Relativistic effects in macroscopically delocalized quantum superpositions

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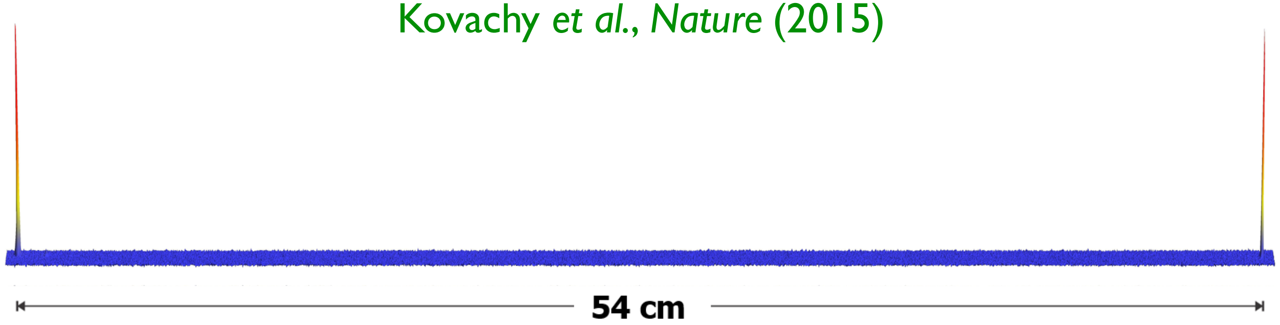
DLR

- Macroscopically delocalized quantum superpositions:
  coherent superposition of spatially separated atomic wave packets.

Kovachy *et al.*, *Nature* (2015)



- Differences in dynamics of superposition components entirely Newtonian.

- Same relativistic effects on superposition components (e.g. atomic clocks).

- Goal (QM + GR): experiment with general relativistic effects acting non-trivially on the quantum superposition.

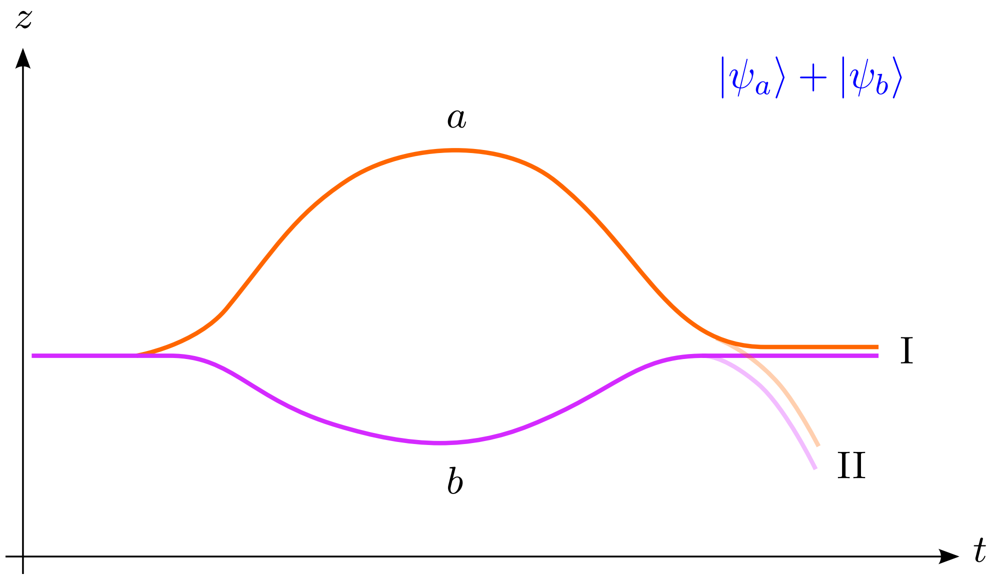
Proper time as *which-way* information

- 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)



Proper time as *which-way* information

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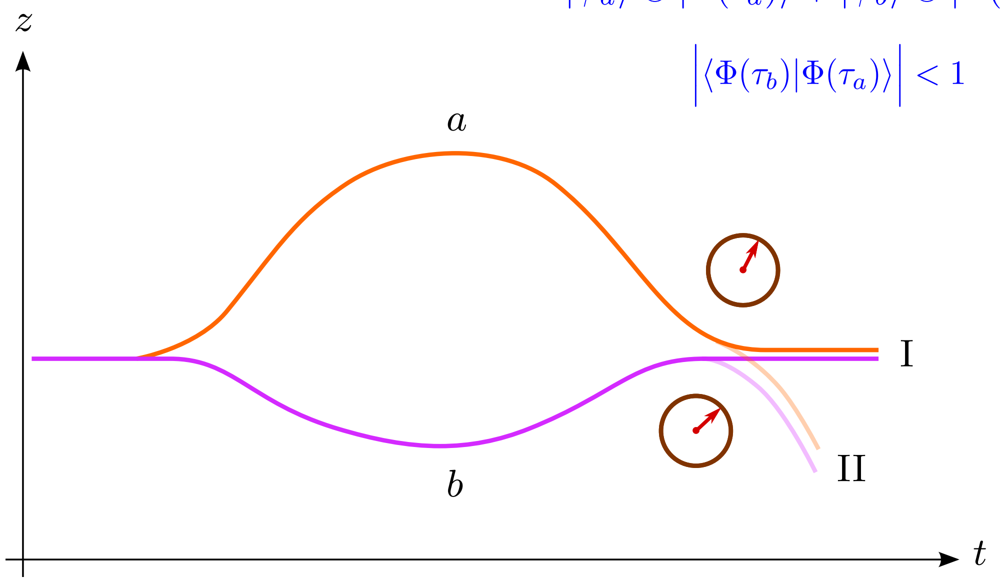
$$|\psi_a\rangle \otimes |\Phi(\tau_a)\rangle + |\psi_b\rangle \otimes |\Phi(\tau_b)\rangle$$

$$\left|\langle\Phi(\tau_b)|\Phi(\tau_a)\rangle\right| < 1$$

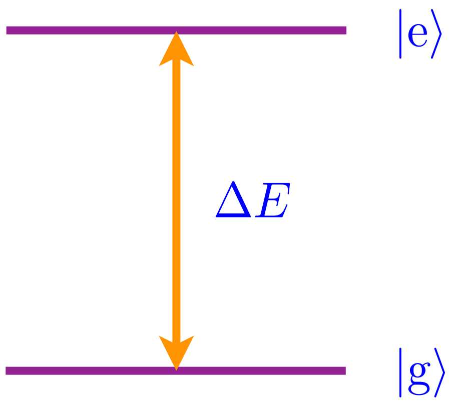


Outline

1. Key elements of quantum-clock interferometry
2. Major challenges in quantum-clock interferometry
3. Doubly differential gravitational-redshift measurement
4. Spacetime curvature and proper-time difference
5. Conclusions

Key elements of quantum-clock interferometry

Quantum clock model



- *Initialization* pulse:

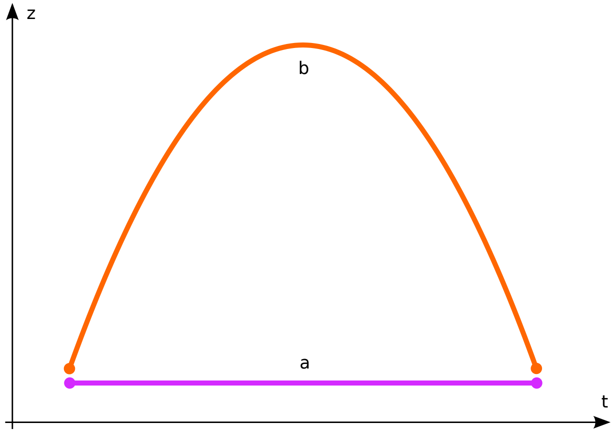
$$|\mathrm{g}\rangle \;\rightarrow\; \big|\Phi(0)\big\rangle = \frac{1}{\sqrt{2}}\Big(|\mathrm{g}\rangle + i\,e^{i\varphi}|\mathrm{e}\rangle\Big)$$

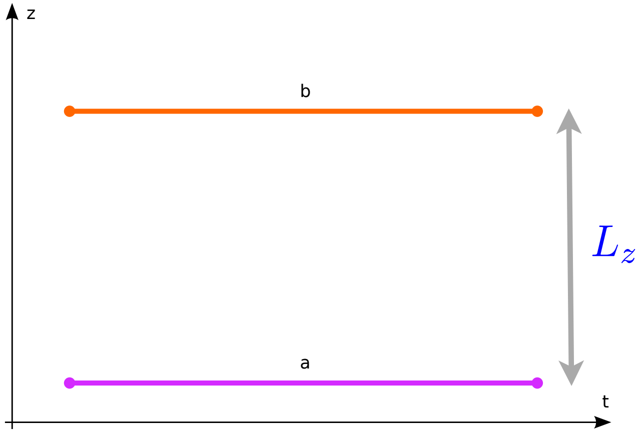
- Evolution:

$$\big|\Phi(\tau)\big\rangle \propto \frac{1}{\sqrt{2}}\Big(|\mathrm{g}\rangle + i\,e^{i\varphi}e^{-i\Delta E\,\tau/\hbar}|\mathrm{e}\rangle\Big)$$

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

- Comparison of independent clocks (after read-out pulse):



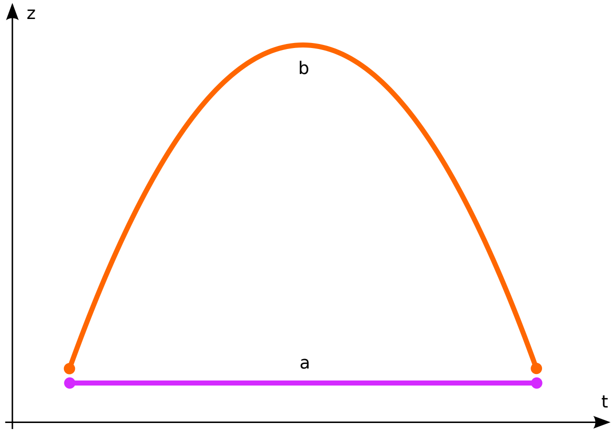


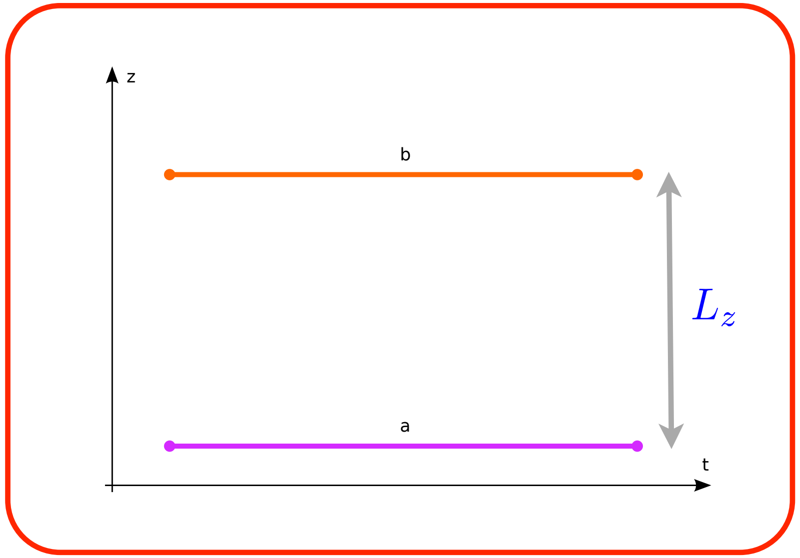
$$\Delta\tau_b - \Delta\tau_a \approx \left(g\, L_z/c^2\right) \Delta t$$

for optical *atomic clocks*

$$\Delta E \sim 1\,\mathrm{eV} \qquad L_z \sim 1\,\mathrm{cm}$$

- Comparison of independent clocks (after read-out pulse):





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for optical *atomic clocks*

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- Theoretical description of the clock:

  - two-level atom (internal state):

$$\hat{H} = \hat{H}_1 \otimes |\mathrm{g}\rangle\langle\mathrm{g}| + \hat{H}_2 \otimes |\mathrm{e}\rangle\langle\mathrm{e}|$$

$$m_1 = m_\mathrm{g}$$

$$m_2 = m_\mathrm{g} + \Delta m$$

$$\Delta m = \Delta E / c^2$$

  - classical action for COM motion:

$$S_n\big[x^\mu(\lambda)\big] = -m_n c^2 \int d\tau = -m_n c \int d\lambda \sqrt{-g_{\mu\nu} \frac{dx^\mu}{d\lambda} \frac{dx^\nu}{d\lambda}} \qquad (n = 1, 2)$$

free fall

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$$m_2 = m_{\mathrm{g}} + \Delta m$$

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  - classical action for COM motion:

$$S_n\big[x^\mu(\lambda)\big] = -m_n c^2 \int d\tau \approx \int_{t_0}^{t} dt' \left(-m_n\, c^2 + \frac{1}{2} m_n \dot{\mathbf{x}}^2 - m_n\, U(t', \mathbf{x}) \right)$$

free fall

- Theoretical description of the clock:

  - two-level atom (internal state):

$$\hat{H} = \hat{H}_1 \otimes |\mathrm{g}\rangle\langle\mathrm{g}| + \hat{H}_2 \otimes |\mathrm{e}\rangle\langle\mathrm{e}|$$

$$m_1 = m_\mathrm{g}$$

$$m_2 = m_\mathrm{g} + \Delta m$$

$$\Delta m = \Delta E / c^2$$

  - classical action for COM motion:

$$S_n\big[x^\mu(\lambda)\big] = -m_n c^2 \int d\tau - \int d\tau\, V_n(x^\mu) \qquad (\, n = 1, 2\,)$$

including external forces

Atom interferometry in curved spacetime (including relativistic effects)

- Wave-packet evolution in terms of
  - *central trajectory* (satisfies classical e.o.m.) $X^\mu(\lambda)$
  - *centered* wave packet $\big|\psi_{\mathrm{c}}^{(n)}(\tau_{\mathrm{c}})\big\rangle$

$\Delta p/m \ll c \qquad \Delta x \ll \ell$ ← curvature radius

- Metric in *Fermi-Walker* coordinates: $X^\mu(\tau_c) = (c\,\tau_c\,,\mathbf{0})$

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu = g_{00}\, c^2 d\tau_c^2 + 2\, g_{0i}\, c\, d\tau_c\, dx^i + g_{ij}\, dx^i dx^j$$

$$g_{00} = -\left(1 + \delta_{ij}\, a^i(\tau_c)\, x^j / c^2\right)^2 - R_{0i0j}(\tau_c, \mathbf{0})\, x^i x^j + O\left(|\mathbf{x}|^3\right)$$

$$g_{0i} = -\frac{2}{3} R_{0jik}(\tau_c, \mathbf{0})\, x^j x^k + O\left(|\mathbf{x}|^3\right)$$

$$g_{ij} = \delta_{ij} - \frac{1}{3} R_{ikjl}(\tau_c, \mathbf{0})\, x^k x^l + O\left(|\mathbf{x}|^3\right)$$

- Expanding the action for the *centered wave packet*:

$$S_n[\mathbf{x}(t)] \approx \int d\tau_c \left[-m_n c^2 - V_n(\tau_c, \mathbf{0}) + \frac{m_n}{2} \mathbf{v}^2 - \frac{1}{2} \mathbf{x}^{\mathrm{T}} \left(\mathcal{V}^{(n)}(\tau_c) - m_n \Gamma(\tau_c) \right) \mathbf{x} - V^{(n)}_{\text{anh.}}(\tau_c, \mathbf{x}) \right]$$

$\Delta p / m \ll c$ $\Delta x \ll \ell$ ← curvature radius

$$\mathcal{V}^{(n)}_{ij}(\tau_c) = \partial_i \partial_j V_n(\tau_c, \mathbf{x})\big|_{\mathbf{x}=\mathbf{0}}$$

Comoving frame:

$$X^\mu(\tau_c) = \big(c\,\tau_c\,,\mathbf{0}\big)$$

$$\hat{H}_n = m_n c^2 + V_n(\tau_c,\mathbf{0}) + \hat{H}_c^{(n)}$$

- Wave-packet evolution: $\big|\psi^{(n)}(\tau_c)\big\rangle = e^{i\,\mathcal{S}_n/\hbar}\,\big|\psi_c^{(n)}(\tau_c)\big\rangle$
  - *propagation phase*

$$\mathcal{S}_n = -\int_{\tau_1}^{\tau_2} d\tau_c\,\big(m_n c^2 + V_n(\tau_c,\mathbf{0})\big)$$

  - *centered wave packet*

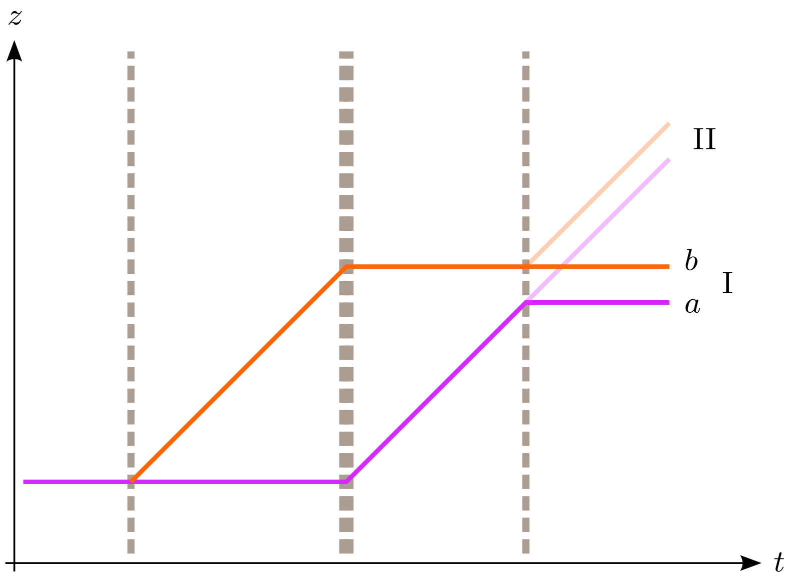
$$i\hbar\,\frac{d}{d\tau_c}\big|\psi_c^{(n)}(\tau_c)\big\rangle = \hat{H}_c^{(n)}\,\big|\psi_c^{(n)}(\tau_c)\big\rangle$$

$$\hat{H}_c^{(n)} = \frac{1}{2m_n}\,\hat{\mathbf{p}}^2 + \frac{1}{2}\,\hat{\mathbf{x}}^{\mathrm{T}}\Big(\mathcal{V}^{(n)}(\tau_c) - m_n\Gamma(\tau_c)\Big)\,\hat{\mathbf{x}}$$

$$\mathcal{V}_{ij}^{(n)}(\tau_c) = \partial_i\partial_j V_n(\tau_c,\mathbf{x})\big|_{\mathbf{x}=\mathbf{0}}$$

gravity-gradient tensor

- Full interferometer (including *laser kicks*):



propagation + *laser* phases

$$|\psi_{\mathrm{I}}\rangle = \frac{1}{2}\left(e^{i\phi_a} + e^{i\phi_b}\right)|\psi_{\mathrm{c}}\rangle$$

- Detection *probability* at the *exit port(s)*:

$$\langle\psi_{\mathrm{I}}|\psi_{\mathrm{I}}\rangle = \frac{1}{2}\left(1 + \cos\delta\phi\right)$$

- *Phase shift*: $\delta\phi = \phi_b - \phi_a + \delta\phi_{\mathrm{sep}}$

For further details:

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

Gravitational Redshift in Quantum-Clock Interferometry

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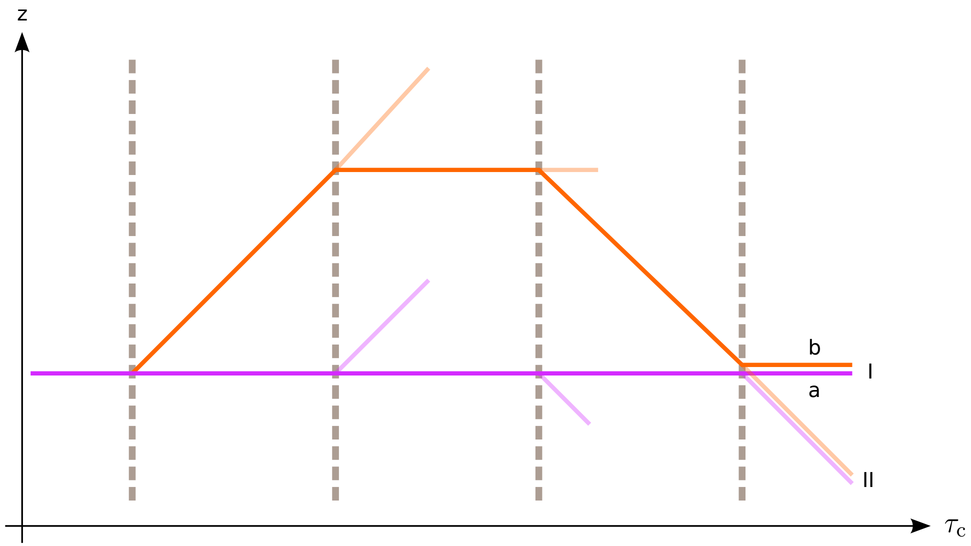
- *Relativistic* description of atom interferometry in *curved spacetime*.
- Including *external forces* and even *guiding potentials*.
- *Relativistic* interpretation of the *separation phase* in open interferometers.

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 $(v_{\text{rec}}/c) \sim 10^{-10}$)

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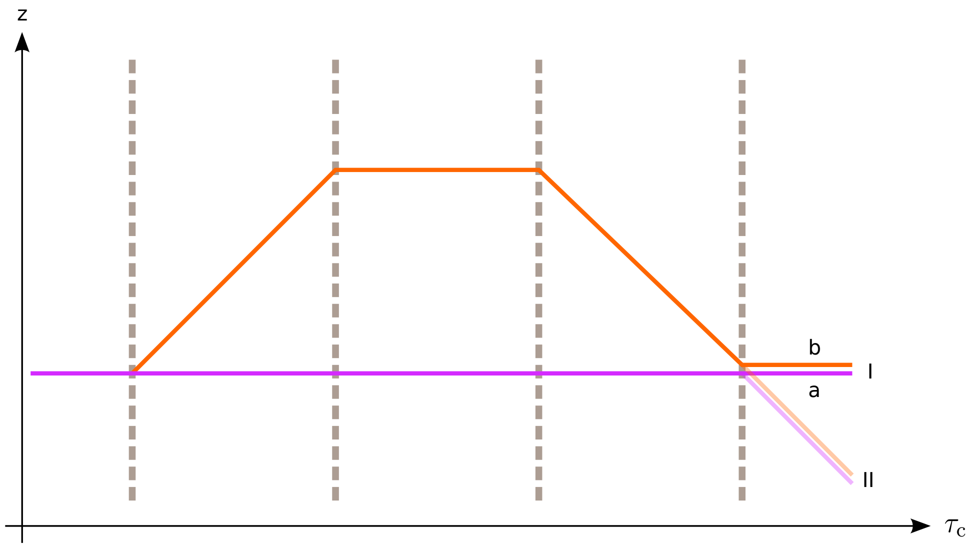

Ramsey-Bordé interferometer

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

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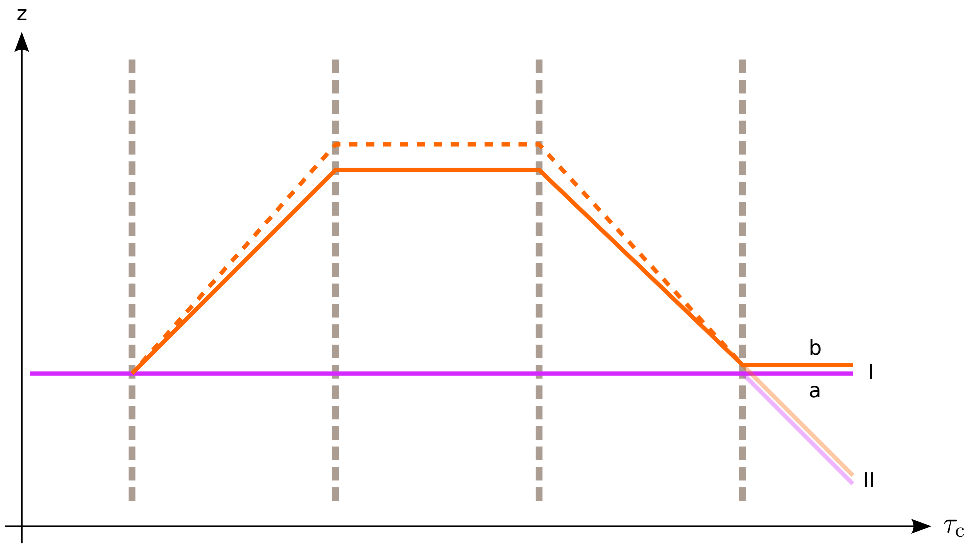
Differential recoil

- Different recoil velocities → different central trajectories:



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

- 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:

$$\langle\Psi_{\mathrm{I}}|\Psi_{\mathrm{I}}\rangle = \frac{1}{2} + \frac{1}{2}\Big|\langle\Phi(\tau_b)|\Phi(\tau_a)\rangle\Big| \cos\delta\phi \qquad \Big|\langle\Phi(\tau_b)|\Phi(\tau_a)\rangle\Big| = \cos\left(\frac{\Delta E}{2\hbar}(\tau_b - \tau_a)\right)$$

- Small effect for feasible parameter range:

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

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

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

Small visibility changes

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

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

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

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Doubly differential gravitational-redshift measurement

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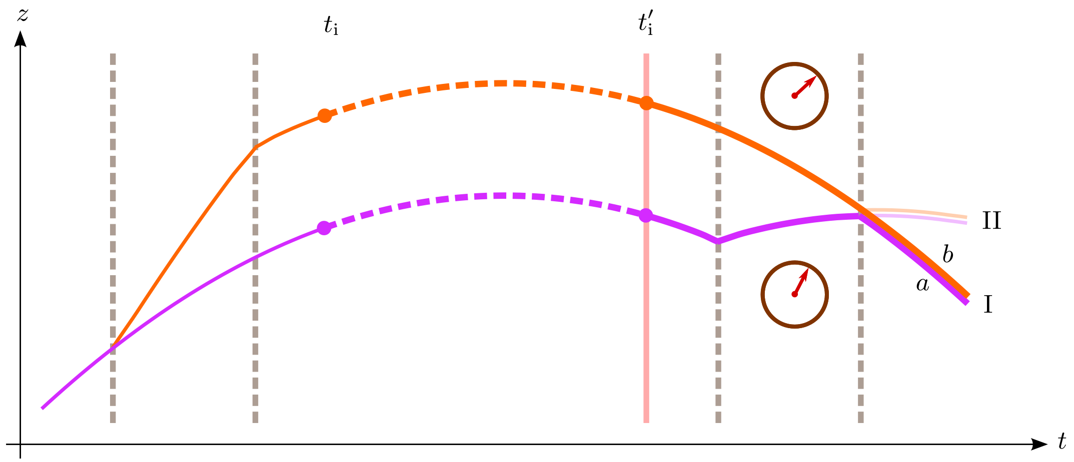
Gravitational Redshift in Quantum-Clock Interferometry

Albert Roura

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):

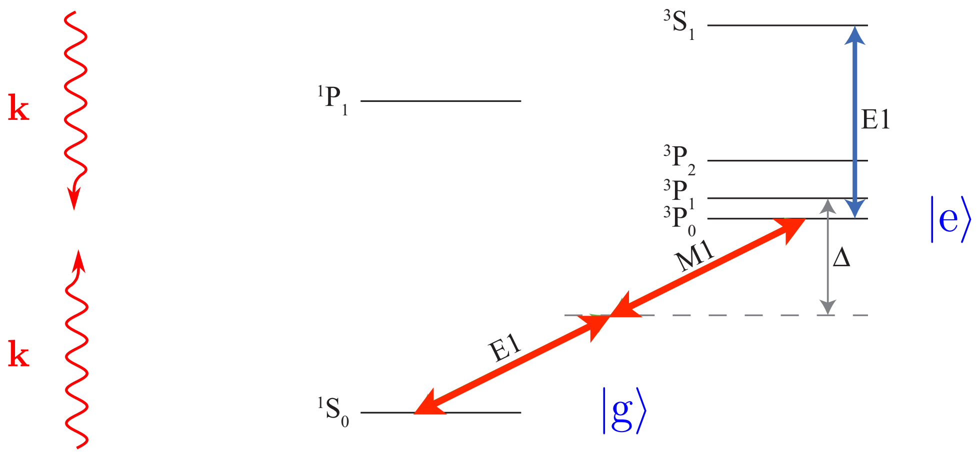
$$
\begin{aligned}
\langle \Psi_\mathrm{I} | \Psi_\mathrm{I} \rangle &= \frac{1}{2} \left(\langle \Psi_\mathrm{I}^{(1)} | \Psi_\mathrm{I}^{(1)} \rangle + \langle \Psi_\mathrm{I}^{(2)} | \Psi_\mathrm{I}^{(2)} \rangle \right) \\
&= \frac{1}{4} \left(1 + \cos \delta\phi^{(1)} \; + \; 1 + \cos \delta\phi^{(2)}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

- 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* (2014)

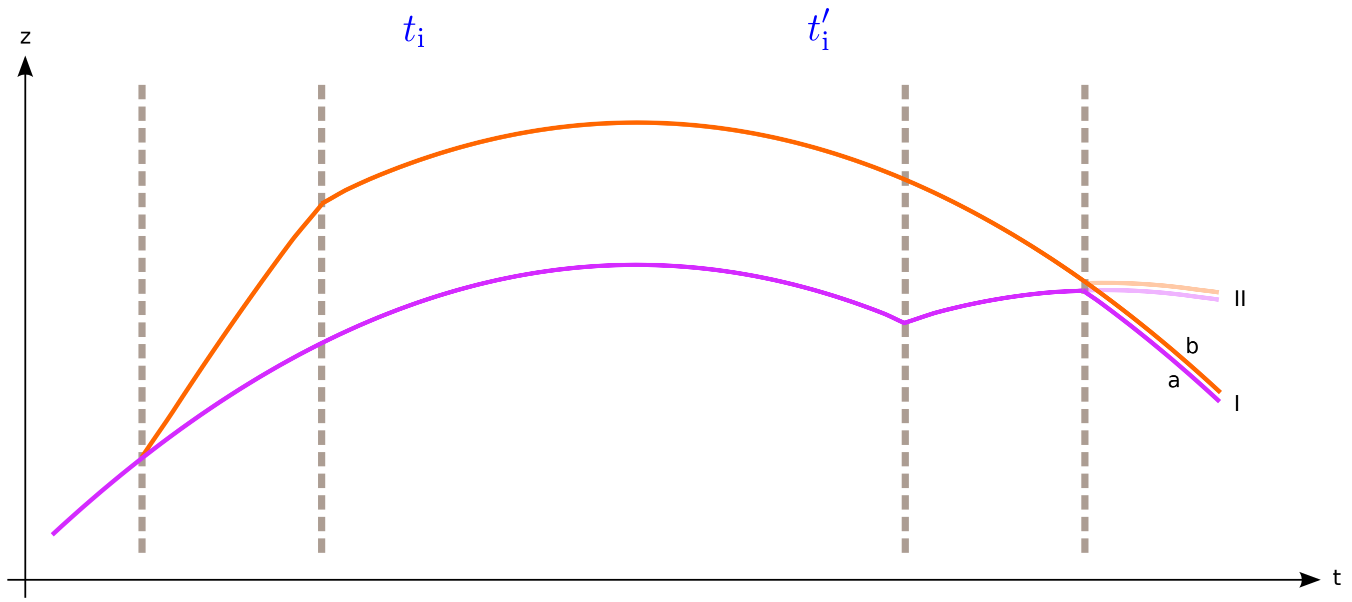
- Two-photon process resonantly connecting the two clock states.

- 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:



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

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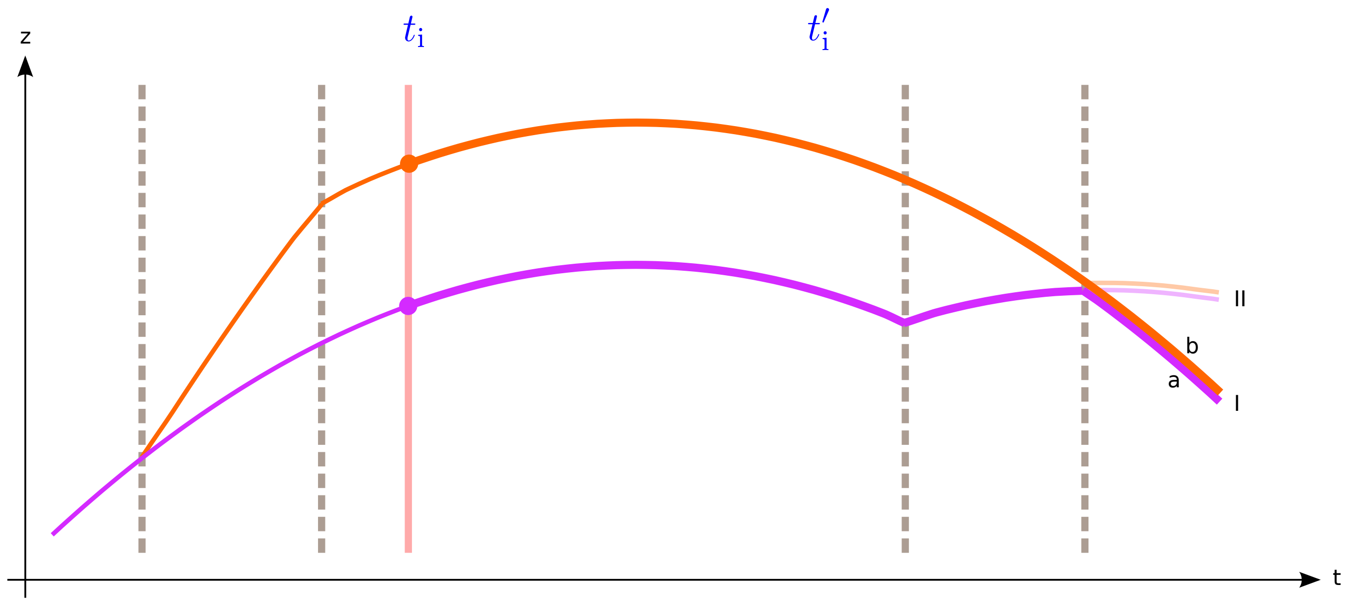

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Laboratory frame

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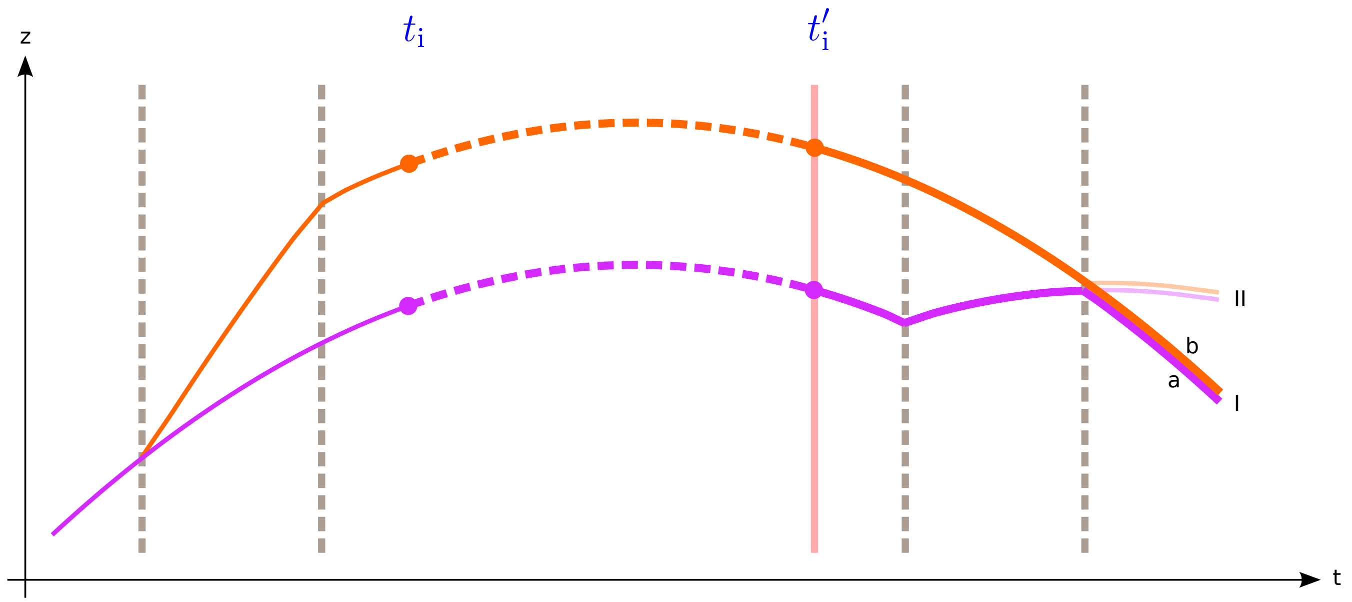

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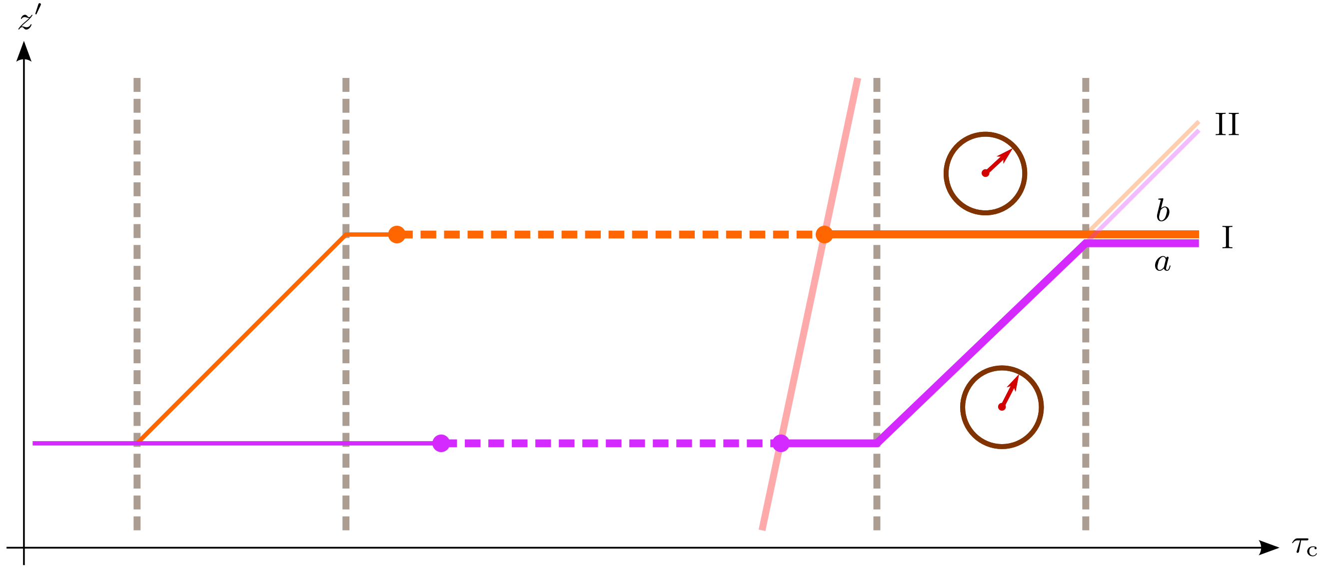
Freely falling frame

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



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

Challenges addressed

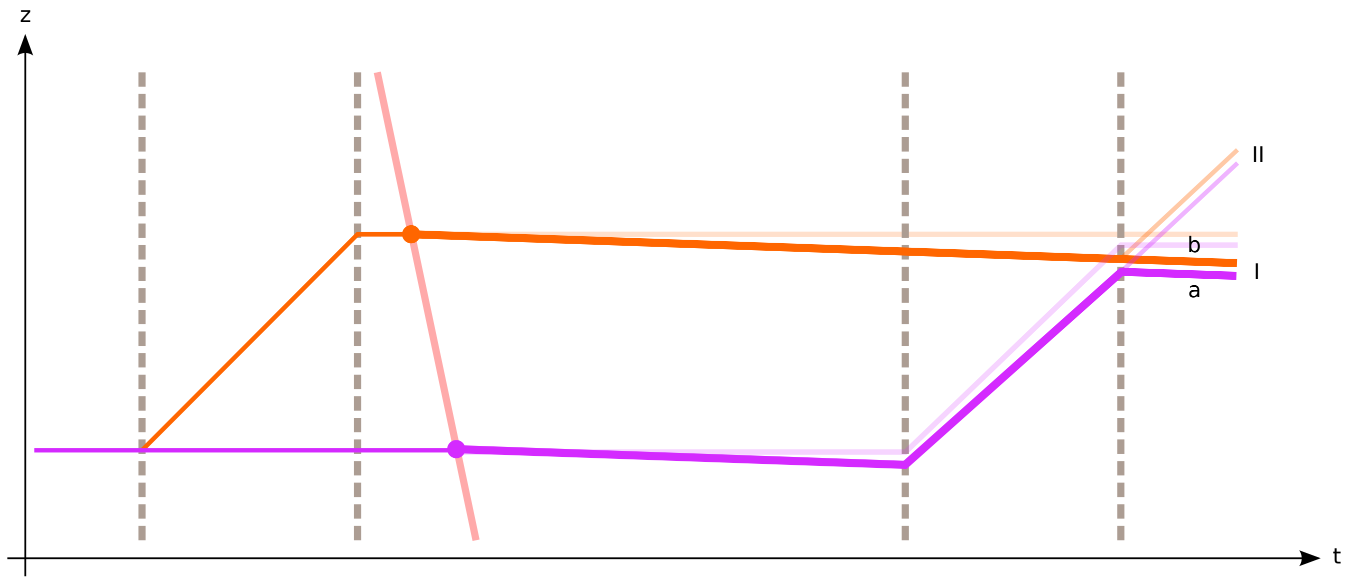
- *Differential phase-shift* measurement → precise measurement, *common-mode* rejection (of noise & systematics)

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

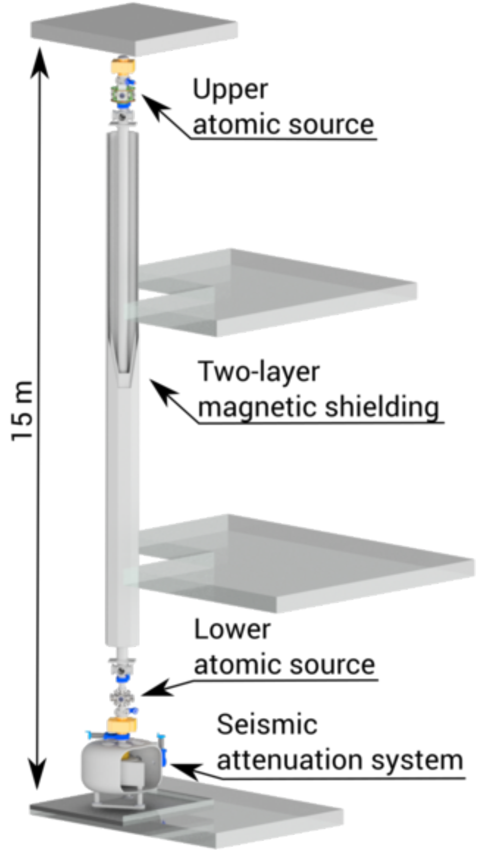
- Almost no recoil from initialization pulse:
  small residual recoil with no impact on gravitational redshift measurement.

  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).

Alternative implementation

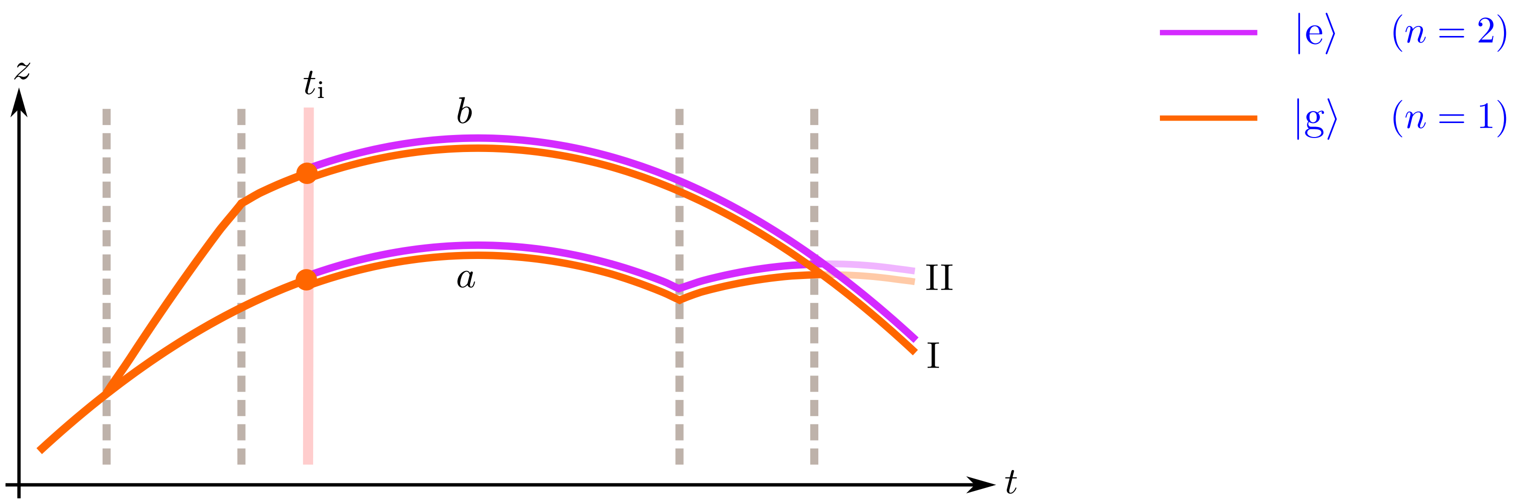
Demanding requirements on the atom optics

- Main challenge: last pair of laser pulses should diffract both internal states efficiently.

- Two possibilities:
  - Bragg diffraction at the magic wavelength ⟶ very demanding requirements on *laser power*
  - Combination of single-photon transitions ⟶ higher *complexity*, *fermionic* isotopes far from *maturity*

- Look for an alternative scheme involving *simple atom optics* with milder requirements on *laser power* that could be implemented at the VLBAI facility.

Quantum-clock interferometry



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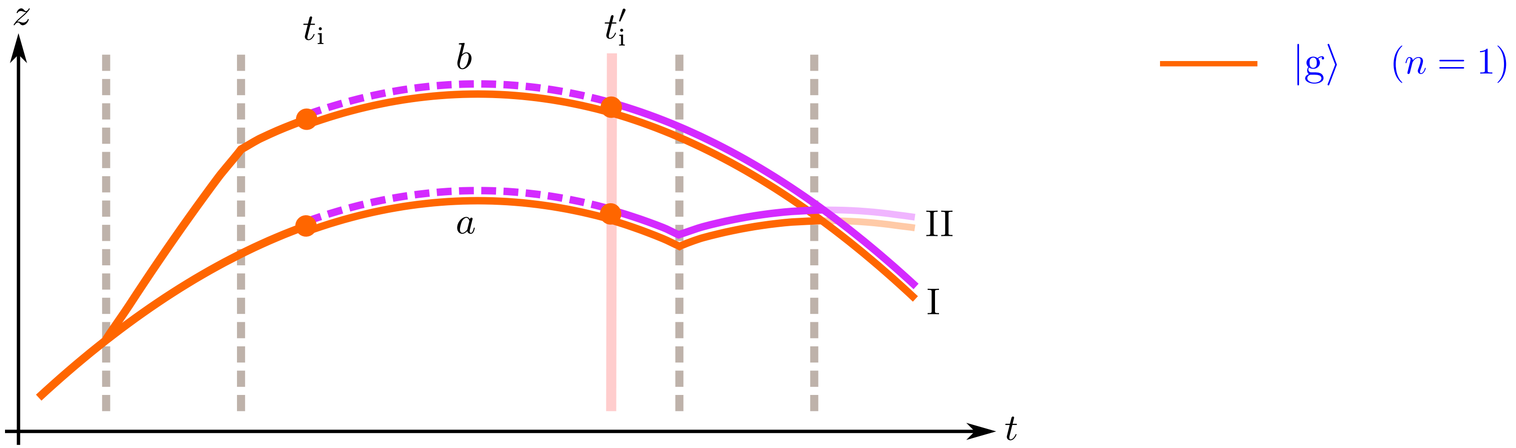
doubly differential measurement

Quantum-clock interferometry



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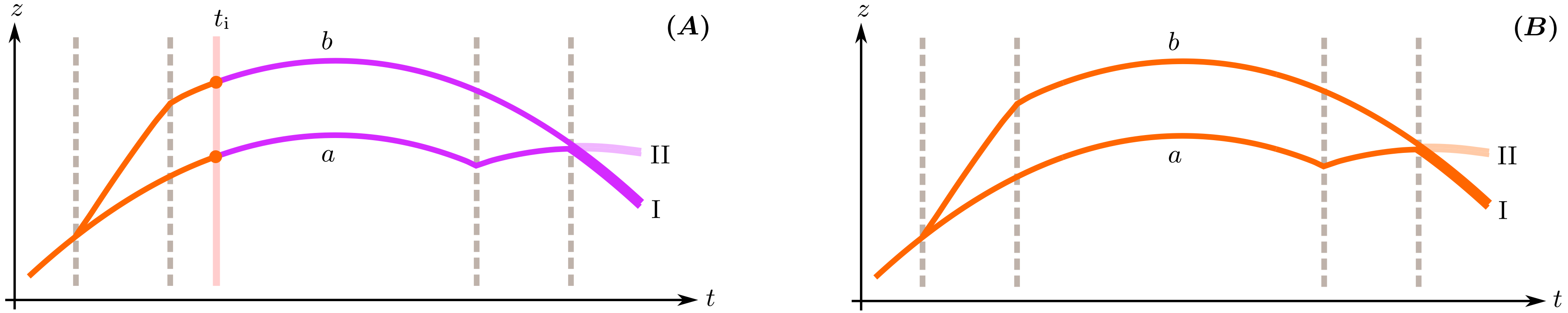
doubly differential measurement

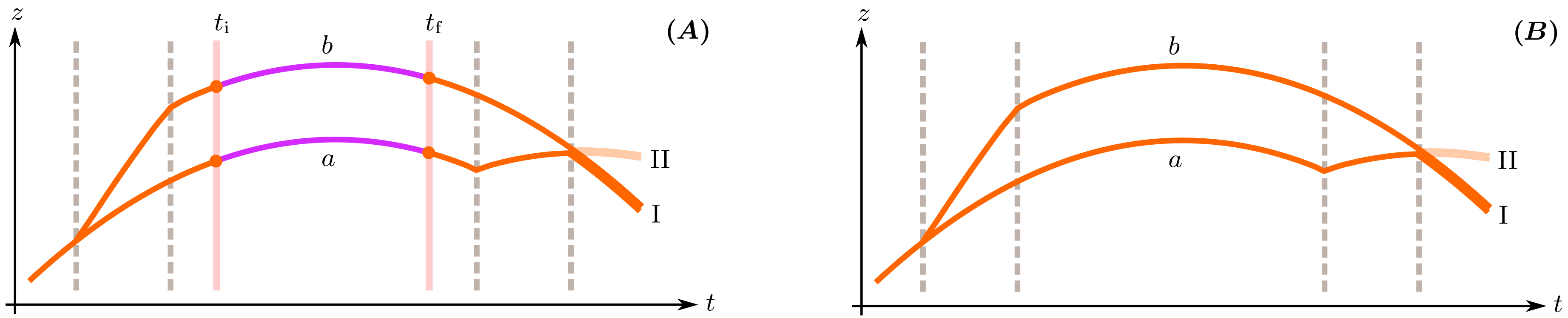
Alternative interferometry scheme



- Differential phase shift between the two shots directly sensitive to gravitational time dilation:

$$\delta\phi_A - \delta\phi_B = -\Delta m\, c^2\, (\Delta\tau_b - \Delta\tau_a)/\hbar = -\Delta m\, g\, \Delta z\, (t_\mathrm{f} - t_\mathrm{i})/\hbar$$

Alternative interferometry scheme



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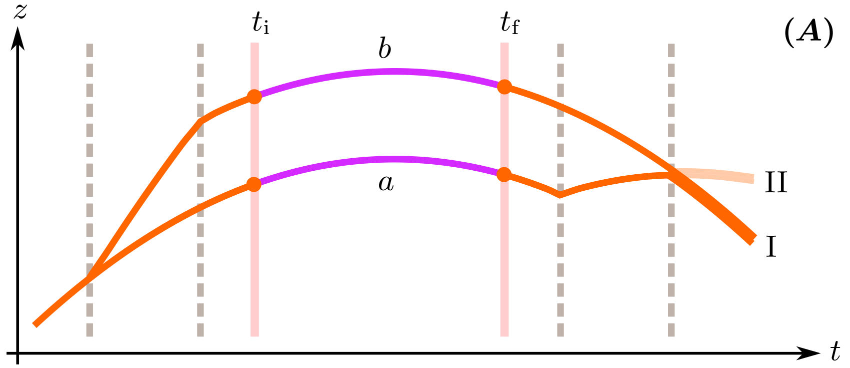
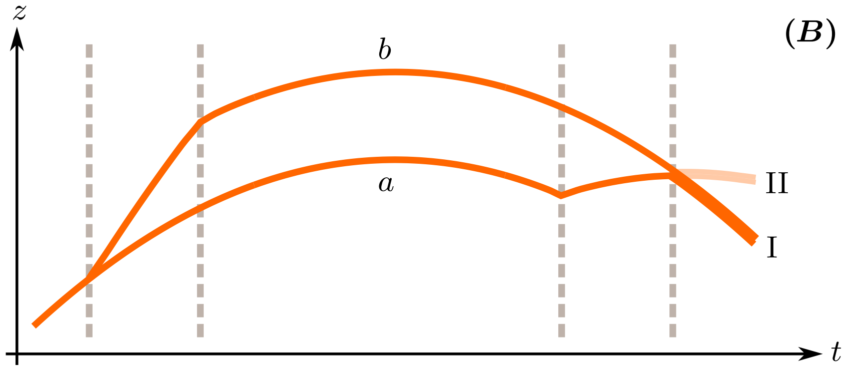
Alternative interferometry scheme



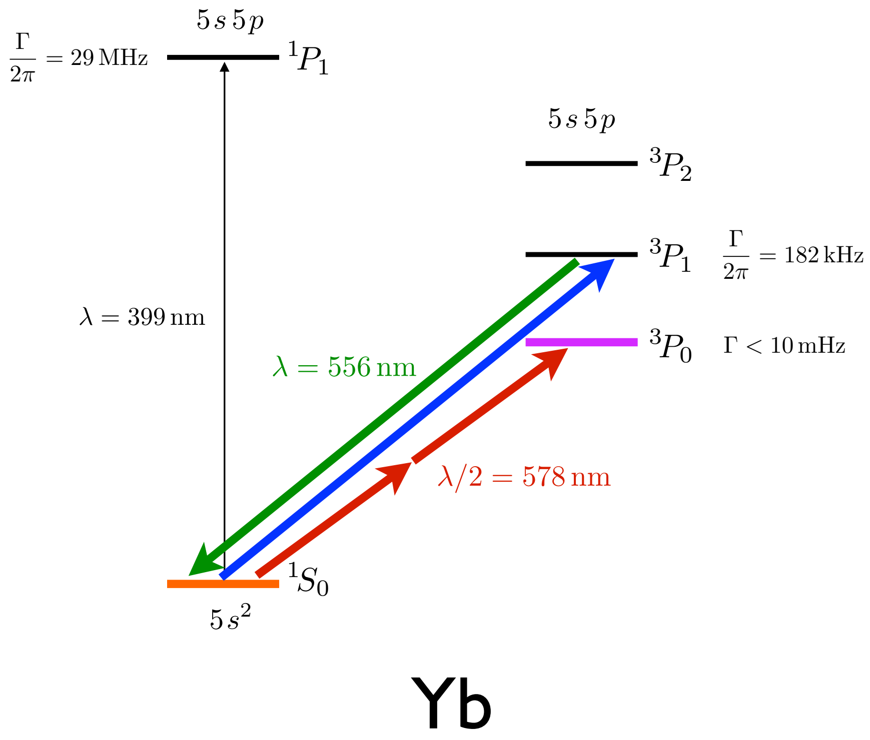


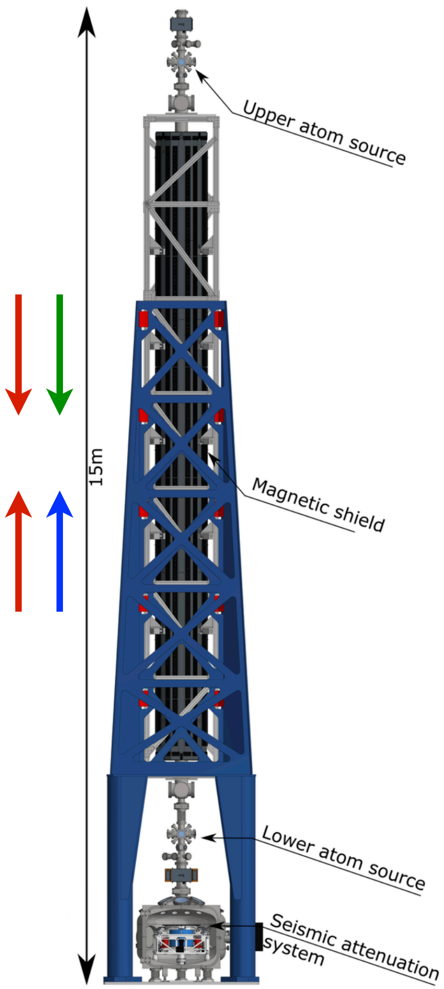
- Test of UGR with a delocalized quantum superposition (*dilaton* model):

$$\delta\phi_A - \delta\phi_B = -\Delta m\, c^2\, (\Delta\bar{\tau}_b - \Delta\bar{\tau}_a)/\hbar = -\Delta m \left(1 + \alpha_{\text{e-g}}\right) g\, \Delta z\, (t_\mathrm{f} - t_\mathrm{i})/\hbar$$

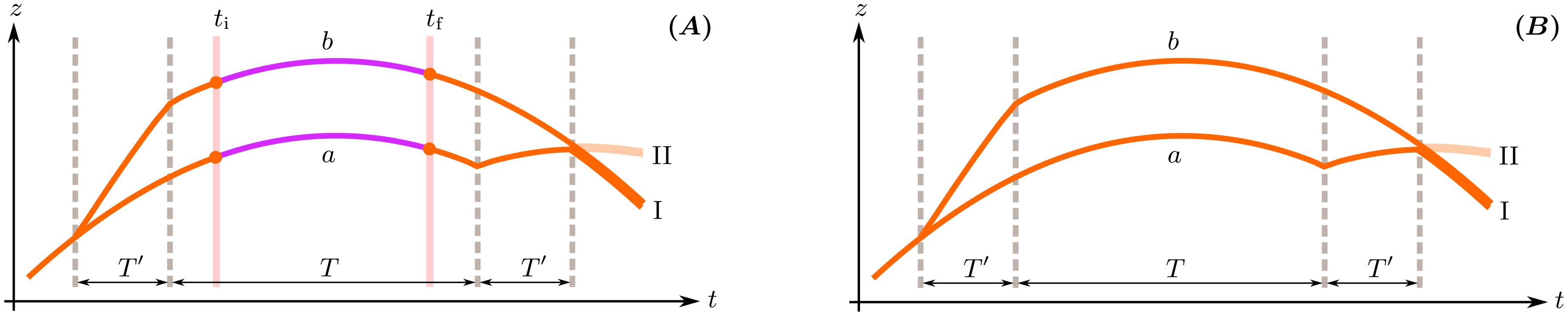
$$\alpha_{\text{e-g}} = \frac{m_1}{\Delta m}\left(\beta_2 - \beta_1\right)$$

Inversion and Bragg diffraction pulses





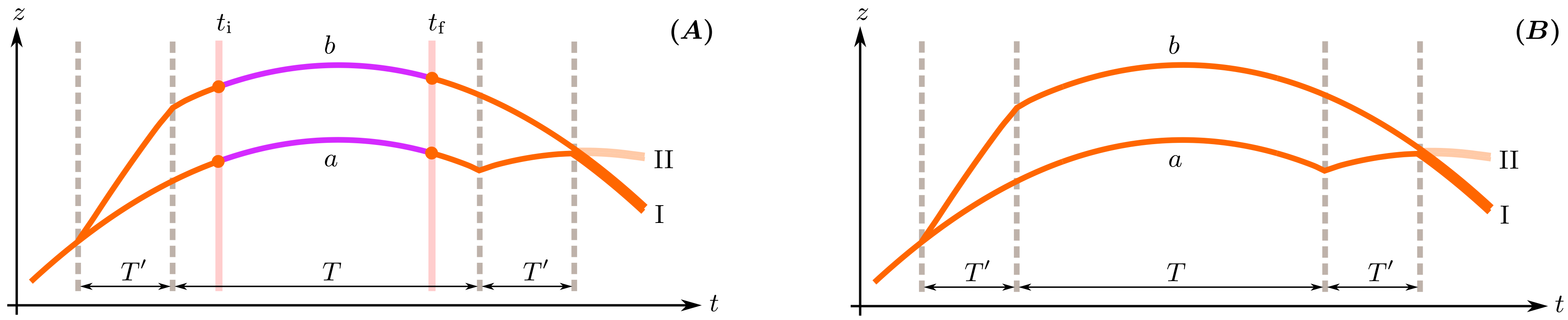
Suppression of vibration noise



- Suppress *vibration noise* through the *simultaneous* operation of a Rb interferometer:

$$\delta\phi_{\mathrm{laser}} = \delta\bar{\varphi} + \mathbf{k}_{\mathrm{eff}} \cdot \mathbf{g}\,(1+\beta_1)\,T'(T+T') + \mathbf{k}_{\mathrm{eff}} \cdot \Delta\mathbf{g}\,T'(T+T') - \sum_j \delta\mathbf{k}_{\mathrm{eff}}^{(j)} \cdot \mathbf{X}_{\mathrm{mirror}}(t_j)$$

Suppression of vibration noise



- Suppress *vibration noise* through the *simultaneous* operation of a Rb interferometer:

$$\left(\delta\phi_A - \left(\frac{k_{\text{eff}}}{k_{\text{eff}}^{\text{Rb}}}\right)\delta\phi_{\text{Rb}}\right) - \left(\delta\phi_B - \left(\frac{k_{\text{eff}}}{k_{\text{eff}}^{\text{Rb}}}\right)\delta\phi'_{\text{Rb}}\right) = -\Delta m\, c^2\,(\Delta\bar{\tau}_b - \Delta\bar{\tau}_a)/\hbar = -\Delta m\,(1+\alpha_{\text{e-g}})\,g\,\Delta z\,(t_{\text{f}} - t_{\text{i}})/\hbar$$

Feasible experimental implementation

- *Simple atom optics* with mild requirements on laser power.
- *Suppression of vibration noise* through simultaneous Rb interferometer.
- Feasible implementation with VLBAI facility in Hannover.

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]

Spacetime curvature and proper-time difference

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**

RESEARCH

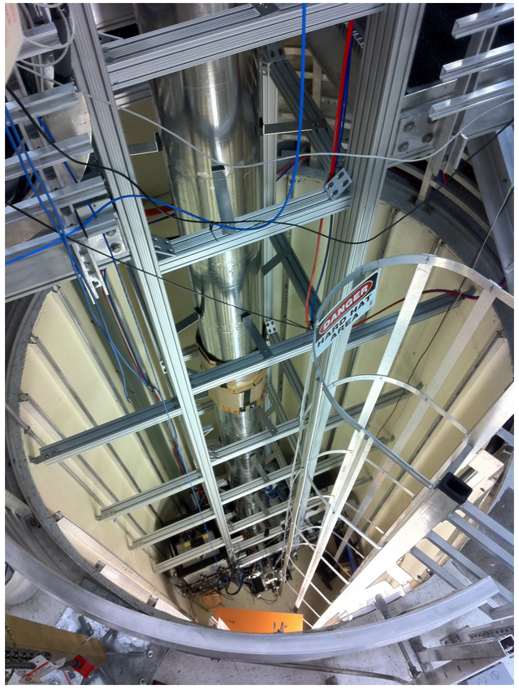
PHYSICS

Observation of a gravitational Aharonov-Bohm effect

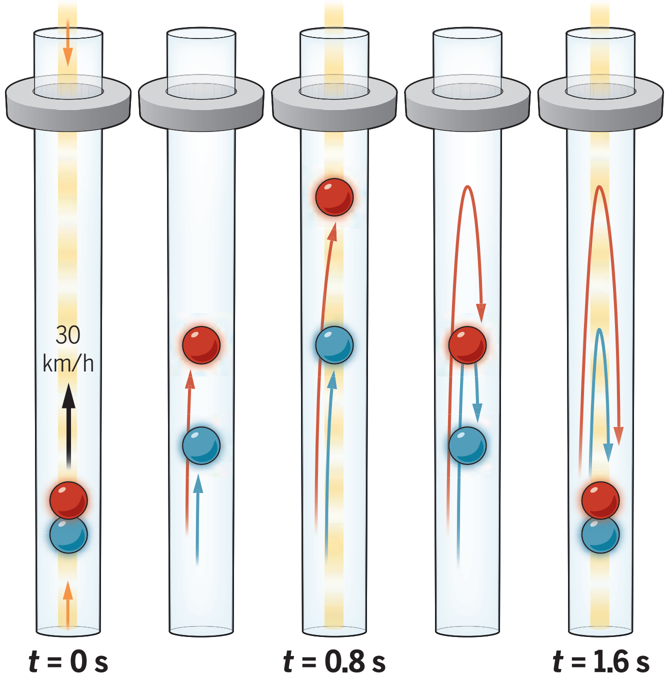
Chris Overstreet[1]†, Peter Asenbaum[1,2]†, Joseph Curti[1], Minjeong Kim[1], Mark A. Kasevich[1]*

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

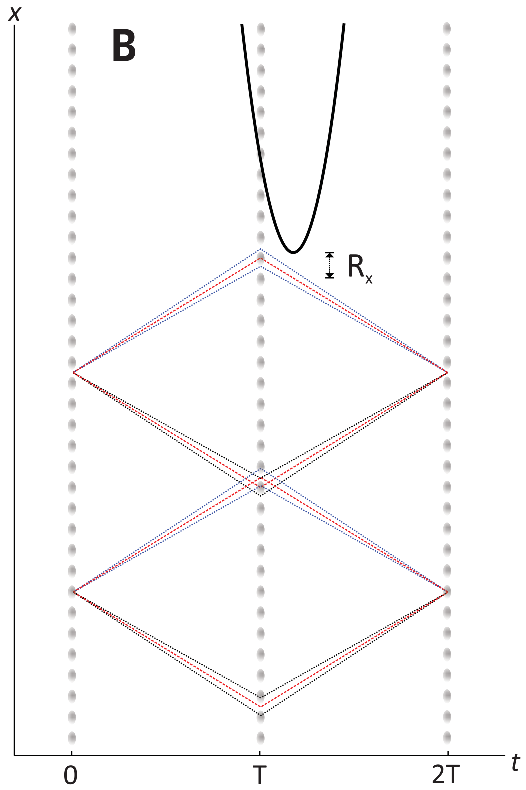
- Effect of spacetime curvature on a delocalized wave function.
- Proper-time time difference between the two atom interferometer arms.
- Gravitational analog of the scalar Aharonov-Bohm effect.



Stanford (USA)



lab frame



freely falling frame

Conclusions

- Measurement of *relativistic effects* in *macroscopically delocalized quantum superpositions* with quantum-clock interferometry.

- Important challenges in *quantum-clock interferometry* and its application to *gravitational-redshift* measurement.

- Promising doubly differential scheme that overcomes them.

- Feasible implementation in facilities soon to become operational.

- If one considers a consistent framework for *parameterizing violations* of Einstein's *equivalence principle*, (e.g. dilaton models)

  both for comparison of *independent clocks* and for the above *quantum-clock interferometry* scheme one obtains

$$\frac{\Delta\bar{\tau}_b - \Delta\bar{\tau}_a}{\Delta\bar{\tau}_a} \approx \left(1 + \alpha_{\text{e-g}}\right)\Big(U(\mathbf{x}_b) - U(\mathbf{x}_a)\Big)/c^2 \qquad \alpha_{\text{e-g}} = \frac{m_1}{\Delta m}\left(\beta_2 - \beta_1\right)$$

test of universality of gravitational redshift

with delocalized quantum superpositions

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

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

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

Christian Ufrecht,[1,*] Fabio Di Pumpo,[1] Alexander Friedrich,[1] Albert Roura,[2] Christian Schubert,[3,†]
Dennis Schlippert,[3] Ernst M. Rasel,[3] Wolfgang P. Schleich,[1,2,4] and Enno Giese[1,3]

[1]*Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQST), Universität Ulm, Albert-Einstein-Allee 11, D-89069 Ulm, Germany*
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[3]*Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, D-30167 Hannover, Germany*
[4]*Hagler Institute for Advanced Study and Department of Physics and Astronomy, Institute for Quantum Science and Engineering (IQSE), Texas A&M AgriLife Research, Texas A&M University, College Station, Texas 77843-4242, USA*

(Received 7 April 2020; accepted 20 October 2020; published 16 November 2020)

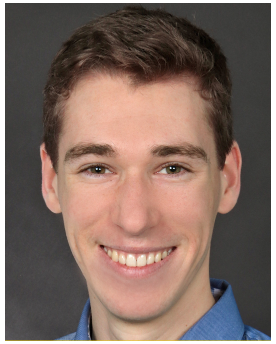
Other current activities

Q-GRAV Project
Interface of Quantum Mechanics and Gravitation

- Main Topics:
  1. Atom interferometry
  2. Matter-wave lensing for cold atoms
  3. Relativistic quantum information

- Team members:

Nadja Augst



Nico Schwersenz

Albert Roura

Q-GRAV Project
Interface of Quantum Mechanics and Gravitation

- Main Topics:
  1. Atom interferometry
  2. Matter-wave lensing for cold atoms
  3. Relativistic quantum information

- Highlighted international collaborations:
  - Atom interferometry experiments on the ISS with NASA's Cold Atom Lab (CAL)
    NASA JPL + Consortium for Ultracold Atoms in Space
  - NASA's Science Definition Team for *DSQL Mission Concept* and follow-up activities
    Recognized with a *NASA Group Achievement Award*

ESA-related activities

- ACES Mission (launch in 01/2025)
  - high-precision measurements with cold atoms in space
  - tests of general relativity, relativistic geodesy, intercontinental time / frequency distribution

  ACES Workshop 2023 organized in Ulm.

- Co-Chair of ESA's *Physical Sciences Working Group* (PSWG).

  Member of ESA's *Space Science Advisory Committee* (SSAC).

DLR

Thank you for your attention.

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aufgrund eines Beschlusses
des Deutschen Bundestages

HORIZON 2020

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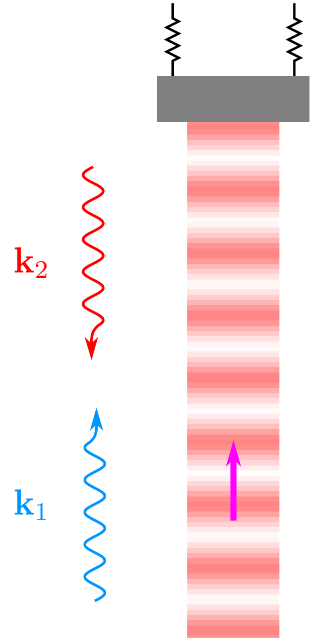
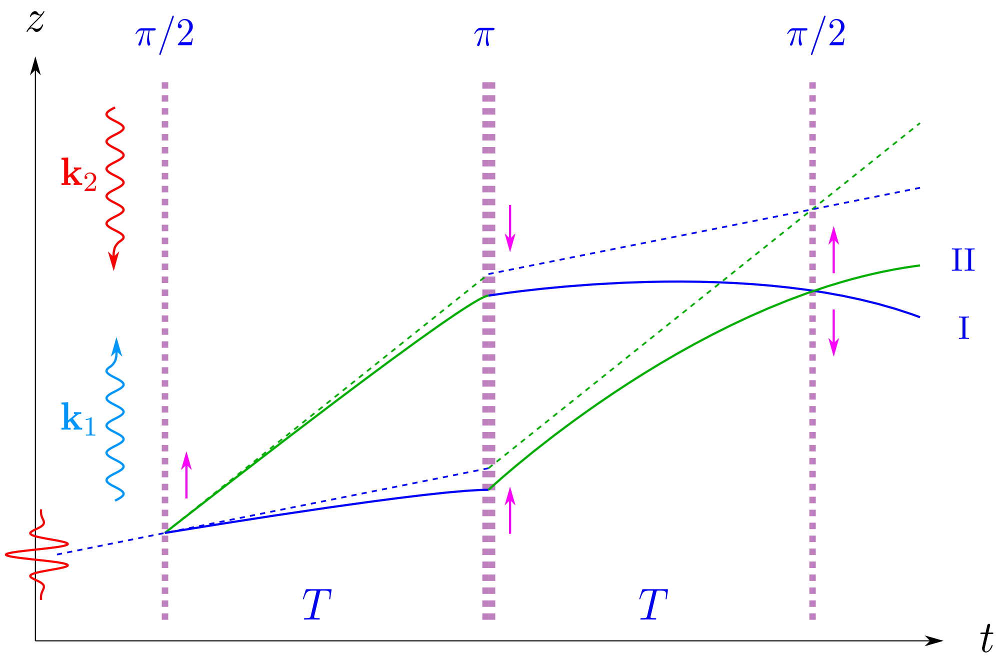
German Aerospace Center

Project Q-GRAV

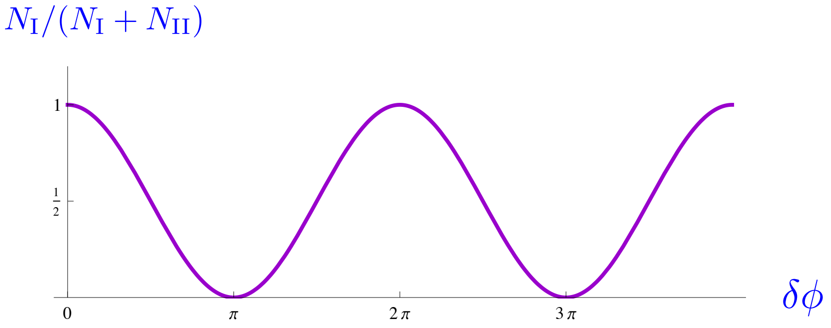
Atom interferometry

Atom interferometers as accelerometers





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



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