Cold muonium beam for atomic physics and gravity experiments

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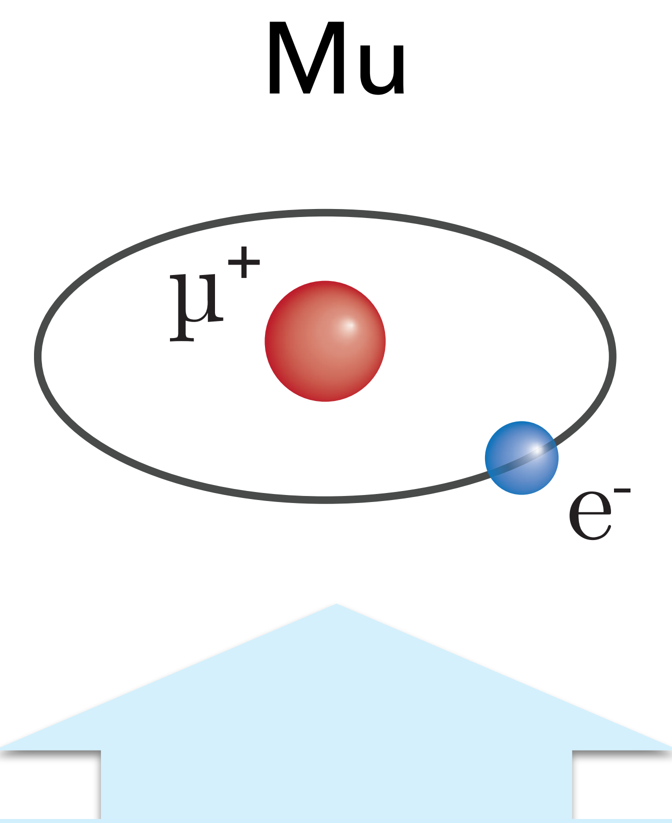
M. Bartkowiak[2], A. Knecht[2], A. Papa[2], N. Ritjoho[2], D. Rousso[2], R. Scheuermann[2], A. Soter[2],
M. De Volder[3], D. M. Kaplan[4] and T. J. Phillips[4]



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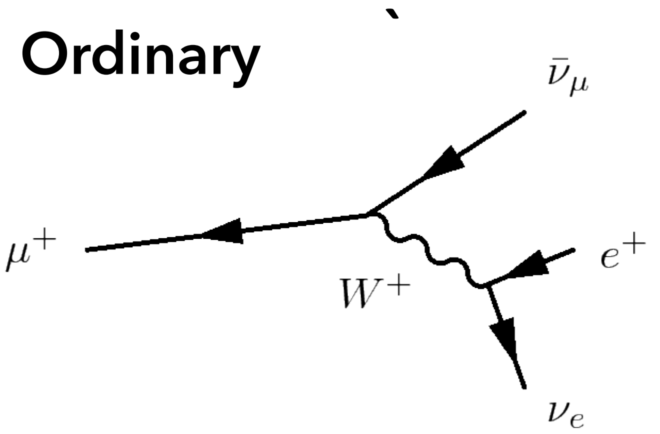
[3] Department Of Engineering, University of Cambridge, UK
[4] Illinois Institute of Technology, Chicago, IL 60616 USA

Fundamental physics with muons in PSI

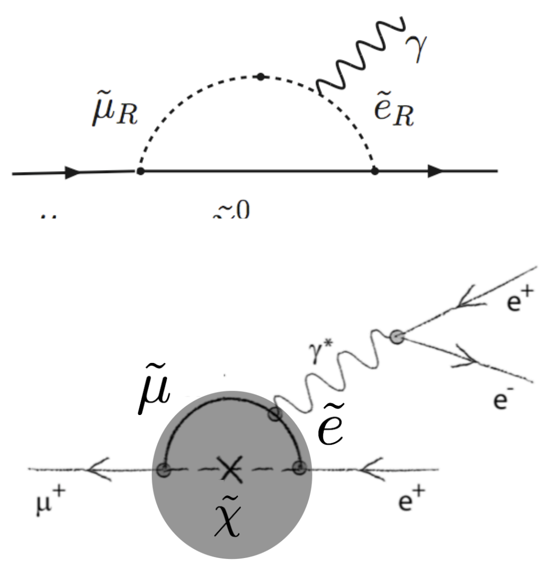
Muon decays

Ordinary



- **precision** measurements of SM

Forbidden



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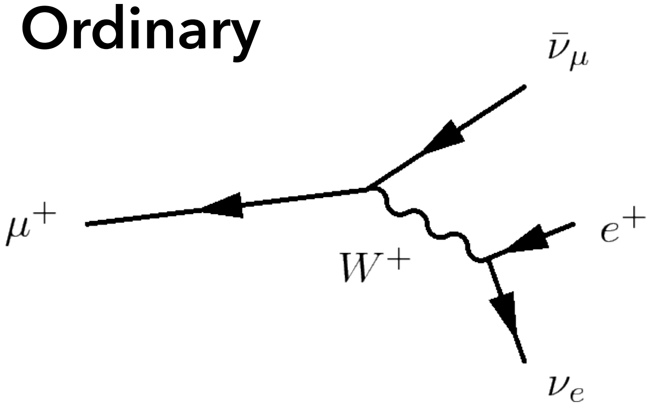

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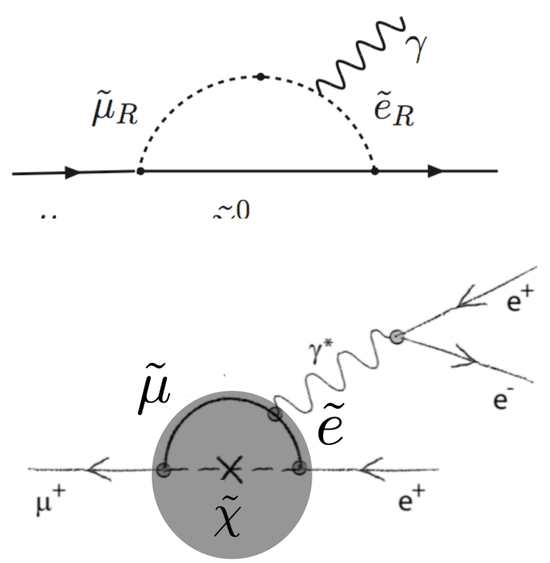

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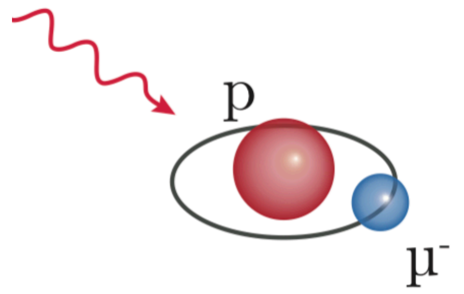
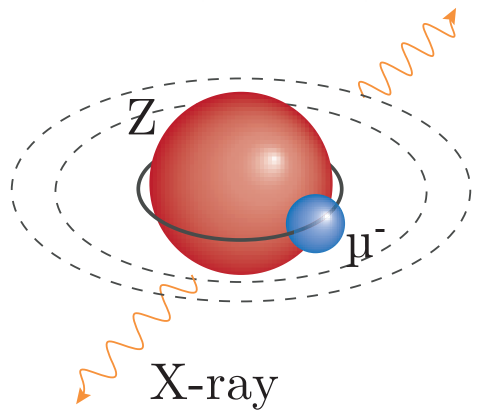
Exotic atoms



Muonic hydrogen, helium

- laser spectroscopy: proton/α **charge radius**



High Z muonic atoms

- X-ray measurements: charge radii and nuclear effects

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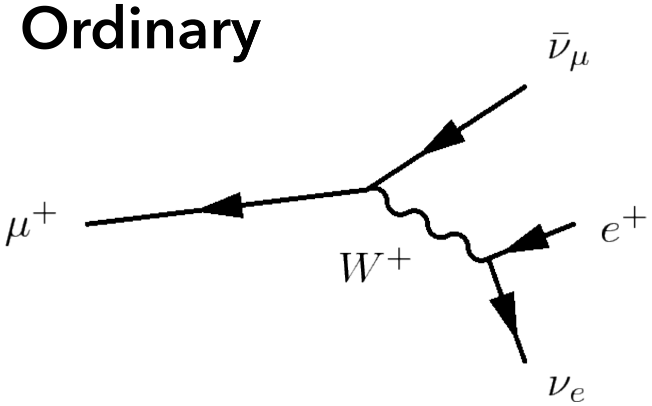

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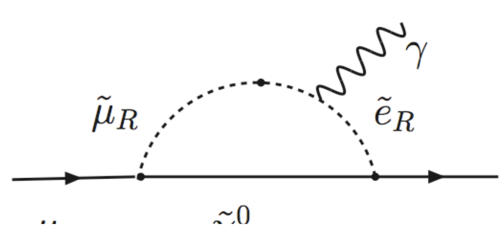

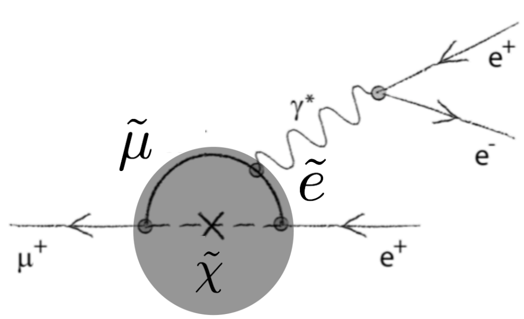

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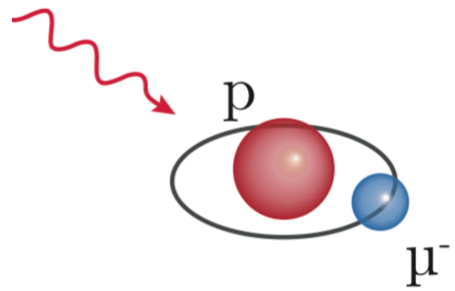

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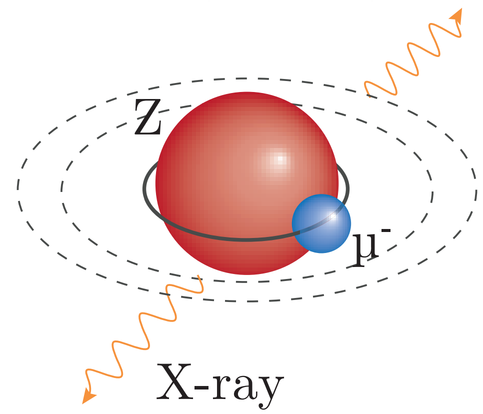

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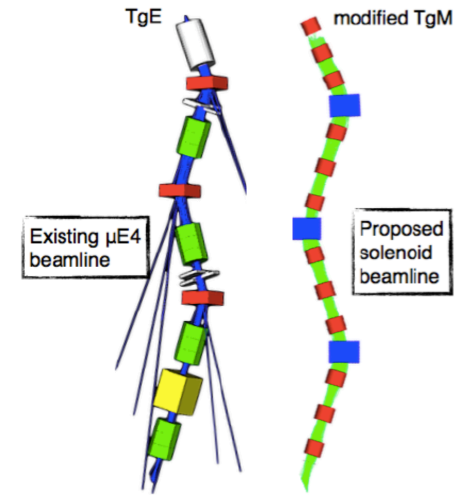
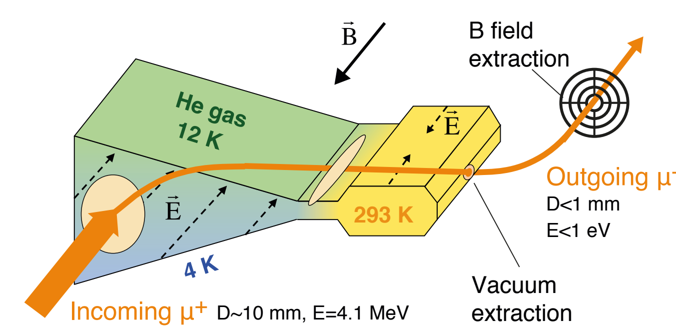
Novel beams



High intensity muon beamline

High brightness muons



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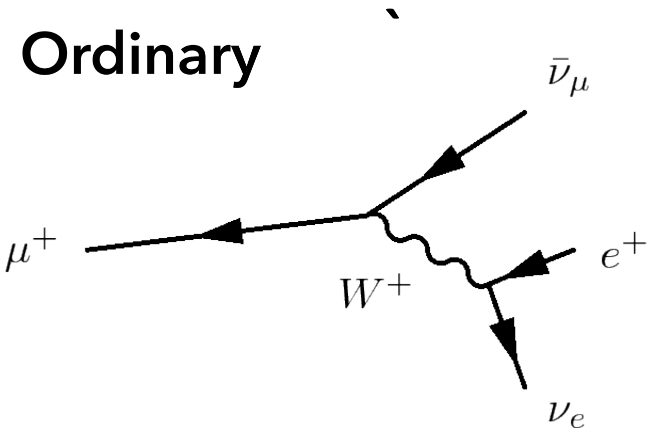

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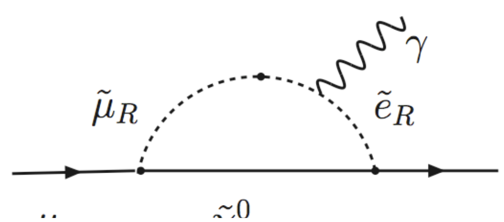

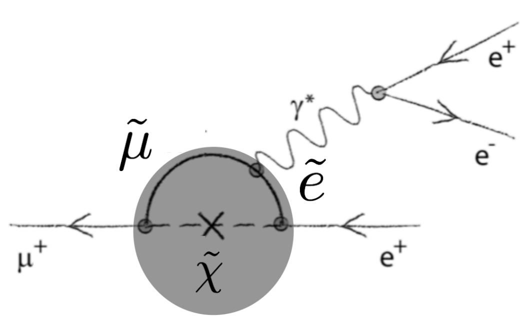

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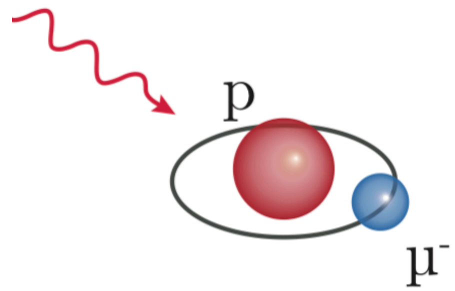

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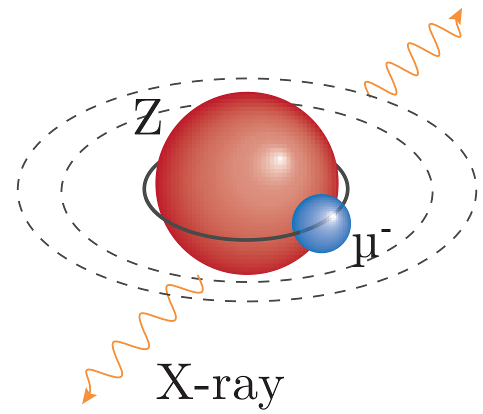

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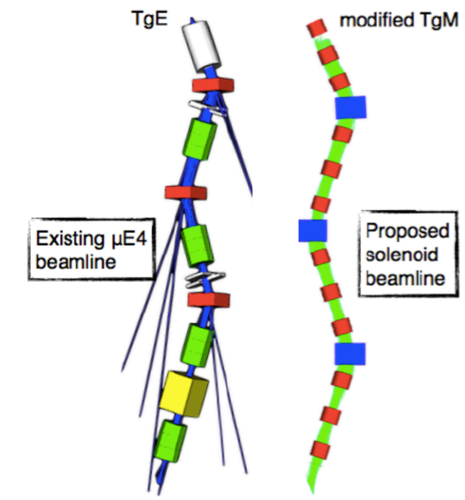

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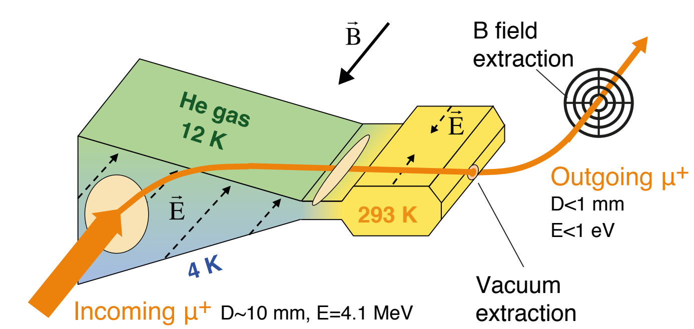
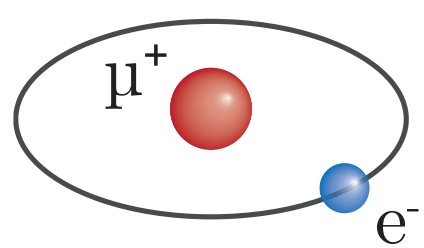
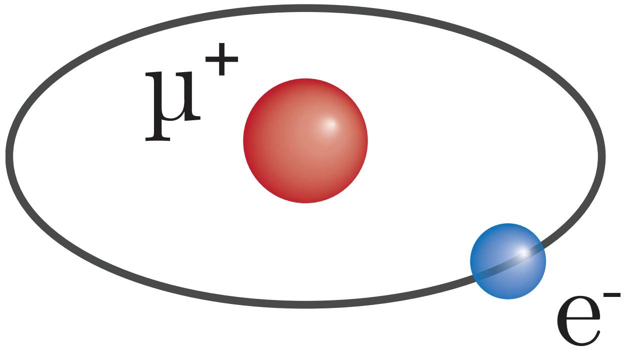


Muonium



- Pure leptonic atom with antimatter content
- Cold atomic beam / cold muon beam

Muonium (Mu), a precision tool in atomic physics



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- pure leptonic system (1st and 2nd gen.)
- no finite size / nuclear effects
- … but, short lifetime ~ 2.2 us

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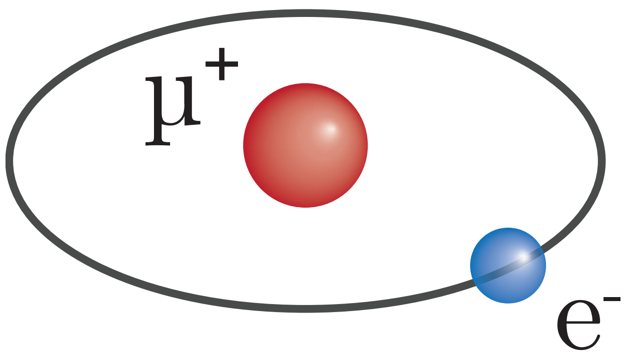

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Mu 1s-2s and HFS spectroscopy

- test of bound-state QED
- fundamental constants:
  m_μ, R_∞, m_μ/m_e, q_μ/q_e ...
- fundamental symmetries

Muonium - antimuonium

- put limits on the charged lepton number violation

1s-2s [4 ppb] V. Meyer et al., PRL 84(6) (2000)
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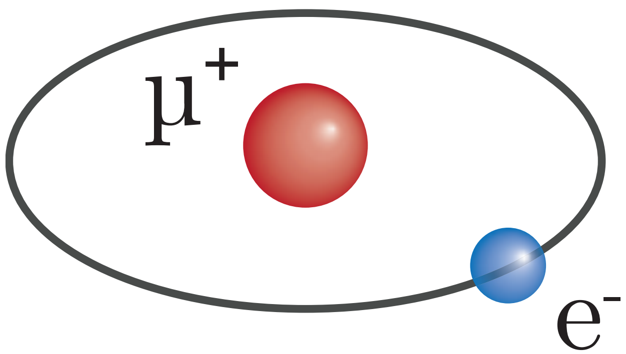

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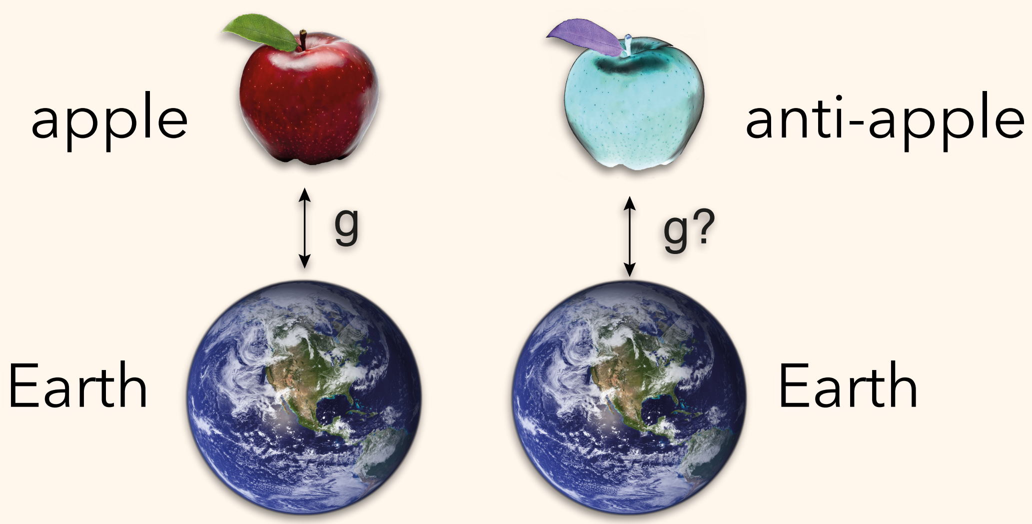

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- **second** generation lepton

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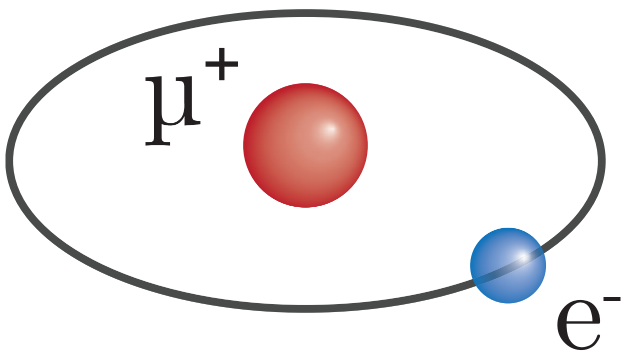

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Muon… …ium

- … the charged lepton …ber violation

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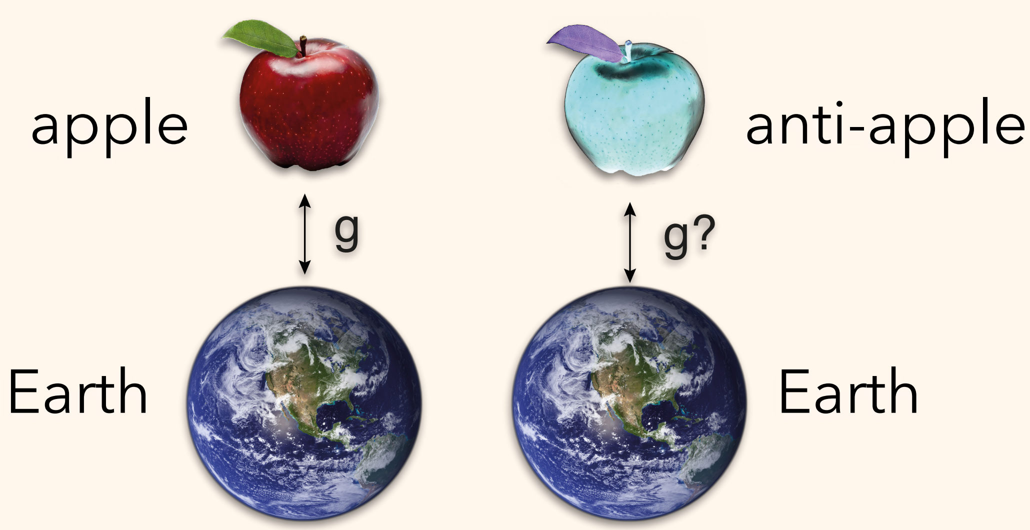

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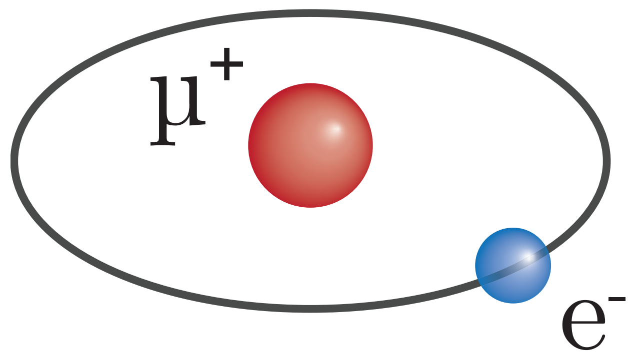

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Mu gravity experiment?

Not possible with present Mu sources

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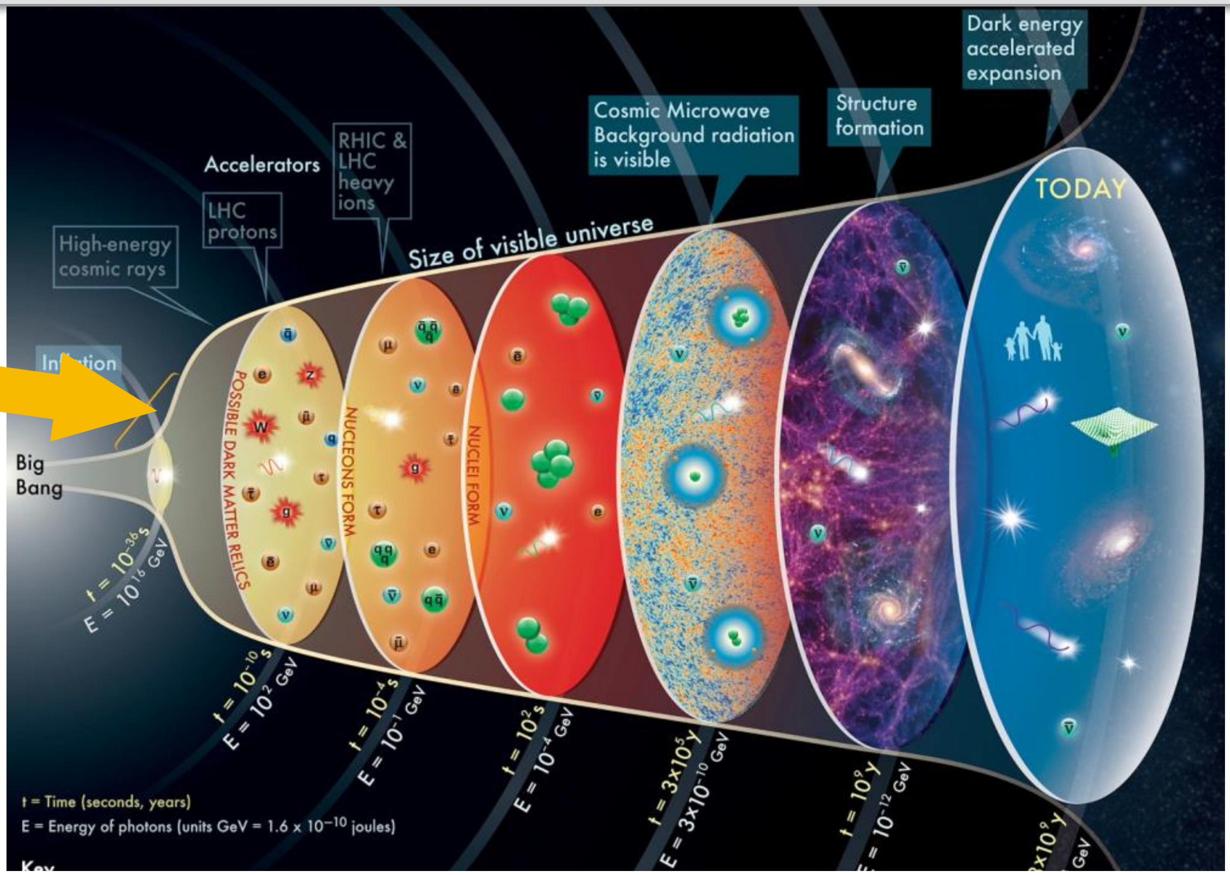
Baryon asymmetry in the Universe: all that matter is matter

… and almost no antimatter!

Something went wrong somewhere here



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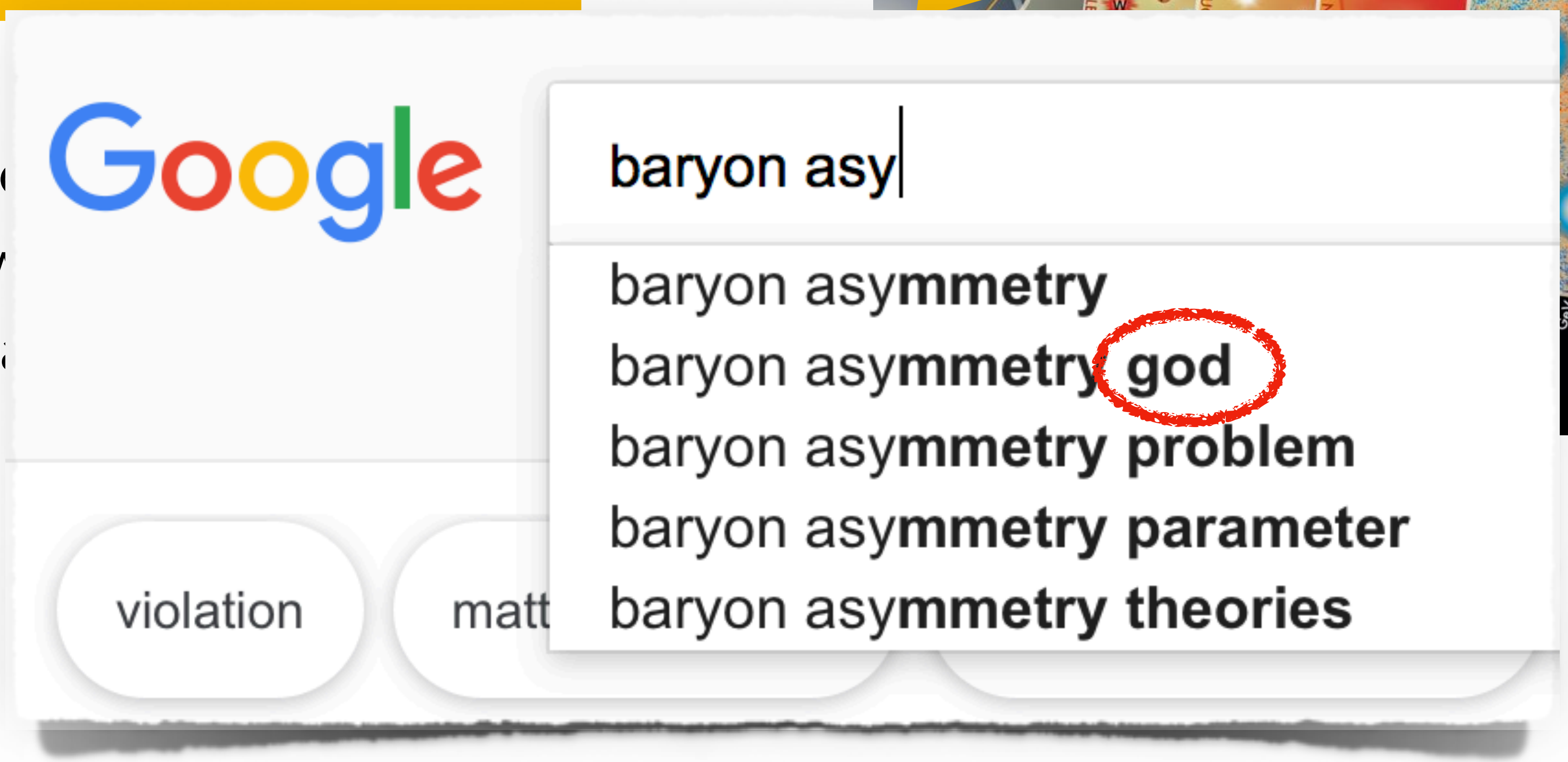

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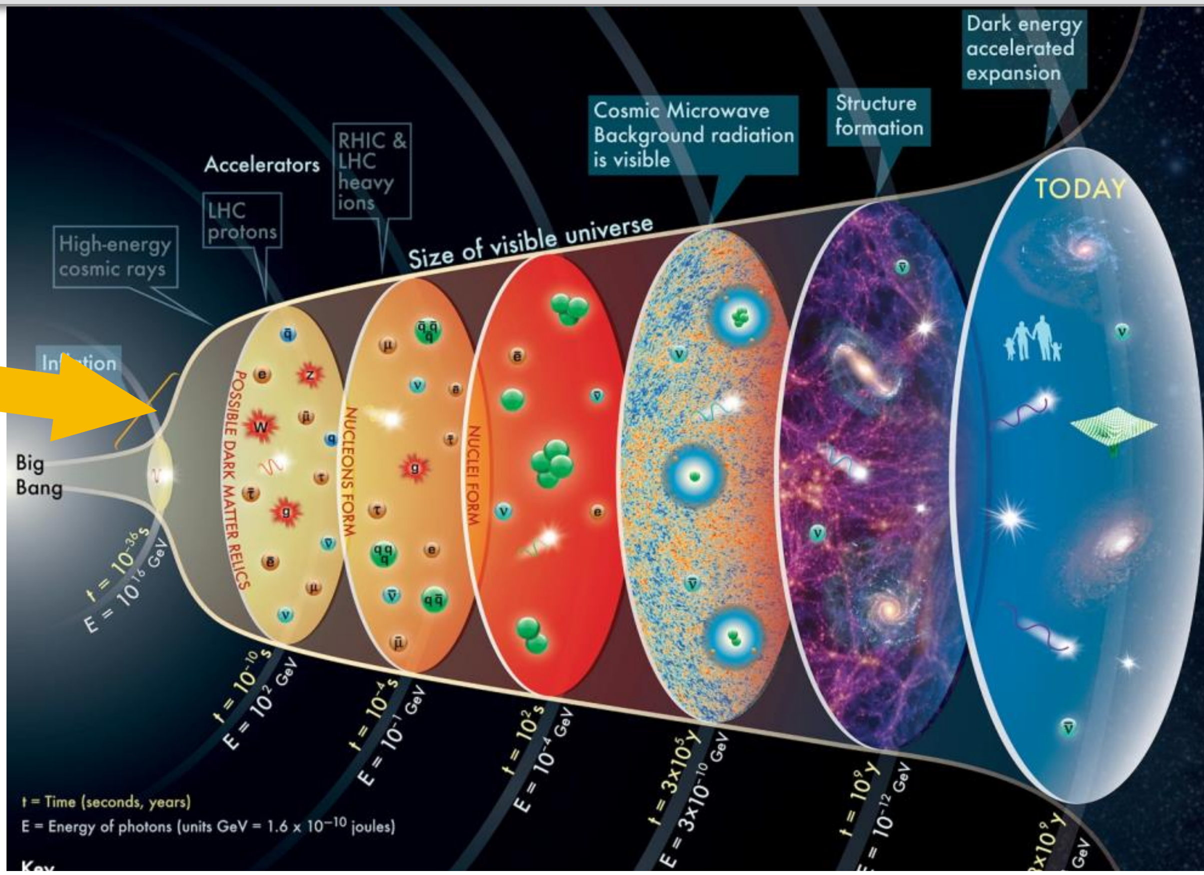

- More CP-violation? CPT violation?
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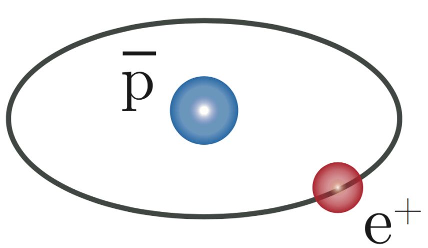
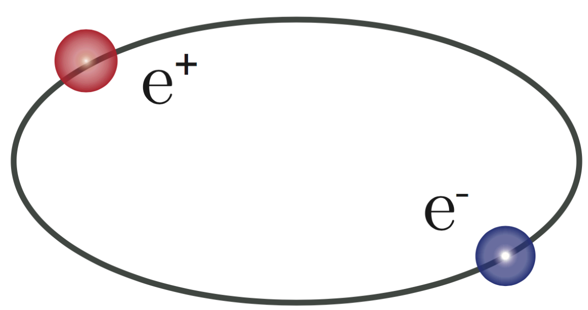
- Motivating to compare matter and antimatter in **any possible experiments**
- **Gravity** (weak equivalence principle) **test:** only 3 neutral candidate:



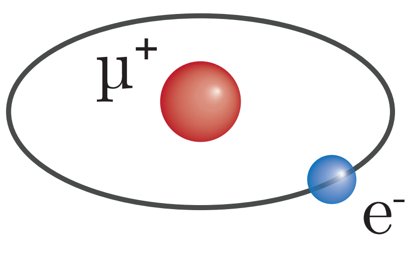
Antihydrogen

- CERN: ALPHA, AEGIS, GBAR



Positronium

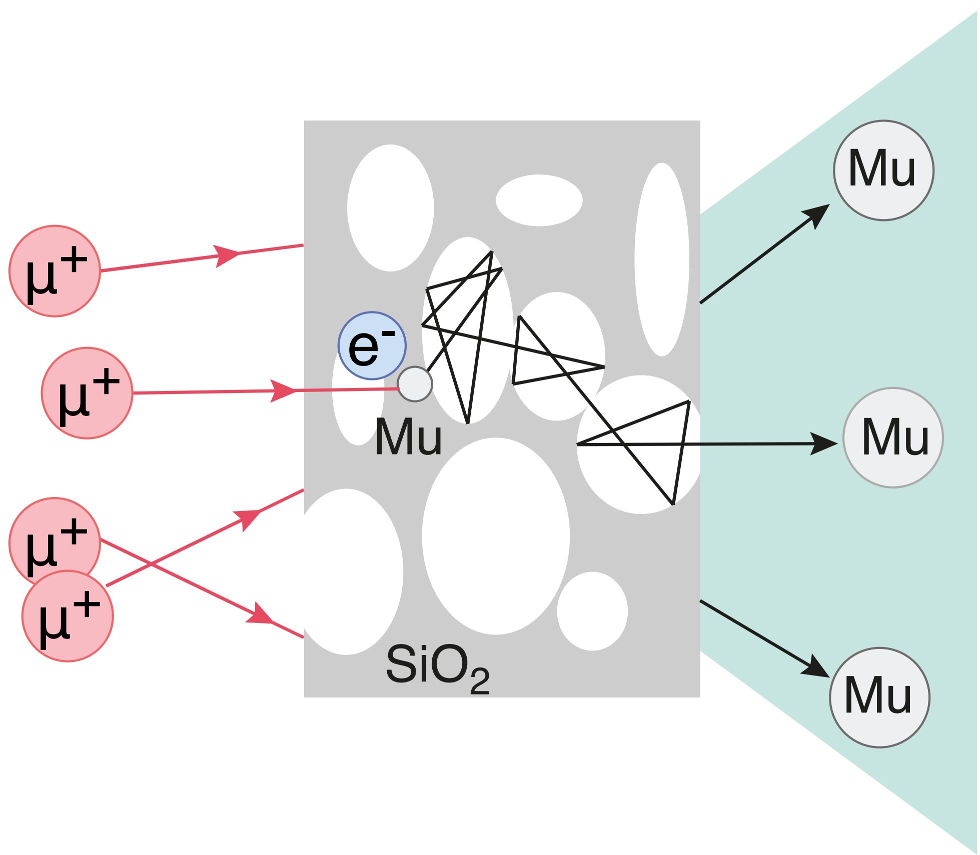
- UCL, ETHZ, Bern, Milano…



Muonium

- PSI?

State-of-the-art $\mu^+ \rightarrow$ Mu conversion



- Large (thermal) energy spread
- Broad angular distribution (~cosθ)
- 3-30 % conversion eff. at T=296 K

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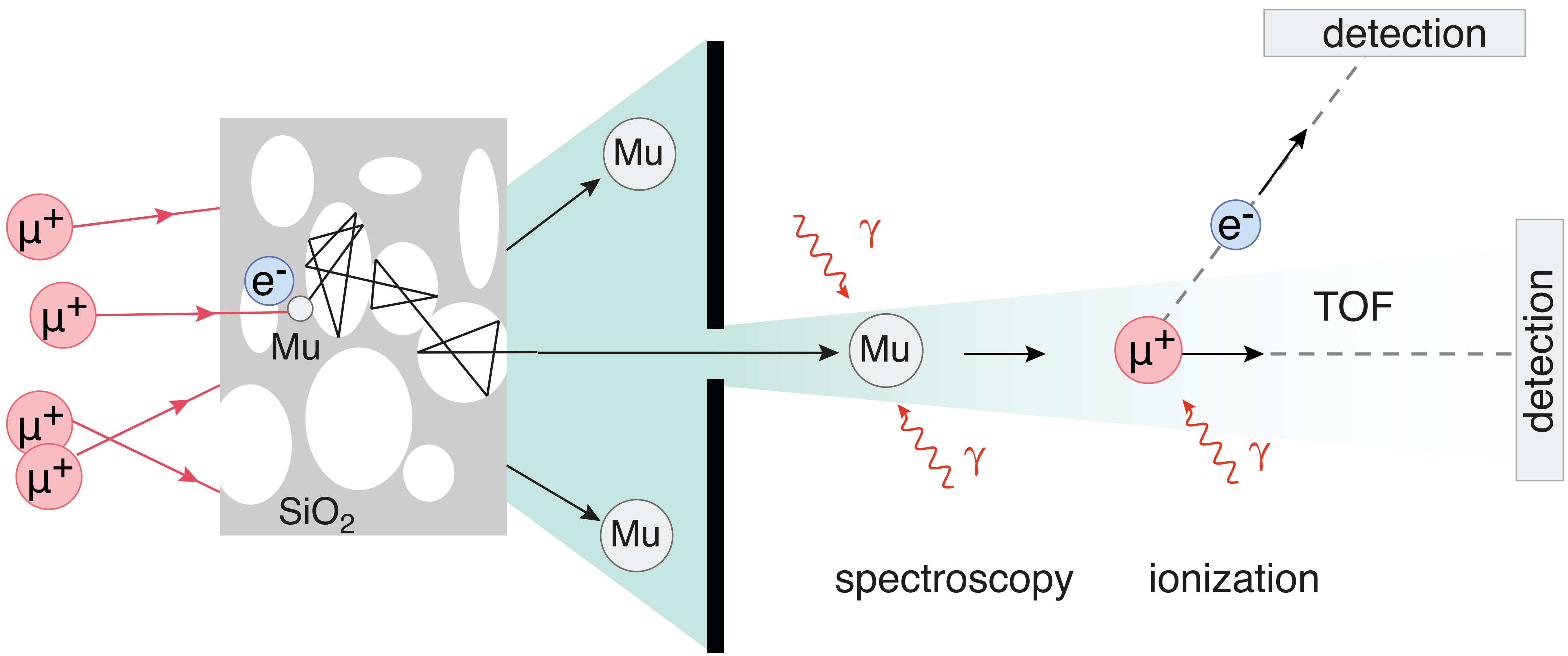

- Large (thermal) energy spread
- Broad angular distribution (~cosθ)
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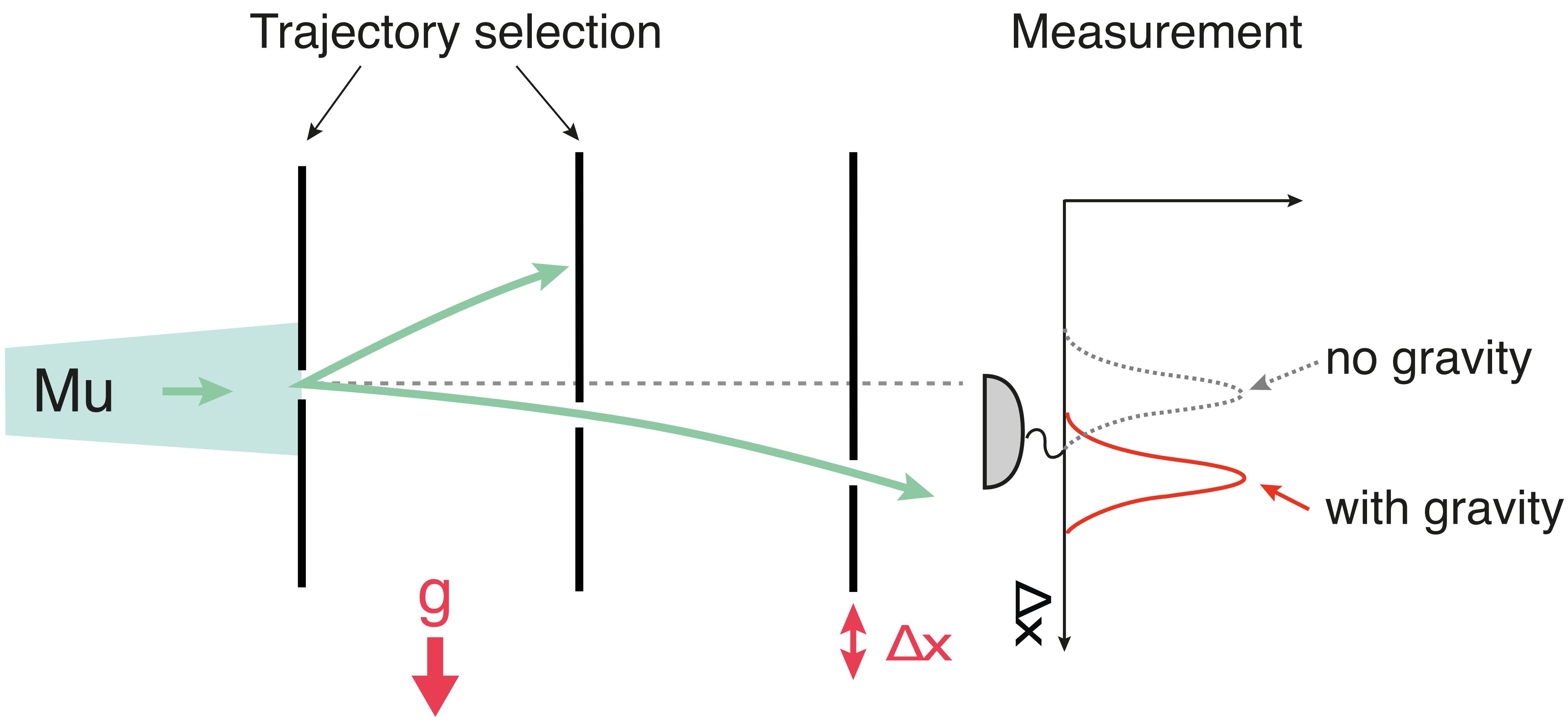
- Most atomic physics experiments need collimation / momentum selection
- High quality beam: essential in case of a gravity experiment

Mu gravity: especially challenging



Trajectory selection by collimation: large losses in atom number!

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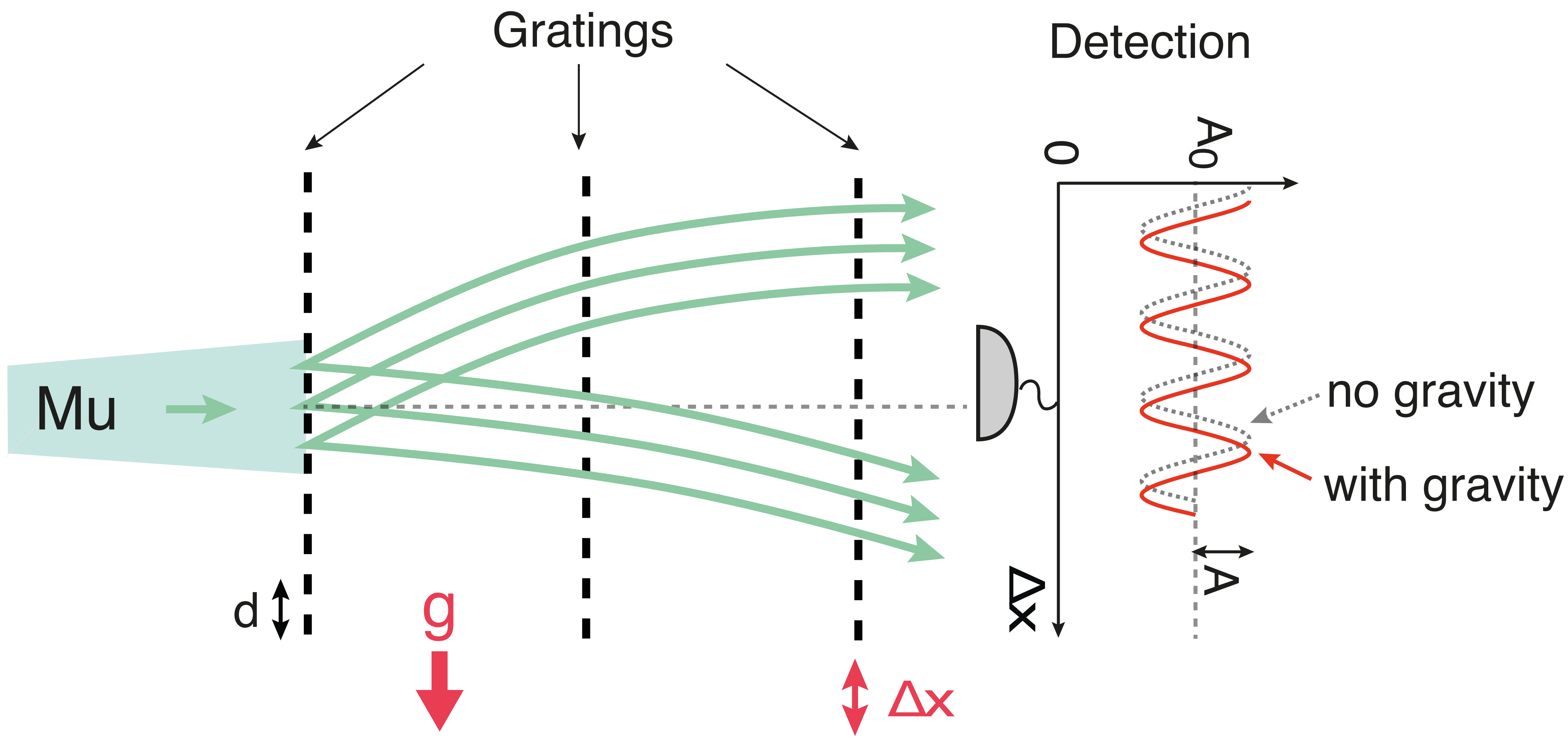
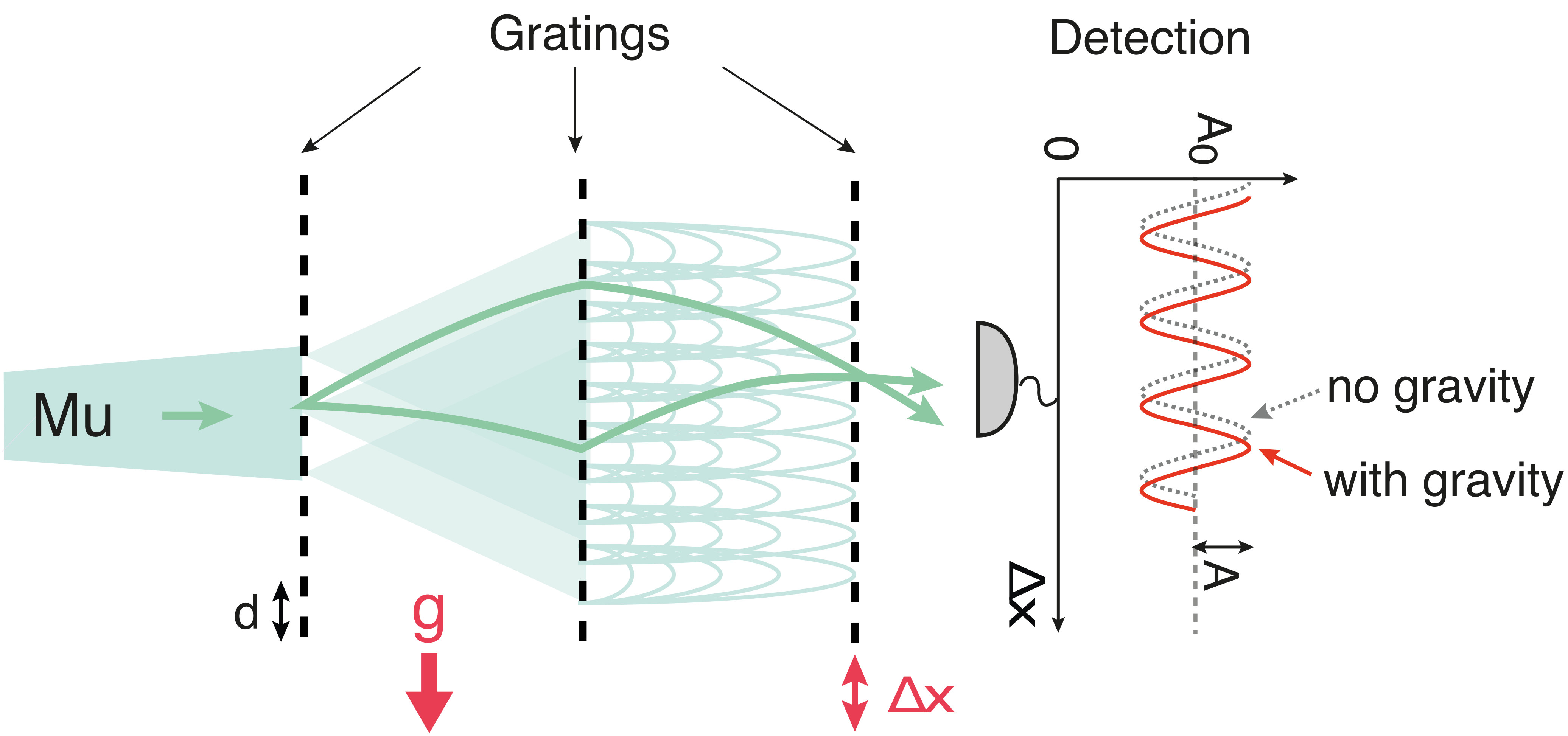


- Increasing intensity: series of collimators = gratings.
- Effects of gravity: vertical shift in the periodic pattern of shadows
- If this effect is small, small grating period (d) needed

- Challenging: Mu falls less than 1 nm during its few us flight!

Mu gravity: especially challenging



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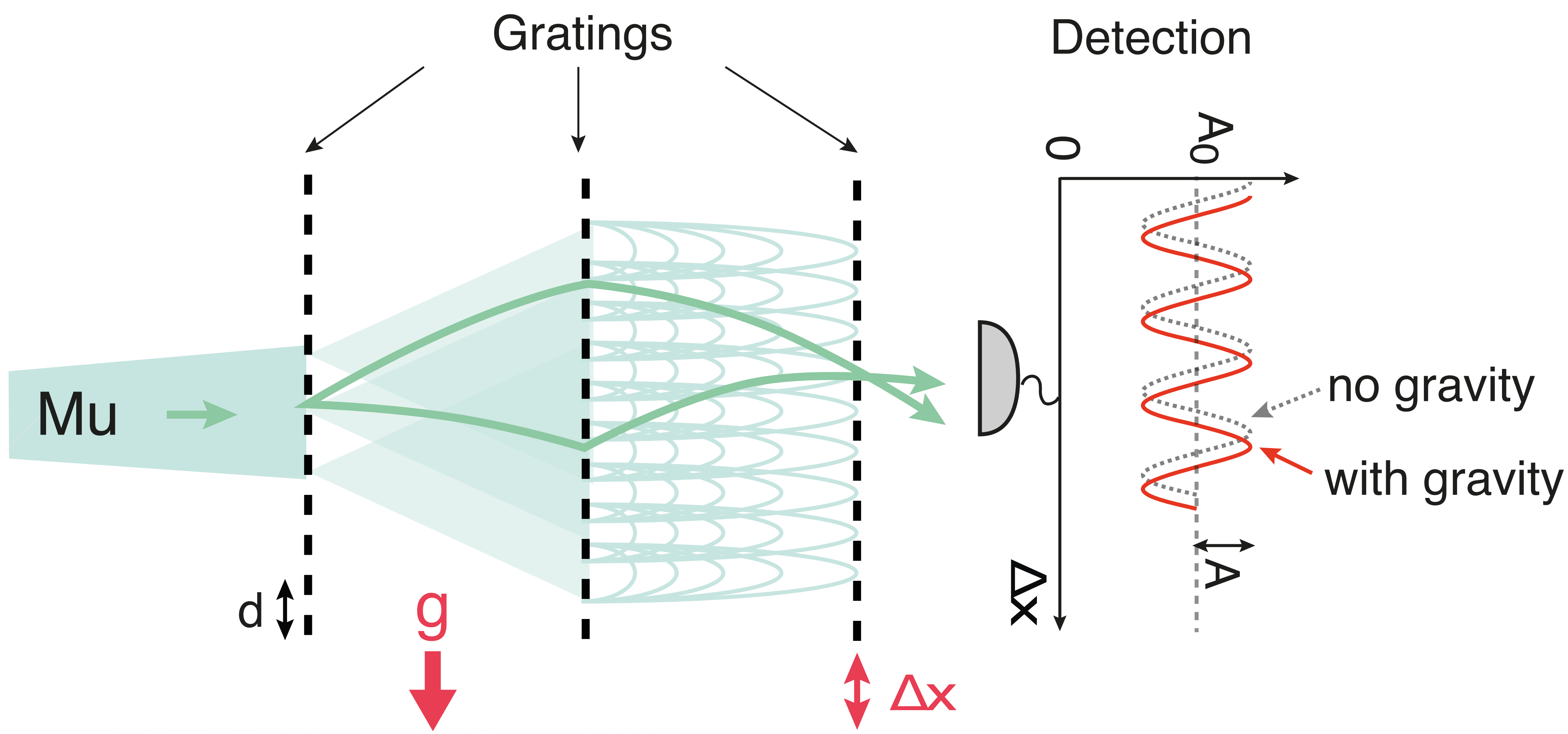

$$\Delta g \approx \frac{1}{2\pi T^2} \frac{d}{C\sqrt{N}}$$

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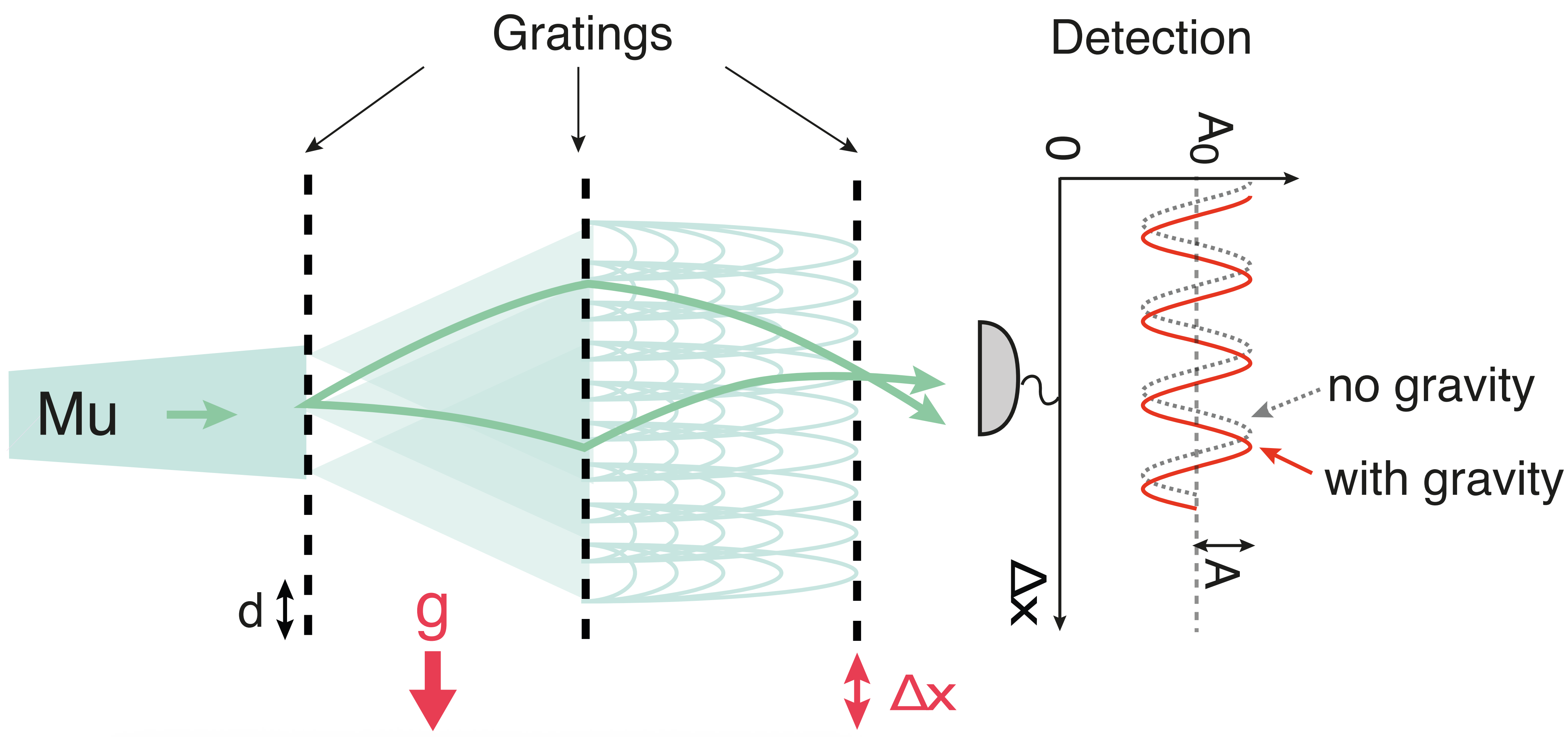

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Interaction time

$\sim \tau =$ few μs !

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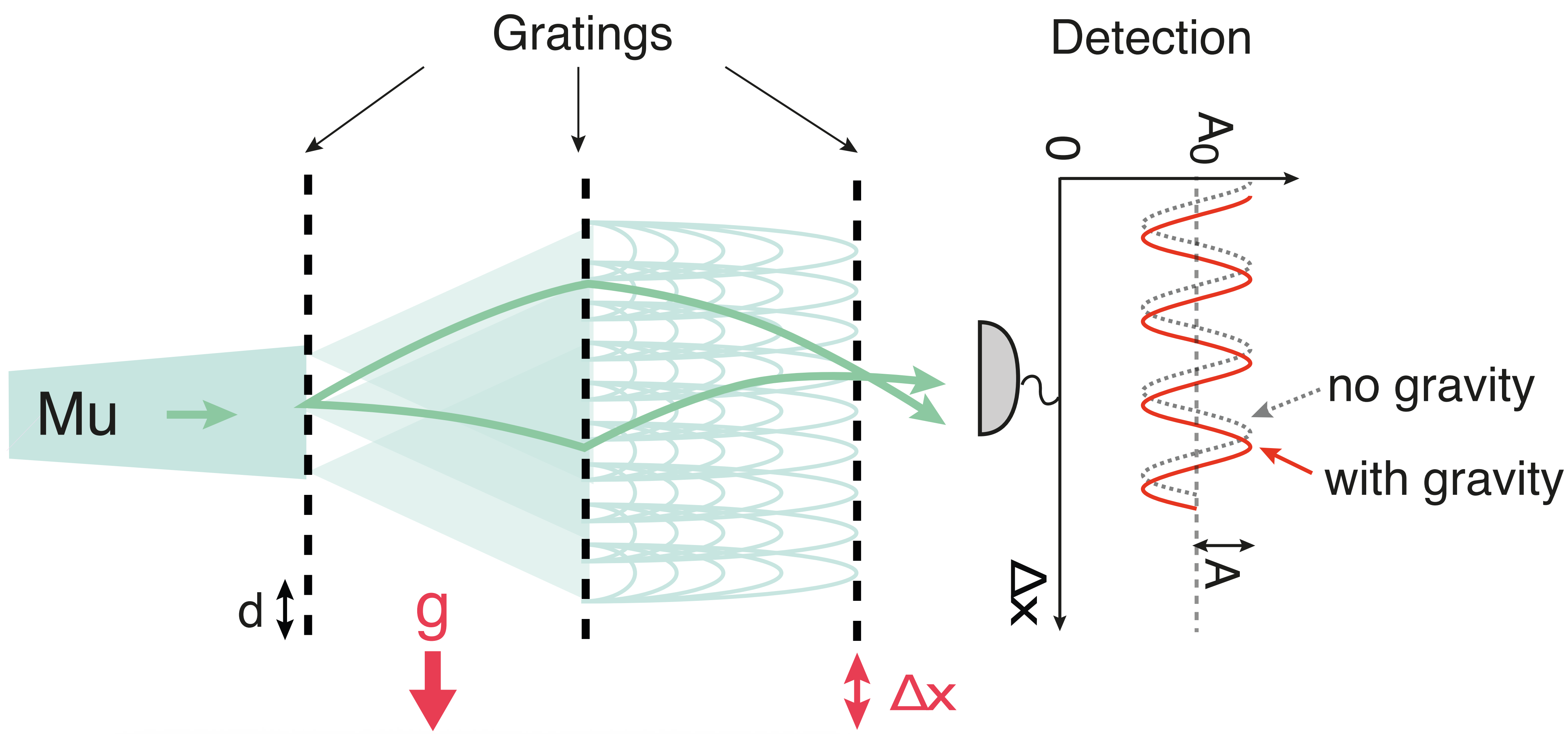

$$\Delta g \approx \frac{1}{2\tau T^2} \frac{d}{C\sqrt{N}}$$

Small grating period (~100 nm)

Interaction time

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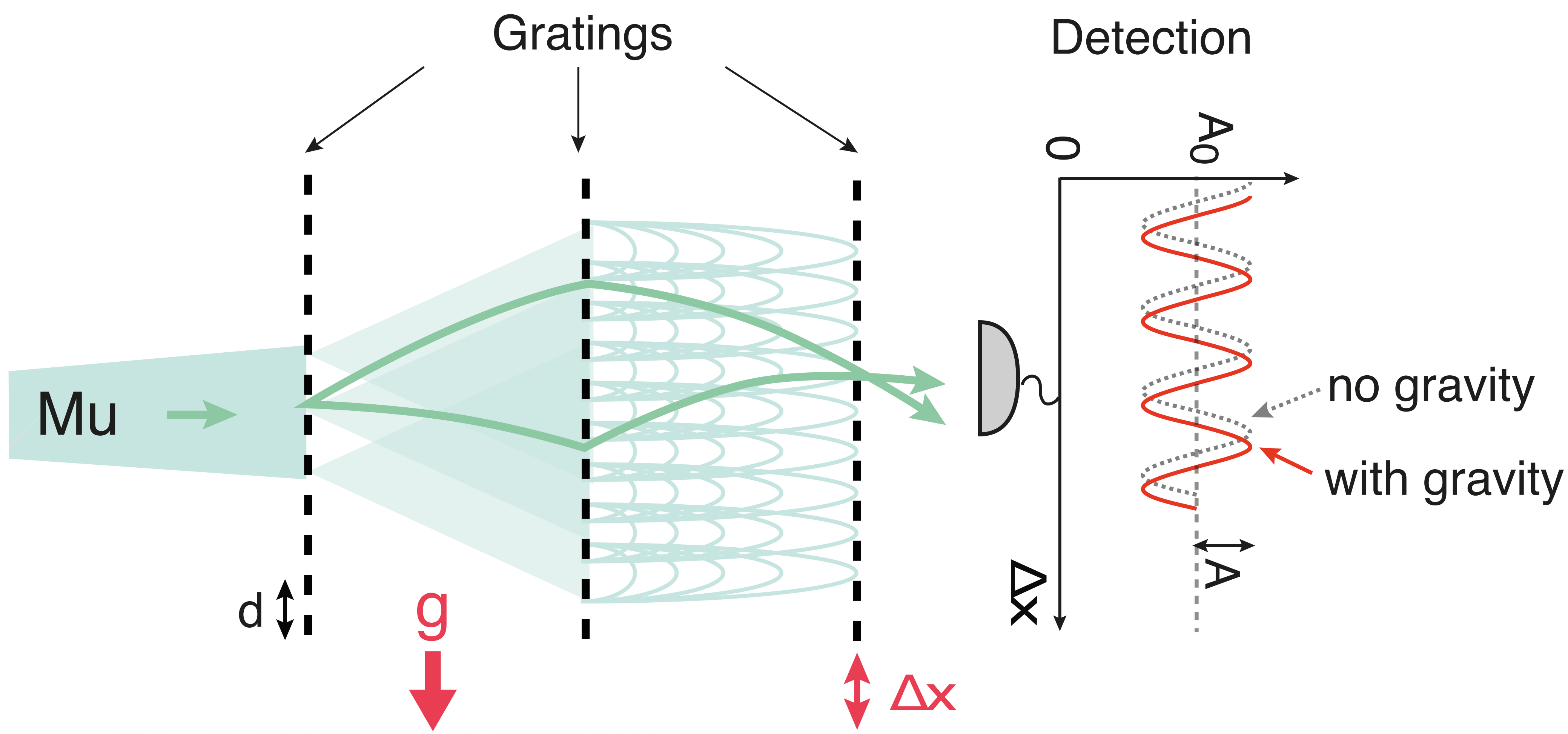

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Small grating period (~100 nm)

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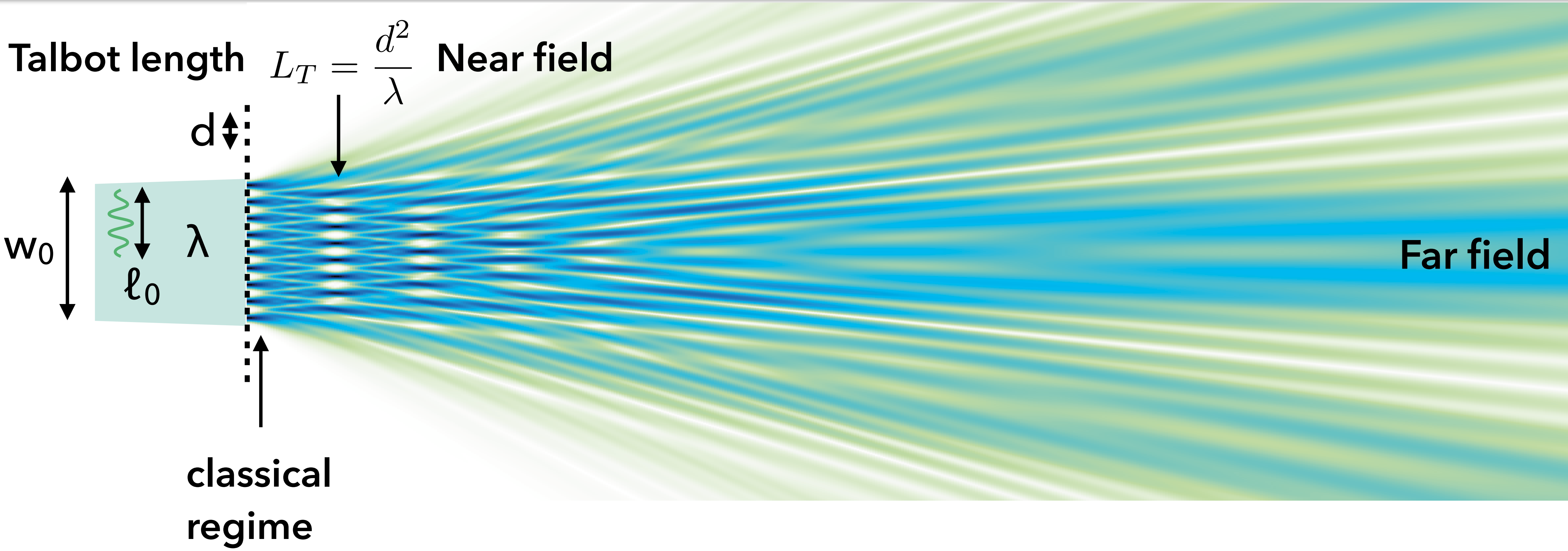
Many atoms $N \sim N_0 b^3 e^{-(t_D+T)/\tau}$
Large contrast $C = A/A_0$

Restrictions on Mu interferometry from gravity

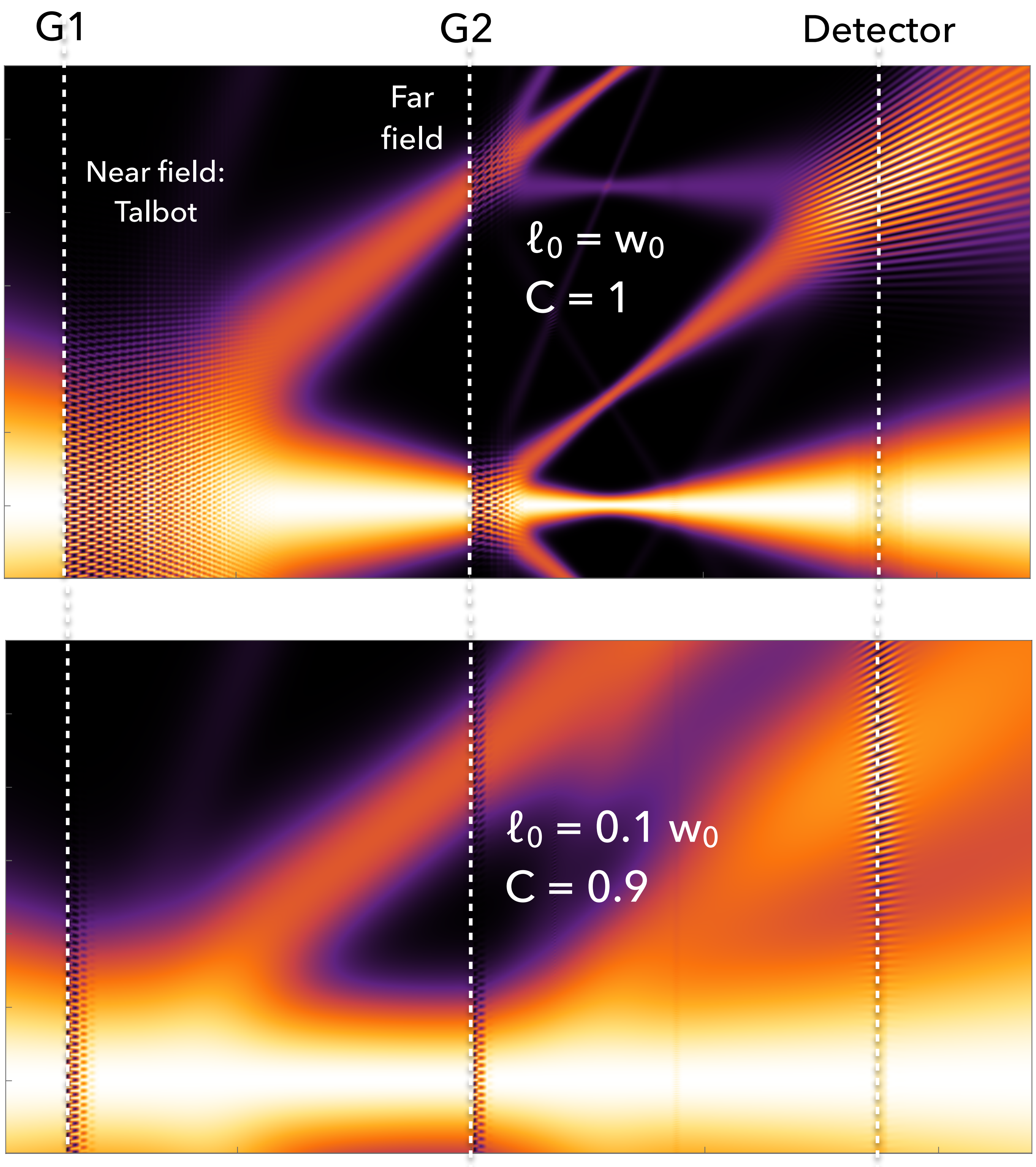


- λ ~ de Broglie wavelength
- d ~ spacing of slits
- L ~ length of the apparatus
- w_0 ~ beam width
- ℓ_0 ~ transverse coherence length

- Mu: λ ~ 0.6 nm
- d ~ 100 nm, L_T ~ 20 μm
- few us TOF, L ~ 20-30 mm

- Mu interferometry: far field!
- contrast depends on beam quality

Contrast vs. coherence length in a Mach-Zehnder interferometer

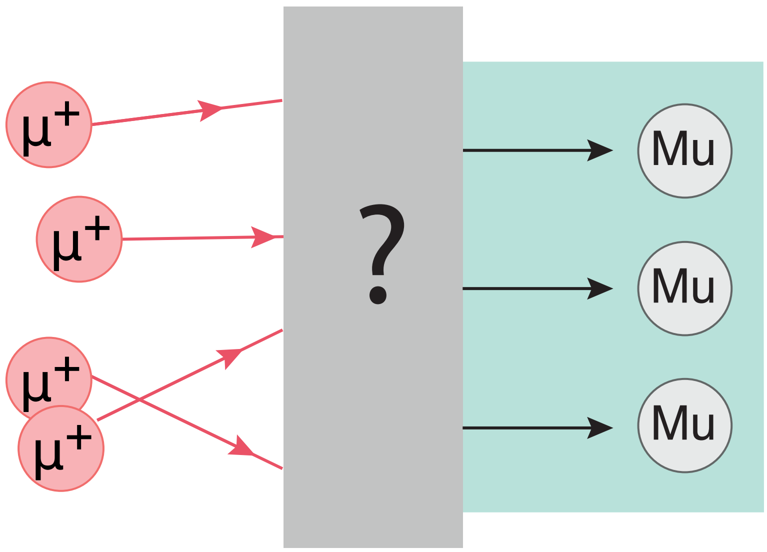


- Model: using mutual intensity functions / Wigner functions for partially coherent / incoherent sources, and realistic beam envelopes
- C ~ 0.3 with coherence length near the slit spacing with Mu

Determining sign of g:
1-2 days with Mu source of $N_0 = 5 \cdot 10^4$/s, C=0.3
>100 days with $N_0 = 5 \cdot 10^3$/s C=0.1

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

Necessity of a novel Mu source



$$\Delta g \approx \frac{1}{2\pi T^2} \frac{d}{C\sqrt{N}}$$

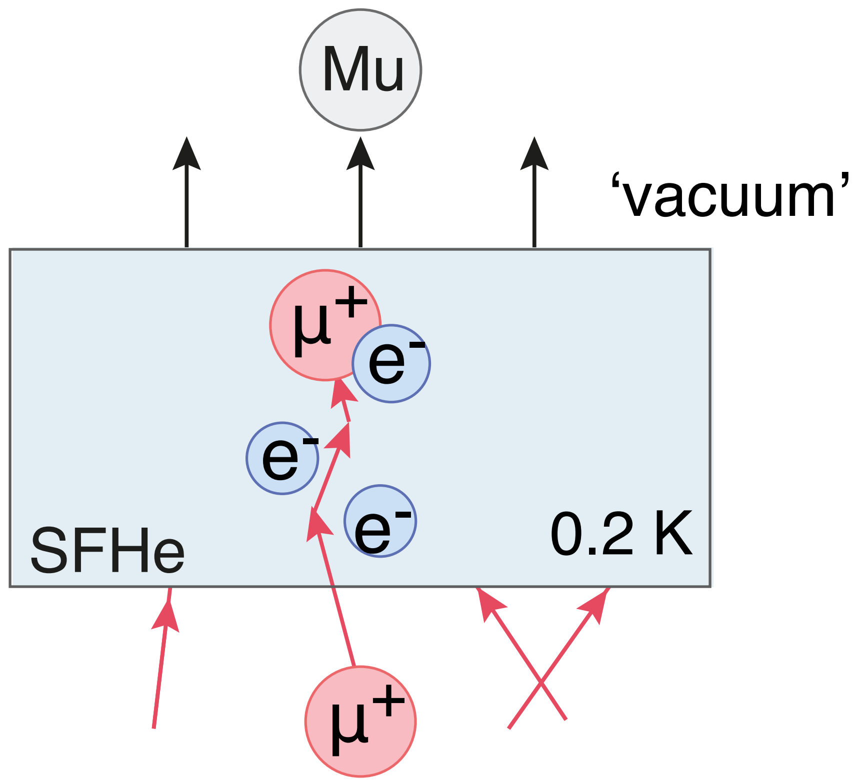
Things to improve:

- small transverse momentum, energy distribution *(high C, N)*
- small source aperture *(high C)*
- large flux (*high N*)

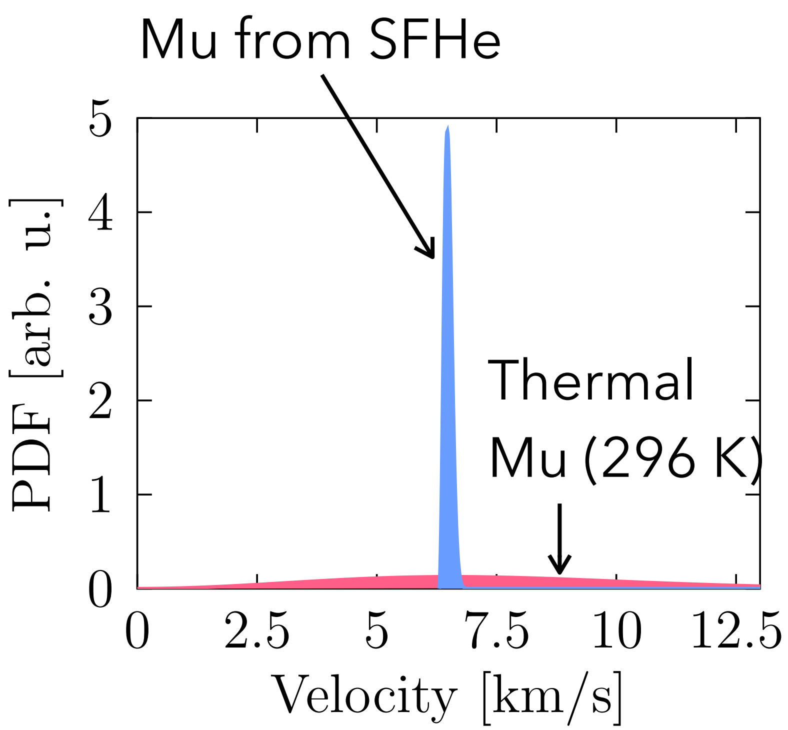
But How?

- collimation of conventional sources: leaves insufficient atom numbers
- cooling conventional sources: almost no Mu emission below 100 K due to increased diffusion times, and atoms sticking to the pore walls

Proposal: Mu production in superfluid helium (SFHe)



- From **chemical potential** E/k_B~270 K: Mu atoms are ejected from bulk SFHe with v = 6.3 mm/μs
- The **cold environment** would ensure low thermal energy spread (~0.1 %), and narrow angular distribution (~30 mrad)



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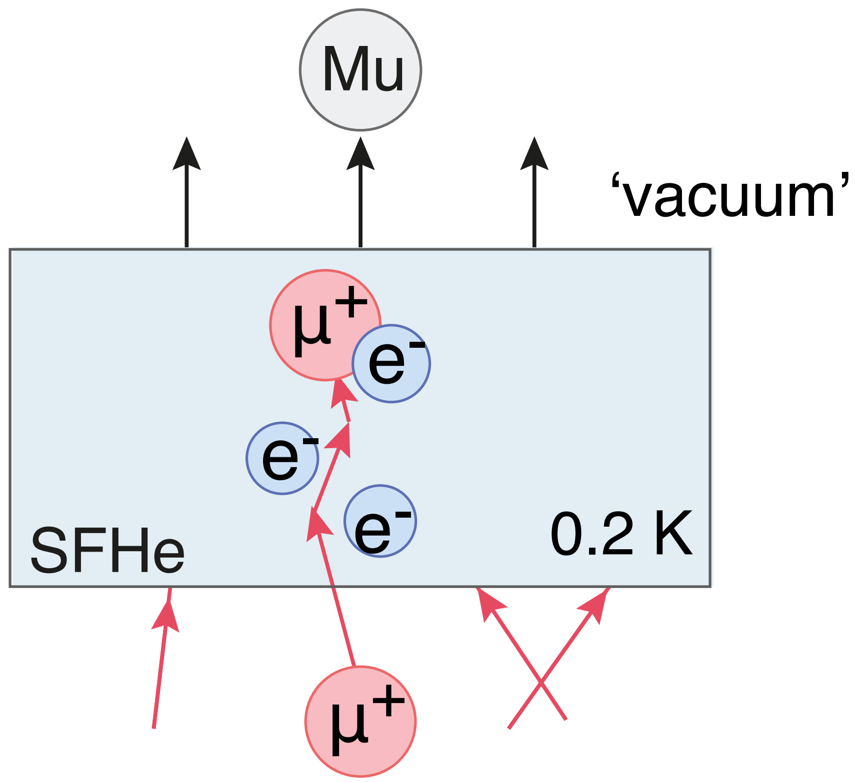

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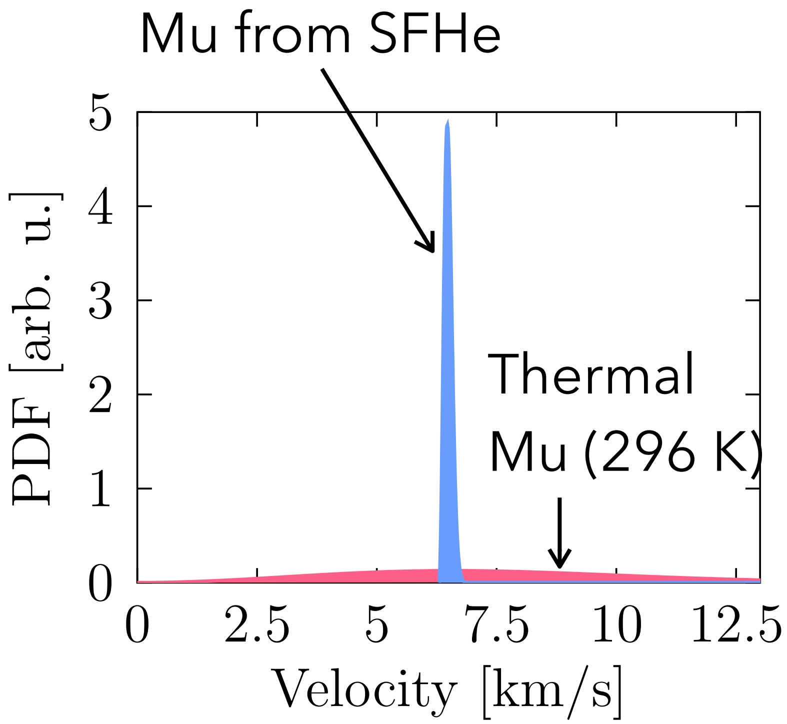
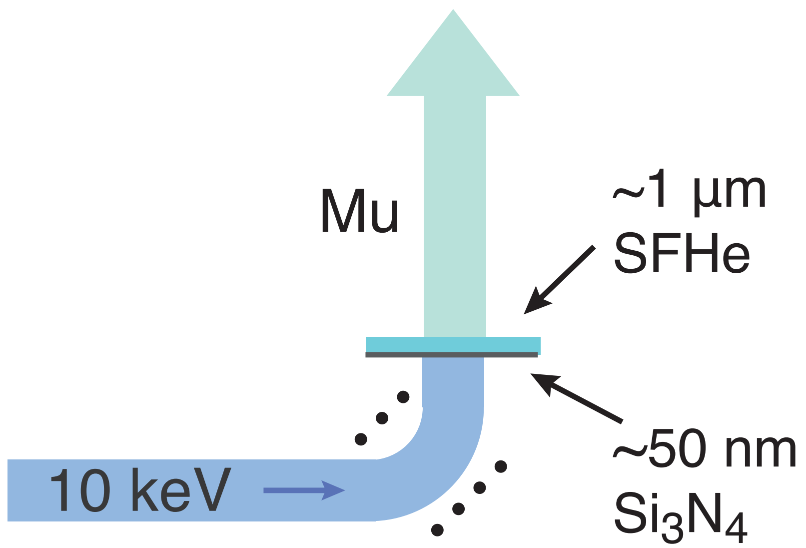
Challenge:

creating Mu atoms close to the SFHe surface to ensure high vacuum Mu production rates



Cold Mu production 1: thin SFHe

- Large vacuum ejection can be ensured by stopping low-energy (~few keV) muons in a thin ~ 1 μm SFHe film



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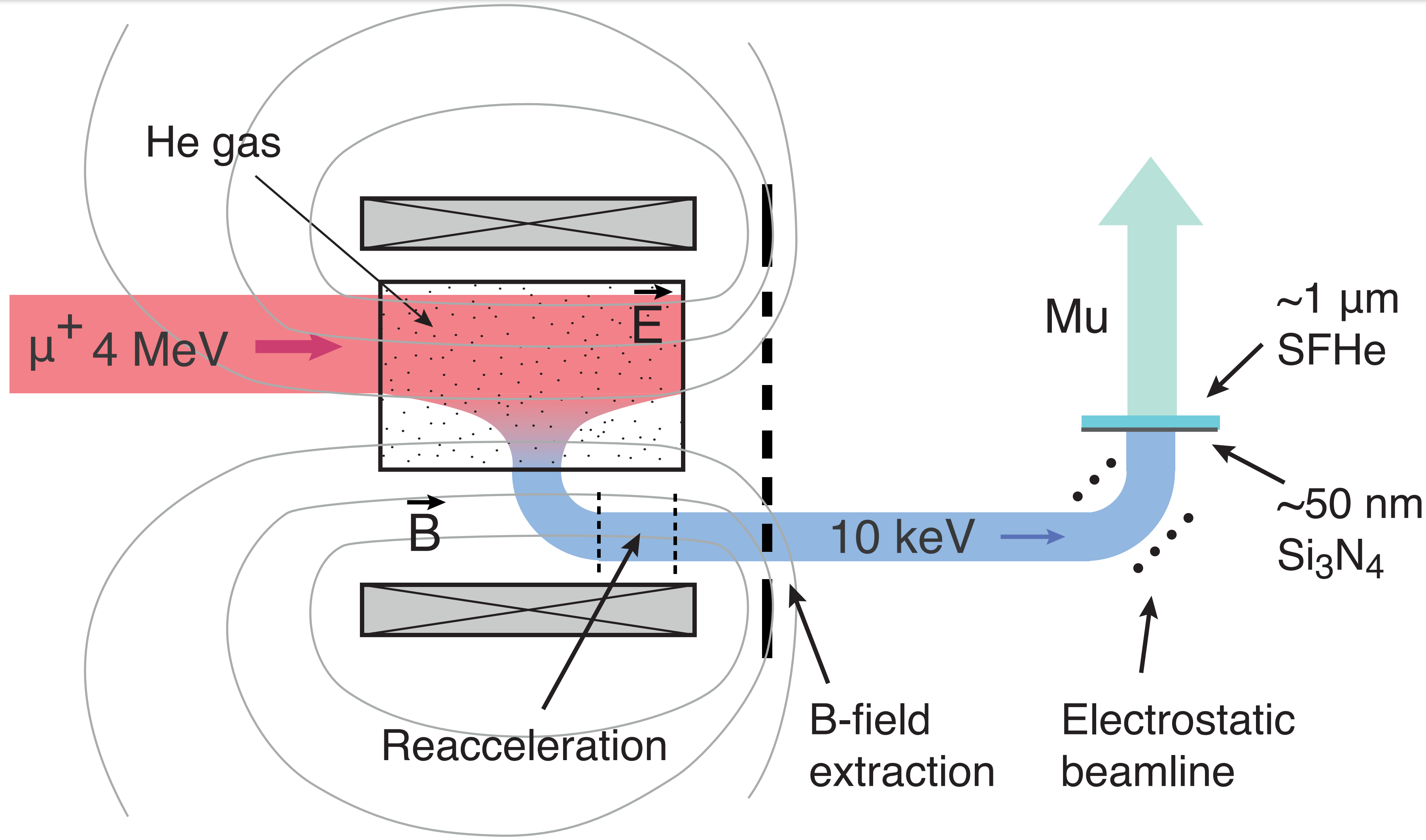
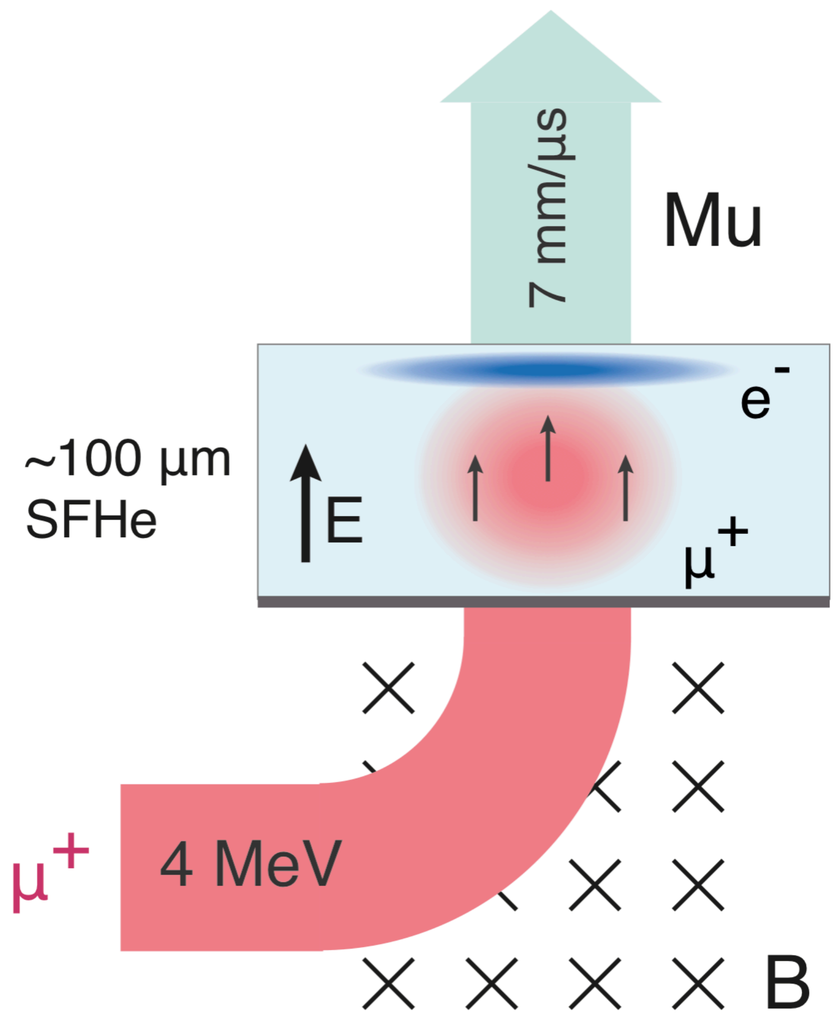


The muCool experiment @ PSI: cryogenic He gas target with complex E-fields and density gradients inside a 5 T solenoid B-field:

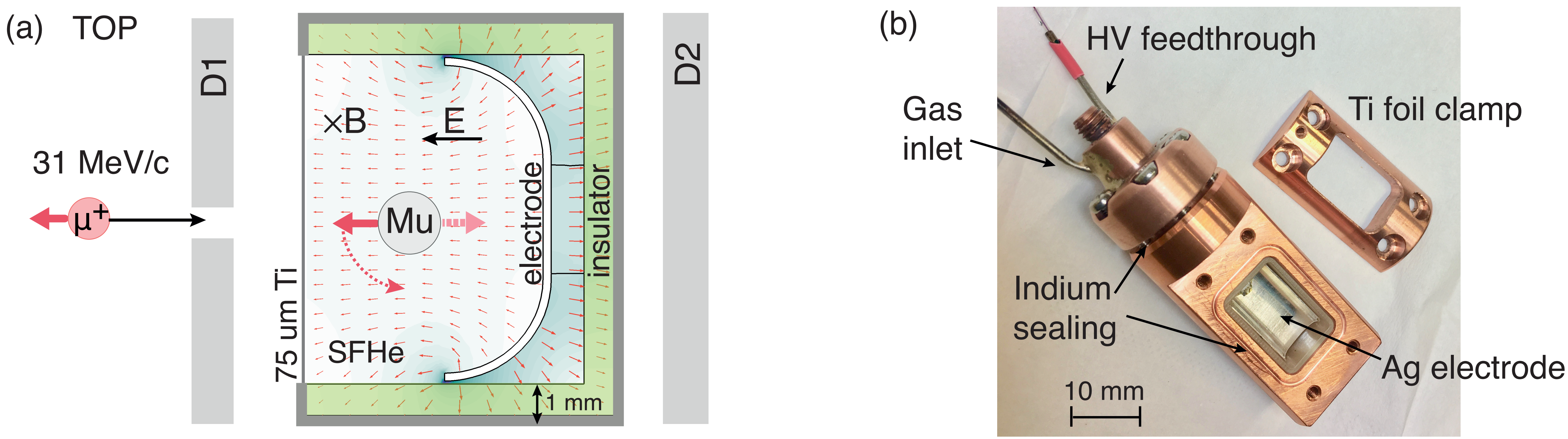
- ~10 keV μ^+ beam with sub-mm (~100 μm) waist, 10^{-3} efficiency
  Compression: demonstrated. Vacuum extraction, reacceleration and B-field extraction needed

Cold Mu production 2: delayed recombination



- Conventional (surface / subsurface) muon beam bent vertically
- Broad stopping distribution in ~100 µm thick layer of SFHe
- Prompt recombination to Mu is prevented by an external E field
- Same E-field is drifting Mu atoms to the surface, where they recombine with externally implanted electrons

MuSR measurement, Dec. 2017



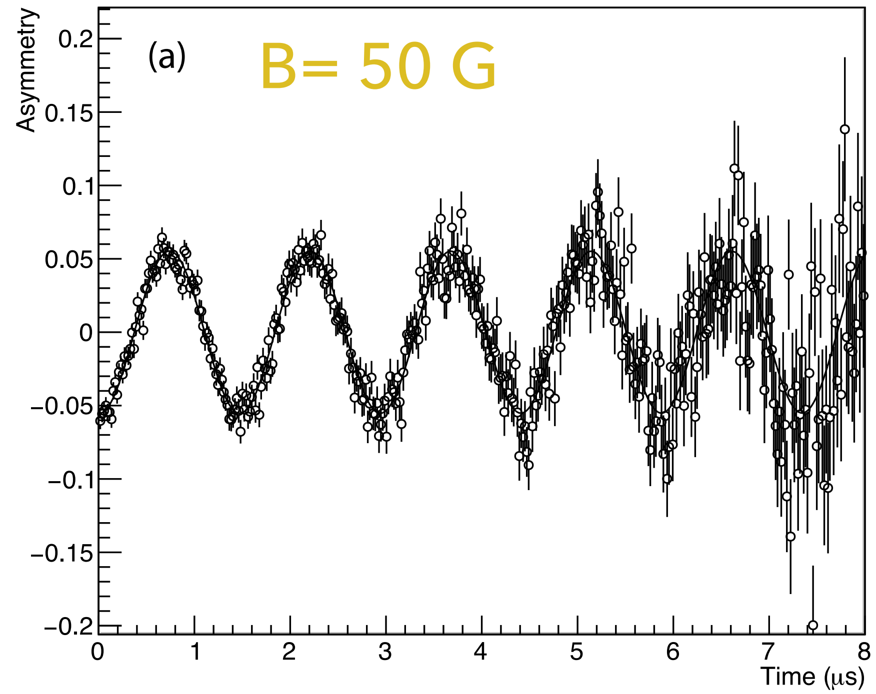
- detecting the precession of muon spin using e⁺ from μ⁺ decay
- identifying Mu by the appearance of a higher frequency component

$$N(t) \sim N_0 e^{-t/\tau_\mu} \left[1 + A_\mu(t)\cos(\omega_\mu t) + A_{\mathrm{Mu}}(t)\cos(\omega_{\mathrm{Mu}} t)\right]$$

$$\omega_{\mathrm{Mu}} \approx 103\,\omega_\mu$$

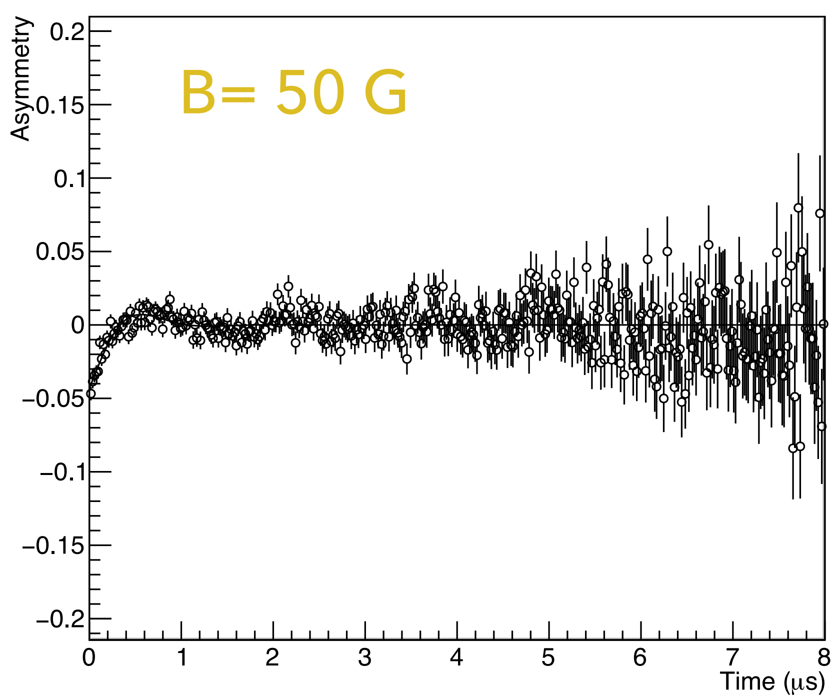
Dec. 2017 μSR measurement (raw data)

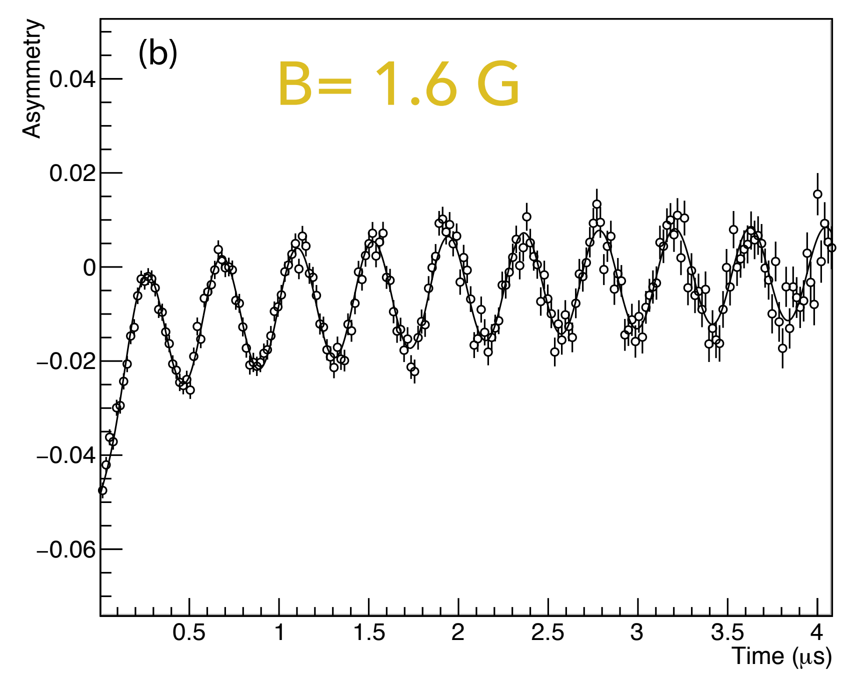
Empty target



- μ^+ decay asymmetry in the silver electrode

Target filled with SFHe





- Disappearance of μ^+ signal
- Appearance of Mu signal

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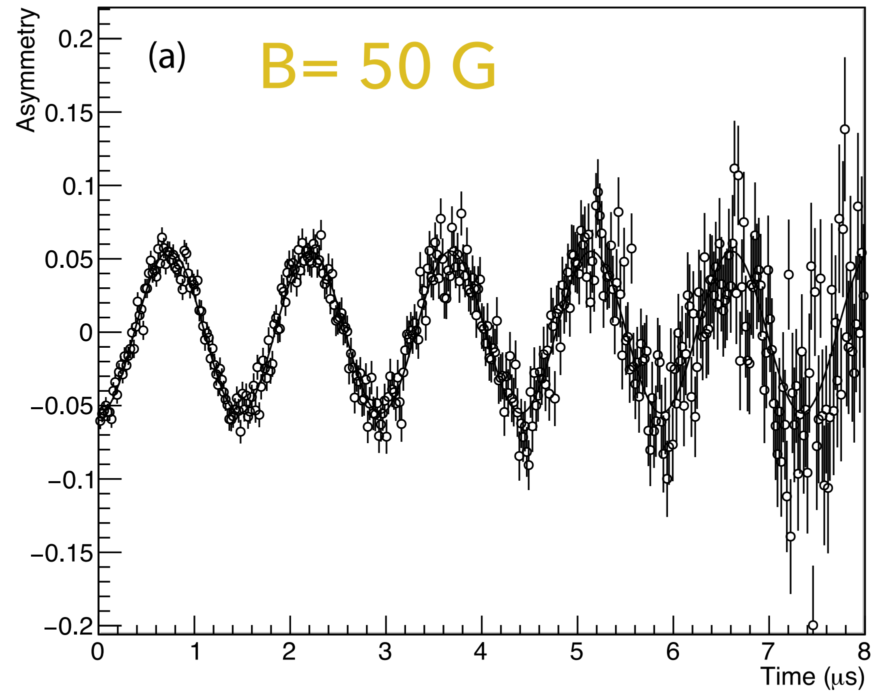

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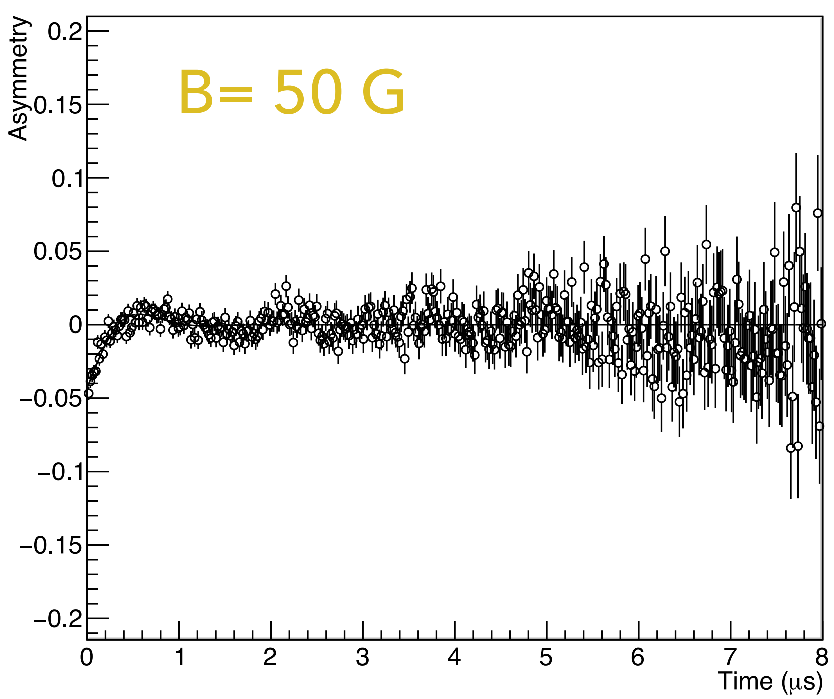

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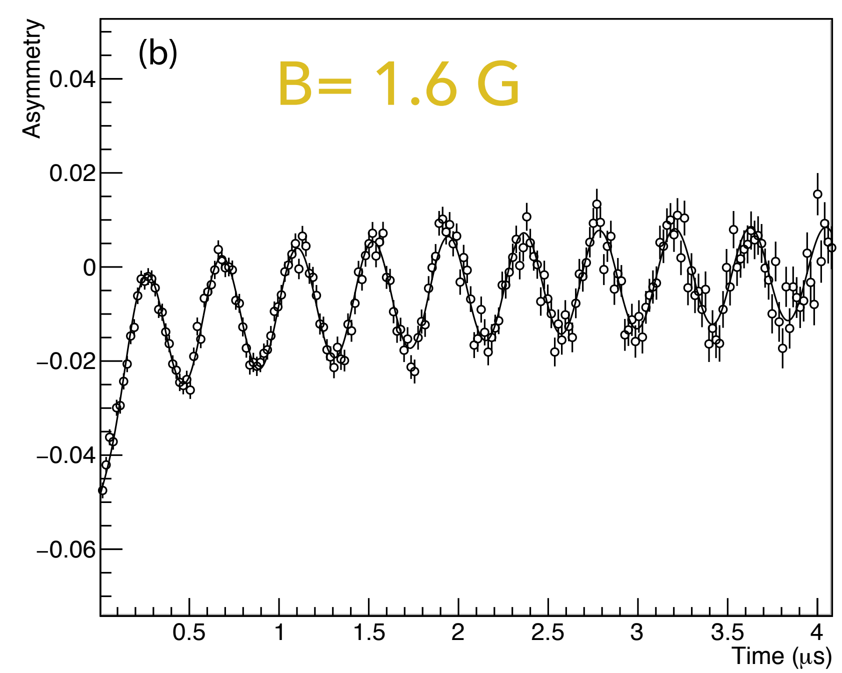

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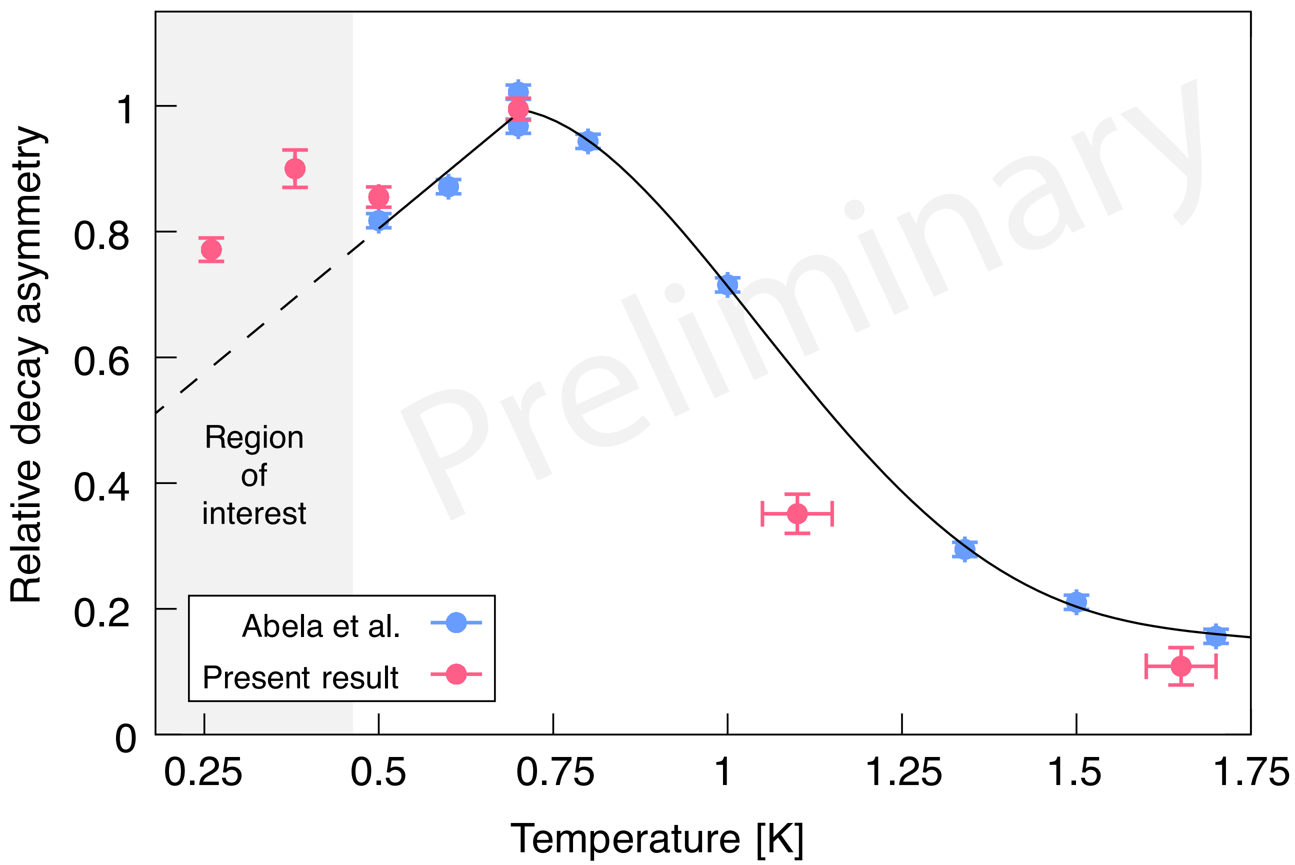
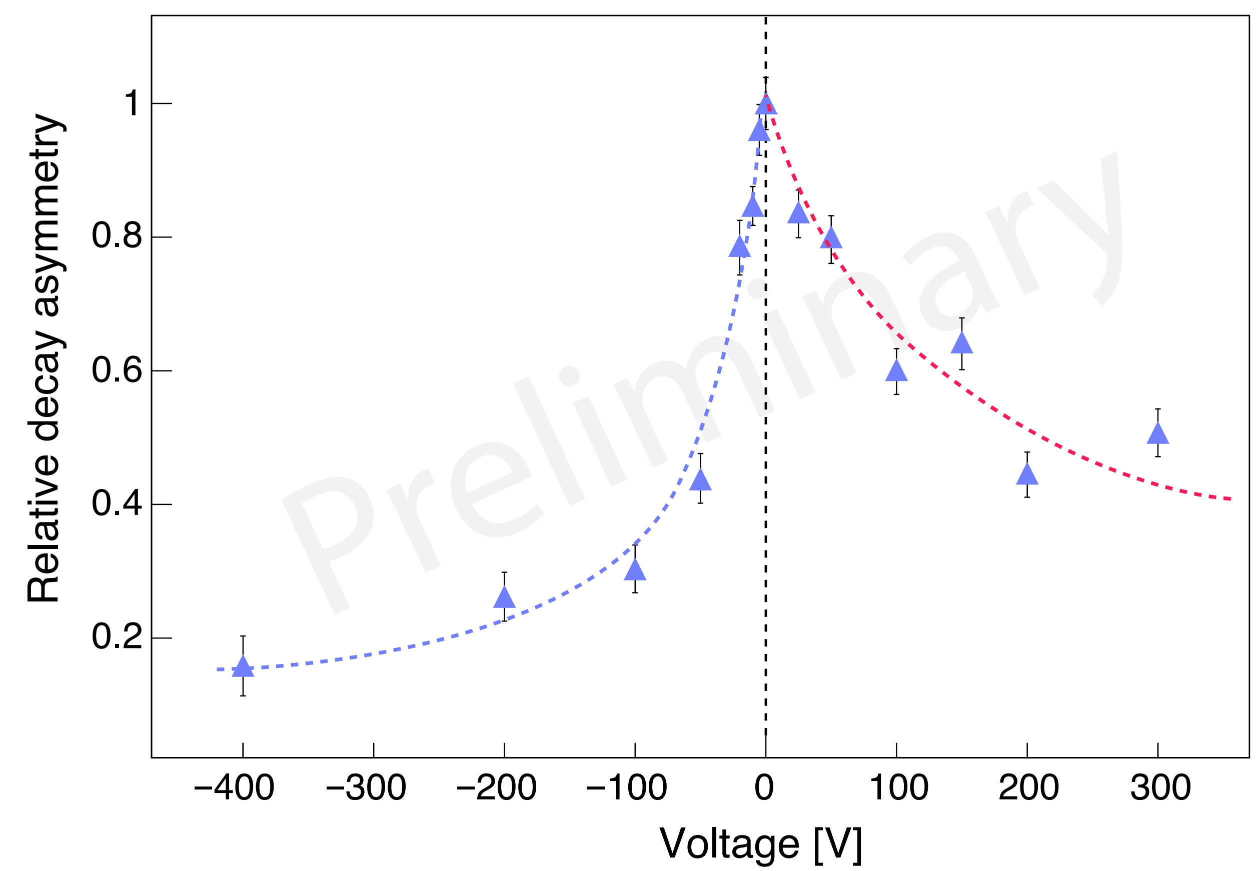
Preliminary results from μSR measurement

Abela et al. JETP Letters 57, 157 (1993)



- Temperature dependence of Mu production efficiency: high (>70%) production rates were found at T=0.26 K



- Electric field dependence of Mu production rates: Mu production can be prevented by applying fields of E~0.6 kV/cm

Next goal - extraction of Mu from SFHe

SFHe surface: A horizontal target…

- Even for a test, we would need a special μ^+ beam (vertically bent low-energy muon, or surface muon beam)

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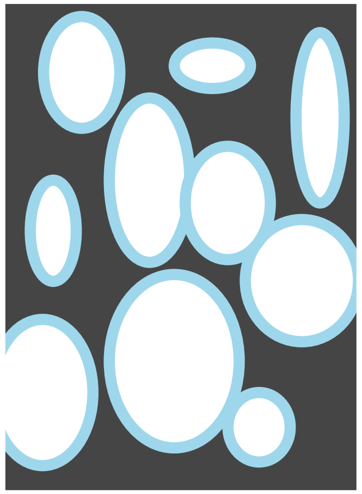
- Large μ^+ stopping power and surface area for Mu escape
- SFHe film prevents atoms sticking to the wall



- e.g. coating mesoporous SiO_2 with SFHe?

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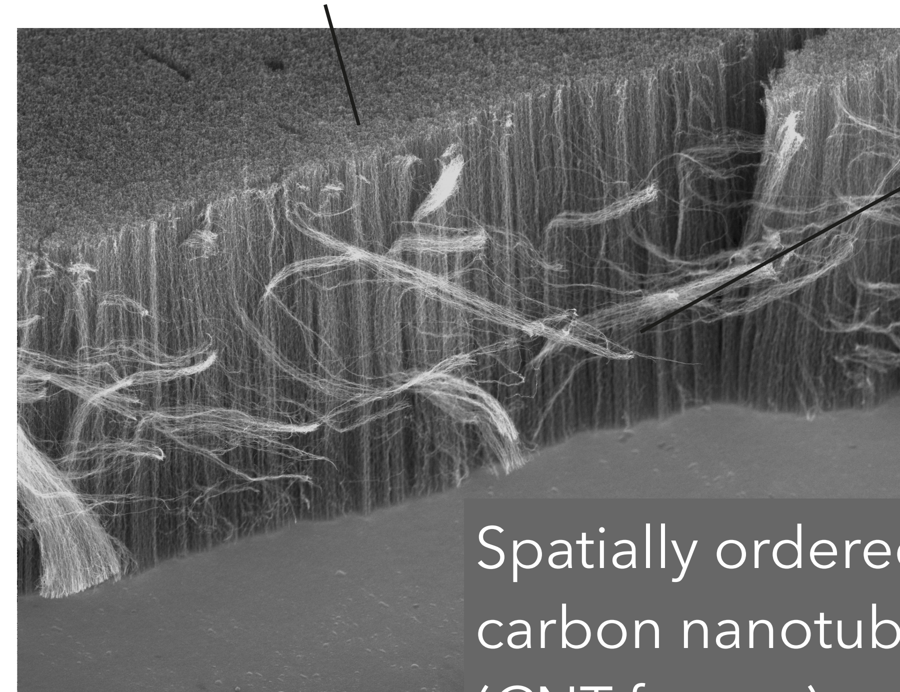
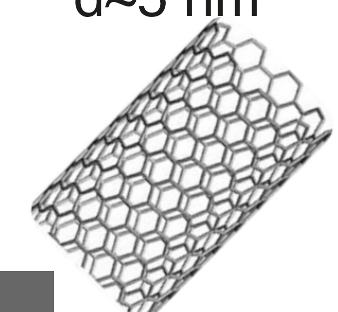
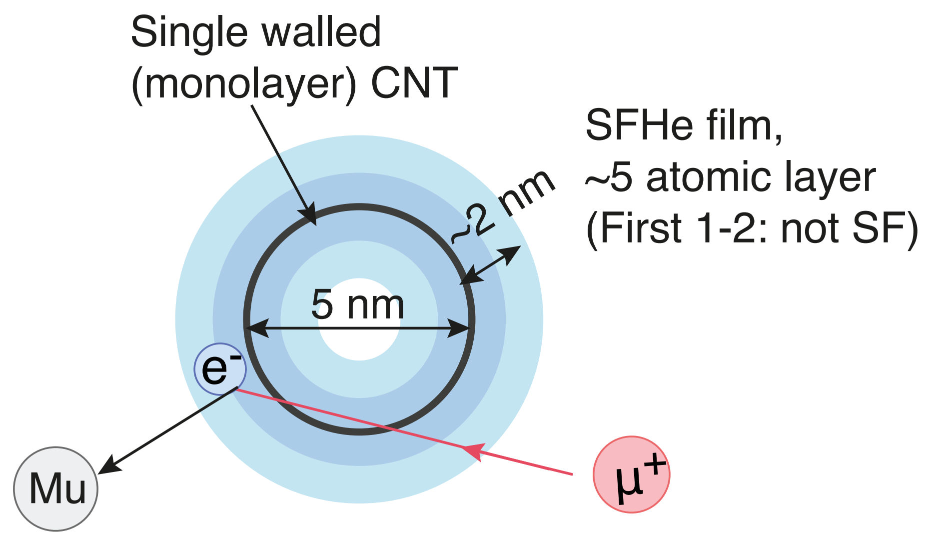
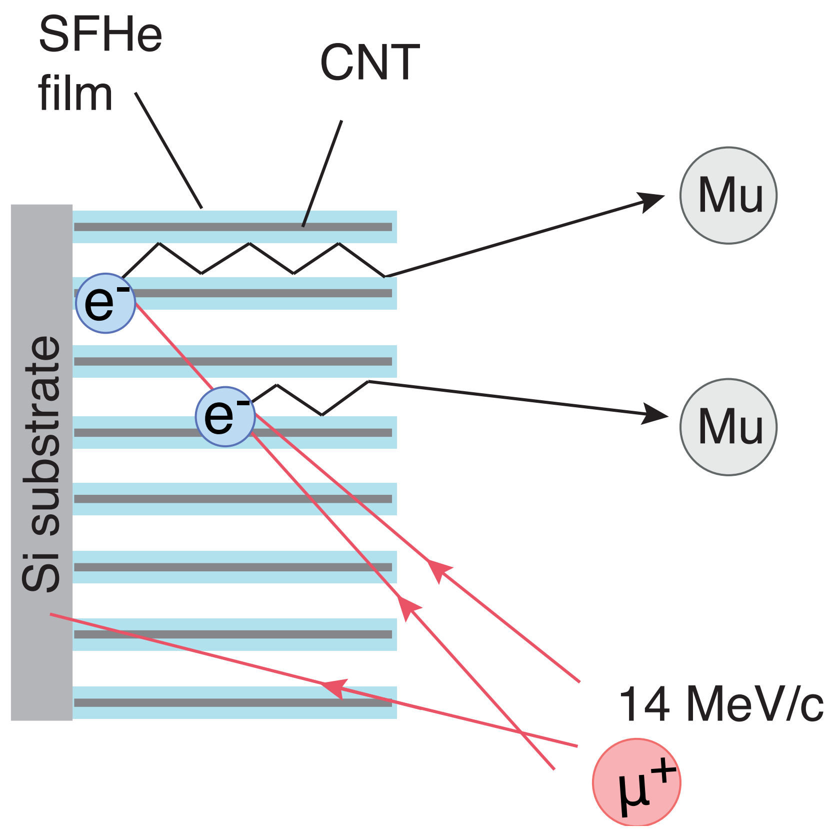




Extra - SFHe coated CNT forests





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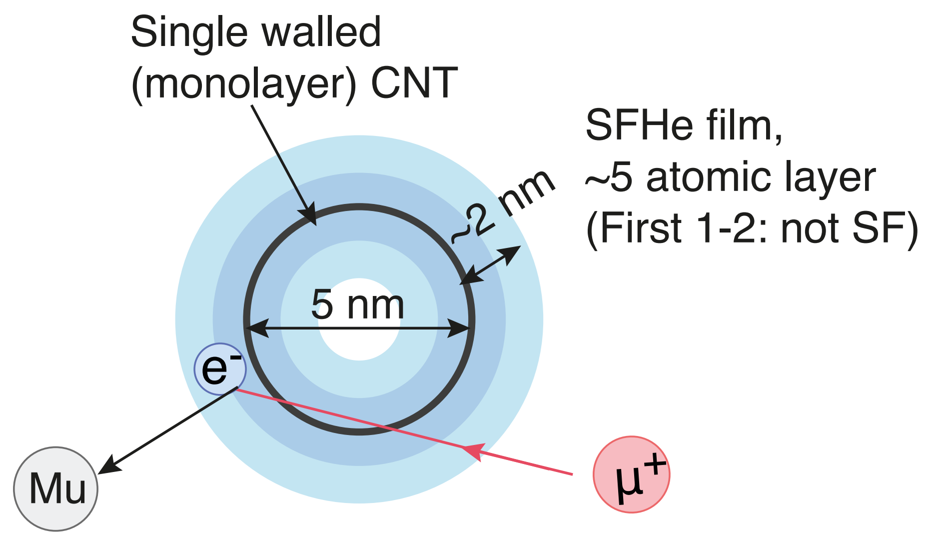

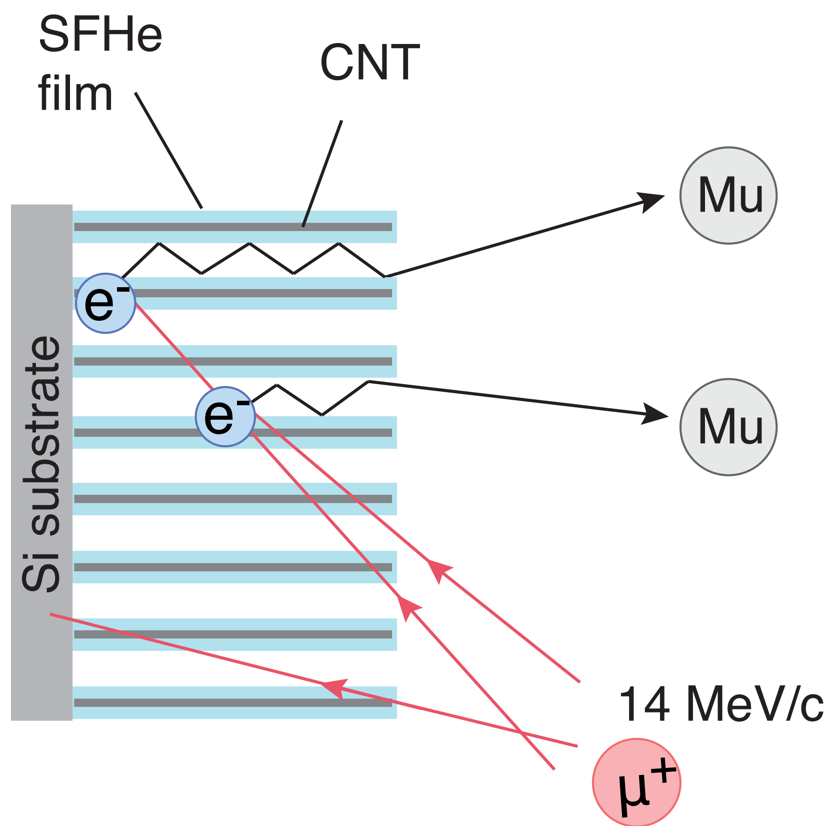

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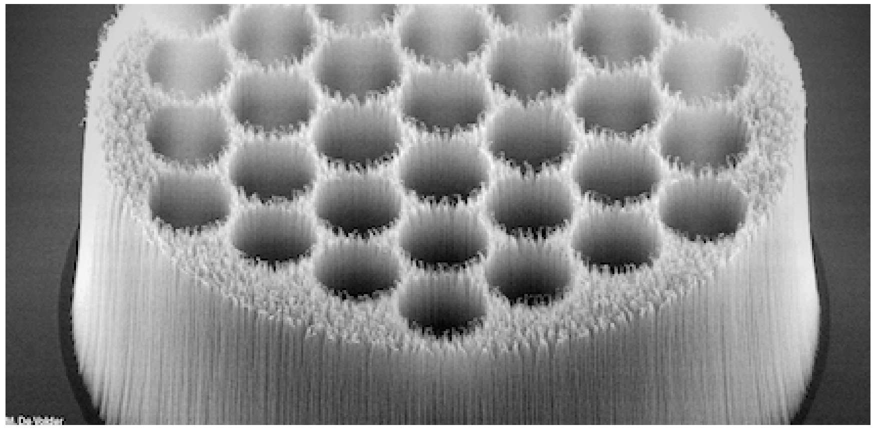
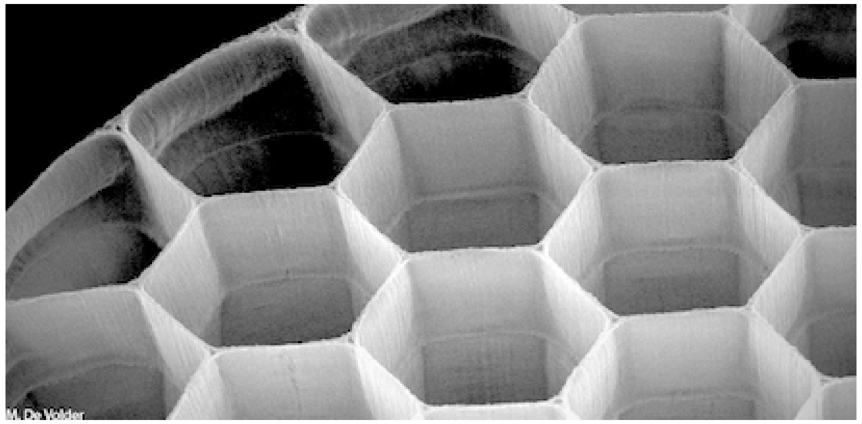
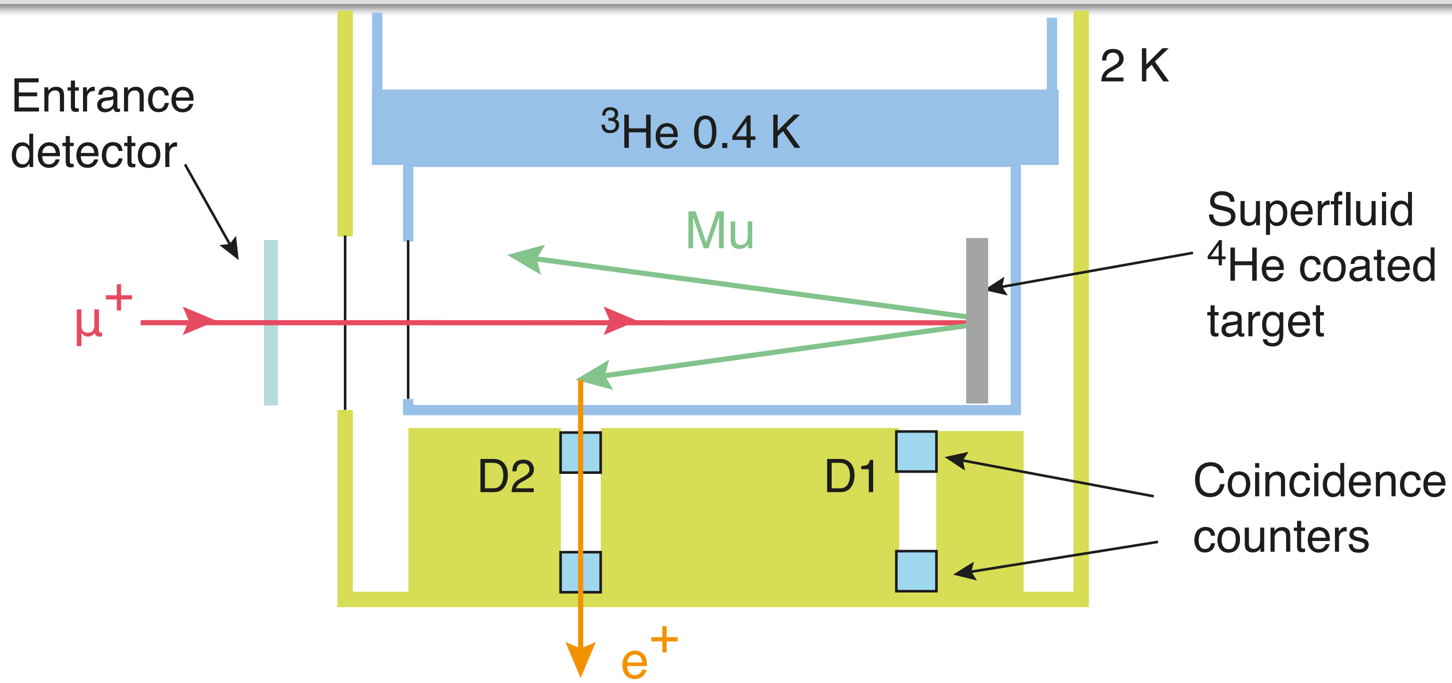


And, the possibility for:



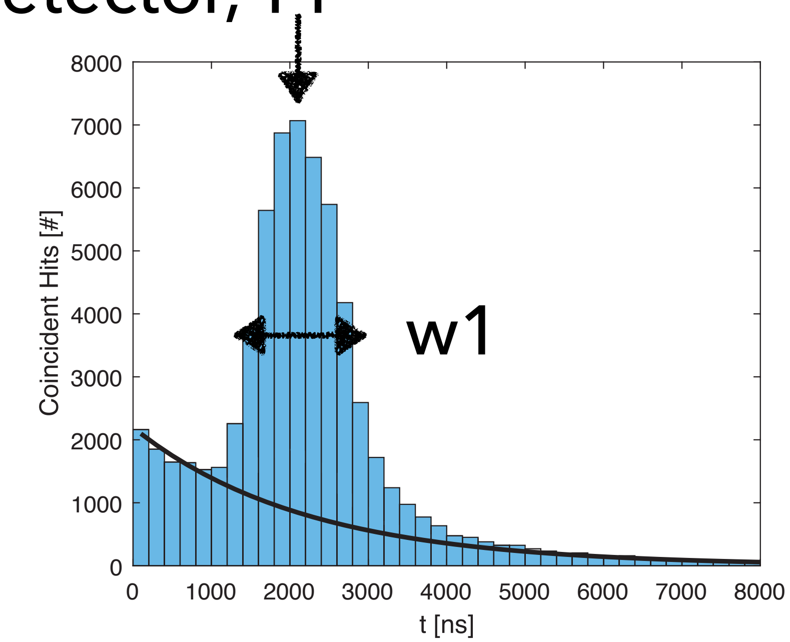
- Prefabricated holes for better Mu extraction
- Free-standing structures for back-implantation



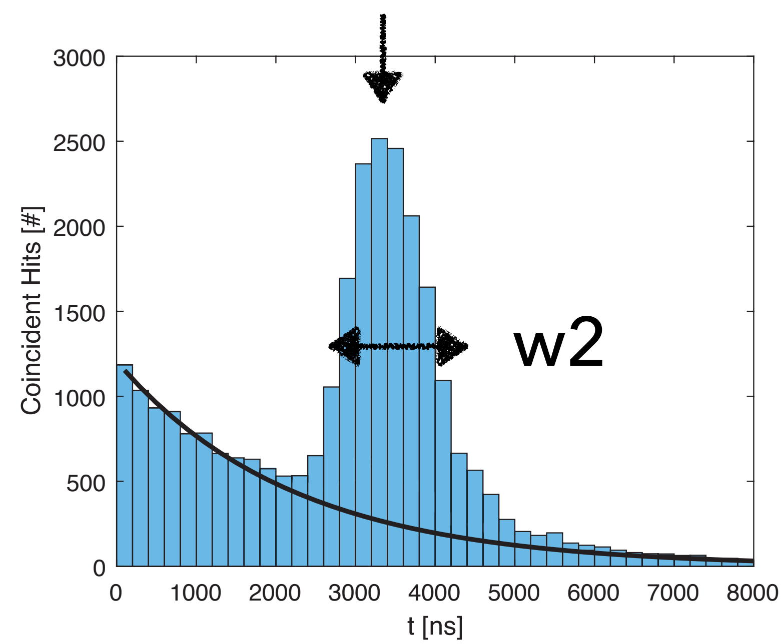
- 3He cryostat (~0.4 K) used to cool target volume with 4He coated targets
- Coincidence counters: detecting fly-by of Mu via positrons from μ^+ decay

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

Near detector, T1

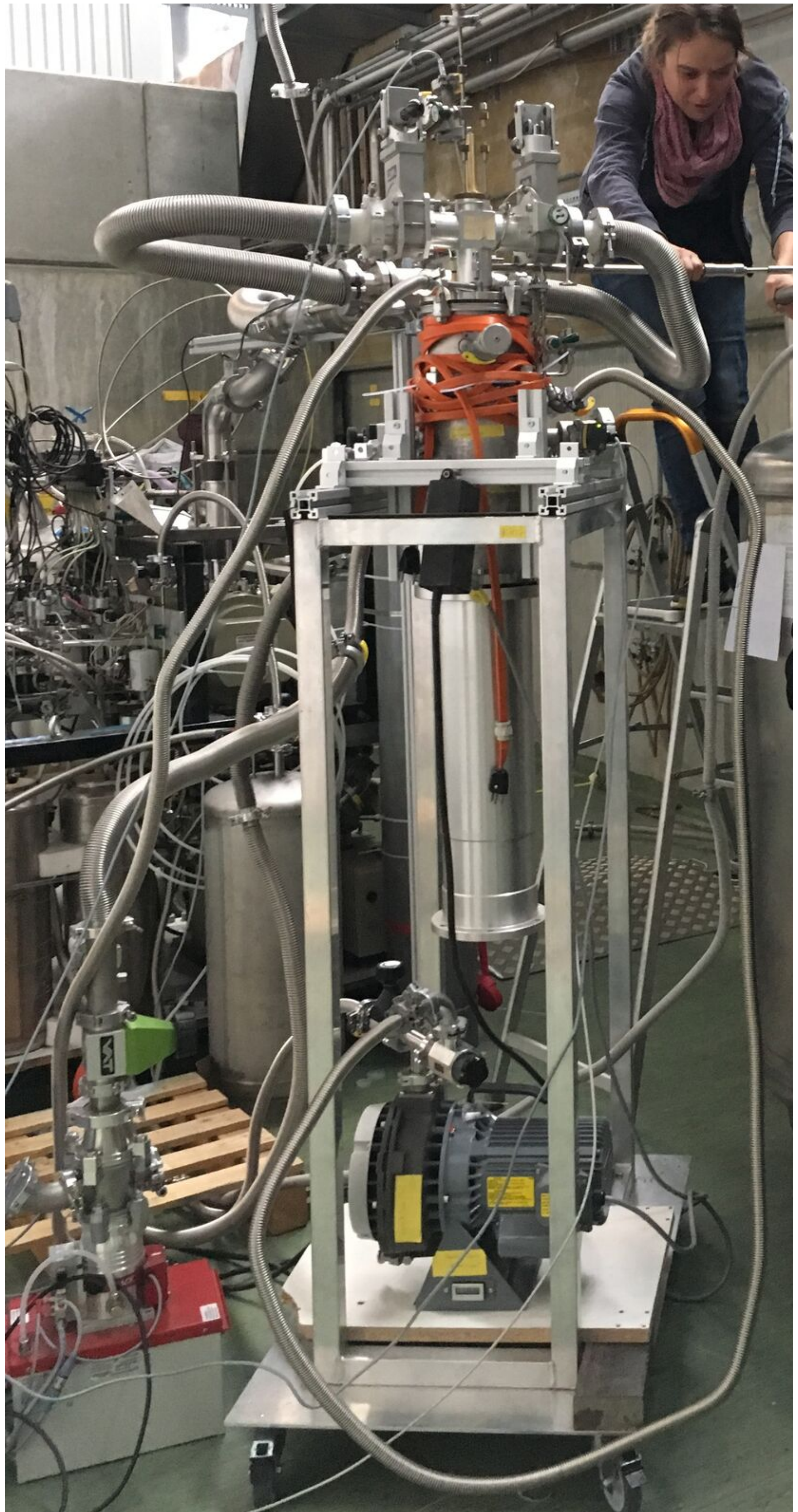


Far detector, T2

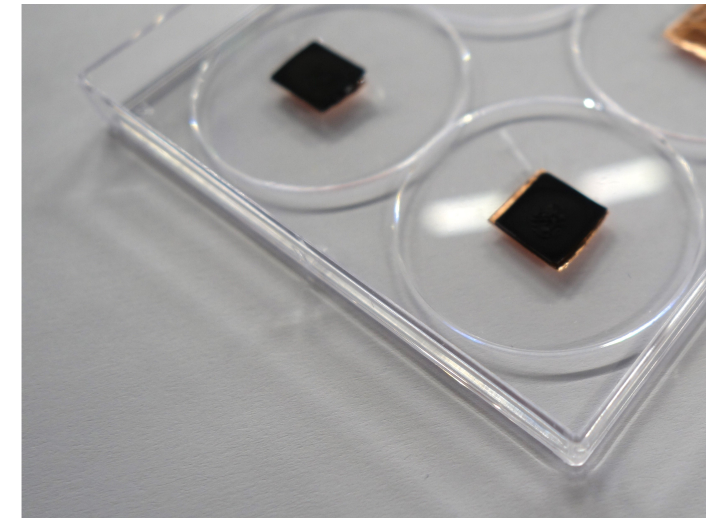


- Emission of Mu from SFHe coated nanostructured materials would prove:
  - Mu atoms can be ejected from the surface of SFHe
  - Mu atoms can reflect from SFHe surfaces

Status: 3He cryostat startup, test of samples

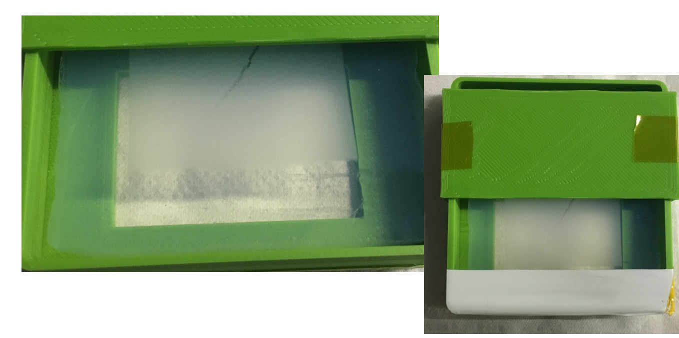


- Beamtime: 3 weeks end-of-the year
- Large cooling power on



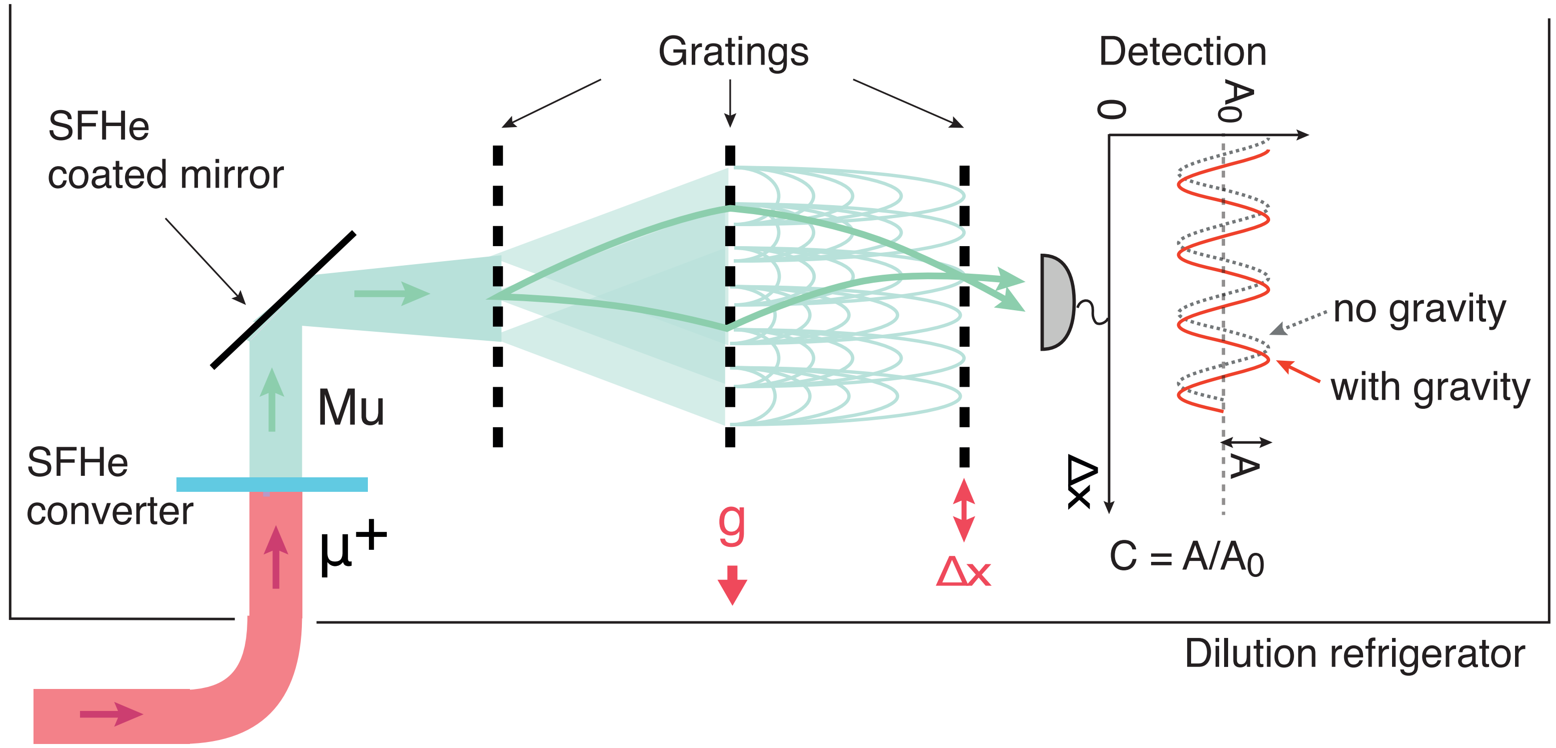
- CNT forests from Cambridge

- Zeolite samples from ETHZ



- Laser ablated aerogel from TRIUMF

Possible future setup for gravity measurement



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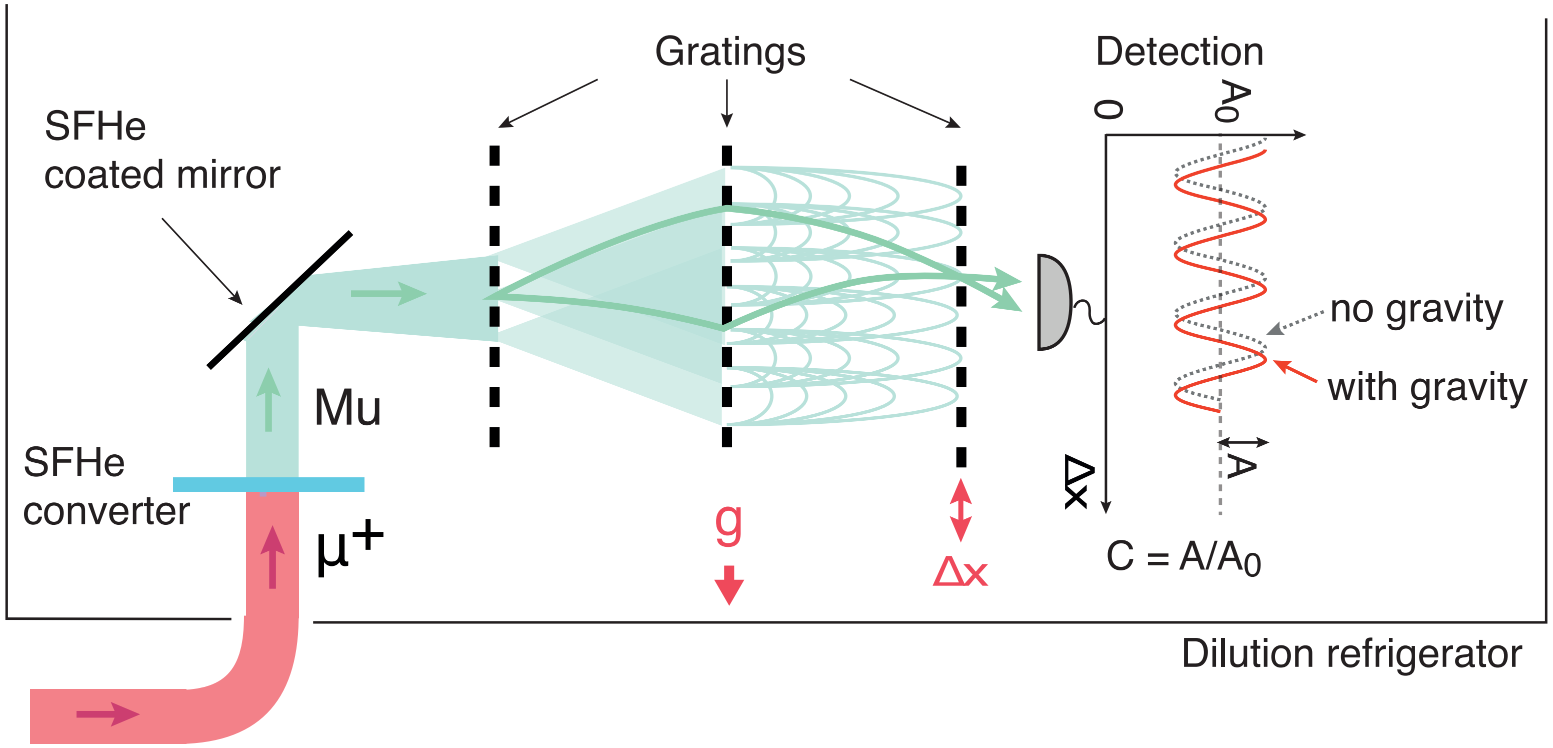
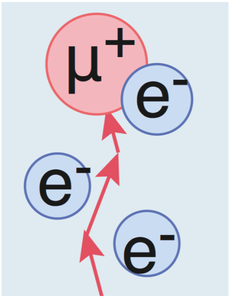


(1) Muonium production in bulk SFHe T<0.5 K



✓ (2017 Dec.)

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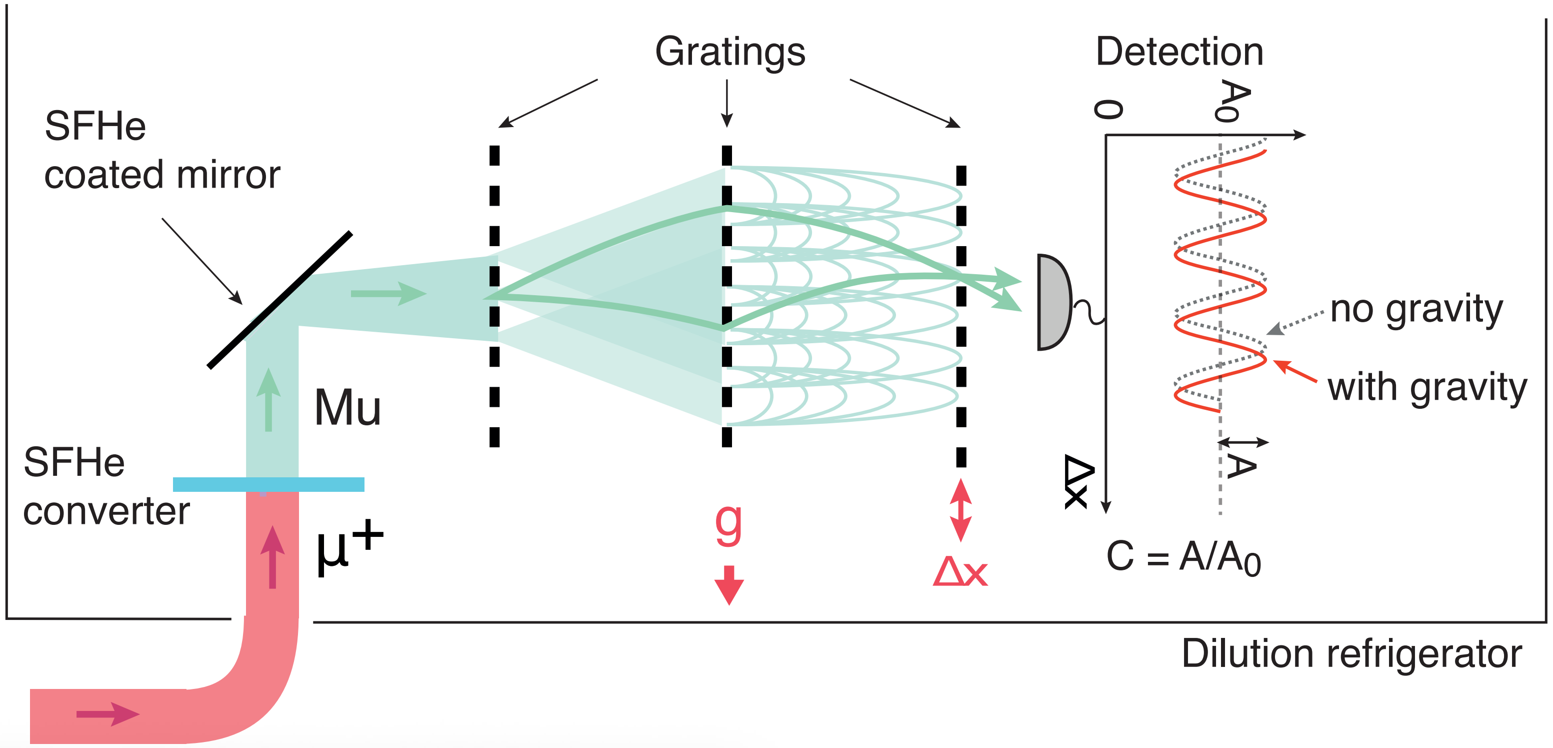

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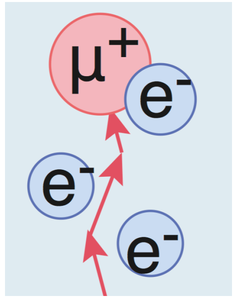
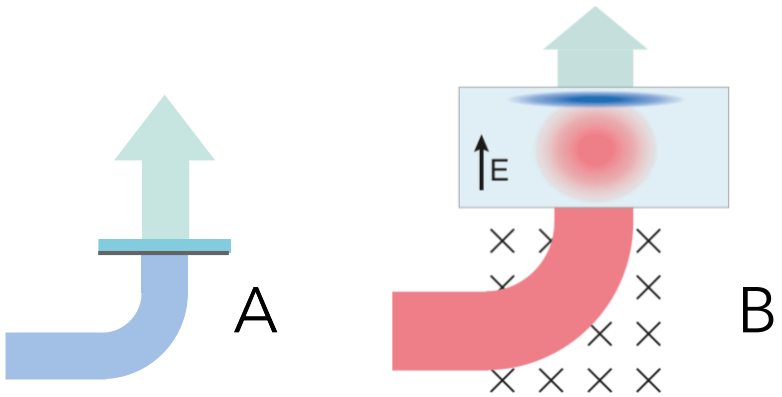


(2) Vacuum emission of Mu from SFHe

(3) Mu reflection from SFHe

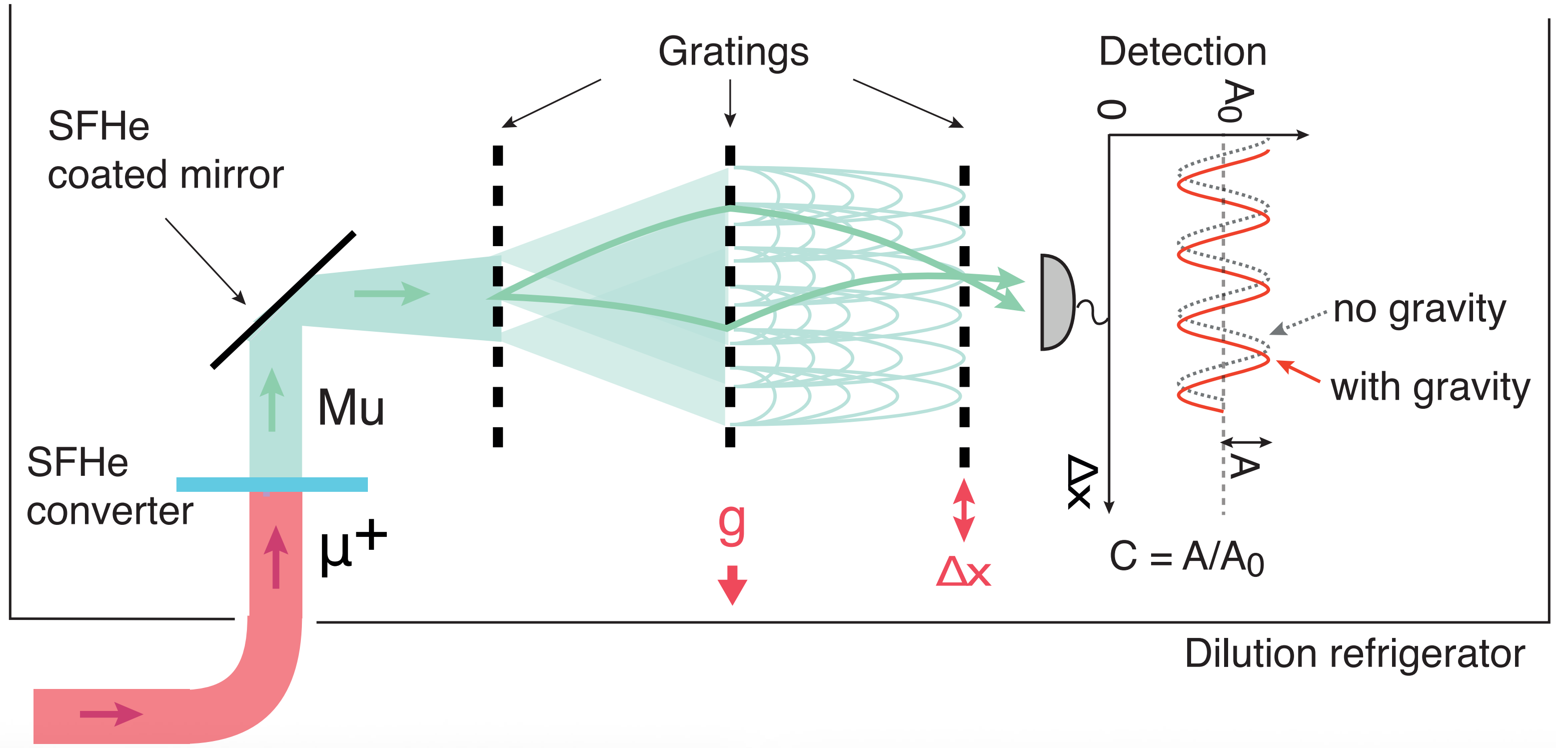


✔ (2017 Dec.)

? (2018 Dec.)

Summary & Outlook

Possible future setup for gravity measurement



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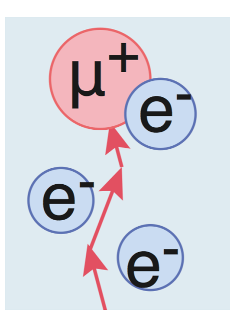

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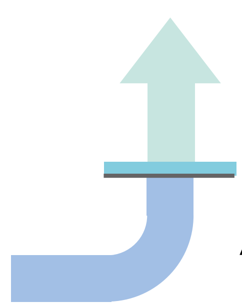
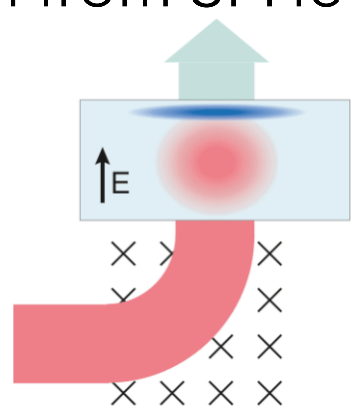


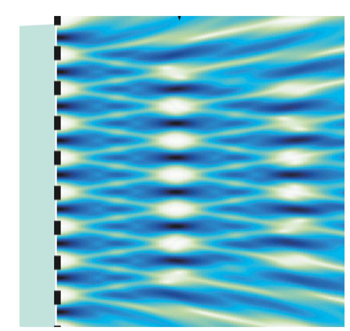
A



B

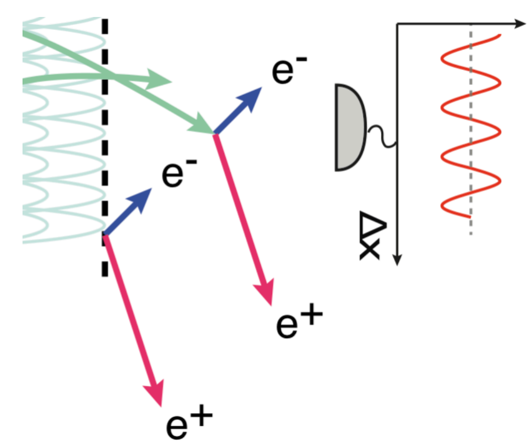
? (2018 Dec.)

(4) Interferometer feasibility



theory

✔?



background study

? (2018 Dec.)

Thank you!

A. Antognini[1,2], P. Crivelli[1], K. Kirch[1,2], D. Taqqu[1]
M. Bartkowiak[2], A. Knecht[2], A. Papa[2], N. Ritjoho[2], D. Rousso[2], R. Scheuermann[2], A. Soter[2],
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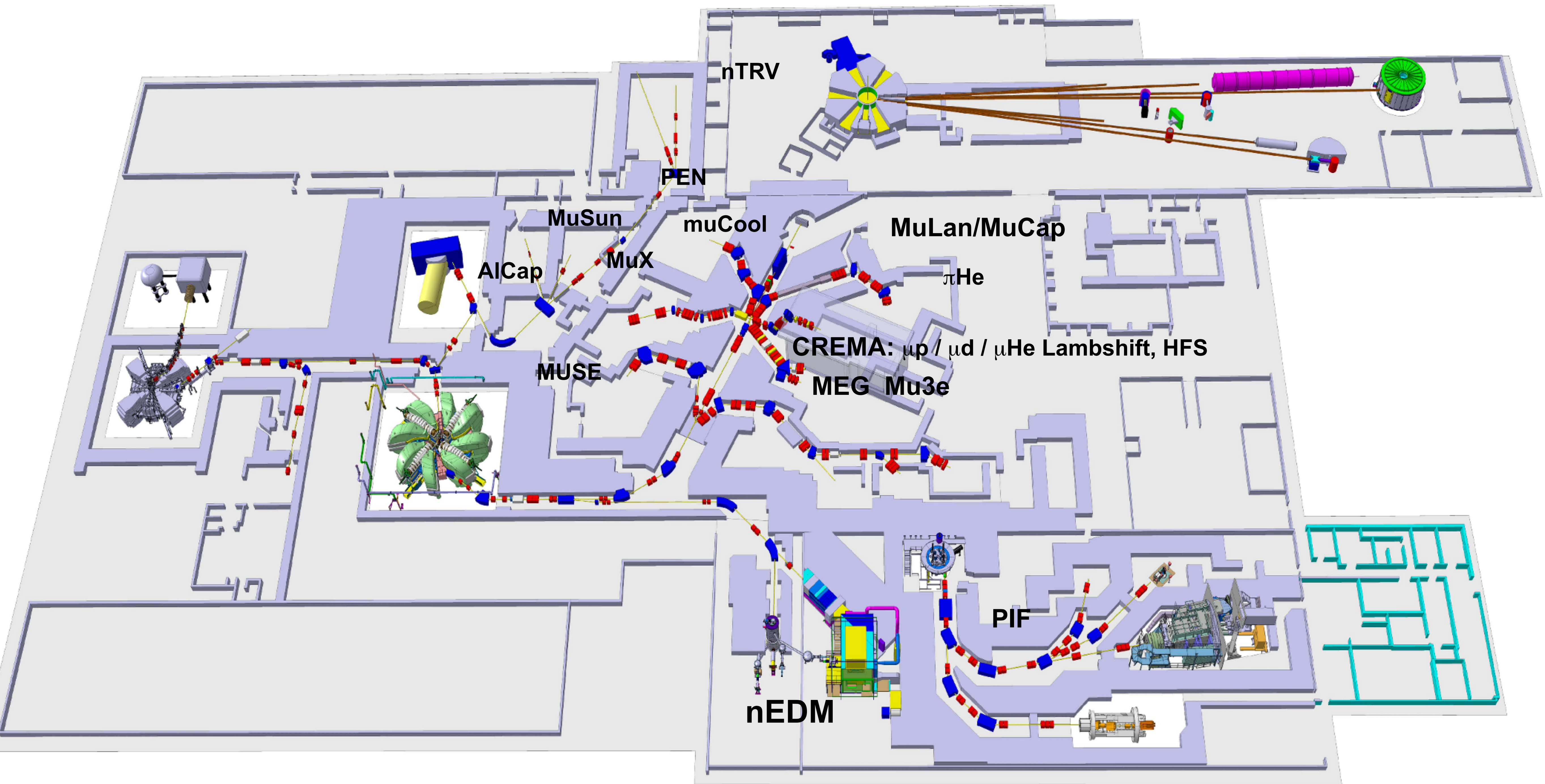
[1] Institute for Particle Physics and Astrophysics, ETH Zurich, 8093 Zurich, Switzerland
[2] Paul Scherrer Institute, 5232 Villigen-PSI, Switzerland
[3] Department Of Engineering, University of Cambridge, UK
[4] Illinois Institute of Technology, Chicago, IL 60616 USA

MARIE CURIE ACTIONS

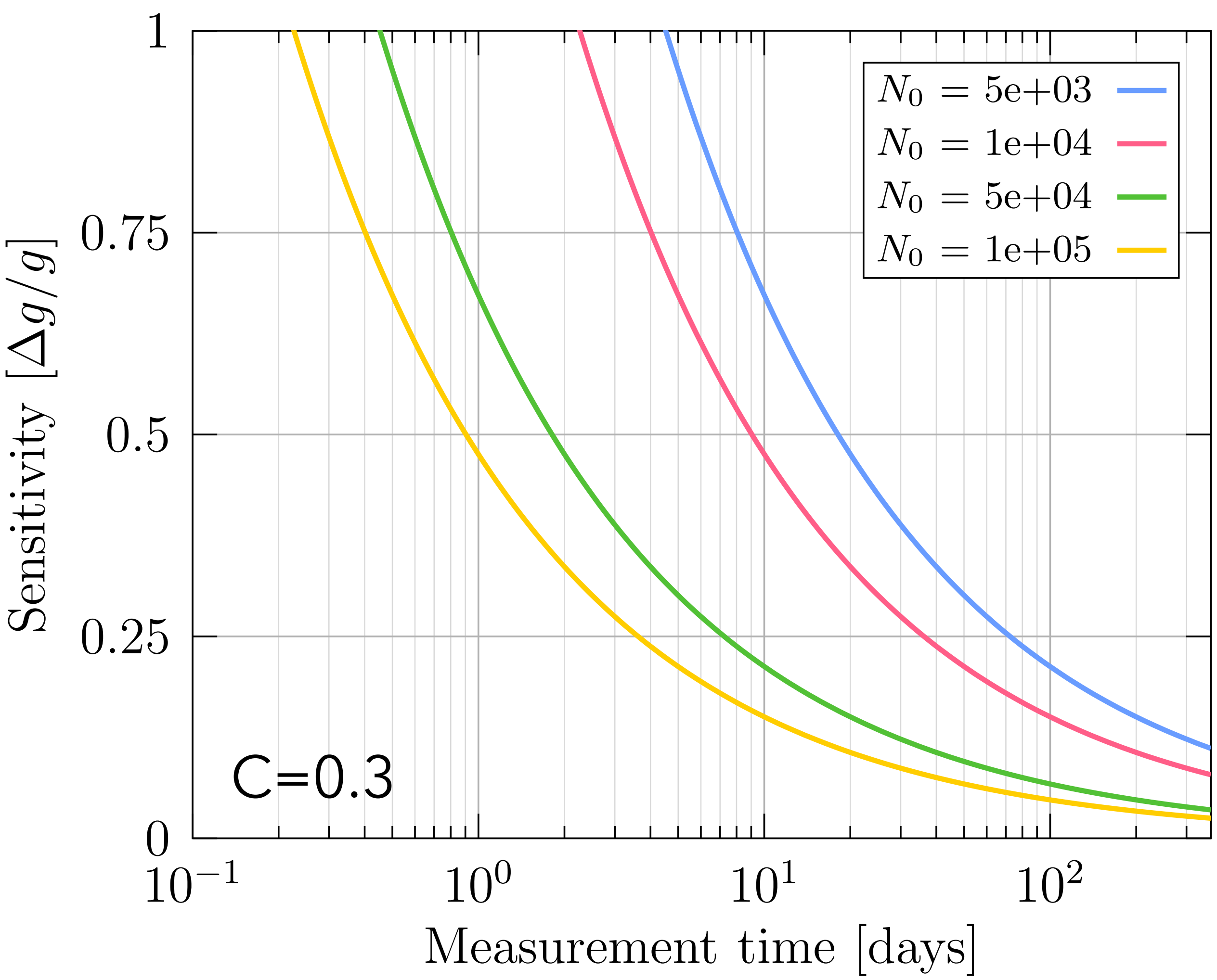
PAUL SCHERRER INSTITUT
PSI

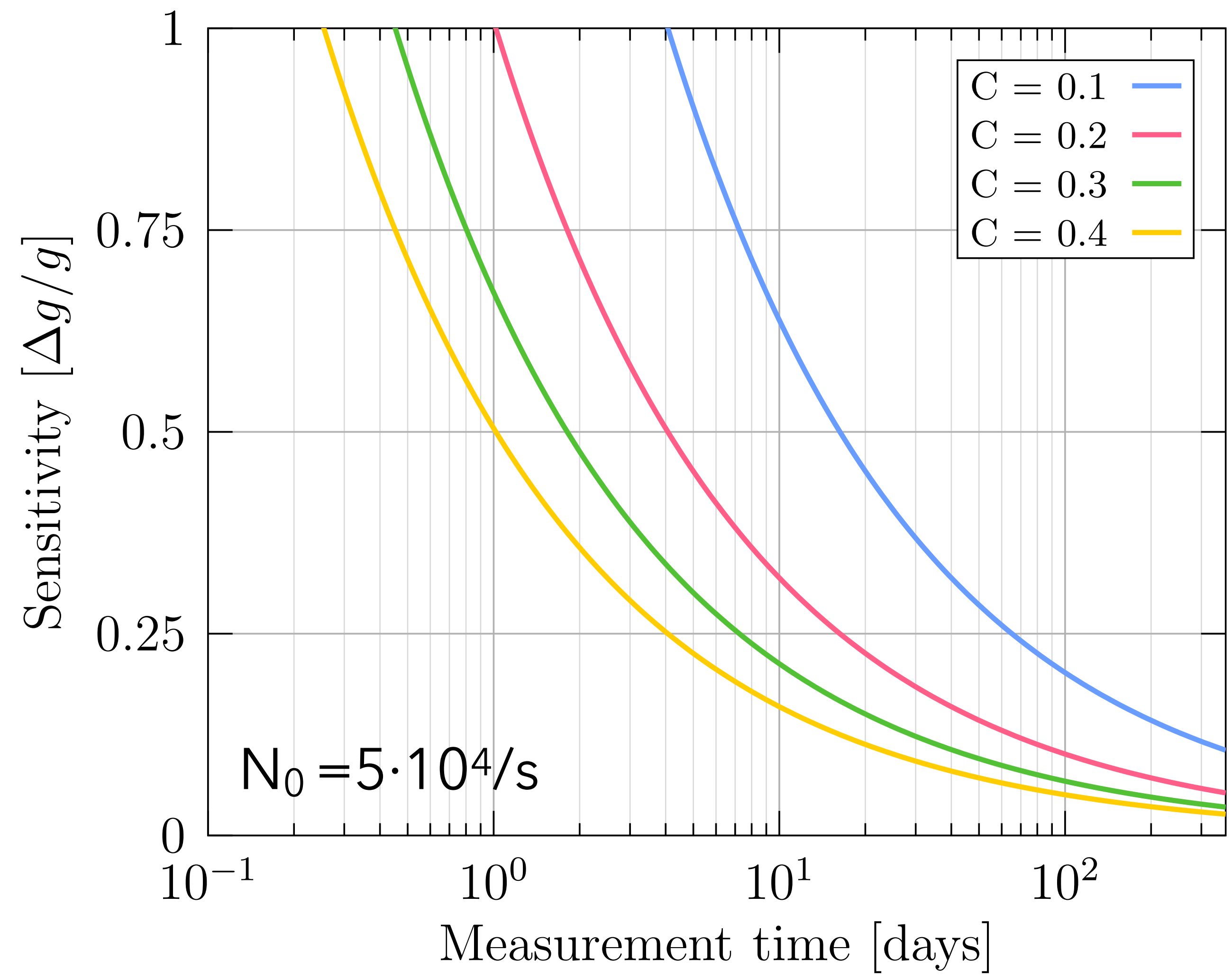
FNSNF
FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

Extra - PSI facilities



Inertial sensitivities



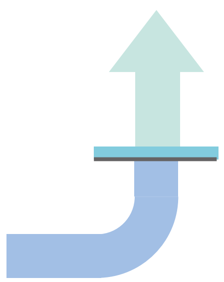
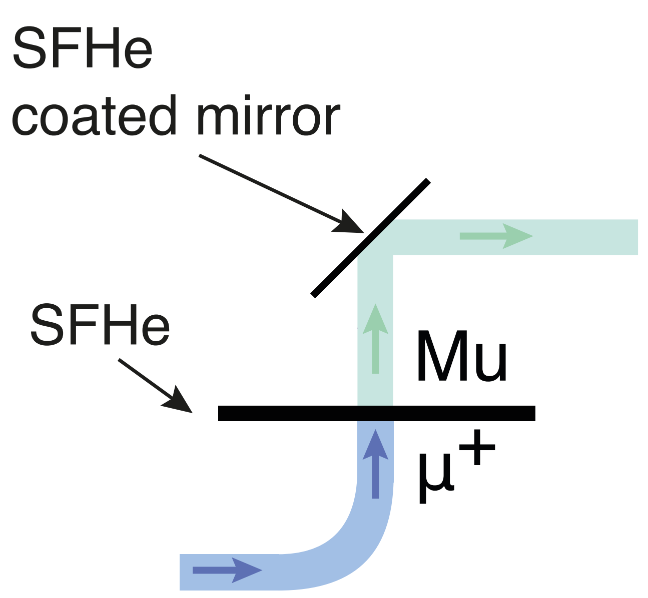


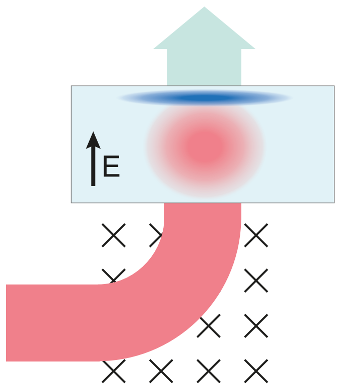
$$\Delta g \approx \frac{1}{C\sqrt{N_0 \cdot e^{-(t_D+T)/\tau}}} \frac{d}{2\pi} \frac{1}{T^2}$$

d = 100 nm, 70% loss on grids,
interaction time T = 8 μs

Determining sign of g:
1-2 days with Mu source of $N_0 = 5\cdot10^4$/s, C=0.3
>100 days with $N_0 = 5\cdot10^3$/s C=0.1

Methods comparison

<table>
<tr><th></th><th>Advantage</th><th colspan="2">Disadvantage</th></tr>
<tr><td></td><td>Produces a pencil-beam of Mu</td><td>- requires special μ^+ beam, expected 10^{-3} loss</td><td rowspan="2">

Need of an atomic mirror</td></tr>
<tr><td>
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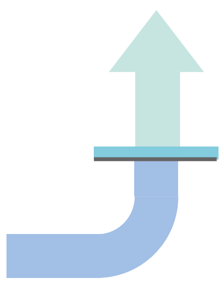
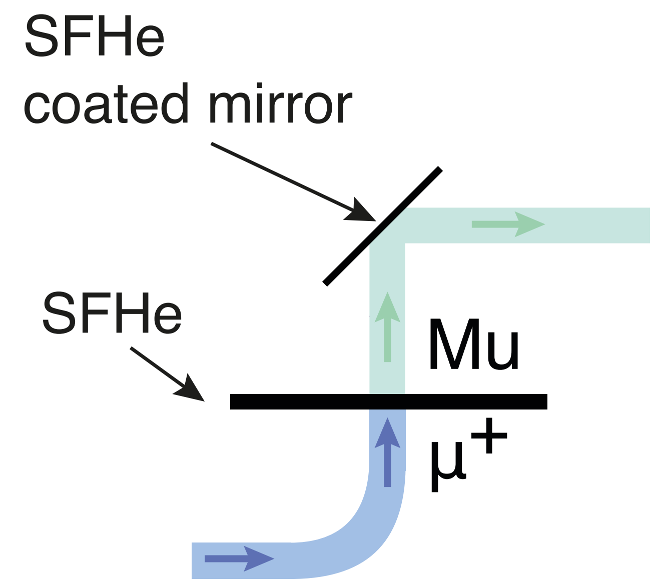
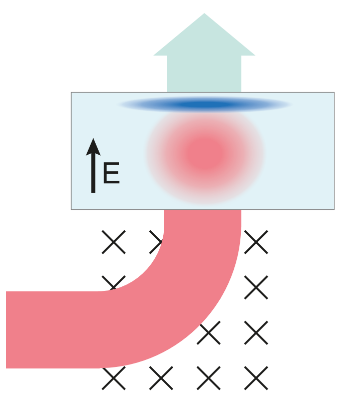
	Produces a pencil-beam of Mu	- requires special μ^+ beam, expected 10^{-3} loss	 Need of an atomic mirror
	Conventional μ^+ beam can be used	- relies on badly known physics / processes - needs extensive cold instrumentation	

Proof-of-principle demonstrations needed:

- Mu production in bulk SFHe at $T < 0.5$ K
- Mu production prohibition with E fields
- Emission of Mu from SFHe
- Reflection of Mu from SFHe surfaces

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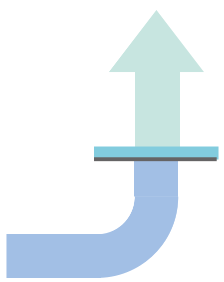
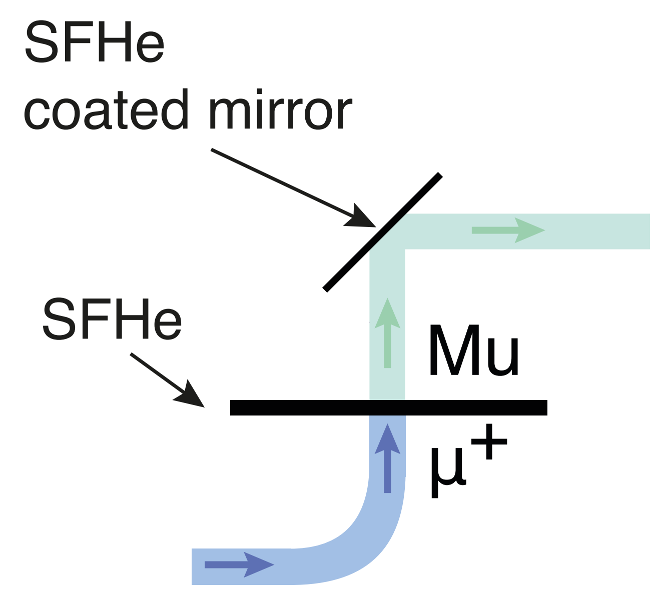
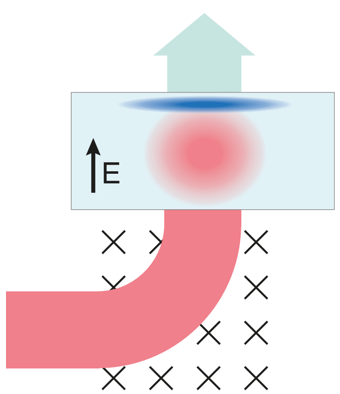
	Produces a pencil-beam of Mu	- requires special μ^+ beam, expected 10^{-3} loss	 Need of an atomic mirror
	Conventional μ^+ beam can be used	- relies on badly known physics / processes - needs extensive cold instrumentation	

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Dec. 2017

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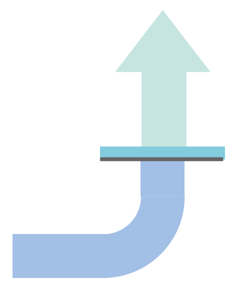
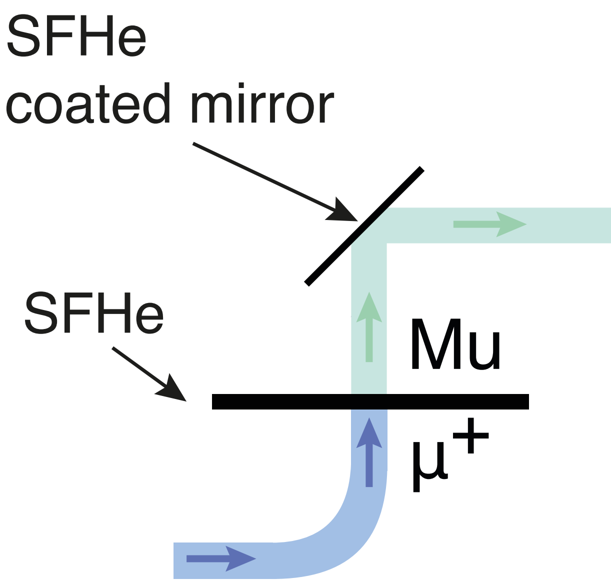
<tr><td></td><td>Produces a pencil-beam of Mu</td><td>- requires special μ^+ beam, expected 10^{-3} loss</td><td rowspan="2">

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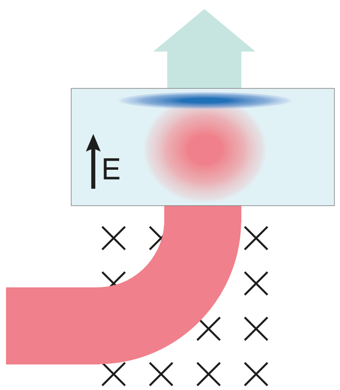
<tr><td>
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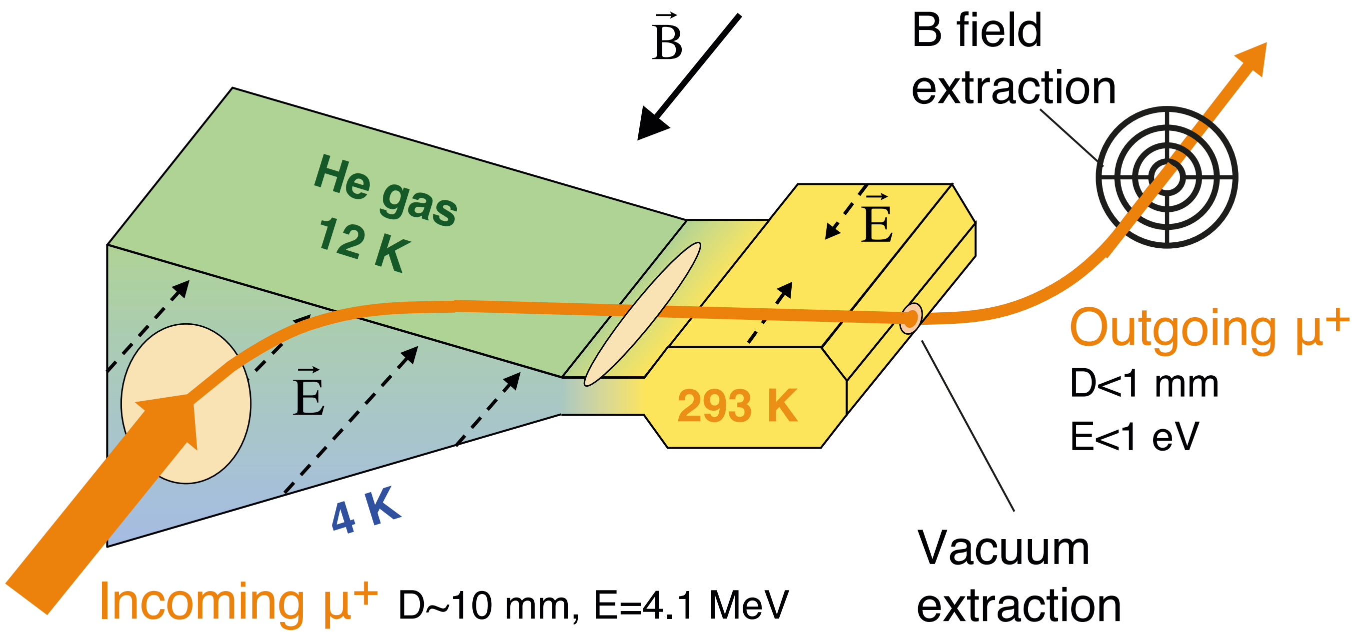
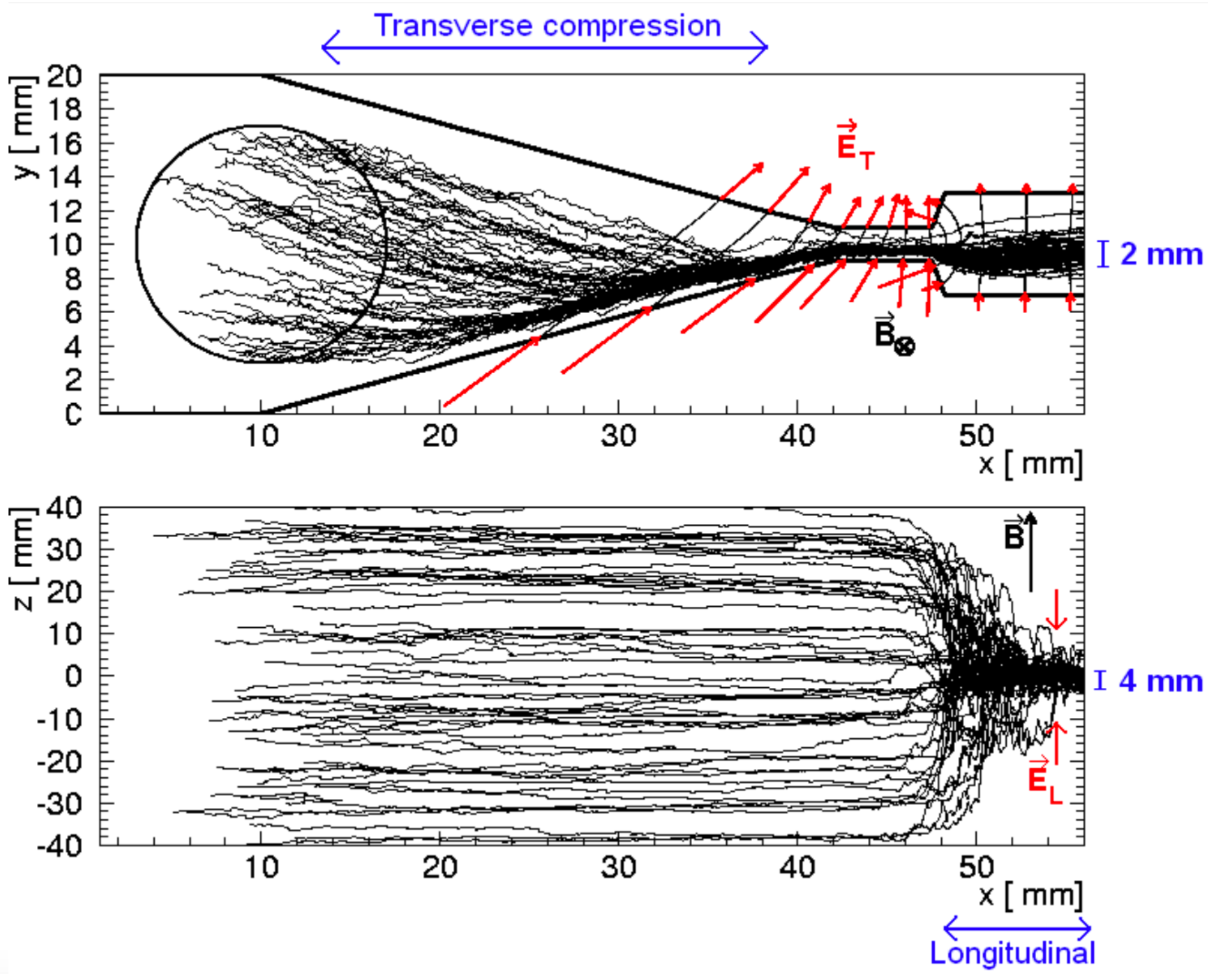
- Mu production in bulk SFHe at T < 0.5 K ✓
- Mu production prohibition with E fields ✓
- Emission of Mu from SFHe
- Reflection of Mu from SFHe surfaces

Dec. 2017

Extra - MuCool working principle



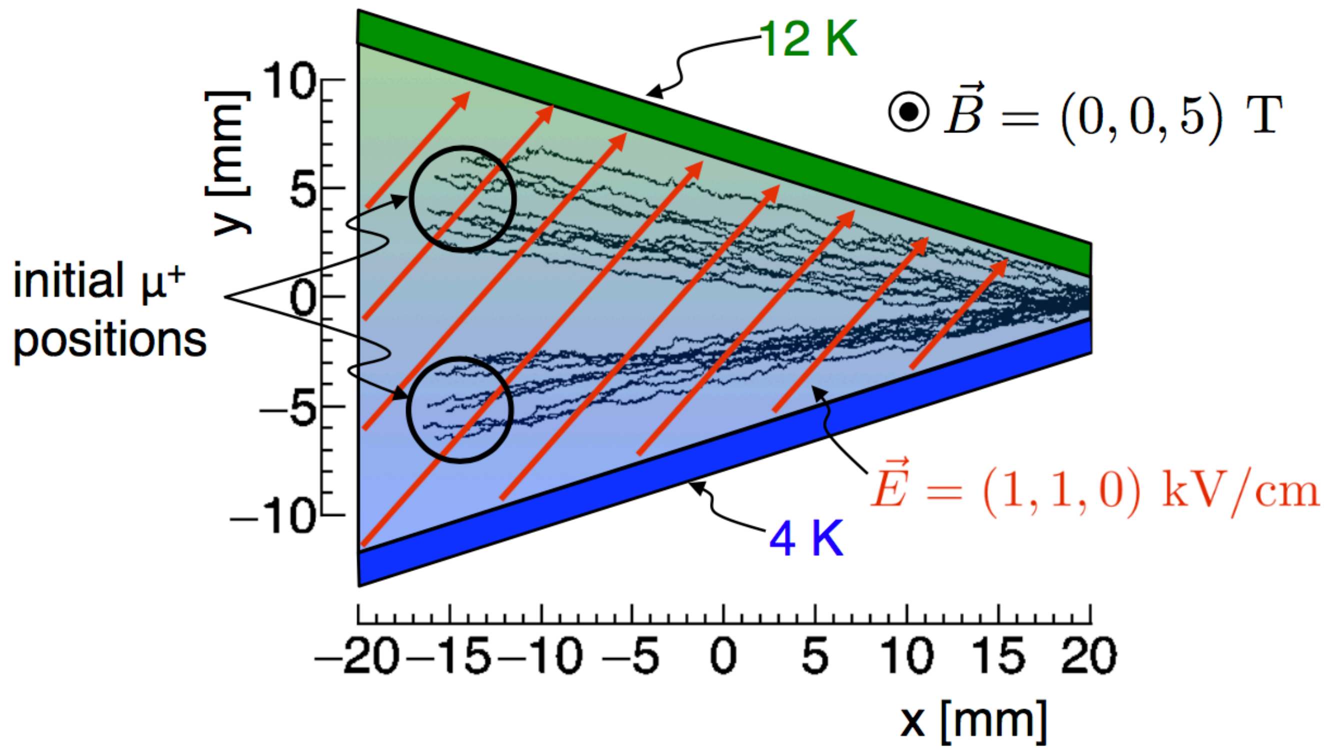


muCool device

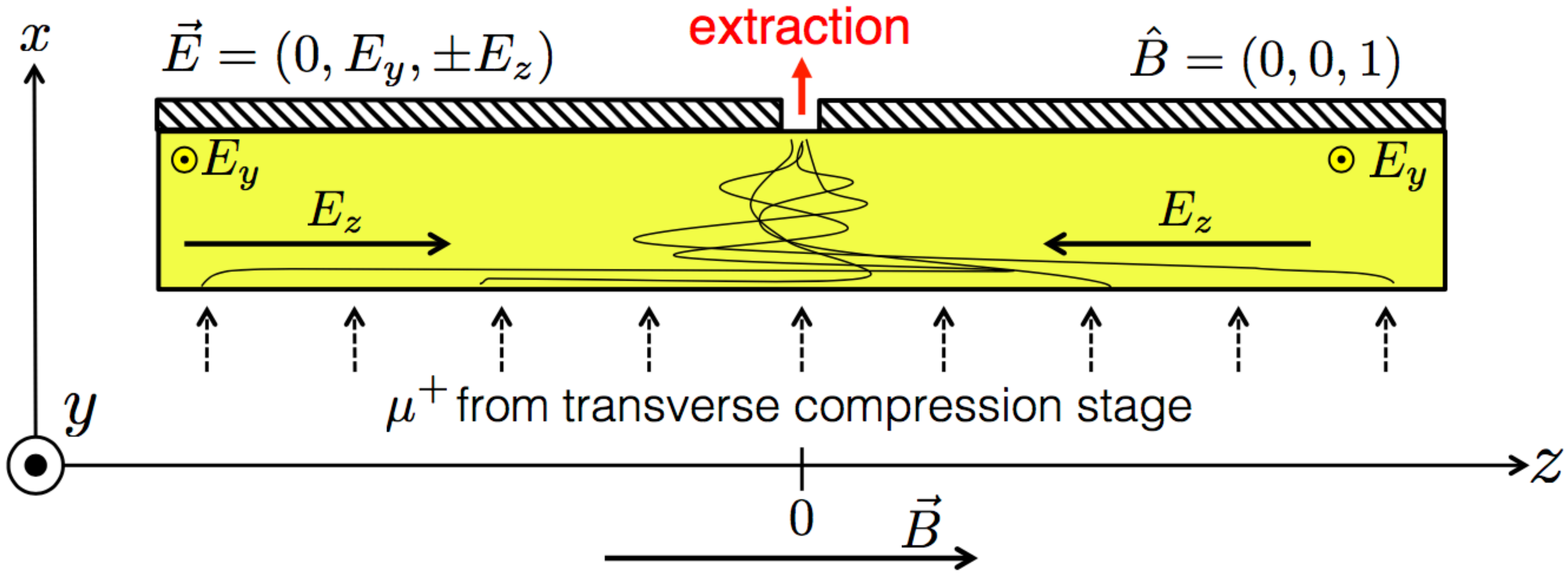
- cryogenic He gas with complex E-fields and density gradients inside a 5 T solenoid
- 10^{10} decrease of 6D phase-space with 10^{-3} efficiency
- the μ^+ swarm extracted to vacuum, and from the B field (10 keV, 10 μm in focus)

$$\vec{v}_D = \frac{\mu E}{1+\omega^2\tau^2}\left[\hat{E} + \omega\tau\hat{E}\times\hat{B} + \omega^2\tau^2(\hat{E}\cdot\hat{B})\hat{B}\right]$$

Extra - MuCool transverse and longitudinal compression



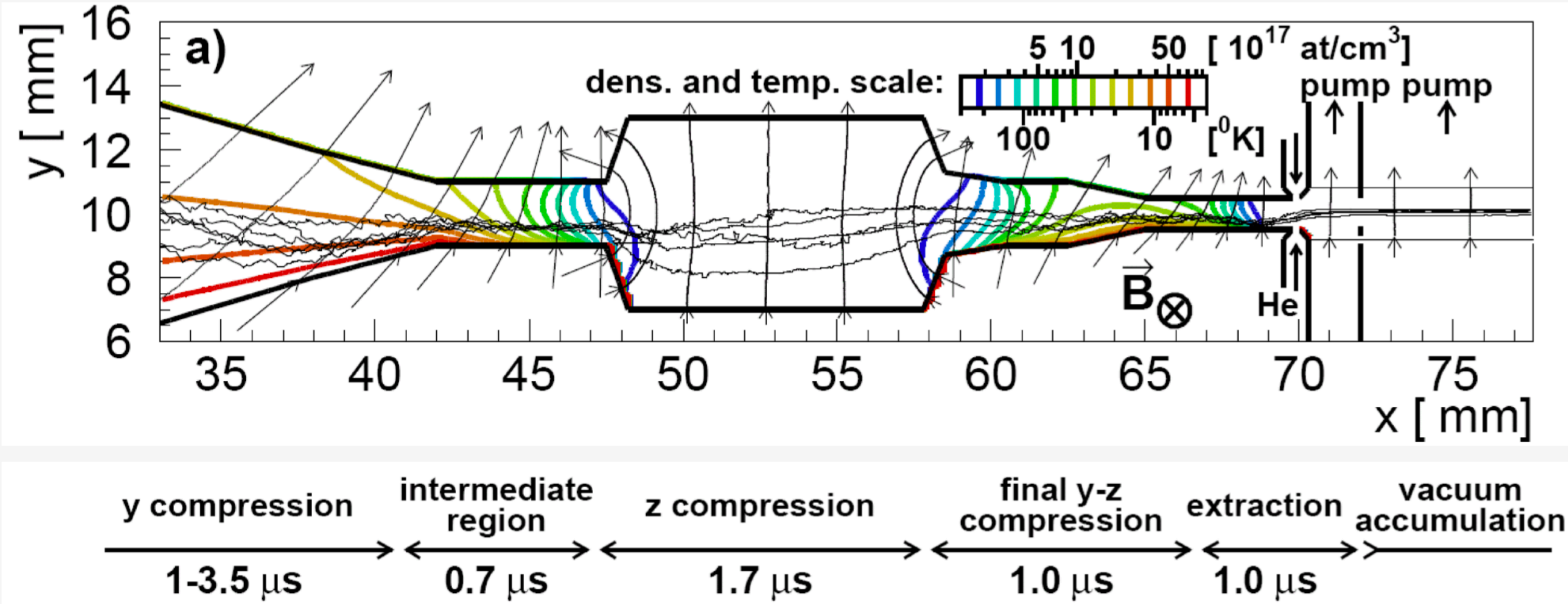
- Transverse compression



- Longitudinal compression

- From the thesis of A. Eggenberger

Extra - MuCool compression times

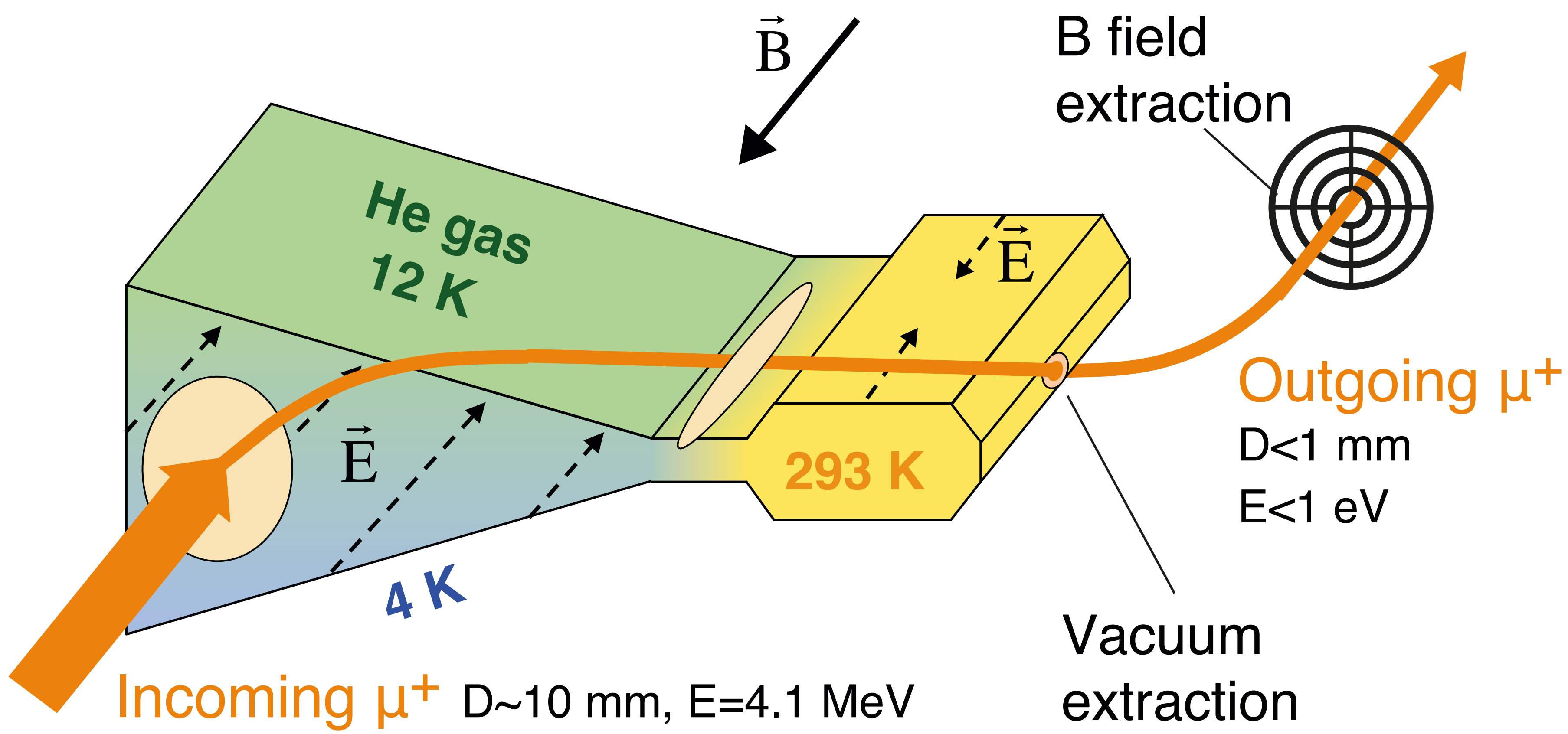


Total compression and extraction times:

- Our beam line: 8 μs
- Ion beam lines: several ms

→ High efficiency ($e^{-8/2.2} = 2 \cdot 10^{-2}$)

From A. Antognini



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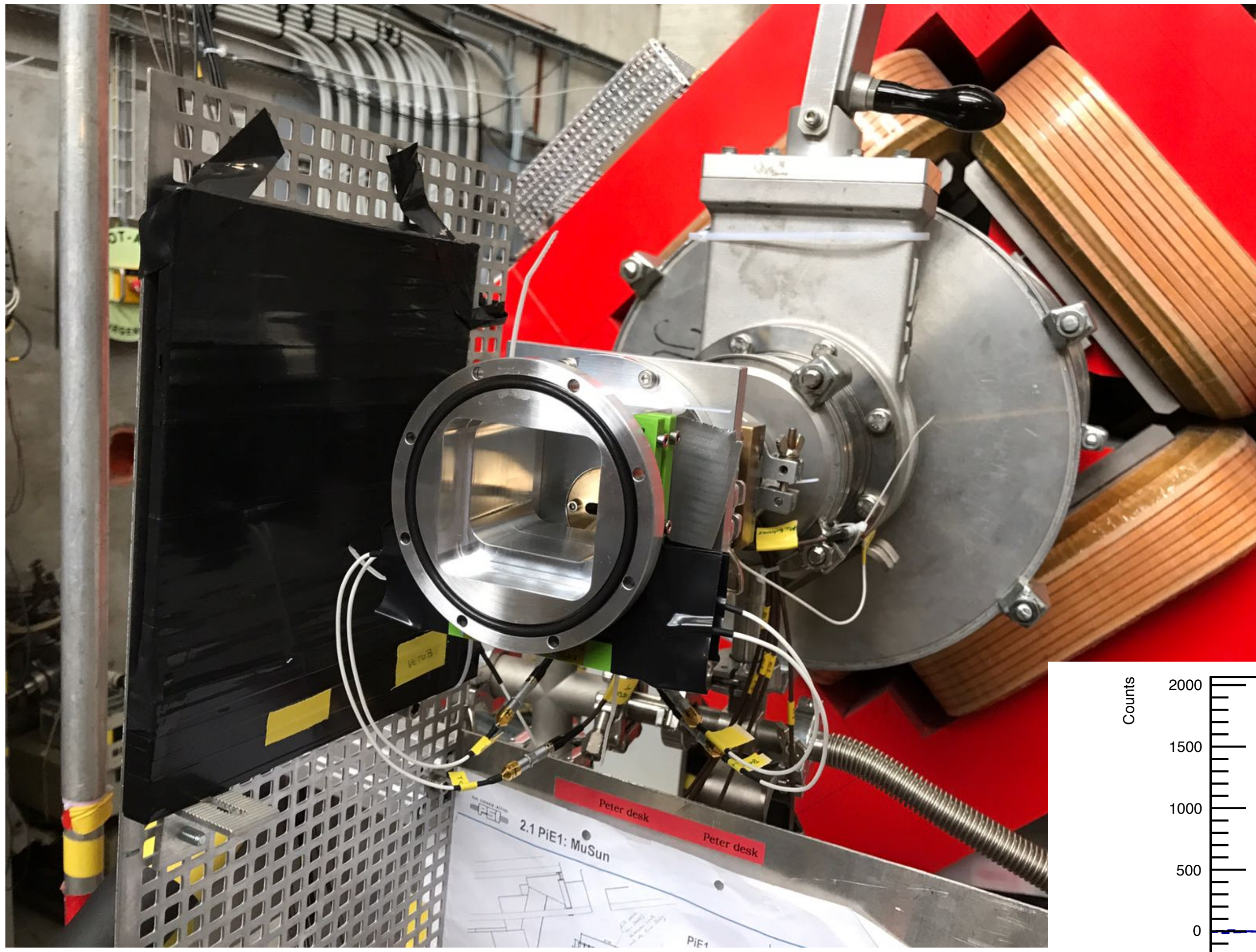
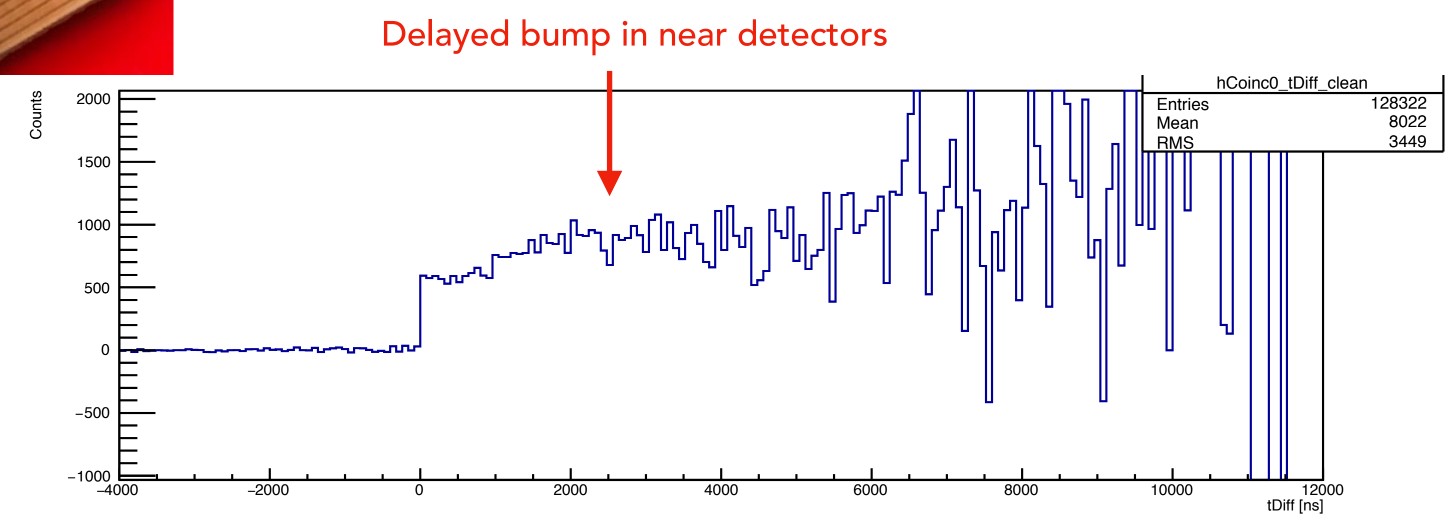
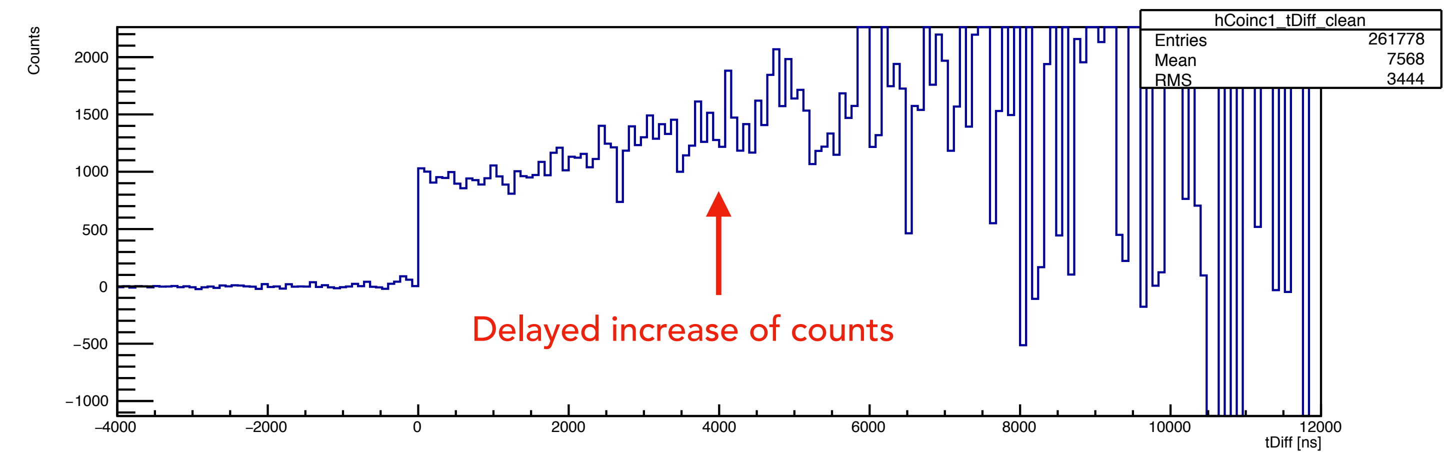
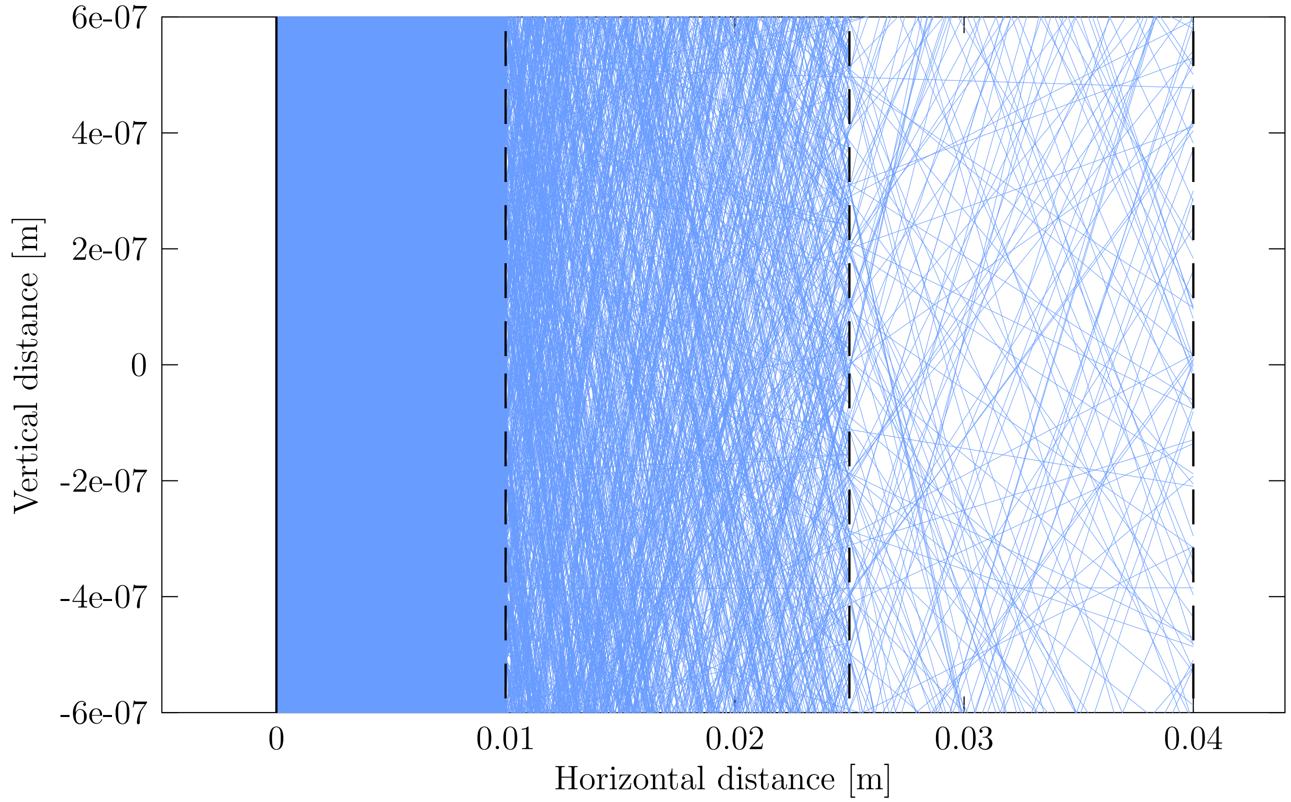
Preliminary measurements at room temperature



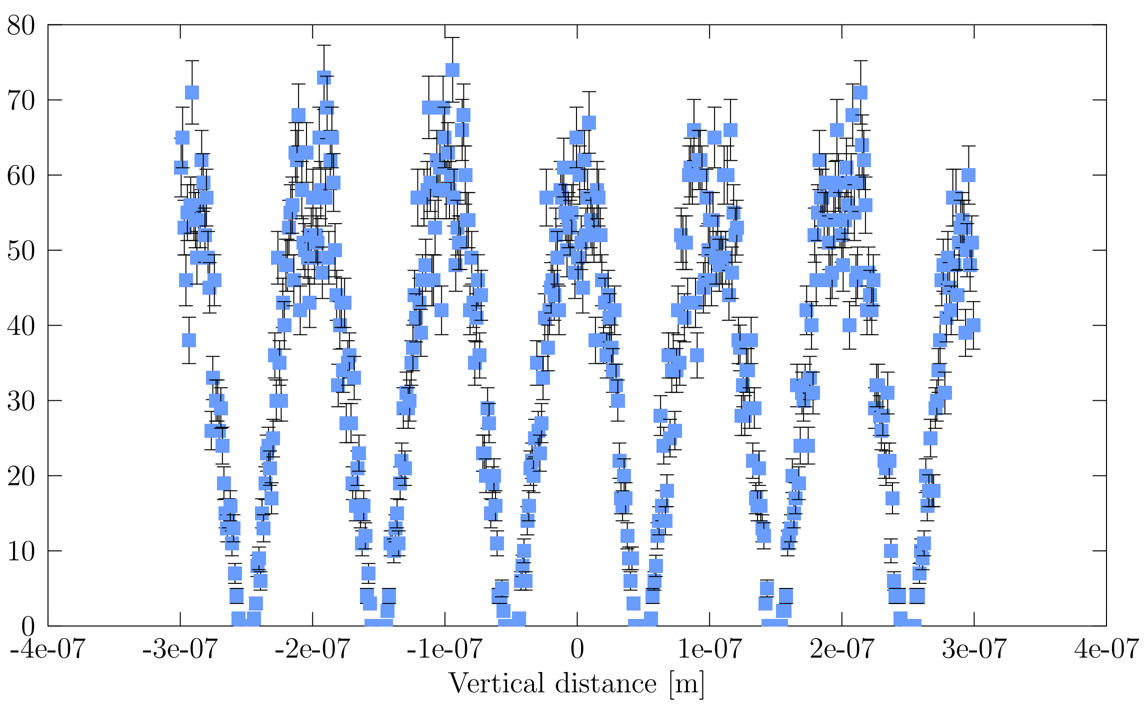


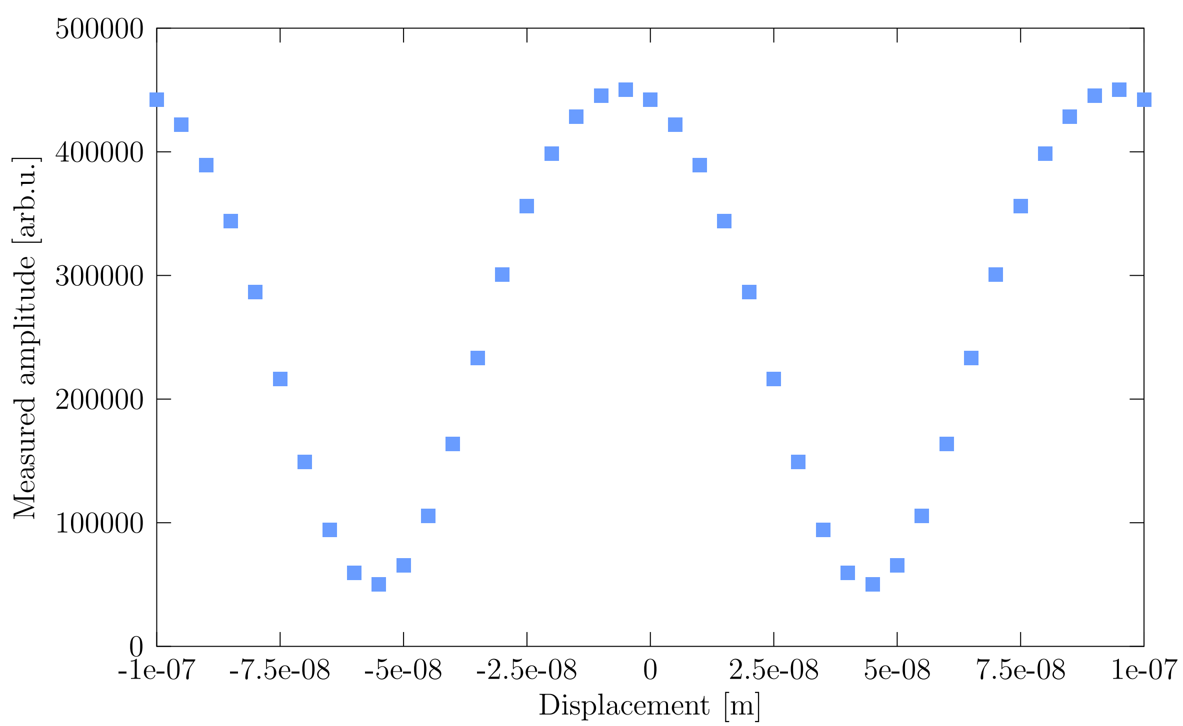


Extra- what if Mu would be classical? - Moire pattern

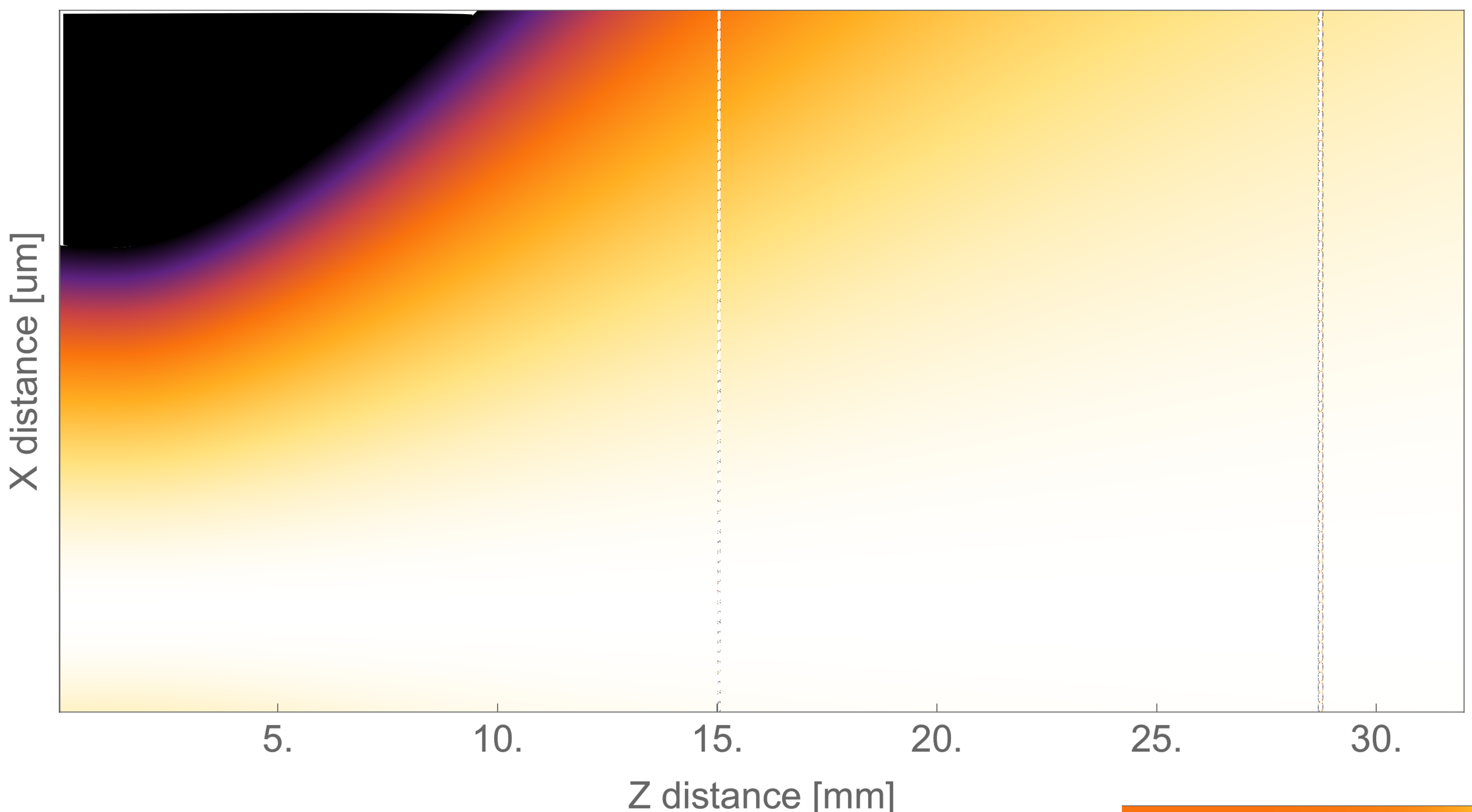


C= 0.9

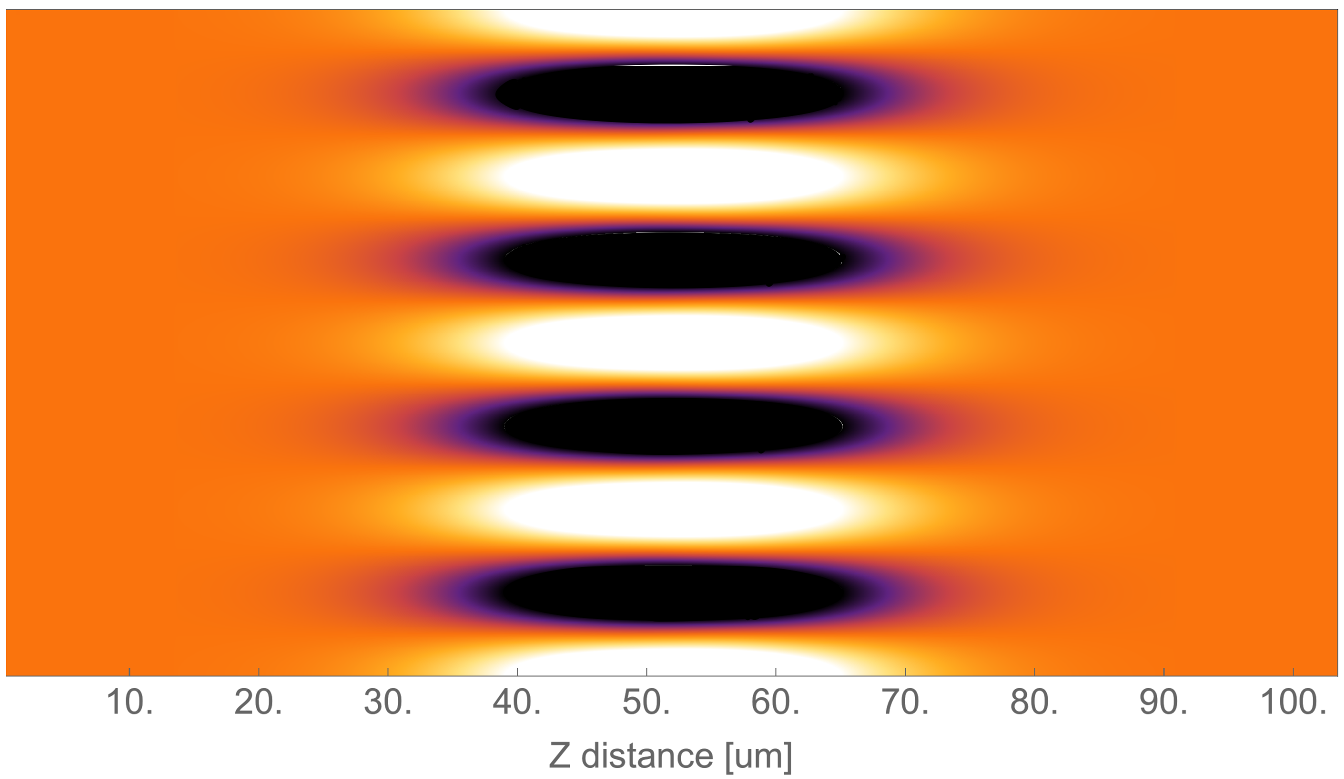




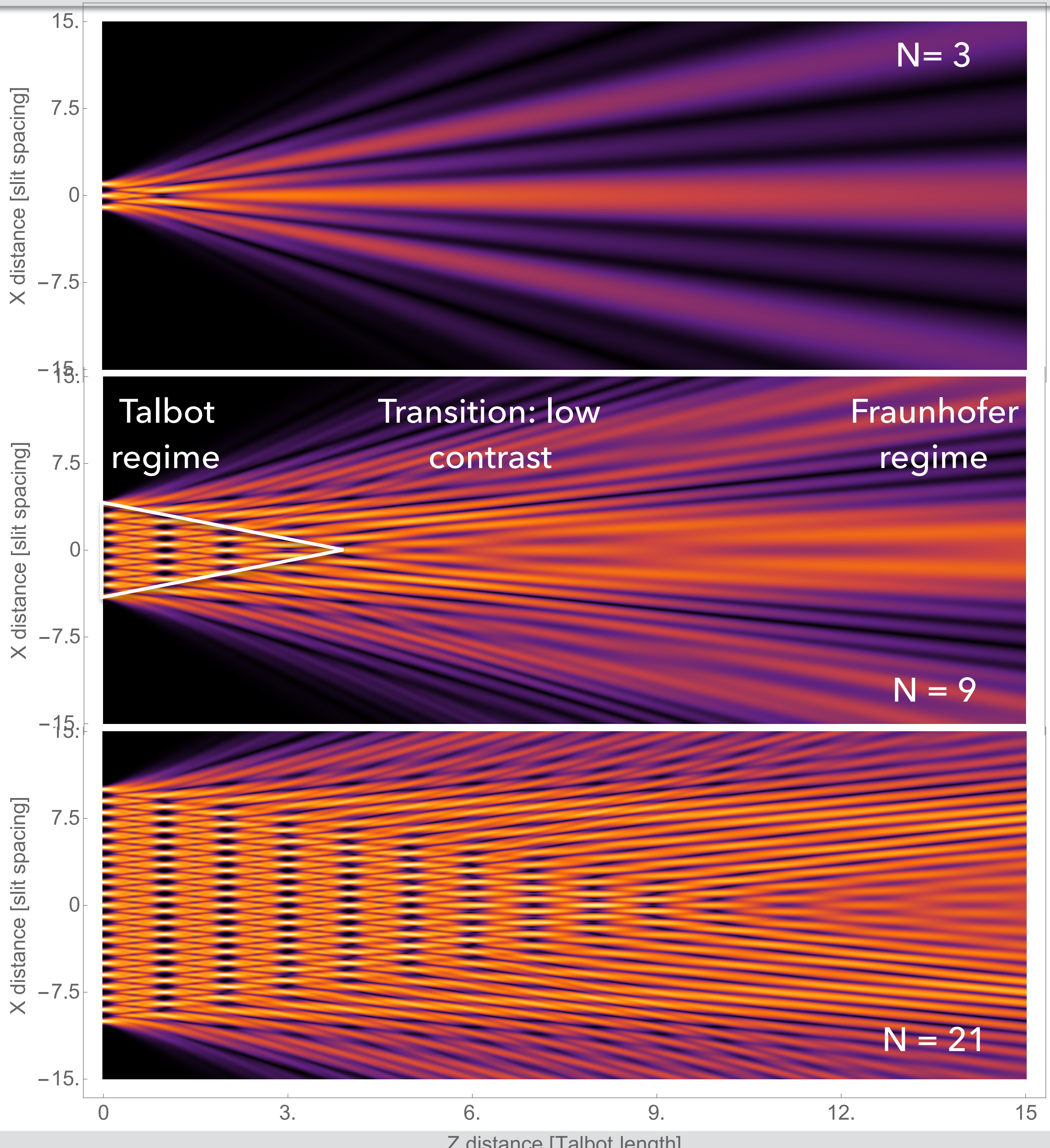
Muonium interferometer, preliminary



C = 0.3, and thin in high contrast region



Extra - Interferometry in near & far field



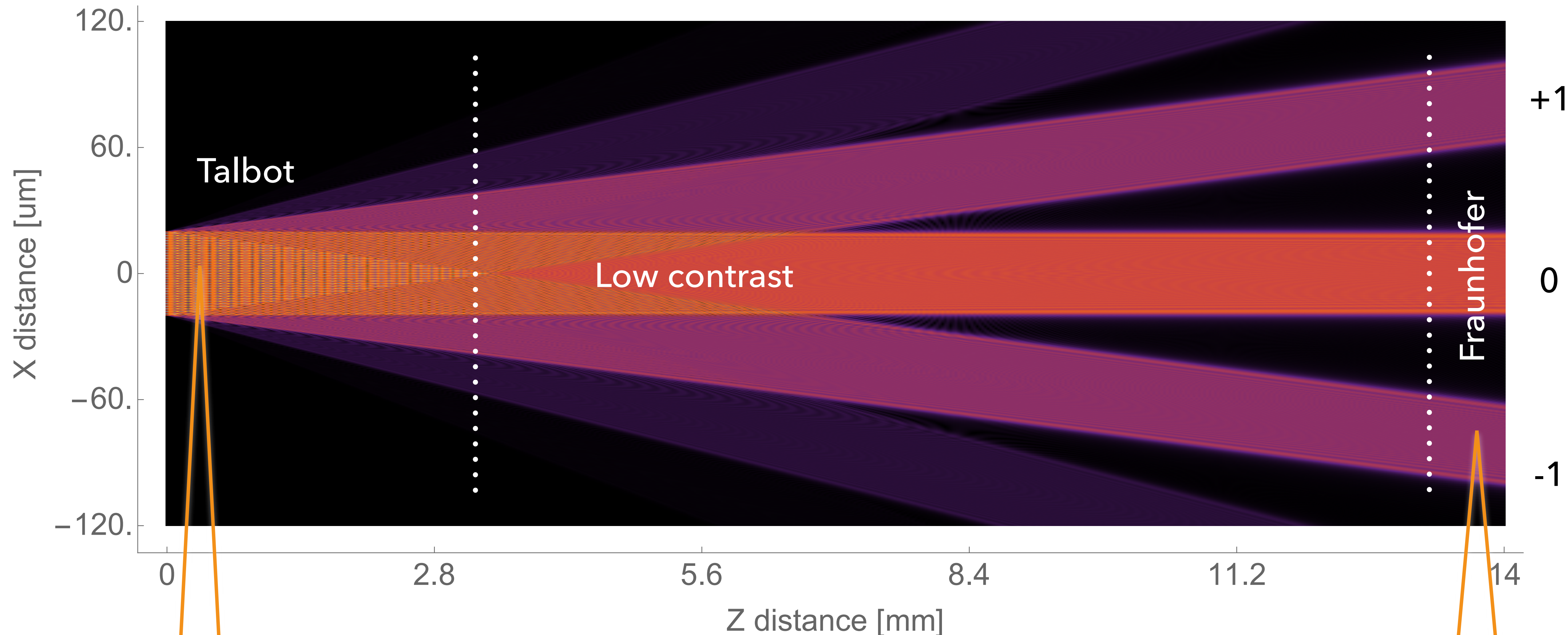
Contrast of the **Talbot-carpet** (near-field) is lost in distances depending on the aperture A (or the # of slits, N = A/d)

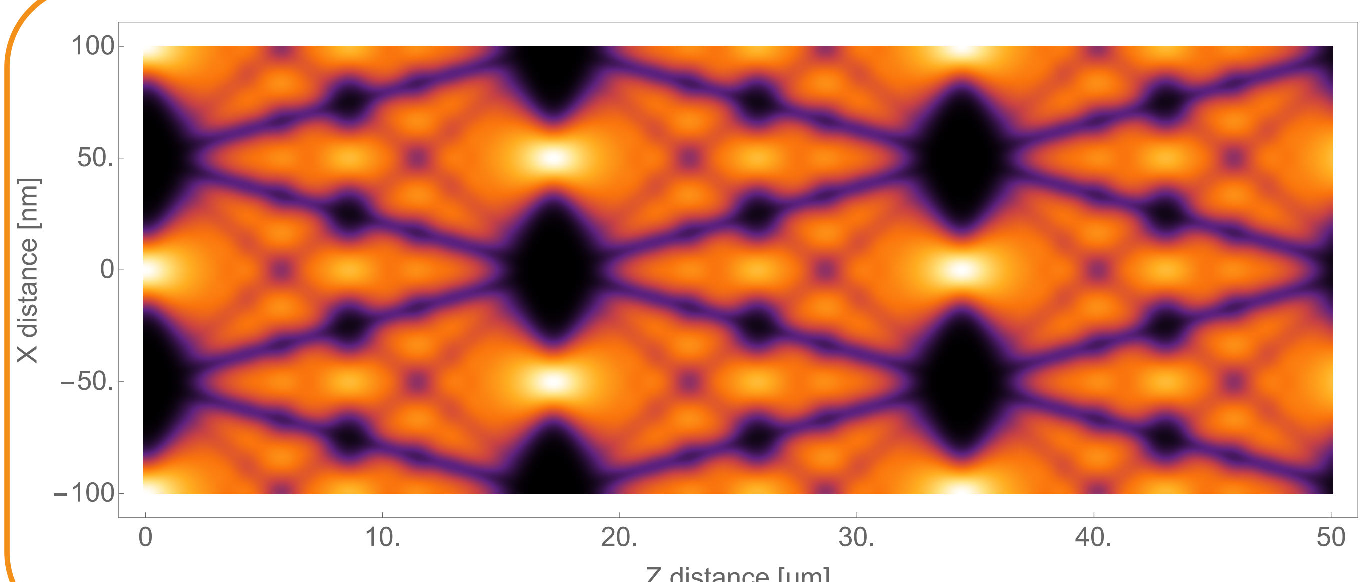
Talbot region is followed by a low-contrast transition region, ending up in the **Fraunhofer fringes** (far field)

The region of "near" and "far" field is influenced by the aperture size.

Extra - near and far field with Mu

Here A = 40 um (d=100 nm, N=400, L_T = 17 um)





Near field (Talbot)

$$L < \frac{1}{2}(N-1)L_T$$

$$L_T = \frac{d^2}{\lambda}$$

(practically can be much smaller!)

Fringes separable when

$$L > \frac{2Ad}{\lambda}$$

(practically can be much larger!)