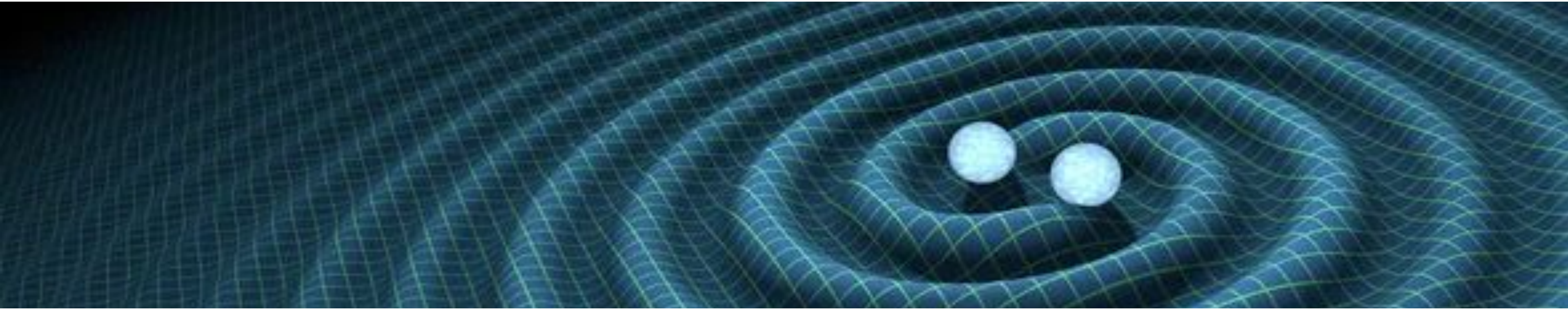


Novel Light Field Imaging for the MAGIS-100 Experiment

https://iopscience.iop.org/article/10.1088/1748-0221/17/08/P08021

Ariel Schwartzman, Jason Hogan, Michael Kagan,
Murtaza Safdari, Sanha Cheong, Sean Gasiorowski
SLAC National Accelerator Laboratory

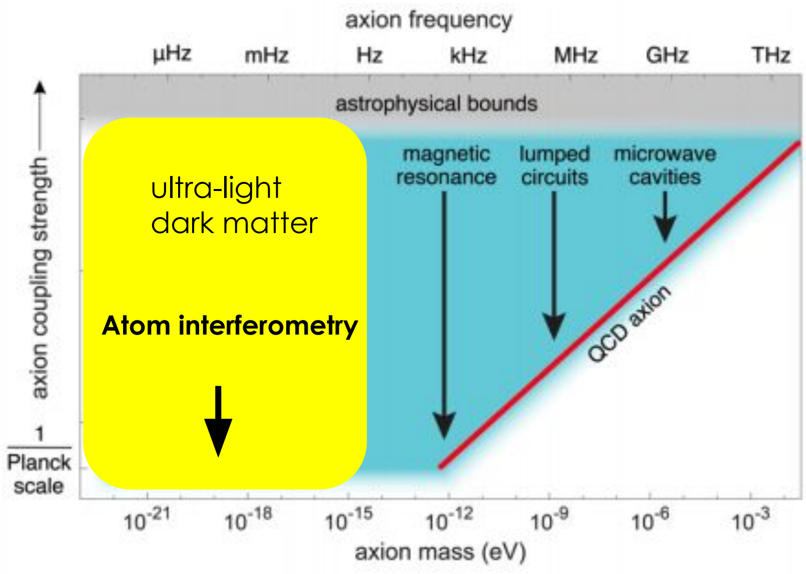
CPAD Workshop 2023, 9-Nov-2023

SLAC NATIONAL ACCELERATOR LABORATORY

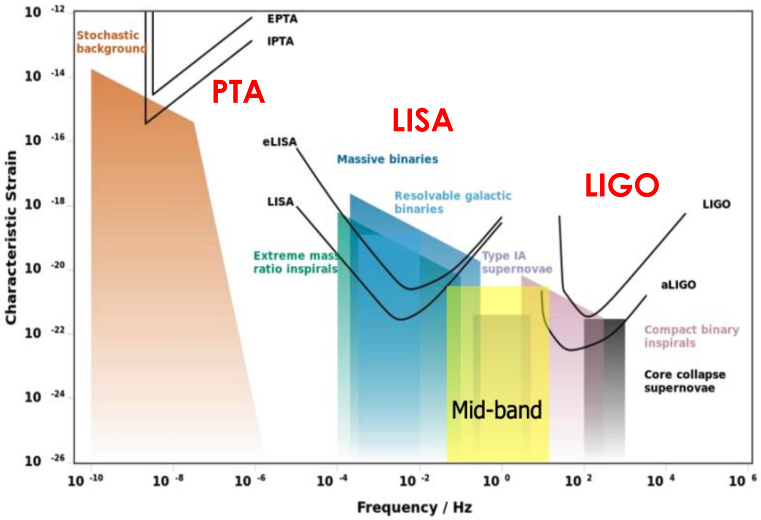
MAGIS-100

Long-baseline Atomic Sensors

Long-baseline atomic quantum sensing is an exciting new field that offers new handles and opportunities to expand the exploration of the physics the universe at the **intersection of the energy, cosmic, and quantum information frontiers**



Ultralight wave dark matter at sensitivities orders of magnitude beyond current limits

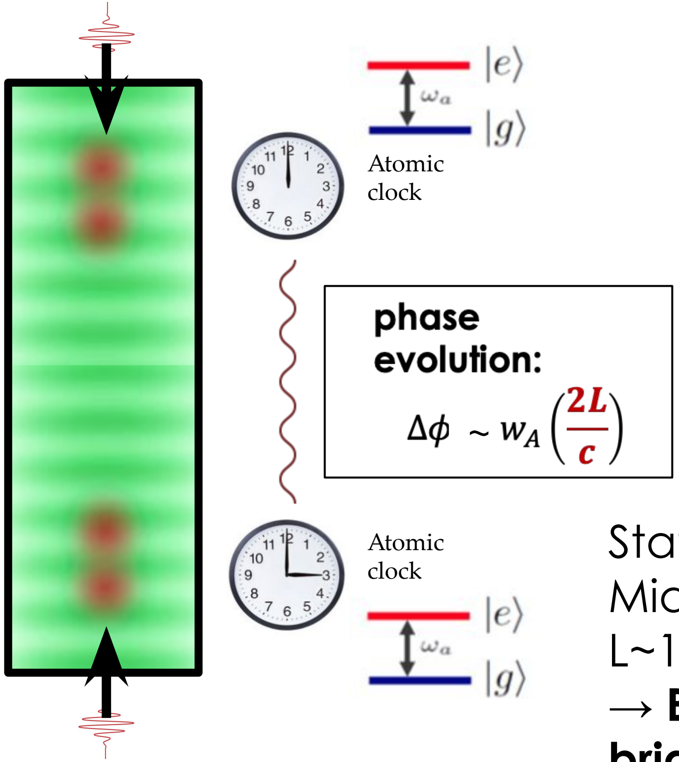


Expand the exploration of **gravitational waves in a new frequency range** particularly sensitive to cosmological sources

Long-baseline Atomic Sensors

Free-falling atoms on each end serve as **inertial references**

Atoms act as **clocks** to measure light travel time across baseline: ***active proof mass***



Two ways for phase to vary:

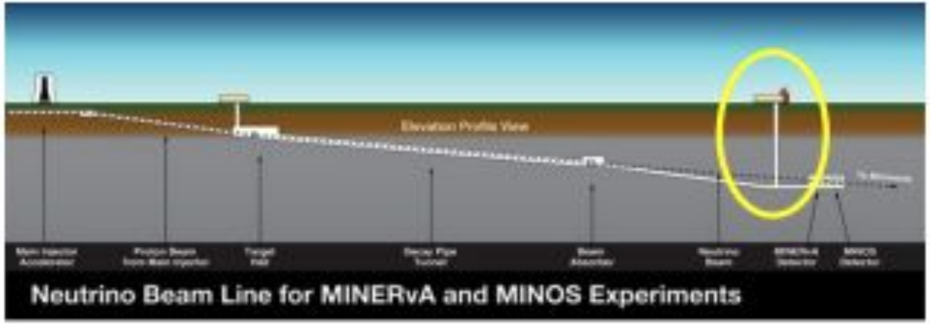
w_A : Dark Matter
L : Gravitational waves

State-of-the-art (Stanford) L~10m
Mid-band GW sensitivity requires L~1Km
→ **Build 100m prototype to bridge the gap between 10m and Km-scale detectors**

Graham et al., PRL **110**, 171102 (2013).
Arvanitaki et al., PRD **97**, 075020 (2018).

MAGIS-100

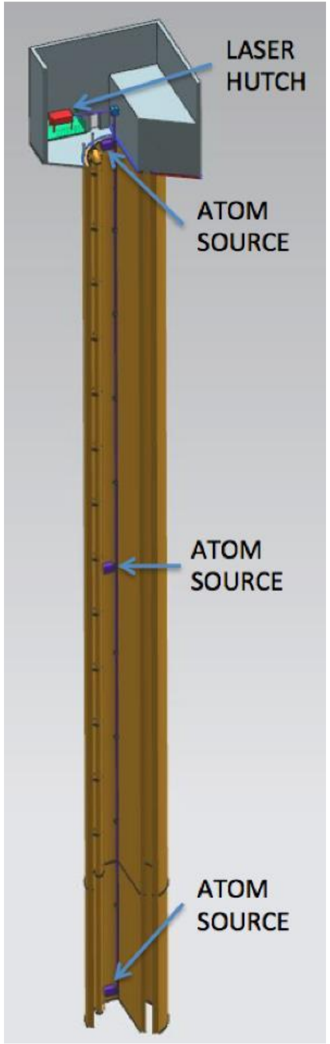
Mater Wave Atomic Gradiometer Interferometric Sensor



https://magis.fnal.gov/

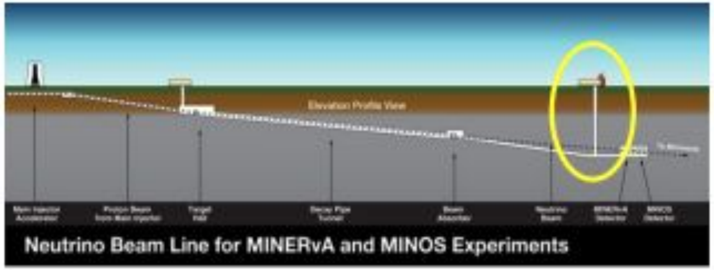
- **100-meter baseline atom interferometer under construction at Fermilab**
- Development platform for a future Km-scale detector
- Search for ultralight dark matter beyond current limits
- Quantum science: test coherence of macroscopic quantum superpositions over large time and length scales
- **International collaboration of 9 institutions, >50 people**

Stanford, Johns Hopkins University, Northwestern University, Fermilab, SLAC, University of Cambridge, Old Dominion University, University of Oxford, University of Liverpool



Many International Efforts

Matter wave Atomic Gradiometer Interferometric Sensor



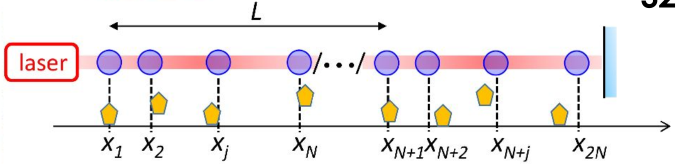
MAGIS-100: Fermilab/ Stanford/SLAC

PROJECTS AND FACILITIES | NEWS

European physicists propose huge underground gravitational-wave laboratory

14 Nov 2019 Michael Banks

32Km!

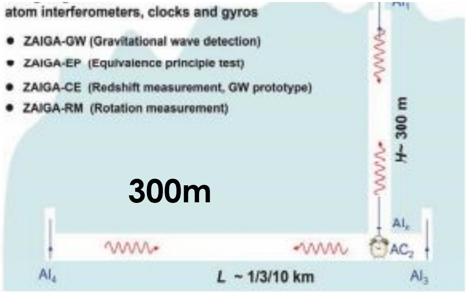


ELGAR: European Laboratory for Gravitation and Atom Interferometric Research

Underground detector with two 32-Km horizonal arm length containing 80 atom interferometers each

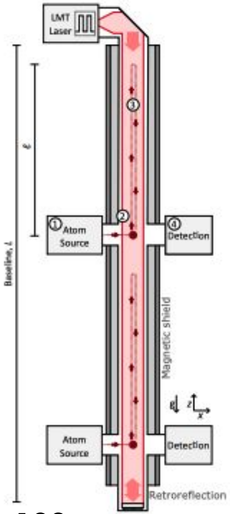
No similar US effort at this scale yet

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



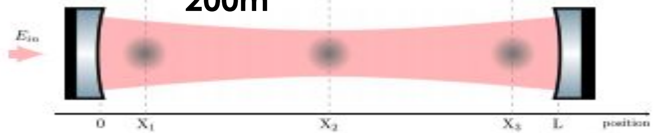
300m

AION (UK)



100m

200m



Matter-wave laser Interferometric Gravitation Antenna (MIGA) Experiment (FRANCE)

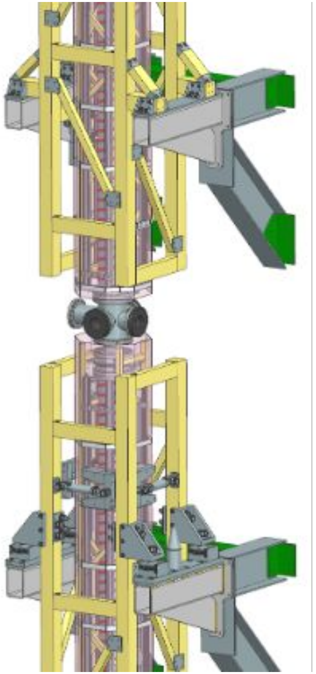
CERN-PBC Report-2023-002

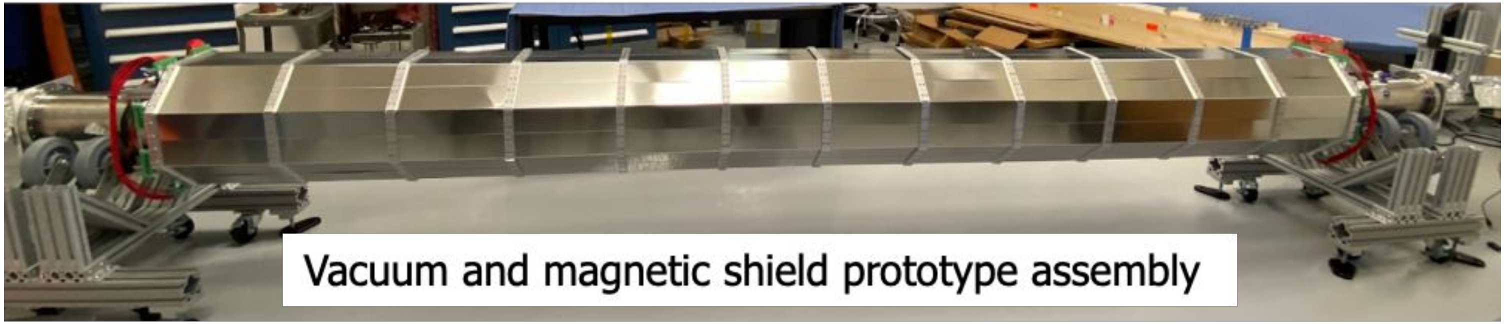
A Long-Baseline Atom Interferometer at CERN: Conceptual Feasibility Study

G. Arduini[1,*], L. Badurina[2], K. Balazs[1], C. Baynham[3], O. Buchmueller[3,4,*], M. Buzio[1], S. Calatroni[1,*], J.-P. Corso[1], J. Ellis[1,2,*], Ch. Gaignant[1], M. Guinchard[1], T. Hakulinen[1], R. Hobson[3], A. Infantino[1], D. Lafarge[1], R. Langlois[1], C. Marcel[1], J. Mitchell[5], M. Parodi[1], M. Pentella[1], D. Valuch[1], H. Vincke[1]

MAGIS-100 Design and Construction

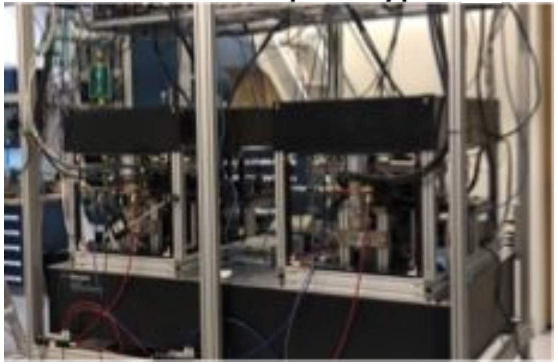
Installation and assembly planning models

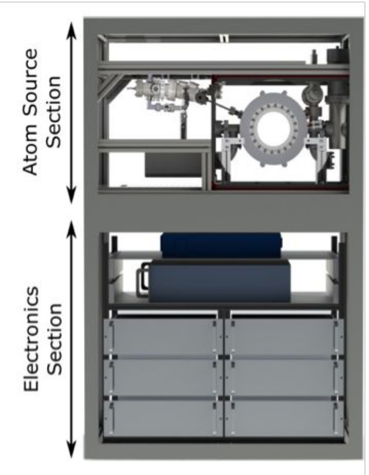




Vacuum and magnetic shield prototype assembly

Sr atom source prototypes





Atom source (CAD) with integrated electronics and environmental enclosure

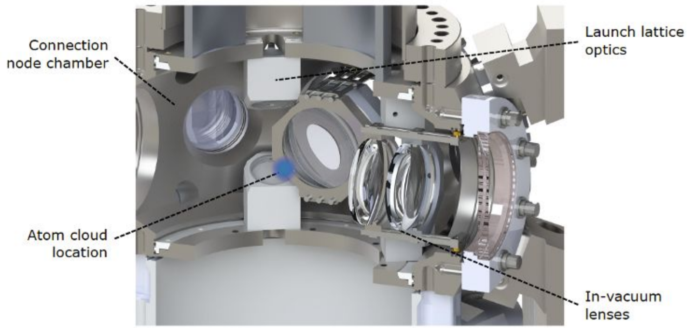
MAGIS-100 Imaging Challenges

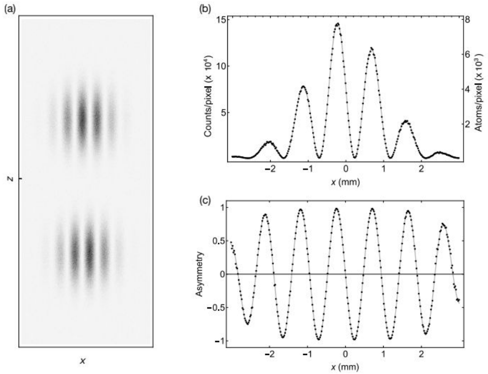
Fluorescence imaging of Sr cold atom clouds:
1mm wide, 100um features

Key challenges for imaging:

- **Maximize light collection** → large aperture lens
- **Large depth of field** → small aperture lens
- **Ability to image the cloud from multiple angles** (measure laser aberration)

Fundamental depth of field vs. numerical aperture limit for any single lens





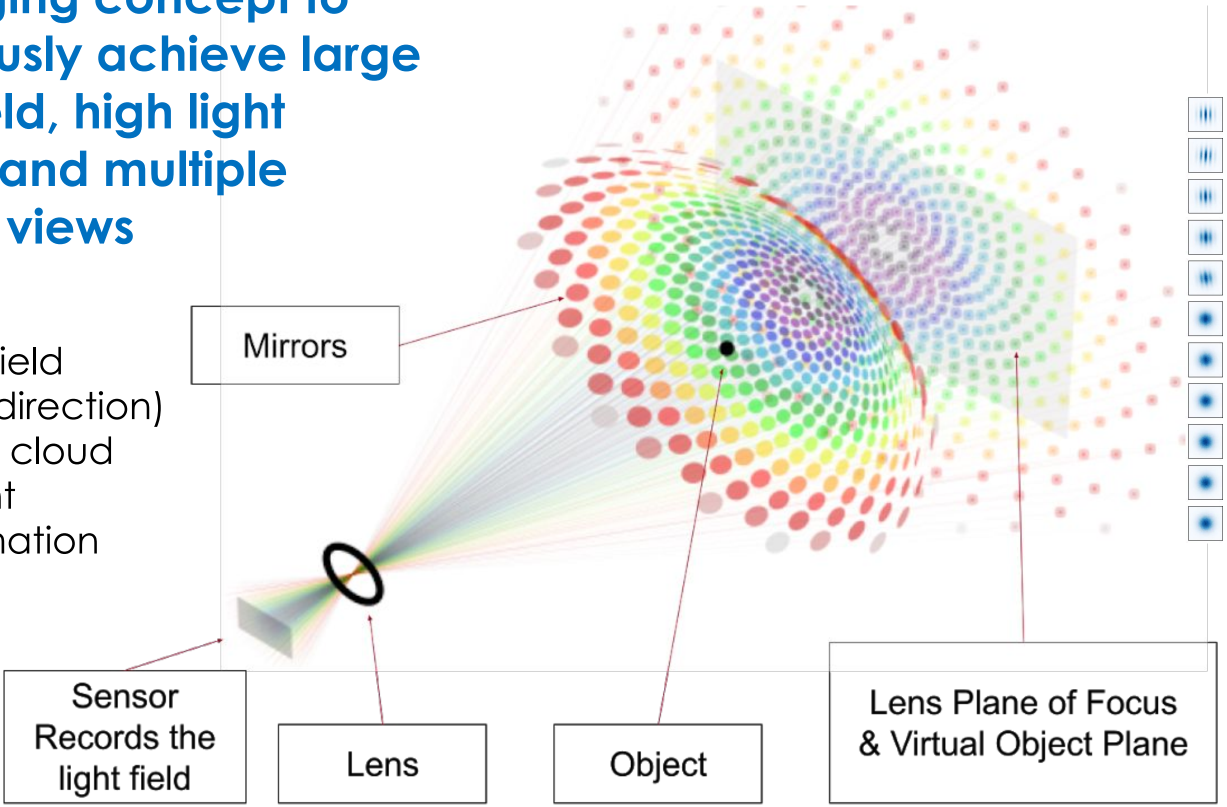
Light-Field Camera Concept

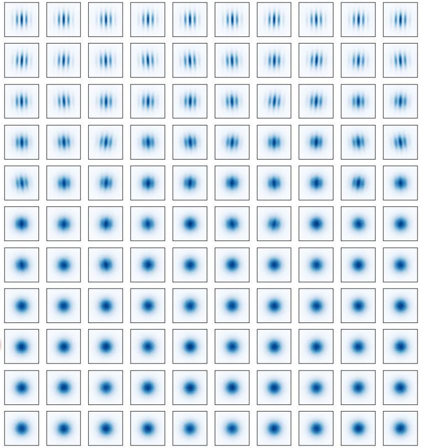
Novel imaging concept to simultaneously achieve large depth of field, high light collection, and multiple (hundreds) views

Capture light field (intensity and direction) from the atom cloud

- more light
- 3D information

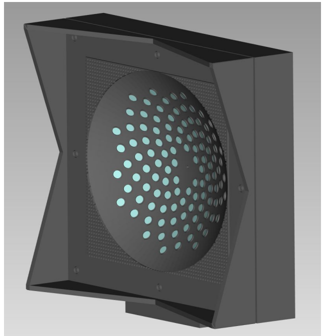
Super-aperture spatially multiplexed light field imaging

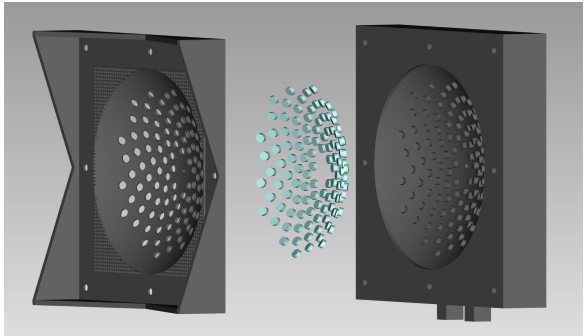


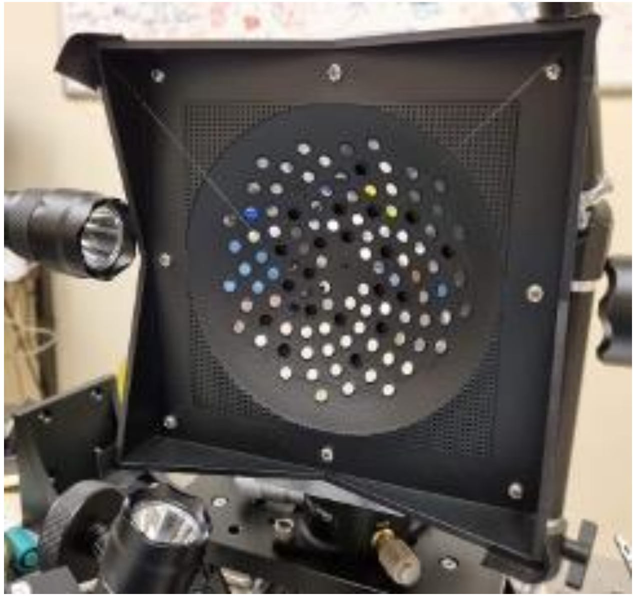


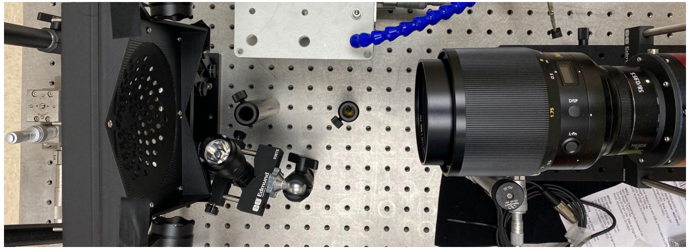
Demonstrator

- 3D printed mechanical support for 5mm mirrors
- Target held with 100 μm fibers
- Optical alignment with In-situ grid ~ 1°



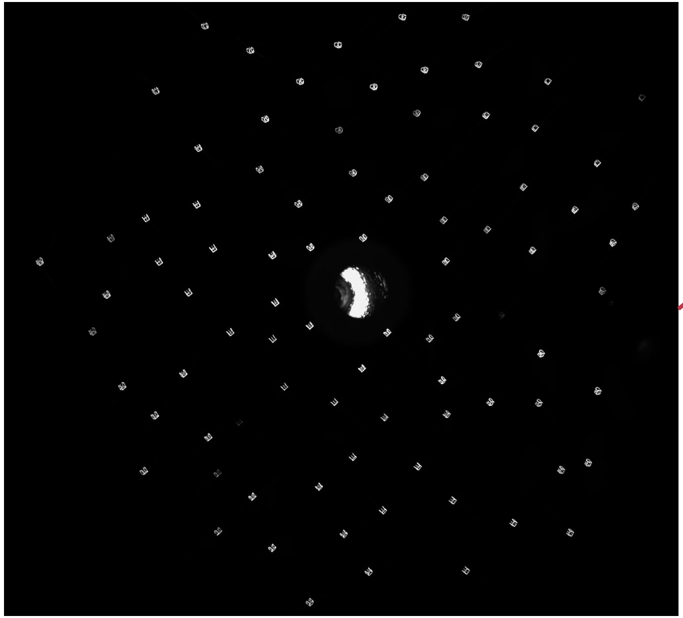


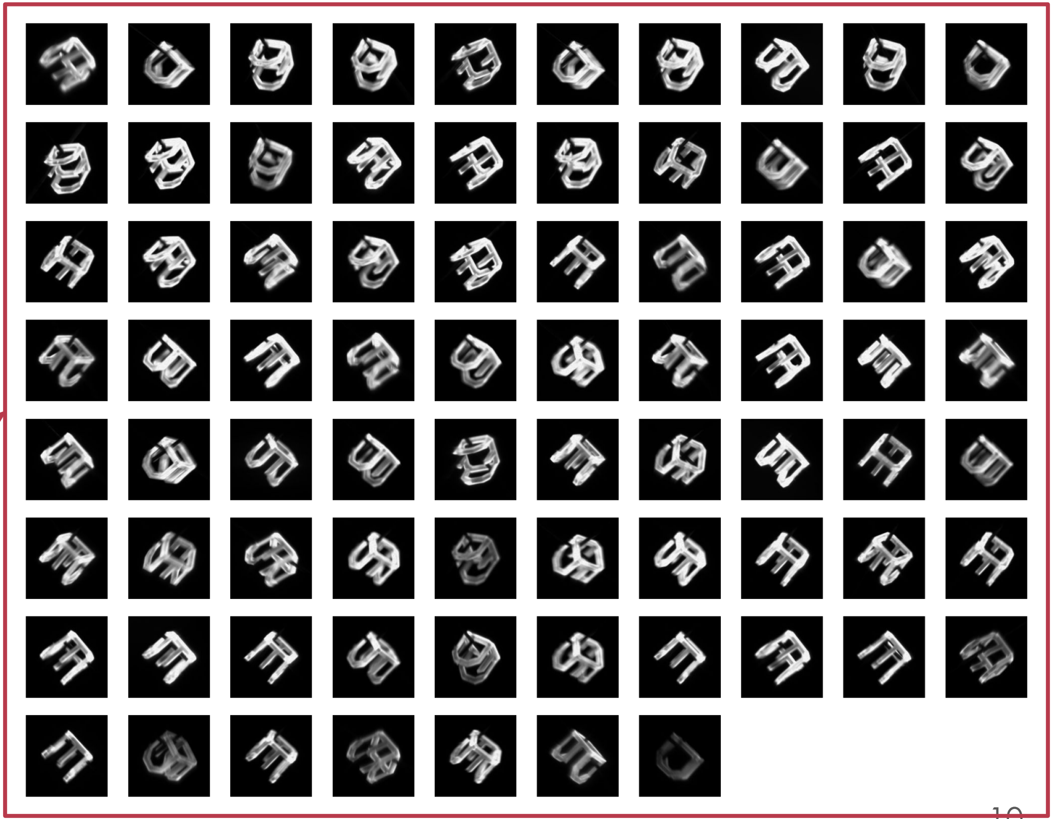




Raw images

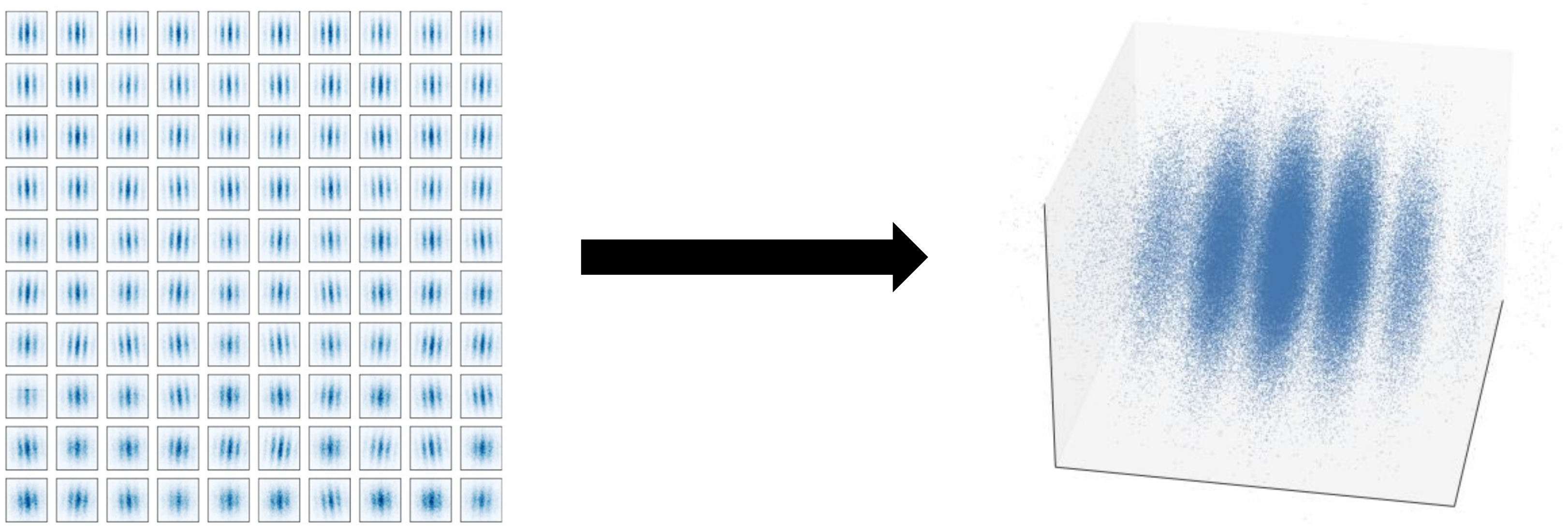
- Patch extraction of each view
- Select good alignment and illumination:
    - 77/90 images





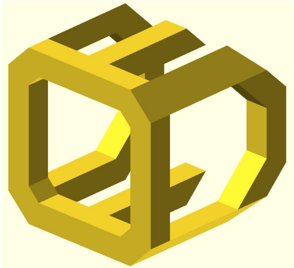
3D Image Reconstruction

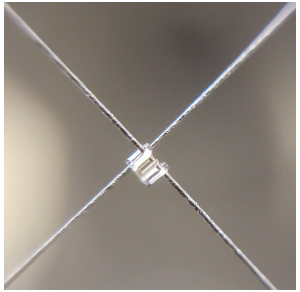
Use gradients through simulator to reconstruct the 3D image from the individual views



Released Open-source package: GradOptics:
Differentiable Ray Tracking and Optics Simulation

3D Reconstruction





PAPER • OPEN ACCESS

Novel light field imaging device with enhanced light collection for cold atom clouds

S. Cheong[1,2], J.C. Frisch[2], S. Gasiorowski[2], J.M. Hogan[1], M. Kagan[2], M. Safdari[1,2], A. Schwartzman[2] and M. Vandegar[2]

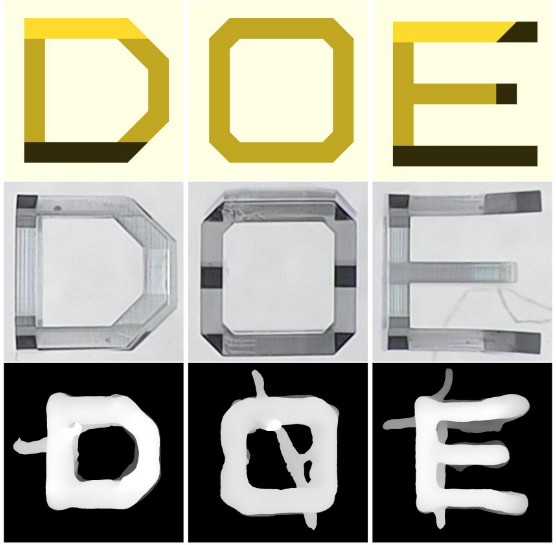
Published 18 August 2022 • © 2022 The Author(s)

Journal of Instrumentation, Volume 17, August 2022

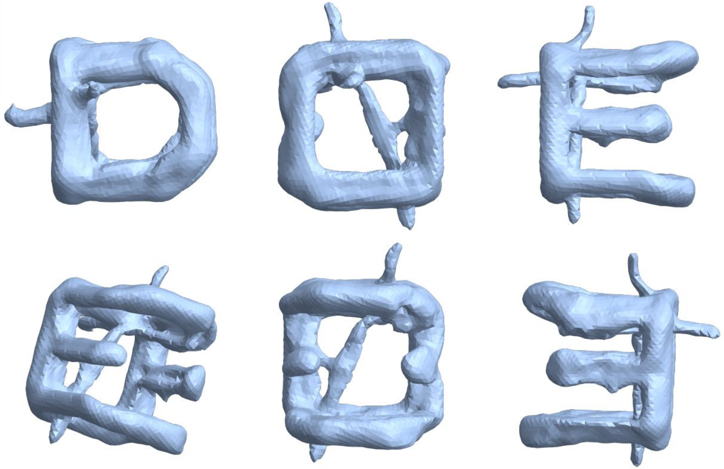
Citation S. Cheong *et al* 2022 *JINST* **17** P08021

DOI 10.1088/1748-0221/17/08/P08021

Comparison of CAD, microscope, and learned depth map

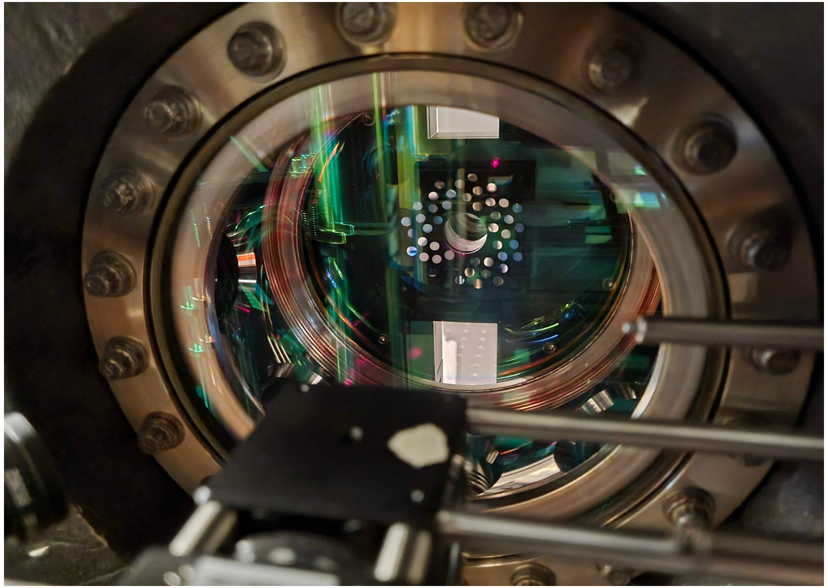


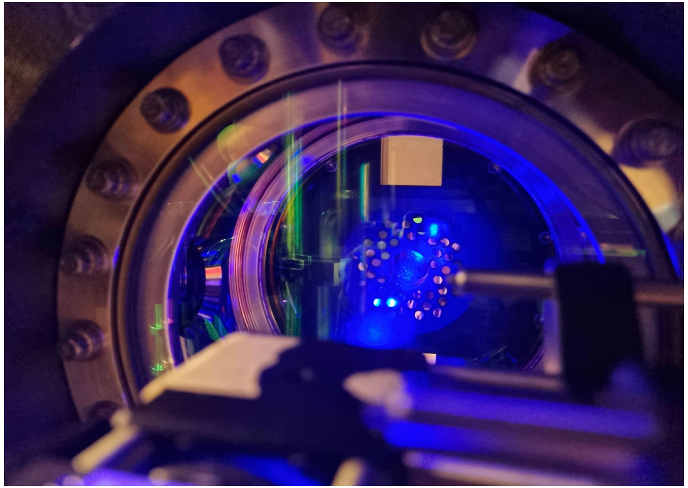
Reconstructed mesh surface



Interpolated views (SDF + Color)

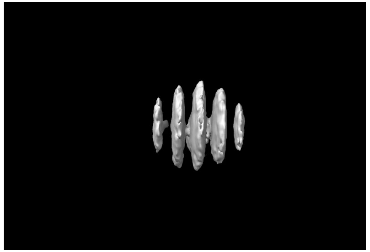
3D Imaging of Atom Clouds

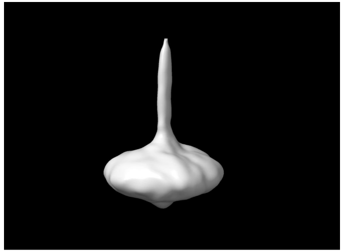




3D light field imaging device installed at Stanford

Imaging various types of atom clouds shapes





Testing reconstruction software with simulation

Summary

- Broad interest from the international community in developing long-baseline atomic sensors for HEP science:
  - **Extend the reach to search for ultralight wave dark matter**
  - **Open a new frequency band of the GW spectrum**
- **MAGIS-100 is a 100-meter-scale atom interferometer experiment under construction at Fermilab**
  - Exciting collaboration between AMO and Particle Physics communities
    - Leverage National Lab and large particle physics detector design/operations expertise
- **Novel light field imaging device can enhance light collection and provide 3D reconstruction** capabilities to MAGIS-100 and future atom interferometer experiments
  - increase physics sensitivity

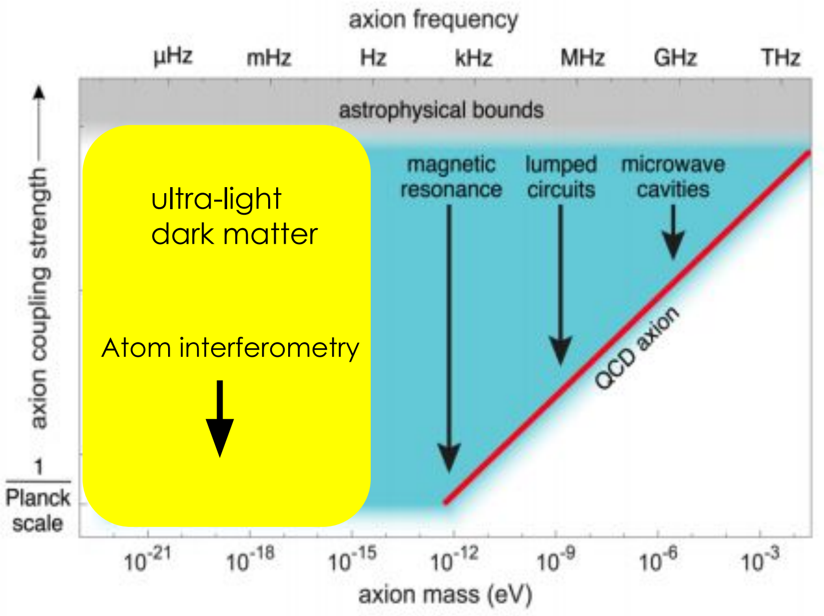
Backup

Exciting Opportunities

- **Ambitious scope** of the various proposed long-baseline atomic experiments is evidence of the enthusiasm of the community in the long-term science prospects of this technology
- The path from 10m to 100m to 1Km and space is a **long-term program** that will enable the exploitation of the **enormous physics potential of mid-band GW and ultra-light dark matter**, with outstanding opportunities for transformative advances in our understanding of the universe
- Km-scale ~$100M projects will require broad international support and National Lab resources and expertise
- **DOE involvement could lead to a LIGO-like international collaboration in ~10 years**
- **The US could become leader in this field and play key roles in the design, construction, and operation of the next generation of long-baseline atomic experiments**

Ultralight Dark Matter

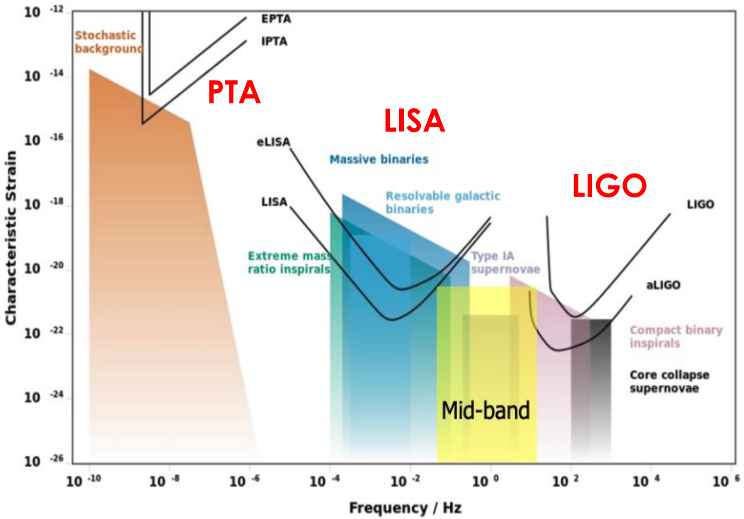
- **Elucidating the nature of dark matter is one of the most important goals in fundamental physics**
- Ultralight dark matter candidates with **$10^{-22} < m < 10^{-12}$ eV** beyond the reach of existing and planned experiments
- In this mass range, DM can be described as a classical field oscillating at a frequency equal to the mass of the dark matter



Detection of ultralight wave dark matter requires a new type of detector capable of sensing the effects of extremely small, time-dependent, low frequency waves: large-scale (quantum network) atom interferometers

Gravitational Waves

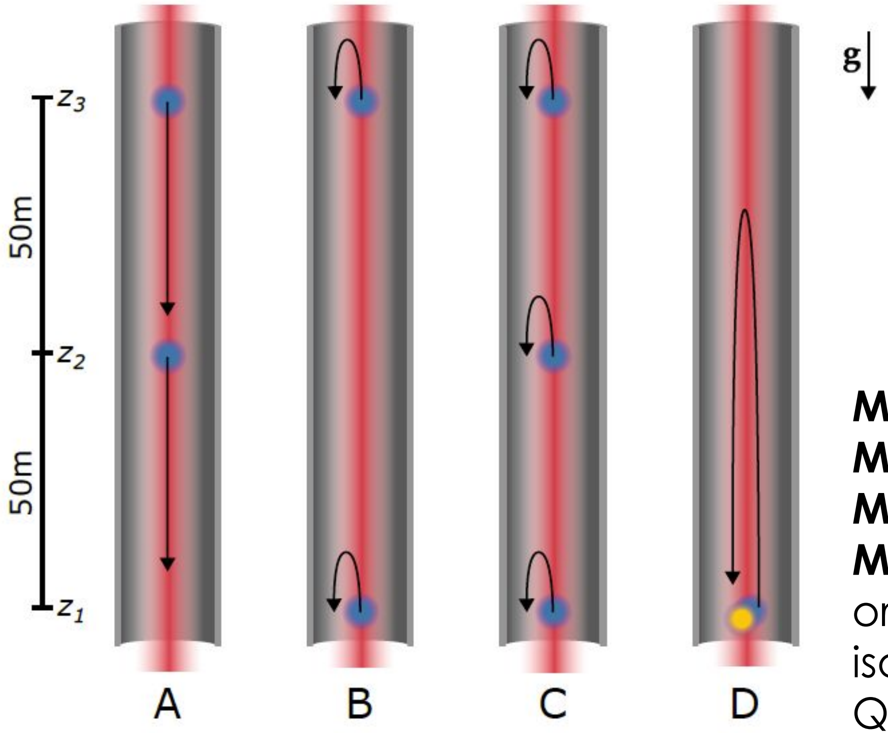
- **Gravitational waves provide an entirely new way to explore the universe**
  - Information about the early universe, back to inflation, not accessible otherwise
- 3G laser interferometer detectors over the next decade will increase sensitivity, but there is a gap in the mid-bad
- Large-scale atom interferometers **can enable the full coverage of the GW spectrum, providing sensitivity in the mid-band**



Many compelling reasons to explore the mid-band:

- Optimal for probing the highest energy scales in the early universe: inflation signals, phase transitions in the early universe beyond the reach of future colliders, cosmic strings
- IMBH mergers
- Localization: predict time and location of merger events
- BH spin and eccentricity

Four operating modes

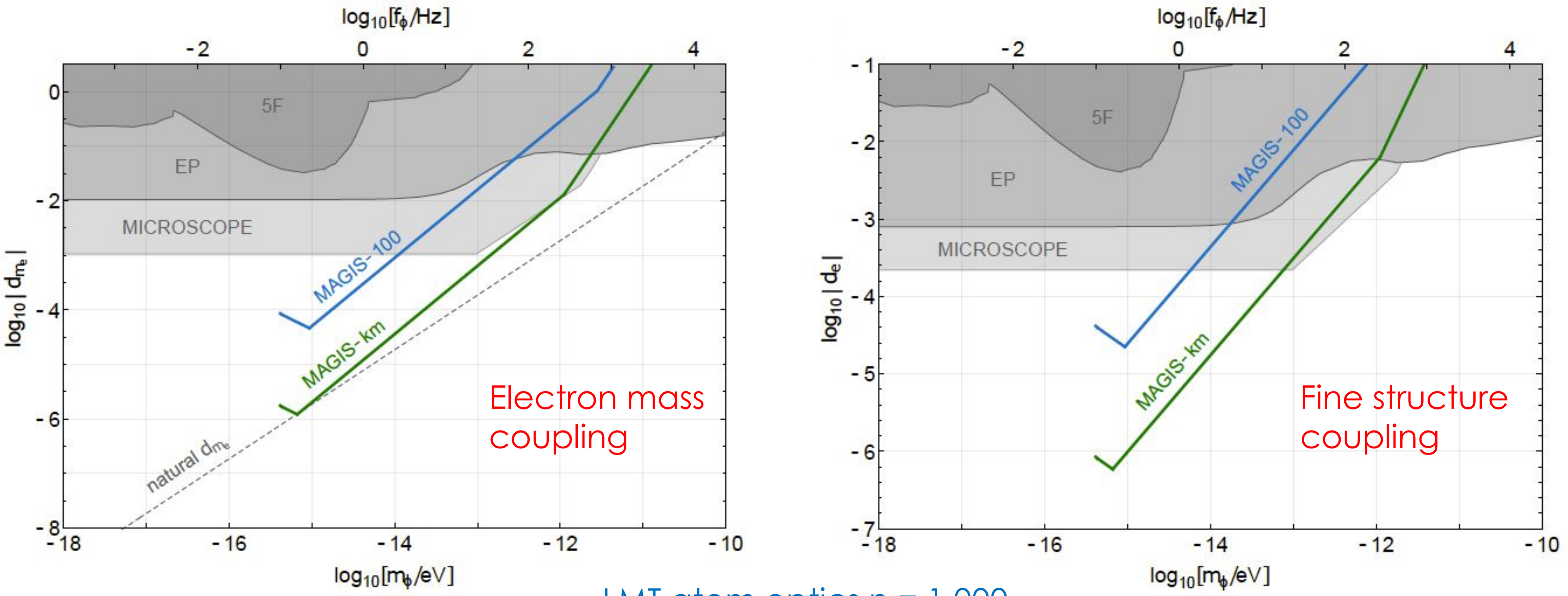


1. Preparation and launching the cold atom clouds
2. Atom interferometry
3. Atom detection: measuring the matter wave interference pattern to determine its phase.

The process is repeated periodically (several Hz), acquiring a time series of phase shift measurements which are the basis for the MAGIS-100 science

Mode A: Maximum drop time (3s) -low frequency
Mode B: Maximum baseline (100m)
Mode C: GGN characterization
Mode D: Dual isotope launch (Dark Matter Fields or new forces that couple differently to the two isotopes / Maximum possible free-fall time for Quantum measurements

Expected sensitivity



LMT atom optics n = 1,000

Ultra-light scalar dark matter:

100-meter baseline and ~1-year data taking will increase reach by many orders of magnitude

Future Opportunities

Km-scale Terrestrial Experiments	Space
• Two possible sites for Km-scale vertical setups in North America: SURF, Snolab • Achieving GW sensitivity requires significant AMO R&D and scale	• Very large (10^7m) baselines • Based on existing AMO technology • Only 2 satellites required (simpler than LISA) • No gravity gradient noise • Ultimate sensitivity

Significant R&D efforts and scale needed: Opportunity to leverage National Lab facilities and expertise in large-scale experiments

Large-scale challenges

Advanced AMO / quantum sensing challenges

Current core competences:
particle accelerator, laser, optics, HEP instrumentation

- **Large UHV systems, alignment, magnetometry, optics, calibration, …**
- **Data analysis**: disentangling multiple sources, noise/aberration corrections, 3D imaging, deep learning, discovery vs precision mode, interferometer sequence **algorithms**
- **Project management:** Future collaboration will be 10+ institutions, 100+ people, $100M+

Develop/Expand Q competences

- Cooling of atoms
- Faster laser pulses
- Operation and control of multiple atom sources
- Improve cold atom preparation cycle to support multiplexed interferometers (multiple simultaneous interferometers) to increase sampling rate and sensitivity
- **Large-scale production** of atom sources
- Advanced quantum sensing methods