Quantum Ensembles: Clocks and Interferometers

SNOWMASS Quantum Sensors Informational Session

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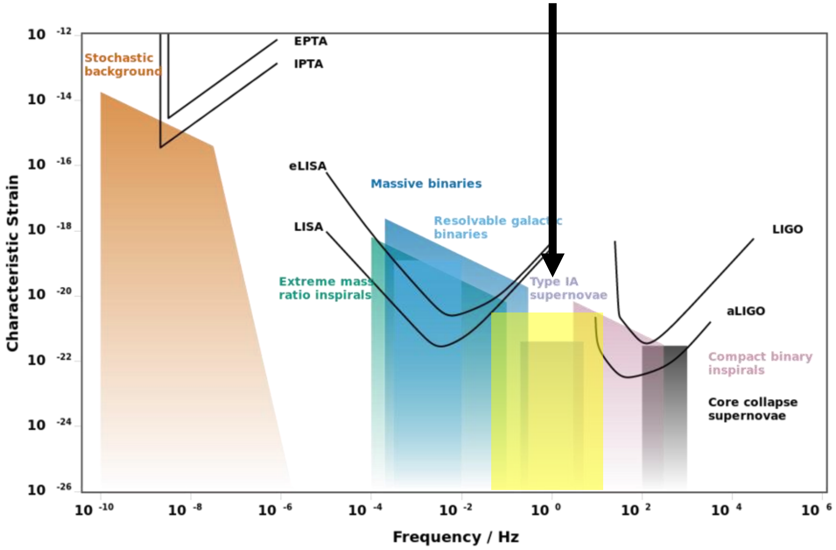
Atomic sensors for gravitational wave detection

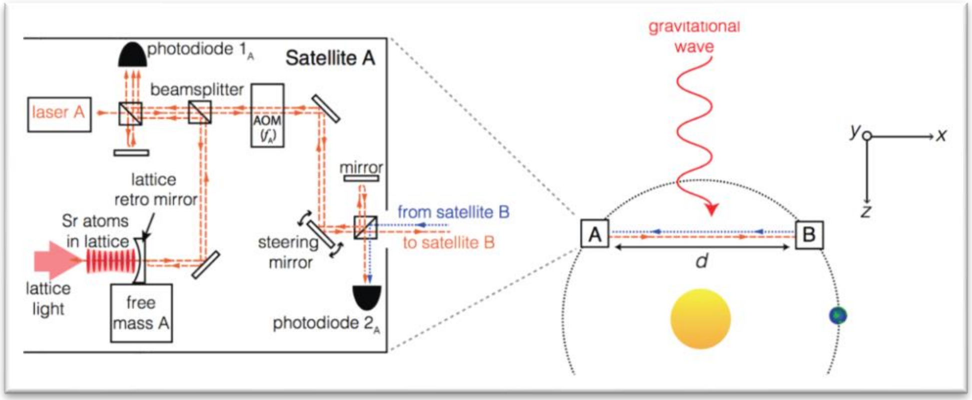
Atomic clocks and **atom interferometry** offer the potential for gravitational wave detection in an *unexplored frequency range* (“mid-band”)

Mid-band: 0.03 Hz to 3 Hz

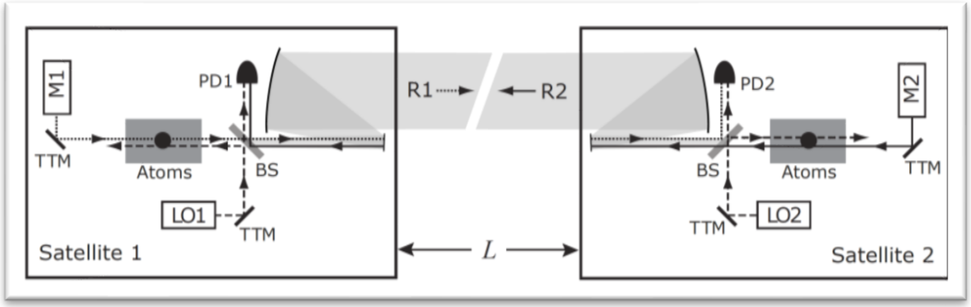


Mid-band science

- LIGO sources before they reach LIGO band
- Optimal for sky localization: predict when and where inspiral events will occur (for multi-messenger astronomy)
- Probe for studying cosmology
- Search for dark matter (dilaton, ALP, …)



Satellite proposal using optical lattice clocks + drag free inertial reference (Kolkowitz et al., **PRD** 2016)



MAGIS: Atom interferometry with clock atoms serving as both inertial reference + phase reference (Hogan, Kasevich, **PRA** 2016)

Sky position determination

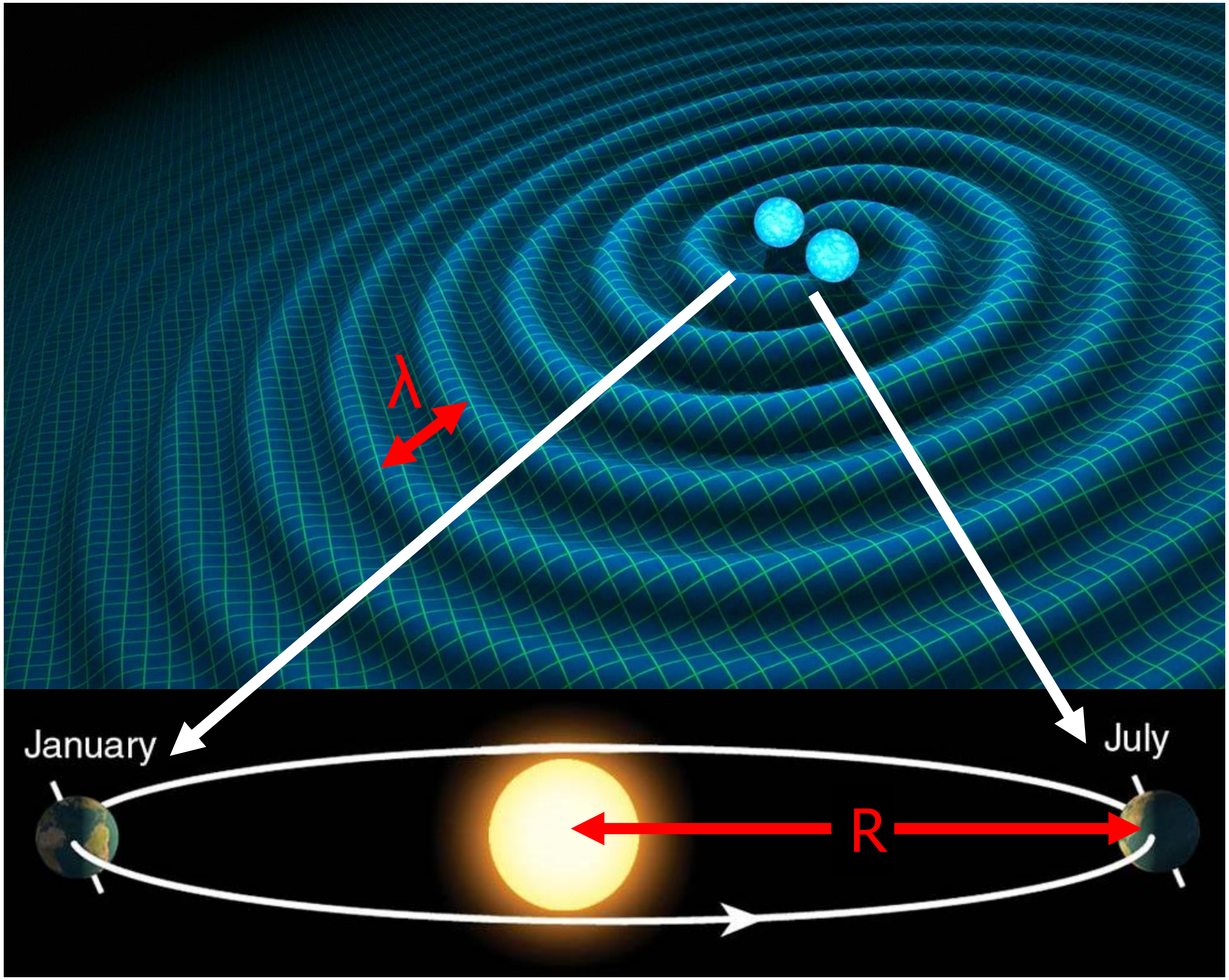
Sky localization precision:

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

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

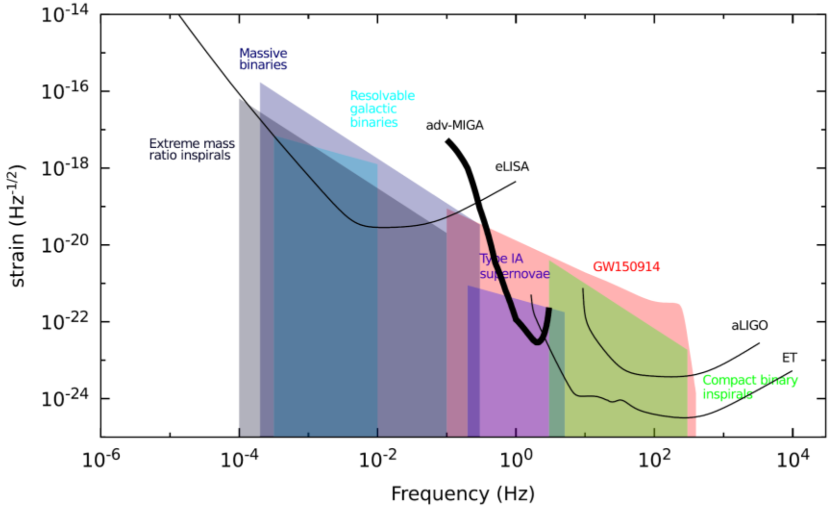


Graham et al., **PRD** 024052 (2018).

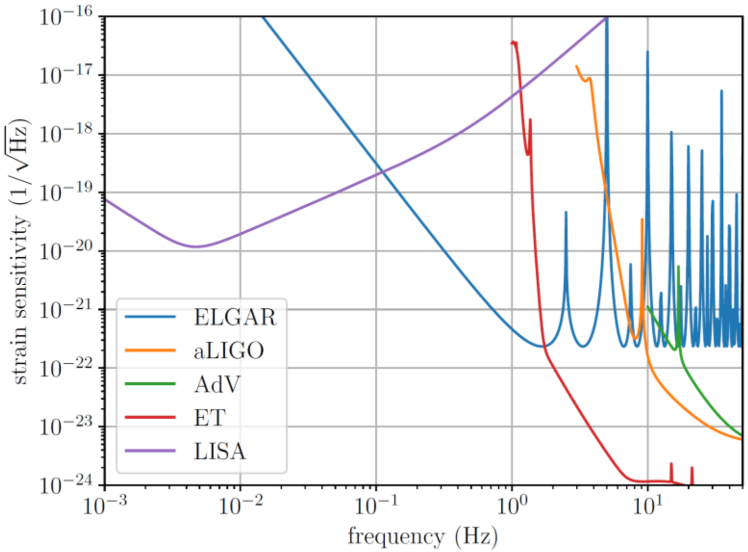
Images: R. Hurt/Caltech-JPL; 2007 Thomson Higher Education

International efforts in atomic sensors for mid-band GW

MIGA: Matter Wave laser Interferometric Gravitation Antenna (France)

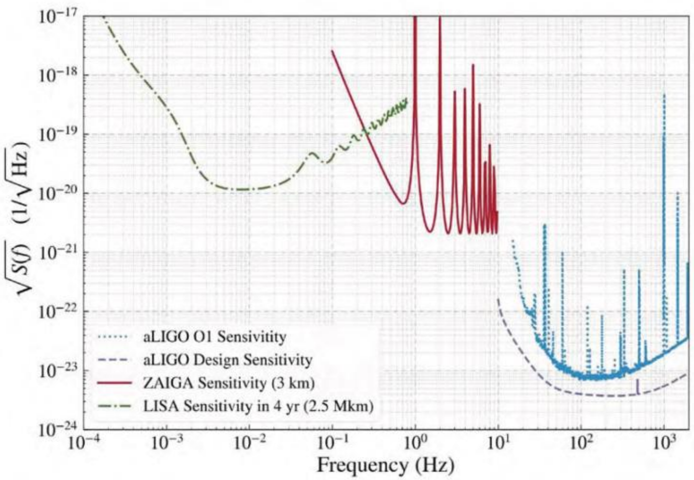


ELGAR: European Laboratory for Gravitation and Atom-interferometric Research

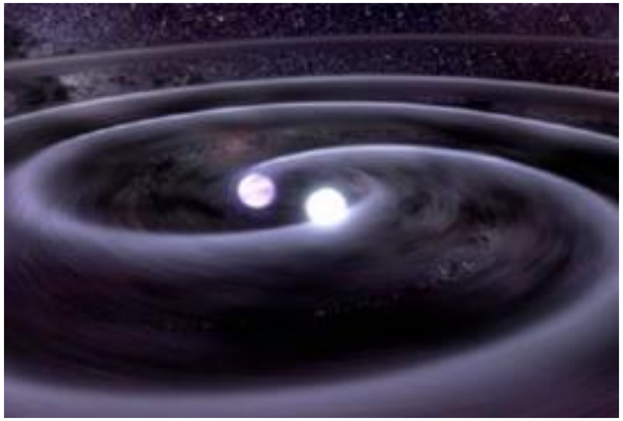


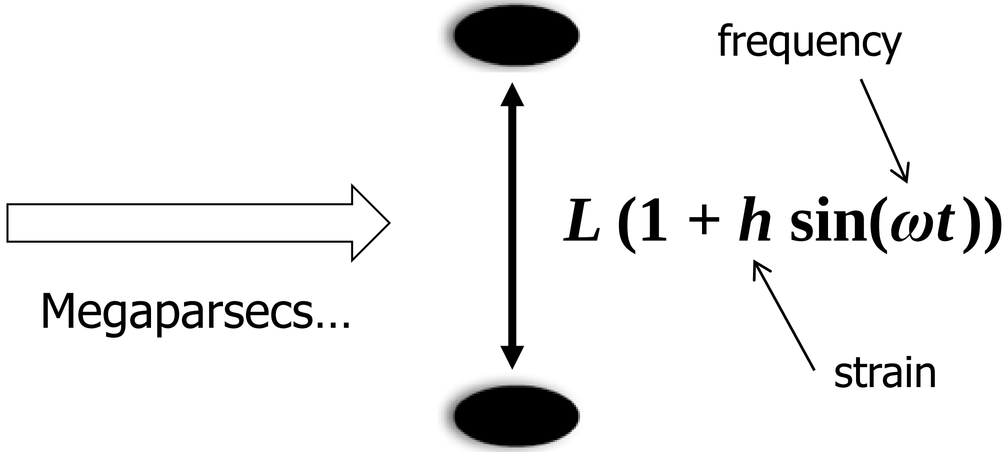
AION: Atom Interferometer Observatory and Network (UK)

ZAIGA: Zhaoshan Long-baseline Atom Interferometer Gravitation Antenna (China)



MAGIS concept





Megaparsecs…

frequency

$$L\,(1 + h\,\sin(\omega t))$$

strain

Matter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor (MAGIS)

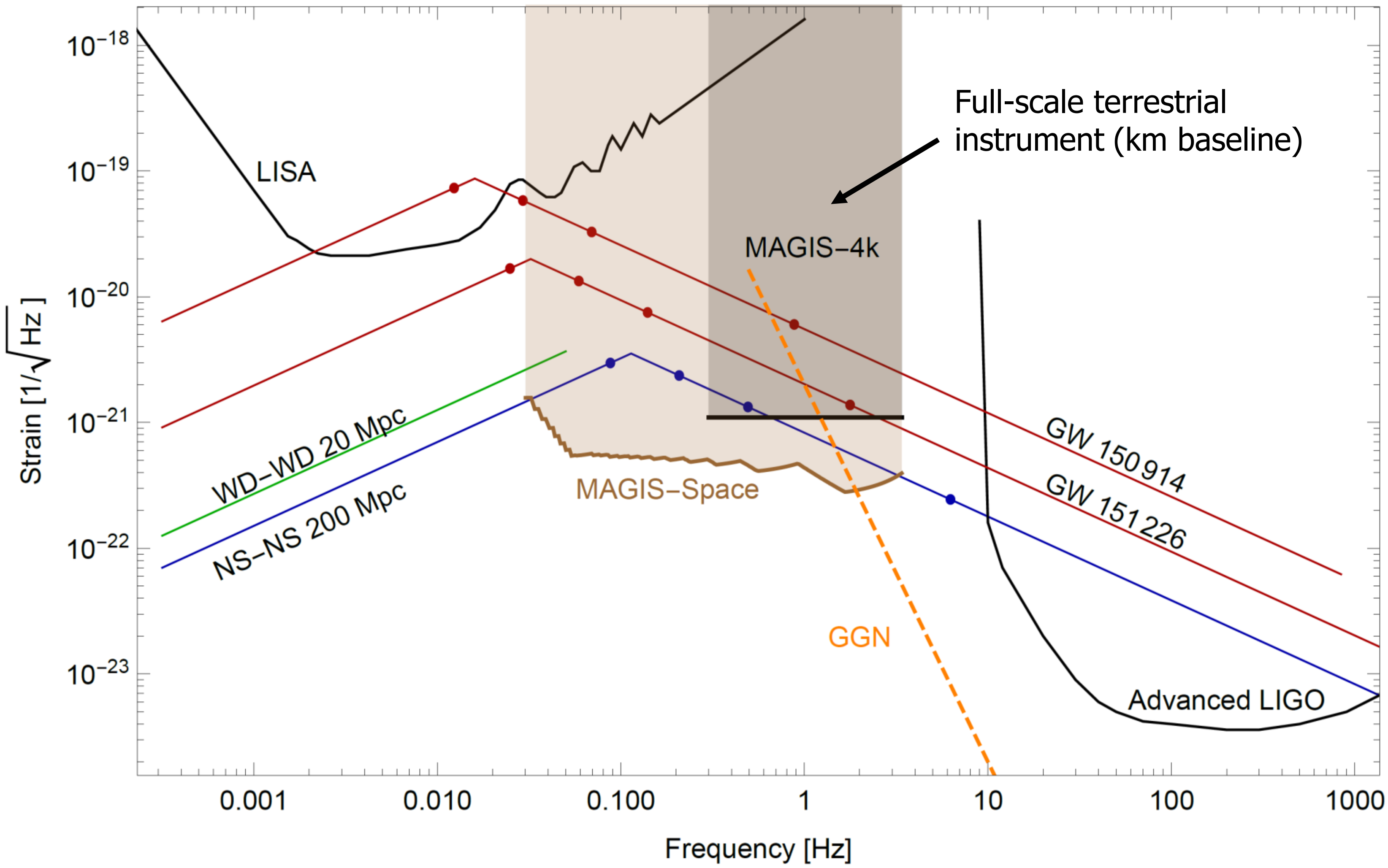
Passing gravitational waves cause a small modulation in the distance between objects.

Detecting this modulation requires two ingredients:

1. **Inertial references**
   - Freely-falling objects, separated by some baseline
   - Must be *insensitive* to perturbations from non-gravitational forces
2. **Clock**
   - Used to monitor the separation between the inertial references
   - Typically measures the time for light to cross the baseline

In MAGIS, atoms play both roles.

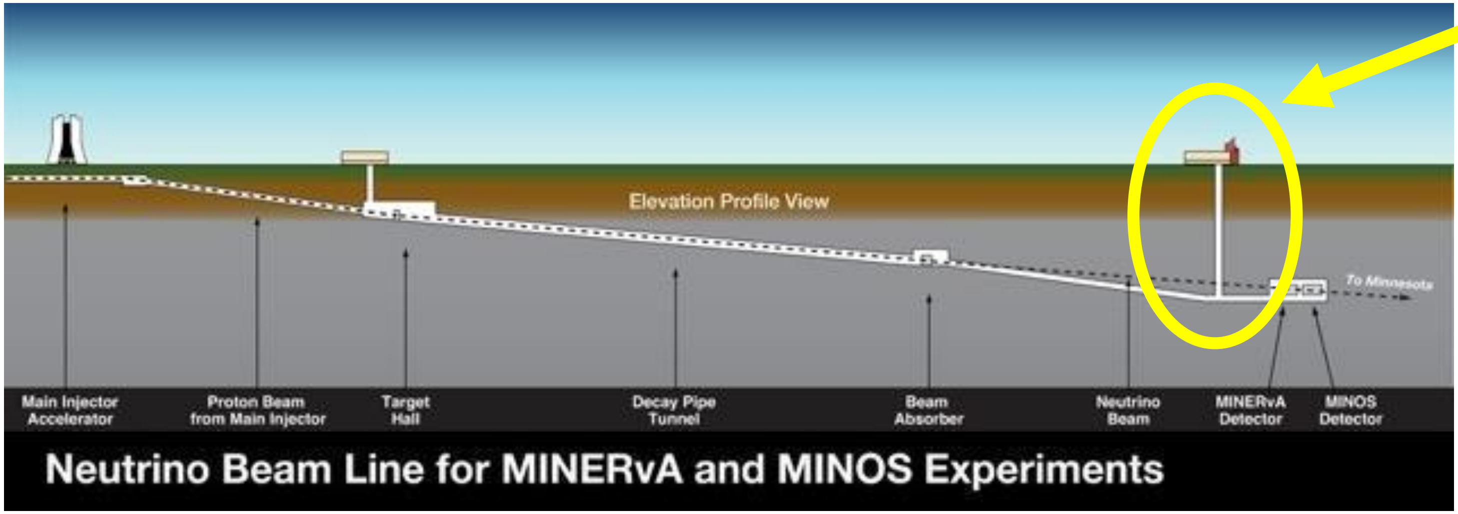
Projected gravitational wave sensitivity

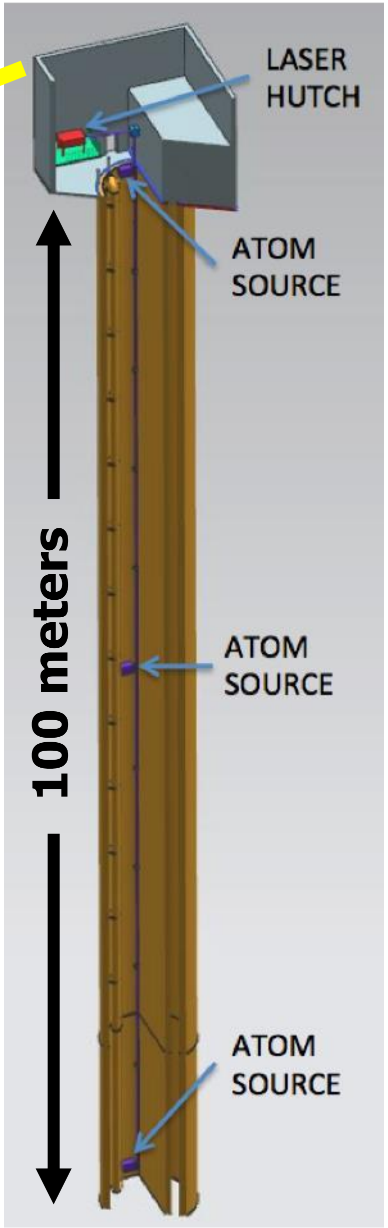


Dots indicate remaining lifetimes of 10 years, 1 year, 0.1 years, and 0.01 years

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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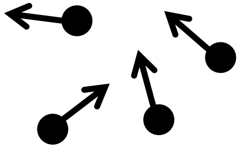
JOHNS HOPKINS UNIVERSITY
Northwestern University
Fermilab
SLAC
UNIVERSITY OF CAMBRIDGE
Northern Illinois University
UNIVERSITY OF OXFORD
UNIVERSITY OF LIVERPOOL

Ultralight dark matter

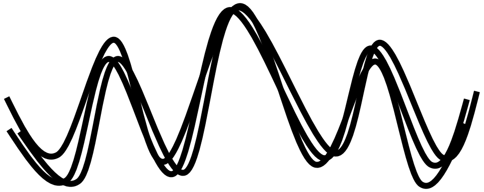
WIMPS

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

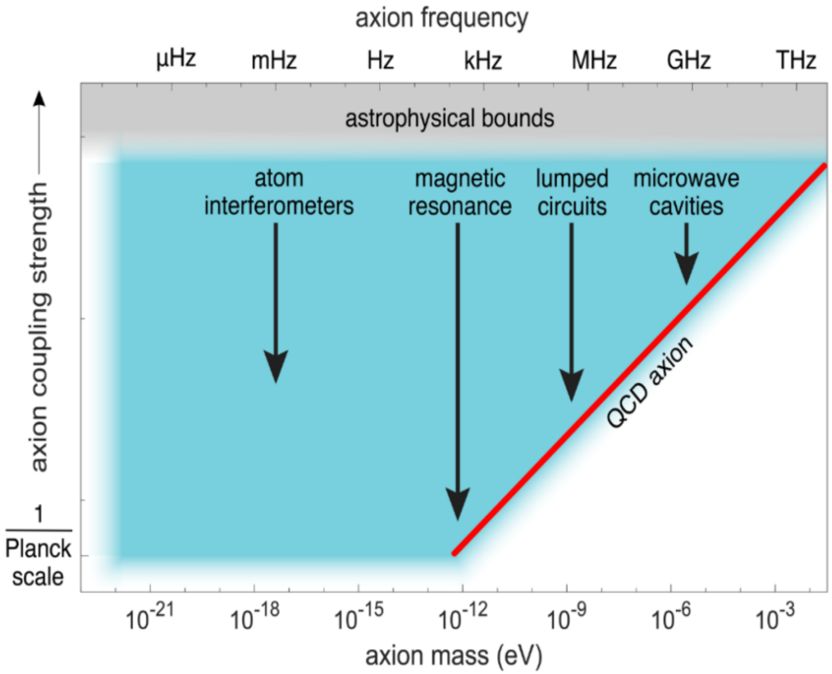


"Ultralight" dark matter (e.g., axions, dilatons, etc.)

- 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)

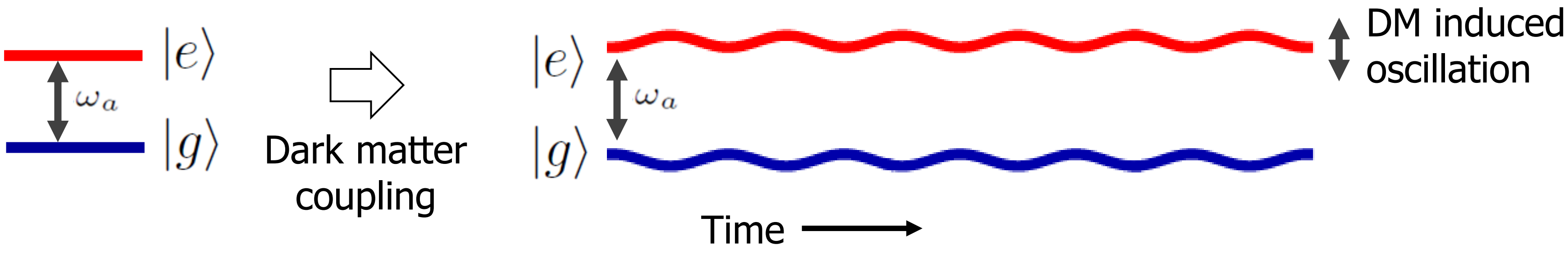
$$\mathcal{L} = +\underbrace{\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2} - \sqrt{4\pi G_N}\phi\left[\underbrace{d_{m_e}m_e\bar{e}e}_{\text{Electron coupling}} - \underbrace{\frac{d_e}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{Photon coupling}}\right] + \underbrace{\ldots}_{\text{e.g.,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

DM scalar field ↓

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

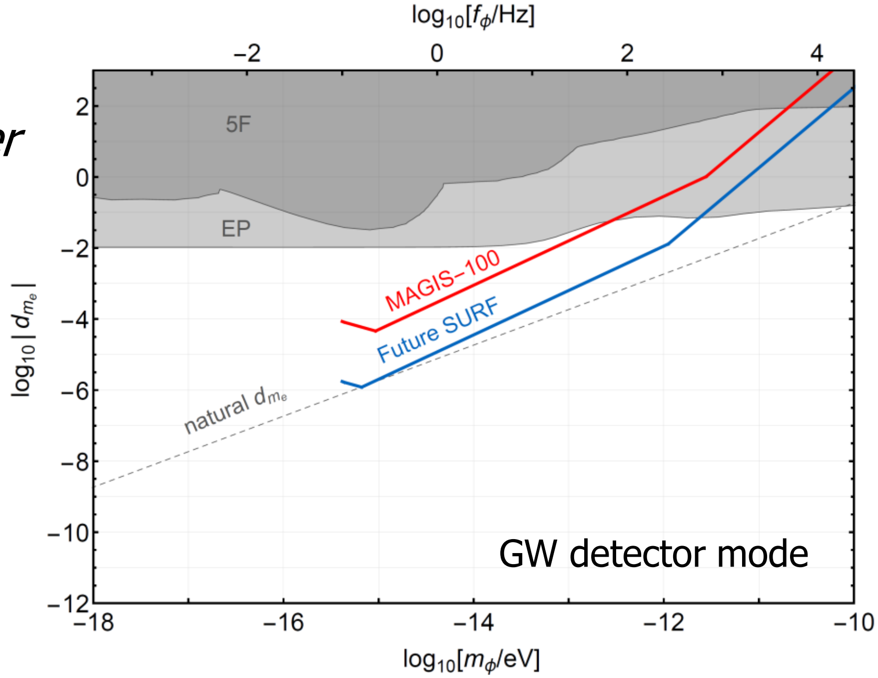
$$\phi_0 \propto \sqrt{\rho_{\mathrm{DM}}}$$ DM mass density

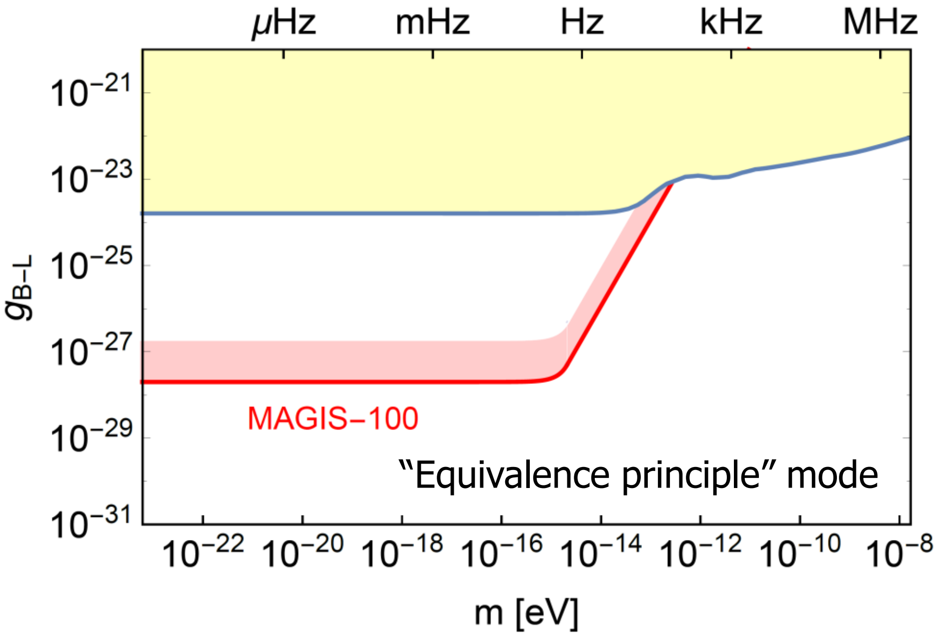
DM coupling causes time-varying atomic energy levels:



Projected sensitivity to dark matter for MAGIS-100

Sensitivity to ultralight scalar dark matter





Sensitivity to B-L coupled new force (“fifth force” search)

~ 1 year data taking

Assuming shot-noise limited phase resolution

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

Arvanitaki et al., PRD **97**, 075020 (2018).

Technical development path for GW detection

MAGIS-100 is a technology demonstrator for future **full-scale terrestrial** and **space-based** gravitational wave detectors

MAGIS detector development

State of the art

Experiments	Proposed Site	Baseline L	LMT Atom optics N	Atom sources	Phase noise $\delta\phi$
MAGIS prototype	Stanford	5 m	10^2	2	10^{-3} rad/$\sqrt{\text{Hz}}$
MAGIS-100 (initial)	FermiLab (MINOS shaft)	100 m	10^3	3	10^{-4} rad/$\sqrt{\text{Hz}}$
MAGIS-100 (final)	FermiLab (MINOS shaft)	100 m	10^4	3	10^{-5} rad/$\sqrt{\text{Hz}}$
Terrestrial	Homestake mine	2 km	10^3	10	10^{-5} rad/$\sqrt{\text{Hz}}$
Satellite	Medium Earth orbit (MEO)	4×10^7 m	10^3	2	10^{-4} rad/$\sqrt{\text{Hz}}$

MAGIS sensor technology R&D effort

Sensor technology	**State of the art**	**Target**	**GW sensitivity improvement**
LMT atom optics	10^2	10^4	100
Spin squeezing	20 dB (Rb), 0 dB (Sr)	20 dB (Sr)	10
Atom flux	$\sim 10^6$ atoms/s	10^8 atoms/s	10

Phase noise reduction targets

Phase noise improvement strategy is a combination of increasing atom flux and using quantum entanglement (spin squeezing).

MAGIS-100 Collaboration

STANFORD
Northwestern University
UNIVERSITY OF LIVERPOOL
Fermilab
SLAC
JOHNS HOPKINS UNIVERSITY
UNIVERSITY OF CAMBRIDGE
UNIVERSITY OF OXFORD
Northern Illinois University

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Robert Plunkett (Fermilab)
Swapan Chattopadhyay (Fermilab/NIU)
Jeremiah Mitchell (NIU)
Roni Harnik (Fermilab)
Phil Adamson (Fermilab)
Steve Hahn (Fermilab)
Steve Geer (Fermilab)
Jonathon Coleman (Liverpool)
Tim Kovachy (Northwestern)
Mark Kasevich (Stanford)
Surjeet Rajendran (John Hopkins)
Peter Graham (Stanford)
Valerie Gibson (Cambridge)
John March-Russell (Oxford)
Jason Hogan (Stanford)
Jan Rudolph (Stanford)
TJ Wilkason (Stanford)
Hunter Swan (Stanford)
Yijun Jiang (Stanford)
Ben Garber (Stanford)
Connor Holland (Stanford)
Megan Nantel (Stanford)
Sam Carman (Stanford)
Ariel Schwartzman (SLAC)

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DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

QuantiSED 2019

GW Detector Comparison

	Inertial reference	Laser phase reference
LIGO	Suspended end mirrors	Second arm
LISA	Drag-free proof masses	Second baseline
MAGIS	Atom	Atom
Atomic clock	Drag-free proof mass	Atom