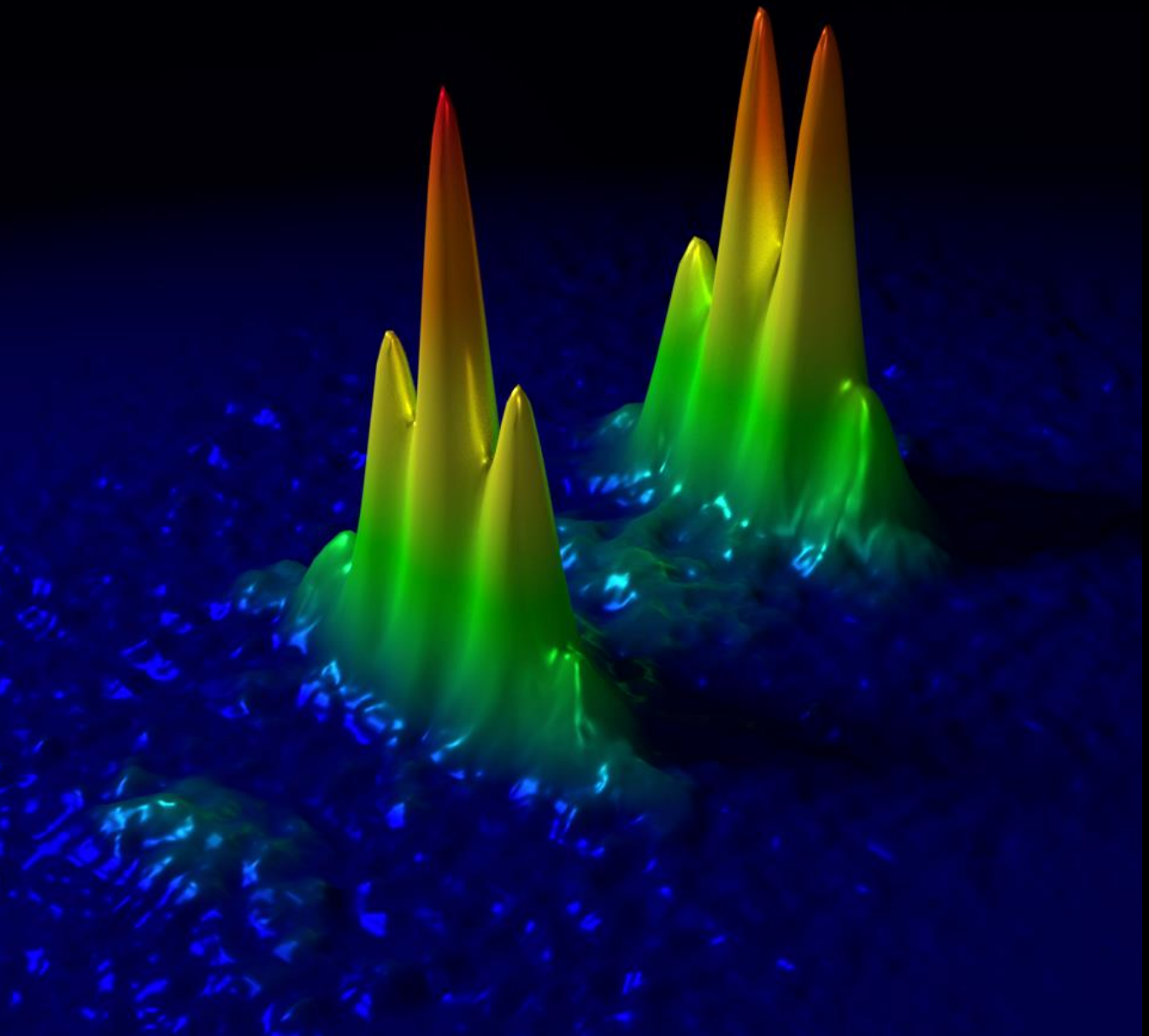
Atom interferometry for fundamental physics



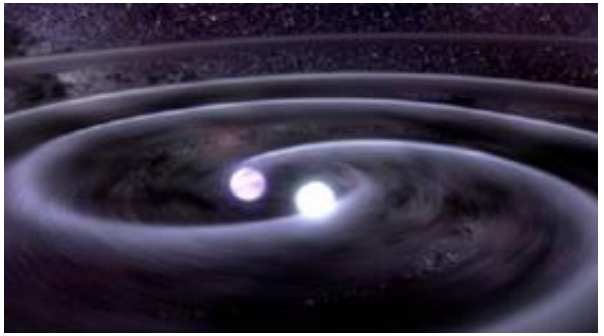
Undergraduate Summer Research Seminar

Jason Hogan

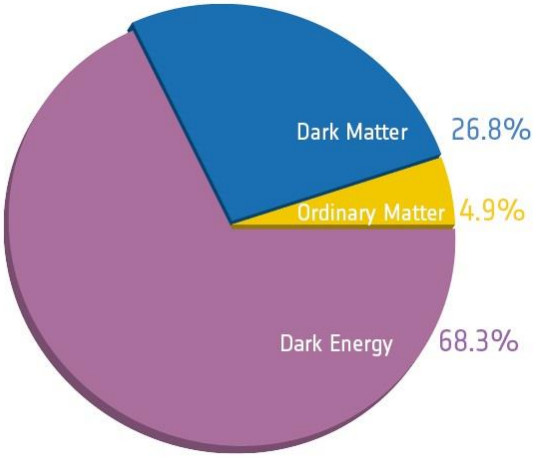
June 28, 2022

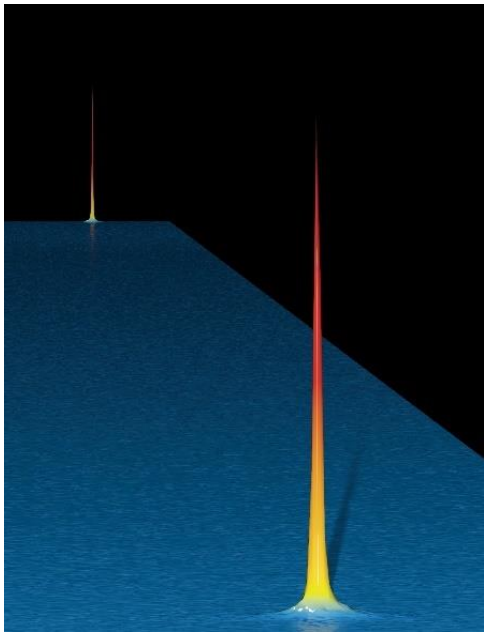
Science applications

- Gravitational wave detection
- Quantum mechanics at macroscopic scales
- QED tests (alpha measurements)
- Quantum entanglement for enhanced readout
- Equivalence principle tests, tests of GR
- Short distance gravity
- Search for dark matter
- Atom charge neutrality



Compact binary inspiral



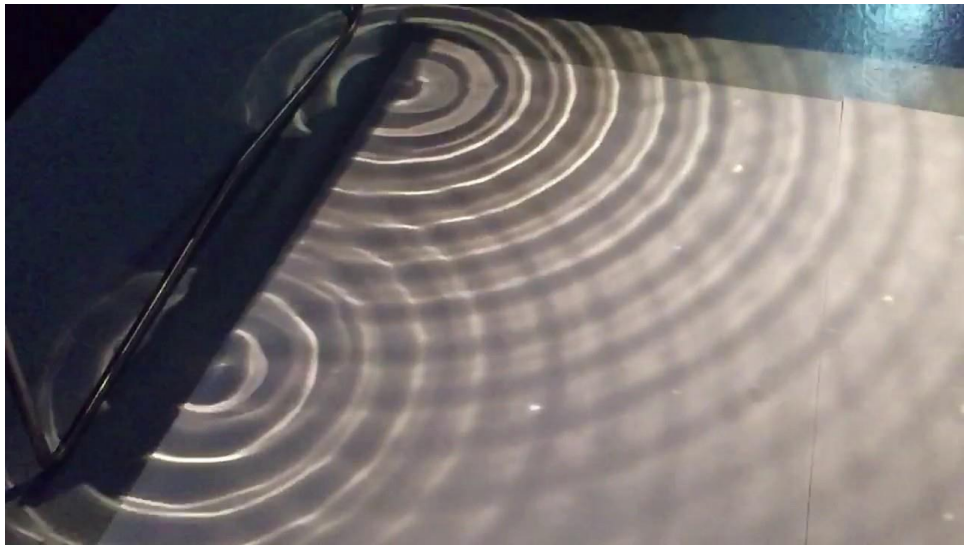


Rb wavepackets separated by 54 cm

Image: https://www2.physics.ox.ac.uk/research/dark-matter-dark-energy

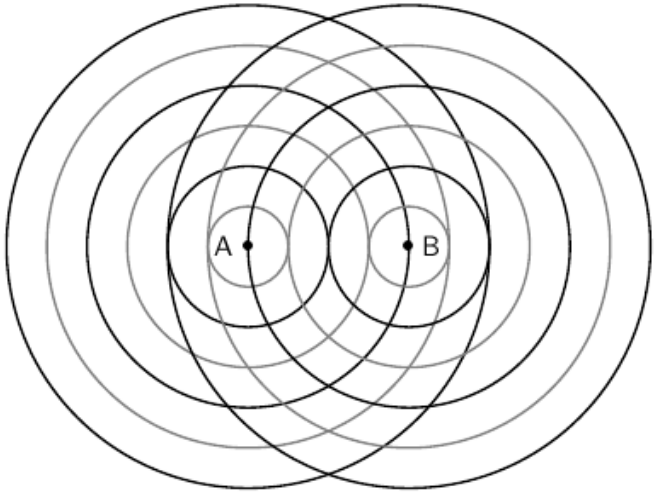
Wave interference

Water waves

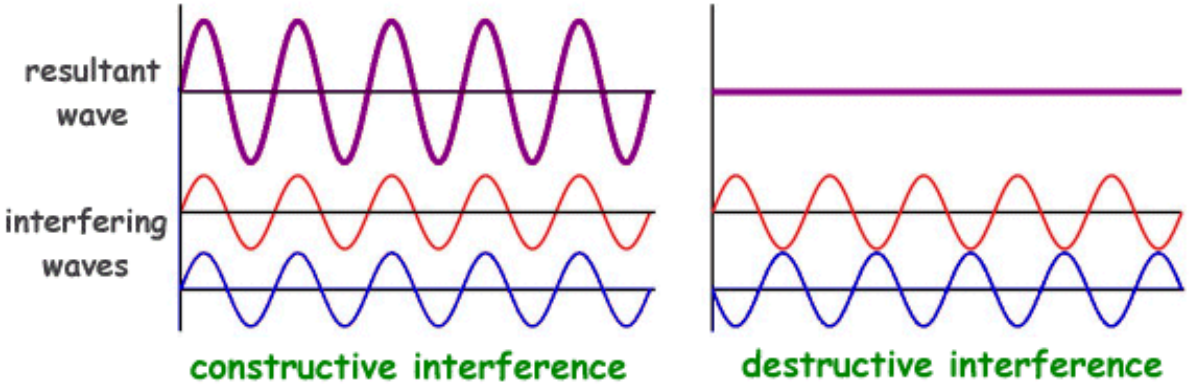


https://www.youtube.com/watch?v=1PuzdU2RvW8

Circular waves interfering



https://archive.cnx.org/resources/0ab30a4799c39b5461f92f3df3a95a1dd280d621/PG12C6_007.png



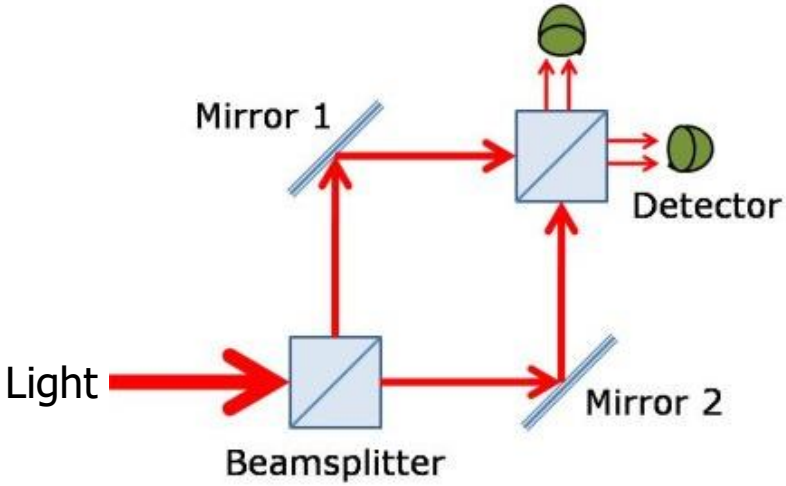
Any kind of wave can interfere in this way:

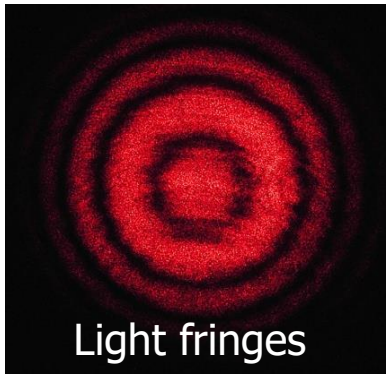
- Water waves
- Electromagnetic waves
- Matter waves
- …

http://www.geon.us/Soul/13M1.html

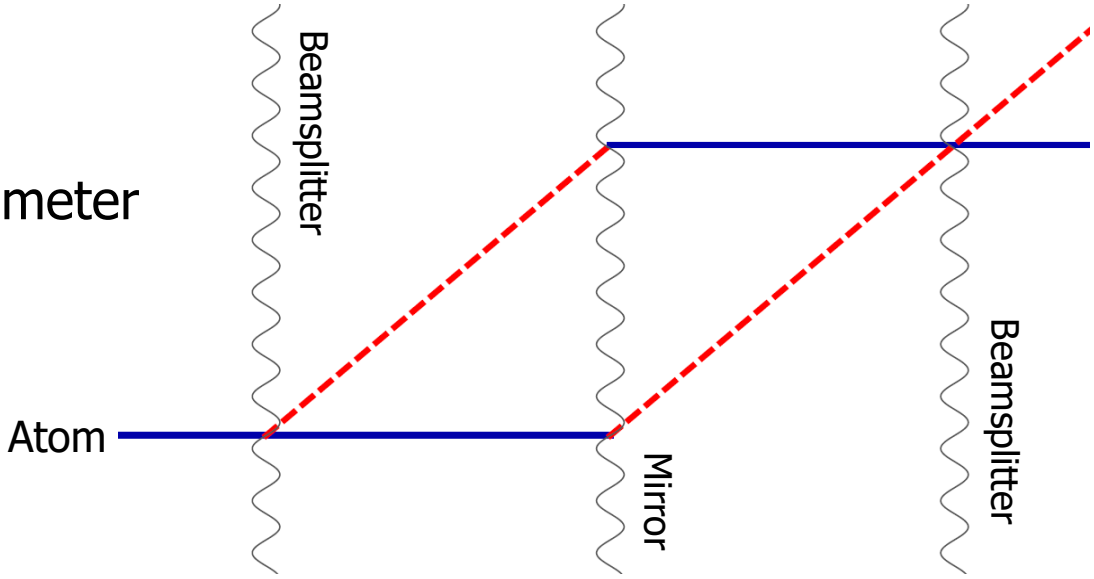
Atom interference

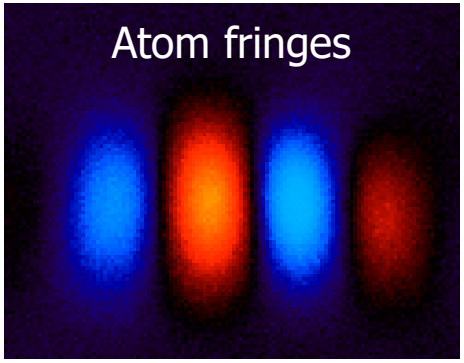
Light interferometer





Atom interferometer

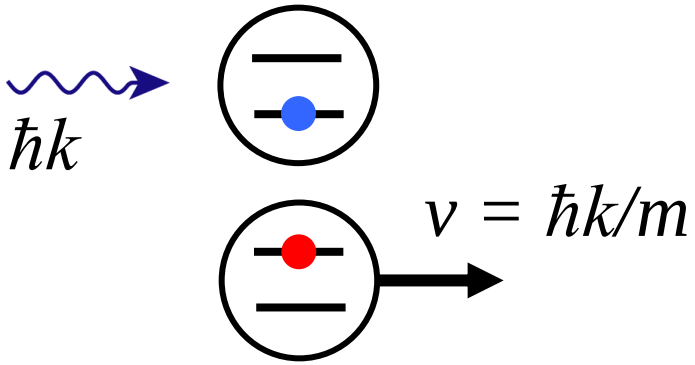




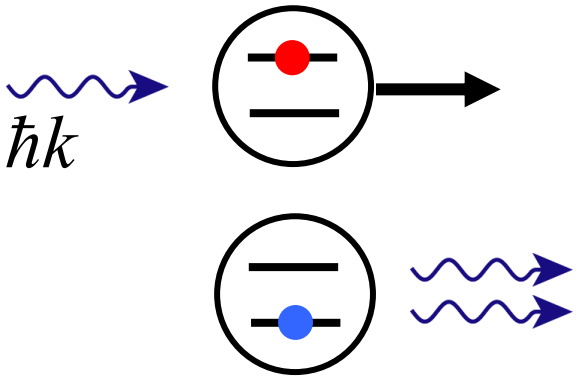
http://scienceblogs.com/principles/2013/10/22/quantum-erasure/
http://www.cobolt.se/interferometry.html

Atom optics using light

(1) Light absorption:

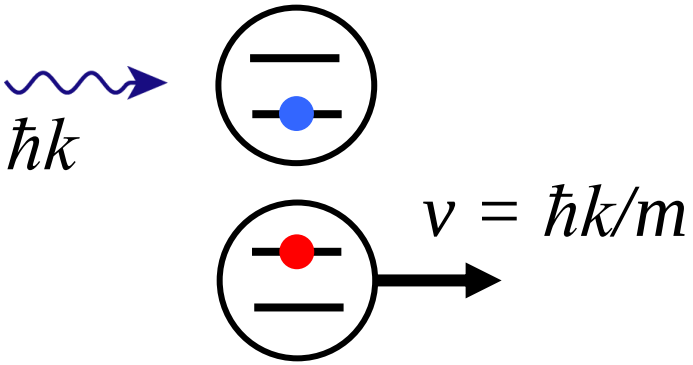


(2) Stimulated emission:

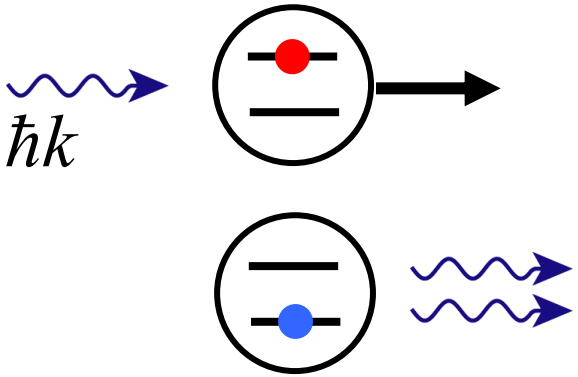


Atom optics using light

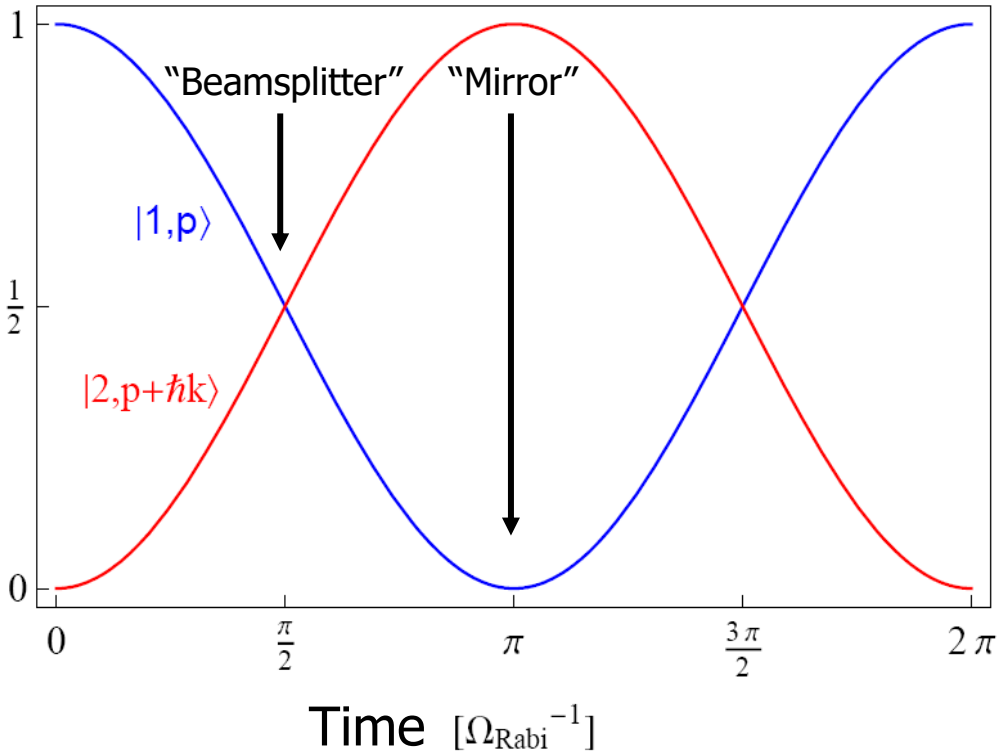
(1) Light absorption:



(2) Stimulated emission:



Rabi oscillations



Light Pulse Atom Interferometry

$$|\text{atom}\rangle = |p\rangle$$

π/2 pulse "beamsplitter"

$$\frac{1}{\sqrt{2}}(|p\rangle + e^{i\Delta\phi}|p+\hbar k\rangle)$$

π pulse "mirror"

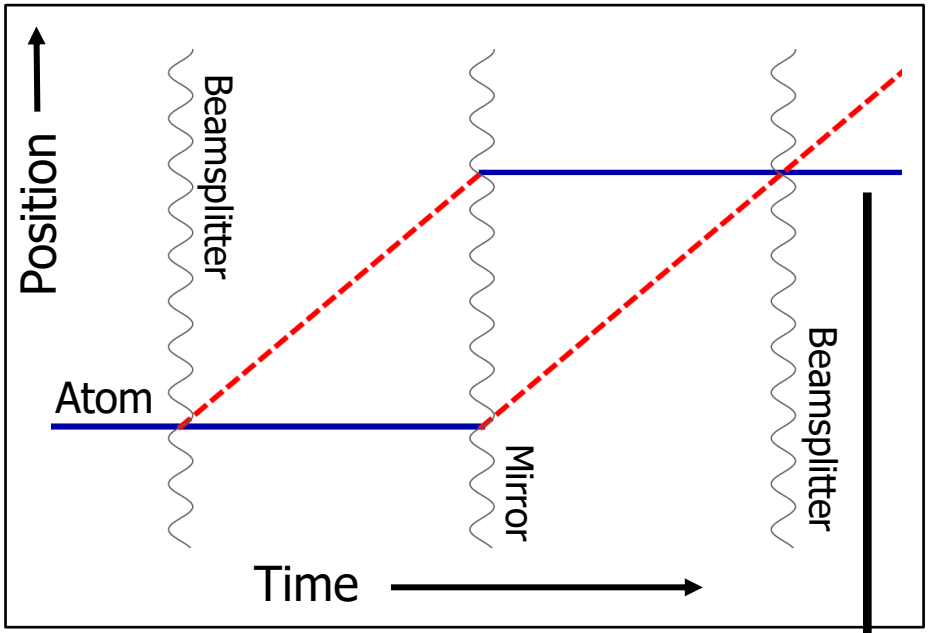
$$\frac{1}{\sqrt{2}}(|p+\hbar k\rangle + e^{i\Delta\phi}|p\rangle)$$

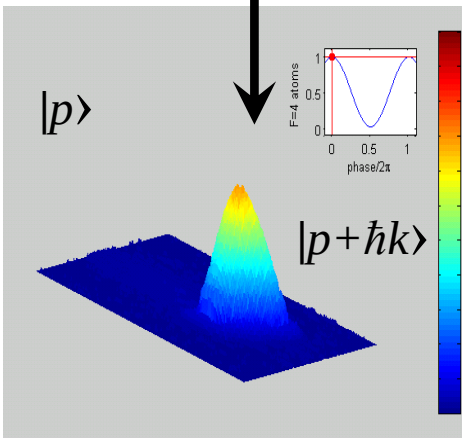
π/2 pulse "beamsplitter"

$$\frac{1}{2}((1+e^{i\Delta\phi})|p\rangle + ((1-e^{i\Delta\phi}))|p+\hbar k\rangle)$$

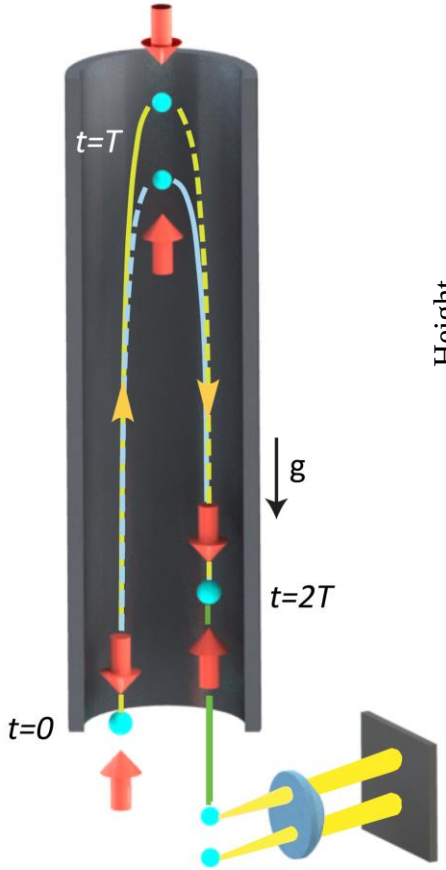
$$\text{Probability in State } |p\rangle = \cos^2\left(\frac{\Delta\phi}{2}\right)$$

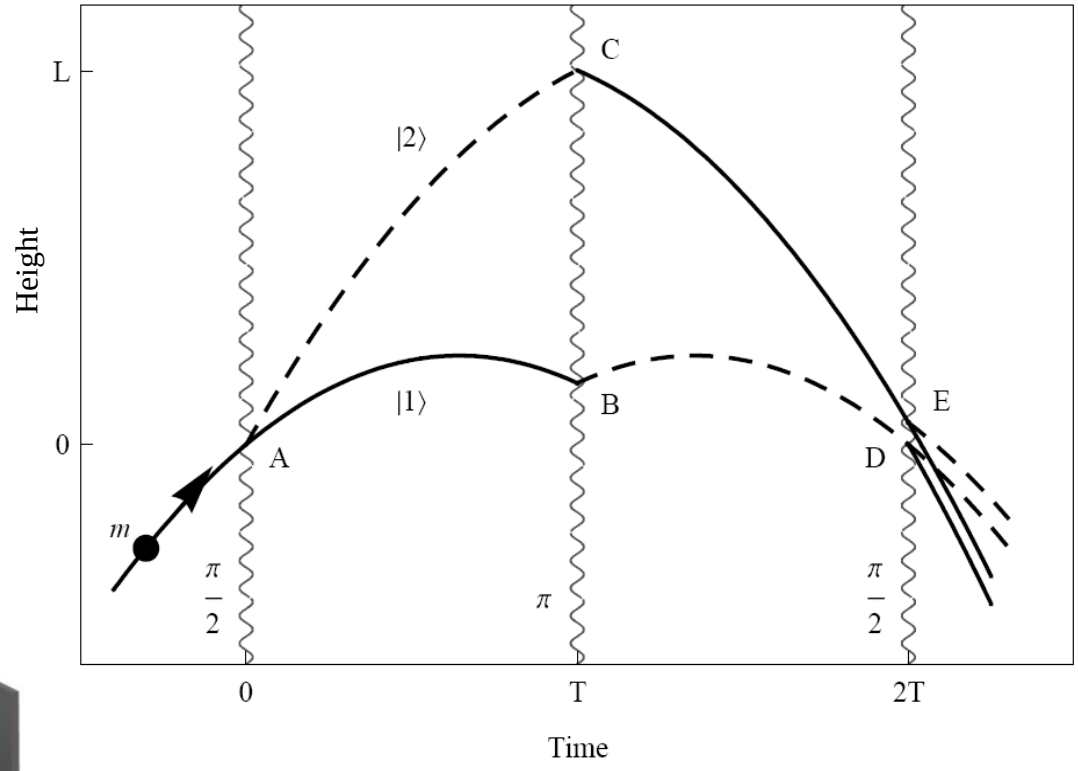
$$\text{Probability in State } |p+\hbar k\rangle = \sin^2\left(\frac{\Delta\phi}{2}\right)$$





Accelerometer sensitivity





$$\Delta\phi = k_{\text{eff}} g T^2$$

Proportional to spacetime area enclosed.

$$\frac{\delta g}{g} \sim \frac{\delta\phi}{k_{\text{eff}} g T^2}$$

Sensitivity

$$\delta\phi \sim \frac{1}{\sqrt{N}}$$

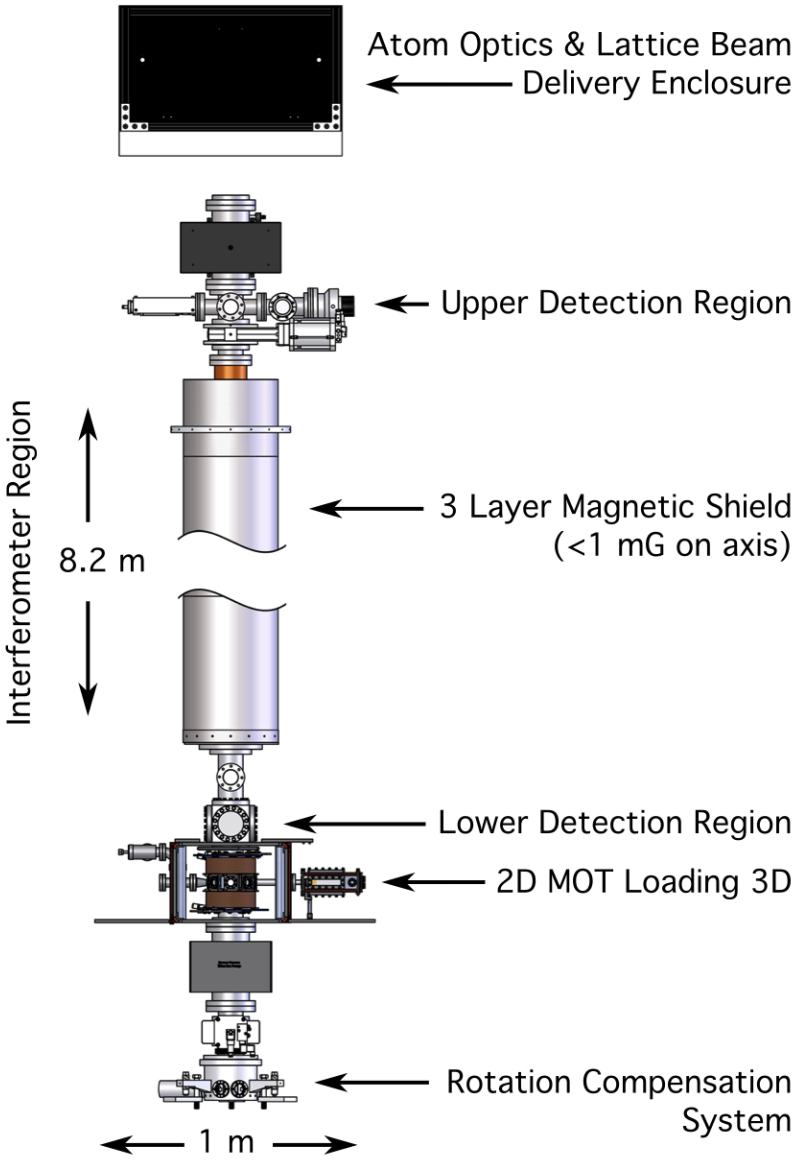
Shot noise

T : Long duration

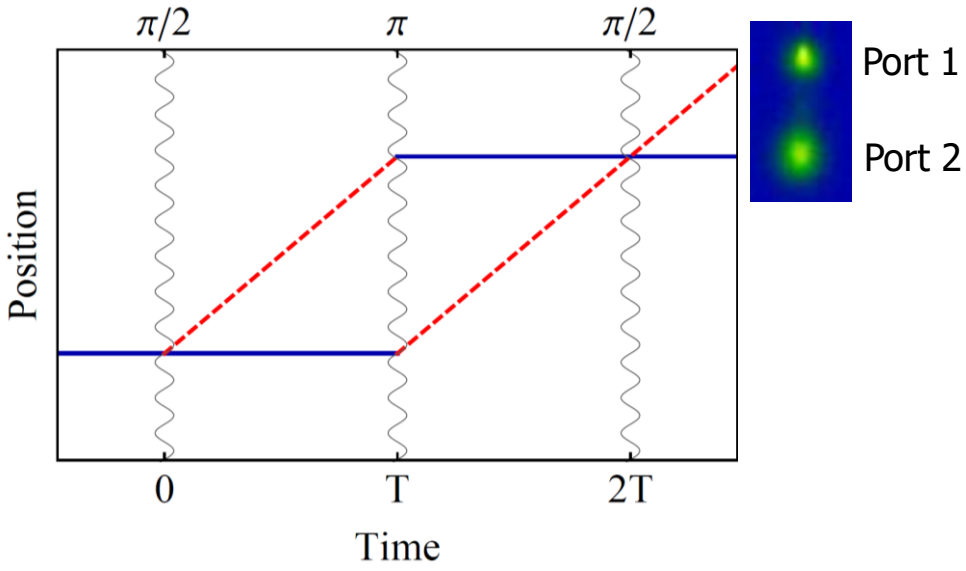
k_{eff} : Large wavepacket separation

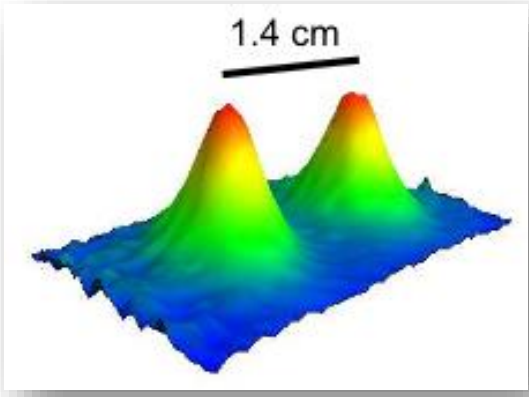
$\delta\phi$: High flux, spin squeezing

Stanford 10-meter scale atomic fountain



Interference at long interrogation time



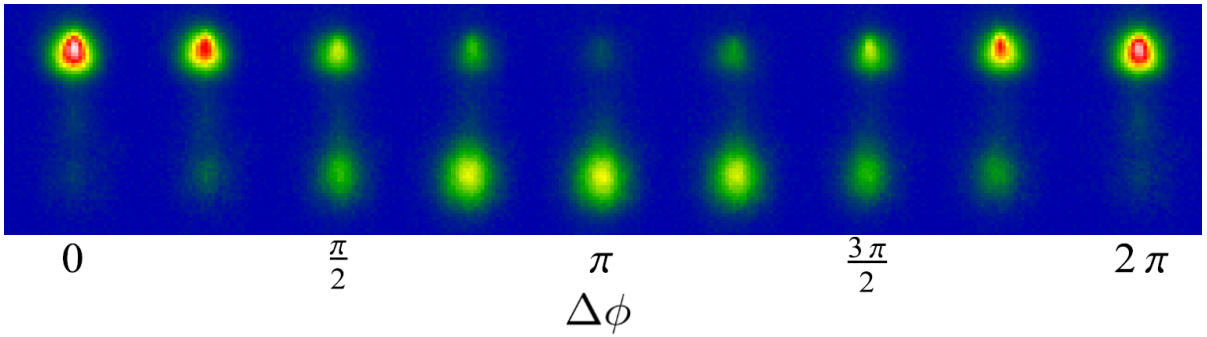


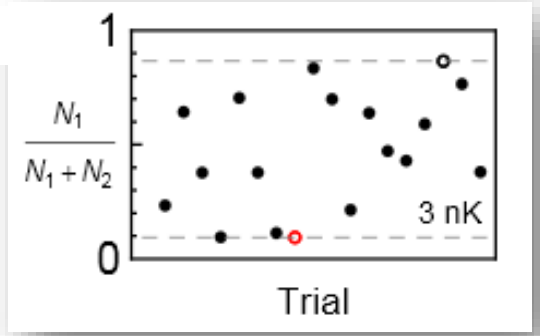
Wavepacket separation at apex (this data 50 nK)

2T = 2.3 seconds

1.4 cm wavepacket separation

Interference (3 nK cloud)



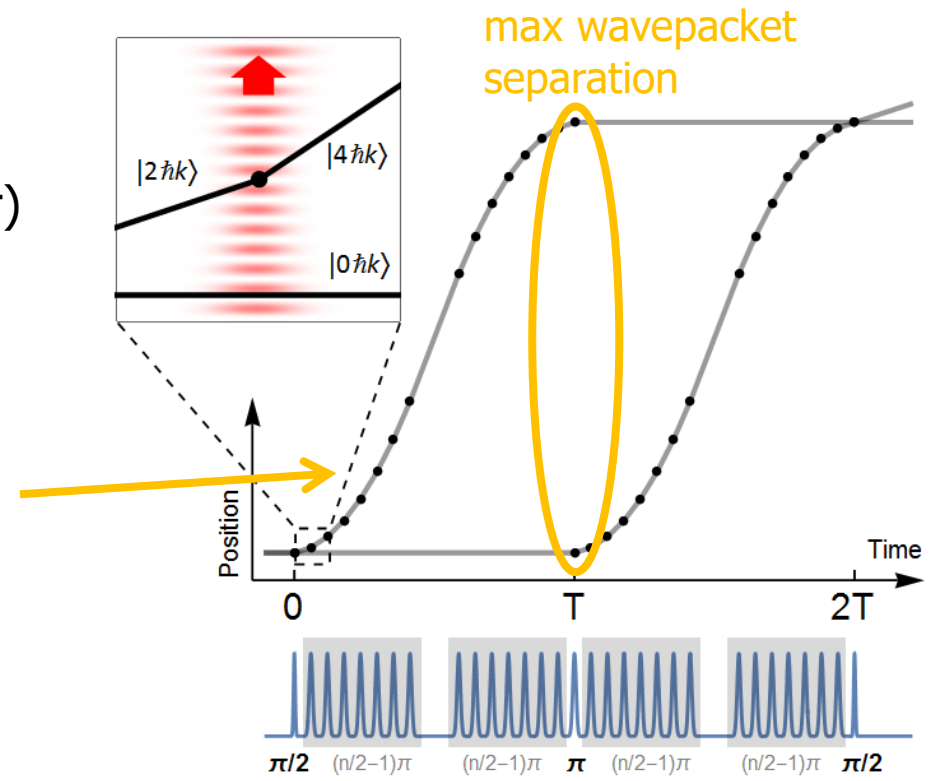


Dickerson, et al., PRL **111**, 083001 (2013).

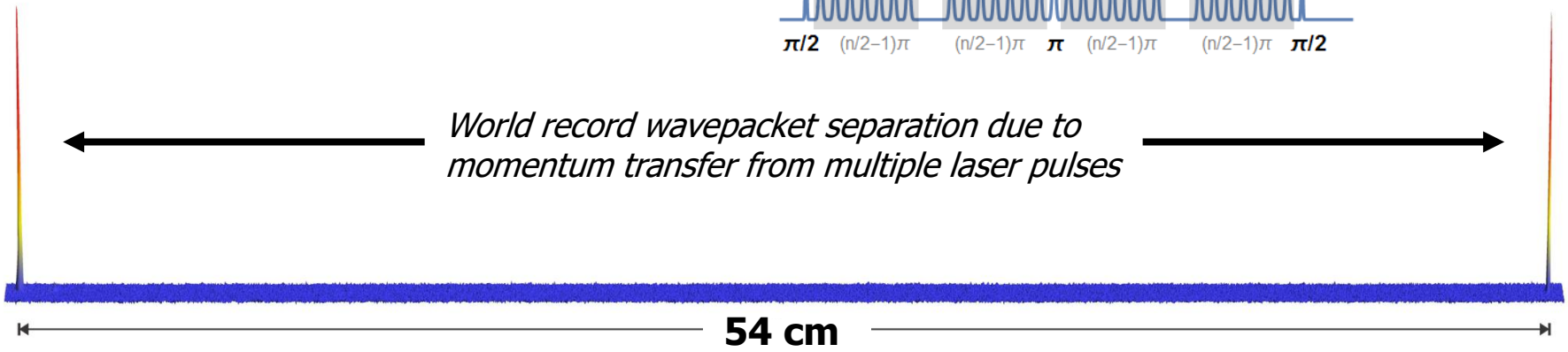
Large space-time area atom interferometry

Long duration (2 seconds), large separation (>0.5 meter) matter wave interferometer

90 photons worth of momentum

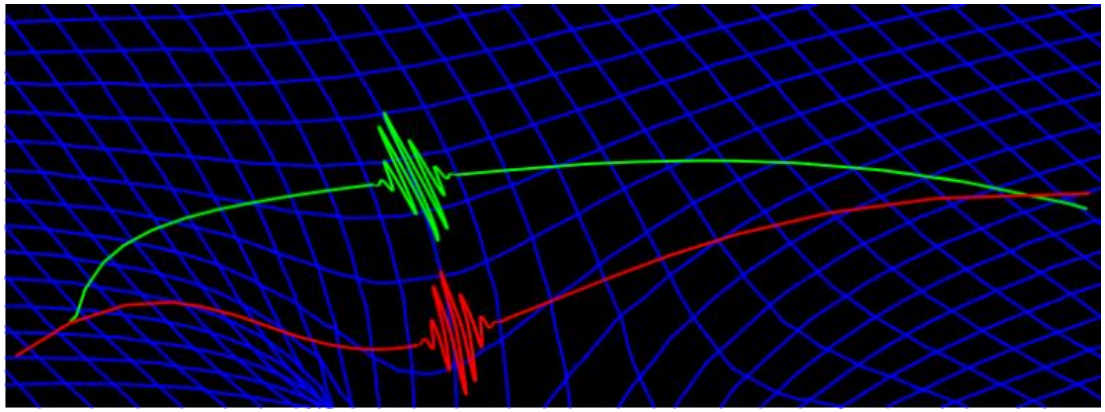


World record wavepacket separation due to momentum transfer from multiple laser pulses



Kovachy et al., *Nature* 2015

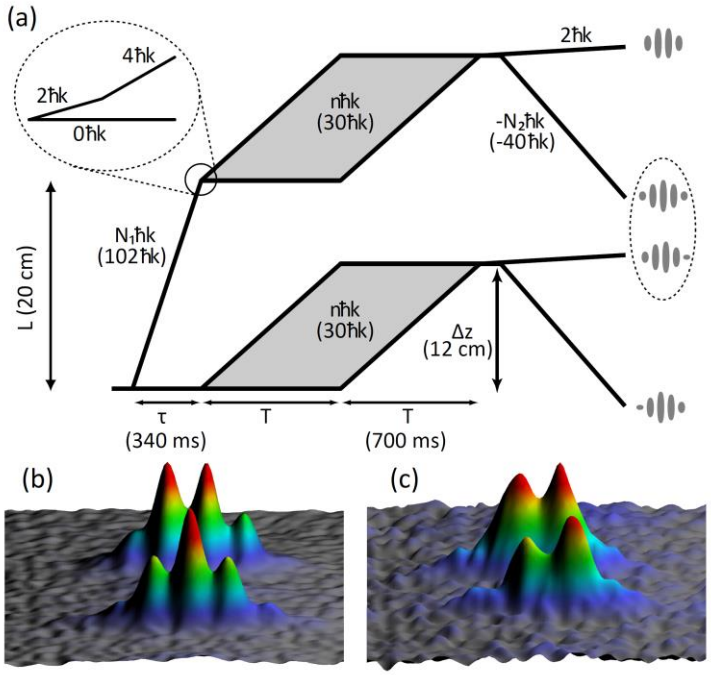
Phase shift from spacetime curvature



In general relativity, gravity is a result of *spacetime curvature*.

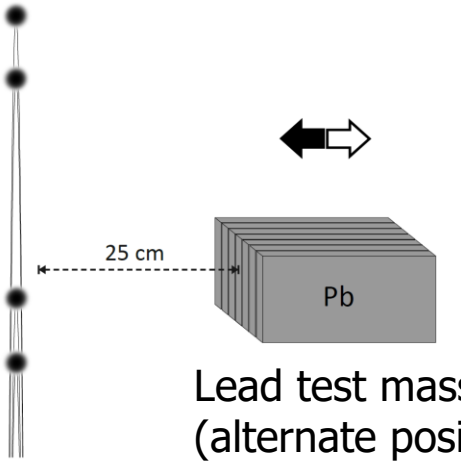
Observed the effect of spacetime curvature across a *single particle's wavefunction.*

Gravity Gradiometer



Interference fringes

Phase shift due to gravity gradient of test mass

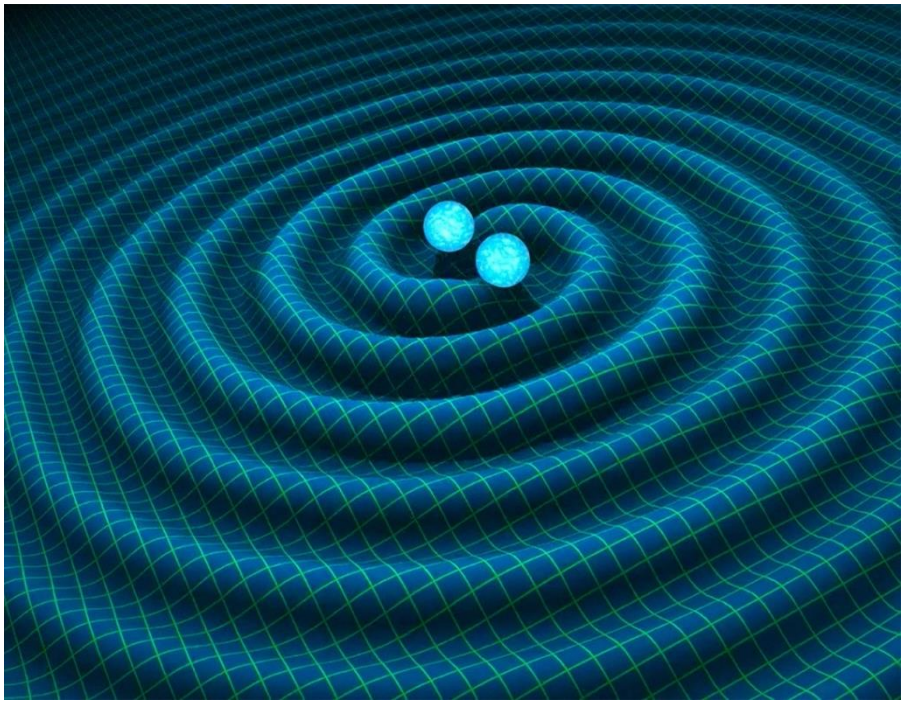


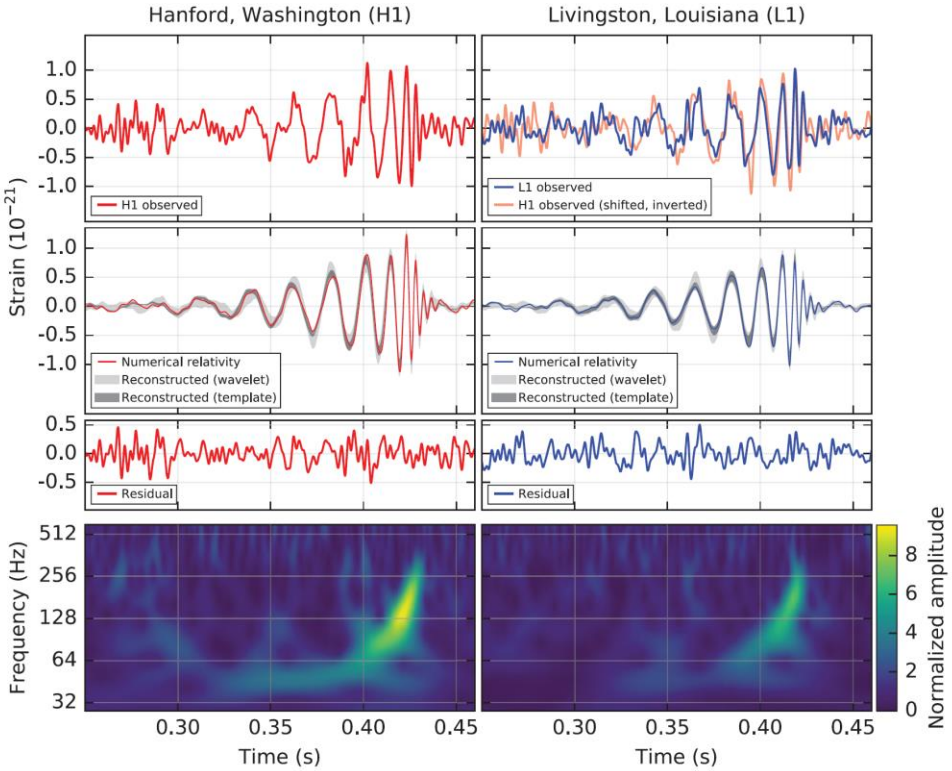
Lead test mass (alternate position)

Asenbaum et al., PRL **118**, 183602 (2017)

Gravitational waves

Gravitational wave astronomy offers a new way to observe the universe

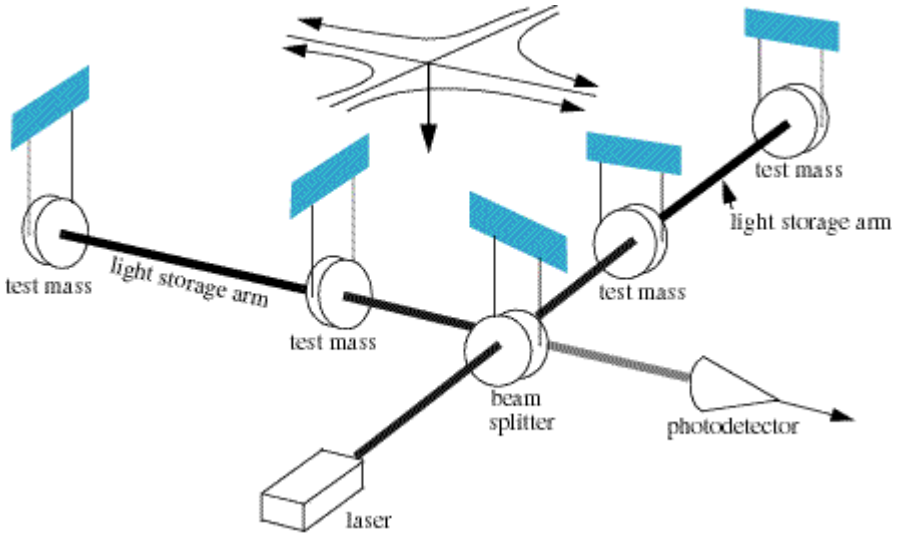




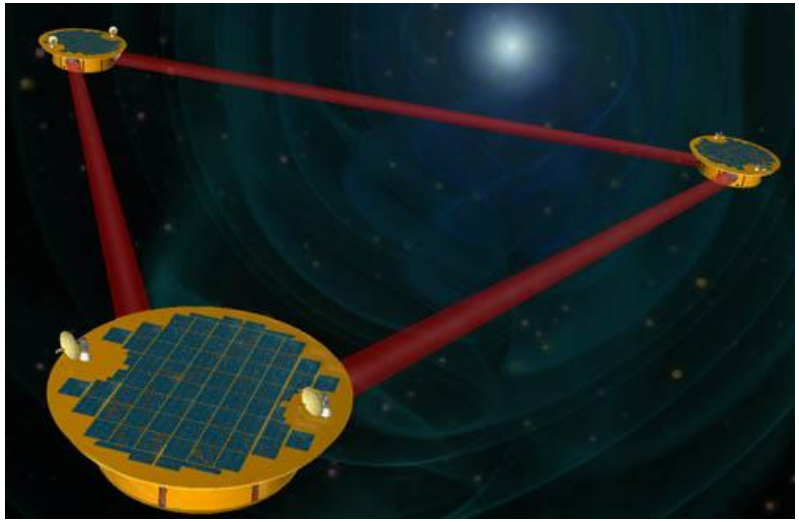
GW 150914 – Merging of two ~30 solar mass black holes

B. P. Abbott et al., PRL **116**, 061102 (2016)

Laser Interferometer Detectors



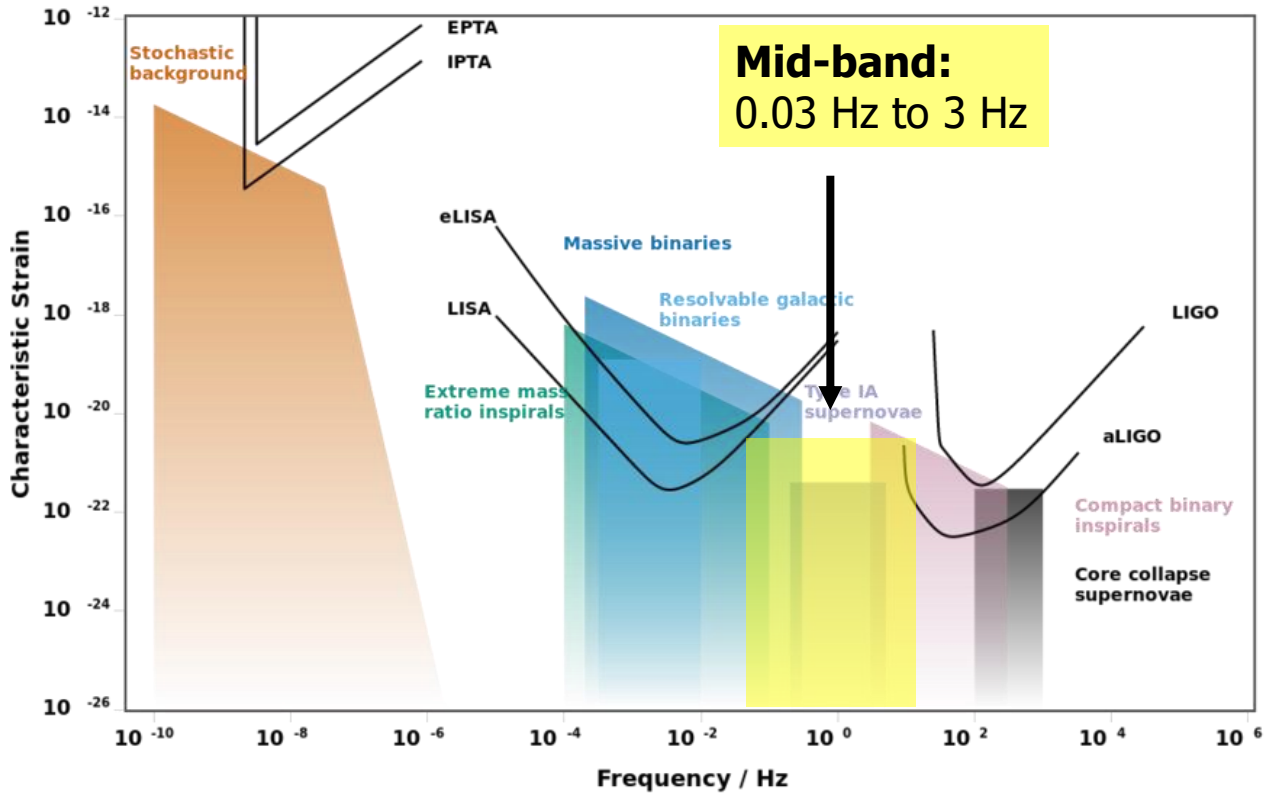
Gound-based detectors: LIGO, VIRGO, GEO (> 10 Hz)



Space-based detector concept: LISA (1 mHz – 100 mHz)

Atomic sensors for gravitational wave detection

Atomic clocks and **atom interferometry** offer the potential for gravitational wave detection in an *unexplored frequency range* ("mid-band")



Mid-band science

- LIGO sources before they reach LIGO band
- Sky localization: predict when and where events will occur (multi-messenger astronomy)
- Cosmological sources
- Wave-like dark matter (dilaton, ALP, …)

Sky position determination

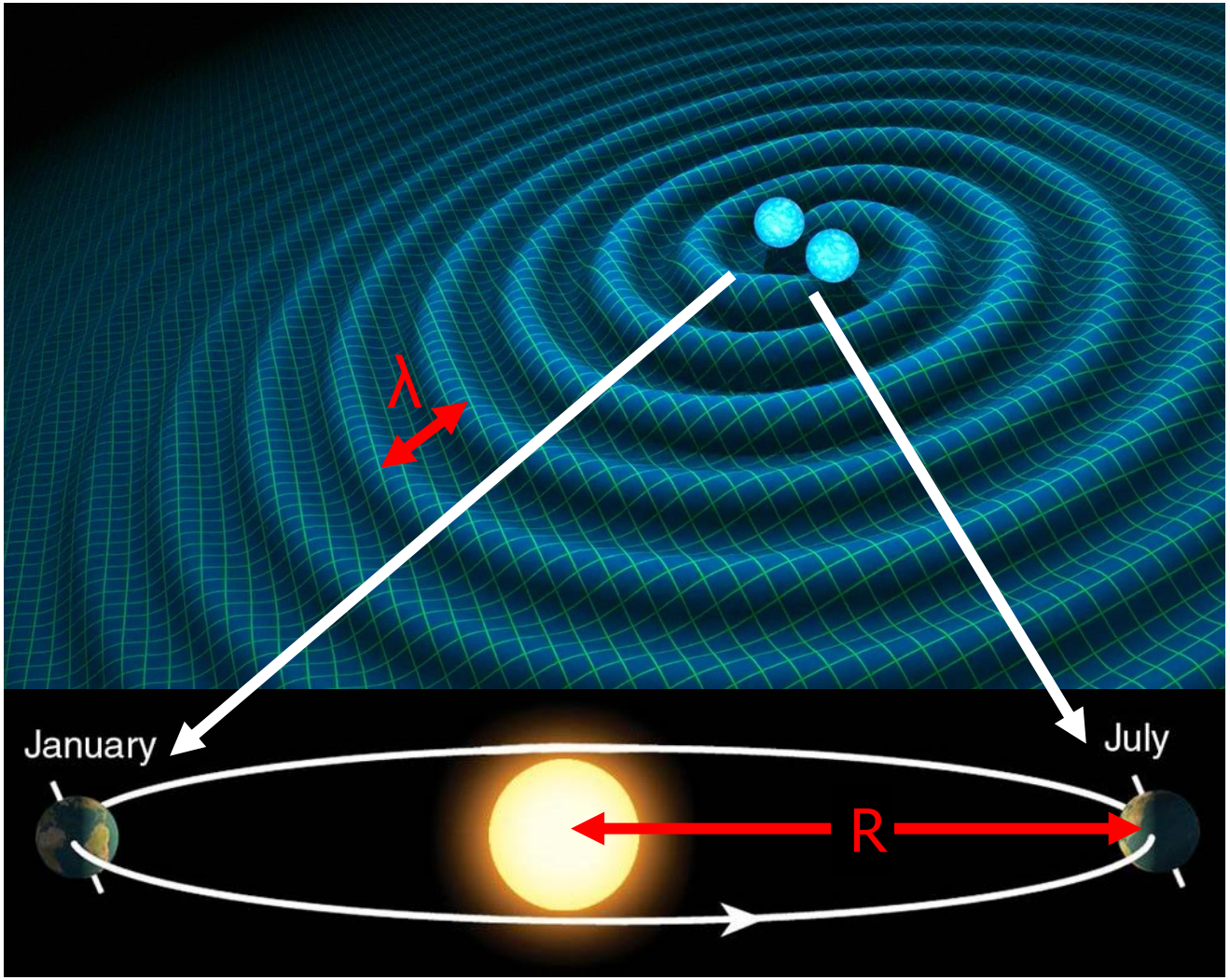
Sky localization precision:

$$\sqrt{\Omega_s} \sim \left(\mathrm{SNR} \cdot \frac{R}{\lambda}\right)^{-1}$$

Mid-band advantages

- Small wavelength λ
- Long source lifetime (~months) maximizes effective R

Benchmark	$\sqrt{\Omega_s}$ [deg]
GW150914	0.16
GW151226	0.20
NS-NS (140 Mpc)	0.19

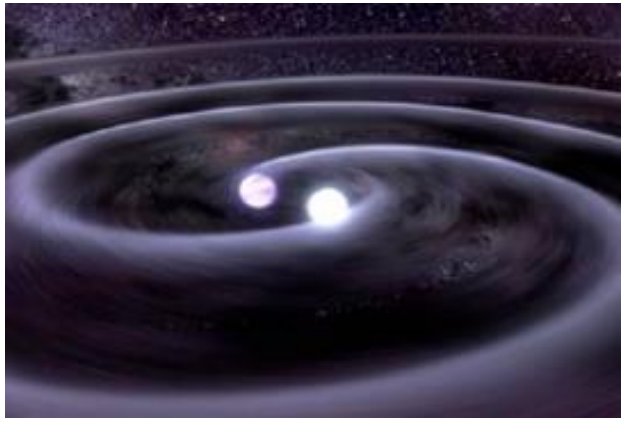


Graham et al., **PRD** 024052 (2018).

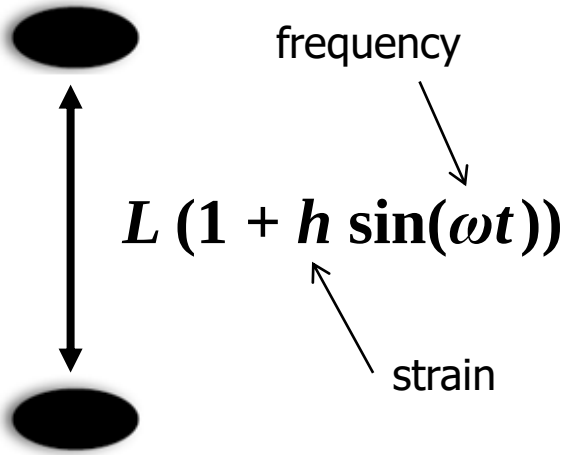
Images: R. Hurt/Caltech-JPL; 2007 Thomson Higher Education

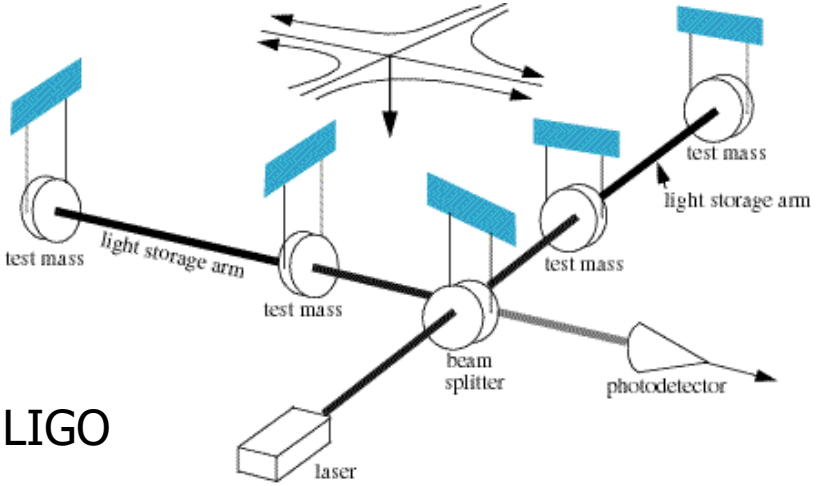
Gravitational Wave Detection

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



Megaparsecs…



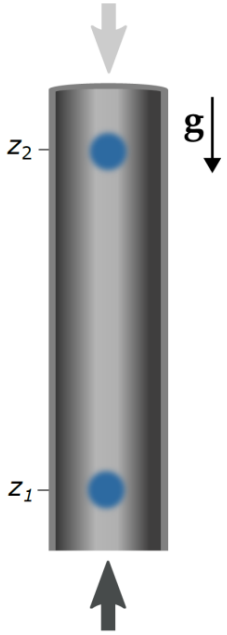


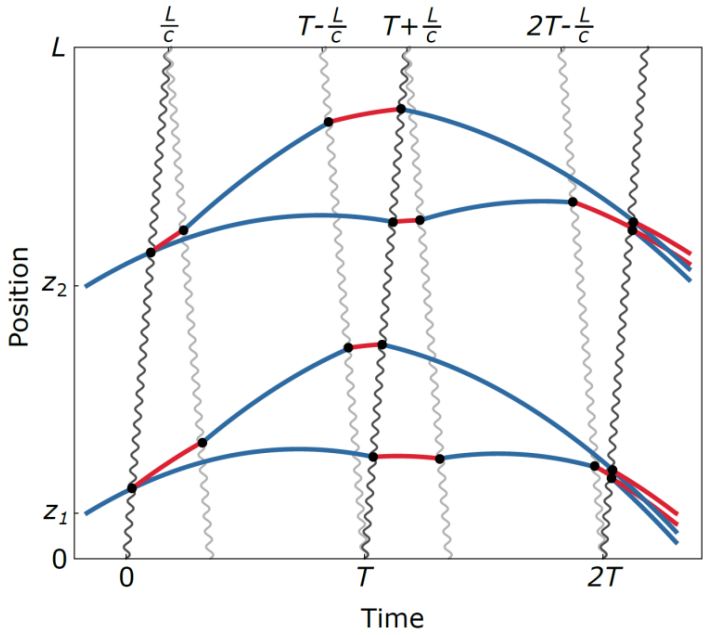
LIGO

- LIGO and other optical interferometers **use two baselines**
- In principle, **only one is required**
- Second baseline needed to reject laser technical noise

Long baseline atom interferometry

- Compare two atomic sensors separated by a large distance
- Differential measurement suppresses laser noise





Mid-band gravitational wave detection

Unexplored frequencies (0.03 Hz to 3 Hz), complementary to LIGO

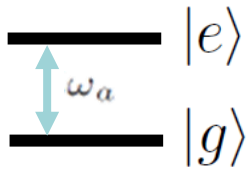
Ultralight wave-like dark matter probe

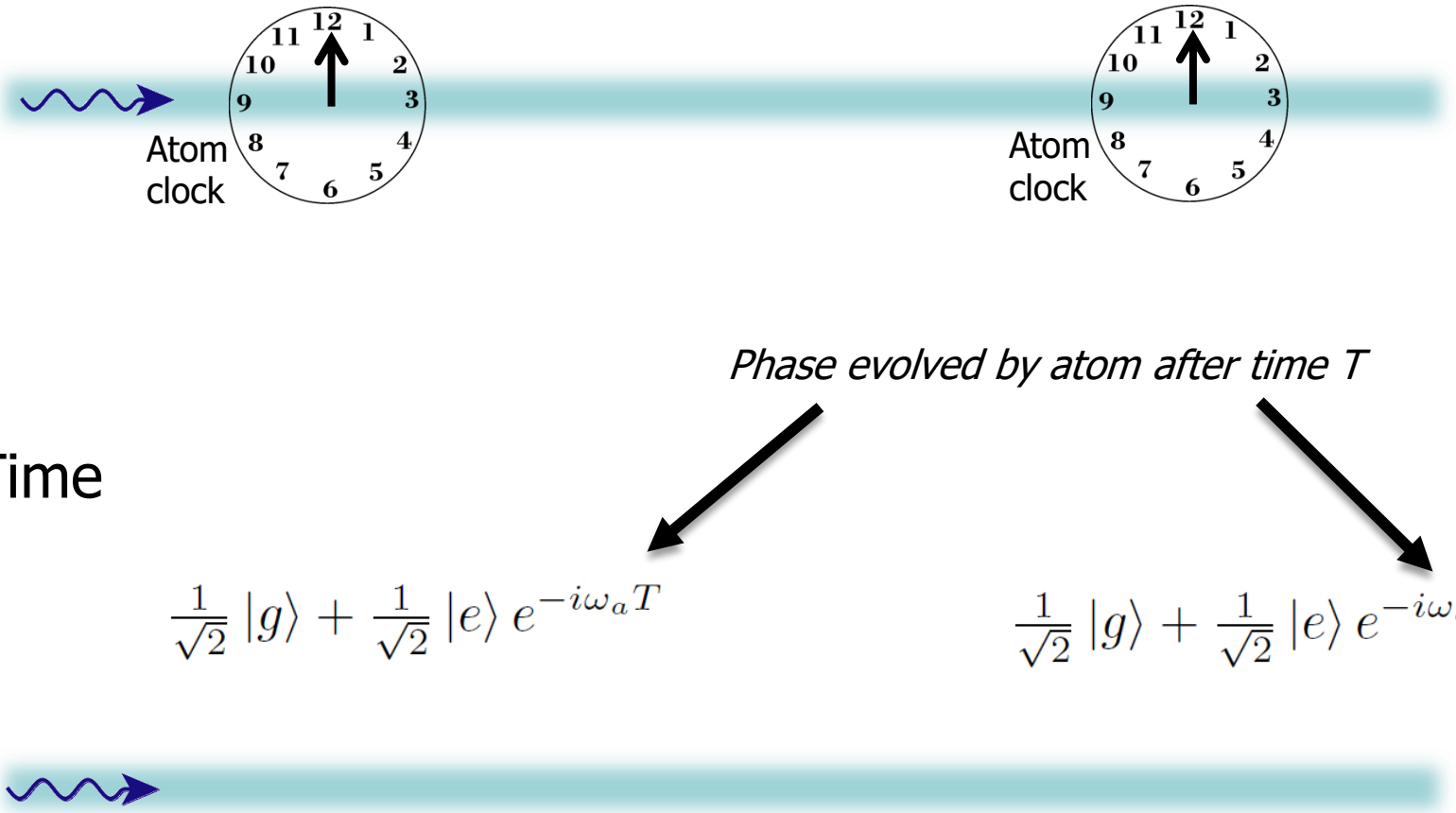
Scalar- and vector-coupled DM candidates $<10^{-14}$ eV (Hz range)

Tests of quantum mechanics at macroscopic scales

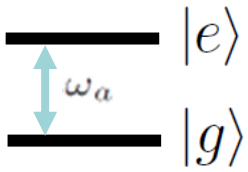
Meter-scale wavepacket separation, duration of seconds

Simple Example: Two Atomic Clocks





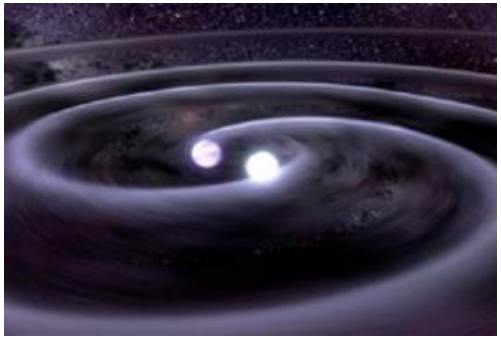
Simple Example: Two Atomic Clocks



$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle$$

$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle$$

Time



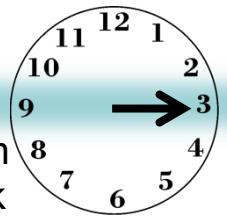
GW changes light travel time

$$\Delta T \sim hL/c$$

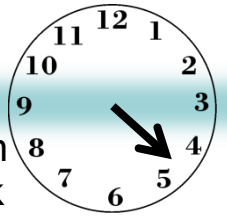
$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle\, e^{-i\omega_a T}$$

$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle\, e^{-i\omega_a (T+\Delta T)}$$

Atom clock

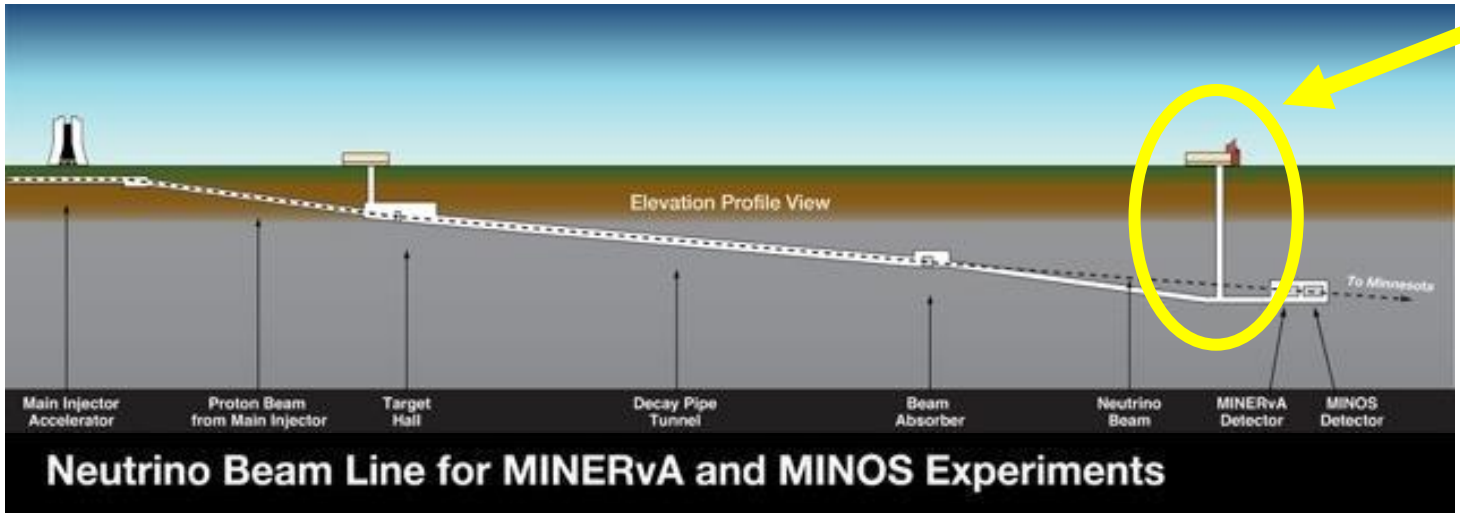


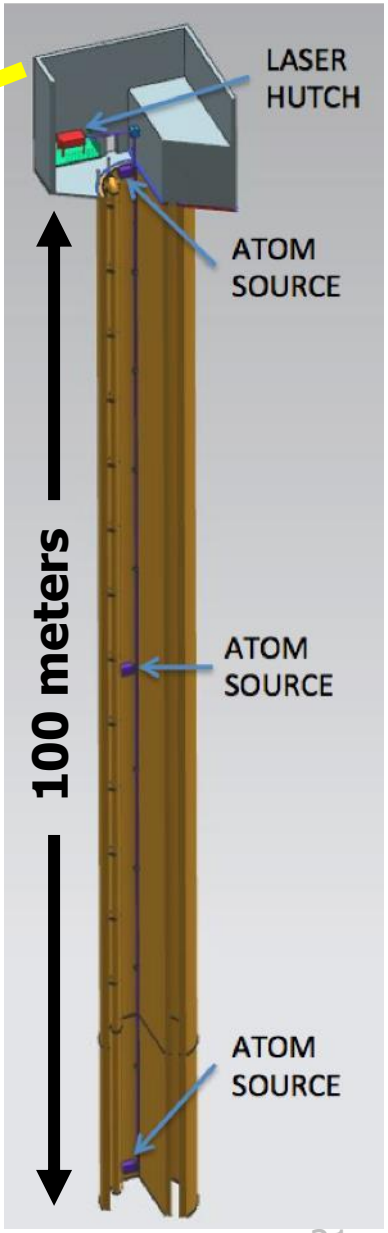
Atom clock



MAGIS-100: Detector prototype at Fermilab

Matter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor





- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Intermediate step to full-scale (km) detector for gravitational waves
- Clock atom sources (Sr) at three positions to realize a gradiometer
- Probes for ultralight scalar dark matter beyond current limits (Hz range)
- Extreme quantum superposition states: >meter wavepacket separation, up to 9 seconds duration

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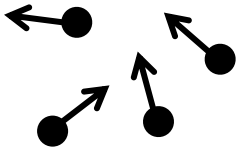
Ultralight dark matter

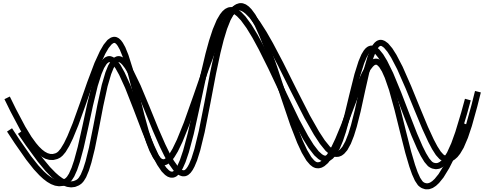
WIMPS

- Mass ~10 - 100 GeV
- Particle-like (deposit energy in detector)

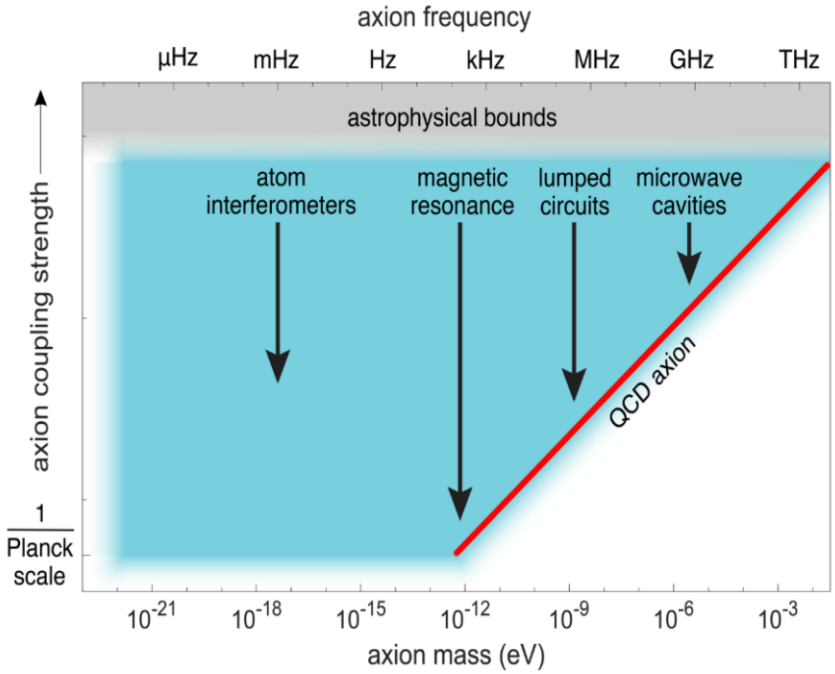


"Ultralight" dark matter (e.g., axions, dilatons, etc.)

- Low mass, high number density
- Would act like a **classical field**



One example is the axion, and axion-like particles



Dark matter BRN report

Ultralight scalar dark matter

Ultralight dilaton DM acts as a background field (e.g., mass ~10^{-15} eV)

$$\mathcal{L} = +\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - \sqrt{4\pi G_N}\phi\left[d_{m_e}m_e\bar{e}e - \frac{d_e}{4}F_{\mu\nu}F^{\mu\nu}\right] + \ldots$$

DM scalar field

Electron coupling

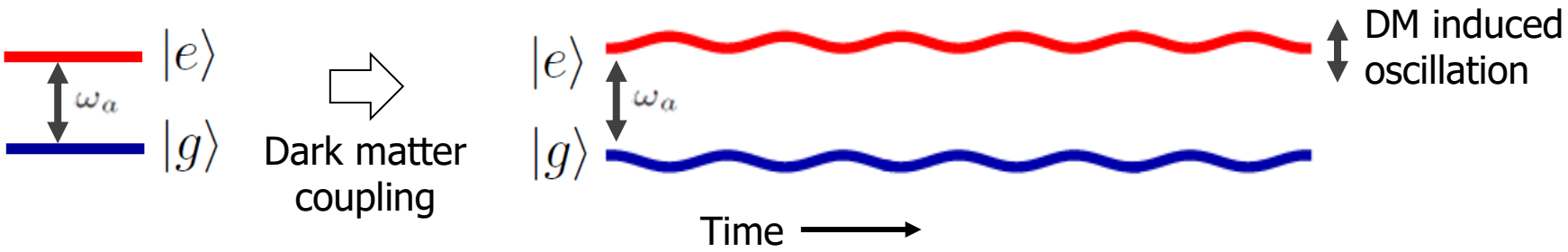
Photon coupling

e.g., QCD

$$\phi(t,\mathbf{x}) = \phi_0\cos\left[m_\phi(t-\mathbf{v}\cdot\mathbf{x})+\beta\right] + \mathcal{O}\left(|\mathbf{v}|^2\right) \qquad \phi_0 \propto \sqrt{\rho_{\rm DM}}$$

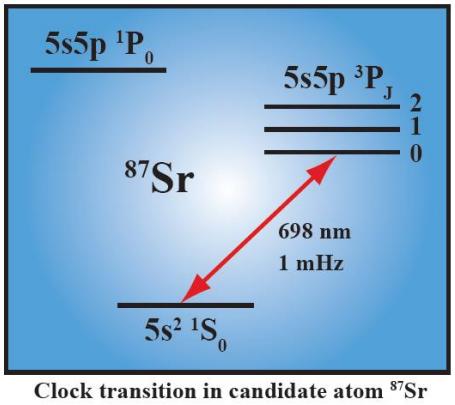
DM mass density

DM coupling causes time-varying atomic energy levels:



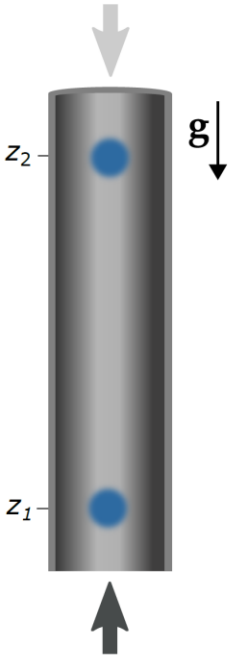
Clock atom interferometry

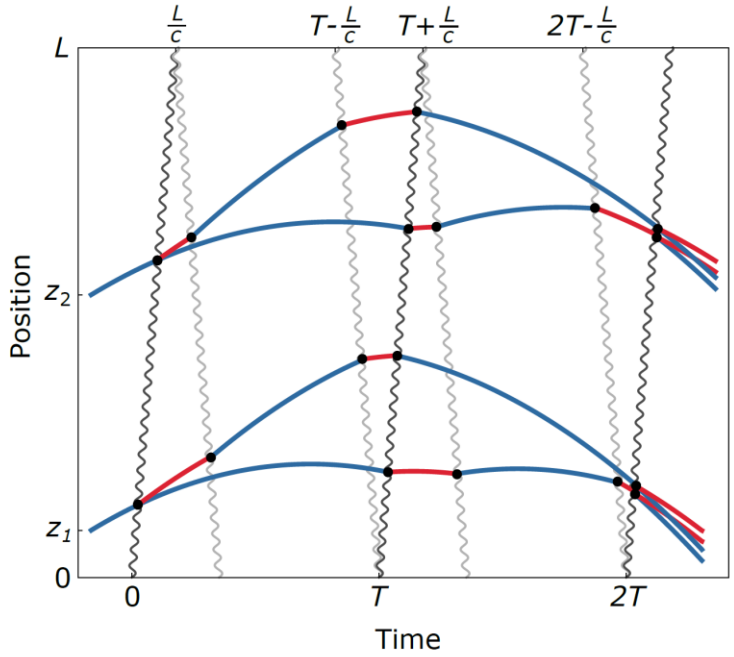
New kind of atom interferometry using **single-photon transitions** between long-lived **clock states**



Clock transition in candidate atom ^{87}Sr

Differential measurement (**gradiometer**) to suppress laser noise





Excited state phase evolution:

$$\Delta\phi \sim \omega_A \, (2L/c)$$

(variations over time T)

Two ways for phase to vary:

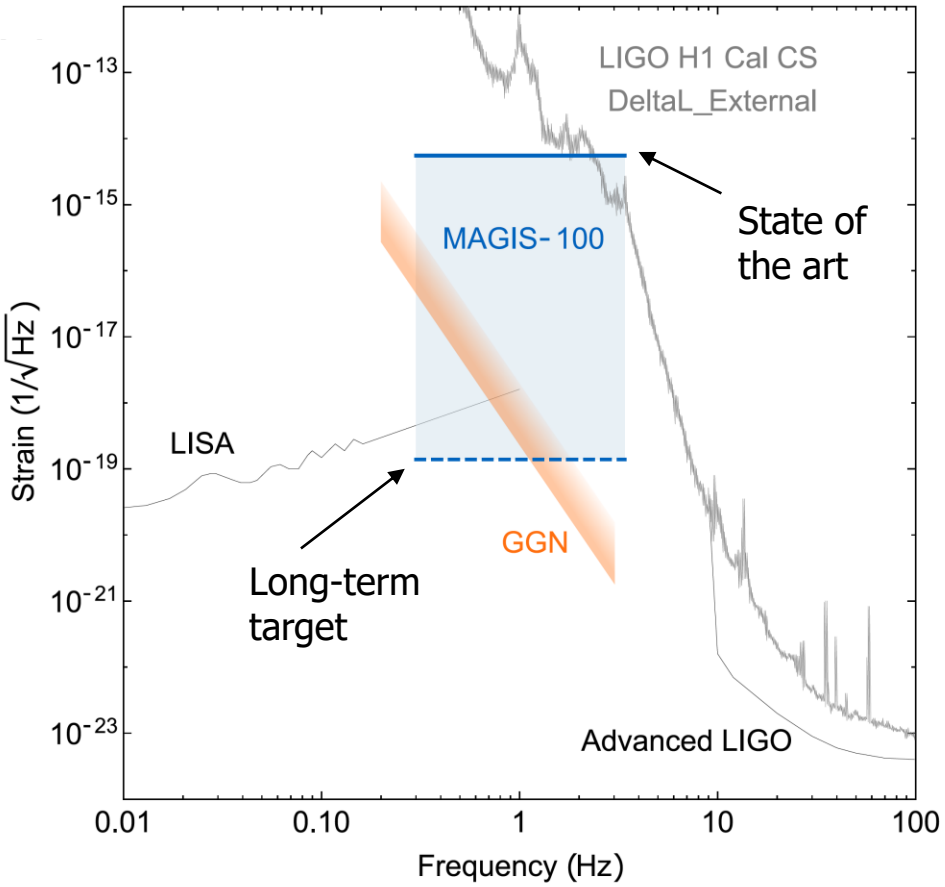
$\delta\omega_A$ *Dark matter*

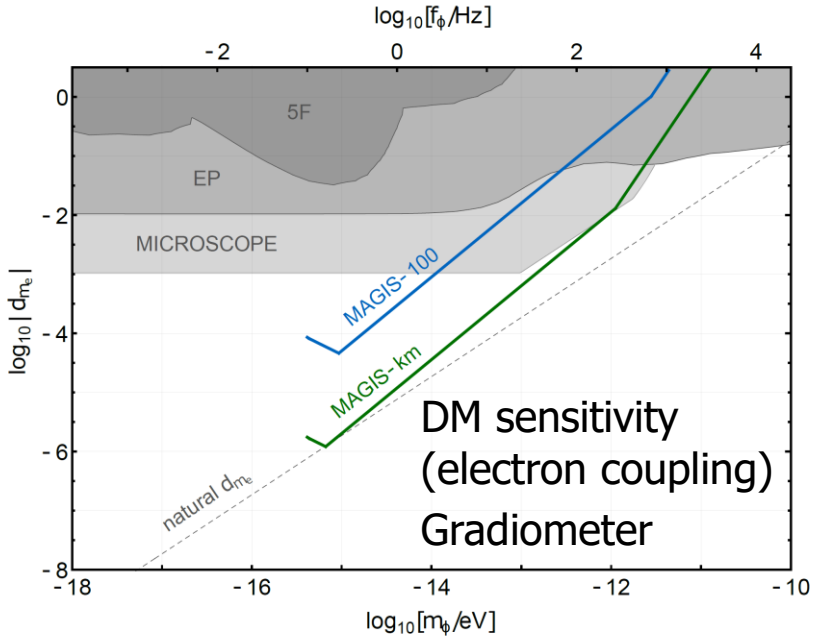
$\delta L = hL$ *Gravitational wave*

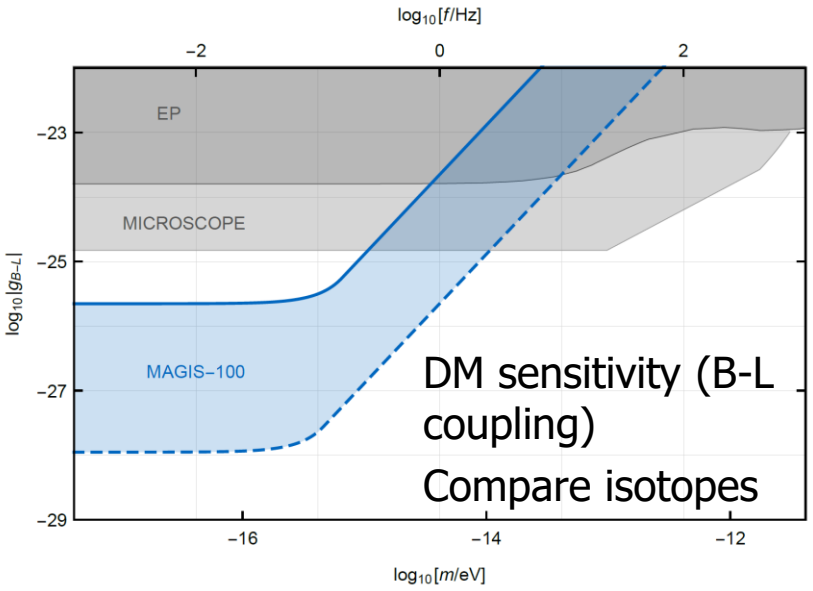
Graham et al., PRL **110**, 171102 (2013).
Arvanitaki et al., PRD **97**, 075020 (2018).

MAGIS-100 projected sensitivity

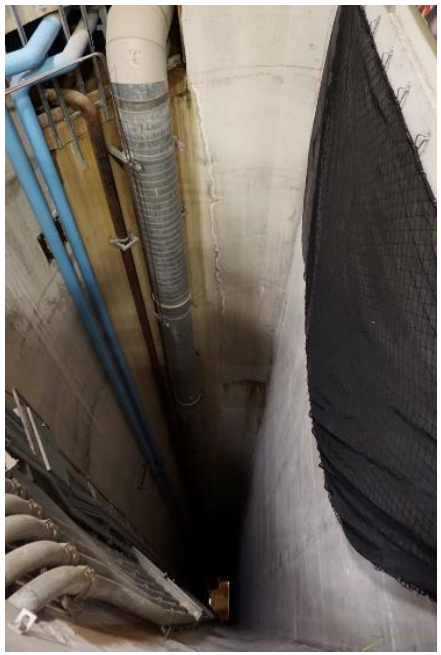
Gravitational wave sensitivity



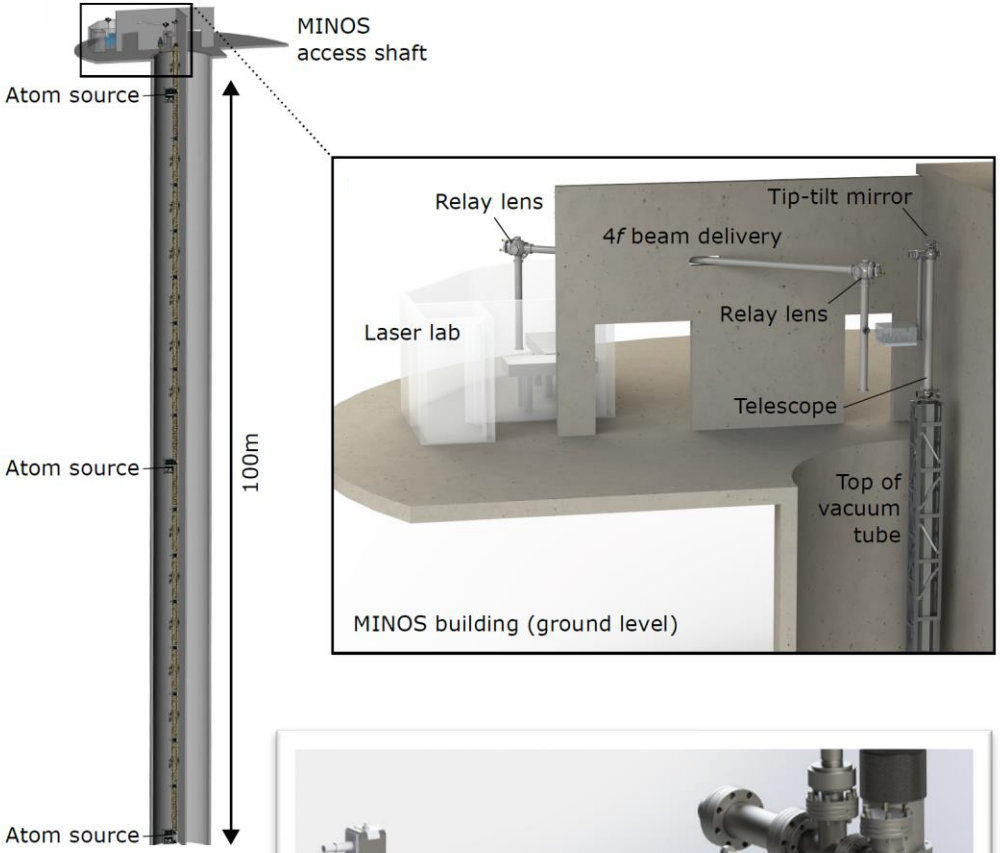


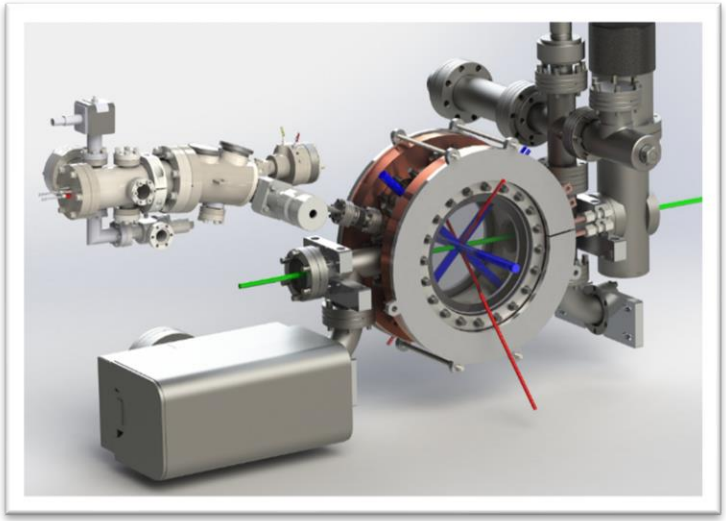


MAGIS-100 design

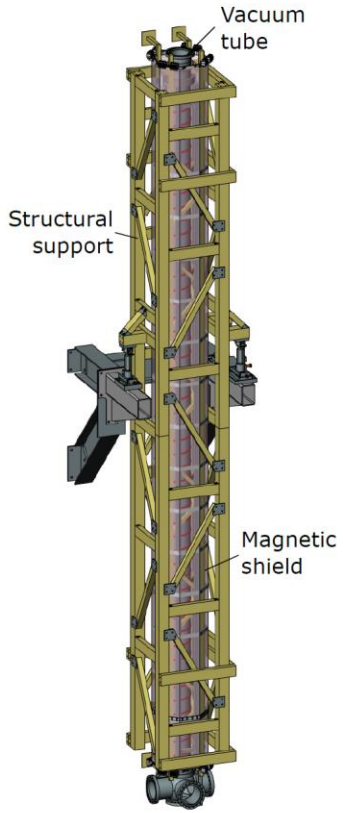


MINOS access shaft



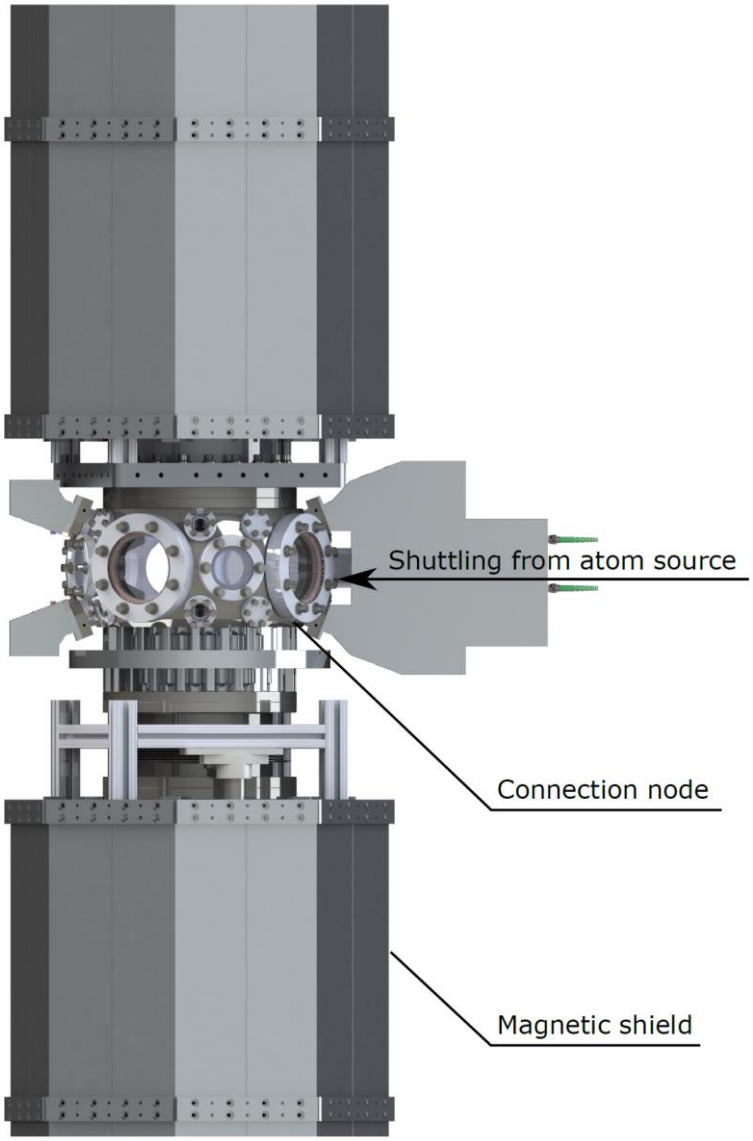


Sr atom sources



Modular section of 100 meter science region

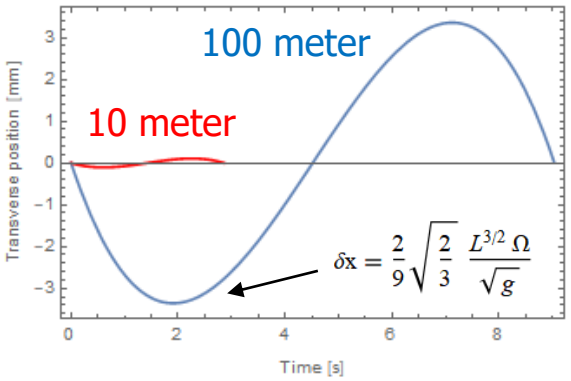
Optical lattice launch



689 nm lattice for vertical atom launching before interferometry

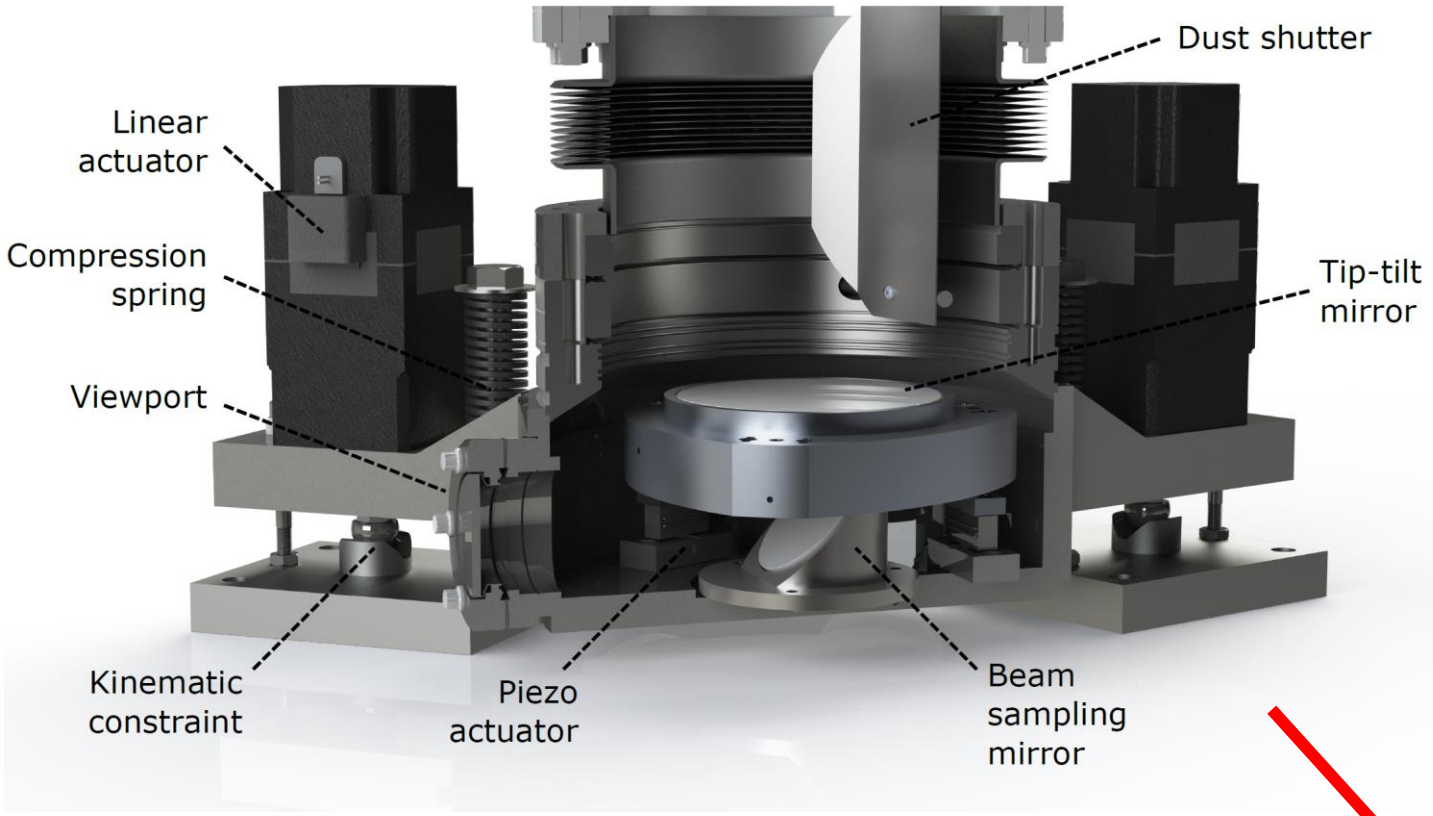
Lattice optics design

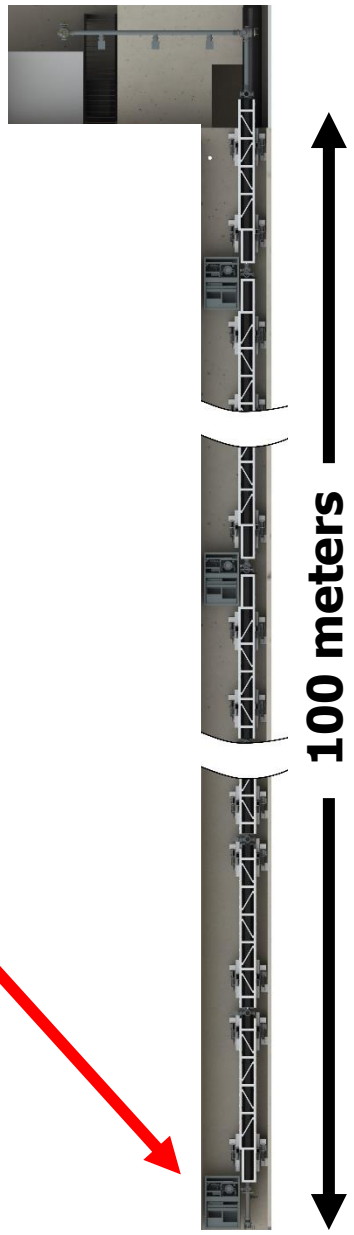
- In-vacuum optics minimize shield gap
- X beam path design supports independent launches for each source
- Dynamic launch angle fine tuning with PZT mirror for Coriolis pre-compensation
- Beam position sensing photodiodes
- Monolithic beam delivery module



Minimum Coriolis displacement launch

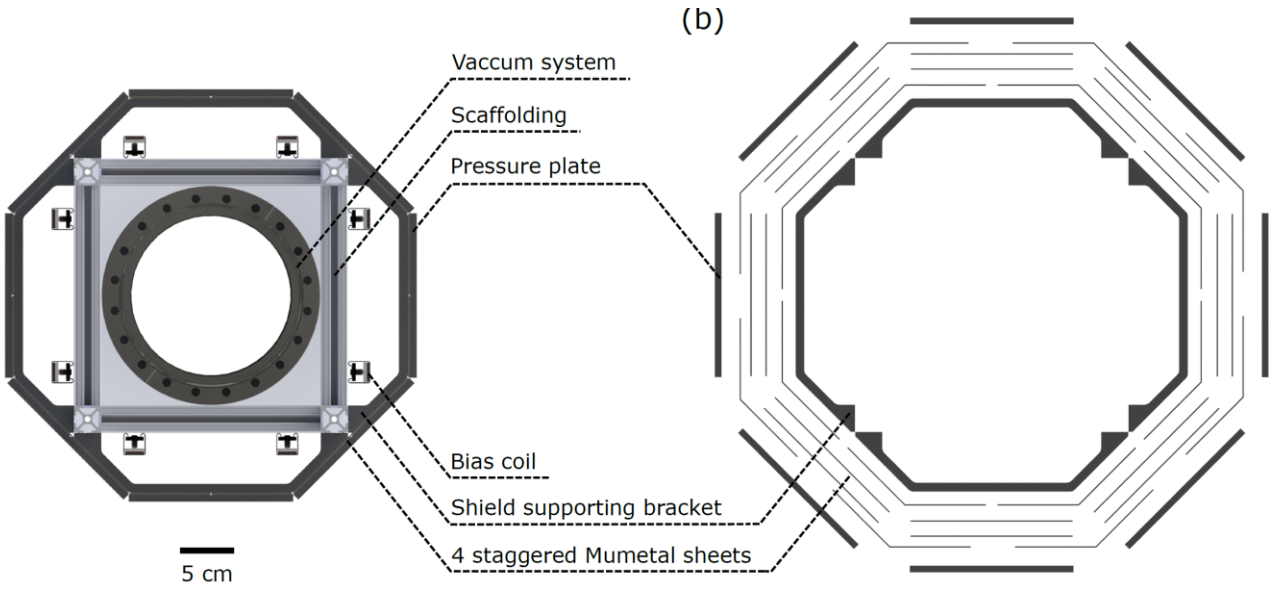
MAGIS-100 tip-tilt mirror for rotation compensation



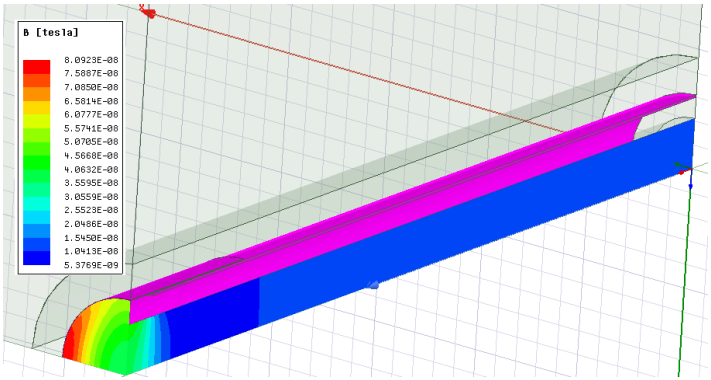


- Mirror at bottom to reflect interferometry laser light
- 3-axis piezo actuators for fine control
- Suppress Coriolis phase shifts by counter-rotating
- Coarse alignment with linear actuators

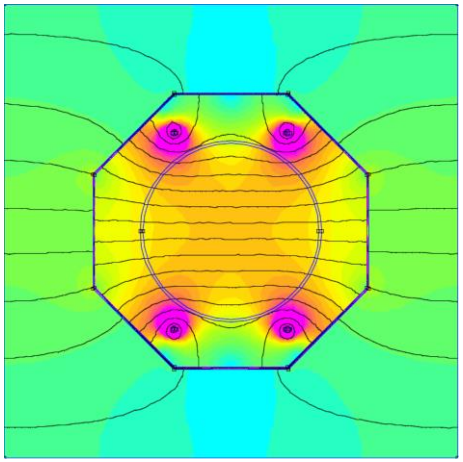
Magnetic shield and bias coils



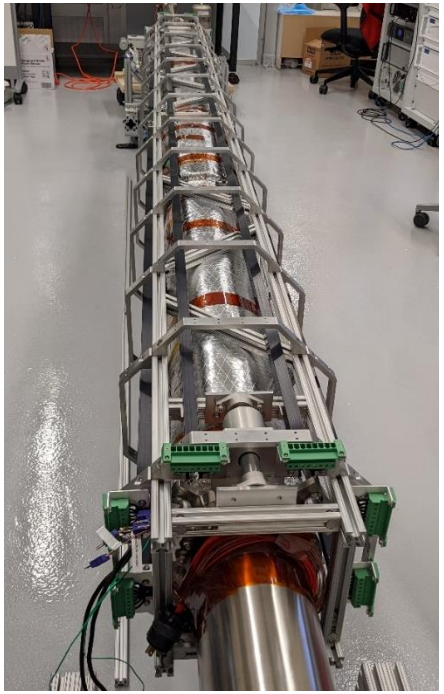
- Octagon shield
- 4 sheet, overlapping design
- Adapted from proven Hannover design
- Internal bias coils



3D horizontal field simulation



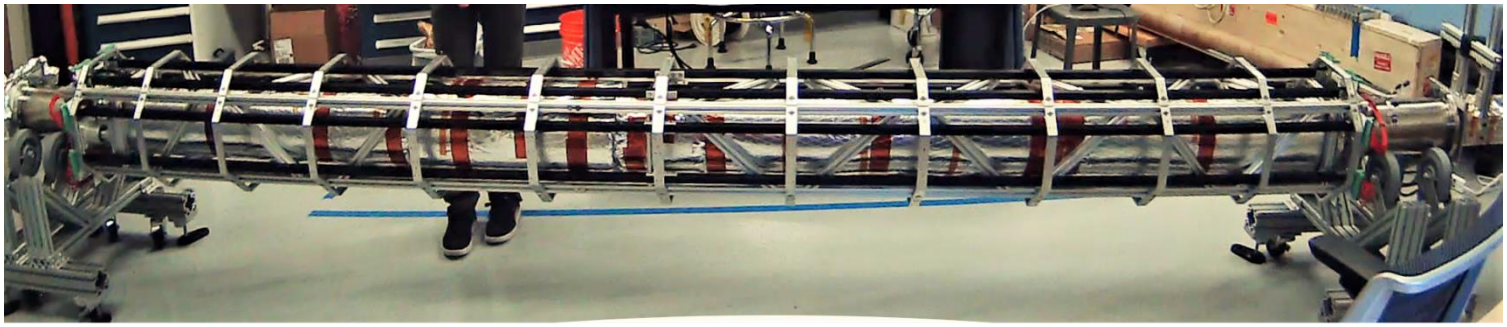
Shield + bias field simulation



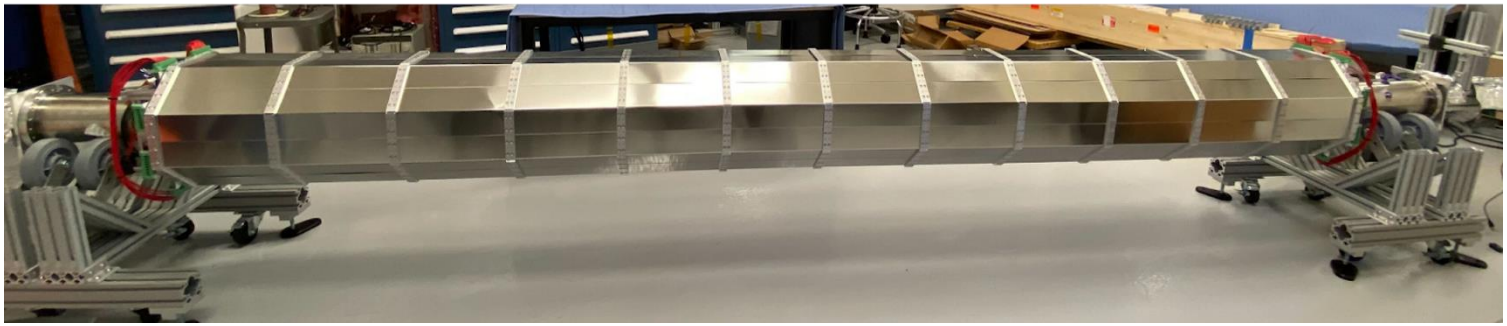
Bias coils installed

Magnetic shield assembly and test

Assembled prototype MAGIS module with horizontal bias coils and magnetic shield

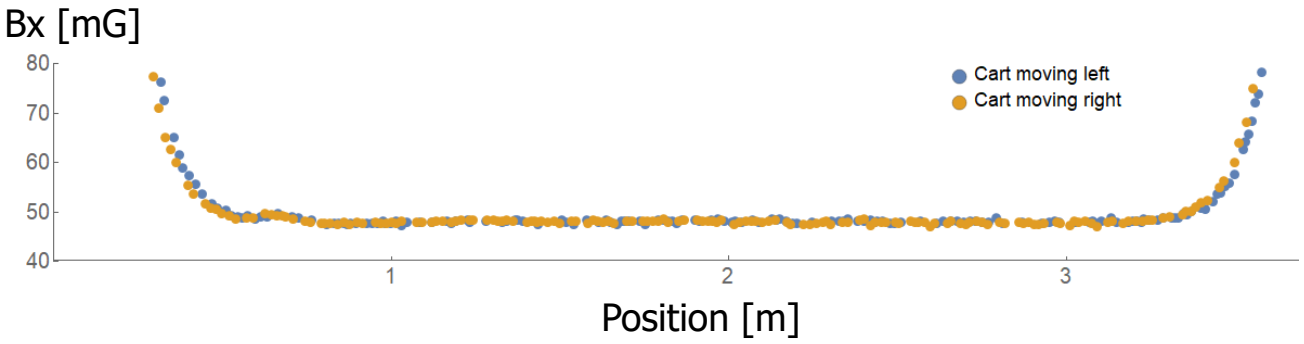


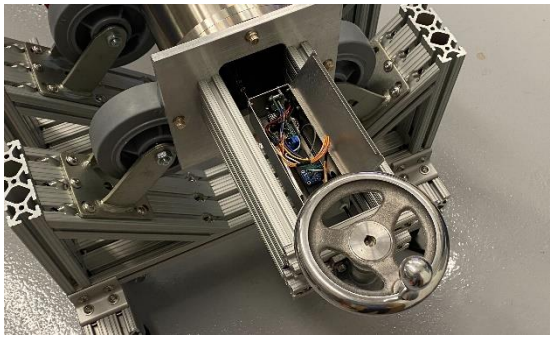
Before shield



With shield

After degauss, magnetic shield meets specifications:

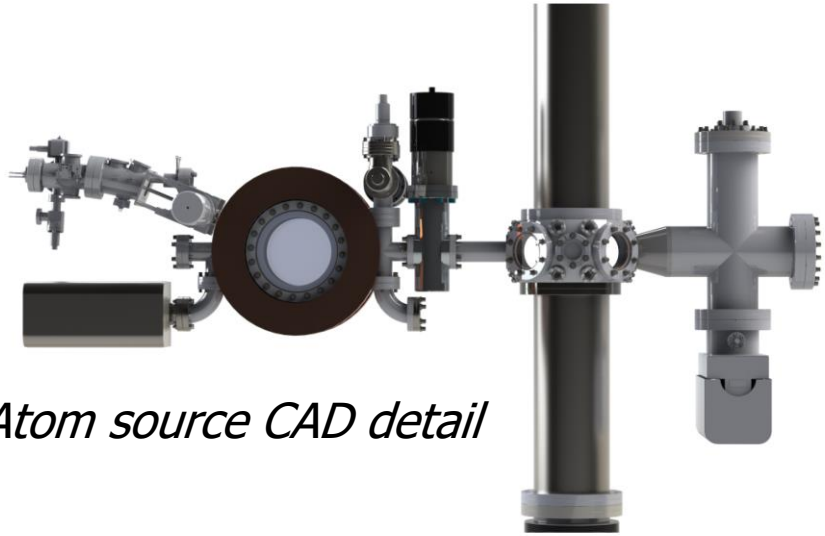




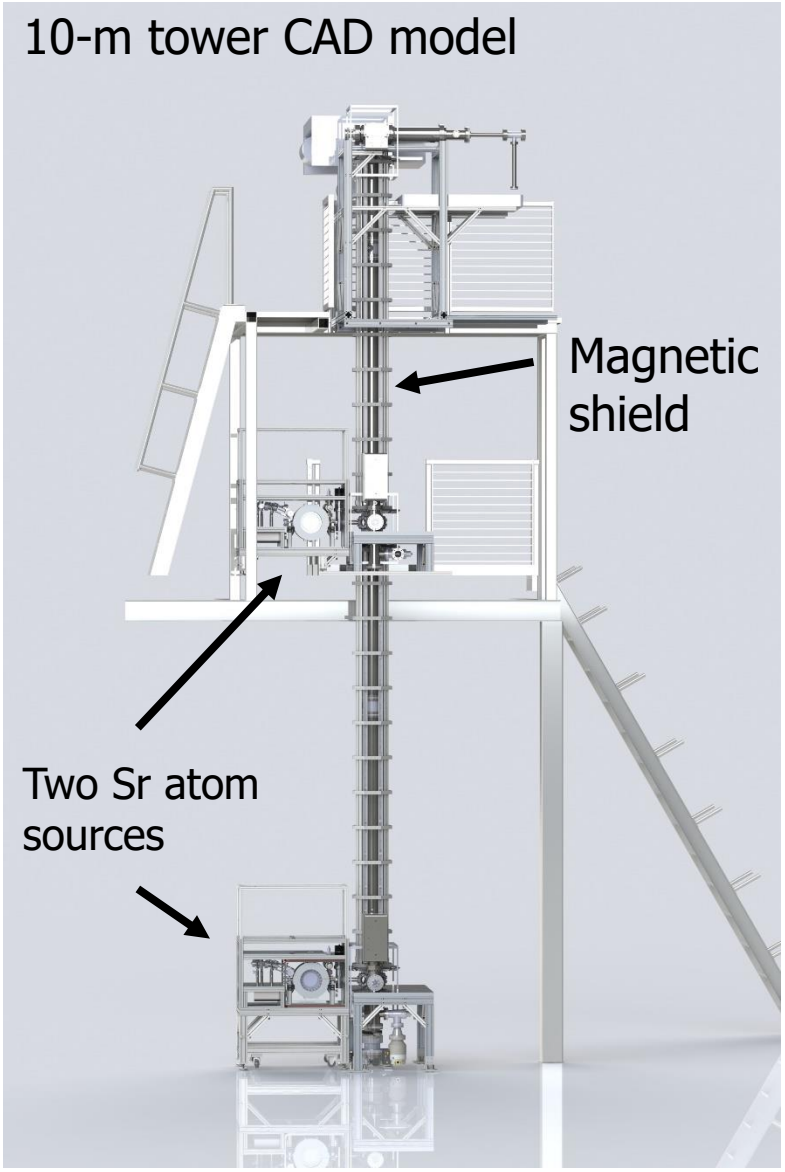
Magnetometer shuttle on suspension wires

Stanford 10-meter Sr prototype

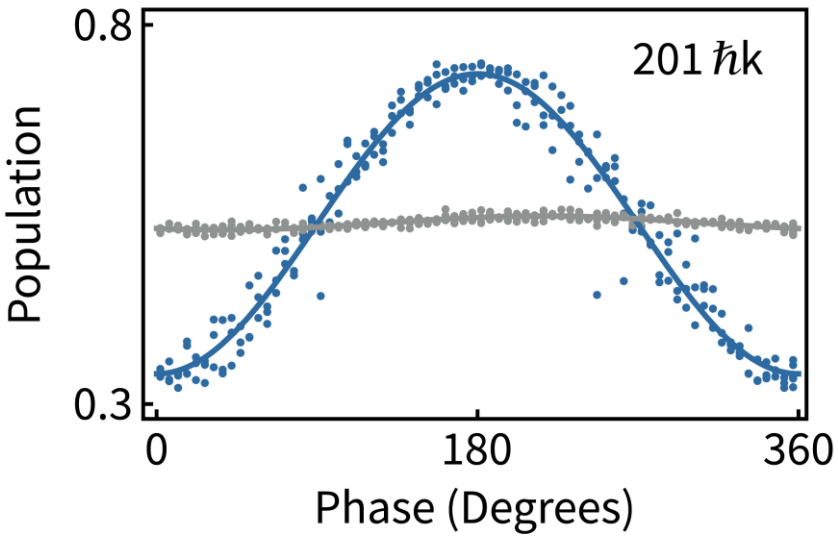
Two assembled Sr atom sources



Atom source CAD detail



Recent LMT atom interferometry results



Example 200 $\hbar k$ interferometer using square drive Floquet atom optics

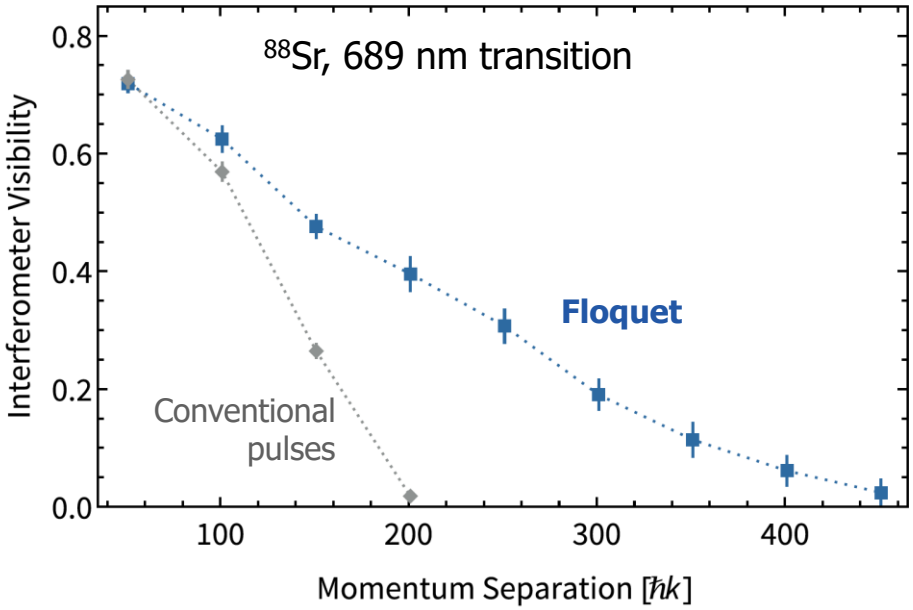
Visibility of 40% (versus 2% uncompensated)

Square drive preferred because of reduced pulse duration compared to sine (less spontaneous emission loss)

- Modulation frequency tuned for each Floquet pulse for max transfer

- Optimized tradeoff between Doppler loss and excess spontaneous emission from Floquet (crossover occurs at ~50 $\hbar k$)

- Able to maintain interferometer visibility out to **400** $\hbar k$ (new record)

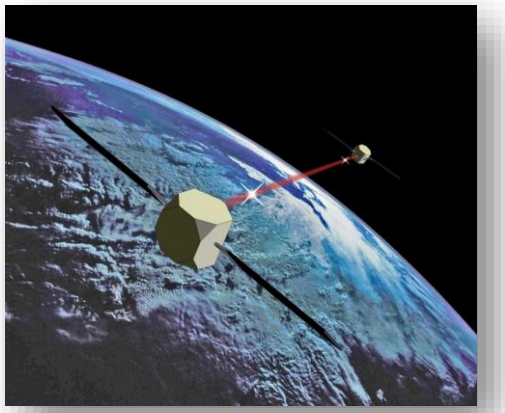


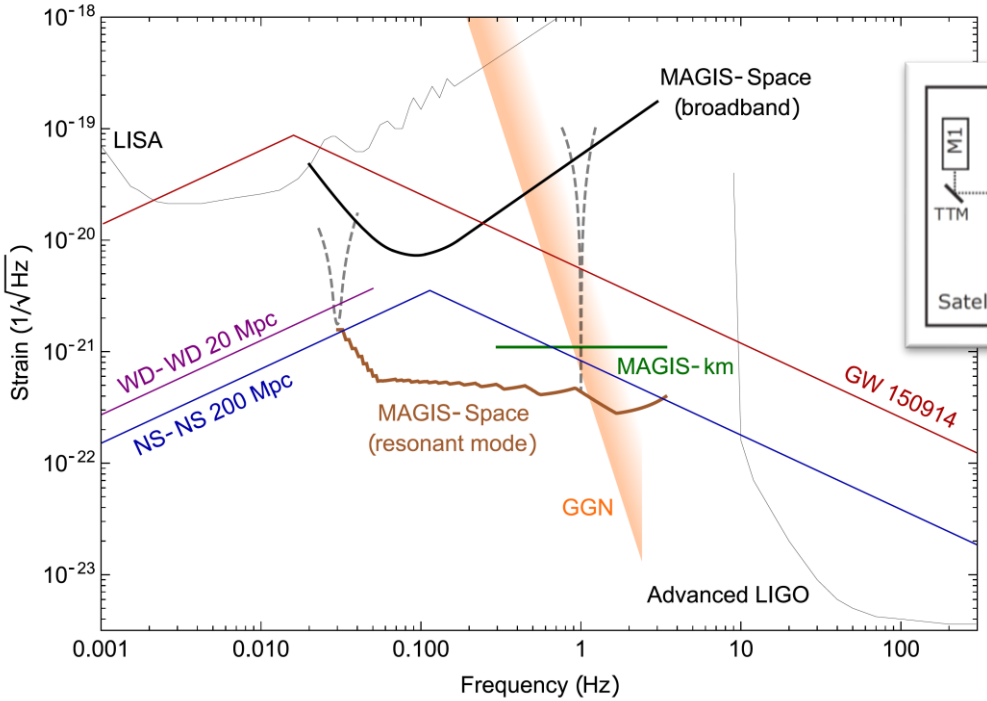
Wilkason et al., arXiv:2205.06965

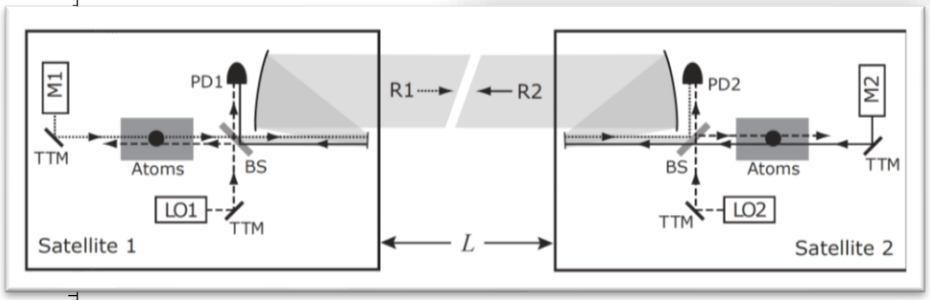
Summary

- MAGIS-100 assembly and commissioning over next 2 years
- On-going work to increase sensitivity of atom interferometry
- Pathfinder for future full-scale detectors on Earth and space

Experiment	(Proposed) Site	Baseline L (m)	LMT Atom Optics n	Atom Sources	Phase Noise $\delta\phi$ (rad/$\sqrt{\text{Hz}}$)
Sr prototype tower	Stanford	10	10^2	2	10^{-3}
MAGIS-100 (initial)	Fermilab (MINOS shaft)	100	10^2	3	10^{-3}
MAGIS-100 (final)	Fermilab (MINOS shaft)	100	4×10^4	3	10^{-5}
MAGIS-km	Homestake mine (SURF)	2000	4×10^4	40	10^{-5}
MAGIS-Space	Medium Earth orbit (MEO)	4×10^7	10^3	2	10^{-4}







Satellite heterodyne laser link proposal
PRA **94**, 033632 (2016)

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MAGIS-100

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Thomas Wilkason
Daniel Wood

Sr Interferometry (Stanford)

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SLAC
GORDON AND BETTY MOORE FOUNDATION
GBMF7945
QuantiSED 2019