Generative AI for Gravitational Wave and Dark Matter Research

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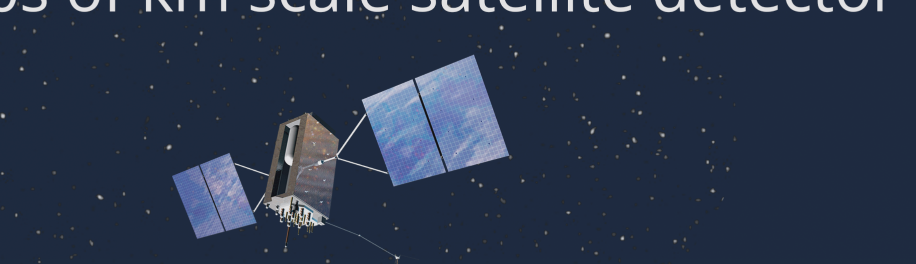
The Atom Interferometer Observatory and Network (AION) project across multiple UK universities and institutions aims to utilise quantum atomic cooling and atom interferometry to detect ultra-light dark matter and gravitiational waves.

By developing an AI simulation of the atomic cooling process based on a physics model, optimisation techniques such as reinforcement learning and Bayesian optimisation can be applied to find the optimal set of parameters for atomic cooling.

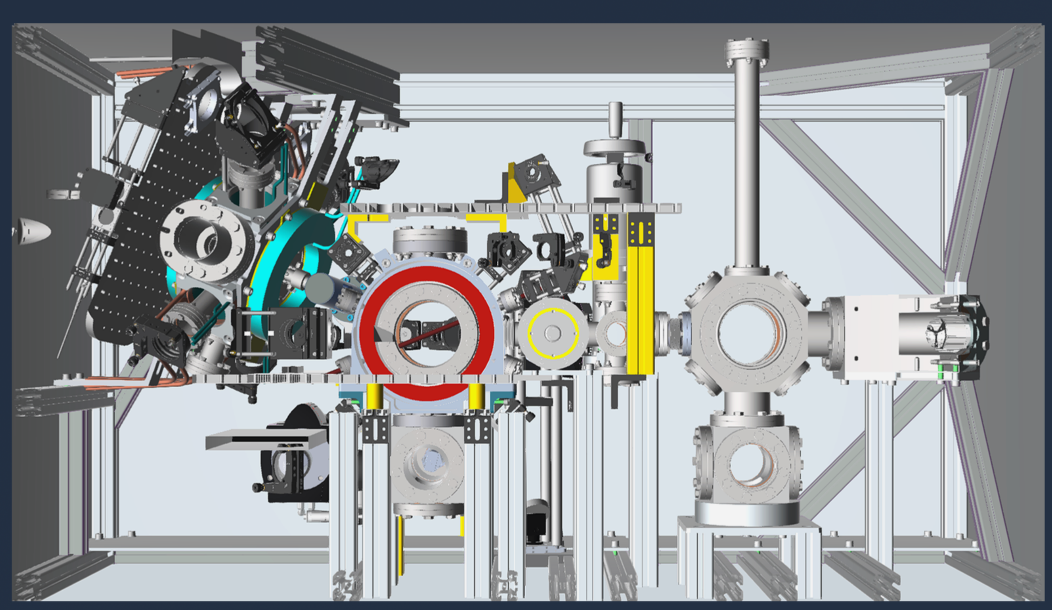
Programme Milestones

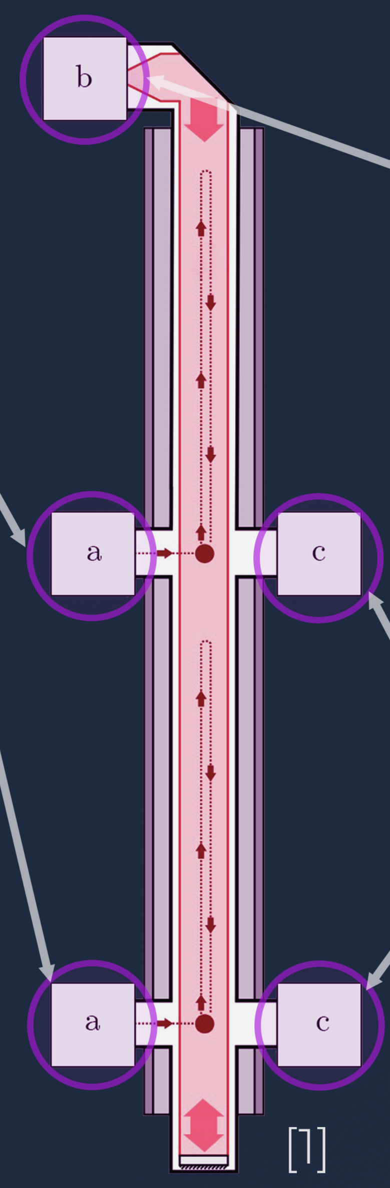
10m detector → 100m detector → km-scale detector → 1000s of km scale satellite detector



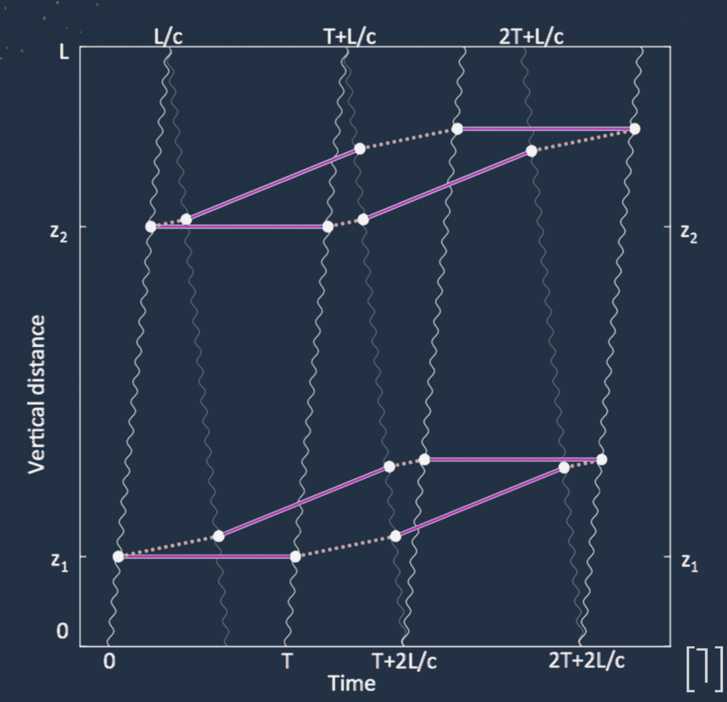
Cold Atom Interferometry

a) A series of cooling techniques are applied to cool a cloud of strontium atoms to micro-Kelvin temperatures. These are then launched vertically into the chamber, shielded from external forces beyond gravity.





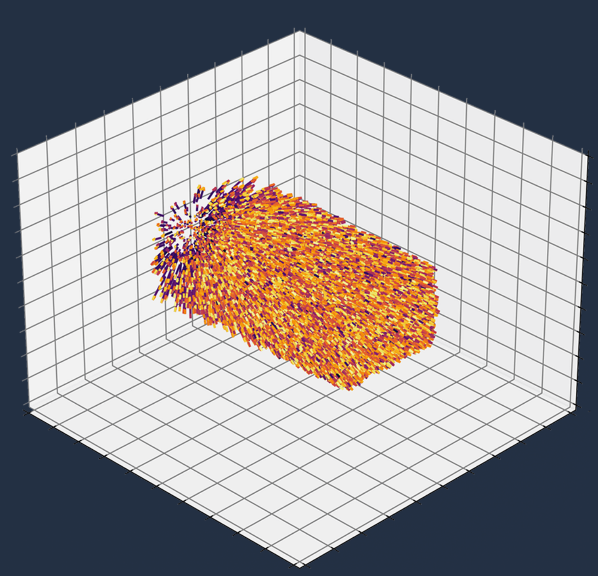
b) Once in free-fall, a series of laser pulses drive the clock transitions of the atoms. A superposition of states is created, before being recombined. The influence of gravitational waves and dark matter on the atom's transition frequency causes an interference pattern.



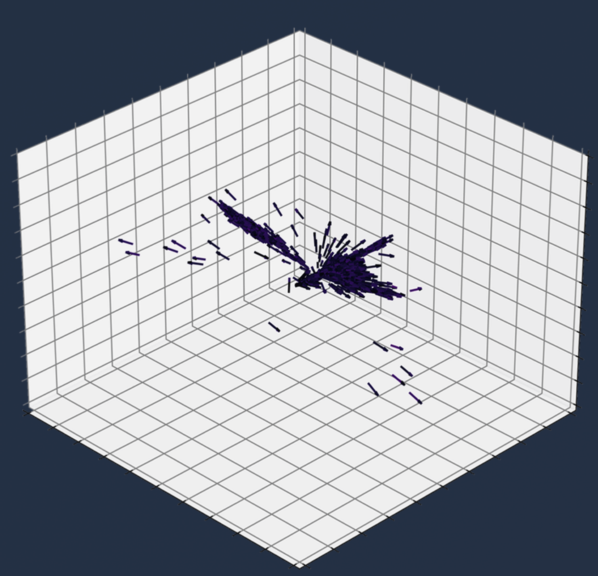
c) The difference in phase measured at each detector cancels out laser noise, and isolates the influence of gravitational waves detected via the light propogation time caused by the strain created in the space between atoms. Dark matter is detected via its differential effects on the atom's transition frequency. [2]

Physics Model

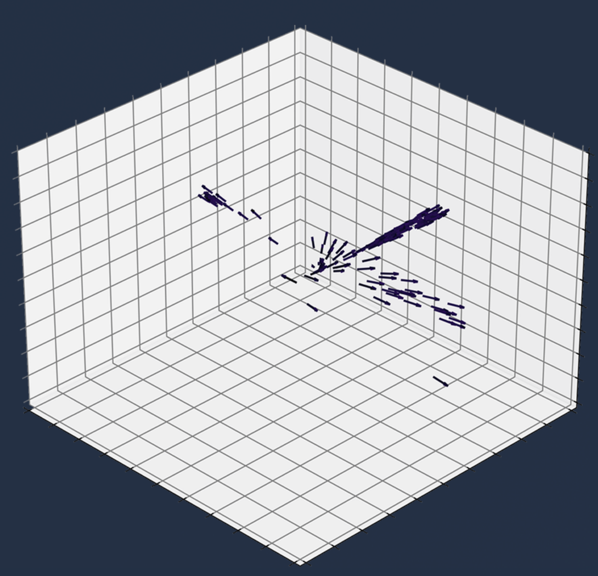
The simulation generates atoms fired from a virtual atomic oven by sampling their angular velocity from a distribution.



A quadrupole magnetic field and intersecting cooling lasers trap the atoms via photon absorption and spontaneous emission.

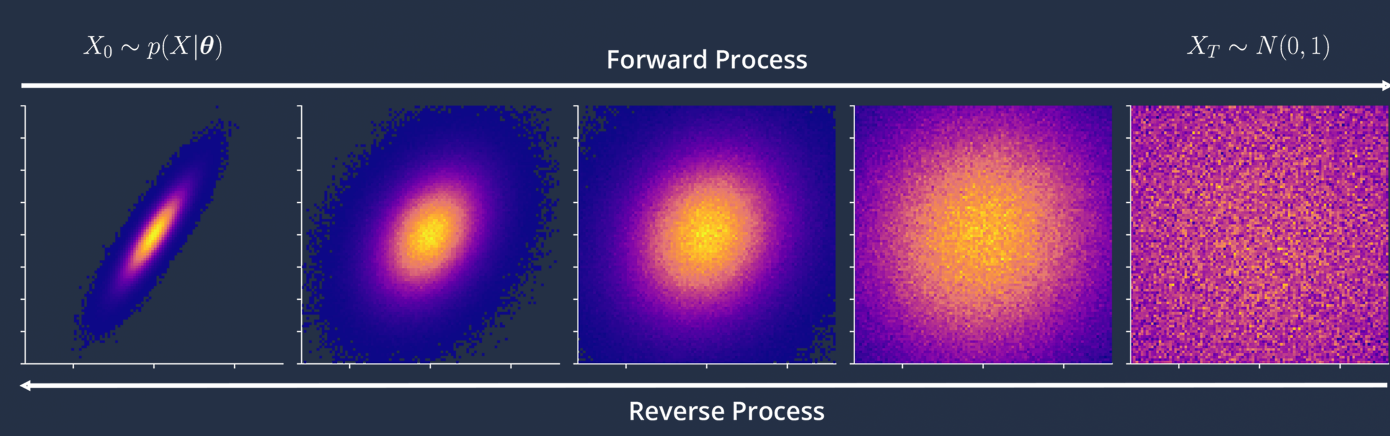


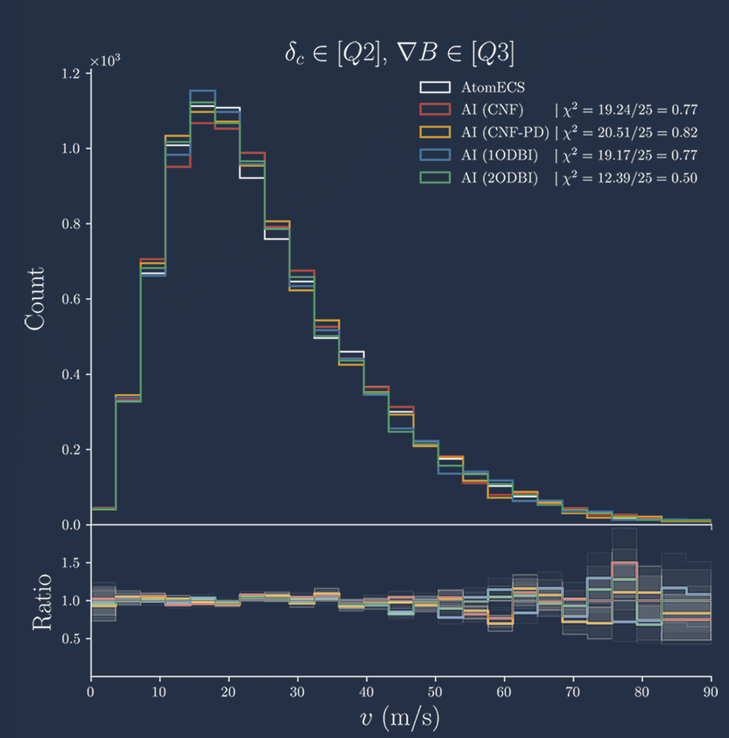
A push beam along the z-axis imparts momentum to the cooled atoms, directing them through a pipe towards the 3D MOT. [3]



Generative AI Simulation

A diffusion proccess was used to model the simulation. This generative technique is most known for use in image generation. [4]





The performance of various models was analysed, including normalising flows and diffusion as well as two adaptations to these models. The diffusion models were found to most accurately capture the relationships in the data obtained from the physics model.

Overall, a speed-up factor of 175x from the physics model was achieved, facilitating the application of optimisation techniques.

By applying Bayesian optimisation, the sets of parameters that gave the highest percentages of appropriately cooled atoms were found.

Rank	δ_c (MHz)	P_c (mW)	w_c (mm)	δ_p (MHz)	P_p (mW)	w_p (mm)	d_p (mm)	∇B (G/cm)	B_v (G)	$\mathcal{P}_{pipe}$ ($\times 10^{-3}$)	$\tilde{v}$ (m/s)	$\sigma_{\vec{r}}$ (mm)	J_τ ($\times 10^3$)
1	-146.44	304.79	11.33	-260.07	2.30	8.01	1.98	27.11	0.16	0.26	9.08	0.36	0.49
2	-139.22	316.48	11.34	-294.06	2.51	8.64	2.04	25.84	-2.44	0.25	10.29	0.35	0.41
3	-180.66	340.39	12.50	-287.02	1.55	7.27	2.51	32.26	0.07	0.19	9.32	0.37	0.34
4	-116.44	210.93	8.95	-176.23	3.81	6.71	2.61	26.35	-0.14	0.15	7.55	0.34	0.32
5	-112.10	334.36	8.47	-181.94	2.92	12.66	2.38	28.24	-1.30	0.25	13.84	0.35	0.32
6	-109.83	325.69	11.12	-176.36	3.01	12.69	2.06	18.65	-1.80	0.31	17.67	0.34	0.32
7	-180.39	337.92	11.92	-346.66	1.76	7.20	2.53	31.39	0.09	0.14	7.27	0.36	0.30
8	-110.94	301.42	9.53	-189.55	3.00	10.95	2.40	26.47	-1.19	0.22	13.01	0.35	0.30
9	-119.46	251.06	9.25	-145.26	3.17	13.33	2.74	28.34	-2.54	0.24	14.83	0.35	0.29
10	-90.73	326.33	10.59	-189.92	2.96	11.18	1.94	15.23	0.73	0.18	11.22	0.35	0.28

References: [1] L. Badurina (2020), [2] E. Pasatembou (2023), [3] X. Chen (2021), [4] J. Ho (2020)