Future Muon and Muonium Physics at Fermilab

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Muons, Inc.

for the collaboration:

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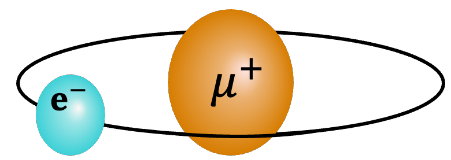
Fermilab ACE Science Meeting: Brief Remarks Session

15 June 2023

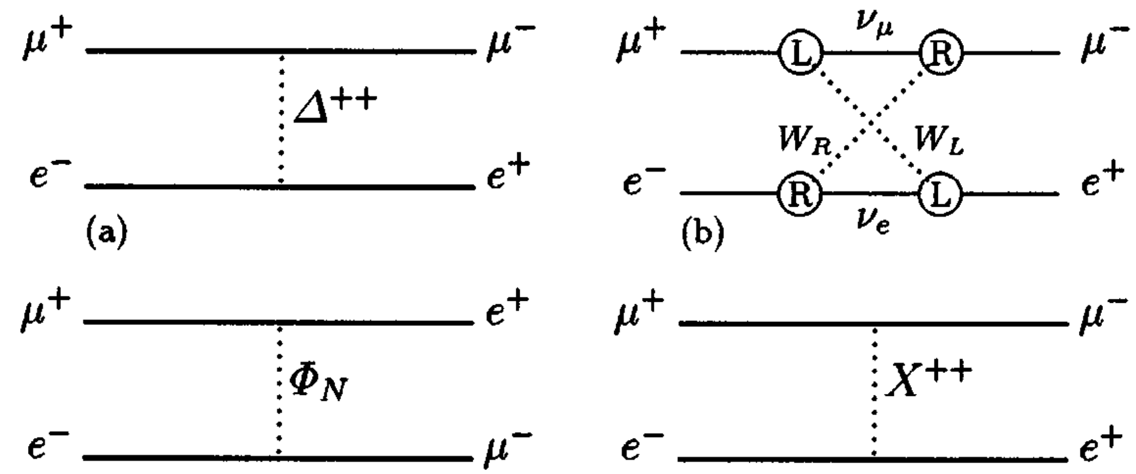
Muonium Physics Goals

Muonium (M): hydrogen-like μ^+e^- atom



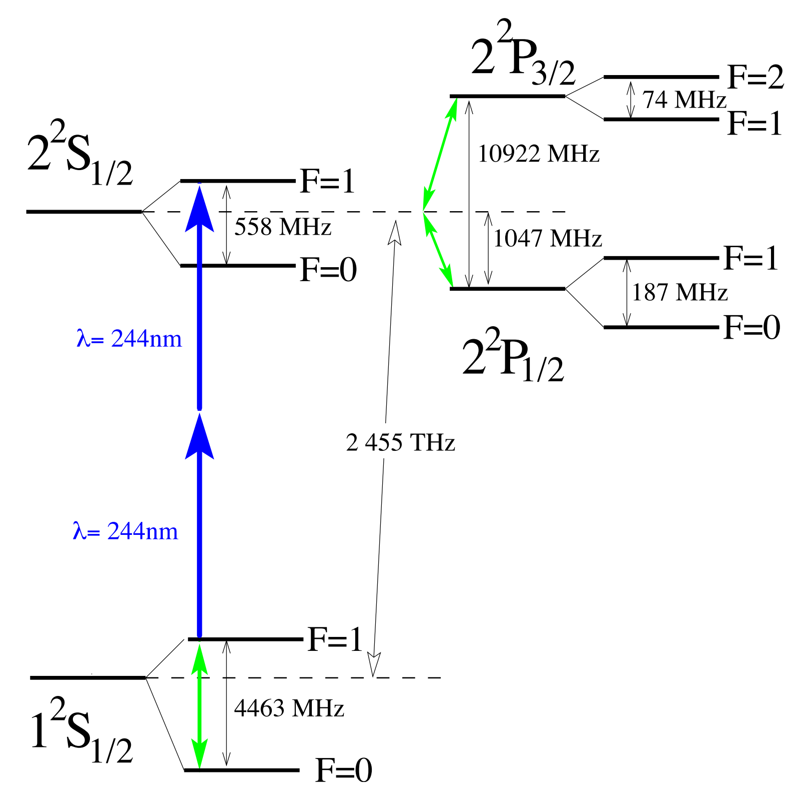
1. **Muonium–antimuonium** (M-$\overline{\text{M}}$) **oscillations**: complementary to Mu2e — *differently* sensitive to CLFV new physics

   - *both* should be sought as sensitively as possible



2. **Muonium spectroscopy**: atomic levels exquisitely predicted by QED (neither strong nor finite-size corrections)

   → clear windows for new physics



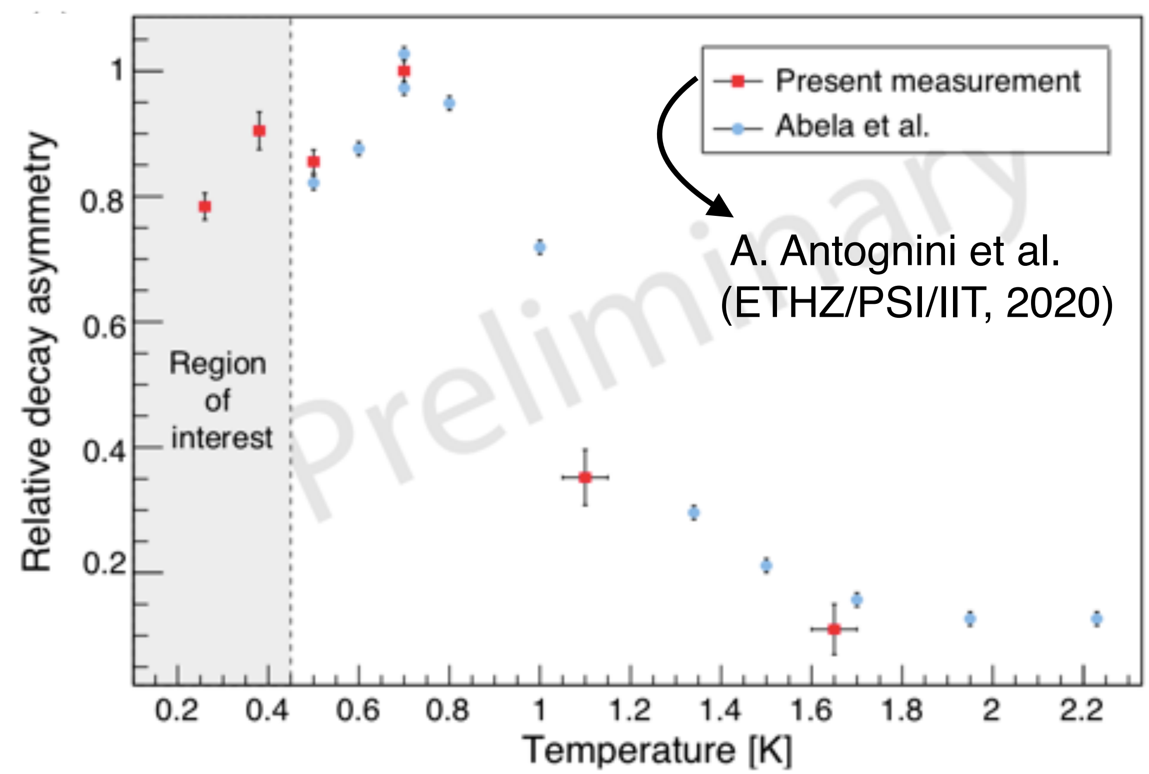
3. **Muonium gravity**: "tabletop" experiment sensitive to possible 5th force

   - $g-2$, leptonic B, & W-mass anomalies → renewed interest
   - *only* way to test 2nd generation's gravitational coupling

Novel Cryogenic M Source

- Want low-divergence beam of slow muonium traveling in vacuum – no such beam anywhere
- Proposals by D. Taqqu of Paul Scherrer Institute:
  - stop slow (keV) muons in ~ μm-thick layer of superfluid He (SFHe)
    - or (T. Phillips, IIT) use ~ 100 μm SFHe layer for ~ 10^2 ↑ intensity?
  - R&D in progress @ PSI & proposed @ Fermilab MTA
  - *essential* for M gravity, potential game-changer for others

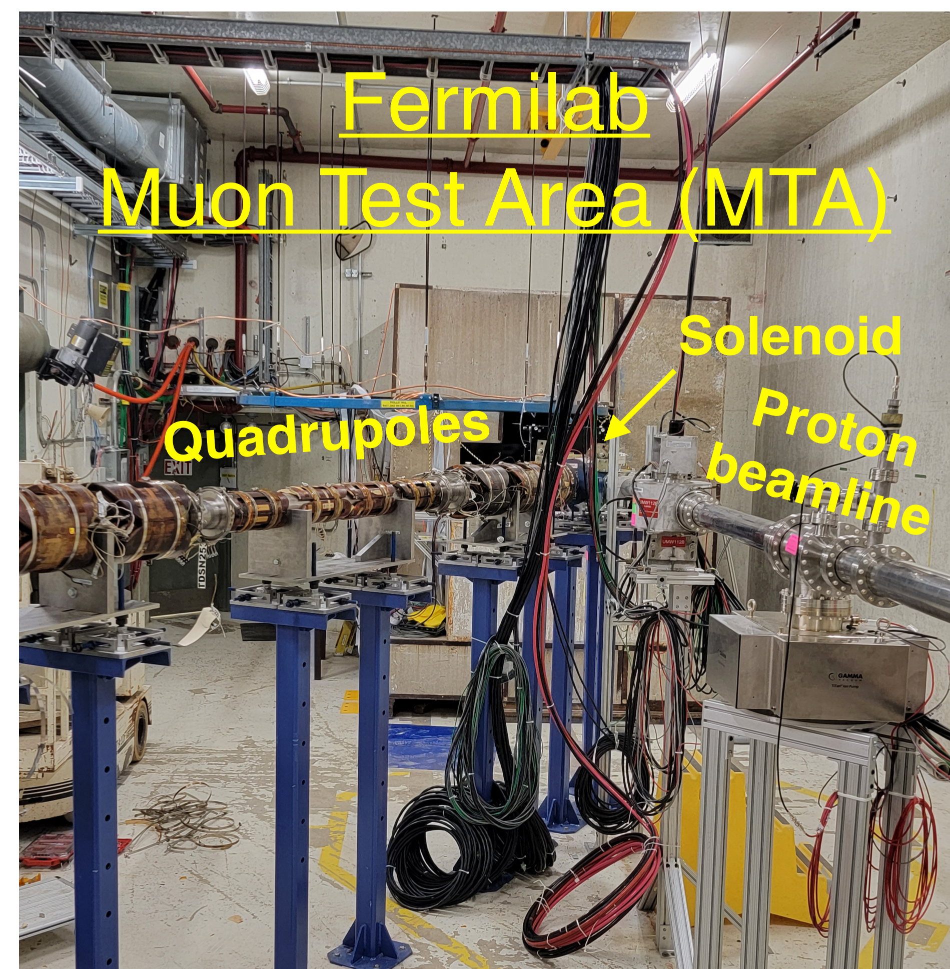
H *immiscible* in SFHe ⇒ μ_M should expel M atoms at 6,300 m/s, ⊥ to SFHe surface



Competitive Landscape

- **PSI**: world's most intense surface-muon beams
  - best previous M-$\overline{\text{M}}$ oscillation limit (MACS, 1999)
  - new M spectroscopy experiments:
    Mu-MASS (PSI, 1S-2S); MuSEUM (J-PARC, hyperfine)
    - together with $g-2$ → potential μ-only α value

- **HIMB** (PSI upgrade): goal x ≈ 30 rate increase
- **PIP-II** ("AMF"): potentially x ~10^2 over HIMB
- **In ≈ 10 years Fermilab could be *world's best* M physics venue!**
  - R&D opportunity <u>now</u> at existing "MTA" low-energy μ beamline @ Fermilab 400 MeV Linac (thx to μCF effort)
  - cost-effective few-M$, few-year program
- Collaboration formed, R&D program proposed
  - beneficial spinoff: <u>first</u> (<u>only</u>) U.S. μSR facility



Conclusions

- $M \to \overline{M}$ & Mu2e complementary, *both are needed*
- $M \to \overline{M}$, M spectroscopy: previous results >20 years old ⇒ good time for new efforts
- M gravity: never feasible before, new technique should make it feasible: *SFHe M production*
- 400 MeV Linac possibly competitive with PSI
- R&D needed to establish feasibility & physics reach
- PIP-II could enable *world-leading* M & LE μ studies

➡ **MTA:** cost-effective **opportunity** to initiate world-leading Fermilab muonium program!

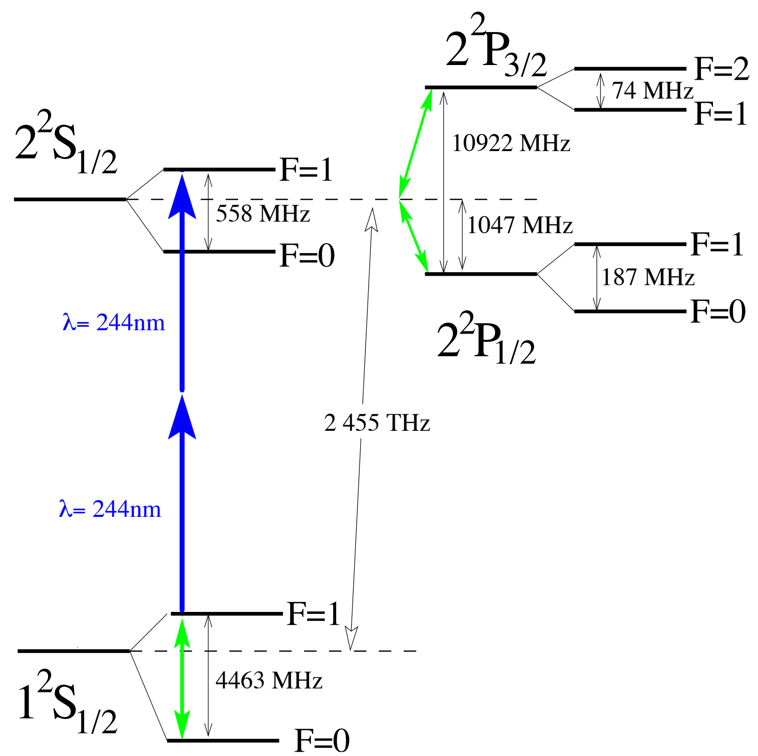
… while 400 MeV Linac still operational

Would also enable μSR at MTA

Backup Slides

Why Muonium?

- Much 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** (1960) 63]
    [A. Czarnecki, G. P. Lepage, W. Marciano, Phys. Rev. D **61** (2000) 073001]
  - decays to e^+ (fast) + e^- (slow), $\tau_M = \tau_\mu = 2.2\ \mu s$ (bound-state correction $\sim 10^{-10}$)
  - readily produced when μ^+ stop in matter
  - chemically, almost identical to hydrogen
  - atomic spectroscopy well studied
  - free of hadronic & finite-size effects
    ⇒ "ideal testbed" for QED, the search for new forces, precision measurement of muon properties, etc.
  - invaluable for materials science
    (world μSR facilities: ISIS@RAL, J-PARC, PSI, RCNP@Osaka, TRIUMF)

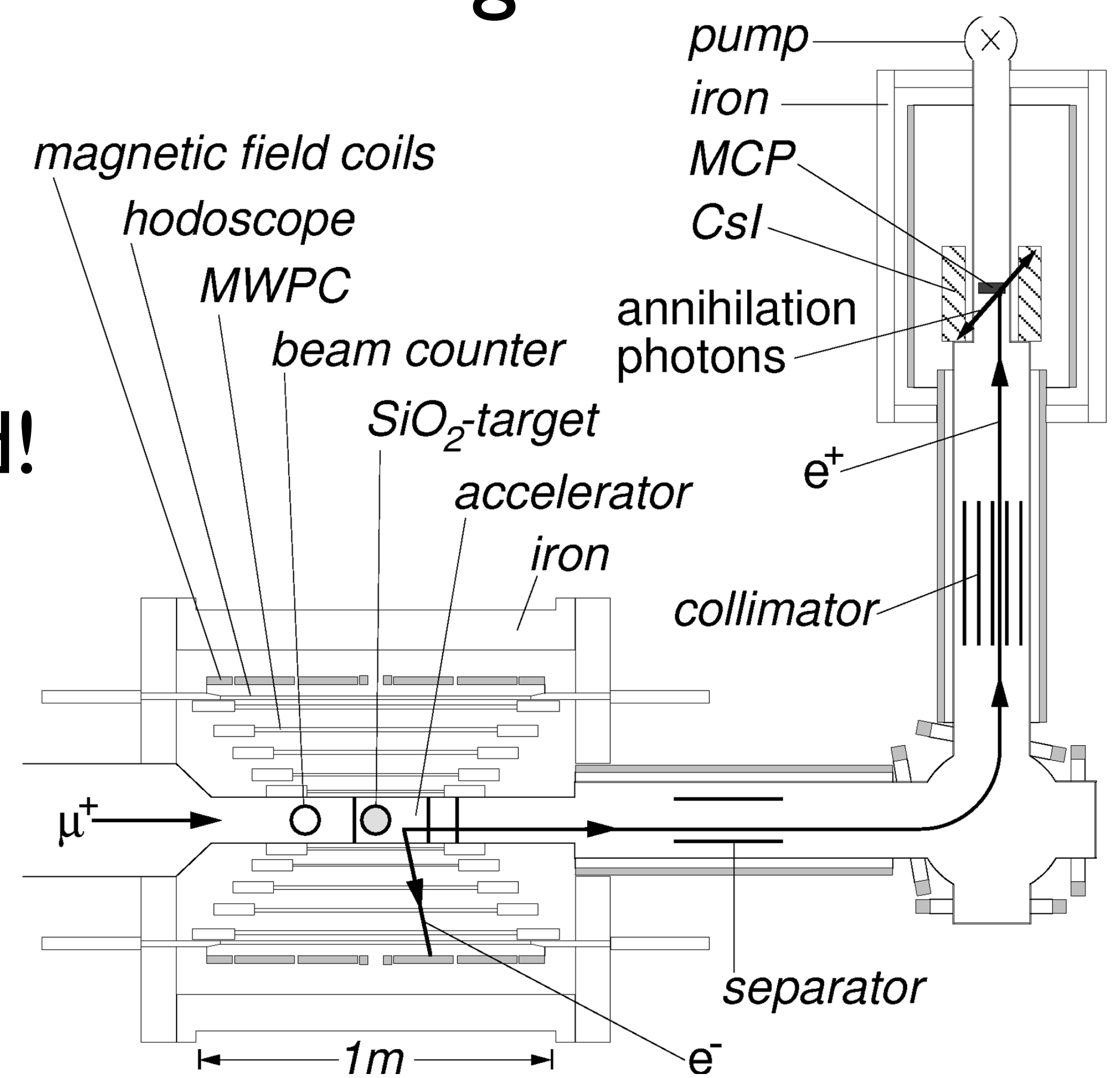


Muonium Double CLFV?

- Muonium-antimuonium (M-$\overline{\mathrm{M}}$) oscillation would be doubly charged-lepton-flavor violating

simultaneous $\left\{ \begin{array}{l} \mu^+ \to e^+ \\ e^- \to \mu^- \end{array} \right.$

- Nothing forbids it *except* lepton-flavor conservation
  - which we know (ν mixing) is violated!
    - but M ↔ $\overline{\mathrm{M}}$ via virtual ν mixing negligible
    - ≈ background-free search for new physics!
    - in some models, more likely than $\mu N \to eN$
- 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** (1999) 49]

Muonium Double CLFV?

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

    Phillips talk

  …(more in a few slides)

Muonium Spectroscopy

49 Page 2 of 9 Hyperfine Interact (2018)

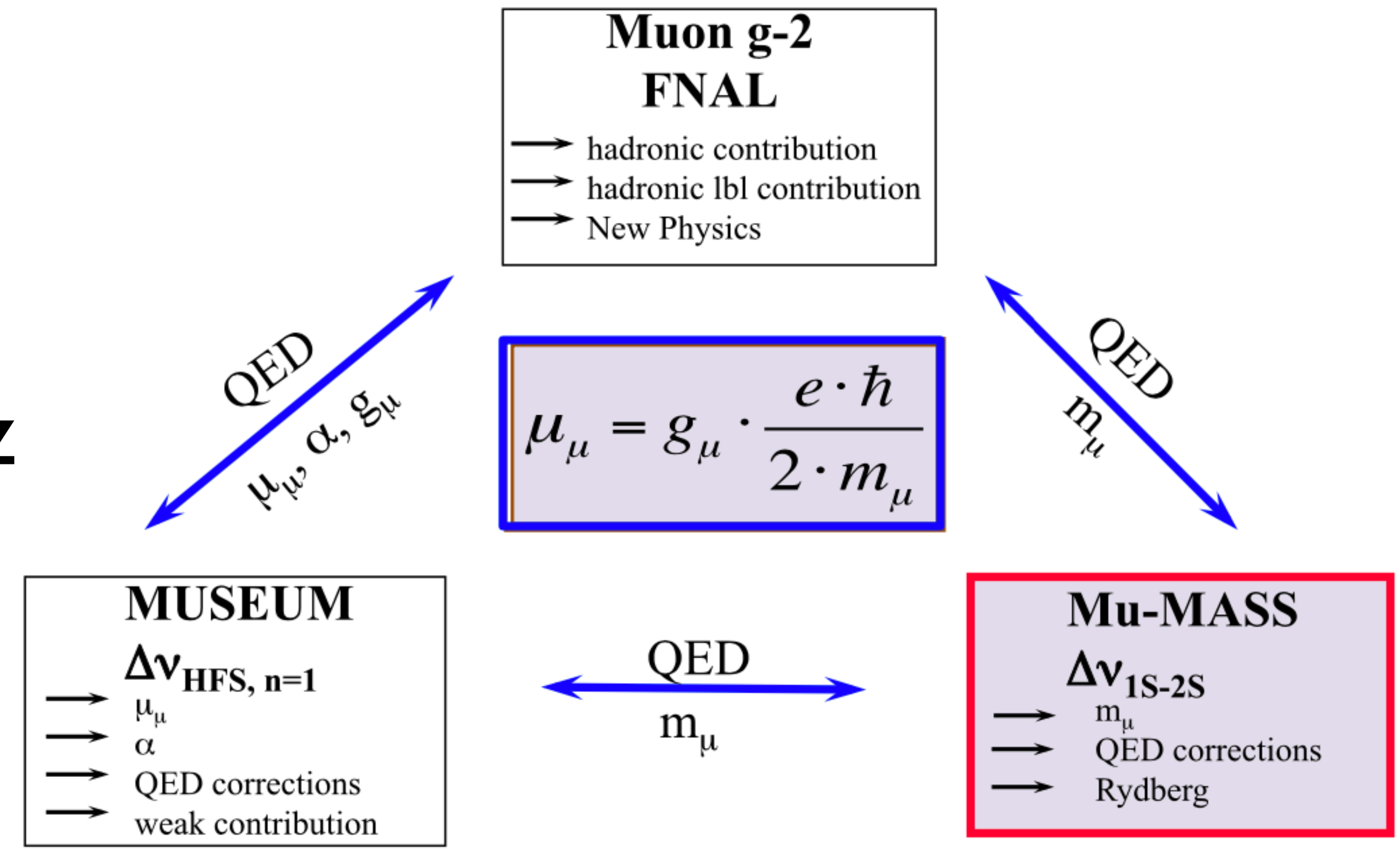


Fig. 1 Fundamental constants in the muon sector and related experiments (adapted from [42])

- 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 (~2 orders higher than current PSI) would help
      - will allow better handle on systematics (per Crivelli)
- Also MUSEUM in progress at J-PARC
  - goal: improve hyperfine sensitivity x10 (1 ppb)

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 quasi-parabolic 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.

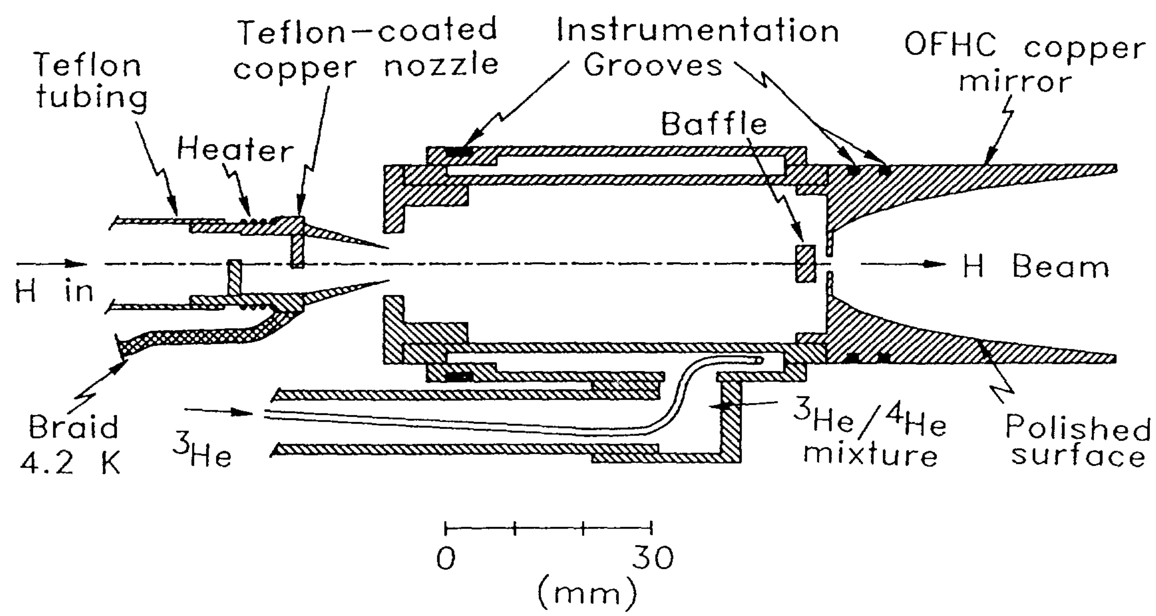


FIG. 2. Schematic diagram of the stabilization cell and mirror. The Teflon-coated copper nozzle is also shown.

- SFHe H mirror an established technique

muCool @ PSI

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

Editors' Suggestion

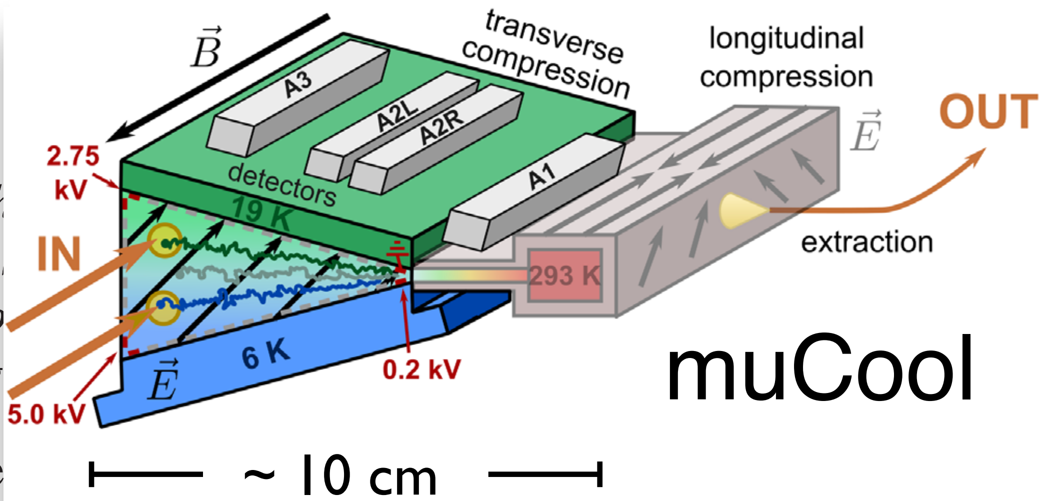
Make M beam stoppable in ~μm SFHe layer

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*
[2]*Paul Scherrer Institute, 5232 Villigen-PSI,*
[3]*Illinois Institute of Technology, Chicago, Illino*
[4]*Dipartimento di Fisica, Università di Pisa and INFN sez. Pisa, Larg*



(Received 5 April 2020; revised 17 August 2020; accepted 15 Septe

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

Photo-ionize for unique, cold slow-μ^+ beam → gateway to J-PARC $g-2$ expt

Muonium Gravity: Motivation

- Possibility of "fifth force"?
  - $g-2$, B-decay and W-mass anomalies: possible eμ nonuniversality?
    - stimulated extensive work
- Observable via M gravity?
  - what $\bar{g}$ sensitivity required? no theor. prediction available

[Glashow, Guadagnoli, Lane, "Lepton Flavor Violation in B Decays?" PRL **114 (2015)** 091801;

Buttazzoa, Greljoa, Isidoria, Marzocca, "*B*-physics anomalies: a guide to combined explanations," JHEP **2017** (2017) 44;

R. Aaij et al. (LHCb Collaboration), "Test of lepton universality in beauty-quark decays," Nat. Phys. 18 (2022) 277;

M. Alguer´o et al., "Unified explanation of the anomalies in semileptonic B decays and the W mass," PRD 106 (2022) 033005 and refs. therein;

S. L. Chen et al., "Combined explanations of B-physics anomalies, (g – 2)e,μ and neutrino masses by scalar leptoquarks," EPJC 82 (2022) 959;

M. D. Zheng et al., "Explaining anomalies of B-physics, muon g – 2 and W mass in R-parity violating MSSM with seesaw mechanism," EPJC 82 (2022) 895;

N Desai, A Sengupta, "Status of leptoquark models after LHC Run-2 and discovery prospects at future colliders, arXiv 2301.01754 (2023);

…]

- Experimental 1st step: 10% measurement already worthwhile, and challenging
  - demonstrate M interferometry & calibration at several-pm level
  - can it be pushed to 1% and beyond? systematics + statistics
    - sensible to start with 10% and proceed step by step

Muonium Gravity: Motivation

- Weak Equivalence Principle of GR:

  $\Longrightarrow$ composition-independent gravitational acceleration

  - assumed to apply to antimatter, but need not in quantum gravity

    [M. M. Nieto, T. Goldman, "The Arguments Against 'Antigravity' and the Gravitational Acceleration of Antimatter," Phys. Rep. 205, 221–281 (1991)]

    – could imply simpler alternative cosmology

    [see e.g. A. Benoit-Lévy and G. Chardin, "Introducing the Dirac-Milne universe," Astron. & Astrophys. 537 (2012) A78]

  - M provides *only possible* 2nd-generation gravitational test

- No *direct* test of antimatter gravity has yet been made

- Best limit ($\Delta g/g \lesssim 10^{-7}$): 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]]

  - relies on assumed virtual-antimatter contribution to nuclear binding energy – untested assumption, inapplicable to M

  - well worth a direct test!

Testing Gravity with Muonium

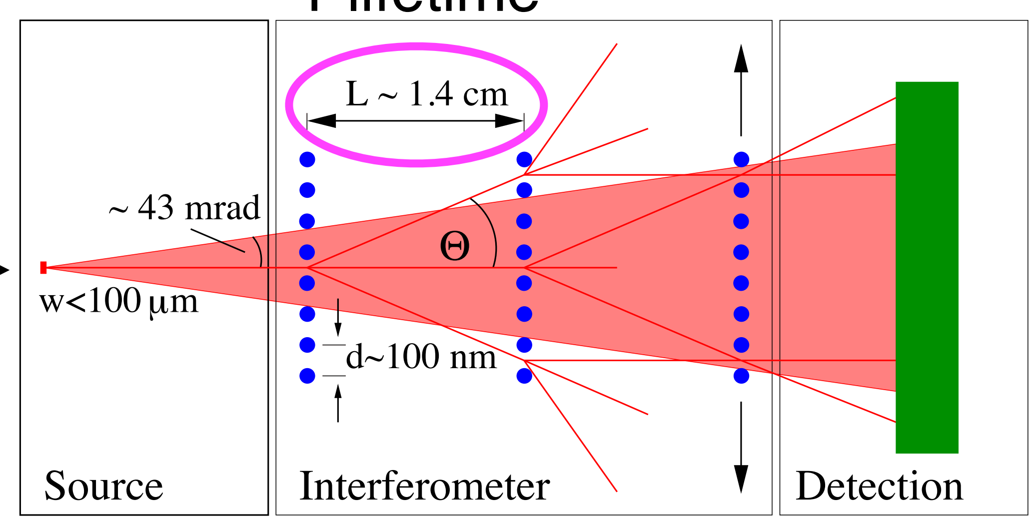
K. Kirch*
Paul Scherrer Institut (PSI), CH-5232 Villigen PSI, Switzerland
(Dated: February 2, 2008)

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

1 lifetime

v_M ~ 6300 m/s

M beam →



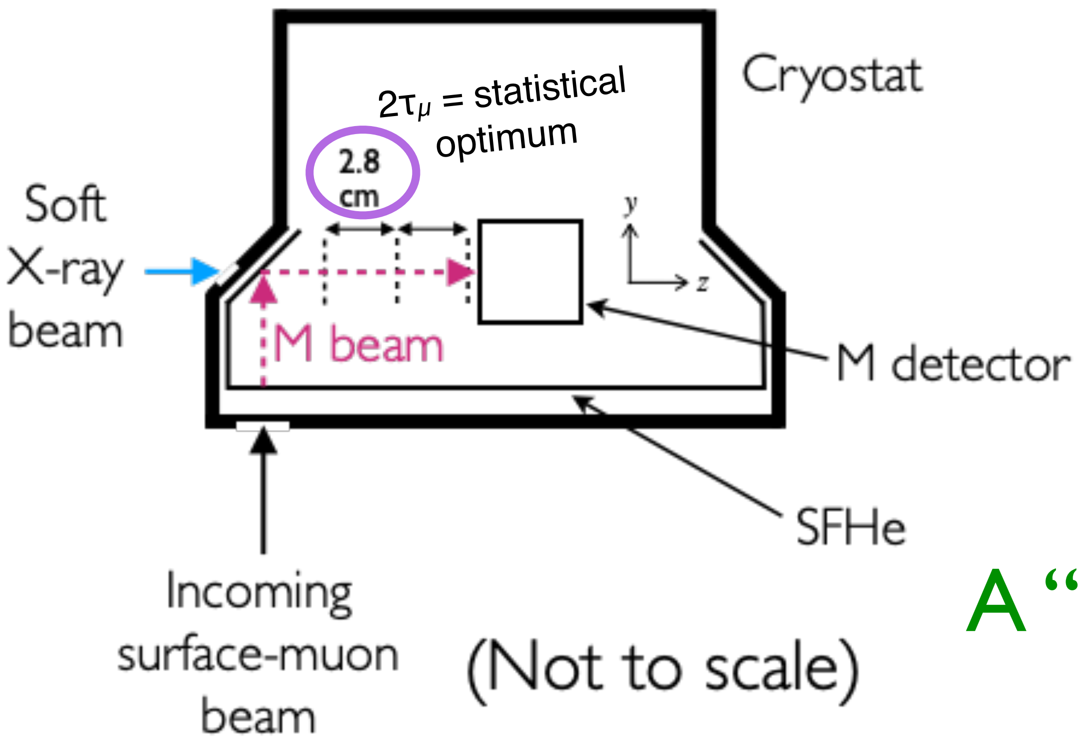
½ gt^2 = 24 pm!

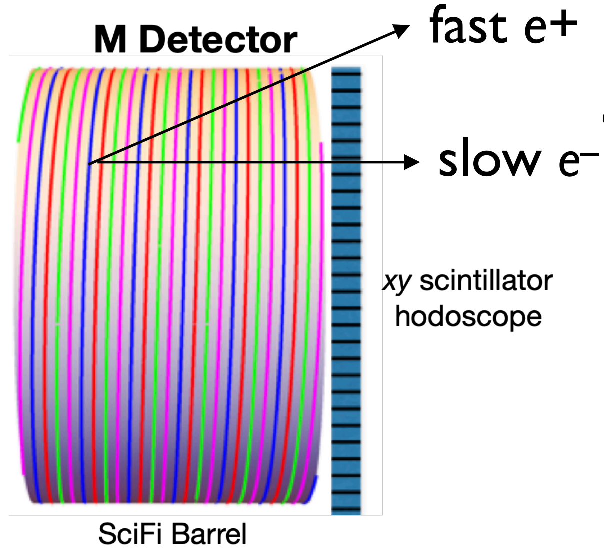
but grows as t^2 ⇒ easier problem with *old* muonium

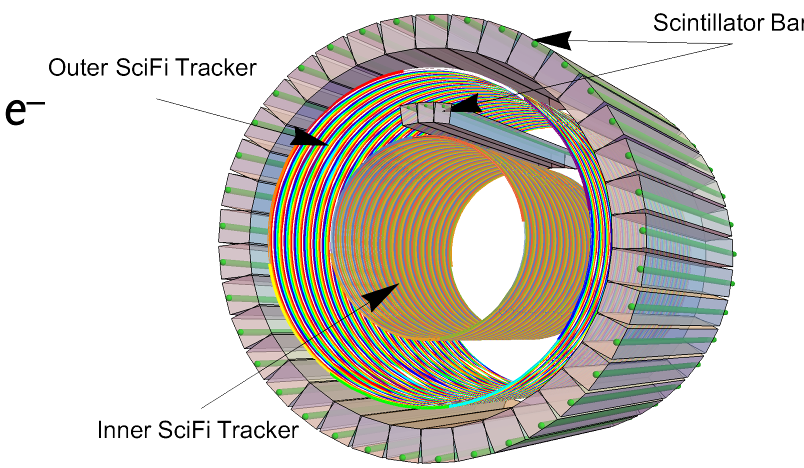
- Need
  - very precise atom interferometer
  - low-divergence, low-$\Delta p/p$ muonium beam

Muonium Gravity Experiment

- Conceptual sketch:







A "ship in a bottle!"

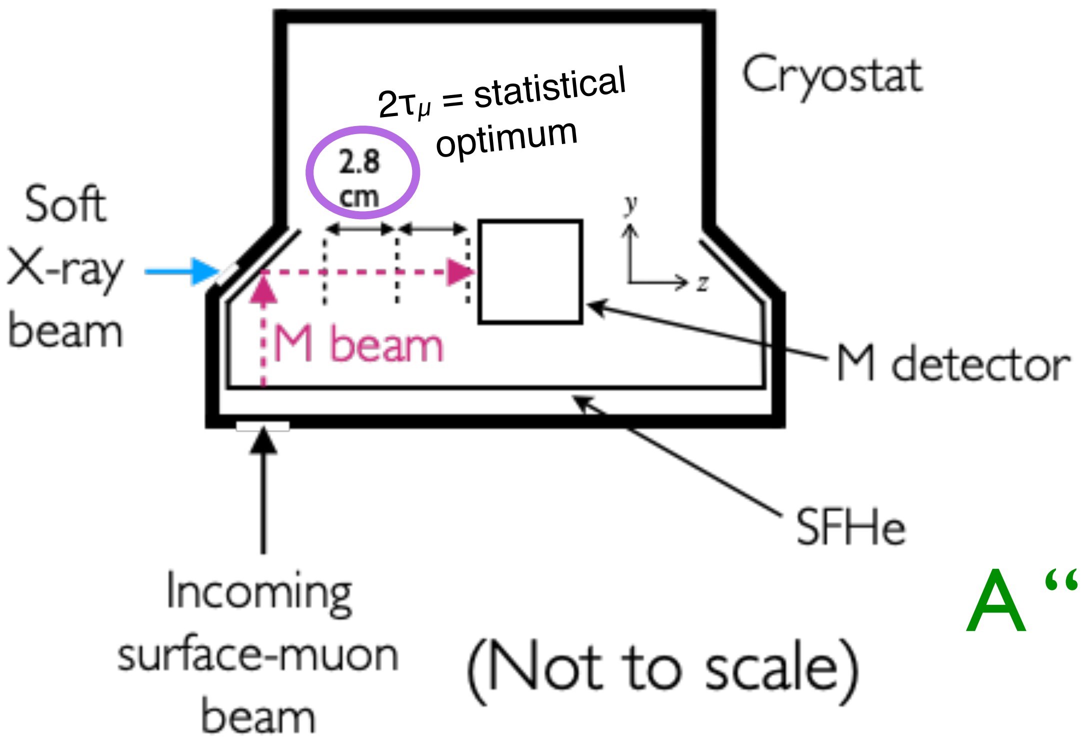
Sensitivity estimate @ 100 kHz:

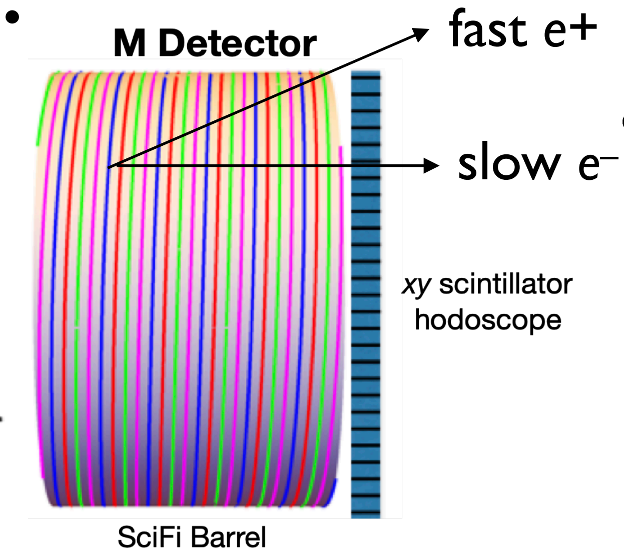
$$S = \frac{1}{C\sqrt{N_0}}\frac{d}{2\pi}\frac{1}{\tau^2}$$
$$\approx 0.3\,\mathrm{g} \;\; \mathrm{per} \sqrt{\#\mathrm{days}}$$

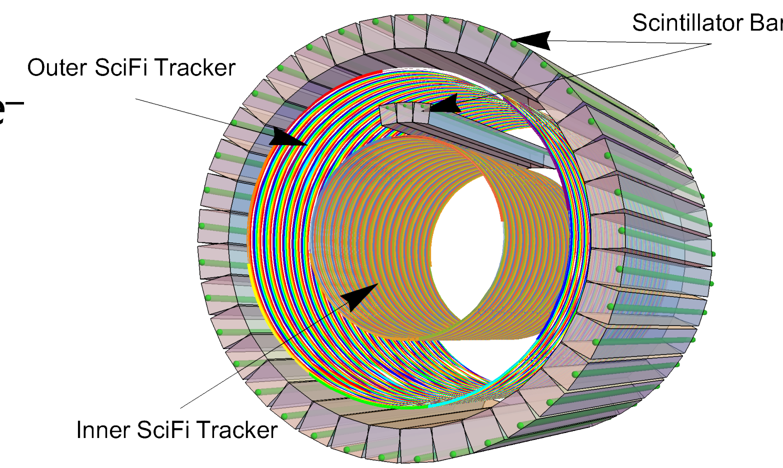
- well-known property of SFHe to coat surface of its container
- 45° section of cryostat reflects vertical M beam emerging from SFHe surface into the horizontal

Muonium Gravity Experiment

- Conceptual sketch:







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

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

where

C = 0.3 (est. contrast)

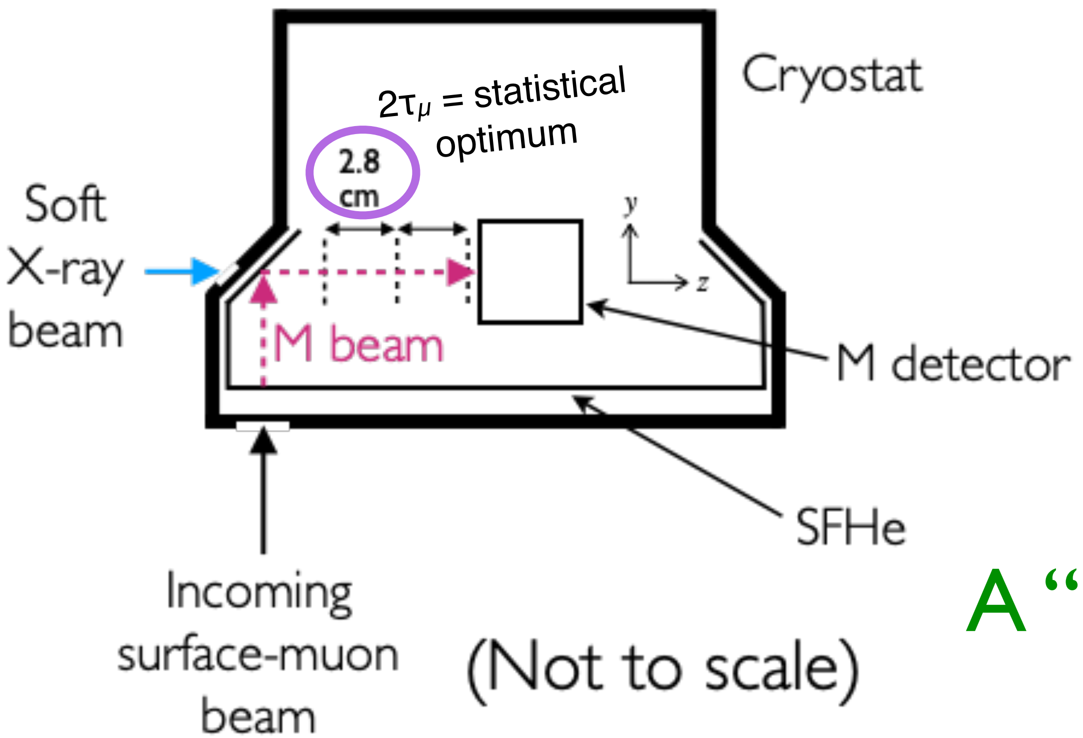
N_0 = # of events

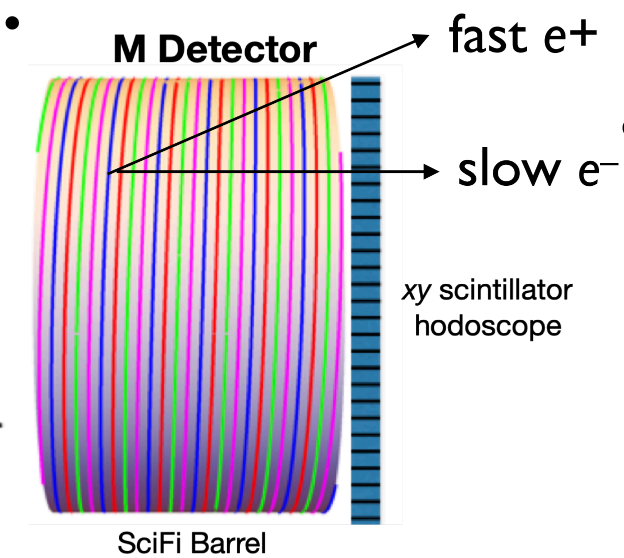
d = 100 nm (grating pitch)

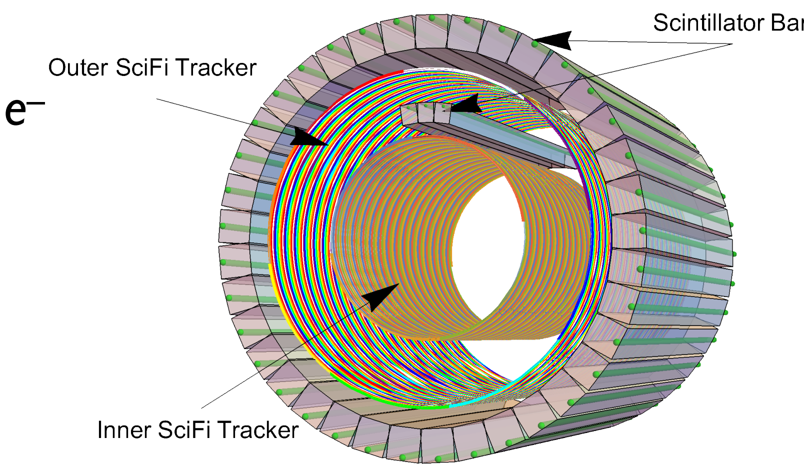
τ = inter-grating time

Muonium Gravity Experiment

- Conceptual sketch:







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where
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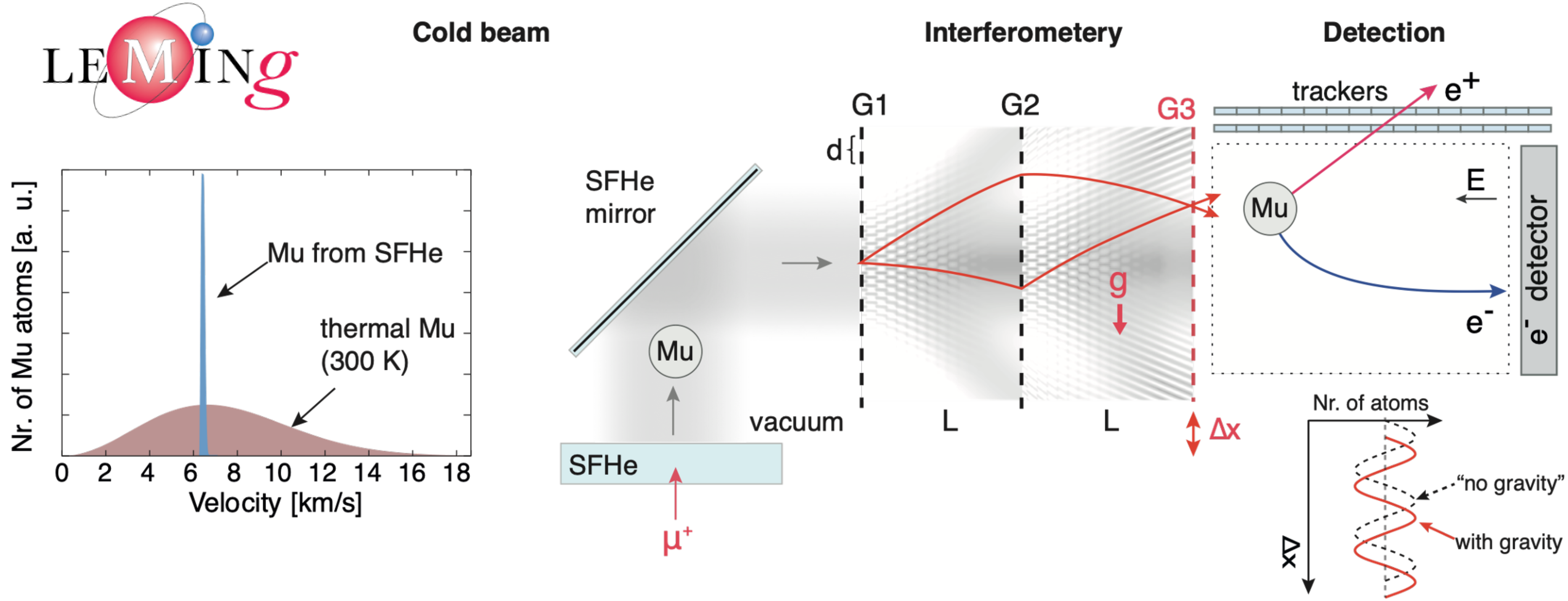
➡ Muonium Antimatter Gravity Experiment (MAGE)

The (friendly) "Competition"

The LEMING experiment at PSI, Switzerland



In R&D phase

- **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

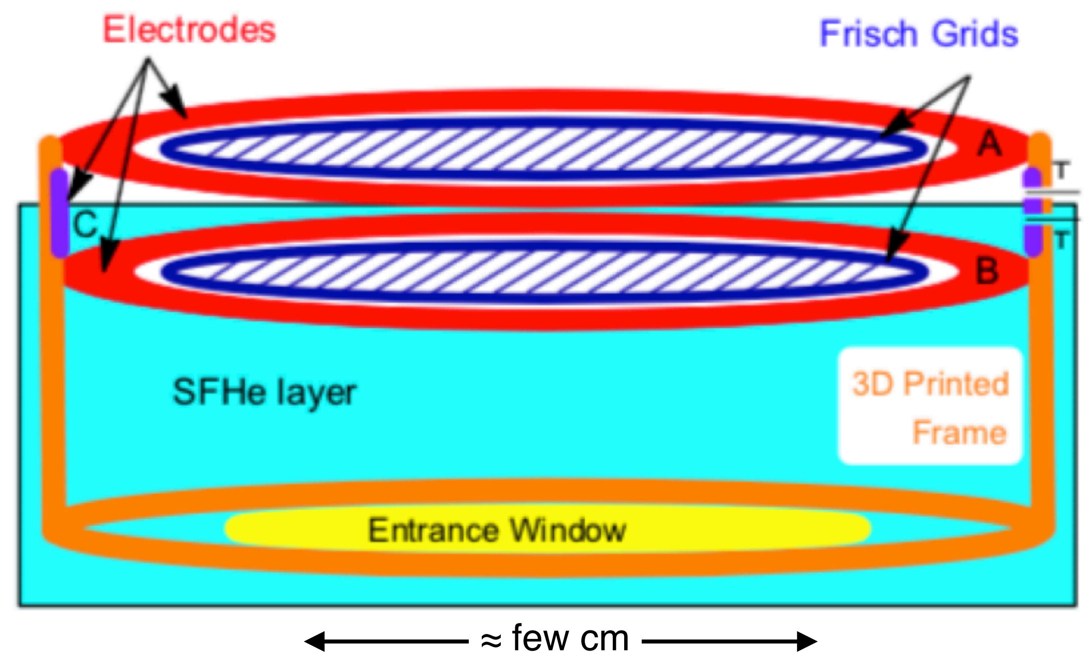
Anna Soter, ETH Zurich

Thick- vs. Thin-film SFHe

Thick-film:

- ≳ 100 μm SFHe layer
- surface e⁻ pool* creates *E* field:
  - drifts μ⁺ to surface, where M formed & expelled to vacuum

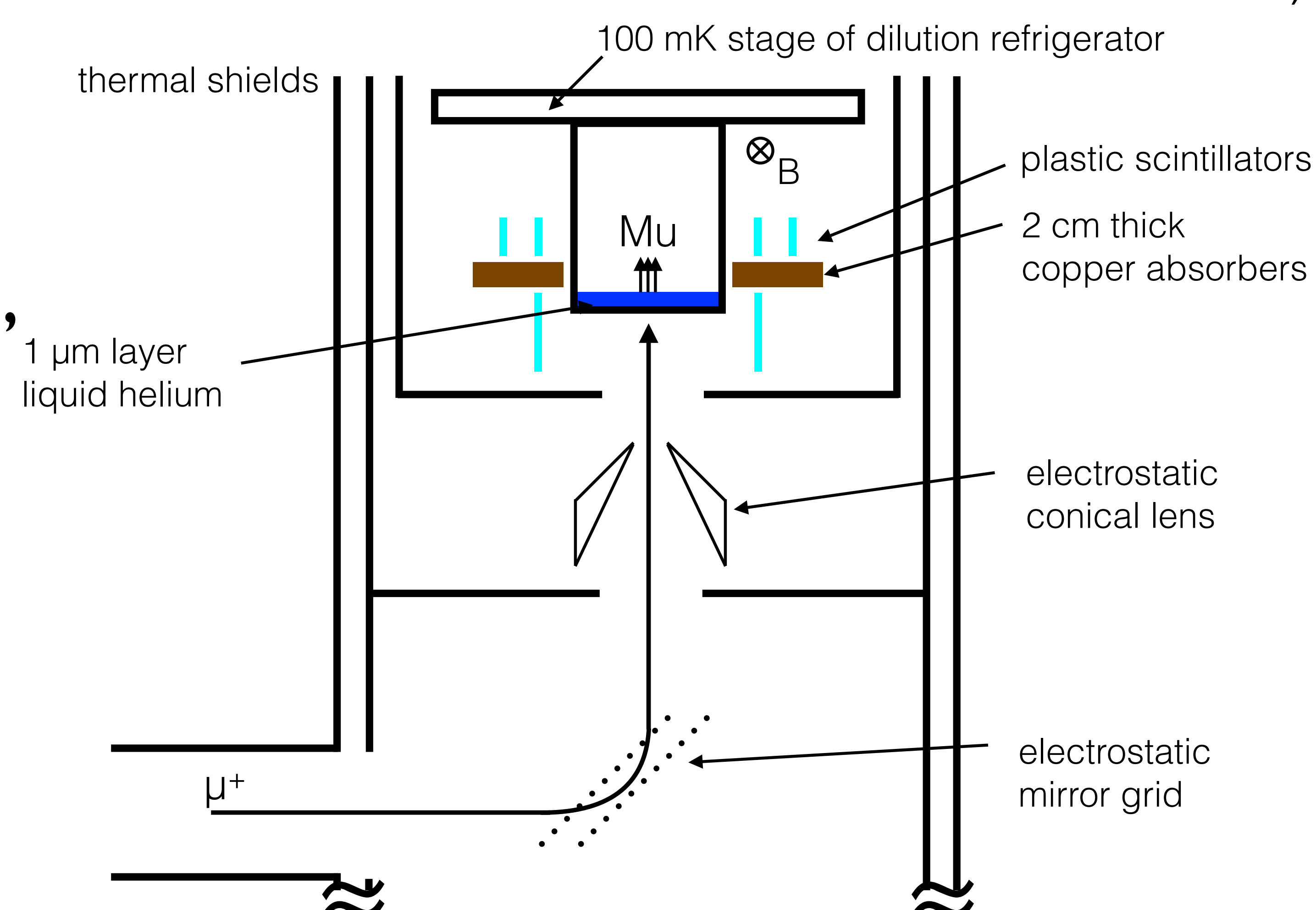
*under exploration at e.g. U of C as potential qbit system (D. I. Schuster *et al.*)



(R&D concept sketches)

Thin-film:

- Under development @ PSI
- ~ 1 μm SFHe layer, no drift field, requires tiny μ⁺ Δ*E*:
  - μ+ form M within SFHe & diffuse at random
  - ≈ 1/2 reach upper surface & expelled to vacuum



The Context: World Low-Energy 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: $p_\mu \approx 40\,\mathrm{MeV}/c$

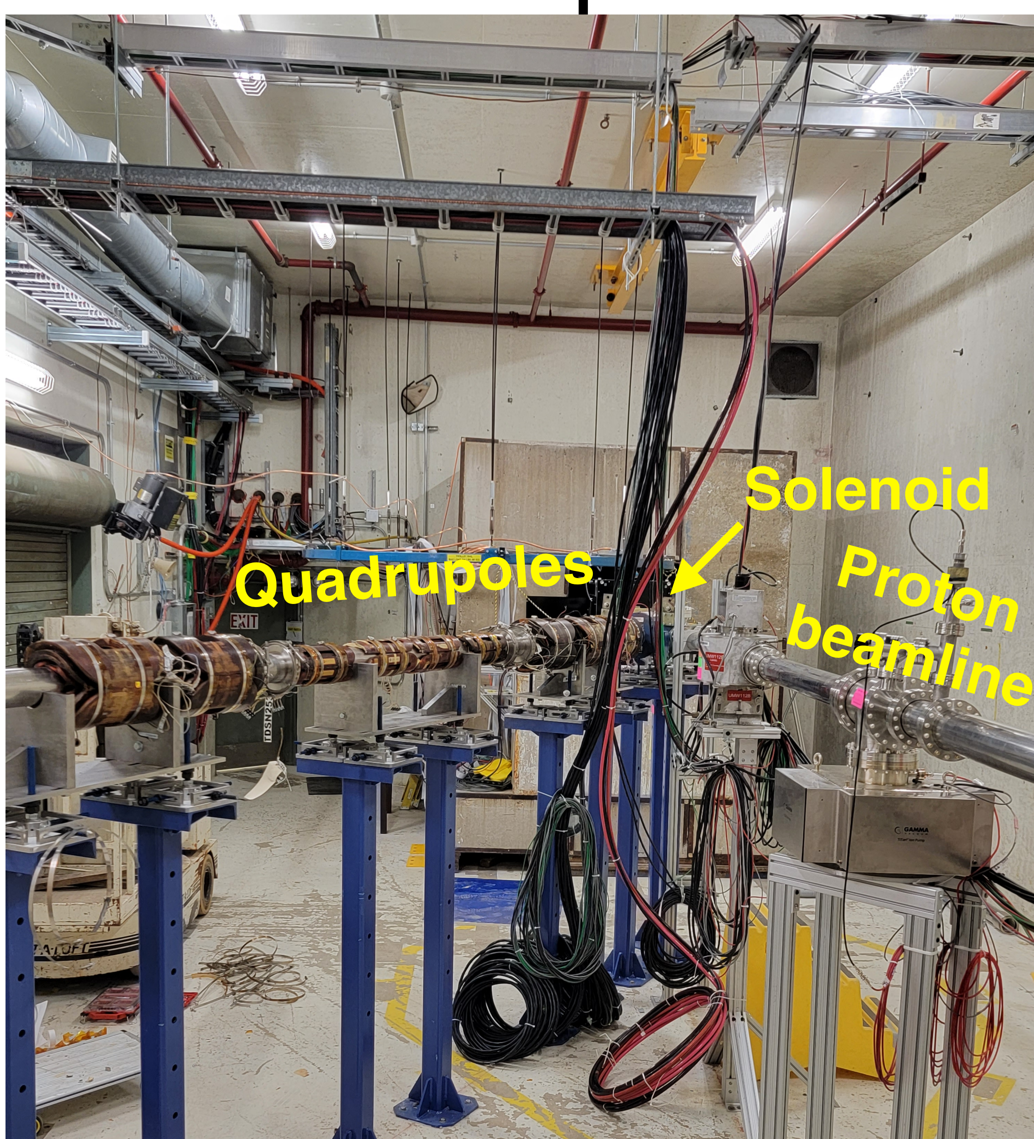
[R. H. Bernstein et al., "Letter of Interest for an Upgraded Low-Energy Muon Facility at Fermilab," SNOWMASS21-RF0-AF0-007]

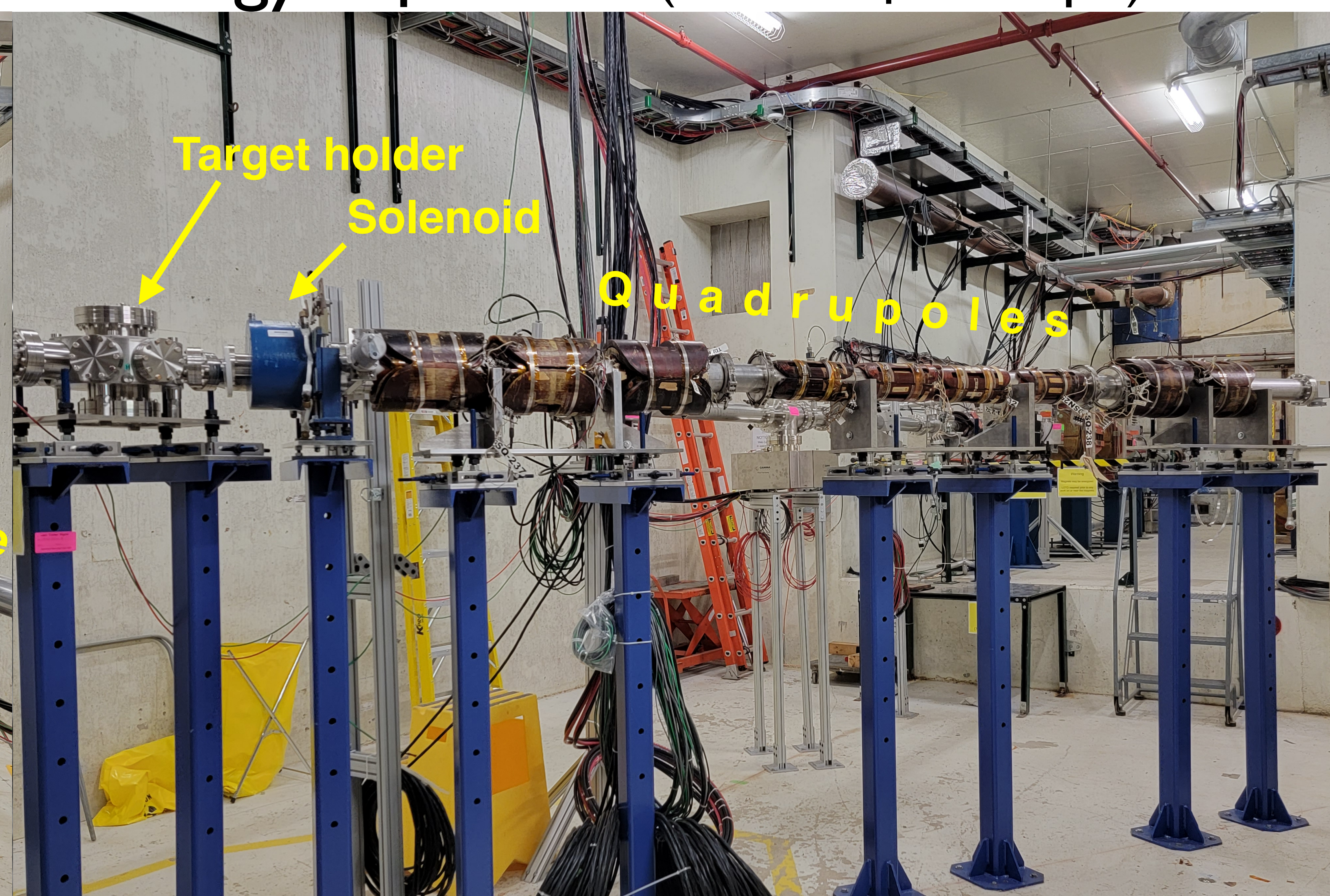
- Used for fundamental physics, μSR (MatSci, chemistry), μCF R&D…
- Oversubscribed, until now none in U.S.
- PSI: current world leader
  - x10 upgrade ("HIMB") in the works
- PIP-II could surpass HIMB (by ~ x10² ?)
- Is FNAL 400 MeV Linac potentially competitive with PSI??? …see below…
  - at minimum, invaluable R&D opportunity

Johnstone & Mazzacane talks

Fermilab “MuCool Test Area”

- Built ~20 years ago for muon collider R&D
  - served by 400 MeV H^- Linac
  - can be Linac major user – <10% (?) goes to Booster
- Now repurposed as Irradiation Test Area (ITA)
- Also provides low-energy π/μ beam (ARPE-E μCF expt.)

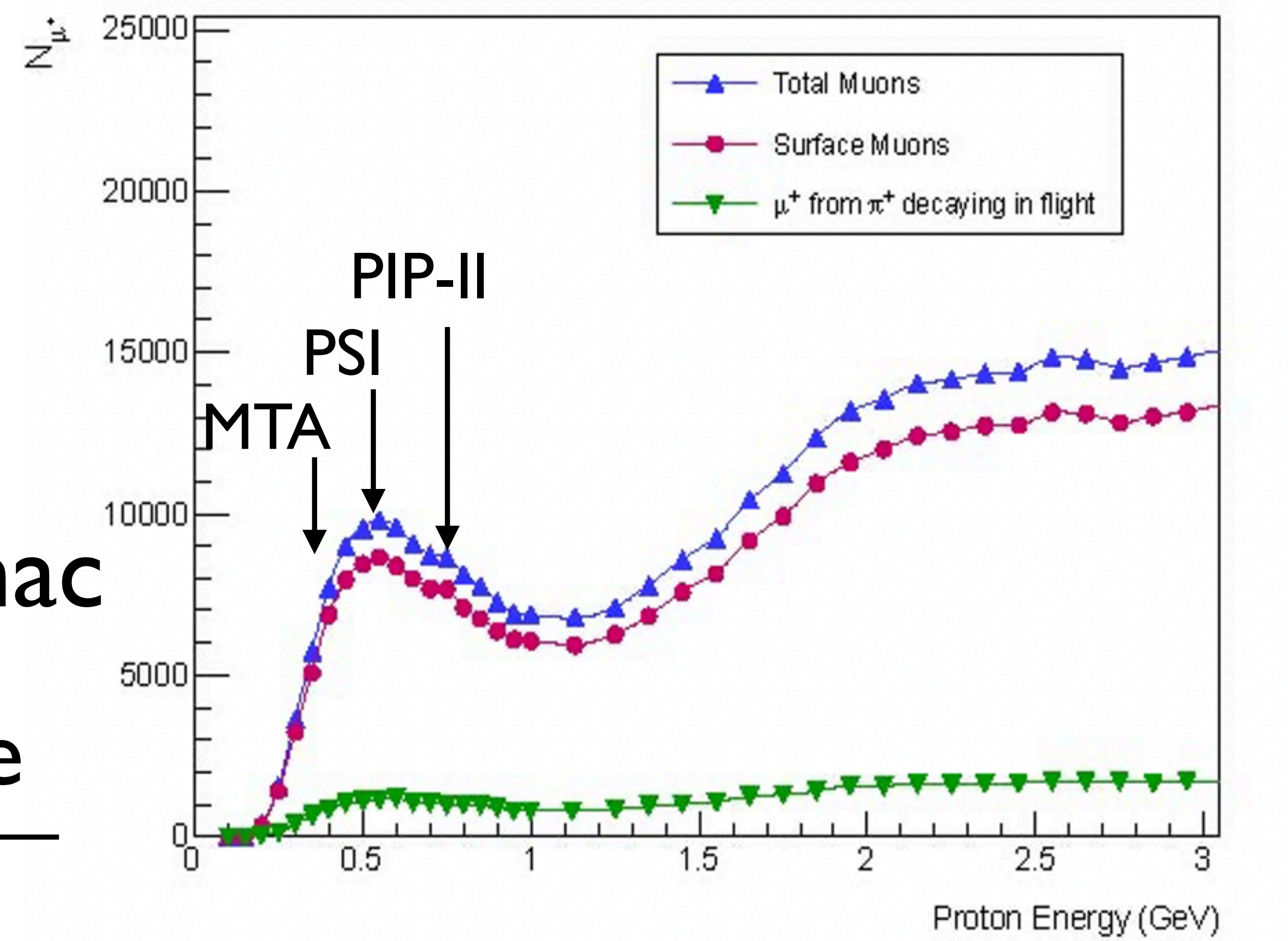




Fermilab vs. PSI

- **PSI**: 590 MeV sector-focused *p* cyclotron
- **MTA**: 400 MeV H^- linac
- **PIP-II**: 800 MeV SC H^- linac

~ a wash: <15% PSI advantage



Variation of μ^+ yield with incident proton energy for muons with momenta ≤ 30 MeV/c; i.e. surface muons

[A. Bungau, R. Cywinski, C. Bungau, PRSTAB **16**, 014701 (2013).]

- PSI makes surface muon beams "parasitically"
  - not to disrupt proton beam before spallation-*n* production target ⇒ thin, low-*Z* target (≈ 6–40 mm C)
  - MTA: can use thick, high-*Z* target, e.g., 3 cm W (÷ n_{slices})

Benefits of High-Z Target

- Ta (Z = 73) target increases π^+ (hence μ^+) yield by factor 2.9 over graphite
  - expect similar factor for W (Z = 74) since π^+ yield ~ $Z^{1/3}$
  - (per Geant) enhances backward production, obviating PSI 90° advantage

TABLE XII. Total cross sections for π^+ and π^-.

Element	σ^+	σ^-	Ratio
H	13.50±0.73	0.03±0.01	45
D	11.42±0.55	1.12±0.06	10.2
Be	27.30±1.40	6.49±0.37	4.3
C	35.00±1.80	6.64±0.41	5.3
Al	53.10±2.90	13.17±0.90	4.0
Ti	67.00±3.60	21.20±1.60	3.2
Cu	77.30±4.30	25.20±2.0	3.1
Ag	91.60±5.10	35.00±3.0	2.6
Ta	101.00±5.60	51.40±4.70	2.0
Pb	104.20±5.80	53.70±4.90	1.95
Th	107.90±5.90	60.40±5.50	1.9

[D.R.F. Cochran *et al.*, "Production of Charged Pions by 730-MeV Protons from Selected Nuclei," Phys. Rev. D **6**, 3085 (1972)]

Comparing MTA and PSI

- Relative rate estimates:

	PSI	MTA	MTA/PSI
Proton Beam Power (MW)	1.2	0.008*	0.0067
Target	40 mm C = 0.103 λ_I	30 mm W = 0.302 λ_I	2.9
$\sigma_{\pi+}$ (mb)	35	101†	2.9 × 0.85
μ^+ survival	≈ 0.001	1	1000
$\mu^+ \to$M conversion	≈ 0.5	≈ 0.1	0.2
Net			≈10(?)

≈ x200 SFHe thick-film advantage – needs R&D to confirm

- Further improvement possible (e.g., multiple target slices, optics & target optimization)
  - current simulations see ≈ 10^{-9} surface μ/POT
  - need full simulation study (in progress)

* Assumes MTA shielding allows full Linac intensity   † Using Ta as proxy for W due to lack of W data

PIP-II Potential

(via RF-separated beams)

- Assume optimistic PIP-II bunch rate to new low-energy muon (LEM) facility (yet to be designed):

	PSI	HIMB*	PIP-II	PIP-II/HIMB
Proton Beam Power (MW)	1.2	1.2	4	3.3
Bunch Intensity	CW	CW	1.9×10^{8}	—
Bunch Rate	CW	CW	162.5 MHz	—
Bunch Rate (LEM)	CW	CW	81.25 MHz	—
Target	40 mm C $= 0.103\ \lambda_I$	20 mm C (eff.), optimal slant	30 mm W $= 0.302\ \lambda_I$	2.9
$\sigma_{\pi+}$ (mb)	35	35	101†	2.9×0.85
μ^+ Capture	6%	26%	TBD‡	1‡
Transmission	7%	40%	TBD‡	1‡
μ^+ Rate (Hz)	5×10^{8}	1.3×10^{10}	$\approx3\times10^{11}$	$\gtrsim 20(?)$

needs R&D to confirm

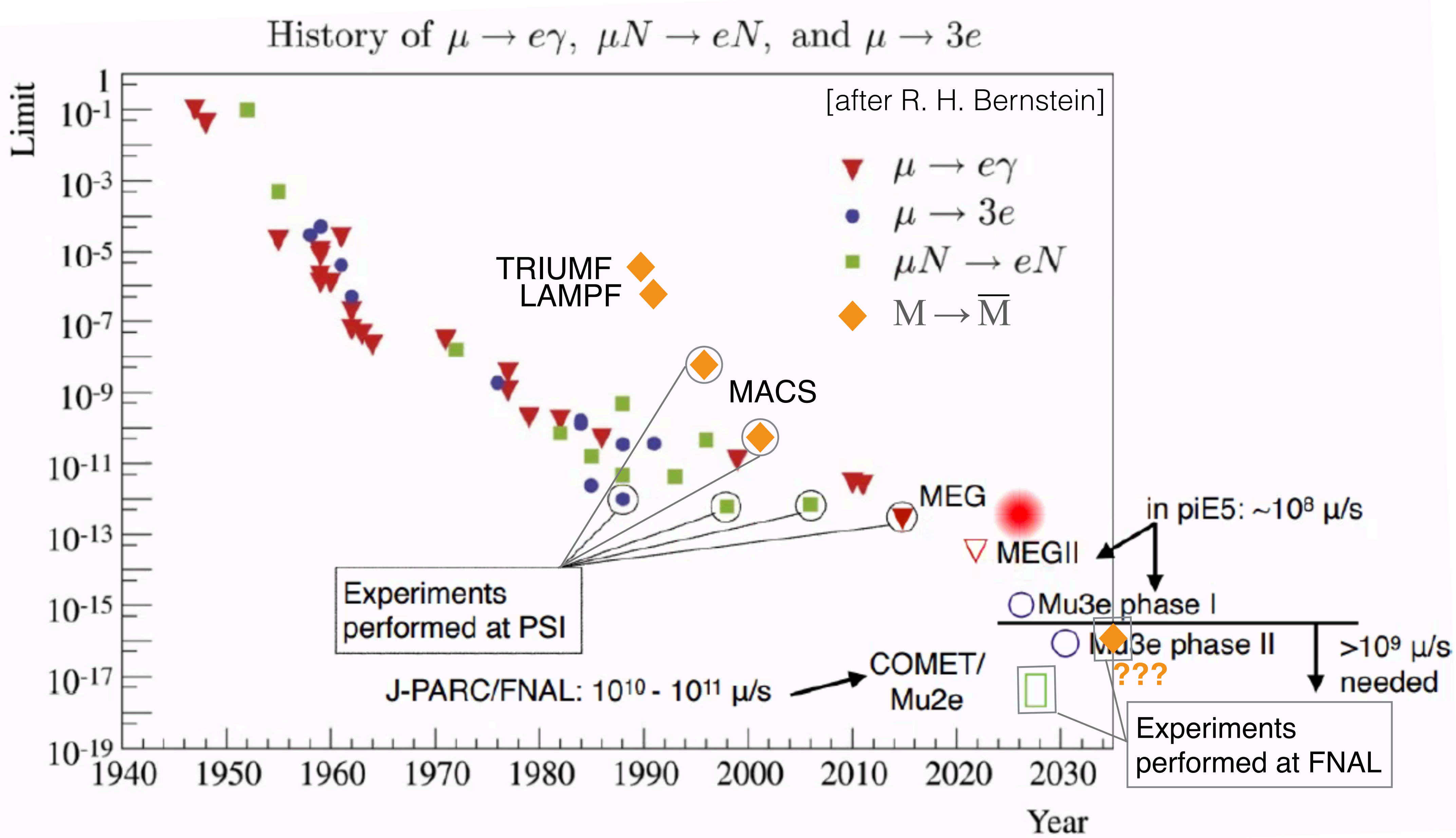
- additional ≈x200 if HIMB thin-film SFHe and PIP-II thick

* Design values [E. Valetov, FNAL APT Seminar, 9/8/22]

† Using Ta as proxy for W due to lack of W data

‡ Assume PIP-II design comparable to HIMB

PIP-II Muonium Potential



PIP-II Muonium Potential

- Is M-$\overline{\text{M}}$ sensitivity > order of magnitude worse than Mu2e sensitivity worth pursuing?

Brief R&D Goal Summary

- Determine and optimize MTA μ^+ yield
- Determine and optimize conditions to maintain drift field in SFHe (~10^8 e/cm^2)*
  - including electron-replenishment efficiency at high rate and resulting dead time (if any)
- Determine conditions to maximize M production in thick-film SFHe (requires dilution refrigerator)
- (If above results favorable) Assemble and install M interferometer and measure M gravity

* as done by e.g. C F Barenghi *et al.*, “Experiments on ions trapped below the surface of superfluid ^{4}He,” J. Phys. C: Solid State Phys. **19** (1986) 1135; http://stacks.iop.org/0022-3719/19/i=8/a=012

Resource Needs

- Modest, ≈ few-M$ program: beamline already installed; additional incremental work in MTA needs only "opportunistic" downtimes
- Concept and technical design study, dilution fridge and labor supported from external grants
  - Lab endorsement of R&D program a prerequisite for successful future grant proposals
- Will submit funding proposal in Feb.
  - Can potentially fund dilution fridge
- Without dilution fridge can start SFHe R&D using IIT equipment; BUT source of helium (on allocation) required
  - We request bench space @ Fermilab with modest helium supply
- Will submit R&D beam-time request to FTBF

Conclusions

- M→$\overline{\text{M}}$ & Mu2e complementary, *both are needed*
- M→$\overline{\text{M}}$, M spectroscopy: previous results >20 years old ⇒ good time for new efforts
- M gravity: never feasible before, new technique should make it feasible: *SFHe M production*
- 400 MeV Linac possibly competitive with PSI
- R&D needed to establish feasibility & physics reach
- PIP-II could enable *world-leading* M & LE μ studies

➡ **MTA:** ^cost-effective^ **opportunity** to initiate world-leading Fermilab muonium program!

... while 400 MeV Linac still operational

Would also enable μSR at MTA

Examples of models possibly favoring $M \rightarrow \bar{M}$

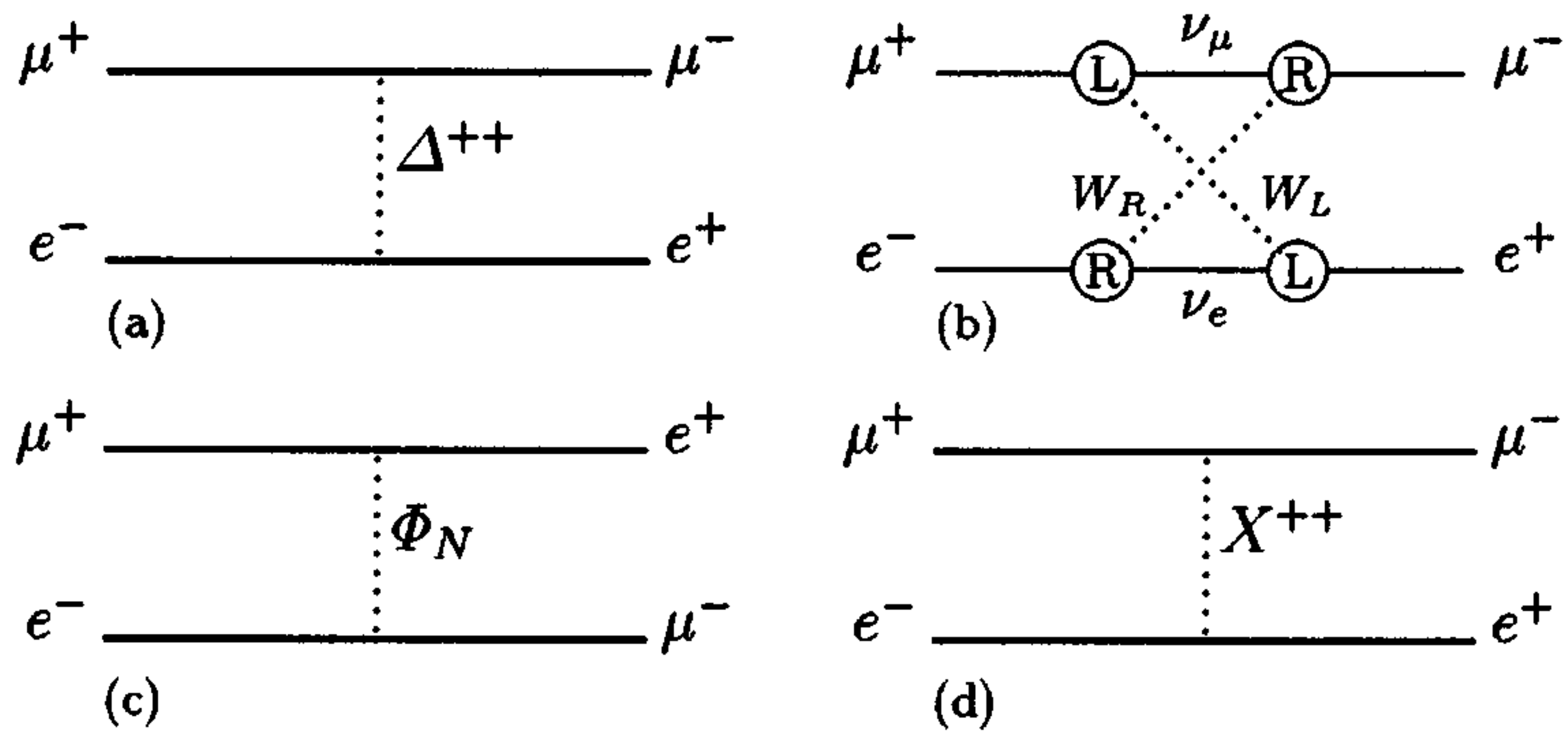


FIG. 1. Muonium-antimuonium conversion in theories beyond the standard model. The interaction could be mediated, e.g., by (a) doubly charged Higgs boson Δ^{++} [3,4], (b) heavy Majorana neutrinos [3], (c) a neutral scalar Φ_N [5], e.g., a supersymmetric τ-sneutrino $\tilde{\nu}_\tau$ [6,7], or (d) a bileptonic flavor diagonal gauge boson X^{++} [8,9].

[L. Willmann et al., “New Bounds from a Search for Muonium to Antimuonium Conversion,” PRL **82** (1999) 49]

"Antigravity"

- What if matter and antimatter repel gravitationally?

  → universe with separated matter and antimatter regions (& makes gravitational dipoles possible)

  - BAU is local, not global ⇒ no need for new sources of CPV

    [A. Benoit-Lévy and G. Chardin, "Introducing the Dirac-Milne universe," Astron. & Astrophys. 537 (2012) A78]

  - repulsion changes expansion rate of universe

    - possible explanation for apparent acceleration – without dark energy

      [D. Hajdukovic, "Quantum vacuum and virtual gravitational dipoles: the solution to the dark energy problem?," Astrophys. Space Sci. 339 (2012) 1]

    - all regions of universe causally connected & older than oldest stars

      [A. Benoit-Lévy and G. Chardin, *ibid.*]

  - virtual gravitational dipoles modify gravity at long distances

    - possible explanation for rotation curves – without dark matter

      [L. Blanchet, "Gravitational polarization and the phenomenology of MOND," Class. Quant. Grav. 24, 3529 (2007);
      L. Blanchet and A.L. Tiec, "Model of dark matter and dark energy based on gravitational polarization," PRD 78, 024031 (2008)]

(from Beam Instrumentation Group): Lab interest in MTA W target

Radiation Testing for PIP-II Beam Instrumentation

Understanding response and survival of various beam instrumentation components in a radiation environment is a challenge for PIP-II. The radiation test area at the end of Fermilab linac is an ideal location to study radiation effect.

- Linac beam energy of 400 MeV is similar to PIP-II linac

Potential areas of study include:

- Testing of PIP-II neutron detectors
- Testing electronics for radiation damage
- Interest from vendors to test radiation hardened electronics
- Testing of radiation damage to optical components needed for PIP-II laser wire profile monitor

Thick-Film SFHe Method

Stop μ^+ in bulk SFHe
Drift to surface with E field before forming Mu
Form Mu with surface e^-

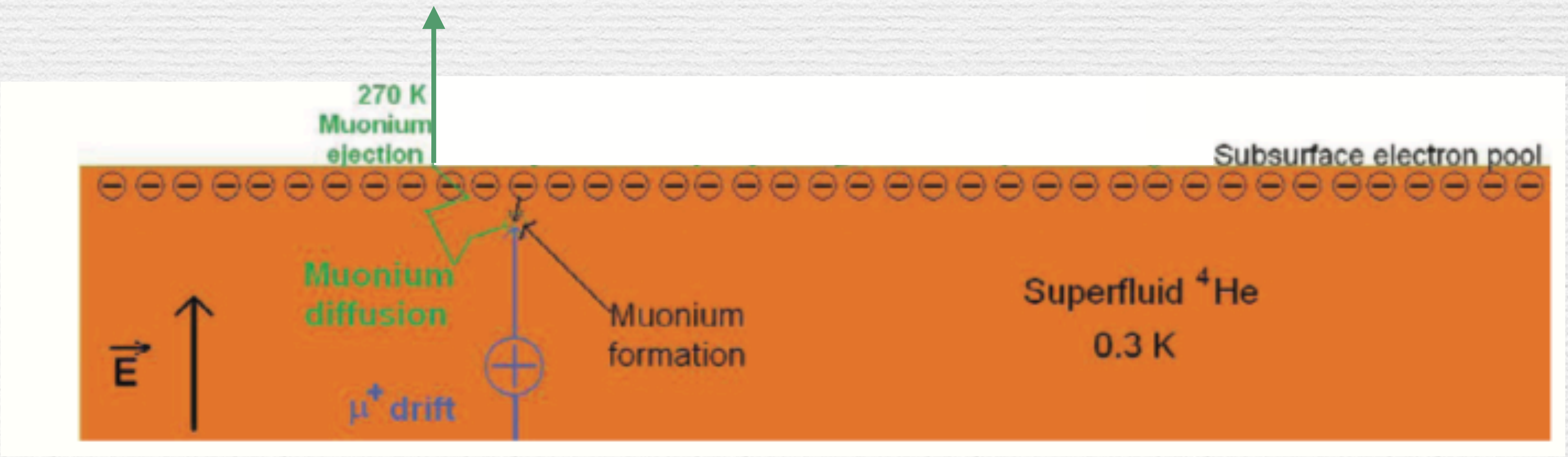
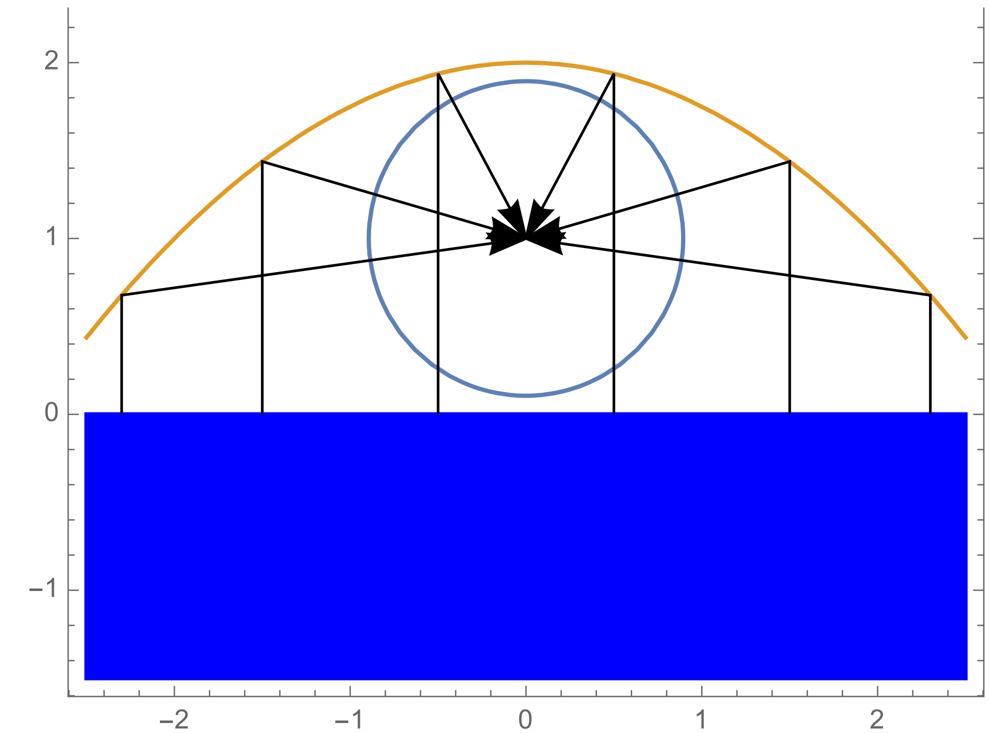


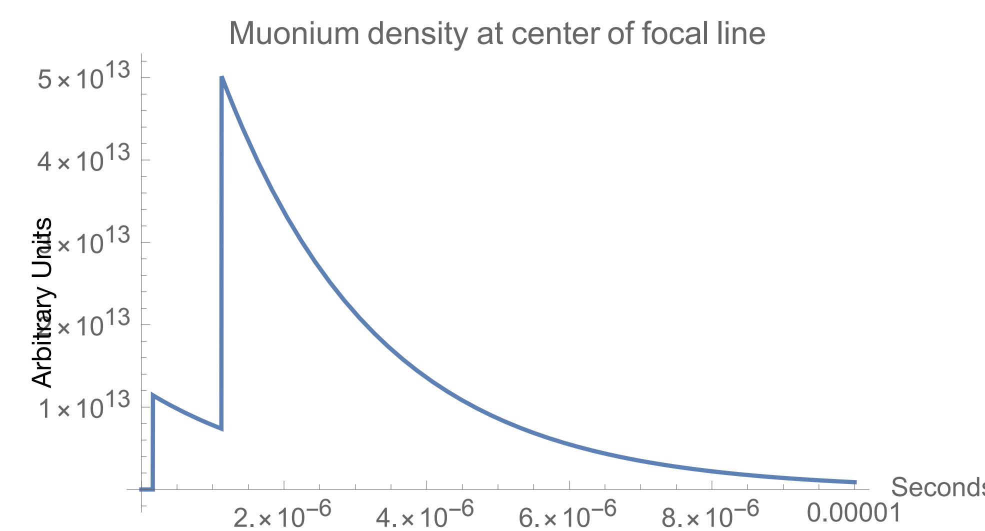
Figure after *D. Taqqu / Physics Procedia 17 (2011) 216-223*

Making Cold μ⁺ from M

- Putting 2D parabolic mirror above SFHe concentrates M beam along a line
- Laser-ionize M to produce 0.5K μ⁺
- Engineering challenge: extract cold μ⁺ from cryostat



- Simulation at right shows intensity vs time following incident μ⁺ pulse
- Mirror increases M density ≈ 5X (dep. on beam size & concentrator height)



Could PSI Adopt Thick-Film SFHe Approach?

- Yes, but they're committed to muCool beam for multiple cold-muon applications
- And in practice, difficult and time-consuming switch
  - we proposed it to them, deemed impractical because:
    - their group too small to pursue multiple approaches in ||
    - muCool → very different apparatus optimization: much lower energy & thinner, smaller-diameter cryostat windows

  ⇒ would need additional dilution fridge to pursue both

Muonium Gravity Experiment

- Important feasibility questions:

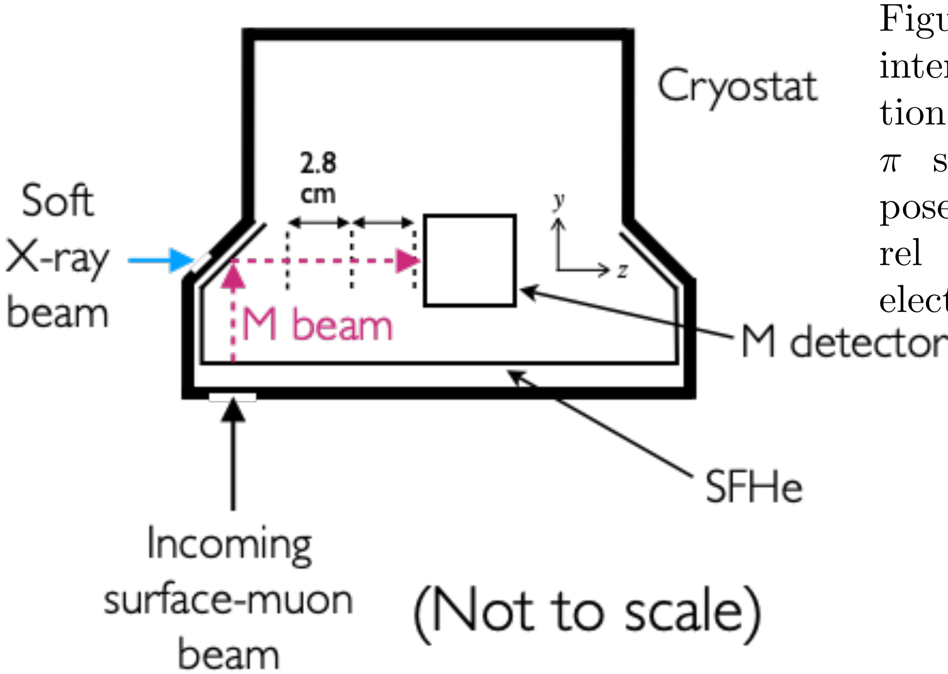
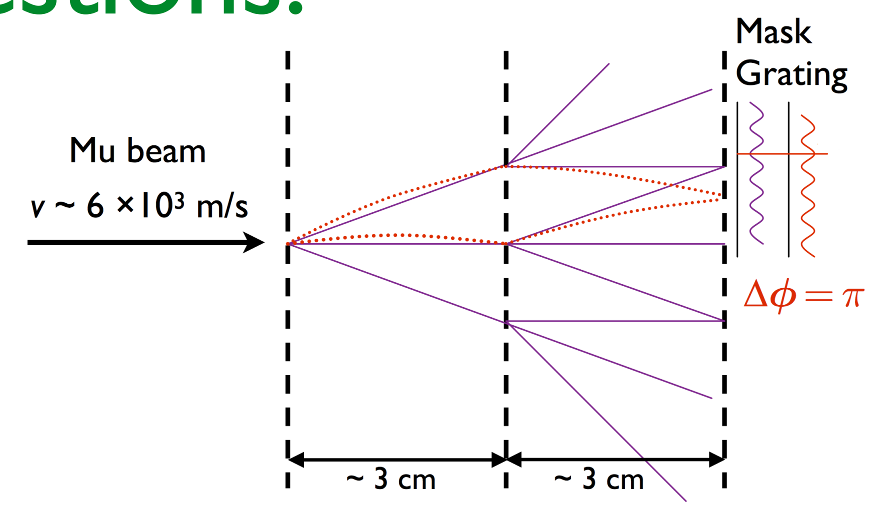
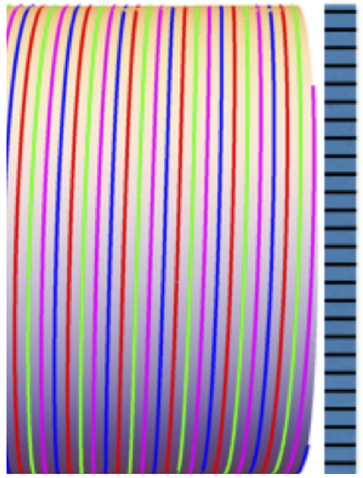


Figure 1: Principle of muonium interferometer, shown in elevation view (phase difference $\Delta\phi = \pi$ shown for illustrative purposes); Mu-decay detectors (barrel SciFi positron tracker and electron MCP) shown at right.





1. Can sufficiently precise diffraction gratings be fabricated?
2. Can interferometer and detector be aligned to a few pm and stabilized against vibration?
3. Can interferometer and detector be operated at cryogenic temperature?
4. How determine zero-degree line?
5. Does Taqqu's scheme work?

Answering the Questions:

1. Can sufficiently precise diffraction gratings be fabricated?
   - our collaborator, Derrick Mancini (a founder of ANL Center for Nanoscale Materials, CNM), thinks so; CNM boasts sub-nm precision – simulation study in progress
2. Can interferometer be aligned, and stabilized against vibration, to several pm?
   - needs R&D, but LIGO & TFG do much better than we need
   - our NASA space-telescope TFG R&D ⇒ sufficient performance

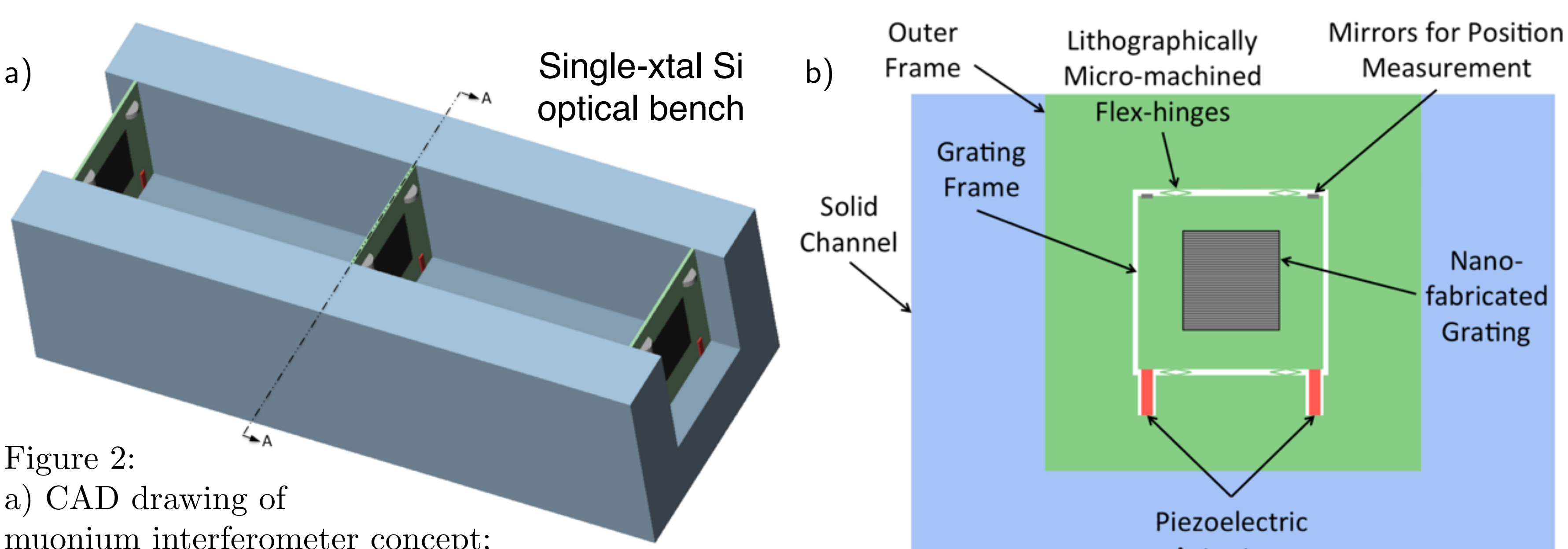


Figure 2:
a) CAD drawing of muonium interferometer concept;
b) Section A-A. In blue-gray is grating support structure: a U-channel machined out of a single-crystal silicon block. Each grating is mounted in a silicon frame connected to an outer frame by flex-hinges; piezo-actuator pair permits small rotations to align the gratings precisely in parallel, as well as scanning of grating 3. Grating frames have mirrors or corner-cube retroflectors at top corners that form part of the laser distance gauges (TFGs) used to measure their position.

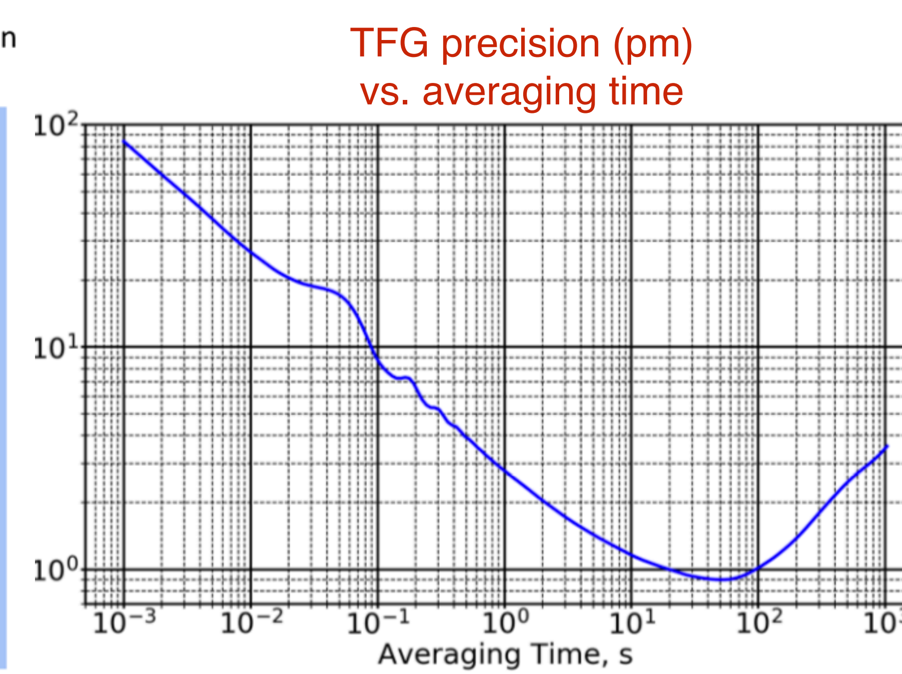


Figure 3. Allan deviation indicating TFG incremental-distance precision vs averaging time.

From Kaplan, D.M.; Roberts, T.J.; Phillips, J.D.; Reasenberg, R.D. Improved performance of semiconductor laser tracking frequency gauge. *J. Instrum.* **2018**, *13*, P03008.

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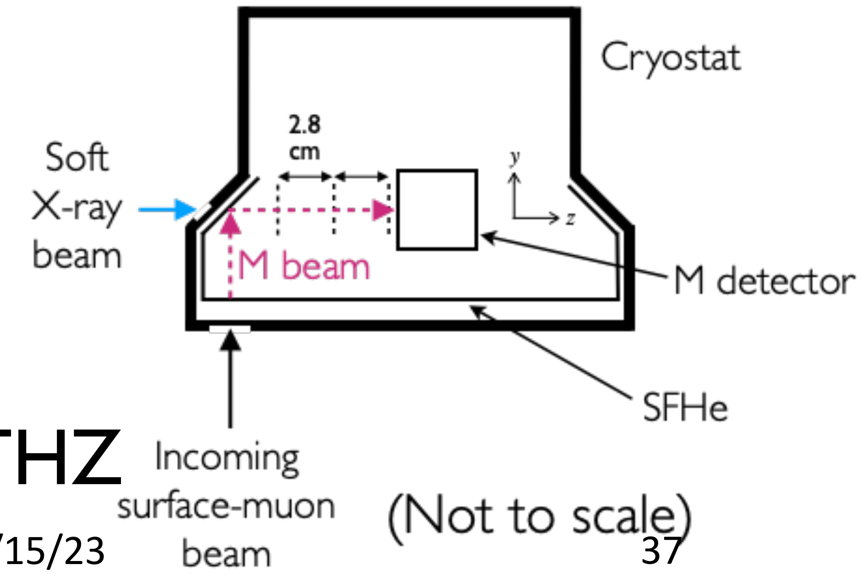
2. Can interferometer be aligned, and stabilized against vibration, to several pm?
   - needs R&D, but LIGO & TFG do much better than we need
   - our NASA space-telescope TFG R&D ⇒ sufficient performance
3. Can interferometer and detector be operated at cryogenic temperature?
   - needs R&D; at least piezos OK; material properties favorable
4. How determine zero-degree phase?
   - use cotemporal soft X-ray beam
5. Does Taqqu's scheme work?
   - needs R&D; we're working on it with PSI & ETHZ



(Not to scale)