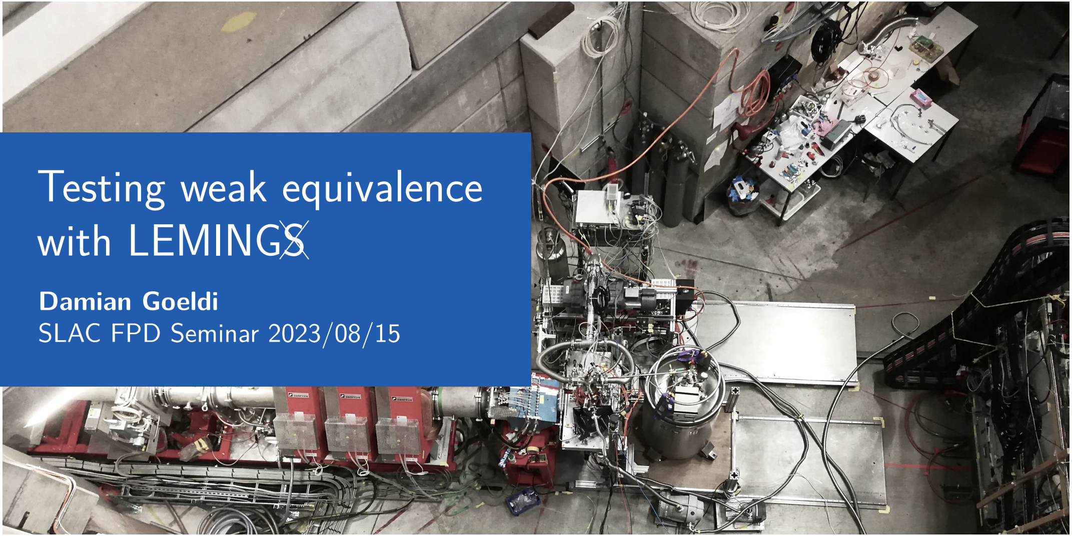
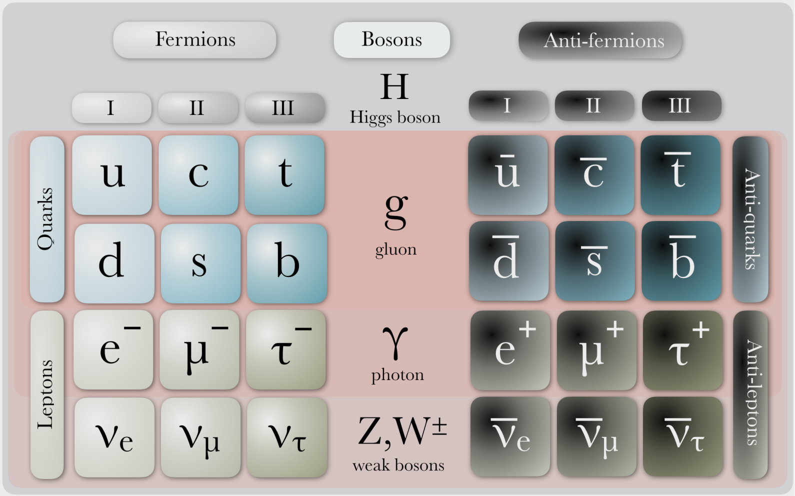


Testing weak equivalence with LEMING~~S~~

Damian Goeldi
SLAC FPD Seminar 2023/08/15

The Standard Model of particle physics



Gravity

We 'know'

- atoms (p, n, e^-)

→ 99 % of mass from strong interaction

We don't know

- antimatter
- 2[nd] and 3[rd] generation

Muonium

Testing weak equivalence with second-generation antileptons

Regular matter mic drop

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

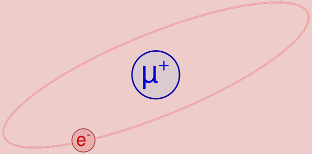
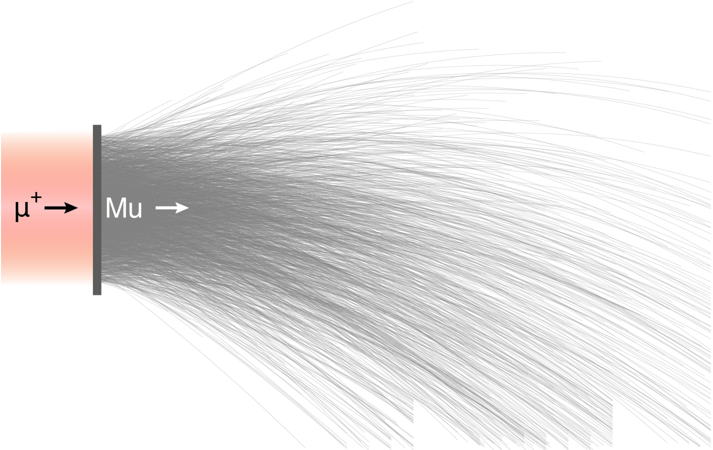


Figure: Wikimedia Commons, Neil deGrasse Tyson

2nd generation leptonic antimatter mic drop

Dropping muonium
Free-falling beam



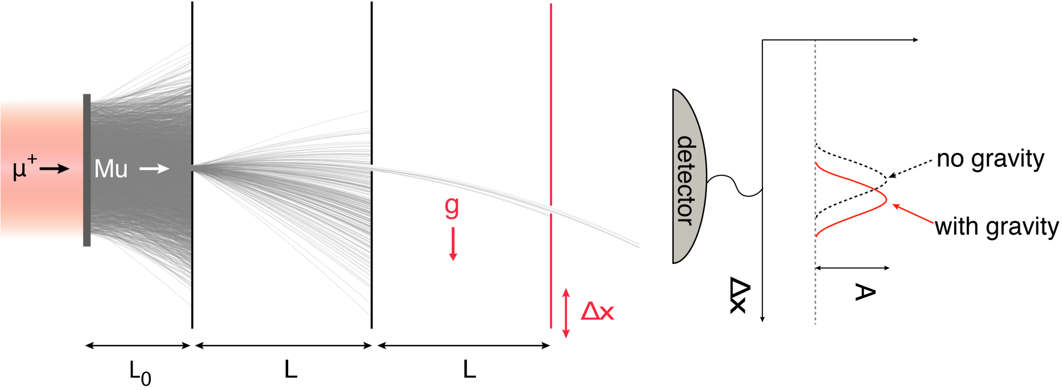
Challenge: lifetime

$$\Delta x = \frac{1}{2} g \Delta t^2$$
$$g = 2\frac{\Delta x}{\Delta t^2}$$

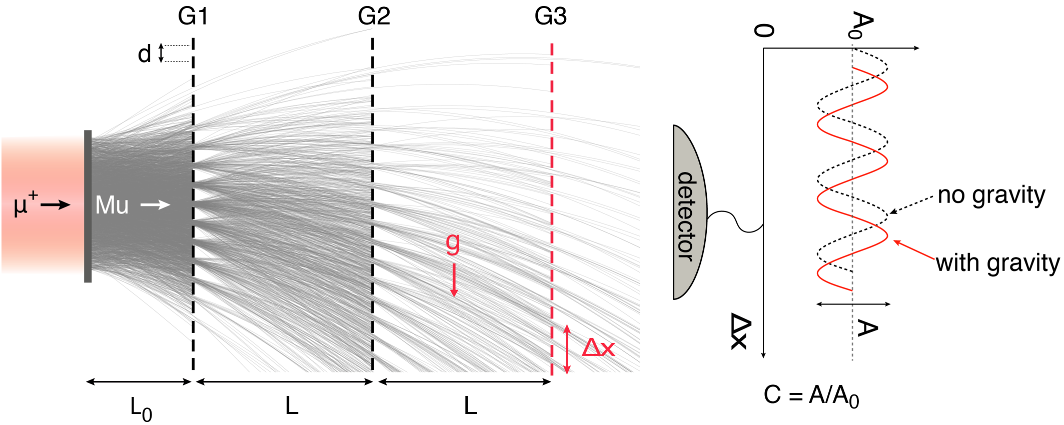
$$\Delta t \approx \tau_\mu = 2.2\,\mu s$$
$$\Delta x < 1\,nm$$

Dropping muonium

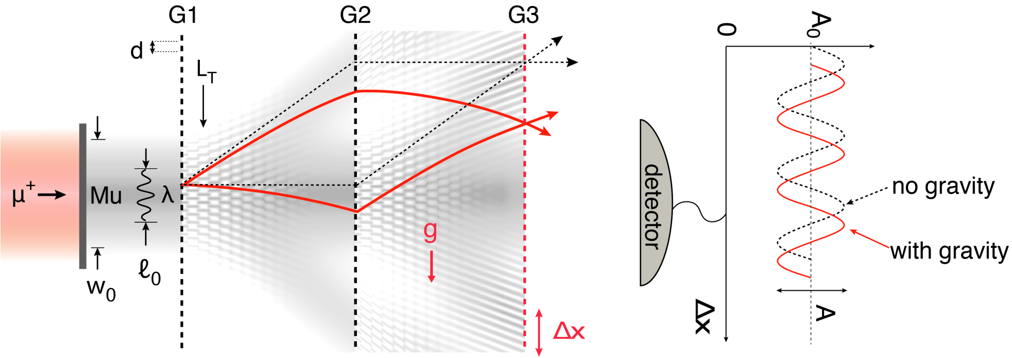
Single-slit collimation



Dropping muonium
Grating collimation

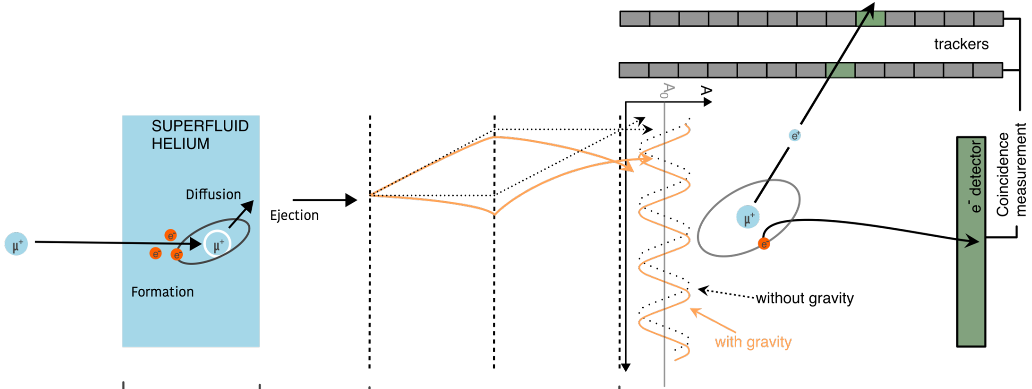


Dropping muonium
Atom interferometry



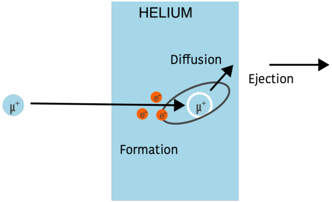
$C = A/A_0$

LEptons in Muonium INteracting with Gravity
LEMING



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

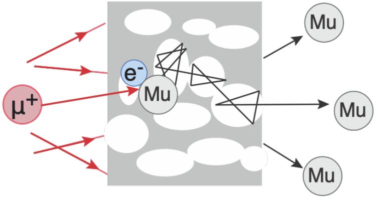
Muonium creation

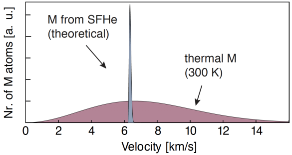


(sub)surface muon beam | Cold Mu formation | Mu Beam in vacuo

Existing thermal beams not suitable

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





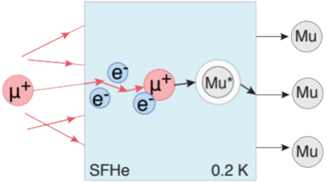
Novel superfluid helium (SFHe) muonium beam

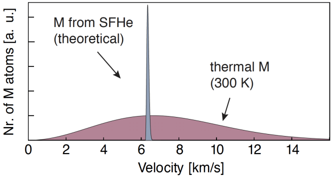
M formation in SFHe

- Small impurity

⇒ Ballistic propagation

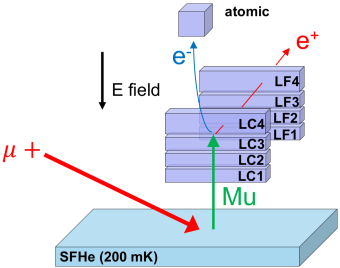
- **Fast diffusion** inside liquid
- Positive chemical potential
- High-speed **surface ejection**



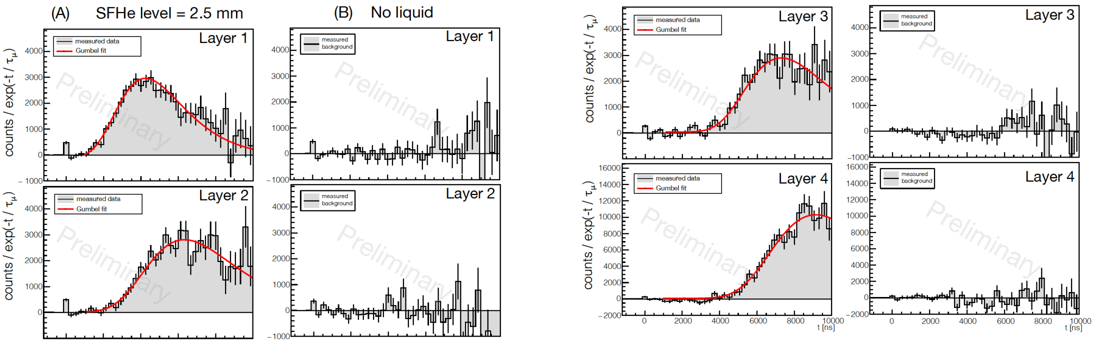


Test beam detector setup

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

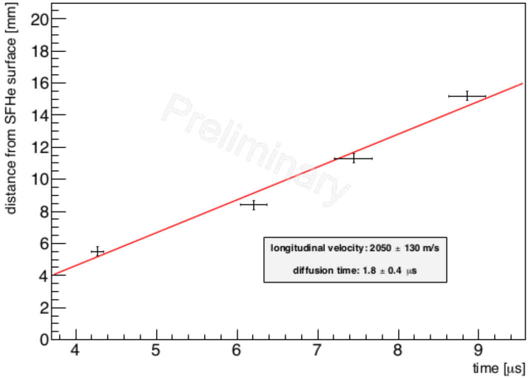


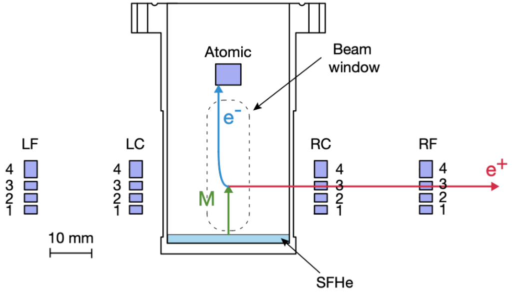
First observation of muonium atoms emitted from superfluid helium



First observation of muonium atoms emitted from superfluid helium

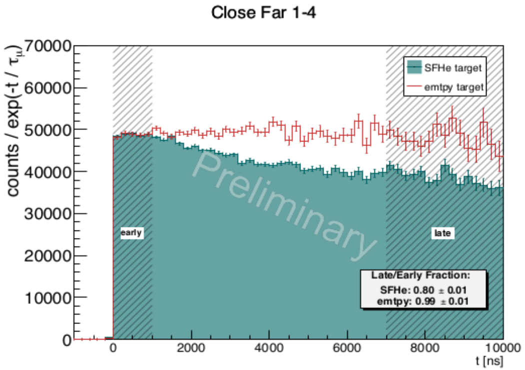
Velocity $\approx 2.1\,\mathrm{km\,s^{-1}}$

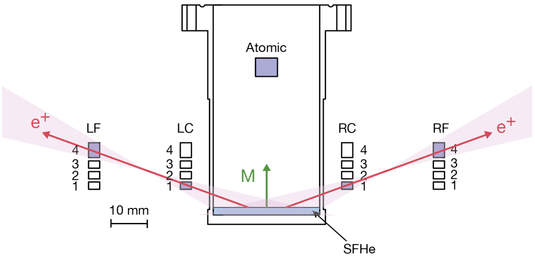




First observation of muonium atoms emitted from superfluid helium

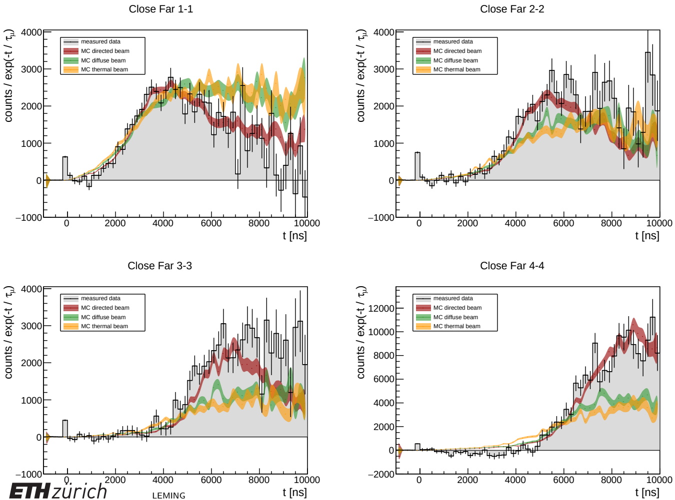
Conversion efficiency ≈ 0.2





First observation of muonium atoms emitted from superfluid helium

Directed beam simulation fits data better than thermal beam



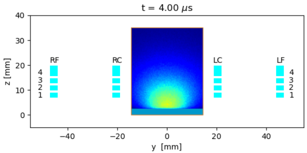


Figure: Thermal beam

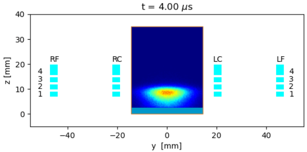
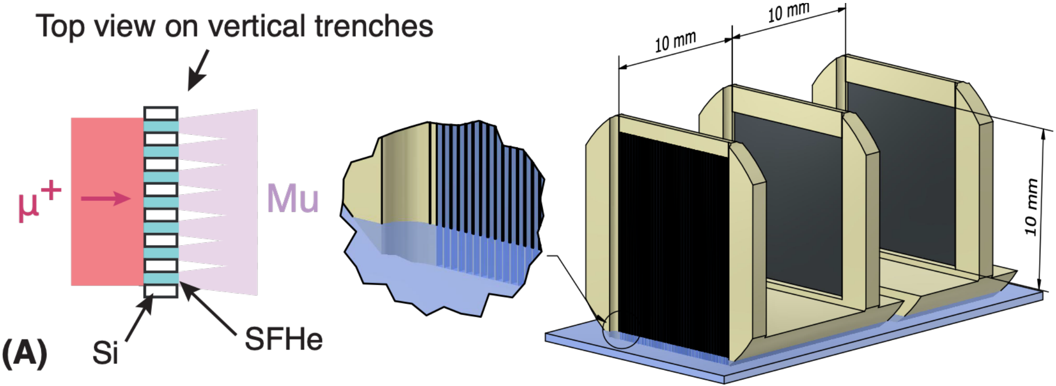


Figure: Directed beam

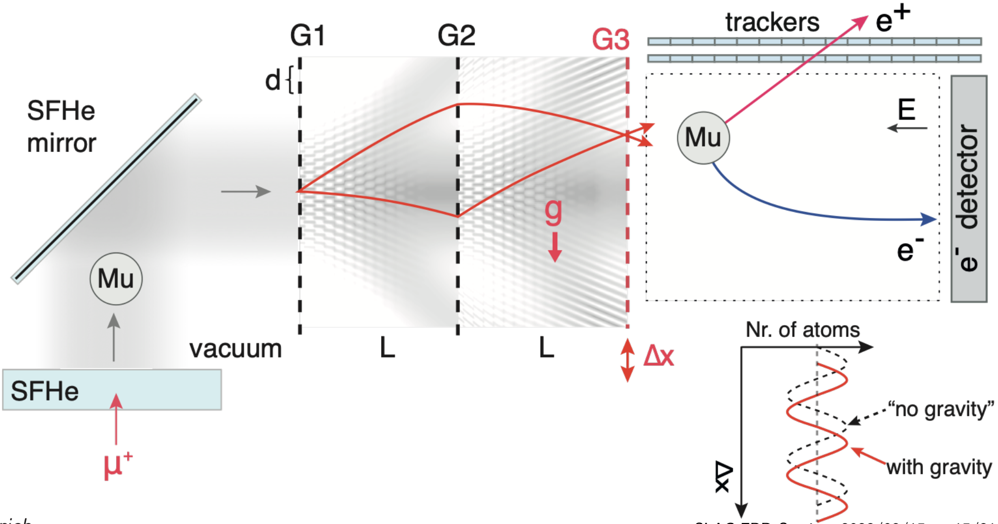
Creating a horizontal muonium beam from superfluid helium

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



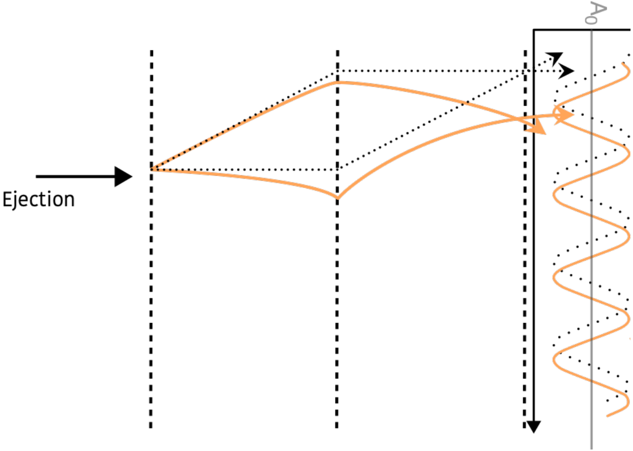
Creating a horizontal muonium beam from superfluid helium

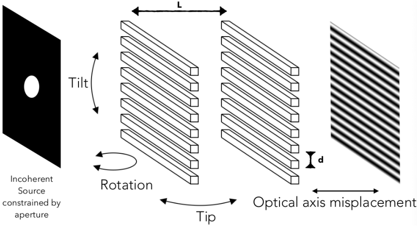
Plan B: SFHe mirror

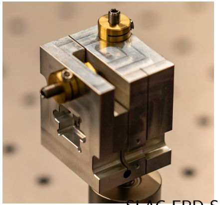


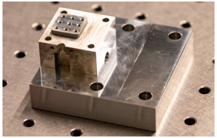
Interferometer

Developing precision stages to achieve required alignment









Interferometer prototype

Success with visible light | Next iteration with soft X-rays

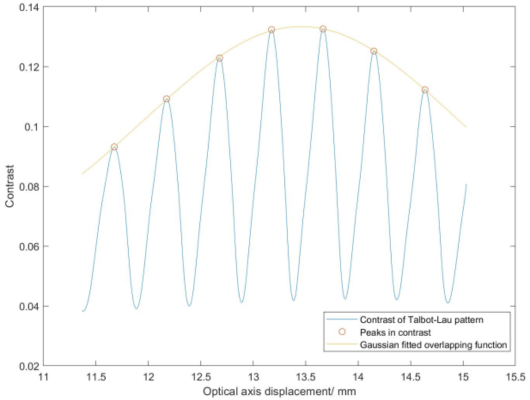


Figure: Experiment

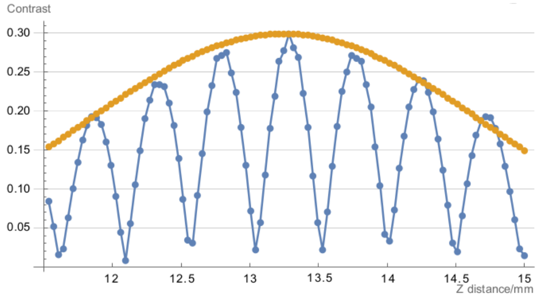


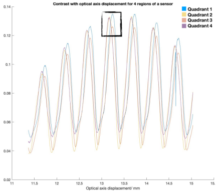
Figure: Simulation

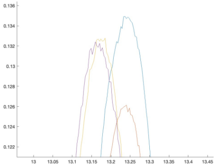
Interferometer contrast

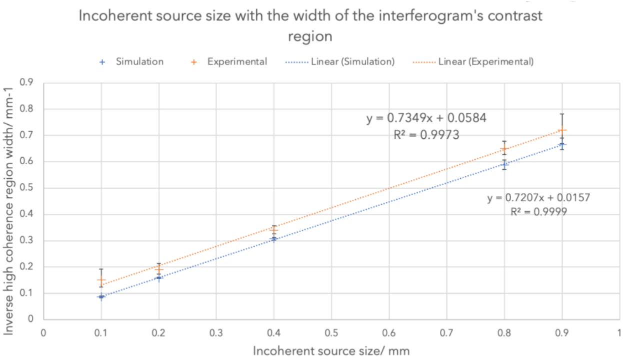
Requirements

- 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





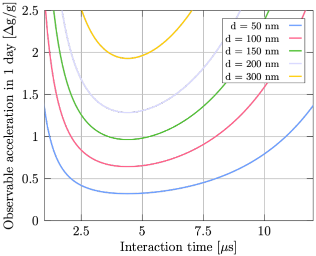


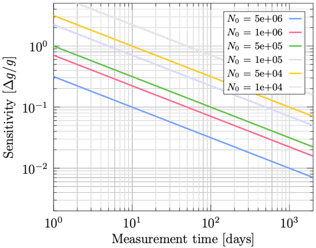
Sensitivity

Trade-off between spatial resolution and statistics

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

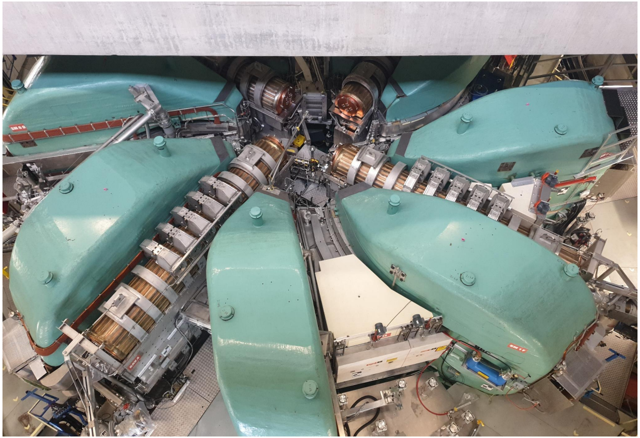
- Grating period $d \approx 100\,\mathrm{nm}$
- Interaction time $T \approx 7\,\mu\mathrm{s}$ to $8\,\mu\mathrm{s}$
- Contrast $C \approx 0.3$
- Atoms from source $N_0 \approx 1 \times 10^6\,\mathrm{s}^{-1} \times t_{\mathrm{measure}}$
- Loss factor $\eta = 0.3$, $\epsilon = 0.5$, $t_0 < \frac{\tau}{2}$
- Need high total detection efficiency $\epsilon \approx 0.5$

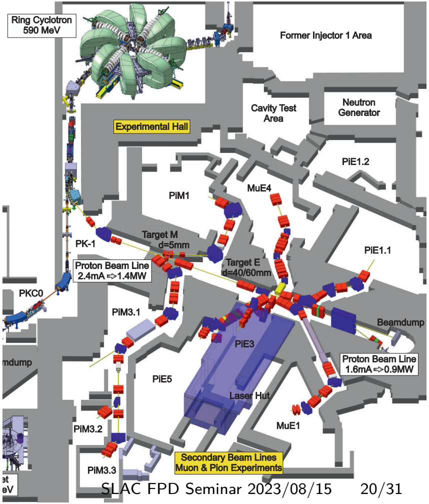




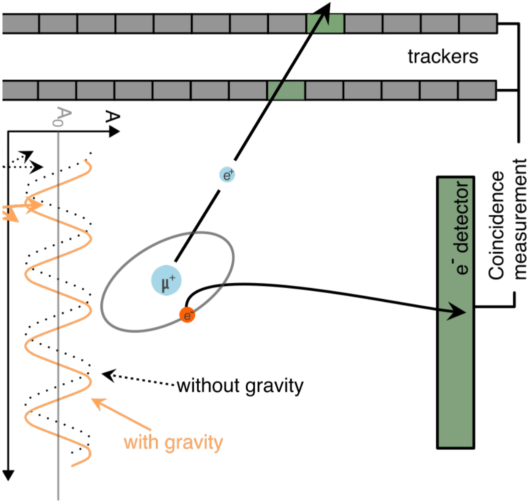
Swiss InfraStructure for Particle physics (CHRISP) at Paul Scherrer Institute (PSI)

Providing $5 \times 10^8\ \mu^+/\mathrm{s}$ @ $28\,\mathrm{MeV}$ from $2.4\,\mathrm{mA}$ protons @ $590\,\mathrm{MeV}$



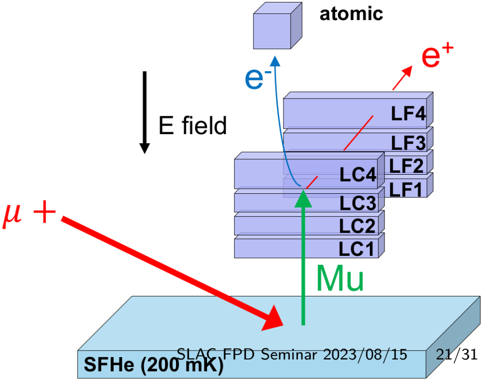


Detection



Michel e^+ tracker

- Hamamatsu S13370 VUV4 SiPMs
- Eljen EJ-204 scintillator bars



Can we operate a commercial VUV4 SiPM below $1\,\mathrm{K}$?

DOI:10.1088/1748-0221/17/06/P06024

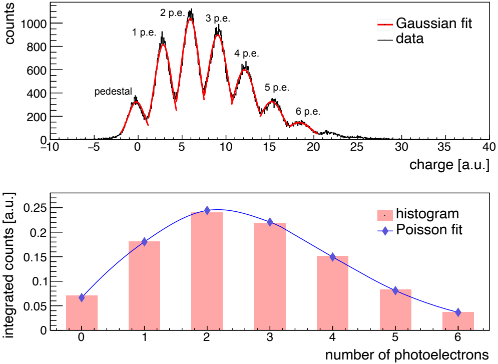
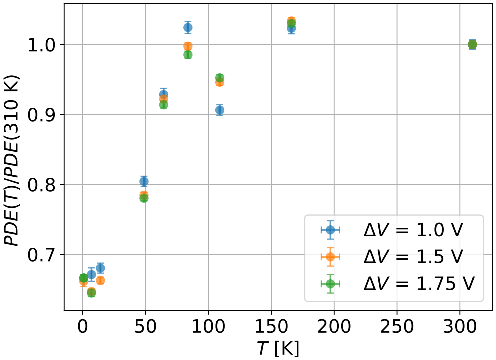
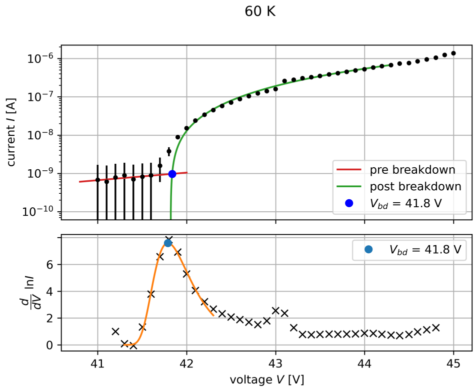


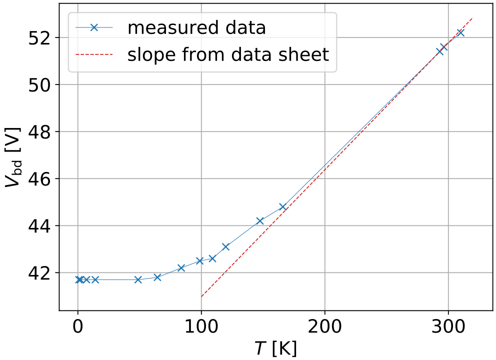
Figure: $T = 0.85\,\mathrm{K}$



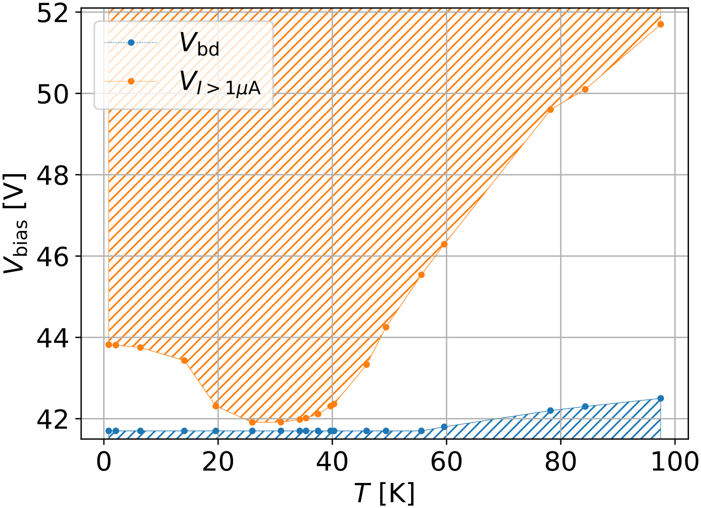
VUV4 characterisation down to below $1\,\mathrm{K}$

Matches behaviour measured in DOI:10.1063/1.1754731





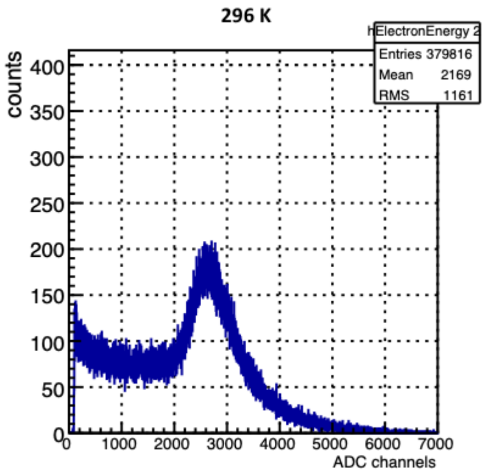
No useful operation below $40\,\mathrm{K}$ But below $20\,\mathrm{K}$

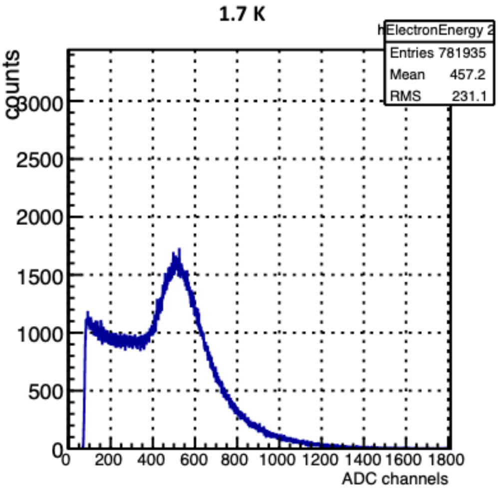


Operational range limited by afterpulsing

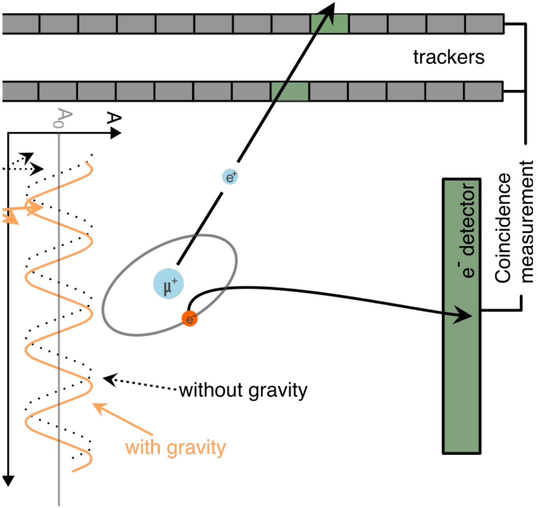
- Self-sustaining AP oscillation from $20\,\mathrm{K}$ to $40\,\mathrm{K}$
- Too much heat dissipation
- Usable overvoltage range of $2\,\mathrm{V}$ below $20\,\mathrm{K}$

Cryogenic positron tracker operation





Atomic e^- detection



Atomic e^- detector

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

Positron tracker scheme only works in vacuum Not SFHe

Required acceleration high voltage breaks down before E_{e^-} reaches scintillator threshold

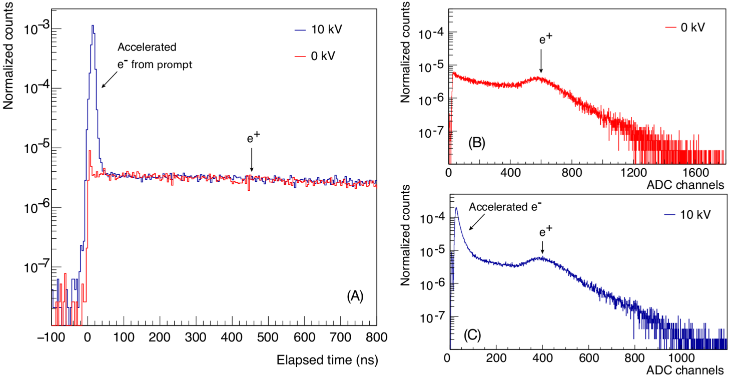


Figure: Time (left) and energy (right) spectra

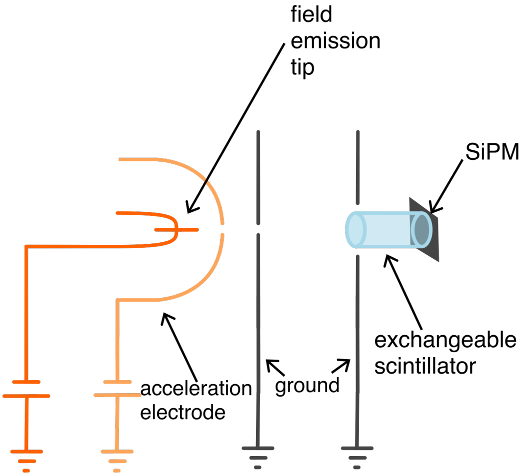
Dry test without SFHe

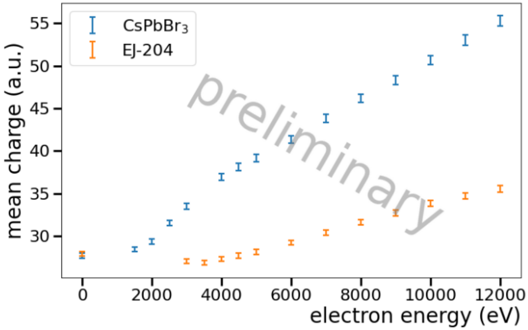
- Operate with HV off and on
- High-energy Michel e^+ from μ^+ decay (always)
- Accelerated e^- from μ^+ hitting chamber walls (only with HV on)
- Success in vacuum below 1 K

HV breakdown in SFHe

Perovskites

Promising alternative scintillators





$CsPbBr_3$ nanocrystals at $T = 4\,\mathrm{K}$

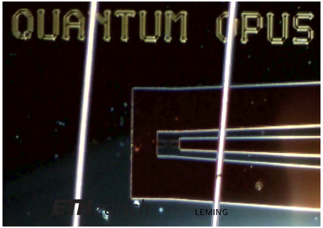
- $2\,\mathrm{keV}$ threshold potentially reachable with HV acceleration

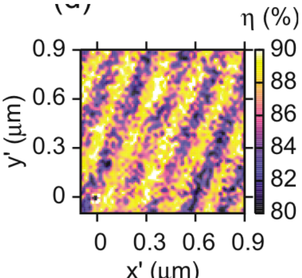
And now for something completely different

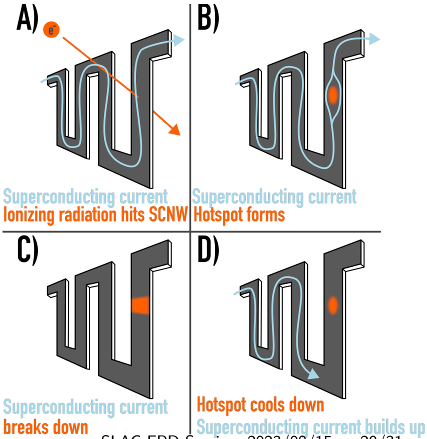
Superconducting nanowire single-photon detectors (SNSPD)

High-efficiency low-threshold cryogenic detector

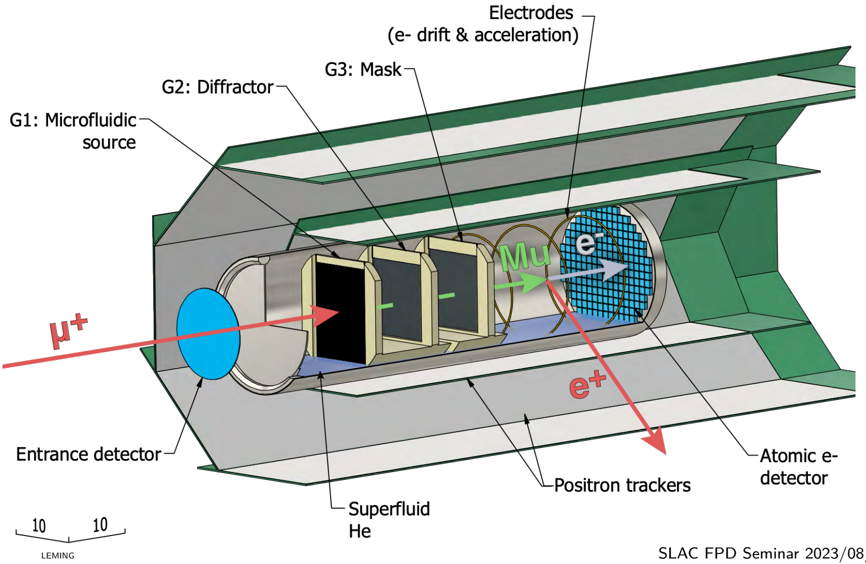
- Designed for γ detection in quantum optics
- e^- detection demonstrated (DOI:10.1063/1.3506692)
- Potentially problematic charge build-up
- Preparing test of commercial SNSPD







Putting it all together



Collaboration

Funded by

Swiss National Science Foundation

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

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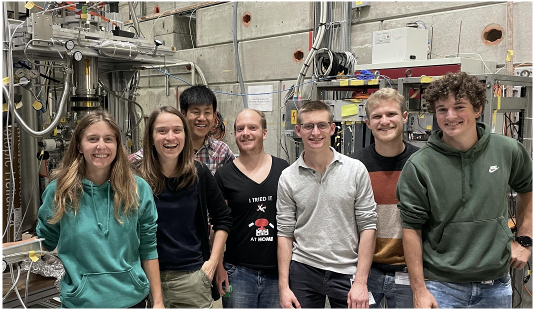

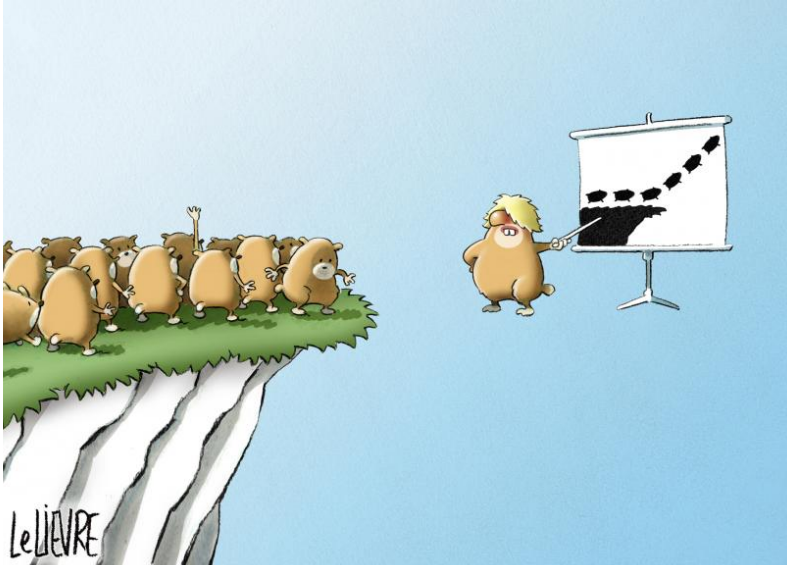
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