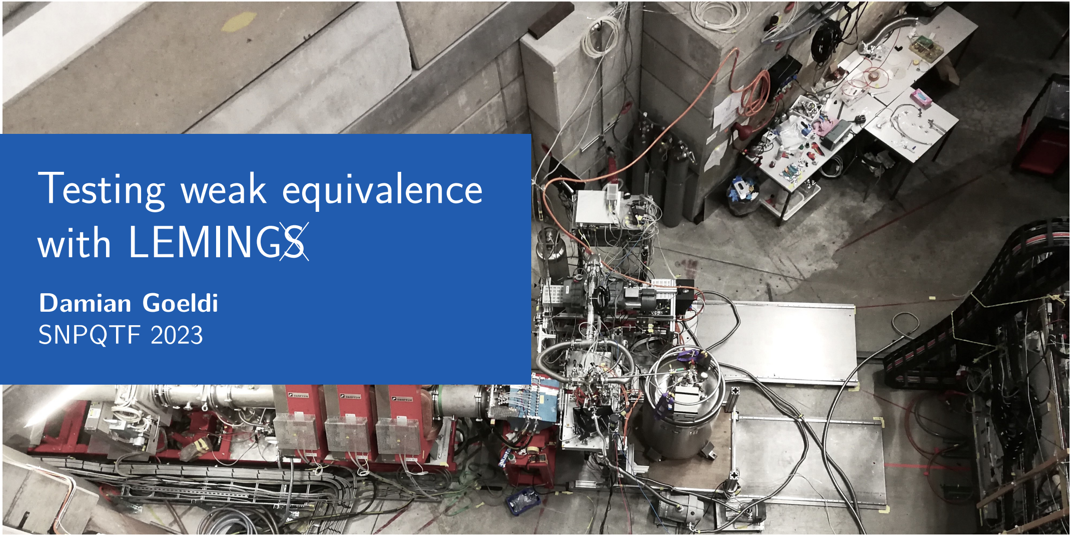
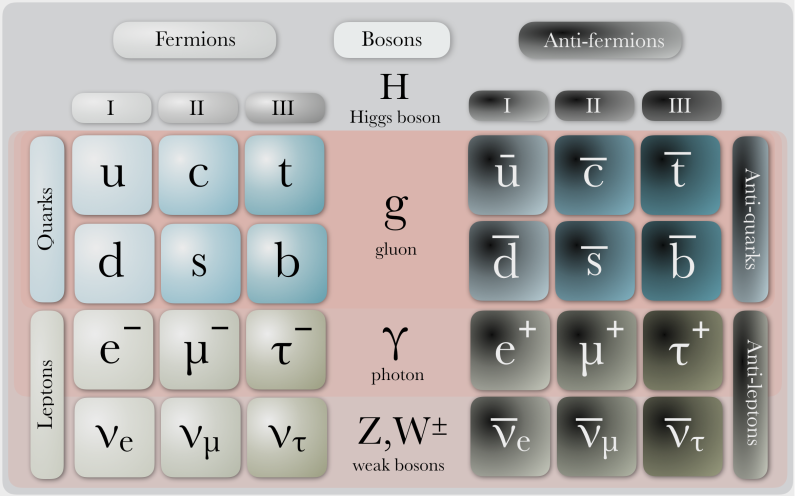
Testing weak equivalence with LEMING~~S~~

Damian Goeldi
SNPQTF 2023



The Standard Model of particle physics



Gravity

We ‘know’

- atoms (p, n, e^-)

→ 99 % of mass from strong interaction

We don’t know

- antimatter
- 2nd and 3rd generation

Muonium

Testing weak equivalence with second-generation antileptons

Regular matter mic drop

$\mu^+ e^- \to M$

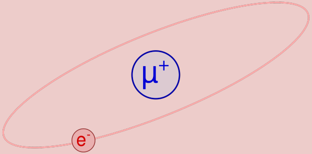
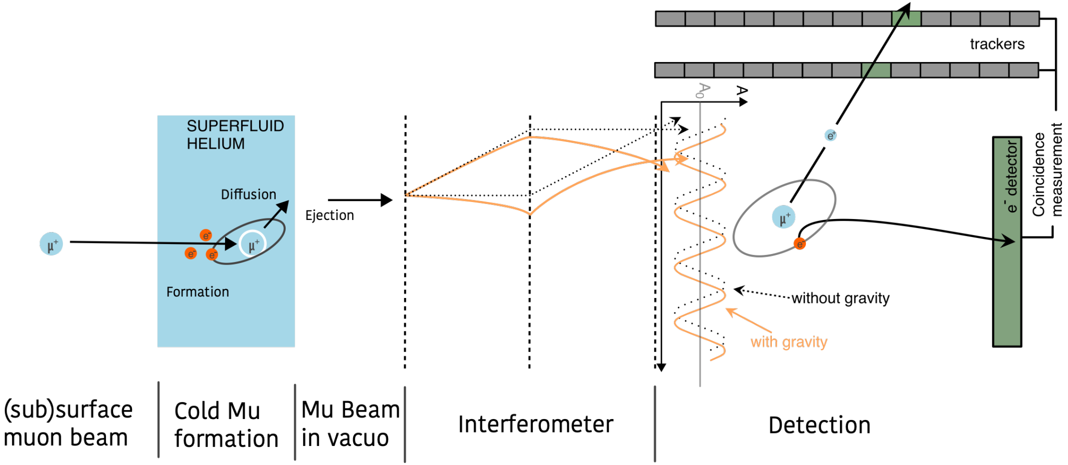


Figure: Wikimedia Commons, Neil deGrasse Tyson

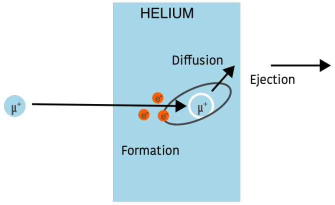
2nd generation leptonic antimatter mic drop

LEptons in Muonium INteracting with Gravity
LEMING



Muonium creation

See Jesse Zhang's poster

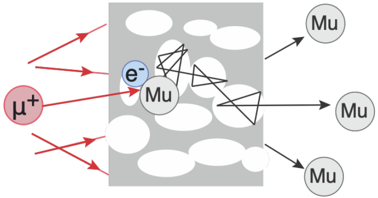


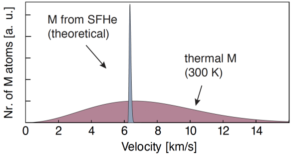
(sub)surface muon beam | Cold Mu formation | Mu Beam in vacuo

Existing thermal beams

not suitable

- Large energy spread
- Broad angular distribution
- *M* production efficiency strongly dependant on diffusion time (implantation depths)





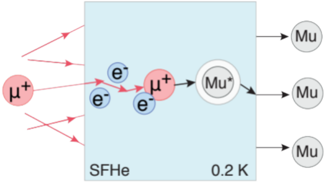
Novel superfluid helium (SFHe) muonium beam

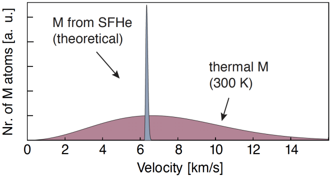
M formation in SFHe

- Small impurity

⇒ Ballistic propagation

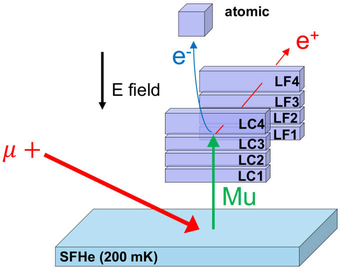
- Fast diffusion inside liquid
- Positive chemical potential
- High-speed surface ejection





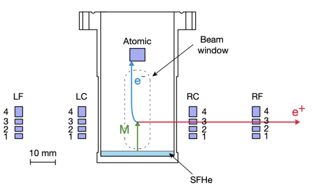
Test beam detector setup

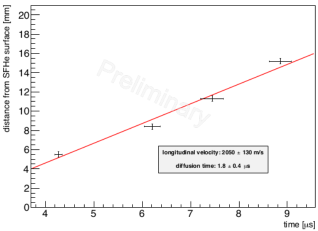
- Stop μ^+ in thin SFHe layer
- M ejected upwards
- Detect decay $e^+ \wedge e^-$

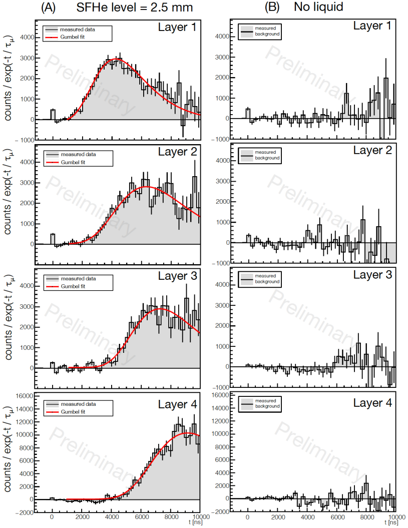


First observation of muonium atoms emitted from superfluid helium

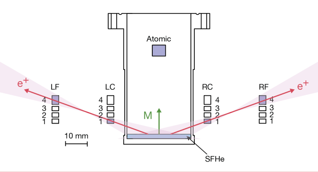
Velocity $\approx 2.1\,\mathrm{km\,s^{-1}}$

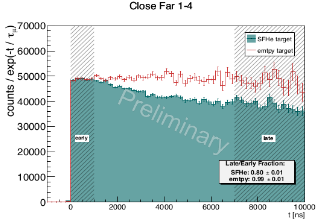






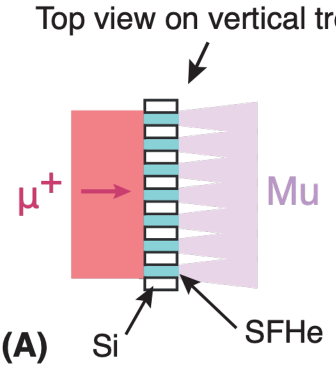
Conversion efficiency ≈ 0.2

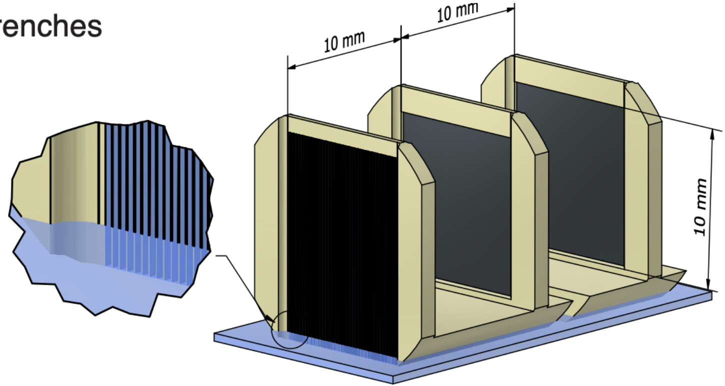




Creating a horizontal muonium beam from superfluid helium

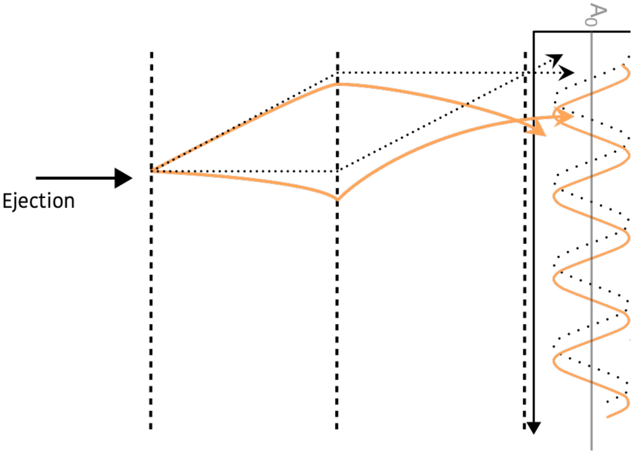
Let SFHe climb up vertical trenches on upstream side of first interferometer grating

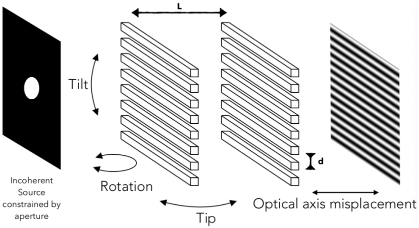


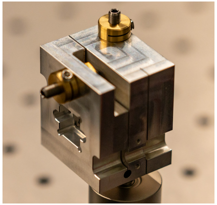


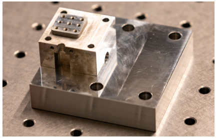
Interferometer

Developing precision stages to achieve required alignment **See Robert Waddy's poster**







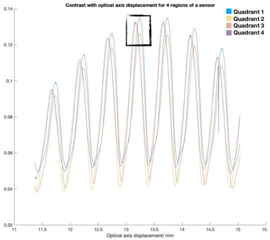


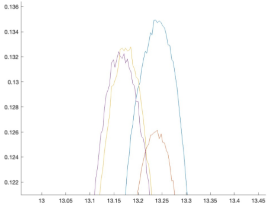
Interferometer contrast

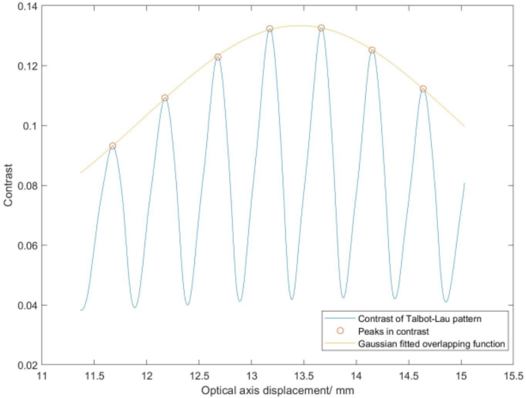
Requirements

- Contrast $C = \frac{A}{A_0} \approx 0.3$
- Not overly sensitive on misalignment

$\Rightarrow$ Fix first two gratings, put third on high-precision stage





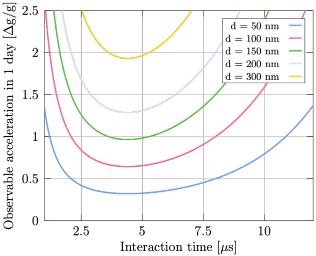


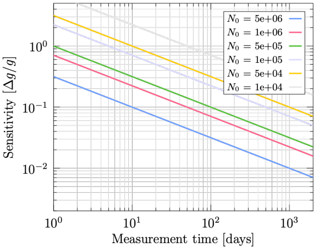
Sensitivity

Trade-off between spatial resolution and statistics

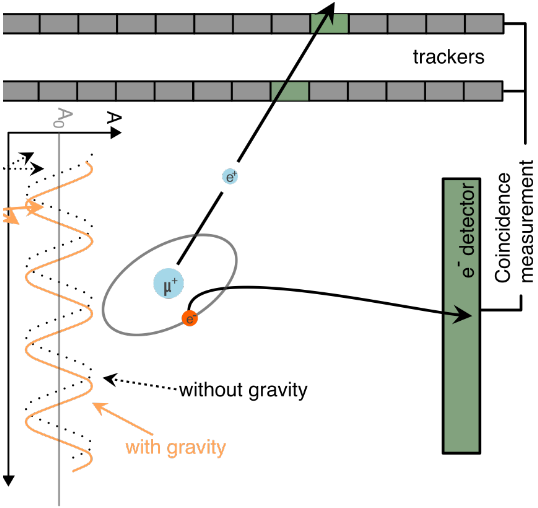
$$\Delta g \approx \frac{d}{2\pi T^2 C \sqrt{N_0 \epsilon \eta^3 \exp\left(-\frac{t_0+T}{\tau}\right)}}$$

- Grating period $d \approx 100\,\mathrm{nm}$
- Interaction time $T \approx 7\,\mu\mathrm{s}$ to $8\,\mu\mathrm{s}$
- Contrast $C \approx 0.3$
- Atoms from source $N_0 \approx 1 \times 10^4\,\mathrm{s}^{-1} \times t_{\mathrm{measure}}$
- Loss factor $\eta = 0.3$, $\epsilon = 0.5$, $t_0 < \frac{\tau}{2}$
- **Need high total detection efficiency $\epsilon \approx 0.5$**



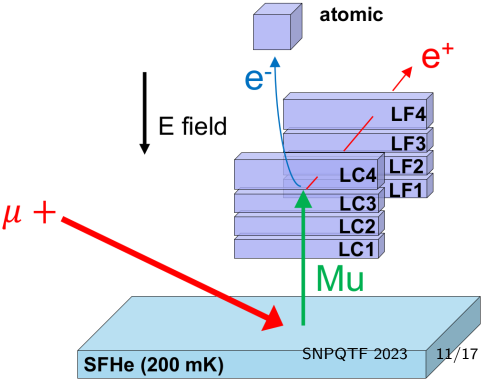


Detection



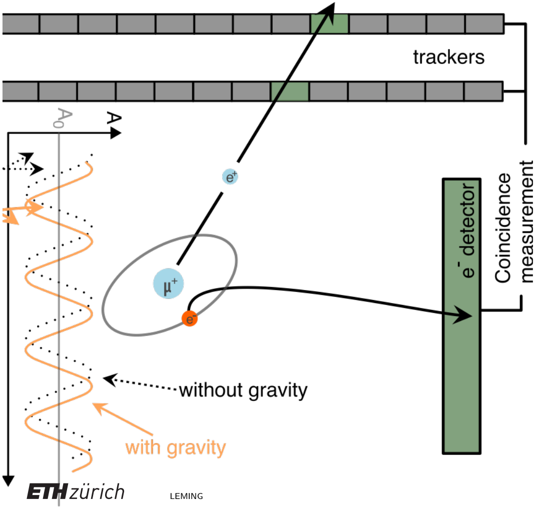
Michel e^+ tracker upgrade

- High-resolution tracker instead of scintillators
- E.g. silicon strips



Atomic e^- detection

See Paul Wegmann's Poster

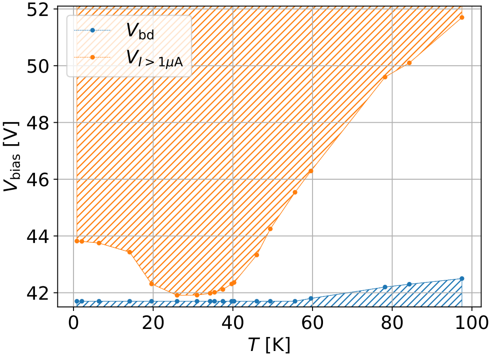


Atomic e^- detector

- High background from μ^+ decaying on gratings, walls, and support
- High-resolution tracker most likely not enough
- Can try to detect atomic e^- in coincidence with Michel e^+
- $E_{e^-} < 1\,\text{keV}$
- HV acceleration in SFHe not possible
- Detection efficiency directly influences sensitivity
- Fast high-efficiency low-threshold cryogenic e^- detector needed

Can we just use a regular scintillator-SiPM combo?

Single γ detection: ✓ (DOI:10.1088/1748-0221/17/06/P06024) e^- detection: ×



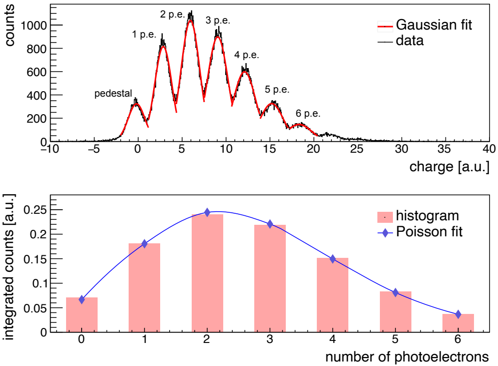
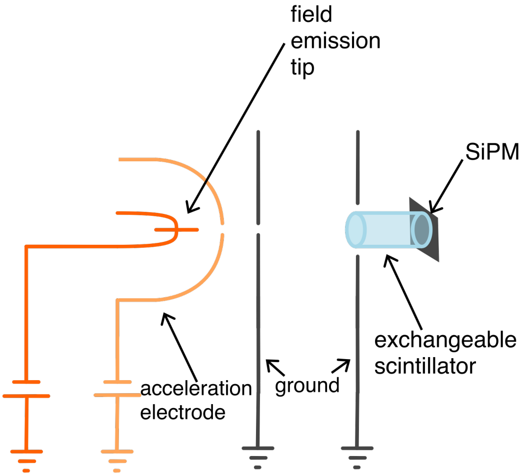


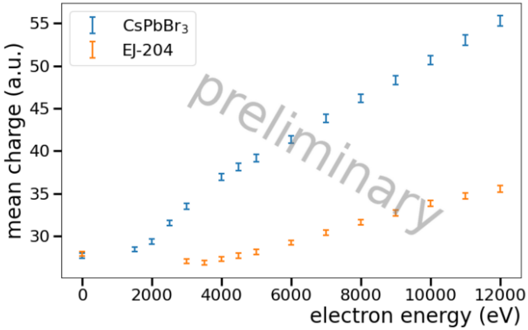
Figure: $T = 0.85$ K

Scintillator threshold too high for atomic e^- detection

Perovskites

Promising alternative scintillators





$CsPbBr_3$ nanocrystals at $T = 4\,K$

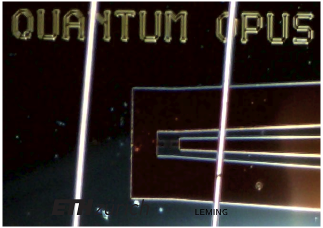
- $2\,keV$ threshold potentially reachable with HV acceleration

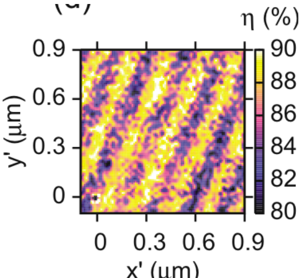
And now for something completely different

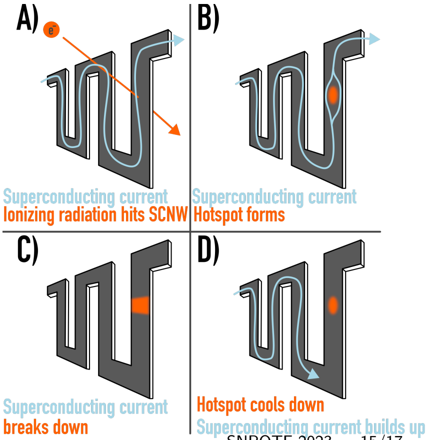
Superconducting nanowire single-photon detectors (SNSPD)

High-efficiency low-threshold cryogenic detector

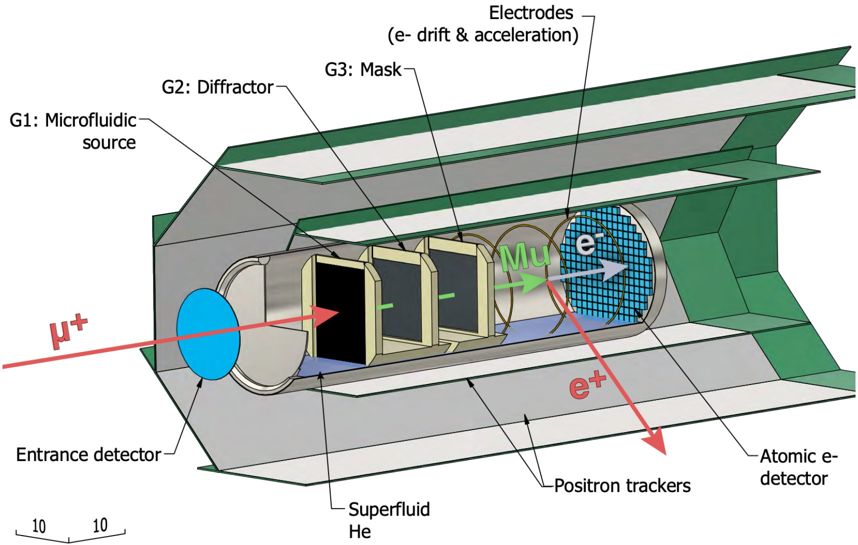
- Designed for γ detection in quantum optics
- e^- detection demonstrated (DOI:10.1063/1.3506692 ↗)
- Potentially problematic charge build-up
- Preparing test of commercial SNSPD







Putting it all together



Collaboration

LEMING

LEMING: A next generation atomic physics and gravity experiment using muonium (M) atoms

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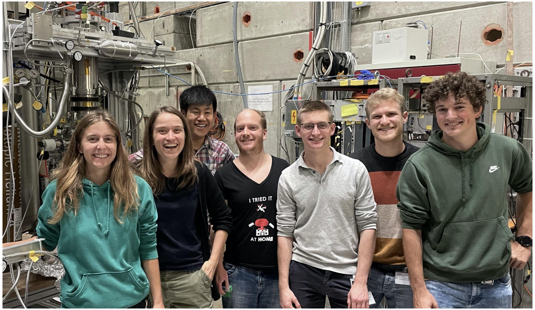

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