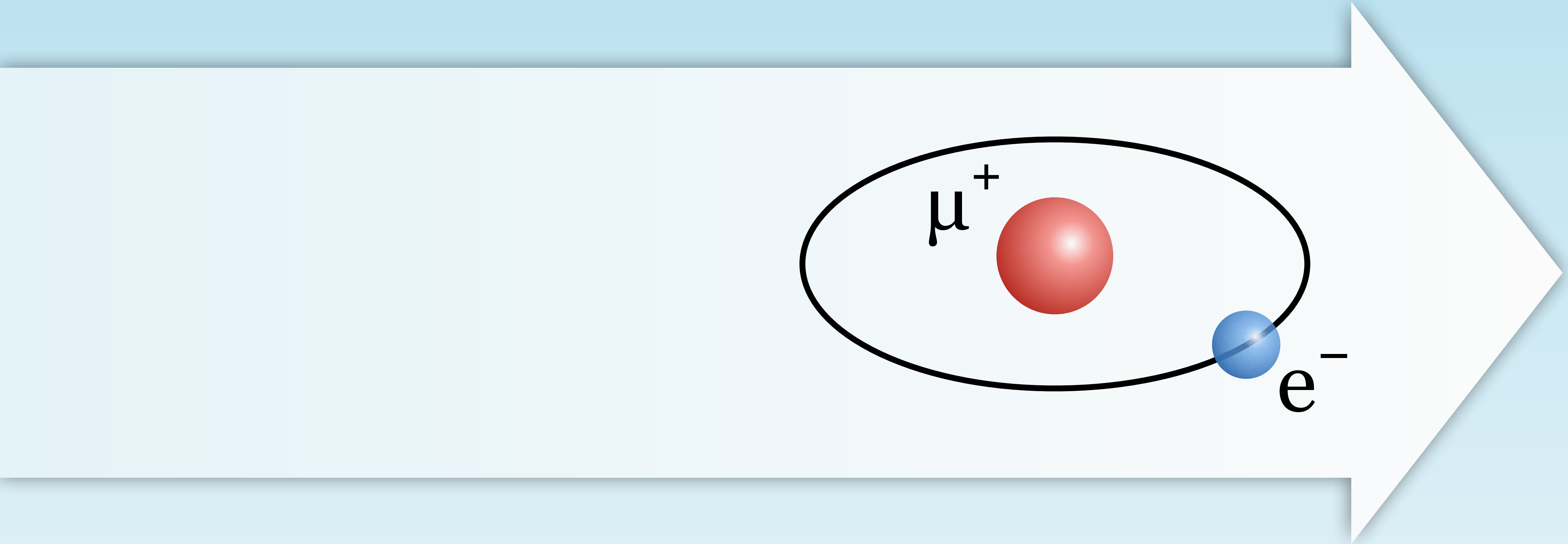
Prospects of a weak equivalence test using muonium atoms



Anna Soter

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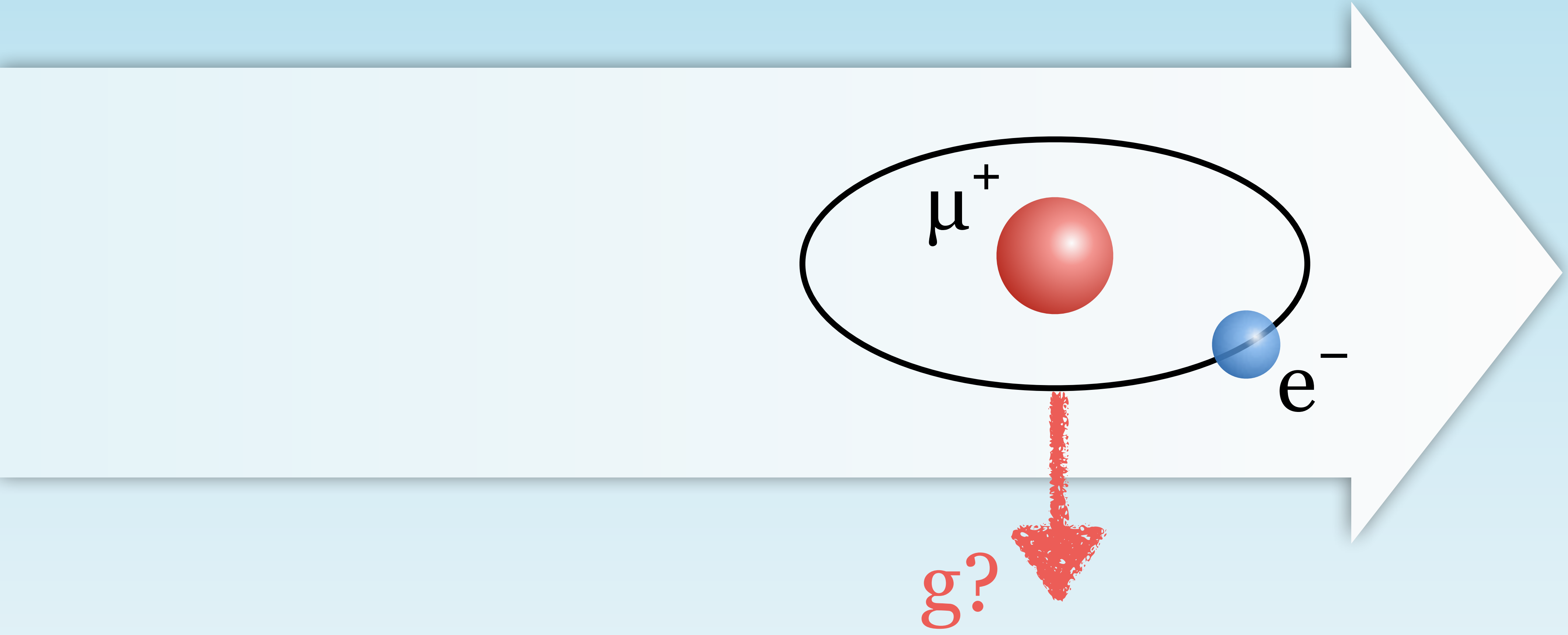
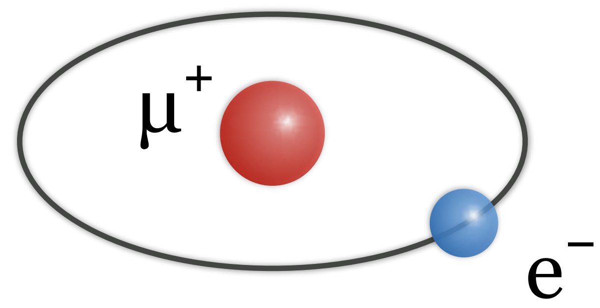
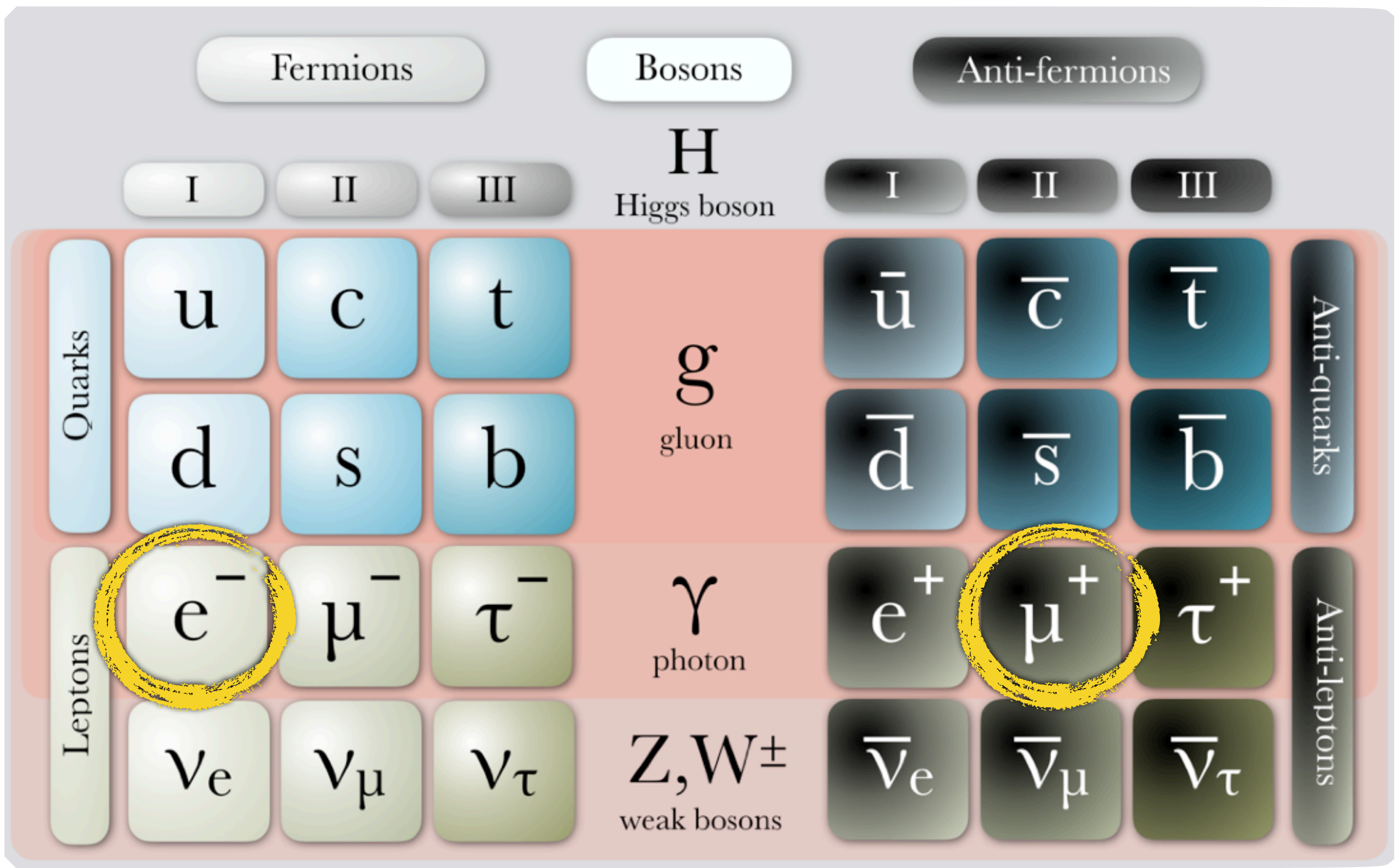


Anna Soter

Fundamental physics using muonium atoms

- Purely leptonic, exotic atom
- No finite size / hadronic effects





1s-2s and HFS Spectroscopy: MuMASS / P. Crivelli

- Fundamental constants (m_μ , μ_μ , R_∞)
- Test of QED and fundamental symmetries (q_μ / q_e)
- Effects many precision measurements, like muon *g-2*

Muonium HFS (22 ppb) or **future Mu-Mass 1 ppb**

Storage ring [~200 ppb]

$$\frac{g-2}{2} = \frac{m_\mu}{e}\frac{\omega_a}{B} = \frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}\frac{\omega_a}{\omega_p}$$

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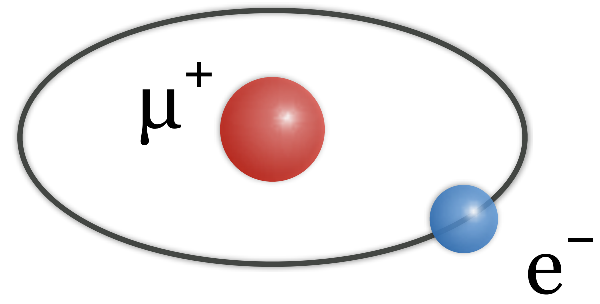

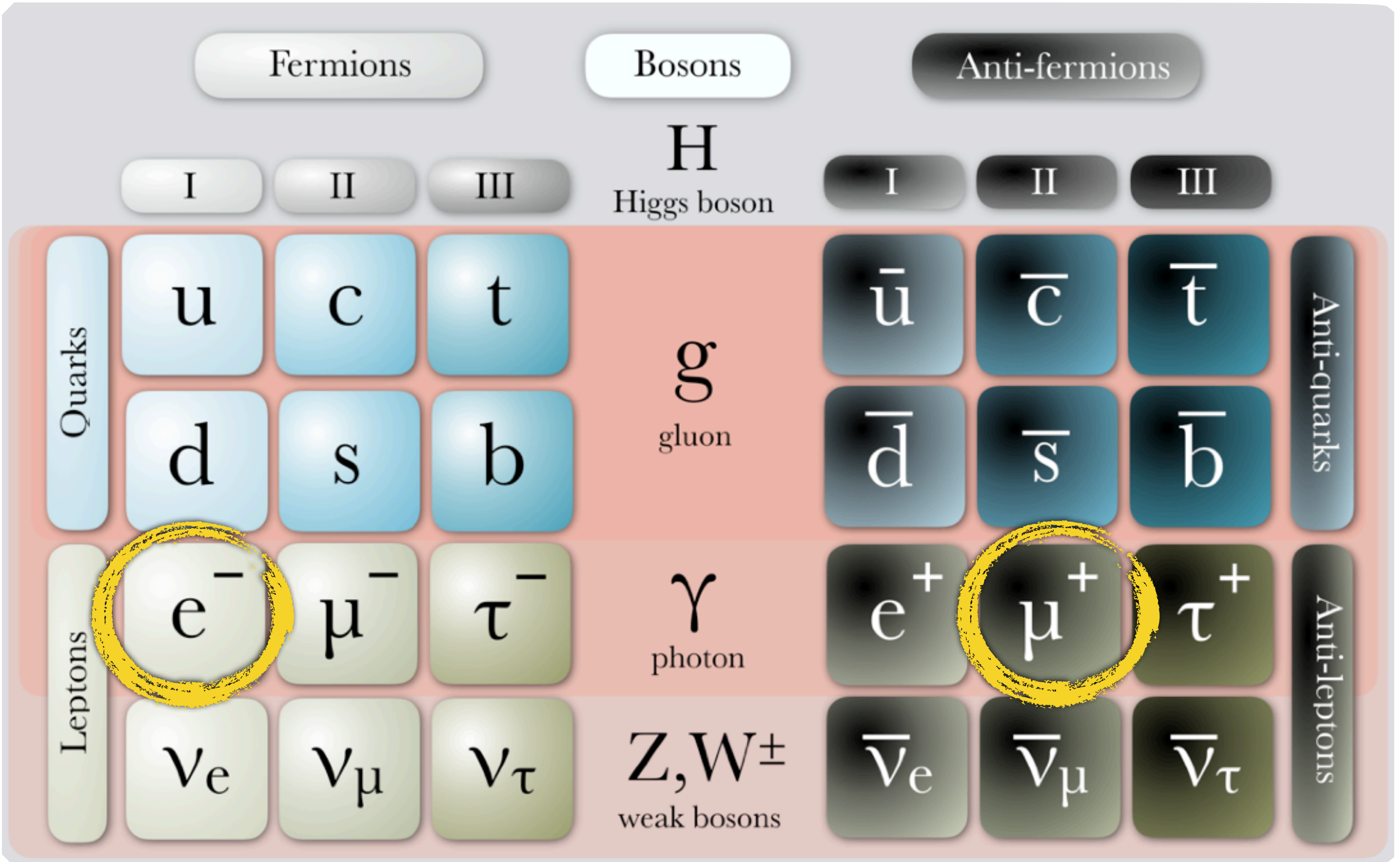

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Electron g-2 + QED [0.26 ppt] → $g_e / 2$

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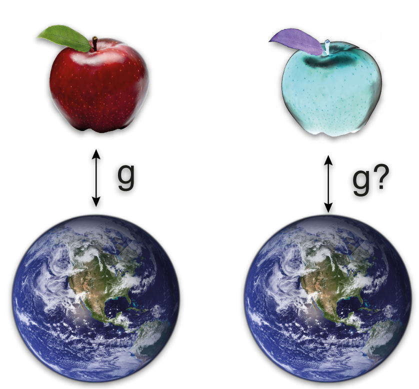

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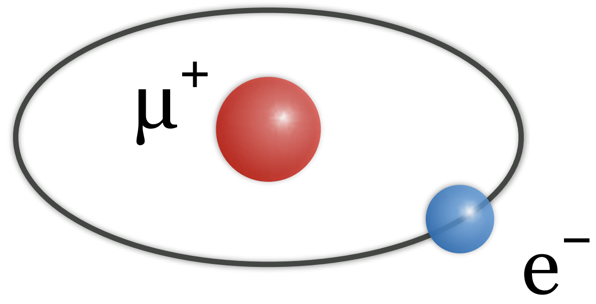

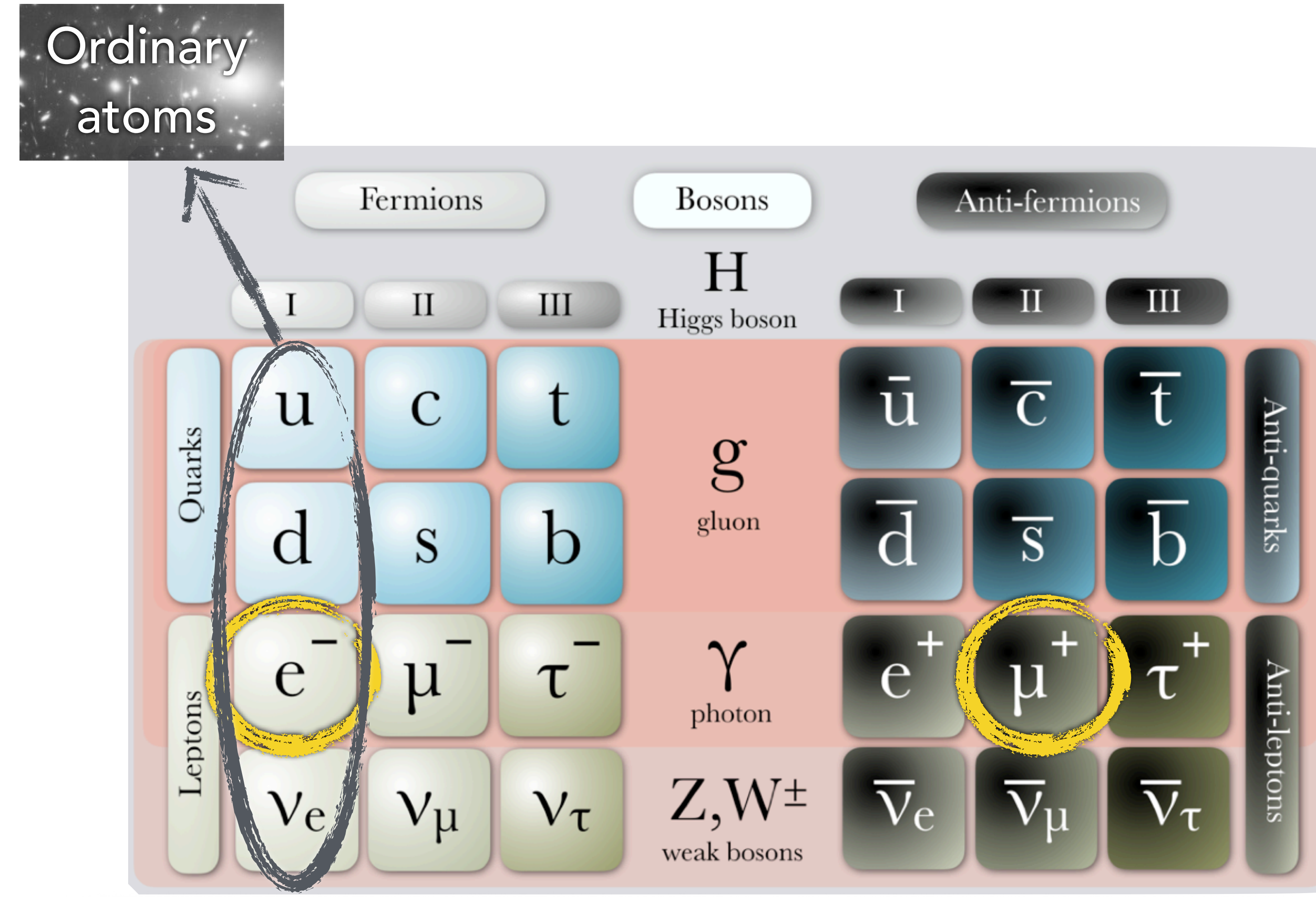

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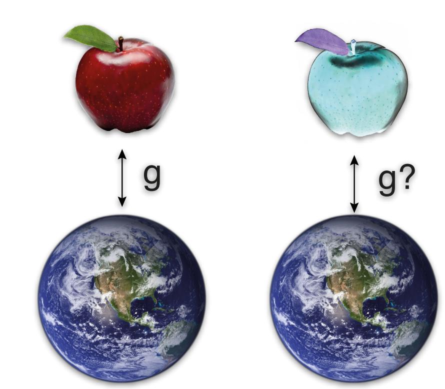

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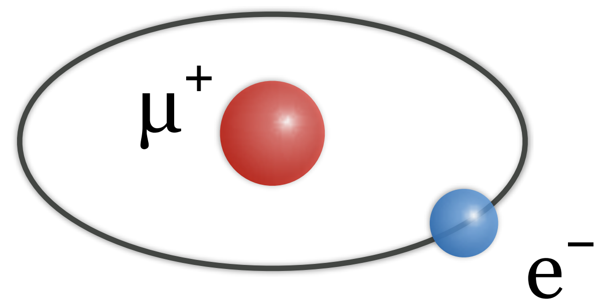

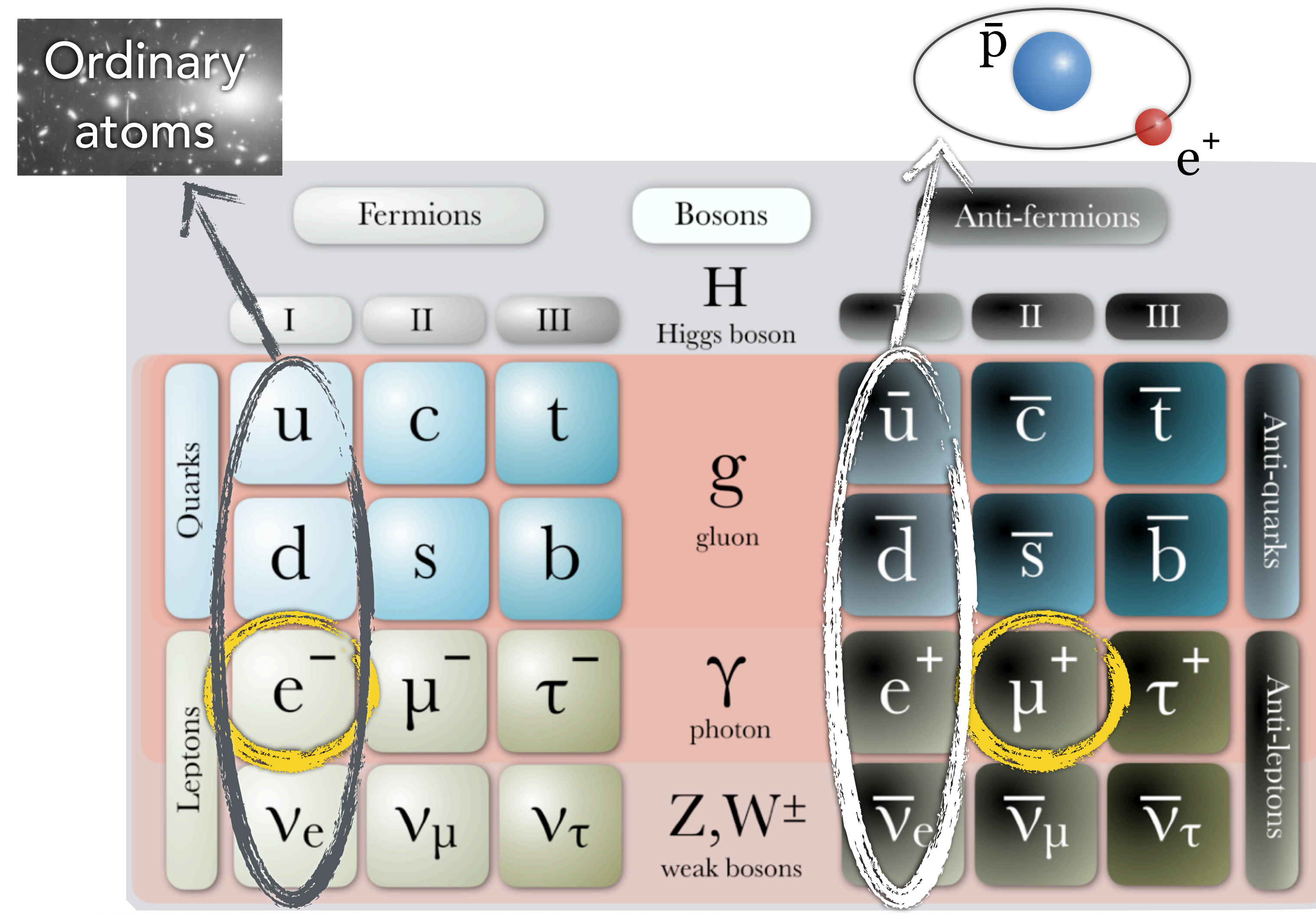

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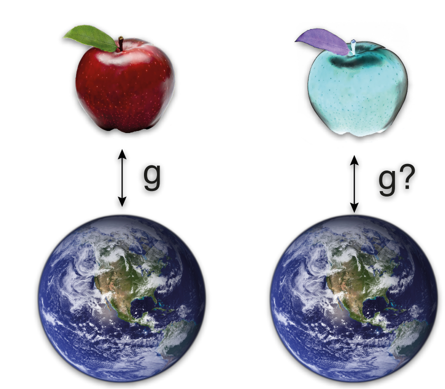

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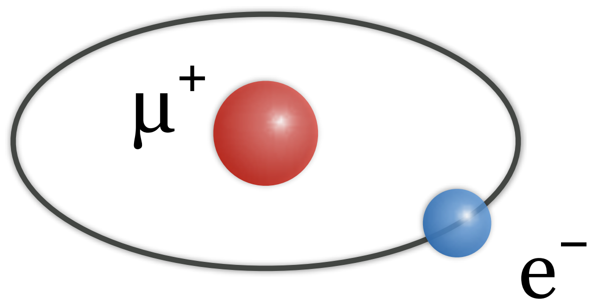

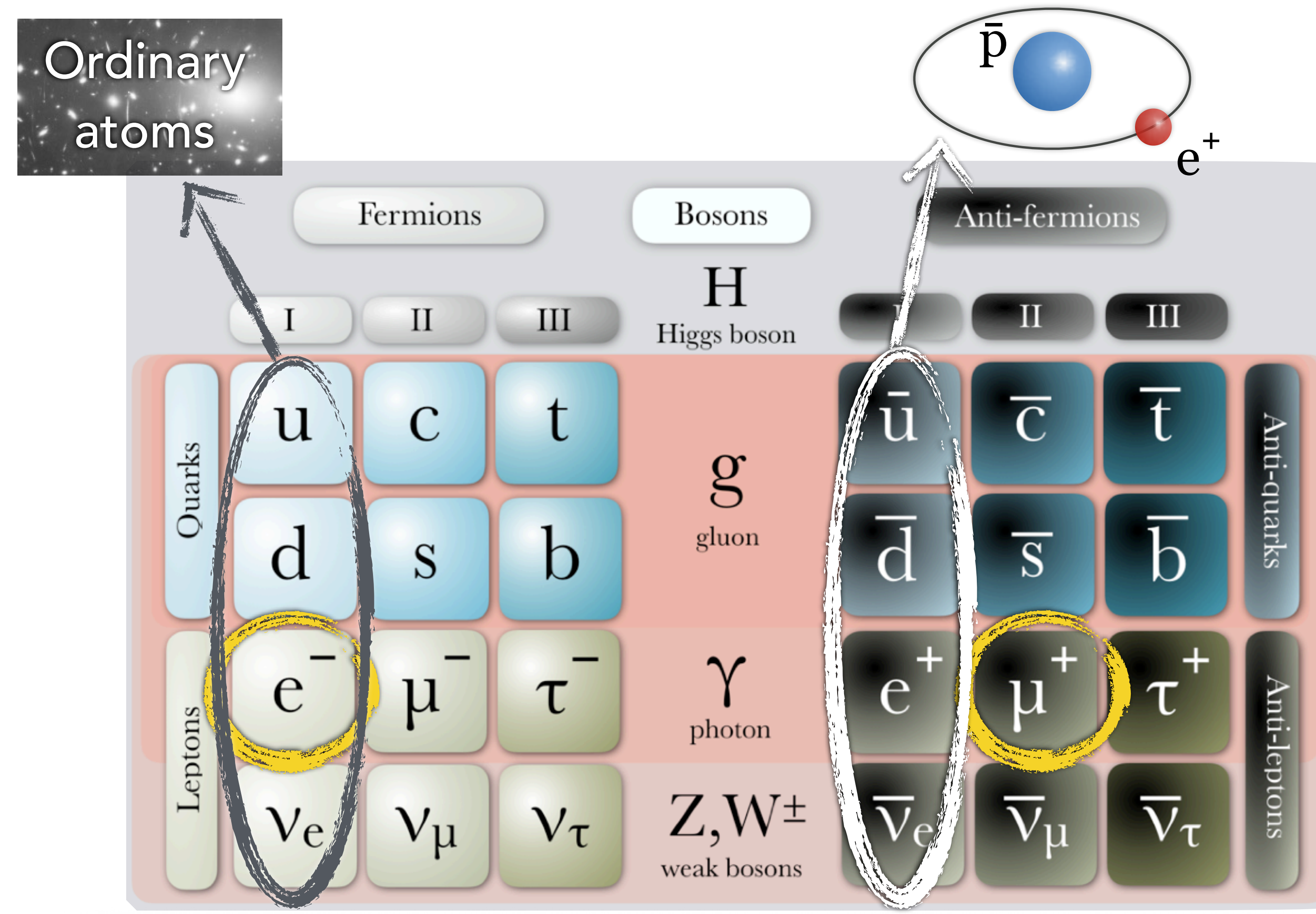

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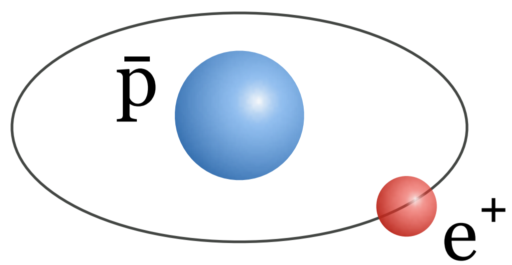
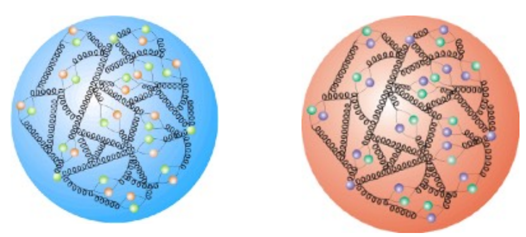
Comparing the neutral candidates for exotic gravity tests

Antihydrogen ($\bar{H}$)



$\bar{p}$ - **composite antimatter**, ~99% of rest mass: binding E

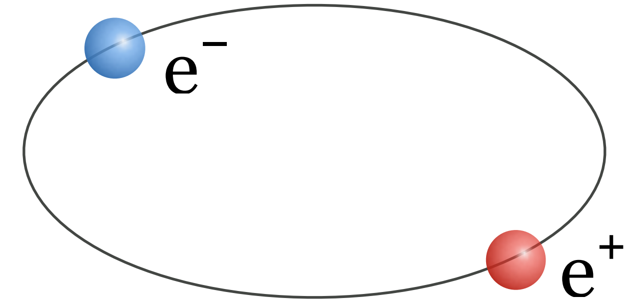


the **only stable candidate**, but:

- hard to produce
- only low number of sufficiently cold atoms

Experiments running at CERN: ALPHA, AEgIS, GBAR

Positronium (Ps)

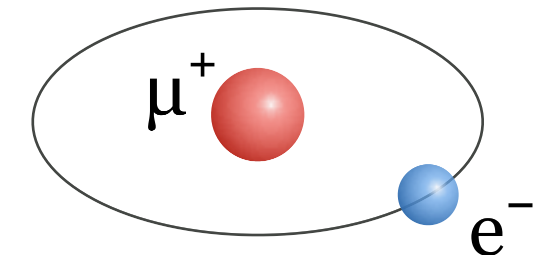


50% antimatter, 1st family. Only **'table-top' candidate**, but:

- extreme **short lifetime (~140 ns)** on the ground state - high-ℓ Rydberg state is needed
- Rydberg Ps: sensitive to external EM forces

Experiments proposed in UCL, ETHZ, Bern, Milano…

Muonium (Mu)

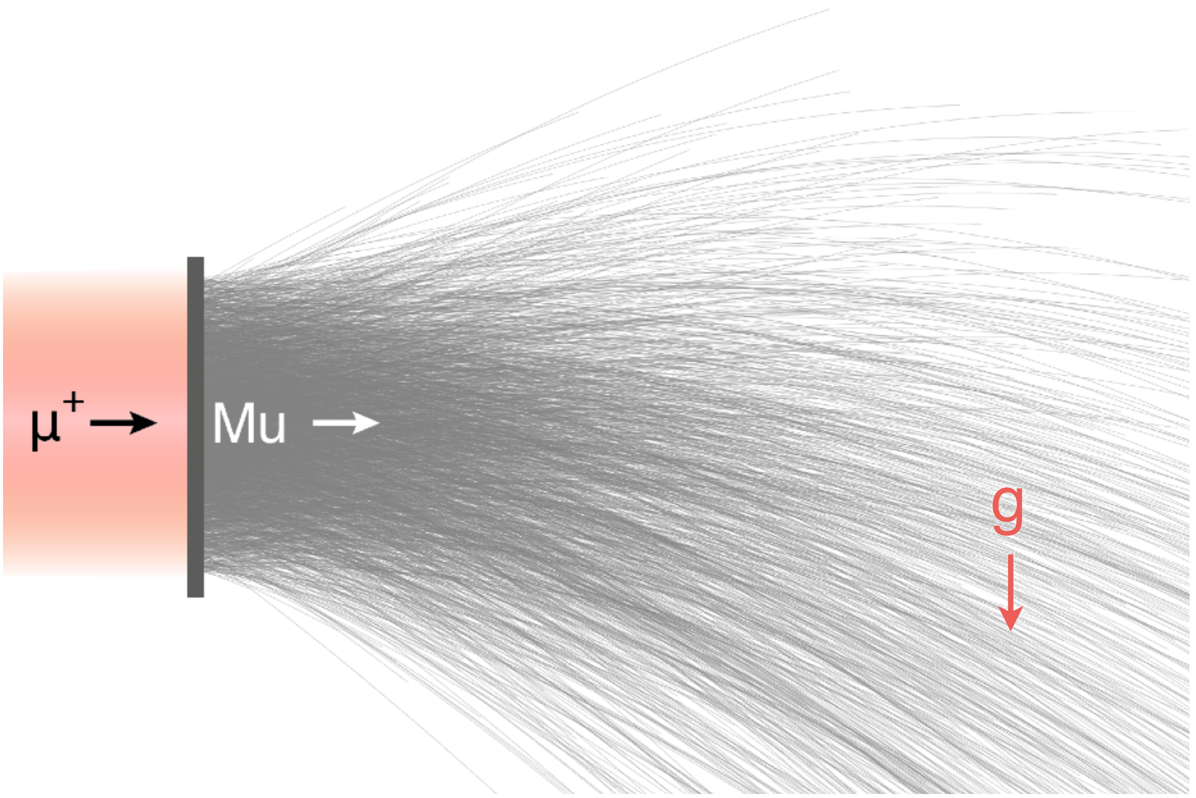


mass is 200:1 dominated by μ^+

- **elementary antiparticle**
- **second generation** lepton

- can be produced in large numbers, with accelerators
- relatively insensitive to external EM forces
- still short lifetime 2.2 us

How to measure gravity of muonium?



Method: free fall of a Mu beam

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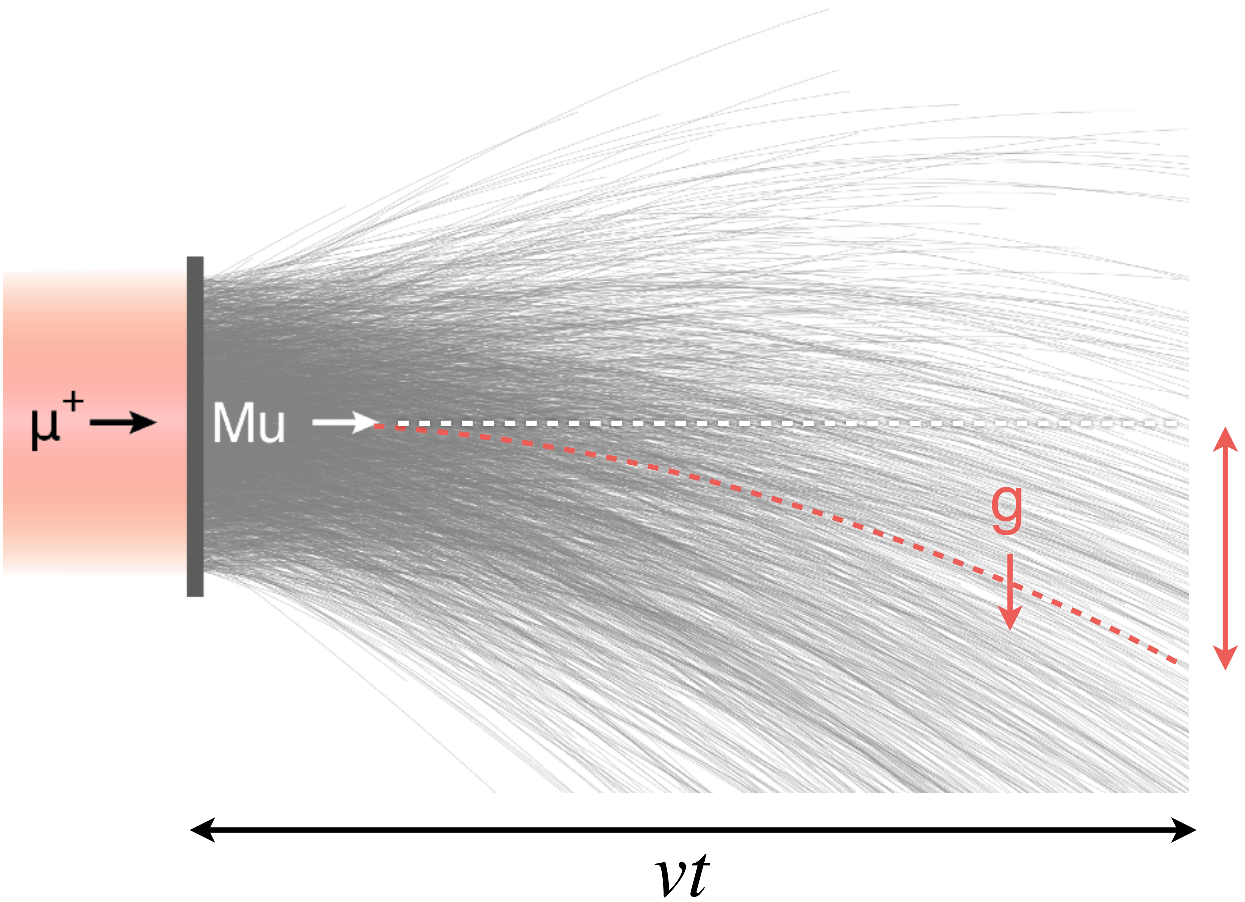

Method: free fall of a Mu beam

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

Inherent challenge: Mu lifetime of 2.2 μs

$$\Delta x < 1 \text{ nm}$$

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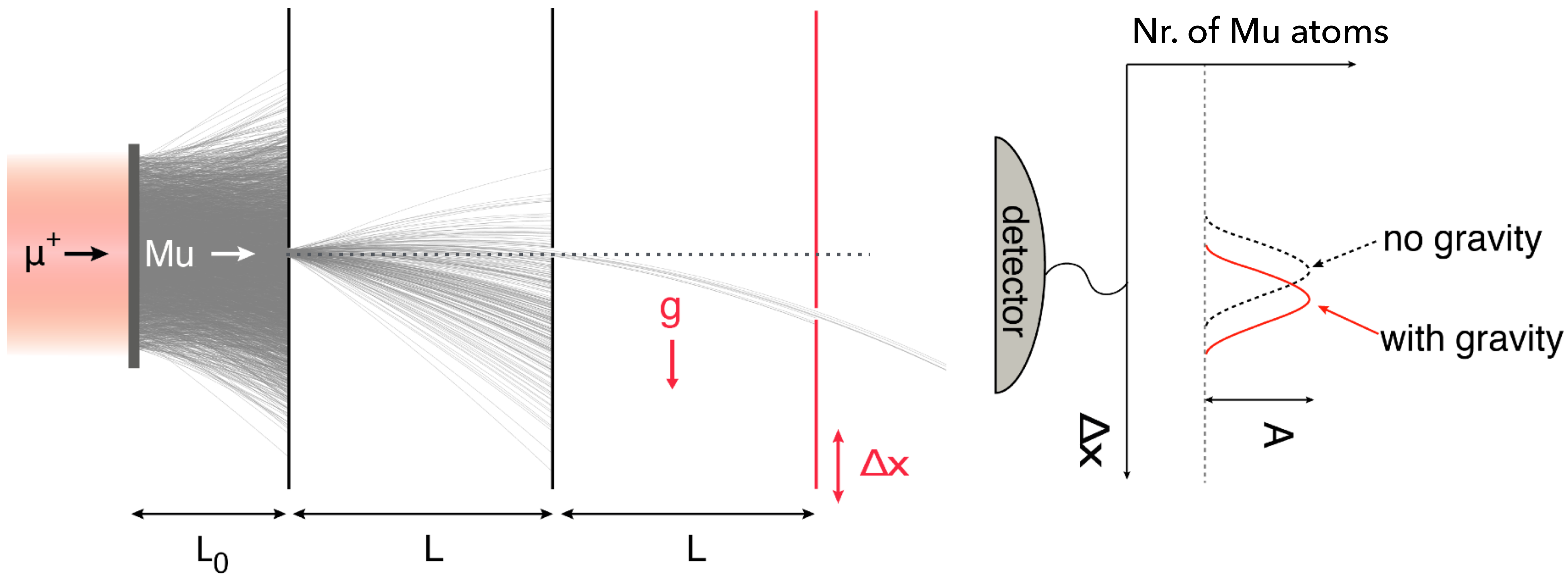

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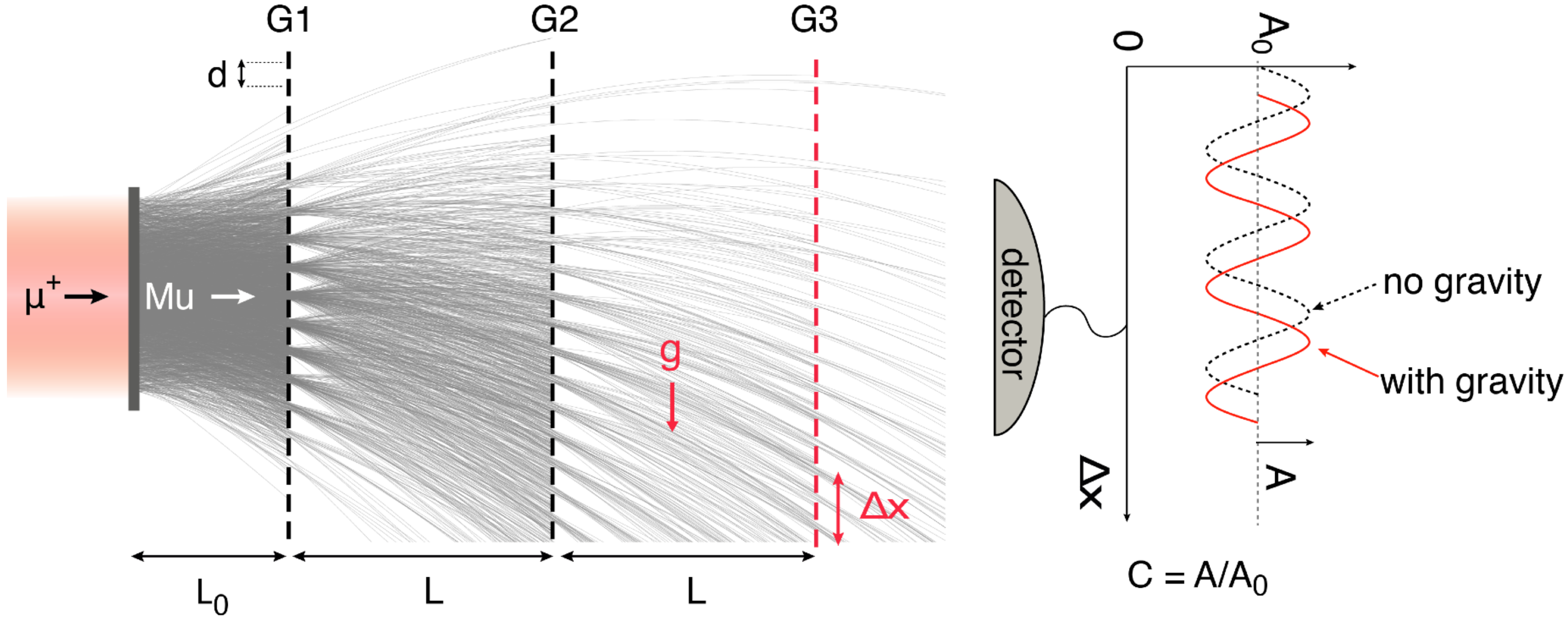
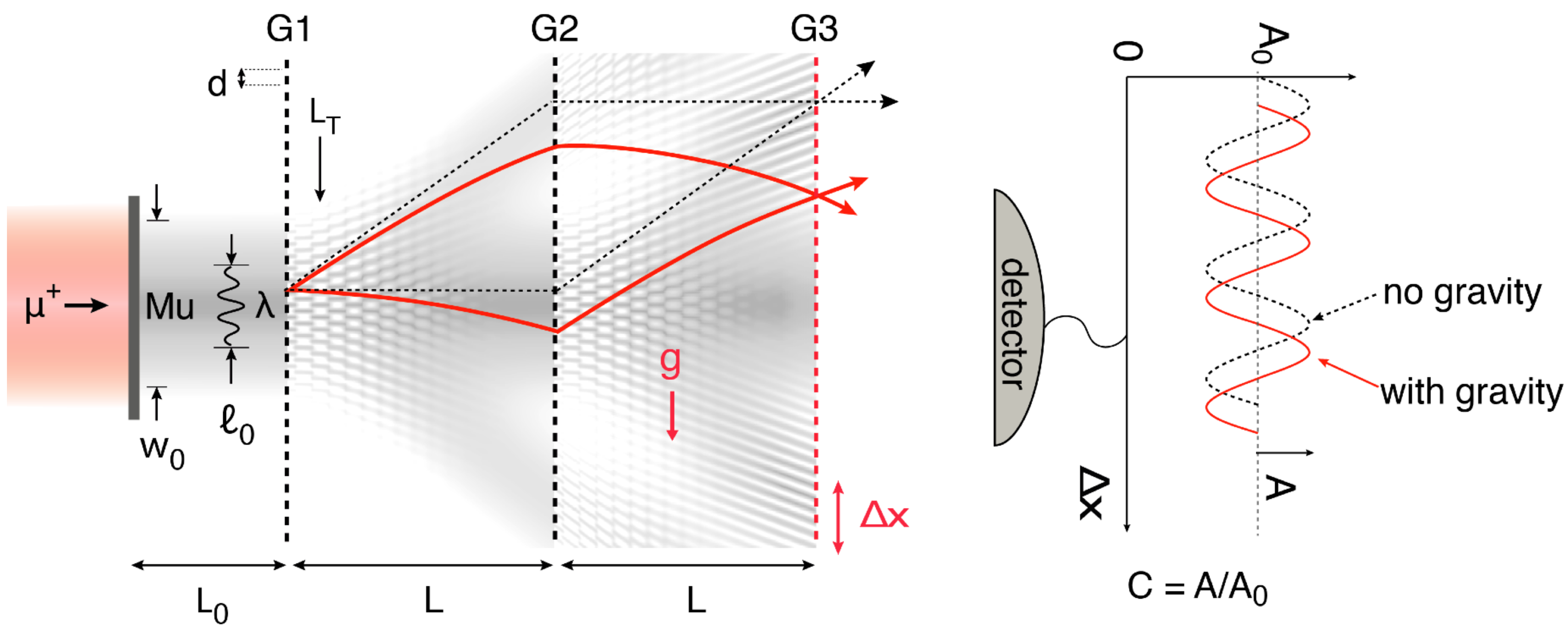


Measuring g of muonium with an atomic interferometer



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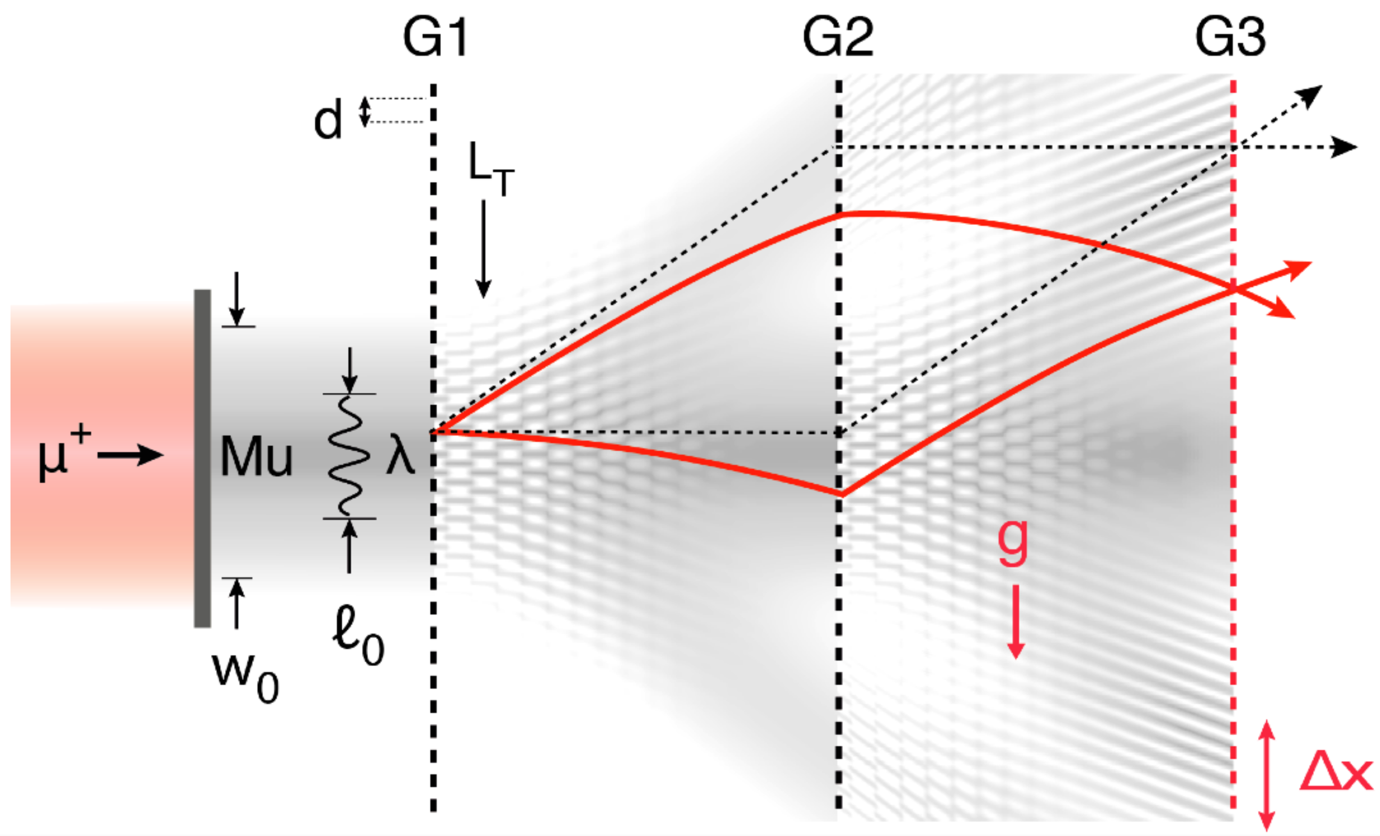
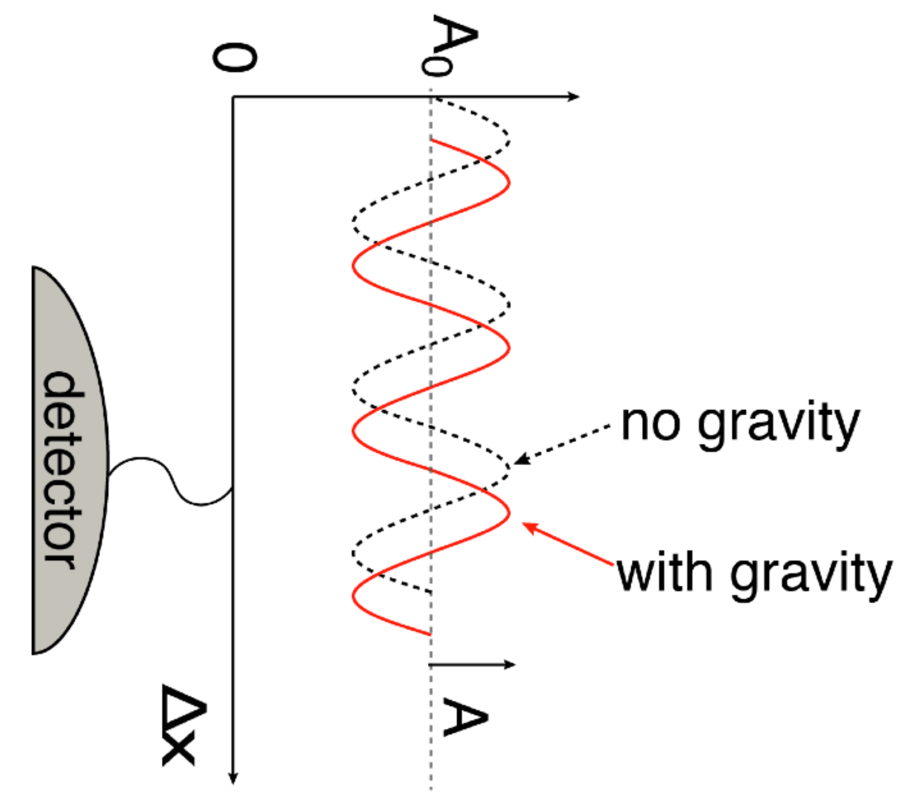




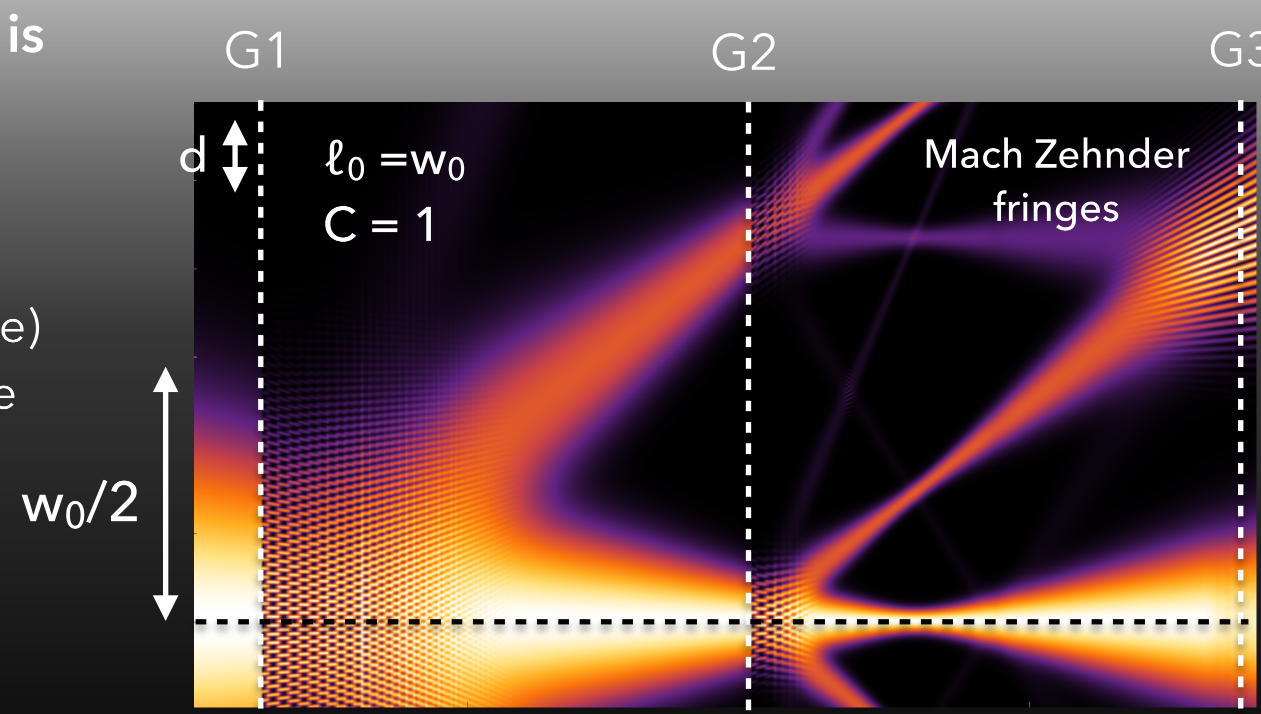
High quality Mu beam is needed

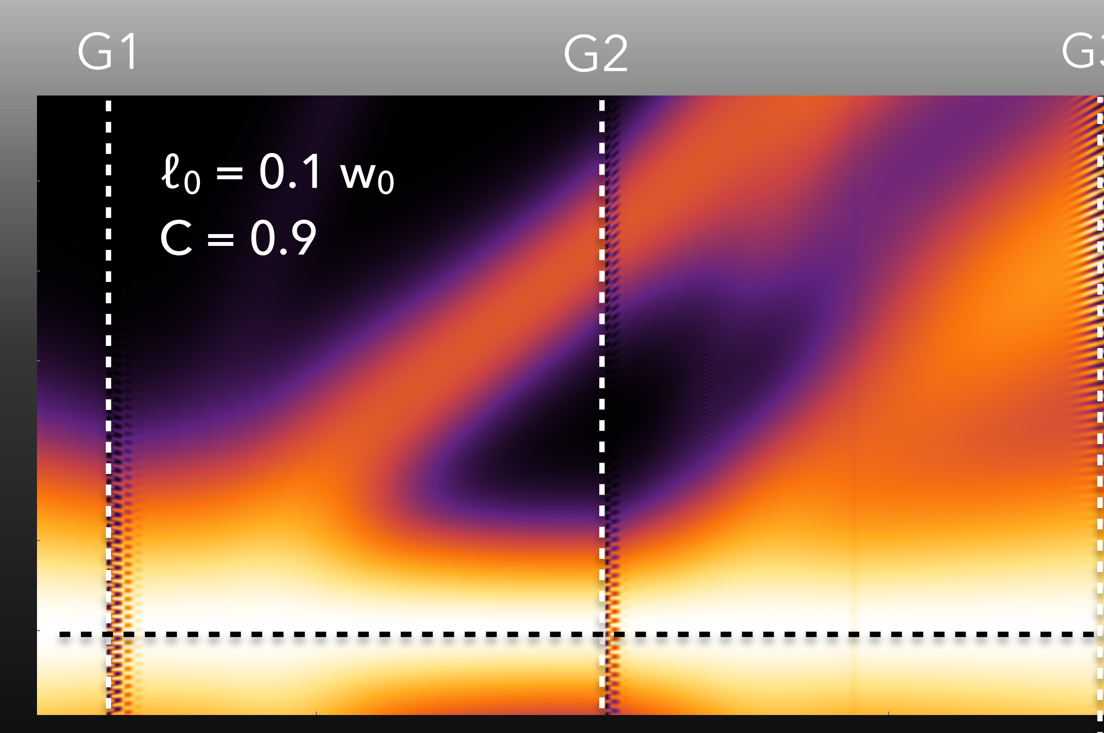
$$L_T \ll L, \quad L_T = \frac{d^2}{\lambda}$$

w_0 ~ beam width (aperture)

ℓ_0 ~ transverse coherence

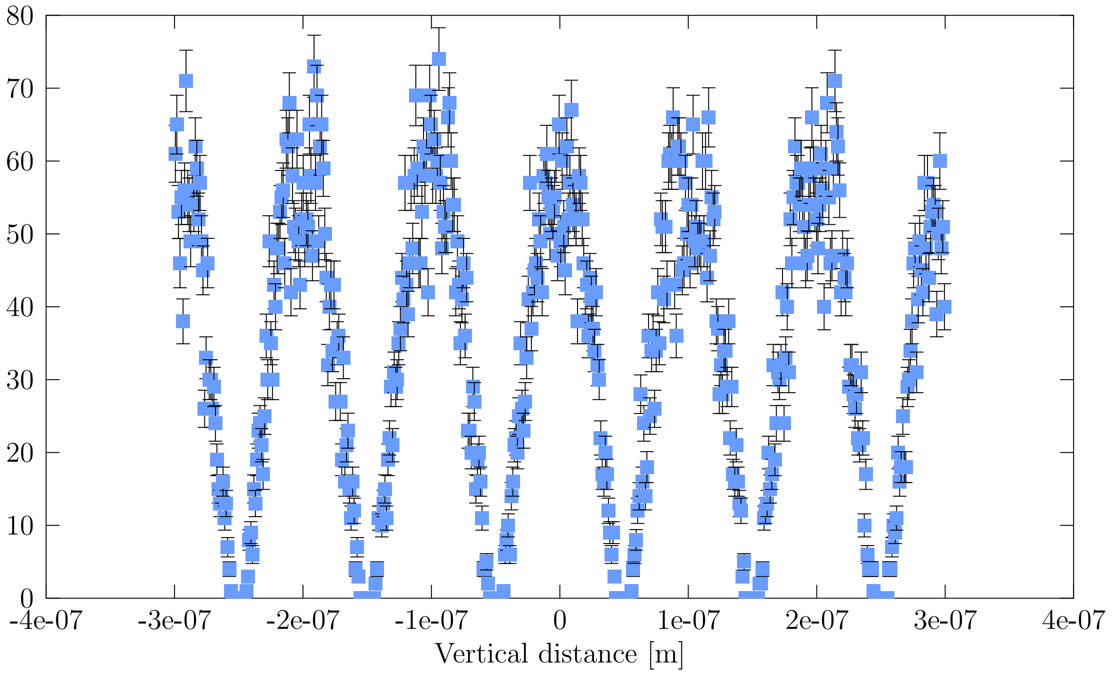
$$\ell_0 \approx \frac{\lambda}{\alpha} \approx \frac{\lambda}{p_\perp / p_\parallel}$$



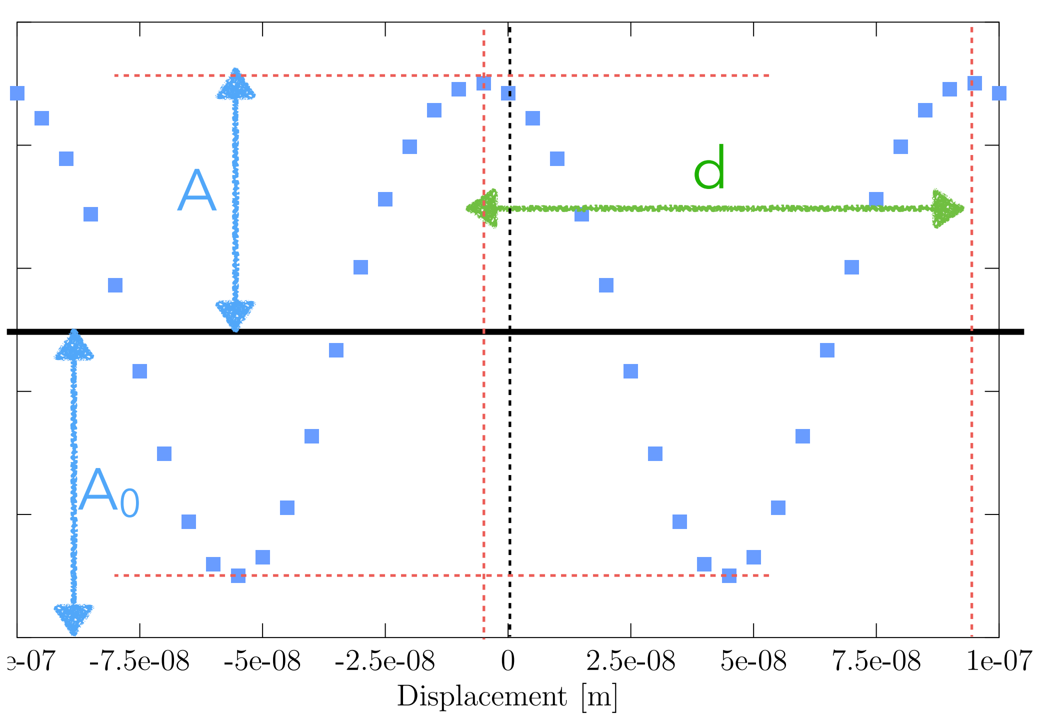


A classical view on the measurement sensitivity

Vertical position of trajectories



Transmission vs 3rd grating position



Measurable acceleration with a phashift on a sinusoidal:

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

See e.g. M.K. Oberthaler et al. Phys. Rev. A 54 (1996) 3165.
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Intrinsic loss: M decay - a trade-off with measurement time.

Other losses should be kept at minimum: large grating transmittance (η~0.3) and detection efficiency (ε=0.5), low dead time ($t_0 < \tau$)

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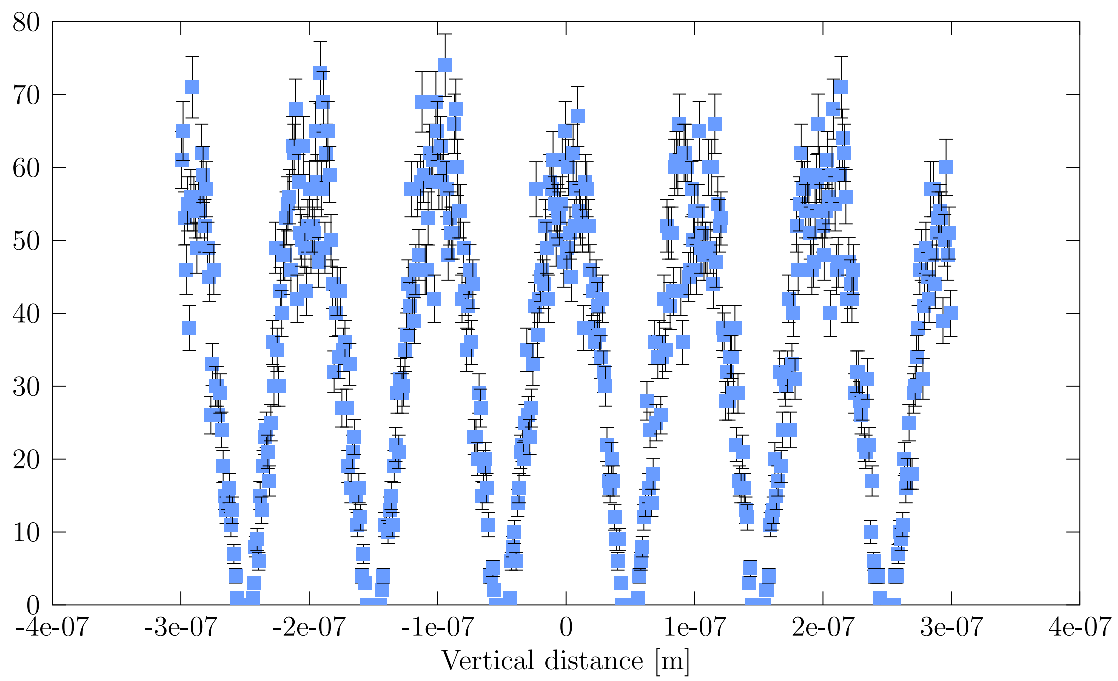

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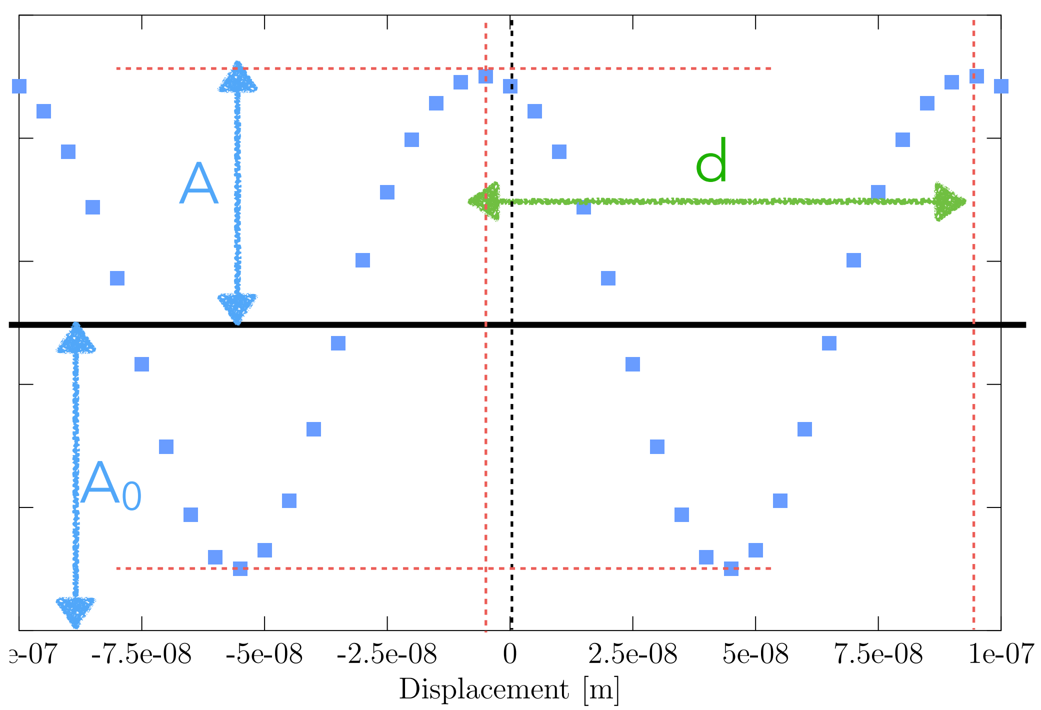

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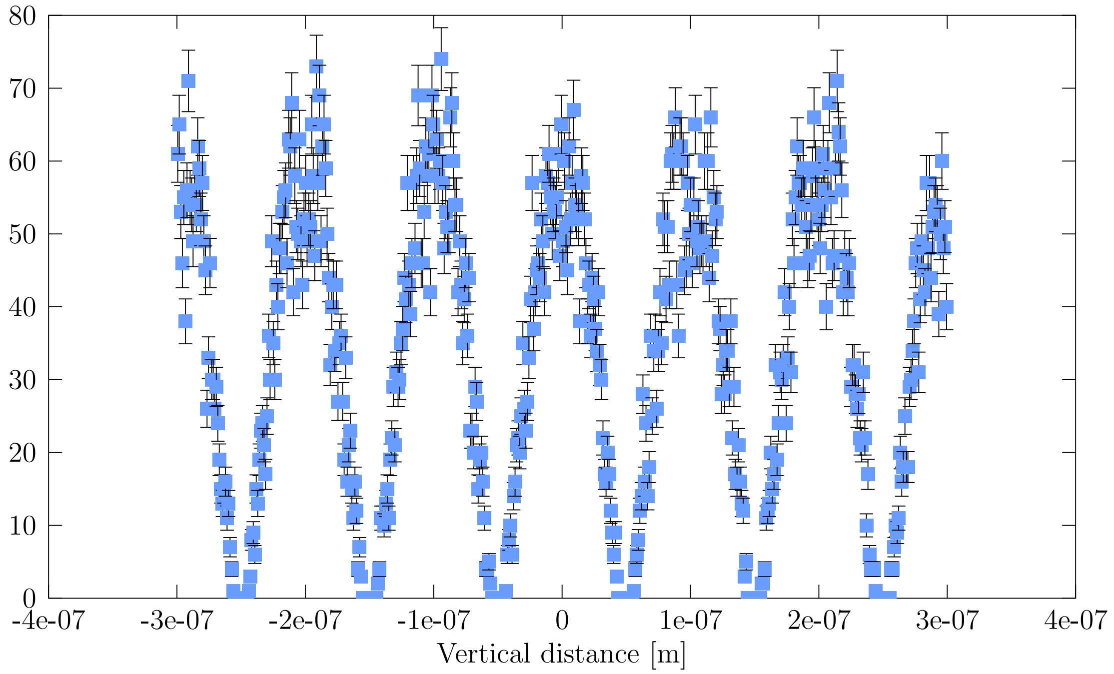

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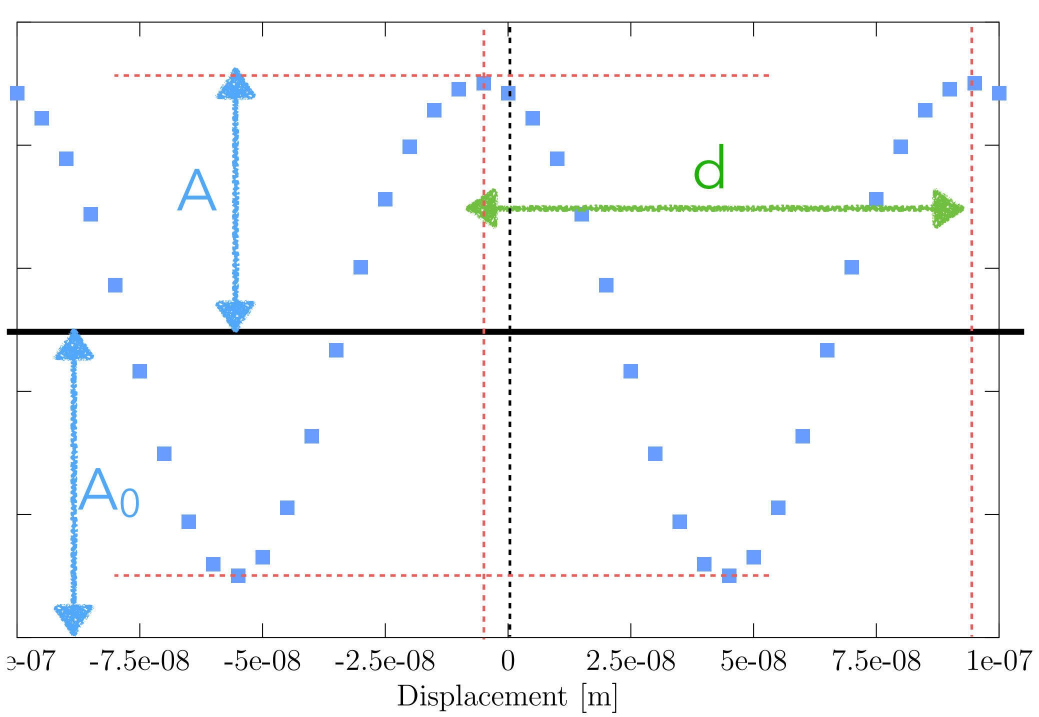

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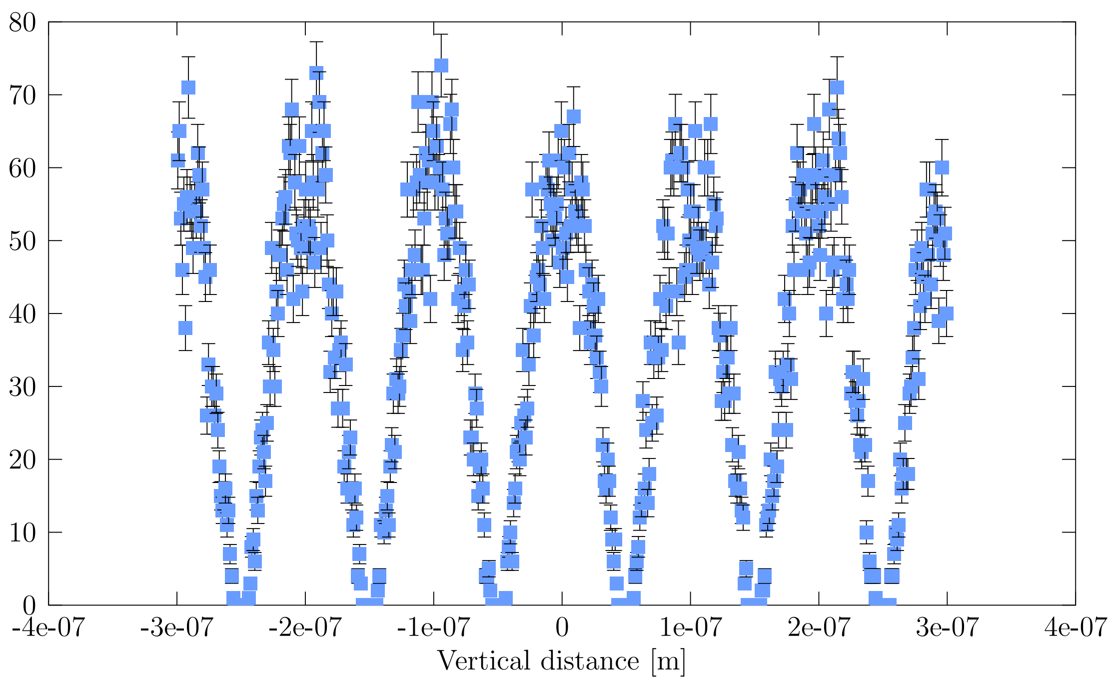

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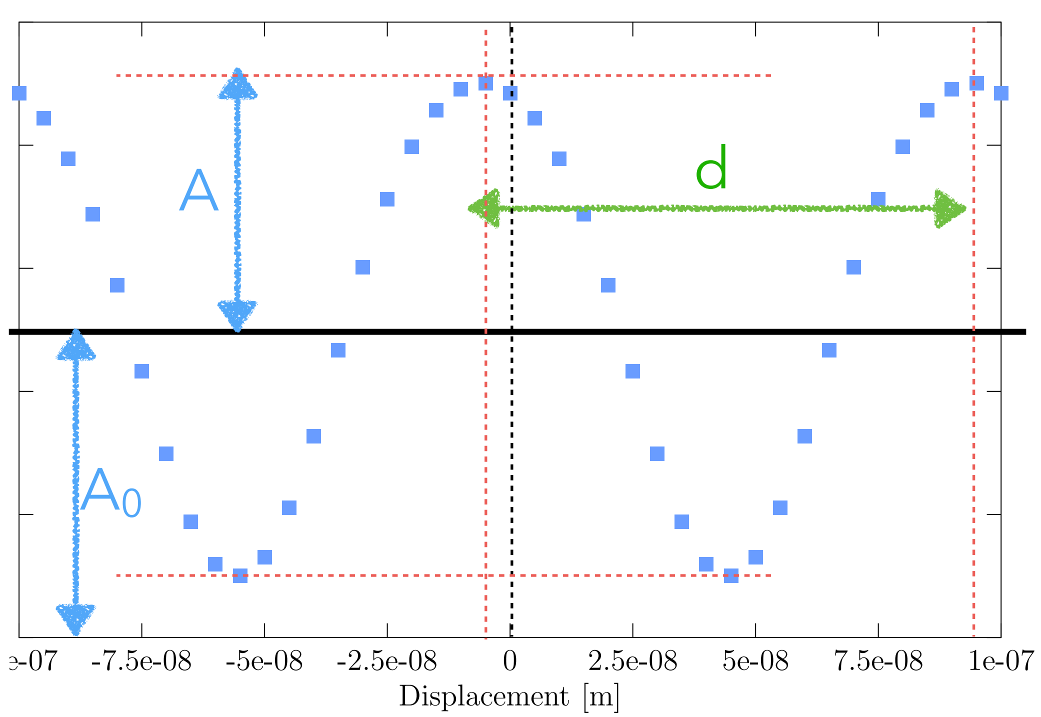

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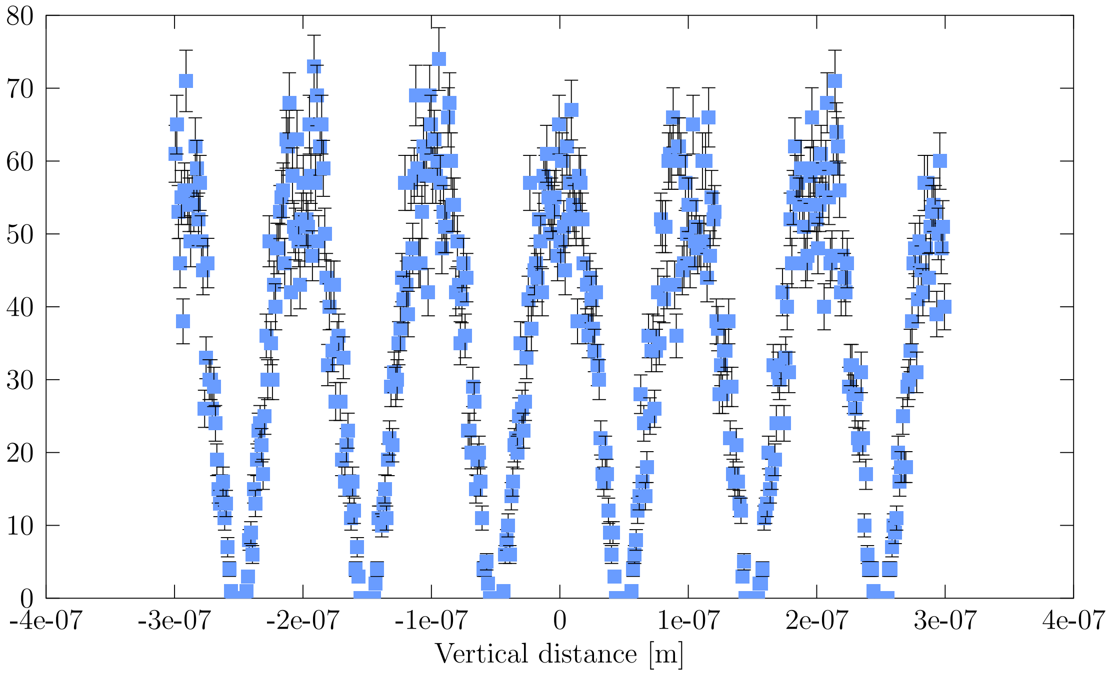

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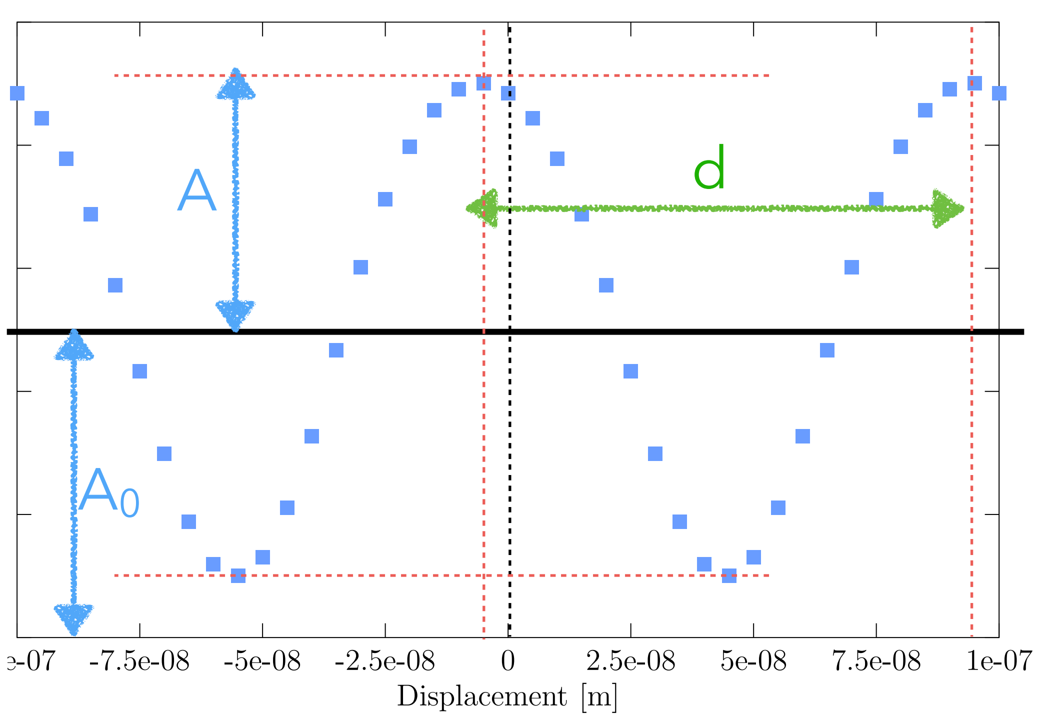

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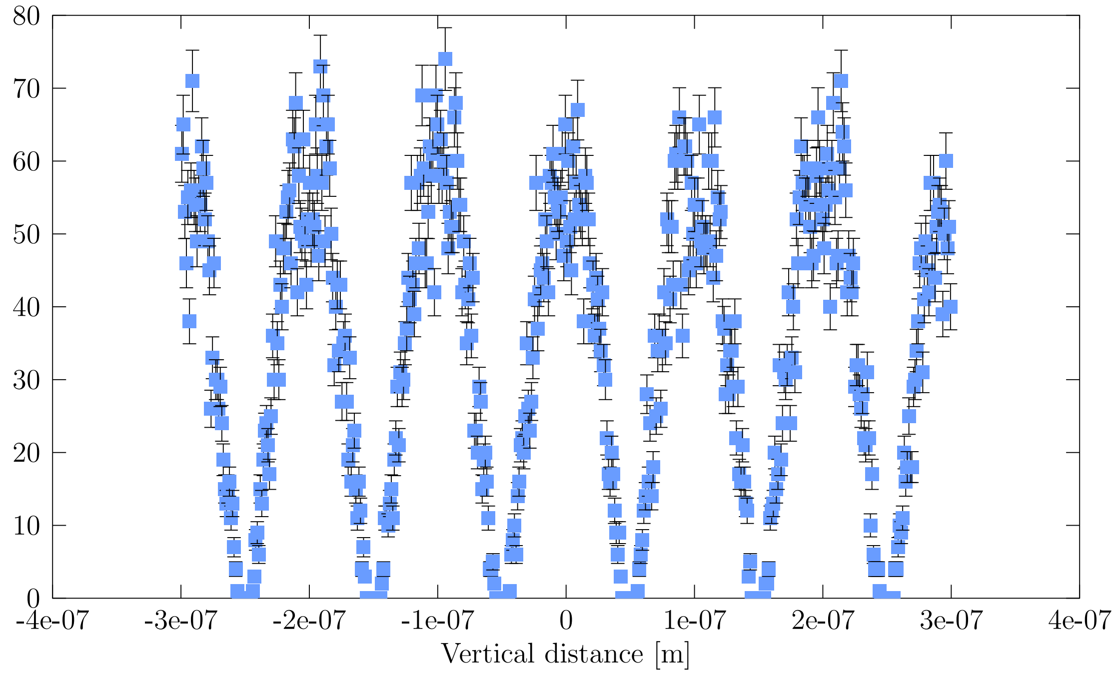

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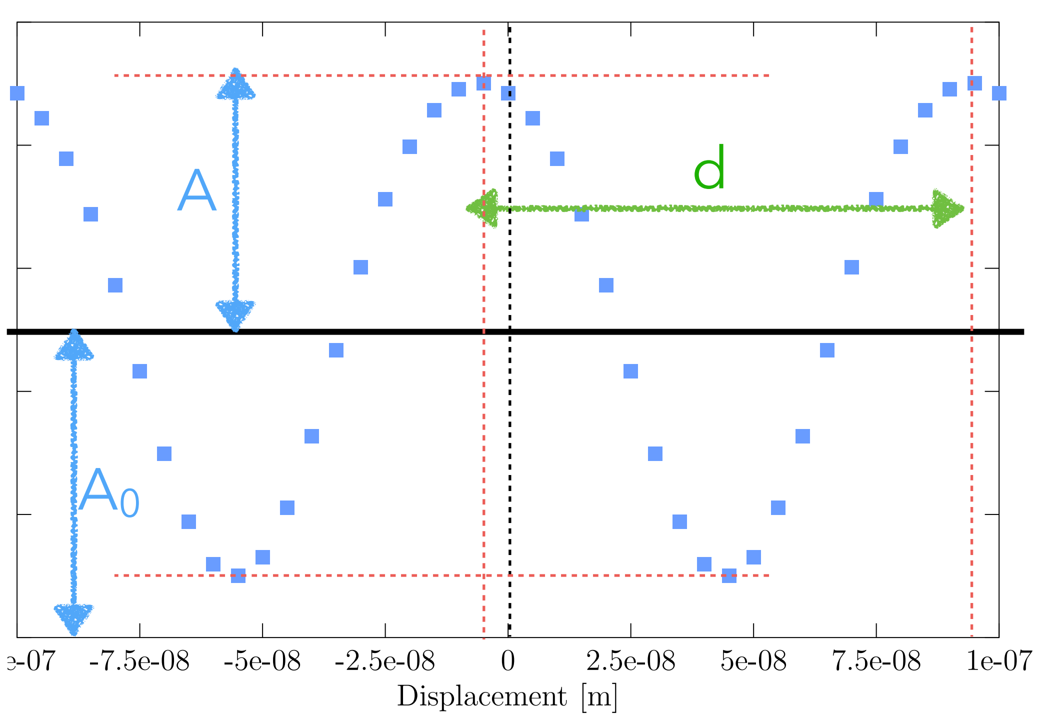

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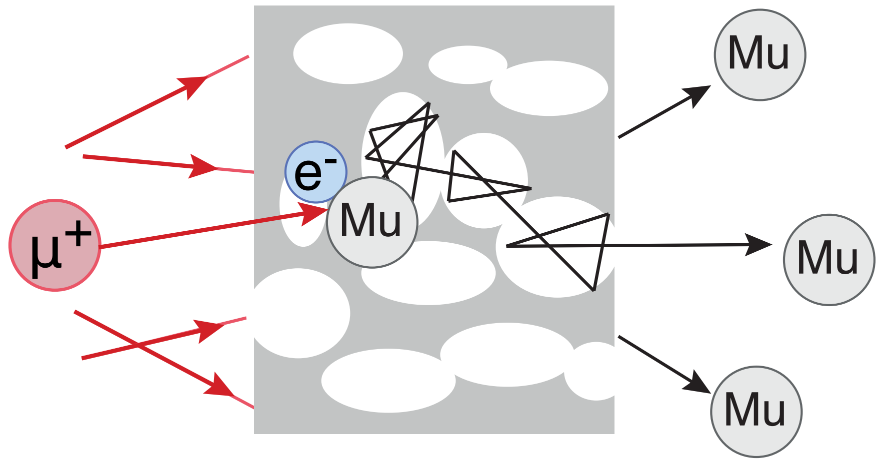
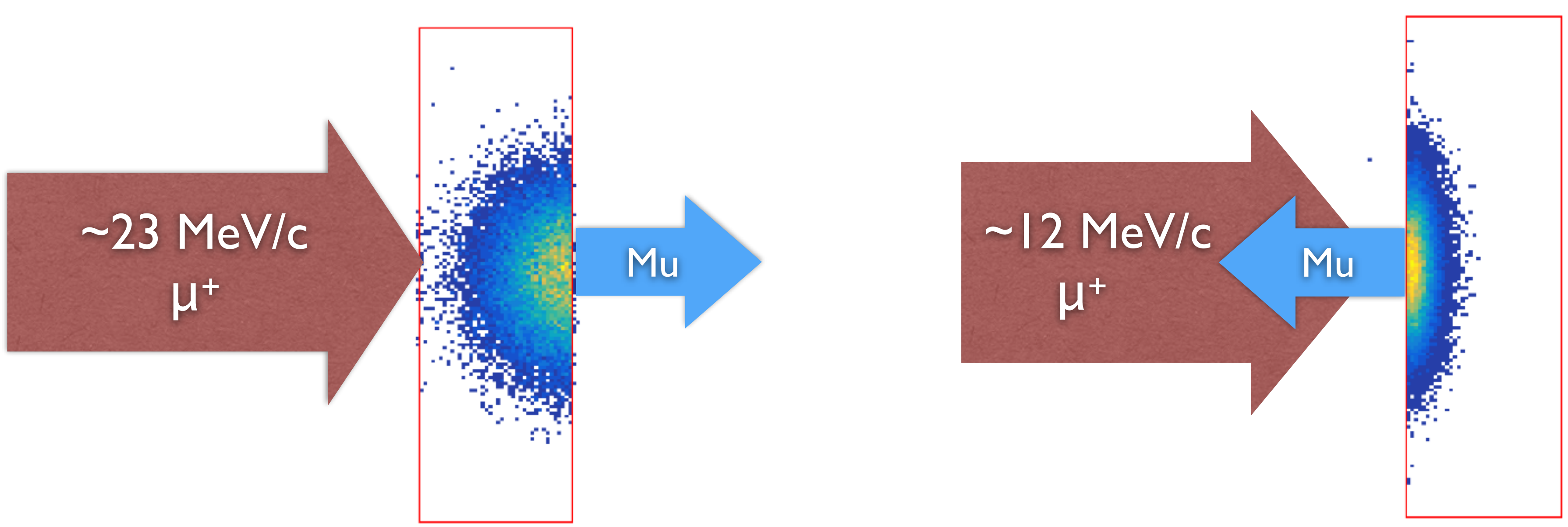
Present state-of-the-art vacuum M sources I.



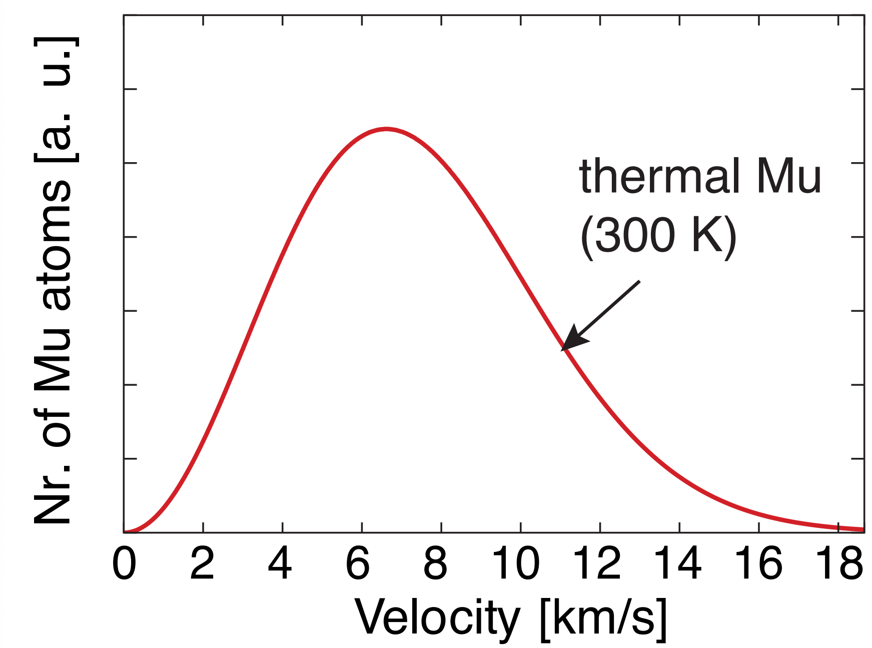
- M converting materials with interconnecting nanoscopic pore stucture (silica aerogel, mesoscopic SiO2)
- Large (thermal) energy spread
- Broad angular distribution (~cosθ)
- μ → vacuum M conversion efficiency: η_M = 0.003 - 0.3, depends strongly on diffusion time (implantation depth)

- Tradeoff between beam intensity (decreases stongly with momentum) and implantation depth

Example of sub-surface muon ranges in d=8 mm silica aerogel

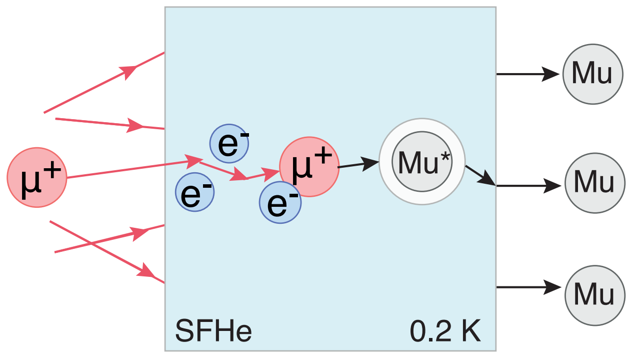


- Back implantation of 22.7 MeV/c μ
- Front implantation of 12.5 MeV/c μ
- Low momentum: η_{Mu} is ~10x larger, but μ yield 10 x smaller



New target concept - muonium from superfluid helium

Creation and diffusion in SFHe



- effective mass with VdW core repulsion for all H isotopes ~ 2.5 M_{He}
- This makes M a relatively small impurity: might avoid hydrodynamic losses (vortex creation)
- thermalization below the roton gap (v≈50 m/s)

- Thermal up-scattering: at 0.2 K phonon density is small:

$$n_{ph} = 2 \times 10^{19} T^3 \text{cm}^{-3} \approx 10^{16}/\text{cm}^3$$

- Small density makes scattering unlikely in μs times:

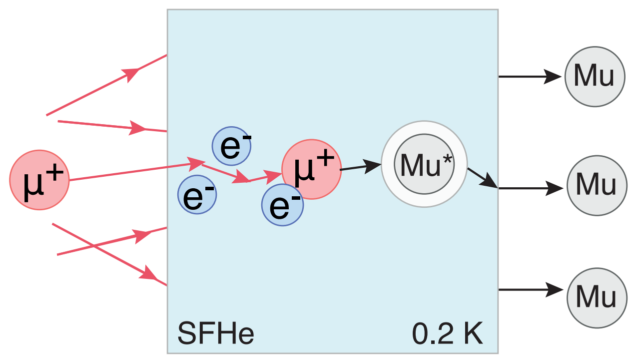
$$\frac{1}{\tau_c} \approx 4.8 \times 10^7 T^7 \approx 5/s$$

- scattering cross section can be modified with 3He concentration

Europhys. Lett., 58 (5), pp. 718–724 (2002)

New target concept - muonium from superfluid helium

Creation and diffusion in SFHe



- effective mass with VdW core repulsion for all H isotopes ~ 2.5 M_{He}
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- thermalization below the roton gap (v≈50 m/s)

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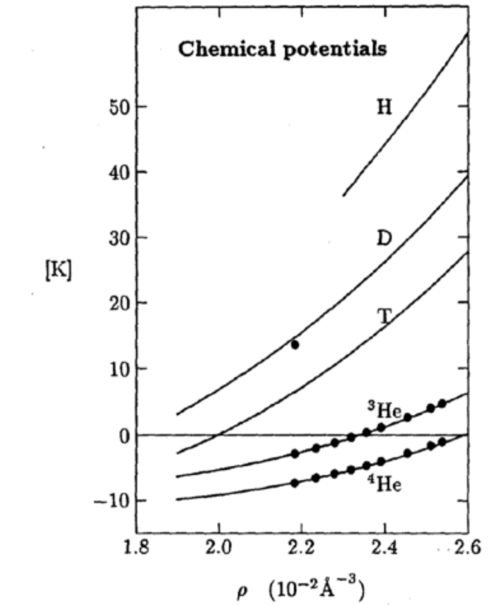
Surface ejection

- M and H, D, T chemical potentials:
- E/k_B~ 270 K and 37 K, 14 K , 7 K

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



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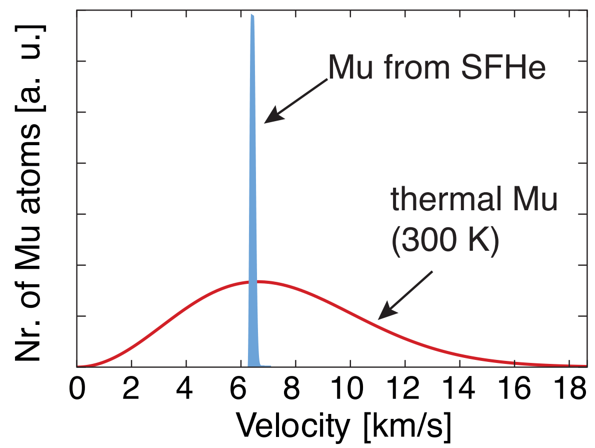
- Low thermal energy spread (+/- 100 m/s)
- Narrow angular distribution (~30 mrad)



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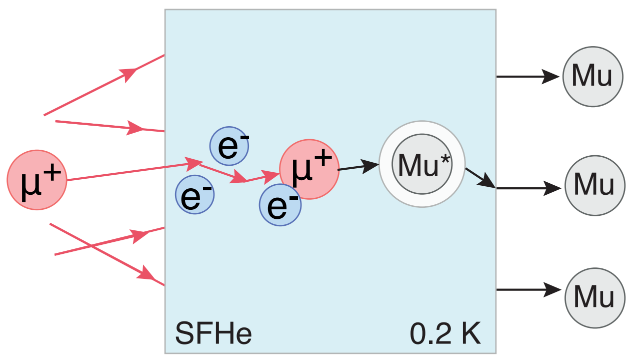

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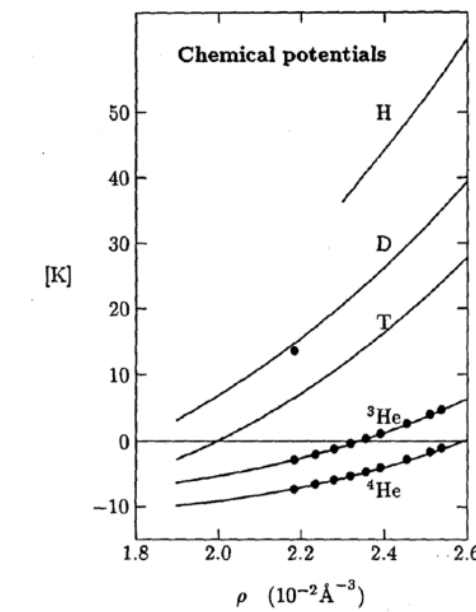

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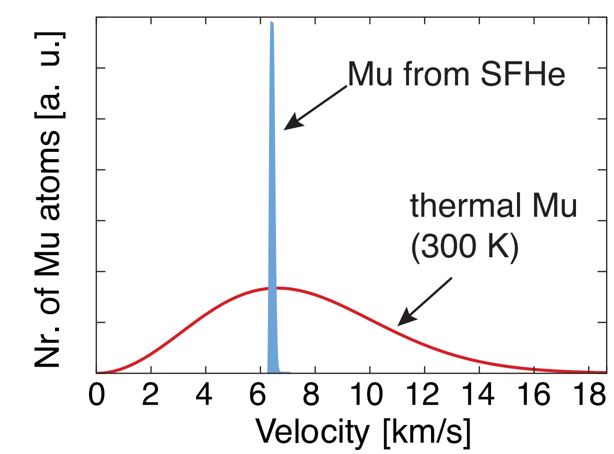
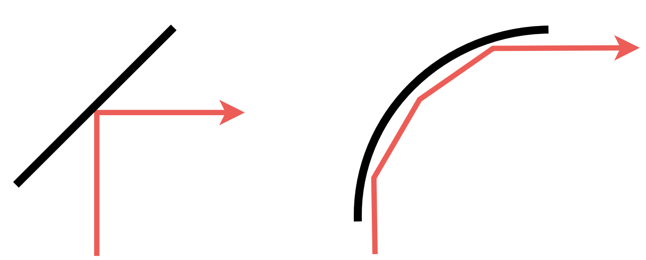
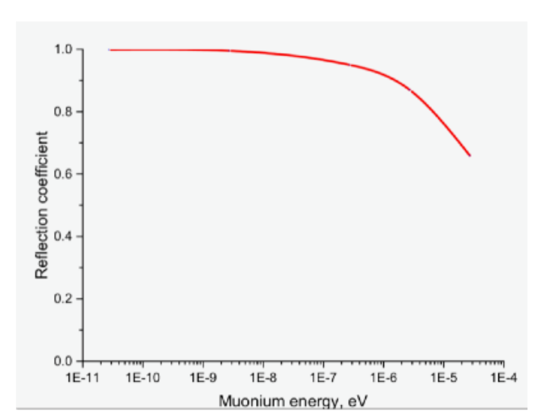


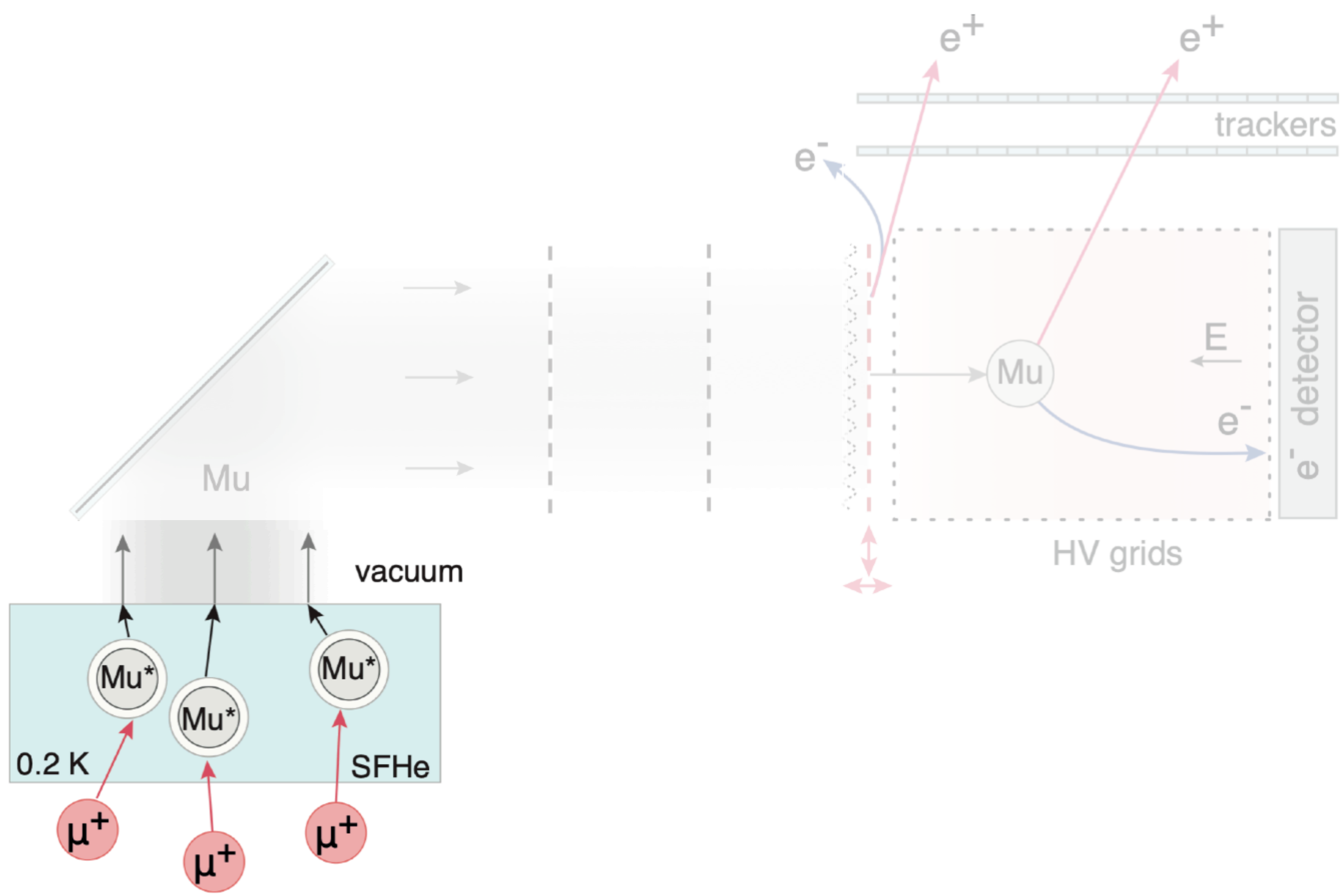
Reflection

- Reflection of a SFHe coated polished surfaces
- whispering gallery modes?





An (overly simplified) experimental setup for measuring gravity



$\mu^+ \rightarrow$ vacuum M conversion

- efficient M production
- fast diffusion to surface
- efficient vacuum emission

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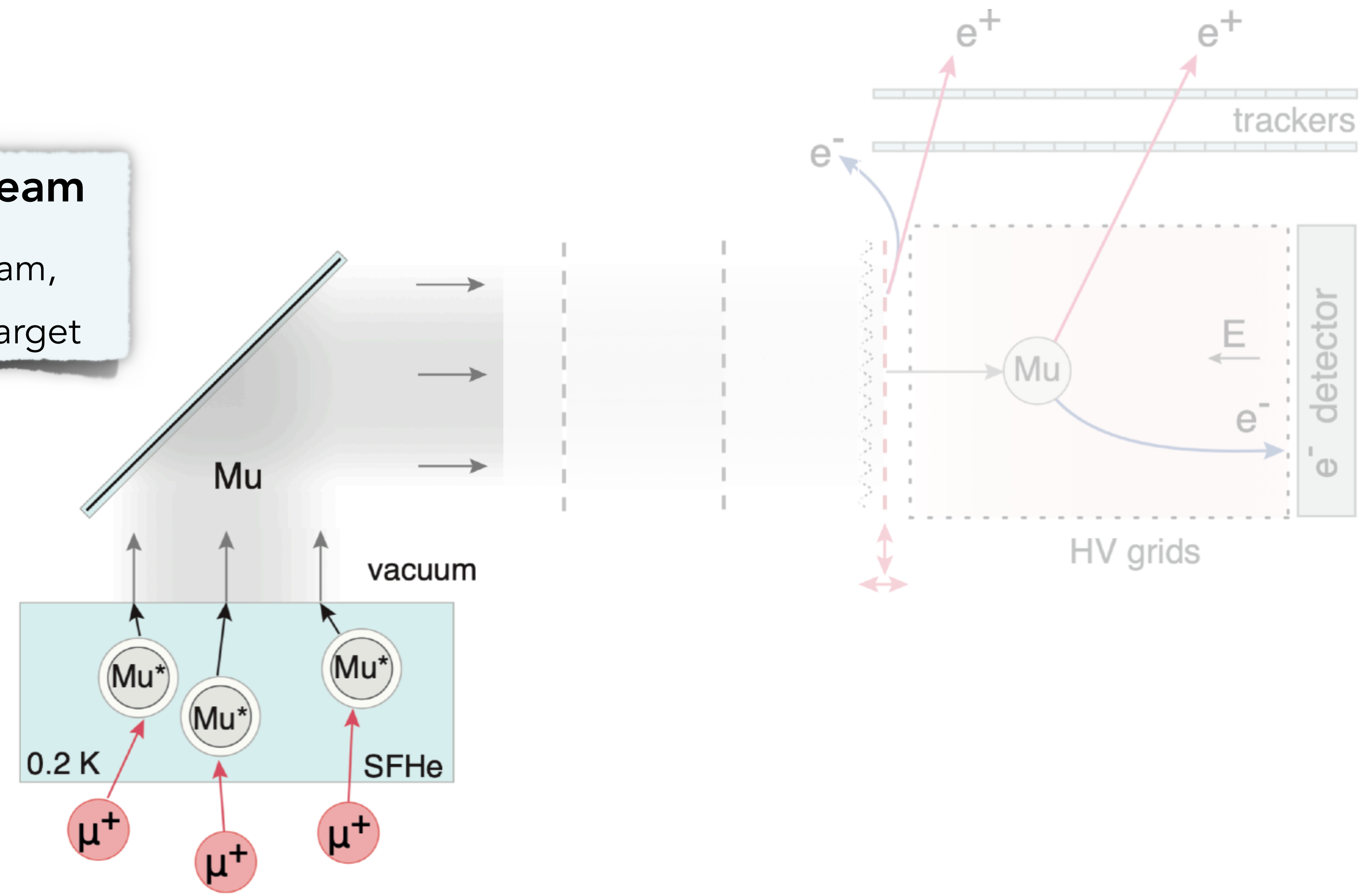

Horizontal M beam

- reflection of Mu beam,
- OR: vertical SFHe target

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- nm-precise fabrication over few mm aperture
- alignment, calibration, and stabilization in cold

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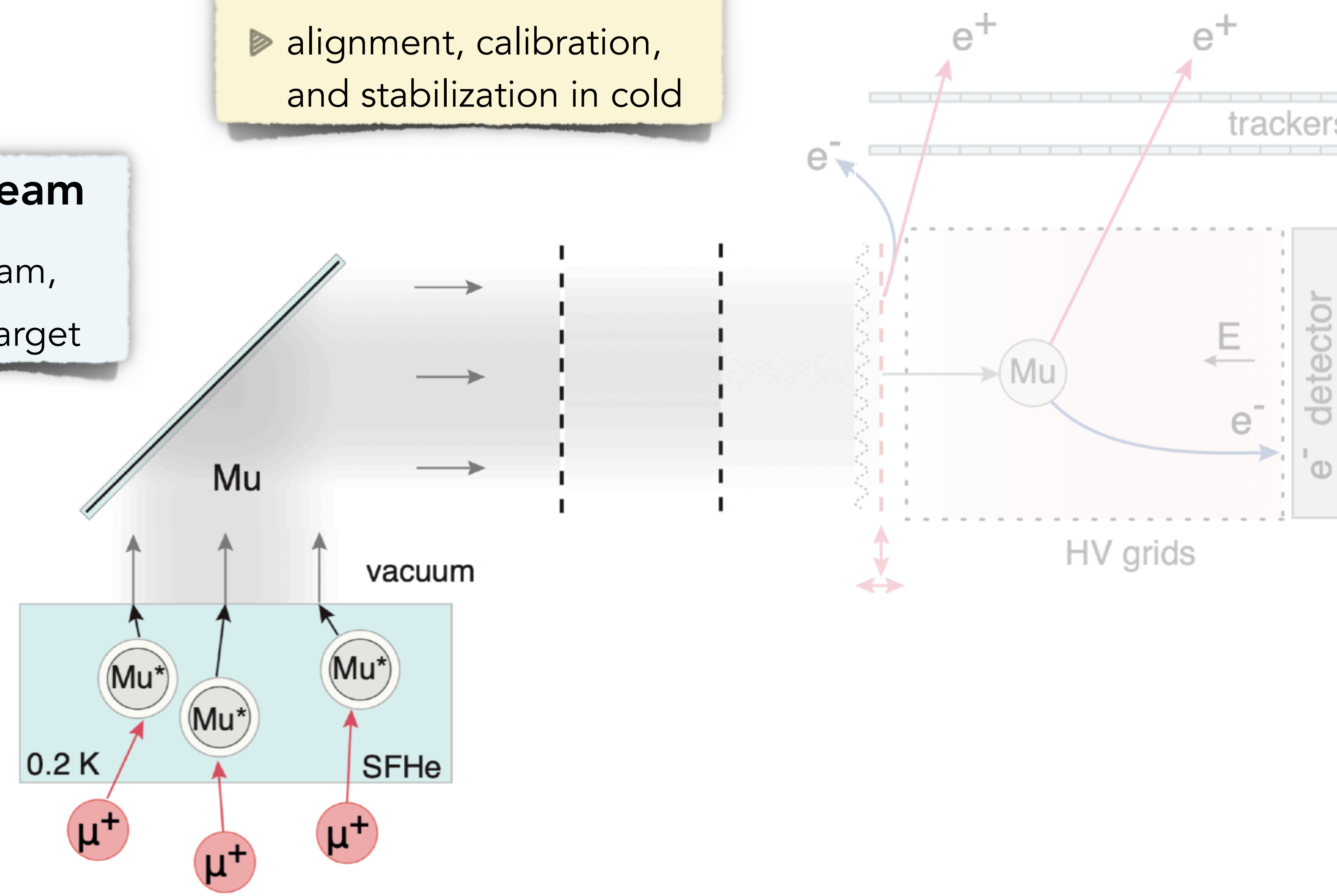

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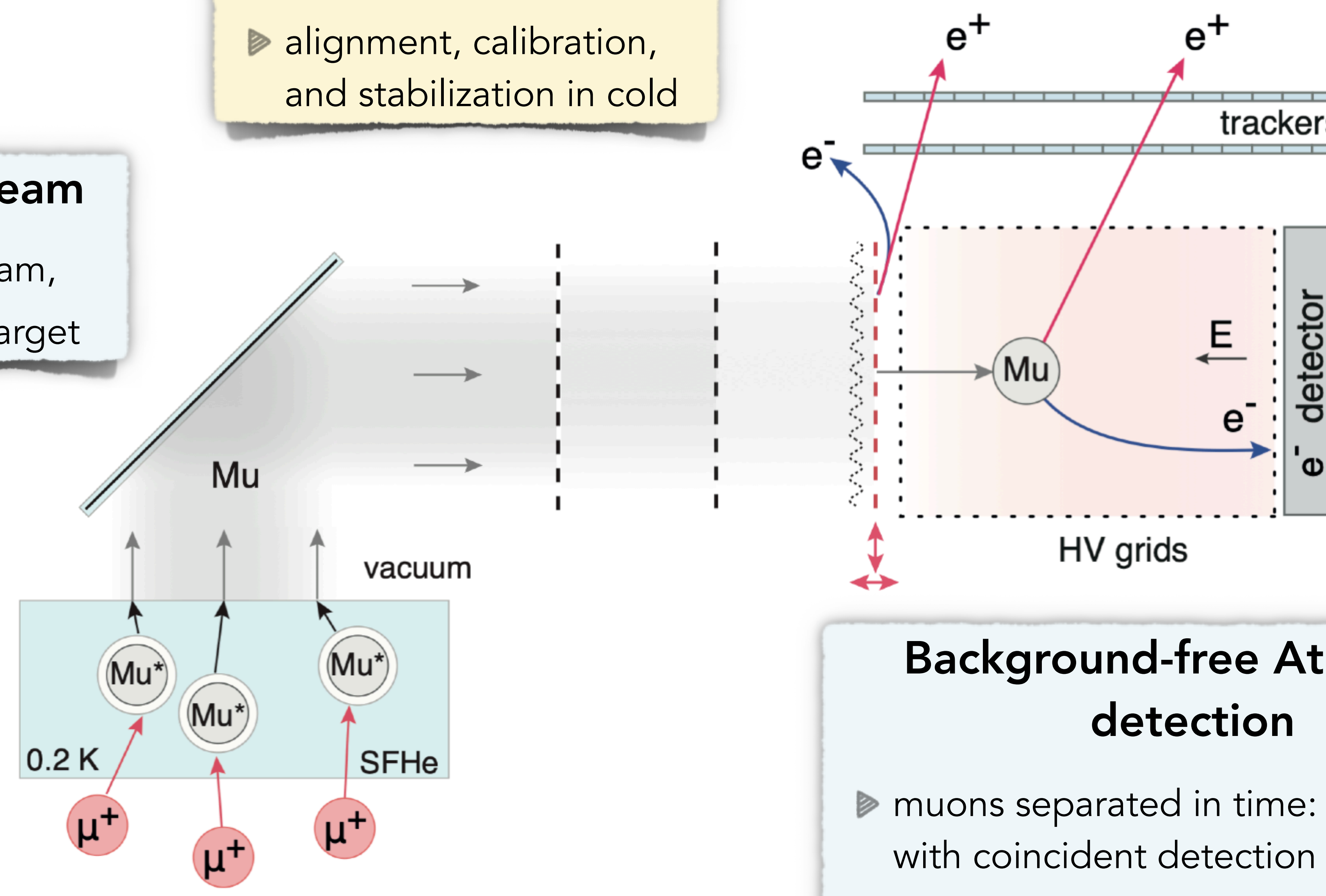
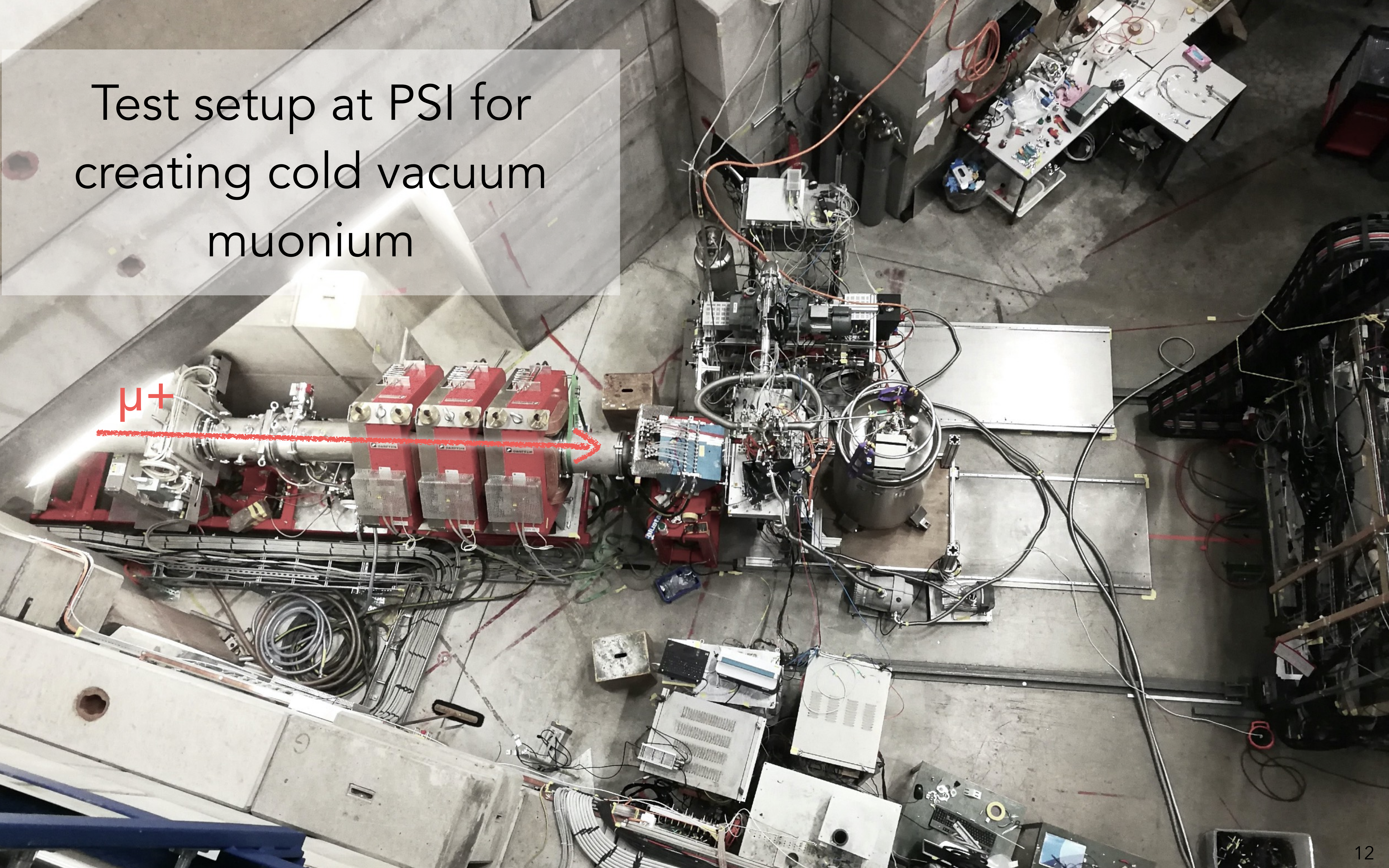


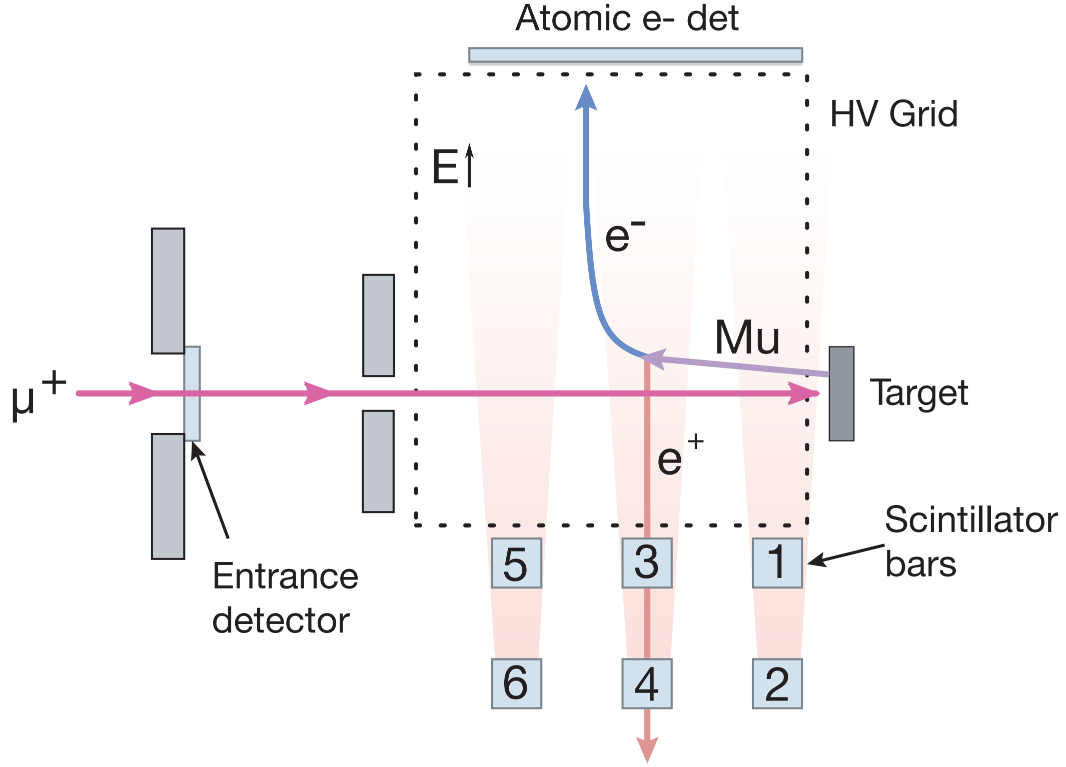
Background-free Atomic M detection

- muons separated in time: e⁺ tracking with coincident detection of atomic e⁻
- high overall efficiency and low background in cryogenic setup

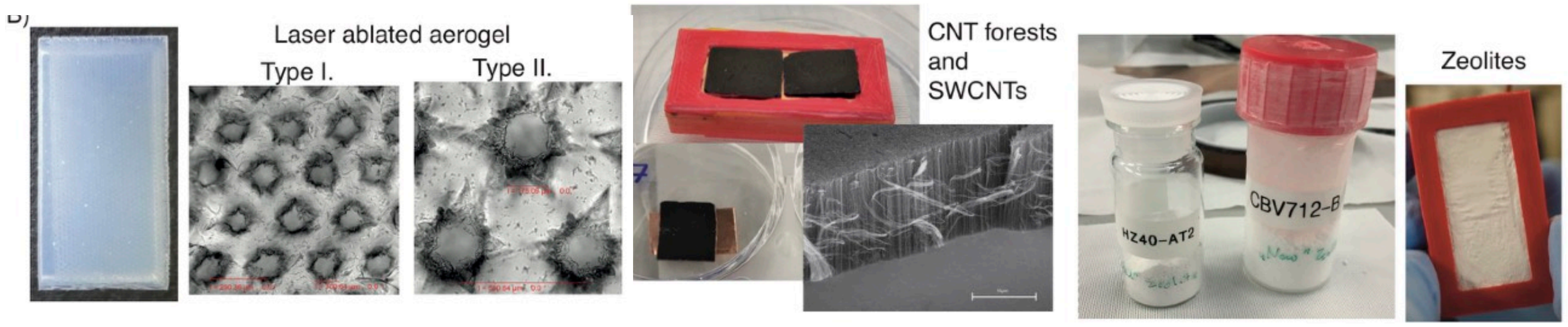
Test setup at PSI for creating cold vacuum muonium



Front implantation of new M emitters at PSI



- Laser ablated aerogel and other previously unknown emitters were implanted at PSI with 12-13 MeV/c sub-surface M beams
- Scintillator bars or a Micromegas system was tracking the positrons, a dedicated ion funnel was developed to measure electrons
- From zeolites η_{Mu} ~ 0.13-0.17, from aerogel, η_{Mu} ~ **0.3-0.35**



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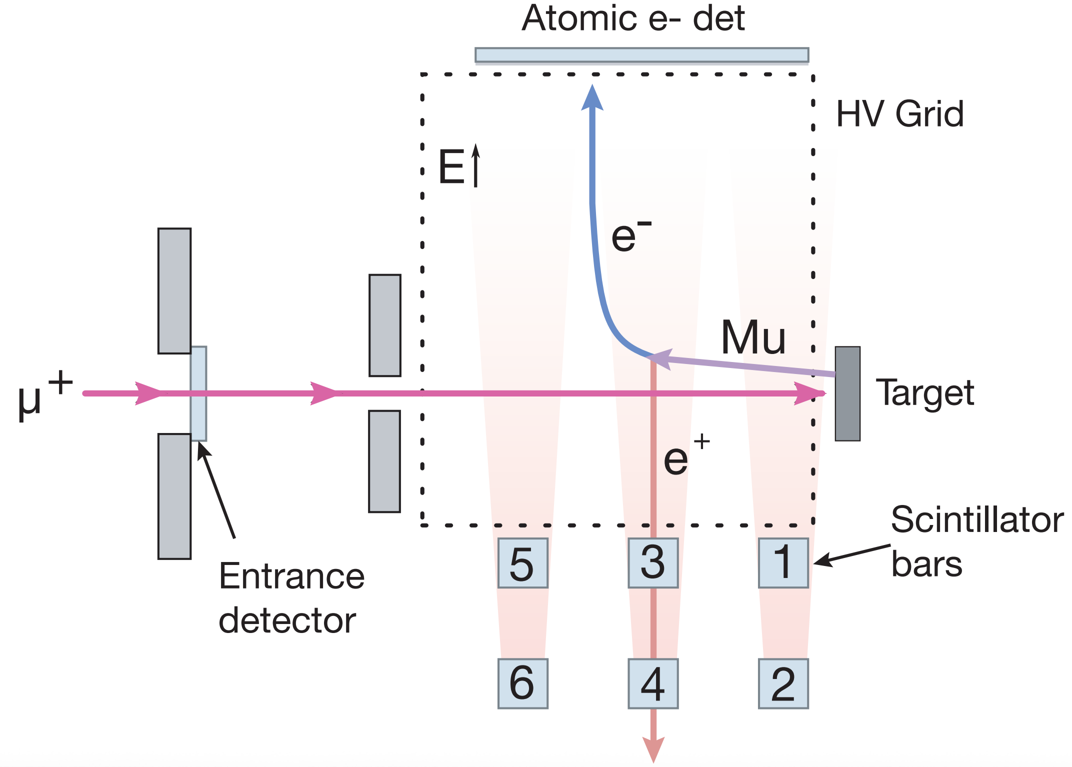

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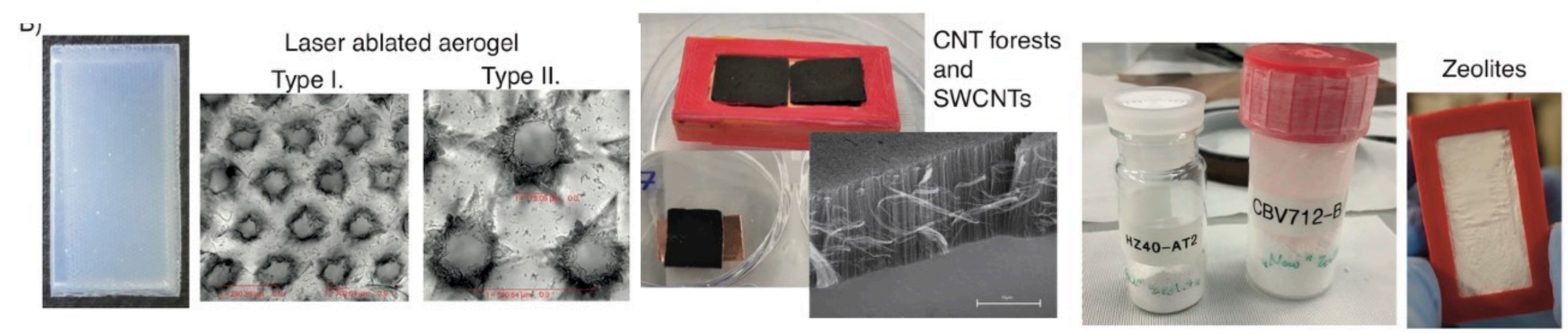

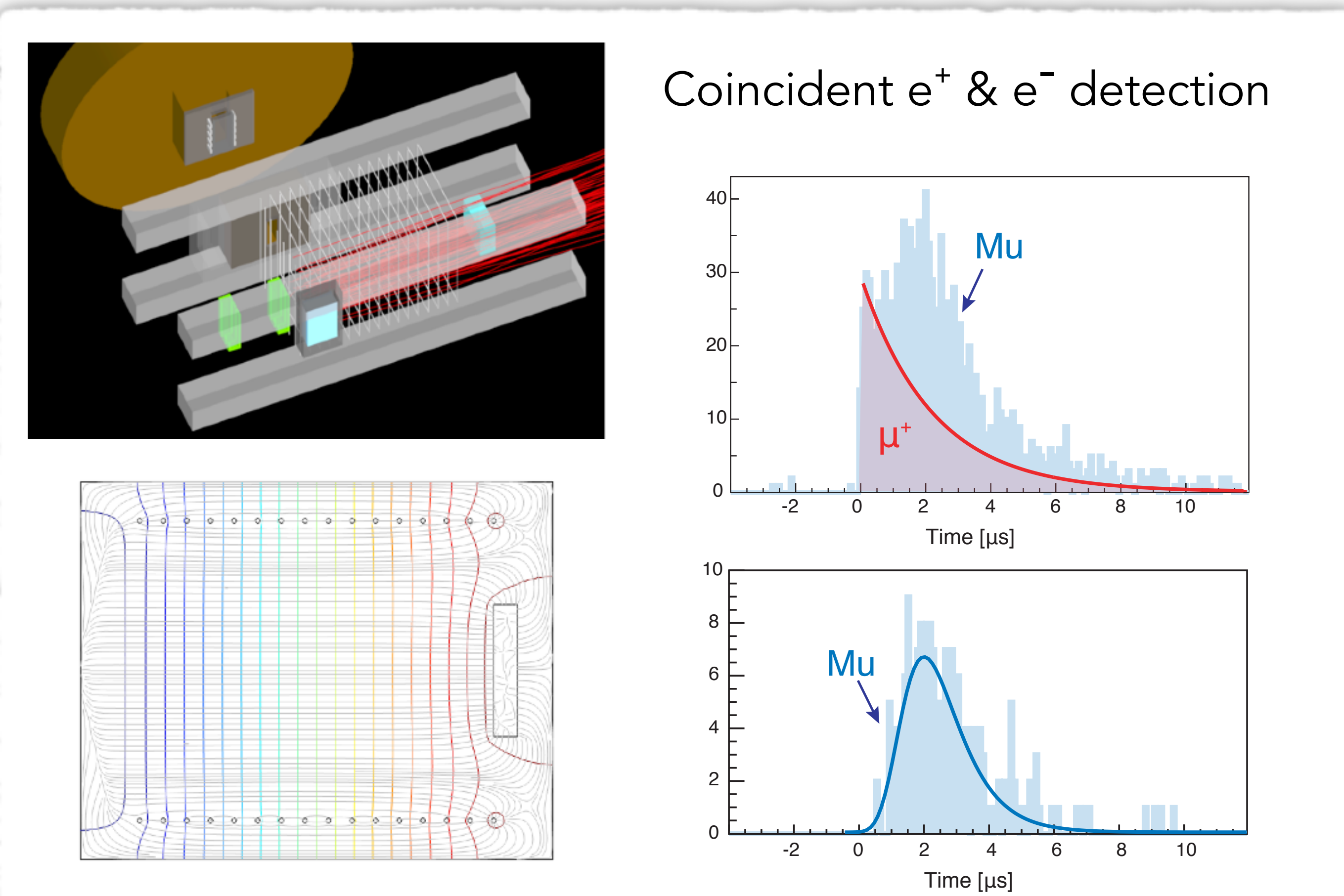

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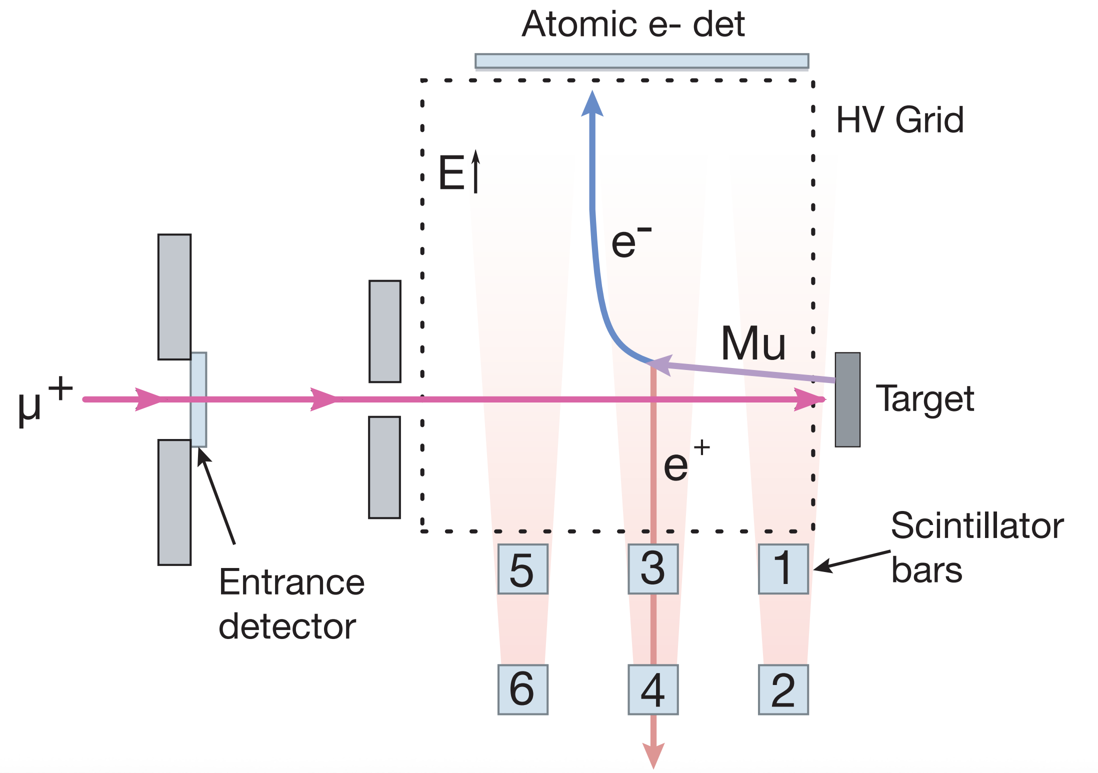

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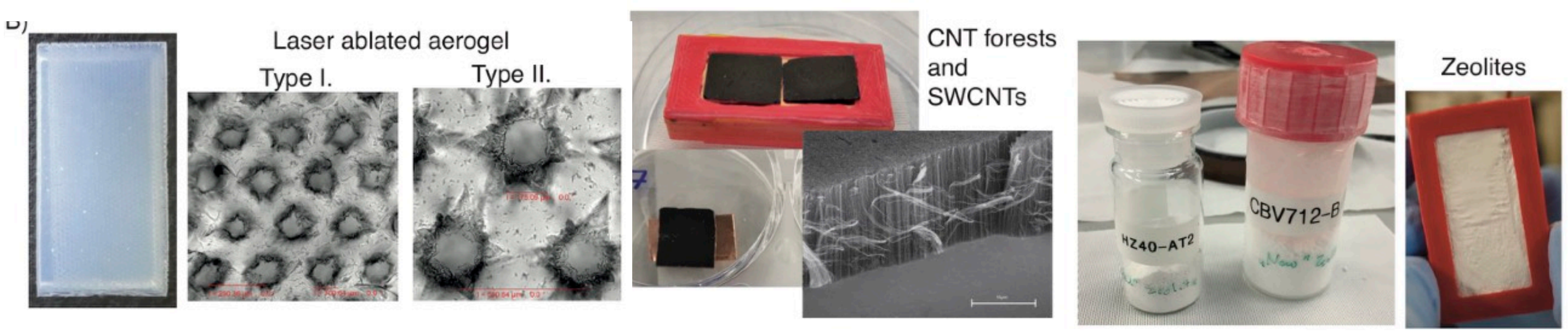
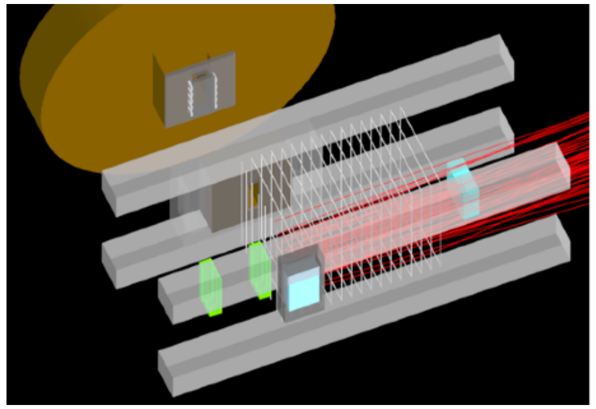
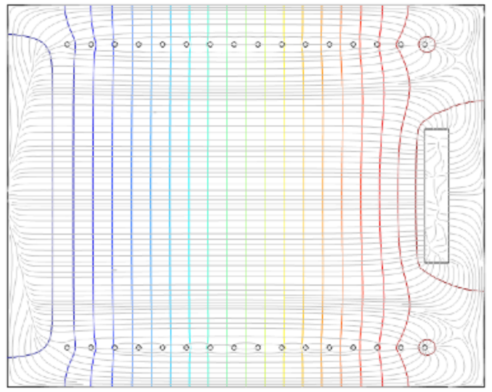
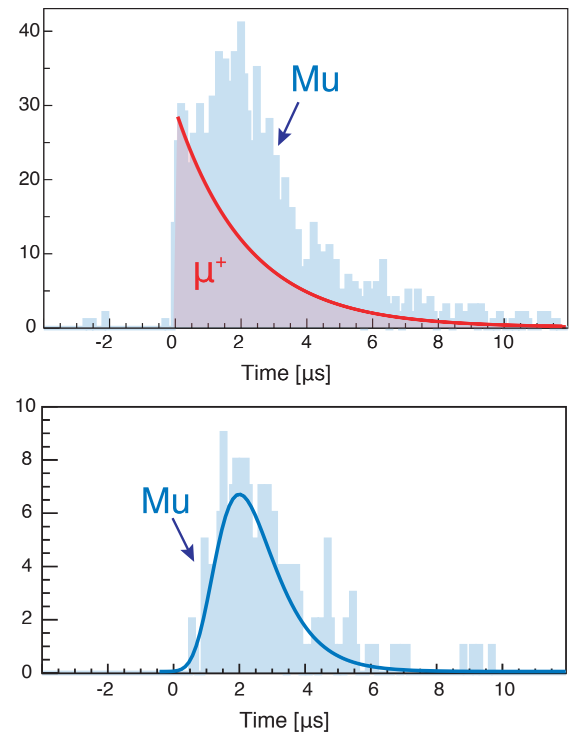


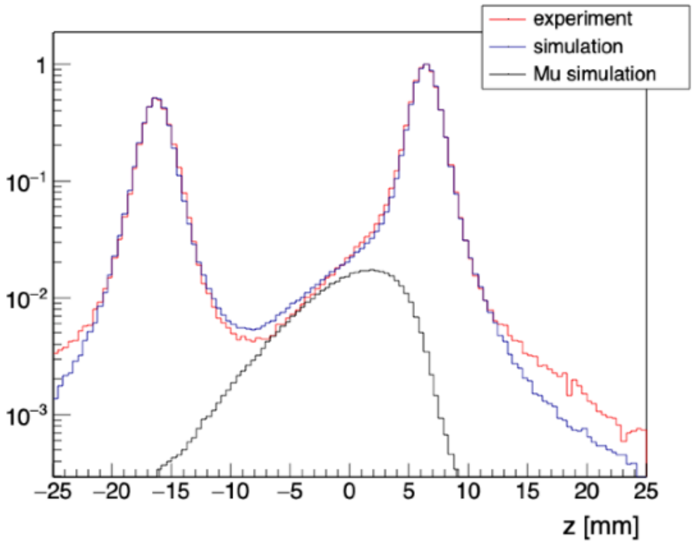




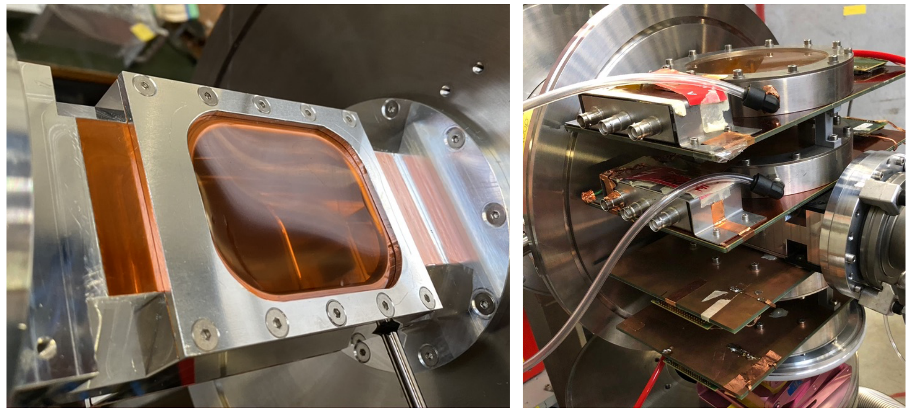
Coincident e⁺ & e⁻ detection



- Preliminary tracker detector data with Mu emission from zeolite

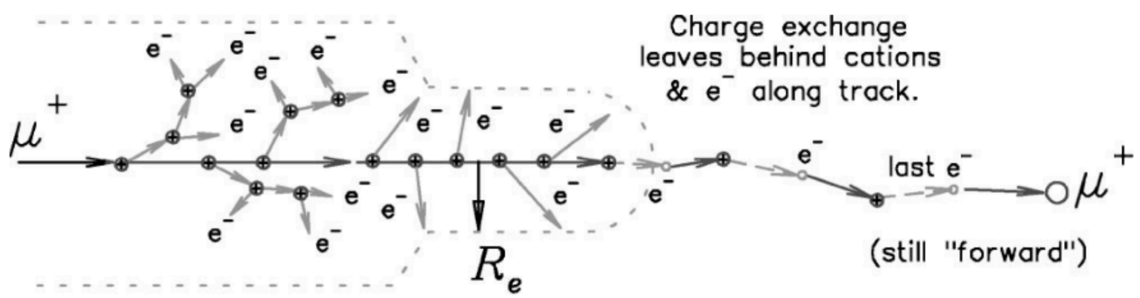


- Micromegas detector

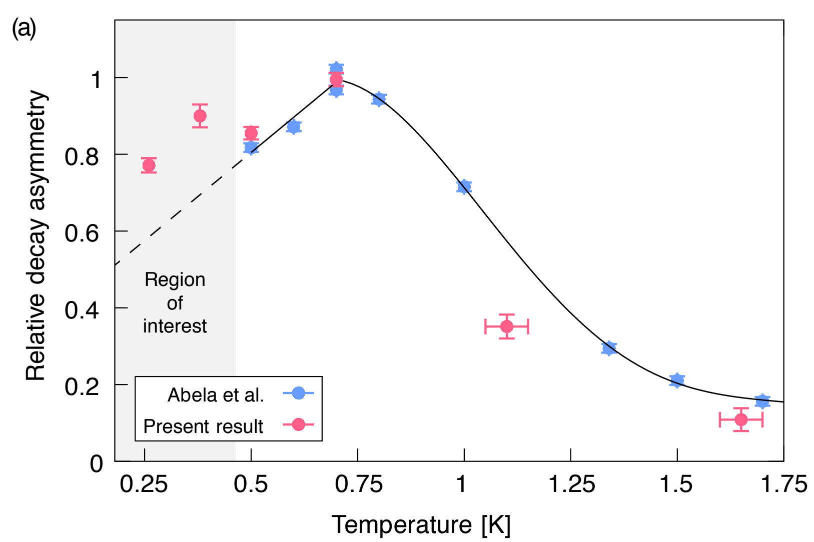


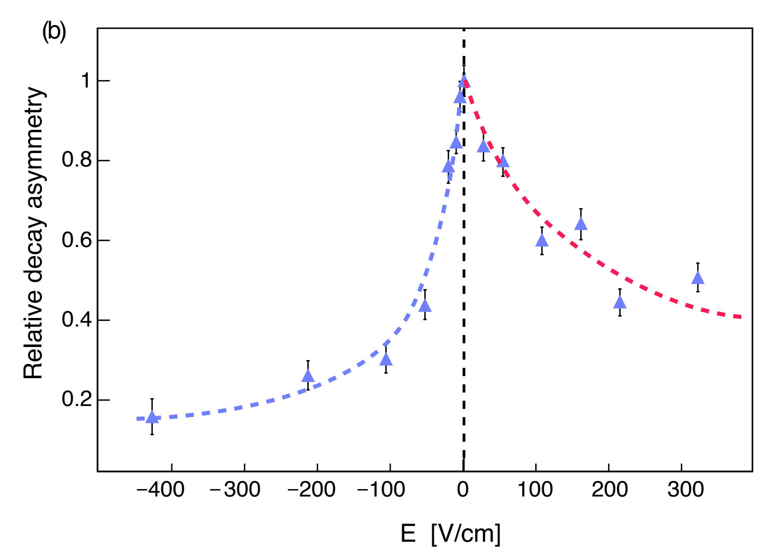
M formation in low temperature SFHe bulk and films

High M formation T< 0.5 K

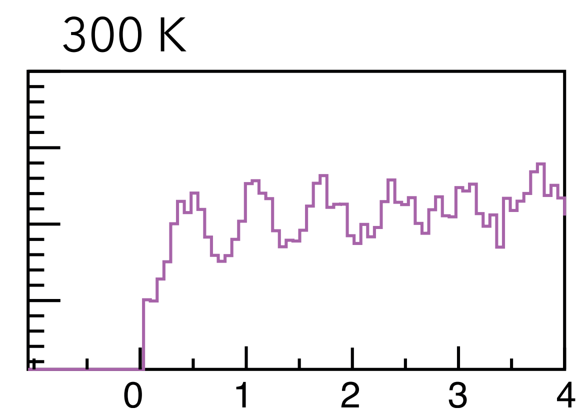


- MuSR experiment in small sample @ Dolly-PSI
- ~70% M formation at the lowest temperatures (0.26 K)
- High sensitivity on external E fields of E > 0.1 kV/cm

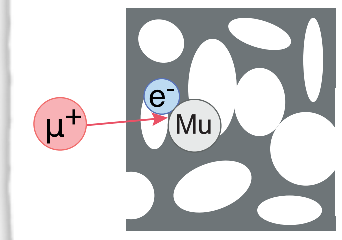




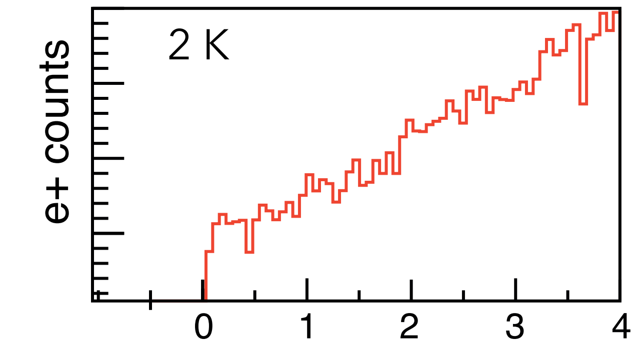
Hints of free M in superfluid-coated nanopores

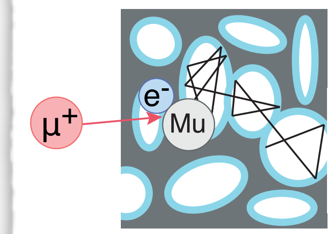


- M precessing in the magnetic field of Earth

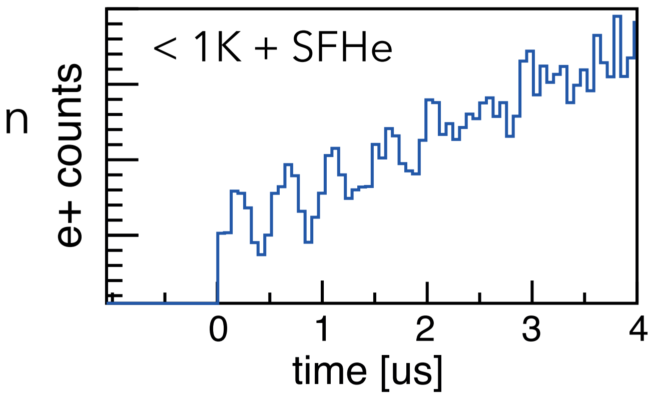


- M dephasing/ sticking to aerogel

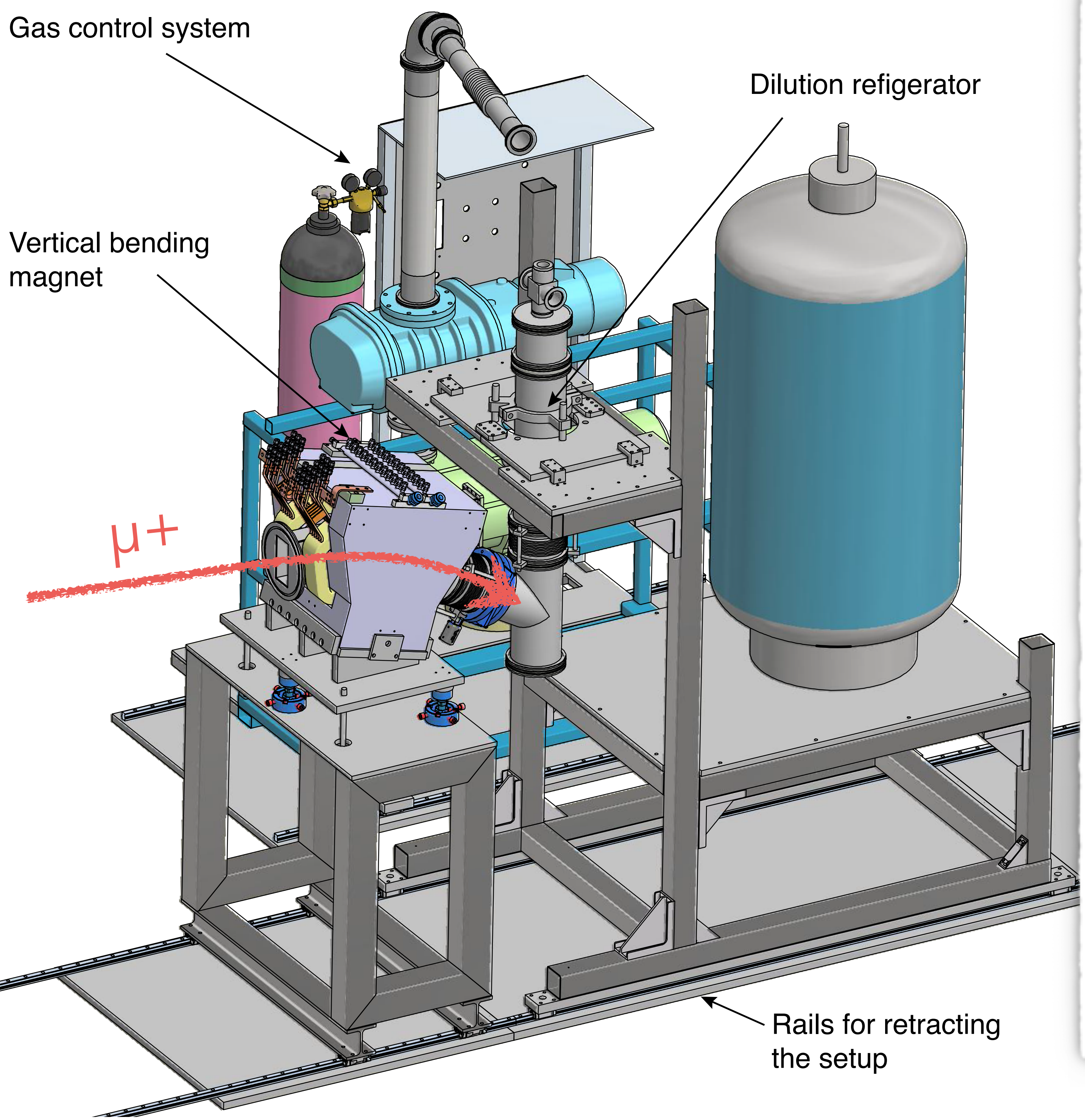




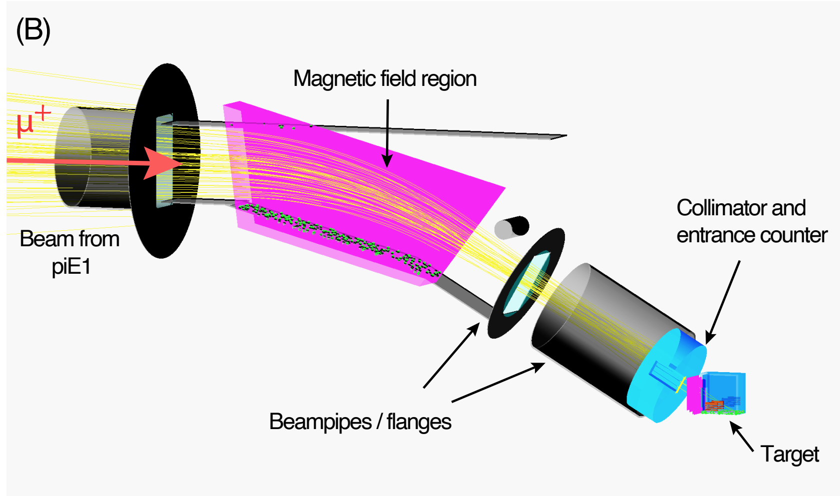
- M precessing in SFHe coated aerogel pores

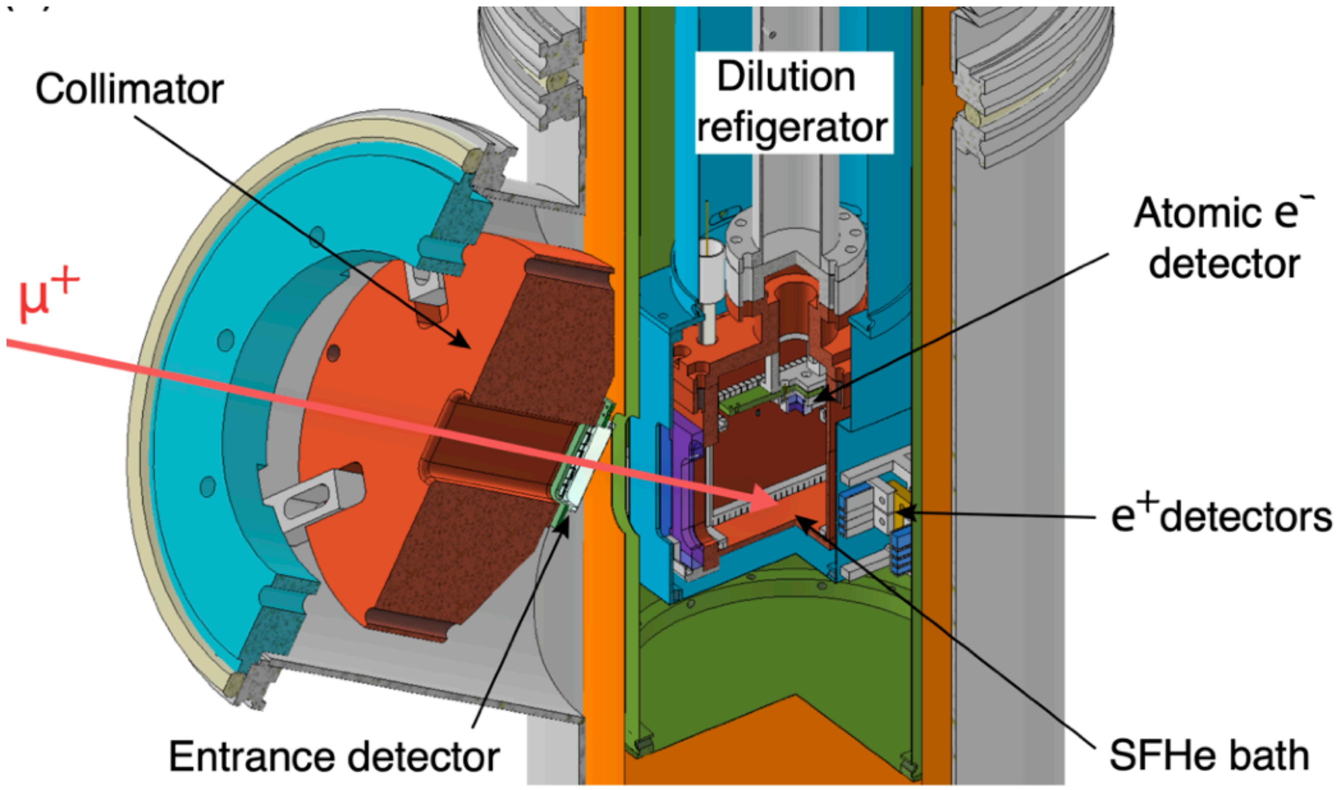


Mu extraction from SFHe, setup 2021



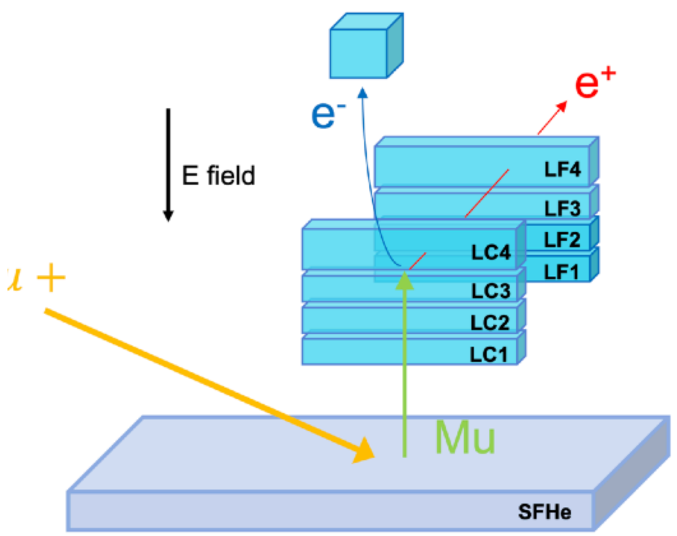
- We modified a dipole magnet for vertical bend and stop muons in the SFHe surface
- Commisioned a dilution refrigerator setup
- Target at 170 mK temperature

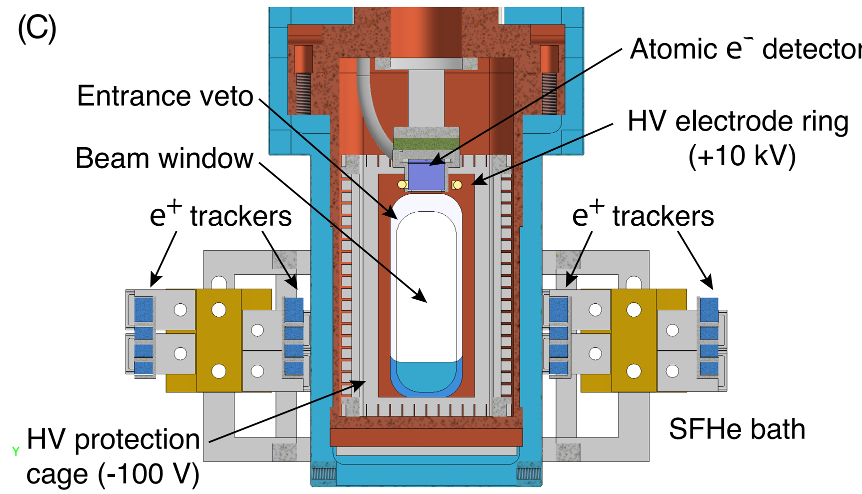




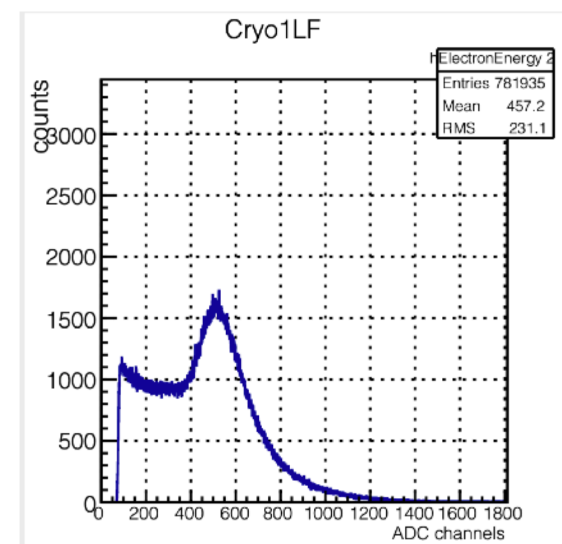
Setup for background-free vacuum Mu detection at 170 mK

- Detection scheme for atomic Mu observation

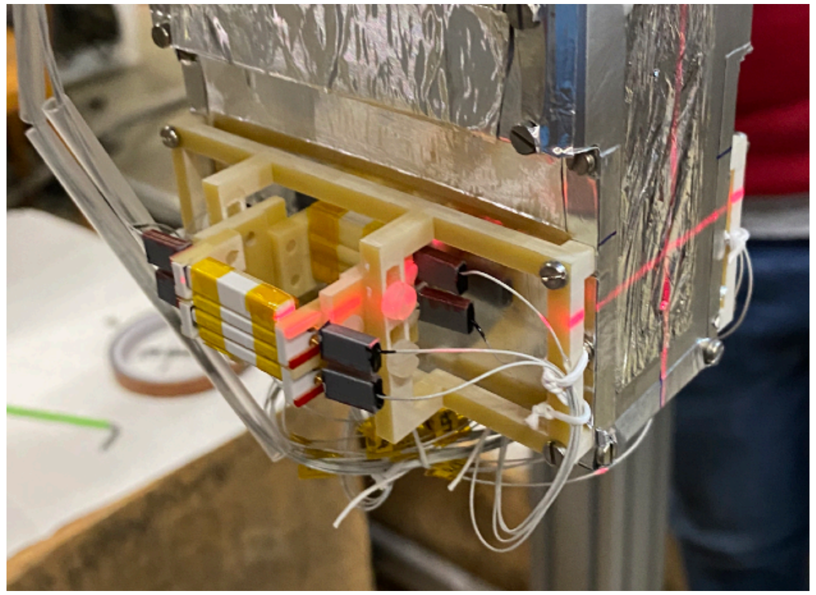


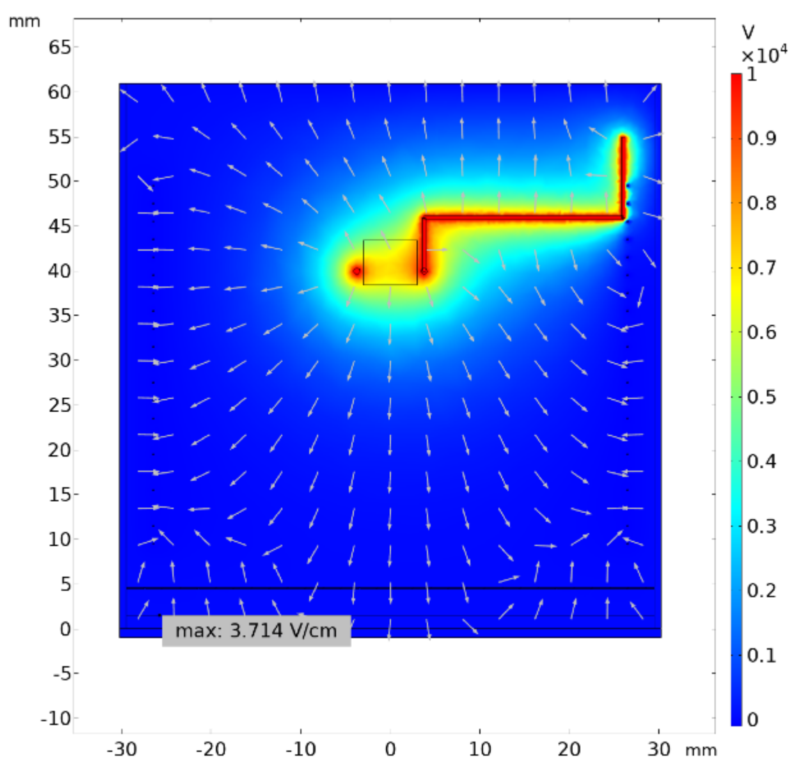


- SiPM+ scintillator trackers reliably operate at min. temp: T<0.2 K

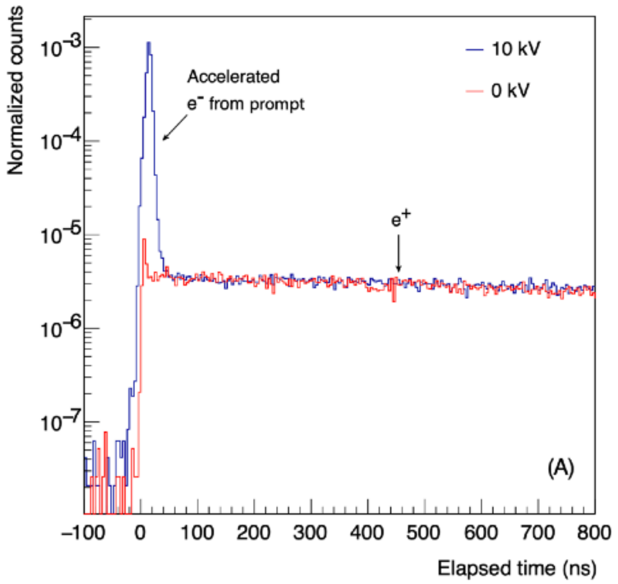


- Positron trackers mounted on the setup

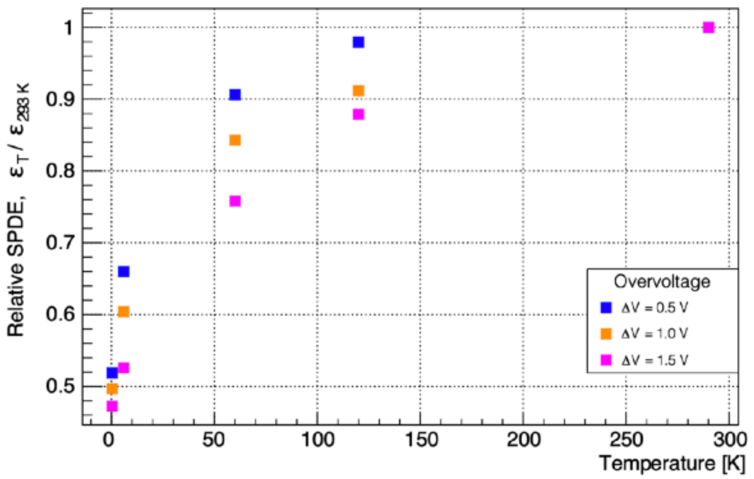




- Detection of slow electrons accelerated to 10 keV



- See Damian Goeldi's talk on Friday!

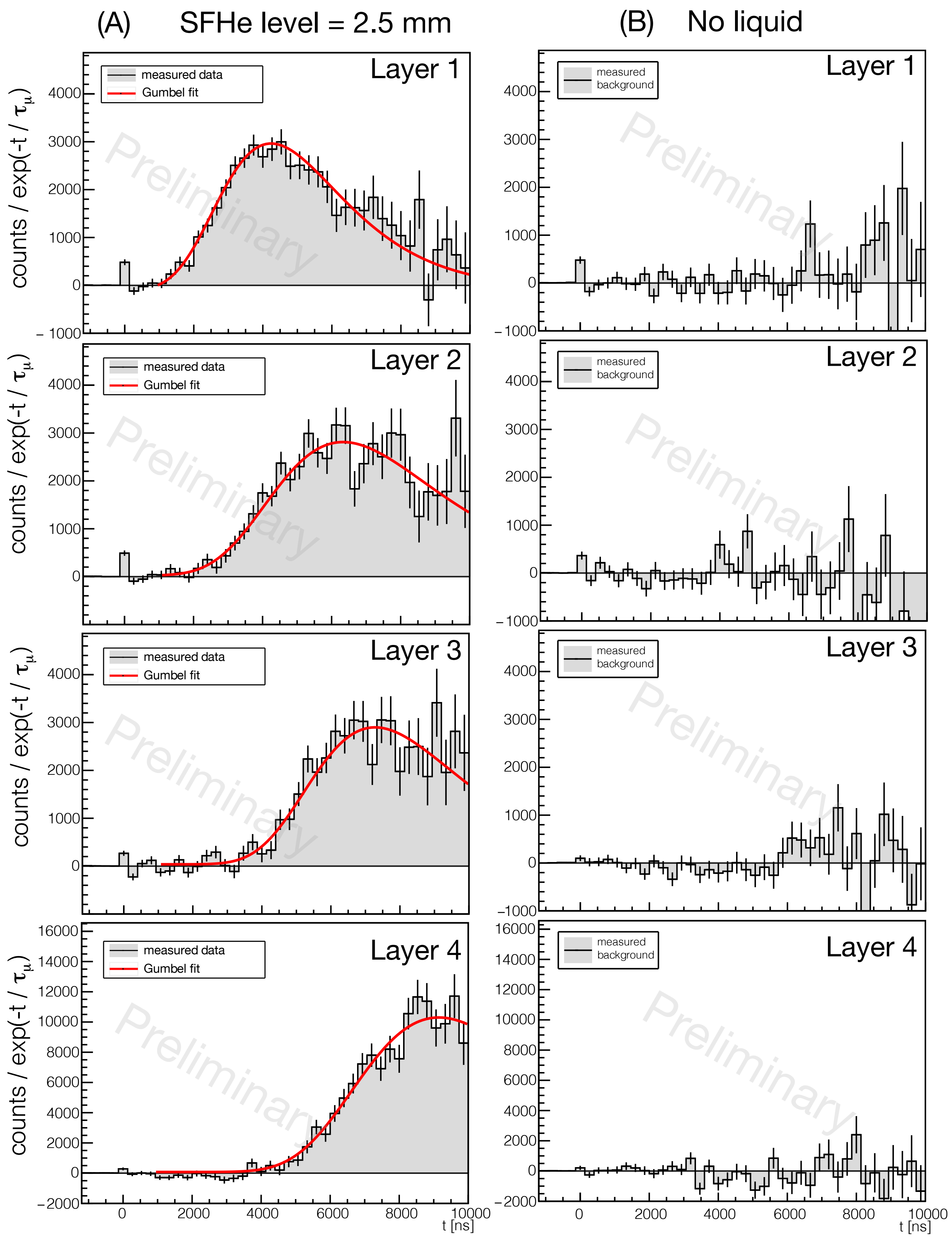


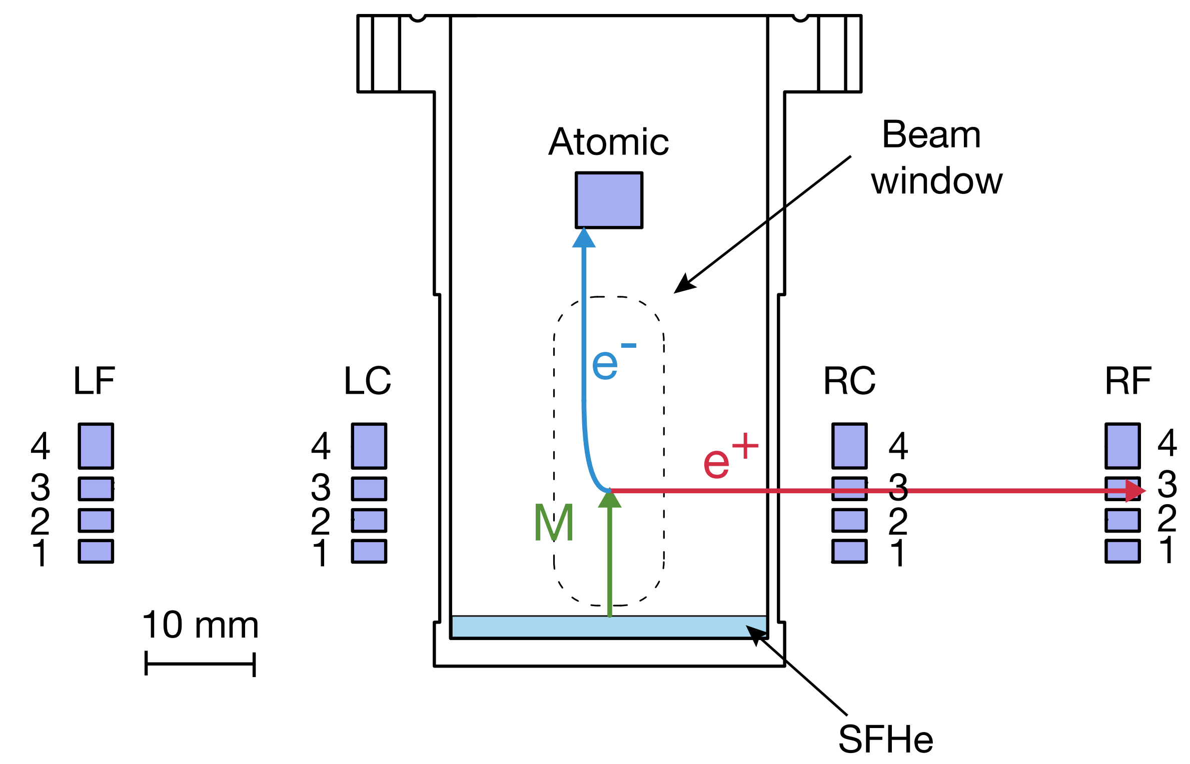
- Temperature dependency of the PDE

- Detectors commissioned at T<0.2 K temperatures in with muon beams.

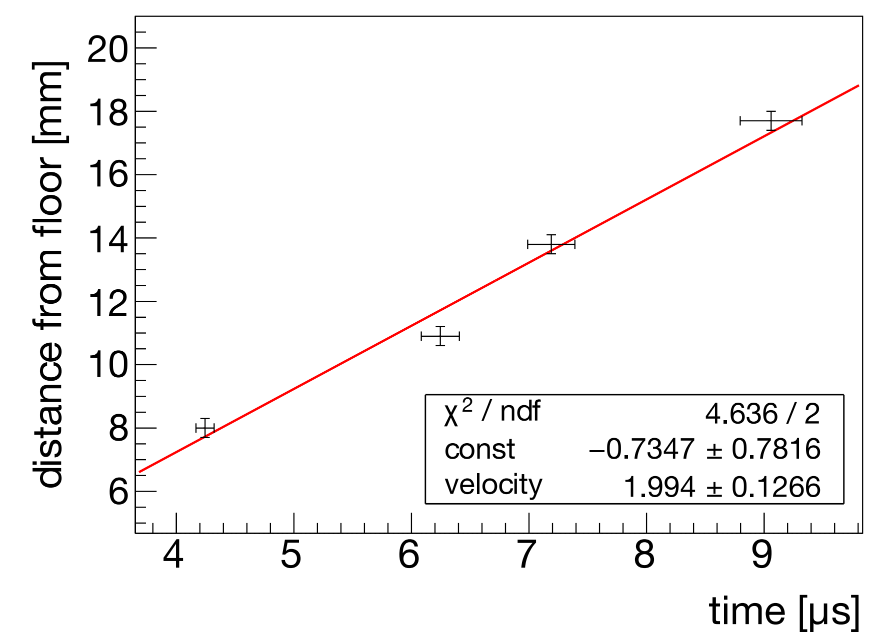
- **Physics run just finished!**

First detection of a cold atomic M beam from SFHe

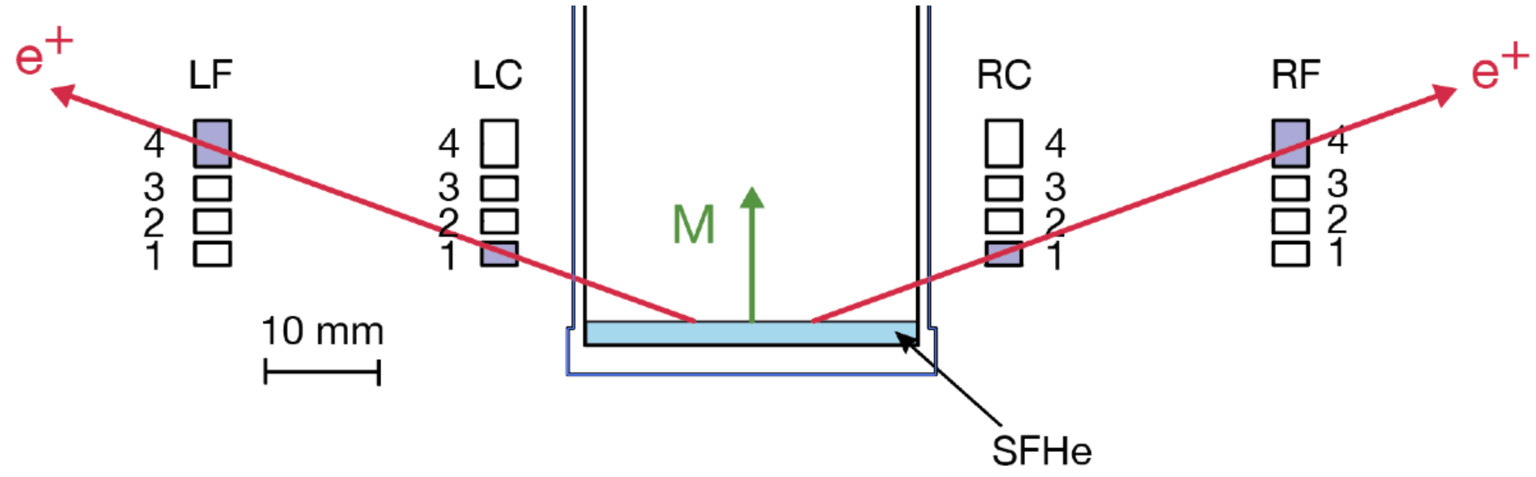




- Passing-by of the atoms are detected in the positron trackers
- Main parameter could be determined in a model-independent way: v~2200 m/s

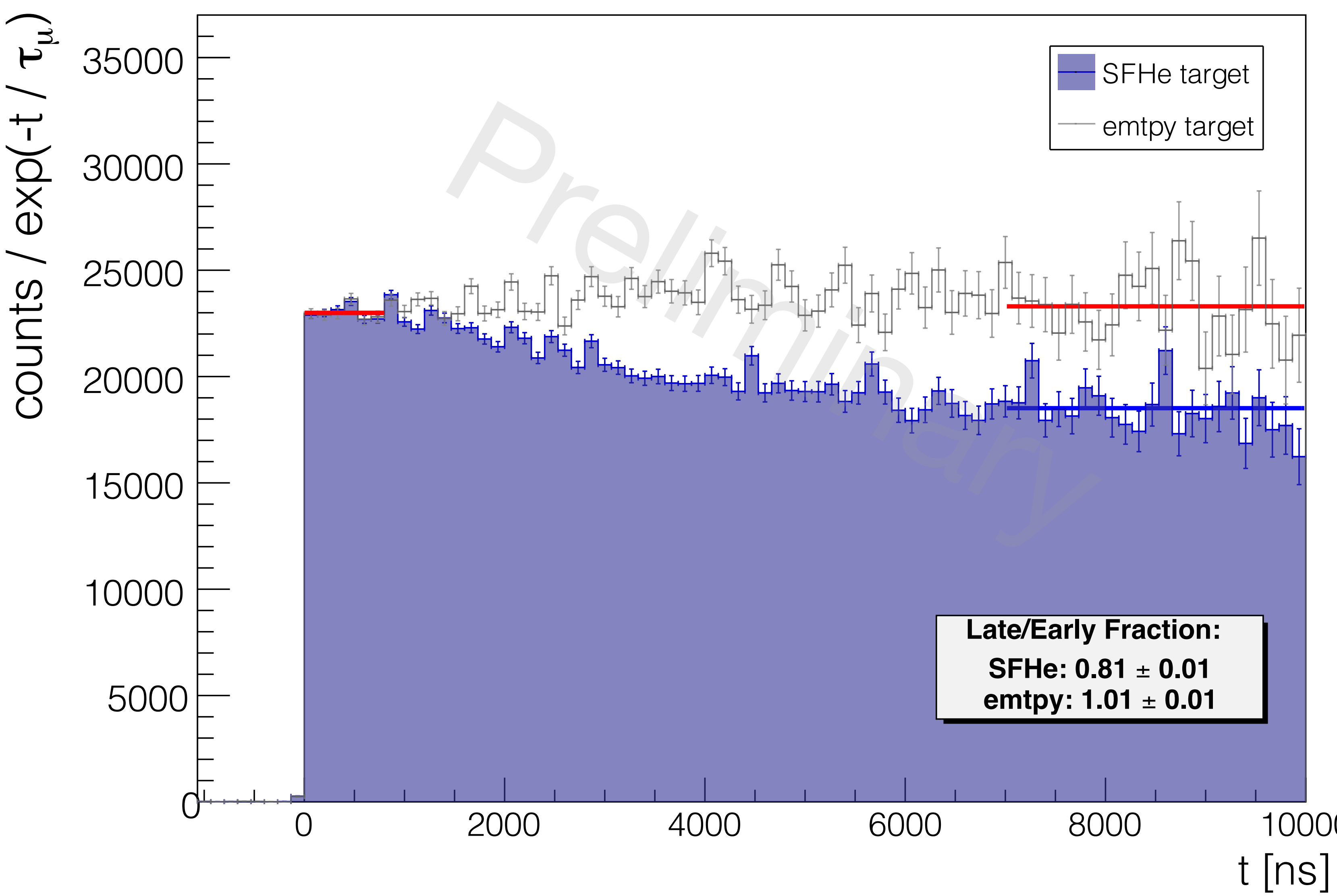


Conversion efficiency

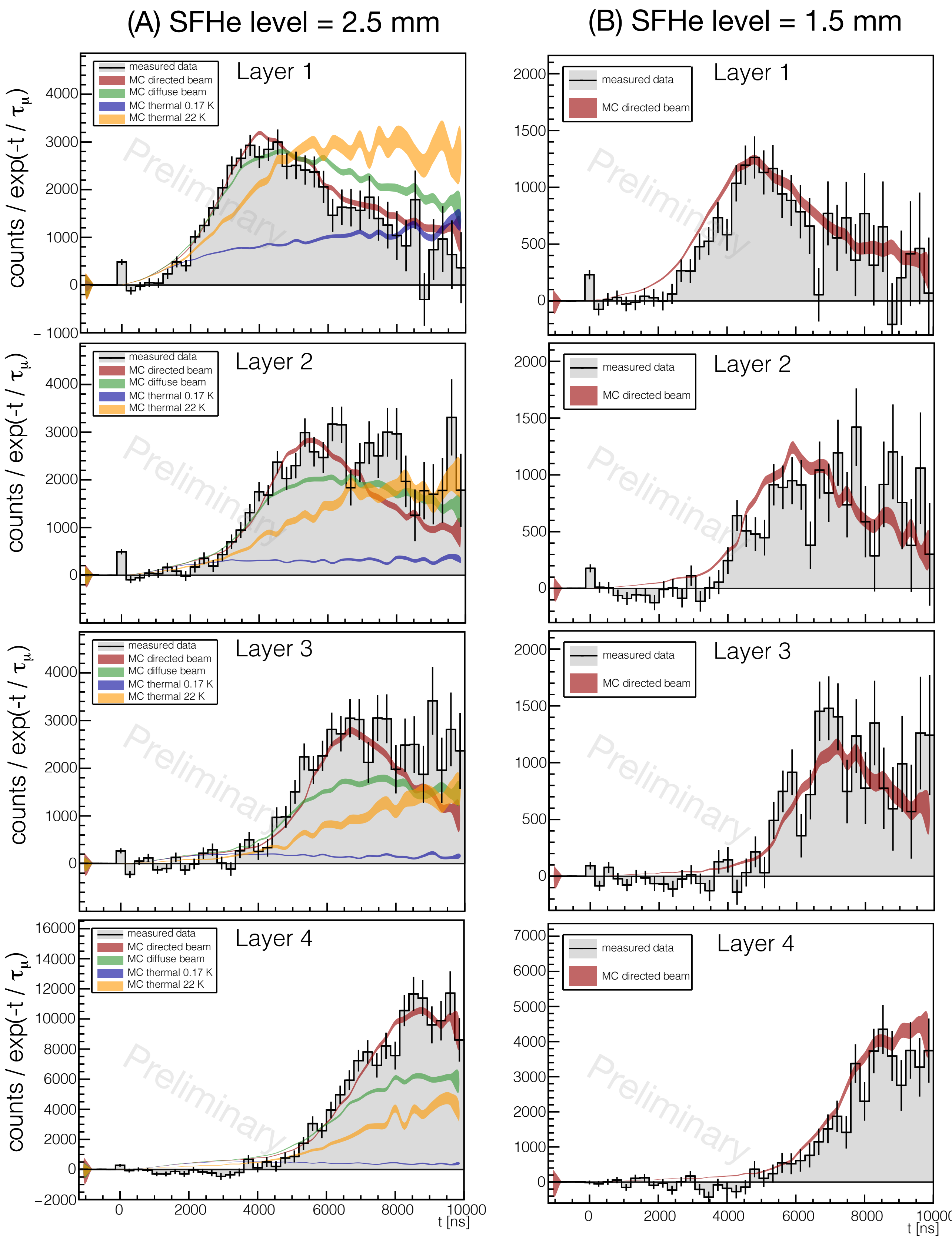


- Leaving of M atoms can be detected by looking at 4-1 coincidences

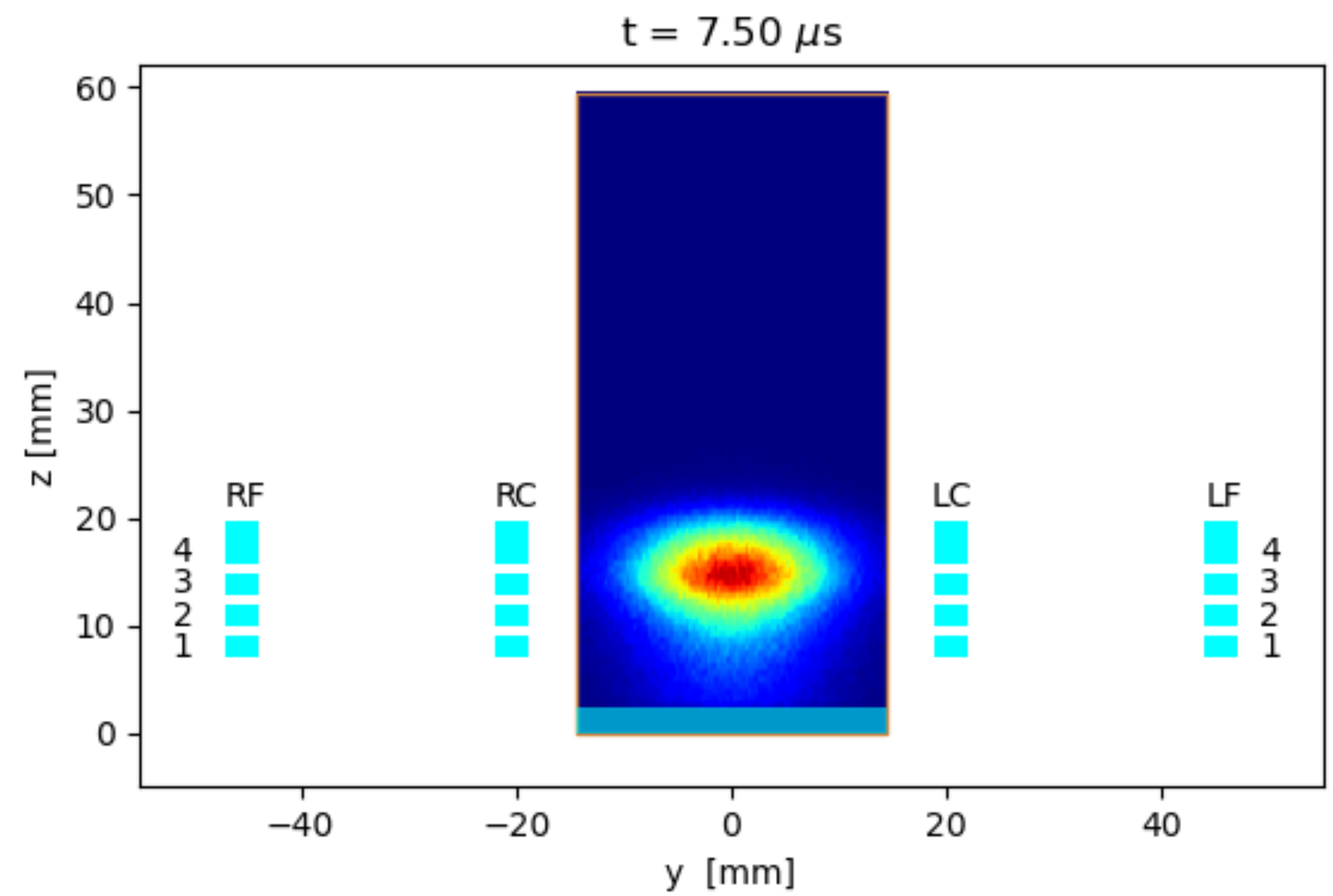
- A lower limit on the stopped muon to vacuum M conversion efficiency: 19%



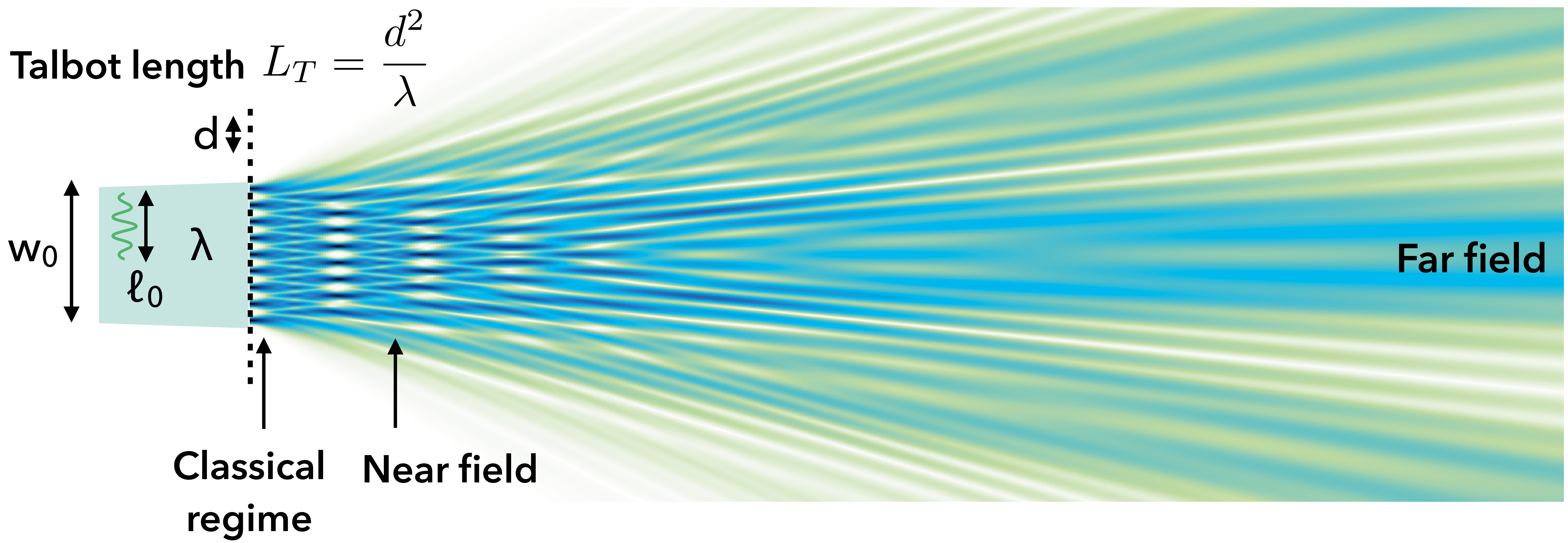
Monte Carlo simulations - thermal and directed atomic M beam



- Simulations seem to verify a directed beam vs. other conceivable solutions
- But: no sensitivity yet in the transverse direction



Interferometer - what kind of interferometry are we doing?



- d ~ spacing of slits
- L ~ length of the apparatus
- λ ~ de Broglie wavelength

$$\lambda = \frac{h}{mv} = \frac{hc}{pc} = \frac{1239.84\ [\mathrm{nm \cdot eV}]}{P\ [\mathrm{eV/c}]}$$

- w_0 ~ beam width
- ℓ_0 ~ transverse coherence length

- Mu from SF: λ ~ 1.6 nm (v=2200 m/s)
- d ~ 100 nm, L_T ~ 6.2 μm
- few 7-8 us interaction ~ 10 mm between gratings
- => we are in the 'quantum regime,' and in the 'aperture near field', but several hundreds Talbot-length away

Different beam qualities with the optimised interferometer geometry

- Model: using mutual intensity functions from statistical optics
- Calculations assume a Gaussian Schell-model beam

w_0 ~ beam width (aperture)
ℓ_0 ~ transverse coherence length

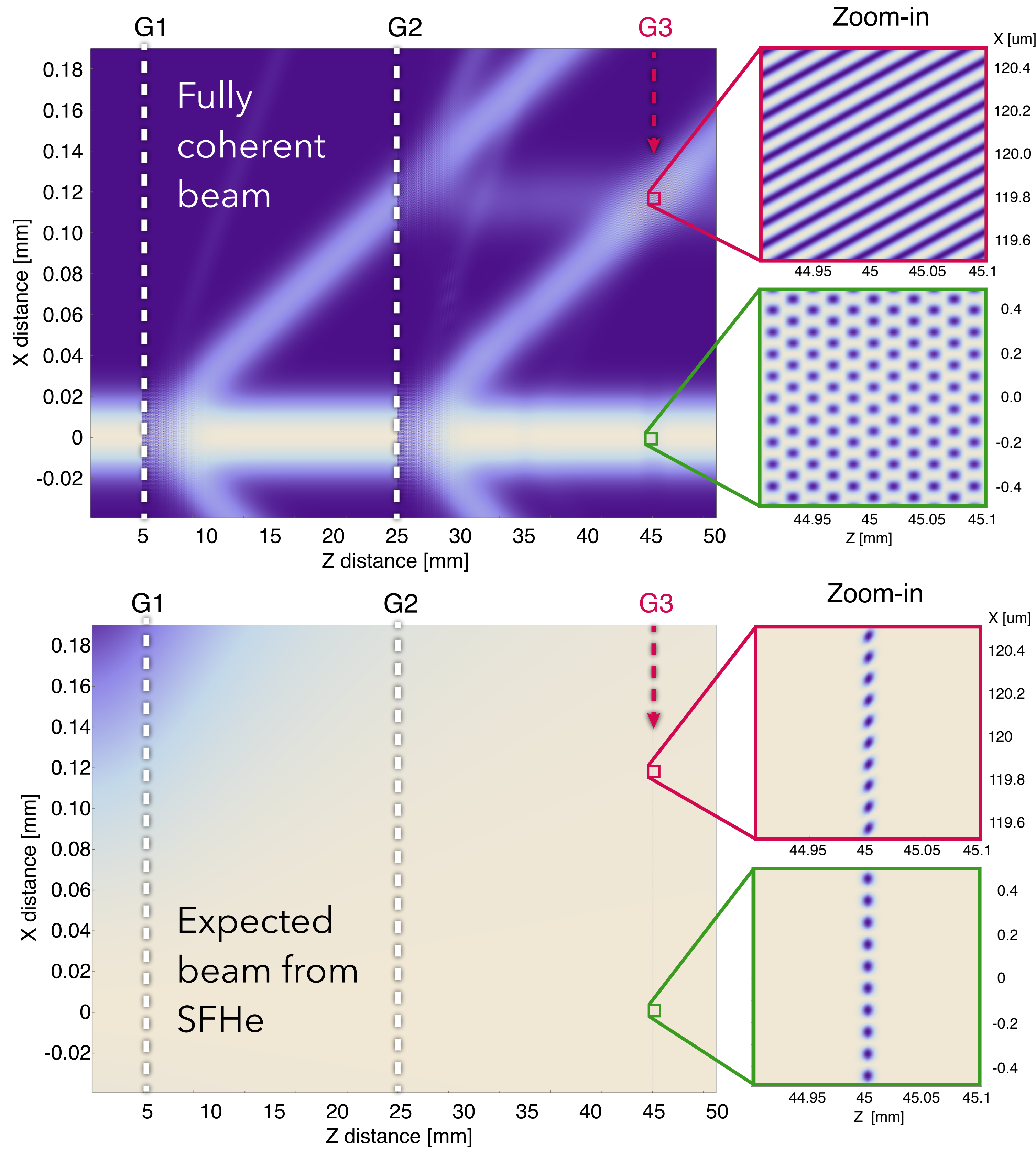
ℓ_0 relates to the angular spread (**α**) of the atoms (via the Cittert-Zernike theorem) as:

$$\ell_0 \approx \frac{\lambda}{\alpha} \approx \frac{1.6 \text{ nm}}{50/2200} = 70 \text{ nm}$$

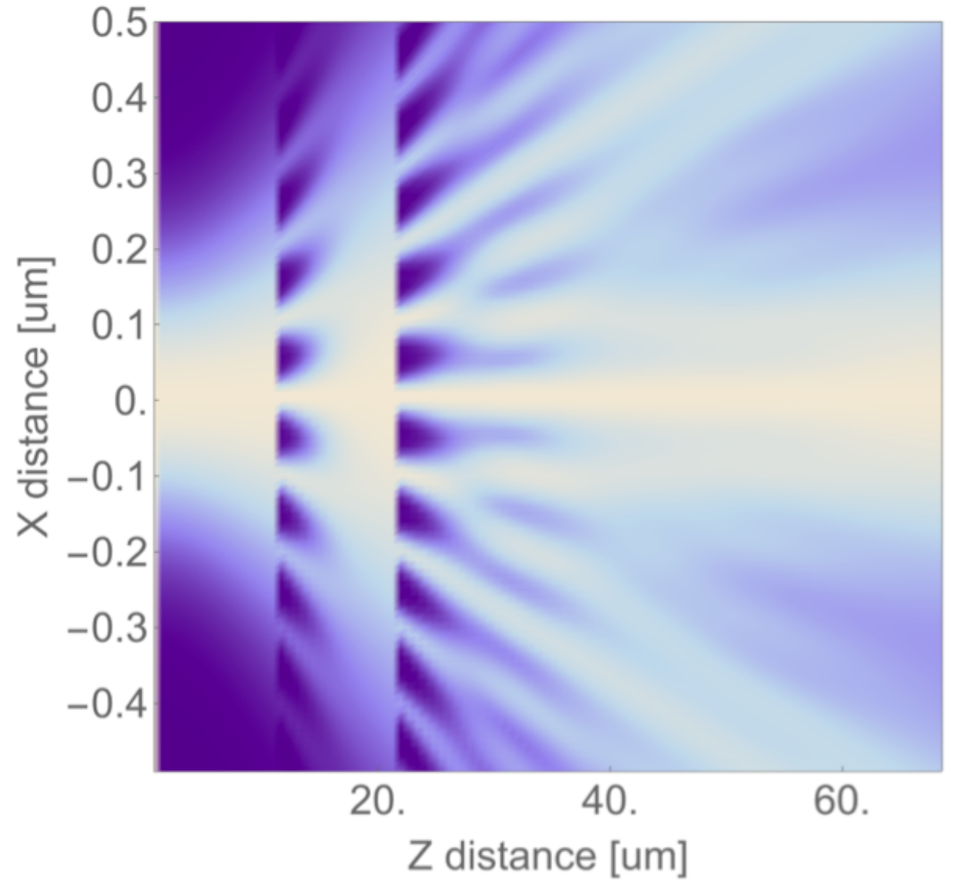
α ~ 22 mrad, and ℓ_0 ~ 70 nm - close to the grating pitch size

- Contrast = 0.3
- Given there is enough high quality Mu atoms, might be feasible!

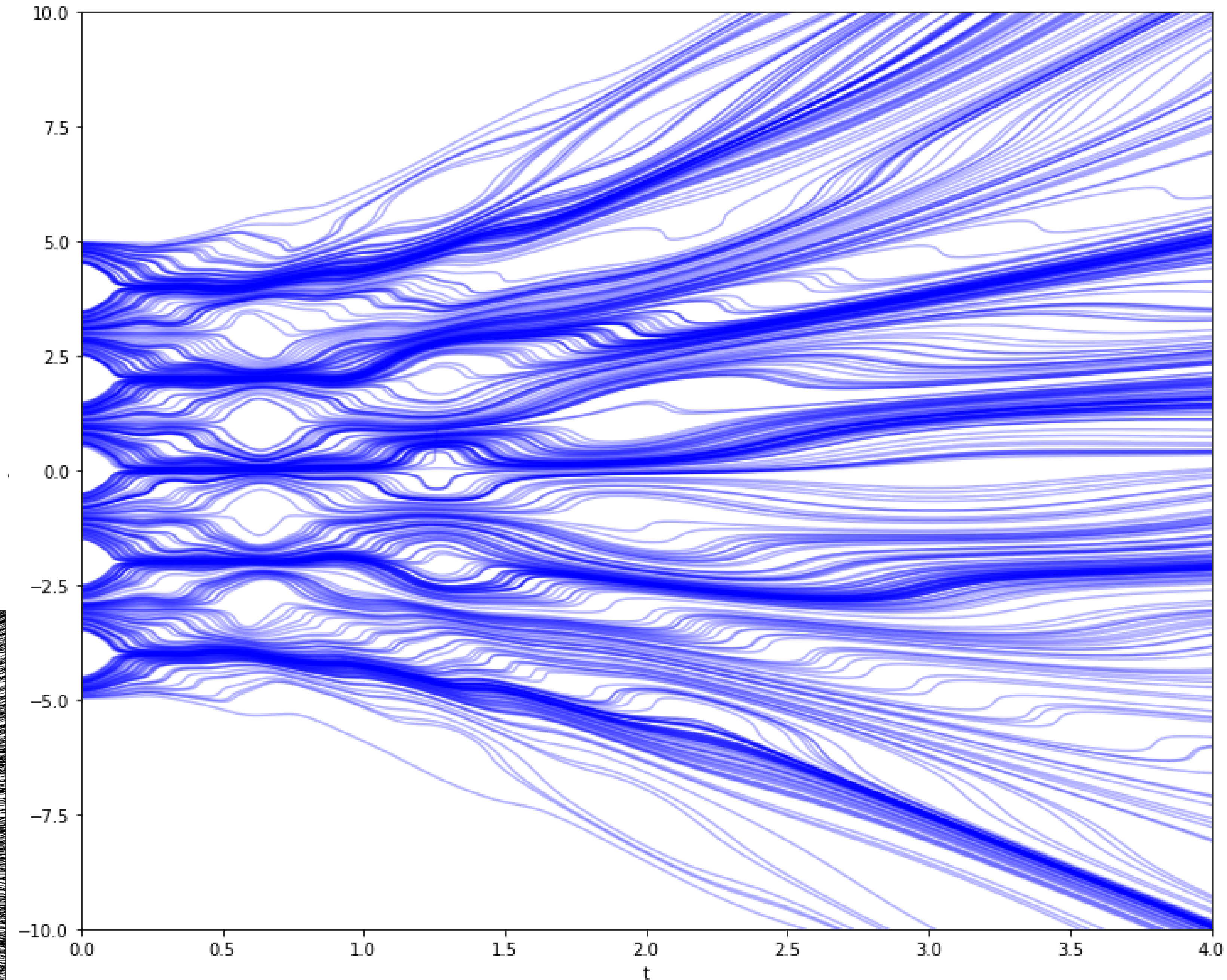
model based on: McMorran et al., PRA 78 (2008)



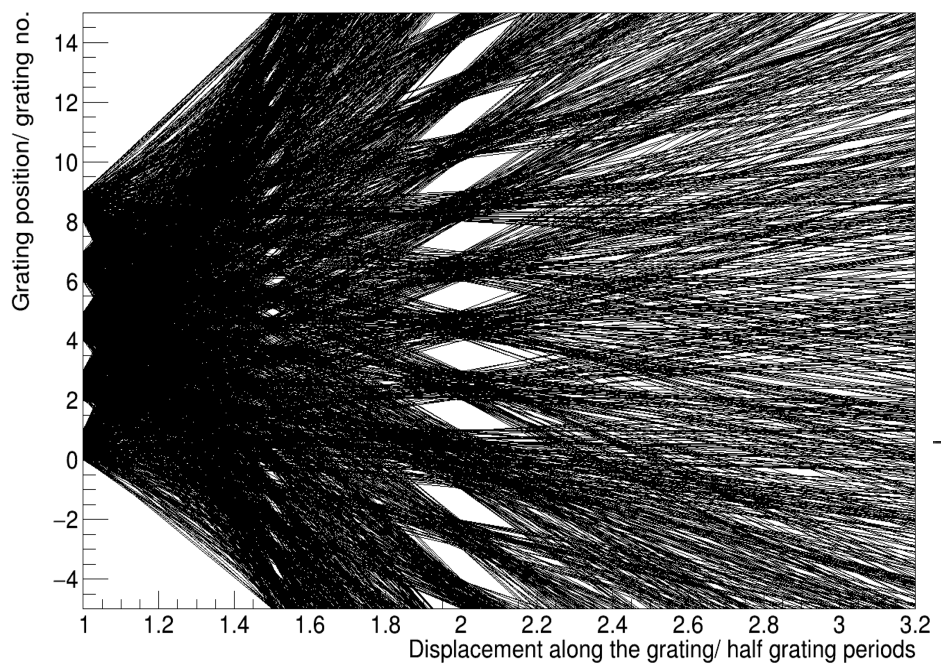
Different approaches in interferometer calculations



- mutual intensity functions from statistical optics



- pilot-wave approach (Boehmian QM)

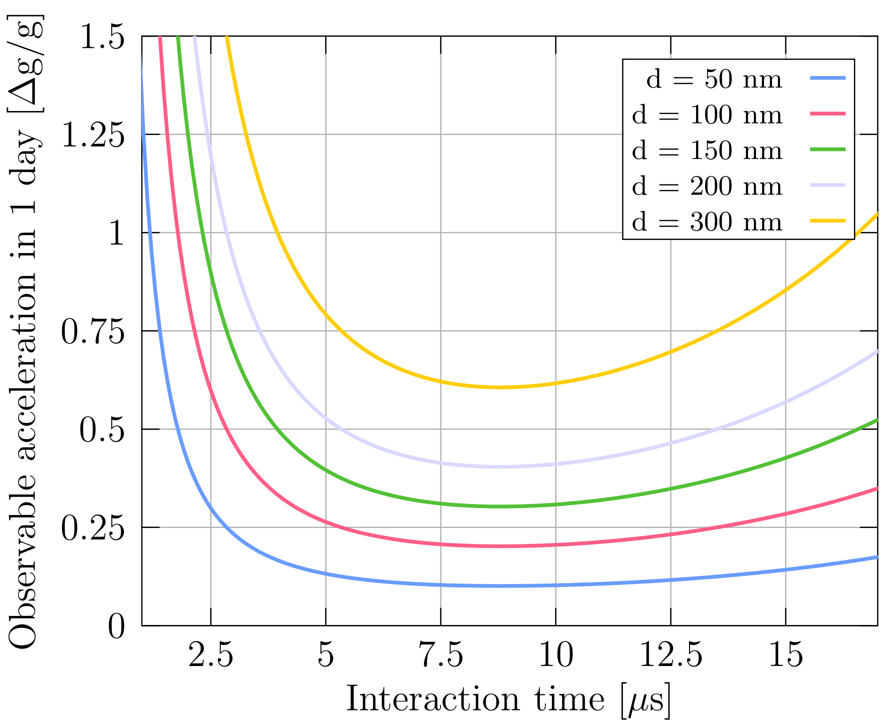


- Classical trajectories
- Ideas from the quantum community are welcome!

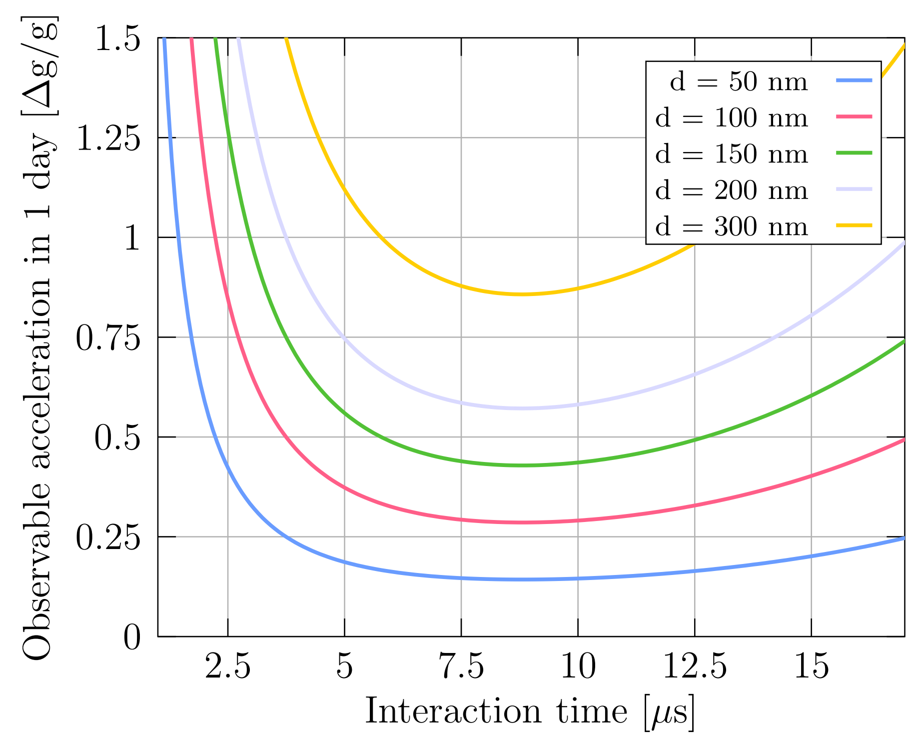
Sensitivity with high intensity muon beams

Optimizing the length of the interferometer

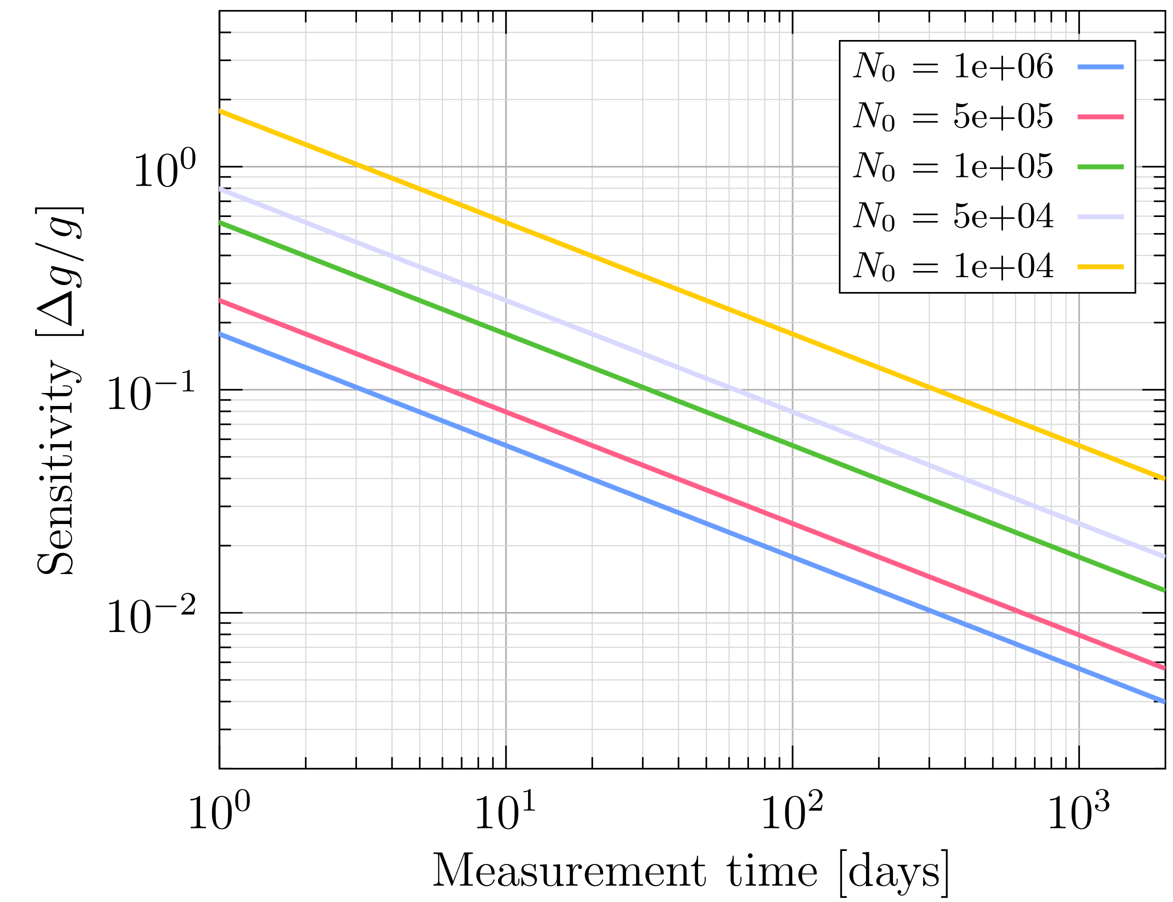
$N_0 = 1\cdot10^6$/s
C=0.3

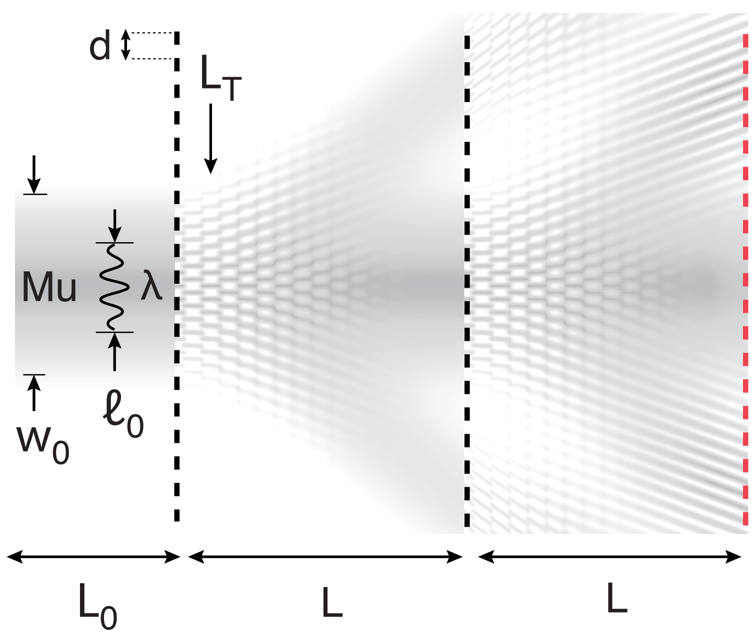


$N_0 = 5\cdot10^5$/s
C=0.3



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





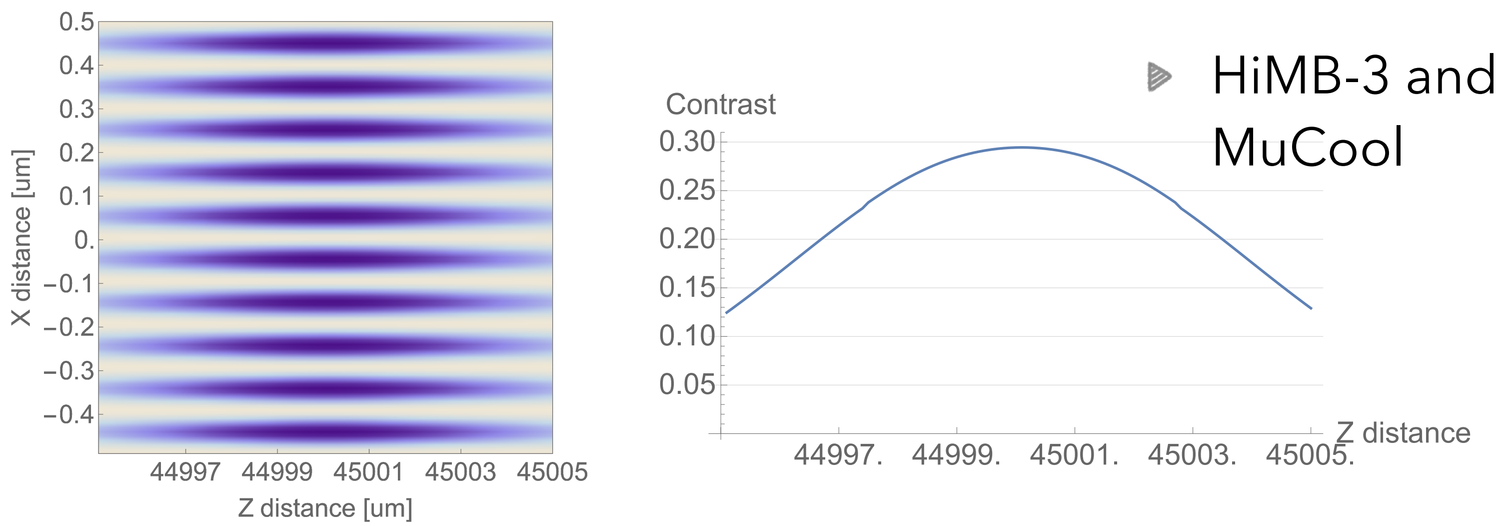
With λ_{Mu} = 1.6 nm (SFHe beam) L_0=3 mm, L=10 mm, d=100 nm, C=0.3
($L_T = d^2/\lambda$ = 6 μm), η=0.3, ε=0.5

Determining sign of g:
few days with M source of $N_0 \sim 5\cdot10^4$/s, C=0.3

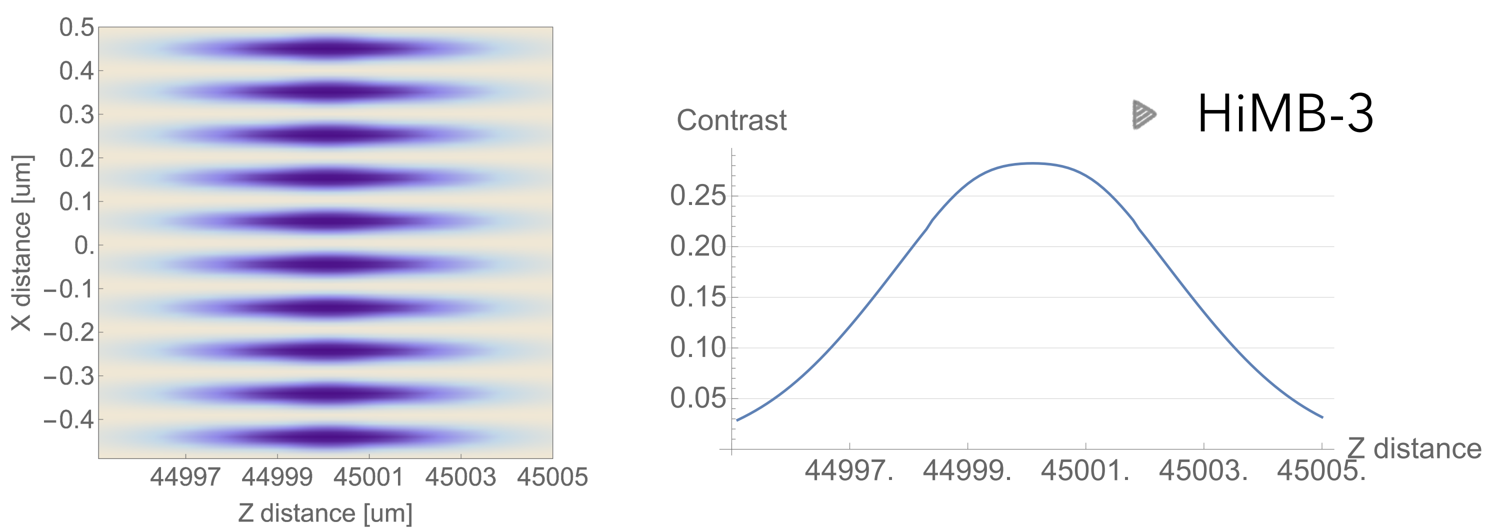
SFHe source expected to give 10^5/s - 10^6/s depending on muon beam schenarios

(Some of the) challenges with the source: size

- Last grating needs Z alignment within ~1 um to stay in the high-contrast region
- Systematic effects from grating imperfection, alignment, vibrations, sig/noise worsen a lot by increasing muon beam size



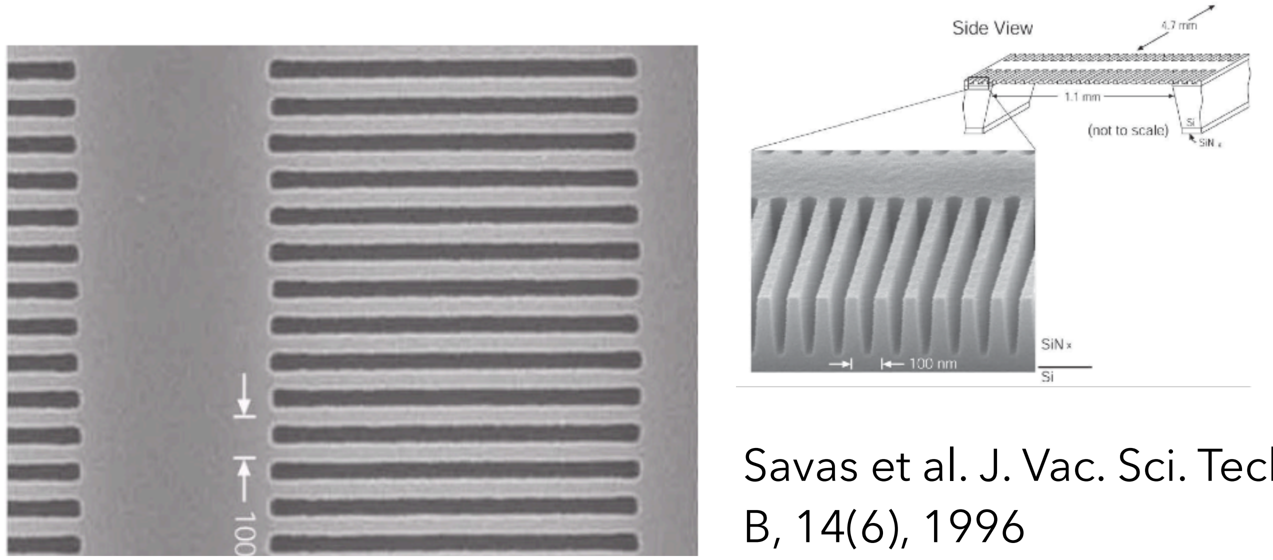
- HiMB-3 and MuCool



- HiMB-3

Grating production

- Free-standing Si_3N_4 gratings with d=100 nm pitch, 100-200 nm thick, discussions with C. David @ PSI
- Challenging to produce $1x1cm^2$ aperture, without waves and bends



Savas et al. J. Vac. Sci. Tech. B, 14(6), 1996

- Tiny beams might be vital to have!

Plans

- To go big! Large cryostat, large source
- New proposed experiment at PSI: LEptons in Muonium Interacting with Gravity (LEMING)
- Decision next week!

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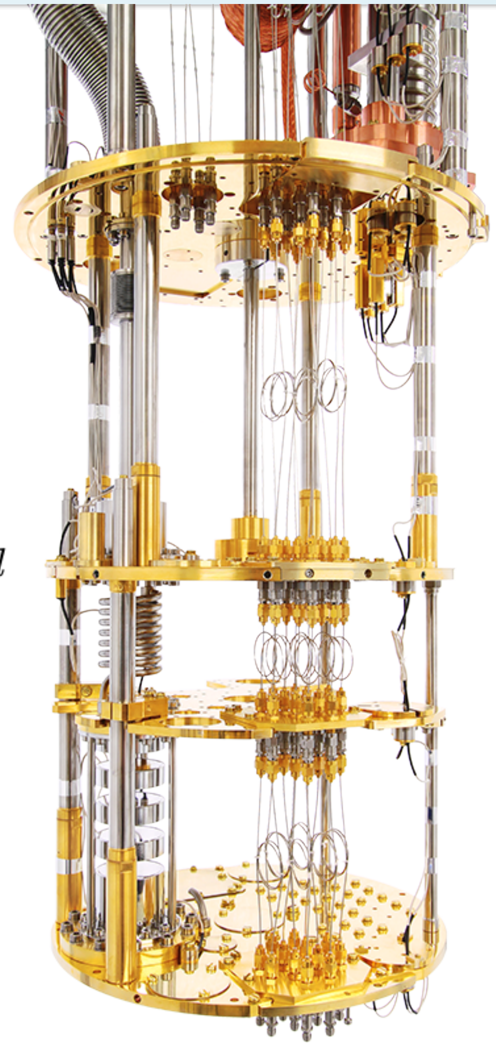
Paul Scherrer Institute, 5232 Villigen-PSI, Switzerland

- **Many outreach to the quantum community!**



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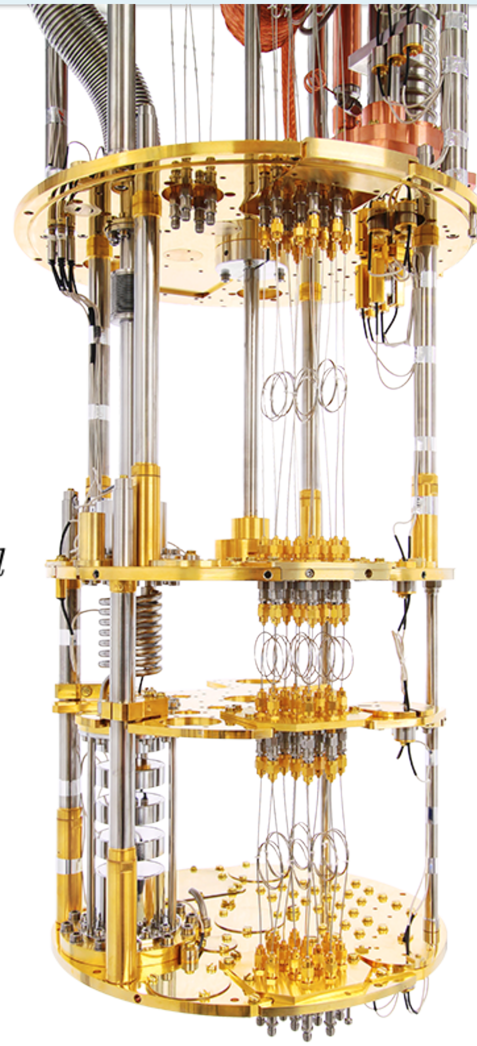

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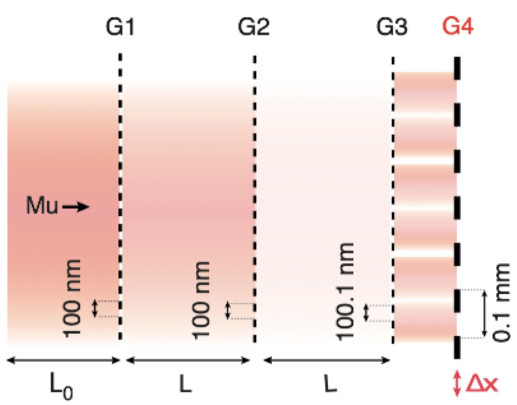
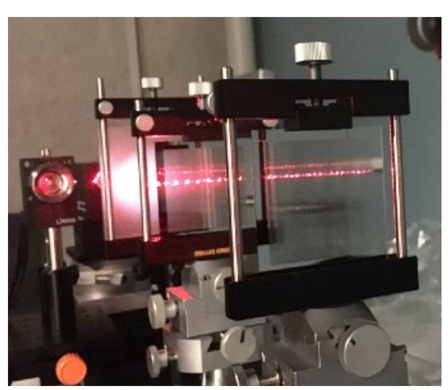
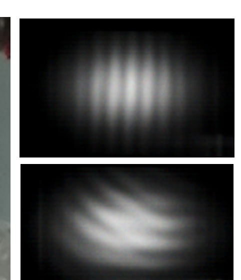
Interferometer studies and prototyping







Moire fringes

- Alignment at room and cryogenic T using soft X-rays in Swiss Light Source (SLS) - 1-2 keV

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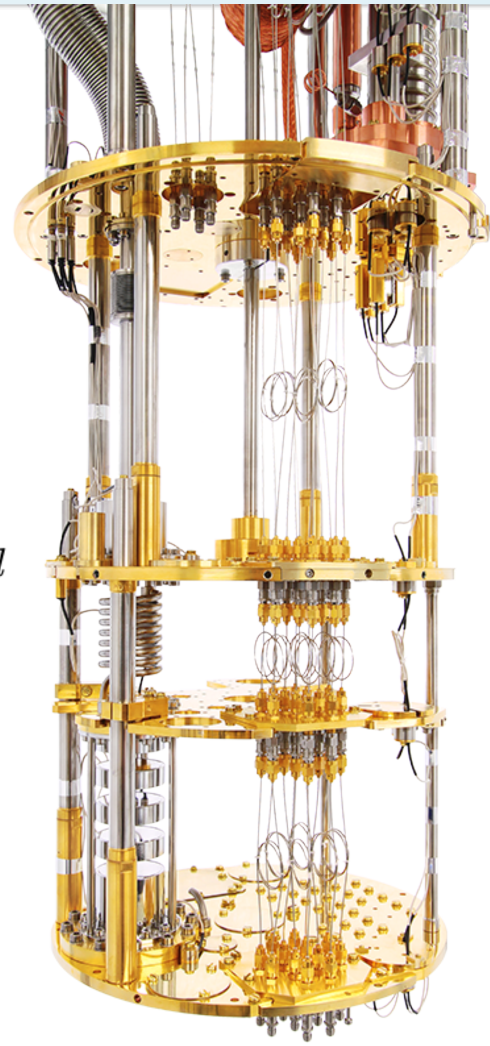
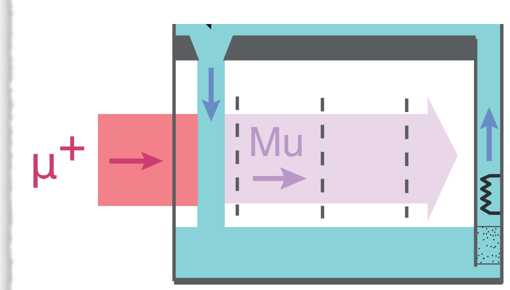
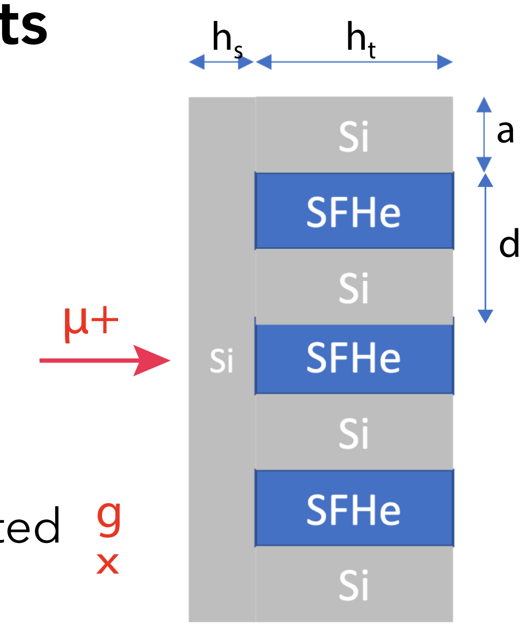


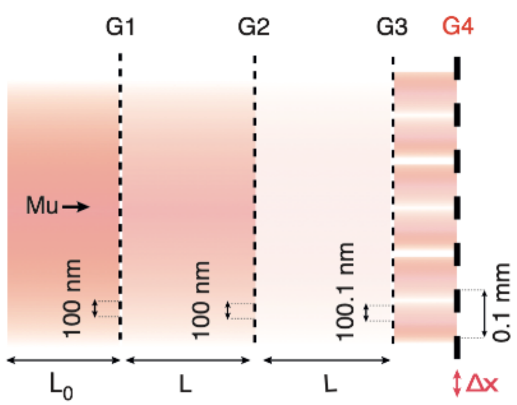
Vertical targets

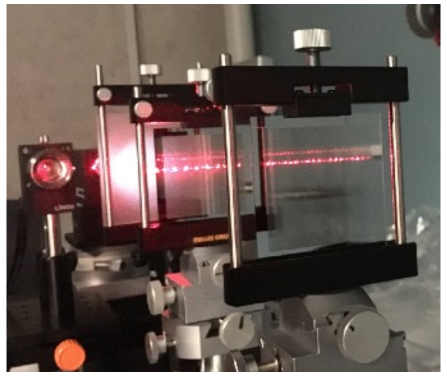


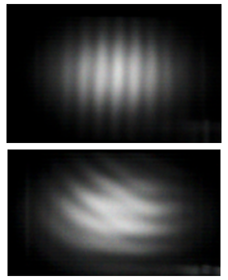


- Cascades or microfluidic SFHe targets self-supported by the capillary force

Interferometer studies and prototyping







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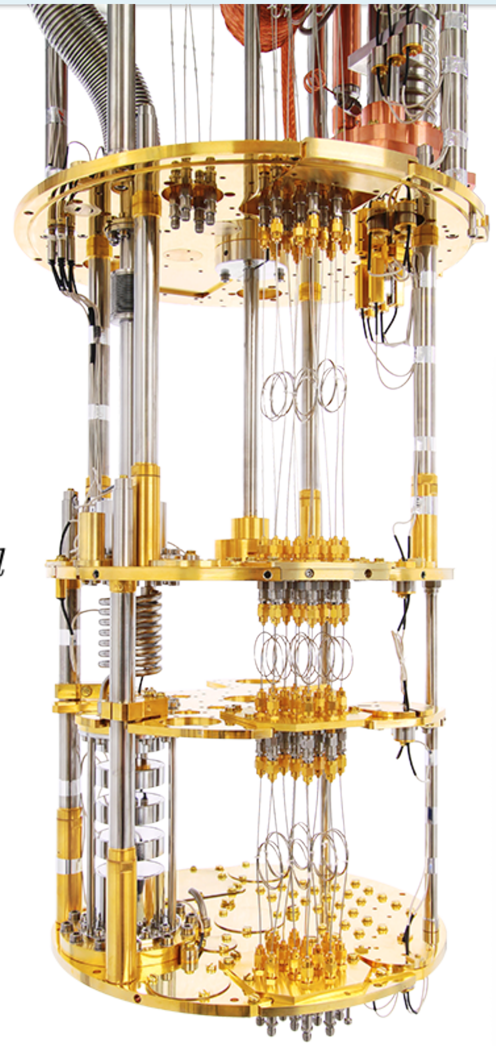

LEMING

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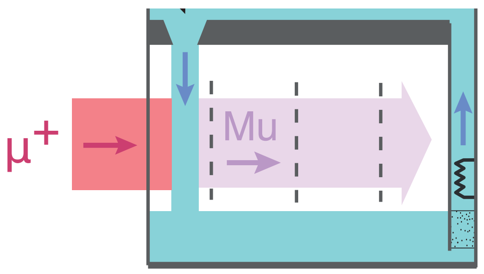

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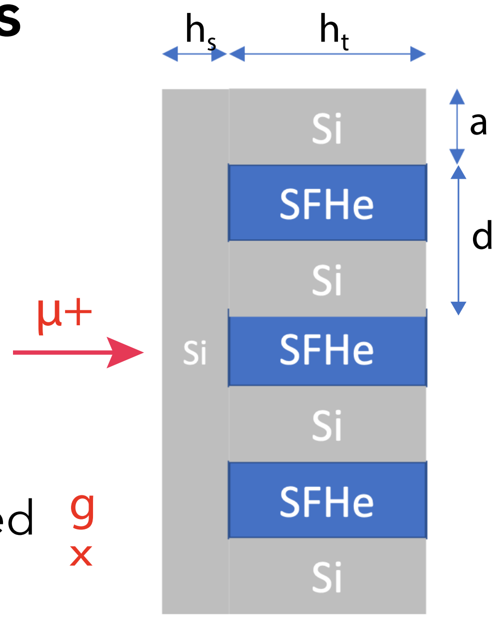

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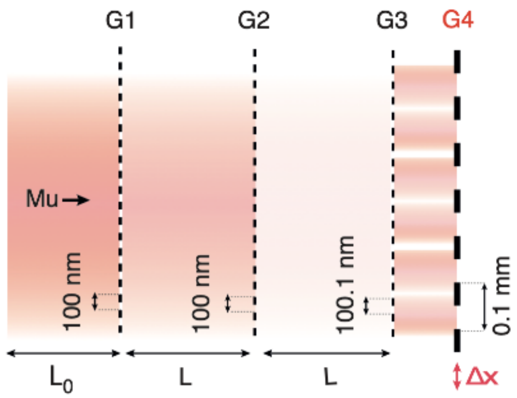

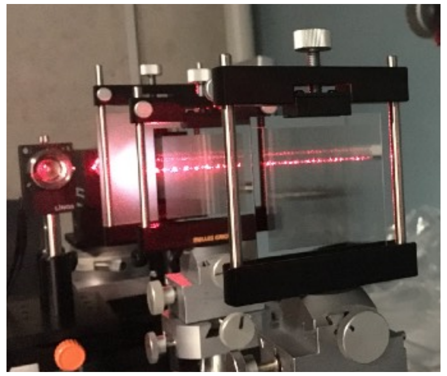

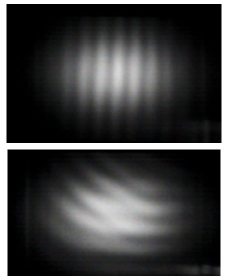

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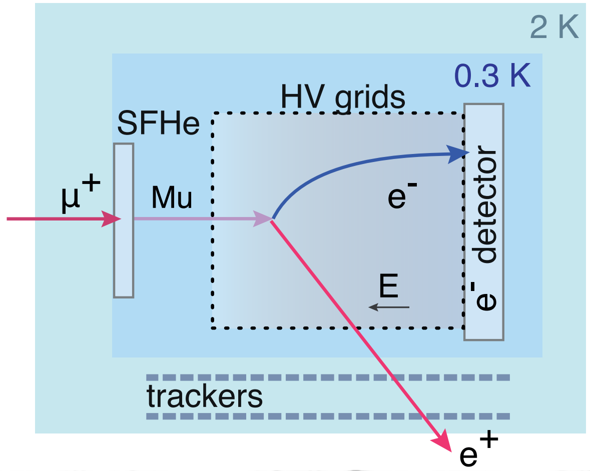
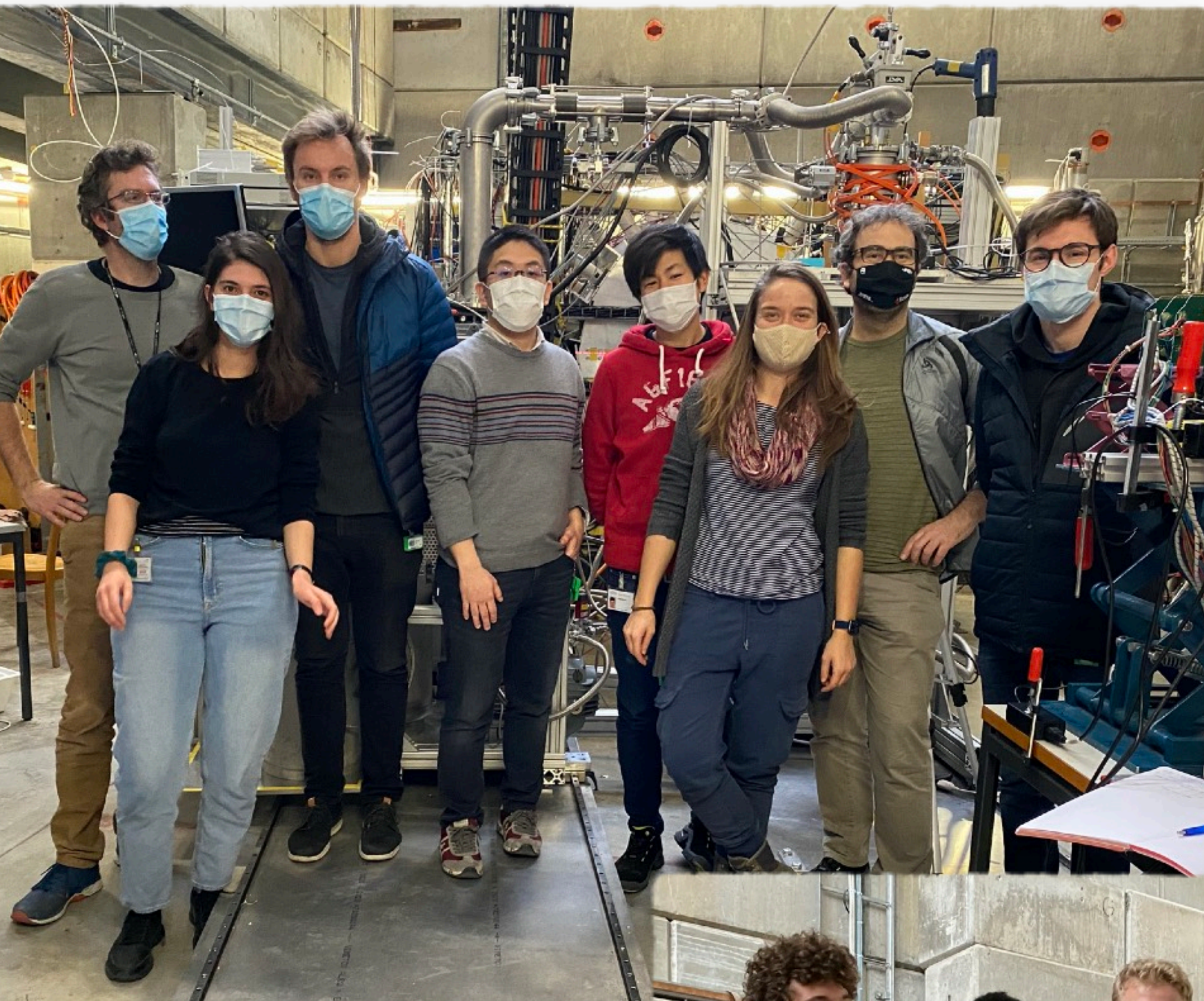
Cryogenic detectors

- cryogenic positron tracker
- atomic electron detection
- direct atom detection (10 meV-threshold): transition edge-type detectors, superconductive nanotubes



Thank you!

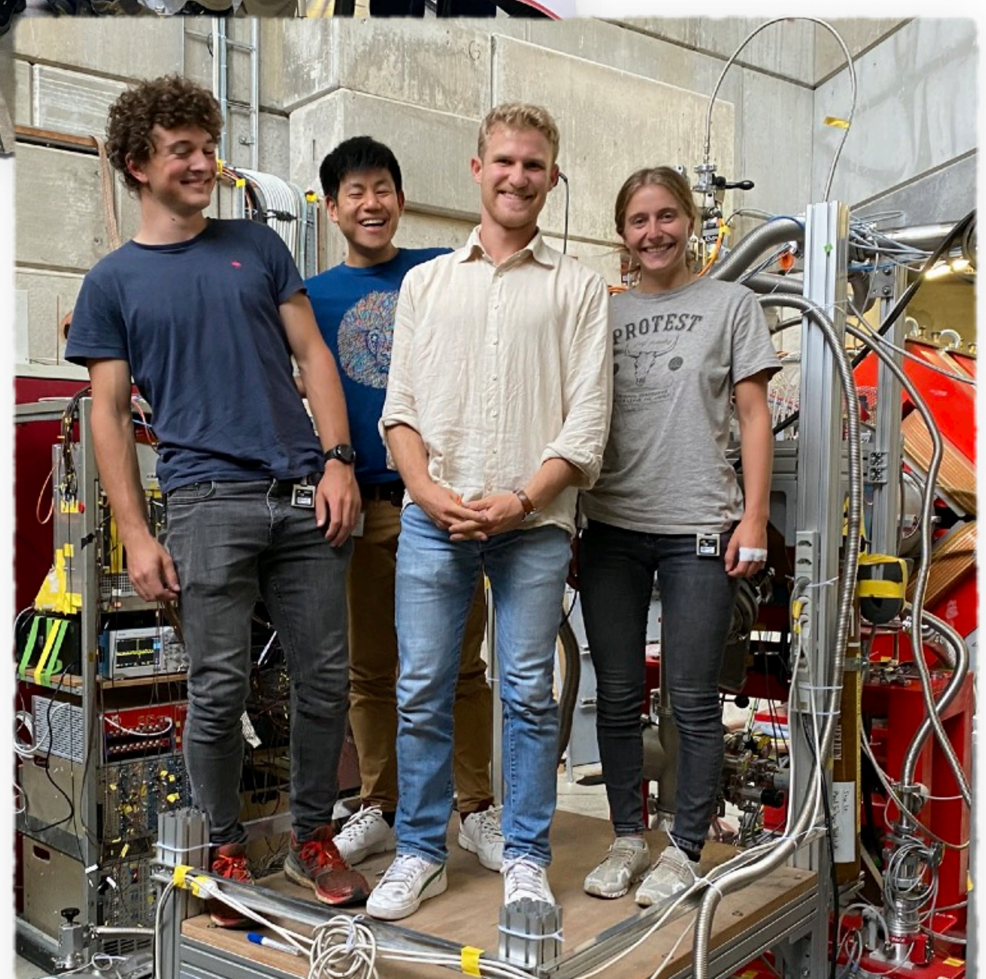


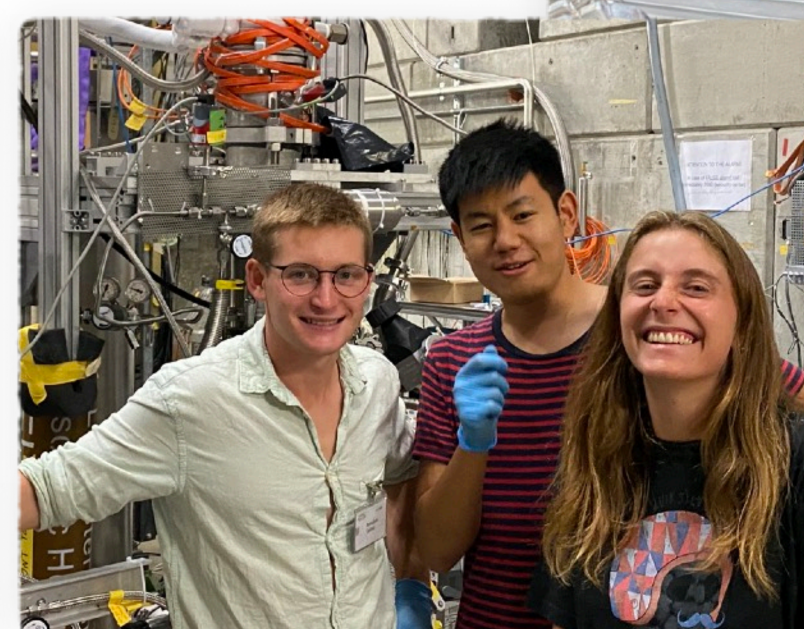
The Low Energy Particle Physics Group

Gilbertas Umbrazunas PhD student - CERN / BASE
Robert Waddy PhD student - ETH
Paul Wegmann Master student - ETH
Jesse Zhang PhD student - ETH

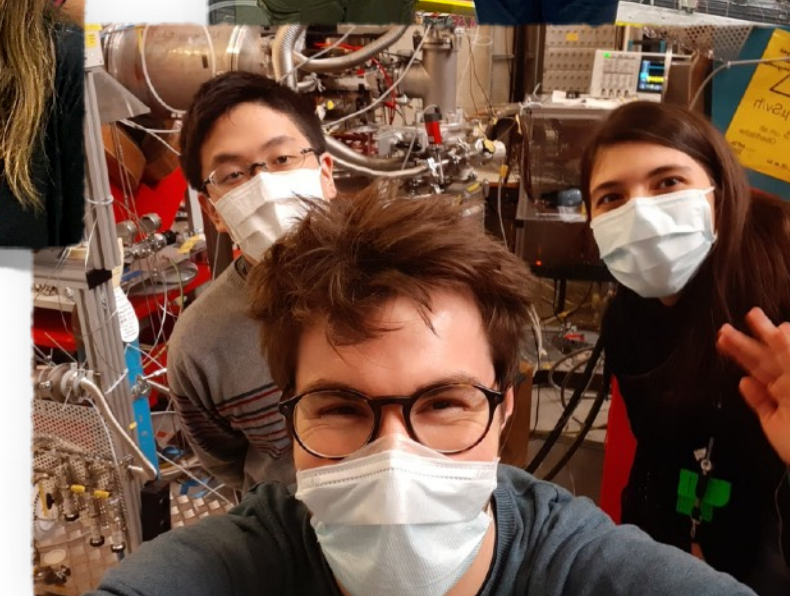
Damian Göldi Post-Doc - ETH
Michael Heiss Post-Doc - ETH

The beamtime teams





+ great ETH undergrads & fantastic collaborators at PSI, CERN, ETH …



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