Searching for Dark Matter with AION
(Atom Interferometer Observatory and Network)

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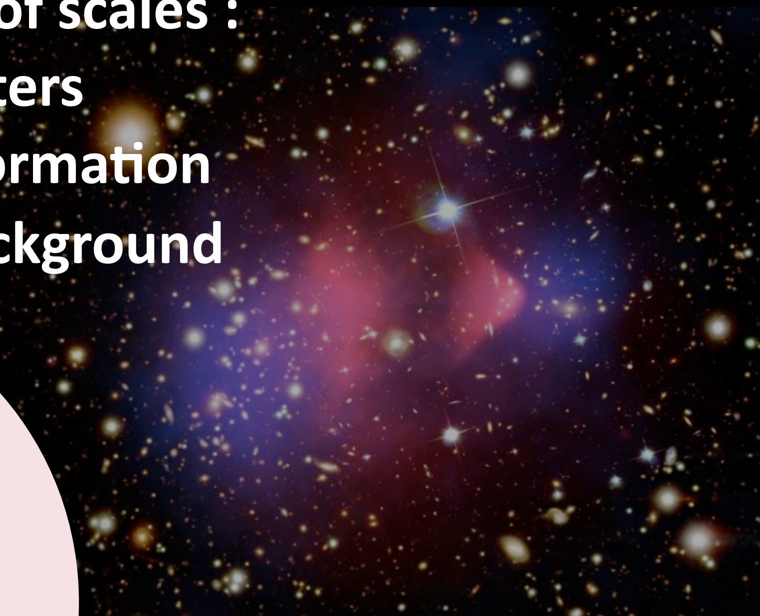
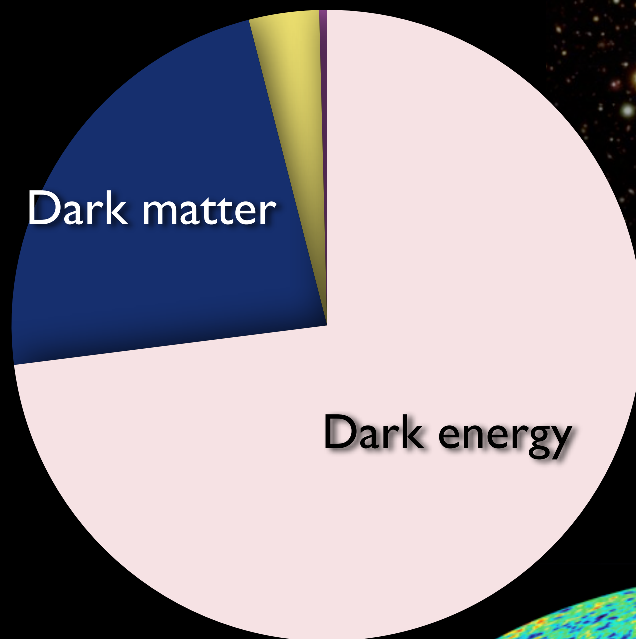
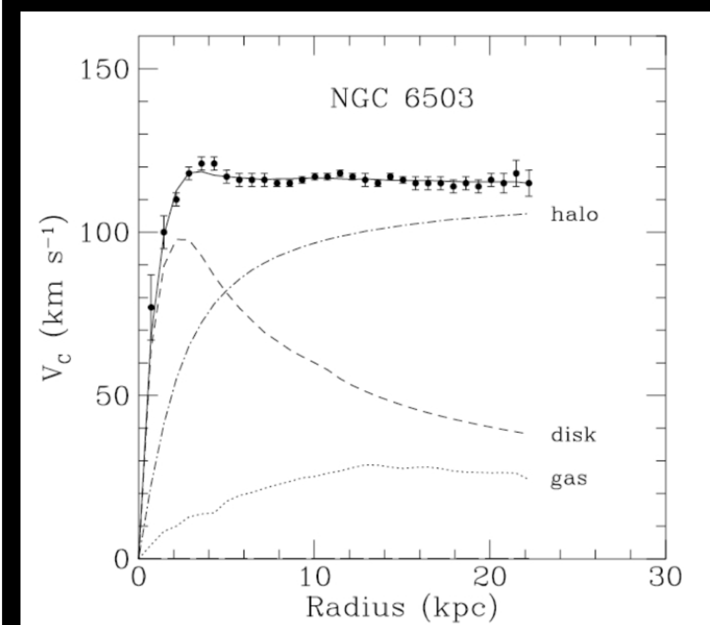
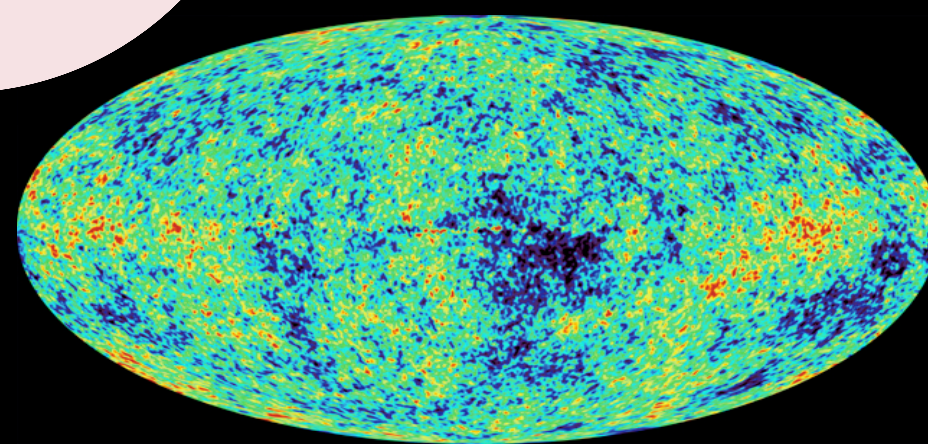
Dark matter

Evidence from a variety of scales :
– galaxy and galaxy clusters
– large scale structure formation
– Cosmic Microwave Background



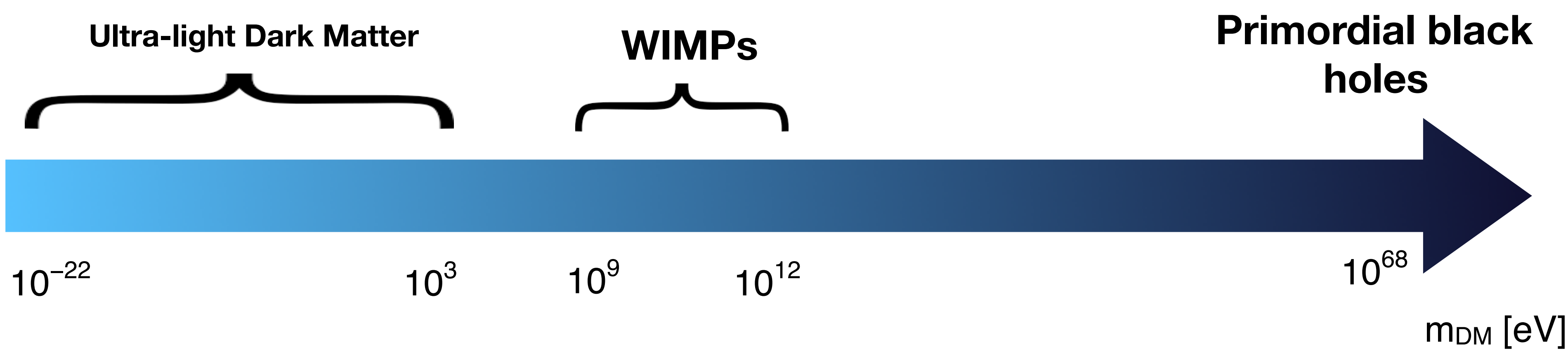




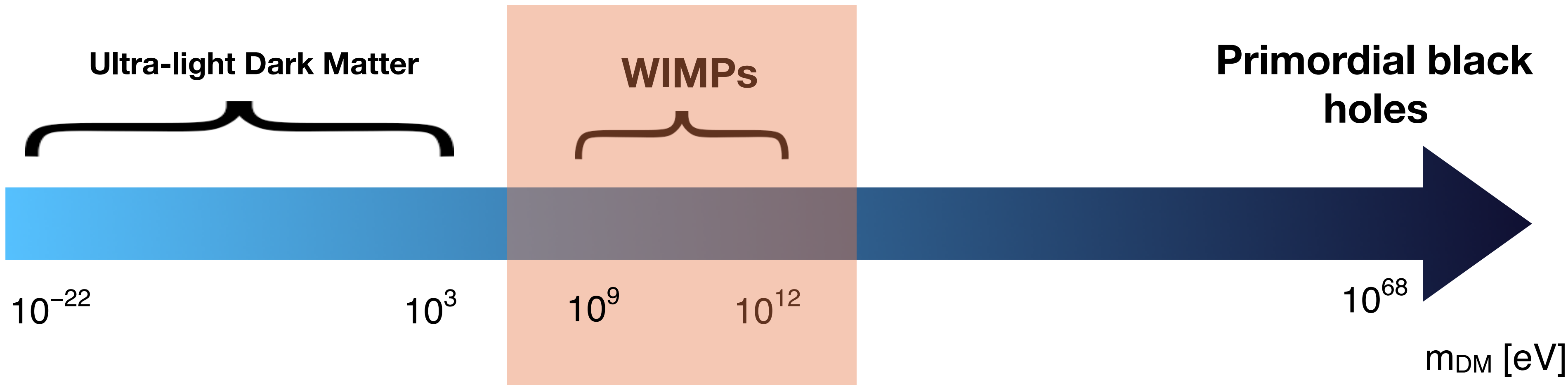


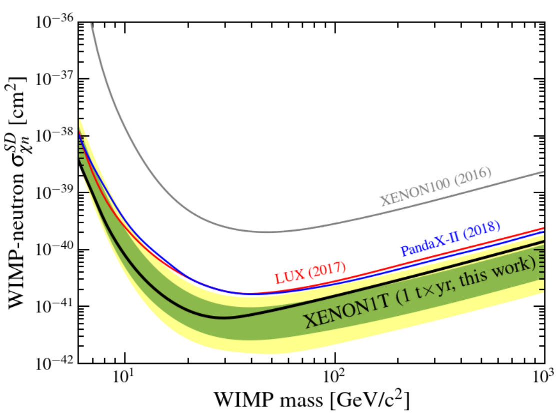
Nature of dark matter? One of the most fundamental questions in physics

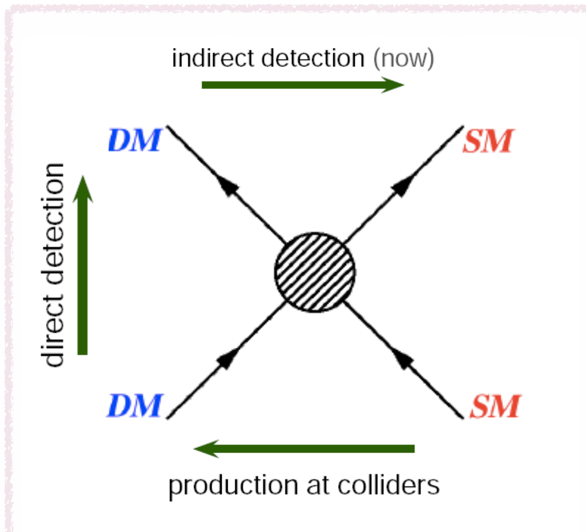
Dark Matter : Landscape of candidates

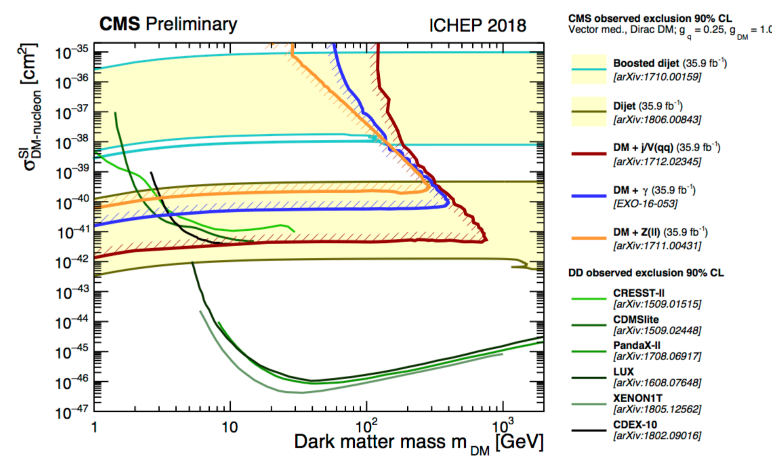


Dark Matter : Landscape of candidates







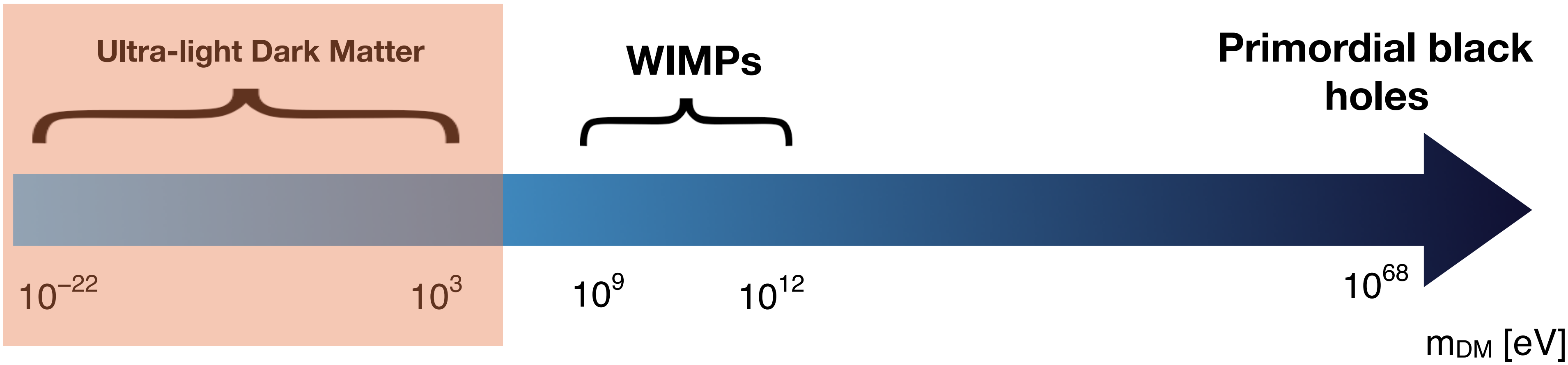


WIMPs very well motivated theoretically, independently from cosmology and particle physics

Direct detection and colliders highly constrained large range of parameter space

Ultra light Dark Matter (ULDM)

An attractive alternative to WIMPs : ULDM covers broad category of theoretical candidates



Axions

- **Proposed by Peccei and Quinn (PQ) as an elegant solution to the 'strong CP problem' : postulated a new global U(1) symmetry that is spontaneously broken at some large energy scale.**
- **Consequence of this mechanism is a new pseudoscalar boson, the axion, which is the Nambu-Goldstone boson of the PQ symmetry.**
- **This PQ symmetry explicitly broken at low energies, so axion acquires a small mass**
- **Properties of axions closely related to those of neutral pions, two-photon interaction plays a key role for most searches**

$$\mathcal{L}_{a\gamma} = \frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = -g_{a\gamma} \, \mathbf{E} \cdot \mathbf{B} \, a$$

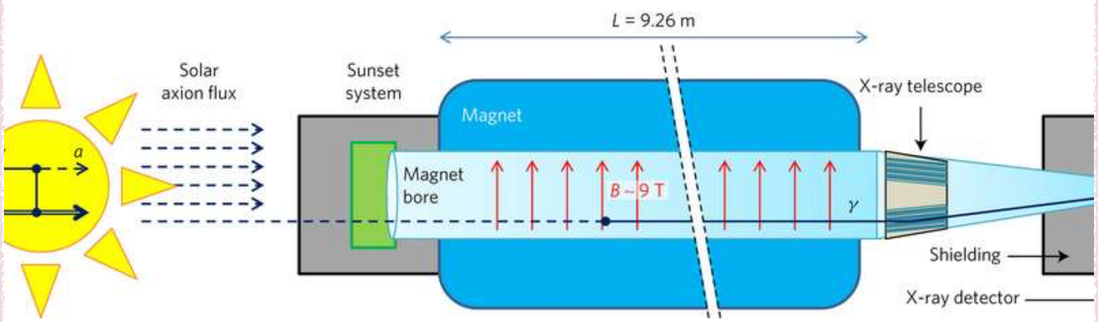
Axion-like particles (ALPs)

- String theory predicts existence of axion-like massive scalar fields.

Ultra light Dark Matter (ULDM)

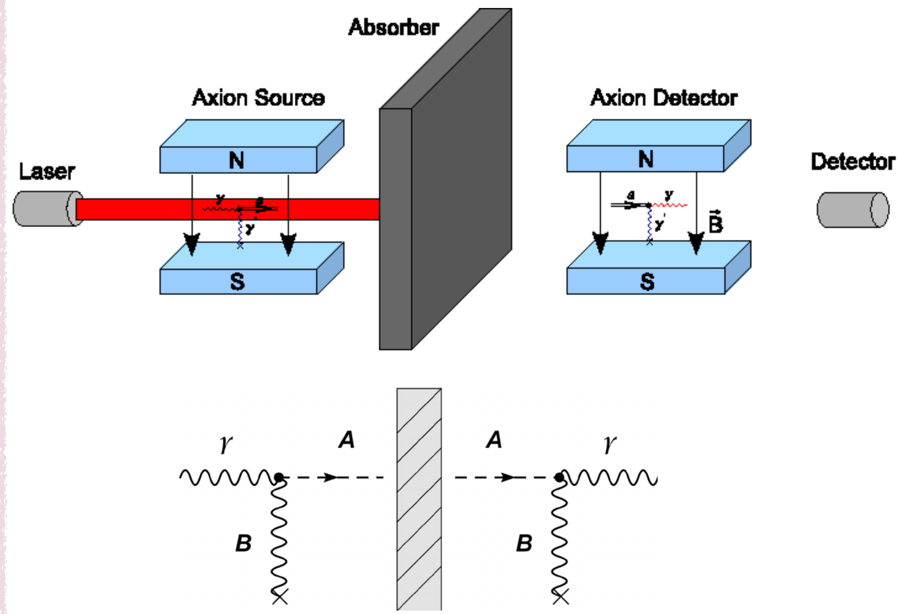
Experiments searching for these include helioscope searches, Light-Shining-Through-Wall, and haloscope searches

Helioscope Searches

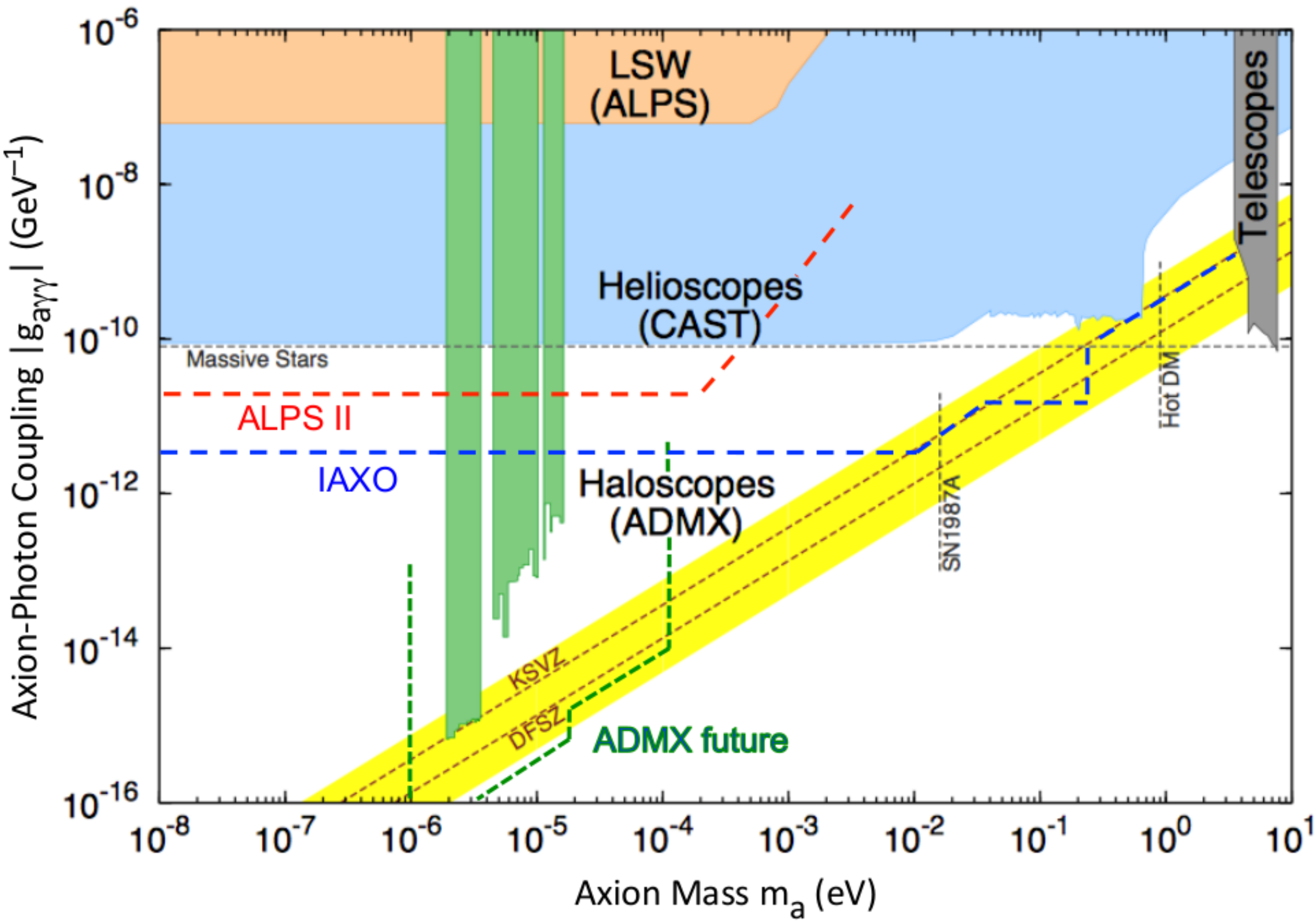


CERN Axion Solar Telescope (CAST) : uses a refurbished LHC test magnet (9T) pointed towards Sun

Light-Shining-Through-Wall



Ultra light Dark Matter (ULDM)



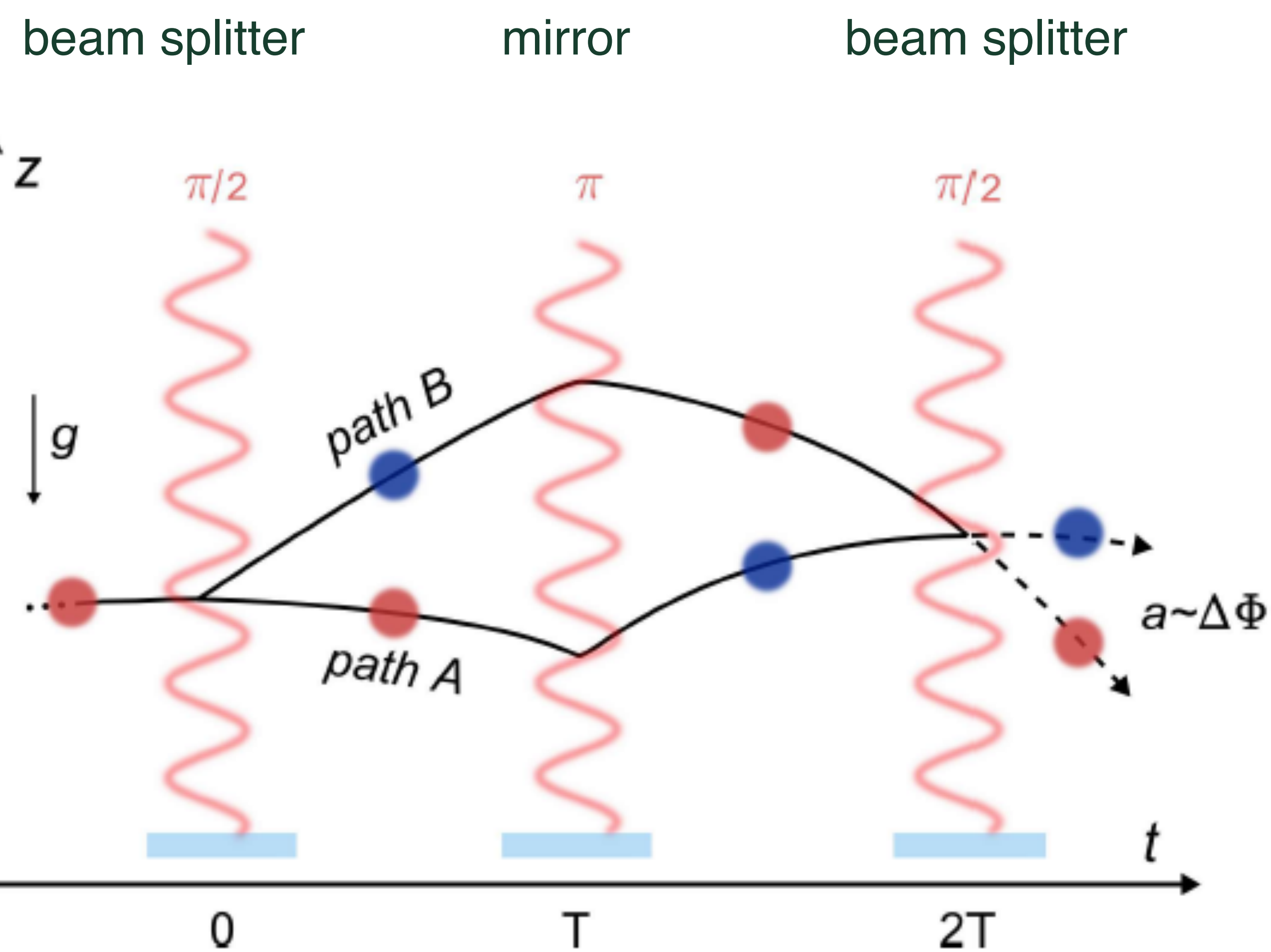
These experiments cover a large range of phase space

But, ULDM candidates with masses in the range 10^{-22}– 10^{-14} eV requires new approaches

Atom Interferometry

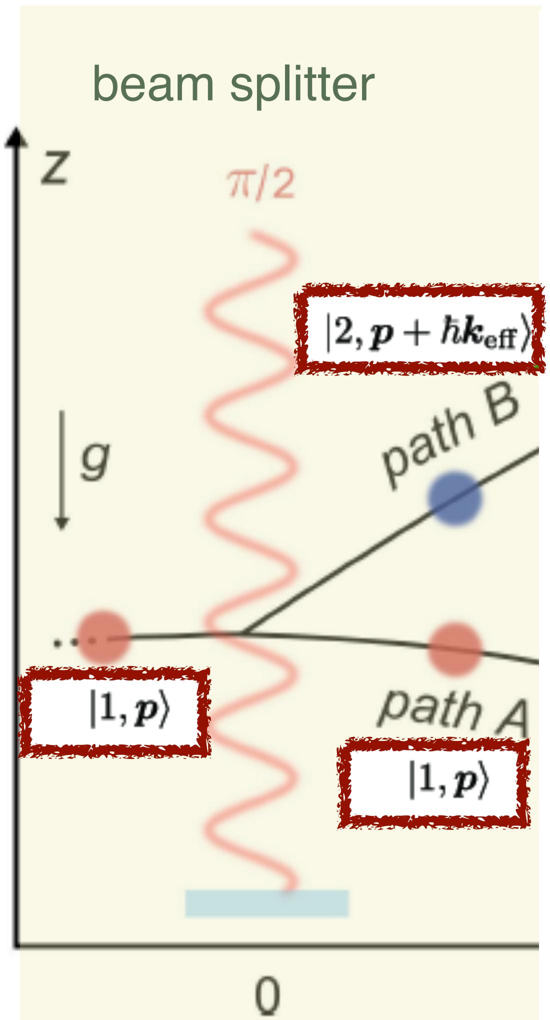
One of the emerging technologies that shows promise to probe this mass range is quantum sensors in the form of atom interferometer.

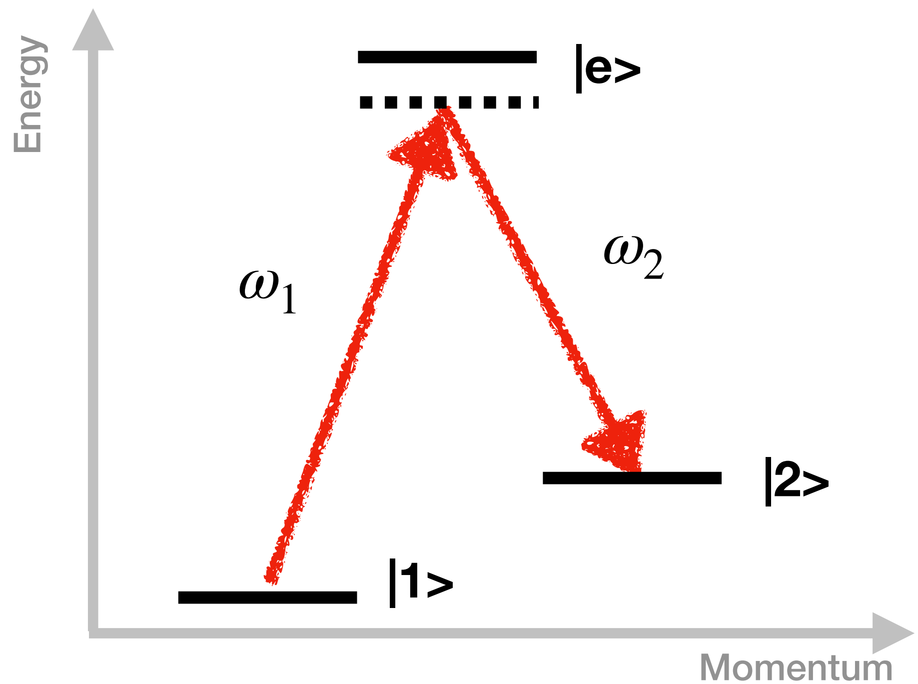
- Exploit the wave-like behavior of matter. Typical de Broglie wavelength of atom much smaller than optical wavelength, atom interferometers are remarkably sensitive devices
- Analogous to laser interferometers by dividing, reflecting and then recombining atomic wavepackets to produce an interference pattern.



Atom Interferometry

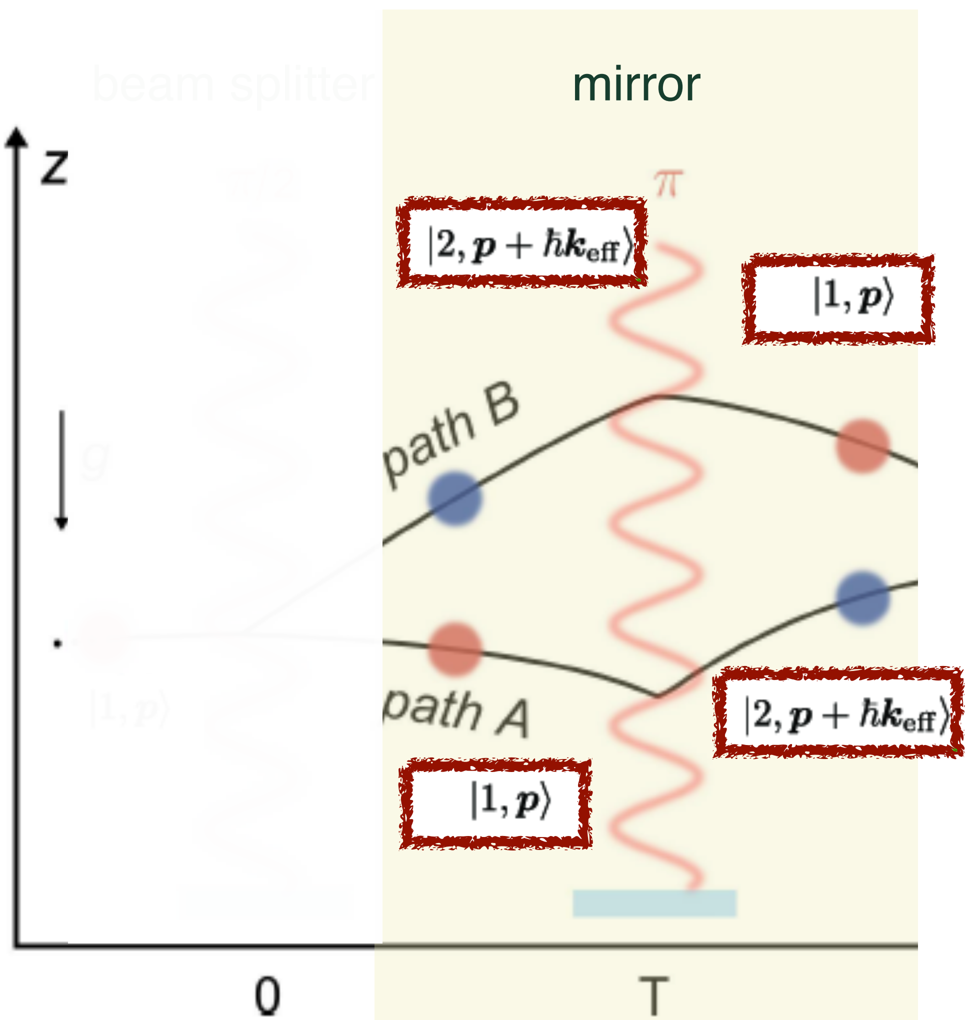
Current-generation interferometers based on two-photon Raman transitions driven by counter propagating beams





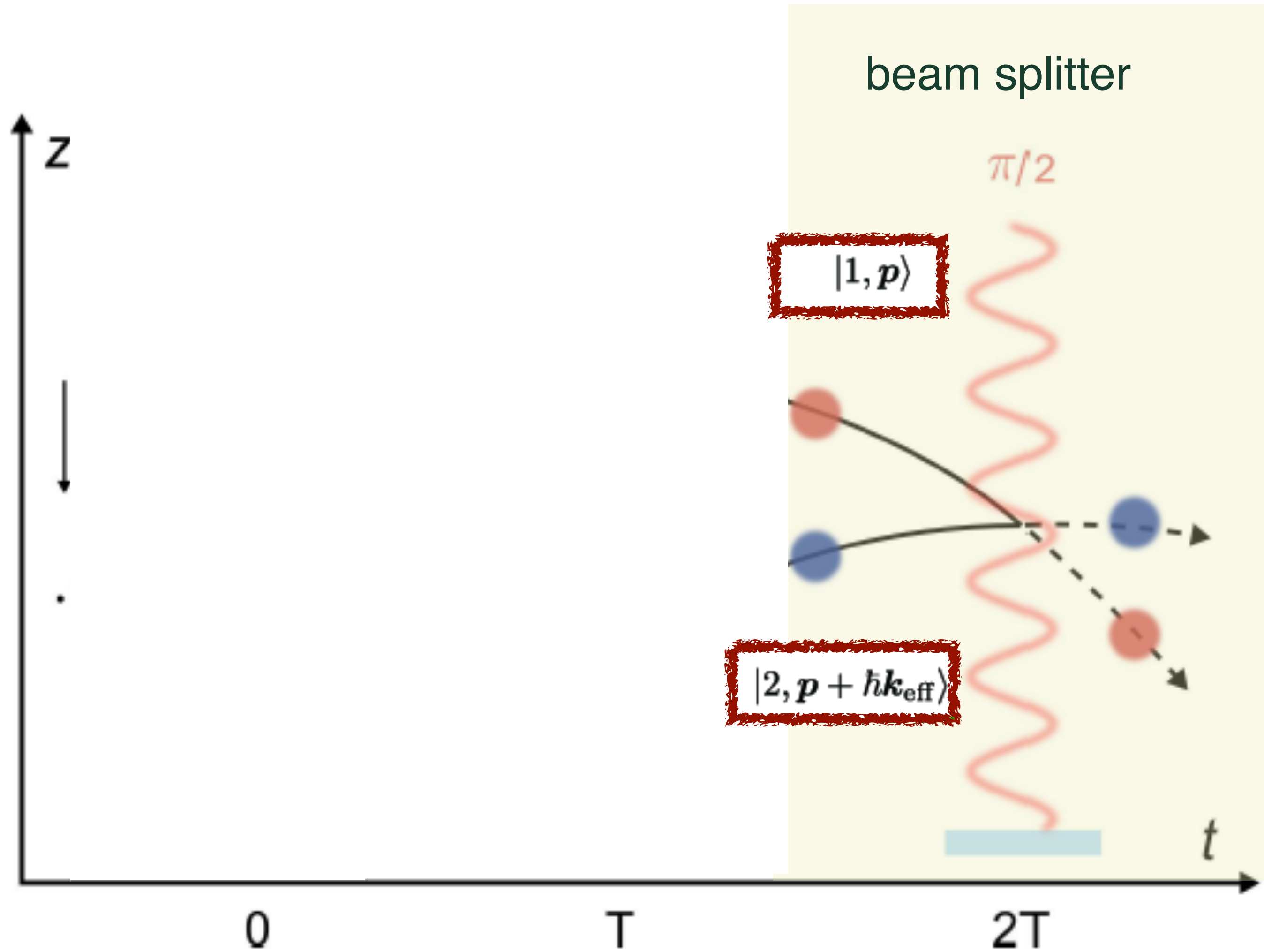
- Atom starts in ground state |1>
- A π/2 optical Raman pulse splits atomic wavefunction into an equal superposition of |1〉 and |2〉
- Transition driven by counter-propagating light beams with frequencies ω_1 and ω_2 ; absorption of photon with frequency ω_1 and stimulated emission of frequency ω_2
- Momentum transfer of $\hbar k_{eff}$ to the wave function component in state |1>

Atom Interferometry

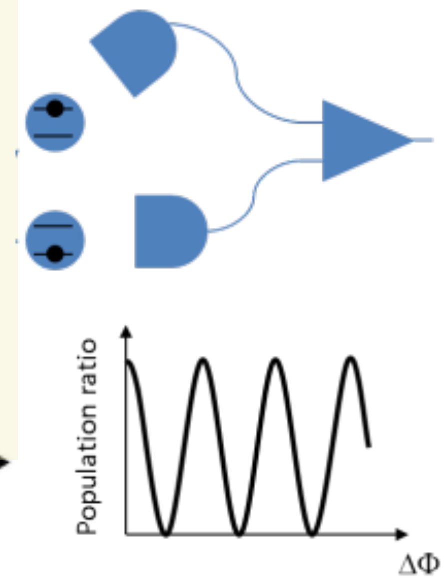


- Two components propagate freely for a time T
- A π pulse swaps the internal states and exchanges momenta

Atom Interferometry



- A π/2 pulse closes interferometer sequence
- Produce interference fringes in the populations of |1> and |2>
- Accumulation of phase along two paths



Any effect that modifies the energy across the 2 arms of the interferometer appears in this interferometer phase, this can be used to constrain new physics that couples to matter.

Atom Interferometer Observatory Network (AION)

A UK-led initiative proposing a series of multi-purpose atom interferometers with progressively increasing baselines to :

- **Explore well-motivated ultra-light dark matter candidates several orders of magnitude beyond current bounds;**
- **Explore mid-frequency band GWs from the very early Universe and astrophysical sources**
- **Potential sensitivity to searches for new particles and fields such as fifth forces, dark energy, precision measurements of variations in fundamental constants, basic physical principles such as foundations of quantum mechanics and Lorentz invariance.**

Atom Interferometer Observatory Network (AION)

Core team

Birmingham
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Y. Singh*

Cambridge
V. Gibson**
U. Schneider*

Imperial College London
O. Buchmueller** [co-coord.]
M. Tarbutt*
B. Sauer*

Kings College London
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Liverpool
T. Bowcock**
J. Coleman** [co-coord.]

National Physical Lab.
W. Bowden***
P. Gill***
R. Hobson***

Oxford
E. Bentine*
C. Foot*
J. March-Russell**
I. Shipsey**

Rutherford Appleton Lab.
P. Majewski**
T. Valenzuela**
I. Willmut**

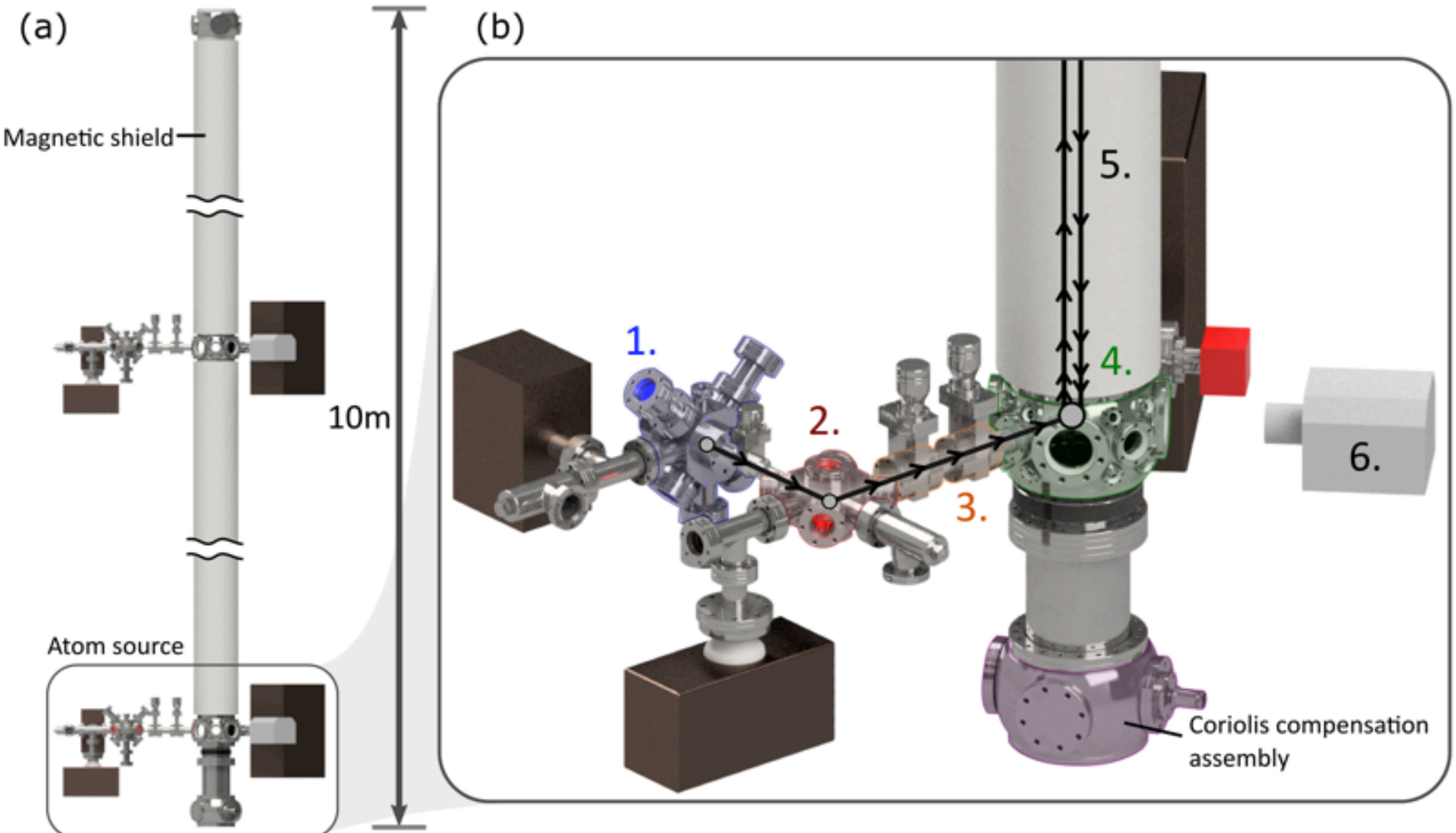
Main UK funding source:
**EPSRC; **STFC, ***NMS*

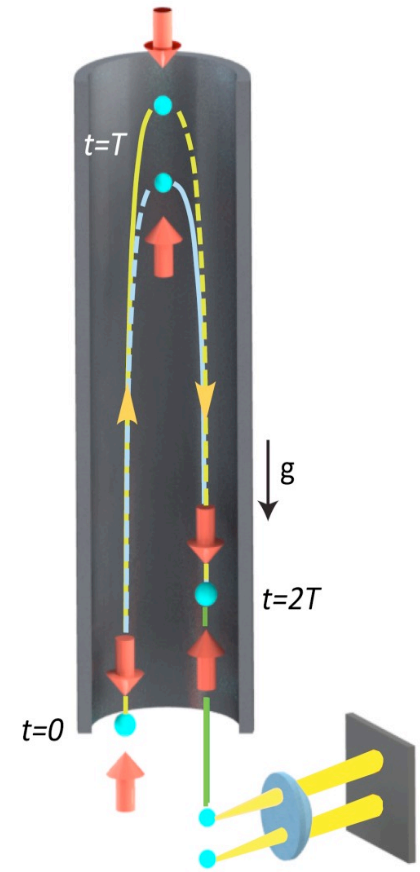
UK
- 8 Institutes
- 22 Core Members
- Many Associates

Atom Interferometer Observatory Network (AION)

Stage 1 : AION-10

Construct 10m atom interferometer following a similar apparatus at Stanford as prototype



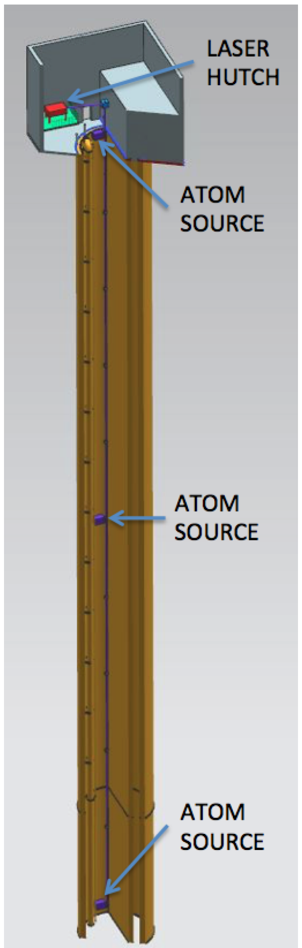


1. Strontium atoms are laser-cooled in a 2D magneto-optical trap (MOT) using the 461nm transition
2. Cooled in a 3D MOT using blue 461nm light and red 689nm light
3. Ultracold atoms are transported to interferometry chamber
4. Atoms are launched upwards
5. Atoms follow a parabolic freefall trajectory, during which interferometry sequence is performed.
6. Interference fringes are detected using an imaging system.

Atom Interferometer Observatory Network (AION)

Stage 2 : AION-100

MAGIS-100



100m atom interferometer is planned that would be sensitive to ULDM

- 2 ensembles of atom interferometers along a single vertical baseline.
- Signal would be a differential phase shift between the two interferometers.
- Potential sensitivity to ULDM in the mass range $10^{-22} - 10^{-14}$

Close collaboration on an international level with the US initiative, MAGIS-100, which pursues a similar goal of an eventual km-scale atom interferometer on a comparable timescale.

Ultra light scalar dark matter

Ultra-light spin 0 particles are expected to form a coherently oscillating classical field

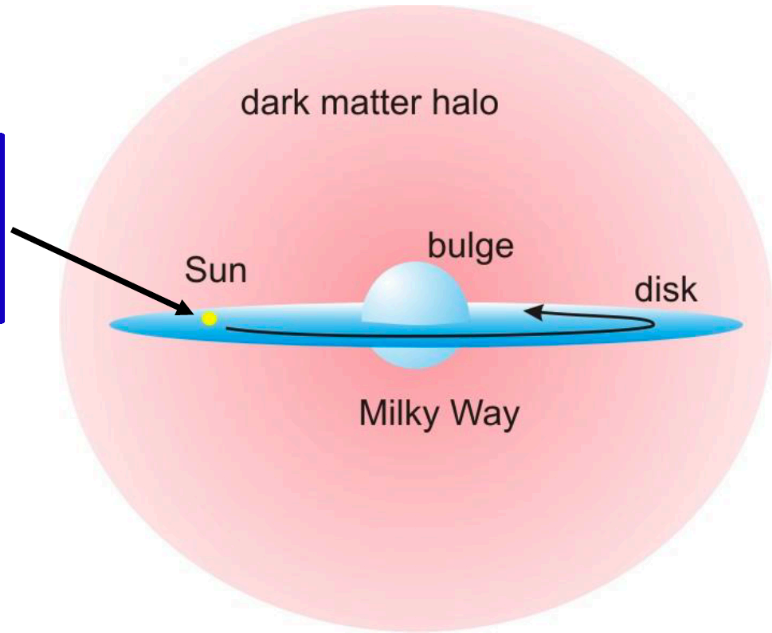
$$\mathcal{L} = \frac{1}{2}((\partial_\mu \Phi)^2 - m^2\Phi^2)$$

$$\phi(t) = \phi_0 cos(E_\phi t/\hbar)$$

Energy density of $\rho = \frac{m^2\phi_0^2}{2}$

$\rho_{DM} \approx 0.4$ GeV/cm^3

$v_{DM} \sim 300$ km/s



Ultra light scalar dark matter

PHYSICAL REVIEW D 97, 075020 (2018)

$$\mathcal{L} = +\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 \; - \sqrt{4\pi G_N}\phi\left[d_{m_e}m_e\bar{e}e - \frac{d_e}{4}F_{\mu\nu}F^{\mu\nu}\right]$$

Scalar field

Electron coupling

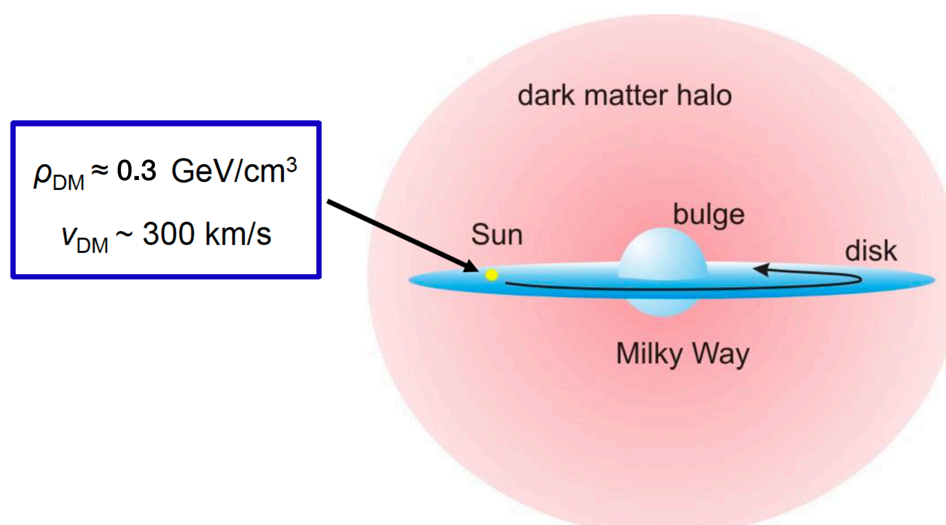
Photon coupling

Bosonic DM with mass << 1eV in highly classical state, approximated by non-relativistic plane wave solution:

$$\phi(t,\mathbf{x}) = \phi_0 \cos\left[m_\phi(t - \mathbf{v}\cdot\mathbf{x}) + \beta\right] + \mathcal{O}(|\mathbf{v}|^2)$$

where amplitude determined by local DM density

$$\phi_0 \simeq \sqrt{2\rho_{\rm DM}}/m_\phi$$



Ultra light scalar dark matter

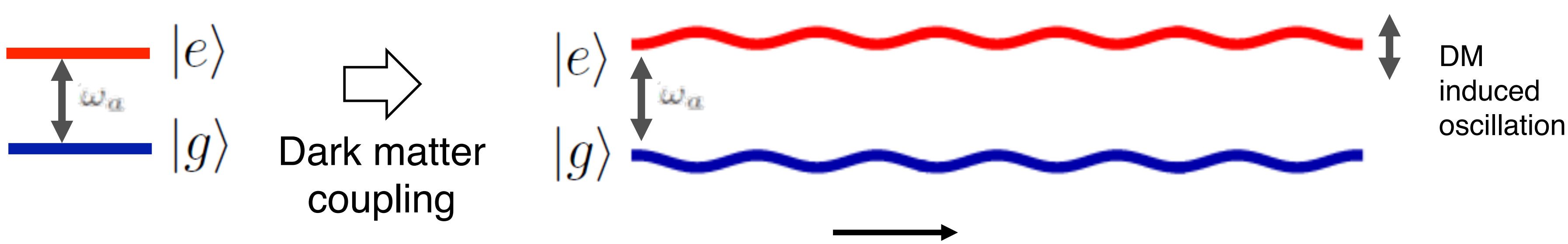
PHYSICAL REVIEW D 97, 075020 (2018)

The DM scalar field oscillation combined with the coupling to matter cause fundamental constants for instance electron mass and fine structure constant to oscillate in time

$$m_e(t, \mathbf{x}) = m_e\left[1 + d_{m_e}\sqrt{4\pi G_N}\phi(t, \mathbf{x})\right]$$

$$\alpha(t, \mathbf{x}) = \alpha\left[1 + d_e\sqrt{4\pi G_N}\phi(t, \mathbf{x})\right].$$

Can search for DM-induced time variations of atomic transition frequencies

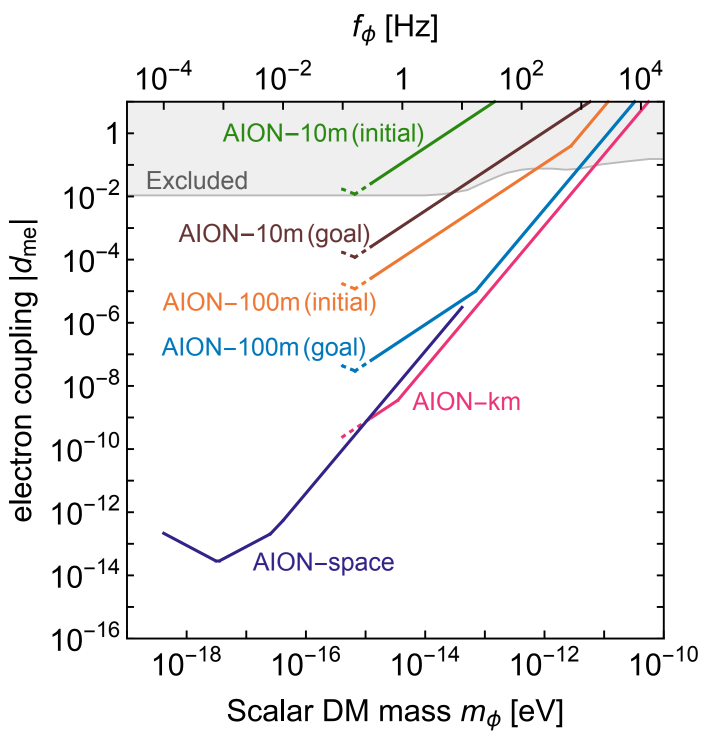


Courtesy of Jason Hogan

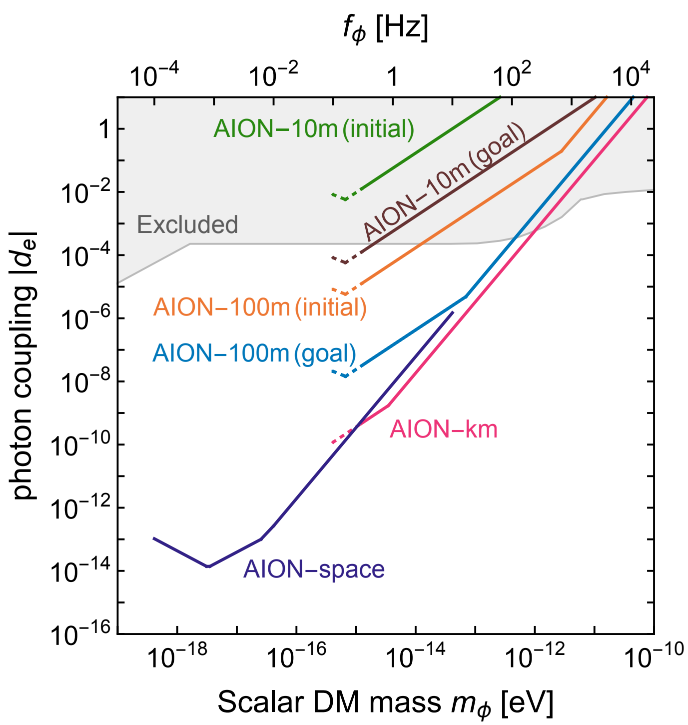
Ultra light scalar dark matter

Based on: Arvanitaki et al., PRD **97**, 075020 (2018)

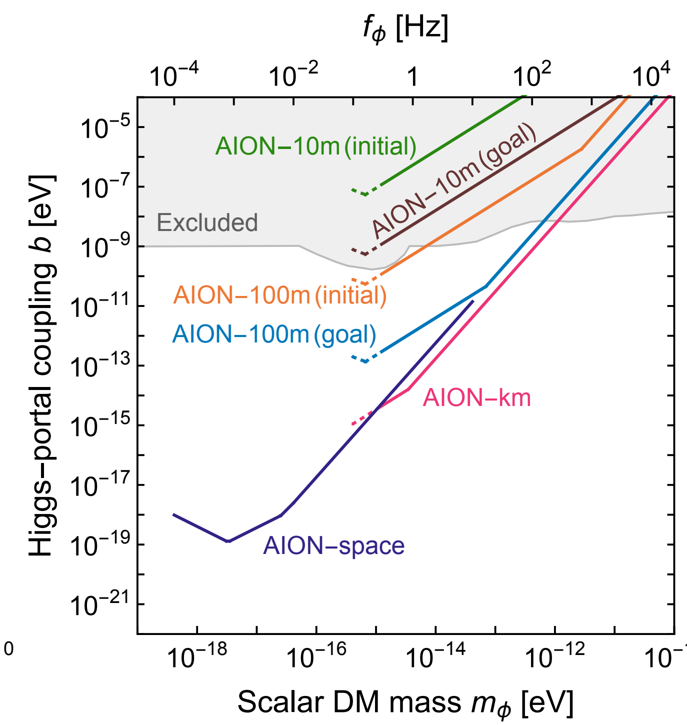
Coupling to electron



Coupling to photon



Higgs portal b coupling



Different configurations of the atom interferometer also open possibility to search for vector dark matter candidates

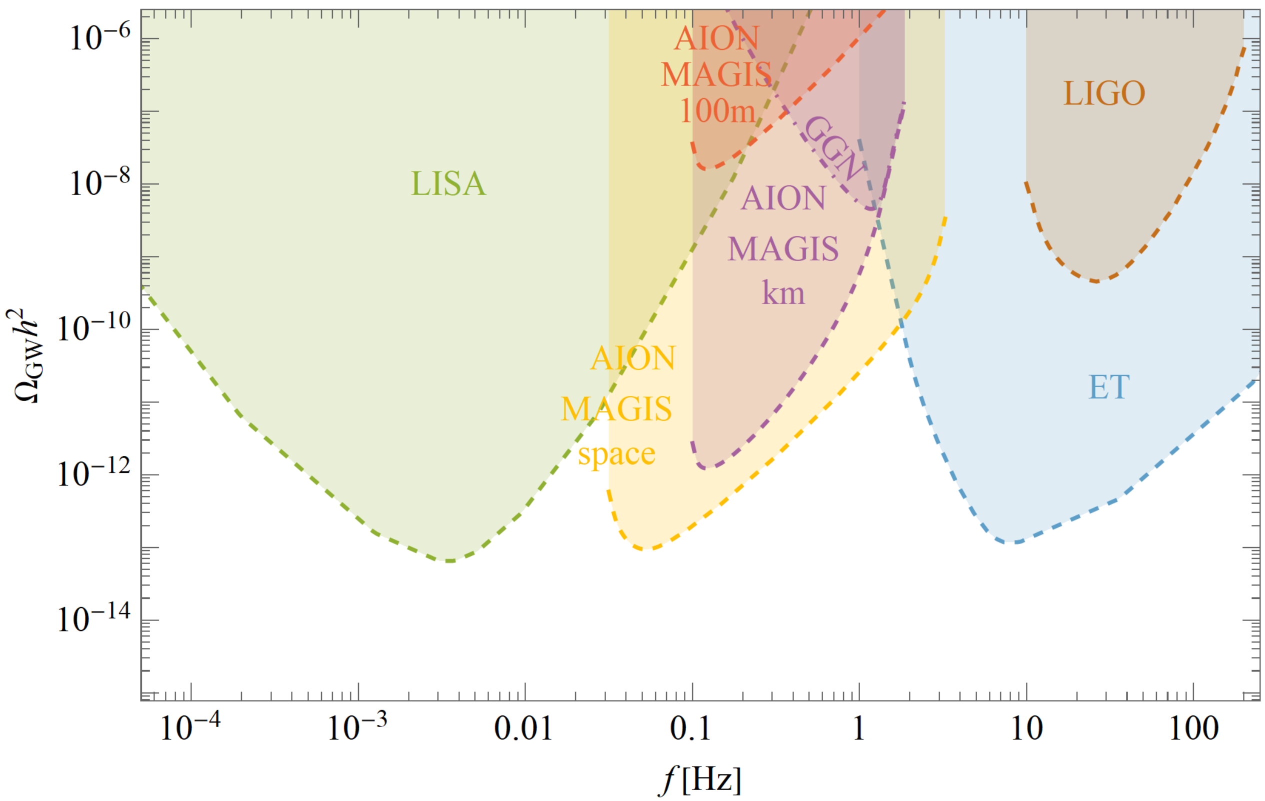
Atom Interferometer Observatory Network (AION)

Stage 3

Build a km scale atom interferometer for gravitational wave detection in the mid-band frequency range, not covered by LIGO or the future planned LISA detector

Mid-band science

- Detect sources BEFORE they reach the high frequency band [LIGO, ET]
- Optimal for sky localization: predict when and where events will occur (for multi-messenger astronomy)



Stage 4 : satellite-based (thousands of kilometres scale) detectors

Atom Interferometer Observatory Network (AION)

AION-10: Stage 1 [year 1 to 3]

- 1 & 10 m Interferometers & Site Development for 100m Baseline

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: Stage 4 [after AION-KM]

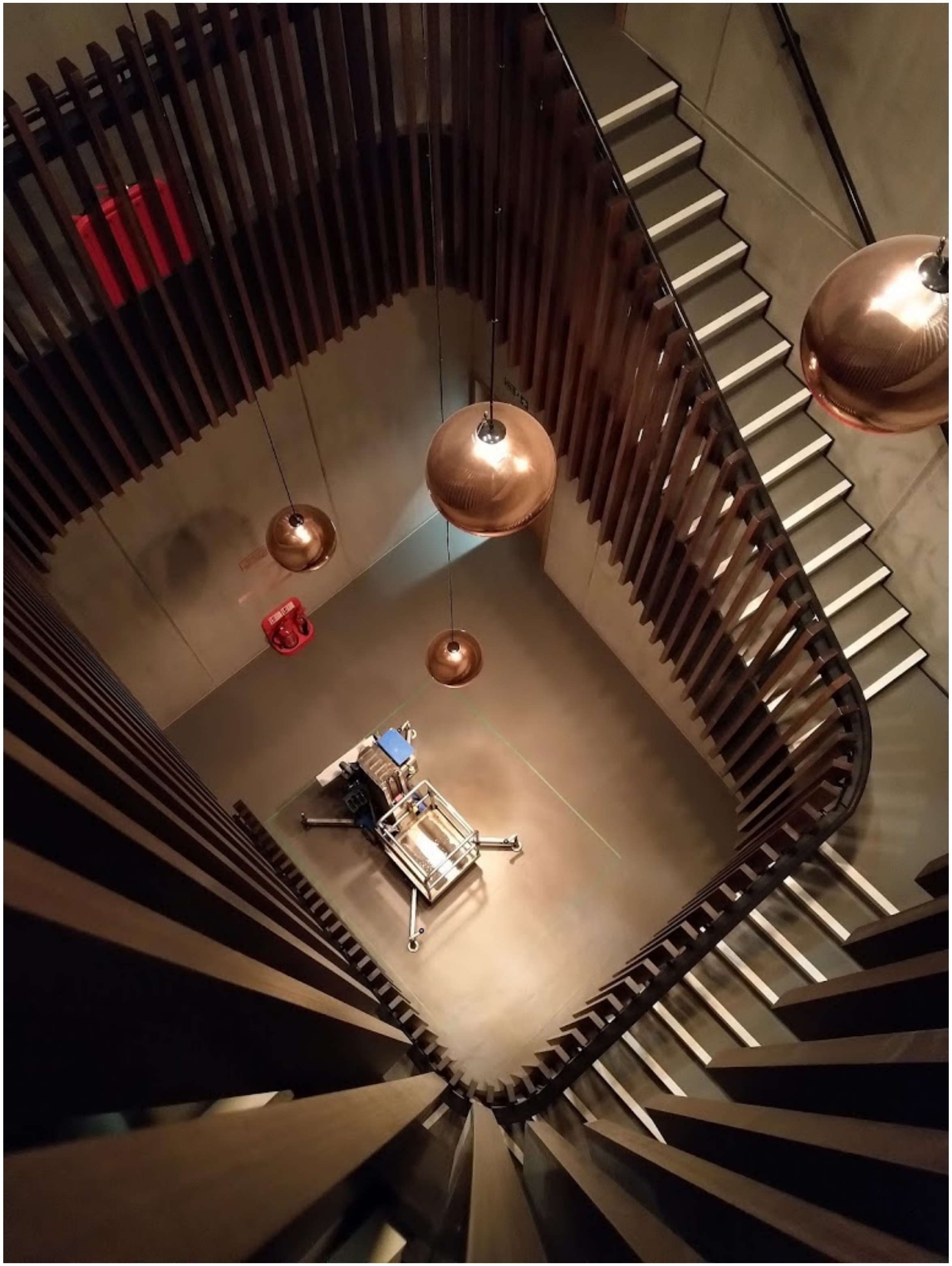
- Space based version

Courtesy of Oliver Buchmueller

AION-10

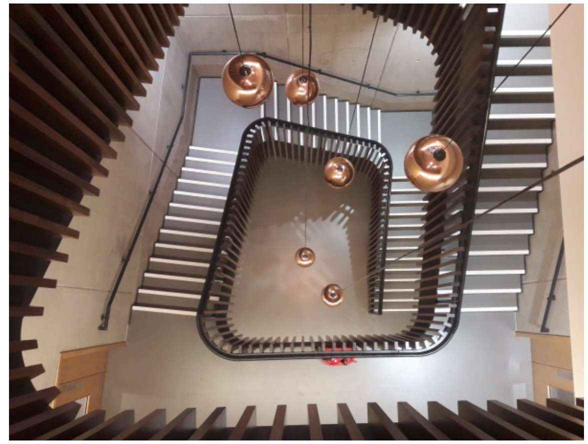
Beecroft building, Oxford physics

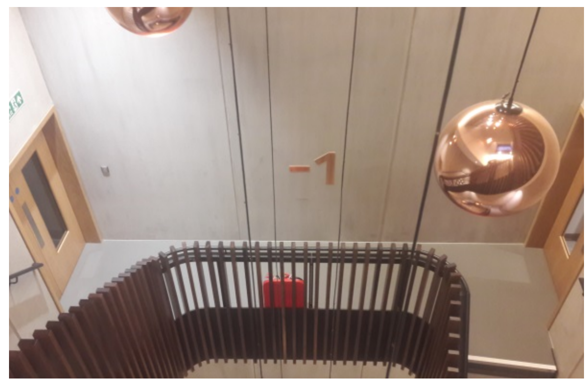
The Beecroft in Oxford is the proposed site, with a backup at RAL (MICE Hall) in case show-stoppers are encountered.

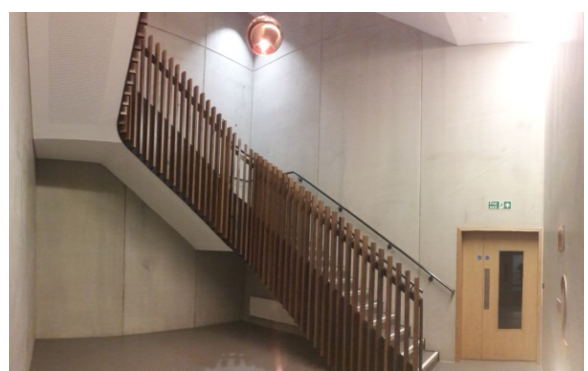


Courtesy of Oliver Buchmueller

Beecroft building, Oxford physics







Ultra-low vibration

Adjacent laser lab reserved for AION use

Vertical space , 12m basement to ground floor

Courtesy of Oliver Buchmueller

Summary

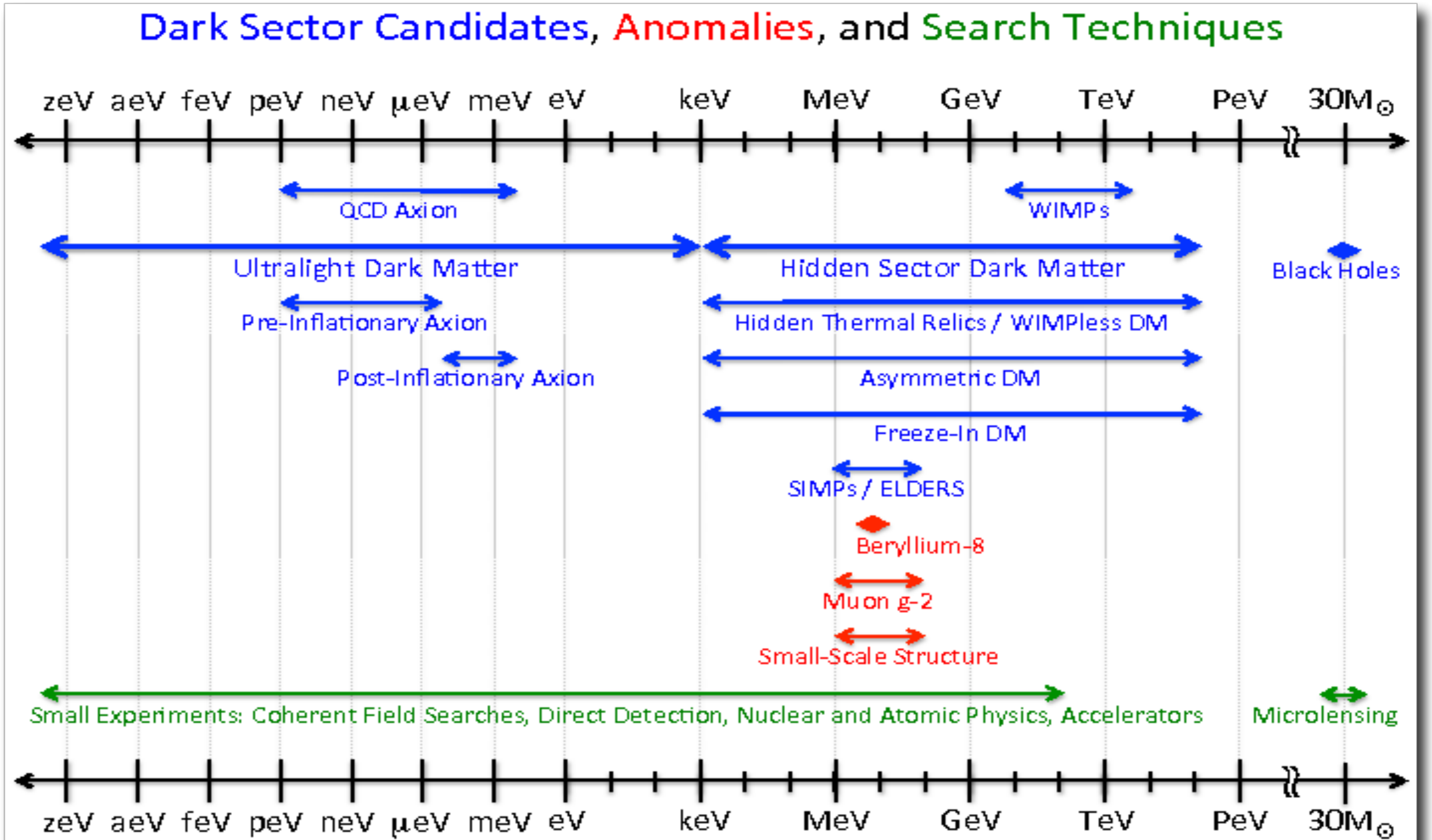
- The AION program is an ambitious multi-staged proposal to build a series of atom interferometers with the capability to probe :
  - Ultra light dark matter in regions of parameter space that is inaccessible to current experiments
  - Gravitational waves in the mid-band frequency range
  - Constrain fundamental constants

- AION foreseen as a staged programme: AION-10, AION-100, AION-KM and AION-SPACE

- Close collaboration with the US initiative, MAGIS-100 and eventual km-scale detectors

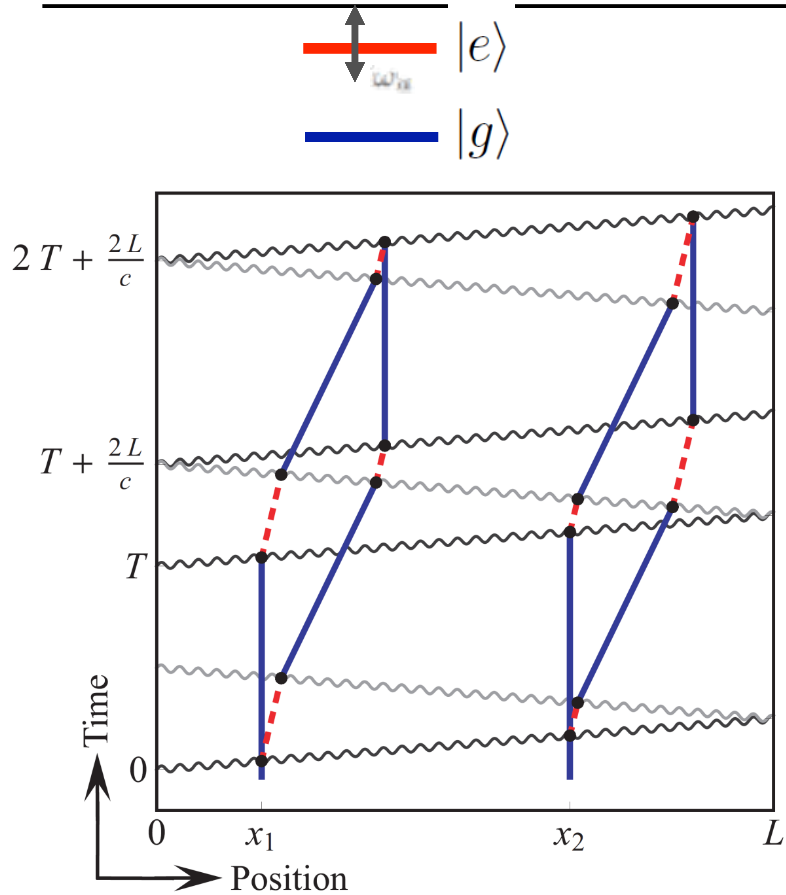
- A lot of details to be worked out - sensitivity studies, work on understanding and pushing the design parameters of the experiment underway but preliminary studies look very promising

BACKUP



Dark Sector Candidates, Anomalies, and Search Techniques
zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV 30M⊙
QCD Axion
WIMPs
Ultralight Dark Matter
Hidden Sector Dark Matter
Black Holes
Pre-Inflationary Axion
Hidden Thermal Relics / WIMPless DM
Post-Inflationary Axion
Asymmetric DM
Freeze-In DM
SIMPs / ELDERS
Beryllium-8
Muon g-2
Small-Scale Structure
Small Experiments: Coherent Field Searches, Direct Detection, Nuclear and Atomic Physics, Accelerators
Microlensing
zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV 30M⊙

Clock gradiometer



Excited state phase evolution:

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

Two ways for phase to vary:

$\delta\omega_A$	*Dark matter*
$\delta L = hL$	*Gravitational wave*

Each interferometer measures the change over time T

Laser noise is common-mode suppressed in the gradiometer

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