AION/MAGIS-100

Jeremiah Mitchell
Valerie Gibson, Noam Mouelle, Yu Zhi

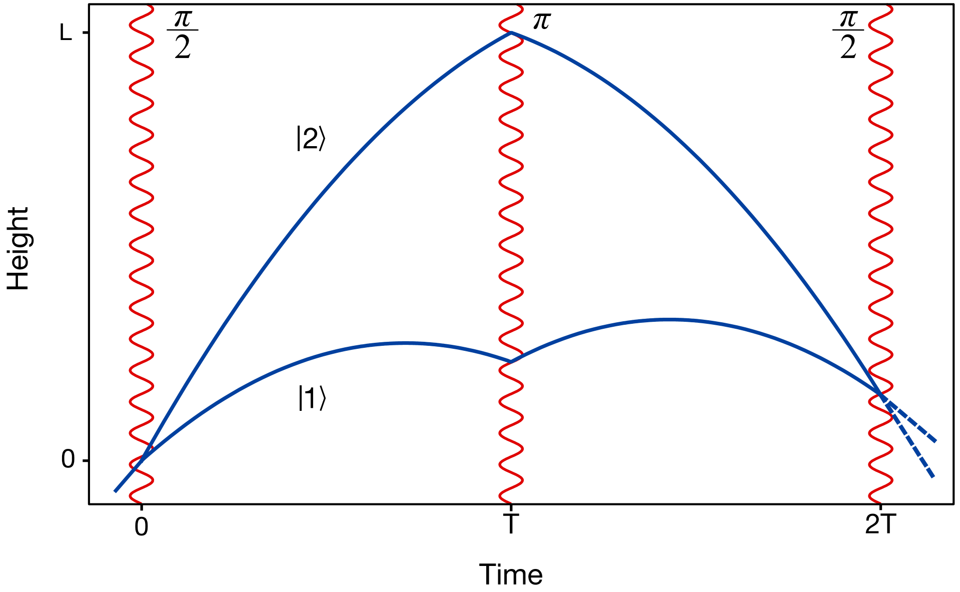
HEP Extravaganza, 6 Dec 2023

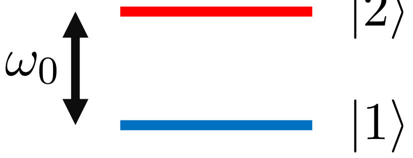
MAGIS-100 UNIVERSITY OF CAMBRIDGE AION

Overview

- What even is AION and MAGIS-100?
- What we have been up to
- Outlook

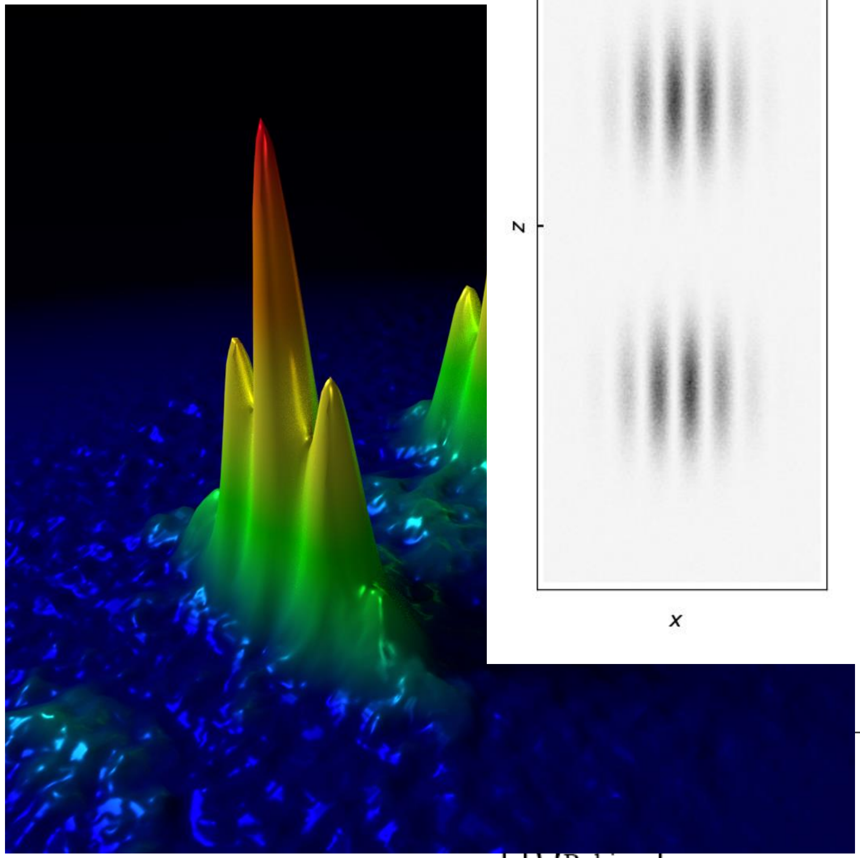
Speedy atom interferometry



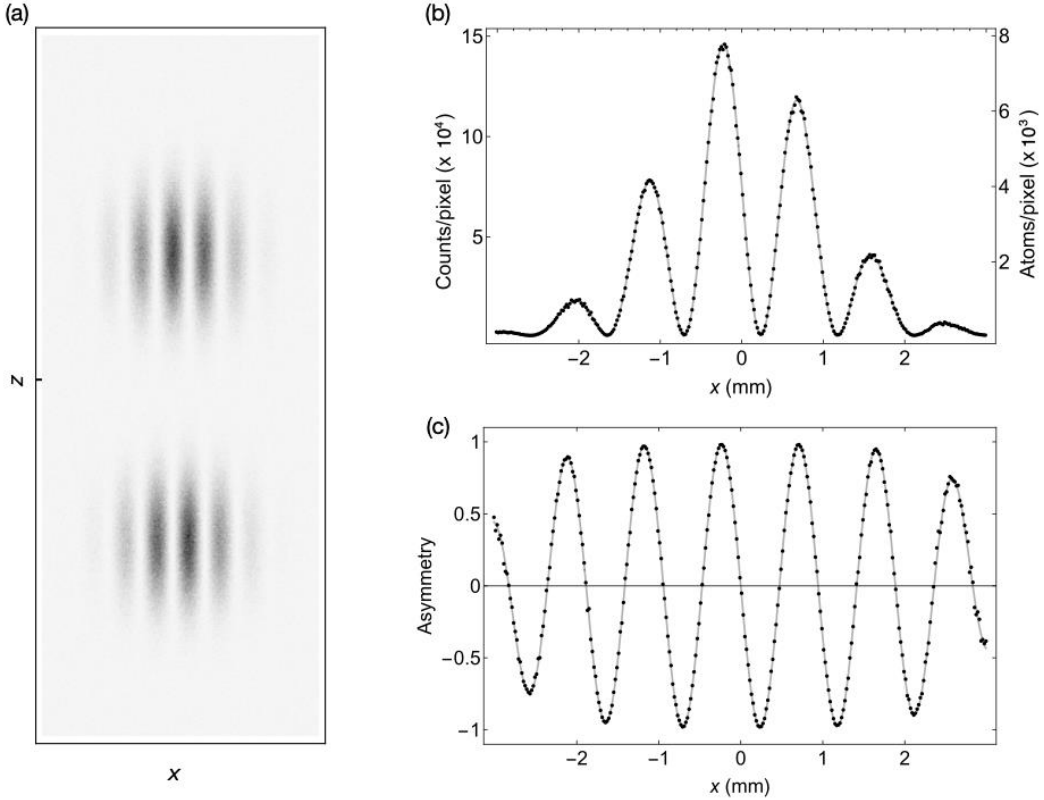


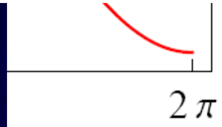
$$H_{int} = -e\mathbf{r} \cdot \mathbf{E}_0 \cos(\phi - \omega_0 t)$$

$$\Omega_{1,2} = -\frac{\langle 1|e\mathbf{r} \cdot \mathbf{E}|2\rangle}{\hbar}$$



Simulation (MAGIS-100)
M. Abe *et al*, Quantum Sci. Technol. **6** 044003 (2021)





Science case

Ultralight scalar dark matter → high density, wave-like characteristics

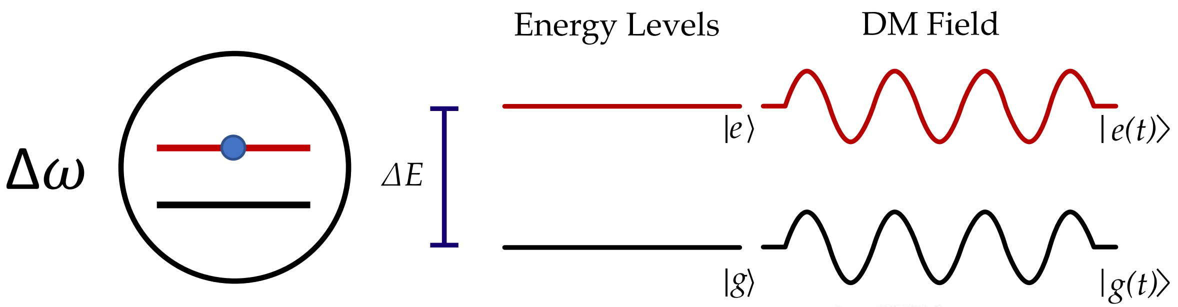
$$\mathcal{L}_\phi \supset \phi(t)\sqrt{4\pi G_N}\left[\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - d_{m_e} m_e \overline{\psi}_e \psi_e\right]$$

Photon Couplings

Electron Mass Couplings

Science case

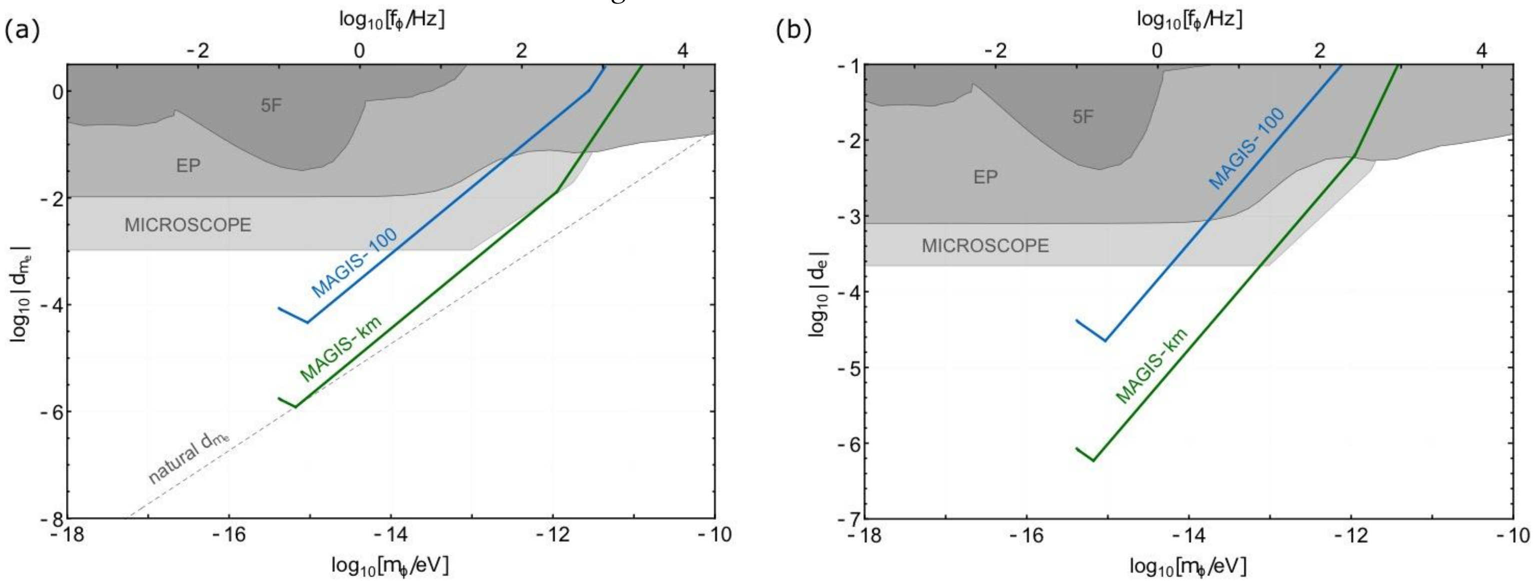
Time varying atom transition frequency



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

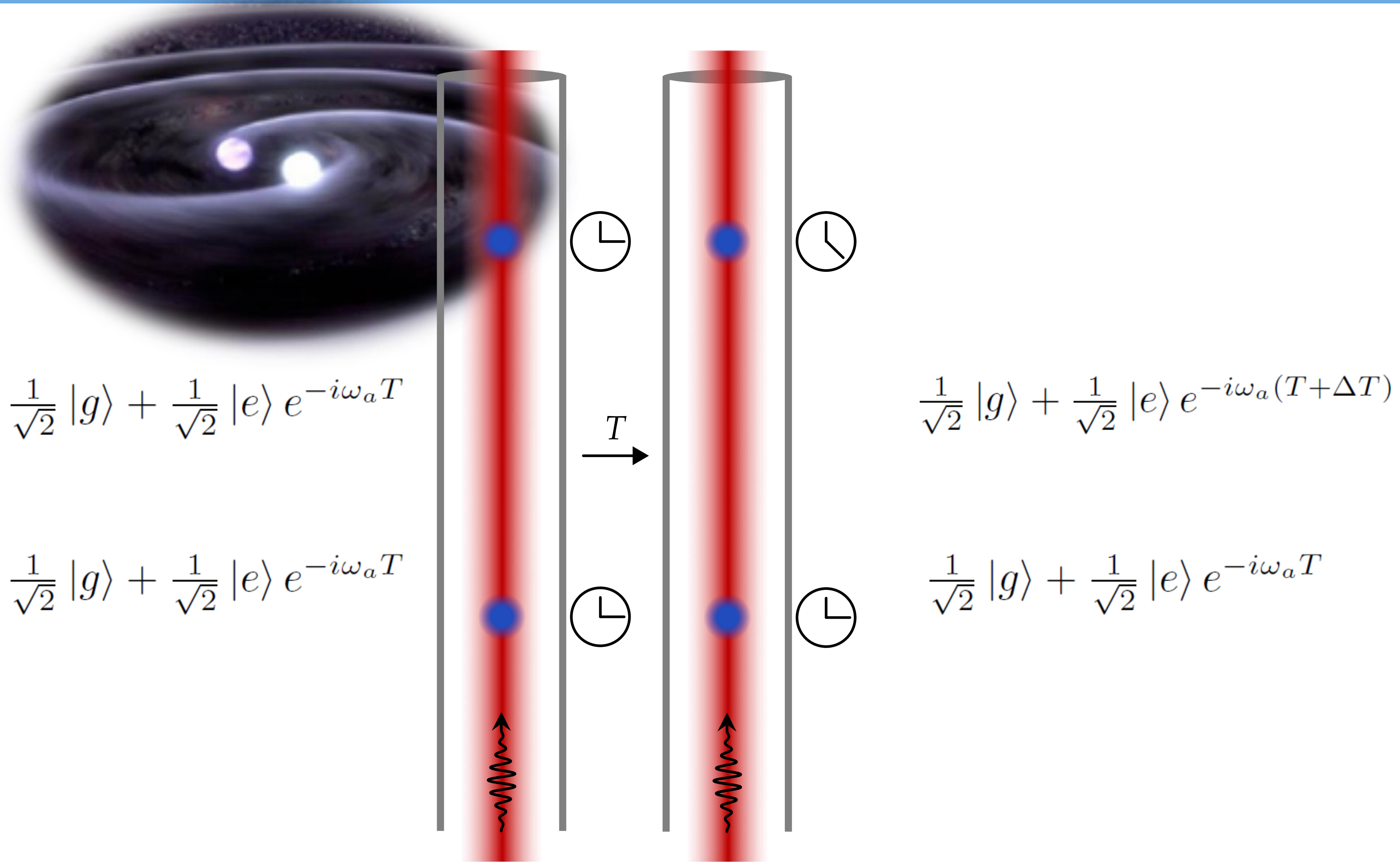
Dark Matter $\delta\omega_A$

Gravitational Waves $\delta L = hL$

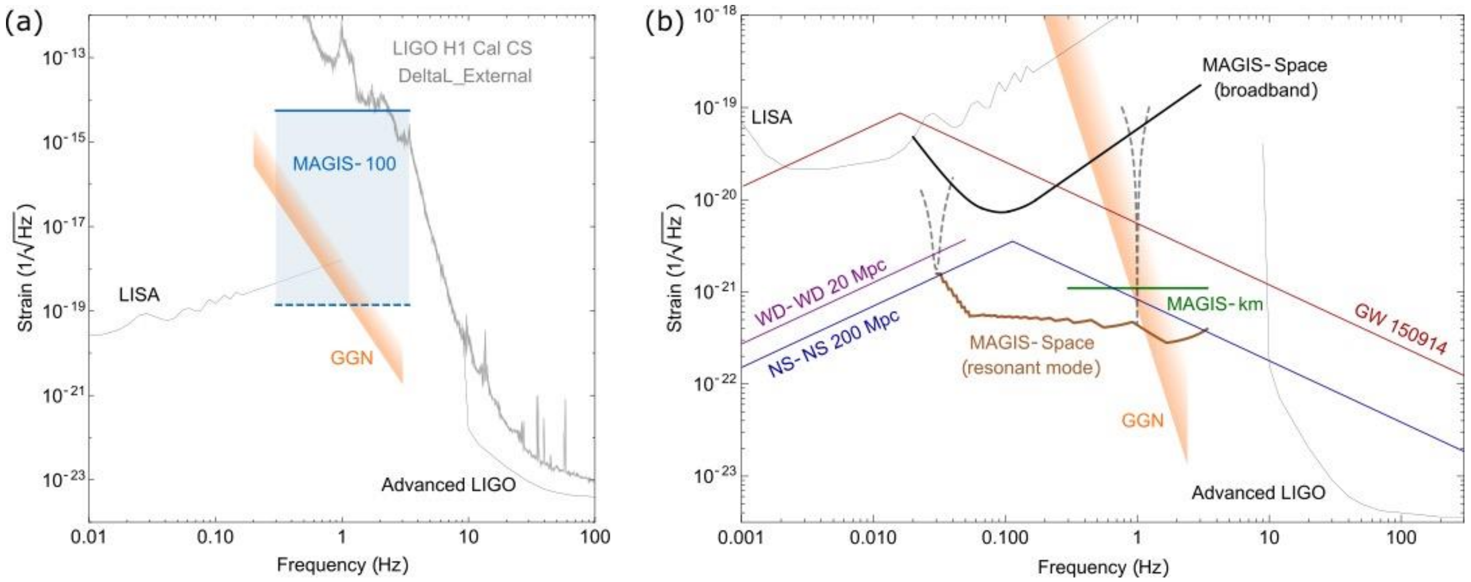


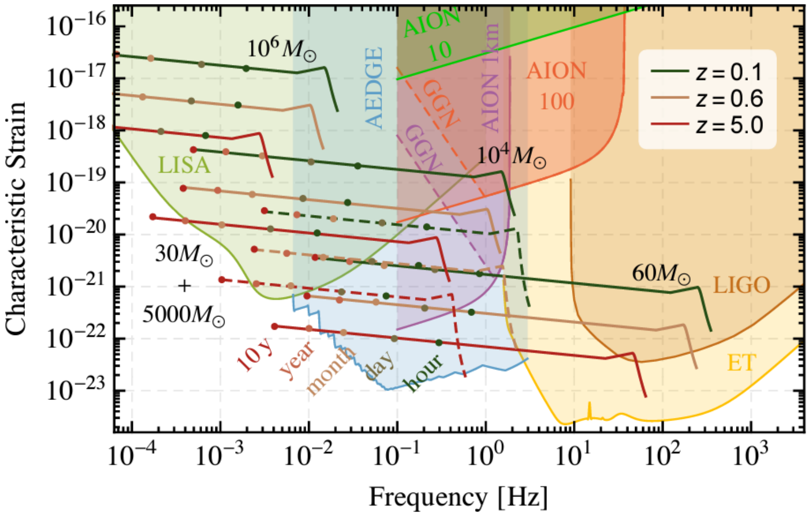
M. Abe *et al.*, *Quantum Sci. Technol.*, **6**, 4, 2021.

Science case



Science case



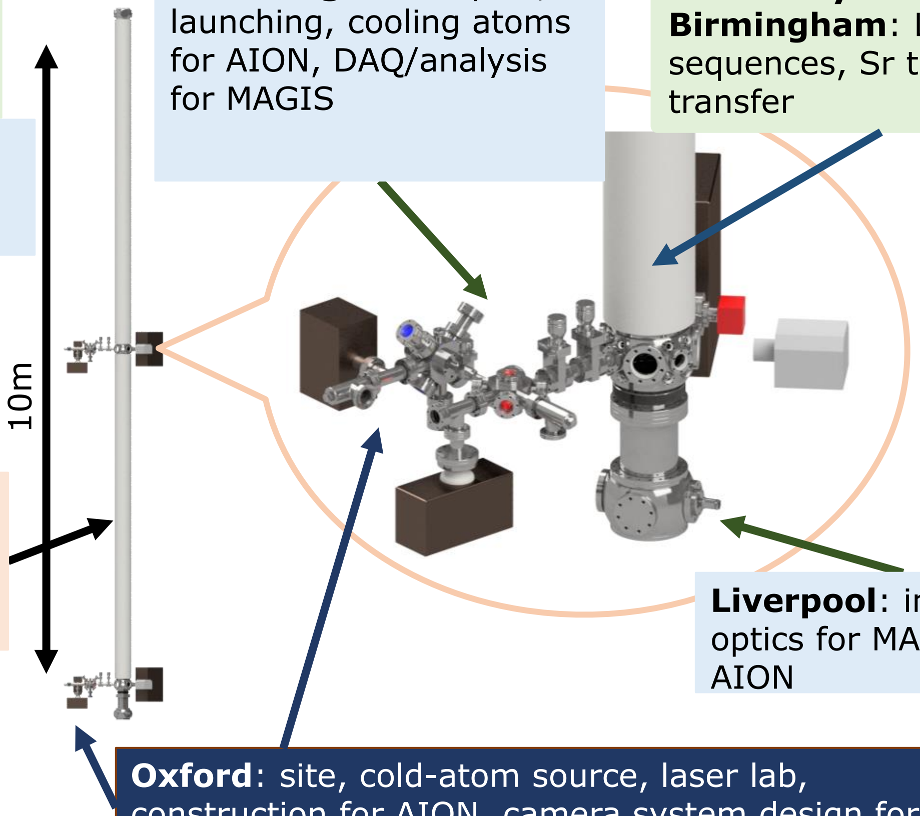


J. Cosmol. Astropart. Phys. **5**, 011 (2020)

AION

Atom **I**nterferometer **O**bservatory and **N**etwork

- UK consortium of 7 institutions
- Develop ultracold strontium laboratories in parallel
- Staged project for increased baseline atom interferometers 10m -> 100m -> 1km
- Investigate technology development and network with MAGIS-100 for large scale science goals



AION

L. Badurina *et al* JCAP05(2020)011

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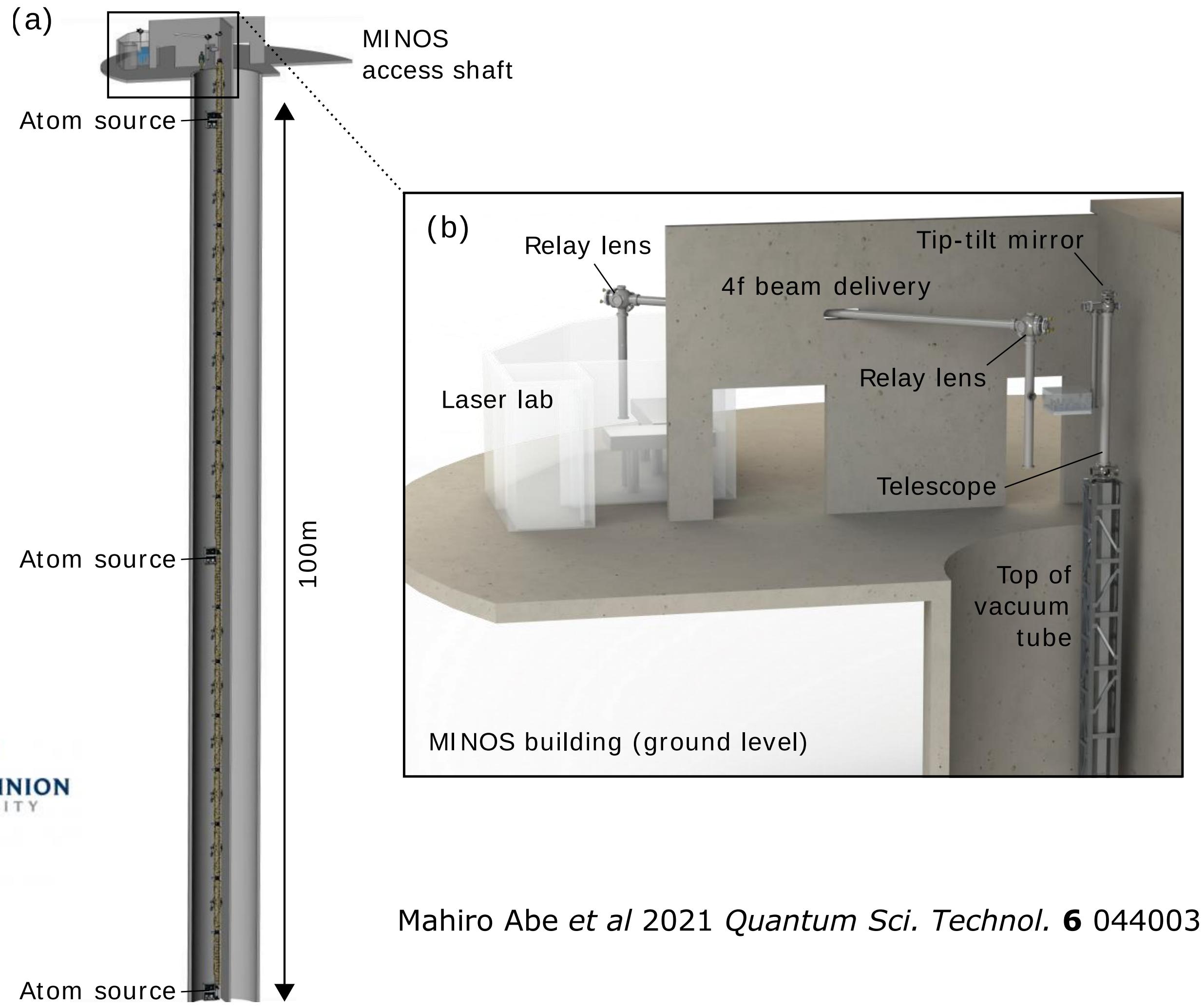
MAGIS-100

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

MAGIS-100

- Long-baseline atom interferometer being built at Fermilab US
- 3 strontium atom sources along vertical baseline
- Test bed experiment for simultaneous atom interferometer control
- Prototype 10m device at Stanford



Mahiro Abe *et al* 2021 *Quantum Sci. Technol.* **6** 044003

STANFORD · Johns Hopkins University · Northwestern University · Fermilab · SLAC · Old Dominion University · University of Cambridge · Northern Illinois University · University of Oxford · University of Liverpool

University of Cambridge

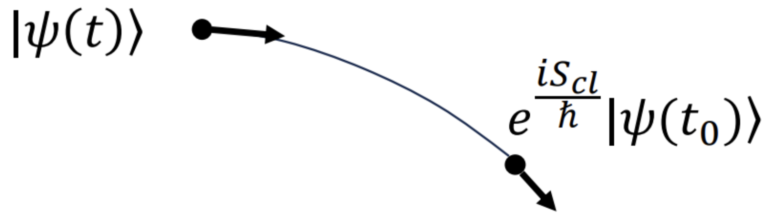
Cambridge activities

- Data acquisition, monitoring, and control
  - Hardware and software for control systems
  - Environmental monitoring
  - Computing infrastructure
- Simulations and data analysis
  - Matter-wave simulations, systematics
  - Offline coordination for MAGIS-100
- AION and MAGIS-100 timing and data synchronization

Matter-wave simulations

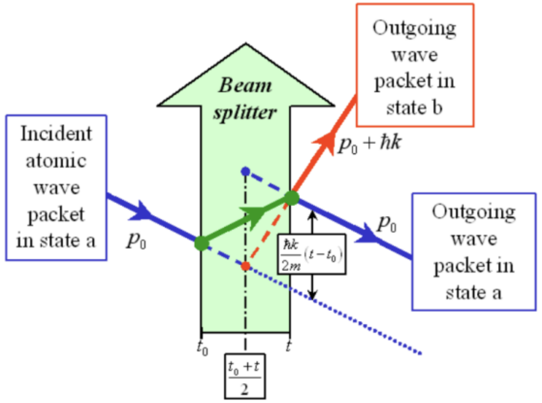
Recap: 3-pulse sequence on on thermal cloud

Simulation of a thermal/diffuse cloud using an ensemble of Gaussian wavepackets (10^5 atoms, 15nK, 1cm)



Allows the use of

- the semi-classical approach[2] for free propagation
- the *ttt*-scheme[3] for atom-laser interactions



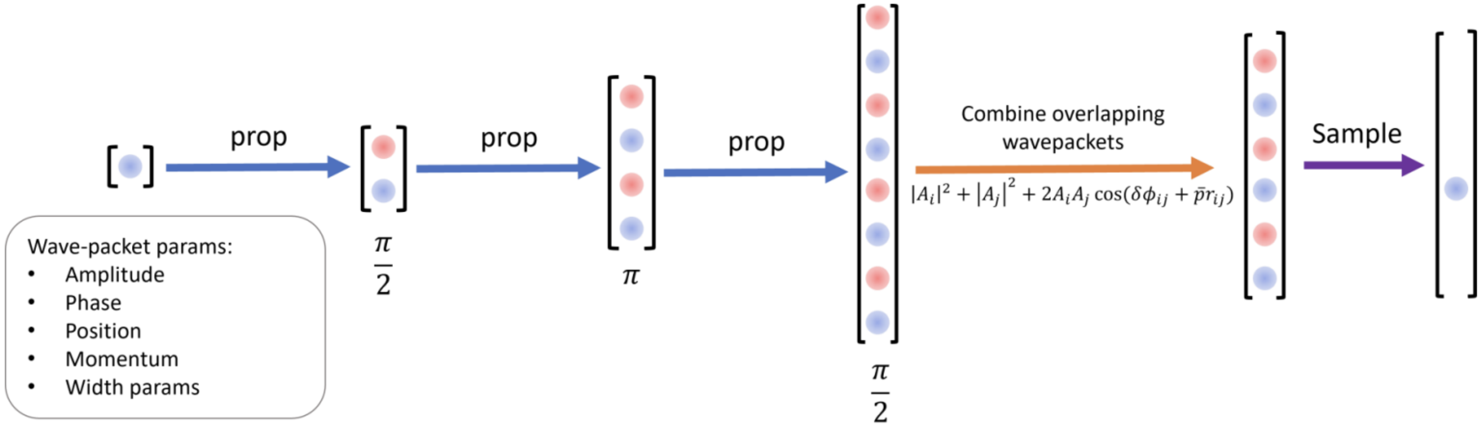
Noam Mouelle's work

Matter-wave simulations

Recap: 3-pulse sequence on on thermal cloud

Code specs:

- Python
- Wavepacket params stored in $N_{atoms} \times N_{paths} \times N_{dim}$ Numpy arrays, allowing the use of vectorization

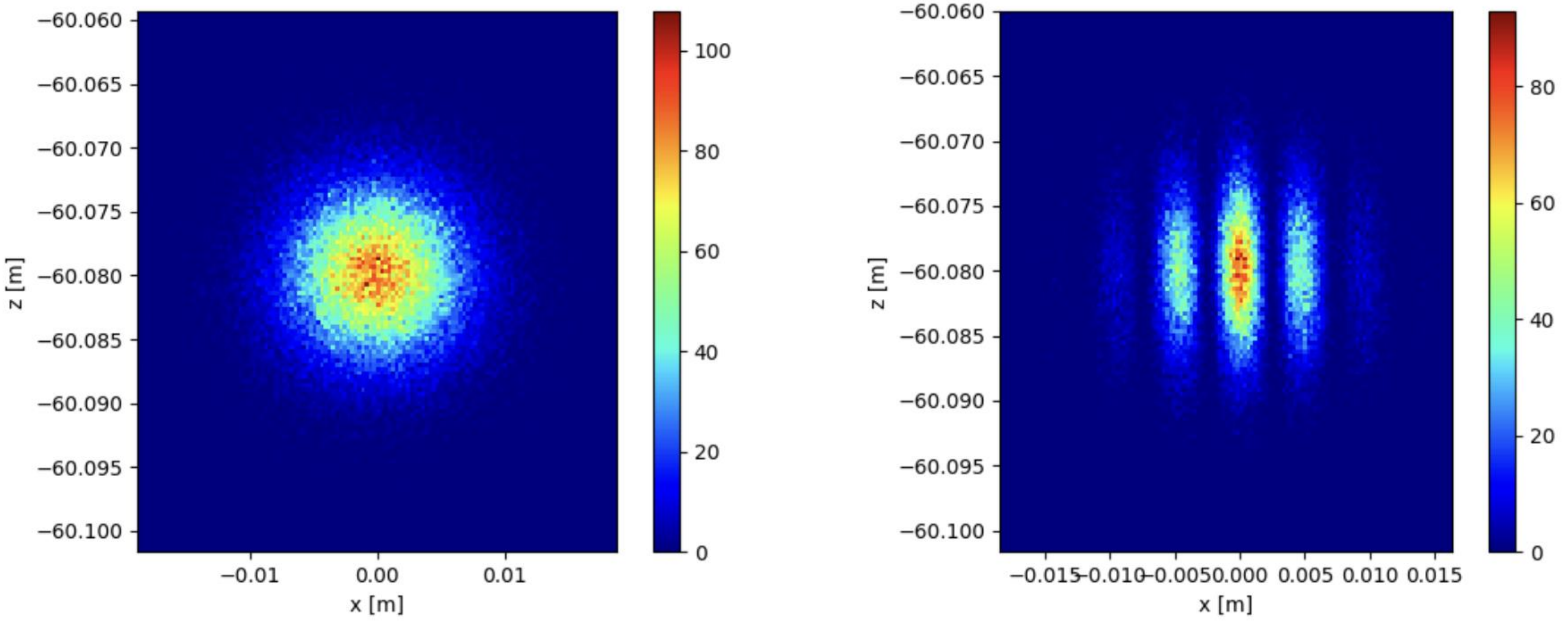


Noam Mouelle's work

Matter-wave simulations

Recap: 3-pulse sequence on on thermal cloud

Binned distributions



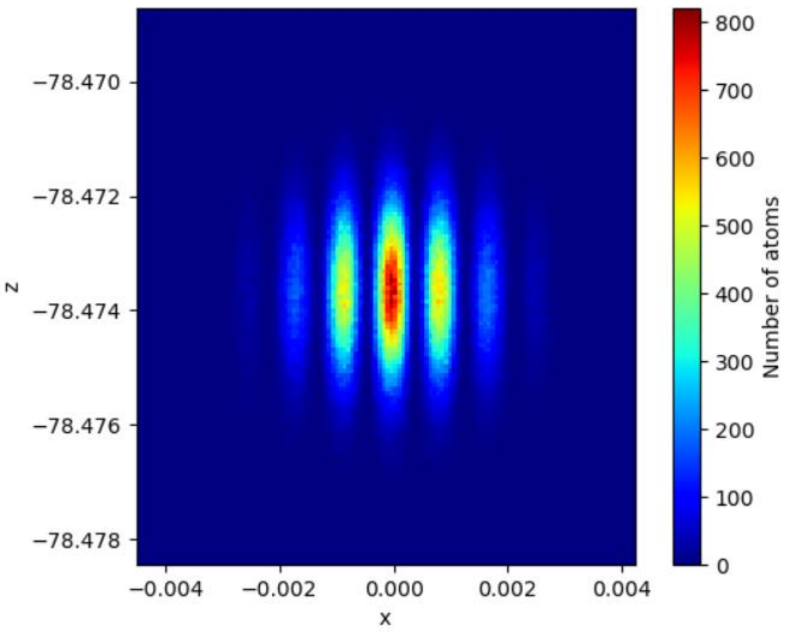
Noam Mouelle’s work

Matter-wave simulations

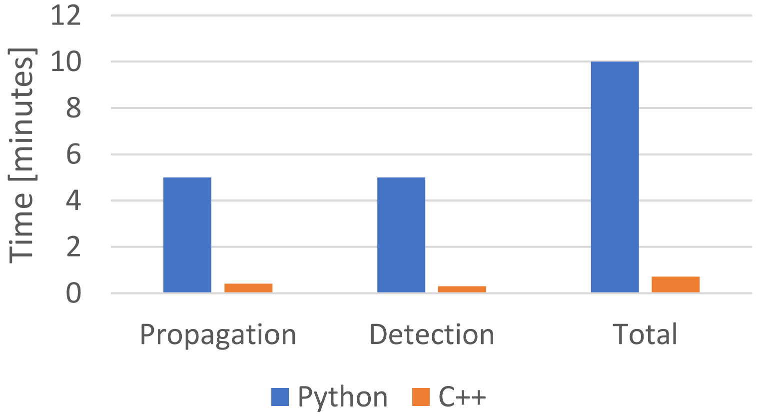
- Developing a MC simulation of atom cloud propagation:
    - Laser wavefront aberration
    - Non-uniform phase-shifts (gravity gradients etc.)

- Recently moved from Python prototype to C++

- Hope to focus on inference of phase shift from images



Simulation time, 1 million atoms, 3 pulse sequence



Noam Mouelle’s work

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Bayesian inference for atom interferometry

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Bayesian Inference (Python)

$$p(\theta|d,M) = \frac{p(d|\theta,M)\,p(\theta|M)}{p(d|M)} = \frac{L(\theta)\,\pi(\theta)}{Z}$$

θ: parameter

$p(\theta|d,M)$: posterior

Simulation → d: data

$L(\theta)$: likelihood

Waveform/DM Field, etc. → M: model

$\pi(\theta)$: prior

Bilby: arXiv:1811.02042

Yu Zhi's work

Bayesian inference for atom interferometry

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Post-Newtonian Gravitational Waves (Inspiral)

$$\tilde{h}(f) = \sqrt{\frac{5}{96}} \frac{\sqrt{A_+^2 F_+^2 + A_\times^2 F_\times^2}}{D_L} \pi^{-2/3} \mathcal{M}_z^{5/6} f^{-7/6} e^{i\Psi(f)}$$

$$\Psi(f) = 2\pi f t_c - \varphi_c - \frac{\pi}{4} + \frac{3}{128}(\pi \mathcal{M}_z f)^{-5/3} - \varphi_P - \varphi_D + \ldots$$

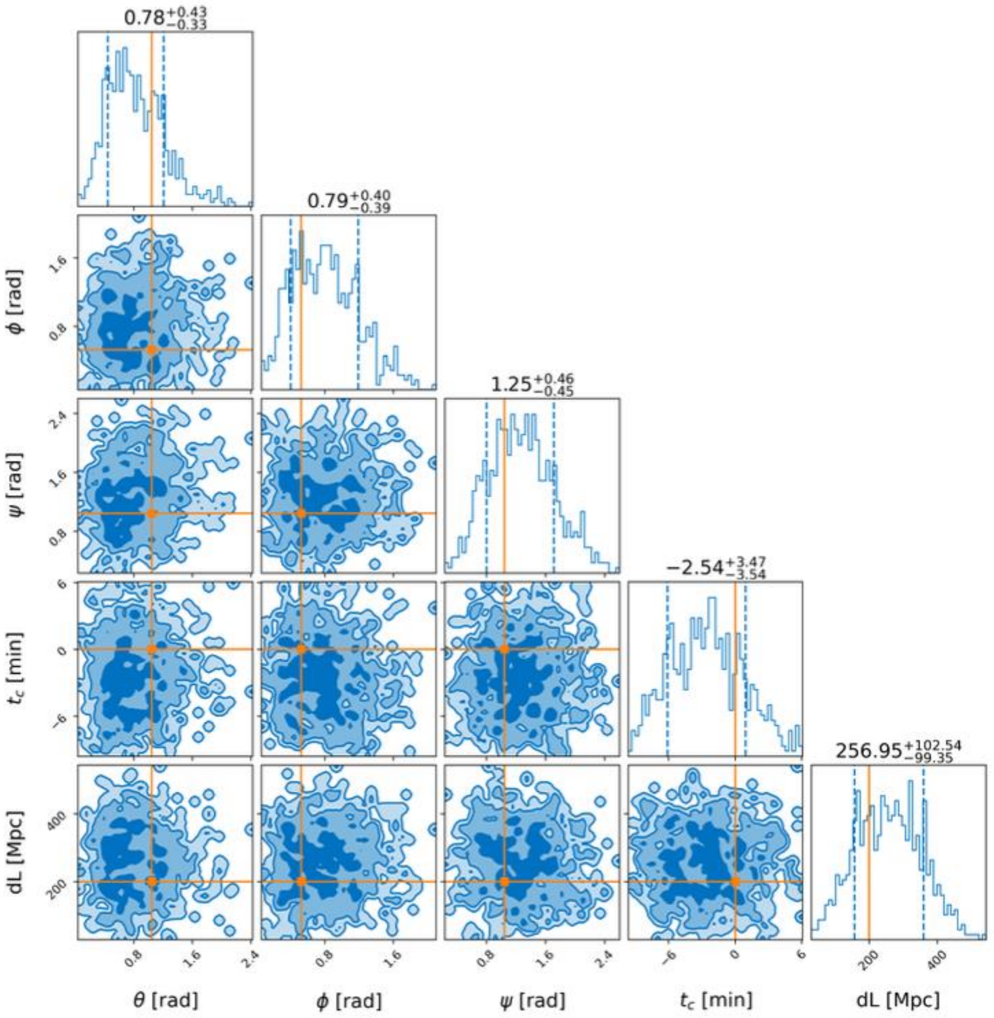
$$\vec{\theta} = \{m_\mu, m_{chirp}, \sqrt{\ }, \varphi, \ , dL\}$$

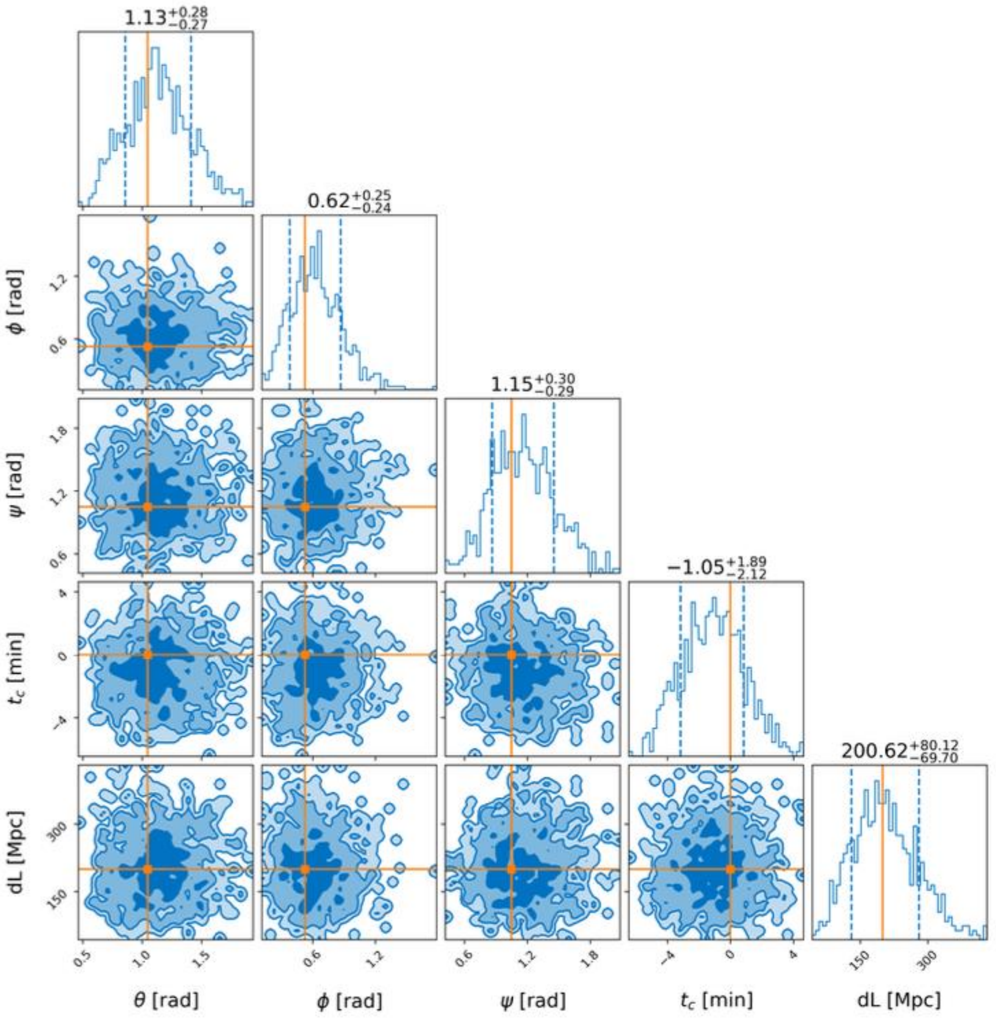
$$d_j = h_j + n_j$$

Gaussian noise given by PSD: $\sigma_j^2 \propto \frac{1}{2\Delta f} P_n(f)$

Yu Zhi's work

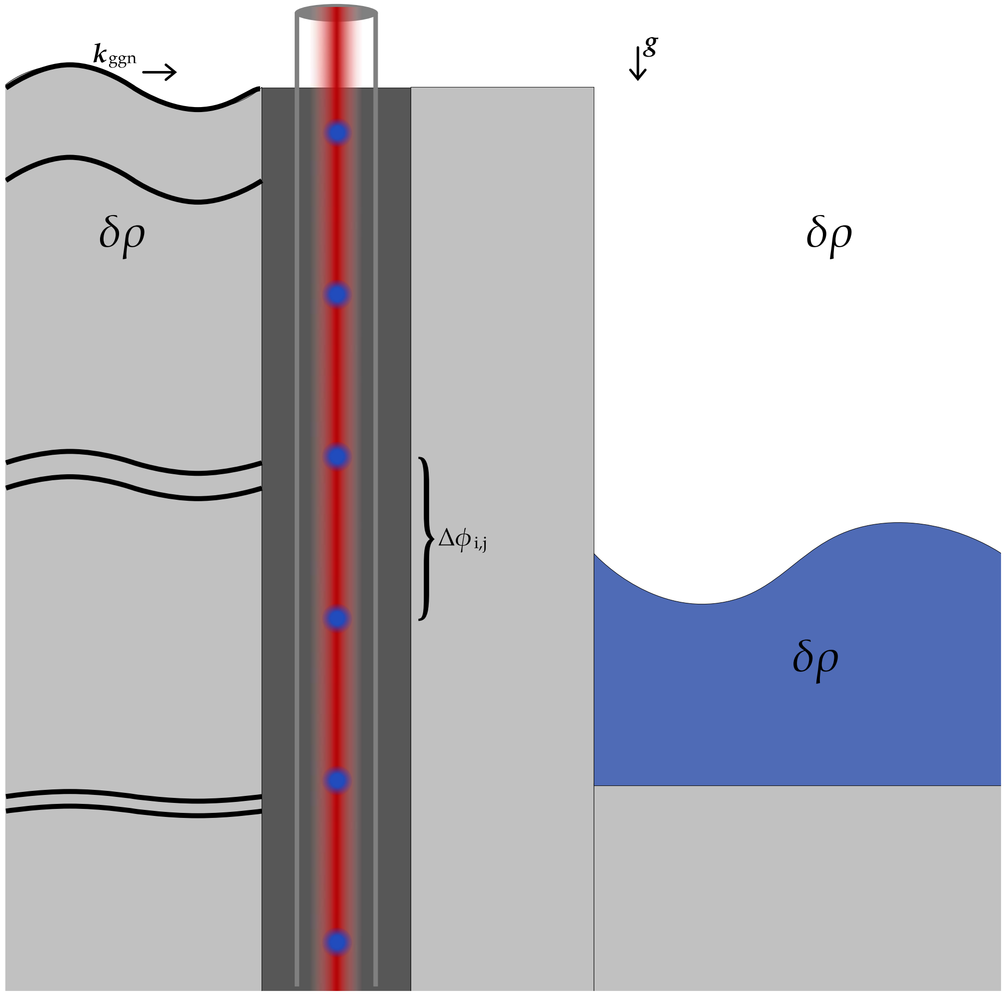
Bayesian inference for atom interferometry

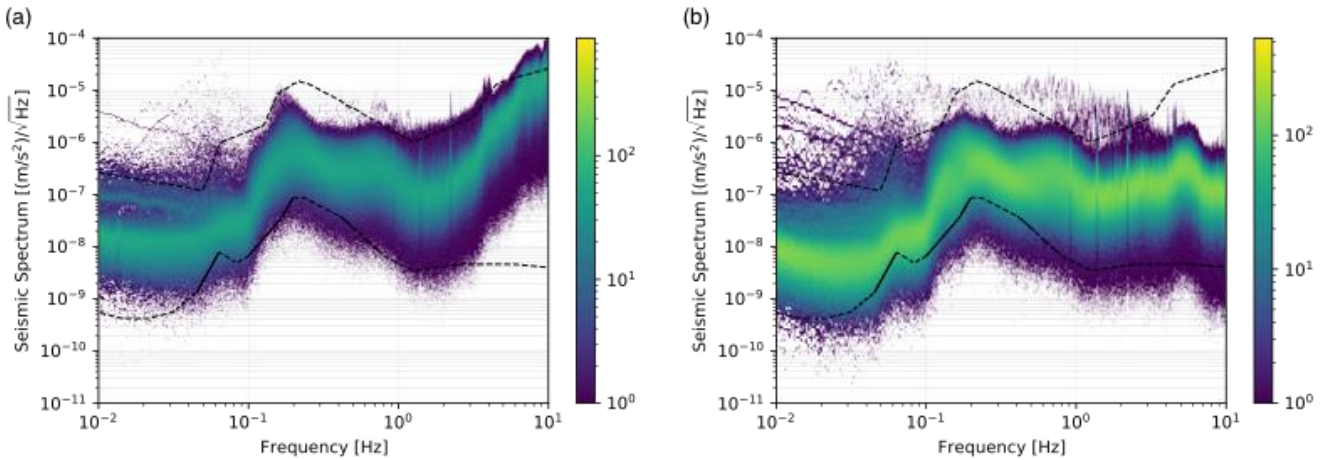


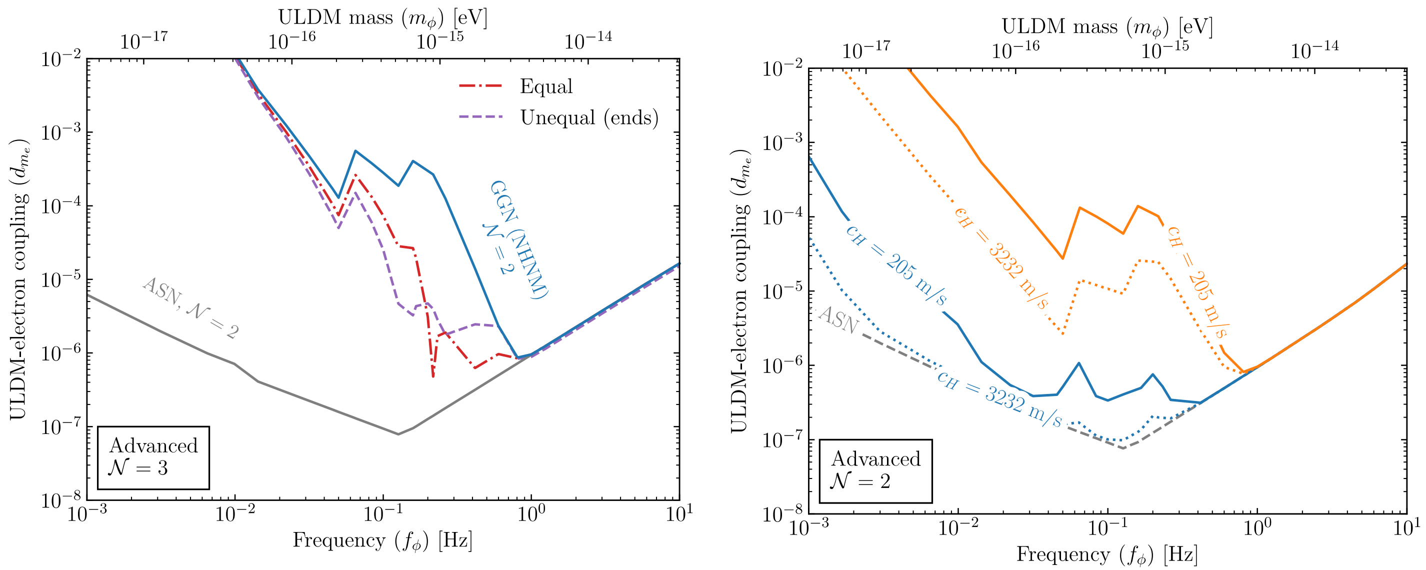


Yu Zhi's work

Environmental noise impacts







J. Mitchell *et al.*, *J. Inst.*, vol. 17, 01, 2022.

Badurina, et al. Phys. Rev. D **107**, 055002

Workshops

- 27 in-person, 10 remote
- International members of earth science (seismologists, atmospheric, geophysics)
- International members of atom interferometry (AION, MAGIS-100, Hannover)
- UKRI funding representatives from NERC and STFC
- Commercial representative from Güralp
- Tutorials from both sides
- Small group discussions

UKRI Natural Environment Research Council

UKRI Science and Technology Facilities Council

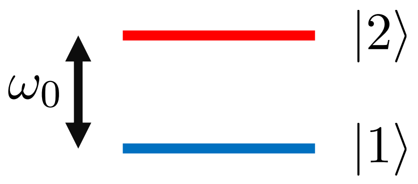
Summary and outlook

- A lot of work in support of AION and MAGIS-100
- Looking forward to hardware and software contributions
- Simulation work making excellent progress
- Closer integration with Cambridge AMO group

Backups

Atom optics

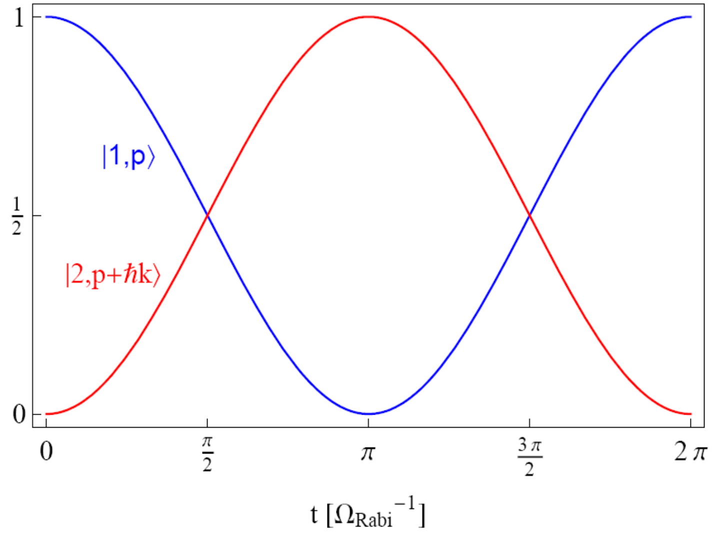
- Two-level system in electromagnetic field



$$|\psi(t)\rangle = c_1(t)\,|1\rangle + c_2(t)\,|2\rangle$$

$$c_1(t) = c_1(0)\cos(\Omega t/2) - ie^{-i\phi}c_2(0)\sin(\Omega t/2)$$
$$c_2(t) = -ie^{-i\phi}c_1(0)\sin(\Omega t/2) + c_2(0)\cos(\Omega t/2)$$

$$\left\|c_1(t)^2\right\| = \cos^2(\Omega t/2)$$
$$\left\|c_2(t)^2\right\| = \sin^2(\Omega t/2)$$



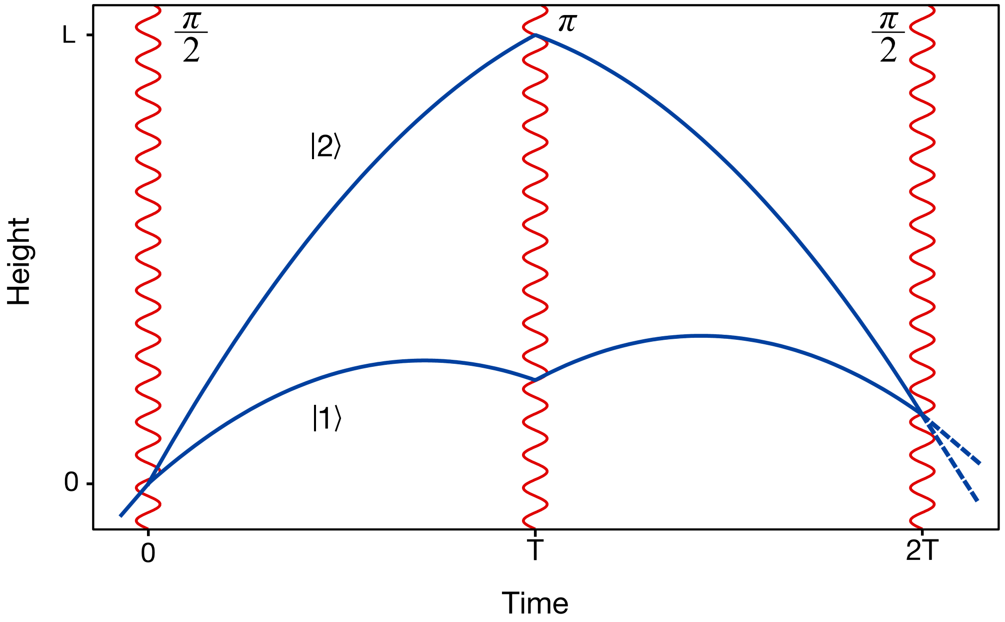
- Beamsplitters, $\pi/2$-pulse

$$|1\rangle \rightarrow \frac{1}{\sqrt{2}}(|1\rangle - ie^{i\phi}\,|2\rangle)$$

- Mirrors, π-pulse

$$|1\rangle \rightarrow -ie^{i\phi}\,|2\rangle$$

Atom interferometry



Phase Shift

$$\Delta\phi = \Delta\phi_{\text{laser}} + \Delta\phi_{\text{propagation}} + \Delta\phi_{\text{separation}}$$

$$\Delta\phi_{\text{laser}} = \sum_{j}^{\text{upper}} \pm\phi_L(t_j, \mathbf{x}_u(t_j)) - \sum_{j}^{\text{lower}} \pm\phi_L(t_j, \mathbf{x}_l(t_j))$$

$$\Delta\phi_{\text{propagation}} = \sum_{\text{upper}} \left(\int_{t_i}^{t_f} (L_c - E_i)\,\mathrm{d}t\right) - \sum_{\text{lower}} \left(\int_{t_i}^{t_f} (L_c - E_i)\,\mathrm{d}t\right)$$

$$\Delta\phi_{\text{separation}} = \langle\mathbf{p}\rangle \cdot \Delta\mathbf{x}$$

Leading order phase shift

$$\Delta\phi = kgT^2$$