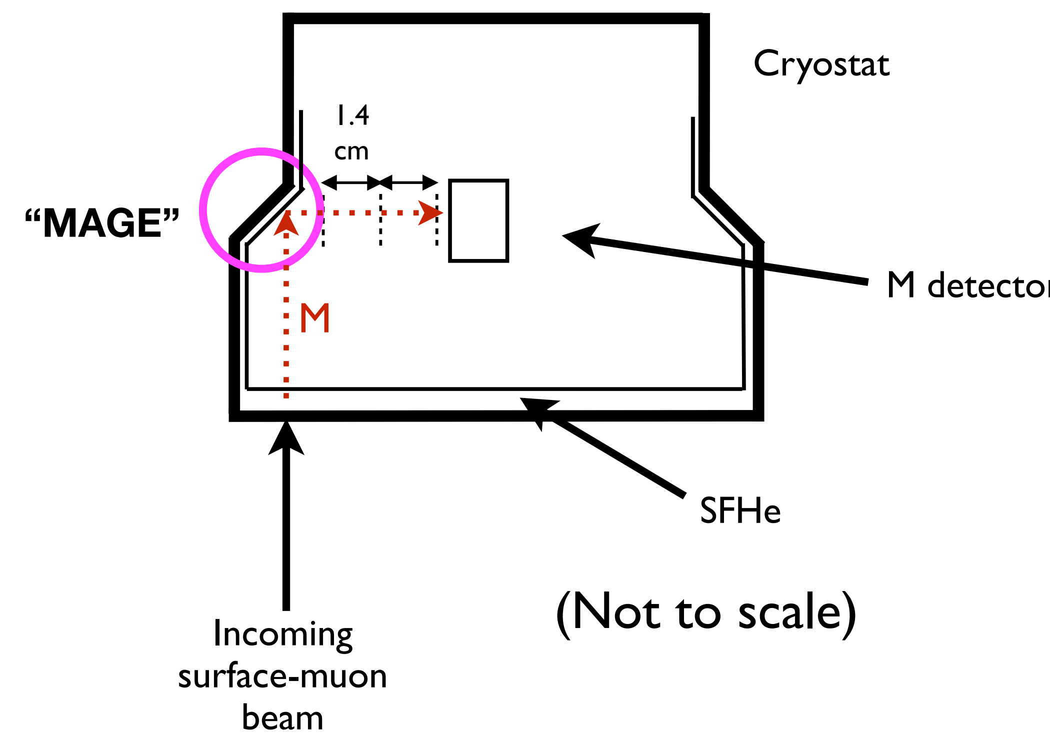
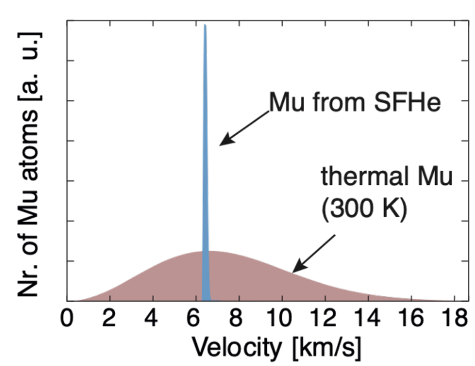
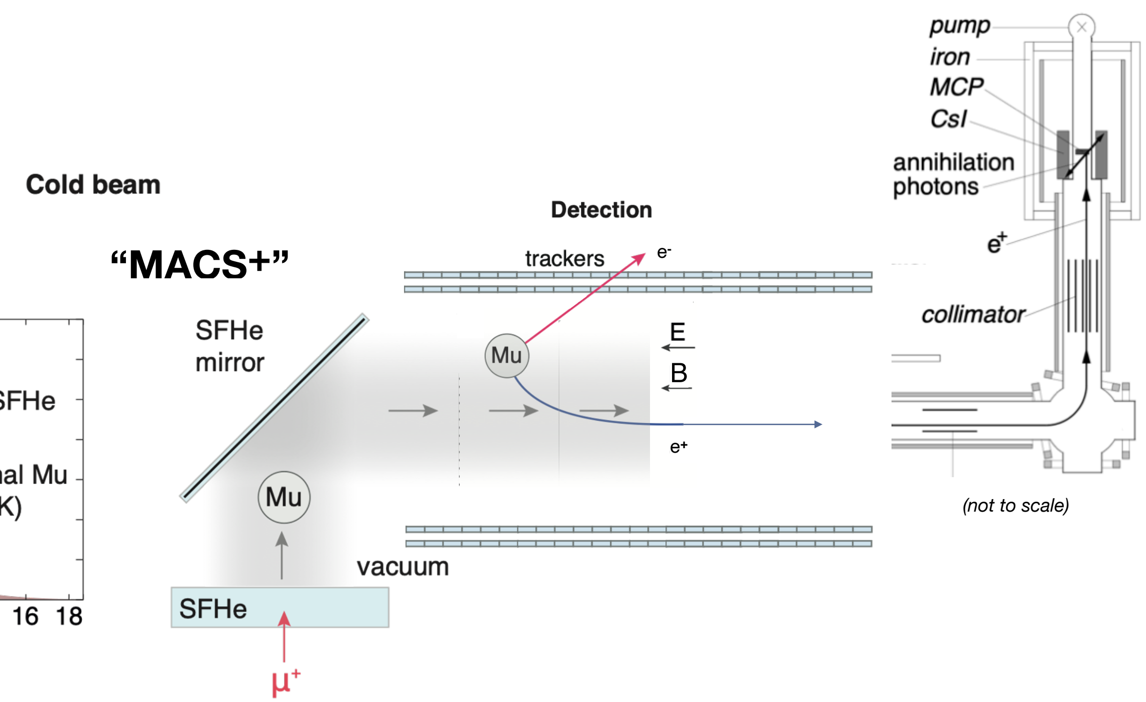
Overview of Slow-Muonium Experiments



Daniel M. Kaplan

ILLINOIS INSTITUTE OF TECHNOLOGY





Workshop on Low-Energy Muon and Muonium Experiments and R&D
Fermilab
14 July 2022

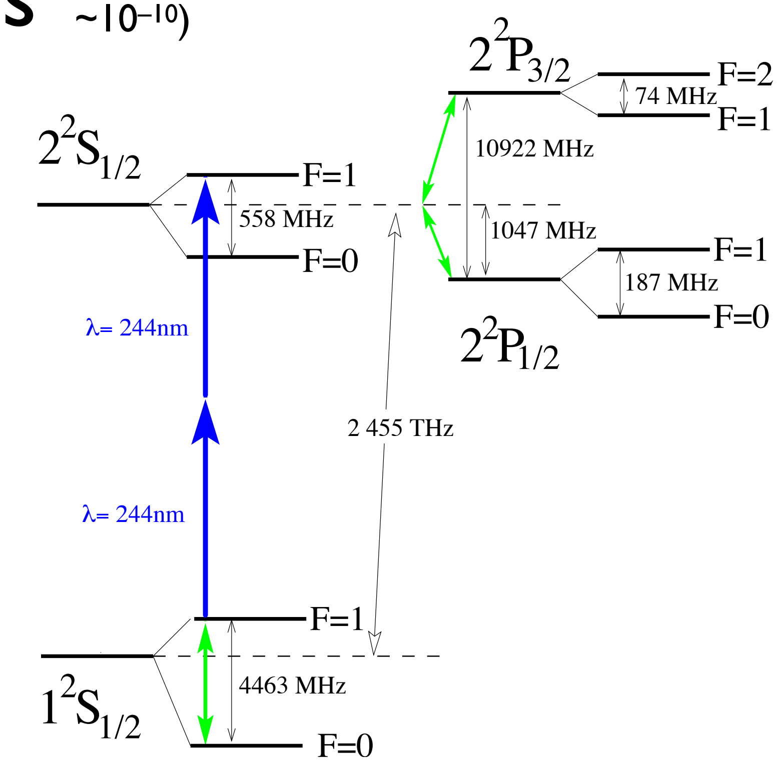
Outline

- Motivation
- Muonium
  - precision spectroscopy
  - oscillation search
- Studying antimatter gravity
- Muonium Antimatter Gravity Experiment
- Fermilab advantages
- Conclusions

Why Muonium?

- Much is known about muonium… (AKA M, or Mu)
  - a *purely leptonic atom*, discovered 1960

    [V. W. Hughes et al., "Formation of Muonium and Observation of its Larmor Precession," Phys. Rev. Lett. 5, 63 (1960)]
  - decays to e^+ (fast) + e^- (slow), $\tau_M = \tau_\mu = 2.2\ \mu s$ (bound-state correction ~10^{-10})
  - readily produced when μ^+ stop in matter
  - chemically, almost identical to hydrogen
  - atomic spectroscopy well studied
  - forms certain compounds (MuCl, NaMu,...)
  - "ideal testbed" for QED, the search for new forces, precision measurement of muon properties, etc.
  - also useful for materials science



Muonium Spectroscopy

49 Page 2 of 9 Hyperfine Interact (2018)

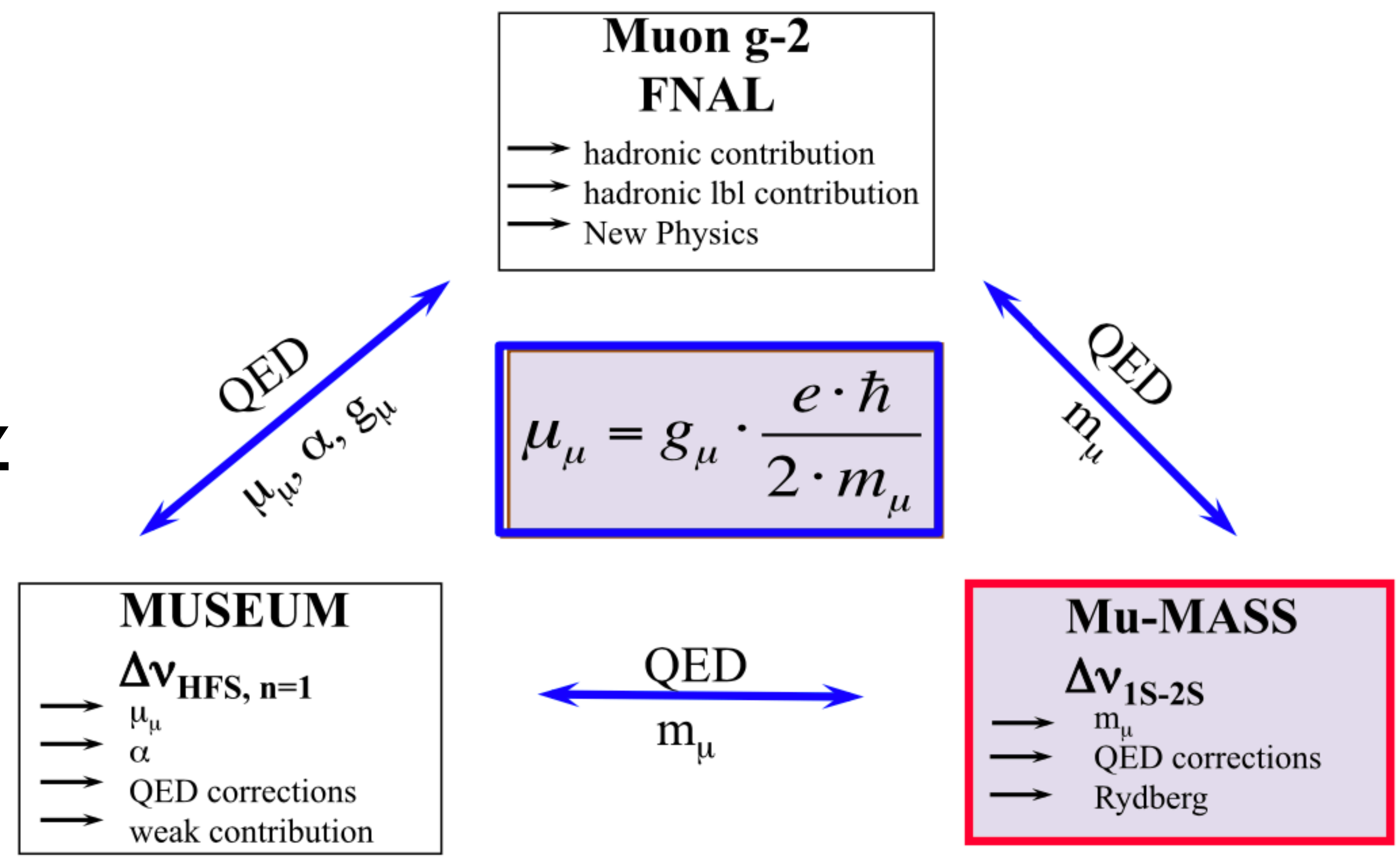


Fig. 1 Fundamental constants in the muon sector and related experiments (adapted from [42])

- M 1S-2S transition frequency (theory) = 2,455,528,935.4(1.4) MHz
  - 0.6 ppb QED prediction!
  - M atom composed of 2 point-like leptons
    - hadronic & finite-size corrections negligible!

[P. Crivelli, "The Mu-MASS (muonium laser spectroscopy) experiment," Hyp. Int. **239** (2018) 1]

- Measured (1999) to 9.8 MHz (4 ppb) at RAL
  - & similar story for M hyperfine splitting: measured (1999) to 12 ppb at LAMPF

[V. Meyer et al., "Measurement of the 1s–2s Energy Interval in Muonium," Phys. Rev. Lett. 84, 1136 (2000);
I. Fan et al., Phys. Rev. A **89**, 032513 (2014)]

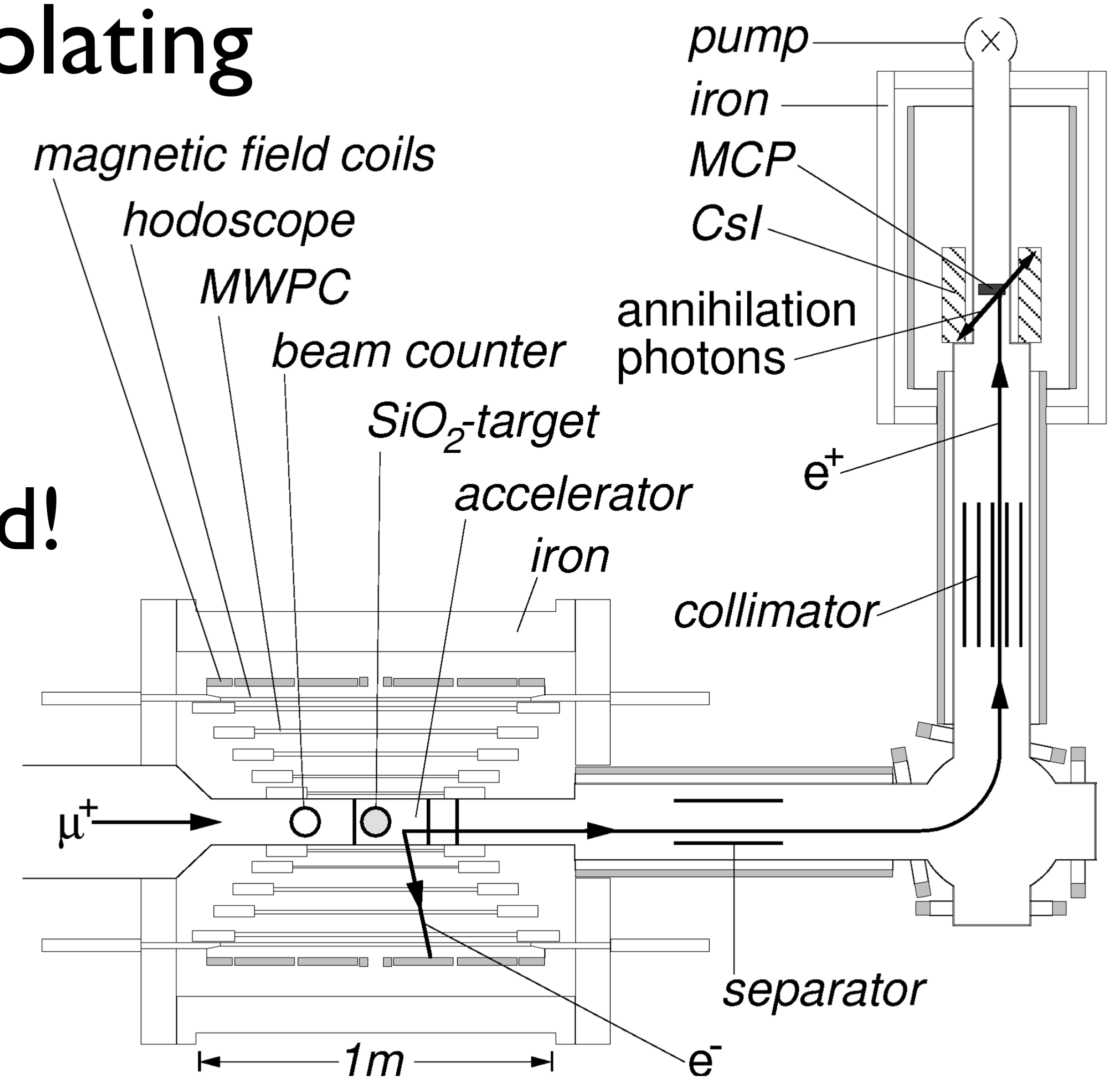
Muonium Spectroscopy

- New 1S-2S experiment, Mu-MASS, now in R&D/commissioning stage at PSI
  - goal: improve sensitivity x1000 (<10 kHz), 4 ppt
  - systematics expected to dominate
    - PIP-II muon rate (~3 orders higher than current PSI) would help – let's discuss!
      - will allow better handle on systematics (per Crivelli)
- Also MUSEUM in progress at J-PARC
  - goal: improve hyperfine sensitivity x10 (1 ppb)

Muonium Double CLFV?

simultaneous $\begin{cases} \mu^+ \to e^+ \\ e^- \to \mu^- \end{cases}$

- Muonium-antimuonium (M-$\overline{\text{M}}$) oscillation would be doubly charged-lepton-flavor violating
- Nothing forbids it *except* lepton-flavor conservation
  - which we know (ν mixing) is violated!
    - but M ↔ $\overline{\text{M}}$ via virtual ν mixing negligible
    - background-free search for new physics!
- Current limit set by MACS (1999) at PSI: $P_{M\overline{M}} \leq 8.3 \times 10^{-11}$ (90% C.L.) in 0.1 T field



Willmann talk

[L. Willmann et al., "New Bounds from a Search for Muonium to Antimuonium Conversion," PRL **82** (1998) 49]

Muonium Double CLFV?

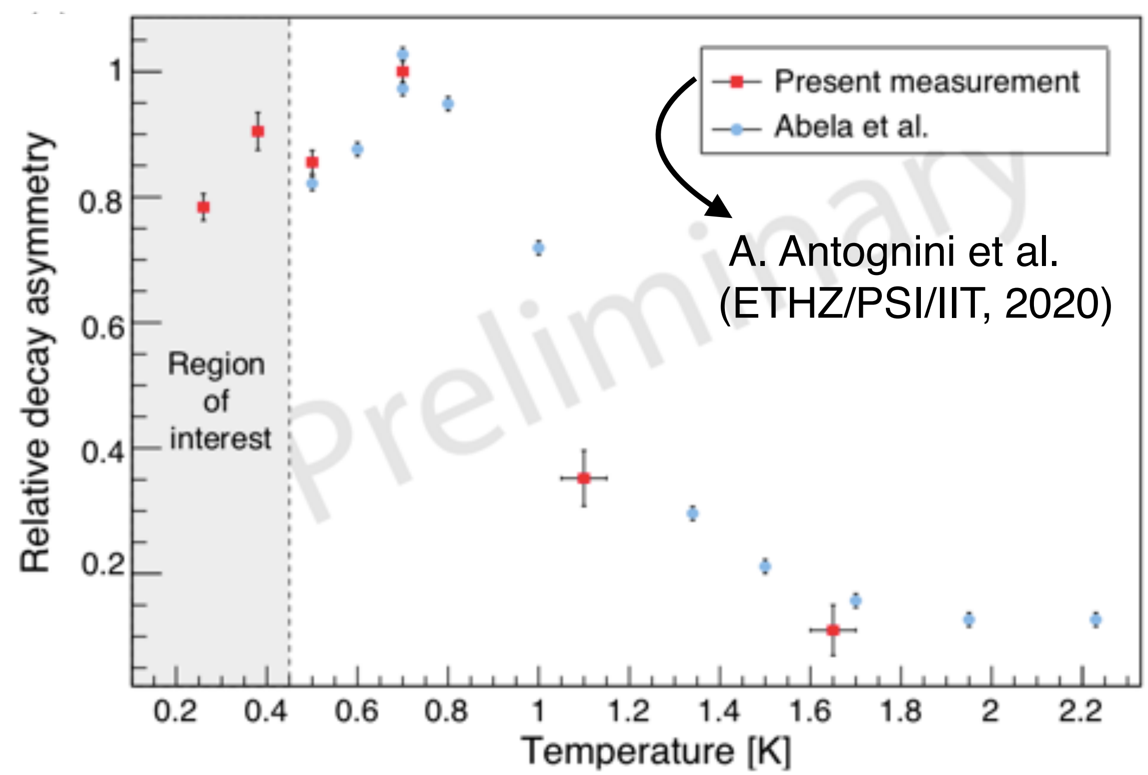
- Can one now do better?
- I think so!
  - now know how to make slow, quasi-monochromatic M source – a game changer!
  - based on behavior of μ^+ in superfluid He

Phillips talk

Novel Cryogenic M Source

- Need low-divergence beam of slow muonium traveling in vacuum – ∃ nowhere
- Proposals by D. Taqqu of Paul Scherrer Institute (Swiss national laboratory ≠ CERN):
  - stop slow (keV) muons in ~ μm-thick layer of superfluid He (SFHe)
    - or (T. Phillips) use ~ 100 μm SFHe layer for ~ 10^2 ↑ intensity?
  - R&D in progress @ PSI & proposed @ Fermilab

H immiscible in SFHe ⇒ μ_M should expel M atoms at 6,300 m/s, ⊥ to SFHe surface



Focusing a Beam of Ultracold Spin-Polarized Hydrogen Atoms with a Helium-Film-Coated Quasiparabolic Mirror

V. G. Luppov
Randall Laboratory of Physics, University of Michigan, Ann Arbor, Michigan 48109-1120
and Joint Institute for Nuclear Research, Dubna, Russia

W. A. Kaufman, K. M. Hill,* R. S. Raymond, and A. D. Krisch
Randall Laboratory of Physics, University of Michigan, Ann Arbor, Michigan 48109-1120
(Received 7 January 1993)

We formed the first "atomic-optics" beam of electron-spin-polarized hydrogen atoms using a quasiparabolic polished copper mirror coated with a hydrogen-atom-reflecting film of superfluid ^{4}He. The mirror was located in the gradient of an 8-T solenoidal magnetic field and mounted on an ultracold cell at 350 mK. After the focusing by the mirror surface, the beam was again focused with a sextupole magnet. The mirror, which was especially designed for operation in the magnetic field gradient of our solenoid, increased the focused beam intensity by a factor of about 7.5.

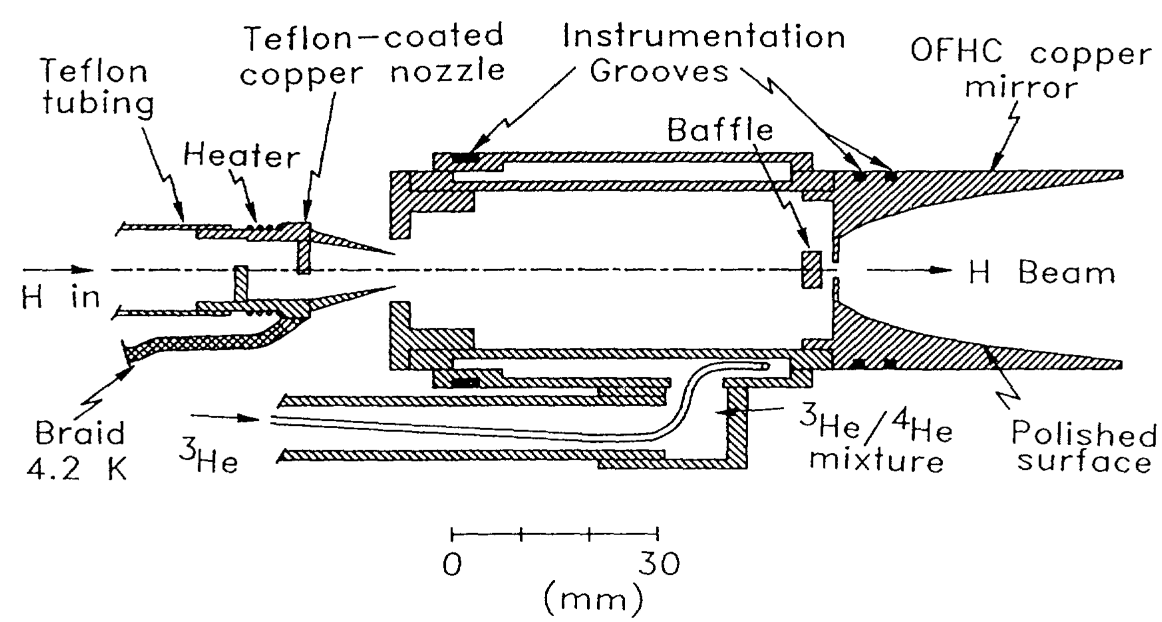


FIG. 2. Schematic diagram of the stabilization cell and mirror. The Teflon-coated copper nozzle is also shown.

- SFHe H mirror an established technique

muCool @ PSI

PHYSICAL REVIEW LETTERS **125,** 164802 (2020)

Editors' Suggestion

Make M beam suitable for stopping in ~μm SFHe layer

Demonstration of Muon-Beam Transverse Phase-Space Compression

A. Antognini,[1,2,*] N. J. Ayres,[1] I. Belosevic,[1,†] V. Bondar,[1] A. Eggenberger,[1] M. Hildebrandt,[2] R. Iwai,[1] D. M. Kaplan,[3] K. S. Khaw,[1,‡] K. Kirch,[1,2] A. Knecht,[2] A. Papa,[2,4] C. Petitjean,[2] T. J. Phillips,[3] F. M. Piegsa,[1,§] N. Ritjoho,[2] A. Stoykov,[2] D. Taqqu,[1] and G. Wichmann[1,‖]

(muCool Collaboration)

[1]*Institute for Particle Physics and Astrophysics, ETH Zürich, 8093 Zürich, Switzerland*
[2]*Paul Scherrer Institute, 5232 Villigen-PSI, Switzerland*
[3]*Illinois Institute of Technology, Chicago, Illinois 60616, USA*
[4]*Dipartimento di Fisica, Università di Pisa and INFN sez. Pisa, Largo B. Pontecorvo 3, 56127 Pisa, Italy*

(Received 5 April 2020; revised 17 August 2020; accepted 15 September 2020; published 15 October 2020)

We demonstrate efficient transverse compression of a 12.5 MeV/c muon beam stopped in a helium gas target featuring a vertical density gradient and crossed electric and magnetic fields. The muon stop distribution extending vertically over 14 mm was reduced to a 0.25 mm size (rms) within 3.5 μs. The simulation including cross sections for low-energy μ^+-He elastic and charge exchange ($\mu^+ \leftrightarrow$ muonium) collisions describes the measurements well. By combining the transverse compression stage with a previously demonstrated longitudinal compression stage, we can improve the phase space density of a μ^+ beam by a factor of 10^{10} with 10^{-3} efficiency.

DOI: 10.1103/PhysRevLett.125.164802

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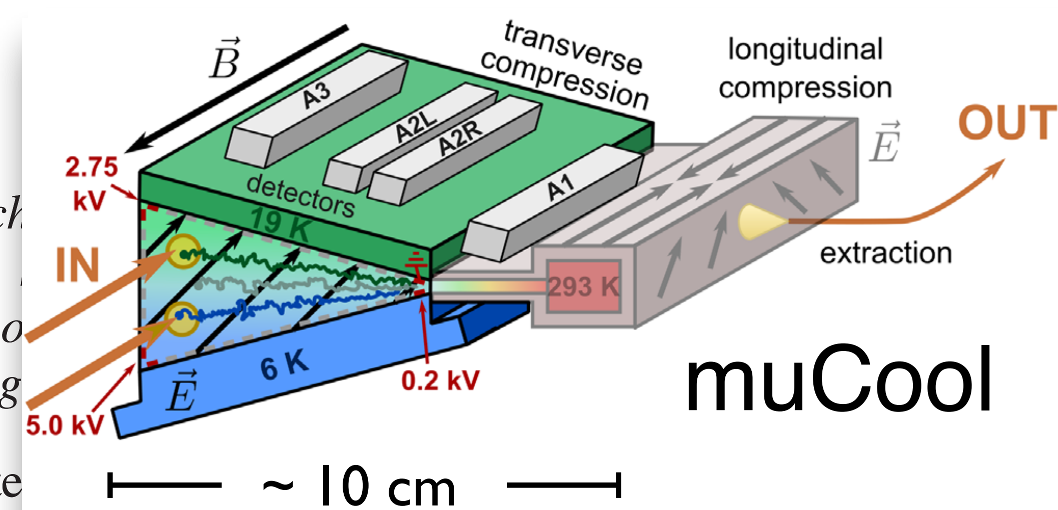

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Can photo-ionize for unique slow-μ^+ beam

DOI: 10.1103/PhysRevLett.125.164802

Muonium Gravity: Motivation

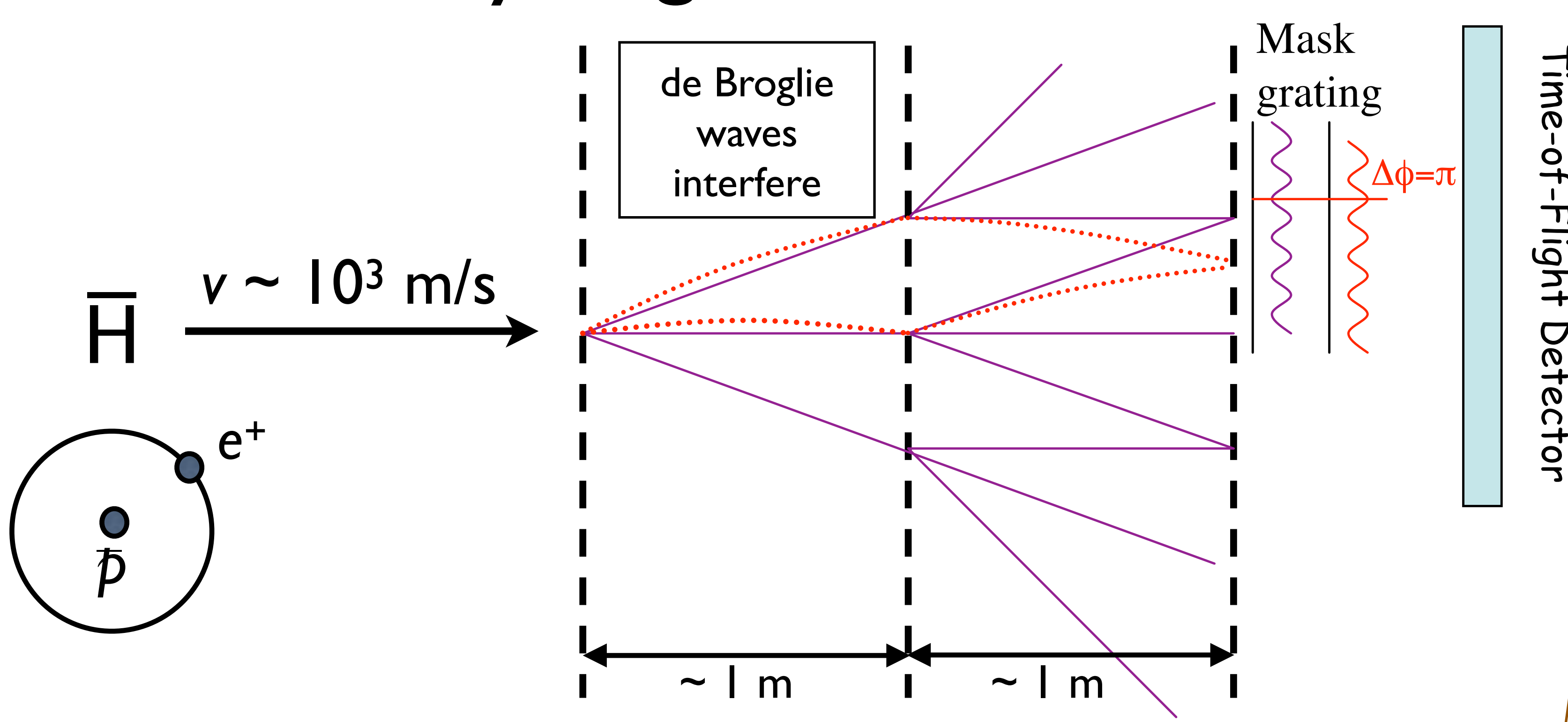
- Weak Equivalence Principle of GR:
  - object's acceleration in gravitational field independent of its composition
    - assumed to apply to antimatter as well as matter
- But no direct test of antimatter gravity has been made
- Best limit ($\Delta g_{\mathrm{H}\text{-}\bar{\mathrm{H}}}/g \lesssim 10^{-7}$): torsion pendulum ("Eöt-Wash") & lunar laser ranging [D.S.M. Alves, M. Jankowiak, P. Saraswat, "Experimental constraints on the free fall acceleration of antimatter," arXiv:0907.4110 [hep-ph] (2009)]
  - relies on assumed contribution of virtual antimatter to nuclear binding energy – untested assumption
  - inapplicable to M

Studying Antimatter Gravity

- Experimentally, still unknown even whether antimatter falls up or down! Or whether $g - \overline{g} = 0$ or ε

GR prediction

  - in principle a simple interferometric measurement with slow antihydrogen beam [T. Phillips, Hyp. Int. 109 (1997) 357]:



$\frac{1}{2}\, gt^2 = 5\ \mu\mathrm{m}$

Small, but *easily measured* with an atom interferometer

In either case, Equivalence Principle must be modified!

  - if $\overline{g} = -g$, antigravity as discussed above
  - if $\overline{g} = g \pm \varepsilon$, need to modify theory of gravity (e.g., scalar + vector + tensor), or add "5th force" to the known 4

Studying Antimatter Gravity

- *Many* $\overline{\mathrm{H}}$ efforts in progress at CERN AD (ALPHA, ATRAP, ASACUSA, AEgIS, GBAR)
  - too various to summarize here…
- All require antiprotons, so possible only at CERN Antiproton Decelerator
  - and measurements on *composite* particle ($\bar{p}$ made of quarks + gluons) theoretically complex
- BUT – another approach also seems feasible...

Studying Antimatter Gravity

& (per Giammarchi@CPT'22) positronium?

- Besides antihydrogen, only *one other* antimatter system conceivably amenable to gravitational measurement:
- Muonium (M or Mu) –
  - a hydrogenic atom with a positive (anti)muon replacing the proton
- Muonium gravity experiment could be *1st* (only?) gravitational measurement of a
  - lepton
  - 2nd-generation particle

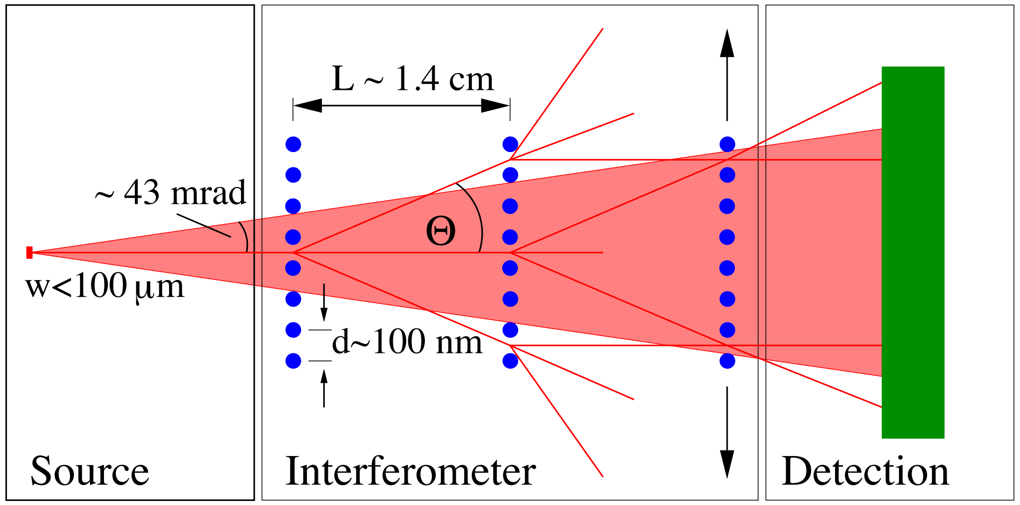
Studying Muonium Gravity

arXiv:physics/0702143v1 [physics.atom-ph]

Testing Gravity with Muonium

K. Kirch*
Paul Scherrer Institut (PSI), CH-5232 Villigen PSI, Switzerland
(Dated: February 2, 2008)

Recently a new technique for the production of muon (μ^+) and muonium ($\mu^+ e^-$) beams of unprecedented brightness has been proposed. As one consequence and using a highly stable Mach-Zehnder type interferometer, a measurement of the gravitational acceleration $\bar{g}$ of muonium atoms at the few percent level of precision appears feasible within 100 days of running time. The inertial mass of muonium is dominated by the mass of the positively charged - antimatter - muon. The measurement of $\bar{g}$ would be the first test of the gravitational interaction of antimatter, of a purely leptonic system, and of particles of the second generation.

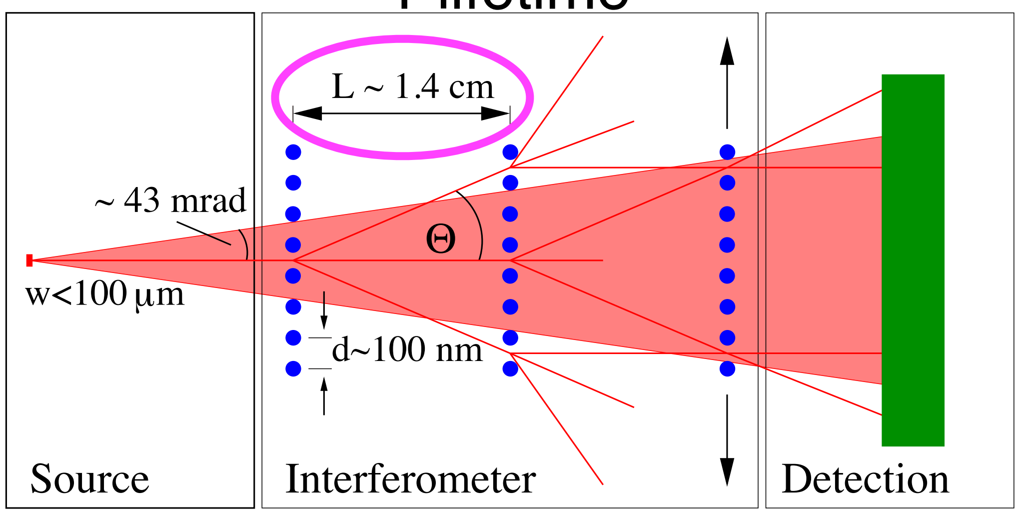


Studying Muonium Gravity

- Adaptation of T. Phillips' $\overline{\mathrm{H}}$ interferometry idea to an antiatom with a 2.2 μs lifetime!

1 lifetime

v ~ 6300 m/s



½ gt^2 = 24 pm!

but grows as t^2 ⇒ easier problem with *old* muonium

- "Same experiment" as Phillips proposed – only harder!
- How might it be done?

Studying Muonium Gravity

Part of the challenge: M production method

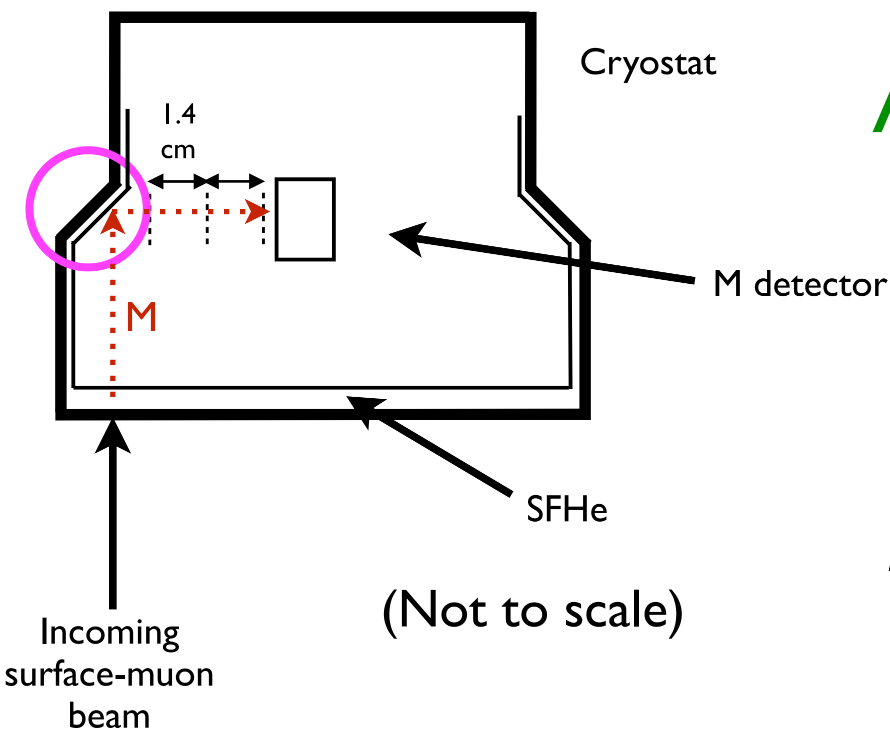
- want *monoenergetic* M for uniform flight time
  - otherwise, interference patterns of different atoms have differing relative phases,
    - so signal could be washed out

      (probably not a problem in practice, since interference phase so small…)

- want narrow, *parallel* M beam for good interferometer acceptance

Muonium Gravity Experiment

- Conceptual sketch:



A "ship in a bottle!"

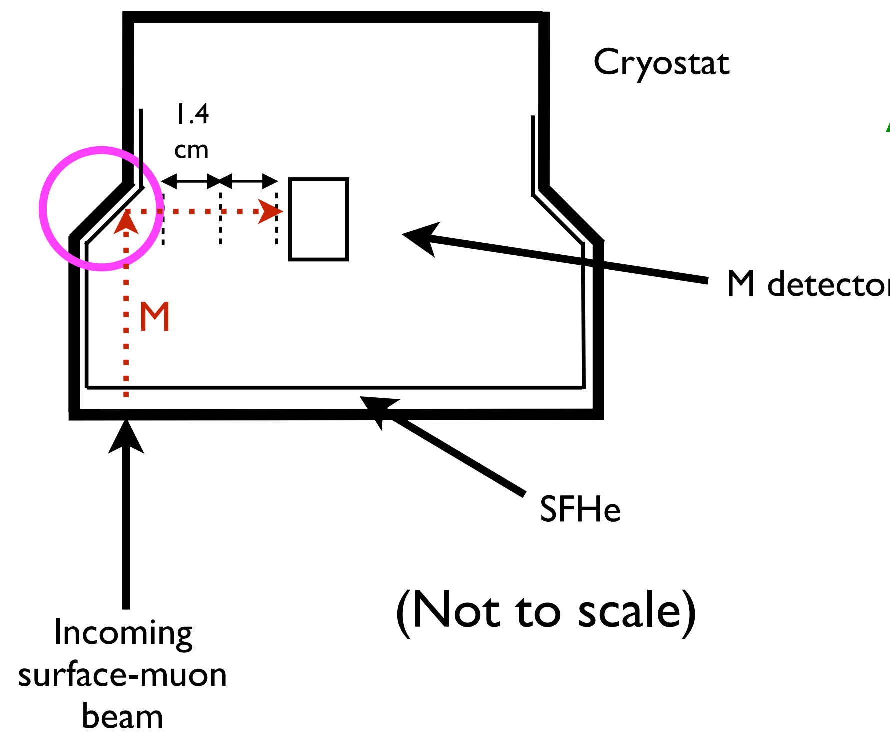
Sensitivity estimate
@ 100 kHz:

$$S = \frac{1}{C\sqrt{N_0}}\frac{d}{2\pi}\frac{1}{\tau^2}$$
$$\approx 0.3\,\mathrm{g\ \ per}\sqrt{\#\mathrm{days}}$$

  - well-known property of SFHe to coat surface of its container
  - 45° section of cryostat reflects vertical M beam emerging from SFHe surface into the horizontal

Muonium Gravity Experiment

- Conceptual sketch:



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$$\approx 0.3\,\mathrm{g} \;\; \text{per} \sqrt{\#\text{days}}$$

sign of $\bar{g}$ with 1 day's data

where

C = 0.3 (est. contrast)

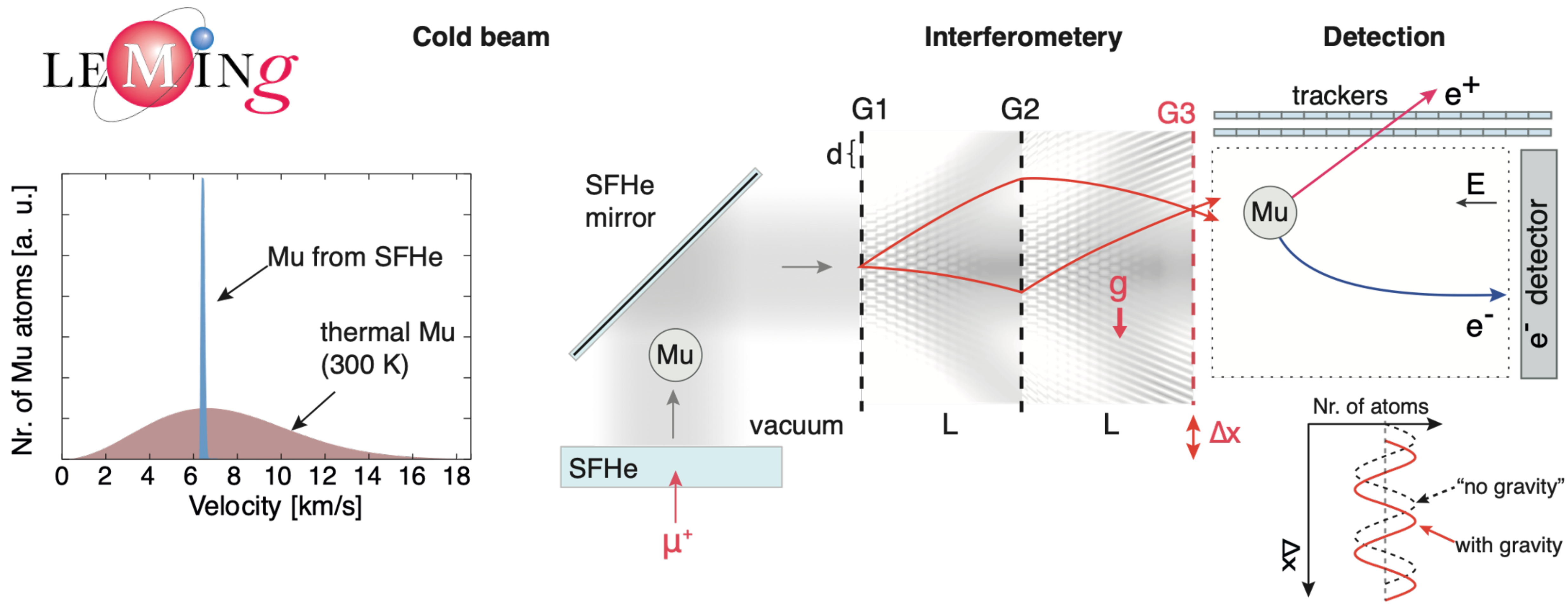
N_0 = # of events

d = 100 nm (grating pitch)

τ = M lifetime

➡ Muonium Antimatter Gravity Experiment (MAGE)

The LEMING experiment at PSI, Switzerland

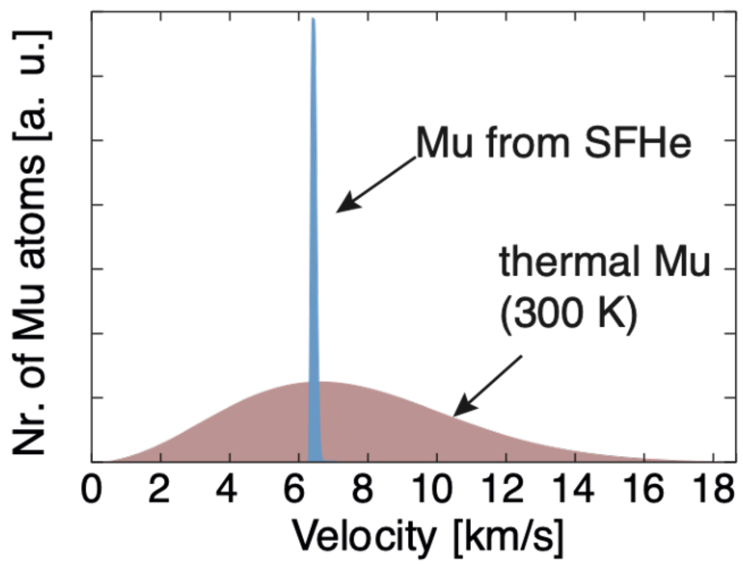


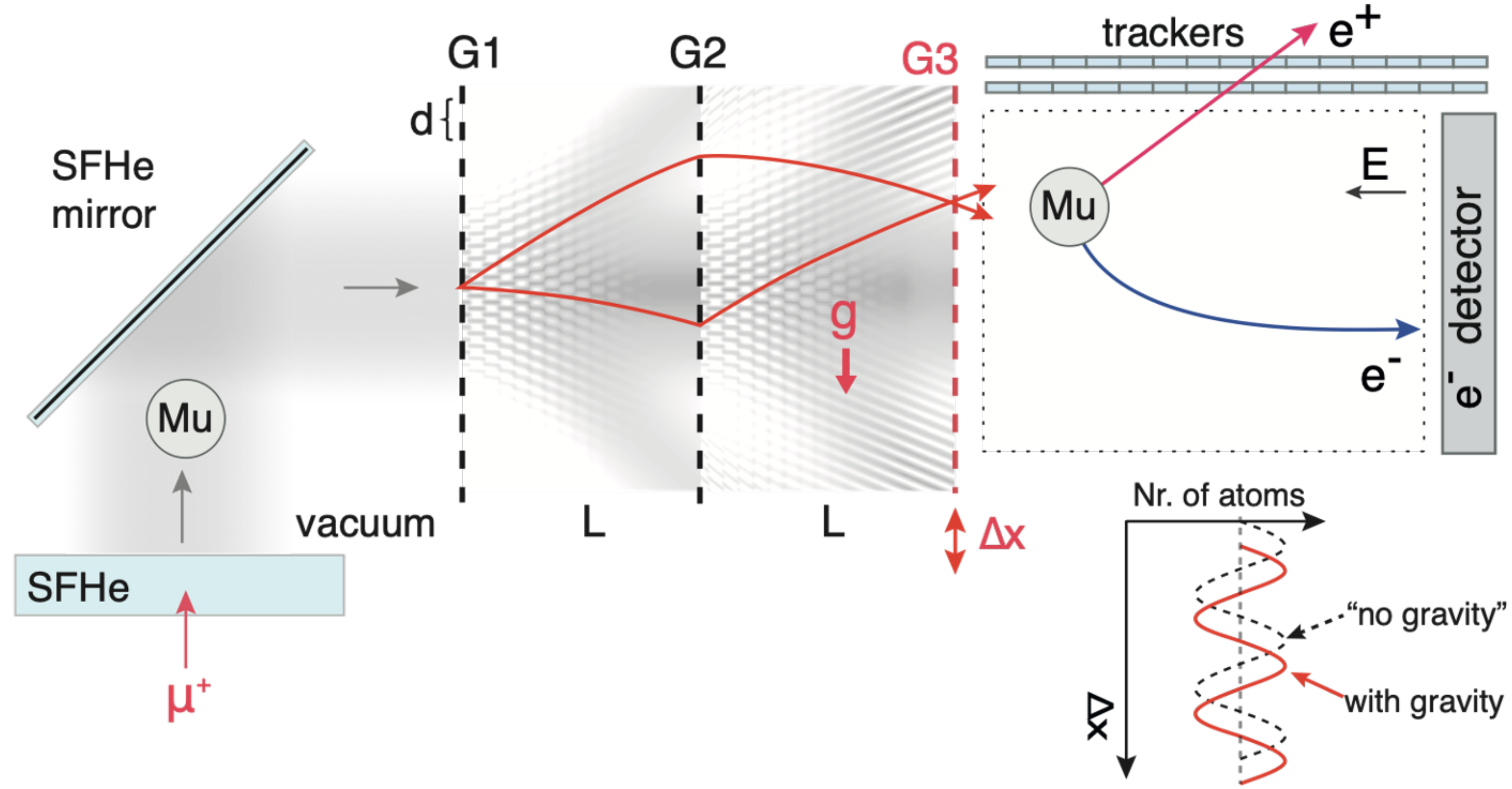
- **LEMING**: **LE**ptons in **M**uonium **IN**teracting with **G**ravity
- Approved at the Paul Scherrer Institute (PSI) in 2022 January, taking advantage of the world's highest intensity cw muon source.
- A novel, ultracold muonium beam development for next generation laser spectroscopy and atom interferometry to measure the gravitational acceleration of (anti)leptons

doi: 10.21468/SciPostPhysProc.5.031

Anna Soter, ETH Zurich

The LEMING experiment at PSI, Switzerland





In R&D phase

- **LEMING**: **LE**ptons in **M**uonium **IN**teracting with **G**ravity
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Anna Soter, ETH Zurich

World Surface-μ Beams

Table 1: Comparison of Surface Muon Facilities and Mu2e*

Facility		Max. (surface) μ rate (Hz)	Type	Comments
PSI [14]	Switzerland	9×10^8	CW	
TRIUMF [15]	Canada	2×10^6	CW	
MuSIC at Osaka [16]	Japan	10^8	CW	
J-PARC [17]	"	6×10^7	pulsed	
ISIS [17]	UK	6×10^5	pulsed	
HIMB at PSI [13]	Switzerland	10^{10}	CW	(design goal)
Mu2e at Fermilab		10^{11}	pulsed	Not surface muons: $p_\mu \approx 40\,\mathrm{MeV}/c$
Mu2e with PIP-II		10^{12}	pulsed	Not surface muons: $p_\mu \approx 40\,\mathrm{MeV}/c$

* R. H. Bernstein et al., "Letter of Interest for an Upgraded Low-Energy Muon Facility at Fermilab," SNOWMASS21-RF0-AF0-007

- Used for:
  - MuSR (MatSci, chemistry), fundamental physics, μCF R&D…
- None in U.S., oversubscribed
- PSI: current world leader
  - x10 upgrade ("HIMB") in the works
- PIP-II could surpass HIMB (by x10^2 ?)
- 400 MeV Linac – competitive w PSI???

See Johnstone & Mazzacane talks

Fermilab "MuCool Test Area"

- Built ~20 years ago for muon collider R&D
  - served by 400 MeV H^- Linac

See Johnstone & Mazzacane talks

- Now being repurposed as Irradiation Test Area (ITA)
- Can also house low-energy π/μ beam (Carol Johnstone)

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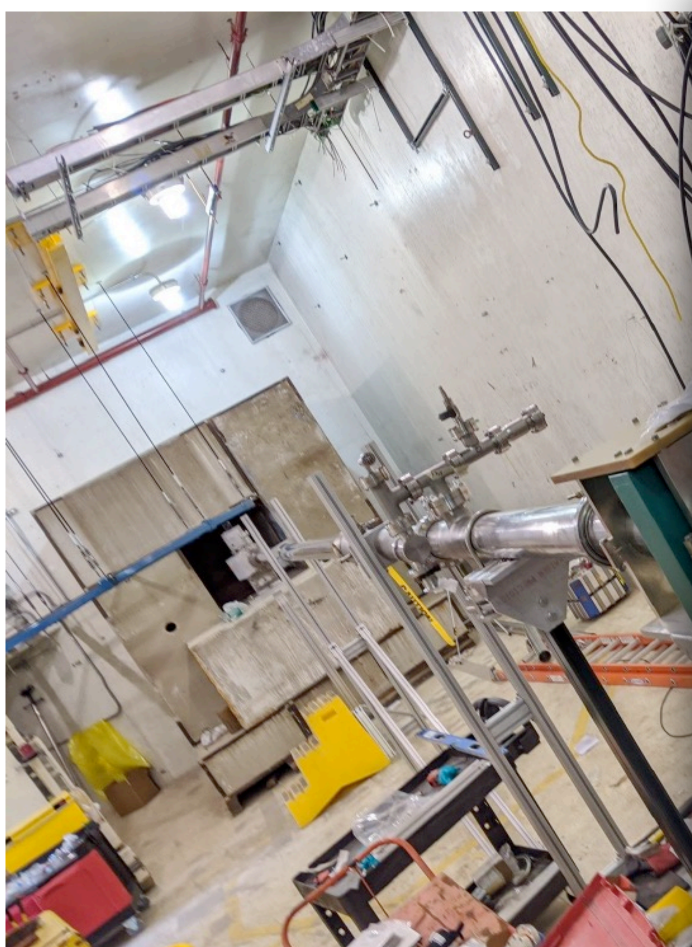
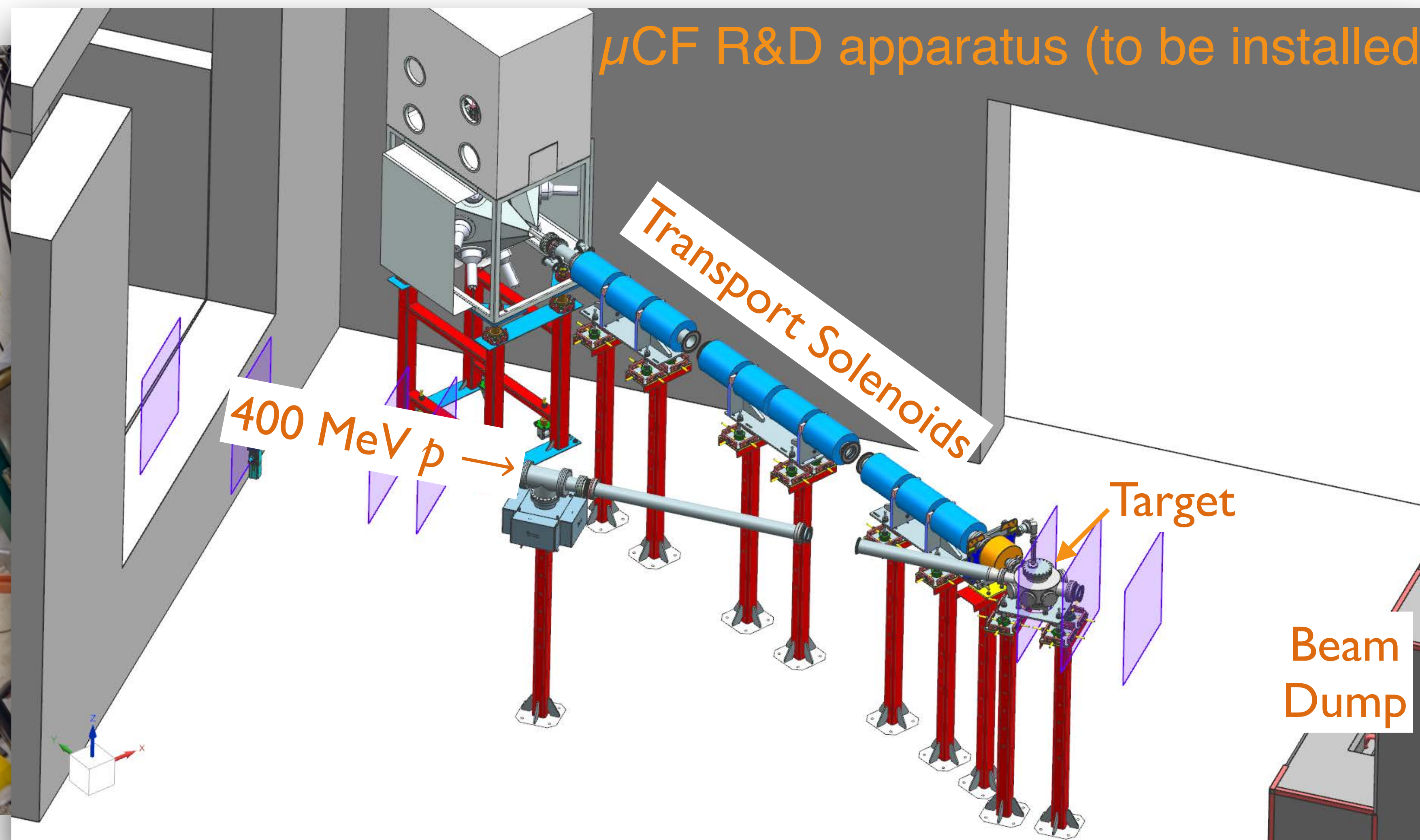




What we (MAGE) want to do

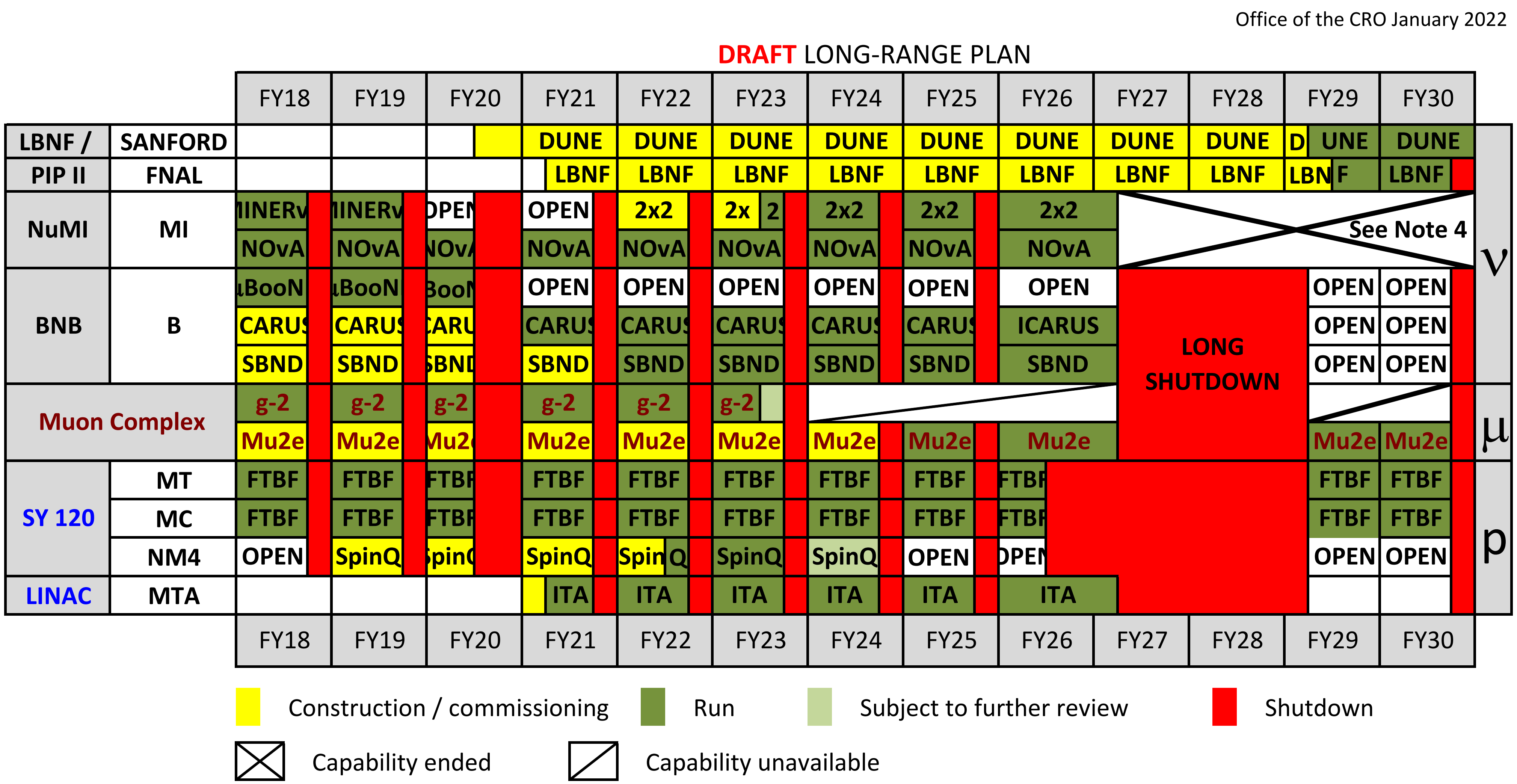
- ETHZ/PSI group investigating option of thin SFHe layer illuminated by "muCool" beam
  - requires narrow μ^+ energy spread ΔE
  - costs ~10^3 in intensity (muon decay in muCool cooler)
- We will explore use of much thicker SFHe layer (can use larger ΔE, without muon cooling)
  - requires maintaining e^- pool on top of SFHe, via W needle electrode (established technique)
  - some MTA time potentially available in 1–2 years
  - still need to line up collaborators and funding!

Also potential game-changer for spectroscopy, M-$\overline{\mathrm{M}}$ oscillation

Potential Fermilab Advantages

- PSI protons heavily shared – limits LEMING intensity
  - whereas most Linac *p don't* go to MI (only ~1% of PIP-II will)
- In longer term, PIP-II linac → x10^n intensity advantage w.r.t. PSI HIMB

Timeline



- Linac experiments possible until FY27
- PIP-II starts ~ FY29

Conclusions

- M spectroscopy, M-$\overline{\text{M}}$ oscillations: previous results >20 years old – can now do substantially better

  ⇒ good time for new efforts

- M gravity: never feasible before
  - new techniques make it feasible
  - could it provide clue to a new, QM theory of gravity?
- 400 MeV Linac: possibly competitive with PSI?
- PIP-II: could enable world-leading M studies

Questions

- What is muon rate in optimized Linac setup?
- Is there room in MTA for
  - M-production R&D apparatus?
  - M experiment(s)?