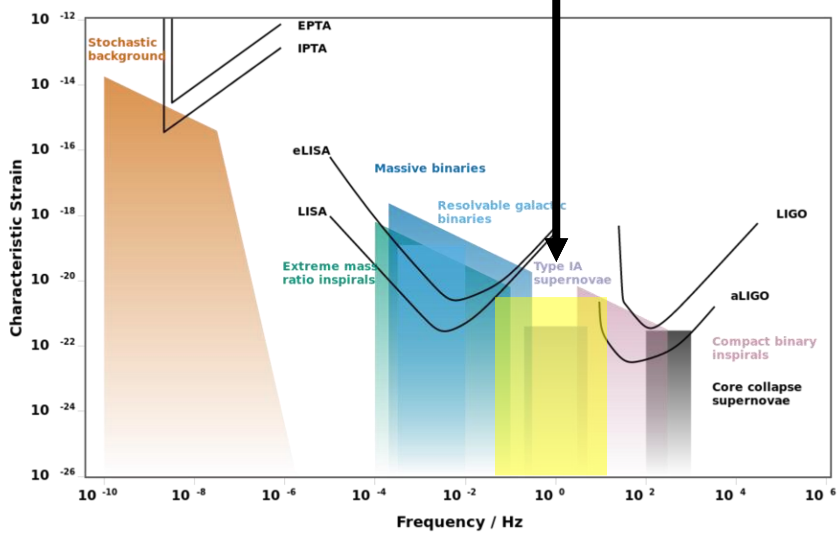
# Atom interferometry at large scales (ground based, space based)

**ECFA Symposium**

Jason Hogan
Stanford University
April 12, 2021

# Long baseline atom interferometry science

**Mid-band:** 0.03 Hz to 3 Hz




## Ultralight wave-like dark matter probe

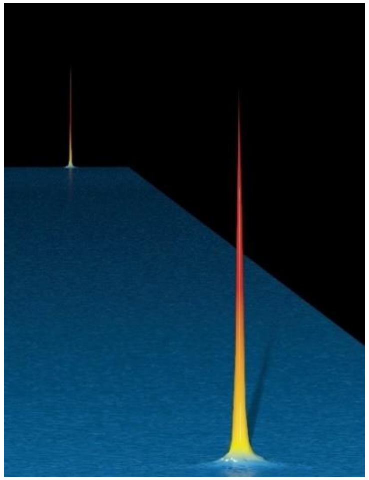
- Mass <$10^{-14}$ eV (Compton frequency in ~Hz range)
- Scalar- and vector-coupled DM candidates
- Time-varying energy shifts, EP-violating new forces, spin-coupled effects

## Mid-band gravitational wave detection

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

## 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

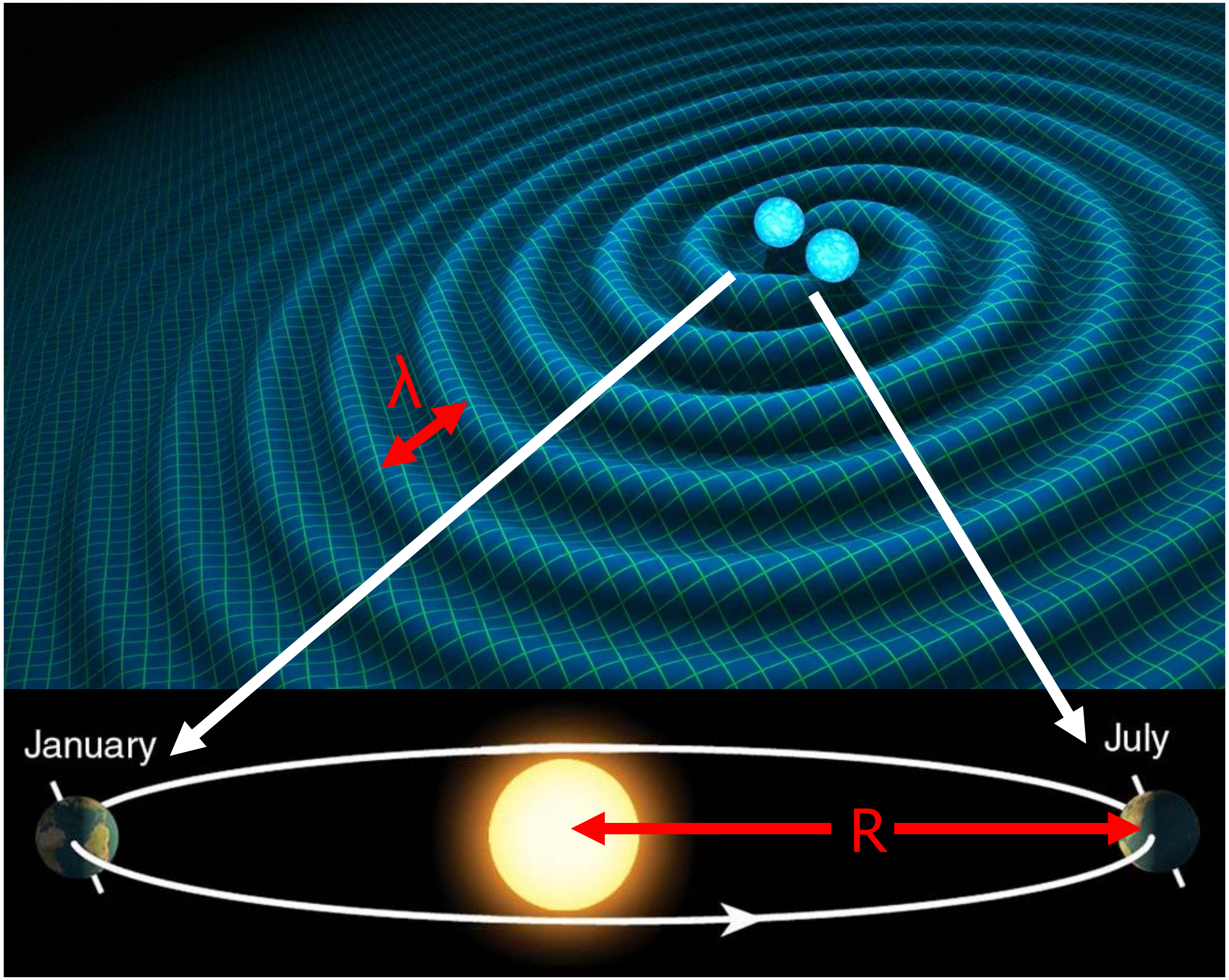
Sky localization precision:

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

**Mid-band advantages**

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

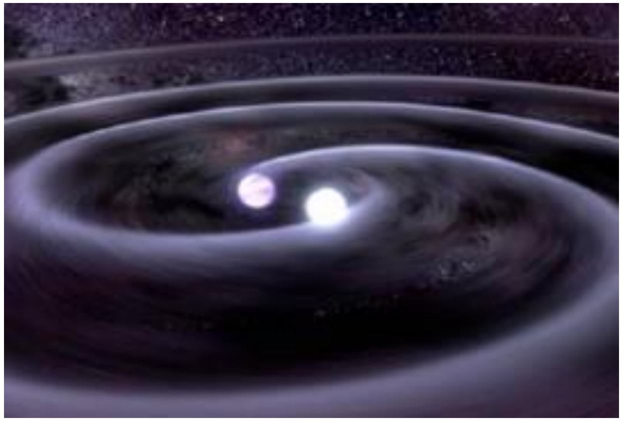
| Benchmark | $\sqrt{\Omega_s}$ [deg] |
|---|---|
| GW150914 | 0.16 |
| GW151226 | 0.20 |
| NS-NS (140 Mpc) | 0.19 |

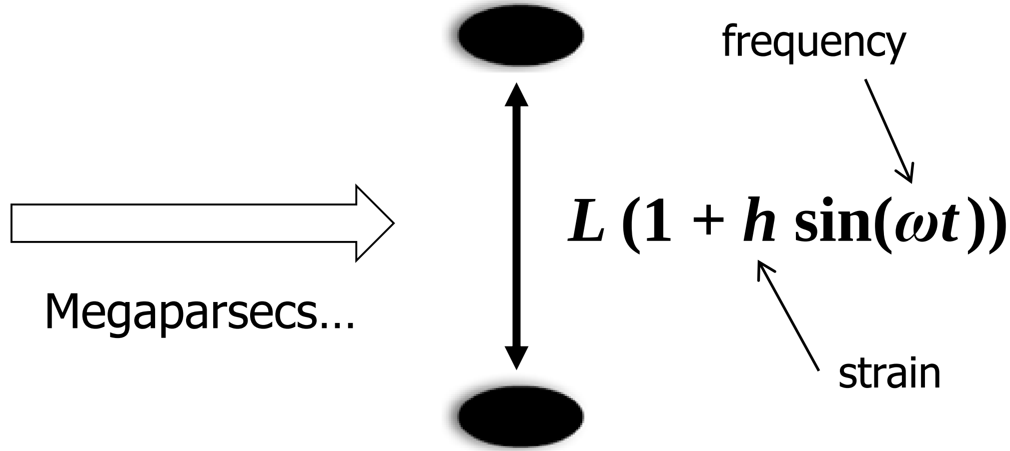



Graham et al., **PRD** 024052 (2018).

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

# MAGIS concept






## **M**atter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor (MAGIS)

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

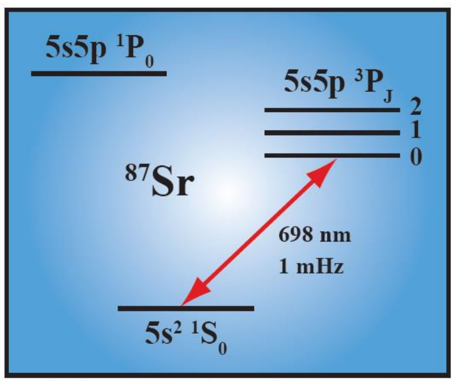
Detecting this modulation requires two ingredients:

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

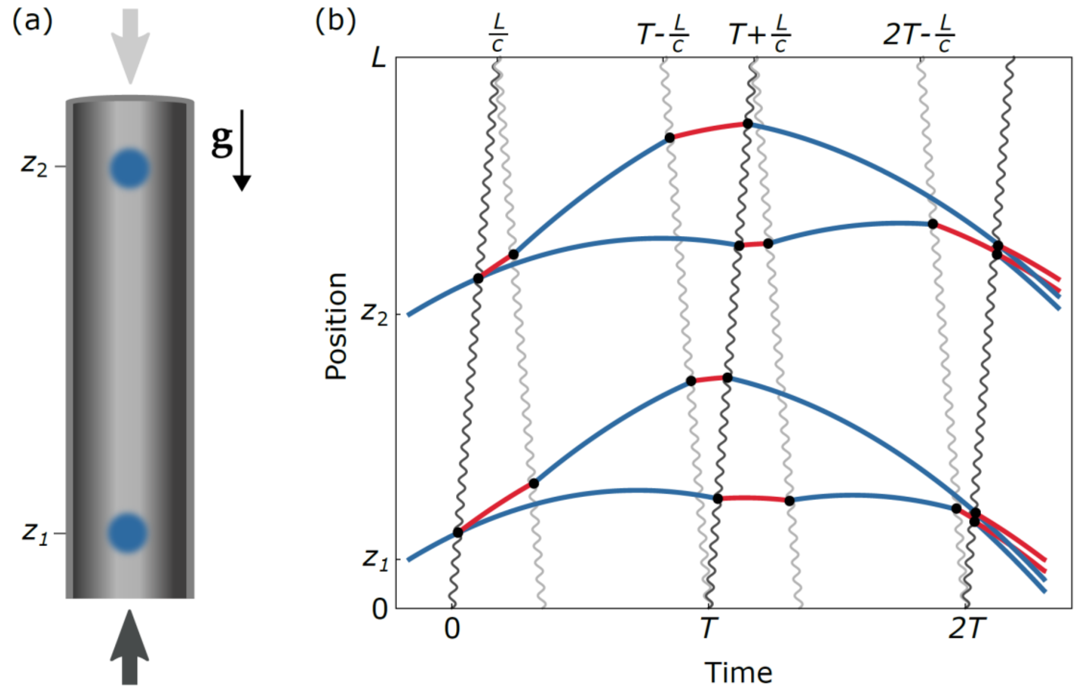
In MAGIS, atoms play both roles.

# Clock atom interferometry

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




Clock transition in candidate atom $^{87}$Sr




Excited state phase evolution:

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

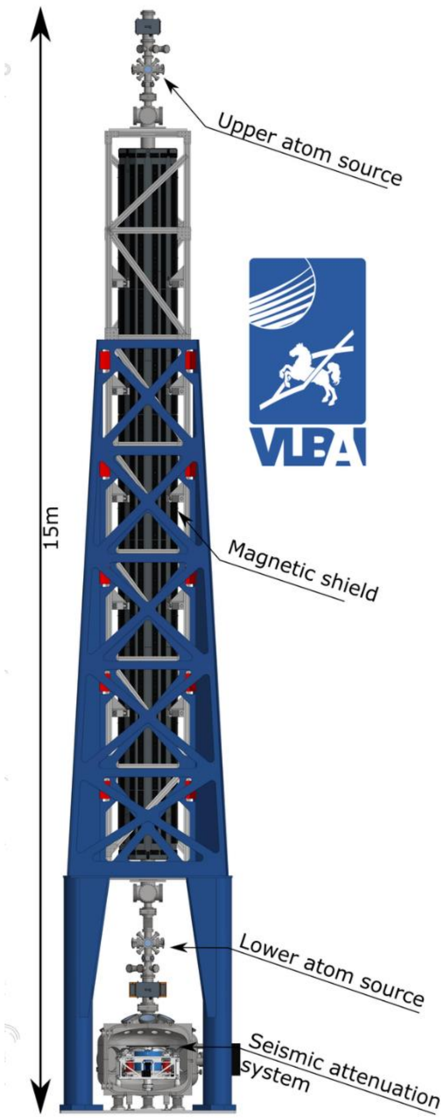
(variations over time T)

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).

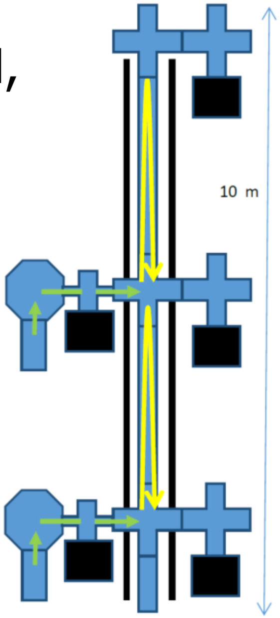
# 10-meter scale atom drop towers




Hannover, Germany

Wuhan, China

AION, UK

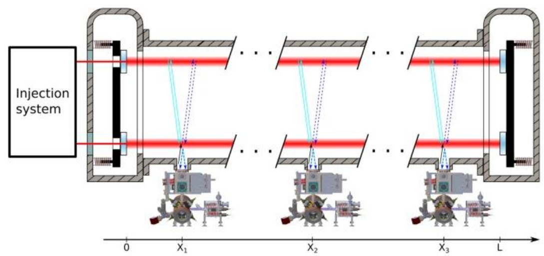


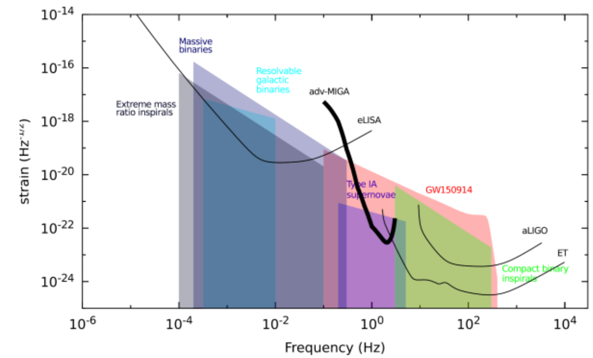

Stanford University

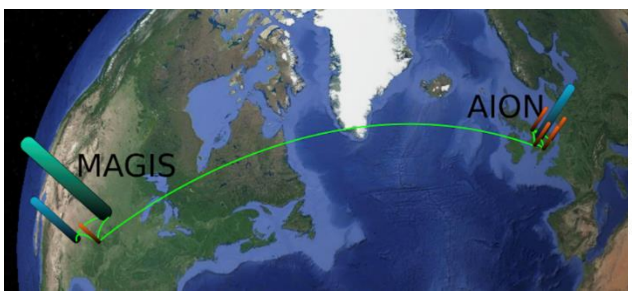
# International efforts in long baseline atomic sensors

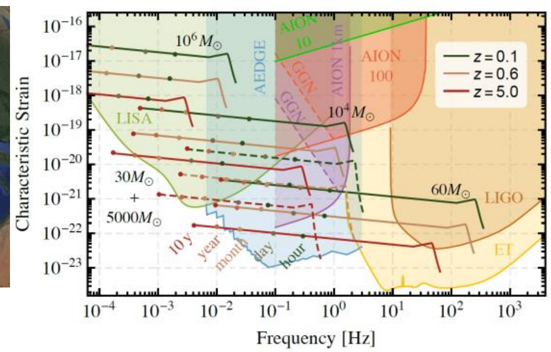
| Project | Baseline Length | Number of Baselines | Orientation | Atom | Atom Optics | Location |
|---|---|---|---|---|---|---|
| MAGIS-100 | 100 m | 1 | Vertical | Sr | Clock AI, Bragg | USA |
| AION | 100 m | 1 | Vertical | Sr | Clock AI | UK |
| MIGA | 200 m | 2 | Horizontal | Rb | Bragg | France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

MIGA: Matter Wave laser Interferometric Gravitation Antenna (France)



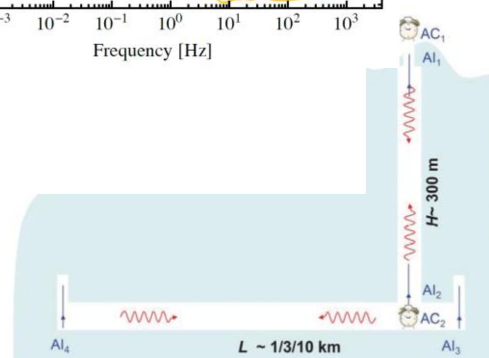



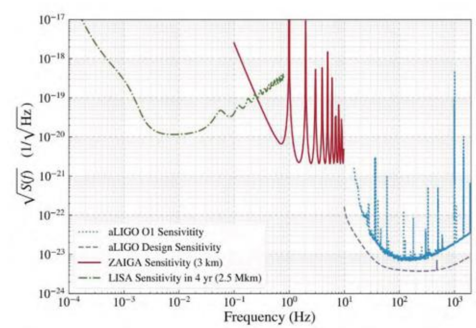




AION: Atom Interferometer Observatory and Network (UK)

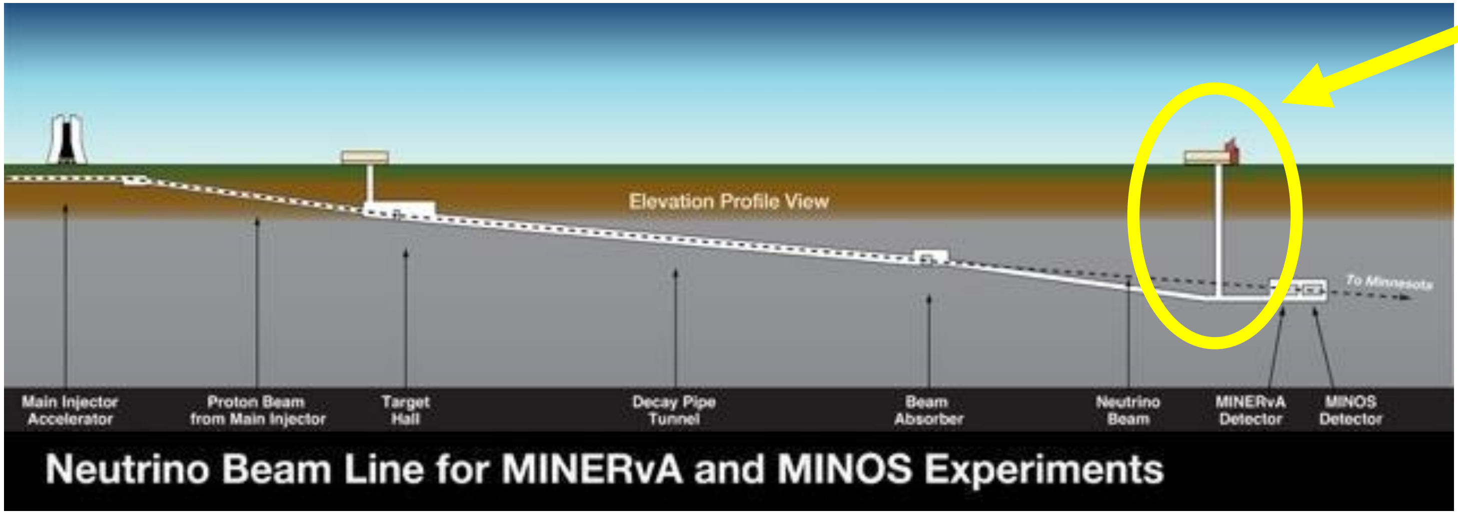
ZAIGA: Zhaoshan Long-baseline Atom Interferometer Gravitation Antenna (China)

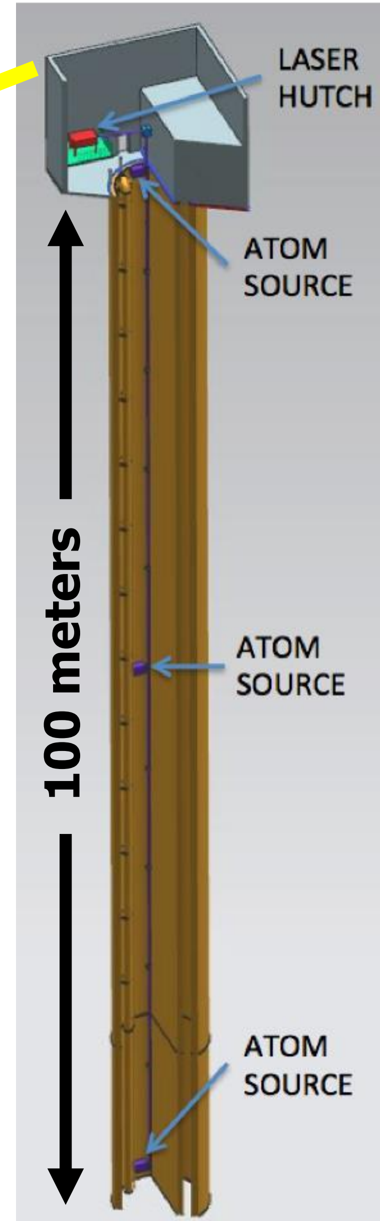


# MAGIS-100: Detector prototype at Fermilab

**M**atter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor

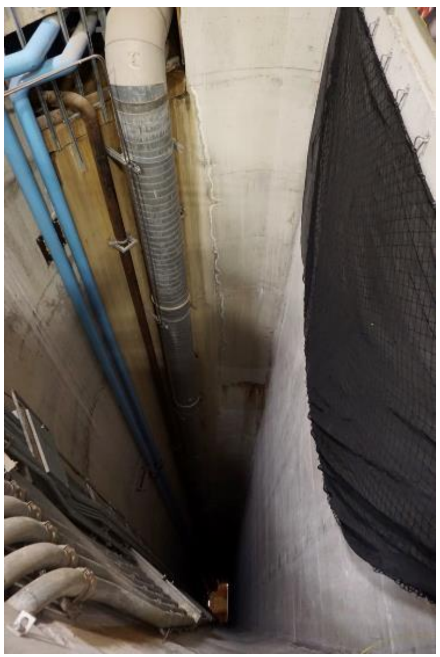


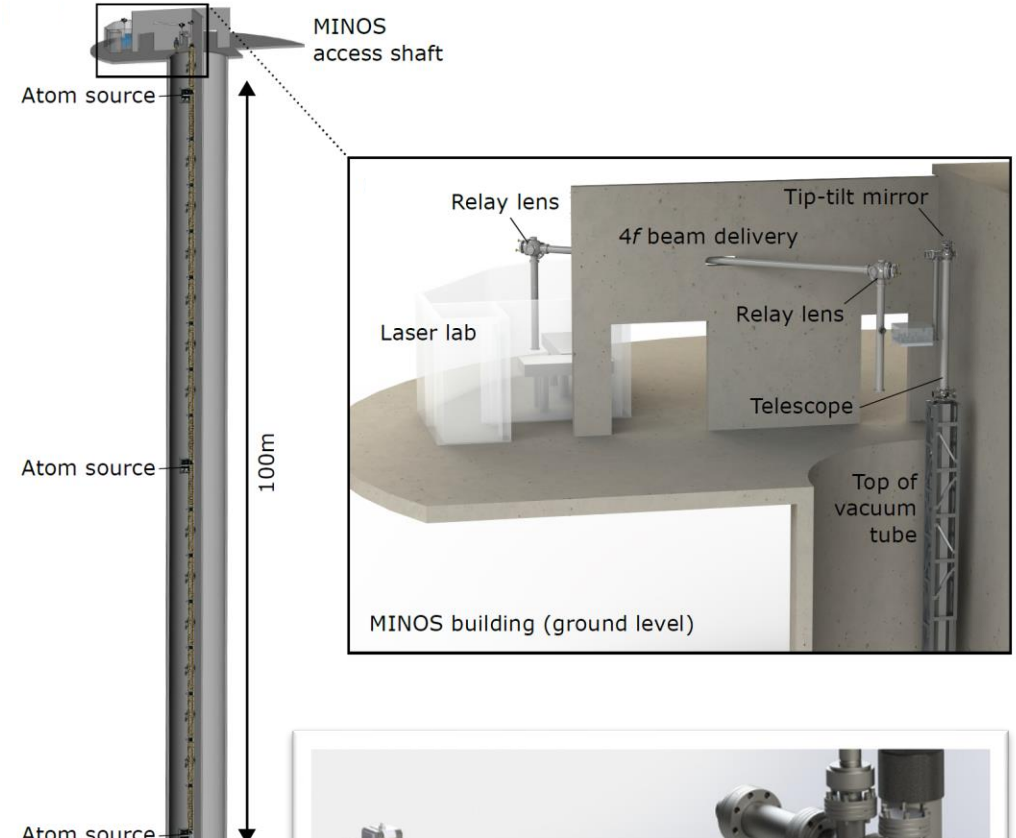

- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Intermediate step to full-scale (km) detector for gravitational waves
- Clock atom sources (Sr) at three positions to realize a gradiometer
- Probes for ultralight scalar dark matter beyond current limits (Hz range)
- Extreme quantum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

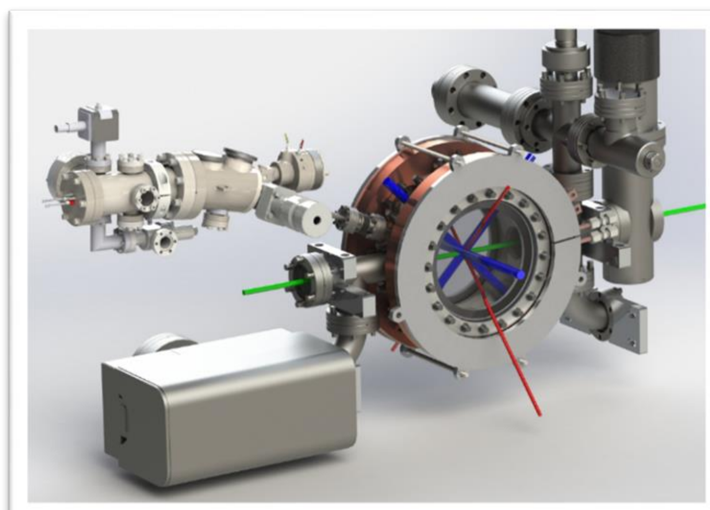
Stanford · Johns Hopkins University · Northwestern University · University of Liverpool · Fermilab · University of Cambridge · Northern Illinois University · University of Oxford · SLAC

# MAGIS-100 design

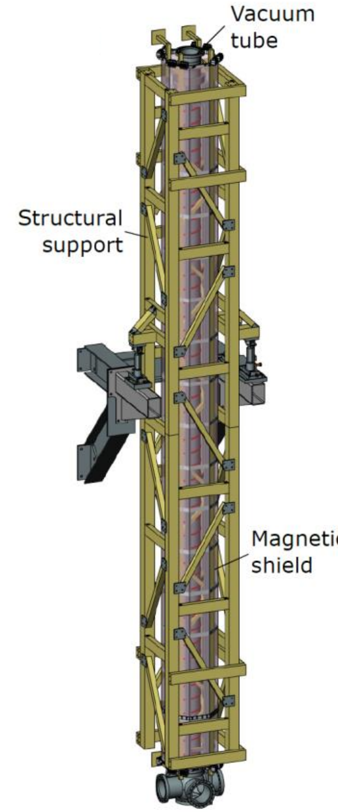


*MINOS access shaft*



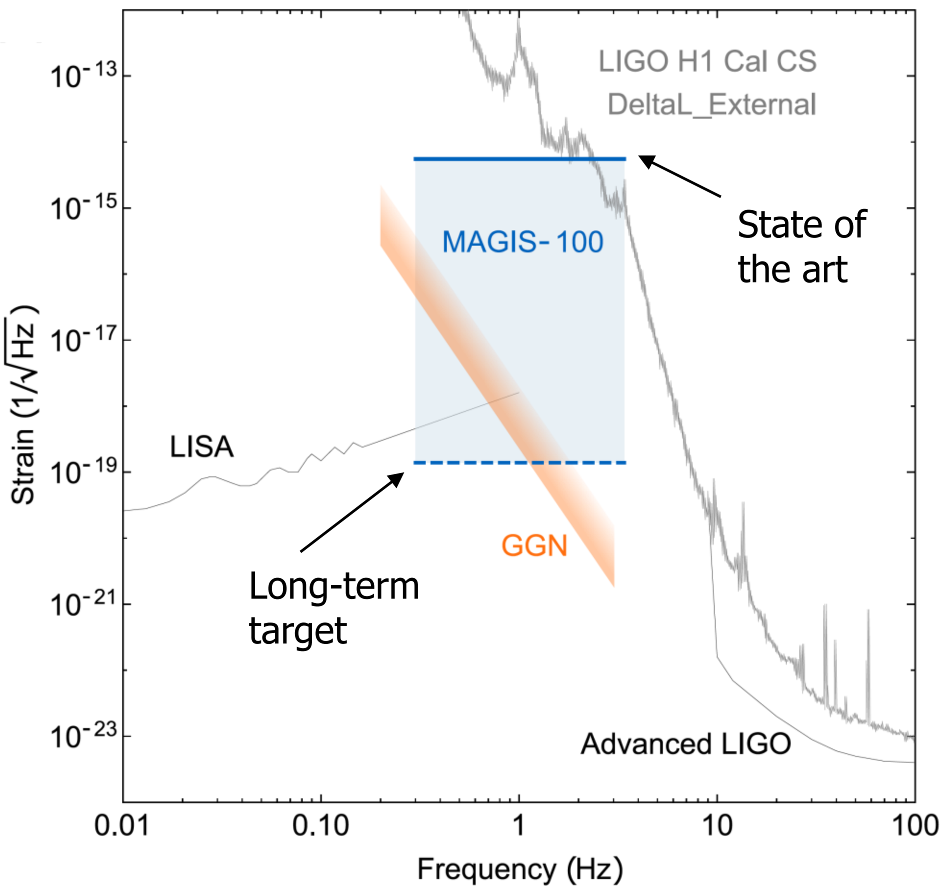
*Sr atom sources*

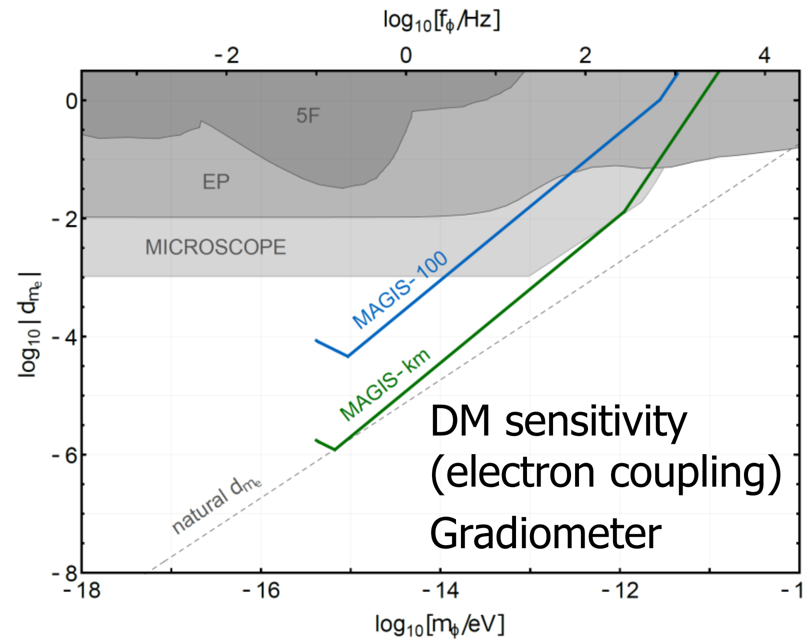



*Modular section of 100 meter science region*

# MAGIS-100 projected sensitivity

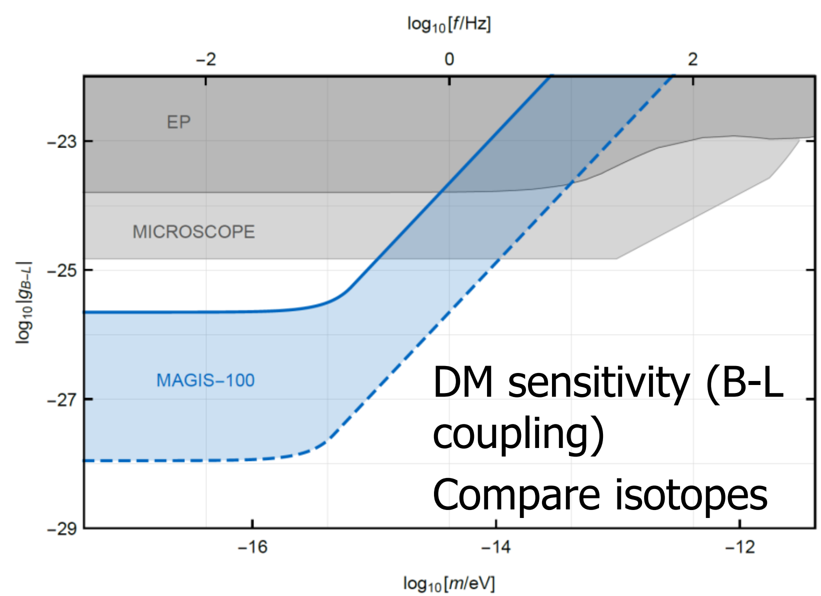
Gravitational wave sensitivity




DM sensitivity (electron coupling)

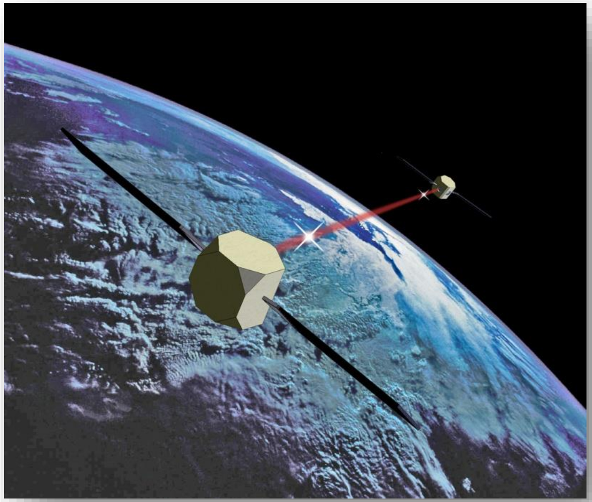
Gradiometer




DM sensitivity (B-L coupling)

Compare isotopes

# MAGIS-style satellite detector



Satellite detector concept

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

Example design

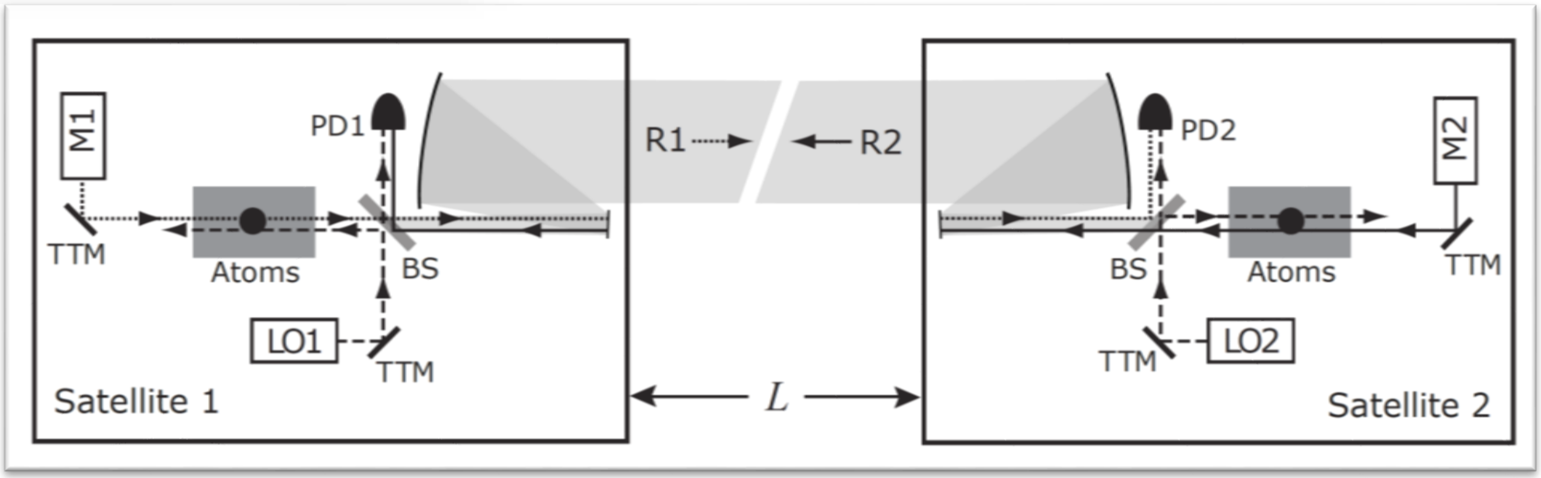
$L = 4 \times 10^7$ meters

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

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

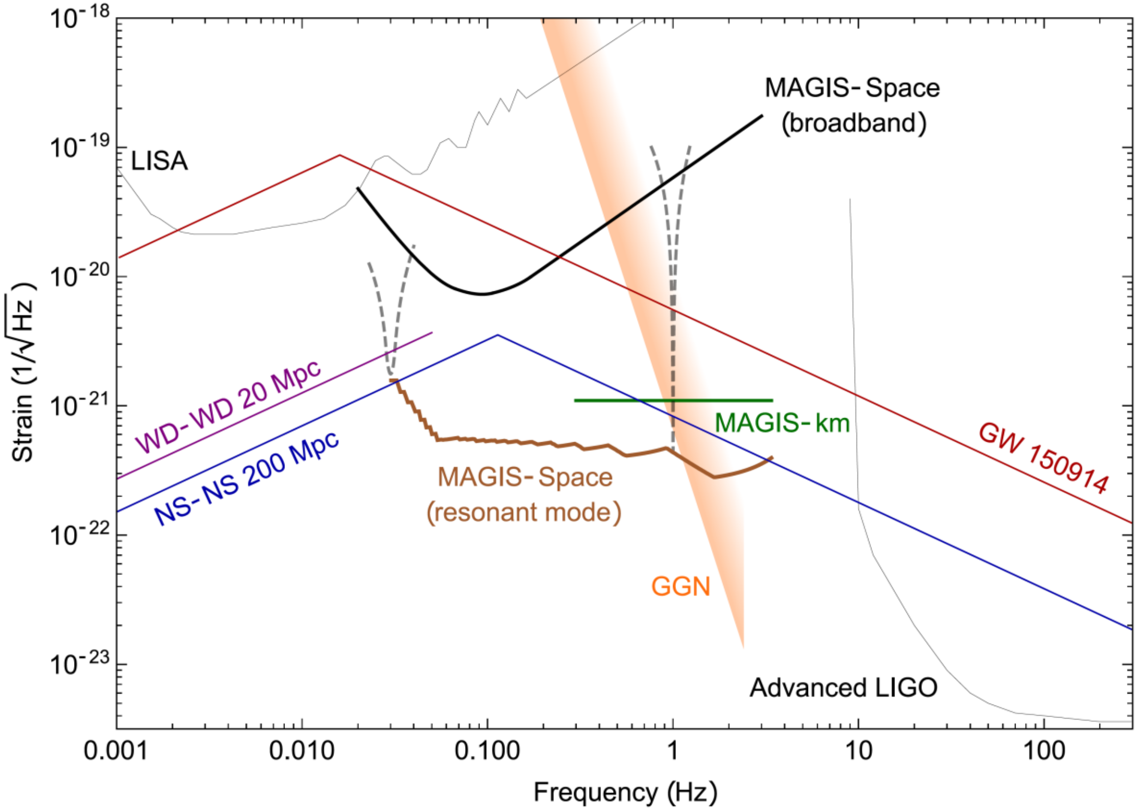
$2TQ < 300\ \mathrm{s}$

$n_p < 10^3$




- 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 | $4 \times 10^4$ | 3 | $10^{-5}$ |
| MAGIS-km | Homestake mine (SURF) | 2000 | $4 \times 10^4$ | 40 | $10^{-5}$ |
| MAGIS-Space | Medium Earth orbit (MEO) | $4 \times 10^7$ | $10^3$ | 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)

# 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 $\hbar k$
- Multiplexed interferometers for high sample rate applications
- Gravity gradient noise mitigation (terrestrial GW detection)

**Additional topics**

- LMT clock atom interferometry demonstration experiments
- Conceptual differences between MAGIS and LISA/LIGO, atomic clocks
- Resonantly enhanced atom interferometry
- MAGIS-100 technical details (laser system design, optical lattice launch, rotation compensation, magnetic shield design)

# MAGIS-100 Collaborators

Mahiro Abe
Philip Adamson
Marcel Borcean
Daniela Bortoletto
Kieran Bridges
Samuel Carman
Swapan Chattopadhyay
Jonathon Coleman
Noah Curfman
Joseph Lykken
Kenneth DeRose
Tejas Deshpande
Savas Dimopoulos
Christopher Foot
Josef Frisch
Benjamin Garber
Steve Geer
Valerie Gibson
Jonah Glick
Peter Graham
Steve Hahn
Roni Harnik
Leonie Hawkins
Sam Hindley
Jason Hogan
Yijun Jiang
James Santucci
Mark Kasevich
Ronald Kellett
Mandy Kiburg
Tim Kovachy
John March-Russell
Jeremiah Mitchell
Martin Murphy
Megan Nantel
Lucy Nobrega
Robert Plunkett
Surjeet Rajendran
Jan Rudolph
Natasha Sachdeva
Murtaza Safdari
Ariel Schwartzman
Ian Shipsey
Hunter Swan
Linda Valerio
Arvydas Vasonis
Yiping Wang
Thomas Wilkason

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

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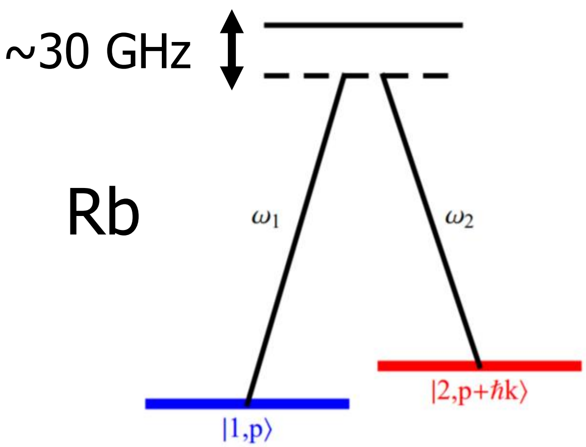
DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA
QuantiSED 2019

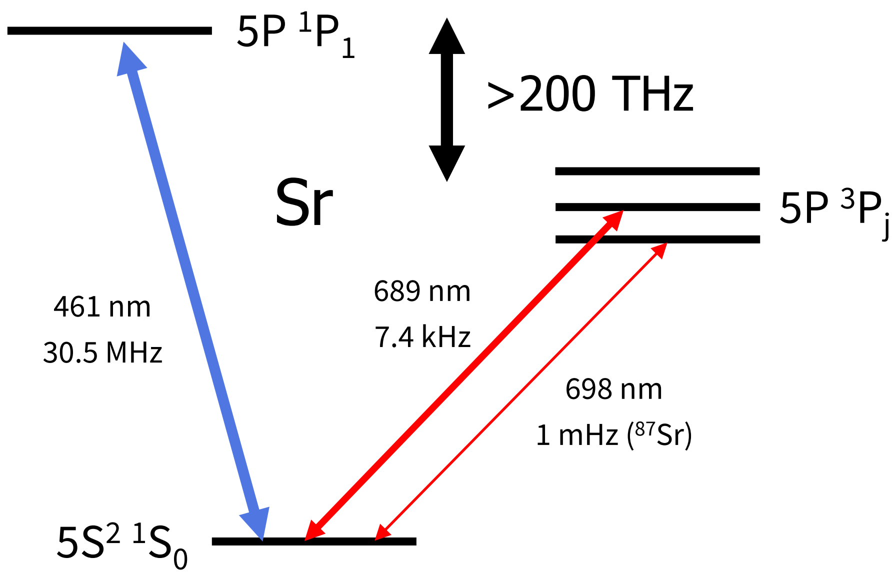
# LMT clock atom interferometer demonstration

# LMT atom optics on the clock transition




**Two-photon transitions**

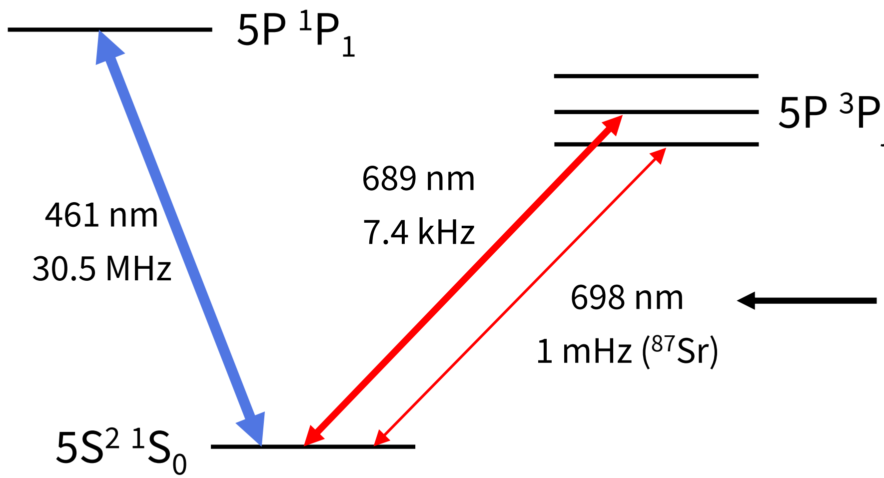
- Conventional atom interferometers use two-photon Raman or Bragg transitions
- Requires large detuning, high power to suppress spontaneous emission
- Current state of the art: ~100 pulses




**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



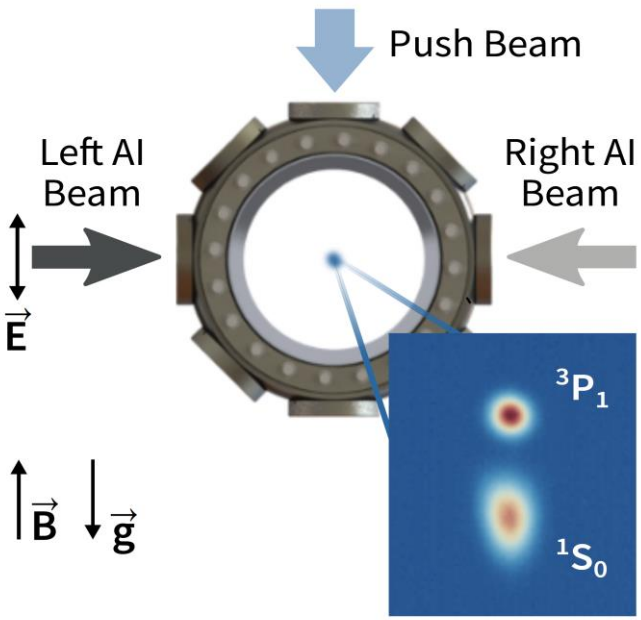

Typical clock transition at 698 nm (150 s lifetime)

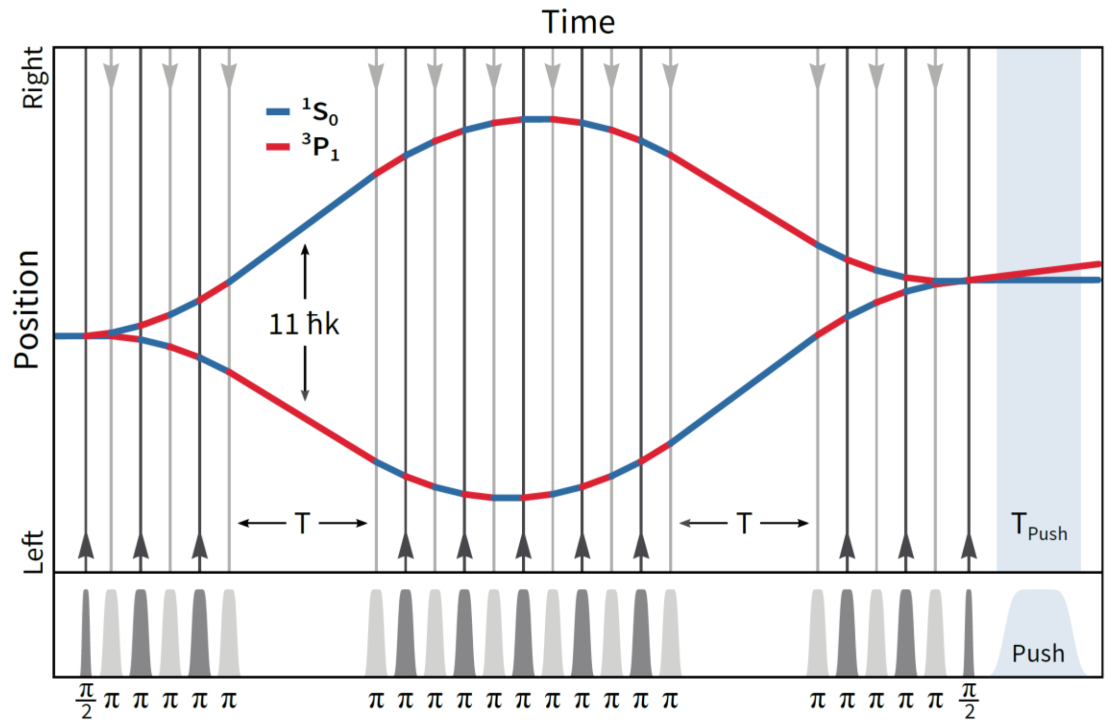
Instead, use **689 nm transition** for initial demonstration of LMT clock atom interferometry

<u>689 transition features:</u>

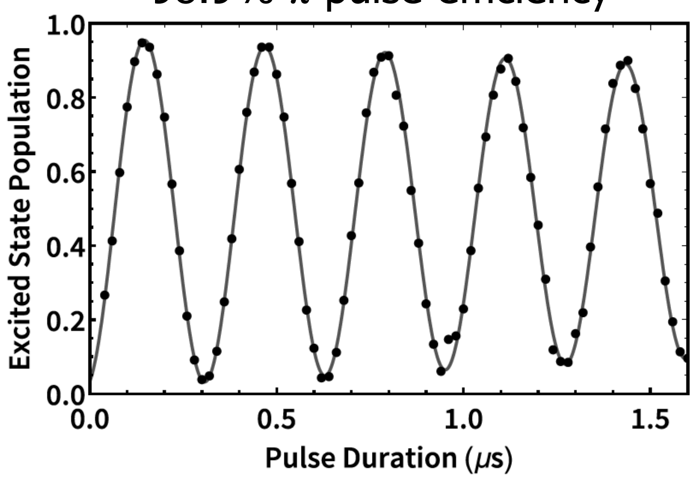
- 1-photon atom interferometry possible
- 22 μs lifetime (limits coherence time?)
- Supports high Rabi frequency (fast pulses)
- Easier technical requirements (laser stability, isotope)

# Clock atom interferometry demonstration




98.9% π-pulse efficiency

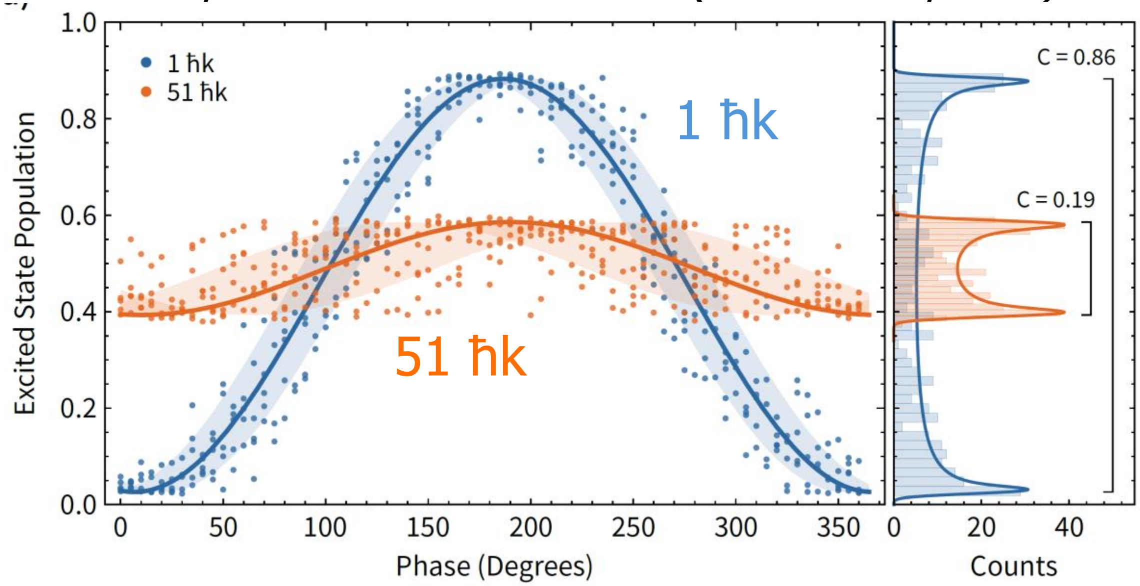



- Perform LMT atom optics using π pulses from alternating directions
- Each π pulse interacts with both arms due to high Rabi Frequency (+2 ħk)

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

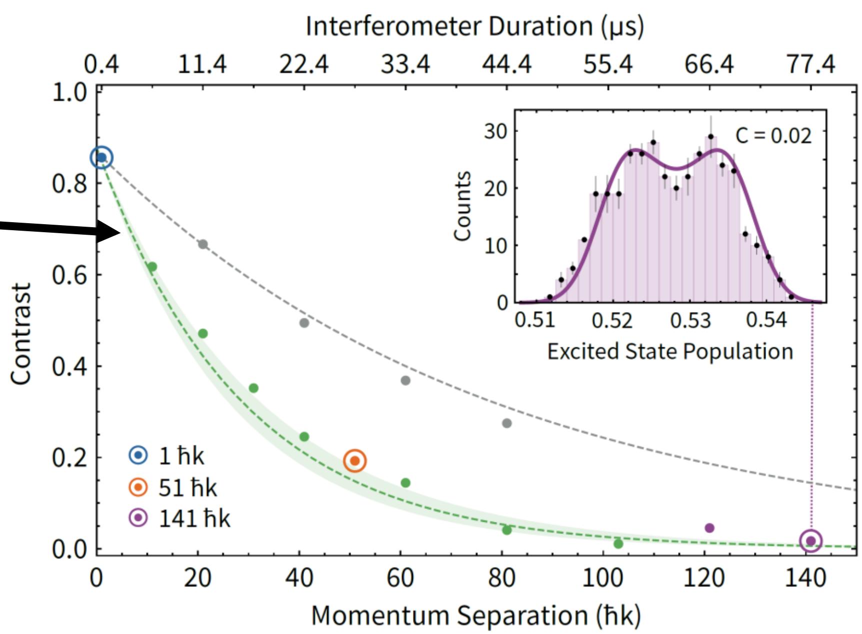
# LMT clock interferometer

*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

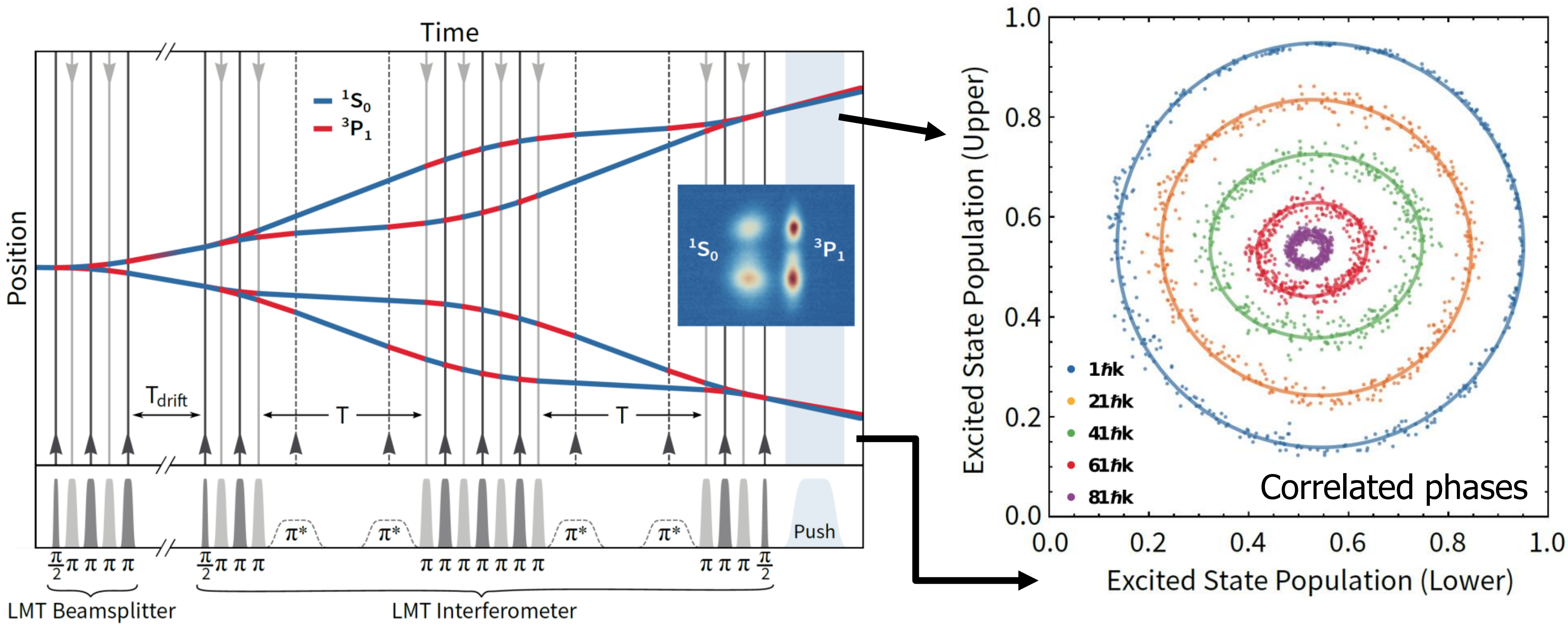



LMT in demo limited by available 689 nm power (~100 mW)

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

# Clock Atom Gradiometer demonstration

*Run two interferometers simultaneously*



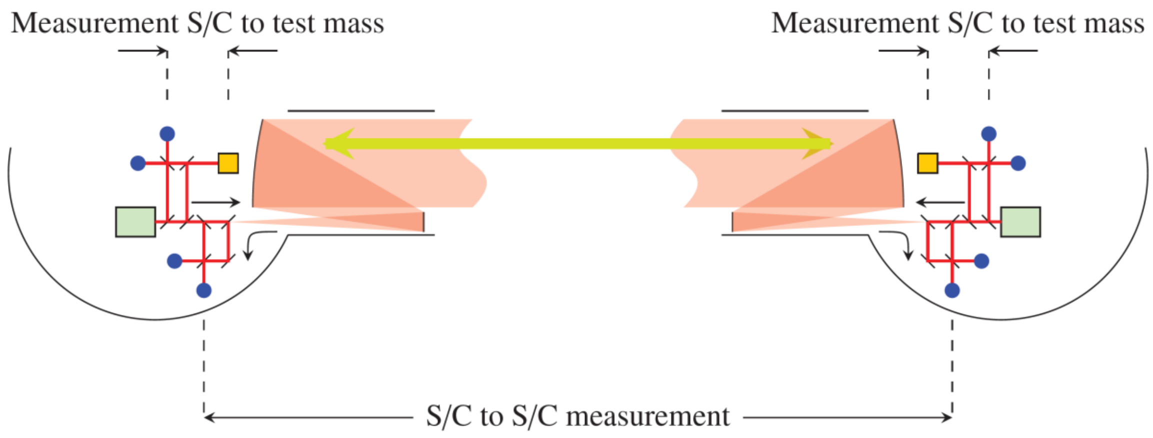

- Laser phase noise is common to the interferometers
- Demonstrated 81 ħk (power limited)
- Demonstrated T > 1 ms (>> lifetime)

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

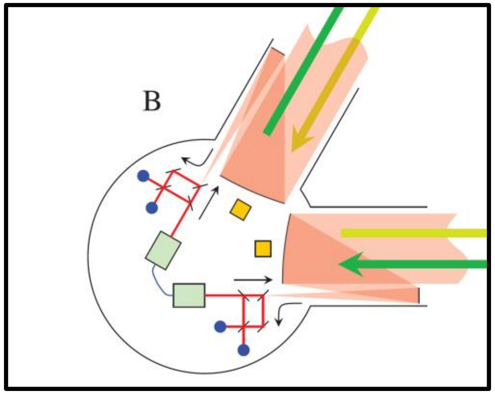
# GW comparison

# Compare to LISA

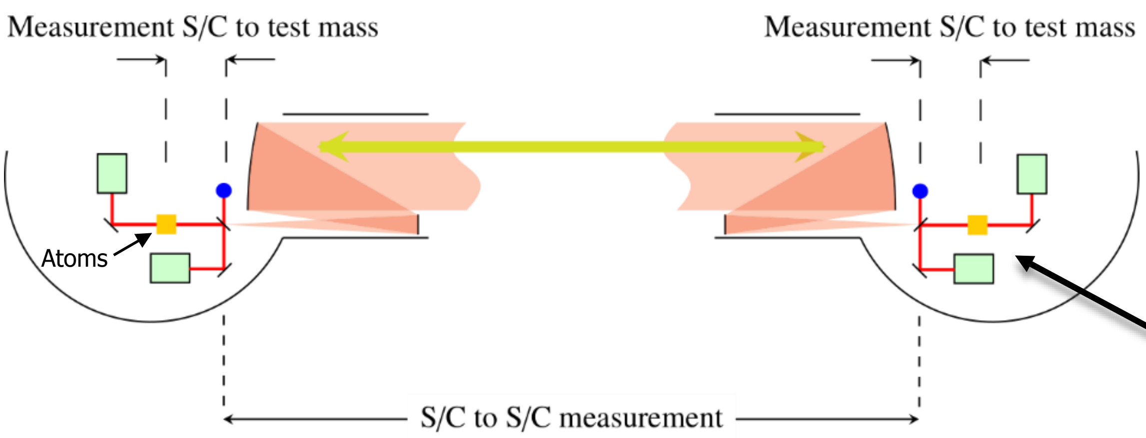
## LISA:



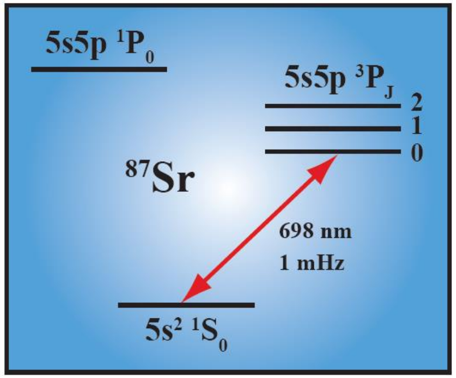

Second baseline needed for phase reference:




## Atom interferometry:

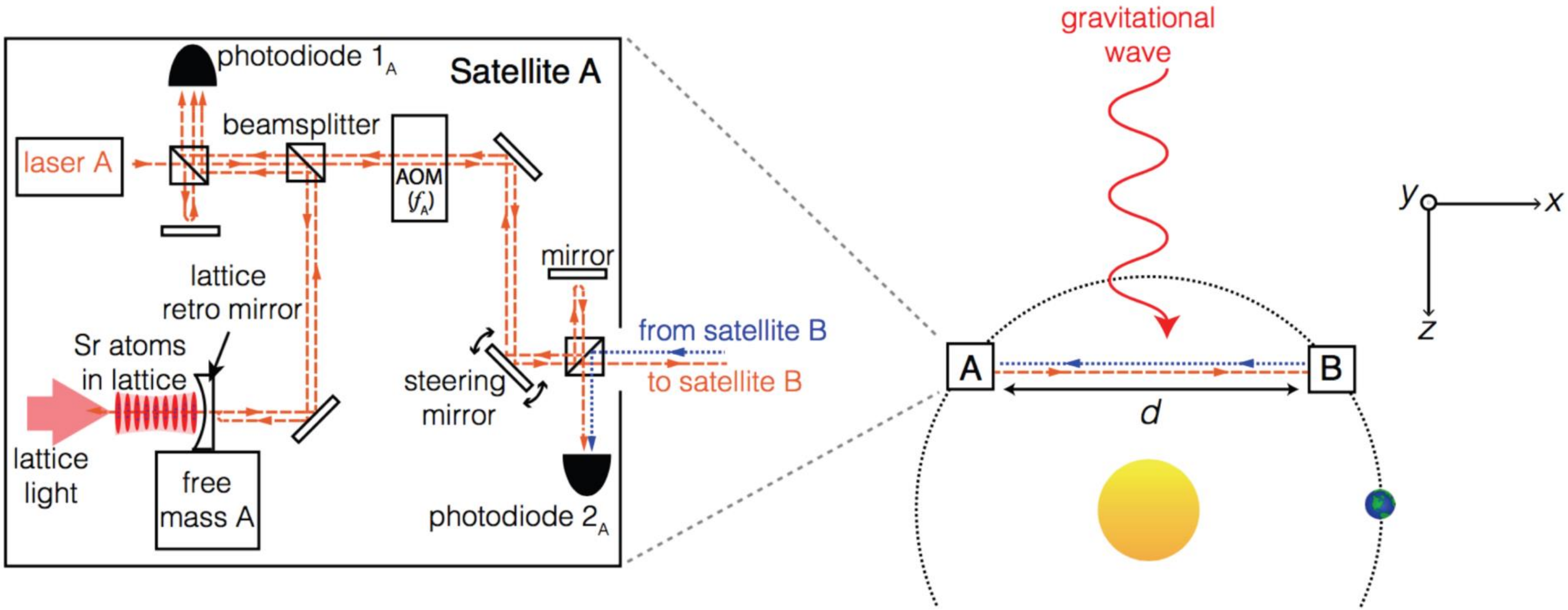



Atom test mass acts as phase reference:




(Figures adapted from LISA yellow book.)

# Lattice clock GW detection




- Optical lattice atomic clocks
- Resonant (dynamical decoupling)
- Drag-free satellites

S. Kolkowitz, I. Pikovski, N. Langellier, M. D. Lukin, R. L. Walsworth, and J. Ye, Phys. Rev. D **94**, 124043 (2016)

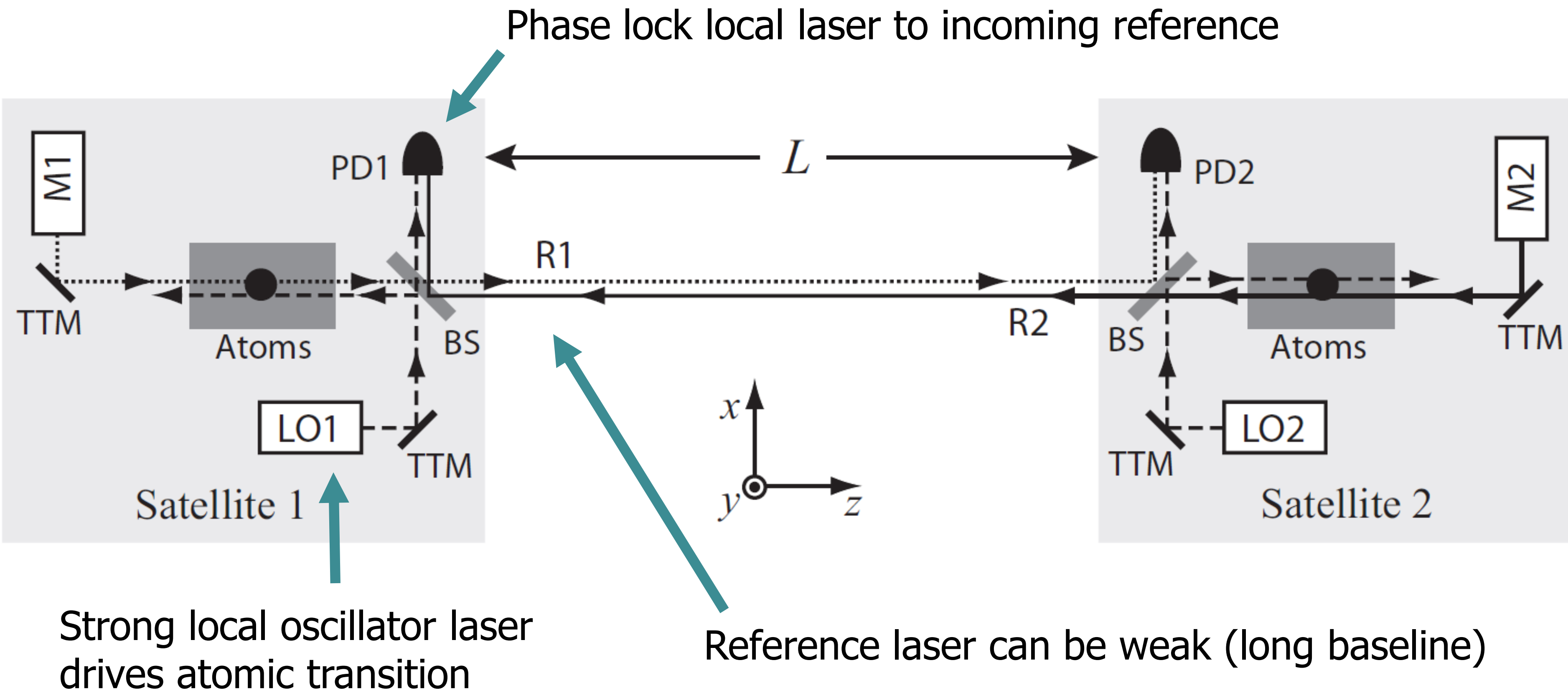
# GW Detector Comparison

| | 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 |

GW detector ingredients:

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

# MAGIS detector configuration




- Heterodyne laser link for long baselines
- Maintains immunity to laser noise and spacecraft motion
- Atom is *proof mass* and *phase reference* -- avoids the need for additional baselines

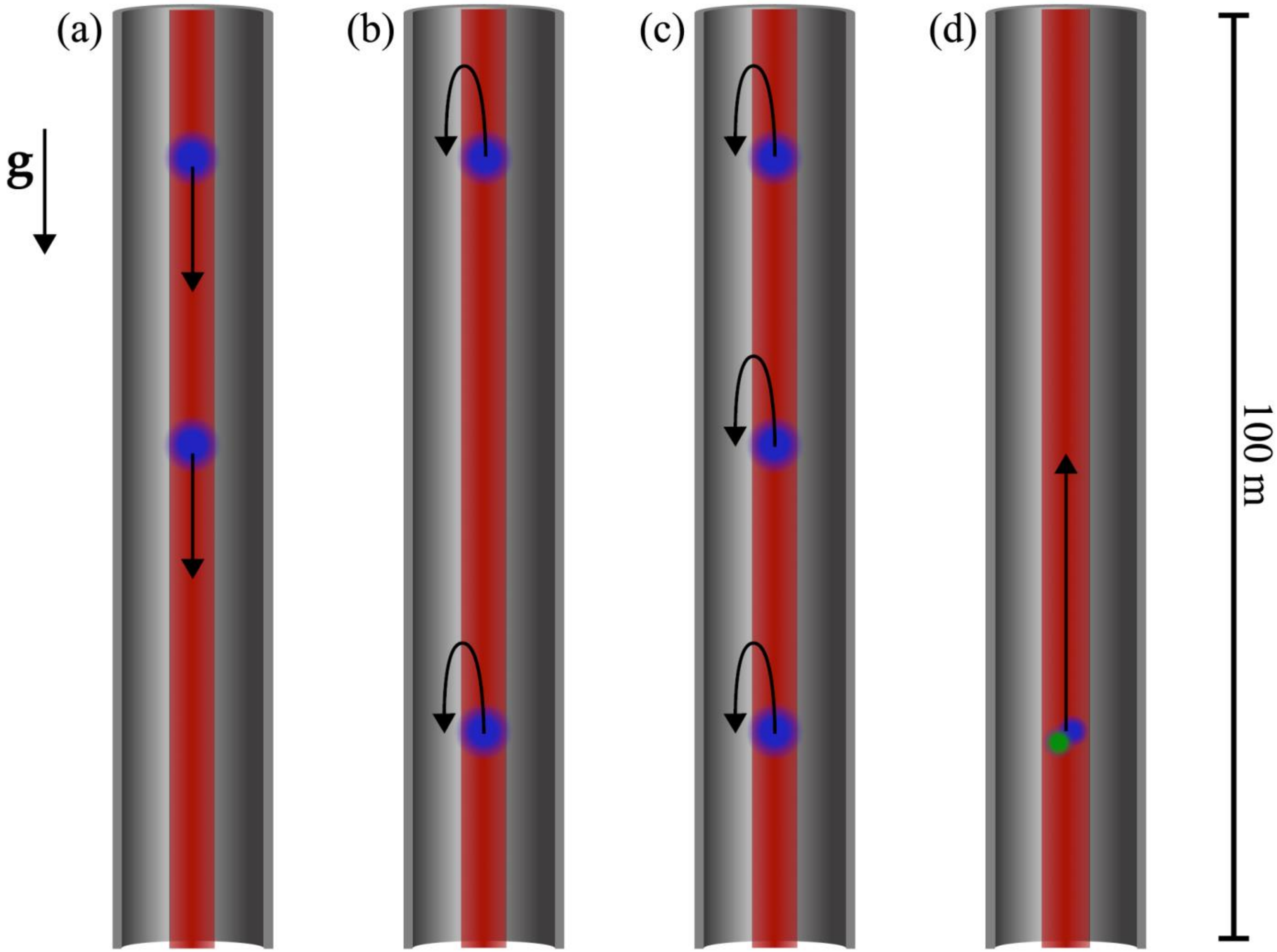
JH and M. Kasevich, PRA **94**, 033632 (2016)

# MAGIS space design requirements

| | Parameter | Constraint | Notes |
|---|---|---|---|
| Spacecraft | Satellite longitudinal acceleration noise | $10^{-9}\ \frac{\text{m/s}^2}{\sqrt{\text{Hz}}}\left(\frac{f}{0.03\ \text{Hz}}\right)^4$ | Residual gravity gradient $T_{zz} < 10$ E |
| | Satellite transverse acceleration noise | $3\times10^{-10}\ \frac{\text{m/s}^2}{\sqrt{\text{Hz}}}\left(\frac{f}{0.03\ \text{Hz}}\right)^2$ | $\lambda/100$ wavefront at $\Lambda = 1$ cm |
| | Satellite pointing stability | $1\ \mu\text{rad}/\sqrt{\text{Hz}}$ | |
| Payload | Telescope aperture | 30 cm | $\lambda/100$ wavefront aberration |
| | Laser pointing stability | $10\ \text{nrad}/\sqrt{\text{Hz}}$ | Tip-tilt mirror servo; atom positioning $\Delta x < 1\ \mu$m |
| | Laser power | 2 W | Primary interferometry laser; one per spacecraft |
| | Interrogation region length | 1 m | Length of UHV vacuum chamber |
| Atom Interferometry | Maximum interferometer duration | $2TQ < 300$ s | Limited by vacuum, spontaneous emission |
| | Maximum atom optics pulses | $n_p < 10^3$ | Includes all LMT and resonant enhancement |
| | Maximum wavepacket separation | $\frac{n\hbar k}{m}T < 1$ m | |
| | AI readout noise | $10^{-4}\ \text{rad}/\sqrt{\text{Hz}}$ | Requires flux of $10^8$ atoms/sec |

# MAGIS-100 technical

# MAGIS-100 configurations




**GW/DM mode**
- 50 meter baseline
- Long drop time

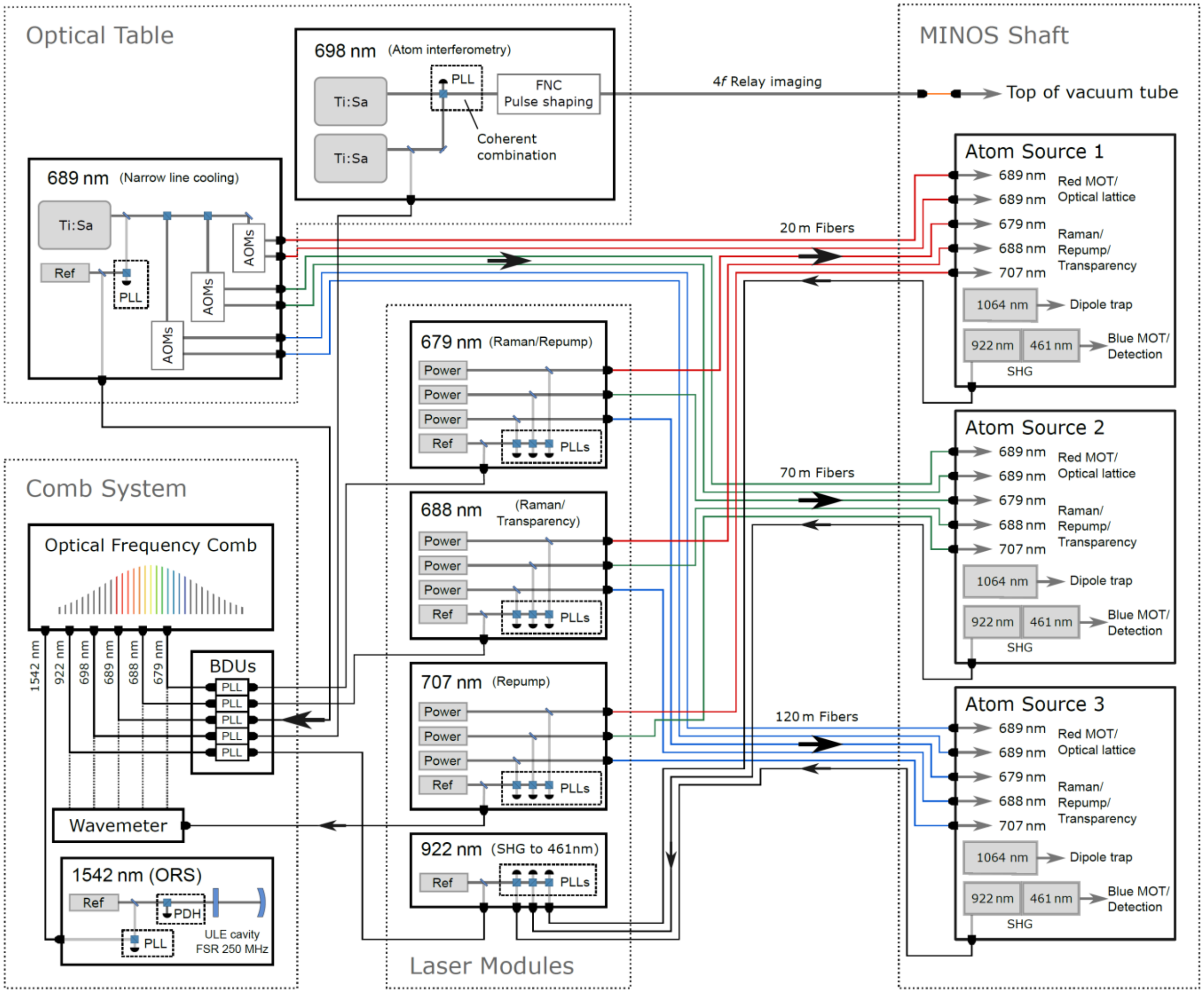
**GW/DM mode**
- 100 meter baseline
- 1 s drop time

**GW mode**
- 1 s drop
- "Curvature" for GG noise

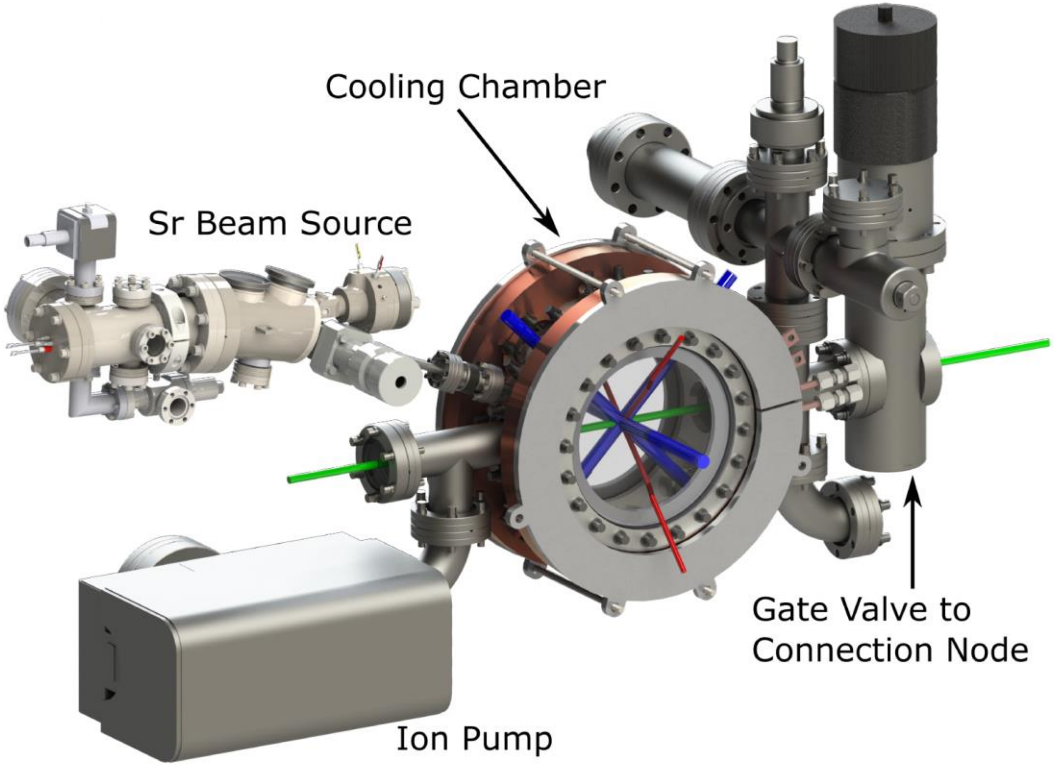
**DM mode**
- Dual isotope for DM search
- 9 s drop time

# MAGIS-100 laser system

- All lasers referenced to optical frequency comb (no spectroscopy locks)
- Comb-stabilized LO laser for each wavelength
- PLL offset lock for all lasers for each atom source (all independently tunable)



# MAGIS-100 atom source vacuum system

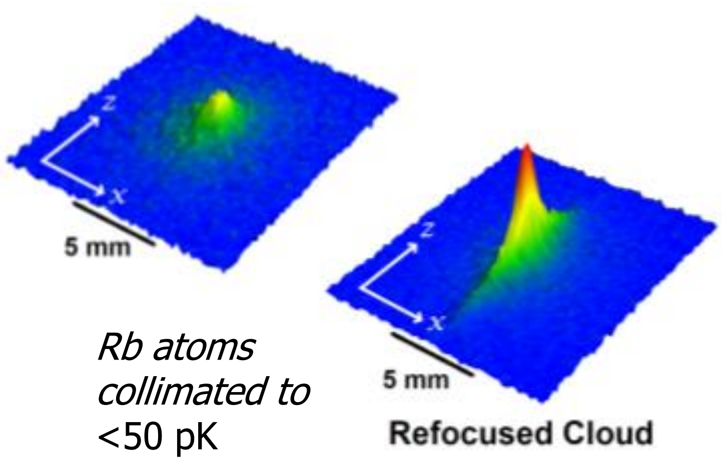



*Based on existing Sr atom source design*

- Commercial Sr beam source (oven, Zeeman slower, 2D MOT)
- 3D cooling vacuum chamber
- Ion pump, ion gauge, TSP
- Magnetic coils (quadrupole for MOT, bias coil set)

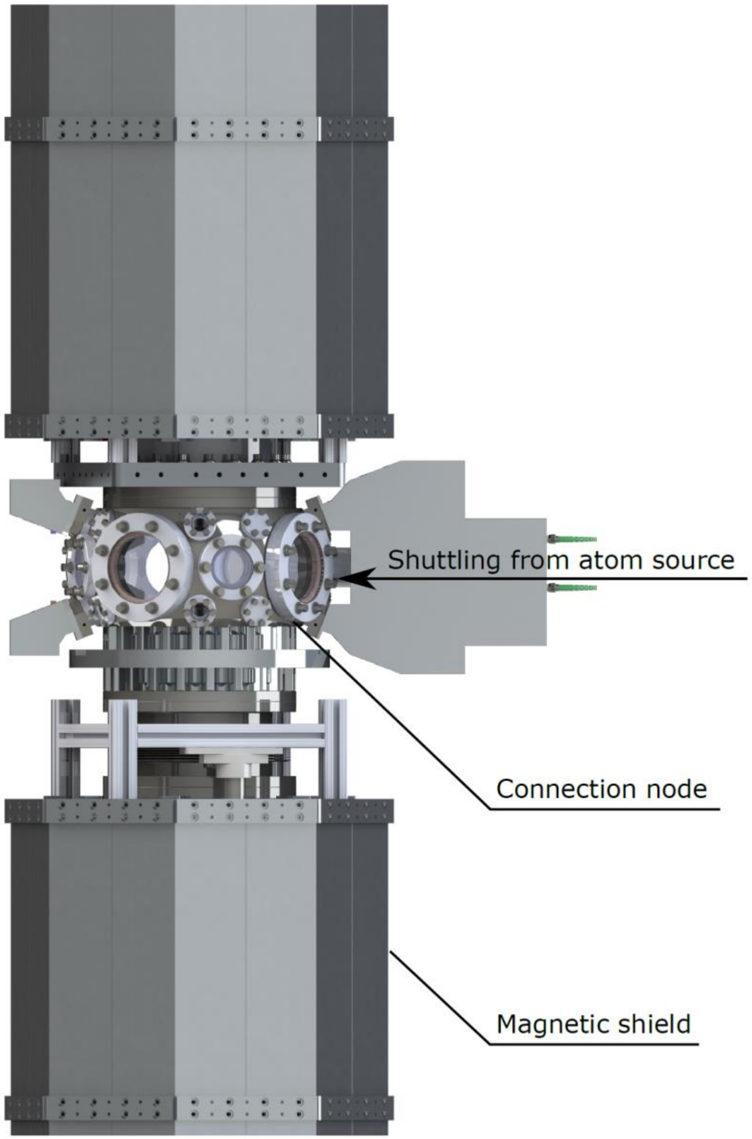
**Atom ensemble preparation cycle**

- Laser cooling (blue MOT/red MOT)
- Evaporative cooling in an optical dipole trap
- Matter wave lensing
- Optical lattice horizontal shuttle to interferometer region
- Launch with vertical optical lattice




*Rb atoms collimated to* <50 pK

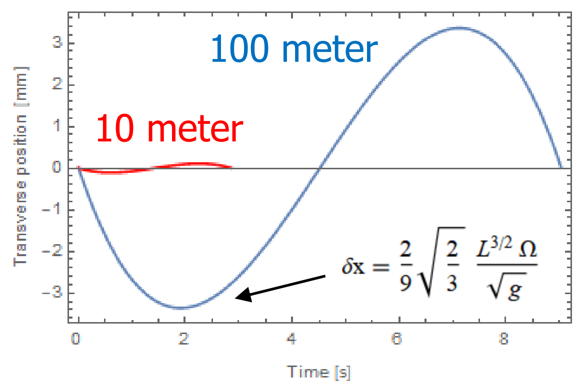
# Optical lattice launch




*689 nm lattice for vertical atom launching before interferometry*

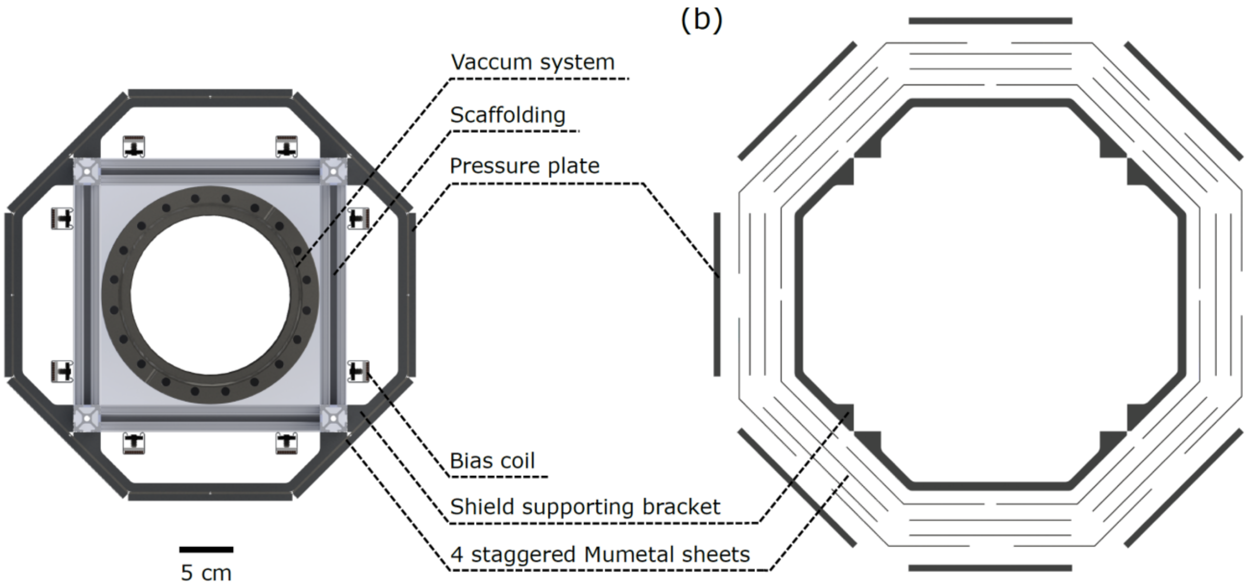
**Lattice optics design**

- 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

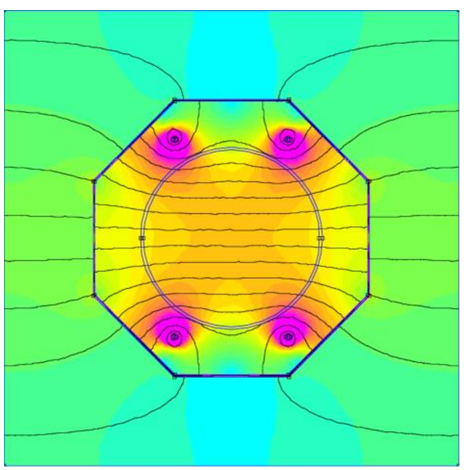



Minimum Coriolis displacement launch

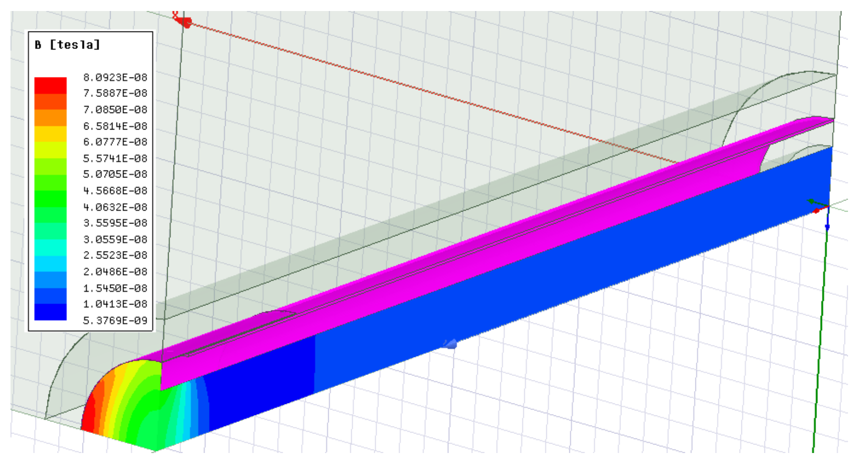
# MAGIS-100 magnetic shield




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

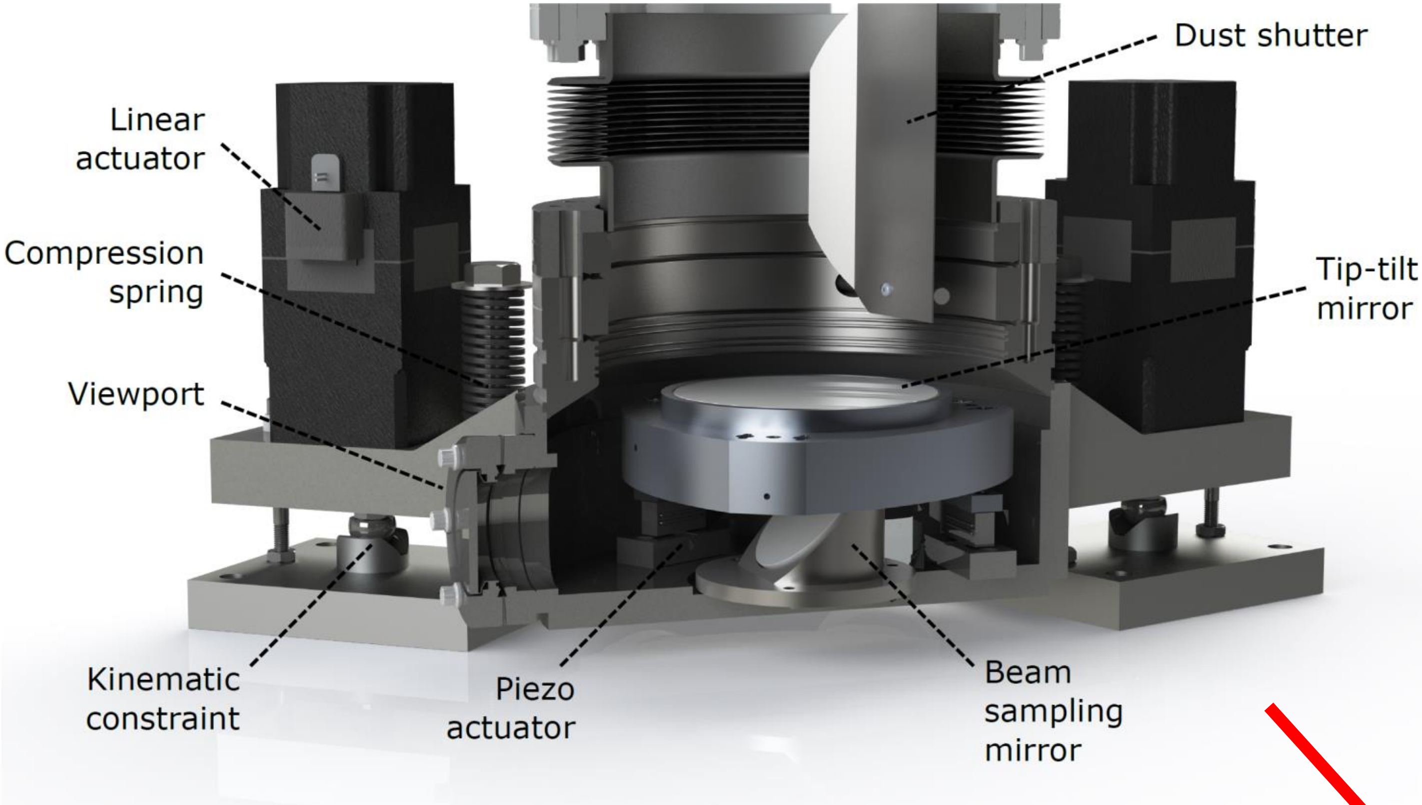


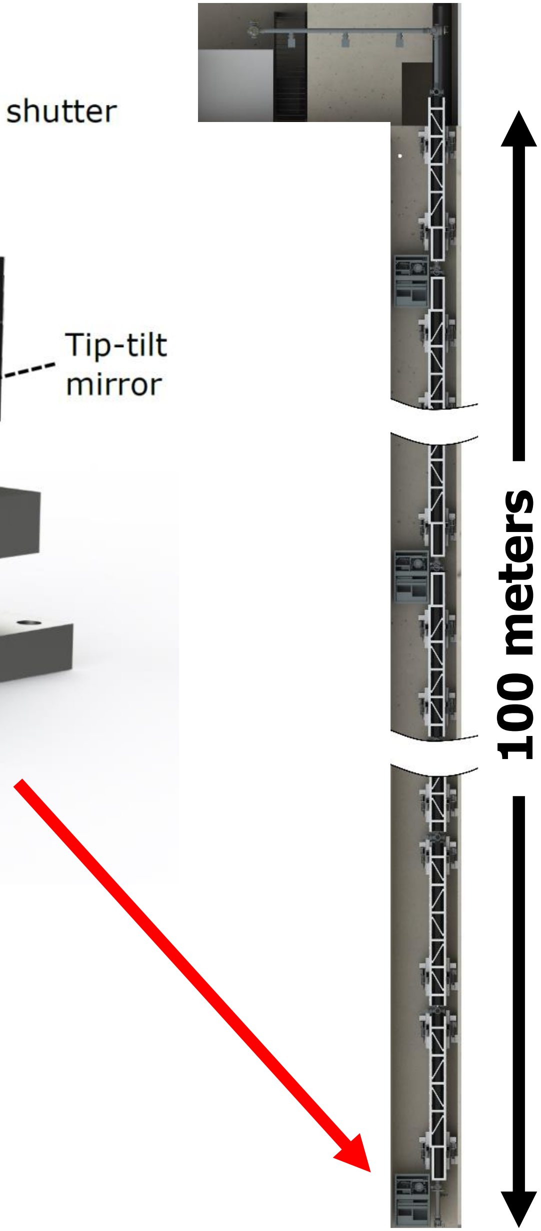
Shield + bias field simulation




3D horizontal field simulation

# MAGIS-100 tip-tilt mirror for rotation compensation



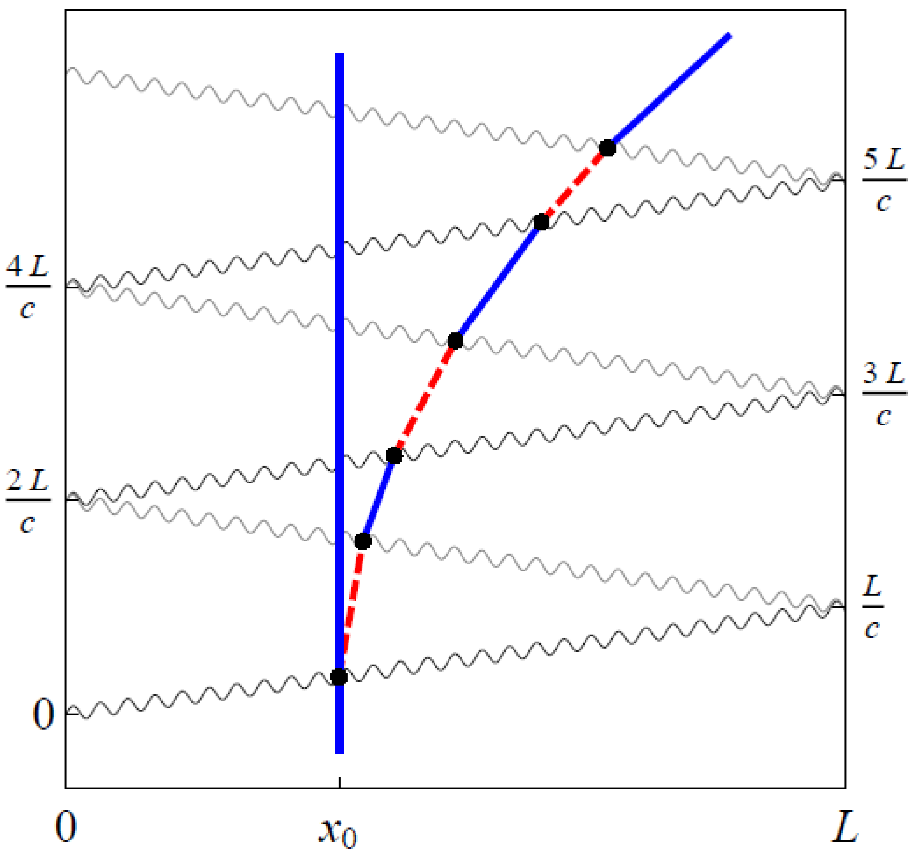

- Mirror at bottom to reflect interferometry laser light
- 3-axis piezo actuators for fine control
- Suppress Coriolis phase shifts by counter-rotating
- Coarse alignment with linear actuators

# LMT and resonant clock atom interferometry

# LMT and Resonant Pulse Sequences

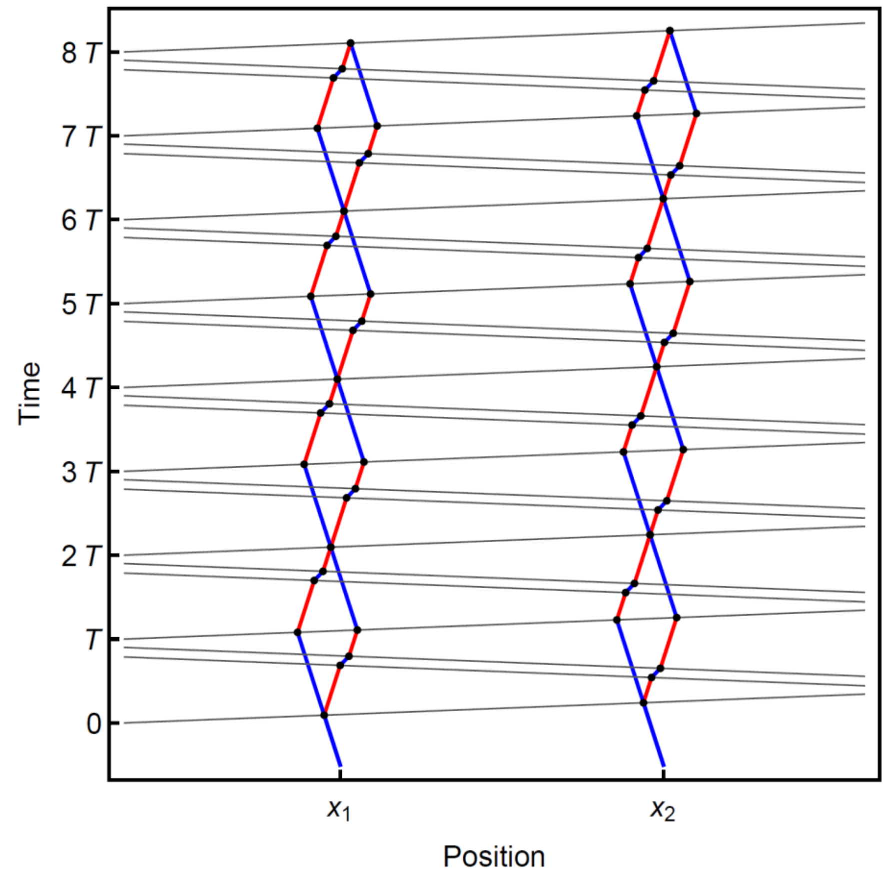
Sequential single-photon transitions remain laser noise immune

**LMT beamsplitter (N = 3)**



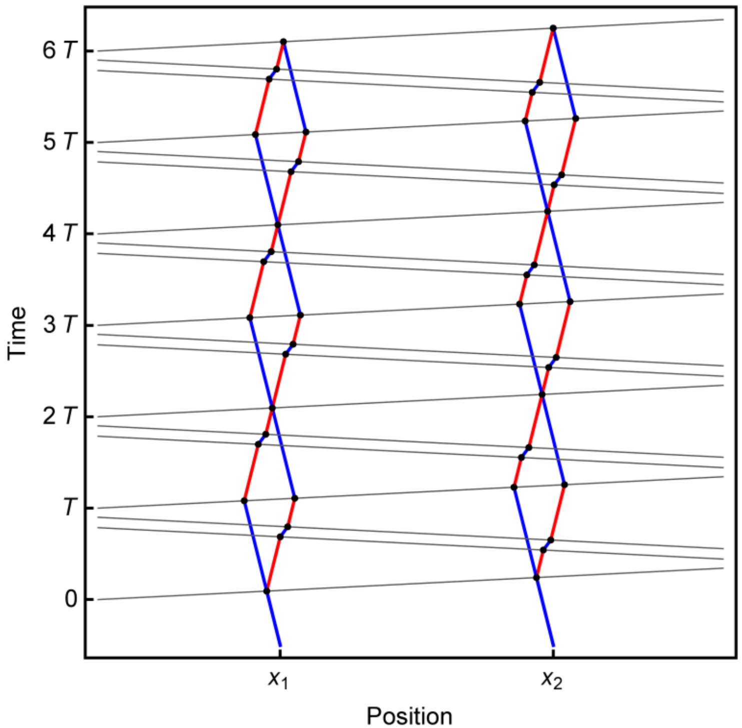

Graham, *et al.*, PRL (2013)

**Resonant sequence (Q = 4)**

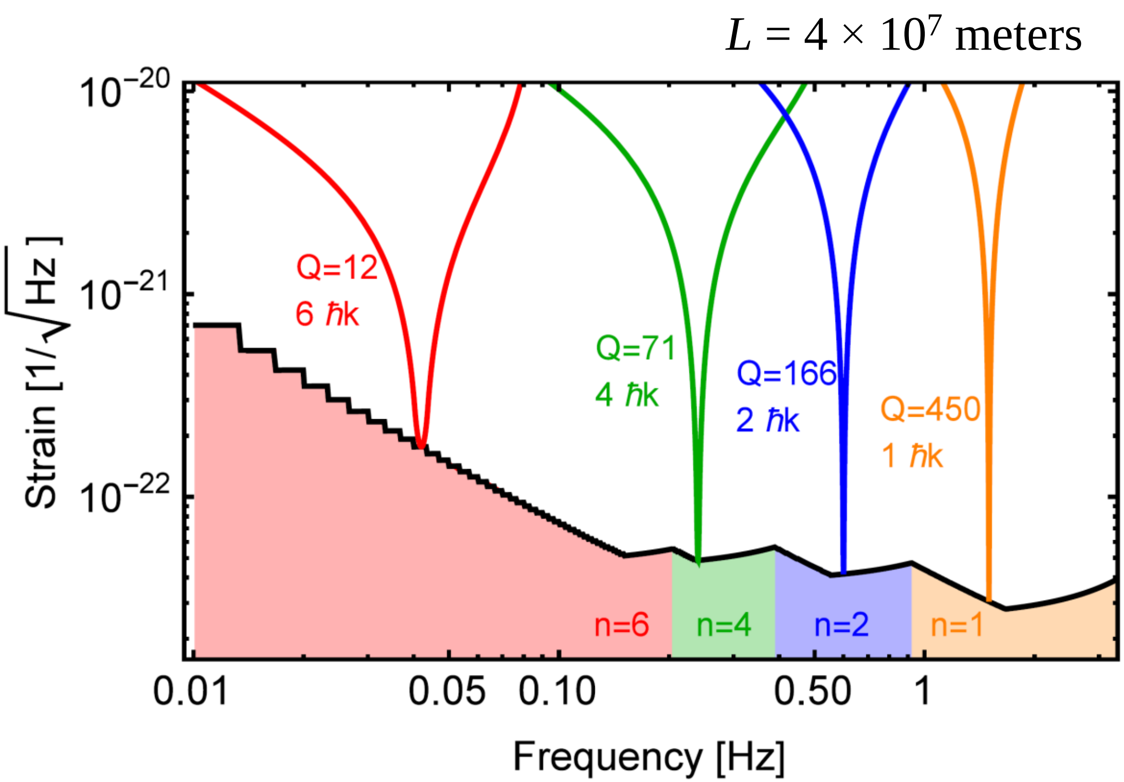



Graham, *et al.*, PRD (2016)

# Resonant Detection Mode




*Resonant interferometer sequences for enhanced, narrow band response*

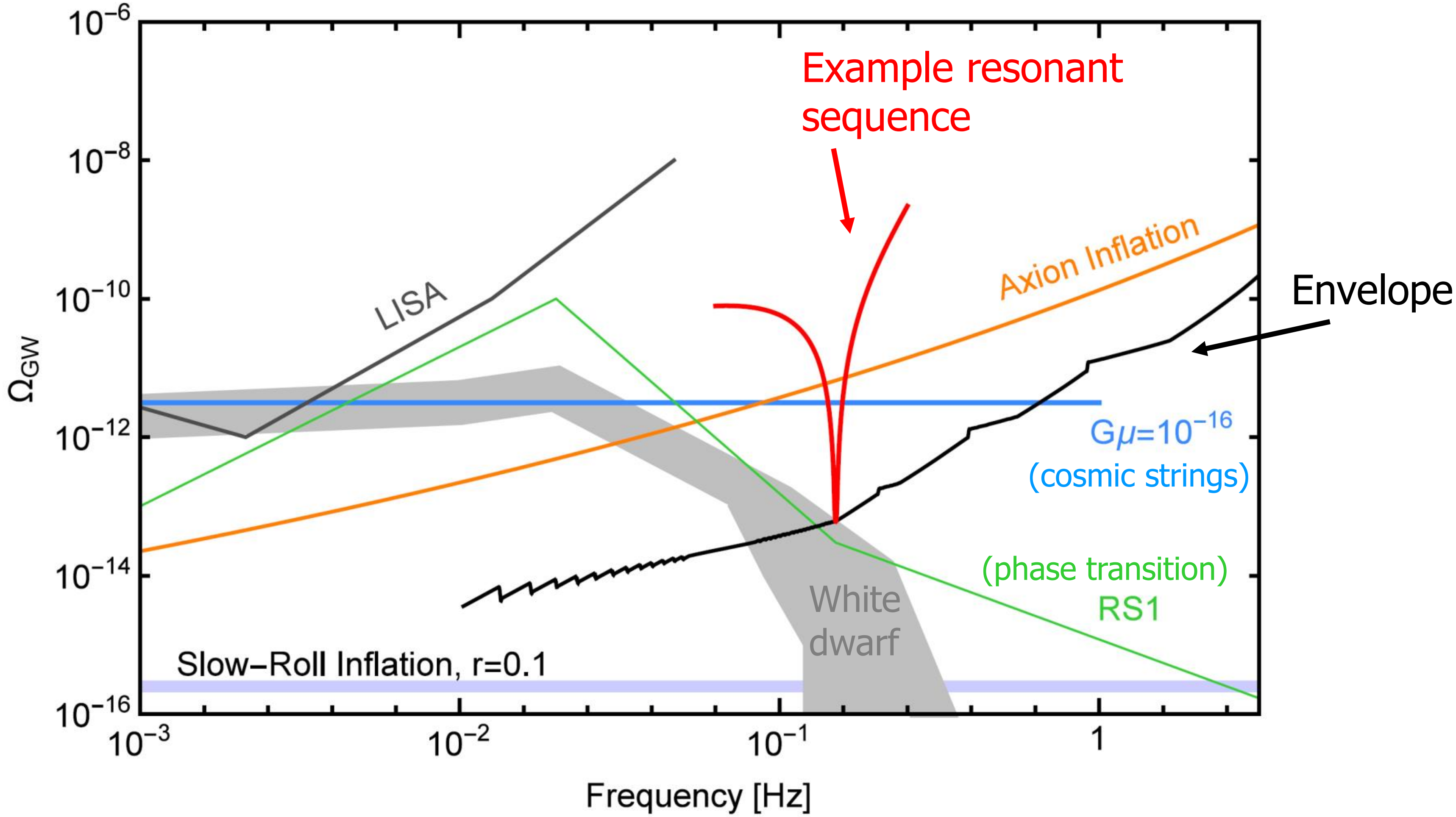



*Optimized sensitivity near 1 Hz*

*Includes constraints on total pulses and source lifetime*

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

# Bounds on stochastic GW sources




*Narrow band sensitivity possible in 1 year*

Graham, *et al.*, arXiv:1606.01860 (2016)