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

Albert Roura

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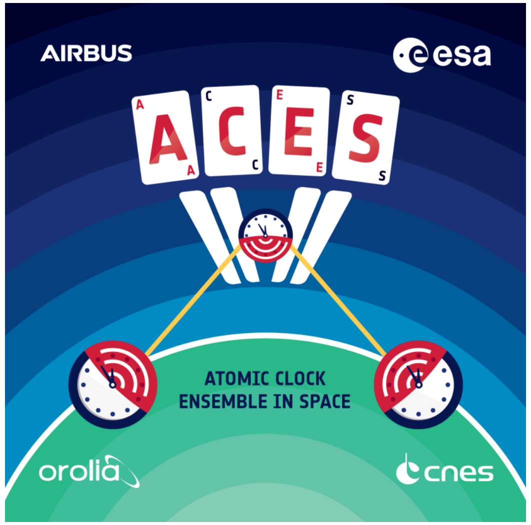
based on [Quantum Sci. Technol. 10, 025004 (2025)]

DLR

Part I

Recent update on the ACES Mission

ACES (Atomic Clock Ensemble in Space)



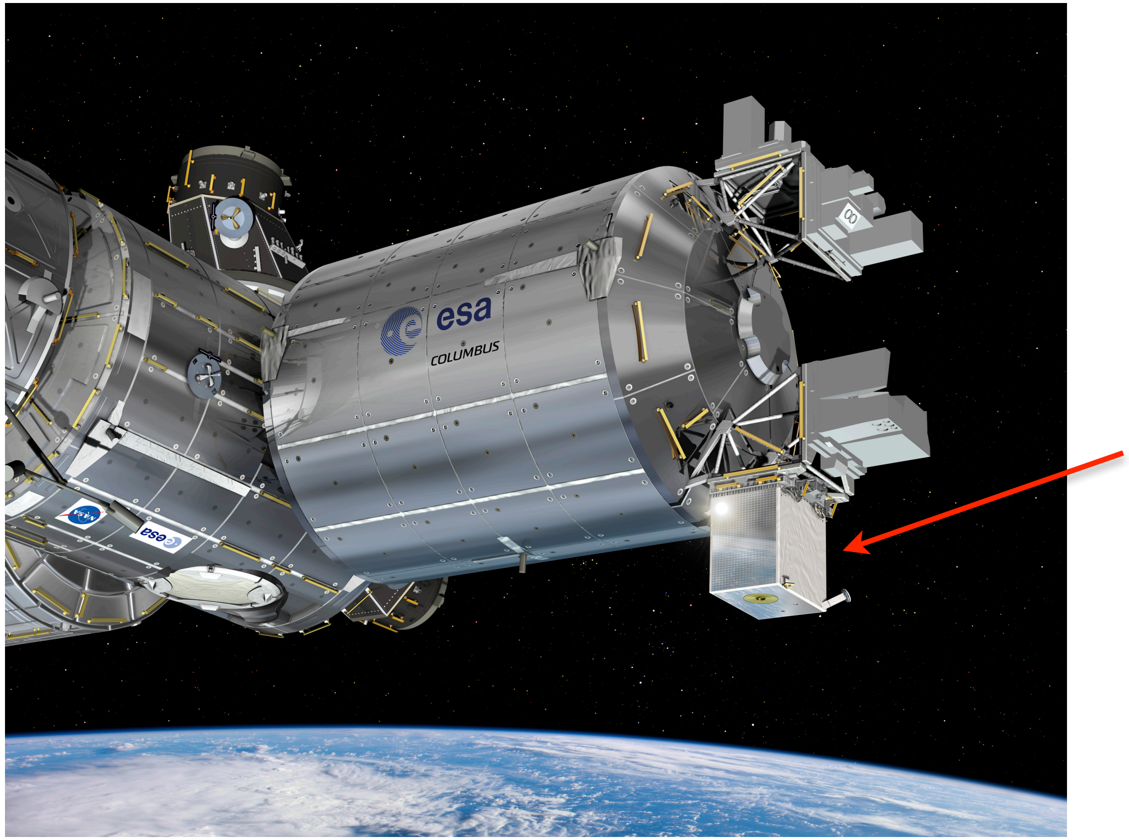
Project scientist: Luigi Cacciapuoti

PI: Christophe Salomon

- Target: first high-precision measurements with cold atoms in space.
- Important milestone for future ESA missions with cold atoms.
- Main scientific goals:
  - measuring gravitational redshift at 10^{-6} level
  - searching for dark matter, variations of fundamental constants
  - intercontinental clock comparison at 10^{-17} level
  - demonstration of chronometric geodesy at $10\,\mathrm{cm}$ level

Successful launch on 21 April 2025
Space X, Falcon 9 rocket

Bartolomeo platform
outside the ISS Columbus module



(recording played 100 times faster)

ACES

Atomic Clock Ensemble in Space

A European facility to test fundamental physics from outside ESA's Columbus module on the International Space Station. By creating a "network of clocks", ACES links its own precise timepieces, PHARAO and SHM, with the most accurate clocks on Earth to compare them and measure the flow of time.

1. **PHARAO**
   a clock which uses laser-cooled caesium atoms

2. **SHM**
   Space Hydrogen Maser, a clock which uses hydrogen atoms

3. **External payload computer (XLPC)**
   ACES computer

4. **PHARAO on-board management unit (OMU)**
   PHARAO clock's on-board computer

5. **PHARAO laser source**
   cools caesium atoms for the PHARAO clock

6. **Single photon avalanche diode (SPAD)**
   a highly sensitive device that can detect single photons of light

7. **Global navigation satellite system (GNSS) antenna**
   provides orbit determination of ACES to perform fundamental physics tests

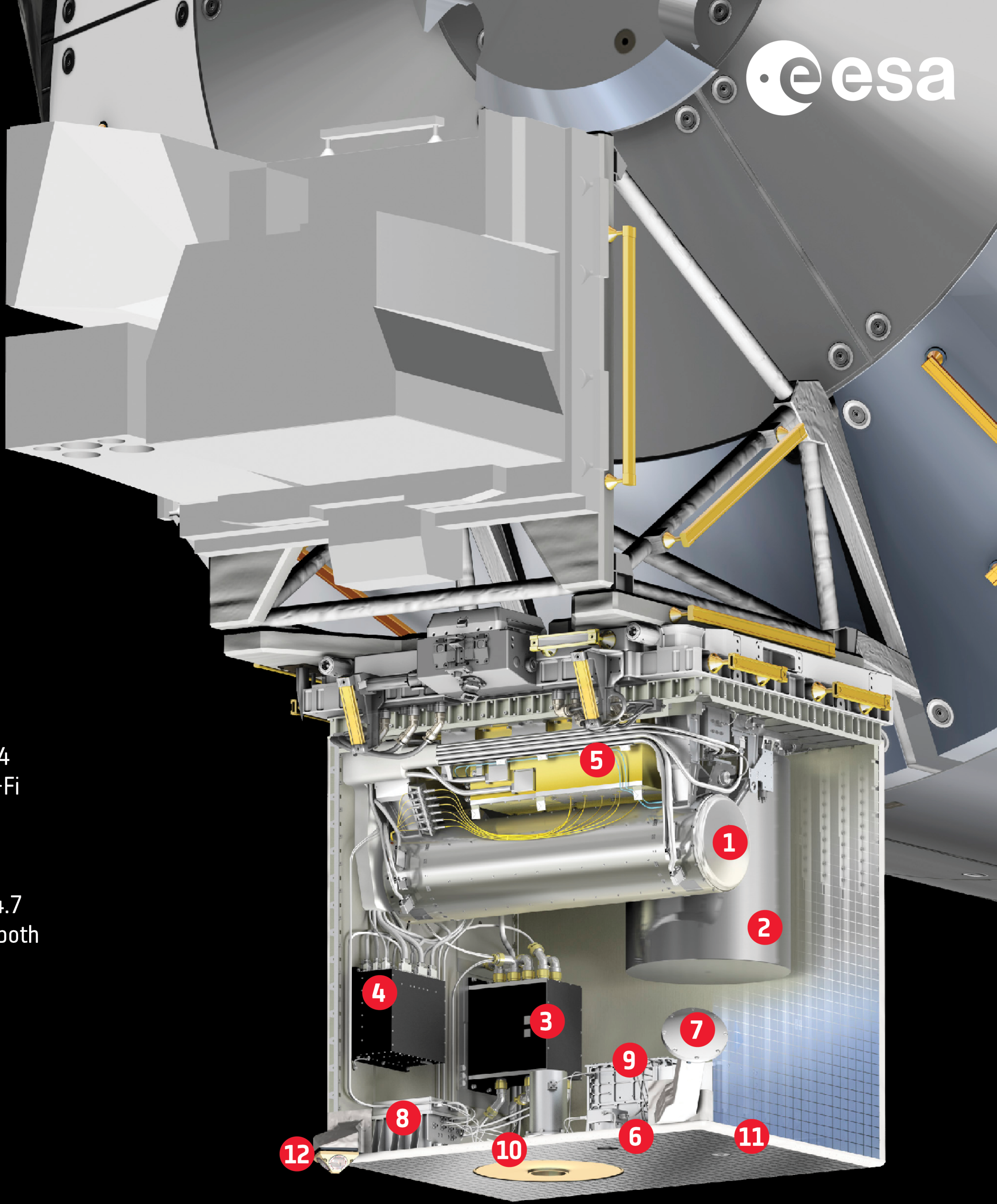
8. **Frequency comparison and distribution package (FCDP)**
   compares PHARAO and SHM and sends the ACES clock signal to the microwave link electronics

9. **Microwave link (MWL)**
   enables the comparison of clocks on Earth and in space through the exchange of microwave signals

10. **S-band microwave link antenna**
    transmits microwave signals with a frequency of 2.4 GHz, within the 2-4 GHz S-band range used for Wi-Fi and mobile phone communications

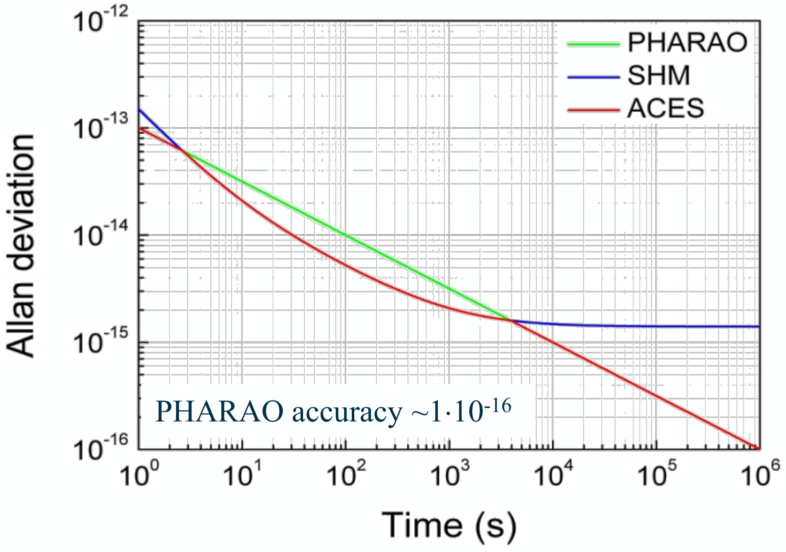
11. **Ku-band microwave link antenna**
    transmits microwave signals with a frequency of 14.7 GHz a receives signals at a frequency of 13.5 GHz, both within the Ku-band range used mostly for satellite communications

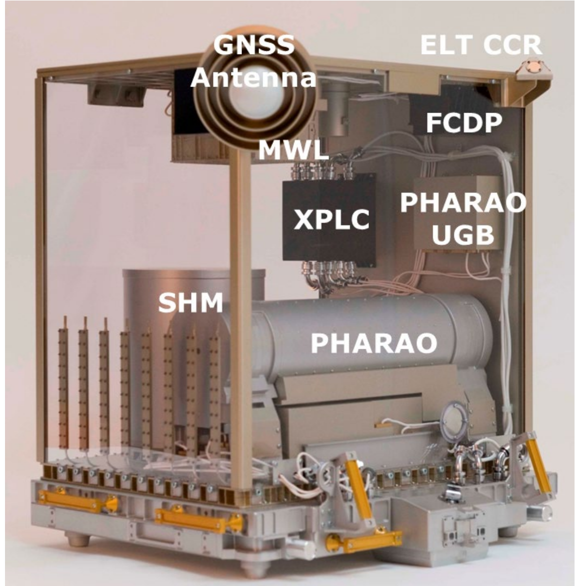
12. **European Laser Timing (ELT) reflector**
    enables the comparison of clocks on Earth and in space by using laser pulses



Highly accurate clock on the ISS:

- Space Hydrogen Maser + Atomic Clock with cold Cs atoms (relative accuracy of 10^{-16}).
- Microwave and Laser links: (intercontinental) comparison of ground clocks at 10^{-17} level.
- First high-precision measurement with cold atoms in space.





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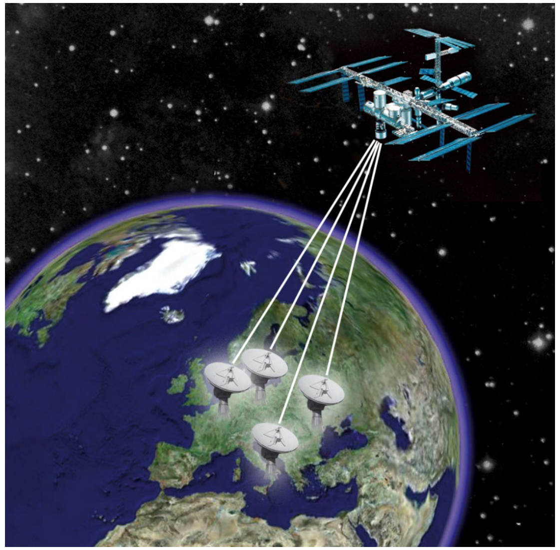
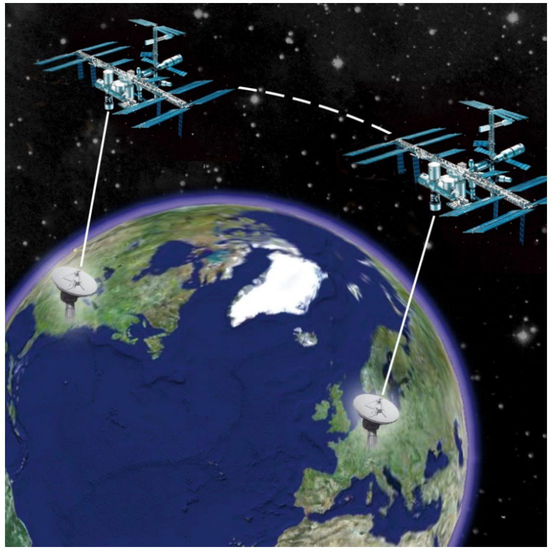
Fundamental Physics measurements:

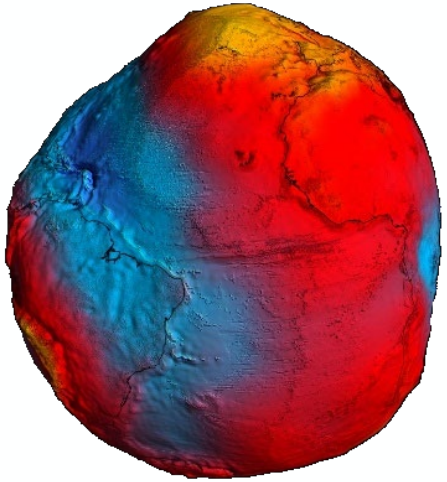
- Gravitational-redshift (relative uncertainty of 10^{-6}).
- Time variations of fundamental constants.
- Search for topological Dark Matter.

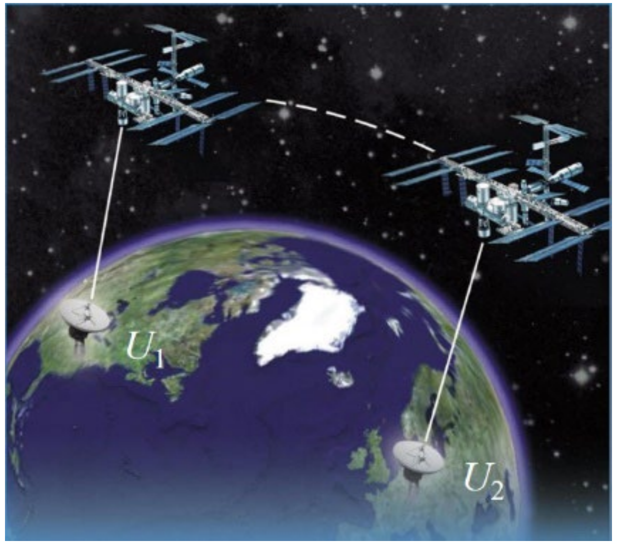




Other applications:

- Relativistic geodesy (determination of local height above geoid with 10 cm accuracy).
- Clock synchronization at 50 ps level.
- Contribution to atomic time scales (TAI).





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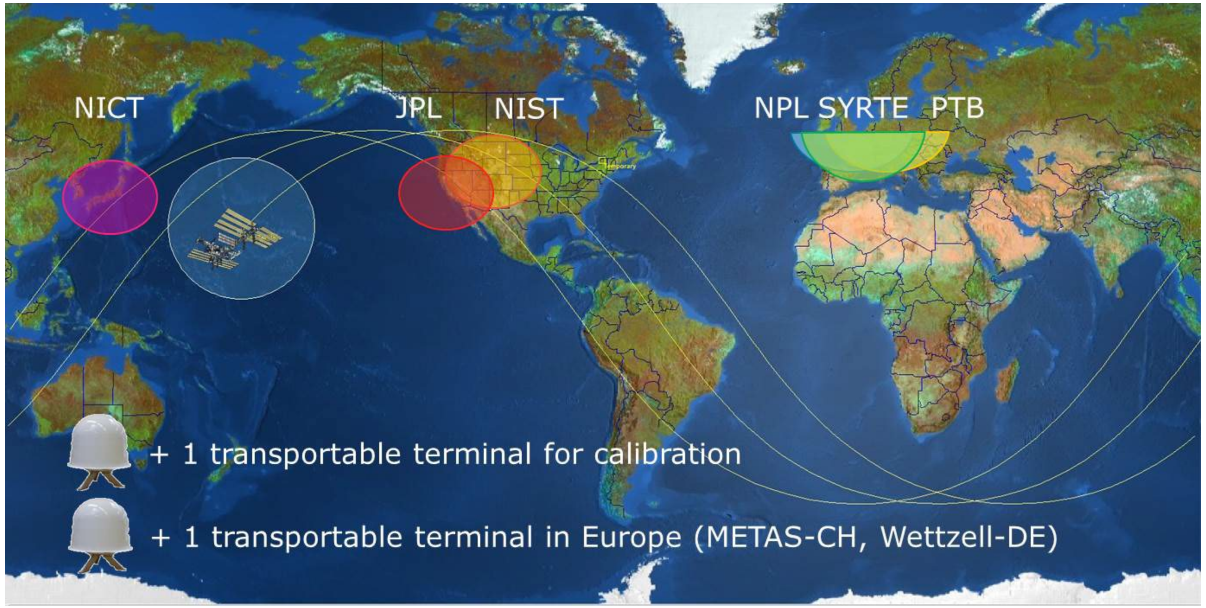

microwave link (MWL)

participating metrological institutes

Other applications:

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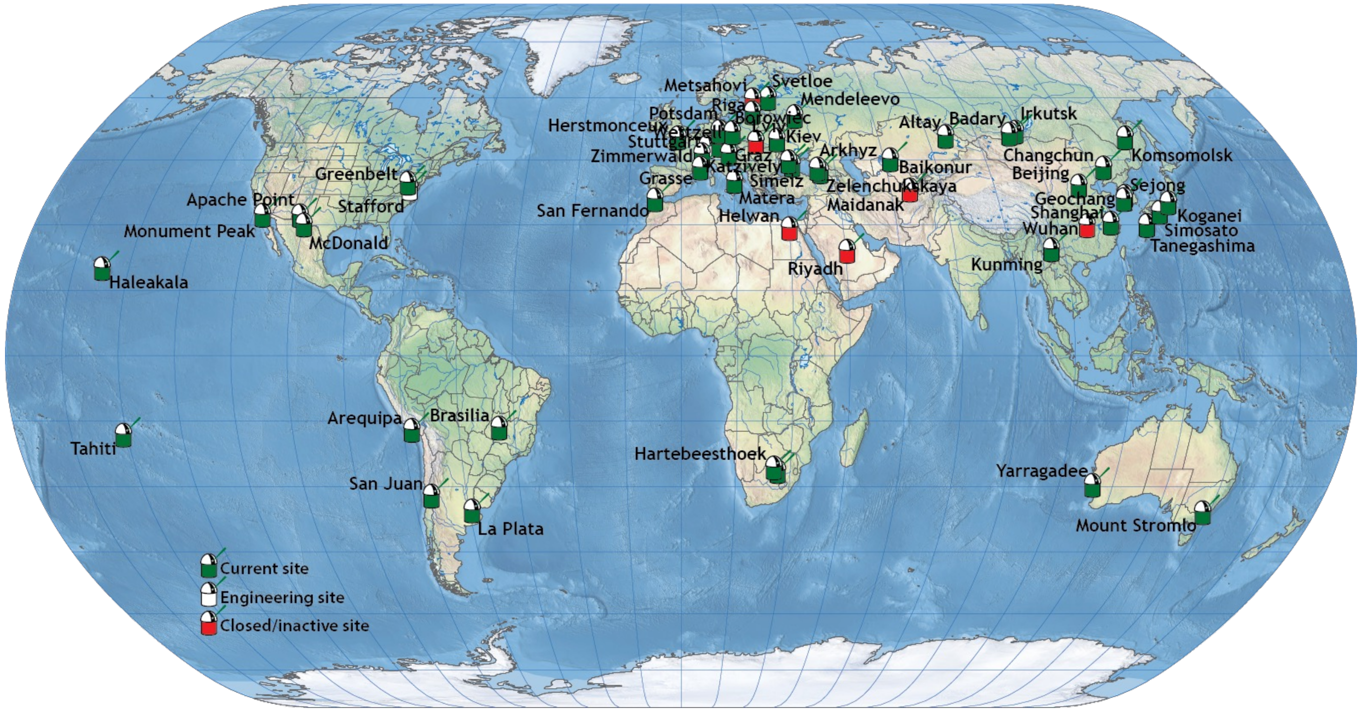
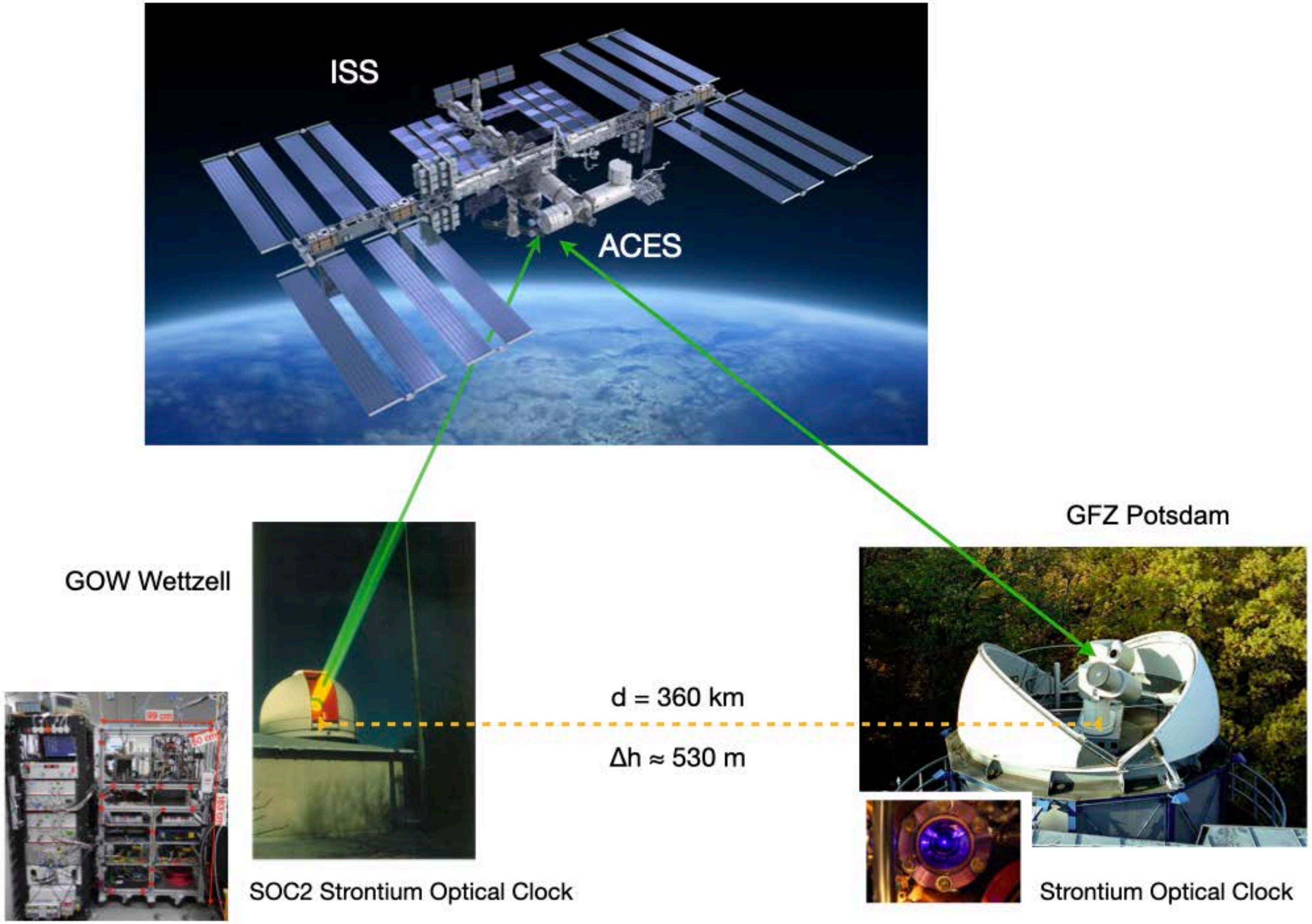


Satellite Laser Ranging (SLR) stations

Ulrich Schreiber



Part II

Detection of ultralight dark-matter fields

- Ultralight scalar field as a Dark Matter candidate:

$$\mathcal{L} = \underbrace{+\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2}_{\text{DM scalar field}} - \sqrt{4\pi G_N}\phi\left[\underbrace{d_{m_e} m_e \bar{e}e}_{\text{Electron coupling}} - \underbrace{\frac{d_e}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{Photon coupling}}\right] + \underbrace{\ldots}_{\text{e.g., QCD}}$$

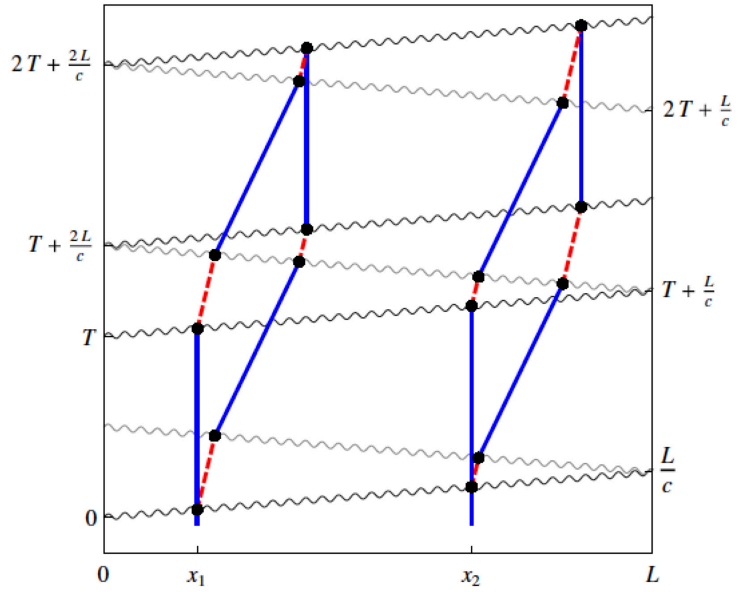
$$\phi\left(t,\mathbf{x}\right) = \phi_0 \cos\left[m_\phi(t - \mathbf{v}\cdot\mathbf{x}) + \beta\right] + \mathcal{O}\left(|\mathbf{v}|^2\right) \qquad \phi_0 \propto \sqrt{\rho_{\mathrm{DM}}}$$

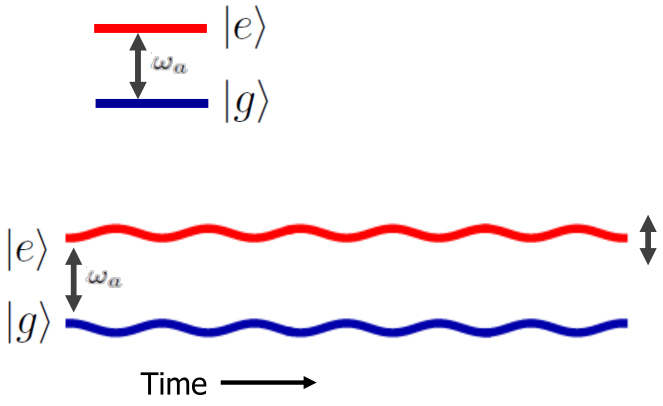
DM mass density

- Behaving as a bosonic condensate oscillating at the Compton frequency (non-relativistic matter-wave)

- Coupling to Standard Model fields $\longrightarrow$ "oscillations" of fundamental constants.

- Oscillations of *transition energies* at *Compton* frequency.

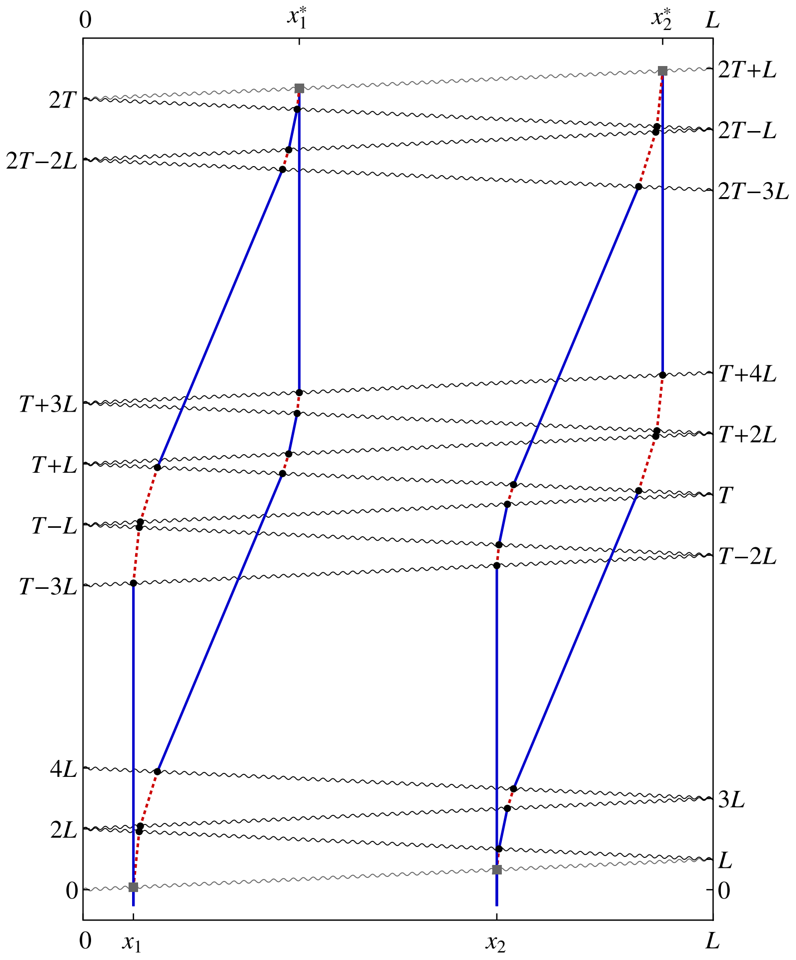




Arvanitaki *et al.*, *Phys. Rev. D* **97**, 075020 (2018)

- *Gradiometry-like* differential measurement with atom interferometers based on *single-photon* diffraction.

- Signal enhancement with LMT *pulse sequences:*

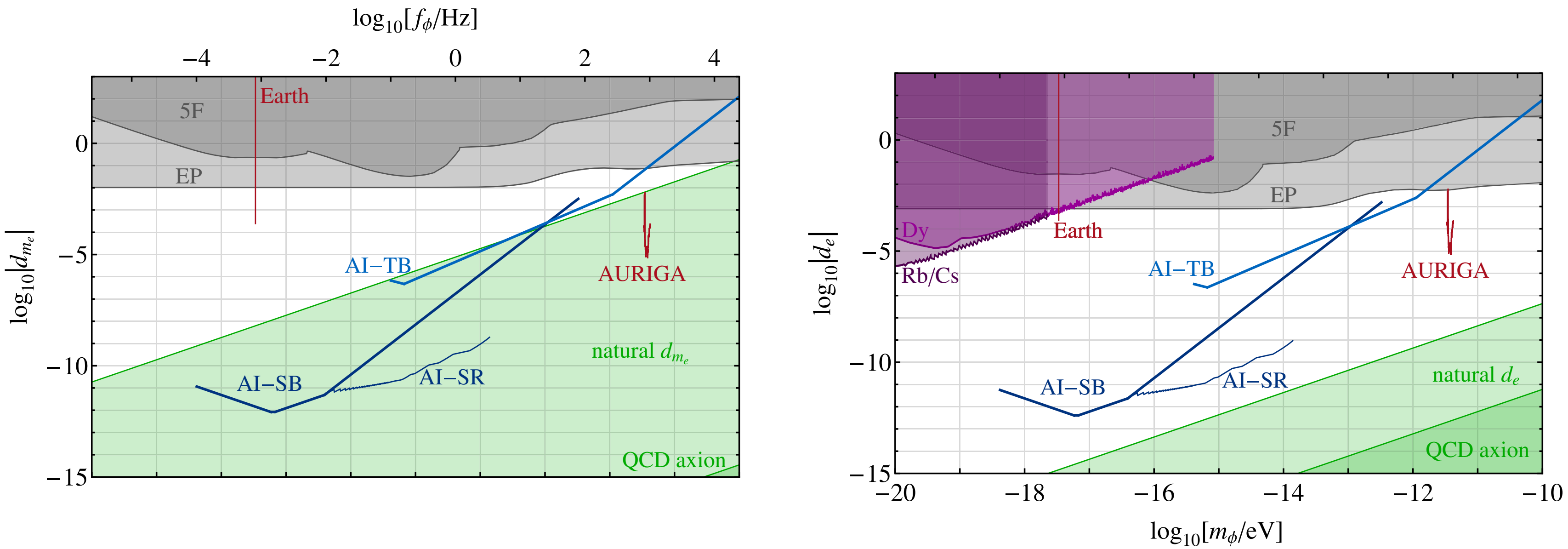


Arvanitaki *et al.*, *Phys. Rev. D* **97**, 075020 (2018)

- Significant coverage of *parameter space*:

$$\mathcal{L} = +\underbrace{\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2}_{\text{DM scalar field}} - \sqrt{4\pi G_N}\phi\left[\underbrace{d_{m_e}m_e\bar{e}e}_{\text{Electron coupling}} - \underbrace{\frac{d_e}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{Photon coupling}}\right] + \underbrace{\ldots}_{\text{e.g., QCD}}$$

$$\phi(t,\mathbf{x}) = \phi_0 \cos\left[m_\phi(t - \mathbf{v}\cdot\mathbf{x}) + \beta\right] + \mathcal{O}\left(|\mathbf{v}|^2\right) \qquad \phi_0 \propto \sqrt{\rho_{\mathrm{DM}}}$$ DM mass density

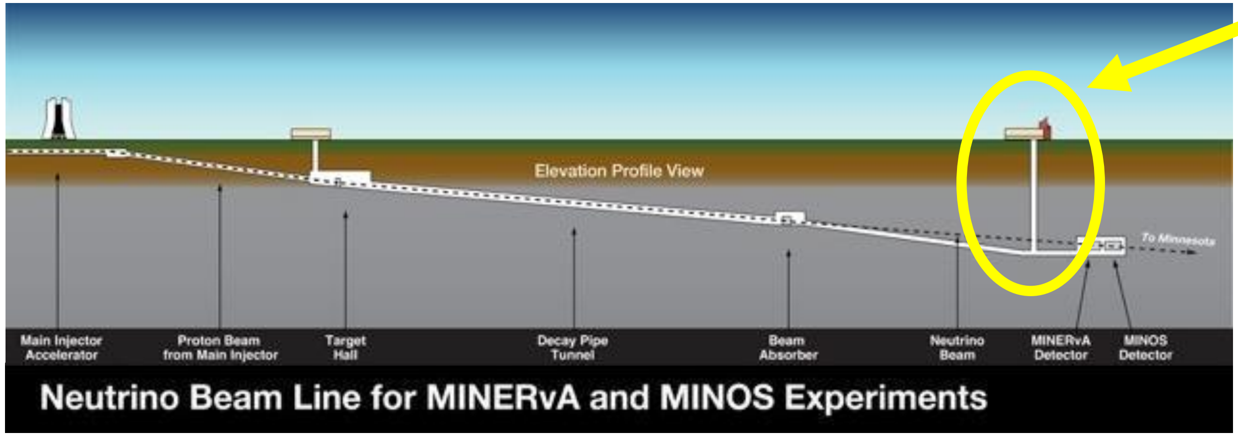


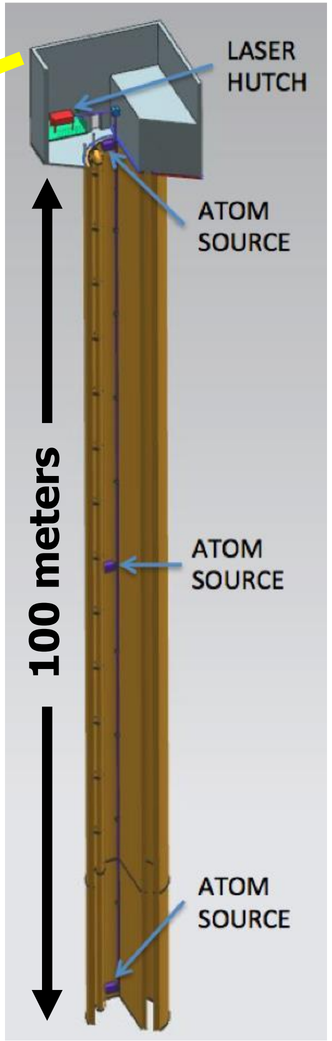
Jason Hogan, AION Workshop

Arvanitaki *et al.*, *Phys. Rev. D* **97**, 075020 (2018)

MAGIS-100: GW detector prototype at Fermilab

Matter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor





- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Intermediate step to full-scale (km) detector for gravitational waves
- Clock atom sources (Sr) at three positions to realize a gradiometer
- Probes for ultralight scalar dark matter beyond current limits (Hz range)
- Extreme quantum superposition states: >meter wavepacket separation, up to 9 seconds duration

STANFORD Fermilab BERKELEY UNIVERSITY OF LIVERPOOL Northwestern University Northern Illinois University

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El-Neaj et al. *EPJ Quantum Technology* (2020) 7:6
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EPJ Quantum Technology
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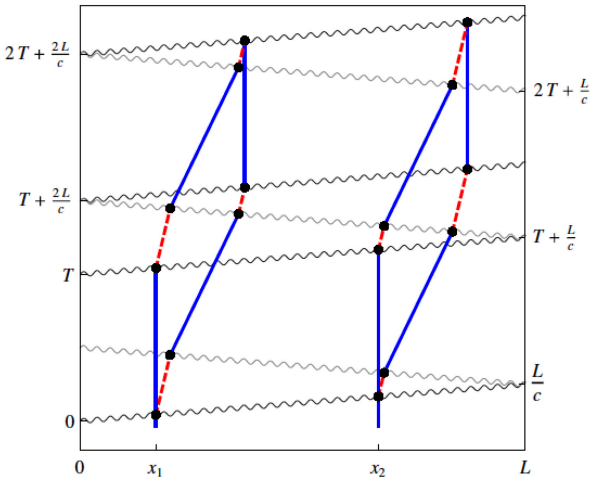
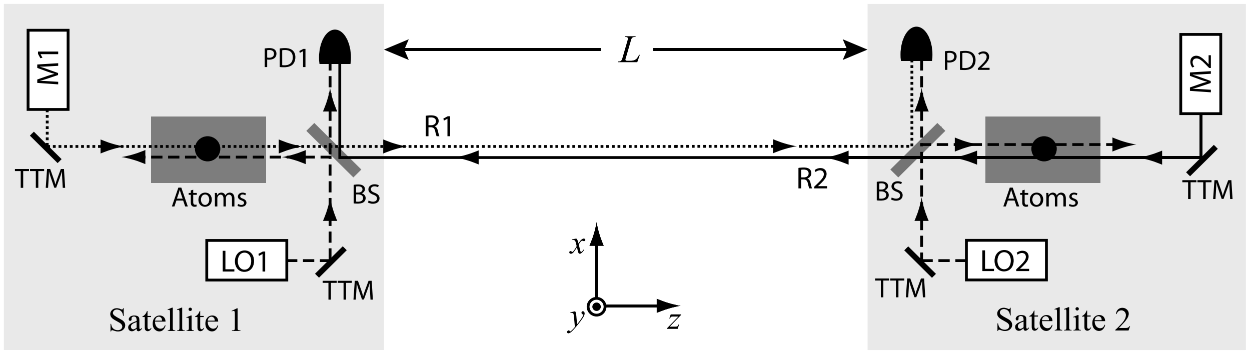
AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration in Space





Part III

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

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?

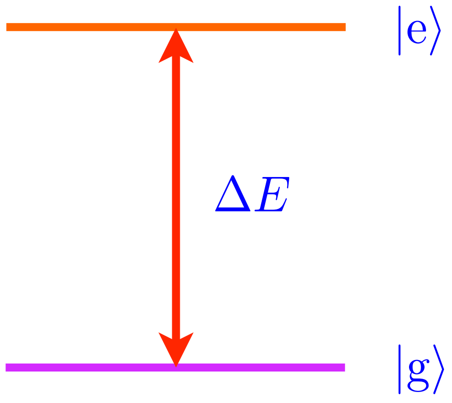
  Yes, local measurement of *relativistic time dilation* with freely falling atoms.

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

Outline

Relativistic effects in freely falling clocks

Quantum clock model



- *Initialization* pulse:

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

- 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:

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

free fall

- 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

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 $\big|\psi_{\mathrm{c}}^{(n)}(\tau_{\mathrm{c}})\big\rangle$

$\Delta p/m \ll c$ $\Delta x \ll \ell$

curvature radius

For further details:

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

Gravitational Redshift in Quantum-Clock Interferometry

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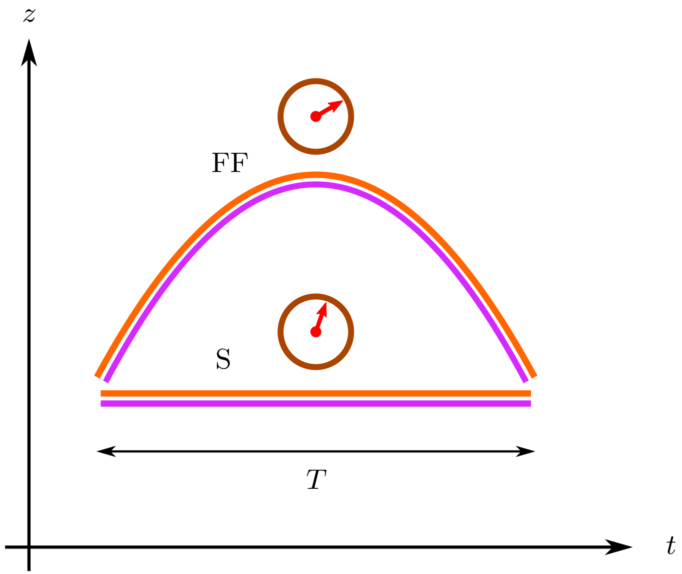
- *Relativistic* description of atom interferometry in *curved spacetime*.
- Including *external forces* and even *guiding potentials*.
- *Relativistic* interpretation of the *separation phase* in open interferometers.

Relativistic time dilation for a freely falling clock



- Freely falling clock (FF):

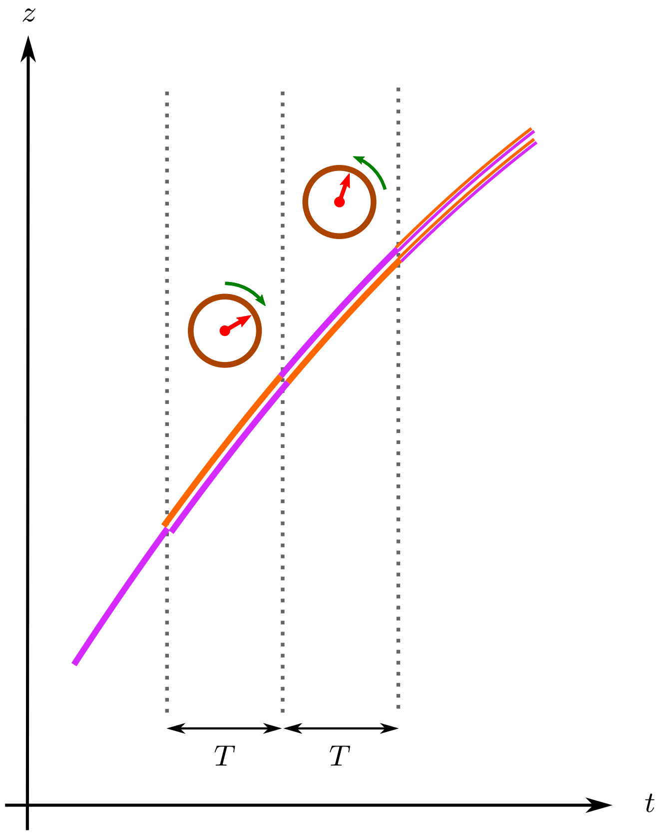
$$\delta\phi = -(\Delta E/\hbar)\left(\left(1 + U_0/c^2\right)T + \frac{1}{24}\frac{g^2T^3}{c^2}\right)$$

- 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



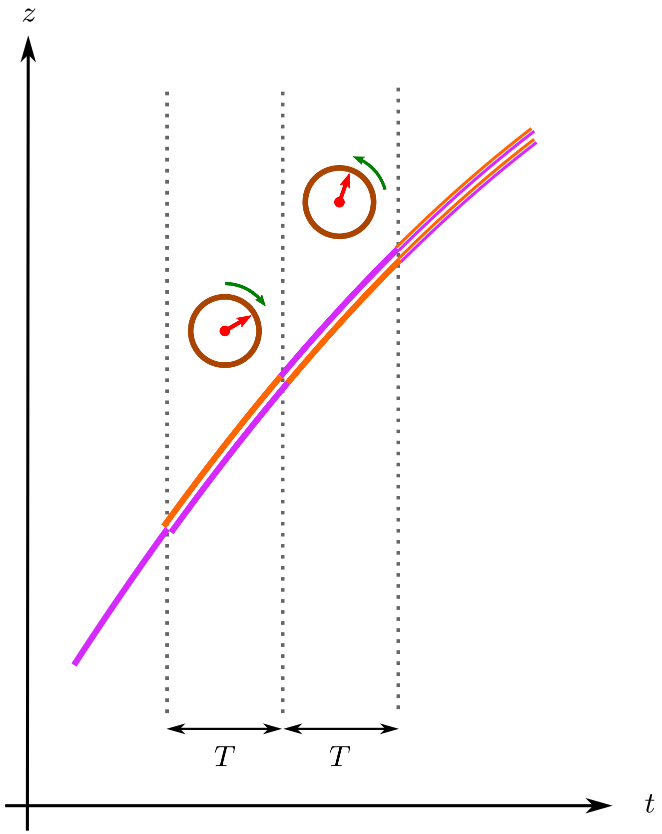
- Simultaneity hypersurfaces in the lab frame. (equal time separation)

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

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

$$\frac{d\tau}{dt} = 1 - \underbrace{\frac{1}{2\,c^2}\left(\frac{d\mathbf{X}}{dt}\right)^2}_{\text{special relativistic}} + \underbrace{\frac{1}{c^2}\,U(t,\mathbf{X})}_{\text{gravitational redshift}}$$

Freely falling clock with internal-state inversion



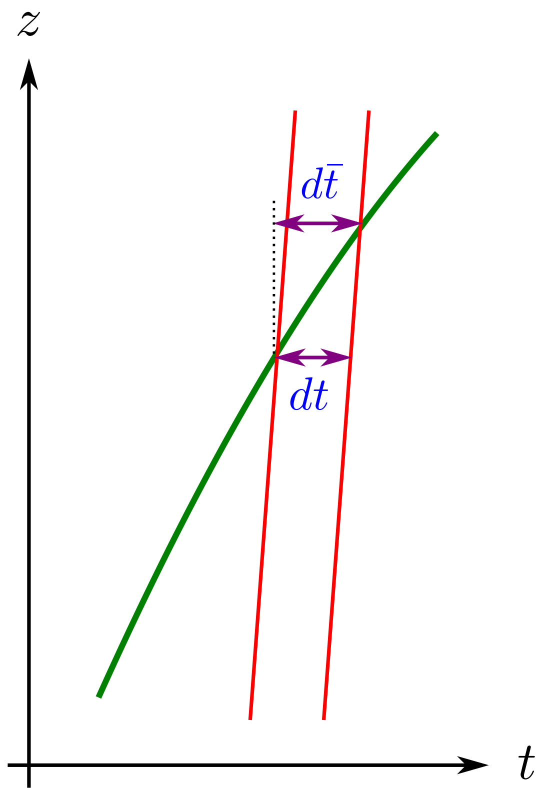
- Possible implementation with *Doppler-free* E2–M1 *two-photon* pulses at $\lambda_2 = 2 \times 698\,\mathrm{nm}$.
- Drawbacks:
  - dedicated high-power laser needed at λ_2
  - residual recoil ($m\,\Delta\mathbf{v} = -\Delta m\,\mathbf{v}$)
- Let us consider atom interferometers based on *single-photon* 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)

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

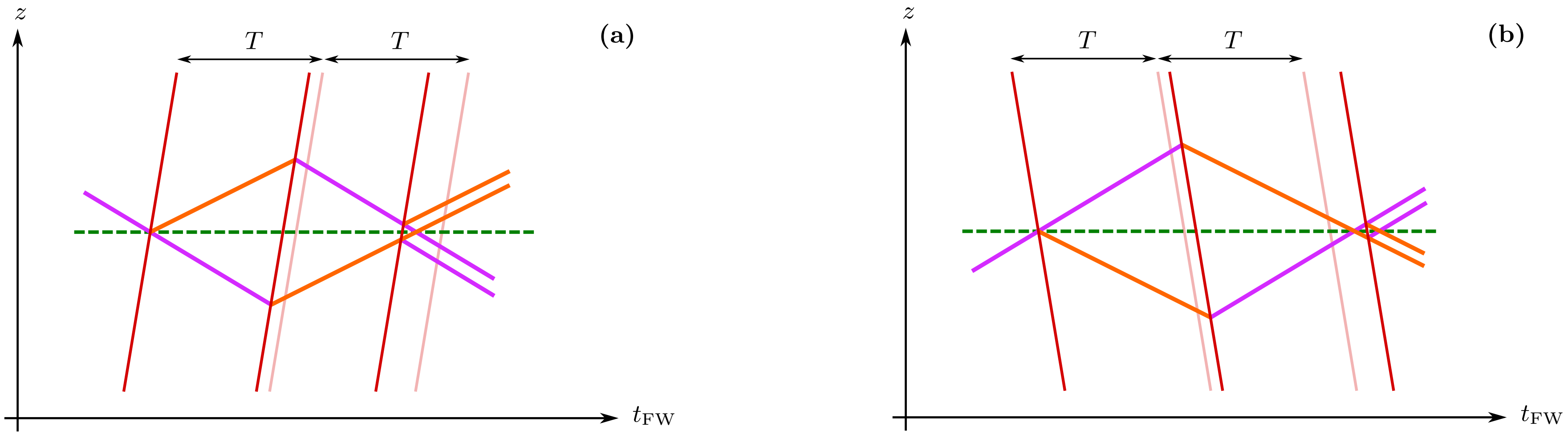
  - Relativistic *time dilation*:

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

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.

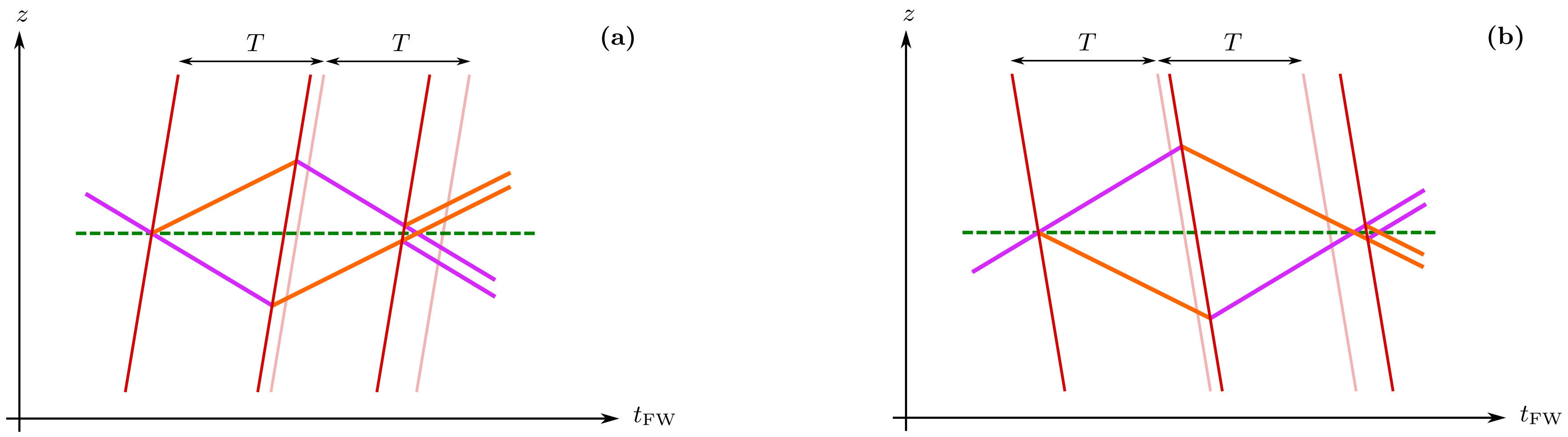
- For an imperfect match of the chirped frequency, with $\Delta\mathbf{g} = \mathbf{g} - \mathbf{g}'$ and $\Delta\bar{\mathbf{v}}_0 = \bar{\mathbf{v}}_0 - \bar{\mathbf{v}}_0'$.

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

- 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*.

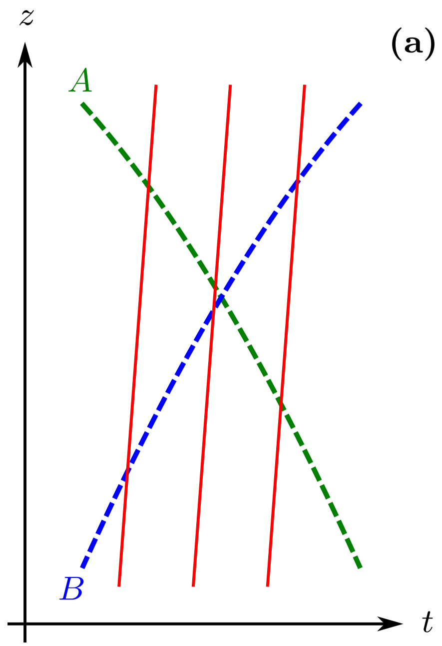
Reversed interferometers

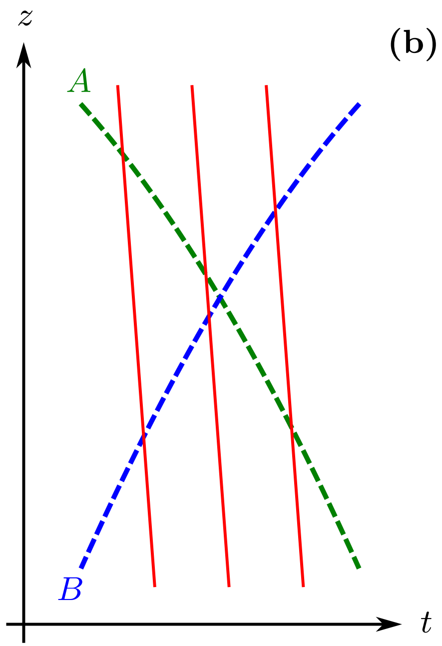


- Uncompensated Doppler contribution cancels out when adding up their phase shifts.

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

“Gradiometric” configuration





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

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

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

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

Experimental implementation

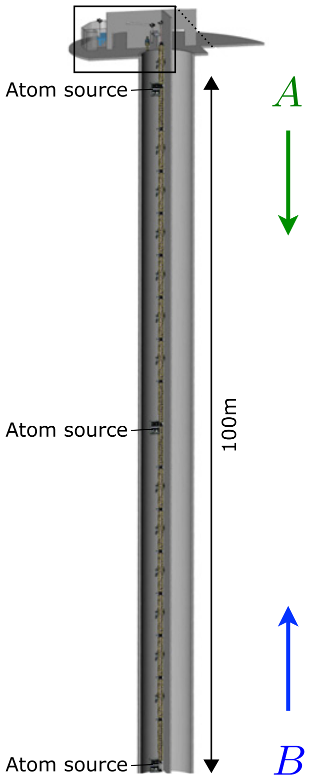
- Gradiometric configuration in MAGIS-100 with two simultaneous interferometers launched from the top and bottom atom source.

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

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

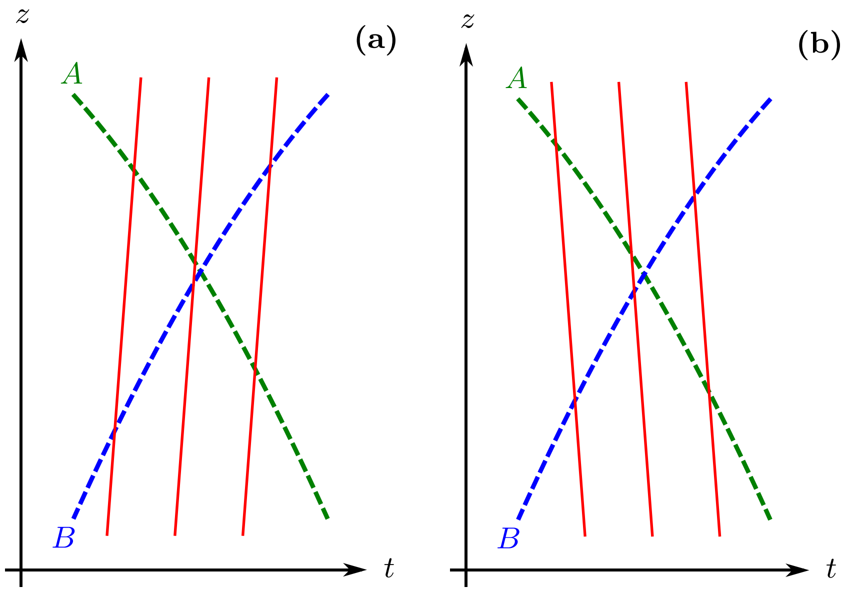
- With $N = 10^5$ detected atoms, a shot-noise-limited sensitivity at the 10^{-5} level can be reached in *a hundred shots*.

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



MAGIS-100

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



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

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

Main systematic effects

- Effects suppressed when adding up the phase shift for *reversed* interferometers:
  - gravity gradients (co-location at 0.1 mm and 0.1 mm/s level → 10^{-4} relative uncertainty)
  - rotations
  - wave-front curvature & light shifts
- Pulse timing requirements: $\Delta T \lesssim 0.1\,\mu\mathrm{s}$ and $\delta \lesssim 300\,\mathrm{Hz}$ → 10^{-5} relative uncertainty
- Magnetic field inhomogeneities: 3 nT / m → 10^{-5} relative uncertainty
- Temperature gradients: 2 K / 100 m → contribution at 10^{-2} level

further improvement through characterization and post-correction

Comparison to quantum-clock interferometry

Quantum-clock interferometry

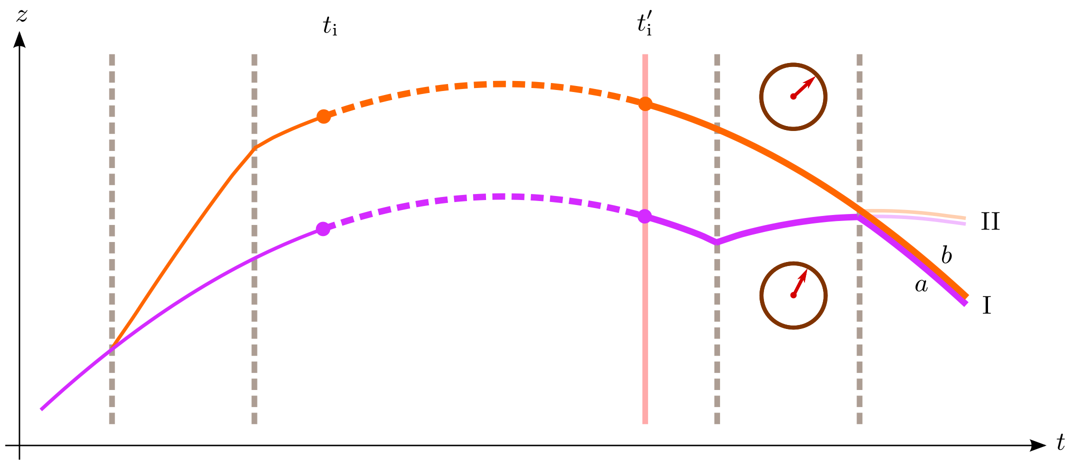
PHYSICAL REVIEW X **10**, 021014 (2020)

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



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.

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:

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PAPER

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

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

Thank you for your attention.

Deutsches Zentrum
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