Atom interferometry for dark matter and gravitational waves

US Cosmic Visions: New Ideas in Dark Matter

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Ultralight scalar dark matter

- Ultralight DM acts as a background field (high occupation number)
- Can cause small oscillations in Standard Model parameters

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

DM scalar field

Electron coupling

Photon coupling

e.g., QCD

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

Fundamental "constants":

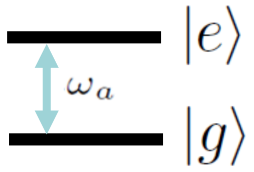
$$m_e(t,\mathbf{x}) = m_e\left[1 + d_{m_e}\sqrt{4\pi G_N}\phi(t,\mathbf{x})\right]$$

$$\alpha(t,\mathbf{x}) = \alpha\left[1 + d_e\sqrt{4\pi G_N}\phi(t,\mathbf{x})\right]$$

Observing DM with atomic sensors

DM coupling causes time-varying atomic energy levels:

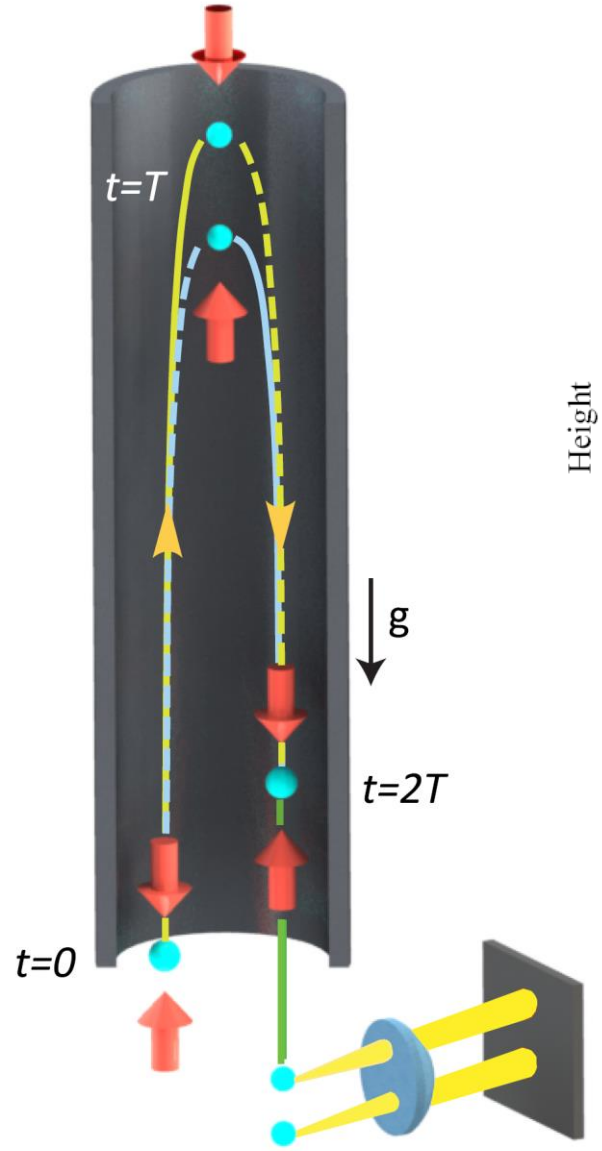
$$\omega_{\mathrm{A}}(t) \simeq \omega_{\mathrm{A}} + \Delta\omega_{\mathrm{A}} \cos(m_\phi t);$$
$$\Delta\omega_{\mathrm{A}} \equiv \omega_{\mathrm{A}} \sqrt{4\pi G_N} \phi_0 \left(d_{m_e} + \xi d_e\right)$$

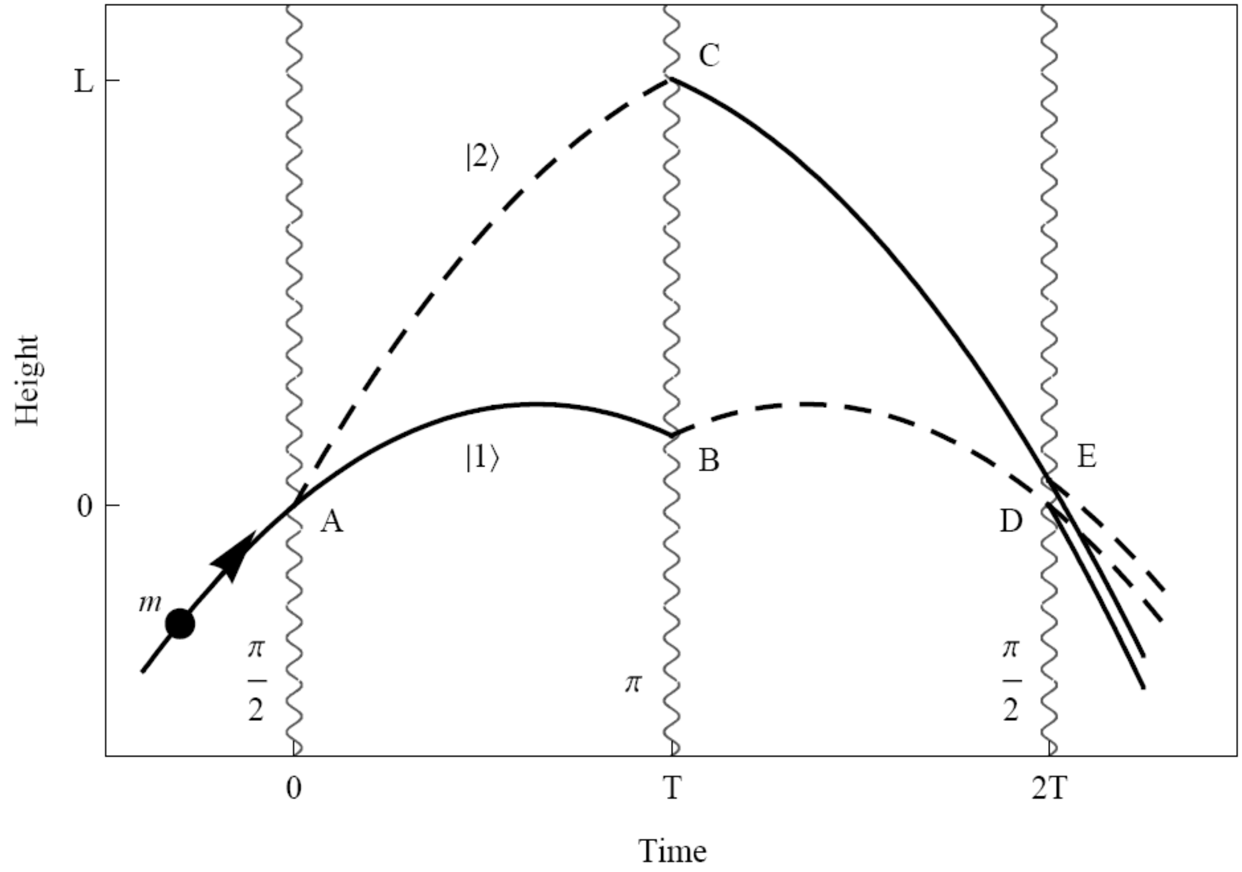


Measurement strategies

- Differential acceleration (EP tests)
- “Clock gradiometer” (GW detector)

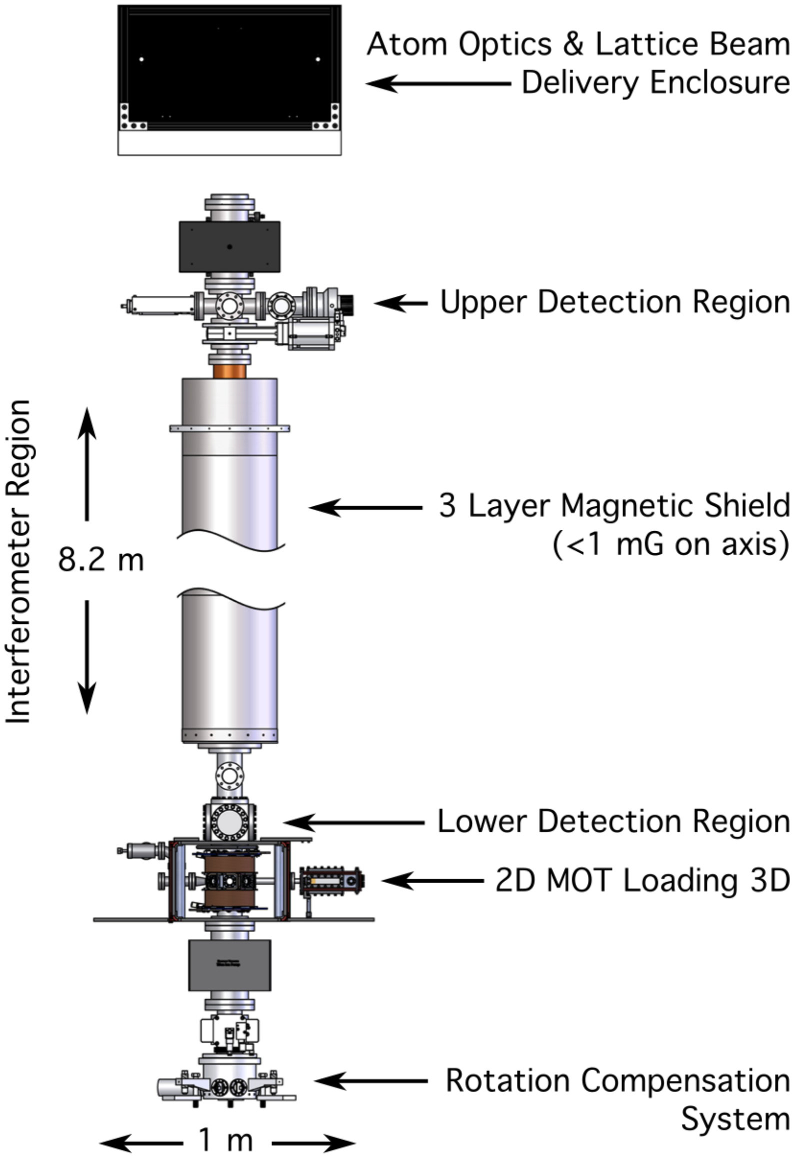
Light Pulse Atom Interferometry

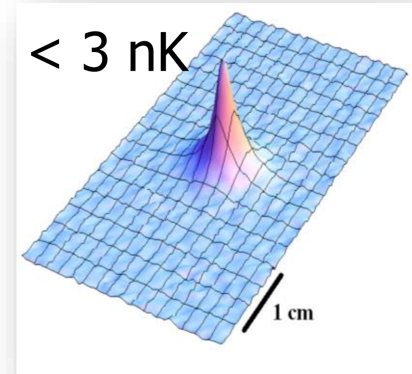


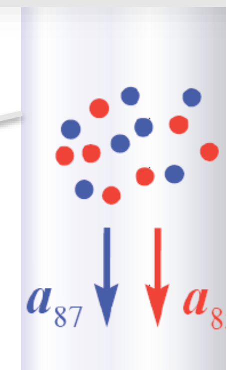


- Long duration
- Large wavepacket separation

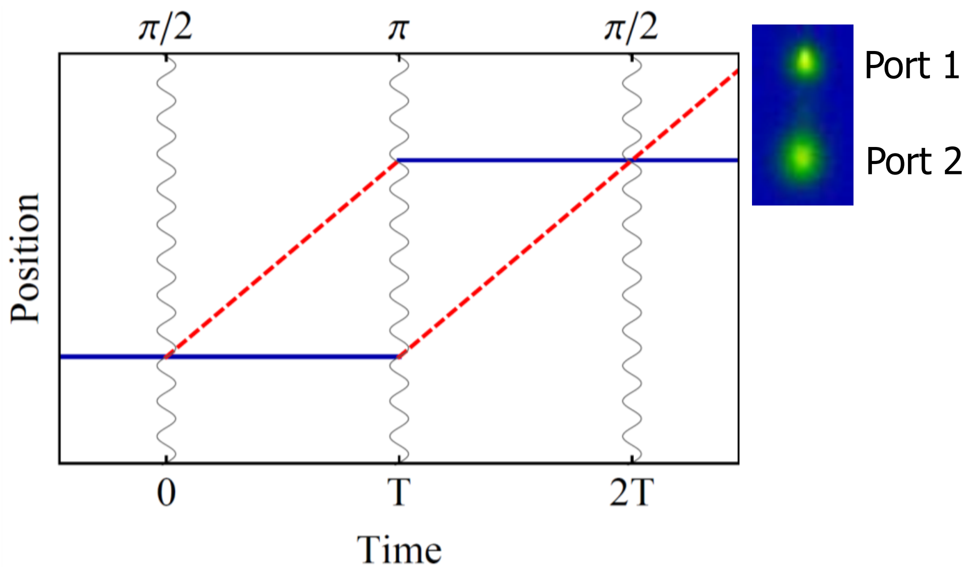
10 meter scale atomic fountain

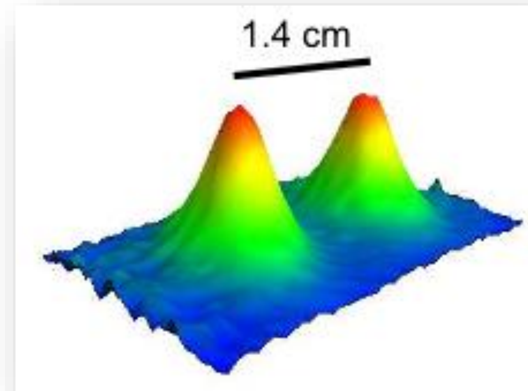






Interference at long interrogation time



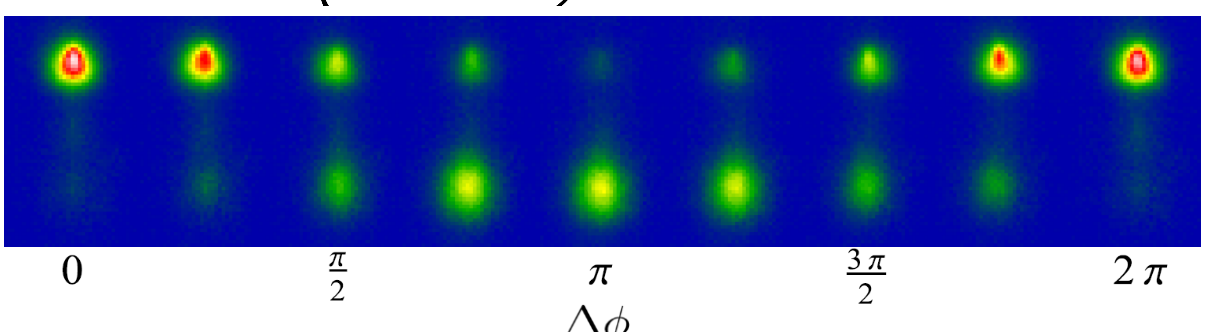


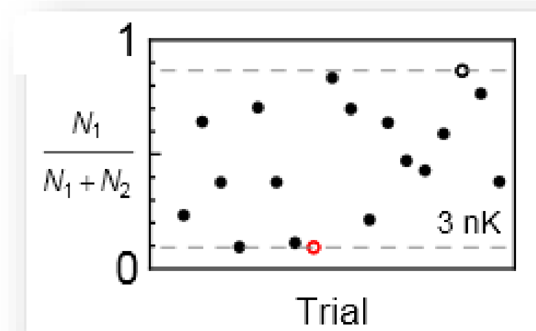
Wavepacket separation at apex (this data 50 nK)

2T = 2.3 sec; Near full contrast
6.7×10^{-12} g/shot (inferred)

Demonstrated statistical resolution:
$\sim 5\times10^{-13}\ g$ in 1 hr (^{87}Rb)

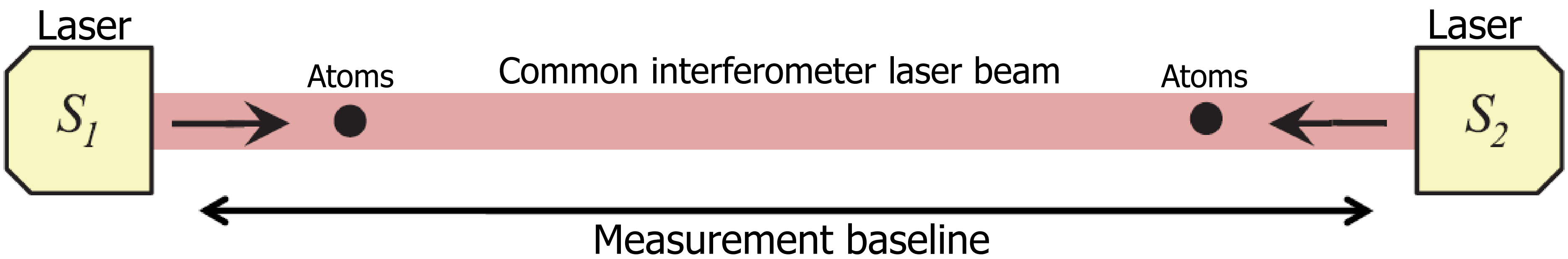
Interference (3 nK cloud)



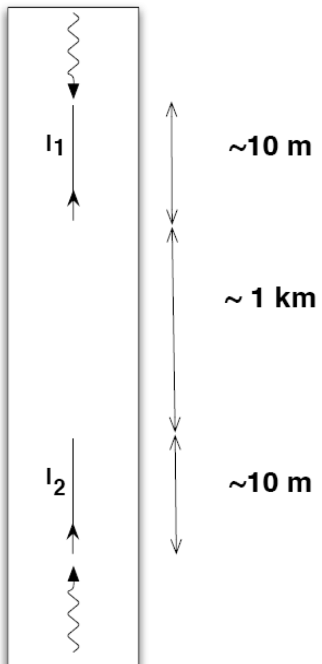


Dickerson, et al., PRL **111**, 083001 (2013).

Gradiometer configuration

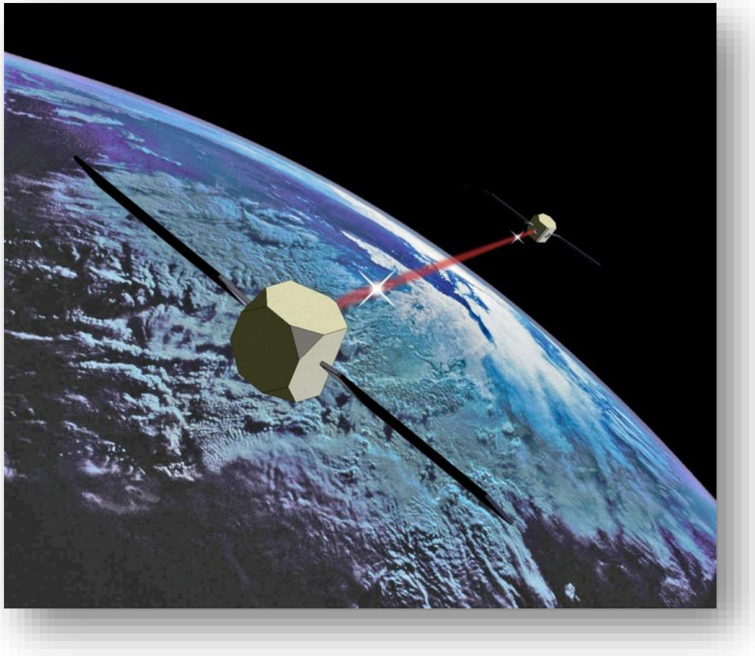


Terrestrial



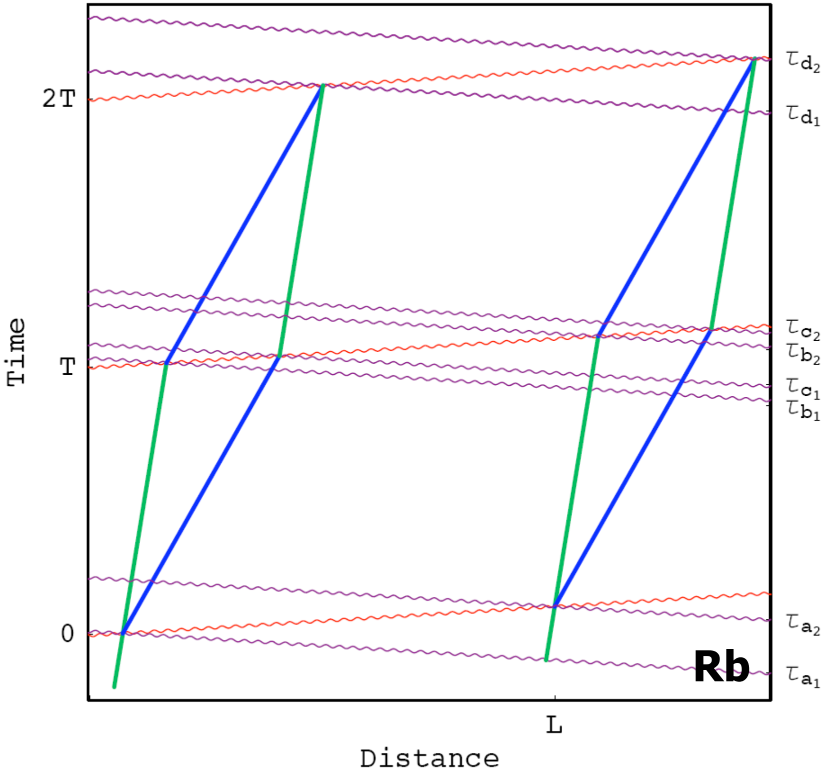
(Vertical mine shaft)

Space

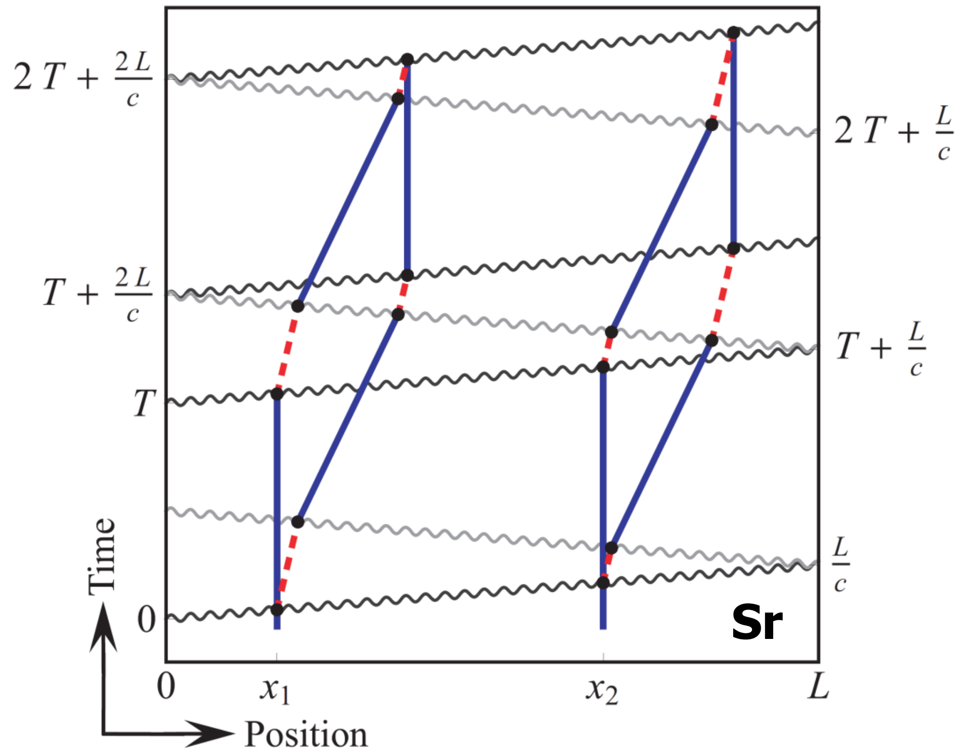


Two-photon vs. single photon transitions

2-photon transitions

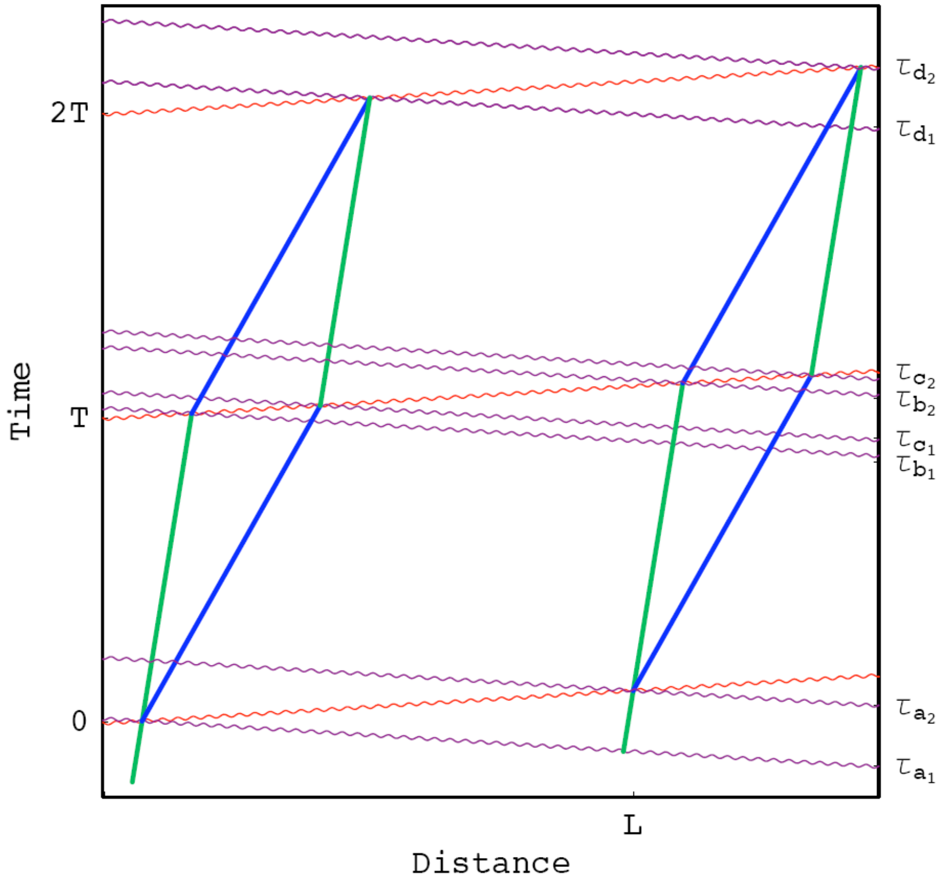


1-photon transitions



Graham, et al., PRD 78, 042003, (2008).
Yu, et al., GRG 43, 1943, (2011).

Two-photon laser frequency noise



Consider a laser frequency error $\delta\omega$ that varies at the GW frequency

Phase error:

$$\delta\phi_L = \delta\omega\,\Delta t \sim \delta\omega\,L/c$$

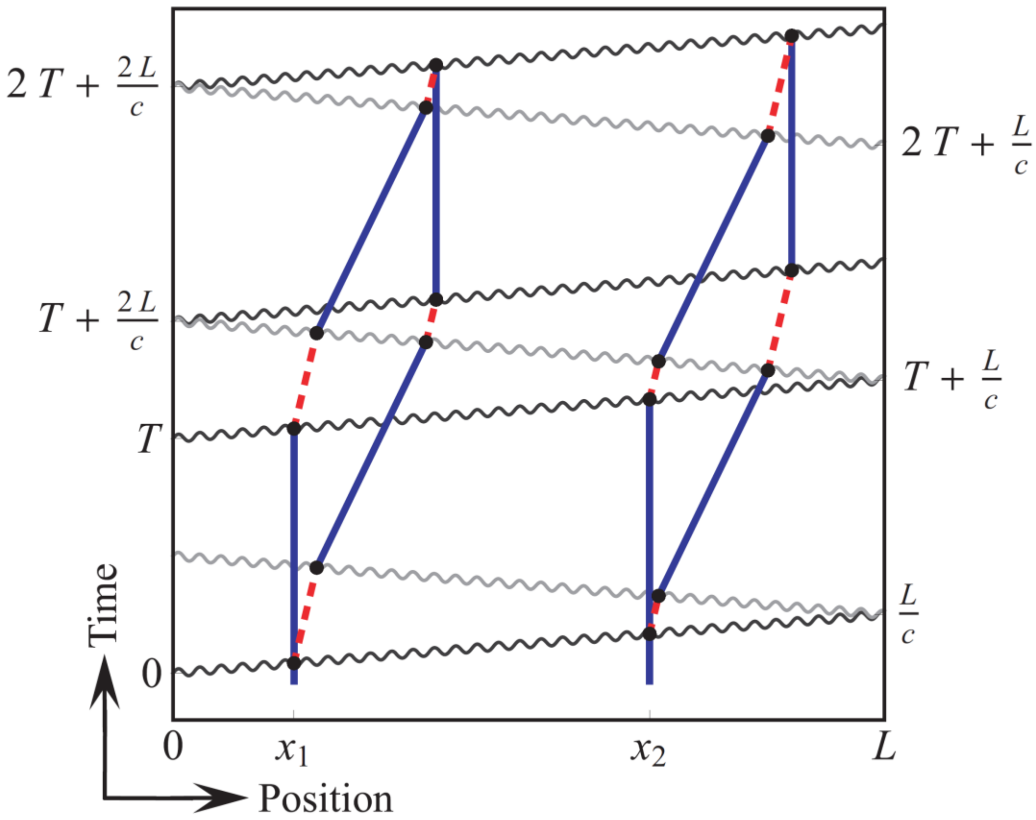
GW Signal:

$$\Delta\Phi_{GW} \sim k\,\delta L \sim khL$$

$$\frac{\delta\omega}{\omega} \ll h \sim 10^{-20}$$

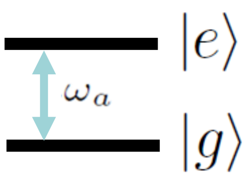
(and even harder with LMT)

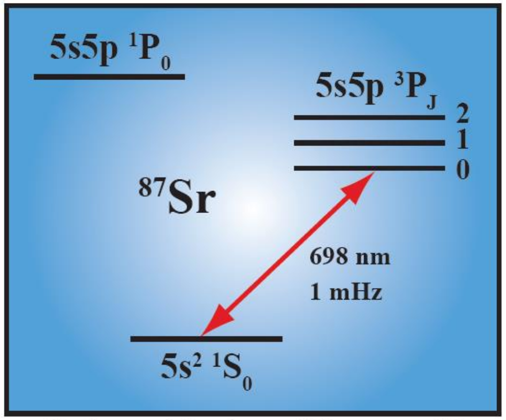
Differential atomic clock



Excited state phase evolution:

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



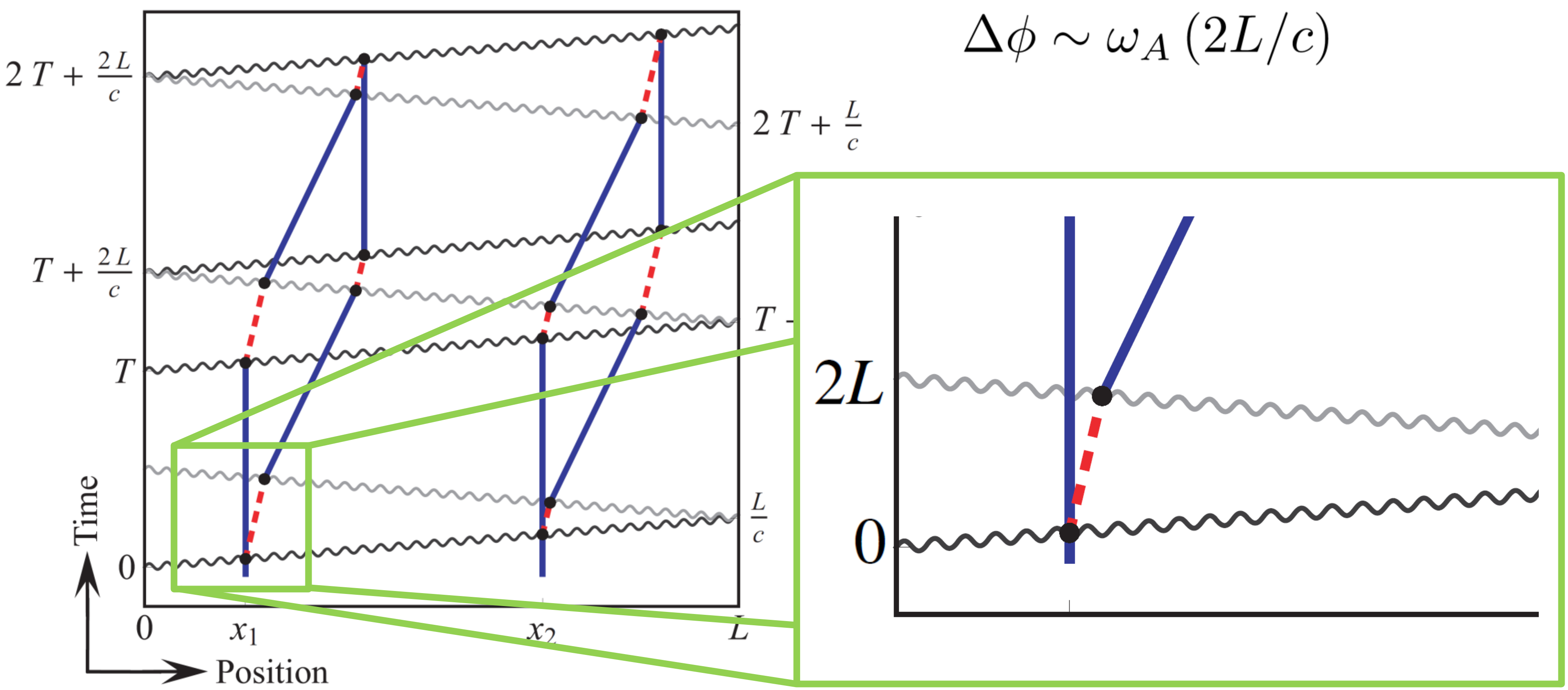


Clock transition in candidate atom ^{87}Sr

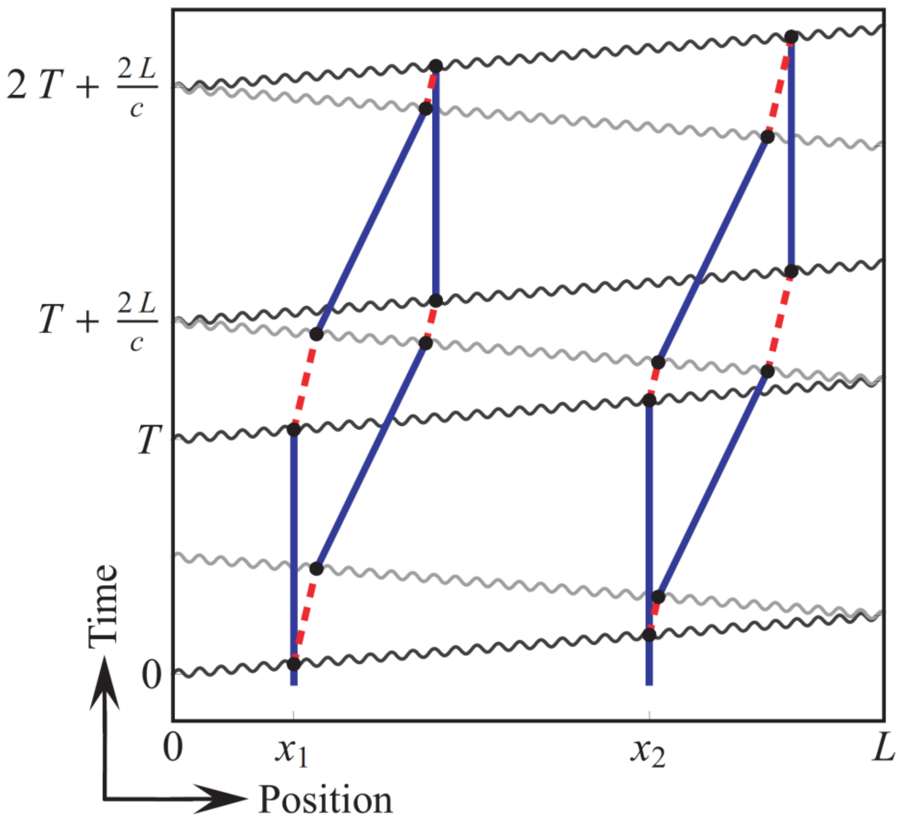
Differential atomic clock

Excited state phase evolution:

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



Differential atomic clock



Excited state phase evolution:

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

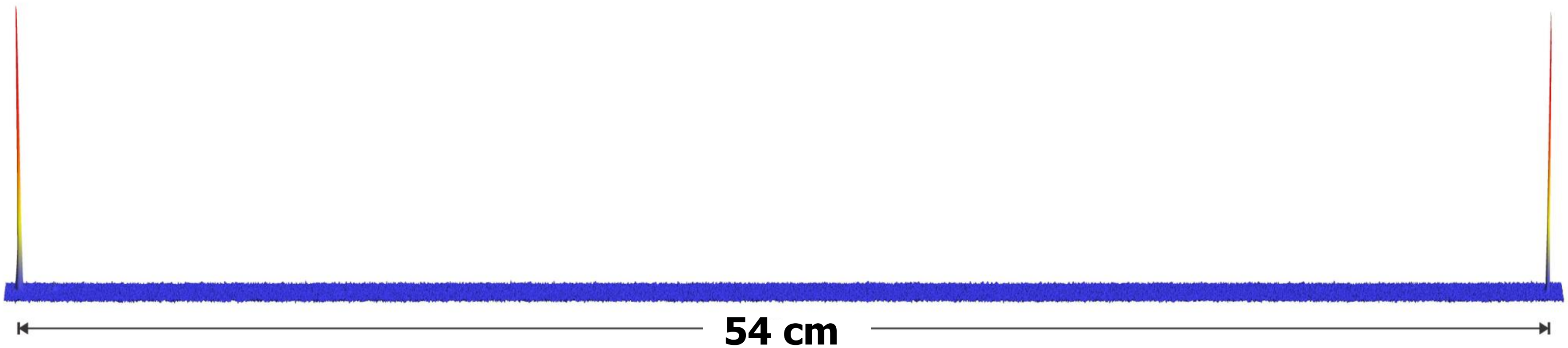
Two ways for phase to vary:

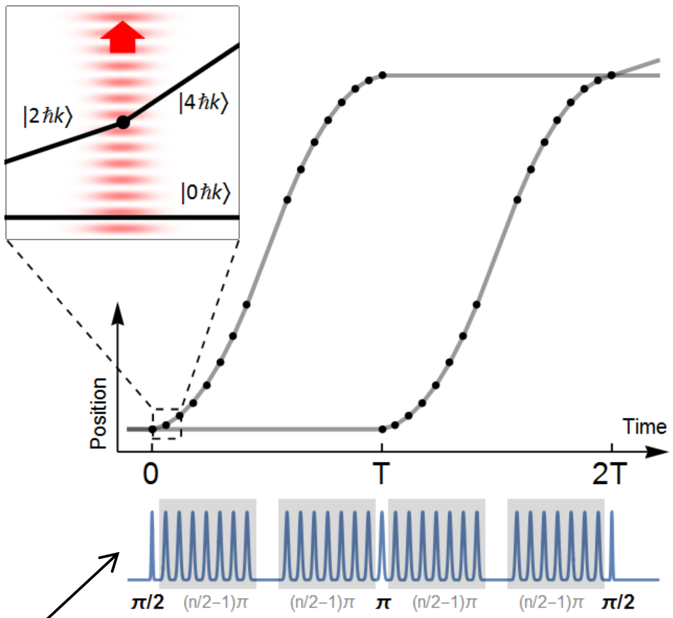
$\delta\omega_A$	*Dark matter*
$\delta L = hL$	*Gravitational wave*

Each interferometer measures the change over time T

Laser noise is common-mode suppressed in the gradiometer

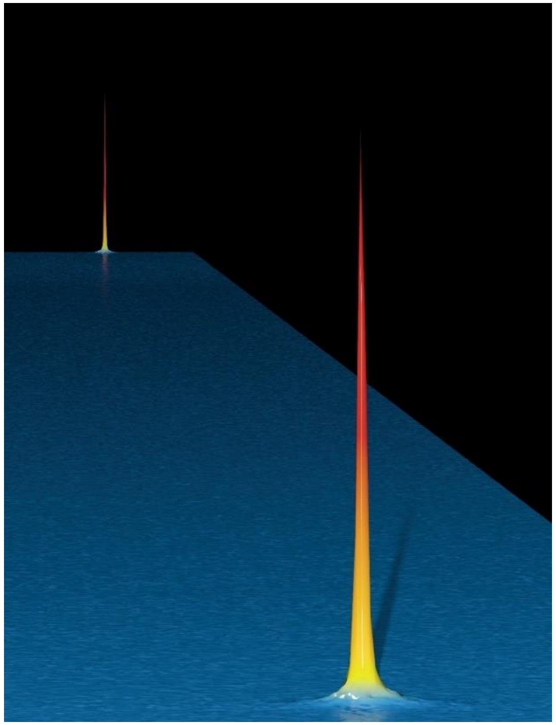
Large momentum transfer demonstration





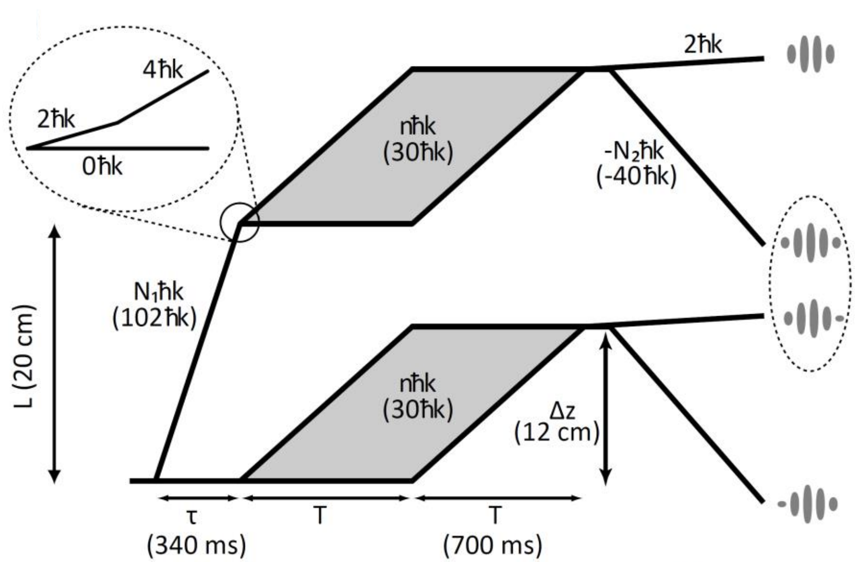
Pulse sequence

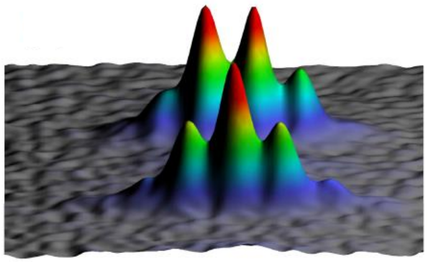
- Enhanced sensitivity
- Multiple pulses to transfer momentum
- Bragg atom optics
- Long duration (>2 s)

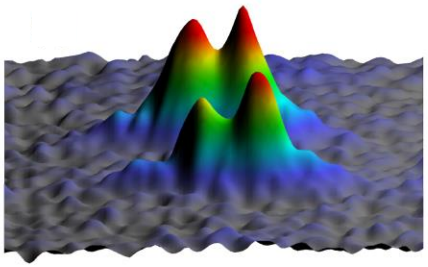


Kovachy et al., *Nature* 2015

Gradiometer Demonstration (Rb)







$\Delta z = 4\,\mathrm{cm}$

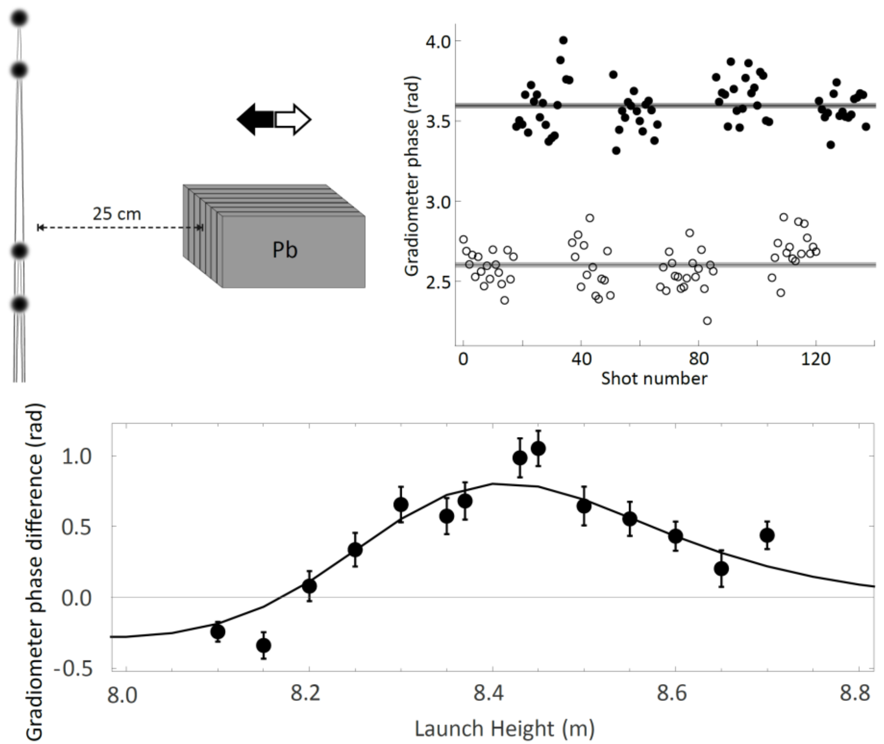
10 ħk

$\Delta z = 12\,\mathrm{cm}$

30 ħk

Gradiometer interference fringes

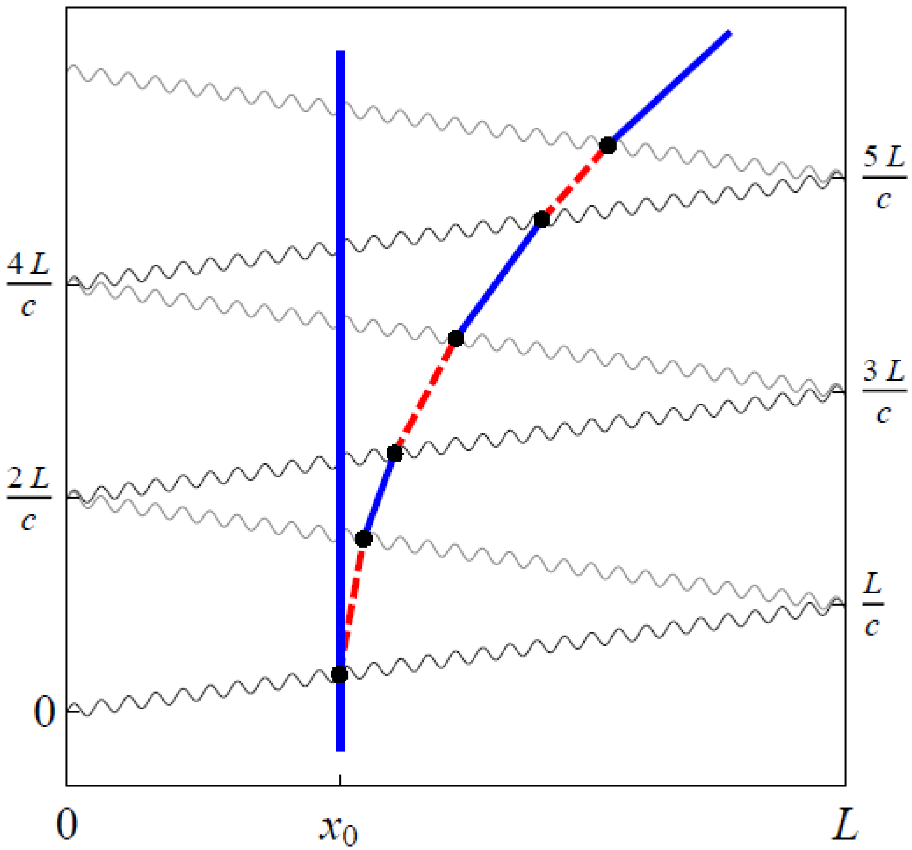
Gradiometer response to 84 kg lead test mass



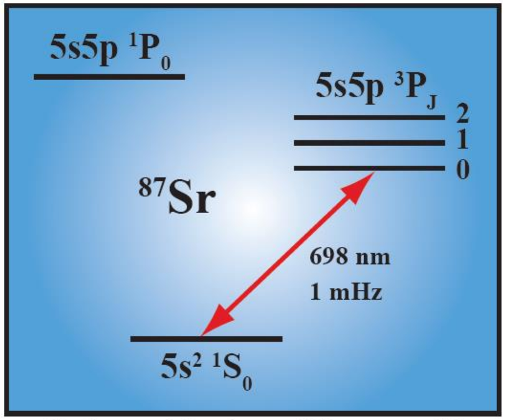
$L = 10\,\mathrm{cm}$, $n = 30$, and $T = 900\,\mathrm{ms}$ ($\Delta z = 16\,\mathrm{cm}$)

LMT using single photon transitions

Example LMT beamsplitter (N = 3)



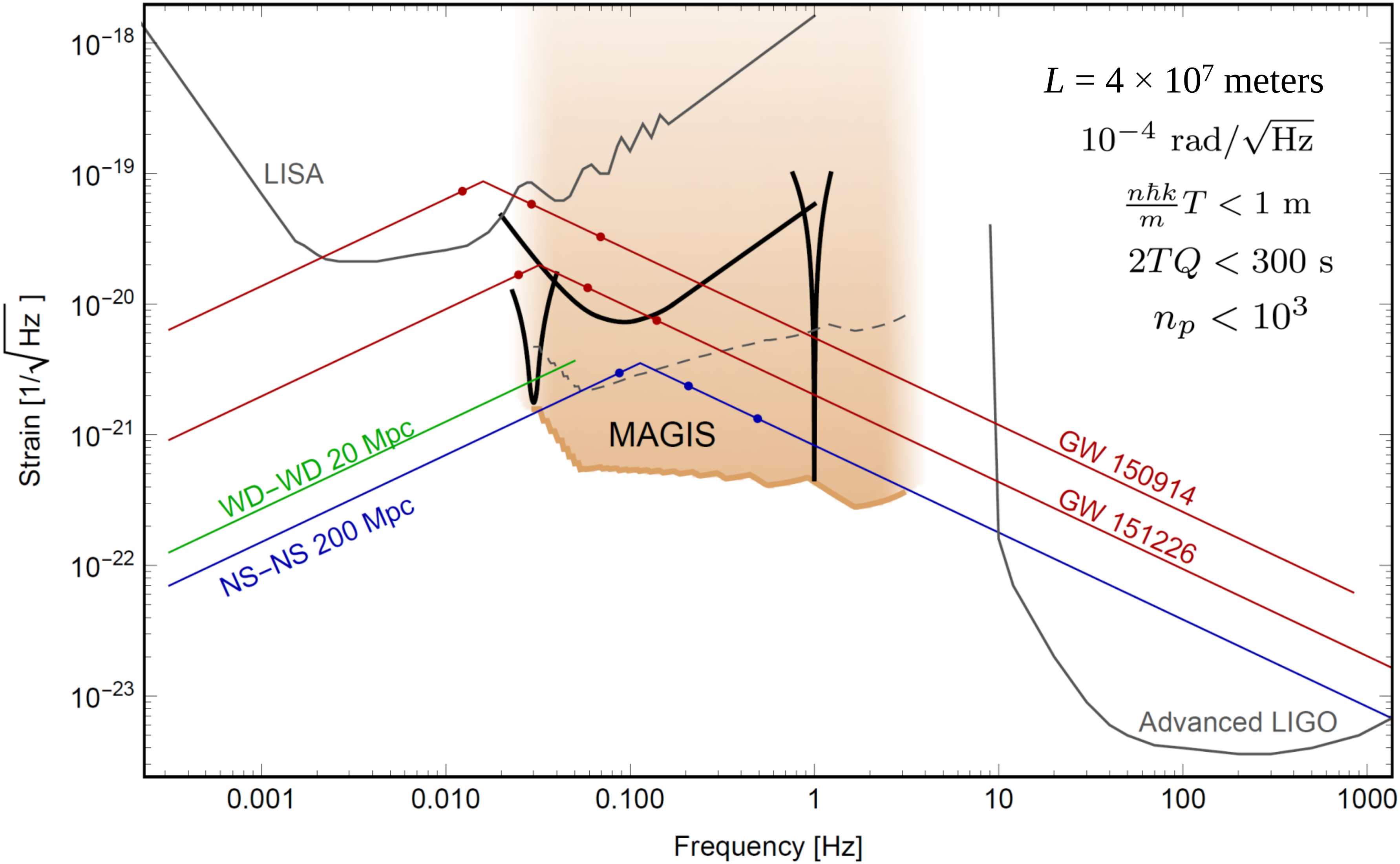
- Sequential single photon transitions
- Alternating directions
- Each pulse is laser noise immune (in a gradiometer)



Clock transition in candidate atom ^{87}Sr

Graham, *et al.*, arXiv:1206.0818, PRL (2013)

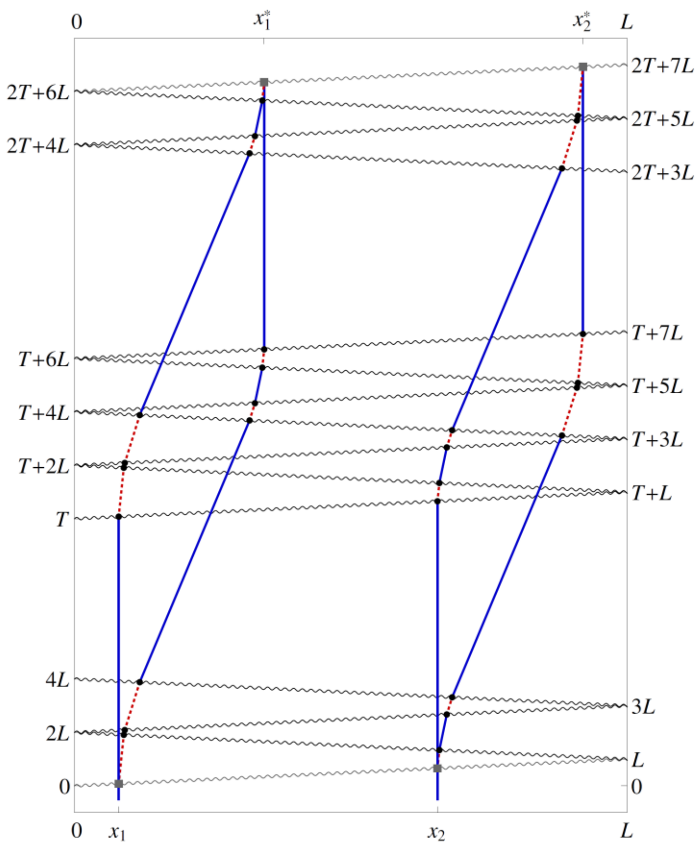
GW Sensitivity

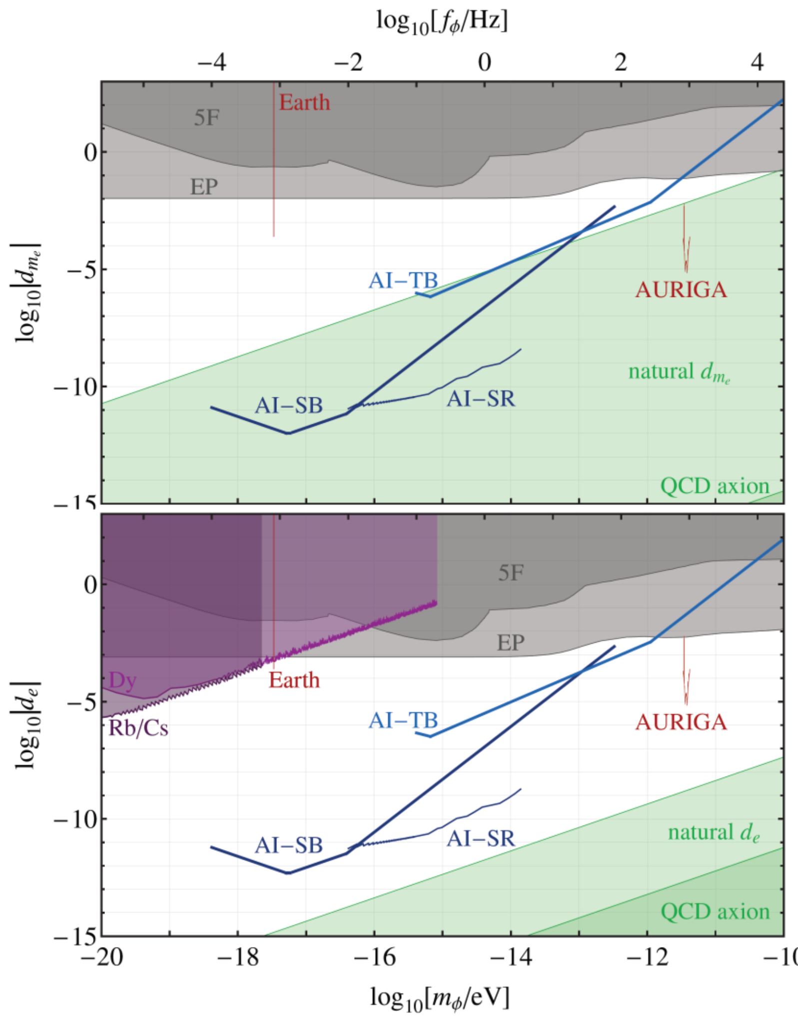


MAGIS: Midband Atomic Gravitational Wave Interferometric Sensor

Scalar dark matter sensitivity

GW detector is simultaneously sensitive to scalar dark matter





Coupling to electrons

Coupling to photons

Arvanitaki, *et al.*, arXiv:1606.04541 [hep-ph] (2016)

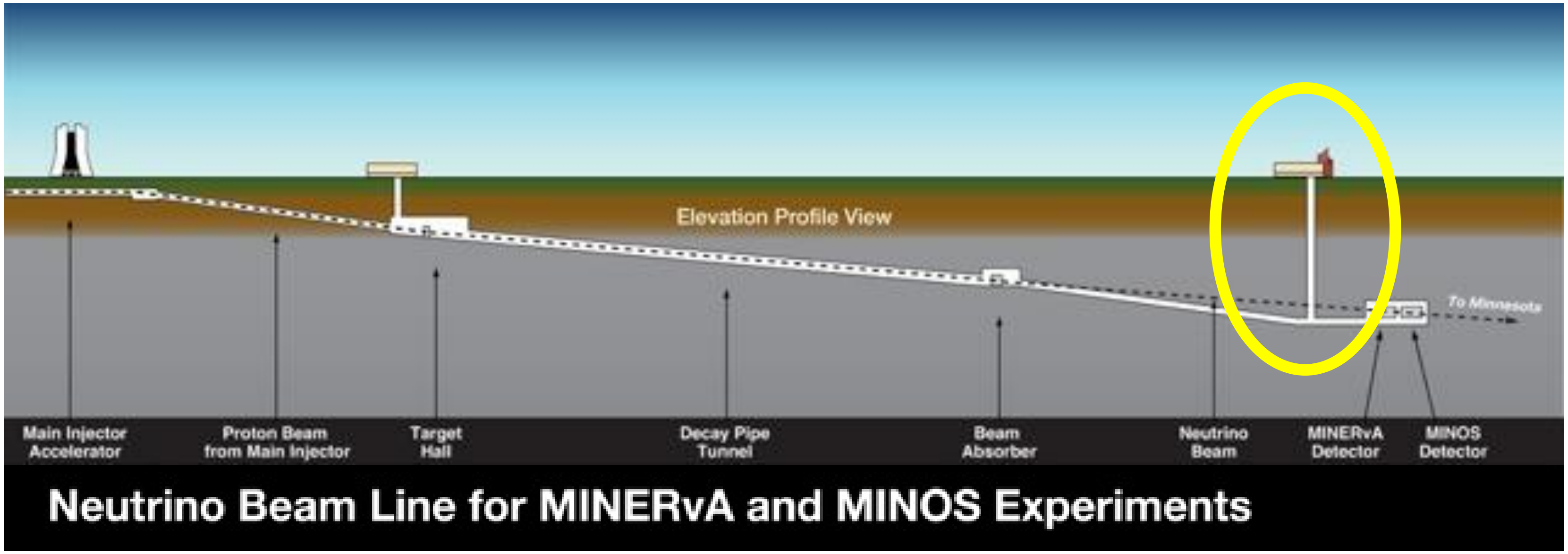
Single photon atom interferometry

Sr gradiometer demonstration experiment

Proof of concept experiment (in progress at Stanford)

- New 10-meter tower with Sr atoms
- AI on the the clock transition
- Compare two Sr interferometers

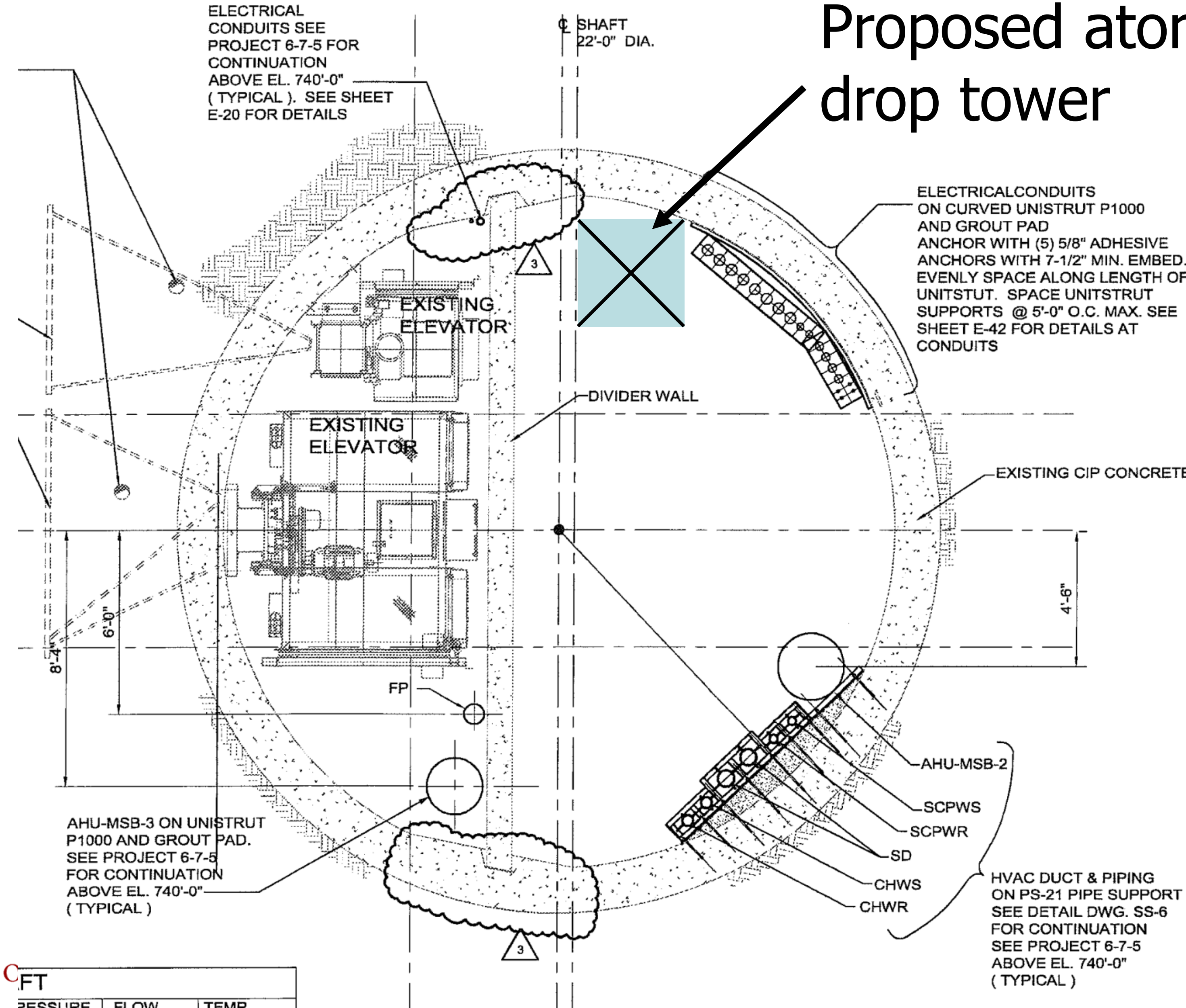
Proposal: 100 meter detector at Fermilab



- MINOS, MINERvA and NOvA experiments use the NuMI beam
- 100 meter access shaft
- Atom DM detector (small scale project)

NuMI Shaft

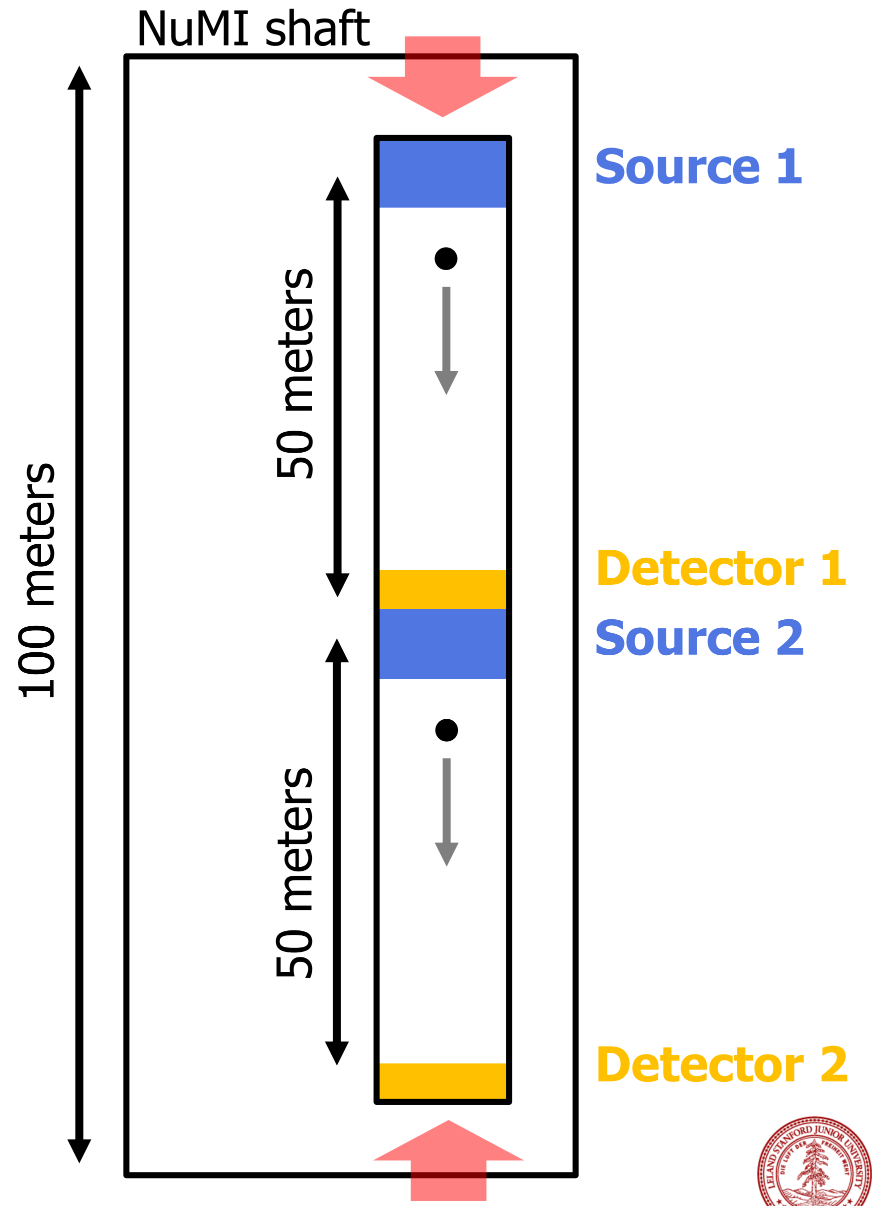
Proposed atom drop tower



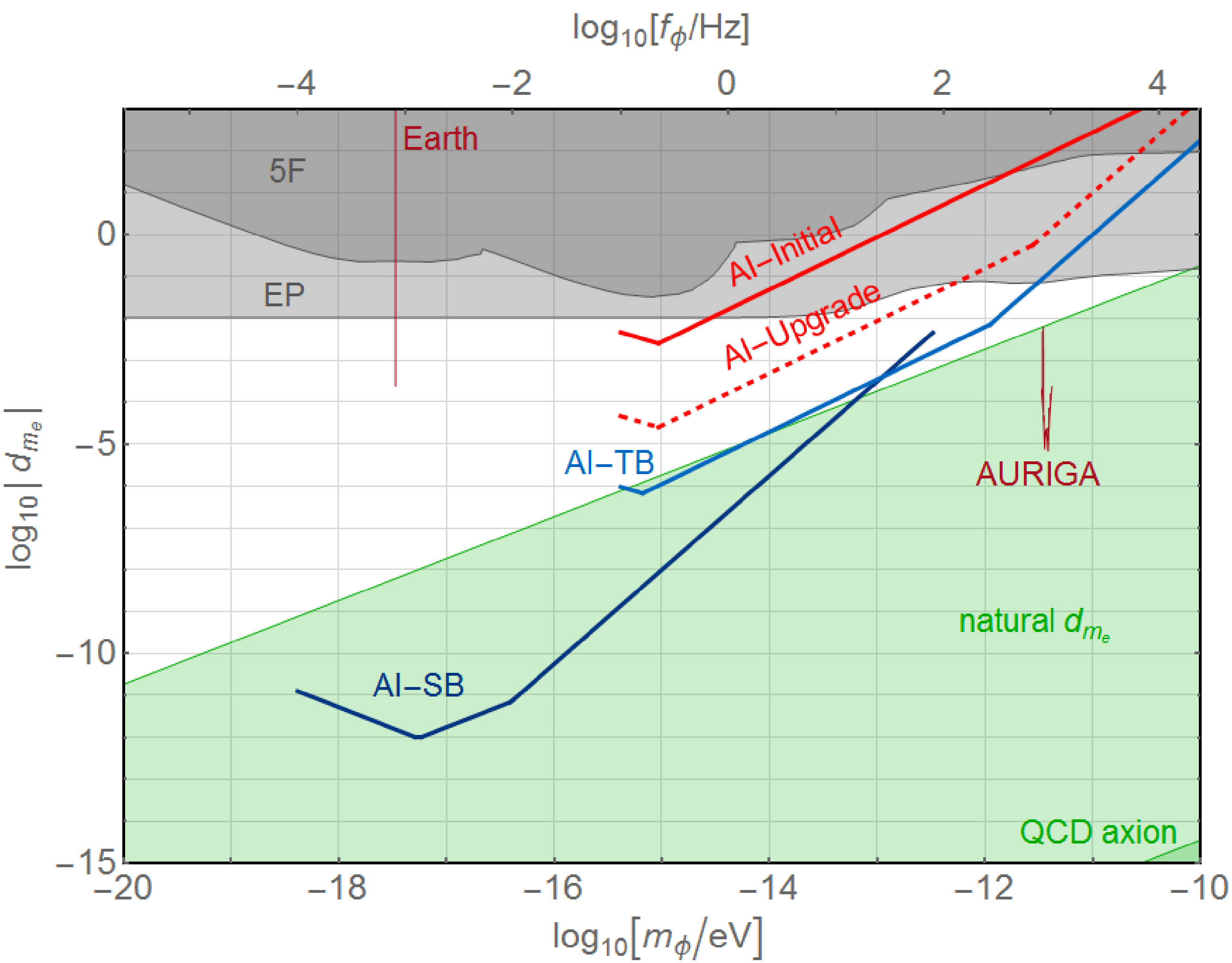
STANFO

NuMI Gradiometer Proposal

- 100-meter Sr clock gradiometer
- Drop atoms from two Sr sources
- >3 seconds free-fall
- Search for DM in range 0.1 Hz – 10 Hz



Proposed Detector Sensitivity



100-meter detector:

Initial: 100 ħk, 1e6/s flux

Upgrade: 1000 ħk, 1e8/s flux

AI-TB: km baseline

AI-SB: Space GW detector

Collaborators

Rb Atom Interferometry

Mark Kasevich
Tim Kovachy
Chris Overstreet
Peter Asenbaum
Daniel Brown

Sr Atom Interferometry

TJ Wilkason
Hunter Swan
Jan Rudolph

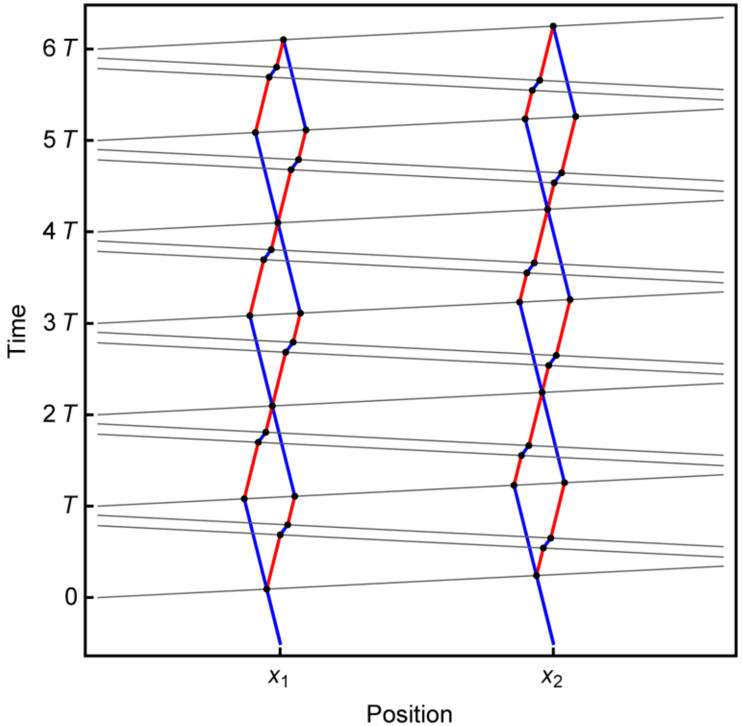
Theory:

Peter Graham
Savas Dimopoulos
Surjeet Rajendran
Asimina Arvanitaki
Ken Van Tilburg
TJ Wilkason

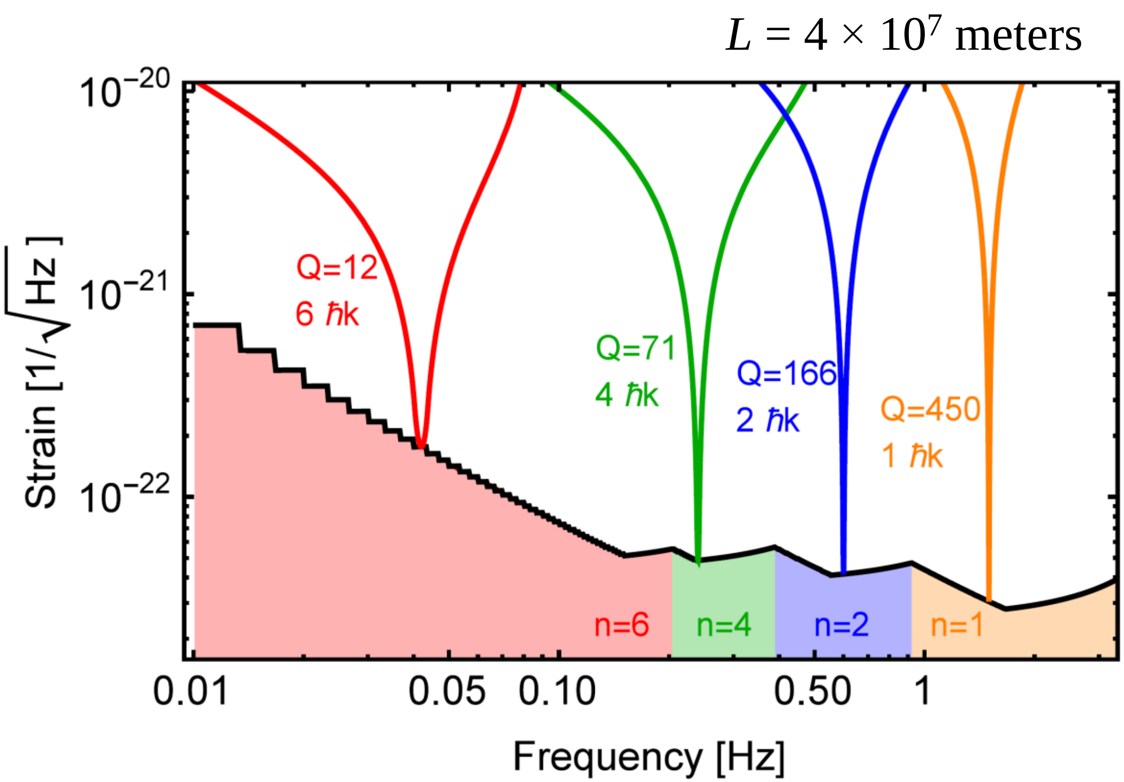
Thanks to:

Joseph Lykken (Fermilab)
Swapan Chattopadhyay (Fermilab)
Rob Plunkett (Fermilab)
Roni Harnik (Fermilab)

Resonant Detection Mode



Resonant interferometer sequences for enhanced, narrow band response



Optimized sensitivity near 1 Hz

Includes constraints on total pulses and source lifetime

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

Differential Acceleration – EP tests

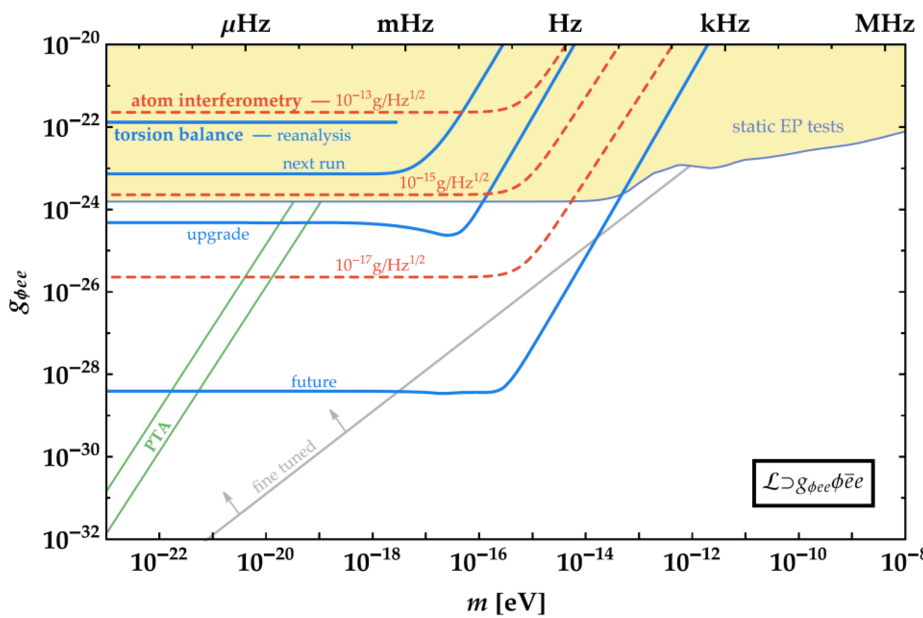
- Scalar field varies in space
- Force points in the direction of the local gradient in the field:

$$F \propto g\sqrt{\rho_{\mathrm{DM}}}\cos(m_{\mathrm{DM}}t)$$

Force is oscillatory and equivalence-principle violating

Example: Coupling to electron mass

Vector coupling (e.g., B-L) has similar phenomenology



P. Graham et al., PRD **93**, 075029 (2016)