Atom interferometry, MAGIS, and MAGIS-100

KITP Conference on Novel Experiments for Fundamental Physics

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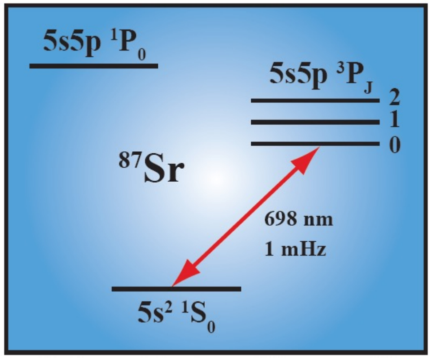
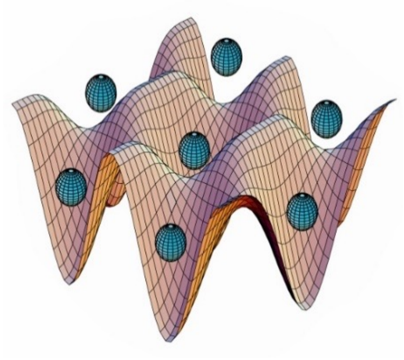
Stanford University
May 4, 2021

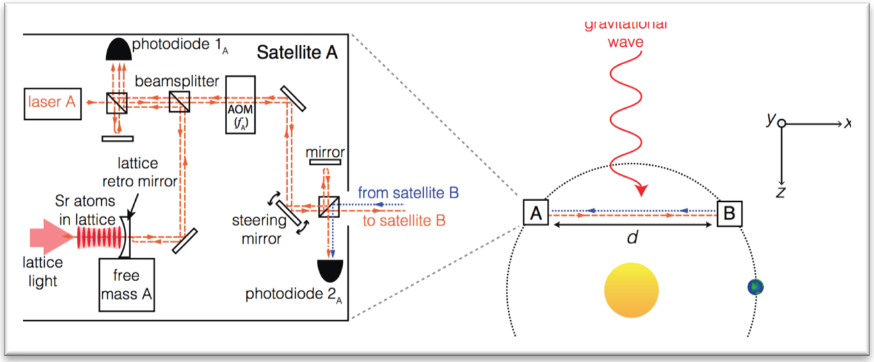
Atomic clocks and atom interferometers



- How can we leverage the incredible gains in stability and accuracy of clocks for fundamental physics?
- Atomic clocks and interferometers offer the potential for gravitational wave detection in an unexplored frequency range
- Development of new “clock” atom interferometer inertial sensors based on narrow optical transitions

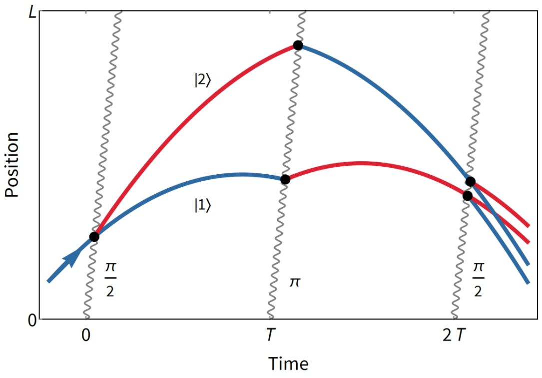
Optical lattice clocks

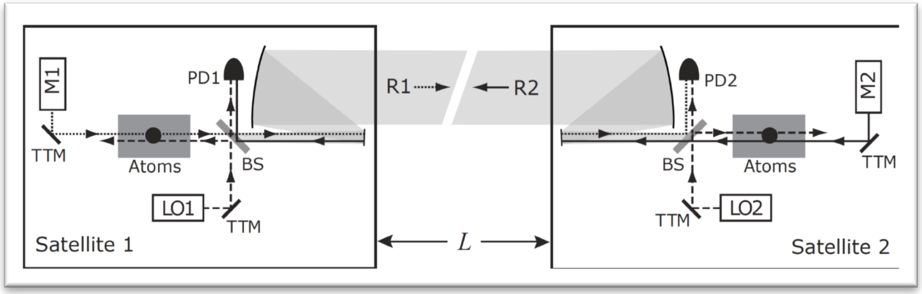




Kolkowitz et al., PRD 2016

Atom interferometers

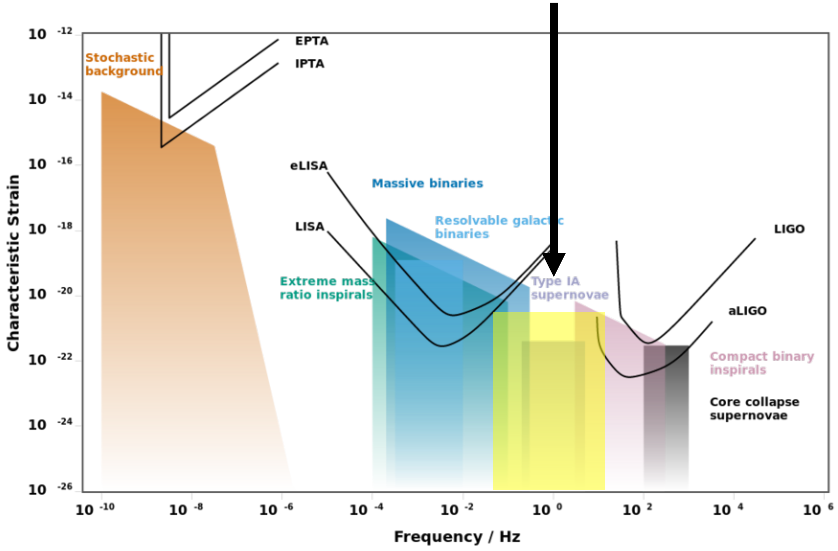




Hogan et al., PRA 2016

Long baseline atom interferometry science

Mid-band: 0.03 Hz to 3 Hz



Mid-band gravitational wave detection

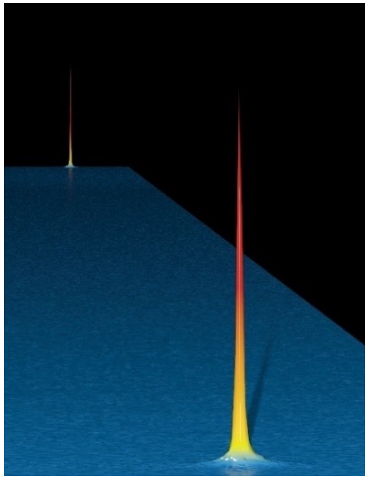
- LIGO sources before they reach LIGO ban
- Multi-messenger astronomy: optimal band for sky localization
- Cosmological sources

Ultralight wave-like dark matter probe

- Mass $<10^{-14}$ eV (Compton frequency in ~Hz range)
- Scalar- and vector-coupled DM candidates
- Time-varying energy shifts, EP-violating new forces, spin-coupled effects

Tests of quantum mechanics at macroscopic scales

- Meter-scale wavepacket separation, duration of seconds
- Decoherence, spontaneous localization, non-linear QM, …



Rb wavepackets separated by 54 cm

Sky position determination

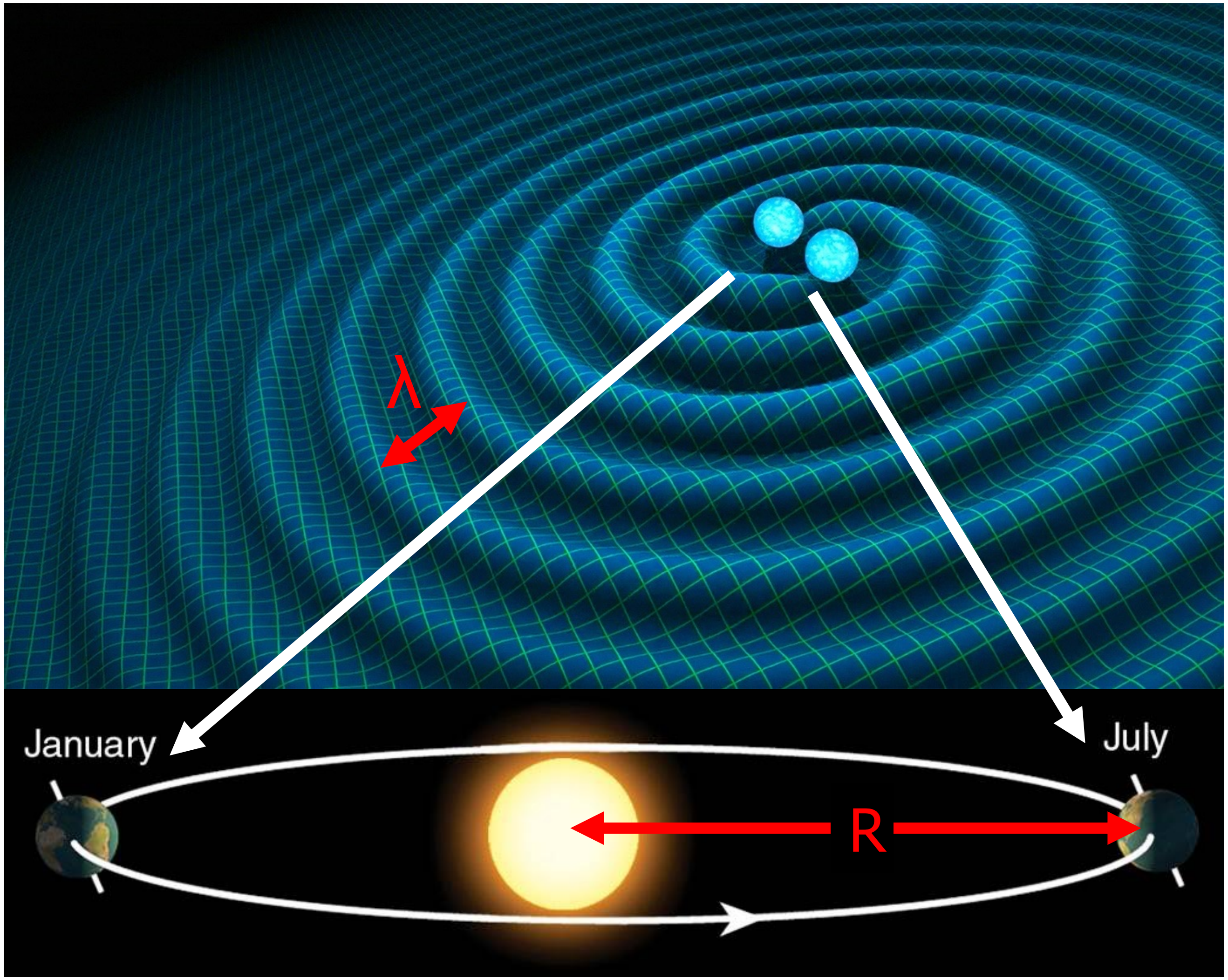
Sky localization precision:

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

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

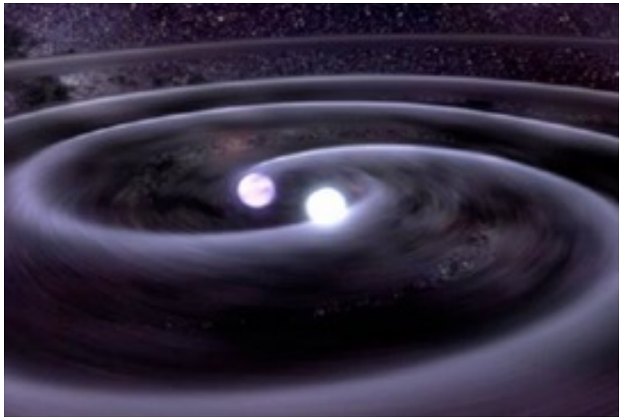


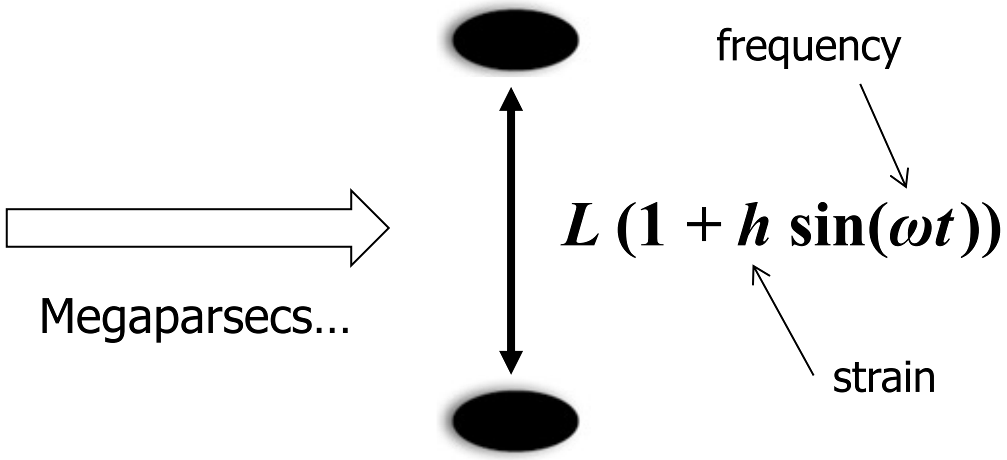
Graham et al., **PRD** 024052 (2018).

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

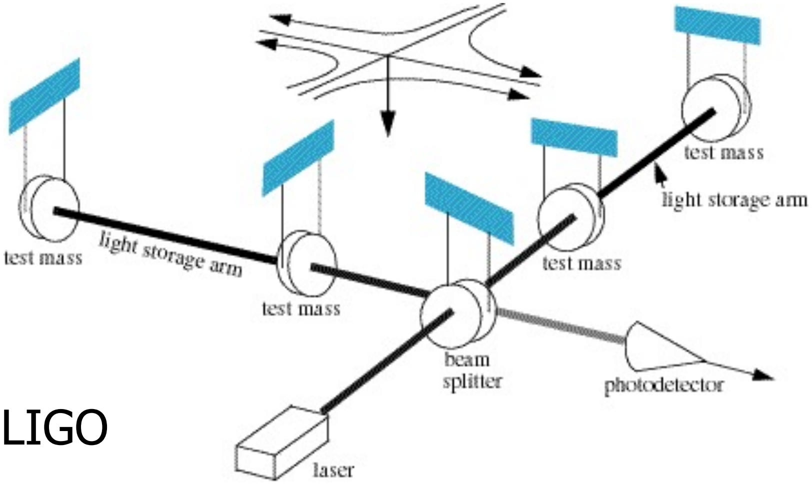
Gravitational Wave Detection

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





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



LIGO

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

MAGIS concept

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

Passing gravitational waves cause a small modulation in the distance between objects.
Detecting this modulation requires two ingredients:

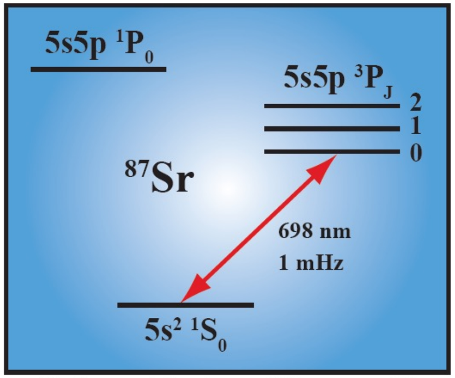
1. **Inertial references**
   - Freely-falling objects, separated by some baseline
   - Must be insensitive to perturbations from non-gravitational forces
2. **Clock**
   - Used to monitor the separation between the inertial references
   - Typically measures the time for light to cross the baseline, via comparison to a precise phase reference (e.g. a clock).

In MAGIS, atoms play both roles.

Atom as “active” proof mass: Atomic coherence records laser phase, avoiding the need of a reference baseline – **single baseline** gravitational wave detector.

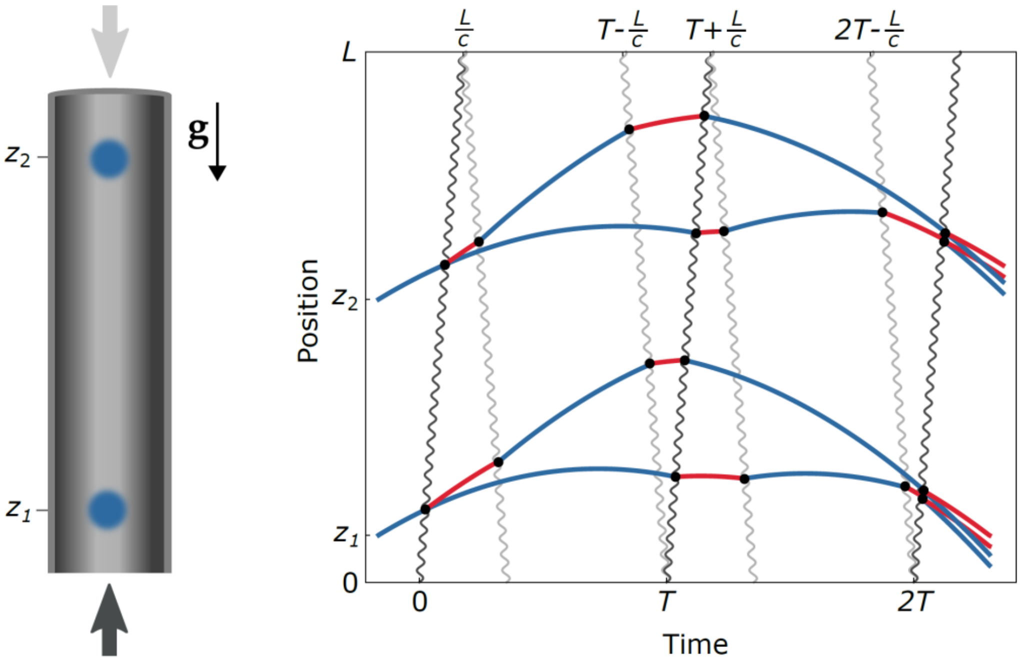
Clock atom interferometry

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:

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

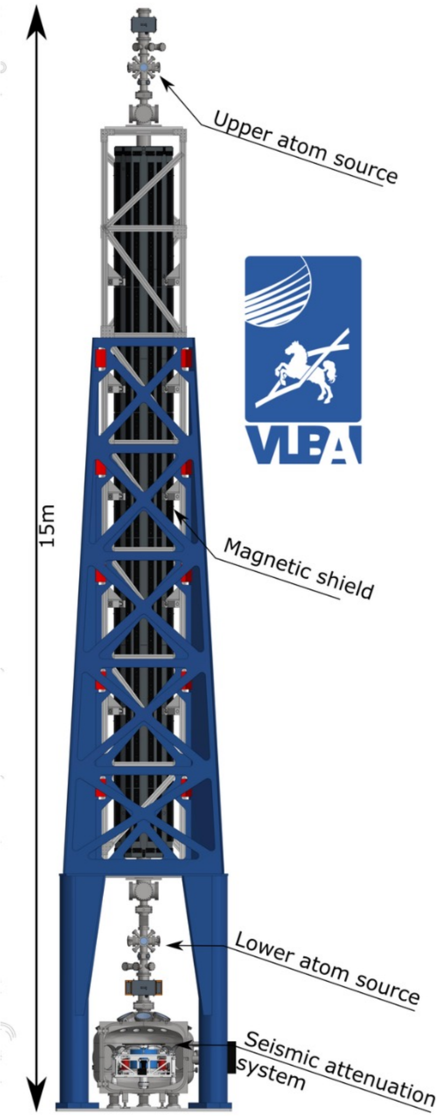
(variations over time T)

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).

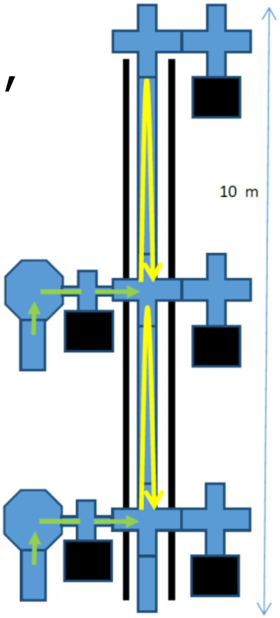
10-meter scale atom drop towers



Hannover, Germany

Wuhan, China

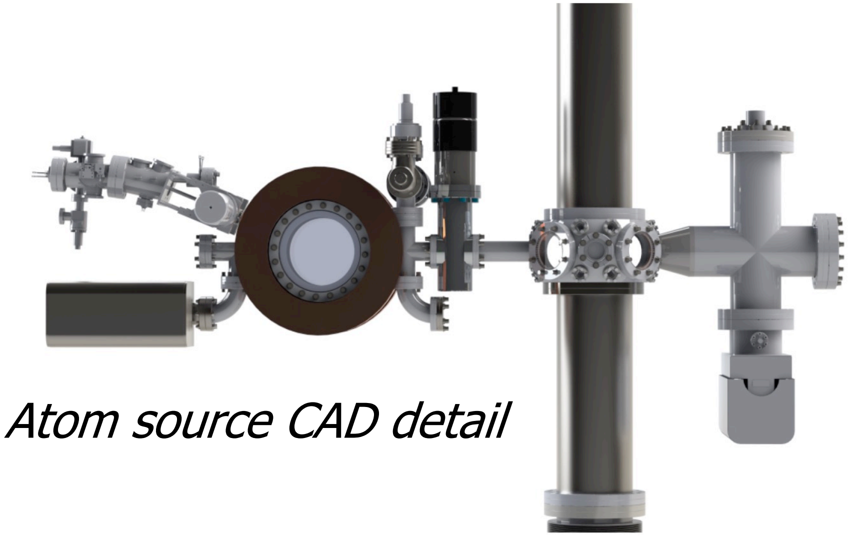
AION, UK



Stanford University

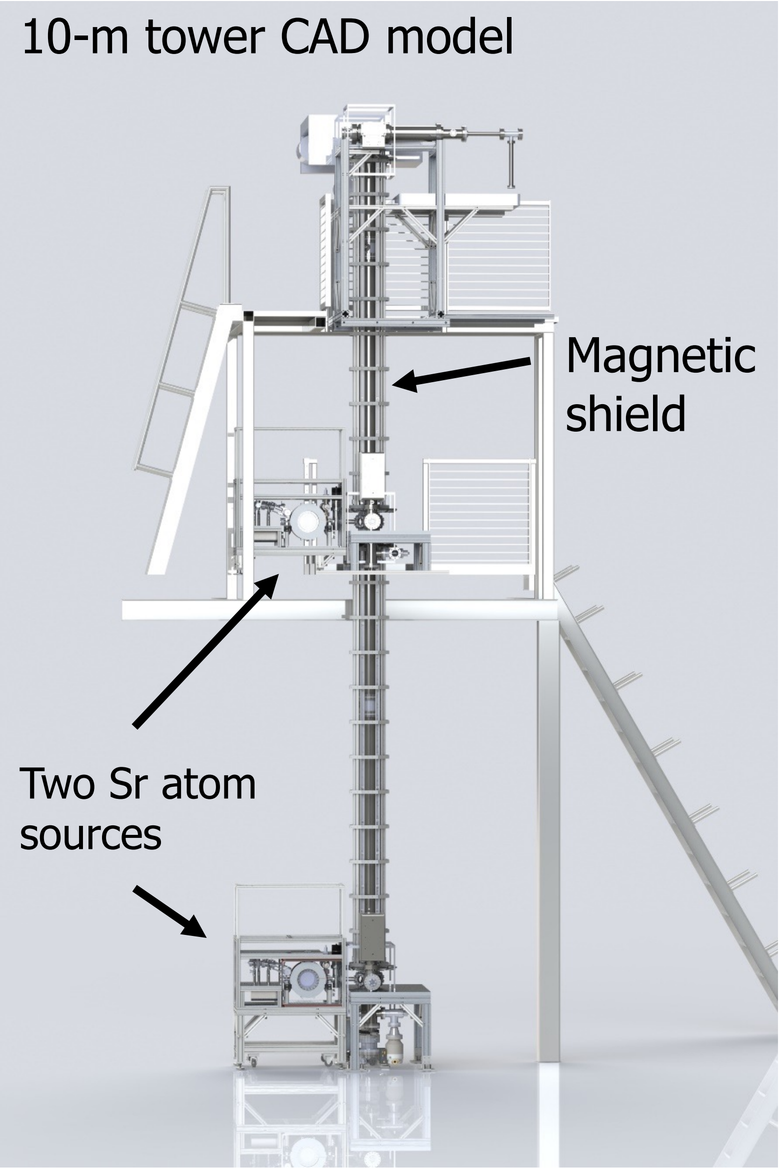
Stanford 10-meter Sr prototype

Two assembled Sr atom sources



Atom source CAD detail

10-m tower CAD model



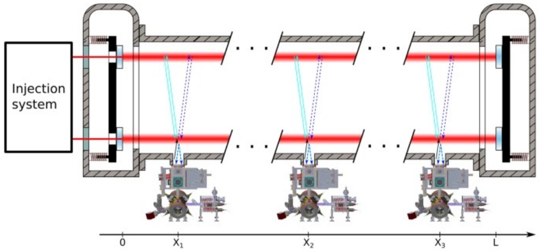
Magnetic shield

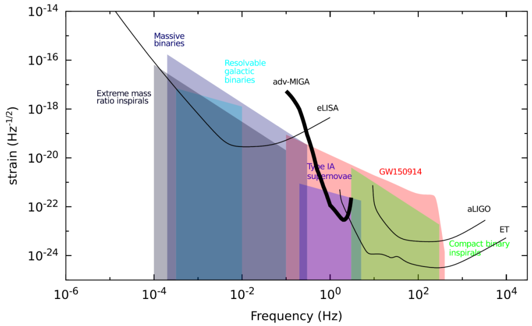
Two Sr atom sources

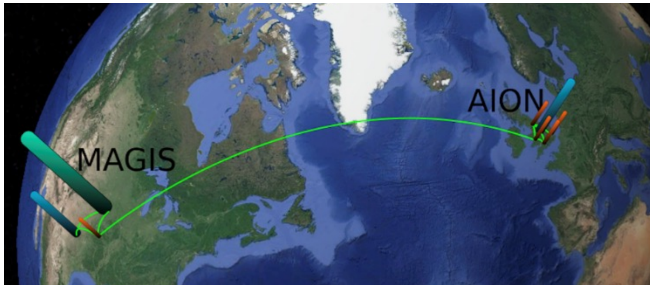
International efforts in long baseline atomic sensors

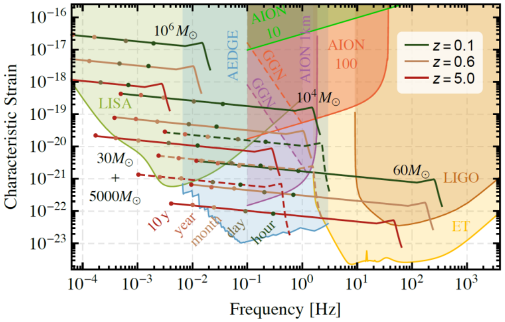
Project	Baseline Length	Number of Baselines	Orientation	Atom	Atom Optics	Location
MAGIS-100	100 m	1	Vertical	Sr	Clock AI, Bragg	USA
AION	100 m	1	Vertical	Sr	Clock AI	UK
MIGA	200 m	2	Horizontal	Rb	Bragg	France
ZAIGA	300 m	3	Vertical	Rb, Sr	Raman, Bragg, OLC	China

MIGA: Matter Wave laser Interferometric Gravitation Antenna (France)



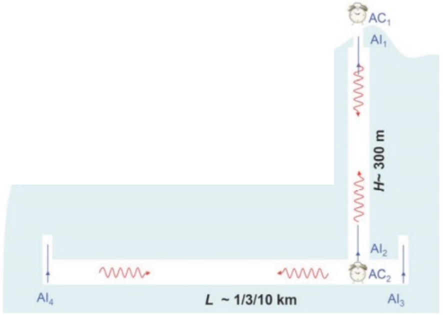


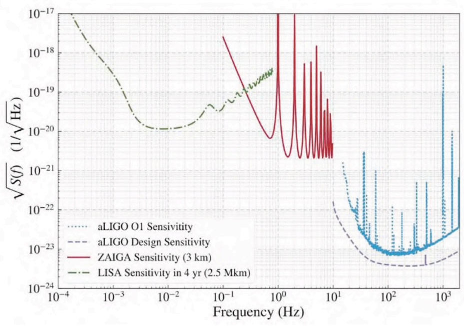




AION: Atom Interferometer Observatory and Network (UK)

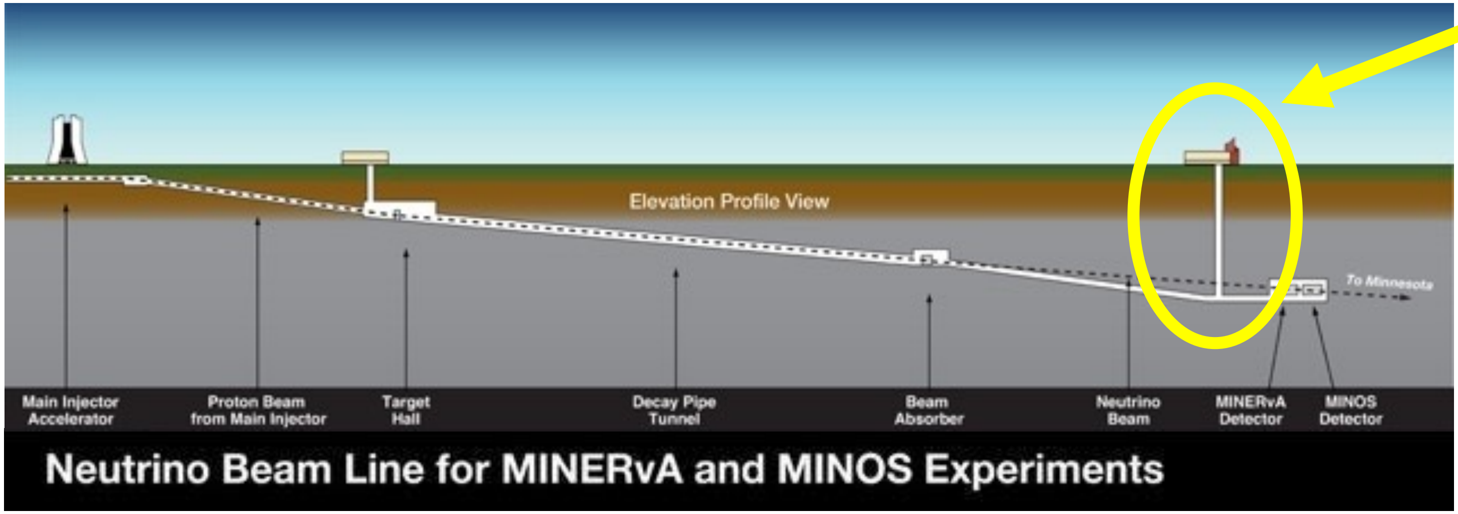
ZAIGA: Zhaoshan Long-baseline Atom Interferometer Gravitation Antenna (China)



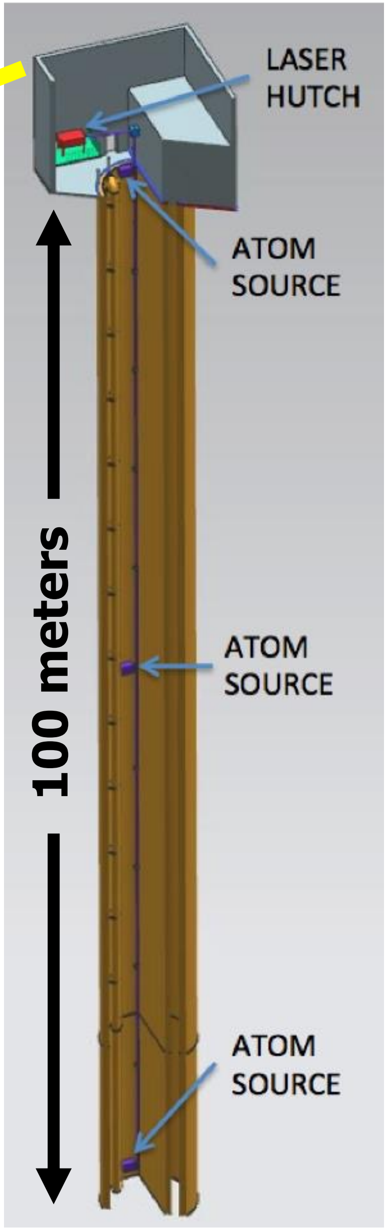


MAGIS-100: Detector prototype at Fermilab

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



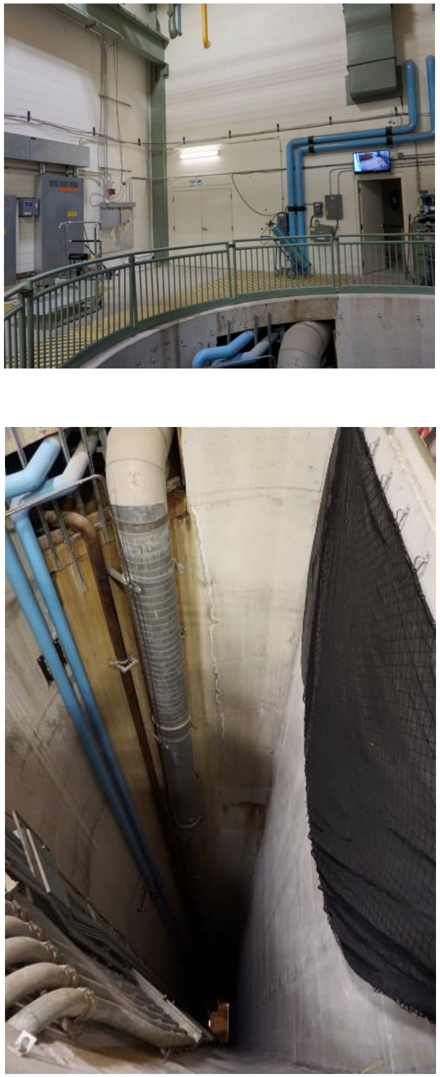
Neutrino Beam Line for MINERvA and MINOS Experiments



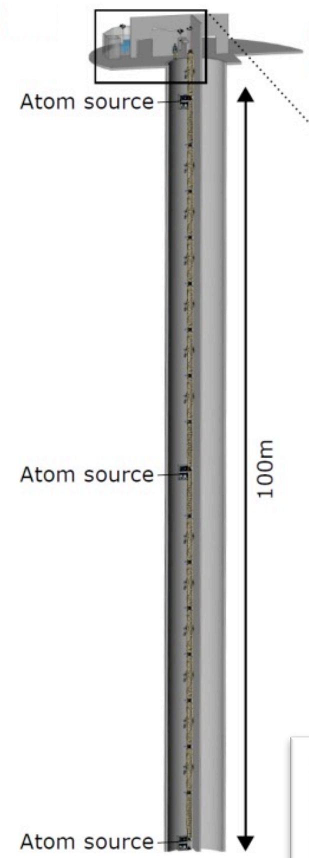
- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Intermediate step to full-scale (km) detector for gravitational waves
- Clock atom sources (Sr) at three positions to realize a gradiometer
- Probes for ultralight scalar dark matter beyond current limits (Hz range)
- Extreme quantum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

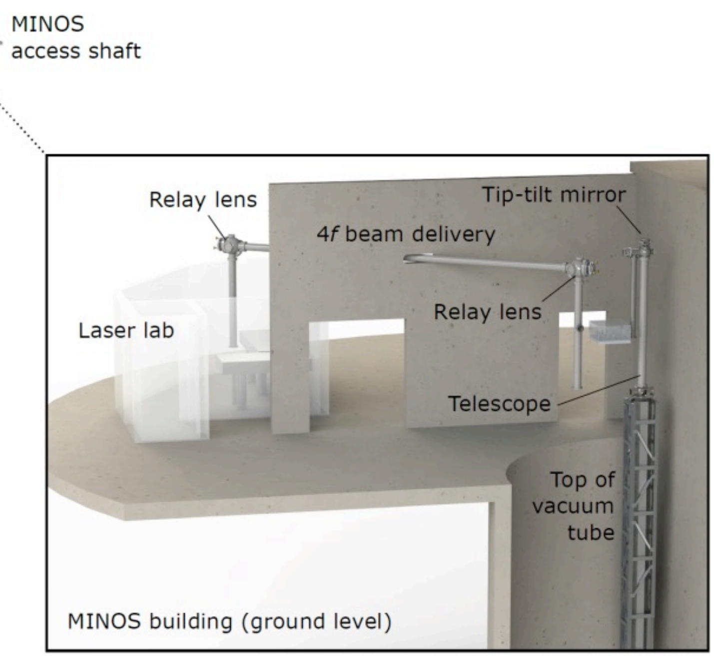
STANFORD
JOHNS HOPKINS UNIVERSITY
Northwestern University
UNIVERSITY OF LIVERPOOL
Fermilab
UNIVERSITY OF CAMBRIDGE
Northern Illinois University
UNIVERSITY OF OXFORD
SLAC

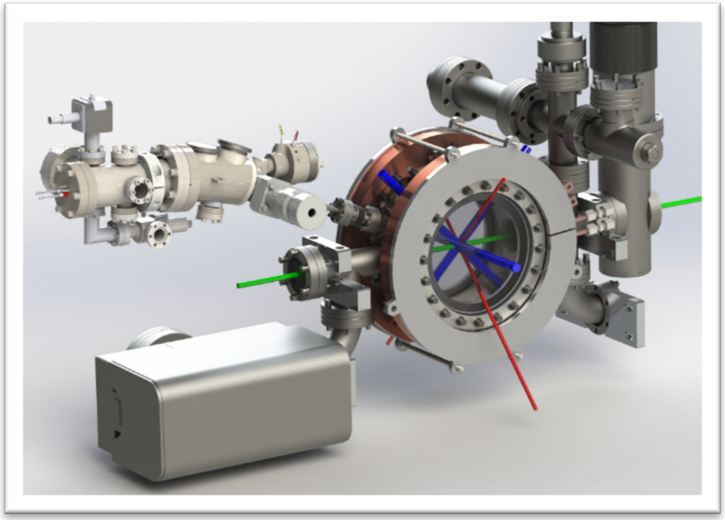
MAGIS-100 design



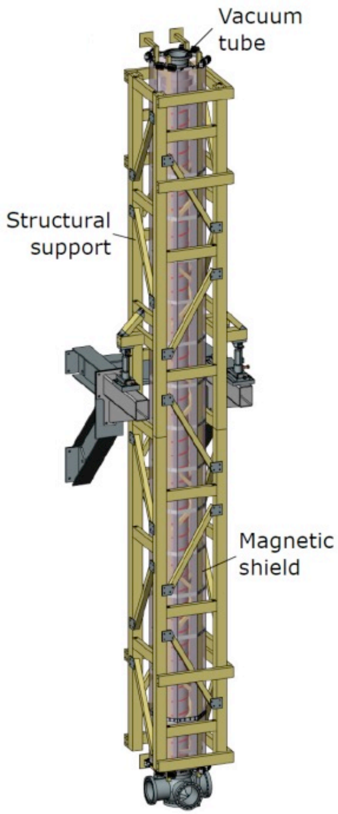
MINOS access shaft







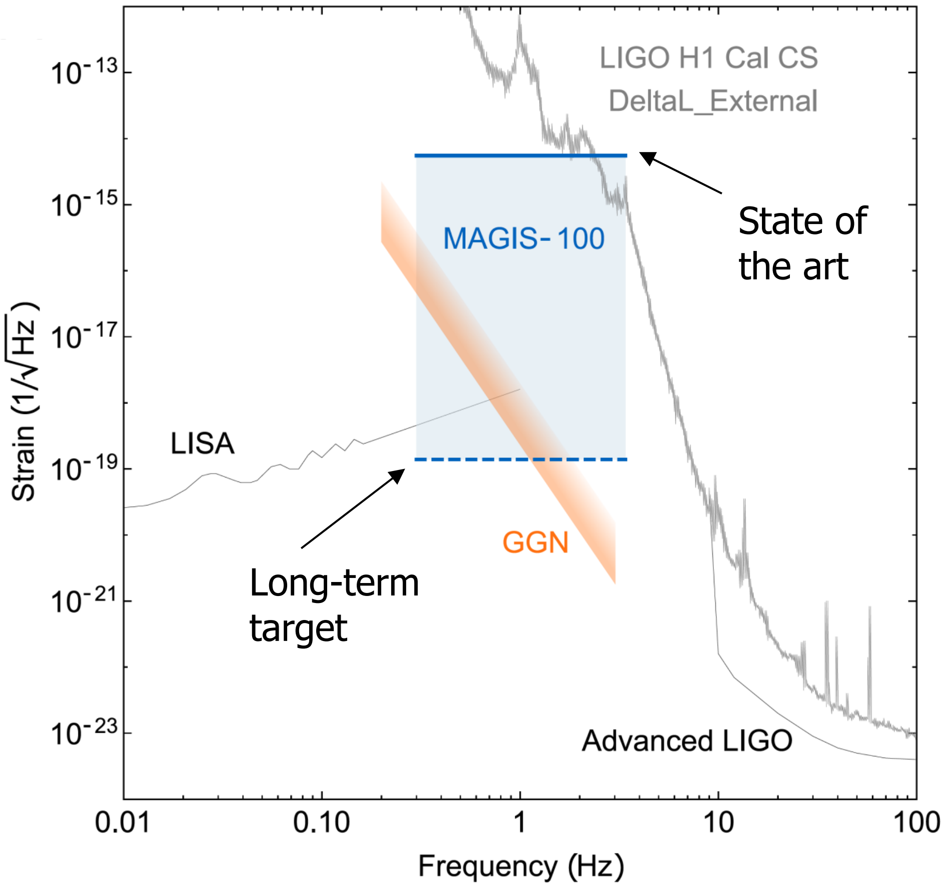
Sr atom sources

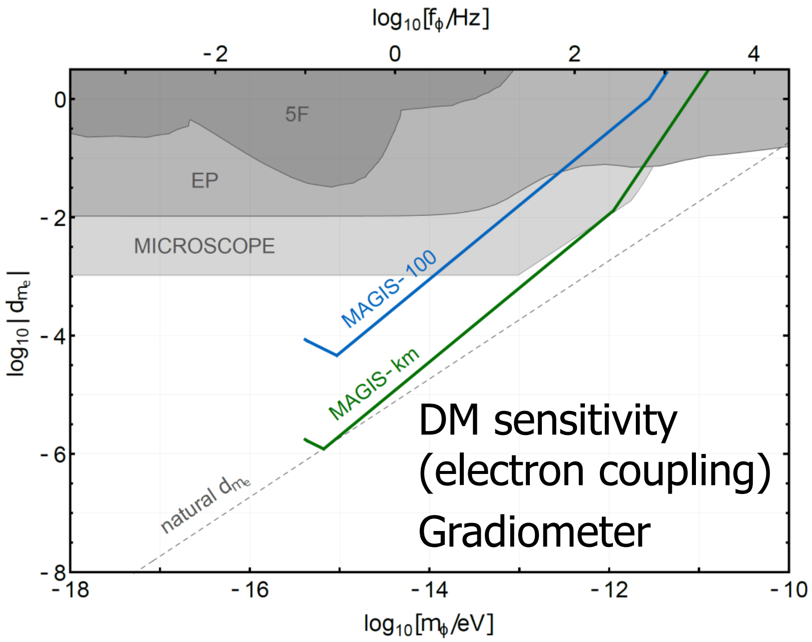


Modular section of 100 meter science region

MAGIS-100 projected sensitivity

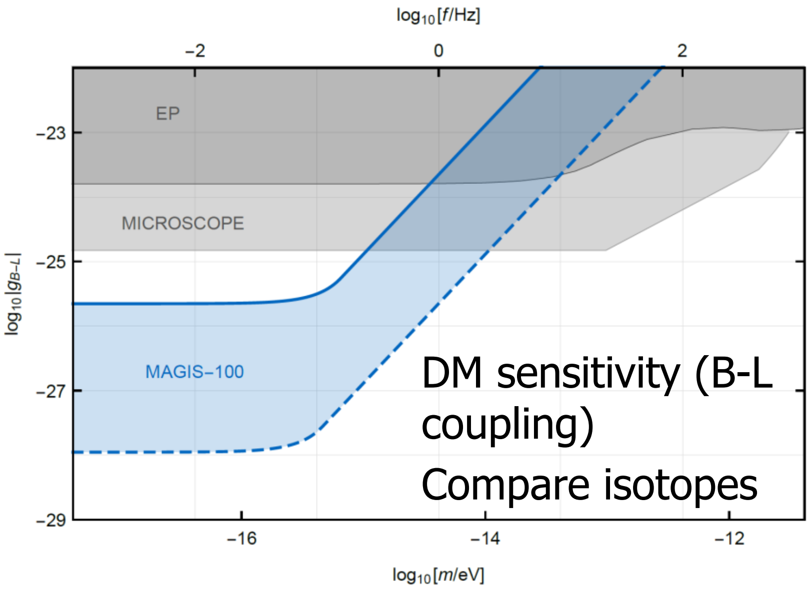
Gravitational wave sensitivity





DM sensitivity (electron coupling)

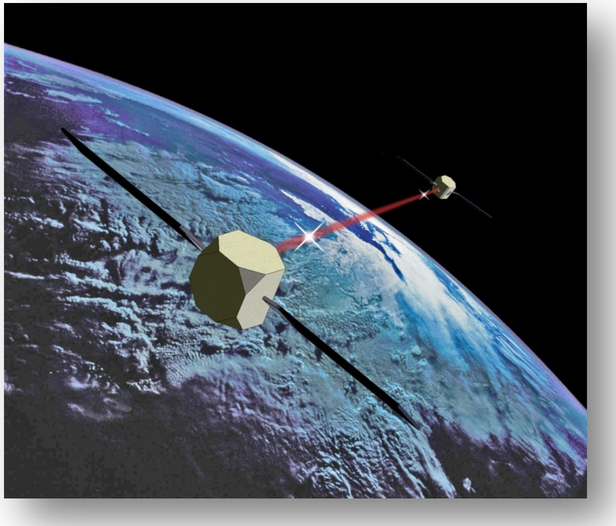
Gradiometer



DM sensitivity (B-L coupling)

Compare isotopes

MAGIS-style satellite detector



Satellite detector concept

- Two spacecraft
- Atom source in each
- Heterodyne laser link
- Resonant/LMT sequences

Example design

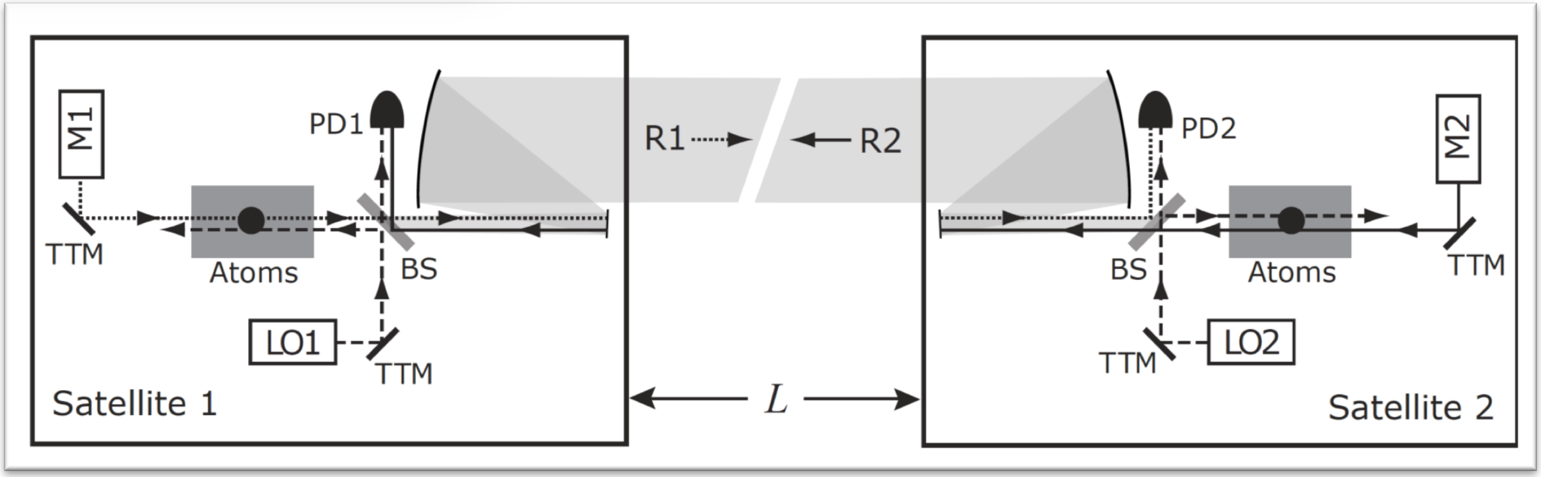
$$L = 4 \times 10^{7}\ \text{meters}$$

$$10^{-4}\ \mathrm{rad}/\sqrt{\mathrm{Hz}}$$

$$\frac{n\hbar k}{m} T < 1\ \mathrm{m}$$

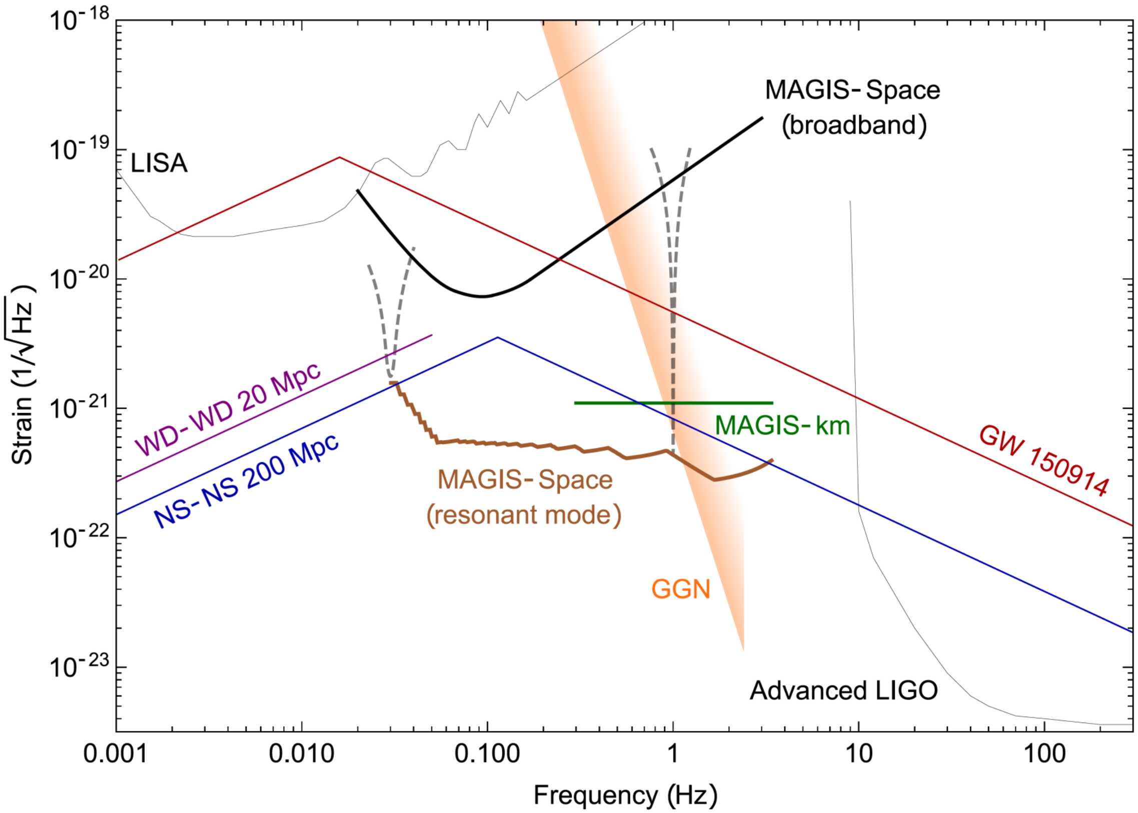
$$2TQ < 300\ \mathrm{s}$$

$$n_p < 10^{3}$$



- Heterodyne link concept analogous to LISA (synthesize ranging between two test masses)
- Decouples atom-laser interaction strength from baseline length (diffraction limit)

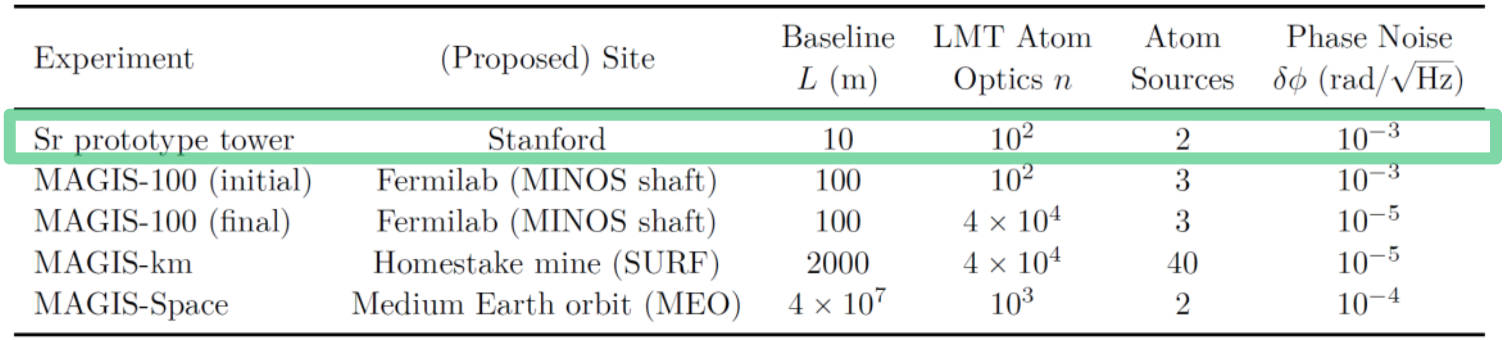
Full scale MAGIS projected GW sensitivity



- Mid-band GW sources detectable from ground and space
- Gravity gradient noise (GGN) likely limits any terrestrial detector at low frequencies
- Longer baselines available in space reduce requirements (e.g., LMT), but can impact frequency response at high frequencies
- Flexible detection strategies possible (broadband vs resonant) with different tradeoffs in sensitivity/bandwidth

Development path

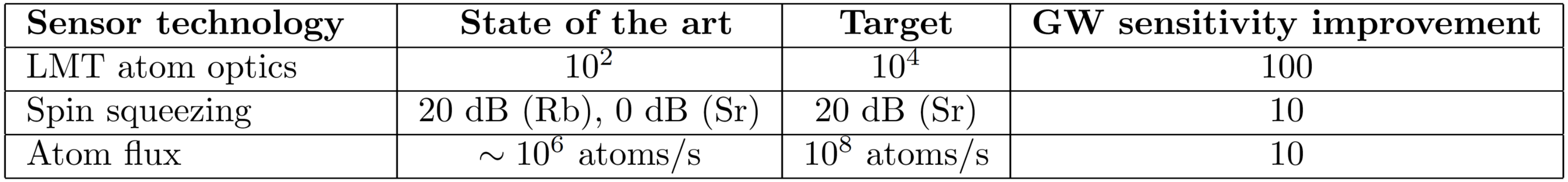
MAGIS detector development



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}

State of the art

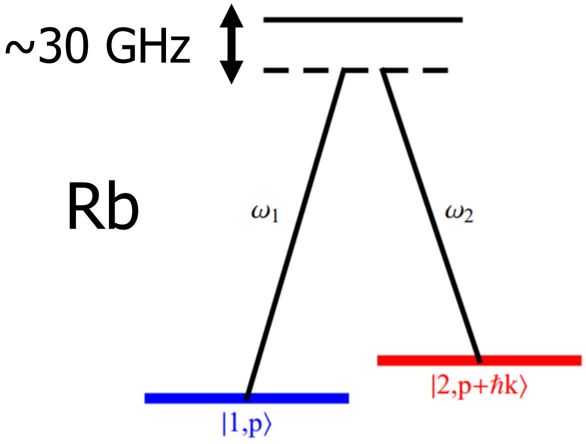
Reaching required sensitivity requires extensive technology development in three key areas:



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

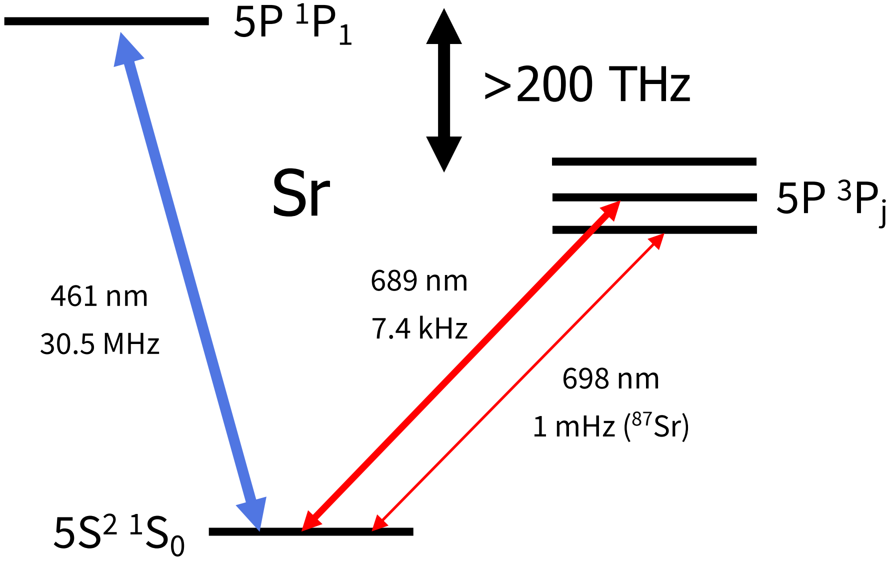
- Phase noise improvement strategy is a combination of increasing atom flux and using quantum entanglement (spin squeezing).
- LMT requirement is reduced in space proposals (longer baselines)

LMT atom optics on the clock transition



Two-photon transitions

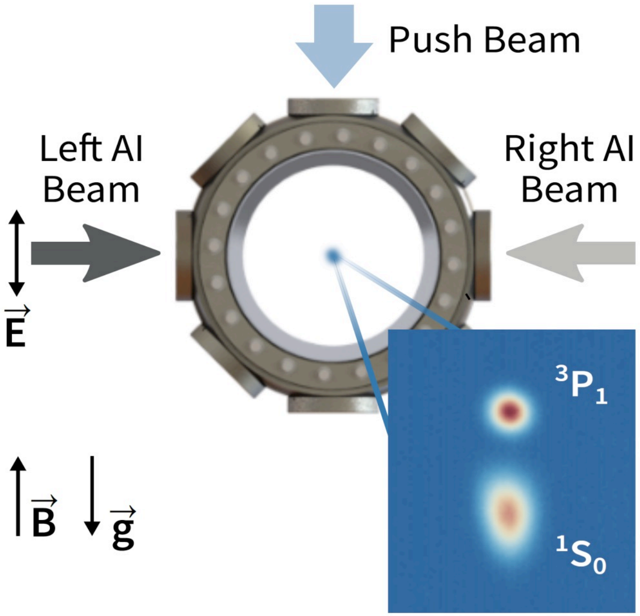
- Conventional atom interferometers use two-photon Raman or Bragg transitions
- Requires large detuning, high power to suppress spontaneous emission
- Current state of the art: ~100 pulses

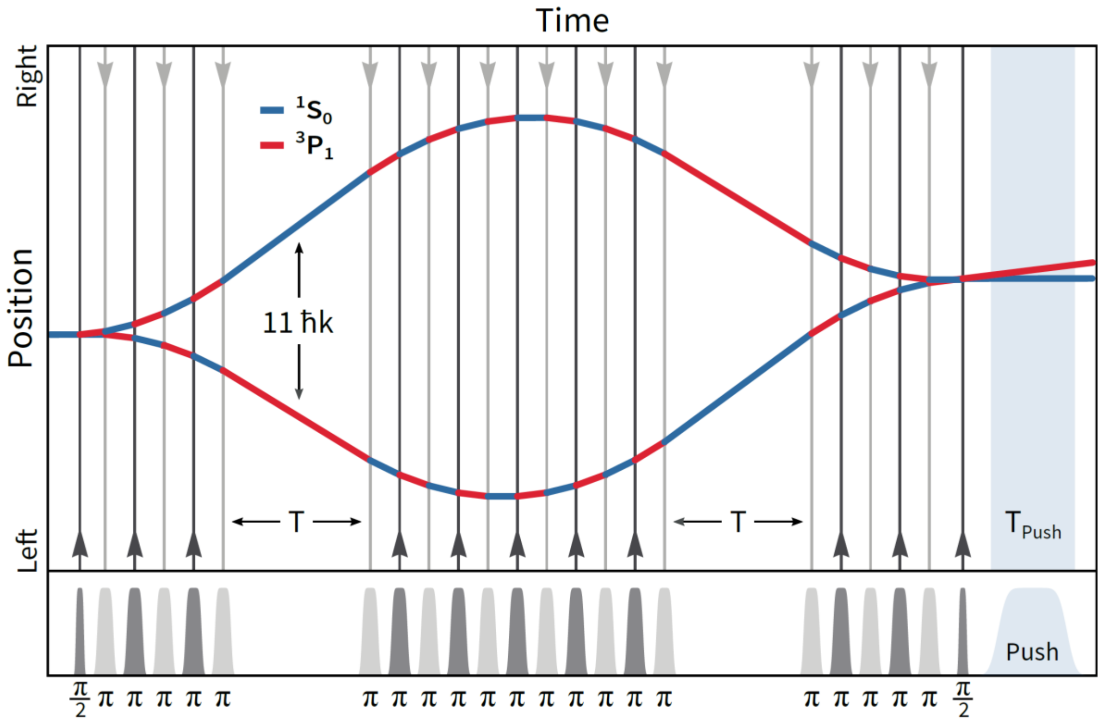


Single photon clock transitions

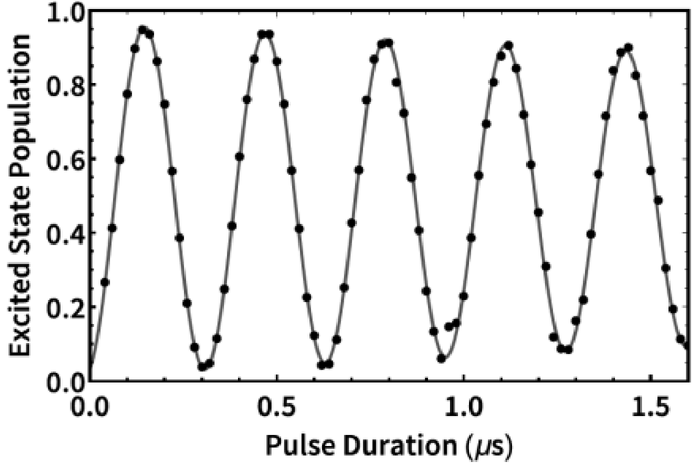
- Requires long-lived excited state
- Reduced spontaneous emission (other levels far detuned)
- Possibility to support > 10^6 pulses

Clock atom interferometry demonstration





98.9% π-pulse efficiency



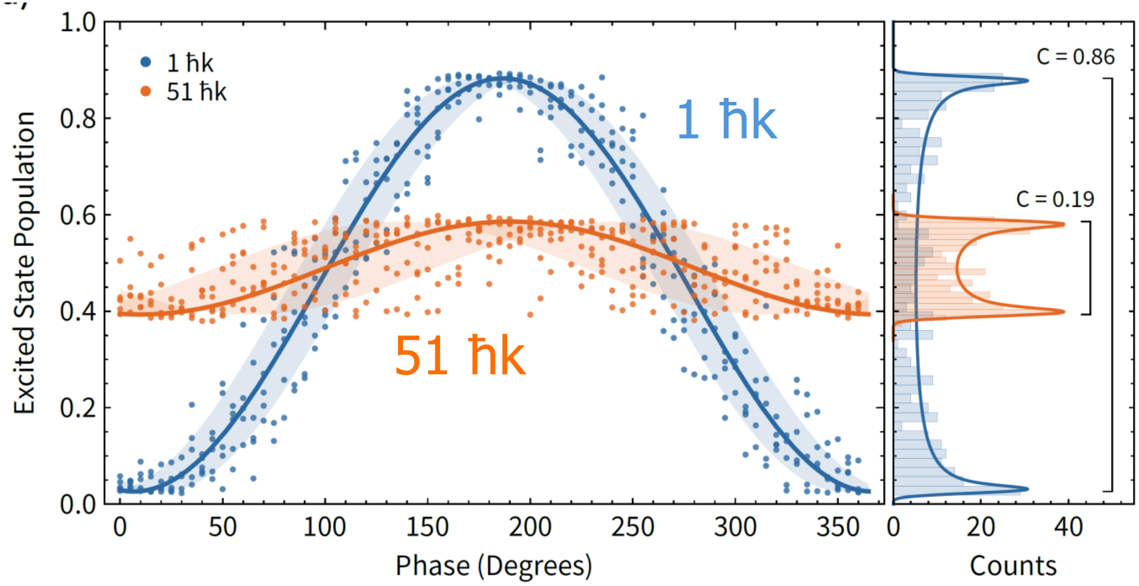
- Perform LMT atom optics using π pulses from alternating directions

- Each π pulse interacts with both arms due to high Rabi Frequency (+2 ħk)

J. Rudolph, PRL **124**, 083604 (2020).

LMT clock interferometer

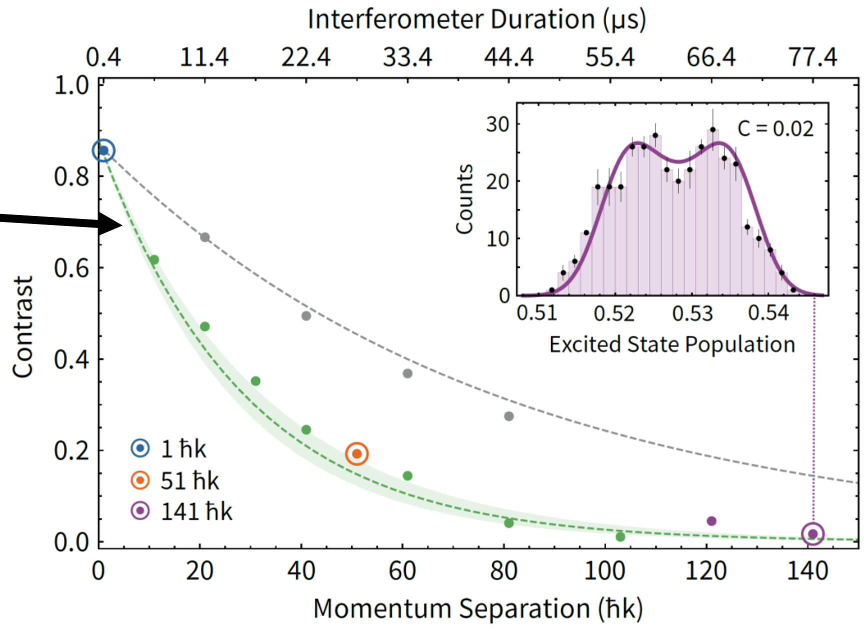
Example: 51 ħk interferometer (100 total π pulses)



First LMT clock interferometers using sequential single-photon transitions

Contrast loss prediction (not a fit) includes excited state decay (22 μs lifetime) + measured π-pulse efficiency

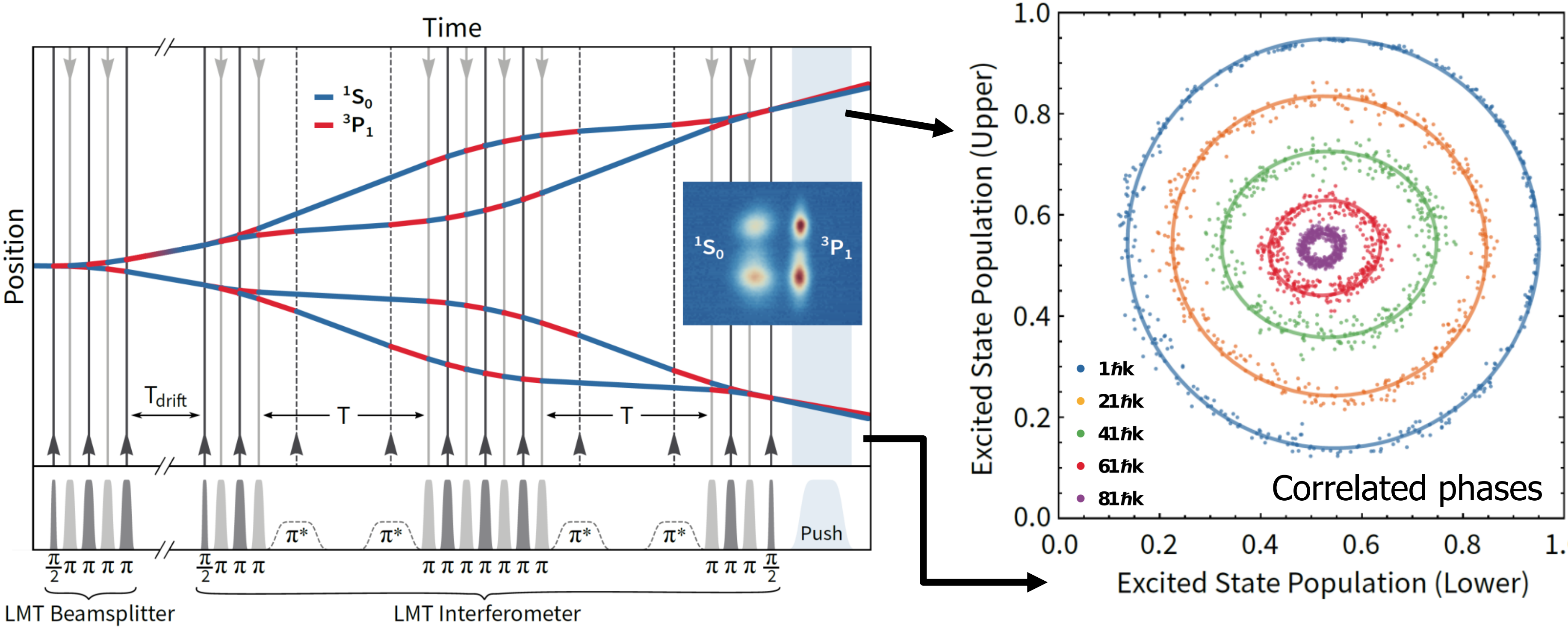
LMT in demo limited by available 689 nm power (~100 mW)



J. Rudolph, PRL **124**, 083604 (2020).

Clock atom gradiometer demonstration

Run two interferometers simultaneously



- Laser phase noise is common to the interferometers
- Demonstrated 81 ħk (power limited)
- Demonstrated T > 1 ms (>> lifetime)

J. Rudolph, PRL **124**, 083604 (2020).

Some challenges and open questions

- Scaling sensors from 10 m baseline to 100 m and then km-scale
- Space-based detectors: space qualification, TRL, etc.
- Incorporating quantum entanglement (spin-squeezing)
- High-flux atom sources
- Extreme LMT >1000 ħk
- Multiplexed interferometers for high sample rate applications
- Gravity gradient noise mitigation (terrestrial GW detection)

MAGIS-100 Collaborators

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