Relativistic effects in atom interferometry

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PART I (Theoretical Framework)

- Propagation phase & wave-packet evolution:
  - two-level atom as a quantum clock
  - matter-wave propagation in curved spacetime

- Full interferometer and separation phase

  Description in different reference frames

- Retardation & relativistic effects on laser pulses

PART II (Experiments)

- Quantum phase from time dilation in atom interferometry and gravitational Aharonov-Bohm effect
- Quantum-clock interferometry
- Atom interferometers as freely falling clocks for time dilation measurements.
- GW detection & search of ultralight dark matter

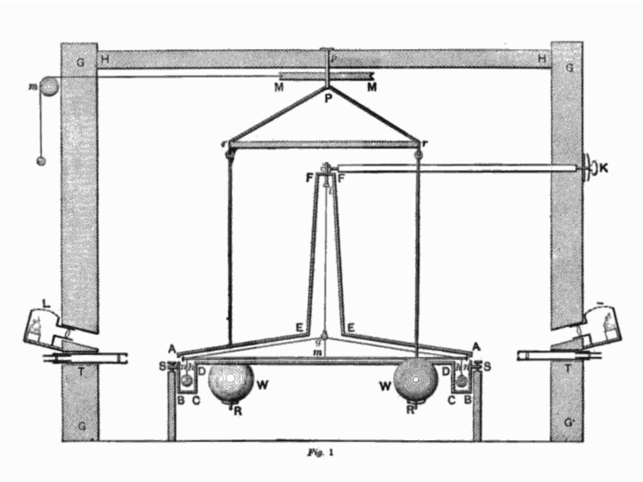
Excursus: Weighing the World

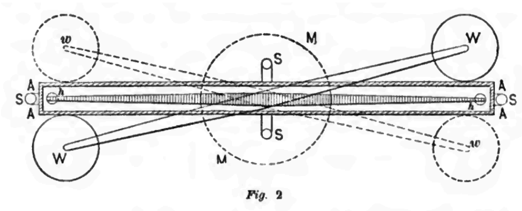
Cavendish experiment (1797–1798)

- Gravimetric (and astronomical) measurements cannot determine Earth's absolute mass:

$$F_{\mathrm{grav}} = (G\,M_\oplus)\,m_{\mathrm{test}}/R_\oplus^2 = m_{\mathrm{test}}\,g$$

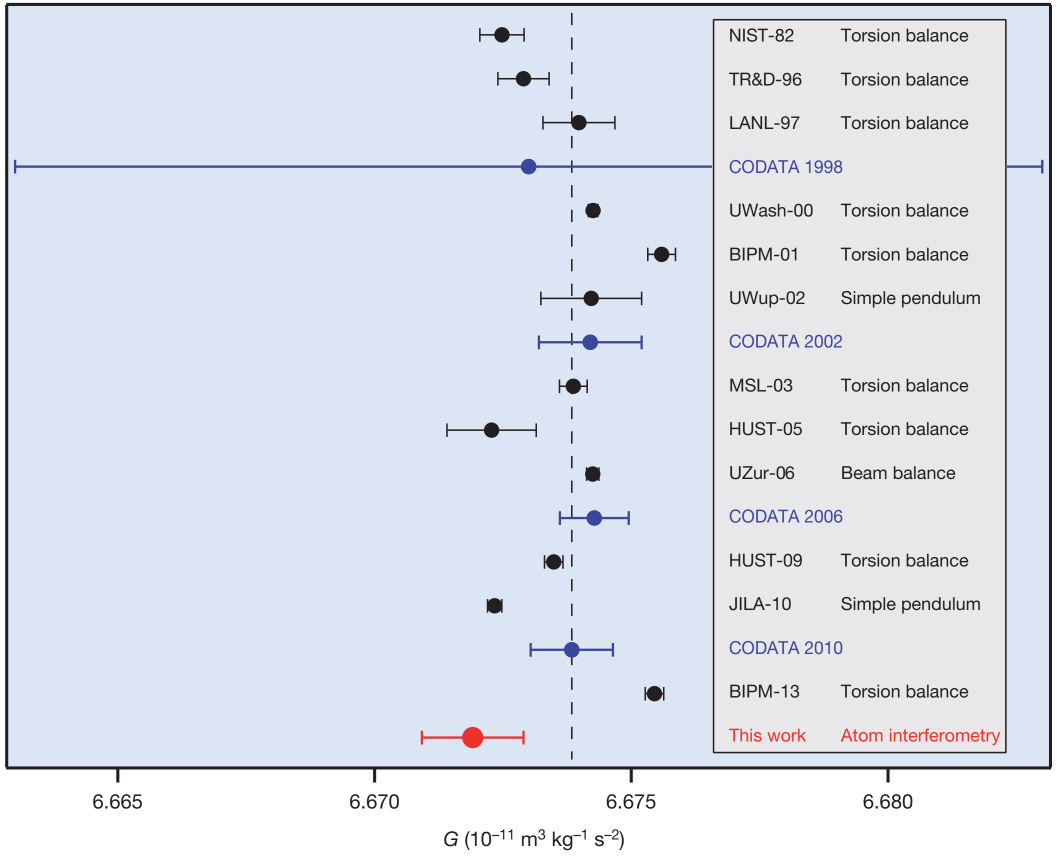
Wikipedia





- Cavendish used a ***torsion balance*** to measure the gravitational force between ***known* masses**.
- He was able to determine Earth's *mean density* (and mass) for the first time: Weighing the World !!
- Nowadays interpreted as a measurement of big G (Newton's gravitational constant).

Big *G* measurements



- Almost all experiments are variants of **Cavendish**'s original experiment.
- By far the **least accurately** measured of all fundamental constants.
- **Discrepancies** much larger than the claimed accuracies.
- Measurements using **atom interferometry** offer an interesting alternative with rather *different systematic effects*.

Big *G* measurements

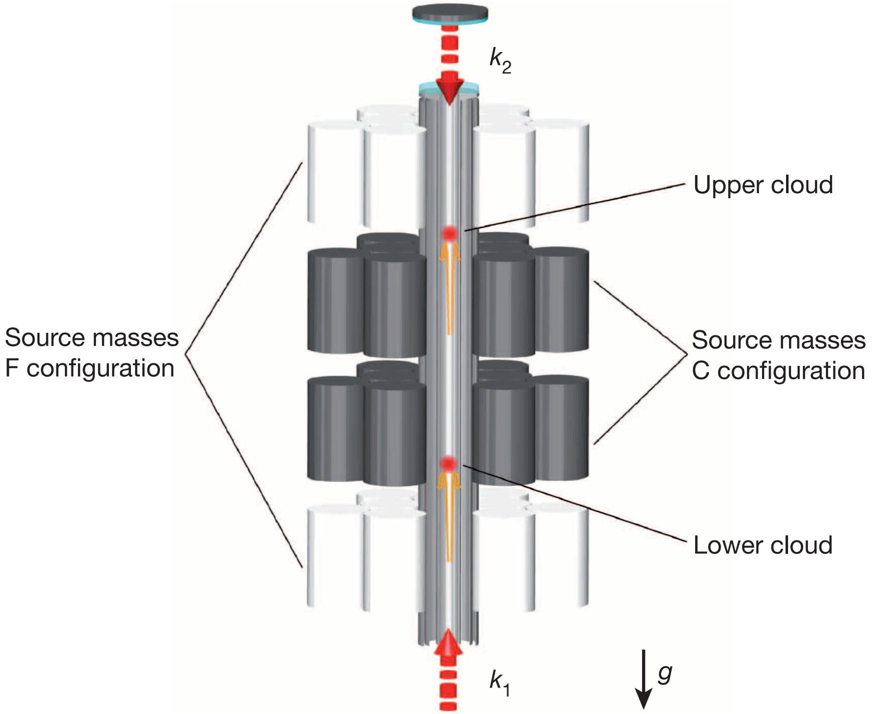
- **Gradiometric** measurement based on *differential* atom interferometry.

- Compare the results for ***different positions*** of well-characterized ***source masses***.
  (effect of Earth's gravity field drops out)

- Infer *G* from the **difference** of gravitational accelerations.

- Important source of ***systematic uncertainties*** connected to *initial* ***position*** and ***velocity*** of the atom clouds.

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

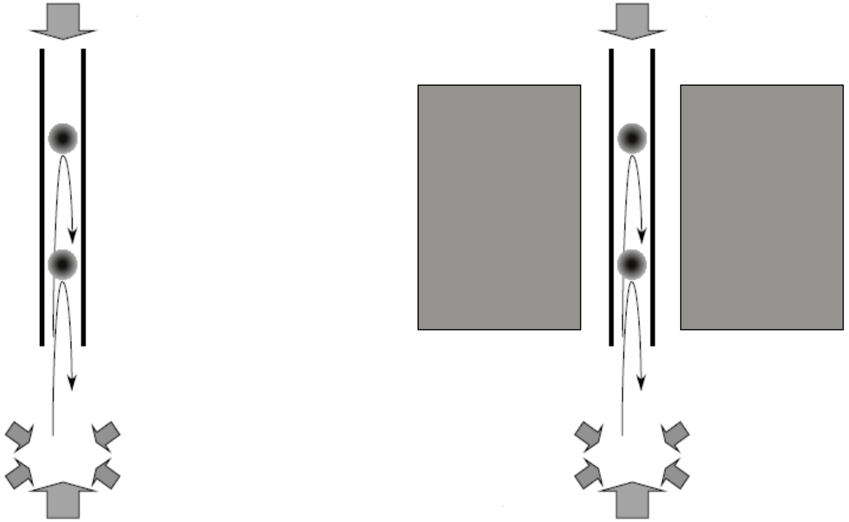


gravitational constant *G*

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

- Very effective method for ***compensating*** the effect of ***gravity gradients*** and mitigating unwanted sensitivity to initial conditions (see Tim Kovachy's lecture): [A. Roura, Phys. Rev. Lett. 118, 160401 (2017)]

- It can be applied to **UFF tests** but also to **gradiometric measurements**.
  In fact, through *self-calibration*, it can be used to directly obtain the gravity gradient, as experimentally demonstrated in [G. D'Amico et al., Phys. Rev. Lett. 119, 253201 (2017)].



- **Proposal** for a measurement of *G* relying on that → *competitive* or even *outperforming* measurements based on *macroscopic* test masses: [G. Rosi, Metrologia 55, 50 (2018)]

See Gabriele Rosi's talk at the conference.

Gravitational Aharonov-Bohm effect

Spacetime curvature and proper-time difference

RESEARCH

PHYSICS

Observation of a gravitational Aharonov-Bohm effect

Chris Overstreet[1]†, Peter Asenbaum[1,2]†, Joseph Curti[1], Minjeong Kim[1], Mark A. Kasevich[1]*

Overstreet *et al.*, *Science* **375**, 226–229 (2022) 14 January 2022

https://doi.org/10.1126/science.abl7152

INSIGHTS | PERSPECTIVES

PERSPECTIVES

FUNDAMENTAL PHYSICS

Quantum probe of space-time curvature

An atom interferometer measures the quantum phase due to gravitational time dilation

By **Albert Roura**

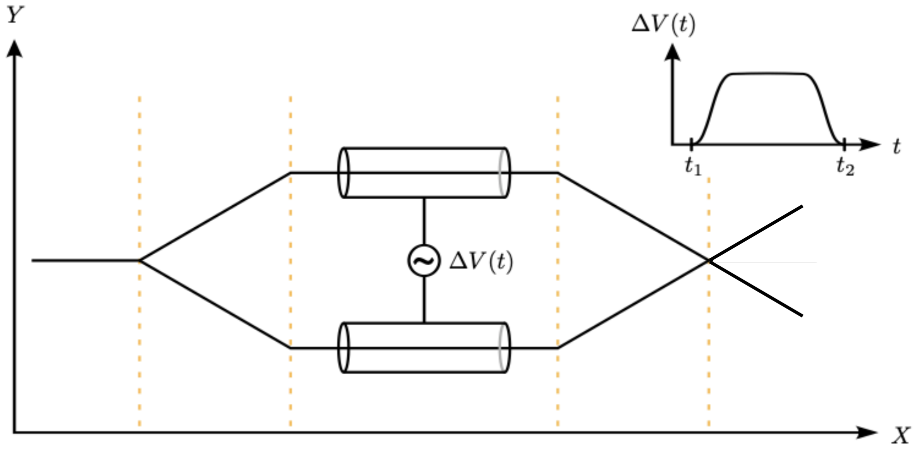
142 14 JANUARY 2022 • VOL 375 ISSUE 6577 science.org SCIENCE

https://doi.org/10.1126/science.abm6854

- Effect of spacetime curvature on a **delocalized wave function**.
- **Proper-time difference** between the two interferometer arms.
- Gravitational analog of the **scalar Aharonov-Bohm** effect.

Scalar Aharonov-Bohm effect

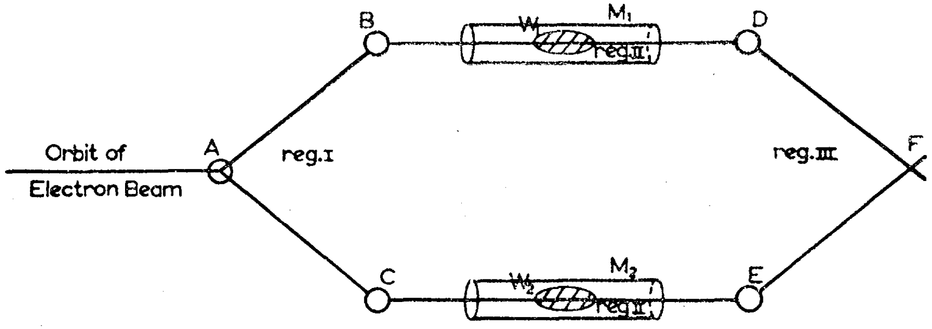
Nadja Augst & A.R.



- Voltage **turned on** when matter wave packets are propagating **inside** the metal shields.
- **No forces** (uniform potential inside the metal shields), but **quantum phase** accumulated.
- Phase difference revealed in the ***interference signal*** when the wave packets are recombined.

Scalar Aharonov-Bohm effect

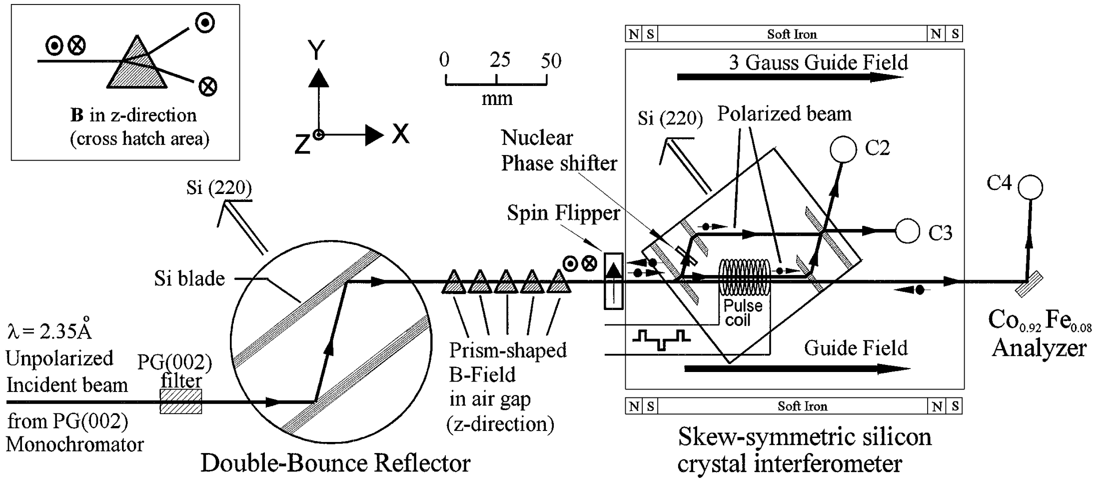
Aharonov & Bohm, *Phys. Rev.* **115**, 485 (1959)



charged particle in a homogeneous *electric* potential

$$qV(t)$$

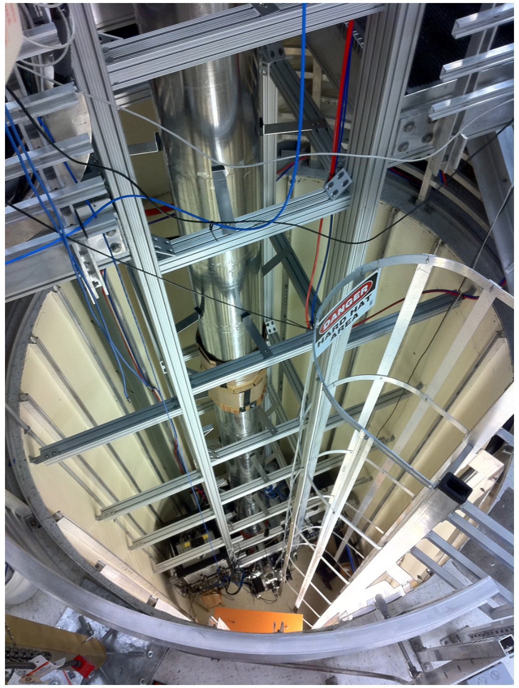
Lee, Motrunich, Allman & Werner, *Phys. Rev. Lett.* **80**, 3165 (1998)



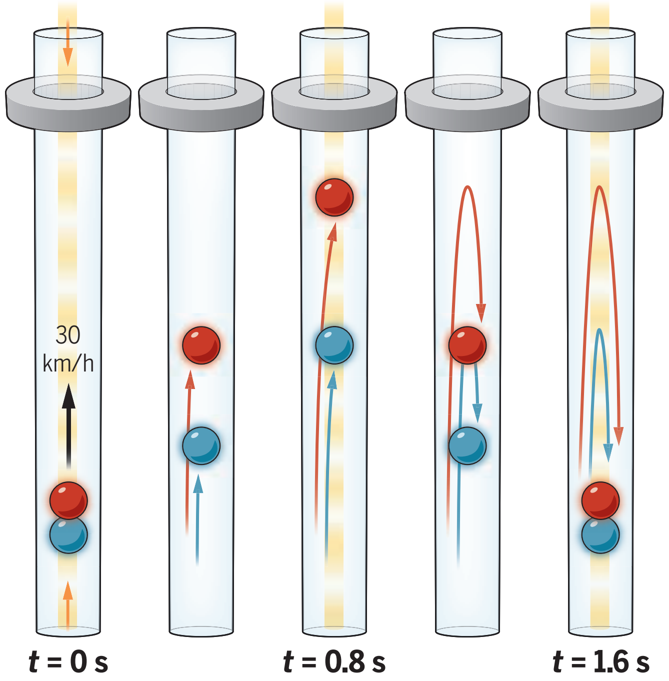
experimental realization with neutron interferometry (*magnetic dipole* in a homogeneous *magnetic* field)

$$\vec{\mu}\cdot\vec{B}(t)$$

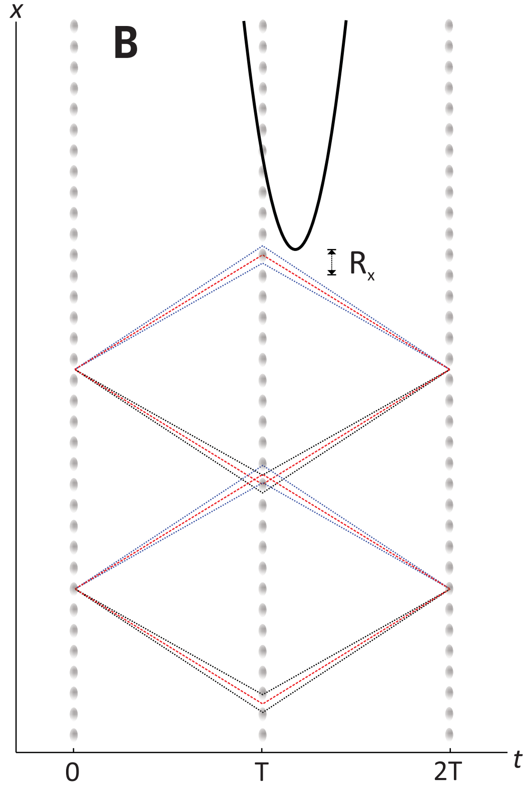
Spacetime curvature and proper-time difference



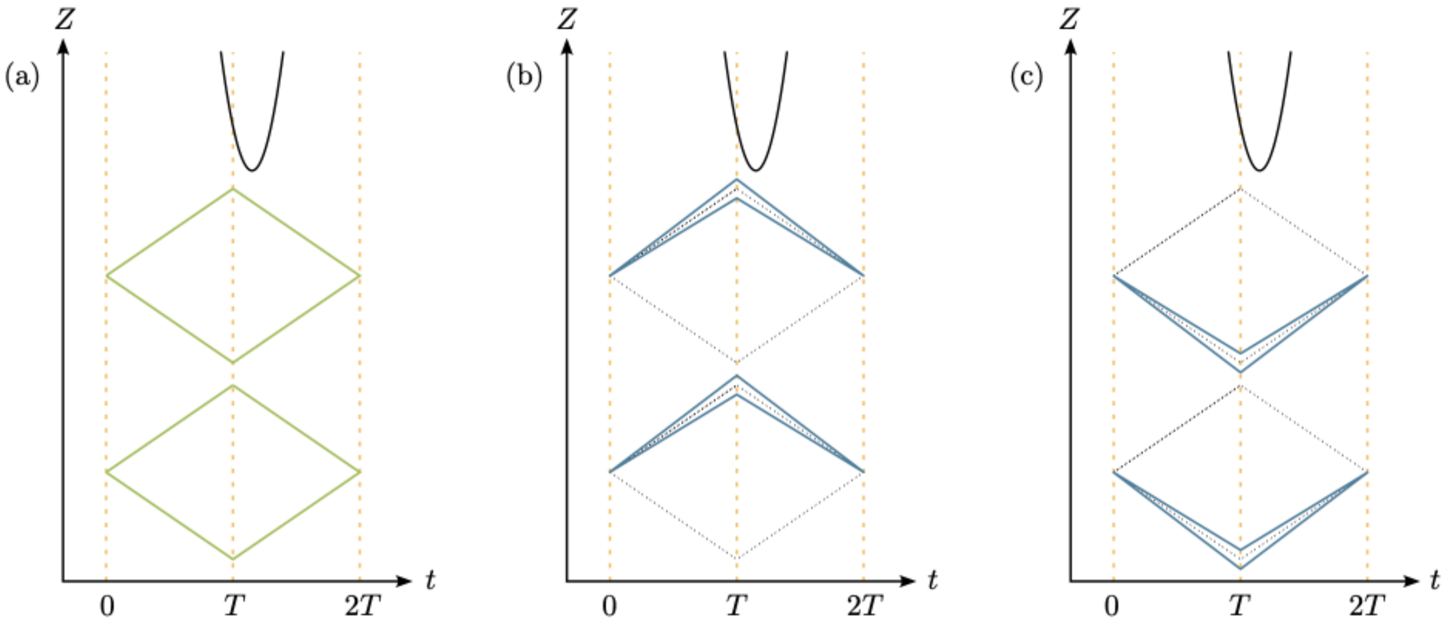
Stanford (USA)



lab frame



freely falling frame



Nadja Augst & A.R.

- Interferometers with *small arm separation* → infer contribution of **laser phases** for *large arm separation*.
- By taking the difference, one can isolate the contribution of the **propagation phase** (*proper-time difference*).
- Then one compares measurements ***with*** and ***without*** source mass → effect induced by its gravitational field.

- ***Perturbative*** treatment of the source mass's gravitational field.

- Difference between ***gradiometric*** *differential phase shifts* **with** and **without** the source mass:

$$\delta\phi_{\text{source}} - \delta\phi_{\text{no source}} = -(m/\hbar) \int_{t_1}^{t_3} dt \left[U_{\text{src}}\big(\mathbf{X}_b^{(0)}(t), t\big) - U_{\text{src}}\big(\mathbf{X}_a^{(0)}(t), t\big) \right]$$

- **Total** phase-shift contribution (*propagation*, *separation* and *laser* phases).

  When ***subtracting*** the contribution of the ***laser phases*** (interferometers with small arm separation), one is left with the ***proper-time difference*** between the two arms.

- *Time dilation* due to ***gravitational potential*** of the source mass, but also due to ***modified trajectories***.

- For the *subset* of measurements with **vanishing differential laser phase**, the contribution due to the modified trajectories also vanishes $\longrightarrow$ purely gravitational **Aharonov-Bohm** terms.

- Interesting interpretation within GR framework in terms of proper times and spacetime curvature. BUT the results can be entirely described with *non-relativistic QM* + *Newtonian gravity* as well !!

- Other examples that do **require** a **relativistic treatment** in the next sections.

  (the mass – energy equivalence $\Delta E = \Delta m\, c^2$ will play a key role)

Quantum-clock interferometry

Proper time as *which-way* information

- Quantum superposition of clocks

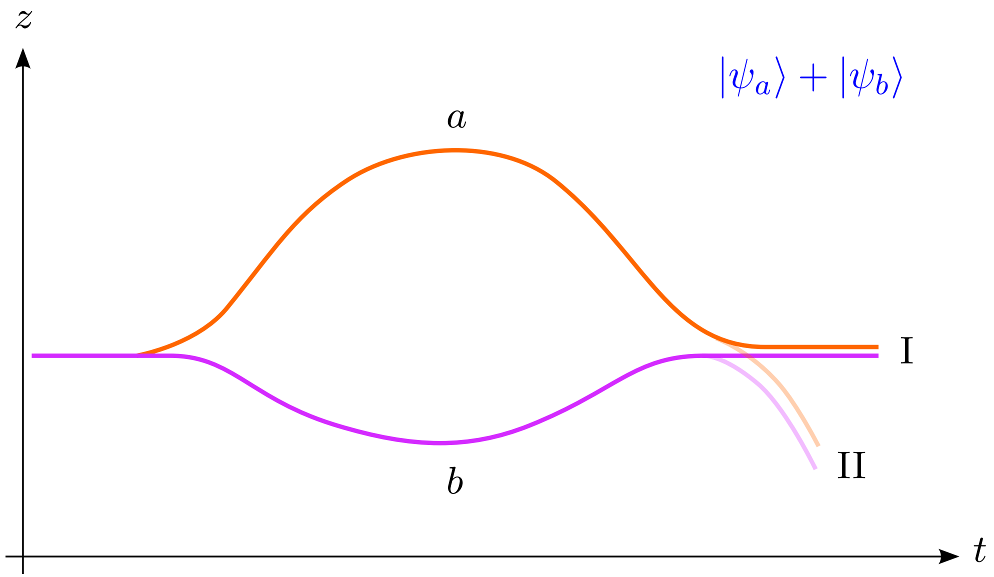
  (COM + internal state)

  experiencing different proper times

→ reduced visibility of interference signal

Zych et al., Nat. Commun. 2, 505 (2011)

Sinha & Samuel, Class. Quantum Grav. 28, 145018 (2011)



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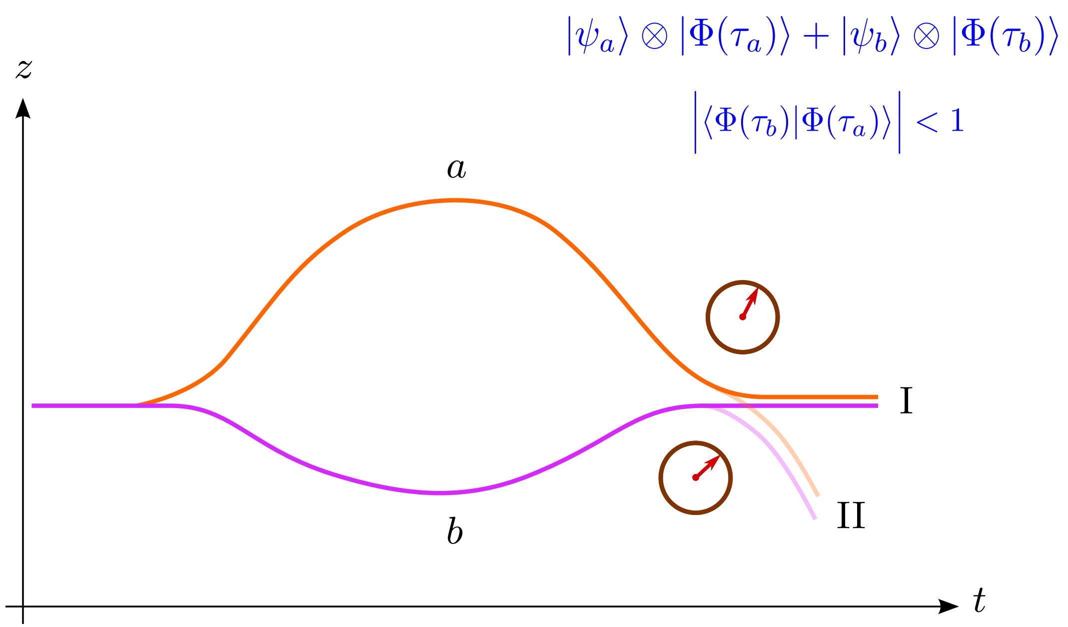
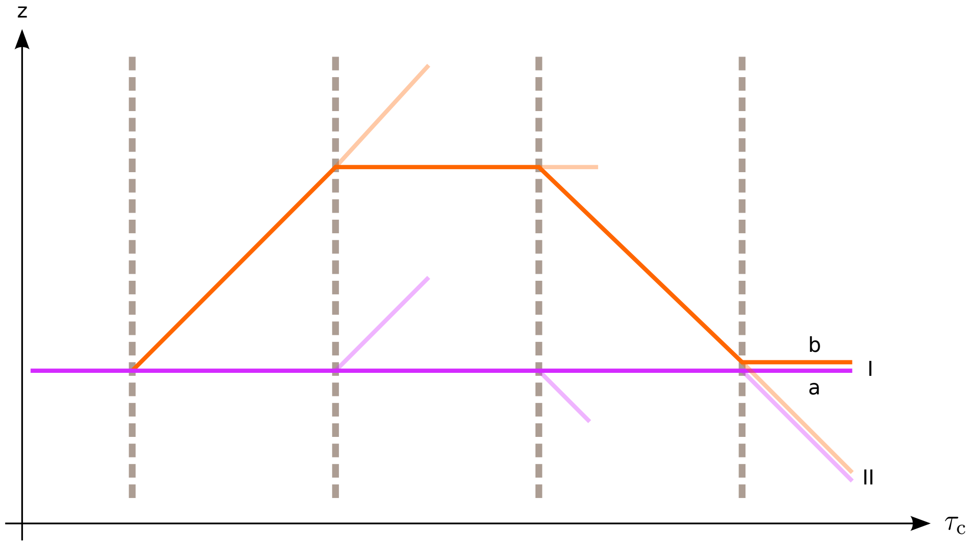


Major challenges in quantum-clock interferometry

Insensitivity to gravitational redshift (in a uniform field)

- Consider a freely falling frame:



Ramsey-Bordé interferometer

- Proper-time difference between the two interferometer branches independent of g.

(small dependence due to pulse timing suppressed by $(v_{\mathrm{rec}}/c) \sim 10^{-10}$)

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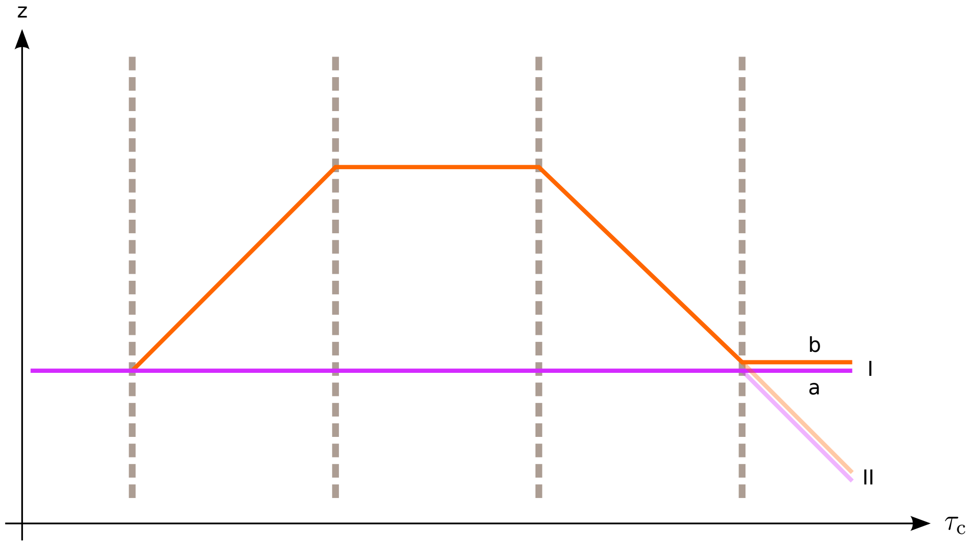

Ramsey-Bordé interferometer

- Proper-time difference between the two interferometer branches independent of g.

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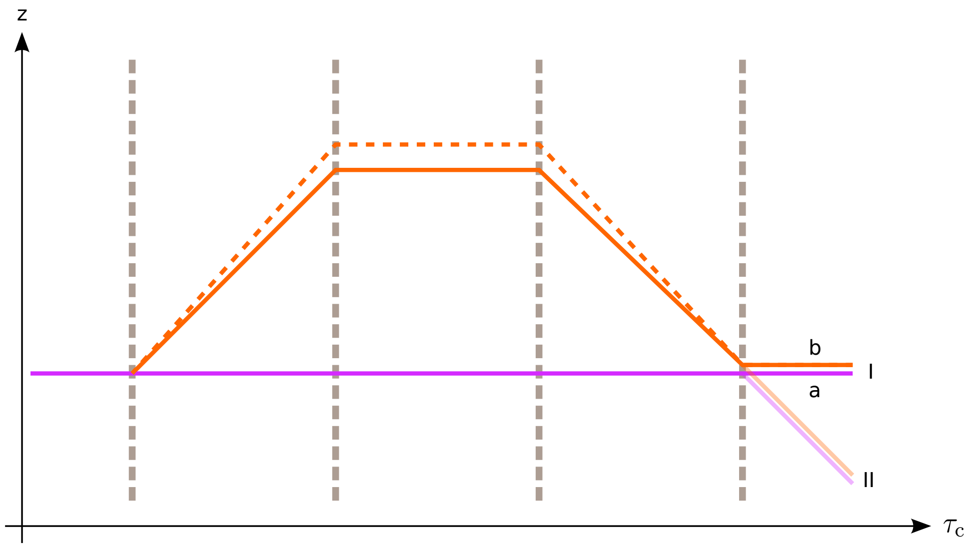
Differential recoil

- Different recoil velocities → different central trajectories:



$$v_{\mathrm{rec}}^{(n)} = \hbar k_{\mathrm{eff}} / m_n$$

- Implied changes of proper-time difference are comparable to signal of interest.

Small visibility changes

- Reduced interference visibility due to deceasing quantum overlap of clock states:

$$\langle \Psi_{\mathrm{I}} | \Psi_{\mathrm{I}} \rangle = \frac{1}{2} + \frac{1}{2} \Big| \langle \Phi(\tau_b) | \Phi(\tau_a) \rangle \Big| \cos \delta\phi$$

$$\Big| \langle \Phi(\tau_b) | \Phi(\tau_a) \rangle \Big| = \cos \left(\frac{\Delta E}{2\hbar} (\tau_b - \tau_a) \right)$$

- Small effect for feasible parameter range:

$$\Delta E / \hbar = \omega_0 \approx 2\pi \times 4 \times 10^2 \,\mathrm{THz}$$

$$\Big| \langle \Phi(\tau_b) | \Phi(\tau_a) \rangle \Big| = \cos \left(\frac{\omega_0}{2} \frac{g\, \Delta z}{c^2} \Delta t \right) \approx 1 - \left(10^{-3}\right)^2 / 2$$

$$\Delta z = 1\,\mathrm{cm} \qquad \Delta t = 1\,\mathrm{s}$$

- Extremely difficult to measure such small changes of visibility, which are masked by other effects leading also to loss of visibility.

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$$\Delta z = 1\,\mathrm{m} \qquad \Delta t = 1\,\mathrm{s}$$

- Extremely difficult to measure such small changes of visibility, which are masked by other effects leading also to loss of visibility.

Doubly differential gravitational-redshift measurement

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

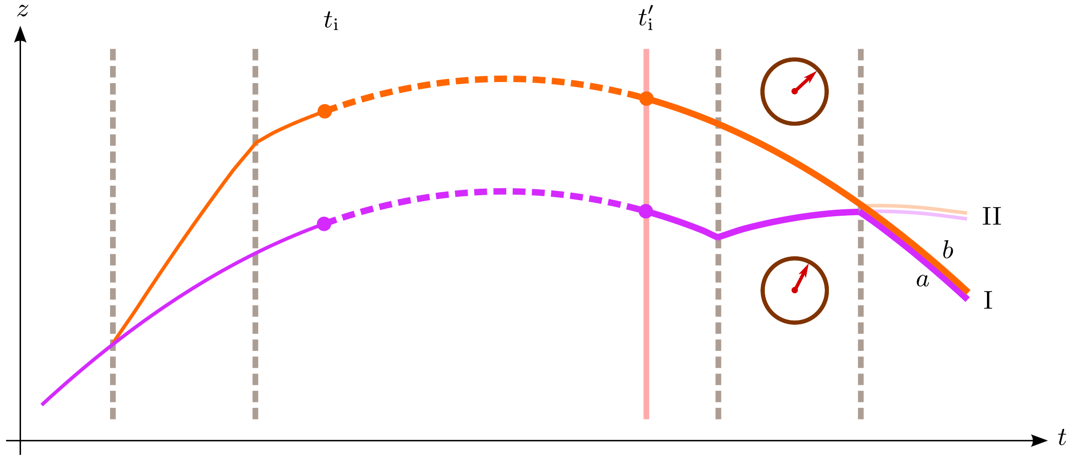
Gravitational Redshift in Quantum-Clock Interferometry

Albert Roura

https://doi.org/10.1103/PhysRevX.10.021014

Quantum superposition of a single clock at two different heights

- Initialization pulse after the spatial superposition has been generated.
- Doubly differential measurement:
  - state-selective detection
  - compare different initialization times



Differential phase-shift measurement

- Detection probability at first exit port (independent of internal state):

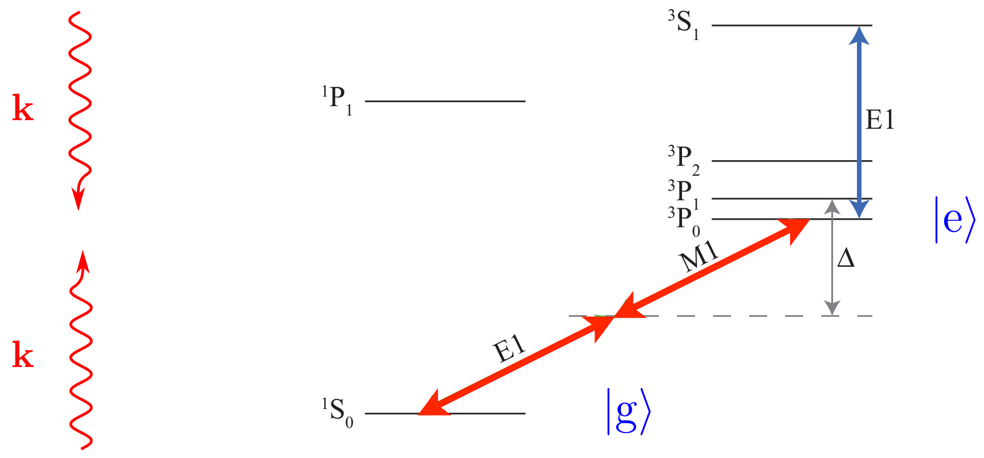
$$
\begin{aligned}
\langle \Psi_{\mathrm{I}} | \Psi_{\mathrm{I}} \rangle &= \frac{1}{2} \Big(\big\langle \Psi_{\mathrm{I}}^{(1)} \big| \Psi_{\mathrm{I}}^{(1)} \big\rangle + \big\langle \Psi_{\mathrm{I}}^{(2)} \big| \Psi_{\mathrm{I}}^{(2)} \big\rangle \Big) \\
&= \frac{1}{4} \Big(1 + \cos \delta\phi^{(1)} \; + \; 1 + \cos \delta\phi^{(2)} \Big) \\
&= \frac{1}{2} + \underbrace{\frac{1}{2} \cos \left(\frac{\delta\phi^{(2)} - \delta\phi^{(1)}}{2} \right)}_{\text{visibility}} \cos \left(\frac{\delta\phi^{(1)} + \delta\phi^{(2)}}{2} \right)
\end{aligned}
$$

- Phase-shift difference directly related to visibility reduction.

- Precise differential phase-shift measurement with state-selective detection much more viable (immune to spurious loss of contrast + common-mode rejection of phase noise)

Two-photon pulse for clock initialization

- Level structure for group-II-type atoms (e.g. Sr, Yb) employed in optical atomic clocks:



Alden *et al.*, *Phys. Rev. A* **90**, 012523 (2014)

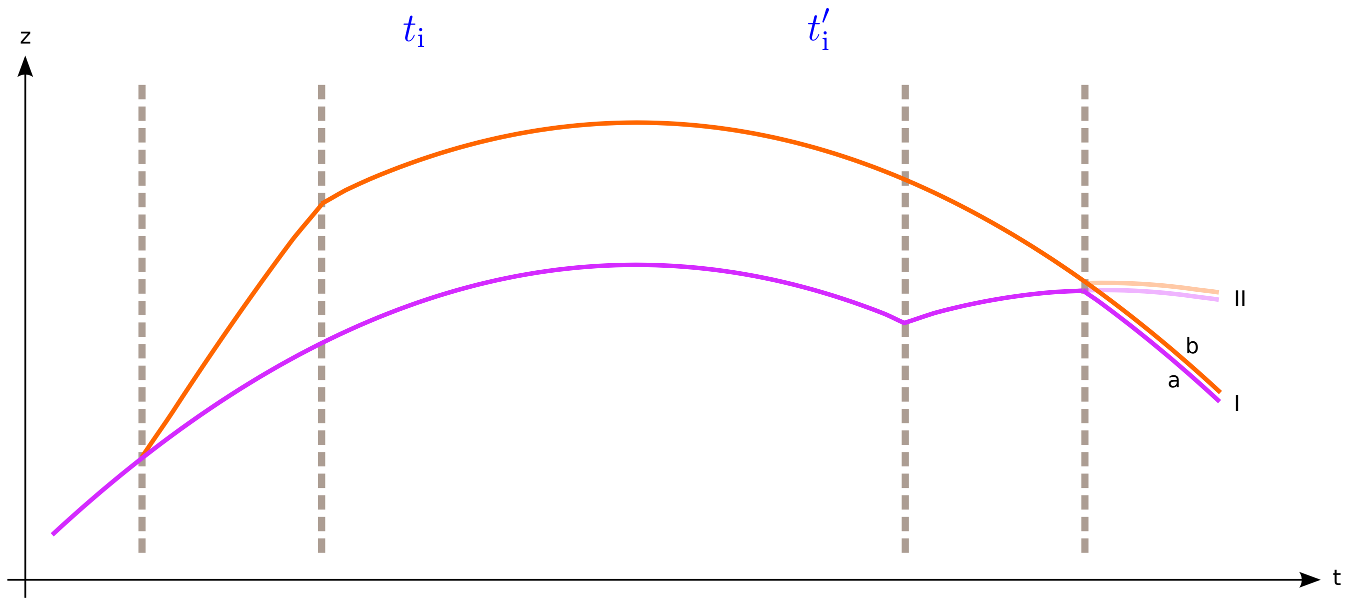
- Two-photon process resonantly connecting the two clock states.

- Equal-frequency counter-propagating laser beams in lab frame $e^{i\omega t}e^{i\mathbf{k}\cdot\mathbf{x}} \times e^{i\omega t}e^{-i\mathbf{k}\cdot\mathbf{x}} = e^{i\,2\omega t}$

  → constant effective-phase **simultaneity** hypersurfaces in **lab frame**.

Laboratory frame

- Compare differential phase-shift measurements for different initialization times:



$$\big(\delta\phi^{(2)}(t'_\mathrm{i}) - \delta\phi^{(1)}(t'_\mathrm{i})\big) - \big(\delta\phi^{(2)}(t_\mathrm{i}) - \delta\phi^{(1)}(t_\mathrm{i})\big) = \frac{\Delta E}{2\hbar}\,(\Delta\tau_b - \Delta\tau_a) = \Delta m\, g\, \Delta z\,(t'_\mathrm{i} - t_\mathrm{i})/\hbar$$

Laboratory frame

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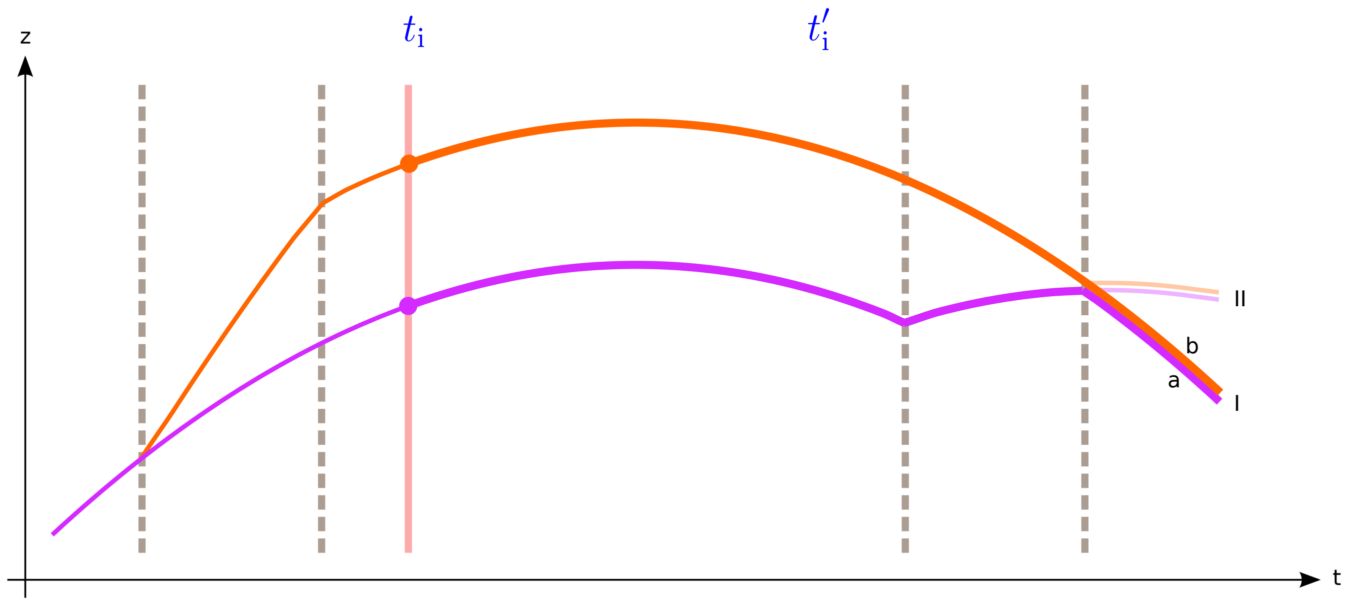

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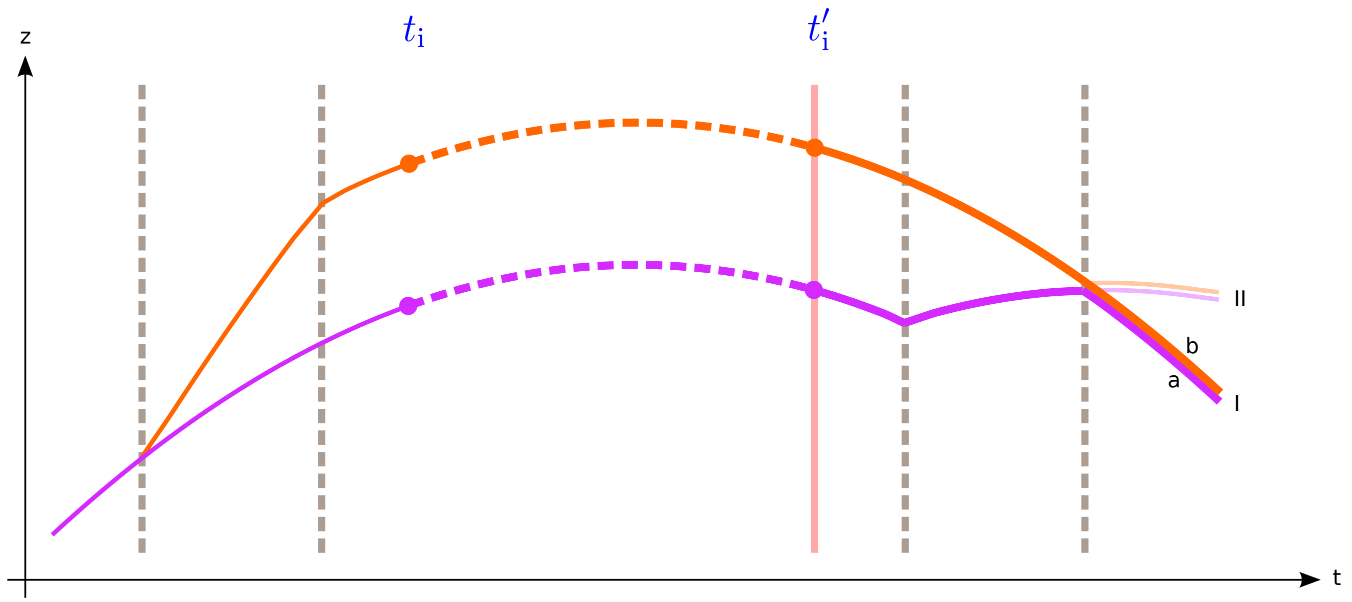

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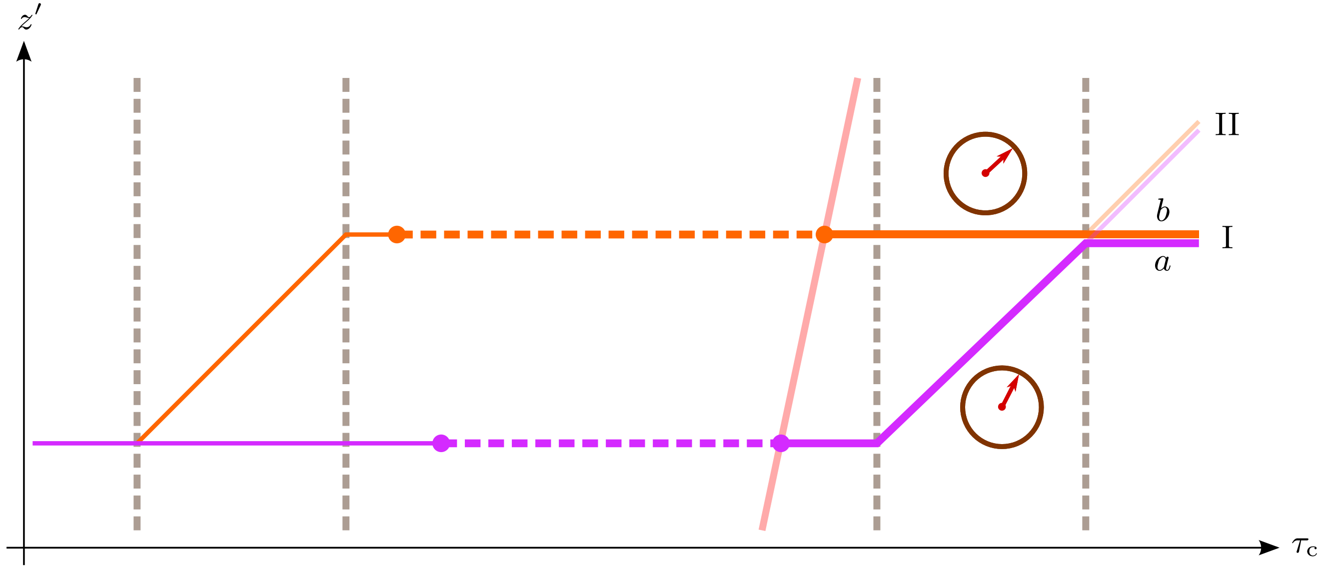
Freely falling frame

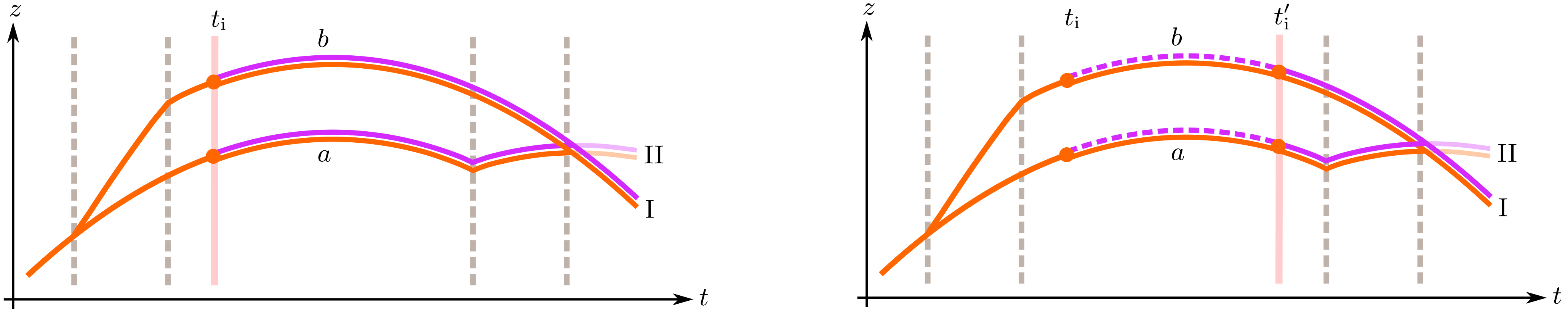
- Relativity of simultaneity: $\Delta\tau_{\mathrm{c}} \approx -v(t)\,\Delta z/c^2 = g\,(t - t_{\mathrm{ap}})\,\Delta z/c^2$



$$\big(\delta\phi^{(2)}(t_{\mathrm{i}}') - \delta\phi^{(1)}(t_{\mathrm{i}}')\big) - \big(\delta\phi^{(2)}(t_{\mathrm{i}}) - \delta\phi^{(1)}(t_{\mathrm{i}})\big) = \frac{\Delta E}{2\hbar}\,(\Delta\tau_b - \Delta\tau_a) = \Delta m\,g\,\Delta z\,(t_{\mathrm{i}}' - t_{\mathrm{i}})/\hbar$$

Laboratory frame

- Compare differential phase-shift measurements for different initialization times:



$$\big(\delta\phi^{(2)}(t'_\mathrm{i}) - \delta\phi^{(1)}(t'_\mathrm{i})\big) - \big(\delta\phi^{(2)}(t_\mathrm{i}) - \delta\phi^{(1)}(t_\mathrm{i})\big) = \frac{\Delta E}{2\hbar}\,(\Delta\tau_b - \Delta\tau_a) = \Delta m\, g\, \Delta z\,(t'_\mathrm{i} - t_\mathrm{i})/\hbar$$

Challenges addressed

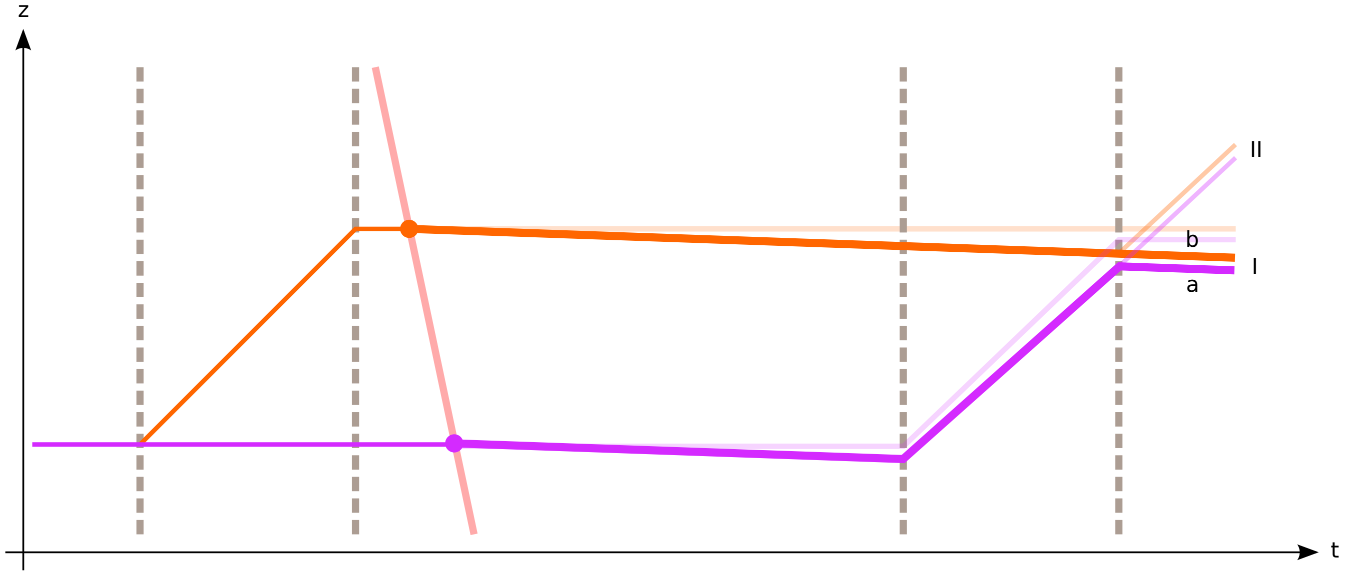
- *Differential phase-shift* measurement → precise measurement, *common-mode* rejection (of noise & systematics)

- Comparing measurements with *different initialization times*
  → sensitive to gravitational redshift + further immunity

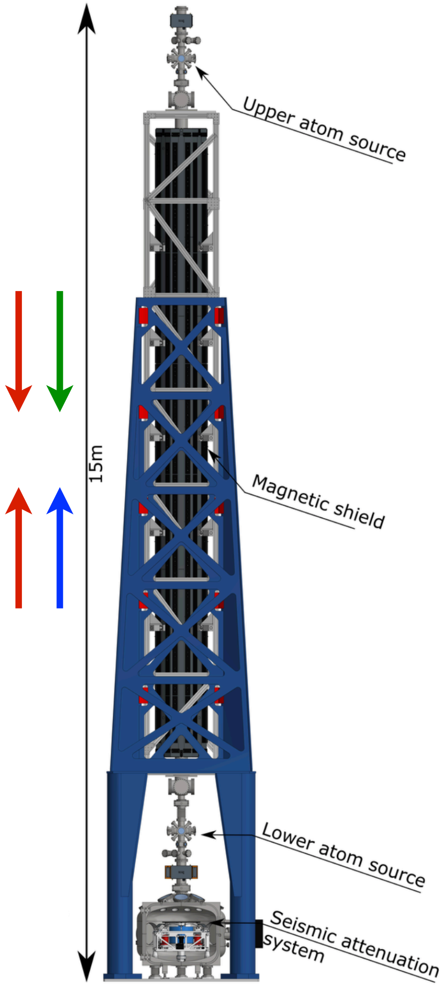
- Almost no recoil from initialization pulse:
  small residual recoil with no impact on gravitational redshift measurement.

  Effect of differential recoil from second pair of Bragg pulses cancels out in doubly differential measurement.

- Residual recoil with no influence on the phase-shift for the excited state:



Feasible implementation



VLBAI (Hannover)

- 10-m atomic fountains operating with Sr, Yb in Stanford & Hannover respectively.
- More than $2\,\mathrm{s}$ of free evolution time.
- Doubly differential phase shift of $3\,\mathrm{mrad}$ for

$$\Delta E/\hbar = \omega_0 \approx 2\pi \times 4 \times 10^2\,\mathrm{THz}$$

$$\Delta z = 1\,\mathrm{cm}$$

$$\Delta t_{\mathrm{i}} = 1\,\mathrm{s}$$

resolvable in a single shot for $N = 10^5$ (shot-noise limited).

Main reference

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

Gravitational Redshift in Quantum-Clock Interferometry

Albert Roura

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https://doi.org/10.1103/PhysRevX.10.021014

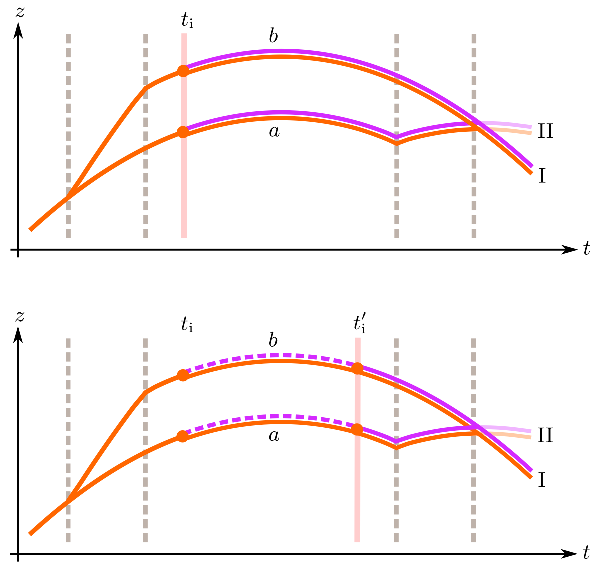
Alternative implementation

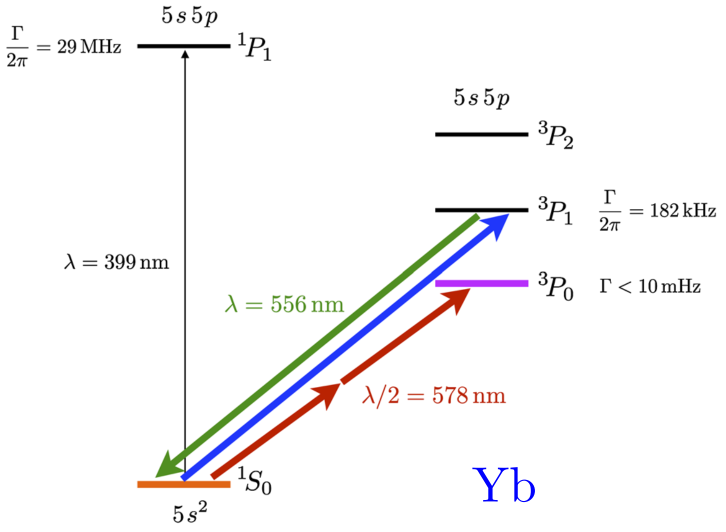
PHYSICAL REVIEW D **104**, 084001 (2021)

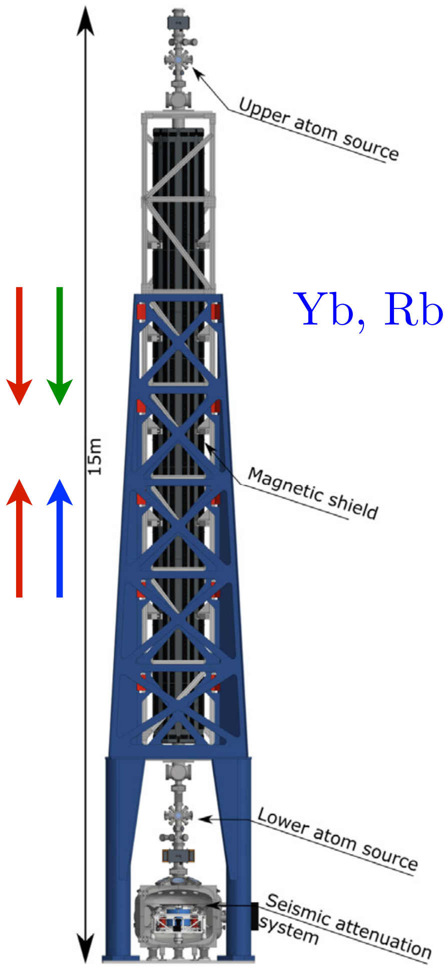
Measuring gravitational time dilation with delocalized quantum superpositions

Albert Roura,[1] Christian Schubert,[2,3] Dennis Schlippert,[2] and Ernst M. Rasel[2]

https://doi.org/10.1103/PhysRevD.104.084001







Alternative implementation

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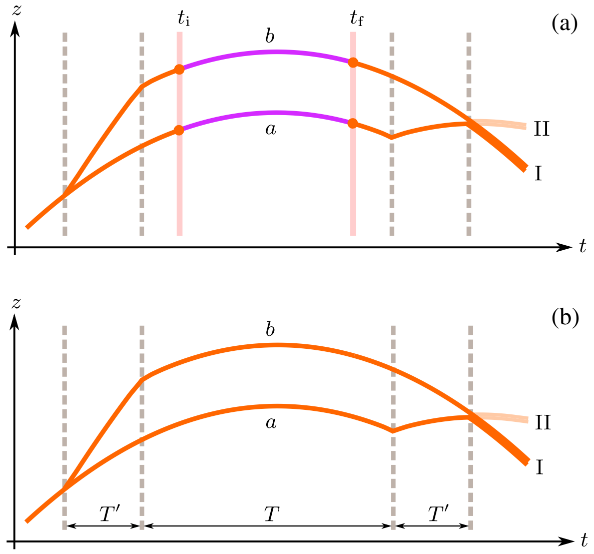

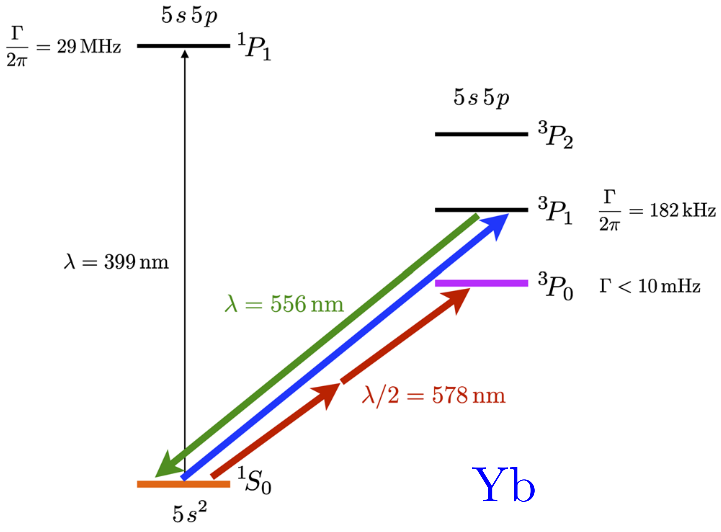

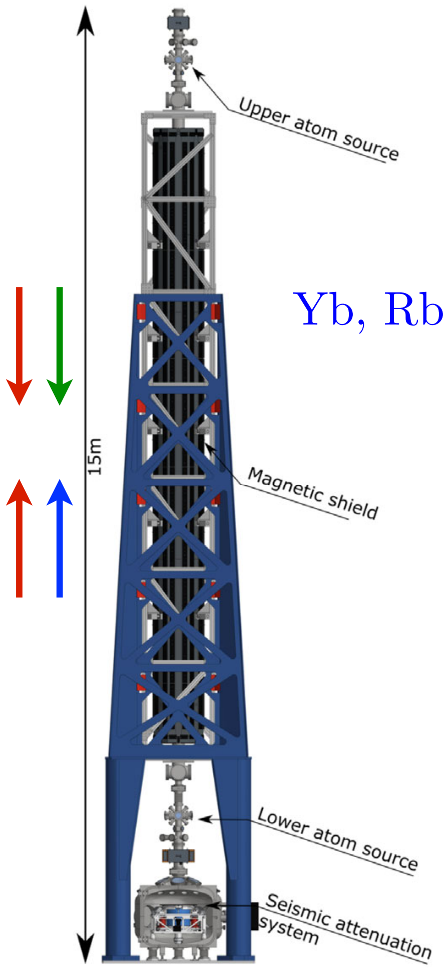

Related references

SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

Interference of clocks: A quantum twin paradox

Sina Loriani[1]*, Alexander Friedrich[2*†], Christian Ufrecht[2], Fabio Di Pumpo[2], Stephan Kleinert[2], Sven Abend[1], Naceur Gaaloul[1], Christian Meiners[1], Christian Schubert[1], Dorothee Tell[1], Étienne Wodey[1], Magdalena Zych[3], Wolfgang Ertmer[1], Albert Roura[2], Dennis Schlippert[1], Wolfgang P. Schleich[2,4,5], Ernst M. Rasel[1], Enno Giese[2]

Loriani *et al.*, *Sci. Adv.* 2019;**5**:eaax8966 4 October 2019

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special relativistic
time dilation

PHYSICAL REVIEW RESEARCH **2**, 043240 (2020)

Atom-interferometric test of the universality of gravitational redshift and free fall

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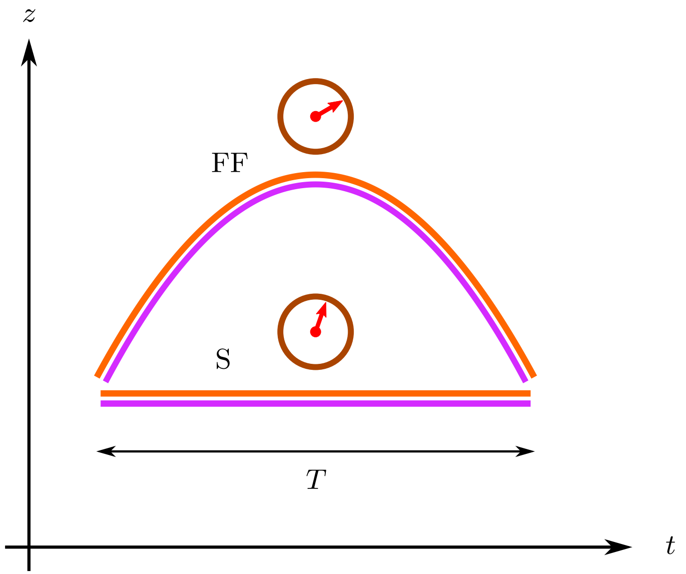
combination of UFF + UGR tests

experimental implementation
less feasible

Atom interferometers as freely falling clocks

Relativistic time dilation for a freely falling clock



- Freely falling clock (FF):

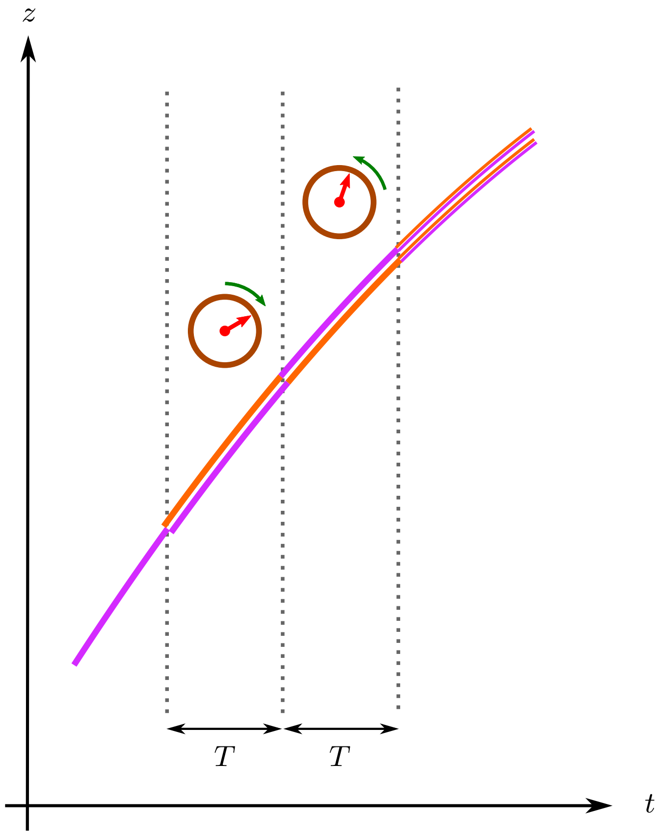
$$\delta\phi = -(\Delta E/\hbar)\left(\left(1 + U_0/c^2\right)T + \frac{1}{24}\frac{g^2T^3}{c^2}\right)$$

- Static clock at constant height (S):

$$\delta\phi = -(\Delta E/\hbar)\left(1 + U_0/c^2\right)T$$

- Natural implementation: compare atomic fountain clock to optical lattice clock.
- BUT accuracy of best atomic fountain clocks insufficient by more than an order of magnitude.

Freely falling clock with internal-state inversion



- Simultaneity hypersurfaces in the lab frame.
  (equal time separation)

- Unbalanced proper times (before and after inversion) due to relativistic time dilation:

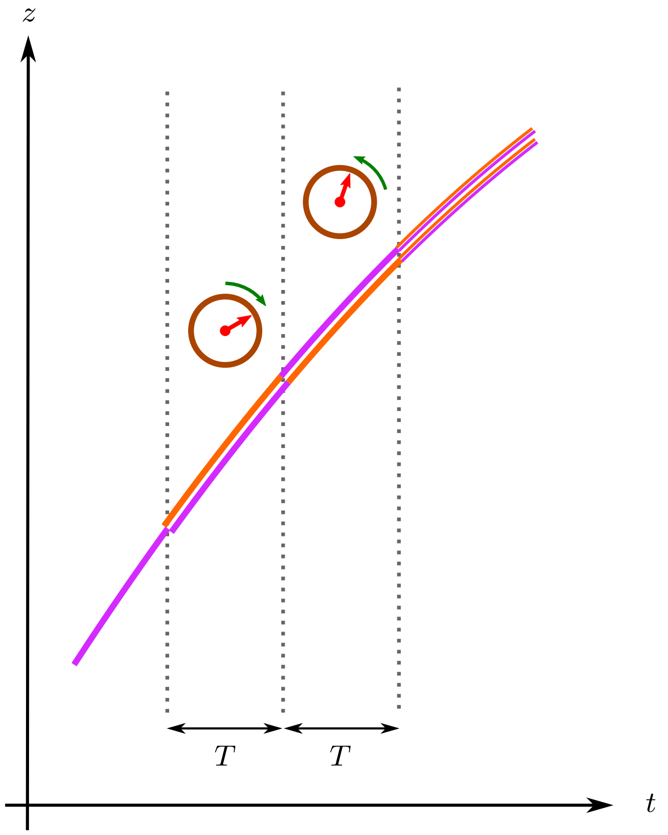
$$\delta\phi = -2\,(\Delta E/\hbar)\left(\mathbf{v}_0 \cdot \mathbf{g}\, T^2 + g^2 T^3\right)/c^2$$

$$\frac{d\tau}{dt} = 1 - \frac{1}{2\,c^2}\left(\frac{d\mathbf{X}}{dt}\right)^2 + \frac{1}{c^2}\,U\left(t,\mathbf{X}\right)$$

special relativistic

gravitational redshift

Freely falling clock with internal-state inversion

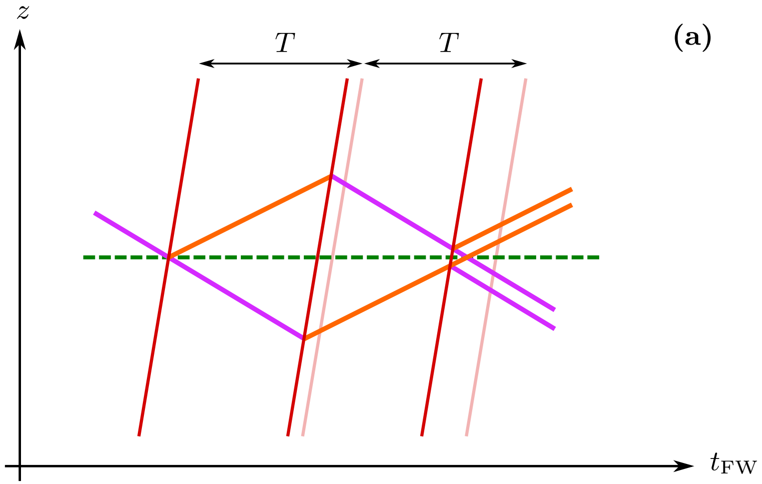


- Possible implementation with *Doppler-free* E2–M1 *two-photon* pulses at $\lambda_2 = 2 \times 698\,\mathrm{nm}$.

- Drawbacks:
  - dedicated high-power laser needed at λ_2
  - residual recoil ($m\,\Delta\mathbf{v} = -\Delta m\,\mathbf{v}$)

- Let us consider atom interferometers based on *single-photon* transitions.

Atom interferometer based on <u>single-photon transitions</u>



- **Freely falling frame** comoving with the *mid-point* world line (Fermi-Walker frame):
  - light rays (laser wave fronts) have fixed slope,
  - shifts due to <u>Doppler effect</u> (*opposite sign* in reversed interferometer) and <u>time dilation</u> (*same sign*).

- Result when ***adding*** up the phase shift for the pair of ***reversed*** interferometers:

$$\left(\delta\phi_{\hat{\mathbf{n}}} + \delta\phi_{-\hat{\mathbf{n}}}\right)/2 = -2\,\frac{\Delta E}{\hbar}\left[\frac{\bar{\mathbf{v}}_0 \cdot \mathbf{g}}{c^2}\,T^2 + \frac{\mathbf{g}^2}{c^2}\,T^3\right] + \delta\phi_{\mathrm{corr}}$$

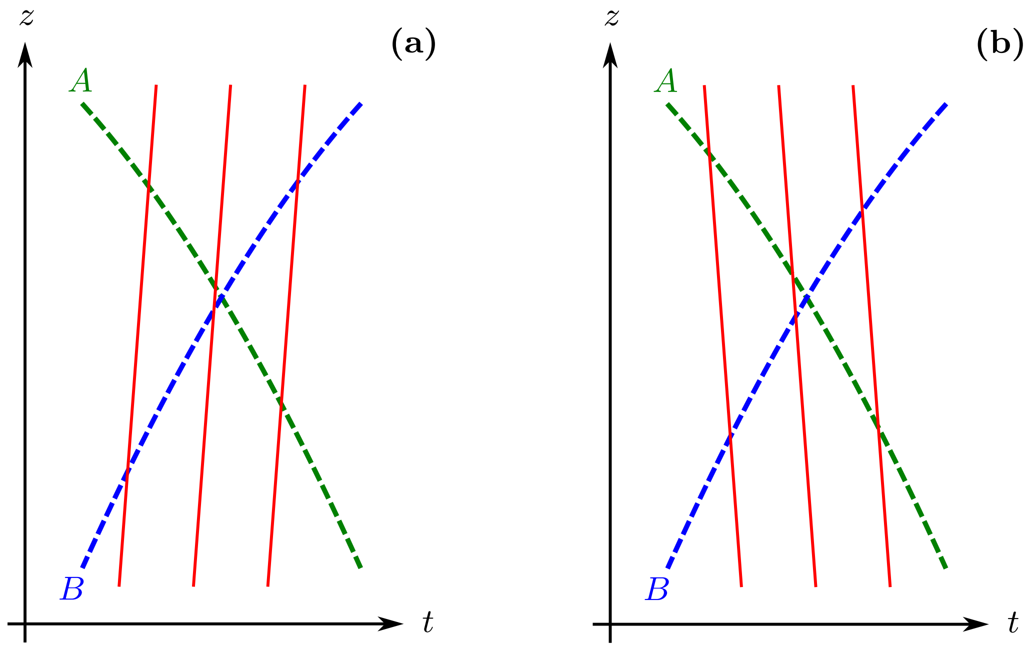
Same result as an ideal **freely falling clock** with *state inversion* at the intermediate time.

Time-dilation measurement with an atom interferometer acting as a **freely falling clock**.

- Uncompensated first-order Doppler contribution cancels out.

- BUT effects of **mirror vibrations** and **laser phase noise** (for reversed interferometers in different shots) do not cancel out → "gradiometric" configuration.

“Gradiometric” configuration



- Differential phase shift between interferometers launched with different velocities (A and B):

$$\delta\phi_A - \delta\phi_B = -2\,(\Delta E/\hbar)\left(\bar{\mathbf{v}}_0^A - \bar{\mathbf{v}}_0^B\right)\cdot \mathbf{g}\,T^2/c^2$$

- Similarly for pair of reversed interferometers:
  (a) and **(b)**

- Comparison between two freely falling clocks.
  (no need for highly stable time reference in lab frame)

Experimental implementation

- Gradiometric configuration in MAGIS-100 with two simultaneous interferometers launched from the top and bottom atom source.

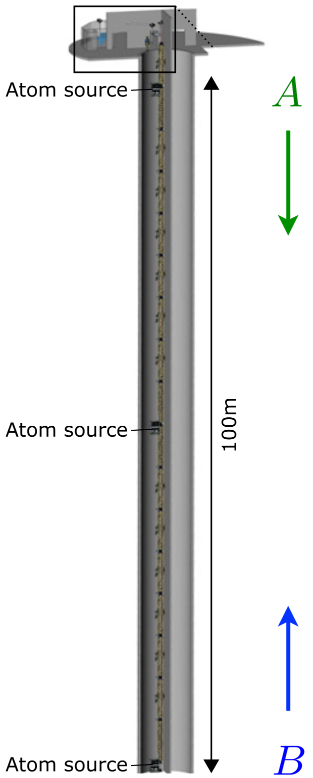
  AOM driven by a stable rf source $\longrightarrow$ second frequency component.

- For $\bar{\mathbf{v}}_0^A = -(20\,\mathrm{m/s})\,\hat{\mathbf{z}}$ and $\bar{\mathbf{v}}_0^B = (40\,\mathrm{m/s})\,\hat{\mathbf{z}}$ respectively, one gets $\delta\phi^A - \delta\phi^B = 35\,\mathrm{rad}$.

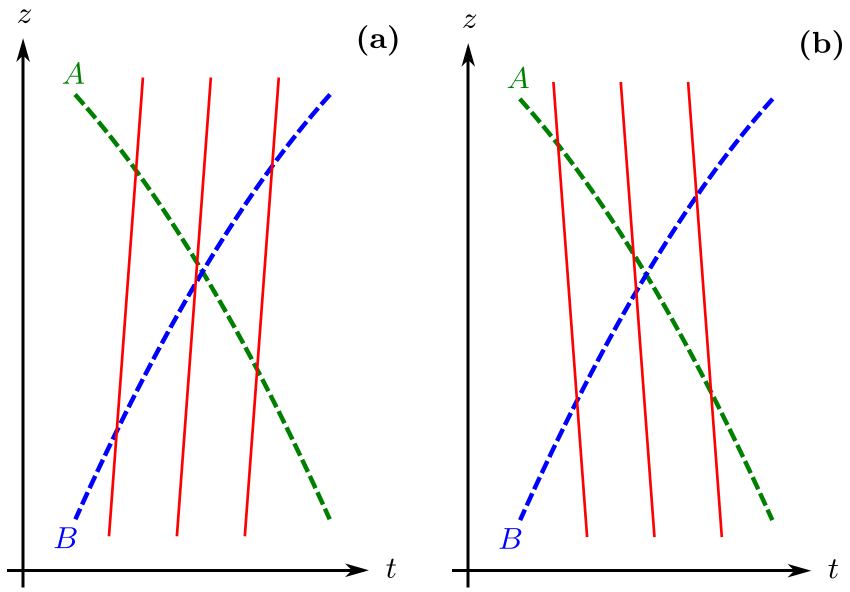
- With $N = 10^5$ detected atoms, a shot-noise-limited sensitivity at the 10^{-5} level can be reached in *a hundred shots*.

- Stanford's 10-m prototype or AION's 10-m fountain could also measure these time dilation effects with about two orders of magnitude lower sensitivity.

Abe *et al.*, *QST* **6**, 044003 (2021)



MAGIS-100



“gradiometric” configuration suppresses laser phase noise and effect of mirror vibrations

$$\delta\phi_A - \delta\phi_B = -2\,(\Delta E/\hbar)\left(\bar{\mathbf{v}}_0^A - \bar{\mathbf{v}}_0^B\right)\cdot \mathbf{g}\,T^2/c^2$$

Main systematic effects

- Effects suppressed when adding up the phase shift for *reversed* interferometers:
  - gravity gradients (co-location at 0.1 mm and 0.1 mm/s level ⟶ 10^{-4} relative uncertainty)
  - rotations (can be compensated with *pivot-point method*)
  - wave-front curvature & light shifts

- Pulse timing requirements: $\Delta T \lesssim 0.1\,\mu\mathrm{s}$ and $\delta \lesssim 300\,\mathrm{Hz}$ ⟶ 10^{-5} relative uncertainty

- Magnetic field inhomogeneities: 3 nT / m ⟶ 10^{-5} relative uncertainty

- Temperature gradients: 2 K / 100 m ⟶ contribution at 10^{-2} level

further improvement through characterization and post-correction

Main reference:

Quantum Sci. Technol. **10** (2025) 025004 https://doi.org/10.1088/2058-9565/ad9e2e

Quantum Science and Technology

PAPER

Atom interferometer as a freely falling clock for time-dilation measurements

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Keywords: atom interferometry, relativistic time dilation, gravitational and relativistic measurements, long-baseline facilities, single-photon clock transition

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Comparison with quantum-clock interferometry

- **Quantum-clock interferometry:** single clock in a *delocalized* quantum *superposition* of two wave packets experiencing different gravitational time dilation.

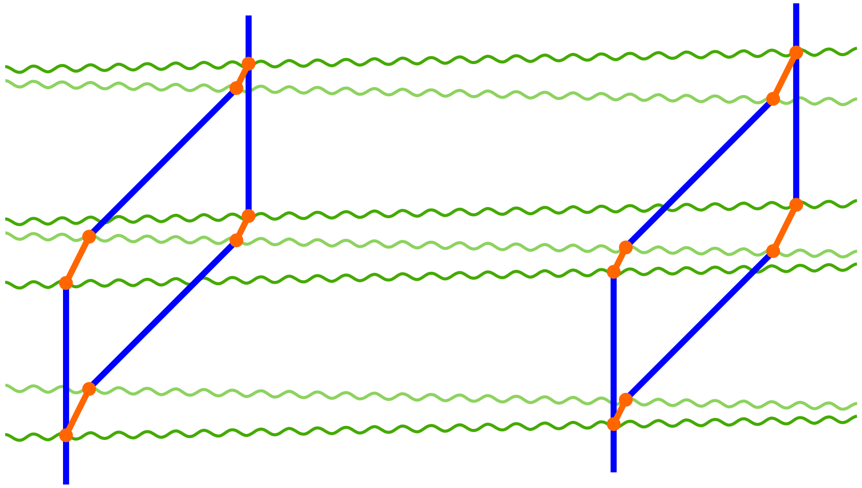
- **Scheme just discussed:** each atom interferometer acts as a *freely falling clock*; comparison between two independent clocks in the "gradiometric" configuration.

- The term **"clock atom interferometry"** is often employed for atom interferometers where the *diffraction pulses* drive a *single-photon transition* between the two internal states (*clock states*).

(alternative with pulses involving several *collinear* frequency components also possible)

GW detection & search of ultralight dark matter

- *Single-baseline GW antenna* and *detection of ultralight dark matter* with a gradiometric configuration of atom interferometers based on pulses driving single-photon transitions (*clock atom interferometry*).
- *Co-propagating* laser wave fronts and pulse envelope ⟶ immunity to phase noise (long baselines)



- Effects of Earth's gravitational field ⟶ consider *freely falling frame* for each interferometer.

Additional shifts of laser wave fronts due to **effect of GW** on *laser propagation* over the long baseline
⟶ can be added **perturbatively** to larger shifts due to *retardation effects* and *time dilation*,
similarly for small oscillations of *internal energy difference* due to **ultralight DM field**

Thank you for your attention.

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