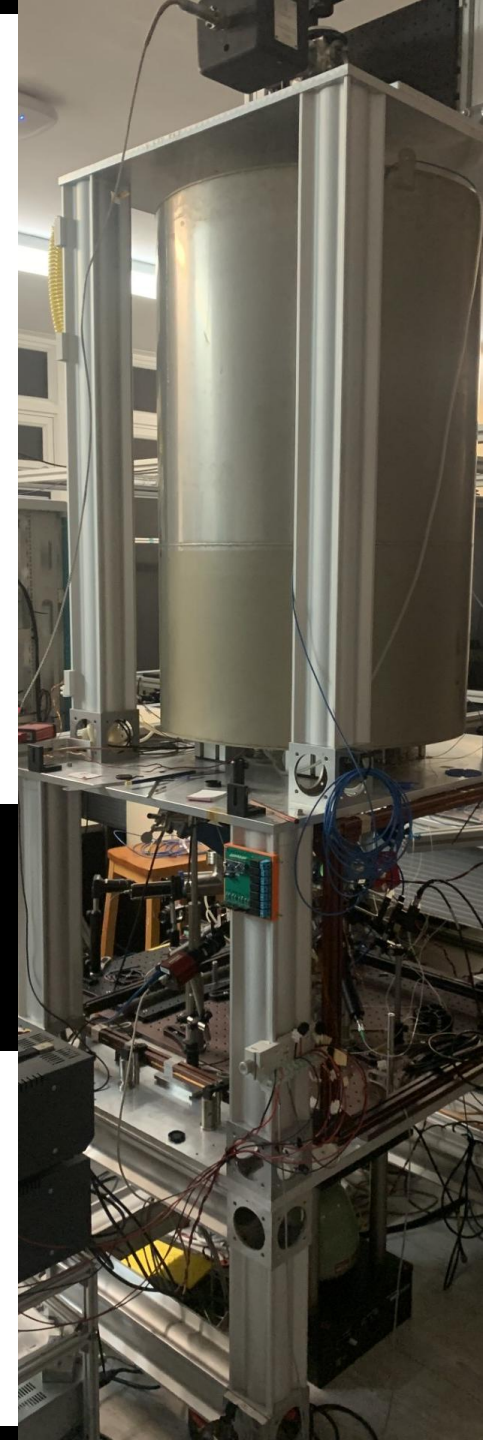


CHETAN PARMAR

Supervised by: Jonathan Tinsley, Jonathon Coleman

ATOM INTERFEROMETRY

*Towards Atomic
Interferometry at Liverpool,
MAGIS, and in Space*



WHY DO WE NEED PRECISION MEASUREMENTS?

Verify theory

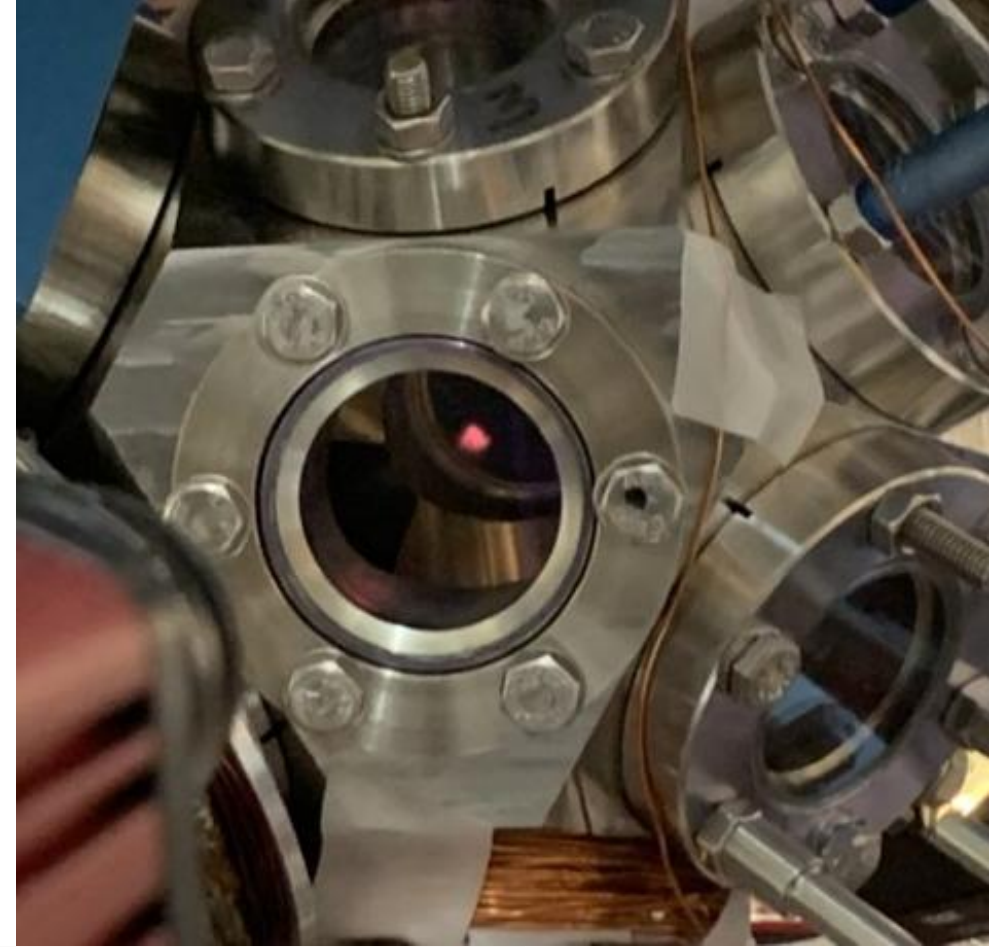
- Precision measurements help verify successful theories; Standard model, General relativity.
- Small deviation between expected and measured results can lead to new physics

Determine constants

- E.g. Fine structure constant α , Gravitational constant G .
- The more accurate a universal constant is, the more accurate subsequent calculations will be.

Technological advancements

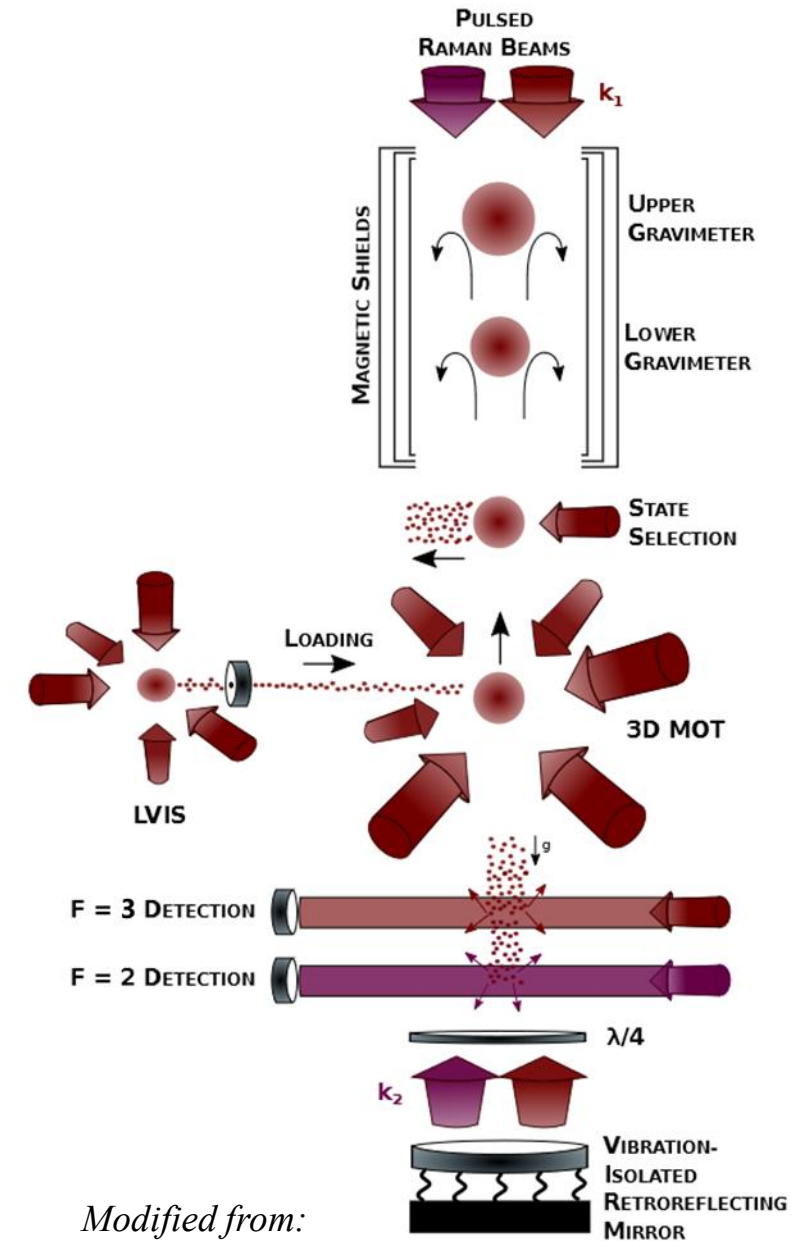
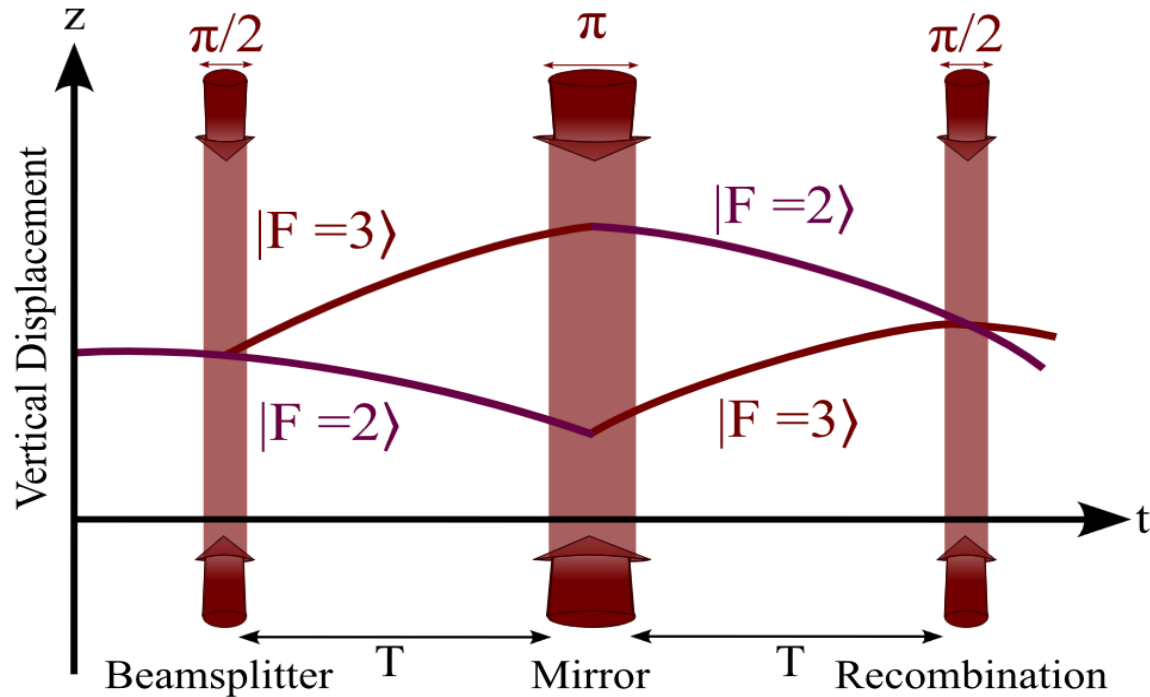
- Atomic clocks are now used at the top of the Network Time Protocol time keeping hierarchy.



ATOM INTERFEROMETRY

Technique to interfere atomic superpositions with fundamental physics applications

- Pulsed Raman laser beams to put the atoms into superposition of spatially separated states, performing a Mach-Zehnder interferometry sequence
- Accumulated phase difference to first order: $\Delta\Phi = k_{\text{eff}} g T^2$



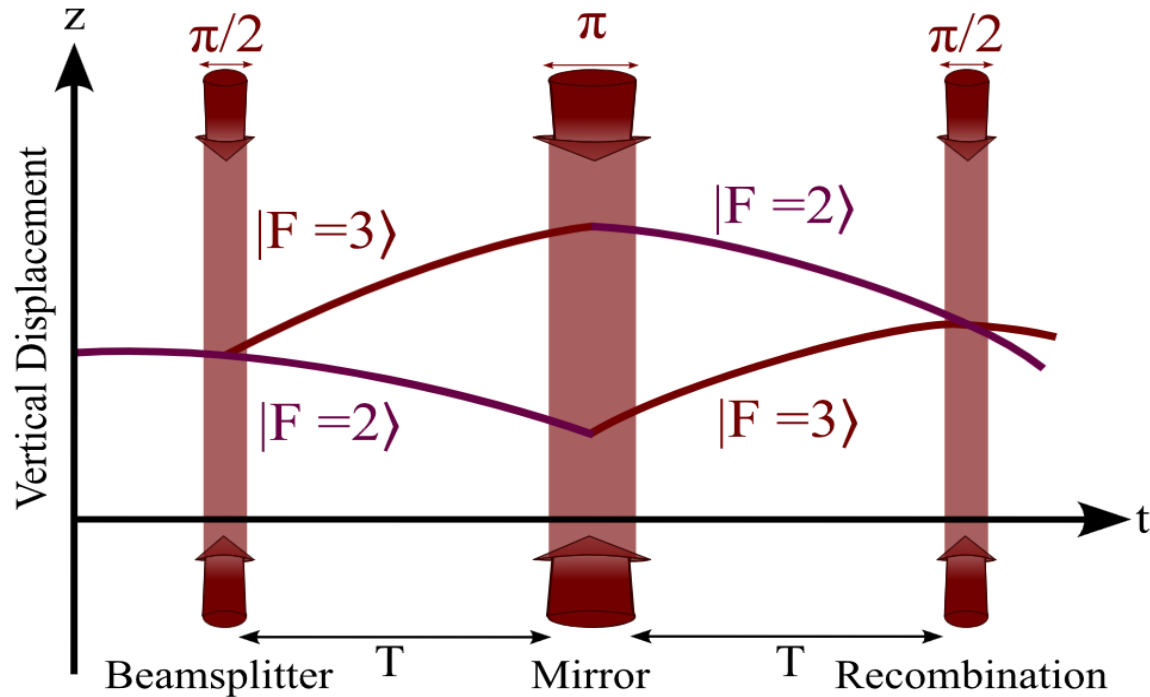
Modified from:
J.N. Tinsley, PhD Thesis (2019)

Atomic
Interferometry

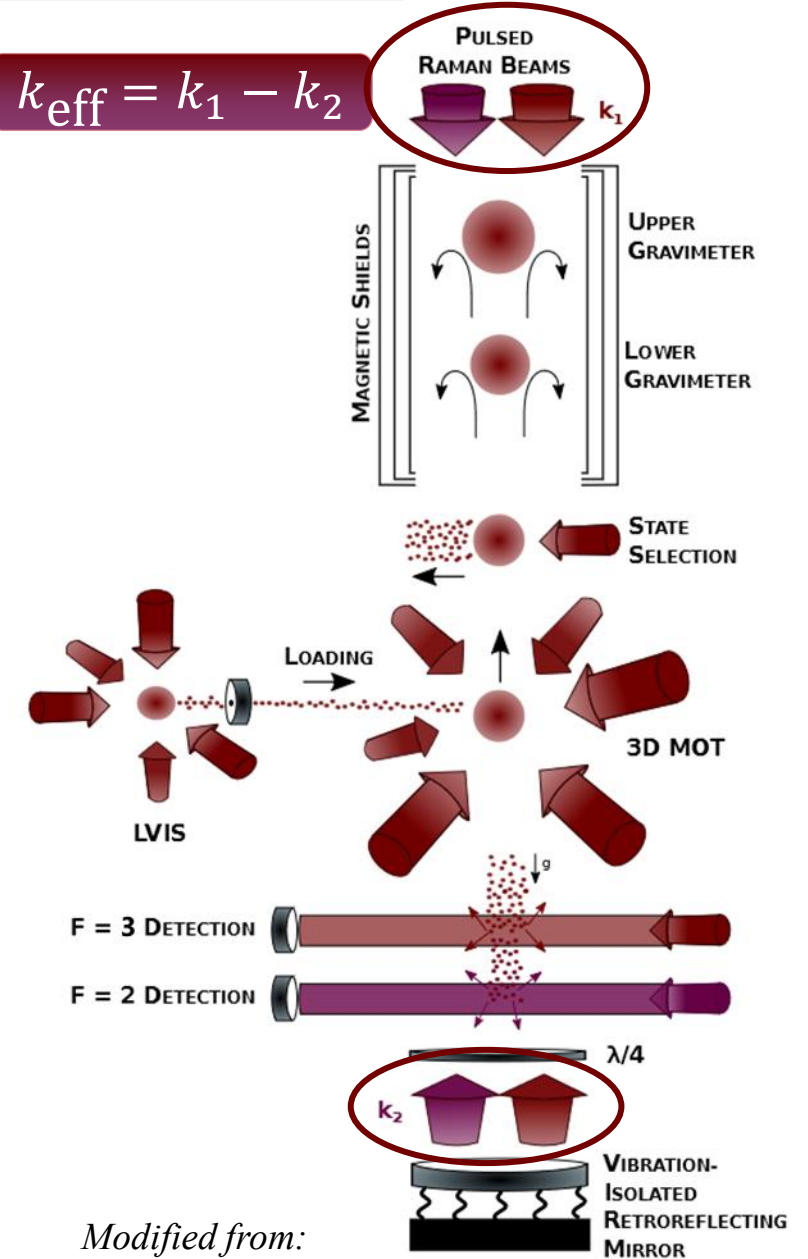
ATOM INTERFEROMETRY

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$$k_{\text{eff}} = k_1 - k_2$$



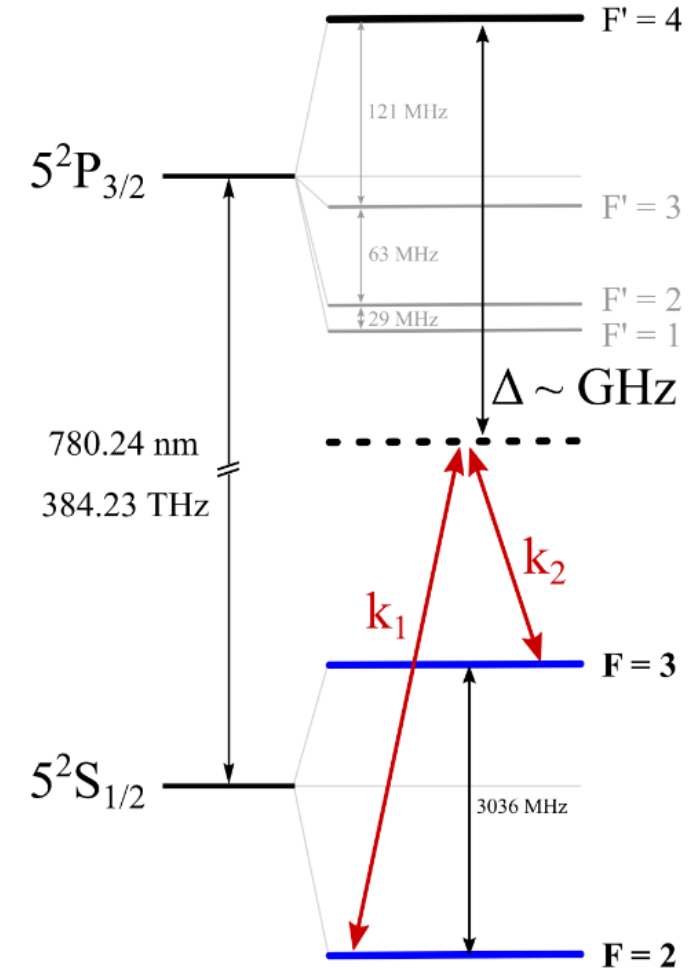
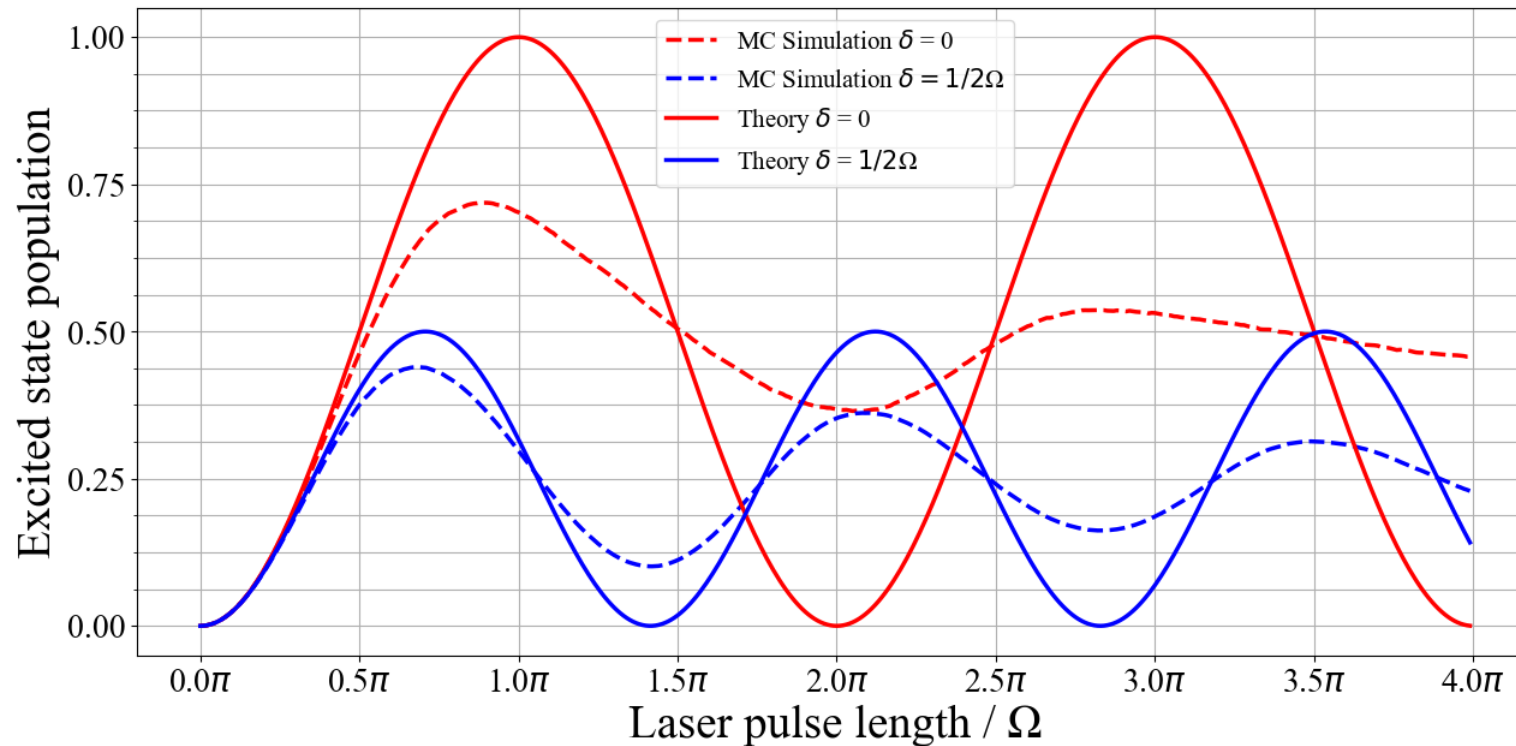
Modified from:
J.N. Tinsley, PhD Thesis (2019)

Atomic
Interferometry

ATOM INTERFEROMETRY

Pulsed Raman laser beams to manipulate atomic states

- Two 780nm laser beams (k_1 and k_2) drive a Raman transition between the two hyperfine ground states via a virtual intermediary state.
- Frequency chirped: stay on resonance as atoms accelerate due to gravity with respect to the beams
- Probability of the atoms being excited varies sinusoidally as a function of pulse time:

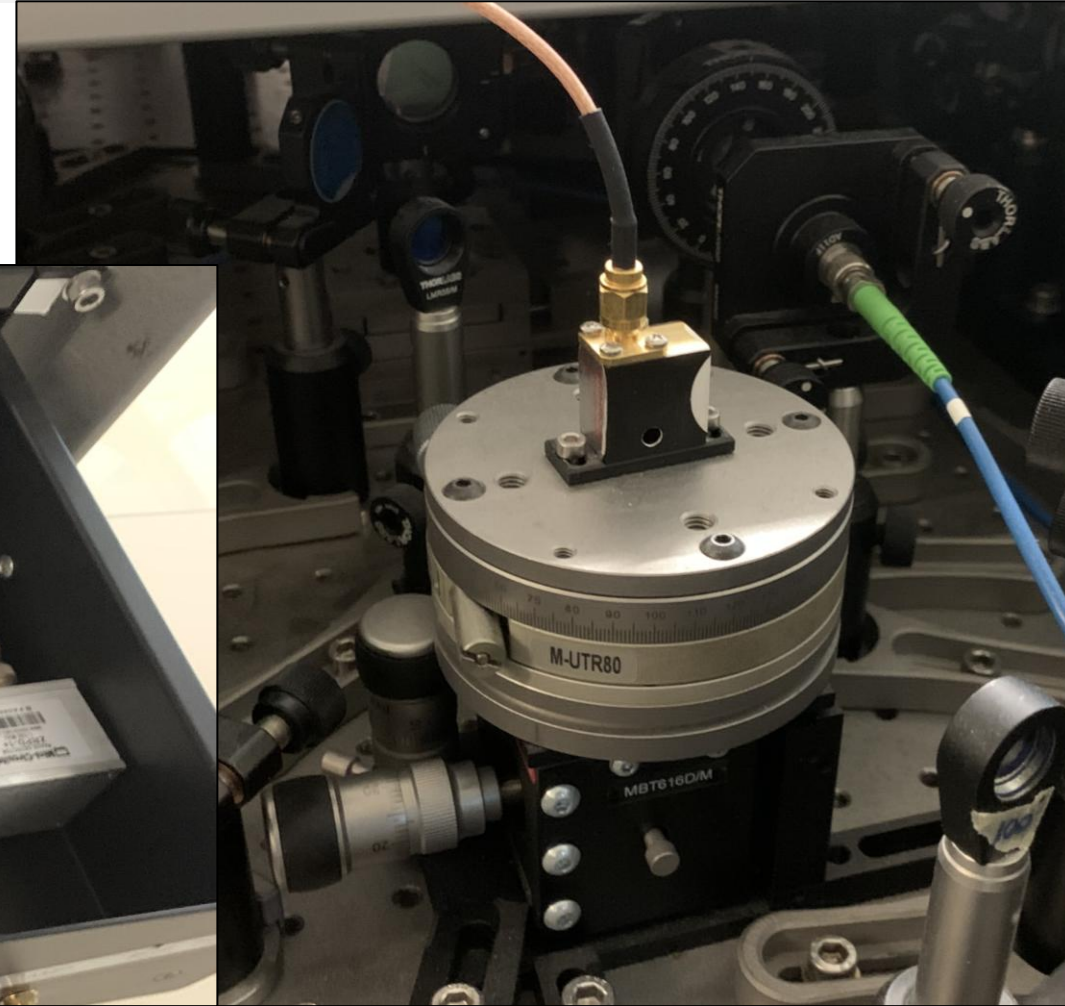
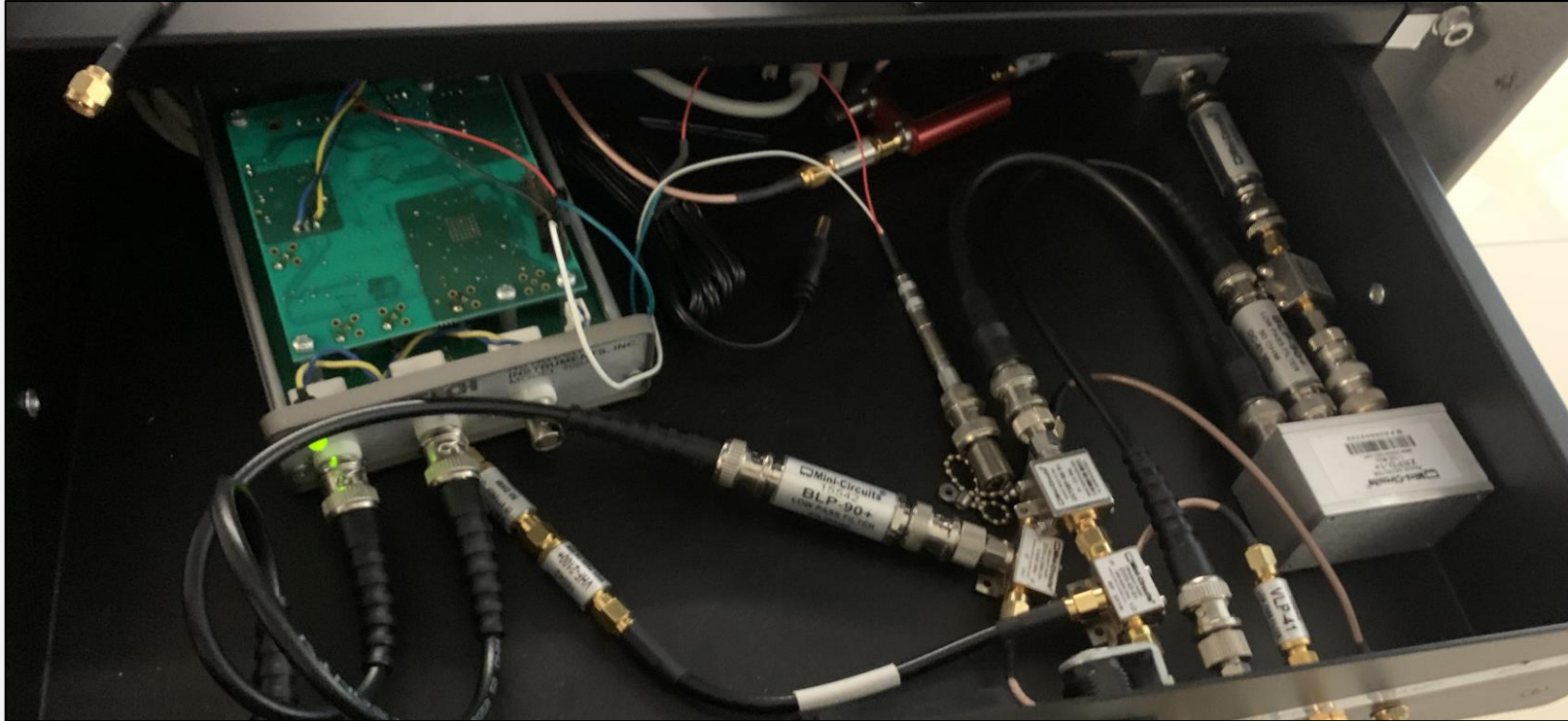


G. Elertas, PhD Thesis (2021)

FREQUENCY CHIRPING

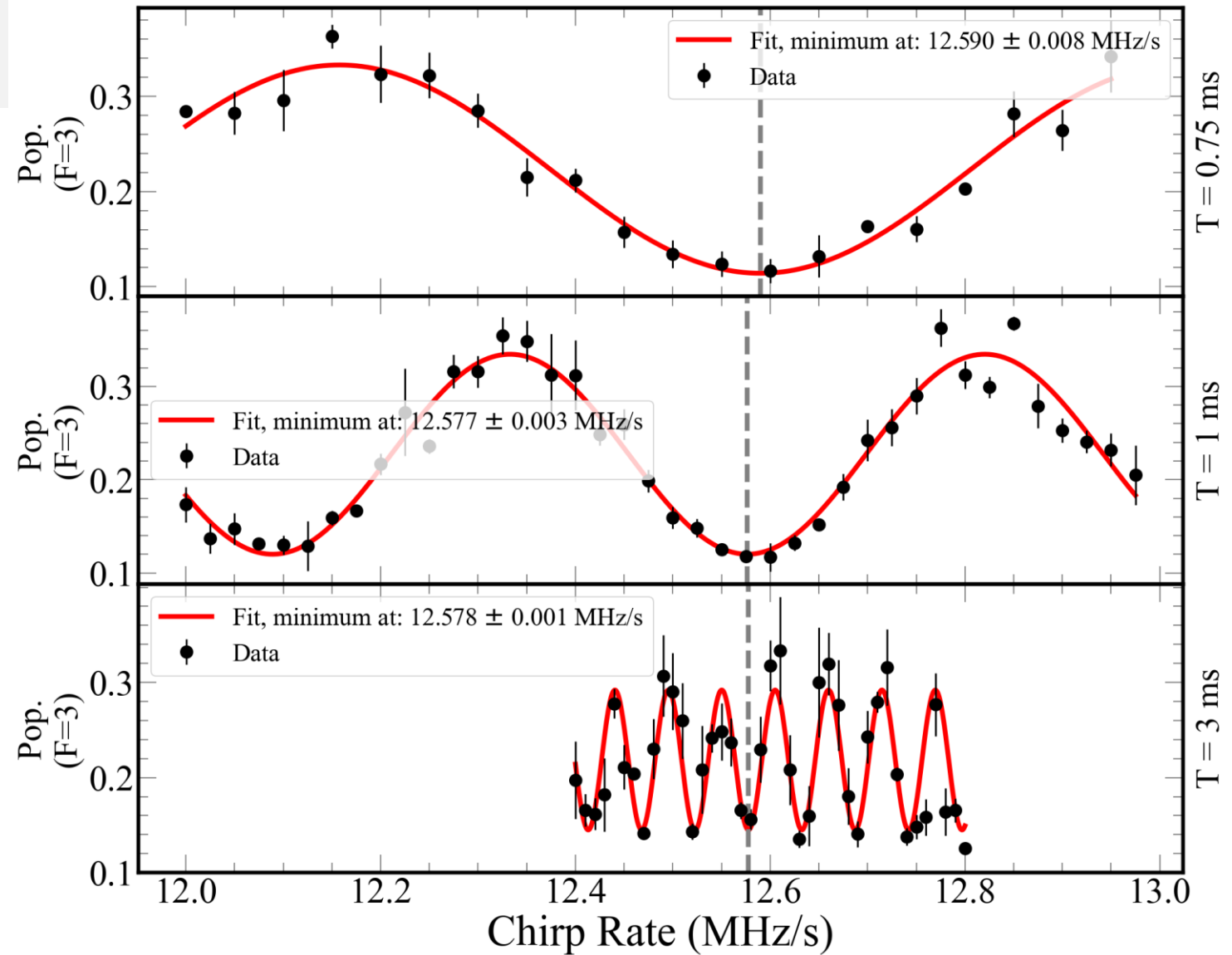
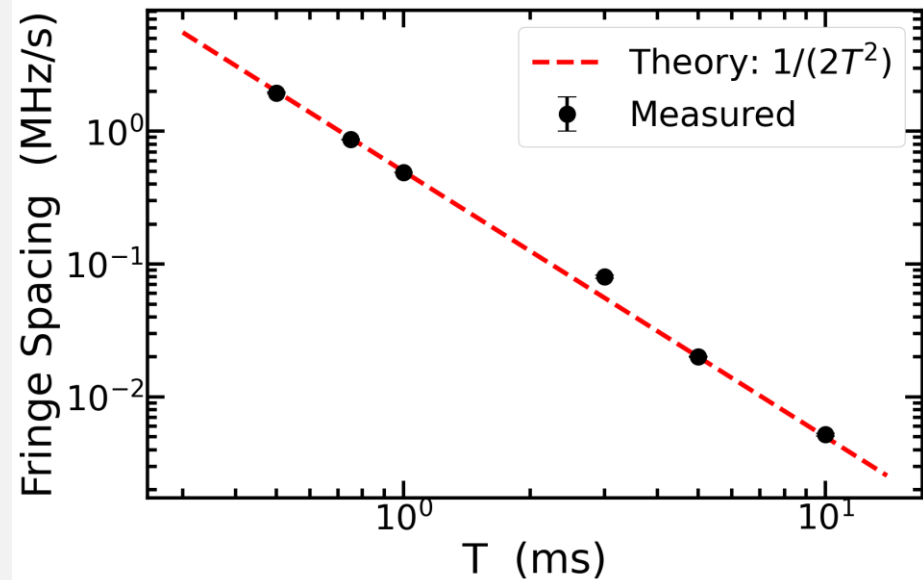
Sweeping beam frequency to maintain resonance as atom cloud accelerates

- Sweeping frequency generated by Direct Digital Synthesiser
- Mixed into Local Oscillator (stable frequency generator)
- Amplified and sent to acousto-optical modulator (AOM)
- Beams pass through AOM – diffracted and frequency shifted



FREQUENCY CHIRPING

- Scanning chirping rate results in fringes
- Fringe spacing depends on interferometry time (T)
- Atoms are accelerating: chirp rate corresponds to rate of change of the doppler shift - always at a minimum
- Increasing T allows the minimum to be found with greater accuracy



FREQUENCY CHIRPING

- Fringes fit to a sin function, nearest minimum to known g found
- Gravity can be found from:

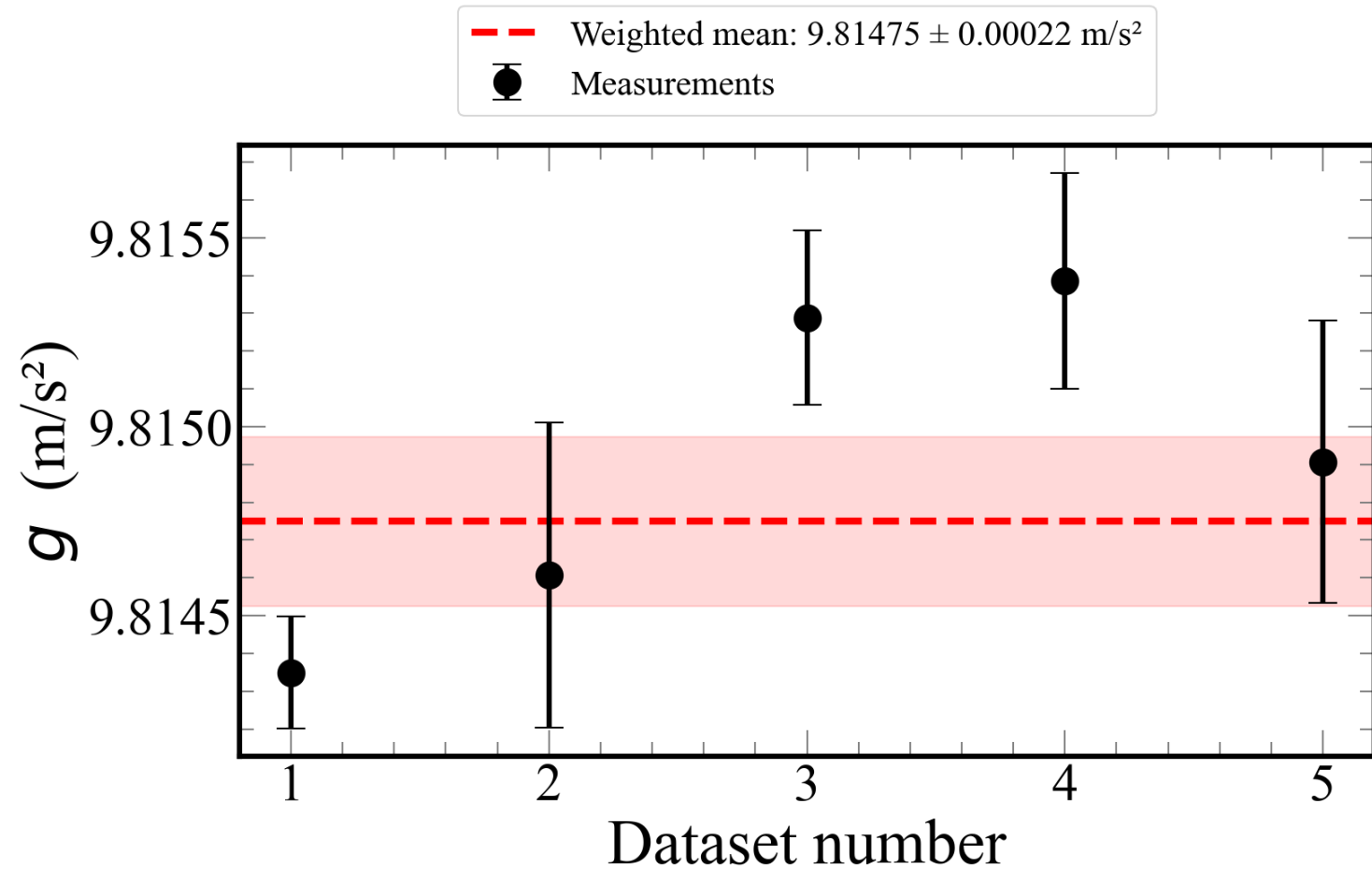
$$\frac{d}{dt} \omega_{\text{eff}} = k_{\text{eff}} \cdot g,$$

Chirp – rate at minima

$$k_{\text{eff}} = k_1 - k_2$$

Next steps:

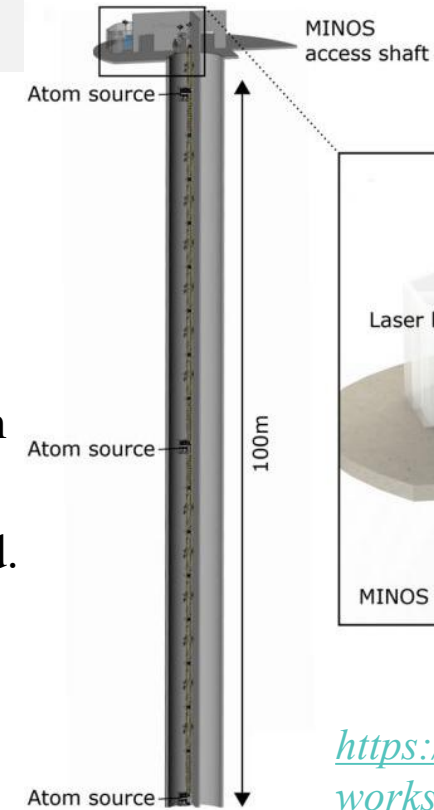
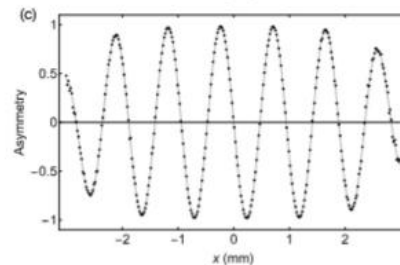
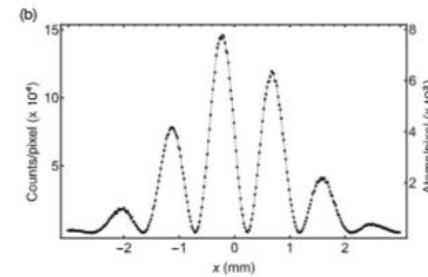
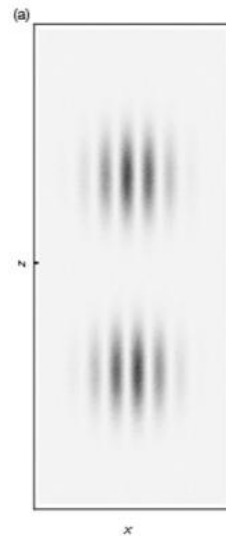
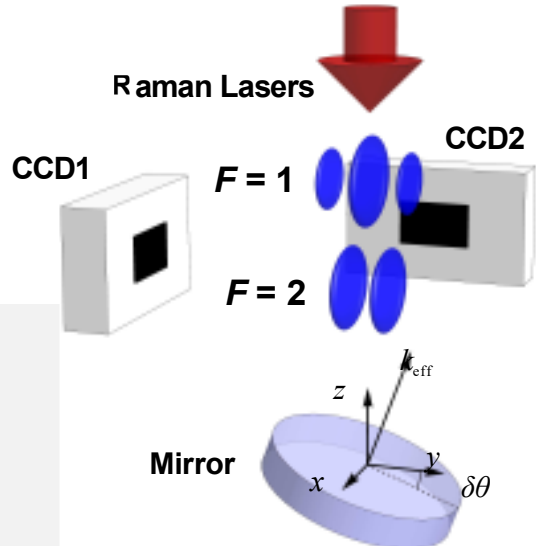
- Compare measurements against gravimeter in the lab
- Launch atoms into the upper region of chamber
 - Longer interferometry time



MAGIS-100

In-construction long-baseline atom interferometer hosted at Fermilab

- Longest vertical atom interferometer in the world when built
- Set bounds on Ultra-Light Dark Matter (ULDM) $10^{-15} \text{eV} < m < \text{eV}$
- Detect gravitational waves at frequencies not covered by laser interferometry experiments.
- ‘Large Momentum Transfer’ – many laser pulses to increase separation
- Application of a ‘phase shear’, (tilting the mirror) at the last pulse, produces a fringe pattern on the atom cloud that can be directly imaged.



<https://magis.fnal.gov/how-it-works/detector/>

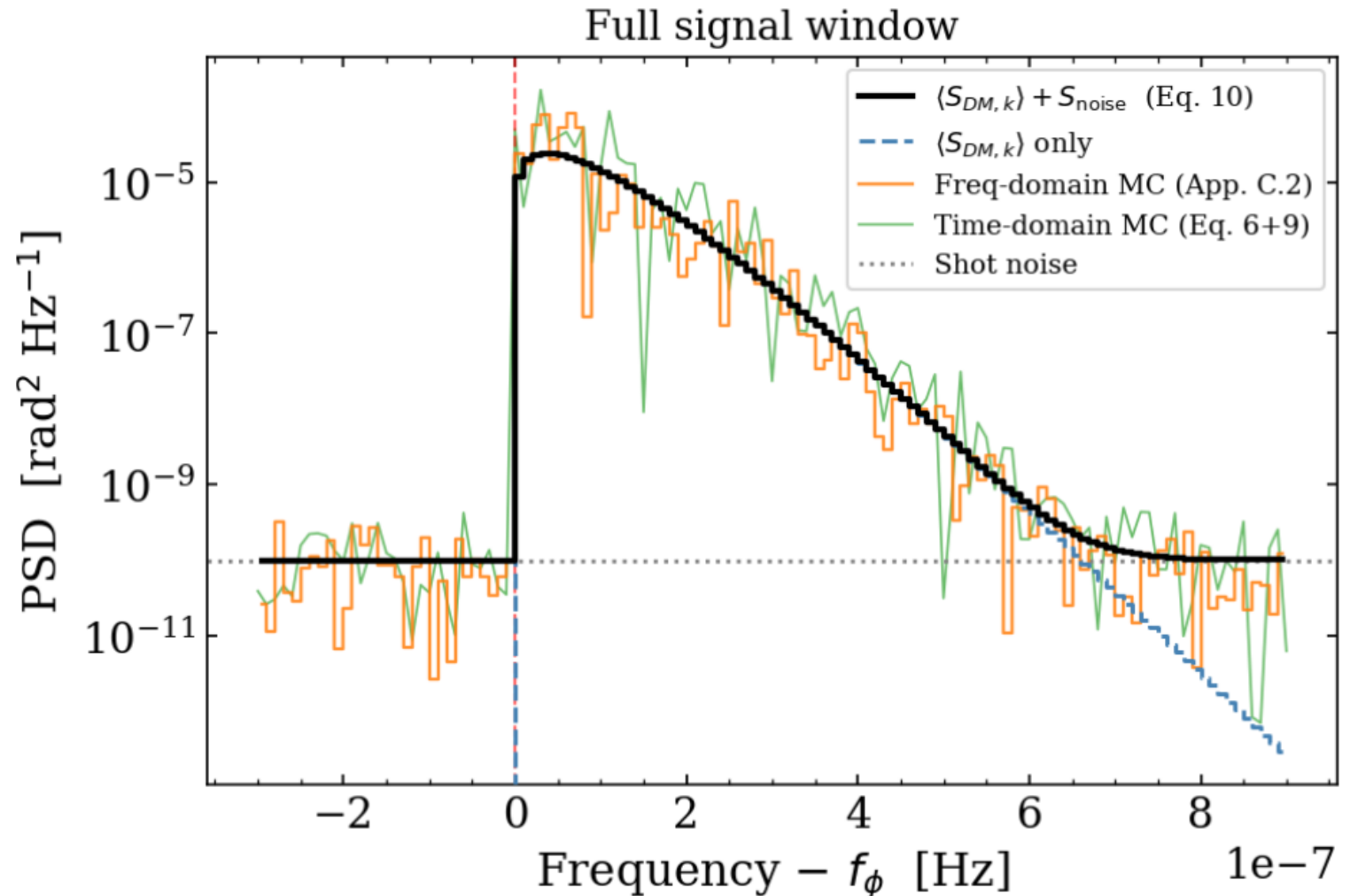
Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100) arXiv:2104.02835v1

Enhanced atom interferometer readout through the application of phase shear arXiv:1305.3298v1

DARK MATTER SIGNAL

Simulated ULDM signal in frequency space

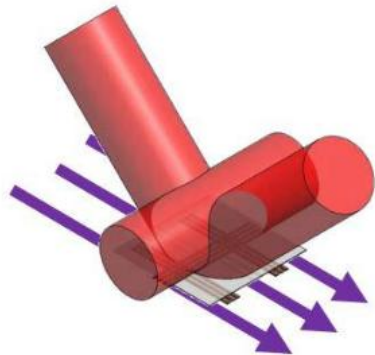
- Constructing a signal simulator and likelihood estimator to parameterise a ULDM signal
- Analytical expected Power Spectral Density from literature
- Monte Carlo method to calculate time series of phase differences in an interferometer for 10^8 samples.
- PSD of MC method matches Analytical equation well
- Next steps
 - Compute likelihood for a given signal
 - Determine test-statistic for discovery



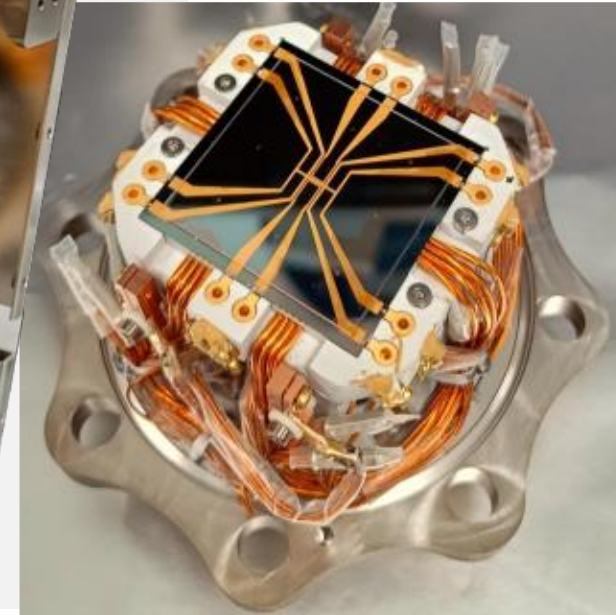
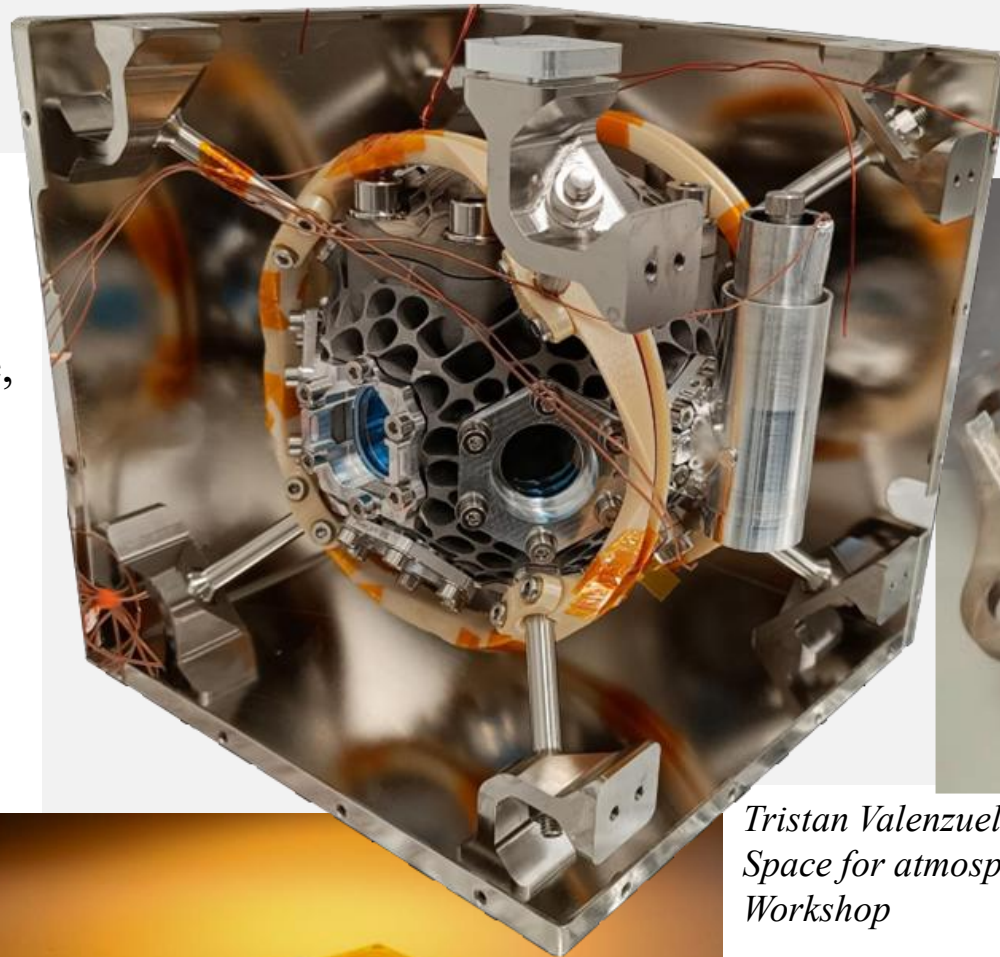
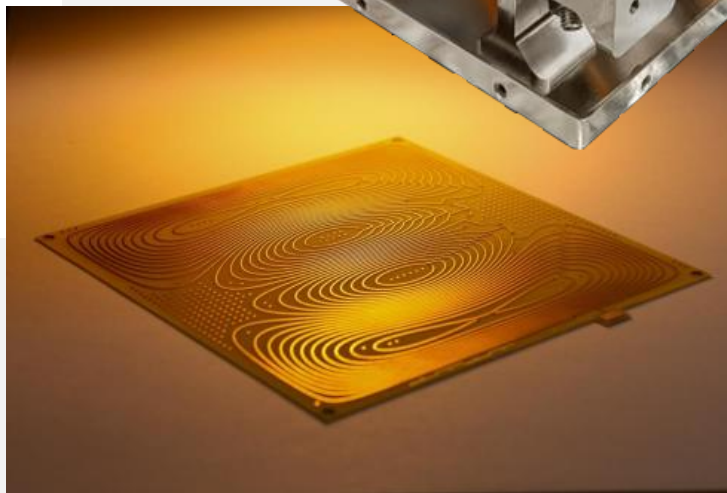
Leonardo Badurina, et Al. “Super-Nyquist ultralight dark matter searches with broadband atom gradiometers”, *Phys. Rev. D* 108 2023 doi.org/10.1103/PhysRevD.108.083016

FUTURE WORK

- I start my 6-month industry placement in July (Quantum Fabrix)
- After, I will spend 6-months at RAL Space, working on space-based atomic interferometry.
- Miniaturised atom interferometer to measure drag in low-Earth orbit
- Limited data on thermosphere density
- Help climate modelling and long-term predictions of satellite orbit decay



Chetan Parmar



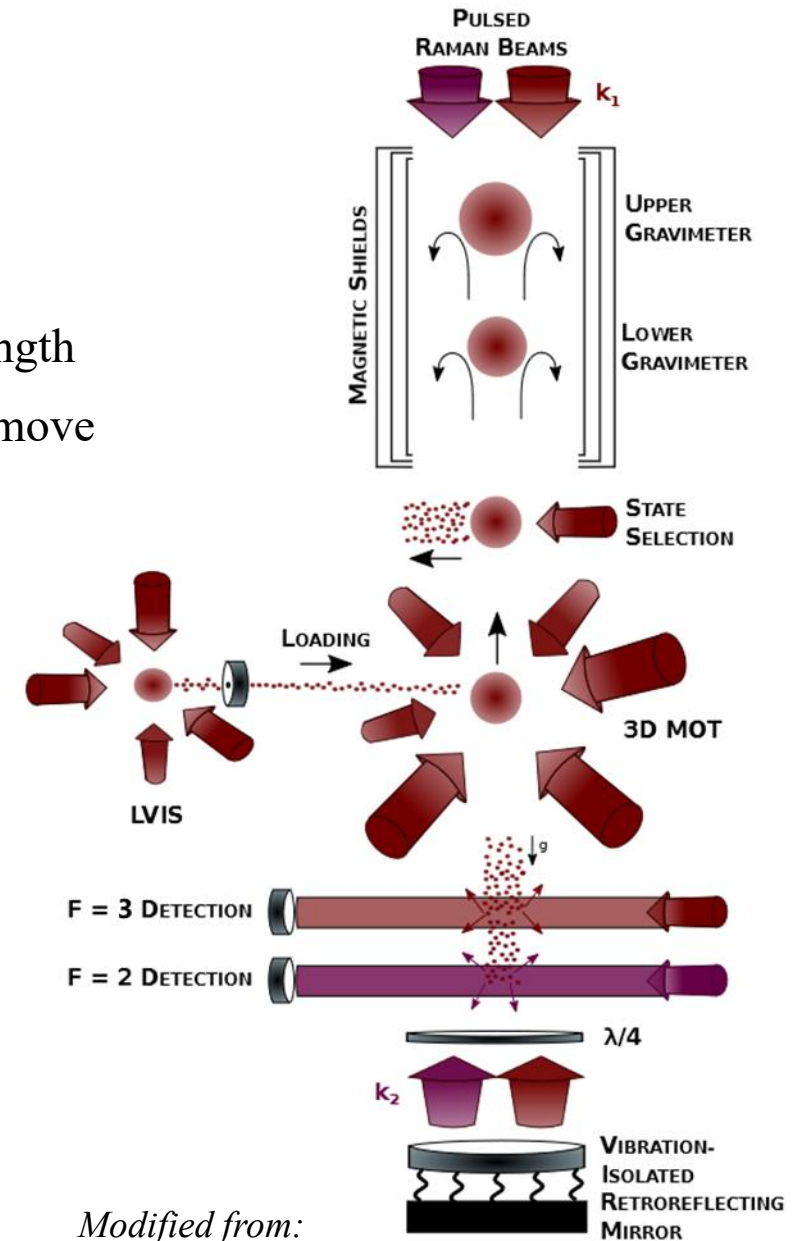
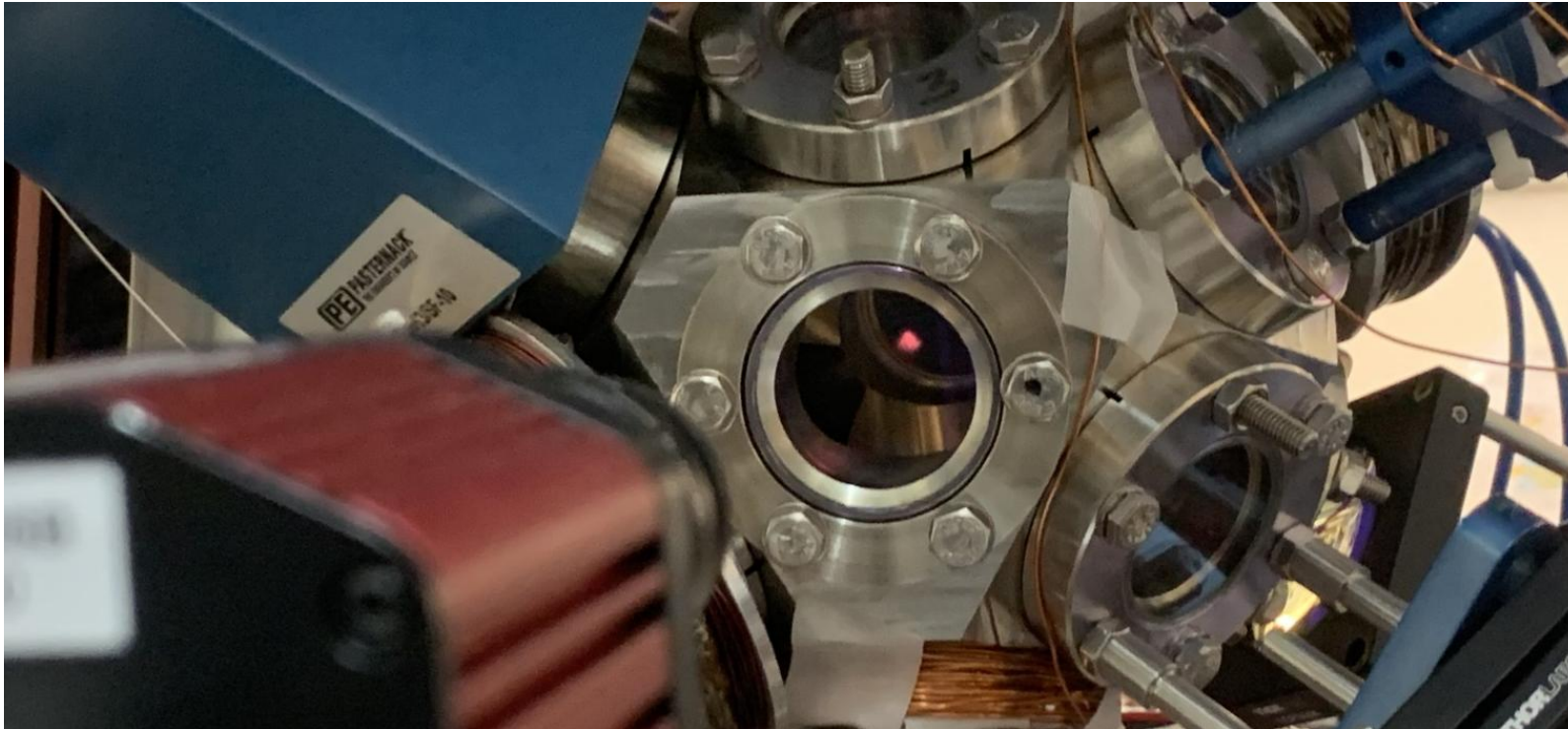
Tristan Valenzuela: Cold Atom Interferometry in Space for atmospheric science, 4th TVLBAI Workshop

Jorge Ferreras et al. "Cold Atom Space Payload Atmospheric Drag Mission (CASPA-ADM)". 36th Annual Small Satellite Conference. 258.2022. doi.org/10.26077/p2t3-te29.

APPENDIX 0: ATOM INTERFEROMETRY

Atoms are loaded and cooled down to 5-15 μ K in a Magneto-Optical Trap (MOT)

- De-Broglie wavelength: $\lambda = h/m_0v$ Cold atoms move slower: Longer wavelength
- A narrow velocity distribution means atoms will stay coherent for longer, and move under the influence of gravity



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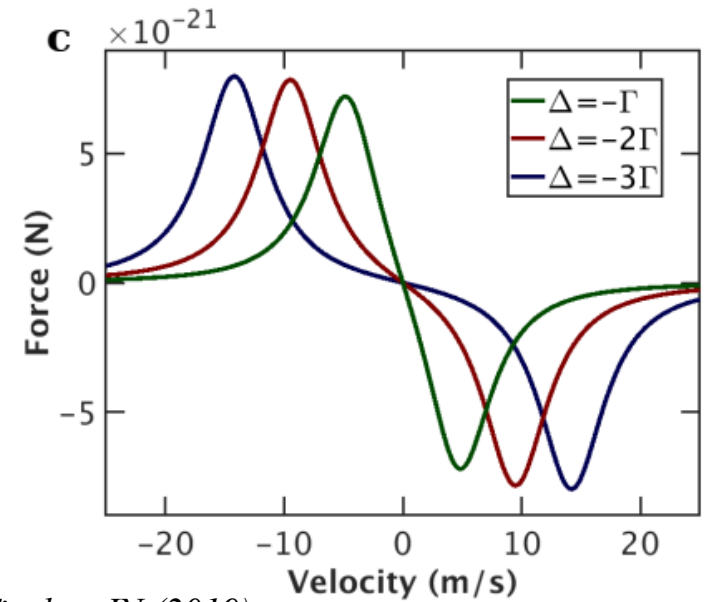
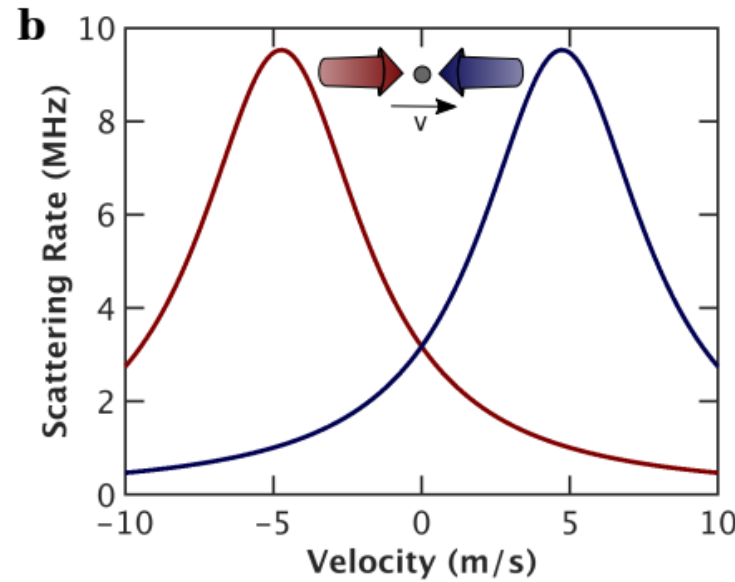
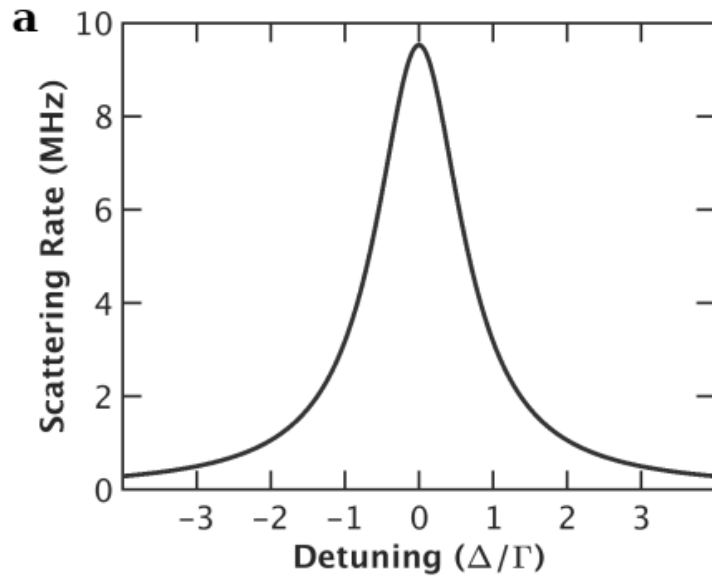
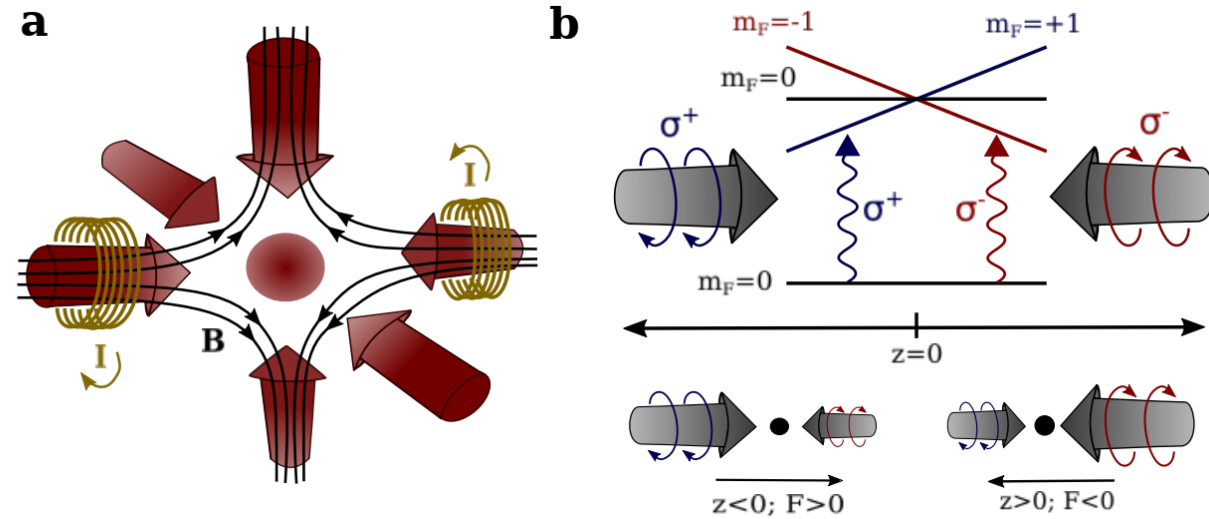
J.N. Tinsley, PhD Thesis (2019)

Atomic Interferometry

APPENDIX 1: LASER COOLING

How do Lasers cool atoms?

- Doppler cooling
- Sisyphus / Polarisation Gradient cooling

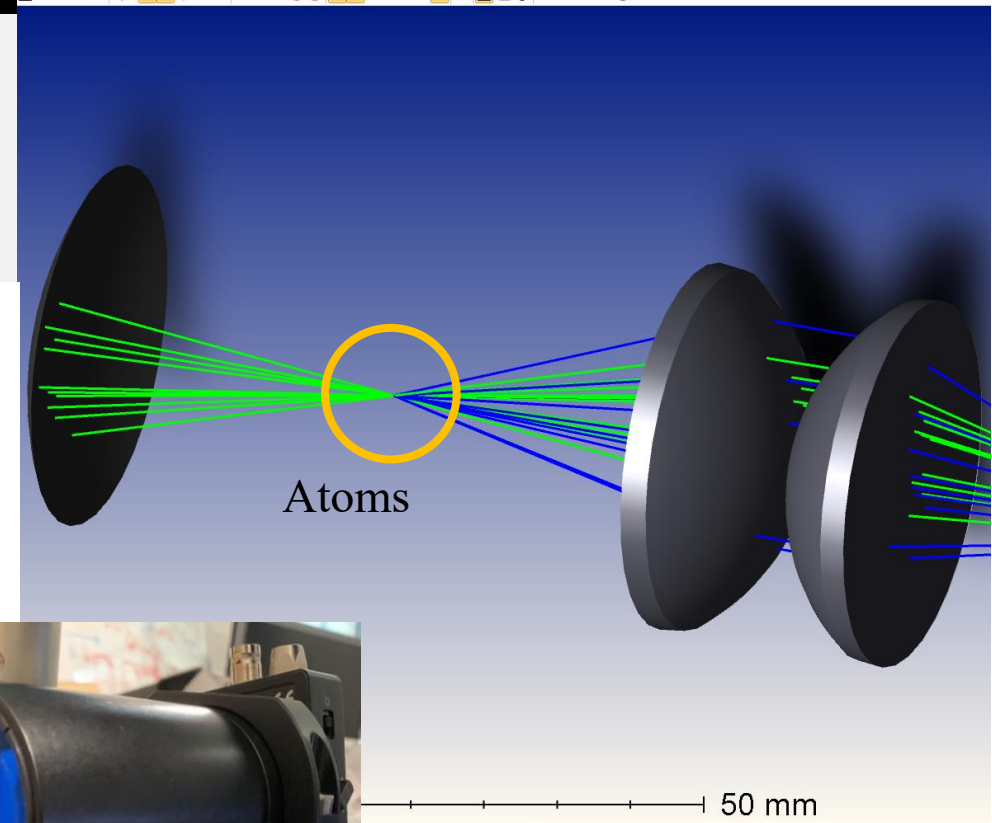
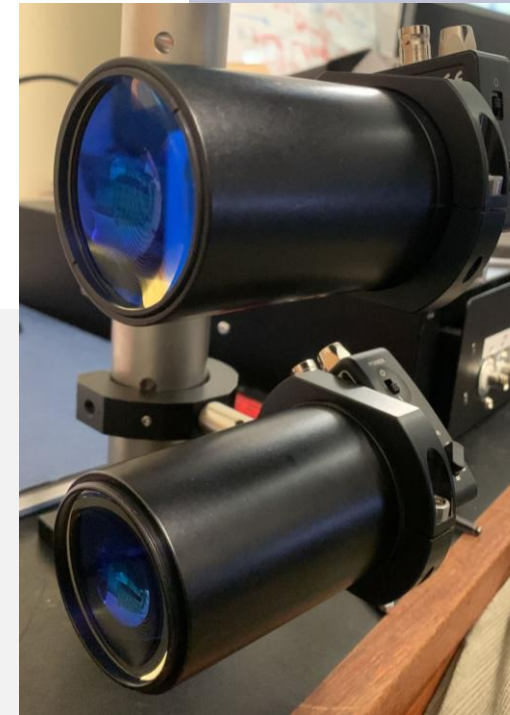
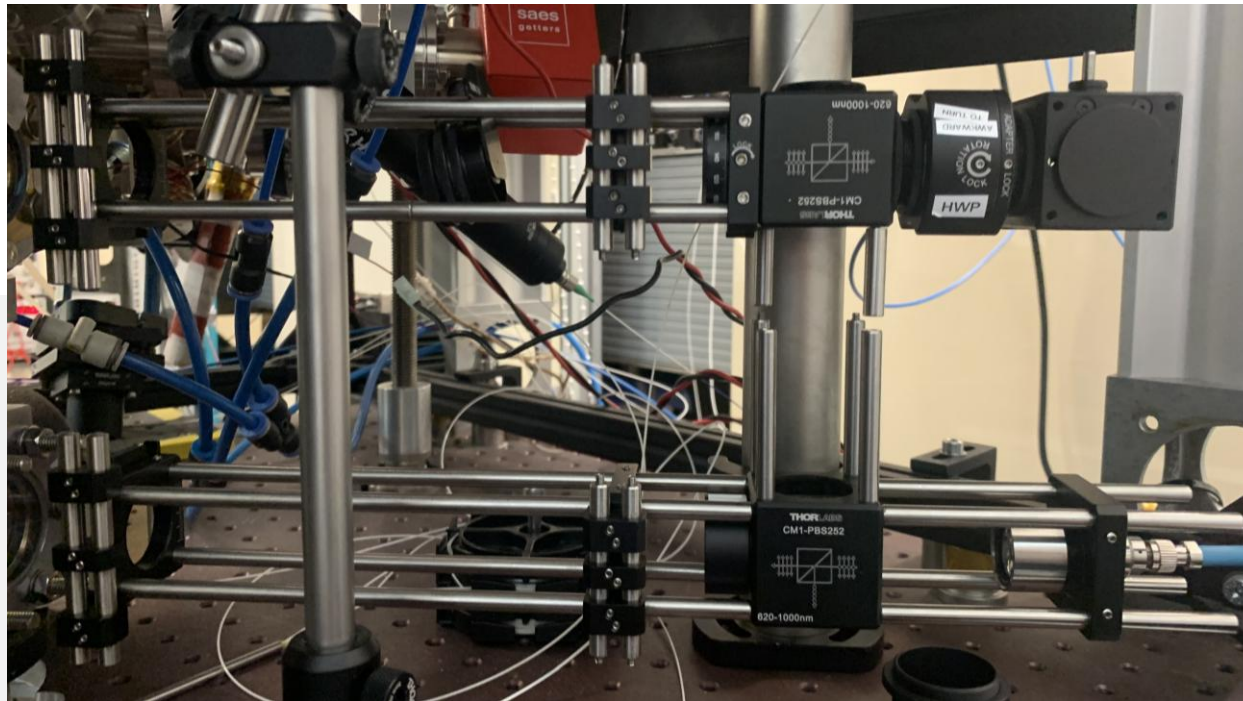


Tinsley, JN (2019)

APPENDIX 2: STATE DETECTION

At the Liverpool interferometer

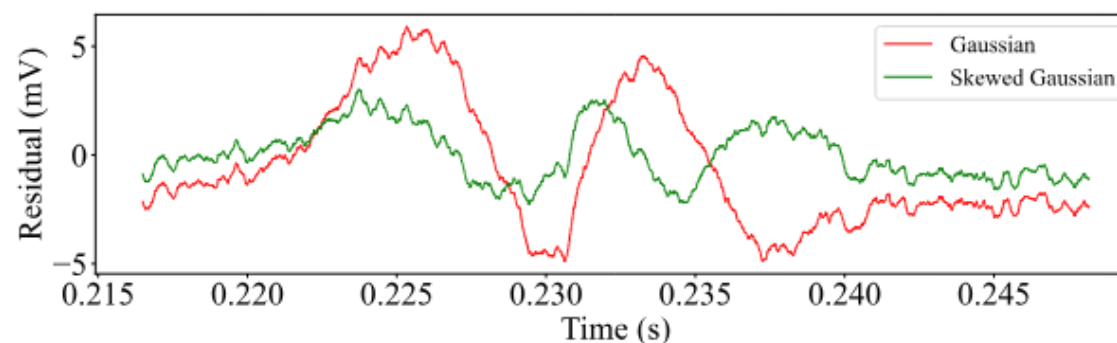
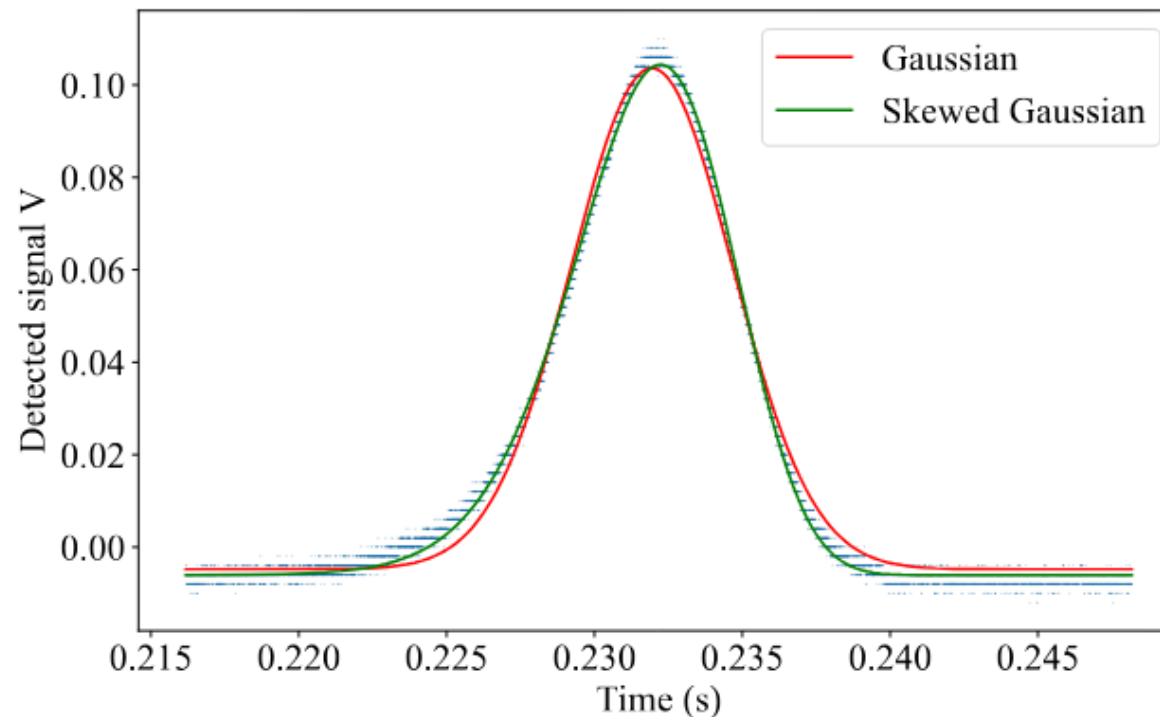
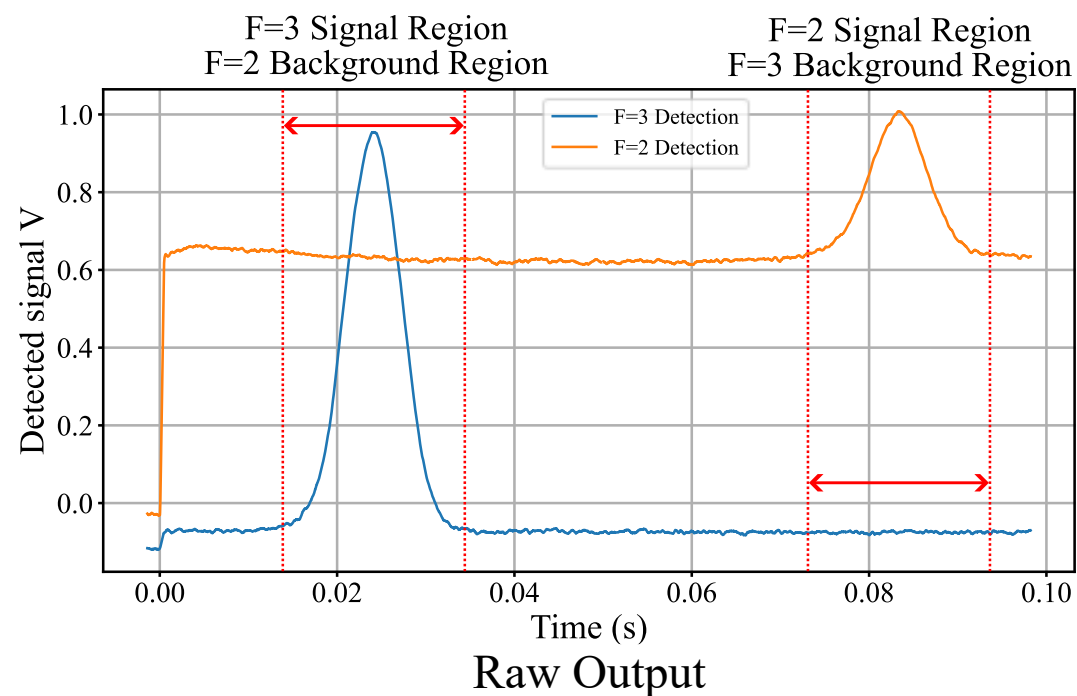
- The phase difference is directly measurable as the relative populations between the two states.
- The relative state populations are measured by fluorescing the atoms with resonant laser light, the brighter they shine, the more atoms are in that state.



APPENDIX 3: OUTPUT

From the Liverpool Interferometer

- Two methods to read the peak sizes
 - Fit the peak to a function (Skewed Gaussian) and integrate
 - Add up all datapoints and subtract an average background.

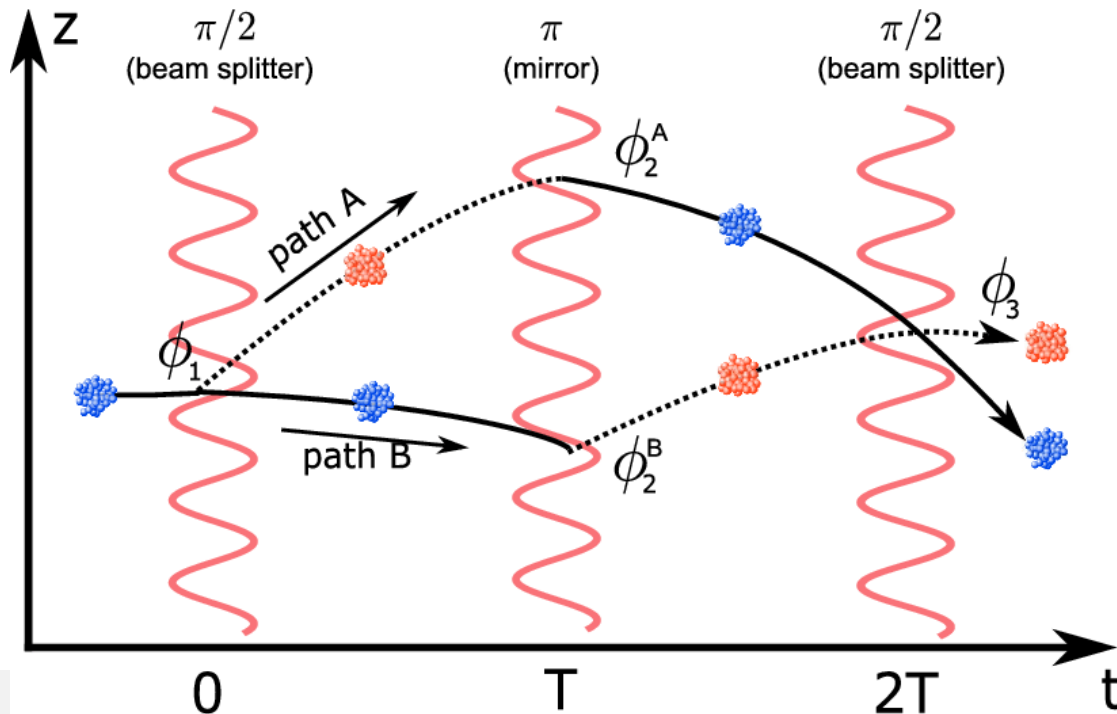


Individual peak fitted to a normal and skewed Gaussian distribution. A perfectly shaped atom cloud should be Gaussian

APPENDIX 4: ATOM INTERFEROMETRY

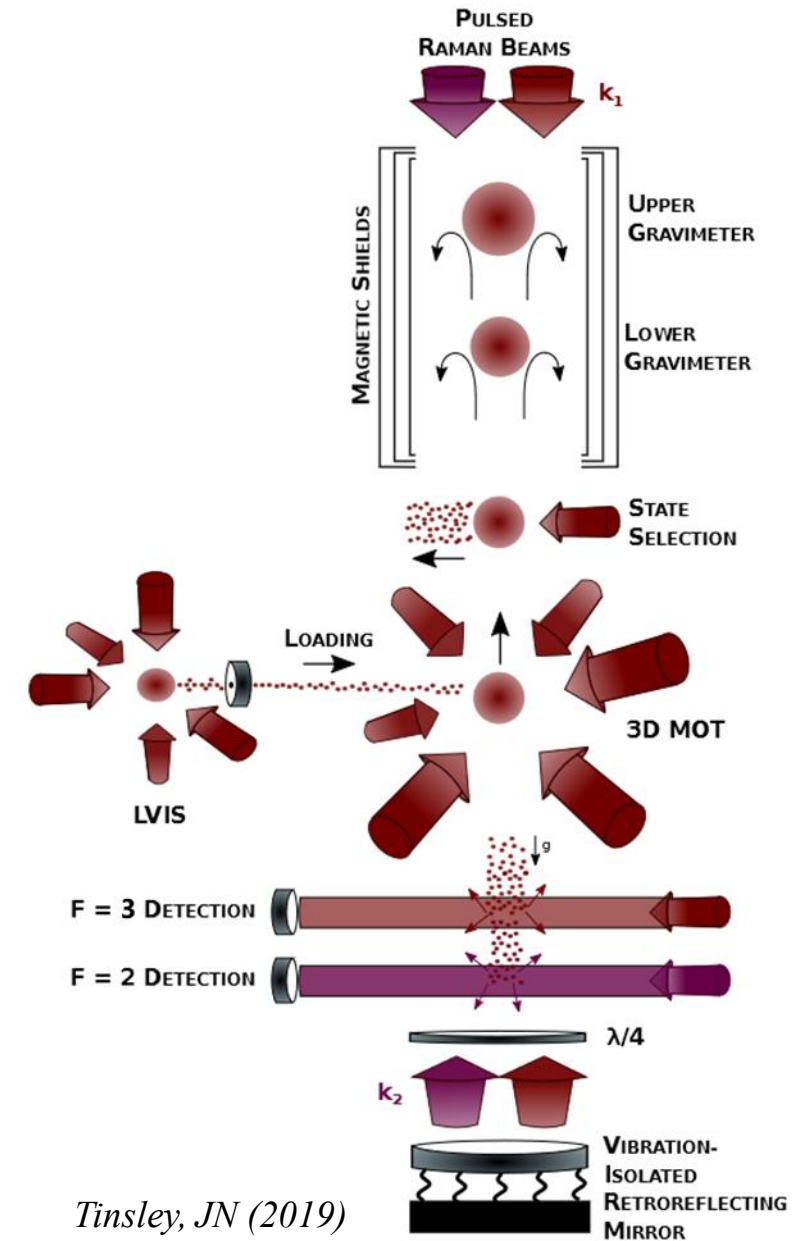
Raman sequence

- The first $\pi/2$ pulse splits the atoms into an equal superposition of two states $|F = 2\rangle$ and $|F = 3\rangle$, which travel along path A and path B.
- The superposition evolves for time T accumulating a phase difference
- Then a π pulse ‘flips’ the states, acting like a mirror
- After another period, T , the states are recombined with another $\pi/2$ pulse.



Frier C(2019)

Chetan Parmar



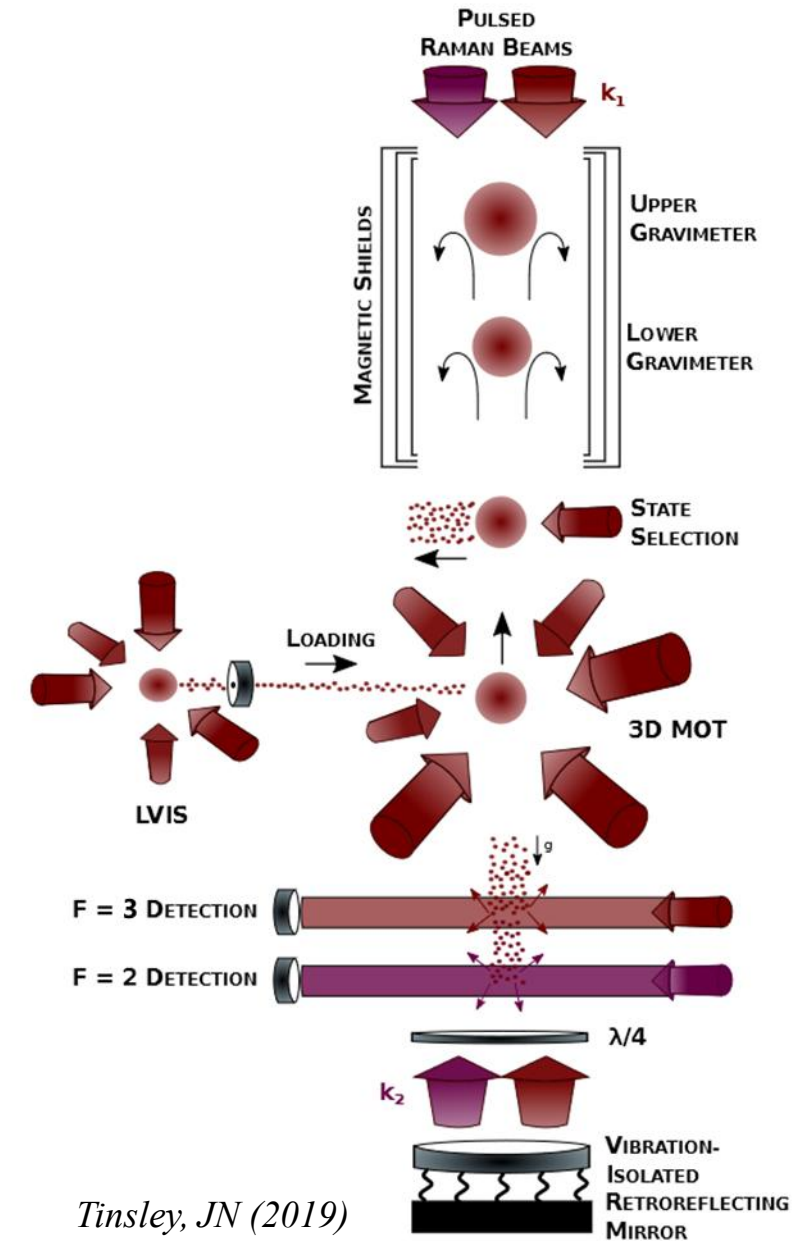
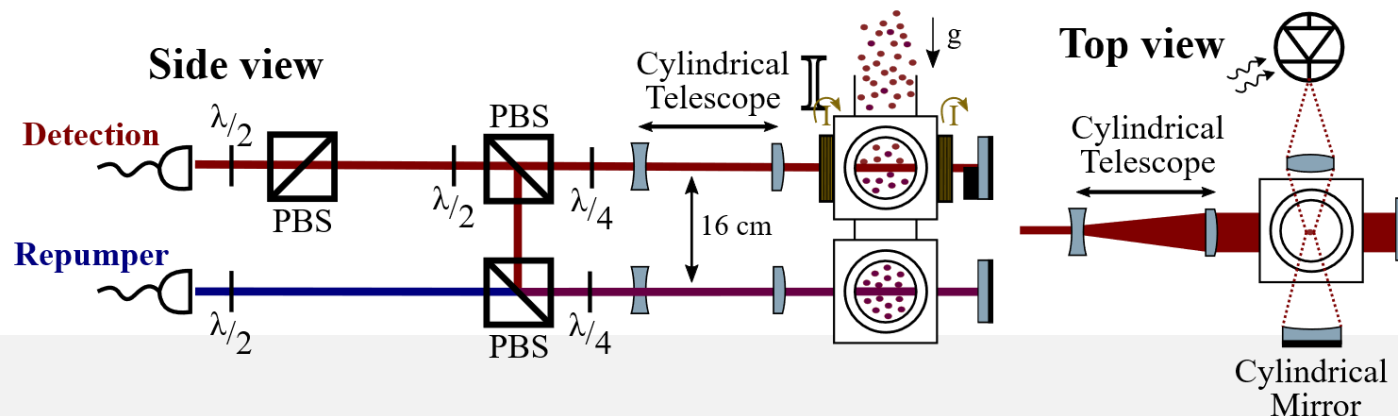
Atomic Interferometry

APPENDIX 5: PHASE DIFFERENCE

Phase difference accumulates due to a path difference between the states

- Accumulated phase difference to first order $\Delta\Phi$:

$$\Delta\Phi = k_{eff} g T^2$$
- To detect the phase difference, we measure the populations of the $|F = 2\rangle$ and $|F = 3\rangle$ states.
 - The atoms pass through two detection stages, which measure the populations of each state.
 - This is done by shining light resonant to atoms in the measured state and detecting how bright they fluoresce.
 - The more atoms in the state the brighter they will shine



APPENDIX 6: RABI OSCILLATIONS

- Measurement of Rabi Oscillations
- Damping due to spontaneous emission
- Fit assumes a constant Rabi frequency

