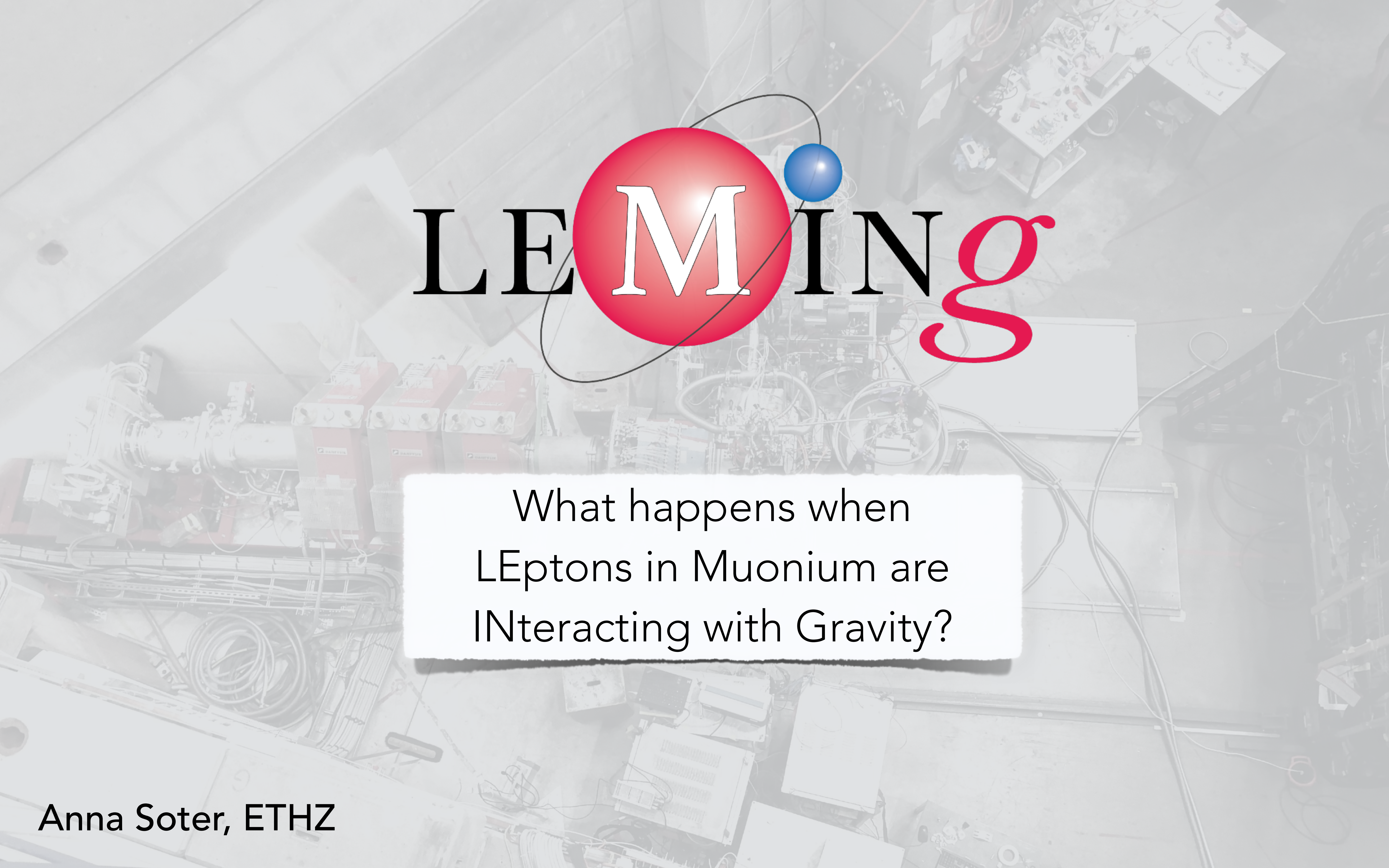
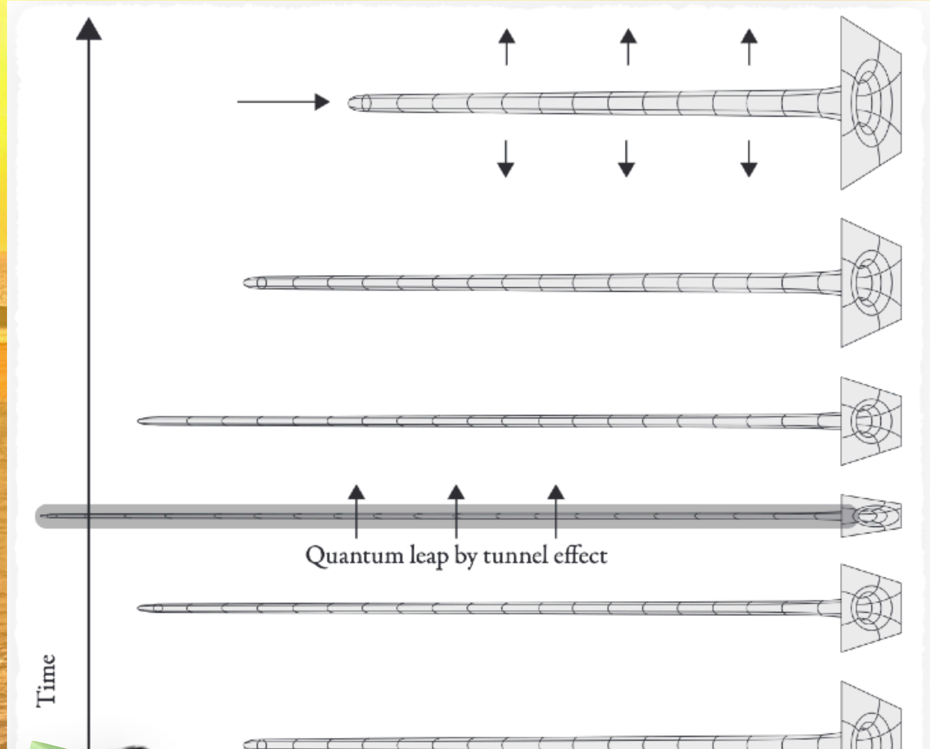


LEMINg

What happens when LEptons in Muonium are INteracting with Gravity?

Anna Soter, ETHZ

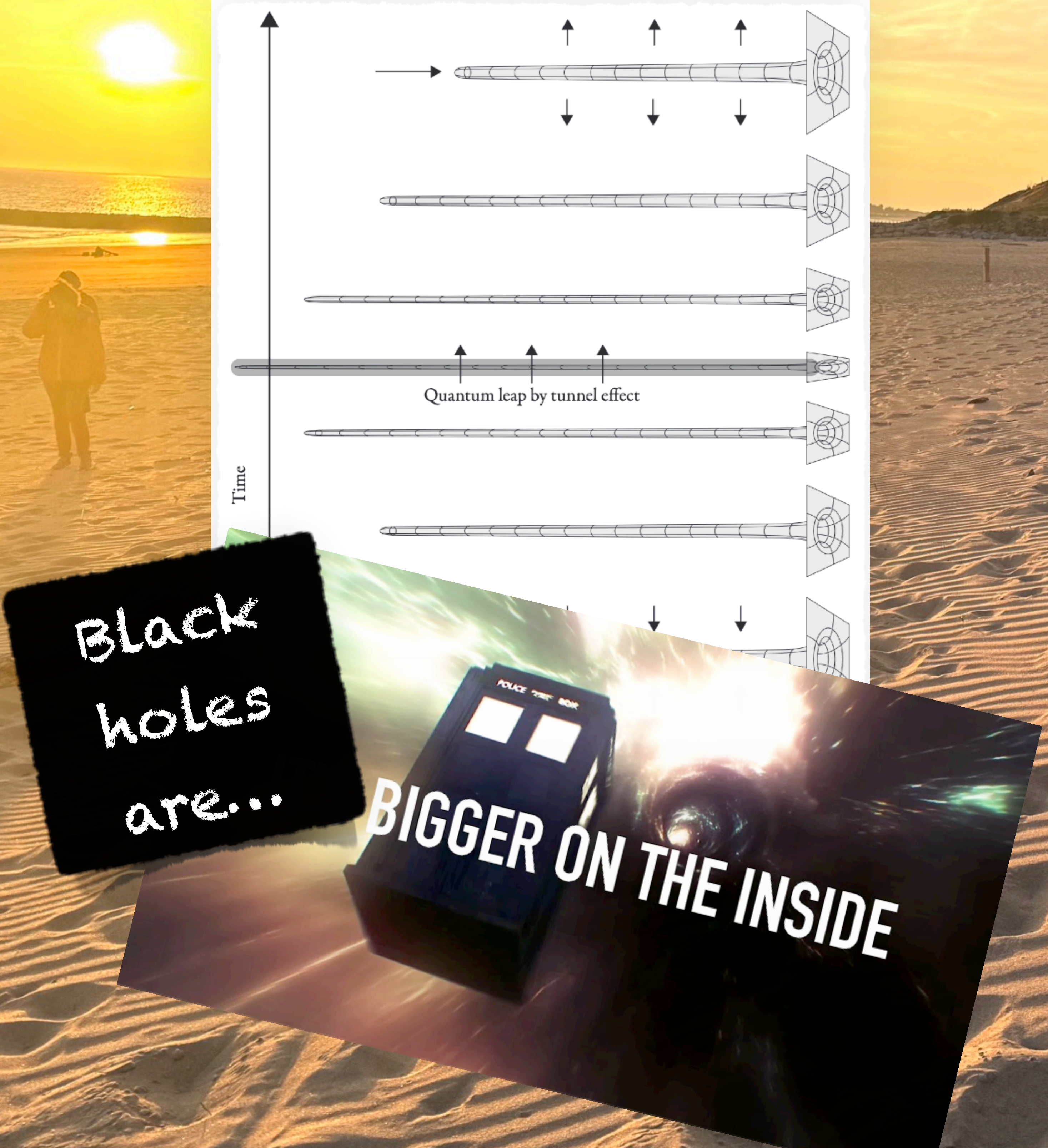
Exciting week with a lot to learn!



Black holes are...

BIGGER ON THE INSIDE

Exciting week with a lot to learn!



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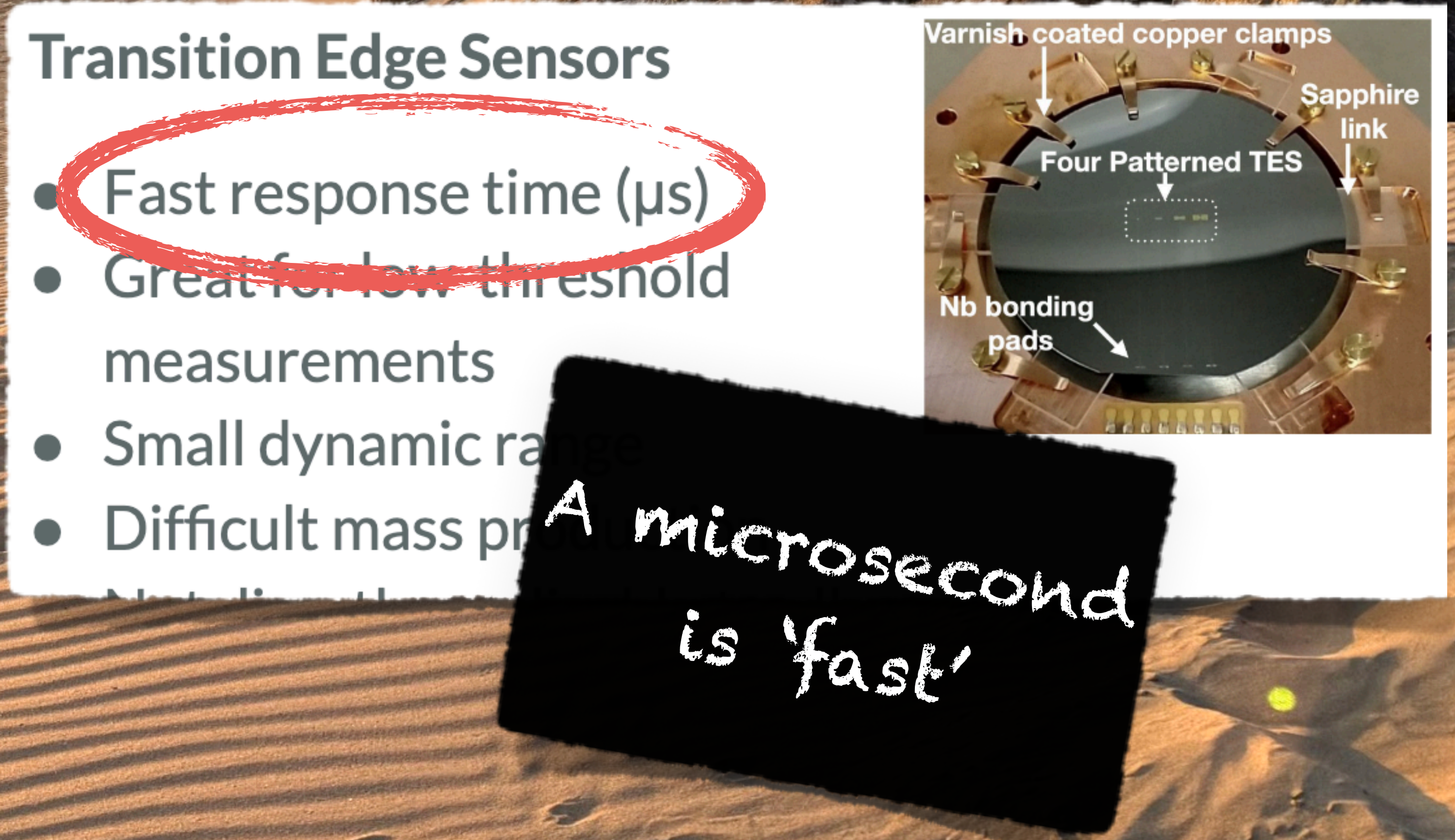


Transition Edge Sensors

- Fast response time (μs)
- ~~Great for low threshold~~ measurements
- Small dynamic ra
- Difficult mass pr

A microsecond is 'fast'

Precision at low energies

Fermions

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

Bosons

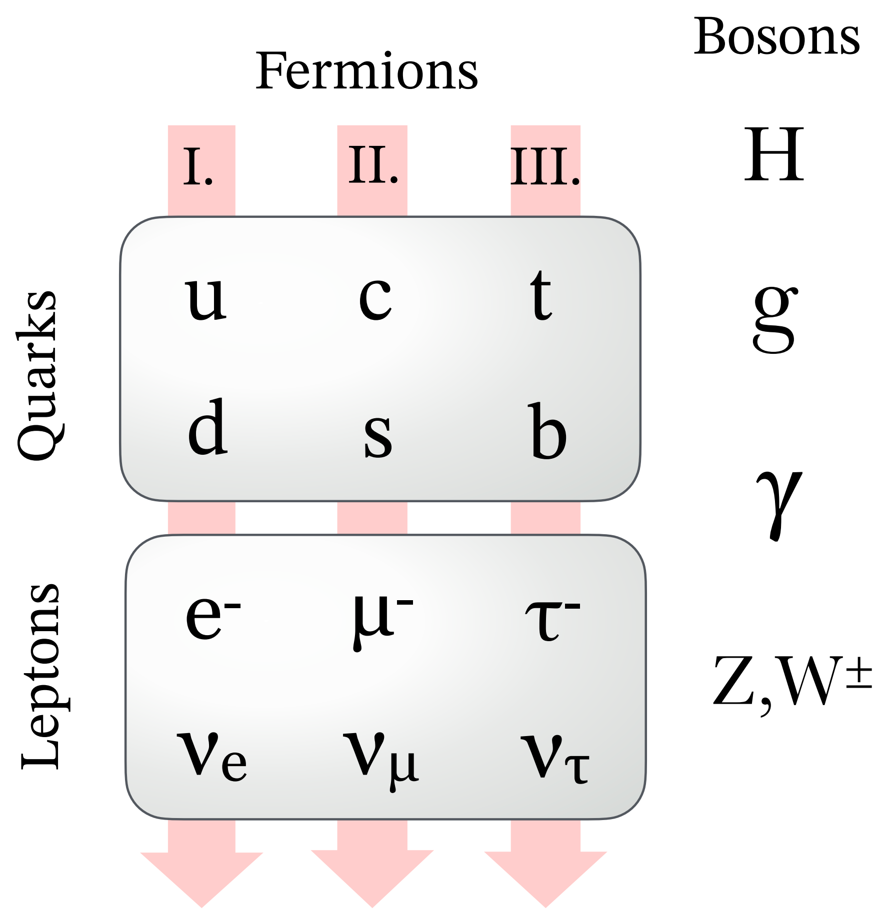
H

g

γ

$Z, W^\pm$

Precision at low energies



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g

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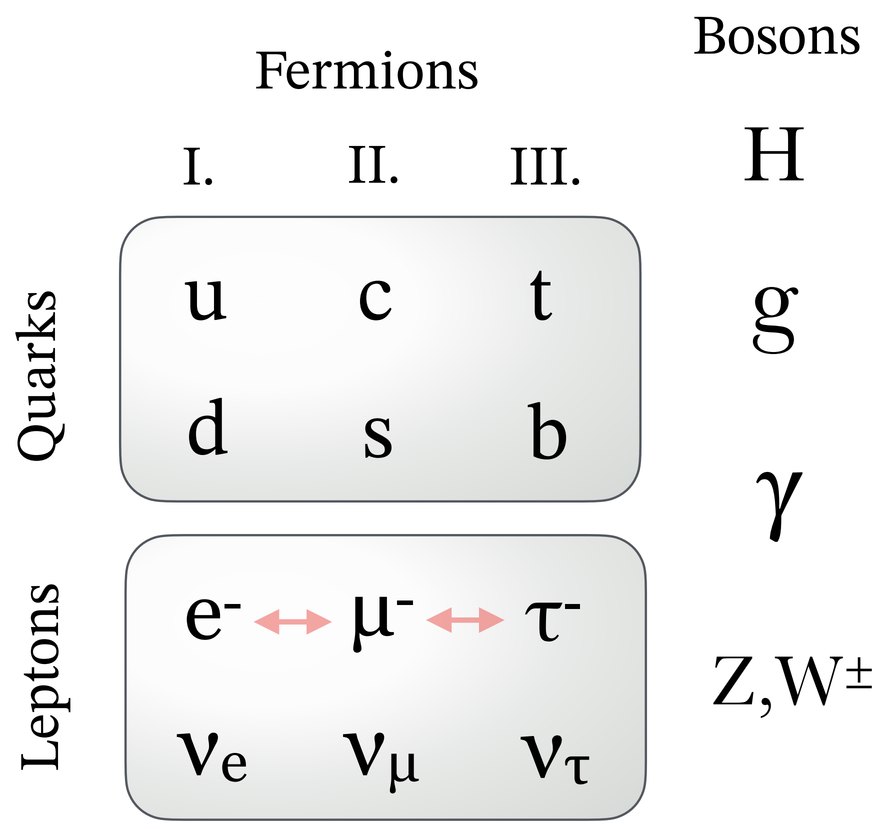
$Z, W^\pm$

- Why 3 generations?

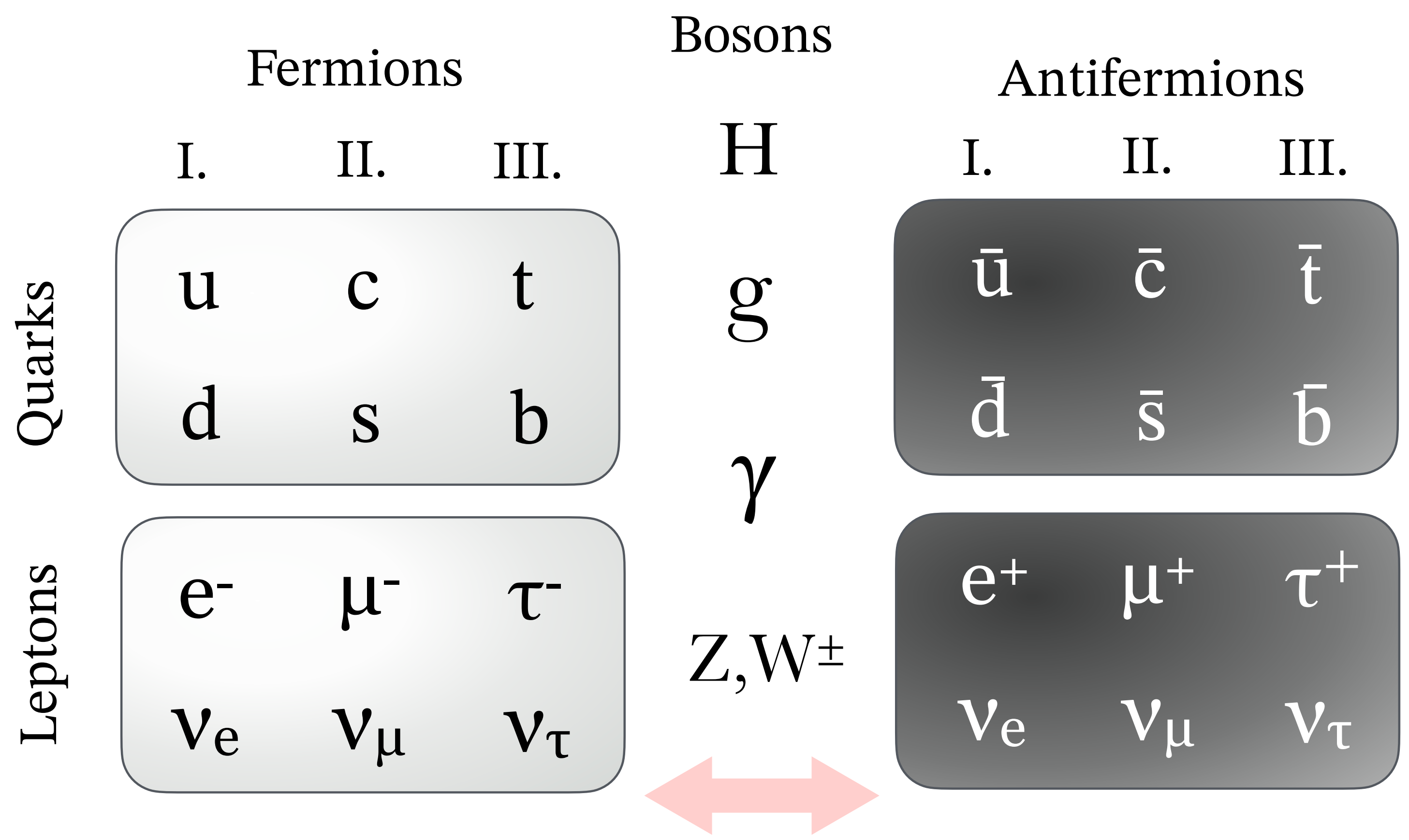
Precision at low energies



	Fermions			Bosons
	I.	II.	III.	H
Quarks	u	c	t	g
	d	s	b	γ
Leptons	e^- ↔	μ^- ↔	τ^-	$Z, W^\pm$
	ν_e	ν_μ	ν_τ	

- Why 3 generations?
- Tensions with lepton flavour universality

Precision at low energies



Fermions

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

Bosons

H

g

γ

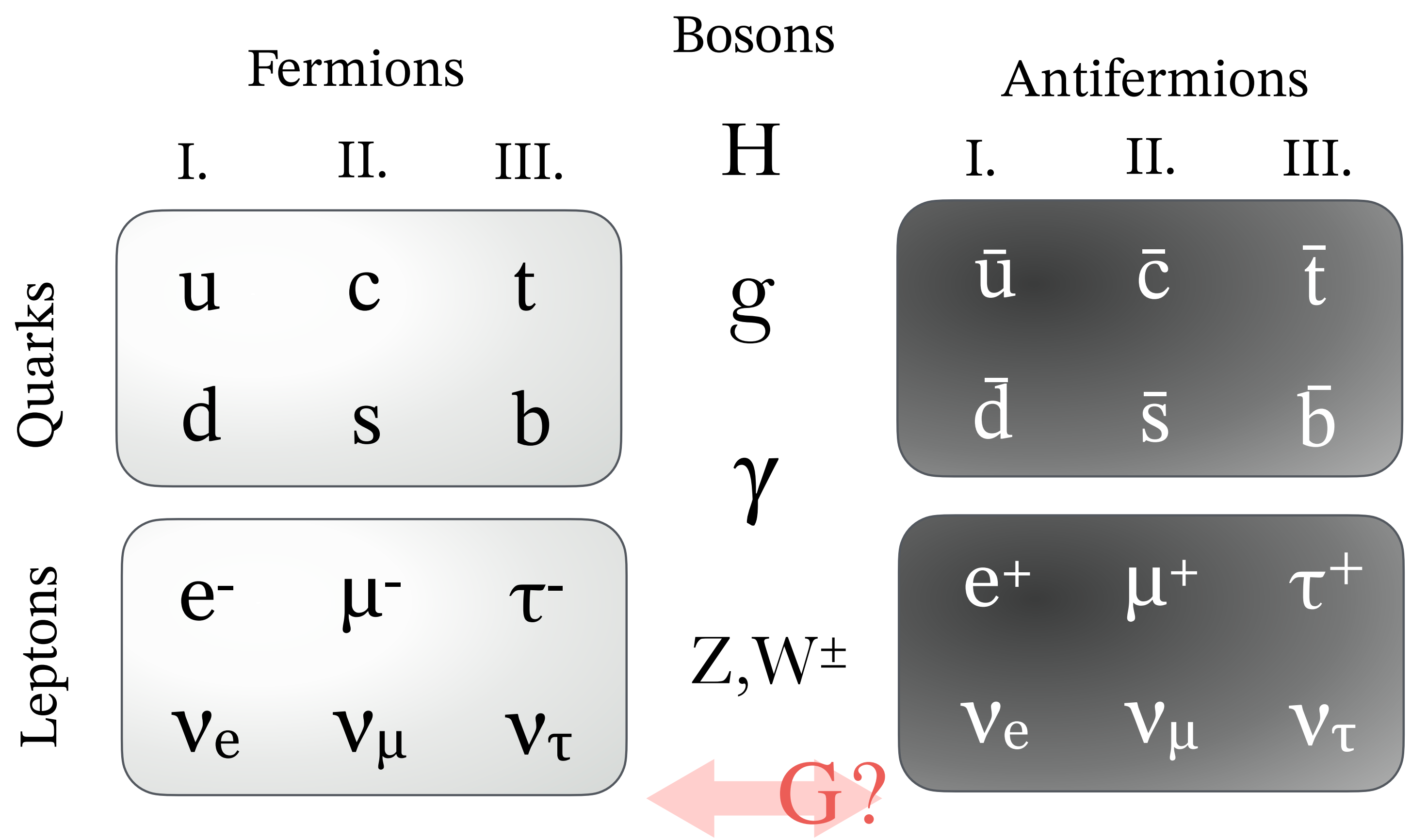
Z,W±

Antifermions

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

- Why 3 generations?
- Tensions with lepton flavour universality
- Origin of baryon asymmetry

Precision at low energies



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,$W^\pm$

G?

Antifermions

I.	II.	III.
$\bar{u}$	$\bar{c}$	$\bar{t}$
$\bar{d}$	$\bar{s}$	$\bar{b}$
e^+	μ^+	τ^+
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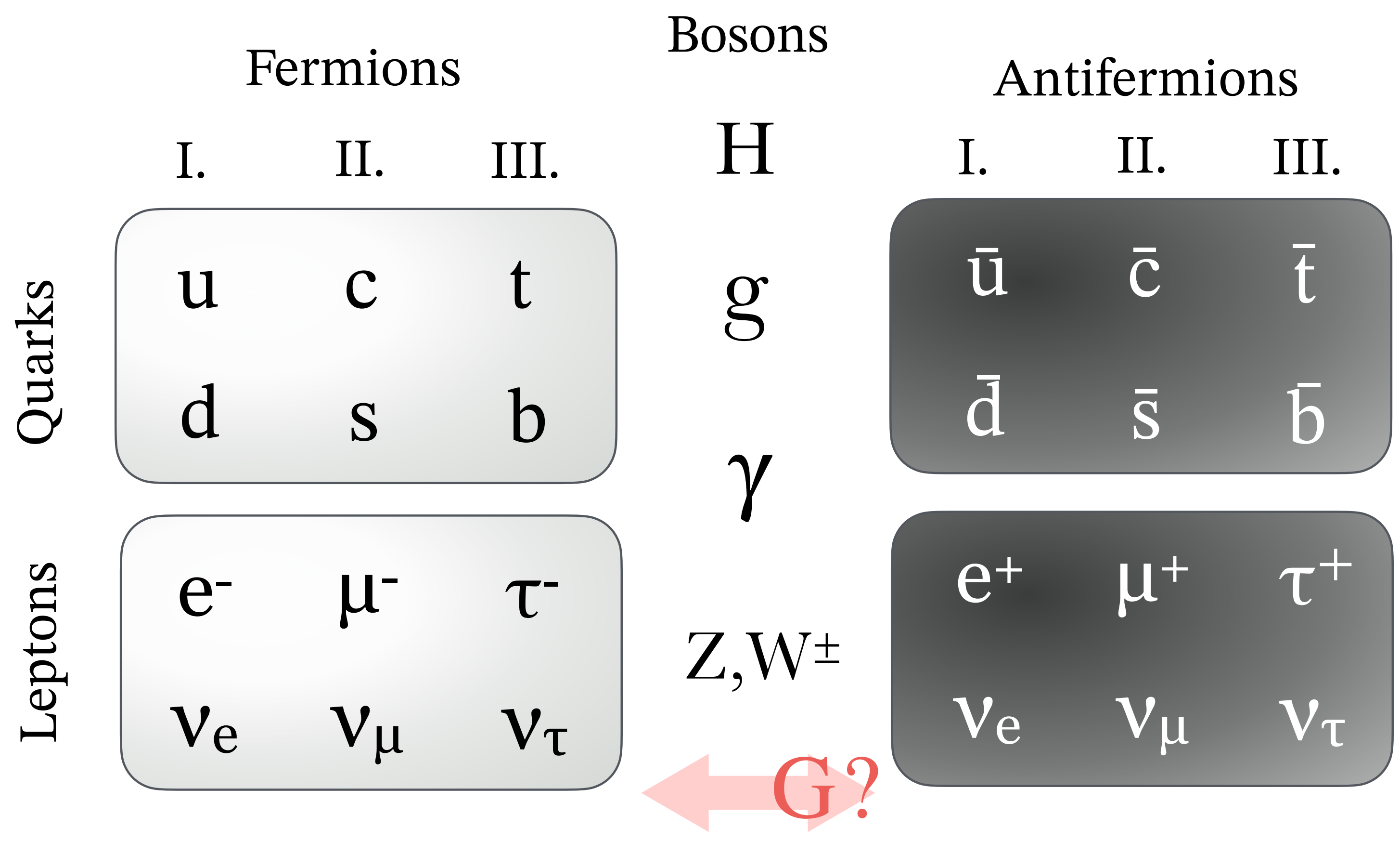
- Connection of **gravity** and **dark sector** to the SM

Precision at low energies



	Fermions			Bosons	Antifermions		
	I.	II.	III.	H	I.	II.	III.
Quarks	u	c	t	g	$\bar{u}$	$\bar{c}$	$\bar{t}$
	d	s	b	γ	$\bar{d}$	$\bar{s}$	$\bar{b}$
Leptons	e^-	μ^-	τ^-	$Z,W^\pm$	e^+	μ^+	τ^+
	ν_e	ν_μ	ν_τ	G?	ν_e	ν_μ	ν_τ

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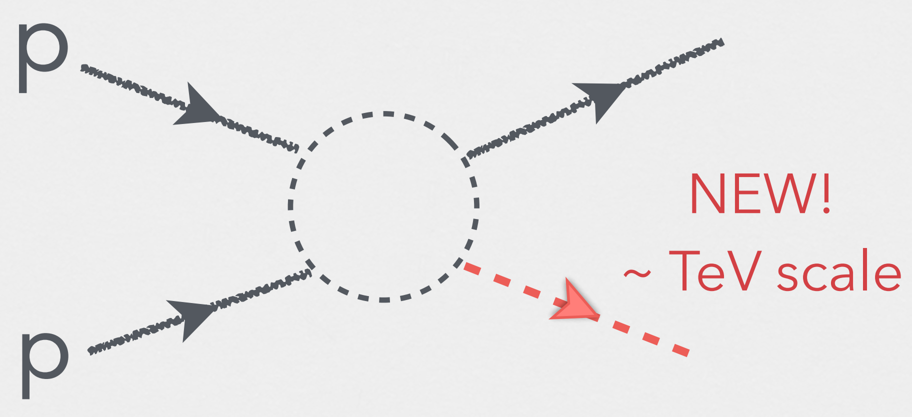
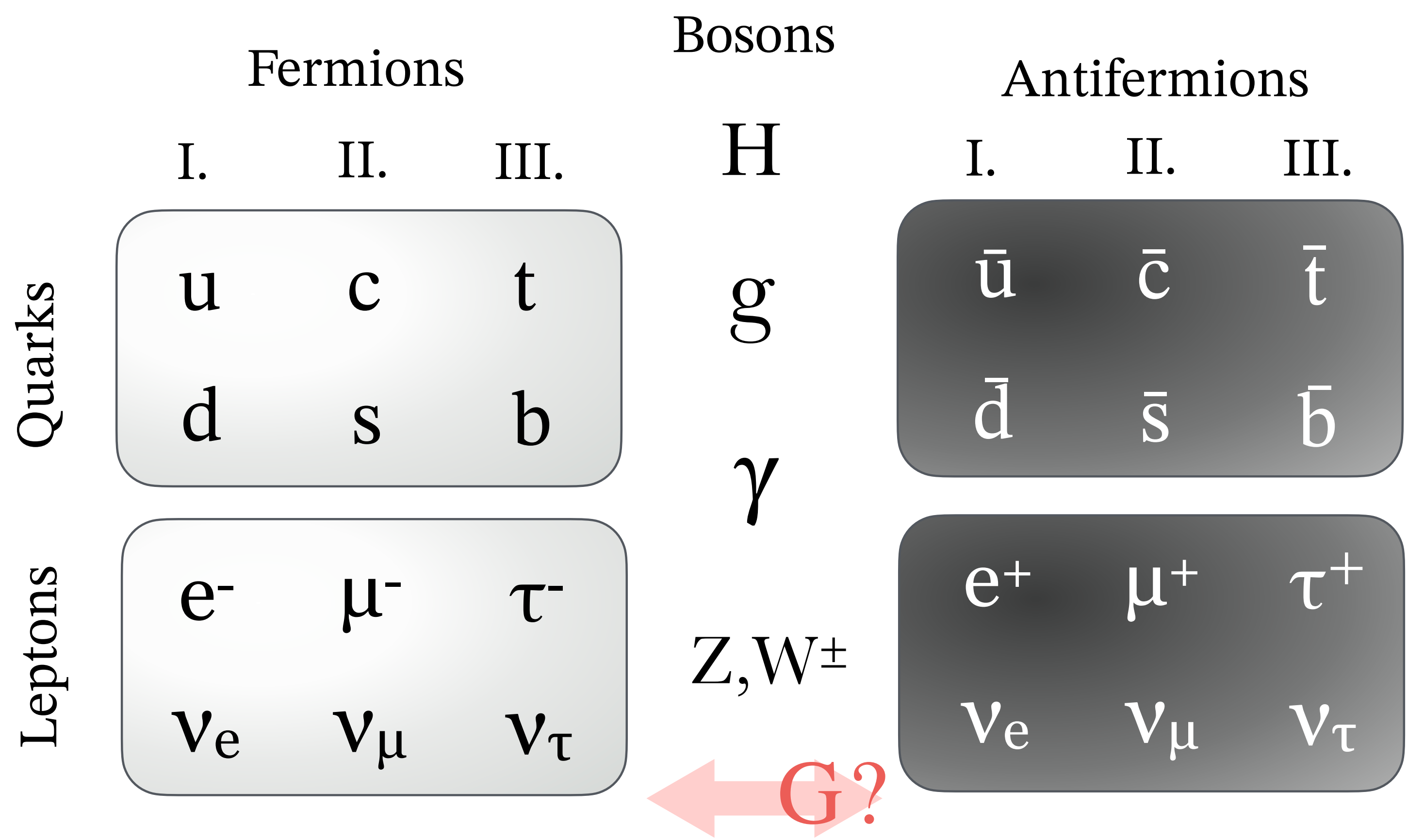
High energy



Precision at low energies



	Fermions			Bosons	Antifermions		
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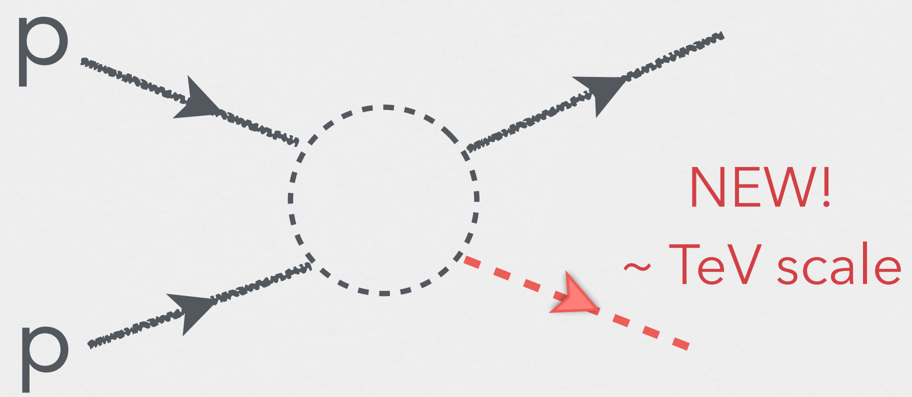
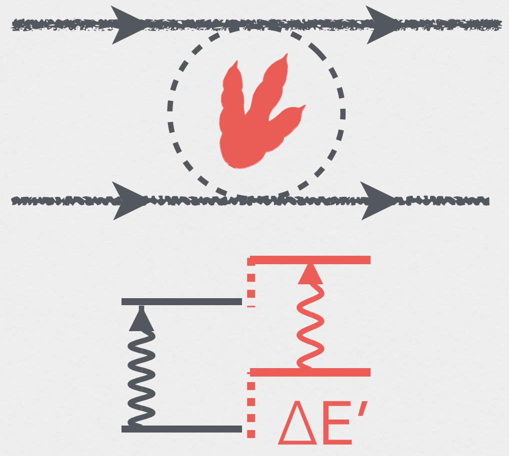
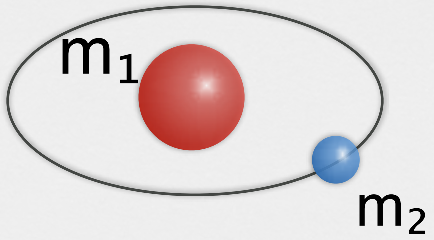


High rate / precision

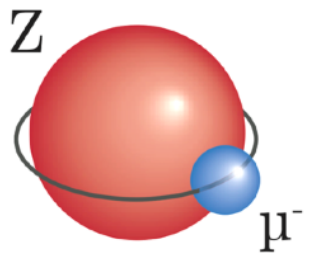


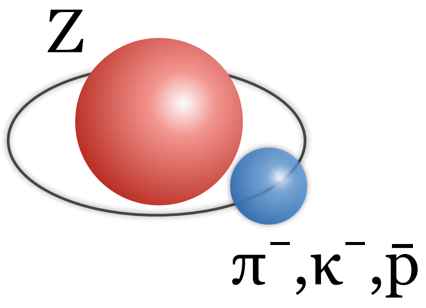
Fundamental physics with exotic atoms

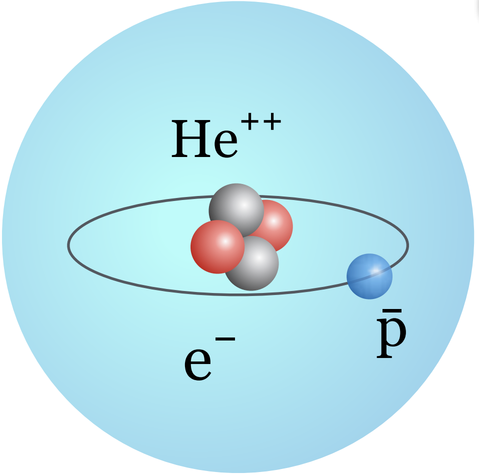


$$E_n \simeq \frac{Z^2 m^*}{m_e}\frac{R_\infty}{n^2} + \text{QED}(\alpha, \ldots) + k m_2^3 R_Z^2 + \varepsilon_{\text{hadronic}} + \varepsilon_{\text{BSM}} \cdots$$

Negative exotic particle

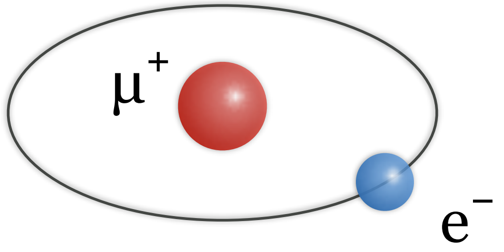




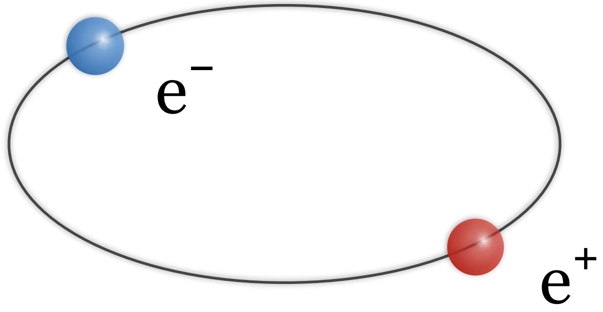


Muonic, pionic, antiprotonic atoms

Positive exotic particle



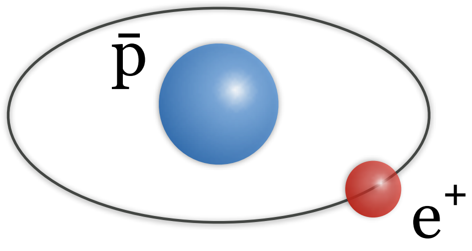
Muonium



Positronium

Fundamental constants, bound-state QED test, fundamental symmetries

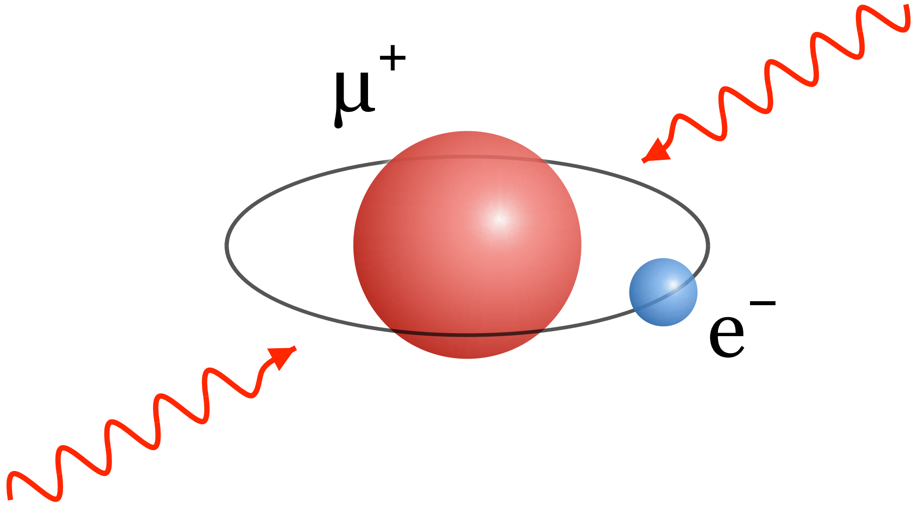
Both exotic

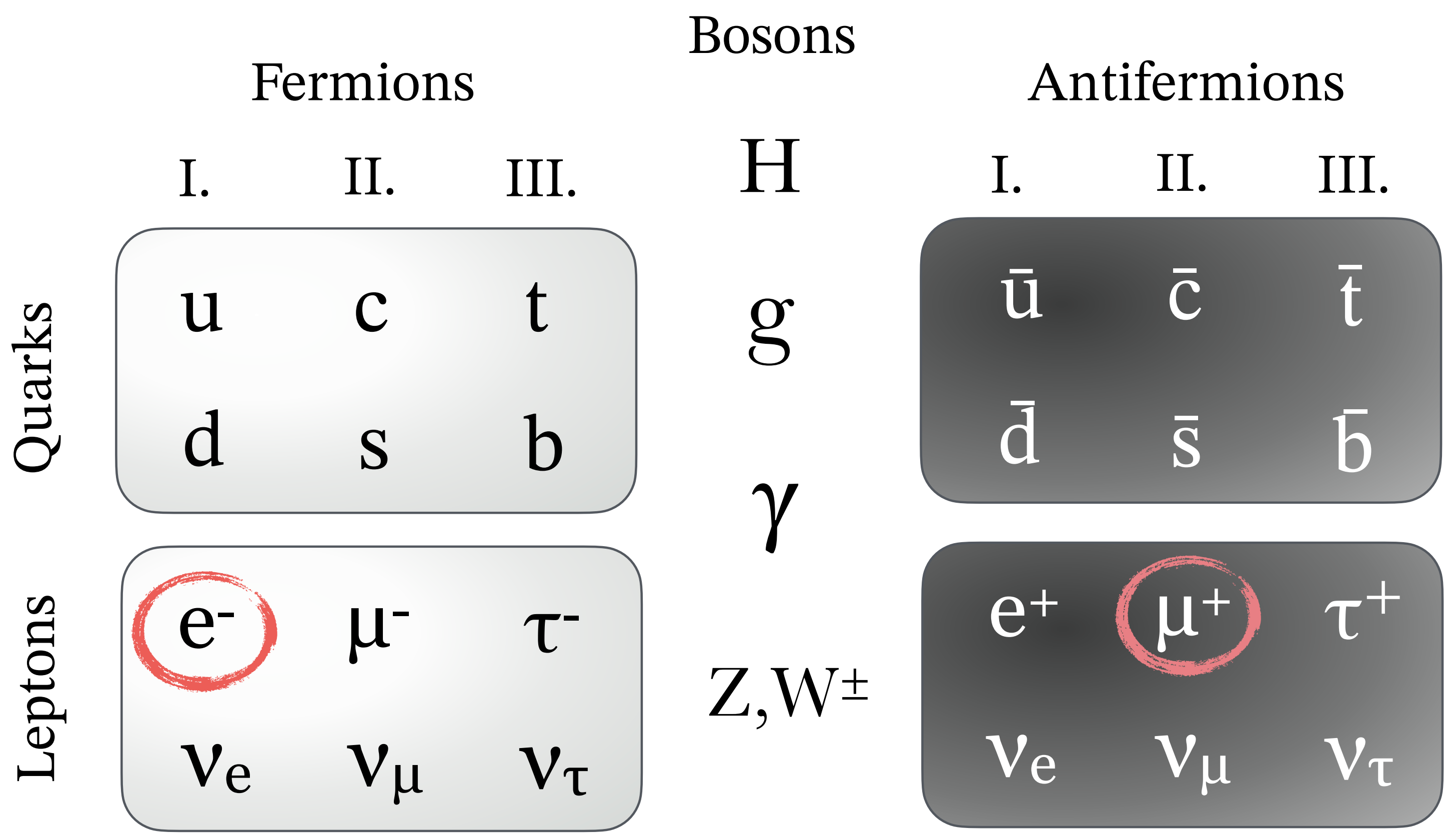


Antihydrogen

Neutral bound states!

Muonium - probing the SM and beyond





	Fermions			Bosons	Antifermions		
	I.	II.	III.	H	I.	II.	III.
Quarks	u	c	t	g	ū	c̄	t̄
	d	s	b	γ	d̄	s̄	b̄
Leptons	e^-	μ^-	τ^-	Z,W±	e^+	μ^+	τ^+
	ν_e	ν_μ	ν_τ		ν_e	ν_μ	ν_τ

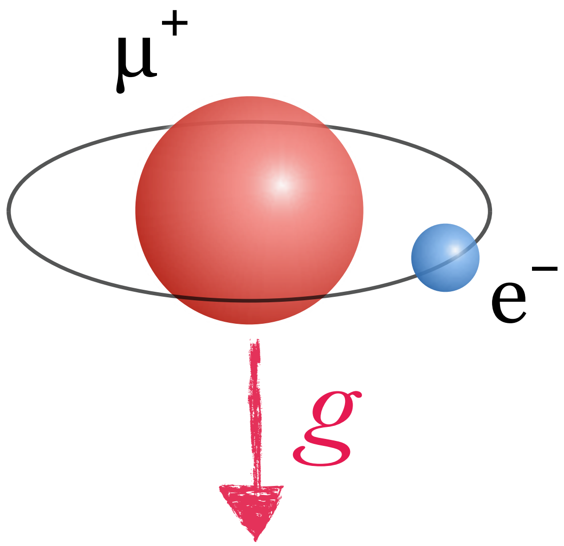
Laser Spectroscopy

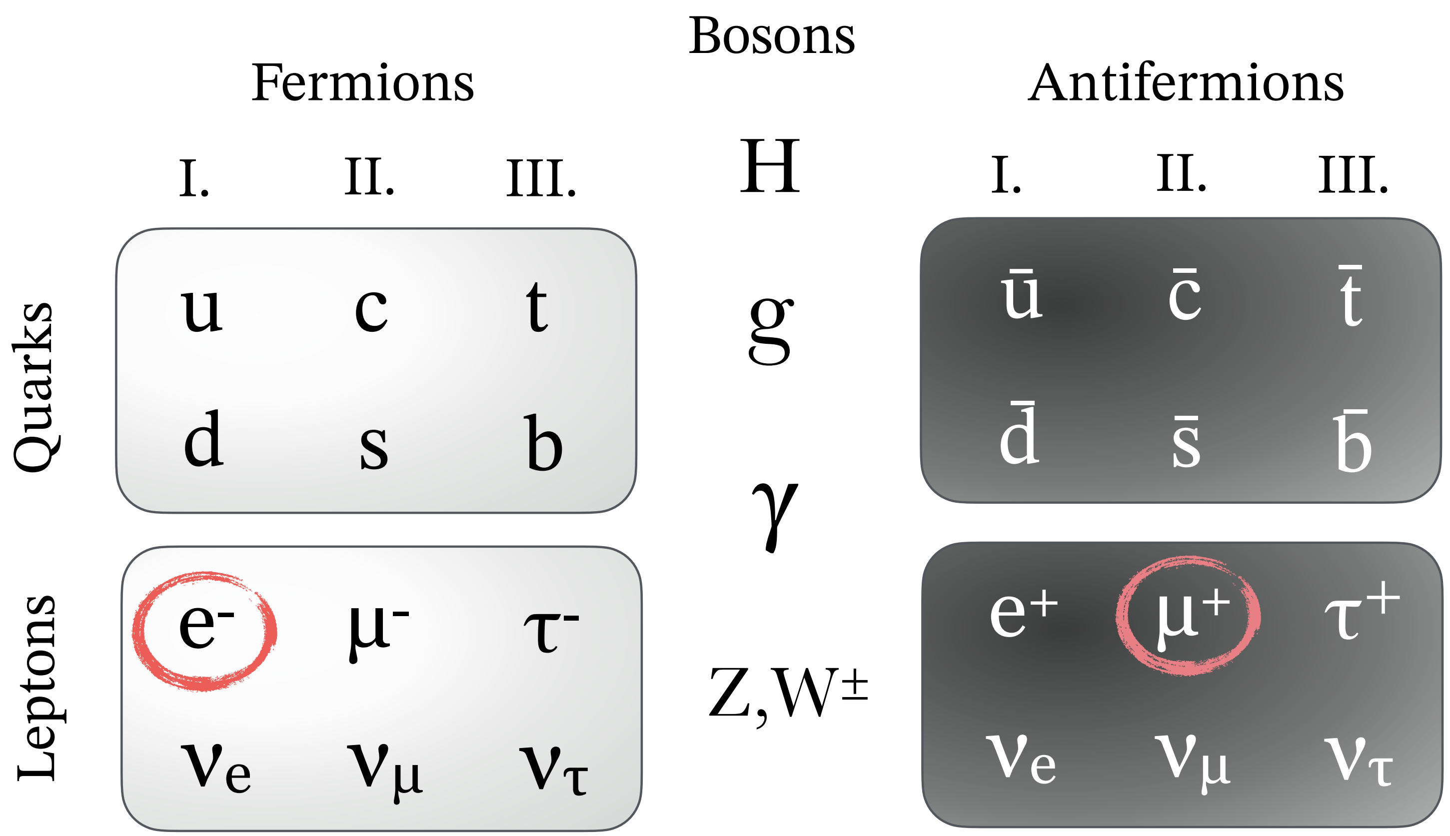
Purely **leptonic** exotic atom, dominated by QED effects:

- Fundamental constants (m_μ , μ_μ , R_∞)
- Test of bound-state QED & symmetries (q_μ / q_e)
- Effects on other precision experiments, e.g. muon *g-2*

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

Muonium - probing the SM and beyond





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				H			
Quarks	u	c	t	g	$\bar{u}$	$\bar{c}$	$\bar{t}$
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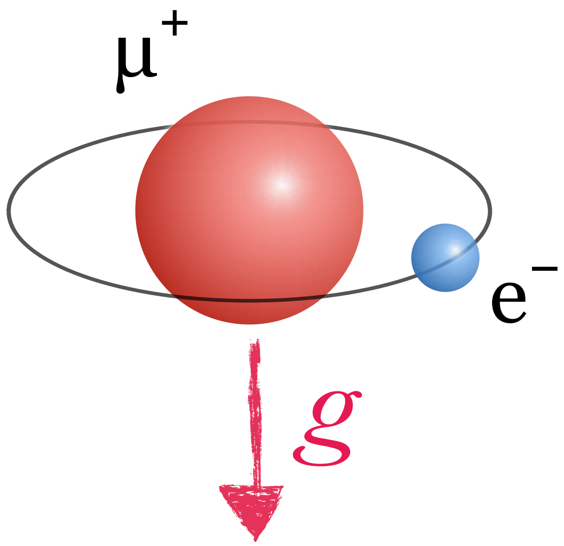
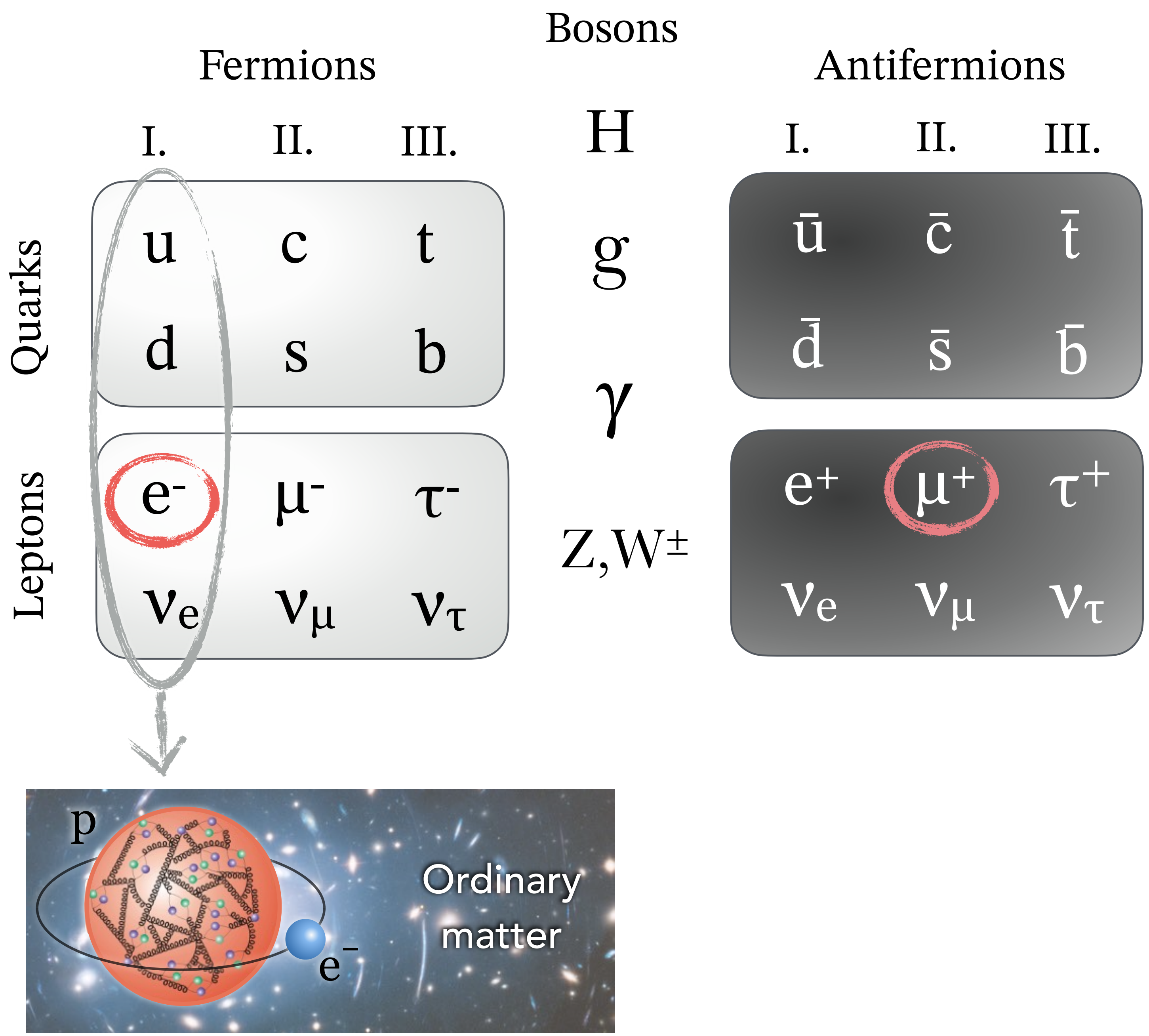
Free fall of Mu

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

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

Muonium - probing the SM and beyond





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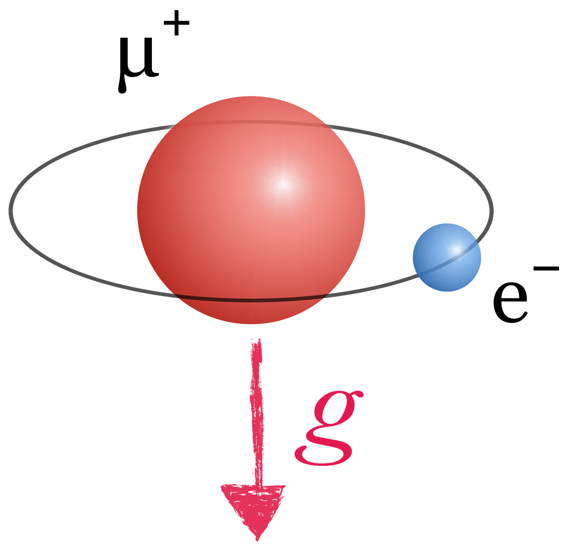

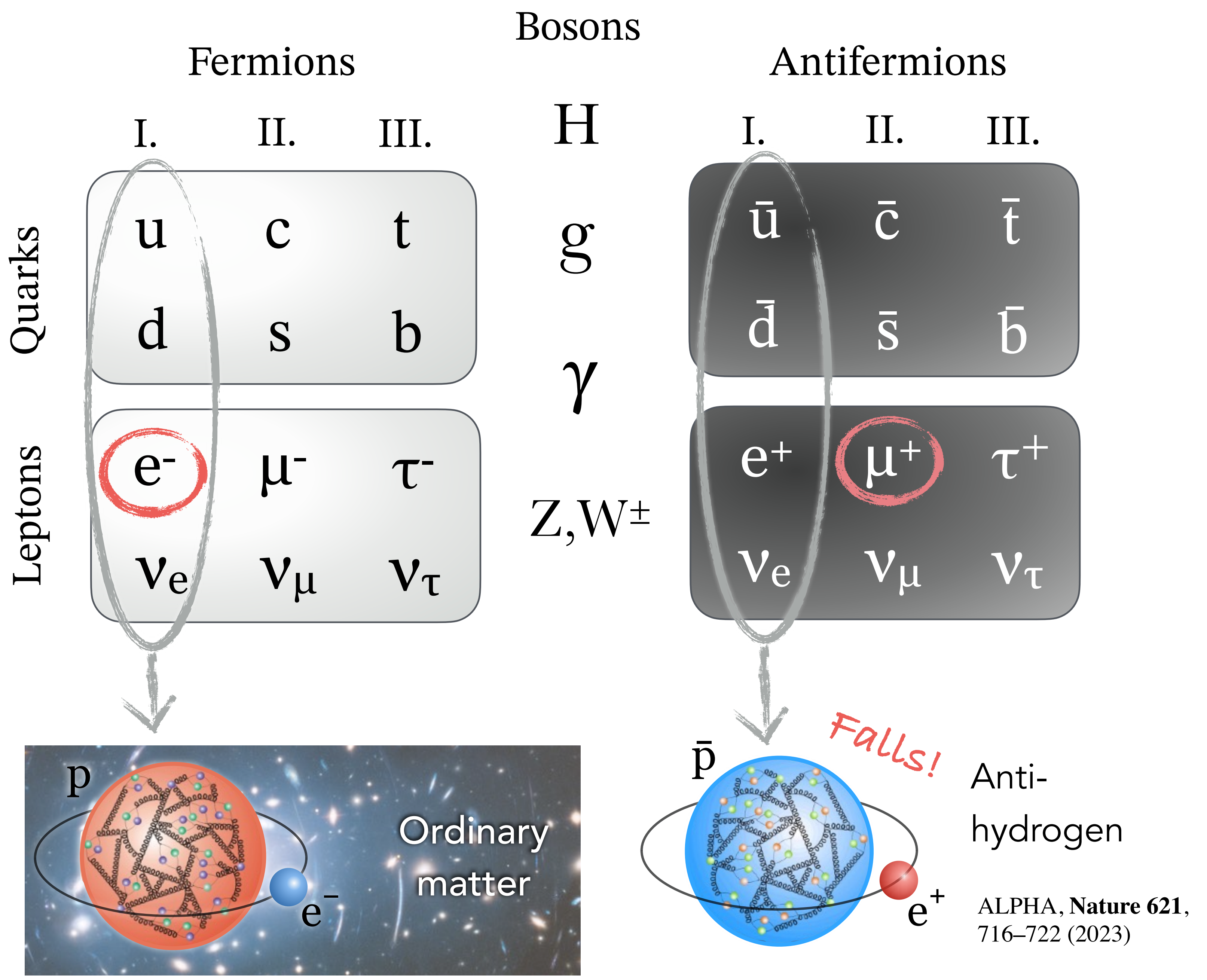

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Quarks	d	s	b	g	$\bar{d}$	$\bar{s}$	$\bar{b}$
Leptons	e^-	μ^-	τ^-	γ	e^+	μ^+	τ^+
Leptons	ν_e	ν_μ	ν_τ	$Z,W^\pm$	ν_e	ν_μ	ν_τ

Anti-hydrogen

ALPHA, **Nature 621**, 716–722 (2023)

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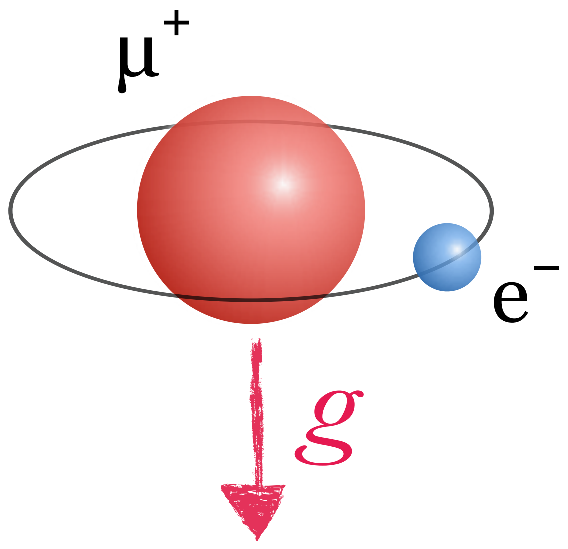

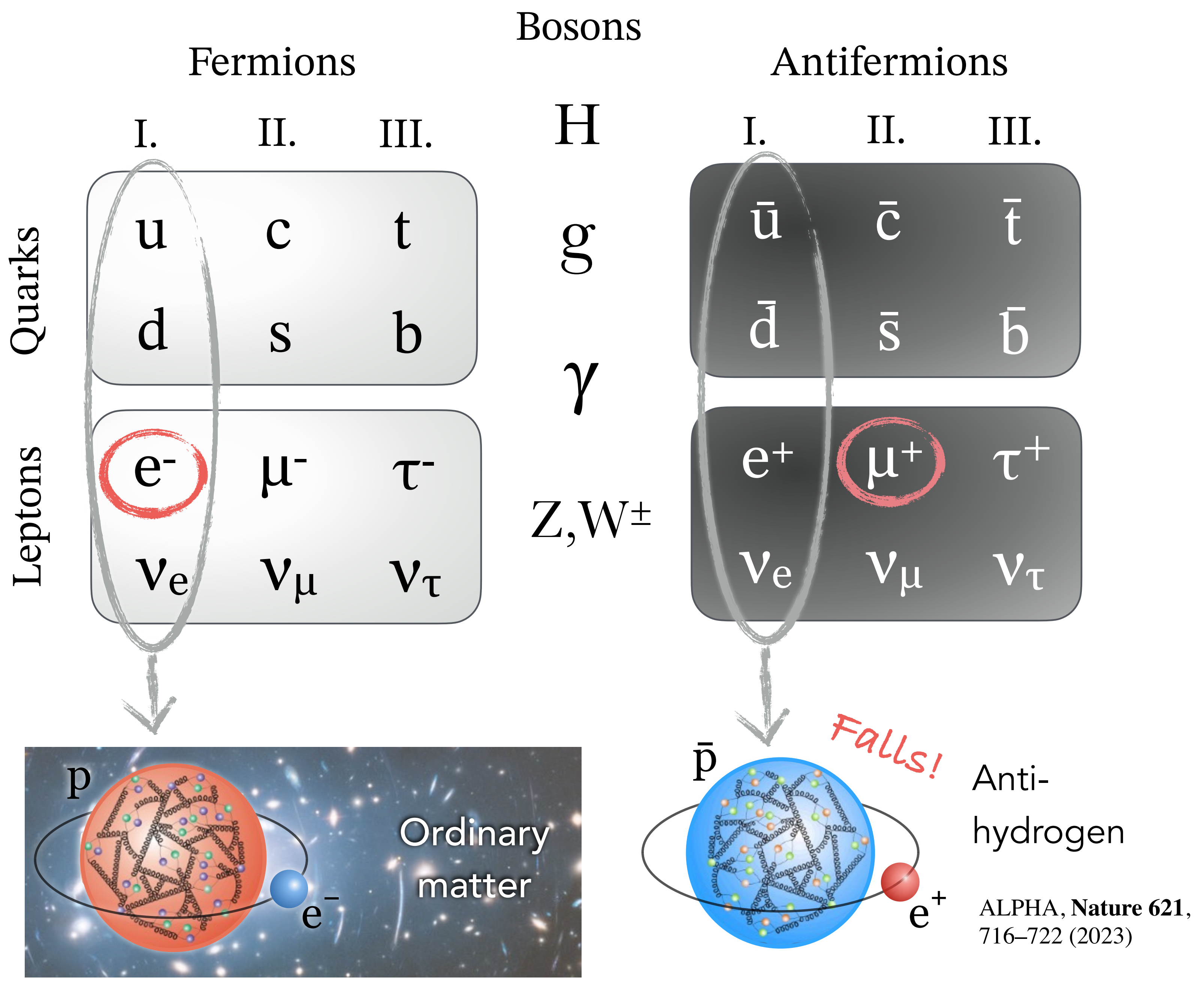

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Hadron mass

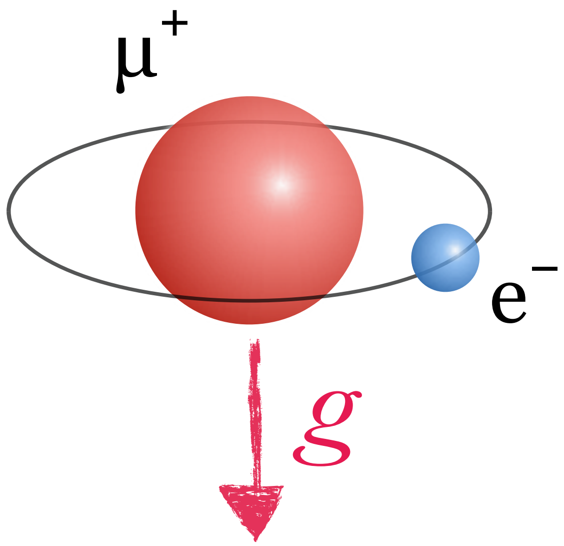
~1% valence quark
99% strong interaction

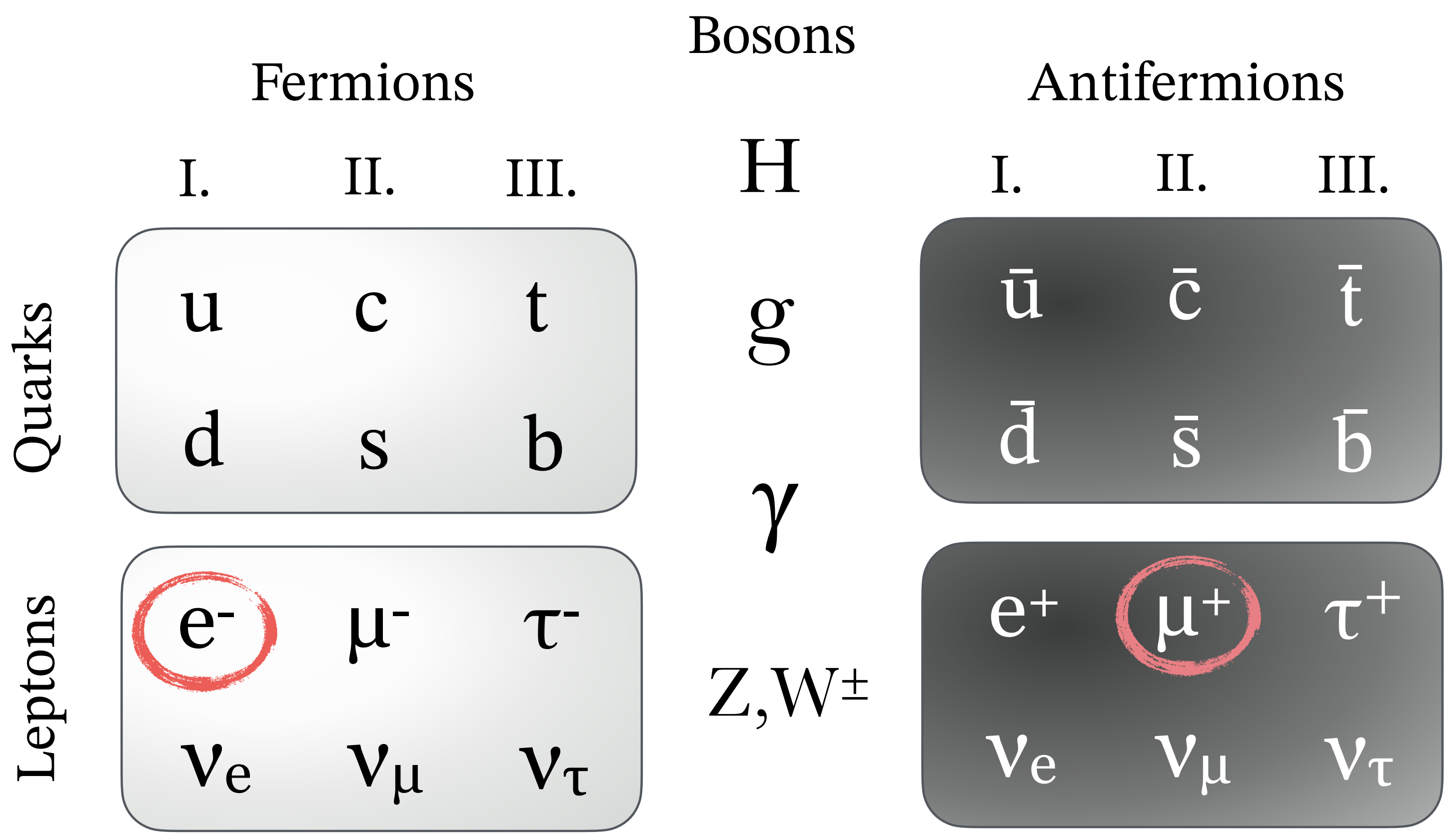
Muonium mass

Binding E

μ^+ mass: 105.6583745(24) MeV/c
e^- mass: 0.5109989461(31) MeV/c²

Muonium - probing the SM and beyond





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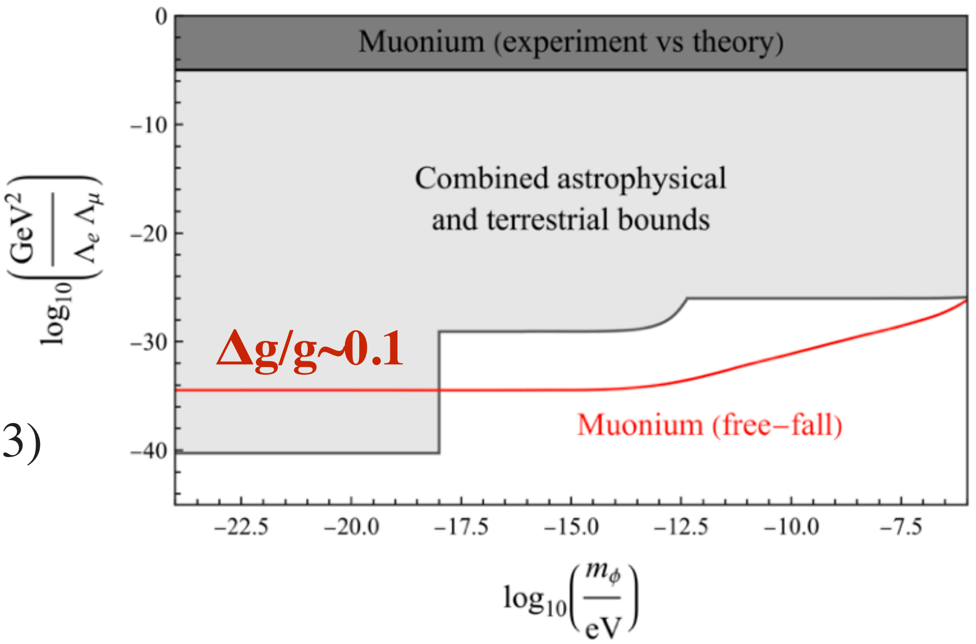
- Possibility to test for flavour-dependent new interactions

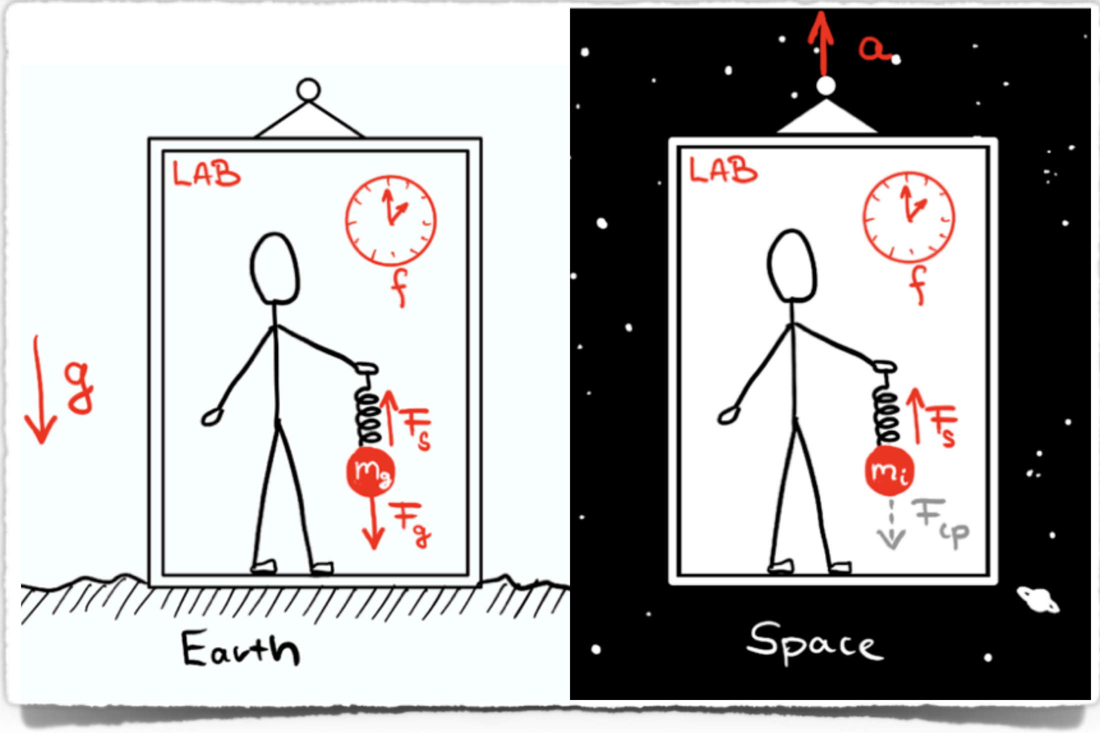


Y. Stadnik PRL 131, 011001 (2023)

WEP and universality of free fall

Foundation of GR. Many formulations since Galilei:

The outcome of any *local* experiment conducted in gravitational field (local g acceleration) must be the same than in an accelerating lab, where a=g.



Various experimental consequences:

- Universality of free fall, $\eta(1,2) = 2\frac{|g_1 - g_2|}{|g_1 + g_2|}$
- Local Lorentz invariance
- Local position invariance:
  - universality of clocks,
  - lack of variation of fundamental constants

Needs to be tested in different experiments sensitive to one of the above

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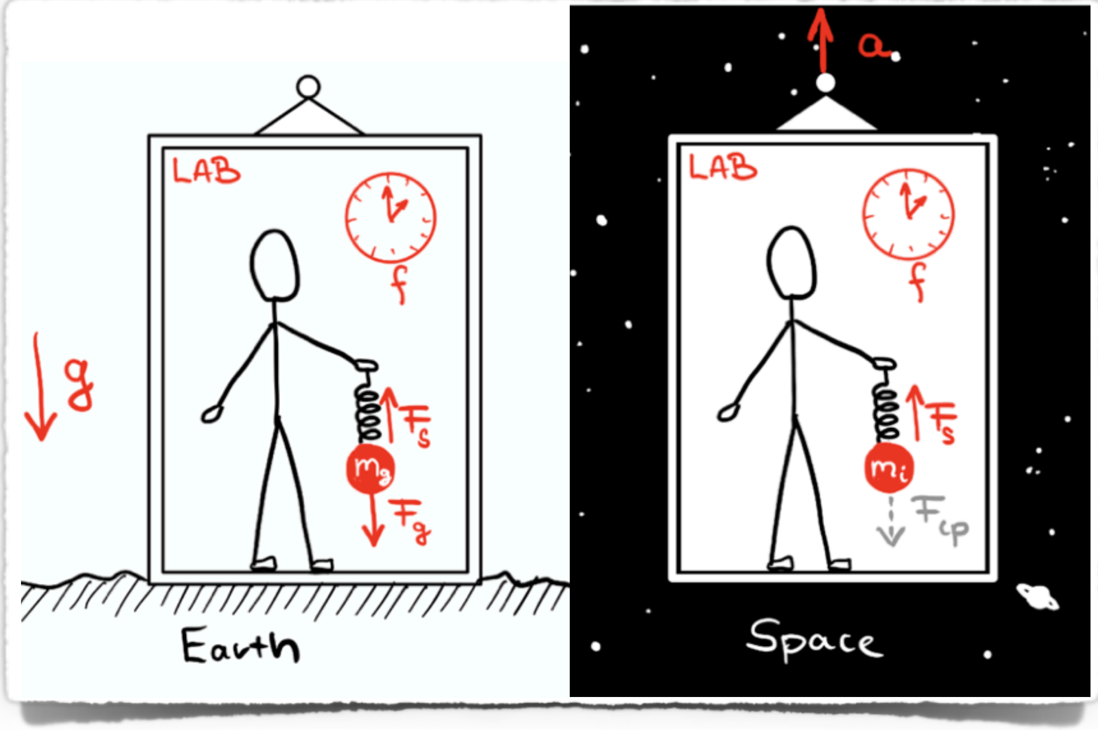

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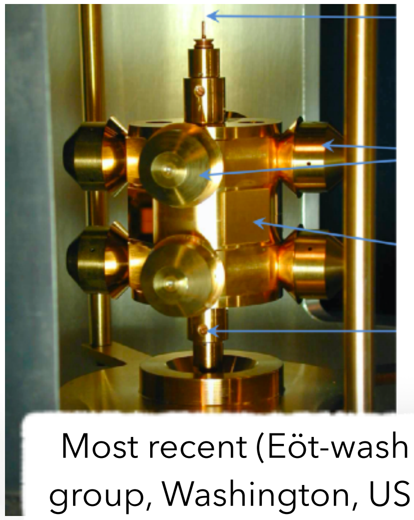
Torsion pendula

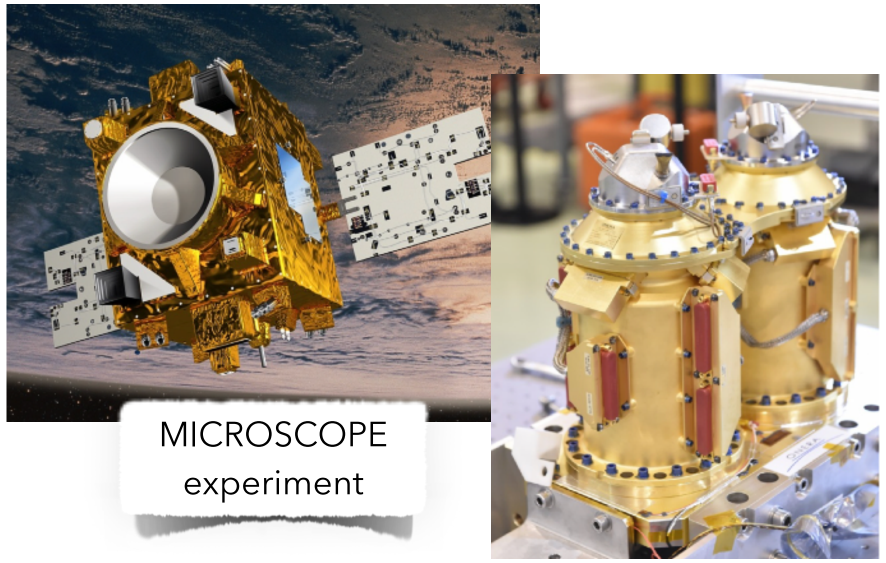

Original setup of Eötvös (1910, Hungary)


Most recent (Eöt-wash group, Washington, US)

$\eta(\mathrm{Be,Ti}) = [0.3 \pm 1.8] \times 10^{-13}$

S.Schlamminger et al, Phys Rev Lett 100 (2008) 041101

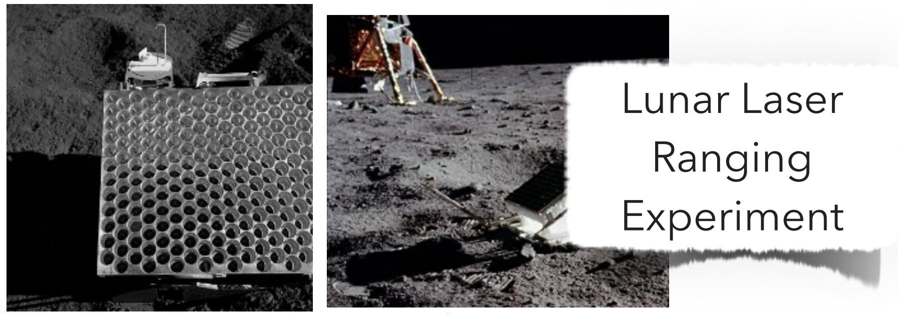
Satellite experiments

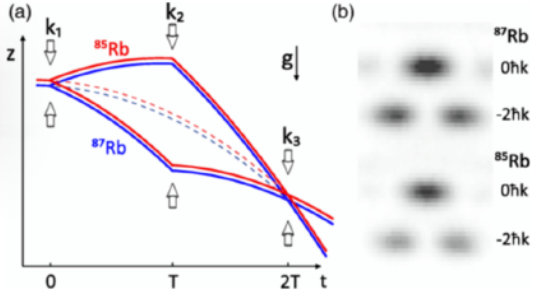

MICROSCOPE experiment

$\eta(\mathrm{Ti,Pt}) = [1 \pm 9(\mathrm{stat}) \pm 9(\mathrm{syst})] \times 10^{-15}$

https://doi.org/10.1103/PhysRevLett.119.231101

Tests on the largest and smallest scales


Lunar Laser Ranging Experiment



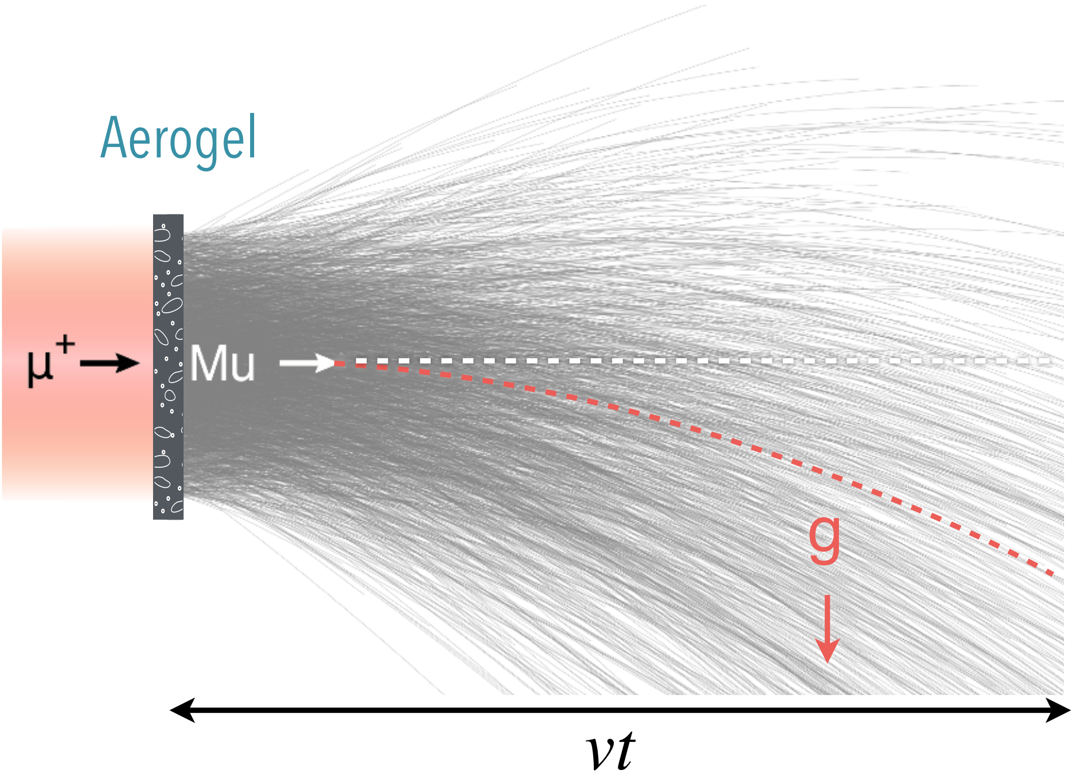
Atom interferometry

$\eta(^{85}\mathrm{Rb}, ^{87}\mathrm{Rb}) = [1.6 \pm 1.8(\mathrm{stat}) \pm 3.4(\mathrm{syst})] \times 10^{-12}$

https://doi.org/10.1103/PhysRevLett.125.191101

The challenges of measuring Mu gravity

Not possible with conventional Mu sources



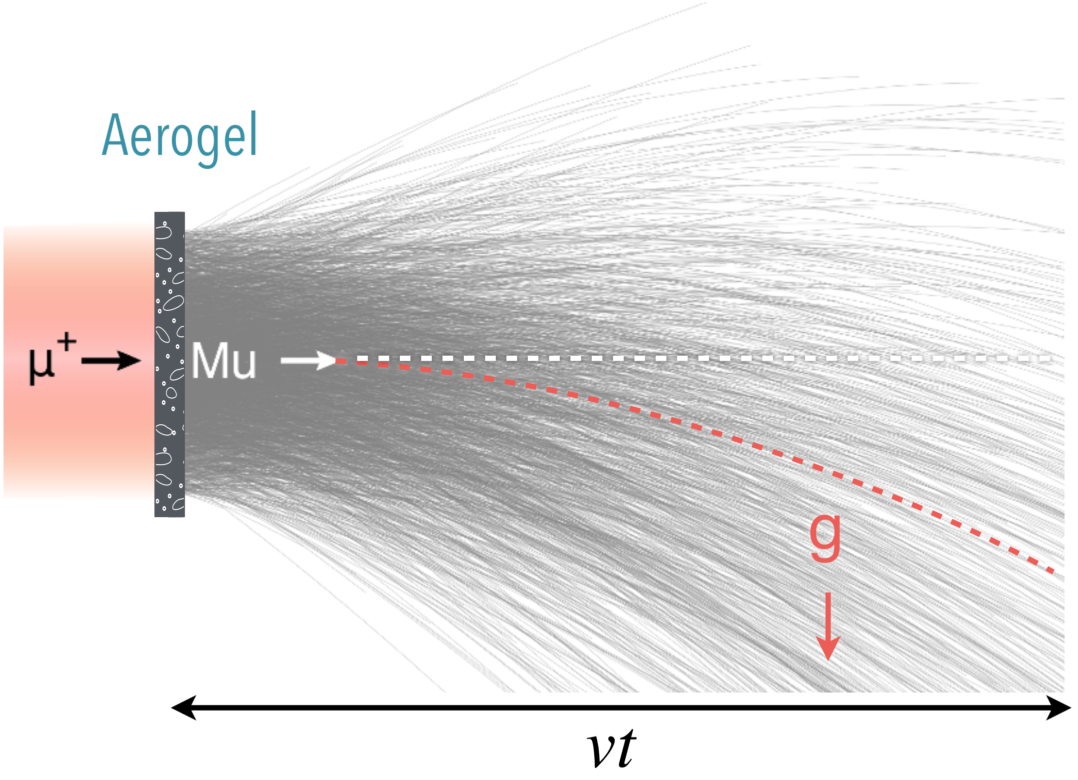
Mu lifetime of 2.2 μs

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

LEMING

The challenges of measuring Mu gravity

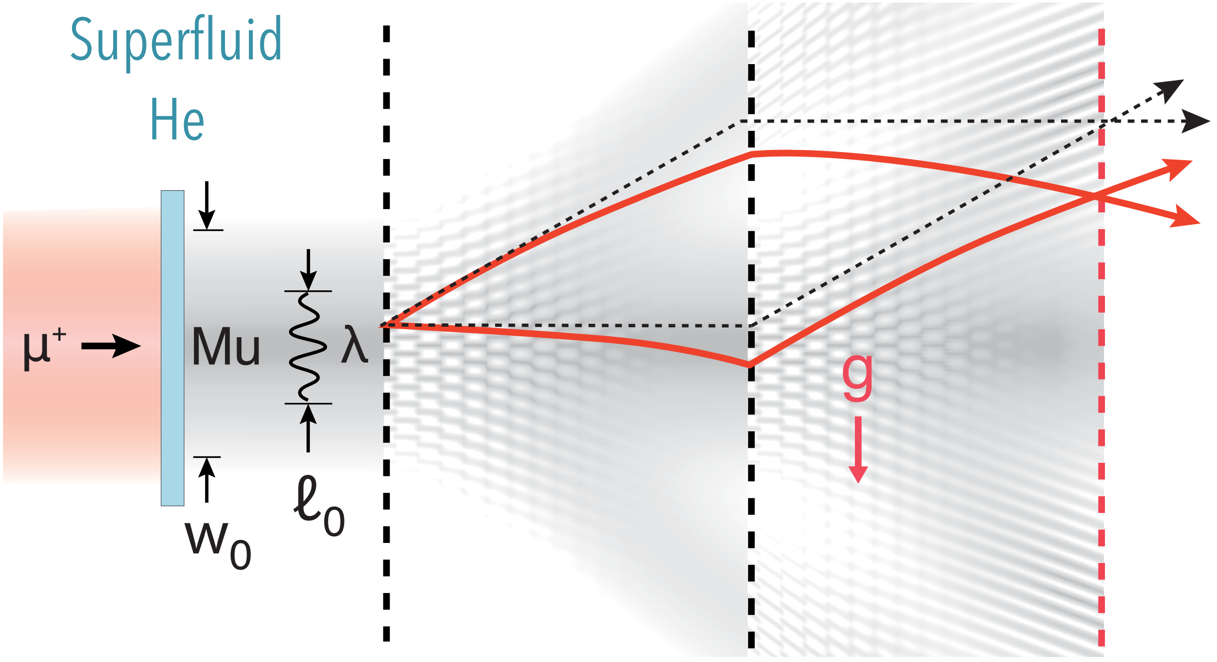
Not possible with conventional Mu sources



Mu lifetime of 2.2 μs

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

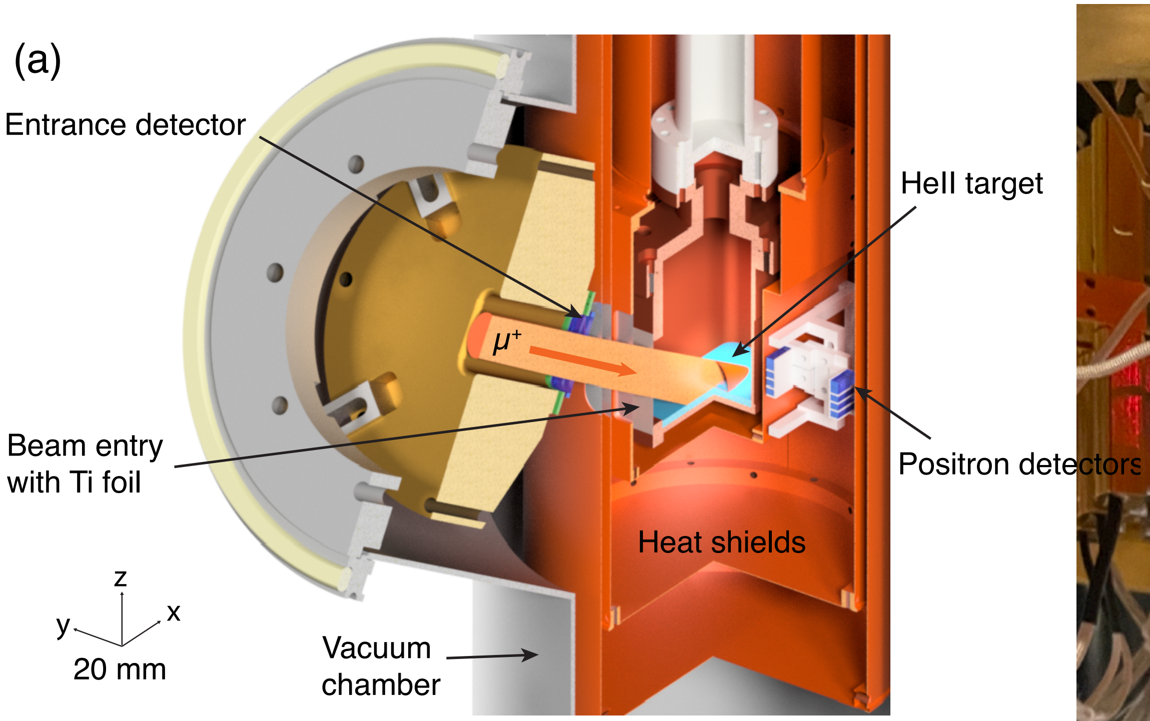
Why it might be possible with LEMING

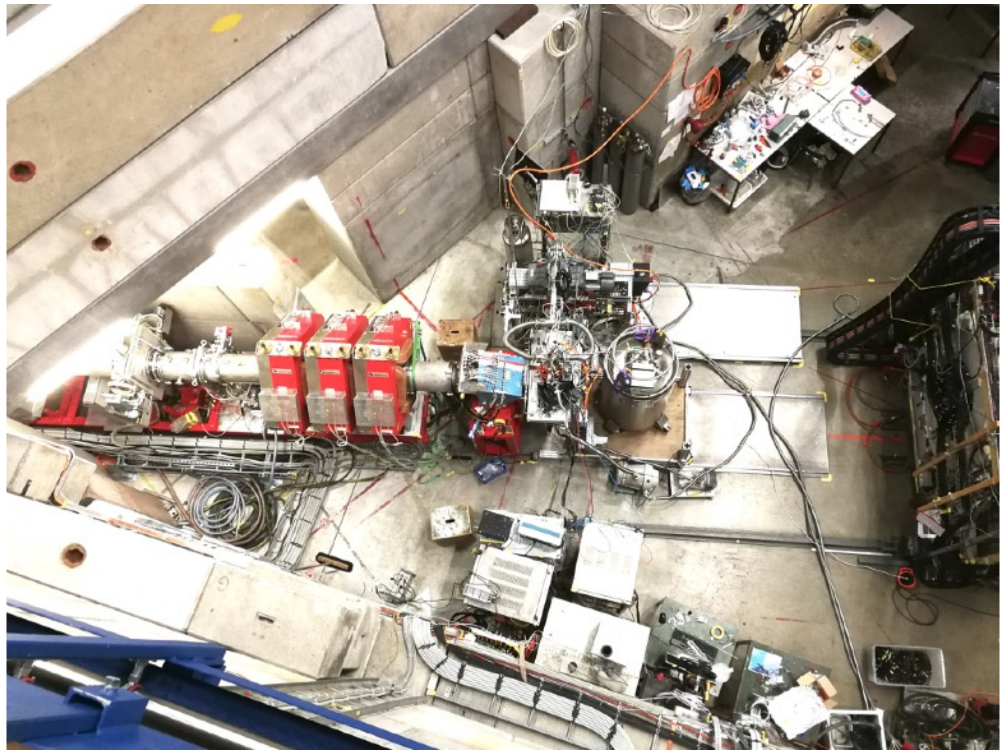


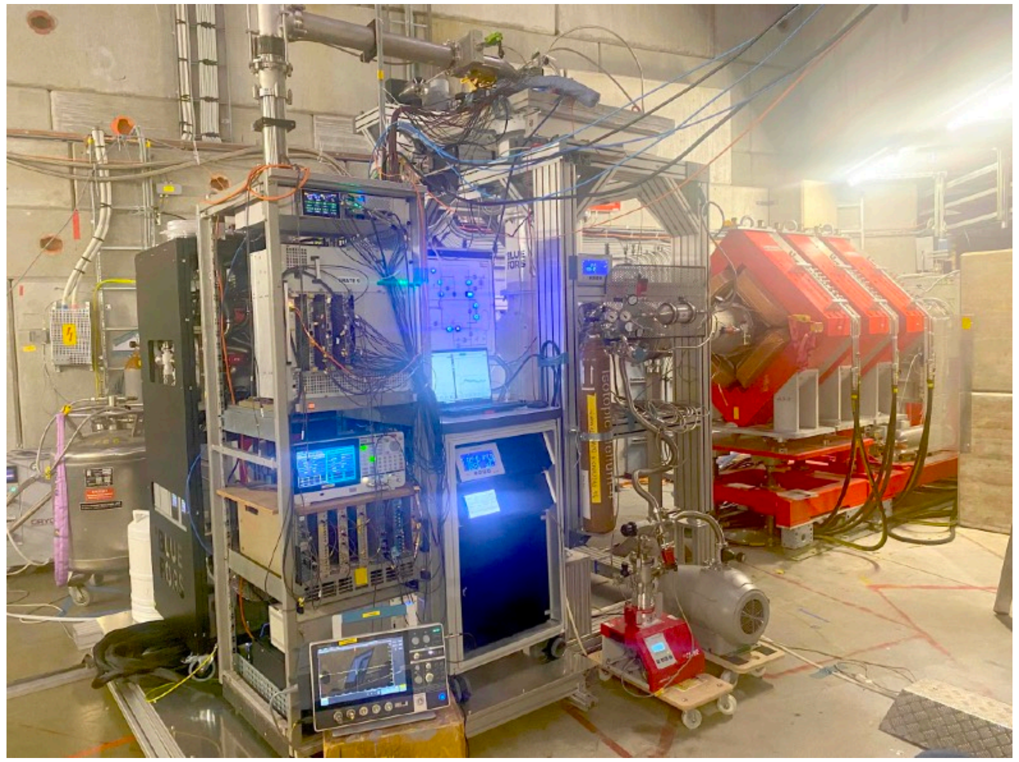
We developed a novel Mu beam amenable to interferometry

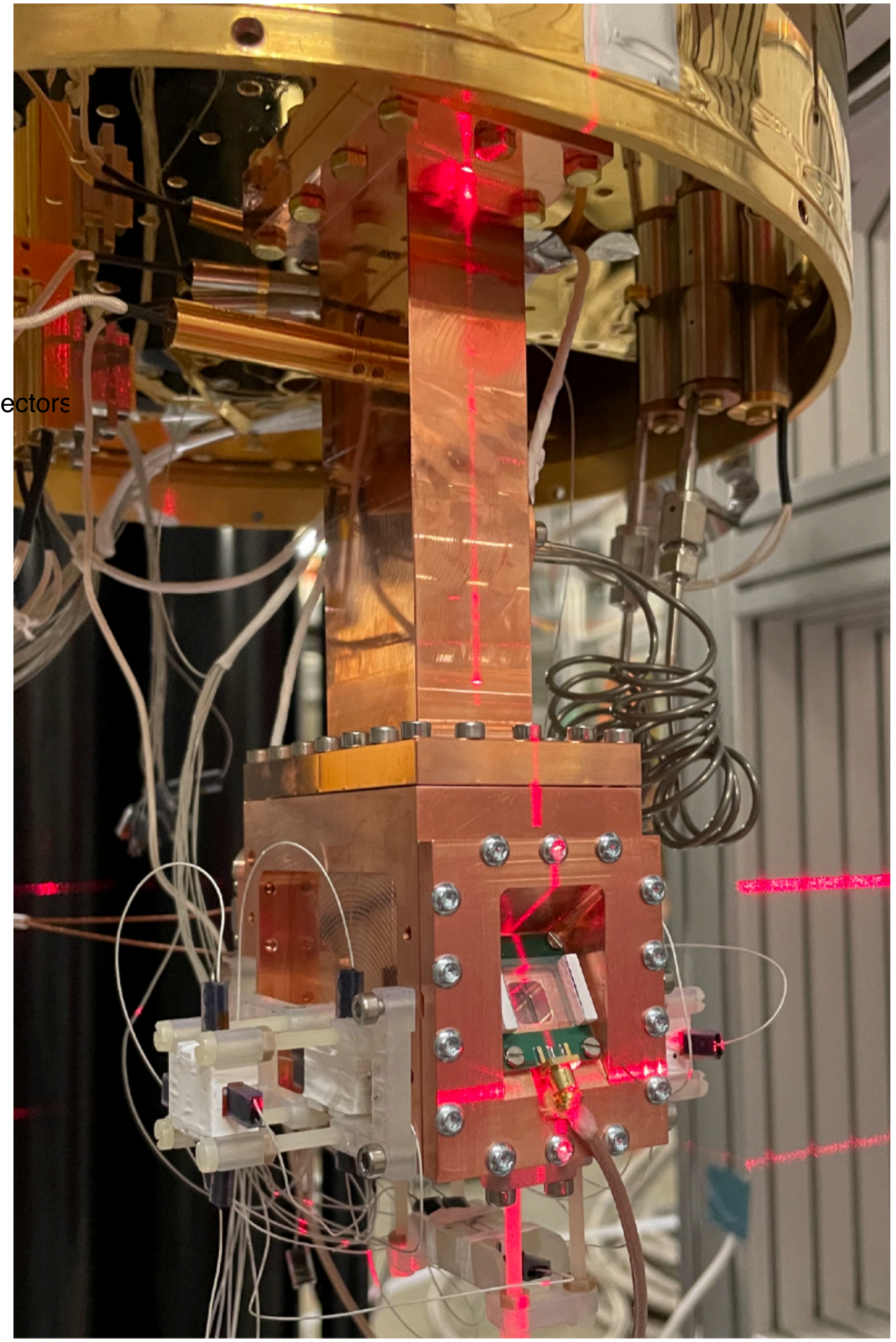
The experimental setup(s)

- Muon beam $p \sim 13$ MeV/c, bent in 30° angle downwards
- Dilution fridge $T \sim 170$ mK now updated, large MXC plate $T \sim 10$ mK
- Cryogenic tracker and low-threshold detectors

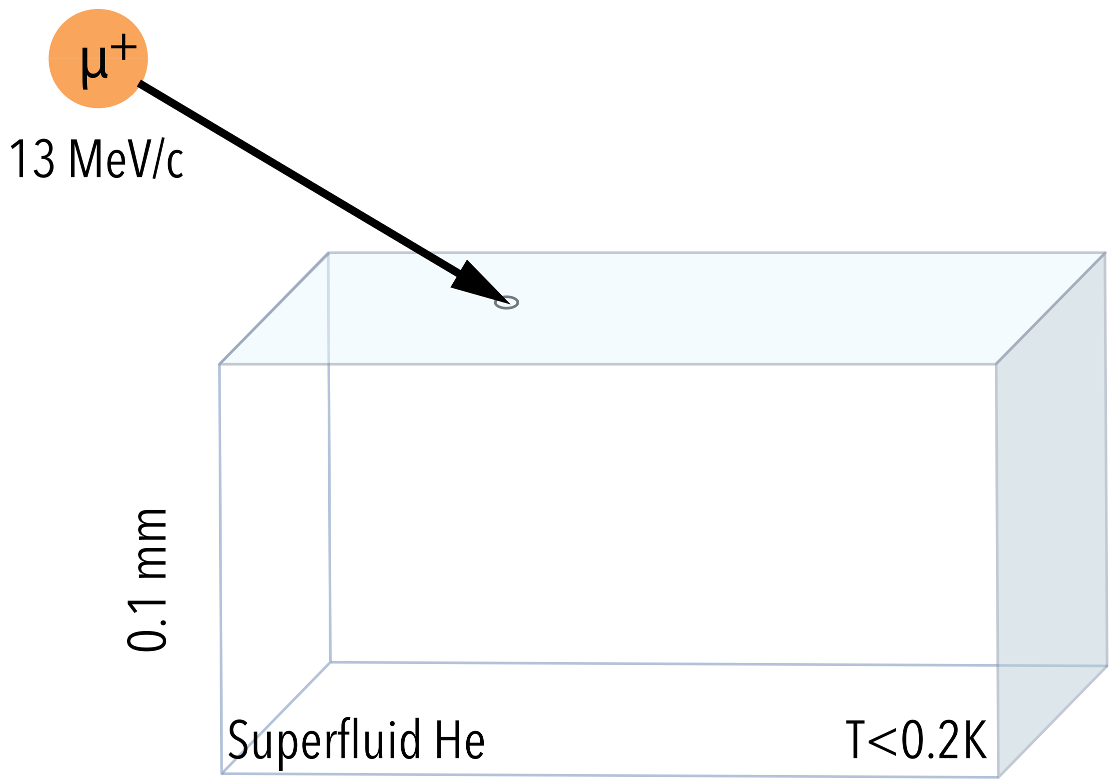








First synthesis of superthermal muonium from SFHe



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(1) Mu stop and recombination $p \approx 70\,\%$

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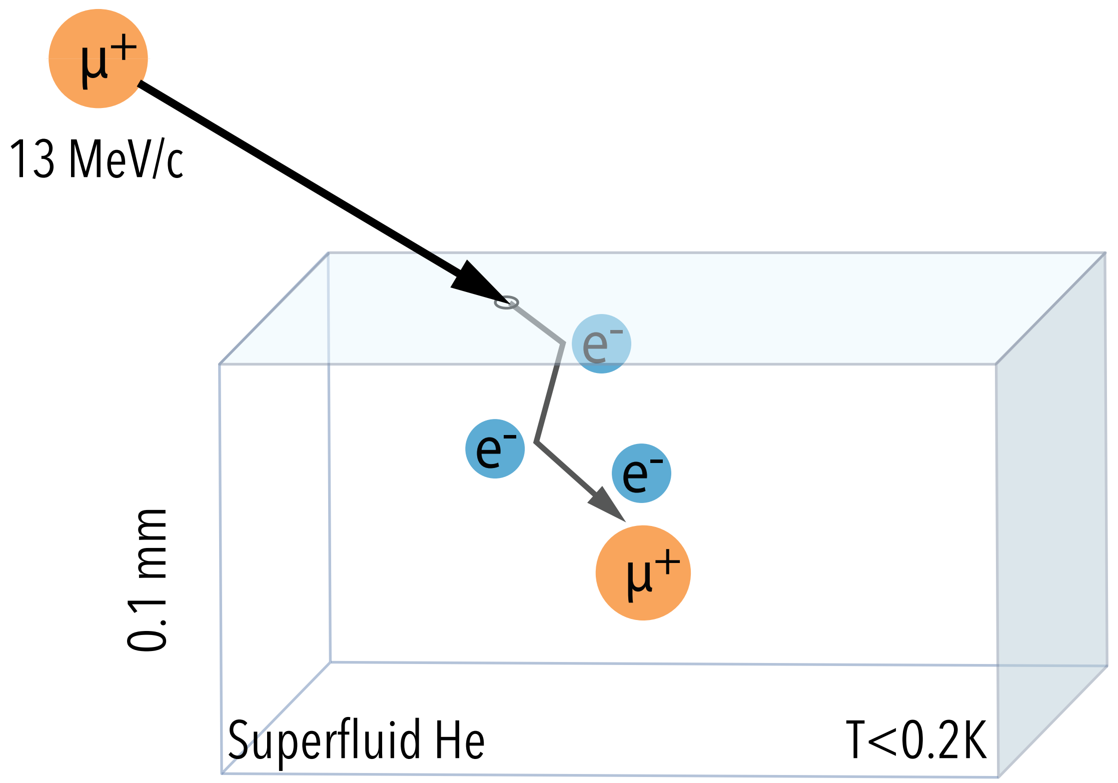

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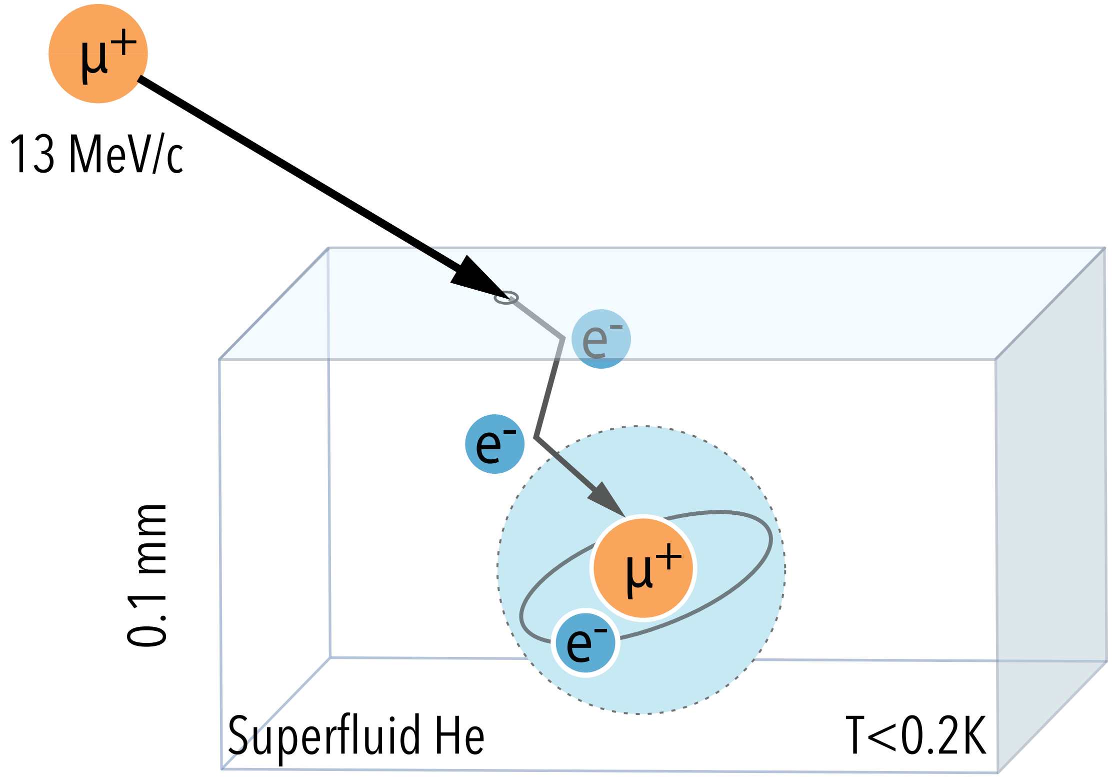

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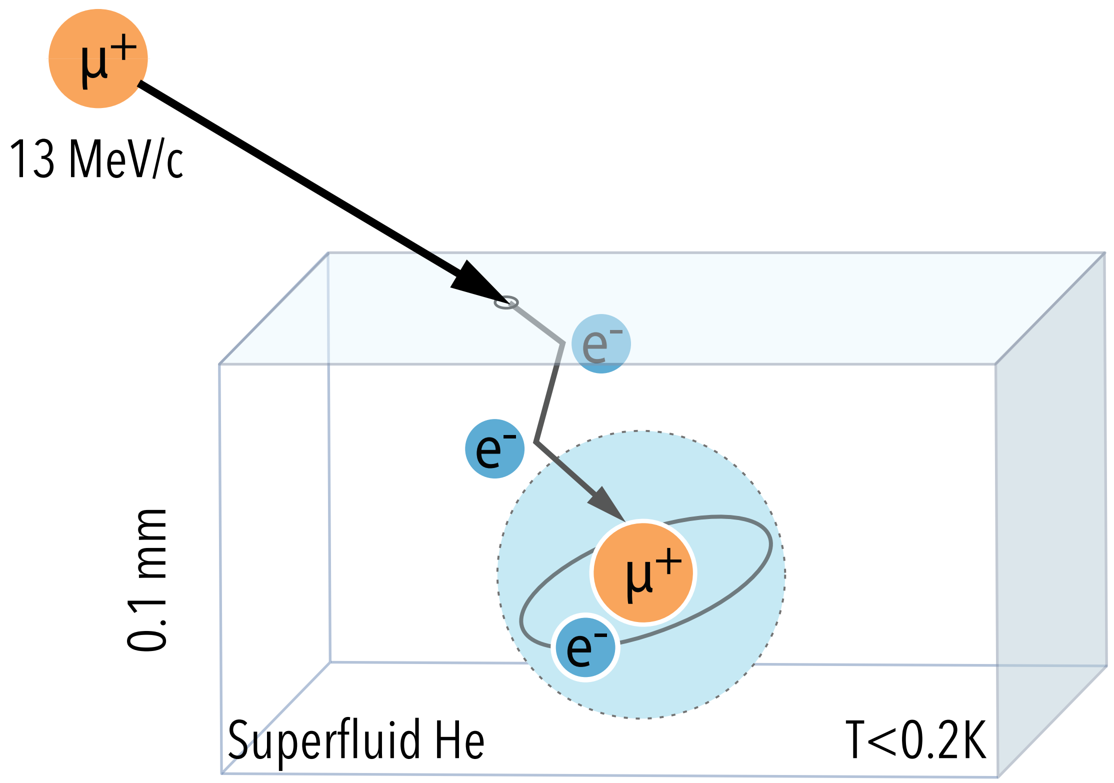

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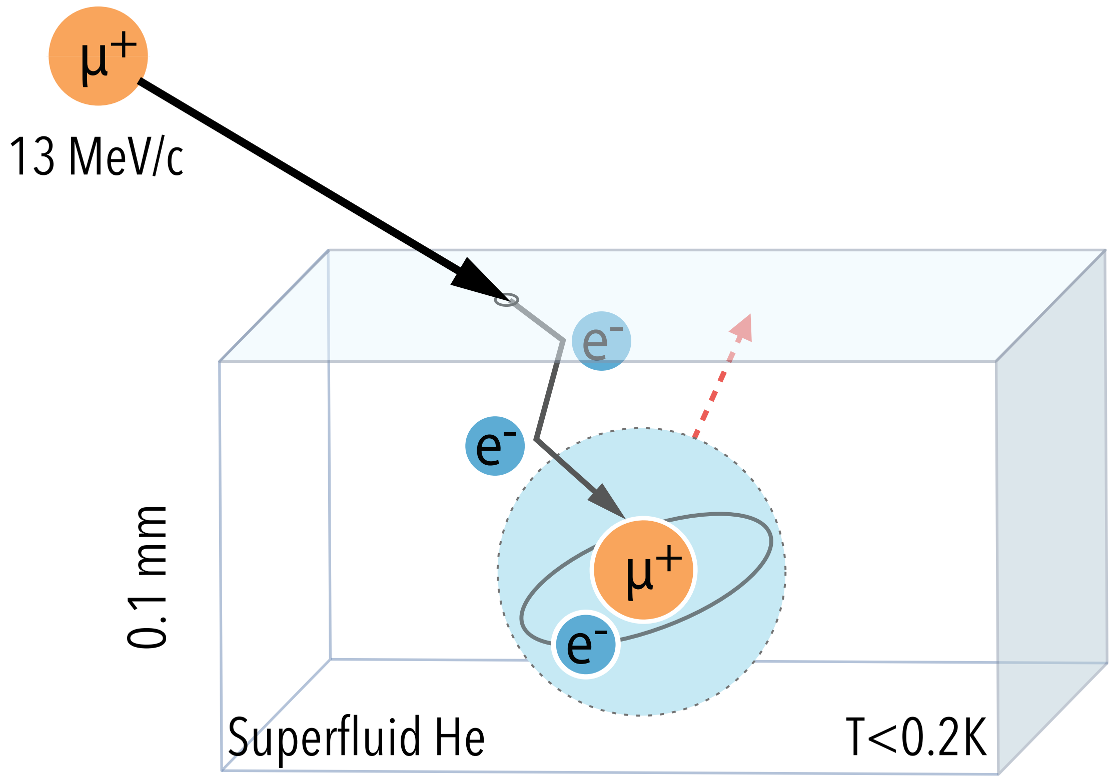

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A. Soter et al., Nature 603, 411–415 (2022)

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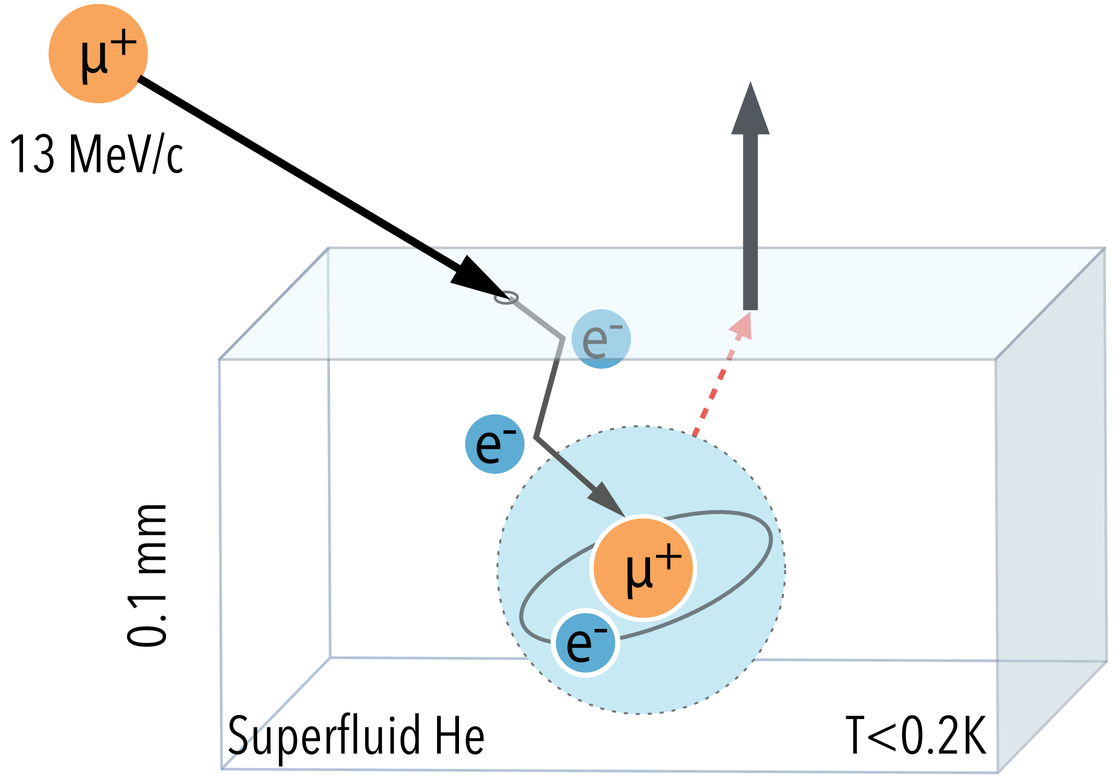

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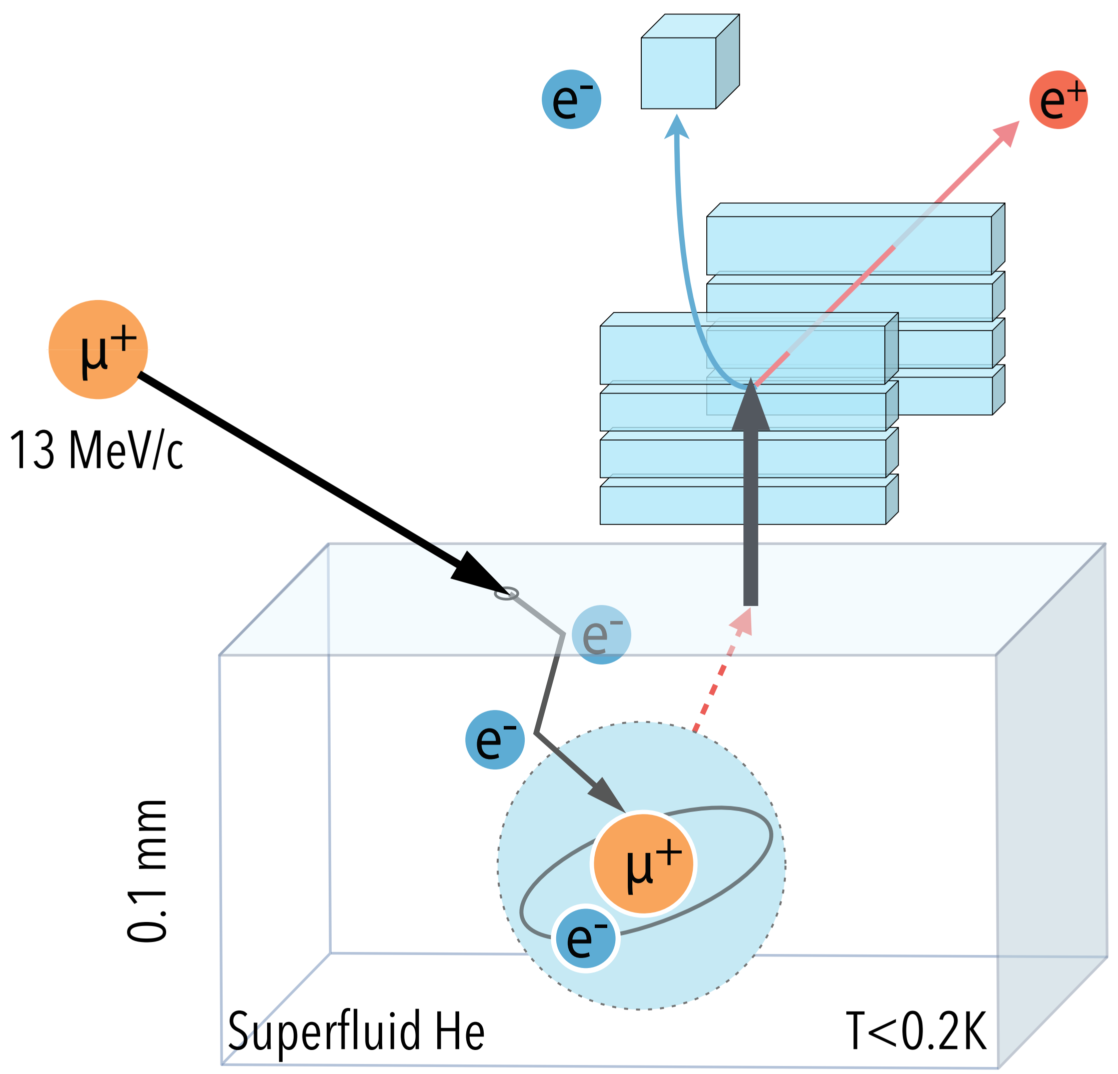

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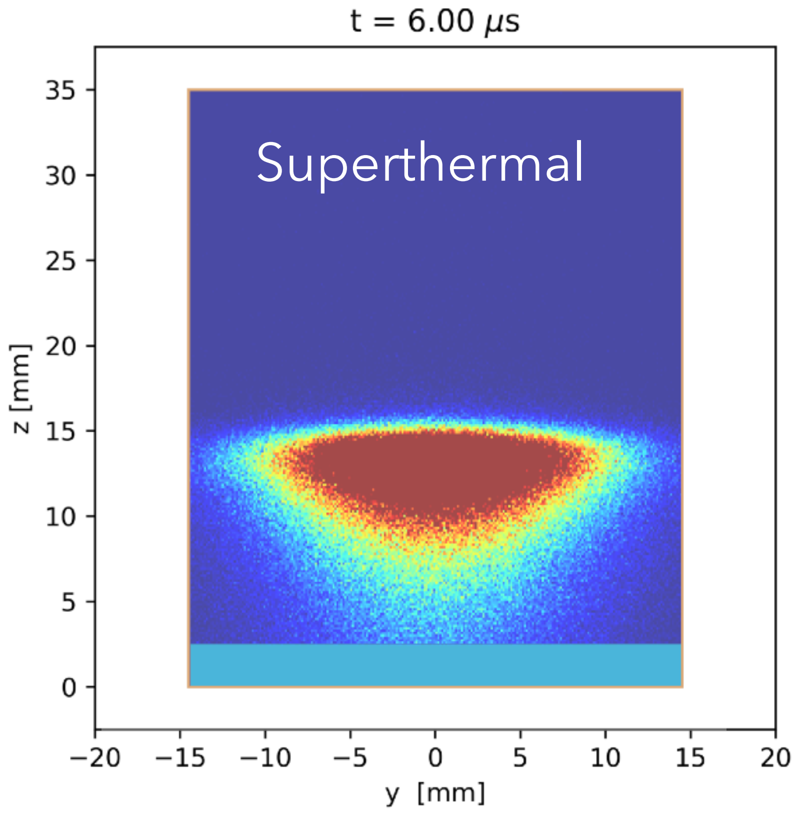
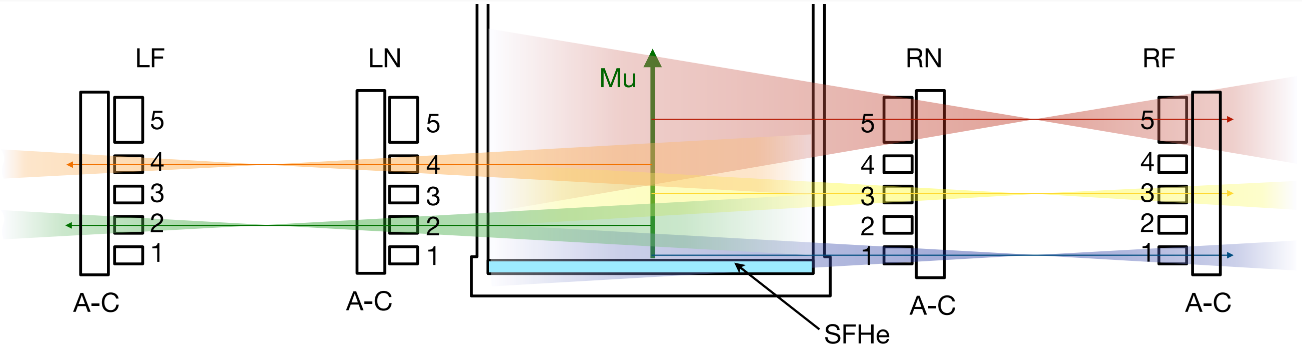
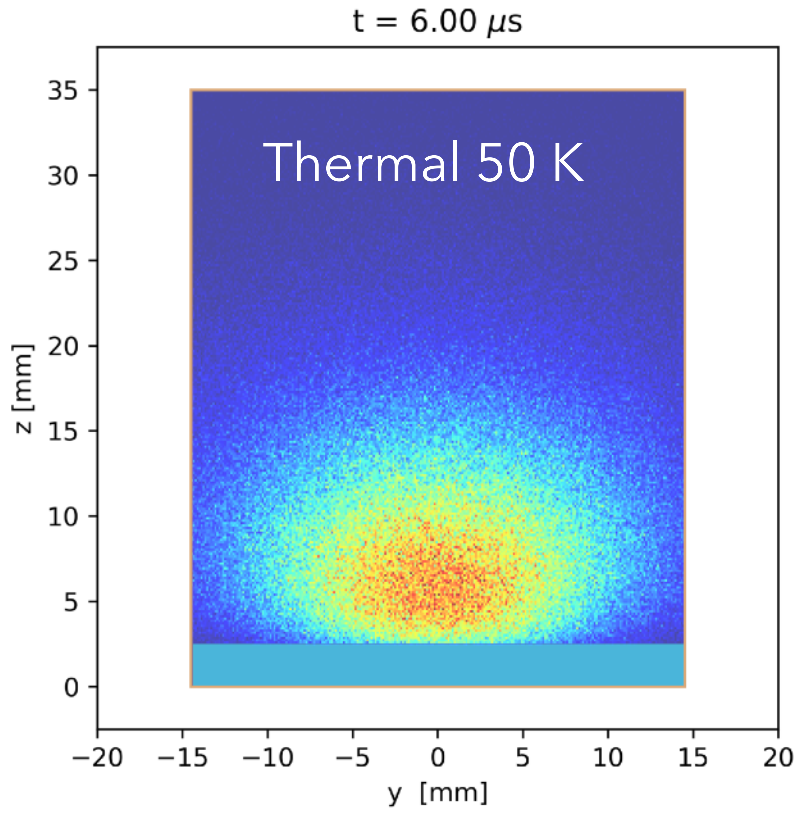
Characterisation of the superthermal Mu beam

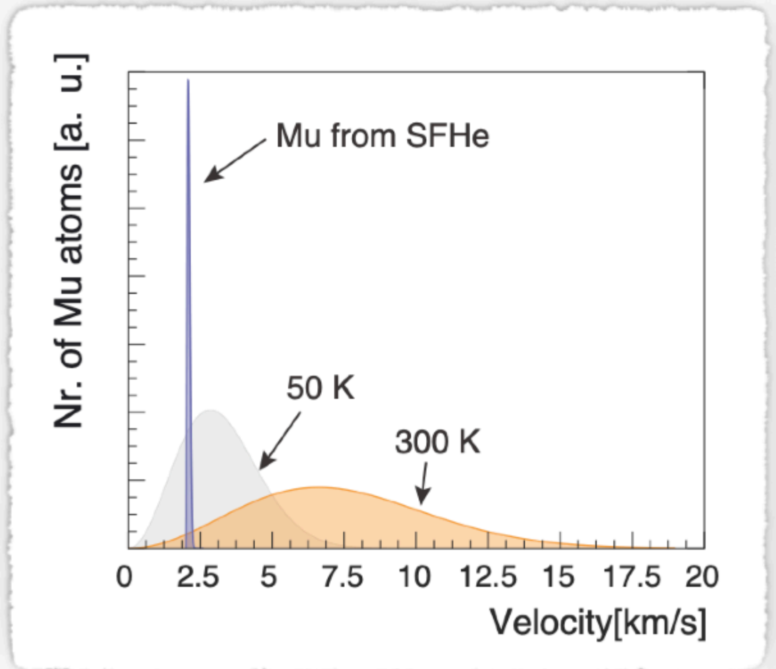




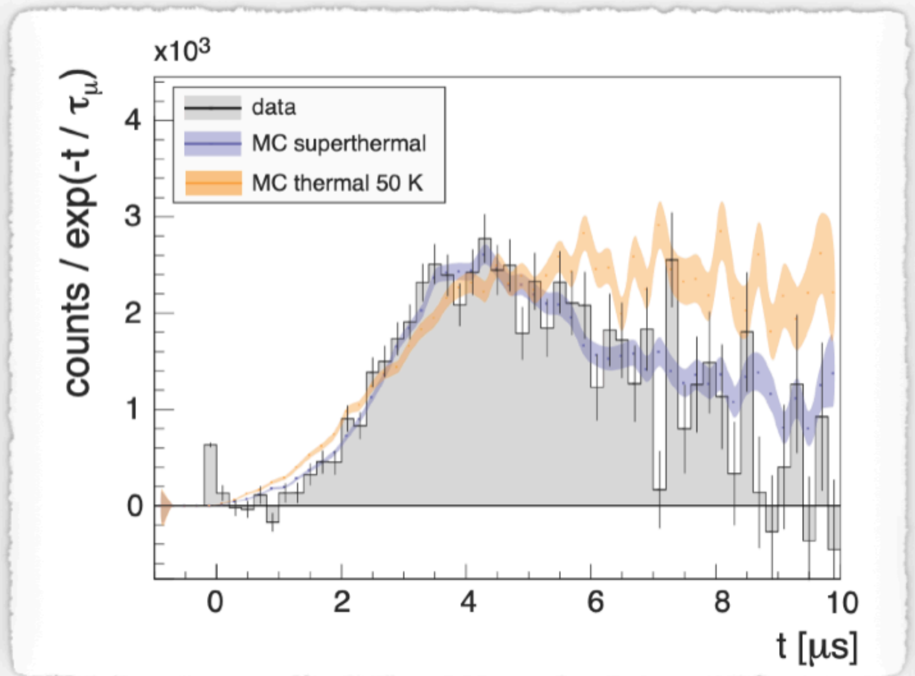
- **Lowest velocity** Mu source $v_x \approx 2175\ \mathrm{m/s}$
- **Narrowest** longitudinal distribution: $\sigma_{v_x} \approx 70\ \mathrm{m/s}$
- **High yield** similar to the best 300 K sources $R(\mu^+ \to \mathrm{Mu_{vac}}) = 10\,\%$



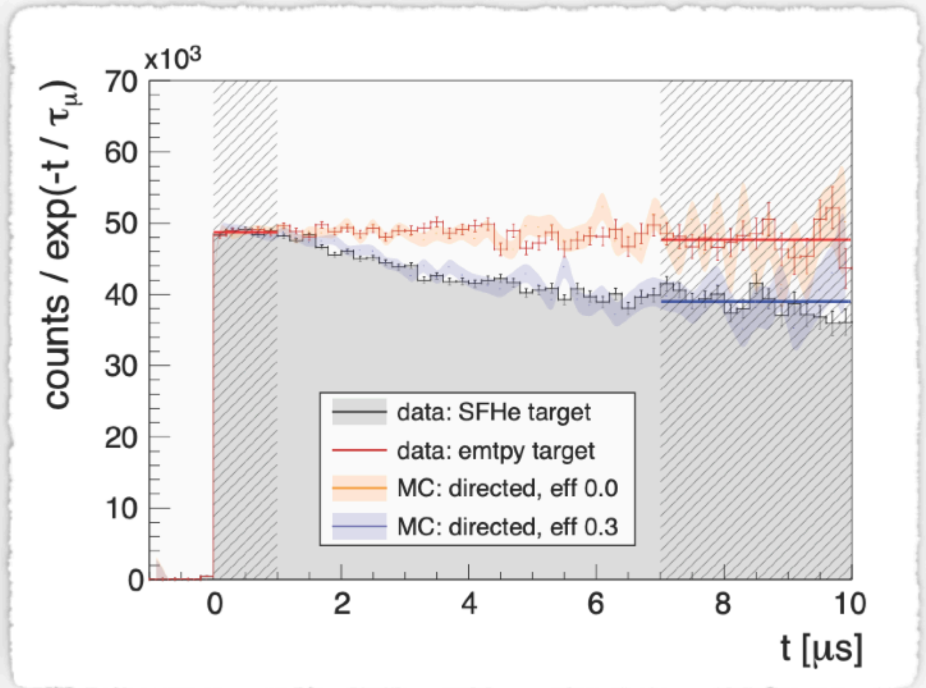
Reconstructed velocity distribution



Time spectra of fly-by



Time spectra of target emission



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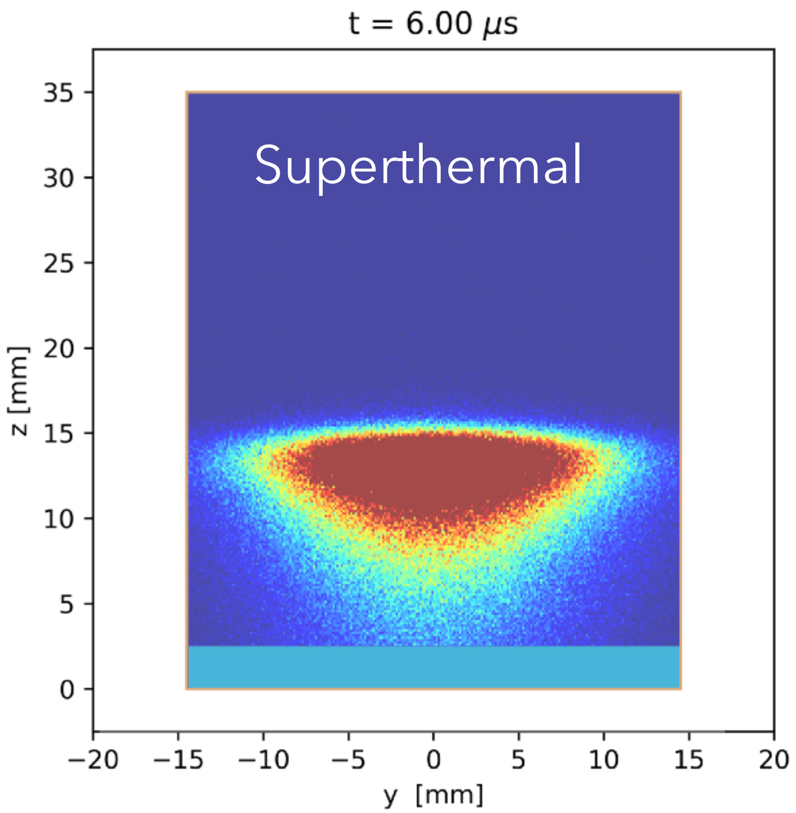

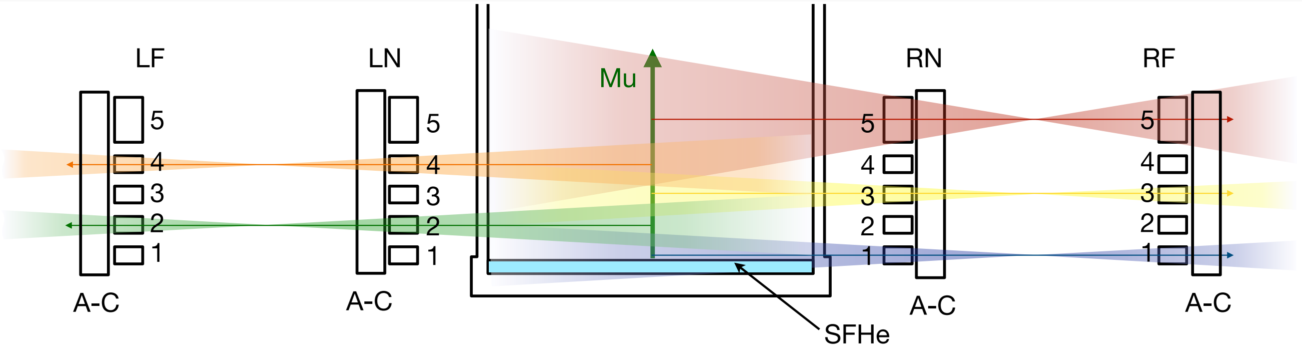

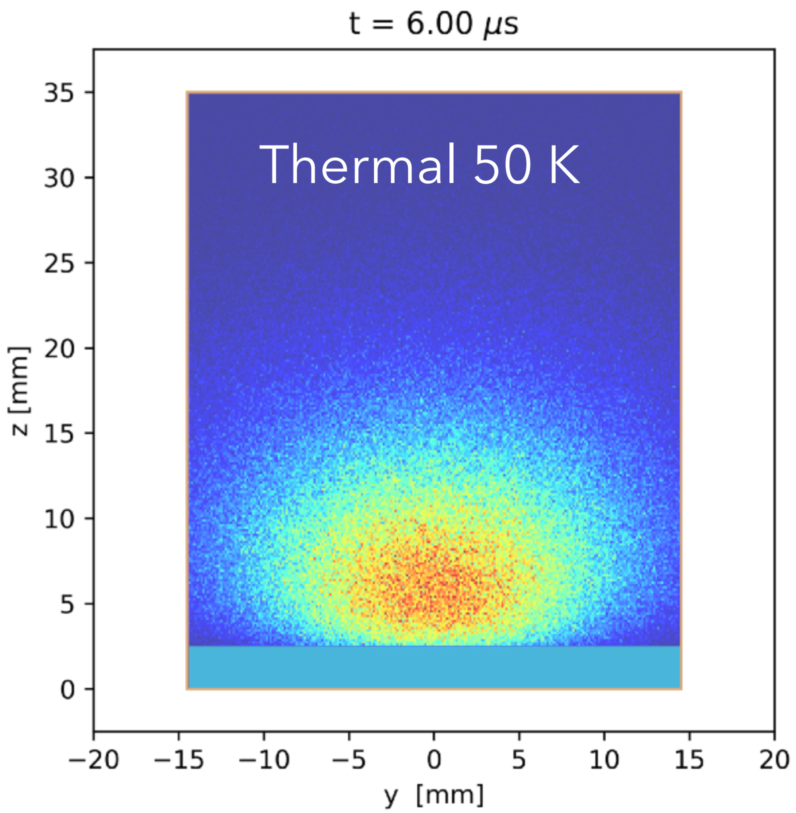

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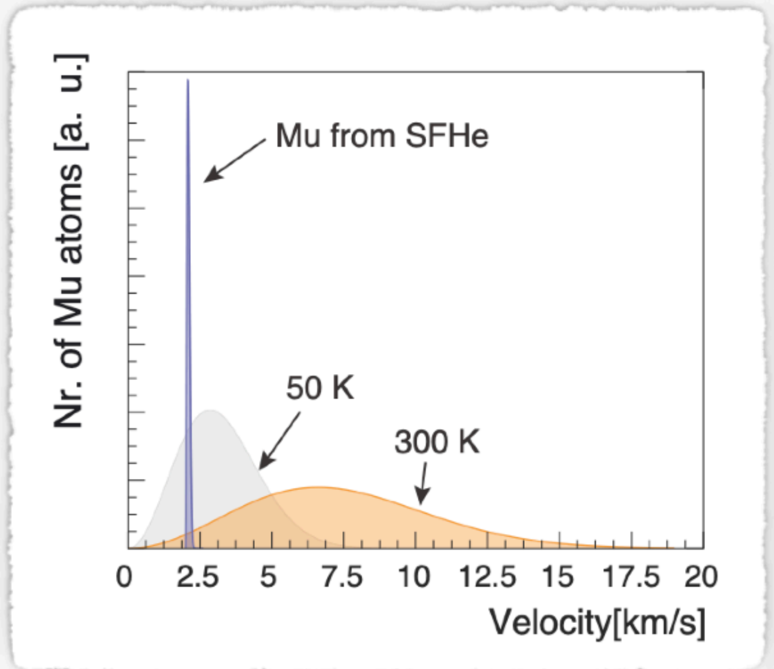

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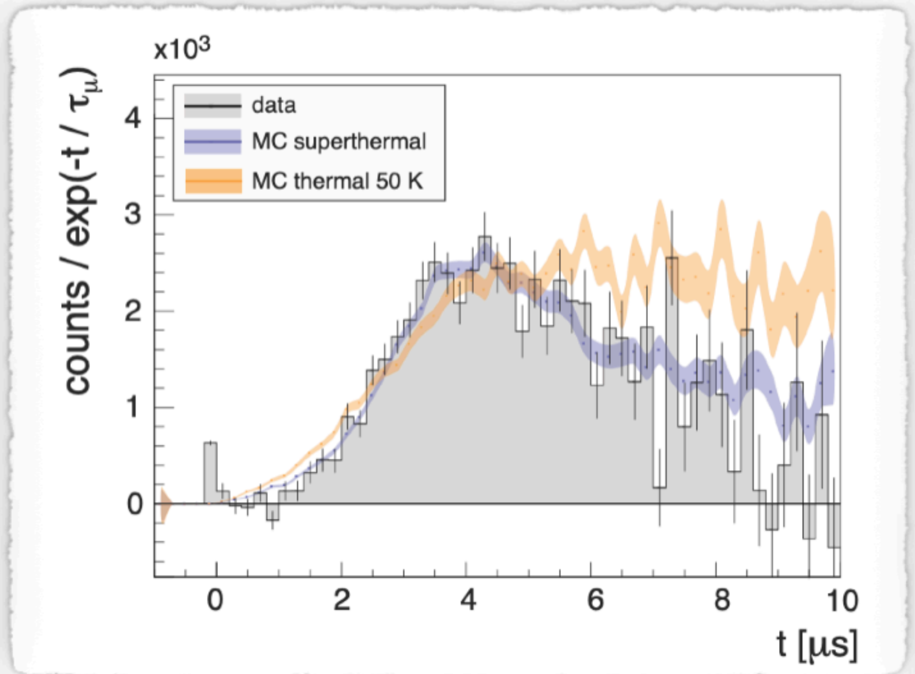
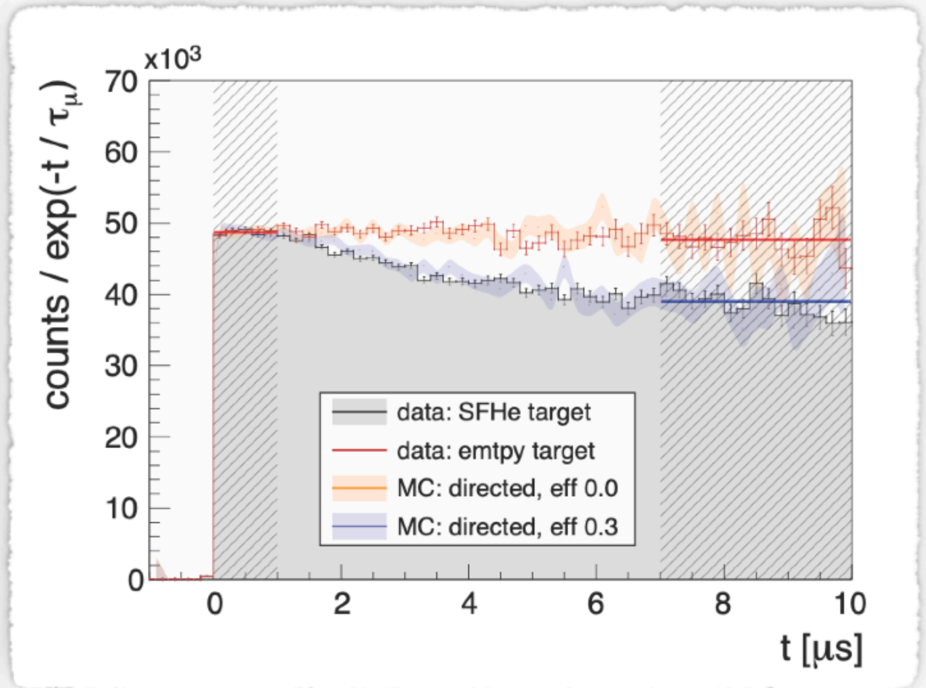


Time spectra of target emission



Amenability of the atomic beam for interferometry

- 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

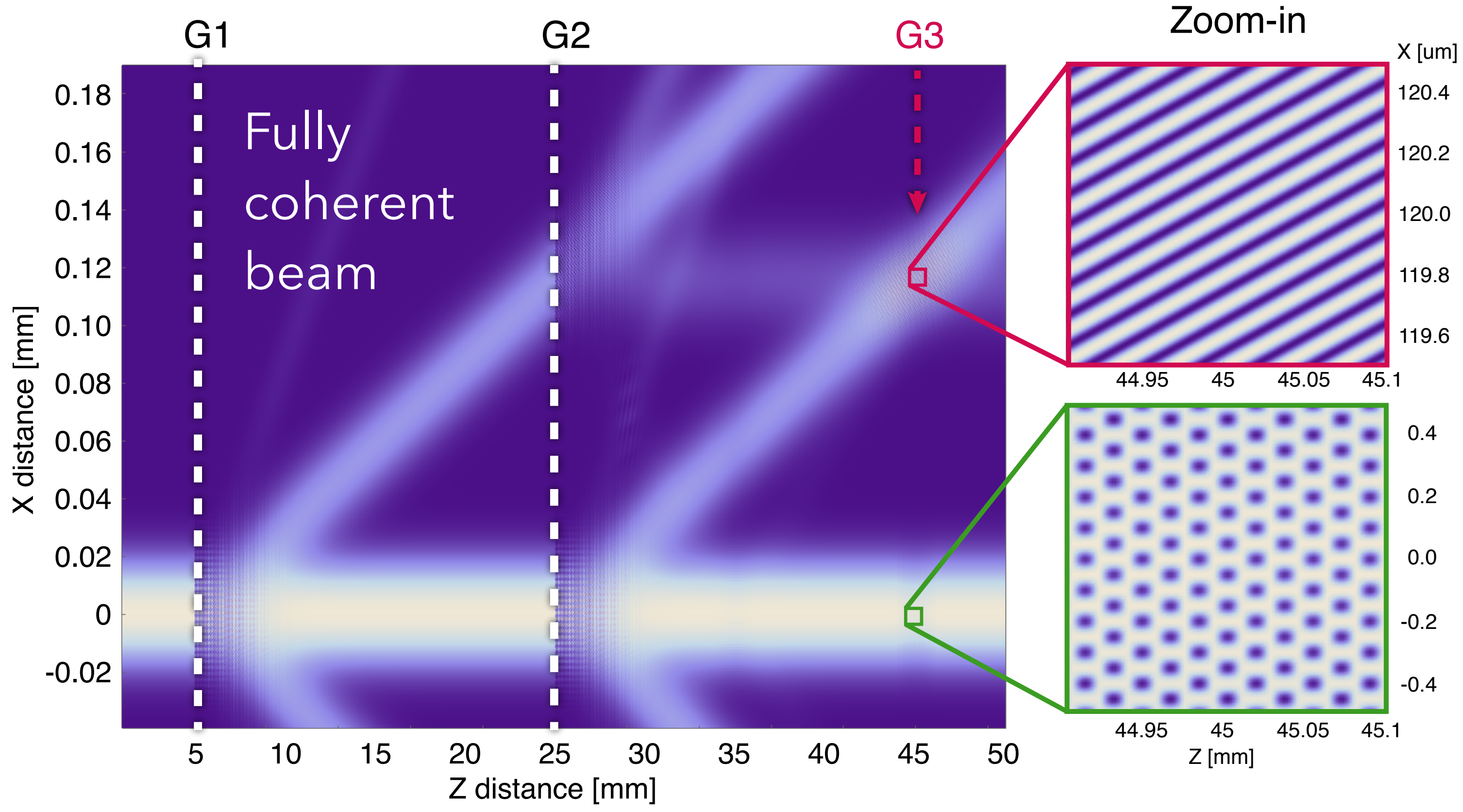
ℓ_0 relates to the angular spread (α) of the atoms (via the Cittert-Zernike theorem) as:

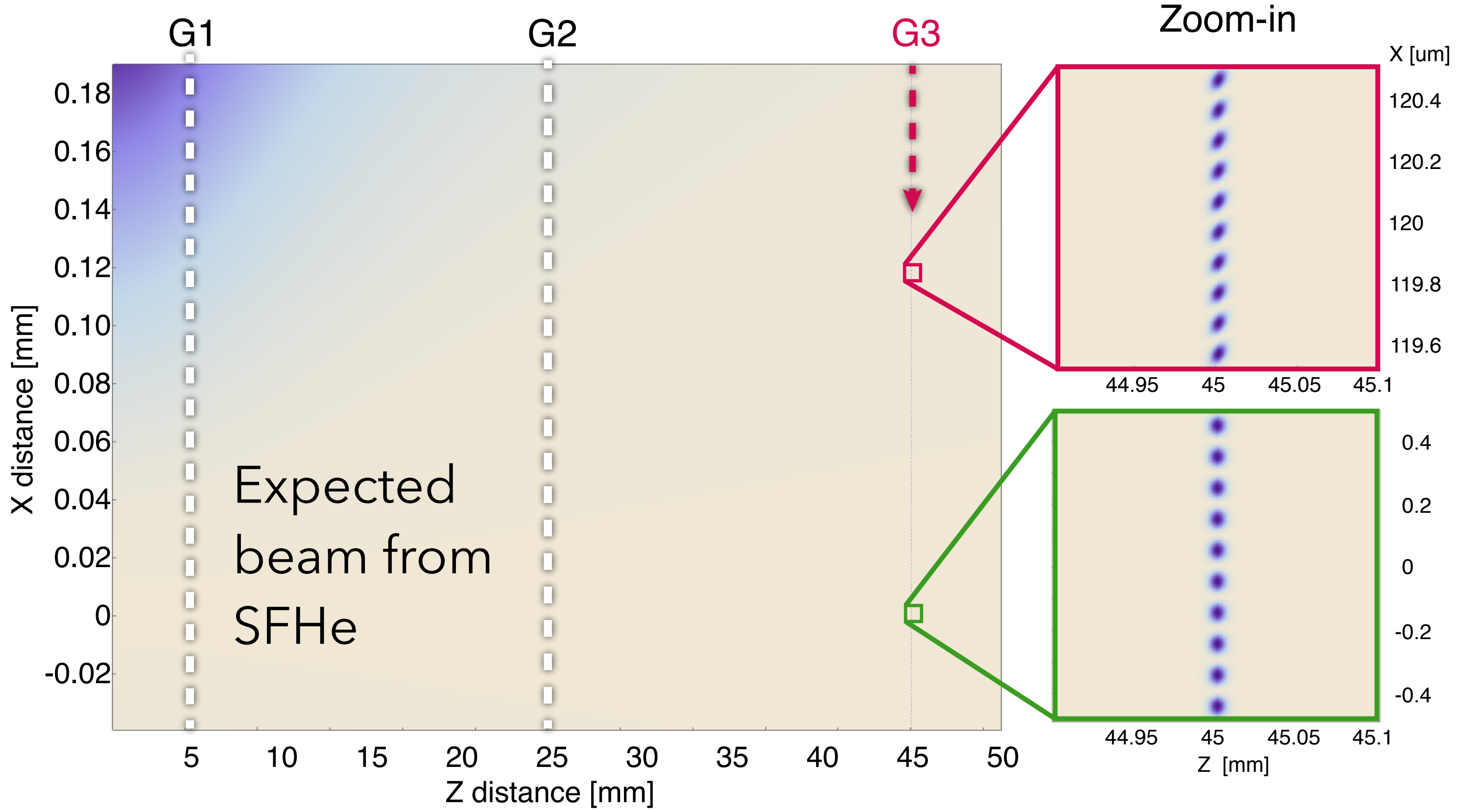
$$\ell_0 \approx \frac{\lambda}{\alpha} \approx \frac{1.6\ \text{nm}}{50/2200} = 70\ \text{nm}$$

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

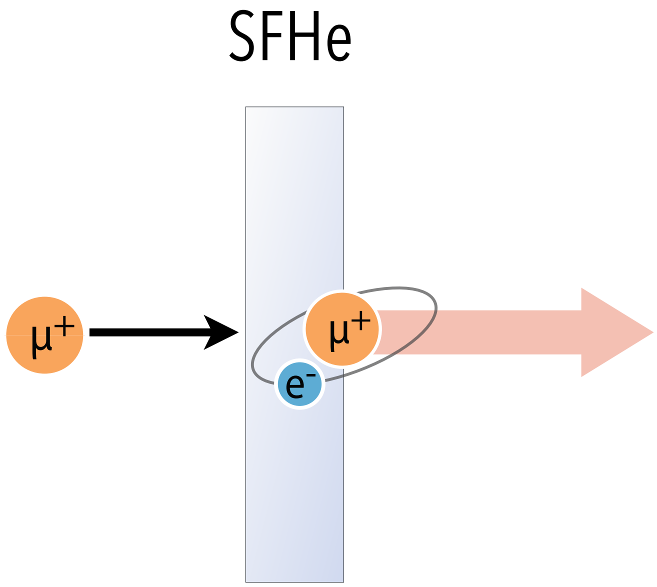
- Contrast = 0.3
- Given there is enough high quality Mu atoms, might be feasible!

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





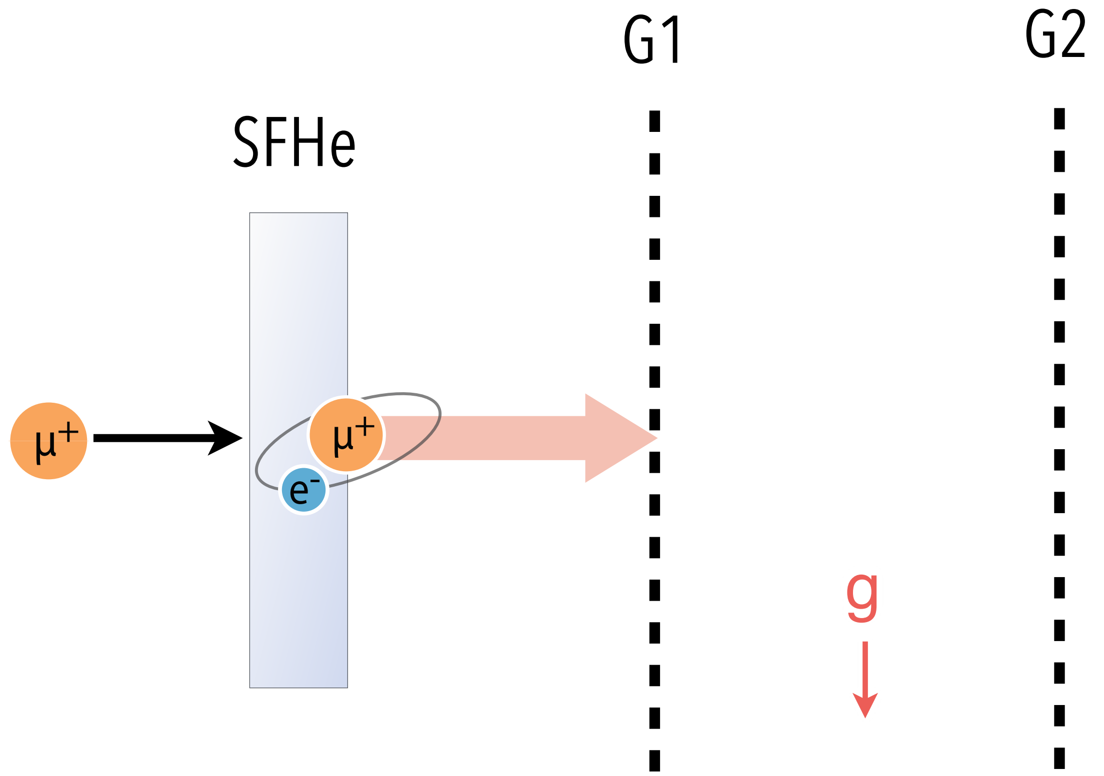
Overview of LEMING



Horizontal cold Mu beam

Atomic mirror / Microfluidic target

Overview of LEMING



Horizontal cold Mu beam

Atomic mirror / Microfluidic target

Interferometer

G1, G2 and mask M

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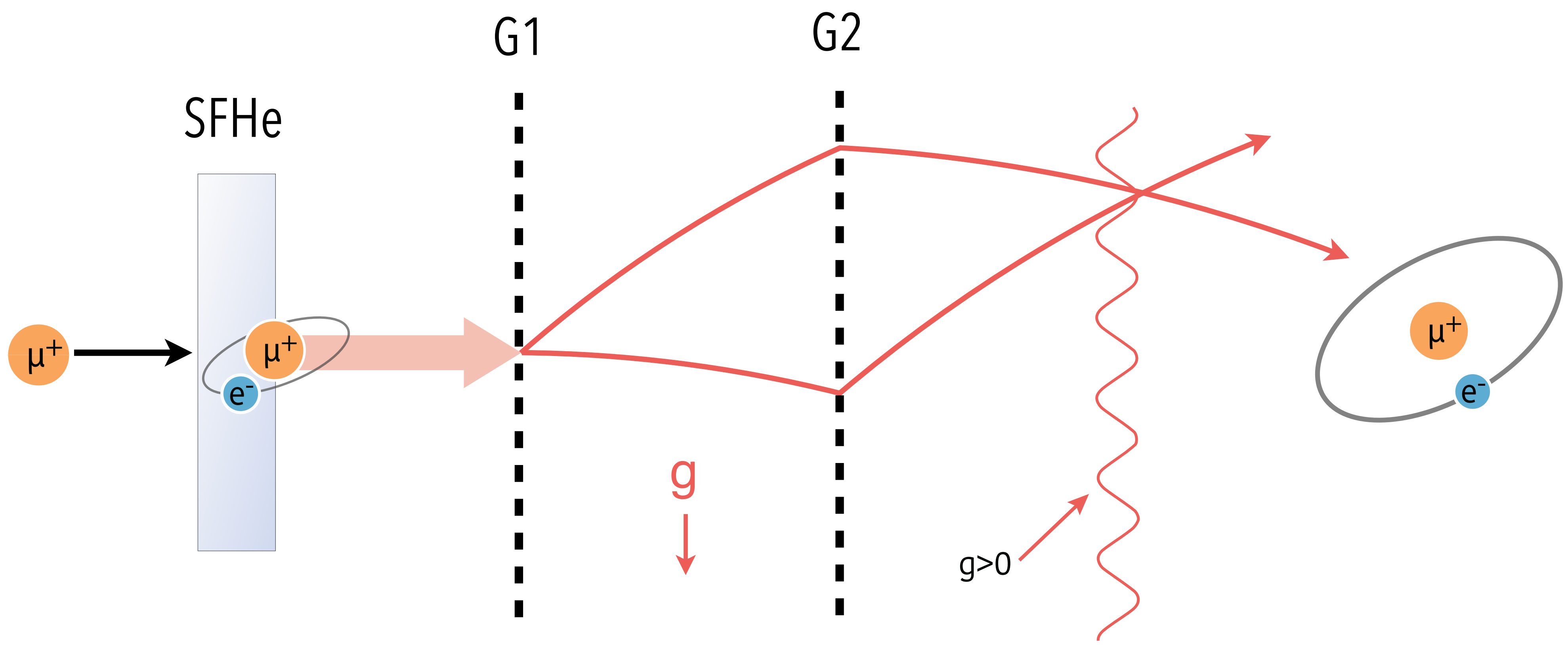

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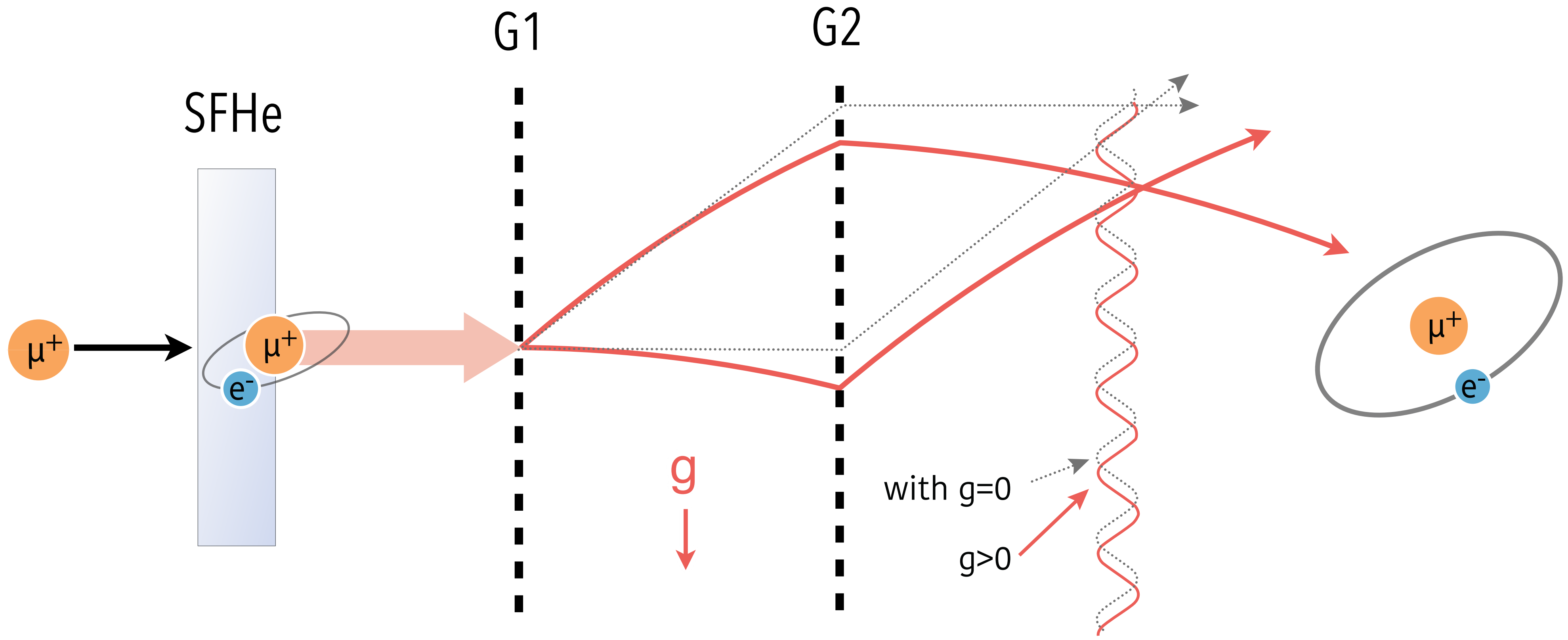

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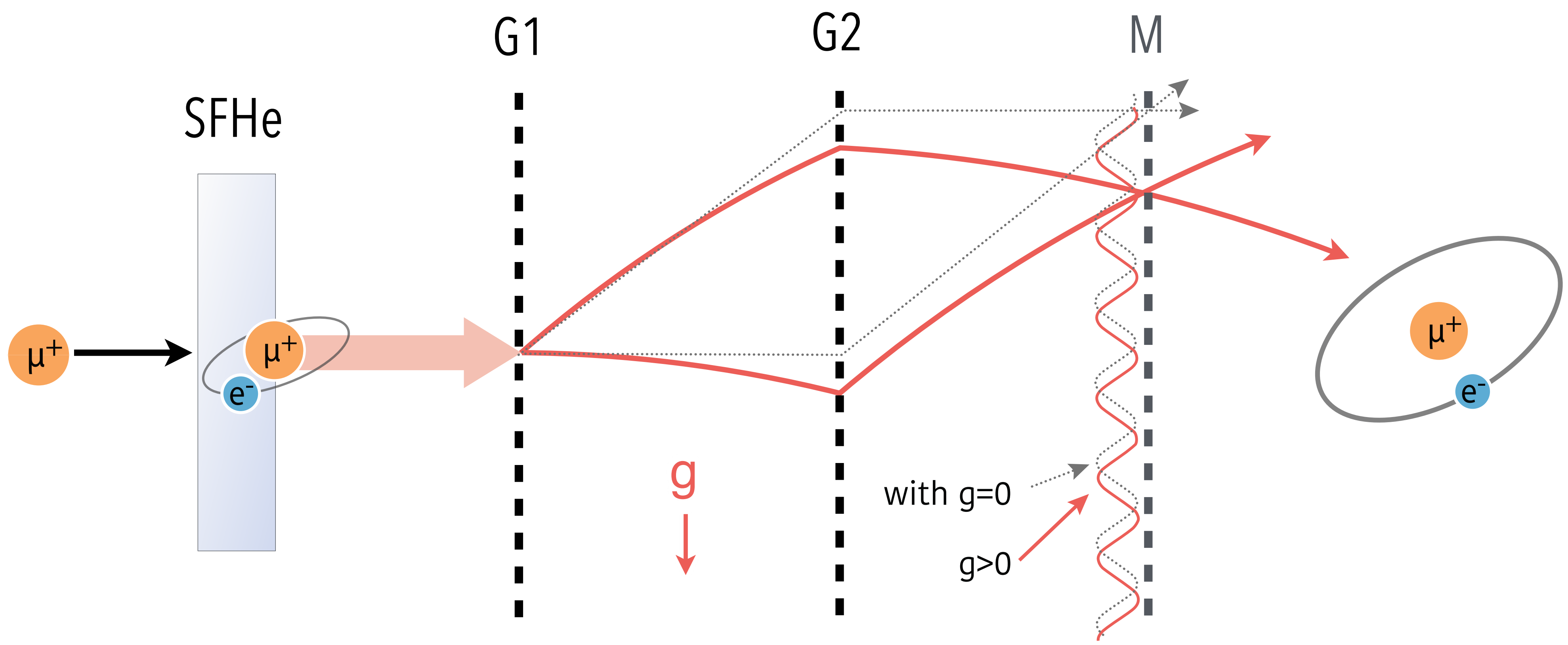

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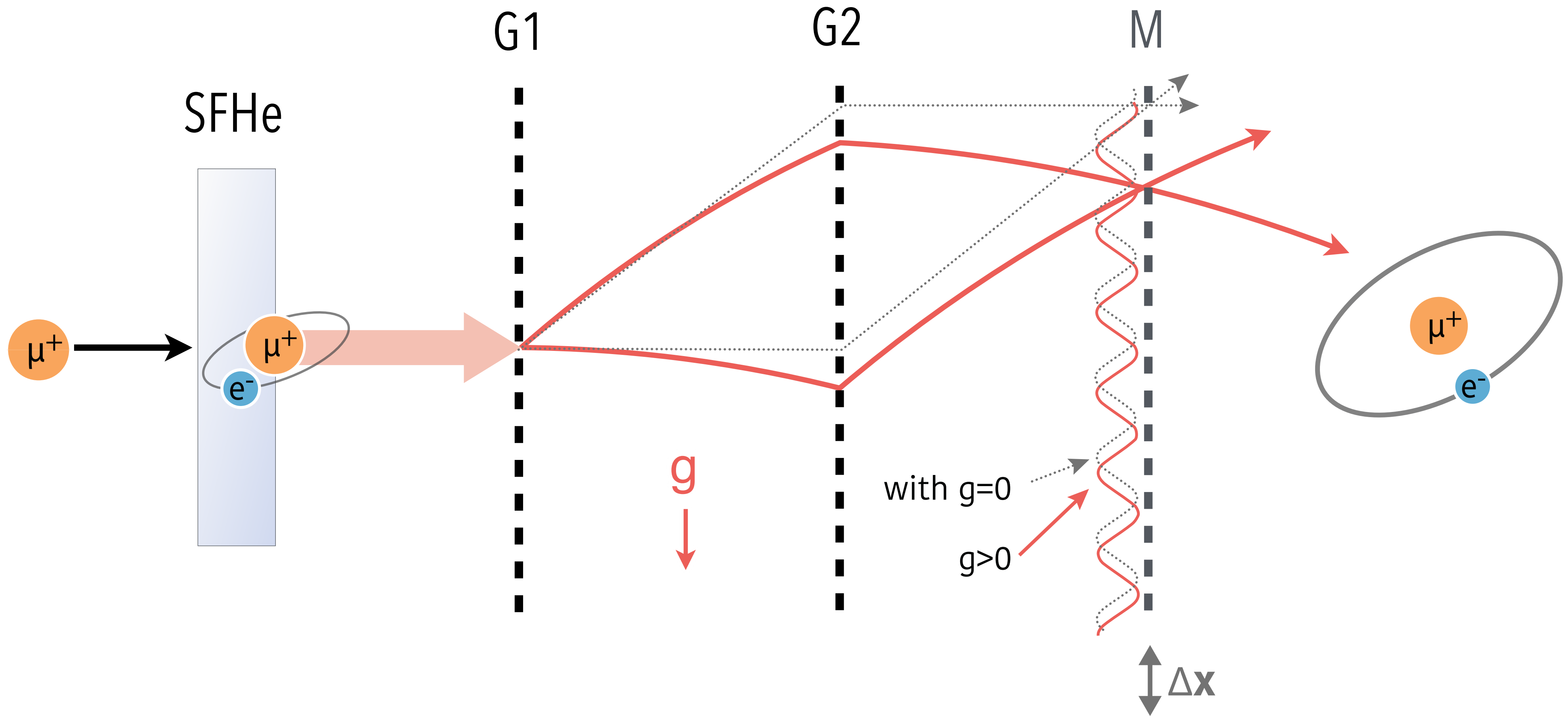

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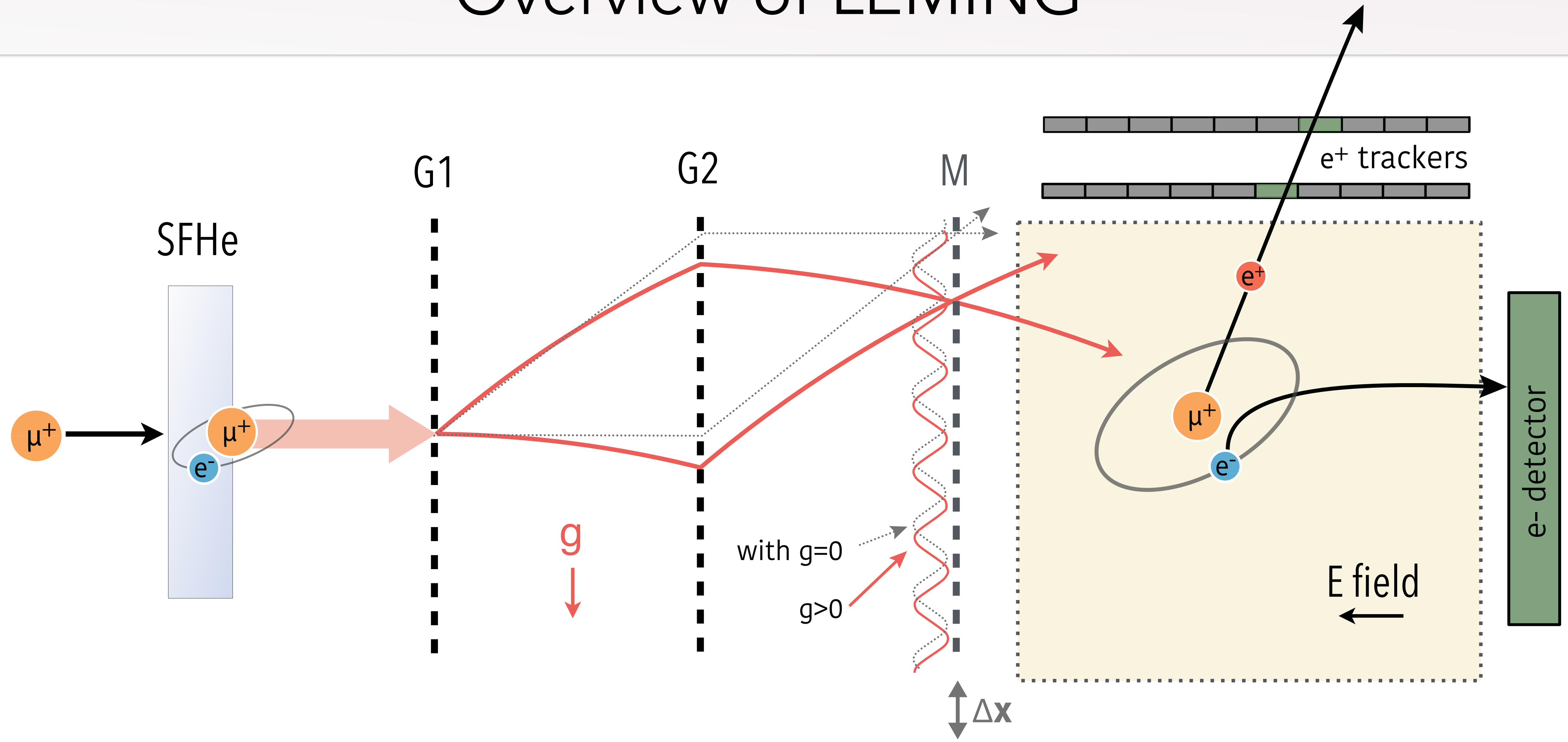

Horizontal cold Mu beam

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G1, G2 and mask M

Detection

e+/e- detectors

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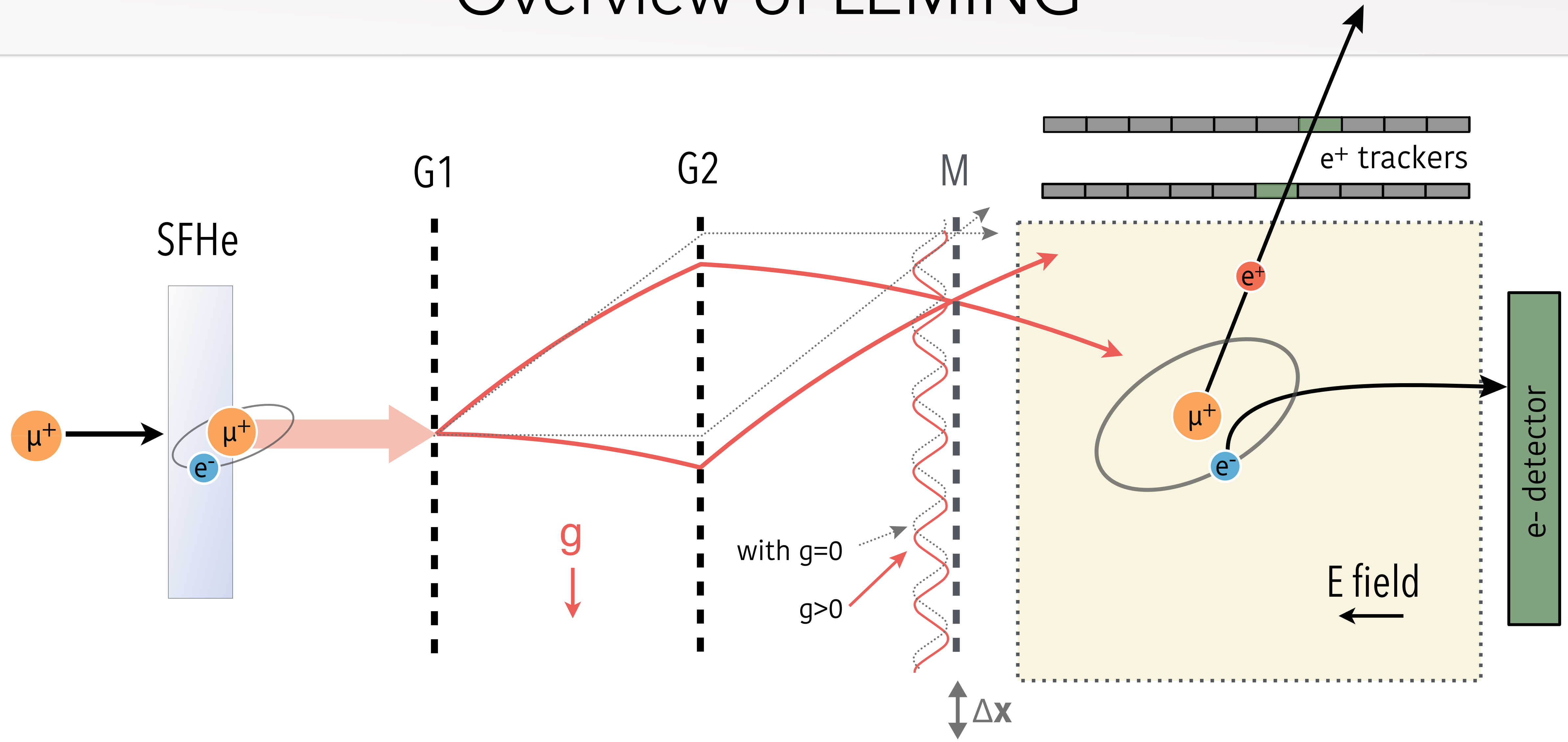

New!

Horizontal cold Mu beam

Atomic mirror / Microfluidic target

Interferometer

G1, G2 and mask M

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e+/e- detectors

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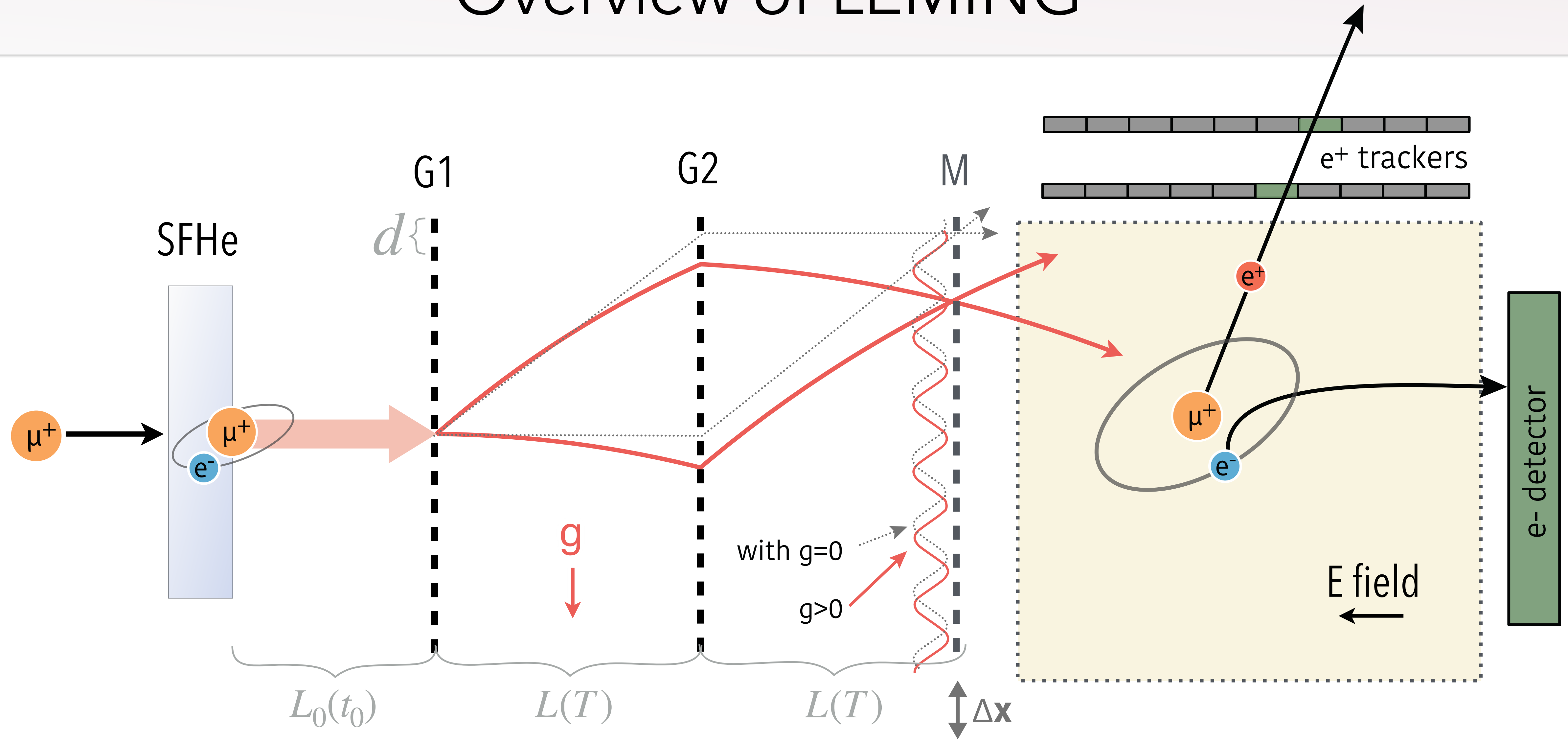


New!

Horizontal cold Mu beam

Atomic mirror / Microfluidic target

Interferometer

G1, G2 and mask M

Detection

e+/e- detectors

Sensitivity

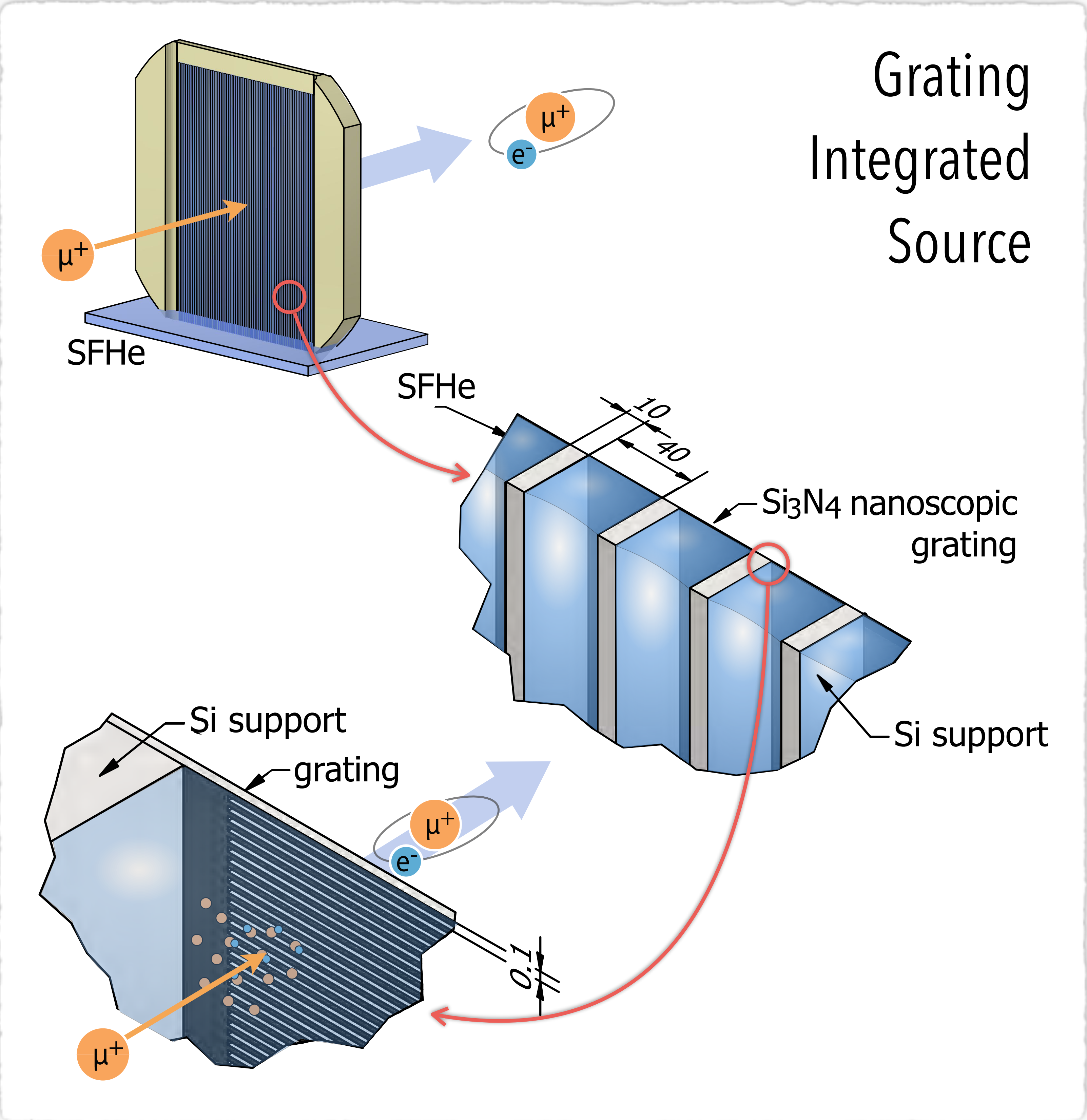
$$\Delta g \approx \frac{1}{2\pi T^2}\frac{d}{C\sqrt{N_0 \varepsilon \eta^3 e^{-(t_0+2T)/\tau}}}$$

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

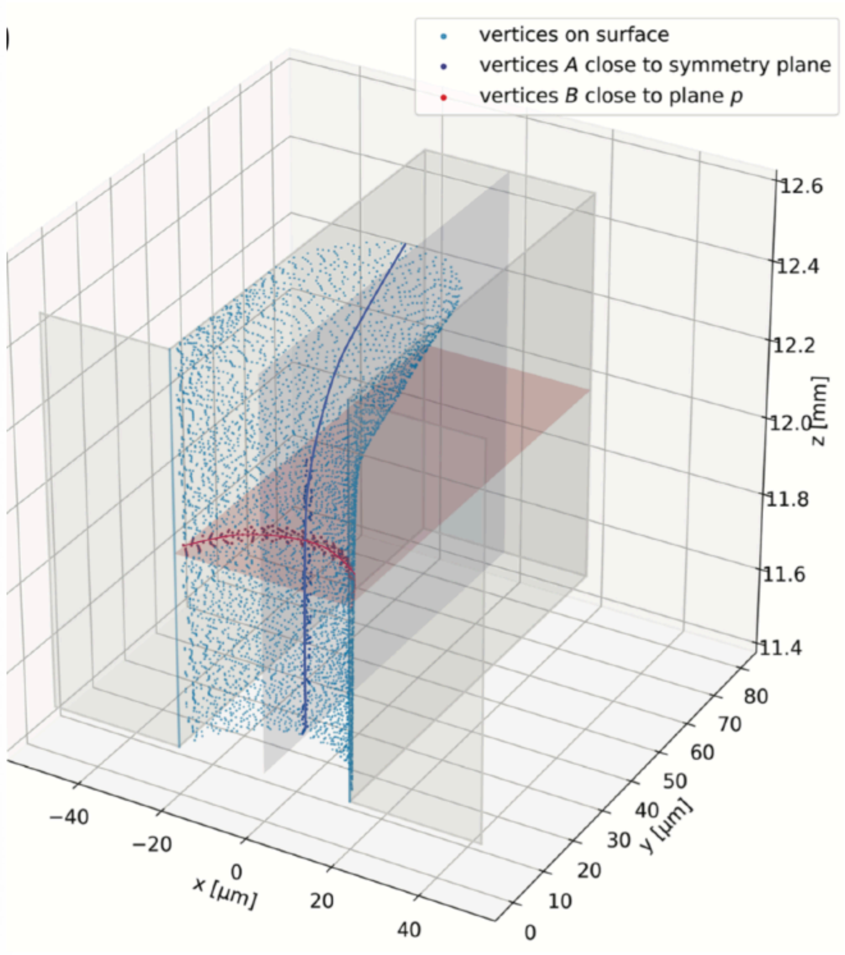
~ 1% sensitivity

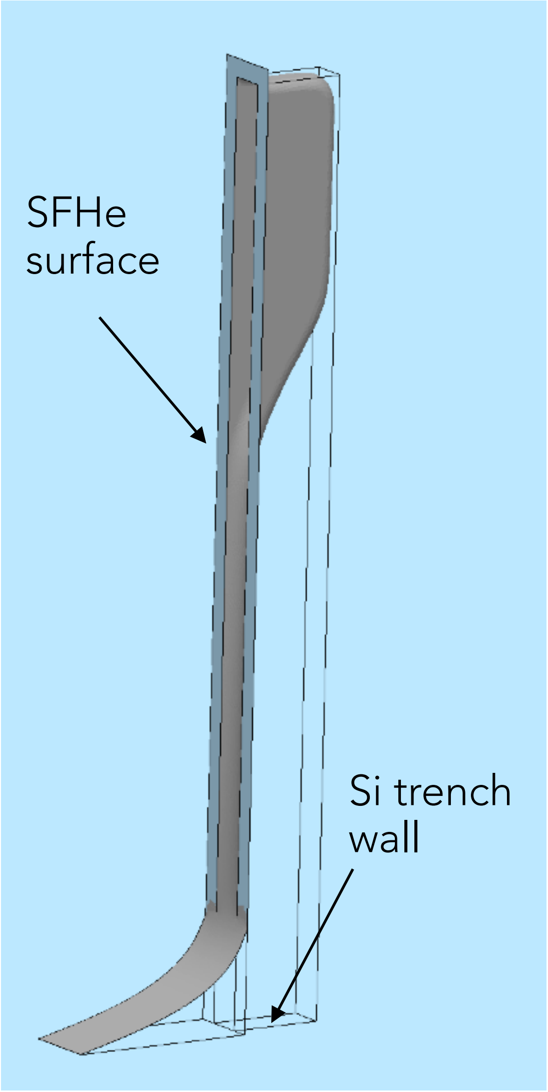
At PSI, world's highest intensity cw muons

Novel source concept - microfluidic grating

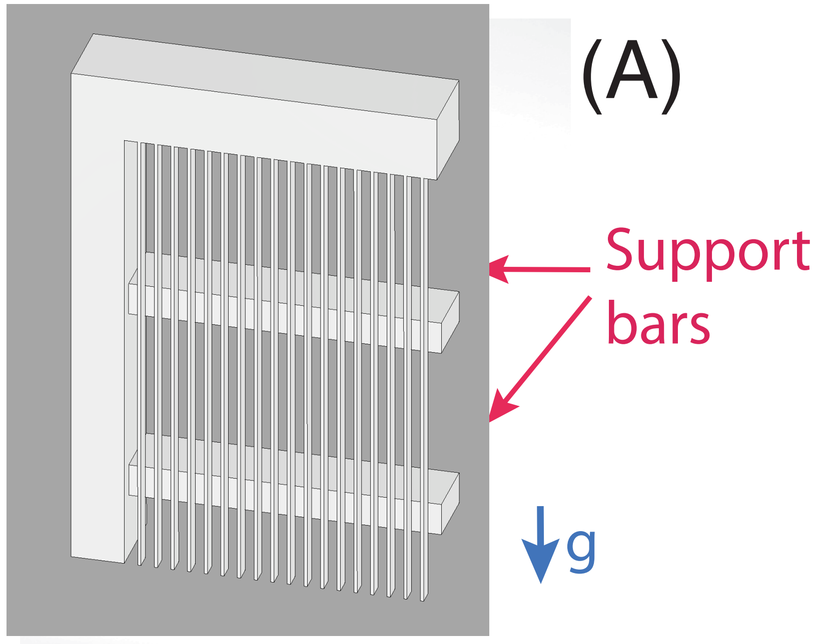


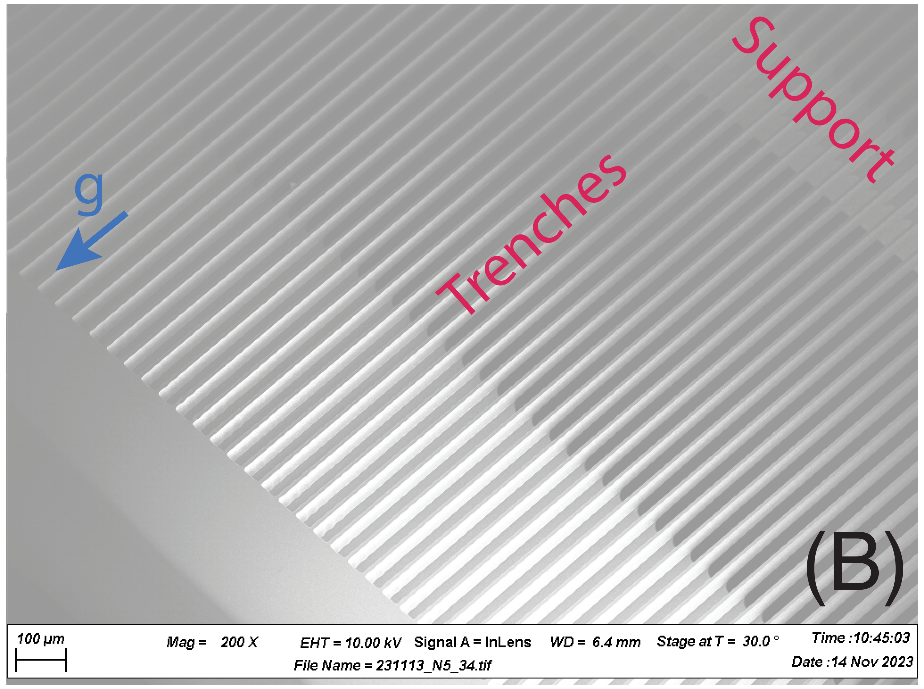
SFHe suspended by the capillary force, between support bars behind the first Si_3N_4 membrane

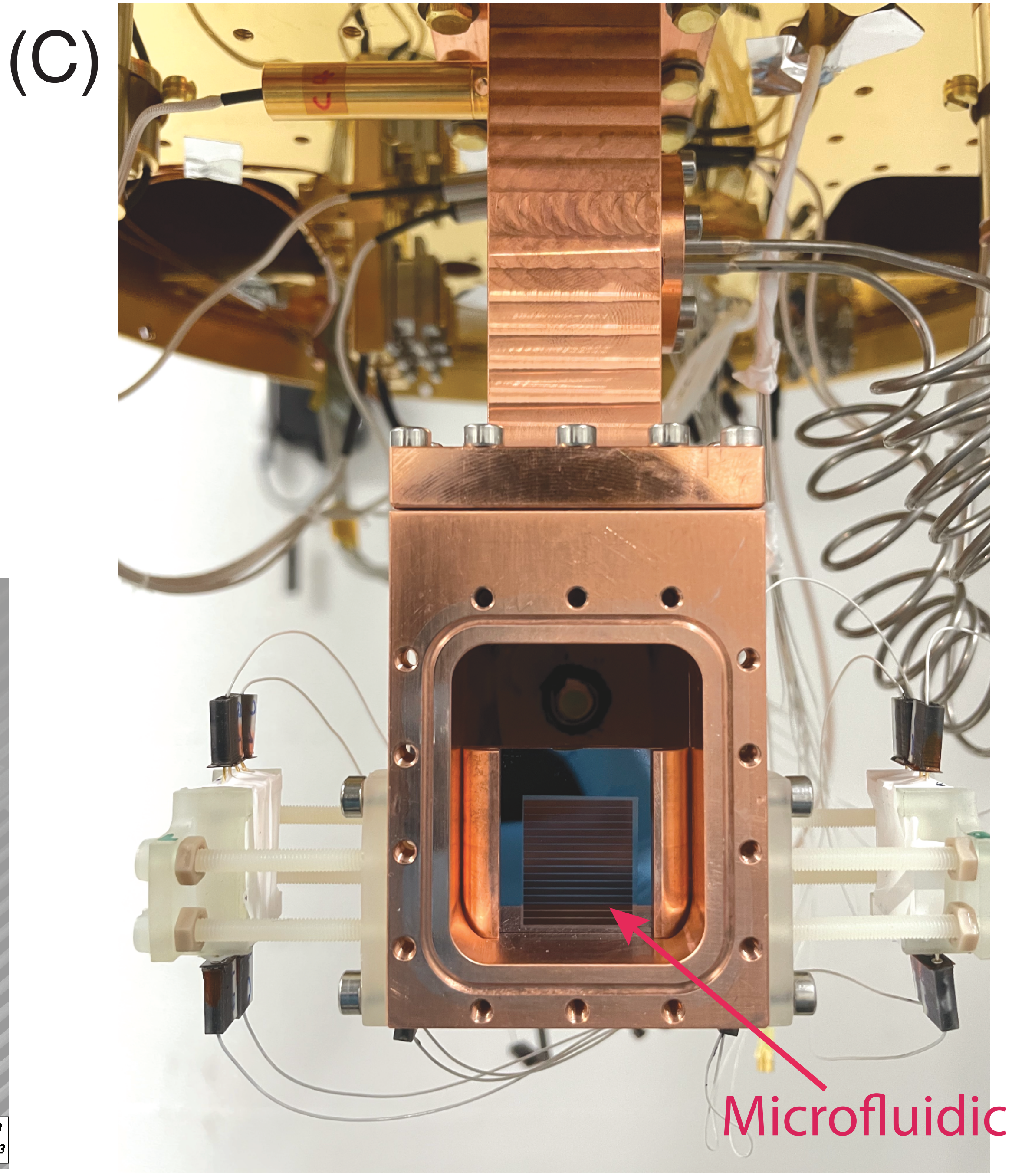


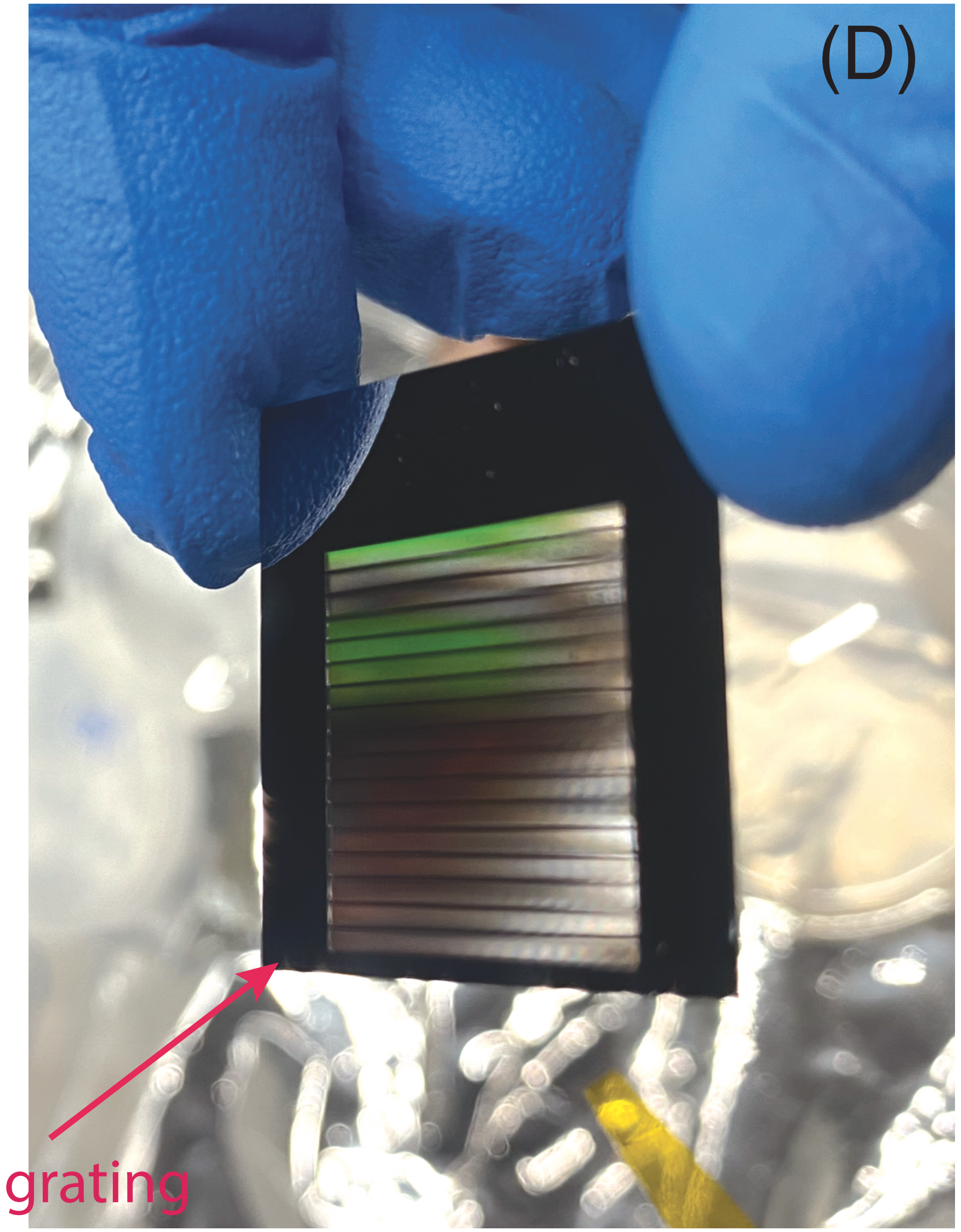


Microfluidic grating prototype









Prototype made by Konstanins Jefimovs, LNQ, PSI

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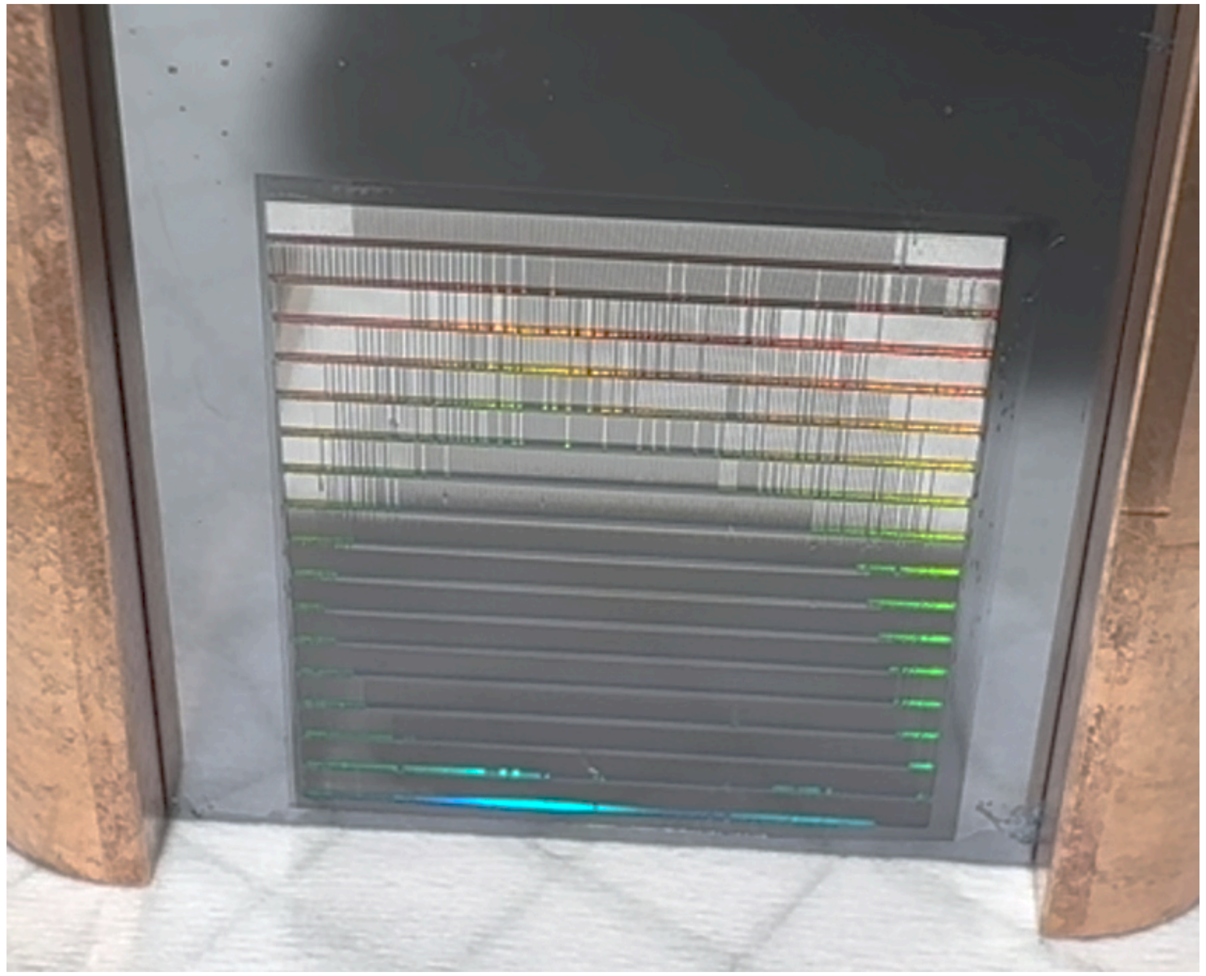
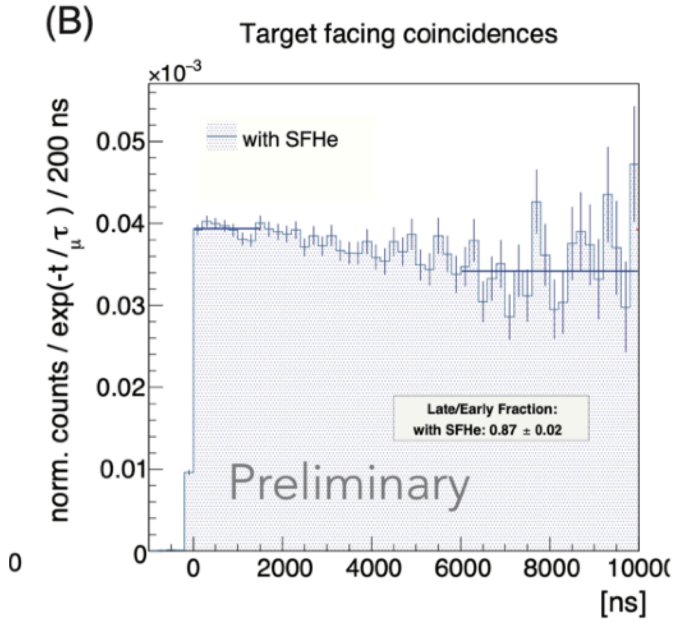
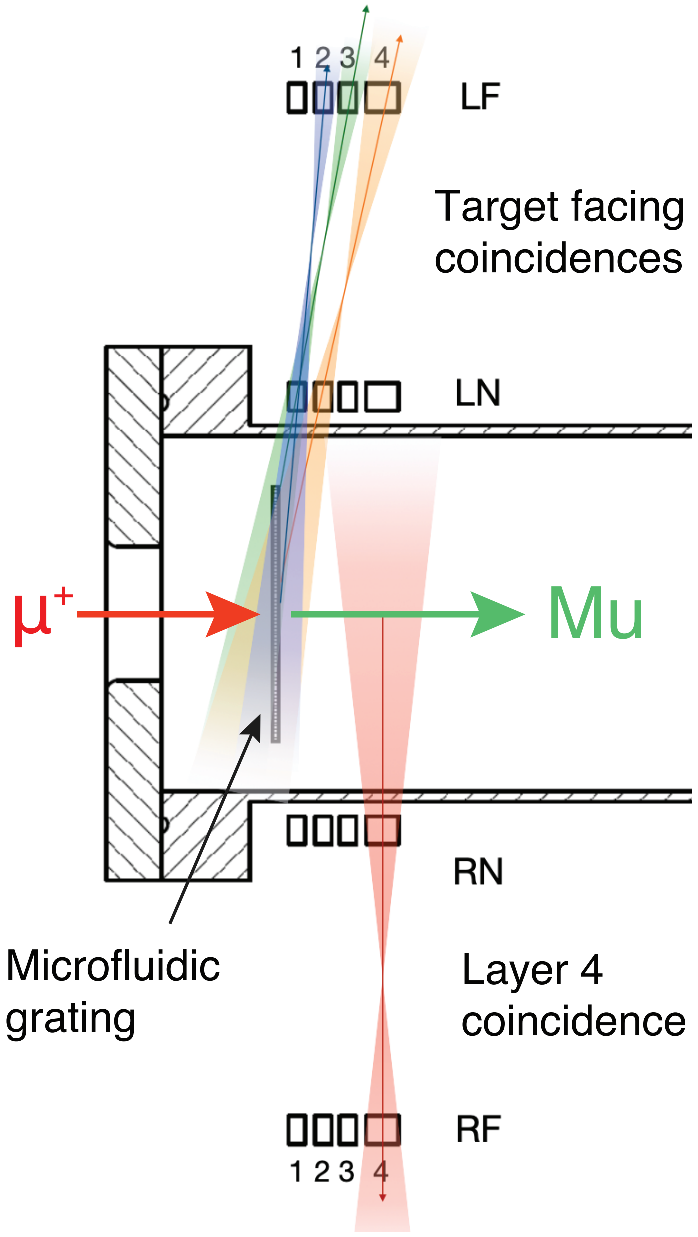


Acetone drying up from the grating

- 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





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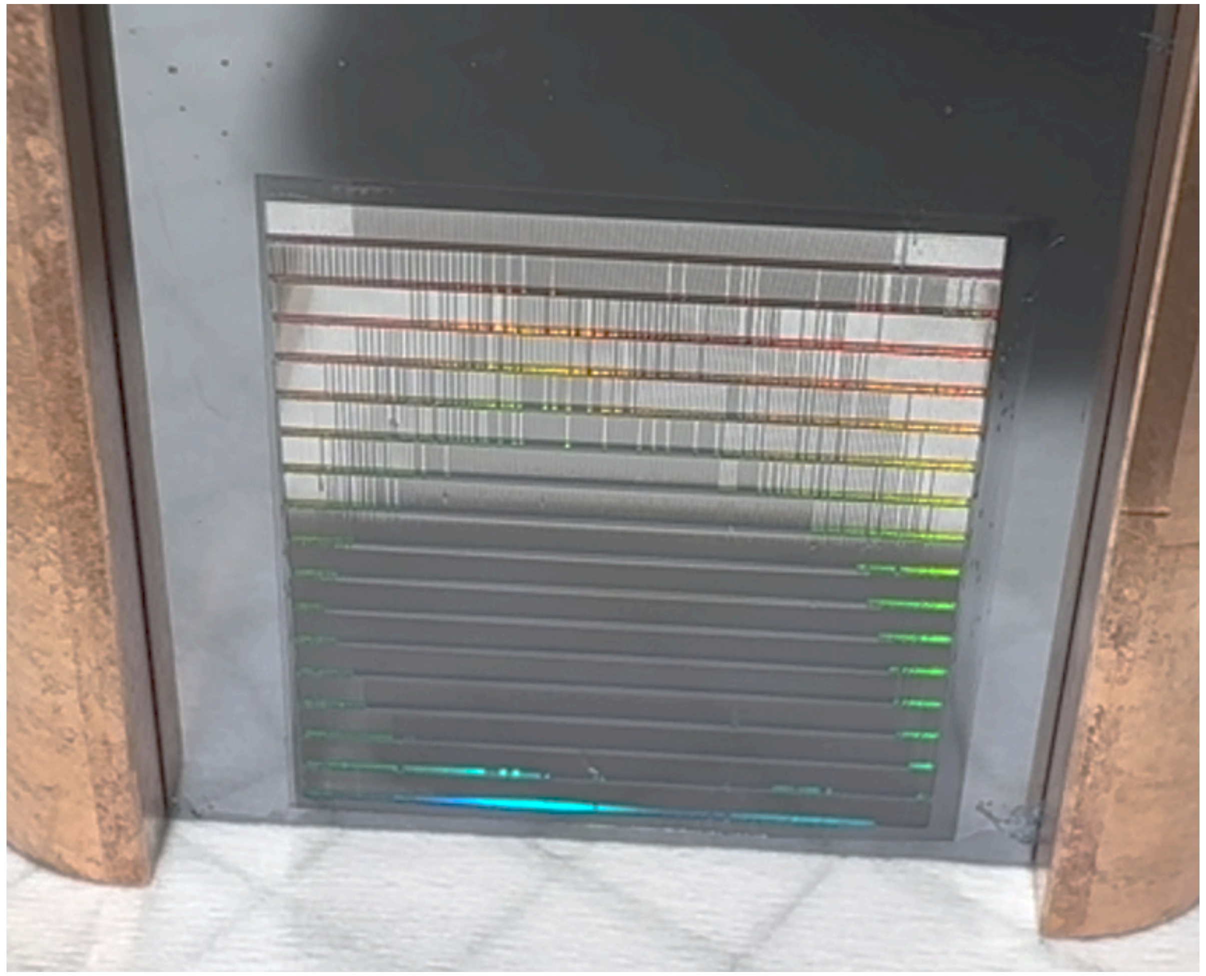

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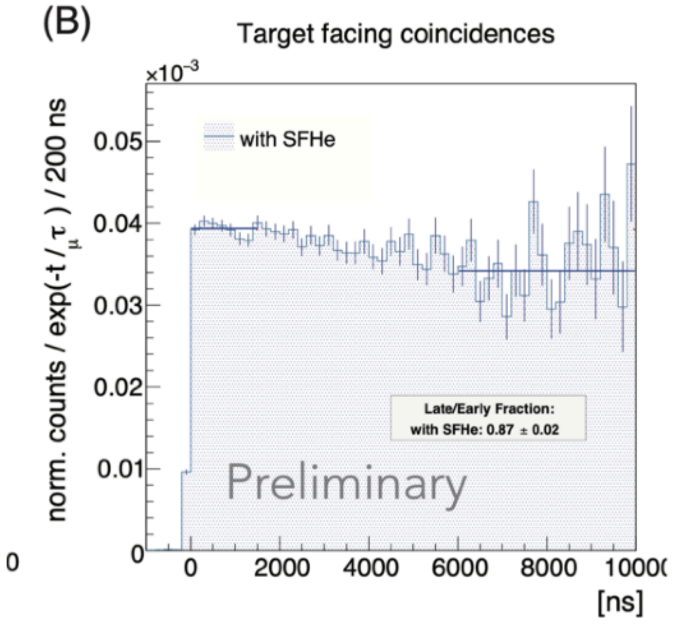
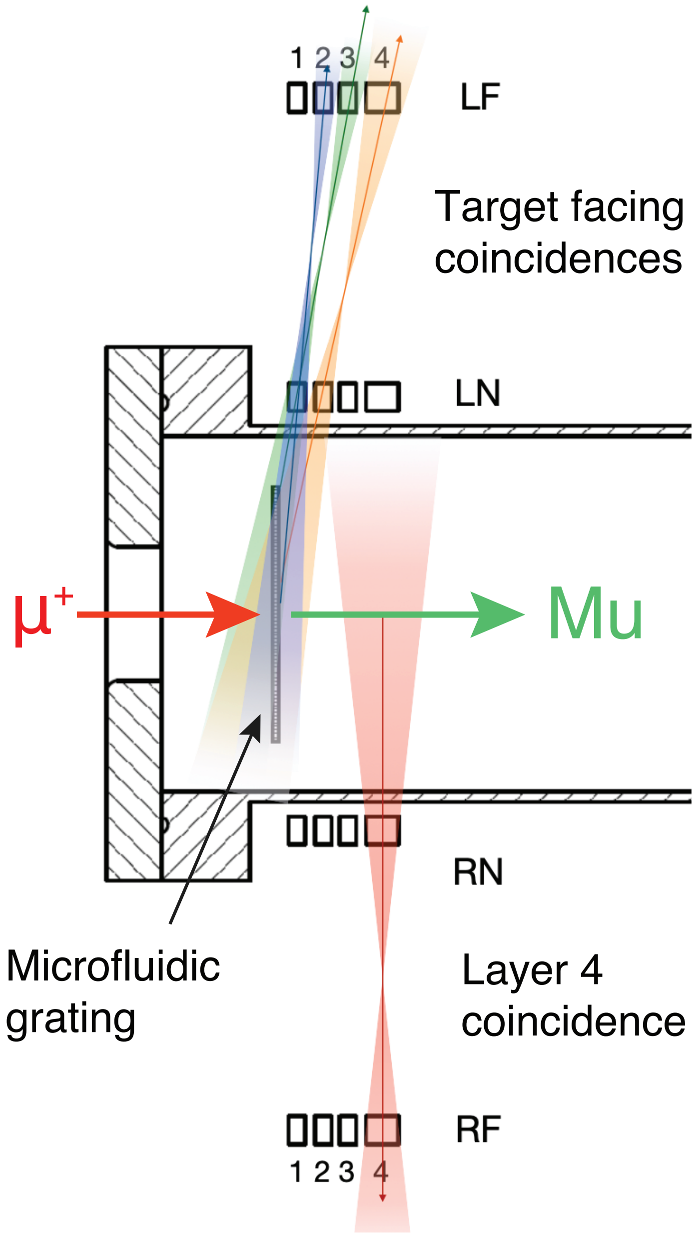
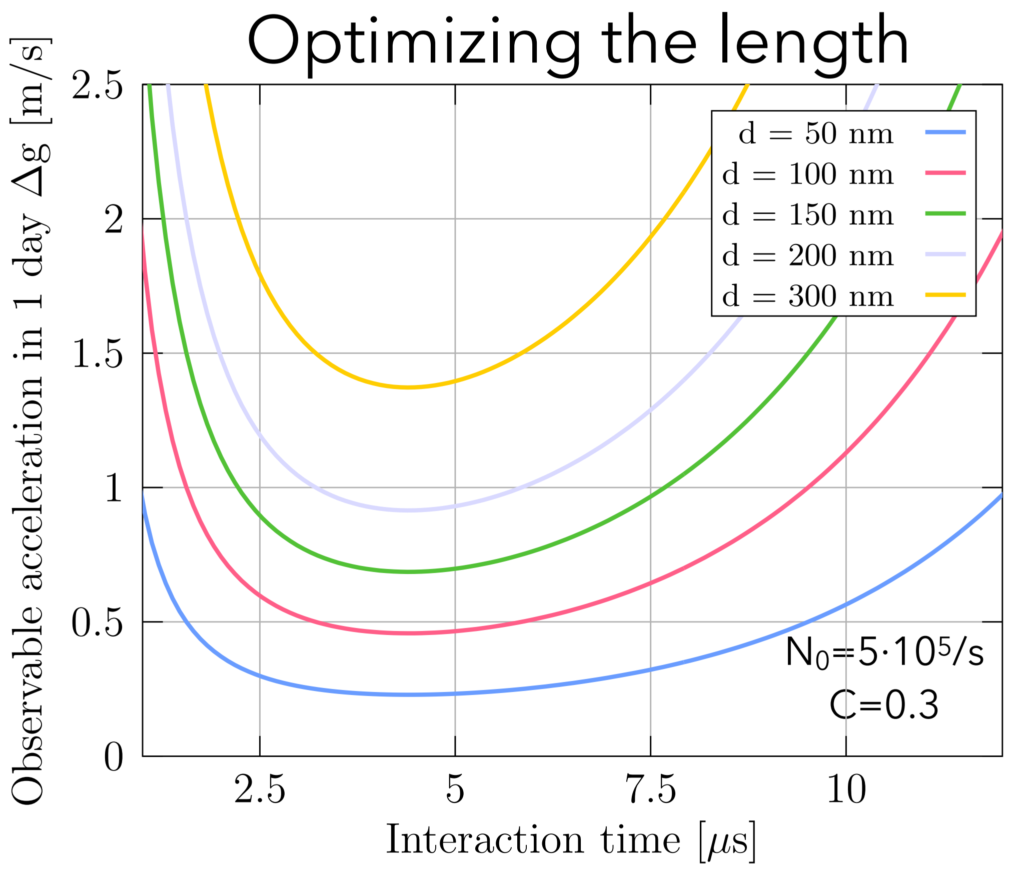




Projected sensitivity with high intensity muon beams



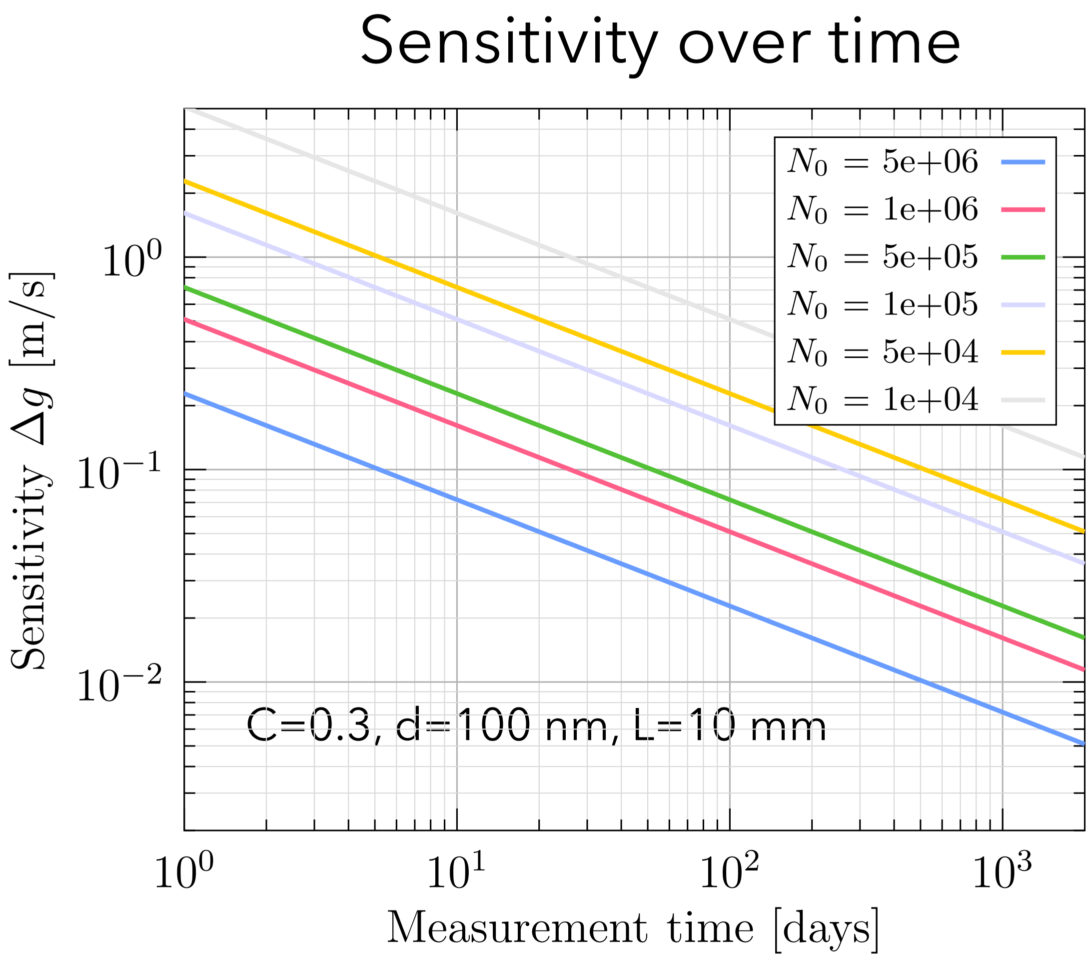
With λ_{Mu} = 1.6 nm (SFHe beam) L_0=3 mm, L=10 mm, d=100 nm, C=0.3 ($L_T = d^2/\lambda$ = 6 μm), η=0.3, ε=0.7

Determining sign of g: less than a day with Mu source of $N_0 > 5\cdot10^5$/s, C > 0.3

SFHe source @PSI:

10^5/s -10^6/s depending on muon beam scenarios

- I(p) ~ $p^{3.5}$
- Δp/p (FWHM) ~ 0.03 -0.1
- ΔE/E ~ 0.06 – 0.2



Beam	p [MeV/c]	Yield [μ^+/s]	1σ [mm]	Yield in d = 10 mm	Aerogel, back implantation 23 MeV/c (3%)	SFHe source, front implantation 12.5 MeV/c (10%)
piE5	**28**	**5×10^8**	**8.5**	**9.8×10^7**	**1.5×10^6**	**0.6×10^6 ***
HiMB-3	28	1×10^{10}	30	1.75×10^8	2.6×10^6	1.1×10^6 *

LEMING plans

Assuming success in 2024:

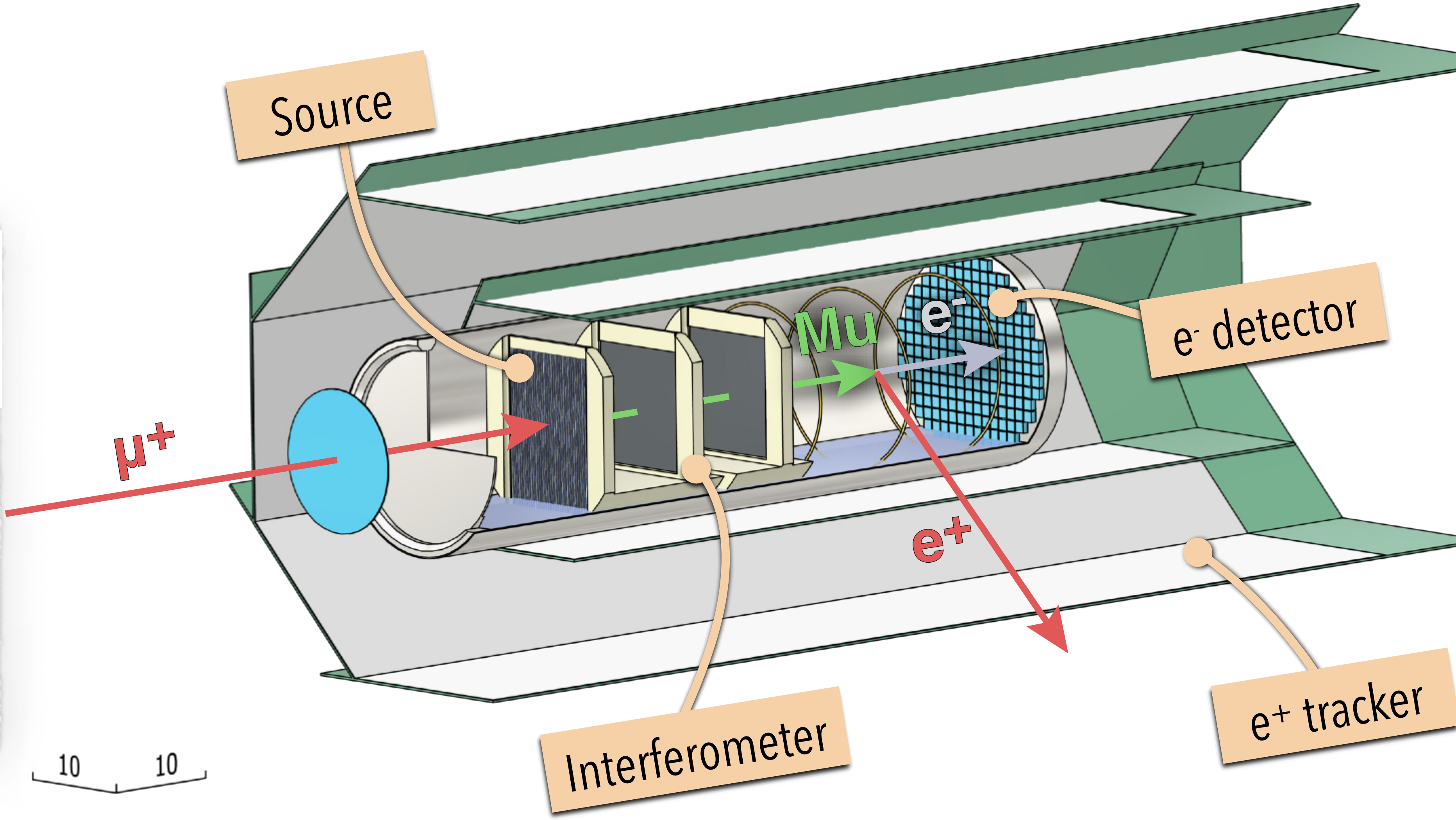
$$\Delta g \approx \frac{1}{2\pi T^2}\frac{d}{C\sqrt{N_0 \epsilon \eta^3 e^{-(t_0+2T)/\tau}}}$$

Grating period
~100 nm

Contrast
C=A /A_0~0.3

Atoms from source
$N_0 > 10^5$/s

Loss factor
$t_0 = 0$ s (!)

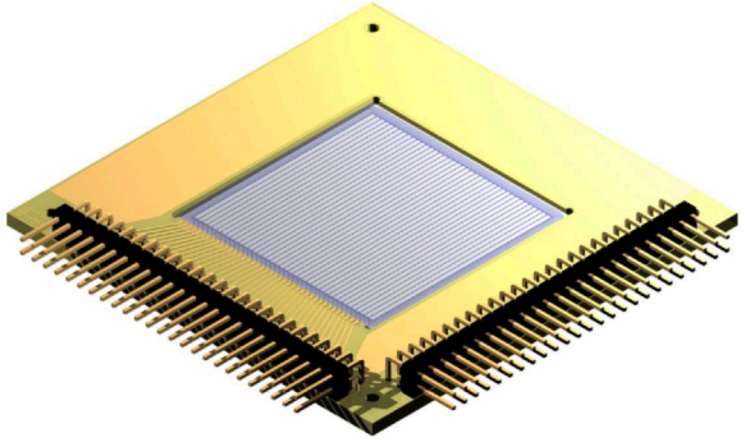


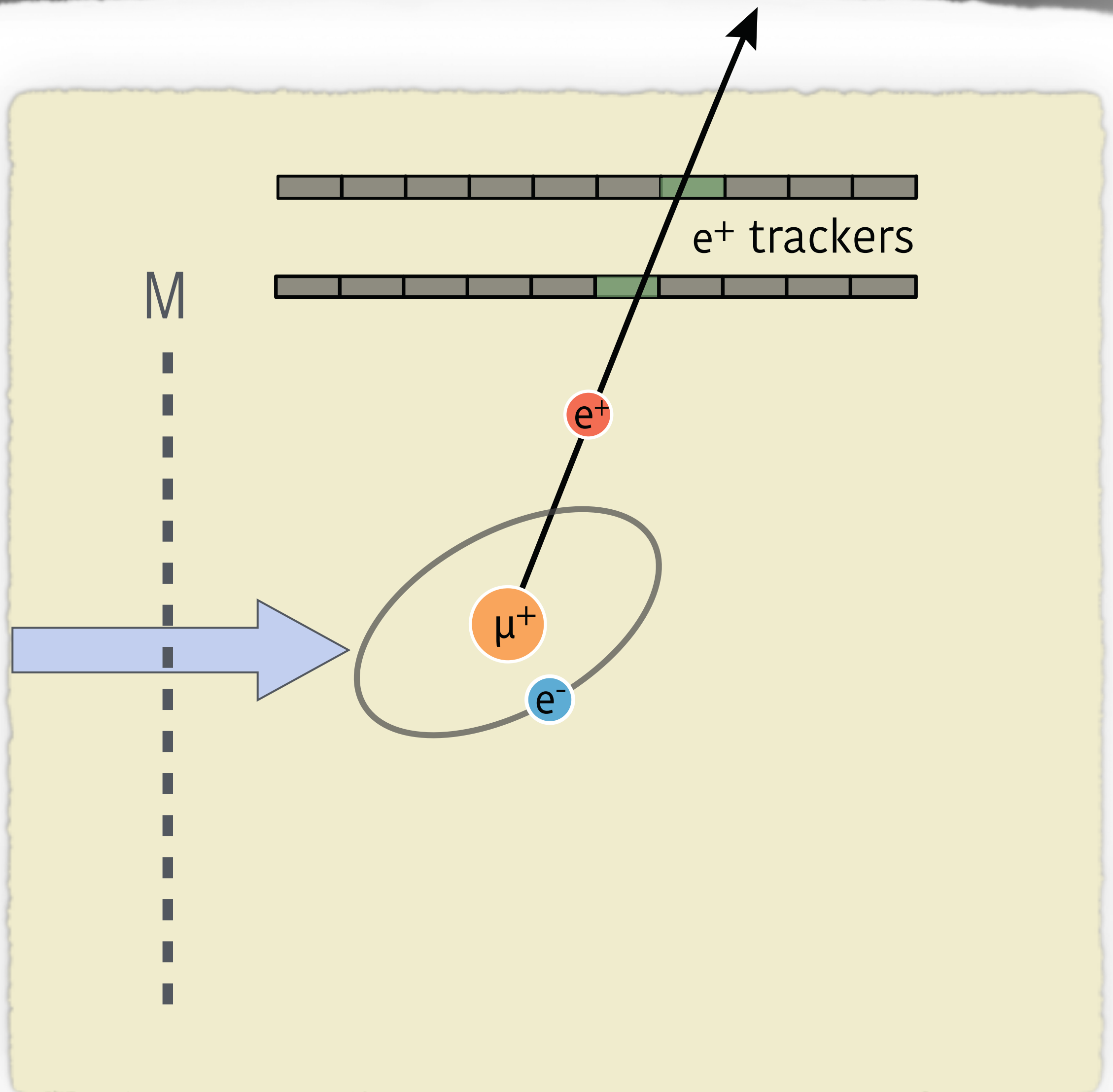
- The test beamtimes are reaching a conclusion
- Experimental layout taking shape, and a full TDR is possible
- Emphasis expected to shift towards the interferometer

Plans 1: Cryogenic detector and source

Positron tracker

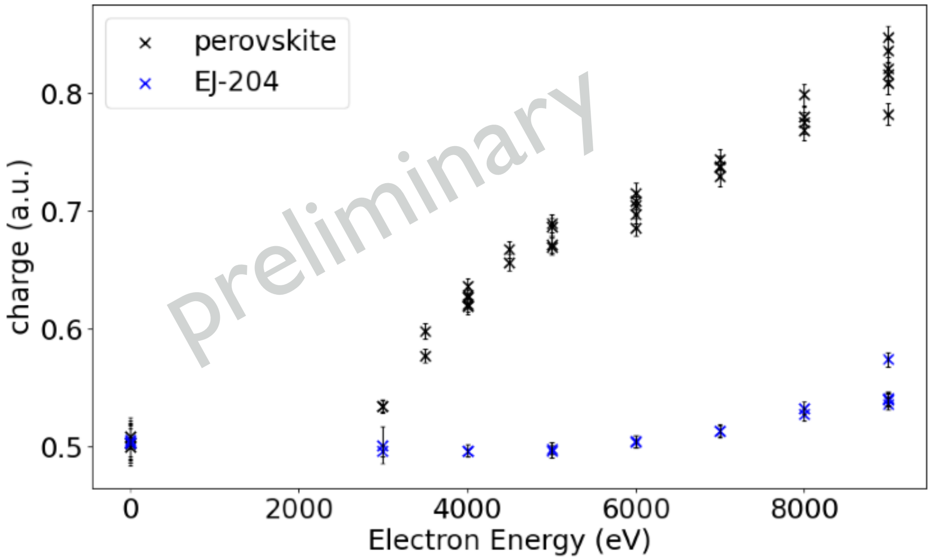
- 1 K temperature, limited cooling power
- low noise, decoupled preamplifiers

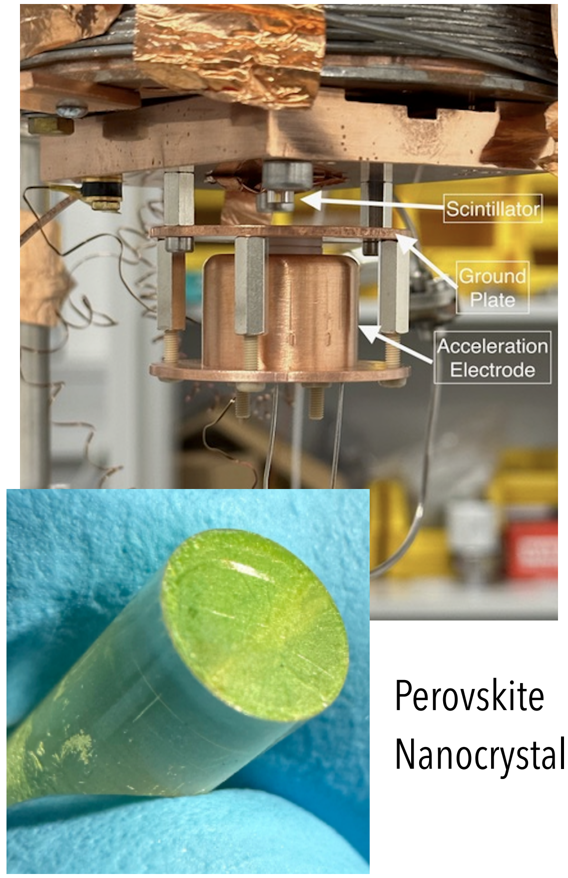




Electron counter

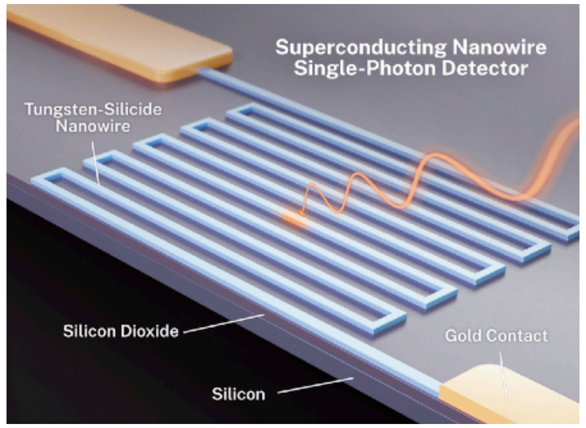
- low threshold (~keV)
- 0.1 K "wet" environment with SFHe film





Perovskite Nanocrystals

- perovskite nanocrystals with an onset at 2.5 keV
- fast TES: superconductive nanowires



Superconductive nanowires

J. Zhang *et al* 2022 *JINST* **17** P06024

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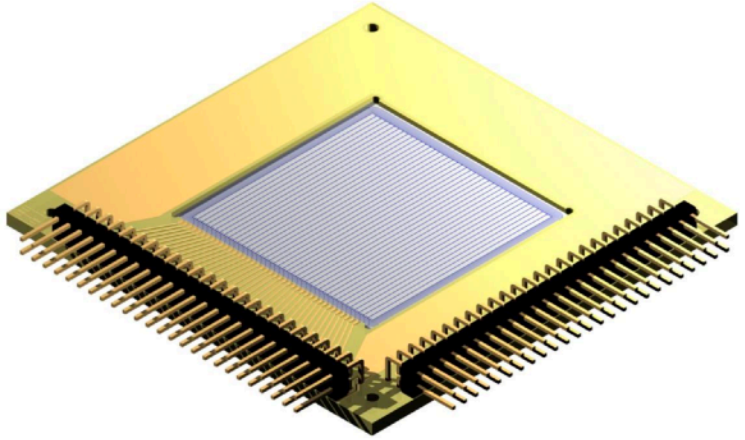
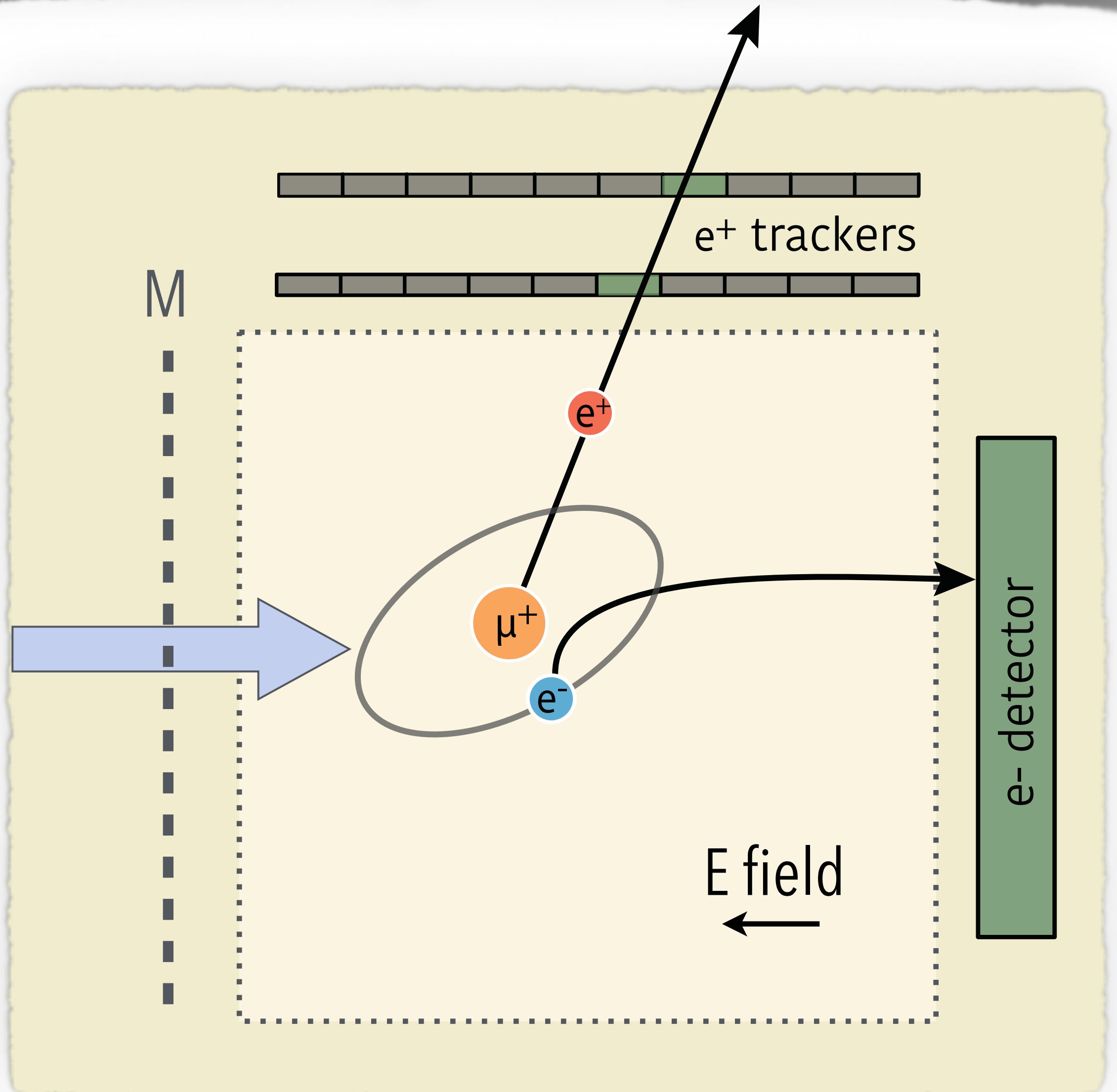
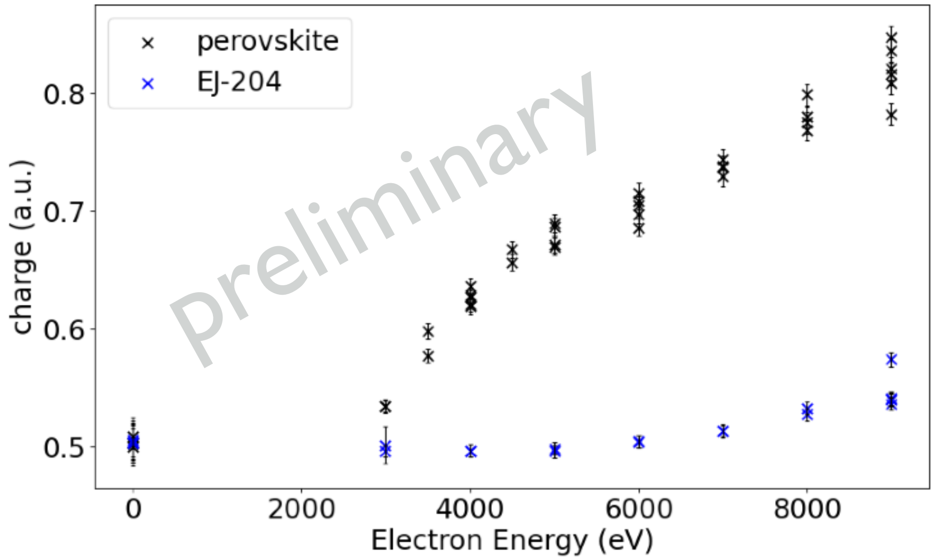
- 1 K temperature, limited cooling power
- low noise, decoupled preamplifiers

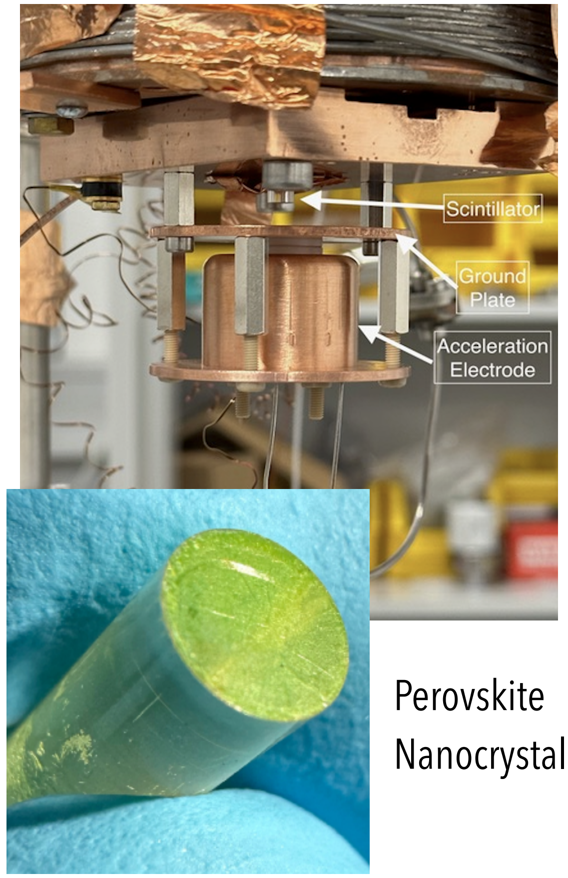




Electron counter

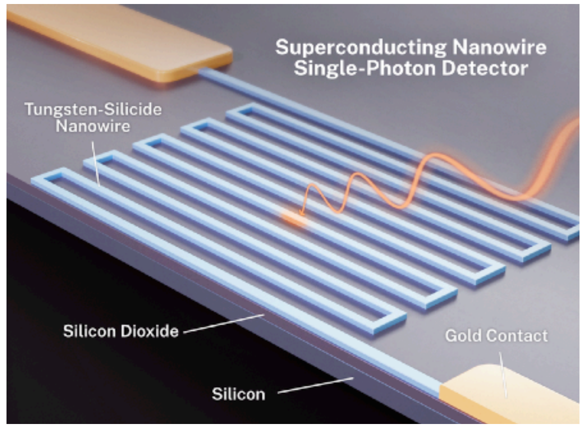
- low threshold (~keV)
- 0.1 K “wet” environment with SFHe film





Perovskite Nanocrystals

- perovskite nanocrystals with an onset at 2.5 keV
- fast TES: superconductive nanowires

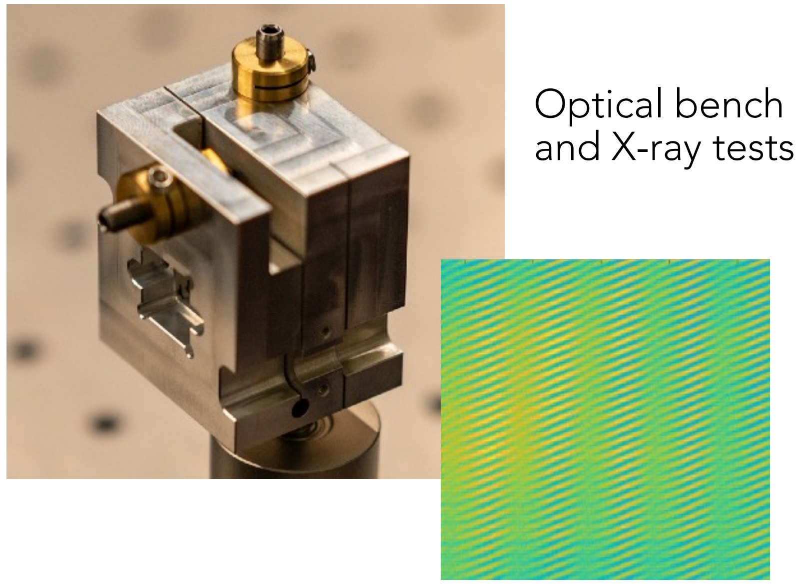


Superconductive nanowires

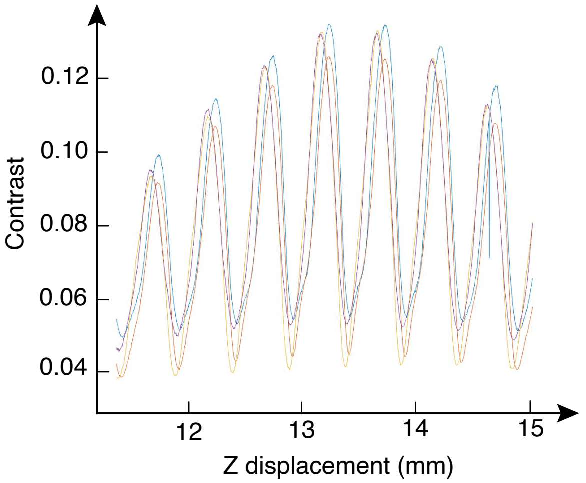
J. Zhang *et al* 2022 *JINST* **17** P06024

Interferometer prototyping

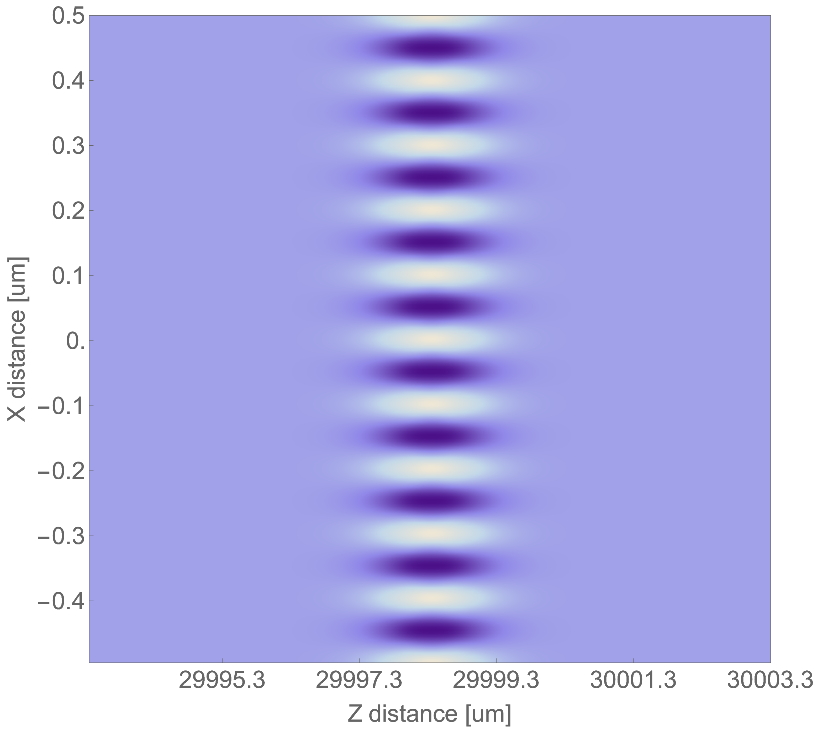
Scanning, stabilization, calibration



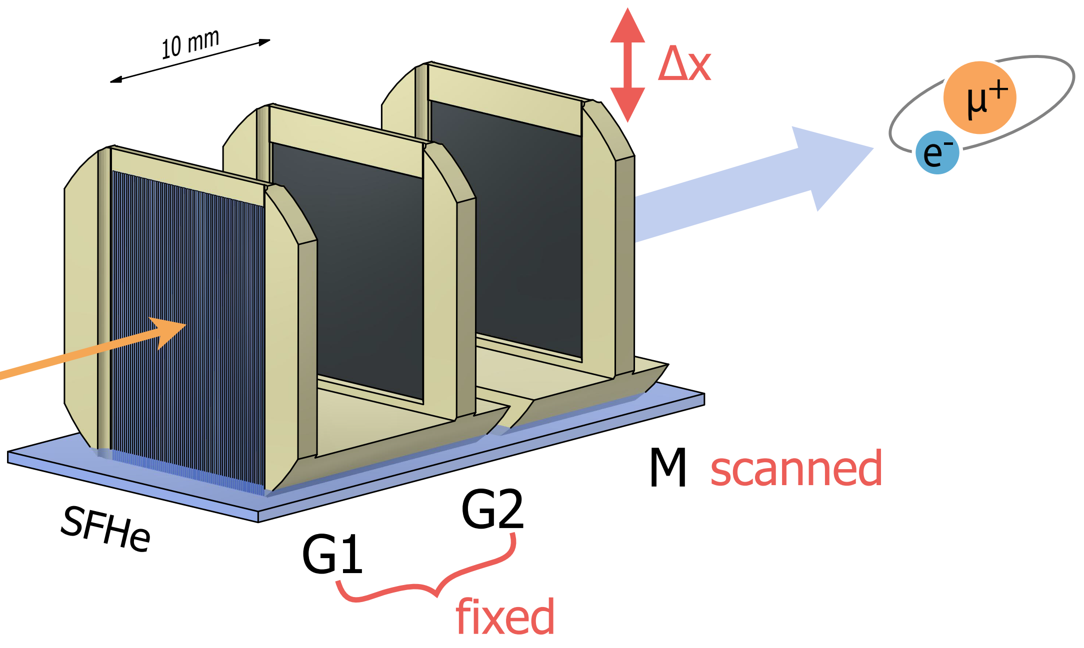
Optical bench and X-ray tests



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

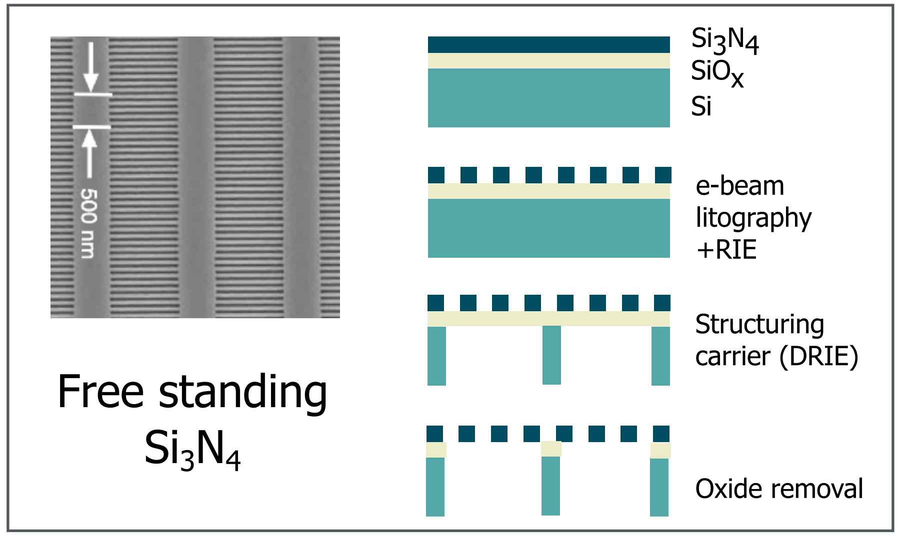


Fabrication



Mono-crystalline Si raft

+

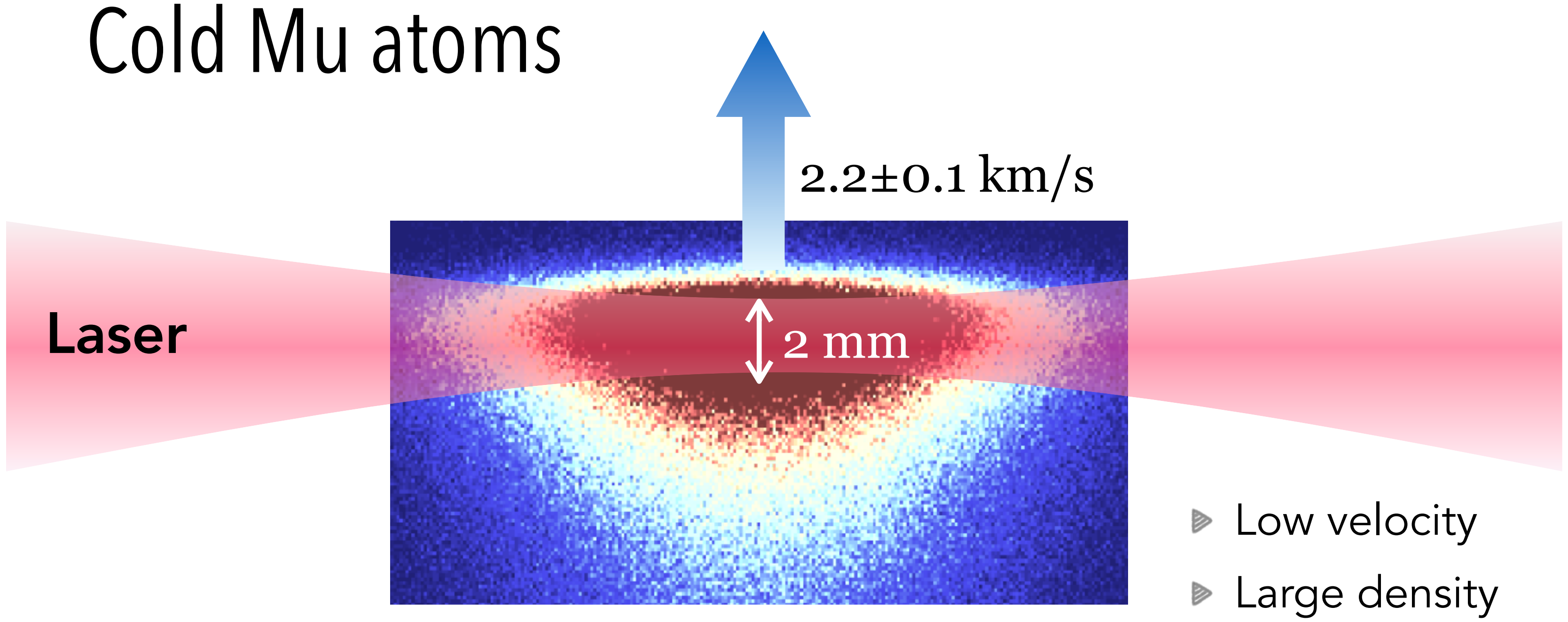


Free standing Si_3N_4

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

Impact beyond gravity, spin-offs

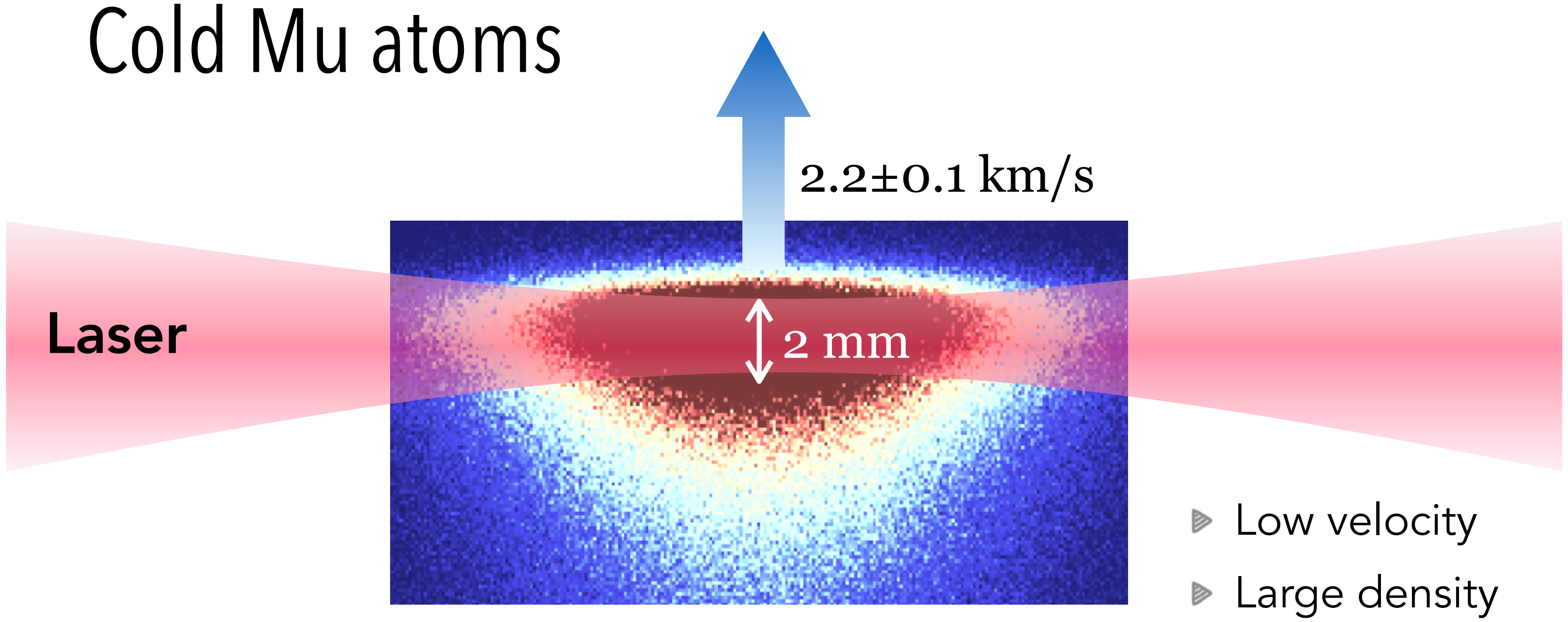
Cold Mu atoms



- Low velocity
- Large density phasespace

Impact beyond gravity, spin-offs

Cold Mu atoms

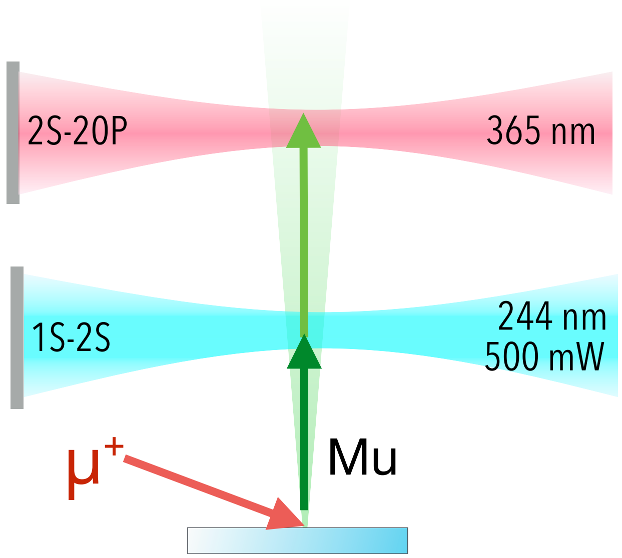


- Low velocity
- Large density phasespace

1S-2S Laser Spectroscopy

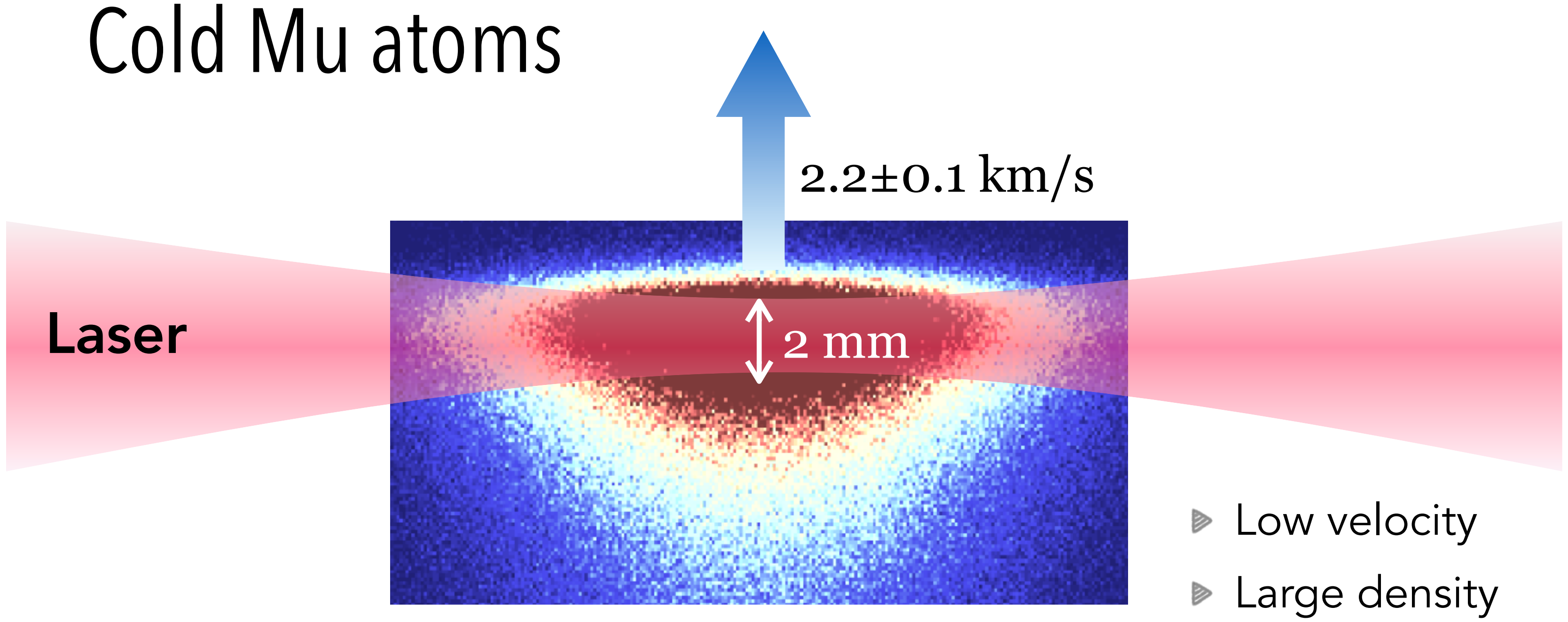
Possibility for sub-kHz (~10^{-12}) spectroscopy

- Statistics $\sim \times 10^3$
- Transit-time broadening $\sim 1/3$
- Second order Doppler shift $\sim 1/10$



Impact beyond gravity, spin-offs

Cold Mu atoms



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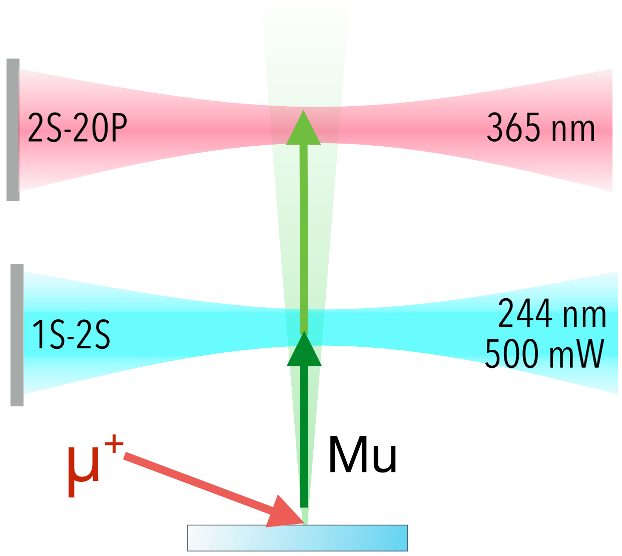
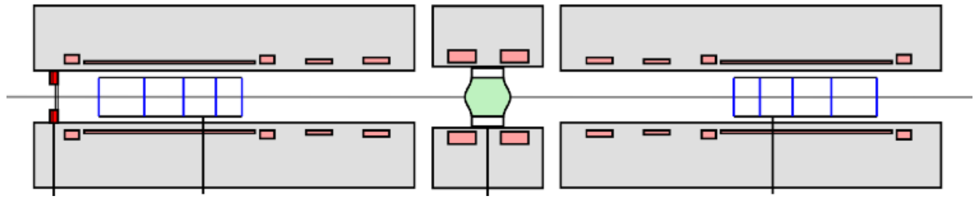


High brightness muon beam

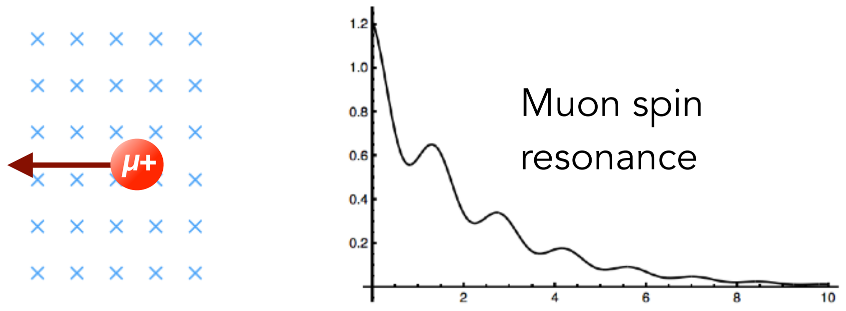
Muon colliders

Sustainable, precision HEP



Alternative to ionization cooling (MICE), *Nature* **578** (53-57) 2020

Solid state physics, muon EDM



Thank you!

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