LEMING: Towards measuring the gravitational acceleration g of Muonium

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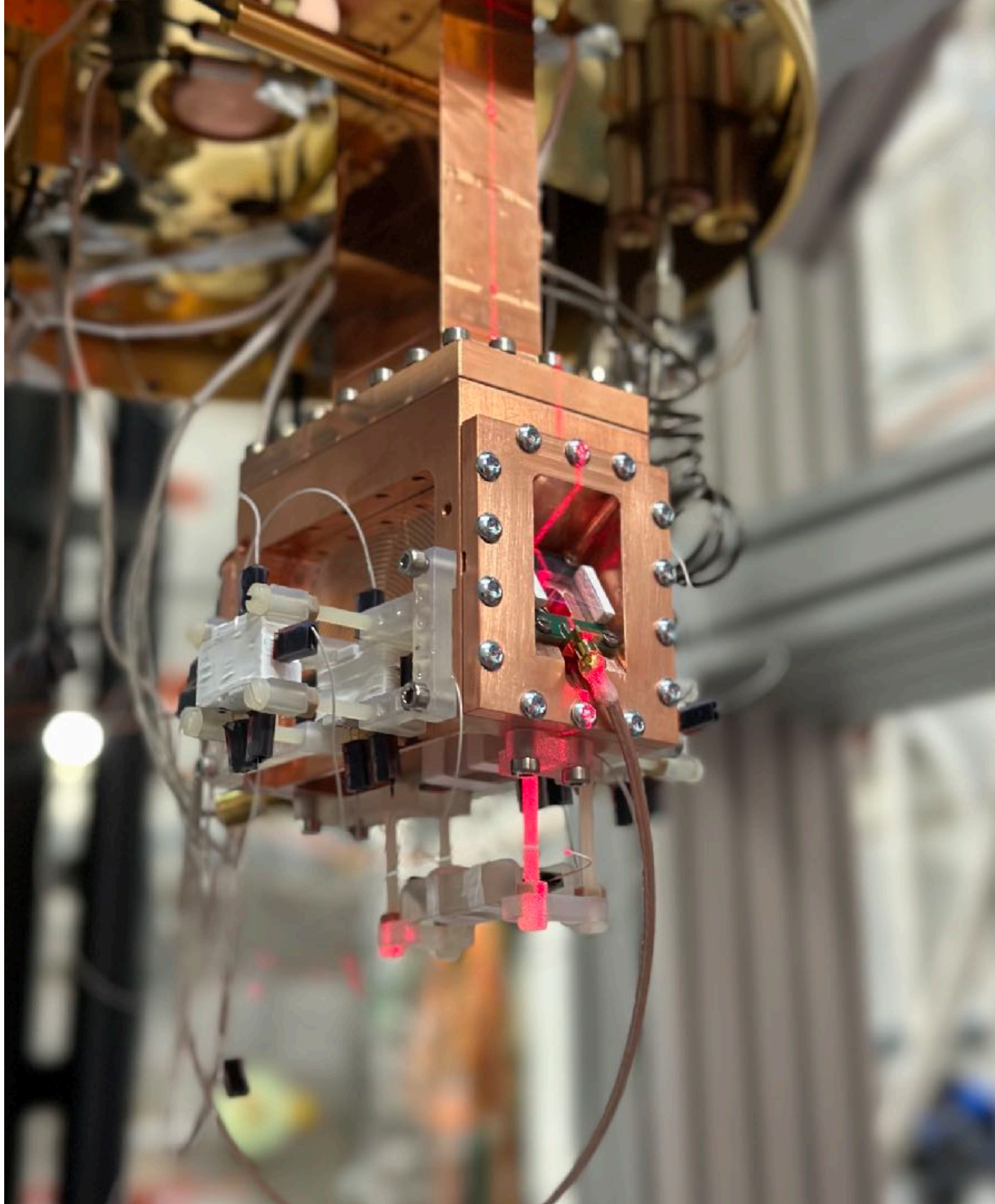


Standard Model

- Why three generations?
- Mass hierarchy
- Many free parameters
- Baryon Asymmetry?
- What about Dark Matter?
- Gravity?
- …

Fermions

	I.	II.	III.
Quarks	u	c	t
	d	s	b
Leptons	e^-	μ^-	τ^-
	ν_e	ν_μ	ν_τ

Bosons

H

g

γ

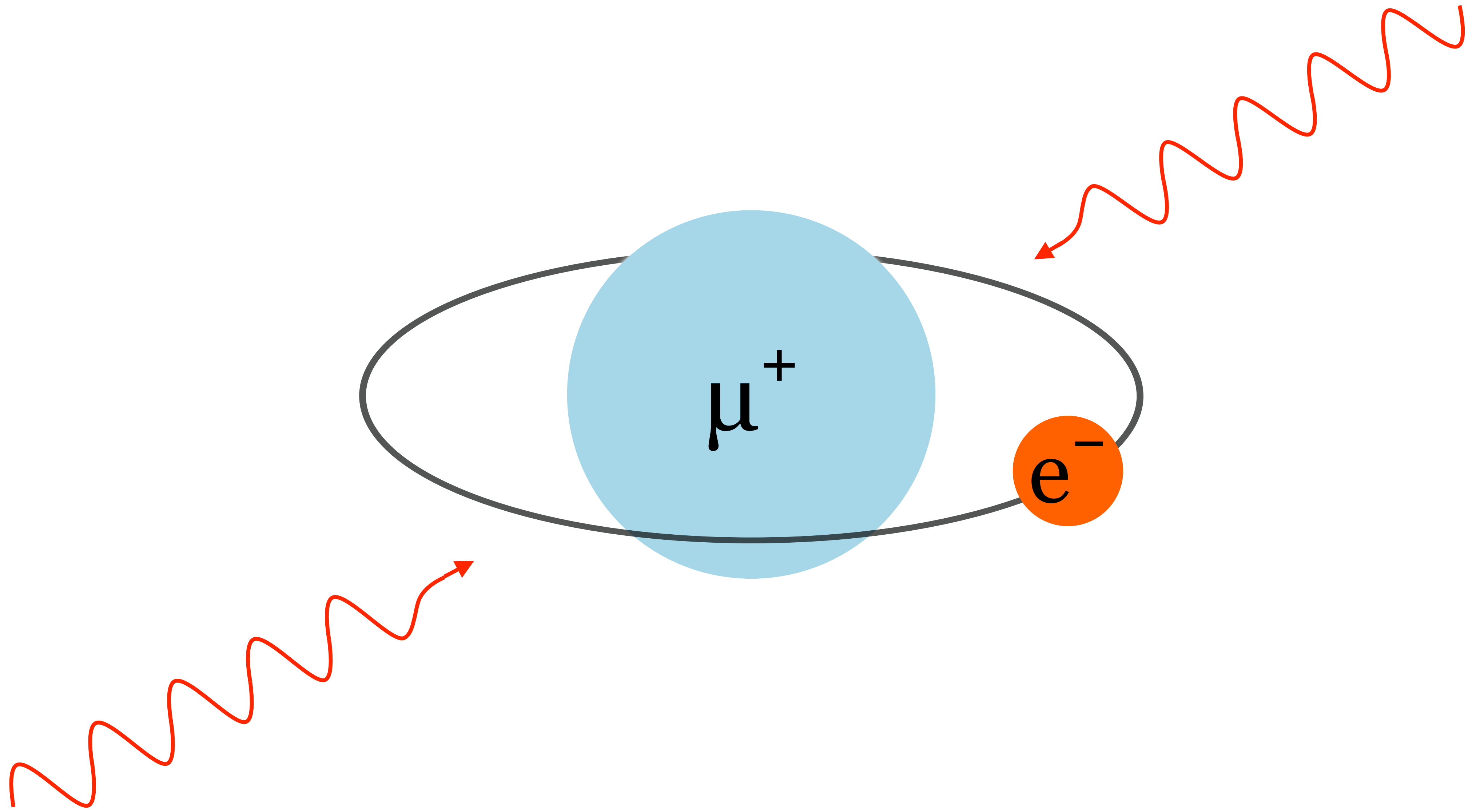
$Z,W^\pm$

Antifermions

I.	II.	III.
$\bar{u}$	$\bar{c}$	$\bar{t}$
$\bar{d}$	$\bar{s}$	$\bar{b}$
e^+	μ^+	τ^+
ν_e	ν_μ	ν_τ

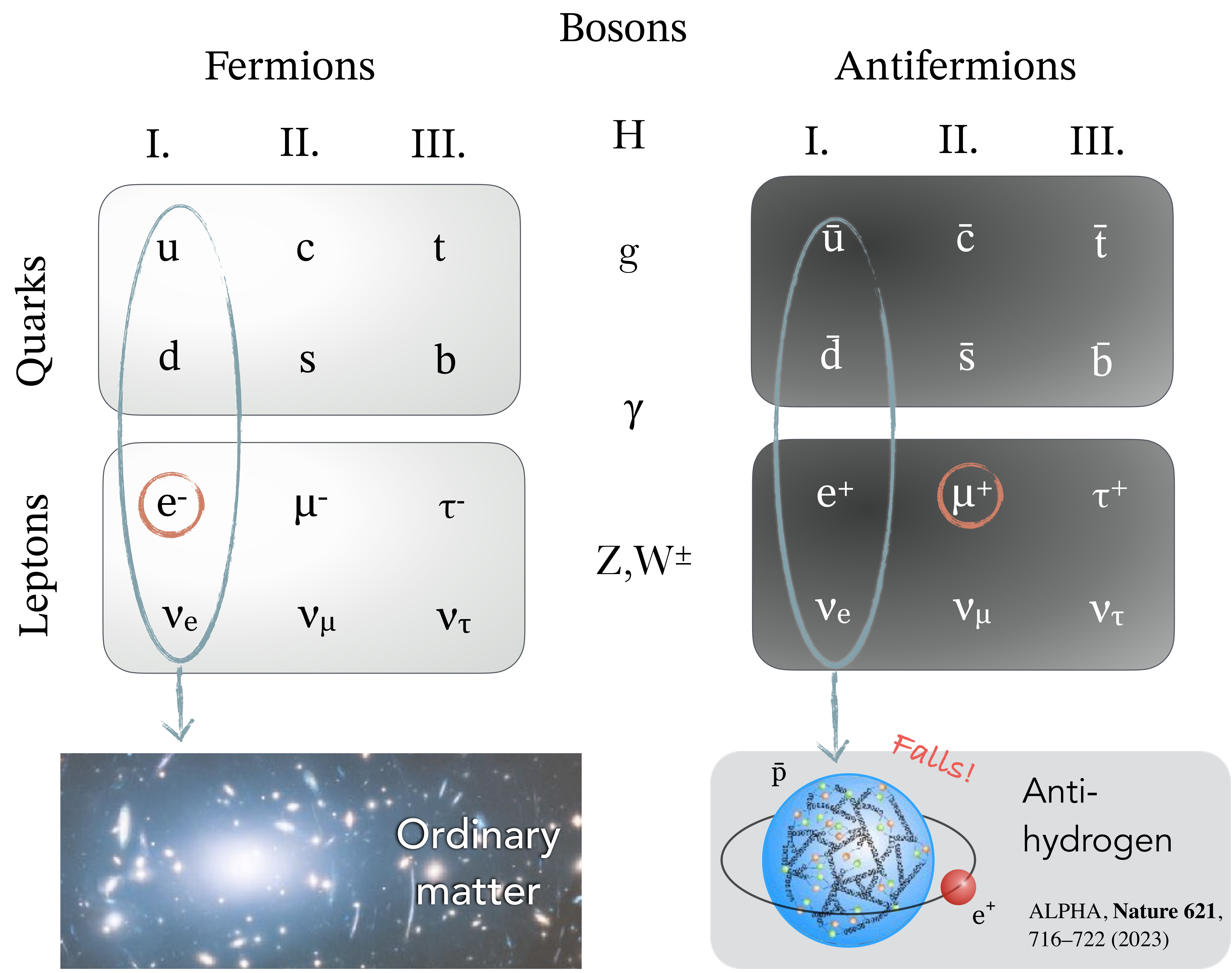
Laser (Precision) Spectroscopy with Muonium

- Purely leptonic exotic atom, dominated by QED effects
- Measurement of **hyperfine structure** (MuSEUM at JPARC) and **1S-2S transition** (MuMASS at PSI)
  - Determine fundamental constants (m_μ, μ_μ, R_∞)
  - Test of bound-state QED & symmetries ($\frac{q_\mu}{q_e}$)
  - Close interplay with other precision experiments, e.g. muon g-2



$$E(1s-2s) \simeq \frac{3}{4} q_e q_\mu R_\infty \left(1 - \frac{m_e}{m_\mu}\right) + \text{QED} + \ldots$$

Standard Model and Beyond

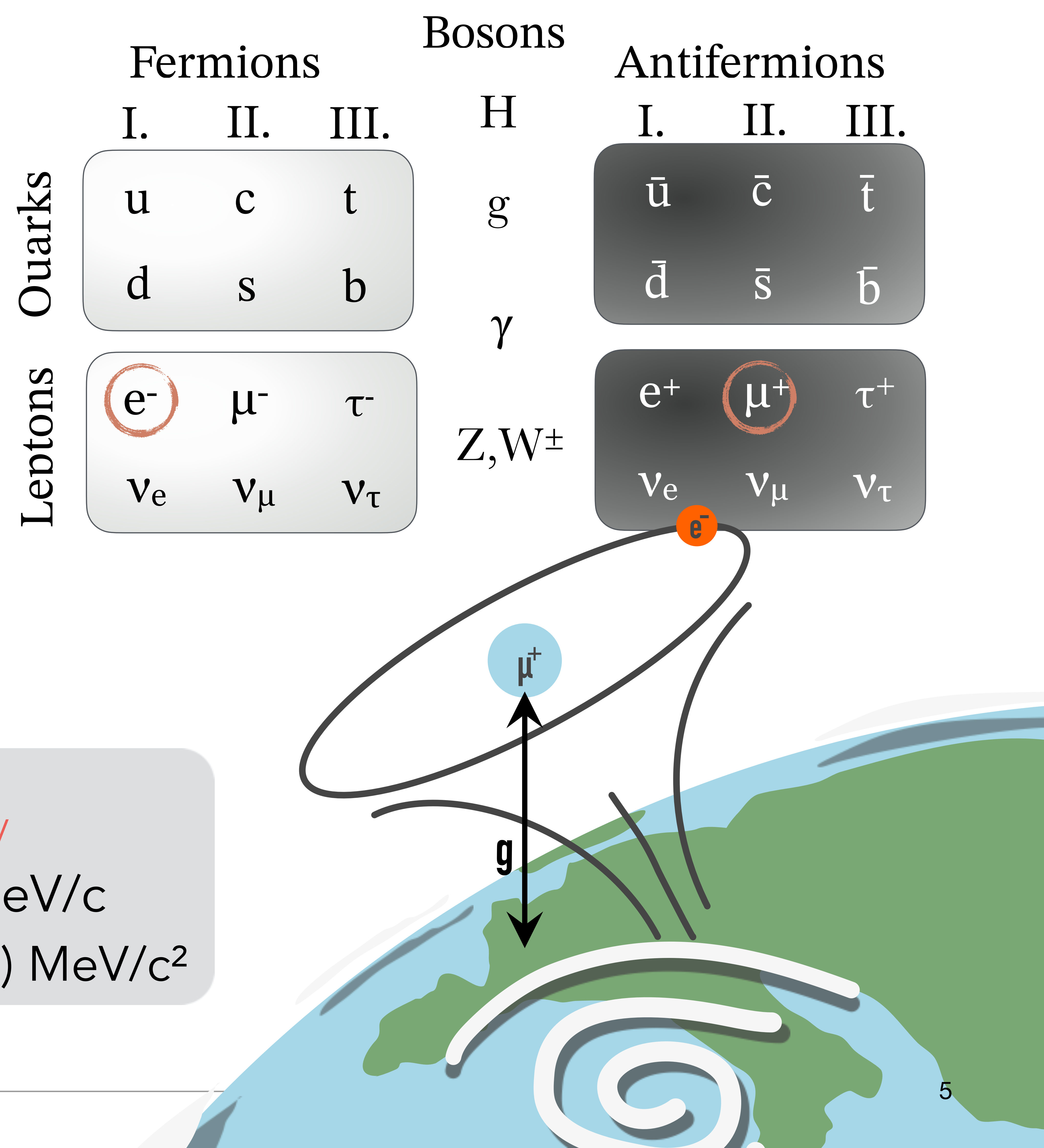


LEMING: LEptons in Muonium INteracting with Gravity

Free fall of Mu

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

- fundamental parameters of SM; no masses generated by QCD
- second generation (anti)fermions of the SM - only possible probe of this sector



Hadron mass

~1% valence quark
99% strong interaction

Muonium mass

Binding 13.7 eV

μ^+ mass: 105.658345(24) MeV/c
e^- mass: 0.5109989461(31) MeV/c²

LEMING: LEptons in Muonium INteracting with Gravity

Free fall of Mu

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

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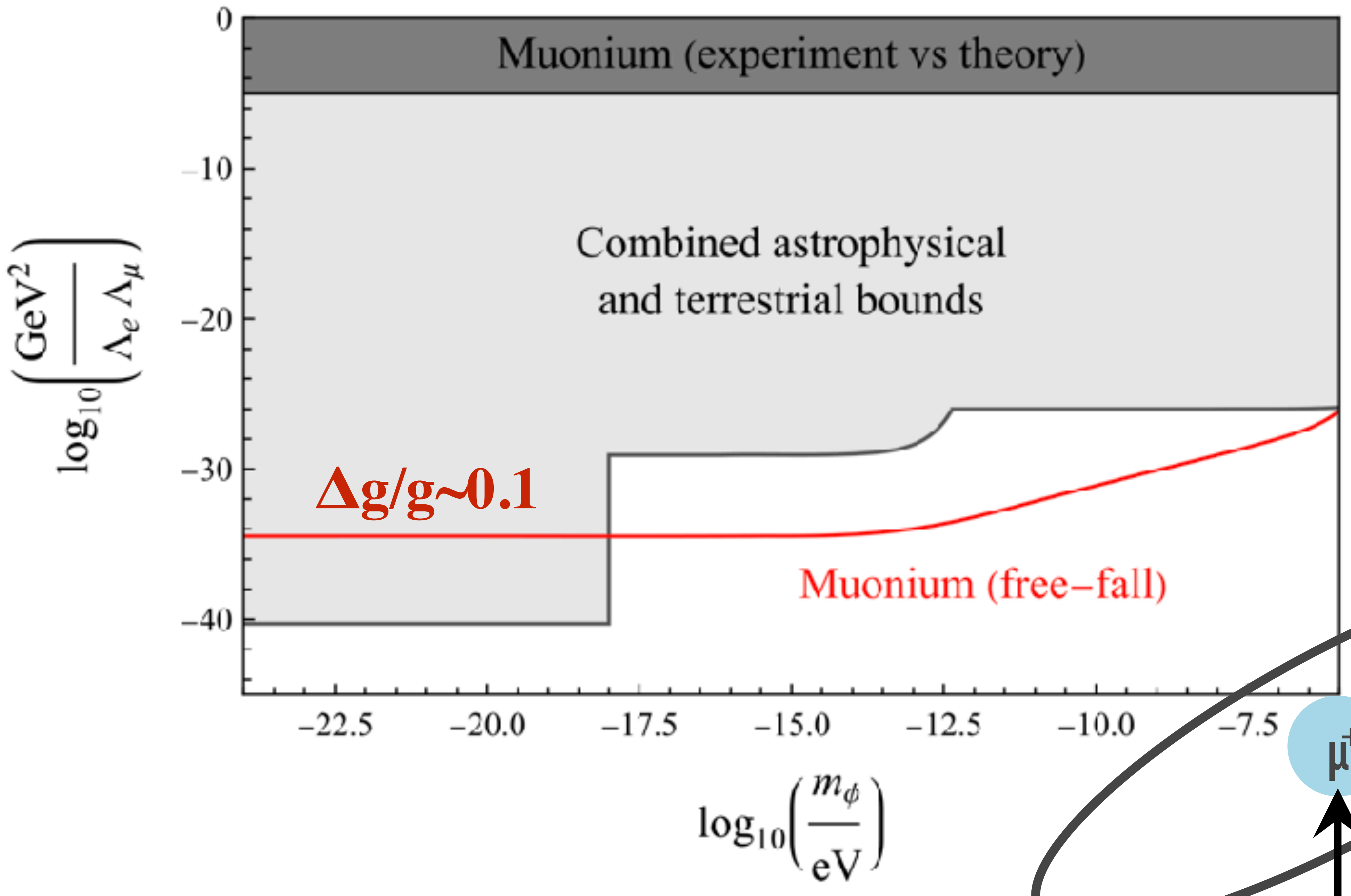
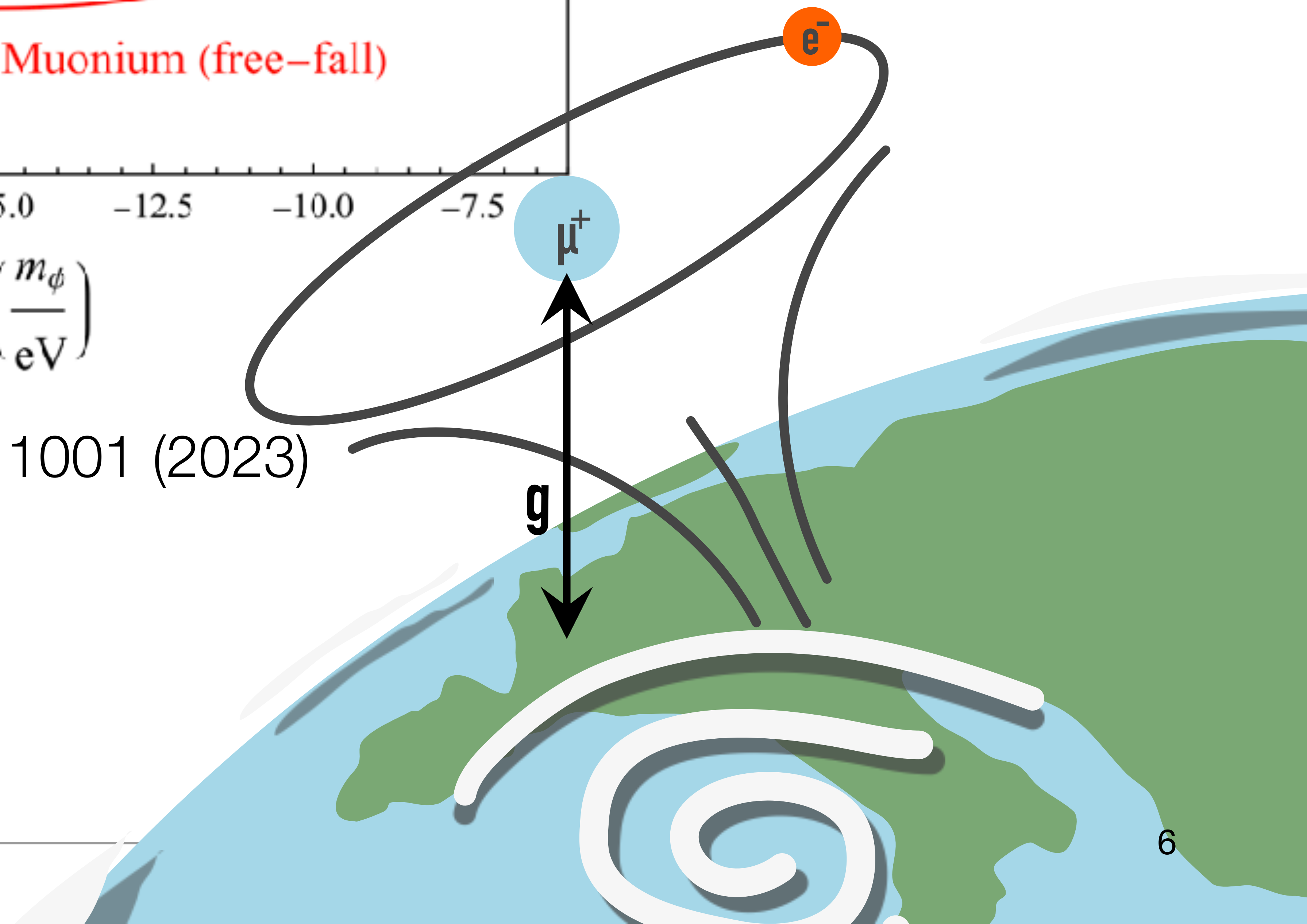
- Validity of WEP in higher generations?
- Possibility to test flavour dependent new interactions



Y. Stadnik PRL 131, 011001 (2023)



How to measure g for Muonium?

Lifetime of Muonium limited by lifetime of μ^+: $\tau = 2.2\,\mu s$

$$\Delta y = \frac{1}{2} g t^2 < 0.5\,\text{nm}$$

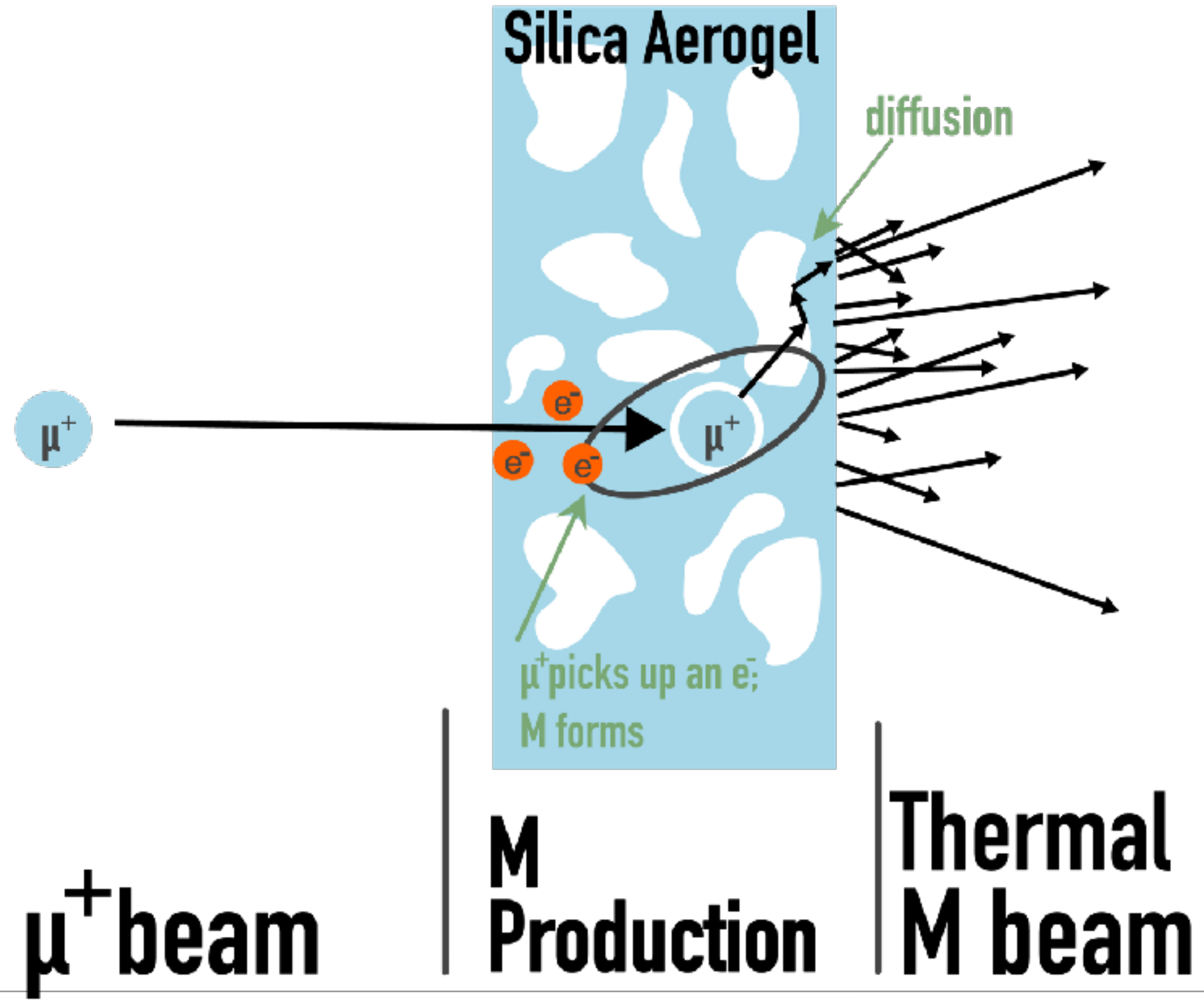
for $t = 4\tau_M$

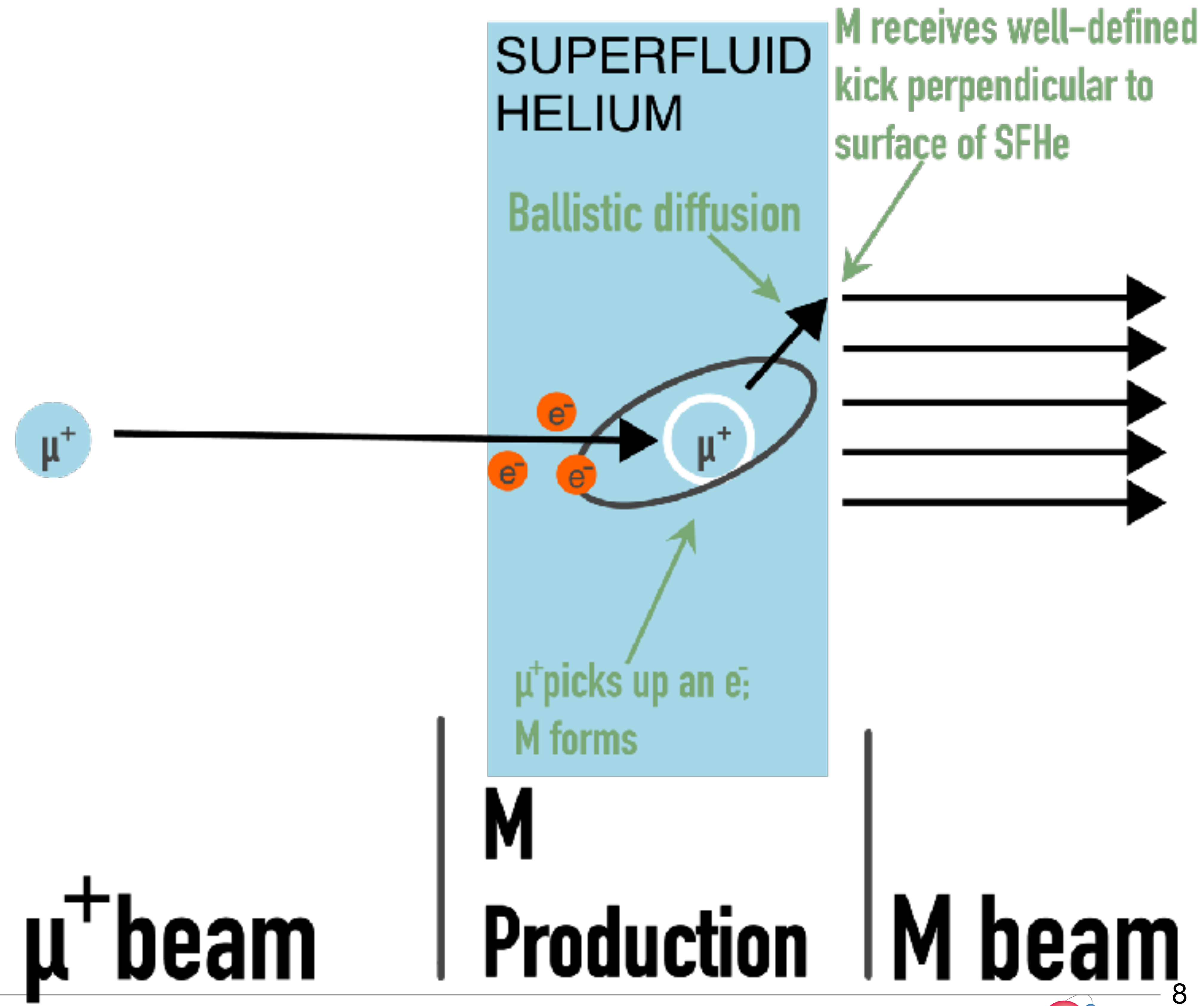
➡ Phase sensitive approach ➡ Interferometry

The need for a novel Muonium source

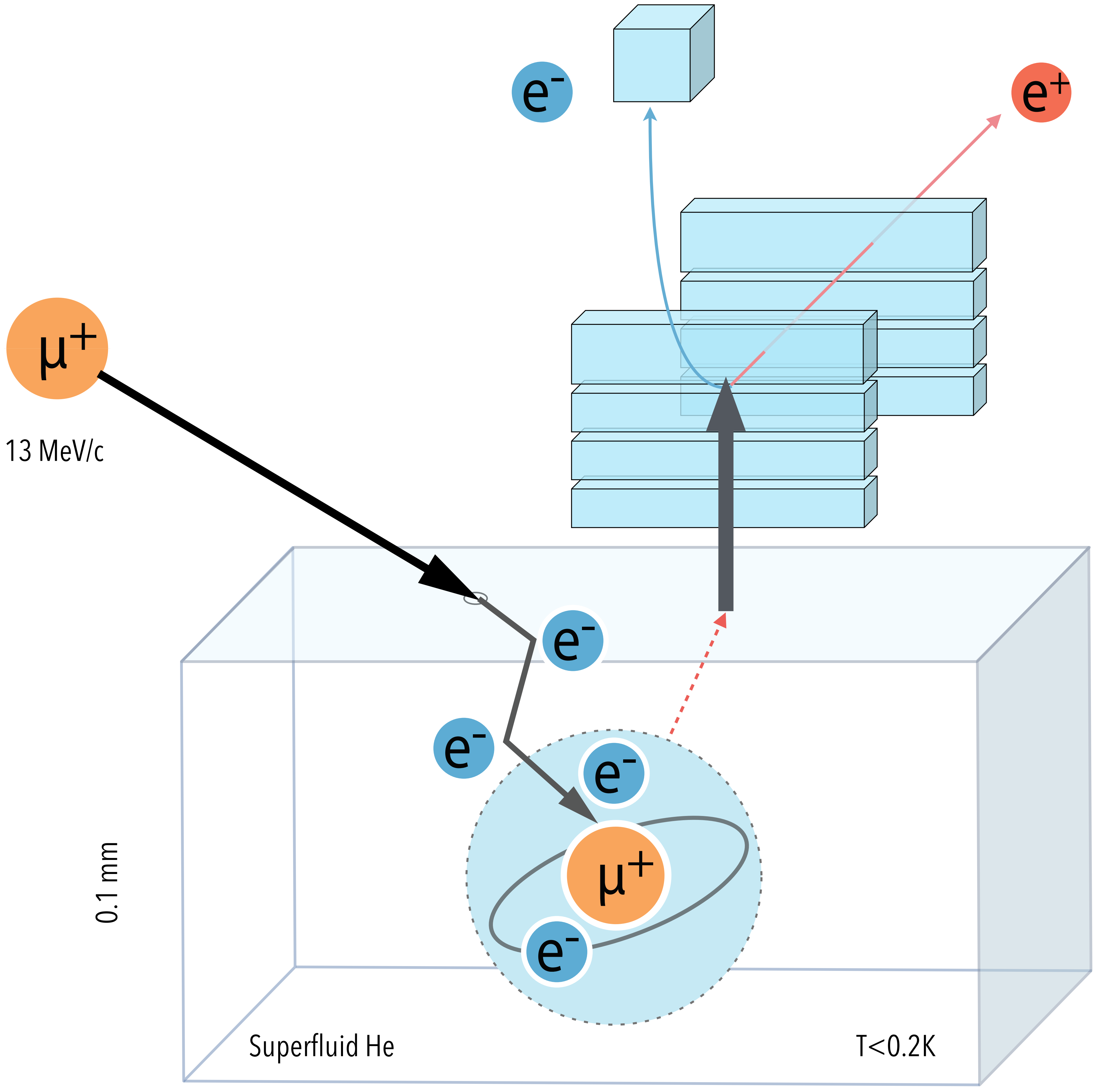
Interferometry not possible with conventional Muonium sources

Novel Muonium source using Superfluid Helium





Cold Muonium Beam using Superfluid Helium



In previous measurements at PSI established 4 previously unknown physics process in SFHe:

(1) Mu stop and recombination with high enough efficiency
(2) Thermalization below the *roton gap*, $v_L \approx 60\ \mathrm{m/s}$
(3) Ballistic diffusion (no collisions), $\tau_d \approx 1\ \mu s$ * to surface
(4) Ejection in the surface normal, due to the large positive chemical potential

Scattering of phonons

- 'small impurity' with effective mass $m_{Mu} \approx m_{He}$
- At 0.2 K phonon density is small: $n_{ph} = 2 \cdot 10^{19} T^3/\mathrm{cm}^3 \approx 10^{16}/\mathrm{cm}^3$
- unlikely to scatter at phonons: $1/\tau_c \propto T^7 \approx 5/\mathrm{s}$

Taqqu, Physics Procedia 17 (2011) 216-223,
Kirch & Khaw: Int. J. of Mod. Phys. 30, (2014)
Soter & Knecht, SciPost Physics Proceedings 031 (2021)

Surface ejection

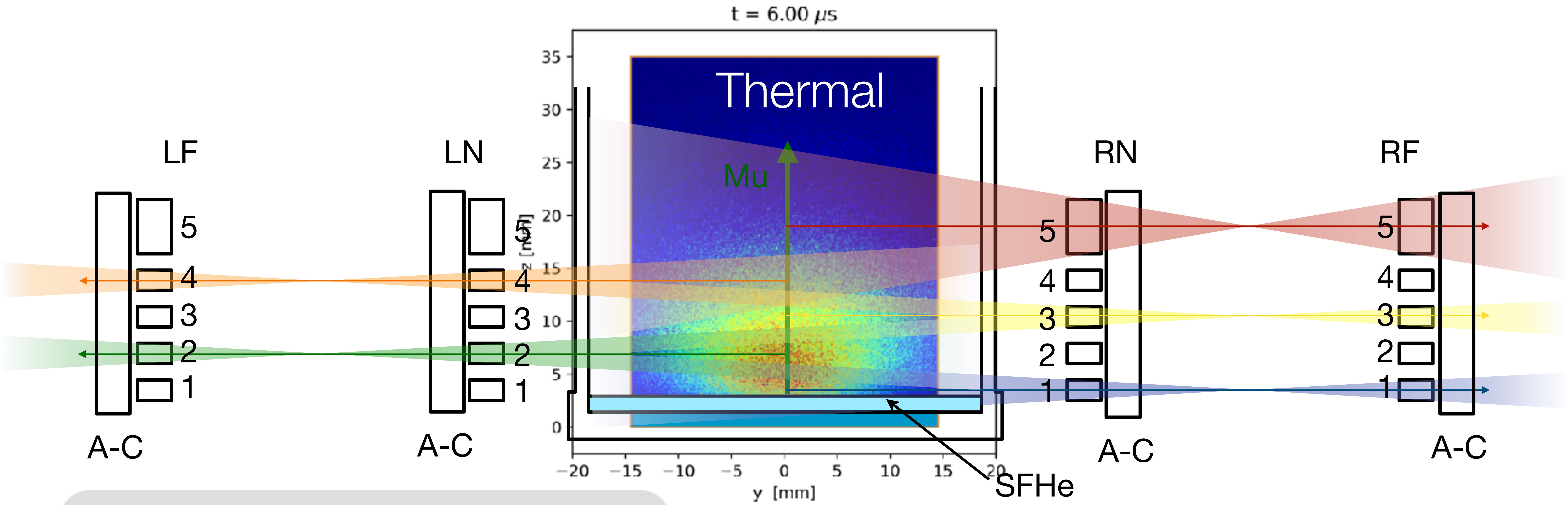
- large chemical potential: $\frac{E}{k_B} \sim 270\ \mathrm{K}$
- Mu are ejected from bulk SFHe with $v_l \approx 6300\ \mathrm{m/s}$

M. Saarela and E. Krotscheck, JLTP 90, 415 (1993)

*other atoms don't do this. Clue for exception: antiprotonic helium in SFHe

A. Soter et al., Nature 603, 411–415 (2022)

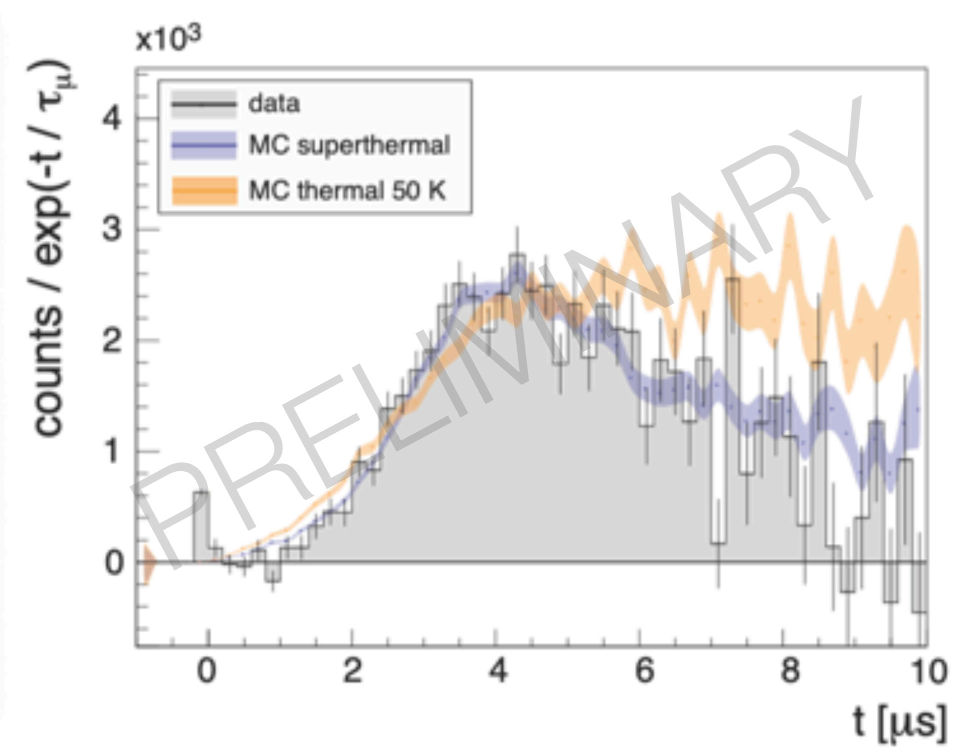
Characterisation of Muonium beam from Superfluid Helium



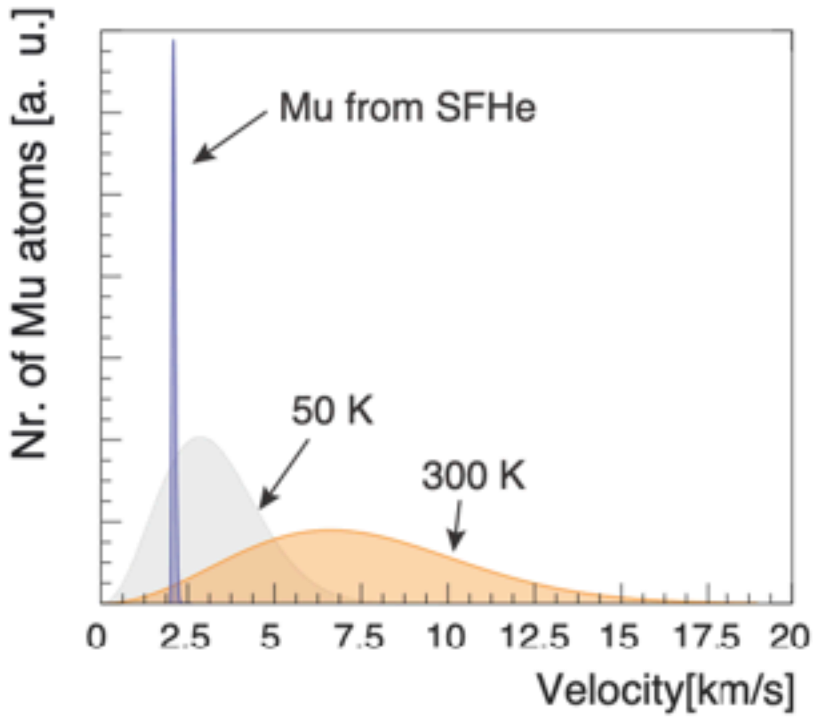
Parameters

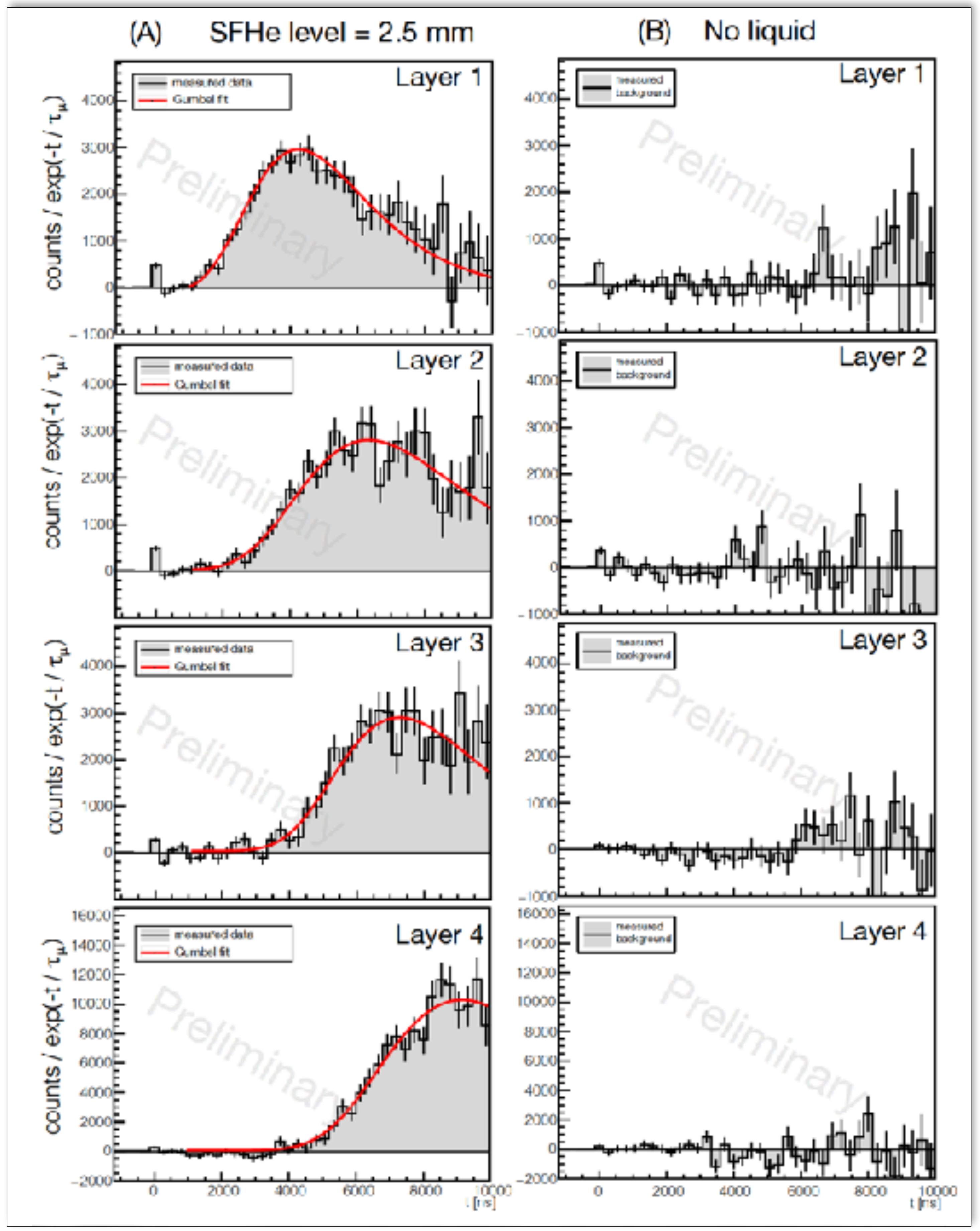
- **Lowest** mean **velocity** Muonium source: $v_{long} \approx 2175$ m/s
- **Narrowest** transversal distribution: $v_{trans} \approx 52.5$ m/s
- **High yield**: $R(\mu^+ \rightarrow \text{Mu}_{\text{vac}}) \approx 10\,\%$

Time-Spectra of fly-by

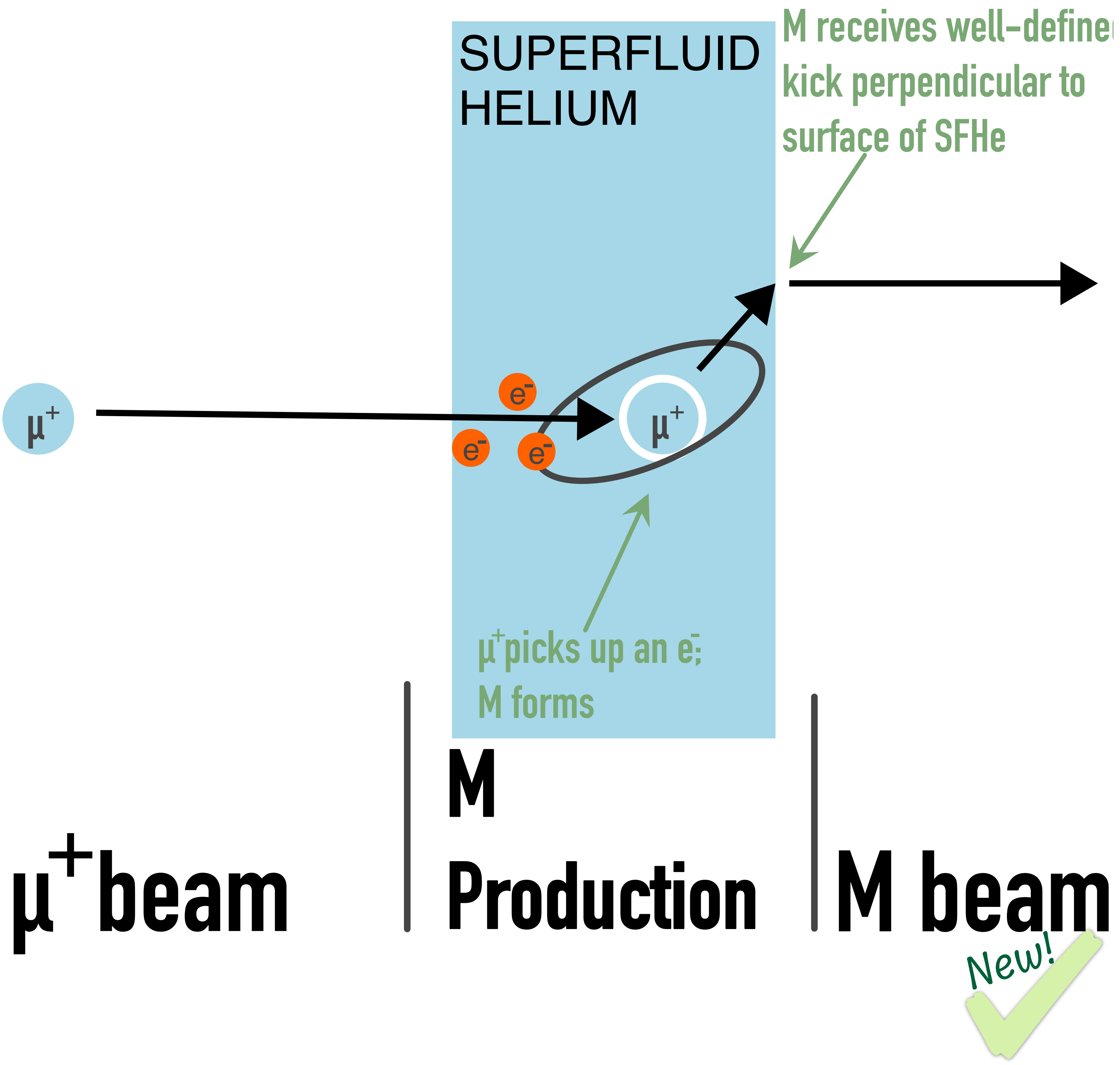


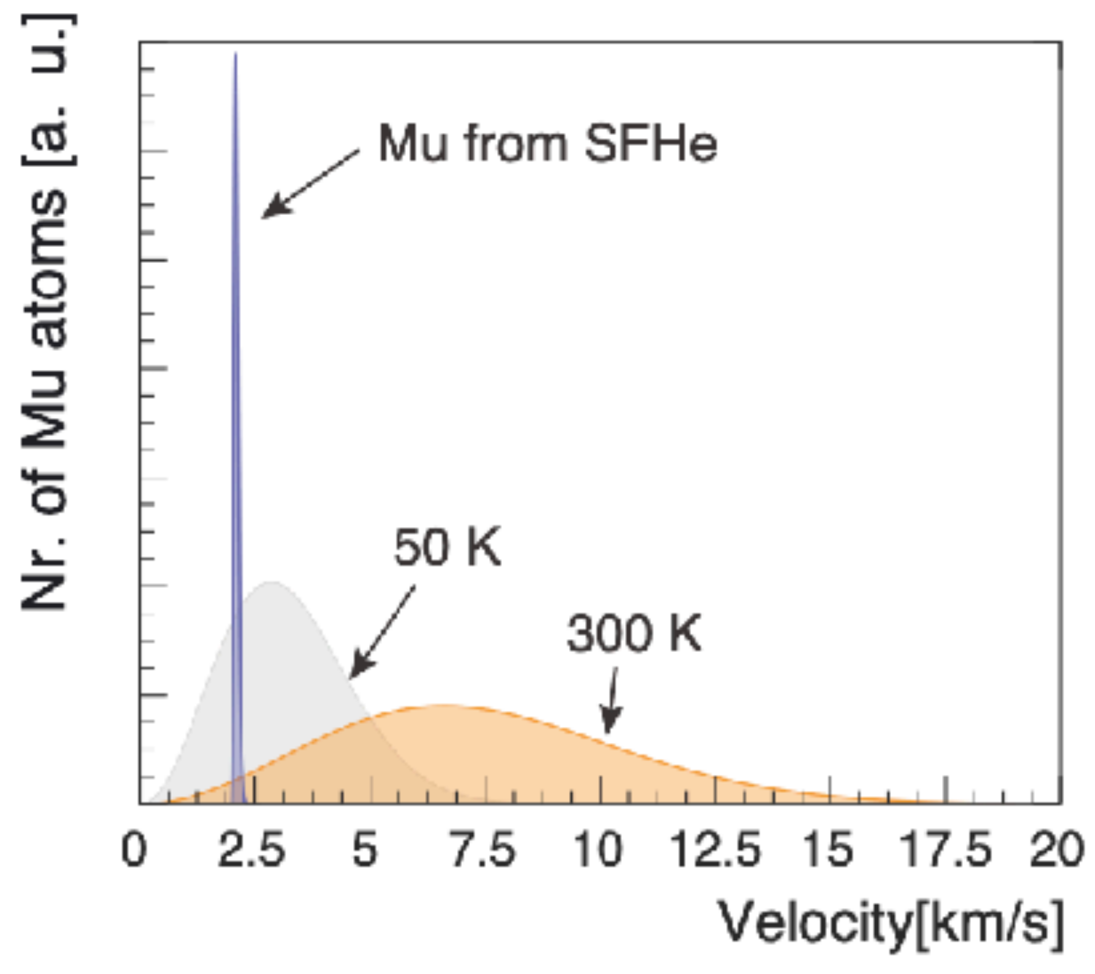
Reconstructed velocity distribution





How to measure g for Muonium?





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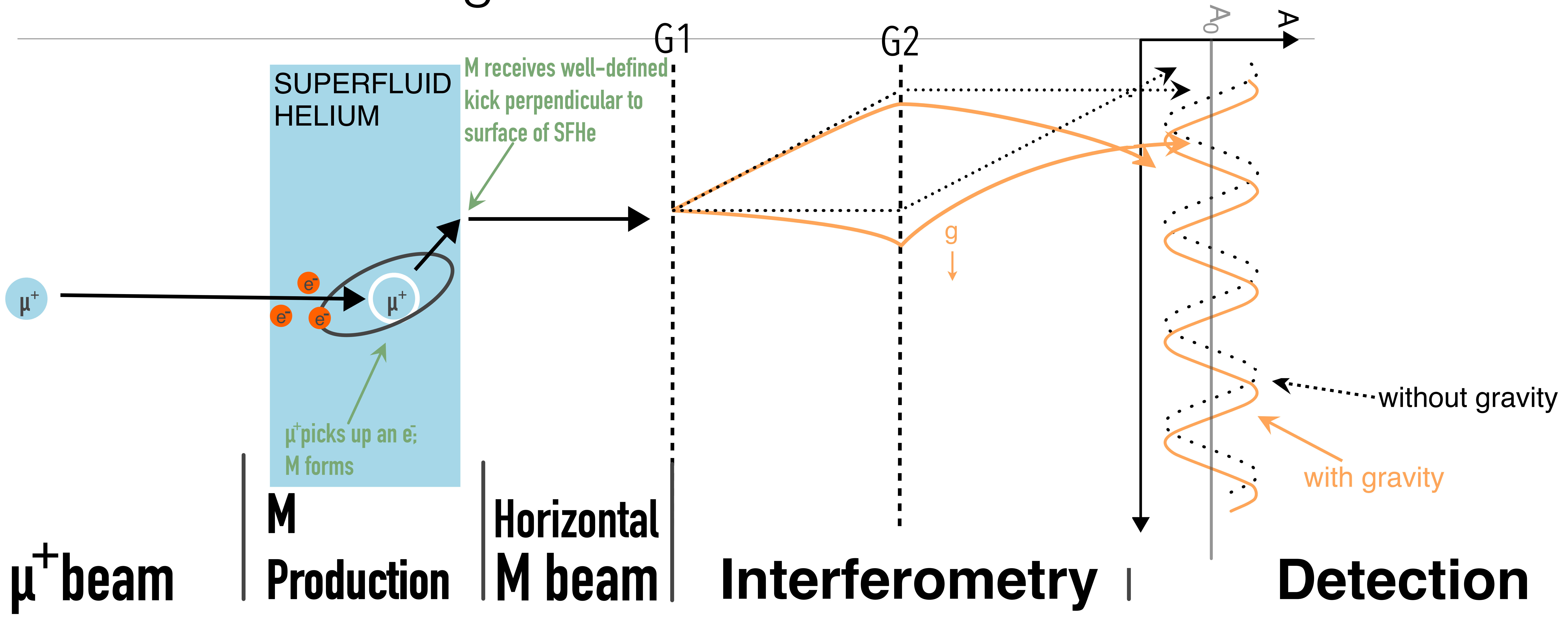

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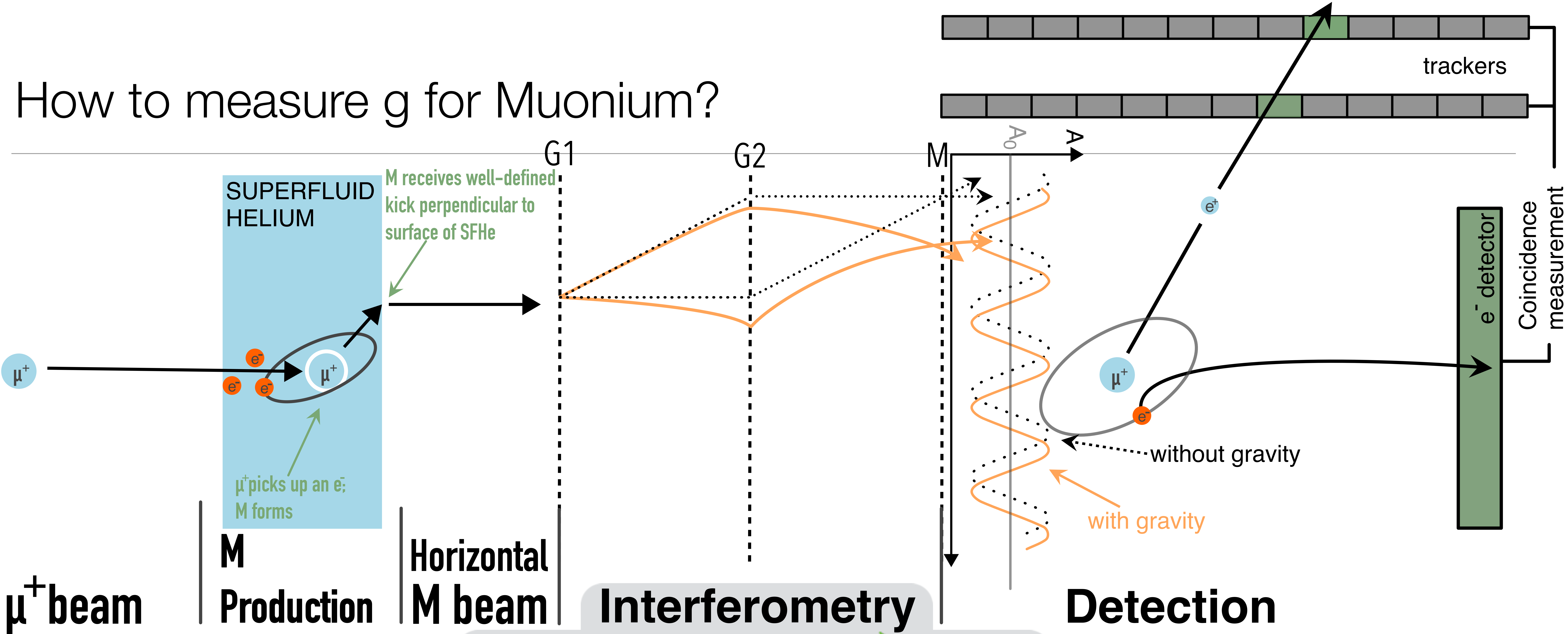


$$\Delta g \approx \frac{1}{2\pi T^2} \frac{d}{C\sqrt{N_0 \epsilon \eta^3 e^{-(t_0+T)/\tau}}}$$

Grating period ($d \sim 100$ nm)

Interaction time: ~7-8 μs

Contrast ($C = A/A_0 \sim 0.3$)

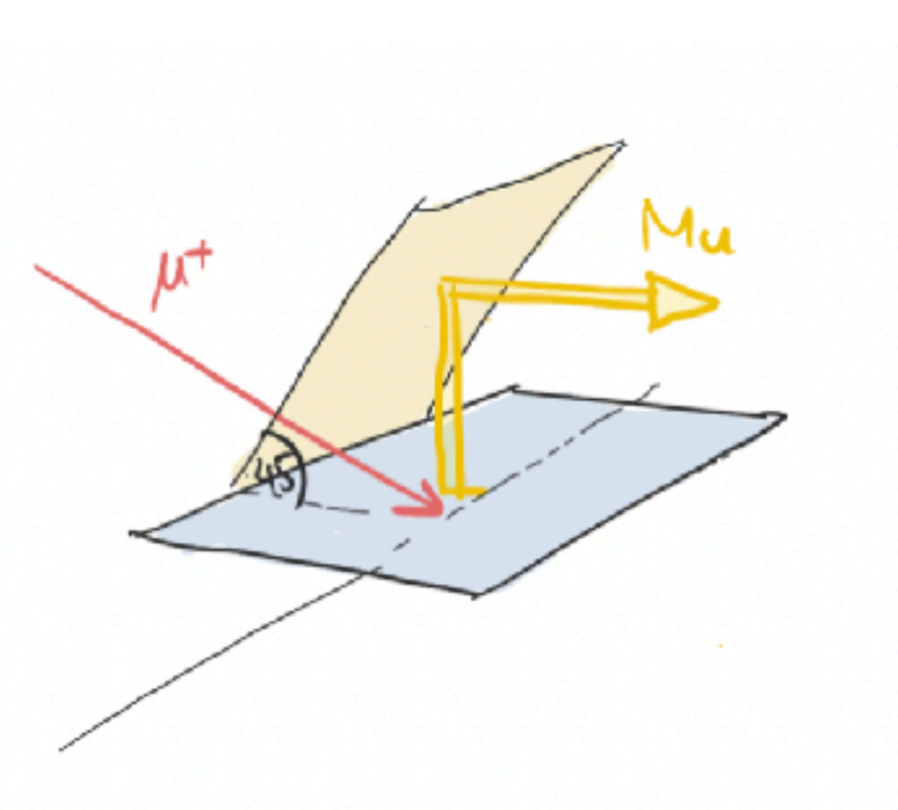
Atoms from source ($N_0 \sim 10^4$/s)

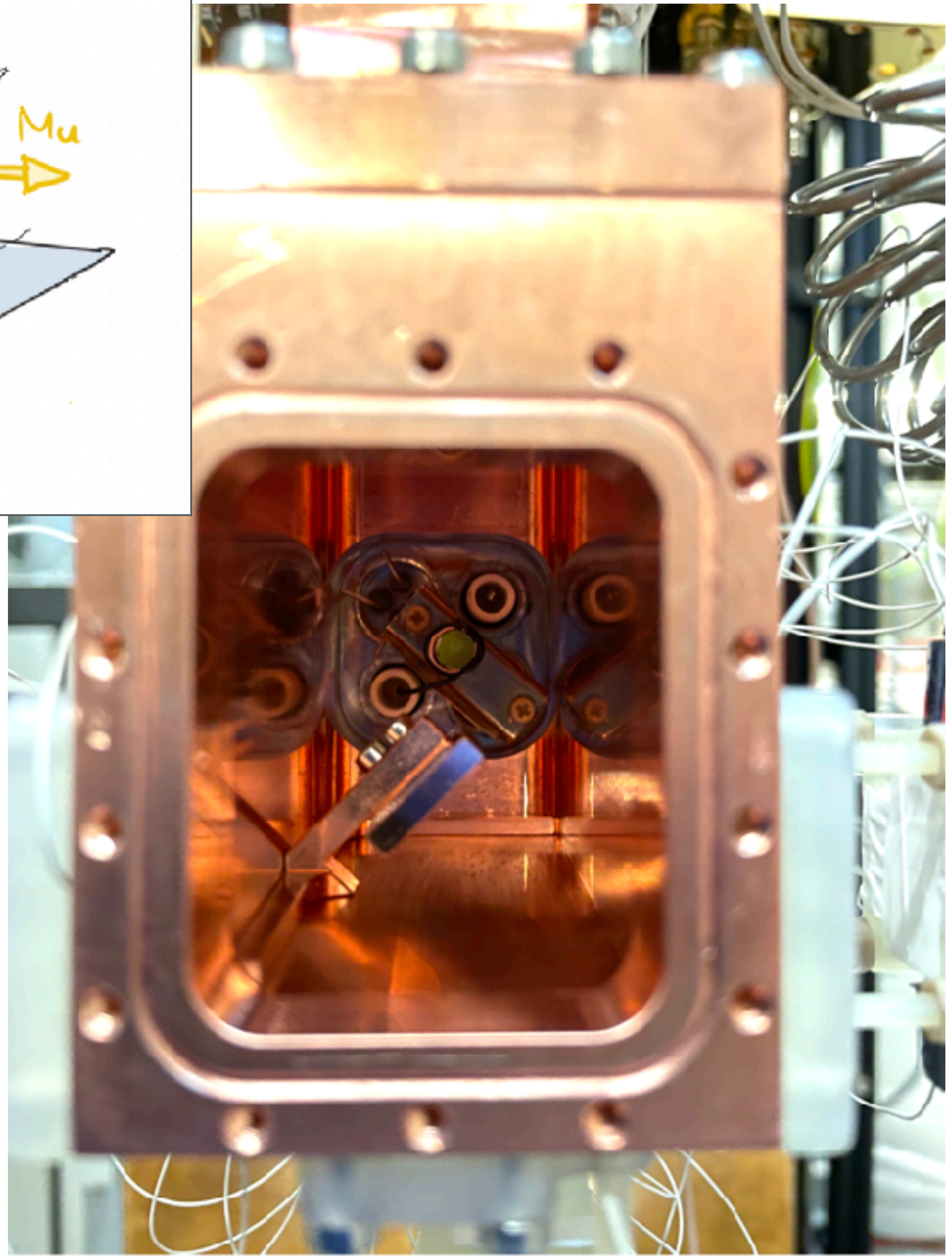
Loss factor ($\eta = 0.3$, $\varepsilon = 0.5$, $t_0 < \tau/2$)

$\frac{\Delta g}{g} \sim$ 1% sensitivity possible; At PSI, world's highest intensity cw muons

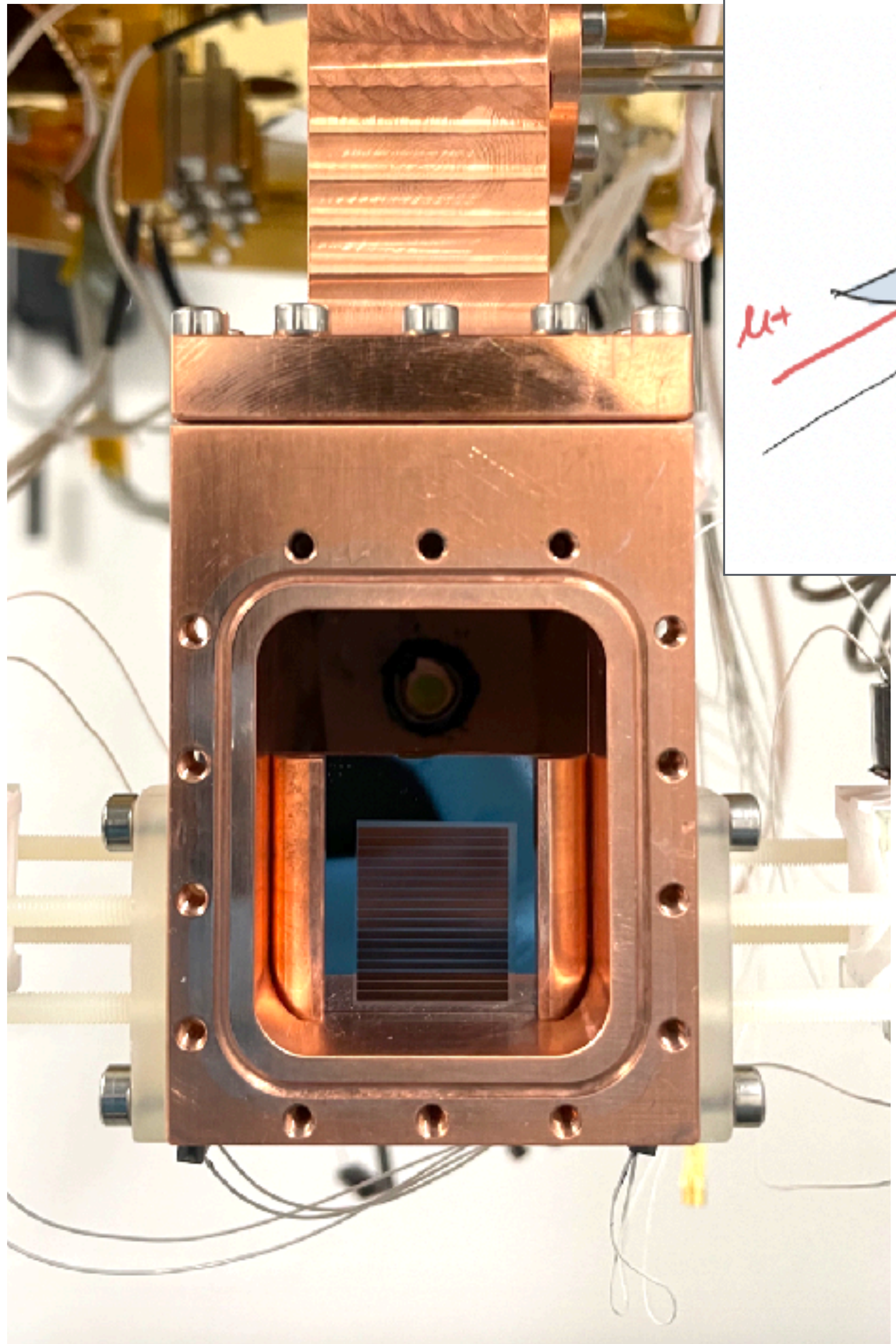
Beamtime 2023 - Horizontal Muonium Beam

Reflection

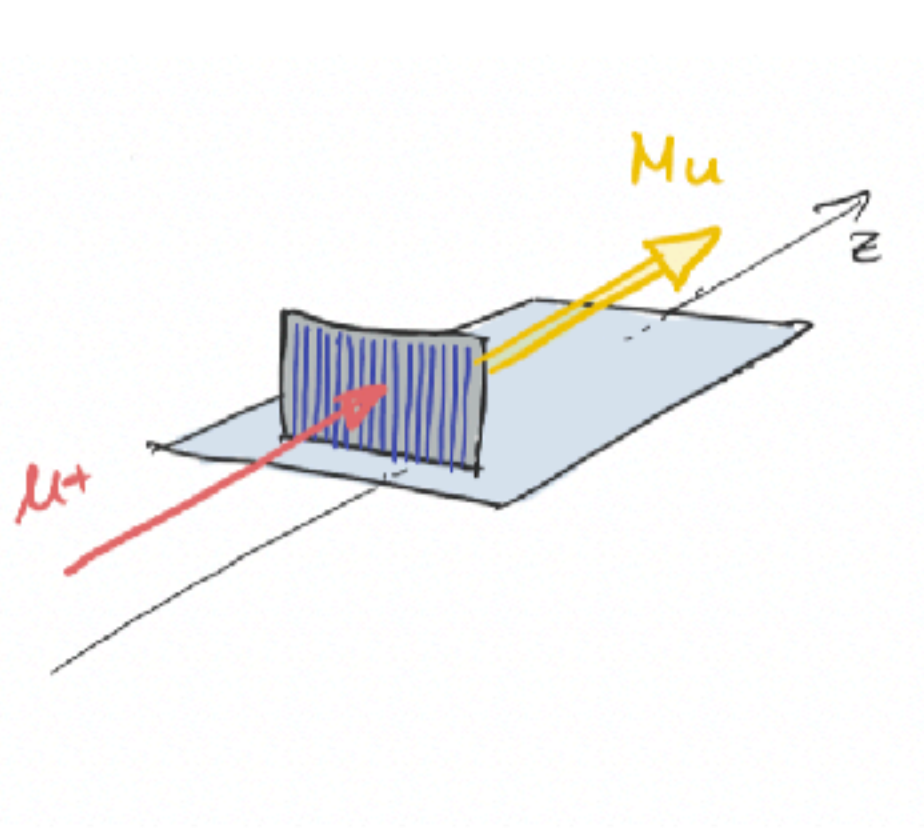




Necessary for the interferometer
Hugely influencing the yield (decay losses)

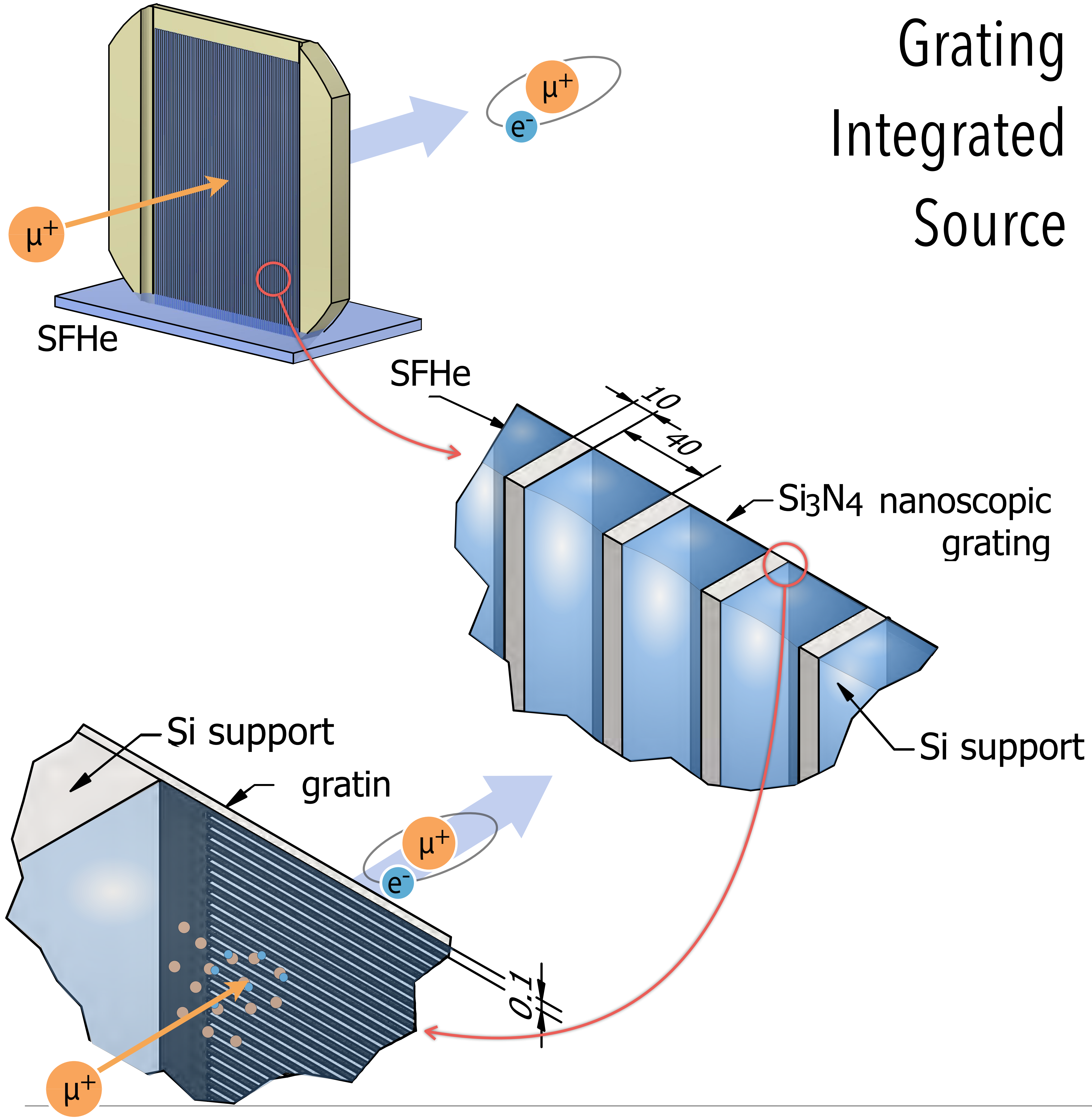


Microfluidic grating

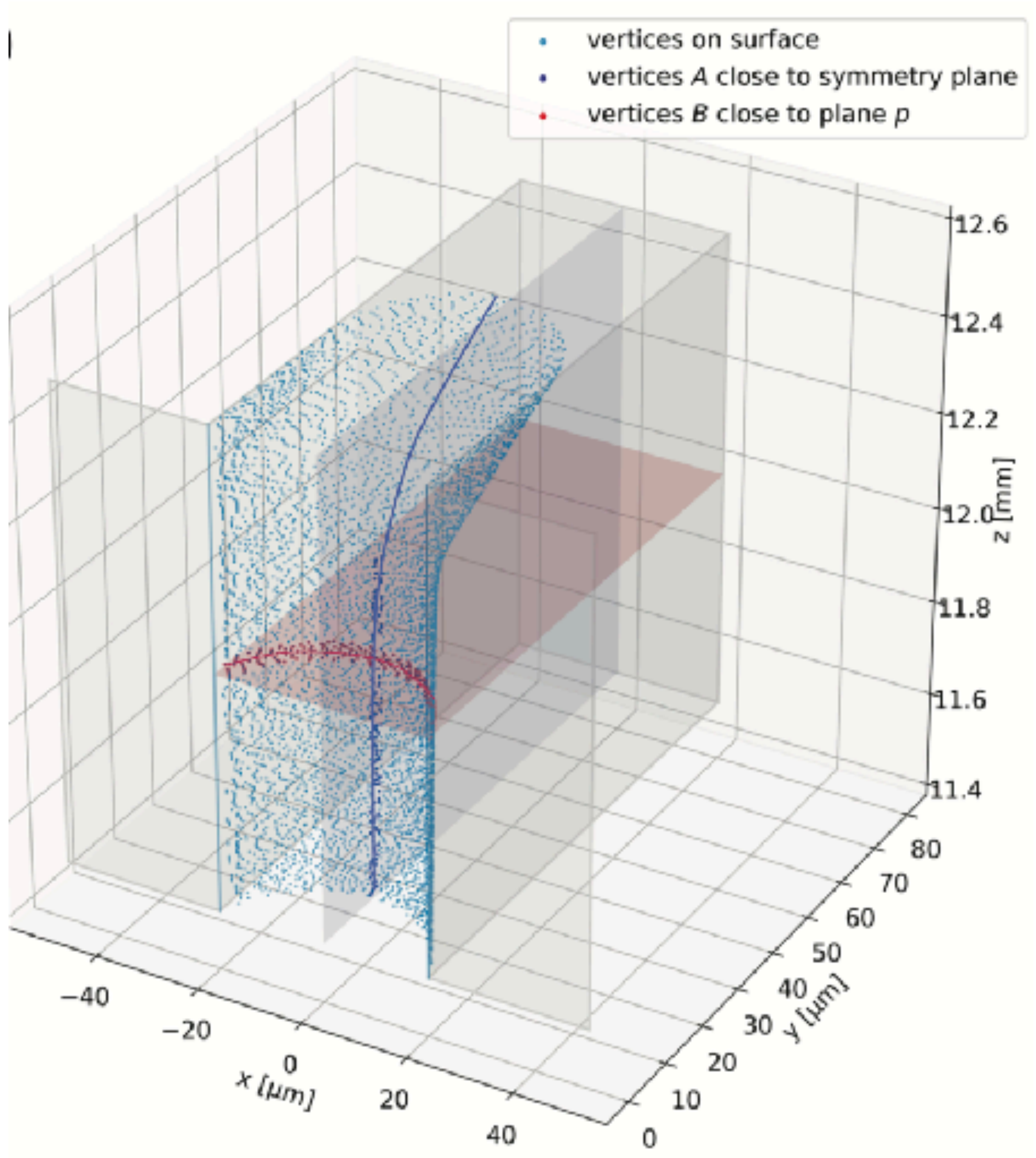


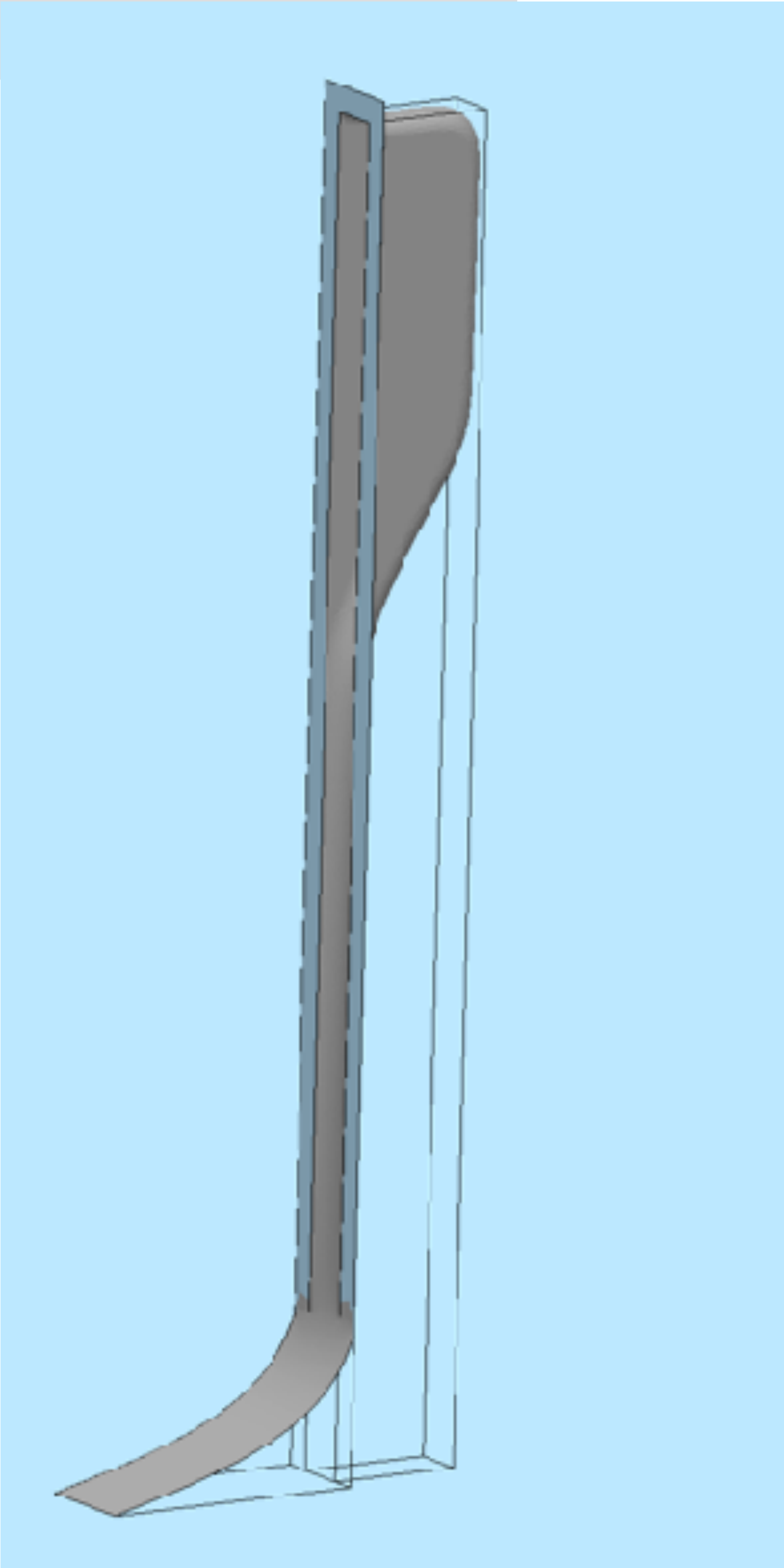
Horizontal Muonium Beam - Concept

Grating
Integrated
Source



SFHe suspended by the capillary force, between support bars behind the first Si3N4 membrane

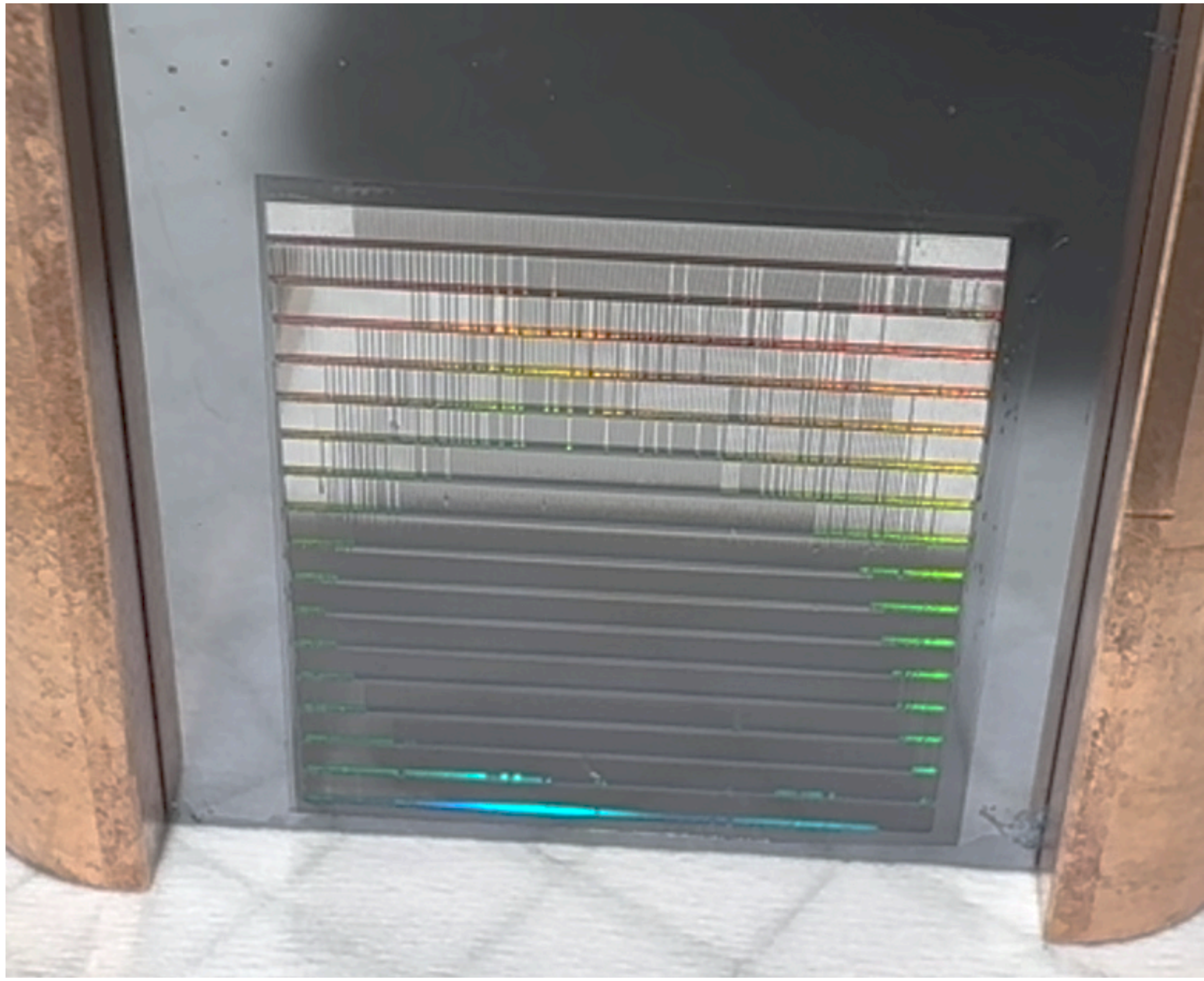




Horizontal Muonium Beam - Microfluidic Target in Action

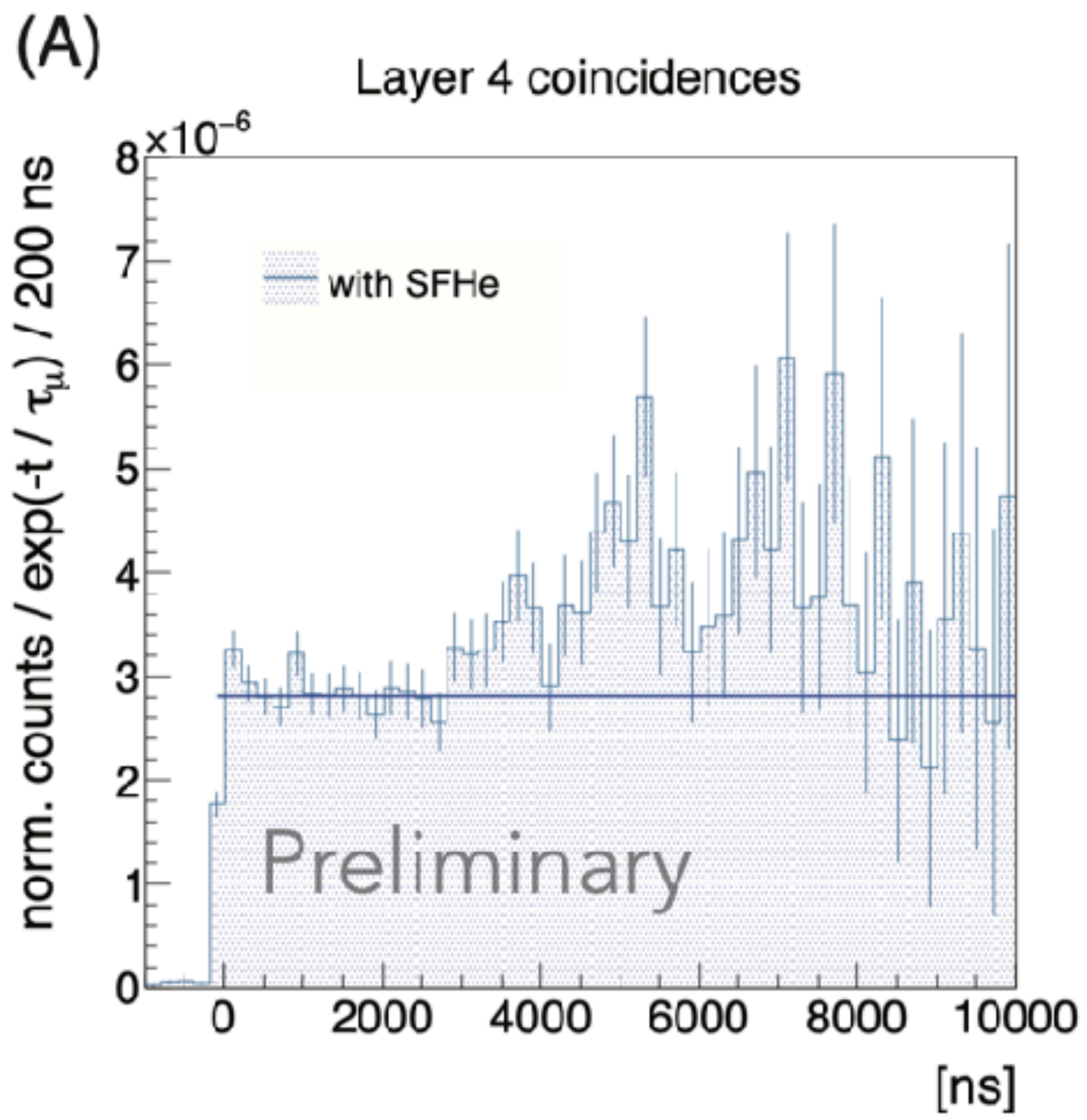
Capillary effect (with acetone)

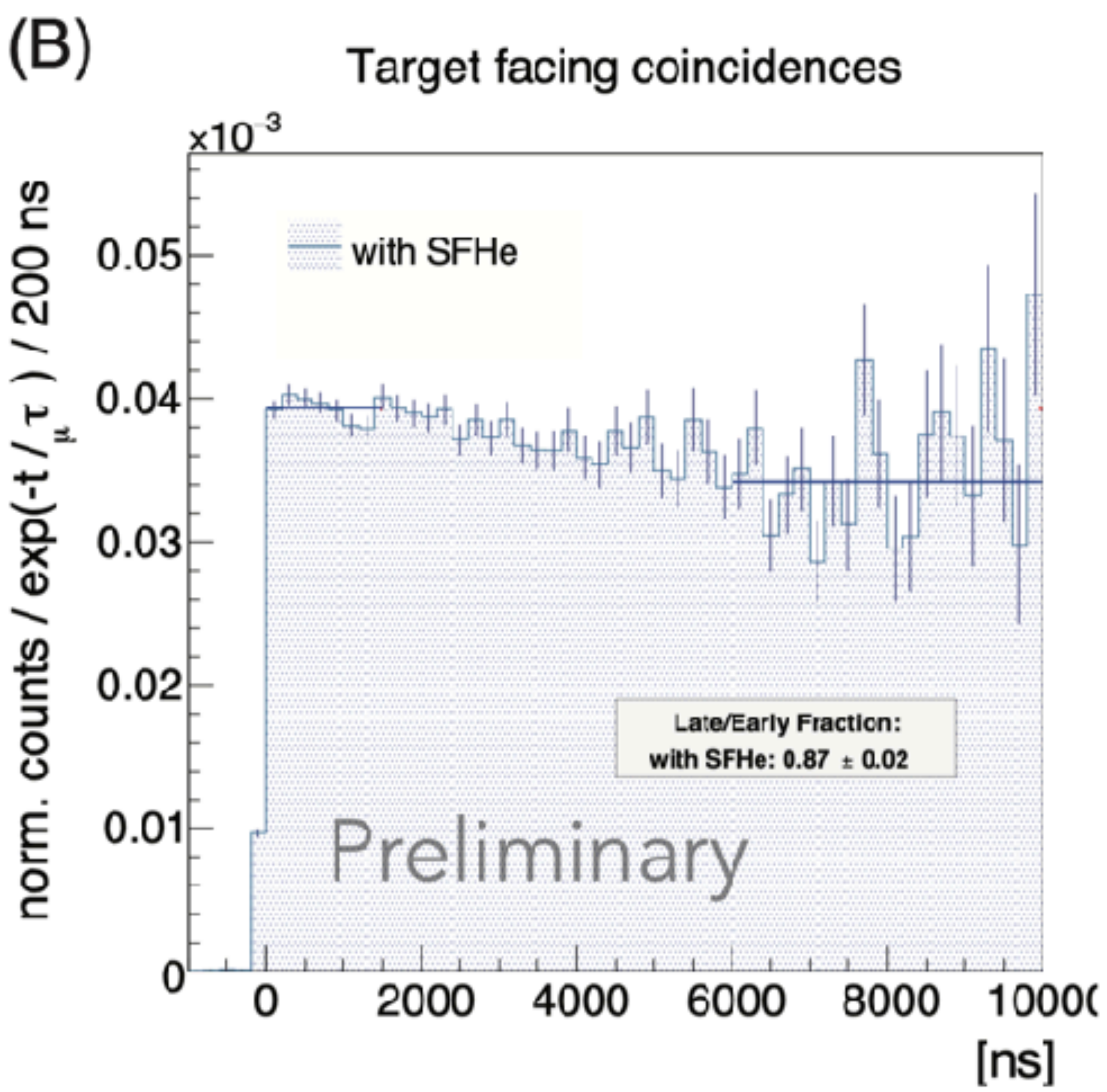
Drying out

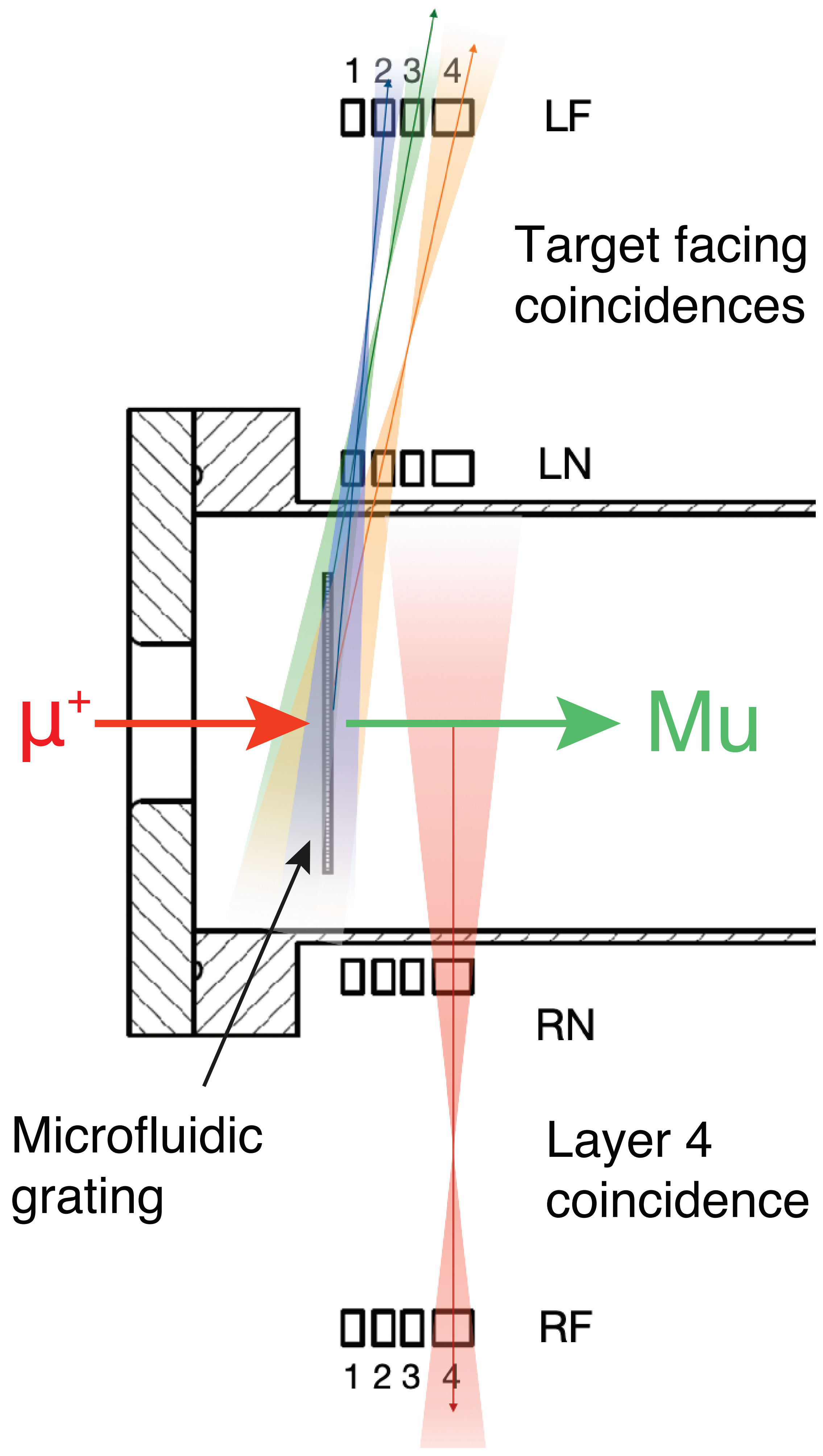


LEMING

Horizontal Muonium Beam - Measurements





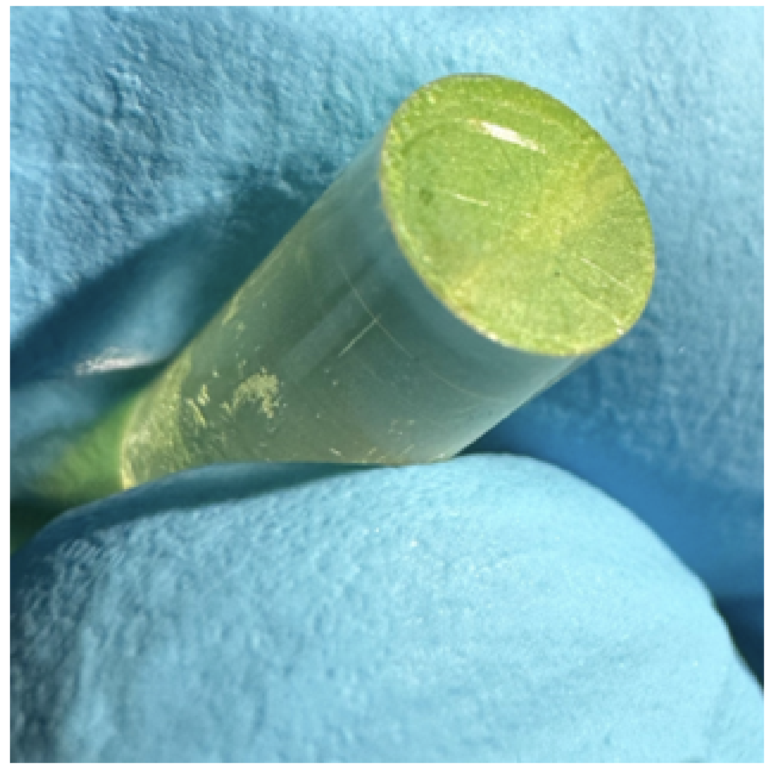


- Clear emission of Mu from the microfluidic target
- Stopped muon to vacuum muonium conversion efficiency seems ca. 1/2 of the free surface emission
- Effected by background, further studies are needed

Ongoing Developments - Cryogenic detectors

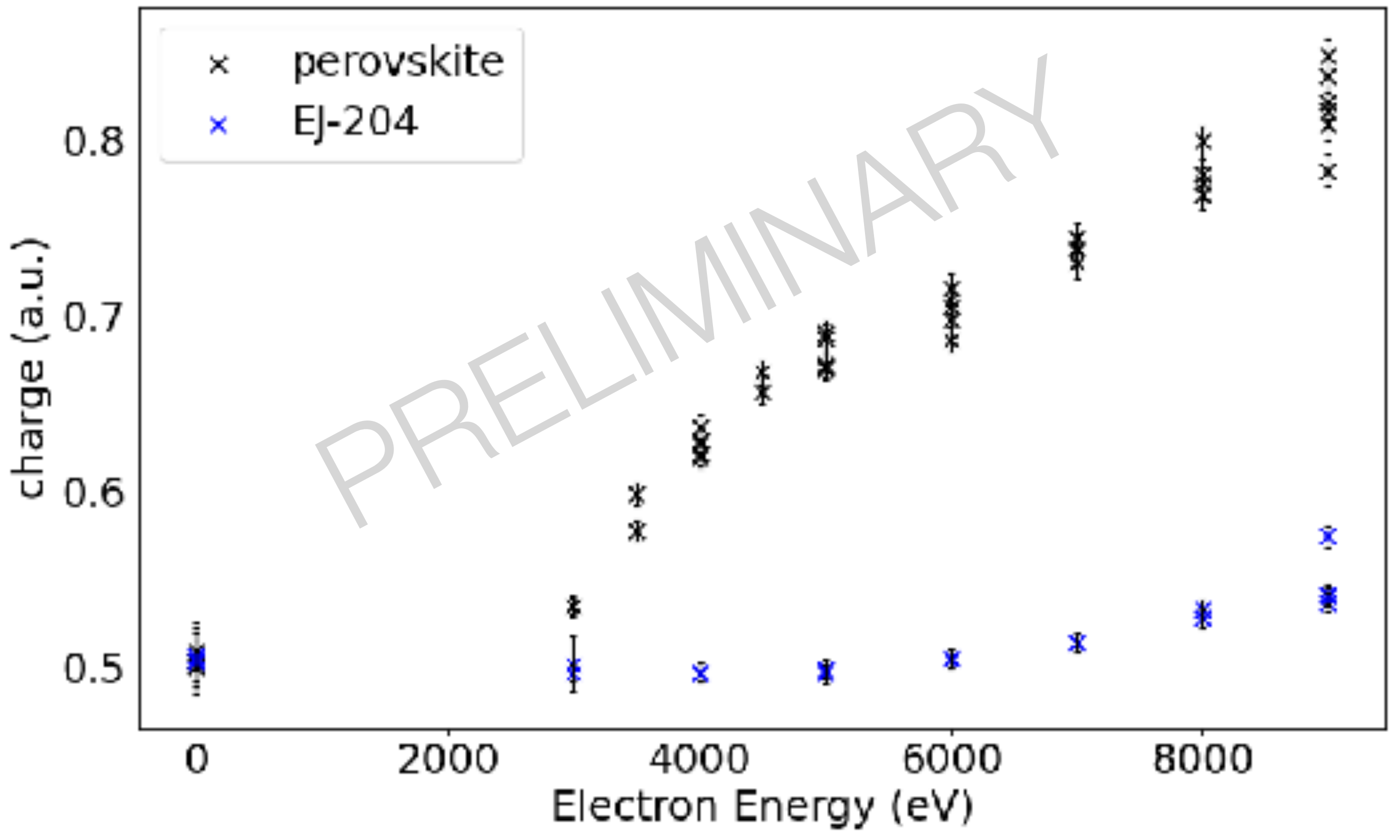
Atomic e^- Detector

- Challenging due to low energy of electron and presence of superfluid helium



Perovskite nanocrystals

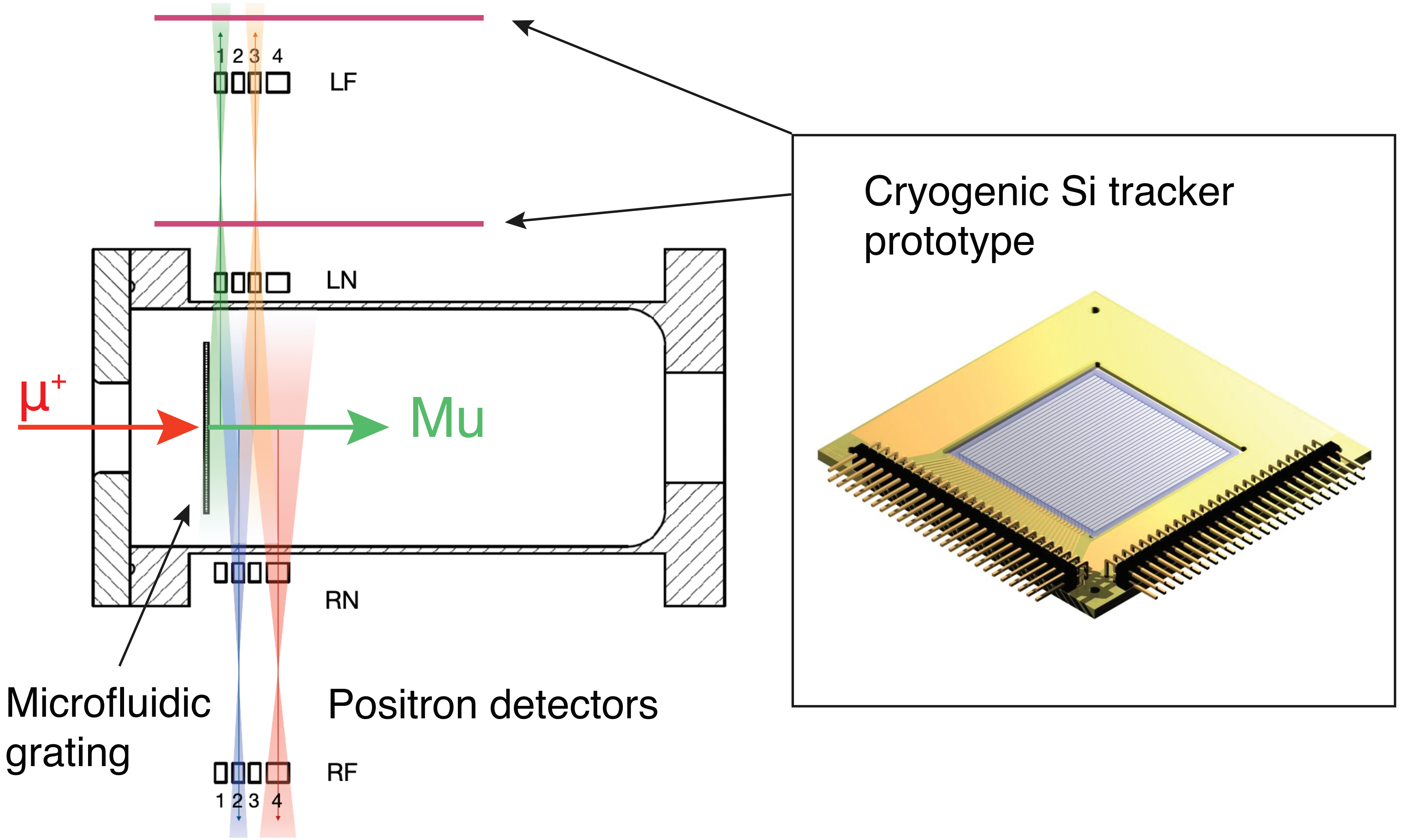
- CsPbBr shows remarkable scintillation properties at cryogenic temperatures [V. B. Mykhaylyk et al., Nature 10, 8601 (2020)]
- CsPbBr has higher light yield than EJ-204 at cryogenic temperatures
- Low voltage onset, 3+ kV



Positron Detectors

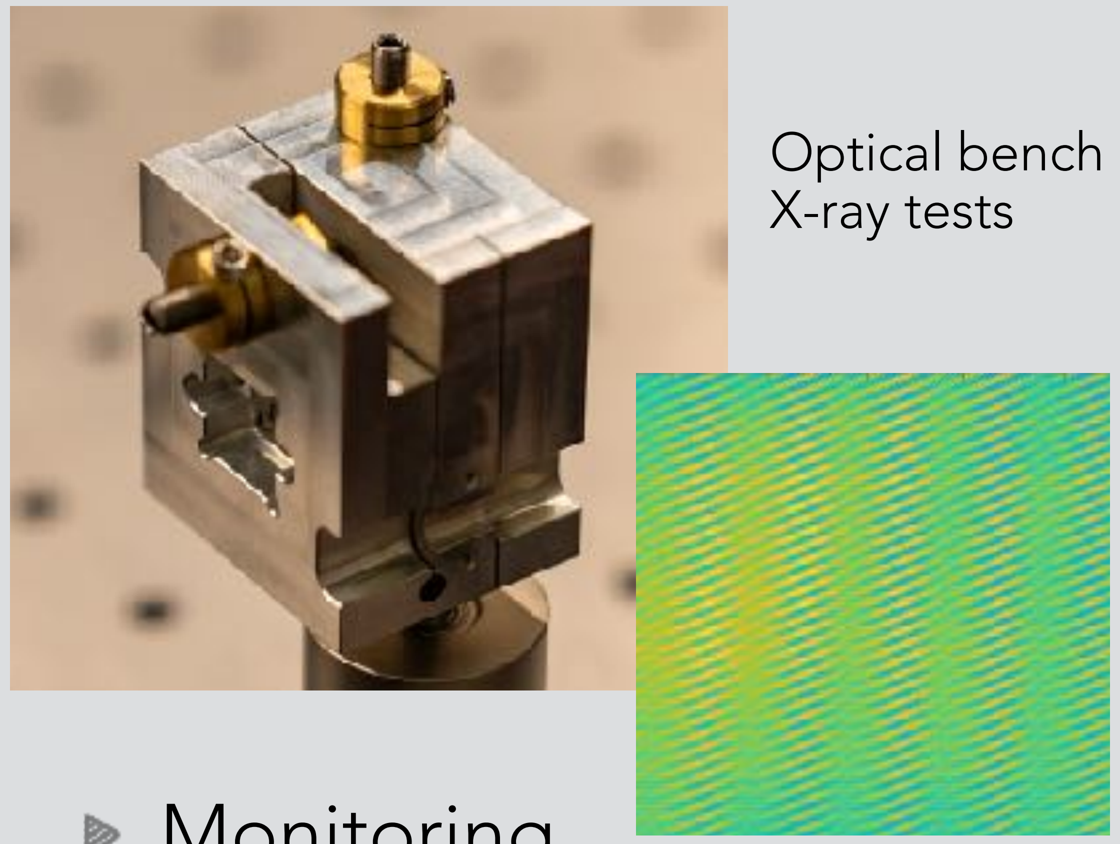
- Upgrade trackers
- Maximize solid angle coverage

Cryogenic Silicon Strip Detectors

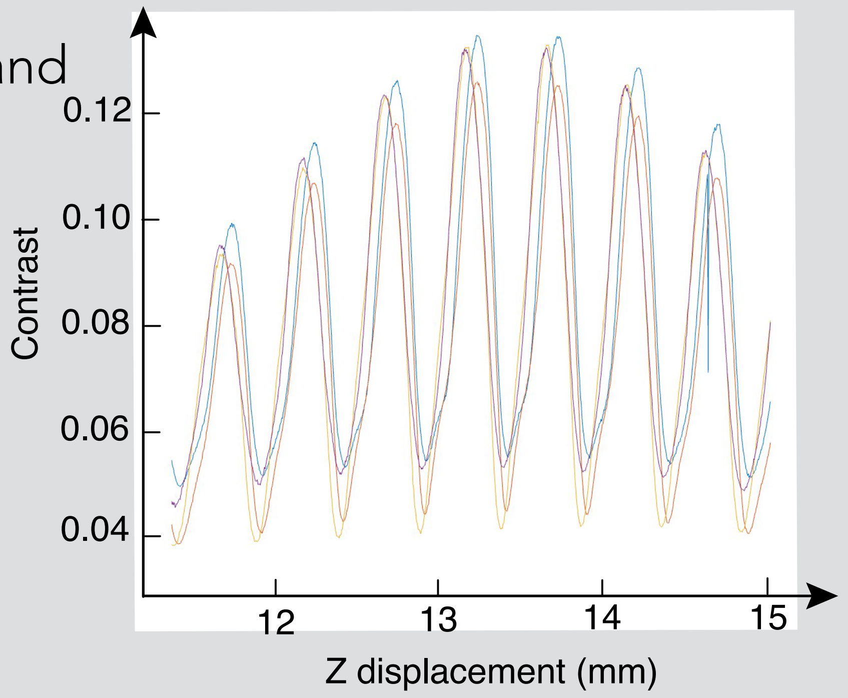


Ongoing Developments - Interferometer

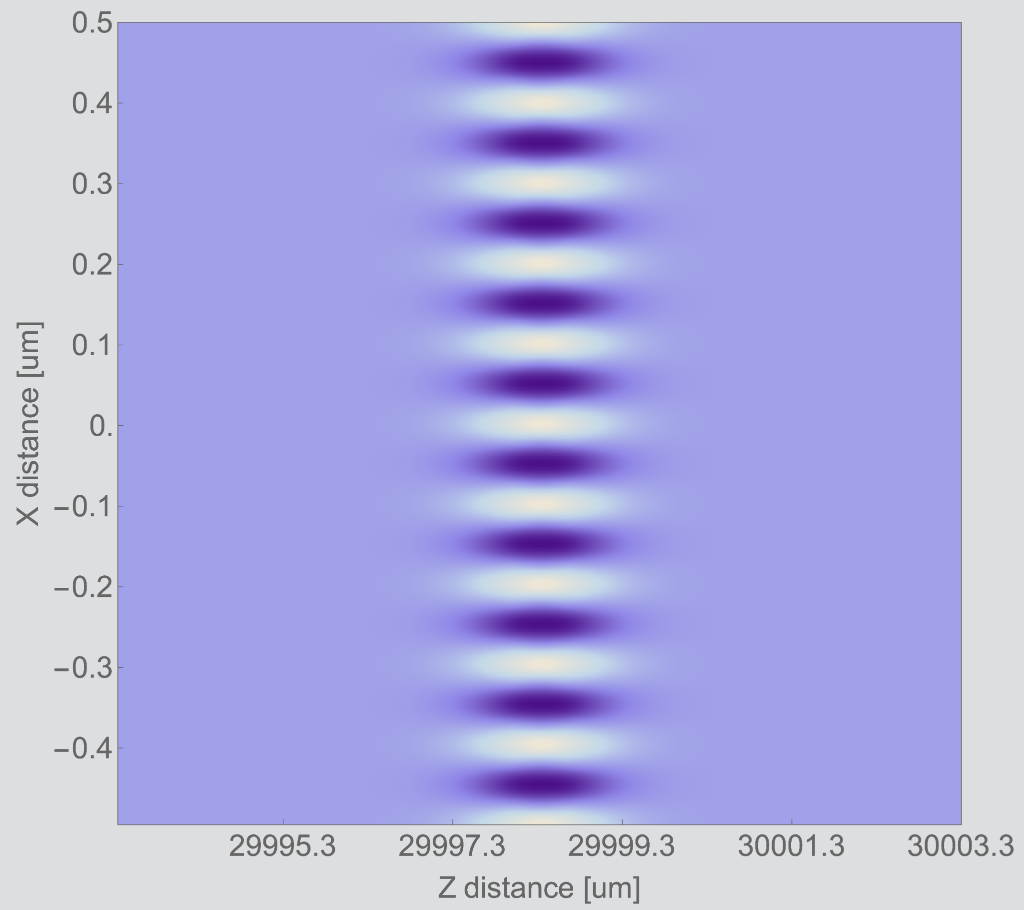
Scanning, stabilization, calibration



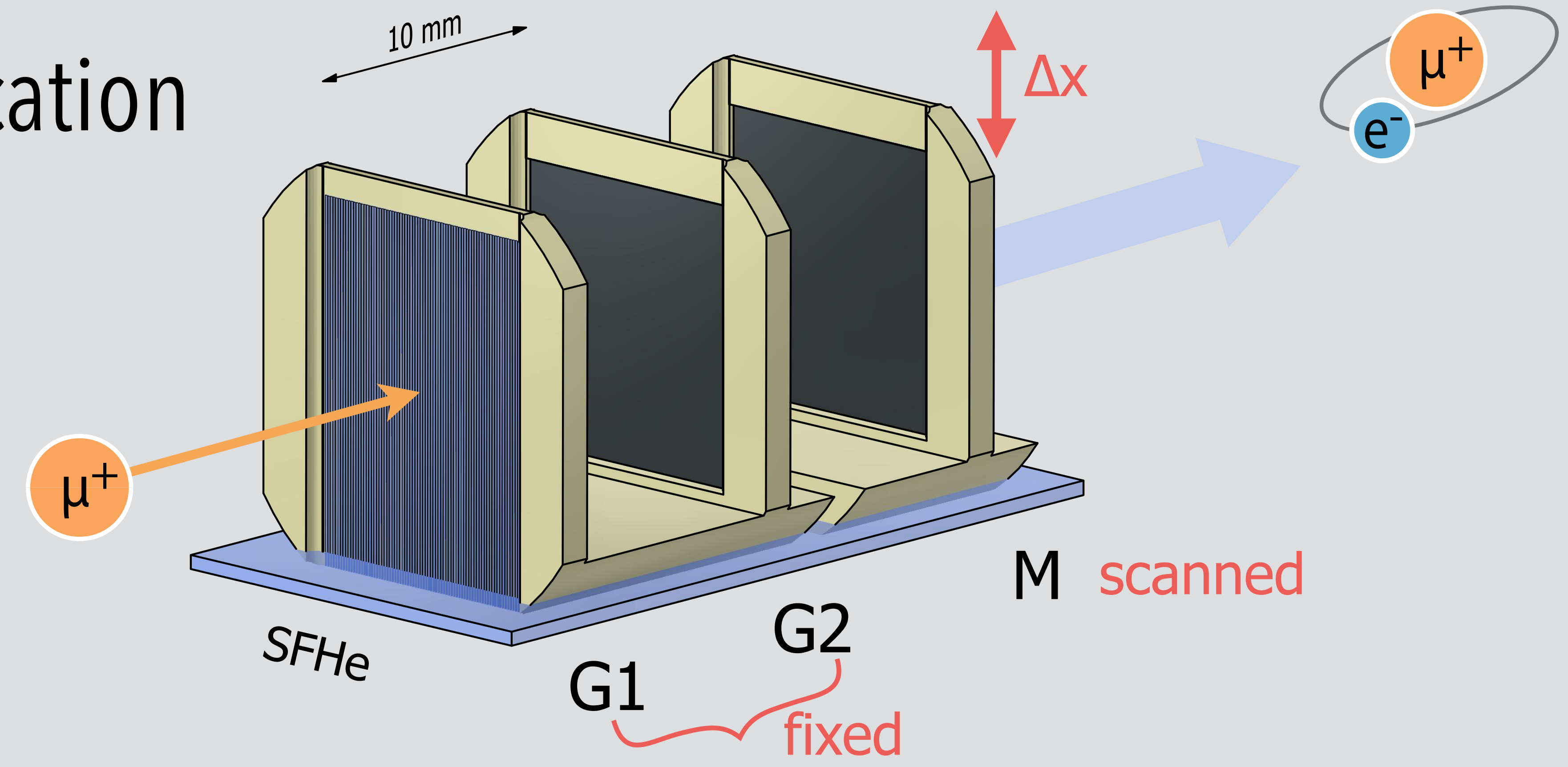
Optical bench and X-ray tests

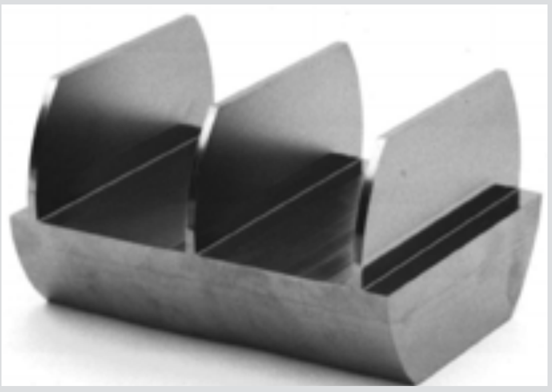


- Monitoring alignment with Fabry-Perot (~10 pm)
- Vertical scanning (~pm) with piezo actuators
- Calibration sources: X-rays and UV laser



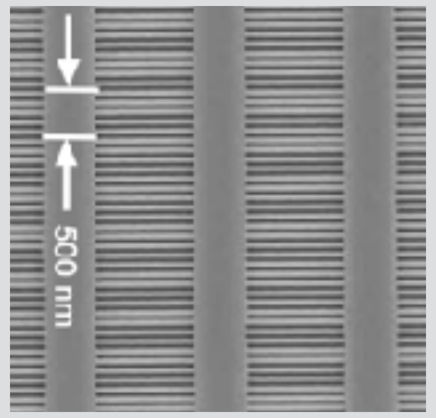
Fabrication



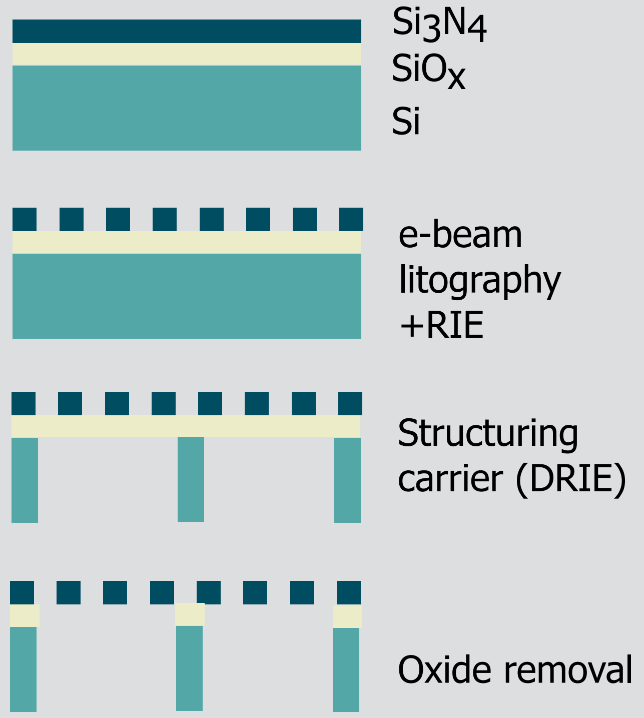


Mono-crystalline Si raft

+



Free standing Si_3N_4



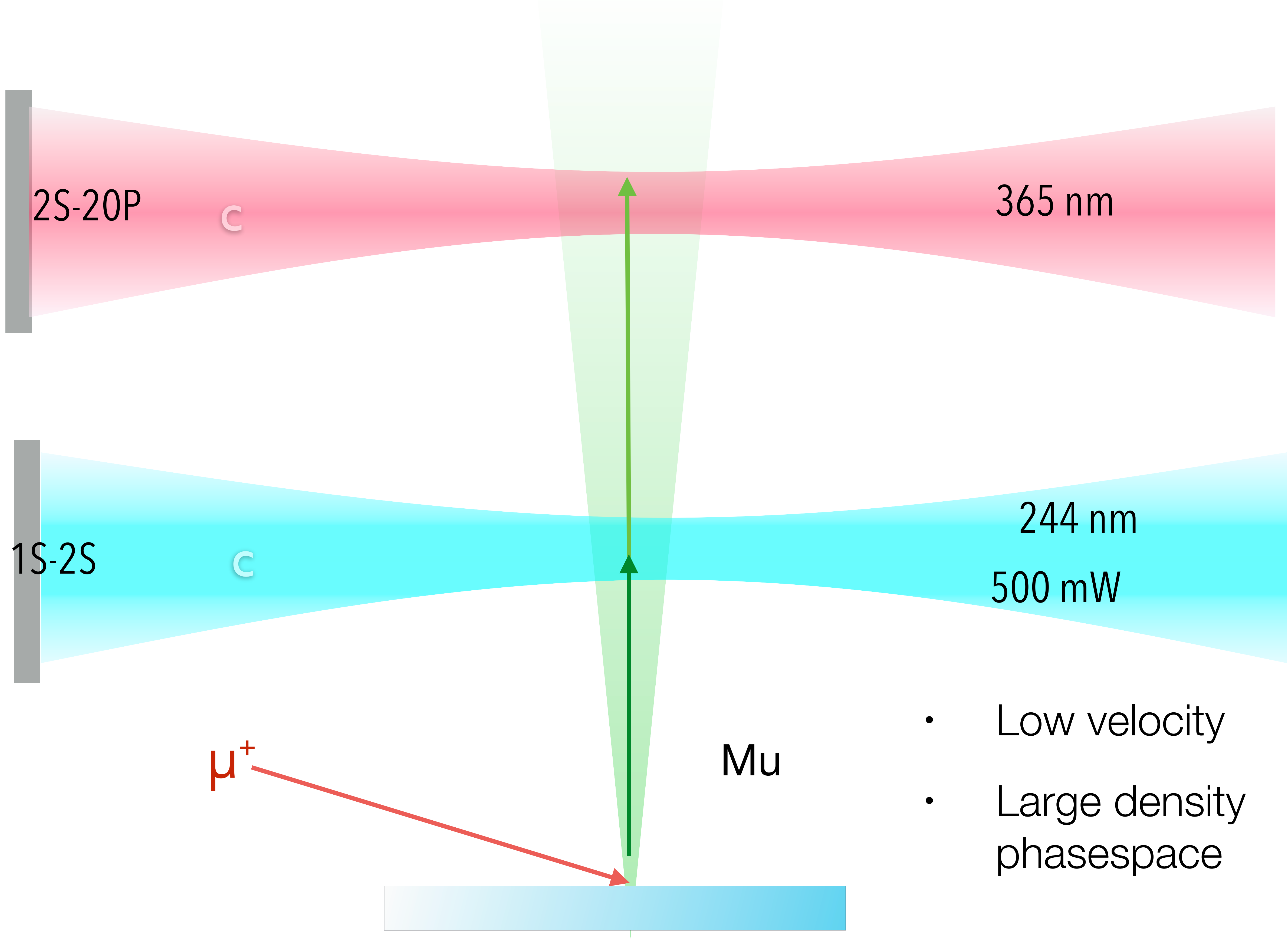
- Fabrication of mono-crystalline Si raft and free standing Si_3N_4 grating separately

Outlook on Spectroscopy

Possible improvements on **Precision Spectroscopy**

- We are producing the **same amount of Mu** compared to room temperature sources but in a **small, directed beam**
- Potential collaboration with MuMASS for 1S-2S spectroscopy
- **Increased statistics** > 1 OM (compared to previous MuMASS source)
- **reduced atom velocity** v
  - **Reduced transit-time broadening** $\sim 1/3$**:**
    - $\Delta\nu \approx 0.4\frac{v}{w}$, with w the waist size
  - **Reduced second order Doppler shift** $\sim 1/10$**:**
    - $\Delta\nu \approx -\nu_0\frac{v^2}{2c^2}$, with $\nu_0 = 2.46 \cdot 10^{15}$ Hz
    - correction via lineshape modelling if velocity distribution known

Mu-Mass



- Low velocity
- Large density phasespace

Thank you for your Attention!