Gravitational redshift in quantum-clock interferometry

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Ben-Gurion University, 16 June 2021

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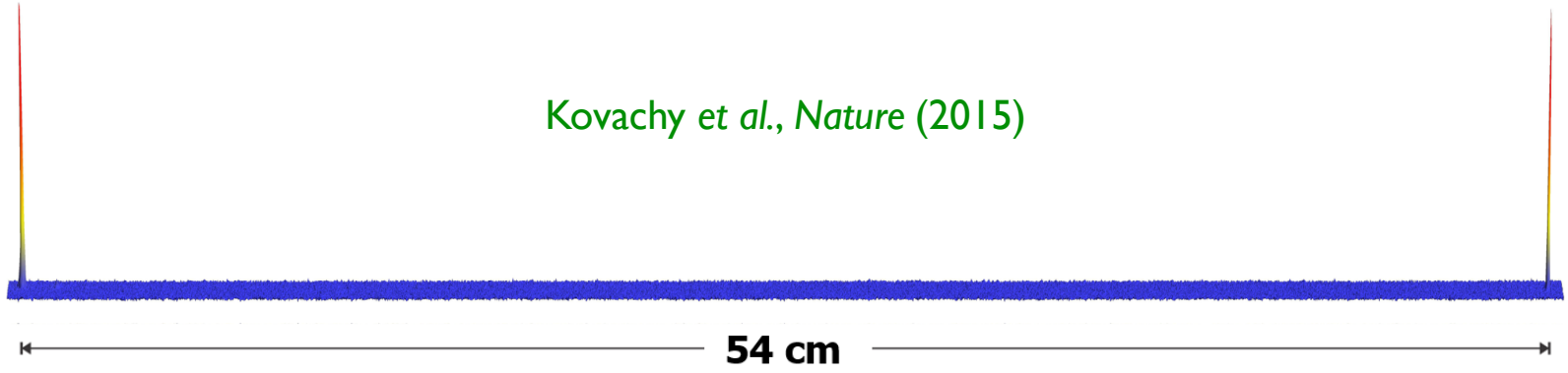
Relativistic effects in macroscopically delocalized quantum superpositions

- *Macroscopically* delocalized quantum superpositions:

  coherent superposition of atomic wave packets



- Differences in *dynamics* of superposition components

  → entirely Newtonian

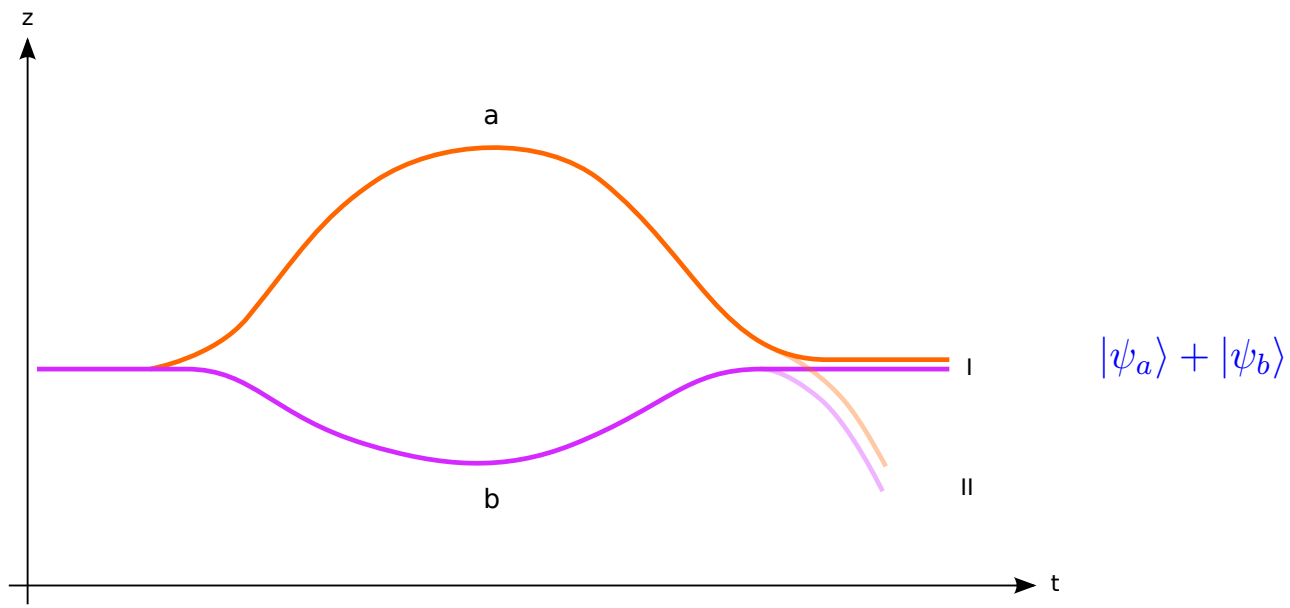
- Same relativistic effects on superposition components

  (e.g. atomic clocks)

★ <u>Goal</u> (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. Comm.* (2011)

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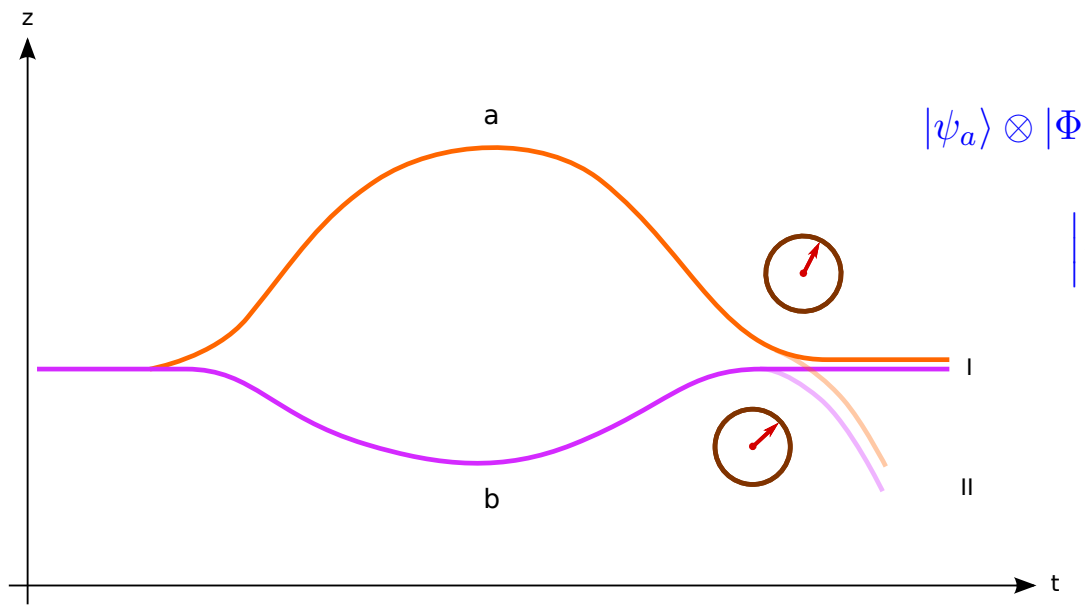


$$|\psi_a\rangle \otimes |\Phi(\tau_a)\rangle + |\psi_b\rangle \otimes |\Phi(\tau_b)\rangle$$

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

→ *reduced visibility* of interference signal

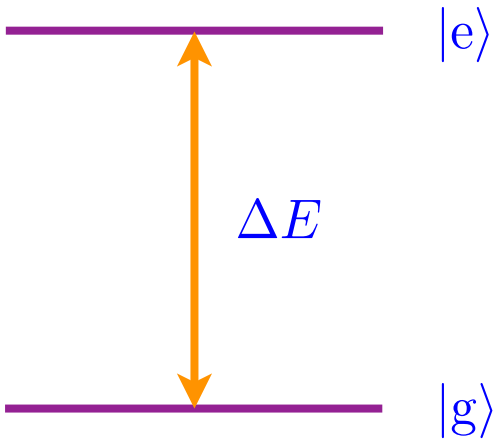
Zych *et al.*, *Nat. Comm.* (2011)

Outline

1. Relativistic effects in macroscopically delocalized quantum superpositions
2. Key elements of quantum-clock interferometry
3. Major challenges in quantum-clock interferometry
4. Doubly differential gravitational-redshift measurement
5. Alternative implementation
6. Conclusion

Key elements of quantum-clock interferometry

Quantum-clock model



- *Initialization* pulse:

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

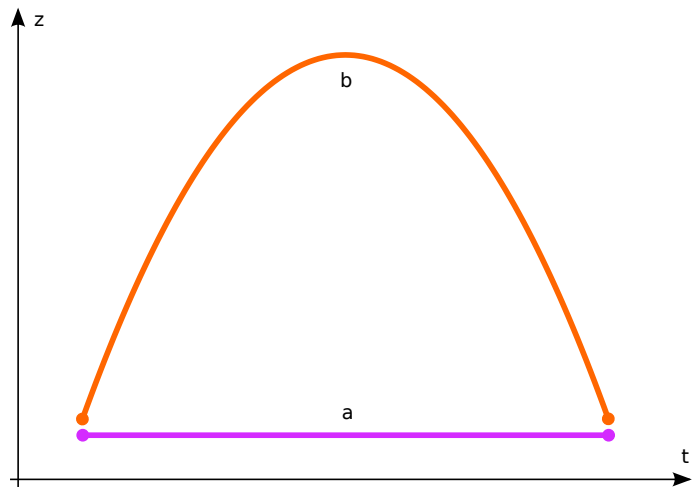
- Evolution:

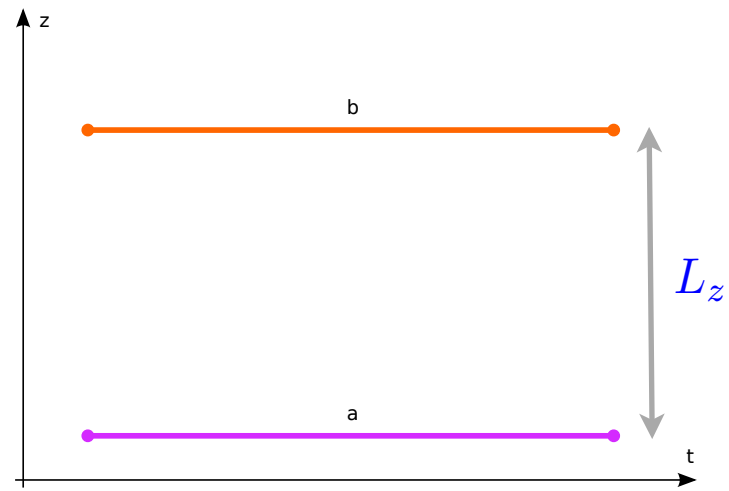
$$\big|\Phi(\tau)\big\rangle \propto \frac{1}{\sqrt{2}}\Big(|\mathrm{g}\rangle + i\, e^{i\varphi} e^{-i\Delta E\,\tau/\hbar}|\mathrm{e}\rangle\Big)$$

- 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):





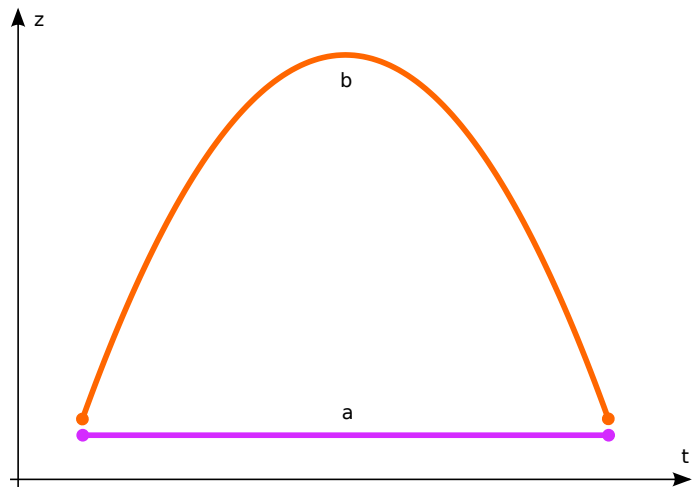
$$\Delta\tau_b - \Delta\tau_a \approx \left(g\, L_z/c^2\right) \Delta t$$

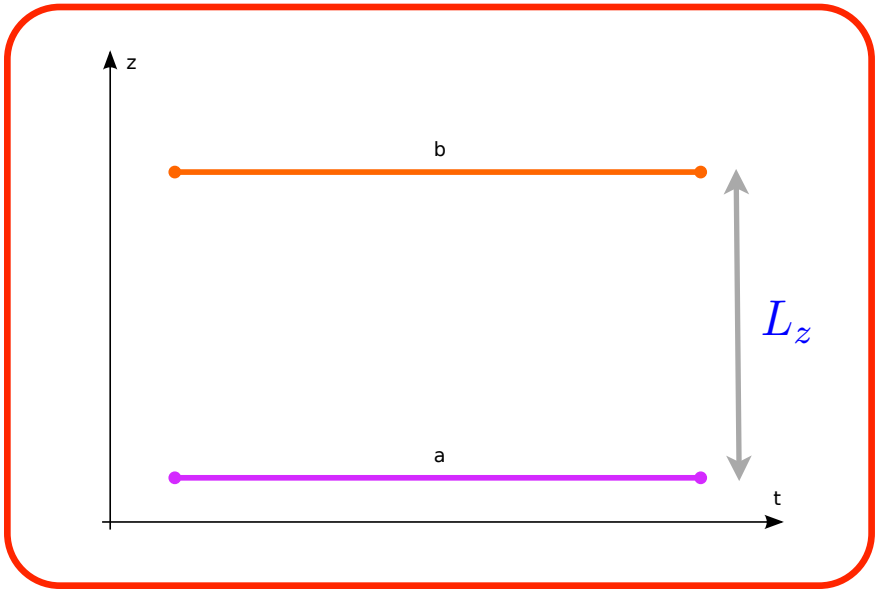
for optical *atomic clocks*

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

- Instead of independent clocks we pursue a quantum superposition at *different heights*.

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





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- Instead of independent clocks we pursue a quantum superposition at *different heights*.

- 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

$$S_n\left[x^\mu(\lambda)\right] = -m_n c^2 \int d\tau - \int d\tau\, V_n(x^\mu)$$

including external forces

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

free fall

$$S_n\left[x^\mu(\lambda)\right] = -m_n c^2 \int d\tau - \int d\tau\, V_n(x^\mu)$$

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 $\left|\psi_{\rm c}^{(n)}(\tau_{\rm c})\right\rangle$

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

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

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

$$\begin{aligned}
g_{00} &= -\big(1 + \delta_{ij}\,a^i(\tau_\mathrm{c})\,x^j/c^2\,\big)^2 - R_{0i0j}(\tau_\mathrm{c},\mathbf{0})\,x^i x^j + O\big(|\mathbf{x}|^3\big)\\
g_{0i} &= -\frac{2}{3}R_{0jik}(\tau_\mathrm{c},\mathbf{0})\,x^j x^k + O\big(|\mathbf{x}|^3\big)\\
g_{ij} &= \delta_{ij} - \frac{1}{3}R_{ikjl}(\tau_\mathrm{c},\mathbf{0})\,x^k x^l + O\big(|\mathbf{x}|^3\big)
\end{aligned}$$

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

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

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

Comoving frame:

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

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

- Wave-packet evolution: $\left|\psi^{(n)}(\tau_c)\right\rangle \;=\; e^{i\mathcal{S}_n/\hbar}\,\left|\psi_c^{(n)}(\tau_c)\right\rangle$

  - *propagation phase*

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

  - *centered wave packet*

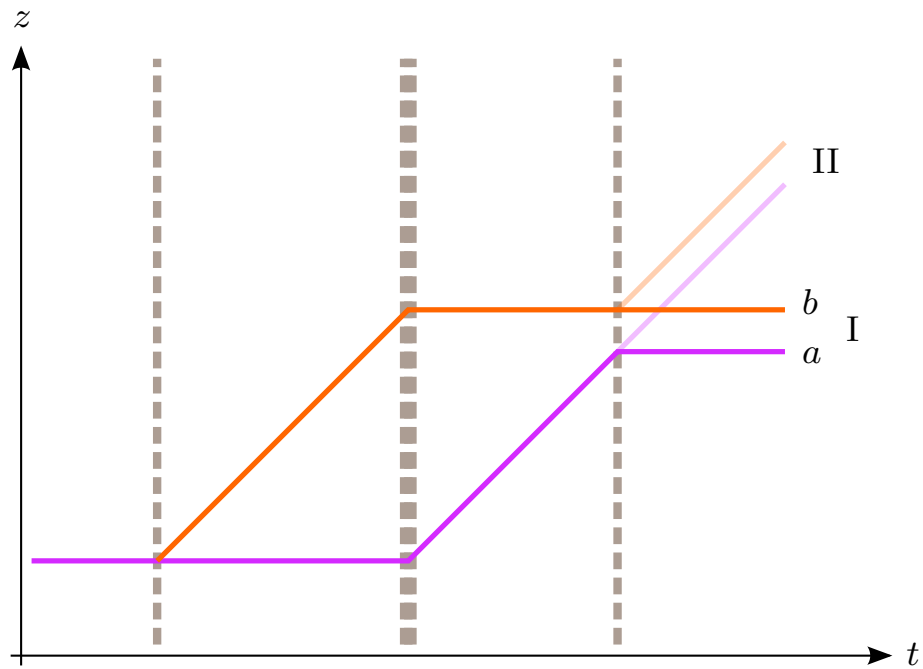
$$i\hbar\,\frac{d}{d\tau_c}\left|\psi_c^{(n)}(\tau_c)\right\rangle = \hat{H}_c^{(n)}\,\left|\psi_c^{(n)}(\tau_c)\right\rangle$$

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

gravity-gradient tensor

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

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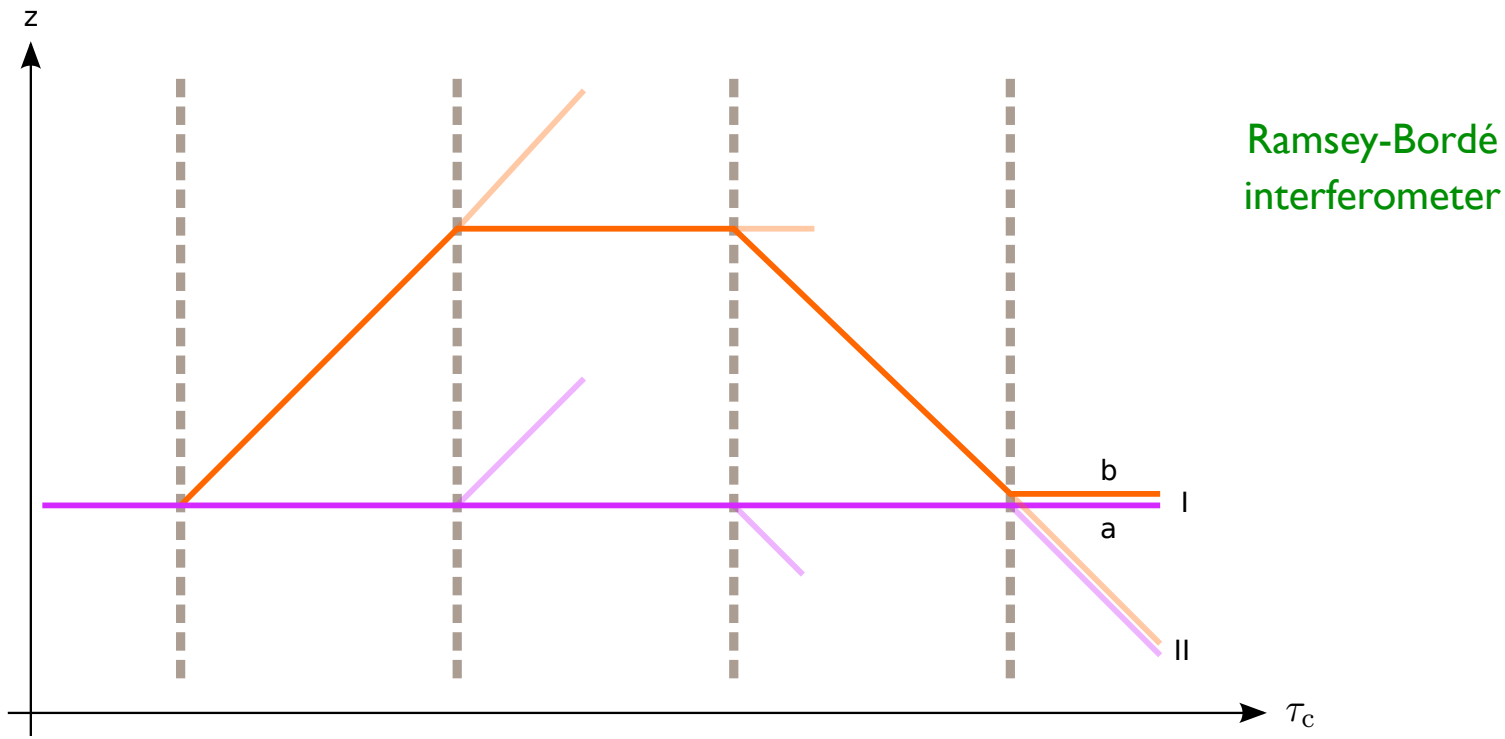
- *Relativistic* description of atom interferometry in *curved spacetime.*
- Including *external forces* and even *guiding potentials*.
- *Relativistic* interpretation of the *separation phase* in open interferometers.

Major challenges in quantum-clock interferometry

Insensitivity to gravitational redshift (in a *uniform field*)

- Consider a freely falling frame:



- Proper-time difference between the two interferometer branches $\longrightarrow$ independent of g

(small dependence due to pulse timing suppressed by $(v_{\rm rec}/c) \sim 10^{-10}$)

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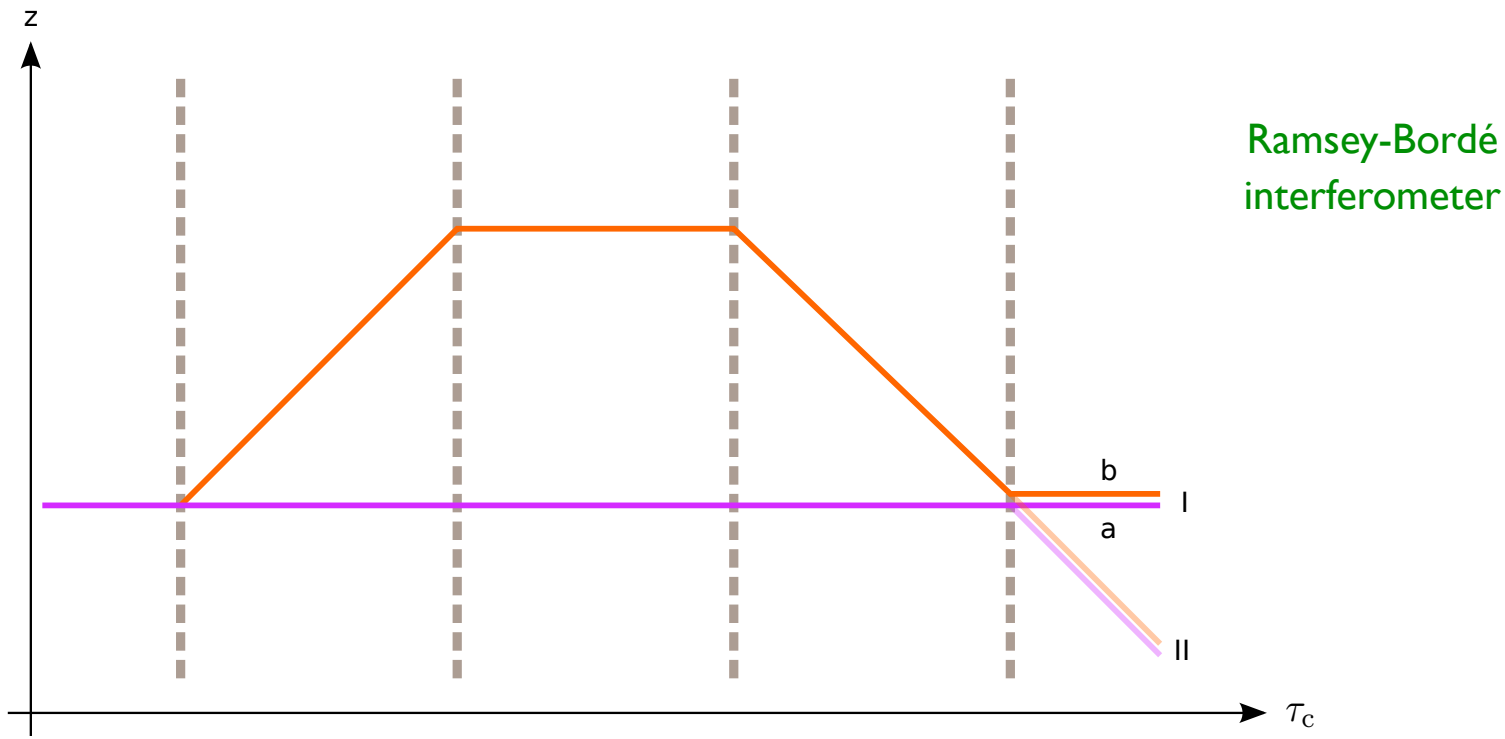

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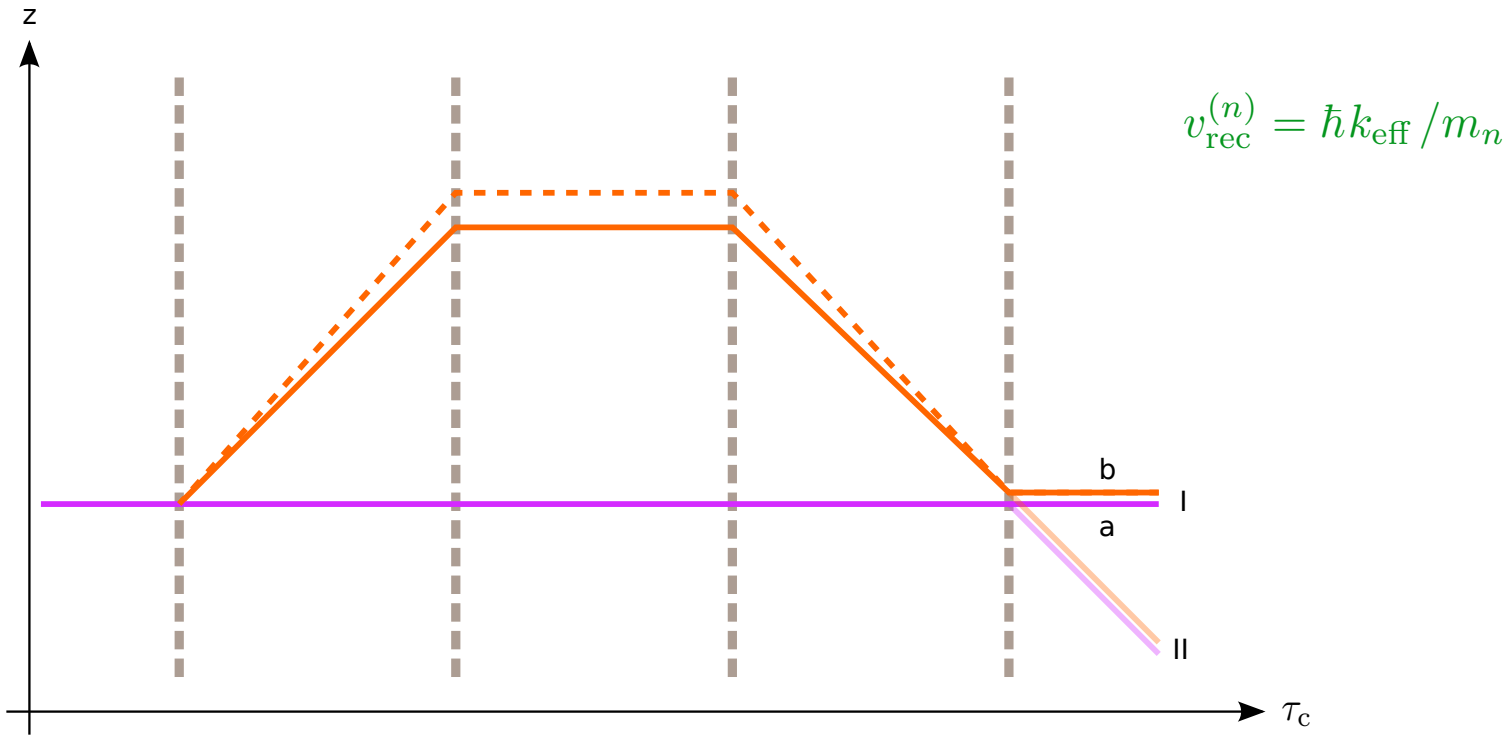
Differential recoil

- Different *recoil velocities* → different *central trajectories*



- 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*:

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

- Small effect for feasible parameter range:

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

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

$$\Delta z = 1 \, \mathrm{cm}$$

$$\Delta t = 1 \, \mathrm{s}$$

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

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Doubly differential gravitational-redshift measurement

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

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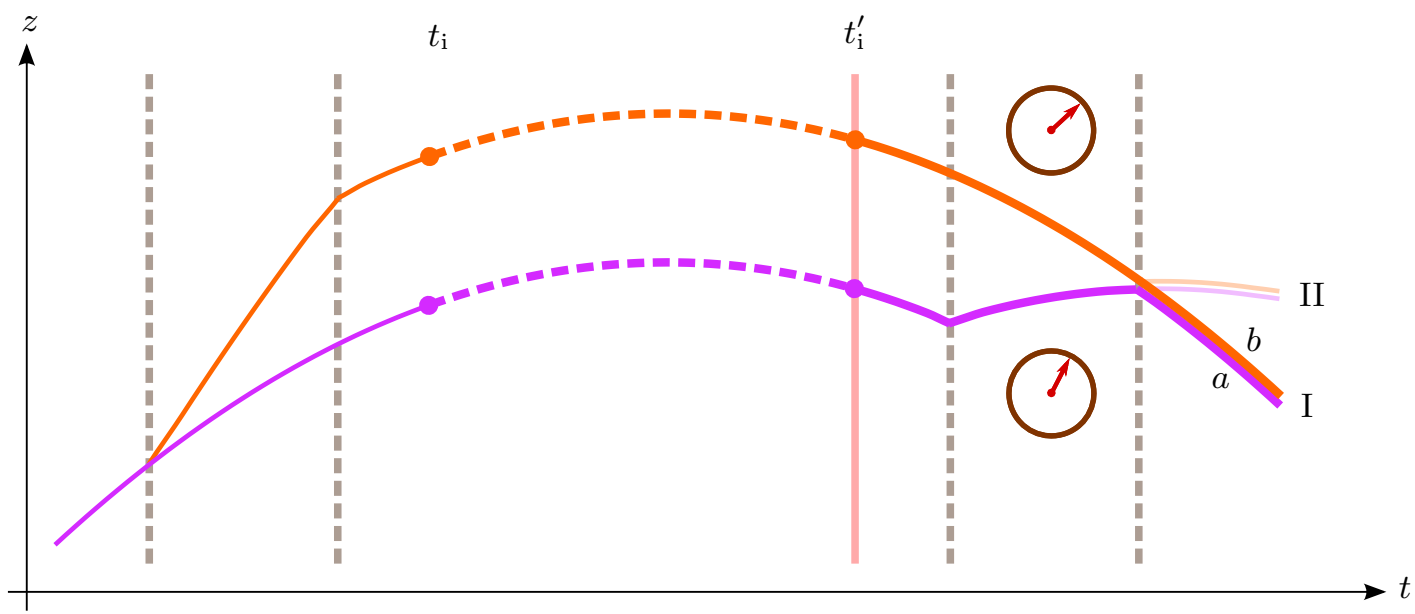


Differential phase-shift measurement

- Detection probability at first exit port (*independent* of *internal state*):

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

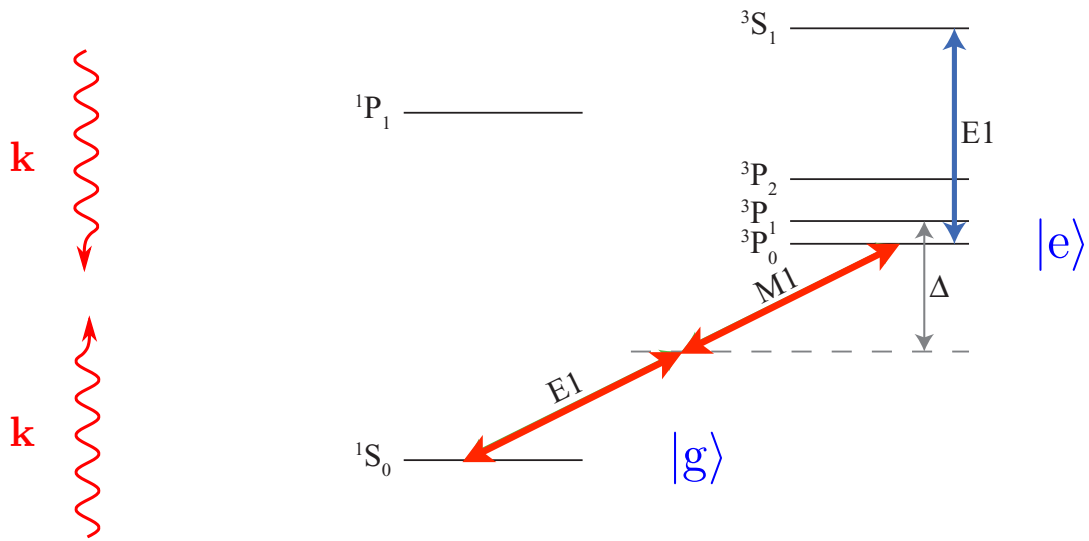
- Phase-shift difference directly related to visibility reduction.

- Precise differential phase-shift measurement involving *state-selective detection* is 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.

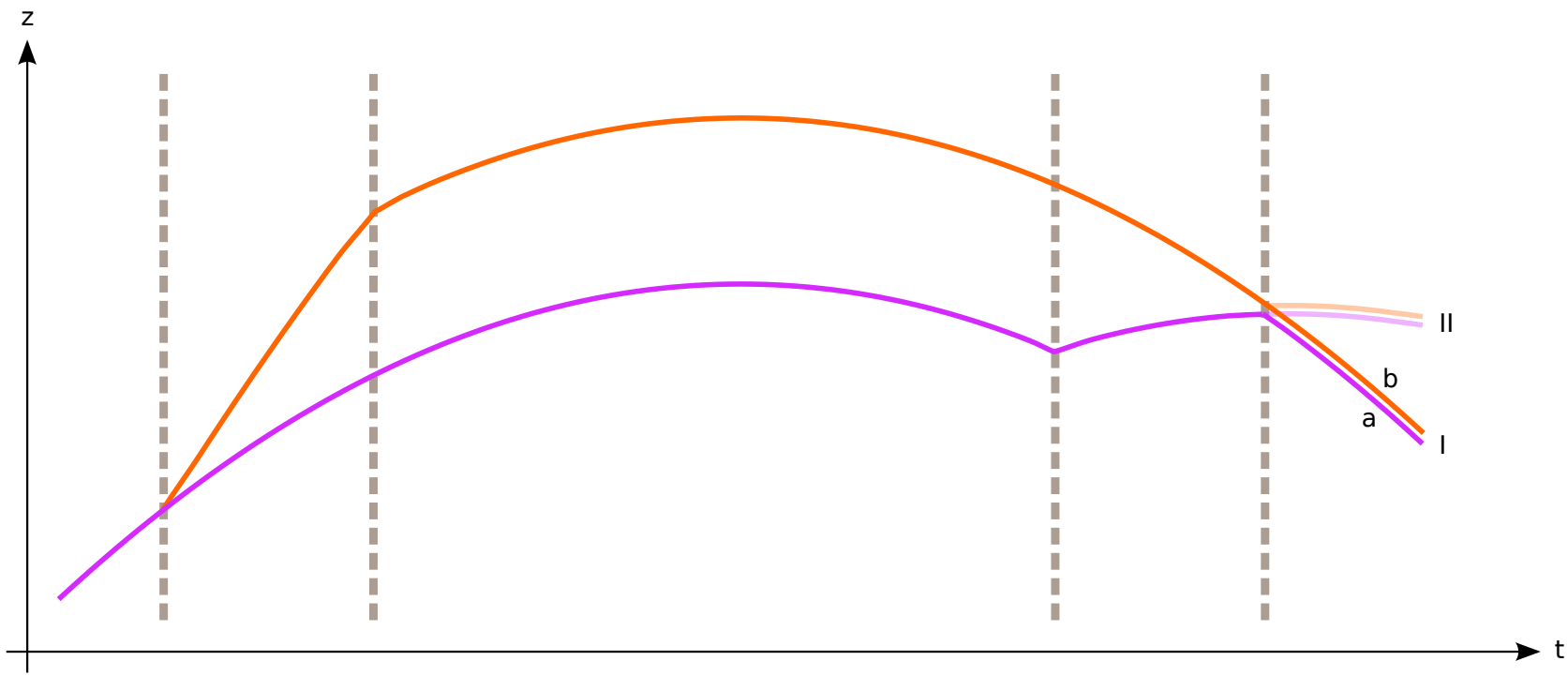
- Equal-frequency *counter-propagating* laser beams in lab frame:

constant *effective phase* → *simultaneity hypersurfaces* in lab frame

$$e^{i\omega t}e^{i\mathbf{k}\cdot\mathbf{x}} \times e^{i\omega t}e^{-i\mathbf{k}\cdot\mathbf{x}} = e^{i\,2\omega t}$$

Laboratory frame

- Compare *differential phase-shift* measurements for different initialization times:



$$\left(\delta\phi^{(2)}(t_{\rm i}') - \delta\phi^{(1)}(t_{\rm i}')\right) - \left(\delta\phi^{(2)}(t_{\rm i}) - \delta\phi^{(1)}(t_{\rm i})\right) = \frac{\Delta E}{2\hbar}\left(\Delta\tau_b - \Delta\tau_a\right) = \Delta m\, g\, \Delta z\, (t_{\rm i}' - t_{\rm i})/\hbar$$

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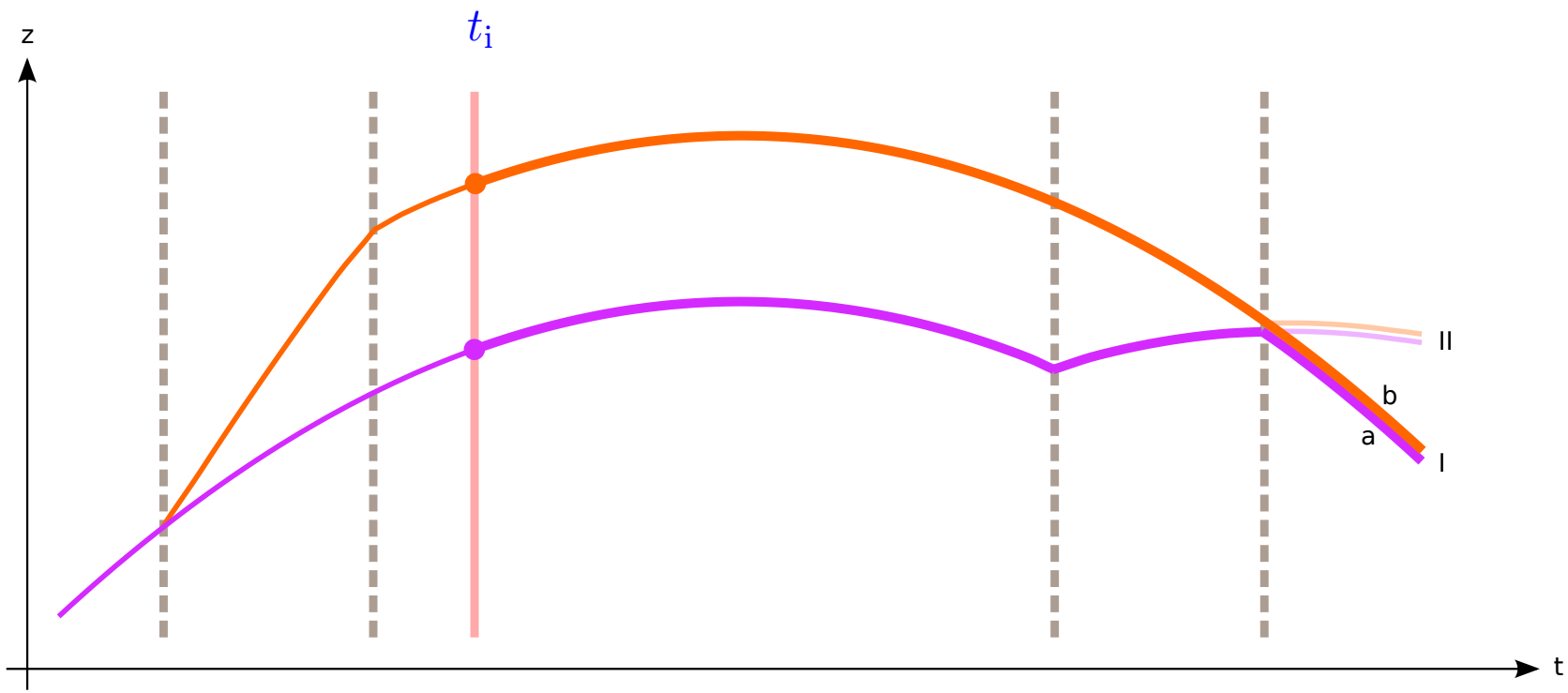

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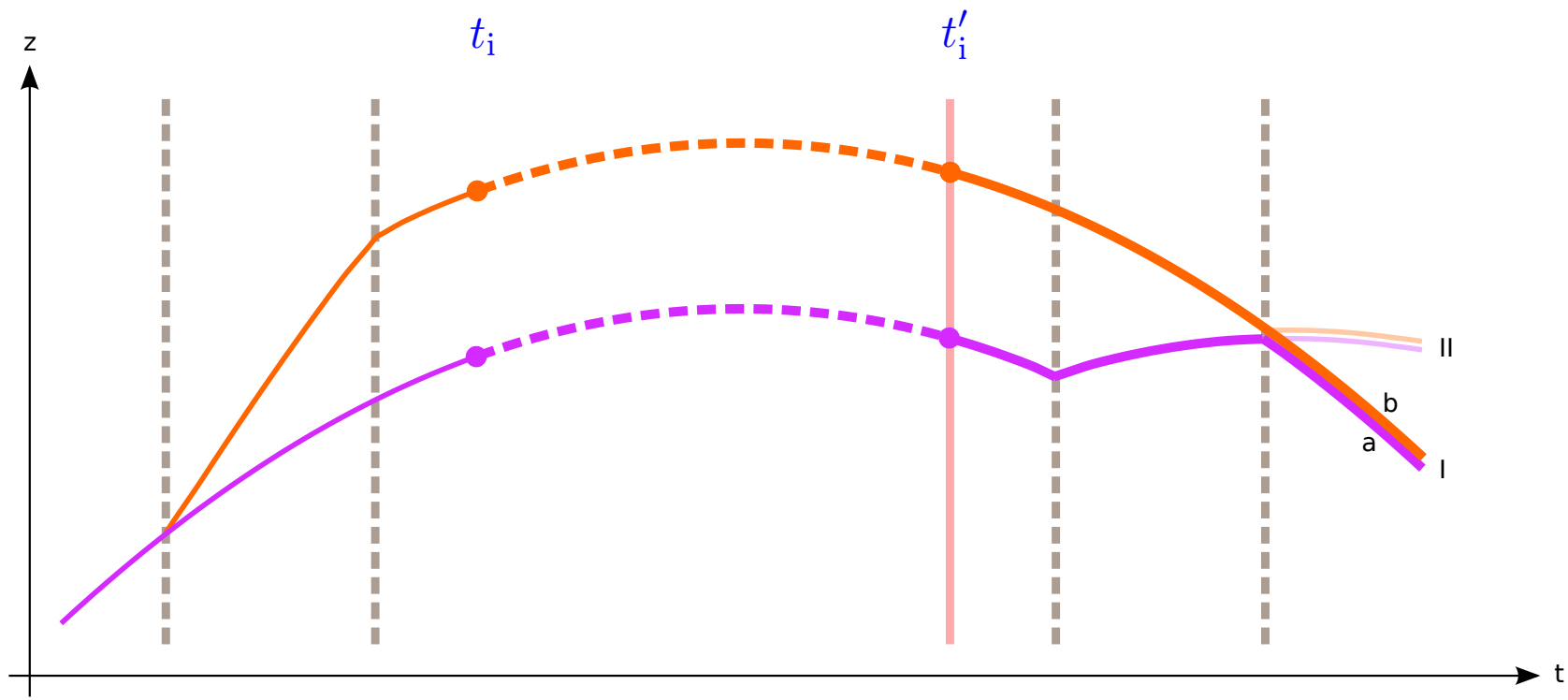

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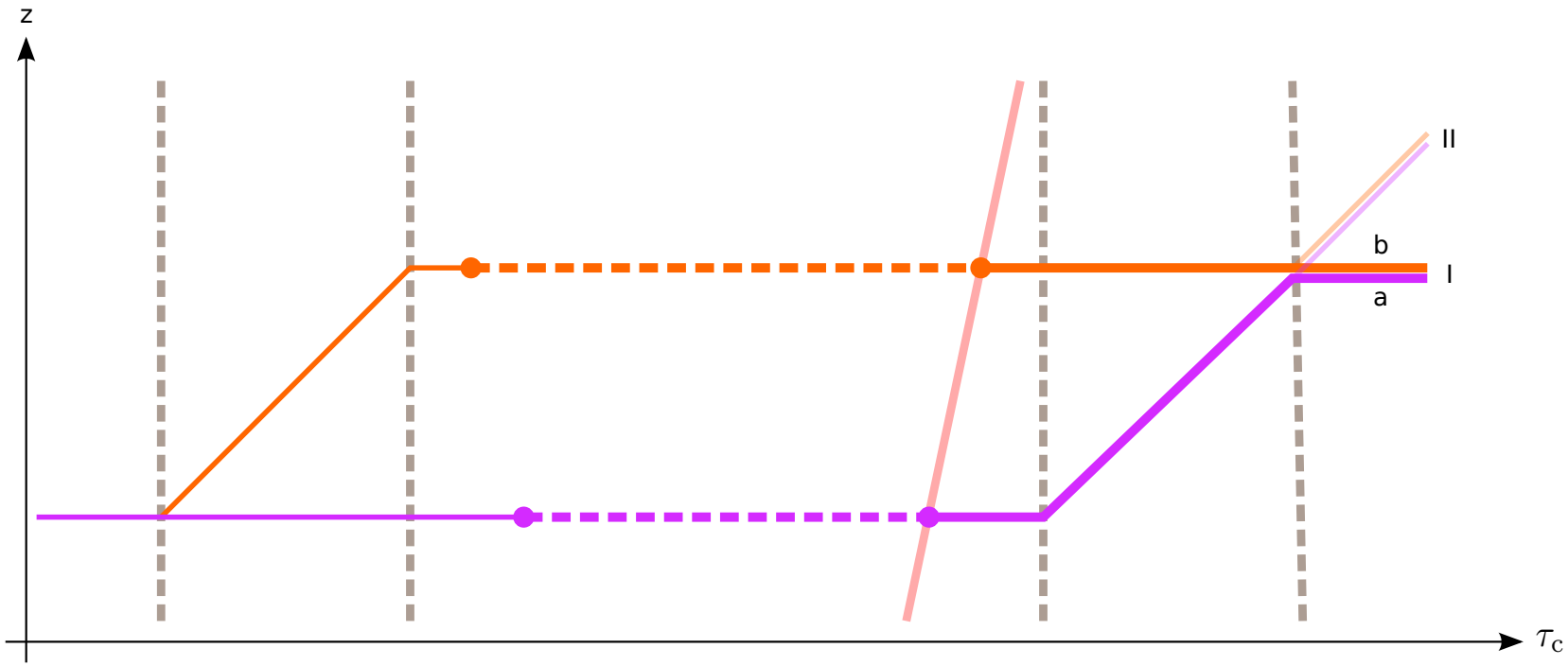
Freely falling frame

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



$$\left(\delta\phi^{(2)}(t_{\rm i}') - \delta\phi^{(1)}(t_{\rm i}')\right) - \left(\delta\phi^{(2)}(t_{\rm i}) - \delta\phi^{(1)}(t_{\rm i})\right) = \frac{\Delta E}{2\hbar}\,(\Delta\tau_b - \Delta\tau_a) = \Delta m\, g\, \Delta z\,(t_{\rm i}' - t_{\rm i})/\hbar$$

Challenges addressed

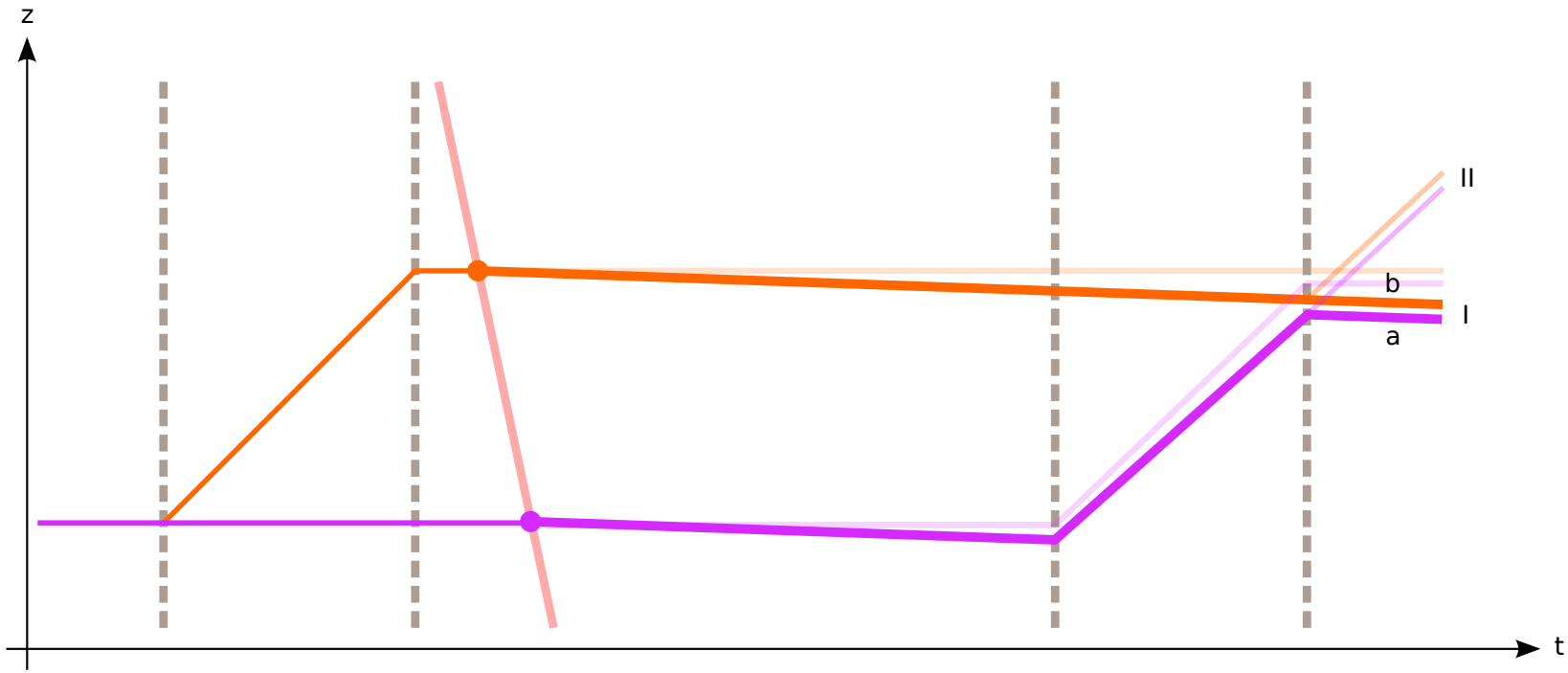
- Differential phase-shift measurement → *precise measurement*, *common-mode rejection* (of *noise* & *systematics*)

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

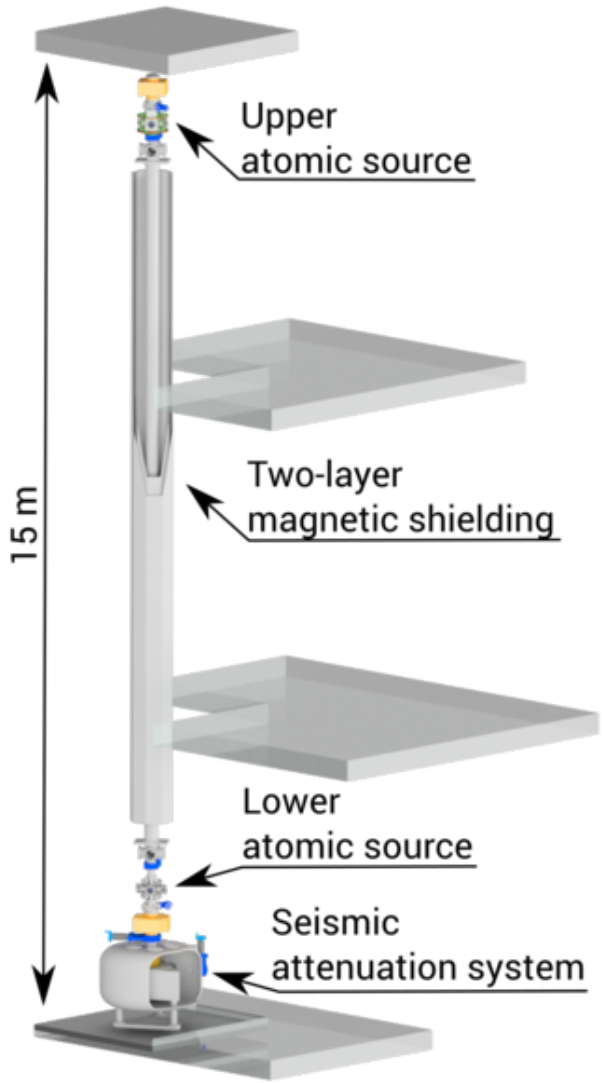
- Almost no recoil from *initialization pulse*,
  small *residual recoil* with no impact on gravitational redshift measurement,

  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



HITec (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 atomic clouds with $N = 10^6$ atoms (*shot-noise* limited)
- More compact set-ups possible with *guided* or *hybrid* interferometry (less mature).

Alternative implementation

Demanding requirements on the atom optics

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

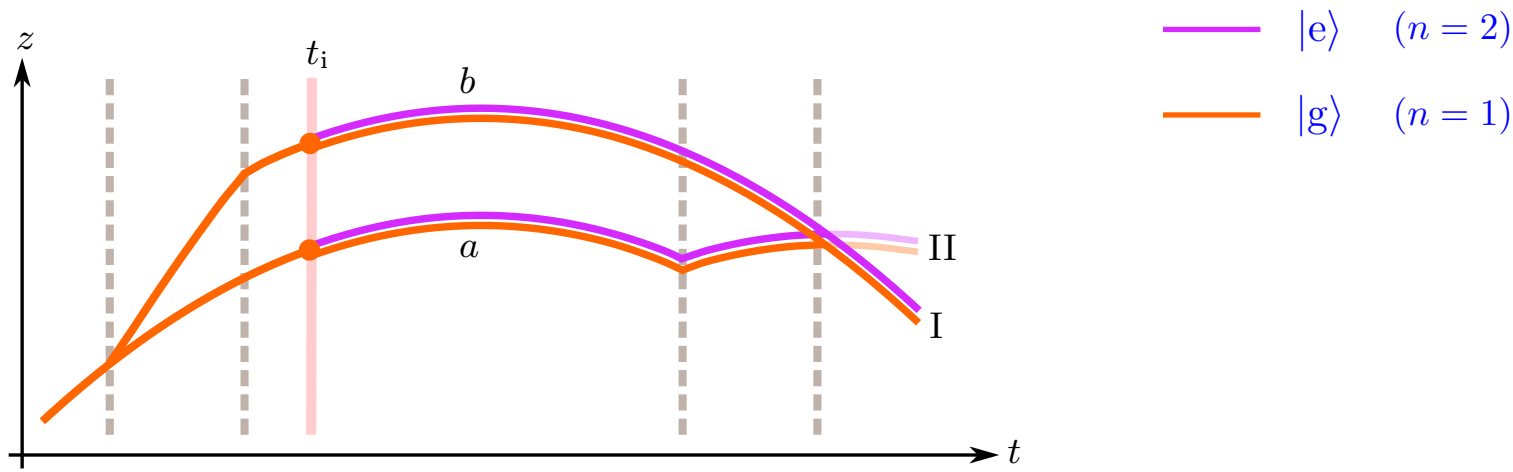
- Two possibilities:

  - 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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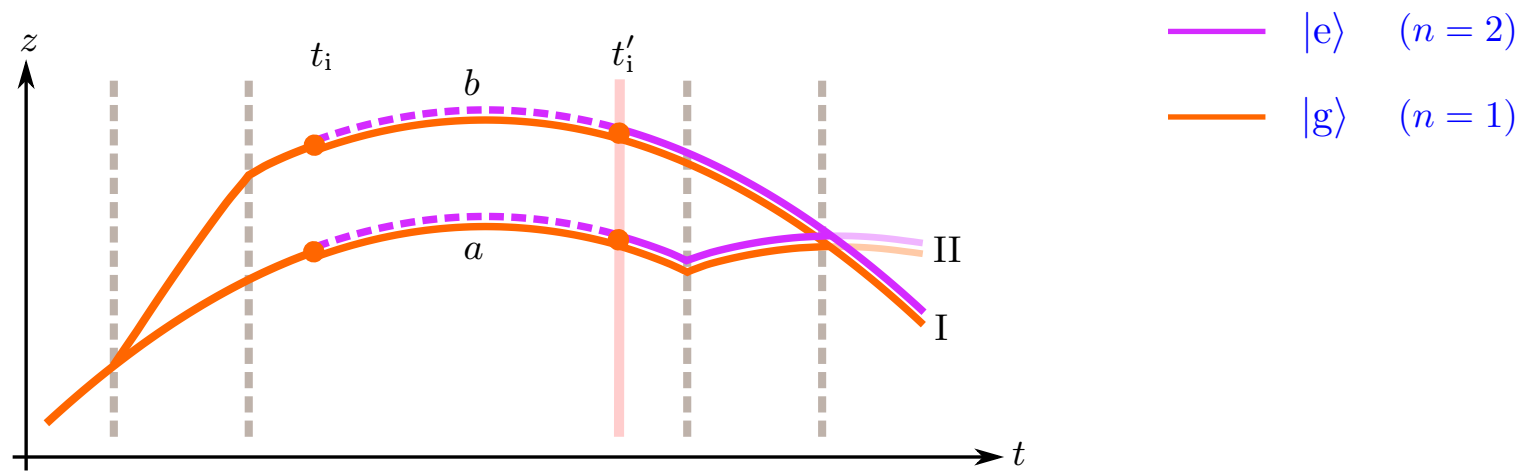
doubly differential measurement

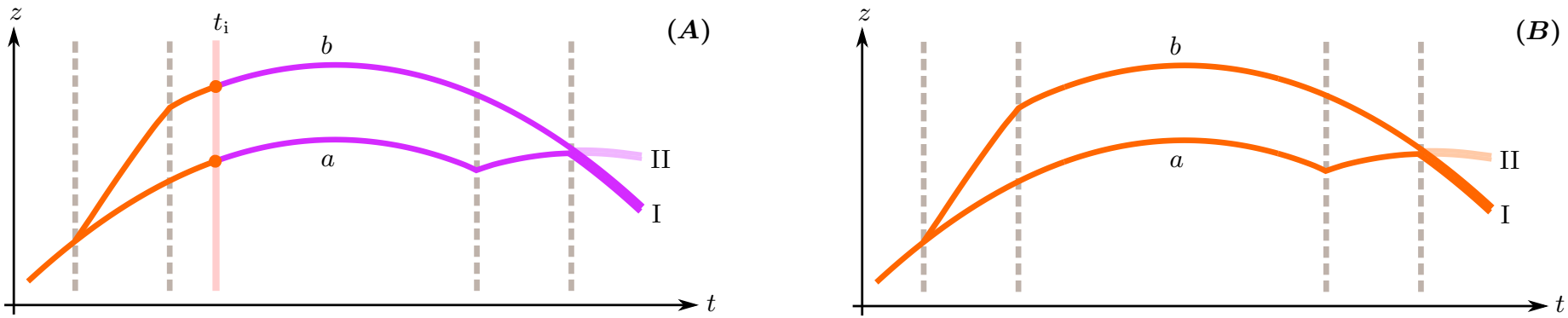
Quantum-clock interferometry



$$\left(\delta\phi^{(2)}(t_\mathrm{i}') - \delta\phi^{(1)}(t_\mathrm{i}')\right) - \left(\delta\phi^{(2)}(t_\mathrm{i}) - \delta\phi^{(1)}(t_\mathrm{i})\right) = \frac{\Delta E}{2\hbar}\left(\Delta\tau_b - \Delta\tau_a\right) = \Delta m\, g\, \Delta z\, (t_\mathrm{i}' - t_\mathrm{i})/\hbar$$

doubly differential measurement

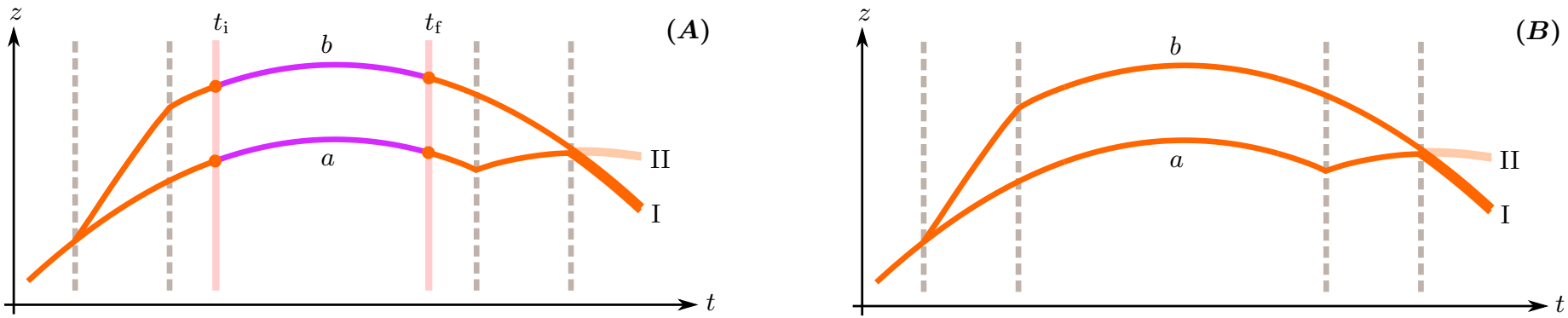
Alternative interferometry scheme



- *Differential phase shift* between the two shots directly sensitive to the *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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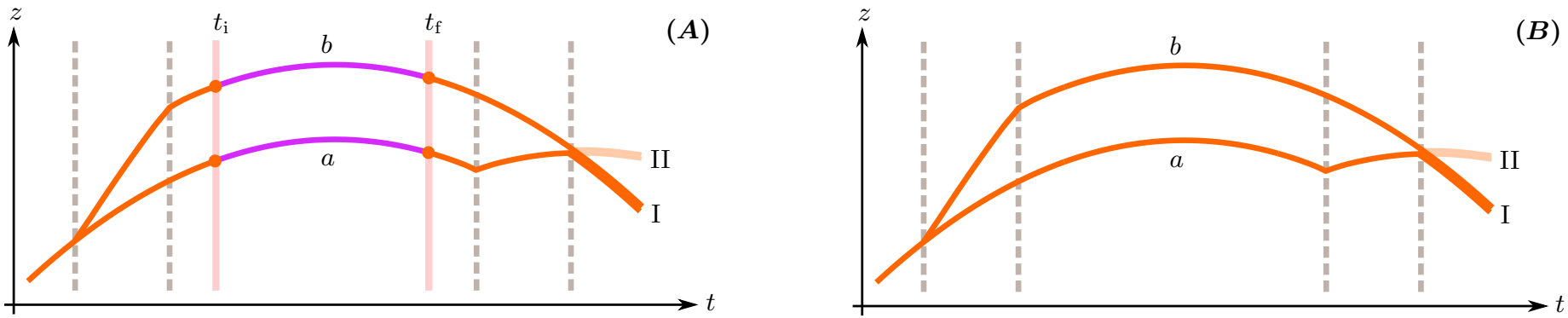
Alternative interferometry scheme

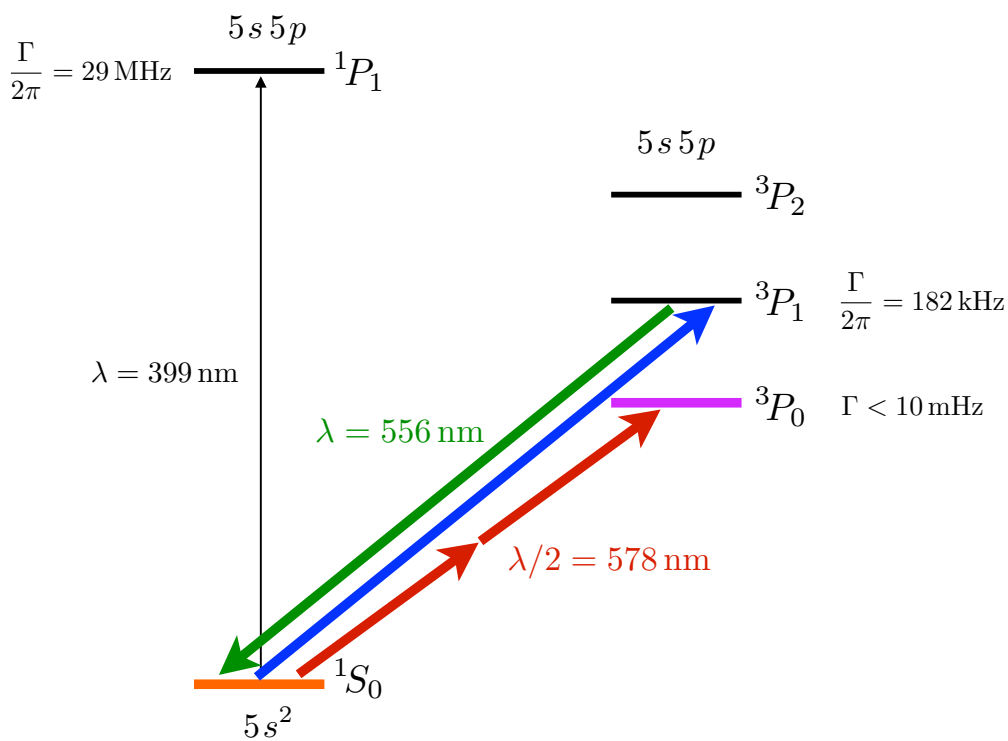


- Test of UGR with a delocalized quantum superposition (*dilaton* model):

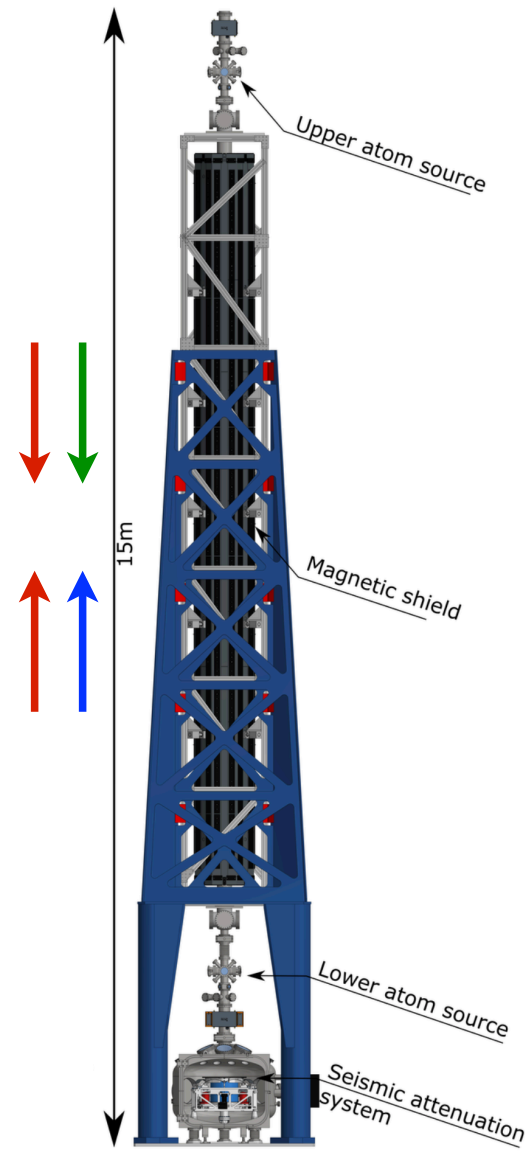
$$\delta\phi_A - \delta\phi_B = -\Delta m\, c^2\, (\Delta\bar{\tau}_b - \Delta\bar{\tau}_a)/\hbar = -\Delta m\, \left(1 + \alpha_{\text{e-g}}\right) g\, \Delta z\, (t_\text{f} - t_\text{i})/\hbar$$

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

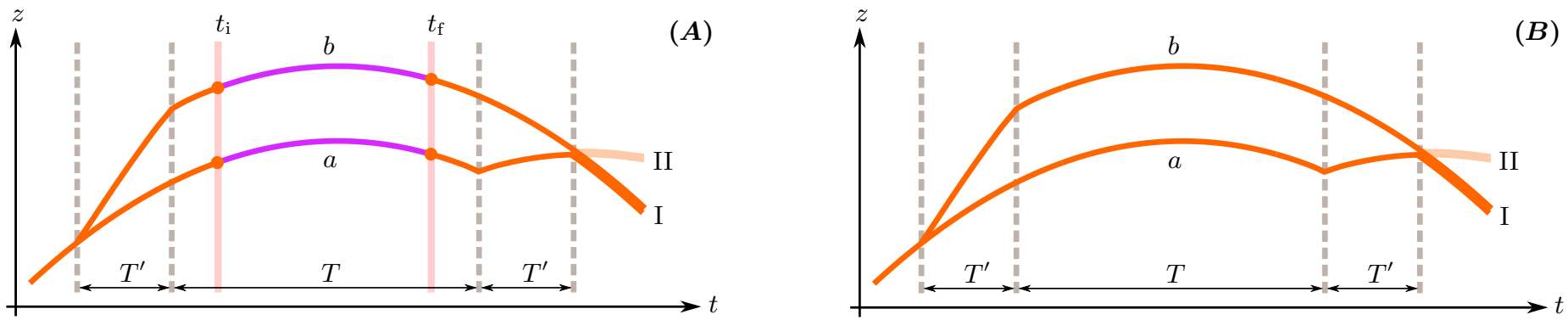
Inversion and Bragg diffraction pulses



Yb



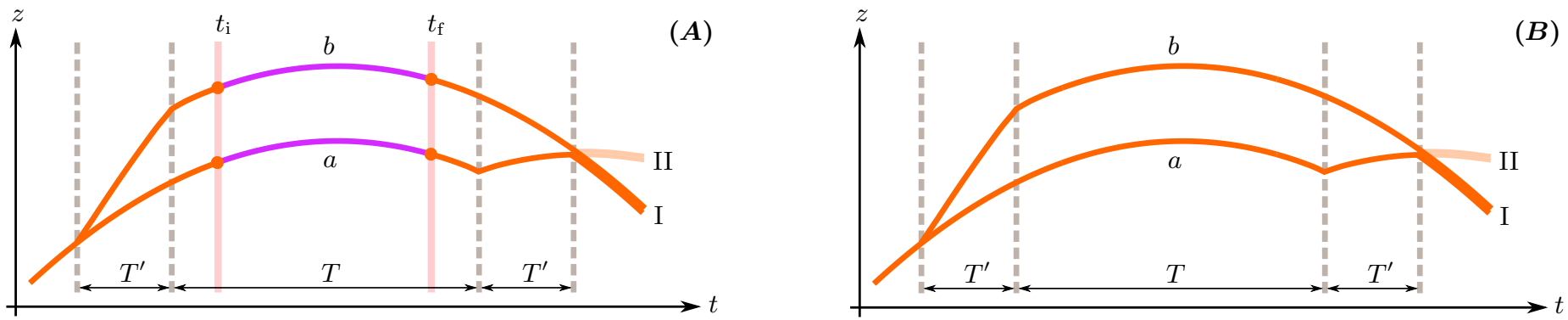
Suppression of vibration noise



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

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

Suppression of vibration noise



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

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

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.

Measuring gravitational time dilation with delocalized quantum superpositions

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

[1] *Institute of Quantum Technologies, German Aerospace Center (DLR), Söflinger Straße 100, 89077 Ulm, Germany*
[2] *Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, D-30167 Hannover, Germany.*
[3] *Institute for Satellite Geodesy and Inertial Sensing, German Aerospace Center (DLR), c/o Leibniz Universität Hannover, DLR-SI, Callinstraße 36, 30167 Hannover, Germany*

(Dated: October 22, 2020)

arXiv:2010.11156

Conclusion

- 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.

  Applicable also to more compact set-ups based on *guided* or *hybrid* interferometry.

- 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

Related work:

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 (IQ^{ST}), 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)

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Bundesministerium
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Deutsches Zentrum
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German Aerospace Center

Project Q-GRAV

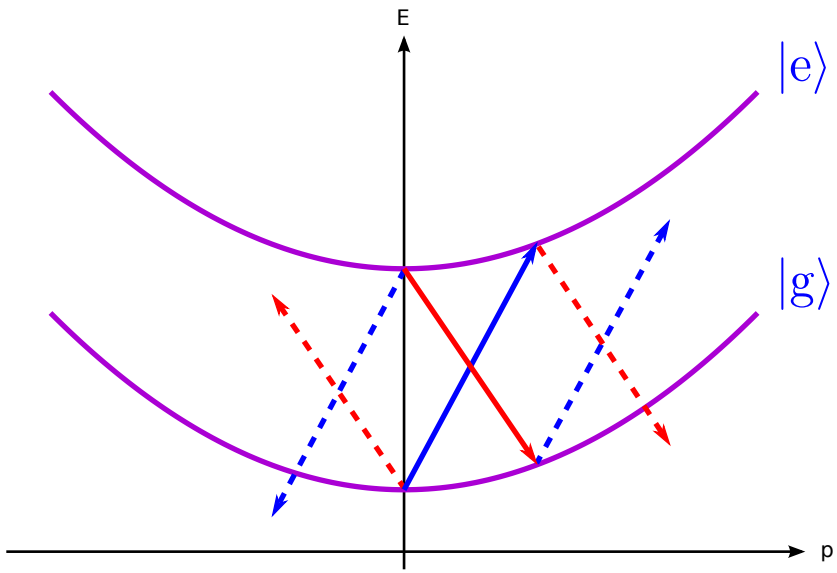
Diffraction of atoms in internal-state superpositions

- Bragg diffraction at the magic wavelength $\longrightarrow$ same Rabi frequency for both internal states.

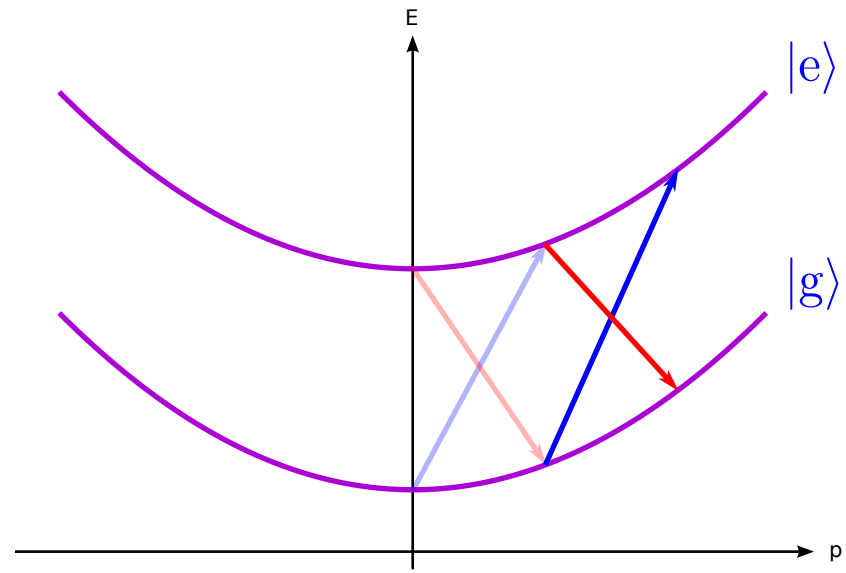
  BUT *high laser power* required due to large detuning.

- Alternative diffraction mechanism based on *simultaneous pair* of single-photon transitions.
  - Applicable to *fermionic* isotopes such as $^{87}\mathrm{Sr}$ and $^{171}\mathrm{Yb}$.
  - Required lasers *already available* in (some of) those facilities.

- Sequence of simultaneous pairs of pulses:



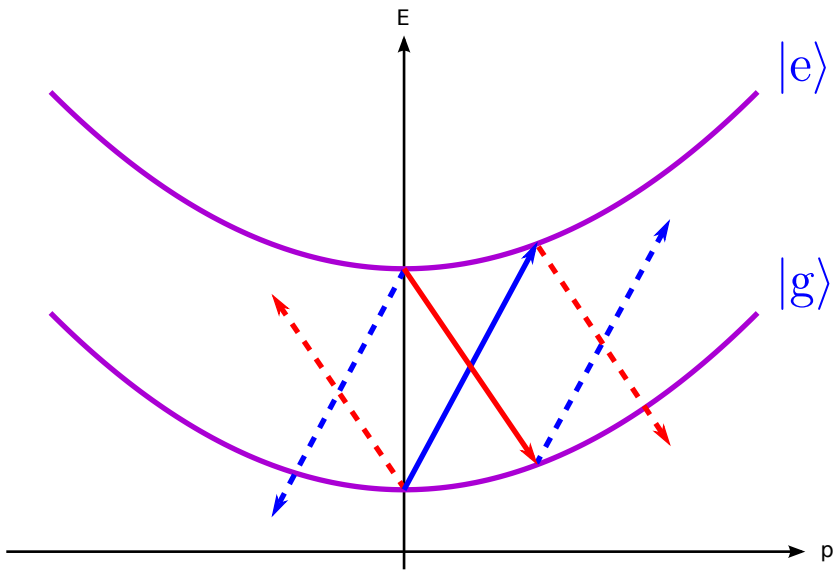
$\pi/2$ pulse



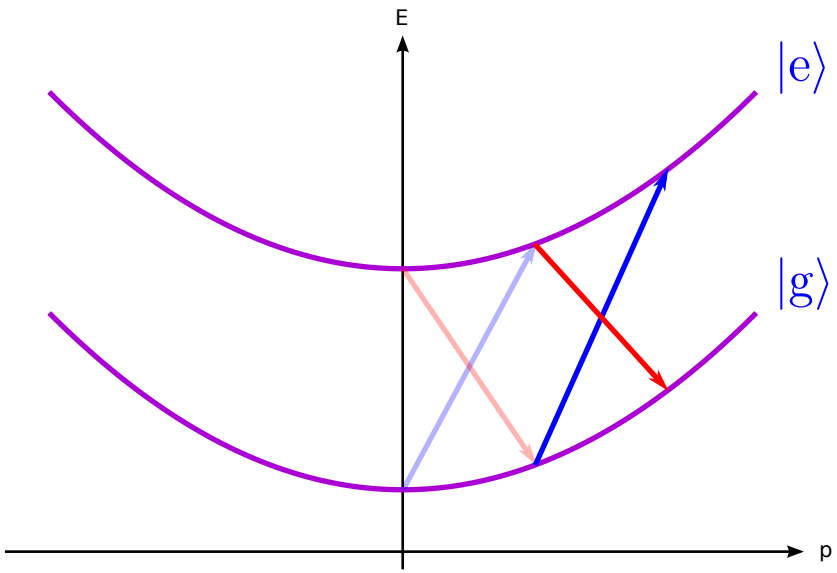
π pulse

- Net result:
  - *internal state* unchanged
  - momentum transfer: *twice single-photon* momentum
  - equal-amplitude superposition: *undiffracted* + *diffracted* wave packet

- Sequence of simultaneous pairs of pulses:



$\pi/2$ pulse



π pulse

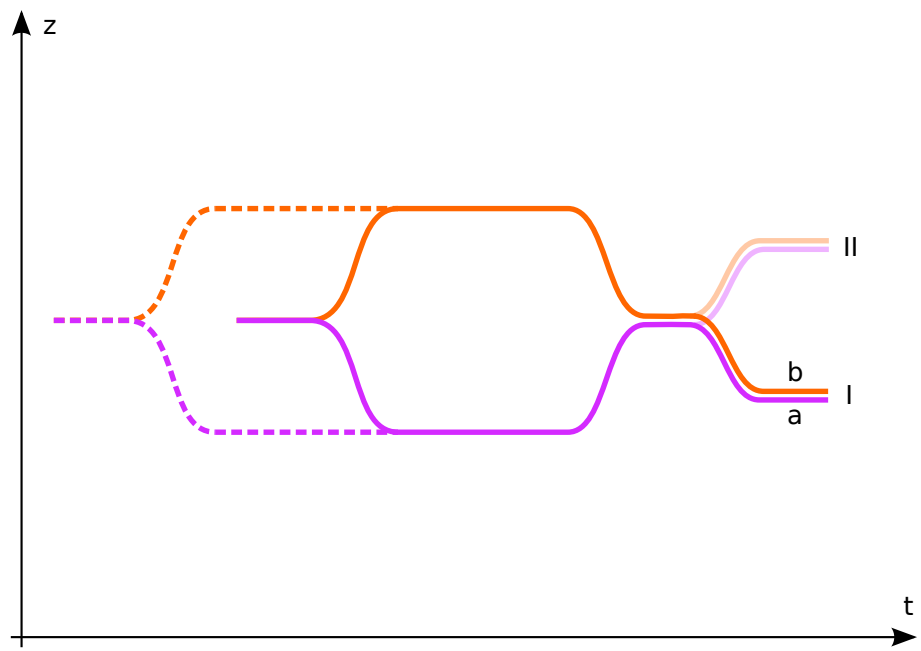
- Same *ac Stark shifts* for both internal states

  ⟶ contributions to *differential phase shift* cancel out.

  Any *light shifts* cancel out in the *doubly differential measurement* (provided that the *laser intensities* are *stable*).

Extension to guided interferometry

- In principle, guided interferometry can be sensitive to the gravitational redshift:



- Nevertheless, the *doubly differential* measurement scheme has many advantages.

Extension to guided interferometry

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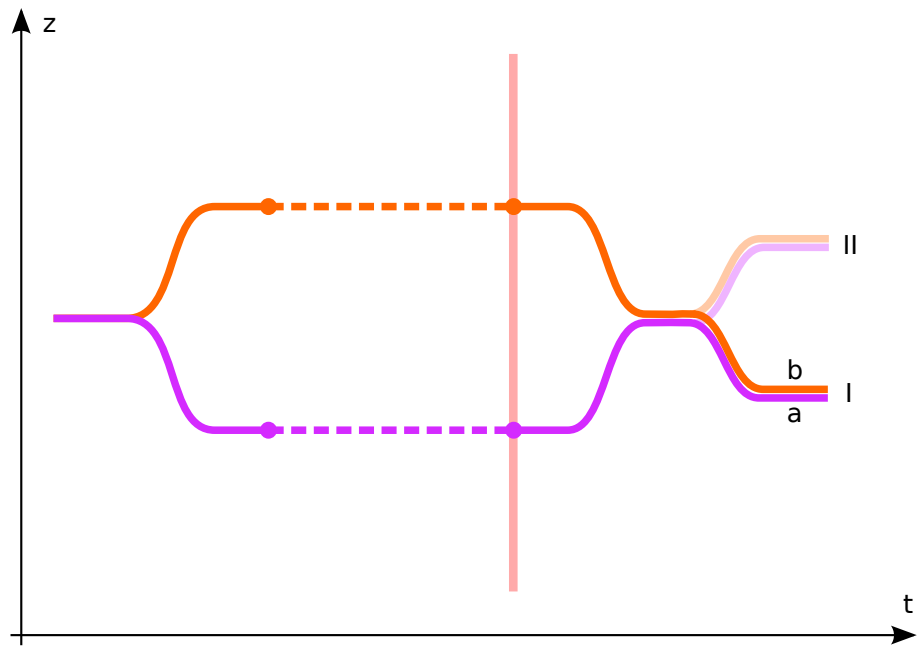
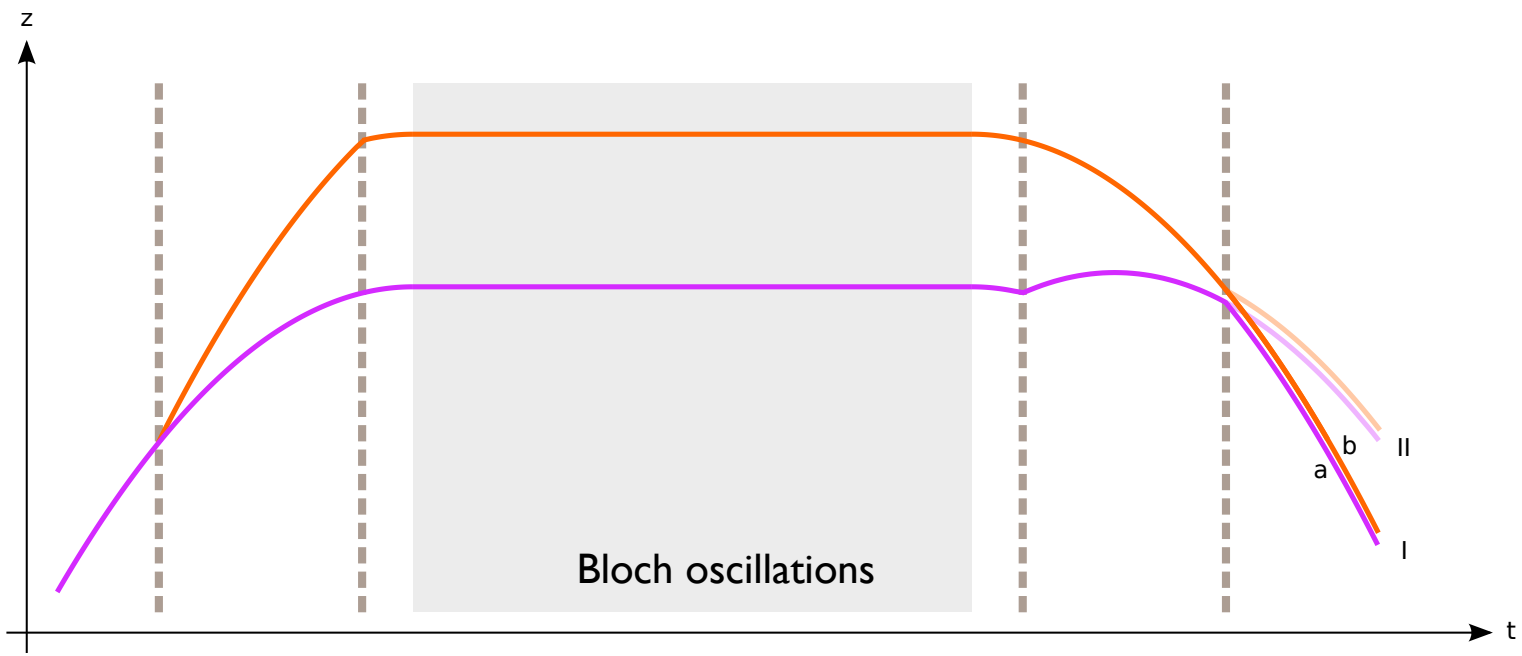


- Nevertheless, the *doubly differential* measurement scheme has many advantages.

Extension to *hybrid* interferometers

- Intermediate stage with atoms held in an optical lattice, where they undergo Bloch oscillations:



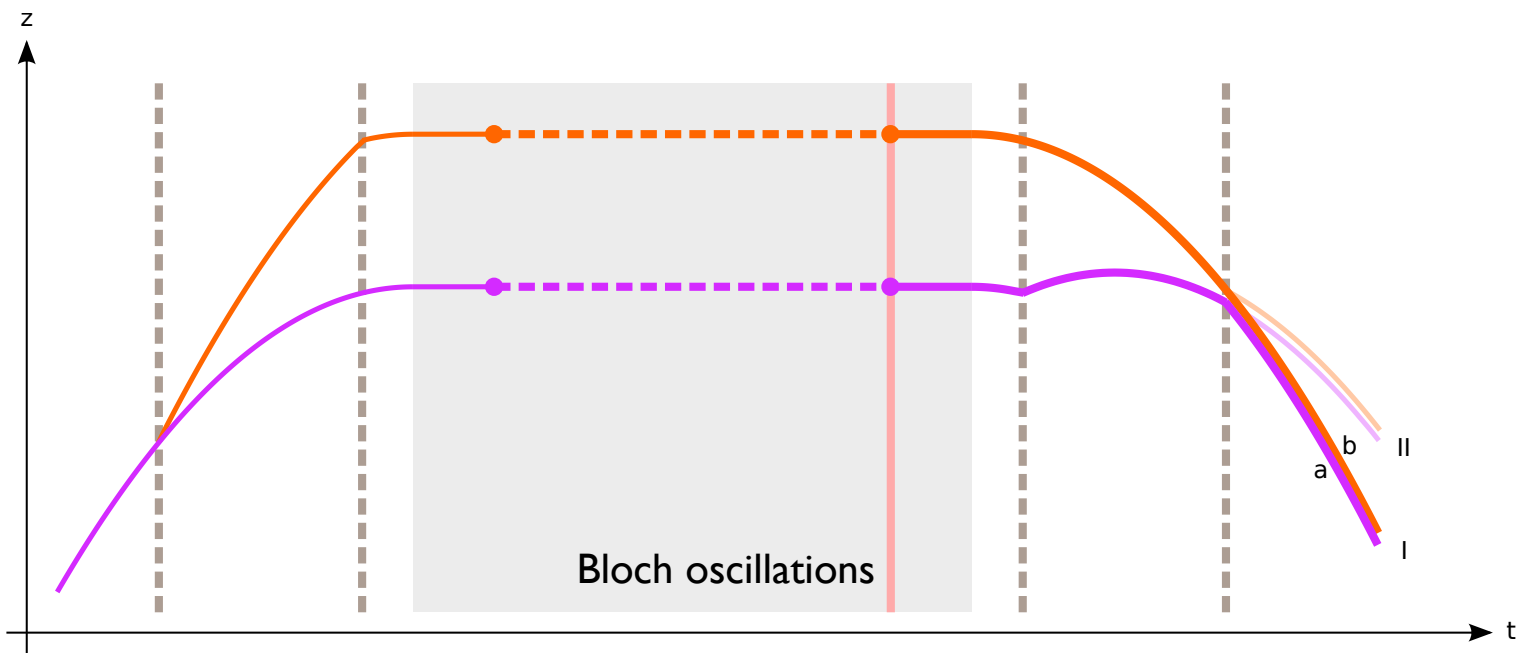
Charriere *et al.*, *Phys. Rev. A* **85** 013639 (2012)

Zhang *et al.*, *Phys. Rev. A* **94** 043608 (2016)

- Similarly to pure *light-pulse* atom interferometers, they are insensitive to the gravitational redshift.

Extension to *hybrid* interferometers

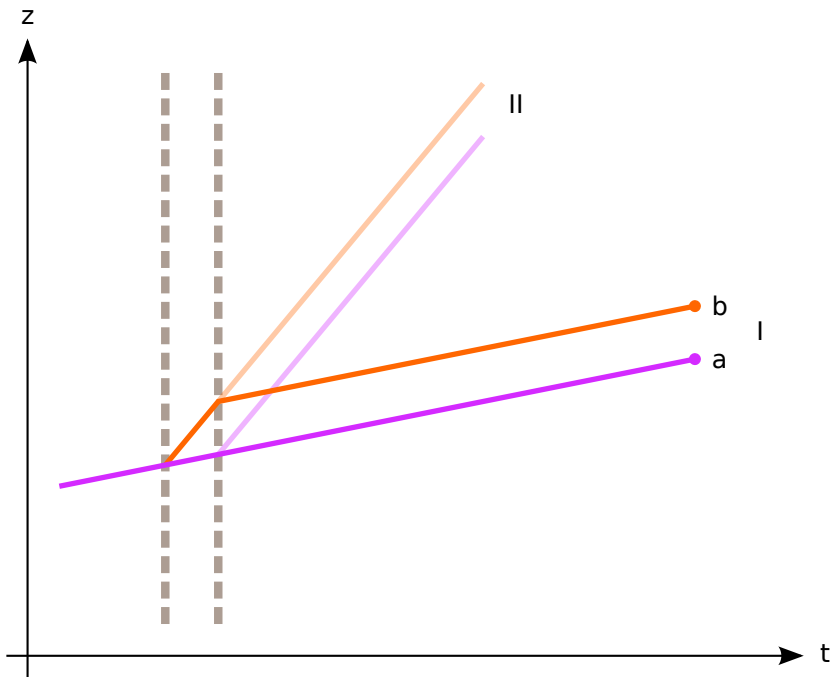
- Intermediate stage with atoms held in an optical lattice, where they undergo Bloch oscillations:

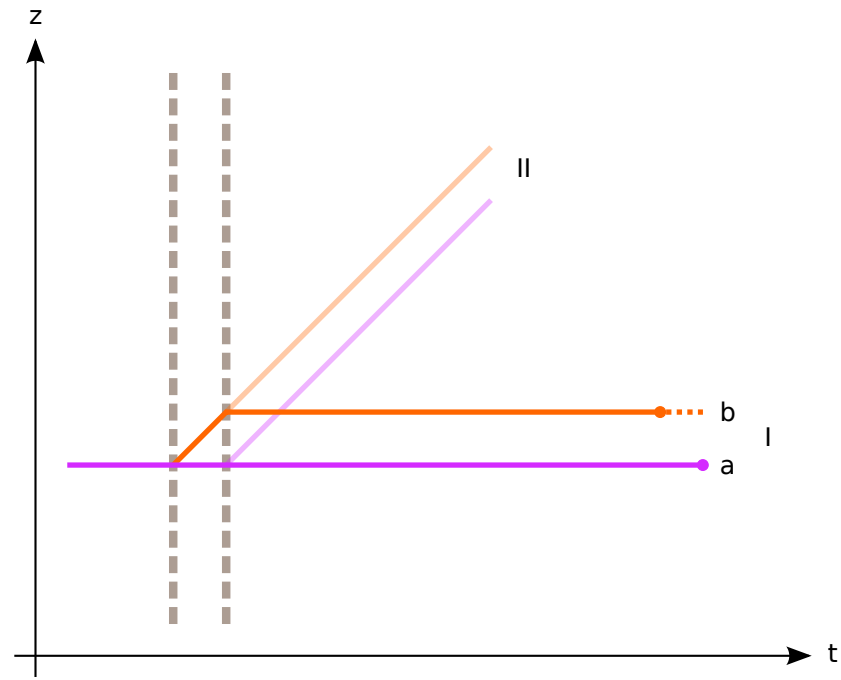


- The *doubly differential* scheme can also be employed for measuring the gravitational redshift.

Other aspects

Proper-time difference in open interferometers



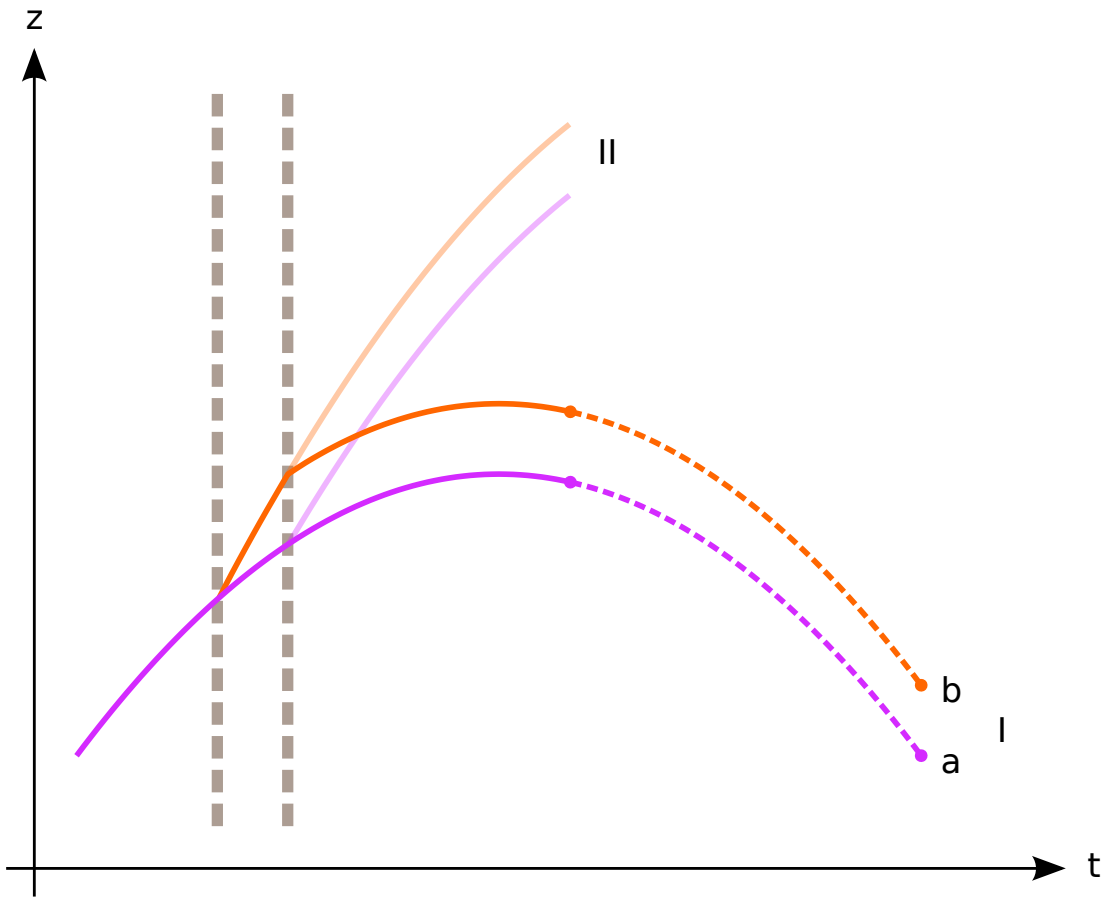


$$\delta\phi_{\rm sep} = -\bar{\mathbf{P}} \cdot \delta\mathbf{X}/\hbar$$

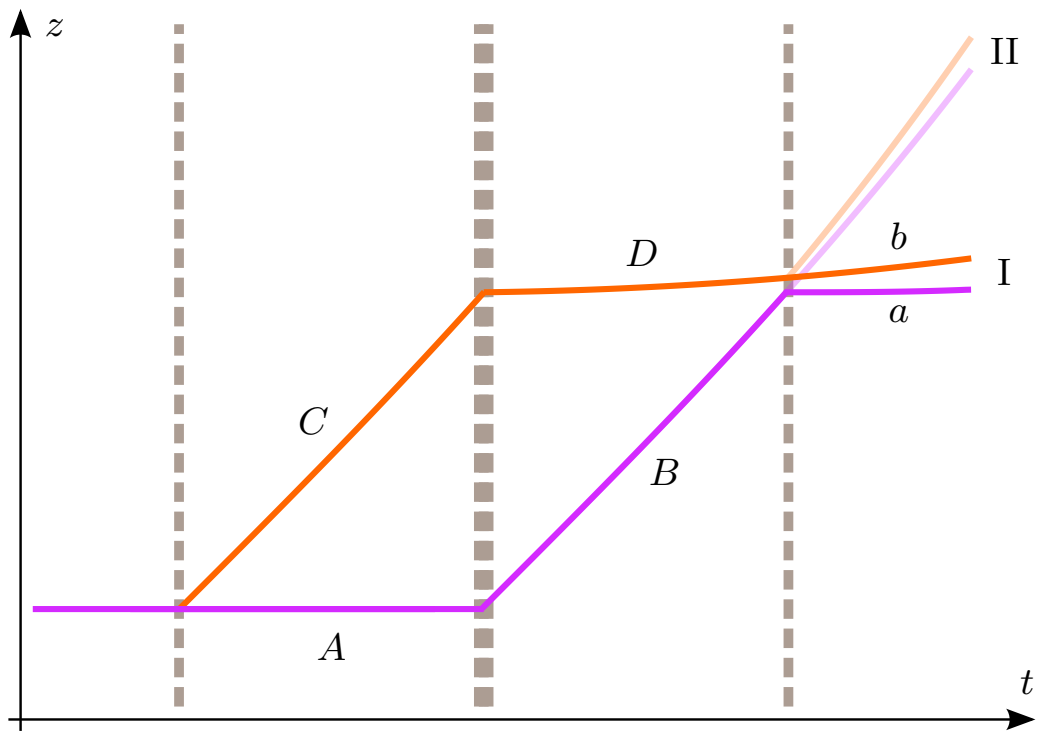
$$\delta\tau_{\rm c} \approx -\bar{\mathbf{v}} \cdot \delta\mathbf{X}/c^2$$

$$\boxed{-mc^2\delta\tau_{\rm c}/\hbar + \delta\phi_{\rm sep} = 0}$$

Proper-time difference in open interferometers

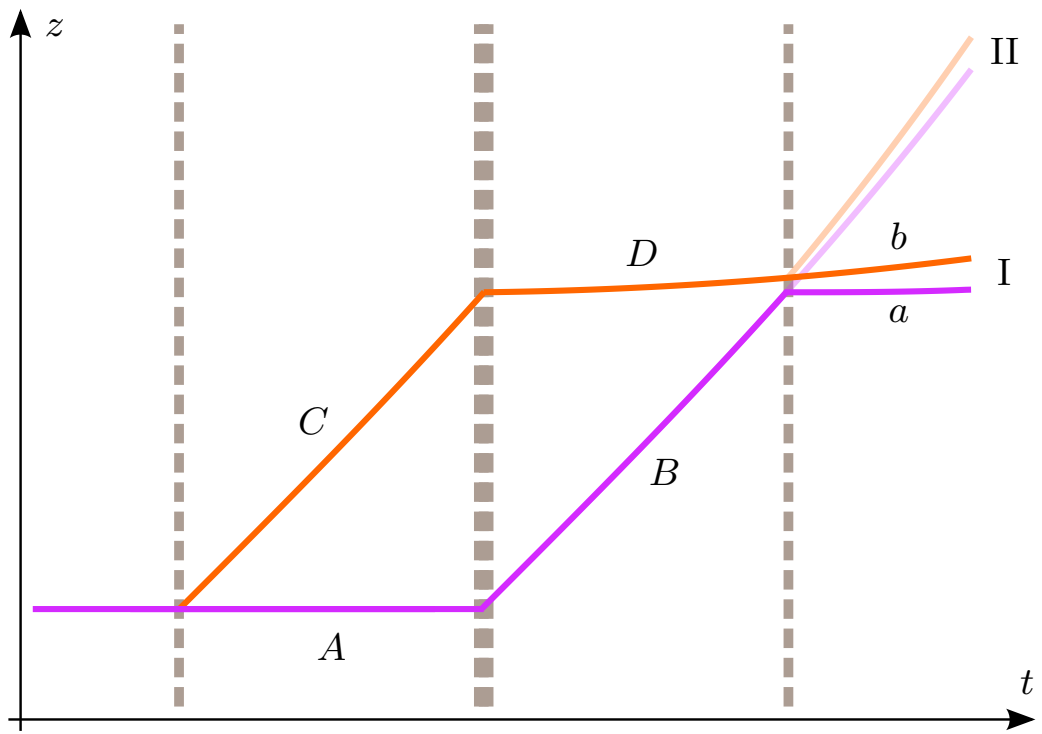


Proper-time difference and gravity gradients



$$-\frac{i}{\hbar}\,V(\Delta z)\,T = -\frac{i}{\hbar}\left(-\frac{1}{2}m\,\Gamma_{zz}\,(\Delta z)^2\right)\,T = \frac{i}{2}\,k_{\mathrm{eff}}\,\Gamma_{zz}\,v_{\mathrm{rec}}\,T^3$$

Proper-time difference and gravity gradients



$$-\frac{i}{\hbar}\,V(\Delta z)\,T = -\frac{i}{\hbar}\left(-\frac{1}{2}m\,\Gamma_{zz}\,(\Delta z)^2\right)T = \frac{i\,\hbar}{2m}\,k_{\rm eff}^2\,\Gamma_{zz}\,T^3$$