Berlin-Oxford collaboration meeting: Instrumentation, Methods and Applications

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Atomic & Laser Physics, University of Oxford

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List of Projects

1. AION – Atom Interferometer Observatory and Network
   Jointly with Dr Elliot Bentine, Profs. Ian Shipsey and Daniela Bortoletto in Oxford. Awaiting funding decision
   https://indico.cern.ch/event/802946/
2. Cold-atom sources for atom interferometry etc.
   Sources of strontium and alkali metals have been developed – willing to share all details.
3. Non-equilibrium properties of quantum gases (EPSRC funded project, mentioned for completeness). Existing collaborations with theorists: Fabian Essler et al. (Oxford), Ludwig Mathey (Hamburg).

AION: An Atom Interferometer Observatory and Network - arXiv:1911.11755

We outline the experimental concept and key scientific capabilities of AION (Atom Interferometer Observatory and Network), a proposed UK-based experimental programme using cold strontium atoms to search for ultra-light dark matter, to explore gravitational waves in the mid-frequency range between the peak sensitivities of the LISA and LIGO/Virgo/ KAGRA/INDIGO/Einstein Telescope/Cosmic Explorer experiments, and to probe other frontiers in fundamental physics.

AION would complement other planned searches for dark matter, as well as probe mergers involving intermediate mass black holes and explore early universe cosmology.

AION would share many technical features with the MAGIS experimental programme in the US, and synergies would flow from operating AION in a network with this experiment, as well as with other atom interferometer experiments such as MIGA, ZAIGA and ELGAR.

Operating AION in a network with other gravitational wave detectors such as LIGO, Virgo and LISA would also offer many synergies.

(Submitted on 26 Nov 2019 (v1), last revised 12 Dec 2019 (this version, v2))

Gravitational Wave Detection with Atom Interferometry

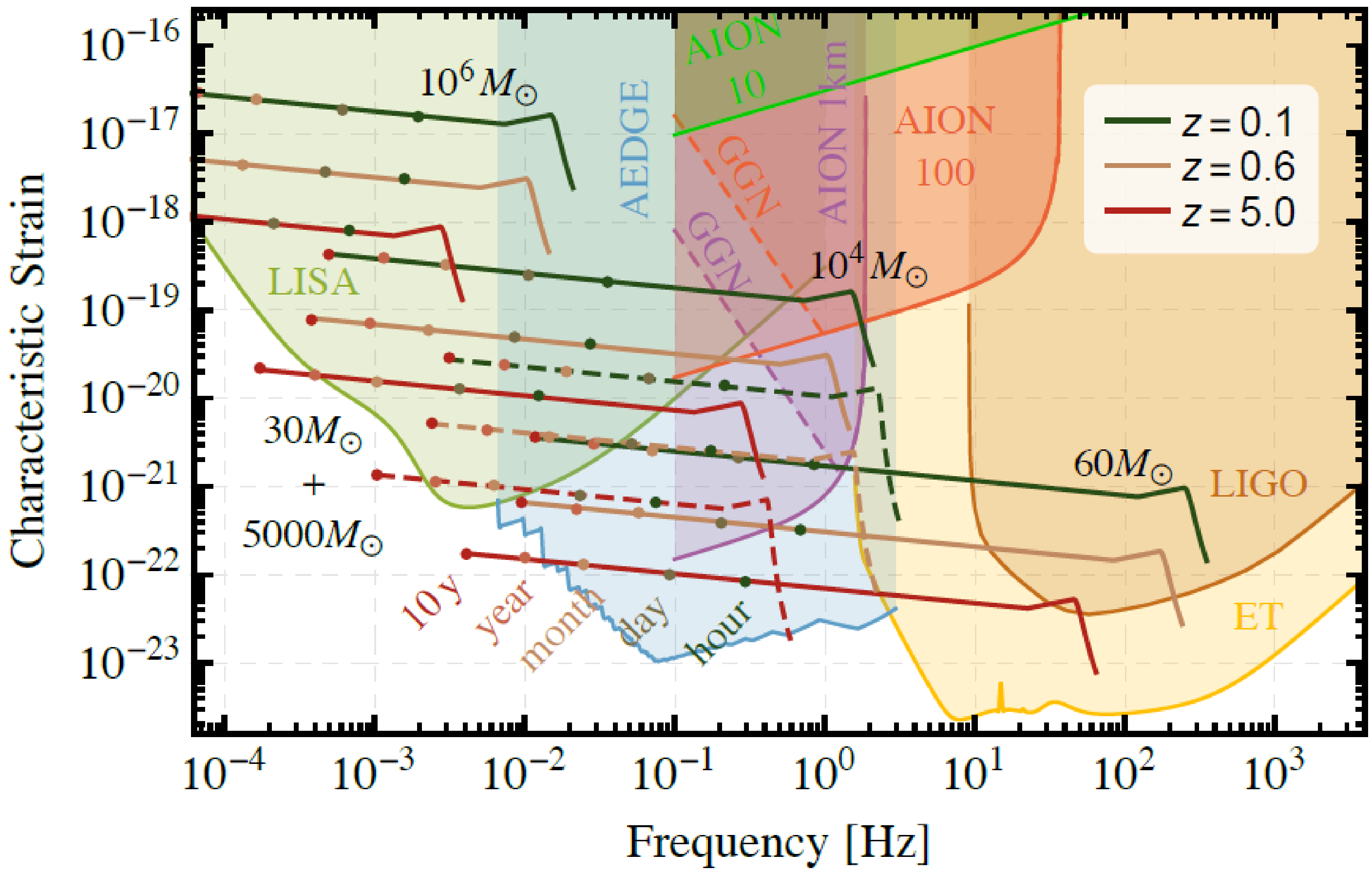


Figure 7. *Comparison of the strain measurements possible with AION and other experiments, showing their sensitivities to mergers at various redshifts of BHs of identical masses adding up to the indicated total masses (solid lines), and of an unequal-mass binary (dashed line), with the indicated remaining lifetimes before merger. Also shown are the possible gravitational gradient noise (GGN) levels in ground-based detectors.*

Sky position determination

Sky localization precision:

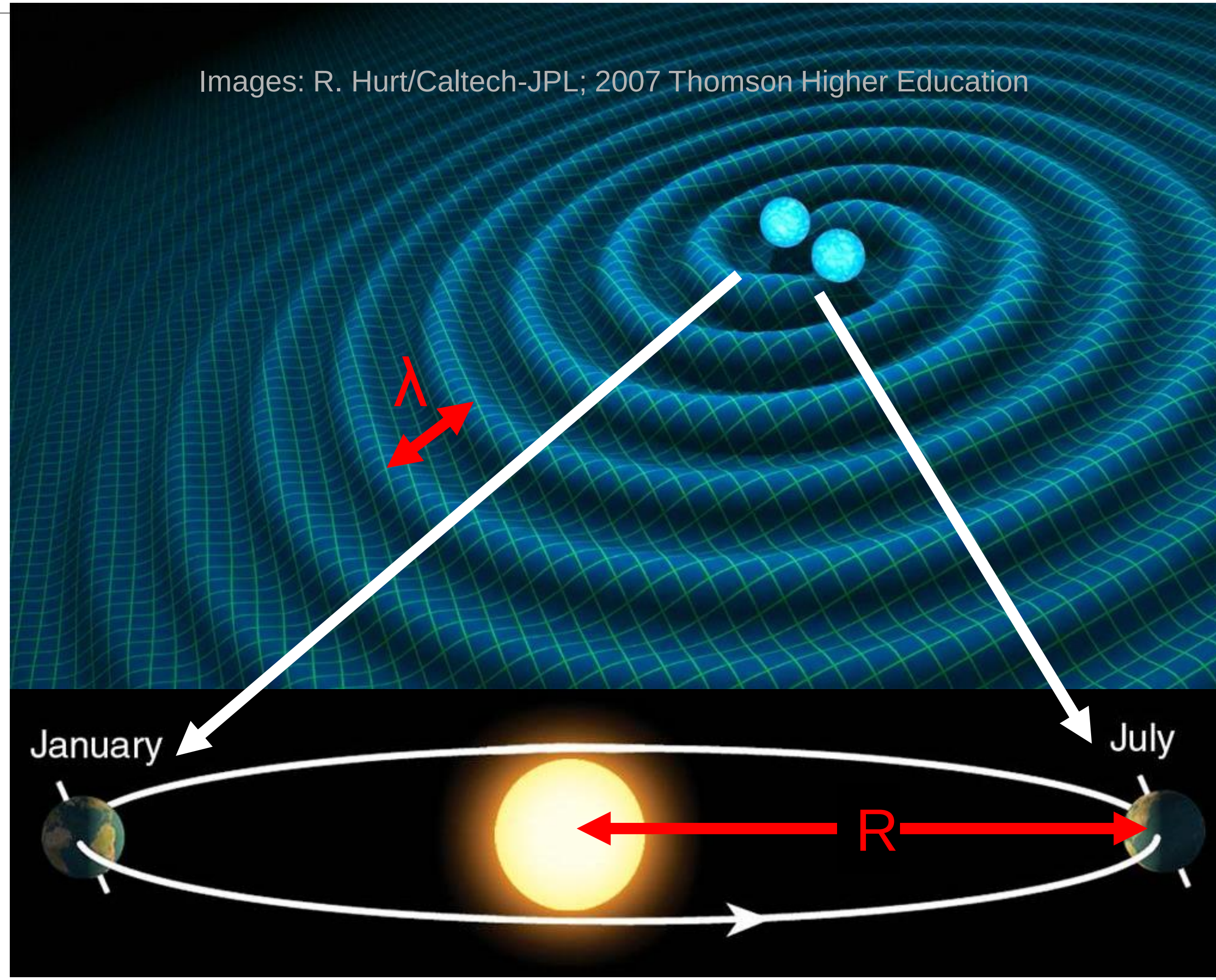
$$\sqrt{\Omega_s} \sim \left(\mathrm{SNR} \cdot \frac{R}{\lambda}\right)^{-1}$$

Mid-band advantages

- Small wavelength λ
- Long source lifetime (~months) maximizes effective R

Benchmark	$\sqrt{\Omega_s}$ [deg]
GW150914	0.16
GW151226	0.20
NS-NS (140 Mpc)	0.19

Courtesy of Jason Hogan!

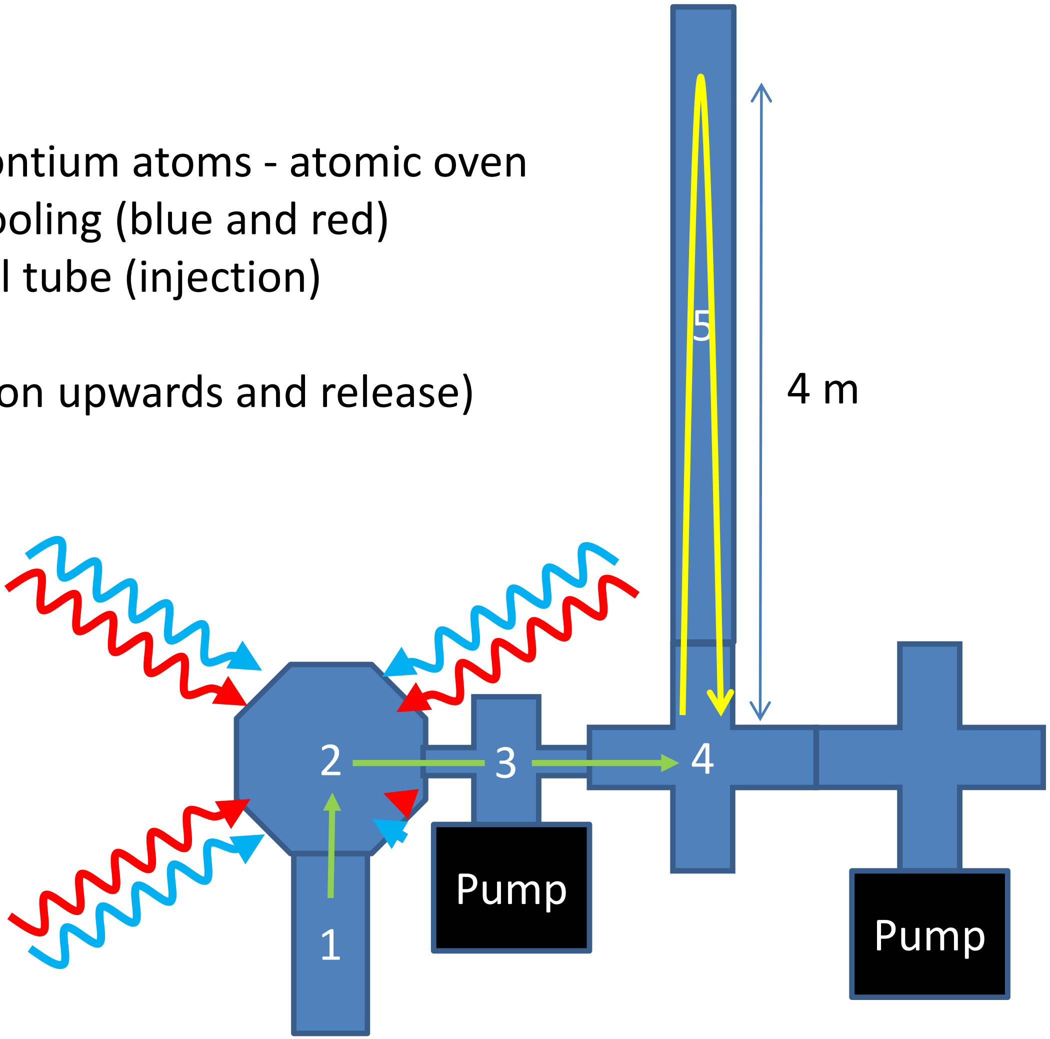


Ultimate sensitivity for terrestrial based detectors is achieved by operating 2 (or more) Detectors in synchronisation mode

AOIN-10: Breakdown into sub-assemblies

Key stages:

1. Source of neutral strontium atoms - atomic oven
2. Two stages of laser cooling (blue and red)
3. Transport into vertical tube (injection)
   - further cooling
4. Launching (acceleration upwards and release)
5. Time of flight



AOIN-10: schematic

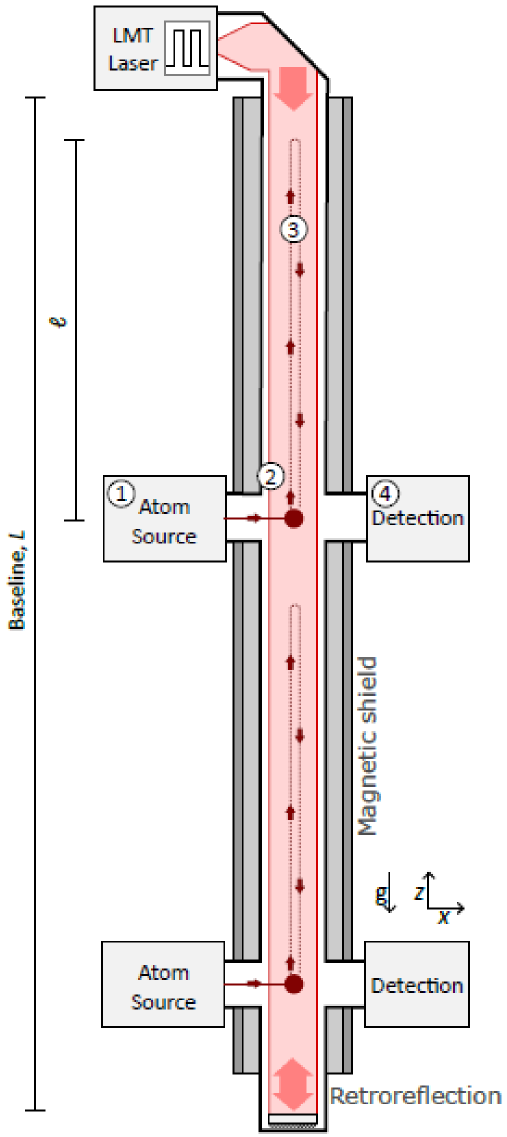
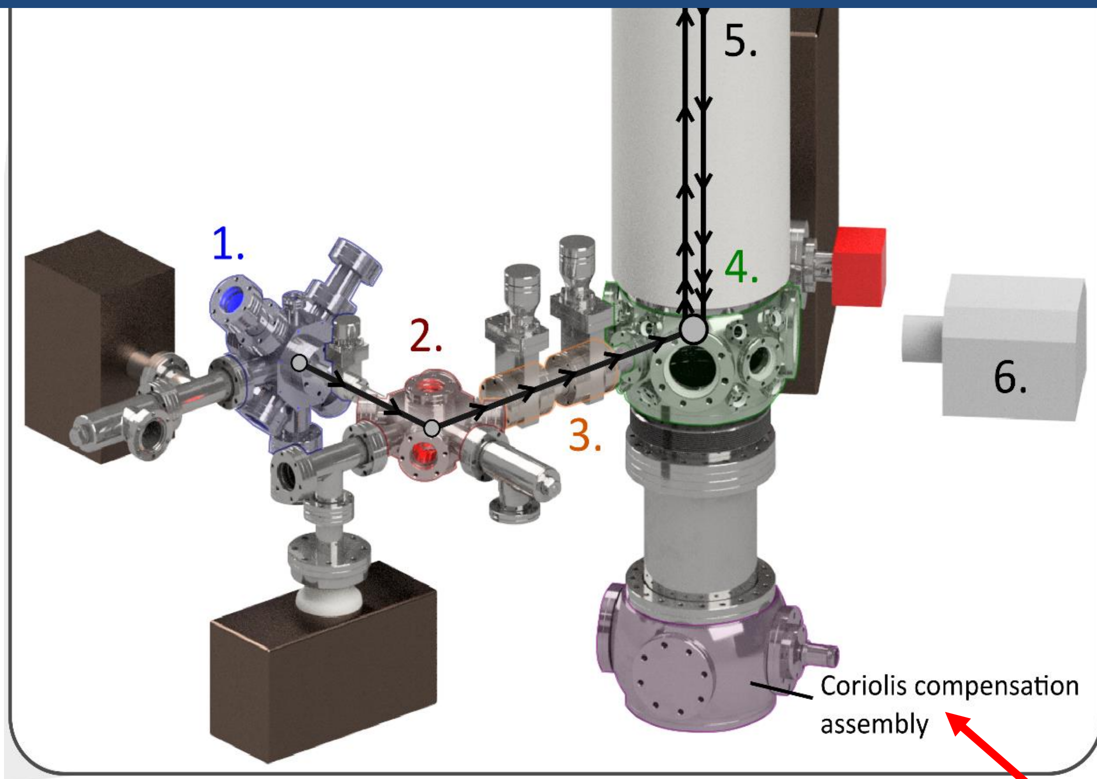


Fig. 2 illustrates the conceptual scheme of AION, for two AIs addressed by a single laser source and arranged vertically. Each AI contains a source of ultracold atoms (1), which are transported to the centre of the vacuum system and launched vertically (2) (launch optics are not shown). The clouds are in free fall for a time $T_{\text{fall}} = \sqrt{8\ell/g}$ (3), during which the atom interferometer sequence is performed using light from the clock laser that simultaneously addresses all the atom interferometers. Finally, the phase accumulated by each atom interferometer is read out individually by imaging the atom clouds (4). Grey boxes indicate the subsystems responsible for producing laser light at the clock transition, the sources of ultracold atoms, and the detection optics and readout. The path taken by the atomic clouds is indicated by the dark red dashed line, and an offset has been added between the upward and downward travelling directions for clarity. The extent of the vacuum system is shown by the thick black line, and the surrounding magnetic shield is shown in grey. Vacuum pumps etc. are omitted for clarity.

First AOIN workshop: https://indico.cern.ch/event/802946/



Key stages:

1. Source of neutral strontium atoms
   - Oxf or MAGIS?
2. Two stages of laser cooling
   - Oxf/NPL
3. Transport into vertical tube (injection)
   - Cam

3a. Further cooling?
   - TBD

4. Launching (acceleration)
   – copy MAGIS?
5. ToF - interferometer sequence
6. Detection – CCD camera

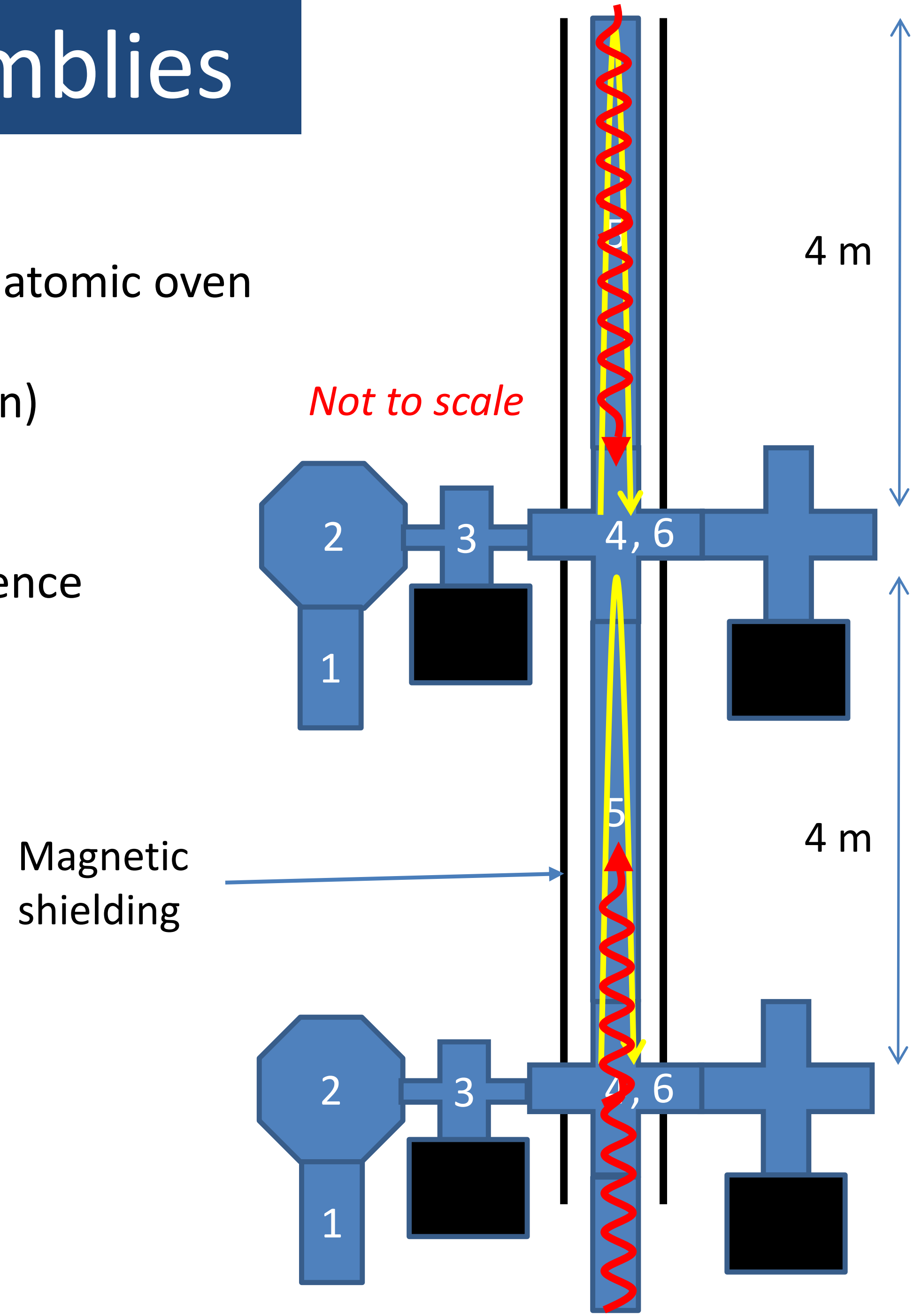
Oxf/MAGIS (existing expts@Stanford)

CAD in the pre-proposal (E.Bentine, June 2019)

AOIN-10: sub-assemblies

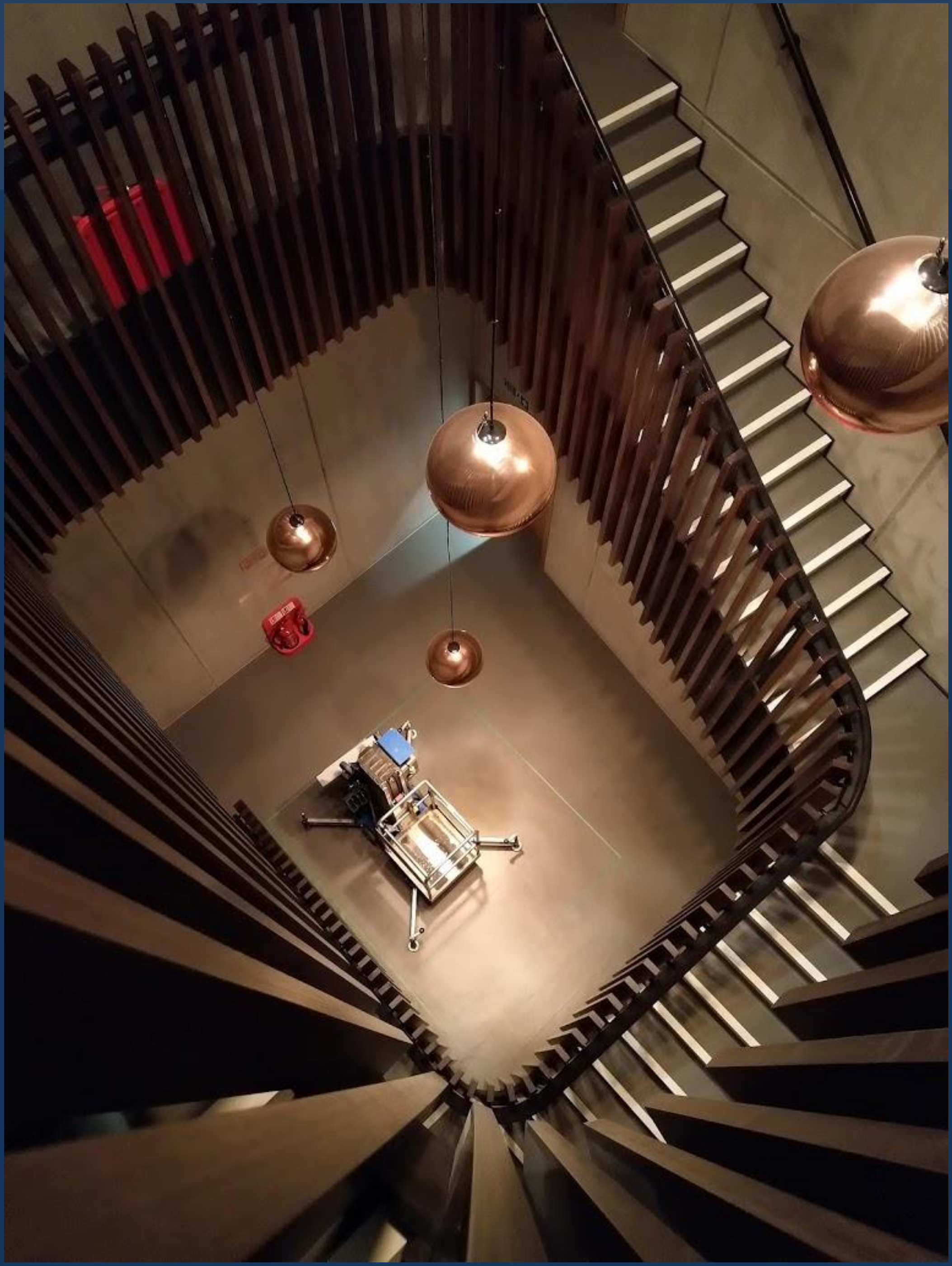
Key stages:

1. Source of neutral strontium atoms - atomic oven
2. Two stages of laser cooling
3. Transport into vertical tube (injection)
   - Further cooling
4. Launching (acceleration)
5. Time of flight - interferometer sequence
6. Detection – CCD camera



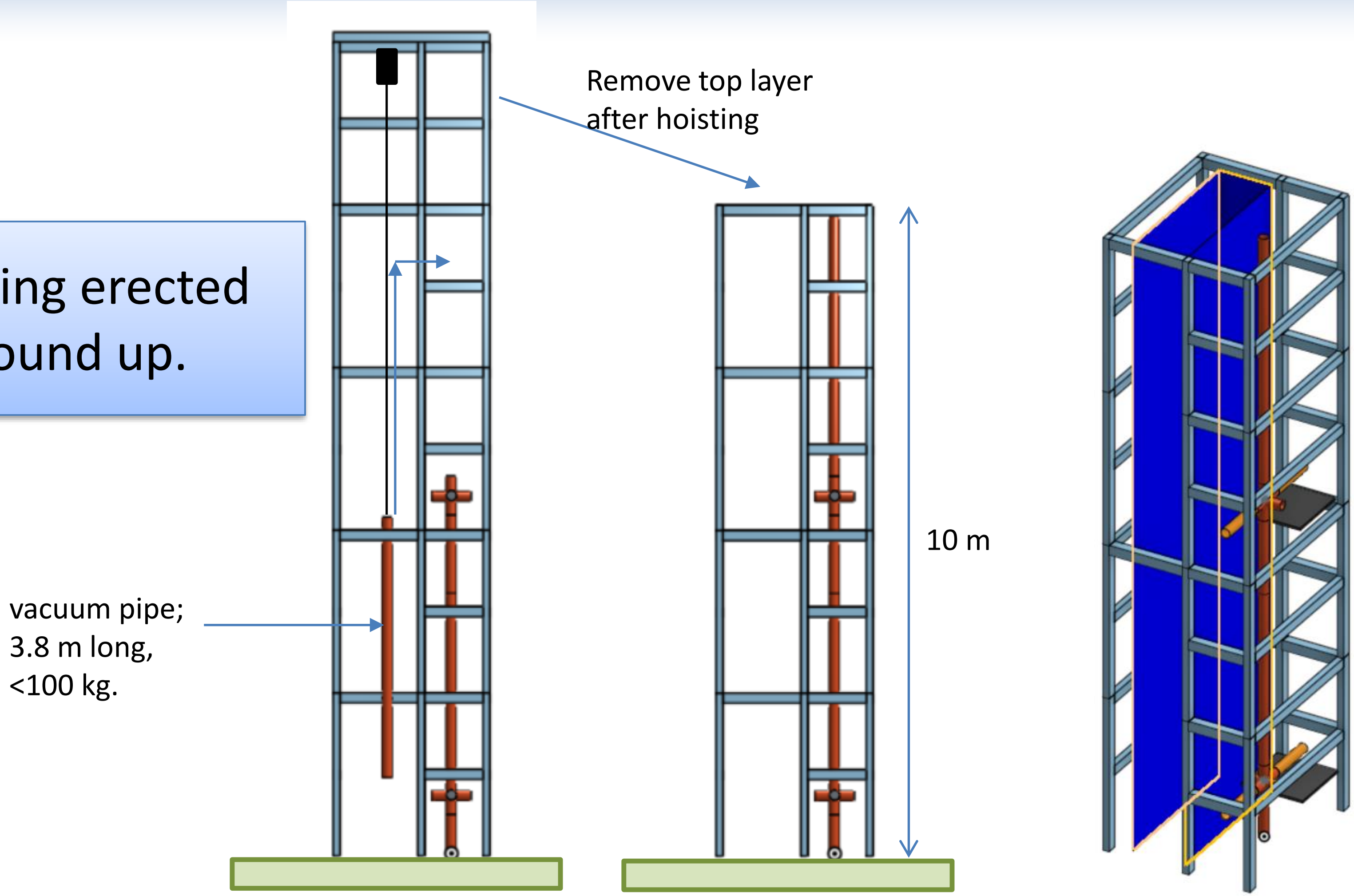
Beecroft building, Oxford Physics

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



Assembly: extruded aluminium support structure

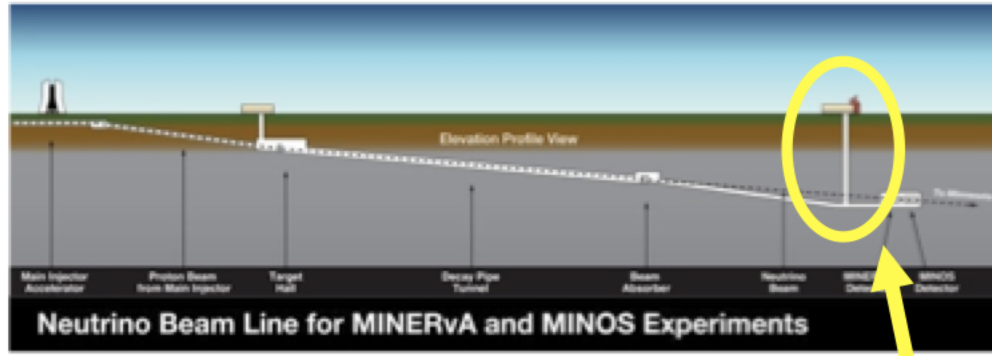
Scaffolding erected from ground up.



MAGIS-100: GW detector prototype at Fermilab

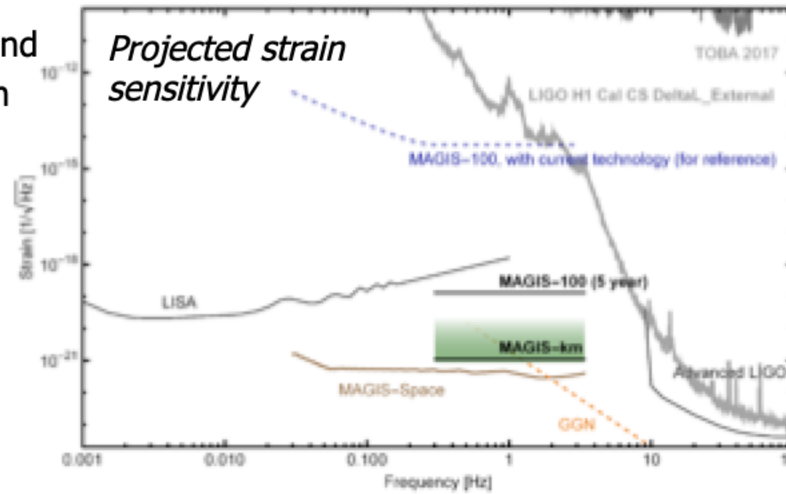
Matter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor

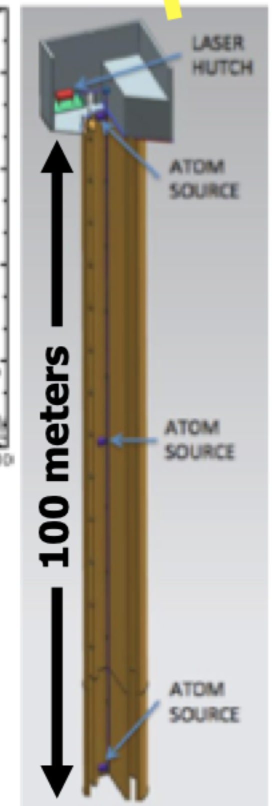
- 100-meter baseline atom interferometry at Fermilab (MINOS access shaft)
- Intermediate step to full-scale (km) detector for gravitational waves



Mid-band science

- LIGO sources before they reach LIGO band
- Optimal for sky localization: predict when and where inspiral events will occur (for multi-messenger astronomy)
- BH, NS, WD binaries
- Probe for studying cosmology
- Search for dark matter (dilaton, ALP, …)
- Extreme quantum superposition states: >meter wavepacket separation, up to 9 seconds duration





Timeline

- 2019 – 2023: MAGIS-100 at Fermilab (100-meter prototype detector) GORDON AND BETTY MOORE FOUNDATION
- *2023 – 2028: Kilometer-scale GW detector (e.g., SURF Homestake site)* **[Proposed]**

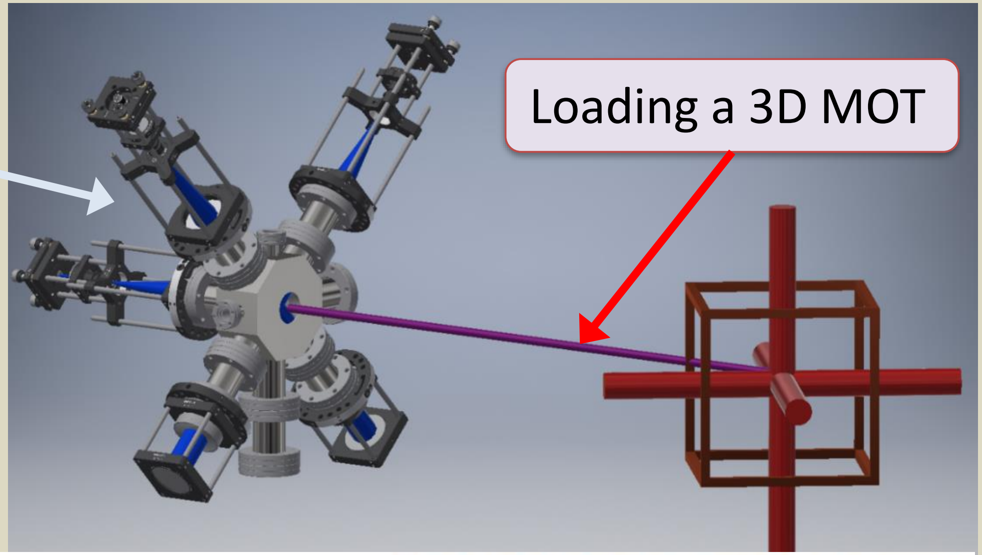
STANFORD UNIVERSITY Fermilab BERKELEY UNIVERSITY OF LIVERPOOL Northwestern University Northern Illinois University

Courtesy of Jason Hogan!

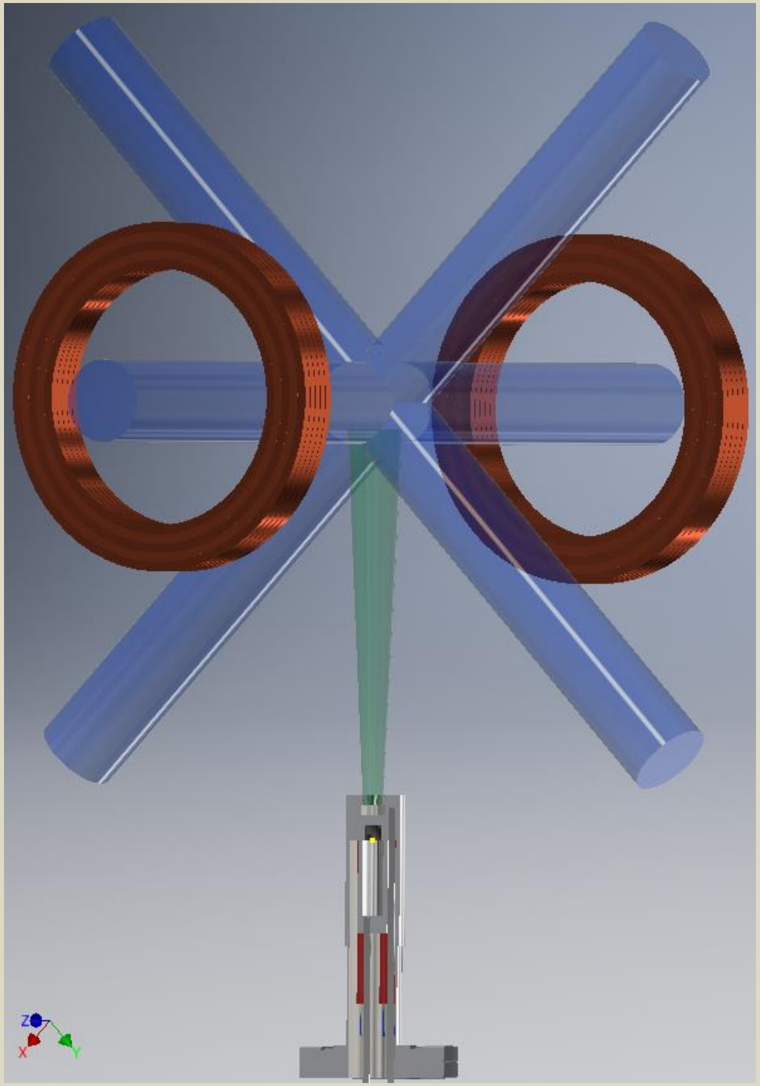
A high-flux source of laser-cooled strontium atoms

2D MOT cold-atom source

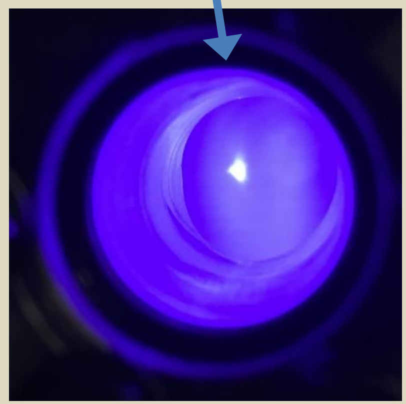
To replace Zeeman slower on existing set ups

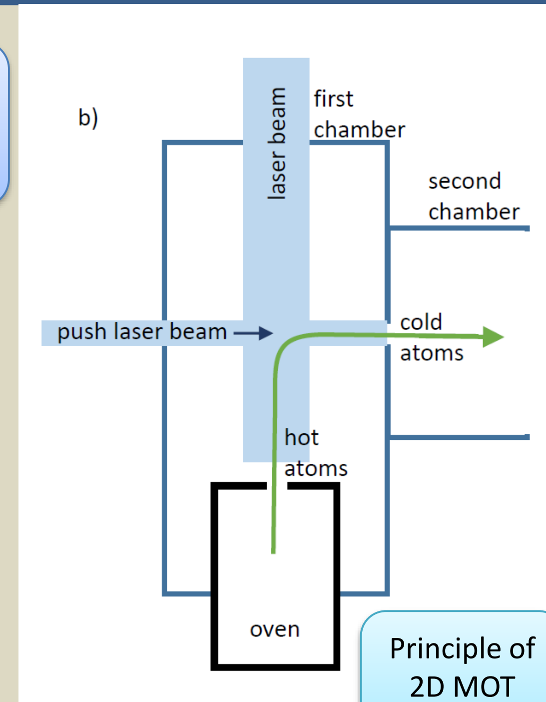


A high-flux source of laser-cooled strontium atoms

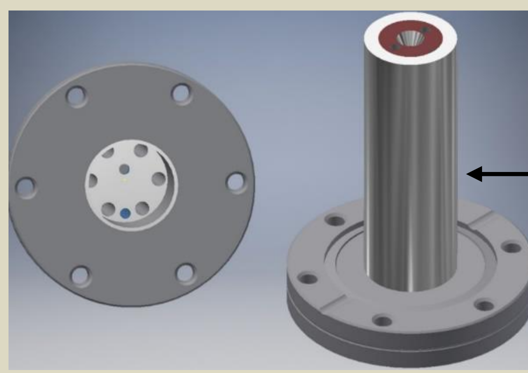


Blue fluorescence from atoms in MOT





Principle of 2D MOT source



Stainless steel oven welded to CF40 flange