Atom interferometers as freely falling clocks for time-dilation measurements

Albert Roura

German Aerospace Center (DLR)
Institute of Quantum Technologies, Ulm

(based on arXiv:2402.11065)

DLR

Motivation

- Applications of atom interferometers based on single-photon transitions:
    - GW detection in mid-frequency band (100-m prototypes not sensitive enough)
    - Search for ultralight dark matter (modest exclusion bounds at early stages)

- Are there other interesting measurements (rather than mere null tests) that can be preformed?

  Yes, local measurement of *relativistic time dilation* with freely falling atoms.

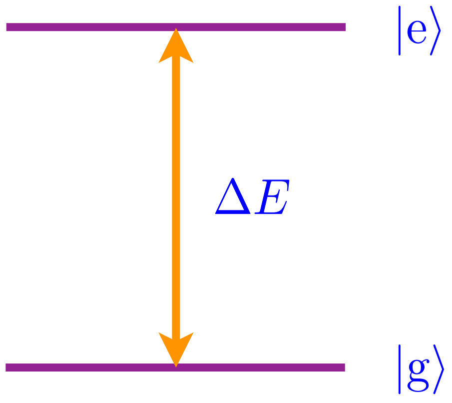
- Useful *methods* for theoretical *modelling* of such interferometers.

Outline

1. Relativistic effects in freely falling clocks
2. Atom interferometer as a freely falling clock
3. Experimental implementation
4. Equivalence principle violations and external forces
5. Discussion and conclusions

Relativistic effects in freely falling clocks

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:

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

- 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:

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

free fall

- 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:

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

free fall

Albert Roura, Institute of Quantum Technologies, 03.04.2024

- 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

Propagation of matter-wave packets in curved spacetime (relativistic description)

DLR

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

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

Comoving frame: $X^\mu(\tau_c) = (c\,\tau_c\,,\mathbf{0})$

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

- 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

For further details:

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

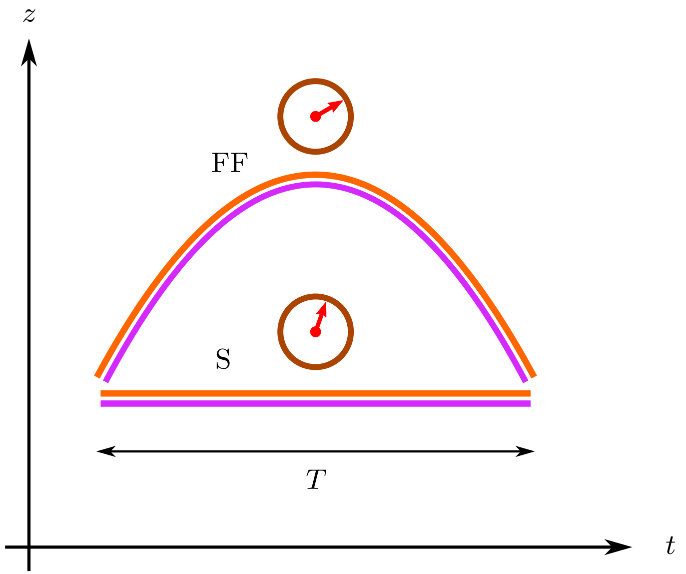
Gravitational Redshift in Quantum-Clock Interferometry

Albert Roura

Institute of Quantum Technologies, German Aerospace Center (DLR), Söflinger Straße 100, 89077 Ulm, Germany and Institut für Quantenphysik, Universität Ulm, Albert-Einstein-Allee 11, 89081 Ulm, Germany

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

Relativistic time dilation for a freely falling clock



- Freely falling clock (FF):

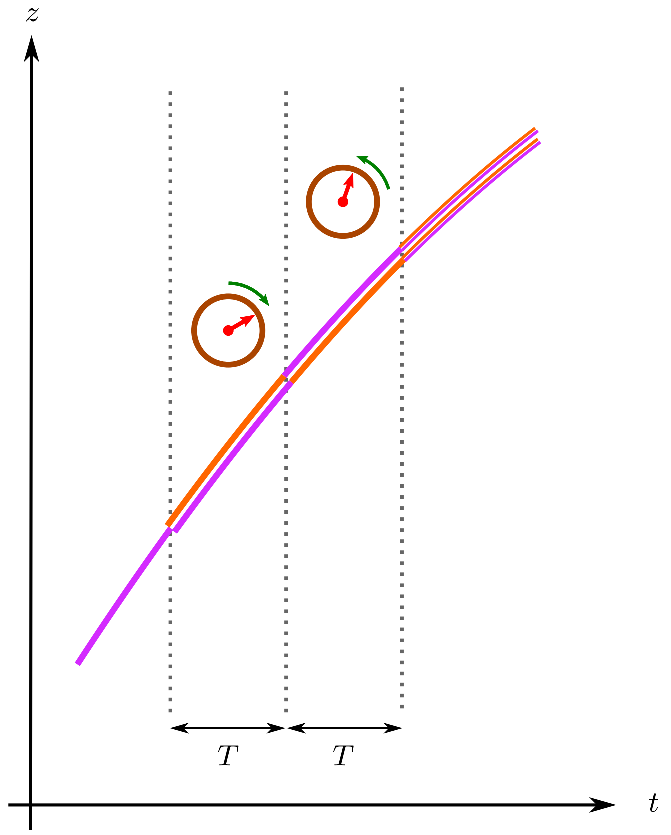
$$\delta\phi = -(\Delta E/\hbar)\left(\left(1 + U_0/c^2\right)T + \frac{1}{24}\frac{g^2T^3}{c^2}\right)$$

- 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:

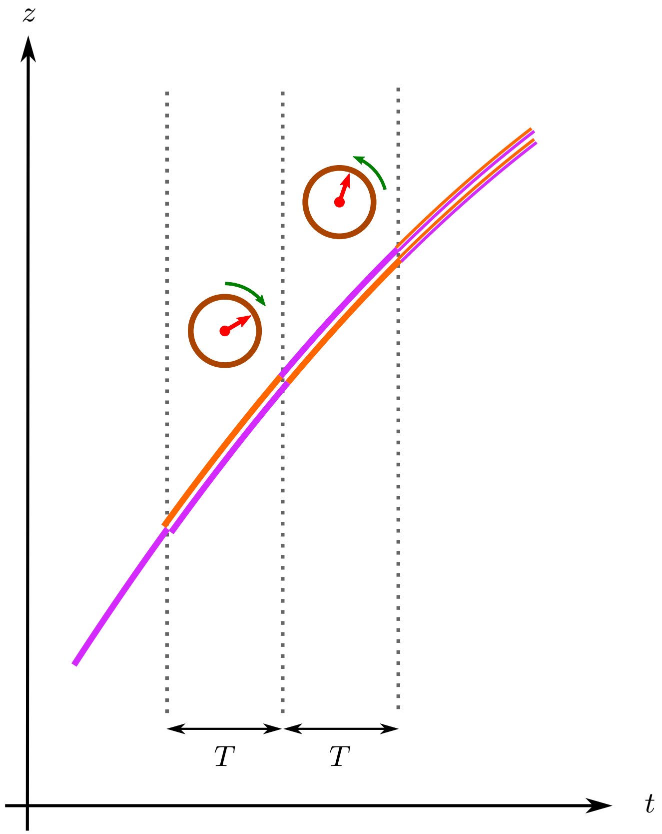
$$\delta\phi = -2\,(\Delta E/\hbar)\left(\mathbf{v}_0\cdot\mathbf{g}\,T^2 + g^2 T^3\right)/c^2$$

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

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 ($m\,\Delta\mathbf{v} = -\Delta m\,\mathbf{v}$)

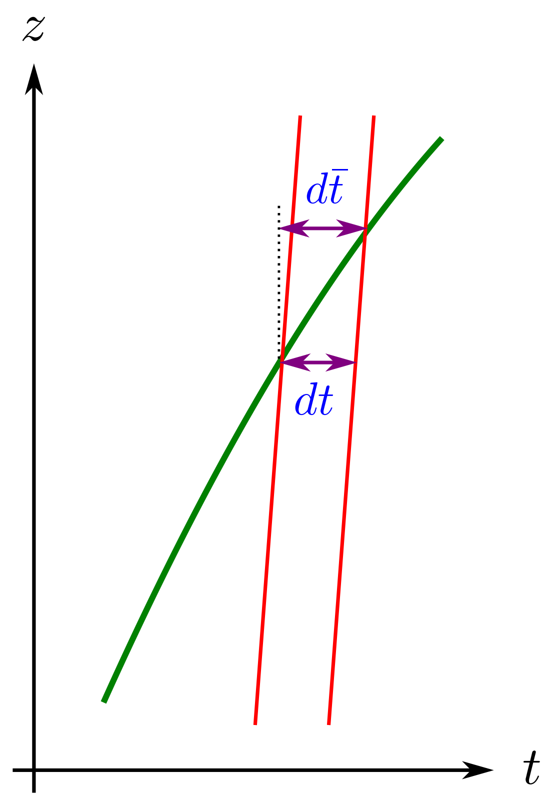
- Let us consider atom interferometers based on *single-photon* transitions.

Atom interferometer as a freely falling clock

Atom interferometer based on single-photon transitions

- Proper time along a freely falling world line (geodesic) and elapsed between two light rays.
  - *Retardation* effect due to the finite speed of light:

$$d\bar{t} = dt + (\hat{\mathbf{n}} \cdot \bar{\mathbf{v}}/c)\, d\bar{t} + O\big(1/c^3\big)$$



Atom interferometer based on single-photon transitions

- Proper time along a freely falling world line (geodesic) and elapsed between two light rays.
  - *Retardation* effect due to the finite speed of light: (stationary spacetime)

$$d\bar{t} = dt + (\hat{\mathbf{n}} \cdot \bar{\mathbf{v}}/c)\, d\bar{t} + O\big(1/c^3\big) \quad \longrightarrow \quad \frac{d\bar{t}}{dt} = \frac{1}{1 - \hat{\mathbf{n}} \cdot \bar{\mathbf{v}}/c}$$

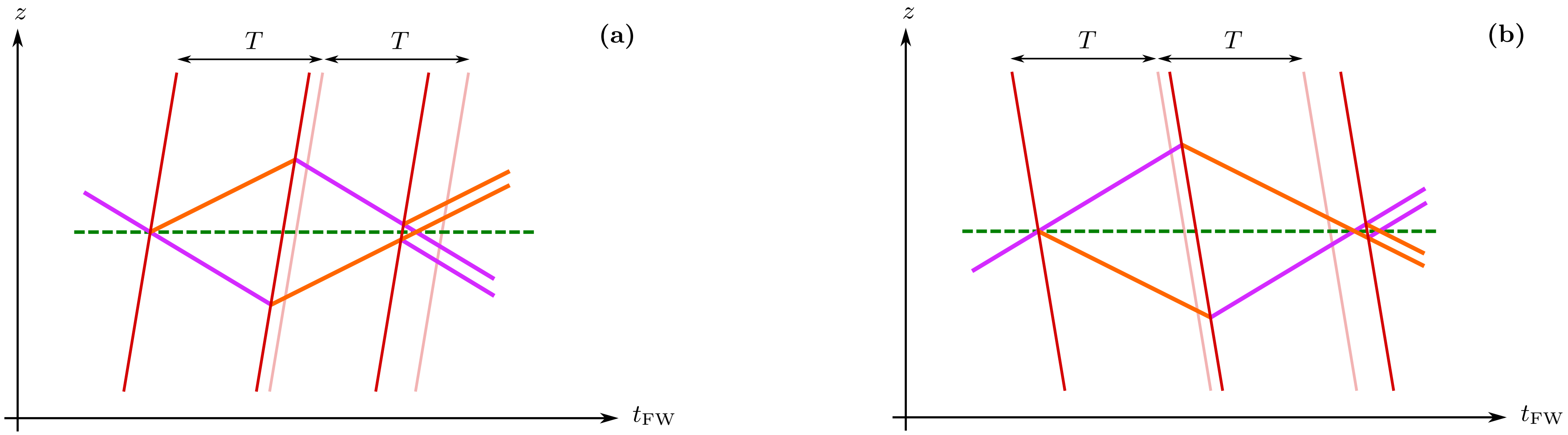
  - Relativistic *time dilation*:

$$\frac{d\bar{\tau}}{d\bar{t}} = 1 - \frac{1}{2\,c^2}\left(\frac{d\bar{\mathbf{X}}}{d\bar{t}}\right)^2 + \frac{1}{c^2}\, U\big(\bar{t}, \bar{\mathbf{X}}\big) + O\big(1/c^4\big)$$

special relativistic

gravitational redshift

Atom interferometer based on single-photon transitions



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

- It is sufficient to calculate the proper times along the *mid-point* world line rather than the actual *arm trajectories* (negligible higher-order corrections to total phase shift).

- Proper time as a function of the phase φ, invariant characterizing each laser wave front:

$$\frac{d\bar{\tau}}{d\varphi} = \frac{d\bar{\tau}}{d\bar{t}} \frac{d\bar{t}}{dt} \left(\frac{dt}{d\varphi} \right) = \frac{d\bar{\tau}}{d\bar{t}} \left(\frac{1}{1 - \hat{\mathbf{n}} \cdot \bar{\mathbf{v}}/c} \right) \left(\frac{dt}{d\varphi} \right)$$

- The Doppler factor can be (partially) compensated through a suitable frequency chirp:

$$\left(\frac{dt}{d\varphi} \right)_{\text{chirp}} = \left(1 - \hat{\mathbf{n}} \cdot \bar{\mathbf{v}}'/c\right) \left(\frac{dt}{d\varphi} \right)_0 \qquad (dt/d\varphi)_0 = 1/\omega_0$$

$$\bar{\mathbf{v}}'(\bar{t}) = \bar{\mathbf{v}}'_0 + \mathbf{g}' \, (\bar{t} - \bar{t}_0)$$

- Phase-shift calculation:

$$\delta\phi = -\frac{\Delta E}{\hbar}\left[\int_0^{\omega_0 T}\left(\frac{d\bar{\tau}}{d\varphi}\right) d\varphi - \int_{\omega_0 T}^{2\omega_0 T}\left(\frac{d\bar{\tau}}{d\varphi}\right) d\varphi\right]$$

- For an approximately uniform gravitational field, $\bar{\mathbf{X}}(\bar{t}) = \bar{\mathbf{v}}_0 + \mathbf{g}\,(\bar{t} - \bar{t}_0)$ and

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

- It agrees with the result for an ideal freely falling clock if $\delta\phi_{\mathrm{corr}}$ can be kept small enough.

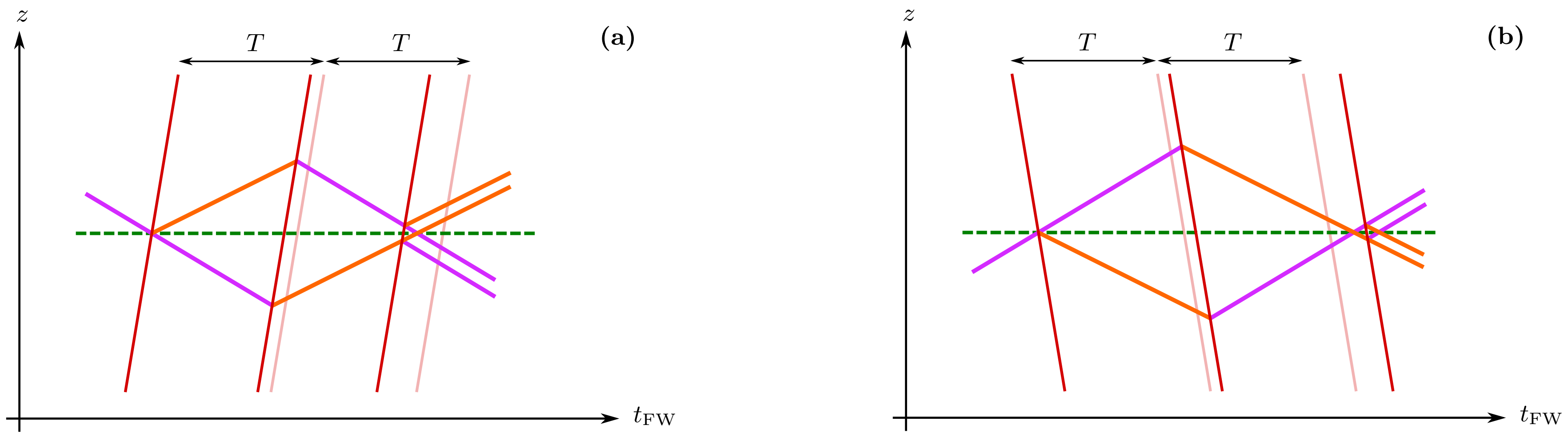
- For an imperfect match of the chirped frequency, with $\Delta\mathbf{g} = \mathbf{g} - \mathbf{g}'$ and $\Delta\bar{\mathbf{v}}_0 = \bar{\mathbf{v}}_0 - \bar{\mathbf{v}}_0'$.

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

- The dominant term is linear in $\hat{\mathbf{n}}$ and can be suppressed by adding up $\delta\phi$ for two interferometers with opposite $\hat{\mathbf{n}}$. (reversed interferometers)

- The above result can be straightforwardly generalized to a time dependent $\Delta\mathbf{g}(\bar{t})$.
  This can naturally account for *laser phase noise* and *vibrations* of retro-reflection *mirror*.

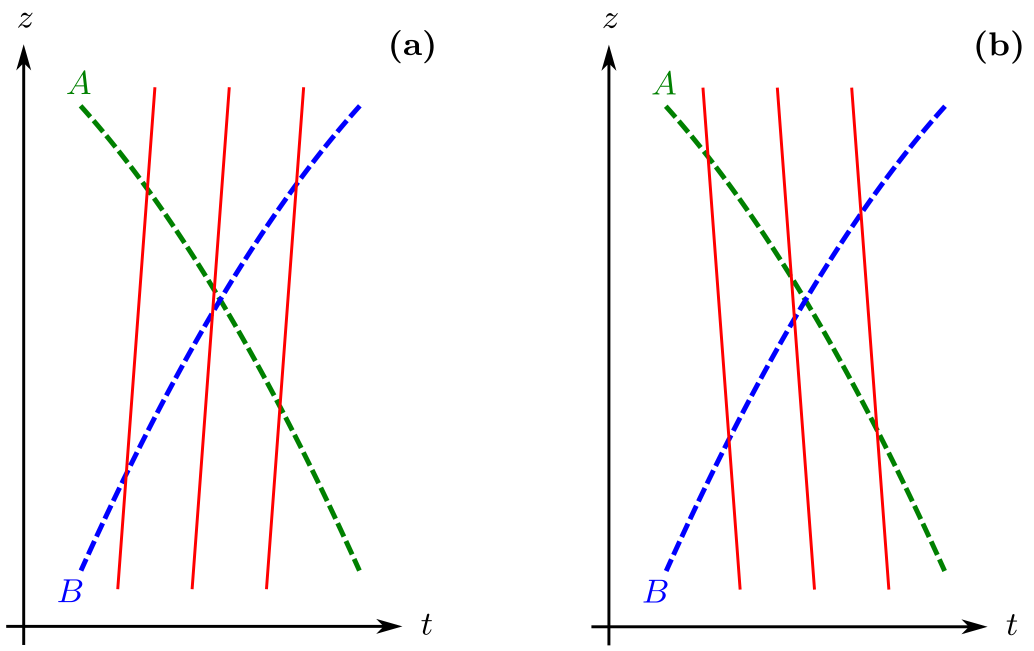
Reversed interferometers



- Uncompensated Doppler contribution cancels out when adding up their phase shifts.

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

"Gradiometric" configuration



$$\omega_{\text{chirp}}(t) = \Bigg[1 + \frac{(\hat{\mathbf{n}}\cdot\bar{\mathbf{v}}'_0)}{c}\frac{(\hat{\mathbf{n}}\cdot\mathbf{g}')}{c}(t-t_0) + \frac{(\hat{\mathbf{n}}\cdot\bar{\mathbf{v}}'_0)^2}{c^2} + 3\,\frac{(\hat{\mathbf{n}}\cdot\bar{\mathbf{v}}'_0)\,(\hat{\mathbf{n}}\cdot\mathbf{g}')}{c^2}(t-t_0)\Bigg]\,\omega_0$$

- 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 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 → 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.

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
  - 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

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
  - 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

Equivalence principle violations & external forces

External forces

- The coupling of neutral atoms to magnetic fields and far detuned radiation can be described with *state-dependent* external potentials.

- Replacement in the action: $m_n\, U(t', \mathbf{X}) \rightarrow m_n\, U(t', \mathbf{X}) + V_n(t', \mathbf{X})$

- Modified mean acceleration:

$$\bar{\mathbf{a}} = \mathbf{g} - \boldsymbol{\nabla}\, \bar{V}_n / m_n \qquad \bar{V}_n \equiv \frac{m_n}{2} \left(\frac{V_1}{m_1} + \frac{V_2}{m_2} \right)$$

- Relative acceleration between the two internal states:

$$\delta\mathbf{a} = -\boldsymbol{\nabla}(\delta V_n)/m_n \qquad \delta V_n \equiv m_n \left(\frac{V_2}{m_2} - \frac{V_1}{m_1} \right)$$

- Fermi-Walker frame (mid-point trajectory with acceleration $\bar{\mathbf{a}}$).

- Modified arm trajectories + separation phase → no net phase-shift contribution.

- Key contribution to the action evaluated along the mid-point trajectory:

$$V_2(t', \bar{\mathbf{X}}) - V_1(t', \bar{\mathbf{X}}) = \Delta m \, \frac{\bar{V}_n(t', \bar{\mathbf{X}})}{m_n} + \bar{m} \, \frac{\delta V_n(t', \bar{\mathbf{X}})}{m_n} \qquad \bar{m} = (m_1 + m_2)/2 \approx m$$

- Result for a uniform (state-dependent) force:

$$\delta\phi = -\frac{\Delta E}{\hbar} \left[2 \left(\bar{\mathbf{v}}_0 \cdot \bar{\mathbf{a}} \, T^2 + \bar{\mathbf{a}}^2 \, T^3 \right) / c^2 + \left(\frac{m}{\Delta m} \right) \left(\delta\mathbf{a} \cdot \bar{\mathbf{v}}_0 \, T^2 + \delta\mathbf{a} \cdot \bar{\mathbf{a}} \, T^3 \right) / c^2 \right]$$

Equivalence principle violations

- Consider a *dilaton model* as a consistent parametrization of equivalence principle violations.

- Replacement in the action: $m_n\, U(t', \mathbf{X}) \;\rightarrow\; m_n\, (1 + \beta_n)\, U(t', \mathbf{X})$

  It can be regarded as a particular case of state-dependent external potential (previous slides).

- The phase-shift result coincides with that for an ideal clock following the mean trajectory:

$$\delta\phi = -2\,(\Delta E/\hbar)\,\big(1 + \alpha_{\text{e-g}}/2\big)\,\big(\bar{\mathbf{v}}_0 \cdot \bar{\mathbf{g}}\, T^2 + \bar{g}^2 T^3\big)\,/c^2$$

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

  Test of universality of gravitational redshift (UGR).

Discussion and conclusions

Comparison to quantum-clock interferometry and other proposals

Quantum-clock interferometry

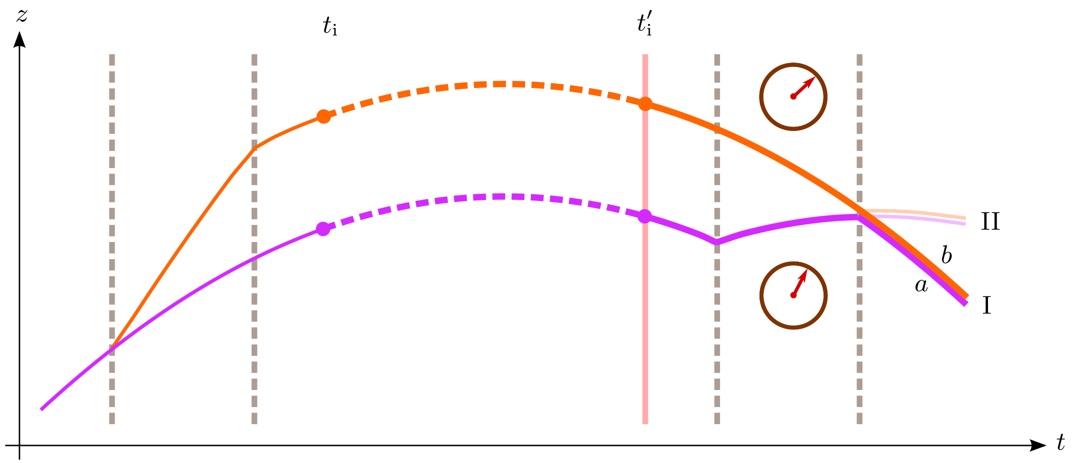
PHYSICAL REVIEW X **10,** 021014 (2020)

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

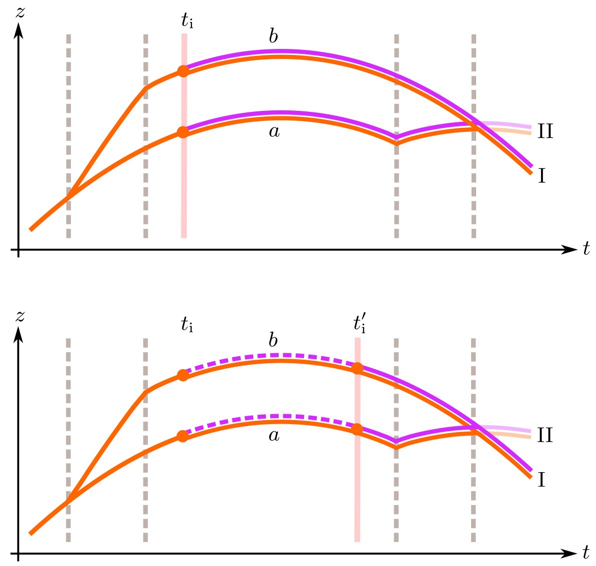


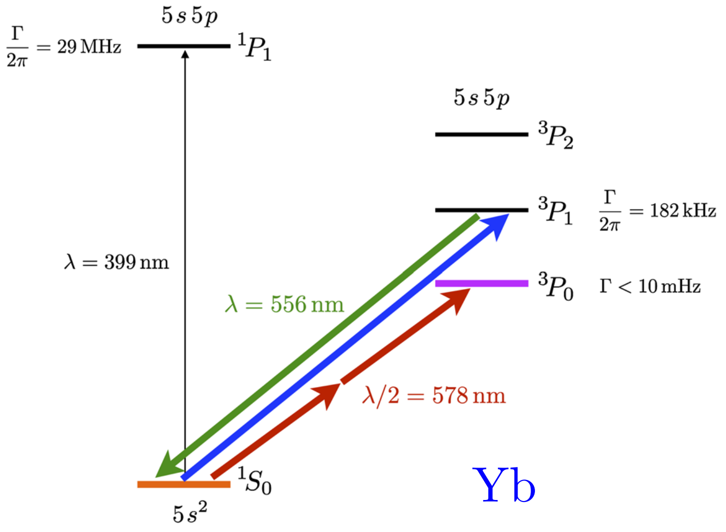
Quantum-clock interferometry

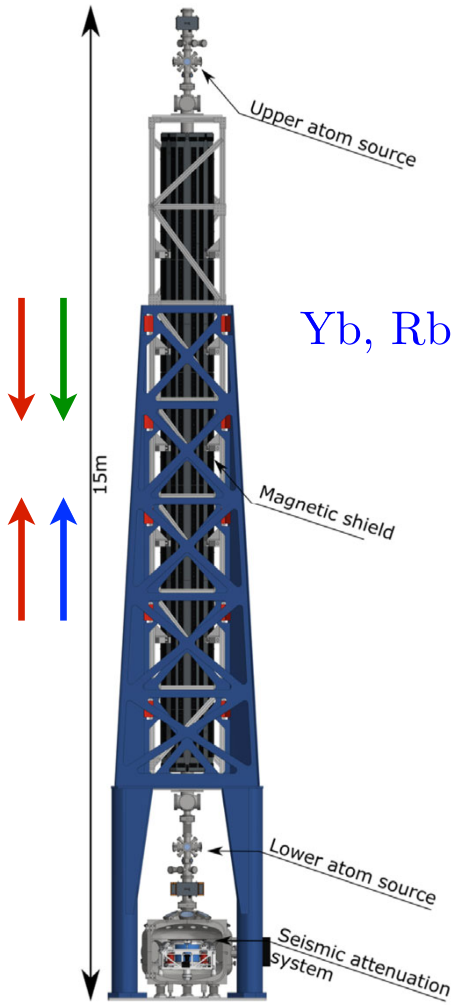
PHYSICAL REVIEW D **104,** 084001 (2021)

Measuring gravitational time dilation with delocalized quantum superpositions

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





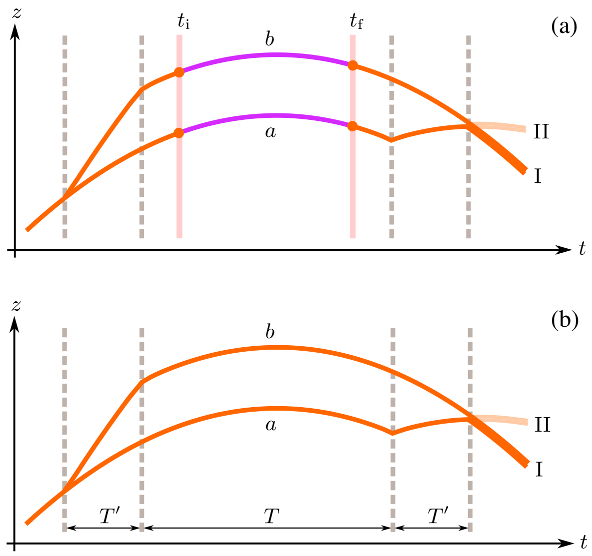


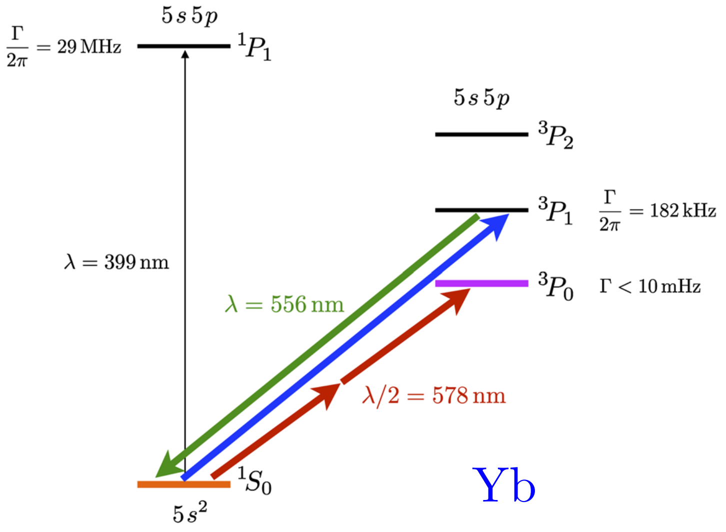
Quantum-clock interferometry

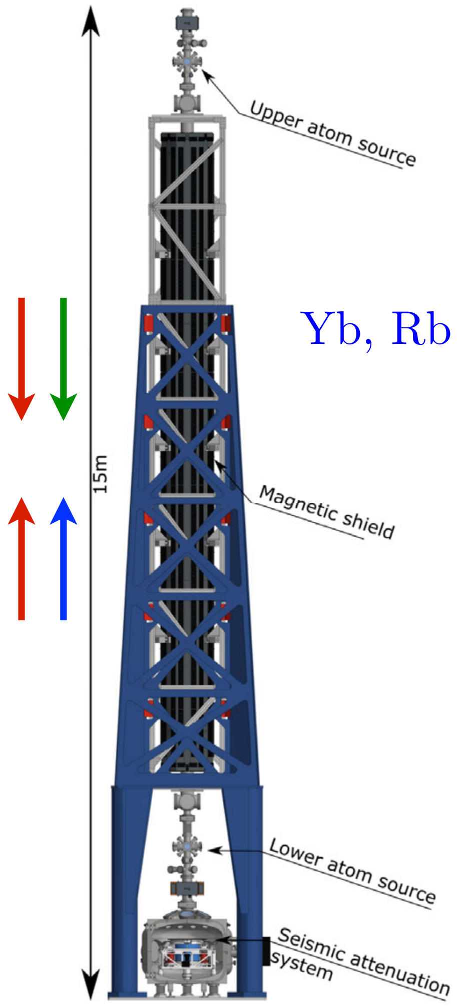
PHYSICAL REVIEW D **104,** 084001 (2021)

Measuring gravitational time dilation with delocalized quantum superpositions

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







Comparison with current proposal

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

- **Current proposal:** each atom interferometer acts as a *freely falling clock*; comparison between two independent clocks in the “gradiometric” configuration.

Albert Roura, Institute of Quantum Technologies, 03.04.2024

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*

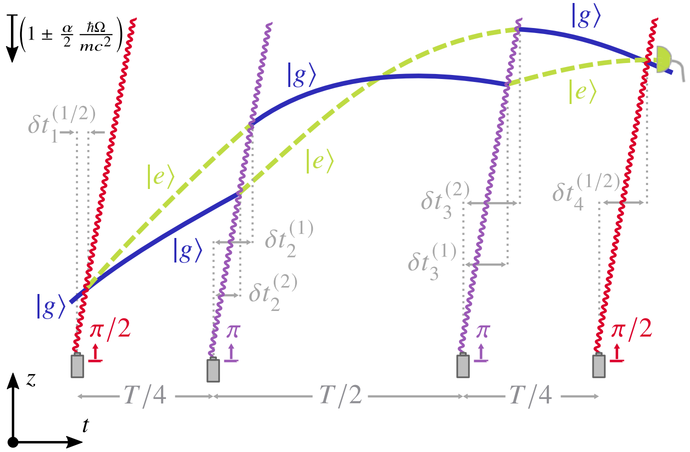
[2]*Institute of Quantum Technologies, German Aerospace Center (DLR), Söflinger Straße 100, D-89077 Ulm, Germany*

[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)

Proposed UGR test with atom interferometry



F. Di Pumpo, A. Friedrich, C. Ufrecht, E. Giese
Phys. Rev. D **107**, 064007 (2023)

- Null test: non-vanishing result in case of gravitational redshift differences for different isotopes (e.g. ^{87}Sr and ^{88}Sr)
- *Forbidden* clock transition for bosonic isotopes such as ^{88}Sr unless a strong transverse magnetic field is applied → not a viable option for precision measurements with VLBAI.
- Little dependence of $\Delta E \propto m_e\, \alpha^2 c^2$ on the nuclear isotope → effects of UGR violations nearly the same for both isotopes.

Conclusions

- Atom interferometers based on single-photon transitions can be used as *freely falling clocks* for time dilation measurements.

- Unprecedented measurement of *relativistic time dilation* in a local measurement with *freely falling* atoms.

- It could be implemented in MAGIS-100 with virtually *no additional requirements*.

  A version with limited sensitivity could also be implemented in Stanford's 10-m prototype or AION's 10-m fountain.

- Main challenge for achieving higher sensitivities → temperature gradients.

  Further improvement through measurements of temperature profile and post-correction.

For further details:

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

Albert Roura
German Aerospace Center (DLR), Institute of Quantum Technologies,
Wilhelm-Runge-Straße 10, 89081 Ulm, Germany

arXiv:2402.11065

Other related activities

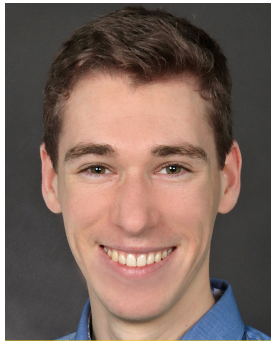
Q-GRAV Project
Interface of Quantum Mechanics and Gravitation

- Main Topics:

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

- Team members:

Nadja Augst



Nico Schwersenz

Albert Roura

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).

Thank you for your attention.

DLR Deutsches Zentrum für Luft- und Raumfahrt
German Aerospace Center

Project Q-GRAV

Albert Roura, Institute of Quantum Technologies, 03.04.2024