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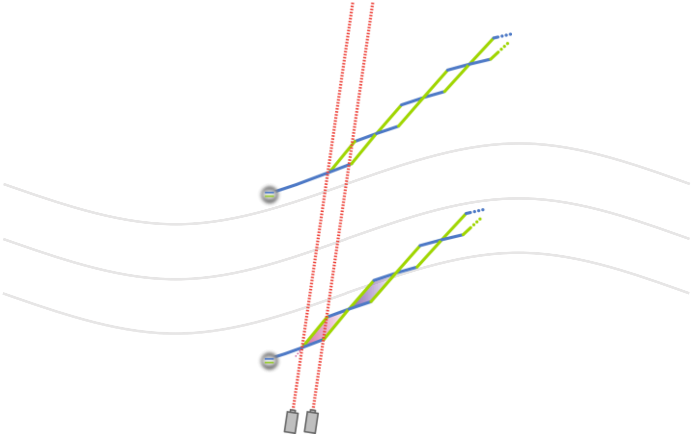

Baseline optimization for large-scale detectors

2nd Terrestrial Very-Long-Baseline Atom Interferometry Workshop, 4 April 2024

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QUANTUS

bundesdruckerei.

IQST

Carl Zeiss Stiftung

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Wolfgang Schleich

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Collaborations:

ProTrainU

IQST

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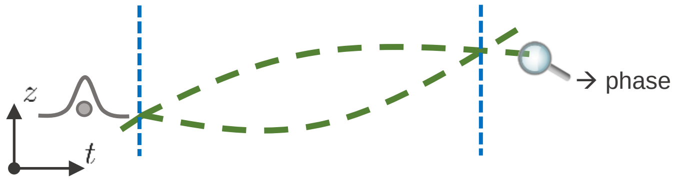
Signals in atom interferometers

Light-pulse atom interferometers



- propagate massive particle through spacetime
- manipulation by light pulses
- inertial sensing and metrology

→ gravimeter, gradiometer, gyroscopes

→ dark-matter and gravitational-wave detection, equivalence-principle violations, fundamental tests

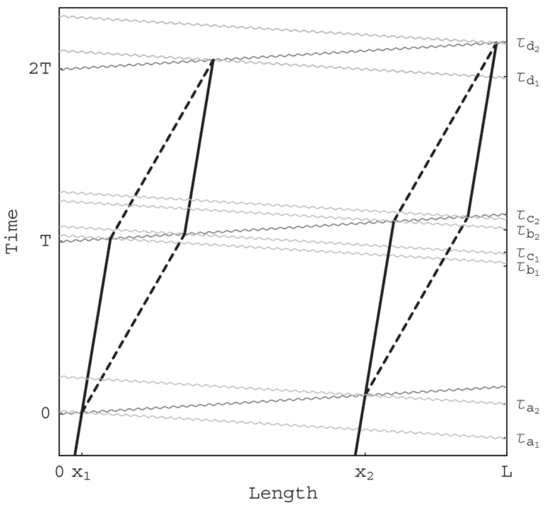
→ however noise: small signals hard to isolate in single interferometer phase

Differential gravitational-wave and dark-matter detection

- use two spatially separated atom interferometers
- differential measurements
- probing at different points in spacetime

  → ultralight dark matter
  Phys. Rev. D ***78****, 122002*

  → gravitational-wave detection
  Phys. Rev. D ***97****, 075020*



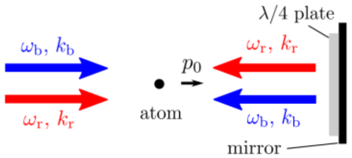
Phys. Rev. D ***78****, 122002*

Diffraction techniques

- different points in spacetime:
  → large separations

Two-photon transition (two directions)

Phys. Rev. A ***101****, 053610*



Phys. Rev. A ***101****, 053610*

- laser-phase noise
  Phys. Rev. D ***78****, 122002*

- no change of internal state for Bragg

Diffraction techniques

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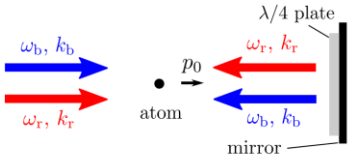
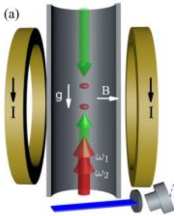


Phys. Rev. A ***101***, *053610*

- laser-phase noise
  Phys. Rev. D ***78***, *122002*
- no change of internal state for Bragg

Single-photon transitions (one direction)

AVS Quantum Sci. ***5***, *044402*



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

- challenging laser requirements
  Phys. Rev. Lett. ***124***, *083604*
  Phys. Rev. Lett. ***119***, *263601*
- but laser-phase noise suppression
  Phys. Rev. Lett. ***110***, *171102*
- “clock” contribution accessible
  Phys. Rev. D ***97***, *075020*

Gravitational-wave vs. dark-matter detection

Dark matter

- laser phase not affected

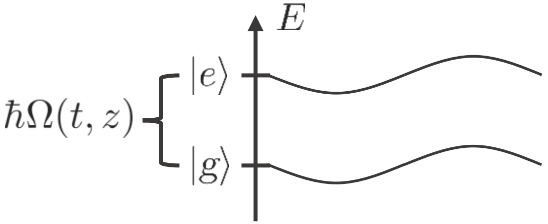
  Phys. Rev. D ***105****, 084065*

- effect on atomic motion

  Phys. Rev. Lett. ***117****, 261301*

  → dark matter: oscillating internal energies

  AVS Quantum Sci. ***5****, 044402*



  → propagation between pulses dominant

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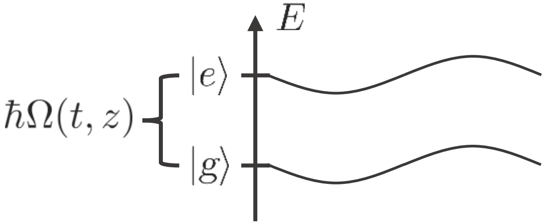


→ propagation between pulses dominant

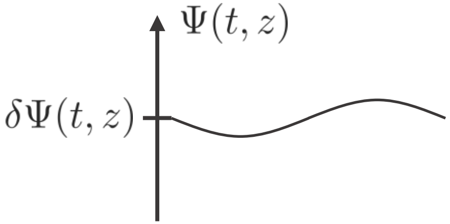
Gravitational waves

- no effect on atomic motion on Newtonian level

- signature on phase of electromagnetic field

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

→ strain induces oscillating laser phase



→ imprinted on atom during light pulse

Mach-Zehnder phase

Dark matter

- dark-matter coupling through clock frequency

AVS Quantum Sci. ***5****, 044404*

$$\Omega(t,z) = \underbrace{\omega_e - \omega_g}_{\Omega} + \underbrace{\bar{\varepsilon}\delta\Omega}_{(\varepsilon_e+\varepsilon_g)\,\varrho_0\Omega/2} \cos\left(\omega t - kz + \phi\right)$$

- phase of single Mach-Zehnder

Phys. Rev. D ***105****, 023006; AVS Quantum Sci.* ***6****, 014404*

$$\varphi(t_0, z_0) = -\int_{t_0}^{t_0+T} \mathrm{d}t\, \Omega(t, z_0) + \int_{t_0+T}^{t_0+2T} \mathrm{d}t\, \Omega(t, z_0)$$

no recoil during Mach-Zehnder

Mach-Zehnder phase

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Dark matter

- dark-matter coupling through clock frequency

AVS Quantum Sci. ***5****, 044404*

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no recoil during Mach-Zehnder

Gravitational waves

- gravitational-wave coupling through light's phase

Class. Quantum Gravity ***38****, 14*

light wave vector

strain

$$\delta\Psi(t,z) = -\frac{k_\ell h}{4k}\left[\sin(\omega t - kz + \phi) - \sin(\omega t_0 + \phi)\right]$$

- phase of single Mach-Zehnder

no recoil during Mach-Zehnder

$$\varphi(t_0,z_0) = -\int_{t_0}^{t_0+2T} \mathrm{d}t\,\delta\Psi(t,z_0)$$

$$\times\left[\delta(t-t_0) - 2\delta(t-T-t_0) + \delta(t-2T-t_0)\right]$$

Multidiamond atom interferometer

- generalization to Q subsequent Mach-Zehnder schemes

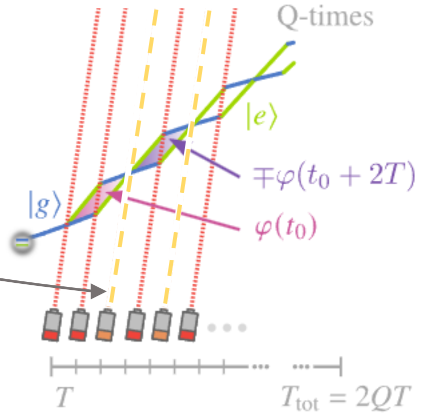
  → sensitivity enhancement
  Phys. Rev. D ***97**, 075020, Phys. Rev. D* ***105**, 023006*

- butterfly-like geometry
  AVS Quantum Sci. ***6**, 014404; Phys. Rev. D* ***105**, 023006*

  → role of arms for subsequent diamonds

interchange can be omitted with yellow pulses

Phys. Rev. D ***105**, 023006*



AVS Quantum Sci. ***6**, 014404*

$$\Phi(t_0, z_0) = \sum_{q=1}^{Q} \underset{\text{retaining}}{\overset{\text{interchanging}}{(\mp 1)^{q-1}}} \varphi\left(t_0 + 2(q-1)T, z_{2(q-1)T}\right)$$

→ interchange: leading-order gravitational phase
$\sum_{q=1}^{Q}(-1)^q kgT^2 = 0$ cancels for even diamonds

Differential multidiamond sensor

- spatially separated atom interferometers

  → differential phase $\delta\Phi = \Phi(t_0 + \tau_L, L + z_0) - \Phi(t_0, z_0)$

  $\tau_L = L/c$

- initial phase ϕ unknown

  → measure signal amplitude

  *Phys. Rev. D **97**, 075020, Phys. Rev. D **105**, 023006*

  $$\Phi_\mathrm{S} = \left[2\int_0^{2\pi} \mathrm{d}\phi\, \delta\Phi^2/(2\pi)\right]^{1/2}$$

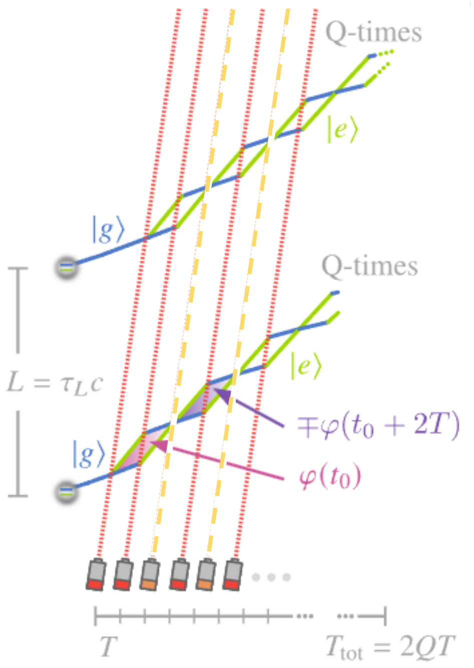
- for $\omega\tau_L \ll 1$ and neglecting recoil in trajectory

  generalization to LMT

  $$\Phi_\mathrm{DM} = \bar{\varepsilon} 4 \delta\Omega \tau_L N \left|\mathcal{Q}_\mp(\omega T, Q)\right|$$

  interrogation-mode function

  $$\Phi_\mathrm{GW} = h 2 k_\ell L N \left|\mathcal{Q}_\mp(\omega T, Q)\right|$$



*AVS Quantum Sci. **6**, 014404*

Resonant-mode detection

- retaining roles of arms

  *Phys. Rev. D **105**, 023006*

$$\mathcal{Q}_+(\omega T, Q) = \frac{1}{2}\sin(Q\omega T)\tan\frac{\omega T}{2}$$

→ resonant mode for $\omega T = \pi$

$$|\mathcal{Q}_+(\pi, Q) = Q|$$

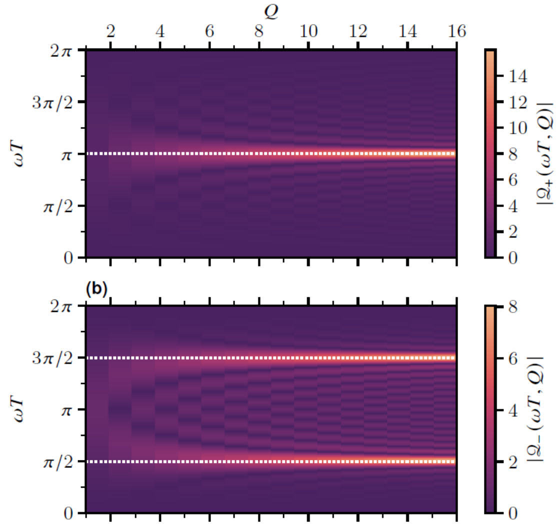
- interchanging roles of arms

  *AVS Quantum Sci. **6**, 014404*

$$\mathcal{Q}_-(\omega T, Q) = \begin{cases} \sin^2\frac{\omega T}{2}\cos(Q\omega T)/\cos\omega T & \text{for } Q \text{ odd} \\ \sin^2\frac{\omega T}{2}\sin(Q\omega T)/\cos\omega T & \text{for } Q \text{ even} \end{cases}$$

→ resonant mode for $\omega T = \pi/2$

$$|\mathcal{Q}_+(\pi/2, Q) = Q/2|$$



*AVS Quantum Sci. **6**, 014404*

Sensitivity to gravitational waves and dark matter

- parameter uncertainty

$\Delta\bar{\varepsilon} = \frac{\Delta\Phi_{\mathrm{DM}}}{4\delta\Omega\tau_L N|\mathcal{Q}_{\mp}|}$ related to $\bar{\varepsilon} = \Delta\bar{\varepsilon}\sqrt{\mathrm{SNR}}$

$\Delta h = \frac{\Delta\Phi_{\mathrm{GW}}}{2k_\ell L N|\mathcal{Q}_{\mp}|}$ related to $h = \Delta\bar{h}\sqrt{\mathrm{SNR}}$

- assume weak time dependence

$$|Q\mathrm{d}\Delta\Phi_S/\mathrm{d}T|_{\omega T=\mathrm{res}} \ll 1$$

→ resonant modes $|\mathcal{Q}_+| = Q$ and $|\mathcal{Q}_-| = Q/2$

→ with $T_{\mathrm{tot}} = 2QT$ find

$$\Delta\bar{\varepsilon} = \frac{\pi}{2}\frac{\Delta\Phi_{\mathrm{DM}}}{N\delta\Omega\omega\tau_L T_{\mathrm{tot}}} \qquad \Delta h = \pi\frac{\Delta\Phi_{\mathrm{GW}}}{Nk_\ell\omega L T_{\mathrm{tot}}}$$

Optimal baselines

- parabola flight

$$T_{\text{tot}} \cong \sqrt{8h/g} - 2v_{\text{r}}/(gQ)$$

suppressed by diamonds

- shot noise $\Delta\Phi_S = \sqrt{2/(\nu n_{\text{at}})}$ with $T_{\text{int}} = \nu T_{\text{tot}}$

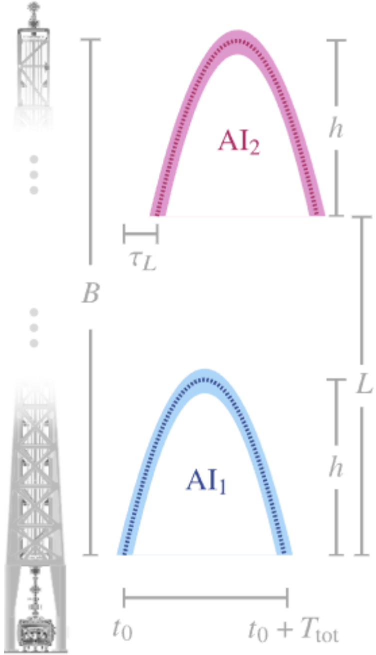
repetitions   integration time

- for $\tau_L = (B-h)/c$ and for DM $\delta\Omega = \bar{\varrho}\Omega/\omega$

- uncertainty $\Delta\bar{\varepsilon} = \frac{\pi c}{\sqrt{2n_{\text{at}}}N\Omega\bar{\varrho}(B-h)\sqrt{T_{\text{tot}}T_{\text{int}}}}$ $\Delta h \sim 1/\omega$

$(B-h)\,h^{1/2}$ $(B-h)\,h^{1/4}$

$h = B/3$ optimization $h = B/5$



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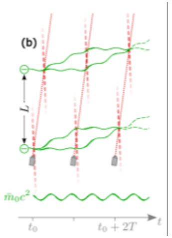
Outlook & improvements

- Recoil and gravity effects in Hamiltonian

- gravitational waves: direct (relativistic) atomic coupling



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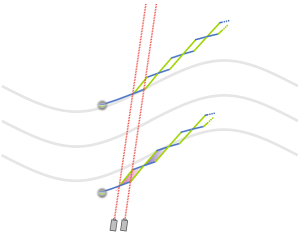
Poster by D. Derr & E. Giese!

- recoil effects in (interrupted) parabola flight

- loops and LMT pulses connected

Contributions to AVS special issue



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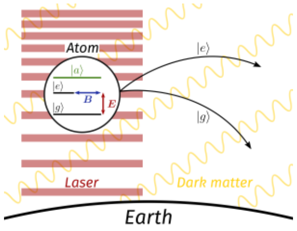

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Thank you for your attention!

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