The MAGIS & AION experiments and Atom Interferometry at Liverpool

Ultracold Group:

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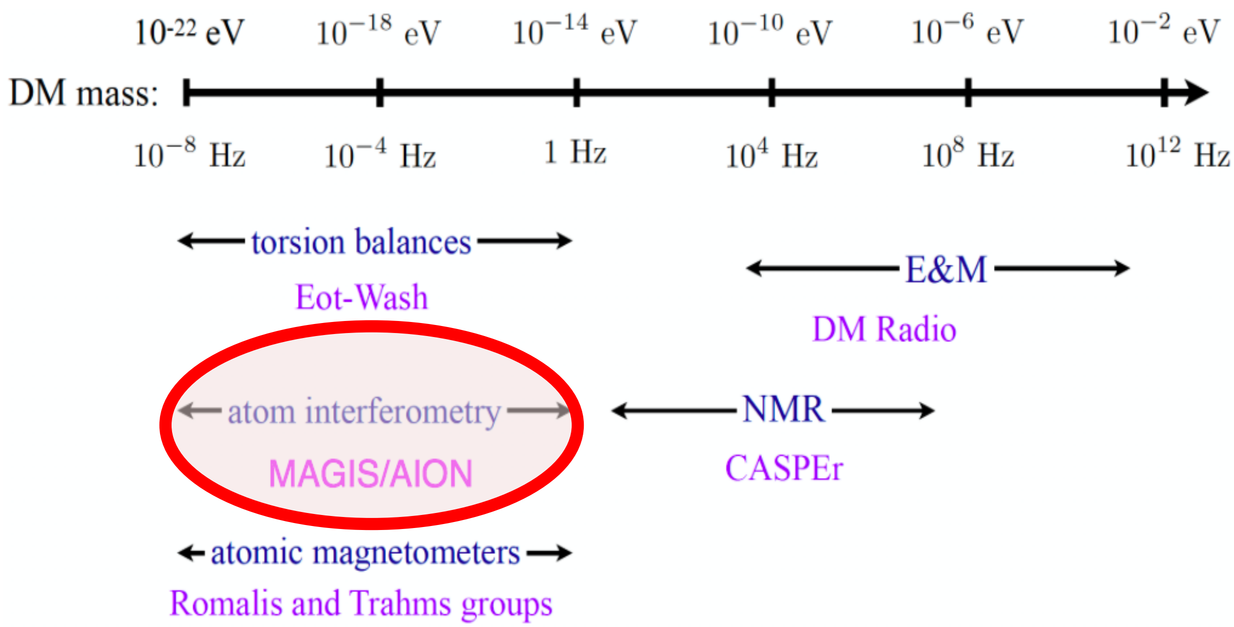
Searches for Light Dark Matter

Dark matter could be coherent waves of light bosons

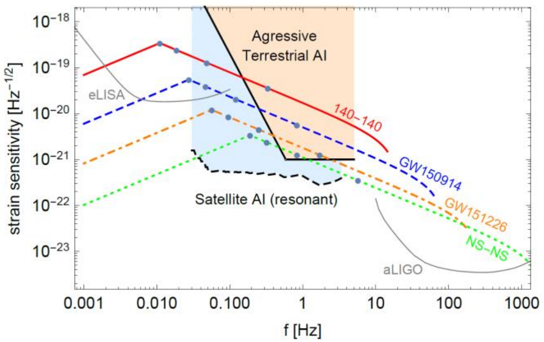
Many detection techniques, **e.g. atom interferometers**



Science Case

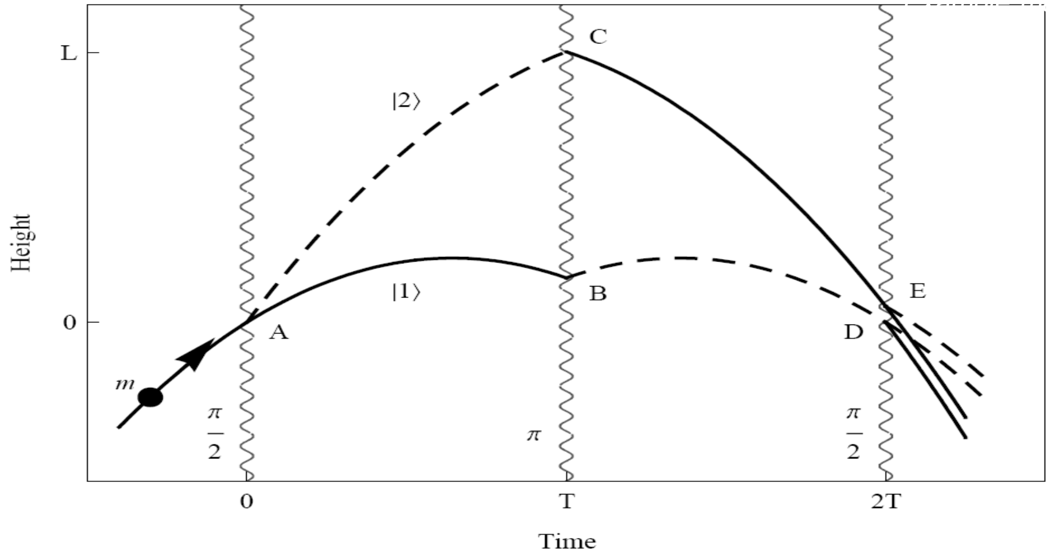
- A new ‘telescope’ for Unexplored Phase Space
- Tests of quantum mechanics at long time / length scales
- Equivalence principle tests (spin dependent gravity)
- Lorentz invariance tests
- “Ultralight” dark matter (e.g., axions, dilatons, etc.)
  - Mass ~10^{-15} eV
  - Would act like a **classical field**

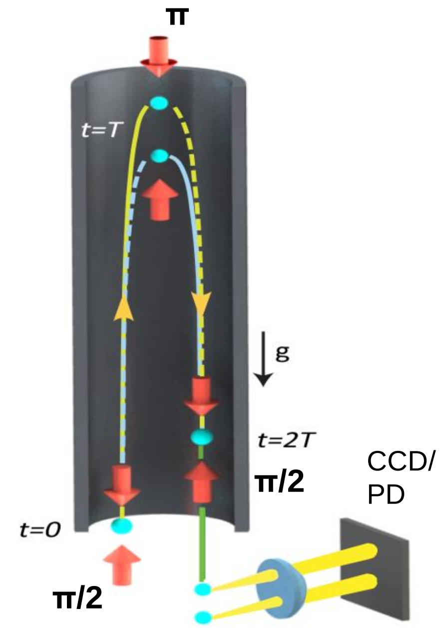
- Testbed for future gravity wave detection in the mid-band frequency range



Strain sensitivities for AI detectors, GW sources and future light interferometer sensitivities. [Localizing Gravitational Wave Sources with Single-Baseline Atom Interferometers P. W. Graham et al., 2018]

Light pulse atom interferometry





Atom interferometry

- Light pulses serve as beamsplitter/mirrors for matter waves
- Atom follow two paths (superposition)
- Paths overlap and interfere
- Measured phase difference is proportional to the fields that interacted with atoms (e.g. for gravity $\mathbf{\Delta\varphi=kgT^2}$)
-

Ultralight scalar dark matter

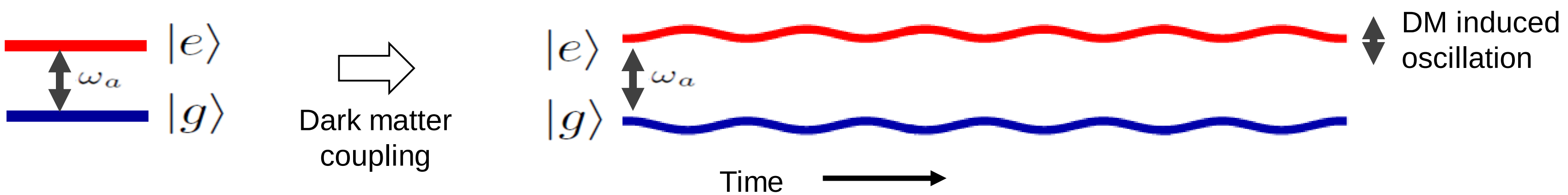
Ultralight dilaton DM acts as a background field (e.g., mass ~10^{-15} eV)

$$\mathcal{L} = \underbrace{+\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2}_{\text{DM scalar field}} - \sqrt{4\pi G_N}\phi\left[\underbrace{d_{m_e}m_e\bar{e}e}_{\text{Electron coupling}} - \underbrace{\frac{d_e}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{Photon coupling}}\right] + \underbrace{\ldots}_{\text{e.g., QCD}}$$

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

$$\phi_0 \propto \sqrt{\rho_{\mathrm{DM}}}$$ DM mass density

DM coupling causes time-varying atomic energy levels:



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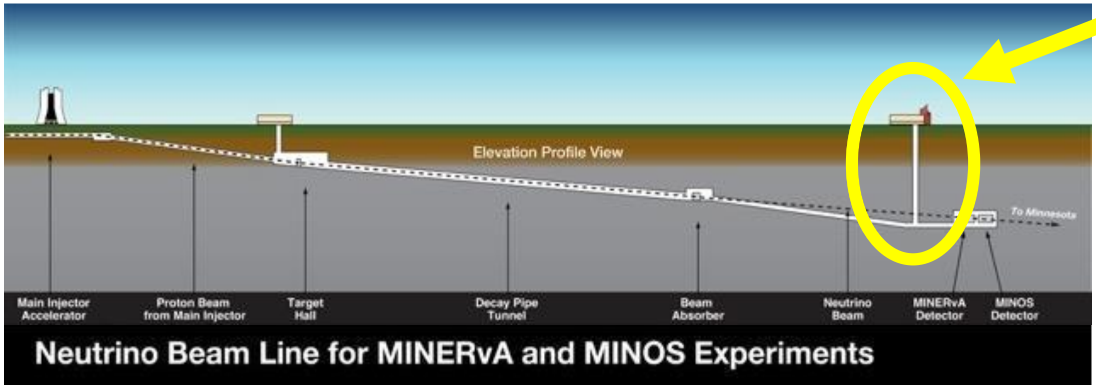
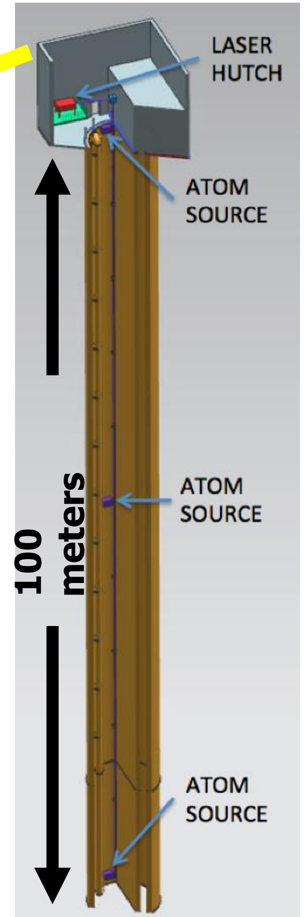
MAGIS-100: DM & GW detector prototype at Fermilab

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





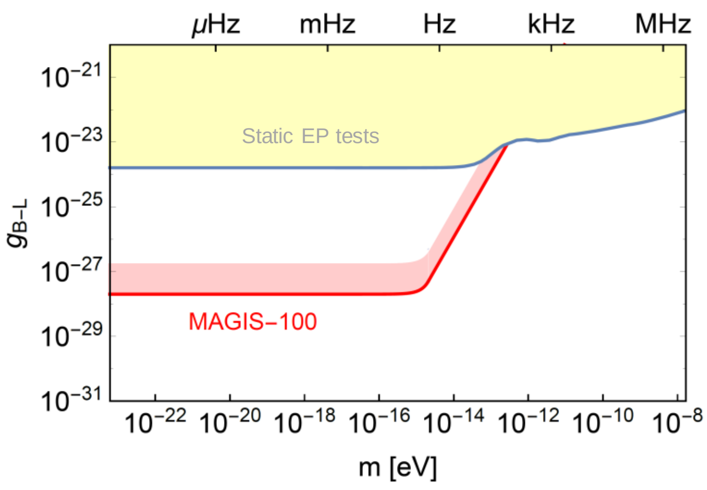
- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Intermediate step to full-scale (km) detector for gravitational waves
- Clock atom sources (Sr) at three positions to realize a gradiometer
- Probes for ultralight scalar dark matter beyond current limits (Hz range)
- Extreme quantum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

STANFORD | Fermilab | Berkeley | University of Liverpool | Northwestern University | Northern Illinois University | University of Oxford | University of Cambridge

Projected sensitivity to dark matter

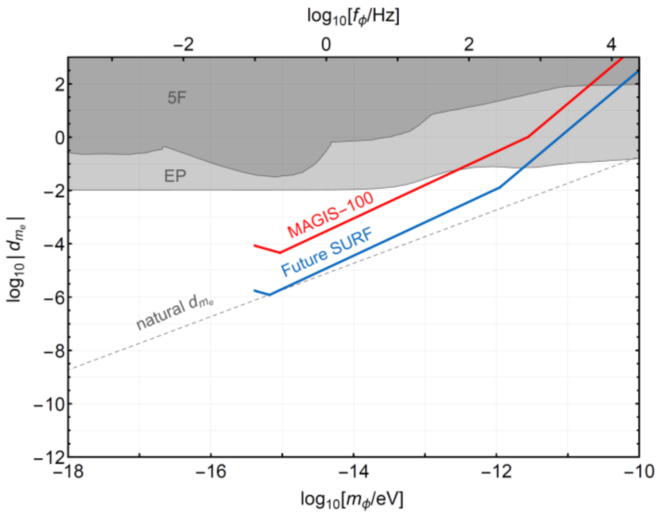
~ 1 year data taking
Assuming shot-noise limited phase resolution

Sensitivity to B-L coupled new force



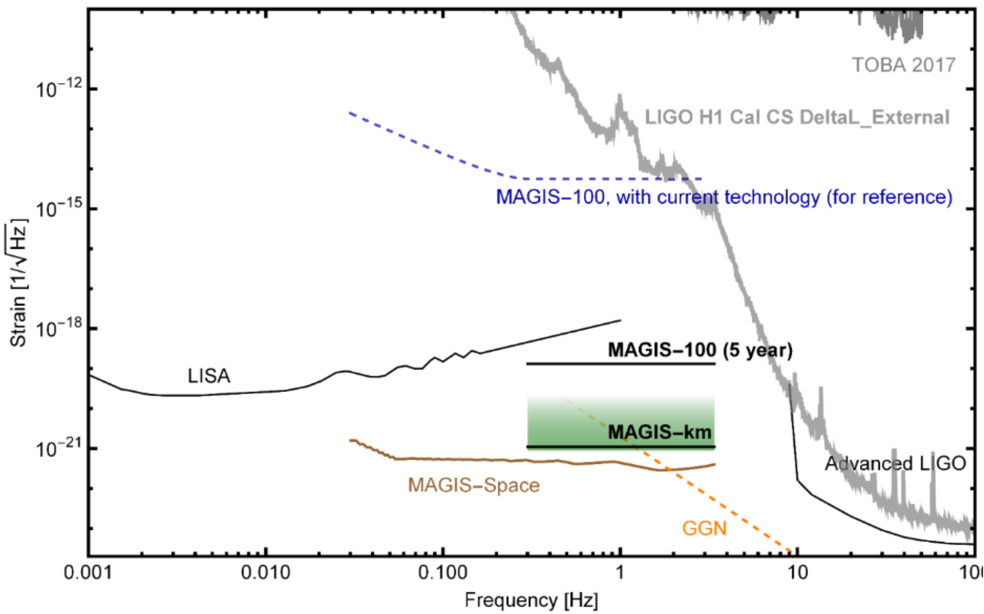
Graham et al. PRD **93**, 075029 (2016).

Sensitivity to ultralight scalar dark matter



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

GW Sensitivity development plan



Phase noise improvements in 5 years:
10x from higher flux
10x from spin squeezing

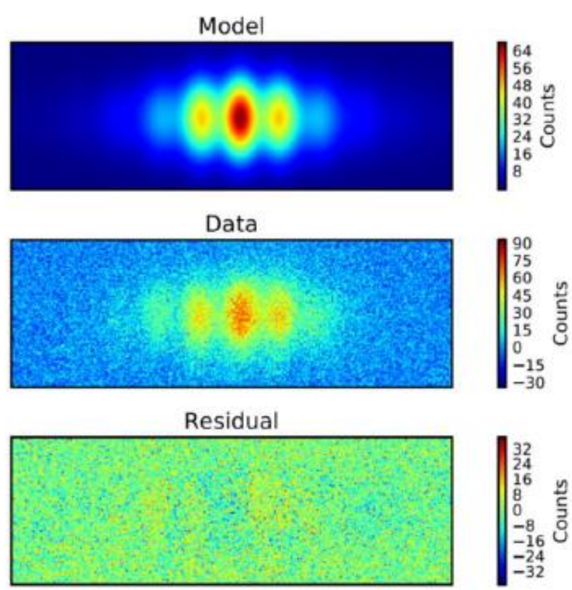
	MAGIS-100 (current)	MAGIS-100 (5 year)	MAGIS-km
Baseline	100 m	100 m	2 km
Phase noise	$10^{-3}/\sqrt{\mathrm{Hz}}$	$10^{-5}/\sqrt{\mathrm{Hz}}$	$0.3 \times 10^{-5}/\sqrt{\mathrm{Hz}}$
LMT	100	4e4	4e4
Atom sources	3	3	30

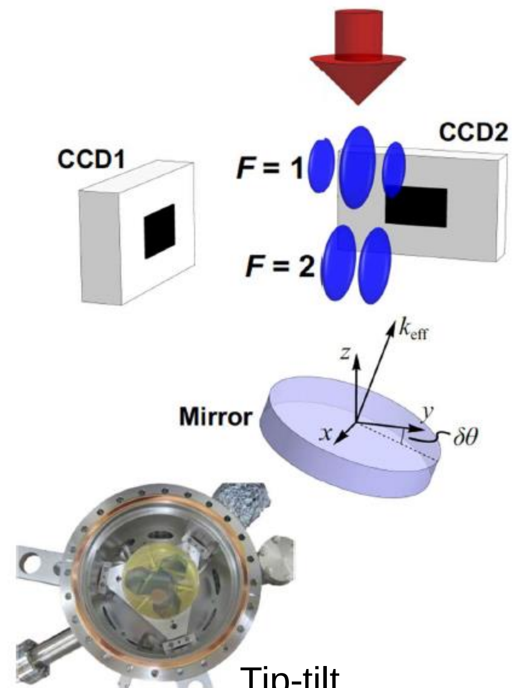
MAGIS-km additional factor of 3x improvement in phase noise from flux + quantum entanglement (spin squeezing)

MAGIS-UK

Liverpool, Oxford and Cambridge

- Deliver the detection subsystem
- Includes fringe detection, image analysis, phase-shear optics, readout and gps time stamping for synchronisation with AION



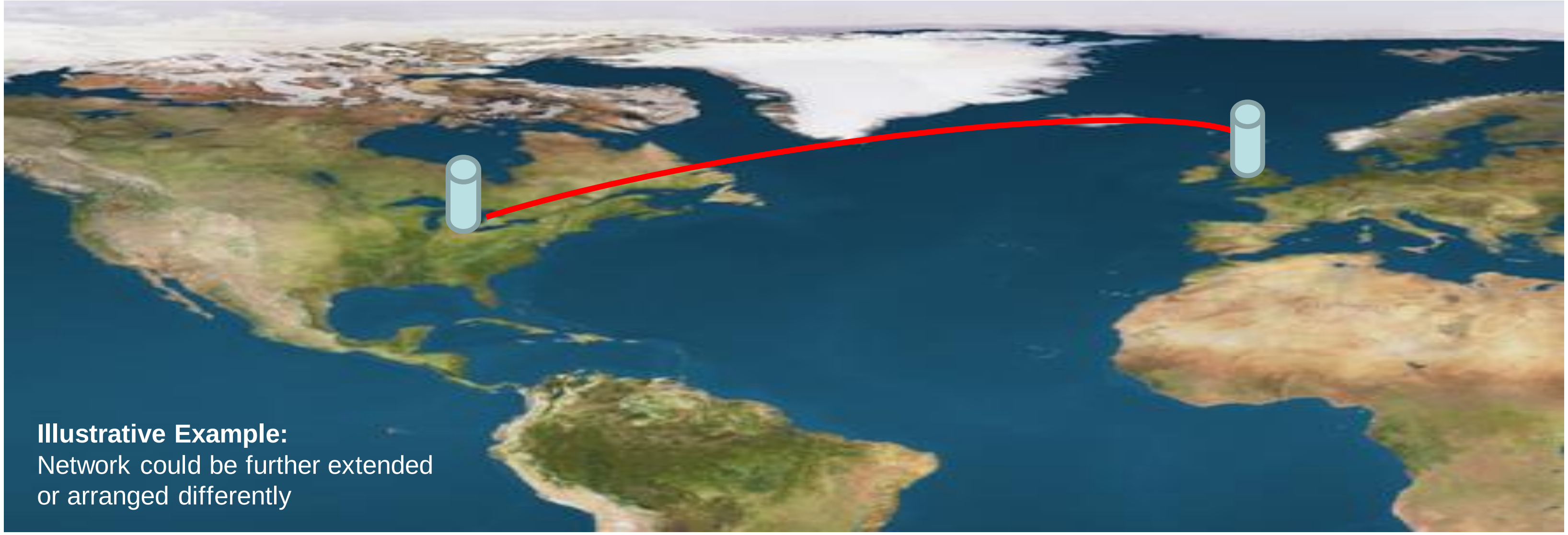


Tip-tilt mirror platform

AION - Proposal

- Networking atom interferometers for fundamental physics
- The program would reach its ultimate sensitivity by operating two detectors in tandem
  - one in the UK and one in the US
- The goal is to build a detector networked with MAGIS
  - a'la LIGO and VIRGO
- Providing Non-common background mode rejection
  - unequivocal proof of any observation
- US-UK collaboration serves as a testbed for full-scale terrestrial (kilometer-scale) and satellite-based (thousands of kilometres scale) detectors and builds the framework for global scientific endeavor

Ultimate Goal: Establish International Network



For more details on AION see
https://arxiv.org/pdf/1911.11755.pdf

AION: An Atom Interferometer Observatory and Network

L. Badurina,[1] E. Bentine,[2] D. Blas,[1] K. Bongs,[3] D. Bortoletto,[2] T. Bowcock,[4] K. Bridges,[4] W. Bowden,[5,6] O. Buchmueller,[6] C. Burrage,[7] J. Coleman,[4] G. Elertas,[4] J. Ellis,[1,8,9] C. Foot,[2] V. Gibson,[10] M. G. Haehnelt,[11,12] T. Harte,[10] S. Hedges,[3] R. Hobson,[5,6] M. Holynski,[3] T. Jones,[4] M. Langlois,[3] S. Lellouch ,[3] M. Lewicki,[1,13] R. Maiolino,[10,11] P. Majewski,[14] S. Malik,[6] J. March-Russell,[15] C. McCabe,[1] D. Newbold,[14] B. Sauer,[6] U. Schneider,[10] I. Shipsey,[2] Y. Singh,[3] M. A. Uchida,[10] T. Valenzuela,[14] M. van der Grinten,[14] V. Vaskonen,[1,8] J. Vossebeld,[4] D. Weatherill,[2] I. Wilmut[14]

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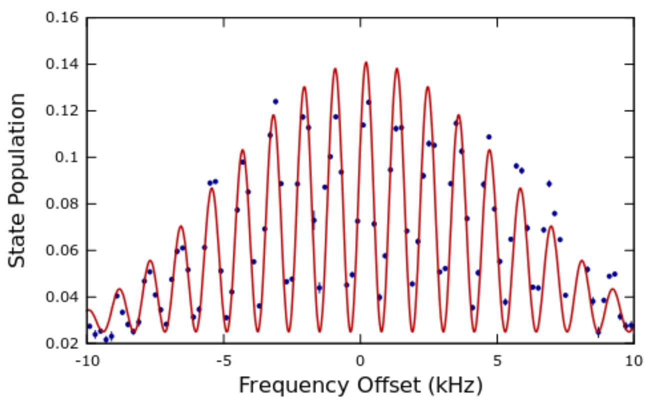
Atom Interferometry in the University of Liverpool

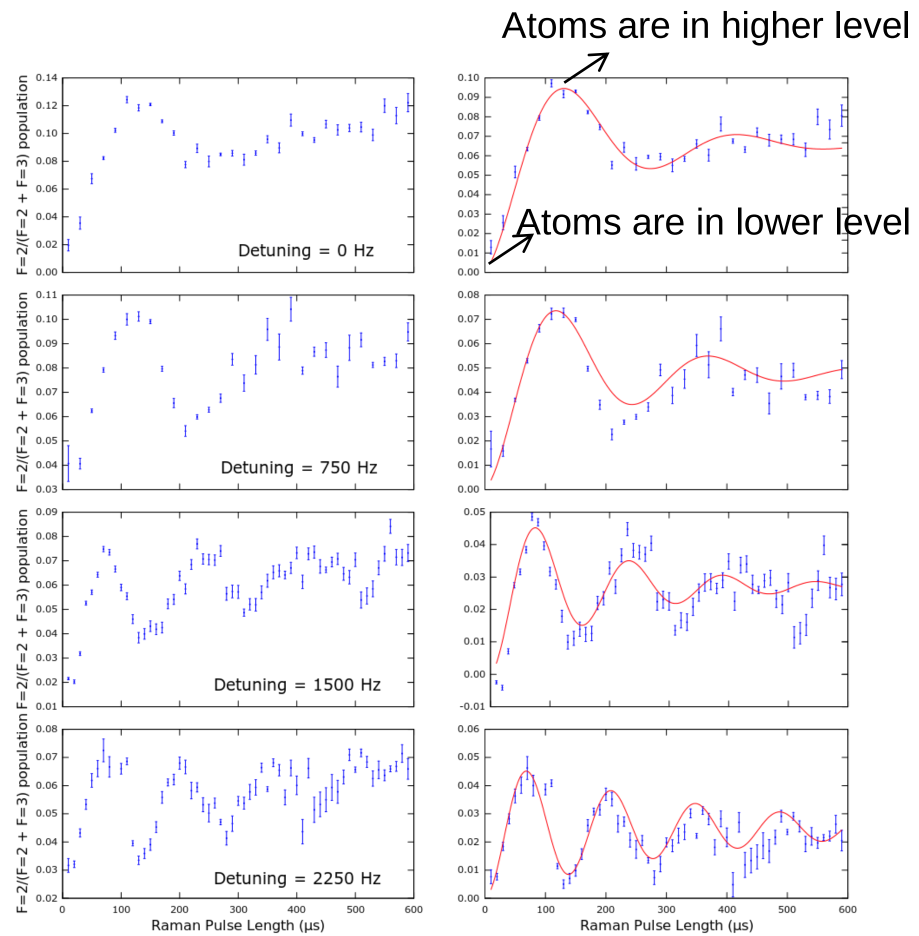
We have developed **Rb-85 interferometer**

Successfully realising:

- The cold atom preparation
- “Mirror” & “Beamsplitter” pulses
- Interference fringes



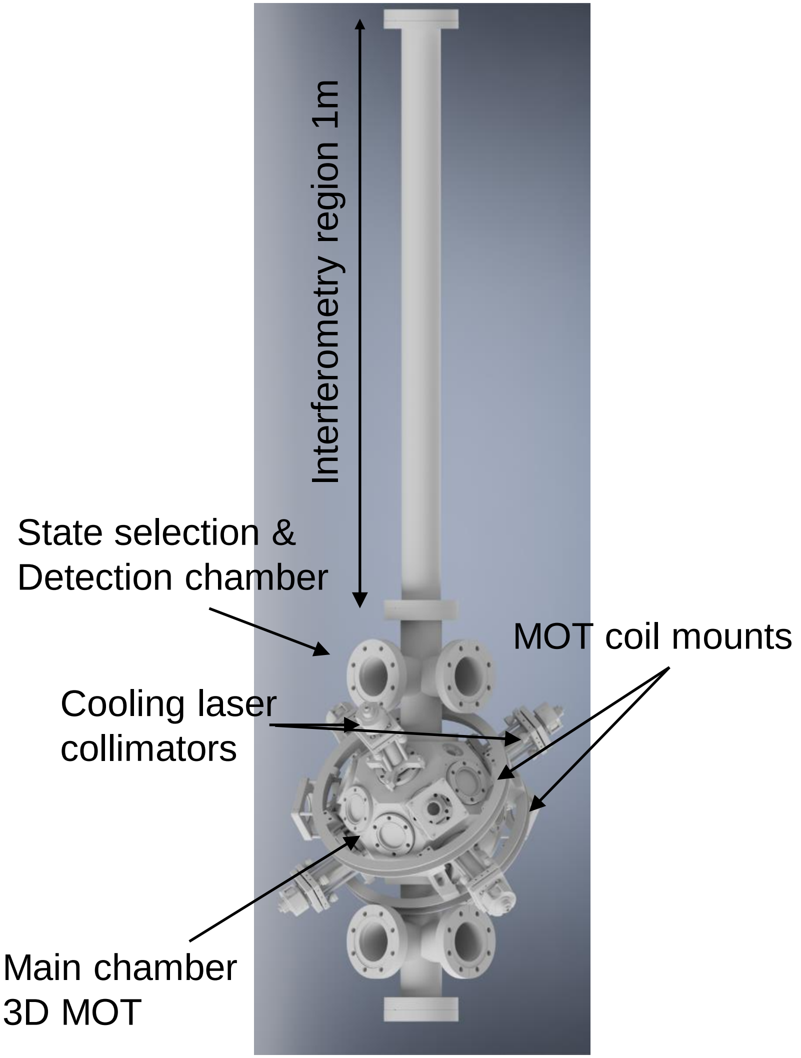
Atomic interference demonstrated trough Ramsey fringes.



Rabi oscillations with increasing detuning from the atomic resonance..

Upgrades

- New UHV chamber
- Can be operated in drop & fountain configuration
- Additional powerful > 5 W laser
- Improved Raman system – more power and detuning
- Atom source – conical mirror MOT
- Active vibration control
- Detection & state preparation improvements



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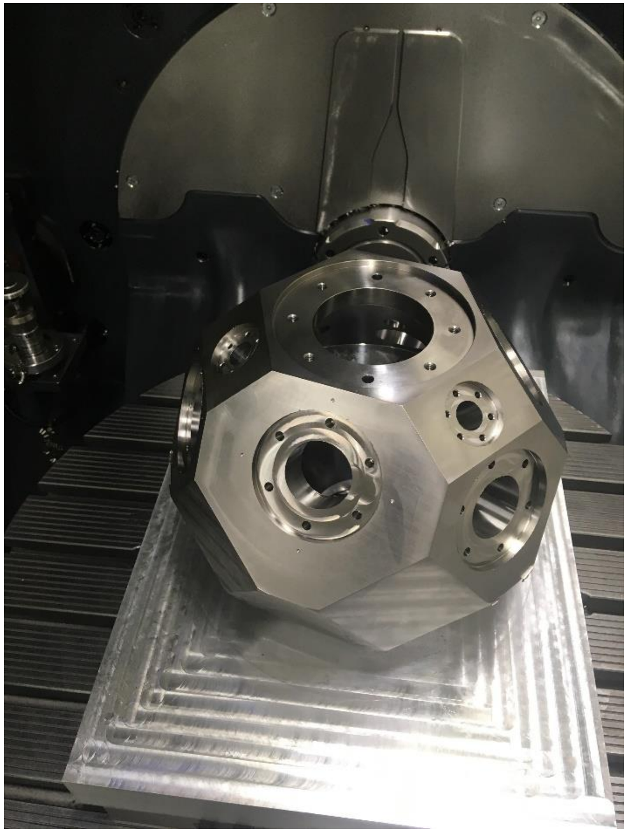
Present Status

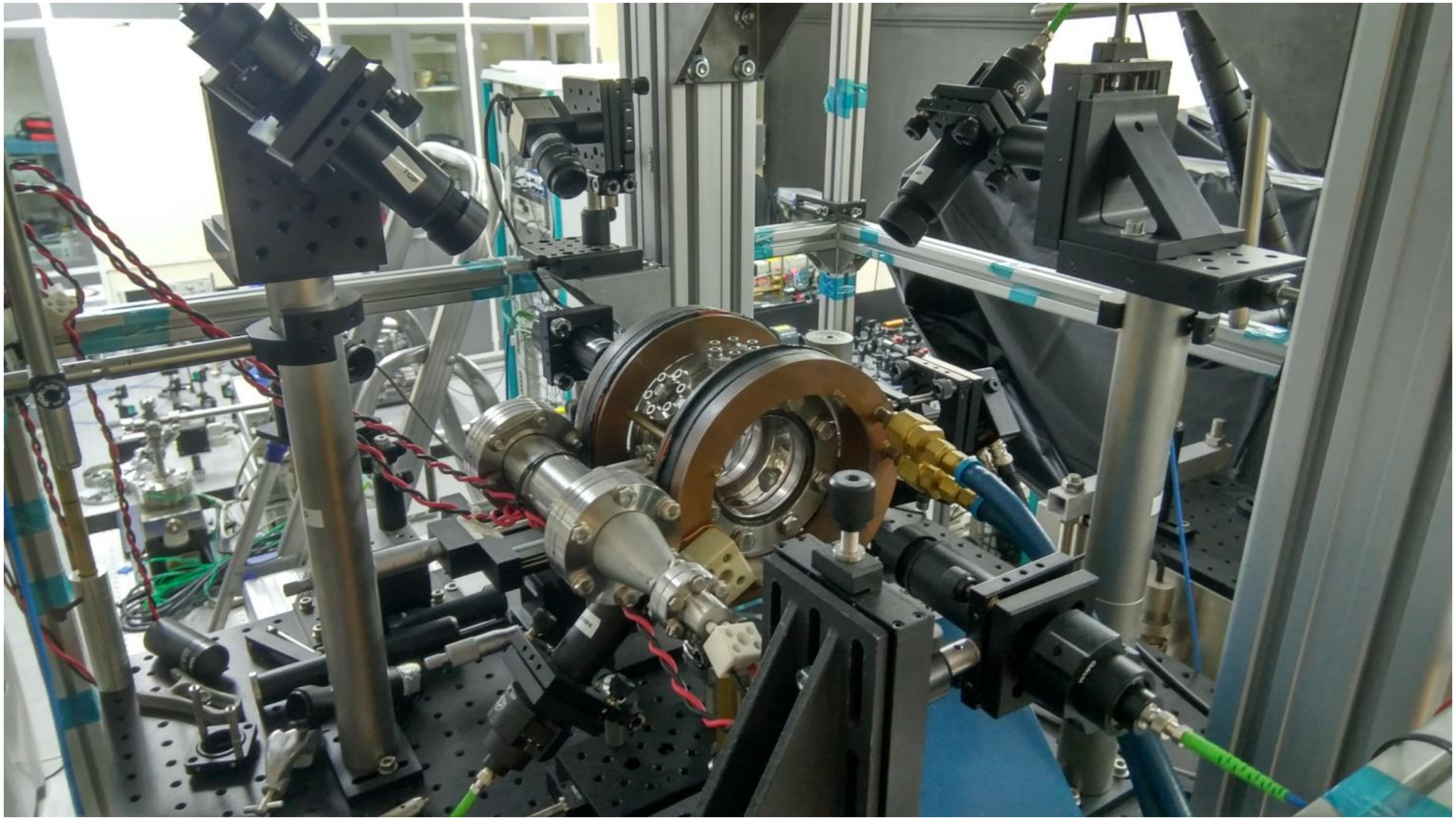
- Atomic and Particle physicists working in collaboration
- Using Atom Interferometry to:
  - Explore the dark sector
  - Prototype for a mid-band gravity wave detector
- New experiment at Fermilab
  - potential to for larger scale ~1 km at SURF
- MAGIS-100 started construction this year
- AION adds additional arm for unequivocal discovery potential
- Small scale experiment at Liverpool
- All components for the upgraded Liverpool atom interferometer has been ordered and it is being constructed

Thank you for attention



I would like to thank Liverpool Physics Workshop which is making the main experimental chamber and K. Bridges for finalising the vacuum chamber design!

Liverpoo Atom Interferometer



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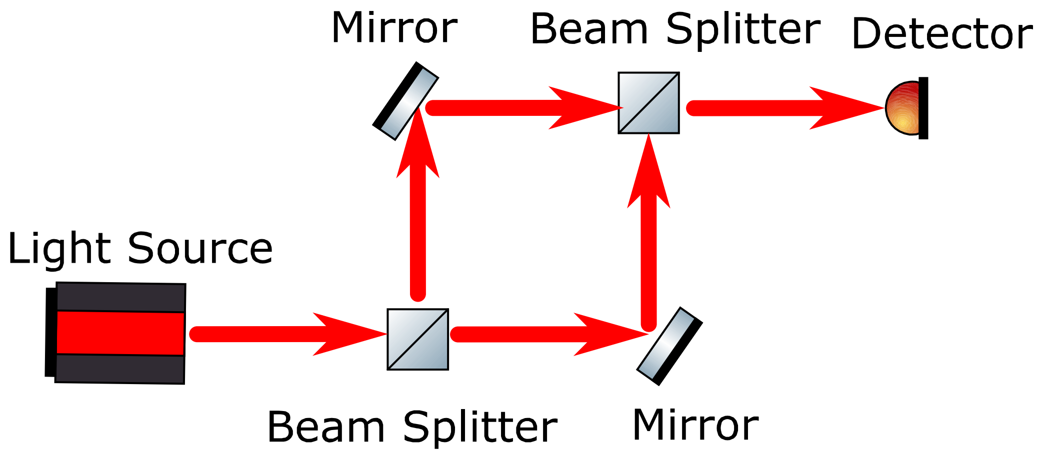
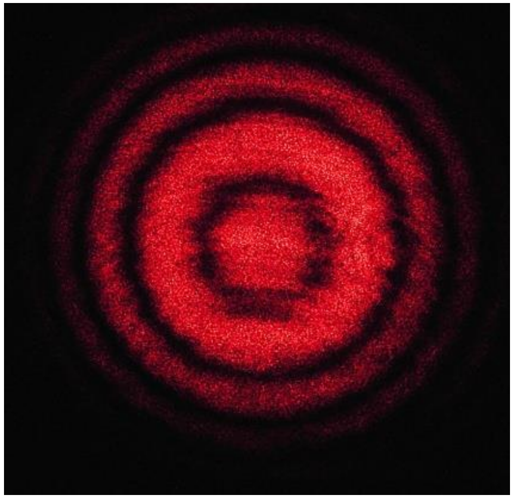
Atom Interferometry 101

Light Interferometer



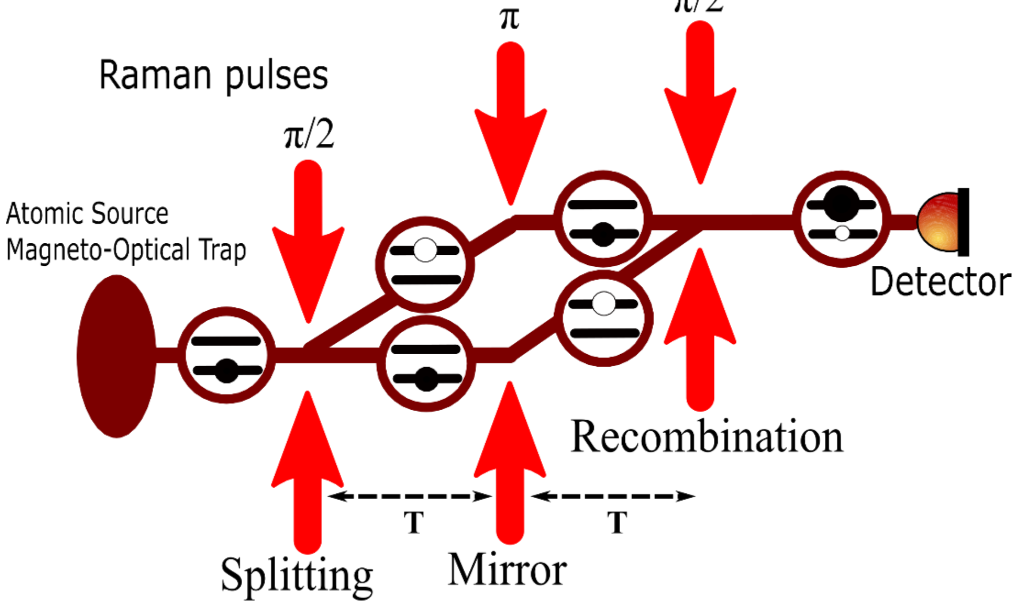
Light fringes



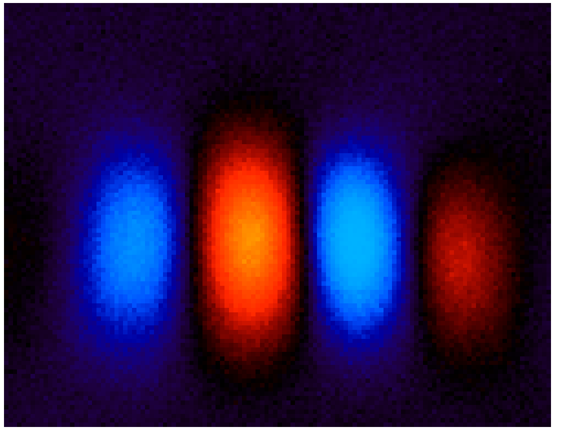
https://www.coboltlasers.com/applications/lasers-for-interferometry

Atom Interferometry 101

Atom Interferometer



Atom fringes



Atom Interferometry in a 10m Fountain, PhD thesis, A. Sugarbaker, Stanford University, 2014

Increasing precision

Excited state population $P_e = 0.5(1-\cos(\Delta\varphi))$

Phase accumulated due to Earth's gravitation field $\Delta\varphi = kgT^2$

Reaching higher sensitivity:

- Longer time **T**
- Upgraded Raman system
  - Large frequency detuning
  - Large momentum transfer
- Faster experiment repetition rate
- Cancelling other effects & fields interacting with atoms (e.g. vibrations, magnetic fields, AC stark shift, etc.)
- Higher signal to noise ratio
  - Higher number of atoms
  - Efficient detection

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Old vs New Laser System

Old Laser System	New Laser System
Only two diode lasers	Additional powerful new laser, 3 lasers
One laser used to drive both Raman system and magneto-optical trap	A separate laser for Raman system – no power and frequency detuning limit
Cannot be operated for atom fountain	Designed for atom fountain
Frequency control and switching is done via acousto-optical modulators and shutters	Frequency control and switching is done via acousto-optical modulators, shutters and optical-fibre switches

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New Laser

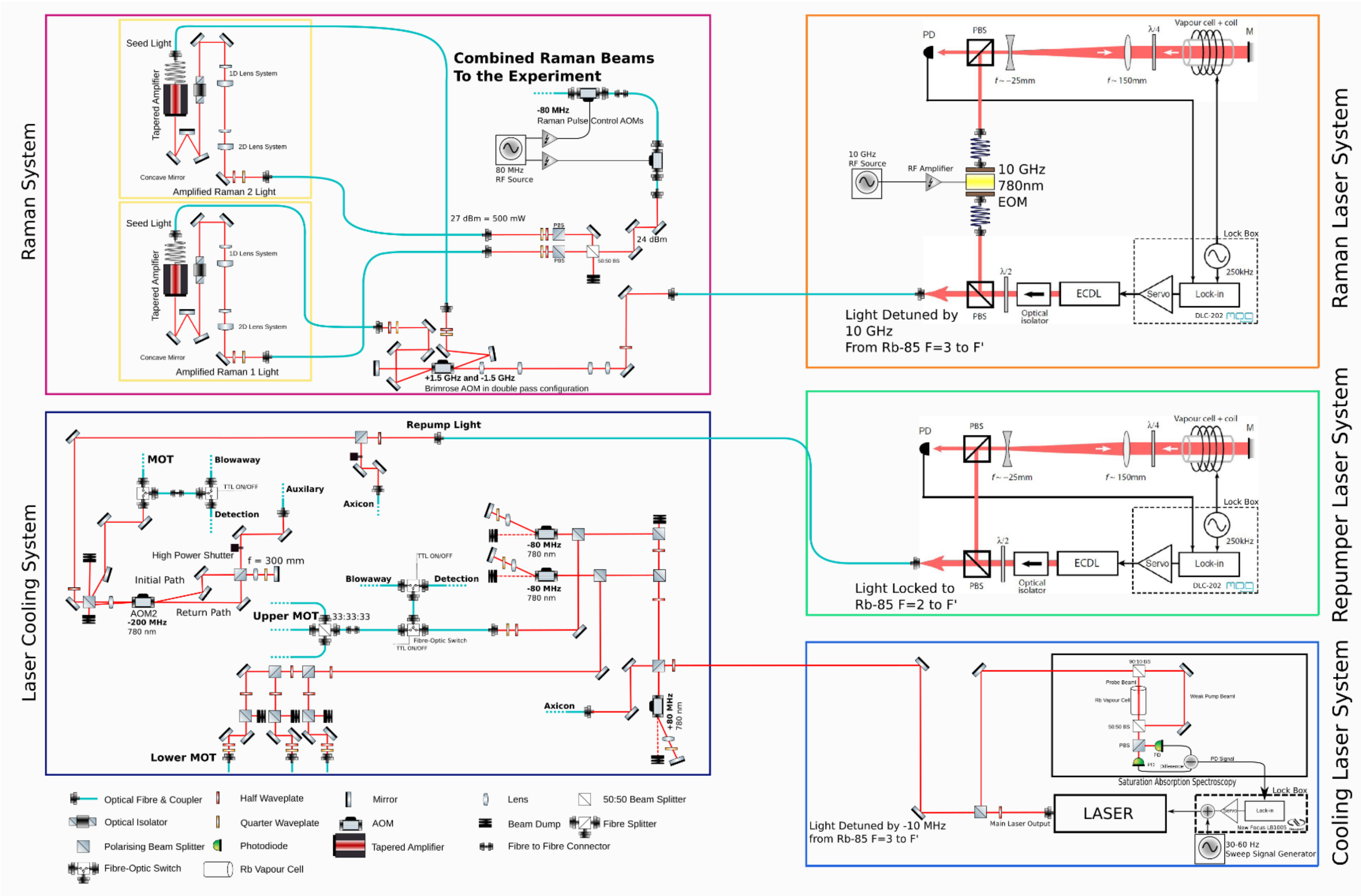
40 mW @ 1560 nm

30 W @ 1560 nm

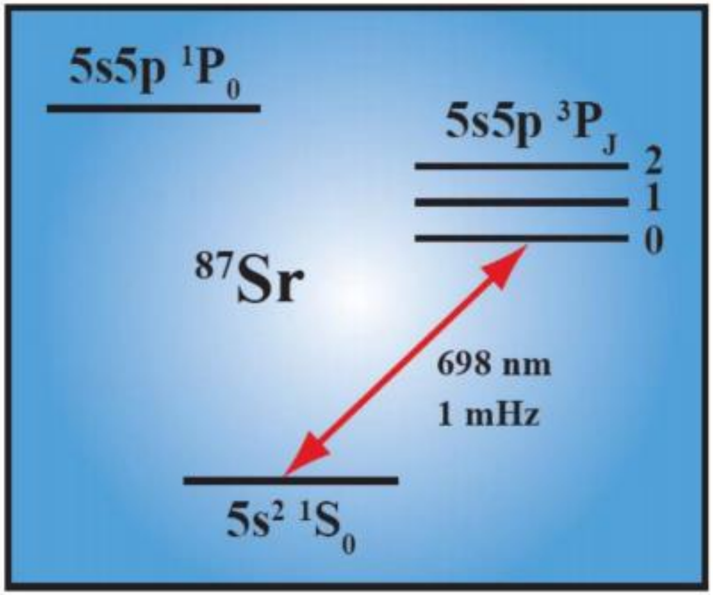
7 W @ 780 nm

- 1560 nm ultra stable single frequency seed laser NKT Koheras AdjustiK
- Amplified by IPG single frequency Erbium amplifier to 30W power
- Frequency doubled to 780 nm using PPLN (periodically poled lithium niobite)   crystal from Covesion

New Laser System



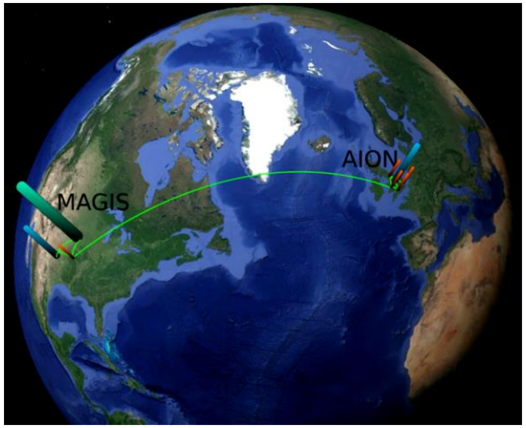
Strontium Clock Transition



Sr has a narrow optical clock transition with a long-lived excited state that atoms can populate for >100 s without decaying

Can have long lived superpositions of ground + excited state with a large energy difference, useful for very precise timing measurements

AION – Atom Interferometer Observatory and Network



- AION is a UK twin project to MAGIS
  It is part of Quantum Sensors for Fundamental Physics program

- Networking atom interferometers for Fundamental physics searches

- Build another detector networked with MAGIS
  LIGO/Virgo style collaboration
  - Non-common background mode rejection
  - Provide unequivocal proof of any observation

AION project, O. Buchmueller, AION workshop 2019

AION Dark Matter Search

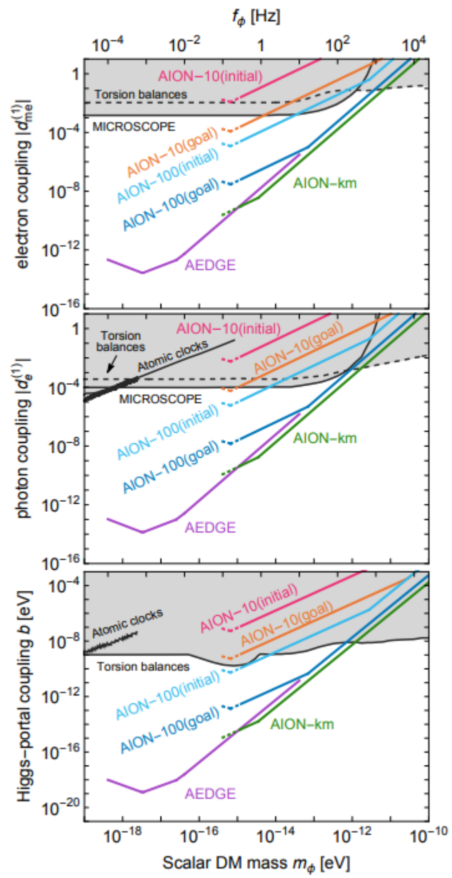


Figure 3. *Sensitivities of different AION scenarios to scalar DM interactions with electrons (top), photons (middle) and the Higgs portal (bottom). The grey regions show parameter space that has already been excluded through searches for violations of the equivalence principle [24], atomic spectroscopy [25] and by the MICROSCOPE experiment [26].*

MAGIS and AION Network

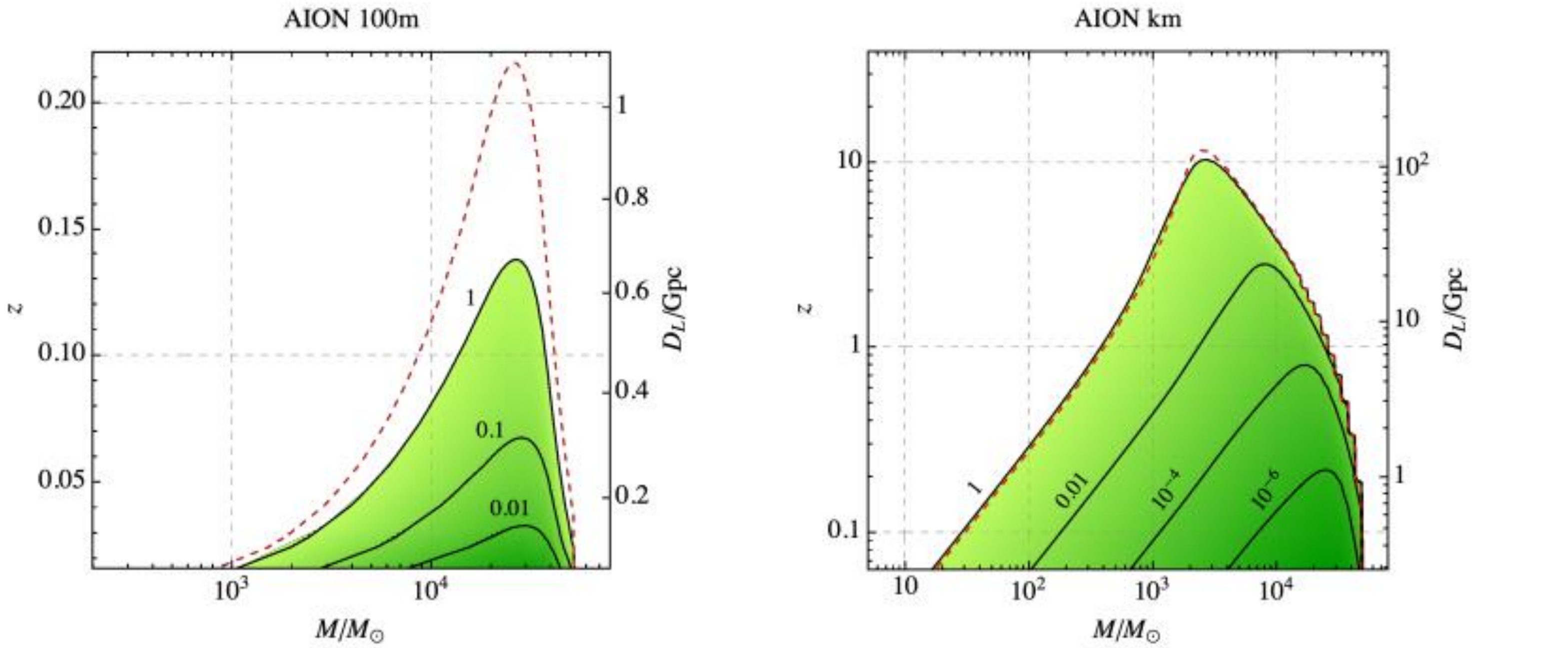


Figure 10. *Left panel: Angular pointing accuracy of AION-100 networked with MAGIS-100 with the shadings corresponding to solid angles* $< (1, 10^{-2}, 10^{-4}, 10^{-6}) \times 4\pi$. *The dashed red contour corresponds to* SNR = 50. *Right panel: Similar for AION-1km networked with MAGIS-1km.*

AION Helping LIGO/VIRGO

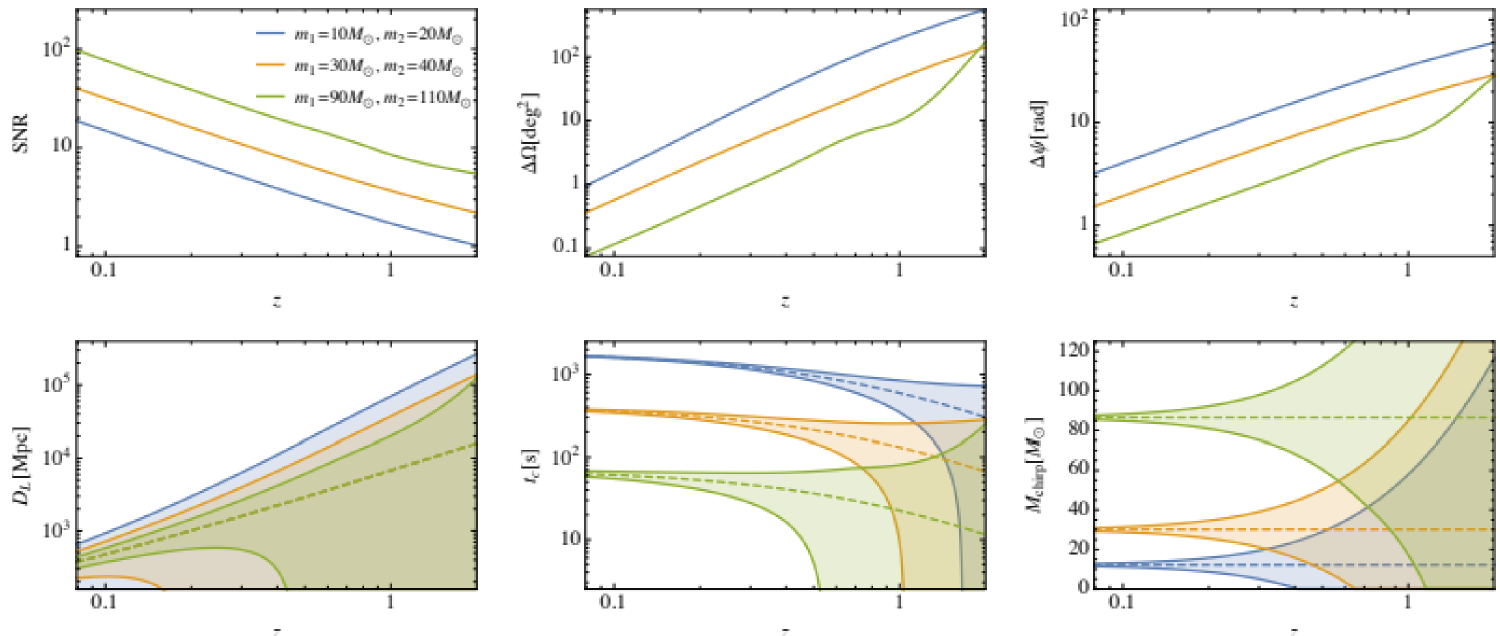


Figure 11. *The SNR (upper left panel), the sky localization uncertainty $\Delta\Omega$ (upper middle panel), the polarization uncertainty $\Delta\psi$ (upper right panel), and the uncertainties in the luminosity distance D_L (lower left panel), the time remaining before merger t_c (lower middle panel) and the chirp mass M_{chirp} (lower right panel), as calculated assuming AION-km measurements for three merging binaries of different BH mass combinations as functions of their redshifts.*

AION design

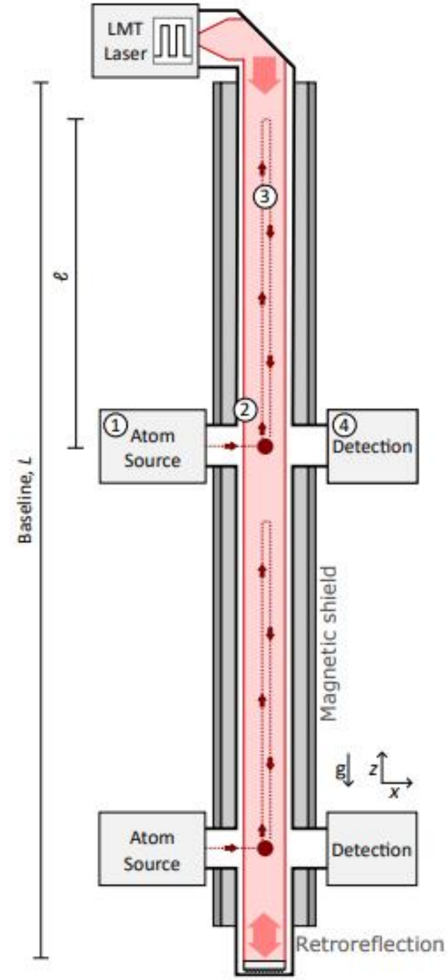


Figure 2. *Conceptual scheme of AION, illustrated for two atom interferometers that are arranged vertically and addressed by a single laser source.*

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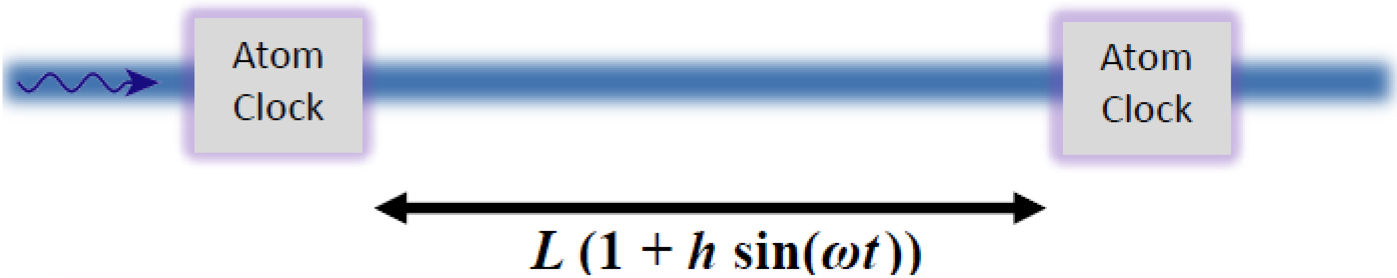
GW Measurement Concept with AI

- Light propagates across the baseline at a constant speed
- Atoms are good clocks and good inertial proof masses (freely falling in vacuum, not mechanically connected to earth)
- Clocks read transit time signal over baseline
- GW changes number of clock ticks associated with transit by modifying light travel time across baseline



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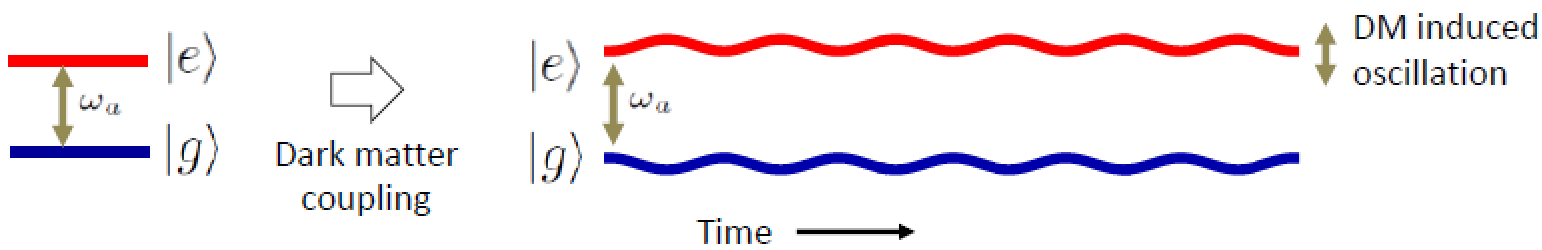
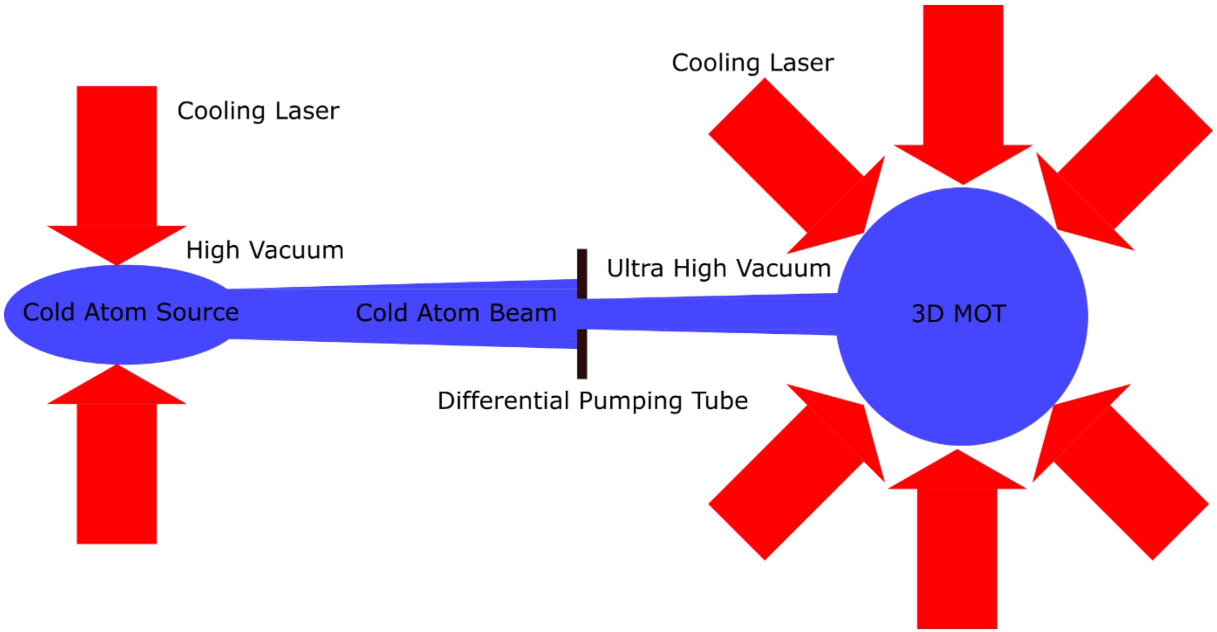
DM Measurement Concept with AI

Ultralight dark matter (e.g., ~10^{-15} eV) acts as a coherent, wavelike background field



This oscillation could be measured with an atom interferometer

Cold Atom Source



Cold atom source supply 3D MOT with already cold atoms significantly decreasing the 3D MOT loading rate from several seconds to less than one second

This increases the overall **repetition rate** of the experiment

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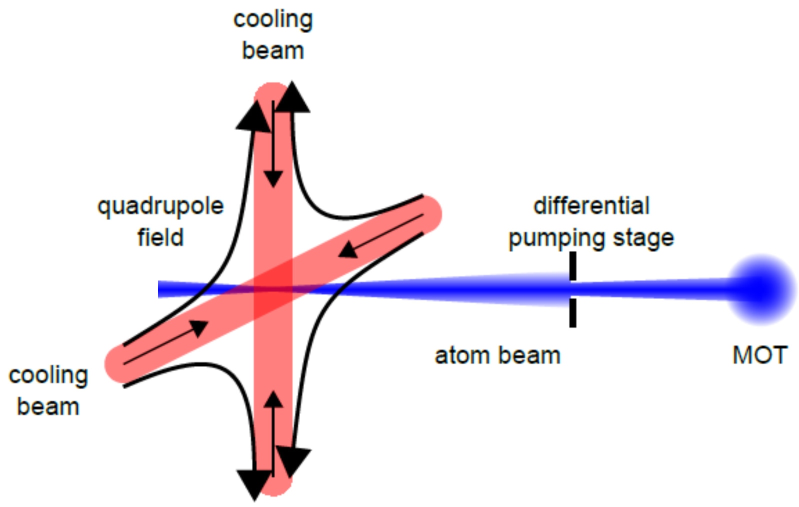
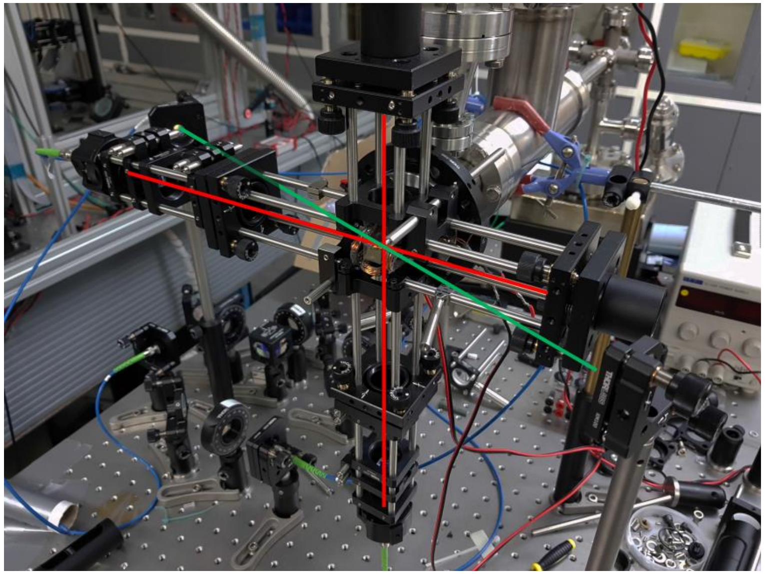
Cold Atom Source
2D MOT

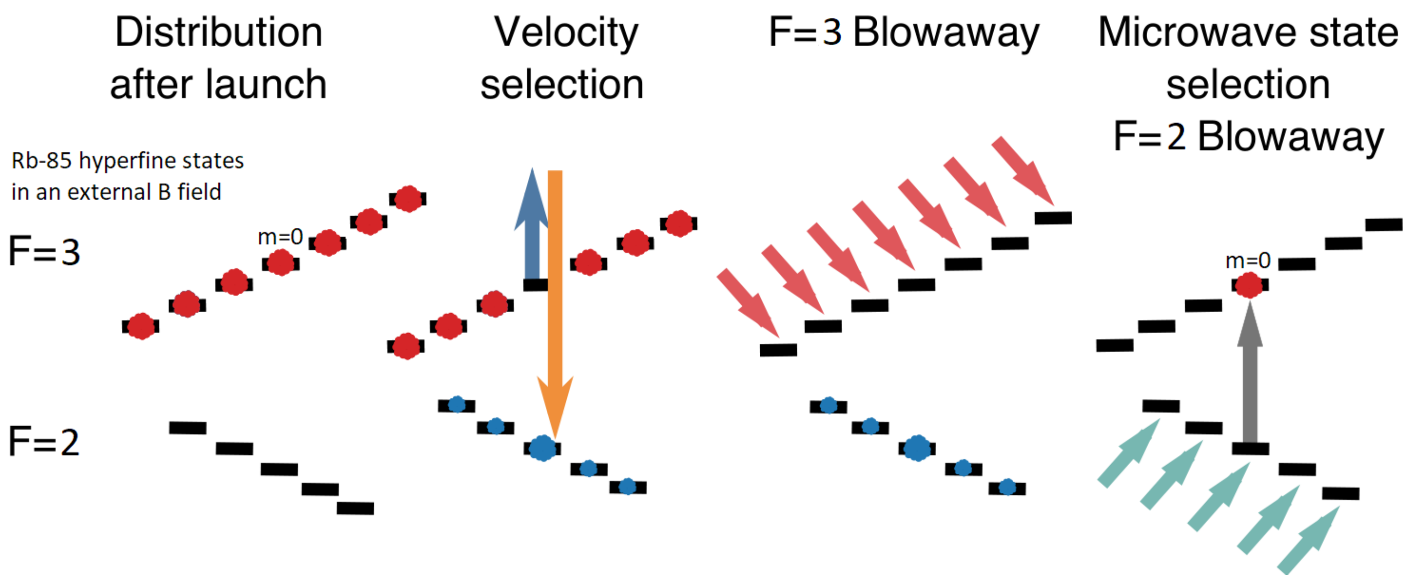




2D MOT, an atom beam is created by subjecting the atoms to magneto-optical trapping transversal to the desired beam axis. [Efficient loading of a magneto-optical trap for experiments with dense ultracold Rydberg gases, H. Busche, Heidelberg, PhD, 2011.]

2D MOT setup. The red lines indicate the path of the cooling beams and the green line indicates the path of the repump beam. [Construction, commissioning and characterisation of a cold atom source for an interferometer, C. Sullivan, Liverpool, master's thesis, 2018.]

Velocity and State Selection



This procedure prepares atoms in a correct velocity class and in the **magnetic insensitive** m=0 sub-state

However, this leads to a significant **reduction of atom number** by a factor of ~100 from ~10^9 to 10^7 atoms

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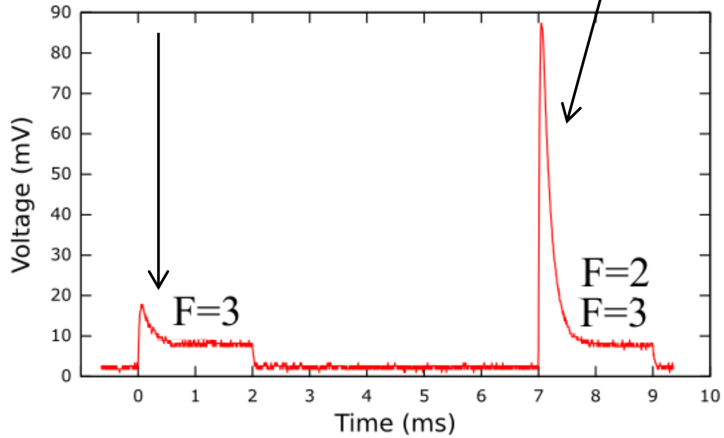
New Detection System

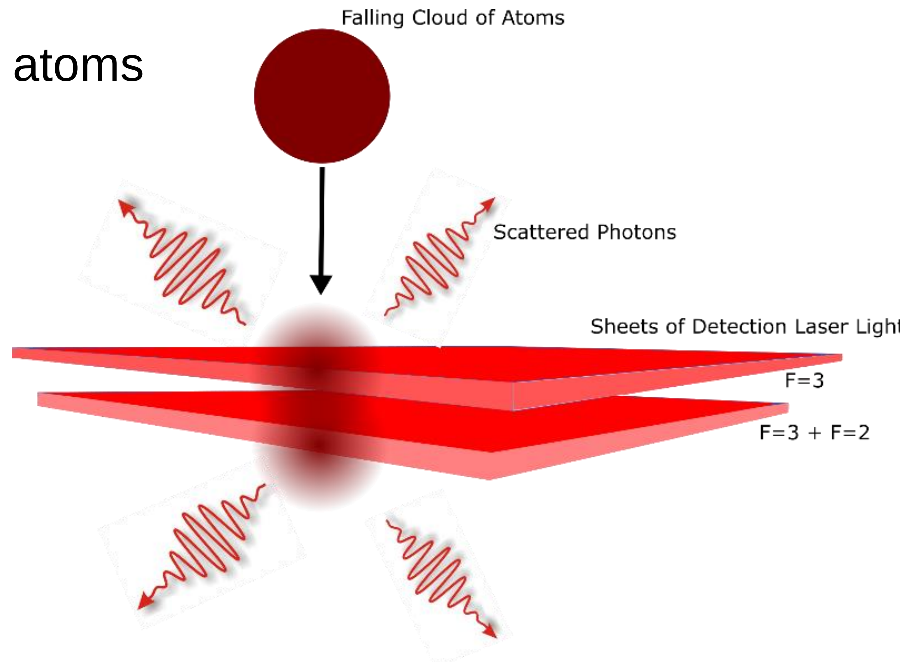
Total number of atoms

Atoms in the excited state



Old detection method, employing photodiode and resonant pulses of laser light

$$Ratio \equiv R = \frac{P_{F=3}}{P_{F=2} + P_{F=3}}$$



Schematics of proposed detection method, scattered photons are imaged with **the new sCMOS camera**

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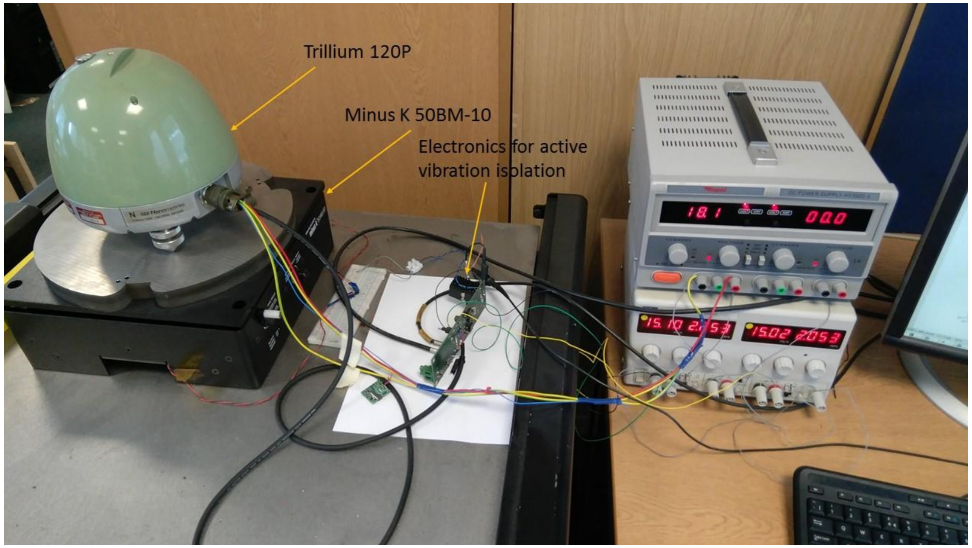
Active Vibration Control Set-up

Minus K passive vibration isolator, damps vibrations **> 0.5 Hz**

Custom made active vibration isolation system damps vibrations of **0.1 – 6 Hz**



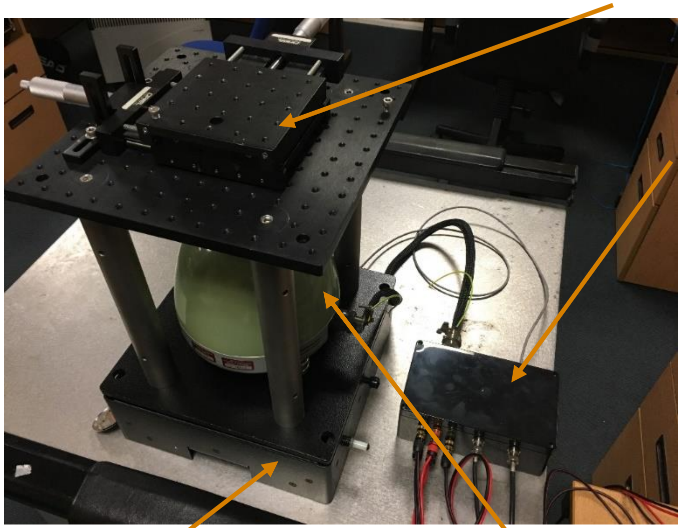
1. Trillium 120P seismometer outputs the analogue signal of vibrations in a vertical direction

2. This signal is filtered out and amplified

3. This signal is used in a feedback loop with voice coil actuators which effectively damps vibrations

Active Vibration Control

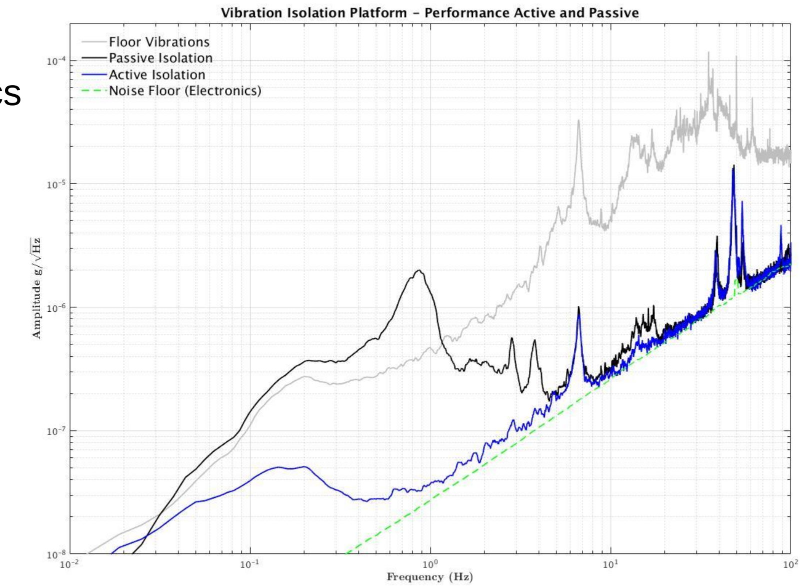
Translation stage for optics



Electronics for active vibration control

Minus-K passive vibration isolation platform

Trillium 120P Seismometer



- A combination of passive and custom made active vibration control
- Minus K passive vibration isolator damps vibrations **≥ 0.5 Hz**
- Custom made active vibration isolation system damps vibrations of **0.1 – 6 Hz**

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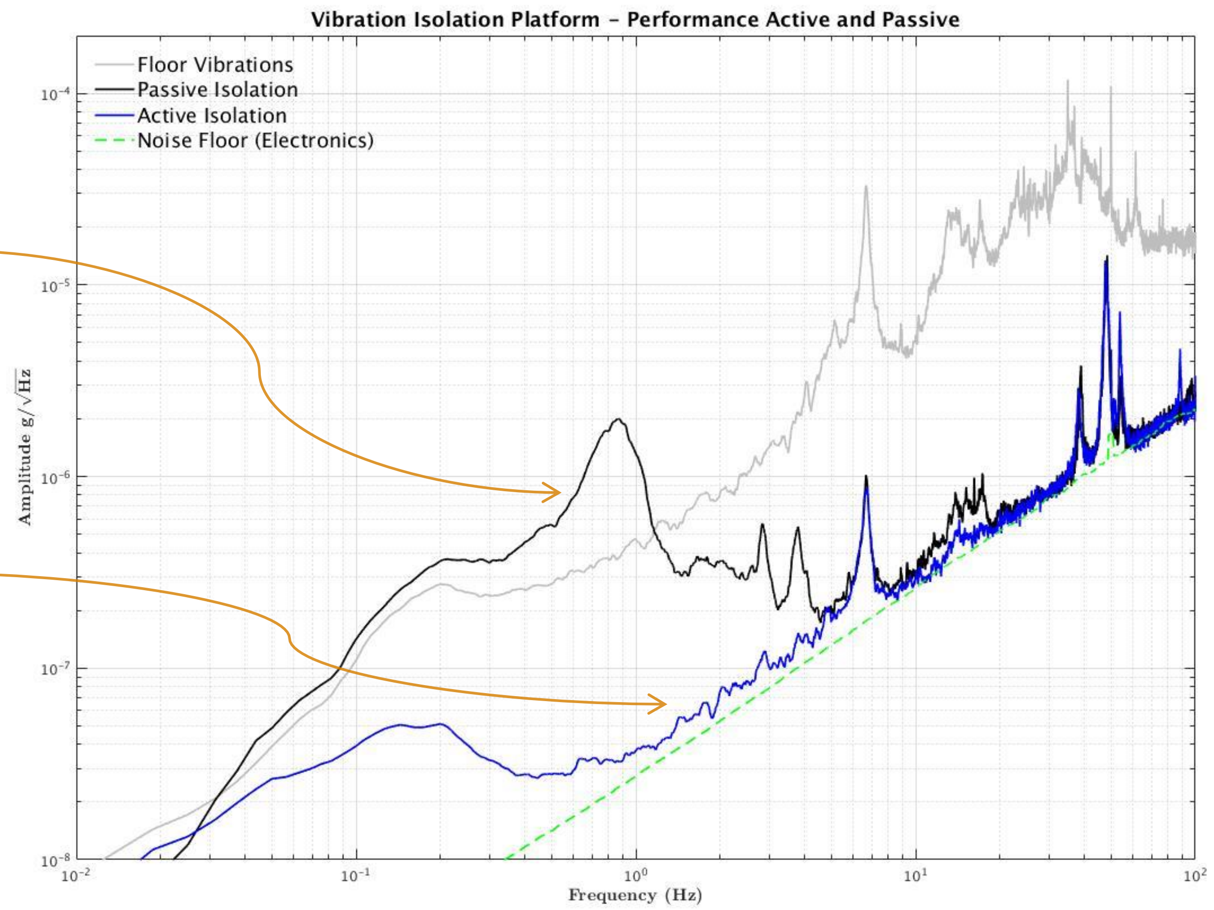
Vibration Isolation Results

- The peak at 0.87 Hz is natural frequency of Minus K platform
- Active vibration isolation is effective from **0.1 – 6 Hz**



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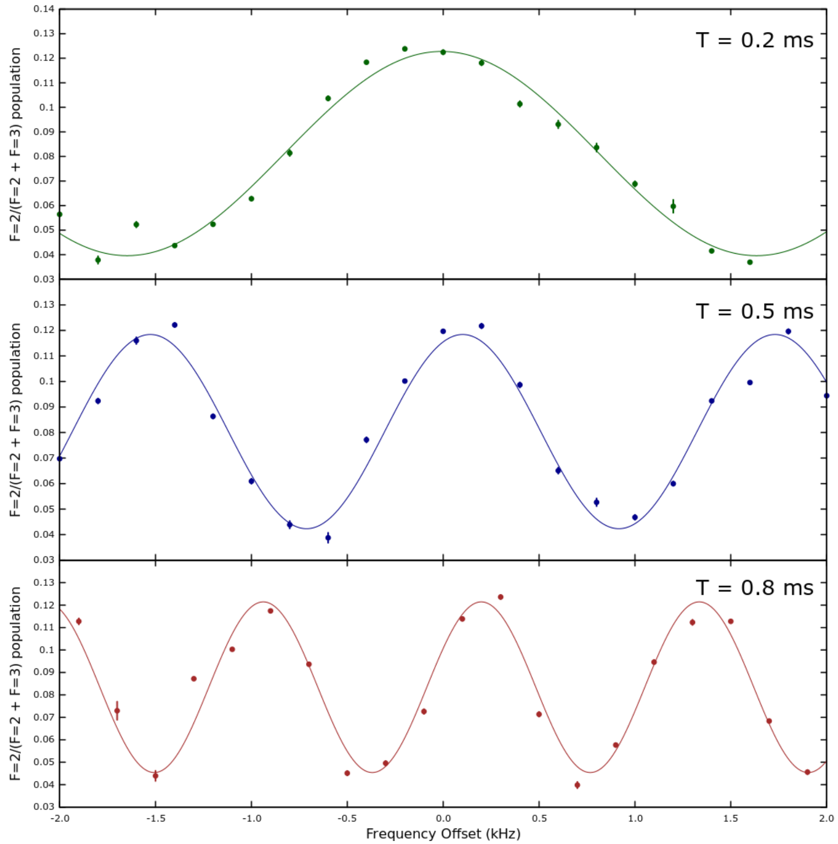
Upgrade Expectations

- New vacuum chamber, fountain configuration
  - Longer interferometer time **$\Delta\varphi = kgT^2$**
  - Larger trapping/cooling and atom optics laser beams
- Vibration Isolation
  - Expected to increase the precision by several orders of magnitude
- Cold atom source
  - Fast repetition rate ~ **1 Hz**
- Velocity-selective Raman beams and magnetic state selection
  - No first order interaction with magnetic fields
- New detection system
  - Increase the signal to noise ratio

Ramsey fringes



Ramsey fringes for varying pulse gap

Technological requirements for a GW detector based on a AI

Sensor technology	State of the art	Goal	GW sensitivity improvement
LMT atom optics	$n = 10^2$	$n = 10^3$	10
Spin squeezing	20 dB (Rb), 0 dB (Sr)	20 dB (Sr)	10
Atom flux	$\sim 10^6$ atoms/s	10^8 atoms/s	10

Goals for MAGIS and current Stanford AI, 2019

Table 1. Technology requirements for a GW detector based on a AI gradiometer configuration to reach a strain sensitivity of $10^{-22}/\sqrt{\mathrm{Hz}}$. The "current" column corresponds to demonstrated results in different experiments. The "required" column implies that all techniques are operationnal in the same experiment.

AI parameter	current	required
LMT order (n)	100	1000
temperature[a]	1 nK	?
interrogation time T (s)	$0.1 - 1$	~ 0.3
AI operating frequency (Hz)	5	20
phase sensitivity (dBrad/$\sqrt{\mathrm{Hz}}$)	-30	-70
detector baseline	300 m	> 3 km
strain sensitivity ($/\sqrt{\mathrm{Hz}}$)	10^{-10}	10^{-22}

Future Gravitational Wave Detectors Based on Atom Interferometry, Remi Geiger, 2016

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