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Gravitational Redshift Tests with Atomic Clocks and Atom Interferometers

Terrestrial Very-Long-Baseline Atom Interferometry Workshop

Fabio Di Pumbo - CERN, 14. March 2023



Coworkers & collaborations



Alexander Friedrich



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William Unruh



THE UNIVERSITY
OF BRITISH COLUMBIA



Christian Ufrecht



universität
ulm

now at **Fraunhofer**
IIS



Enno Giese



TECHNISCHE
UNIVERSITÄT
DARMSTADT



Wolfgang Schleich



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Leibniz
Universität
Hannover



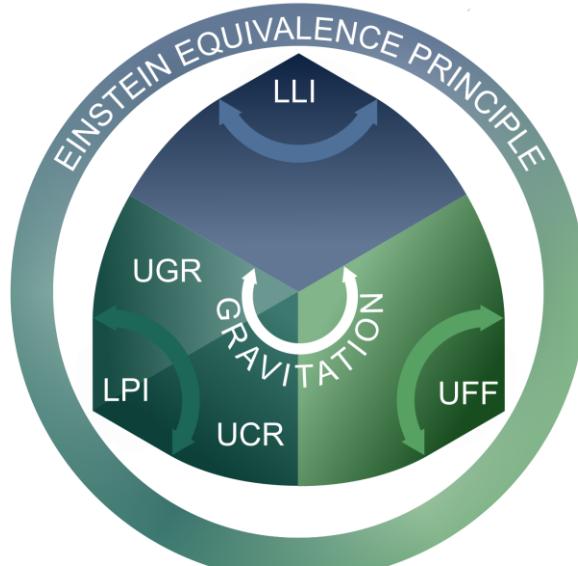
Carl Zeiss
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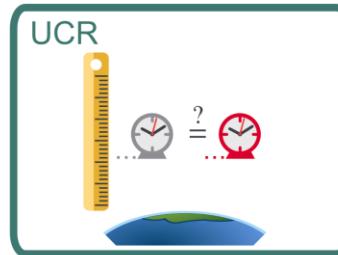
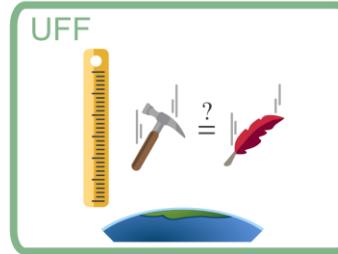
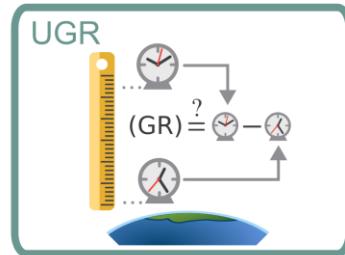
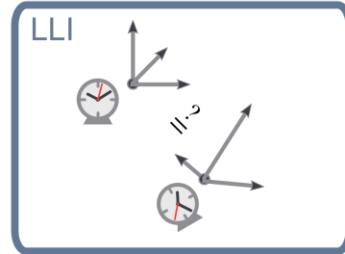
IQST



Einstein equivalence principle

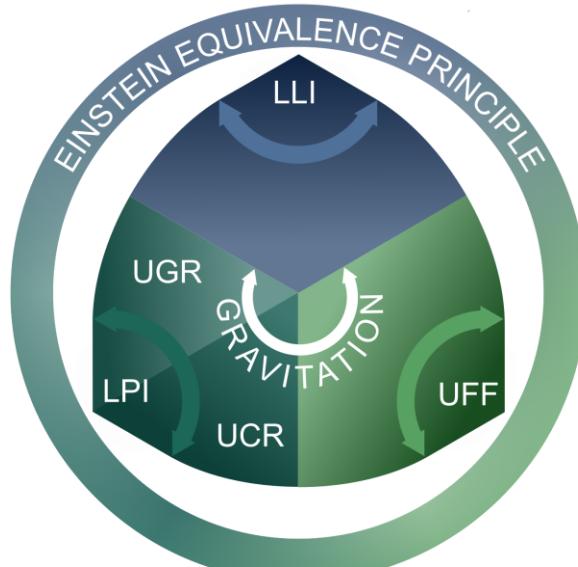


Phys. Rev. D **107**, 064007

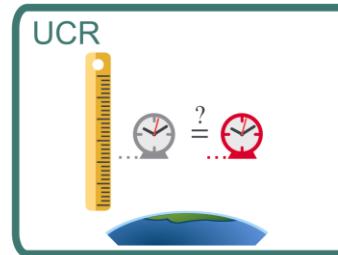
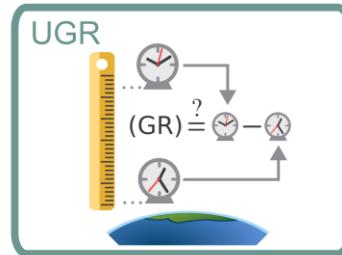
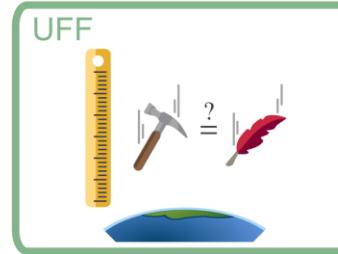
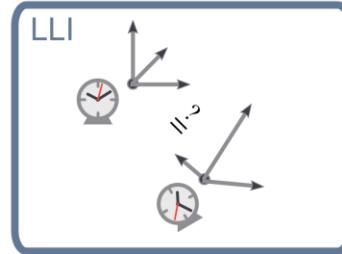




Einstein equivalence principle



Phys. Rev. D 107, 064007

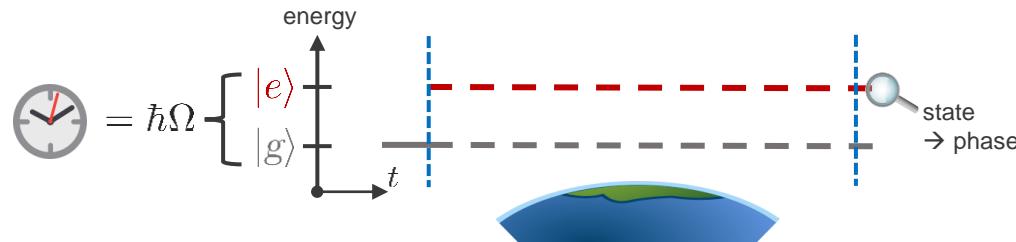


- Einstein equivalence principle fulfilled → metric theory of gravitation



Internal superposition

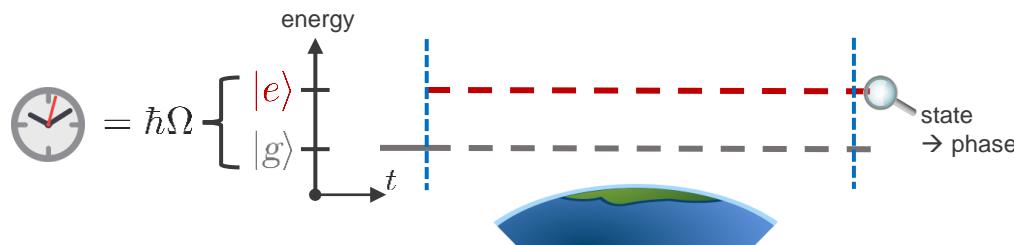
- two-level atom
- internal frequency Ω
- measured: (proper)time





Internal superposition

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Spatial superposition

- center-of-mass states
- position \hat{X} , momentum \hat{P}
- measured: accelerations

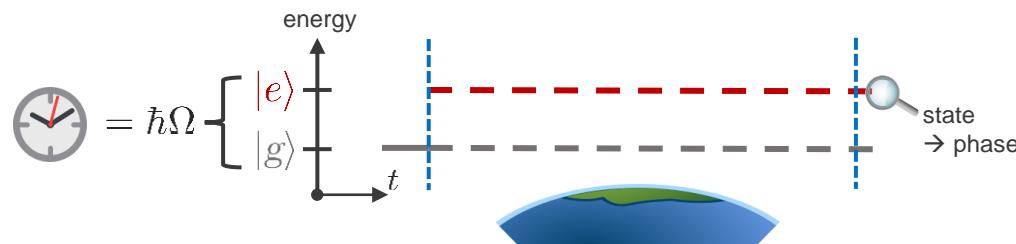




Clocks & atom interferometers

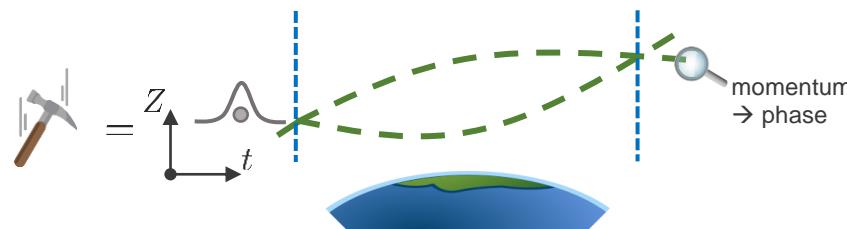
Internal superposition

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- measured: (proper)time



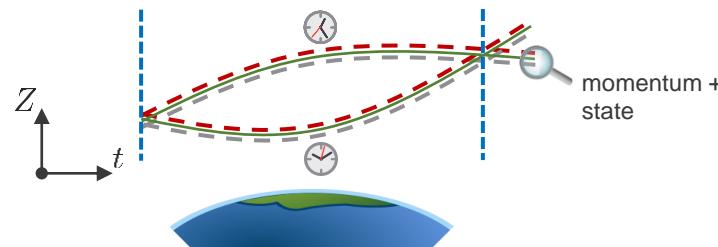
Spatial superposition

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- measured: accelerations



Combination

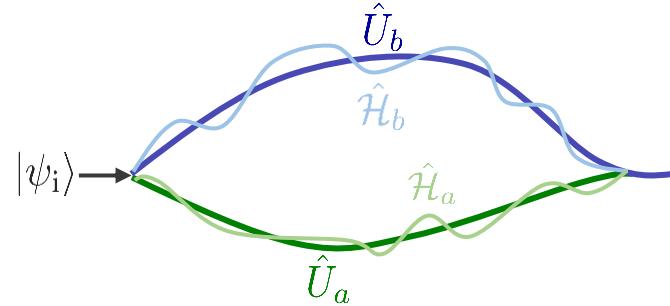
- clock on every branch
- quantum-clock interferometry



Interference signal from overlap

$$\langle \psi_i | \hat{U}_a^\dagger \hat{U}_b | \psi_i \rangle = C \exp(i\varphi)$$

↑ contrast ↓ phase



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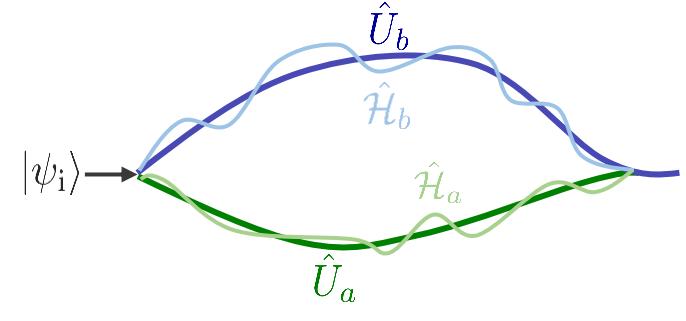
Phase from perturbation

Phys. Rev. A 101, 053615

$$\hat{H}_{a/b} = \hat{H}_{a/b}^0 + \hat{\mathcal{H}}_{a/b}$$

unperturbed perturbed

→ classical counterpart



→ $\int dt (\hat{\mathcal{H}}_b - \hat{\mathcal{H}}_a)$ along trajectory
(+ wave packet effects)

Interference signal from overlap

$$\langle \psi_i | \hat{U}_a^\dagger \hat{U}_b | \psi_i \rangle = C \exp(i\varphi)$$

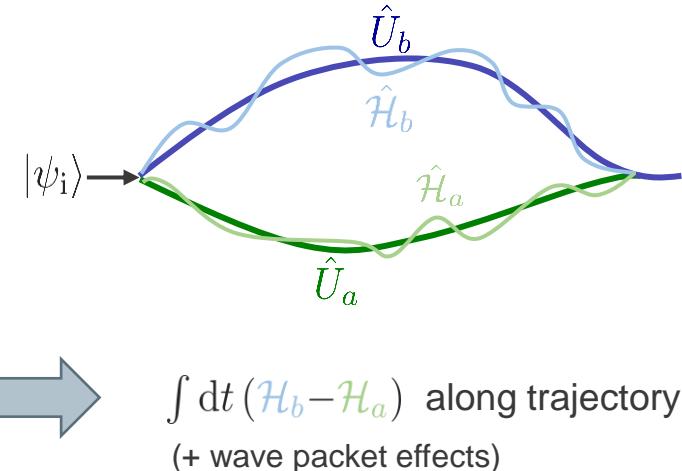
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unperturbed perturbed

Phys. Rev. A 101, 053615
classical counterpart
trajectory from $H_{a/b}^0$



Overview of perturbations

equivalence violations
PRX Quantum 2, 040333
(talk by E. Giese)

mass defect
Nat. Commun. 2, 505

non-inertial effects
Phys. Rev. A 103, 023305

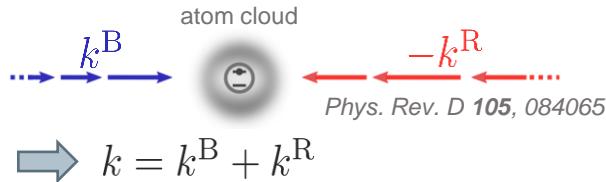
+ further relativistic perturbations (talk by E. Giese)

Phys. Rev. D 107, 064007; Phys. Rev. D 105, 084065



Free-fall test with atom interferometers

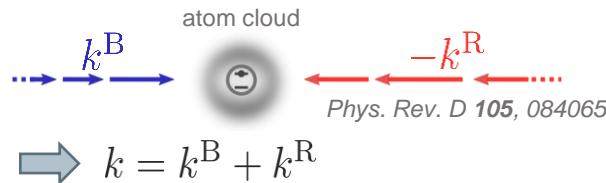
- spatial superposition via short light pulses





Free-fall test with atom interferometers

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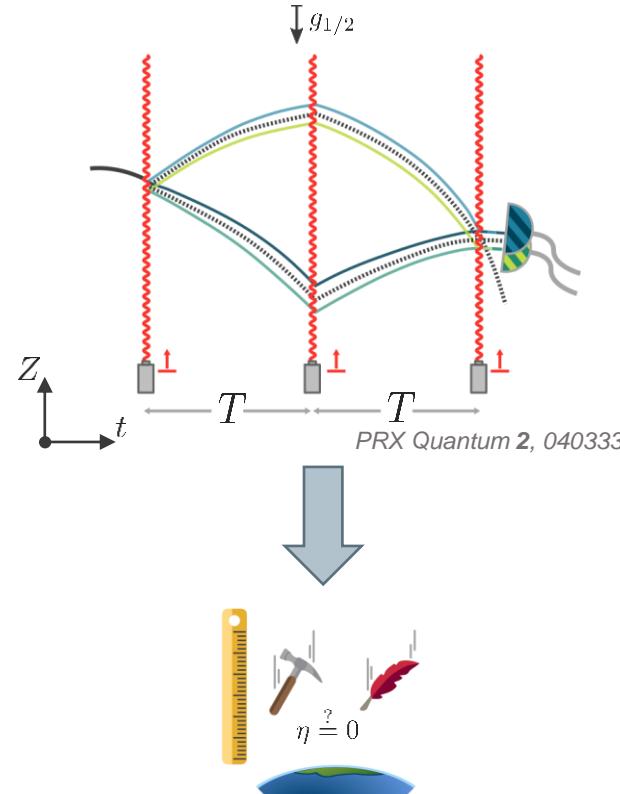


- Mach-Zehnder atom interferometer

→ two different masses

→ differential phase $-\eta kgT^2$

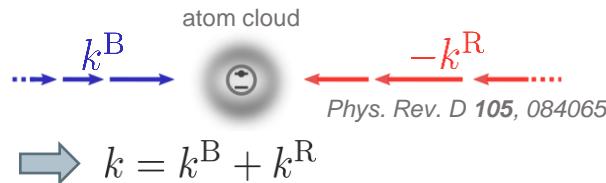
→ Eötvös parameter $\eta = (g_1 - g_2) / g$





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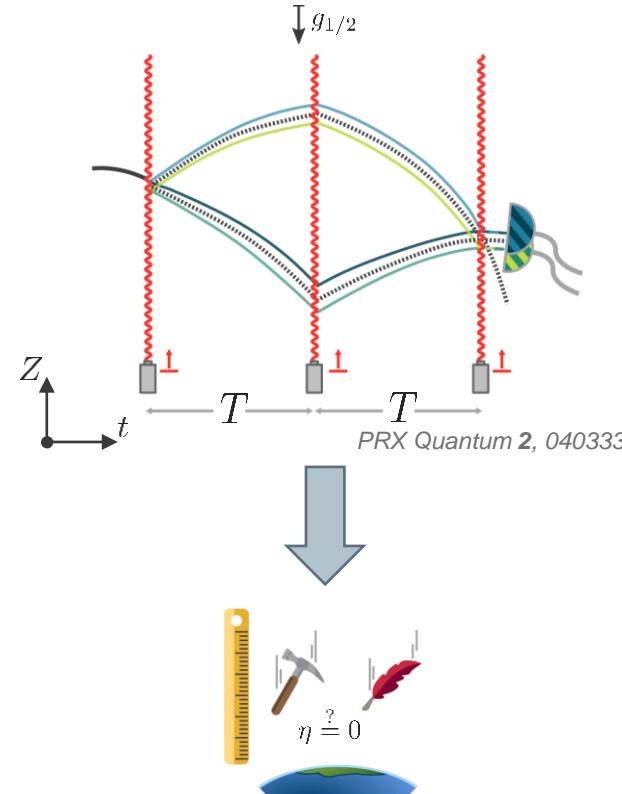
→ Eötvös parameter $\eta = (g_1 - g_2) / g$

- different masses via

➤ atomic species *Phys. Rev. Lett.* **112**, 203002

➤ isotopes *Phys. Rev. Lett.* **125**, 191101

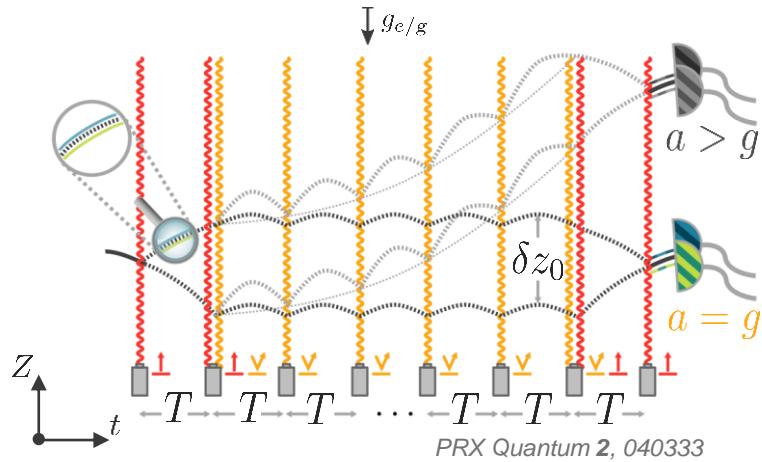
➤ internal states *Chin. Phys. Lett.* **37**, 043701





Redshift test with quantum-clock interferometry

- replace middle light pulse of Mach-Zehnder
- N levitating pulses \rightarrow acceleration a
- different masses via internal states
 \rightarrow quantum-clock interferometry





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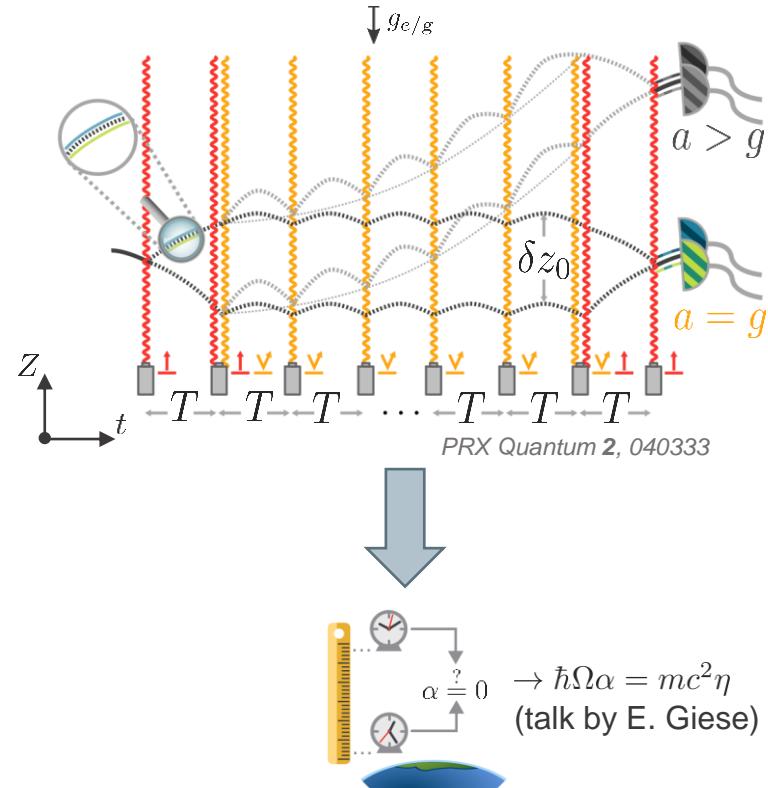
\rightarrow differential phase

$$-\Omega(a/g + \alpha)\delta\tau$$

↑
UGR violation

$$\text{with } \delta\tau = \delta z_0 g N T / c^2$$

\rightarrow UGR test for $a = g$





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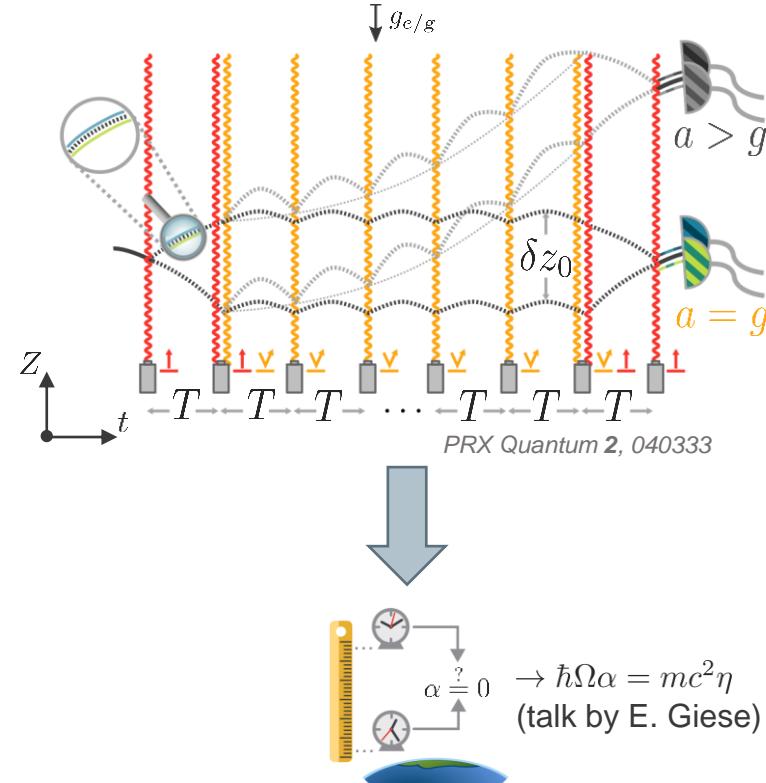
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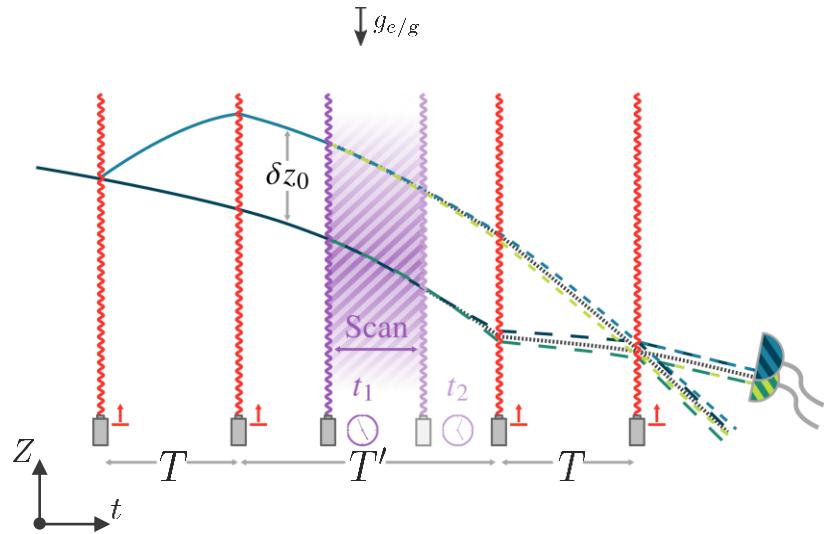
projected UGR sensitivity: $\alpha < 10^{-3}$

PRX Quantum 2, 040333

\rightarrow clock-based tests: $\alpha < 10^{-5}$

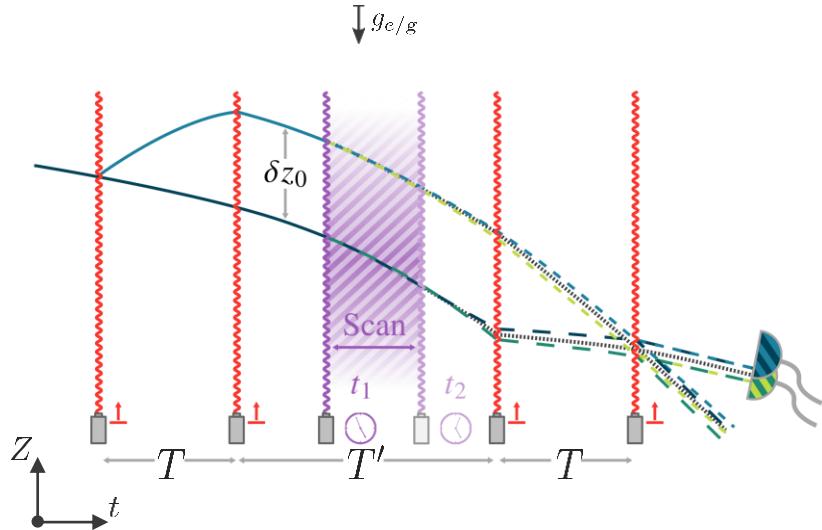
Phys. Rev. Lett. 121, 231102





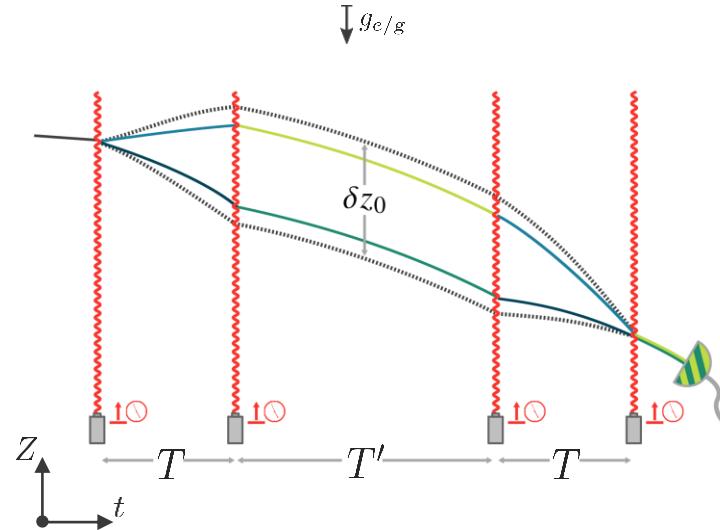
$$-\Omega(1 + \alpha) \delta z_0 g (t_2 - t_1) / c^2$$

Phys. Rev. X 10, 021014



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Phys. Rev. X 10, 021014



$$\mp \Omega(1 + \alpha) \delta z_0 g T' / c^2 - 2 k g T (T' + T) (1 + \eta_{g/e})$$

Phys. Rev. Research 2, 043240

→ both schemes: $-\Omega(1 + \alpha) \delta \tau$



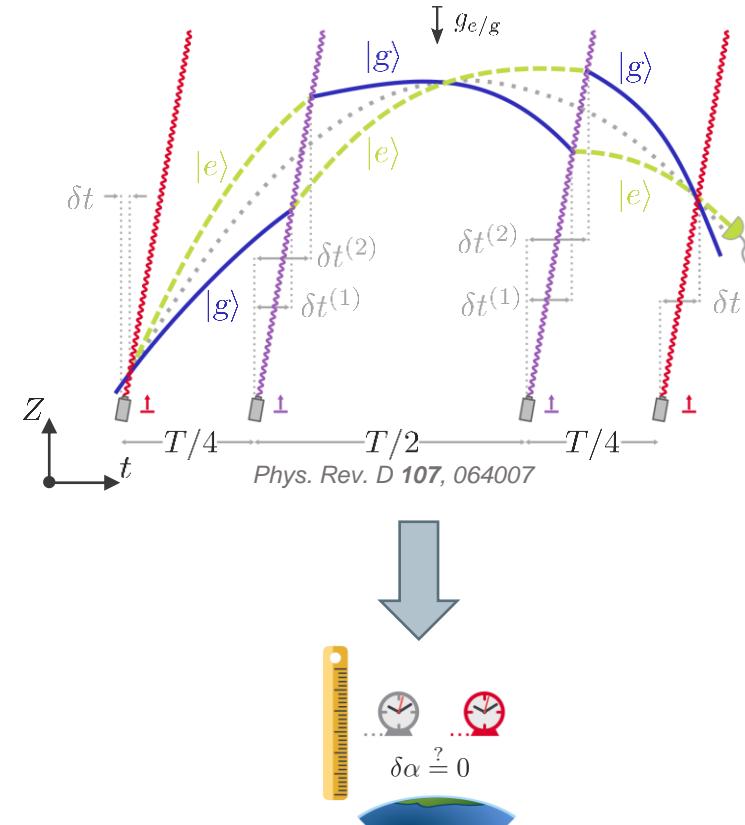
Clock-rate tests with quantum-clock interferometry

- competitive clock-rate test?



Clock-rate tests with quantum-clock interferometry

- competitive clock-rate test?
 - UCR test instead of UGR test
 - internal-state transitions
 - phase of single quantum clock
- $3\Omega\Delta\tau(1 + \alpha/2) / (16T) + \text{corrections}$
with $\Delta\tau = g^2 T^3 / (3c^2)$





Clock-rate tests with quantum-clock interferometry

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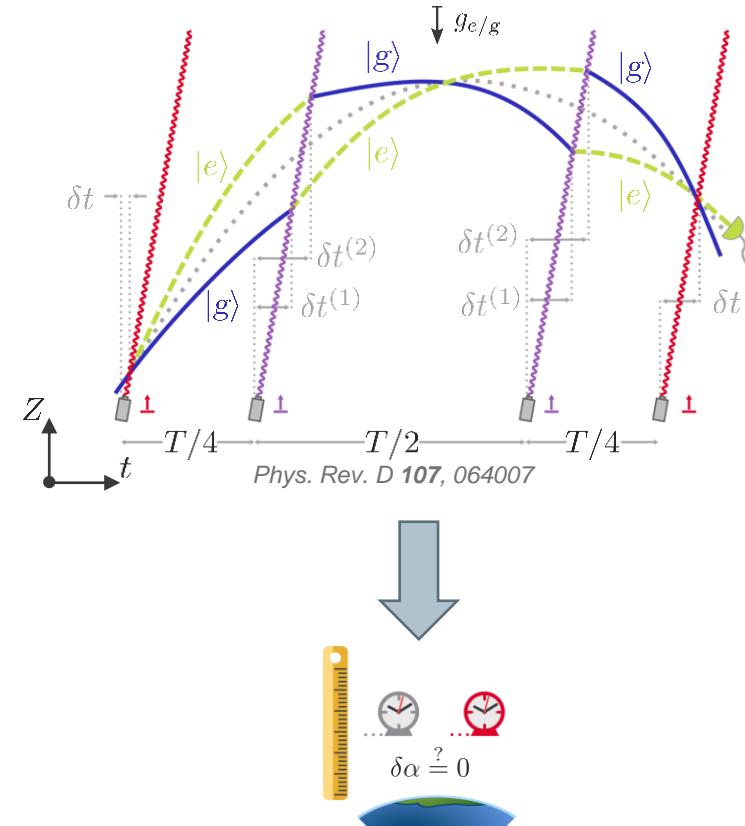
- two different isotopes

→ α_1 and α_2 : $\delta\alpha = \alpha_1 - \alpha_2$

→ differential measurement

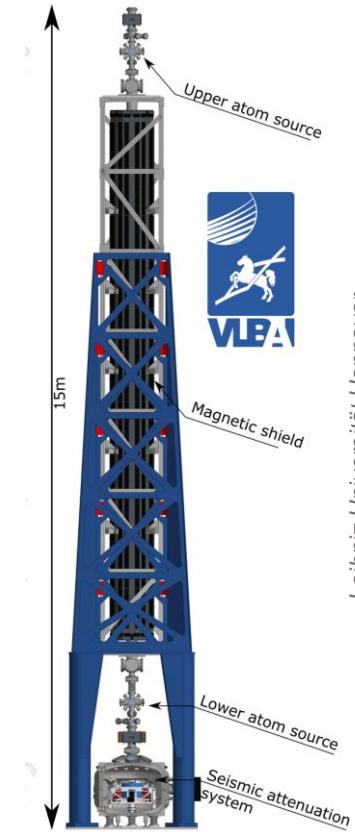
$$3\Delta\tau\delta\alpha/32T + \text{corrections}$$

UCR violation





Implementation in Very Long Baseline Atom Interferometry (VLBAI)



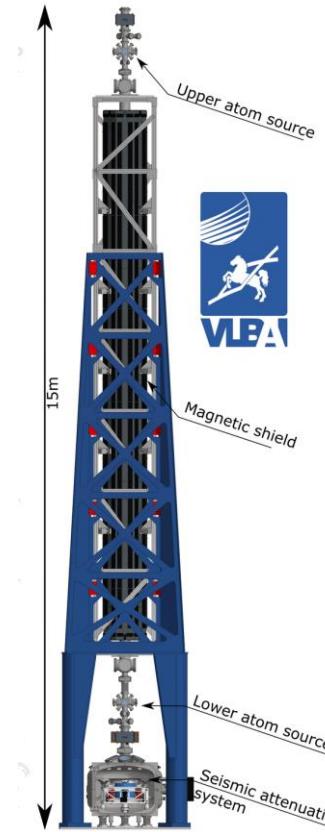


Implementation in Very Long Baseline Atom Interferometry (VLBAI)

experimental parameters:

$$T = 3 \text{ s} \quad 2 \cdot 10^6 \text{ rep}/140 \text{ d} \quad 10^7 \text{ atoms} \quad 6 \text{ s cycle time}$$

CPT and Lorentz Symmetry, pp. 37; Phys. Rev. Lett. **124**, 083604



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Hannover



Sensitivity estimates & parameters

Implementation in Very Long Baseline Atom Interferometry (VLBAI)

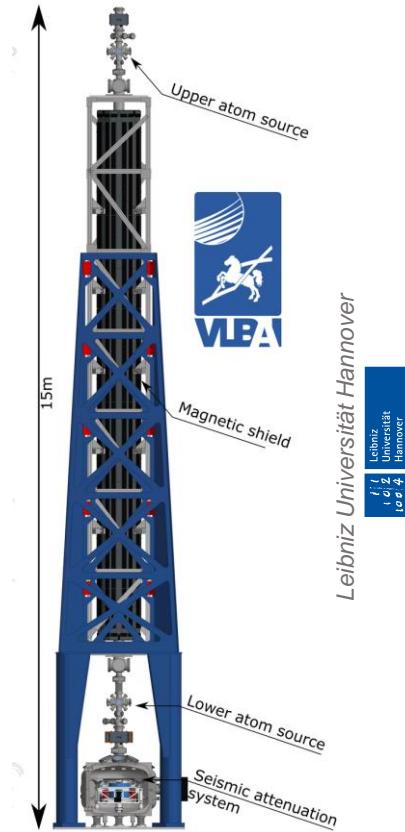
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CPT and Lorentz Symmetry, pp. 37; Phys. Rev. Lett. **124**, 083604

requirements from other perturbations:

speed of light: $\Delta Z_0 < 2.5 \text{ mm}$	accelerations: $\Delta a_0 < 2 \cdot 10^{-6} \text{ m/s}^2$	gradients: $\Delta v_0 < 2 \cdot 10^{-8} \text{ m/s}$
$\Delta v_0 < 0.8 \text{ mm/s}$		→ mitigation





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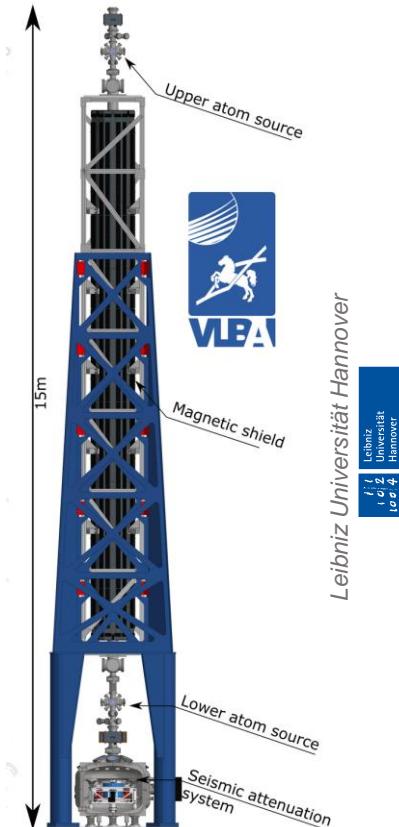
$$\begin{array}{ll} {}^{87}\text{Sr} \text{ and } {}^{88}\text{Sr}: & {}^{174}\text{Yb} \text{ and } {}^{176}\text{Yb}: \\ \delta\alpha < 1.2 \cdot 10^{-7} & \delta\alpha < 10^{-7} \end{array}$$

Phys. Rev. D **107**, 064007

atomic clocks:

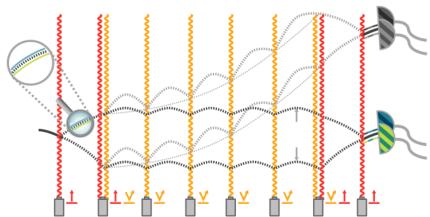
$$\begin{aligned} &< 2.2 \cdot 10^{-7} \\ &\text{Nature Phys. } \mathbf{14}, 882 \\ &\sim 10^{-7} \end{aligned}$$

Phys. Rev. Lett. **126**, 011102

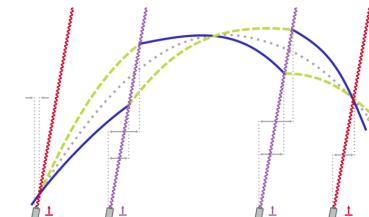




Conclusion



PRX Quantum **2**, 040333 (2021)



Phys. Rev. D **107**, 064007 (2023)

Thank you for your attention!

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fabio.di-pumpo@uni-ulm.de

