

# Fundamental Interactions

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Terrestrial Very-Long-Baseline Atom Interferometry Workshop

CERN, Geneva



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Theoretical Quantum Optics

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# Collaboration



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# Differential measurements

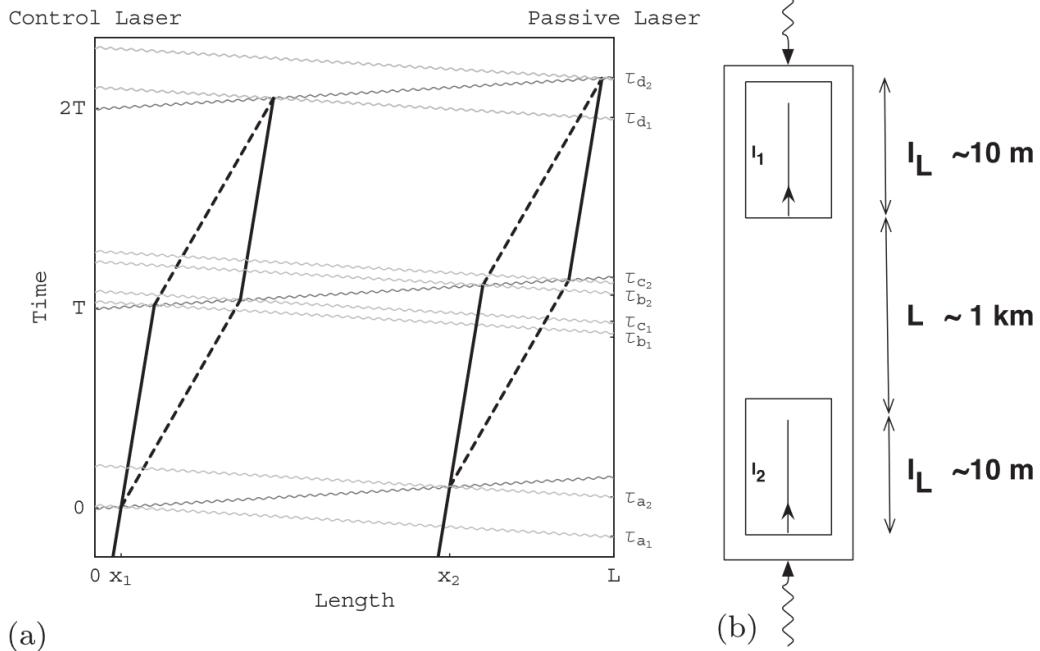
- Two (possibly large-baseline) light-pulse atom interferometers
- Spatially separated
- Differential measurements
- Probing different points in spacetime

⇒ gravitational-wave detection

Phys. Rev. D **78**, 122002

⇒ dark matter detection

Phys. Rev. D **97**, 075020



(a)

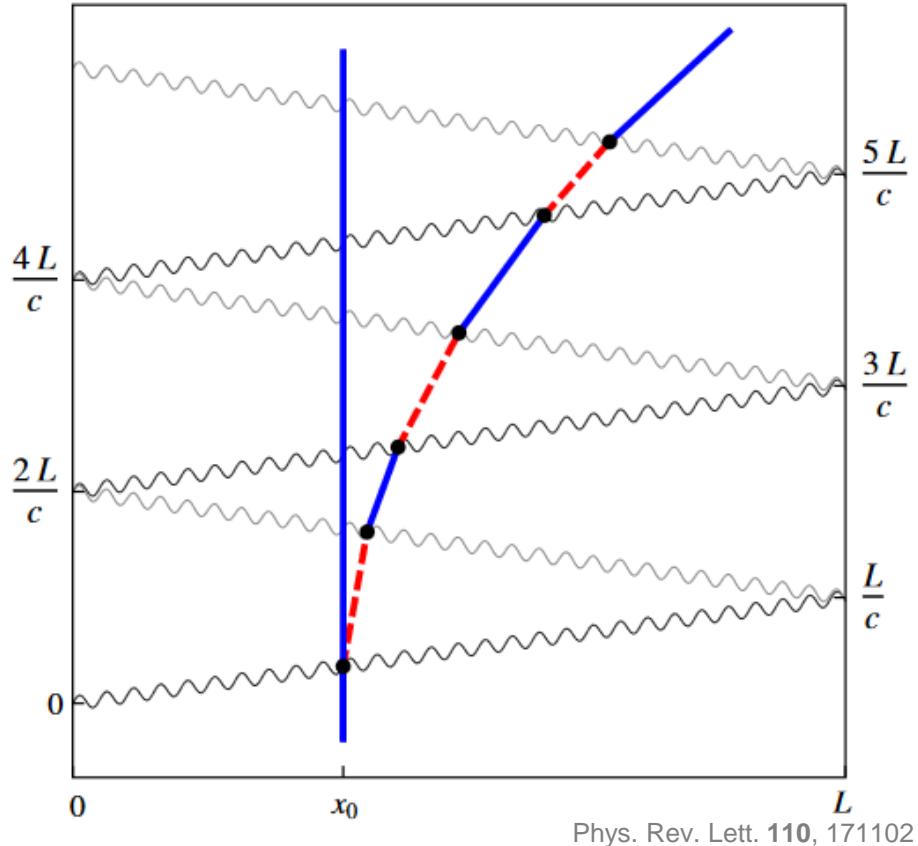
Phys. Rev. D **78**, 122002

(b)

# Finite speed of light

- Different points in spacetime  
 $\Rightarrow$  finite speed of light
- Two-photon transitions  
 $\Rightarrow$  laser phase noise
- Solution:  
 $\Rightarrow$  single-photon transitions

Phys. Rev. Lett. 110, 171102



# Single-photon transitions for AI

- Different internal states

⇒ “clock” contributions for dark matter detection

Phys. Rev. D **97**, 075020

- Optical transitions

⇒ larger momentum transfer

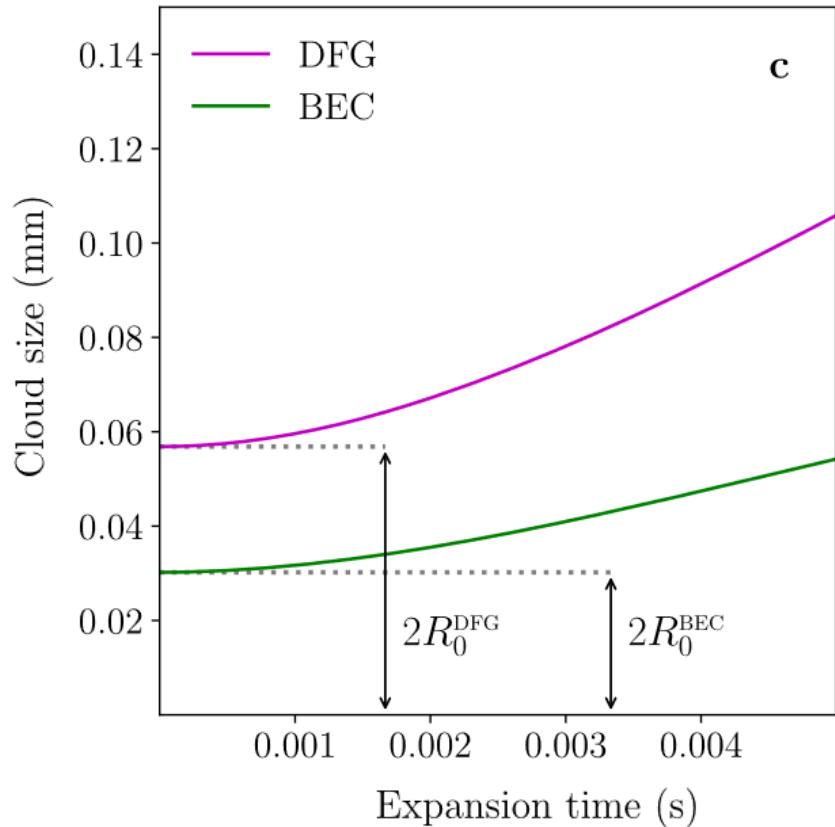
- Narrow transitions

⇒ suppressed spontaneous emission

⇒ extremely low Rabi frequencies

# Fermionic species

- Weakly-allowed clock transitions
  - ⇒ direct transition possible
  - ⇒ lower laser power
- Problems
  - Spontaneous emission and atom loss
    - ⇒ increased shot noise, loss of coherence
  - Degenerate Fermi gases
    - ⇒ increased cloud size and expansion rate



# Bosonic species

- No weakly-allowed clock transitions
- Lifetime limited by two-photon E1-M1 process

Phys. Rev. A **69**, 042510

- Bose-Einstein condensation possible

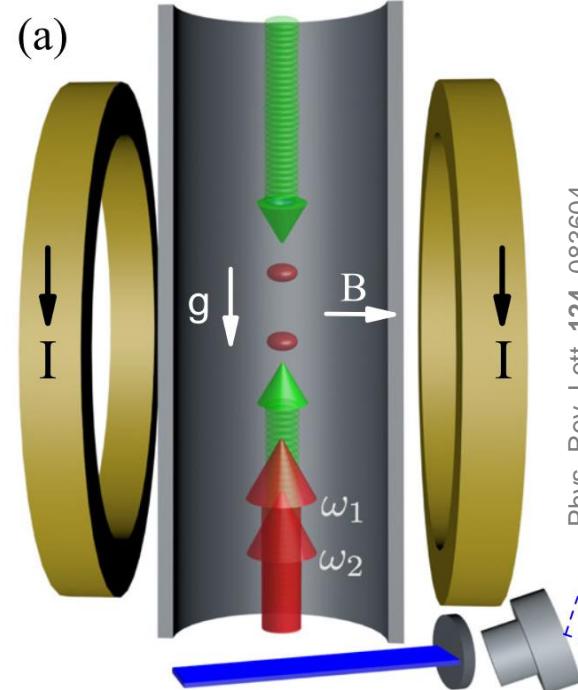
⇒ low expansion rates

- No direct excitation with feasible laser power

⇒ magnetically-induced transition

Phys. Rev. Lett. **96**, 083001

Phys. Rev. Lett. **119**, 263601



Phys. Rev. Lett. **119**, 263601

Phys. Rev. Lett. **124**, 083604

# Interaction

- Electric dipole coupling

$$\hat{d} = d_{ag} |a\rangle\langle g| + \text{h.c.}$$

- Magnetic dipole coupling

$$\hat{\mu} = \mu_{ae} |a\rangle\langle e| + \text{h.c.}$$

- Hamiltonian of three-level system

$$\hat{H} = \sum_j \hat{H}_j(\hat{p}, \hat{z}, \varrho) |j\rangle\langle j| - \hat{d}\mathbf{E}(\hat{z}, t, \varrho) + \hat{\mu}\mathbf{B}_0(\varrho)$$

motion of atom in state  $|j\rangle$       electric wave      static magnetic field

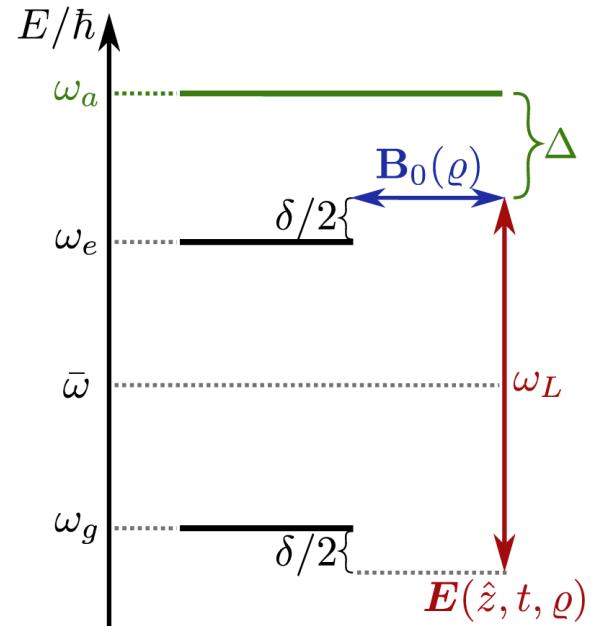
possible dark matter

$$\hat{H}_j(\hat{p}, \hat{z}, \varrho) = m_j(\varrho)c^2 + \frac{\hat{p}^2}{2m_j(\varrho)} + m_j(\varrho)g\hat{z}$$

mass defect     $m_jc^2 = \hbar\omega_j$

Phys. Rev. A **98**, 042106

Phys. Rev. A **100**, 052116



# Standard-Model extension



- Including light, classical dilaton field  $\varrho(t, z)$
- Dark matter (background fields)
- Consistent violation of equivalence principle (sourced by mass)

Nucl. Phys. B 423, 532

- Lagrangian including all sectors

Phys. Rev. D 82, 084033

$$\mathcal{L} = \mathcal{L}_{\text{EM}} + \mathcal{L}_{\text{mat}} + \mathcal{L}_{\text{EH}}$$

↑                   ↑                   ↑  
electromagnetic   matter   Einstein-Hilbert

- Electromagnetic sector  $\mathcal{L}_{\text{EM}} = -\frac{\sqrt{-g}}{4\mu_0} F_{\mu\nu} F^{\mu\nu}$
- ↑                   ↑  
magnetic susceptibility   field strength
- determinant of metric
- $\rightarrow -\frac{\sqrt{-g}}{4\mu_0} (1 - \varrho d_e) F_{\mu\nu} F^{\mu\nu}$
- ↑                   ↑  
linear dilaton field   coupling constant

⇒ light in gravity and dilaton fields

Phys. Rev. D 105, 084065

# Matter sector

- Leptonic part

Phys. Rev. D **82**, 084033

$$\sqrt{-g} \sum_{i=e,u,d} \bar{\psi}_i [i\hbar c \not{D} - m_i c^2] \psi_i \rightarrow \sqrt{-g} \sum_{i=e,u,d} \bar{\psi}_i [i\hbar c \not{D} - \underbrace{[1 + \varrho \tilde{d}_{m_i}] m_i c^2}_{=m_i(\varrho)}] \psi_i$$

leptons      Dirac operator      mass

linear dilaton field      coupling constant

lepton mass effectively dilaton dependent

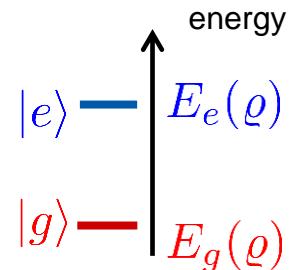
- Gauge bosons (photons, gluons, ...)

$\Rightarrow$  couplings effectively dilaton dependent

- Masses and internal structure depend on dilaton

effective coupling coefficient

$$m_j(\varrho) \cong m_j[1 + \beta_j \varrho]$$



- Linear expansion of state-dependent mass

Phys. Rev. D **105**, 084065  
PRX Quantum **2**, 040333

# Metric and Dilaton

- Einstein-Hilbert action

Phys. Rev. D 82, 084033

$$\mathcal{L}_{\text{EH}} = \sqrt{-g} \frac{c^4}{16\pi G} \left[ R - 2g^{\mu\nu} \partial_\mu \varrho \partial_\nu \varrho - \frac{2\varrho^2}{\lambda_\varrho^2} \right]$$

↑ Newtonian constant      ↑ Ricci scalar      ↑ kinetic term      ↑ Dilaton Compton wavelength  
 $\lambda_\varrho = \hbar/(cm_\varrho)$   
 Klein-Gordon type

- Metric
- Dilaton as perturbation
- Infinite massive plane at  $z = 0$ :

$$g_{\mu\nu} = \eta_{\mu\nu} + \delta_\mu^0 \delta_\nu^0 2g z/c^2$$

↑ Minkowski      ↑ gravitational acceleration

- Dilaton
- Wave equation
- Solution

$$(\partial_0^2 - \partial_j^2) \varrho = \frac{\varrho}{\lambda_\varrho^2} + \frac{g}{c^2} (2z\partial_j^2 + \partial_z) \varrho$$

inhomogeneity  
through gravity



$$\varrho \cong \underbrace{\bar{\varrho}_0 \cos(\omega_\varrho t - k_\varrho z + \phi_\varrho)}_{\text{oscillating background}} + \underbrace{\bar{\beta} s g z / c^2}_{\text{linear gravitation contribution}}$$



dark matter



EEP violation



# Light propagation

- Modified Maxwell equations

$$\nabla_\mu(1 - \varrho d_e)F^{\mu\nu} = 0$$

- Geometrical optics Ansatz for vector potential

Int. J. Mod. Phys. D 27, 1843010

$$A^\nu = (a^\nu + \epsilon b^\nu) e^{-i\Phi/\epsilon} + \mathcal{O}(\epsilon^2)$$

↑  
amplitude
↑  
phase with four momentum
 $K_\mu = \partial_\mu \Phi$

- Leading order: Eikonal equation

Phys. Rev. D 101, 121501(R)

Phys. Rev. D 105, 084065

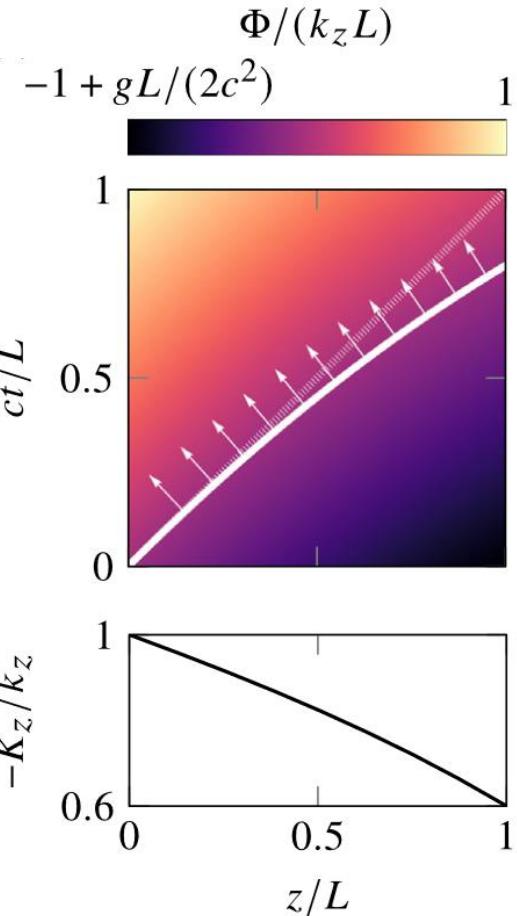
$$g^{\mu\nu}\partial_\mu\Phi\partial_\nu\Phi = 0$$

$$\Phi = ck_0t - qr - k_z z \left[ 1 - \frac{k_0^2}{k_z^2} \frac{gz}{2c^2} \right]$$

↑  
transverse coordinates
↑  
modified wave vector

⇒ no effects of dilaton

⇒ modified momentum transfer



# Amplitude modulation

- Amplitude of electric field modified by
  - Gravity
  - Dilaton
- Higher-order effect on diffraction

$$\hat{H} = \sum_j \hat{H}_j(\hat{p}, \hat{z}, \varrho) |j\rangle\langle j| - \hat{\mathbf{d}}\mathbf{E}(\hat{z}, t, \varrho) + \hat{\mu}\mathbf{B}_0(\varrho)$$

possible dark matter

static magnetic field

electric wave

$\hat{H}_j(\hat{p}, \hat{z}, \varrho) = m_j(\varrho)c^2 + \frac{\hat{p}^2}{2m_j(\varrho)} + m_j(\varrho)g\hat{z}$

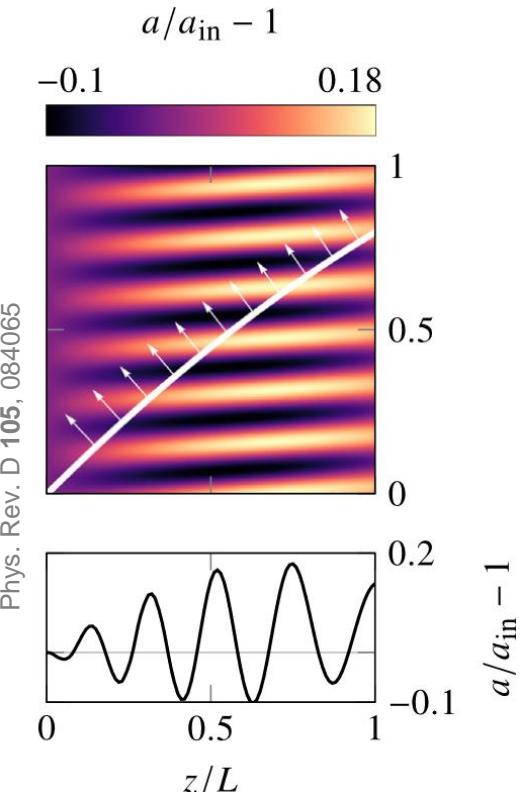
$m_j(\varrho) \cong m_j[1 + \bar{\beta}_j \varrho]$  effective coupling

$|j\rangle$  motion of atom in state

$\mathbf{E}(\hat{z}, t, \varrho) = \mathbf{E}_0(\varrho) e^{i[\kappa(\hat{z}) - \varphi_L(t)]} + \text{h.c.}$

$\kappa(\hat{z}) = k\hat{z} [1 - g\hat{z}/(2c^2)]$

$\varphi_L = \phi_0 + \omega_L t + \alpha t^2/2$



# Effective single-photon transition

- Modified rotating wave approximation  
(due to static  $B_0$ )
- Hamiltonian in co-rotating and displaced frame

$$\hat{H}_{\text{rot}} = \frac{\hbar}{2} \begin{pmatrix} 2[\hat{\nu}_a + \Delta] & \Omega_B(\varrho) & \Omega_E(\varrho) \\ \Omega_B(\varrho) & 2\hat{\nu}_e + \delta & 0 \\ \Omega_E(\varrho) & 0 & 2\hat{\nu}_g - \delta \end{pmatrix}$$

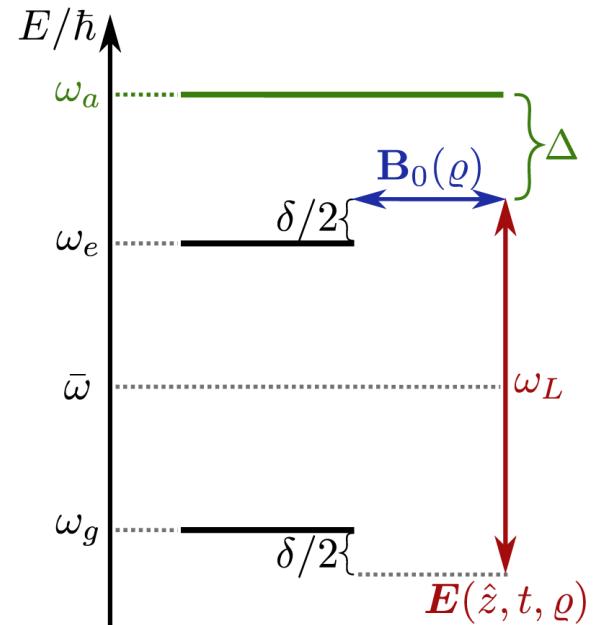
Rabi frequencies

$$\Omega_E(\varrho) = -2d_{ag}E_0(\varrho)/\hbar$$

$$\Omega_B(\varrho) = 2\mu_{ae}B_0(\varrho)/\hbar$$

- Adiabatic elimination of  $|a\rangle$

Eur. Phys. J. Plus **129**, 12    Mathematics for Industry **11**, 127



- Effective Rabi frequency  $\Omega = -\Omega_B(0)\Omega_E(0)/(2\Delta)$
- Stark shift  $\Delta\omega_{ac} = [\Omega_E^2(0) - \Omega_B^2(0)]/(4\Delta)$

# Finite pulse duration

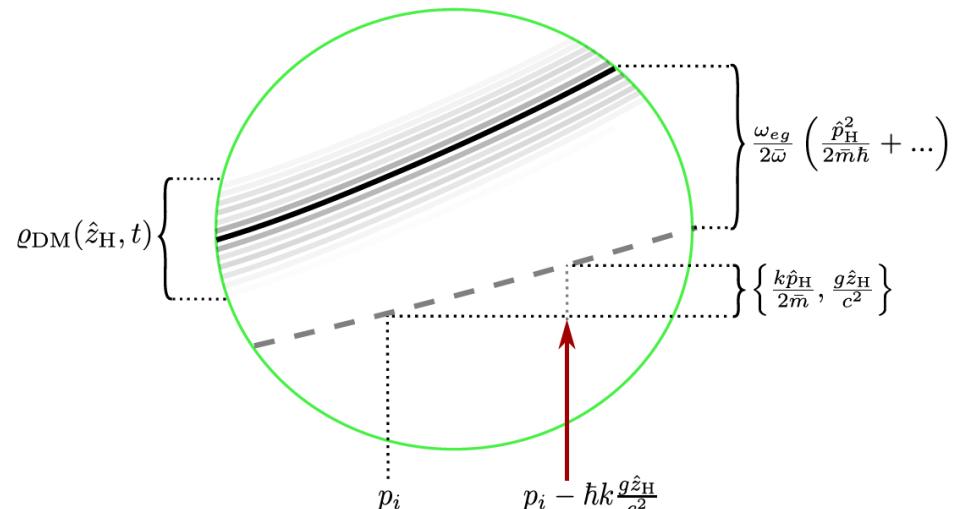
- Resonance condition with c.m. motion

$$\begin{aligned}\hat{\nu}_H &= \left( \omega_{eg} + \frac{\hat{p}k}{\bar{m}} + \Delta\omega_{ac} \right) - \omega_L \\ &\quad - (\alpha + kg)t + \bar{\omega}(\beta_e - \beta_g)\varrho(\hat{z}_H, t) \\ &\quad + \frac{\omega_{eg}}{\bar{\omega}} \left( -\frac{\hat{p}_H^2}{2\bar{m}\hbar} + \frac{\bar{m}g\hat{z}_H}{\hbar} - \frac{\omega_k}{4} \right) \\ &\quad - \left\{ \frac{k\hat{p}_H}{2\bar{m}}, \frac{g\hat{z}_H}{c^2} \right\}\end{aligned}$$

- Time dependent operator-valued detuning

Phys. Rev. A **99**, 033619

⇒ phase contributions on scale of pulse duration



# Light propagation effects

- Modified kick potential

Phys. Rev. D **105**, 084065

$$\hat{V} = -\hbar \sum_{\ell} k_{\ell} \hat{z} \left[ 1 - \frac{g \hat{z}}{2c^2} \right] \delta(t - t_{\ell})$$

↑ momentum transfer pulse  $\ell$

↓ time pulse  $\ell$   
including propagation delay

gravitational bending

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

- Perturbative treatment

Phys. Rev. A **101**, 053615

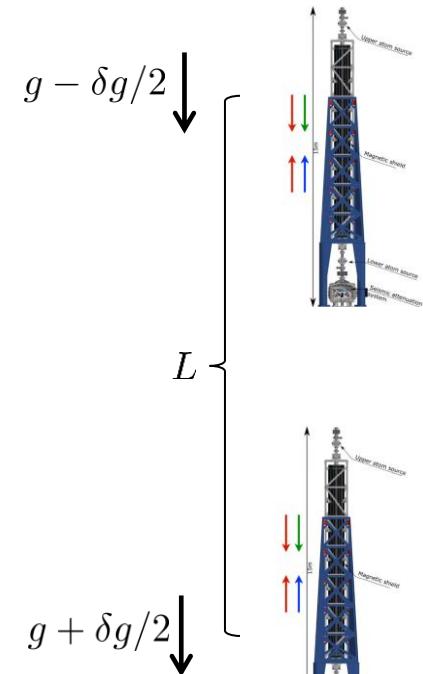
- Effect of vertical Bragg-MZ configuration (no dark matter)

$$\frac{\delta\varphi}{kgT^2} = -\frac{\delta g}{g} \left( 1 + \beta + 3 \frac{v_T - gT}{c} \right) + \frac{gL}{c^2}$$

velocity of upper branch at mirror

- Spatial oscillation of dark matter in horizontal configuration

Phys. Rev. D **105**, 084065



Phys. Rev. D **104**, 084001

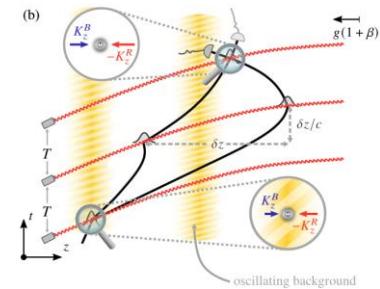
# Thank you for your attention



F. Di Pumbo, A. Friedrich, A. Geyer, Ch. Ufrecht, E. Giese

*Light propagation and atom interferometry in gravity and dilaton fields*

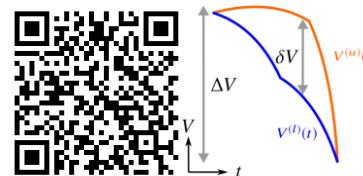
Physical Review D **105**, 084065 (2022)



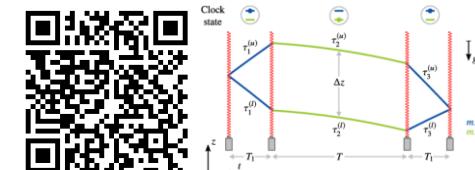
Phys. Rev. D **107**, 064007



PRX Quantum **2**, 040333



Phys. Rev. A **101**, 053615



Phys. Rev. Res. **2**, 043240



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