ICHEP2018 SEOUL
XXXIX INTERNATIONAL CONFERENCE ON high Energy PHYSICS
JULY 4 - 11, 2018 COEX, SEOUL

MAGIS-100 @ FERMILAB

Jon Coleman – University of Liverpool
on behalf of the collaboration

July 5, 2018

STANFORD
UNIVERSITY OF CALIFORNIA BERKELEY
NIU Northern Illinois University
UNIVERSITY OF LIVERPOOL
Fermilab

The Collaboration

Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100)

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Part of the Proposed Fermilab Quantum Initiative:

http://www.fnal.gov/pub/science/particle-detectors-computing/quantum.html#magis

Science Motivation

Quantum initiative

- Atom de Broglie wavepackets in superposition separated by up to 10 meters
- Durations of many seconds, up to 9 seconds (full height launch)
- Testbed for the application of quantum entanglement
- Spin squeezed atom sources to reduce sensor noise below the standard quantum limit

Dark sector physics

- Time-dependent signals caused by ultra-light dark matter candidates
- Dark matter that affects fundamental constants: electron mass, fine structure constant
- Time-dependent EP violations from B-L coupled dark matter
- New forces

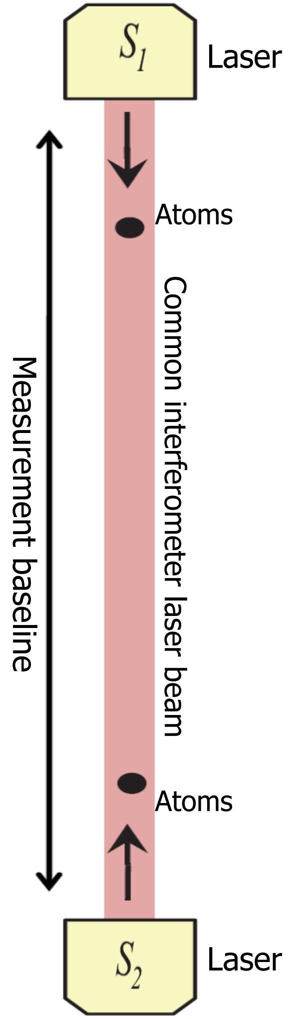
Gravitational wave detector development

- Probe for studying cosmology
- Explores range of frequencies not covered by other detectors
- LIGO sources before they reach LIGO band
- Predict when and where events will occur

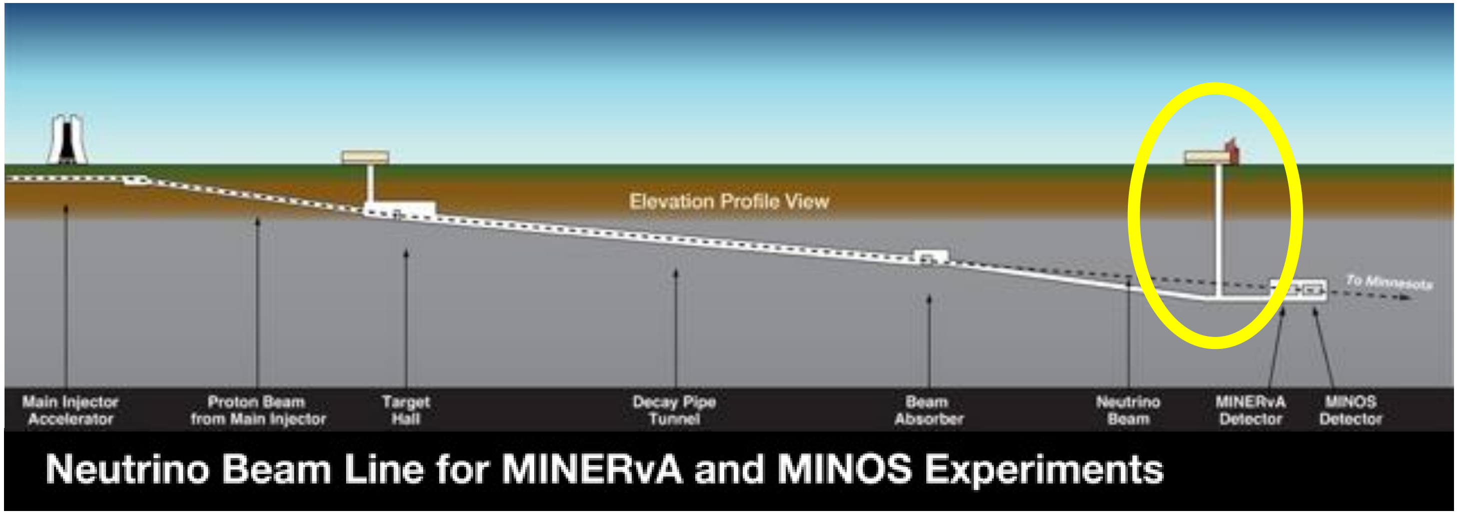
MAGIS

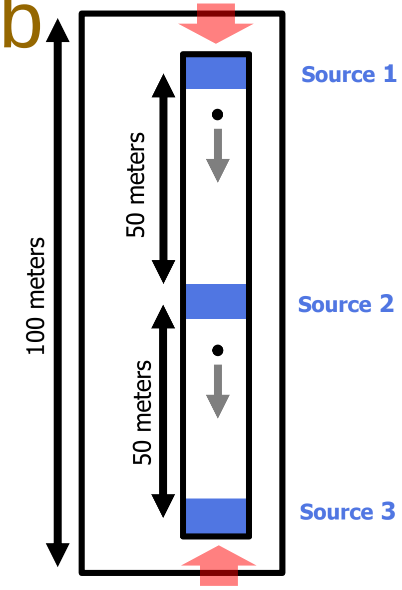
Matter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor

- Compare two atom ensembles separated by baseline
- Atoms as inertial test masses, follow geodesics
- Atoms as clocks
- Common laser phase noise



MAGIS-100 detector at Fermilab

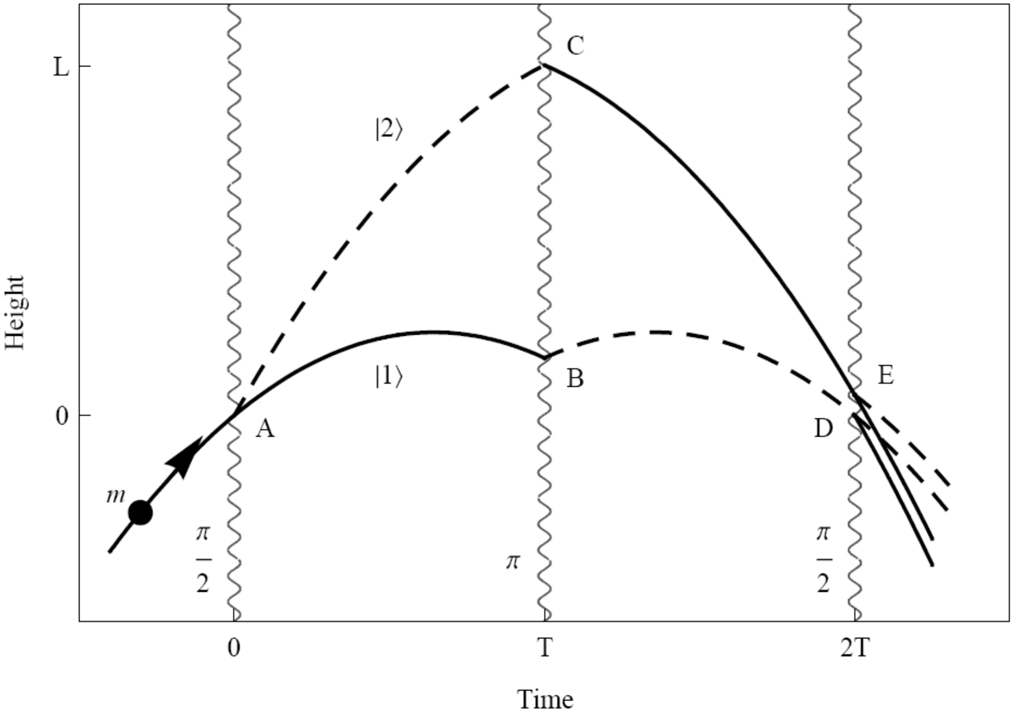




- MINOS, MINERvA and NOvA experiments use the NuMI beam
- 88 m at Fermilab, permitting a 100 m-scale baseline atom interferometry
- Intermediate step to full-scale detector for GWs

Light Pulse Atom Interferometry

8.7 m at Stanford supporting the present 10 m-scale experiment



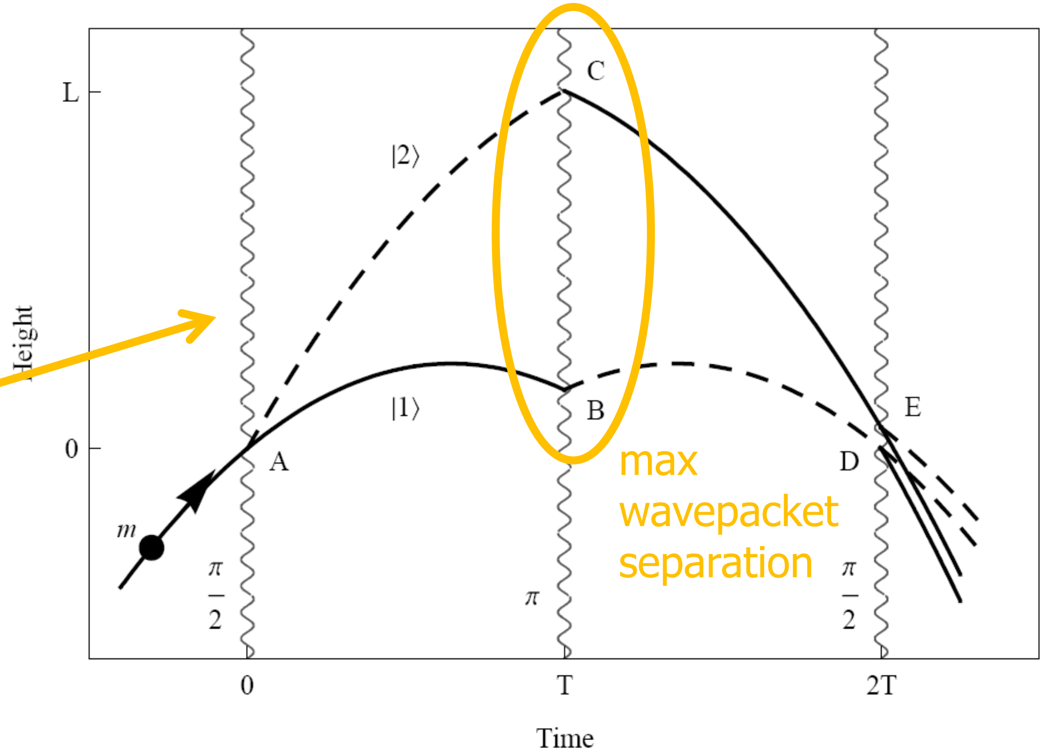
Increase acceleration sensitivity:

- Long duration
- Large wavepacket separation

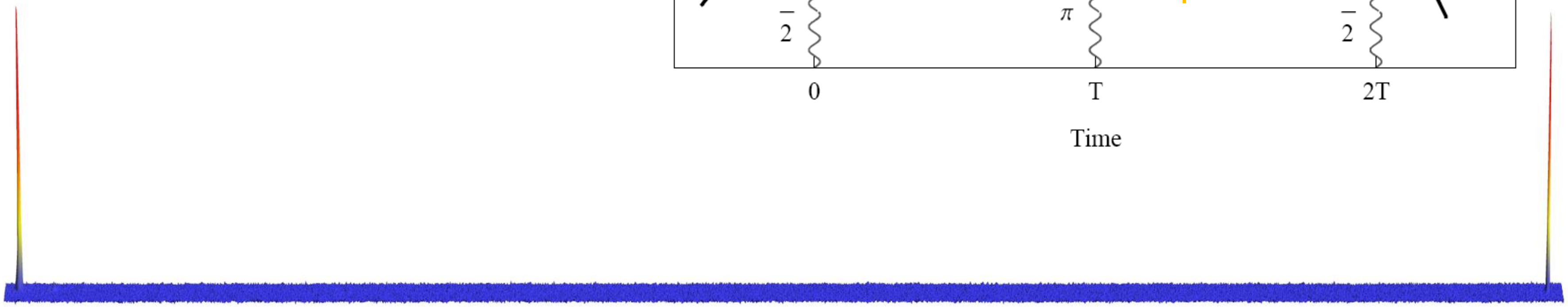
Large space-time area atom interferometry

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

90 photons worth
of momentum



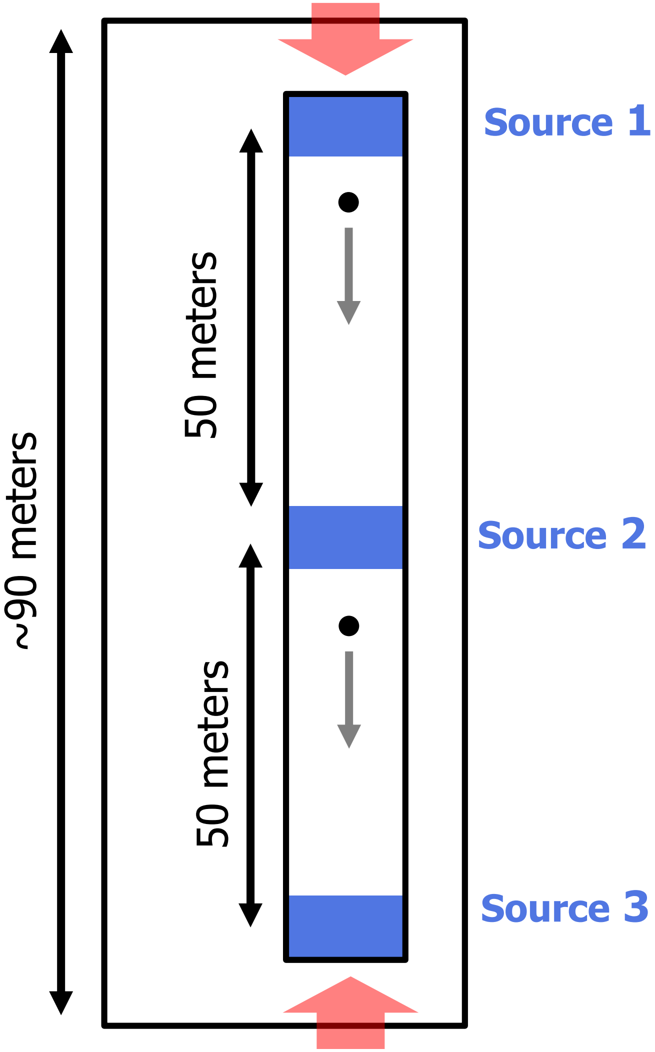
max wavepacket separation



54 cm

Kovachy et al., *Nature* 2015

MAGIS-100 Configuration



Detector modes of operation

I. Max drop time >3 seconds (sources 1,2)

II. Max free fall with launch (sources 2,3)

III. Max baseline (sources 1,3)

IV. Newtonian noise rejection (sources 1,2,3)

V. Extreme QM, 4 - 9 s (drop 1 or launch 3)

Multiple ways to detect DM Axions

1. Affects fundamental constants such as the electron mass or fine structure constant will change the energy levels of the quantum states used in the interferometer

2. Causes accelerations: can be searched for by comparing the accelerometer signals from two simultaneous quantum interferometers run with different Sr isotopes

3. Affects precession of nuclear spins, such as general axions. Searched for by comparing simultaneous, co-located interferometers with the Sr atoms in different quantum states with differing nuclear spins

Ultralight scalar dark matter

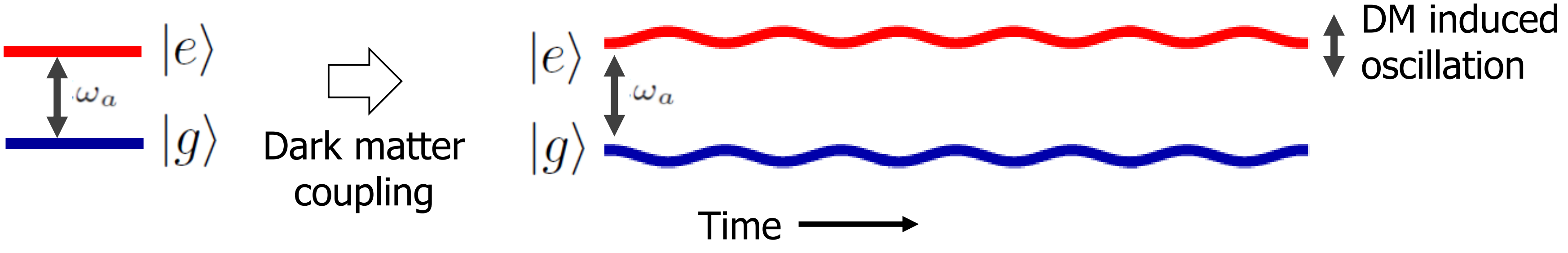
Ultralight dilaton DM acts as a background field (e.g., mass ~10^{-15} eV)

$$\mathcal{L} = \underbrace{+\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2}_{\text{DM scalar field}} - \sqrt{4\pi G_N}\phi\left[\underbrace{d_{m_e} m_e\bar{e}e}_{\text{Electron coupling}} - \underbrace{\frac{d_e}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{Photon coupling}}\right] + \underbrace{\ldots}_{\text{e.g., QCD}}$$

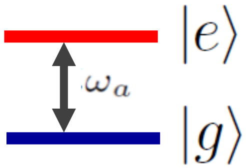
$$\phi\left(t,\mathbf{x}\right) = \phi_0\cos\left[m_\phi(t - \mathbf{v}\cdot\mathbf{x}) + \beta\right] + \mathcal{O}\left(|\mathbf{v}|^2\right)$$

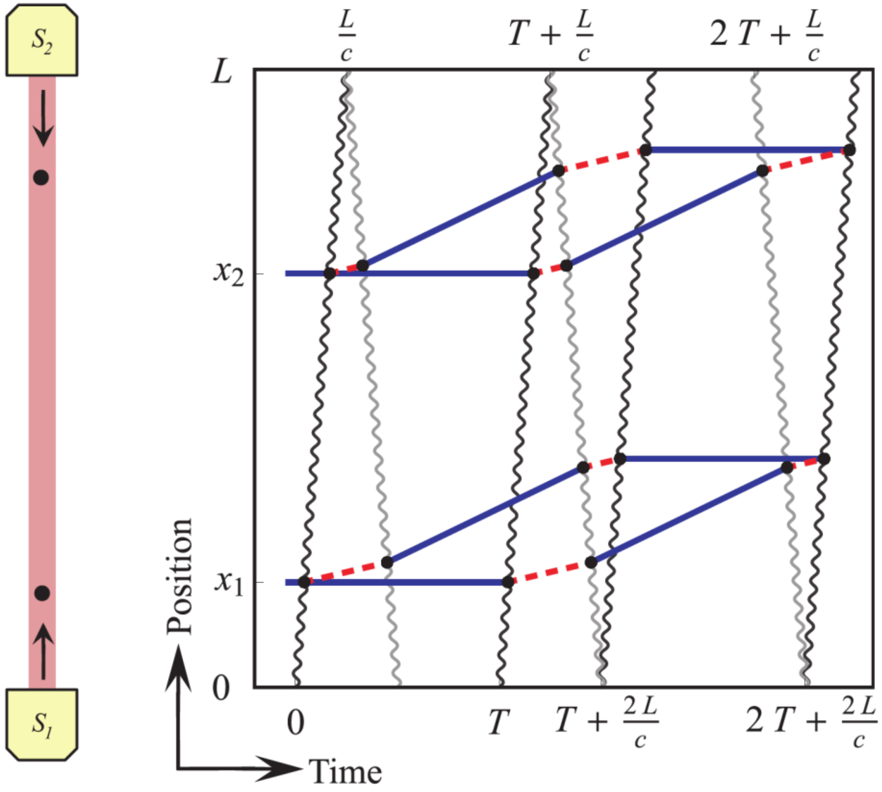
$$\phi_0 \propto \sqrt{\rho_{\mathrm{DM}}}$$ DM mass density

DM coupling causes time-varying atomic energy levels:



Differential atom interferometer response





Excited state phase evolution:

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

Two ways for phase to vary:

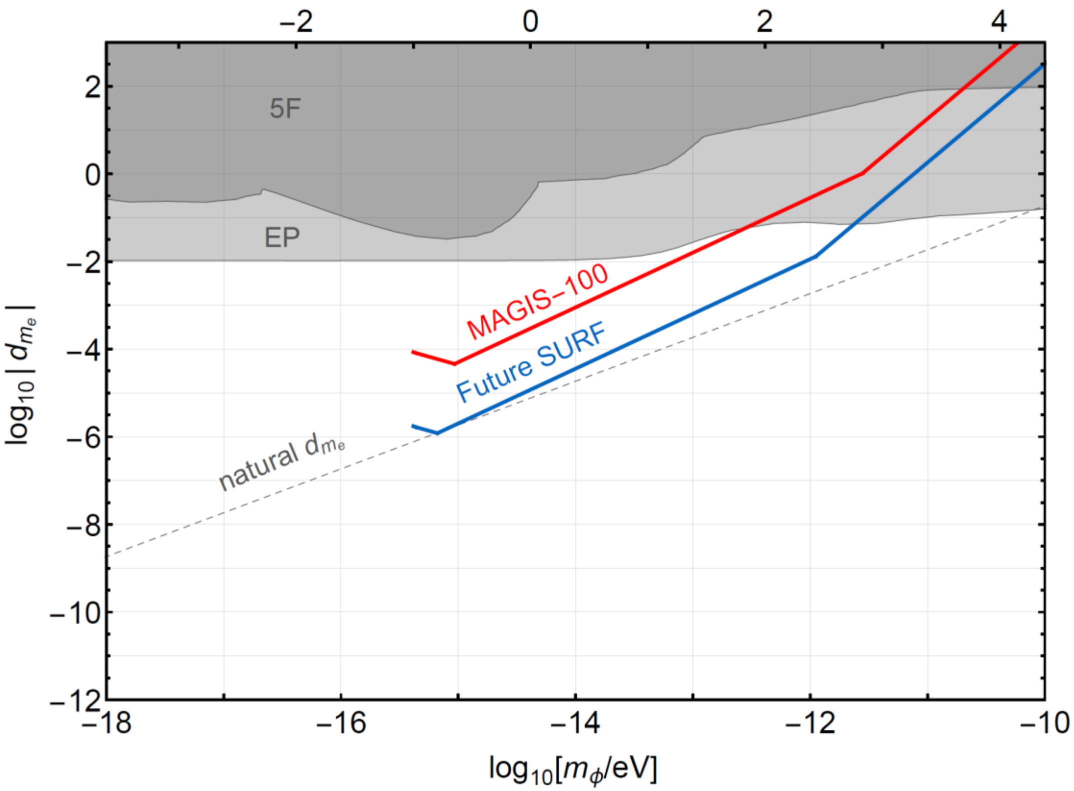
$\delta\omega_A$	*Dark matter*
$\delta L = hL$	*Gravitational wave*

Each interferometer measures the change over time T

Laser noise is common-mode suppressed in the gradiometer

Graham et al., PRL **110**, 171102 (2013).
Arvanitaki et al., arXiv:1606.04541 (2016).

Via coupling to the electron mass

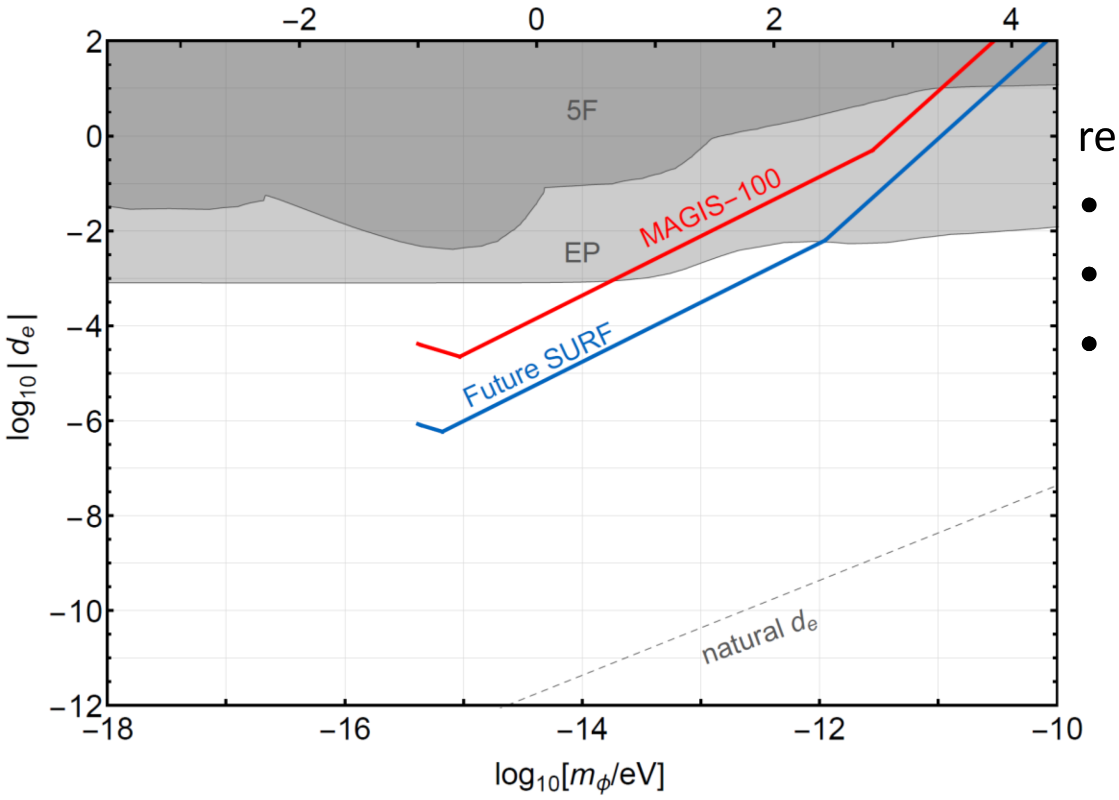


red curve:

- 10^{15} dropped atoms
- shot-noise limited phase resolution
- corresponds to 1 year of data taking

- Sensitivity to ultralight dark matter field coupling to the electron mass
  - with strength d_{me},
- shown as a function of the mass of the scalar field m
  - (or alternatively the frequency of the field - top scale)

Sensitivity via coupling to α

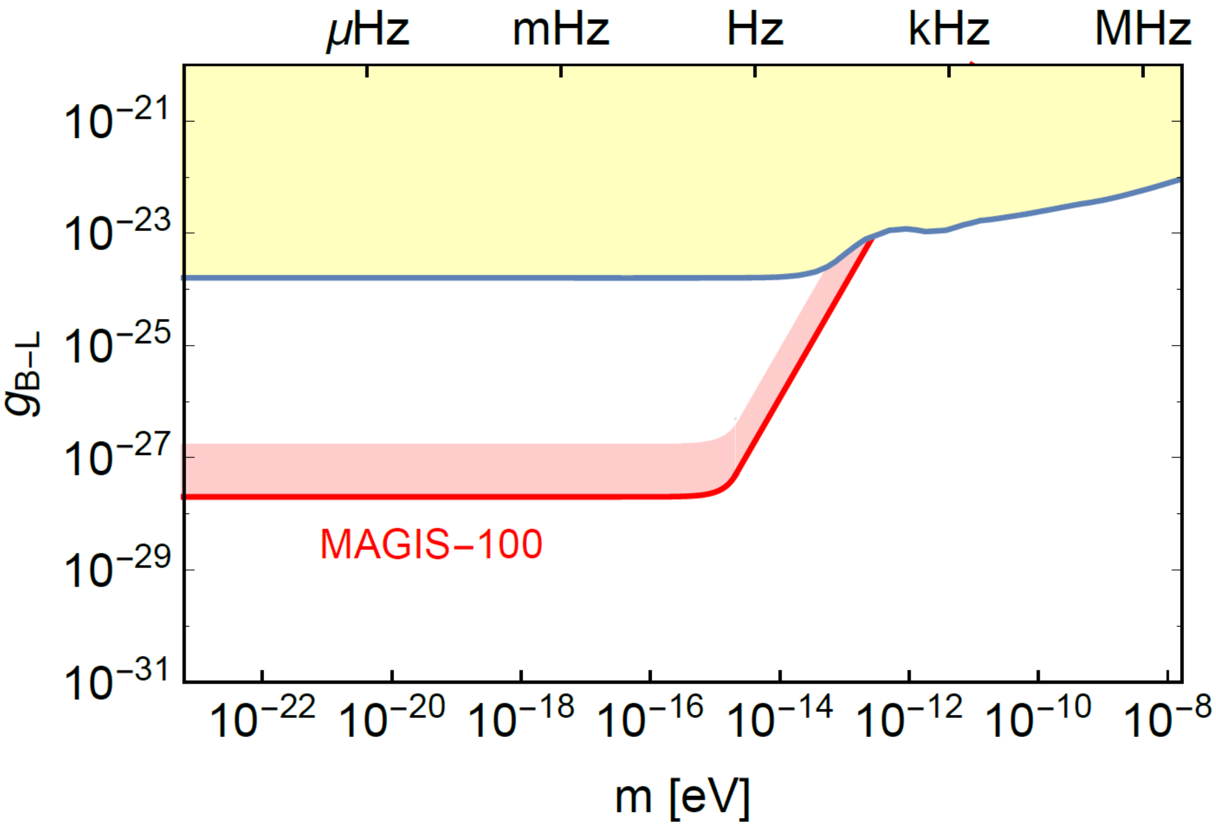


red curve:

- 10^{15} dropped atoms
- shot-noise limited phase resolution
- corresponds to 1 year of data taking

- Sensitivity to dark matter via coupling to the fine structure constant
  - with strength d_e,
- shown as a function of the mass of the scalar field *m*
  - (or alternatively the frequency of the field - top scale).

B-L Coupled Forces



Assumes:

- 50 m launch,
- 1000 ~ħ*k* atom optics
- 10^8 atoms/s flux
- shot noise limited

Sensitivity to a B-L coupled new force, with $10^{-16} g/\sqrt{Hz}$ acceleration sensitivity

Strategy

Current: 10-meter demonstration experiments at Stanford

- Macroscopic quantum mechanics
- Prototype clock interferometer apparatus

First step: 100-meter baseline at Fermilab

- Quantum initiative
- Dark sector
- Gravitational wave detector development

Second step: km-scale at Sanford lab, DUNE shaft

- Increased sensitivity to dark sector
- Full-scale GW detector
- Many quantum nodes for noise rejection

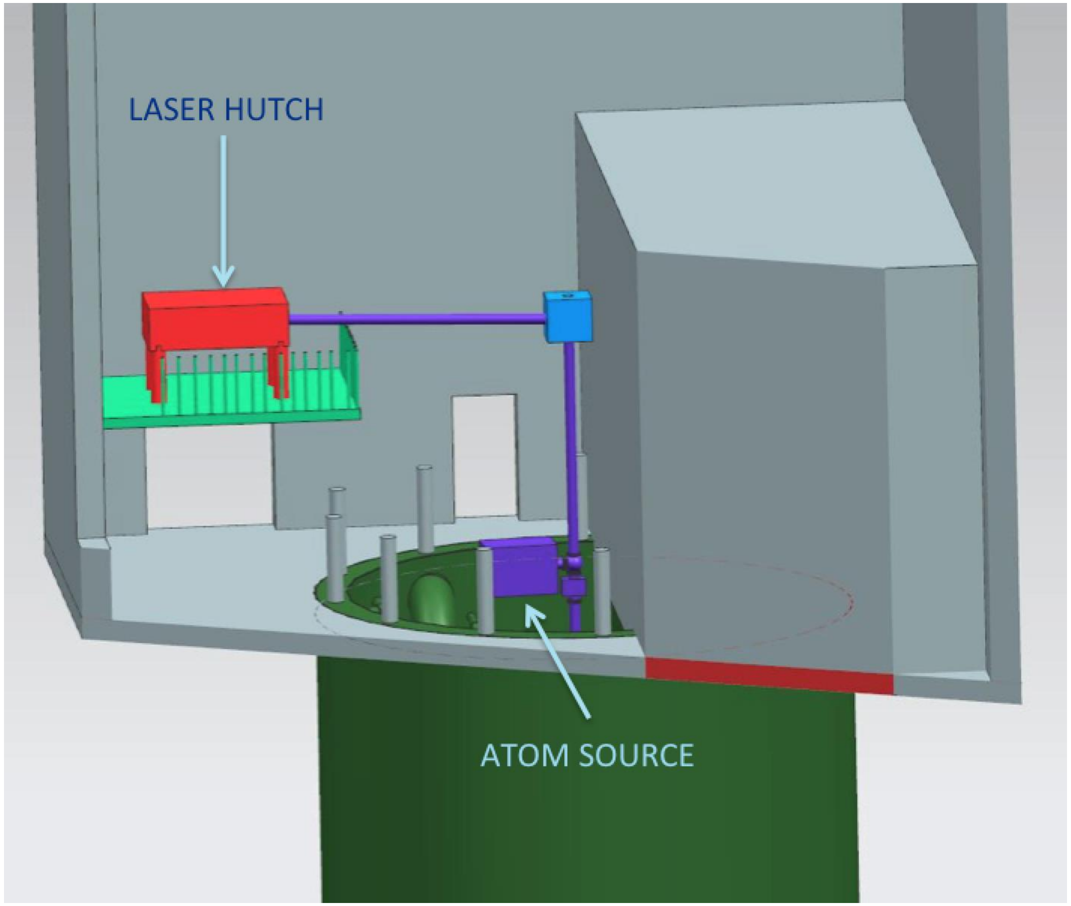
Summary & Present Status

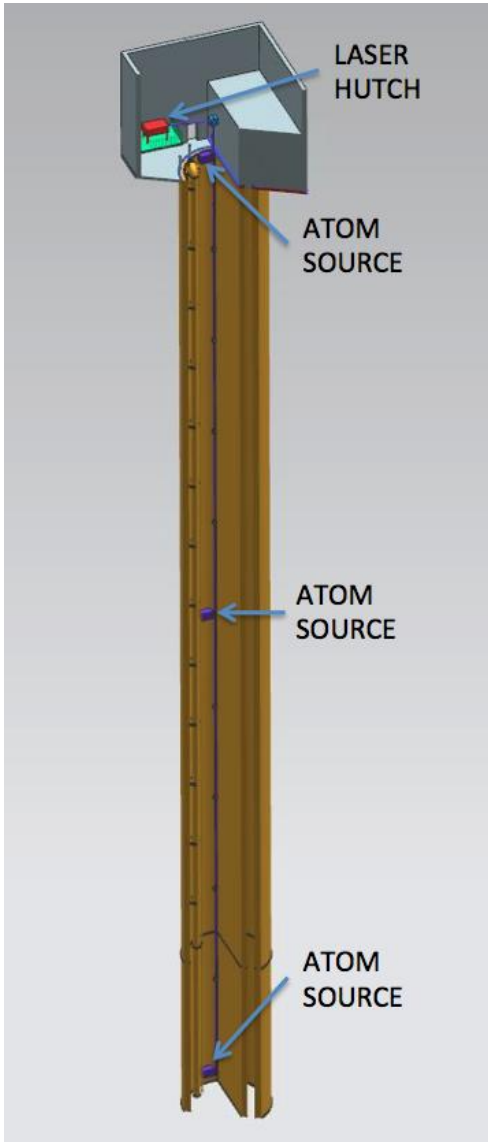
- New experiment at Fermilab
  - potential to scale much larger to SURF
- Using Atom Interferometry to:
  - Explore the dark sector
  - Test quantum mechanics at Large Distance Scales
  - Prototype for a mid-band gravity wave detector
- Proposal currently with the Fermilab PAC

Questions or Comments?

Backup

CAD model





Images from Linda Valerio (Fermilab)

Surrounding area at top of shaft.

coleman@liverpool.ac.uk - ICHEP 2018

Immediate area at top. Compressor will be removed.

Systematics

- Laser frequency noise
- Laser wavefront aberrations
- Magnetic fields
- Seismic vibration
- Coriolis effects
- Laser pointing jitter
- AC Stark shifts
- Initial cloud kinematics
- Mean field shifts
- Imaging aberrations
- Gravity Gradient Noise (GGN)

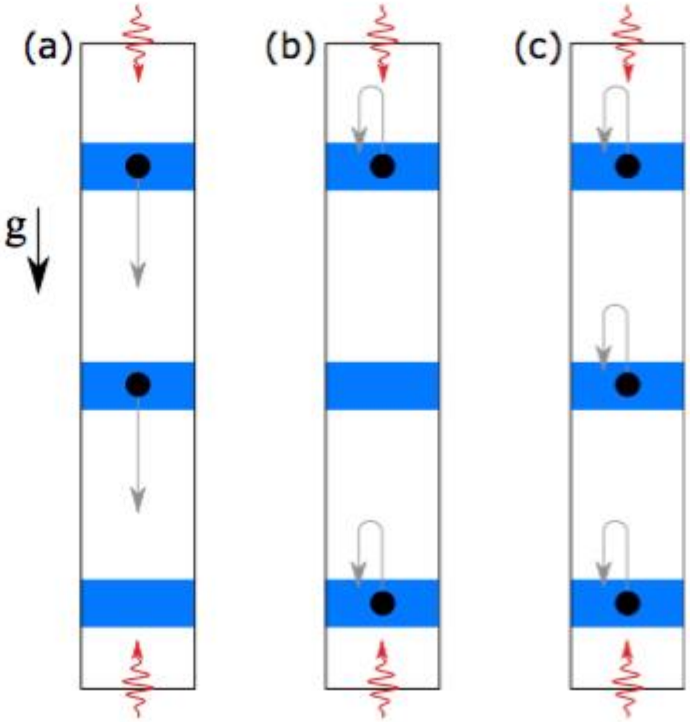
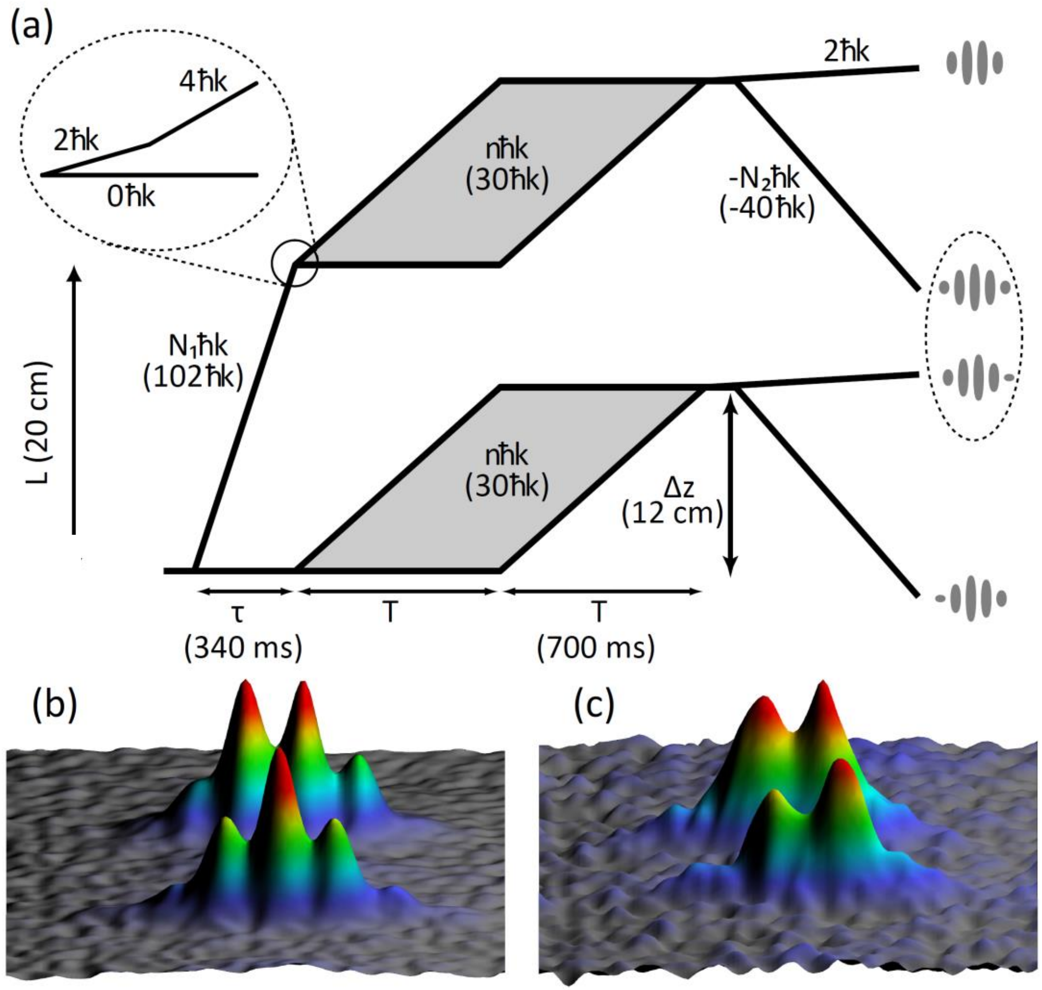


Figure 10: MAGIS-100 configurations. The basic detector design consists of three atom sources (blue bands) placed along the vacuum tube at the top, middle, and bottom. Light pulses (red) travel along the vacuum tube and interact with atoms at each of these locations. (a) Maximum drop time gradiometer. The top and middle atom source are dropped 50 meters and are detected at the middle at bottom locations, respectively. (b) Maximum baseline gradiometer. The top and bottom sources are launched on short (~ meter-scale) trajectories and detected at the top and bottom. (c) GGN characterization. All three sources can be used with short launches in order to explore Newtonian noise variation along the baseline (see Sec. 3.4.1).

Gravity Gradiometer



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

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

10 ħk

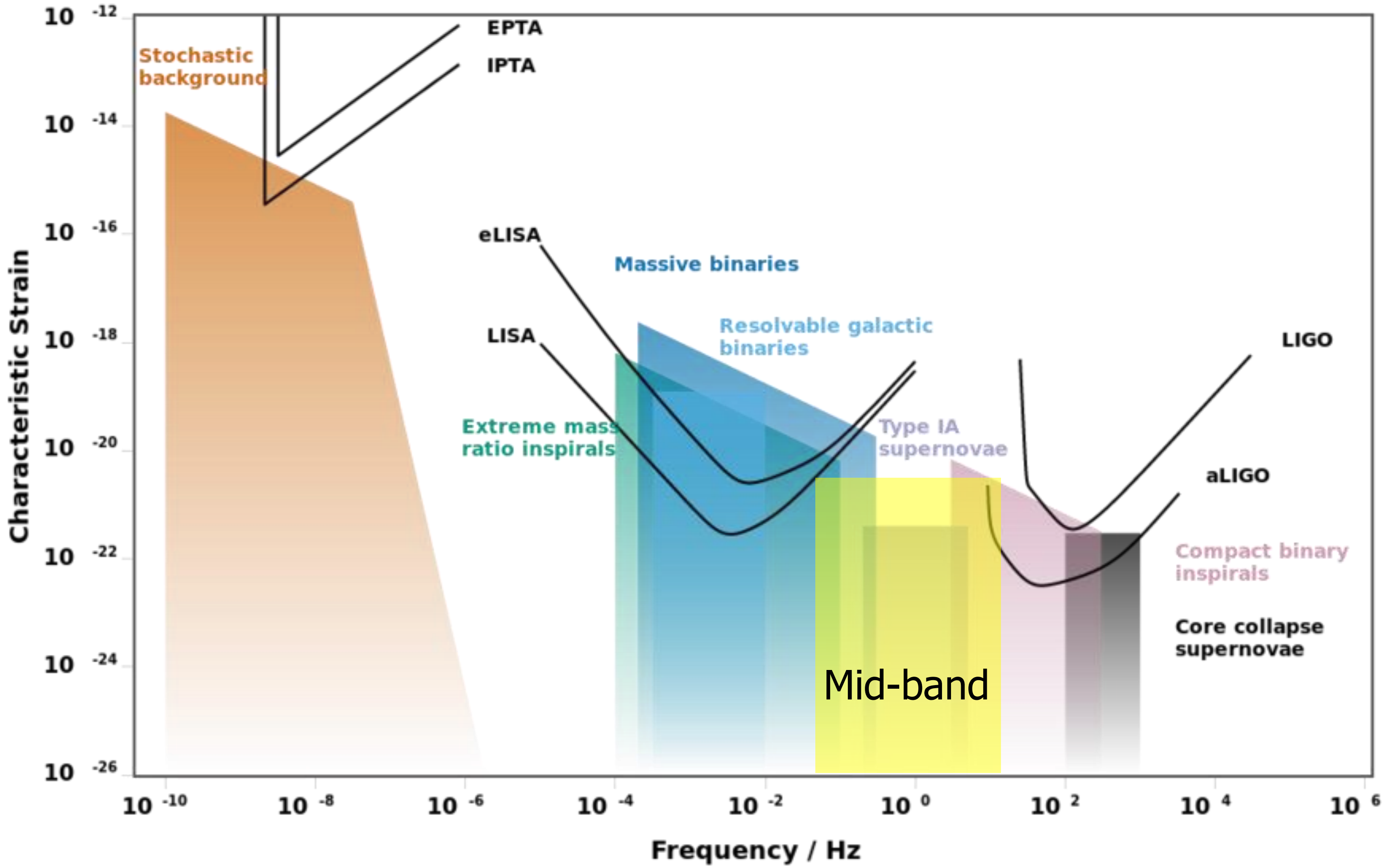
30 ħk

Phase shear readout of two interferometers

Gradiometer interference fringes

P. Asenbaum et al., PRL 2017.

Gravitational wave frequency bands

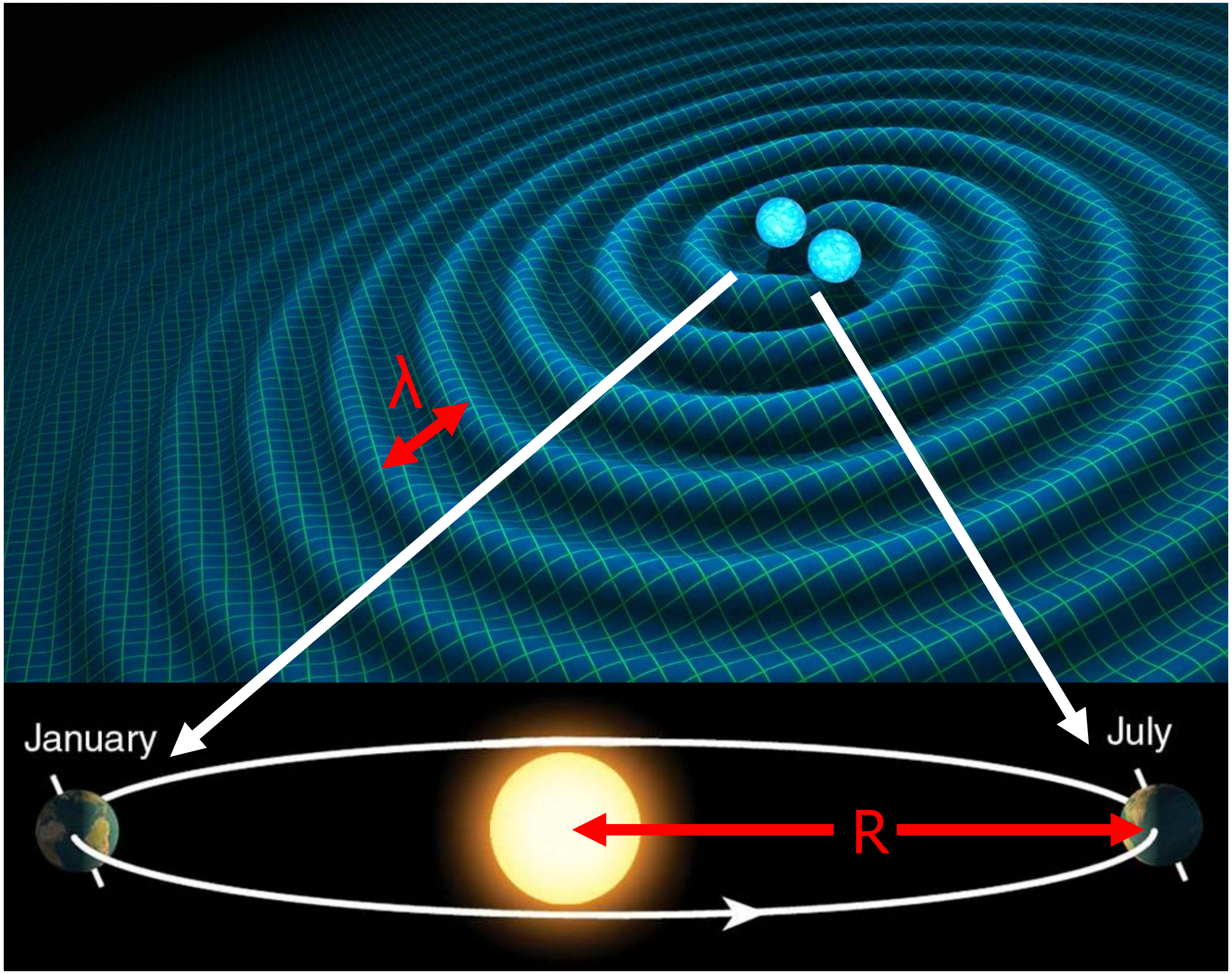


There is a gap between the LIGO and LISA detectors (0.1 Hz – 10 Hz).

Moore et al., CQG **32**, 015014 (2014)

Sky position determination

Sky localization precision ~λ/R

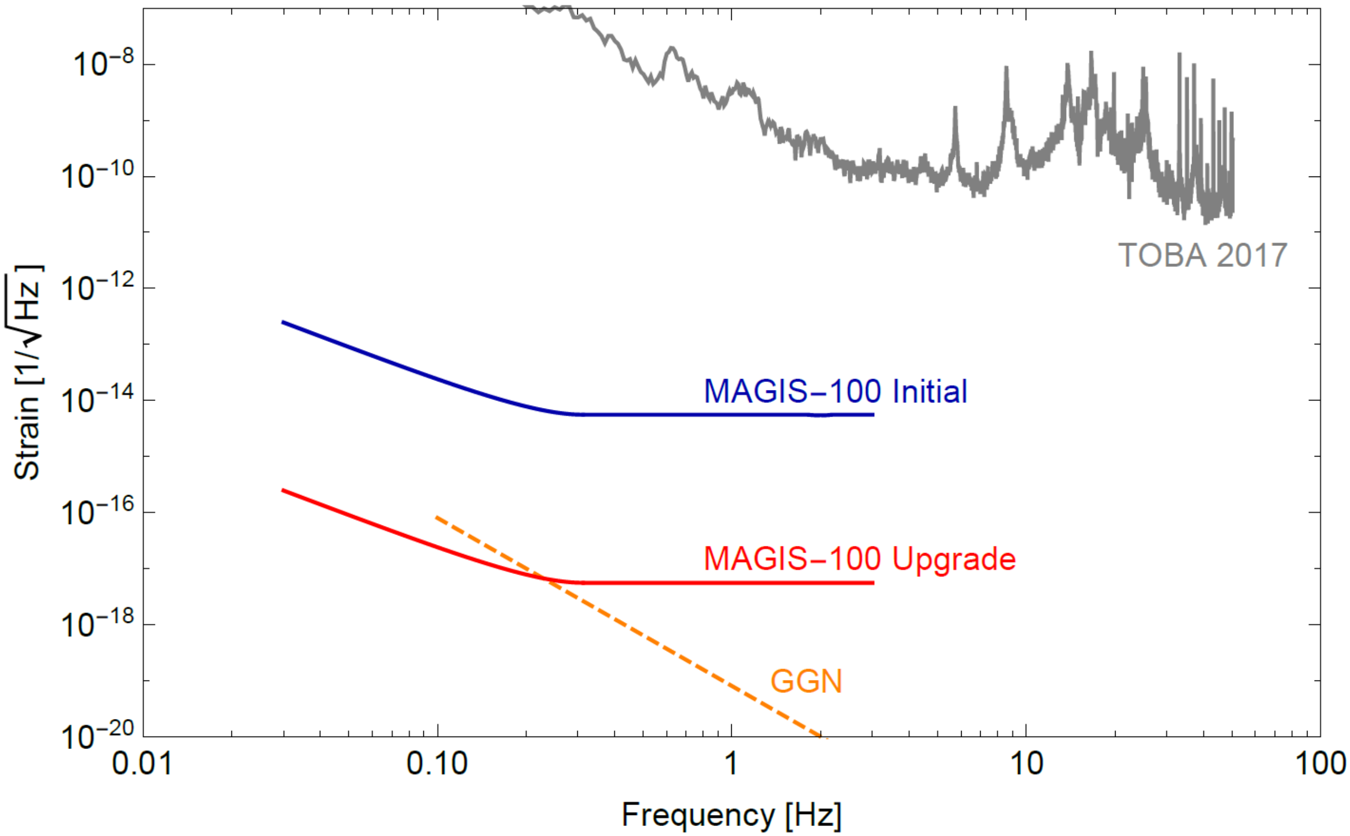


Mid-band advantages

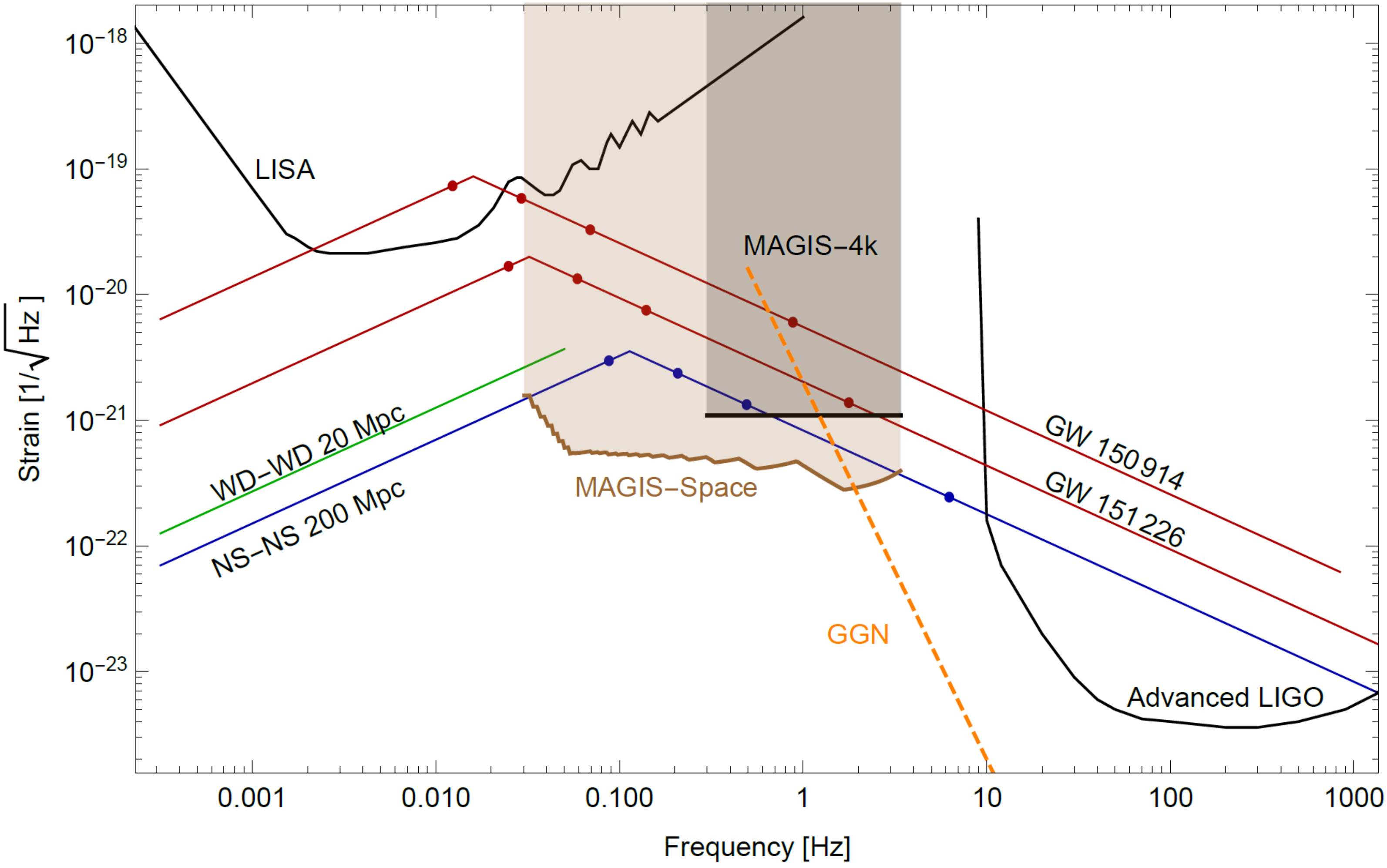
- Small wavelength λ
- Long source lifetime (~months) maximizes effective R

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

GW sensitivity



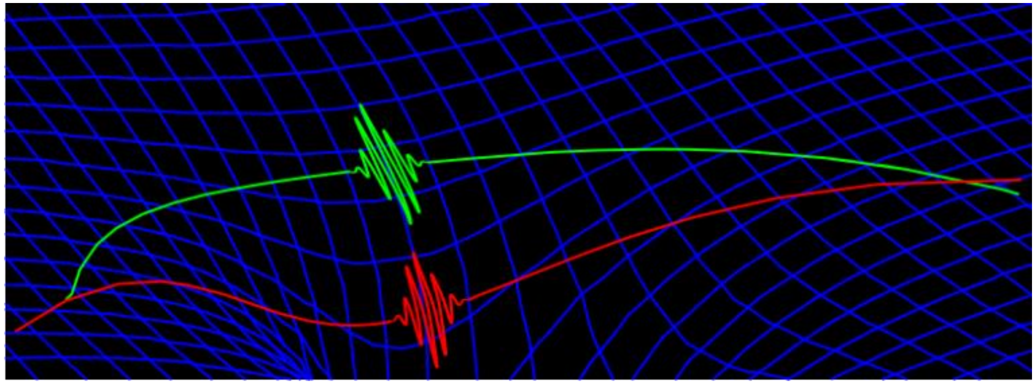
Full-scale GW Sensitivity



Dots indicate remaining lifetimes of 10 years, 1 year and 0.1 years

Phase shift from tidal force

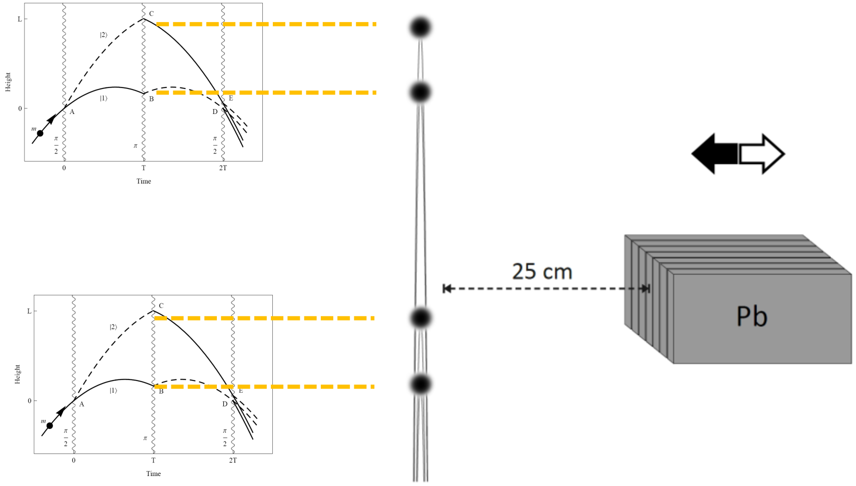
Spacetime curvature across a *single particle's* wavefunction

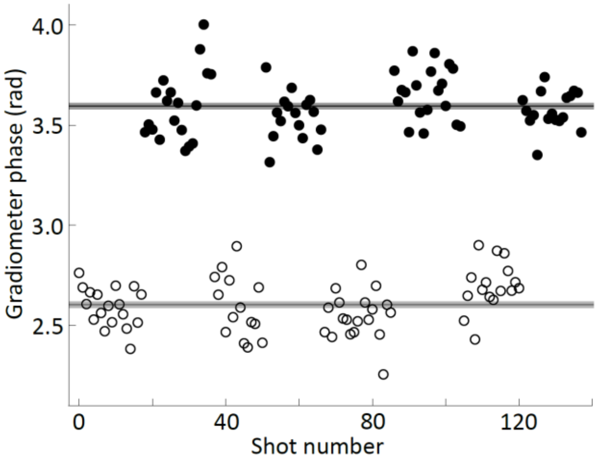


GR: gravity = curvature

Curvature-induced phase shifts as first *true manifestation* of gravitation in a quantum system

Gradiometer response to 84 kg lead test mass

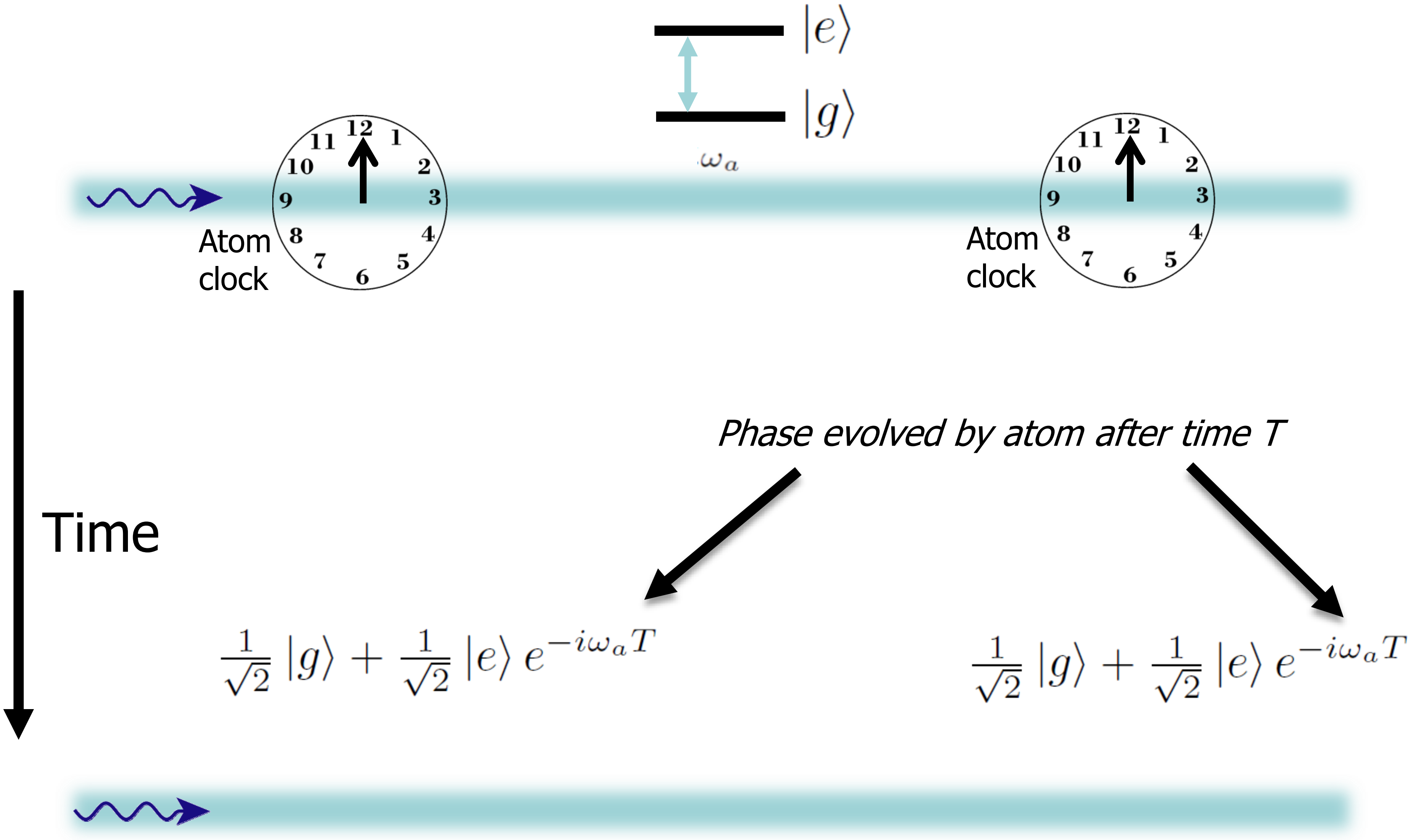




$L = 32$ cm $\Delta z = 7$ cm

P. Asenbaum et al., PRL 2017.

Simple Example: Two Atomic Clocks



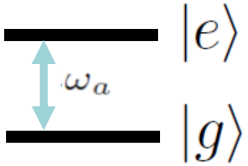
Phase evolved by atom after time T

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

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

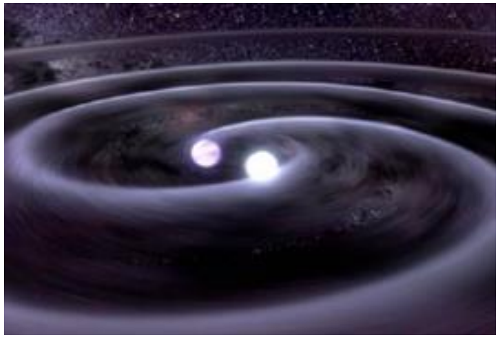
Simple Example: Two Atomic Clocks

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



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

Time

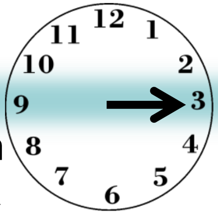


GW changes light travel time

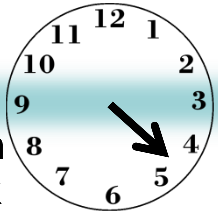
$\Delta T \sim hL/c$

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

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



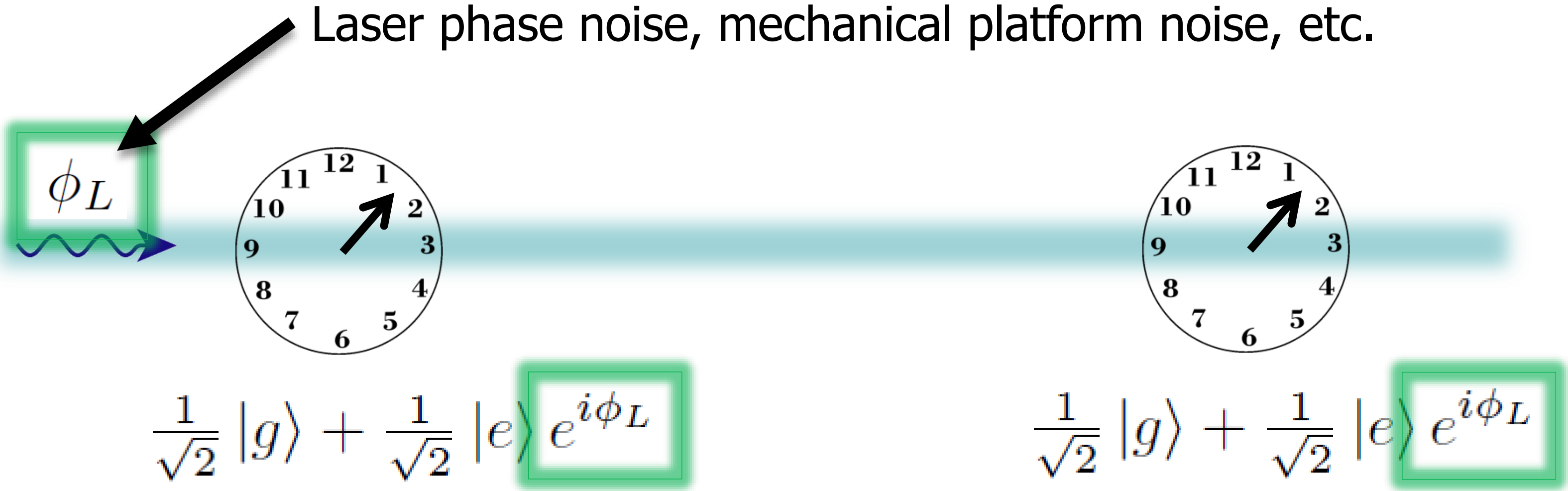
Atom clock



Atom clock

Phase Noise from the Laser

The phase of the laser is imprinted onto the atom.



Laser phase noise, mechanical platform noise, etc.

$\boxed{\phi_L}$

$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle \boxed{e^{i\phi_L}}$$

$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle \boxed{e^{i\phi_L}}$$

*Laser phase is **common** to both atoms – rejected in a differential measurement.*