Towards Atom Interferometry for LEMING

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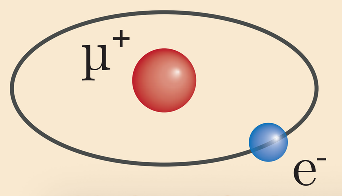
0 Cold Mu Beam development

Muonium



- 2-body leptonic exotic atom
- 2.2 us lifetime

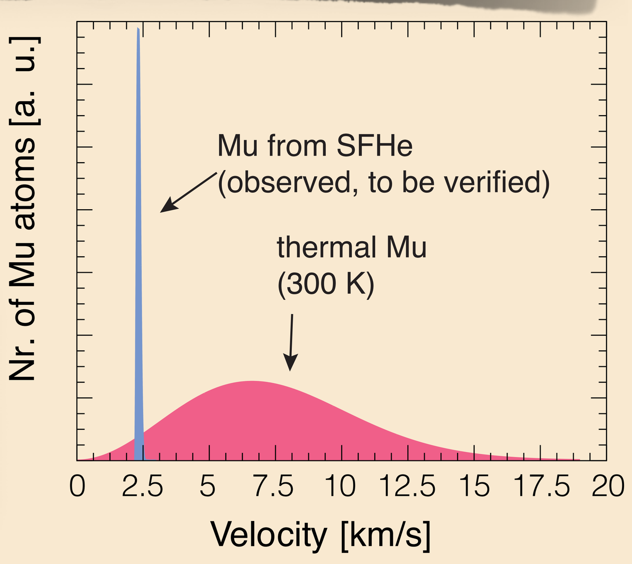
Superthermal muonium: Using a newly developed technique of muonium formation in superfluid helium - **See J. Zhang's poster**

Precision spectroscopy: test of bound-state QED, fundamental constants: m_μ, R_∞, m_μ/m_e, q_μ/q_e, …

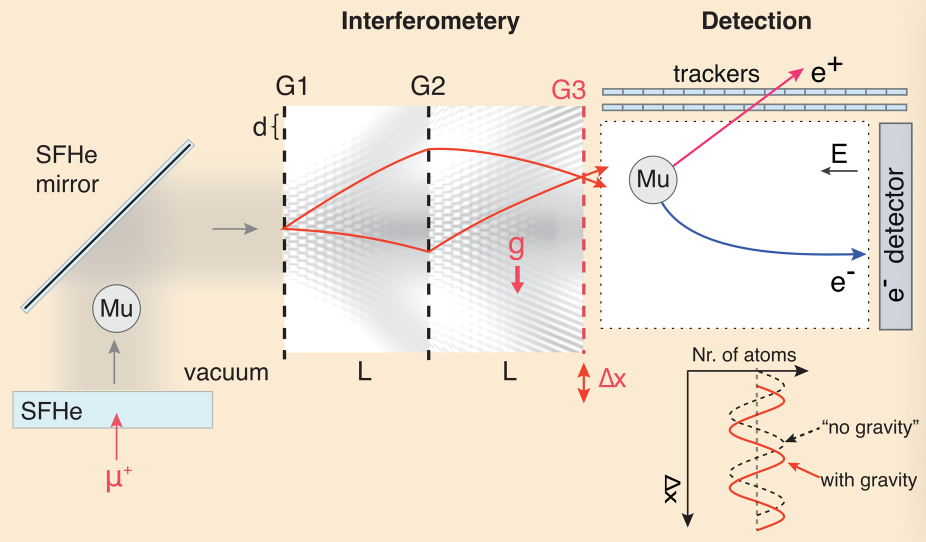
Gravity (WEP) test with Mu

μ+ is an **elementary** antiparticle and **second generation** lepton

Test of the weak equivalence principle in the absence of binding energies from the strong interaction



1 Interferometer setup



Achromatic Mach-Zehnder interferometry

G1 & 2: Prepare the transverse coherence of the partially incoherent atomic beam, and form a fringe pattern in a distance of equal L behind G2.

G3: Samples the pattern through its displacement. Measuring the fringes. Traversing muonium is counted by particle detectors.

2 Sensitivity and design parameters

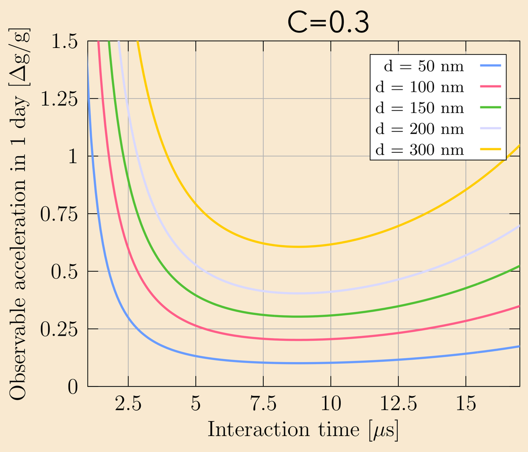
$$\Delta g \approx \frac{1}{2\pi T^2}\frac{d}{C\sqrt{N_0\varepsilon\eta^3 e^{-(t_0+T)/\tau}}}$$

- Grating period (d~100 nm)
- Interaction time: ~7-8 μs
- Loss factor ($\eta=0.3$, $\varepsilon=0.5$, $t_0<\tau/2$)
- Atoms from source ($N_0 \sim 10^4$/s)
- Contrast ($C=A/A_0\sim0.3$)

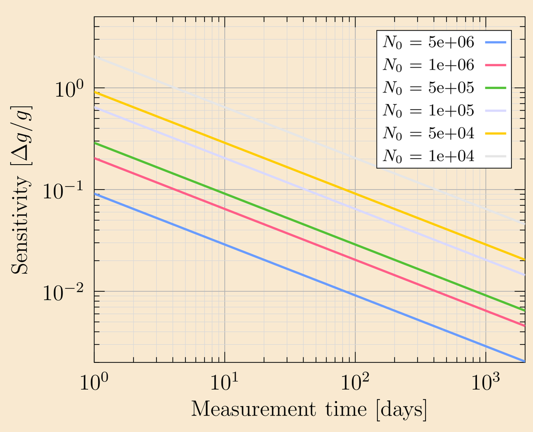
Error in g as measured from an atomic beam

- Sub-nm alignment and stabilisation
- Mechanically strong grating: 100nm pitch and a 30% open fraction
- Operation at 150mK temperature in a SFHe chamber for ~100 days
- Optimising the length of the interferometer:

$N_0=1\cdot10^6$/s, $L_0=3$ mm, C=0.3



Sensitivity over time with different sources (C=0.3, d=100 nm), using the optimised length



Tradeoff: statistics and interactions time Gravitational shift increases quadratically with time, but the Mu lifetime is exponentially limited to 2.2 μs.

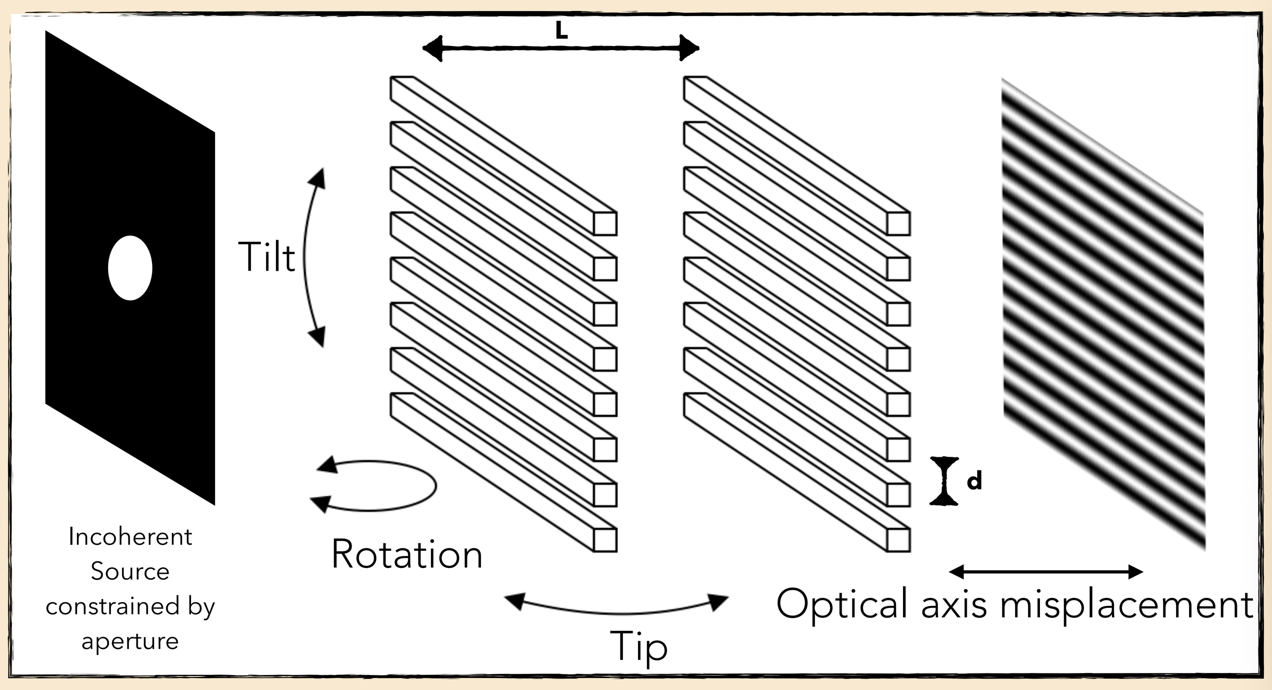
Beam	p [MeV/c]	Yield [μ^+/s]	1σ [mm]	Yield in d = 10 mm	Aerogel, back implantation 23 MeV/c (3%)	Aerogel, SiO2 front implantation 12.5 MeV/c (8%)	SFHe source, front implantation 12.5 MeV/c (20%)
piE5	28	5×10^8	8.5	9.8×10^7	1.5×10^6	5.4×10^5	0.6×10^6 *
HiMB-3	28	1×10^{10}	30	1.75×10^8	2.6×10^6	8.3×10^5	1.1×10^6 *
HiMB-5	28	1×10^{10}	50	6.3×10^7	9.5×10^5	3×10^5	3.7×10^5 *
HiMB-cool	0.01	5×10^5	0.5	5×10^5	-	2×10^5 **	1.5×10^5 **

* assuming the measured lower limit (19%) stopped muon-to-muonium conversion @ 12.5 MeV/c

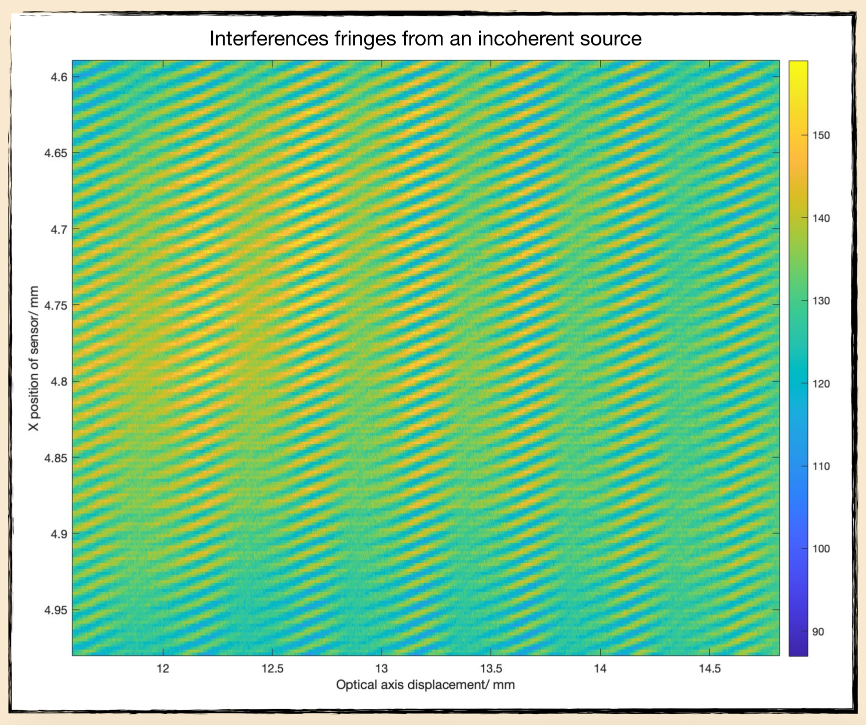
Efficiencies from RT targets: Beer et al 2014 (23 MeV/c)

** Expected rates, with 20-50 keV beam from muCool. No diffusion time loss is expected. Might be advantageous

3 Tests of the theory with visible light

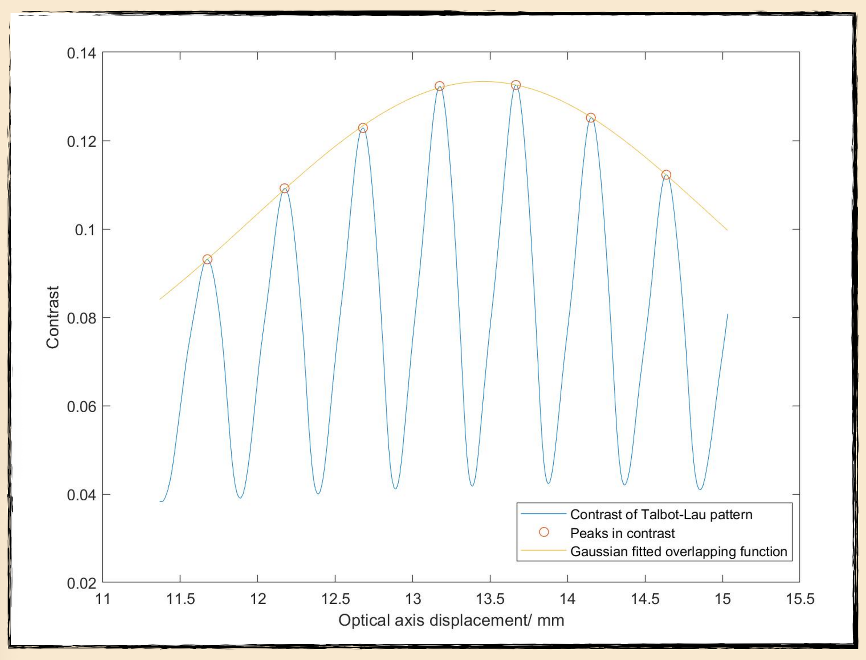


- **Optical setup:** Gratings of d = 10um placed at L = 50mm distance. The interferogram is projected onto a bare CCD of 1.85um pixel pitch.
- Gratings can be individually aligned with a total of 7 degrees of freedom.



Goal:

- Verify simulations
- Establish coarse alignment of G1 & 2
- Reduce degrees of freedom for the final setup



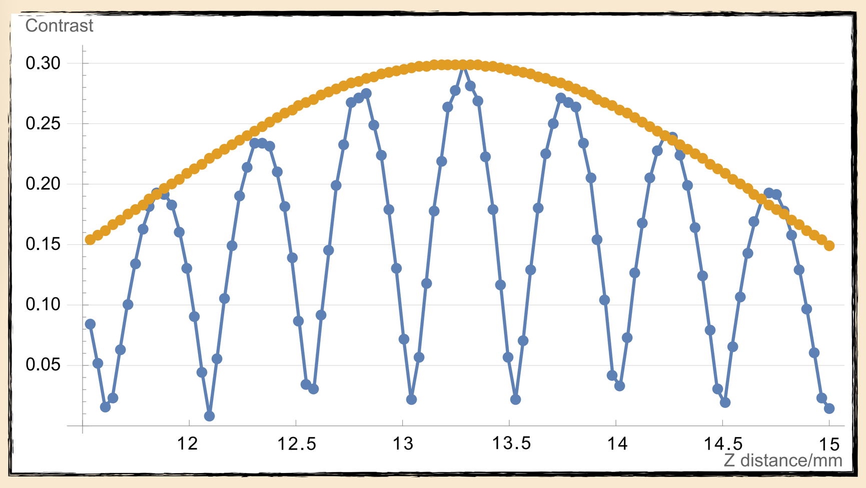
Experimental results

from our to visible light interferometer with 10um gratings, 635nm incoherent light

Interference Fringes: The coherence of the light source modulates the fringes

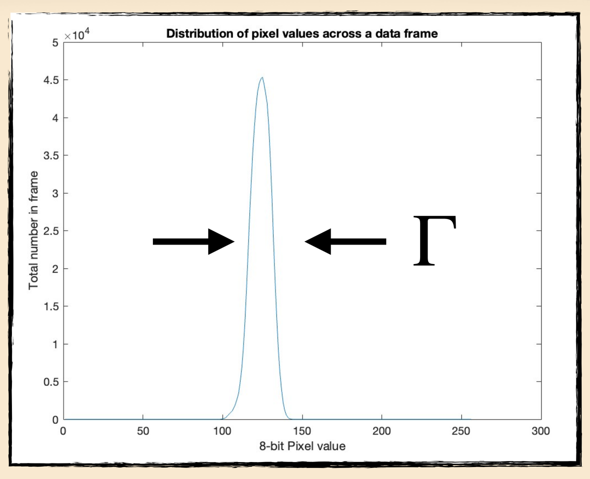
Contrast: determined by the ratio of the width of the distribution of intensity versus the mean value

High contrast region: For a partially incoherent source the transverse coherence is described by van Cittert-Zernike theorem, and depends on the source size and distance from the interferometer:



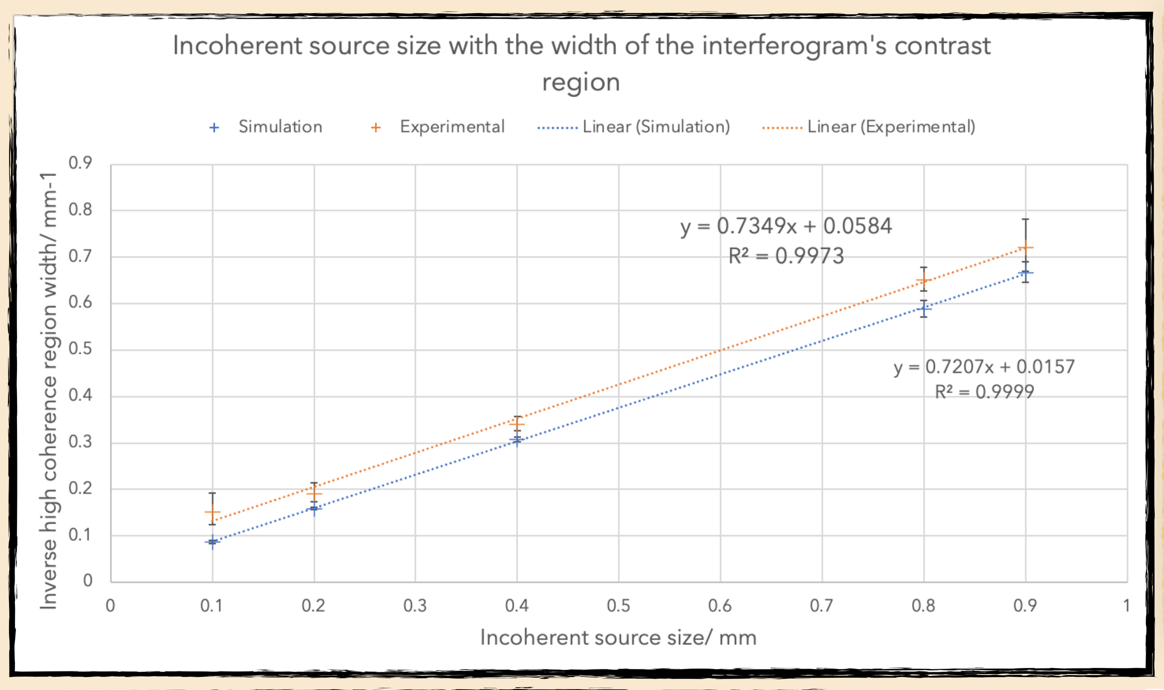
Simulated results

A simulation using a Gaussian-Schell model beam, of the experimental setup

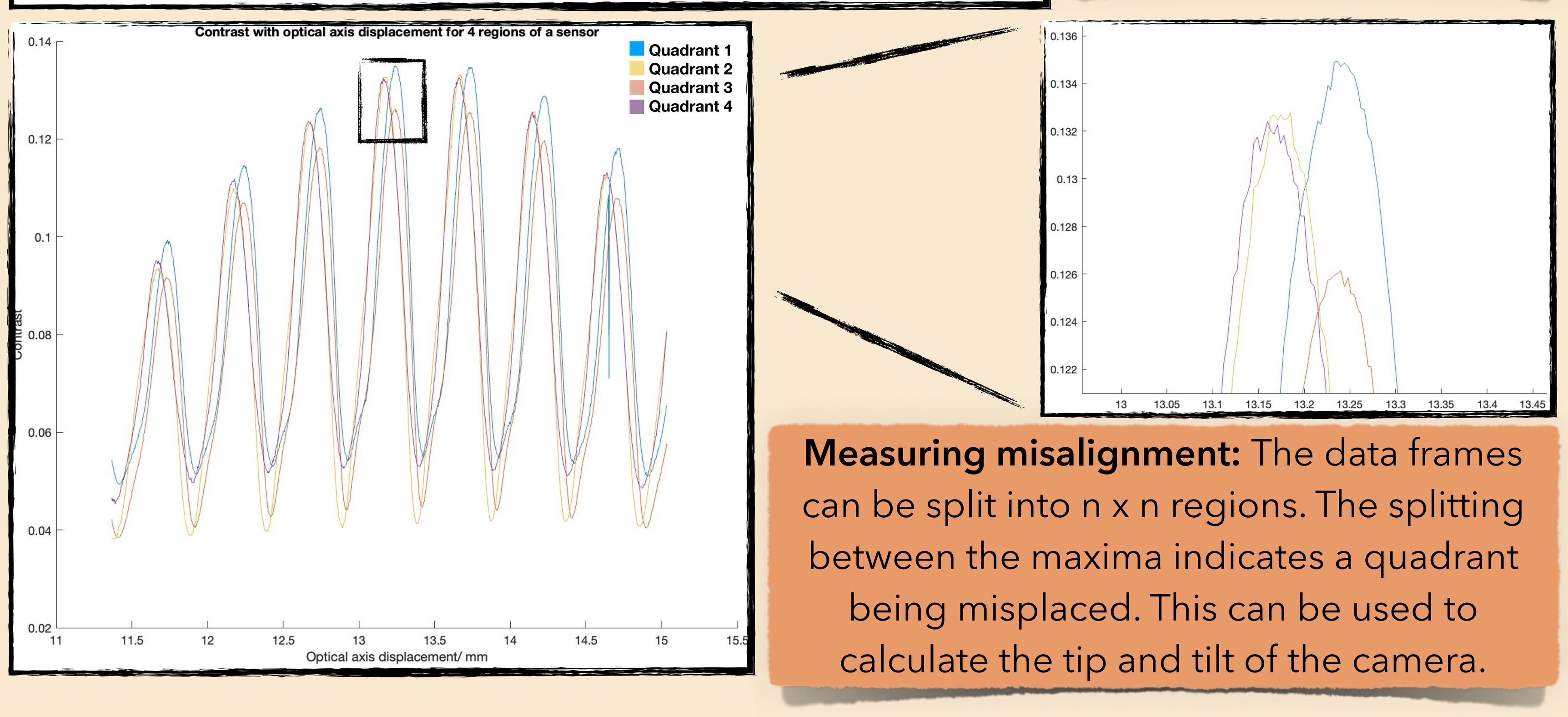


$$l = \frac{D\lambda}{d}$$

- D: Distance to source
- d: Source size
- l: transverse coherence length



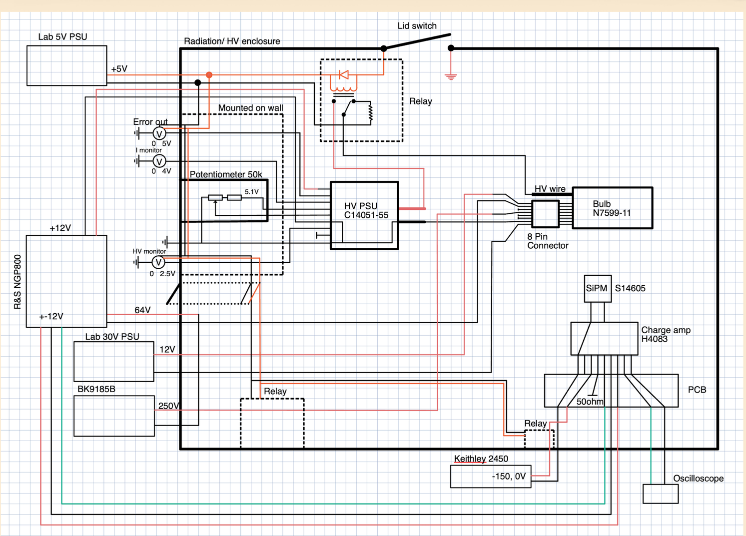
Scaling of the high contrast region: The width of the region in which the interferometer fringes can be observed scales inversely with the size of an incoherent source. The gradient of this scaling is dependent on both the wavelength and distance of the source from the interferometer.



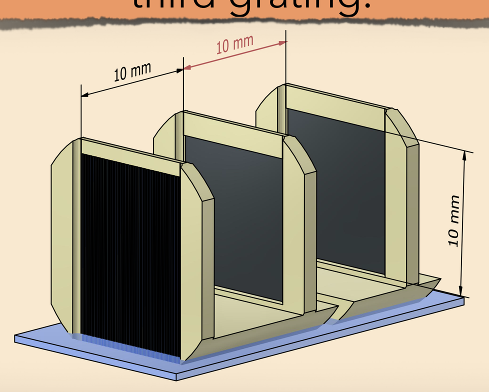
Measuring misalignment: The data frames can be split into n x n regions. The splitting between the maxima indicates a quadrant being misplaced. This can be used to calculate the tip and tilt of the camera.

4 2023 Outlook

Scaling down the wave and testing the interferometer with soft X-Rays. We have constructed a setup with 4.5 keV X-Rays

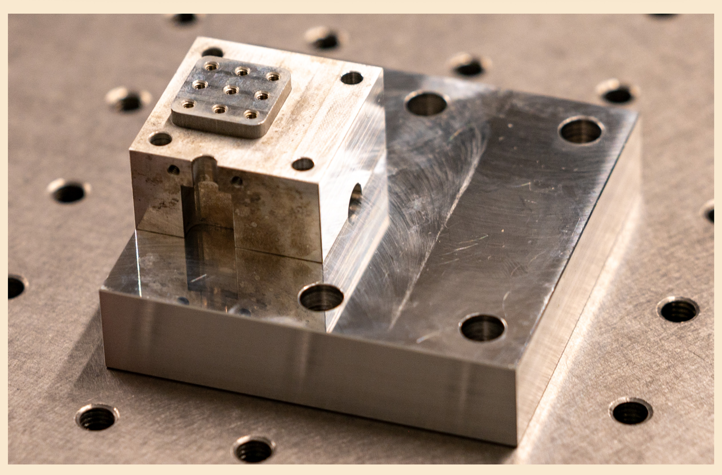


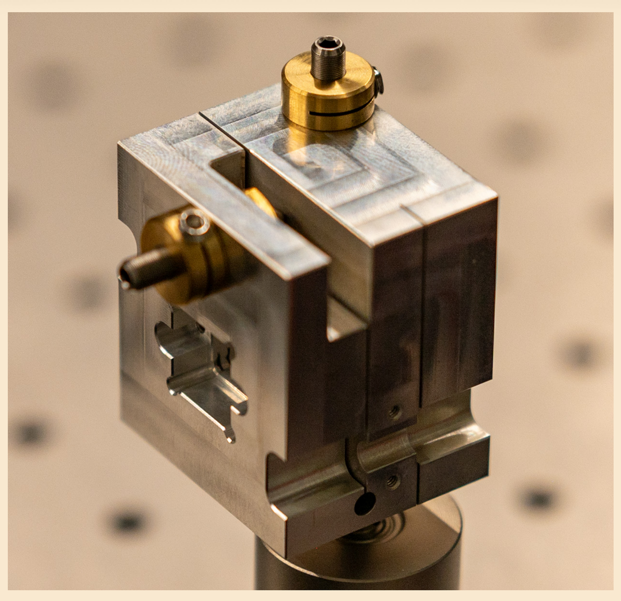
Add a third, measurement, grating, instead of using a high resolution sensor. Establishing an alignment procedure for this third grating.



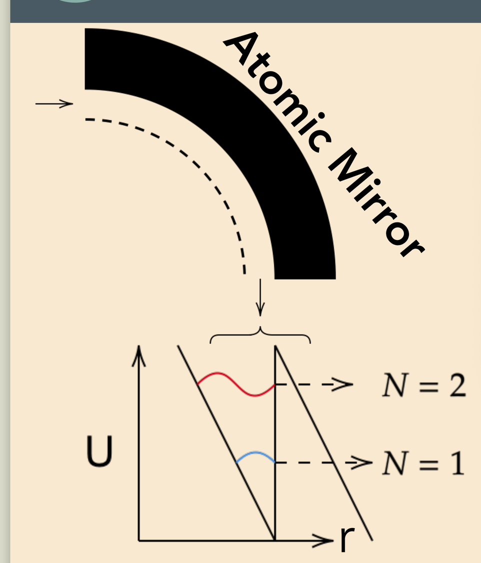
New model removing degrees of freedom in our setup via precision mechanics. Wire EDM and 5 axis milling allows us to commission precision pieces

Developing a vertical stage with low vibrations. Piezo movement without cantilevers.





5 Alternatives to interferometry



- Dynamic range close to cold neutrons: gravitational states from "bouncing" and connecting technology may be probed
- **Whispering gallery modes:** The trapping potential defined by the surface potentials and curvature can be set (by choice of radius) to trap two radial spatial modes.

Nesvizhevsky, V., Voronin, A., Cubitt, R. et al. Neutron whispering gallery. Nature Phys 6, 114–117 (2010). https://doi.org/10.1038/nphys1478