Long-Baseline Atom Interferometry: Science Opportunities and Experimental Methods

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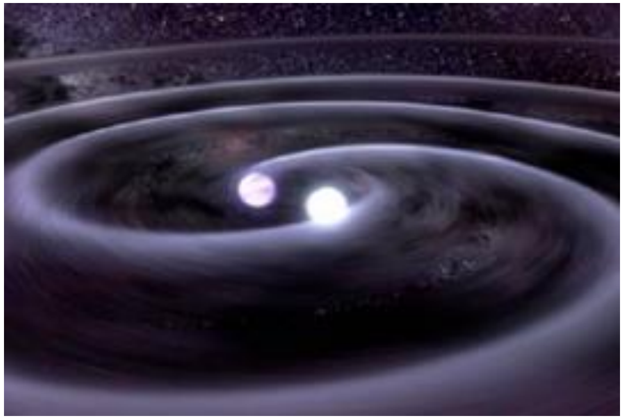
FOMO 2026 Summer School

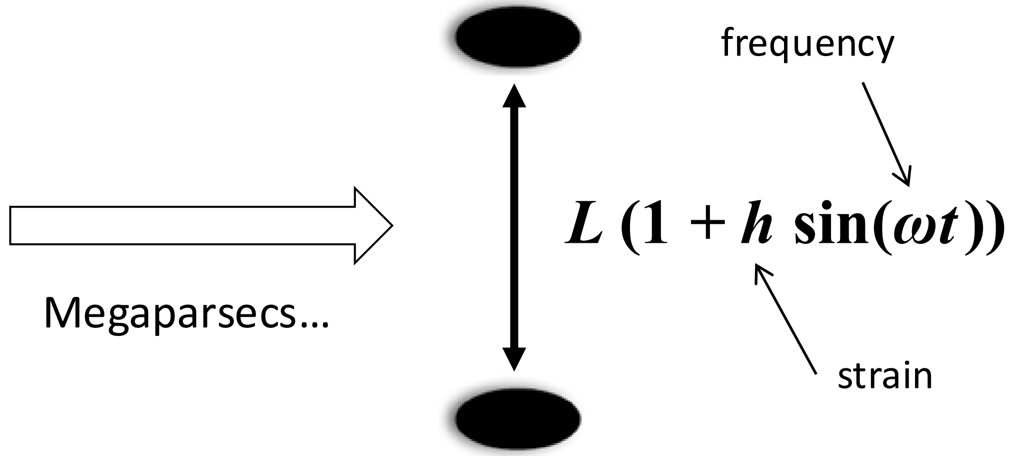
Summary

- Introduction to two of the science motivations for long-baseline atom interferometry
  - Gravitational wave detection
  - Dark matter searches
- Differences between single-photon and two-photon atom optics and implications for long-baseline atom interferometry
- Overview of some examples of systematic effects and experimental techniques

Gravitational Wave Detection

$$ds^2 = dt^2 - (1 + h\sin(\omega(t-z)))dx^2 - (1 - h\sin(\omega(t-z)))dy^2 - dz^2$$





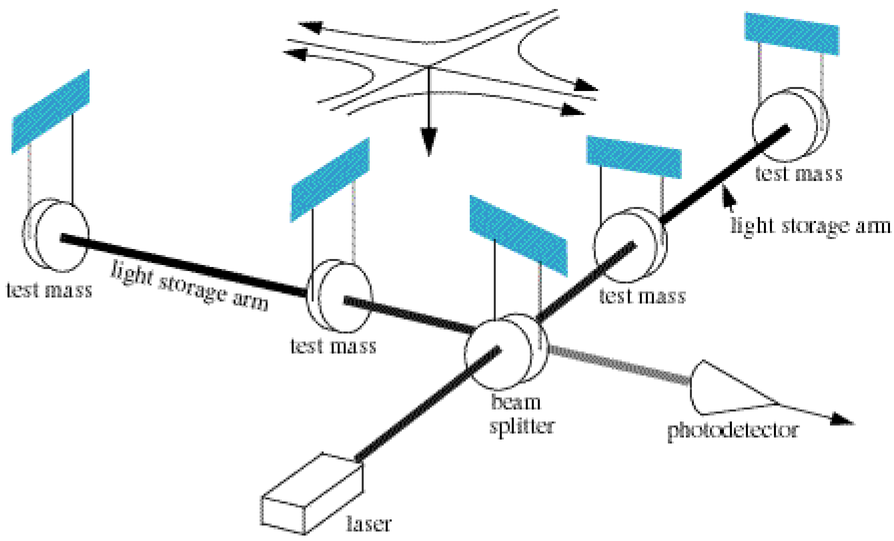
Gravitational waves science:

New carrier for astronomy: Generated by moving mass instead of electric charge

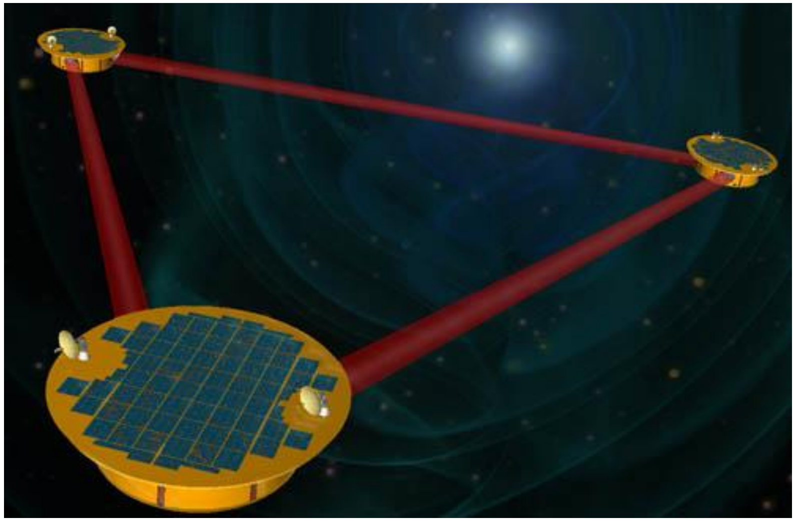
Probing the early universe: Can see to the earliest times in the universe, study corresponding high energy scales

Tests of gravity: Extreme systems (e.g., black hole binaries) test general relativity

Laser Interferometer Detectors

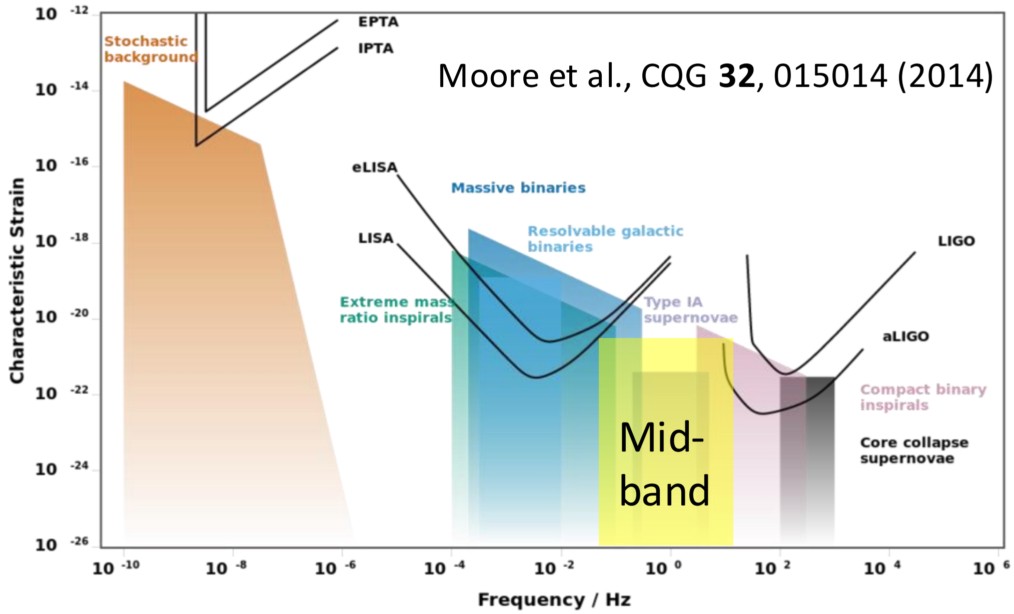


Gound-based detectors: e.g. LIGO, VIRGO, KAGRA, planned ET,… (> ~3 Hz)



Space-based detector: planned LISA mission (1 mHz – 100 mHz), also proposals to extend LISA concept to higher frequencies (e.g., DECIGO)

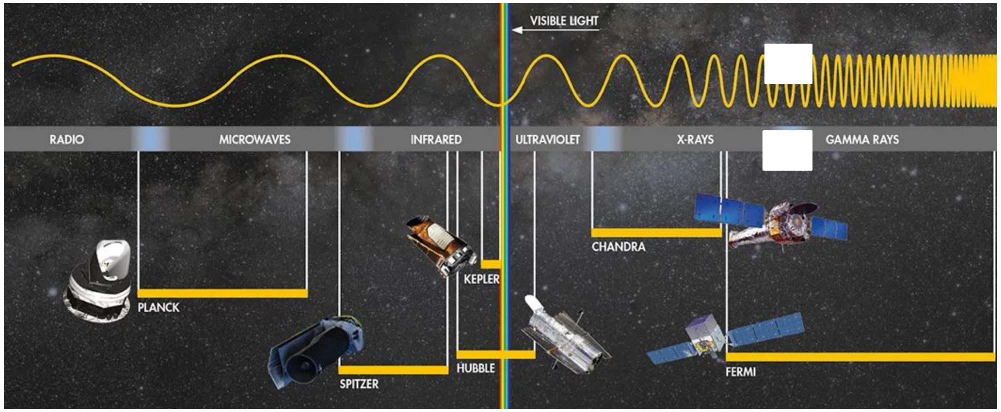
Gravitational wave frequency bands



Atom interferometers: Aim to fill gap between peak sensitivities of LIGO and LISA detectors in ~ 0.1 Hz – 3 Hz "mid-band" range

Mid-band Science

Mid-band discovery potential
-Historically, every new band/modality has led to discovery
-Observe LIGO sources earlier in their evolution



https://c02.purpledshub.com/uploads/sites/48/2020/09/Electromagnetic-spectrum-a0f874b.jpg

Cosmological signals that give insight into high energy physics
-Operating in mid-band instead of lower frequencies advantageous for avoiding white dwarf confusion noise

Promising for sky localization [Baum et al., JCAP05(2024)027]
-Predict *when* and *where* events will occur (before they reach LIGO band)
-Observe run-up to coalescence using electromagnetic telescopes

Astrophysical Sources
White dwarf binaries (Type IA supernovae), black hole binaries, intermediate mass black holes, and neutron star binaries

Mid-band Science

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

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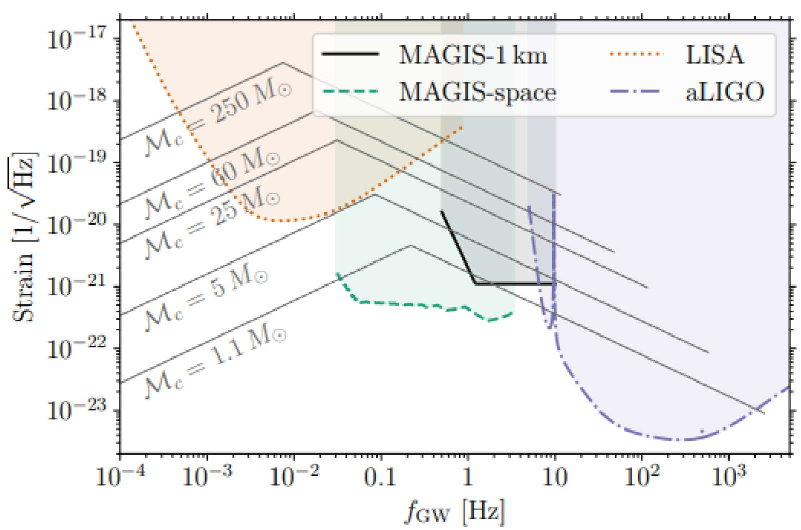
Published: *May 2, 2024*

Gravitational wave measurement in the mid-band with atom interferometers

Sebastian Baum,[a,b,c] **Zachary Bogorad**[a,b] **and Peter W. Graham**[a,b]



Mid-band Science

Distance at which signal observable with SNR of 5

Chirp Mass $\mathcal{M}_c$	"5 × (MAGIS-1 km)" lifetime	"5 × (MAGIS-1 km)" $d_L(\rho \sim 5)$	"MAGIS-space" lifetime	"MAGIS-space" $d_L(\rho \sim 5)$
$1.1\,M_\odot$	40 days	30 Mpc	200 yr	100 Mpc
$5\,M_\odot$	3 days	100 Mpc	16 yr	500 Mpc ($z \sim 0.1$)
$25\,M_\odot$	5 h	400 Mpc ($z \sim 0.1$)	1 yr	3 Gpc ($z \sim 0.5$)
$60\,M_\odot$	1 h	600 Mpc ($z \sim 0.1$)	3 months	5 Gpc ($z \sim 1$)
$250\,M_\odot$	7 min	—	8 days	20 Gpc ($z \sim 2$)

Mid-band Science

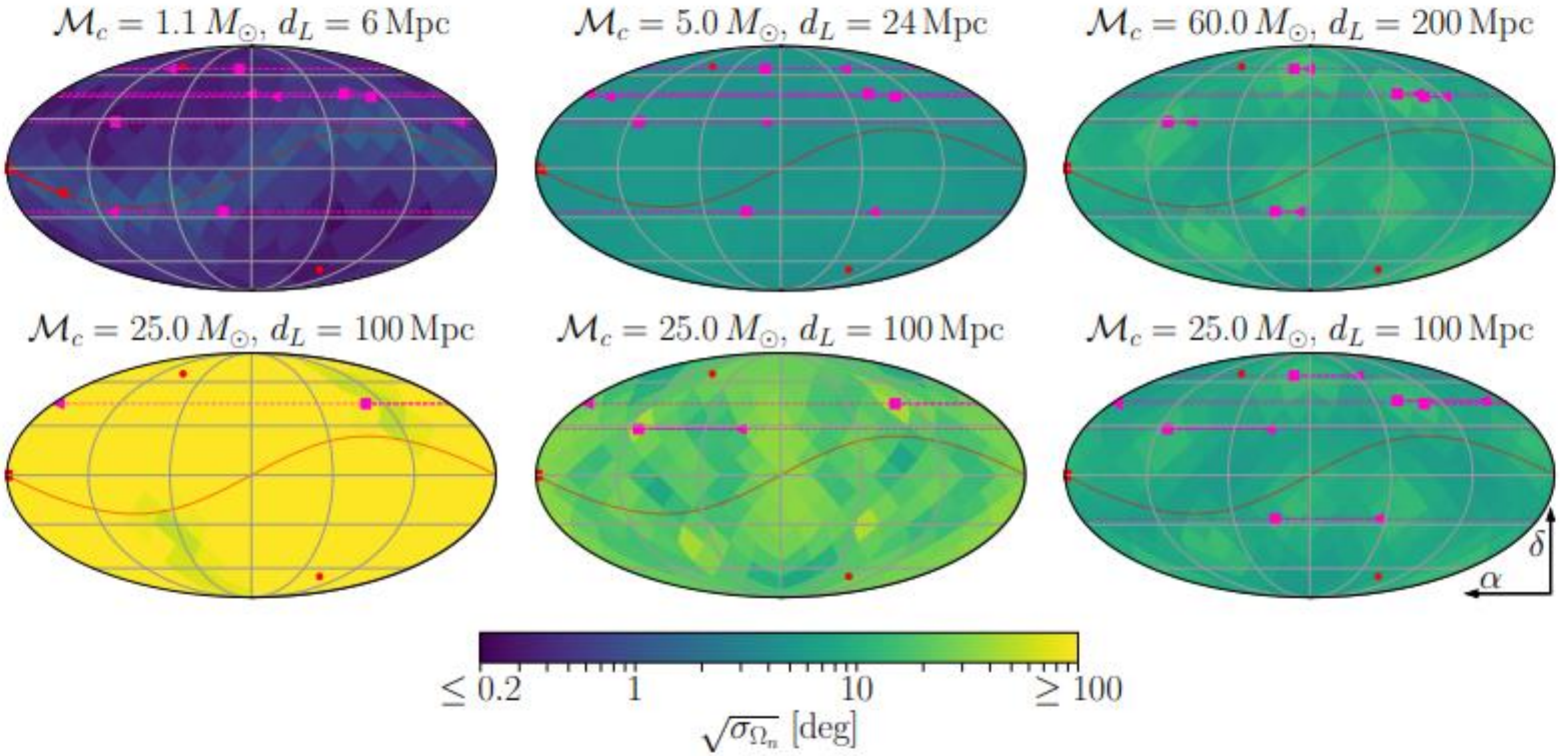


Figure 9. *Sky-localization error* ($\sqrt{\sigma_{\Omega_n}}$) [see eq. (3.9)] as a function of the source's sky-location for "MAGIS-1 km", otherwise the same as figure 8.

Mid-band Science

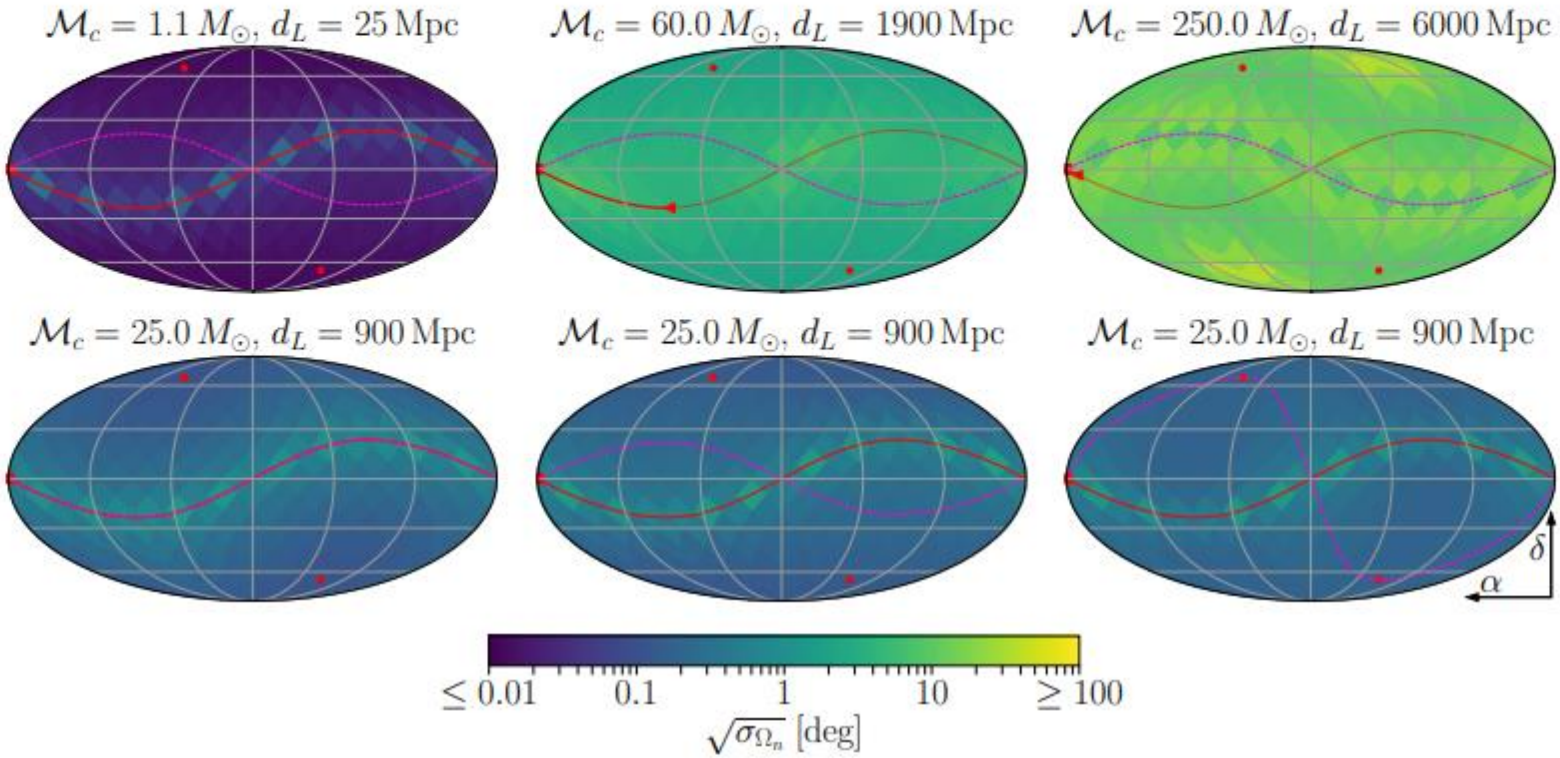
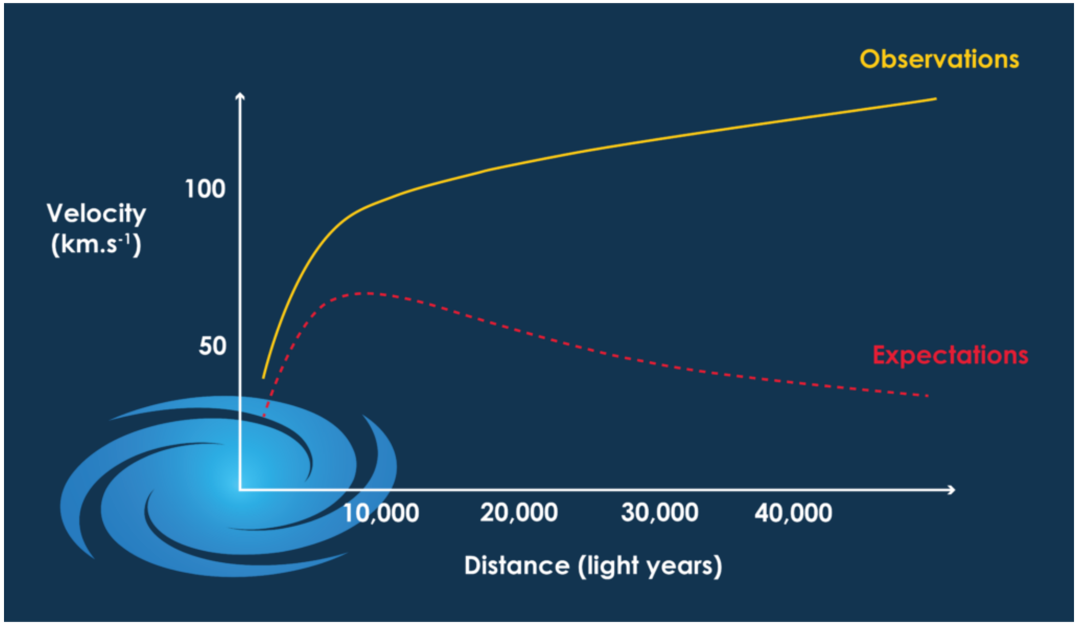


Figure 7. *Sky-localization error* ($\sqrt{\sigma_{\Omega_n}}$) [see eq. (3.9)] as a function of the source's sky-location for a "MAGIS-space" detector, otherwise the same as figure 6.

Dark Matter

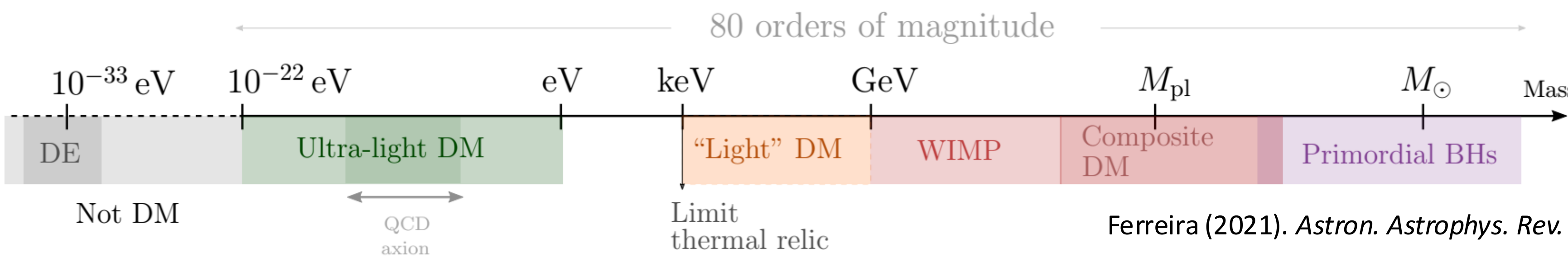


https://www.euclid-ec.org/what-is-and-what-could-be-dark-matter/

Galactic rotation curves not consistent with luminous matter only

Other evidence includes gravitational lensing not explained by luminous matter, dynamics of galaxy interactions, structure of cosmic microwave background, etc…

Dark Matter

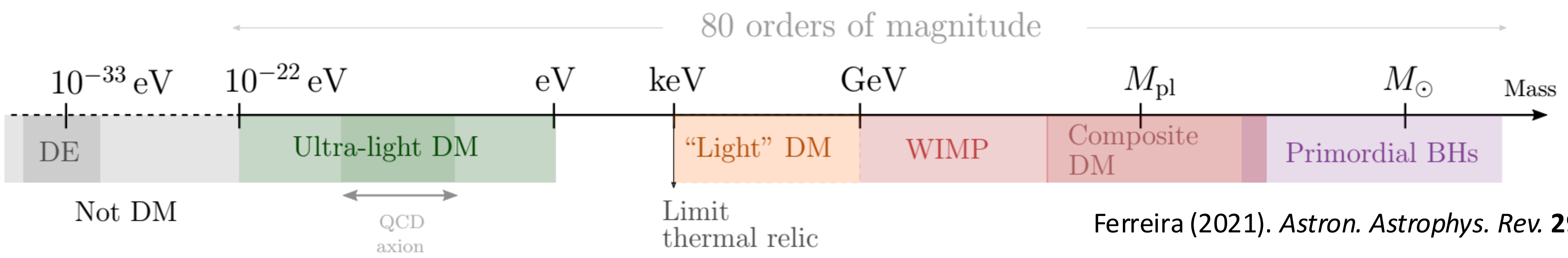


Ferreira (2021). *Astron. Astrophys. Rev.* **29**, 7

For reference, mass of an electron is about 0.5 MeV

Local dark matter density needed to explain astrophysical observations: 0.4 GeV/cm^3

Dark Matter

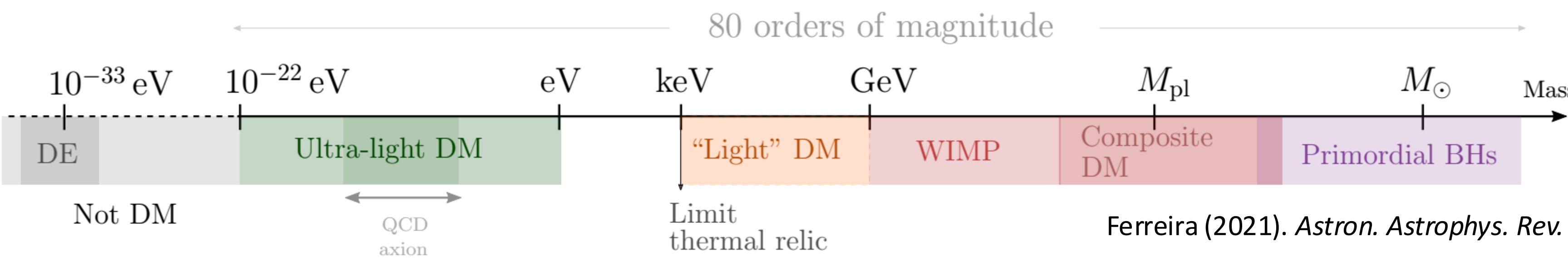


Ferreira (2021). *Astron. Astrophys. Rev.* **29**, 7

- Ultralight dark matter: must be made of bosons

- Why might this be?

Dark Matter



Ferreira (2021). *Astron. Astrophys. Rev.* **29**, 7

- Ultralight dark matter: must be made of bosons
- Why might this be?
- As the mass of individual dark matter particles gets very small, need many dark matter particles per unit phase space volume to achieve needed mass density while keeping velocity small enough to be consistent with gravitational dynamics of galaxy
- Pauli exclusion principle forces this very light dark matter to be bosonic

Wavelike Dark Matter

- "Bosonic clumping" of many dark matter particles into coherently oscillating waves
- Oscillate at Compton frequency associated with characteristic dark matter mass

$$f_{\text{Compton}} = \frac{m_{\text{DM}} c^2}{h}$$

- Wavelike DM can have various spins and couplings to ordinary matter
- We will discuss a couple examples

Wavelike Dark Matter

- A nice community review

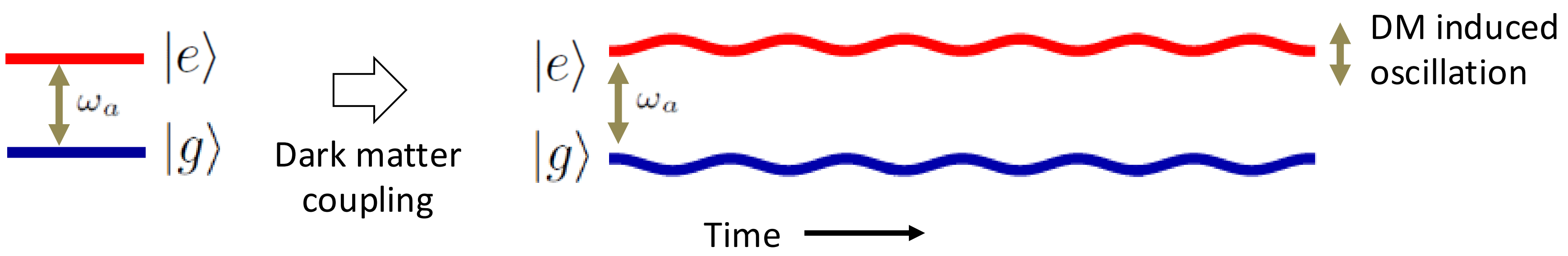
Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Snowmass 2021 White Paper
New Horizons: Scalar and Vector Ultralight Dark Matter

D. Antypas,[1,2] A. Banerjee,[3] C. Bartram,[4] M. Baryakhtar,[4] J. Betz,[5] J. J. Bollinger,[6] C. Boutan,[7] D. Bowring,[8] D. Budker,[2,1,9] D. Carney,[10] G. Carosi,[11,4] S. Chaudhuri,[12] S. Cheong,[13,14] A. Chou,[8] M. D. Chowdhury,[15] R. T. Co,[16] J. R. Crespo López-Urrutia,[17] M. Demarteau,[18] N. DePorzio,[19] A. V. Derbin,[20] T. Deshpande,[21] M. D. Chowdhury,[15] L. Di Luzio,[22,23] A. Diaz-Morcillo,[24] J. M. Doyle,[19,25] A. Drlica-Wagner,[8,26,27] A. Droster,[9] N. Du,[11] B. Döbrich,[28] J. Eby,[29] R. Essig,[30] G. S. Farren,[31] N. L. Figueroa,[1,2] J. T. Fry,[32] S. Gardner,[33] A. A. Geraci,[21] A. Ghalsasi,[34] S. Ghosh,[35,36] M. Giannotti,[37] B. Gimeno,[38] S. M. Griffin,[39,40] D. Grin,[41] D. Grin,[41] H. Grote,[42] J. H. Gundlach,[4] M. Guzzetti,[4] D. Hanneke,[43] R. Harnik,[8] R. Henning,[44,45] V. Irsic,[46,47] H. Jackson,[9] D. F. Jackson Kimball,[48] J. Jaeckel,[49] M. Kagan,[13] D. Kedar,[50,51] R. Khatiwada,[8,52] S. Knirck,[8] S. Kolkowitz,[53] T. Kovachy,[21] S. E. Kuenstner,[14] Z. Lasner,[19,25] A. F. Leder,[9,10] R. Lehnert,[54] D. R. Leibrandt,[6,51] E. Lentz,[7] S. M. Lewis,[8] Z. Liu,[55] J. Manley,[56] R. H. Maruyama,[35] A. J. Millar,[57,58] V. N. Muratova,[20] N. Musoke,[59] S. Nagaitsev,[8,27] O. Noroozian,[60] C. A. J. O'Hare,[61] J. L. Ouellet,[32] K. M. W. Pappas,[32] E. Peik,[62] G. Perez,[3] A. Phipps,[48] N. M. Rapidis,[14] J. M. Robinson,[50,51] V. H. Robles,[63] K. K. Rogers,[64] J. Rudolph,[14] G. Rybka,[4] M. Safdari,[13,14] M. Safdari,[14,13] M. S. Safronova,[5] C. P. Salemi,[32] P. O. Schmidt,[62,65] T. Schumm,[66] A. Schwartzman,[13] J. Shu,[67] M. Simanovskaia,[14] J. Singh,[14] S. Singh,[56,5] M. S. Smith,[18] W. M. Snow,[54] Y. V. Stadnik,[61] C. Sun,[68] A. O. Sushkov,[69] T. M. P. Tait,[70] V. Takhistov,[29] D. B. Tanner,[71] D. J. Temples,[8] P. G. Thirolf,[72] J. H. Thomas,[52] M. E. Tobar,[73] O. Tretiak,[1,2] Y.-D. Tsai,[70,8] J. A. Tyson,[74] M. Vandegar,[13] S. Vermeulen,[42] L. Visinelli,[75,76] E. Vitagliano,[77] Z. Wang,[78] D. J. Wilson,[15] L. Winslow,[32] S. Withington,[47] M. Wooten,[9] J. Yang,[7] J. Ye,[50,51] B. A. Young,[79] F. Yu,[80] M. H. Zaheer,[5] T. Zelevinsky,[81] Y. Zhao,[82] and K. Zhou[13]

Wavelike Dark Matter

- Example: scalar dark matter field
- Can cause oscillations in fundamental constants such as electron mass of fine structure constant
- One consequence: time-varying atomic energy levels



Wavelike Dark Matter

- A scheme to search for this kind of dark matter:

PHYSICAL REVIEW D **97,** 075020 (2018)

Search for light scalar dark matter with atomic gravitational wave detectors

Asimina Arvanitaki,[1,*] Peter W. Graham,[2,†] Jason M. Hogan,[3,‡] Surjeet Rajendran,[4,§] and Ken Van Tilburg[2,5,6,‖]

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[6]*Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, New York 10003, USA*

(Received 25 August 2016; published 16 April 2018)

Wavelike Dark Matter

- Example: vector dark matter field that exerts composition dependent forces (e.g., with an effective "charge" proportional to baryon (protons, neutrons) minus lepton (electrons) number)

- Effect would look like a time-varying equivalence principle violation

Wavelike Dark Matter

- Search using a differential measurement between co-located, simultaneous interferometers with different species or isotopes

PHYSICAL REVIEW D **93,** 075029 (2016)

Dark matter direct detection with accelerometers

Peter W. Graham,[1] David E. Kaplan,[1,2,3,4] Jeremy Mardon,[1] Surjeet Rajendran,[3] and William A. Terrano[5,6]

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[5]*Center for Experimental Nuclear Physics and Astrophysics, University of Washington, Seattle, Washington 98195-4290, USA*
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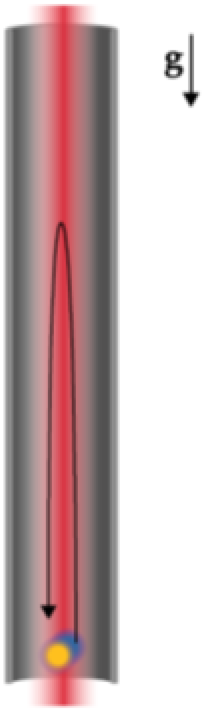
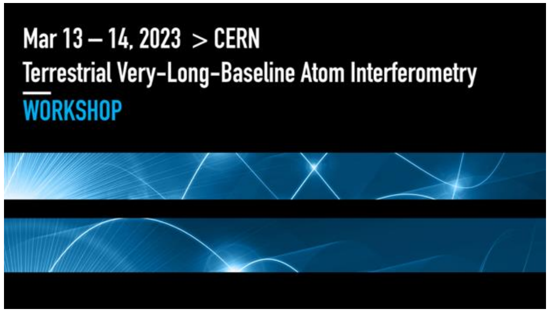
(Received 14 January 2016; published 20 April 2016)



Global Efforts in Long-Baseline Atom Interferometry

- Growing global community in this area

- Example: CERN Very-Long-Baseline Terrestrial Atom Interferometry Workshop, March 13-14 (2023): ~200 registered participants. https://indico.cern.ch/event/1208783/



MAGIS-100 in US (Abe et al., QST 6, 044003 (2021))

AION in UK (Badurina et al., J. of Cosmology and Astrophysics 05 (2020) 011)

MIGA in France (Canuel et al., Scientific Reports 8, 14064 (2018))

ZAIGA in China (Zhan et al., International Journal of Modern Physics D 29, 1940005 (2020))

VLBAI in Germany (Hartwig et al., New Journal of Physics 17, 035011 (2015))

Naval Postgraduate School in US

Proposed 100 m AICE instrument at CERN (Baynham et al., arXiv:2509.11867v2 (2025))

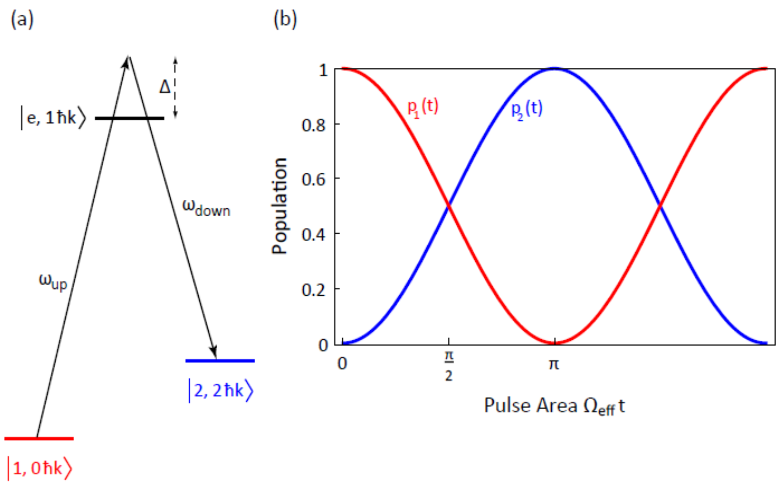
Community studies of future km scale detectors

- Community is also studying prospects for future space-based detectors (Abou El-Neaj et al., EPJ Quantum Technology 7, 6 (2020)), synergies with related proposals using optical lattice clocks in space (Kolkowitz et al., PRD 94, 124043 (2016))

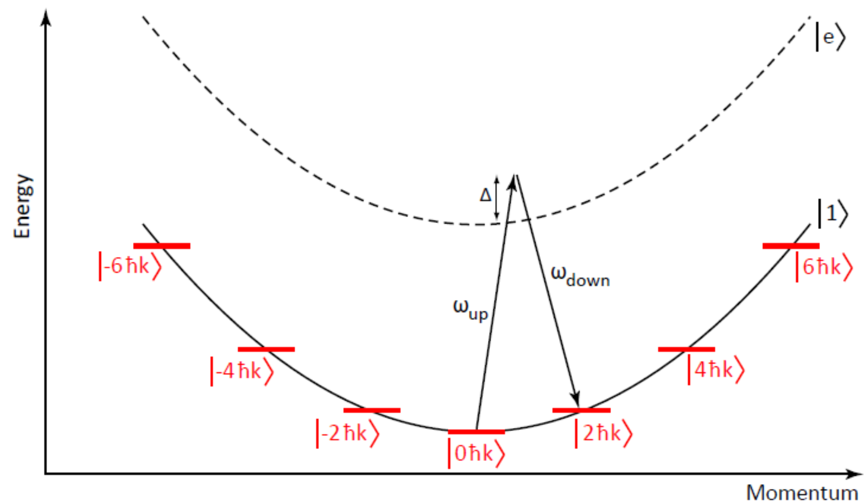
Workshop summary/roadmap: Abend et al., AVS Quantum Science 6, 024701 (2024)

Clock Atom Interferometry

- Atom interferometers often use two-photon transitions that create an effective two-level system between different "ground states"



Raman transition

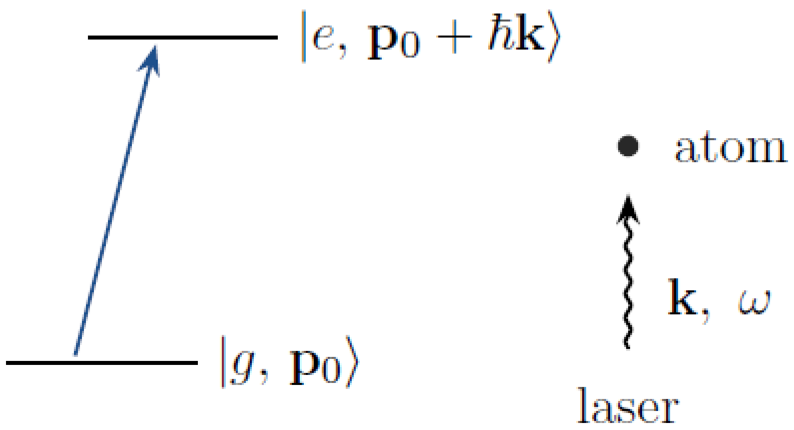


Bragg transition

- Emerging technique relevant to long-baseline atom interferometry: single-photon transitions resonantly driving between a ground and excited state

Clock Atom Interferometry

- Requires metastable excited state that does not undergo spontaneous emission decay too rapidly
  - "Clock transitions," e.g. in Sr and Yb, are natural candidates



- Dynamics of a driven two-level system

Clock Atom Interferometry

- What are the key differences between single-photon atom optics used for clock atom interferometry and two-photon atom optics?

- How does this impact how these two approaches respond to laser frequency noise?

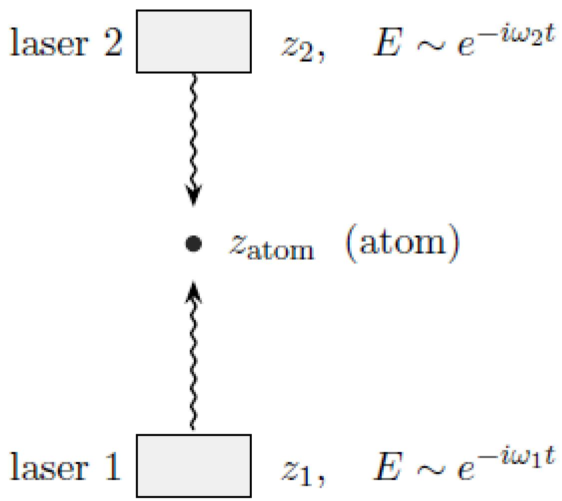
Two-Photon Atom Optics: a Perspective in Terms of Finite Light Travel Time

- What are the key differences between single-photon atom optics used for clock atom interferometry and two-photon atom optics?

- Understanding the associated atom interferometer phases from the point of view of finite light travel time can help us understand this

Two-Photon Atom Optics: a Perspective in Terms of Finite Light Travel Time

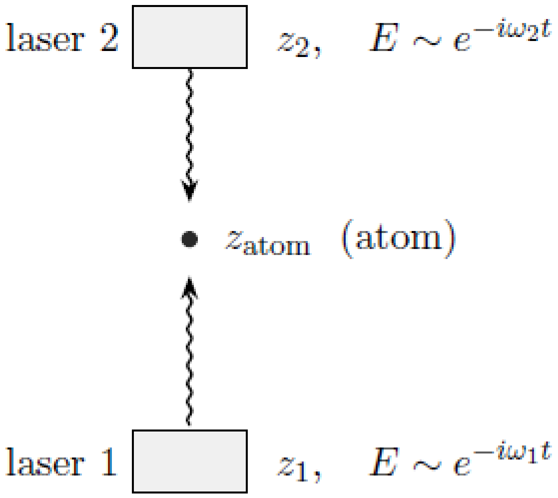
- Two-photon transition driven by counter-propagating laser beams
- Laser 1 at frequency ω_1
- Laser 2 at frequency ω_2
- For simplicity, assume $\omega_1 = \omega_2 = \omega$



The two-laser geometry. Laser 1 (below, always on) and laser 2 (above, pulsed) drive the atom at z_{atom}.

Two-Photon Atom Optics: a Perspective in Terms of Finite Light Travel Time

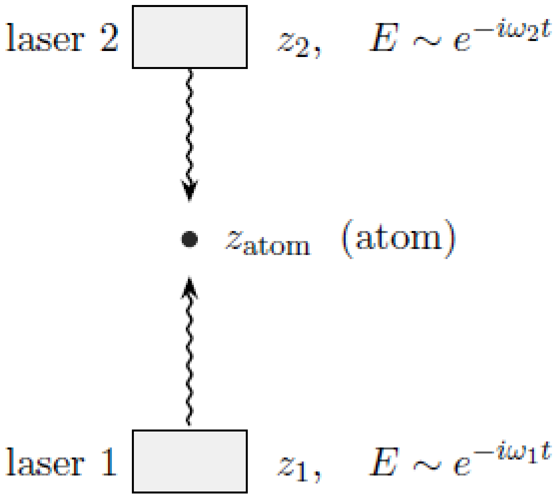
- Transition requires a three-way coincidence between pulse from laser 1, light from laser 2, and the atom
- What is the phase imprinted on the atom by this transition?



The two-laser geometry. Laser 1 (below, always on) and laser 2 (above, pulsed) drive the atom at z_{atom}.

Two-Photon Atom Optics: a Perspective in Terms of Finite Light Travel Time

- Imprinted phase: depends on the phases of the light from lasers 1 and 2, respectively, that drive the transition
- First, let's focus on laser 2



The two-laser geometry. Laser 1 (below, always on) and laser 2 (above, pulsed) drive the atom at z_{atom}.

Two-Photon Atom Optics: a Perspective in Terms of Finite Light Travel Time

- Consider transition that happens at time t_0
- For this to happen, pulse must have left laser 2 at time:

$$t_2 = t_0 - \frac{z_2 - z_{\text{atom}}}{c}$$

- Light leaves laser 2 with phase:

$$\phi_2 = -\omega t_2$$

- How does the phase of the light change as it propagates from the laser to the atom?

Two-Photon Atom Optics: a Perspective in Terms of Finite Light Travel Time

- How does the phase of the light change as it propagates from the laser to the atom?
- It remains the same.
- Approximation of a plane wave propagating in –z direction, with initial phase ϕ_2 at the position and time of emission from the laser:

$$E(z,t) \sim \exp\left[i(-k(z-z_2) - \omega(t-t_2) + \phi_2)\right]$$

Two-Photon Atom Optics: a Perspective in Terms of Finite Light Travel Time

- How does the phase of the light change as it propagates from the laser to the atom?

- It remains the same.

- Approximation of a plane wave propagating in –z direction, with initial phase ϕ_2 at the position and time of emission from the laser:

$$E(z,t) \sim \exp\left[i(-k(z-z_2) - \omega(t-t_2) + \phi_2)\right]$$

$$z_{\text{atom}} - z_2 = -c(t_0 - t_2)$$

$$\omega = ck$$

Two-Photon Atom Optics: a Perspective in Terms of Finite Light Travel Time

- How does the phase of the light change as it propagates from the laser to the atom?

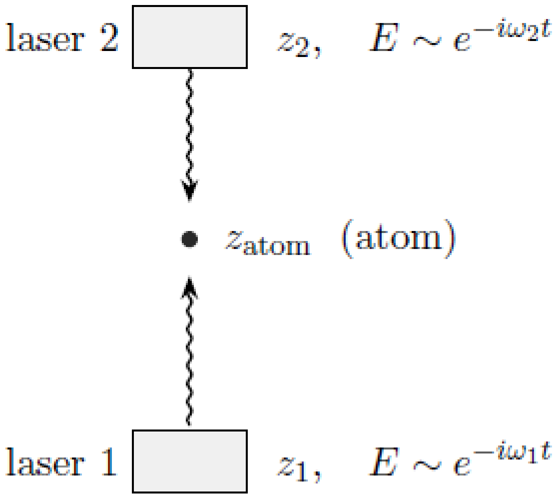
- It remains the same.

- Approximation of a plane wave propagating in –z direction, with initial phase ϕ_2 at the position and time of emission from the laser:

$$E(z_{\mathrm{atom}}, t_0) \sim E(z_2, t_2) \sim \exp\left[i\phi_2\right]$$

Two-Photon Atom Optics: a Perspective in Terms of Finite Light Travel Time

- Imprinted phase: depends on the phases of the light from lasers 1 and 2, respectively, that drive the transition
- Now, let's focus on laser 1



The two-laser geometry. Laser 1 (below, always on) and laser 2 (above, pulsed) drive the atom at z_{atom}.

Two-Photon Atom Optics: a Perspective in Terms of Finite Light Travel Time

- Consider transition that happens at time t_0
- For this to happen, light must have left laser 1 at time:

$$t_1 = t_0 - \frac{z_{\text{atom}} - z_1}{c}$$

- Light leaves laser 1 with phase to drive the transition at this time:

$$\phi_1 = -\omega t_1$$

- As for laser 2, the light that drives this transition has the same phase when it reaches the atom as when it left the laser

Two-Photon Atom Optics: a Perspective in Terms of Finite Light Travel Time

- Transition that transfers momentum $+2\hbar k$
- Absorption of upward going photon from laser 1 beam
- Stimulated emission of downward-going photon into beam from laser 2
- Imprinted phase on the atom from light-atom interaction:

$$\phi_1 - \phi_2 = -\omega(t_1 - t_2)$$

Two-Photon Atom Optics: a Perspective in Terms of Finite Light Travel Time

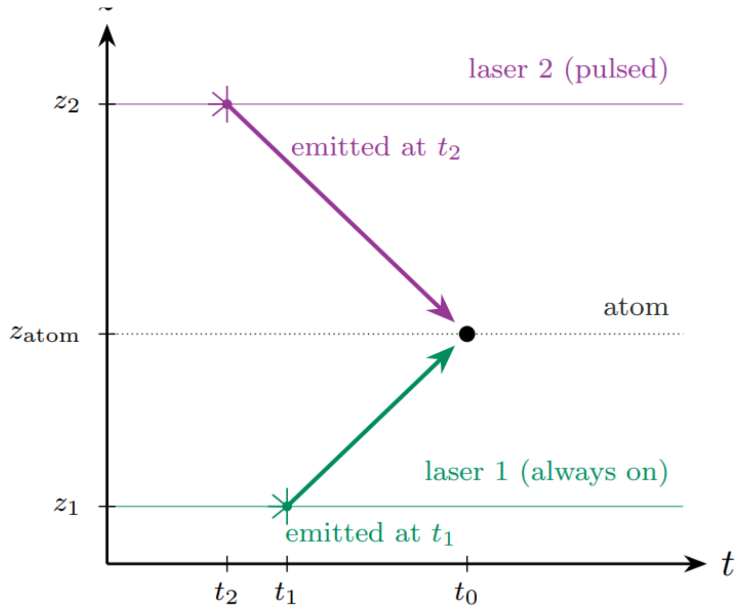
- Transition that transfers momentum $-2\hbar k$
- Absorption of downward going photon from laser 2 beam
- Stimulated emission of upward-going photon into beam from laser 1
- Imprinted phase on the atom from light-atom interaction:

$$\phi_2 - \phi_1 = \omega(t_1 - t_2)$$

Two-Photon Atom Optics: a Perspective in Terms of Finite Light Travel Time

- Summary: for transition that transfers momentum +/-2ħk, imprinted phase is:

$$\mp\omega\,(t_1 - t_2) = \mp\omega\left(\frac{2\,z_{\text{atom}}}{c} - \frac{z_1 + z_2}{c}\right) = \pm\,2k\,z_{\text{atom}} \mp k\,\frac{z_1 + z_2}{c}$$

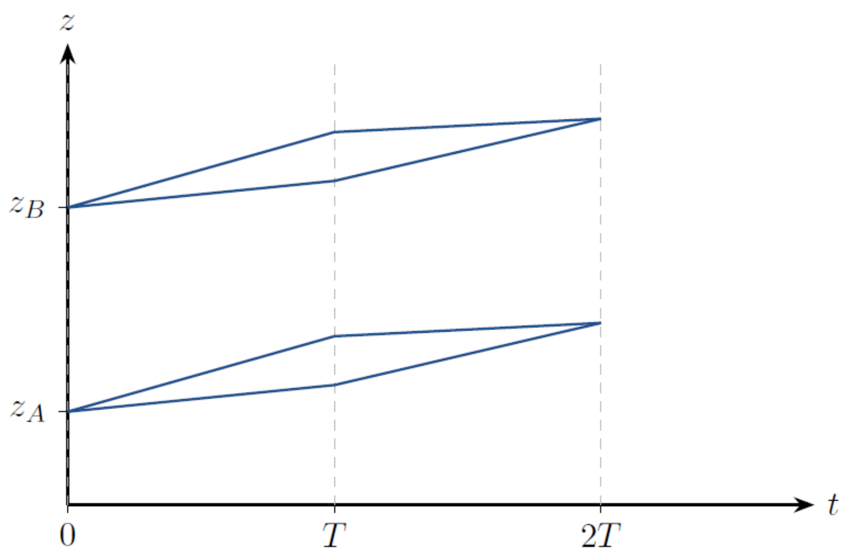


Cancels over the full interferometer

- This finite light travel time picture recovers the usual result

Two-Photon Atom Optics: Laser Noise Cancellation

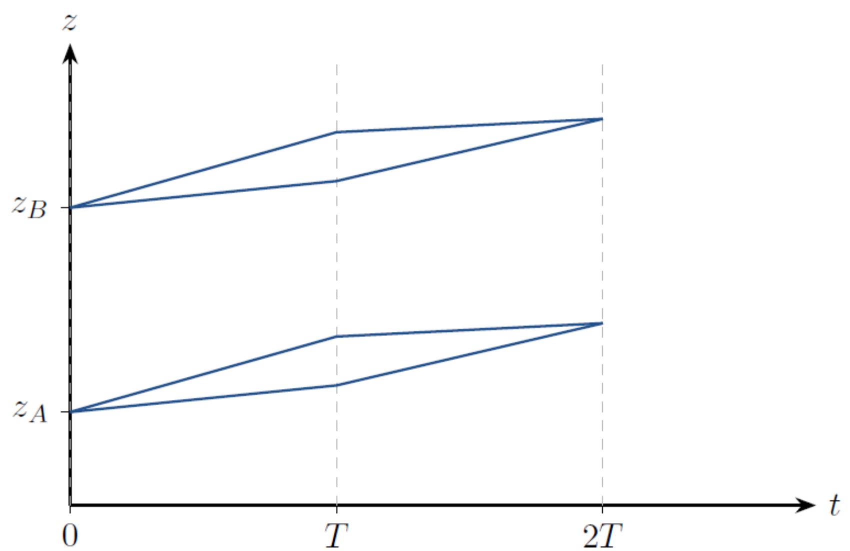
- Consider a gradiometer configuration: two atom interferometers spaced over a baseline and driven by the same lasers
- One key goal: make a differential measurement between the two interferometers to suppress the influence of laser noise
- This works well when laser noise influences the phase of both interferometers in the same way



Two-Photon Atom Optics: Laser Noise Cancellation

- Can our finite light travel time help us understand how well this cancellation works?
- Example: consider a fluctuation δω in the laser frequency for the first beam splitter interaction only
- Impact of fluctuation on differential phase between interferometers:

$$2\frac{\delta\omega}{c}(z_B - z_A)$$

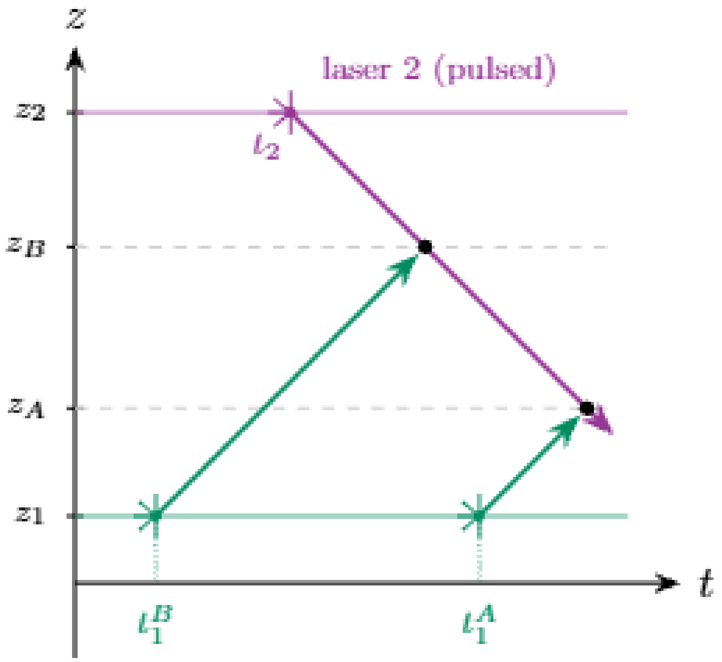


Two-Photon Atom Optics: Laser Noise Cancellation

- Why is the impact of the frequency fluctuation not just common between the two interferometers?

- In order for the needed three-way coincidence two occur, light needs to leave laser 1 at different times for the respective interferometers at heights z_A and z_B:

$$t_1^A - t_1^B = 2\frac{z_B - z_A}{c}$$



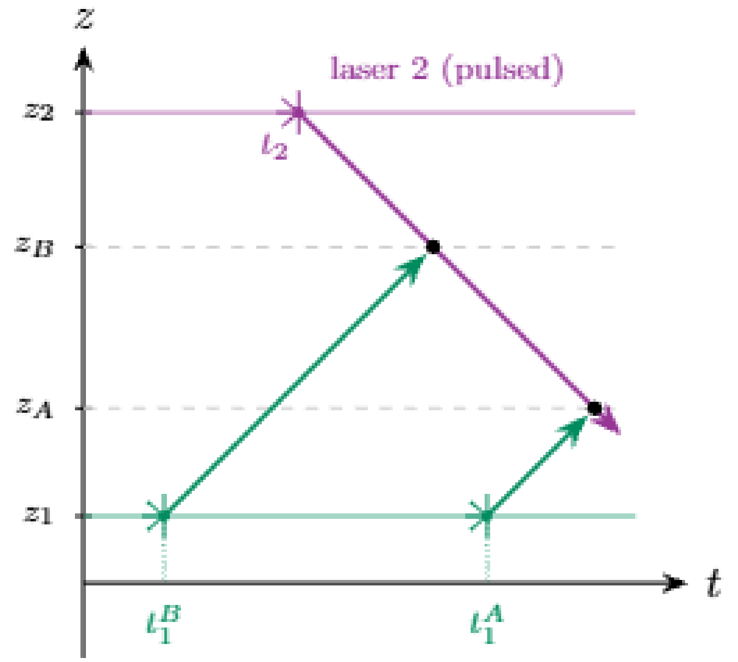
Two-Photon Atom Optics: Laser Noise Cancellation

- Why is the impact of the frequency fluctuation not just common between the two interferometers?

- During this time, laser 1 acquires the following extra phase due to the frequency fluctuation:

$$-\delta\omega(t_1^A - t_1^B)$$

$$t_1^A - t_1^B = 2\frac{z_B - z_A}{c}$$



Two-Photon Atom Optics: Laser Noise Cancellation

- Plugging in some numbers for an example short-baseline interferometer

- Where n pulses used to increase momentum transfer to $2n\hbar k$, phase contribution is multiplied by n

$$\delta\omega = 2\pi \times 100 \text{ Hz}$$

$$n = 10$$

$$z_B - z_A = 1 \text{ m}$$

$$2n\frac{\delta\omega}{c}(z_B - z_A) = 0.04 \text{ mrad}$$

Two-Photon Atom Optics: Laser Noise Cancellation

- How about a long-baseline interferometer?

$$\delta\omega = 2\pi \times 1 \text{ Hz}$$

$$n = 1000$$

$$z_B - z_A = 1000 \text{ m}$$

$$2n\frac{\delta\omega}{c}(z_B - z_A) = 40 \text{ mrad}$$

Two-Photon Atom Optics: Laser Noise Cancellation

- How about a long-baseline interferometer?

$$\delta\omega = 2\pi \times 1 \text{ Hz}$$

$$n = 1000$$

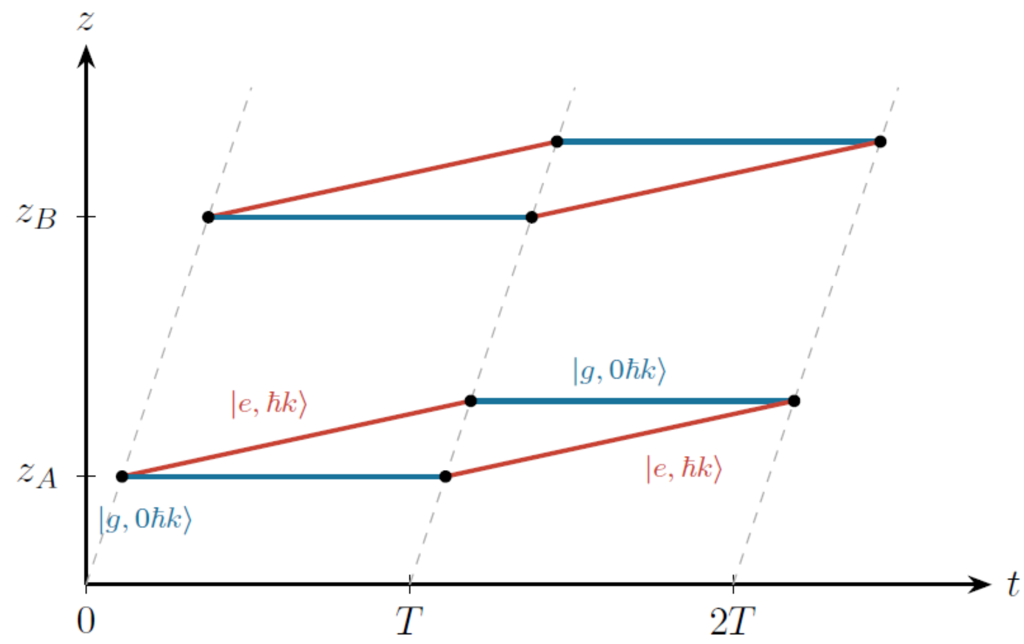
$$z_B - z_A = 1000 \text{ m}$$

$$2n\frac{\delta\omega}{c}(z_B - z_A) = 40 \text{ mrad}$$

How to mitigate?

Single-Photon Atom Optics: Laser Noise Cancellation

- Driven by one laser at a time, does not require the three-way coincidence between pulse from laser 1, light from laser 2, and the atom that we need for the two-photon case
- Pulse leaves laser at a given time
- Same pulse, with same phase, interacts with both interferometers
- Common imprinted laser phase

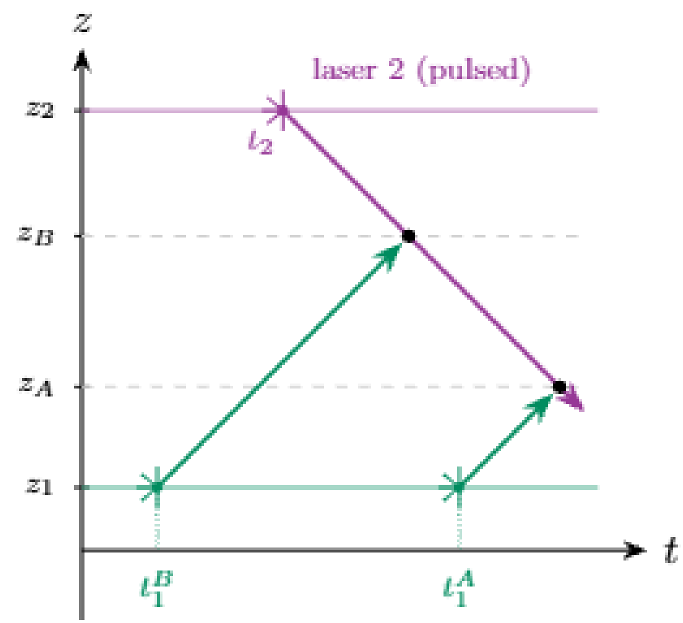


Single-Photon Atom Optics: the Origin of the Phase Response to Accelerations

- Two-photon atom optics: phase response to acceleration comes from changes in the phase imprinted by light-atom interactions due to motion of the atom relative to a frame of reference in which the lasers are held at fixed positions

- Example: sensitivity to gravitational acceleration from the Earth comes about through motion of freely falling atom relative to lab frame

- As we saw before, the fact that phase imprinted by a given light-atom interaction depends on the atom's position can be understood as coming from the requirement of the aforementioned three-way coincidence, together with the finite light travel time



Single-Photon Atom Optics: the Origin of the Phase Response to Accelerations

- Single-photon case:
  - Just 1 laser
  - Light leaves that laser at a specified time with a particular phase
  - The phase of the light pulse remains the same as it freely propagates to the atom
  - The phase imprinted on the atom is thus the same as the phase of the light when the light left the laser
  - Does not depend on the atom's position

- So how does the sensitivity of the interferometer phase to an acceleration, such as gravitational acceleration from Earth, come about?

Single-Photon Atom Optics: the Origin of the Phase Response to Accelerations

- Single-photon case:
  - Just 1 laser
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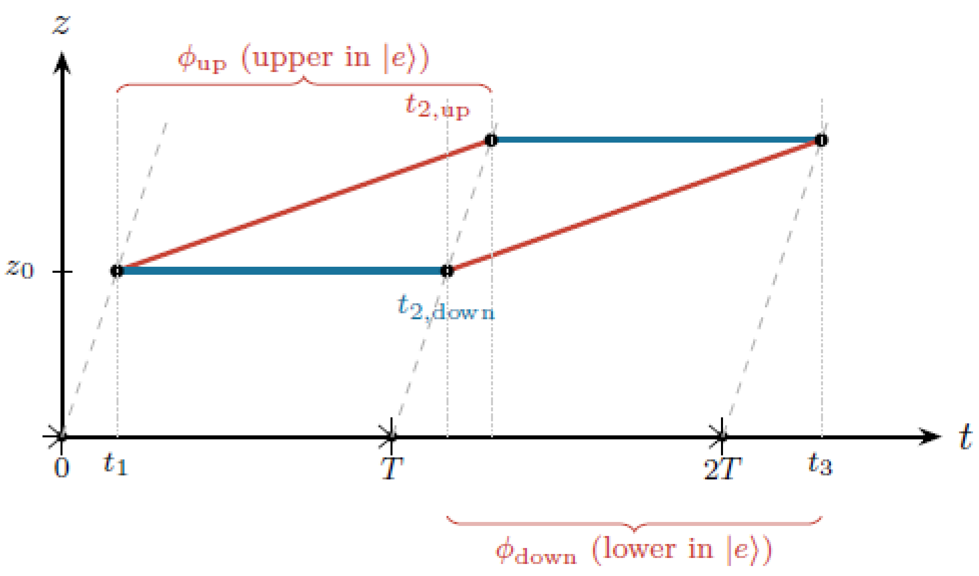
  - The phase imprinted on the atom is thus the same as the phase of the light when the light left the laser
  - Does not depend on the atom's position

- So how does the sensitivity of the interferometer phase to an acceleration, such as gravitational acceleration from Earth, come about?

- The position of the atom affects when the pulse reaches the atom, and therefore the time at which the transition switches the atom between ground and excited internal state

Single-Photon Atom Optics: the Origin of the Phase Response to Accelerations

- Dominate contribution to interferometer phase comes from differences in time the two interferometer arms spend in the excited internal state



Schematic of interferometer, parabolic trajectories due to gravity not drawn

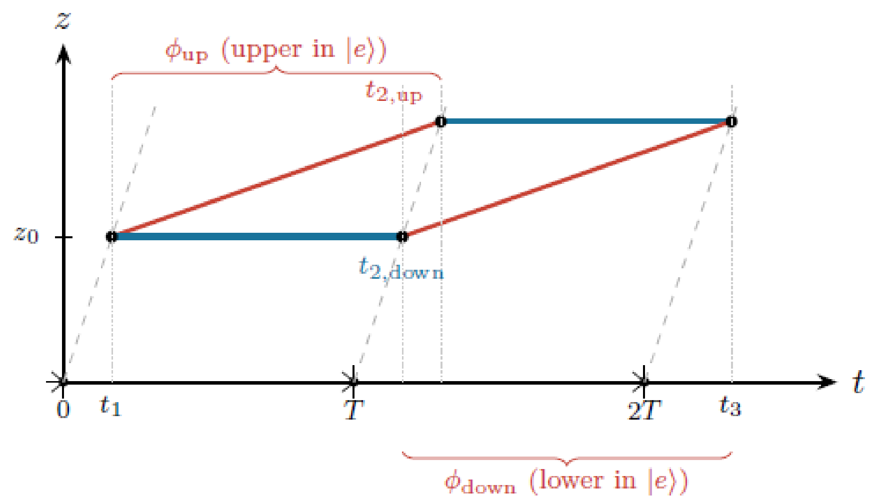
Single-Photon Atom Optics: the Origin of the Phase Response to Accelerations

- Before first pulse, atom has trajectory:

$$z(t) = z_0 - \frac{1}{2}gt^2$$

- First pulse reaches atom and drives beam splitter at time:

$$t_1 = \frac{z_0}{c}$$



Schematic of interferometer, parabolic trajectories due to gravity not drawn

Single-Photon Atom Optics: the Origin of the Phase Response to Accelerations

- Before first pulse, atom has trajectory:

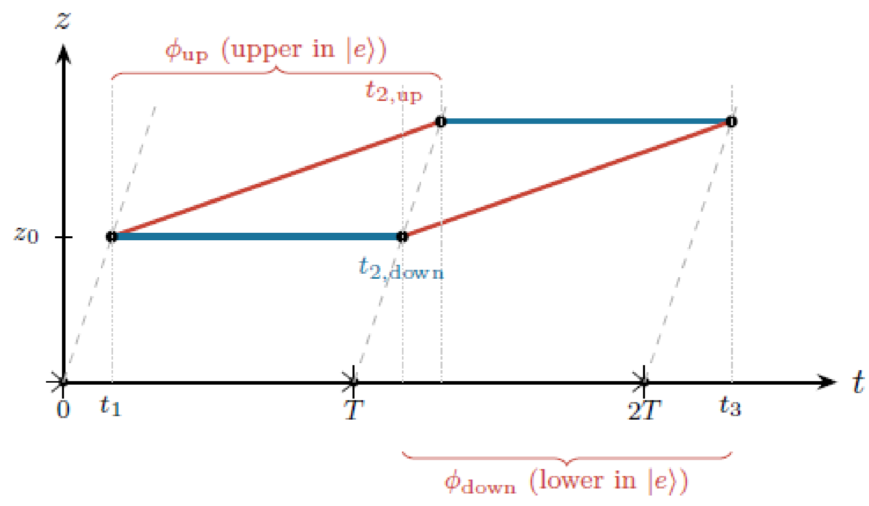
$$z(t) = z_0 - \tfrac{1}{2}gt^2$$

- First pulse reaches atom and drives beam splitter at time:

$$t_1 = \frac{z_0}{c}$$

- Second (mirror) pulse reaches upper arm at time:

$$t_{2,\mathrm{up}} \approx T + \frac{1}{c}\left(z_0 + \frac{\hbar k}{m}T - \tfrac{1}{2}gT^2\right)$$



Schematic of interferometer, parabolic trajectories due to gravity not drawn

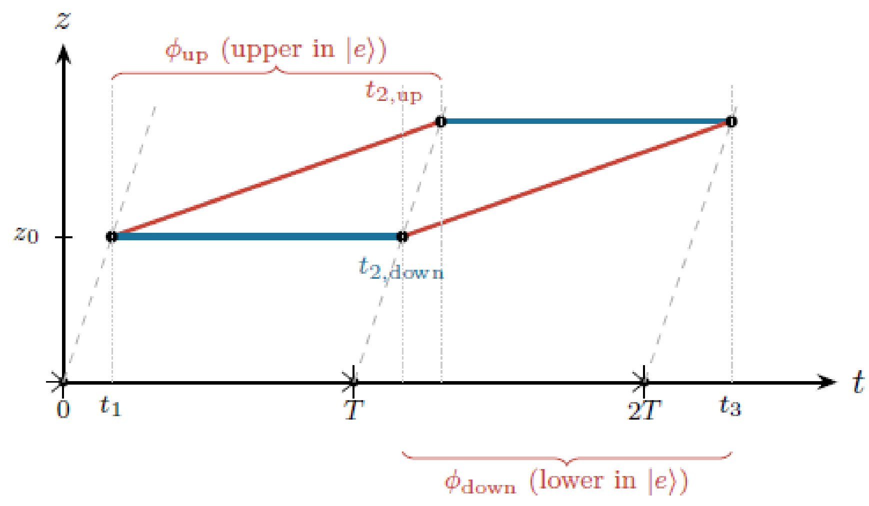
Single-Photon Atom Optics: the Origin of the Phase Response to Accelerations

- Between t_1 and $t_{2,up}$, upper arm accumulates phase

$$\phi_{\text{up}} = -\omega_0 \left(t_{2,\text{up}} - t_1\right)$$

- This comes from excitation energy $\hbar\omega_0$ of excited internal state

- For typical optical transitions, ω_0 ~ hundreds of THz



Schematic of interferometer, parabolic trajectories due to gravity not drawn

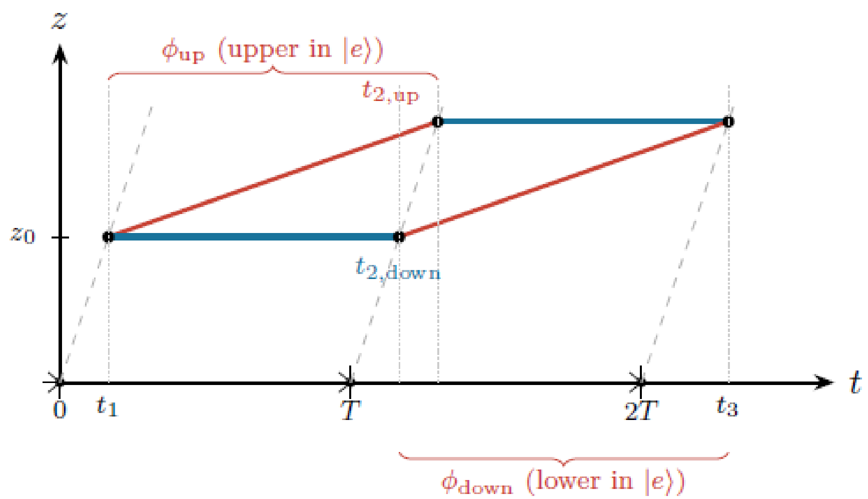
Single-Photon Atom Optics: the Origin of the Phase Response to Accelerations

- Second (mirror) pulse reaches lower arm at time:

$$t_{2,\text{down}} \approx T + \frac{1}{c}\left(z_0 - \tfrac{1}{2}gT^2\right)$$

- Third (final beam splitter) pulse reaches atom at time

$$t_3 \approx 2T + \frac{1}{c}\left(z_0 + \frac{\hbar k}{m}T - \tfrac{1}{2}g\,(2T)^2\right)$$



Schematic of interferometer, parabolic trajectories due to gravity not drawn

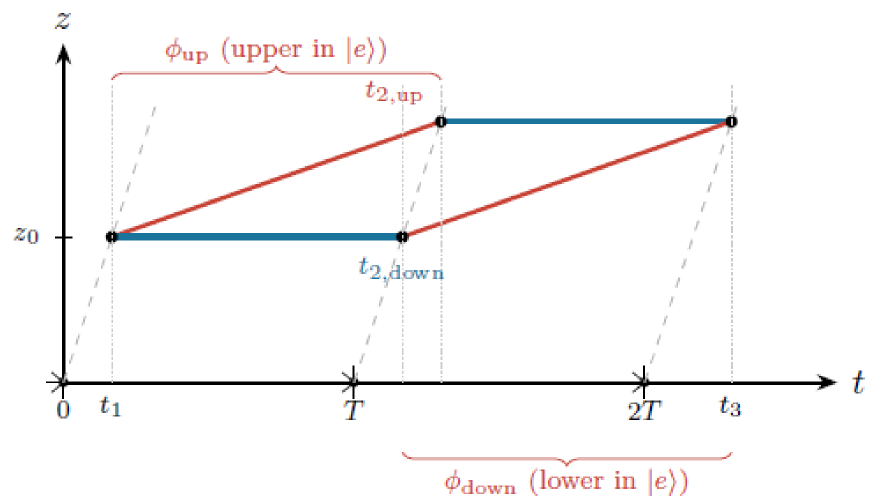
Single-Photon Atom Optics: the Origin of the Phase Response to Accelerations

- Between $t_{2,down}$ and t_3, lower arm accumulates phase:

$$\phi_{\text{down}} = -\omega_0 \left(t_3 - t_{2,\text{down}}\right)$$

- Phase shift simplifies to:

$$\Delta\phi = \phi_{\text{up}} - \phi_{\text{down}} = -\frac{\omega_0}{c}\, gT^2$$



Schematic of interferometer, parabolic trajectories due to gravity not drawn

Single-Photon Atom Optics: the Origin of the Phase Response to Accelerations

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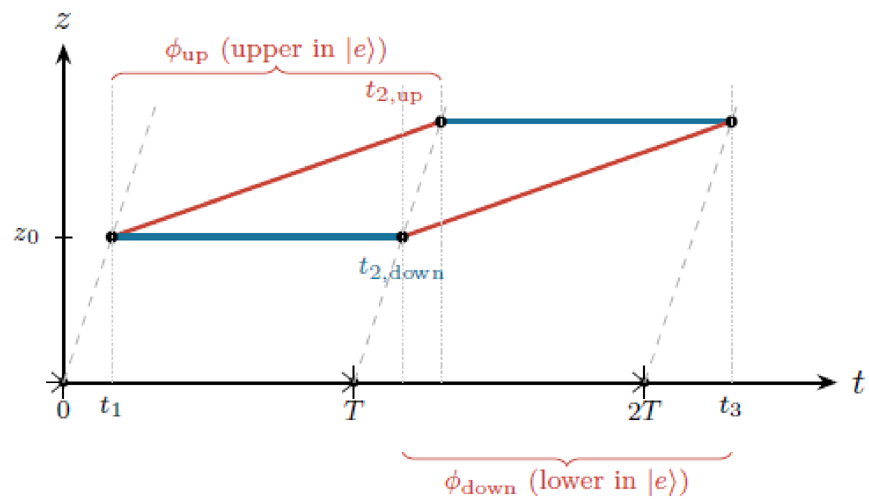

Schematic of interferometer, parabolic trajectories due to gravity not drawn

Single-Photon Atom Optics: the Origin of the Phase Response to Accelerations

- If the laser is on resonance with $\omega = \omega_0$, phase shift looks similar to the form one gets for two-photon atom optics (reduced by a factor of 2 because the momentum splitting is only 1 ħk)

$$\Delta\phi = -kgT^2$$

- Despite this similarity, origins of the phase shift are very different in the two cases

Two-Photon Atom Optics: Laser Noise Cancellation

- How about a long-baseline interferometer?

$$\delta\omega = 2\pi \times 1 \text{ Hz}$$

$$n = 1000$$

$$z_B - z_A = 1000 \text{ m}$$

$$2n\frac{\delta\omega}{c}(z_B - z_A) = 40 \text{ mrad}$$

How to mitigate without using single photon atom optics?

Horizontal Baseline Noise Cancellation

SCIENTIFIC REPORTS

OPEN

Exploring gravity with the MIGA large scale atom interferometer

B. Canuel[1,2], A. Bertoldi[1,2], L. Amand[1,3], E. Pozzo di Borgo[1,4], T. Chantrait[1,3], C. Danquigny[1,4], M. Dovale Álvarez[5], B. Fang[1,3], A. Freise[5], R. Geiger[1,3], J. Gillot[1,2], S. Henry[6], J. Hinderer[1,7], D. Holleville[1,3], J. Junca[1,2], G. Lefèvre[1,2], M. Merzougui[1,8], N. Mielec[1,3], T. Monfret[9], S. Pelisson[1,2], M. Prevedelli[10], S. Reynaud[1,11], I. Riou[1,2], Y. Rogister[1,7], S. Rosat[1,7], E. Cormier[1,12], A. Landragin[1,3], W. Chaibi[1,8], S. Gaffet[1,9,13] & P. Bouyer[1,2]

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Class. Quantum Grav. 37 (2020) 225017 (35pp)
https://doi.org/10.1088/1361-6382/aba80e

ELGAR—a European Laboratory for Gravitation and Atom-interferometric Research

B Canuel[1,*], S Abend[2], P Amaro-Seoane[3,4,5,6], F Badaracco[7,8], Q Beaufils[9], A Bertoldi[1], K Bongs[10], P Bouyer[1], C Braxmaier[11,12], W Chaibi[13], N Christensen[13], F Fitzek[2,14], G Flouris[15], N Gaaloul[2], S Gaffet[16], C L Garrido Alzar[9], R Geiger[9], S Guellati-Khelifa[17], K Hammerer[14], J Harms[7,8], J Hinderer[18], M Holynski[10], J Junca[1], S Katsanevas[19], C Klempt[2], C Kozanitis[15], M Krutzik[20], A Landragin[9], I Làzaro Roche[16], B Leykauf[20], Y-H Lien[10], S Loriani[2], S Merlet[9], M Merzougui[13], M Nofrarias[21,22], P Papadakos[15,23], F Pereira dos Santos[9], A Peters[20], D Plexousakis[15,23], M Prevedelli[24], E M Rasel[2], Y Rogister[18], S Rosat[18], A Roura[25], D O Sabulsky[1], V Schkolnik[20], D Schlippert[2], C Schubert[2,31], L Sidorenkov[9], J-N Siemß[2,14], C F Sopuerta[21,22], F Sorrentino[26], C Struckmann[2], G M Tino[27], G Tsagkatakis[15,23], A Viceré[28,29], W von Klitzing[30], L Woerner[11,12] and X Zou[1]

Horizontal Baseline Noise Cancellation


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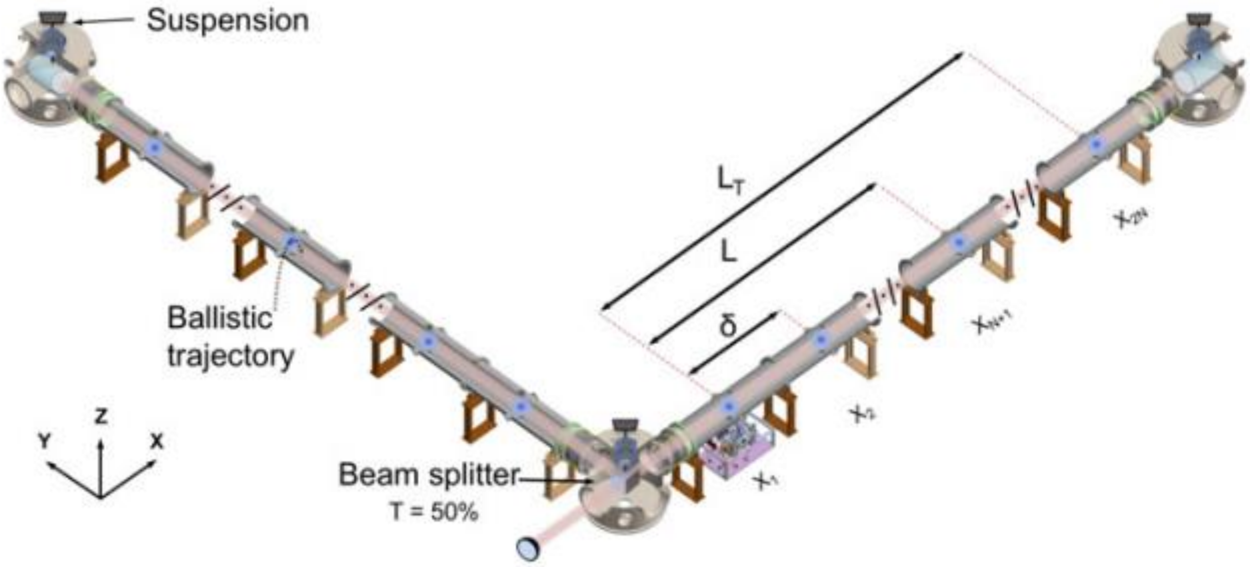
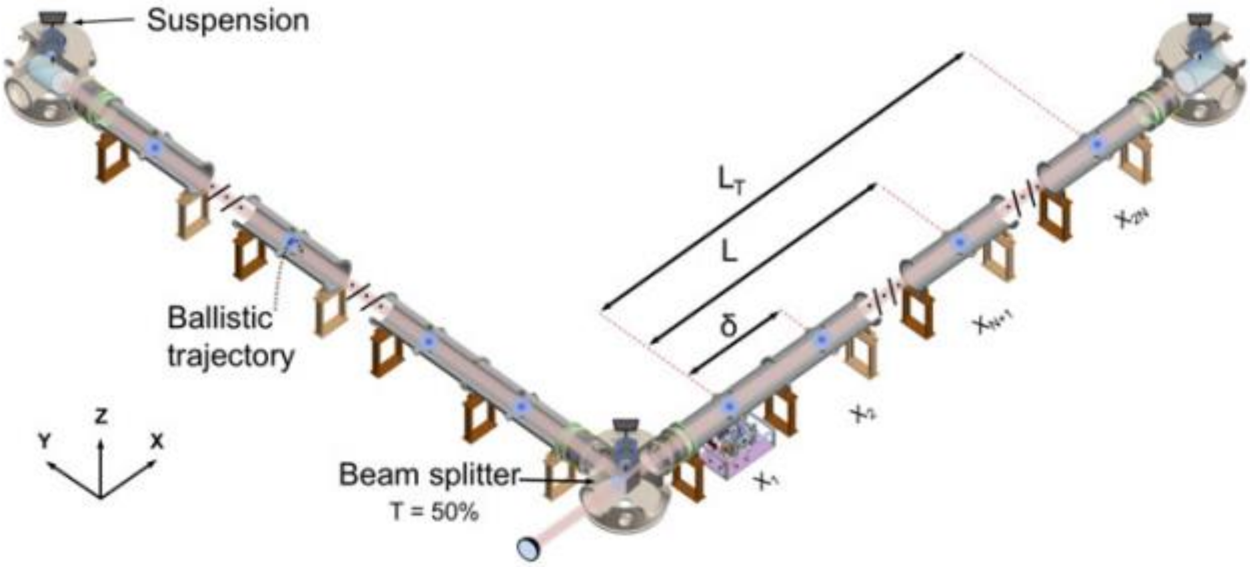


Horizontal Baseline Noise Cancellation

- Two orthogonal arms driven by common laser
- Set distances between interferometers to be the same for both arms so that laser noise cancels when taking a differential measurement between the two arms

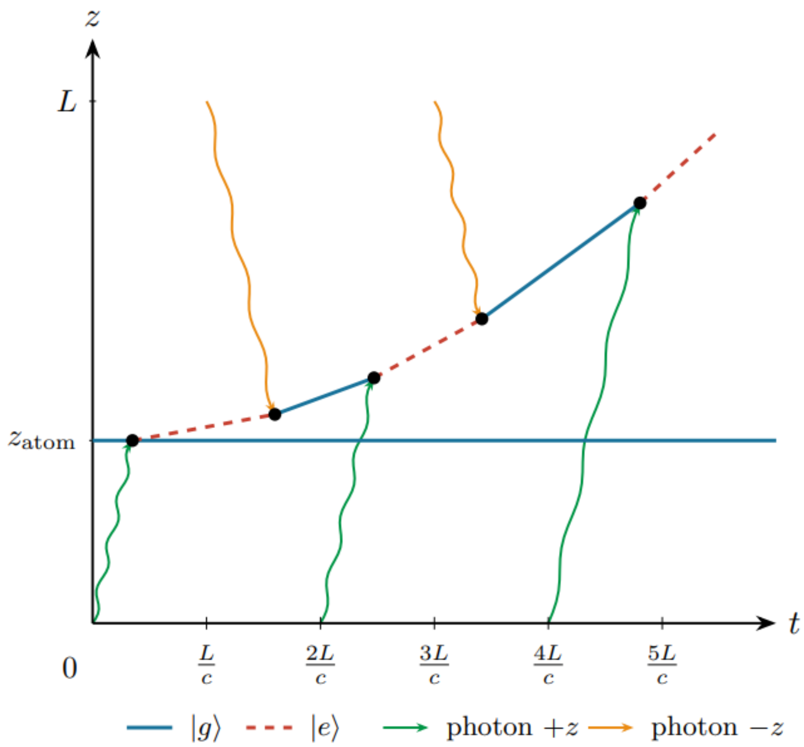
$$2n\frac{\delta\omega}{c}(z_B - z_A) = 40 \text{ mrad}$$

- Gravitational wave signal remains, as for the two arms of LIGO



Large Momentum Transfer with Single-Photon Atom Optics

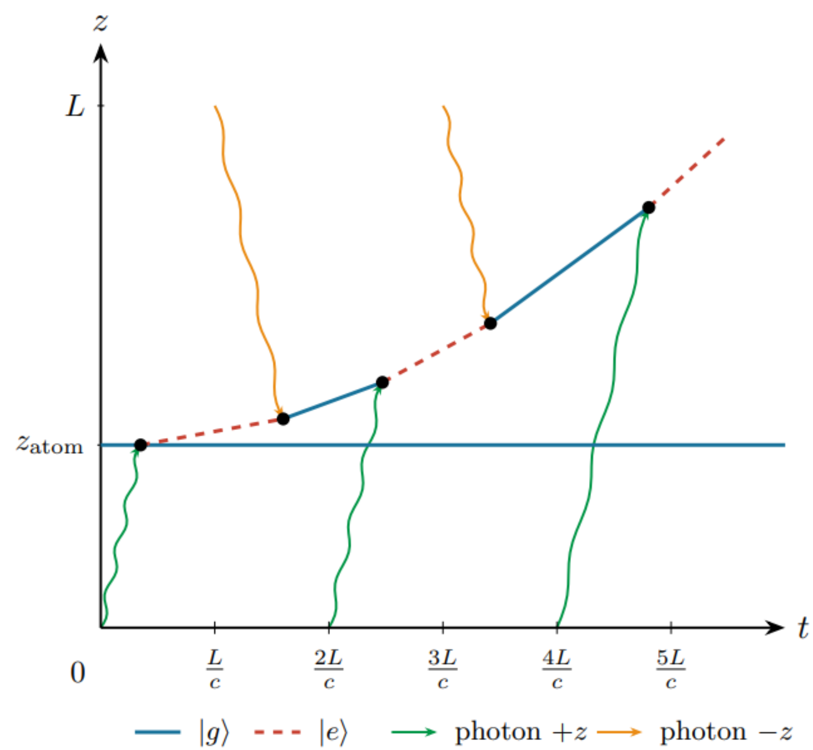
- Send alternating pulses from opposite directions to increase momentum difference between arms



- Amplifies dependence of phase shift on position of atom (z_{atom})

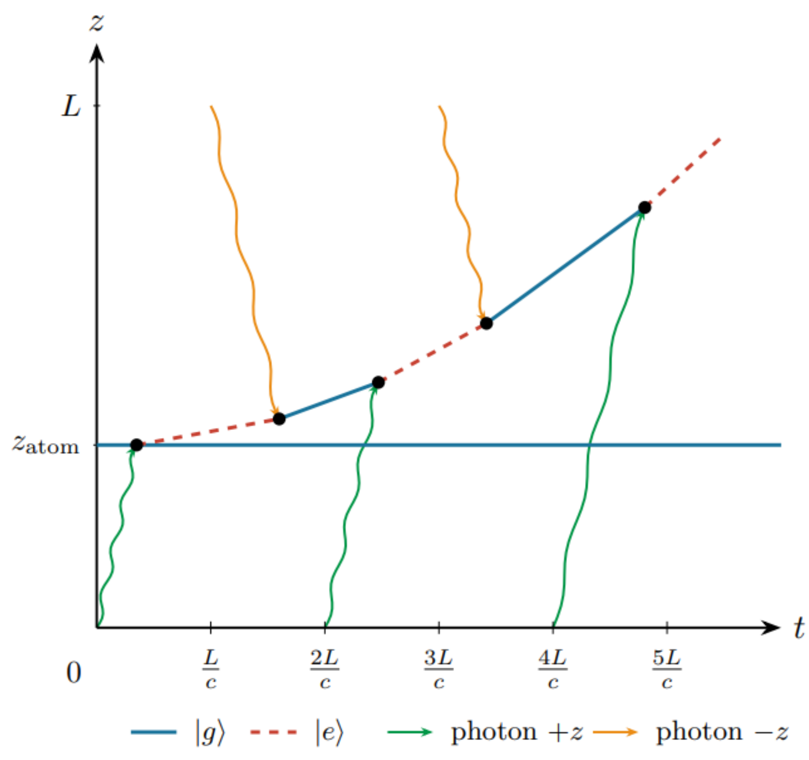
Large Momentum Transfer with Single-Photon Atom Optics

- Upward-going pulses: kicked arm spends less time in exited state by amount z_{atom}/c
- Phase contribution: $(\omega_0/c)\ z_{atom}$



Large Momentum Transfer with Single-Photon Atom Optics

- Upward-going pulses: kicked arm spends less time in exited state by amount z_{atom}/c
- Phase contribution: $(\omega_0/c)\, z_{atom}$
- Downward-going pulses: kicked arm spends less time in exited state by amount z_{atom}/c
- Phase contribution: $(\omega_0/c)\, z_{atom}$
- n pulses give phase contribution: $n(\omega_0/c)\, z_{atom}$
- For laser on resonance, this is: nkz_{atom}



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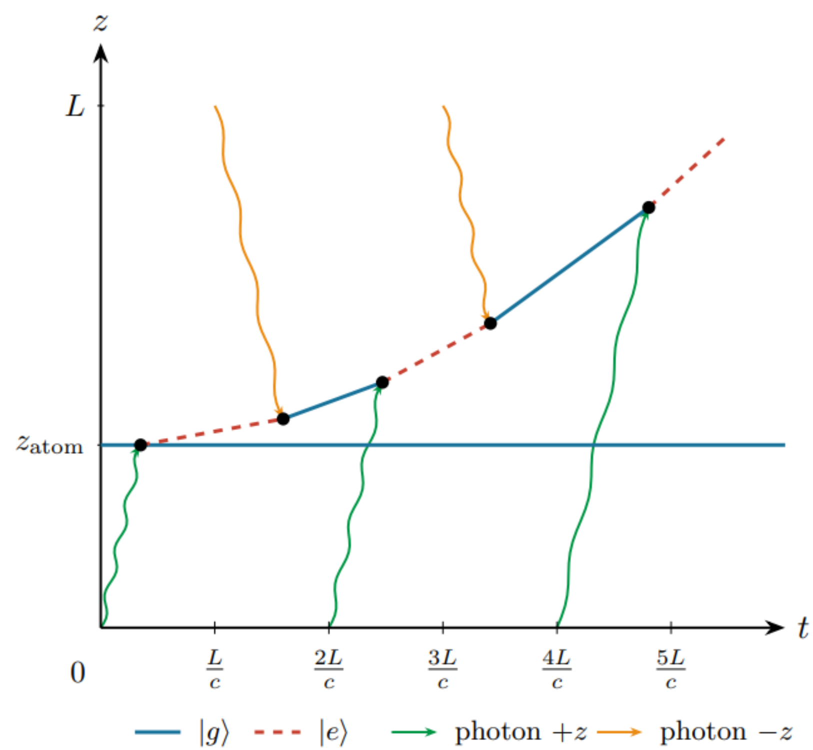
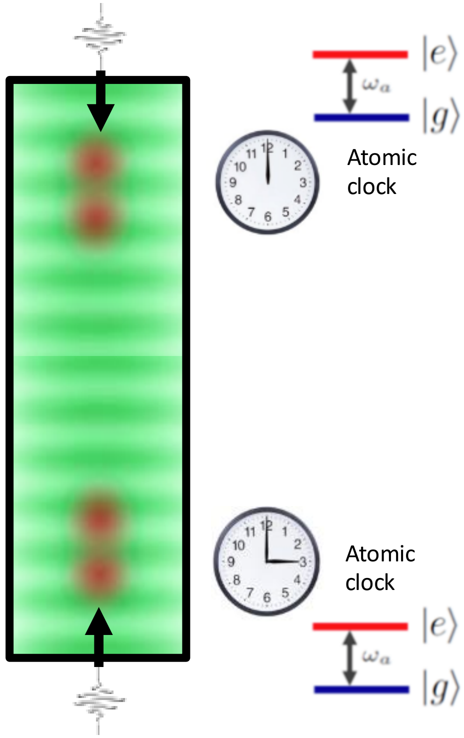


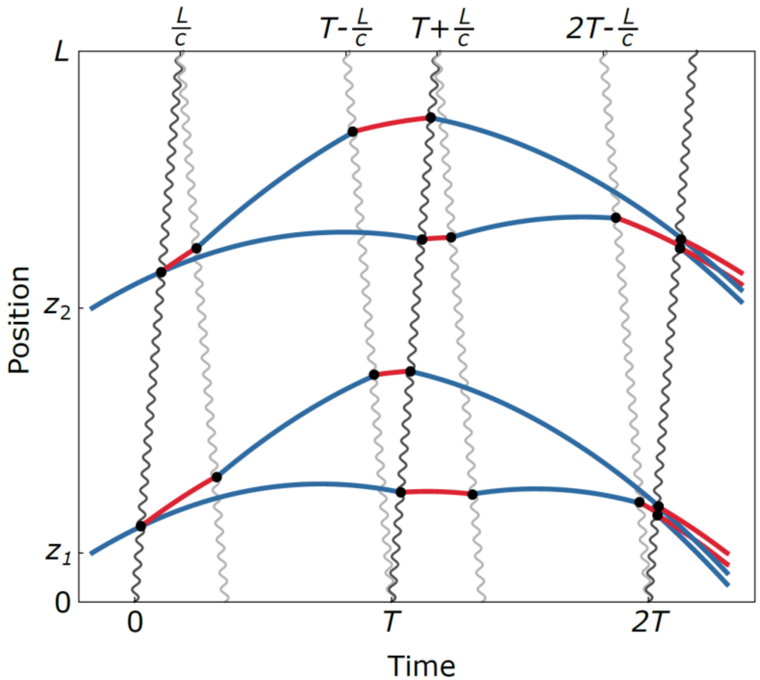
Measurement Concept

Freely-falling atoms on each end serve as **inertial references**

Atoms act as **clocks** to measure light travel time across baseline: “active proof mass”

Multiple pulses across baseline coherently enhance signal





Differential phase evolution:

$$\Delta\phi \sim \omega_0 L/c$$

Two ways for phase to vary:

$\delta\omega_0$ *Dark Matter*

$\delta L = hL$ *Gravitational Wave*

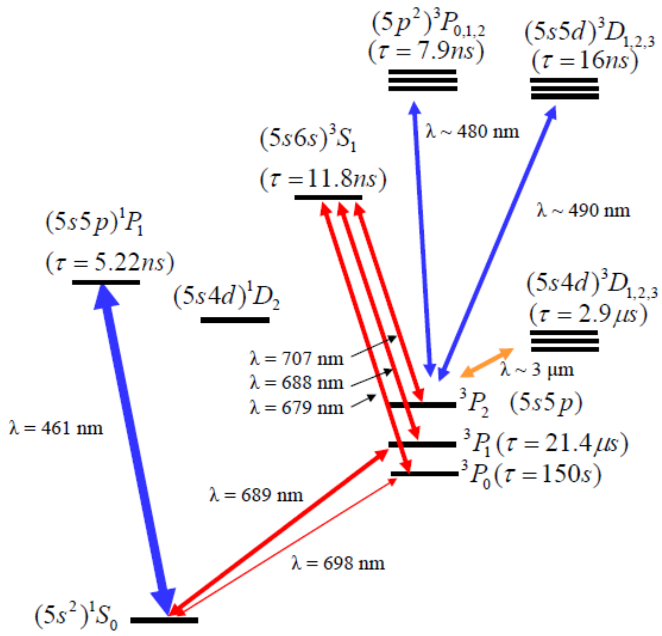
Yu and Tinto, GRG 43, 1943 (2011); Graham et al., PRL 110, 171102 (2013); Arvanitaki et al., PRD 97, 075020 (2018); Norcia et al., PRA 96, 042118 (2017)

Strontium clock atom interferometry

Sr has a narrow optical clock transition at 698 nm with a long-lived excited state (natural lifetime >100 s)

Atom optics based on single-photon transitions on this 698 nm line

Can also use stronger 689 nm line, can drive transitions faster but shorter exited state lifetime



Some References

698 nm transition (boson, transition induced by magnetic field)

PRL **119**, 263601 (2017) PHYSICAL REVIEW LETTERS week ending 29 DECEMBER 2017

Atom Interferometry with the Sr Optical Clock Transition

Liang Hu,[*] Nicola Poli,[†] Leonardo Salvi, and Guglielmo M. Tino[‡]
Dipartimento di Fisica e Astronomia and LENS - Università di Firenze, INFN - Sezione di Firenze, Via Sansone 1, I-50019 Sesto Fiorentino, Italy
(Received 15 August 2017; published 27 December 2017)

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IOP Publishing Classical and Quantum Gravity
Class. Quantum Grav. **37** (2020) 014001 (27pp) https://doi.org/10.1088/1361-6382/ab4d18

Sr atom interferometry with the optical clock transition as a gravimeter and a gravity gradiometer

Liang Hu[1], Enlong Wang, Leonardo Salvi, Jonathan N Tinsley, Guglielmo M Tino[2] and Nicola Poli[3,4]

Dipartimento di Fisica e Astronomia and LENS—INFN Sezione di Firenze, Università degli Studi di Firenze, Via Sansone 1, 50019 Sesto Fiorentino, Italy

Some References

698 nm transition (fermion)

Article | Open access | Published: 17 June 2026

A prototype differential atom interferometer for fundamental physics

C. F. A. Baynham, R. Hobson, O. Buchmüller, D. Evans, L. Hawkins, L. Iannizzotto Venezze, A. Josset, D. Lee, E. Pasatembou, B. E. Sauer, M. R. Tarbutt, T. Walker, O. Ennis, U. Chauhan, A. Brzakalik, S. Dey, S. Hedges, B. Stray, M. Langlois, K. Bongs, T. Hird, S. Lellouch, M. Holynski, B. Bostwick, J. Chen, Z. Eyler, V. Gibson, T. L. Harte, C. C. Hsu, M. Karzazi, C. Lu, B. Millward, J. Mitchell, N. Mouelle, B. Panchumarthi, J. Scheper, U. Schneider, X. Su, Y. Tang, K. Tkalčec, M. Zeuner, S. Zhang, Y. Zhi, L. Badurina, A. Beniwal, D. Blas, J. Carlton, J. Ellis, C. McCabe, G. Parish, D. Pathak Govardhan, V. Vaskonen, T. Bowcock, K. Bridges, A. Carroll, J. Coleman, G. Elertas, S. Hindley, C. Metelko, H. Throssell, J. N. Tinsley, E. Bentine, M. Booth, D. Bortoletto, N. Callaghan, C. Foot, C. Gómez-Monedero, K. Hughes, A. James, T. Leese, A. Lowe, J. March-Russell, J. Sander, J. Schelfhout, I. Shipsey, D. Weatherill, D. Wood, S. N. Balashov, M. G. Bason, K. Hussain, H. Labiad, P. Majewski, A. L. Marchant, D. Newbold, Z. Pan, Z. Tam, T. C. Thornton, T. Valenzuela, M. G. D. van der Grinten, I. Wilmut, K. Clarke, A. Vick & AION Collaboration — Show fewer authors

Nature **654**, 622–628 (2026) | Cite this article

Some References

689 nm transition

PHYSICAL REVIEW LETTERS **124,** 083604 (2020)

Large Momentum Transfer Clock Atom Interferometry on the 689 nm Intercombination Line of Strontium

Jan Rudolph,[1,*] Thomas Wilkason,[1] Megan Nantel,[2] Hunter Swan,[1] Connor M. Holland,[1] Yijun Jiang (姜一君),[2] Benjamin E. Garber,[1] Samuel P. Carman,[1] and Jason M. Hogan[1,†]
[1]*Department of Physics, Stanford University, Stanford, California 94305, USA*
[2]*Department of Applied Physics, Stanford University, Stanford, California 94305, USA*

PHYSICAL REVIEW LETTERS **133,** 243403 (2024)

Robust Quantum Control via Multipath Interference for Thousandfold Phase Amplification in a Resonant Atom Interferometer

Yiping Wang,[1,*] Jonah Glick,[1,*] Tejas Deshpande,[1,*] Kenneth DeRose,[1,*] Sharika Saraf,[1] Natasha Sachdeva,[1,2] Kefeng Jiang,[1] Zilin Chen,[1] and Tim Kovachy[1,†]
[1]*Department of Physics and Astronomy and Center for Fundamental Physics, Northwestern University, Evanston, Illinois 60208, USA*
[2]*Q-CTRL, Quantum Applications and Algorithms Division, Santa Monica, California 90401, USA*

(Received 2 July 2024; revised 23 September 2024; accepted 31 October 2024; published 11 December 2024)

PHYSICAL REVIEW LETTERS **129,** 183202 (2022)

Editors' Suggestion Featured in Physics

Atom Interferometry with Floquet Atom Optics

Thomas Wilkason,[1] Megan Nantel,[2] Jan Rudolph,[1] Yijun Jiang (姜一君),[2] Benjamin E. Garber,[1] Hunter Swan,[1] Samuel P. Carman,[1] Mahiro Abe,[1] and Jason M. Hogan[1,*]
[1]*Department of Physics, Stanford University, Stanford, California 94305, USA*
[2]*Department of Applied Physics, Stanford University, Stanford, California 94305, USA*

(Received 14 May 2022; accepted 1 September 2022; published 24 October 2022)

Some References

698 nm transition (boson, driven by three-photon transition using collinear beams)

Collinear feature means that laser noise cancellation benefits of single-photon transitions are maintained

PHYSICAL REVIEW X **15**, 031051 (2025)

Collinear Three-Photon Excitation of a Strongly Forbidden Optical Clock Transition

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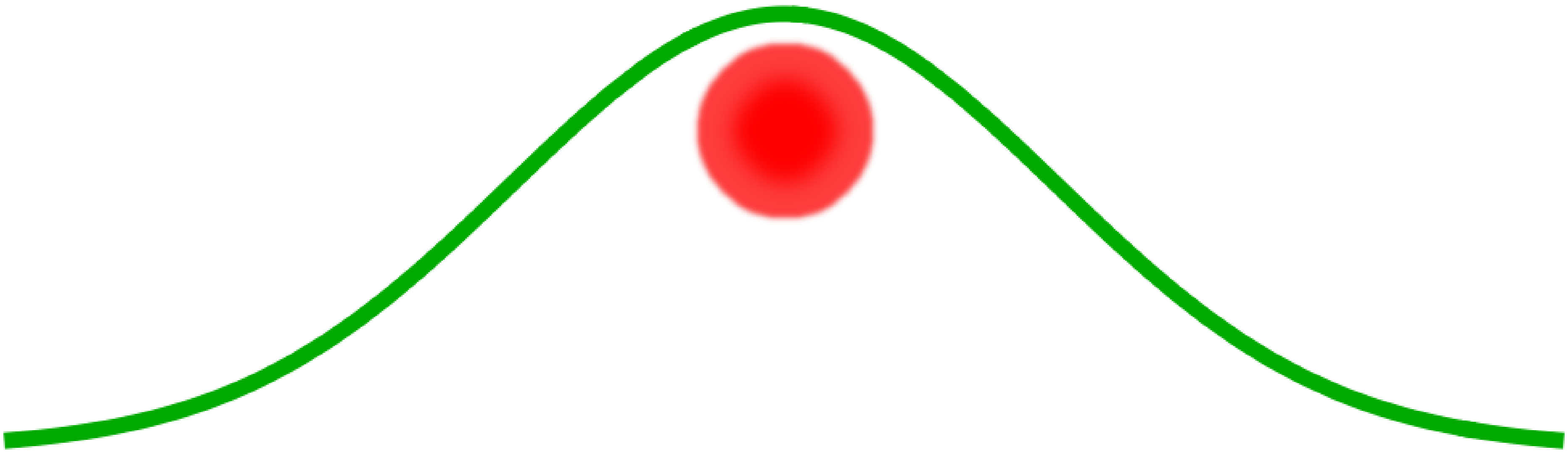
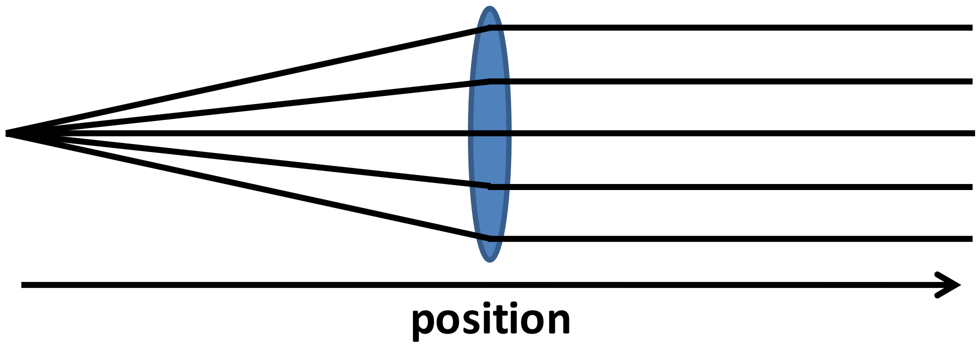
Well-Collimated Atoms

- Want atom cloud to stay small compared to laser beam size to reduce effects from large scale intensity and wavefront inhomogeneities
- For interferometers with long durations, want lower velocity spread
- Begin with laser cooling, often followed by evaporative cooling
- Often want to reduced velocity spread even further



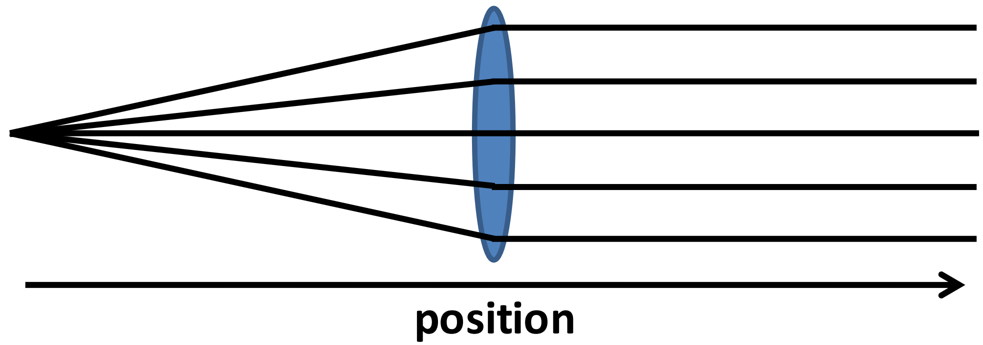
Atom Lens Collimation

Optical Collimation:

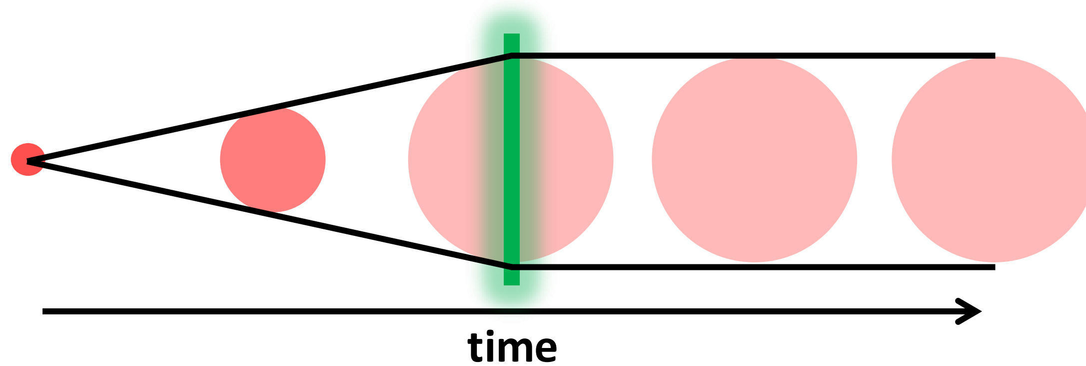


Atom Lens Collimation

Optical Collimation:



Atom Collimation:



Useful feature: conserves atom number

Atom Lens Collimation

- How to create an atom lens?

Atom Lens Collimation

- How to create an atom lens?

- Expose atom to a harmonic potential

Atom Lens Collimation

- How to create an atom lens?
- Expose atom to a harmonic potential
- Why harmonic?
- How much reduction in the velocity spread and corresponding effective temperature is possible for a given initial cloud size and expanded cloud size at the lens?
- For how much time should one expose the atoms to the lens to achieve ideal collimation?
- Is this time always the same, or does it depend on the initial cloud size and/or the cloud size at the lens?
- See problem session

Atom Lens Collimation: Bonus Questions

- The analogy to light optics in a previous slide used ray tracing. We know that ray tracing can often be a good approximation for light optics. For atom optics, one could consider tracing classical trajectories within an ensemble as the analogy of ray tracing. To what extent is this valid?

Atom Lens Collimation: Bonus Questions

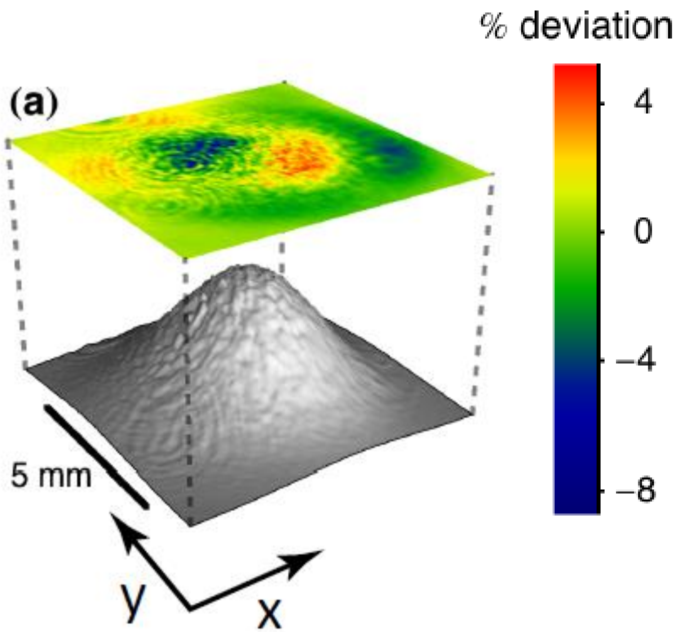
- The analogy to light optics in a previous slide used ray tracing. We know that ray tracing can often be a good approximation for light optics. For atom optics, one could consider tracing classical trajectories within an ensemble as the analogy of ray tracing. To what extent is this valid?
- Consider quantum mechanics in phase space via the Wigner function provides one way to approach this question
- Bonus questions in problem session will introduce the Wigner function and address the question above

Atom Lens Collimation

- Various ways to create harmonic potential for lens, e.g. magnetic potential or optical dipole potential

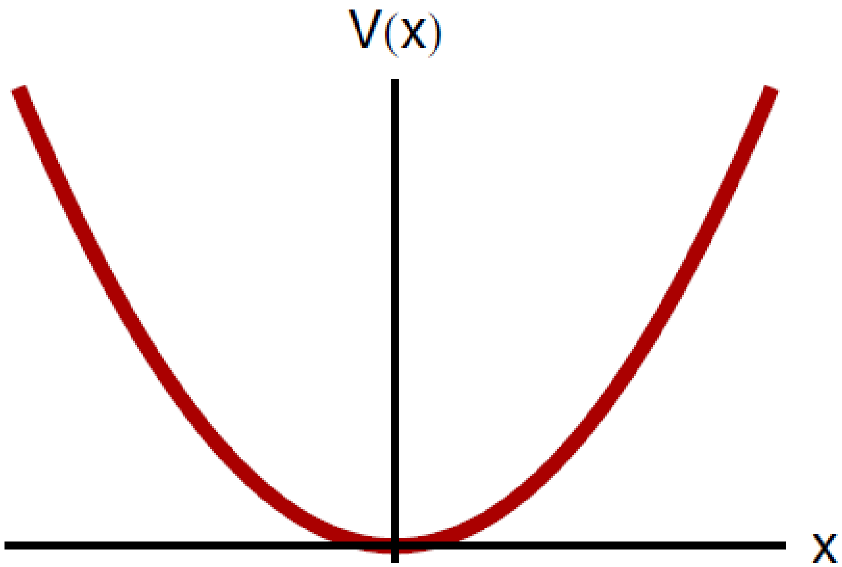
- Optical potentials can often be convenient

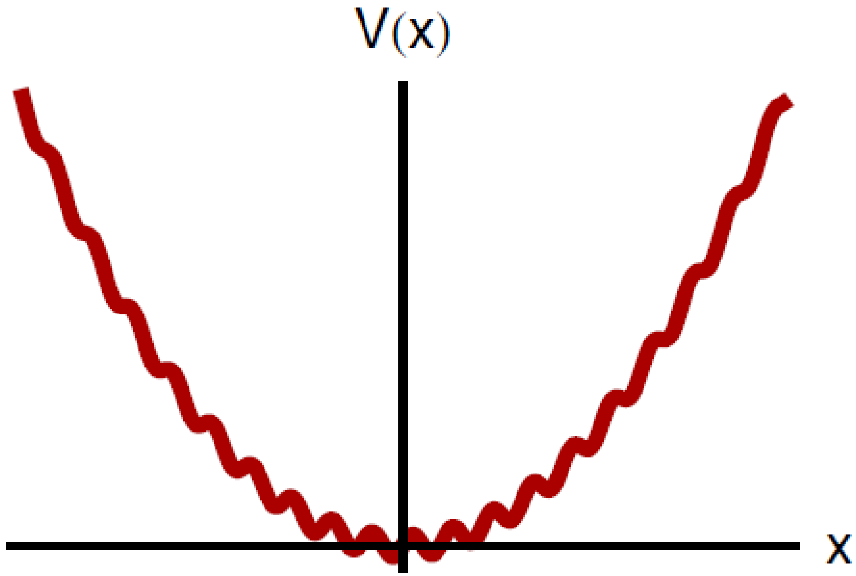
- But laser beams often have small intensity ripples that correspond to ripples in the trap potential



Atom Lens Collimation

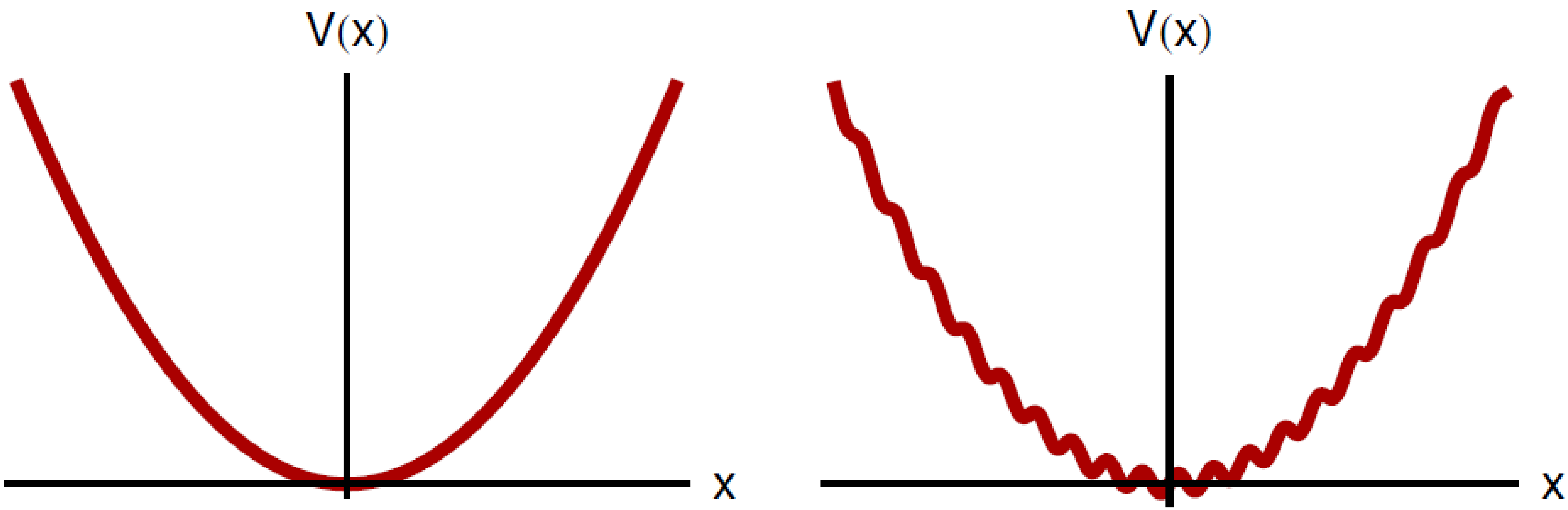
- But laser beams often have small intensity ripples that correspond to ripples in the trap potential
- Is this an issue?





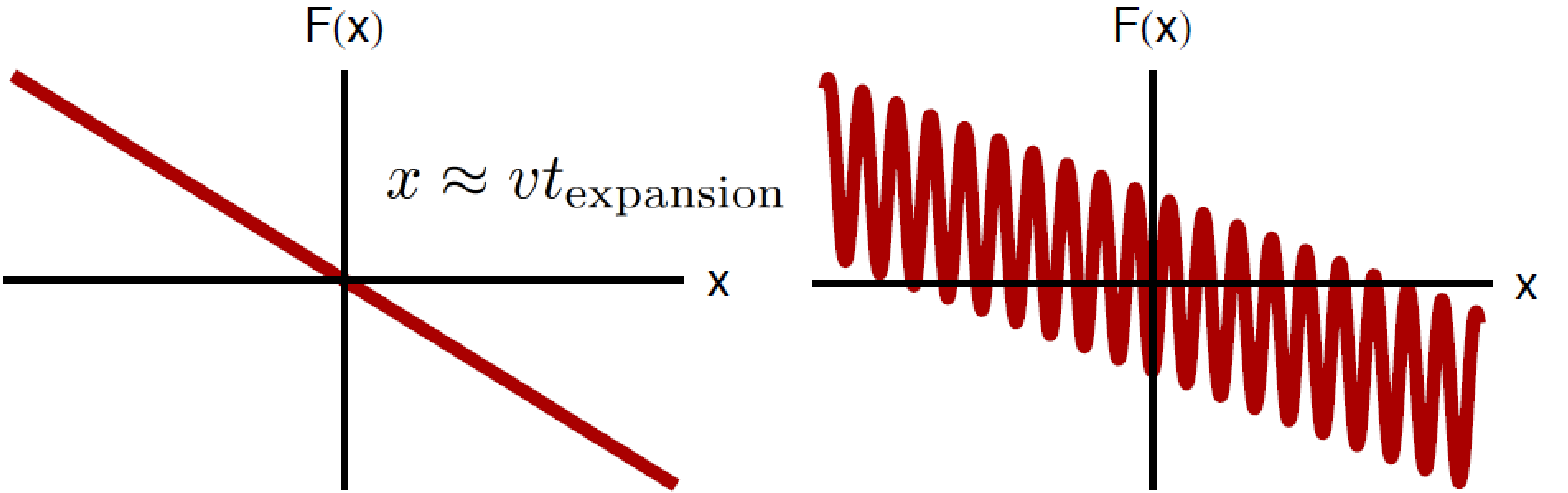
Atom Lens Collimation

- (a) Yes, this will have a huge effect on lensing performance
- (b) Only a minor issue, since the energy of the perturbations is small relative to the energy scale of the harmonic trap



Atom Lens Collimation

- It will have a huge effect
- Force depends on spatial derivation of potential, can be very large even for small potential variations if they vary over short distance scales



$x \approx v t_{\text{expansion}}$

Atom Lens Collimation

- How to reduce the problematic ripples?

- Free propagation allows high spatial frequency perturbations to diffract out of beam

- For transverse wavelength λ_t of perturbation, one gets "spatial sidebands" on the beam that propagate away from main beam at angle λ/ λ_t

$$u(x,y) = (1 + \delta\cos(k_t x))u_0(x,y)$$

$$u(x,y) = u_0(x,y) + \frac{1}{2}\exp{(ik_t x)}u_0(x,y) + \frac{1}{2}\exp{(-ik_t x)}u_0(x,y)$$

$$k_t = 2\pi/\lambda_t$$

Atom Lens Collimation

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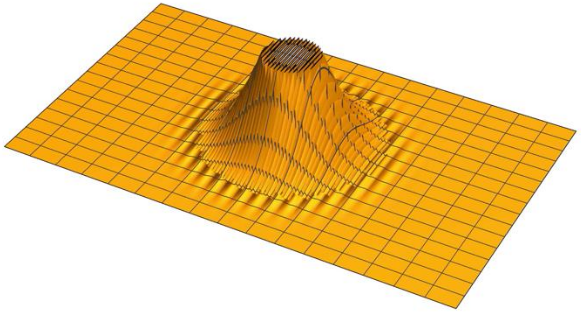

Atom Lens Collimation

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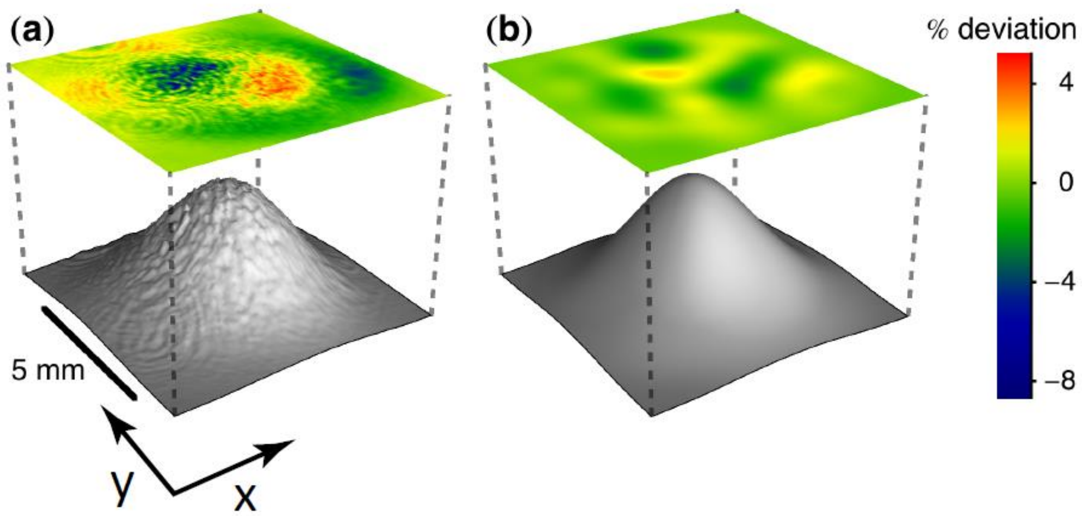

Atom Lens Experiment Results

PHYSICAL REVIEW LETTERS **127,** 100401 (2021)

Editors' Suggestion   Featured in Physics

Collective-Mode Enhanced Matter-Wave Optics

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[5]*Institut für Physik, Humboldt-Universität zu Berlin, Newtonstraße 15, D-12489 Berlin, Germany*
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[7]*Laboratoire de Collisions Agrégats Réactivité, CNRS, IRSAMC, Université de Toulouse, 118 Route de Narbonne, F-31062 Toulouse, France*

(Received 13 November 2020; revised 14 June 2021; accepted 25 June 2021; published 30 August 2021)

In contrast to light, matter-wave optics of quantum gases deals with interactions even in free space and for ensembles comprising millions of atoms. We exploit these interactions in a quantum degenerate gas as an adjustable lens for coherent atom optics. By combining an interaction-driven quadrupole-mode excitation of a Bose-Einstein condensate (BEC) with a magnetic lens, we form a time-domain matter-wave lens system. The focus is tuned by the strength of the lensing potential and the oscillatory phase of the quadrupole mode. By placing the focus at infinity, we lower the total internal kinetic energy of a BEC comprising 101(37) thousand atoms in three dimensions to $3/2\, k_B \cdot 38^{+6}_{-7}$ pK. Our method paves the way for free-fall experiments lasting ten or more seconds as envisioned for tests of fundamental physics and high-precision BEC interferometry, as well as opens up a new kinetic energy regime.

DOI: 10.1103/PhysRevLett.127.100401

Coriolis Forces

- Experiments carried out on surface of Earth
- In the lab frame, there are Coriolis forces due to Earth's rotation

$$\vec{a}_{\text{Cor}} = -2\vec{\Omega}_{\text{Earth}} \times \vec{v}$$

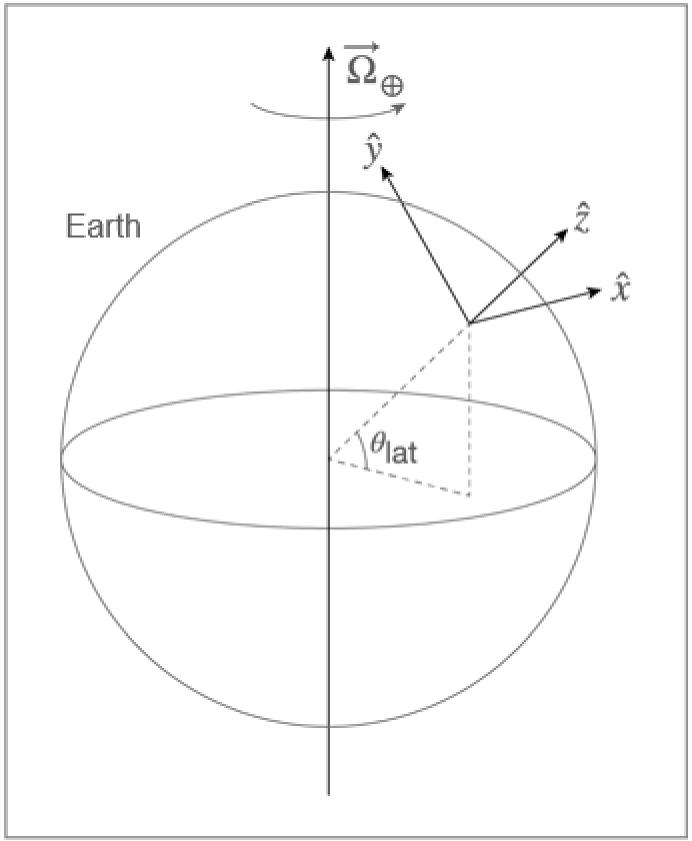
Coriolis Forces

- Consider interferometer axis along z
- Interferometer sensitive to Coriolis acceleration along z

$$\left|\vec{\Omega}_{\text{Earth}}\right| \approx 7.3 \times 10^{-5}$$

$$\Omega_y = \left|\vec{\Omega}_{\text{Earth}}\right| \cos\left(\theta_{\text{lat}}\right)$$

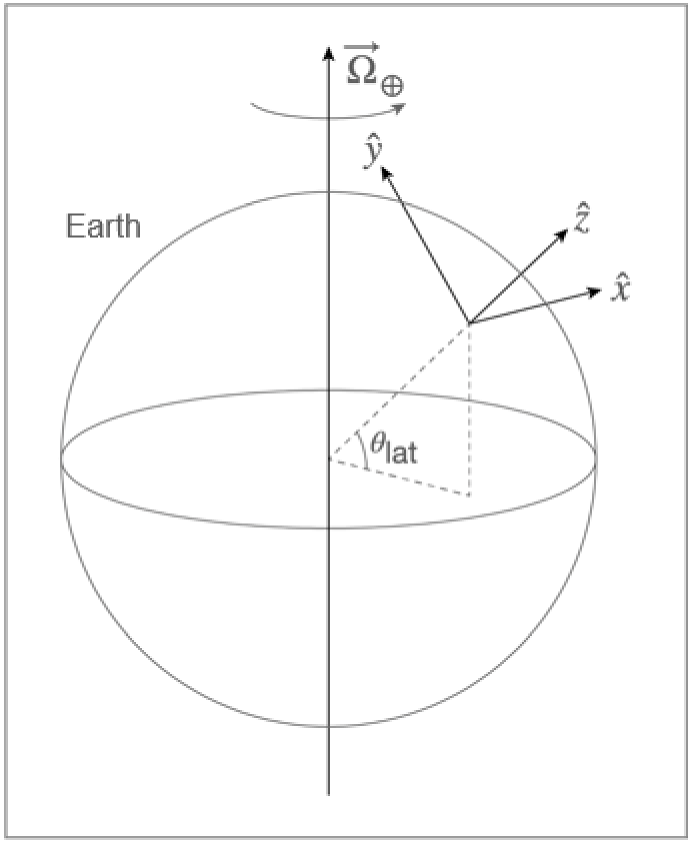
$$a_z = 2\Omega_y v_x$$



Coriolis Forces

- Consider $\theta_{\text{lat}} \approx 42^\circ$ and v_x = 1 mm/s
- Interferometer sensitive to Coriolis acceleration along z

$$a_z \approx 5 \times 10^{-8} \text{m/s}^2$$



Coriolis Forces

- Leading phase shift contribution for nħk momentum splitting

$$\Delta\phi_{\text{Coriolis}} \approx 2nkv_x\Omega_yT^2$$

- Example numbers: n = 20, T = 1 s, v_x = 1 mm/s, k= 2π/(780 nm)

$$\Delta\phi_{\text{Coriolis}} \approx 17 \text{ rad}$$

Coriolis Forces

- In general, there is a spread in v_x across the atom ensemble

$$\Delta\phi_{\text{Coriolis}} \approx 2nkv_x\Omega_y T^2$$

- How does this spread affect the interferometer signal?

Coriolis Forces

- In general, there is a spread in v_x across the atom ensemble

$$\Delta\phi_{\text{Coriolis}} \approx 2nkv_x\Omega_y T^2$$

- How does this spread affect the interferometer signal?

- Phase averaging when detection averages over v_x

- Reduction in interferometer contrast

Coriolis Forces

Selected for a Viewpoint in *Physics*
PRL **108,** 090402 (2012) PHYSICAL REVIEW LETTERS week ending 2 MARCH 2012

Influence of the Coriolis Force in Atom Interferometry

Shau-Yu Lan,[1,*] Pei-Chen Kuan,[1] Brian Estey,[1] Philipp Haslinger,[2] and Holger Müller[1,3]
[1]*Department of Physics, University of California, Berkeley, California 94720, USA*
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(Received 31 October 2011; published 27 February 2012)

Selected for a Viewpoint in *Physics*
PRL **111,** 083001 (2013) PHYSICAL REVIEW LETTERS week ending 23 AUGUST 2013

Multiaxis Inertial Sensing with Long-Time Point Source Atom Interferometry

Susannah M. Dickerson, Jason M. Hogan, Alex Sugarbaker, David M. S. Johnson, and Mark A. Kasevich*
Department of Physics, Stanford University, Stanford, California 94305, USA
(Received 24 April 2013; published 19 August 2013)

Coriolis Forces

- Compensate for Coriolis forces by rotating the effective k vector (corresponding to the direction of momentum transfer after absorption of a photon from one beam and emission of photon into the other beam nominally travelling in the opposite direction) against the rotation of the Earth

- An inertial observer (e.g., floating in space) would see the direction of the effective k vector remain constant in time

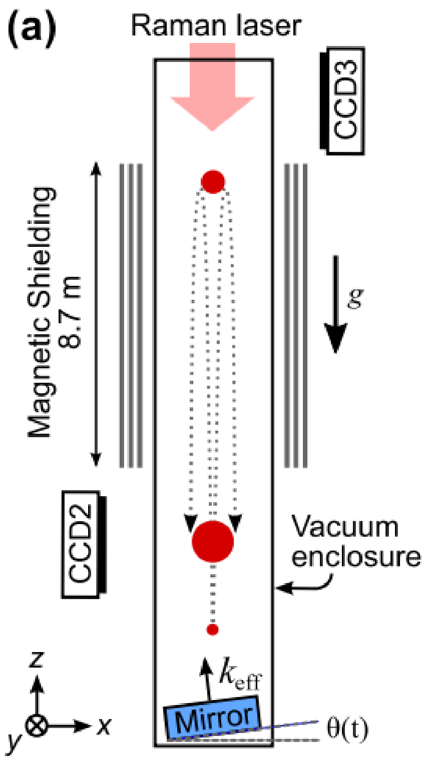
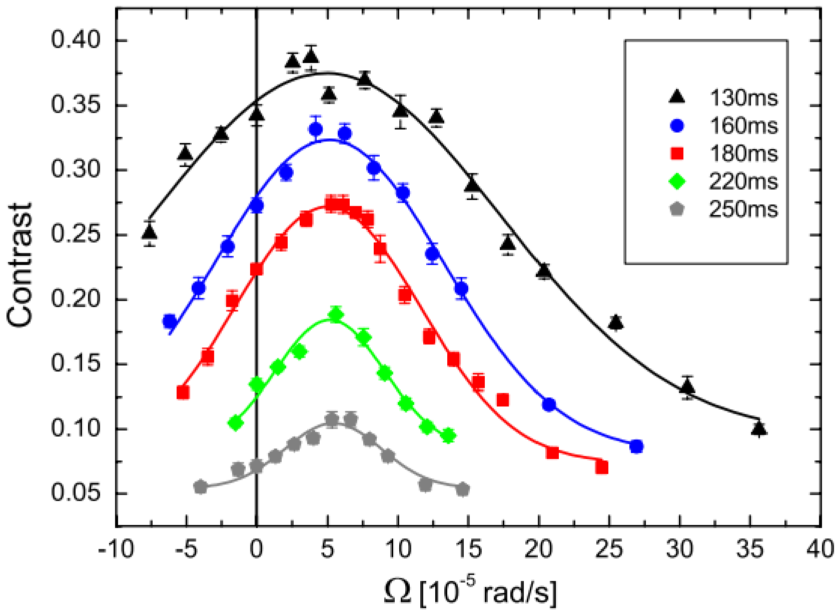


Figure from Dickerson et al., PRL 2013

Coriolis Forces

- Applying appropriate rotation compensation can restore interferometer contrast
- Can optimize counter-rotation to maximize contrast



Coriolis Forces

- In general, there is a spread in v_x across the atom ensemble

$$\Delta\phi_{\text{Coriolis}} \approx 2nkv_x\Omega_y T^2$$

- How does this spread affect the interferometer signal?

- Phase averaging when detection averages over v_x

- Reduction in interferometer contrast

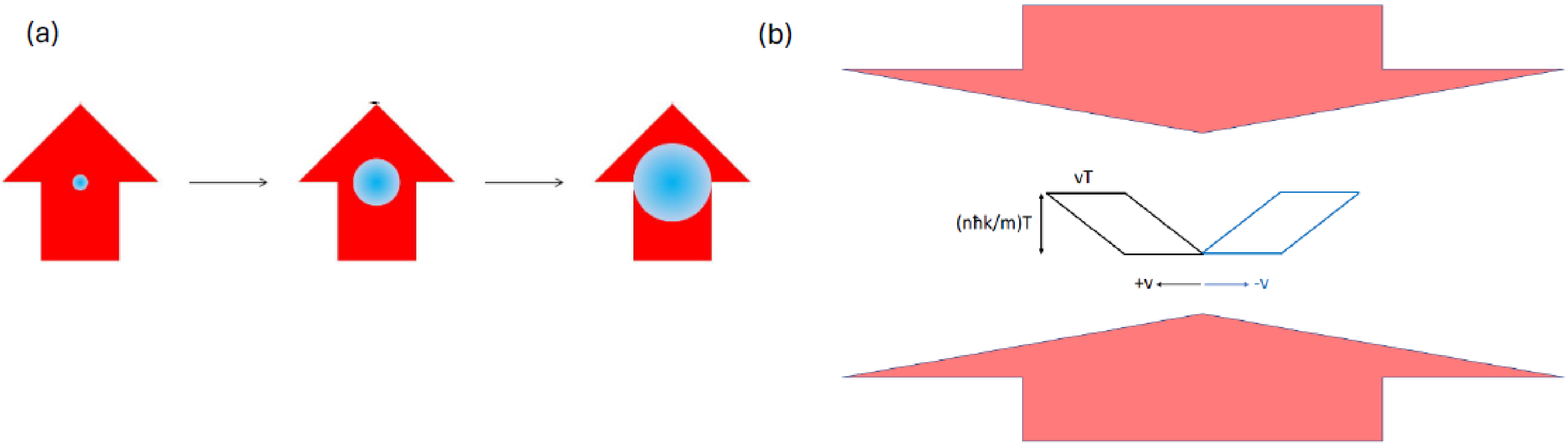
- But what if we resolve v_x in the detection process?

Coriolis Forces

- Point source atom interferometry (PSAI): atom cloud expands from small size to the final position where atom is detected is well-correlated with initial atom velocity

$$x_f = x_0 + v_0 T_e$$

$$x_f \approx v_0 T_e$$



Coriolis Forces

- Point source atom interferometry (PSAI): atom cloud expands from small size to the final position where atom is detected is well-correlated with initial atom velocity

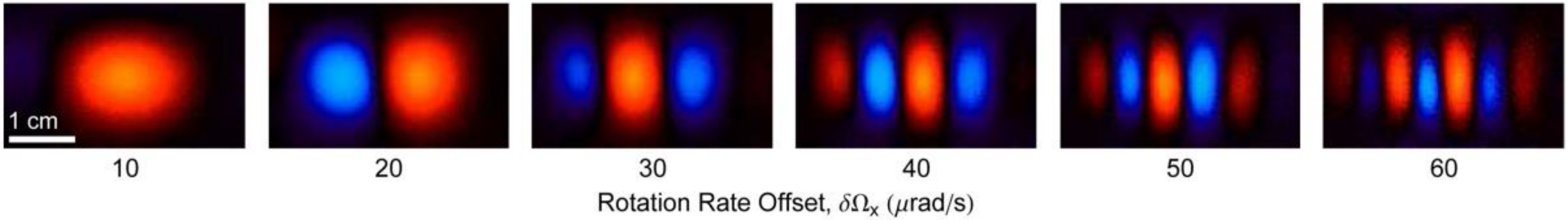
$$x_{\mathrm{f}} = x_0 + v_0 T_{\mathrm{e}}$$

$$x_{\mathrm{f}} \approx v_0 T_{\mathrm{e}}$$

- If one uses a camera for spatially resolved detection of a PSAI, how does the spread in Coriolis phase shifts across the ensemble manifest?

Coriolis Forces

- Spatially varying phase leads to spatial fringes



- Fringe frequency encodes information about the difference between Earth's rotation and the counter-rotation of the effective k vector direction

- Provides a way to calibrate rotation compensation

- Provides a way to measure Earth's rotation

Figure from Dickerson et al., PRL 2013

Rotation Compensation

- Earth's rotation leads to velocity dependent Coriolis forces on atoms

- Mitigation strategy: counter-rotate angle of laser beams against Earth's rotation

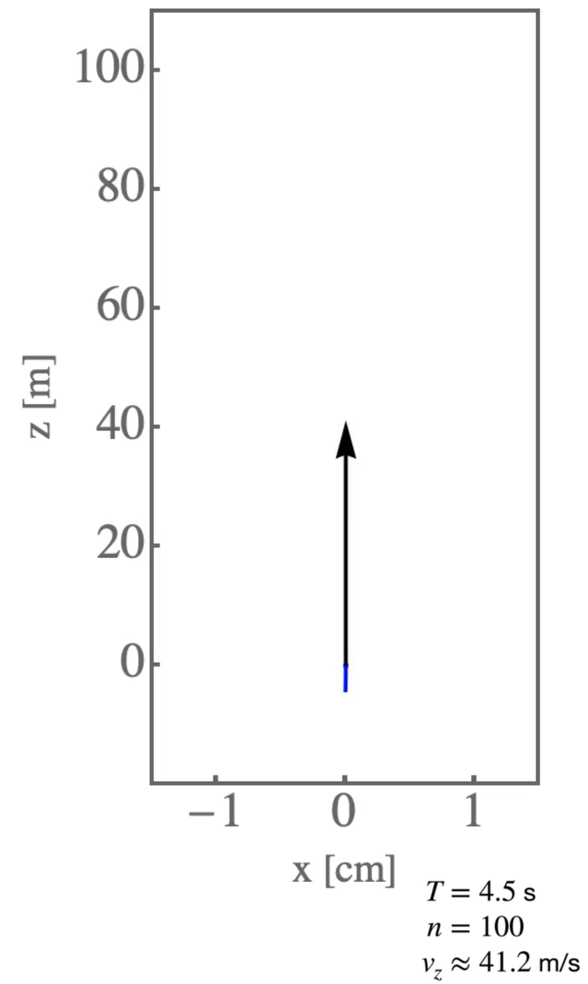
- 10-meter-scale interferometers: beam deflections on the mm scale (smaller than a cm scale beam)

- 100-m-scale interferometers: beam deflections on the cm scale (also need to consider Coriolis deflections of atom trajectories)

Hogan et al., Proc. Int. Sch. Phys. 'Enrico Fermi' Atom Interferometry and Space Physics, 411-447 (2009); Lan et al., PRL 108, 090402 (2012); Dickerson et al., PRL 111, 083001 (2013)

Challenges of Scaling Traditional Scheme to Longer Baselines

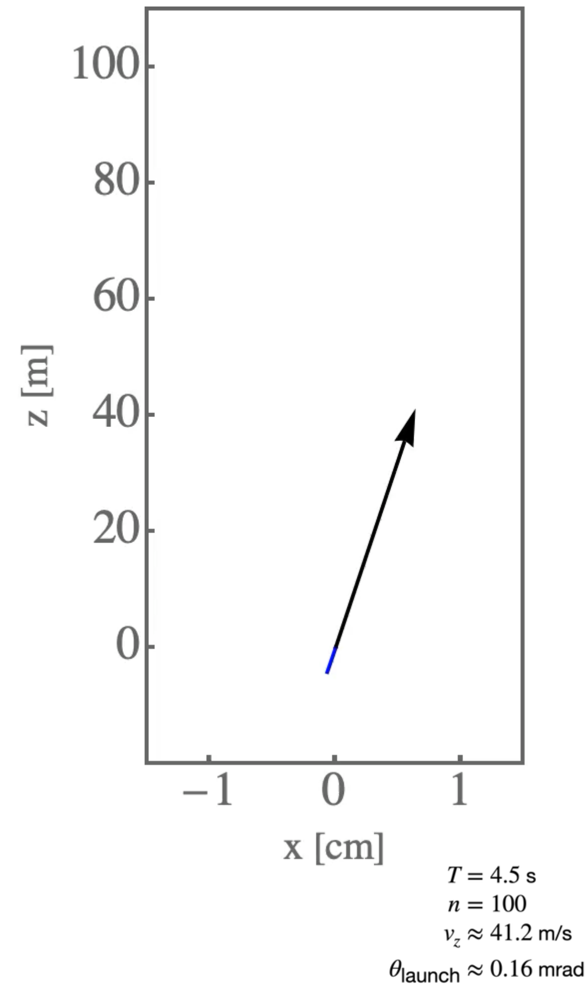
- For large launch velocities to reach tall launch heights, Coriolis forces can significantly deflect atoms transversely from the z axis



Challenges of Scaling Traditional Scheme to Longer Baselines

- For large launch velocities to reach tall launch heights, Coriolis forces can significantly deflect atoms transversely from the z axis

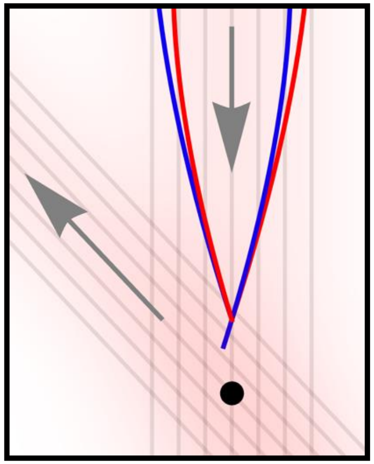
- Tuning the launch angle can help with this



Challenges of Scaling Traditional Scheme to Longer Baselines

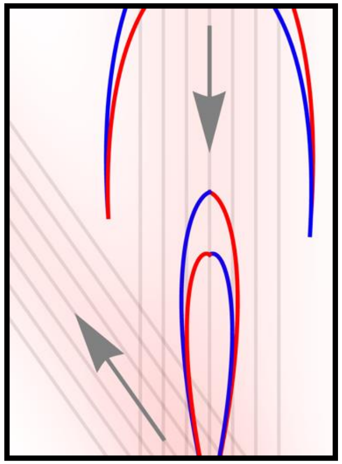
- Traditional approach: "pivot point" of the interferometer beam set by the location of the retro mirror at the bottom of the interferometer
- Engineering constraints in long baseline interferometers can cause the position at which the interferometer begins to be far from the retro mirror
- Longer lever arm between pivot point and atoms causes center of the interferometer beam to transversely shift misalign from the atom cloud as the beam is rotated

Atoms not centered on the reflected interferometer beams experience a weaker effective Rabi frequency



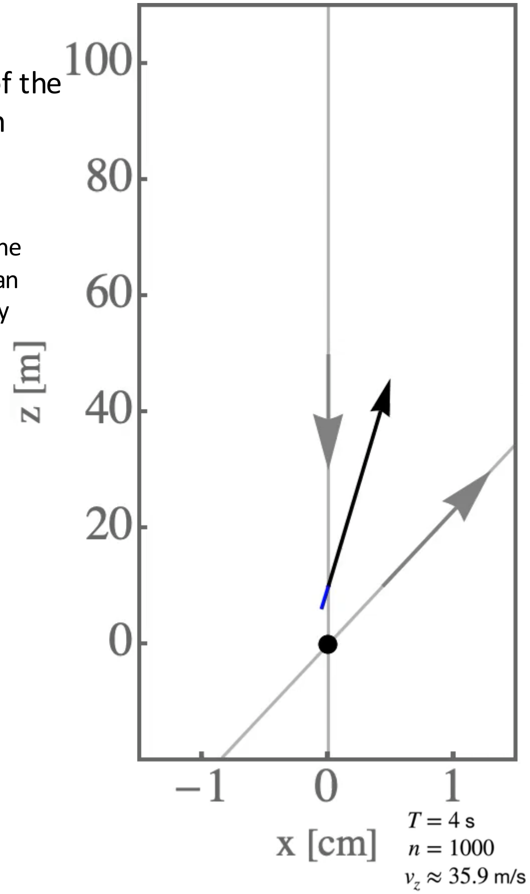
Lateral offset : 4.3 mm

In a gradiometer configuration, the reflected interferometer beam can miss the atoms more dramatically

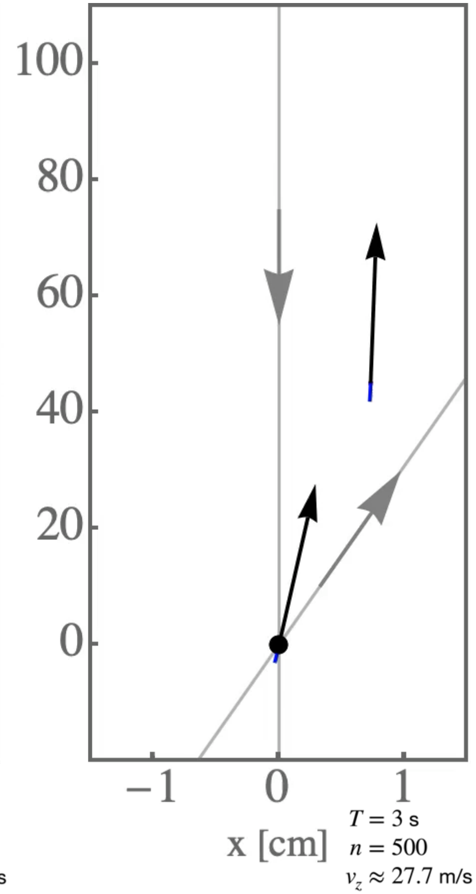


Lateral offset : 1.5 cm

Dual-isotope Differential Accelerometer Configuration

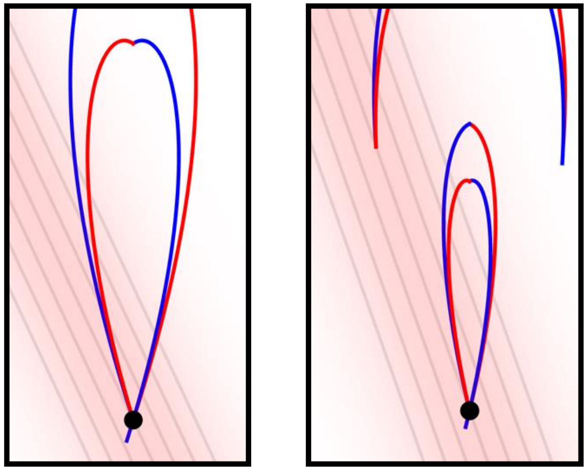


Gradiometer Configuration

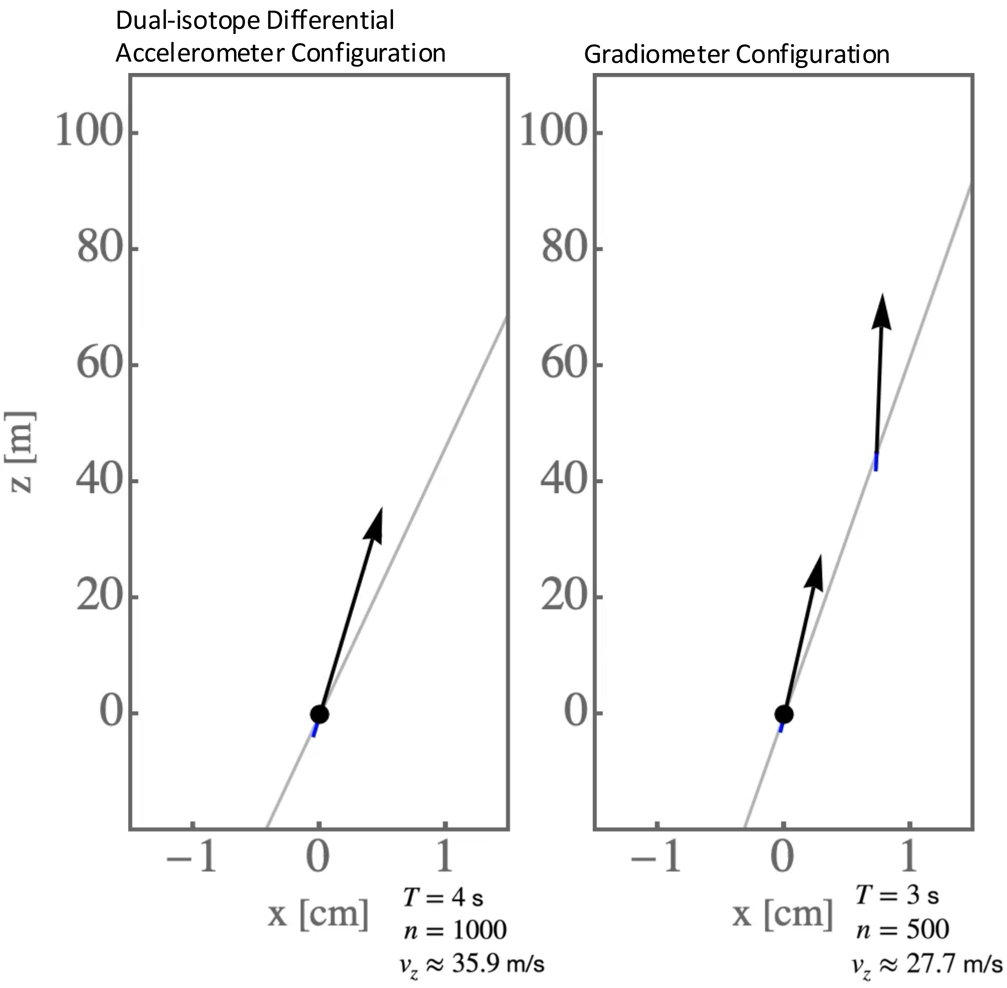


New Scheme for Scaling to Longer Baselines

- Needs for rotation compensation that keeps atoms centered on laser beams when pulses occurs:
  - Keep the 'downward' and 'upward' propagating beams collinear
  - Adjust the pivot point along the baseline
- This approach also requires the ability to adjust the initial kinematics of the of the different atom clouds individually



The atoms stay aligned with the interferometer beam during the key atom optics operations

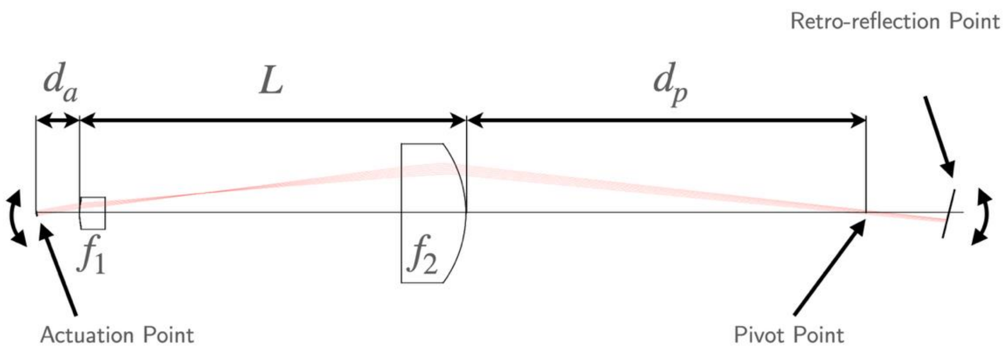


New Scheme for Scaling to Longer Baselines

Leverage beam expansion telescope to set pivot point and keep initial and retro-reflected beams collinear

- The optical configuration associated with the pivot point scheme consists of having piezo-actuated mirrors on each end of the baseline
- The scheme leverages the telescope used to expand the interferometer beam to a cm-scale waist
- The point along the baseline that the interferometer beam pivots can be tuned by adjusting d_a

$$d_p \approx (f_2 + M^2 f_1) - M^2 d_a$$

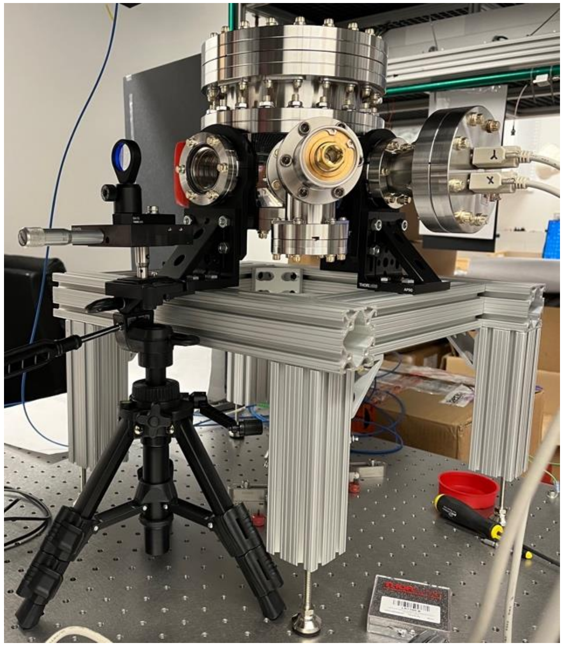


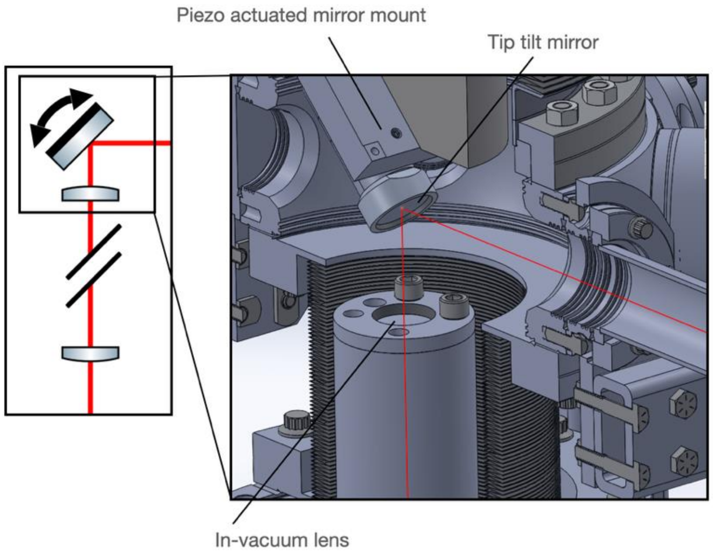
Glick,…, TK, AVS Quantum Science 6, 014402 (2024)

Pivot Point Method — Tip Tilt System

- interferometer beam will reflect off a piezo-actuated mirror just before the first telescope lens

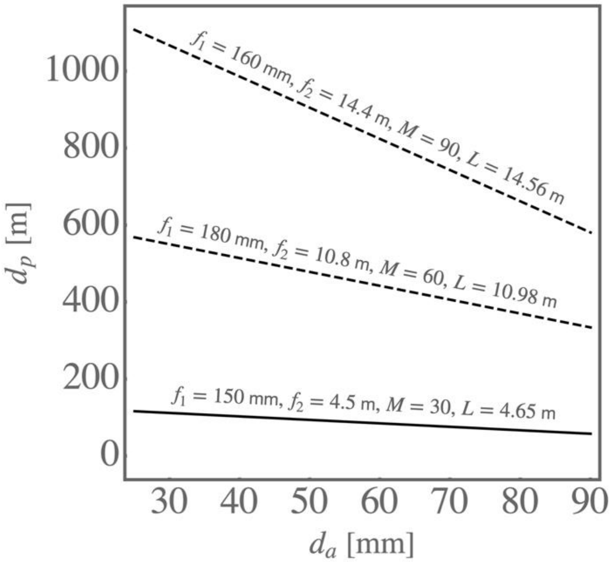
- 10 mrad total angular range





Challenges of Scaling to km Baselines

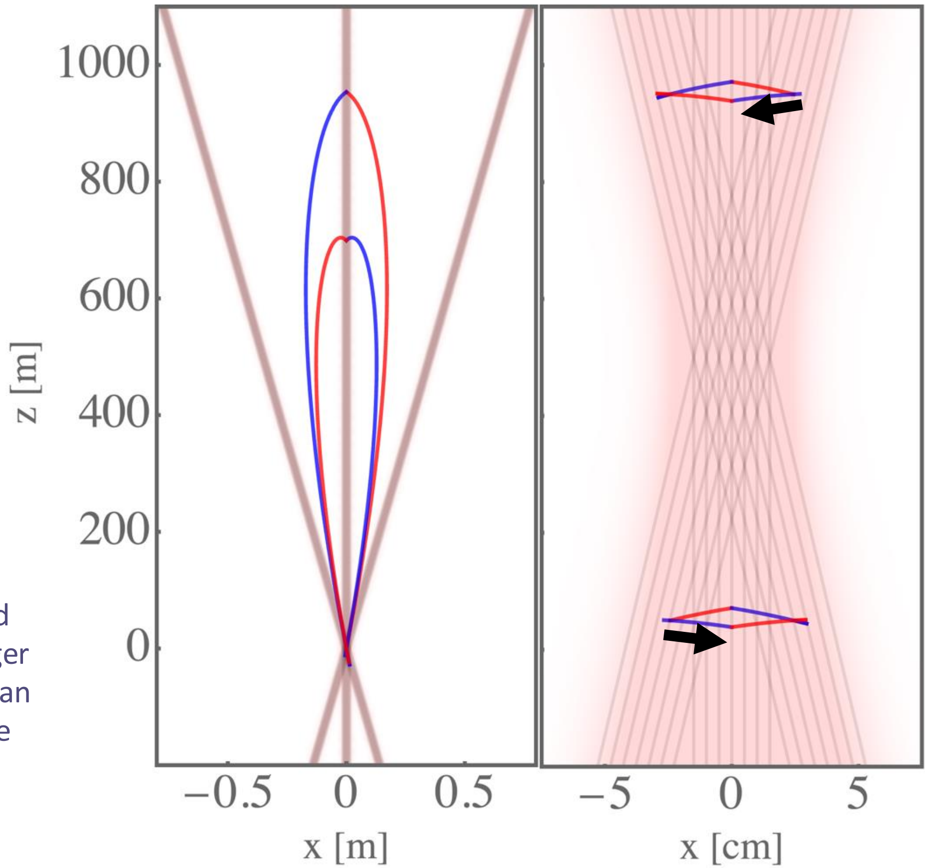
- Larger diameter vacuum tubes and optics required
  - In a dual-isotope configuration, where the atom trajectories span the full length of the baseline, the deflection of the interferometer beam is large — meter-scale diameters on optical components and vacuum tubes are required
  - In a gradiometer configuration, the deflection of the beam is smaller (owing to the smaller *T*) and requirements for the gradiometer configuration are more relaxed
- Telescope lengths might need to be increased



Is it realistic to extend this method to a longer baseline, or would is an alternate approach be required?

Dual-isotope Differential Accelerometer Configuration

Gradiometer Configuration

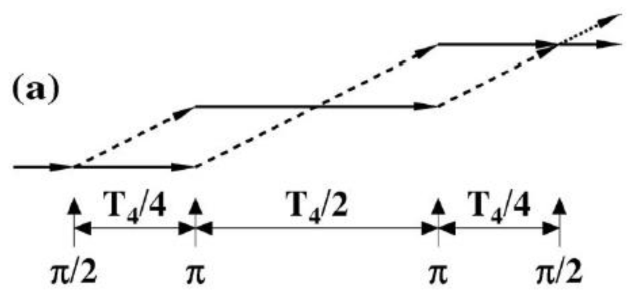


$T = 13$ s
$n = 3000$
$v_z \approx 117.4$ m/s

$T = 1$ s
$n = 3000$

Multiloop Interferometry

- Multiple loops provide an alternative way to suppress Coriolis phase shifts without requiring rotation of the beam
- Suppresses response to constant and low-frequency signals, which one sometimes wants to measure



PHYSICAL REVIEW A **74**, 023615 (2006)

Atom interferometer as a selective sensor of rotation or gravity

B. Dubetsky and M. A. Kasevich
Department of Physics, Stanford University, Stanford, California 94305-4060, USA
(Received 10 April 2006; published 21 August 2006)

Multiloop Interferometry

- Also provides a way to resonantly amplify signals that undergo multiple oscillations over interferometer duration
- Filters away noise at other frequencies
- Analogy to a lock-in amplifier used to detect small electronic signals

PHYSICAL REVIEW D **94**, 104022 (2016)

Resonant mode for gravitational wave detectors based on atom interferometry

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(Received 7 June 2016; published 10 November 2016)

Gravity Gradients

Gravity gradients couple to errors/jitter in initial atom position and velocity to cause unwanted phase shifts (i.e., effective gravitational acceleration experienced depends on initial kinematics)

$$g_{\mathrm{A}} - g_{\mathrm{B}} = T_{zz}[\Delta z + \Delta v\, T] \equiv T_{zz}\Delta\bar{z}$$

Typical value: $T_{zz} \sim 3 \times 10^{-7}$ g/m

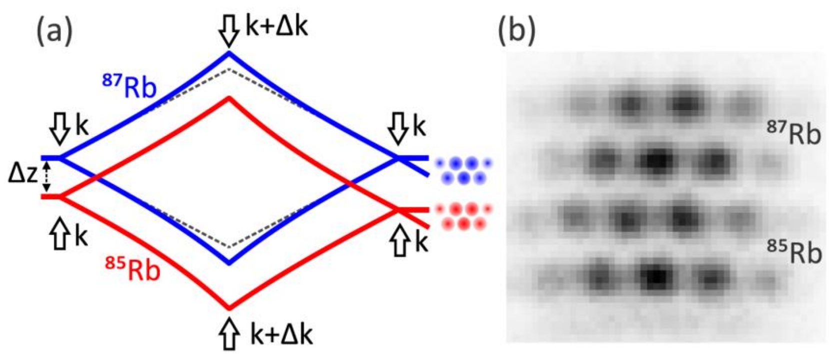
But value can vary depending on mass distribution of the Earth in surrounding areas, local buildings, pits, etc….

Gravity Gradient Compensation

Gravity gradients couple to errors/jitter in initial atom position and velocity to cause unwanted phase shifts (i.e., effective gravitational acceleration experienced depends on initial kinematics)

$$g_{\mathrm{A}} - g_{\mathrm{B}} = T_{zz}[\Delta z + \Delta v\, T] \equiv T_{zz}\Delta \bar{z}$$

Roura PRL 118, 160401 (2017): proposes jumping frequency for mirror pulses



$$-\left(nkT_{zz}T^2 + 2n\Delta k\right)(\Delta z + \Delta v_z T)$$

$$\Delta k/k = -T_{zz}T^2/2$$

Appropriate choice of frequency jump compensates gravity gradient phase shift

D'Amico et al., PRL 119, 253201 (2017)
Overstreet et al., PRL 120, 183604 (2018)

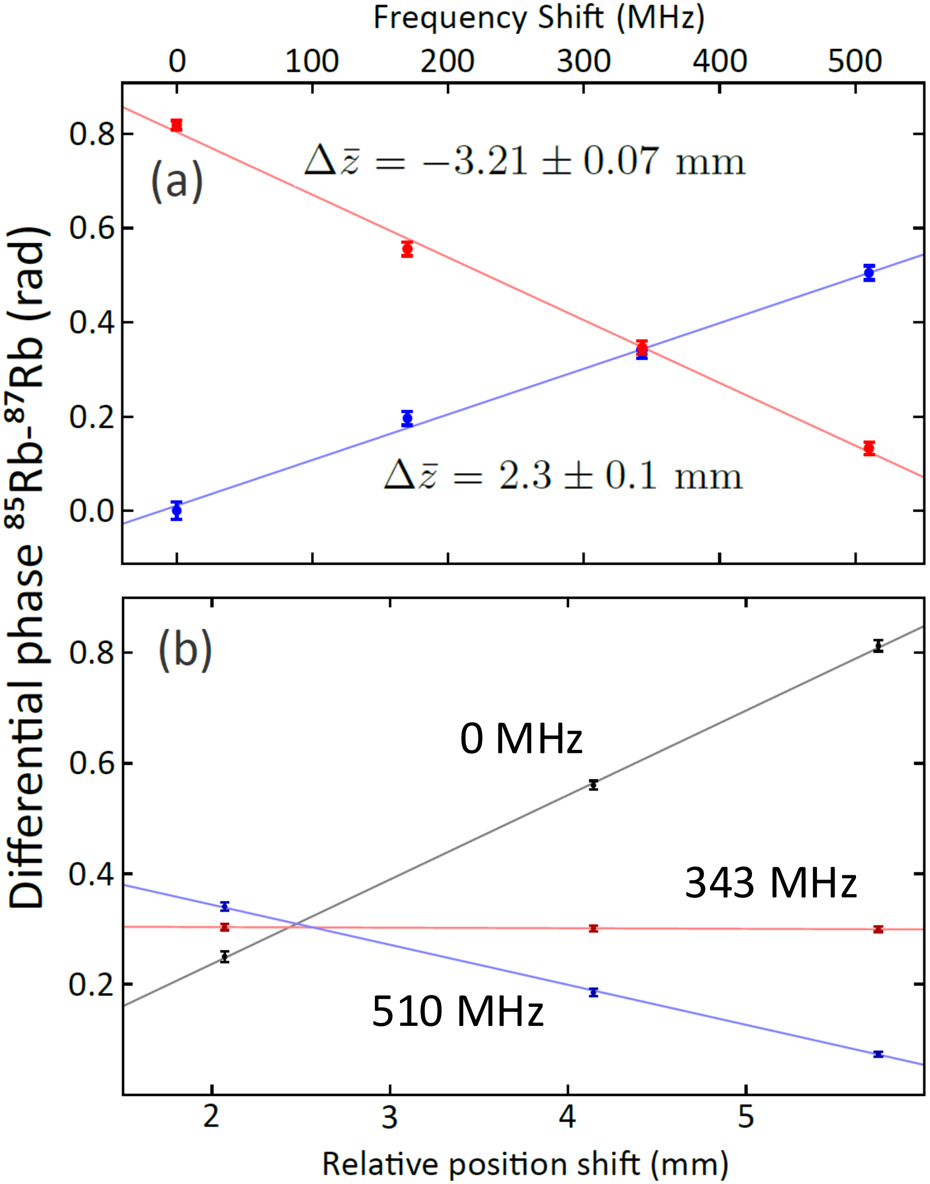
Gravity Gradient Compensation Example

- Apply relative position shift between Rb-85 and Rb-87 before interferometer using a combination of Raman and Bragg pulses

-Raman pulses allow selective addressing of isotopes due to different hyperfine splittings

- Factor of 100 reduction in phase shift from coupling of gravity gradient to initial kinematic offsets

- By finding relative position shift for which phase shift is insensitive to the value of the frequency jump, can reduce $\Delta\bar{z}$

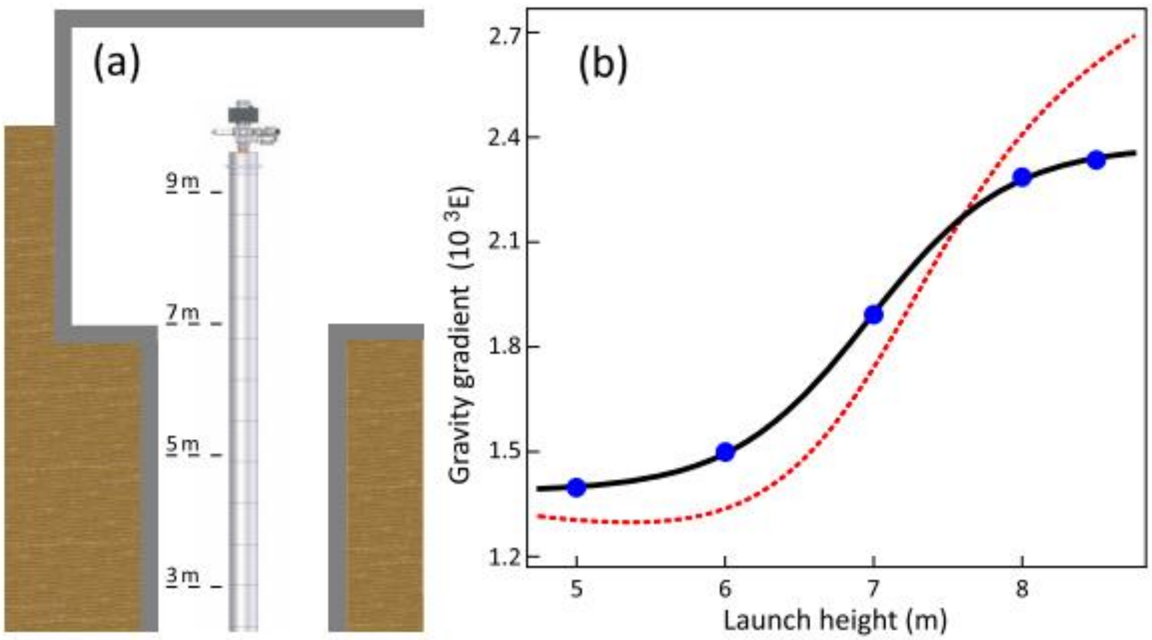


Overstreet et al., PRL 2018

Gravity Gradient Compensation

For long-baseline, gravity gradient can vary substantially over the distance spanned by the interferometer

Example from Stanford 10 m Rb tower



Asenbaum et al., PRL 118, 183602 (2018)

Gravity Gradient Compensation

PHYSICAL REVIEW A **103**, 023305 (2021)

Generalized gravity-gradient mitigation scheme

Christian Ufrecht*
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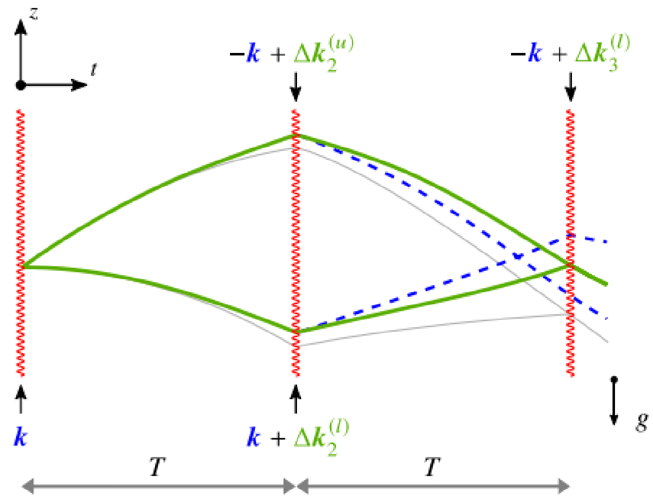
(Received 28 August 2020; revised 22 January 2021; accepted 22 January 2021; published 3 February 2021)

A major challenge in high-precision light-pulse atom interferometric experiments such as in tests of the weak equivalence principle is the uncontrollable dependency of the phase on initial velocity and position of the atoms in the presence of inhomogeneous gravitational fields. To overcome this limitation, mitigation strategies have been proposed, however, valid only for harmonic potentials or only for small branch separations in more general situations. Here we provide a mitigation formula for anharmonic perturbation potentials including local gravitational effects that vary on length scales much smaller than the spatial extent probed by the atoms and originate, e.g., from buildings that surround the experiment. Furthermore, our results are applicable to general interferometer geometries with arbitrary branch separation and allow for compensation of Coriolis effects in rotating reference frames.

DOI: 10.1103/PhysRevA.103.023305



Frequency Jumps vs. Multi-Loop

Frequency jumps: Can preserve DC/low frequency response

Multi-loop: alternative approach to suppress gravity gradient effects, rolls off response for frequencies below loop frequency

For 10 m or greater launch, frequency jump will be hundreds of MHz to GHz

For two-photon transitions on a broad line (e.g., for dual species interferometry), such a jump can be small compared to detuning from excited state, so will not affect Rabi frequency very much

Not obvious how to make this work for resonant single-photon transitions—multi-loop approach (or a creative new solution) may be needed

Benefit of multi-loop approach: can also suppress phase shifts from Coriolis forces

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Not obvious how to make this work for resonant single-photon transitions—multi-loop approach (or a creative new solution) may be needed

Benefit of multi-loop approach: can also suppress phase shifts from Coriolis forces

Can you think of a better solution?

Magnetic Fields

- Even if atoms prepared in state with no first order Zeeman shift, second order Zeeman shifts can cause forces on atoms due to gradients in magnetic fields

- Energy shift: $\frac{1}{2}\hbar\alpha\left|\vec{B}\right|^2$

- Force of magnitude: $\hbar\alpha B_0\frac{\partial B_z}{\partial z}$

  Bias magnetic field (defines quantization axis, relative to which laser polarization is defined)

- Example for Rb: $\alpha_{85} = 2\pi \times 1.3\ \mathrm{kHz/G^2},\ \alpha_{87} = 2\pi \times 0.58\ \mathrm{kHz/G^2}$

- Magnetic shields using high permeability material typically used to reduce magnetic field and magnetic field gradients in interferometer region

Magnetic Fields: Example

PHYSICAL REVIEW LETTERS **125,** 191101 (2020)

Atom-Interferometric Test of the Equivalence Principle at the 10^{-12} Level

Peter Asenbaum,[*] Chris Overstreet,[*] Minjeong Kim, Joseph Curti, and Mark A. Kasevich[†]
Department of Physics, Stanford University, Stanford, California 94305, USA

(Received 26 June 2020; accepted 5 October 2020; published 2 November 2020)

Parameter	(-0.41 ± 0.036) mG/m	Uncertainty
Magnetic gradient	–5.9	0.5

Error budget in units of 10^{-12} g.

- Bias field: 41 mG
- Effective gradient: (-0.41 ± 0.036) mG/m

- Gradient measured via interferometry with Zeeman sensitive states
- Reaching these levels required a magnetic shield

Magnetic Fields: Example

REVIEW OF SCIENTIFIC INSTRUMENTS **83**, 065108 (2012)

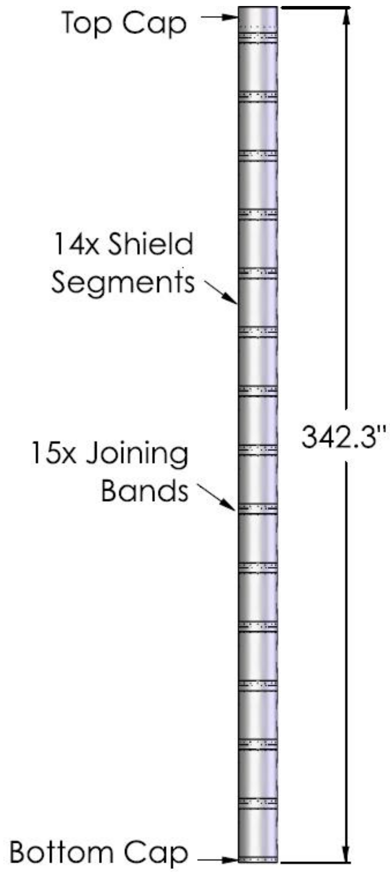
A high-performance magnetic shield with large length-to-diameter ratio

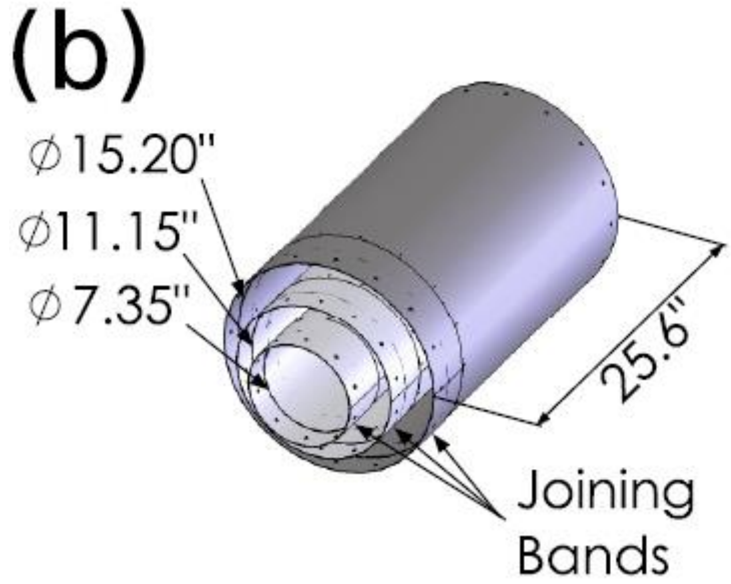
Susannah Dickerson,[a] Jason M. Hogan, David M. S. Johnson, Tim Kovachy,
Alex Sugarbaker, Sheng-wey Chiow, and Mark A. Kasevich
Department of Physics, Stanford University, Stanford, California 94305, USA

(Received 12 March 2012; accepted 8 May 2012; published online 15 June 2012)

Magnetic Fields: Example

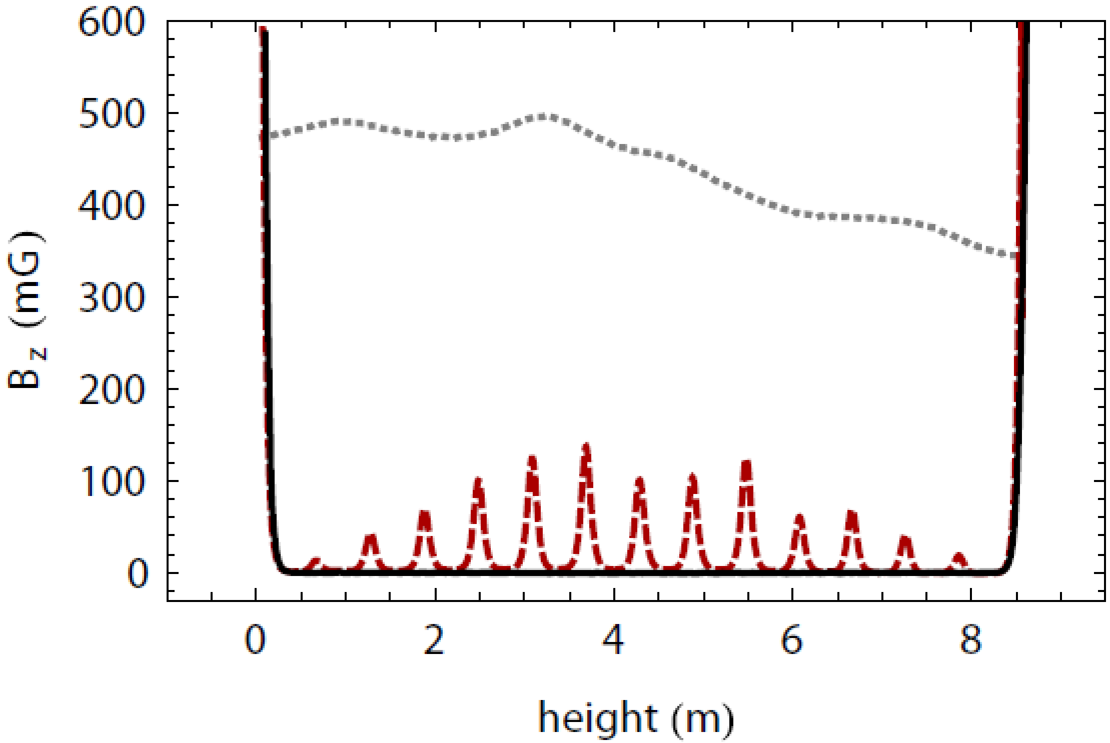
- Initial shield design





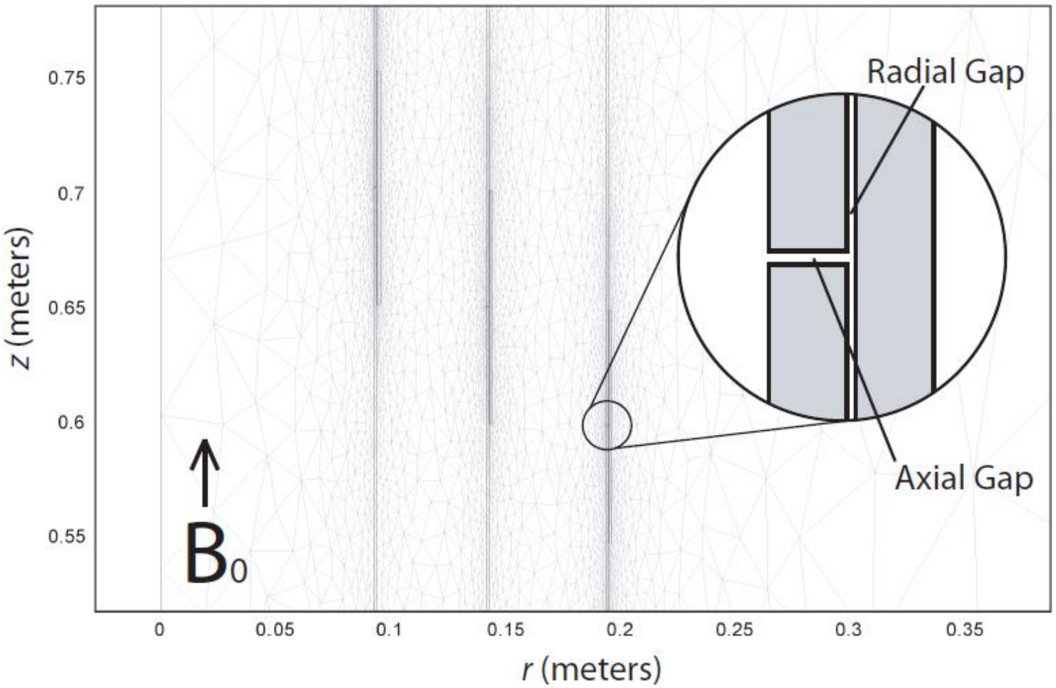
Magnetic Fields: Example

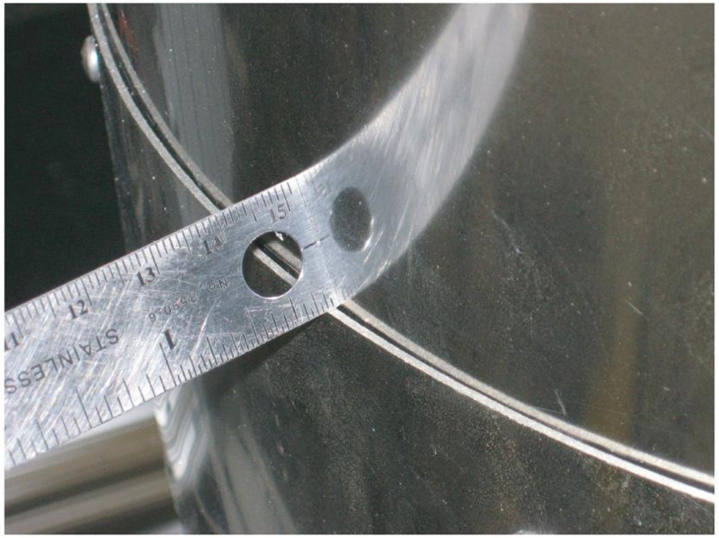
- A problem: why the spikes?



Magnetic Fields: Example

- Magnetic flux leakage through the small gaps between segments
- Because the shield is so large, it draws in a lot of flux, so even a bit of it leaking is a problem
- Confirmed with finite element simulations





Magnetic Fields: Example

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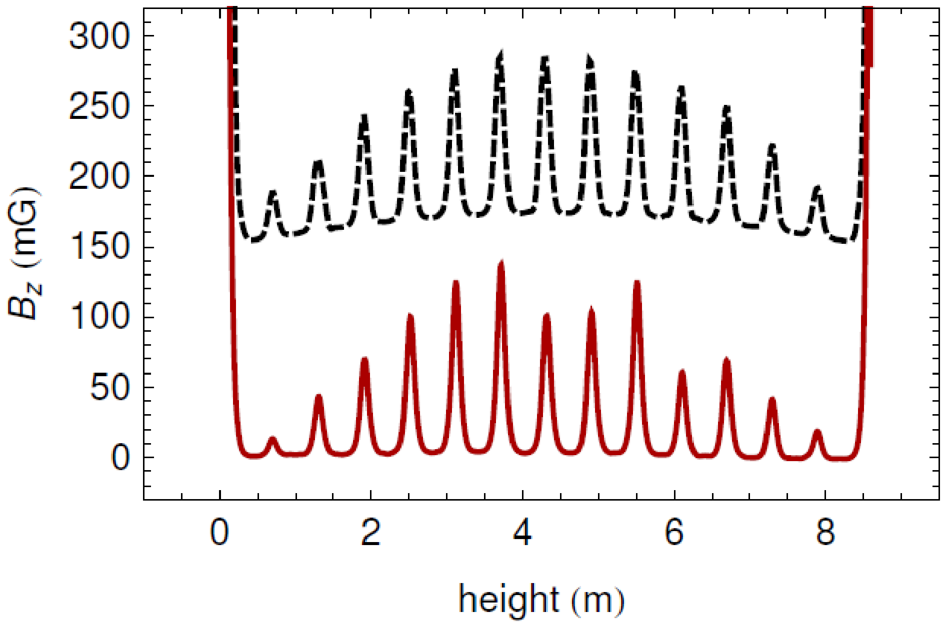


Simulation (vertically offset for visualization)

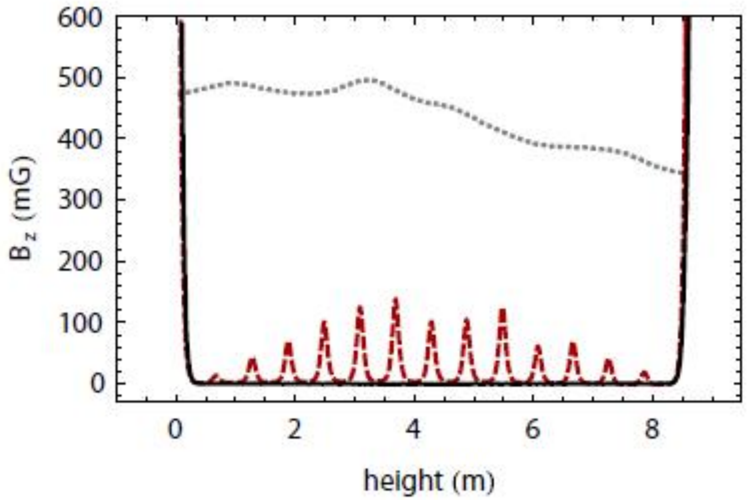
Data

Magnetic Fields: Example

- In the end, welded the whole shield together and annealed it in once piece

Magnetic Fields: Example

- In the end, welded the whole shield together and annealed it in once piece



No shield

Before weld

After weld

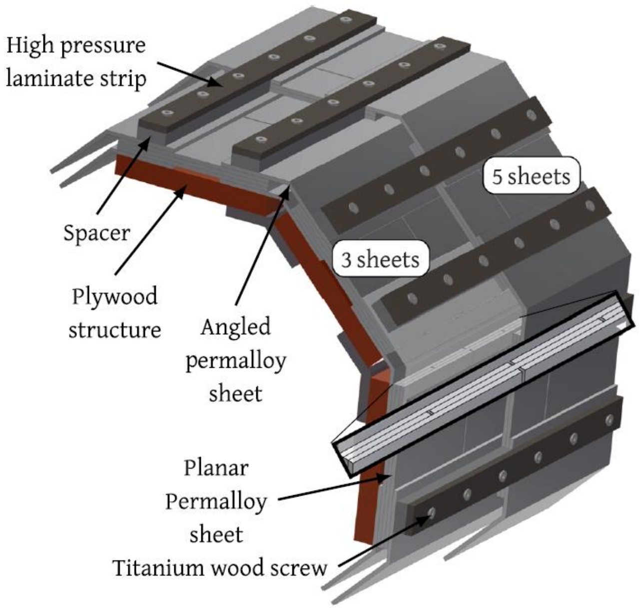
Large Scale Magnetic Shielding

- Lesson from Stanford 10 m Rb tower: for large length-to-diameter ration, small gaps in shield can lead to large magnetic field leakage

- Suppressed with single-piece welded shield, but limited scalability to longer baselines

- Hannover VLBAI: developed and demonstrated scalable multi-piece design

- MAGIS-100 shield design adapted from VLBAI design



Wodey et al., RSI 91, 035117 (2020)

Large Scale Magnetic Shielding

A scalable high-performance magnetic shield for very long baseline atom interferometry

Cite as: Rev. Sci. Instrum. 91, 035117 (2020); doi: 10.1063/1.5141340
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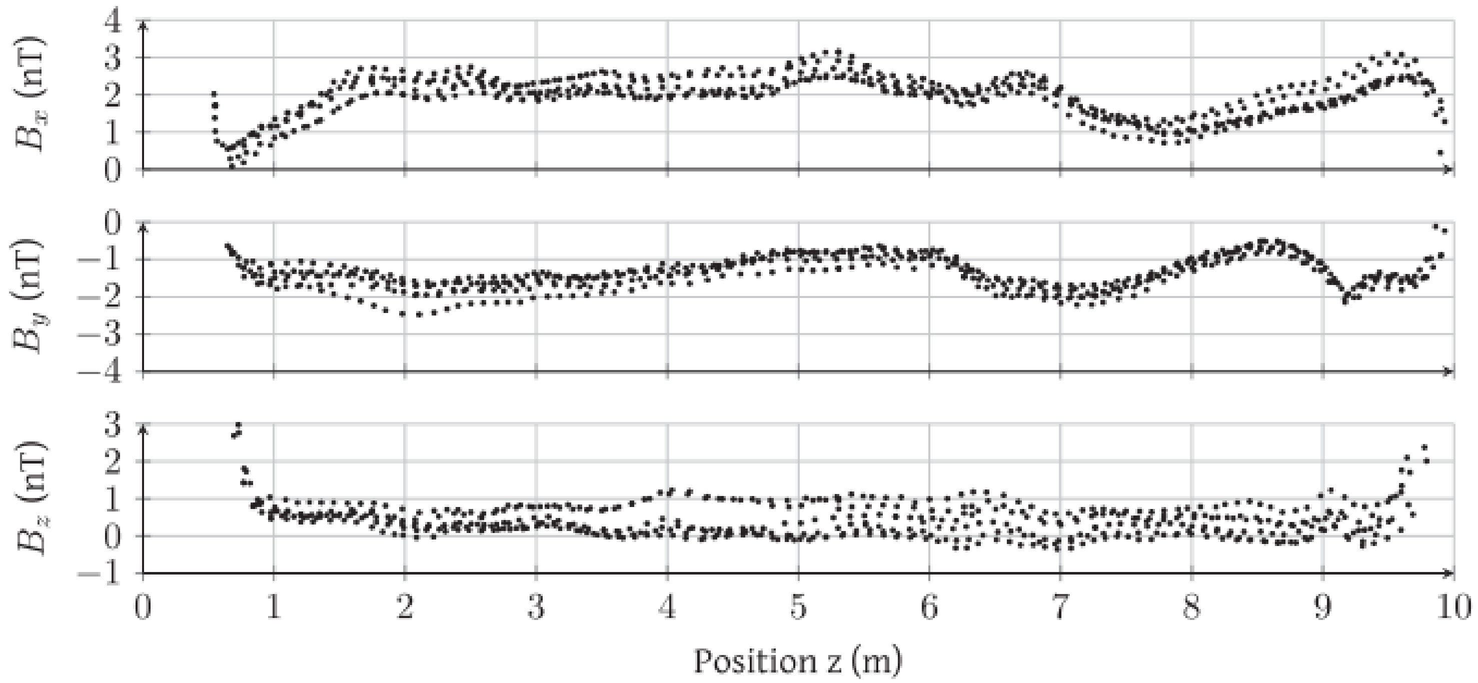
ABSTRACT

We report on the design, construction, and characterization of a 10 m-long high-performance magnetic shield for very long baseline atom interferometry. We achieve residual fields below 4 nT and longitudinal inhomogeneities below 2.5 nT/m over 8 m along the longitudinal direction. Our modular design can be extended to longer baselines without compromising the shielding performance. Such a setup constrains biases associated with magnetic field gradients to the sub-pm/s^2 level in atomic matterwave accelerometry with rubidium atoms and paves the way toward tests of the universality of free fall with atomic test masses beyond the 10^{-13} level.

Large Scale Magnetic Shielding



Laser Wavefront Perturbations

- Real laser beams are not idealized plane waves
- This has important consequences for atom interferometry
- Introducing/reviewing some background optics material can help us understand this

Background Optics

- In general, Maxwell's equations give us a wave equation with multiple components
- See, for example, the wave equation for the electric field vector

$$\nabla^2 \vec{E} - \frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2} = 0.$$

Background Optics

- A simplification: what if we can factor out the vector part of the field?

$$\vec{E}(\vec{r},t) = \vec{E}_0 \, U(\vec{r},t)$$

- When might it be valid to do this?

Background Optics

- A simplification: what if we can factor out the vector part of the field?

$$\vec{E}(\vec{r},t) = \vec{E}_0\, U(\vec{r},t)$$

- When might it be valid to do this?

- Well-collimated beam that travels predominantly in one direction, so that we can factor out the polarization component (i.e., whether the polarization is linear, right circular, left circular, etc…), which must be perpendicular to the direction of energy flow

Background Optics

- A simplification: what if we can factor out the vector part of the field?

$$\vec{E}(\vec{r},t) = \vec{E}_0\, U(\vec{r},t)$$

- We then get a simpler scalar wave equation

$$\nabla^2 U - \frac{1}{c^2}\frac{\partial^2 U}{\partial t^2} = 0$$

Background Optics

- For a monochromatic (i.e., single frequency) wave travelling nominally in the z direction, factor out a plane wave part

envelope

$$U(\vec{r},t) = u(\vec{r})\, e^{i(kz-\omega t)}$$

$$\left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} + 2ik\,\frac{\partial u}{\partial z} - k^2 u + \frac{\omega^2}{c^2} u\right] e^{i(kz-\omega t)} = 0.$$

$$k = \omega/c$$

Background Optics

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} + 2ik\frac{\partial u}{\partial z} = 0.$$

- What approximations might we make to simplify this further?

Background Optics

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} + 2ik\,\frac{\partial u}{\partial z} = 0.$$

- Paraxial approximation: u does not change significantly over the scale of one wavelength $\lambda = 2\pi/k$
- Specifically, assume: $$\frac{\Delta u}{u} = \frac{\partial_z u\,\lambda}{u} \ll 1 \quad \Longrightarrow \quad \frac{\partial u}{\partial z} \ll \frac{u}{\lambda} \sim k\,u$$

$$\frac{\partial^2 u}{\partial z^2} \ll k\,\frac{\partial u}{\partial z}$$

- Often a good approximation for well-collimated laser beams

Background Optics

- Paraxial wave equation:

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + 2ik\,\frac{\partial u}{\partial z} = 0$$

- Basis of solutions: Hermite-Gaussian modes

- Family of these modes exists for any choice of $w_0 > 0$

Background Optics

$$u_{\ell,m}(x,y,z) = U_0 \, \frac{w_0}{w(z)} \, H_\ell\!\left(\frac{\sqrt{2}\,x}{w(z)}\right) H_m\!\left(\frac{\sqrt{2}\,y}{w(z)}\right) e^{-\frac{x^2+y^2}{w(z)^2}} \, e^{-i\Psi(z)} \, e^{ik\frac{x^2+y^2}{2R(z)}},$$

for integers $\ell, m \geq 0$, with

$$w(z) \equiv w_0\sqrt{1+\left(\frac{z}{z_R}\right)^2}, \qquad z_R \equiv \frac{\pi w_0^2}{\lambda} \quad \left(\lambda = \tfrac{2\pi}{k}\right),$$

$$R(z) \equiv z\left(1+\left(\frac{z_R}{z}\right)^2\right), \qquad \Psi(z) = \arctan\!\left(\frac{z}{z_R}\right)(\ell+m+1).$$

Here H_i is the ith Hermite polynomial (the same special functions that appear in the quantum harmonic oscillator); the first few are

$$H_0(x) = 1, \qquad H_1(x) = 2x, \qquad H_2(x) = 4x^2 - 2.$$

Background Optics

- Special case that often well-approximates laser beams—Gaussian beam:

$$u_{0,0}(x,y,z) = U_0 \, \frac{w_0}{w(z)} \, e^{-\frac{r^2}{w(z)^2}} \, e^{-i\Psi(z)} \, e^{ik\frac{r^2}{2R(z)}}, \qquad r^2 = x^2 + y^2$$

$$\Psi(z) = \arctan\left(\frac{z}{z_R}\right)$$

Gouy phase

- <u>The phase gradient along z is not just k</u>

Background Optics

- The fact that the phase of a Gaussian beam has more complex spatial dependence than a plane wave has important implications for atom interferometry

- Also important to consider higher spatial frequency beam distortions

Laser Wavefront Perturbations

- What is the impact of laser wavefronts (surfaces of constant phase) deviating from being planar?

- Causes the phase imprinted on the atom from atom-light interaction to depend on transverse position of atom

- E.g., coupling of atom cloud expansion to wavefront curvature of Gaussian beam

Laser Wavefront Perturbations

PHYSICAL REVIEW A **72**, 023602 (2005)

Phase shifts in precision atom interferometry due to the localization of atoms and optical fields

A. Wicht
Institute for Experimental Physics, Heinrich-Heine-Universität Düsseldorf, Universitätsstr. 1, D-40225 Düsseldorf, Germany

E. Sarajlic, J. M. Hensley, and S. Chu
Physics Department, Stanford University, Stanford, California 94305 USA
(Received 16 November 2004; published 1 August 2005)

Momentum transfer goes as the gradient of the phase of the field

$$\vec{p} = \hbar \vec{\nabla} \phi$$

Reduces to k for plane wave but in general different

Laser Wavefront Perturbations

- Atom interferometers used to measure photon recoil velocity

$$v_r = \frac{p_z}{m} = \frac{\hbar(\vec{\nabla}\phi)_z}{m}$$

- If phase gradient well-known, can infer absolute mass m

- Combined with several other measurements, this allows determination of fine structure constant

Laser Wavefront Perturbations

Measurement of the fine-structure constant as a test of the Standard Model

RICHARD H. PARKER, CHENGHUI YU, WEICHENG ZHONG, BRIAN ESTEY, AND HOLGER MÜLLER Authors Info & Affiliations

SCIENCE • 13 Apr 2018 • Vol 360, Issue 6385 • pp. 191-195 • DOI: 10.1126/science.aap7706

Laser Wavefront Perturbations

Table 1. Error budget. For each systematic effect, more discussion can be found in the listed section of the supplementary materials. N/A, not applicable.

Effect	Section	$\delta\alpha/\alpha$ (ppb)
This study		
Laser frequency	1	−0.24 ± 0.03
Acceleration gradient	4A	−1.79 ± 0.02
Gouy phase	3	−2.60 ± 0.03
Beam alignment	5	0.05 ± 0.03
Bloch oscillation light shift	6	0 ± 0.002
Density shift	7	0 ± 0.003
Index of refraction	8	0 ± 0.03
Speckle phase shift	4B	0 ± 0.04
Sagnac effect	9	0 ± 0.001
Modulation frequency wave number	10	0 ± 0.001
Thermal motion of atoms	11	0 ± 0.08
Non-Gaussian waveform	13	0 ± 0.03
Parasitic interferometers	14	0 ± 0.03
Total systematic error	All previous	−4.58 ± 0.12
Statistical error	N/A	±0.16
Other studies		
Electron mass (*16*)	N/A	±0.02
Cesium mass (*6, 15*)	N/A	±0.03
Rydberg constant (*6*)	N/A	±0.003
Combined result		
Total uncertainty in α	N/A	±0.20

Laser Wavefront Perturbations

Article | Published: 02 December 2020

Determination of the fine-structure constant with an accuracy of 81 parts per trillion

Léo Morel, Zhibin Yao, Pierre Cladé & Saïda Guellati-Khélifa

Nature **588**, 61–65 (2020) | Cite this article

Laser Wavefront Perturbations

Table 1 | Error budget on α

Source	Correction ($\times 10^{-11}$)	Relative uncertainty ($\times 10^{-11}$)
Gravity gradient	−0.6	0.1
Alignment of the beams	0.5	0.5
Coriolis acceleration		1.2
Frequencies of the lasers		0.3
Wave-front curvature	0.6	0.3
Wave-front distortion	3.9	1.9
Gouy phase	108.2	5.4
Residual Raman light shift	2.3	2.3
Index of refraction	0	<0.1
Internal interaction	0	<0.1
Light shift (two-photon transition)	−11.0	2.3
Second-order Zeeman effect		0.1
Phase shifts in Raman phase-lock loop	−39.8	0.6
Global systematic effects	**64.2**	**6.8**
Statistical uncertainty		**2.4**
Relative mass of ^{87}Rb[a]: 86.9091805310(60)		3.5
Relative mass of the electron[b]: 5.48579909065(16) $\times 10^{-4}$		1.5
Rydberg constant[b]: 10,973,731.568160(21) m^{-1}		0.1
Total: α^{-1} = 137.035999206(11)		**8.1**

For each systematic effect, more discussion can be found in Methods.
[a]From ref. [13].
[b]From https://pml.nist.gov/cuu/Constants/.

Laser Wavefront Perturbations

- In addition to Gaussian beam contributions, smaller scale beam distortions also relevant
- Can modify imprinted phase and momentum kick

PHYSICAL REVIEW LETTERS **121,** 073603 (2018)

Observation of Extra Photon Recoil in a Distorted Optical Field

Satyanarayana Bade,[1] Lionel Djadaojee,[1] Manuel Andia,[1,*] Pierre Cladé,[1,†] and Saïda Guellati-Khelifa[1,2,‡]
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(Received 8 December 2017; revised manuscript received 19 June 2018; published 16 August 2018)

Characterizing Laser Wavefront: Example

- Map local k vector at different points using atom arrays

PHYSICAL REVIEW LETTERS **134,** 143601 (2025)

Multi-Axis Inertial Sensing with 2D Matter-Wave Arrays

K. Stolzenberg, C. Struckmann, S. Bode, R. Li, A. Herbst, V. Vollenkemper, D. Thomas, A. Rajagopalan, E. M. Rasel, N. Gaaloul, and D. Schlippert*

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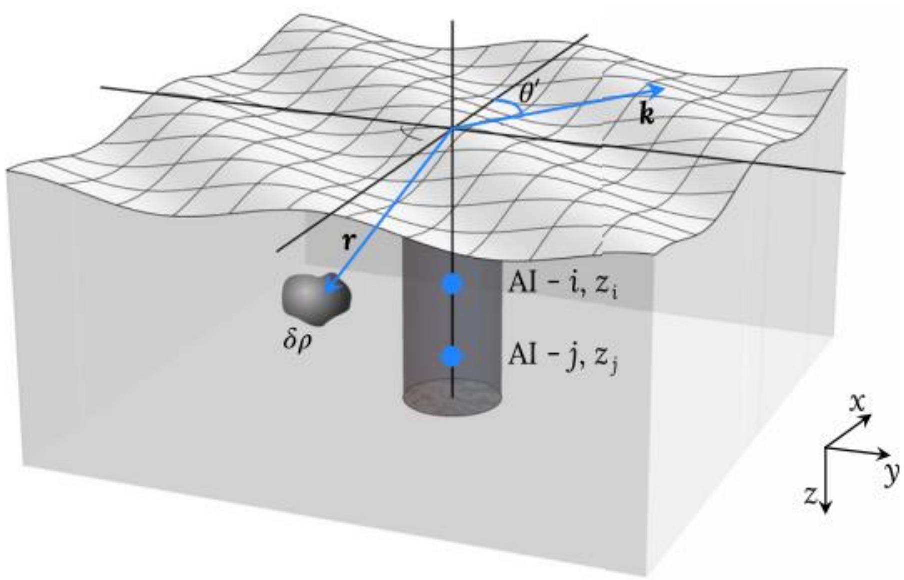
(Received 19 July 2024; revised 21 February 2025; accepted 26 February 2025; published 9 April 2025)

Newtonian Gravity Gradient Noise (GGN)

- Seismic waves passing through Earth cause spatially varying density fluctuations
- Cause time-dependent gravity gradients that are a noise background in long-baseline atom interferometers
- Atmospheric density fluctuations can also cause GGN



Newtonian Gravity Gradient Noise (GGN)

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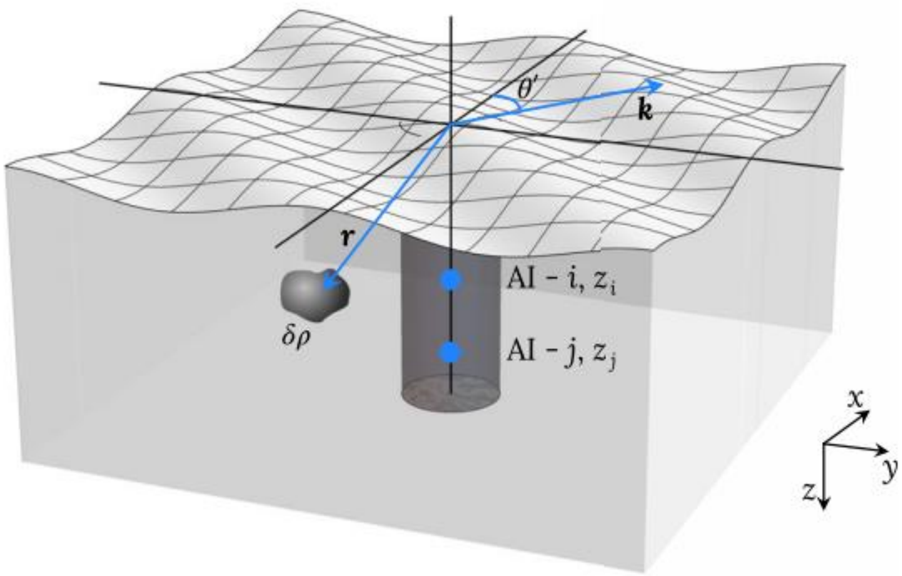
- Atmospheric density fluctuations can also cause GGN

What strategies can one use to mitigate GGN for horizontal and vertical configurations?



Badurina et al., PRD 107, 055002 (2023)

Newtonian Gravity Gradient Noise (GGN)

PHYSICAL REVIEW D **93,** 021101(R) (2016)

Low frequency gravitational wave detection with ground-based atom interferometer arrays

W. Chaibi,[1,*] R. Geiger,[2,†] B. Canuel,[3] A. Bertoldi,[3] A. Landragin,[2] and P. Bouyer[3]
[1]*ARTEMIS, Université Côte d'Azur, CNRS and Observatoire de la Côte d'Azur, F-06304 Nice, France*
[2]*LNE-SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, 61 avenue de l'Observatoire, 75014 Paris, France*
[3]*LP2N, Laboratoire Photonique, Numérique et Nanosciences Université Bordeaux-IOGS-CNRS:UMR 5298, rue Mitterrand, F-33400 Talence, France*
(Received 23 June 2015; published 15 January 2016)

- Array of atom interferometers over a horizontal baseline

Newtonian Gravity Gradient Noise (GGN)

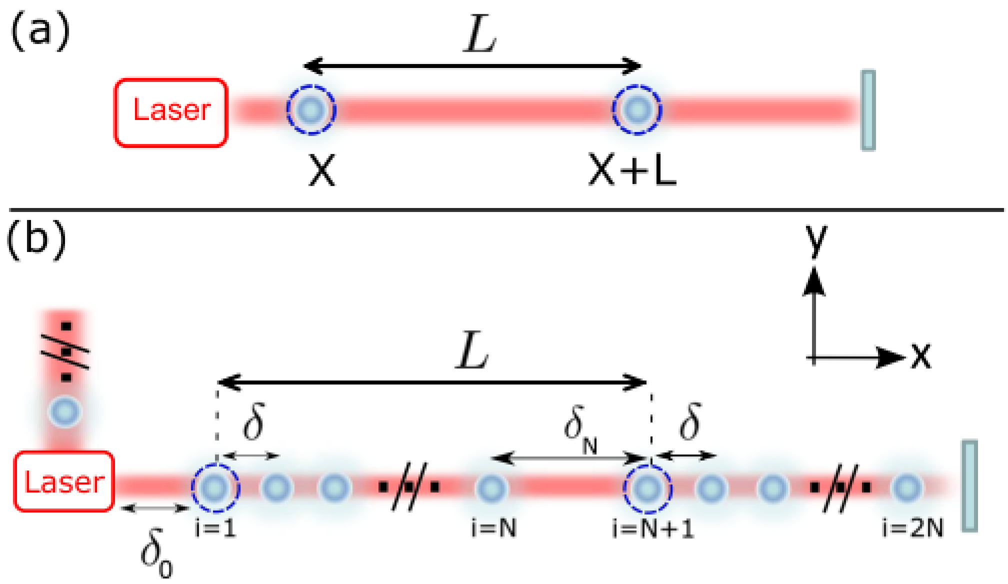


FIG. 1. (a) A single gradiometer using two AIs at positions X and $X + L$, interrogated by a common laser beam. (b) An array of N AI gradiometers used for sampling the spatial variations of the NN. The separation between the gradiometers is δ. The array allows one to repeat the experiment sketched in (a) N times and average the NN. The use of two orthogonal arms injected by a common laser enables one to reject laser frequency noise (the second arm in the y direction is only partially represented here for clarity).

Newtonian Gravity Gradient Noise (GGN)

- GGN of frequency $f = \omega/(2\pi)$ has a certain correlation length along the baseline depending on the speed of sound v_u

$$\mathcal{L}_\rho(\omega) = v_u/2f$$

- For interferometers spaced well beyond correlation length, GGN is uncorrelated

Newtonian Gravity Gradient Noise (GGN)

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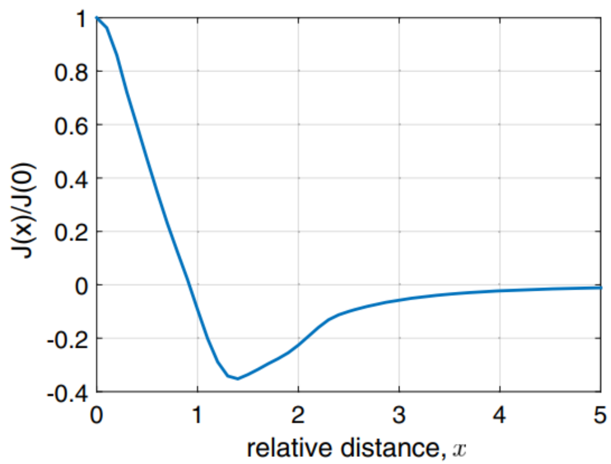

FIG. 2. Spatial behavior of the normalized NN correlations between two distant points separated by the relative distance $x = |X_j - X_i|/\mathcal{L}_\rho(\omega)$, where $\mathcal{L}_\rho(\omega)$ is the NN correlation length. The anticorrelation is a consequence of mass conservation between adjacent cells of fluctuating density.

Newtonian Gravity Gradient Noise (GGN)

- Averaging across N uncorrelated measurements in the array yields suppression of GGN contribution by a factor of $N^{1/2}$

- Can do even better by choosing the spacings to leverage anticorrelations in the averaging

Newtonian Gravity Gradient Noise (GGN)

- Estimated noise rejection performance

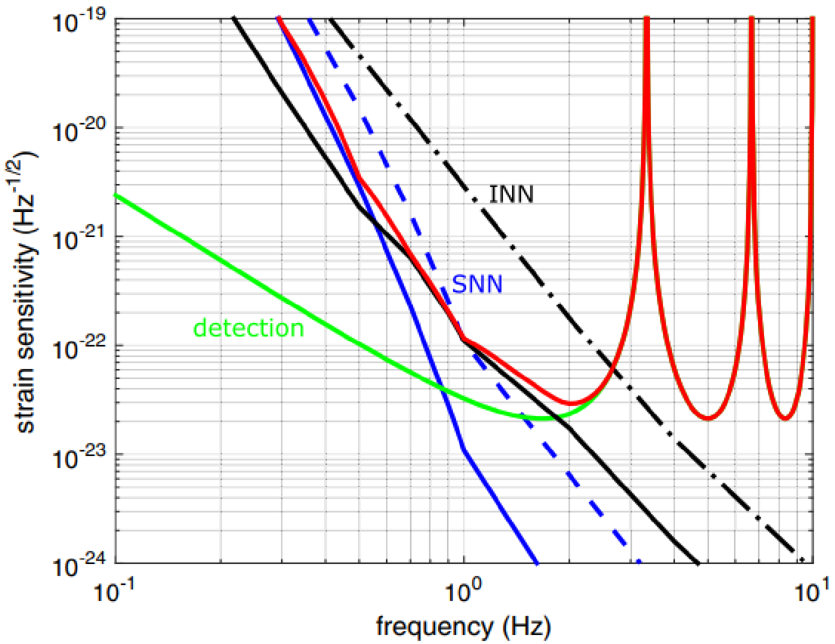

FIG. 3. Strain sensitivity curve for an AI array with $N = 80$, $\delta = 200$ m, $\delta_0 = \delta_N = 500$ m, $L = 16.3$ km and $L_a = 32.6$ km. The AI phase noise is -140 dB rad^2/Hz with the interrogation time $T = 0.3$ s, and $n = 1000$ LMT beam splitters. Green: Detection noise. Dotted-dashed black (dashed blue): INN (SNN) for two test masses separated by the baseline L. Solid black line (blue): Residual INN (SNN) after NN rejection with the AI array. Red: Overall sensitivity curve.

L_a : total arm length

SNN: seismic Newtonian noise

INN: infrasound Newtonian noise (from the atmosphere)

Newtonian Gravity Gradient Noise (GGN)

PHYSICAL REVIEW D **107**, 055002 (2023)

Ultralight dark matter searches at the sub-Hz frontier with atom multigradiometry

Leonardo Badurina,[1,*] Valerie Gibson,[2] Christopher McCabe,[1] and Jeremiah Mitchell[2]

[1]*Theoretical Particle Physics and Cosmology Group, Department of Physics, King's College London, Strand, London WC2R 2LS, United Kingdom*

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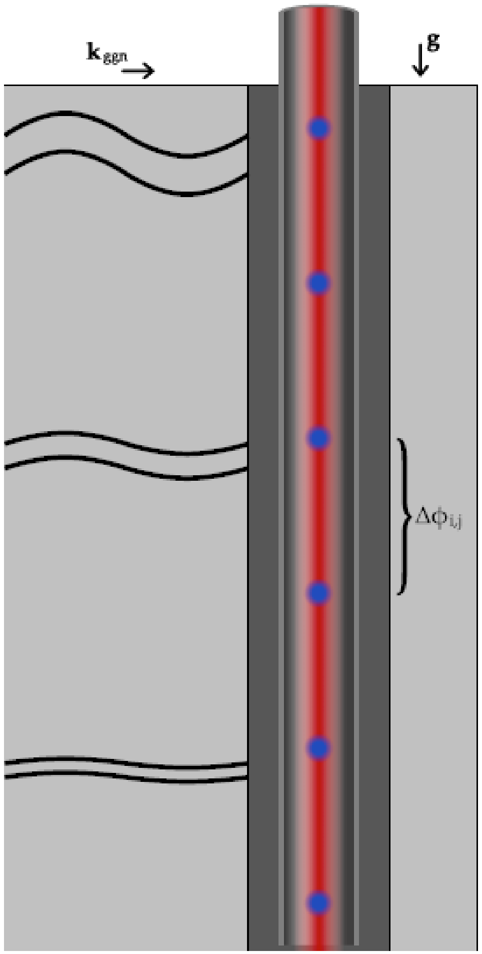
(Received 13 November 2022; accepted 10 February 2023; published 3 March 2023)

- Array of atom interferometers over a vertical baseline
- Analysis for seismic GGN

Newtonian Gravity Gradient Noise (GGN)

-Potential mitigation strategy: array of atom interferometers along baseline to distinguish between nonlinear dependence of GGN signal on position and a linear dependence from GW or DM signal



-From Badurina et al., GGN potential after sum over frequencies ω_a weighted by Fourier amplitude of seismic noise

$$V(z_i,t) \propto \sum_a \xi_a \left[-2\exp\left(-q\frac{\omega_a z_i}{c_H}\right) + (1+\sqrt{q/s})\exp\left(-\frac{\omega_a z_i}{c_H}\right)\right]\cos(\omega_a t + \tilde{\theta}_a),$$

Dimensionless ~1 parameters, depend on local geology

Rayleigh wave speed

Random phase

Chaibi et al., PRD 93, 021101(R) (2016); Mitchell et al., JINST 17, P01007 (2022); Badurina et al., PRD 107, 055002 (2023); Carlton et al., PRD 111, 082003 (2025)

Newtonian Gravity Gradient Noise (GGN)

PHYSICAL REVIEW D **107,** 055002 (2023)

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Newtonian Gravity Gradient Noise (GGN)

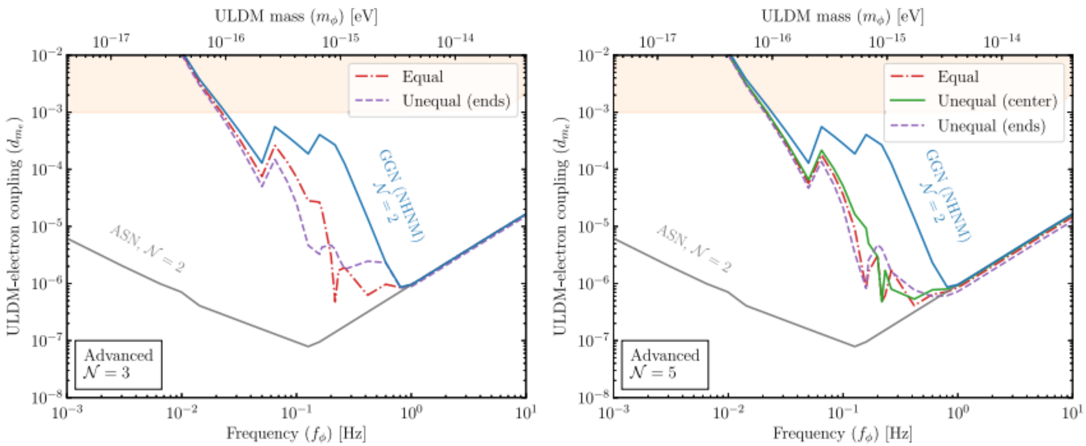

FIG. 9. Projected 95% C.L. exclusion curves for an atom multigradiometer using the advanced parameters with $\mathcal{N}=3$ (left panel) and $\mathcal{N}=5$ (right panel) assuming GGN is modeled by the NHNM. The grey and blue lines show the exclusion curve for a single atom gradiometer ($\mathcal{N}=2$) for ASN only and in an ASN and GGN background, respectively. The red dot-dashed, purple dashed, and green solid lines show the atom multigradiometer exclusion curves for the equally-spaced, unequally-spaced (ends), and unequally-spaced (center) configurations defined in Fig. 8, respectively. The multigradiometer exclusion curves regain parts of parameter space between ~0.1 Hz and ~1 Hz and have a similar sensitivity to the $\mathcal{N}=2$ configuration at higher frequencies. The orange shaded region is excluded by MICROSCOPE [25].

N: number of interferometers
ASN: atom shot noise
NHNM: Peterson's new high noise model of the seismic noise spectrum
Δt: time between interferometers
T_{int} : total measurement time

TABLE I. The experimental parameters for the different atom interferometer scenarios considered in this work. The "intermediate" and "advanced" designs could be implemented in versions of future vertical gradiometers, such as AION-100 and MAGIS-100, and AION-km, respectively. Δz_{max} refers to the maximum gradiometer length given the choice of interferometer parameters. We also consider scenarios where Δz is shorter than the maximum value.

Design	L (m)	T (s)	n	Δz_{max} (m)	N_{atom}	Δt (s)	T_{int} (s)
Intermediate	100	1.4	1000	85	10^8	1.5	10^8
Advanced	1000	1.7	2500	970	10^{10}	1.0	10^8

Newtonian Gravity Gradient Noise (GGN)

- Even with mitigations, GGN will be a limitation to the sensitivity of terrestrial long-baseline atom interferometers at lower frequencies

- A future spaceborne detector would offer the potential to avoid this

Newtonian Gravity Gradient Noise (GGN)

El-Neaj et al. *EPJ Quantum Technology* (2020) 7:6
https://doi.org/10.1140/epjqt/s40507-020-0080-0

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RESEARCH **Open Access**

AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration in Space

Newtonian Gravity Gradient Noise (GGN)

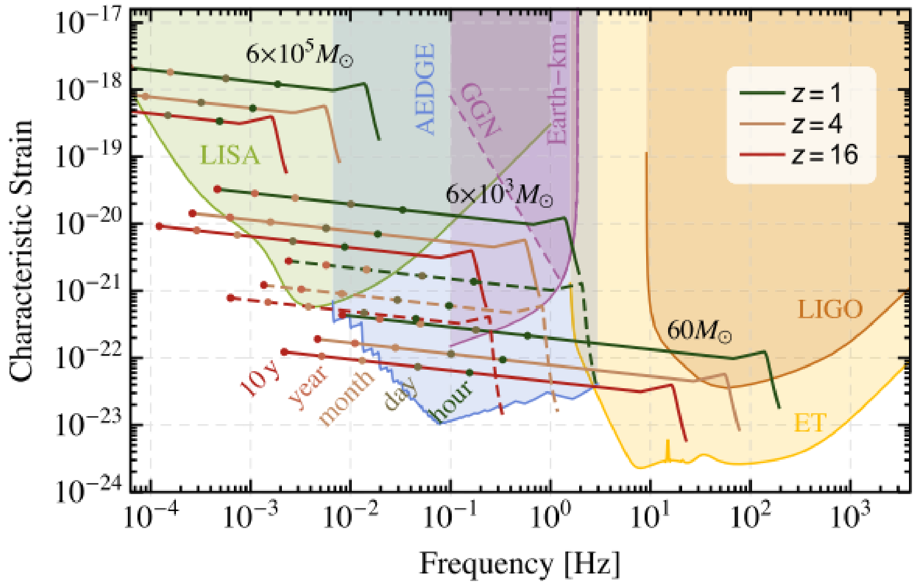
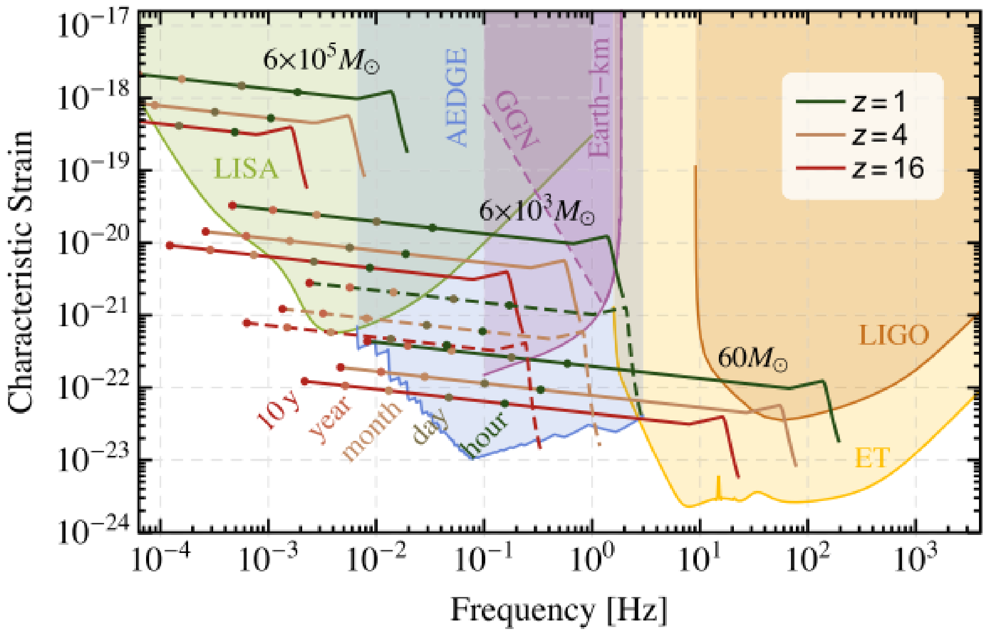


Figure 3 Comparison of the strain measurements possible with AEDGE and other experiments, showing their sensitivities to BH mergers of differing total masses at various redshifts z, indicating also the time remaining before the merger. The solid lines correspond to equal mass binaries and the dashed ones to binaries with very different masses, namely $3000M_\odot$ and $30M_\odot$. Also shown is the possible gravitational gradient noise (GGN) level for a km-scale terrestrial detector, which would need to be mitigated for its potential to be realized. This figure illustrates the potential for synergies between AEDGE and detectors observing other stages of BH infall and merger histories

Motivation for Space

Sensitivity scenario	L [m]	T_{int} [sec]	$\delta\phi_{noise}$ [$1/\sqrt{Hz}$]	$n_p^{max} = 2Q(2n-1)+1$ [number]
Earth-km	2000	5	0.3×10^{-5}	40,000
AEDGE	4.4×10^7	300	10^{-5}	1000

- Avoid GGN: extend to lower frequencies
- Longer interferometer duration available due to microgravity, can be leveraged to increase sensitivity, e.g. with multiloop/resonant sequences
- Much longer baseline available: eases requirements on number of pulses and phase resolution (R&D still needed)



Heterodyne Laser Links

PHYSICAL REVIEW A **94**, 033632 (2016)

Atom-interferometric gravitational-wave detection using heterodyne laser links

Jason M. Hogan and Mark A. Kasevich
Department of Physics, Stanford University, Stanford, California 94305, USA
(Received 22 March 2015; revised manuscript received 17 August 2016; published 28 September 2016)

Heterodyne Laser Links

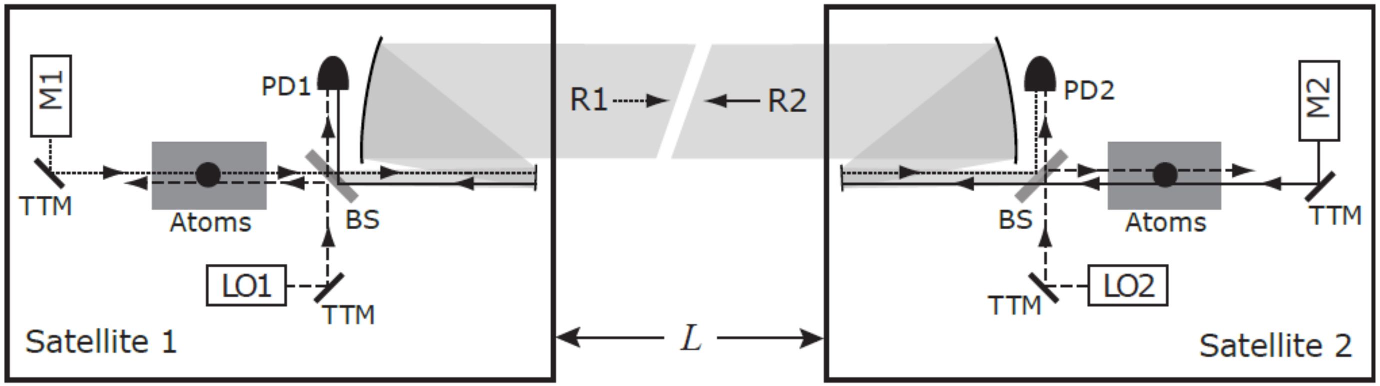


FIG. 2. Schematic of the proposed design. M1 and M2 are the master lasers, with beams depicted as dotted and solid lines, respectively. The reference beams propagating between the satellites are denoted R1 (dotted) and R2 (solid) and originate from telescopes each each satellite. LO1 and LO2 are local oscillator lasers (dashed beam lines) that are phase locked to the incoming reference laser beams (R2 and R1, respectively). PD1 (PD2) is a photodetector used to measure the heterodyne beatnote between the incoming reference beam R2 (R1) and the local oscillator laser LO1 (LO2) in order to provide feedback for the laser link. BS is a (non-polarizing) beam splitter where the heterodyne beatnote is formed. Tip-tilt mirrors (TTM) allow for fine control of the pointing direction of each laser. All adjacent parallel beams are nominally overlapped, but for clarity they are shown here with a small offset.

- Problem: do not want interferometer beam to be too wide since this dilutes intensity, but narrower beams dramatically diverge over long baselines

- High power local oscillator lasers at each satellite phase locked to a reference beam delivered from other satellite

- Orient beam splitters and lasers so that phase of local oscillator light delivered to atoms is insensitive to beam splitter motion from satellite vibration

- Width of local beam not constrained by divergence over long baseline

Resonant Detection

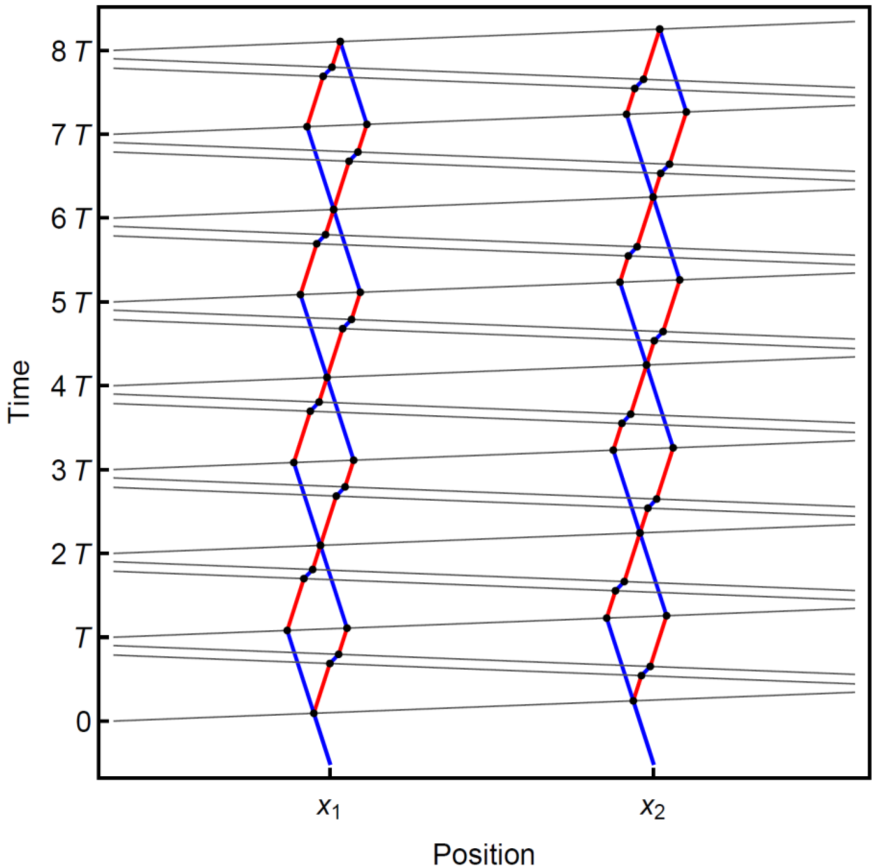
PHYSICAL REVIEW D **94,** 104022 (2016)

Resonant mode for gravitational wave detectors based on atom interferometry

Peter W. Graham,[1] Jason M. Hogan,[2] Mark A. Kasevich,[2] and Surjeet Rajendran[3]
[1]*Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305, USA*
[2]*Department of Physics, Stanford University, Stanford, California 94305, USA*
[3]*Berkeley Center for Theoretical Physics, Department of Physics, University of California, Berkeley, California 94720, USA*
(Received 7 June 2016; published 10 November 2016)

Resonant Detection

Resonant sequence (Q = 4)



Graham, *et al.*, PRD 94, 104022 (2016)

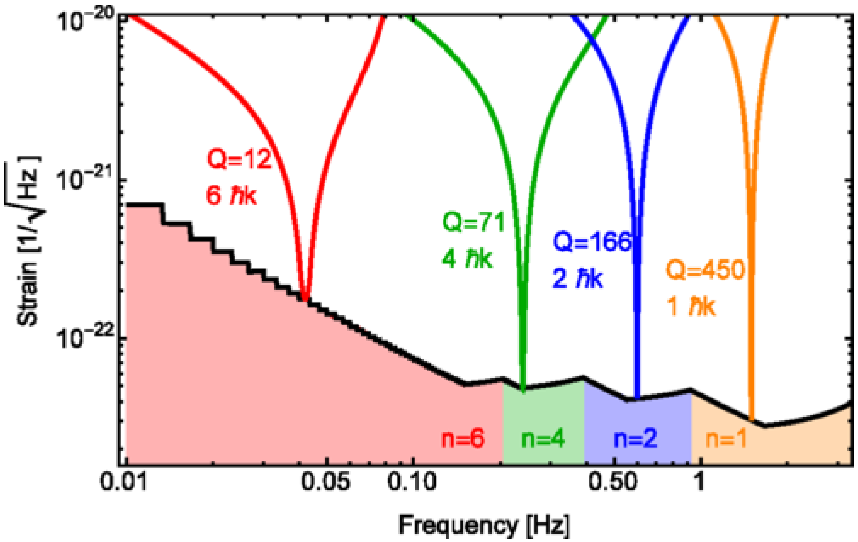
- Multiple interferometer loops (Q loops) amplify interferometer's phase response signal oscillating at the resonance frequency by a factor proportional to Q
- Analogy to lock-in detection
- Comes at the cost of decreased bandwidth
- With same hardware, can rapidly tune resonance frequency and switch between resonant and non-resonant modes by adjusting pulse timing sequences
- Many GW sources have frequencies that evolve in time
- Can also apply broadband dynamical decoupling sequences (Zaheer et al., arXiv:2302.12956 (2023))

Graham, *et al.*, PRD 94, 104022 (2016); Coslovsky et al., Slow Light, Fast Light and OptoAtomic Prevision Metrology X (2017); Jaffe et al. PRL 121, 040402 (2018); Kim et al., arXiv:2201.11888 (2022); Chiow and Yu, PRD 97, 044403 (2018)

Resonant Detection

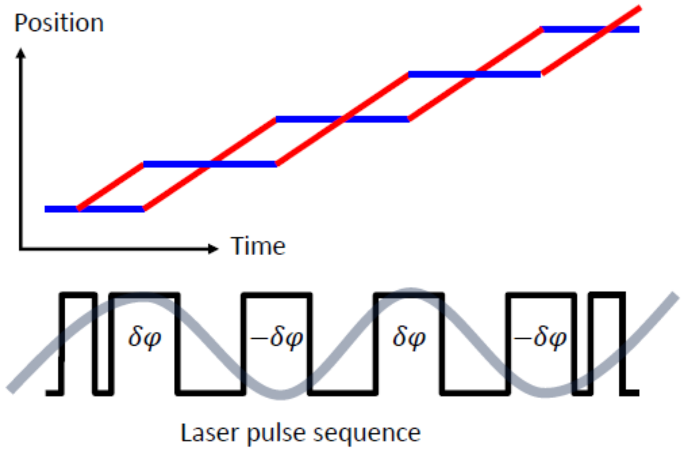
- At lower frequencies, can be favorable to combine resonant atom interferometer with a modest amount of increased momentum splitting

- Opportunities to develop and test techniques in ground-based experiments



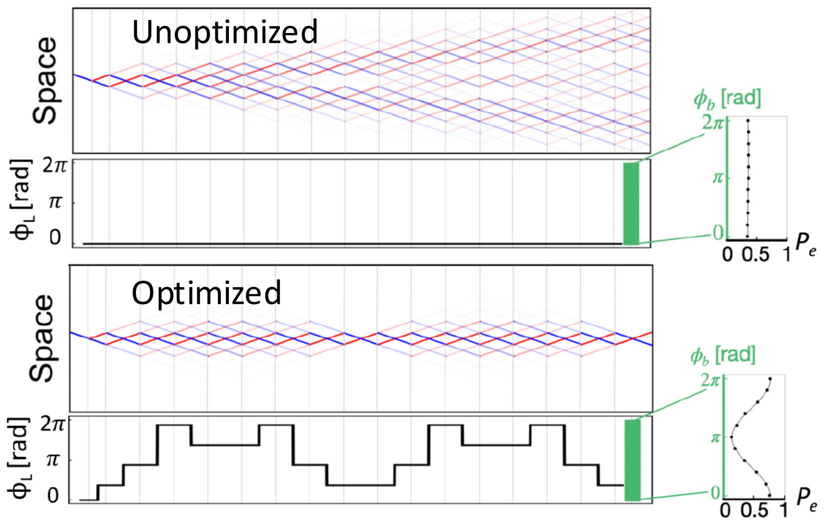
Graham, *et al.*, PRD 94, 104022 (2016)

Surprising Systematic Effect from Spontaneous Emission



- <u>Challenge</u>: pulse infidelities accumulate for large loop numbers

- <u>Solution</u>: Apply quantum optimal control to multipath interference between many spatial trajectories to make interferometer as a whole correct for errors in individual mirror pulses



Wang,…,TK, PRL 133, 243403 (2024)

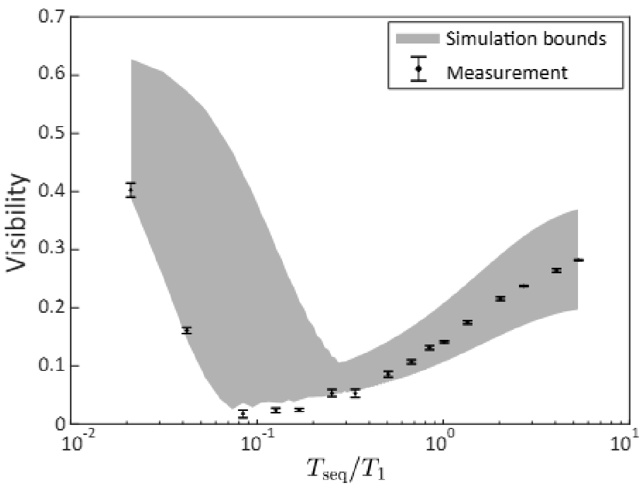
Implement with Sr-88 atom interferometer at Northwestern, using single-photon transitions on 689 nm line

Graham, *et al.*, PRD 94, 104022 (2016); Coslovsky et al., Slow Light, Fast Light and OptoAtomic Prevision Metrology X (2017); Jaffe et al. PRL 121, 040402 (2018); Kim et al., arXiv:2201.11888 (2022); Chiow and Yu, PRD 97, 044403 (2018), Zaheer et al., arXiv:2302.12956 (2023))

Why is the Visibility so Big for a "Bad" Sequence

-Experimenting with a far from optimal sequence, with mirror pulse laser phases alternating between +π/2 and -π/2

-After extending to 128 pulses, fringe visibility was much stronger than it should have been based on simulations that had otherwise been reliable in describing experiments, continued to increase with more pulses (up to 504 pulses), extending past excited state lifetime

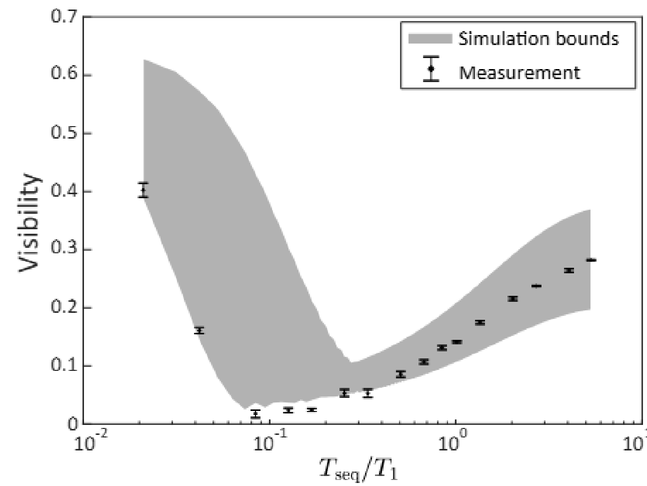


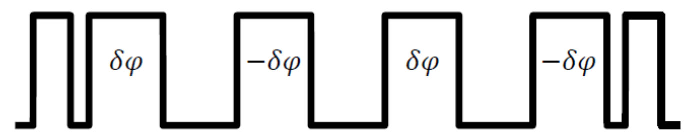
Why is the Visibility so Big for a “Bad” Sequence?

-Previous simulations modelled atoms that had undergone spontaneous emission decay as an incoherent background

-Phase of this surprisingly strong interference fringe had strongly suppressed sensitivity to the oscillating signals we were studying

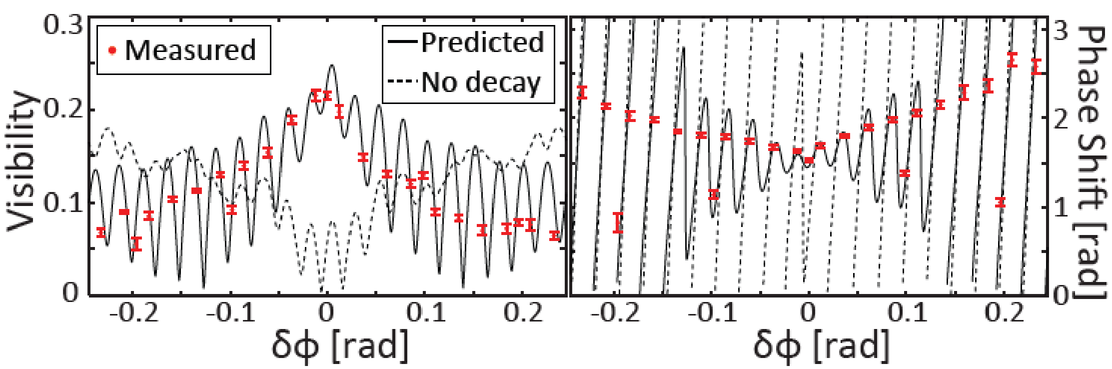
-What was wrong with our understanding of the experiment?





As a test signal, add resonantly oscillating laser phase with amplitude δϕ to pulse sequence

Ideal behavior: for N loops, interferometer phase Θ scales as 2N δϕ



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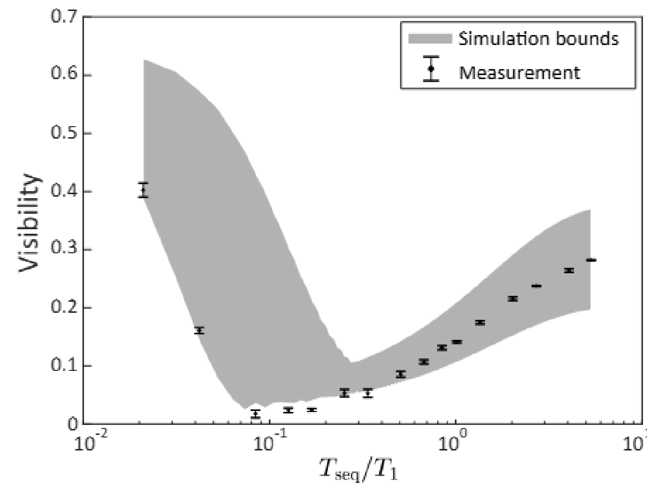
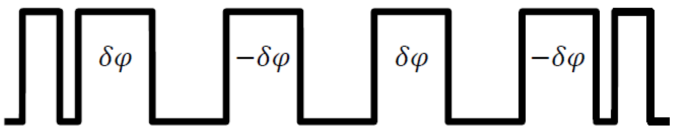


The role of dissipation (in the form of spontaneous emission) was more subtle than we had realized



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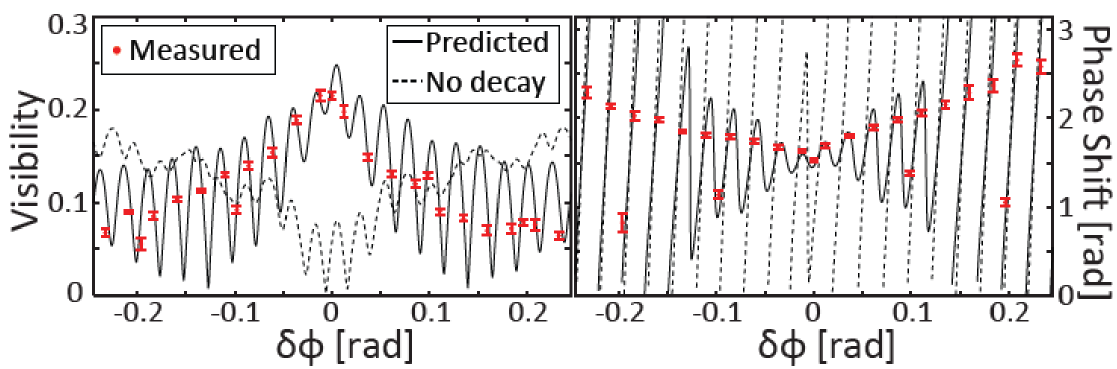
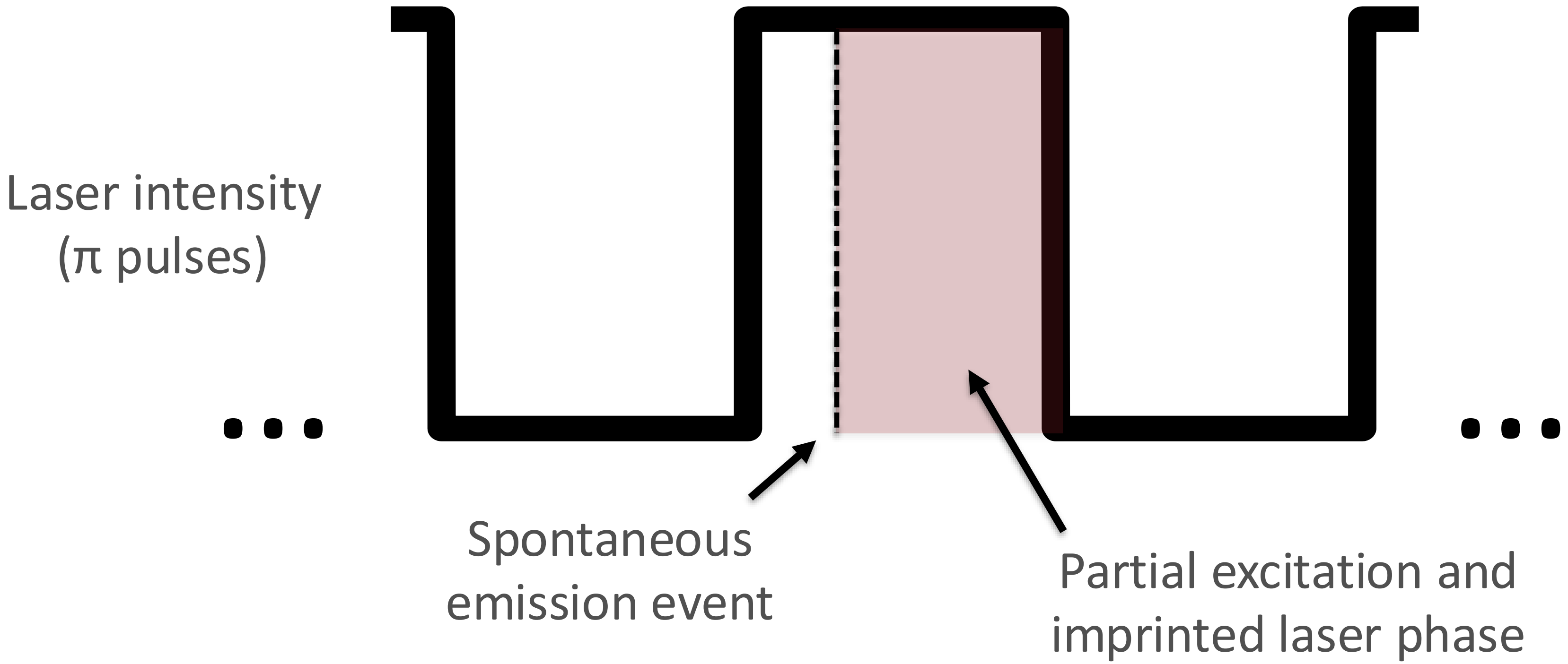


Surprising Systematic Effect from Spontaneous Emission

-Interplay between spontaneous emission and many-pulse sequences

-Atoms can spontaneously decay to ground state midway through a mirror pulse

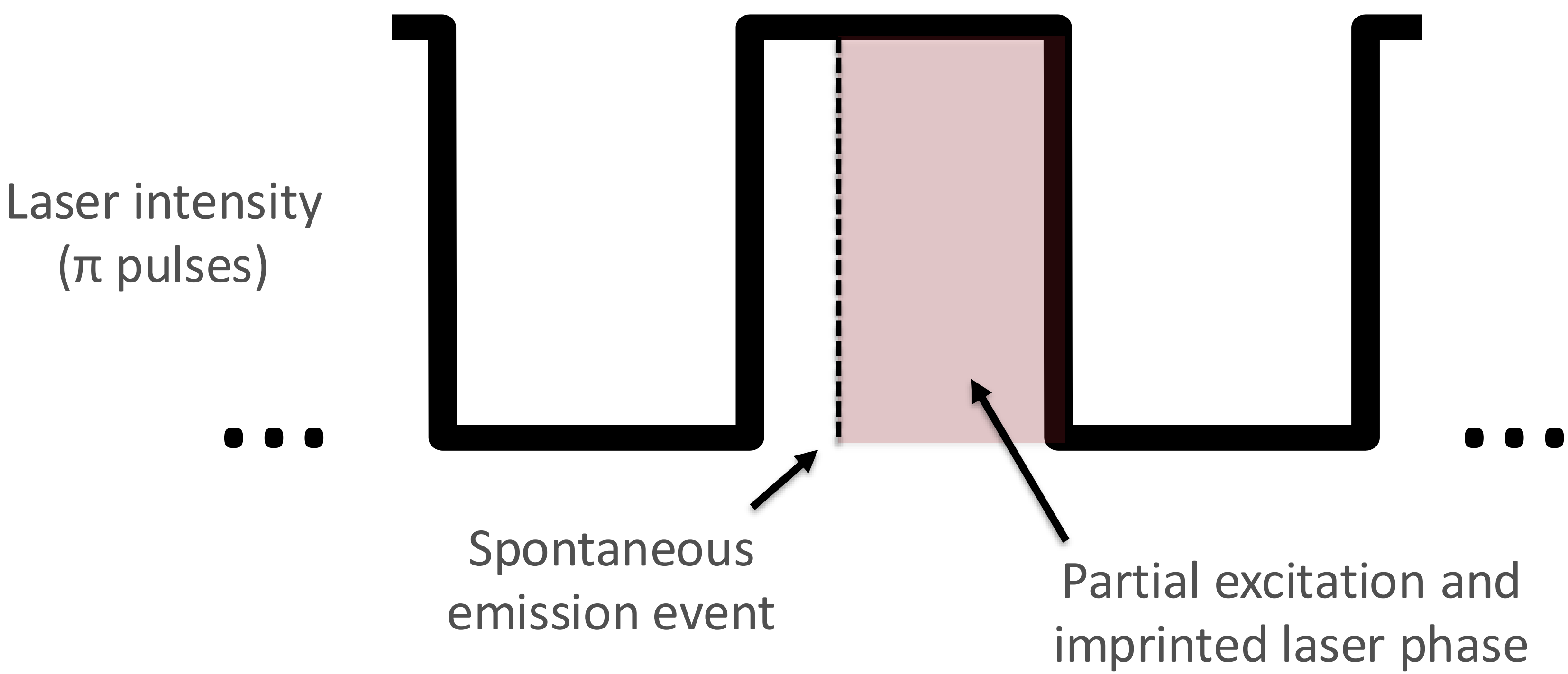


Surprising Systematic Effect from Spontaneous Emission

-Interplay between spontaneous emission and many-pulse sequences

-Atoms can spontaneously decay to ground state midway through a mirror pulse

-Remainder of mirror pulse can once again put the atom in superposition



Surprising Systematic Effect from Spontaneous Emission

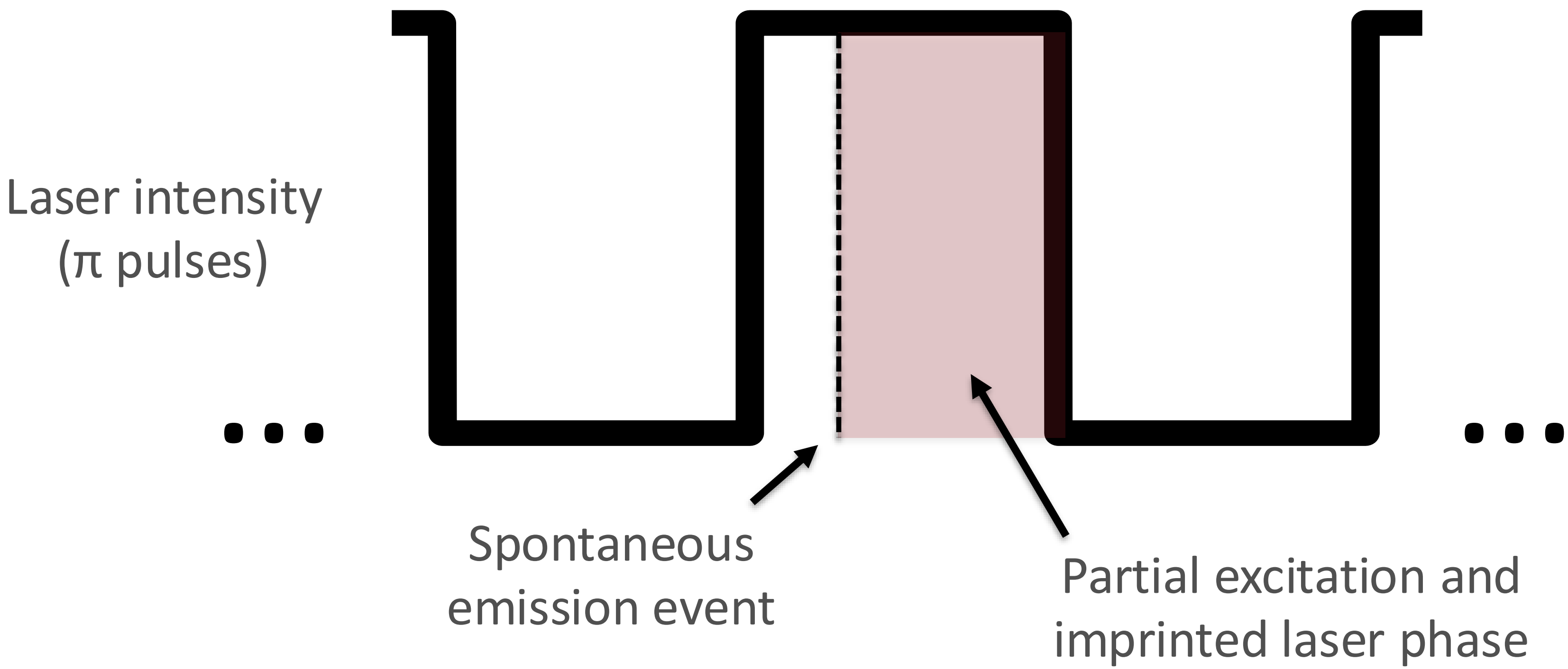
-Interplay between spontaneous emission and many-pulse sequences

-Atoms can spontaneously decay to ground state midway through a mirror pulse

-Remainder of mirror pulse can once again put the atom in superposition

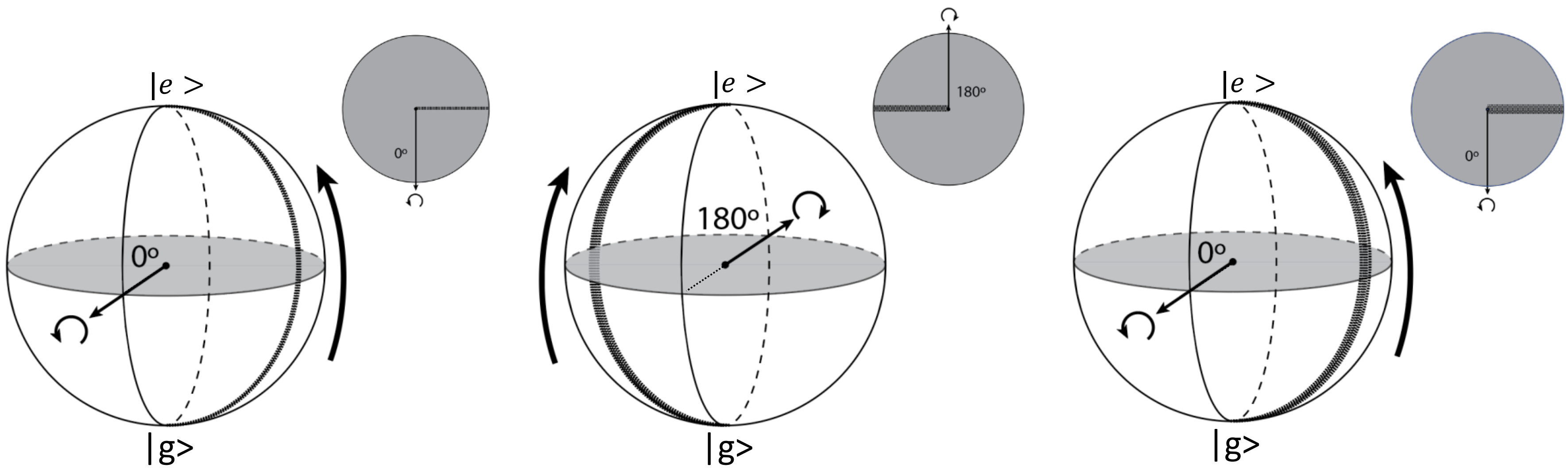
-Can there be a nonzero average interference pattern generated by atoms that underwent spontaneous emission at different points in time?

-To visualize, helpful to work in momentum space, with each momentum value having a Bloch sphere corresponding to ground and excited internal states (excited state has extra photon recoil momentum kick)



Dissipation-Induced Cumulative Phase

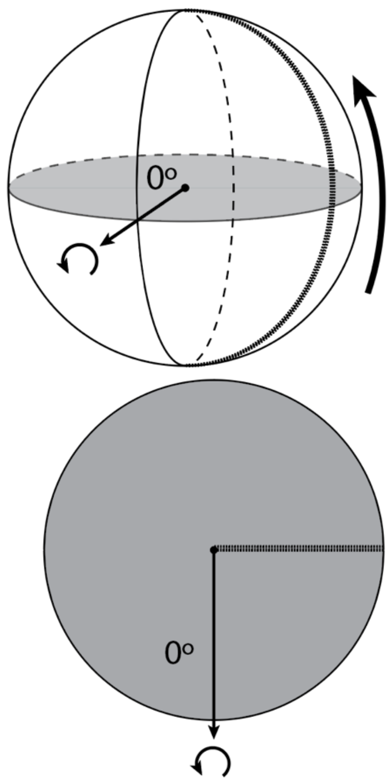
- Visual Aid: Create a separate Bloch sphere of only decayed atoms
  - Atomic states distribute along “arcs” for π pulses
  - Top of arc: atoms that decayed at beginning of π pulse and then rotated
  - Bottom of arc: atoms that decayed at end of π pulse
  - Each arc manipulated by subsequent pulses

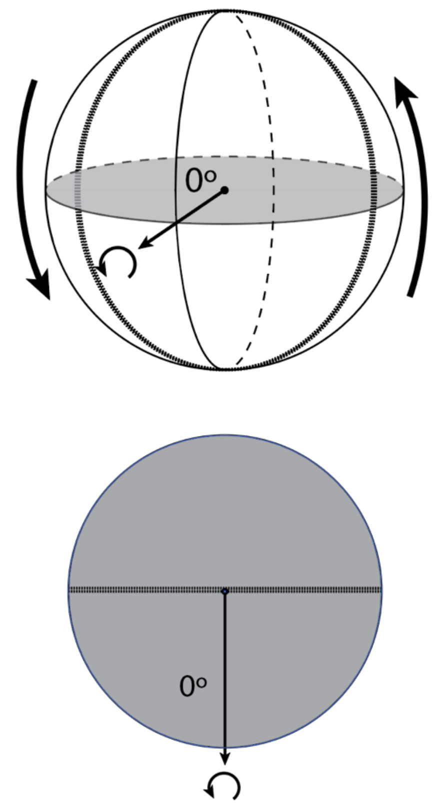


Decayed atoms re-emerge with a common phase component

Cancellation of Cumulative Phase

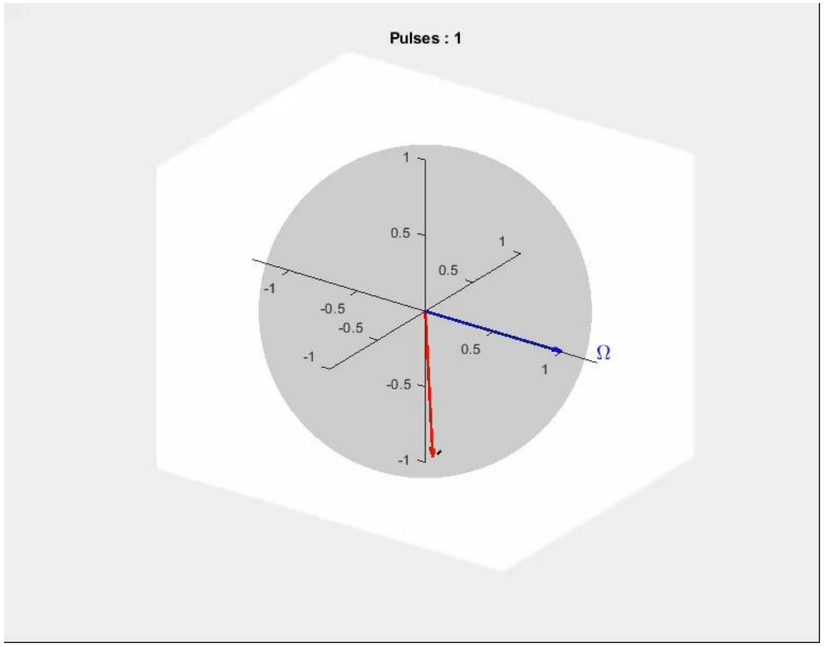
If all laser pulses have phase 0, arcs generated by back-to-back pulses will oppose each other, averaging cumulative phase to 0





Cumulative Phase Buildup

- Red vector points to averaged state
- Cumulative phase is horizonal component
- Assume zero detuning (i.e., zero frequency difference between laser and atomic transition frequencies)



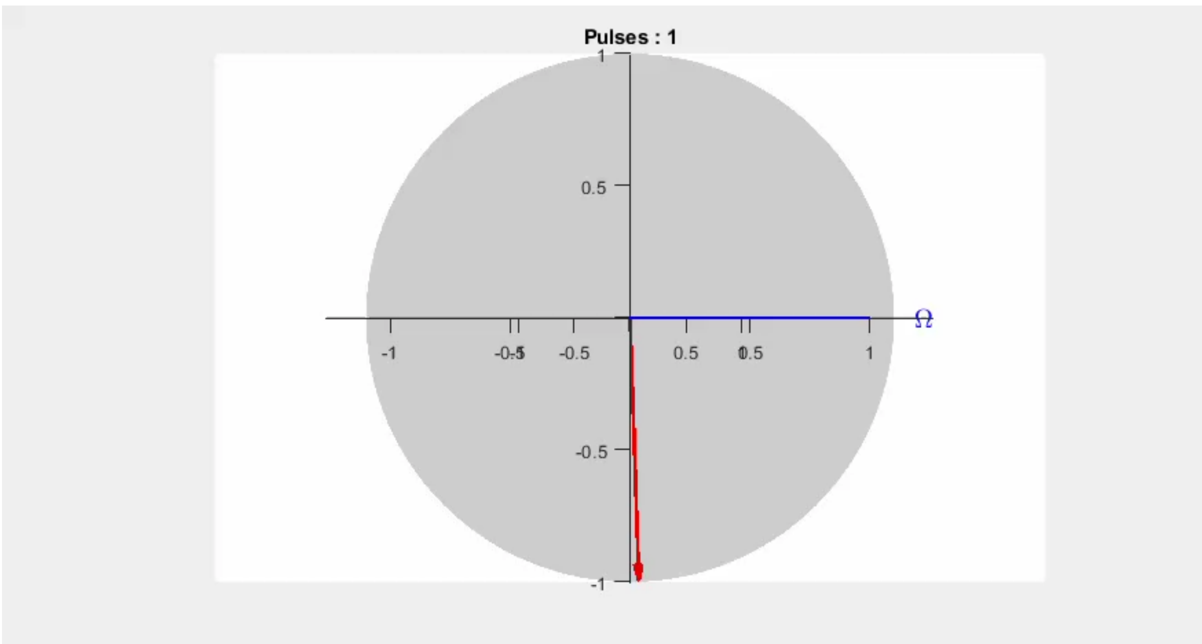
(Atoms continuously added to ground state)

Phase sequence:

$0, \pi, 0, \pi$ ...

Cumulative Phase Cancellation

- Red vector points to averaged state
- Cumulative phase is horizonal component
- Assume zero detuning



Phase sequence:
0, 0, 0, ...

(Atoms continuously added to ground state)

Suppressing Cumulative Phase More Generally

- Pulse sequence with all 0 phases suppresses cumulative phase but is highly susceptible to mirror pulse infidelities
- Can devise more general pulse sequence constraints that suppress cumulative phase while allowing optimization against infidelities
- One of many possibilities is below

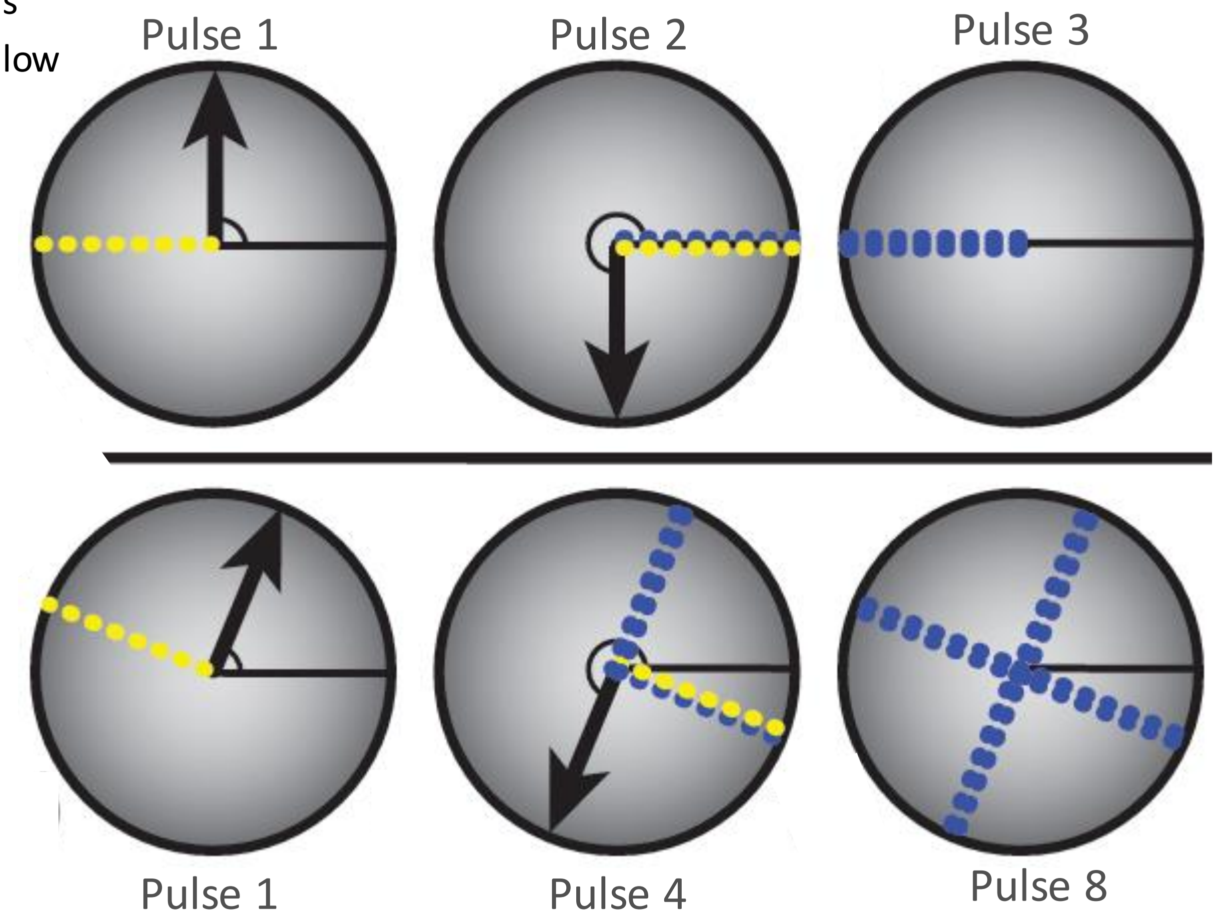
Phase sequence:

$0, \pi, 0, \pi$ …

Phase sequence:

$\phi_1, \phi_2, \phi_2+\pi, \phi_1+\pi,$

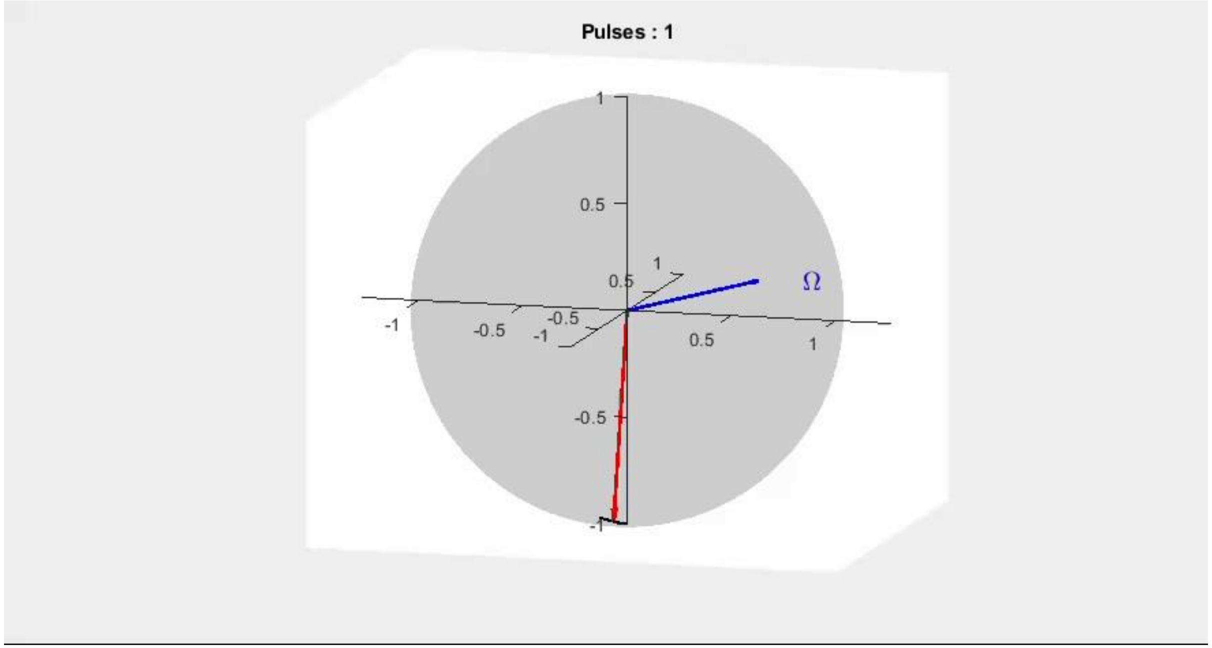
+ mirror



Wang,…,TK, PRL 133, 243403 (2024)

Suppressing Cumulative Phase More Generally

- Red vector points to averaged state
- Cumulative phase is horizonal component
- Assume zero detuning



Atoms continuously added to ground state

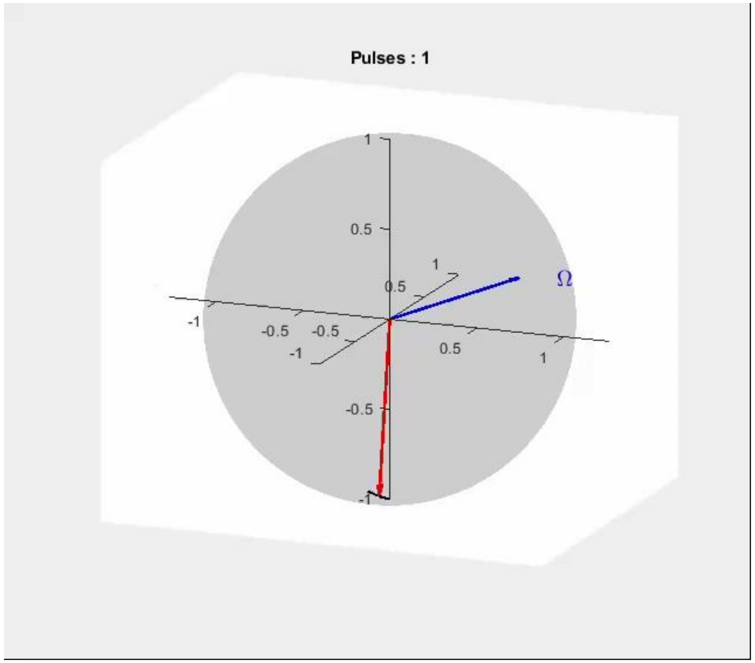
Phase sequence:

$$\phi_1, \phi_2, \phi_2 + \pi, \phi_1 + \pi,$$

+ *mirror*

What if there is a detuning?

- Red vector points to averaged state
- Cumulative phase is horizonal component
- Nonzero detuning of laser from atomic resonance
- Can still suppress cumulative phase
- But does the suppression still work for the simple zero phase pulse sequence with a detuning?



Atoms continuously added to ground state

Phase sequence:

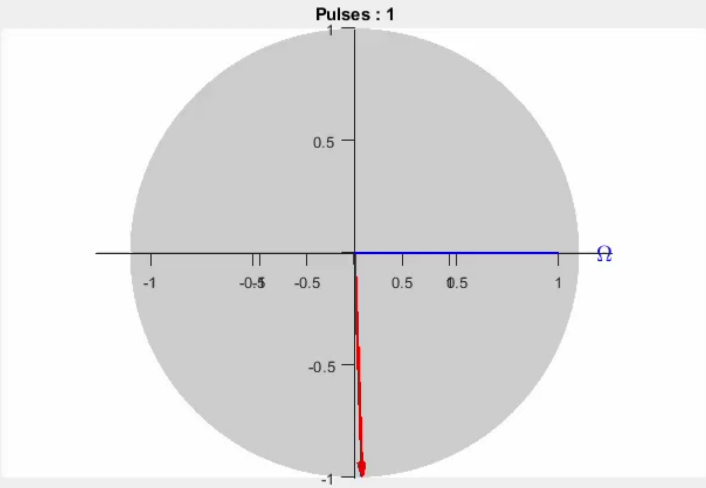
$\phi_1, \phi_2, \phi_2 + \pi, \phi_1 + \pi,$

+ *mirror*

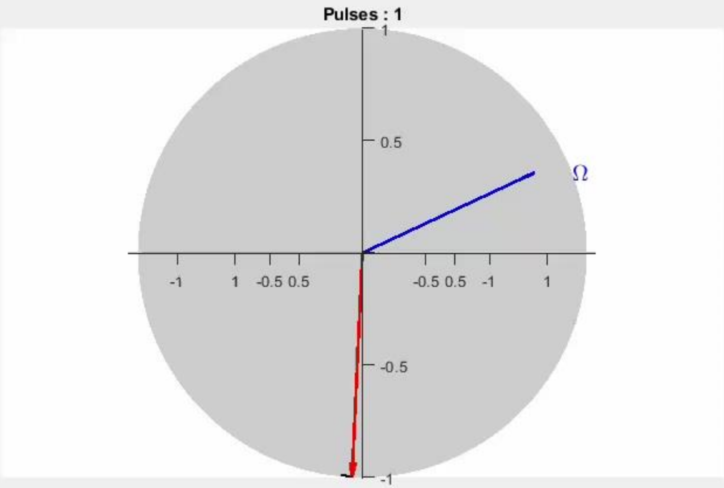
Detuning Dependence of Cumulative Phase for Zero Phase Sequence

- Sequence of zero phase π pulses, in the laser reference frame
  - Red vector points to averaged state
  - Cumulative phase is horizonal component
- Detuning breaks the symmetry that led to cancellation for this pulse sequence

Zero detuning



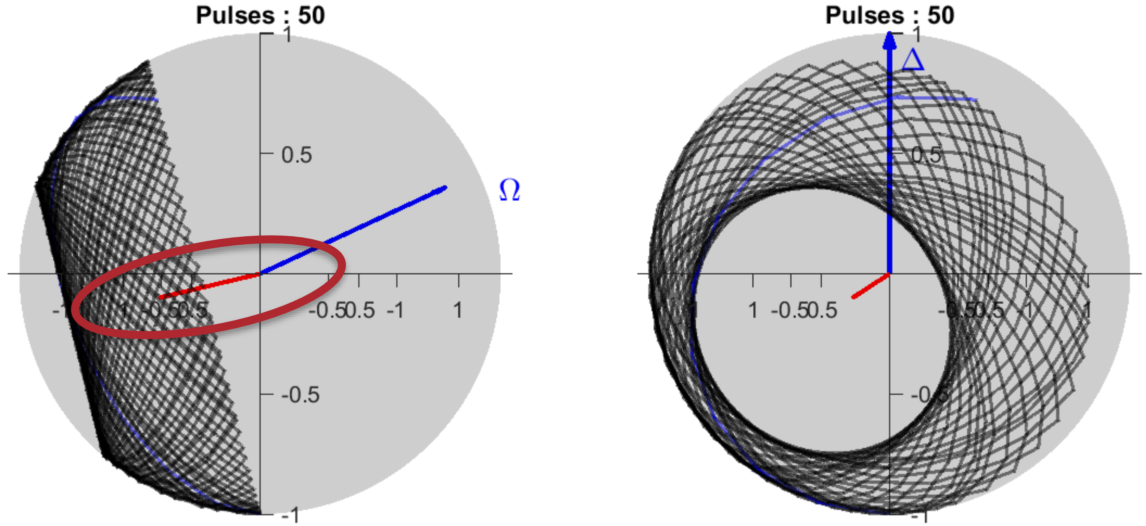
Detuned



Atoms continuously added to ground state

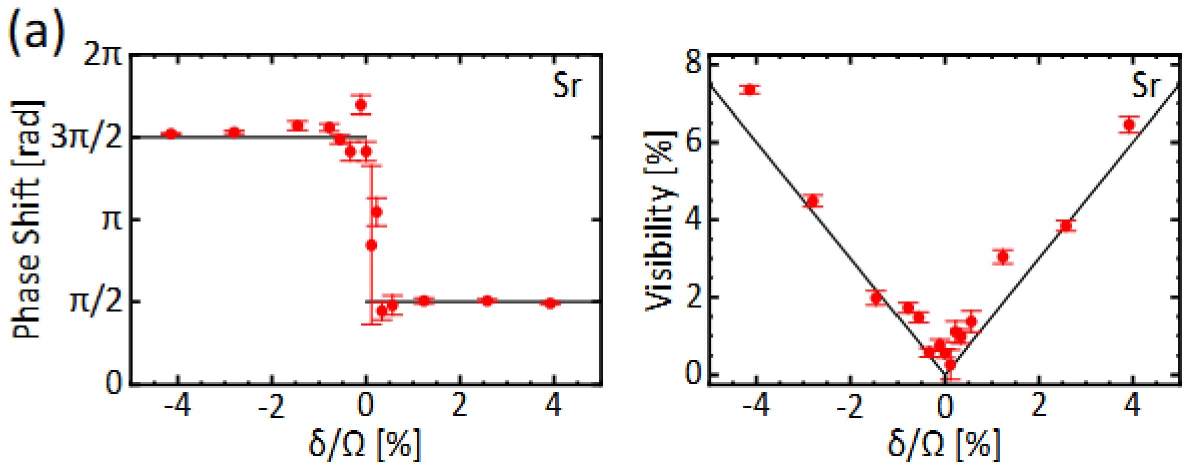
Detuning Dependence of Cumulative Phase

- Large horizontal component from the averaged state when there is detuning (for zero phase sequence)



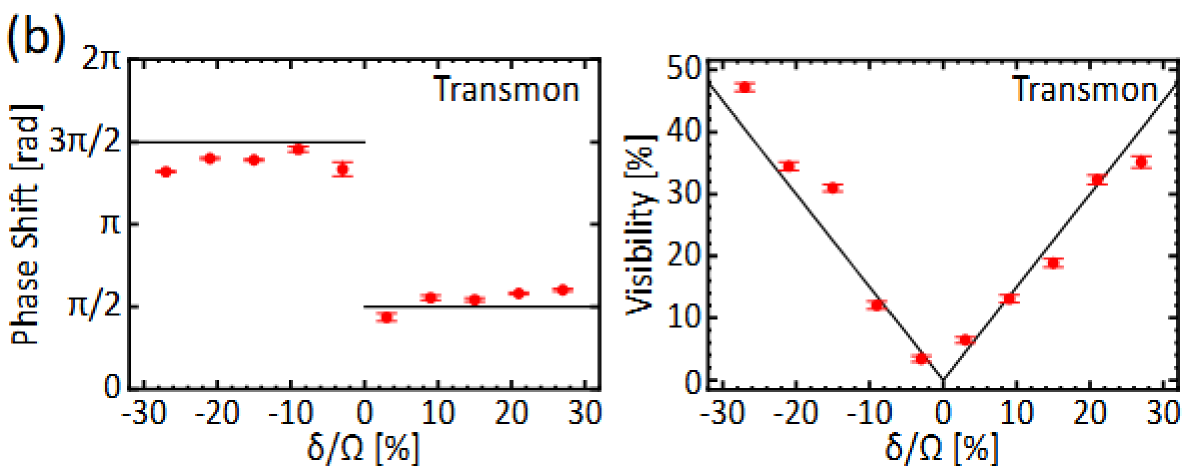
Experimental Observation of Detuning-Dependent Features

- Phase shift and visibility gain strong dependence on detuning
- Systematic that could make it challenging to interpret measurement results if this effect not appropriately accounted for/mitigated
- Consistent with theory (solid black curves)



Experimental Observation of Detuning-Dependent Features

- Implemented analogous pulse sequence (i.e., sequence with many π pulses for sensing of time-dependent signals) in superconducting qubit
- Saw similar behavior
- Effect may be a general interplay of dissipation + certain types of sequences with many pulses



A Few Open Questions

- What if multi-photon instead of single-photon transitions are used?
- What if the Rabi frequency is small or on the order of the typical Doppler shift associated with atom recoil due to spontaneous emission?
- What if many pulses transfer momentum in the same direction instead of periodically reversing the momentum?