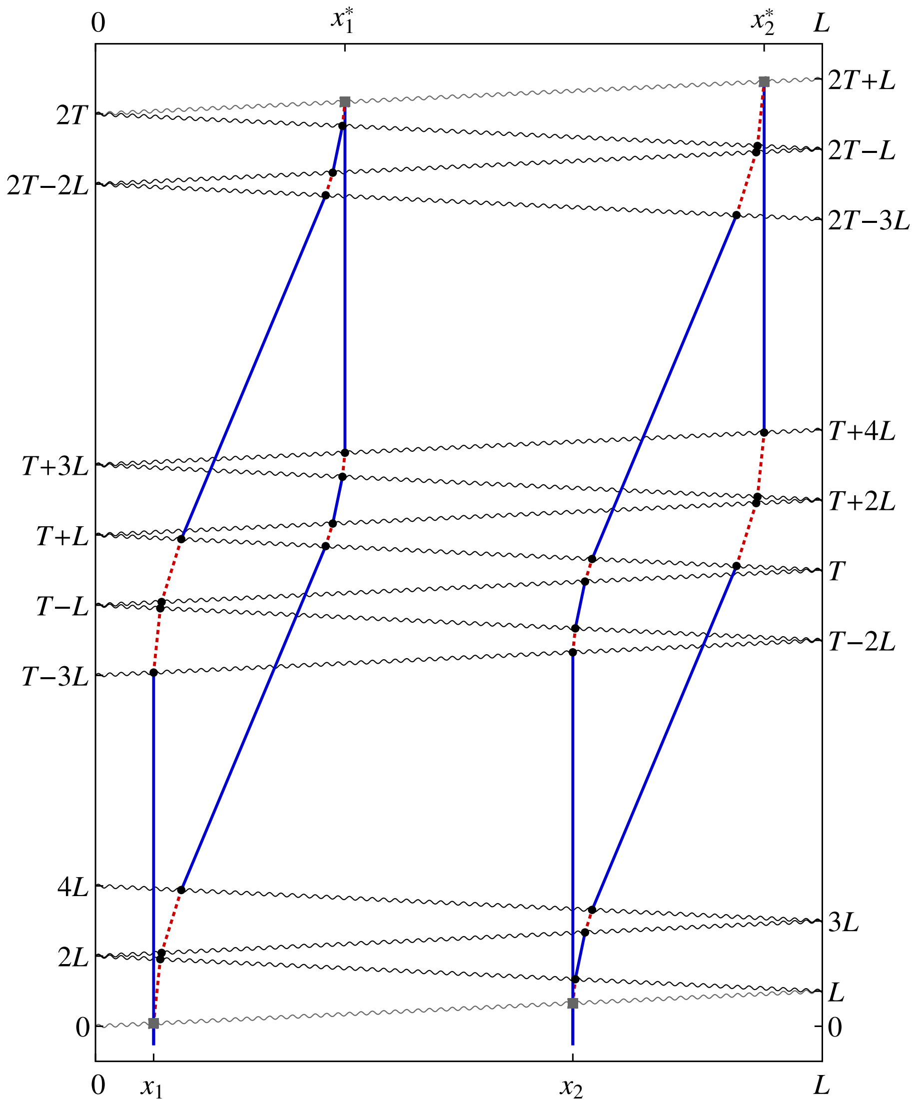




Arvanitaki *et al.*, *Phys. Rev. D* **97**, 075020 (2018)

- *Gradiometry-like* differential measurement with atom interferometers based on *single-photon* diffraction.

- Signal enhancement with LMT *pulse sequences*:



Arvanitaki *et al.*, *Phys. Rev. D* **97**, 075020 (2018)

- Significant coverage of *parameter space* for ultralight scalar field as DM candidate:

$$\mathcal{L} = +\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - \sqrt{4\pi G_N}\,\phi\left[d_{m_e}m_e\bar{e}e - \frac{d_e}{4}F_{\mu\nu}F^{\mu\nu}\right] + \ldots$$

DM scalar field

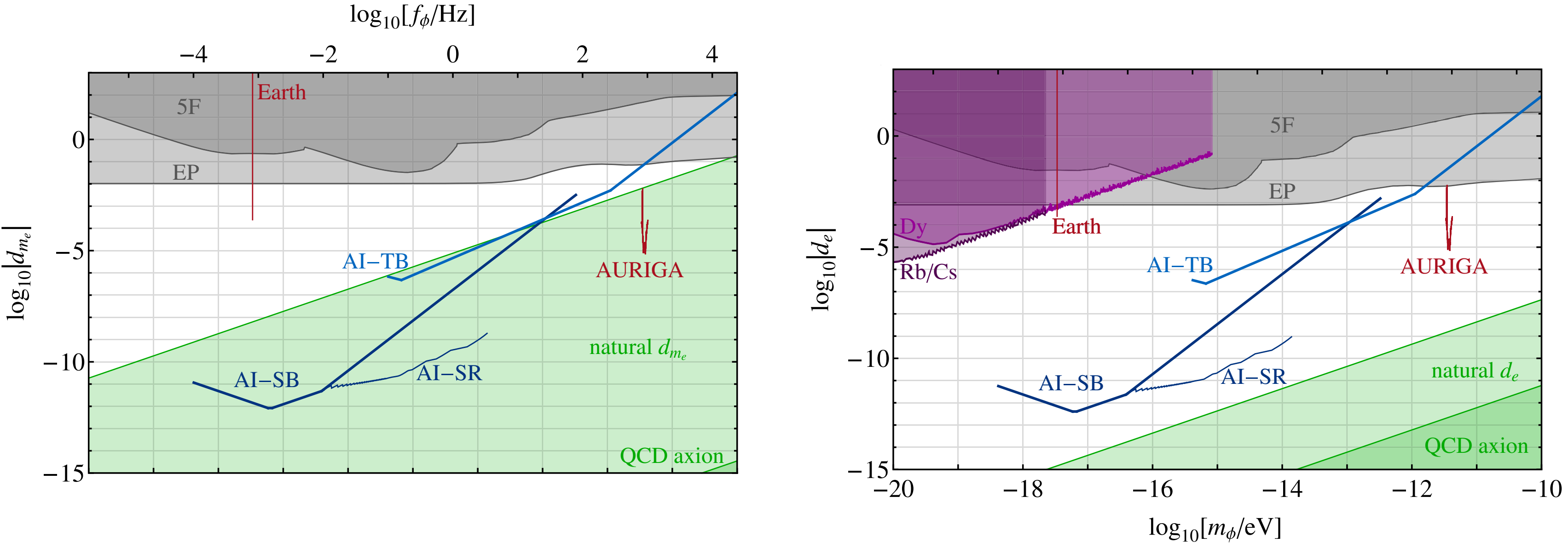
Electron coupling

Photon coupling

e.g., QCD

$$\phi\,(t,\mathbf{x}) = \phi_0\cos\left[m_\phi(t-\mathbf{v}\cdot\mathbf{x})+\beta\right] + \mathcal{O}\left(|\mathbf{v}|^2\right) \qquad \phi_0 \propto \sqrt{\rho_{\rm DM}}$$

DM mass density

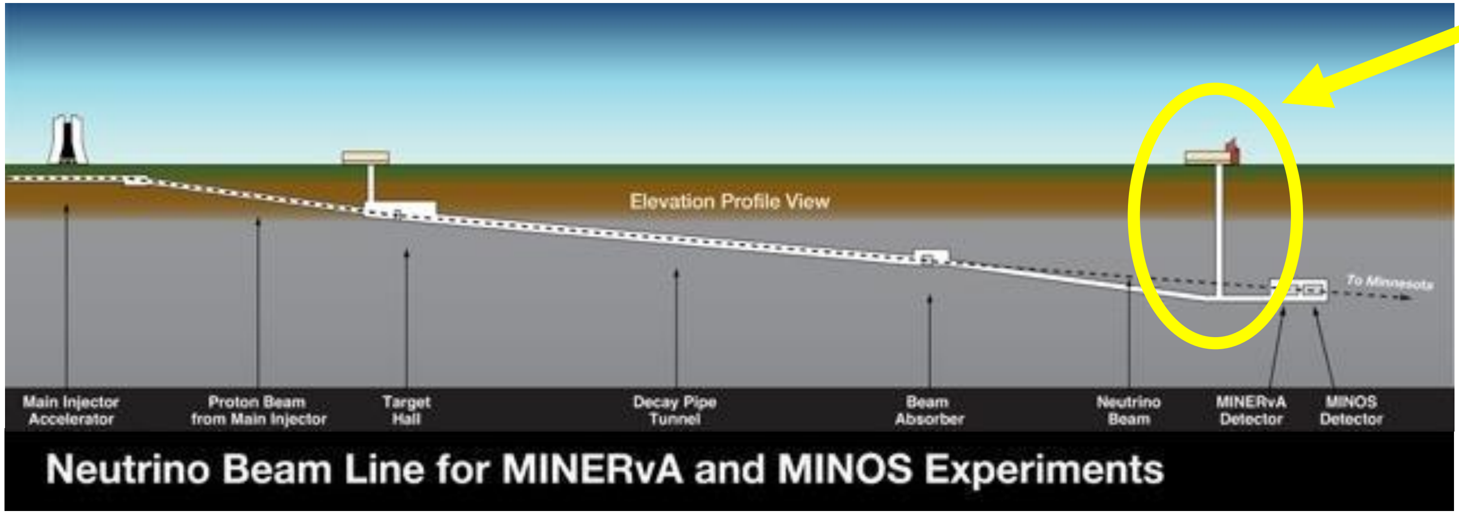


Jason Hogan, AION Workshop

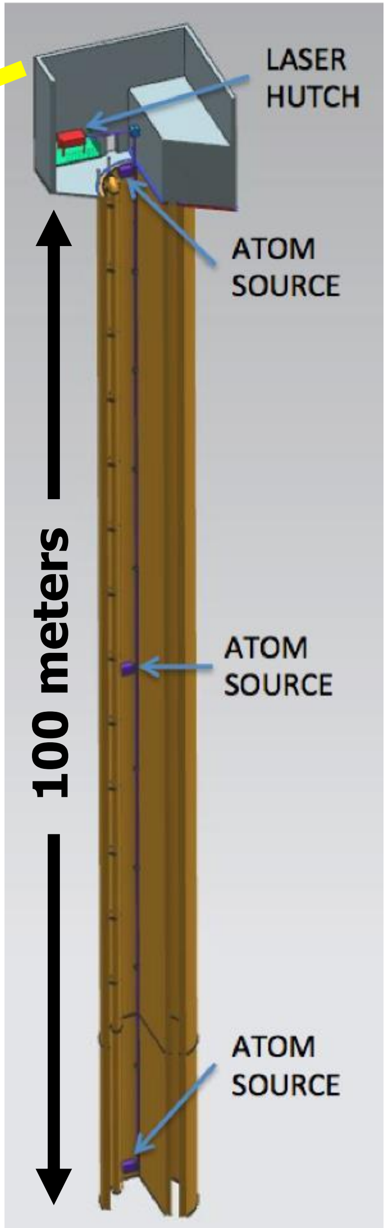
Arvanitaki *et al.*, *Phys. Rev. D* **97**, 075020 (2018)

MAGIS-100: GW detector prototype at Fermilab

Matter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor

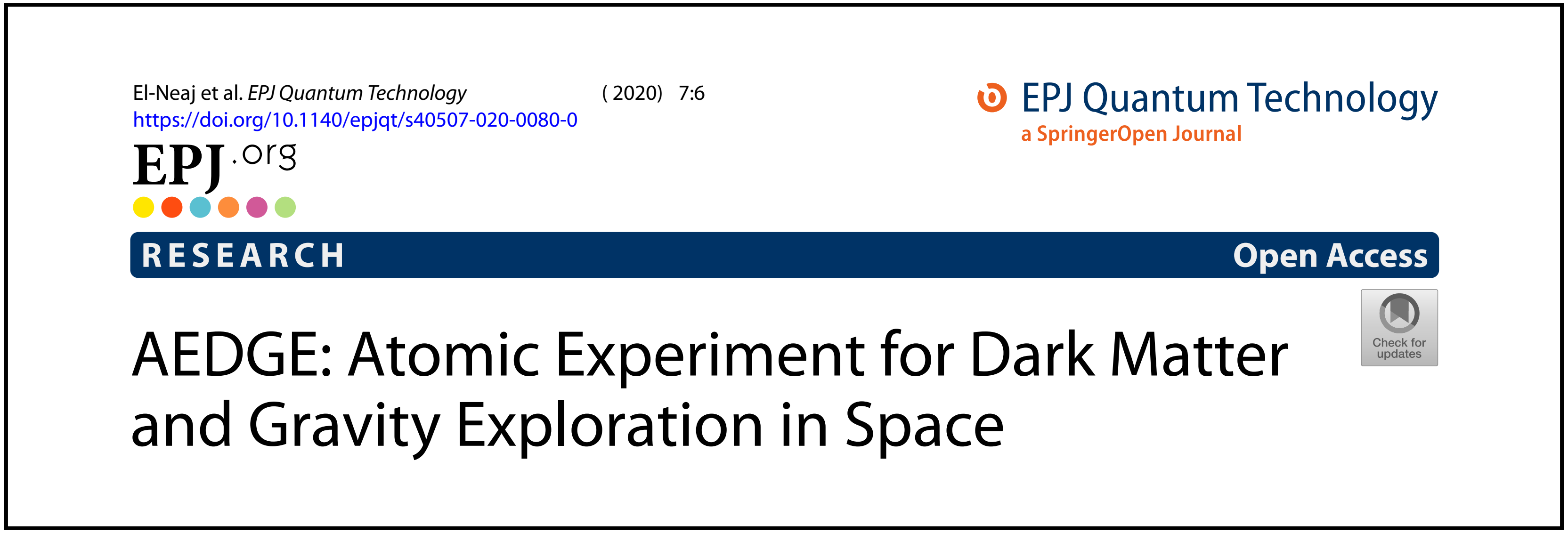


Neutrino Beam Line for MINERvA and MINOS Experiments



- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Intermediate step to full-scale (km) detector for gravitational waves
- Clock atom sources (Sr) at three positions to realize a gradiometer
- Probes for ultralight scalar dark matter beyond current limits (Hz range)
- Extreme quantum superposition states: >meter wavepacket separation, up to 9 seconds duration

STANFORD Fermilab BERKELEY UNIVERSITY OF LIVERPOOL Northwestern University Northern Illinois University



El-Neaj et al. *EPJ Quantum Technology* (2020) 7:6
https://doi.org/10.1140/epjqt/s40507-020-0080-0

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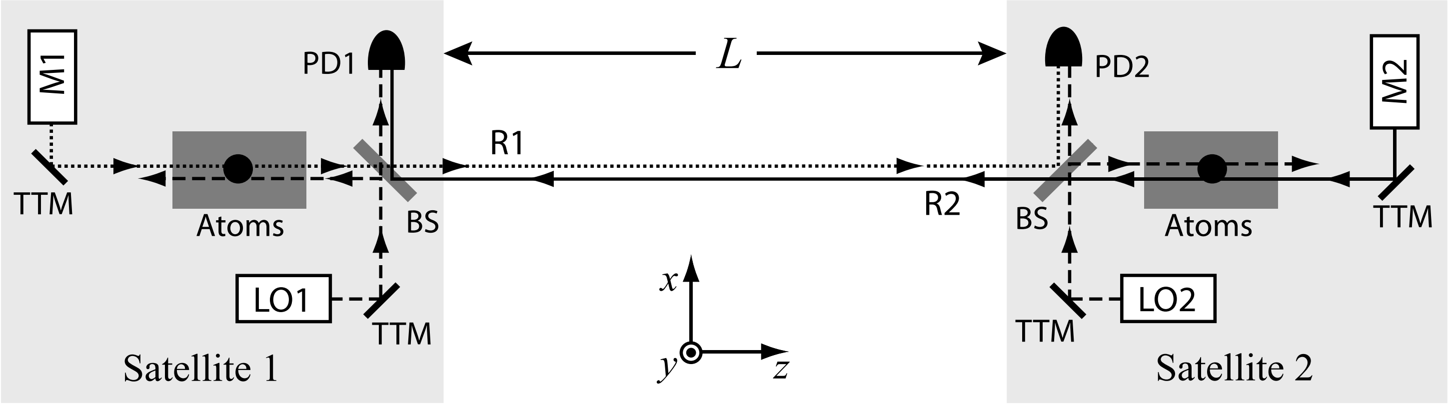
AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration in Space



J. Hogan and M. Kasevich, *Phys. Rev. A* **94**, 033632 (2016)

PART V

Gravitational time-dilation in macroscopically delocalized quantum superpositions

PHYSICAL REVIEW X **10,** 021014 (2020)

Gravitational Redshift in Quantum-Clock Interferometry

Albert Roura

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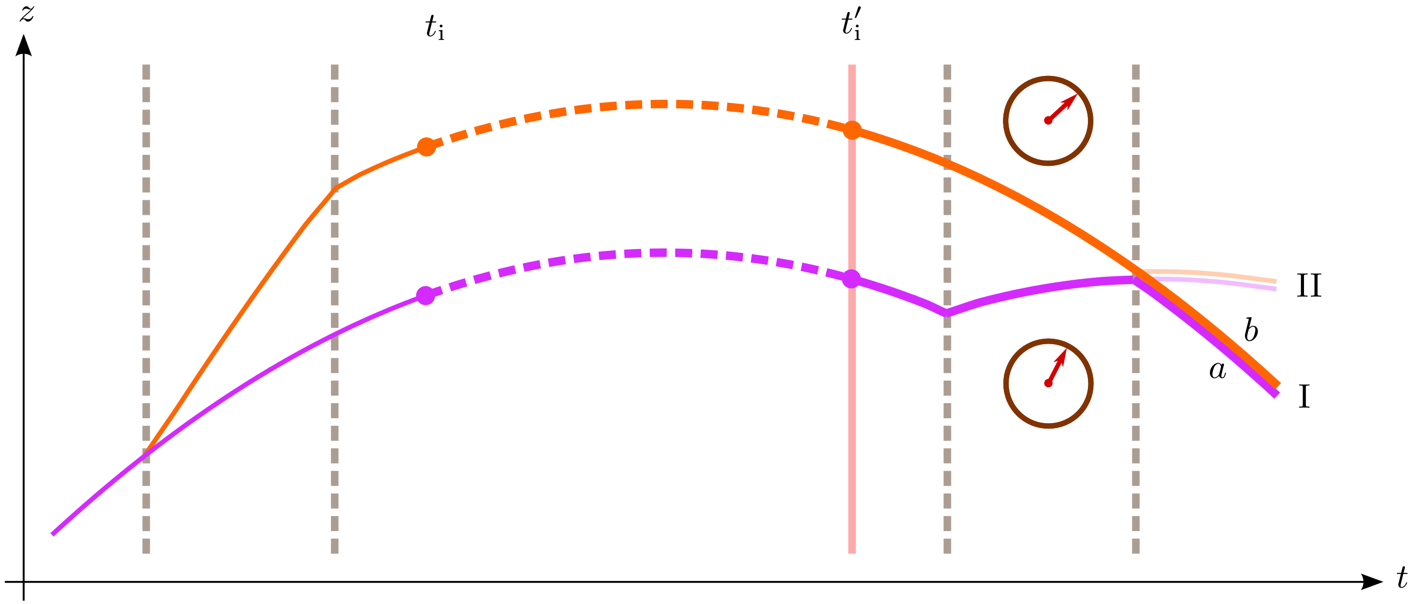
Söflinger Straße 100, 89077 Ulm, Germany and Institut für Quantenphysik,
Universität Ulm, Albert-Einstein-Allee 11, 89081 Ulm, Germany



QUANTUS group @ Ulm University

Wolfgang Schleich

Albert Roura

Wolfgang Zeller

Matthias Meister

Enno Giese

Stephan Kleinert

Christian Ufrecht

Jens Jenewein

Sabrina Hartmann

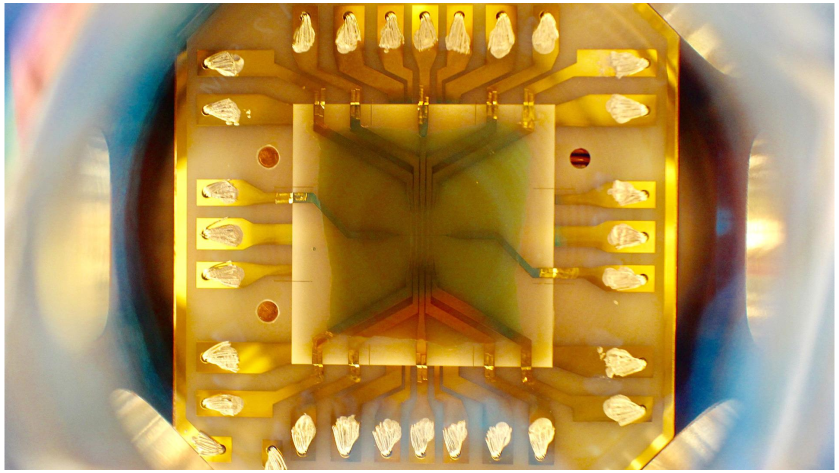
Alexander Friedrich

Fabio Di Pumpo

Eric Glasbrenner

Starting a new group at the recently founded

Institute of Quantum Technologies (Ulm)



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des Deutschen Bundestages

HORIZON 2020

Q-SENSE
European Union H2020 RISE Project

Summary

I. *Long-time* atom interferometry for *precision measurements*

II. *Fine-structure constant* and *atomic mass* measurements

III. *Gravitational* measurements: *UFF tests* and *G*

IV. Searching for *dark energy* and *dark matter*

V. *Gravitational time-dilation* in macroscopically *delocalized quantum superpositions*