LEMING

Progress report

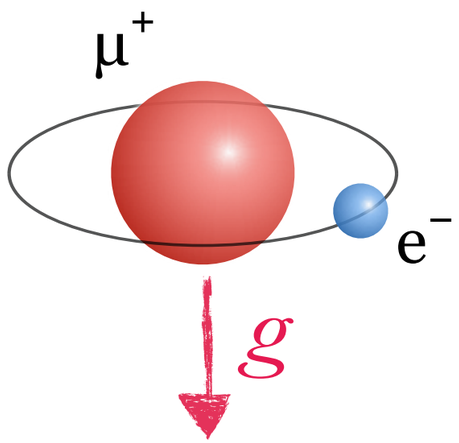
A. Antognini*, E. Dourassova‡, K. Kirch*, F. Lancellotti, R. Gartner‡, D. Goeldi,
C. Regenfus, A. Soter†, D. Taqqu, R. Waddy‡, P. Wegmann‡, J. Zhang ‡
Institute for Particle Physics and Astrophysics, ETH Zurich, 8093 Zurich, Switzerland

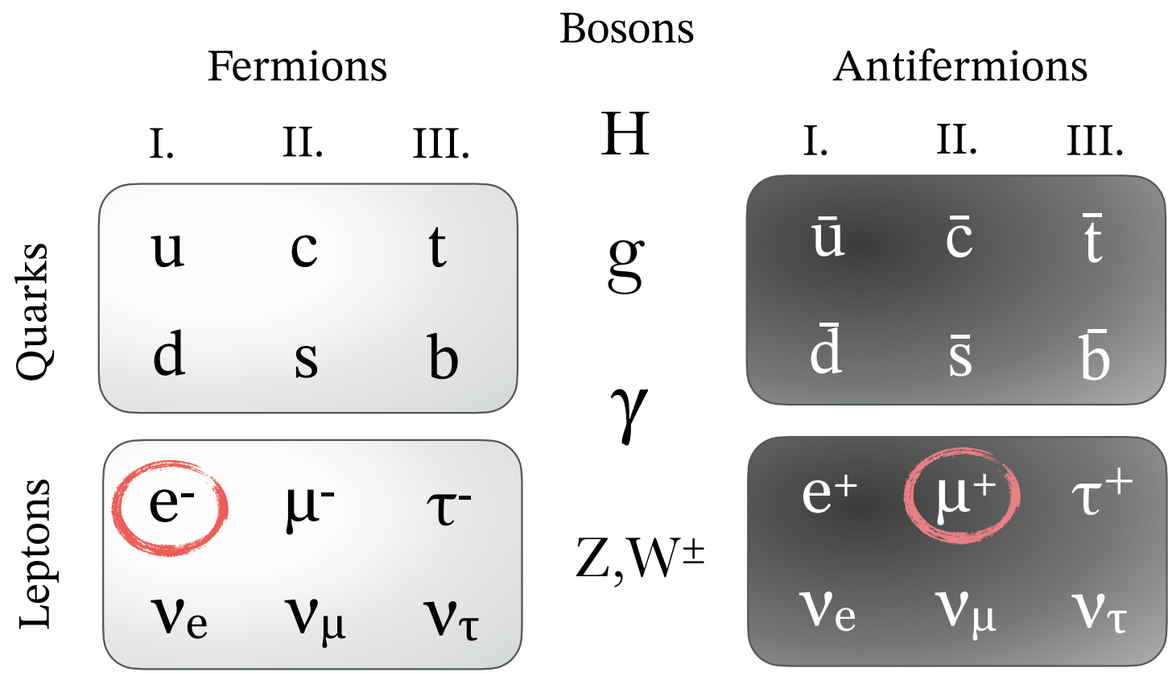
M. Bartkowiak, K. Jefimovs, A. Knecht, R. Scheuermann
Paul Scherrer Institute, 5232 Villigen-PSI, Switzerland

F. Wauters
Johannes Gutenberg University of Mainz, 55122 Mainz, Germany

January 24, 2025

Muonium - probing the SM and beyond



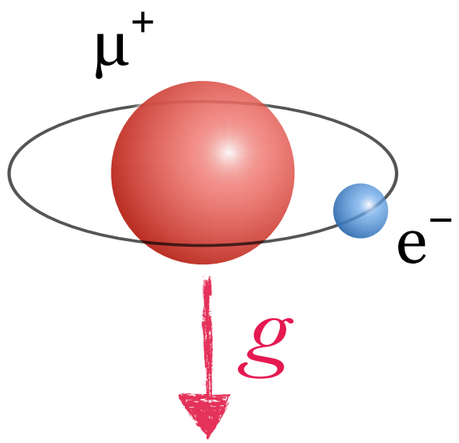


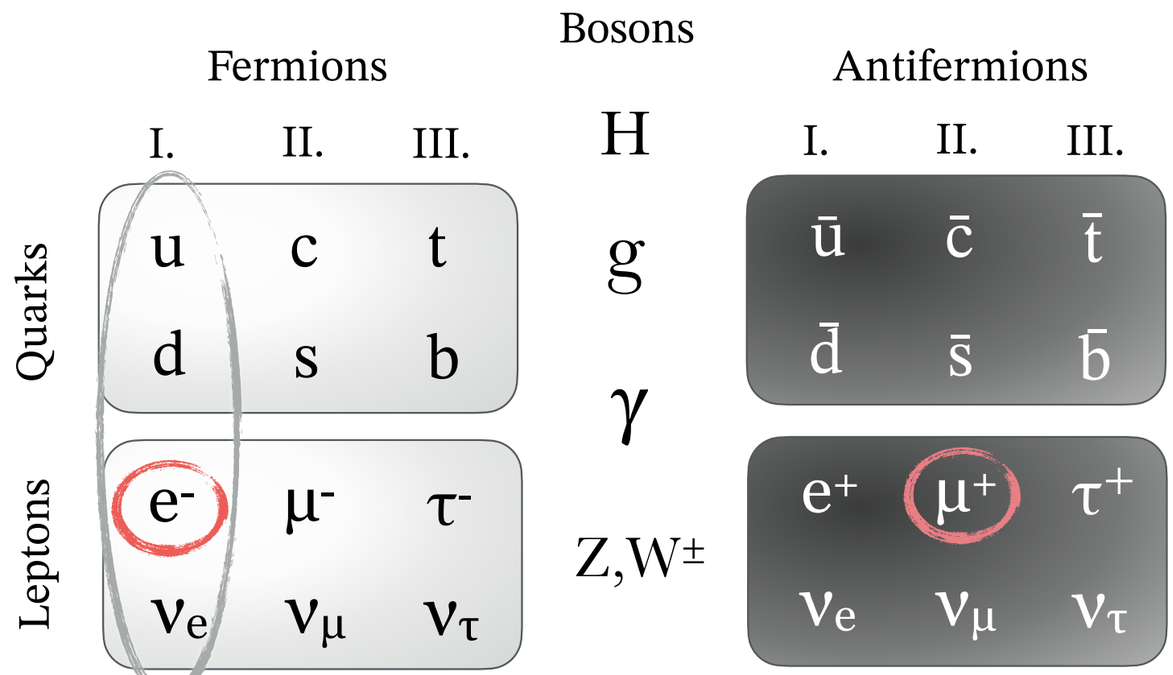
Free fall of Mu

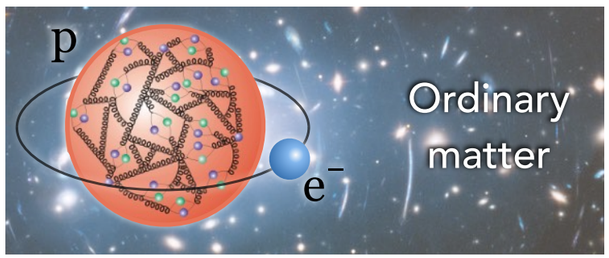
Test of the Weak Equivalence Principle by measuring the coupling of gravity to:

- **fundamental parameters** of SM, in the absence of masses generated by the strong interaction
- **second generation** (anti)fermions of the SM - only possible probe of this sector

Muonium - probing the SM and beyond





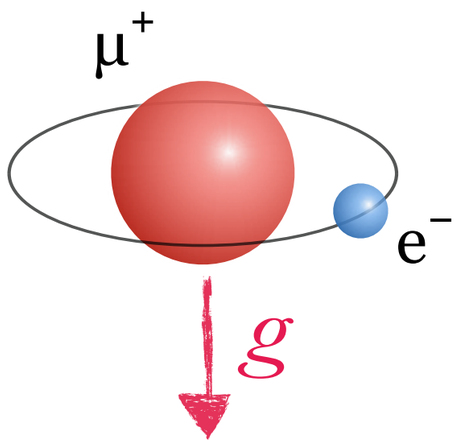


Free fall of Mu

Test of the Weak Equivalence Principle by measuring the coupling of gravity to:

- **fundamental parameters** of SM, in the absence of masses generated by the strong interaction
- **second generation** (anti)fermions of the SM - only possible probe of this sector

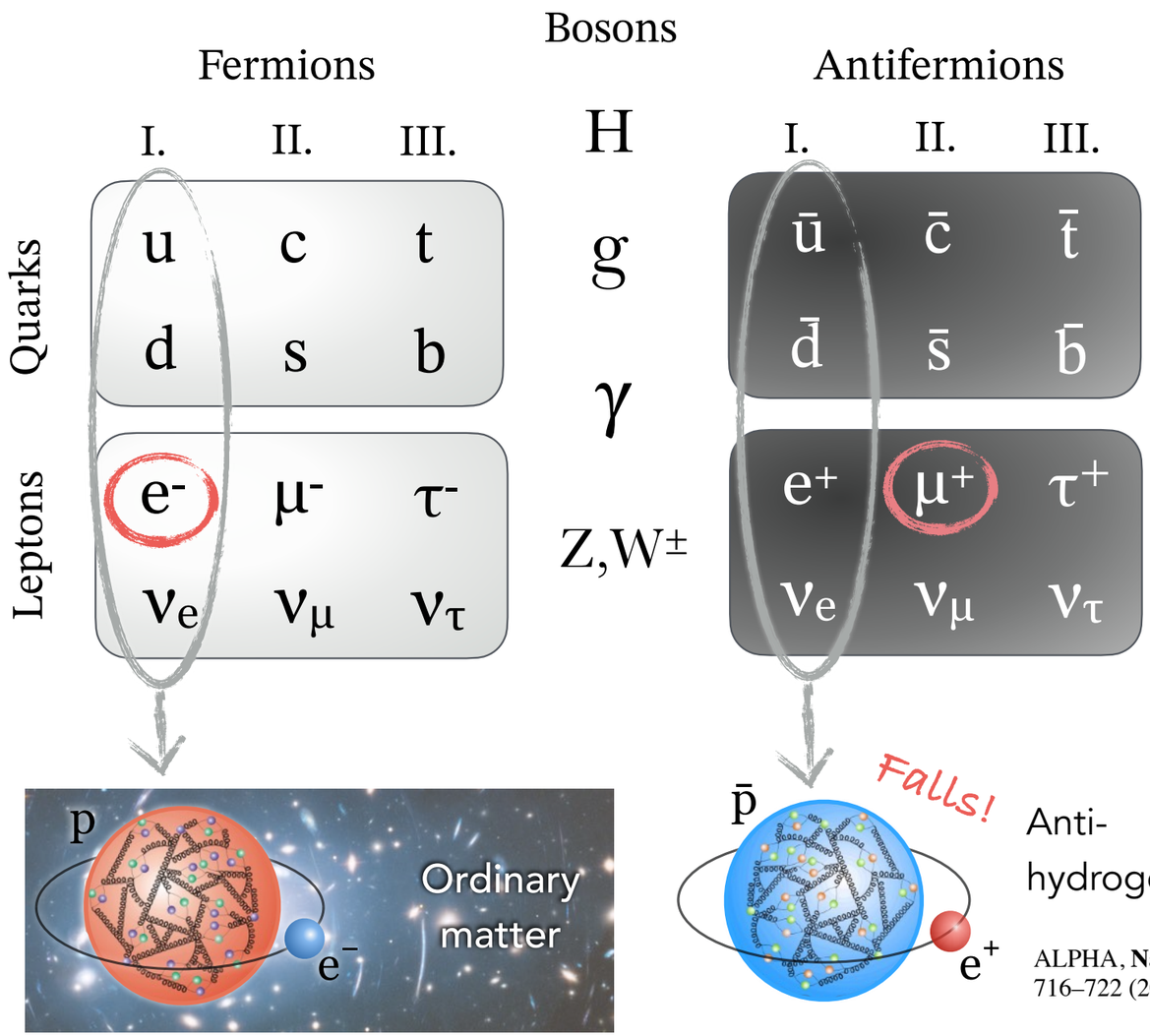
Muonium - probing the SM and beyond



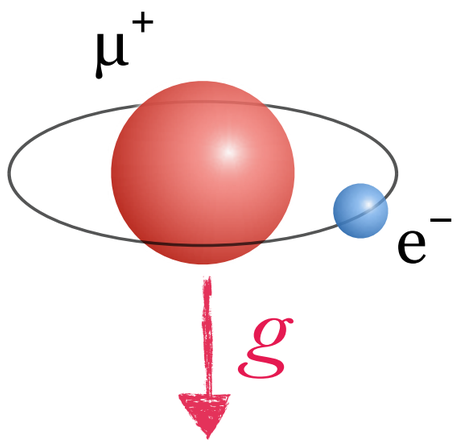
Free fall of Mu

Test of the Weak Equivalence Principle by measuring the coupling of gravity to:

- **fundamental parameters** of SM, in the absence of masses generated by the strong interaction
- **second generation** (anti)fermions of the SM - only possible probe of this sector



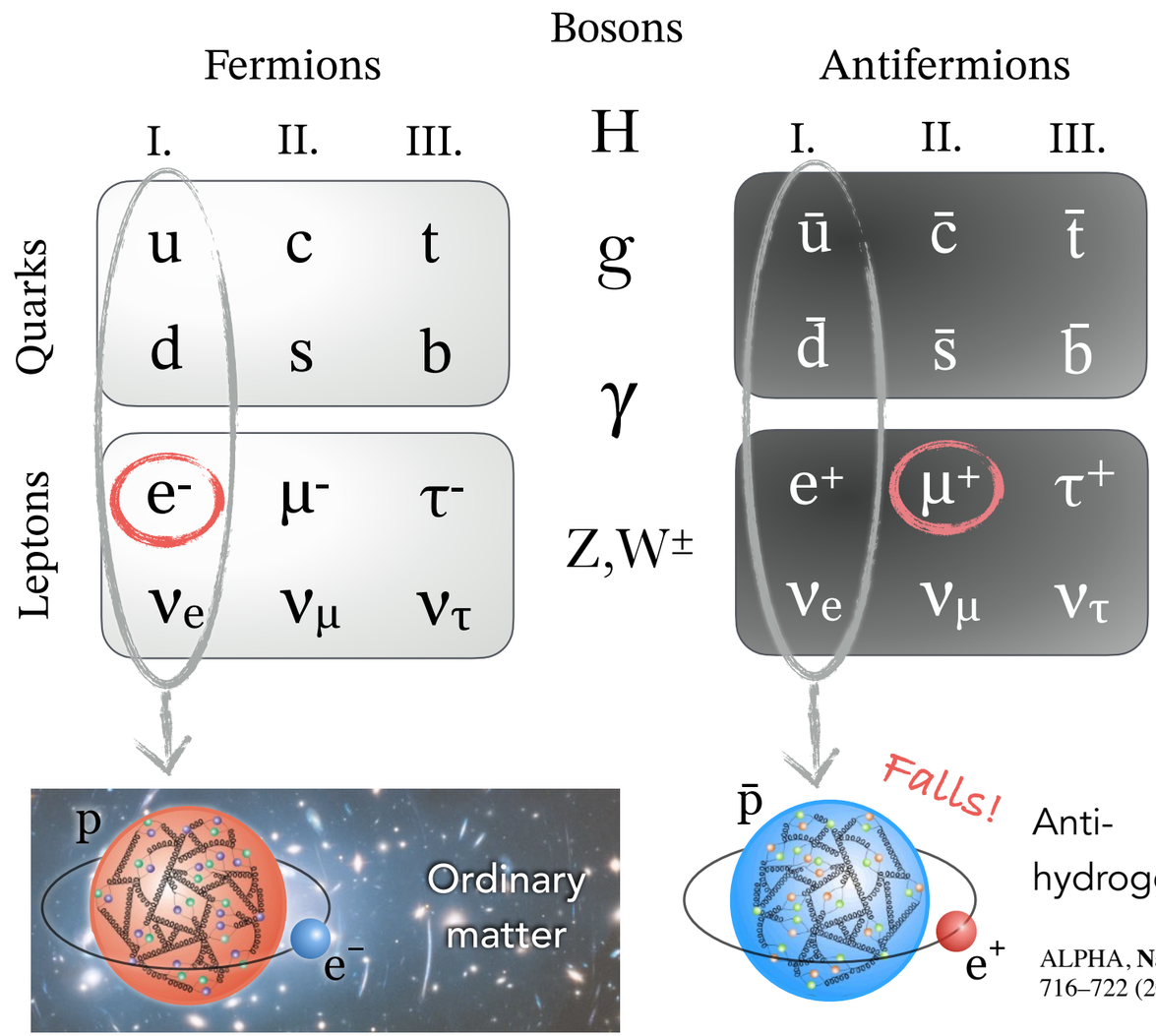
Muonium - probing the SM and beyond



Free fall of Mu

Test of the Weak Equivalence Principle by measuring the coupling of gravity to:

- **fundamental parameters** of SM, in the absence of masses generated by the strong interaction
- **second generation** (anti)fermions of the SM - only possible probe of this sector



ALPHA, **Nature 621**, 716–722 (2023)

Hadron mass

~1% valence quark

99% strong interaction

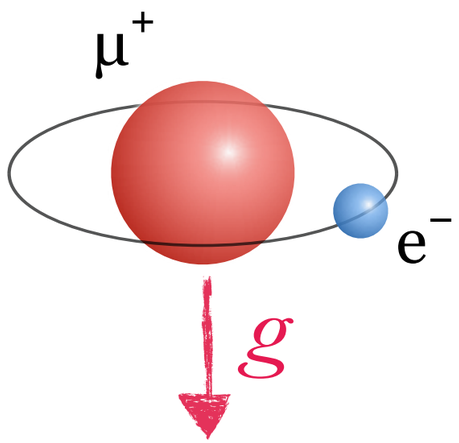
Muonium mass

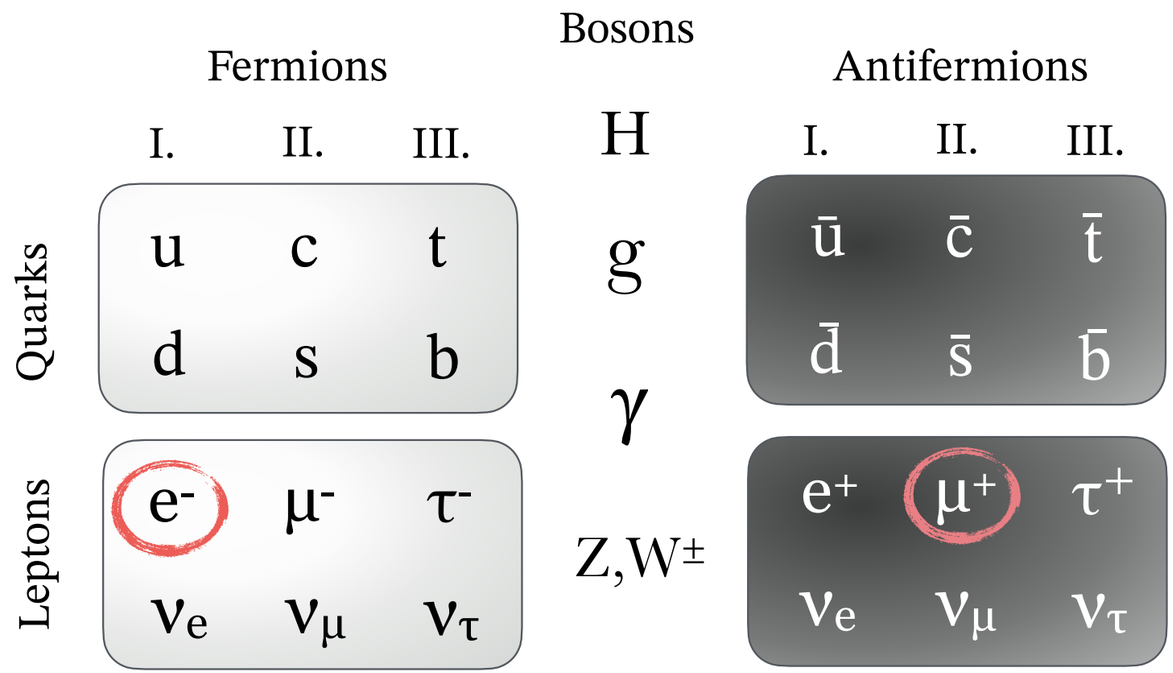
Binding E

μ^+ mass: 105.6583745(24) MeV/c

e^- mass: 0.5109989461(31) MeV/c²

Muonium - probing the SM and beyond





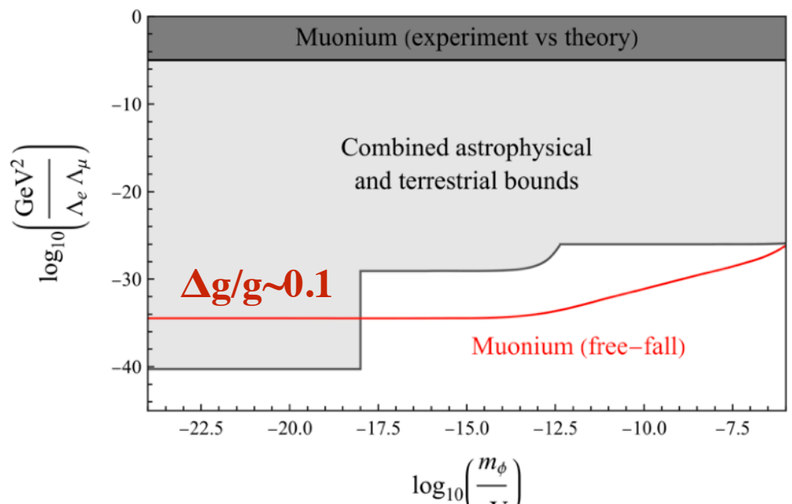
Free fall of Mu

Test of the Weak Equivalence Principle by measuring the coupling of gravity to:

- **fundamental parameters** of SM, in the absence of masses generated by the strong interaction
- **second generation** (anti)fermions of the SM - only possible probe of this sector

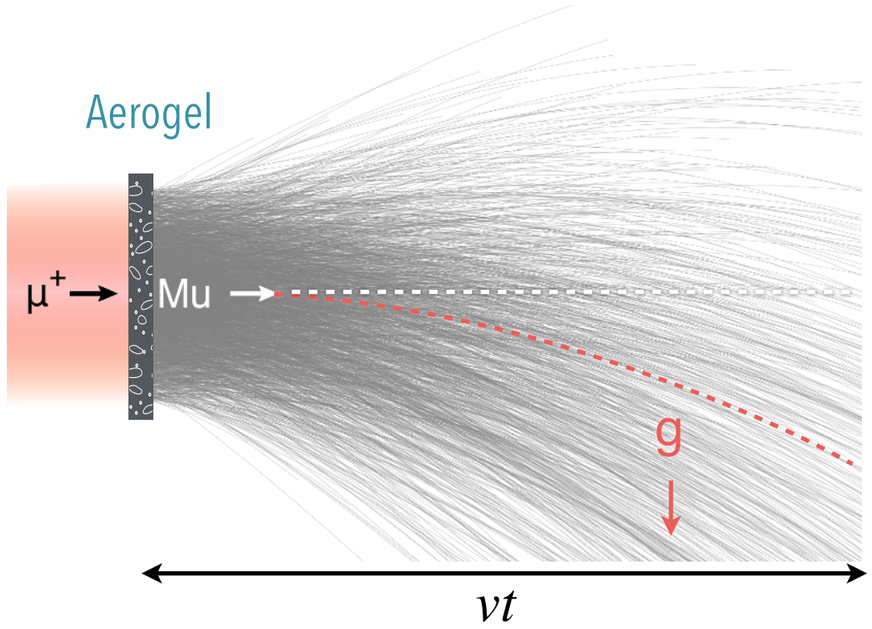
- Possibility to test for flavour-dependent new interactions

Y. Stadnik PRL 131, 011001 (2023)



The challenges of measuring Mu gravity

Not possible with conventional Mu sources

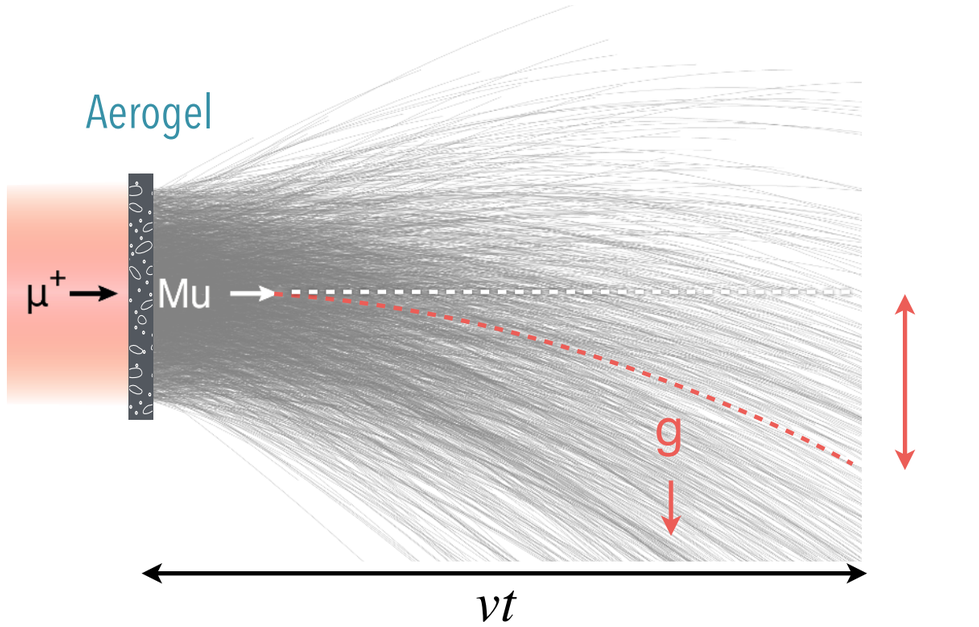


Mu lifetime of 2.2 μs

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

The challenges of measuring Mu gravity

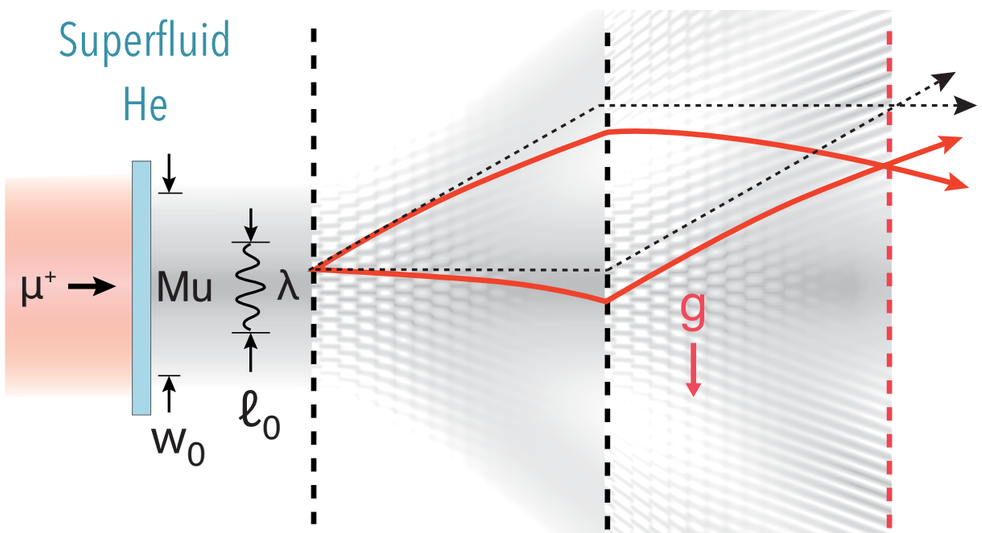
Not possible with conventional Mu sources



Mu lifetime of 2.2 μs

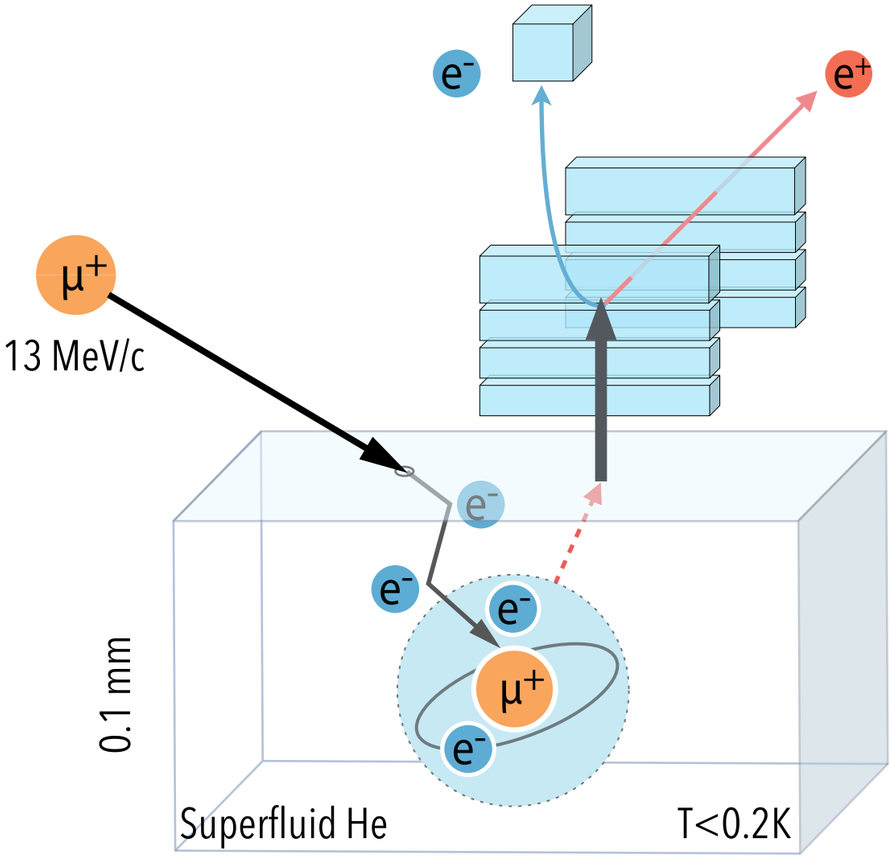
$$\Delta x = \frac{1}{2} g t^2 < 1 \text{ nm}$$

Why it might be possible with LEMING

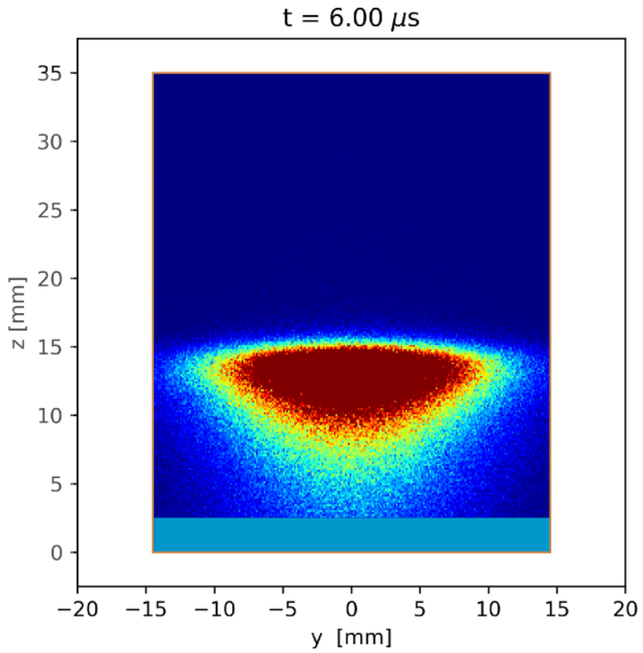


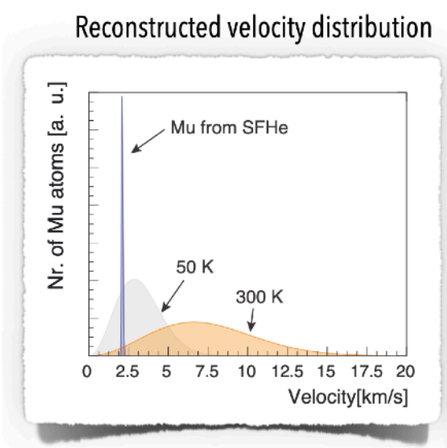
We developed a novel Mu beam amenable to interferometry

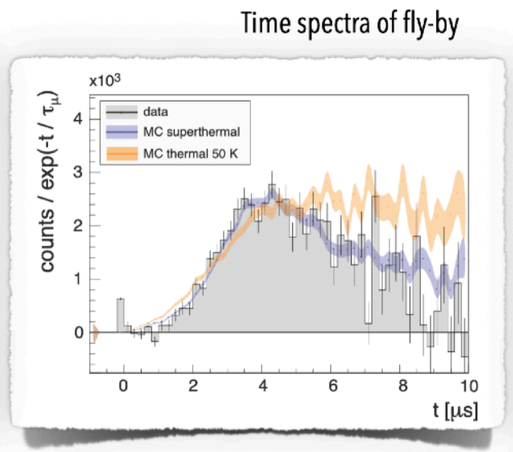
Superthermal muonium from SFHe

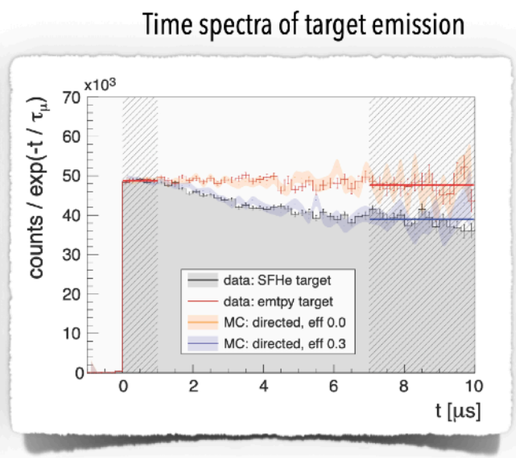


- **Lowest velocity** Mu source $v_x \approx 2175\ \mathrm{m/s}$
- **Narrowest** longitudinal distribution: $\sigma_{v_x} \approx 70\ \mathrm{m/s}$
- **High yield** similar to the best 300 K sources $R(\mu^+ \rightarrow \mathrm{Mu}_{\mathrm{vac}}) = 10\,\%$

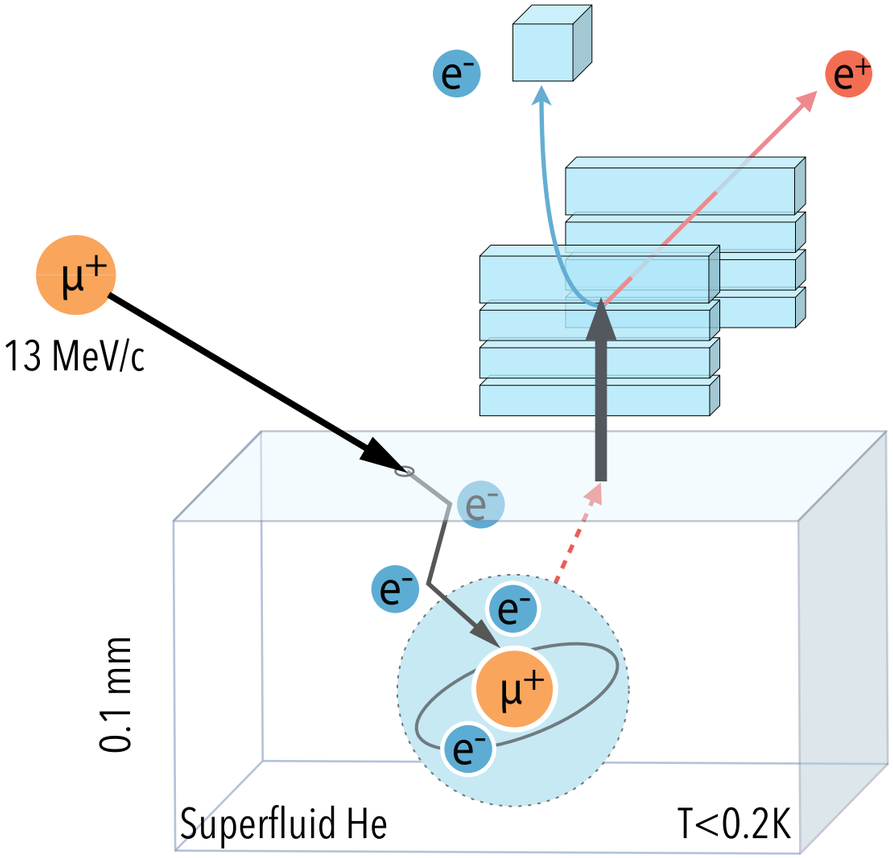




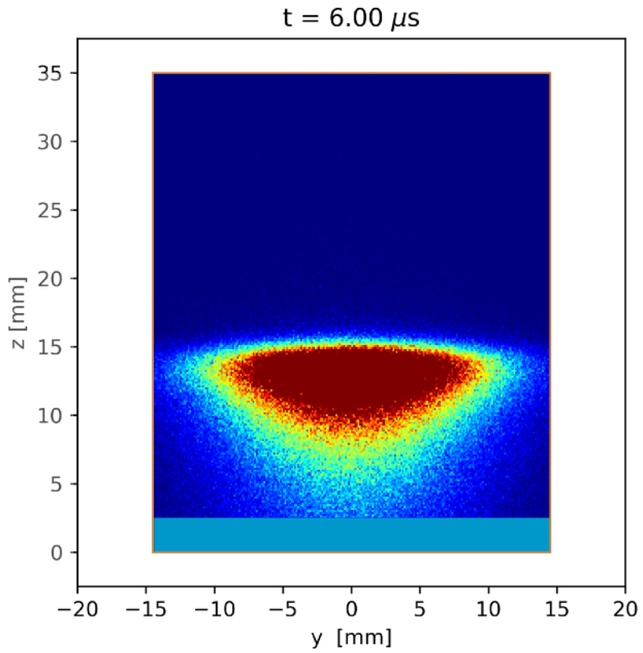


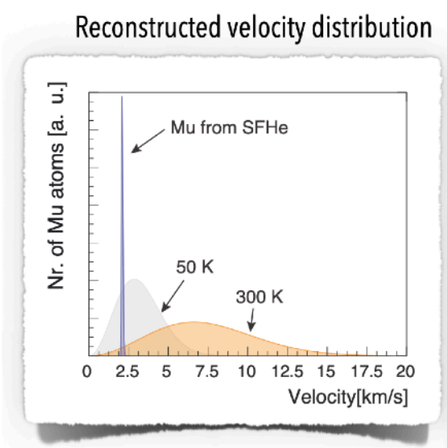


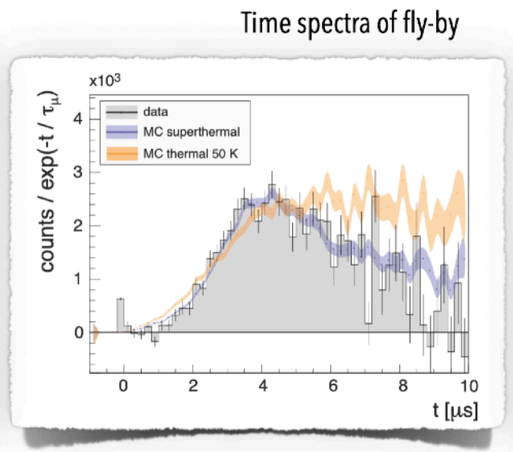
Superthermal muonium from SFHe

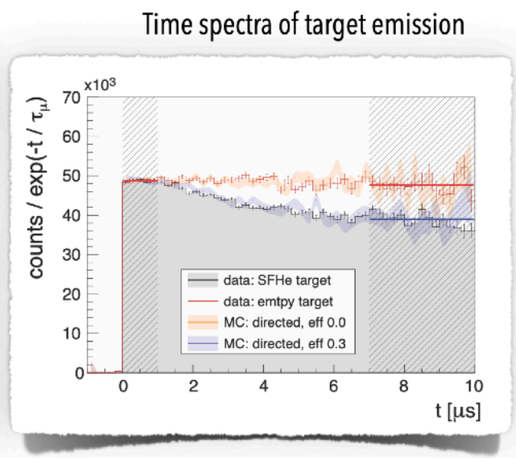


- **Lowest velocity** Mu source $v_x \approx 2175\ \mathrm{m/s}$
- **Narrowest** longitudinal distribution: $\sigma_{v_x} \approx 70\ \mathrm{m/s}$
- **High yield** similar to the best 300 K sources $R(\mu^+ \rightarrow \mathrm{Mu}_{\mathrm{vac}}) = 10\,\%$

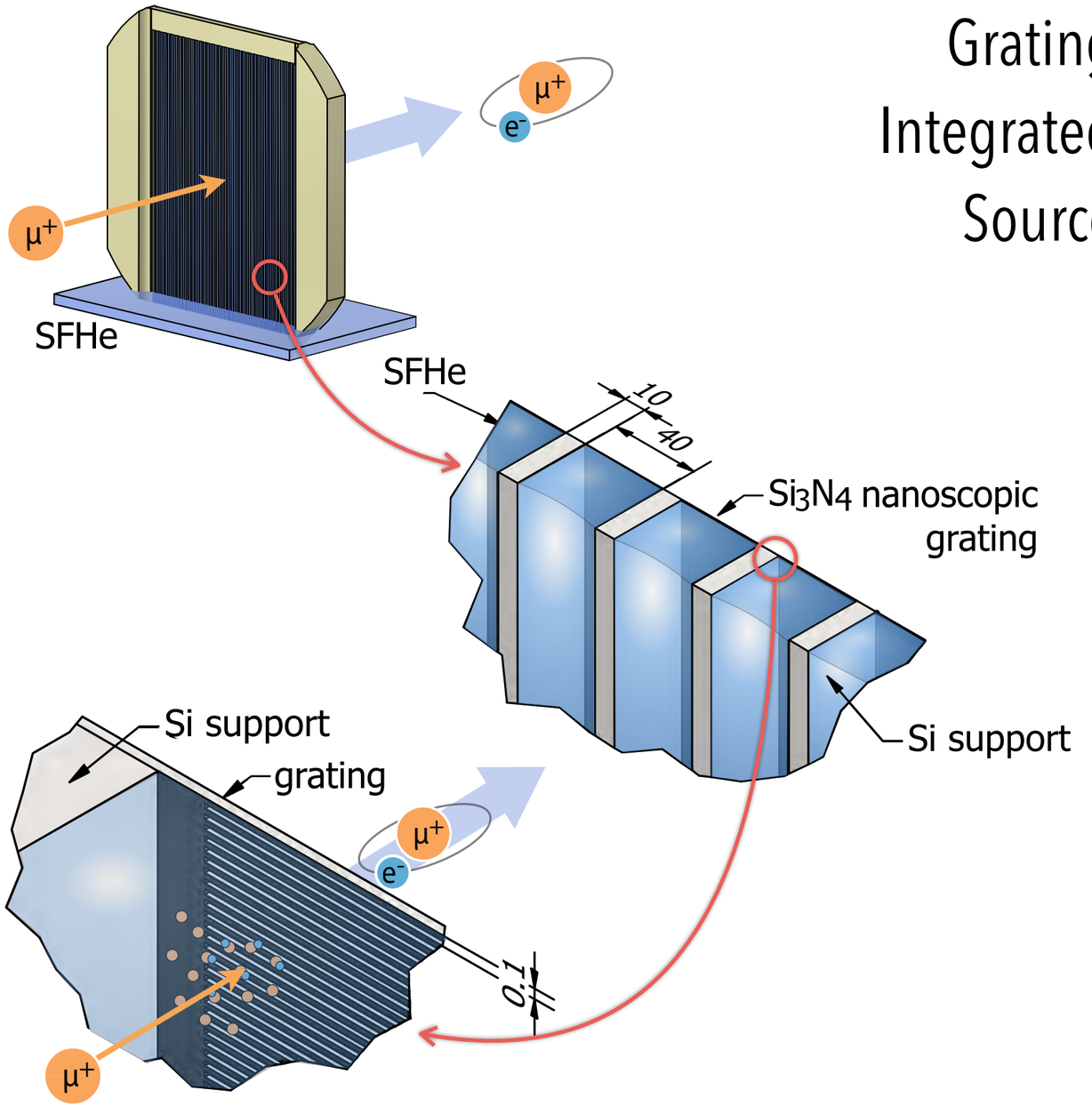






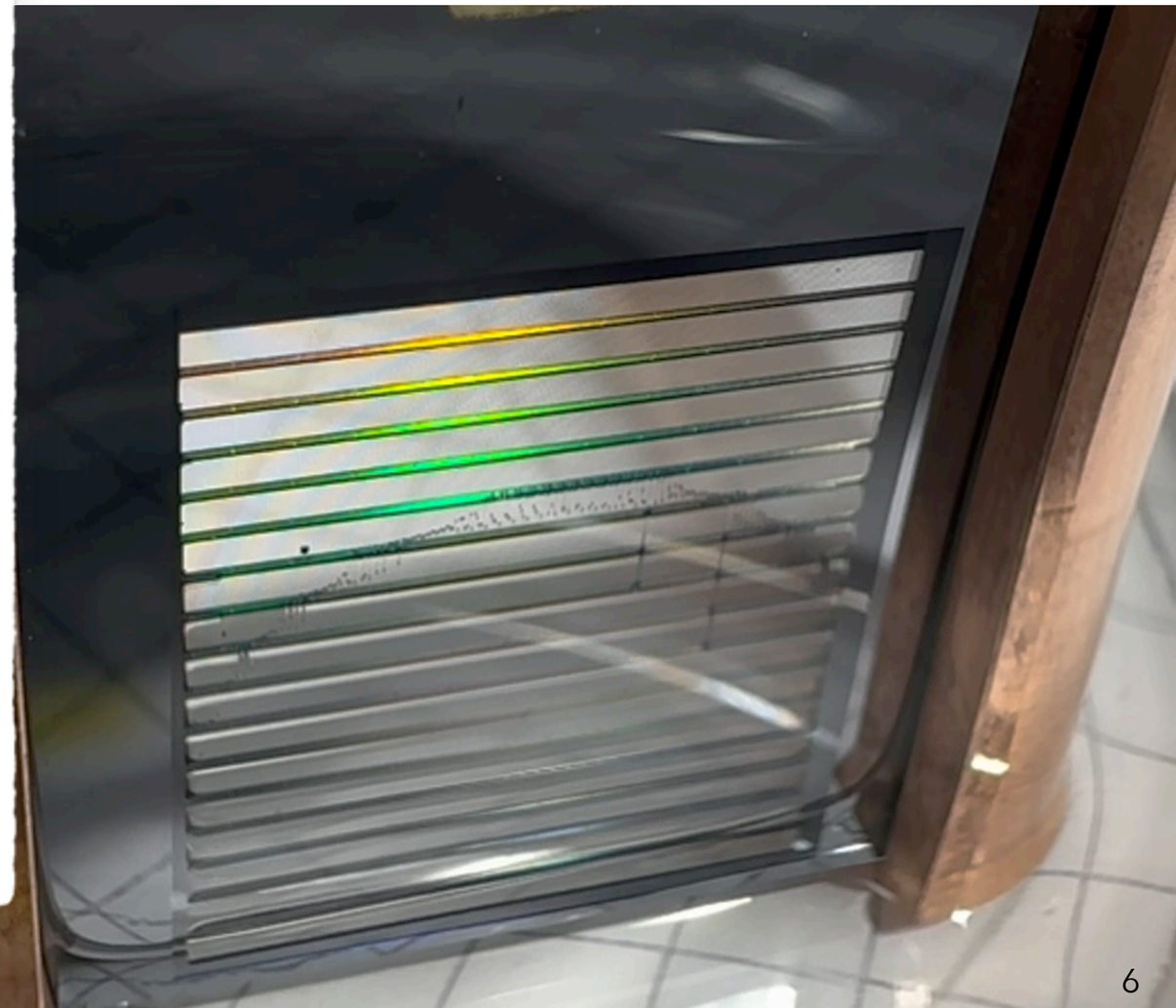


Novel source concept - microfluidic grating

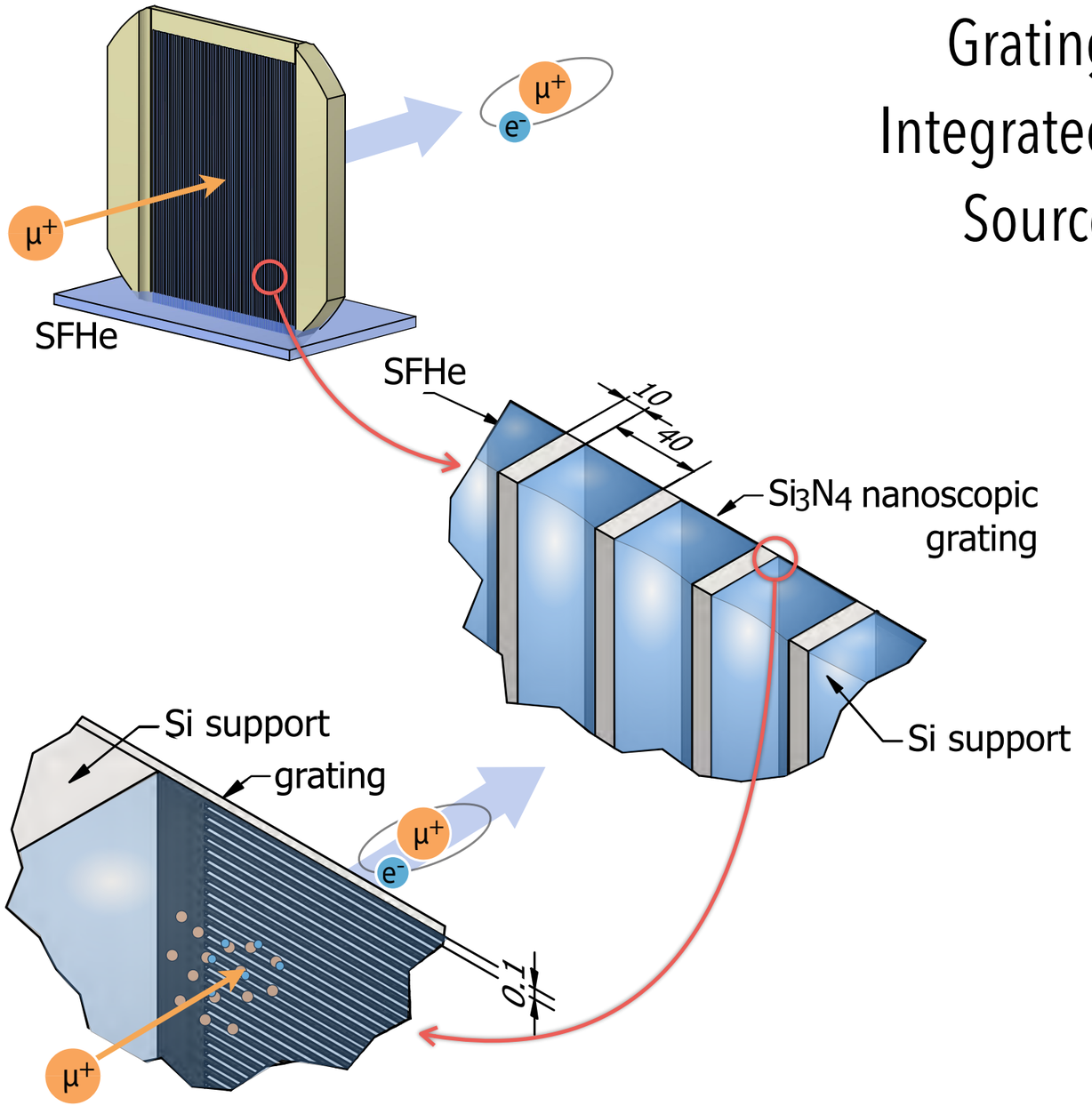


Grating Integrated Source

SFHe suspended by the capillary force, between support bars behind the first Si_3N_4 membrane

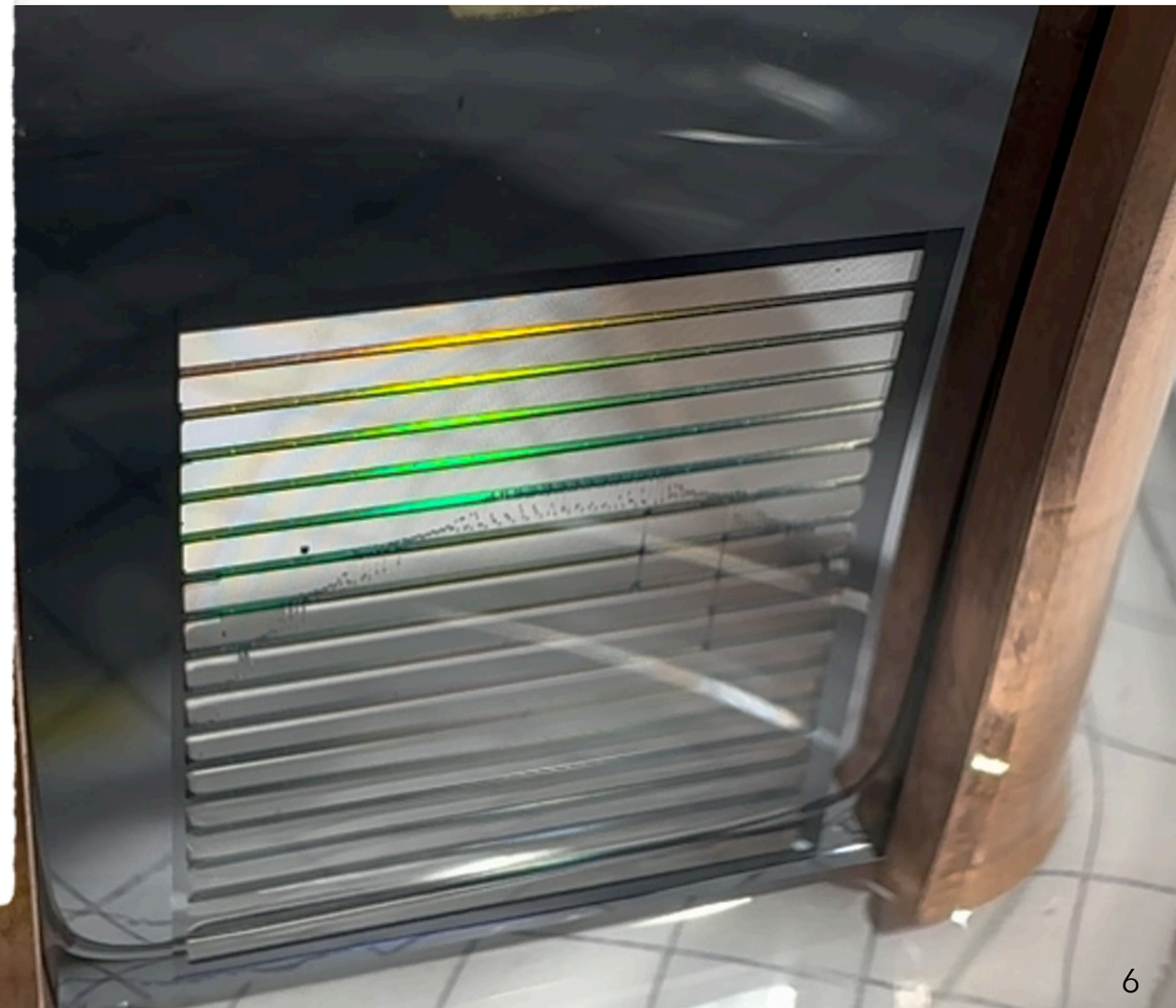


Novel source concept - microfluidic grating



Grating Integrated Source

SFHe suspended by the capillary force, between support bars behind the first Si_3N_4 membrane

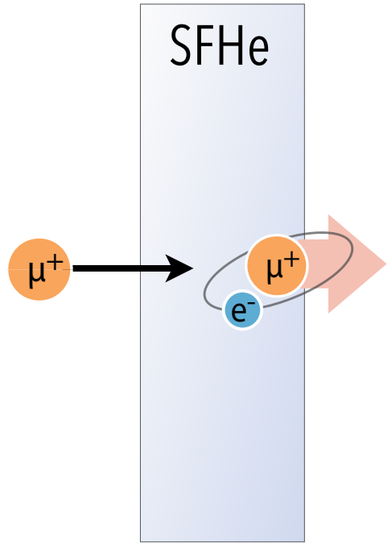


Overview of LEMING, and 2025 updates

Horizontal cold Mu beam

Interferometer

Detection

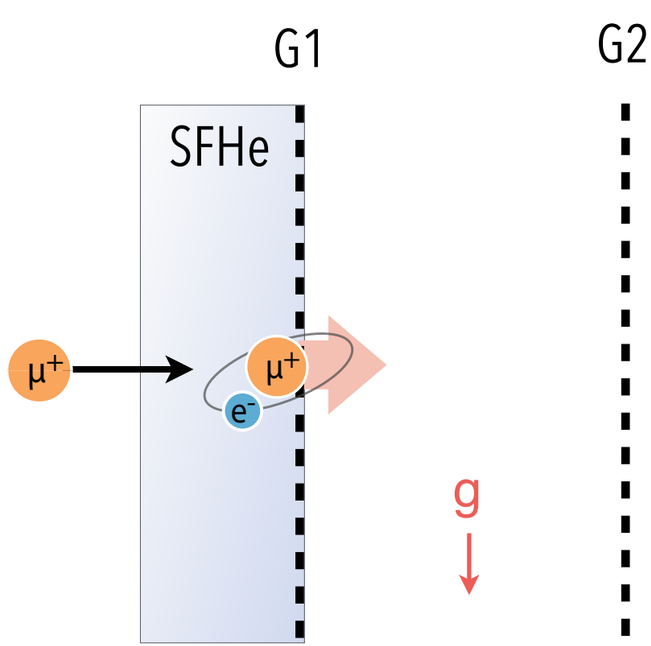


Overview of LEMING, and 2025 updates

Horizontal cold Mu beam

Interferometer

Detection

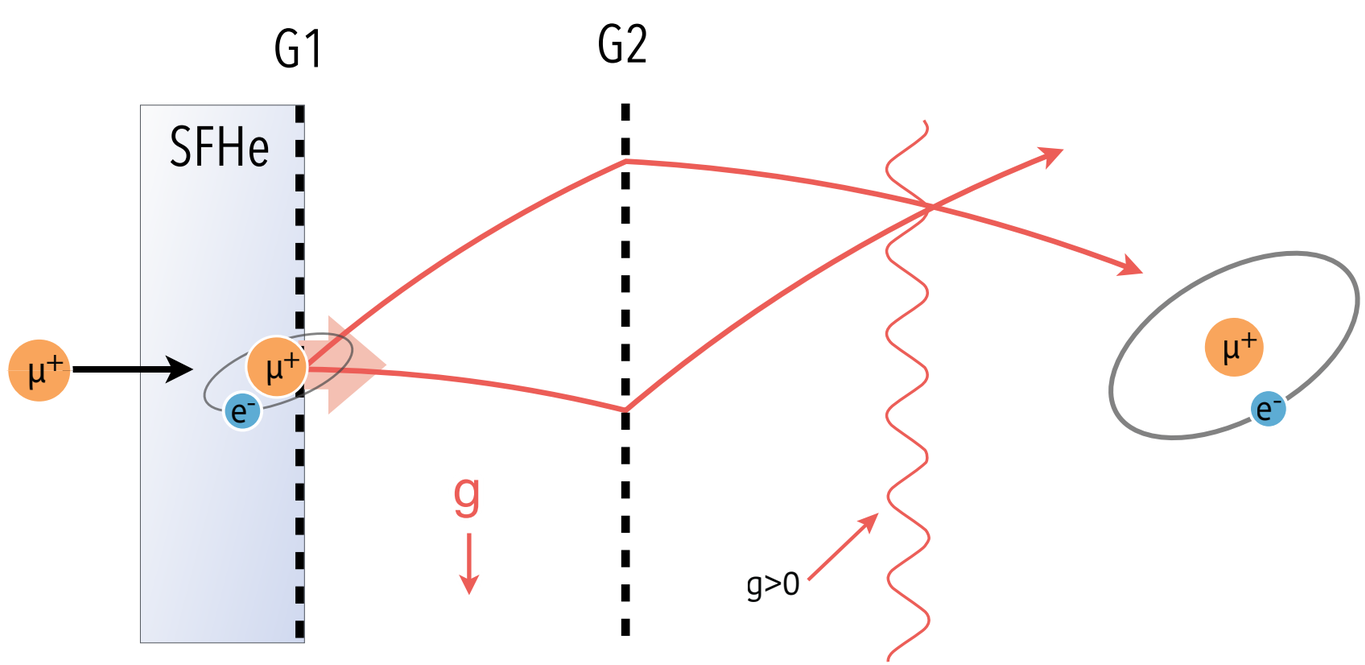


Overview of LEMING, and 2025 updates

Horizontal cold Mu beam

Interferometer

Detection

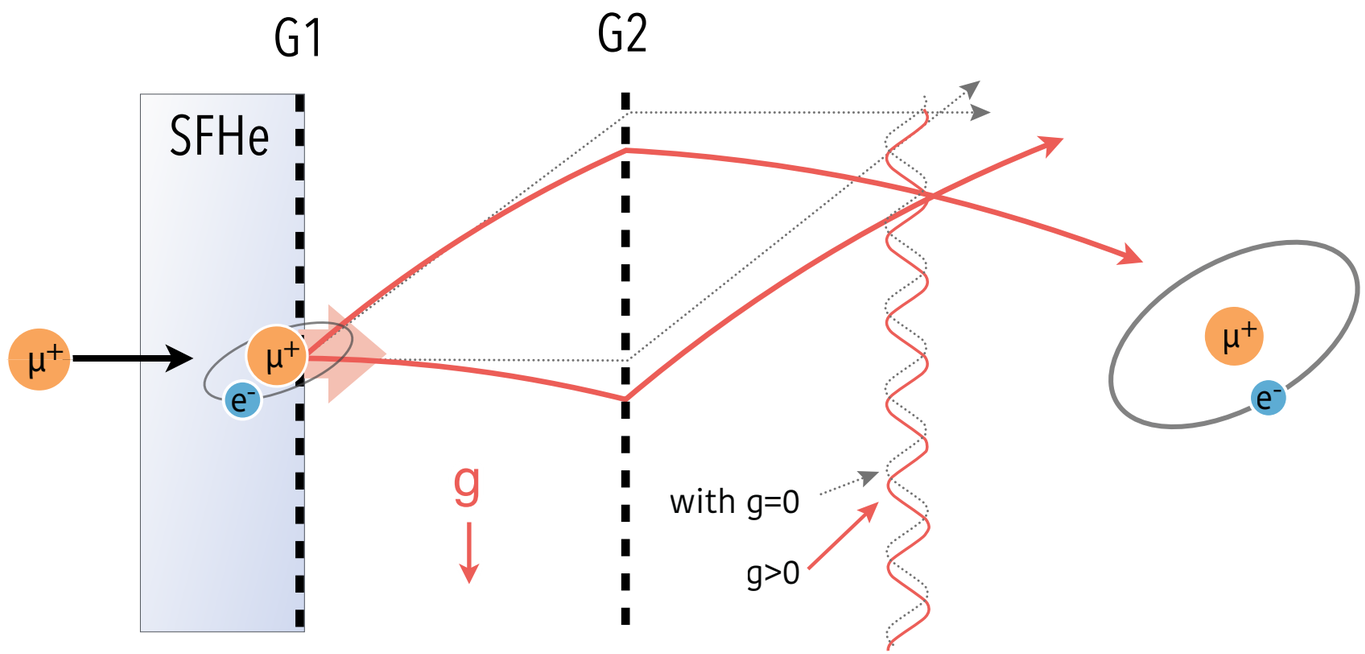


Overview of LEMING, and 2025 updates

Horizontal cold Mu beam

Interferometer

Detection

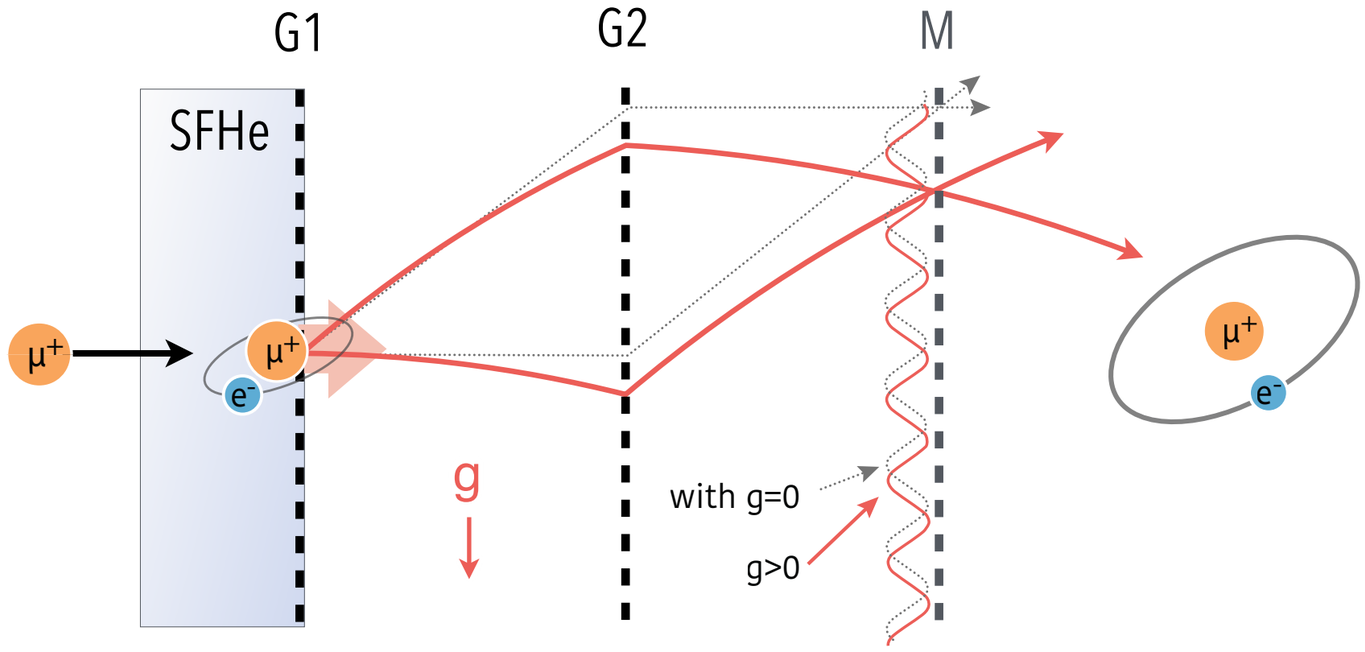


Overview of LEMING, and 2025 updates

Horizontal cold Mu beam

Interferometer

Detection

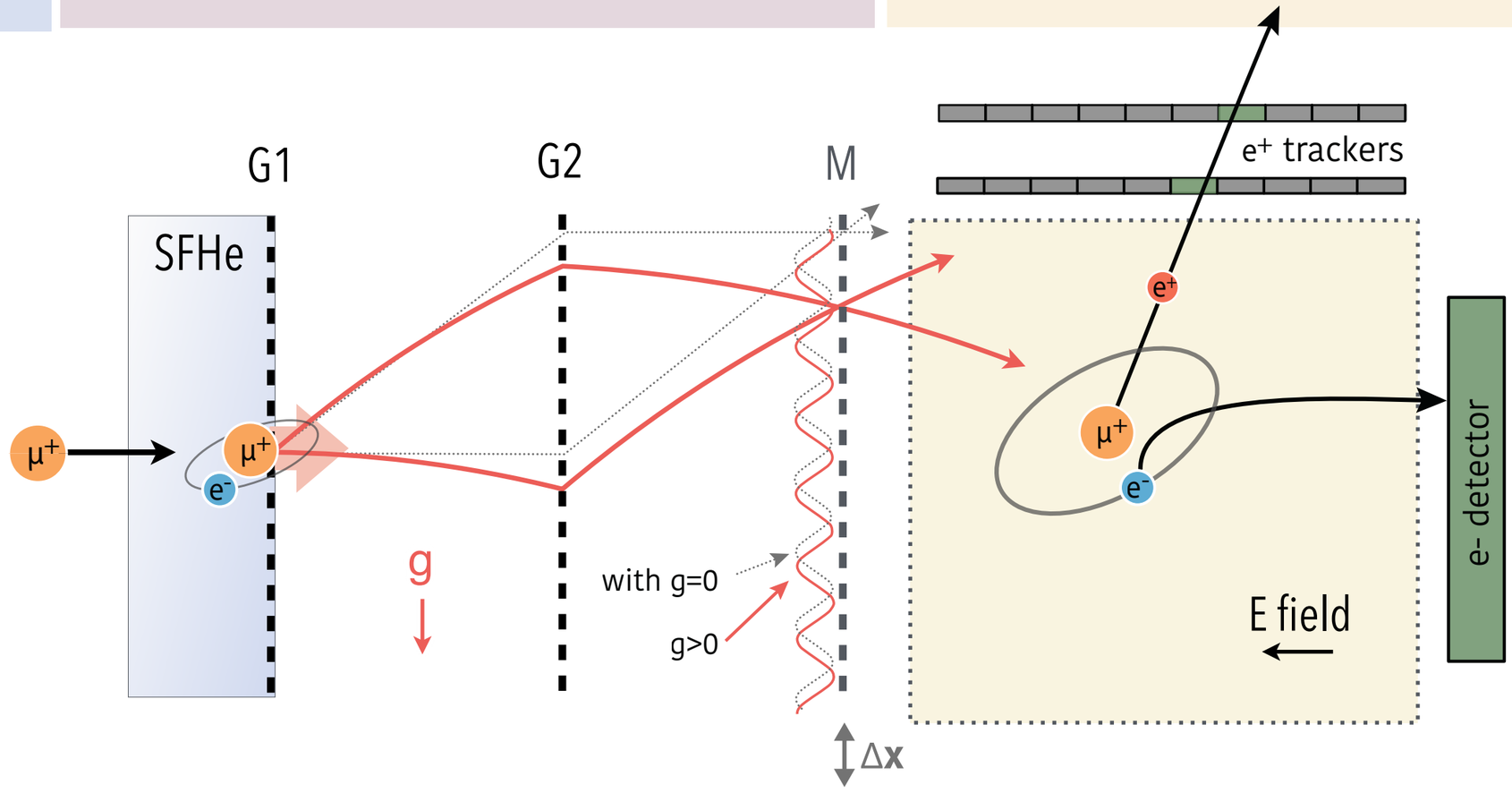


Overview of LEMING, and 2025 updates

Horizontal cold Mu beam

Interferometer

Detection



Overview of LEMING, and 2025 updates

Horizontal cold Mu beam

Interferometer

Detection

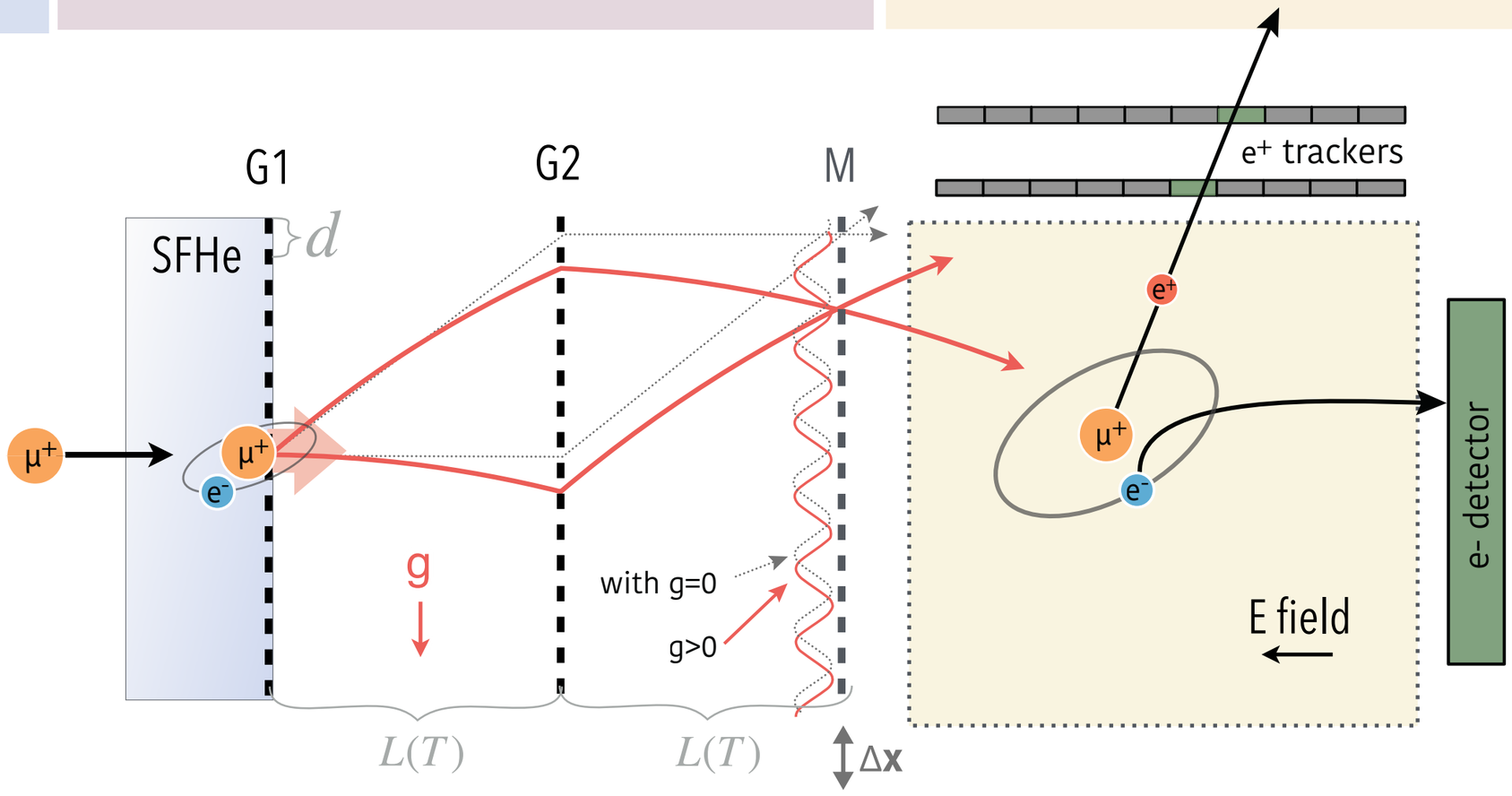
Sensitivity

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

$d = 100$ nm
$T \approx 4$ μs
$L \approx 10$ mm

~ 1% sensitivity

~100 days @ PiE5



Overview of LEMING, and 2025 updates

Horizontal cold Mu beam

- Microfluidic target with 1st grating integrated
- Emission from from micron-sized slits

Interferometer

Detection

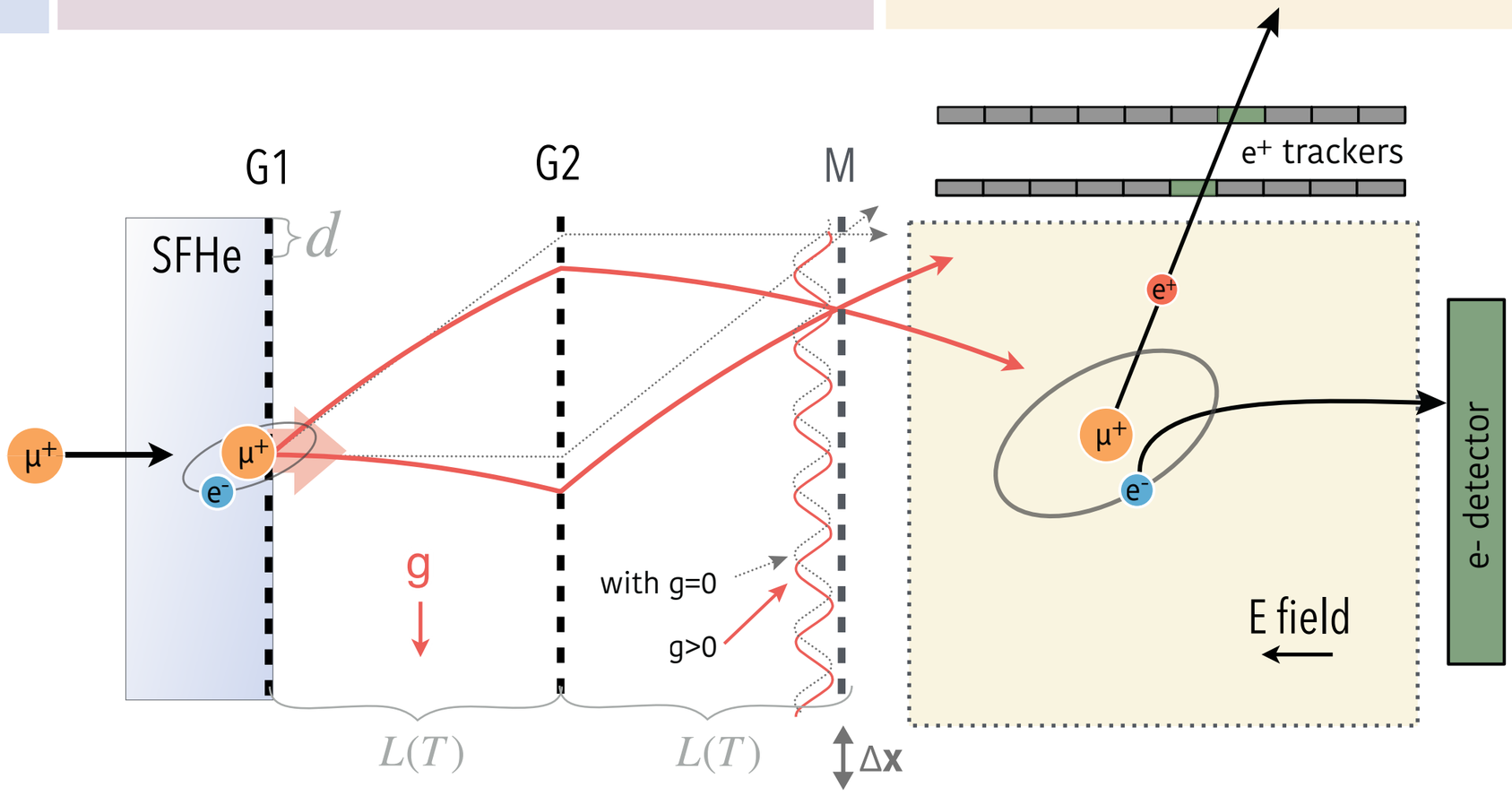
Sensitivity

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

$d = 100$ nm
$T \approx 4$ μs
$L \approx 10$ mm

~ 1% sensitivity

~100 days @ PiE5



Overview of LEMING, and 2025 updates

Horizontal cold Mu beam

- Microfluidic target with 1st grating integrated
- Emission from from micron-sized slits

Interferometer

- First cryogenic prototype for Talbot interferometry
- Below-nm displacement and vibration measurements

Detection

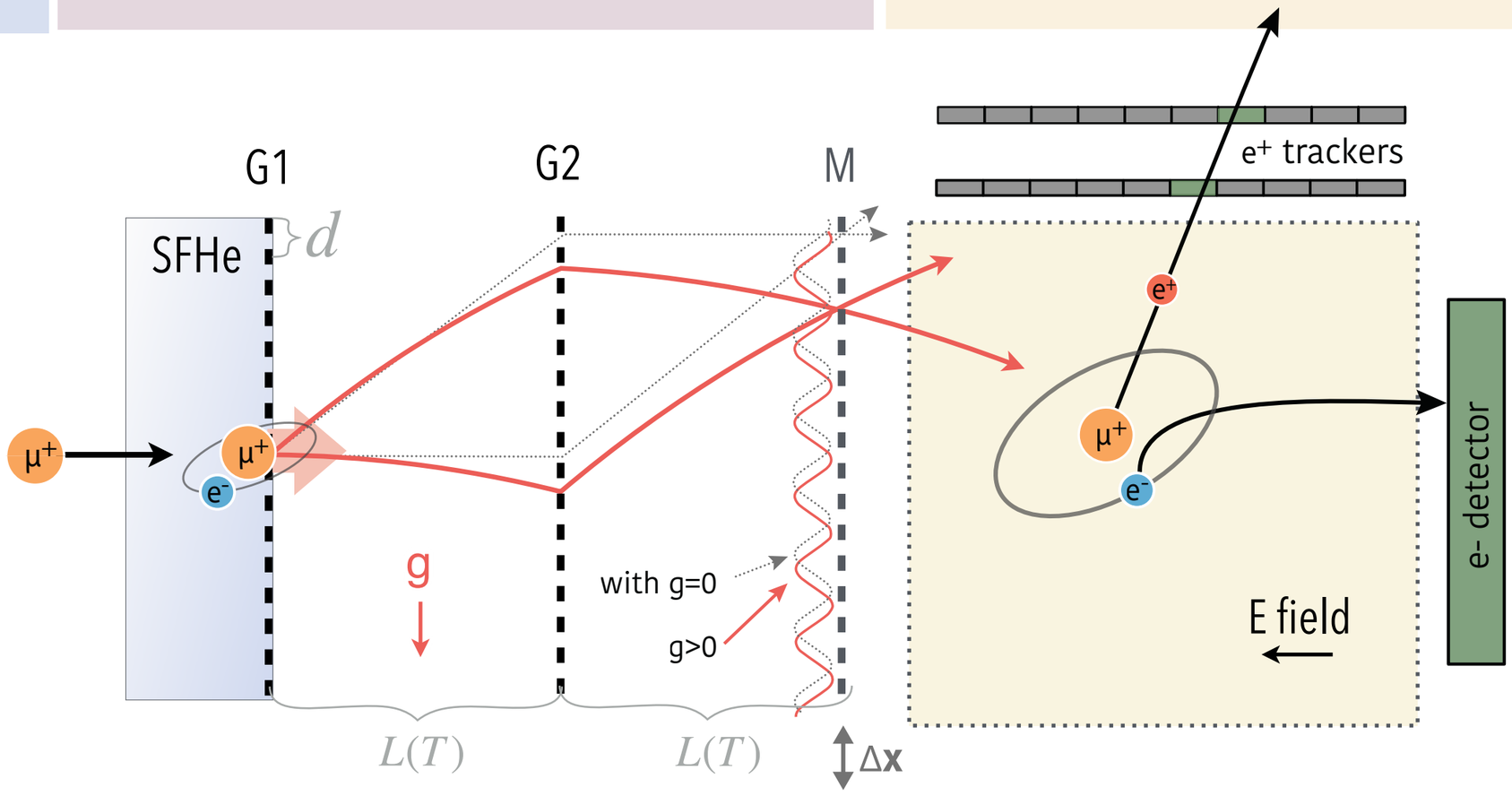
Sensitivity

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

$d = 100$ nm
$T \approx 4$ μs
$L \approx 10$ mm

~ 1% sensitivity

~100 days @ PiE5



Overview of LEMING, and 2025 updates

Horizontal cold Mu beam

- Microfluidic target with 1st grating integrated
- Emission from from micron-sized slits

Interferometer

- First cryogenic prototype for Talbot interferometry
- Below-nm displacement and vibration measurements

Detection

- Si strip detectors for e+ tracking
- Observation of below-keV e- < 100 mK

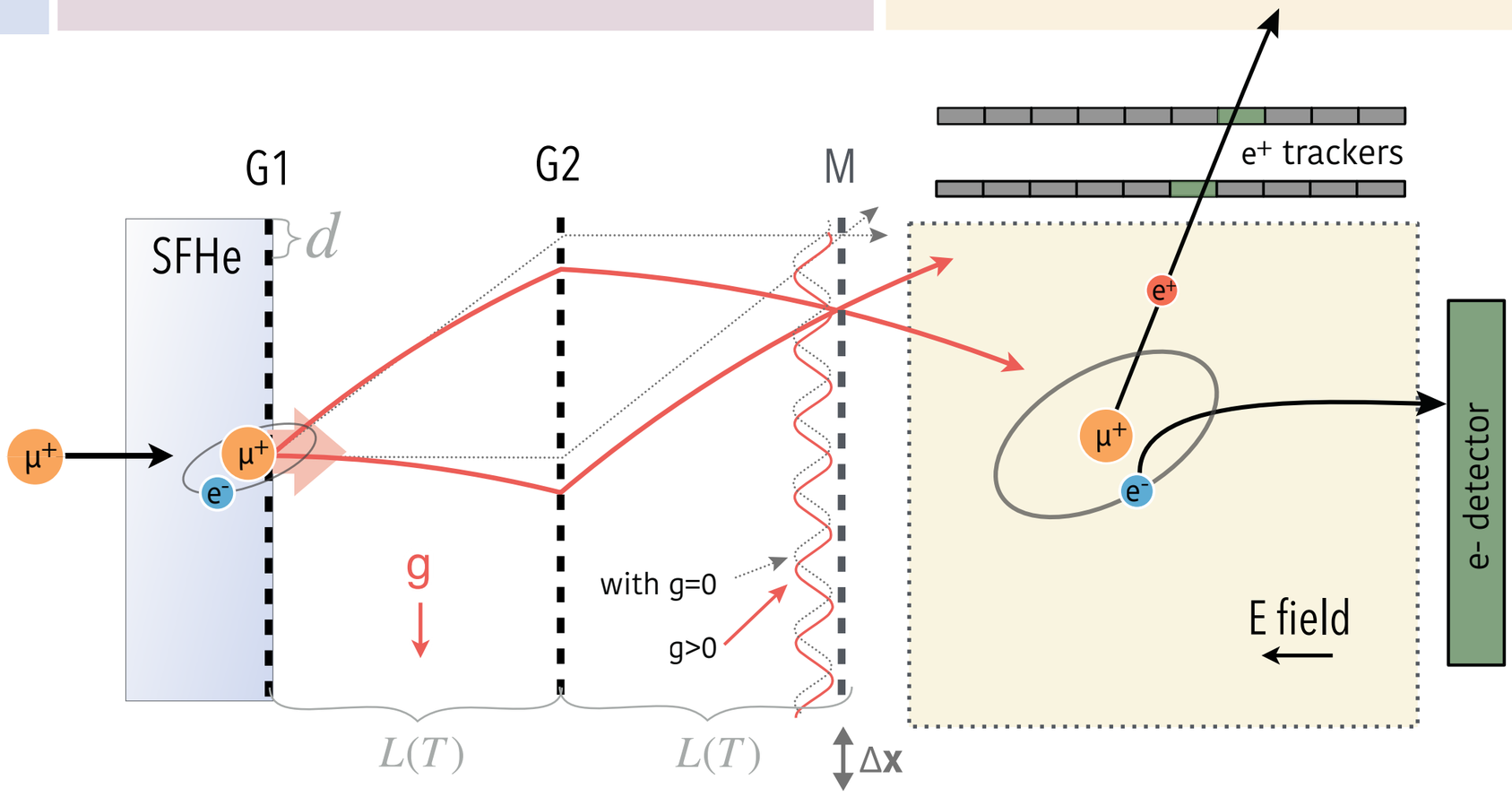
Sensitivity

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

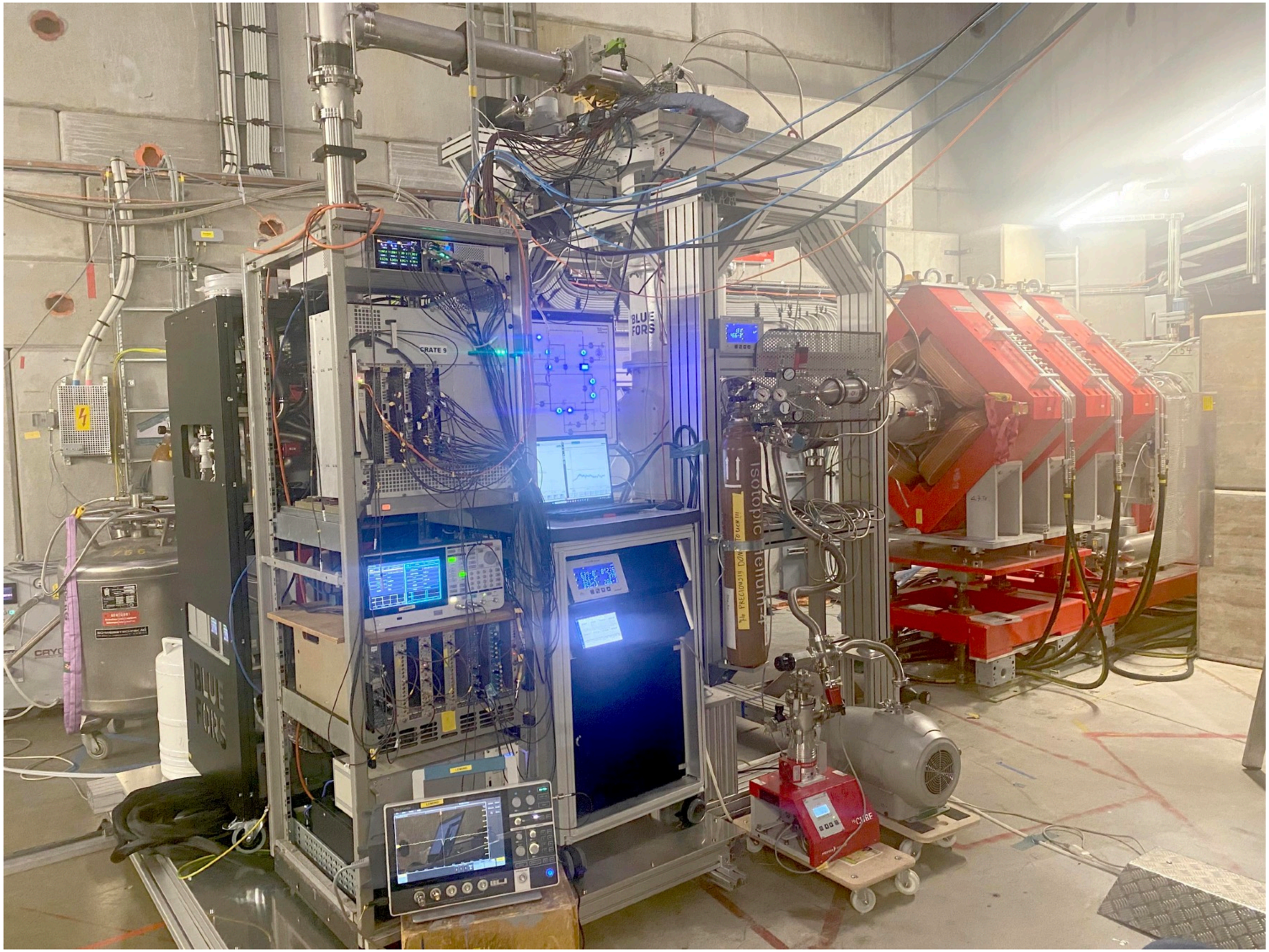
$d = 100$ nm
$T \approx 4$ μs
$L \approx 10$ mm

~ 1% sensitivity

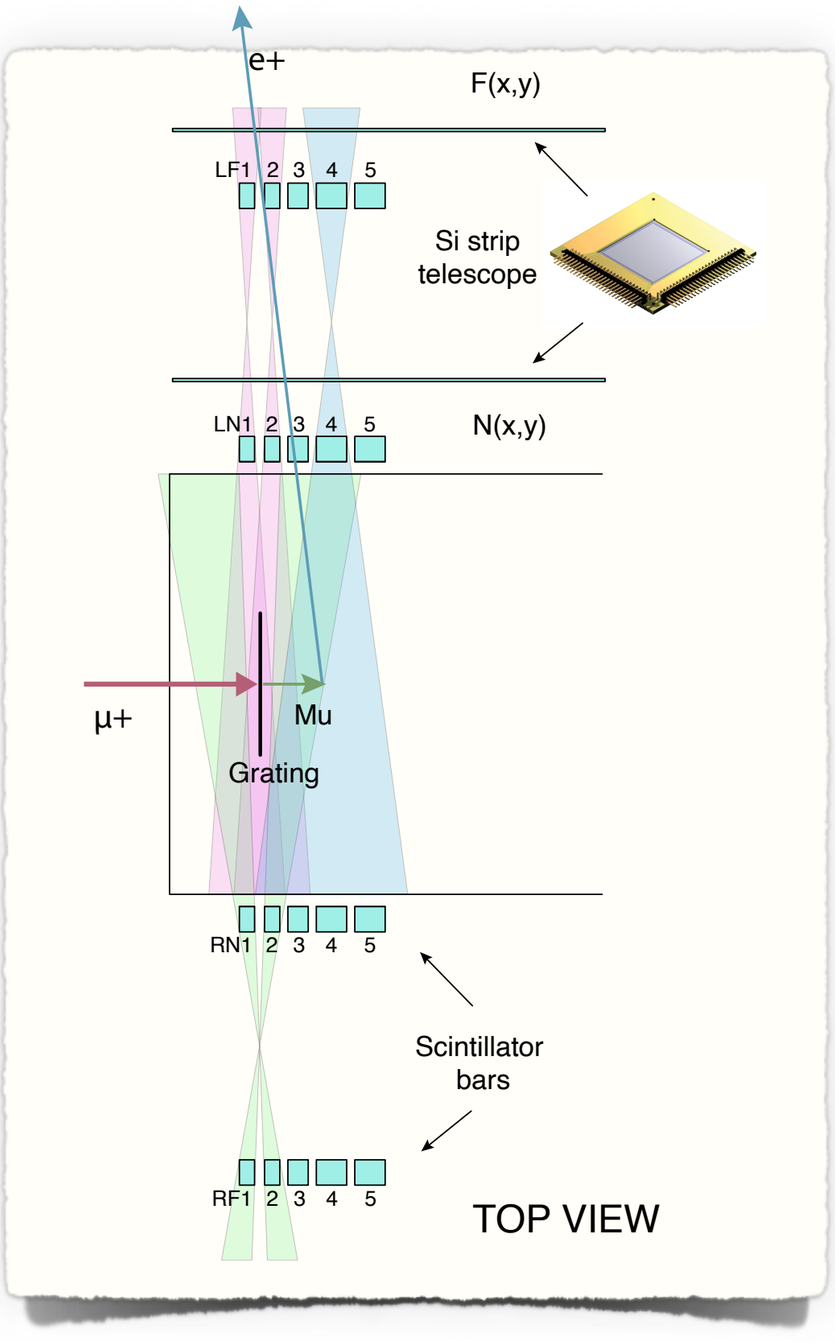
~100 days @ PiE5



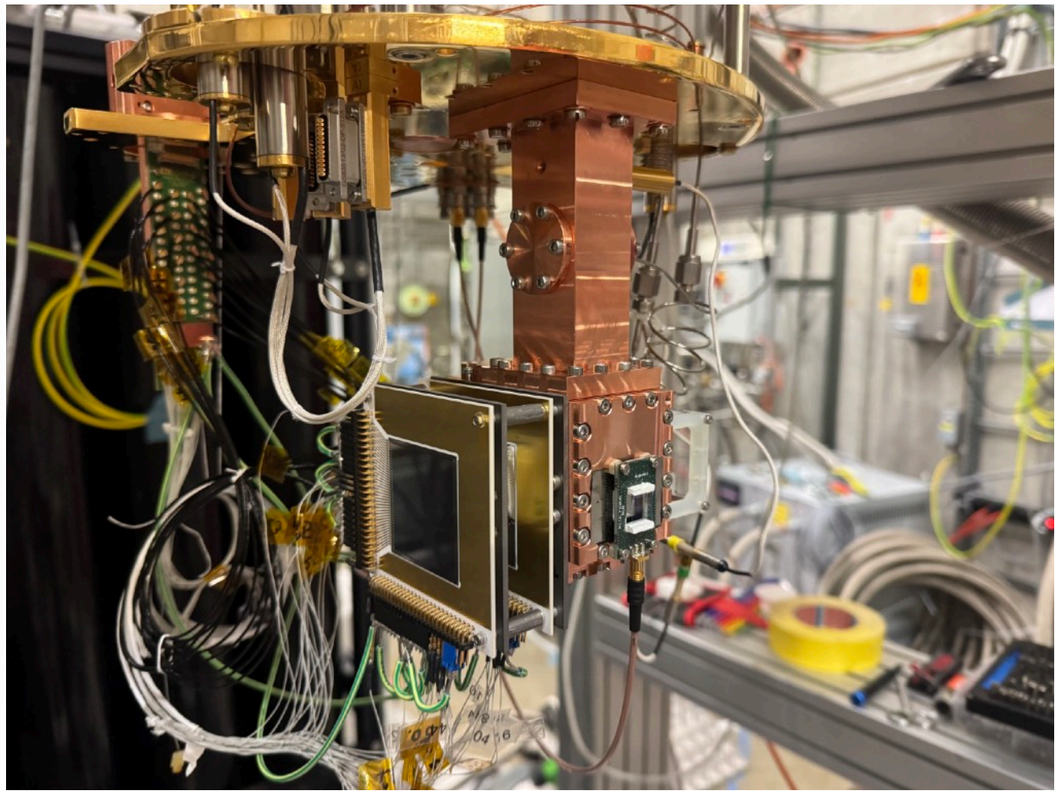
Setup in piE1

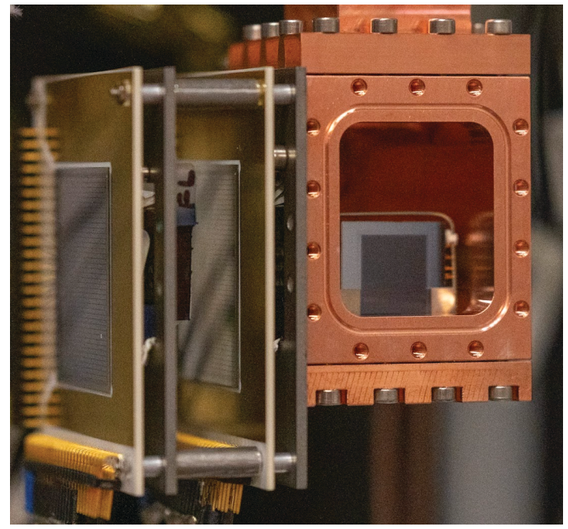


Setup 2024

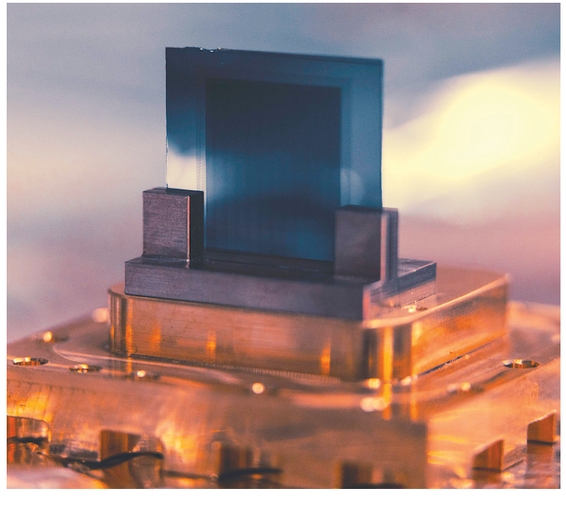


- New positron detectors: Si strip tracker detectors in a telescope configuration
- New microfluidic Mu converters with optical gratings

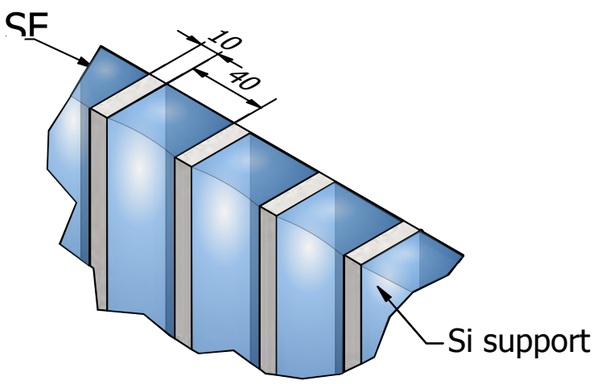


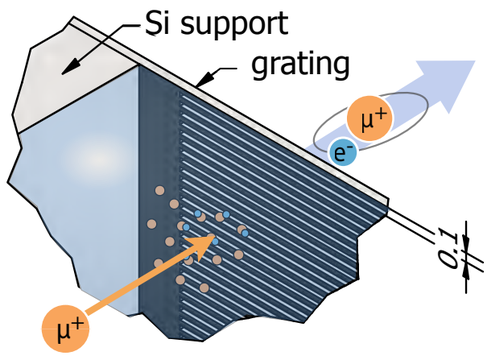


- Microfluidic source with grating

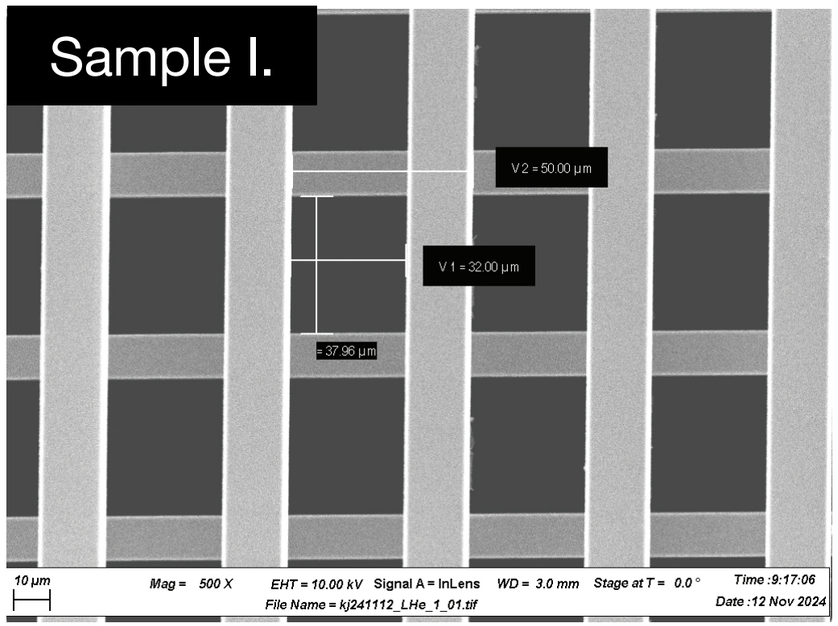


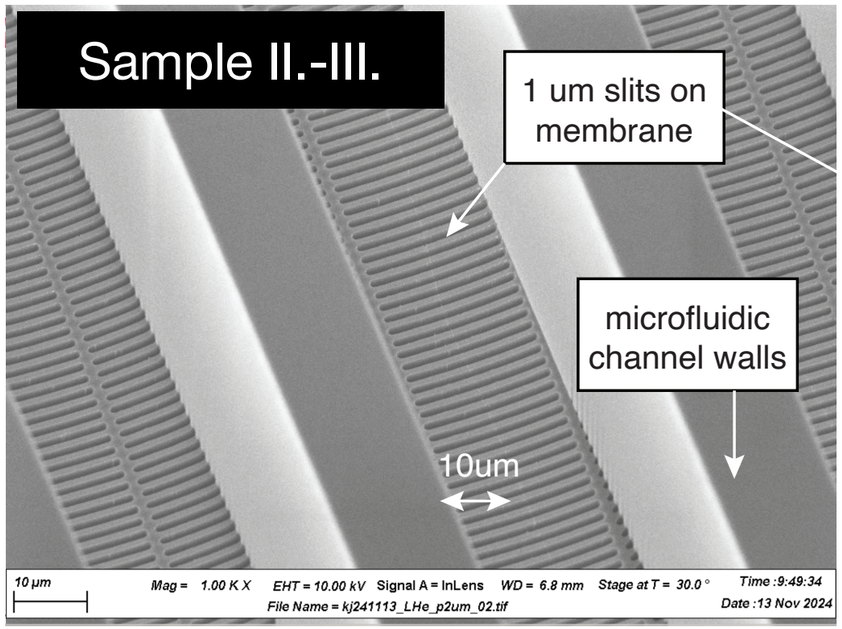
Microfluidic channels + 1 um gratings





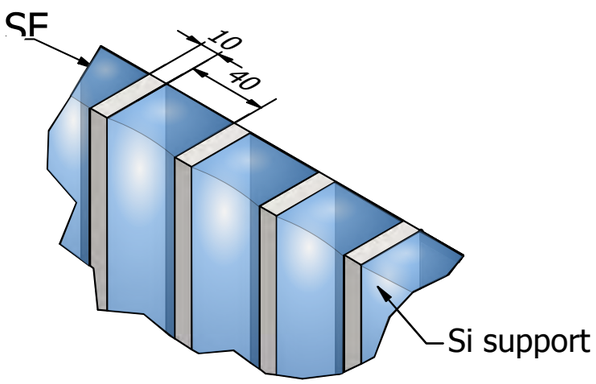
Gratings and photos
from K. Jefimovs @ PSI

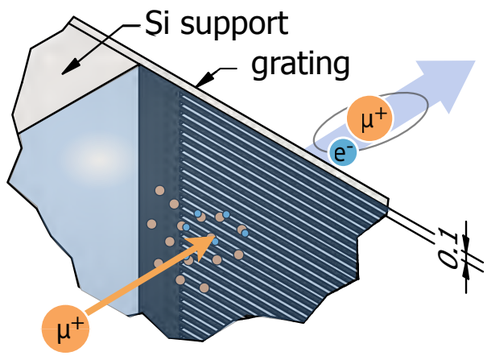




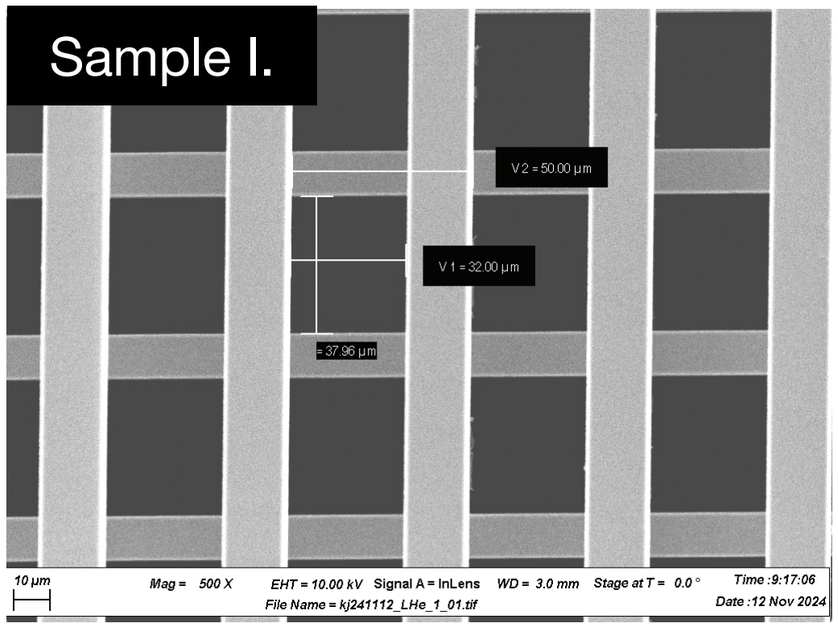
- Sample I: grating with large opened aperture (32x38 um)
- Sample II-III: First microfluidic structures with a $d = 2\ \mu\mathrm{m}$ grating for near field (Talbot) interferometry

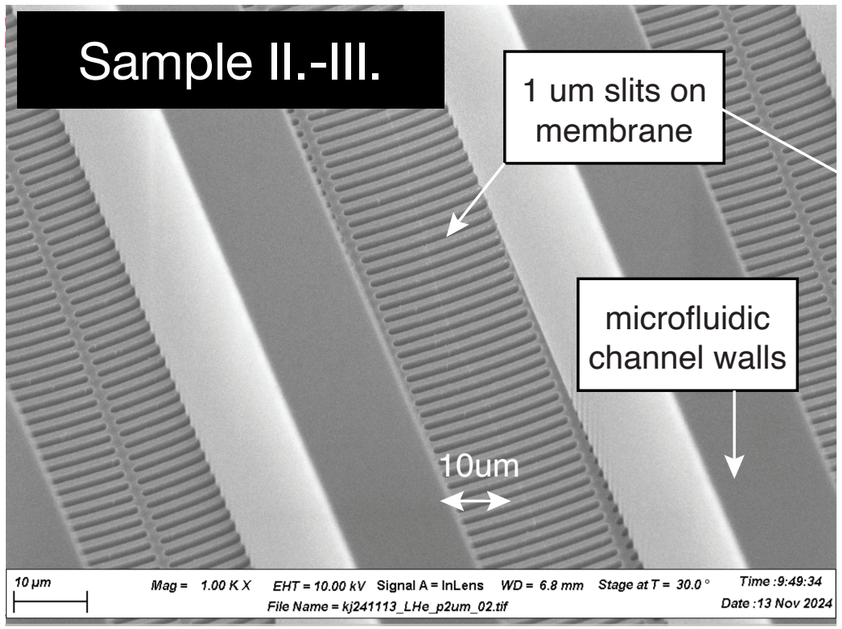
Microfluidic channels + 1 um gratings



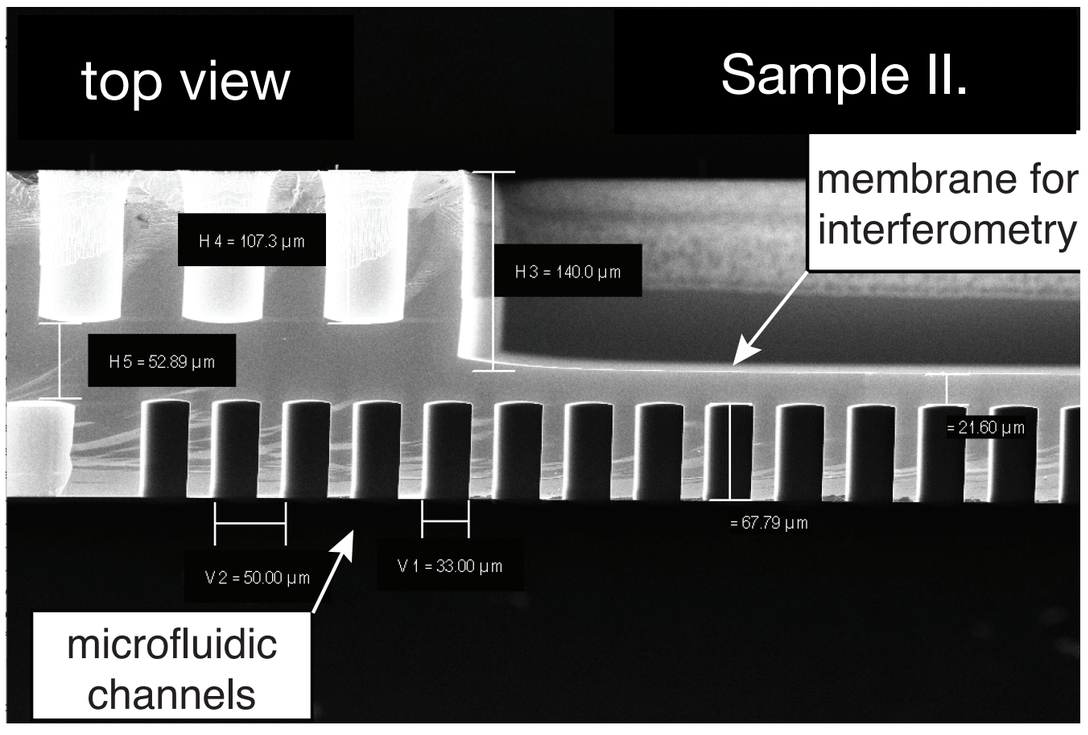


Gratings and photos
from K. Jefimovs @ PSI

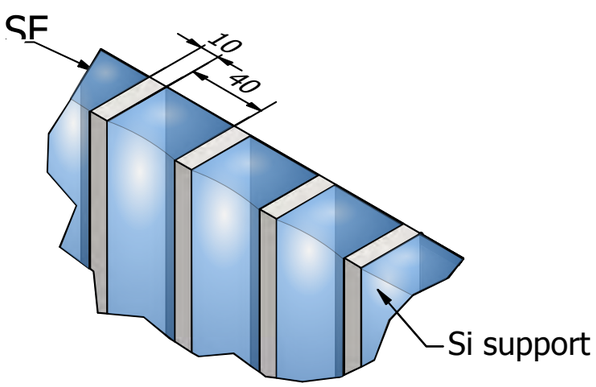


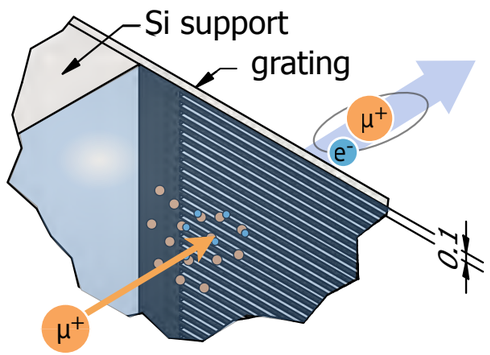


- Sample I: grating with large opened aperture (32x38 um)
- Sample II-III: First microfluidic structures with a $d = 2\ \mu\mathrm{m}$ grating for near field (Talbot) interferometry

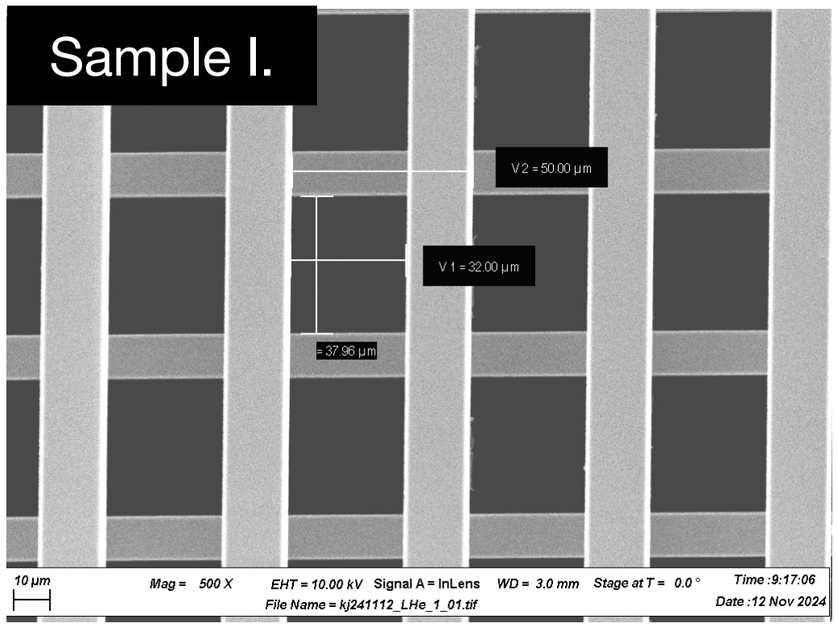


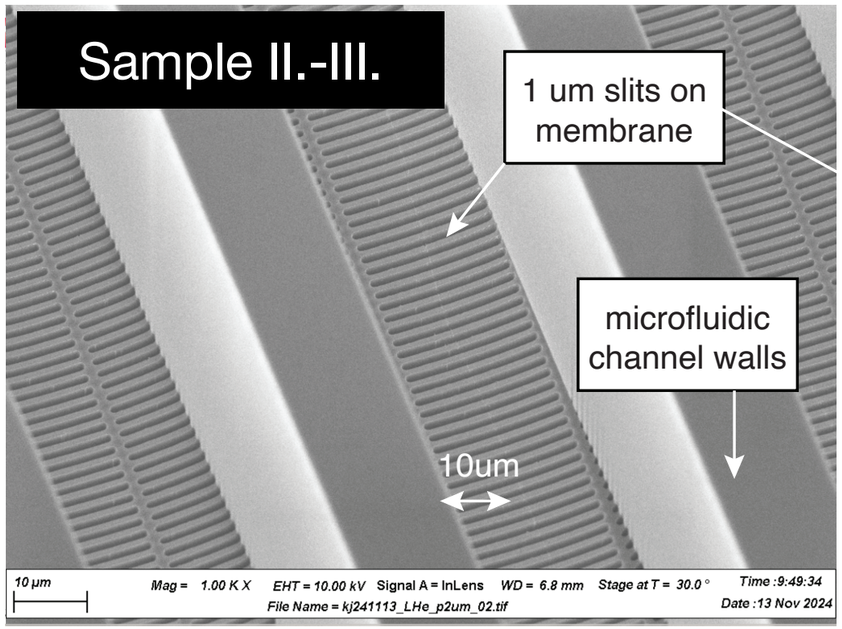
Microfluidic channels + 1 um gratings



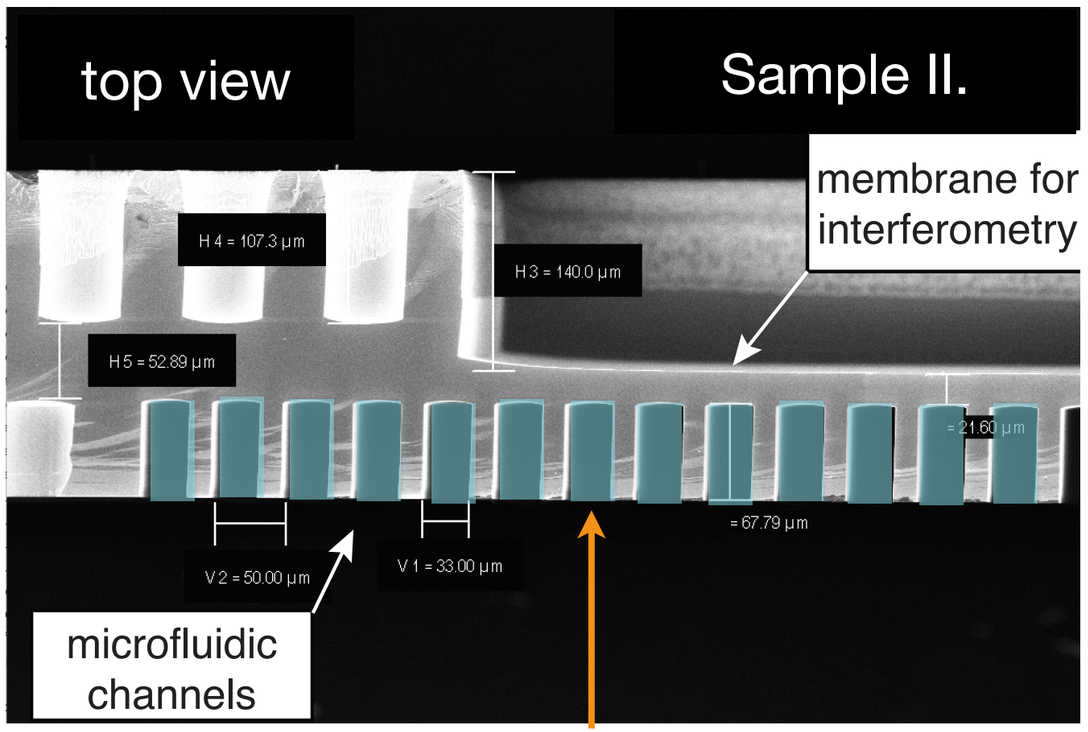


Gratings and photos
from K. Jefimovs @ PSI



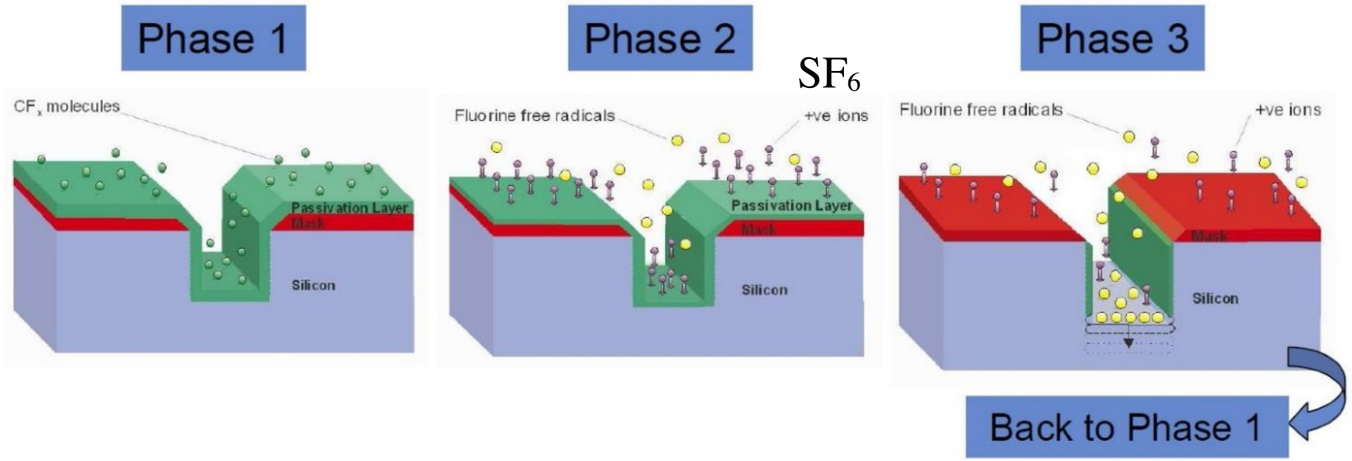


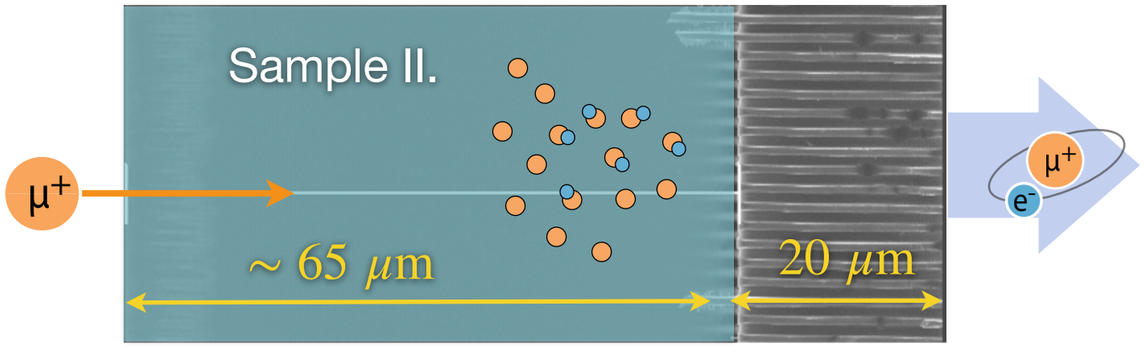
- Sample I: grating with large opened aperture (32x38 um)
- Sample II-III: First microfluidic structures with a $d = 2\ \mu\mathrm{m}$ grating for near field (Talbot) interferometry

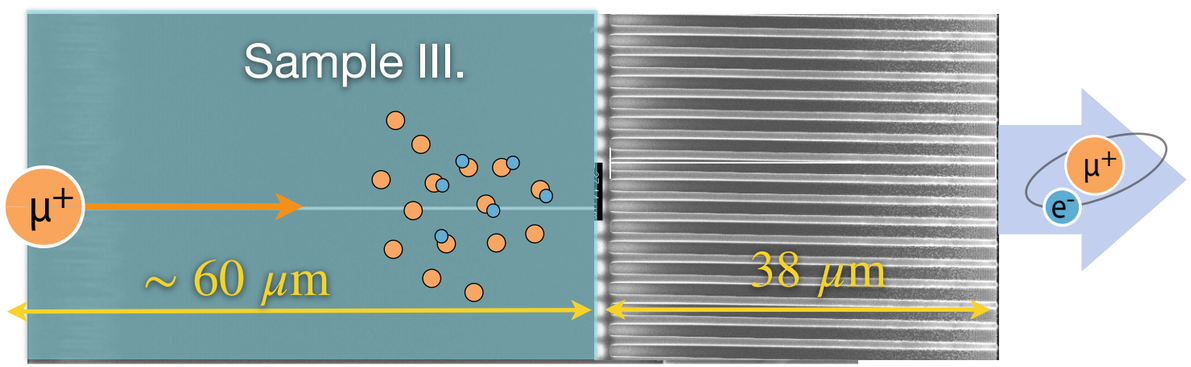


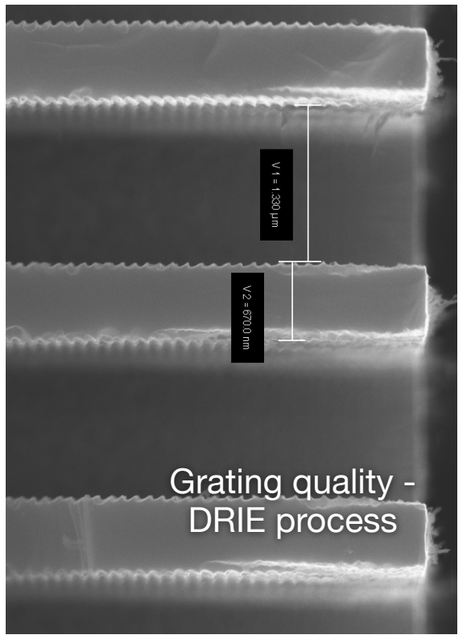
Microfluidic channels + 1 um gratings

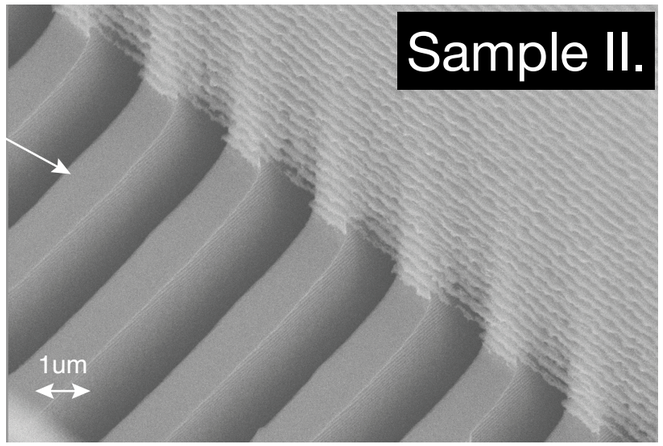
- Patterning with electron beam or laser
- Deep reactive-ion etching (DRIE)
- Difficulties controlling the Si membrane thickness (20- 40 um)
- Known steps for improvement





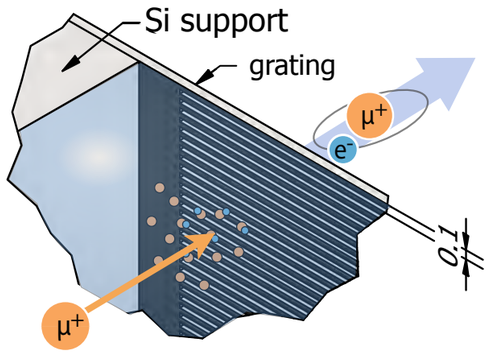




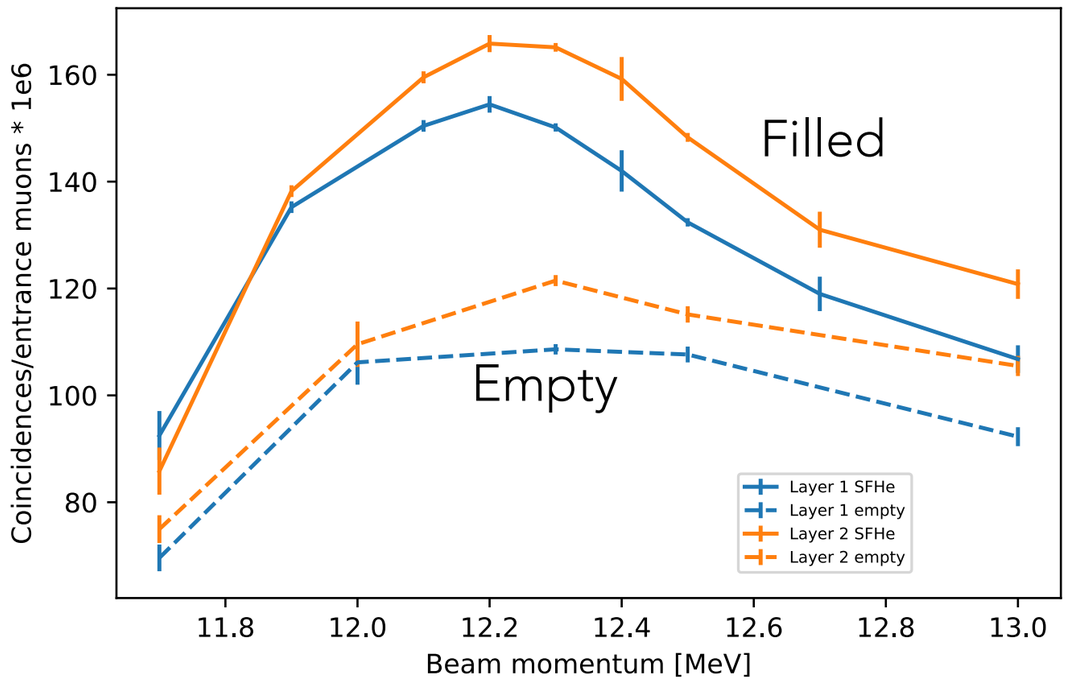


Gratings and photos from K. Jefimovs @ PSI

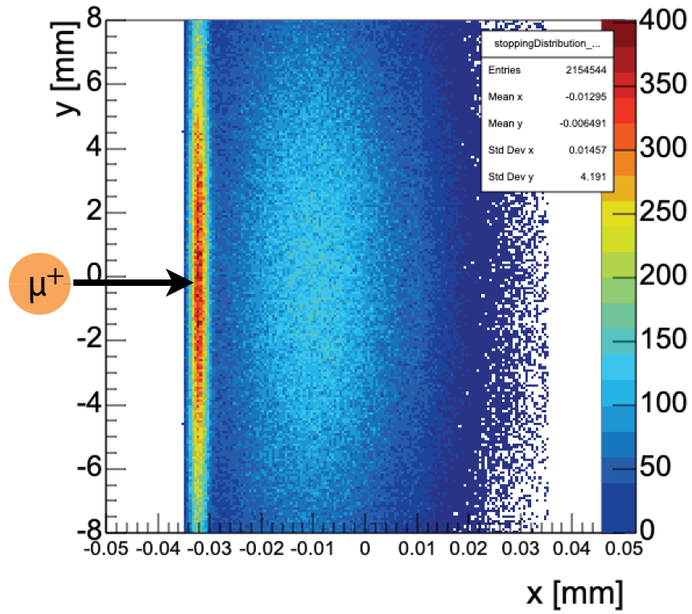
Microfluidic source - ranging



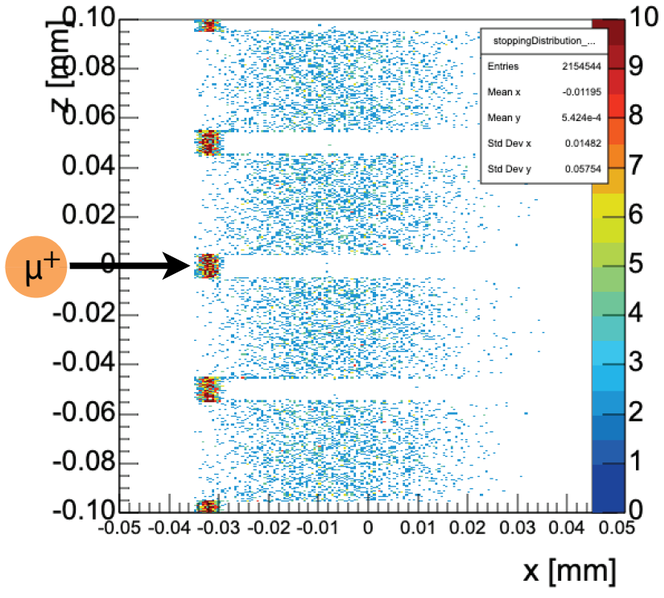
Measurement - stopping in grating



Stopping simulation in grating



Top view zoomed

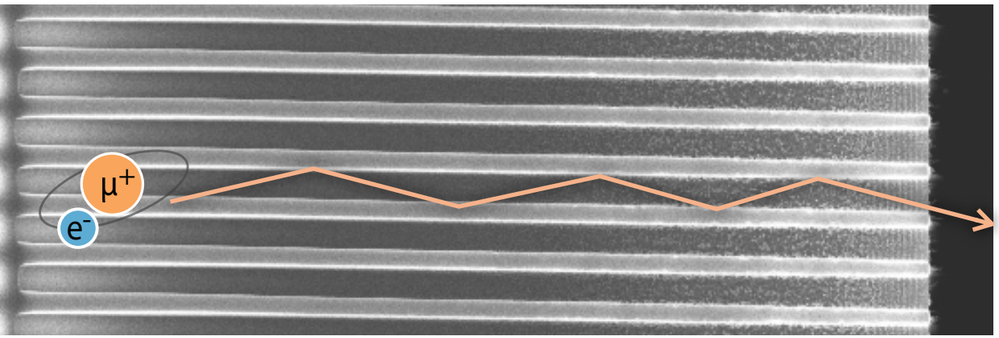


- Beamline is ~0.3 MeV/c off
- Ranging indicates we could tolerate more SFHe
- Design can be optimized on: trench depth, stopping close to the surface
- ~100 nm SiN membrane in front as degrader,
- double the trench width

Emission from micron-sized gratings

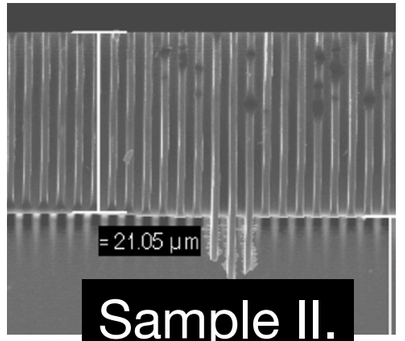
- Emission indicates Mu can travel trough long channels and bounce back from Si

$$z_0 = 20 - 40\ \mu\text{m}$$

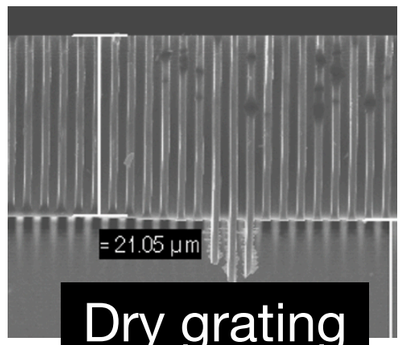


- Decrease in emitter Mu in Sample I. vs II. (~60%) can be explained with the restricted aperture alone
- Long channels increase diffusion time (lifetime loss)

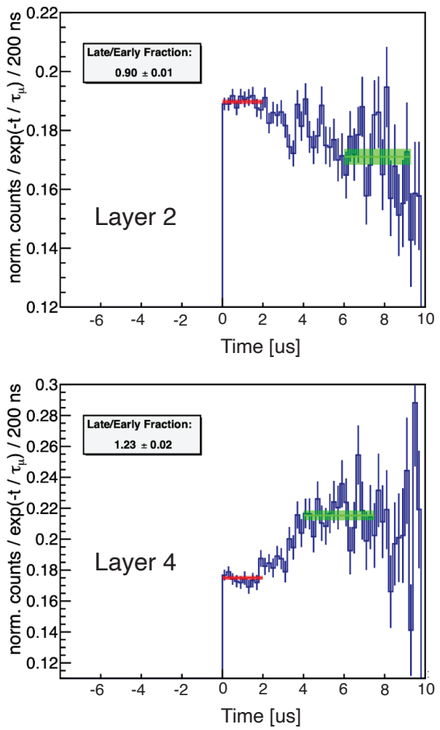
Sample I. + SFHe

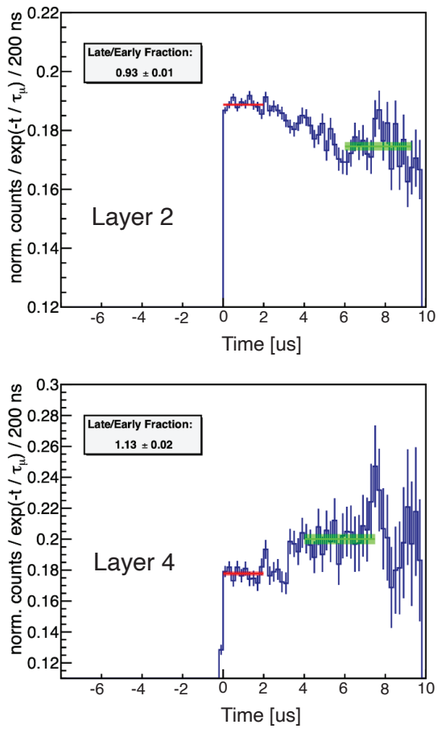


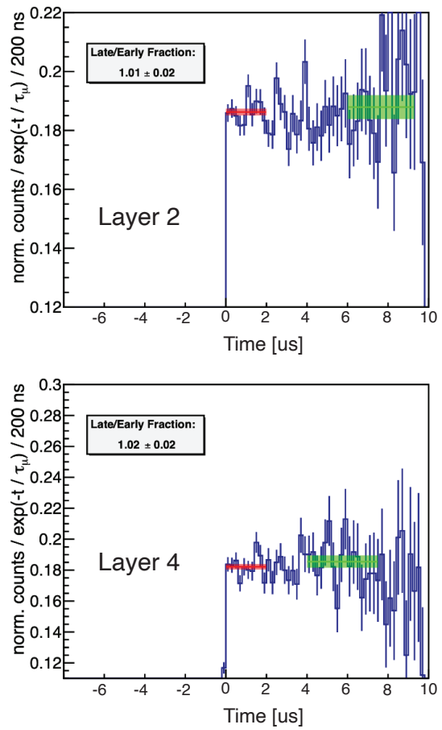
Sample II. + SFHe



Dry grating (no SFHe)



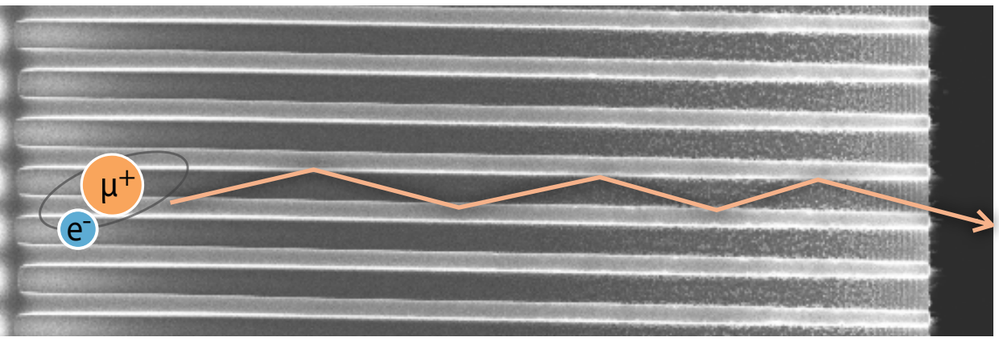




Emission from micron-sized gratings

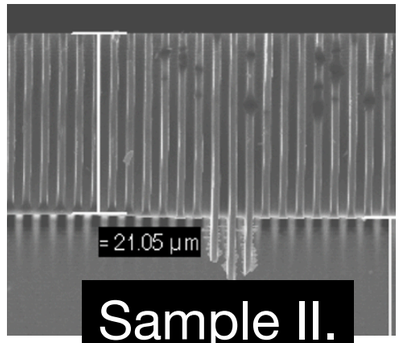
- Emission indicates Mu can travel trough long channels and bounce back from Si

$z_0 = 20 - 40\ \mu\mathrm{m}$

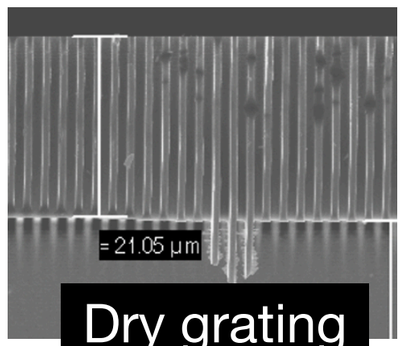


- Decrease in emitter Mu in Sample I. vs II. (~60%) can be explained with the restricted aperture alone
- Long channels increase diffusion time (lifetime loss)

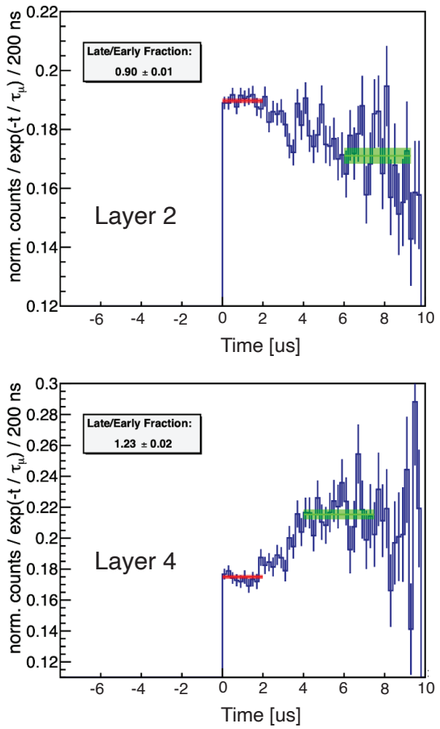
Sample I. + SFHe

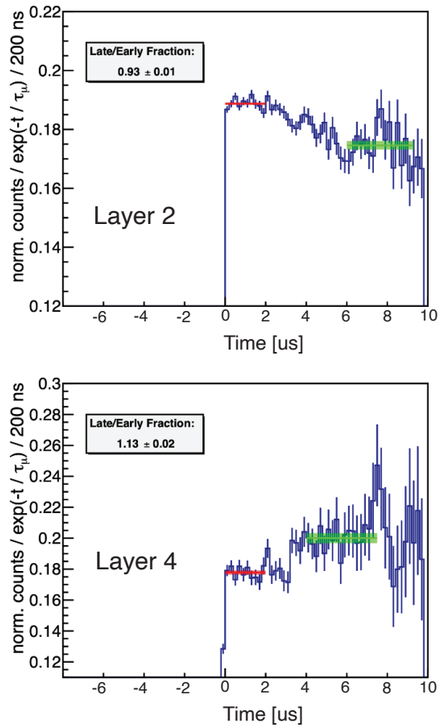


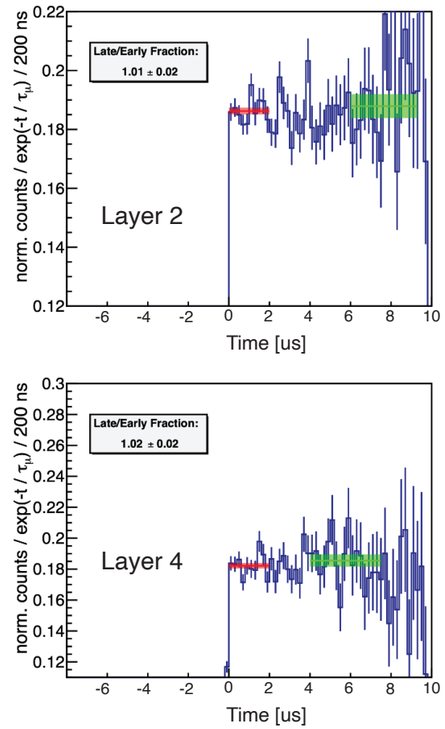
Sample II. + SFHe



Dry grating (no SFHe)



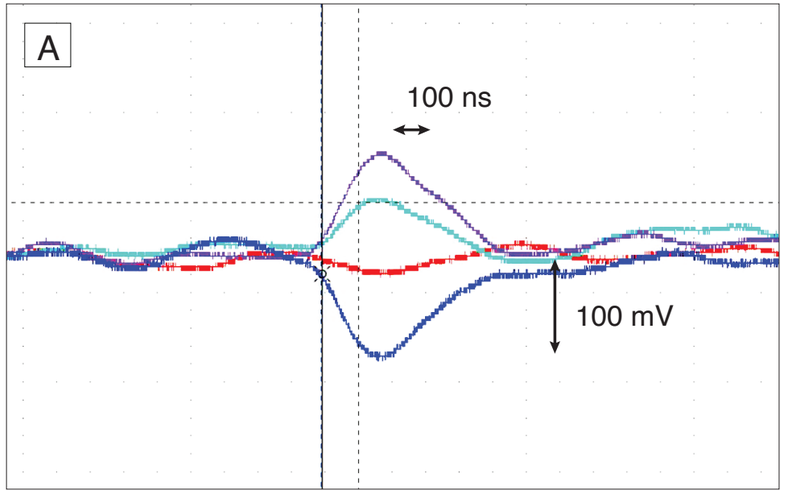


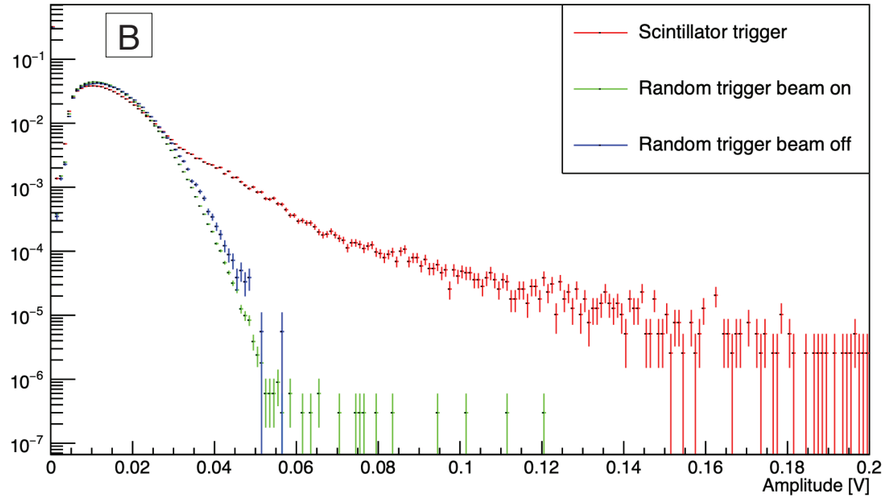


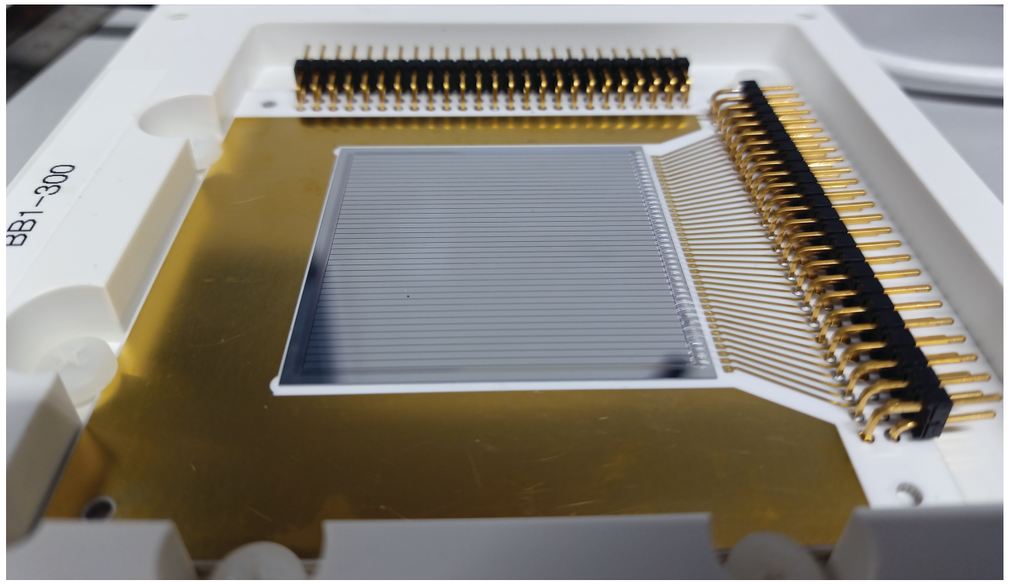
In 2025: $z_0 < 10\ \mu\mathrm{m}$ and microfluidic channel optimization ➡ attempt to Mu interferometry

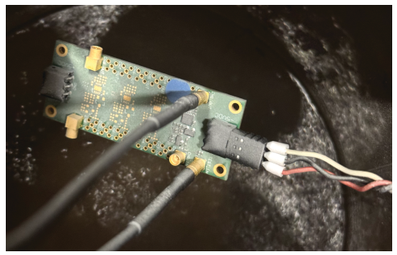
Si strip detector observing positrons at < 100 mK

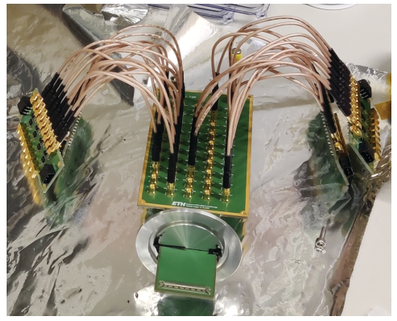
- Double-sided strips, 40x1 mm
- 32 channel (of 120) connected (no pysics run)
- Preamplifiers cooled to intermediate T
- Observed Michels at 60 mK temperatures, but with low (8% efficiency)

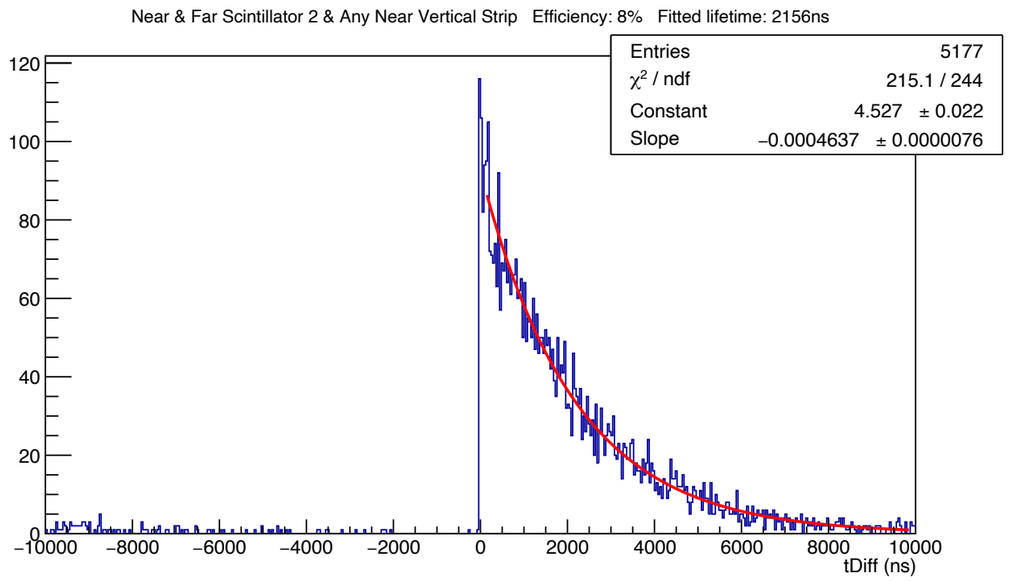






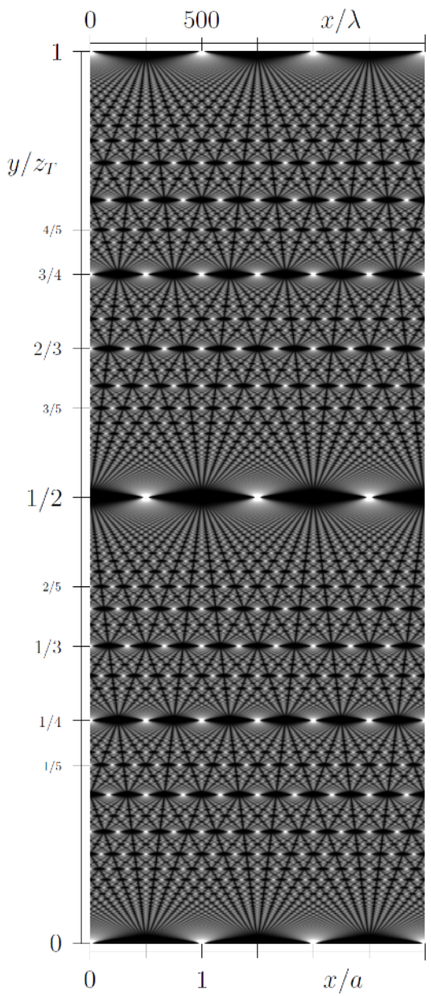


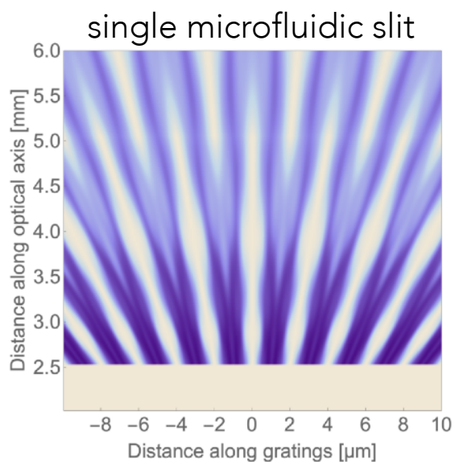


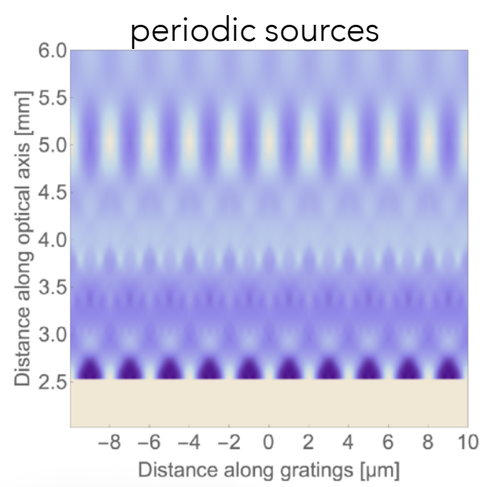


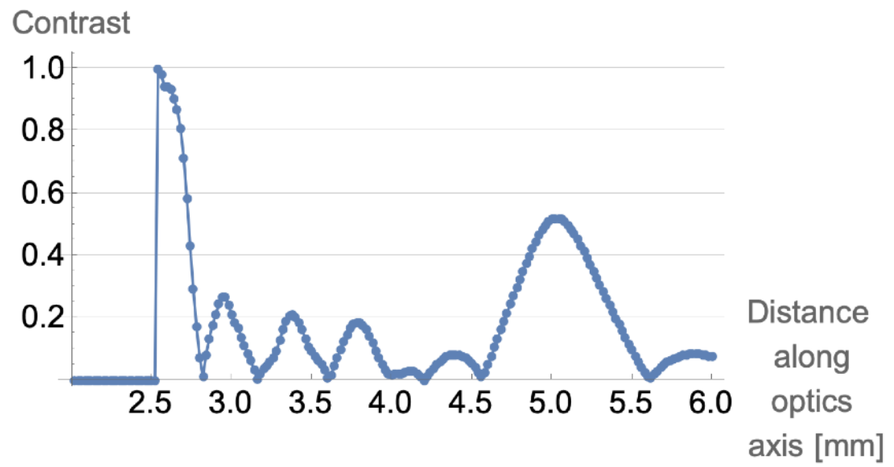
Design of the first Mu interferometer

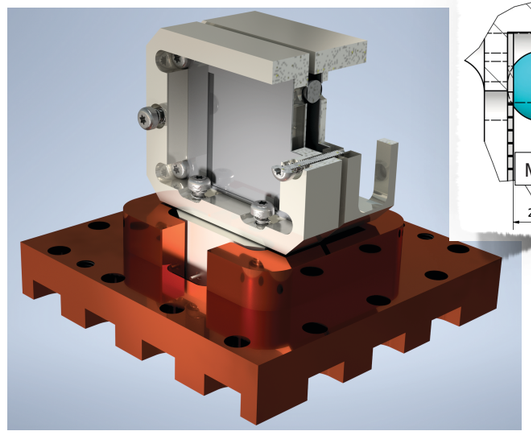
- With $d = 2\ \mu\mathrm{m}$, the Talbot-length of Mu is on the ~ 5 mm scale.
- Setup is optimized for the 1/2 Talbot lenght, with an expected contrast of 0.5
- No contrast from Moire-fringes (classical shadow) with a=0.5

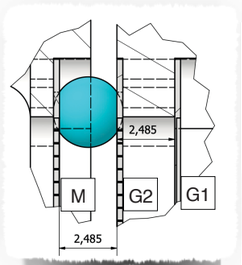


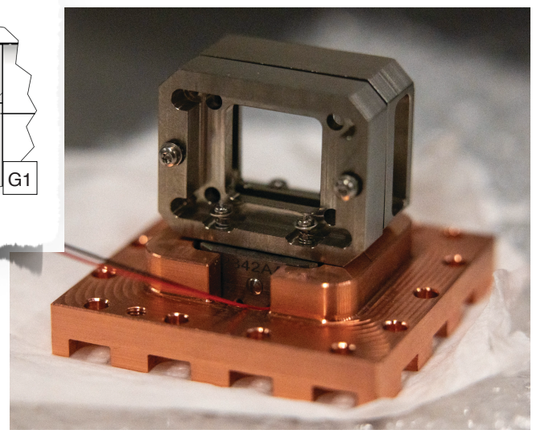








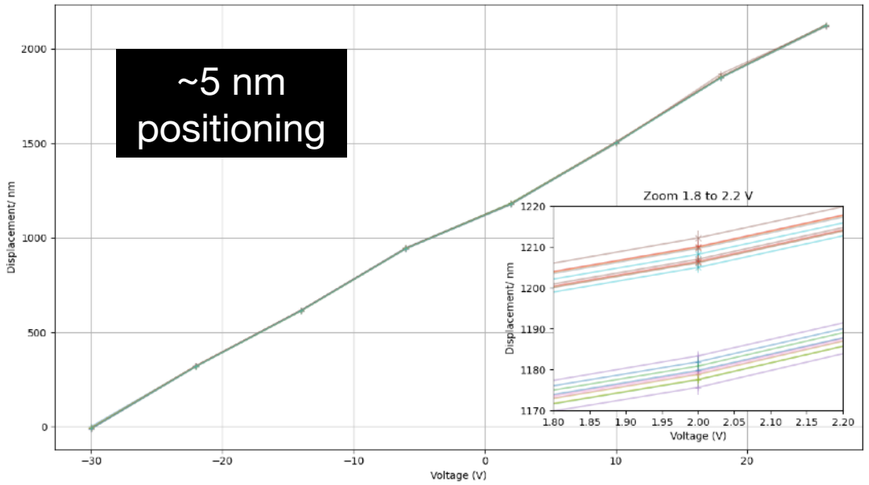


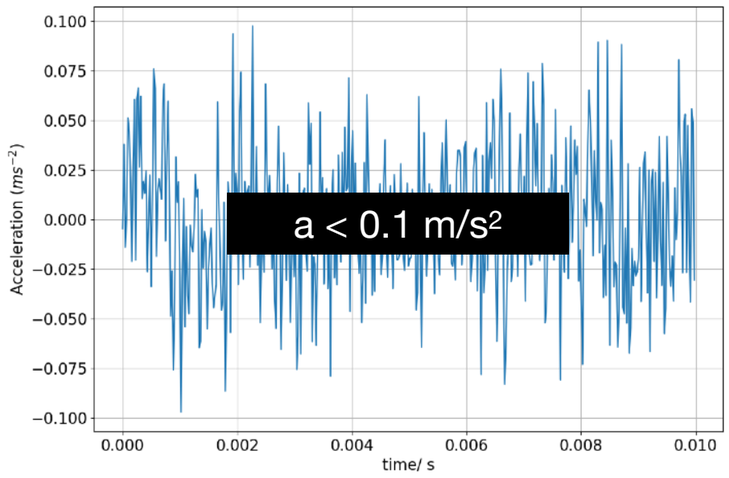


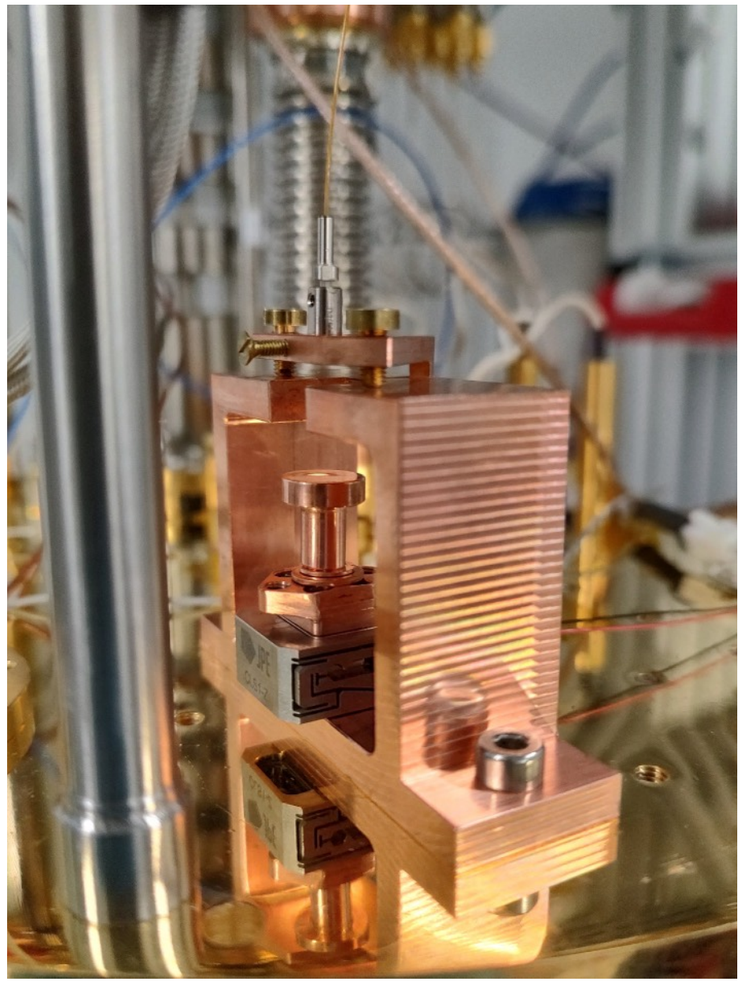
- Self-aligning design on the um scale, based on pivoting and guiding around um-precise Si balls

Study of nanopositioning and vibrations

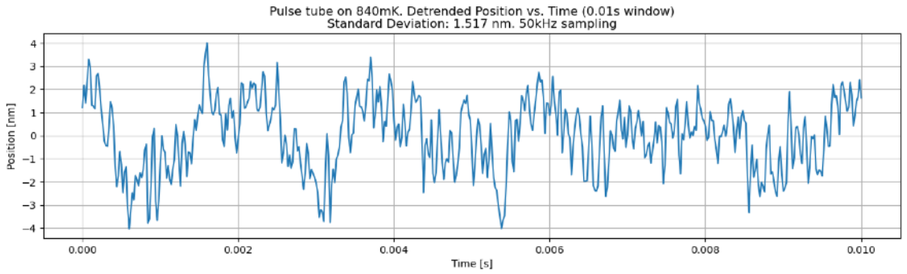
- Cryogenic Fabry-Perot probe, measuring relative displacements on a pm-scale
- Vertical piezo stage, with ~30 nm hysteresis, and < 5 nm reproducibility on the full 2 um range
- Accelerometers operated in the cryostat

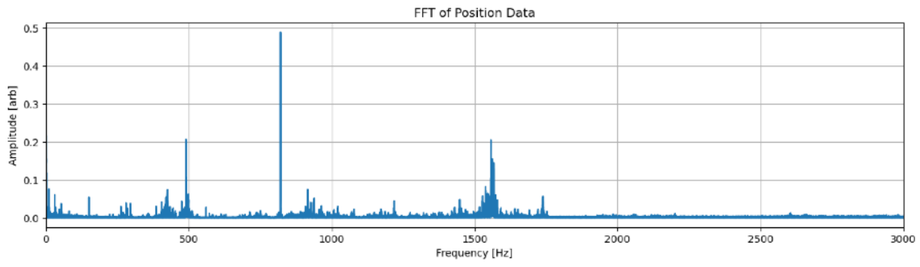






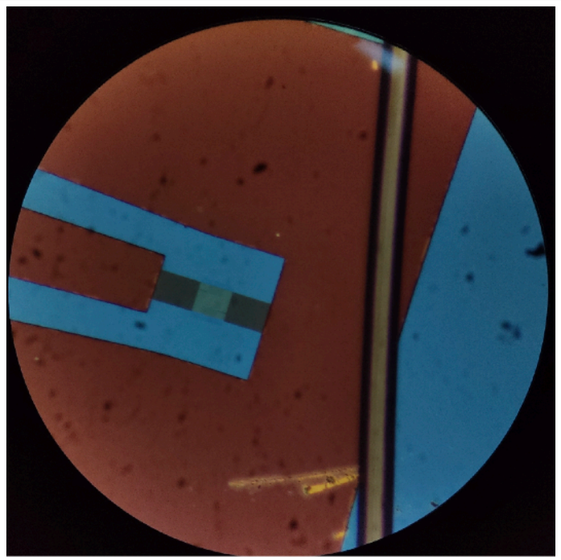
PT on measurements
-still acceptable for 1st interferometry

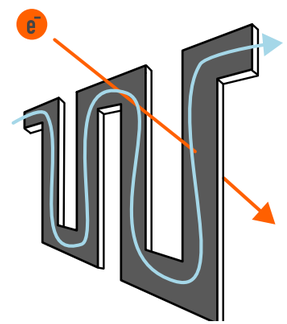


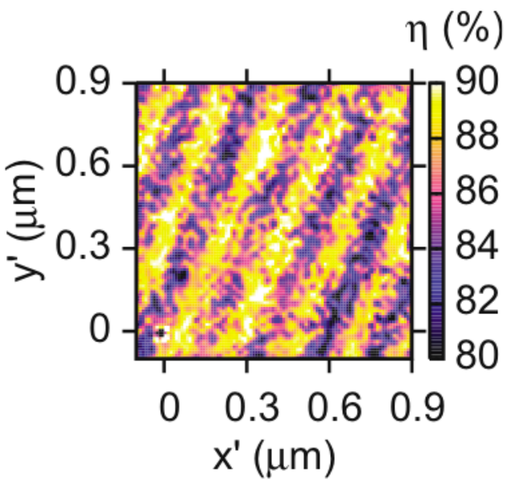


Below 1 keV electron detection

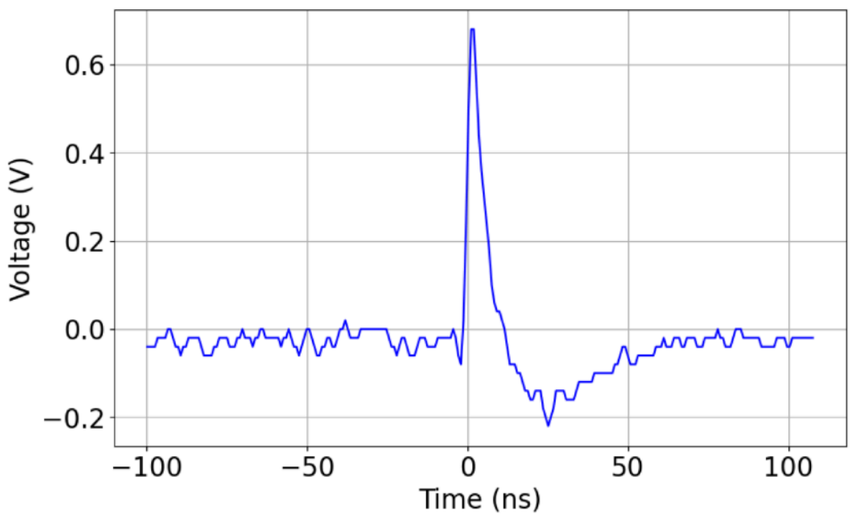
- Continuing issues with HV electrodes
- Meandering (nanoscopic) superconductive wires on a Si substrate, operated close to the critical currents
- Limited size $16 \times 16\ \mu\mathrm{m}^2$
- Improvements on the way, constant discussions with the company

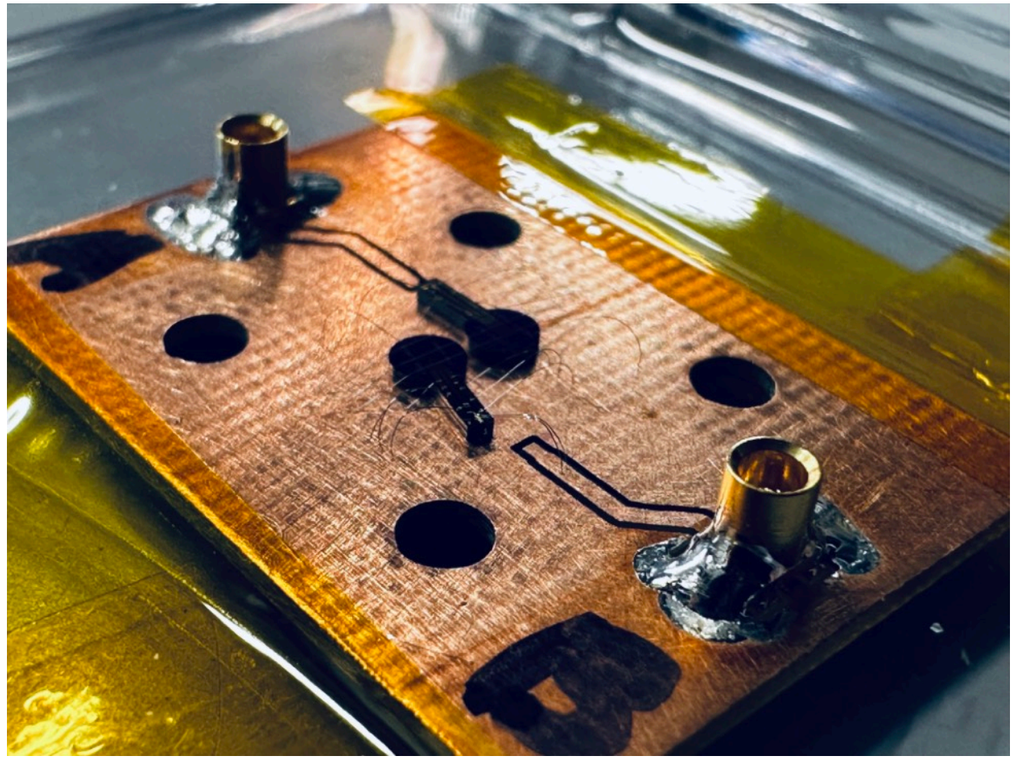






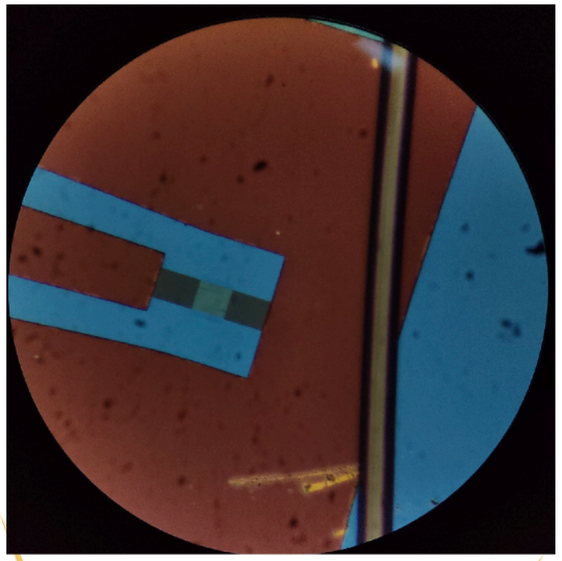
Detection efficiency of SCNW for single electrons (30 keV) from [M. Rosticher *et al.*, Appl. Phys. Lett. **97,** 18 (2010)]

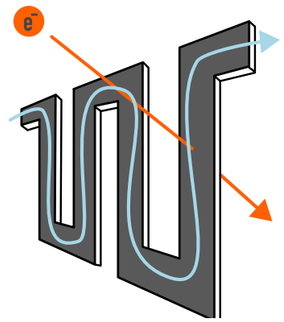


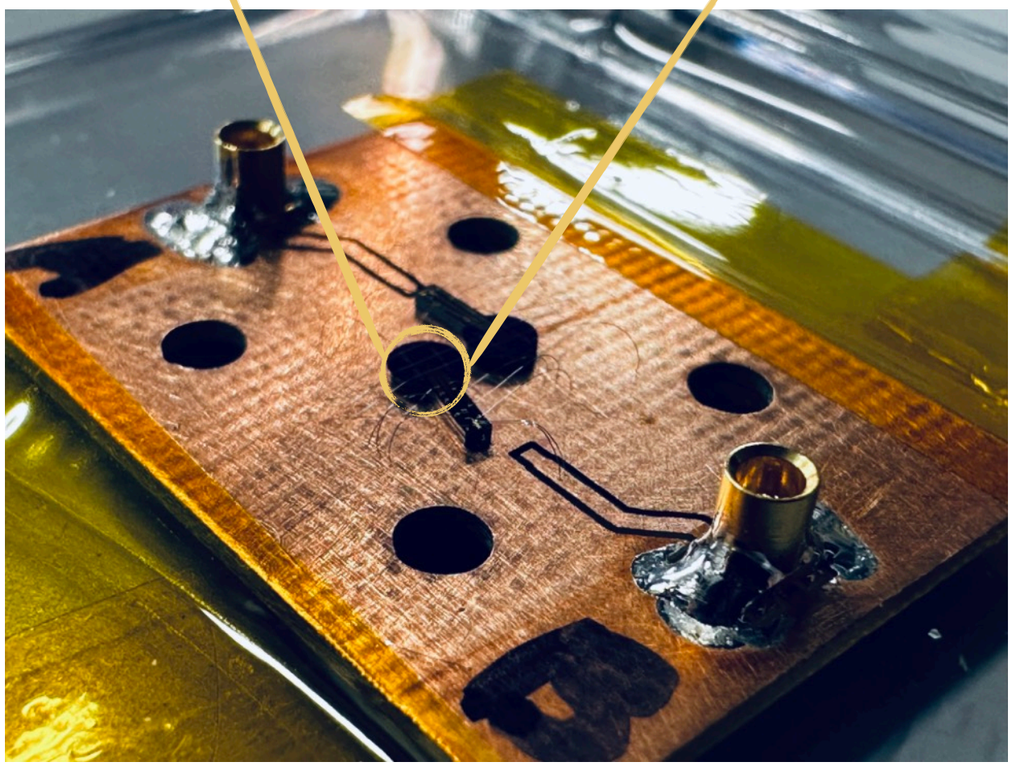


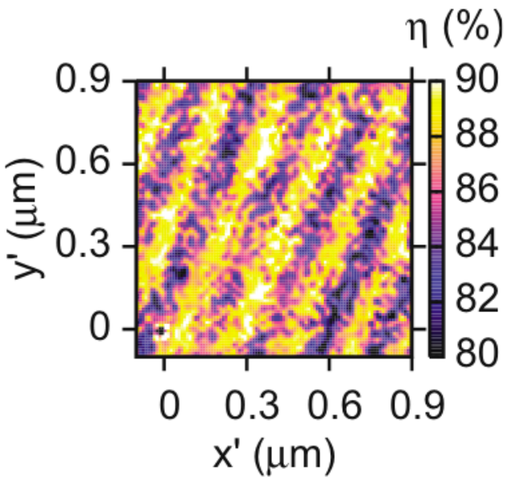
Below 1 keV electron detection

- Continuing issues with HV electrodes
- Meandering (nanoscopic) superconductive wires on a Si substrate, operated close to the critical currents
- Limited size $16 \times 16\ \mu\mathrm{m}^2$
- Improvements on the way, constant discussions with the company

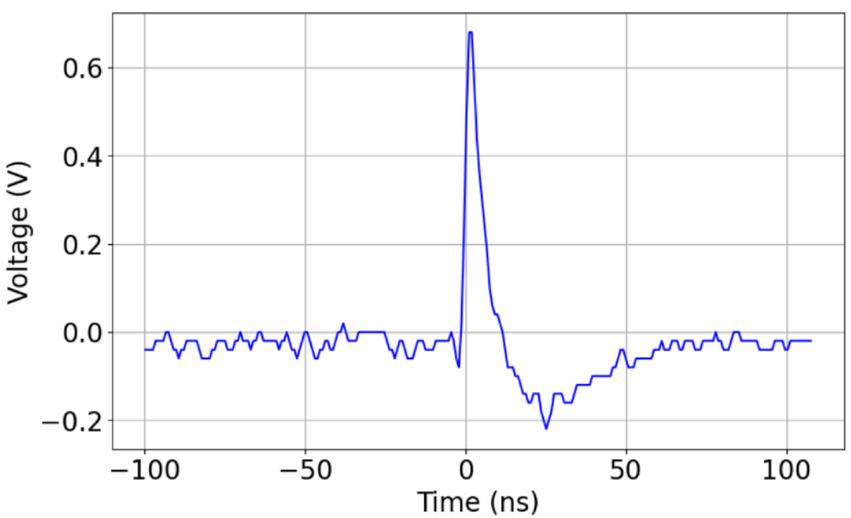






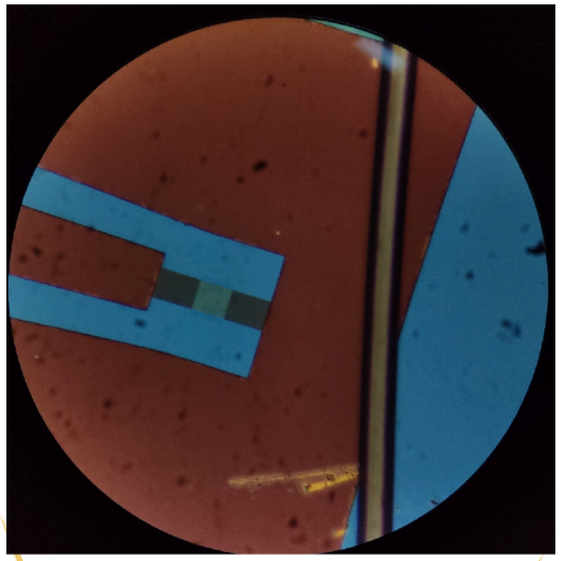


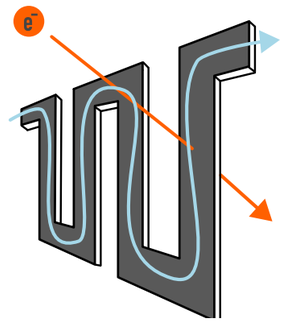
Detection efficiency of SCNW for single electrons (30 keV) from [M. Rosticher *et al*., Appl. Phys. Lett. **97,** 18 (2010)]

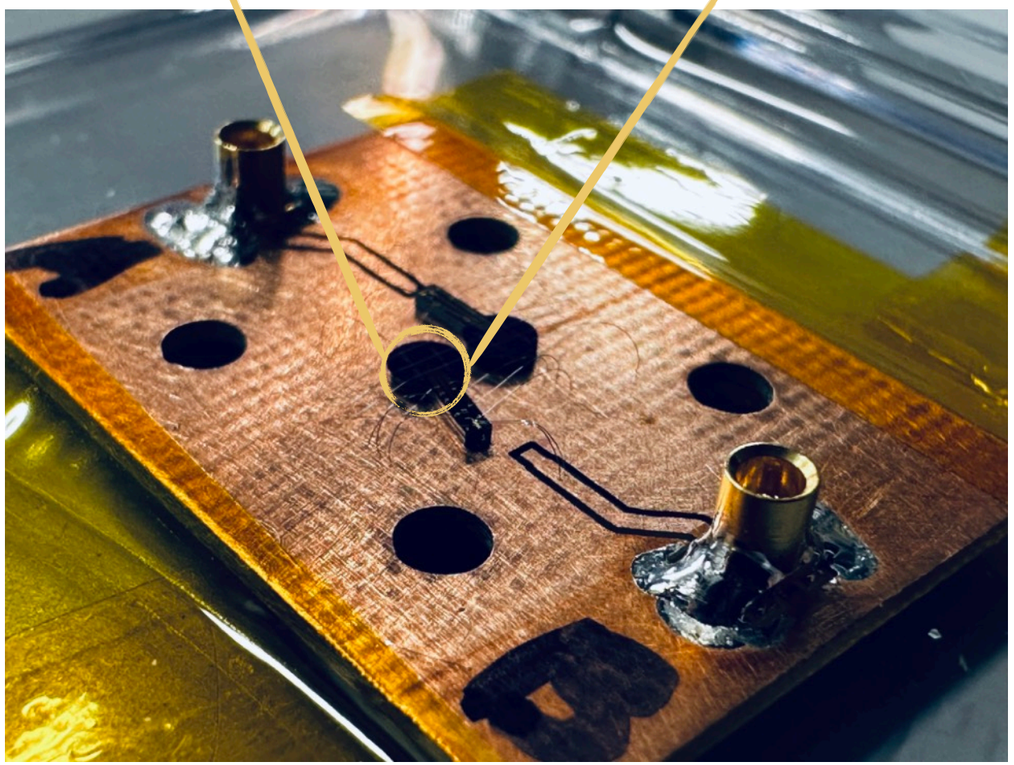


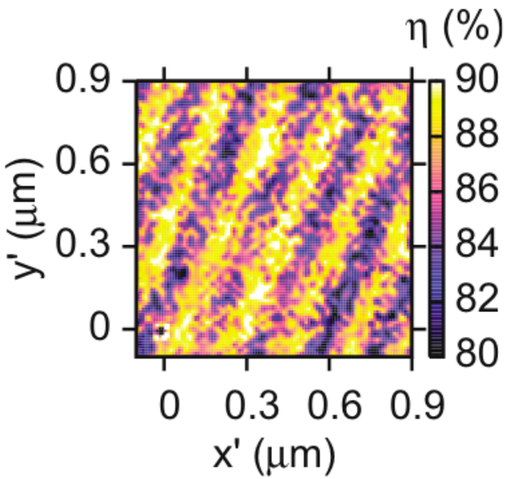
Below 1 keV electron detection

- Continuing issues with HV electrodes
- Meandering (nanoscopic) superconductive wires on a Si substrate, operated close to the critical currents
- Limited size $16 \times 16\ \mu\mathrm{m}^2$
- Improvements on the way, constant discussions with the company

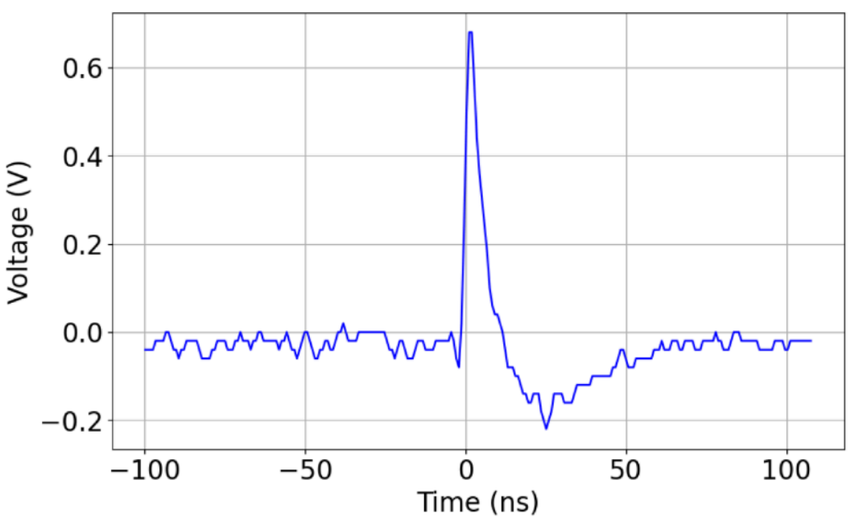








Detection efficiency of SCNW for single electrons (30 keV) from [M. Rosticher *et al*., Appl. Phys. Lett. **97,** 18 (2010)]

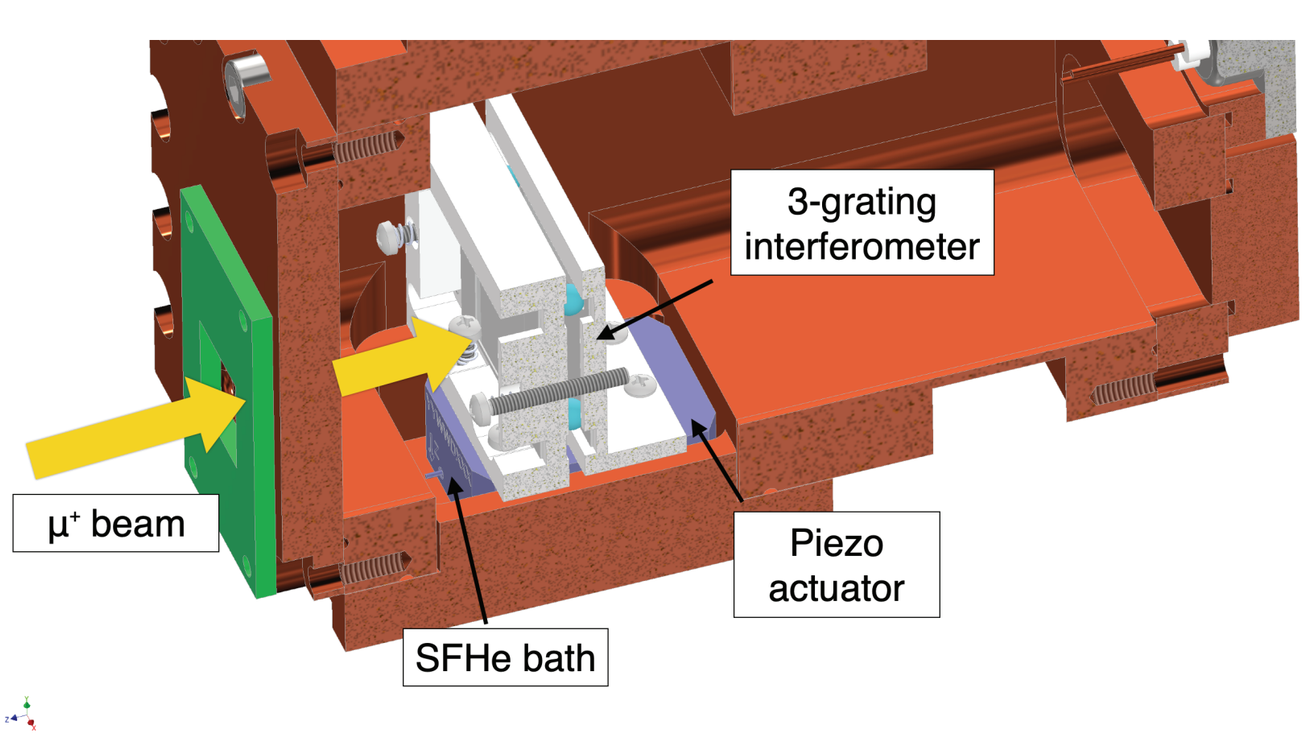


Beamtime 2025

3 weeks of beamtime at piE1 requested for:

- Characterisation of 2 microfluidic gratings, (V1 - thin SiN membrane degrader in front, V2 - less risky, optimized version of the 2024 gratings),
- Commissioning of a Si strip telescope at both sides, (320 channels) and the new DAQ. Detailed tomography of the beam, including atomic electron coincidences

week nr	duration	task
1	3-4 days	setup, beam alignment, cooldown
	2 days	alignment and momentum tuning on dry V1 grating, Si tracker commissioning, BG measurement
	1 day	ranging on SFHe filled grating atomic electron detector commissioning.
2	2 days	characterization of emitted Mu, using the Si trackers and atomic e detector
	2 days	warmup, mounting V2 grating and cooldown. Reparations of the detectors if necessary
	3 days	Ranging and characterization of Mu emission from V2 Si target
3	2 days	Warmup, disassembly, mounting the better microfluidic grating with the 3-grating setup and cooldown
	5 days	vertical scans of the third grating, attempt on observing an interference pattern

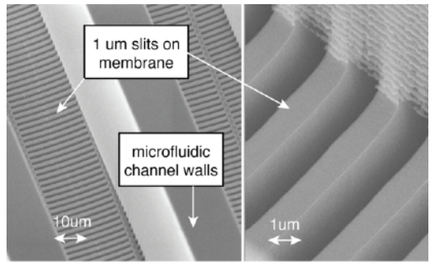


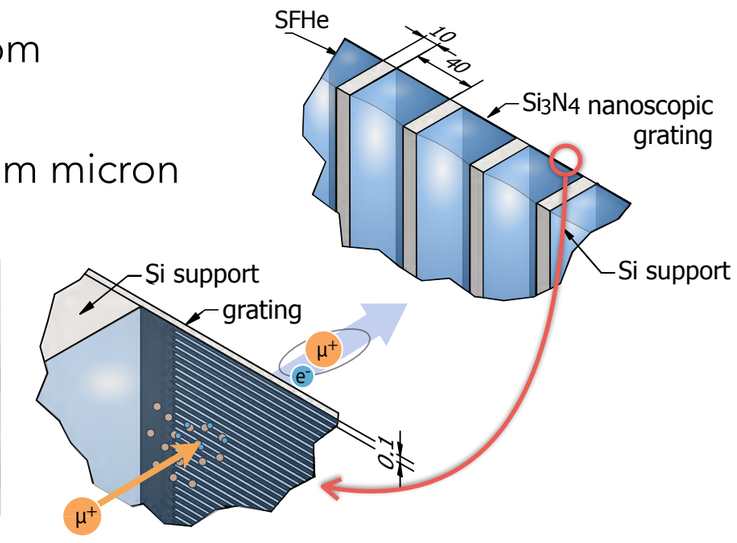
LEMING summary & further plans

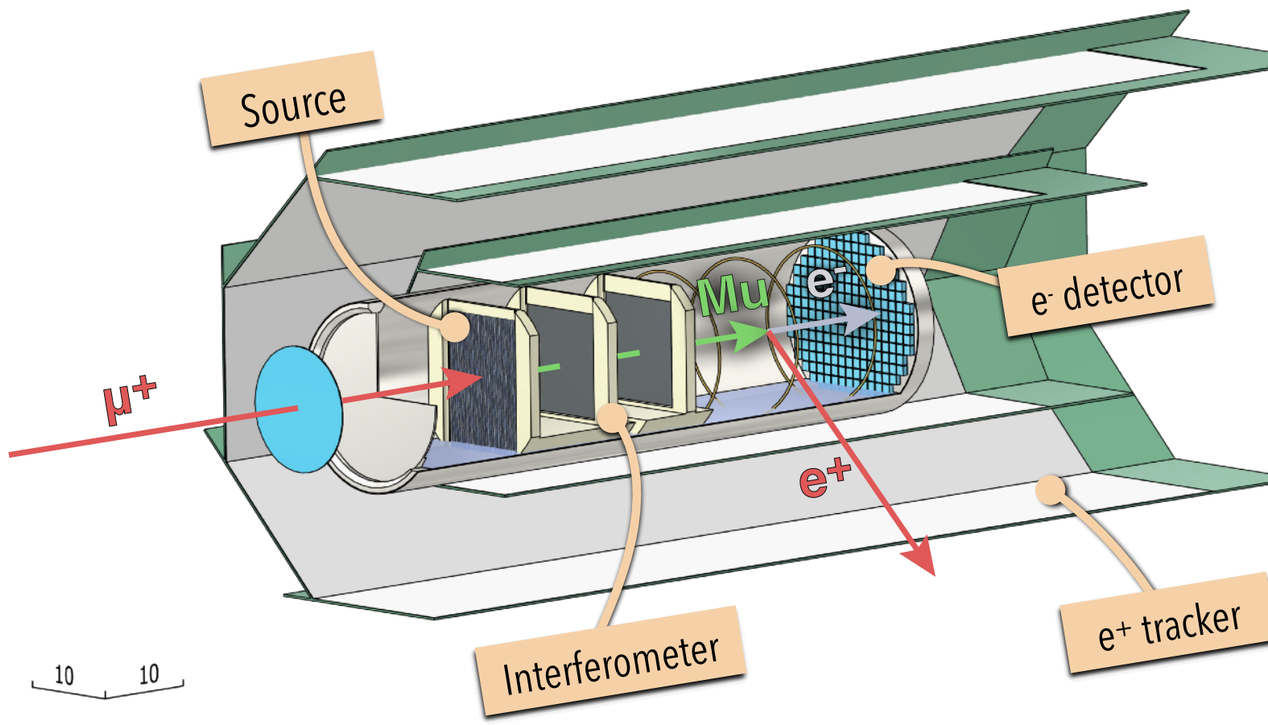
Goal: measurement of gravitational acceleration of muonium, and next generation laser spectroscopy

Status:

- Novel Mu source from superfluid helium
- Cold Mu mission from micron sized gratings

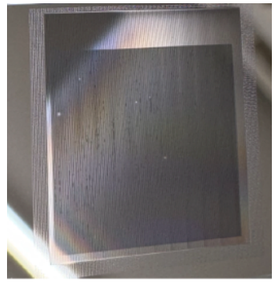


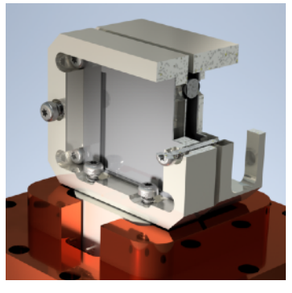




Plans:

- Construction of the first Talbot interferometer
- Further optimization of stopping
- Demonstration of Mu (Talbot) interferometry



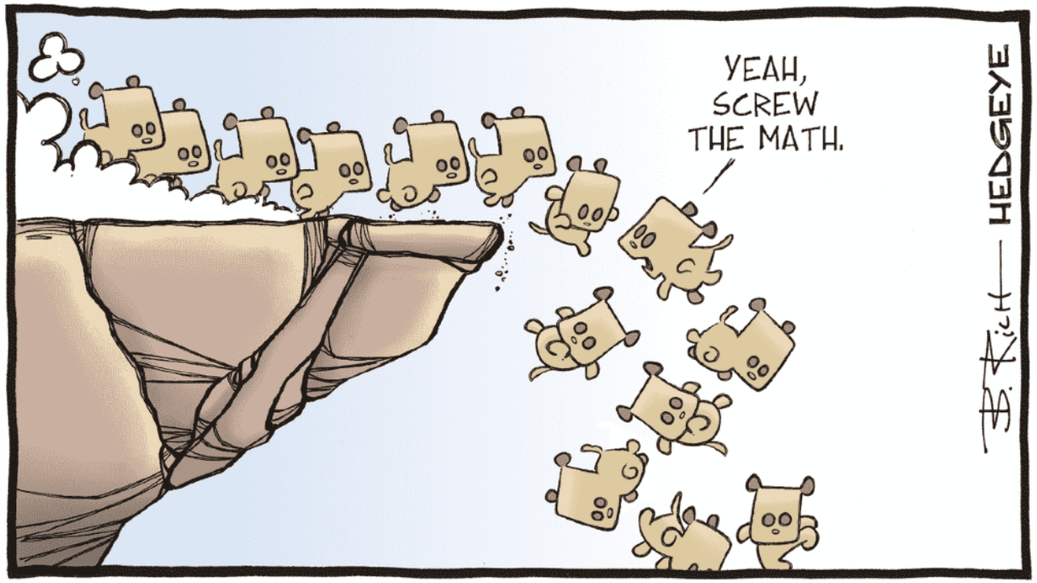


Timeline

Thank you!

LEMING

SNSF
Starting
Grant



The expected experimental outcome when
LEptons in Muonium INteracting with Gravity: