AION:

Atom Interferometer Observatory & Network

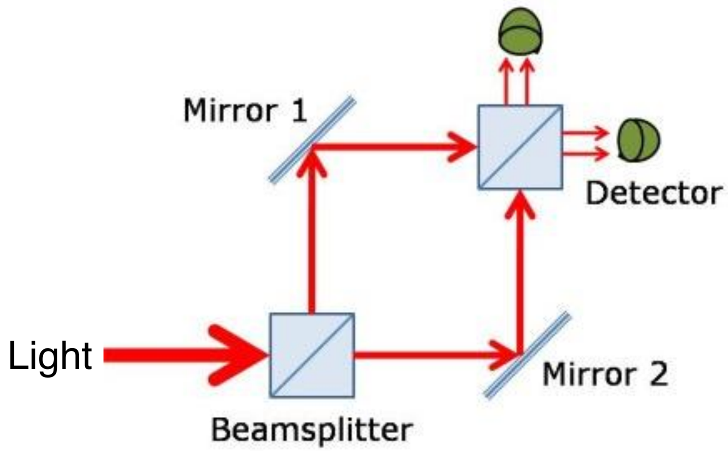
- **Lecture 1:**
  - Principles of atom interferometers
  - AION project
  - Search for ultralight dark matter
  - Quantum technology for fundamental physics
- **Lecture 2:**
  - Measurements of gravitational waves
  - Probes of fundamental physics, astrophysics & cosmology
  - STE-QUEST

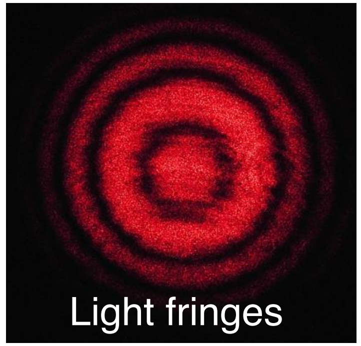
John Ellis

KING'S College LONDON

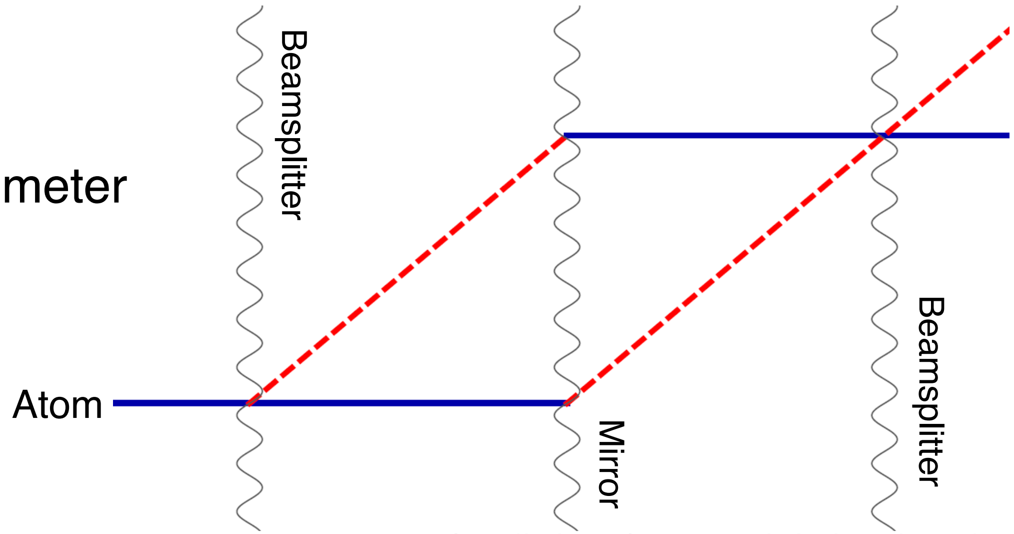
Principle of Atom Interferometry

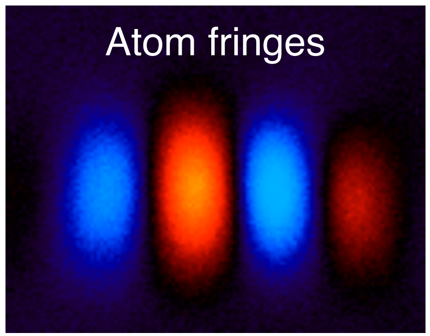
Light interferometer





Atom interferometer

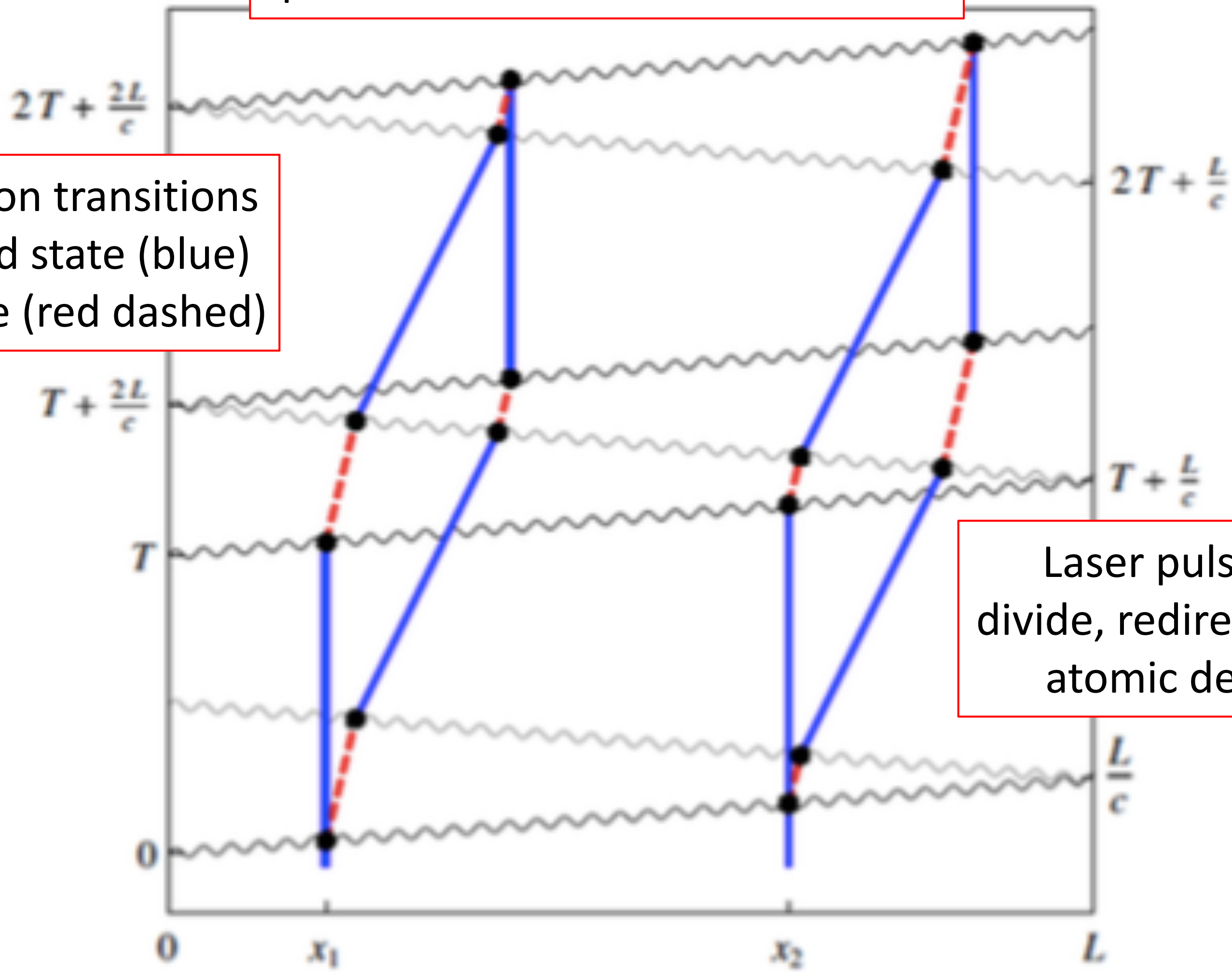




http://scienceblogs.com/principles/2013/10/22/quantum-erasure/
http://www.cobolt.se/interferometry.html

Principle of Atom Interferometry

Space-time diagram of operation of pair of cold-atom interferometers



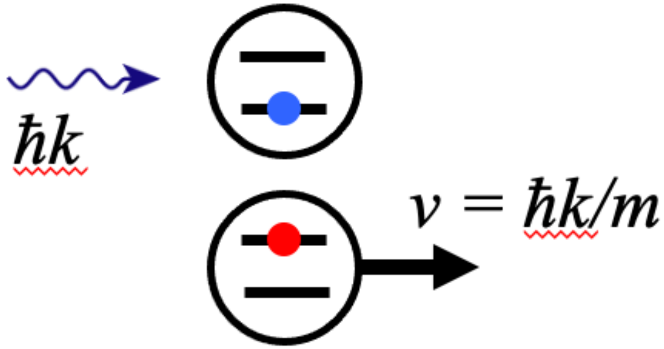
Use single-photon transitions between ground state (blue) and excited state (red dashed)

Laser pulses (wavy lines) divide, redirect, and recombine atomic de Broglie waves

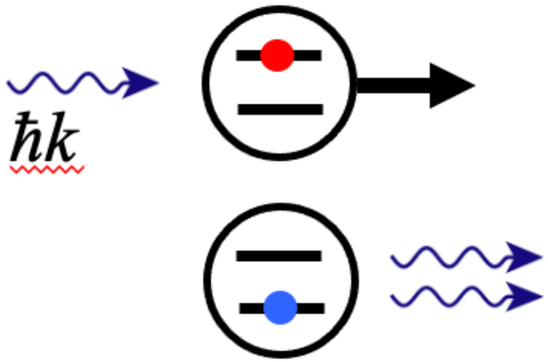
Interference patterns sensitive to interactions with dark matter & modulation of light travel time caused by GWs

Optics for Atom Interferometry

(1) Light absorption:

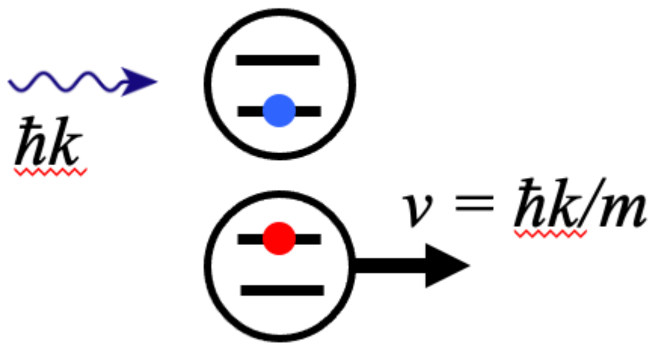


(2) Stimulated emission:

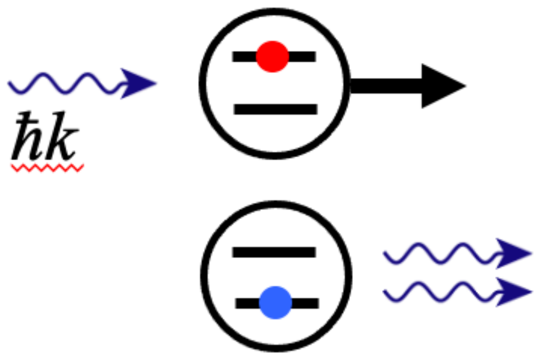


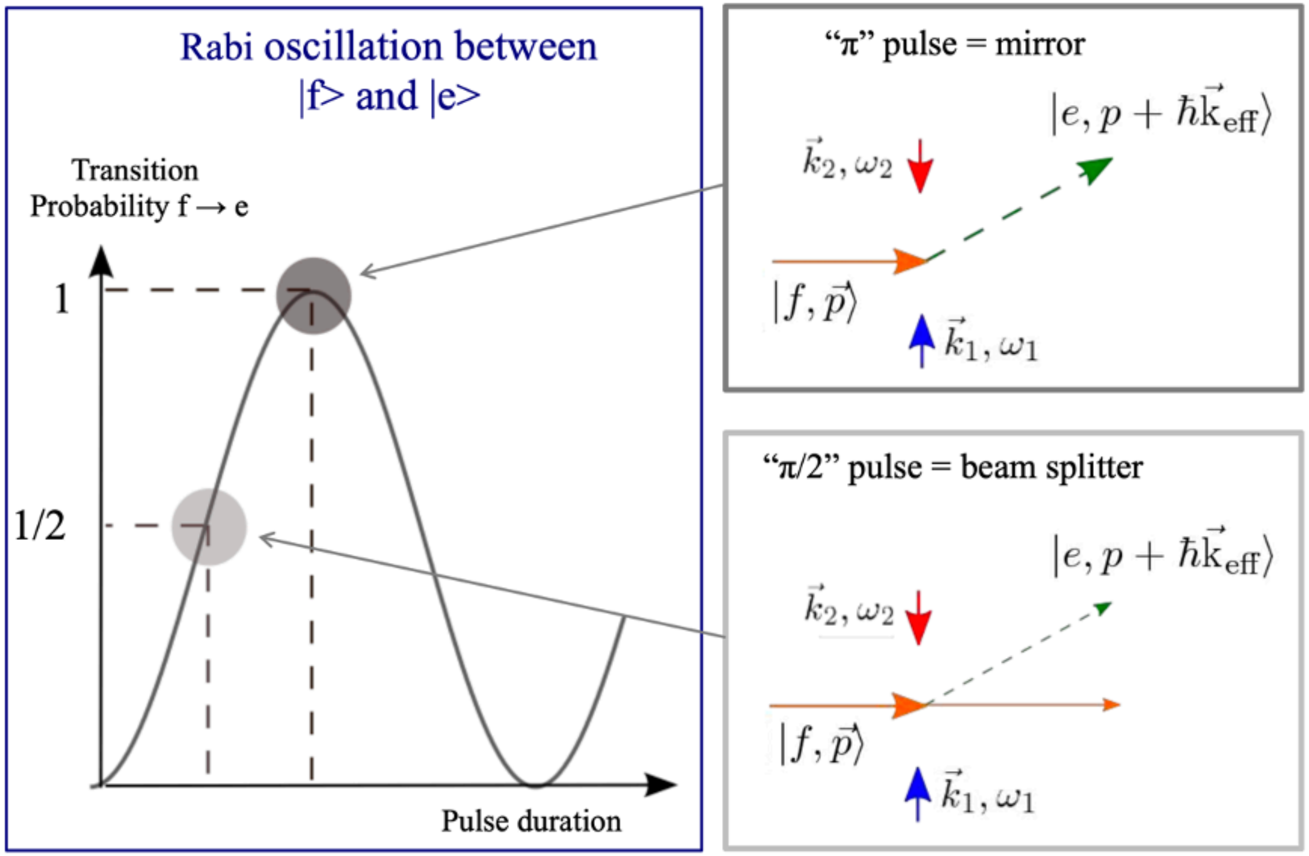
Optics for Atom Interferometry

(1) Light absorption:



(2) Stimulated emission:





Optics for Atom Interferometry

$$|\text{atom}\rangle = |p\rangle$$

π/2 pulse "beamsplitter"

$$\frac{1}{\sqrt{2}}(|p\rangle + e^{i\Delta\phi}|p + \hbar k\rangle)$$

π pulse "mirror"

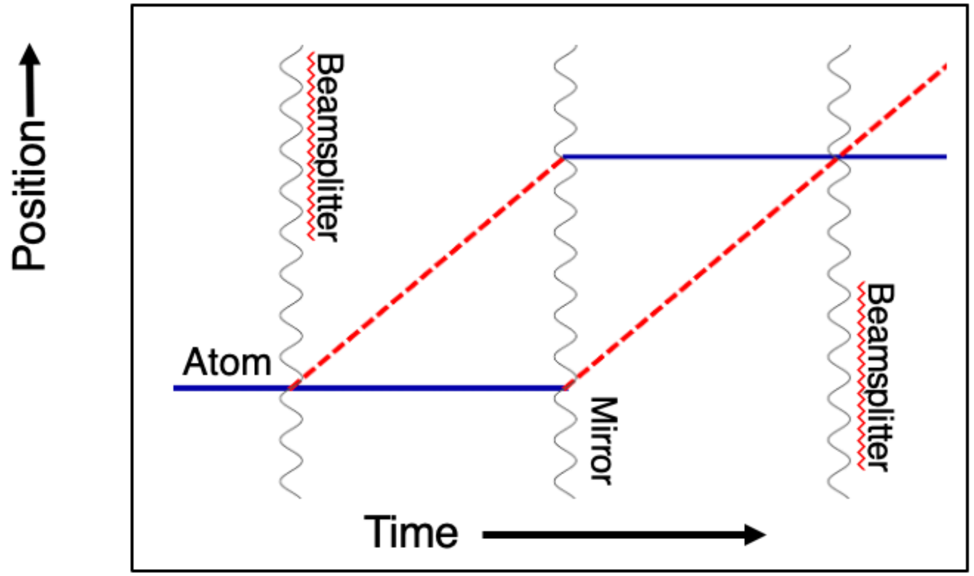
$$\frac{1}{\sqrt{2}}(|p + \hbar k\rangle + e^{i\Delta\phi}|p\rangle)$$

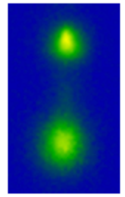
π/2 pulse "beamsplitter"

$$\frac{1}{2}((1 + e^{i\Delta\phi})|p\rangle + ((1 - e^{i\Delta\phi}))|p + \hbar k\rangle)$$

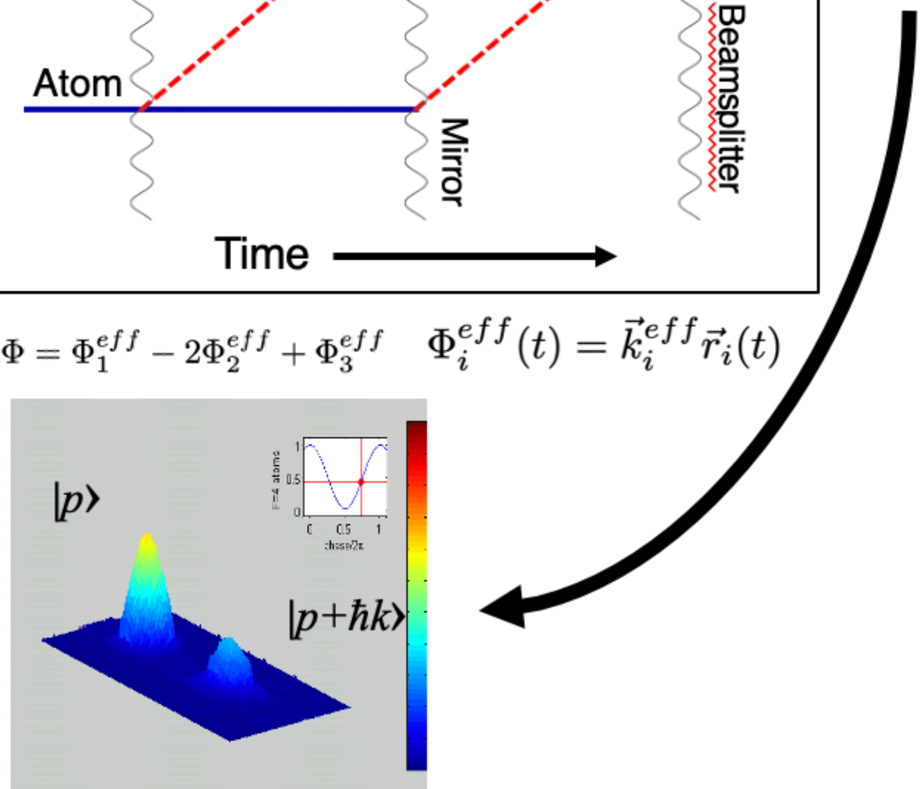
$$\text{Probability in State } |p\rangle = \cos^2\left(\frac{\Delta\phi}{2}\right)$$

$$\text{Probability in State } |\hbar k + k\rangle = \sin^2\left(\frac{\Delta\phi}{2}\right)$$

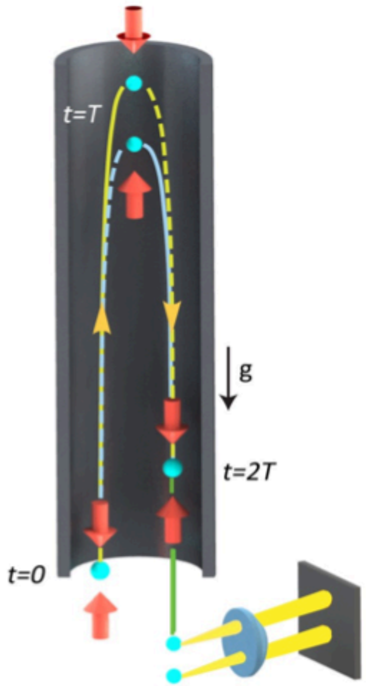


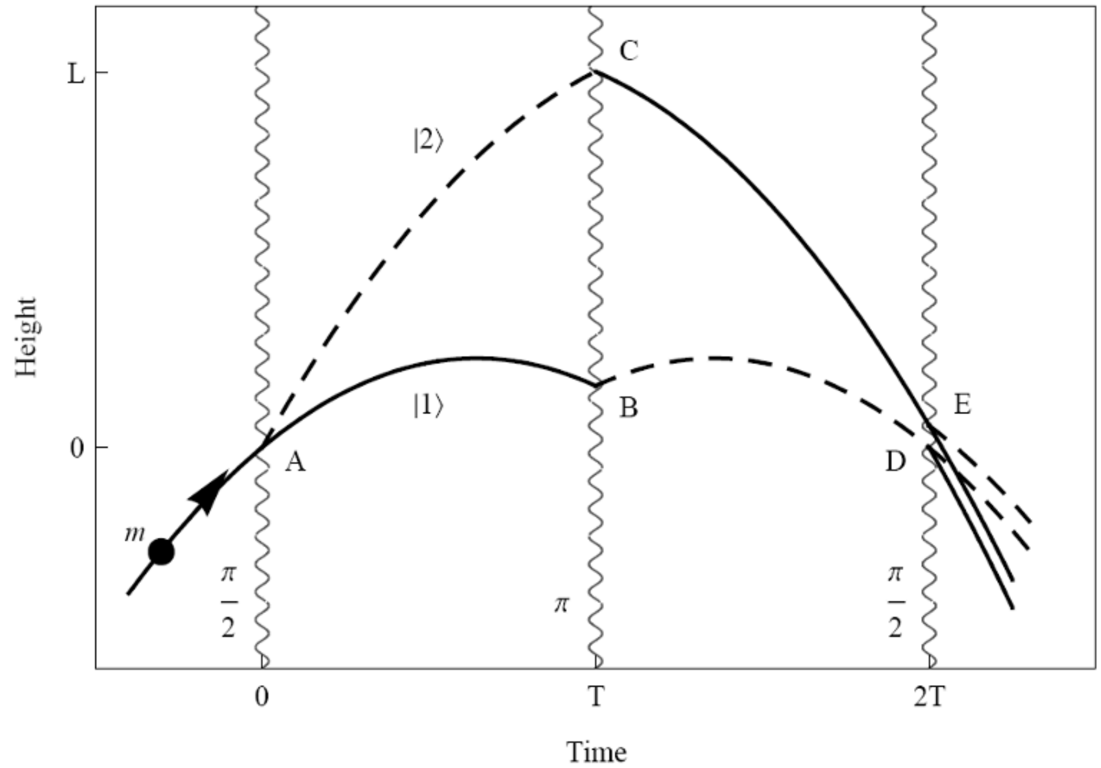


$$\Delta\Phi = \Phi_1^{eff} - 2\Phi_2^{eff} + \Phi_3^{eff} \qquad \Phi_i^{eff}(t) = \vec{k}_i^{eff}\vec{r}_i(t)$$



Optics for Atom Interferometry





$$\Delta\phi = k_{\text{eff}}\, g T^2$$

Proportional to spacetime area enclosed.

$$\frac{\delta g}{g} \sim \frac{\delta\phi}{k_{\text{eff}}\, g T^2}$$

Sensitivity

$$\delta\phi \sim \frac{1}{\sqrt{N}}$$

Shot noise

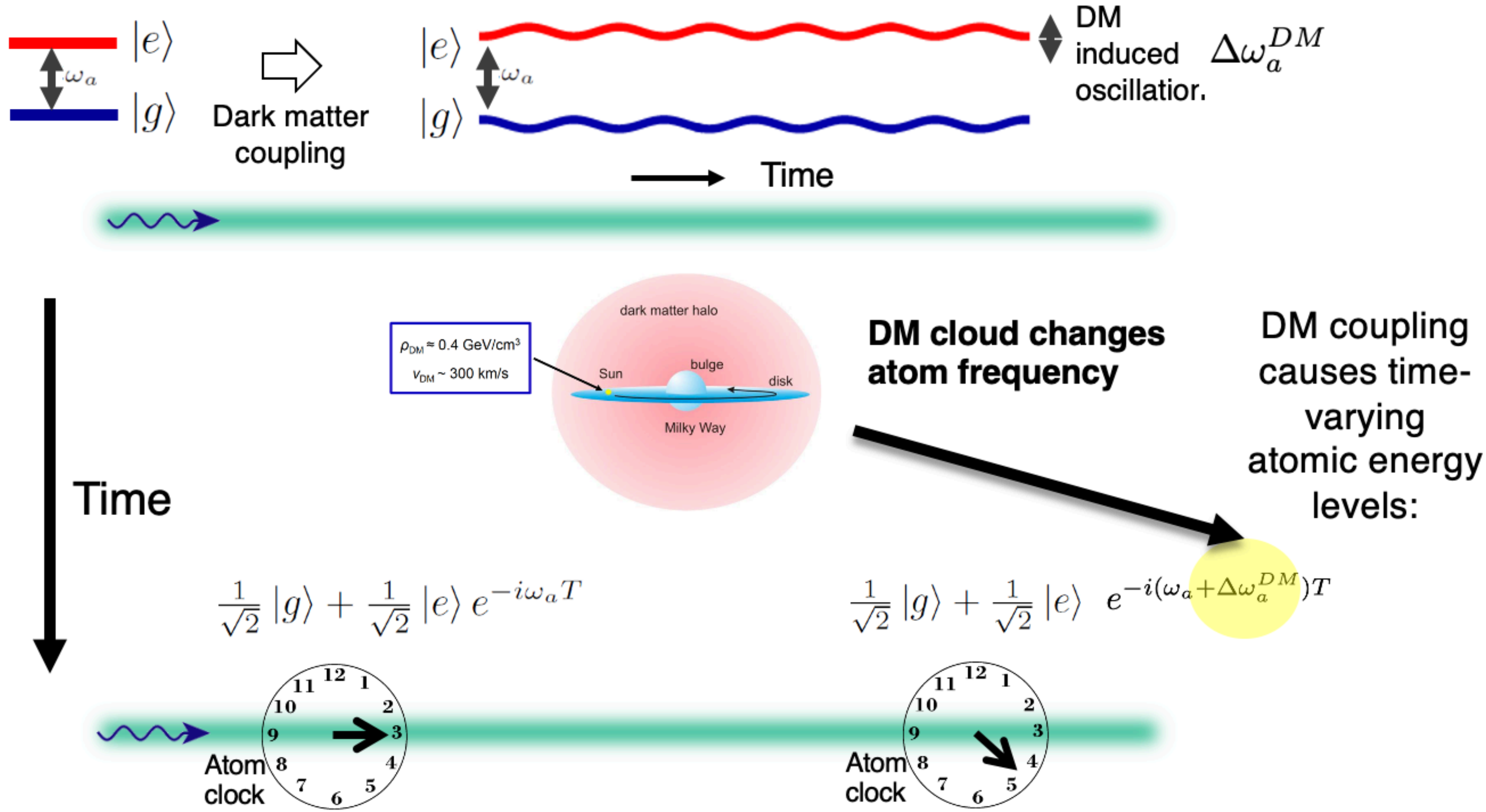
T :	Long duration
k_{eff} :	Large wavepacket separation
$\delta\phi$:	High flux, spin squeezing

Three contributions:

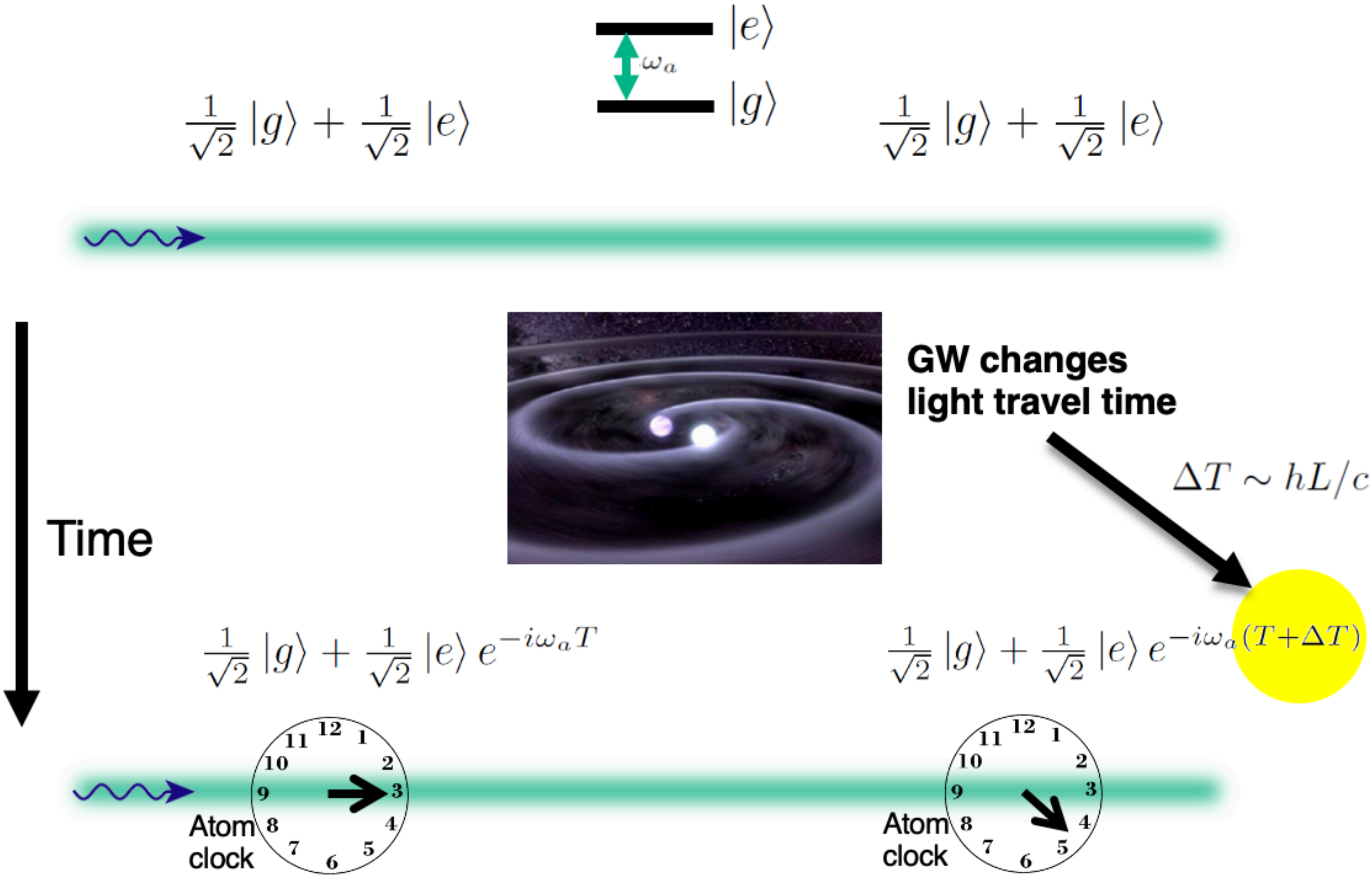
- Laser phase at each node
- Propagation phase along each path
- Separation phase at end of interferometer

$$\Delta\phi_{\text{total}} = \Delta\phi_{\text{prop}} + \Delta\phi_{\text{laser}} + \Delta\phi_{\text{sep}}$$

Effect of Dark Matter on Atom Interferometer



Effect of Gravitational Wave on Atom Interferometer



AION Collaboration

L. Badurina, S. Balashov[2], E. Bentine[3], D. Blas[1], J. Boehm[2], K. Bongs, A Beniwal[1]
D. Bortoletto, Bowcock[5], W. Bowden[6,*], C. Brew[2], O. Buchmueller[6], J. Coleman, J. Carlton
G. Elertas, J. Ellis[1,&], C. Foot[3], V. Gibson[7], M. Haehnelt[7], T. Harte[7], R. Hobson[6,*],
M. Holynski, A. Khazov[2], M. Langlois[4], S. Lellouch[4], Y.H. Lien[4], R. Maiolino[7],
P. Majewski[2], S. Malik[6], J. March-Russell, C. McCabe, D. Newbold[2], R. Preece[3],
B. Sauer[6], U. Schneider[7], I. Shipsey[3], Y. Singh, M. Tarbutt[6], M. A. Uchida[7],
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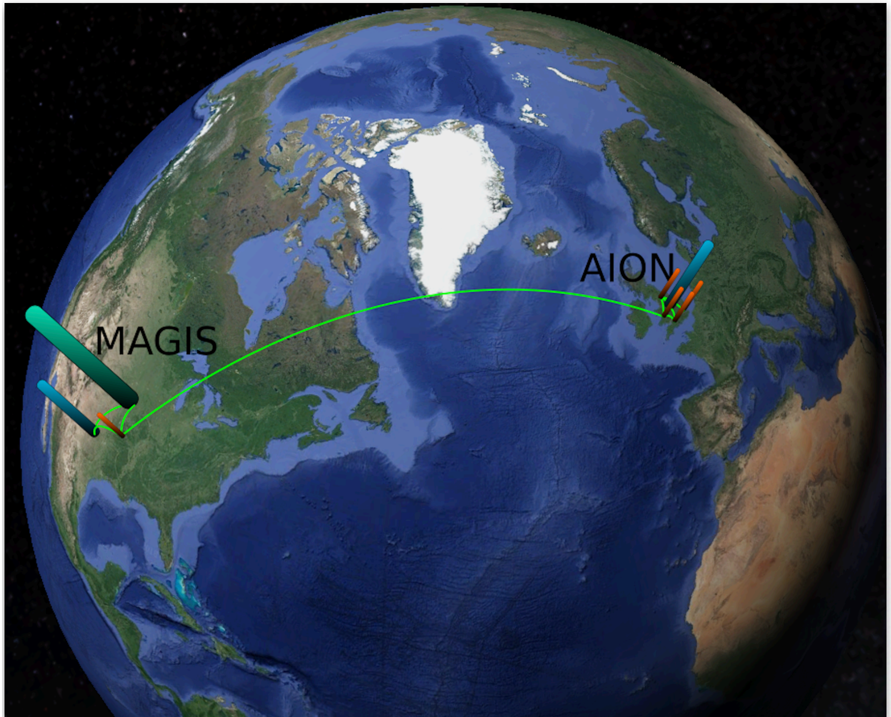
[1]Kings College London, [2]STFC Rutherford Appleton Laboratory, [3]University of Oxford, [4]University of Birmingham, [5]University of Liverpool, [6]Imperial College London, [7]University of Cambridge



Network with MAGIS project in US

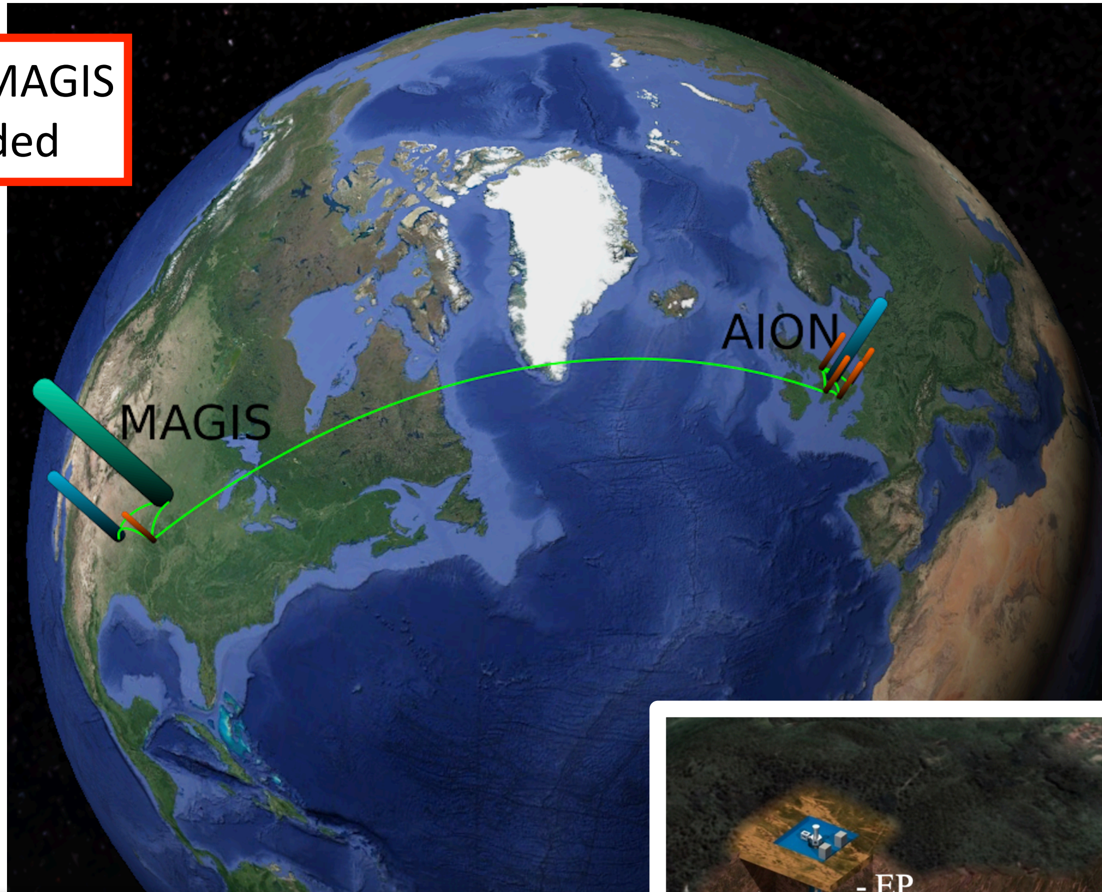
MAGIS Collaboration (Abe et al): arXiv:2104.02835

AION

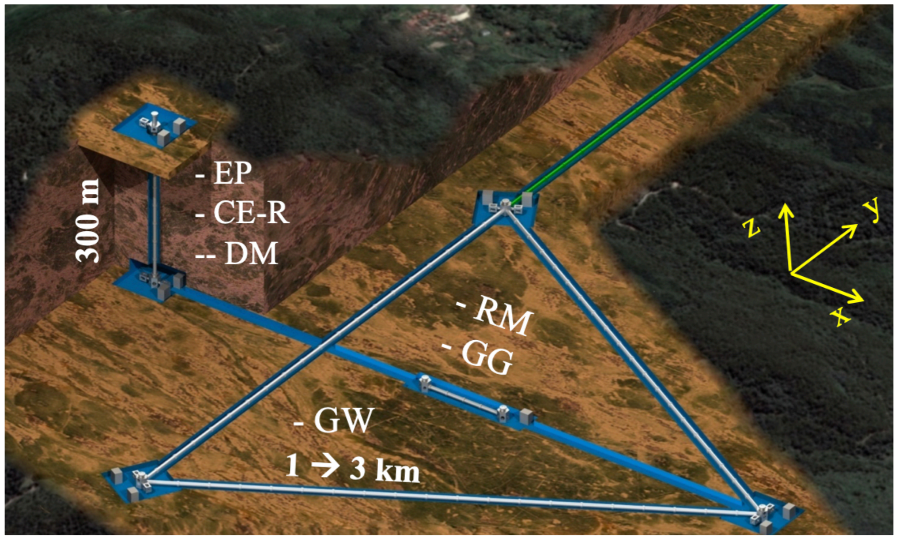
Atom Interferometer Observatory &

Network

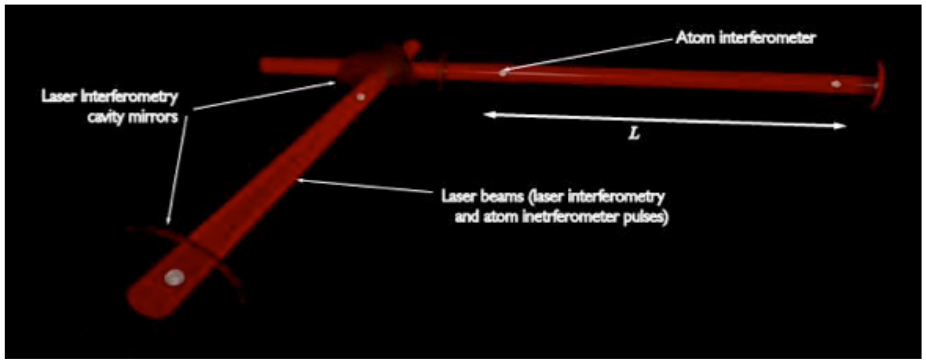
Partnership with MAGIS could be extended

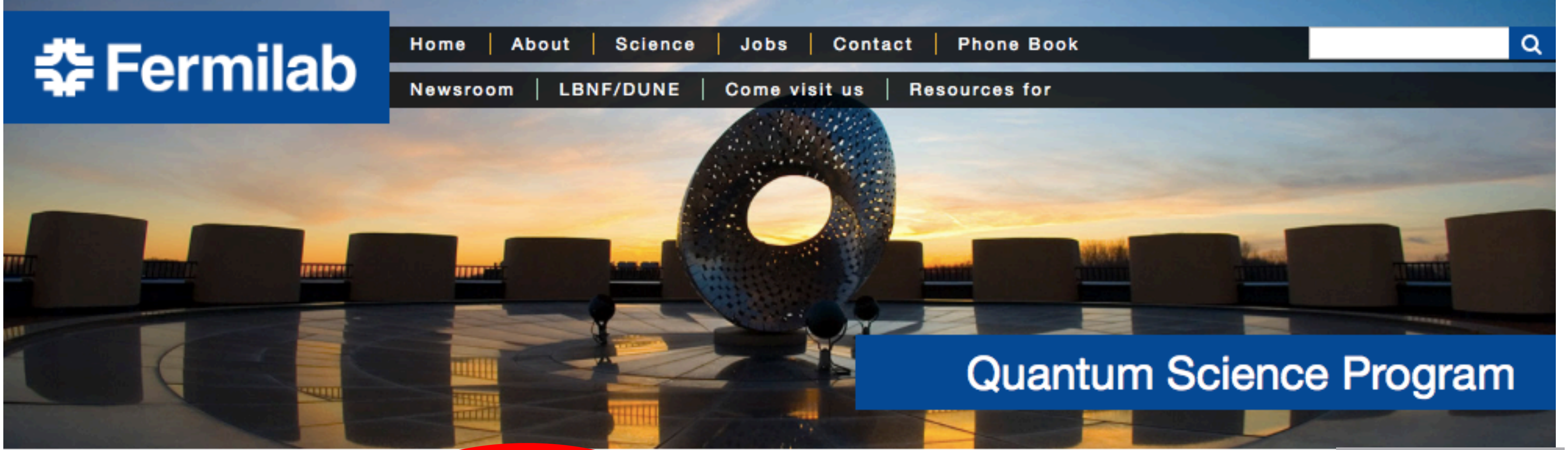


ZAIGA (China)

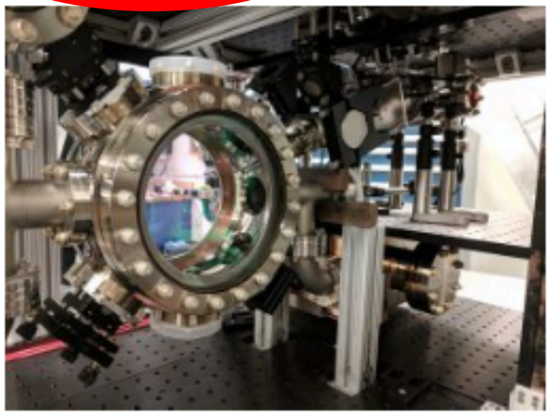


MIGA (France)





MAGIS-100



Fermilab seeks to host MAGIS-100 — the 100-meter Matter-wa
Gradiometer Interferometric Sensor — which will test quantum
macroscopic scales of space and time.

The laboratory is developing a sensitive prototype detector tha
precisely measure properties of the cosmos.

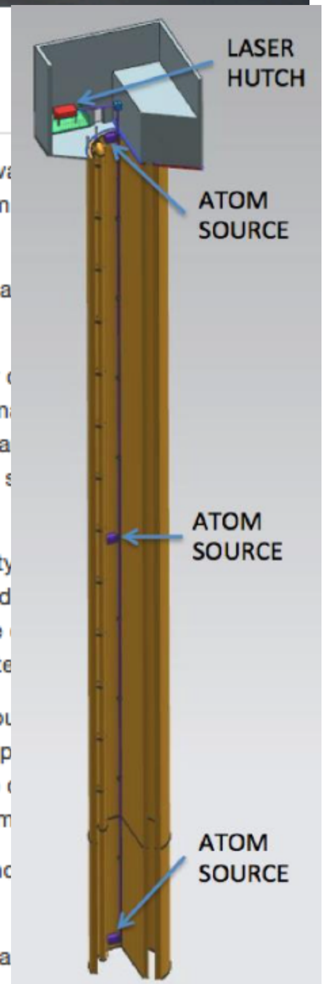
One of these is dark matter. Physicists have offered a number o
models describing dark matter, a mysterious substance that m
quarter of the universe. Some of these models suggest that da
made of ultralightweight particles. MAGIS-100 will be used to s
particular those that predict varying atomic energy levels.

A longer-term goal for MAGIS-100 is to establish the sensitivity
technique to gravitational waves in the frequency range around 1 hertz, where there are few existing or proposed d
waves, predicted by Einstein a century ago but discovered for the first time only in 2015, are ripples in space-time
accelerating masses, such as stars and galaxies. MAGIS-100 creates atom matter waves in superposition separate

The MAGIS-100 prototype would make use of an existing vertical shaft on the Fermilab site that leads to undergrou
will perform precision quantum measurements using clouds of ultracold falling atoms, whose phases can be manip
using lasers, aiding in the test for lightweight dark matter particles. The length of the 100-meter drop expands the
technology by about a factor of 10 and provides opportunities for significant advances in the systematics of this im

MAGIS-100 combines the unique physical features of the Fermilab site with the laboratory expertise in vacuum and
ol are pa

MAGIS Collaboration (Coleman et al): arXiv:1812.00482



AION – Staged Programme

AION

- AION-10: Stage 1 [year 1 to 3]
  - 1 & 10 m Interferometers & site investigation for 100m baseline

Initial funding from UK STFC

- AION-100: Stage 2 [year 3 to 6]
  - 100m Construction & commissioning
- AION-KM: Stage 3 [> year 6]
  - Operating AION-100 and planning for 1 km & beyond
- AION-SPACE (AEDGE): Stage 4 [after AION-km]
  - Space-based version

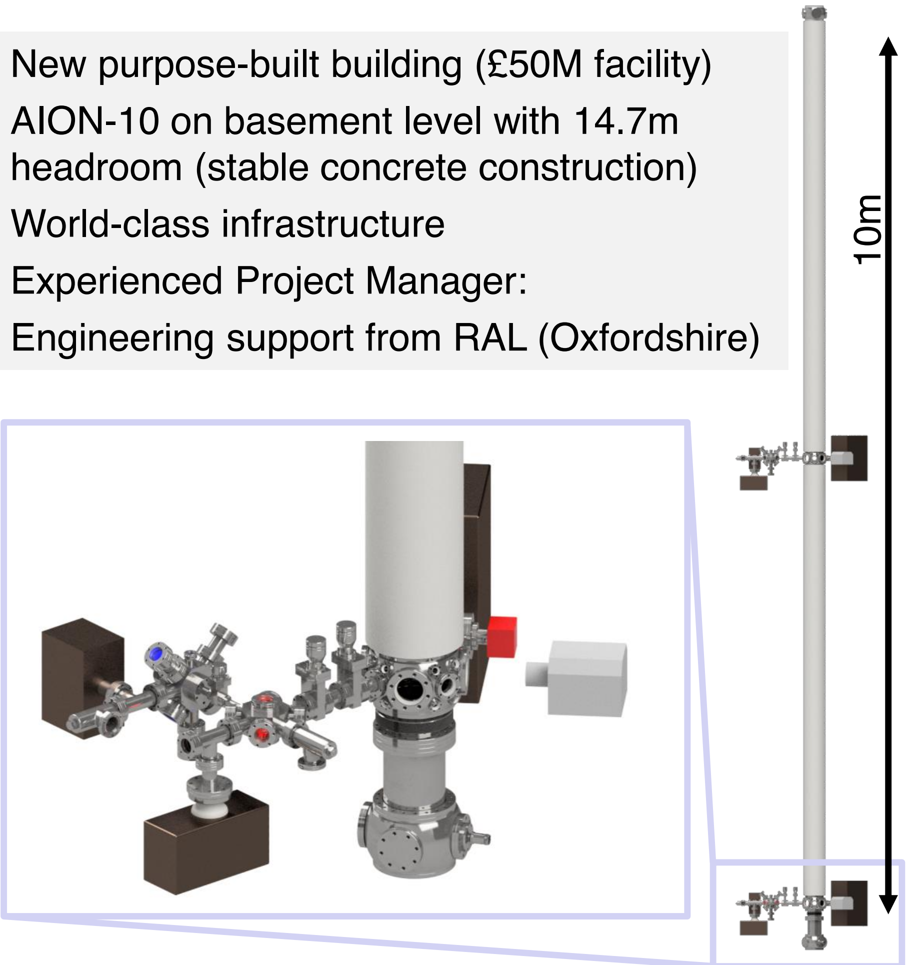
AION Collaboration (Badurina, ..., JE et al): arXiv:1911.11755

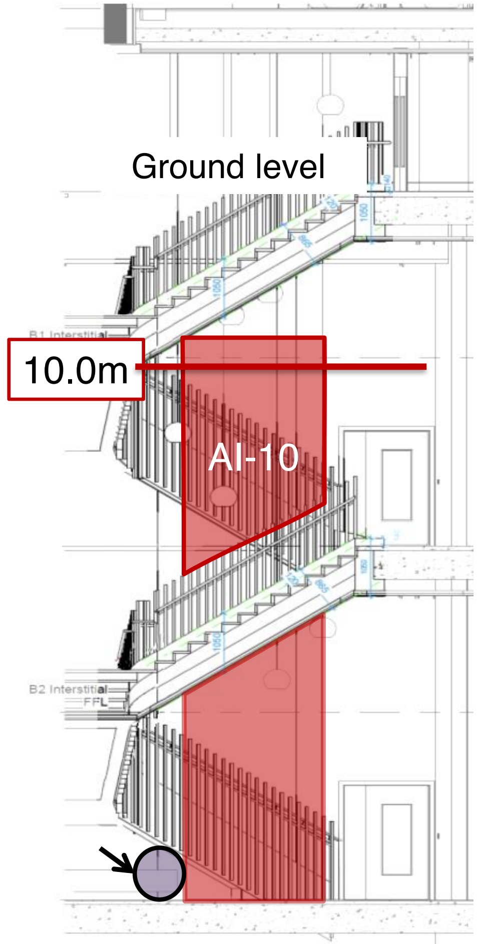
Planned Location of AION-10m

AION-10 @ Beecroft building, Oxford Physics

AION Project: Physics Beyond Colliders Annual Workshop

- New purpose-built building (£50M facility)
- AION-10 on basement level with 14.7m headroom (stable concrete construction)
- World-class infrastructure
- Experienced Project Manager:
- Engineering support from RAL (Oxfordshire)

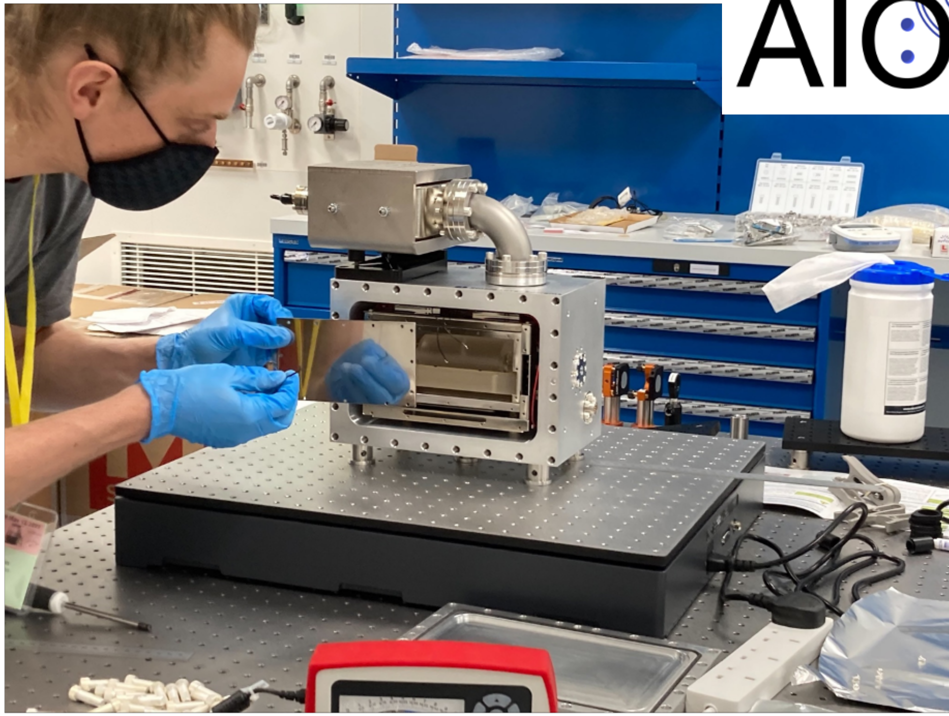




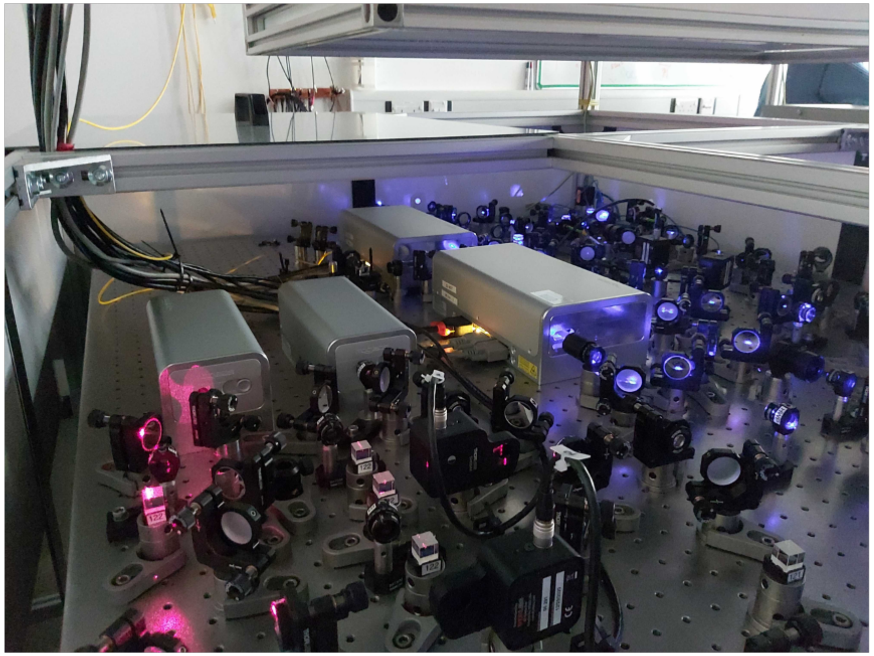
Planned Location of AION-10m

AION

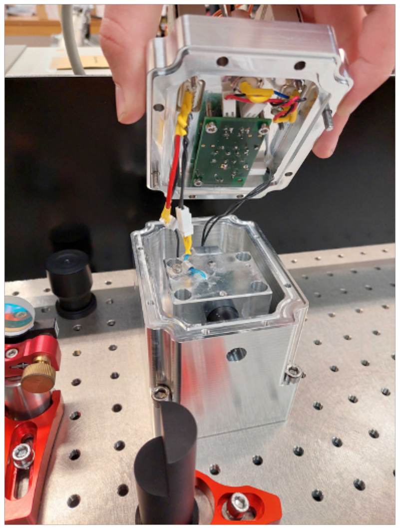
Laboratory Equipment



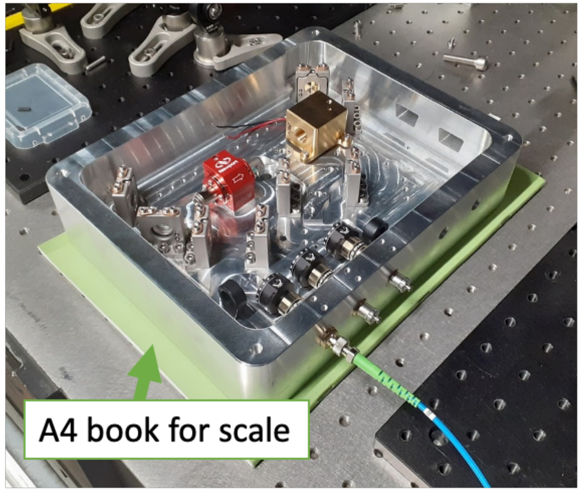
Imperial College London/Rutherford Appleton Laboratory
(Dr Richard Hobson)



University of Birmingham

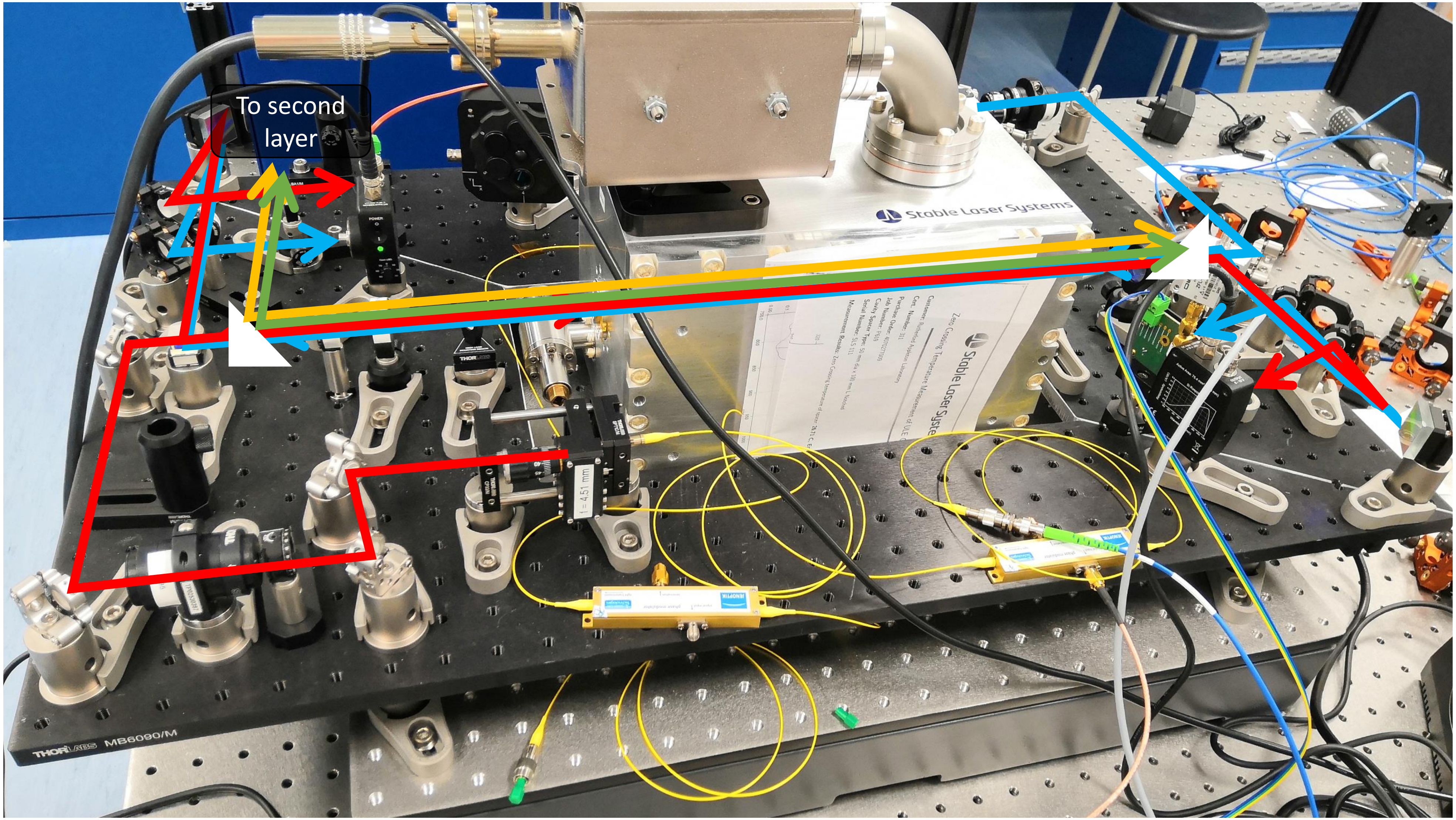


University of Cambridge



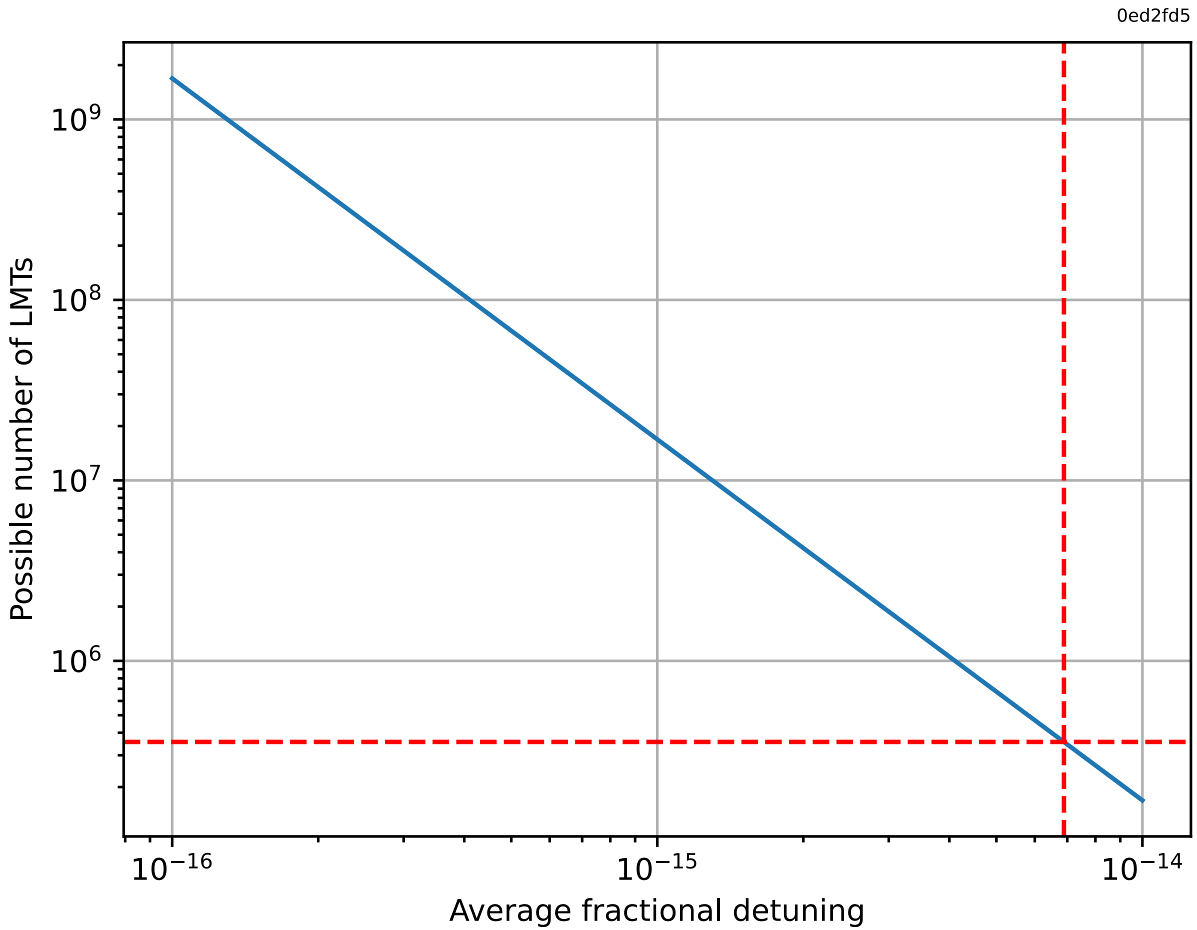
University of Oxford

Laser Stabilisation



Laser Stabilisation

How useful is 7×10^{-15} ?



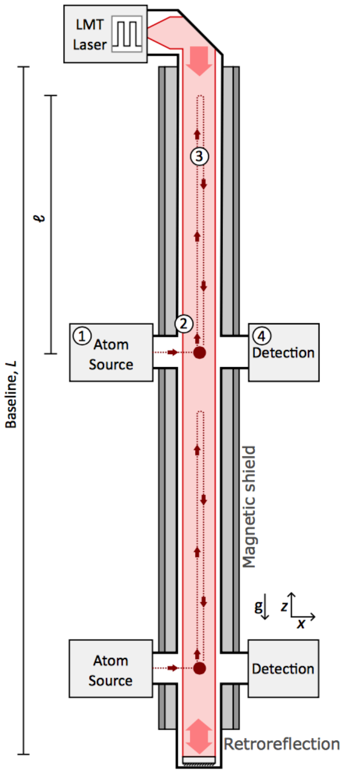
- Plot shows the possible number of LMTs assuming
  - A Rabi frequency of 8 kHz
  - A desired contrast of 90%
  - That the laser is detuned throughout the atoms' flight by the amount shown

- At a 3 Hz linewidth, that's
  $n_{max} = 350\,000$

Exceeds science objective by large margin

AION Design Parameters

Table 1. *List of basic parameters: length of the detector L; interrogation time of the atom interferometer T_{int}; phase noise $\delta\phi_{noise}$; and number of momentum transfers LMT. The choices of these parameters largely determine the sensitivities of the projection scenarios. It should be noted that at a 100m detector it will be conceptually possible to increase the interrogation time of the atom interferometer beyond 1.4 sec.*



Sensitivity Scenario	L [m]	T_{int} [sec]	$\delta\phi_{noise}$ $[1/\sqrt{Hz}]$	LMT [number n]
AION-10 (initial)	10	1.4	10^{-3}	100
AION-10 (goal)	10	1.4	10^{-4}	1000
AION-100 (initial)	100	1.4	10^{-4}	1000
AION-100 (goal)	100	1.4	10^{-5}	40000
AION-km	2000	5	0.3×10^{-5}	40000

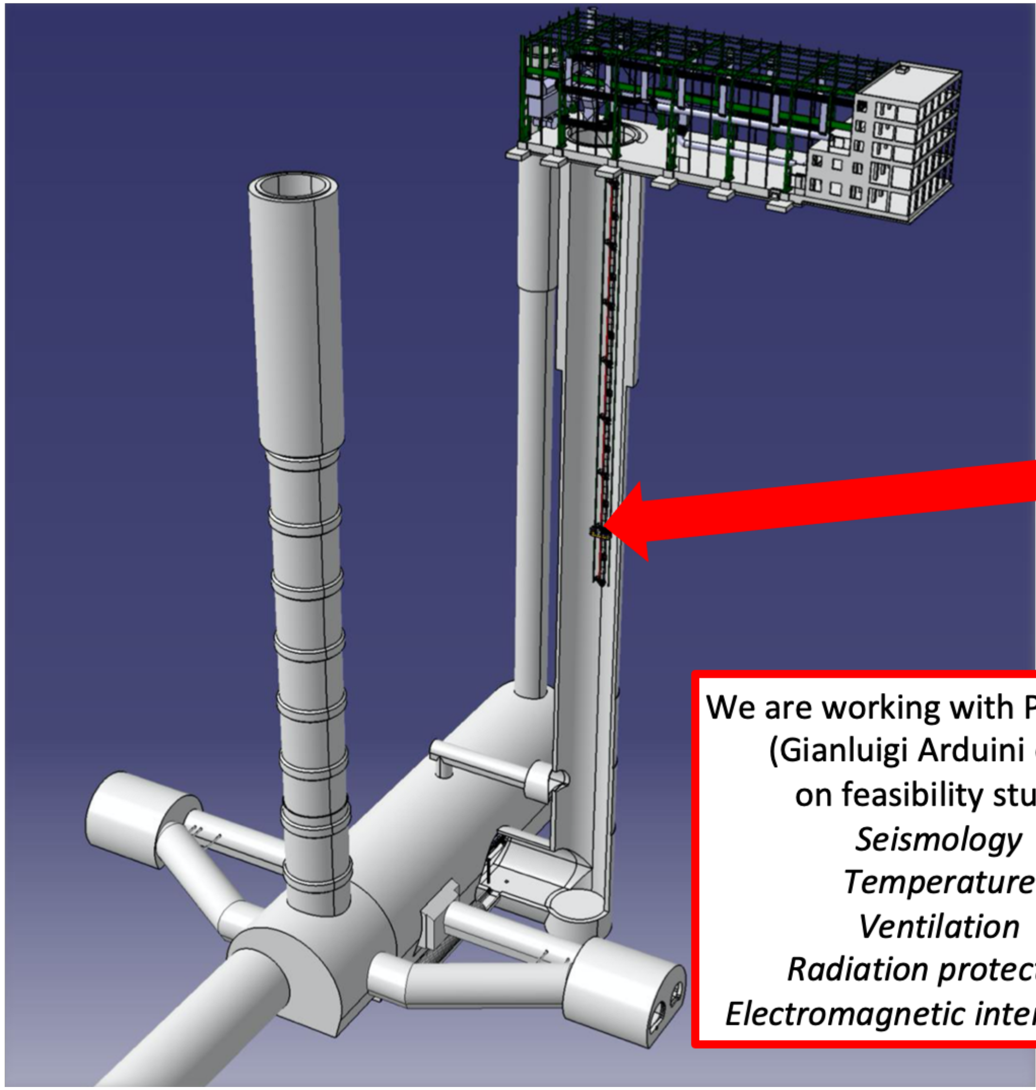
Initial targets and final goals

AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755

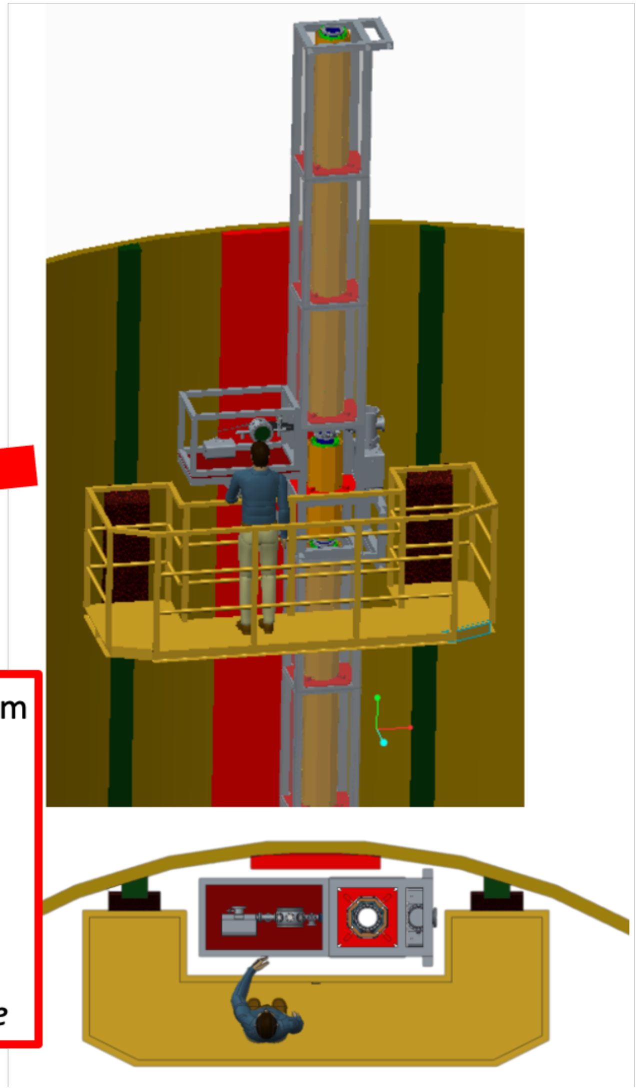
Possible Site for AION 100m (1km?) Boulby Mine STFC Laboratory

Possible CERN Location of AION-100m

General view of LHC Point 4



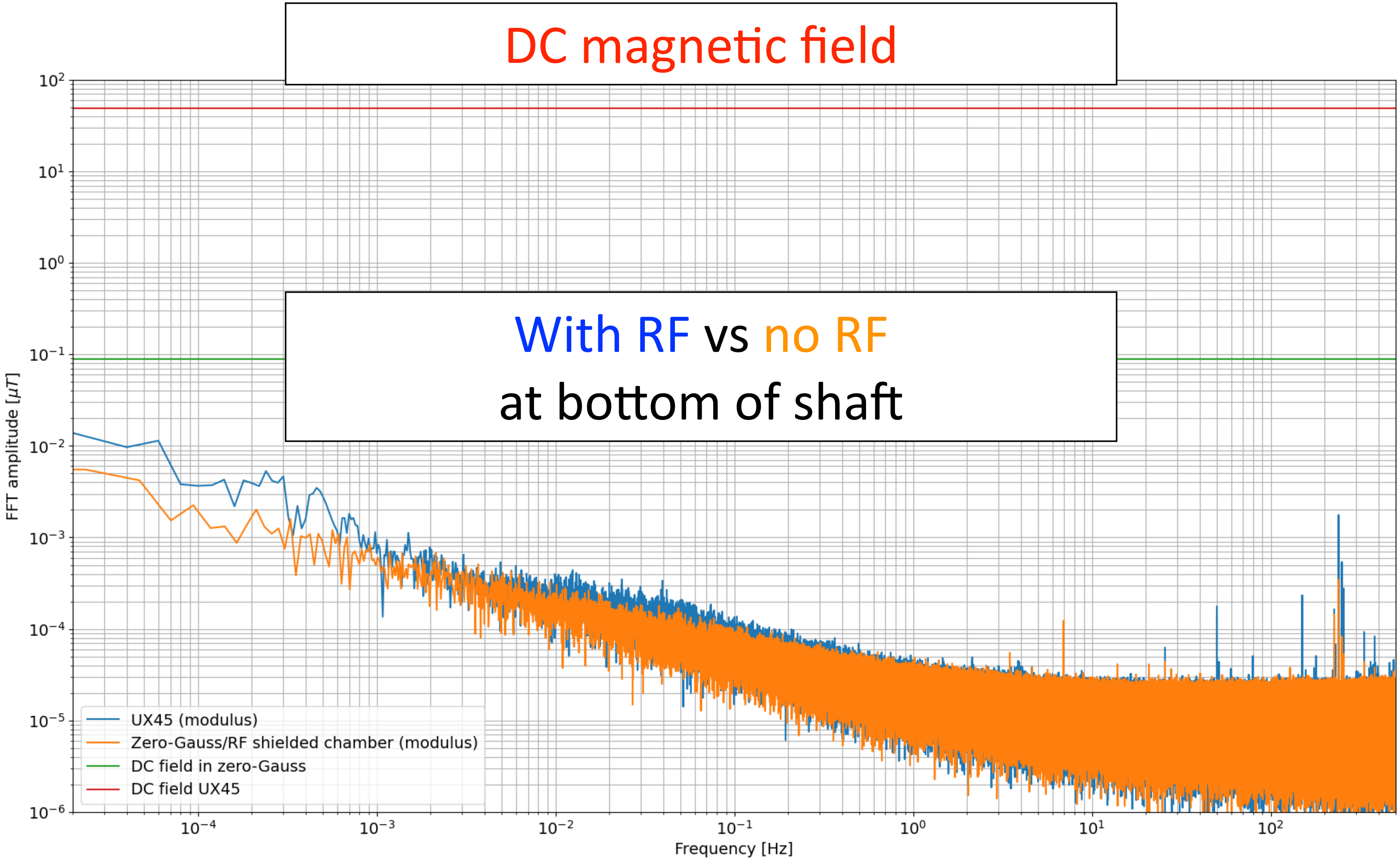
Possible layout in PX46 shaft



We are working with PBC Team (Gianluigi Arduini et al) on feasibility study:

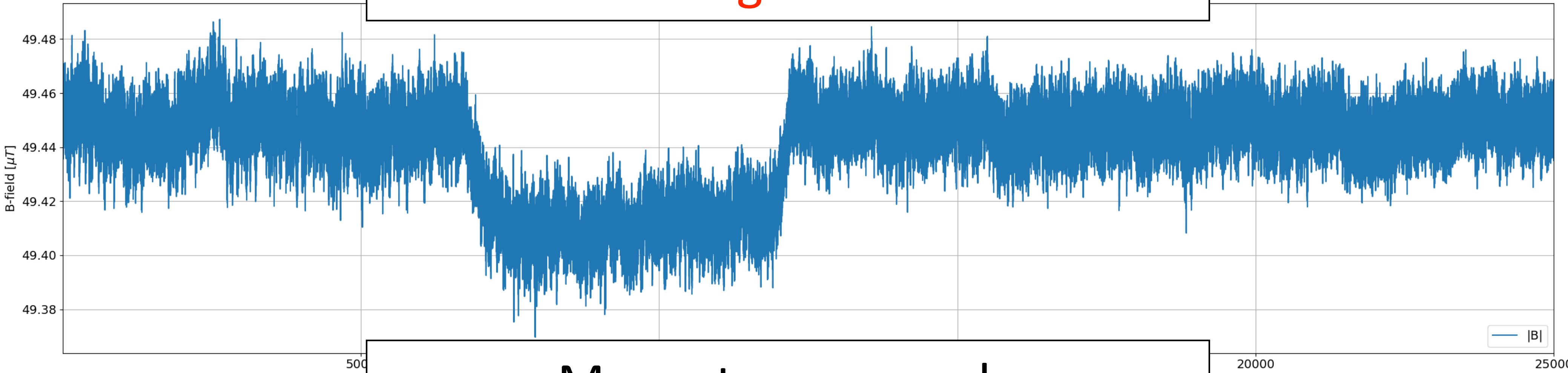
Seismology
Temperature
Ventilation
Radiation protection
Electromagnetic interference

Electromagnetic Studies for AION-100 at CERN

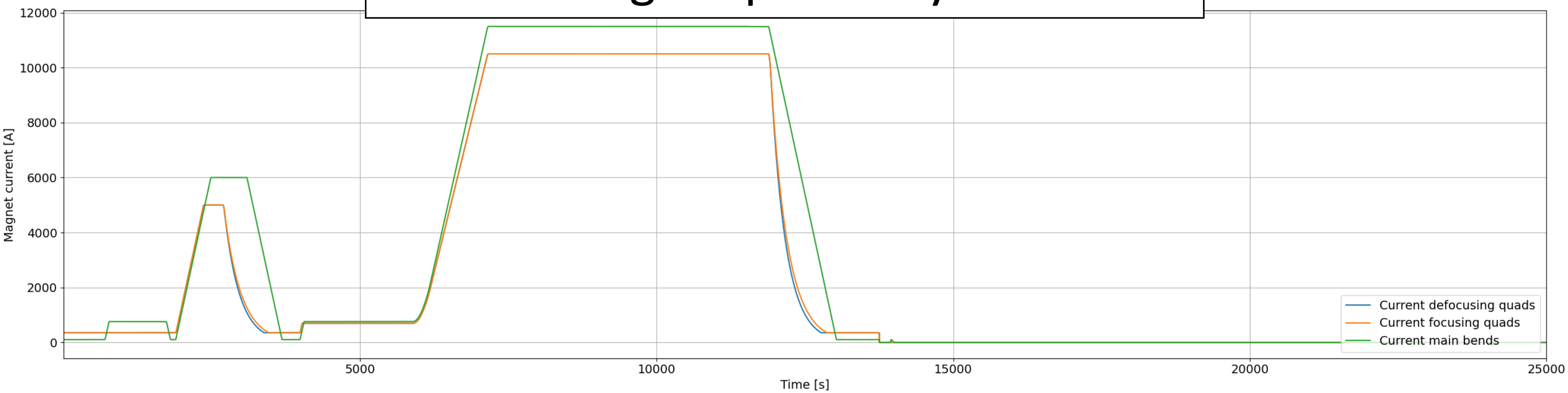


Electromagnetic Studies for AION-100 at CERN

DC magnetic field



Magnet power cycle



Richard Hobson "Change in magnetic field can easily be compensated"

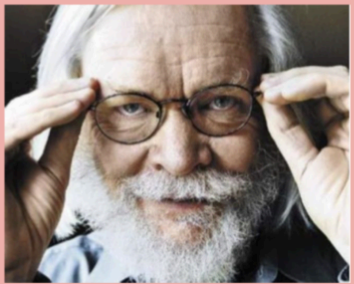
AION Phenomenology Team

The team at KCL:


Leonardo
Badurina


Ankit
Beniwal


John
Carlton


John
Ellis


Chris
McCabe

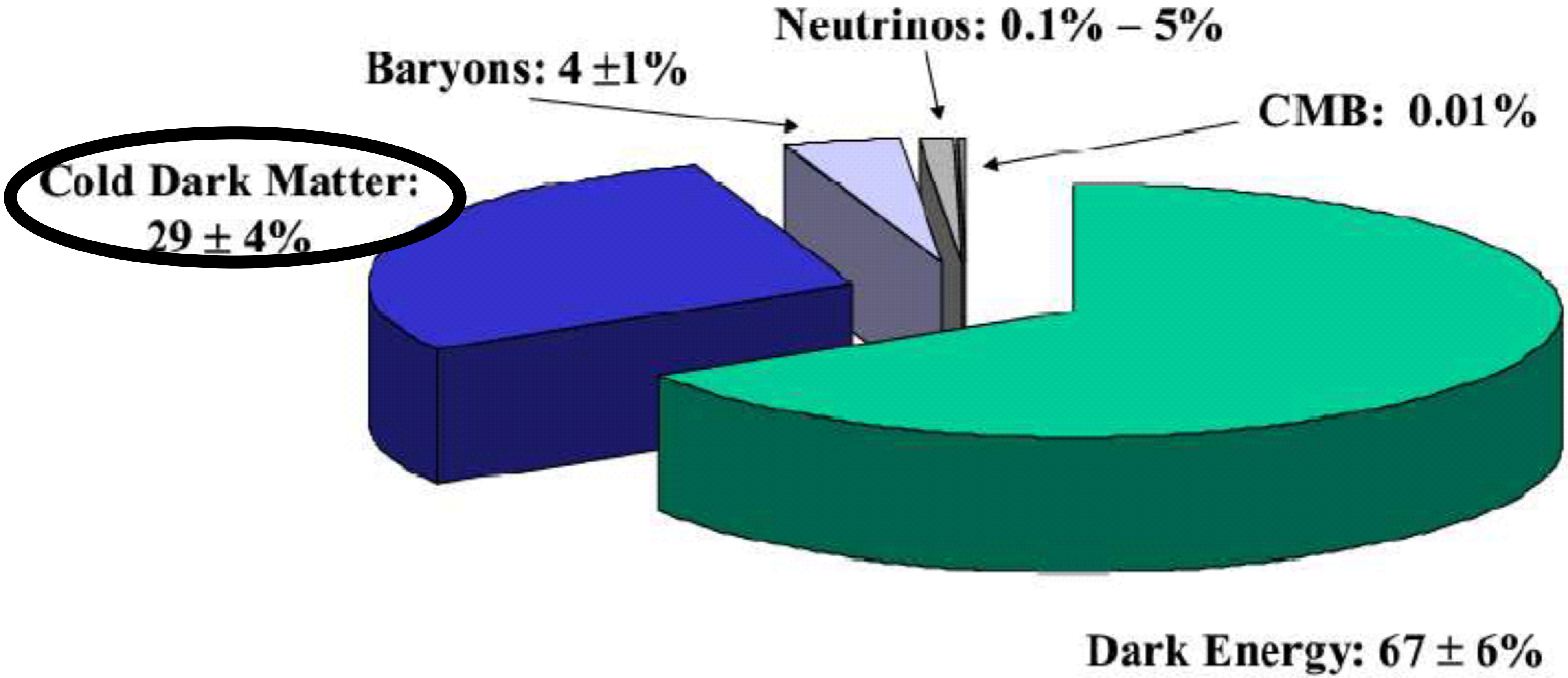
and elsewhere:


Jeremiah Mitchell
University of Cambridge


Diego Blas
UAB (Barcelona)

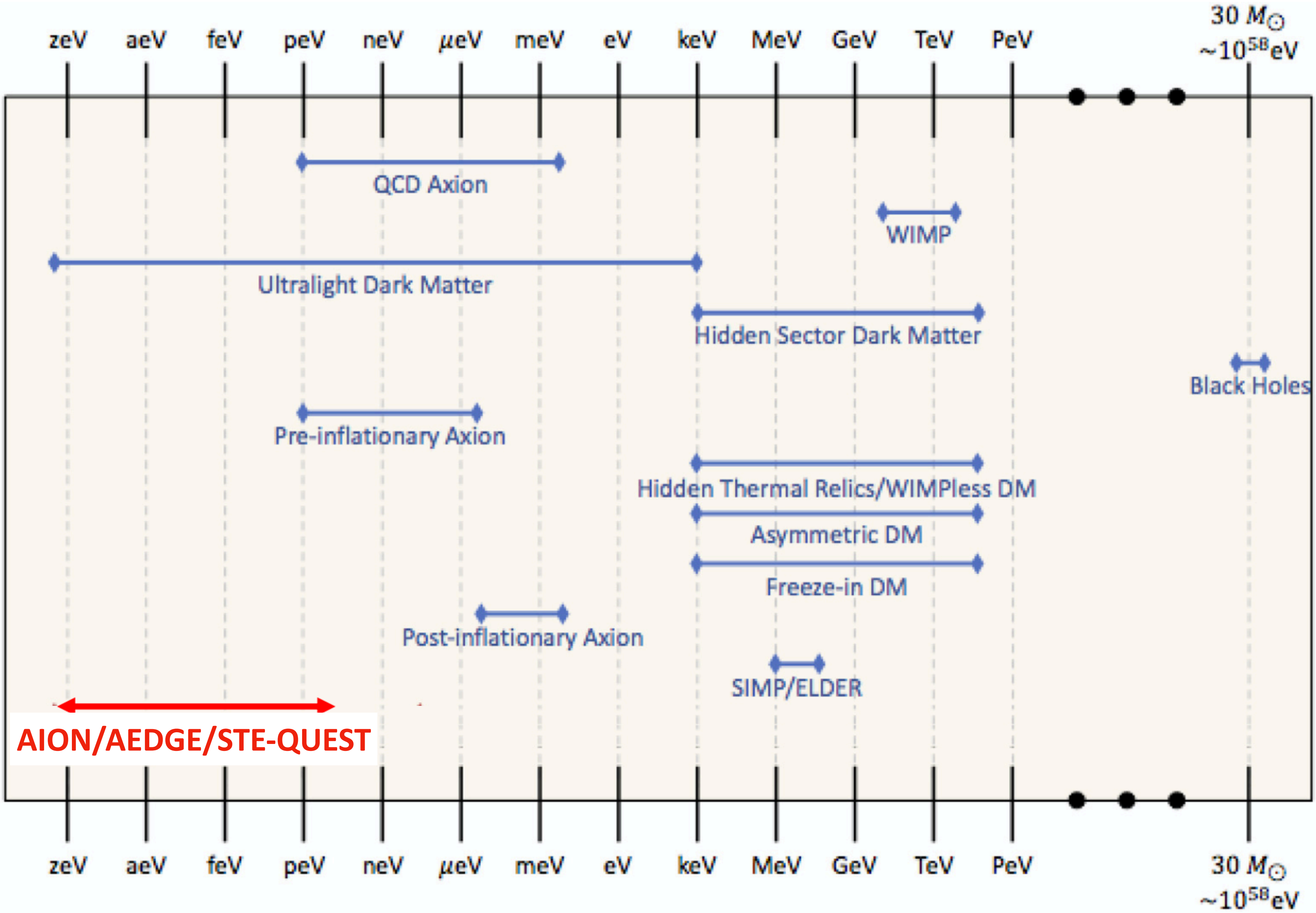
+ ...

Strange Recipe for a Universe



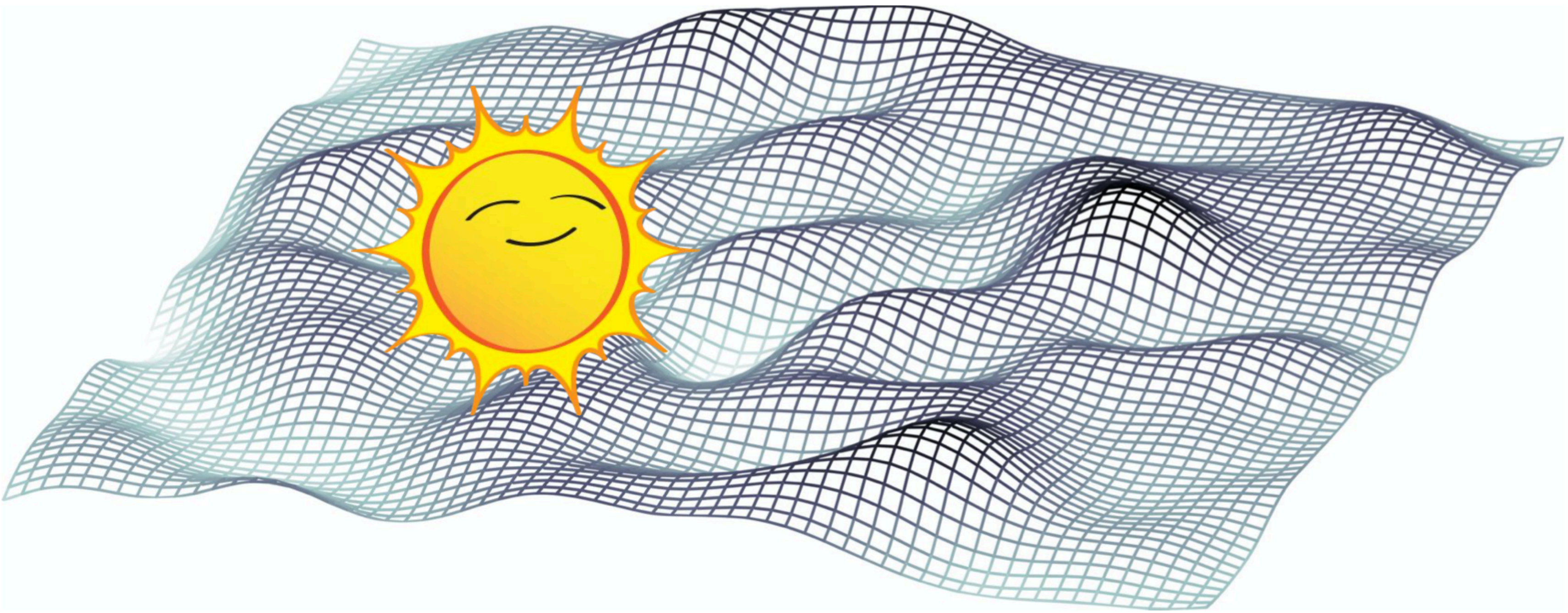
The 'Standard Model' of the Universe
indicated by astrophysics and cosmology

Search for Ultralight Dark Matter



Ultralight Dark Matter

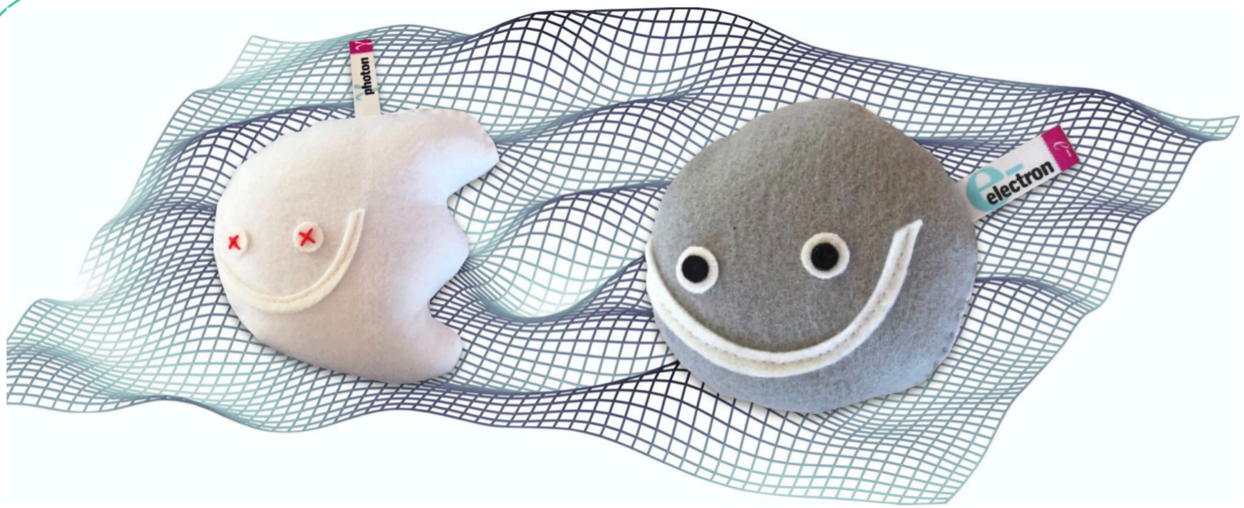
A scalar ULDM ***ϕ*(x**, *t)* field would be present throughout the Solar System



The wavelength depends on the ULDM mass: $\lambda \sim 10^8\,\mathrm{km}\left(\frac{10^{-15}\,\mathrm{eV}}{m_\phi}\right)$

Ultralight Dark Matter

Interactions with the ULDM field lead to oscillations in fundamental 'constants'



Time-dependent electron mass:

$$m_e(t, \mathbf{x}) = m_e \left[1 + \frac{d_{m_e}}{M_{\rm Pl}} \phi(t, \mathbf{x})\right]$$

Time-dependent electromagnetic fine structure constant:

$$\alpha(t, \mathbf{x}) = \alpha \left[1 + \frac{d_e}{M_{\rm Pl}} \phi(t, \mathbf{x})\right]$$

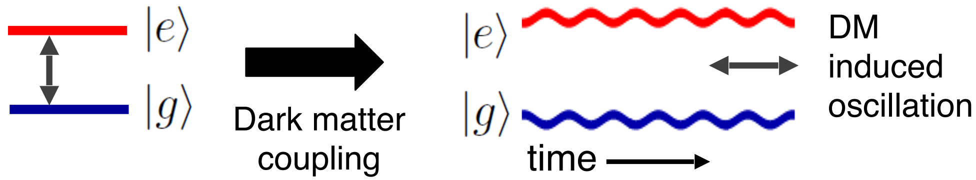
Tiny oscillations induced in transition energies:

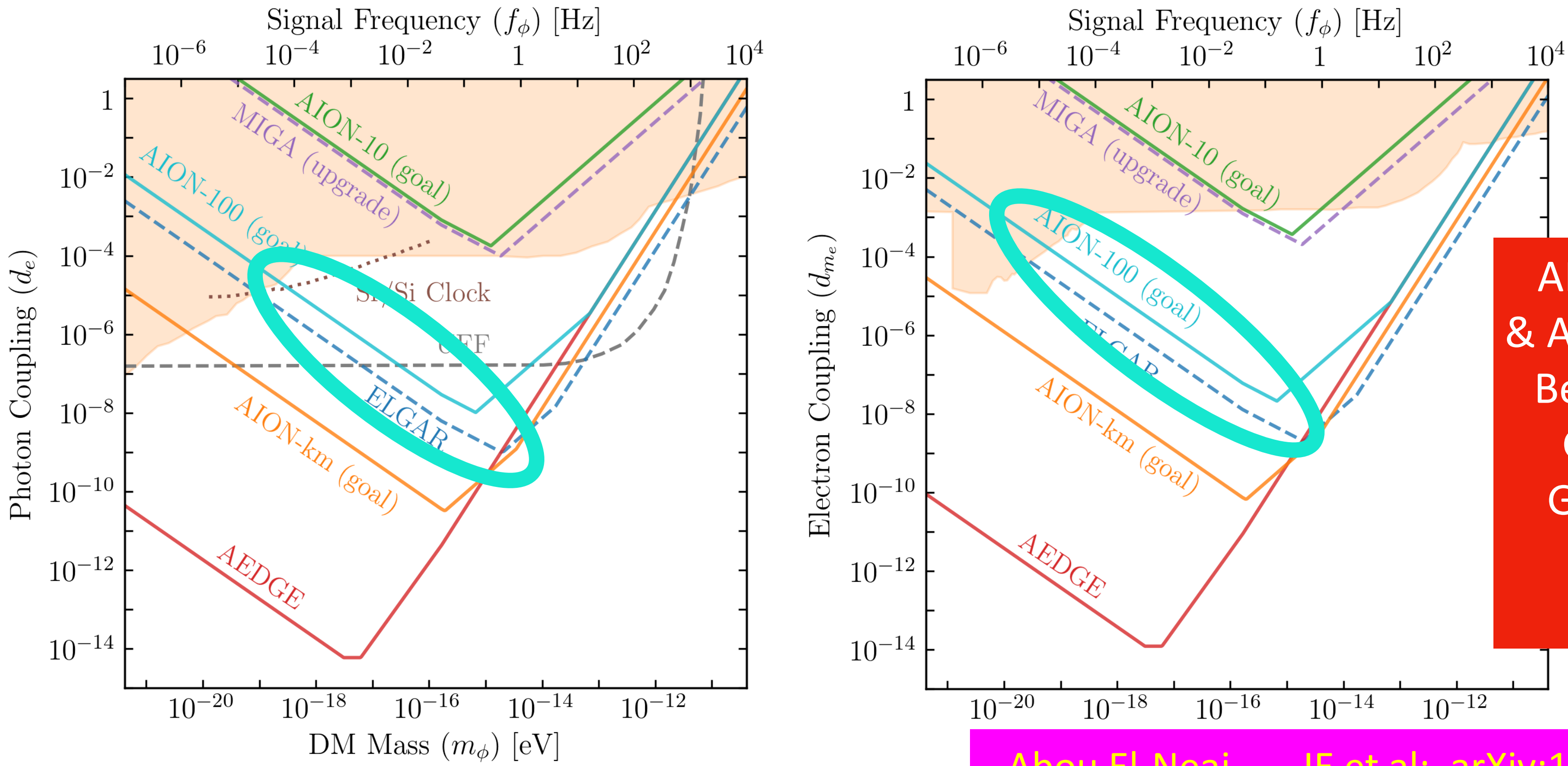
$$\frac{\delta\omega_{\rm Sr}}{\omega_{\rm Sr}} = \frac{\sqrt{2\rho_{\rm DM}}}{m_{\rm DM}} \frac{(d_{m_e} + \xi d_e)}{M_{\rm Pl}} \cos(m_{\rm DM} t)$$

Searches for Ultralight Dark Matter

Linear couplings to gauge fields and matter fermions

$$\mathcal{L}_{\text{int}\phi} = \kappa\phi\left[+\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_g\beta_3}{2g_3}F^A_{\mu\nu}F^{A\mu\nu} - \sum_{i=e,u,d}(d_{m_i}+\gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right]$$





AION-100 & AION-1km: Beware of Gravity Gradient Noise (GGN)

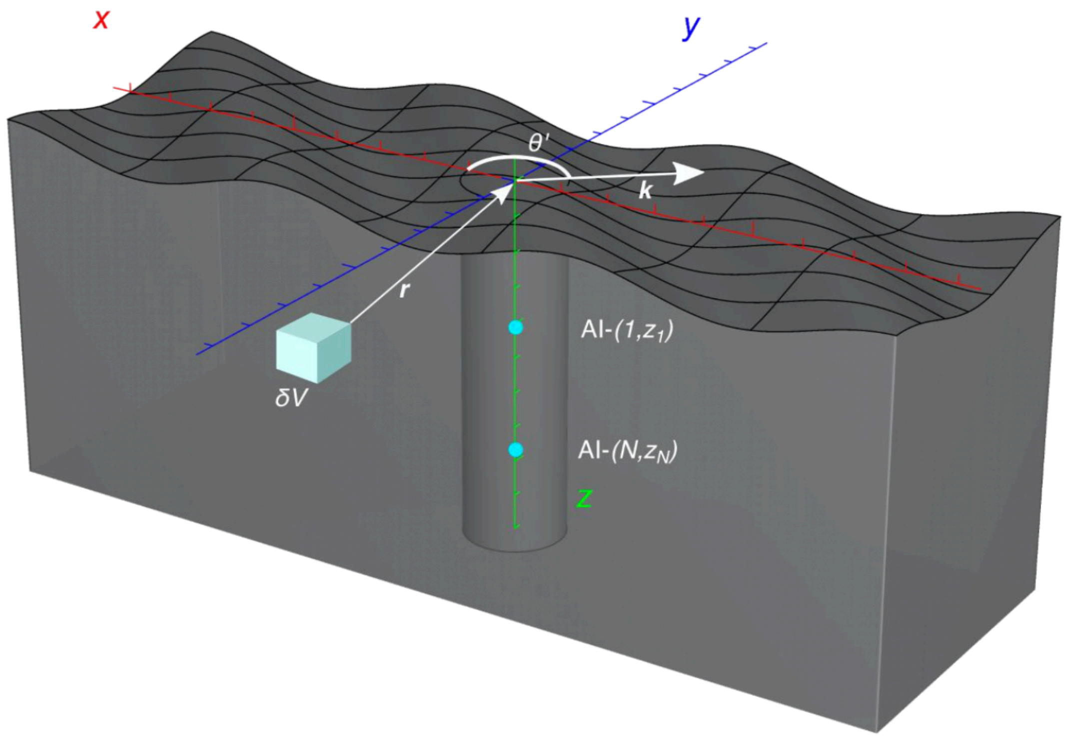
Abou El-Neaj, …, JE et al:, arXiv:1908.00802

Gravity Gradient Noise

Seismic waves on the surface (Rayleigh waves) change the gravitational field experienced by the atoms and lead to a phase shift

$$\Phi_{\text{Rayleigh}} = \left(\widetilde{A}e^{-qkz_0} + \widetilde{B}e^{-kz_0}\right)\xi_V \cos(\omega T + \Theta)$$

$$\widetilde{A}, -\widetilde{B} \propto \frac{\sin\left(\frac{\omega T}{2}\right)^2}{\omega^2}$$



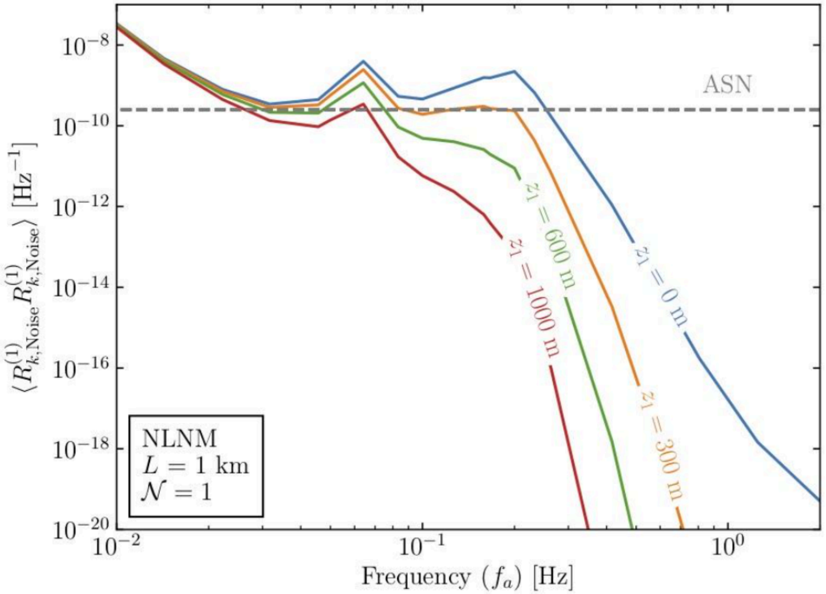
We consider the simplest scenario: Isotropic sourcing around the shaft, single geological stratum present (so only the fundamental Rayleigh mode)

LB, V. Gibson, J. Mitchell, C. McCabe, in preparation

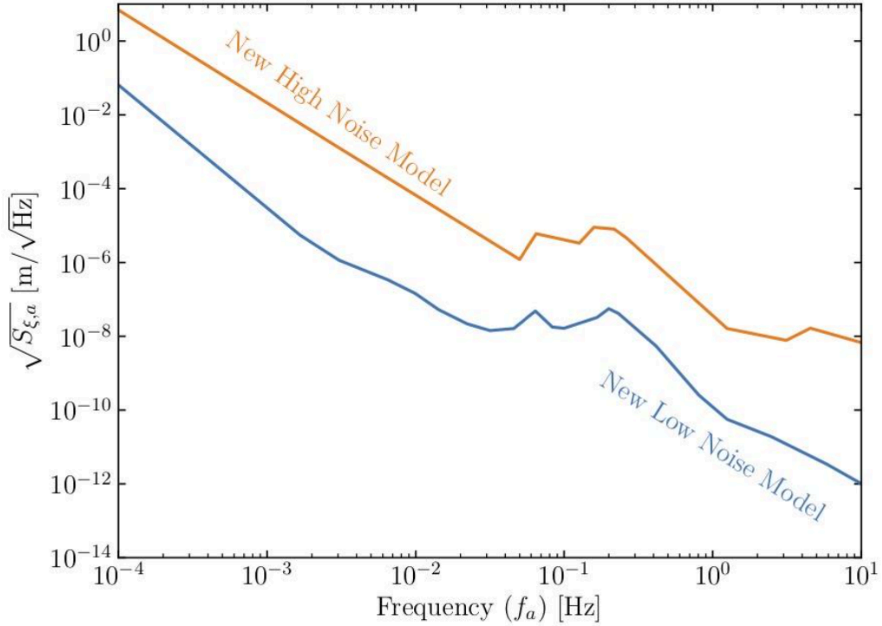
Gravity Gradient Noise

$$\Phi_{\text{Rayleigh}} = \left(\widetilde{A}e^{-qkz_0} + \widetilde{B}e^{-kz_0}\right)\xi_V \cos(\omega T + \Theta)$$

Exponential suppression and frequency dependence



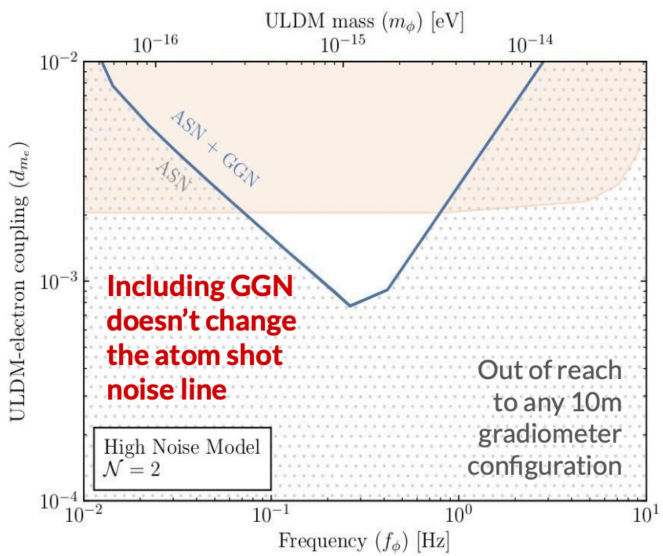
Vertical displacement (Rayleigh distributed)

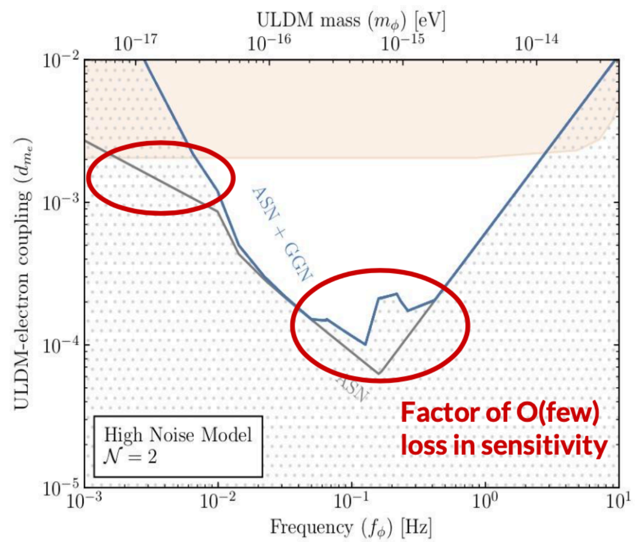


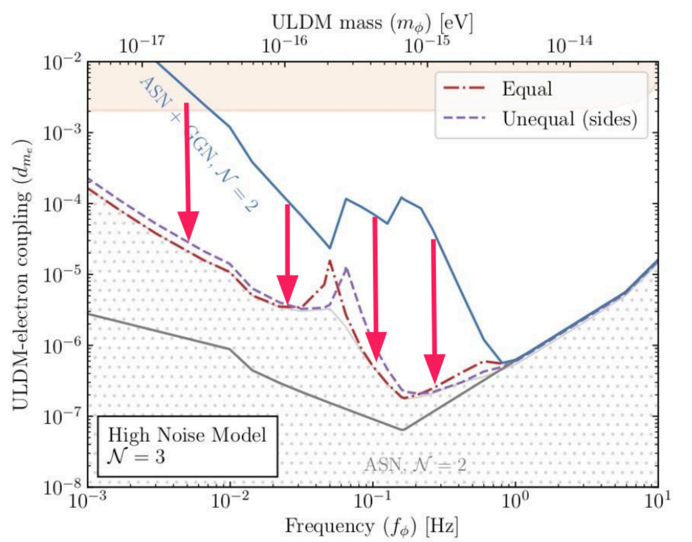
LB, V. Gibson, J. Mitchell, C. McCabe, in preparation

Gravity Gradient Noise

Unimportant for AION-10	Not large for AION-100	Important for AION-1km







AION-100 & AION-1km: Beware of Gravity Gradient Noise (GGN)

Abou El-Neaj, …, JE et al:, arXiv:1908.00802

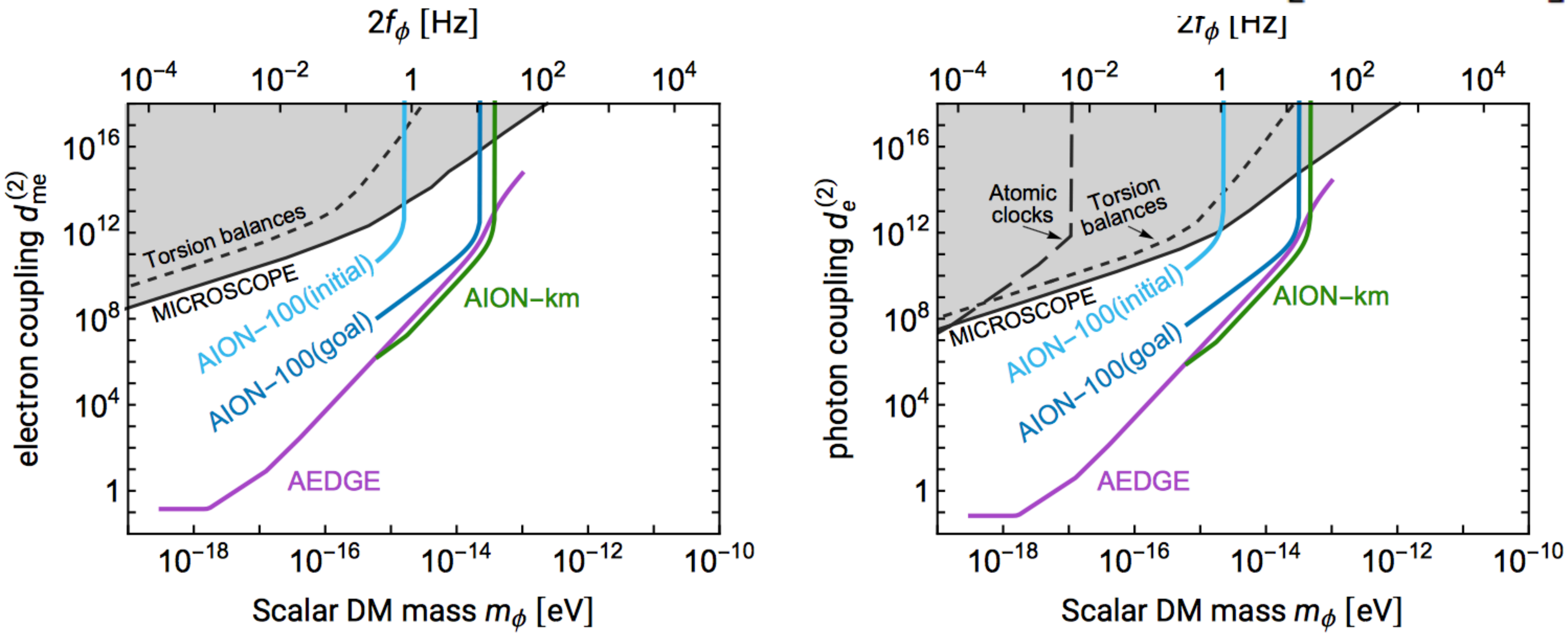
AEDGE: Bertoldi, …, JE et al: arXiv:1908.00802

Sensitivities to Quadratic DM Interactions

AION

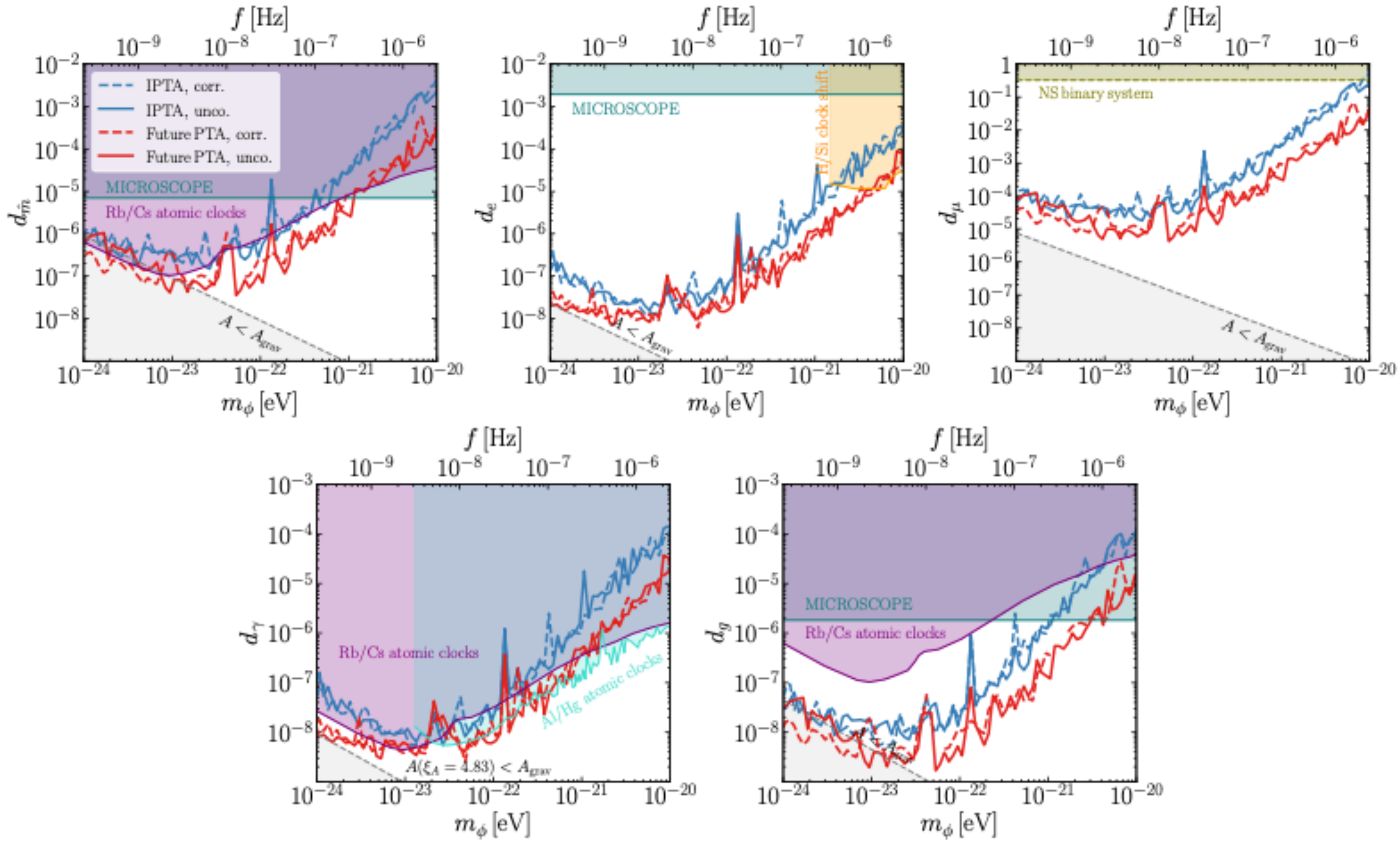
$$\mathcal{L}_{\rm int}^{f} = -\sum_{f=e,p,n} m_f \left(\frac{\phi c}{\Lambda'_f}\right)^2 \bar{f} f, \qquad m_f \to m_f \left[1 + \left(\frac{\phi}{\Lambda'_f}\right)^2\right],$$

$$\mathcal{L}_{\rm int}^{\gamma} = \left(\frac{\phi}{\Lambda'_\gamma}\right)^2 \frac{F_{\mu\nu}F^{\mu\nu}}{4} \qquad \alpha \to \frac{\alpha}{1-(\phi/\Lambda'_\gamma)^2} \simeq \alpha \left[1 + \left(\frac{\phi}{\Lambda'_\gamma}\right)^2\right]$$



Constraints from Pulsar Timing Arrays

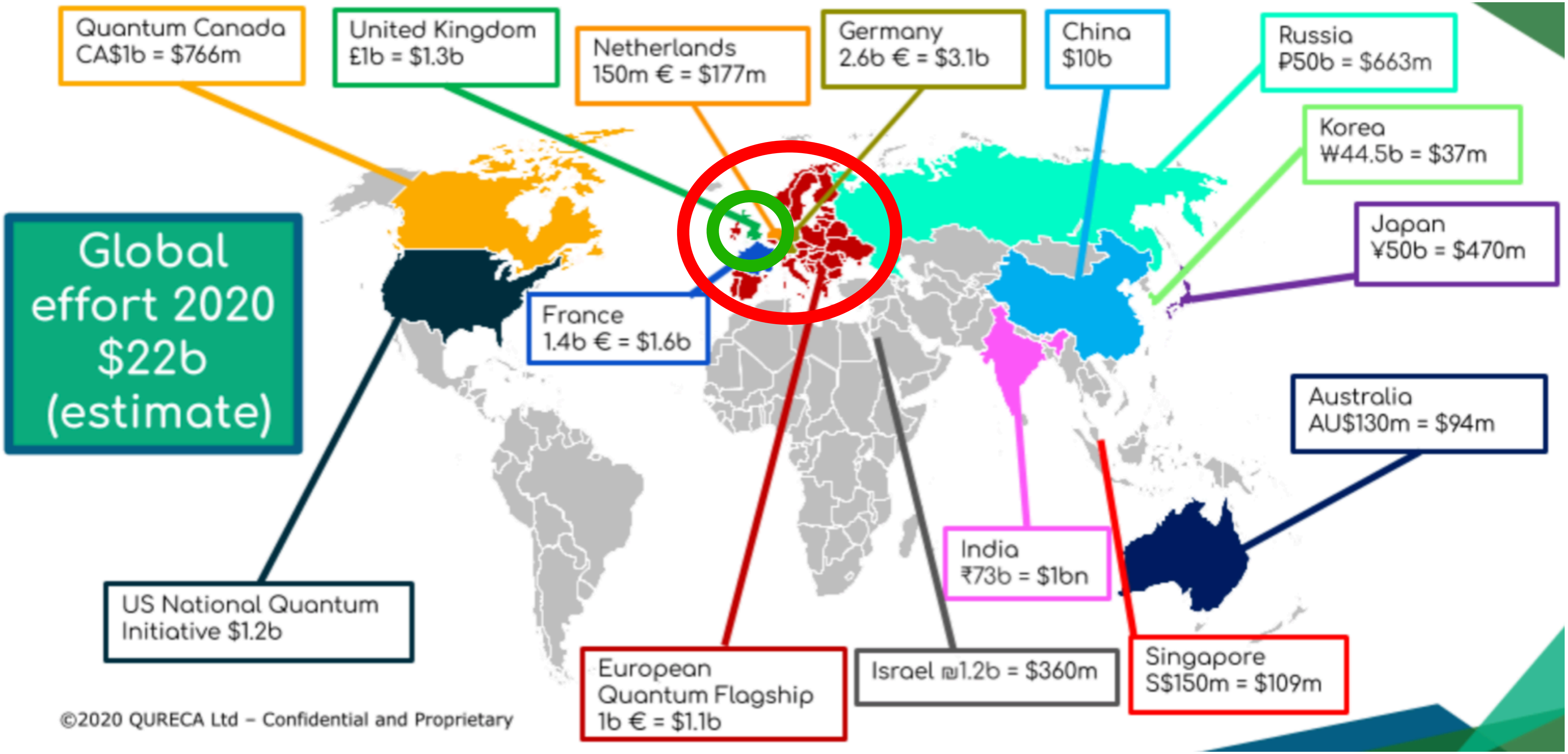
Couplings can modify pulsar properties



Becomes relevant for lower masses

Kaplan, Mitridate & Trickle, arXiv:2205.06817

Quantum Science & Technology Programmes



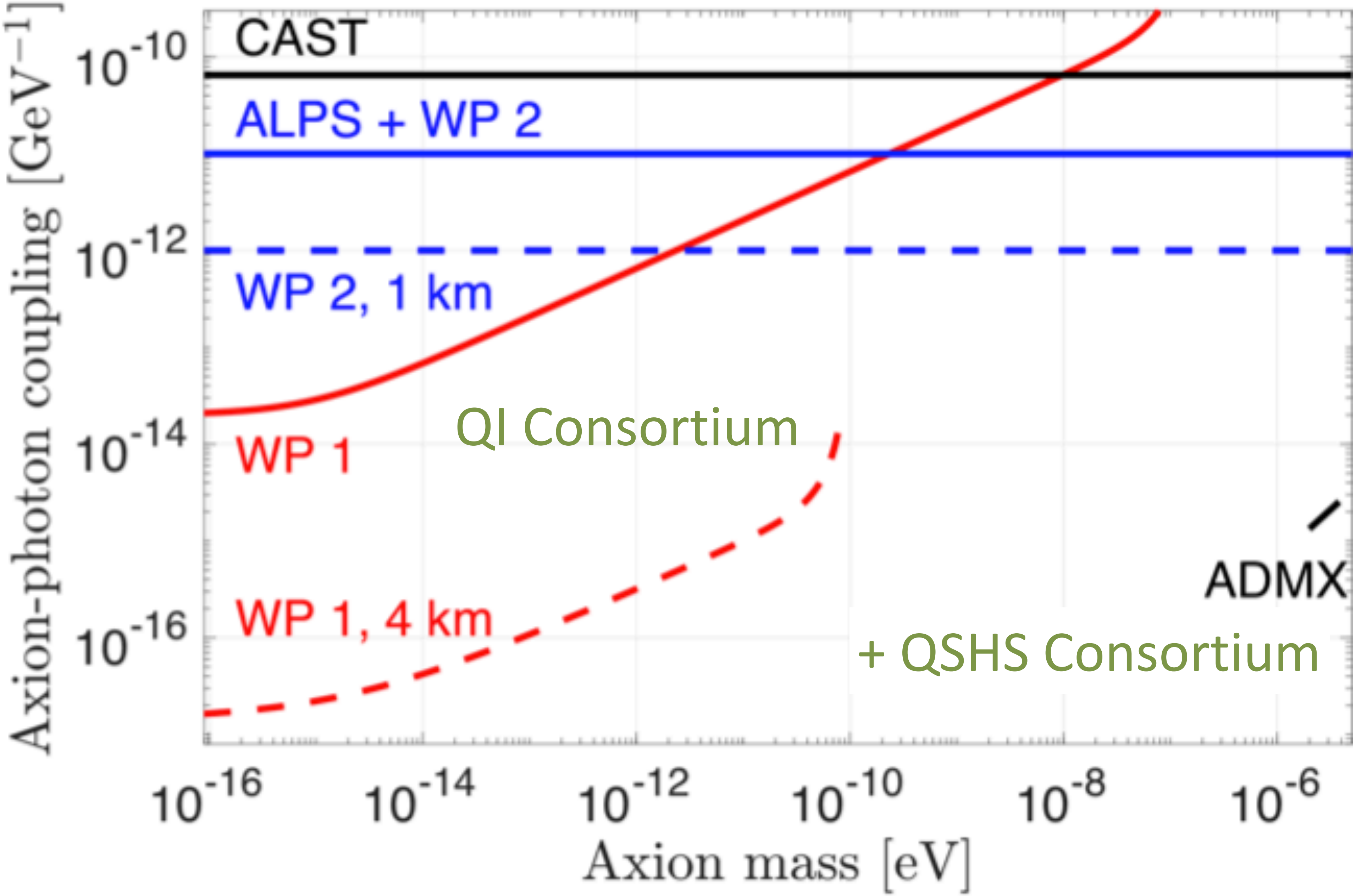
UK National Quantum Technology Programme

- *Phase 1 2015-2019, Phase 2 2020-24 (total investment Phase 1+2= £1B)*
- *Phase 2 investments:*
  - *Industry led projects to drive innovation and commercialisation of QT (£173m over 6 years)*
  - Renewal of the QT Research Hubs (£94m over 5 years)
  - Research training portfolio (£25m over 5 years)
  - Quantum Sensors for Fundamental Physics programme (£40m over 4 years)
  - National Quantum Computing Centre to drive development in this new technology

Seven samurai … including AION

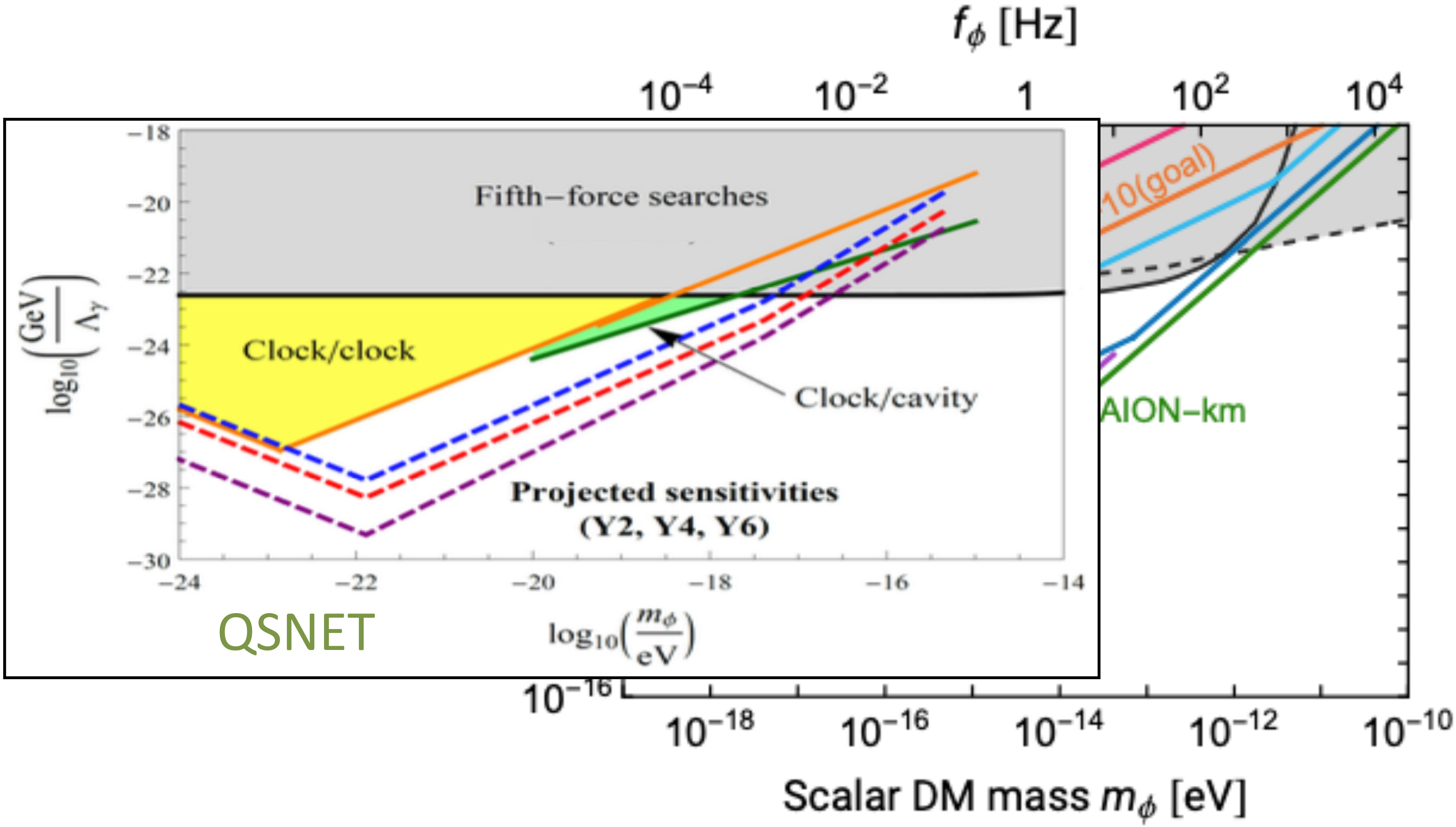
Quantum Technologies for Fundamental Physics:

Axion-Like Particles



Quantum Technologies for Fundamental Physics:

Ultralight Scalar Dark Matter Searches



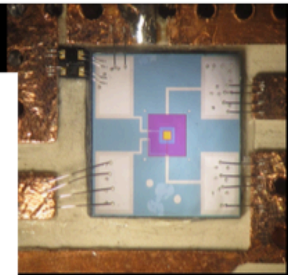
Quantum Sensors for the Hidden Sector

QSHS Quantum Sensors for the Hidden Sector

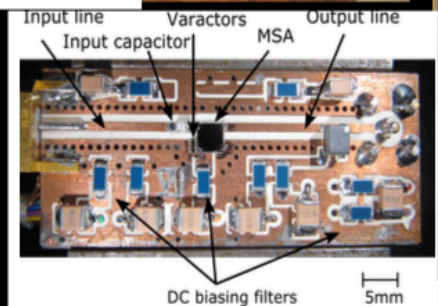
Sheffield, Cambridge, Oxford, RHUL, Lancaster, UCL, NPL, Liverpool

- Search for axions, etc., via conversion to microwaves in a high magnetic field
- Initial focus on QCD axion
- Collaboration with US ADMX experimental team

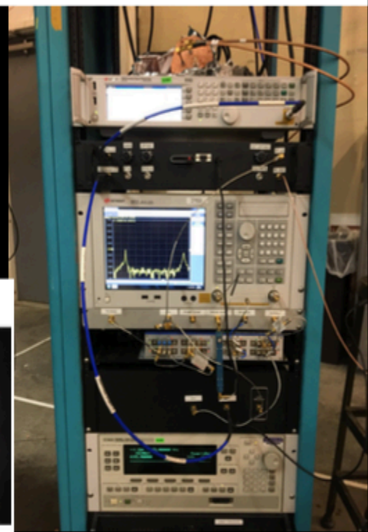
ADMX SQUID washer



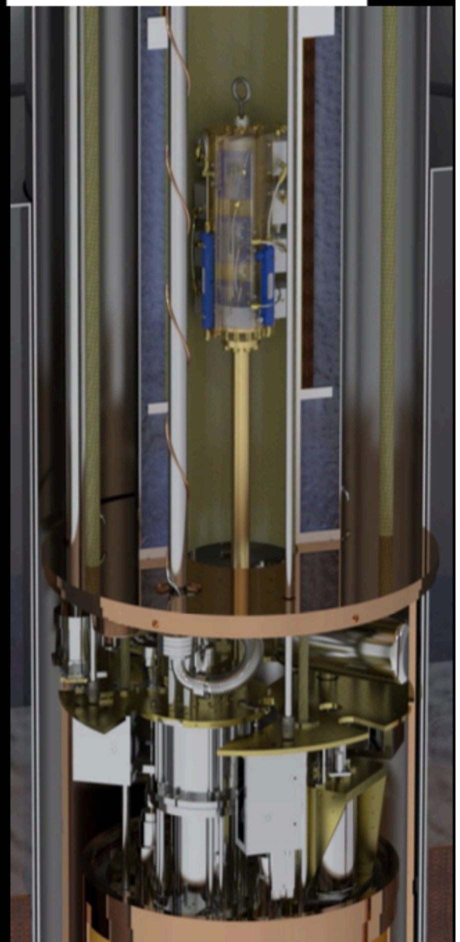
ADMX Microwave SQUID amplifier



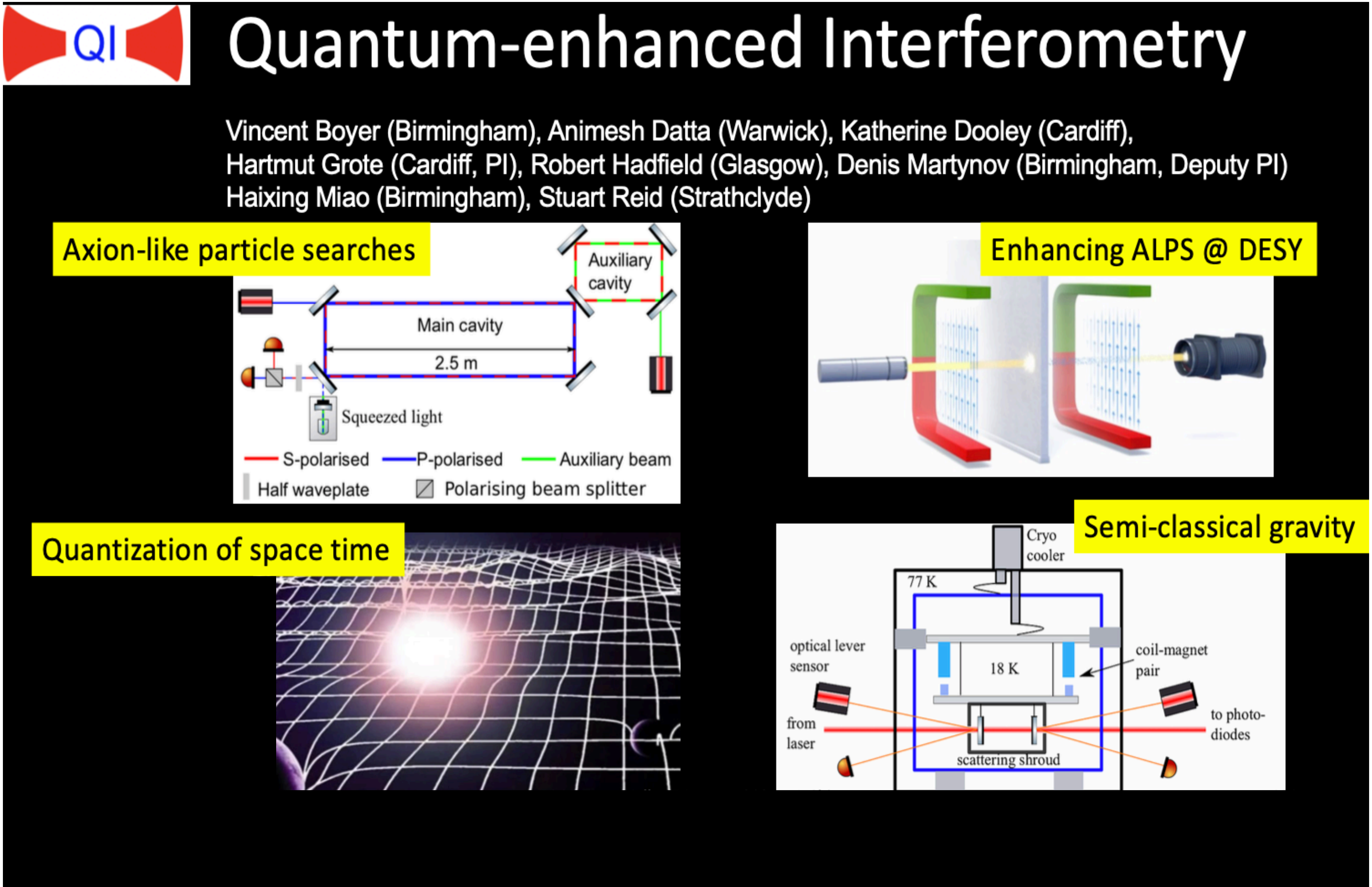
Resonant feedback test



ADMX SQUID housing



Quantum-Enhanced Interferometry



Clock Network to Measure Stability of Fundamental Constants

A network of clocks for measuring the stability of fundamental constants

G. Barontini, V. Boyer, X. Calmet, M. Chung, N. Fitch, R. Godun, J. Goldwin, V. Guarrera, I. Hill, M. Keller, J. Kronjaeger, H. Margolis, C. Mow-Lowry, P. Newman, L. Prokhorov, B. Sauer, M. Schioppo, M. Tarbutt, A. Vecchio, S. Worm

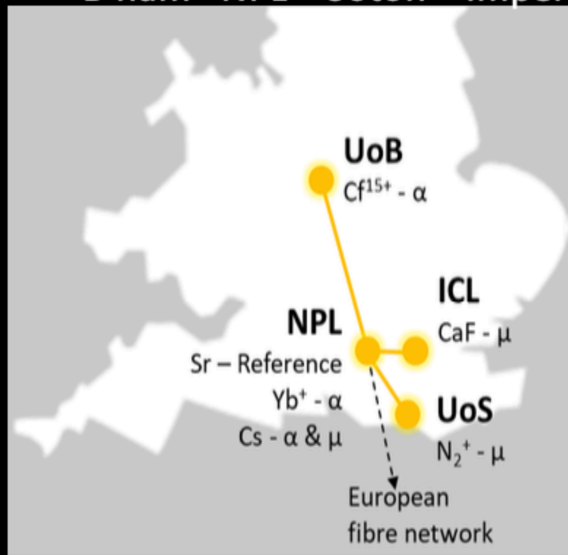
QT Hubs
- Sensors & timing
- Communications
- Computing & simulation

7 international institutions

B'ham NPL Soton Imperial

- Network of clocks across the UK, linked to Europe
- Search for variations in the fine-structure constant
- Search for variations in the proton/electron mass ratio

Clock	WP	Variations of fund. Constant
Ion clock Yb^+ (467 nm)	1	α
Atomic clock Sr (698 nm)	1	Stable reference
Atomic clock Cs (32.6 mm)	1	μ
Highly-charged ion clock Cf^{15+} (618 nm)	2	α
Molecular clock CaF (17 μm)	3	μ
Molecular ion clock N_2^+ (2.31 μm)	3	μ



e Giovanni Barontini talk
UK HEP Forum

Quantum-Enhanced Superfluid Technologies for Dark Matter & Cosmology

Quest-DMC

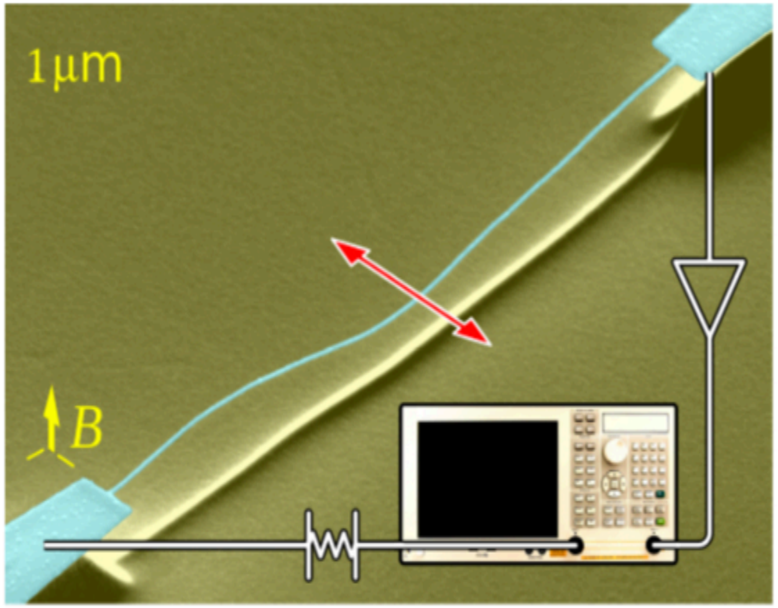
ROYAL HOLLOWAY UNIVERSITY OF LONDON

Lancaster University

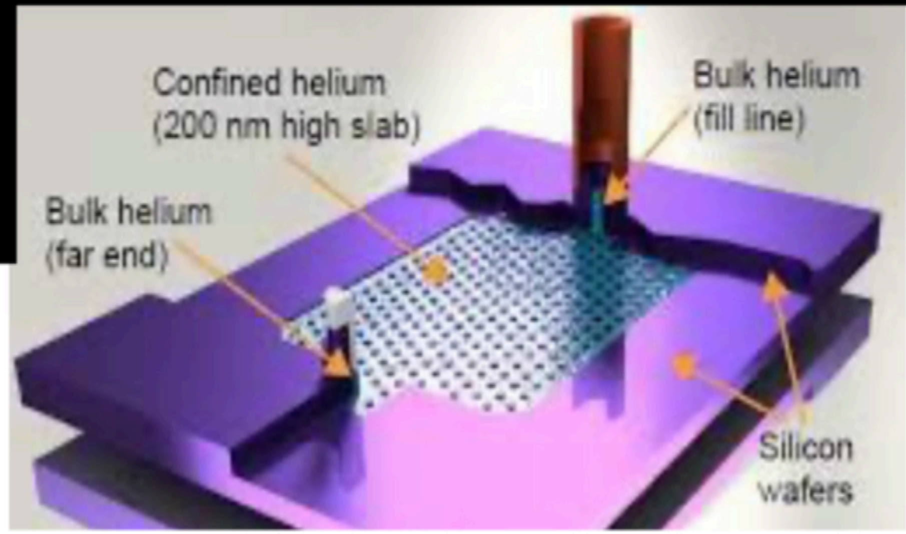
University of Sussex

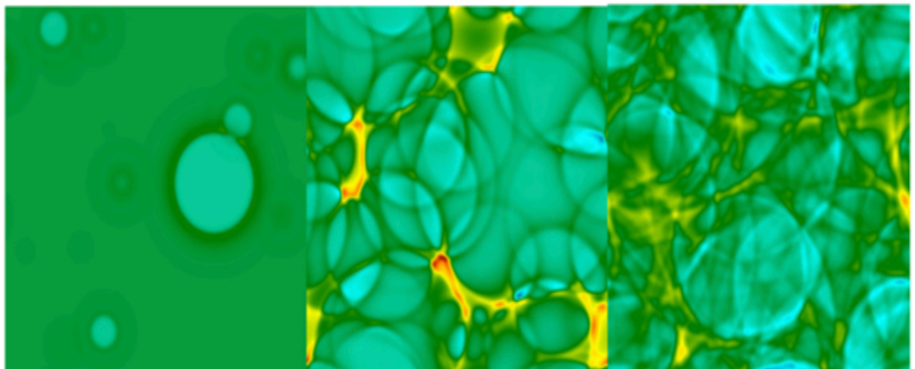
UNIVERSITY OF OXFORD

Detection of sub-GeV dark matter with a quantum-amplified superfluid ^3He calorimeter.



Phase transitions in extreme matter





[redacted]

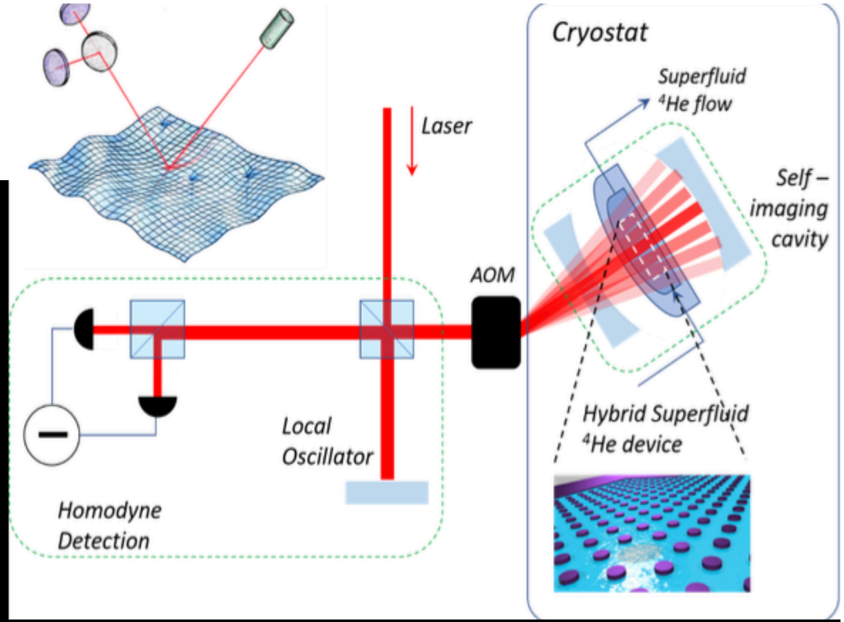
Quantum Simulators for Fundamental Physics

QSimFP

Team:

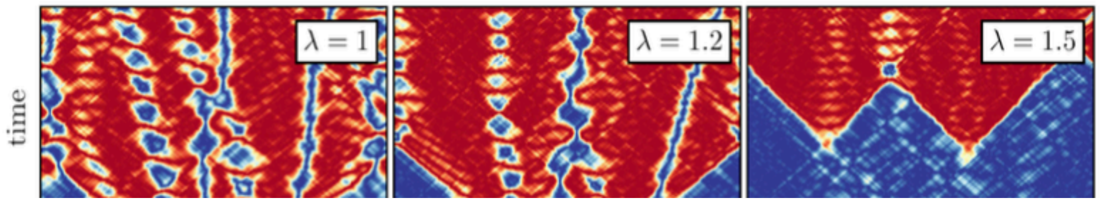
Silke Weinfurtner talk

Carlo F Barenghi (Newcastle),
Thomas Billam (Newcastle),
Ruth Gregory (Durham),
Gregoire Ithier (RHUL),
Zoran Hadzibabic (Cambridge),
Friedrich Koenig (St. Andrews),
Jorma Louko (Nottingham), Ian Moss (Newcastle),
John Owers-Bradley (Nottingham),
Hiranya Peiris (UCL),
Andrew Pontzen (UCL), Xavier Rojas (RHUL),
Pierre Verlot (Nottingham),
Silke Weinfurtner (Nottingham).



Science goals:

- Quantum simulation of decay of false vacuum
- Quantum wave-modes around analogues of black holes



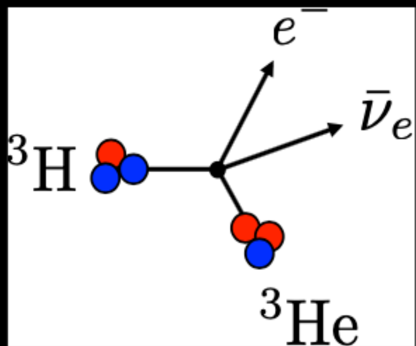
Quantum Technologies for Neutrino Mass Consortium

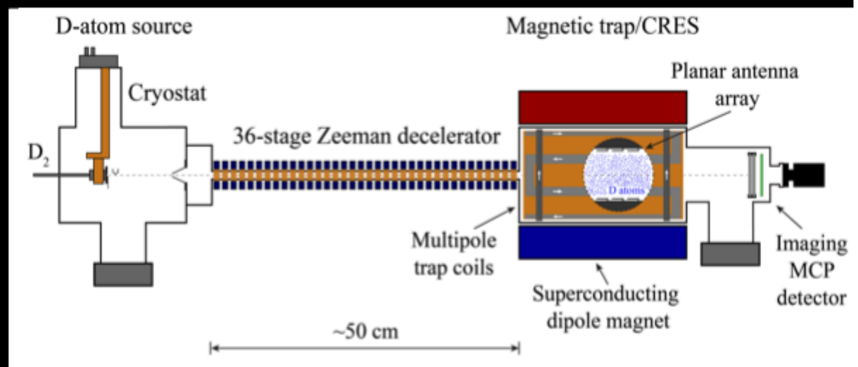
F. Deppisch[1], J, Gallop[2], L. Hao[2], S. Hogan[1], L.Li[3], R. Nichol[1], Y. Ramachers[4], R. Saakyan[1](PI), D. Waters[1], S. Withington[5]

A collaboration of particle, atomic and solid state physicists, electronics engineers and quantum sensor experts

Initial goal:

- Technology demonstration for measuring neutrino mass in ^3H β-decay





Ultimate goal:

- Measurement at a tritium facility, e.g., Culham