# **Atom interferometers as freely falling clocks for time-dilation measurements**

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(based on [arXiv:2402.11065](https://arxiv.org/abs/2402.11065))



## **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:

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

• Evolution:

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



- Theoretical description of the clock:
	- ‣ two-level atom (internal state):

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

$$
m_1 = m_g
$$

$$
m_2 = m_g + \Delta m
$$

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

‣ classical action for COM motion:

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

free fall



- Theoretical description of the clock:
	- ‣ two-level atom (internal state):

 $\hat{H} = \hat{H}_1 \otimes |g\rangle\langle g| + \hat{H}_2 \otimes |e\rangle\langle e|$  *m*<sub>2</sub> = *m*<sub>g</sub> +  $\Delta m$ 

$$
m_1 = m_g
$$

$$
m_2 = m_g + \Delta m
$$

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

‣ classical action for COM motion:

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

free fall



- Theoretical description of the clock:
	- ‣ two-level atom (internal state):

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

$$
m_1 = m_g
$$

$$
m_2 = m_g + \Delta m
$$

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

‣ classical action for COM motion:

$$
S_n[x^{\mu}(\lambda)] = -m_n c^2 \int d\tau - \int d\tau V_n(x^{\mu})
$$
 (*n* = 1,2)  
including external forces



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

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

$$
\Delta p/m \ll c \qquad \qquad \Delta x \ll \ell \qquad \qquad \text{curvature radius}
$$



‣ *propagation phase* 

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

‣ *centered wave packet*

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

$$
\hat{H}_{\rm c}^{(n)} = \frac{1}{2m_n} \hat{\mathbf{p}}^2 + \frac{1}{2} \hat{\mathbf{x}}^{\rm T} \Big( \mathcal{V}^{(n)}(\tau_{\rm c}) - m_n \Gamma(\tau_{\rm c}) \Big) \hat{\mathbf{x}}
$$

 $\hat{\mathbf{x}}$   $V_{ij}^{(n)}(\tau_c) = \partial_i \partial_j V_n(\tau_c, \mathbf{x})$  $\vert_{\mathbf{x}=0}$ 



10 Albert Roura, Institute of Quantum Technologies, 03.04.2024

For further details:





- **Relativistic description of atom interferometry in** *curved spacetime*.  $\kappa$  description or atom interferometry in c*urved space*
- **EXTHE 11 Including external forces and even** *guiding potentials***.** superposition has already between generating performance
- **Relativistic interpretation of the separation phase in open interferometers.** *ic* interpretation of the separation priase in open in





 $\blacksquare$  Freely falling clock (FF):

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

■ 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:

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



special relativistic extending the 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:
	- **Exercise dedicated high-power laser needed at**  $\lambda_2$
	- **•** residual recoil ( $m \Delta v = -\Delta m v$ )
- 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:

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





## **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)

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

‣ Relativistic *time dilation*:

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



- **EXTED THE 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**  $\varphi$ **, 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

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

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



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

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

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

## **"Gradiometric" configuration**



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



 $\delta \phi_A - \delta \phi_B = -2 \left( \Delta E / \hbar \right) \left( \bar{\mathbf{v}}^A_0 - \bar{\mathbf{v}}^B_0 \right)$  $\int \cdot$  g  $T^2/c^2$ 

- **EXA)** Similarly for pair of reversed interferometers: **(a)** and **(b)**
- **EXECOMPARISON 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  $\longrightarrow$  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.

## **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  $\longrightarrow 10^{-4}$  relative uncertainty)
	- ‣ rotations
	- ‣ wave-front curvature & light shifts
- **■** Pulse timing requirements:  $\Delta T \lesssim 0.1 \,\mu\text{s}$  and  $\delta \lesssim 300 \,\text{Hz}$   $\longrightarrow$   $10^{-5}$  relative uncertainty
- **•** Magnetic field inhomogeneities:  $3 \text{ nT} / \text{m} \longrightarrow 10^{-5}$  relative uncertainty
- **Temperature gradients: 2 K / 100 m**  $\rightarrow$  **contribution at**  $10^{-2}$  **level**

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- **Temperature gradients: 2 K / 100 m**  $\rightarrow$  **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:**  $m_n U(t', \mathbf{X}) \to m_n U(t', \mathbf{X}) + V_n(t', \mathbf{X})$
- Modified mean acceleration:

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

■ Relative acceleration between the two internal states:

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



- **Fermi-Walker frame** (mid-point trajectory with acceleration  $\bar{a}$ ).
- **Modified arm trajectories + separation phase**  $\rightarrow$  **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:  $m_n U(t', \mathbf{X}) \to m_n (1 + \beta_n) U(t', \mathbf{X})$

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:

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

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

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) PHYSICAL REVIEW X 10, 021014 (2020)

PHYSICAL REVIEW X 10, 021014 (2020)

Gravitational Redshift in Quantum-Clock Interferometry Gravitational Redshift in Quantum-Clock Interferometry Gravitational Redshift in Quantum-Clock Interferometry

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(Received 29 September 2019; revised manuscript received 12 February 2020; accepted 5 March 2020; published 20 April 2020)

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### Quantum superposition of a single clock at two different heights

- Initialization pulse after the spatial superposition paths with different generated.<br>
paths with different generated the interference signal the interferences on the interference signal the inter tialization pulse after the spatial superposition s been generated. Light-pulse atom interferometry with elements employed in optical time different gravitation atomic clocks is a promising candidate for that purpose, but it suffers from major challenges including its suffers including its suffers from major challenges including its suffers including its suffers of  $\alpha$ memethone penso entor this opener couporposition  $\mathcal{L}$  are eventually recombined. Light-pulse atom interferometry with elements employed in optical in optica The creation of delocalization of delocalization superposition  $\mathcal{L}$ relativistic effects is an important milestone in future research at the interface of gravity and quantum mas been generated. This milestone could be achieved by generating a superposition of  $\alpha$
- · Doubly differential measurement:  $\boldsymbol{\eta}$  antoromatic models shippers in  $\boldsymbol{\eta}$ the novel scheme presented here, which is based on initializing the clock when the spatially separate  $s_{\rm s}$  already between generated and performing a double  $\epsilon$  $\bullet$  Doubly differential measurement:  $\mathcal{L}_{\mathcal{L}_{\mathcal{L}}(\mathcal{L}_{\mathcal{L}_{\mathcal{L}}})}$  and formulation field. All of these differentials can be over  $\mathcal{L}_{\mathcal{L}_{\mathcal{L}}(\mathcal{L}_{\mathcal{L}_{\mathcal{L}}})}$
- state-selective detection white a new generation of  $10^{-10}$  foundations that will solve  $\frac{1}{\sqrt{2}}$ state-selective detection the novel scheme presented here, which is based on initializing the spatially separate the spatially separate  $\mathcal{L}$  $\triangleright$  state-selective detection  $\blacksquare$
- $\triangleright$  compare different initialization times mnare different initialization fimes.  $\blacksquare$ interferometry schemes and the effects that can be measured with them, a general formalism for a comnare different initialization times approach also offers significant advantages for more compact setups based on guided interferometry or  $\longrightarrow$  compare different initialization times



## **Quantum-clock interferometry**









shown in a nonrelativistic calculation [34].

the superposition of internal states) after the superposition

III. QUANTUM-CLOCK INTERFEROMETRY A natural way of observing time-dilation effects in delocalized quantum superpositions is by performing a quantum-clock interferometry experiment [31] with the same kind of atoms employed in optical atomic clocks, such as Sr or Yb. In this case, one prepares an equalamplitude superposition of the two internal clock states which is the initial state of as the initial state of a light-pulse atomic interferometer, where the atomic wave packet is split, redirected, and finally recombined by a series of laser pulses acting as diffraction gratings. As emphasized in Ref. [32], any differences in the time dilation along the two arms lead to a contrast reduction of the interferometric signal. However, this effect is far too small to be observable within the parameter regimes accessible to current experiments [33]. Furthermore, this kind of interferometer is insensitive to gravitational time dilation in a uniform field. This lack of sensitivity can be easily understood by considering a freely falling frame [33], where the central trajectories correspond to straight lines independent of the gravitational acceleration g, and has also been explicitly

MEASURING GRAVITATIONAL TIME DILATION WITH … PHYS. REV. D 104, 084001 (2021)

#### will need to be employed instead. Substantial efforts instead. Substantial efforts in this substantial effort  $\Omega$ in the near future because several future because severa large-scale projects [50,51] will rely on atom interferompulses but the same laser-pulse sequence otherwise. The m clock interfere by the proper time spent by the atoms in the excited state **Quantum-clock interferometry**

that all the diffraction pulses in both shots act on the same  $\alpha$ 



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rather than simultaneously. This can be accomplished in









## **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.



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a single twin is in a superposition of twin is in a superposition of two different world lines, aging the super simultaneously at different rates, illustrated in Fig. 1B. We show that light-pulse atom interferometers can implement the scenario where

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dilation, were milestones in the development of modern physics and

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### Interference of clocks: A quantum twin paradox and a set of clocks and a set of the state of the state of the  $\frac{d}{dx}$ stitute for Advanced Study and Department of Physics and Astronomy, Institute for

Sina Loriani $^{1*}$ , Alexander Friedrich $^{2*}$ †, Christian Ufrecht $^{2}$ , Fabio Di Pumpo $^{2}$ , Stephan Kleinert $^{2}$ ,  $\hskip1cm$ Sina Conain , Alexander Friedrich , Christian Offetti, Fabio Di Fumpo , Stephan Klemerc , Theory (1998) (1998)<br>Sven Abend<sup>1</sup>, Naceur Gaaloul<sup>1</sup>, Christian Meiners<sup>1</sup>, Christian Schubert<sup>1</sup>, Dorothee Tell<sup>1</sup>, Étienne Wodey<sup>1</sup>, Magdalena Zych<sup>3</sup>, Wolfgang Ertmer<sup>1</sup>, Albert Roura<sup>2</sup>, Dennis Schlippert<sup>1</sup>, Wolfgang P. Schleich<sup>2,4,5</sup>, Ernst M. Rasel<sup>1</sup>, Enno Giese<sup>2</sup> (15, 21, 23, 24). For these geometries, a single atomic clock in a superposition of two different trajectories undergoes special-relativistic time German German Aerospace Center (Denistian Menic<br>Filmon Model Mendelen Zeel 3 Wellmann Euenne wouey , maguaiena zych , wong Wolfgang P. Schleich<sup>2,4,3</sup>, Ernst M. Rasel', Enno Gies

with clock transitions during the pulse sequence are not sensitive to gravitational time dilation in a linear

The phase of matter waves depends on proper time and is therefore susceptible to special-relativistic (kinematic) Loriani et al., Sci. Adv. 2019; 5: eaax8966 4 October 2019 1 of 100 o



## **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 **pulses is highlighted by inclined lines and leads to time delays of the sequence of the sequence**, the sequence, the sequen  $\blacksquare$  pulse and another  $\blacksquare$  pulse after a time  $\blacksquare$  that interferences them. The finite propagation speed of both light  $\sum_{i=1}^n$  and  $\sum_{i=1}^n$  superposition of both internal states so that both internal states so that both  $\sum_{i=1}^n$  $\mathcal{L}$
- *Forbidden* clock transition for bosonic isotopes such as <sup>88</sup>Sr unless a strong transverse magnetic field is applied not a viable option for precision measurements with VLBAI. atom interferometer, where a superposition of both internal states a superposition of both internal states  $\mu$ **Example a momentum**  $\blacksquare$  **in addition for the internal transition for bosonic isotopes such a** internal states, before at time T interference both branches. We show the finite speed of light by inclined li **Liot** a viable option for precision measurement
- **■** Little dependence of  $\Delta E \propto m_e \, \alpha^2 c^2$  on the nuclear isotope  $\rightarrow$  effects of UGR violations nearly the same for both isotopes. wave-packet contributions from the derivative with respect to the derivative with respect to the derivative with respect to  $\mathbf{e}_{\mathbf{S}}$

transfer, both wave packets corresponding to the two internal states are centered along the same spacetime trajectory. Panel (b) shows the

UNIVERSALITY-OF-CLOCK-RATES TEST USING ATOM … PHYS. REV. D 107, 064007 (2023)

FIG. 4. State-dependent functions λðσ<sup>Þ</sup>

pulses, which leads to time delays δt

along different branches.

branches encoded in the functions λðσ<sup>Þ</sup>

all pulses, as well as well as well as a

3. Atomic clocks



## **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.

 $\blacksquare$  Main challenge for achieving higher sensitivities  $\rightarrow$  temperature gradients. Eurther improvement through measurements of temperature profile and post-correction.



For further details:

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

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dented measurement of  $\overline{\text{arXiv:}2402.11065}$ which is out of reach even for the best atomic-foundations. The best atomic second second second second se

fields. Here we present a novel measurement scheme that enables their use as freely falling clocks



## **Other related activities**

## **Q-GRAV Project**



## **Interface of Quantum Mechanics and Gravitation**

■ Main Topics:  $\mathbf{C}$ 

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

**E** Team members:







)<br>DLR



Nadja Augst Nico Schwersenz Albert Roura  $\frac{1}{2}$ 

44 Albert Roura, Institute of Quantum Technologies, 03.04.2024

## **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.**



**Project Q-GRAV**

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