Introduction to Vertical Long-Baseline Atom Interferometry

Ulrich Schneider (University of Cambridge) and Tim Kovachy (Northwestern University)

Terrestrial Very-Long-Baseline Atom Interferometry Workshop

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Summary

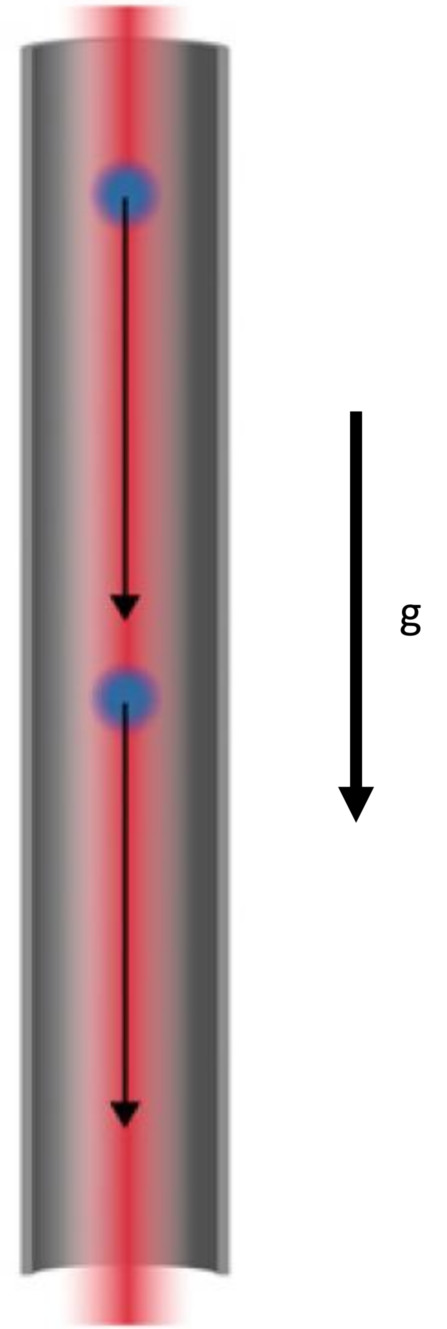
- This talk: general considerations for long-baseline vertical atom interferometry
  - Tim (Part 1): considerations for atom interferometry at the 100 m scale, lessons learned from 10 m scale apparatus
  - Ulrich (Part 2): prospects and considerations for km-scale baselines

- Part 1
  - Laser noise cancellation over a single baseline using single-photon transitions
  - Suppressing unwanted phase shifts from the coupling of atom kinematics to gravity gradients and rotations
  - Challenges of gravity gradient and rotation compensation for long vertical baselines
  - Opportunities and challenges of tall launch/drop heights
  - Infrastructure, access, and installation in a tall vertical shaft (covered in talk by Rob Plunkett)
  - Large-scale magnetic shielding
  - Impact of gravity gradient noise in a vertical shaft and possible mitigations

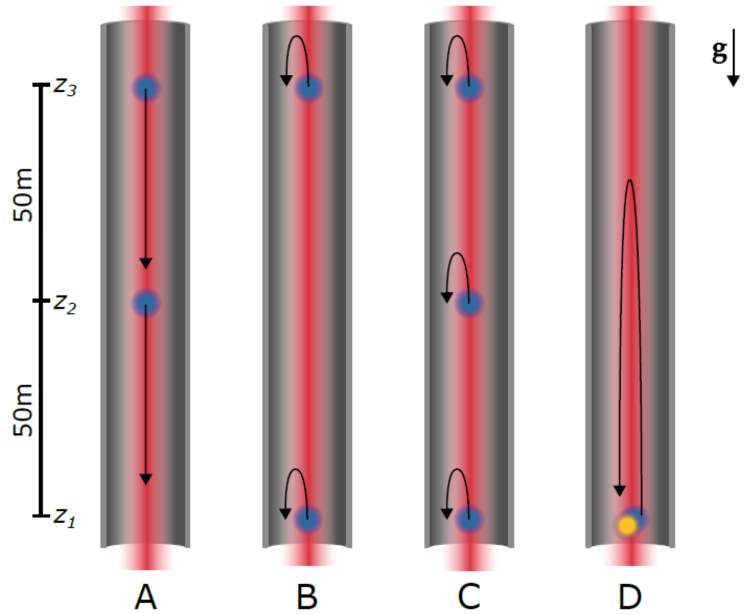
- Part 2
  - Sensitivity scaling
  - Power requirements
  - 1000m baselines possible, limits for LMT
  - Multiplexing
  - phase shear readout / referencing cameras at significant distances
  - monitoring dimensional stability using optical interferometers

Why Vertical?

- Trajectories of freely falling atom clouds are colinear with laser beam
- Freely falling atoms remain centered in the laser beam, do not "fall out of" the beam
- Note: some corrections to this statement arise when deflections from Coriolis forces considered



Various Detector Operation Modes (Examples)



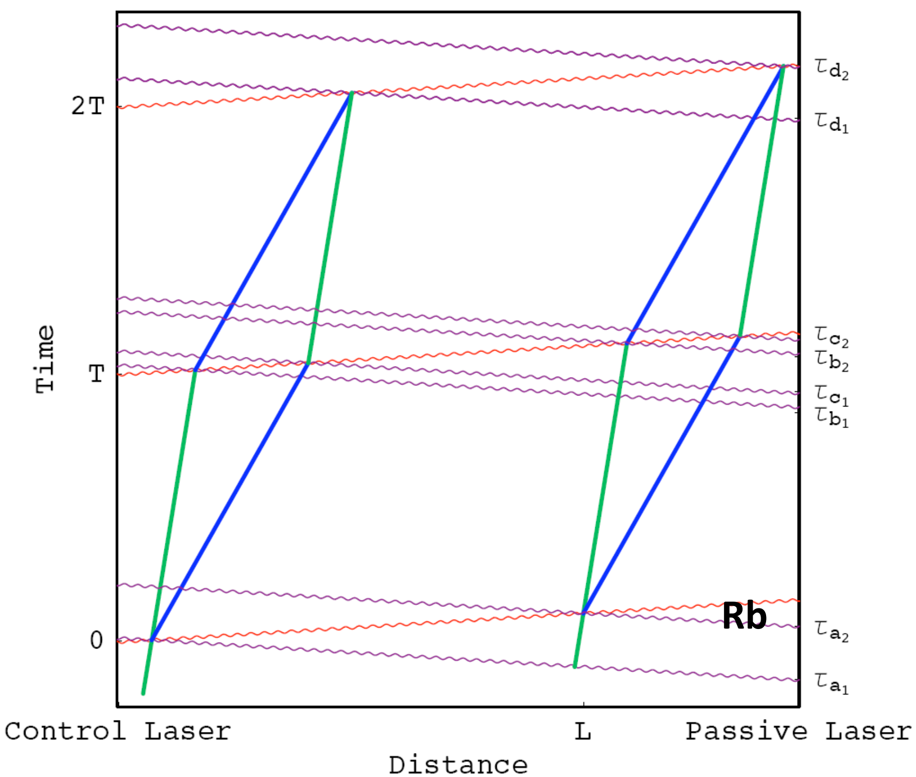
- (A): Maximum drop time
- (B): Maximum gradiometer baseline
- (C): Multi-interferometer gradiometry, useful for characterizing Newtonian gravity gradient noise
- (D) Dual species mode. Alternative dark matter search mode involving a differential measurement between co-located, simultaneous interferometers with different atomic species.

Two-photon vs. single-photon AI

-In contrast to horizontal configurations, for vertical configurations only 1 baseline direction available

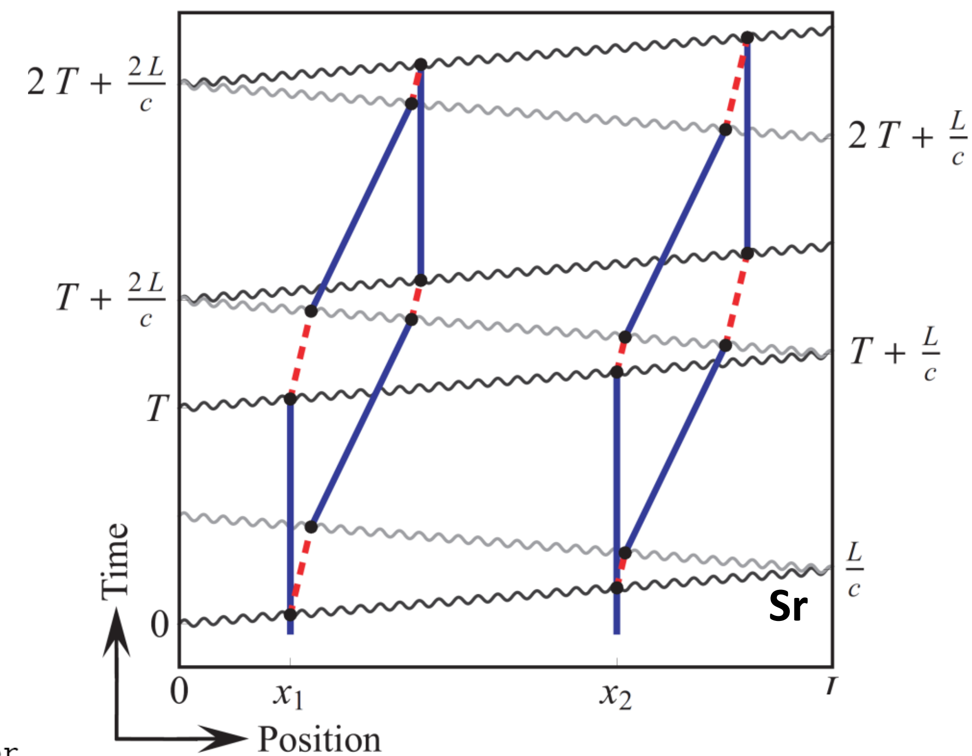
-Need to suppress laser noise over a *single* baseline, 1-photon transitions offer advantage for long baseline lengths

2-photon transitions



Laser phase **not** fully common

1-photon transitions



Laser noise suppressed

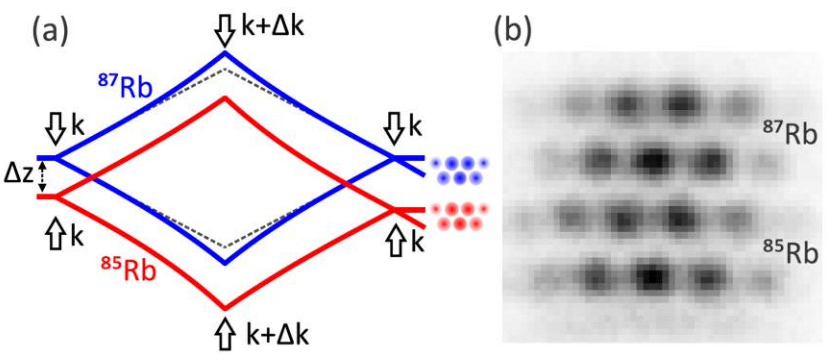
Yu, et al., GRG 43, 1943, (2011).
Graham, et al., PRL 110, 171102, (2013).

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



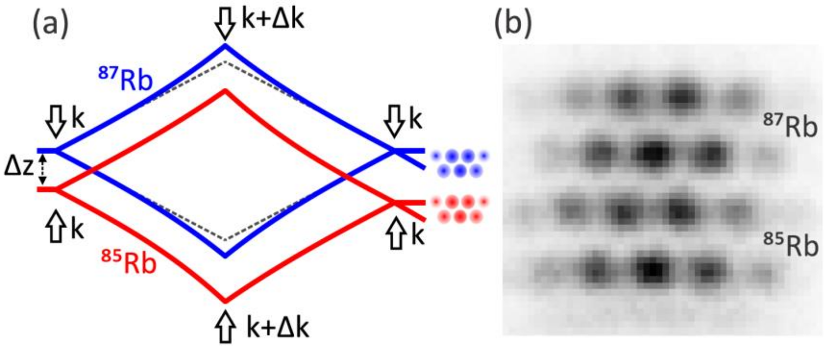
$$-\left(nkT_{zz}T^2 + 2n\Delta k\right)(\Delta z + \Delta v_z T)$$

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

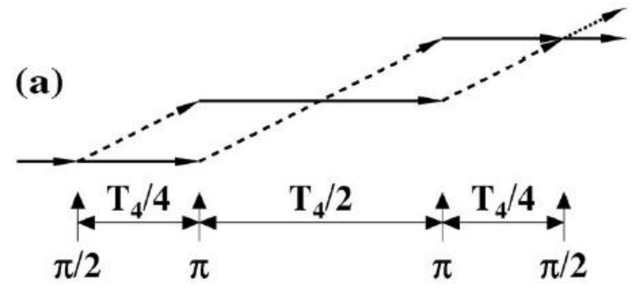
Appropriate choice of frequency jump compensates gravity gradient phase shift

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

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

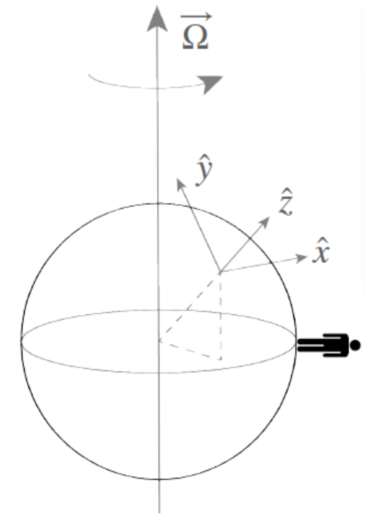
For 10 m or greater launch, frequency jump will be hundreds of MHz to GHz

For Bragg transitions on a broad line (e.g., for dual species interferometry), such a jump can be small compared to detuning, 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

Rotation Compensation

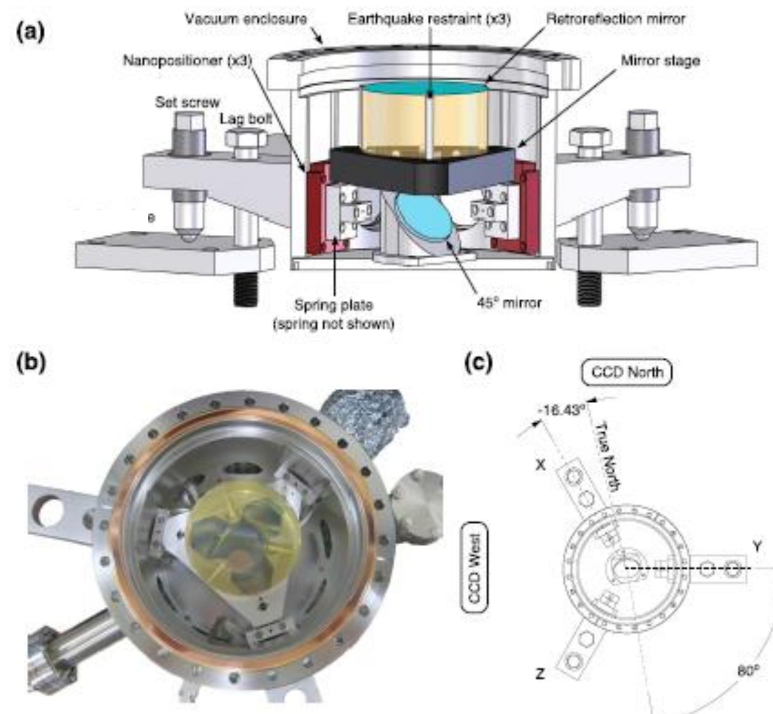


- Earth's rotation leads to velocity dependent Coriolis forces on atoms

- 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)



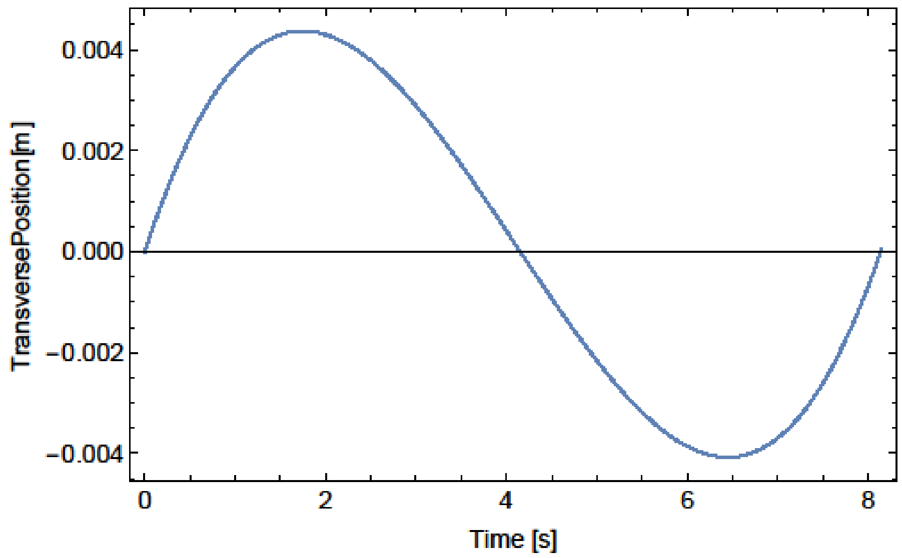
Hogan et al., Proc. Int. Sch. Phys. 'Enrico Fermi' Atom Interferometry and Space Physics, 411-447 (2009); Lan et al., PRL 108, 090402 (2012); Dickerson et al., PRL 111, 083001 (2013)

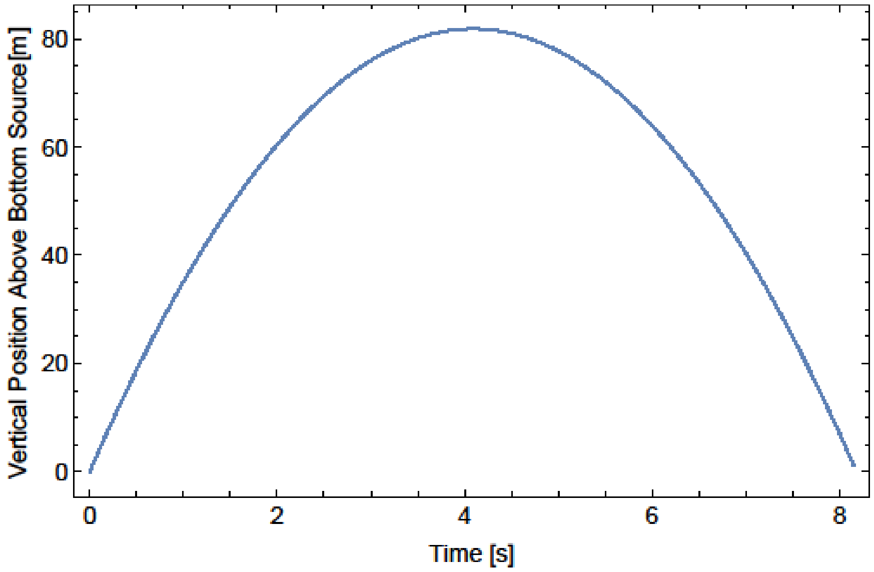
Coriolis Trajectory Deflections

- Coriolis forces cause atom trajectories to be deflected, becomes more pronounced for taller launches

- Can reduce maximum transverse deflections by launching at an appropriate angle

- Example below for 80 m launch (e.g., for dual species interferometer)





Choice of Pivot Point

- Upper tip-tilt mirror before telescope, lower tip-tilt mirror retroreflects beam

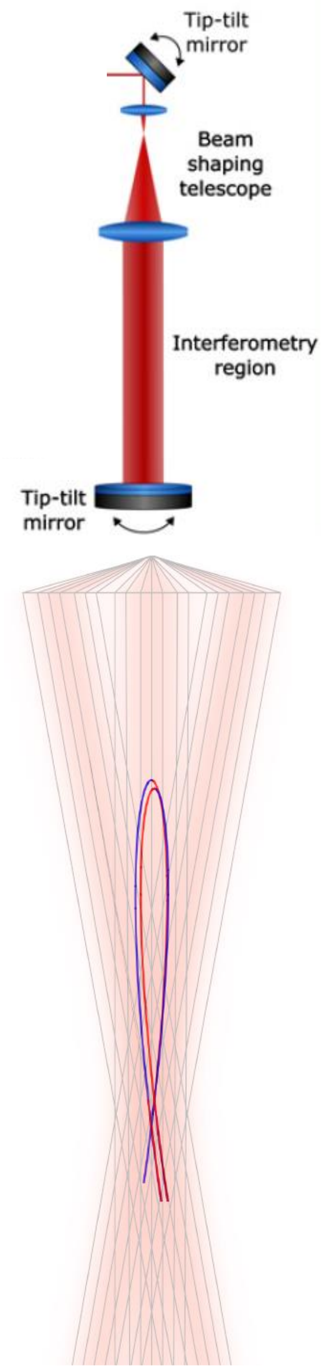
- Can adjust point about which beam rotates (pivot point) based, e.g., on position of upper mirror

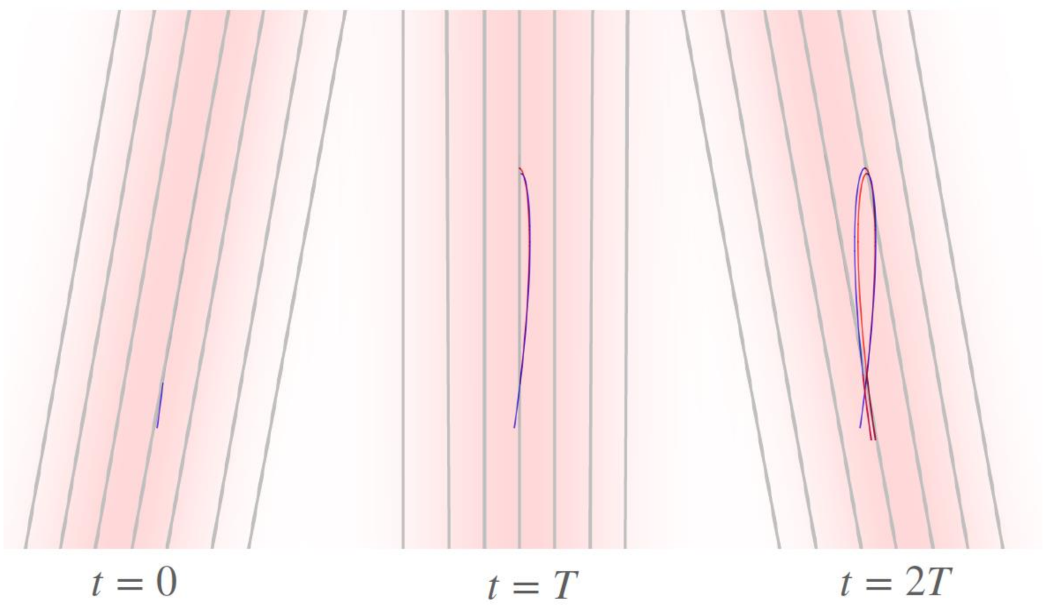
- For tall launch example on previous slide, set initial beam angle and pivot point so that for initial beam splitter, mirror, and final beam splitter pulses, atom trajectories centered in beam

  Is rotation compensation scalable to km baselines?

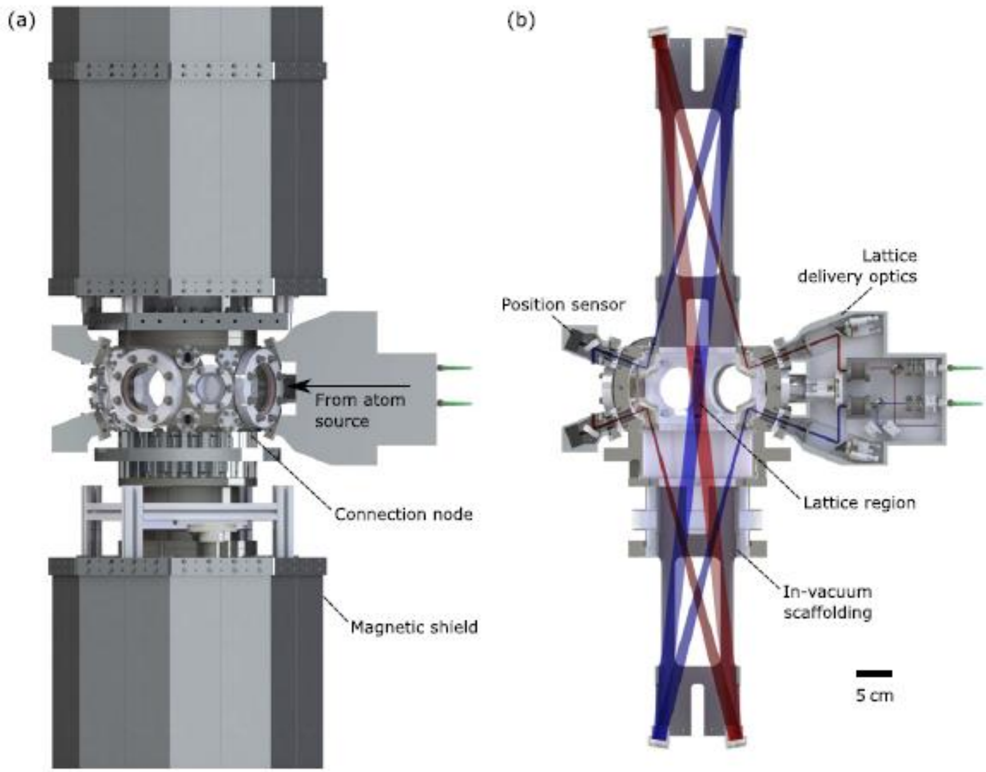
  -beam deflections would grow to ~10 cm, seems to require wider vacuum pipe

  -multi-loop interferometers offer an alternative way to mitigate Coriolis phase shifts, may be needed anyway in single-photon-based interferometers to mitigate gravity gradients (drawback of reducing low frequency response)





Tall Launches/Drops: Opportunities and Challenges

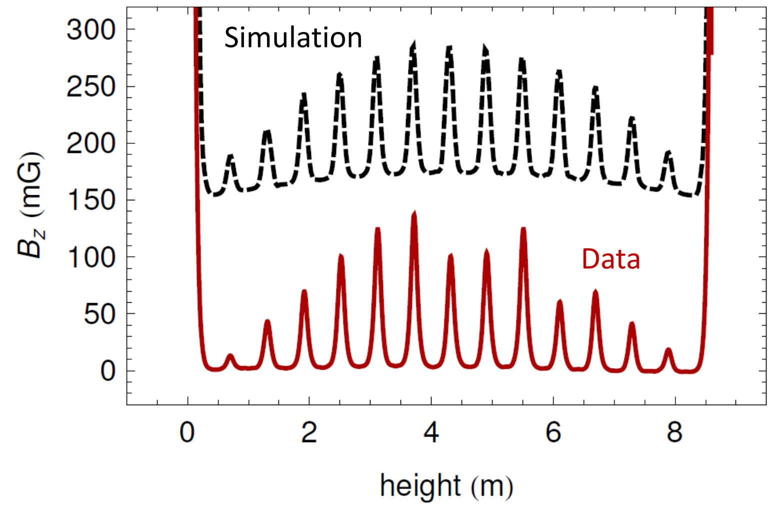


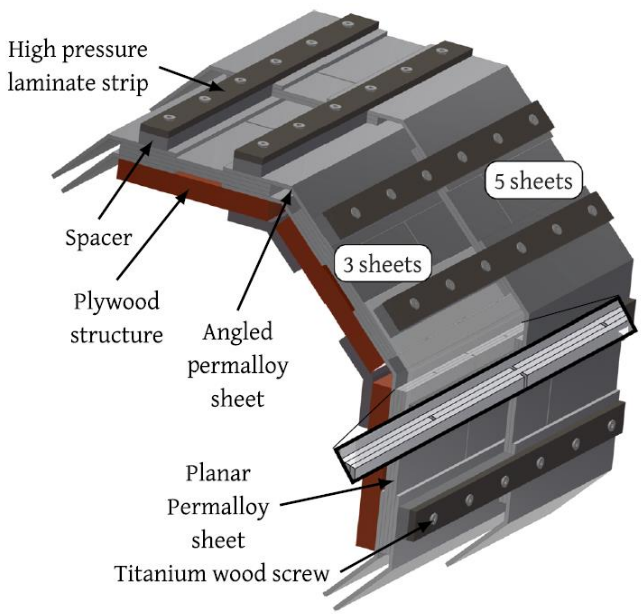
- Opportunity to boost sensitivity with increased interrogation time
- Taller launches leads to larger Coriolis deflections
  - Important to have flexibility to launch at a slight angle to reduce deflections
- Higher laser power needed for taller launches
- Multiplex interferometers to increase sensor bandwidth?
  - Local launch lattices minimize effects on atoms elsewhere along the baseline

Abe et al., Quantum Sci. Tech. 6, 044003 (2021)

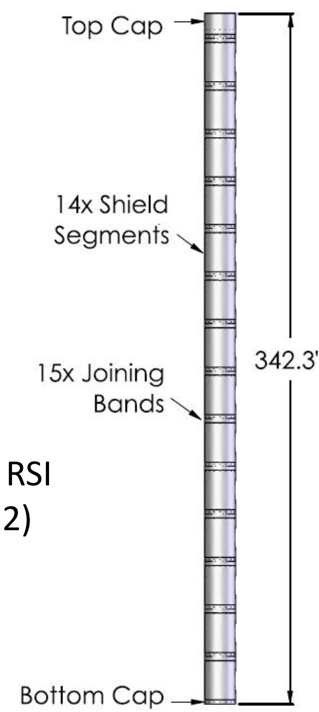
Large Scale Magnetic Shielding

- 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)



Dickerson et al., RSI 83, 065108 (2012)

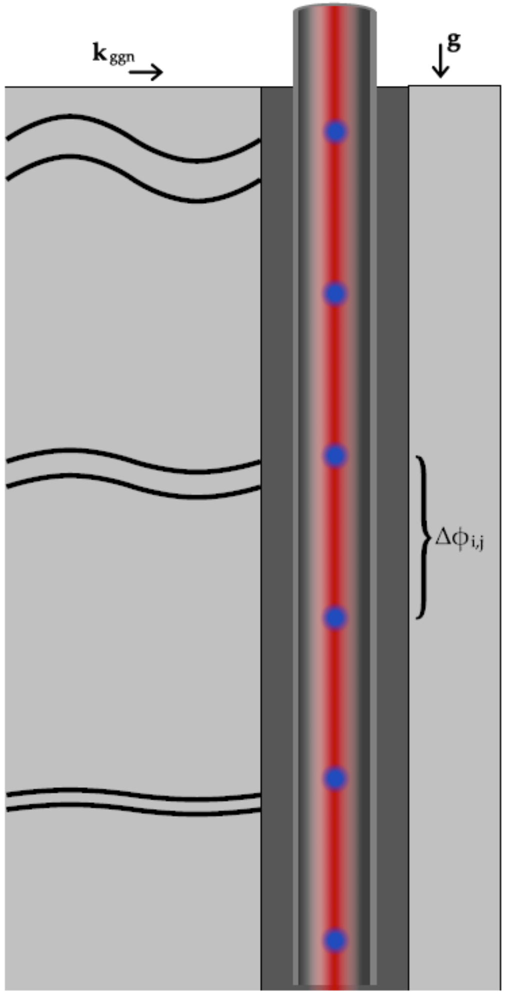
Gravity Gradient Noise for Vertical Baselines

- Seismic gravity gradient noise (GGN): seismic waves disturb local mass distribution, cause oscillating gravity gradient that is a noise background (especially important at lower frequencies)

- GGN signal has nonlinear variation along baseline (in contrast to many science signals of interest)

- MIGA collaboration: array of AIs along horizontal baseline to distinguish spatial dependence of GGN vs. science signal
  - Chaibi et al., PRD 93, 021101(R) (2016)

- Recent work has investigated application of this idea to vertical baselines, leveraging exponential decay with depth
  - Mitchell et al., JINST 17, P01007 (2022)
  - Badurina et al., arXiv:2211.01854 (2022)



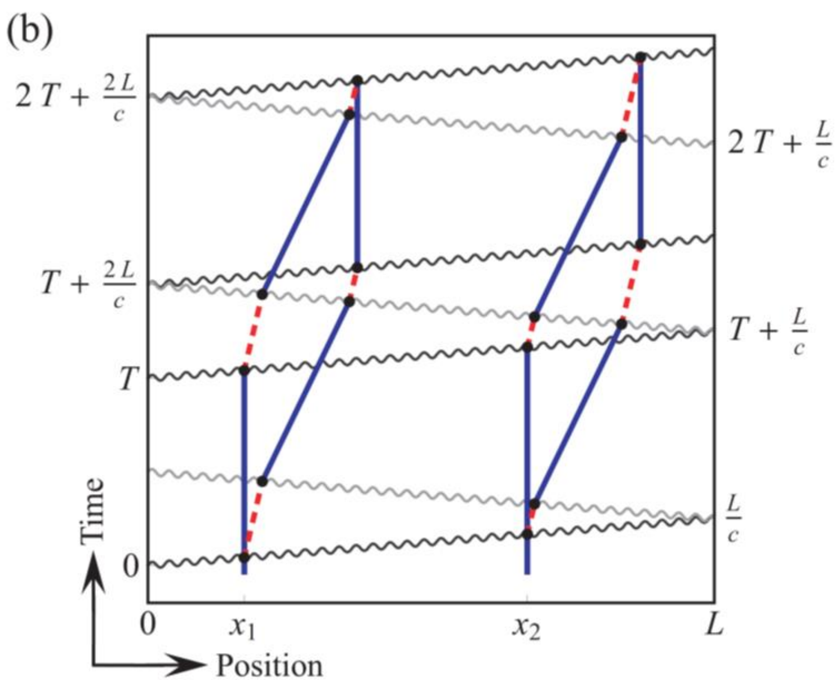
- Potential to improve deeper underground

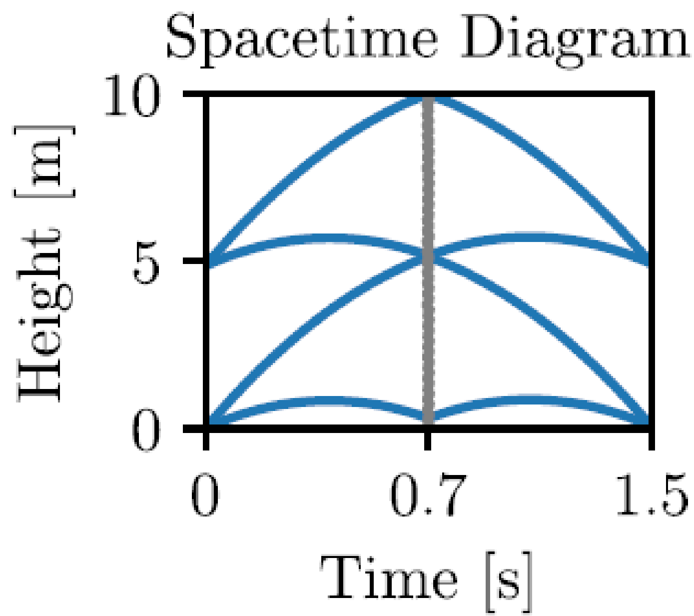
Gravity Gradient Noise for Vertical Baselines

- Still many open questions
- Detailed analysis of atmospheric GGN effects for vertical baseline ongoing
- Impact of layers in the ground with different densities
- Human-generated sources of time-dependent gravity gradients
- GGN will likely be an important factor in site selection for future instruments
- Input from Earth Scientists will be valuable

https://indico.cern.ch/event/1244165/

Part II - Diagrams





- Include gravity
- Instantaneous LMT

Peak sensitivity for scalar dark matter

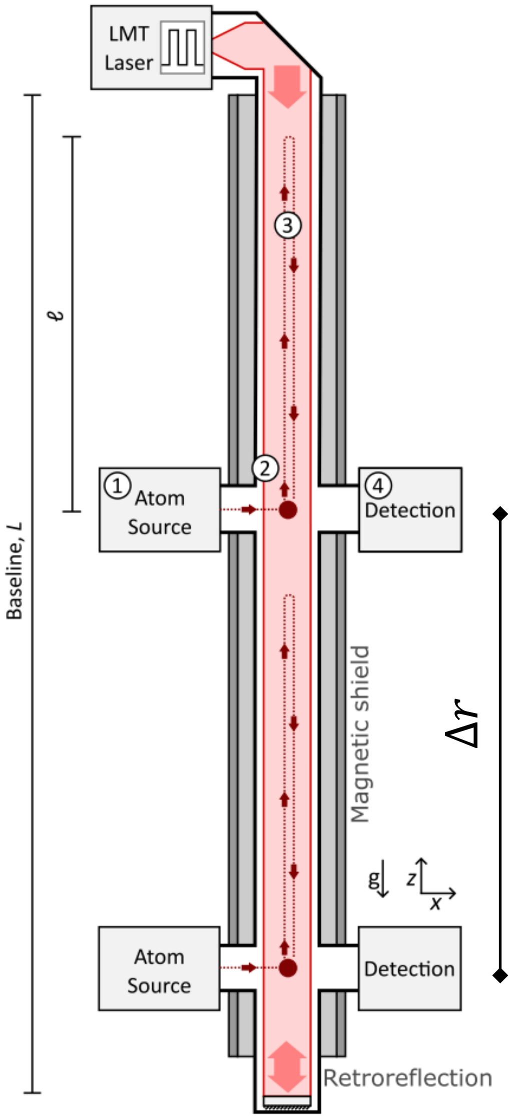
$$d^{best} \sim \left(\frac{1}{T}\right)^{5/4} \frac{1}{C\, n\, \Delta \mathrm{r}} \left(\frac{\Delta t}{N_{at}}\right)^{\frac{1}{2}} \left(\frac{1}{T_{int}}\right)^{\frac{1}{4}}$$

- T interferometer duration
- C contrast
- n number of LMT
- Δr Separation between interferometers
- Δt time between successive interferometer sequences
- N_{at} number of atoms
- T_{int} total integration time

Badurina, Blas, McCabe (AION), PRD **105**, 023006 (2022)

Baseline

$$d^{best} \sim \left(\frac{1}{T}\right)^{5/4} \frac{1}{C\, n\, \Delta r} \left(\frac{\Delta t}{N_{at}}\right)^{\frac{1}{2}} \left(\frac{1}{T_{int}}\right)^{\frac{1}{4}}$$

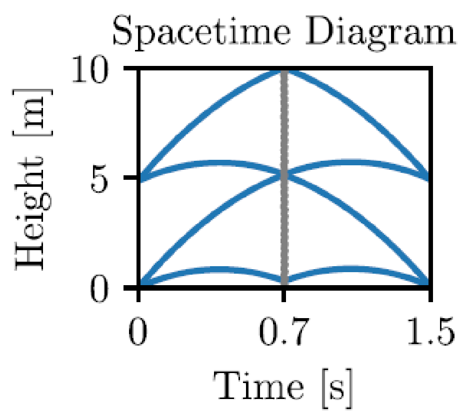


L influences Δr but also T and n.

$\frac{L}{2} > n\, v_r\, T \quad v_r \approx 6.6$ mm/s for Sr

What is optimal Δr?

Short baselines



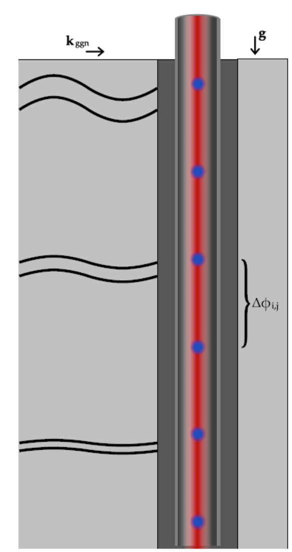
e.g. L=10 m

$\Delta r \approx$ 5m

$n_{max} \approx 1000$

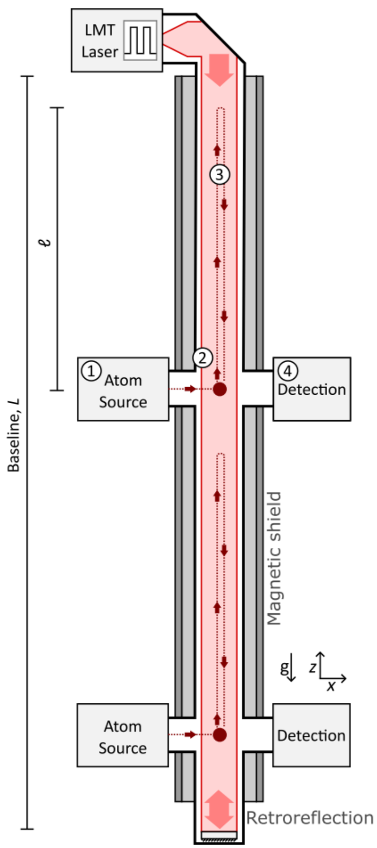
Long baselines:

- GGN effects
- Achievable n?

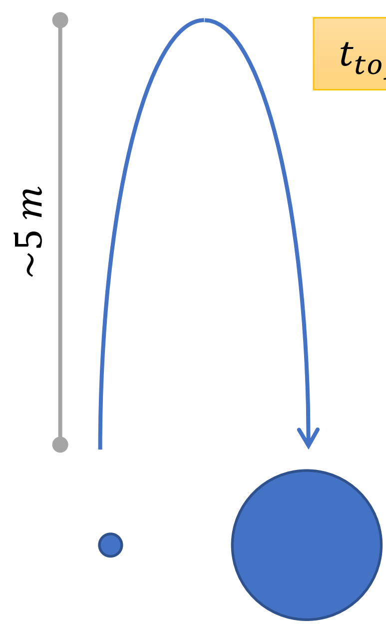


Cloud temperature

$$d^{best} \sim \left(\frac{1}{T}\right)^{5/4} \frac{1}{C\, n\, \Delta r} \left(\frac{\Delta t}{N_{at}}\right)^{\frac{1}{2}} \left(\frac{1}{T_{int}}\right)^{\frac{1}{4}}$$

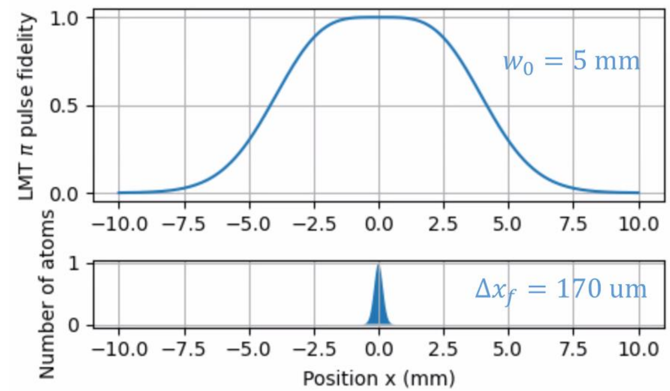


Atomic trajectory



$t_{tof} \approx 2s$

$d \propto \sqrt{T} \times t_{tof}$



Plot by Richard Hobson, AION

High Fidelity $\mathrm{F} > 1 - 10^{-5}$
per pulse requires
$T < 30\ pK$

Achievable by combination of
- laser cooling,
- evaporative colling,
- delta-kick cooling

Laser power constraints

$$d^{best} \sim \left(\frac{1}{T}\right)^{5/4} \frac{1}{C\; n\; \Delta r}\left(\frac{\Delta t}{N_{at}}\right)^{\frac{1}{2}}\left(\frac{1}{T_{int}}\right)^{\frac{1}{4}}$$

Single-photon $n_{LMT} = 40{,}000 \rightarrow \tau_\pi \lesssim 10\ us$

- Finite contrast requires high fidelity of individual pulses

  Homogeneity: $\frac{w_0}{\sigma_{cloud}} > 50$

- Spontaneous-emission limit → clock line required

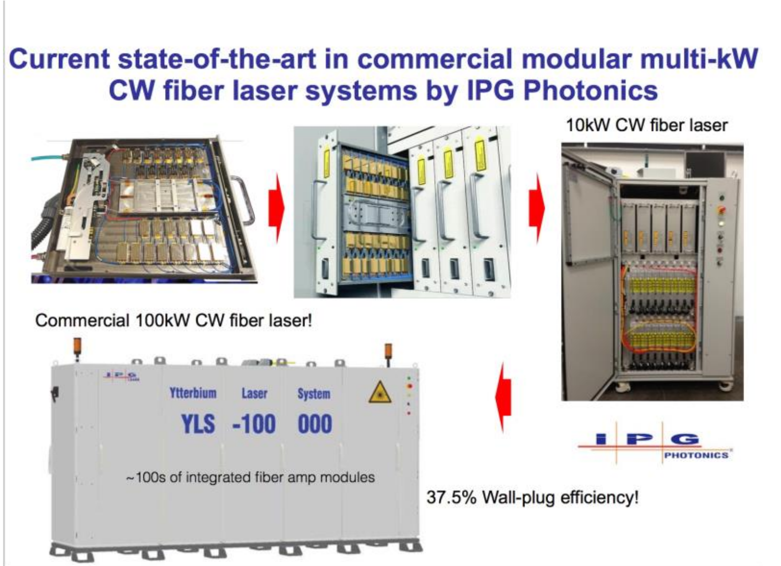
  → kilowatt level power requirements

Work by Lellouch, Stray, Ennis, Hedges, Holynski (AION, Birmingham)

Mitigations

- Composite pulses
- Cavity-assisted schemes (?)

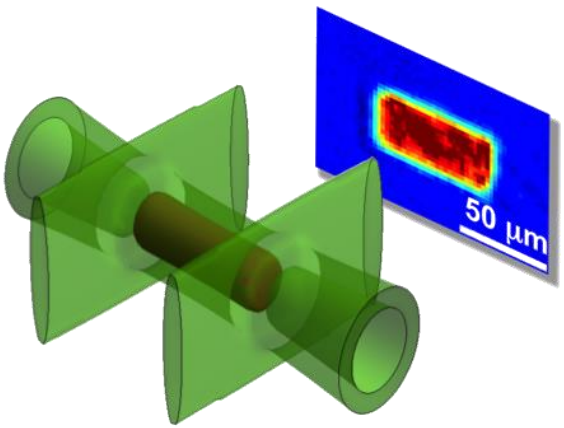
  → Laser R&D required



Atom number

$$d^{best} \sim \left(\frac{1}{T}\right)^{5/4} \frac{1}{C\, n\, \Delta r} \left(\frac{\Delta t}{N_{at}}\right)^{\frac{1}{2}} \left(\frac{1}{T_{int}}\right)^{\frac{1}{4}}$$

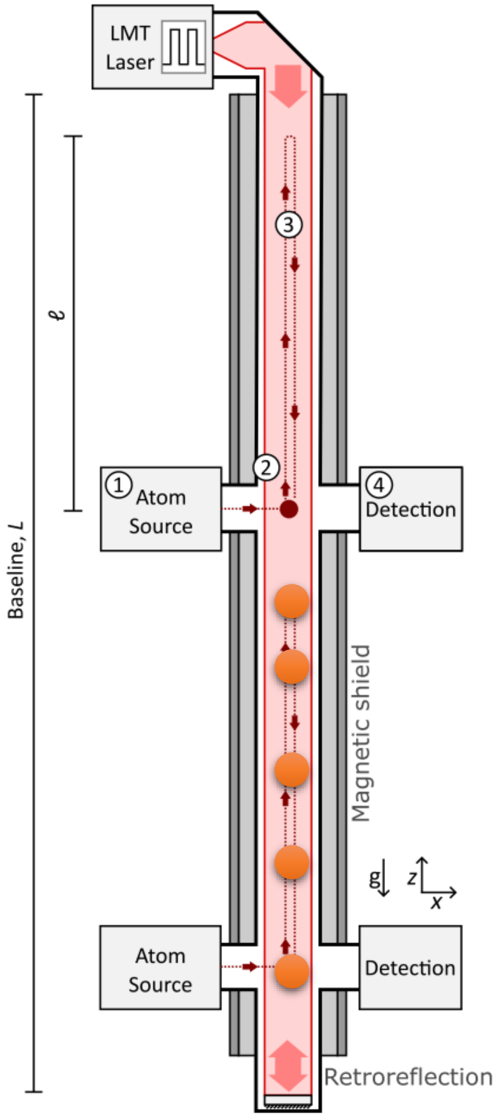
- Assuming shot noise limited operation
  → Squeezing can provide significant benefit (AION,…)
- Current number for spin-polarized fermions $N = 10^5 - 10^6$
  → Scaling up to 10^{10}
- Trade-off with repetition rate Δt
- Requires high flux atom sources
  e.g. Oxford, AION
- Requires large volume traps for evaporation
  e.g. blue-detuned box traps
- Can we avoid or parallelize evaporative cooling (for fermions)?



Hadzibabic group, Cambridge

Multiplexing

$$d^{best} \sim \left(\frac{1}{T}\right)^{5/4} \frac{1}{C\, n\, \Delta r} \left(\frac{\Delta t}{N_{at}}\right)^{\frac{1}{2}} \left(\frac{1}{T_{int}}\right)^{\frac{1}{4}}$$



Using Doppler shifts on clock transition

\+ higher effective repetition rate

reduced aliasing at same long T

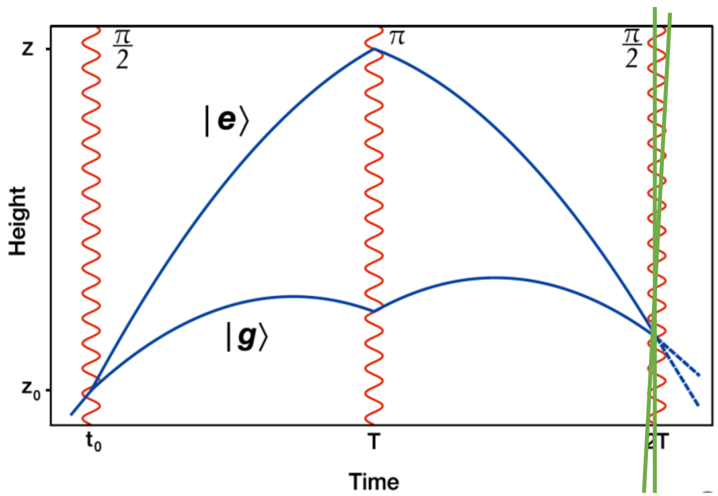
- Increase number of sources
- Velocity-selective launching
  - E.g. via shelving on clock transition

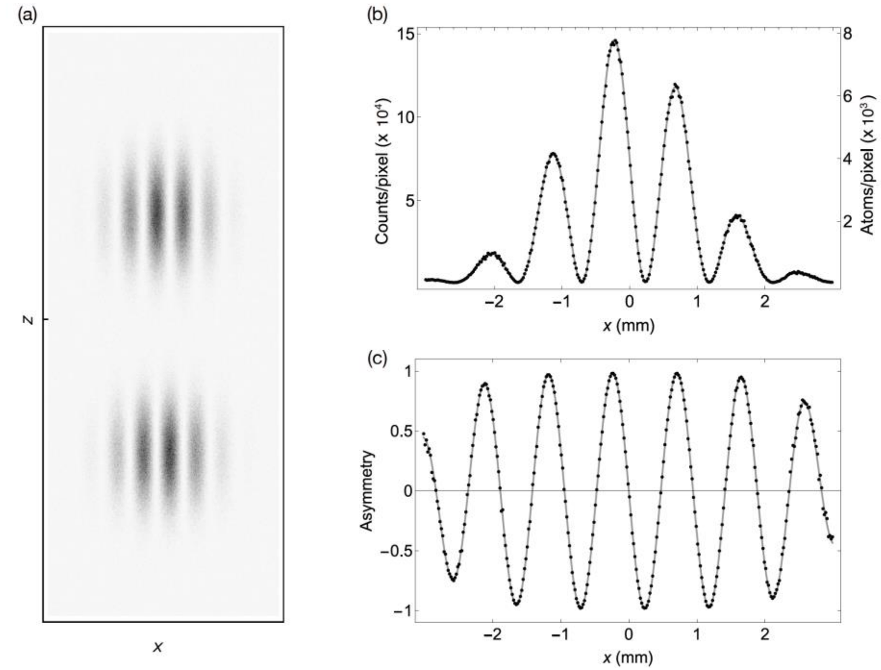
\+ reduced Doppler shifts

higher contrast at same n

\- Reduced atom number per shot

Singe-shot readout: Phase-shear

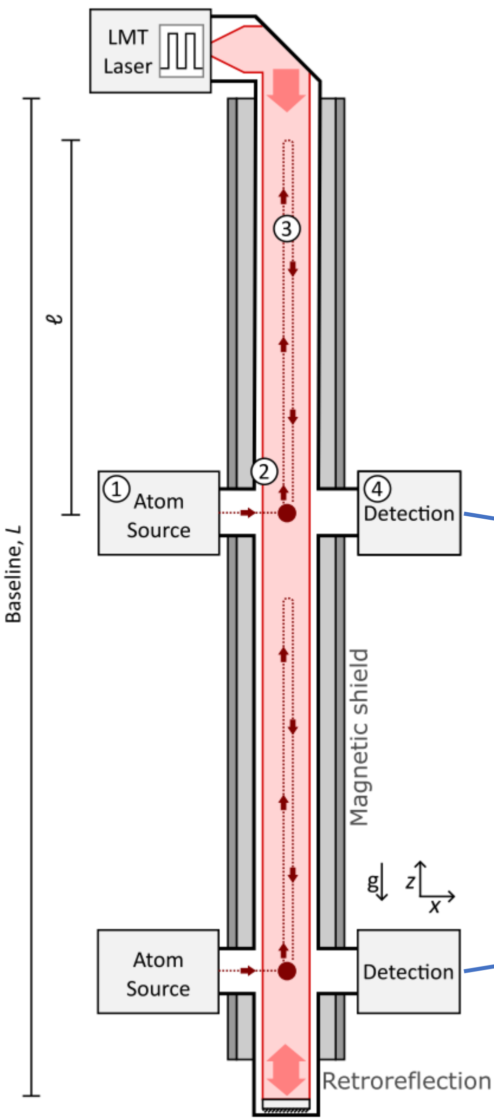




Simulated picture, MAGIS

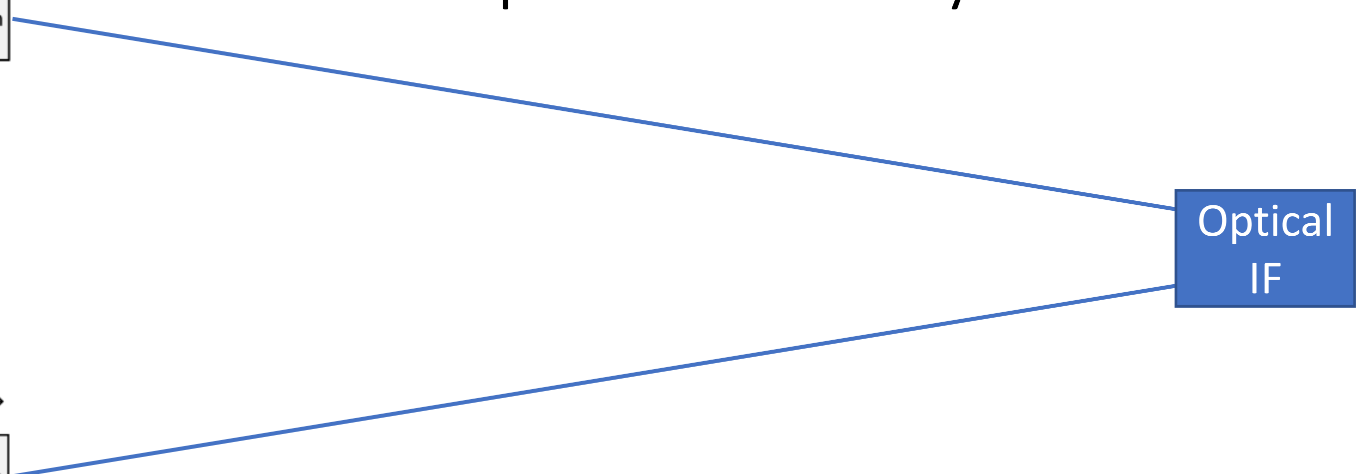
- Phase information mapped onto real space fringes
- Fringe position measured relative to camera axis
  - → Require relative stability between camera positions at different interferometers at $10 - 100$nm level.

Positional stability



- Camera positions need to be stable to within 10-100nm
- Initial atom positions and launch optics less critical but remain non-trivial

→secondary optical interferometers to ensure positional stability



→ Challenge: measuring horizontal distances in long thin mineshaft..

AION Scenarios

Sensitivity Scenario	L [m]	T_{int} [sec]	$\delta\phi_{\text{noise}}$ $[1/\sqrt{\text{Hz}}]$	LMT [number n]
AION-10 (initial)	10	1.4	10^{-3}	100
AION-10 (goal)	10	1.4	10^{-4}	1000
AION-100 (initial)	100	1.4	10^{-4}	1000
AION-100 (goal)	100	1.4	10^{-5}	40000
AION-km	2000	5	0.3×10^{-5}	40000